WHAT CMS UNCOVERED ABOUT THE BOSON

A. David (CERN) *for the CMS Collaboration*

17’600 hours ago in a conference
17’000 km away…

STAR HIGGS

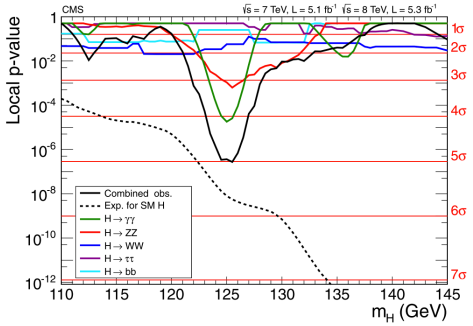
Episode 2012
A NEW PARTICLE

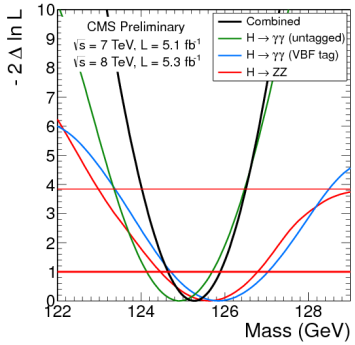
a.david@cern.ch @CMSexperiment @ICHEP2014

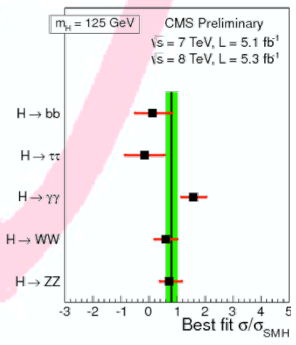
“Higgsdependence” day recap

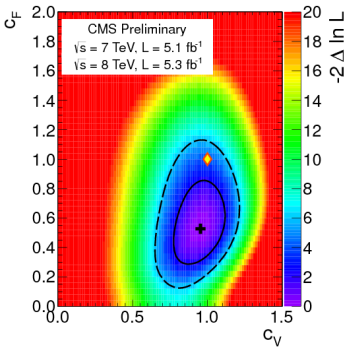
[http://cern.ch/go/q8jx]

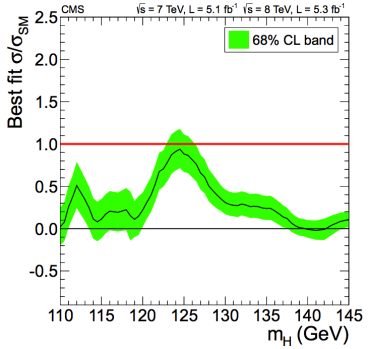
- **5σ significance.**
  - Just under the SM expectation:
    $\mu = \sigma/\sigma_{SM} = 0.80 \pm 0.20$ (at 125 GeV).
  - $m_X = 125.3 \pm 0.6$ GeV.
  - “Proto-couplings” compatible with SM.
- ***“More data needed…”***







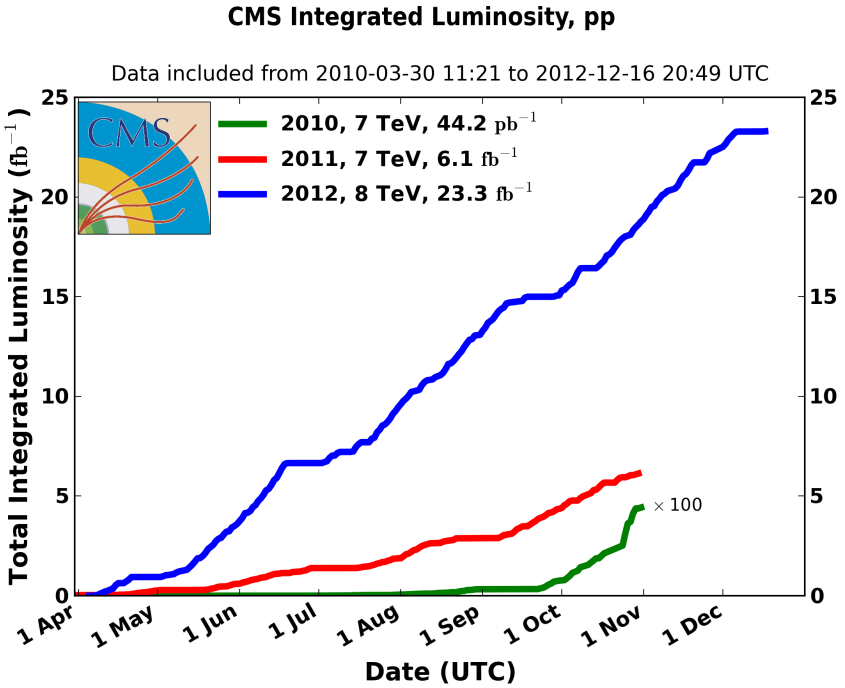




The LHC Run 1: a bountiful harvest

[http://cern.ch/go/K8Tj] [http://cern.ch/go/ZW9S]

- LHC delivered ~30 fb^{-1}.
- **Challenge:** precision physics with ~20 simultaneous proton-proton collisions.



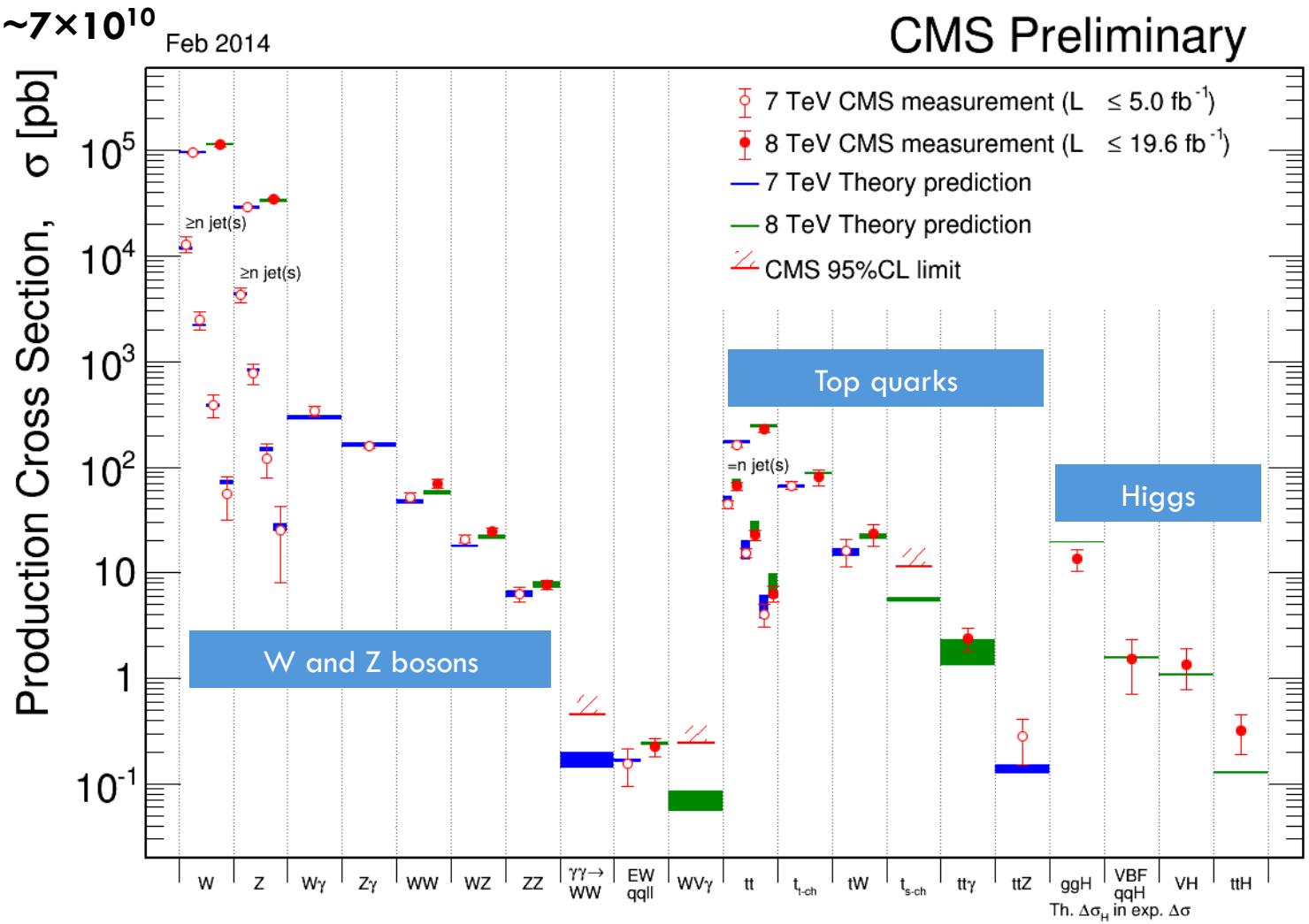
Event with 78 reconstructed vertices over some 10 cm.

On the shoulders of giants: detector makers & theory calculators

"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi [http://cern.ch/go/lf9C] [http://cern.ch/go/KD8D]

Inelastic collisions: ~7×10¹⁰

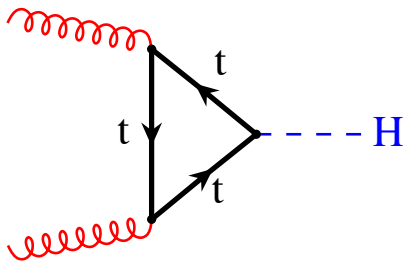
Six orders of magnitude of EWK, top, and Higgs Physics



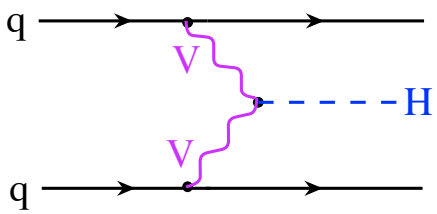
How SM Higgses come to be

[http://cern.ch/go/cWH8] [http://cern.ch/go/SnJ8]

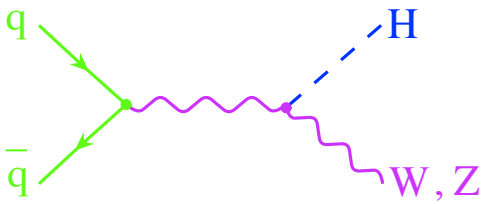
- **Gluon fusion**



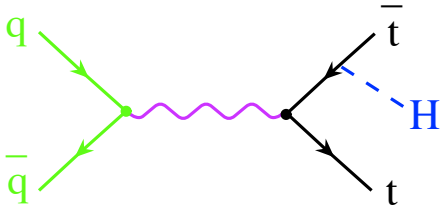
- **VBF**

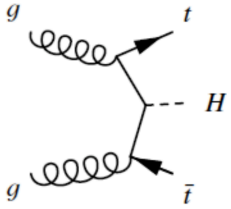


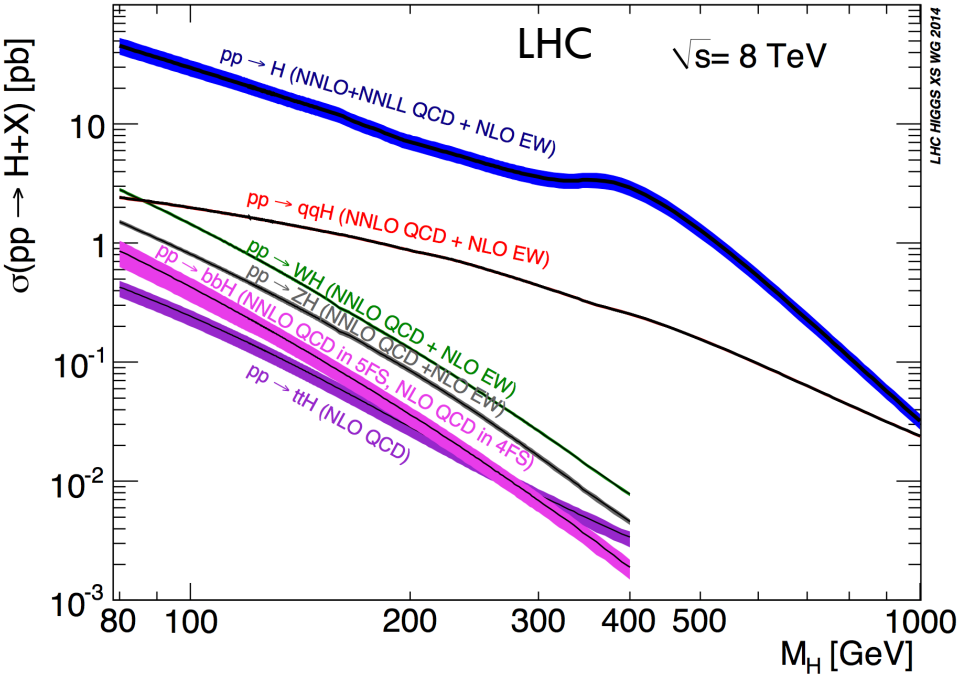
- **WH, ZH**



- **bbH, ttH**



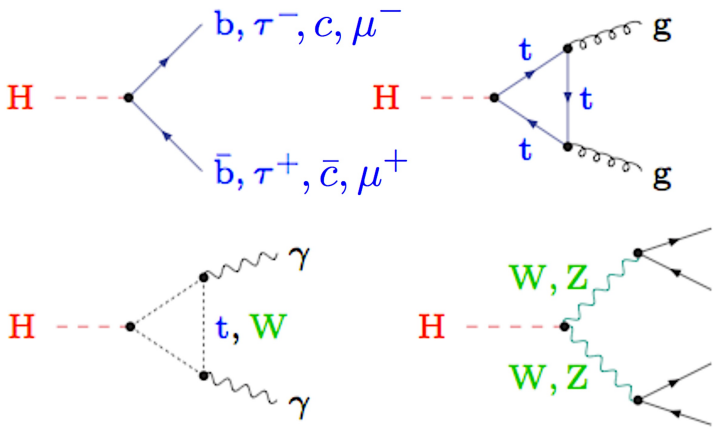


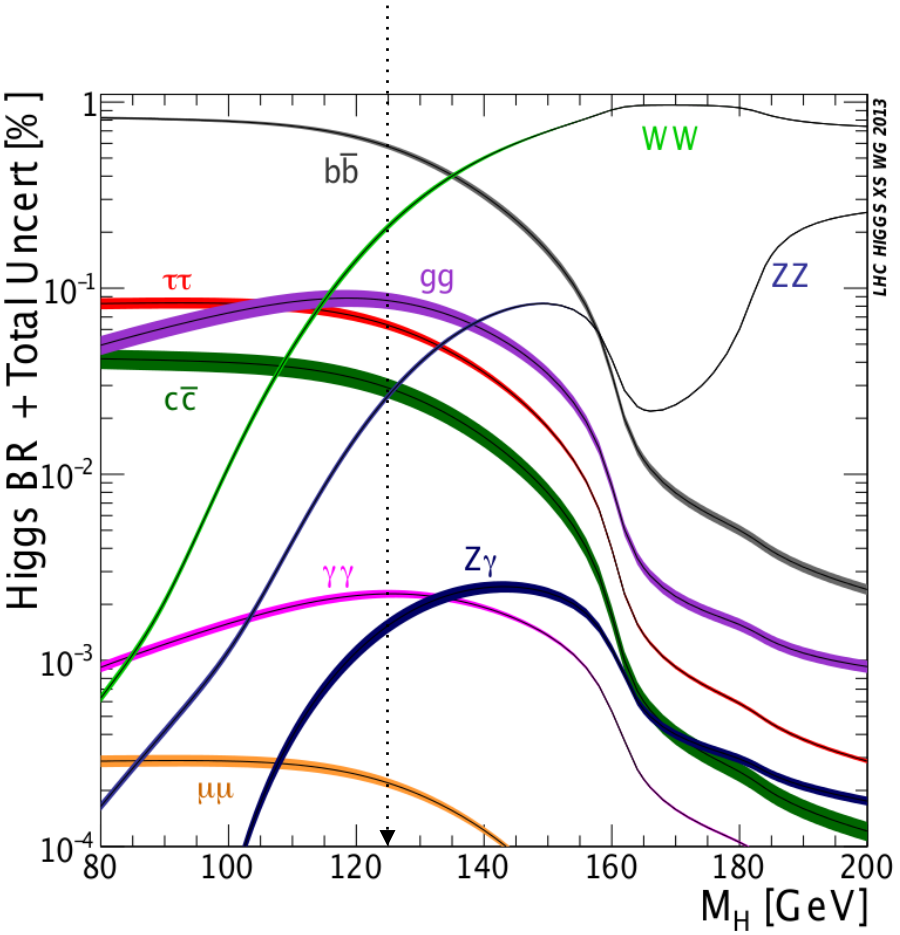


How SM Higgses pass away

[http://cern.ch/go/qkh6]

- Couplings and kinematics drive BR ($b\bar{b}$, WW, ττ, ZZ).
  - Decays to photons (γγ, Zγ) through loops.





CMS Higgs @ICHEP2014

[http://cern.ch/go/Rqt8]

15 talks

- **A. Vartak** – $H \to ZZ \to 4\ell$
- **L. Quertenmont** – Off-shell production
- **M. Kenzie** – $H \to \gamma\gamma$
- **M. Sani** – Mass measurements
- **L. Bianchini** – Top-Higgs production

- **P. Govoni** – $H \to WW$
- **C. Vernieri** – VH, $H \to b\bar{b}$
- **J. Steggemann** – Signatures with leptons
- **C. Veelken** – (N)MSSM searches
- **D. Trocino** – Invisible Higgs searches
- **M. Chen** – Combination of measurements
- **E. Di Marco** – J^P from decays to bosons

- **O. Bondu** – Searches with two Higgs
- **O. Gonzalez Lopez** – High-mass searches
- **S. Zenz** – Upgrades

4 posters

- **S. Mukherjee** – $H \to \gamma\gamma$ differential prospects
- **S. Malhotra** – Combination of measurements
- **C.-P. Chang** – $Z^{(*)}\gamma$ searches
- **S. Fink** – tH, $Hb\bar{b}$ prospects

Oversimplified big picture

★ "seen" ☆ "tried"	$H\to b\bar{b}$	$H\to\tau\tau$	$H\to WW$	$H\to ZZ$	$H\to\gamma\gamma$	$H\to Z^{(*)}\gamma$	$H\to$inv.	$H\to\mu\mu$	$H\to c\bar{c}$ $H\to HH$
ggH		★	★	★	★	☆		☆	
VBF	☆	★	★	☆	★	☆	☆	☆	
VH	★	☆	☆	☆	☆		☆		
ttH	☆	☆	☆		☆				

- **Still much to explore on the rarer ends.**
  (to the right and to the bottom) (and outside this picture)

STAR HIGGS

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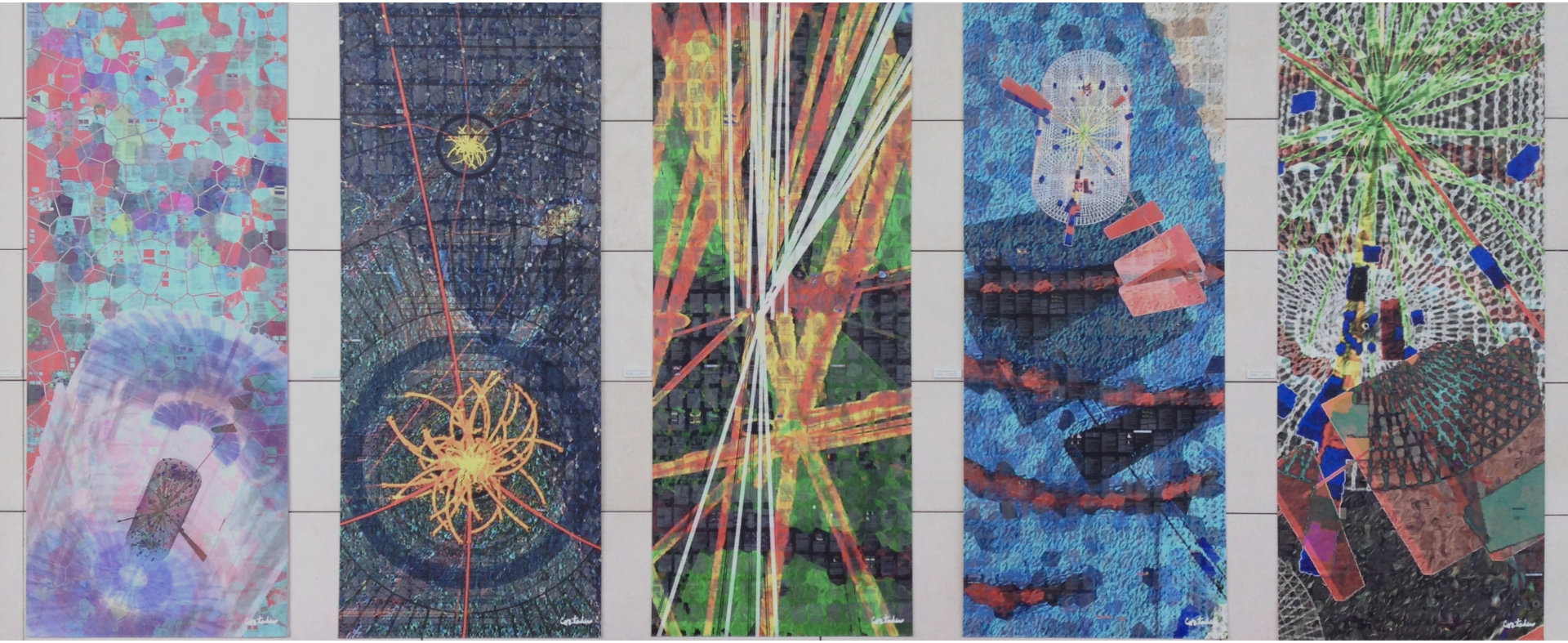
Episode 2014

THE SM HIGGS STRIKES BACK

a.david@cern.ch @CMSexperiment @ICHEP2014

All out & just outside in the foyer



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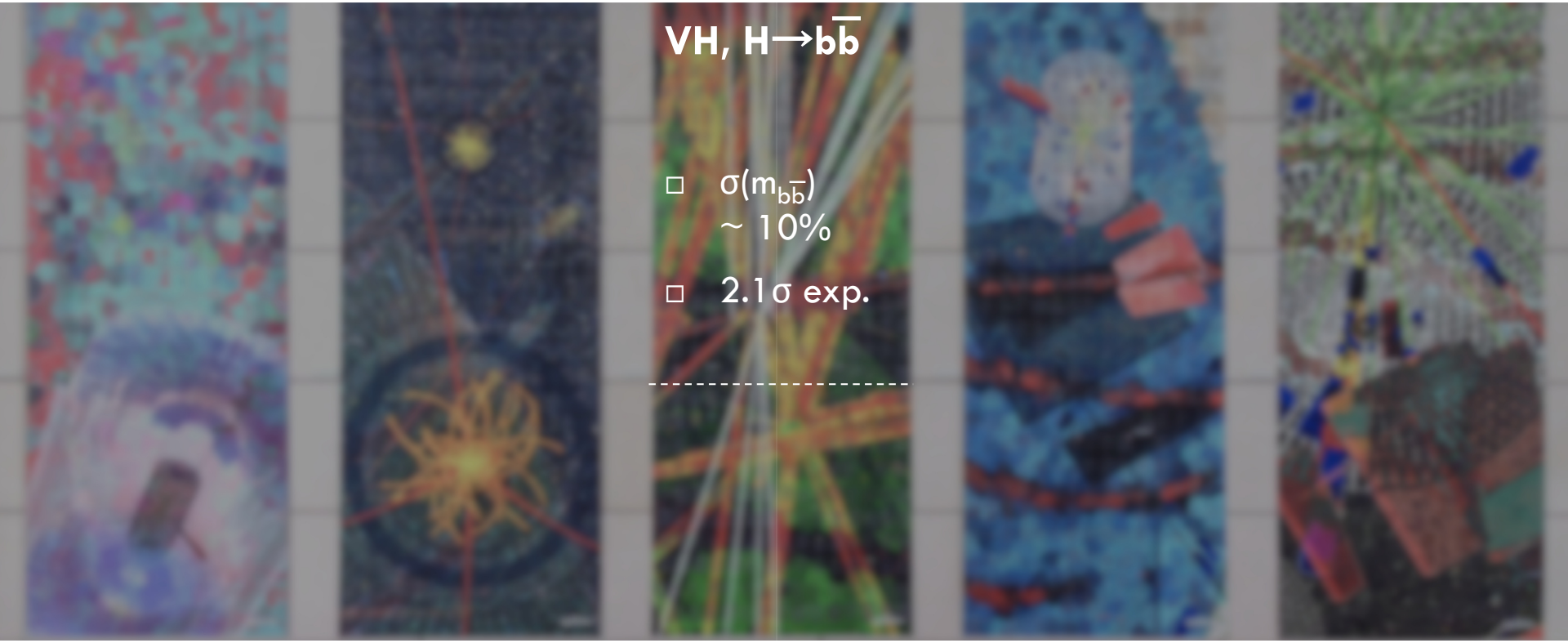

VH, H→$b\bar{b}$

- $\sigma(m_{b\bar{b}})$ ~ 10%
- 2.1σ exp.

PRD 89 (2014) 012003

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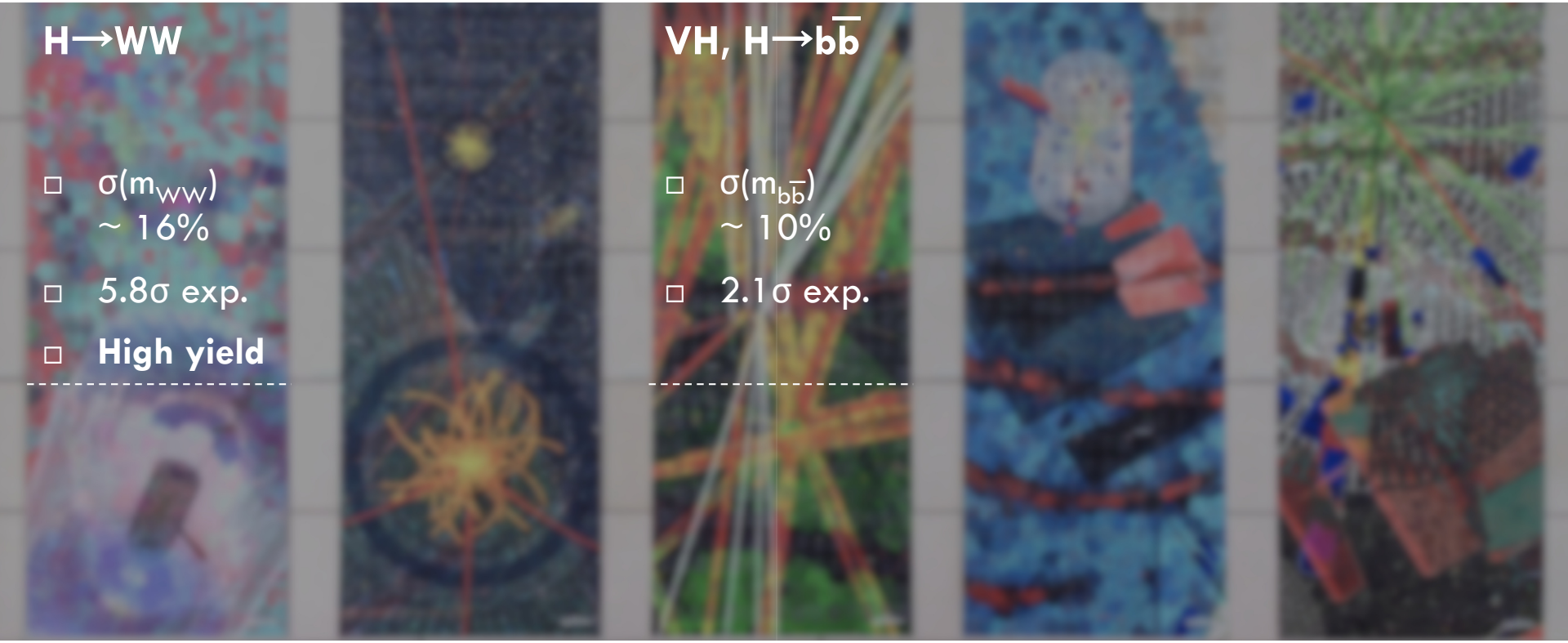

H→WW

- $\sigma(m_{WW})$ ~ 16%
- 5.8σ exp.
- **High yield**

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JHEP 01 (2014) 096

PRD 89 (2014) 012003

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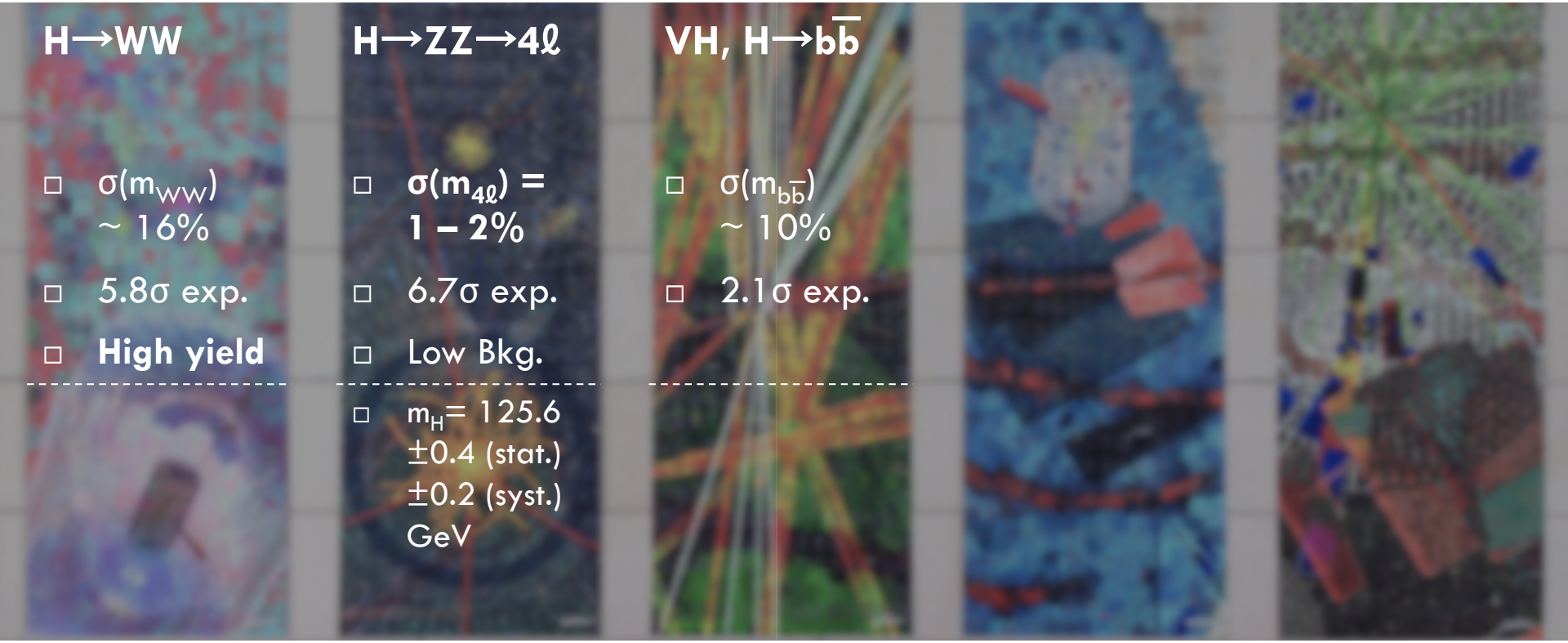

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H→ZZ→4ℓ

- **$\sigma(m_{4\ell})$ = 1 – 2%**
- 6.7σ exp.
- Low Bkg.
- m_H= 125.6 ±0.4 (stat.) ±0.2 (syst.) GeV

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PRD 89 (2014) 092007

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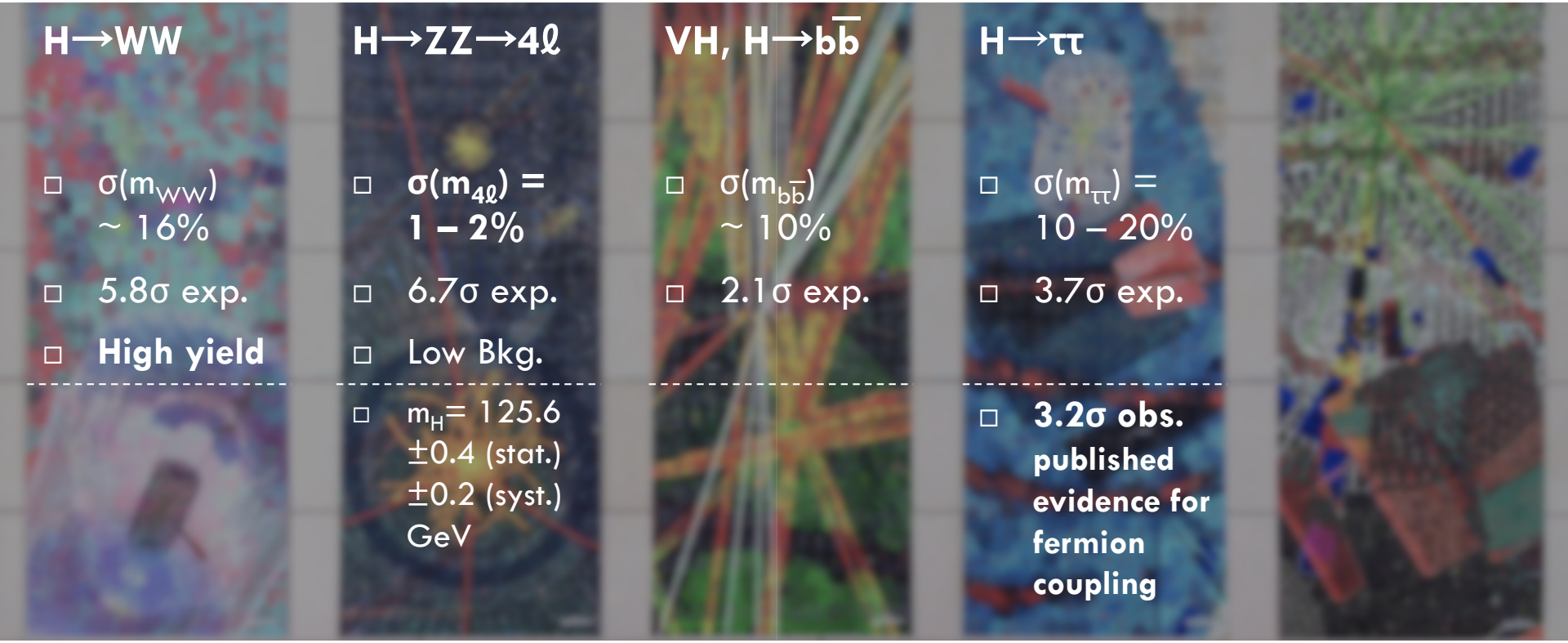

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PRD 89 (2014) 012003

H→ττ

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- **3.2σ obs. published evidence for fermion coupling**

JHEP 05 (2014) 104

All out & just outside in the foyer

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JHEP 05 (2014) 104

Fermion decay combination
3.8σ obs. (4.4σ exp.)
Nature Physics, doi:10.1038/nphys3005

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PRD 89 (2014) 092007

Off-shell production
arXiv:1405.3455
(accepted by PLB)

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JHEP 05 (2014) 104

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All out & just outside in the foyer

$H \to WW$	$H \to ZZ \to 4\ell$	$VH, H \to b\bar{b}$	$H \to \tau\tau$	$H \to \gamma\gamma$
□ $\sigma(m_{WW})$ ~ 16%	□ **$\sigma(m_{4\ell})$ = 1 – 2%**	□ $\sigma(m_{b\bar{b}})$ ~ 10%	□ $\sigma(m_{\tau\tau})$ = 10 – 20%	□ **$\sigma(m_{\gamma\gamma})$ = 1 – 2%**
□ 5.8σ exp.	□ 6.7σ exp.	□ 2.1σ exp.	□ 3.7σ exp.	□ 5.2σ exp.
□ **High yield**	□ Low Bkg.			
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JHEP 01 (2014) 096	**PRD 89 (2014) 092007**	**PRD 89 (2014) 012003**	**JHEP 05 (2014) 104**	**arXiv:1407.0558 (subm. to EPJC)**

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JHEP 01 (2014) 096

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PRD 89 (2014) 012003

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arXiv:1407.0558
(subm. to EPJC)

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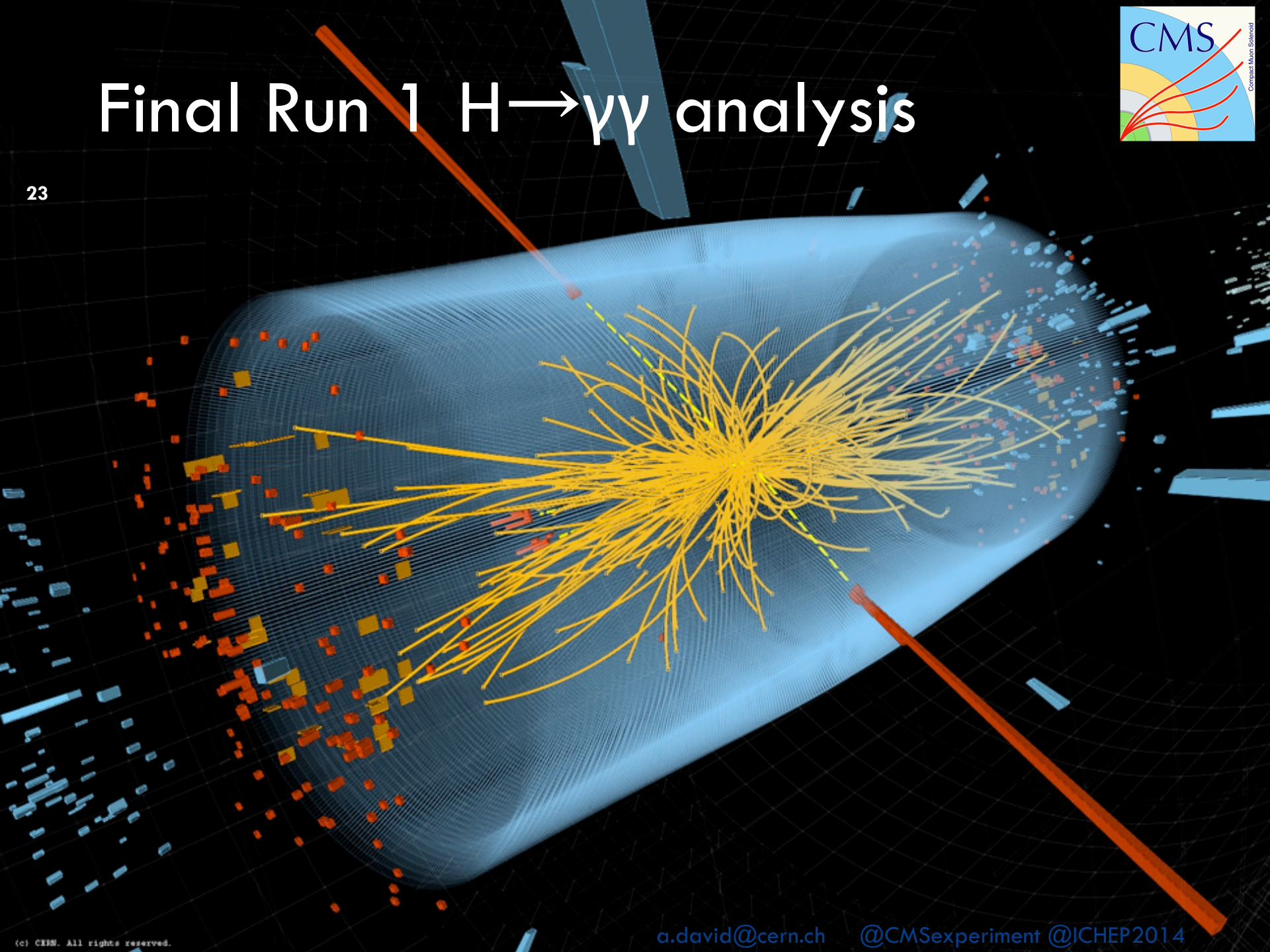
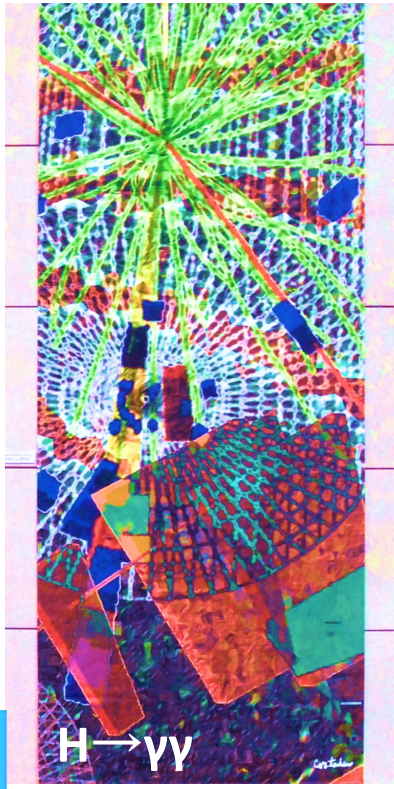
Final Run 1 $H \rightarrow \gamma\gamma$ analysis



Final Run 1 H→γγ analysis

[arXiv:1407.0558, submitted to EPJC]

- **Final calibration** of the CMS ECAL for Run 1 data.
- **Improved simulation/understanding** of:
  - ECAL noise evolution with time.
  - Effect of out-of-time collisions.
  - Amount and distribution of material in front of ECAL.
- **Improved** description of **energy scale uncertainties.**
- **25 event categories** targeting all production modes.
- **New background modeling**
  considers multiple functional forms simultaneously.



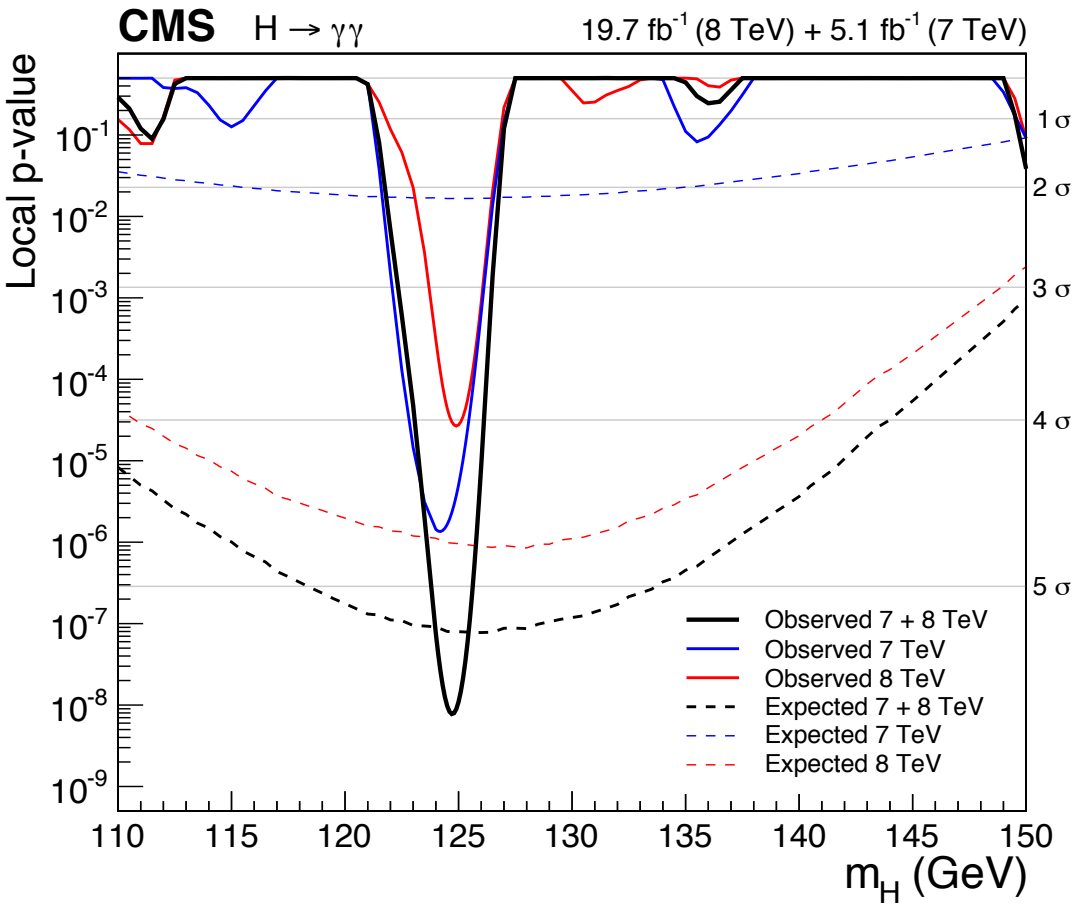
arXiv:1407.0558
(subm. to EPJC)

	Improved energy resolution	New event selection	Background modeling
Improvement on expected sensitivity since preliminary result:	~9%	~9%	~7%

H→ γγ significance

[arXiv:1407.0558, submitted to EPJC]

- Significance:
  5.7σ obs.
  (5.2σ exp.)



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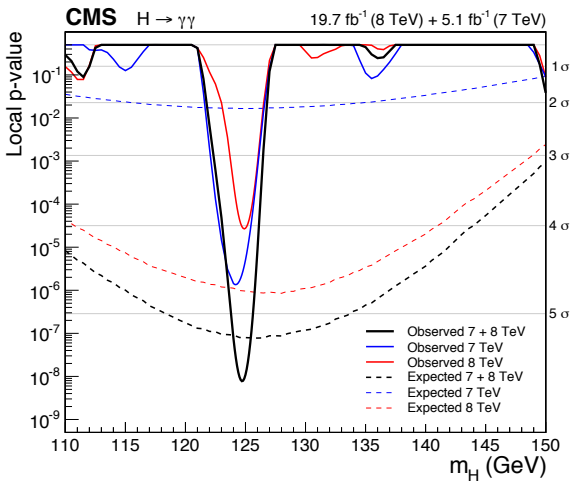

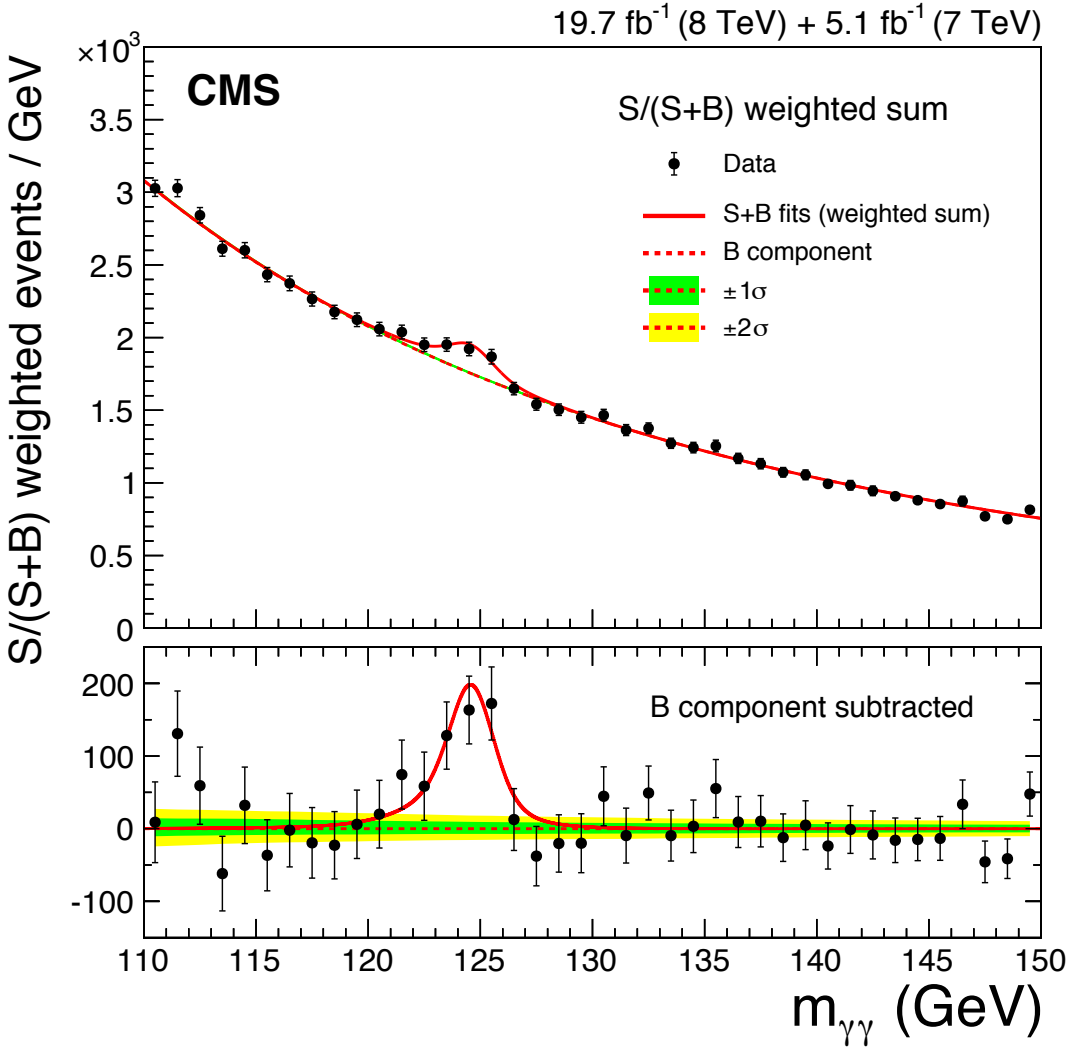

H→ γγ mass measurement

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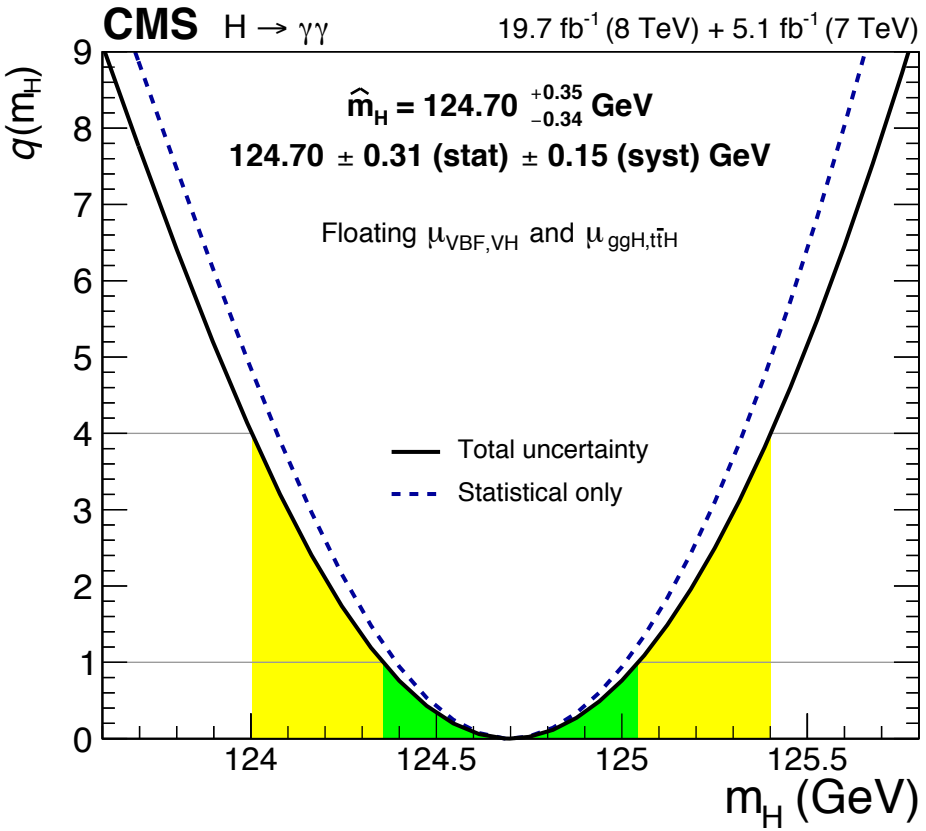
$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$



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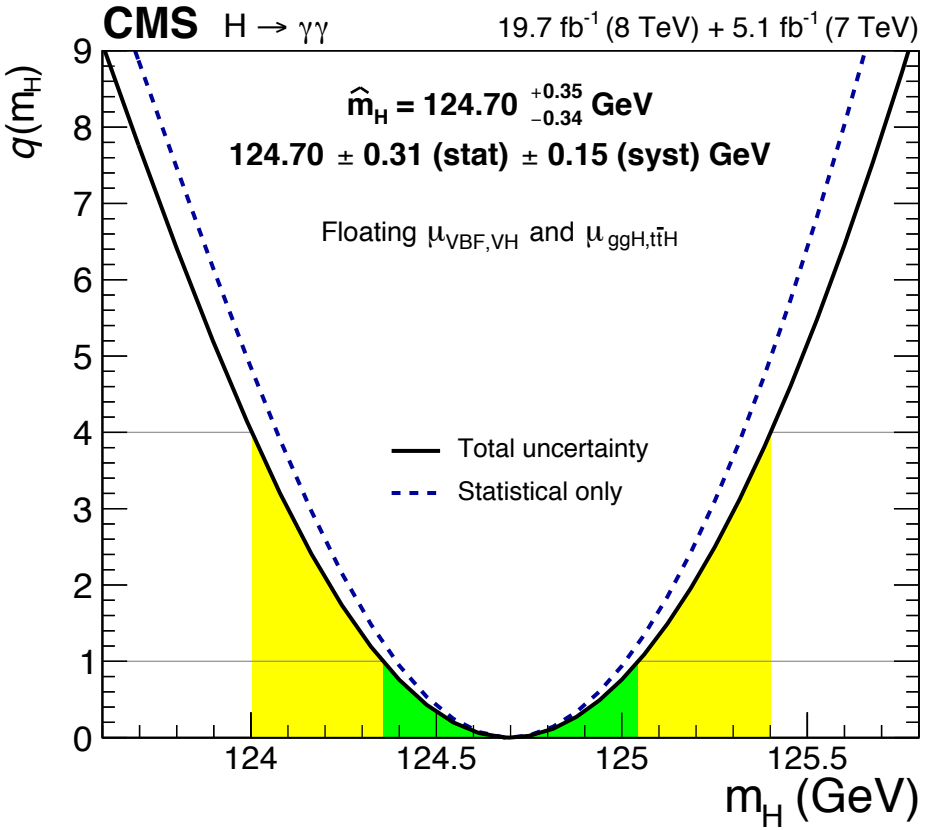
Calibration

E(γ) scale & resolution correction uncertainty:

±0.05 GeV on m_H

m_Z scale, electrons



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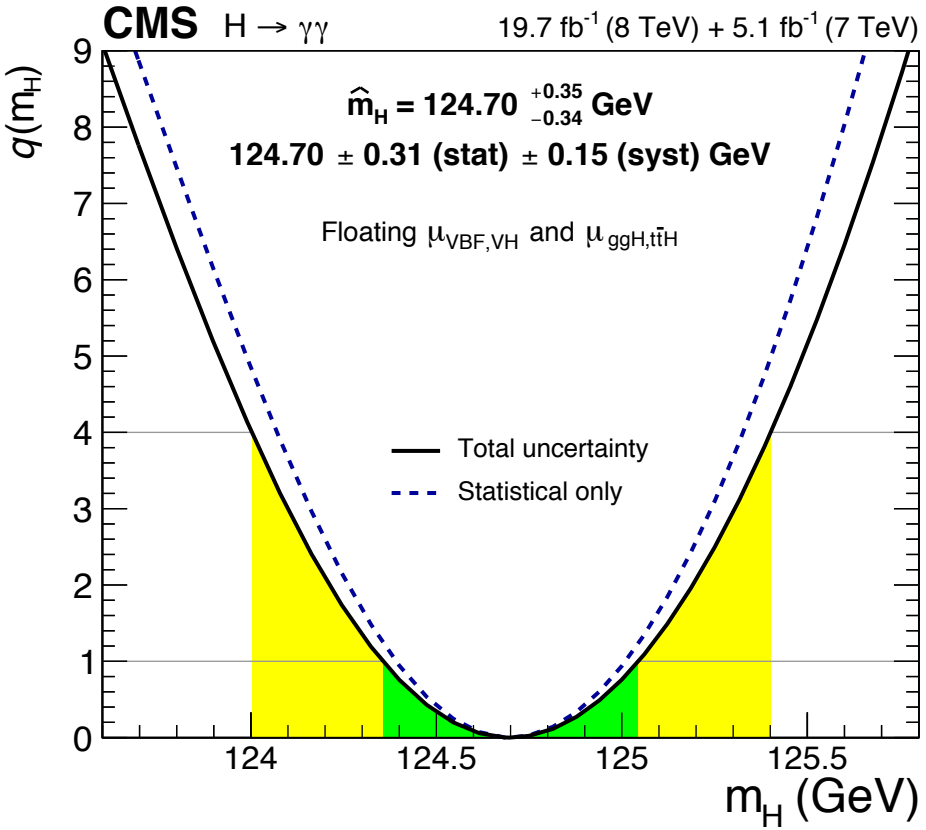

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Large p_T Z boson data

Non-linearity uncertainty: **±0.10 GeV**

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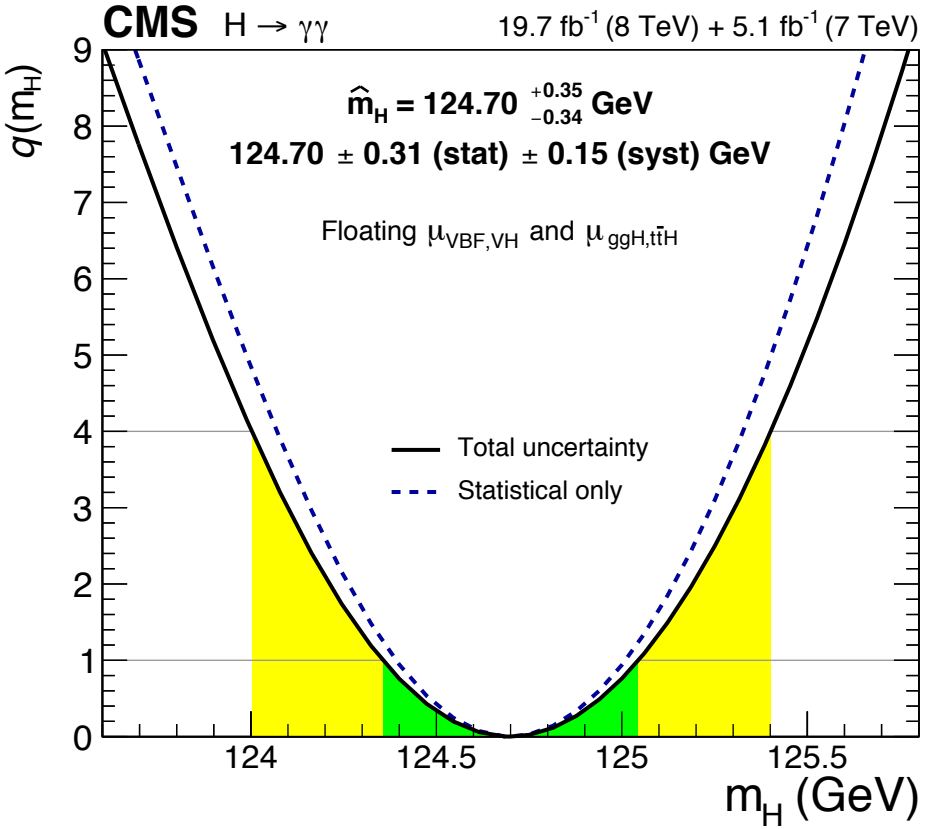

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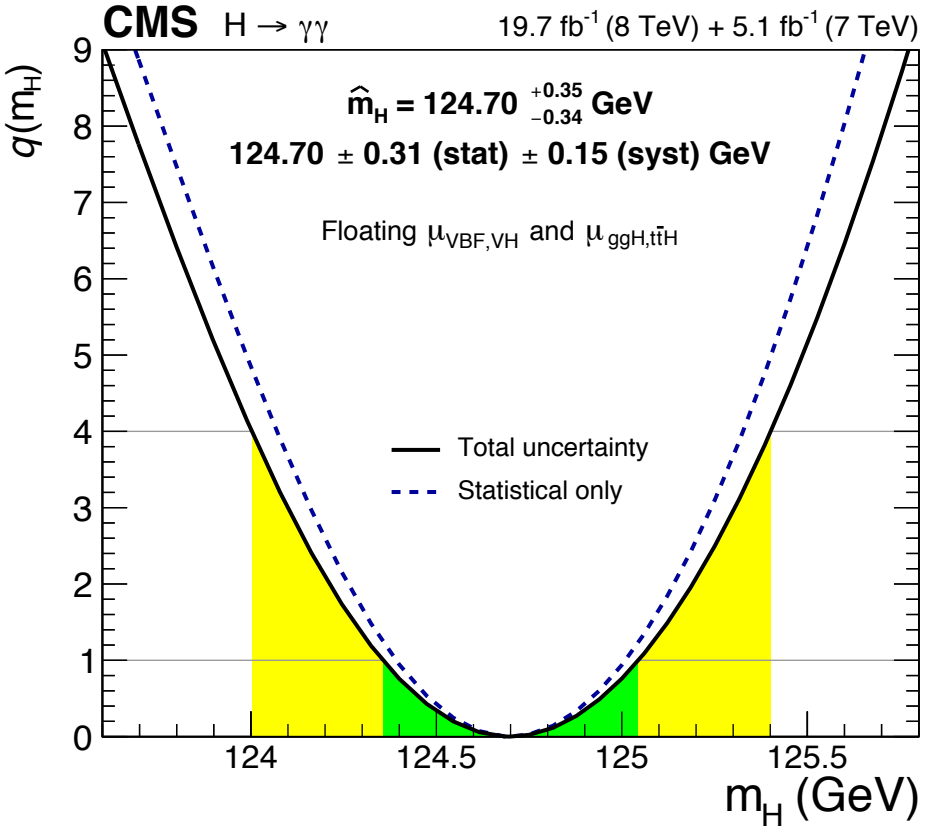
m_H scale, electrons

m_H scale, **photons**



a.david@cern.ch @CMSexperiment @ICHEP2014

H→ γγ mass measurement

[arXiv:1407.0558, submitted to EPJC]

$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$

Calibration
E(γ) scale & resolution correction uncertainty:
±0.05 GeV on m_H

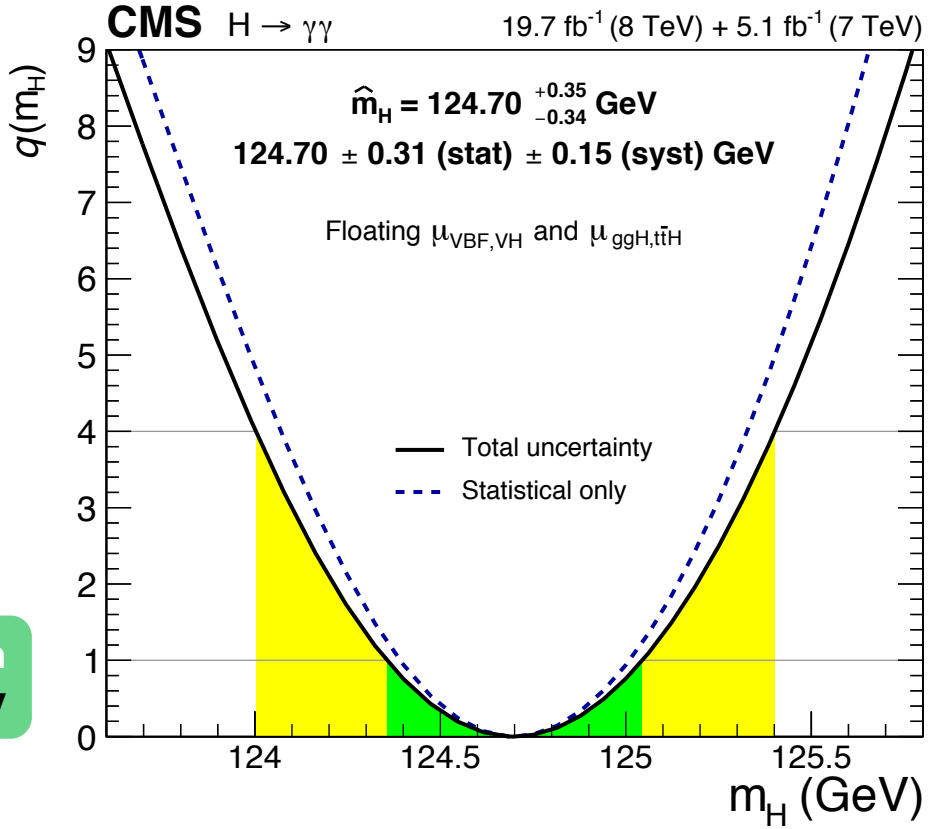
m_Z scale, electrons

Large p_T Z boson data
Non-linearity uncertainty: **±0.10 GeV**

m_H scale, electrons

From simulation
Data-MC electron-photon differences: **±0.10 GeV**

m_H scale, photons

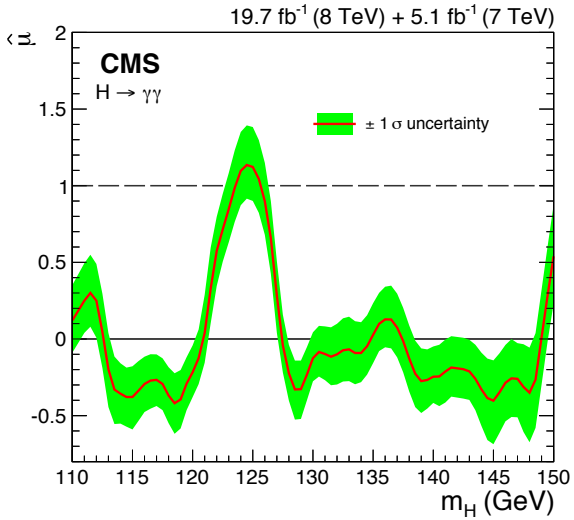


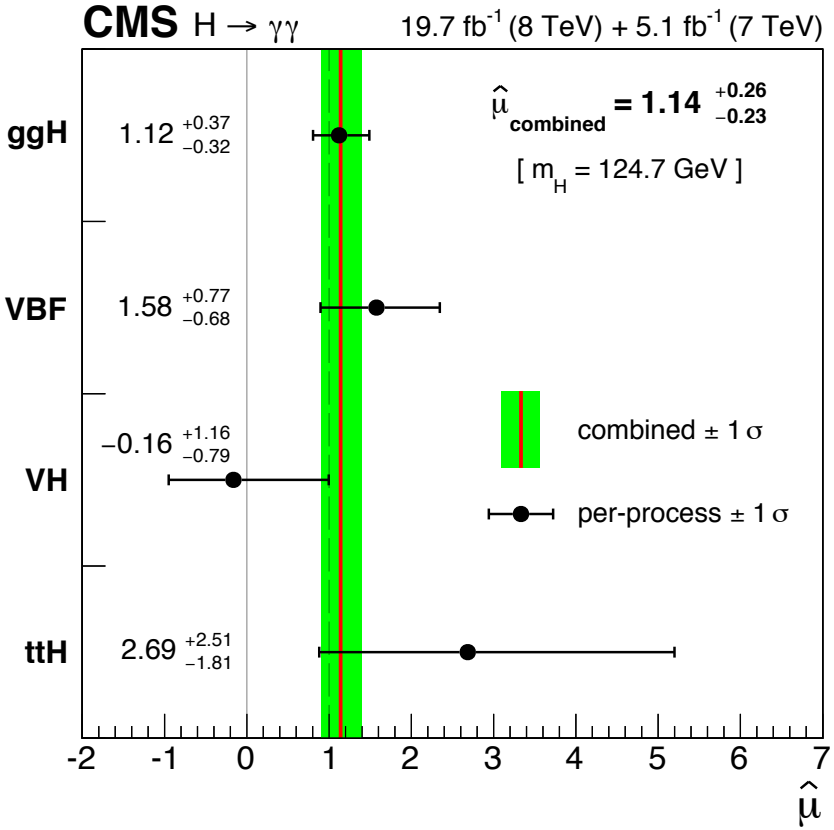
a.david@cern.ch @CMSexperiment @ICHEP2014

H→ γγ signal strength

[arXiv:1407.0558, submitted to EPJC]

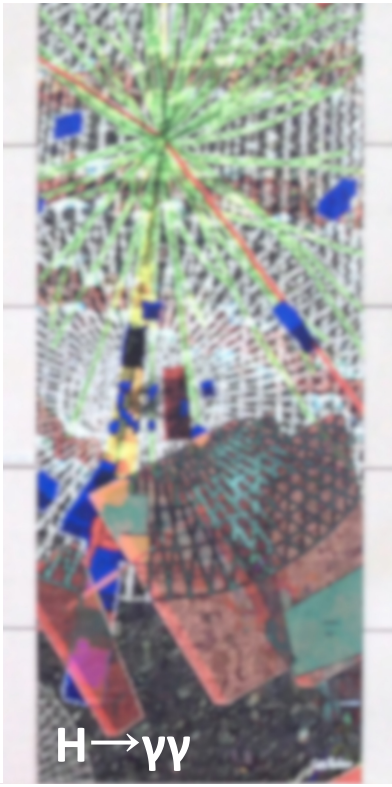
$$\sigma/\sigma_{\mathrm{SM}} = 1.14^{+0.26}_{-0.23}\left[\pm 0.21(\mathrm{stat.})^{+0.13}_{-0.09}(\mathrm{theo.})^{+0.09}_{-0.05}(\mathrm{syst.})\right]$$





A combination of final results

PRD 89 (2014) 092007



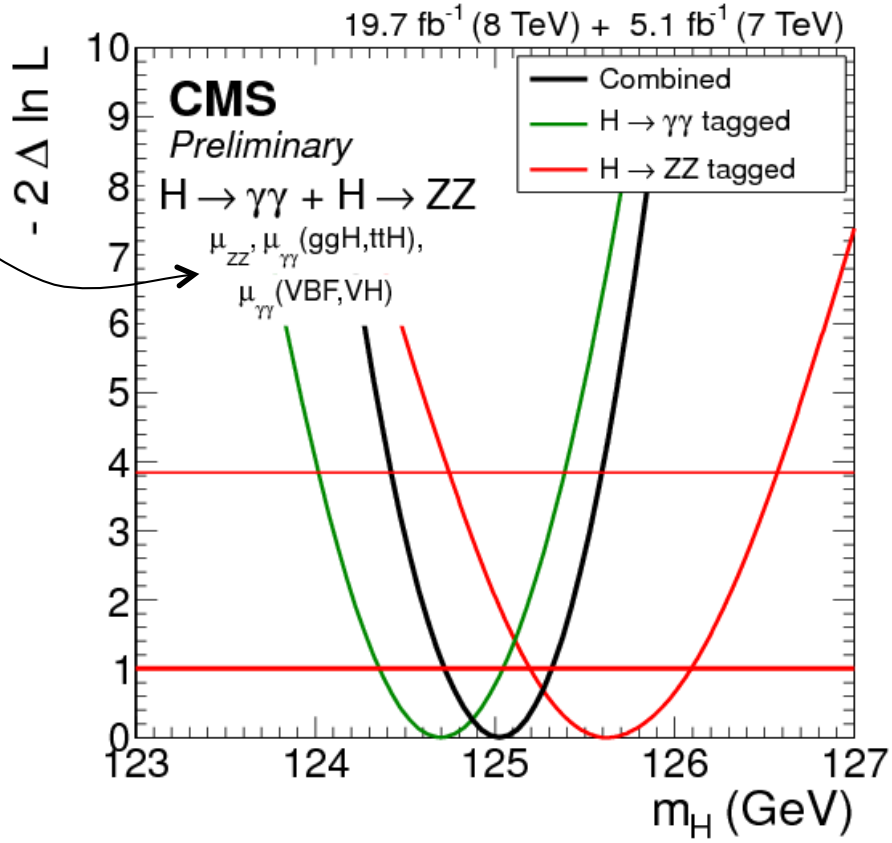
arXiv:1407.0558
(subm. to EPJC)

High-resolution channels: combined mass measurement

Combined mass measurement

[CMS-PAS-HIG-14-009]

- Float 3 signal strengths to not depend on yields.

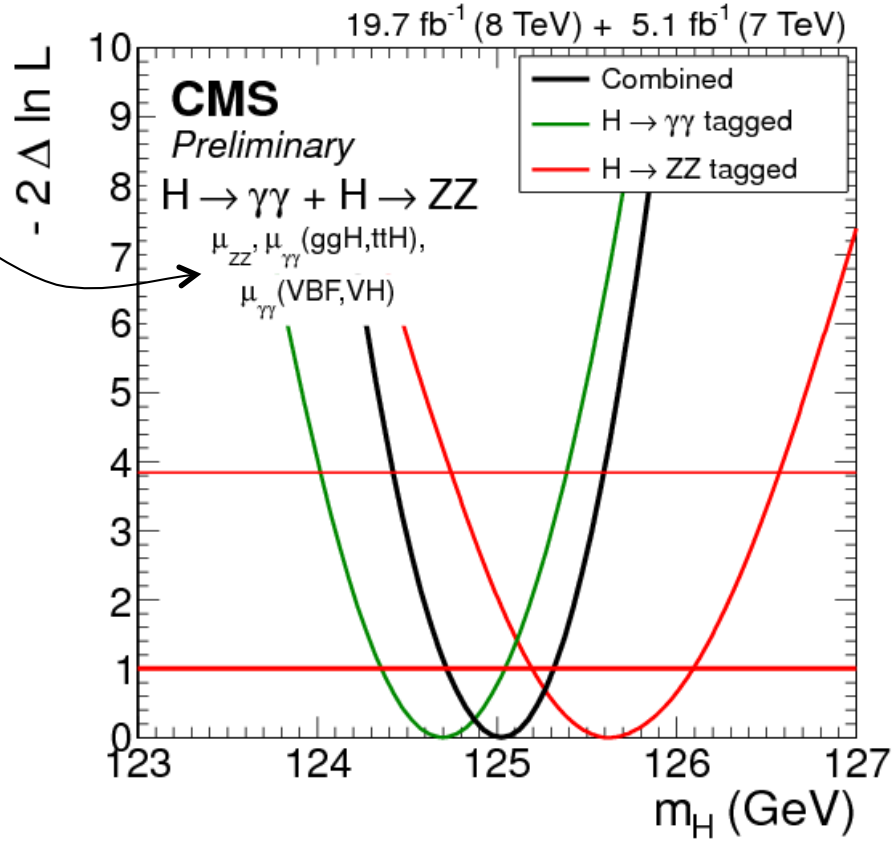


Combined mass measurement

[CMS-PAS-HIG-14-009]

$$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat.}) {}^{+0.13}_{-0.15}(\text{syst.}) \right] \text{GeV}$$

- Float 3 signal strengths to not depend on yields.

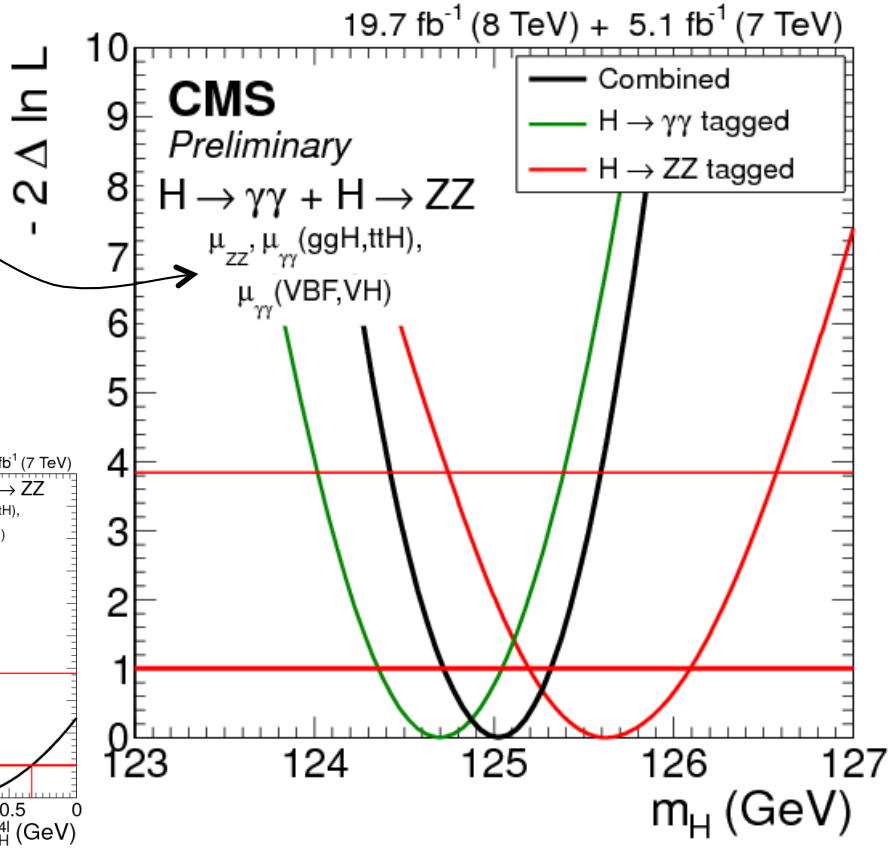


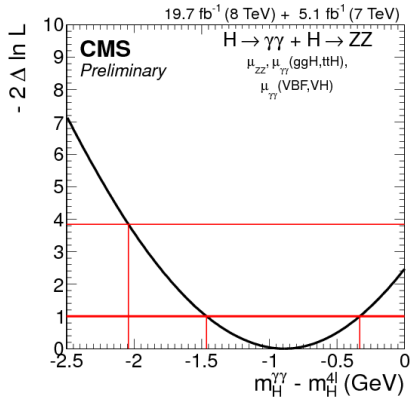
Combined mass measurement

[CMS-PAS-HIG-14-009]

$$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat.}) {}^{+0.13}_{-0.15}(\text{syst.}) \right] \text{GeV}$$

- Float 3 signal strengths to not depend on yields.
- **H→γγ and H→ZZ→4ℓ** results compatible at 1.6σ level.





One model

One model


Fiat 124

Fiat 126

One model


Fiat 125
a very high-performance saloon
$2898
Willys Motors
(AUSTRALIA) PTY. LTD.
STAND No. 8
79 YARRABANK ROAD, SOUTH MELBOURNE. 69-7411
594 ELIZABETH STREET, MELBOURNE. Phone 34-1519


Fiat 124


Fiat 126
CB 29070

One model


Fiat 125 ±0.3
a very high-performance saloon
$2898
Willys Motors
(AUSTRALIA) PTY. LTD.
STAND No. 8
79 YARRABANK ROAD, SOUTH MELBOURNE. 69-7411
594 ELIZABETH STREET, MELBOURNE. Phone 34-1519

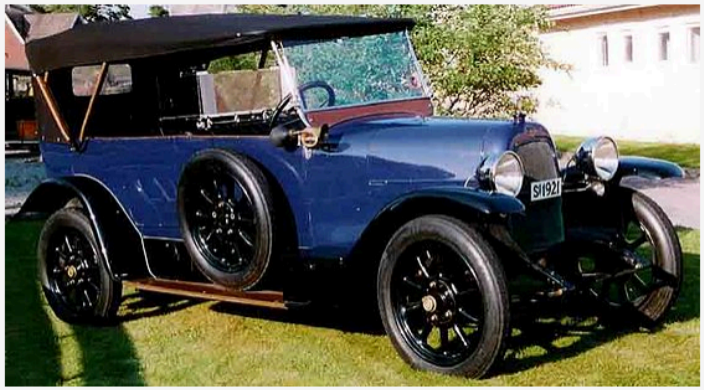

Fiat 124


Fiat 126
CB 29070

Other models?

[http://cern.ch/go/X6rC]

Fiat 505

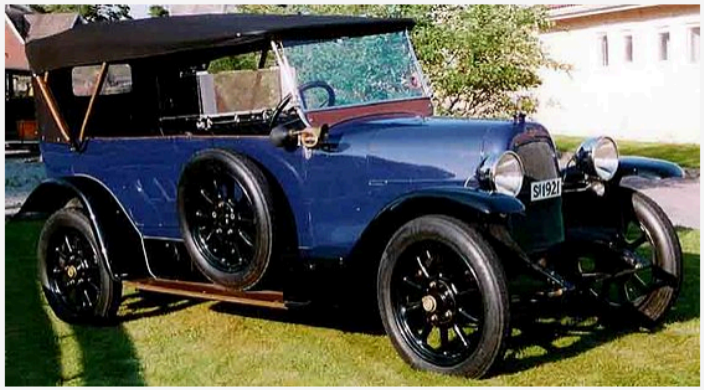


Other models?

[http://cern.ch/go/X6rC]

Fiat 1400/1900

Fiat 505



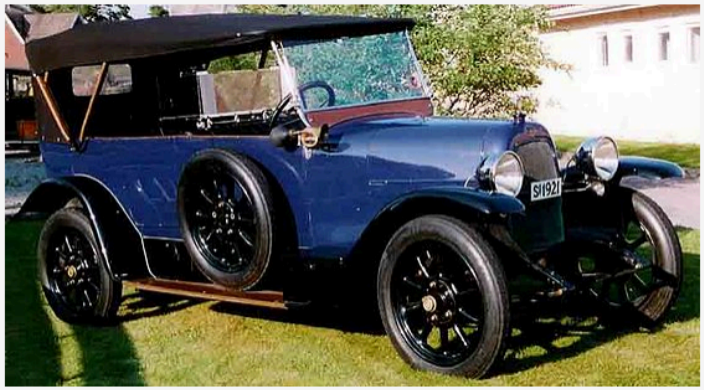
Other models?

[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 505



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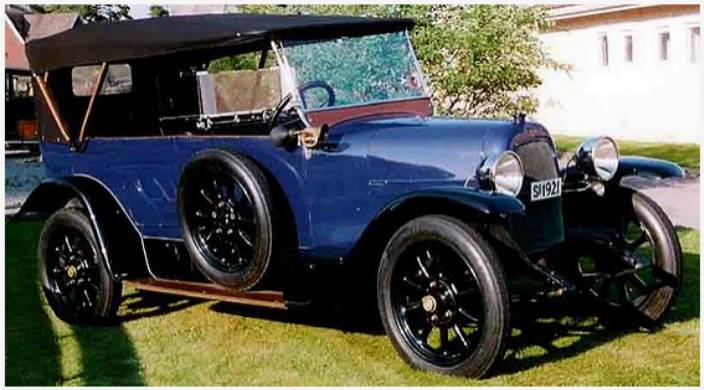
[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 2300

Fiat 505



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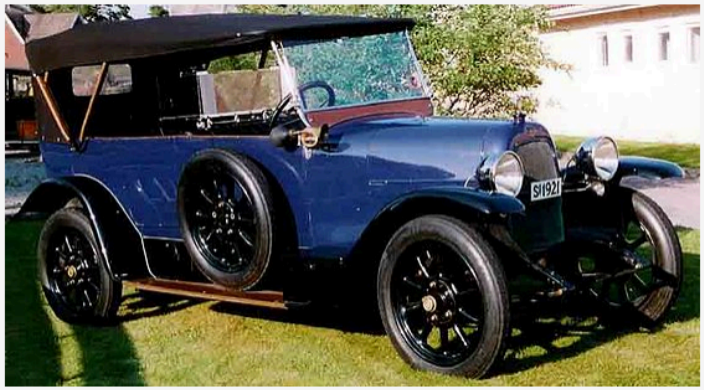
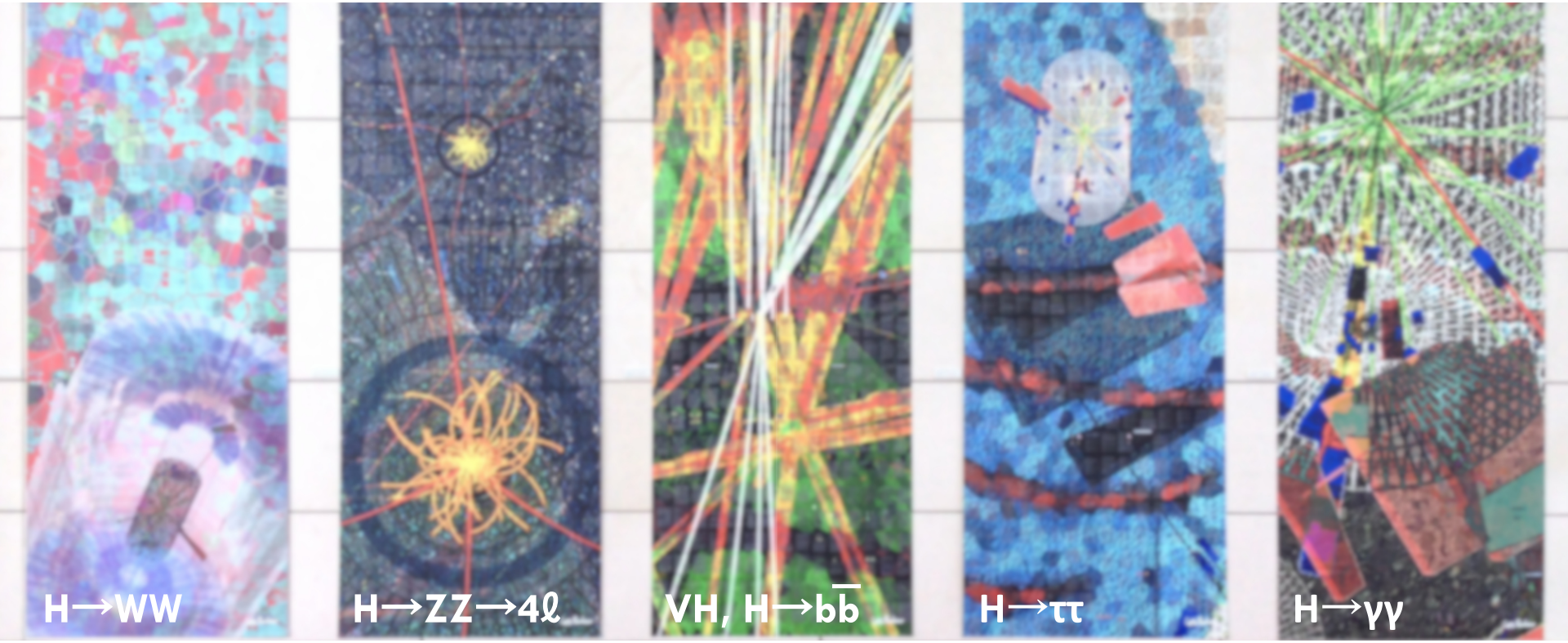


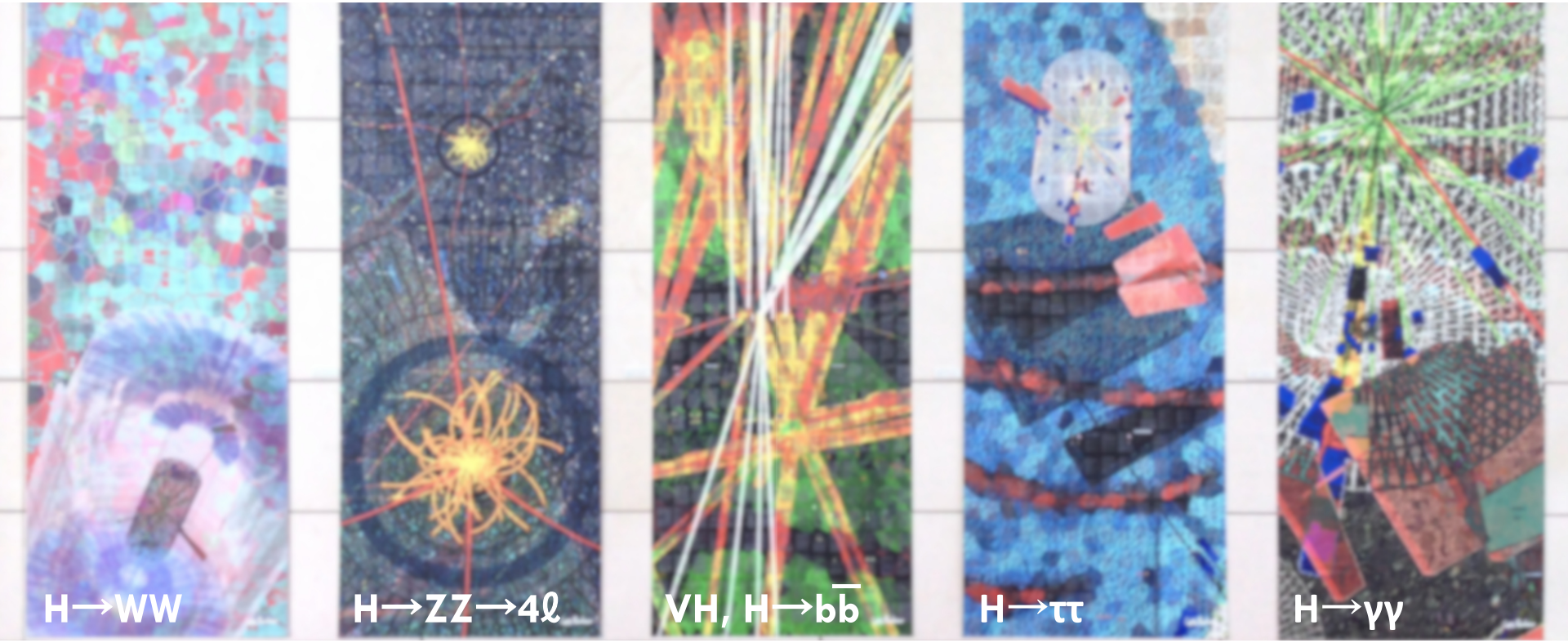
Fiat Seicento

A combination of final results



JHEP 01(2014) 096 | PRD 89 (2014) 092007 | PRD 89 (2014) 012003 | JHEP 05 (2014) 104 | arXiv:1407.0558 (subm. to EPJC)

A combination of final results

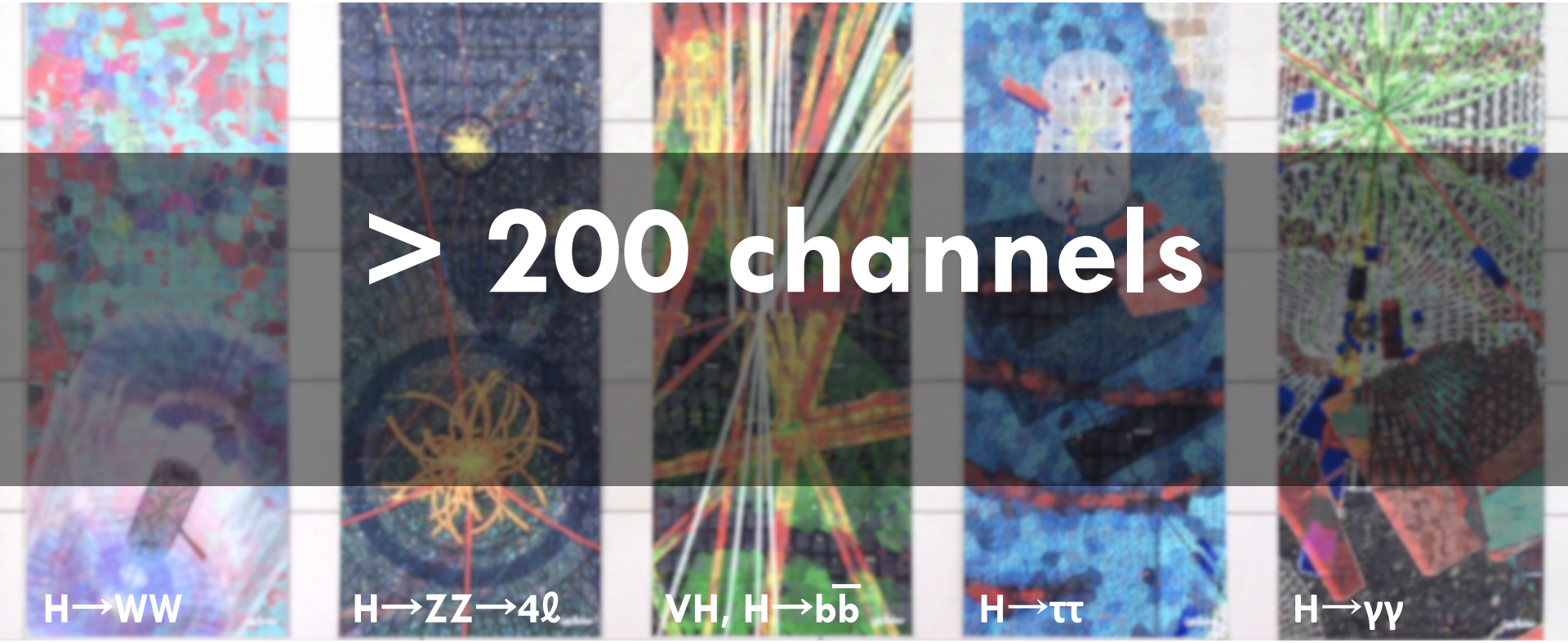


JHEP 01(2014) 096 | PRD 89 (2014) 092007 | PRD 89 (2014) 012003 | JHEP 05 (2014) 104 | arXiv:1407.0558 (subm. to EPJC)

Also include further ttH searches:

- JHEP 05(2013)145 – ttH, H→bb̄ (7 TeV).
- CMS-PAS-HIG-13-019 – ttH, H→bb̄ and H→ττ (8 TeV).
- CMS-PAS-HIG-13-020 – ttH, with H decaying to multiple leptons.

A combination of final results



JHEP 01(2014) 096 | PRD 89 (2014) 092007 | PRD 89 (2014) 012003 | JHEP 05 (2014) 104 | arXiv:1407.0558 (subm. to EPJC)

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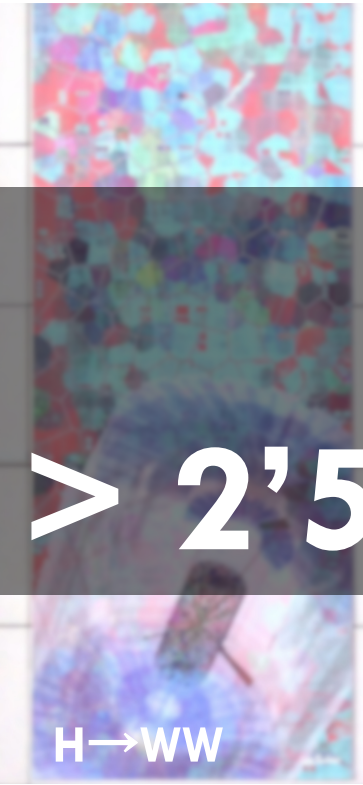
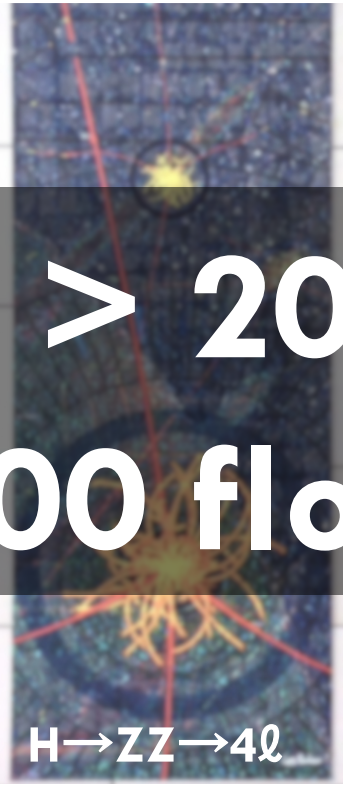
A combination of final results

> 200 channels

> 2'500 floating parameters



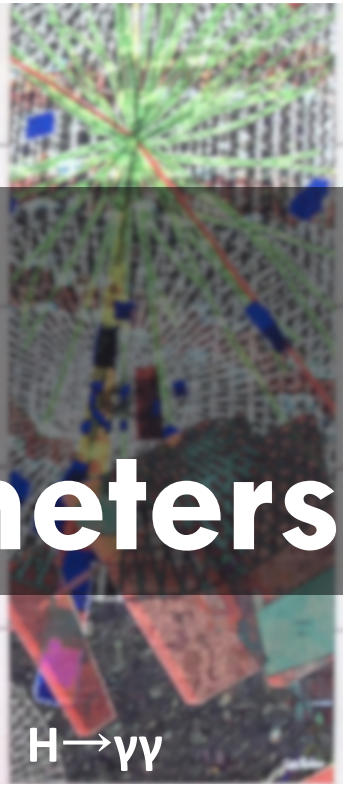
JHEP 01(2014) 096



PRD 89 (2014) 092007

PRD 89 (2014) 012003

JHEP 05 (2014) 104



arXiv:1407.0558
(subm. to EPJC)

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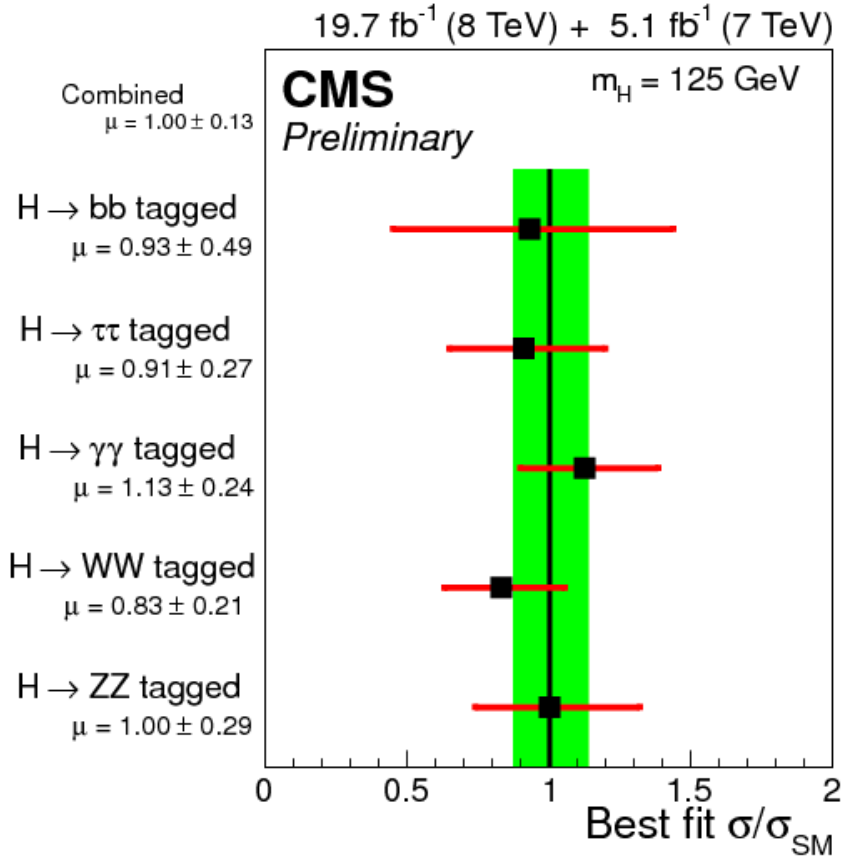
Signal strength

[CMS-PAS-HIG-14-009]

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

- Grouped by dominant decay:
  - $\chi^2/\mathrm{dof} = 0.9/5$
  - p-value = 0.97 (asymptotic)

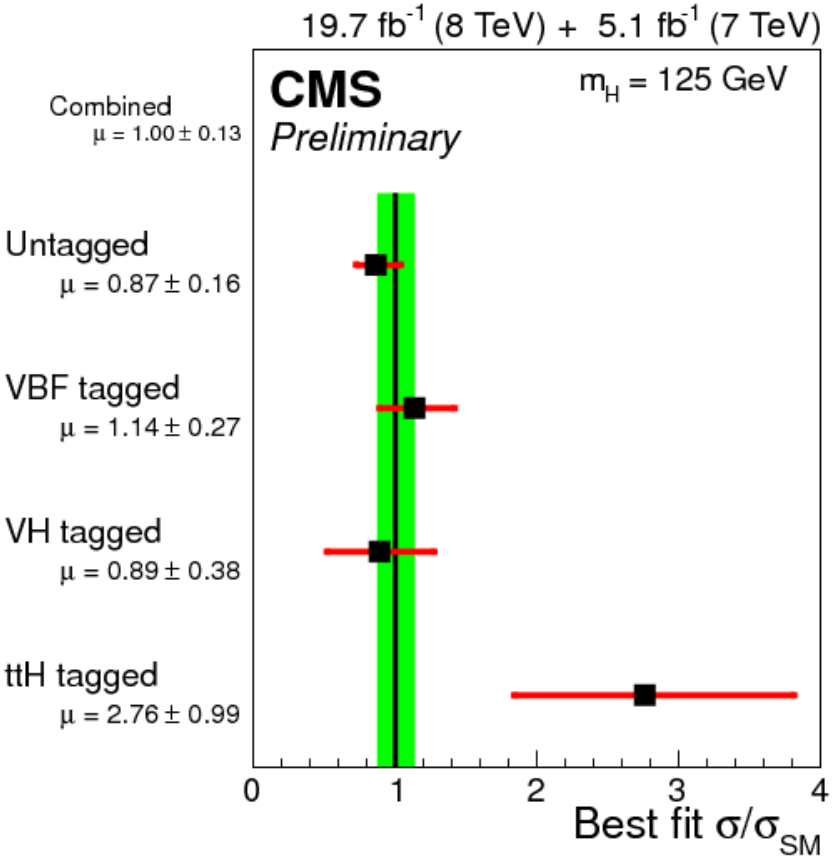


Signal strength

[CMS-PAS-HIG-14-009]

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

- Grouped by production tag:
  - $\chi^2/\mathrm{dof} = 5.3/4$
  - p-value = 0.26 (asymptotic)
- **ttH-tagged 2.0σ above SM.**

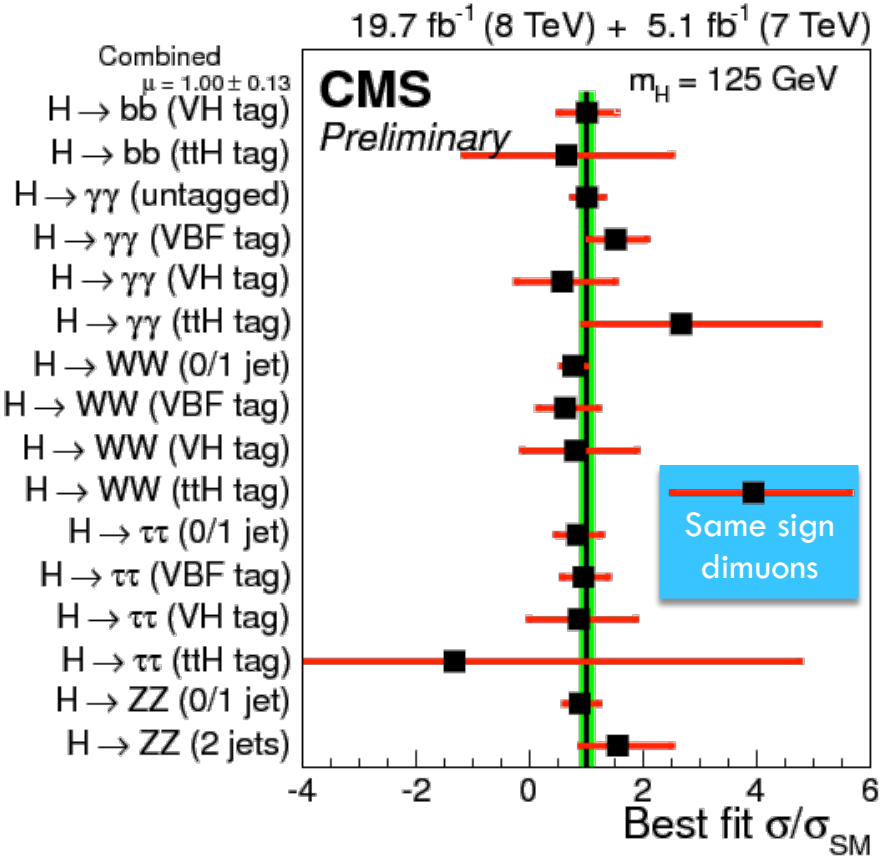


Signal strength

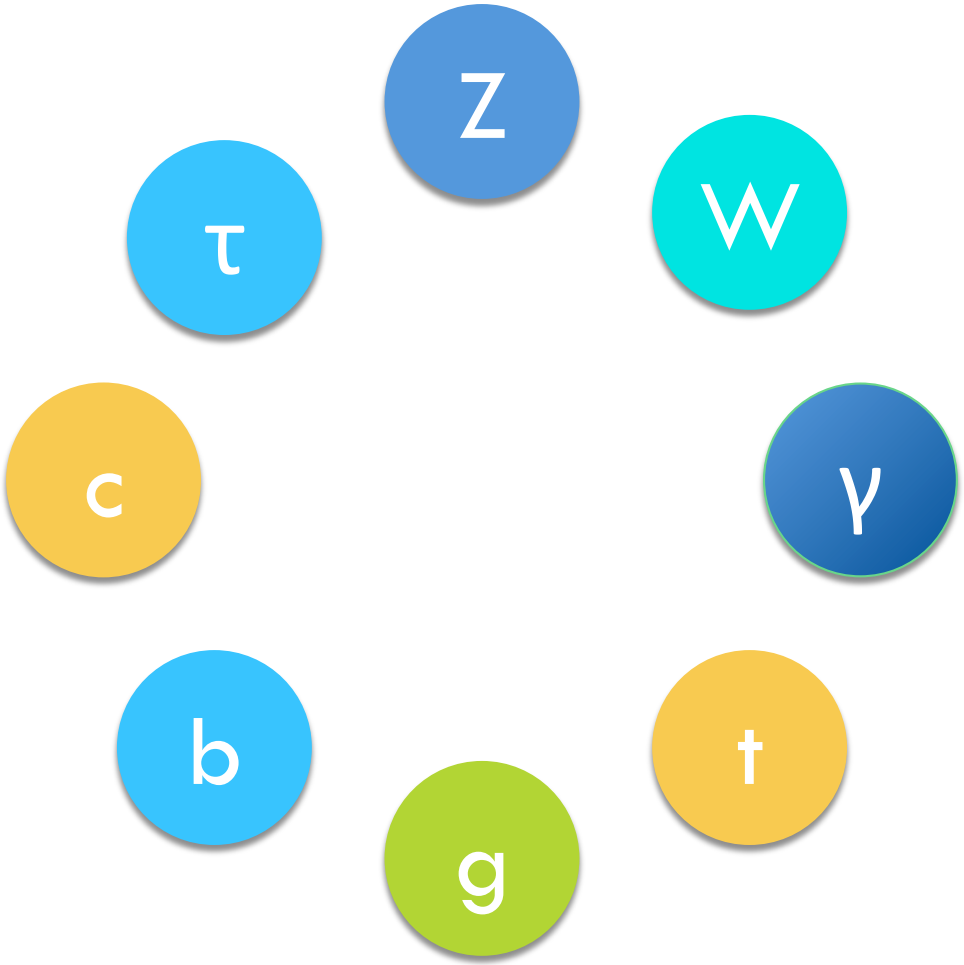
[CMS-PAS-HIG-14-009]

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

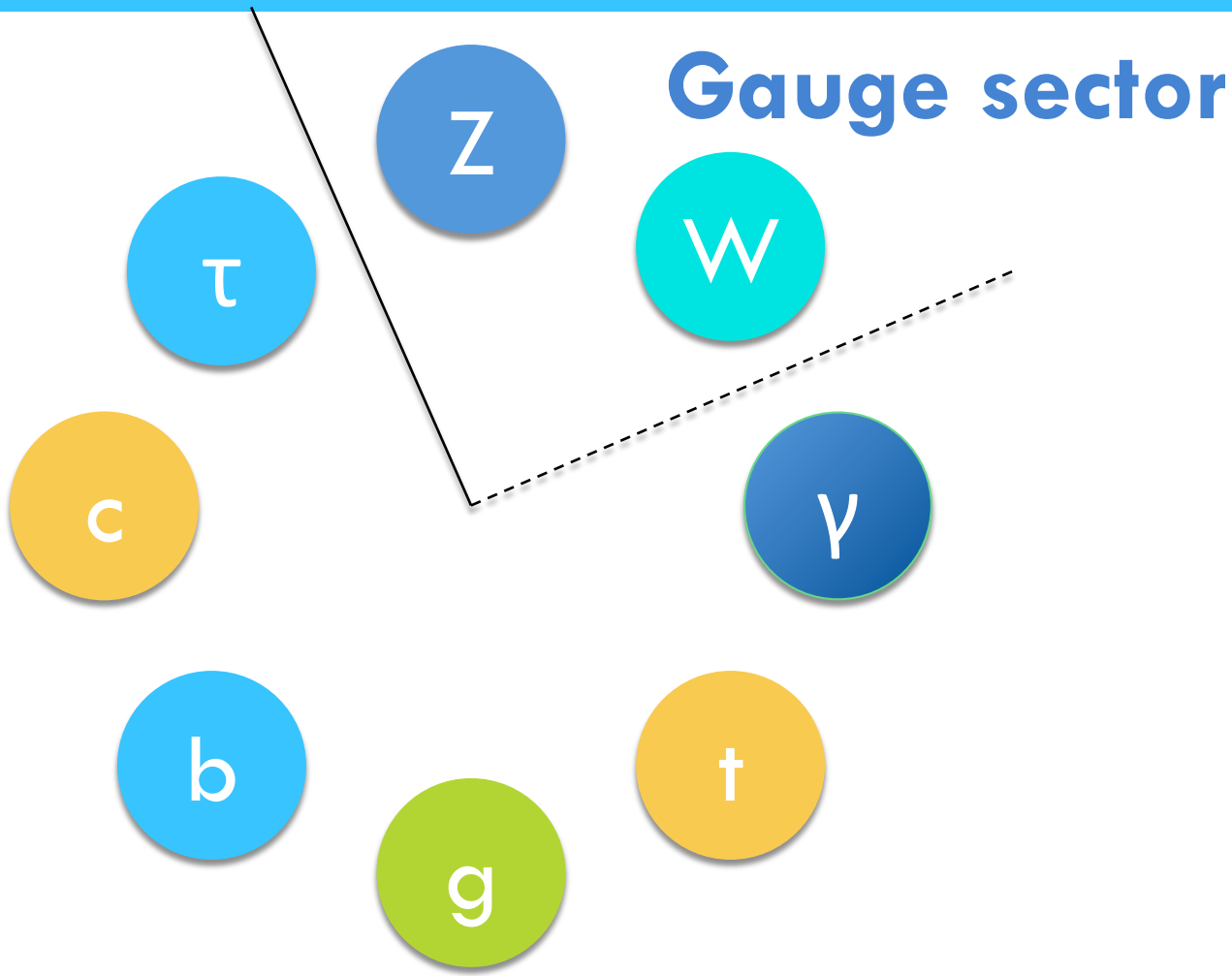
- Grouped by production tag and dominant decay:
  - χ^2/dof = 10.5/16
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above SM.
  - **Driven by one channel.**



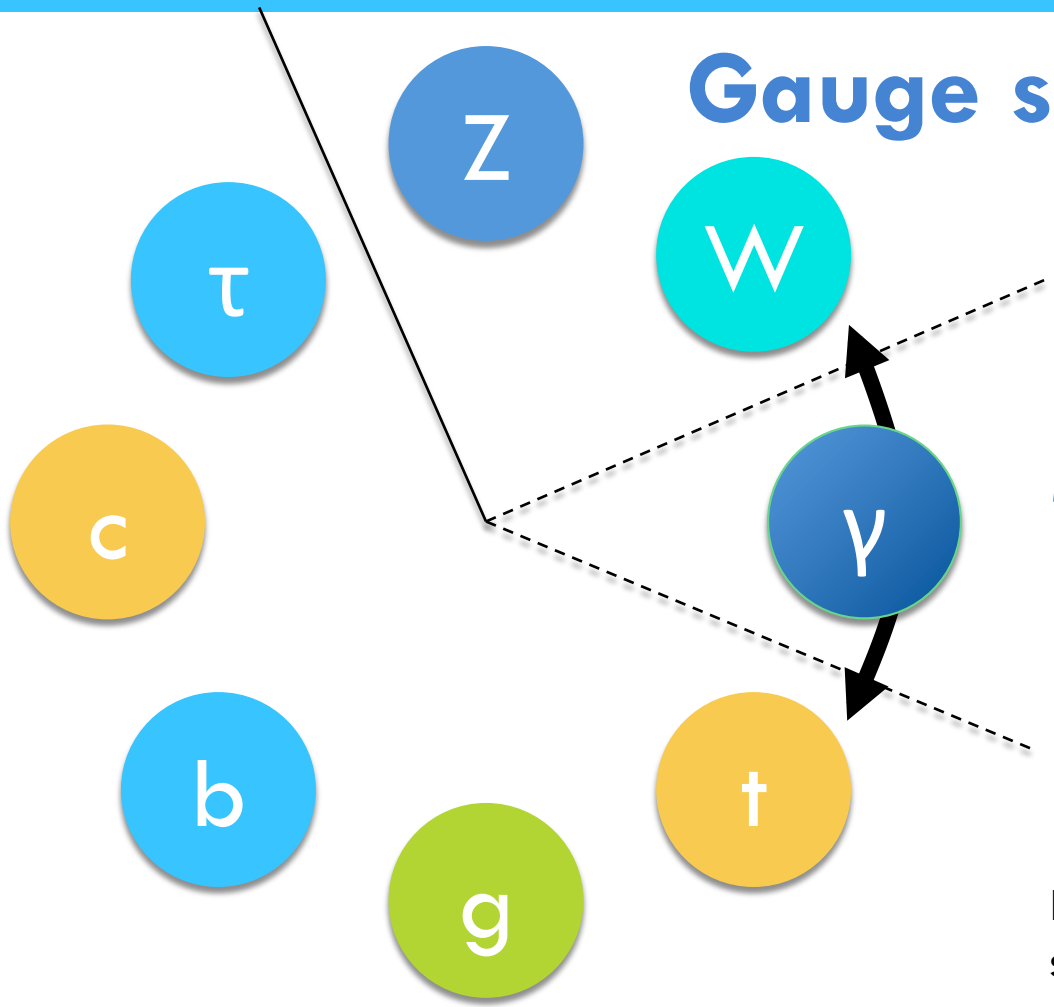
Scalar coupling structure



Scalar coupling structure

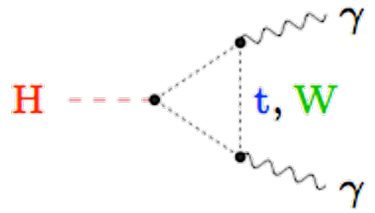


Scalar coupling structure



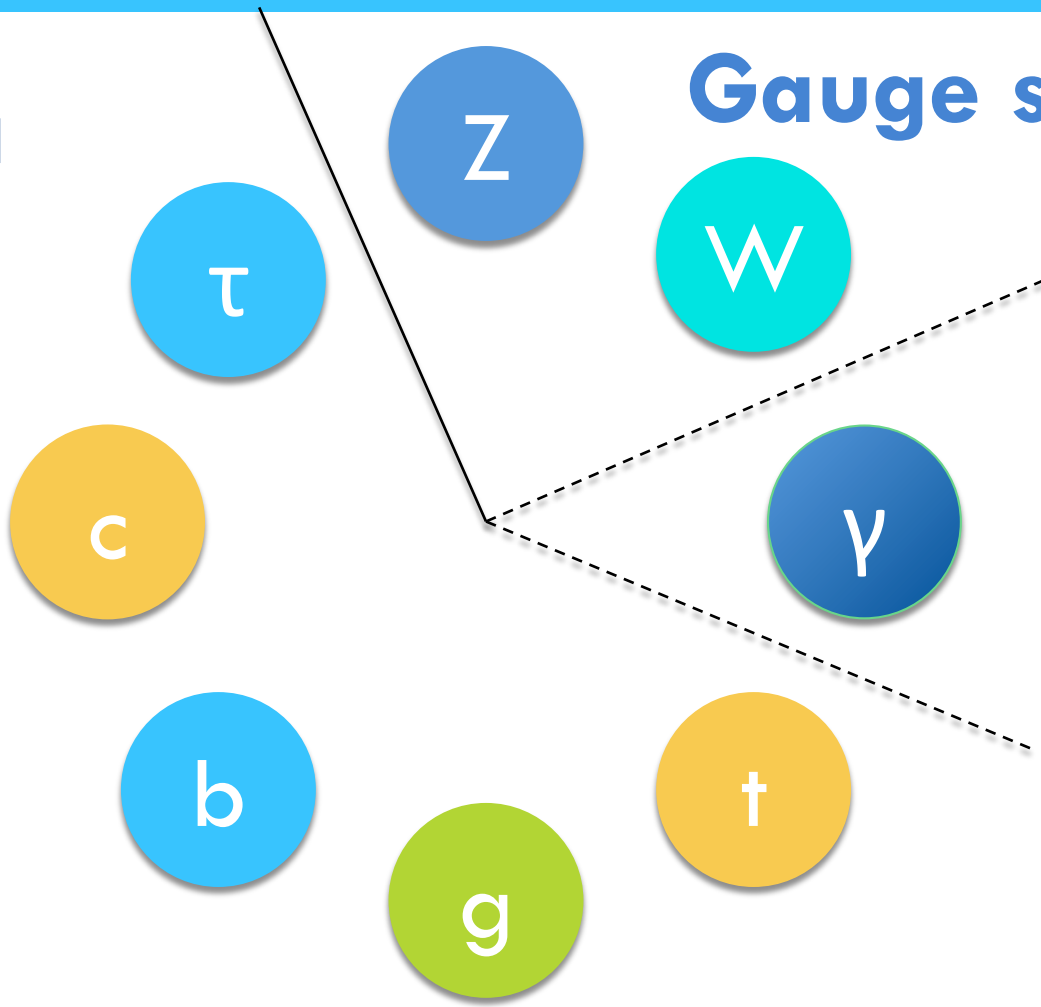
Gauge sector

Mixed sector



Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure



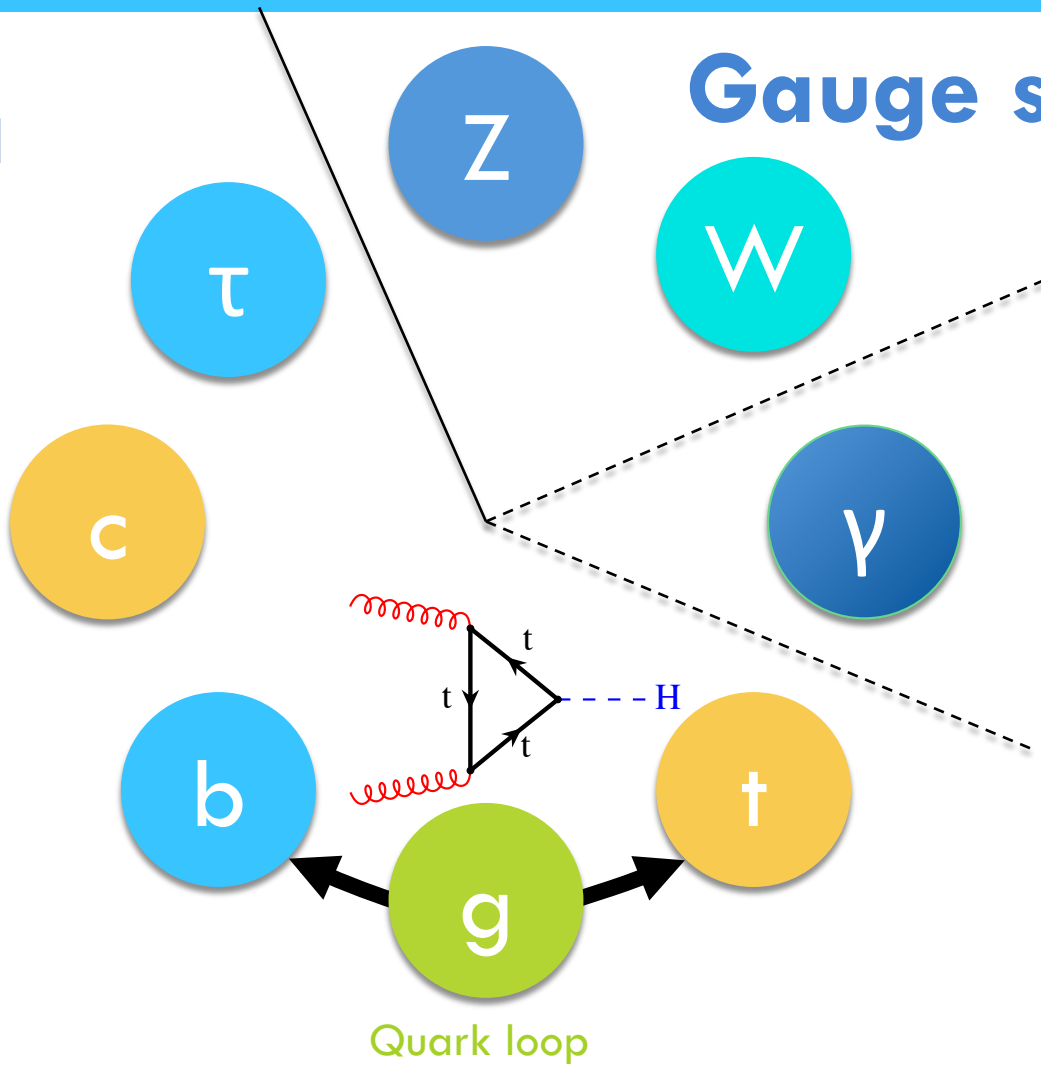
Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure

Yukawa sector

Gauge sector

Mixed sector



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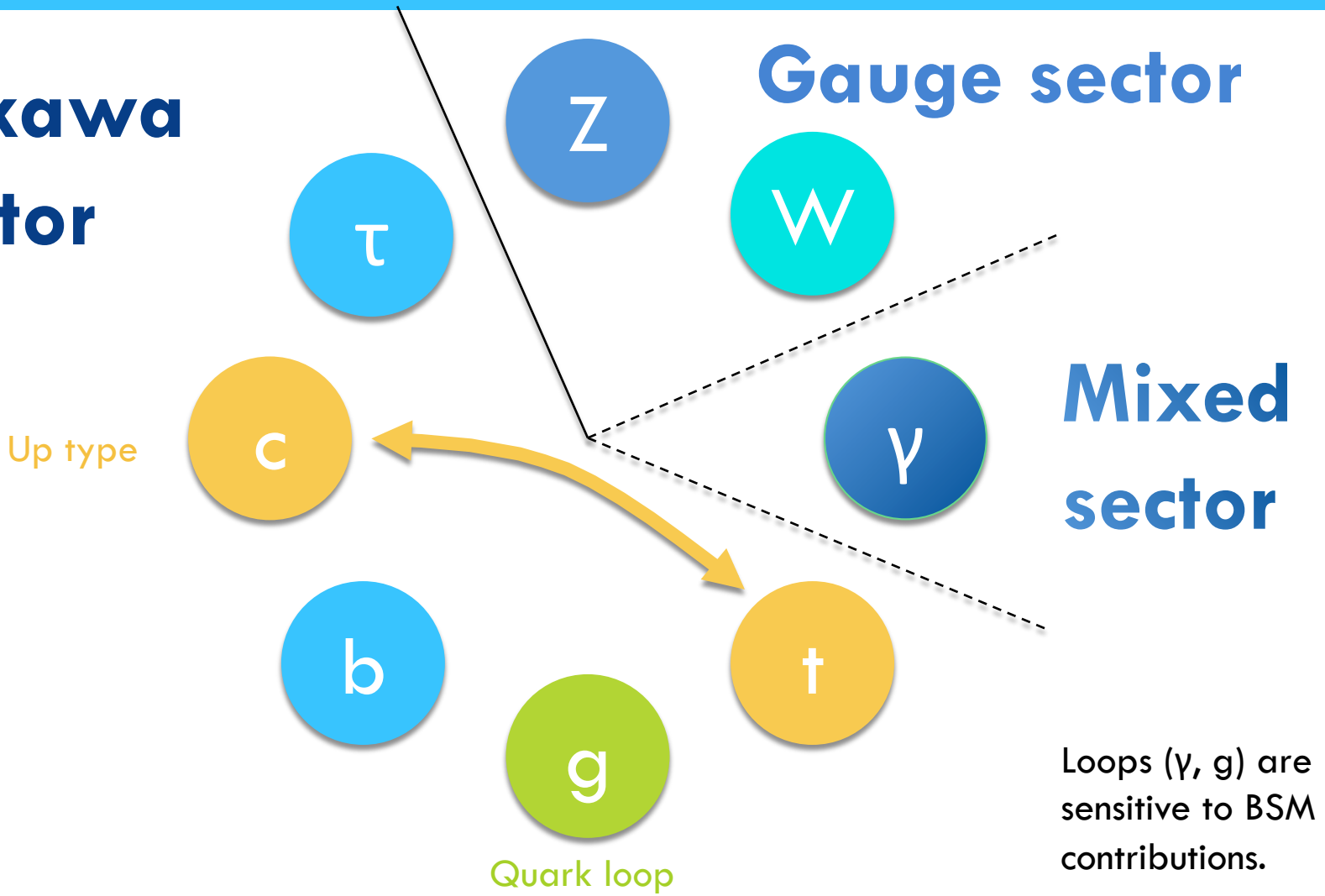
Scalar coupling structure



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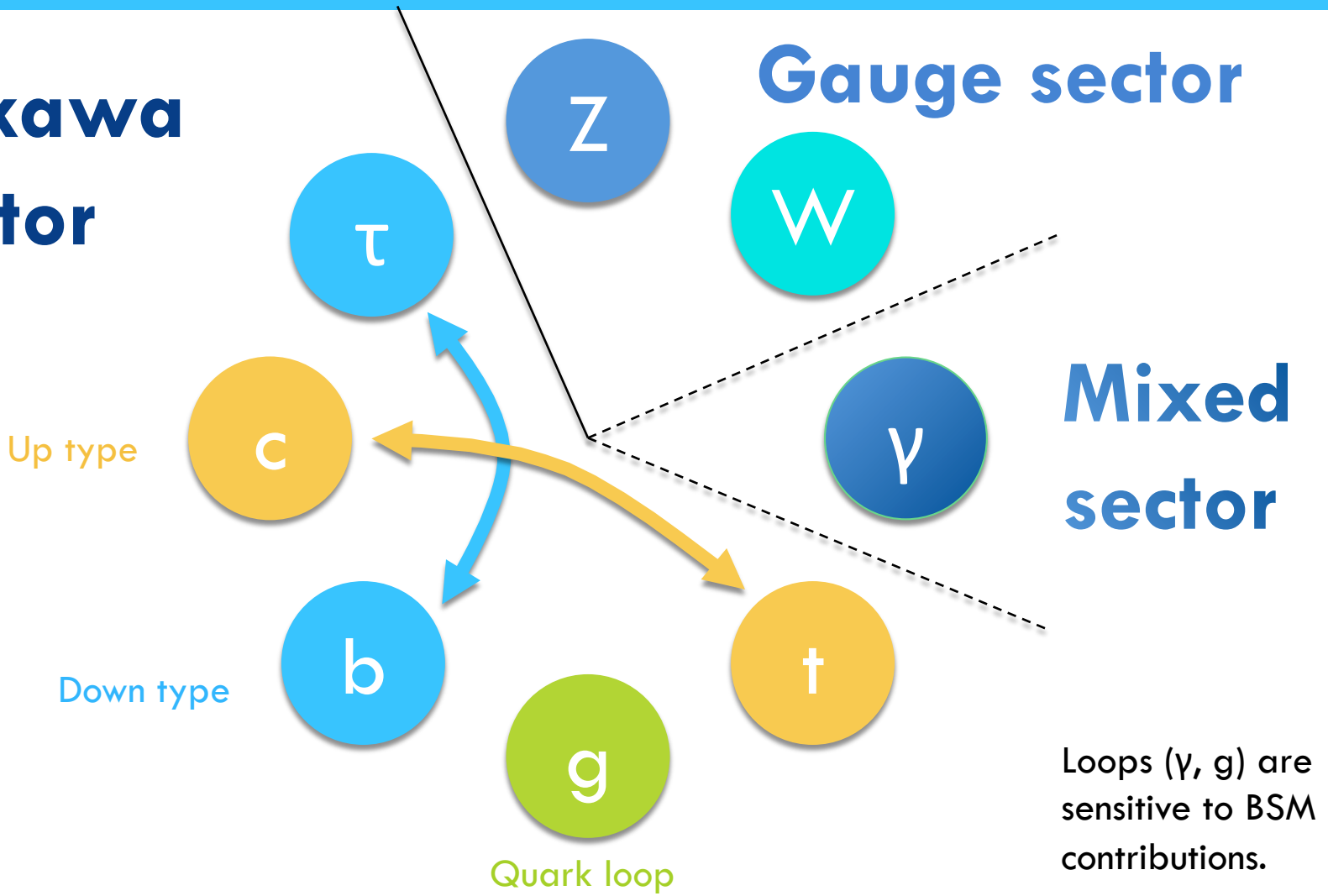
Scalar coupling structure



Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa^2_g(\kappa_b, \kappa_t, m_H) \\ \kappa^2_g \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa^2_W$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa^2_Z$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa^2_t$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa^2_W$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa^2_Z$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa^2_b$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa^2_\tau$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa^2_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_\gamma \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_{(Z\gamma)} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa^2_t$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa^2_t$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa^2_b$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa^2_\tau$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa^2_H(\kappa_i, m_H) \\ \kappa^2_H \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

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Currently undetectable decay modes

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$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} : \text{see Section 3.1.2}$$

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$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa^2_b$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa^2_\tau$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa^2_H(\kappa_i, m_H) \\ \kappa^2_H \end{cases}$$

- Loops resolved at NLO QCD and LO EWK accuracy.
- Peg the as-of-yet unmeasured to “closest of kin”.

Scalar coupling deviations framework

[arXiv:1307.1347]

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$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa^2_g(\kappa_b, \kappa_t, m_H) \\ \kappa^2_g \end{cases}$$

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Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa^2_W$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa^2_Z$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa^2_b$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa^2_\tau$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa^2_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_\gamma \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_{(Z\gamma)} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa^2_t$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa^2_t$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa^2_b$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa^2_\tau$$

Total width

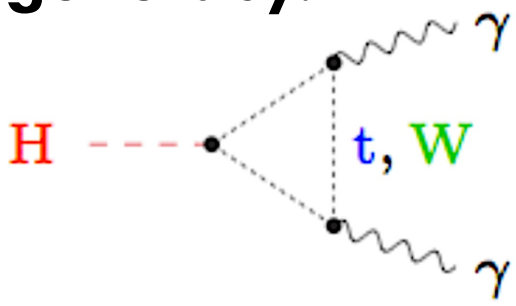
$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa^2_H(\kappa_i, m_H) \\ \kappa^2_H \end{cases}$$

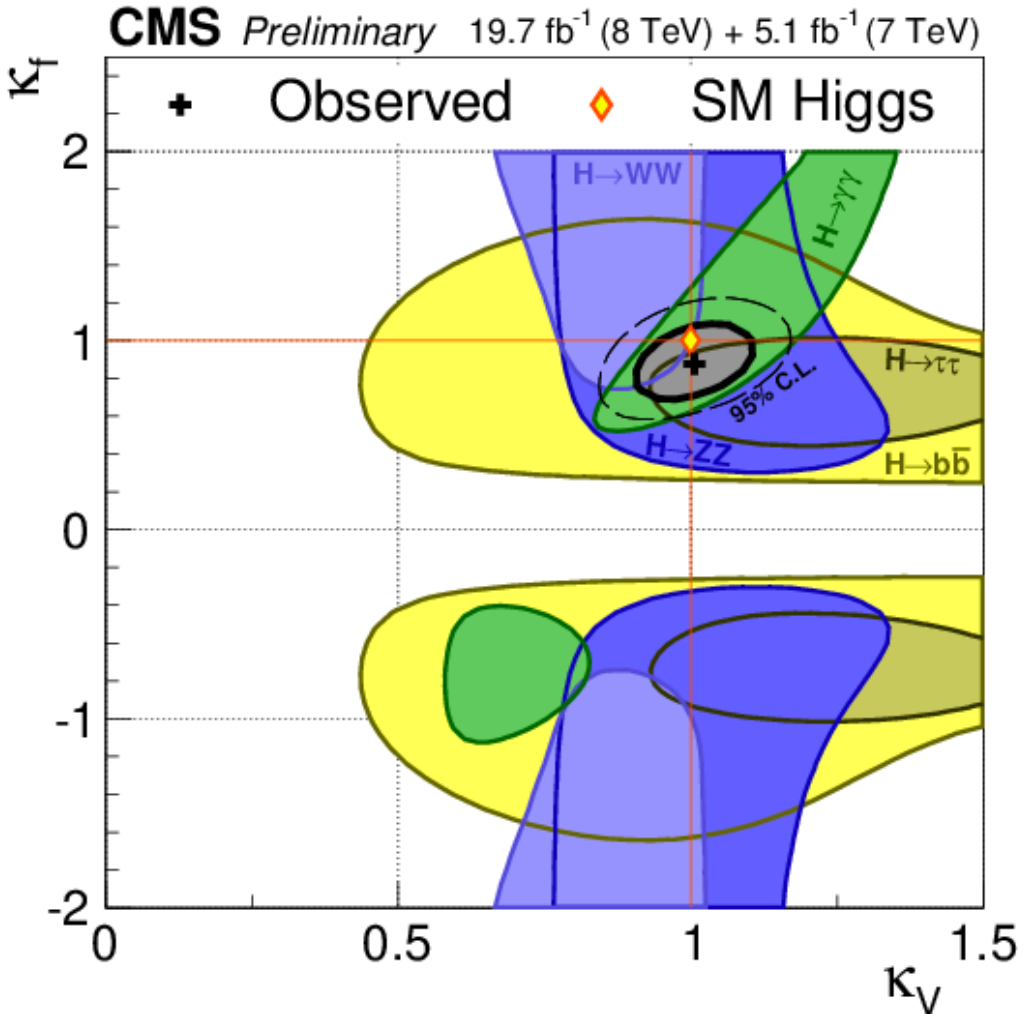
- Total width as dependent function of all κ_i.
- Total width scaled as free parameter: κ_H.

Coupling deviations

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- Scaling the couplings to fermions (κ_f) and vector bosons (κ_V).
- **Destructive interference in H→ γγ decay loop breaks degeneracy.**

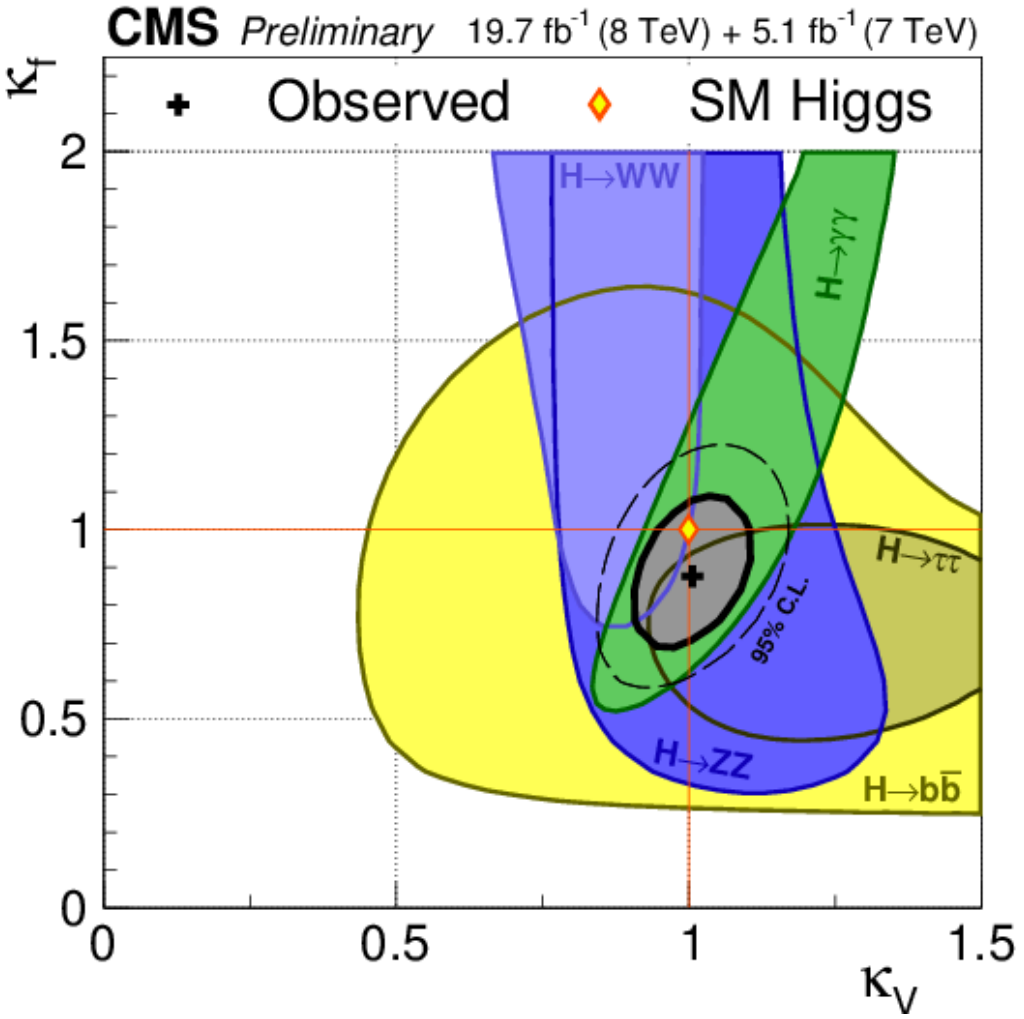




Coupling deviations

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

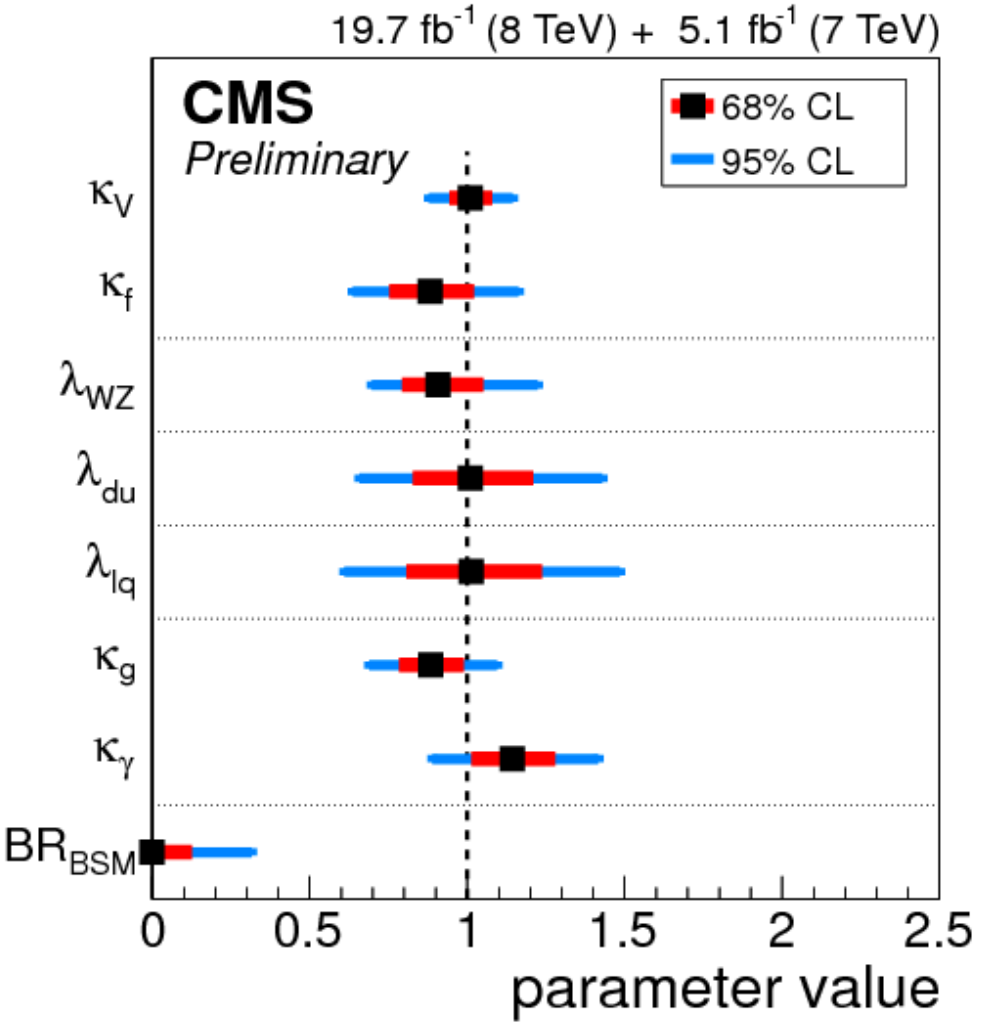
- Scaling the couplings to fermions (κ_f) and vector bosons (κ_V).
- **All decay channels converging around SM expectation.**



Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- Summary of the fits of **six benchmarks models** probing:
  - Fermions and vector bosons.
  - Custodial symmetry.
  - Up/down fermion coupling ratio.
  - Lepton/quark coupling ratio.
  - BSM in loops: gluons and photons.
  - Extra width: BR_{BSM}.
- **No significance deviations from SM.**

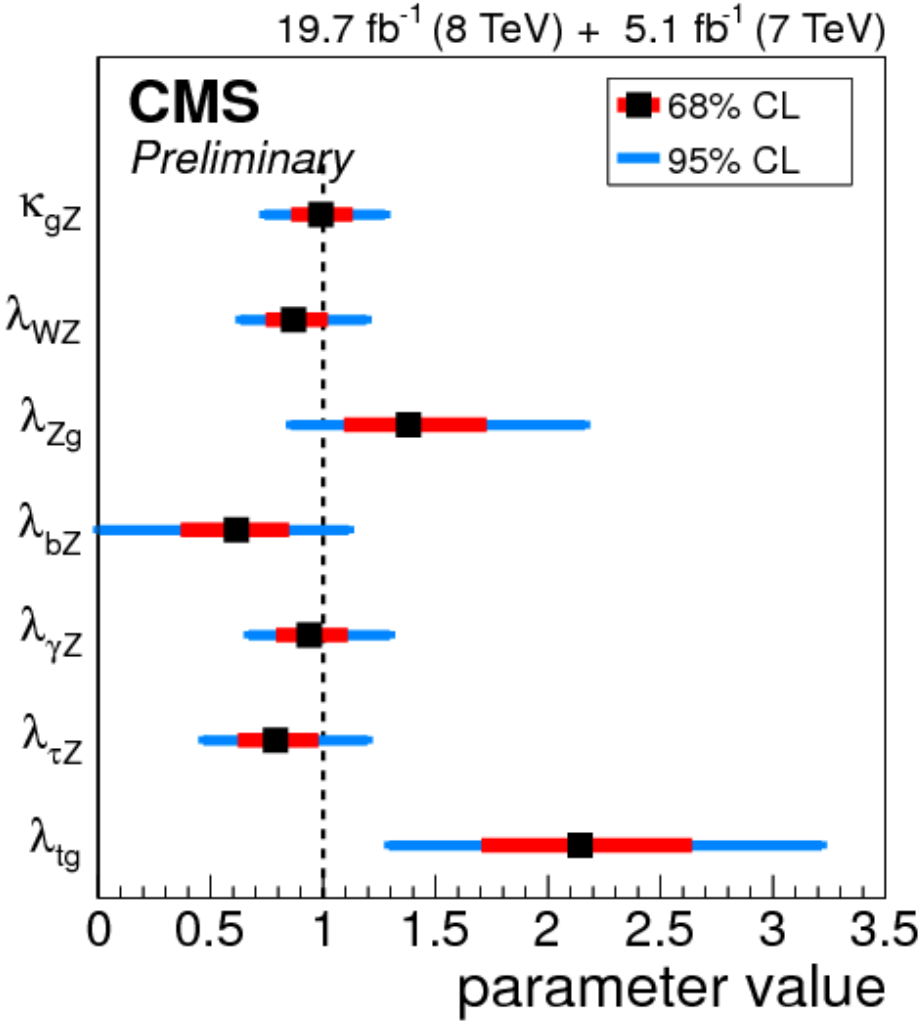


$\lambda_{xy} = \kappa_x/\kappa_y$

Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- Most general benchmark floating the total width.
  - Same ttH-related excess in $\lambda_{tg} = \kappa_{top}/\kappa_{gluon}$.

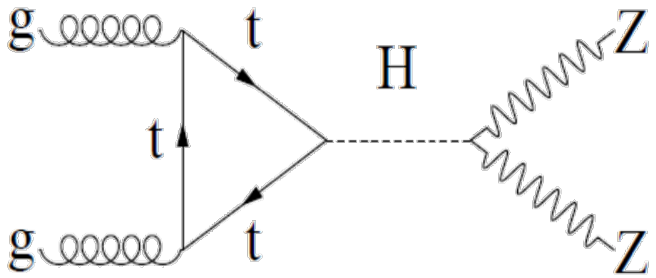


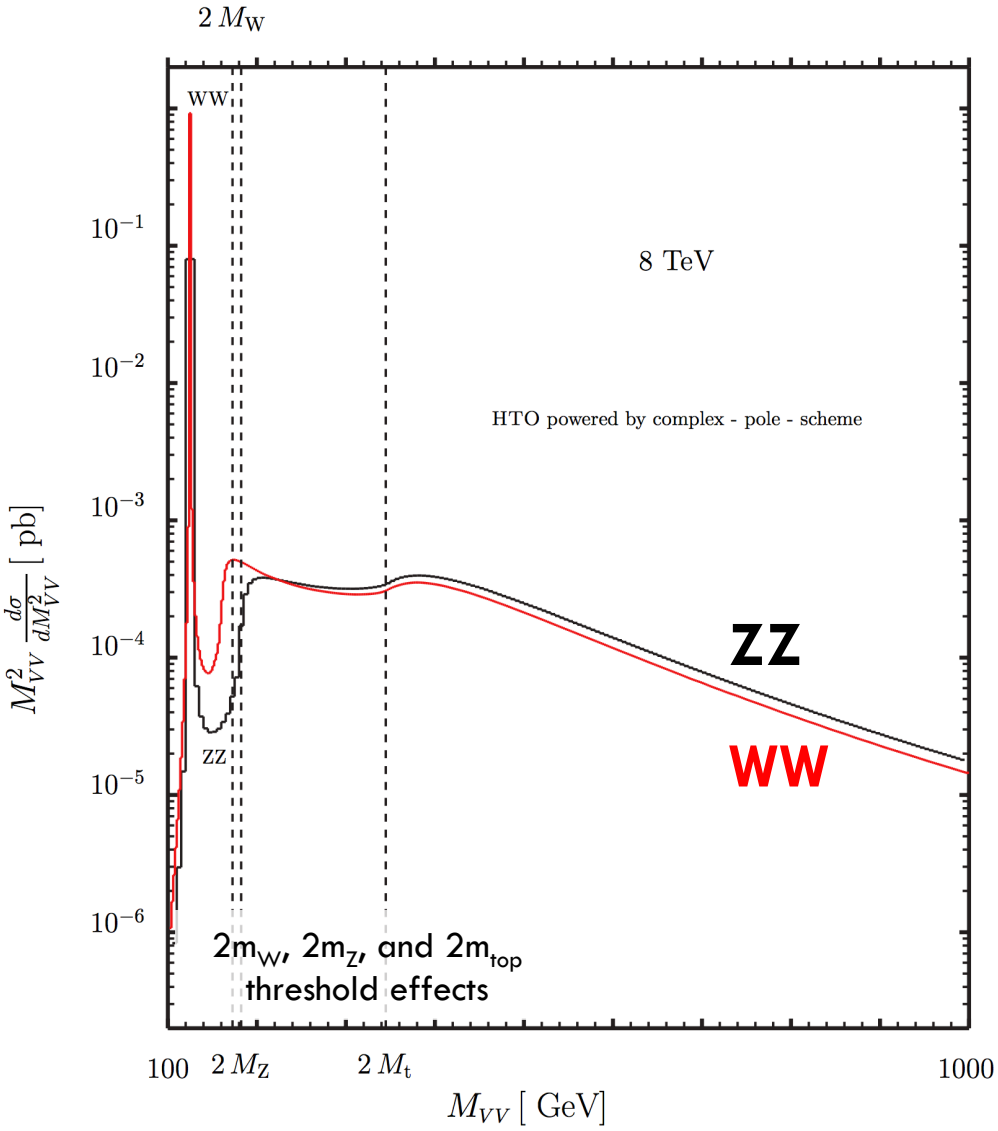
$\lambda_{xy} = \kappa_x/\kappa_y$; $\kappa_{xy} = \kappa_x\kappa_y/\kappa_H$

H* – going off-shell

[arXiv:1405.3455, accepted by PLB] [arXiv:1206.4803]

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$





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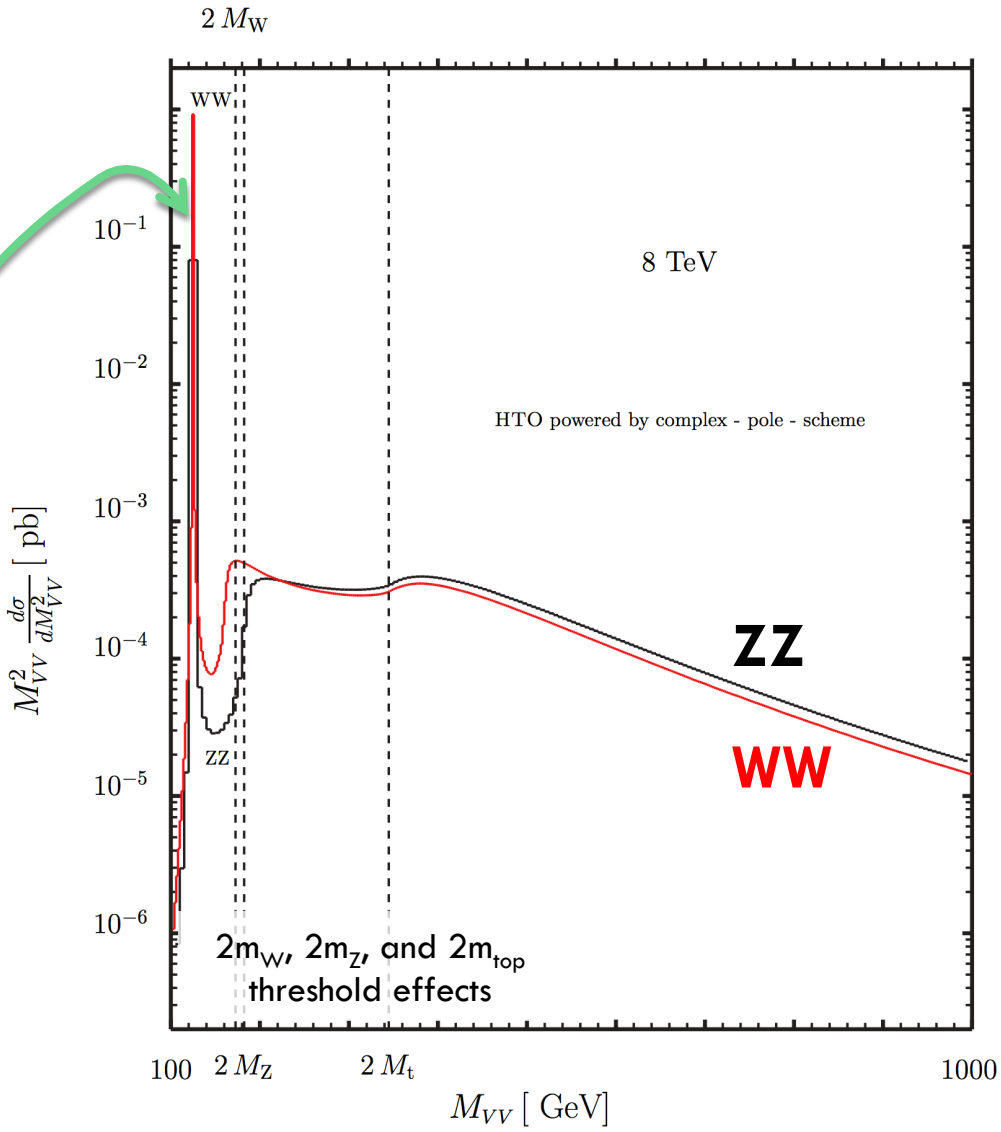
$m_{ZZ} \sim m_H$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$



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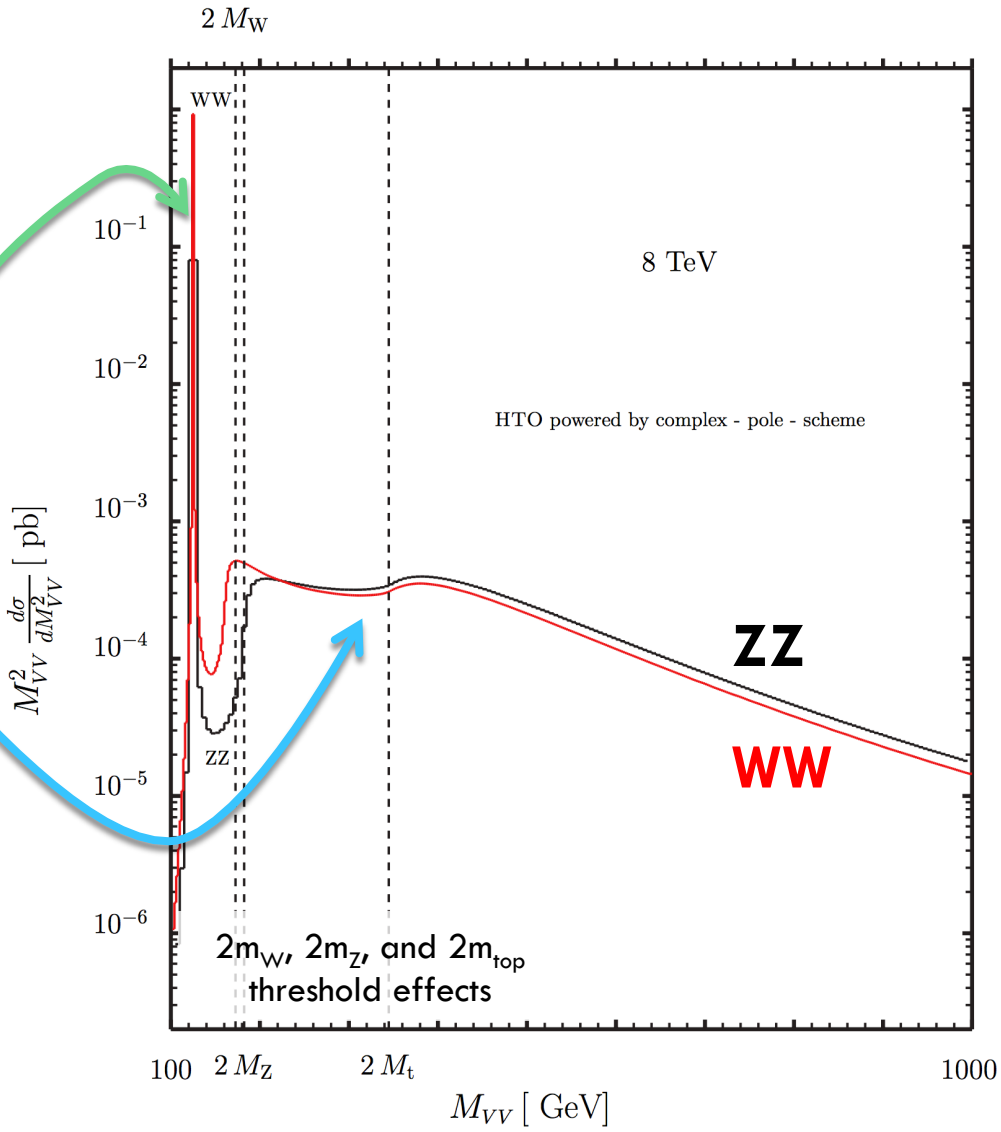
$m_{ZZ} \sim m_H$: $\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$

$m_{ZZ} \gg m_H$: $\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$



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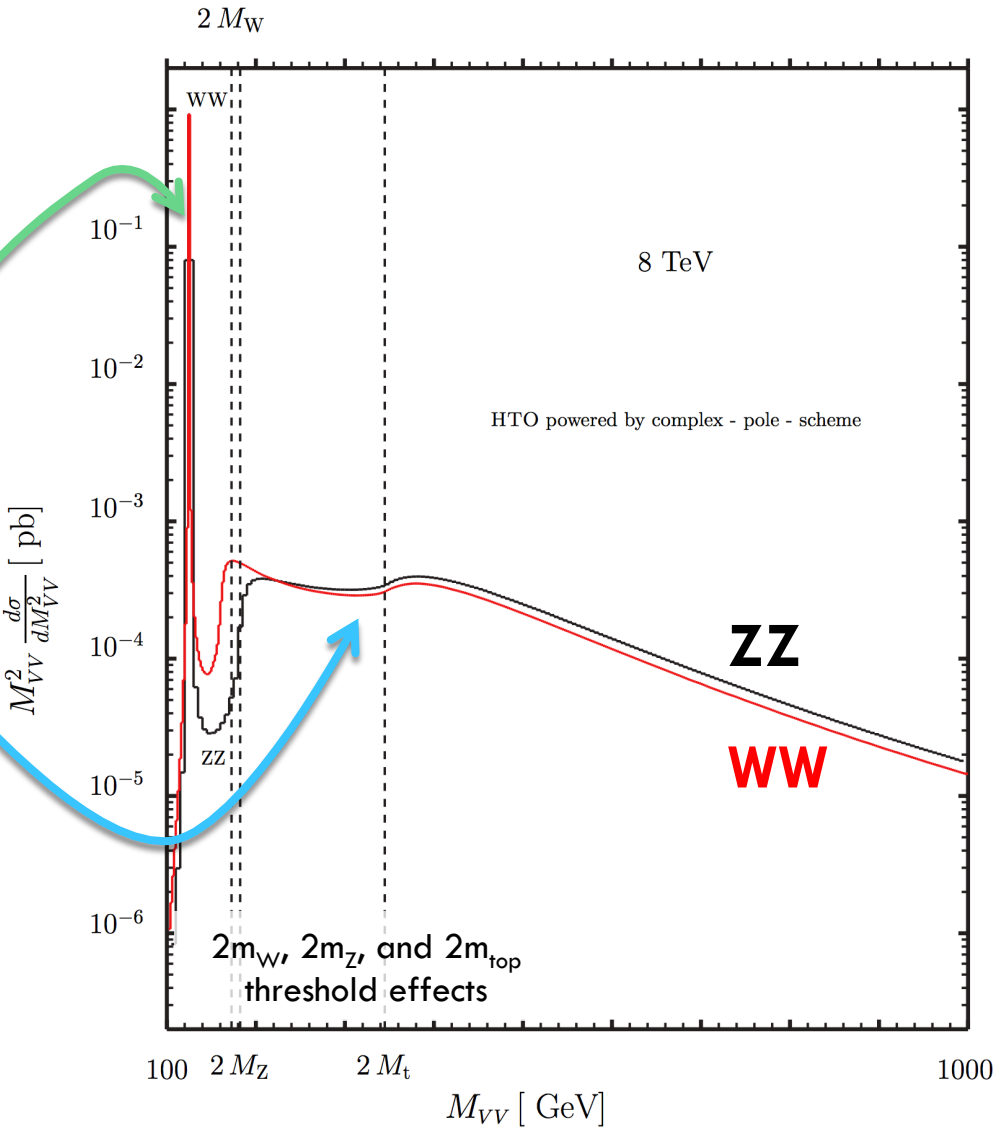
$m_{ZZ} \gg m_H$: $\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$

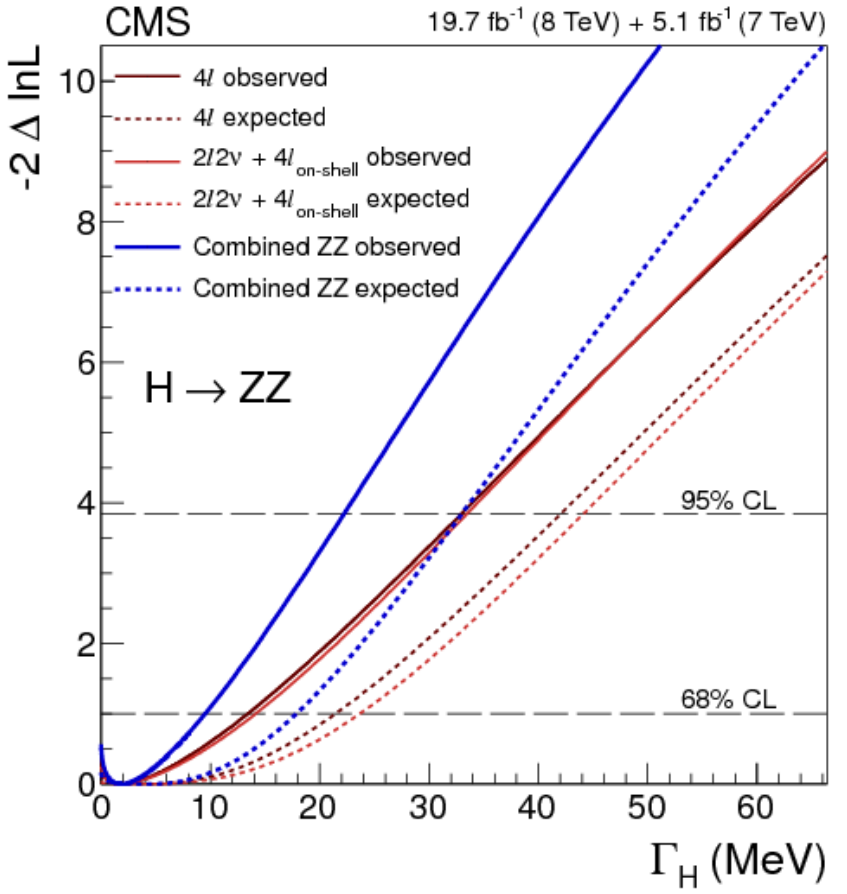
$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$



H* – off-shell decay to ZZ

[arXiv:1405.3455, accepted by PLB]

- Two channels exploited:
  - ZZ→4ℓ
    - 2D: $m_{4\ell}$ and gg vs. $q\bar{q}$ discriminant.
  - ZZ→2ℓ2ν
    - Jet-inclusive m_T shape.
- Observed limit lower than expected.



Obs. (exp.)	4ℓ	2ℓ2ν	Combined
Γ_H/Γ_H^{SM} (95% CL)	< 8.0 (10.1)	< 8.1 (10.6)	< 5.4 (8.0)

Spin zero amplitude in H→VV

[CMS-PAS-HIG-14-014]

- Anomalous couplings formalism:
  - a_1 is the SM amplitude.
  - Λ_1 is a higher-term of an expansion in momentum.
  - a_2 and a_3 control the CP-even and CP-odd amplitudes.
- Parameterized using fractions of cross-sections: f_{a1}, f_{a2}, f_{a3}, $f_{\Lambda 1}$.

$$
\begin{aligned}
A(X_{J=0} \rightarrow V_1 V_2) \sim\ & v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q^2_{Z_1} + q^2_{Z_2}}{(\Lambda_1)^2} \right] m_Z^2 \epsilon^*_{Z_1} \epsilon^*_{Z_2} \right. \\
& + a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu} \\
& + a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu} \\
& \left. + a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu} \right)
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& + \left. a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu} \right)
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$$+ a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu}$$
$$+ a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu}$$
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a_2 terms
CP-even (scalar)

Spin zero amplitude in H→VV

[CMS-PAS-HIG-14-014]

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$$+ a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu}$$

$$+ a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu}$$

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a_2 terms
CP-even (scalar)

a_3 terms
CP-odd
(pseudoscalar)

Spin zero amplitude in H→VV

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ZZ, WW: $+ \; a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu}$

Zγ*: $+ \; a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu}$

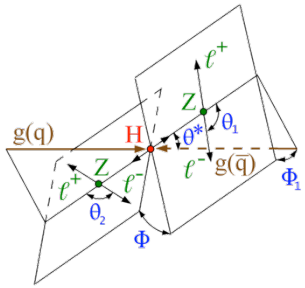
γ*γ*: $+ \; a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu} \Big)$

a_2 terms CP-even (scalar)

a_3 terms CP-odd (pseudoscalar)

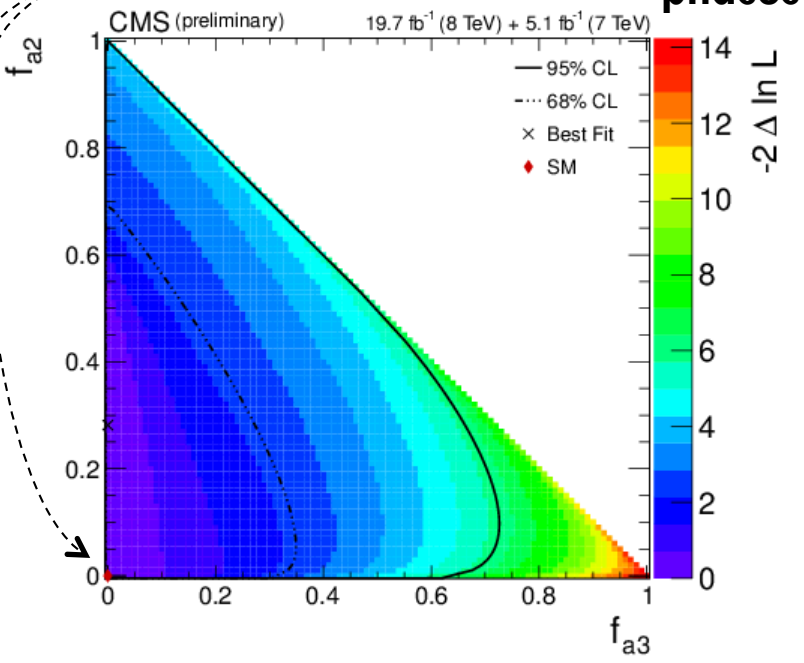
Spin zero amplitude in H→ZZ→4ℓ

[CMS-PAS-HIG-14-014]

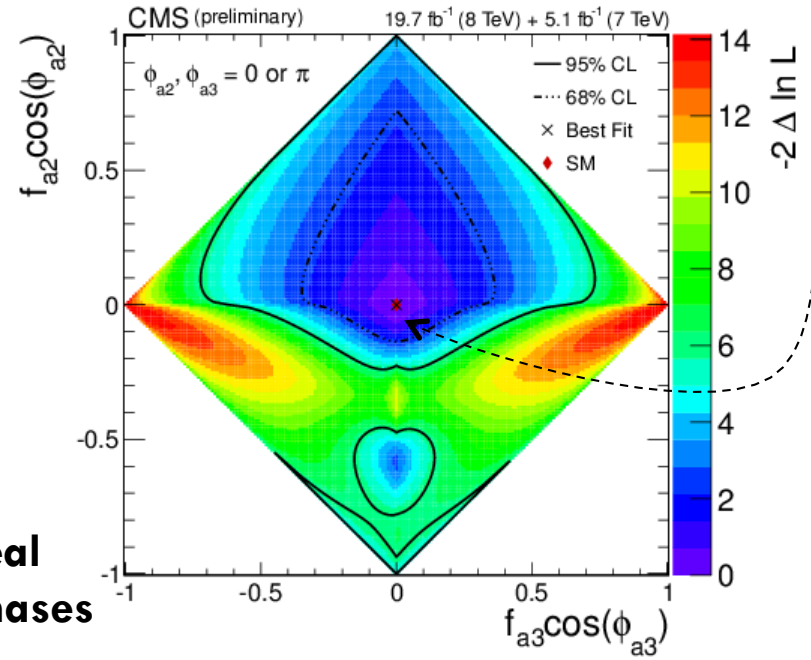


- Full final state available:
  - **Kinematic discriminants** reduce 8D to 2D or 3D.
- 2D scans of anomalous coupling fractions.
  - Assuming real phases and floating the phases.
- **No significant deviations from SM found.**

Floating phases



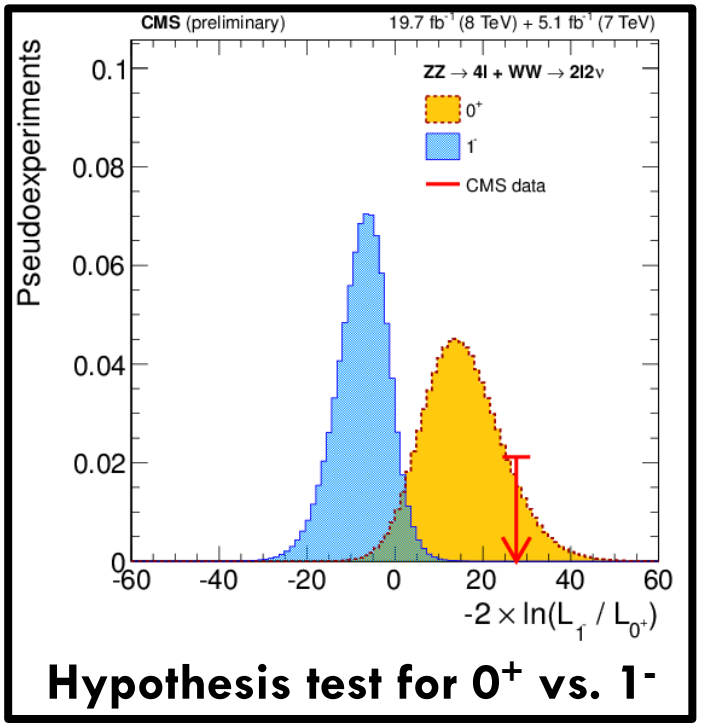
Real phases



H→VV combination on J>0 states

[CMS-PAS-HIG-14-012] [CMS-PAS-HIG-14-014]

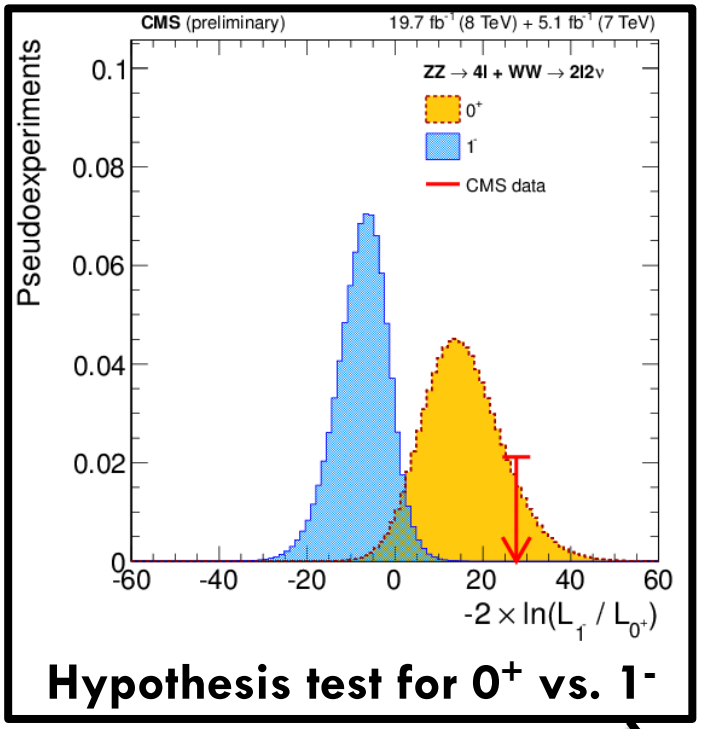
- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.

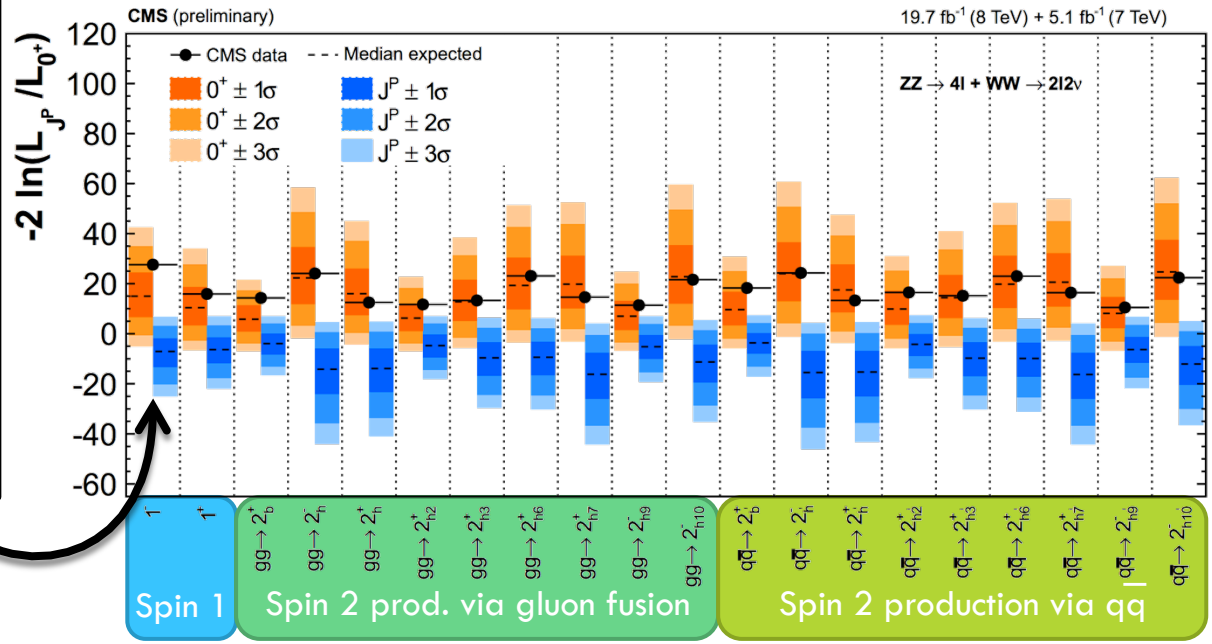


H→VV combination on J>0 states

[CMS-PAS-HIG-14-012] [CMS-PAS-HIG-14-014]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CL_S.





a.david@cern.ch

Other models?

[http://cern.ch/go/r8kv]

Fiat Turbina

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[http://cern.ch/go/r8kv]

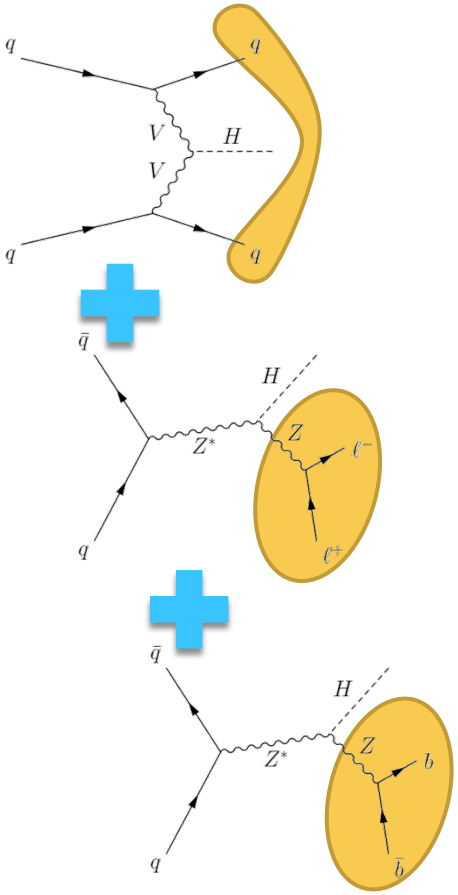
Fiat Turbina

Fiat Phylla at Triennale Design Museum (Milan), 2009.

Invisible Higgs search combination

[arXiv:1404.1344, submitted to EPJC]

- Combination of **VBF, Z(ℓℓ)H, and Z(b$\bar{\text{b}}$)H** searches: **BR(H→inv) < 0.58** (0.44 exp.) at 95% CL.



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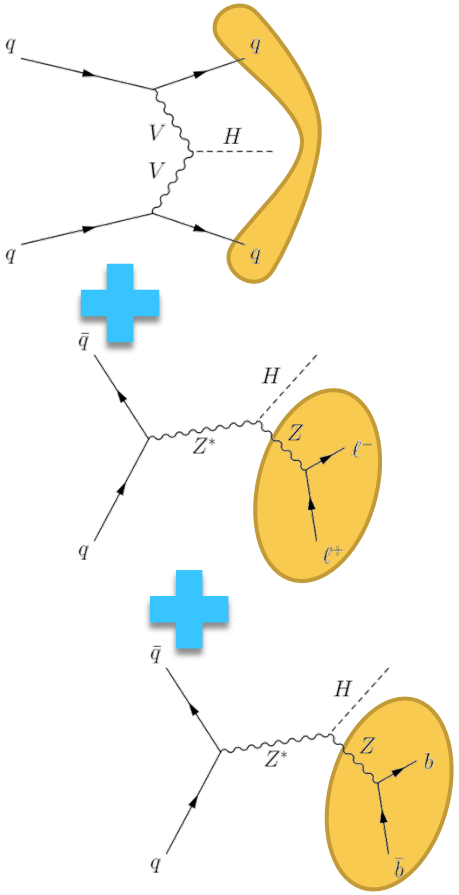
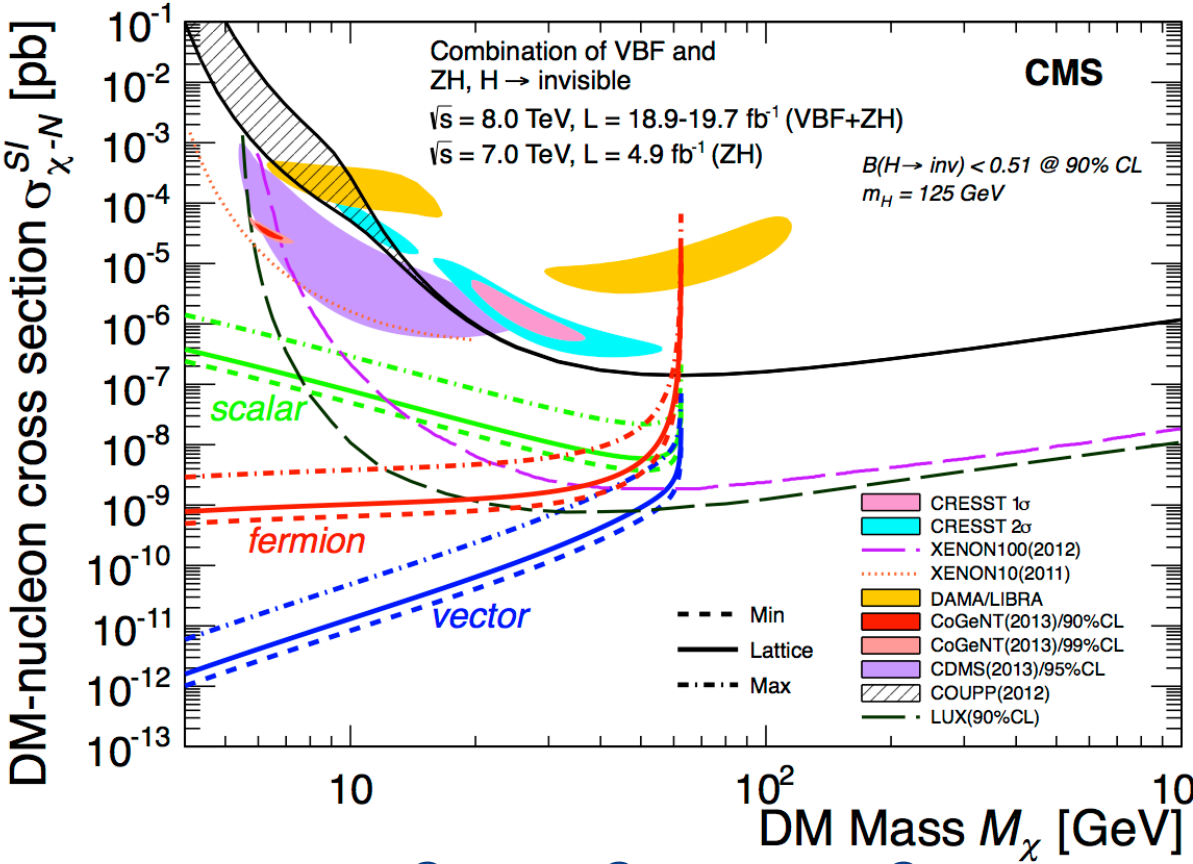
- Combination of **VBF, Z(ℓℓ)H, and Z(b$\bar{b}$)H** searches: **BR(H→inv) < 0.58** (0.44 exp.) at 95% CL.
- **Competitive limits for low mass DM in "Higgs portal" models.**



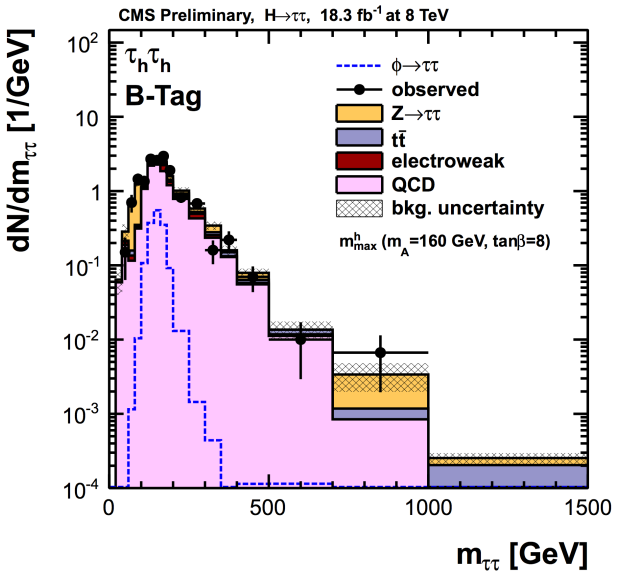


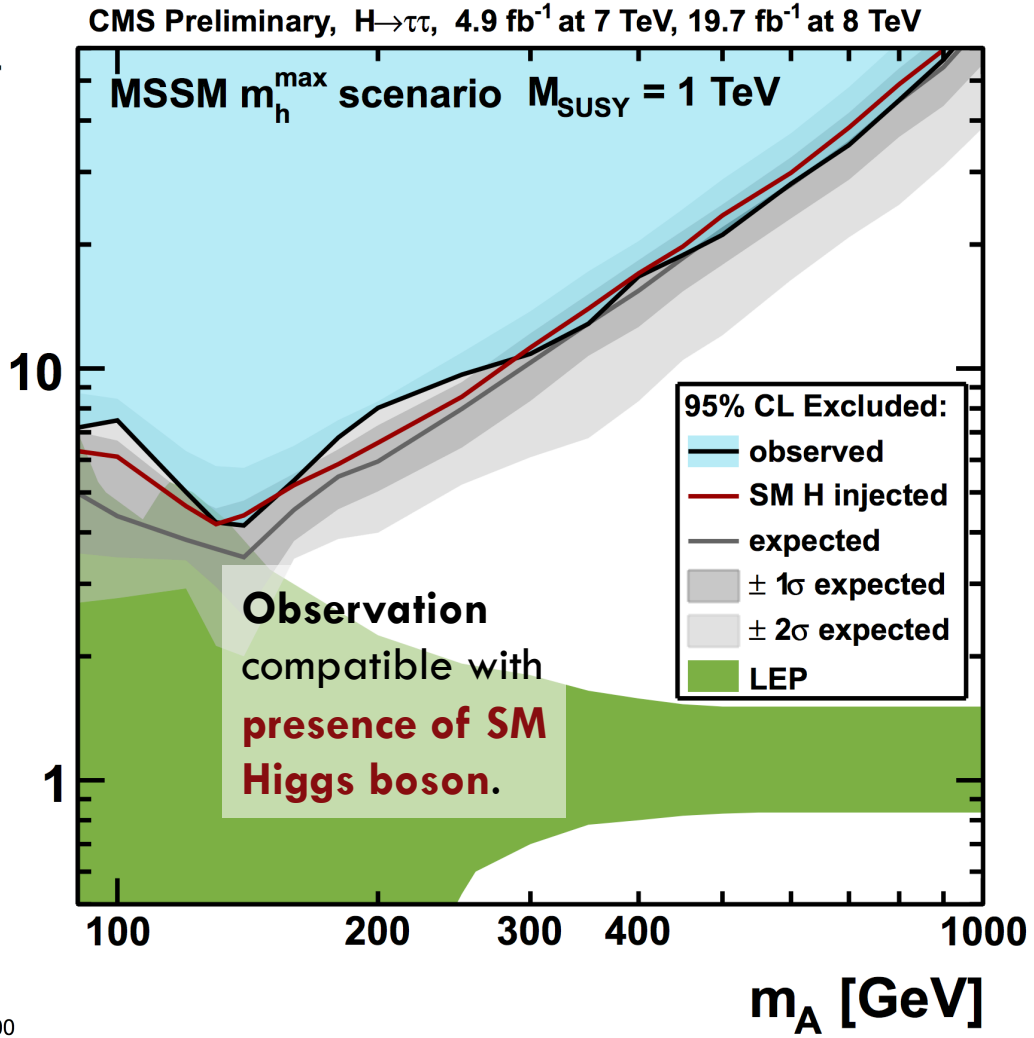
Search for MSSM $\Phi \rightarrow \tau\tau$

[CMS-PAS-HIG-13-021]

Not shown: model-independent limits on $gg \rightarrow \Phi$ and $gg \rightarrow \Phi b\bar{b}$.

- Minimal SuperSymmetric Model predicts:
  - **h^0, H^0, A^0: generically Φ.**
  - H^+ and H^-.
- Based on SM analysis but:
  - **Using extra b-tags (production).**
  - **Extended to up to $m_{\tau\tau}$ = 1.5 TeV:**





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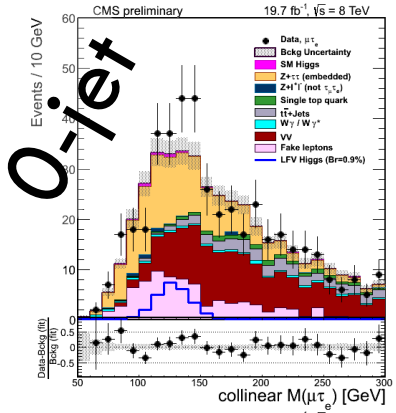
Search for H→μτ

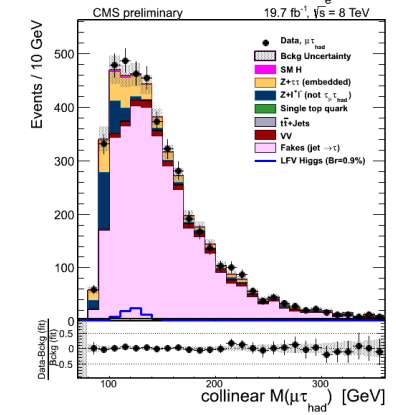
[CMS-PAS-HIG-14-005]

- **τ lepton flavor violation not as well constrained as μe (MEG).**
- Based on SM H→ττ analysis. **Different kinematics allows good SM H rejection.**
  - **BR(H→μτ) < 1.57%** at 95%CL (expected limit of 0.75%)

$\mu\tau_e$



$\mu\tau_{had}$



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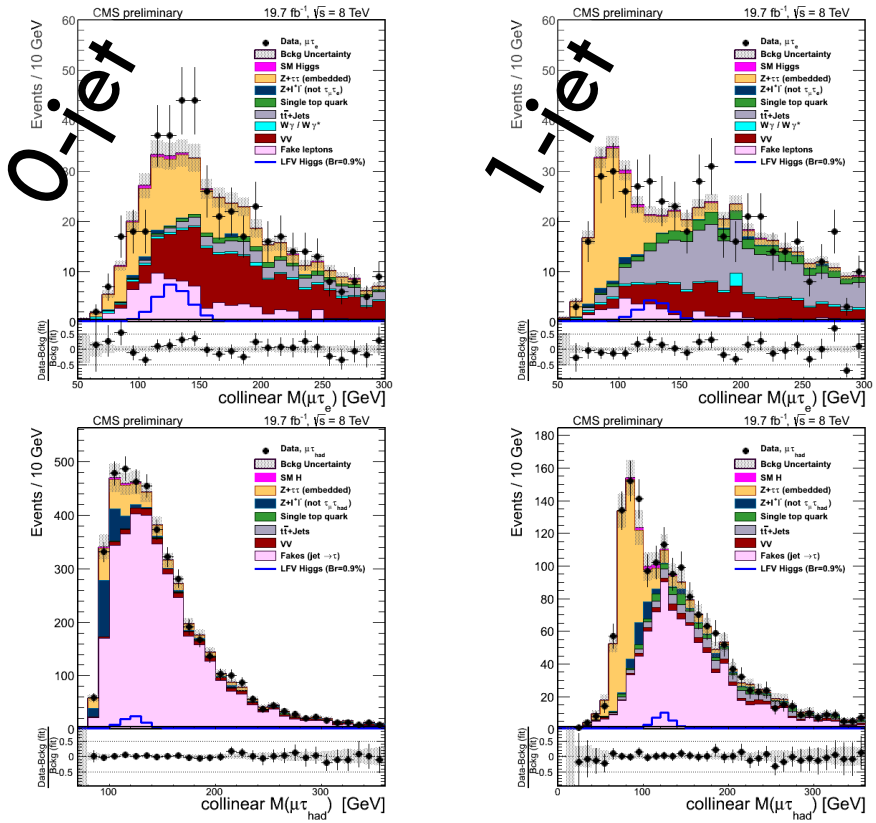

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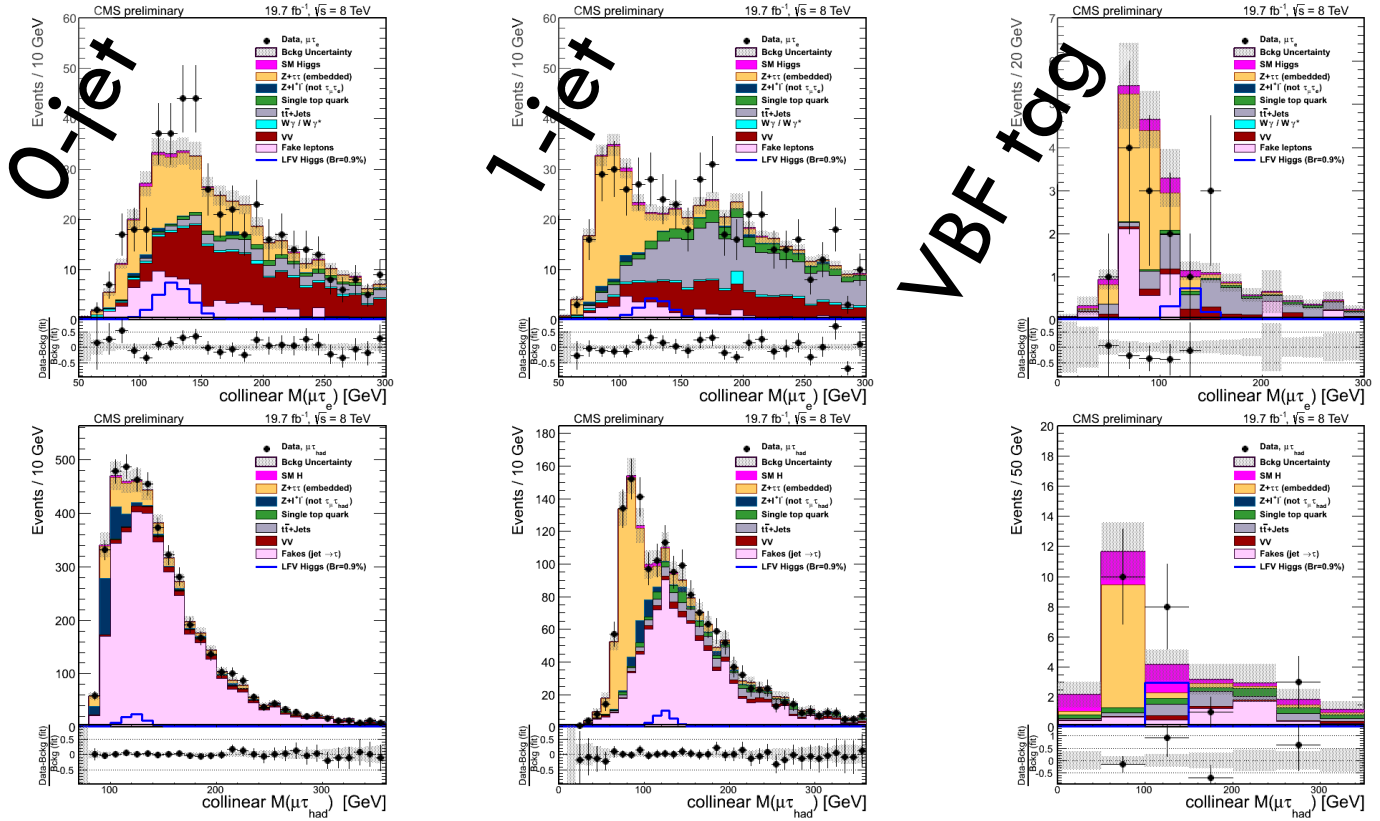
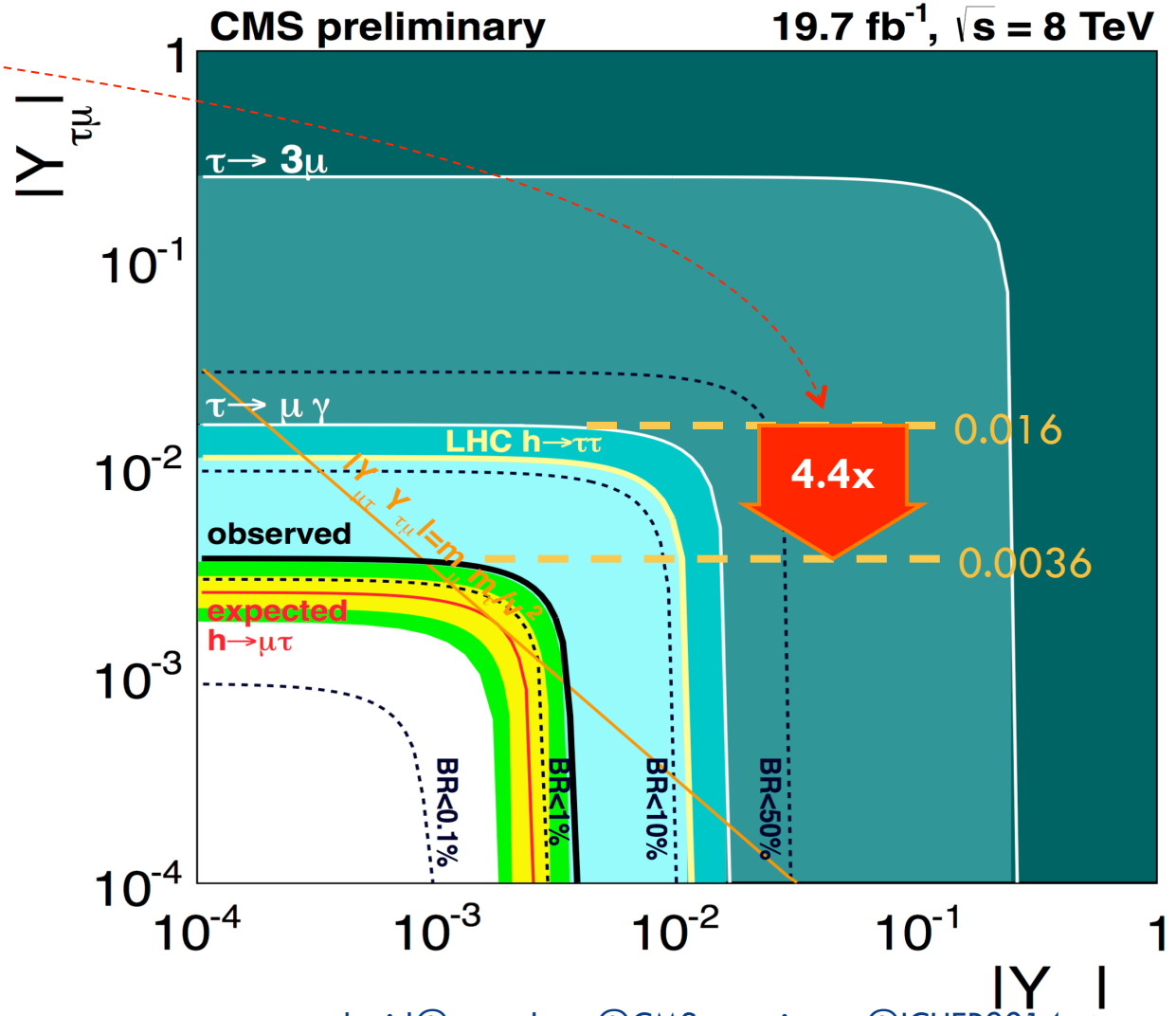


Search for H→μτ

[CMS-PAS-HIG-14-005]

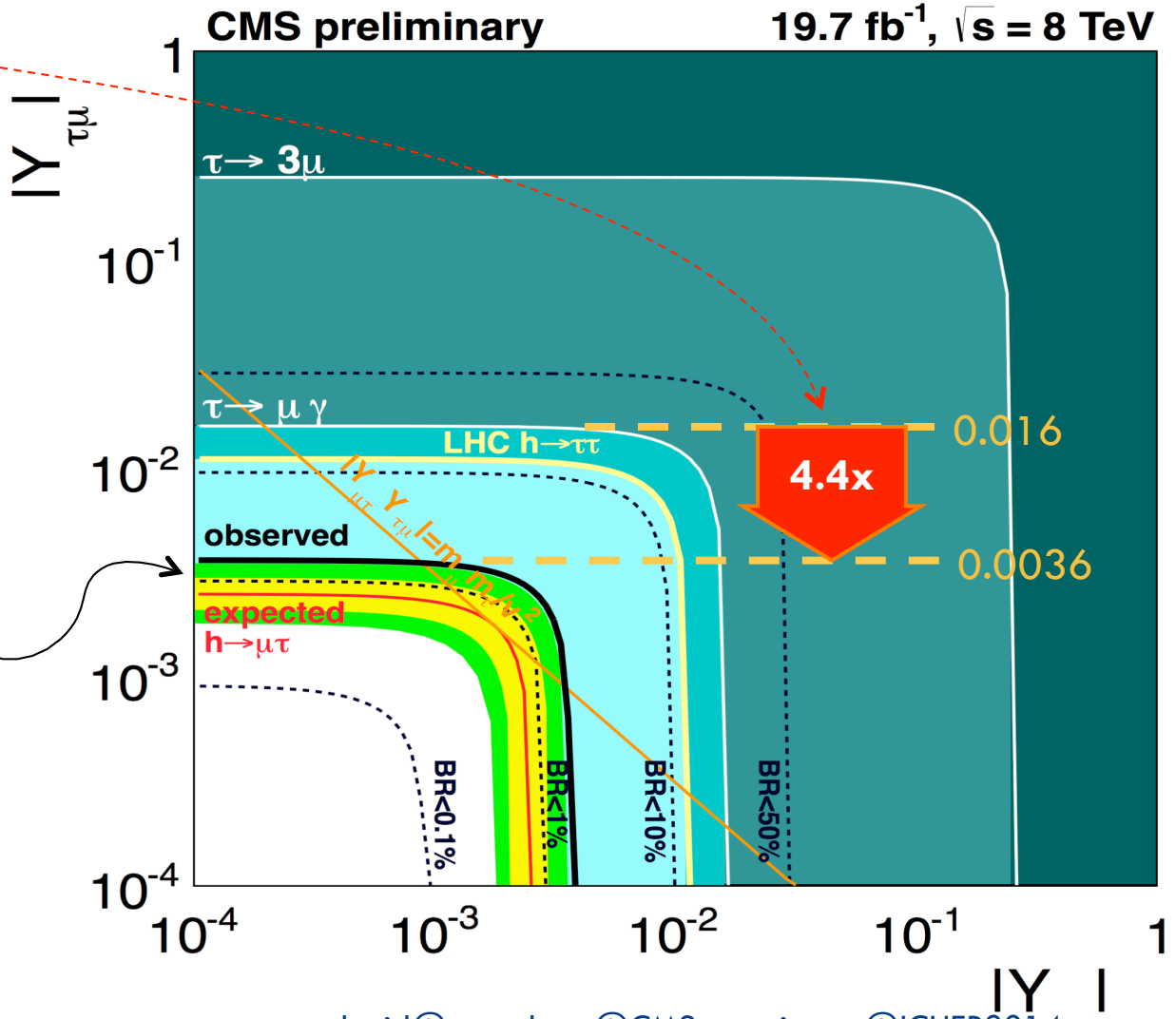
- **Best limits on τ anomalous Yukawa couplings.**



Search for H→μτ

[CMS-PAS-HIG-14-005]

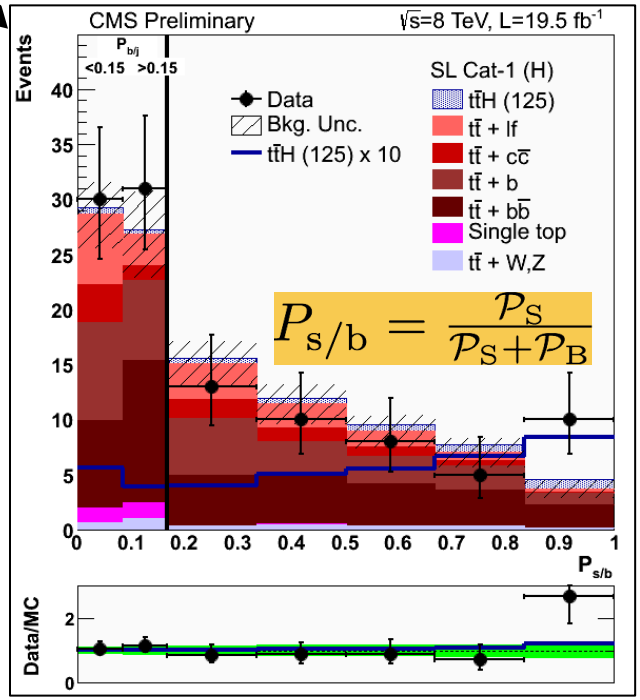
- **Best limits on τ anomalous Yukawa couplings.**
  - Higgs flavor sector could hold surprises.



New search for ttH with H→bb̄

[CMS-PAS-HIG-14-010]

- Improved performance:
  - Event probability ($P_{s/b}$) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified W→jj (**SL Cat-1**).
  - Reduced dependency on tt+HF modeling.
- **Clearly a hot topic for Run 2.**



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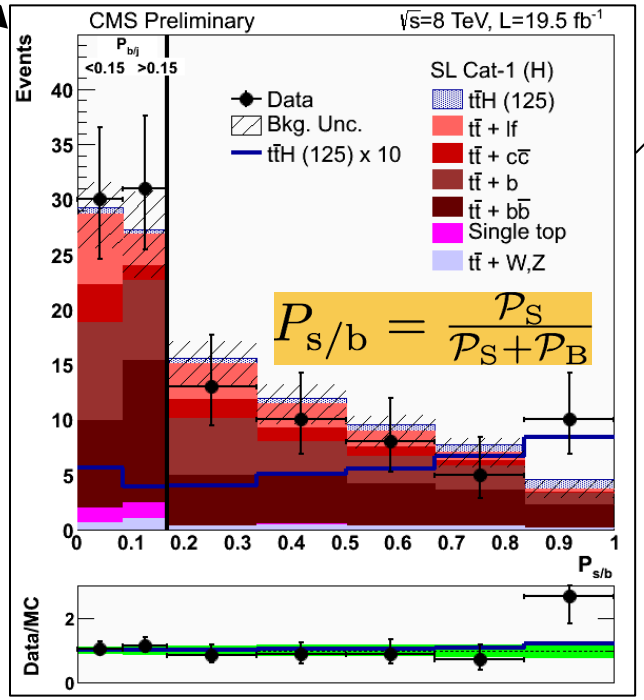
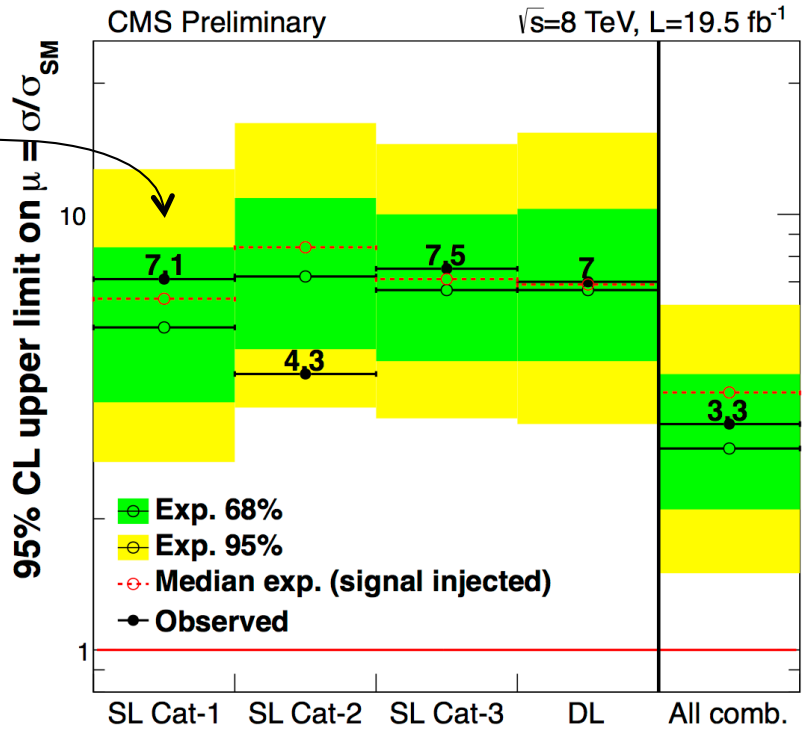
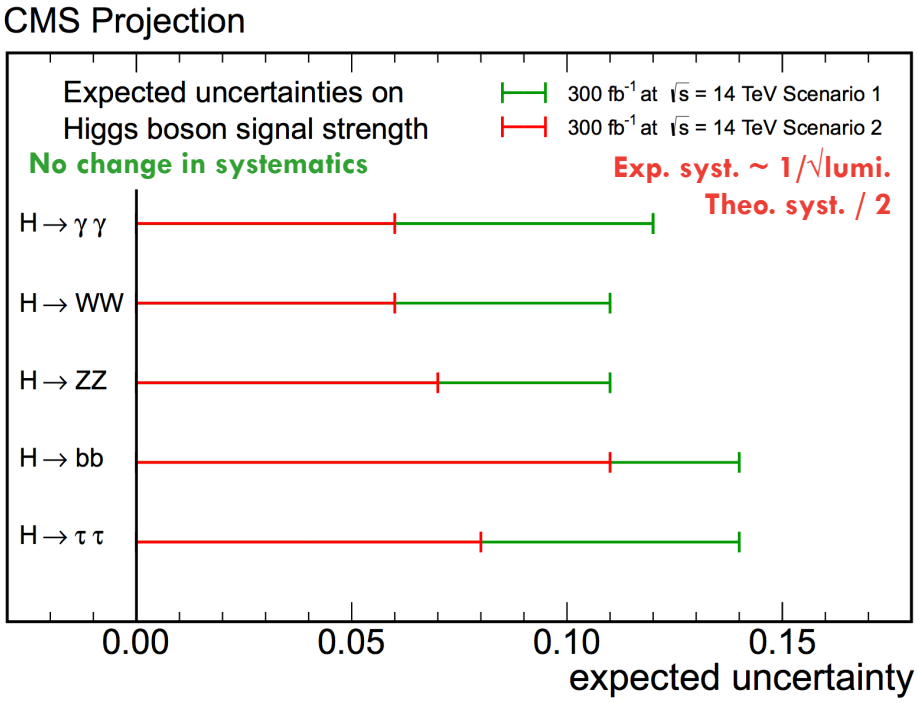




Looking ahead

[arXiv:1307.7135] [CMS-PAS-HIG-13-007]

- 300 fb^{-1} at 14 TeV:
  - Vast improvement over present datasets.
  - **Room for theory improvements.**



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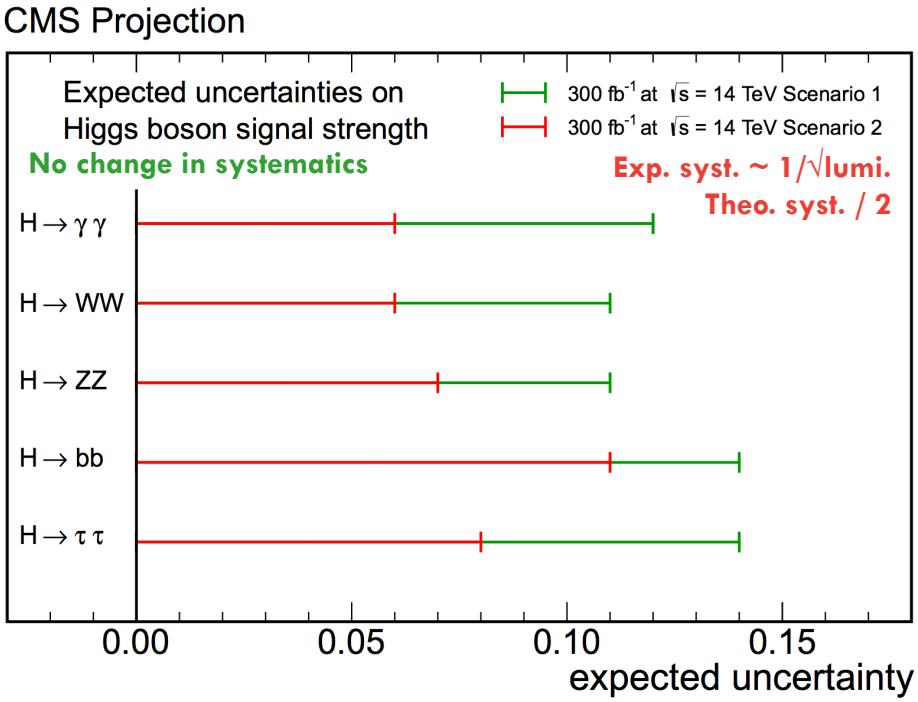
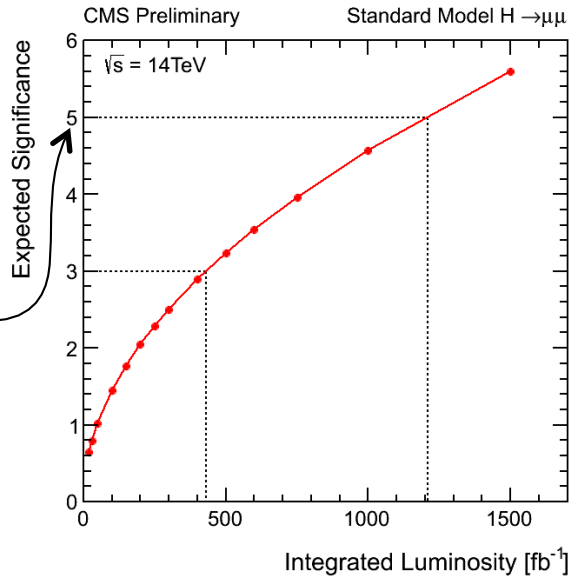
- For (HL-LHC) 3000 fb^{-1}:
  - **H→μμ at > 5σ.**
  - Can we get to the Higgs self-coupling?

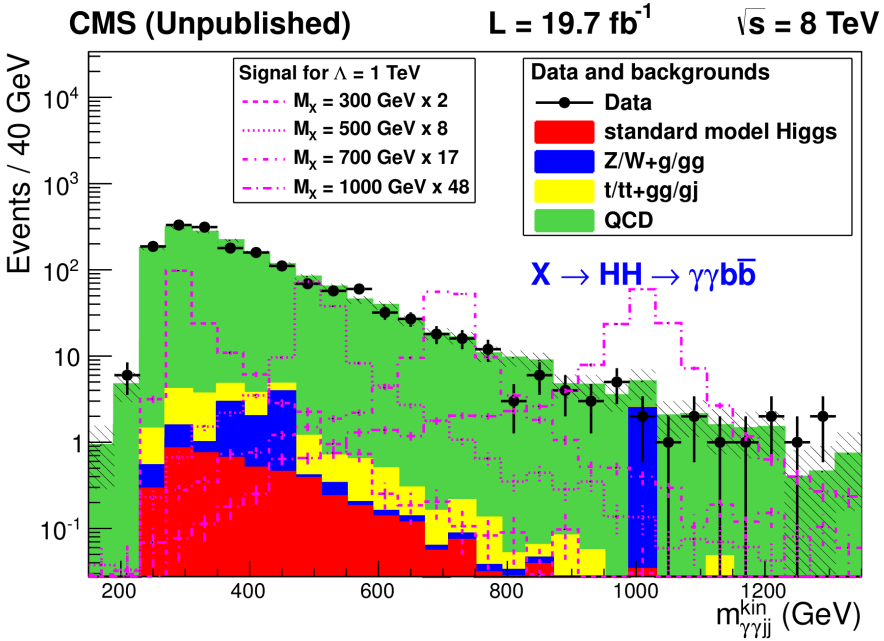




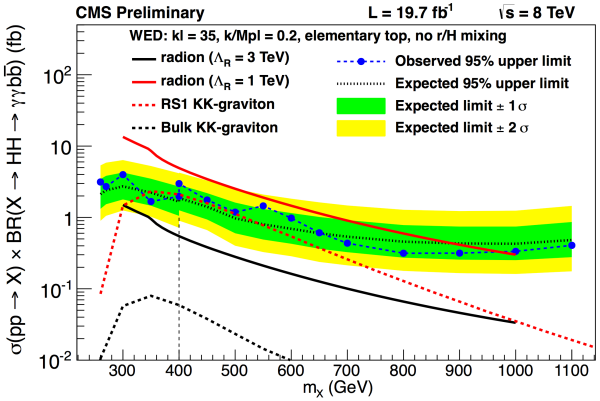
X→HH→bb̄γγ and the future

[CMS-PAS-HIG-13-032]

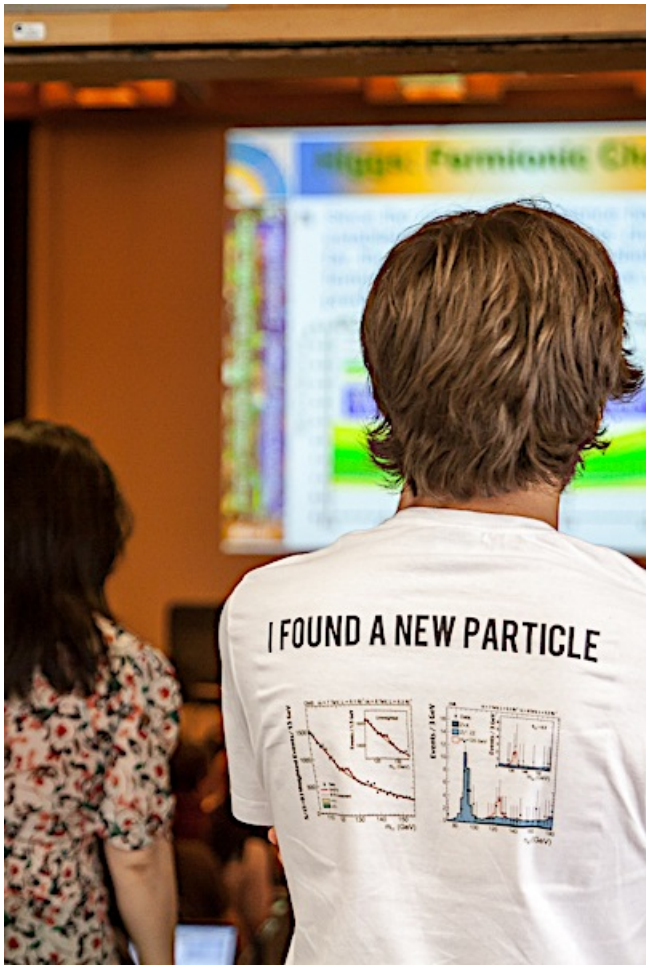
- **First step towards two-Higgs measurements at the HL-LHC.**



- For now setting limits on radion production from warped extra dimensions.



Summary



- **CMS closed a major chapter in the characterization of this Higgs boson.**
  - Main decay channels:
    - Final Run1 results published or submitted.
    - First combination of final results.
  - **Most precise Higgs mass measurement:**

$$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat.}) {}^{+0.13}_{-0.15}(\text{syst.}) \right] \text{GeV}$$

  - No new Higgs physics beyond the SM. Yet.

- **We continue to turn all stones.**
  - Few surprises need more work/data for a clear resolution.

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Conclusion

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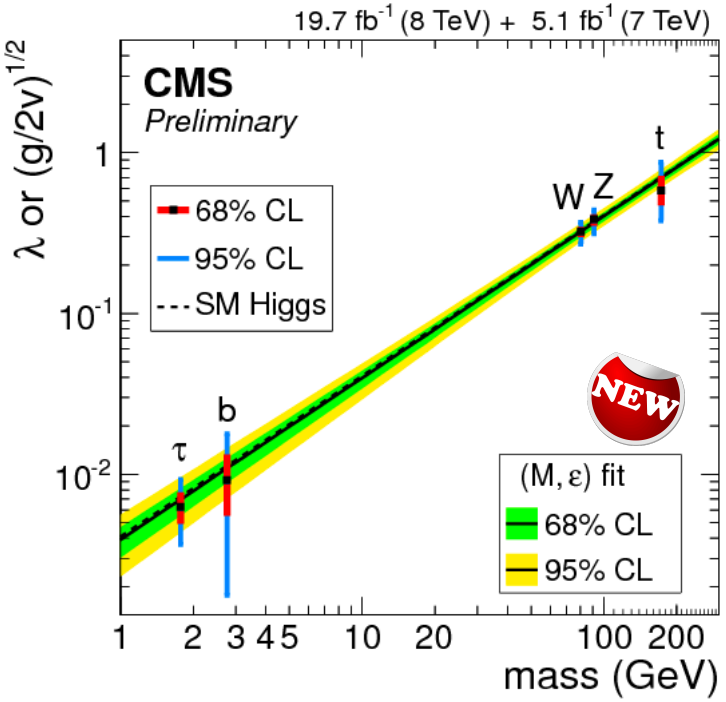
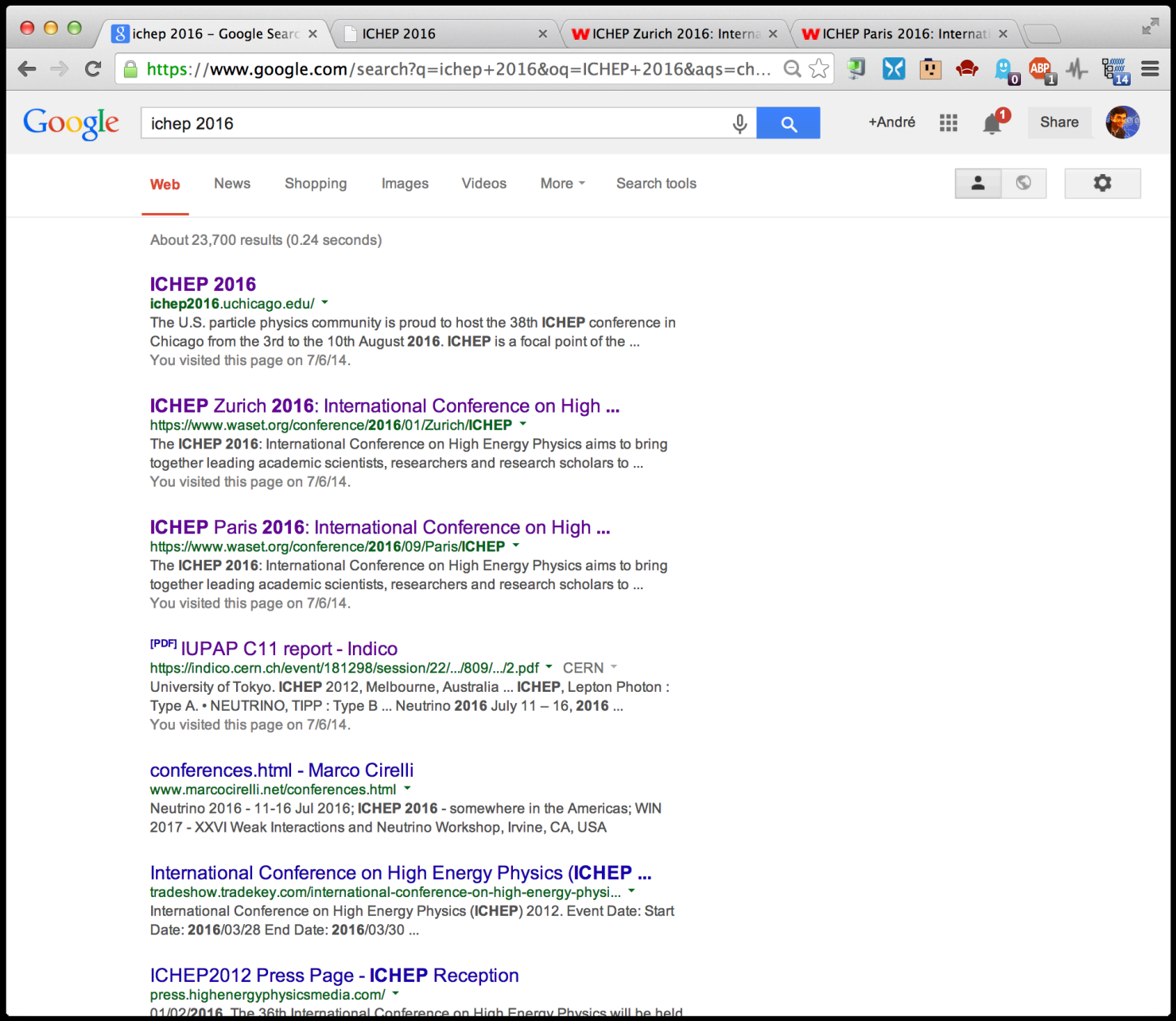


- **We've just started and there's a long and exciting way to go:**
  - Go from O(10%) measurements to differential.
  - Go from "seen" to O(%) measurements.
  - Go from limits on rare things to observations.
  - Reduce theory uncertainties.
  - Explore the full potential of the LHC and its upgrades.
- **All it takes is one deviation to point us on the right way beyond the SM.**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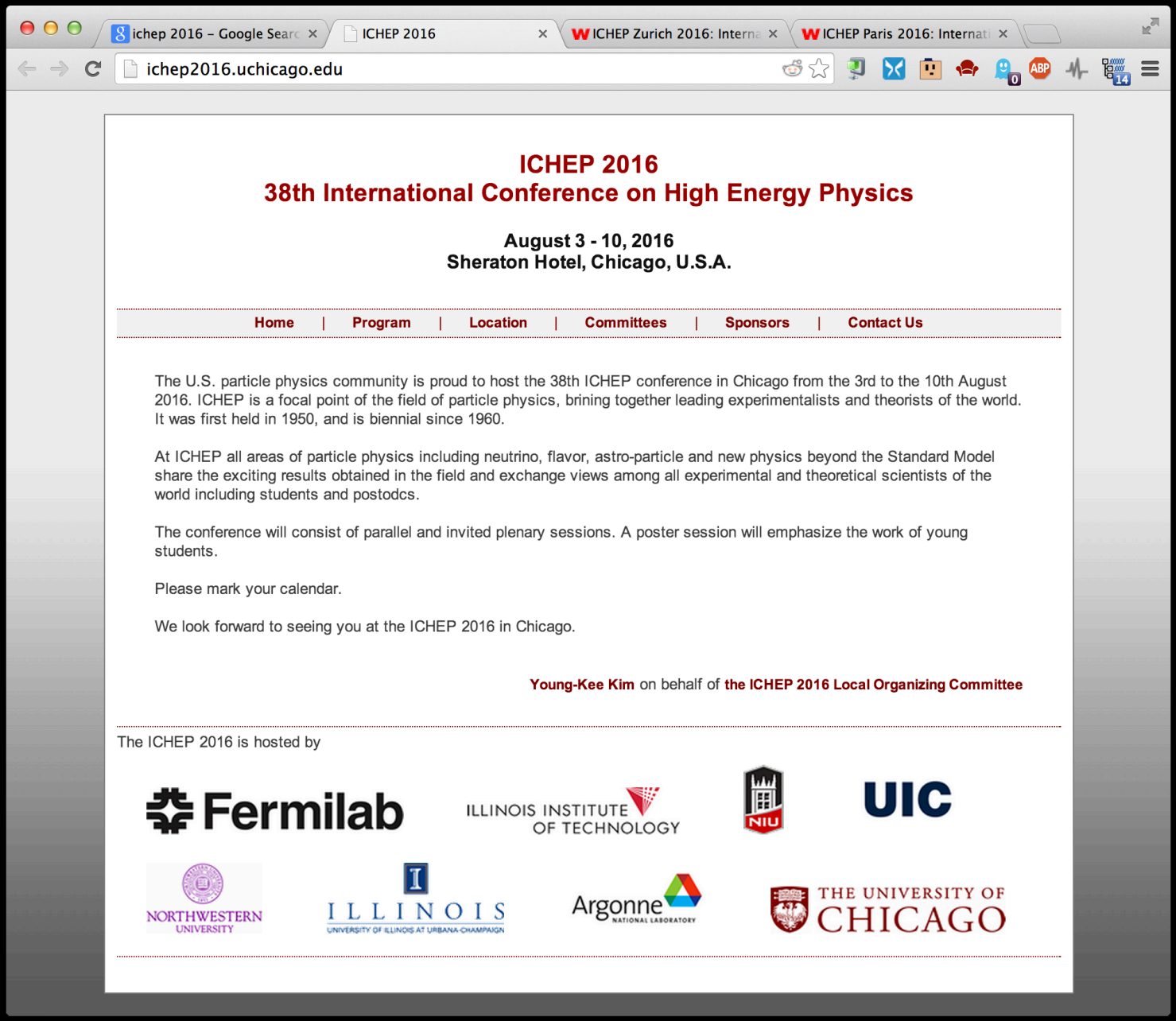
Neutrino 2016 - 11-16 Jul 2016; ICHEP 2016 - somewhere in the Americas; WIN 2017 - XXVI Weak Interactions and Neutrino Workshop, Irvine, CA, USA
International Conference on High Energy Physics (ICHEP ...
tradeshow.tradekey.com/international-conference-on-high-energy-physi...
International Conference on High Energy Physics (ICHEP) 2012. Event Date: Start Date: 2016/03/28 End Date: 2016/03/30 ...
ICHEP2012 Press Page - ICHEP Reception
press.highenergyphysicsmedia.com/
01/02/2016. The 36th International Conference on High Energy Physics will be held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- Conference Objectives
- Important Dates
- Call for Papers
- Conference Committee

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The **ICHEP 2016: International Conference on High Energy Physics** aims to bring together leading academic scientists, researchers and research scholars to exchange and share their experiences and research results about all aspects of High Energy Physics. It also provides the premier interdisciplinary and multidisciplinary forum for researchers, practitioners and educators to present and discuss the most recent innovations, trends, and concerns, practical challenges encountered and the solutions adopted in the field of High Energy Physics.

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We encourage you to contribute to and help shape the conference through paper submissions. For the technical research track, we invite high quality submissions of papers describing original and unpublished results of conceptual, constructive, empirical, experimental, or theoretical work in all areas of High Energy Physics. The conference solicits contributions of full-length papers, short papers, posters and abstracts, that address the themes and topics for the conference, including figures, tables and

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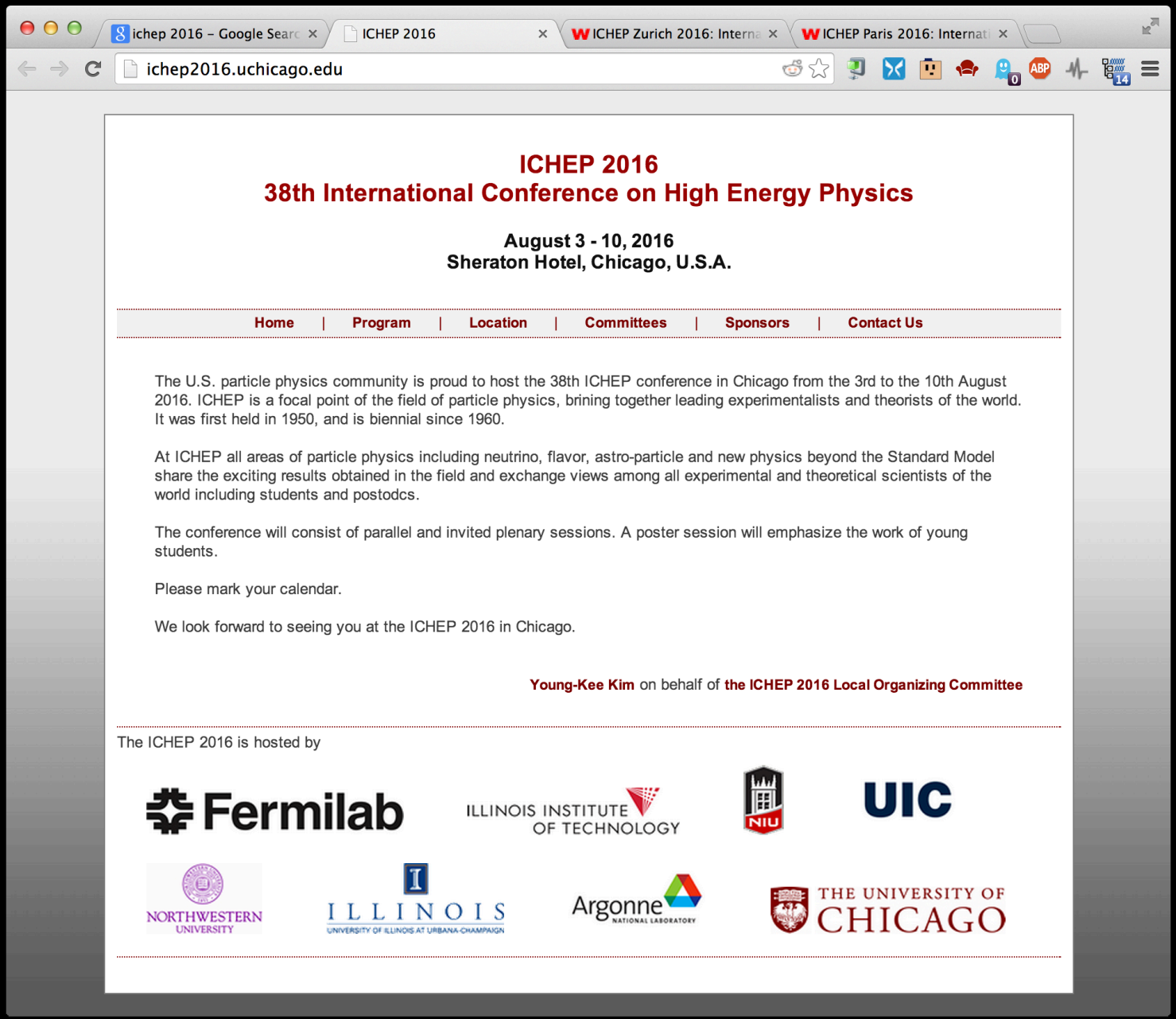
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18’000 hours from now in a conference 7’000 km away…

STAR HIGGS

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THE RETURN OF THE LHC

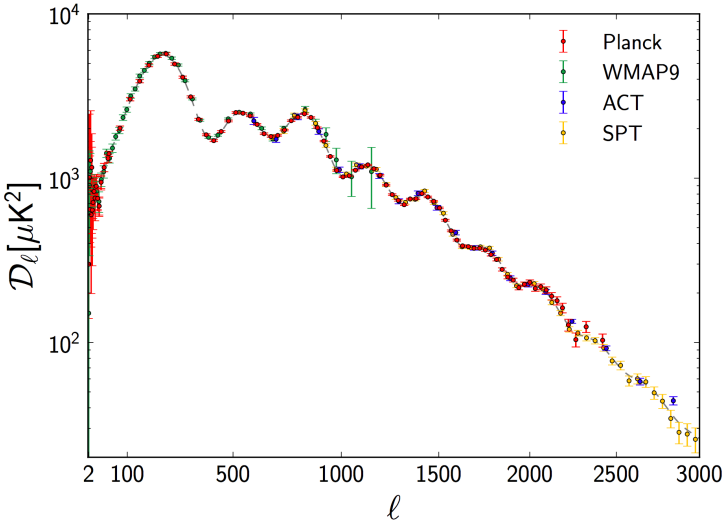
Connection to the Dark Universe ?
*Super*symmetry ?
*Compo*siteness ?
*Top-Higg*s coupling ?
More bosons ?
Deviations from SM ?

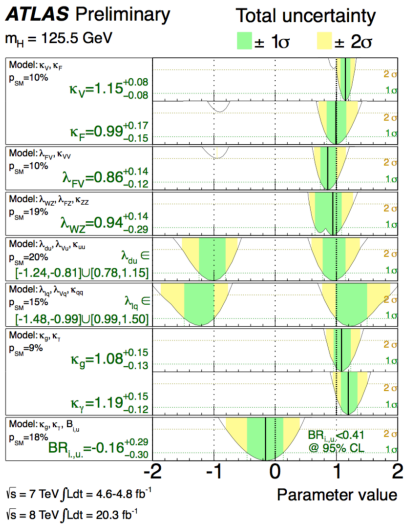
...

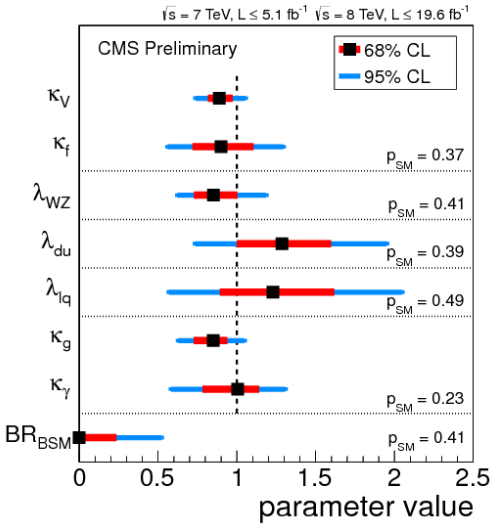
The ~~beautiful~~ ~~boring~~ 2014 Universe

[arXiv:1303.5062] [ATLAS-CONF-NOTE-2014-009] [CMS-PAS-HIG-14-009]

- **Up above:** "Simple six-parameter ΛCDM".
- **Down below:** (Not-as-simple) ~20-parameter Standard Model of Particle Physics.







Looking forward to LHC combination and surprises at higher energy: PeV neutrinos, LHC 13 TeV, …

Further reading

"…and references therein."

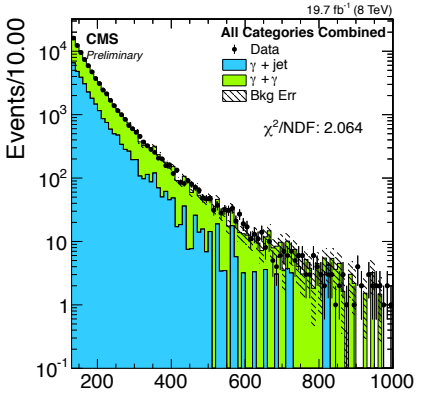
- All CMS Higgs results: http://cern.ch/go/6qmZ
  - **Results released during ICHEP 2014:**

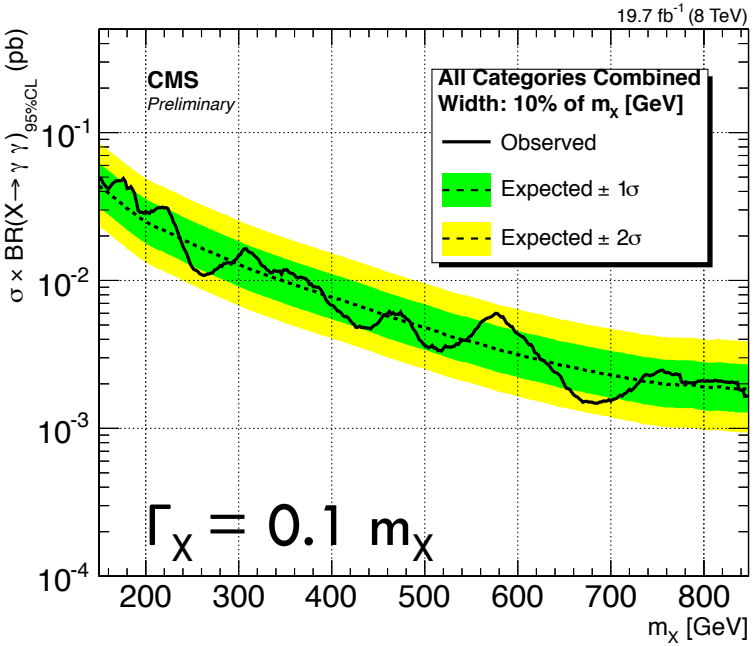
- "Observation of the diphoton decay of the Higgs boson and measurement of its properties"
  arXiv:1407.0558, submitted to EPJC
- "Precise determination of the mass of the Higgs boson and studies of the compatibility of its couplings with the standard model"
  CMS-PAS-HIG-14-009, http://cds.cern.ch/record/1728249
- "Constraints on anomalous HVV interactions using H to 4ℓ decays"
  CMS-PAS-HIG-14-014, http://cds.cern.ch/record/1728251
- "Constraints on Anomalous H→WW Interactions using Higgs boson decays to W^+W^- in the fully leptonic final state"
  CMS-PAS-HIG-14-012, http://cds.cern.ch/record/1728250
- "Search for Lepton Flavour Violating Decays of the Higgs Boson"
  CMS-PAS-HIG-14-005, http://cds.cern.ch/record/1740976
- "Search for ttH production using the Matrix Element Method"
  CMS-PAS-HIG-14-010, http://cds.cern.ch/record/1728332
- "Search for an Higgs Like resonance in the diphoton mass spectra above 150 GeV"
  CMS-PAS-HIG-14-006, http://cds.cern.ch/record/1714076
- "Search for $H^+ \rightarrow cs$ decay"
  CMS-PAS-HIG-13-035, http://cds.cern.ch/record/1728343

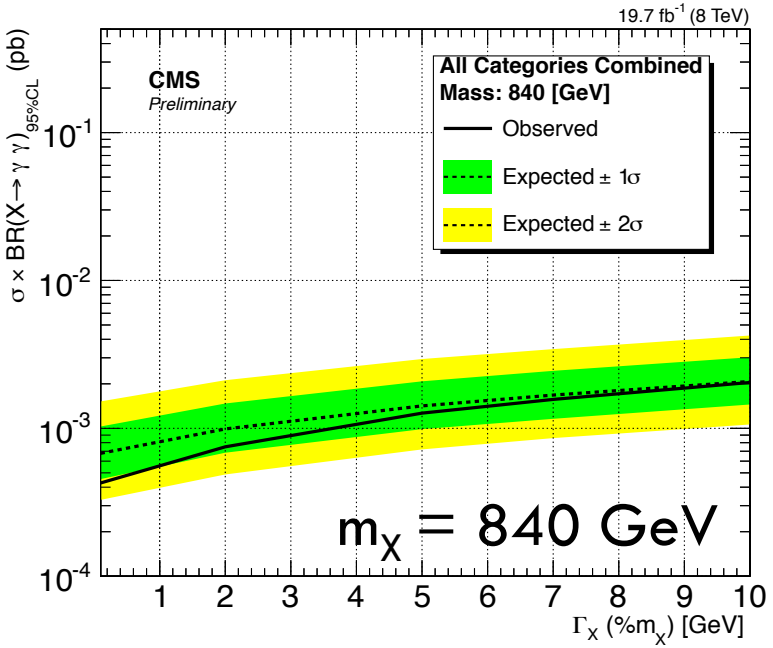
High-mass diphoton searches

[CMS-PAS-HIG-14-006]

- Simplified cut-based selection.
- Signal model: double Crystal-Ball ⊗ Breit-Wigner.
  - Signal width and mean scale appropriately with m_H.
- **Limits on σ×BR as a function of Γ_X and m_X.**

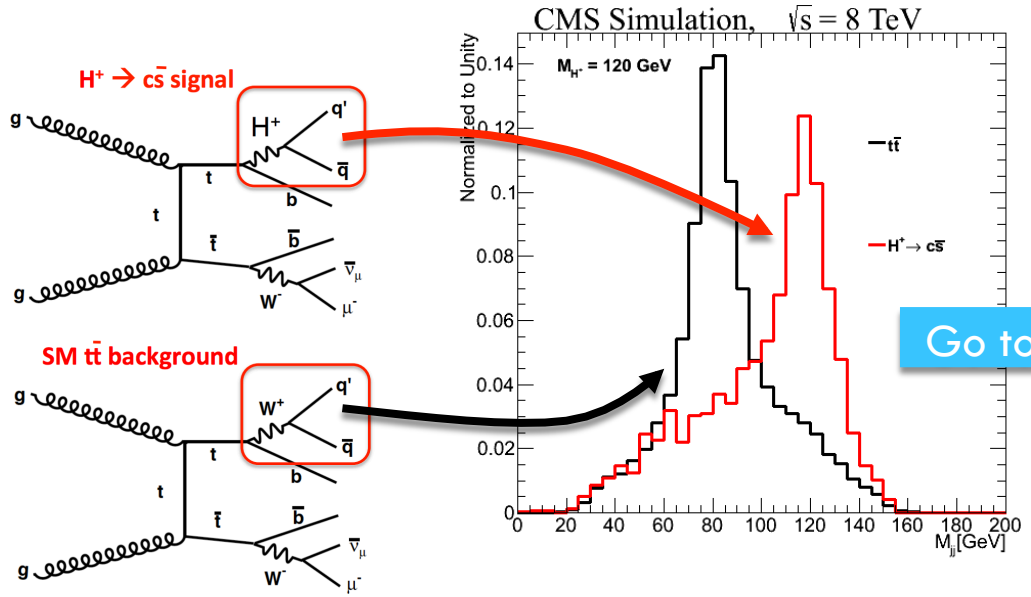




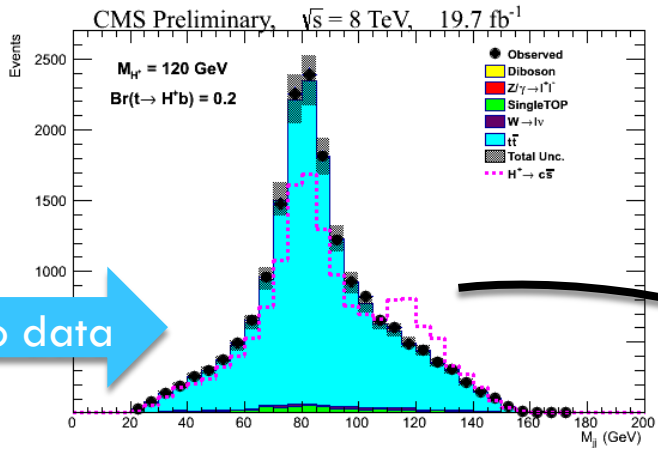


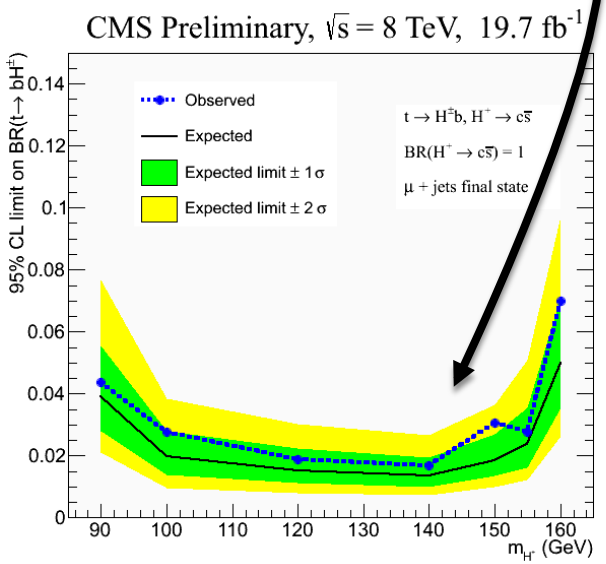
$H^+ \rightarrow cs$ in decays of $t \rightarrow H^+ + b$

[CMS-PAS-HIG-13-035]



Go to data





- 2 jets + 2 b-tagged jets + lepton and MET.
- Mass reconstructed using m_W and m_t constraints and likelihood fit.

More turned stones

- MSSM $\Phi \rightarrow b\bar{b}$
  PLB 722 (2013) 207
- MSSM $\Phi \rightarrow \mu\mu$
  CMS-PAS-HIG-12-011,
  http://cds.cern.ch/record/1453716
- NMSSM $H \rightarrow 4\mu + X$ short-lived
  CMS-PAS-HIG-13-010,
  http://cds.cern.ch/record/1563546

For discussion

CMS ECAL operation and calibration

The path towards the ultimate Run 1 photon energy determination.

Challenges of *in situ* operations

Light yield variations:

- scintillation light → temperature dependence: $\Delta S/S \sim -2\%/^{\circ}\mathrm{C}$ @ 18 °C
- crystal transparency → radiation dose-rate dependence

Photo-detector response:

- APD → gain temperature dependence: $\Delta G/G \sim -2\%/^{\circ}\mathrm{C}$
  gain High-Voltage dependence: $\Delta G/G \sim 3\%/\mathrm{V}$
  direct ionization effects, a.k.a. "spikes"
- VPT → response dependence on the incremental charge at the cathode

Tracker material in front of ECAL:

- photon conversions
- bremsstrahlung losses for electrons

3.8 T solenoidal magnetic field:

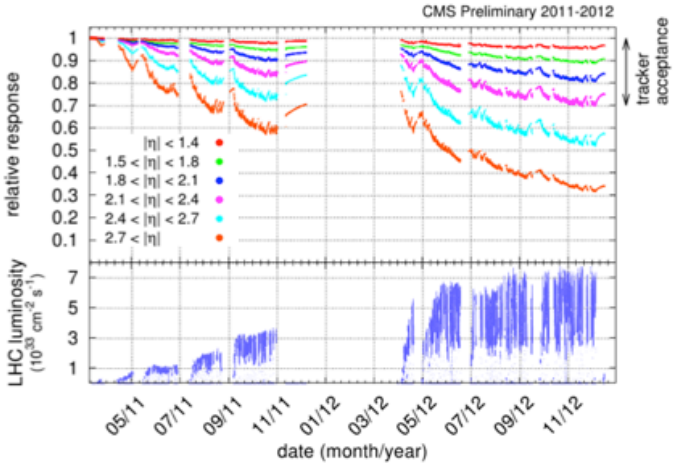
- spread of the e, γ energy along φ, at $\approx$ constant η

→ **Excellent environmental stability** (×2 to ×3 better than required) [3]
→ **Dedicated monitoring system and calibration techniques** [4, 5]
→ **Specific energy reconstruction algorithms and corrections**

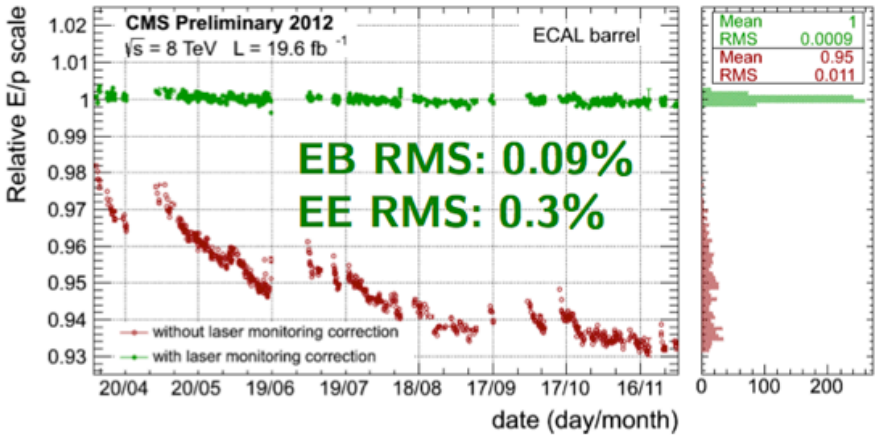
[http://cern.ch/go/PT9c]

Monitoring and calibration signals

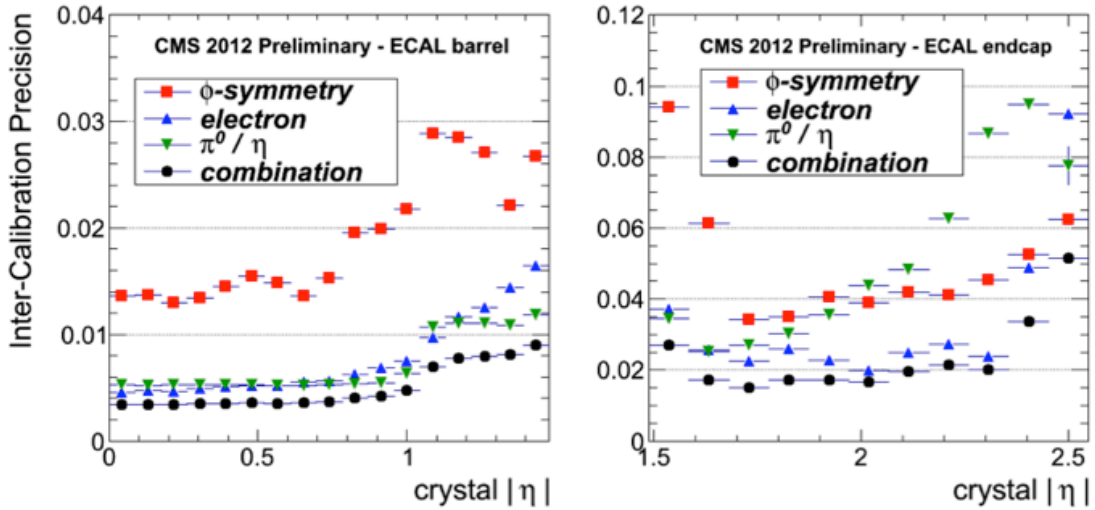
Laser monitoring measurements



Validation of the corrections with E/p



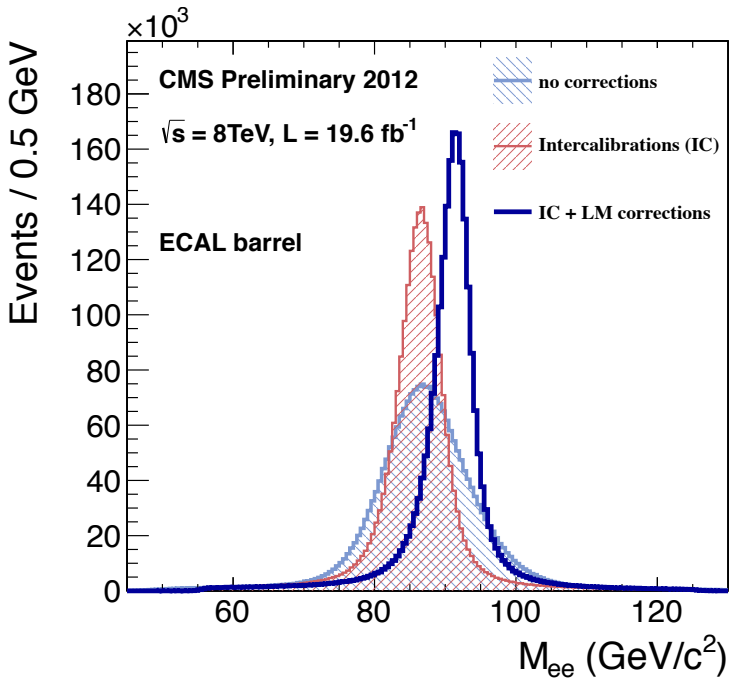
Inter-calibration precision

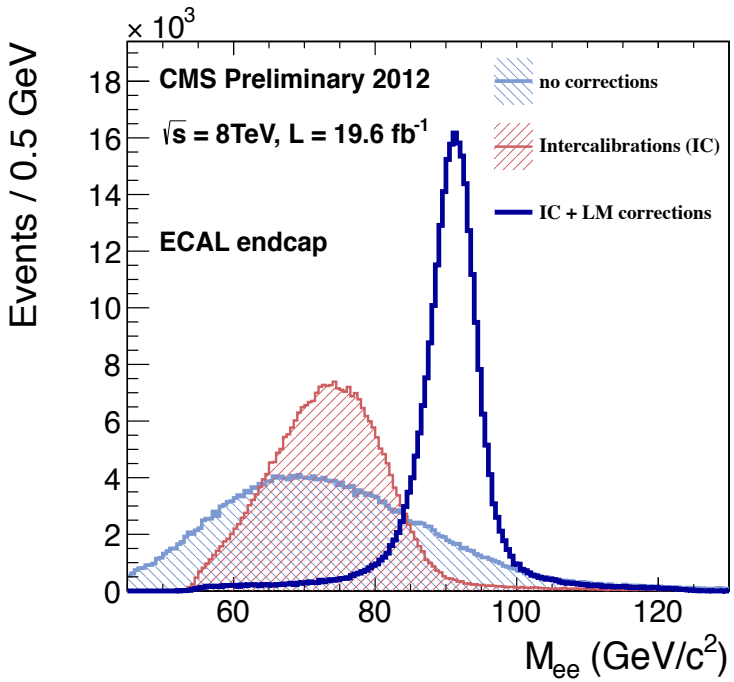


[F. De Guio's talk]

ECAL channel inter-calibration

- Derive individual corrections *in situ* by equalising the response to diphoton resonances (η, π^0).
  - Cross check using ϕ invariance of energy flow.
  - And E/p ratio for electrons.
- Effect of inter-calibration (IC) and light monitoring (LM) corrections:

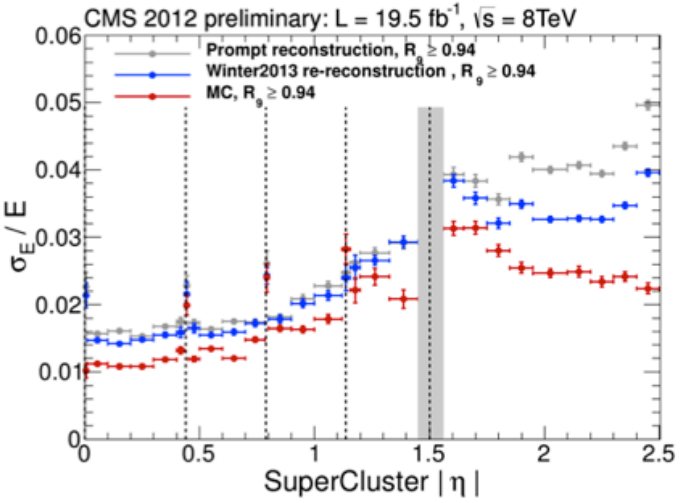


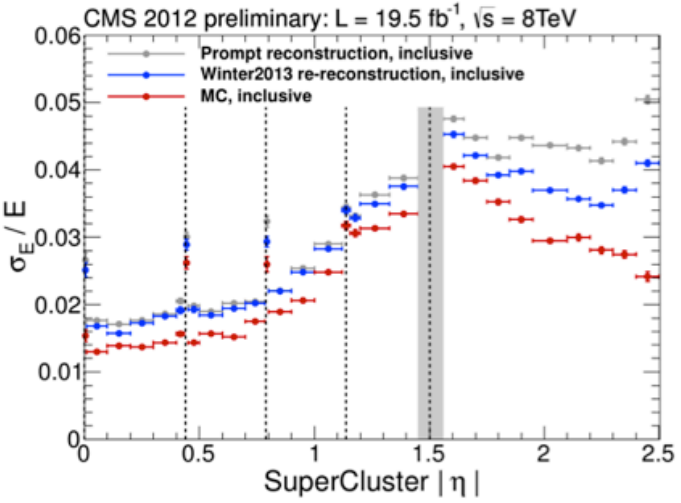


[http://cern.ch/go/PT9c]

Performance: energy resolution

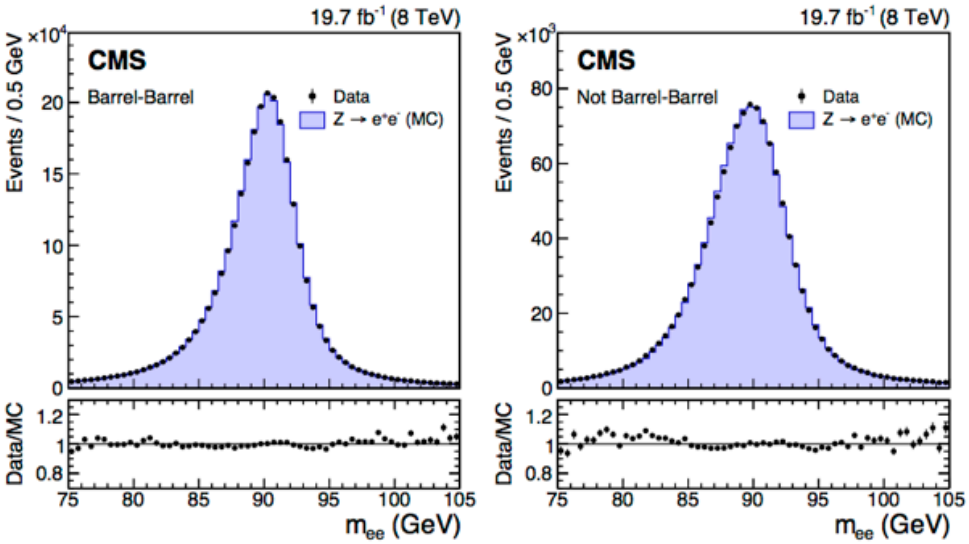
With electrons from Z





↑ Fit to $Z \to ee$ of a Breit-Wigner convolved with a Gaussian function [4]

→ Simulation tuned to match performance observed *in situ* with $Z \to ee$ events



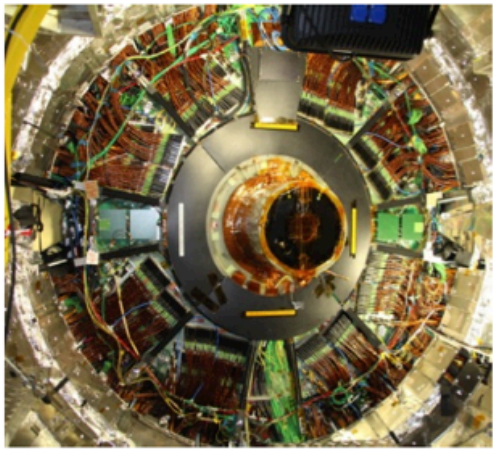
Accurate simulation

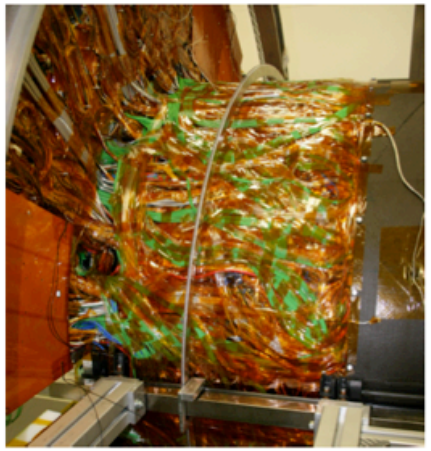
Noise model:

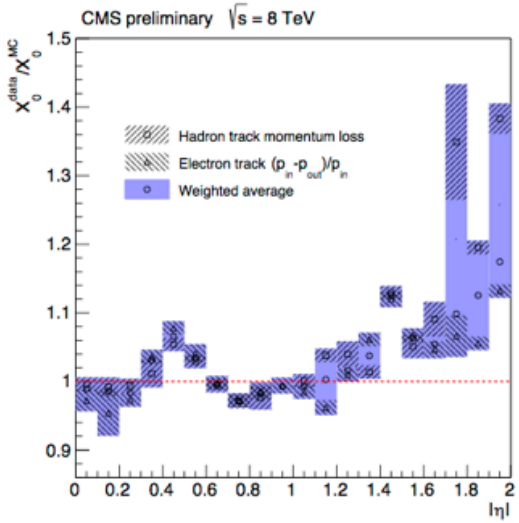
- realistic noise with sample-correlations and channel-to-channel variations
- increase of the APD dark current (expected)
- transparency variations for realistic light-yield (and corresponding photo-statistics)

Material description:

- including in-homogeneities in φ of services in front of the endcaps
- for systematic uncertainties, being implemented in current simulation







Light propagation effects in the crystals (only relevant for upgrade studies)

Varying conditions used for a "run-dependent" simulation [N. Marinelli's talk]

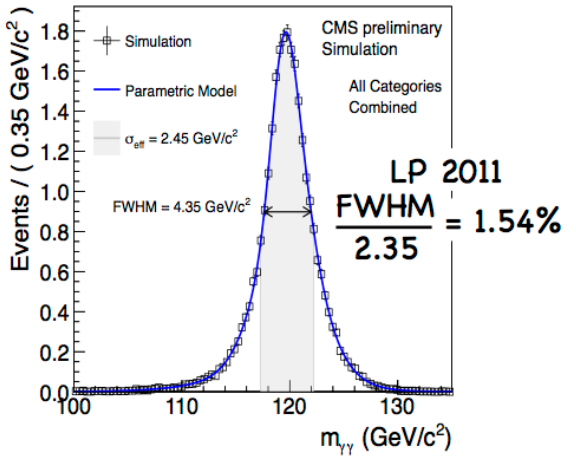
Performance evolution

- The energy resolution measured in data with $Z \rightarrow ee$ is used to model the expected $H \rightarrow \gamma\gamma$ signal in the simulation
- **Steady progress and excellent results**

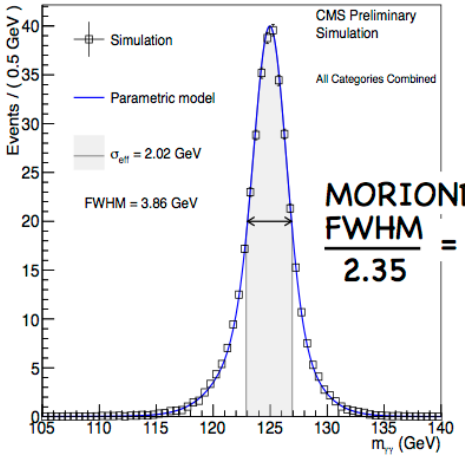
PROMPT reconstruction within 48h from data taking

RECONSTRUCTION with improved conditions

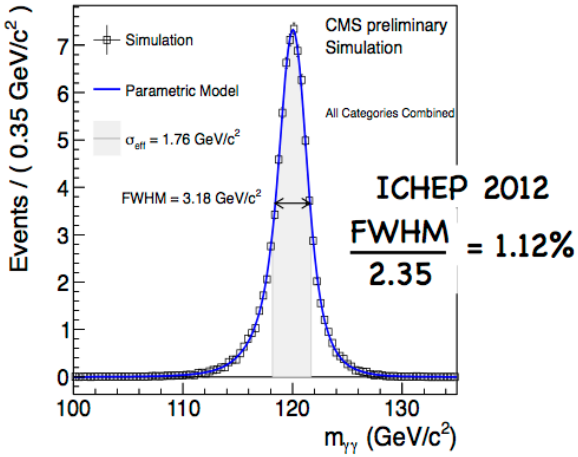
7TeV 8TeV



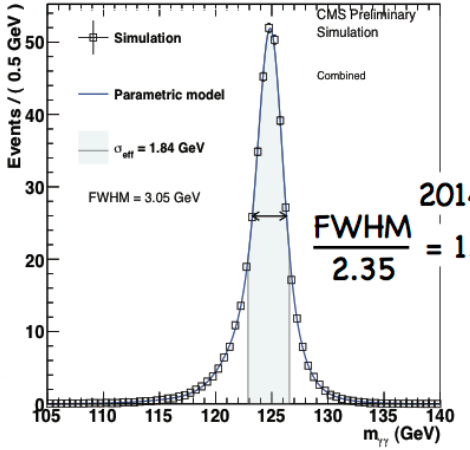
LP 2011
$\frac{FWHM}{2.35}$ = 1.54%



MORIOND 2013
$\frac{FWHM}{2.35}$ = 1.31%



ICHEP 2012
$\frac{FWHM}{2.35}$ = 1.12%



2014
$\frac{FWHM}{2.35}$ = 1.04%

ECAL-related systematic uncertainties on m_H

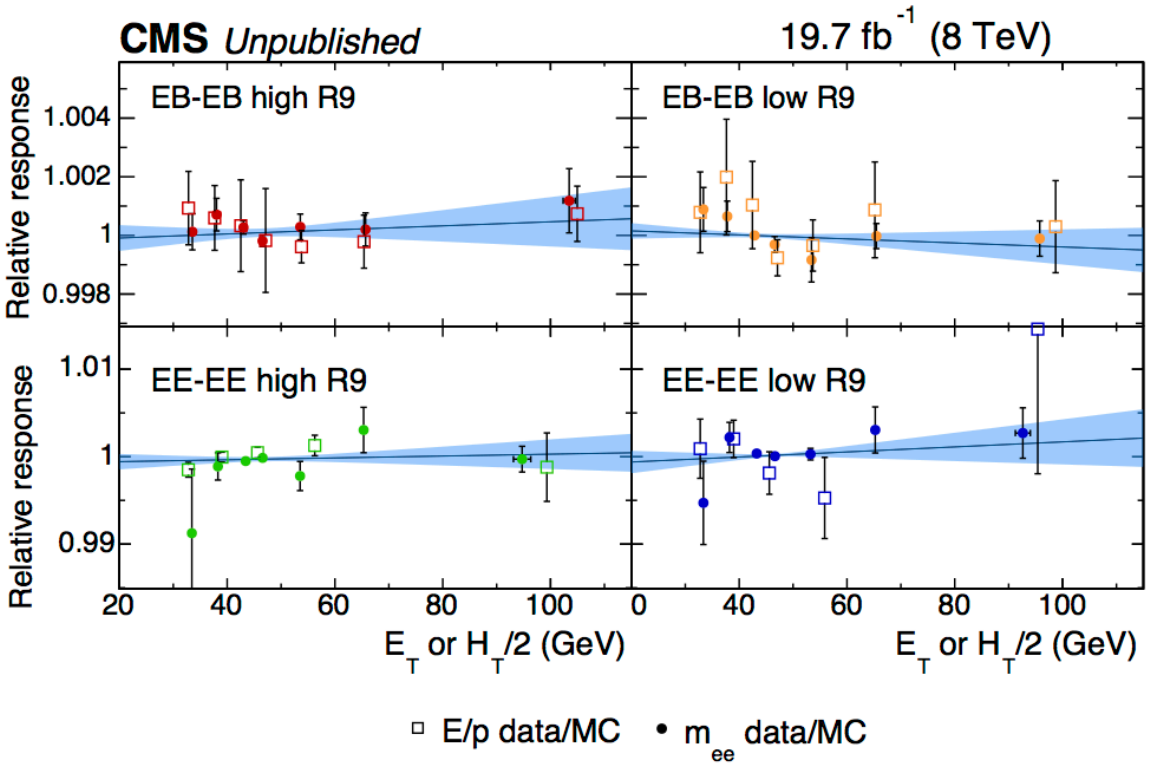
From $H \to \gamma\gamma$:

$$m_H = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst}) \text{ GeV}$$

- Electron/photon differencies in the simulation ..... 0.10 GeV
  - material distribution ..... 0.07 GeV
  - **longitudinal light-yield non-uniformity ..... 0.02 GeV**
  - Geant4 ..... 0.06 GeV
  - ★ uncertainty on the single contribution: $\approx$ 10 MeV

  N.B.: the detector response to electrons and photons shows differences at the level of 0.5%. What matters is the *difference of these differences* between data and simulation.
- **Residual non-linearity in scale ..... 0.10 GeV**
- Photon energy scale corrections ..... 0.05 GeV
- Z line shape ..... 0.01 GeV
- Checked and negligible contribution: gain switch of the electronics

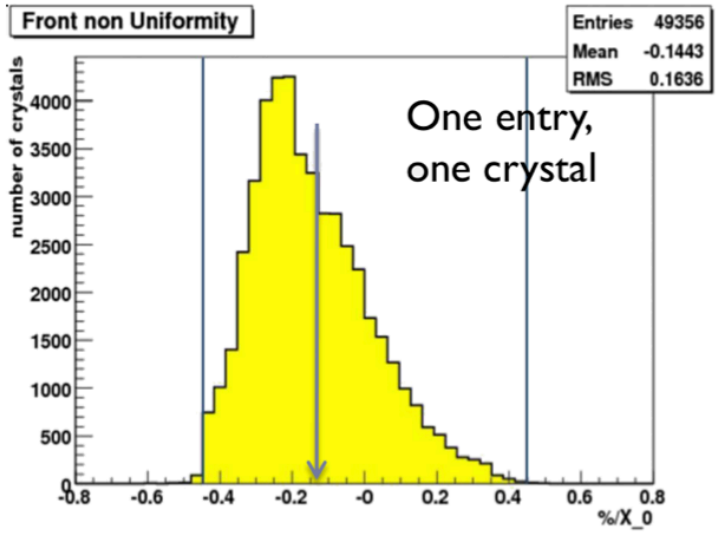
More detail: residual non-linearity in scale

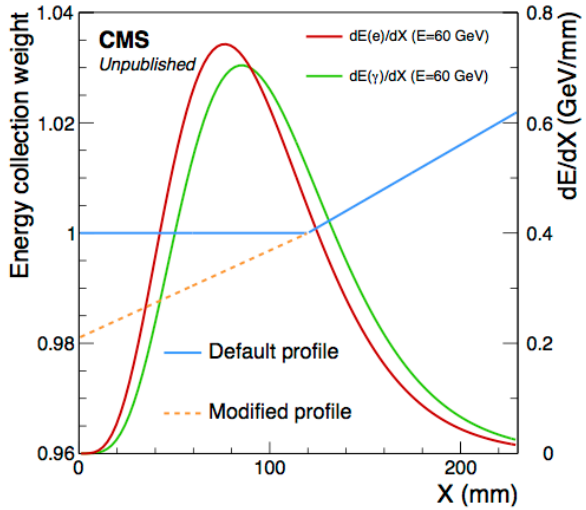


- Residual non-linearity of the energy response in data relative to simulation, relevant in the extrapolation from the energy scale measured at the Z peak ($\approx$ 90 GeV) to the Higgs boson mass ($\approx$ 125 GeV)
  1. electron E/p vs. E_T with electrons from Z and W decays
  2. di-electron invariant mass vs. $H_T = E_T^1 + E_T^2$ in $Z \to ee$ events
- **0.08% effect on the Higgs boson mass**

More detail: longitudinal non-uniformity (NUF)

- **R&D achievements: adequate uniformity of longitudinal light yield**
  - one face of each barrel crystal depolished





- Simulation: rear non-uniformity of 0.15%, front part assumed uniform
- Ionizing radiation found to induce additional NUF of 30% of its initial value (worst case scenario) at the end of Run1 [6]

→ simulation modified to account for these effects

- at most **0.06% effect on the energy scale**, anti-correlated between converted and un-converted photons → **0.015% effect on the mass**

Final Run 1 $H \rightarrow \gamma\gamma$ analysis details

H→ γγ – energy regression

[arXiv:1407.0558, submitted to EPJC]

- Use the raw supercluster energy and several other input variables
  - To model shower shape, position etc. (label inputs as **x**)
  - Correct for local containment of showers, bremsstrahlung losses, etc.
- Use specialised BDT (not TMVA) to predict full probability distribution for E_{true}/E_{raw}
  - Distribution is given by a double CB which has six free params (μ, σ, α_L, α_R, n_L, n_R)
  - "Regress" the non-parametric dependence of each of these variables on the BDT input variables whilst minimising the likelihood,

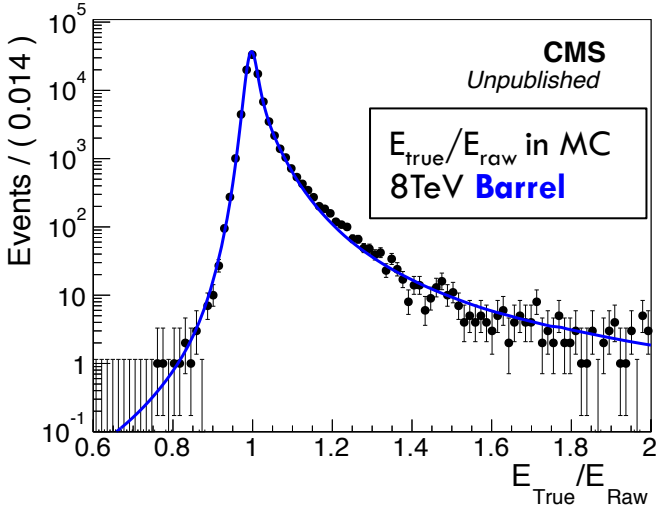
$$-\ln\mathcal{L} = -\sum_{MCphotons} \ln p(E_{true}/E_{raw}|\mu(\vec{x}),\sigma(\vec{x}),\alpha_L(\vec{x}),\alpha_R(\vec{x}),n_L(\vec{x}),n_R(\vec{x}))$$

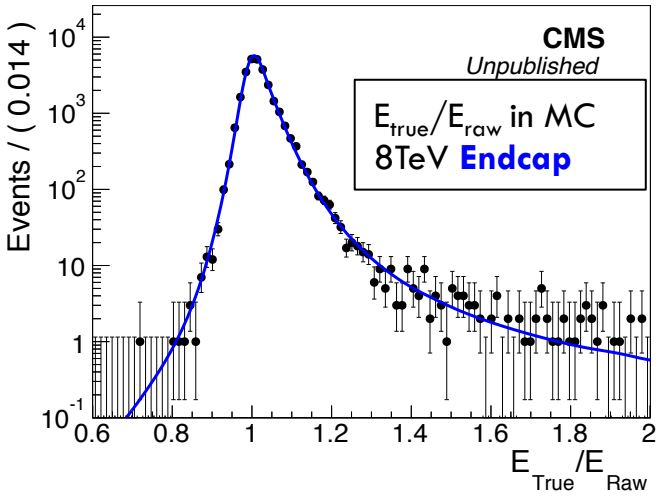
Best estimate for the true energy:

$$E(\vec{x}, E_{raw}) = \mu(\vec{x})E_{raw}$$

Per photon energy resolution:

$$\frac{\sigma_E(\vec{x}, E_{raw})}{E(\vec{x}, E_{raw})} = \frac{\sigma(\vec{x})}{\mu(\vec{x})}$$



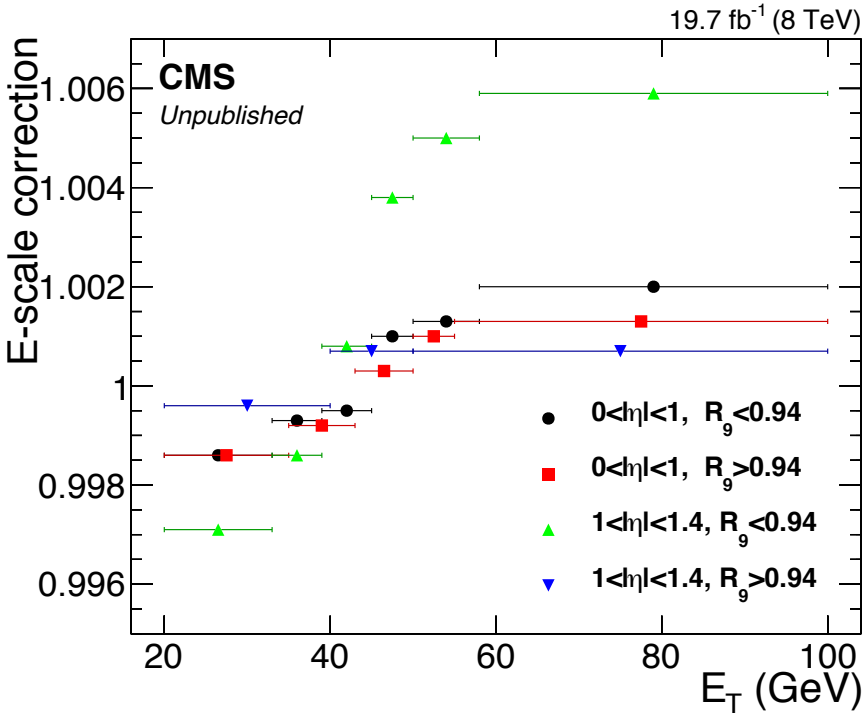


H→ γγ – energy scale and resolution corrections

[arXiv:1407.0558, submitted to EPJC]

- Apply residual scale corrections to the data and subsequent smearings to the MC
- resolve differences between data and MC from Z→ee decays (with electrons reconstructed as photons)
- Employ a new multistep procedure:

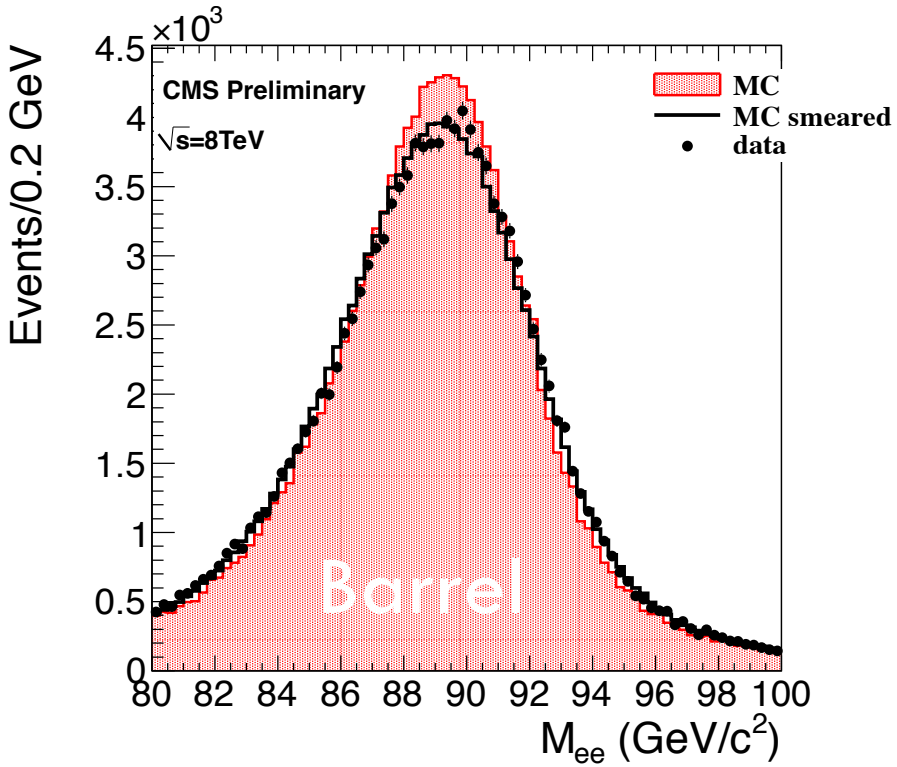
  - Split data and MC into 59 run ranges, 4 η bins and 2 R_9 bins.
  - Fit Z line shape and find scale correction from data→MC in run × |η| bins.
  - Simultaneously fit scale with a Gaussian smearing term for MC in |η| × R_9.
    - In the barrel (for 8 TeV) the smearing term has an energy dependence by parameterisation through: $b/\sqrt{E_T} + c$
  - Then have a further residual scale correction in E_T × |η| × R_9.

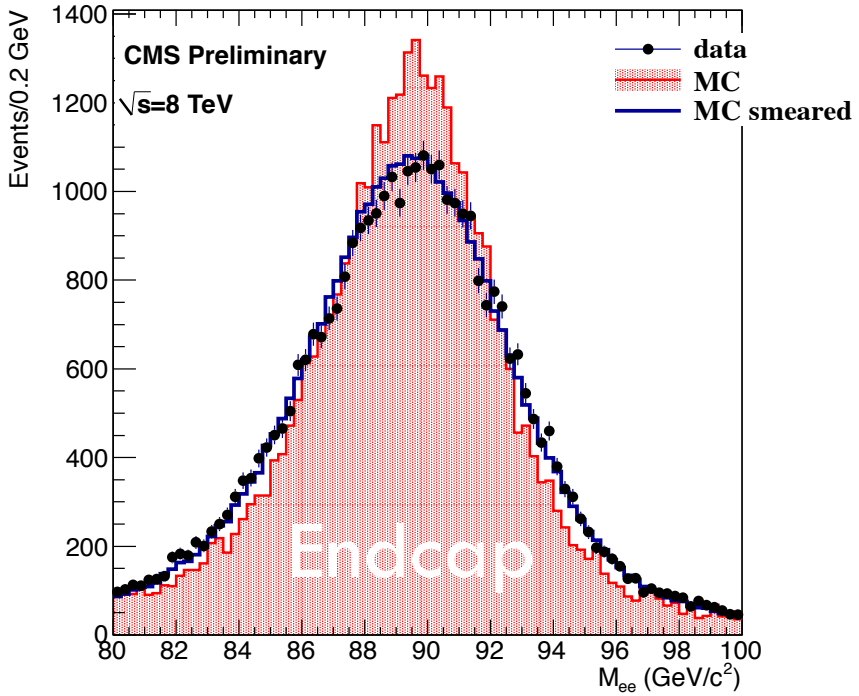


H→ γγ – energy scale and resolution corrections

[arXiv:1407.0558, submitted to EPJC]

- Corrections have uncertainties which enter the analysis as a systematic uncertainties.

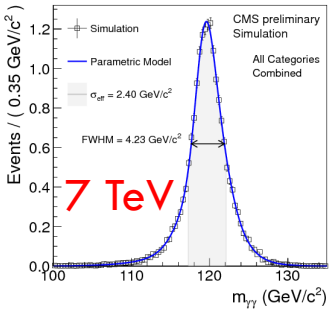


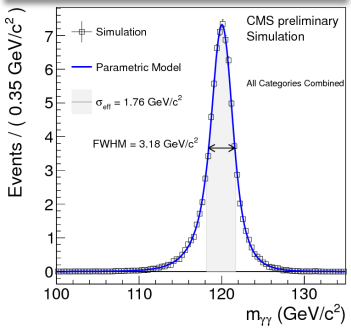


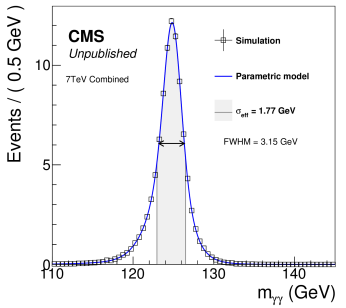
Evolution of $m_{\gamma\gamma}$ resolution

[HIG-11-010] [HIG-12-015] [HIG-13-001] [arXiv:1406.0558, submitted to EPJC]

EPS – Jul 2011	ICHEP – Jul 2012	Moriond – Feb 2013	ICHEP – Jul 2014
FWHM = **4.23 GeV**	**3.18 GeV**		**3.15 GeV**

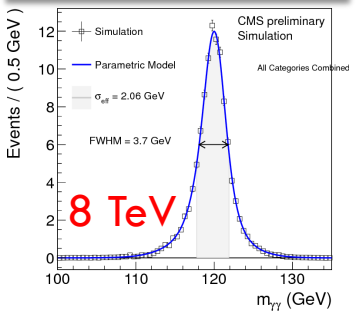


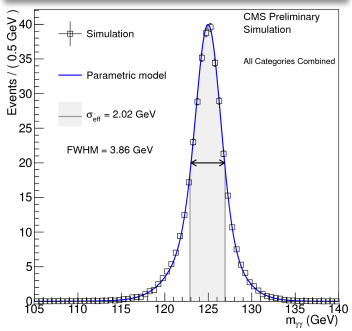


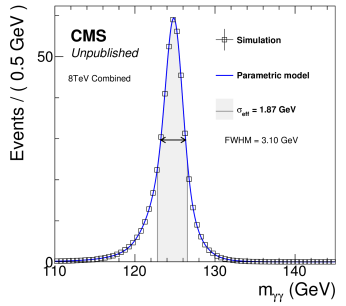


7 TeV: 25% improvement in the first year

3.7 GeV	3.9 GeV	3.1 GeV





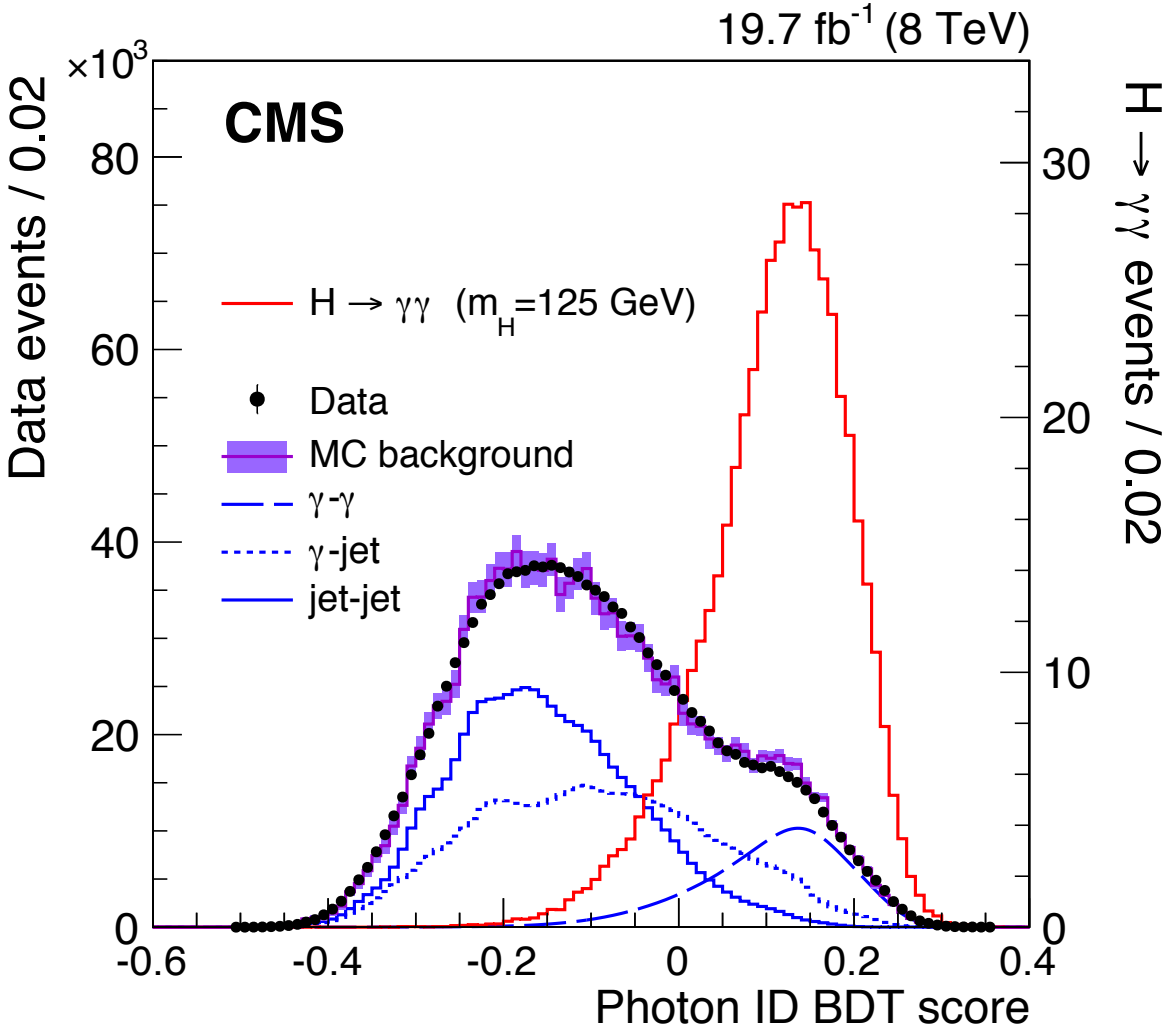


8 TeV: 20% improvement in the last year

H→ γγ photon ID MVA

[arXiv:1407.0558, submitted to EPJC]

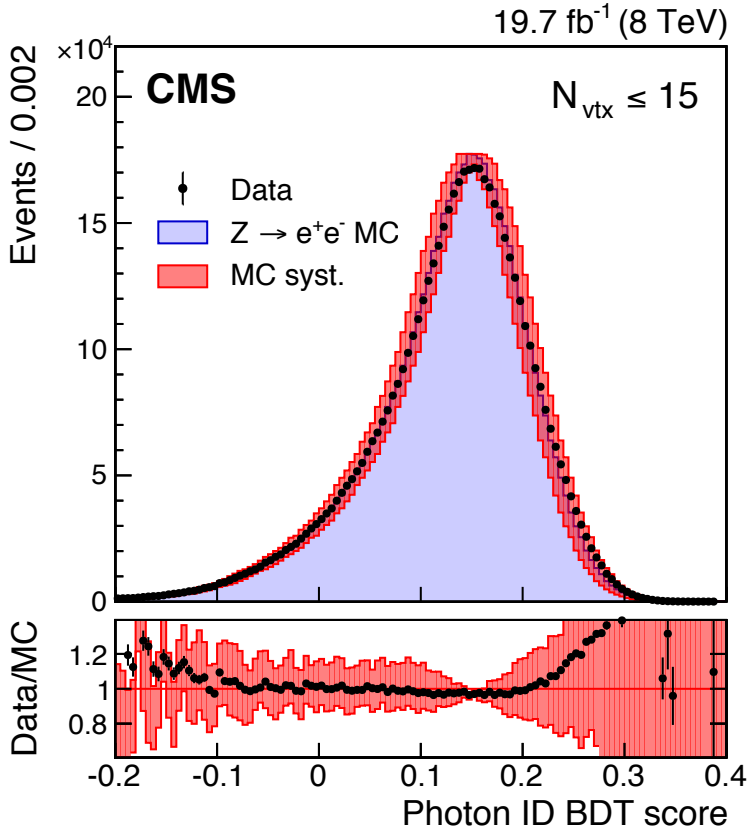
- Use a BDT to reject photon fakes. (mainly π^0)
  - Uses shower shape & isolation variables.
- **Provides estimate of the per-photon quality.**

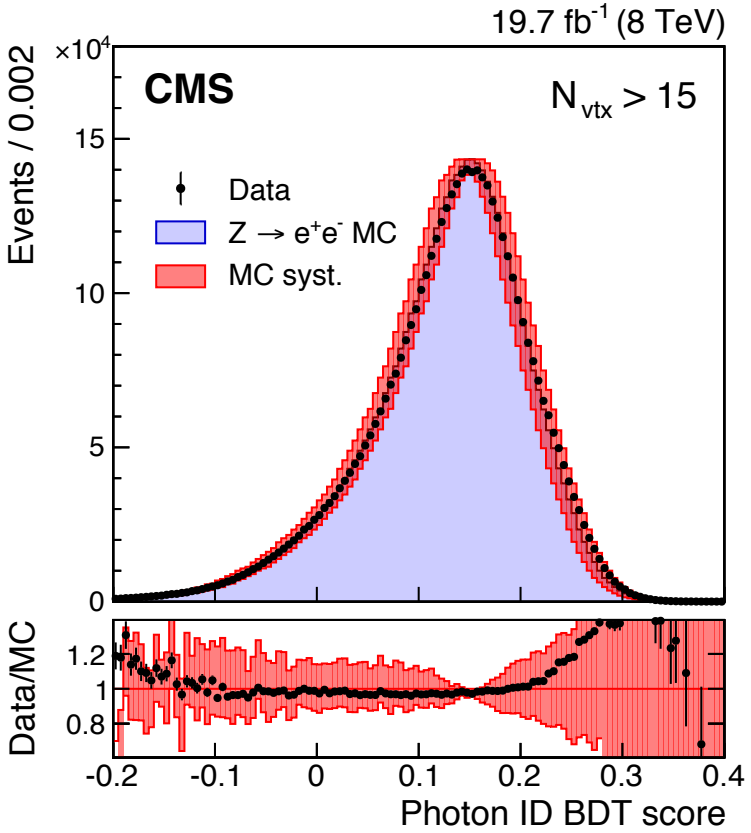


H→ γγ photon ID MVA

[arXiv:1407.0558, submitted to EPJC]

- Photon ID output (including systematic band) for Z→ee events.



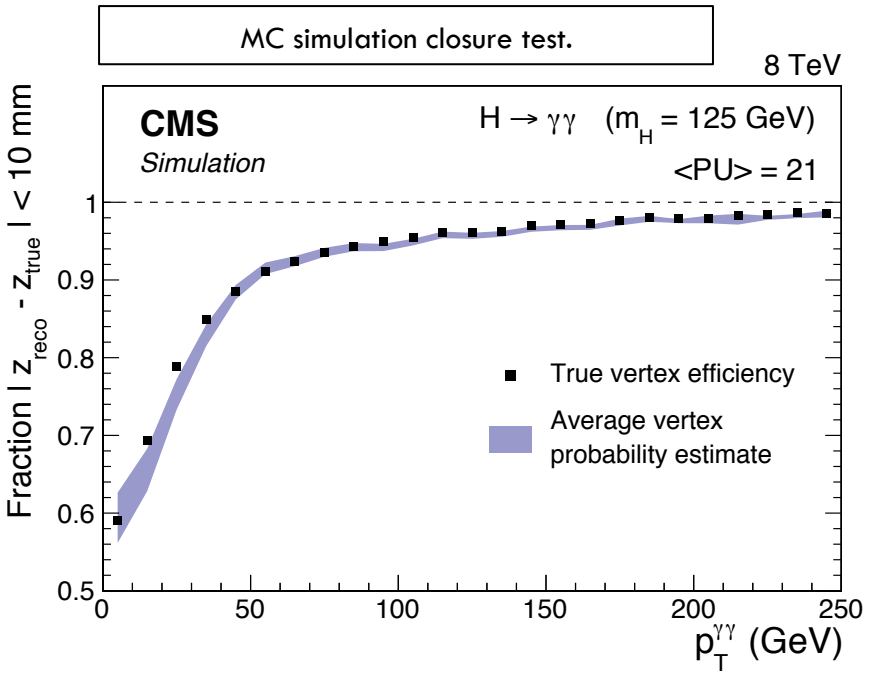


H→ γγ – vertexing

[arXiv:1407.0558, submitted to EPJC]

- Resolution on opening angle has negligible effect **iff** selected vertex is within 10 mm of true position.
- Use a BDT to select vertex. Input variables designed to consider:
  - Hardness of interactions (sum p_T).
  - Recoil and asymmetry between the diphoton system and other tracks from the given vertex.
  - Converted photon track information.

- **Test performance in Z→μμ events** (remove μ tracks and re-reco vertices) and also γ+jet events.
- **Construct BDT to complement resolution estimate** whose output definition will map correct vertex efficiency (probability).
- **Exploit this information later when estimating the per event resolution.**

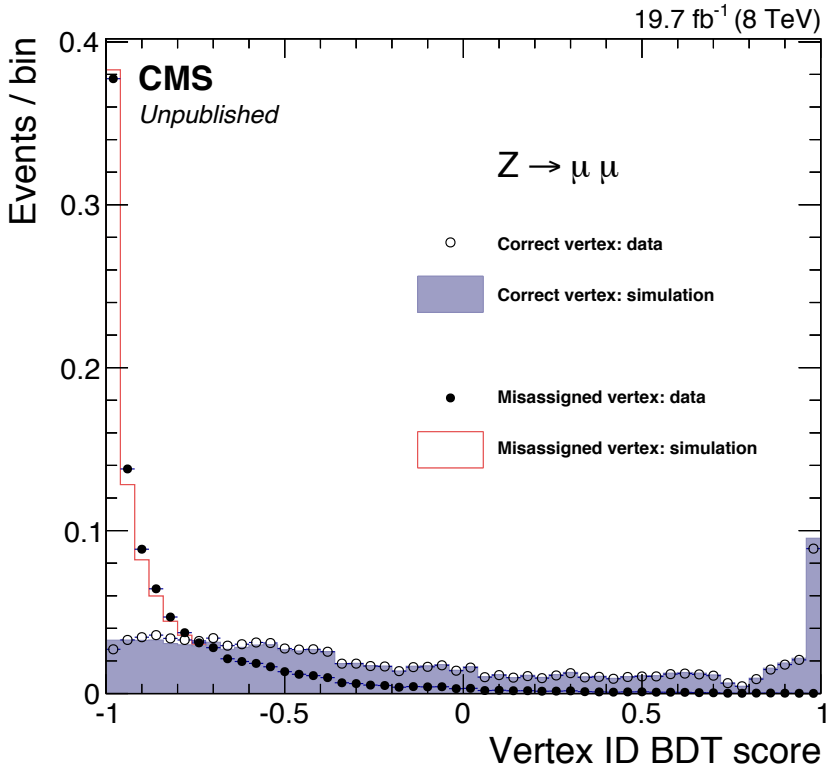


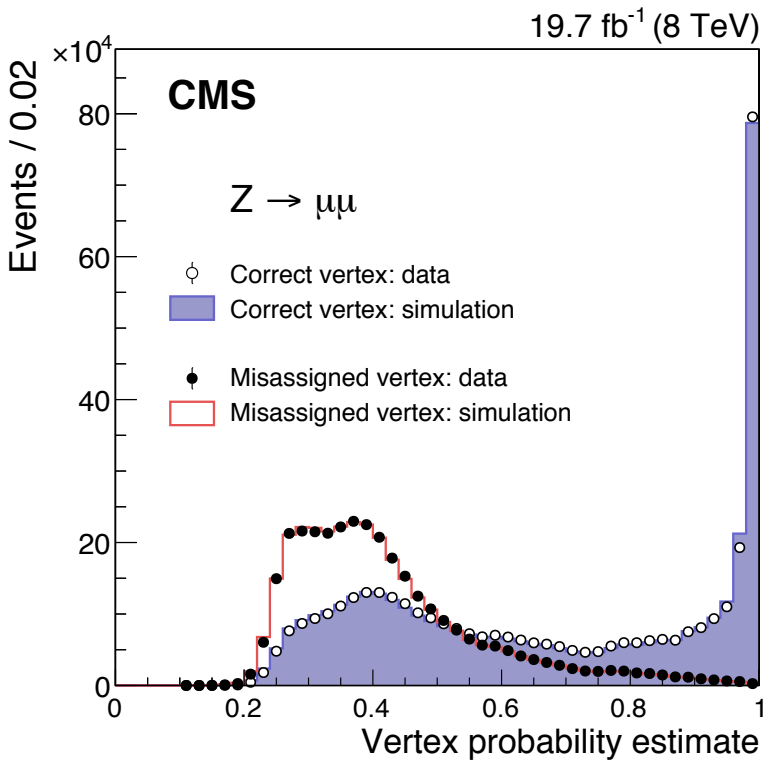
H→ γγ – vertexing

[arXiv:1407.0558, submitted to EPJC]

- Performance in Z→μμ events.

  Remove μ tracks and redo vertex reconstruction.

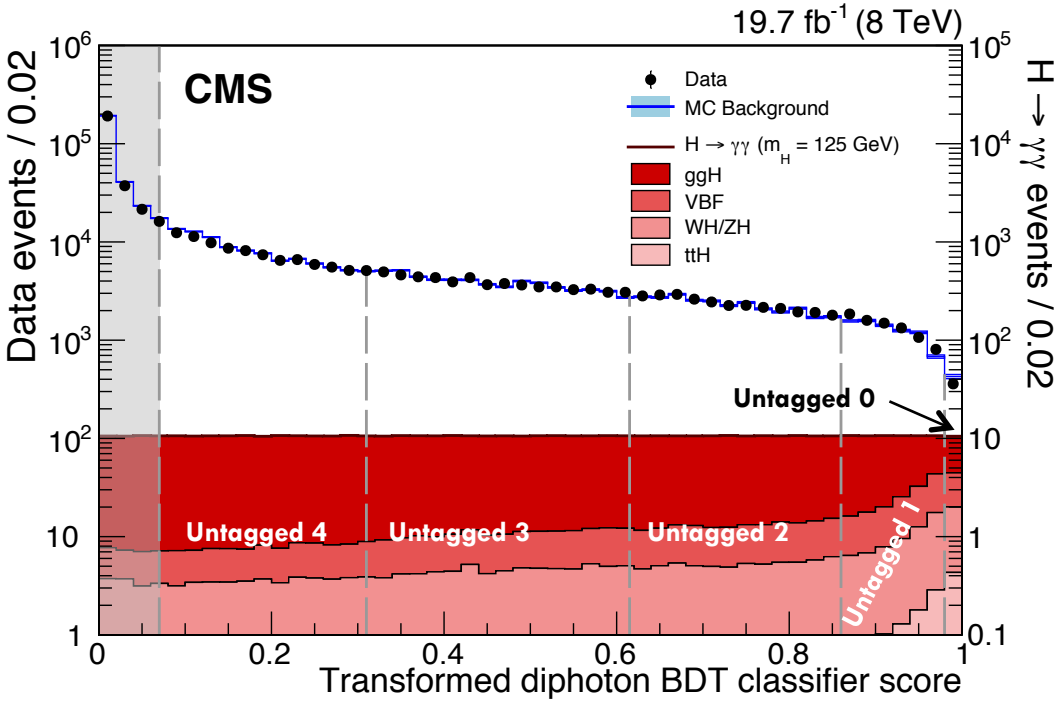




H→ γγ – diphoton MVA score

[arXiv:1407.0558, submitted to EPJC]

- Event classifier which collapses event information into one discriminant.
  - Assigns a high score to events with:
    - Signal-like kinematics. (mainly high $p_T^{\gamma\gamma}$)
    - Good diphoton mass resolution (i.e. good photon resolution and high vertex probability)
    - High photon quality.
  - Independent of mass.
- Place a cut on classifier value to cut out background.
- Categorise events using bins in the classifier value
- Use this as input to a further BDT which focuses on VBF di-jet + di-photon selection.

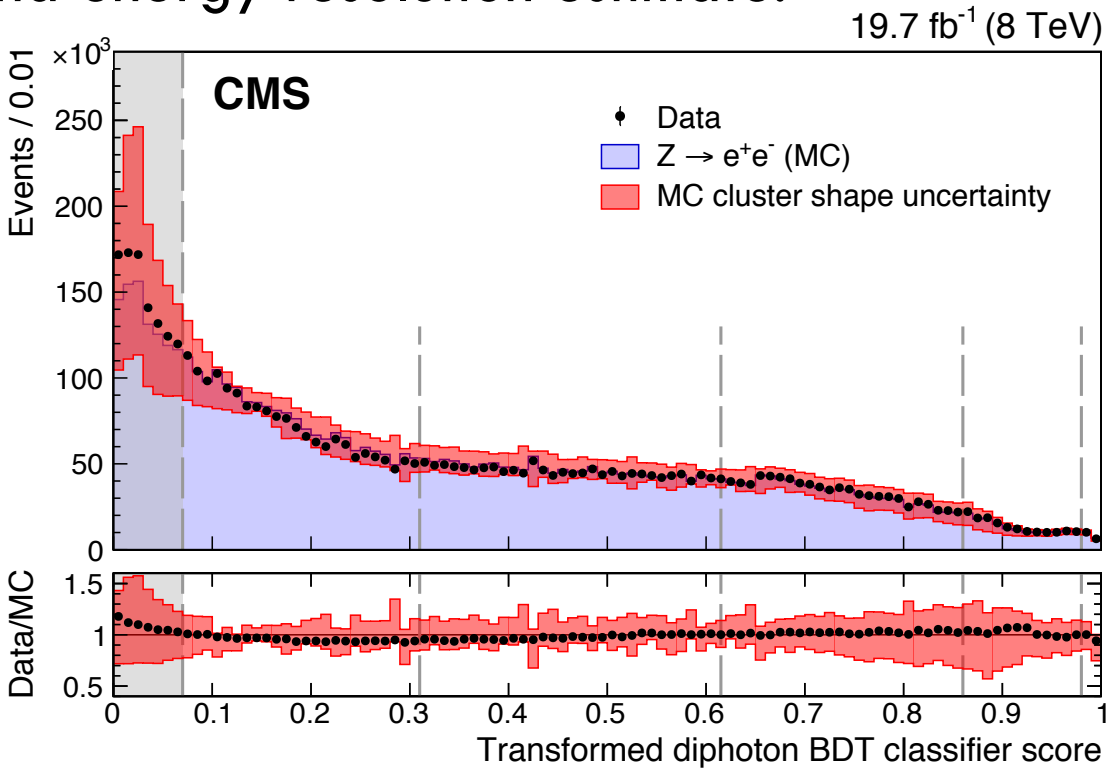


Diphoton BDT output transformed to be flat for total signal

H→ γγ – diphoton MVA score

[arXiv:1407.0558, submitted to EPJC]

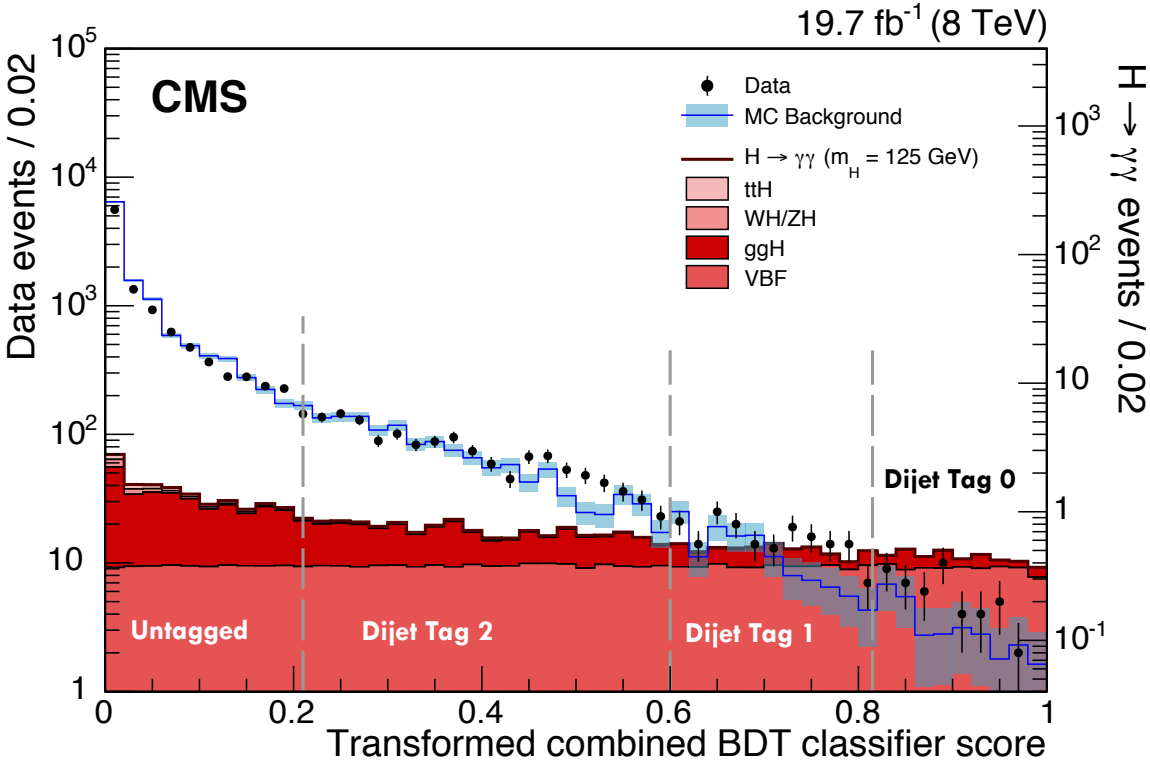
- Classifier output is validated with Z→ee.
- Define systematics for shape distortions that affect categorisation:
  photon ID quality and energy resolution estimate.



H→ γγ – diphoton dijet MVA score

[arXiv:1407.0558, submitted to EPJC]

- Use dijet variables to pick out VBF-like topology.
- Use output to define a set of dijet categories.
  - Optimized for VBF signal strength alone.



H→ γγ event category selection

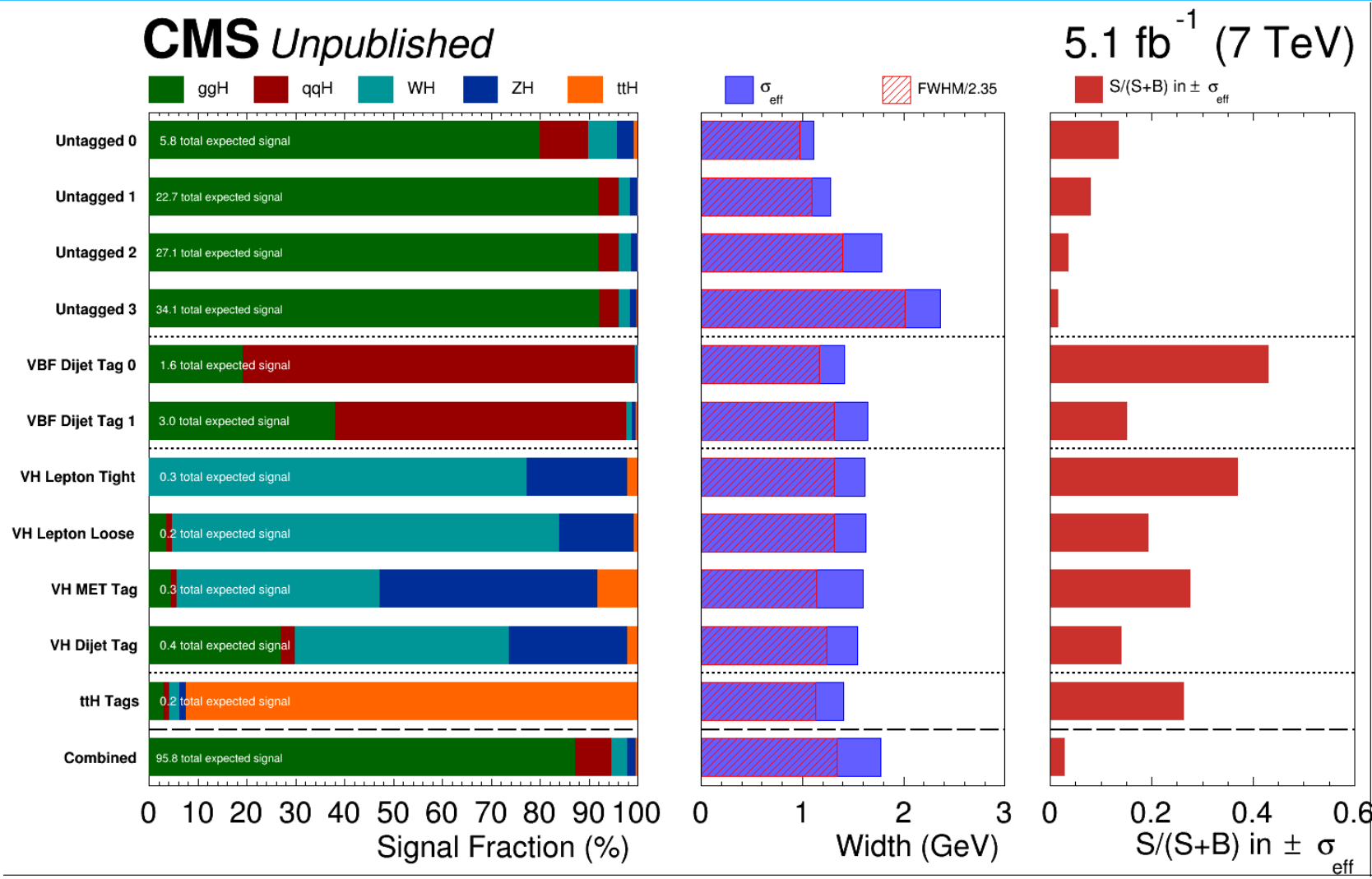
[arXiv:1407.0558, submitted to EPJC]

Label	No. of classes 8 GeV	7 GeV	Main requirements
$t\bar{t}H$ lepton tag	1	$\star$	$p_T^\gamma(1) > m_{\gamma\gamma}/2$ 1 b-tagged jet + 1 electron or muon
VH tight ℓ tag	1	1	$p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$ e or μ, $p_T > 20$ GeV, and $\not{E}_T > 45$ GeV OR 2e or 2μ, $p_T > 10$ GeV; $70 < m_{\ell\ell} < 110$ GeV
VH loose ℓ tag	1	1	$p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$ e or μ, $p_T > 20$ GeV
VBF dijet tag 0-2	3	2	$p_T^\gamma(1) > m_{\gamma\gamma}/2$ 2 jets; dijet and combined diphoton-dijet BDTs used
VH $\not{E}_T$ tag	1	1	$p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$ $\not{E}_T > 70$ GeV
$t\bar{t}H$ multijet tag	1	$\star$	$p_T^\gamma(1) > m_{\gamma\gamma}/2$ 1 b-tagged jet + 4 more jets
VH dijet tag	1	1	$p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8$ jet pair, $p_T > 40$ GeV and $60 < m_{jj} < 120$ GeV
Untagged 0-4	5	4	The remaining events, classified using diphoton BDT

$\star$ For the 7 TeV dataset, events in the $t\bar{t}H$ lepton tag and multijet tag classes are selected first, and combined to form a single event class.

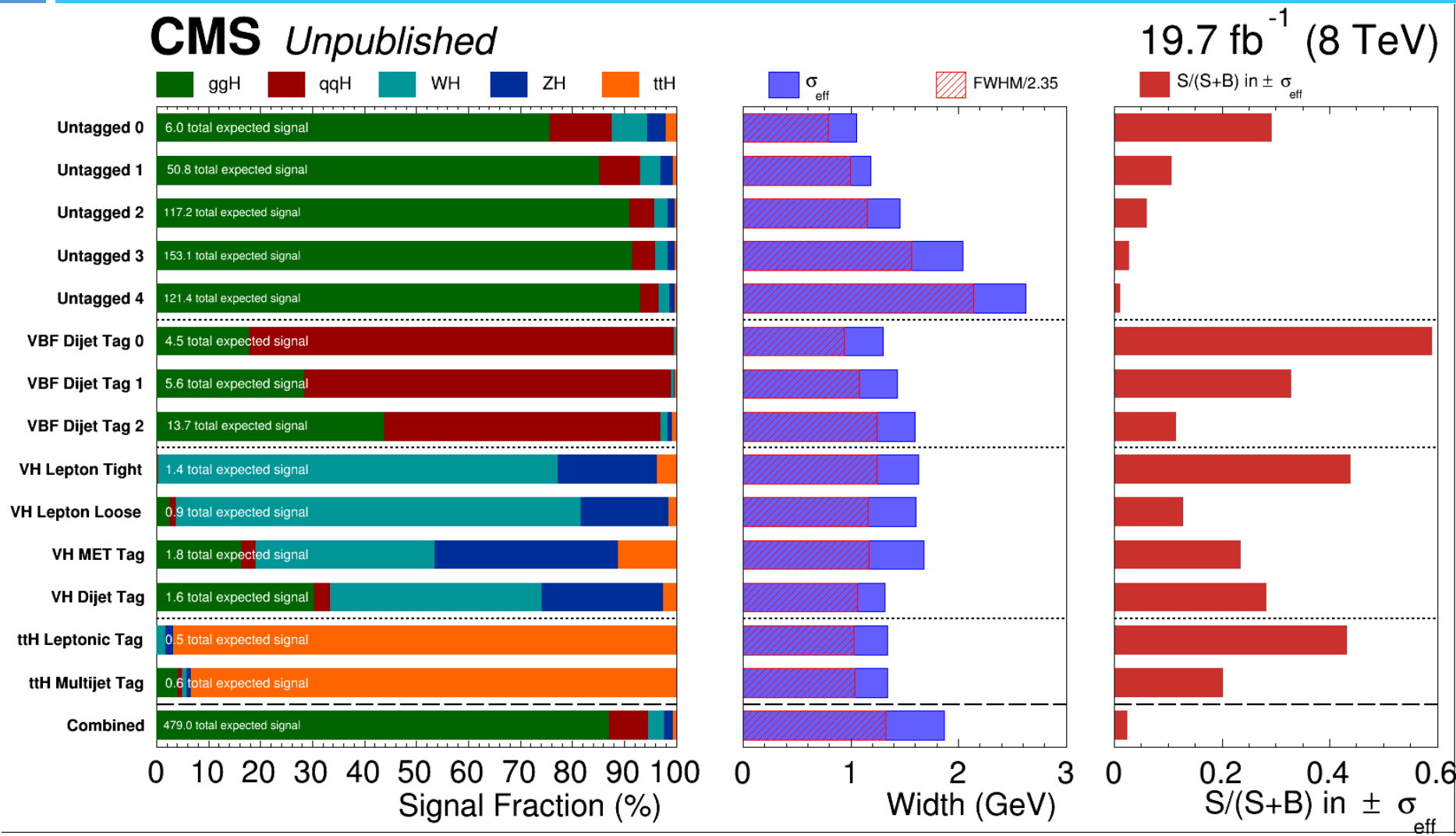
H→ γγ event categories

[arXiv:1407.0558, submitted to EPJC]



H→ γγ event categories

[arXiv:1407.0558, submitted to EPJC]

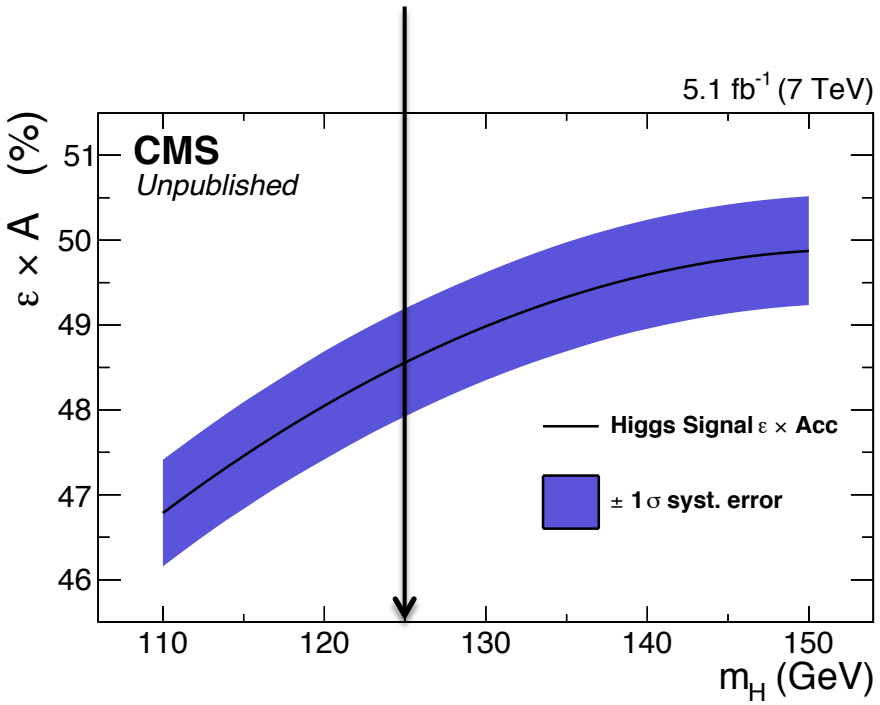


H→ γγ – A× ε

[arXiv:1407.0558, submitted to EPJC]

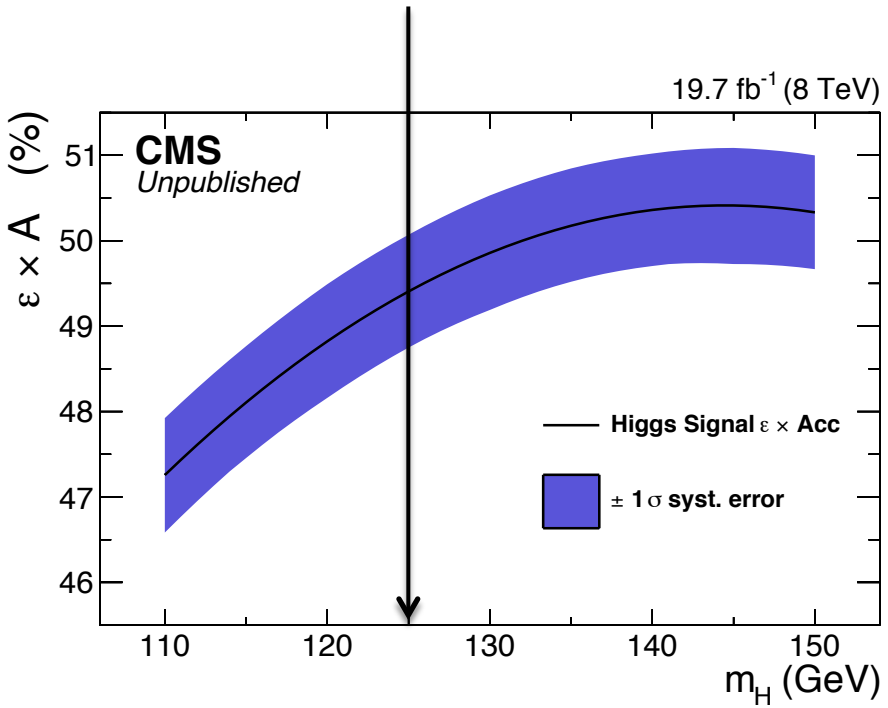
7 TeV

48.6%



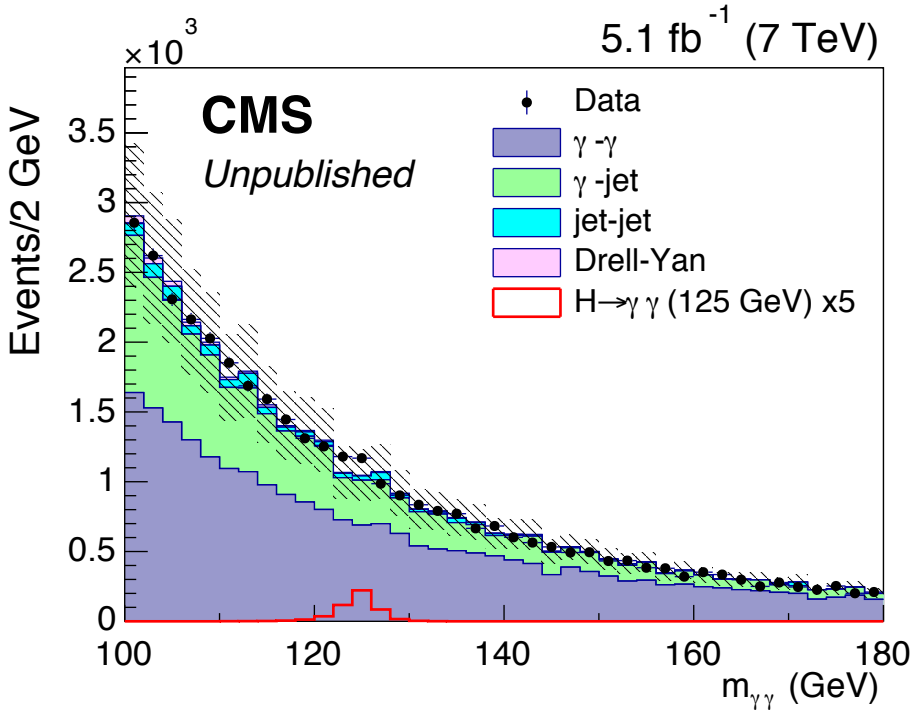
8 TeV

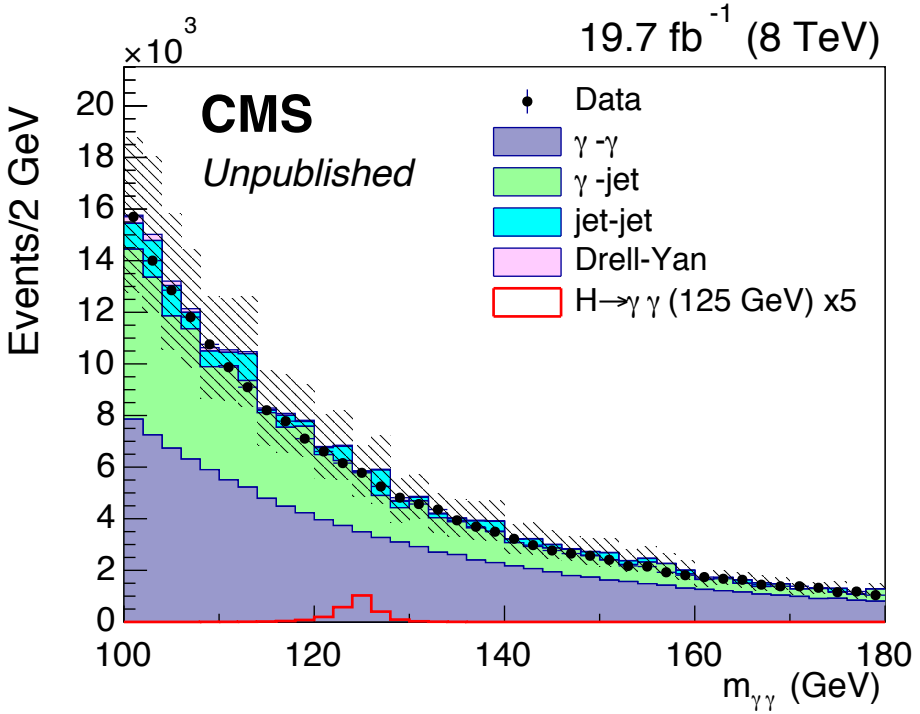
49.3%



H→ γγ – MC comparison

[arXiv:1407.0558, submitted to EPJC]



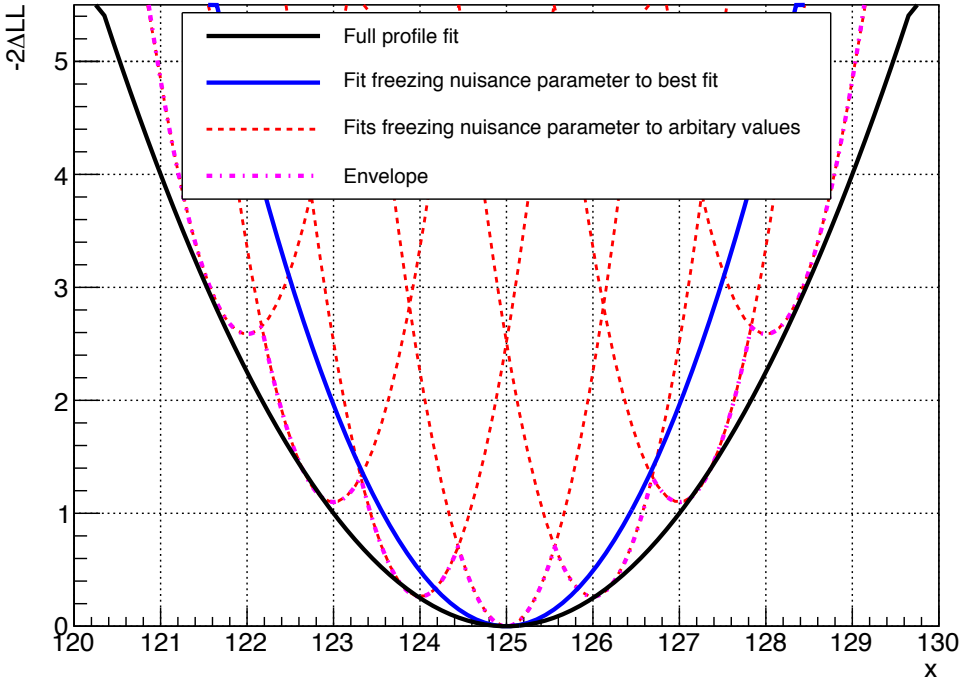


H→ γγ – BG estimation

[arXiv:1407.0558, submitted to EPJC]

- Imagine a simple case with one POI, x, and one nuisance parameter, θ
  - Black line – standard likelihood scan of x profiling θ
  - Blue line – standard likelihood scan of x freezing θ (stat. only)
  - Red lines – standard likelihood scans of freezing θ to different values
  - Pink line – Envelope around this

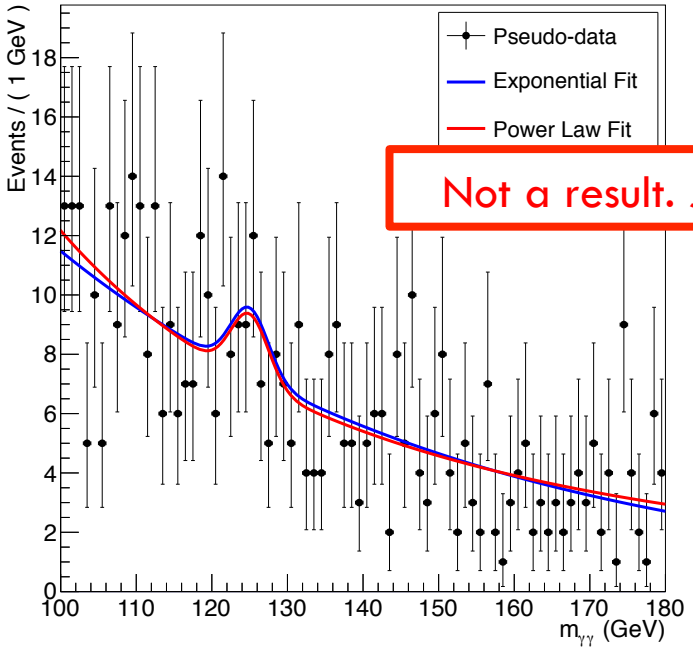
- If you sample enough of the infinite θ phase-space eventually you can reproduce the black curve with the pink "envelope".

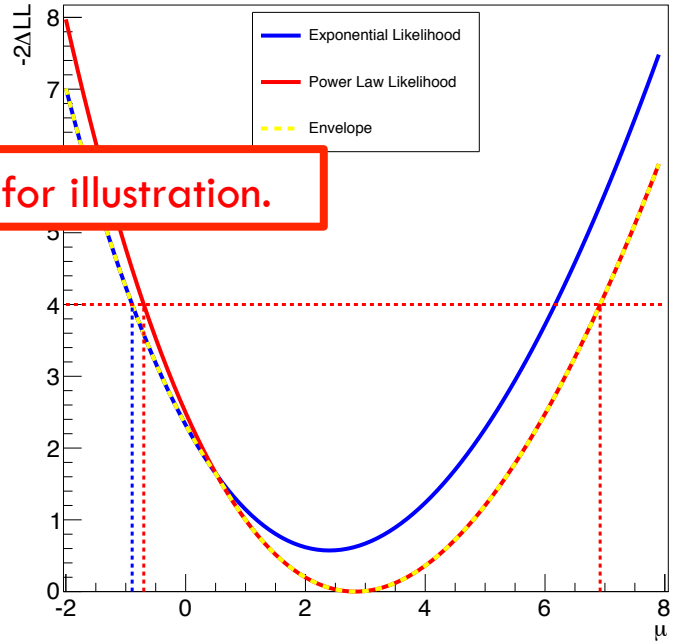


H→ γγ – BG estimation

[arXiv:1407.0558, submitted to EPJC]

- Consider a toy example with
  - One single category.
  - Two function choices, $e^{-p\,m}$ and m^{-p}, both with 1 free parameter.
- Profile "envelope" best fit is for m^{-p}.
  - But 2σ interval is enlarged by the envelope.
- **Envelope method can only increase uncertainty.**





Not a result. Just for illustration.

H→ γγ – BG estimation

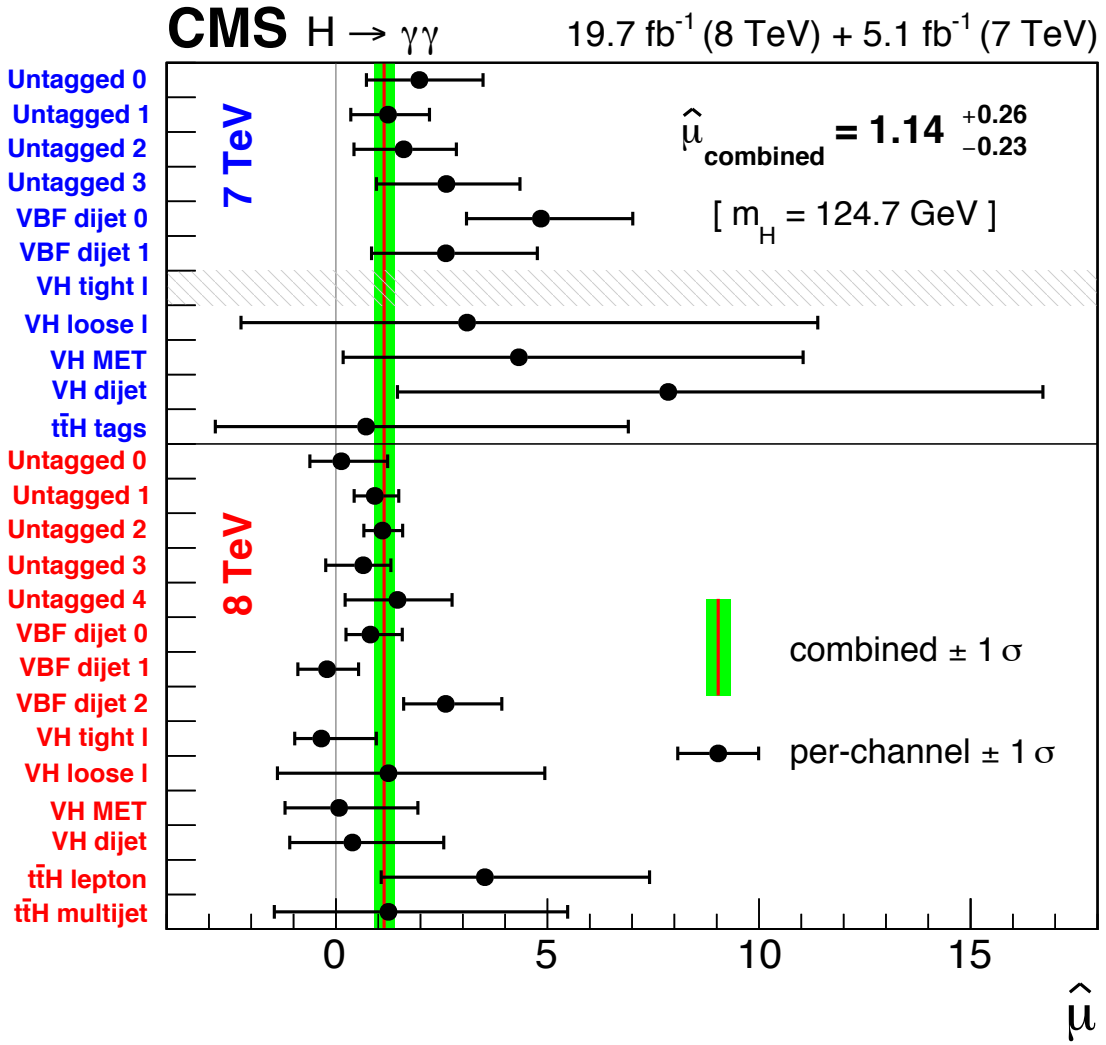
[arXiv:1407.0558, submitted to EPJC]

- In principle **would like to sample the "infinite" phase space of all possible functions.**
  - In practice this is impossible.
- Instead, **choose from four classes** which we expect can reasonably cover the phase-space:
  - Power law sum.
  - Exponential sum.
  - Laurent series.
  - Bernstein polynomials.
- **Lowest order** selected by loose G.O.F test.
- **Highest order** selected by loose variant of the F-test.

H→ γγ – channel compatibility

[arXiv:1407.0558, submitted to EPJC]

- 3 alternative analyses:
  - Check validity of MVA selection, categorisation, background model and VBF selection.
  - All compatible at < 1σ level.
- Compatibility with preliminary result:
  - Using jackknife techniques to estimate correlations <2σ.
- Compatibility between 7 TeV and 8 TeV datasets:
  - At the level of 2σ.
- Compatibility across categories shown on right.



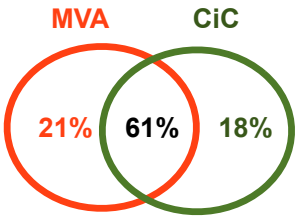
H→ γγ – channel compatibility

[arXiv:1407.0558, submitted to EPJC]

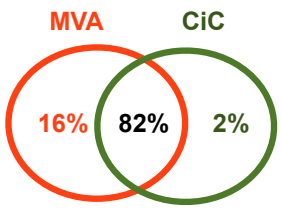
- Jack-knife provides estimate of expected width, σ(δμ), between two correlated analyses using sub-samples of each dataset.
  - Used Bernstein polynomial background model for simplicity.

Analysis 1	Analysis 2	σ(δμ)	δμ (obs)	Linear correlation
Final MVA 8 TeV	Final CiC 8 TeV	0.20	0.19	74%
Final MVA 7 TeV	Final CiC 7 TeV	0.42	0.17	72%
Final MVA 8 TeV	Moriond MVA 8 TeV	0.21	0.22	71%
Final CiC 8 TeV	Moriond CiC 8 TeV	0.21	0.03	76%
Final MVA (Envelope) 8 TeV	Final MVA (Bernsteins) 8 TeV	0.22	0.35	-

CiC – MVA Overlap (Final **Data** 8 TeV)

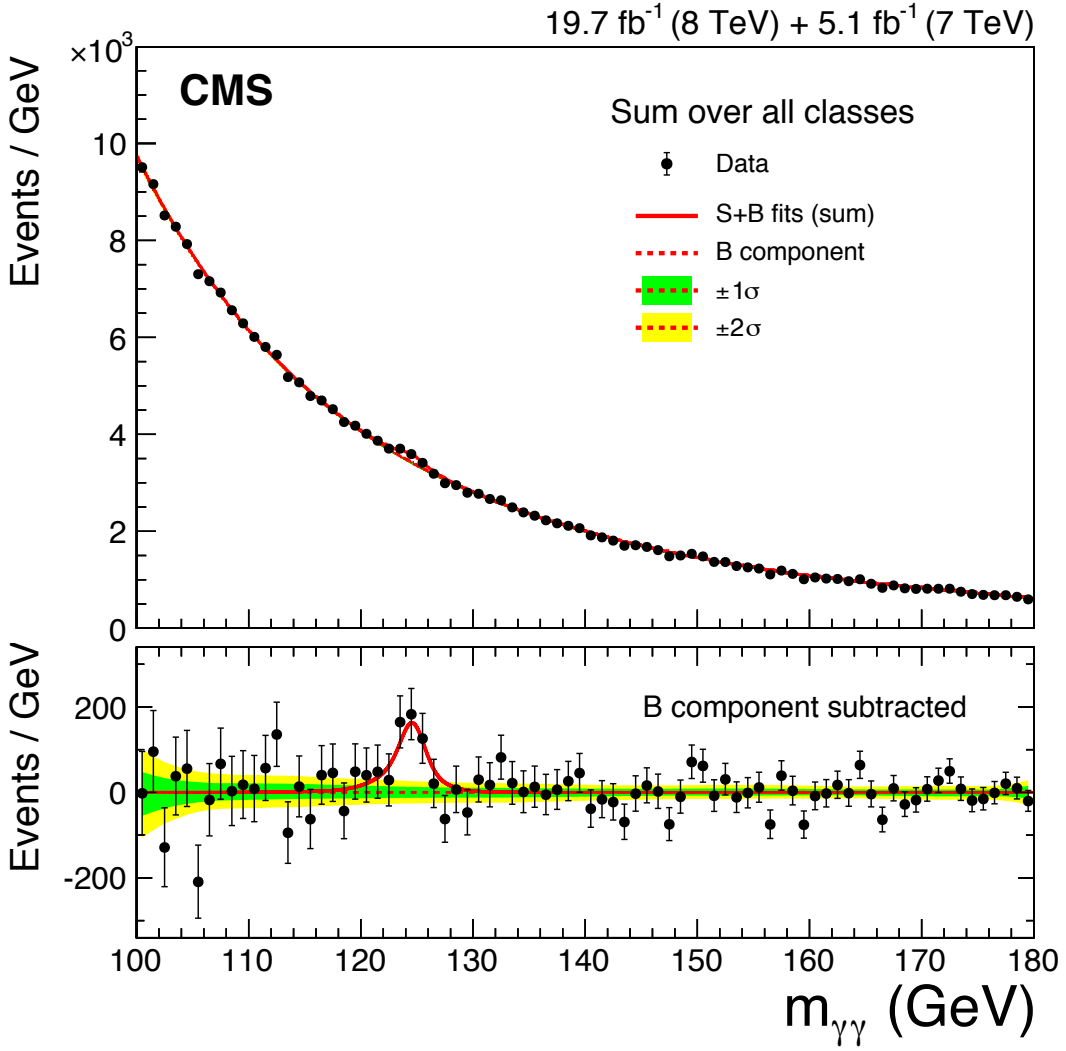


CiC – MVA Overlap (Final **Signal** 8 TeV)



H→ γγ – all selected events

[arXiv:1407.0558, submitted to EPJC]



More on the combination

The challenge of combining

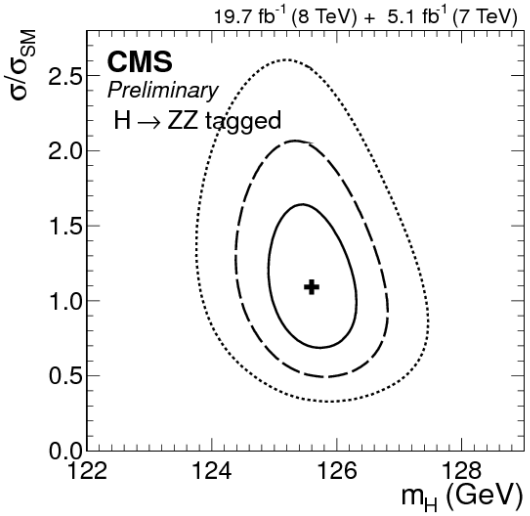
[CMS-PAS-HIG-14-009]

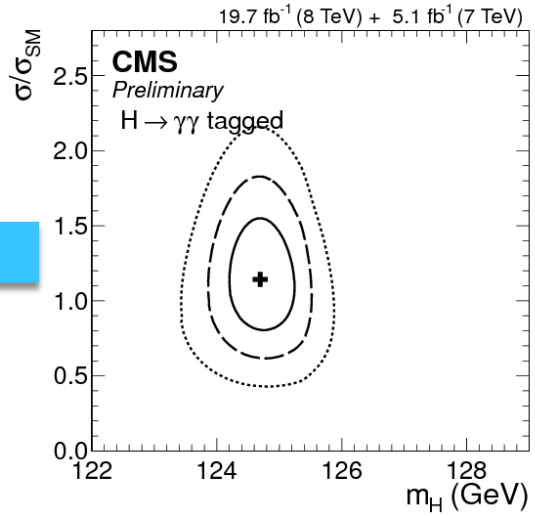
- Include **five main decays** and searches for **ttH production.**
- **207 channels.**
- **2519 parameters.**
  - 219 H→γγ background parameters.

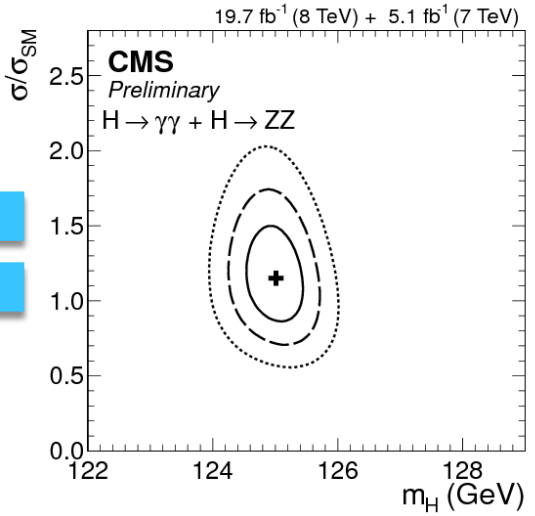
Decay tag and production tag		Expected signal composition	σ_{m_H}/m_H	Luminosity (fb^{-1}) No. of categories 7 TeV	8 TeV
$H \to \gamma\gamma$ [20], Section 2.1				*5.1*	*19.7*
$\gamma\gamma$	Untagged	76–93% ggH	0.8–2.1%	4	5
	2-jet VBF	50–80% VBF	1.0–1.3%	2	3
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70–80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	≈65% VH (WH/ZH ≈ 5)	1.0–1.3%	1	1
	Leptonic $t\bar{t}H$	≈95% $t\bar{t}H$	1.1%	1†	1
	Multijet $t\bar{t}H$	>90% $t\bar{t}H$	1.1%		1
$H \to ZZ^{(*)} \to 4\ell$ [18], Section 2.2				*5.1*	*19.7*
4μ, 2e2μ, 4e	2-jet	42% VBF + VH	1.3, 1.8, 2.2%‡	3	3
	Other	≈90% ggH		3	3
$H \to WW^{(*)} \to \ell\nu\ell\nu$ [17], Section 2.3				*4.9*	*19.4*
eμ + μμ, eμ	0-jet	96–98% ggH	eμ: 16%‡	2	2
	1-jet	82–84% ggH	eμ: 17%‡	2	2
	2-jet VBF	78–86% VBF		2	2
	2-jet VH	31–40% VH		2	2
3ℓ3ν WH	SF-SS, SF-OS	≈100% WH, up to 20% ττ		2	2
$\ell\ell + \ell'\nu$jj ZH	eee, eeμ, μμμ, μμe	≈100% ZH		4	4
$H \to \tau\tau$ [19], Section 2.4				*4.9*	*19.7*
$e\tau_h$, $\mu\tau_h$	0-jet	≈98% ggH	11–14%	4	4
	1-jet	70–80% ggH	12–16%	5	5
	2-jet VBF	75–83% VBF	13–16%	2	4
$\tau_h\tau_h$	1-jet	67–70% ggH	10–12%	-	2
	2-jet VBF	80% VBF	11%	-	1
eμ	0-jet	≈98% ggH, 23–30% WW	16–20%	2	2
	1-jet	75–80% ggH, 31–38% WW	18–19%	2	2
	2-jet VBF	79–94% VBF, 37–45% WW	14–19%	1	2
ee, μμ	0-jet	88–98% ggH		4	4
	1-jet	74–78% ggH, ≈17% WW *		4	4
	2-jet CJV	≈50% VBF, ≈45% ggH, 17–24% WW *		2	2
$\ell\ell + LL'$ ZH	$LL' = \tau_h\tau_h, \ell\tau_h, e\mu$	≈15% (70%) WW for $LL' = \ell\tau_h$ (eμ)		8	8
$\ell + \tau_h\tau_h$ WH		≈96% VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\tau_h$ WH		ZH/WH ≈ 5%, 9–11% WW		2	4
VH with $H \to bb$ [16], Section 2.5				*5.1*	*18.9*
W(ℓν)bb	$p_T(V)$ bins	≈100% VH, 96–98% WH	≈10%	4	6
W($\tau_h\nu$)bb		93% WH		-	1
Z(ℓℓ)bb	$p_T(V)$ bins	≈100% ZH		4	4
Z(νν)bb	$p_T(V)$ bins	≈100% VH, 62–76% ZH		2	3
$t\bar{t}H$ with $H \to$ hadrons [14, 28], Section 2.6				*5.0*	*19.3*
$H \to bb$	$t\bar{t}$ lepton+jets	≈90% bb but ≈24% WW in ≥6j + 2b		7	7
	$t\bar{t}$ dilepton	45–85% bb, 8–35% WW, 4–14% ττ		2	3
$H \to \tau_h\tau_h$	$t\bar{t}$ lepton+jets	68–80% ττ, 13–22% WW, 5–13% bb		-	6
$t\bar{t}H$ with $H \to$ leptons [29], Section 2.6				-	*19.6*
2ℓ-SS		WW/ττ ≈ 3		-	6
3ℓ		WW/ττ ≈ 3		-	2
4ℓ		WW : ττ : ZZ ≈ 3 : 2 : 1		-	1

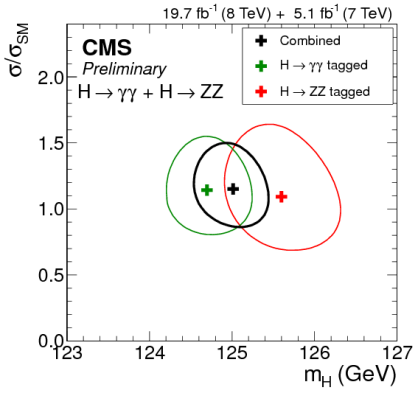
Combined m_H measurement

[CMS-PAS-HIG-14-009]





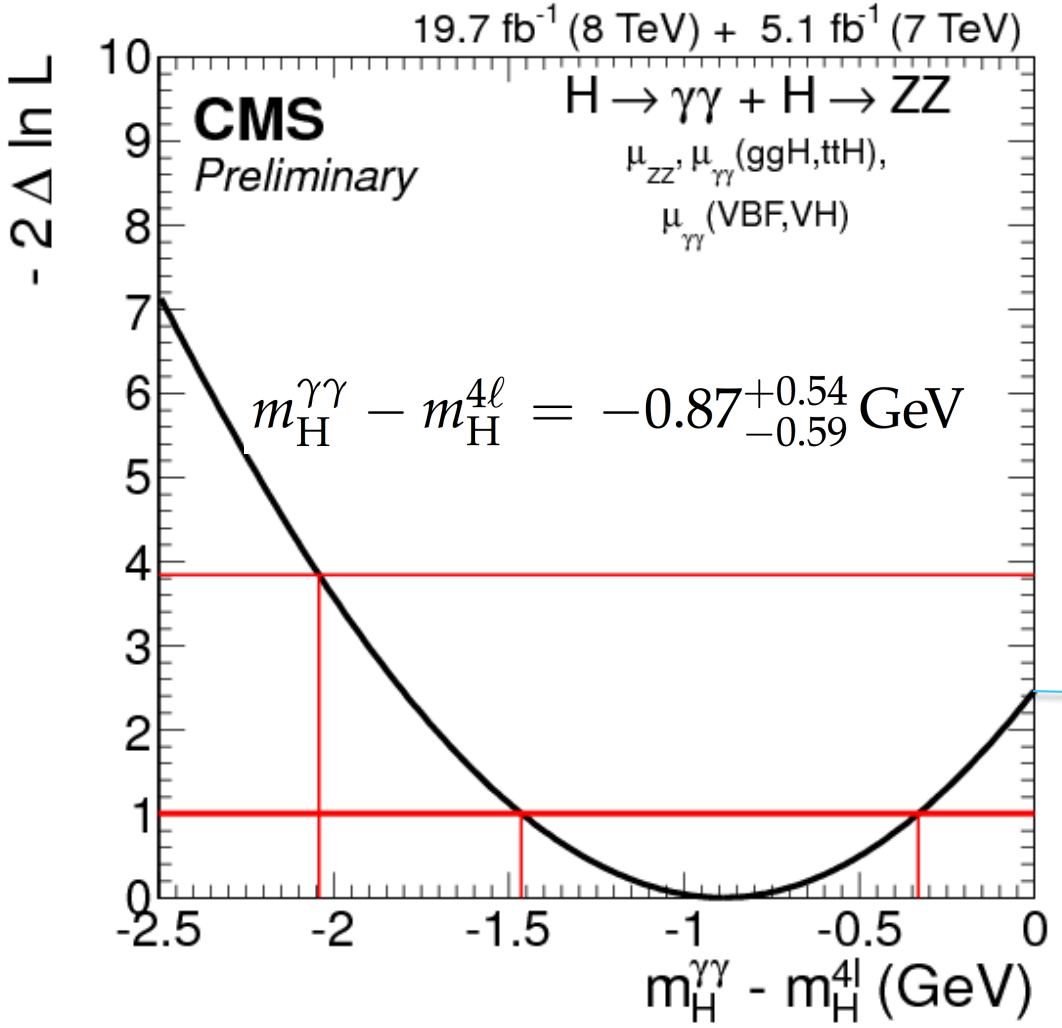




Combined m_H measurement

[CMS-PAS-HIG-14-009]

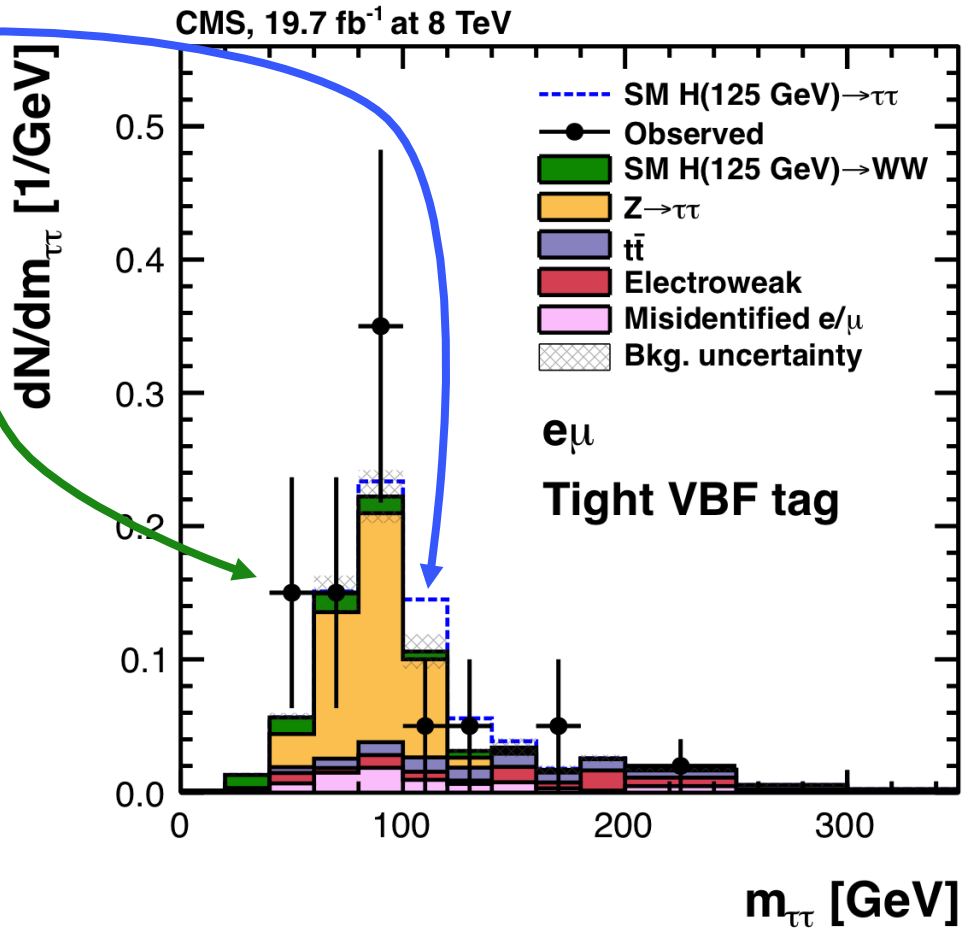
- Opposite sign from ATLAS.



Extra Higgs sensitivity in H→ττ analysis

[JHEP 05 (2014) 104] [CMS-PAS-HIG-14-009]

- H→ττ analysis has **sensitivity** to:
  - **H→ττ decays**, and
  - **H→WW decays.**
- H→WW treatment:
  - **In combination: signal.**
    - 3.9σ obs. (3.9σ exp.)
  - **In H→ττ paper: SM background.**
    - 3.2σ obs. (3.7σ exp.)



H→VV results in combination

[JHEP 01 (2014) 096] [PRD 89 (2014) 092007] [CMS-PAS-HIG-14-009]

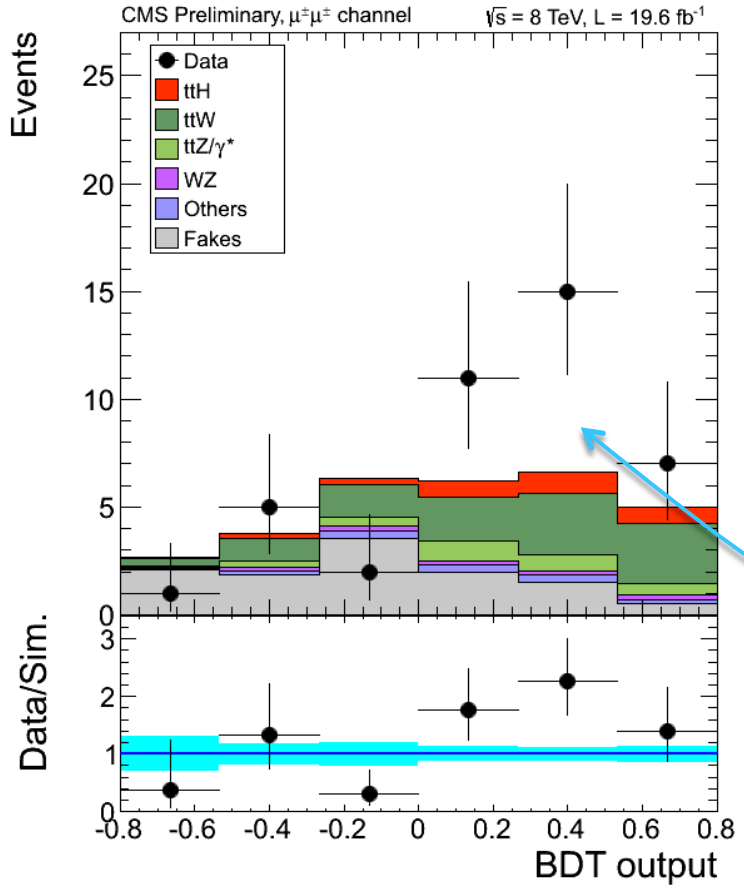
- What changed?
  - **BR(H→VV) changes by 4 – 5%.**
    - H→WW and H→ZZ paper results evaluated at H→ZZ m_H result: **m_H = 125.6 GeV**.
    - Combined mass slightly lower: **m_H = 125.0 GeV**.
  - In the combination **H→WW includes the ttH, H decaying to multi-lepton result:** $\sigma/\sigma_{SM} = 3.7 \pm 1.5$.

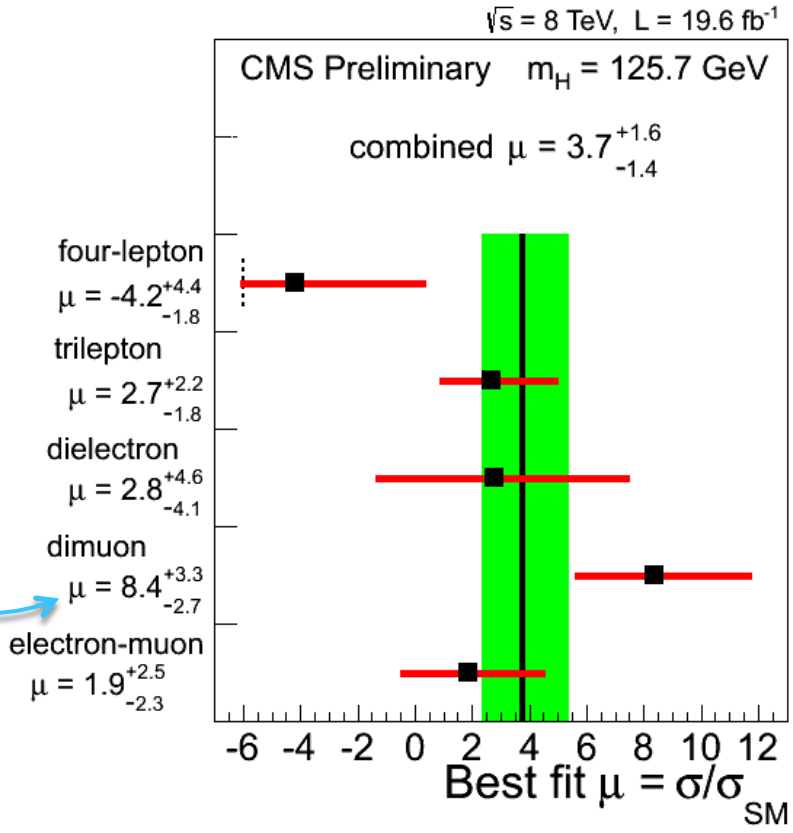
σ/σ_{SM}	Individual publication	Combination
H→ZZ	0.93	1.00
H→WW	0.72	0.83

ttH multi-leptons

[CMS-PAS-HIG-13-020] [http://cern.ch/go/FKr9]

- Very extensive cross-checks performed: http://cern.ch/go/Xv8S





Significance of excesses

[CMS-PAS-HIG-14-009]

Channel grouping	Significance (σ)	
	Observed	Expected
$H \to ZZ$ tagged	6.5	6.3
$H \to \gamma\gamma$ tagged	5.6	5.3
$H \to WW$ tagged	4.7	5.4
Grouped as in Ref. [17]	*4.3*	*5.4*
$H \to \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [19]	*3.9*	*3.9*
$H \to bb$ tagged	2.0	2.3
Grouped as in Ref. [16]	*2.1*	*2.3*

Combined production measurement

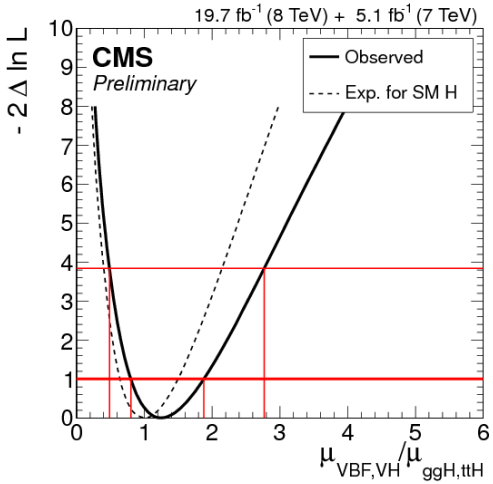
[CMS-PAS-HIG-14-009]

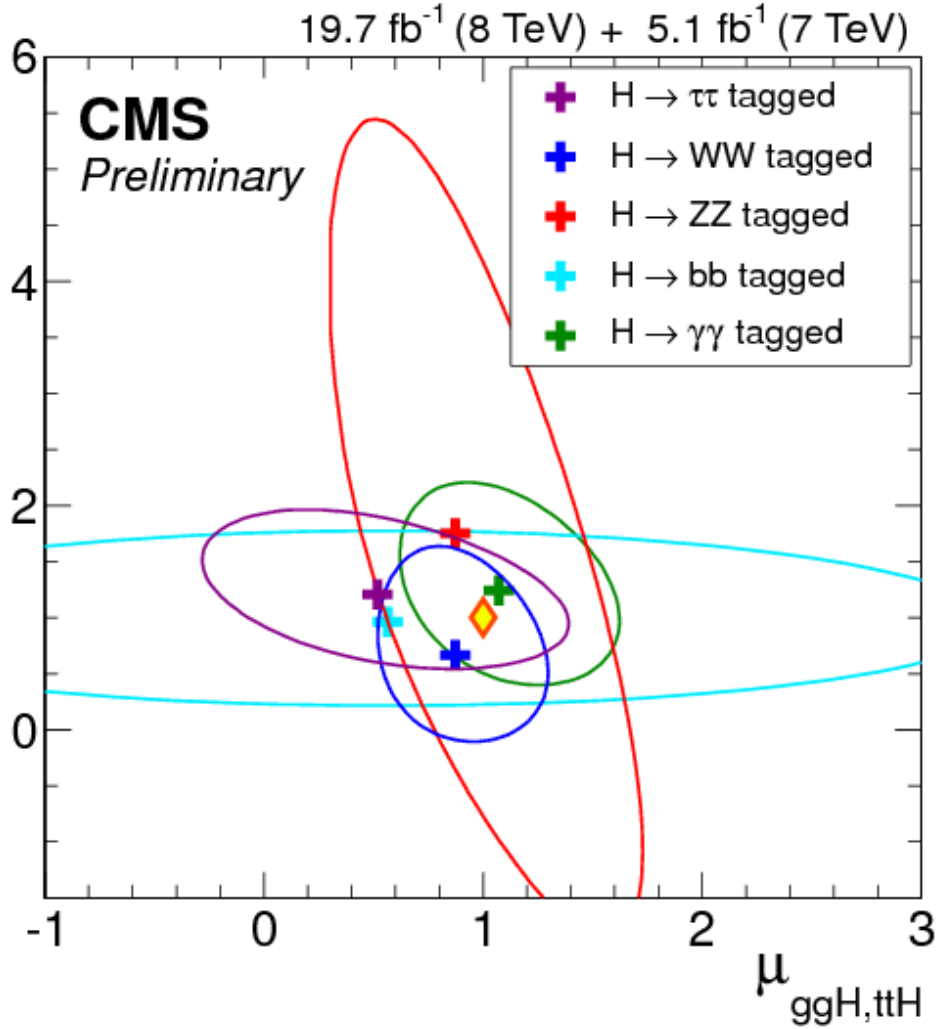
Channel grouping	Best fit $(\mu_{ggH,t\bar{t}H}, \mu_{VBF,VH})$
$H \to ZZ$ tagged	$(0.88, 1.75)$
$H \to \gamma\gamma$ tagged	$(1.07, 1.24)$
$H \to WW$ tagged	$(0.87, 0.66)$
$H \to \tau\tau$ tagged	$(0.52, 1.21)$
$H \to bb$ tagged	$(0.57, 0.96)$

Combined best fit $\mu_{VBF,VH}/\mu_{ggH,t\bar{t}H}$

Observed (expected)

$1.25^{+0.63}_{-0.45}$ $(1.00^{+0.49}_{-0.35})$





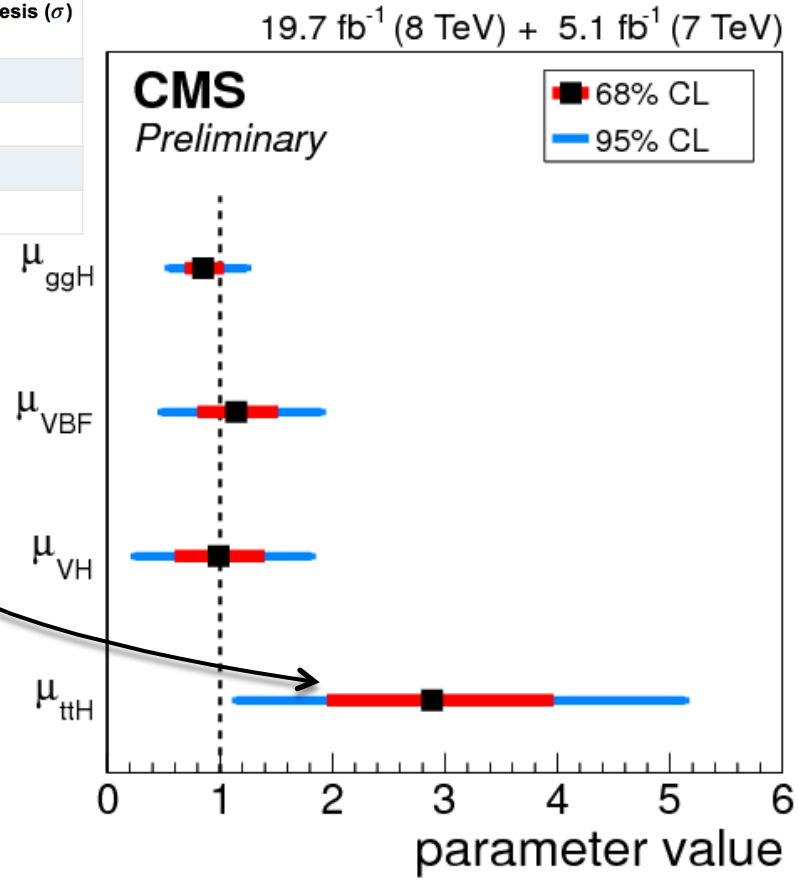
Production mode scaling assuming SM BR structure

[CMS-PAS-HIG-14-009]

NEW

- $\mu_{ggH} = 0.85\ ^{+0.11}_{-0.09}\ (\text{stat.})\ ^{+0.11}_{-0.08}\ (\text{theo.})\ ^{+0.10}_{-0.09}\ (\text{syst.})$

Parameter	Best fit result (68% CL) for full combination	Observed significance (σ)	Expected sensitivity (σ)	Pull to SM hypothesis (σ)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
μ_{VBF}	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
μ_{VH}	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0.0
μ_{ttH}	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1

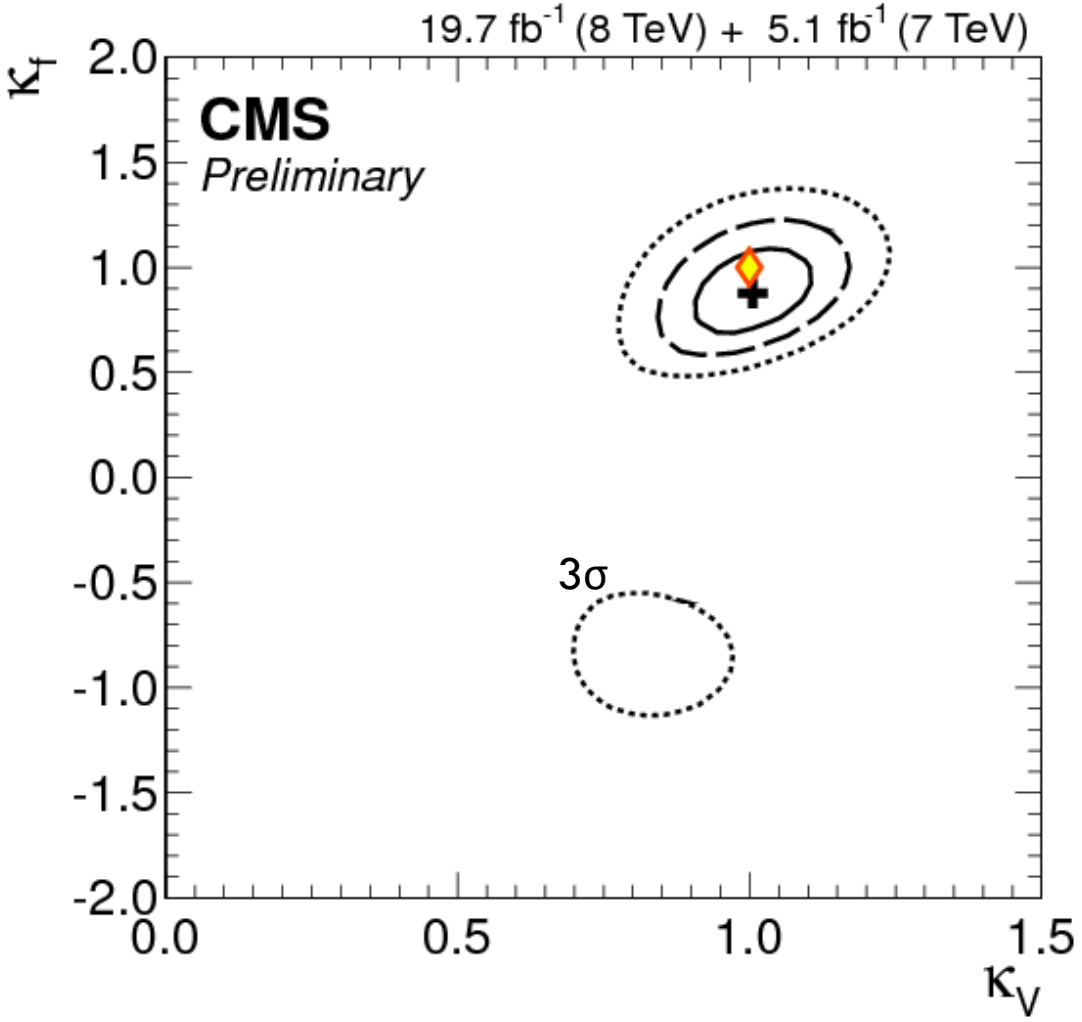


Parameter	Best fit result (68% CL) for 7 TeV data	Best fit result (68% CL) for 8 TeV data
μ_{ggH}	$1.00^{+0.36}_{-0.32}$	$0.80^{+0.19}_{-0.17}$
μ_{VBF}	$1.78^{+0.97}_{-0.91}$	$1.02^{+0.39}_{-0.36}$
μ_{VH}	$0.69^{+0.98}_{-0.66}$	$1.06^{+0.45}_{-0.43}$
μ_{ttH}	$0.00^{+2.13}_{-0.00}$	$3.22^{+1.14}_{-1.00}$

Coupling deviations

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

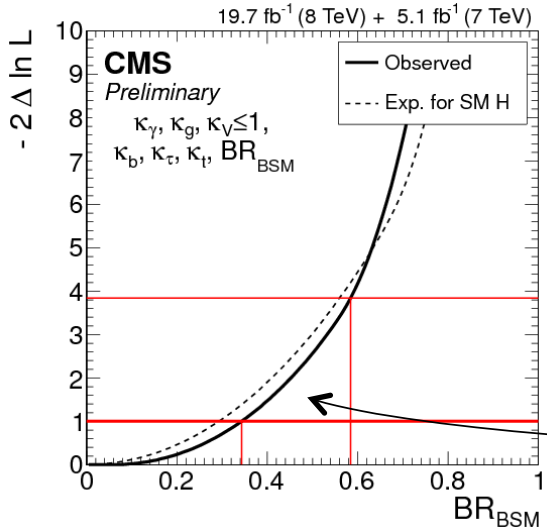
- Scaling the couplings to fermions (κ_f) and vector bosons (κ_V).
- **Interference in H→ γγ decay resolves degeneracy.**

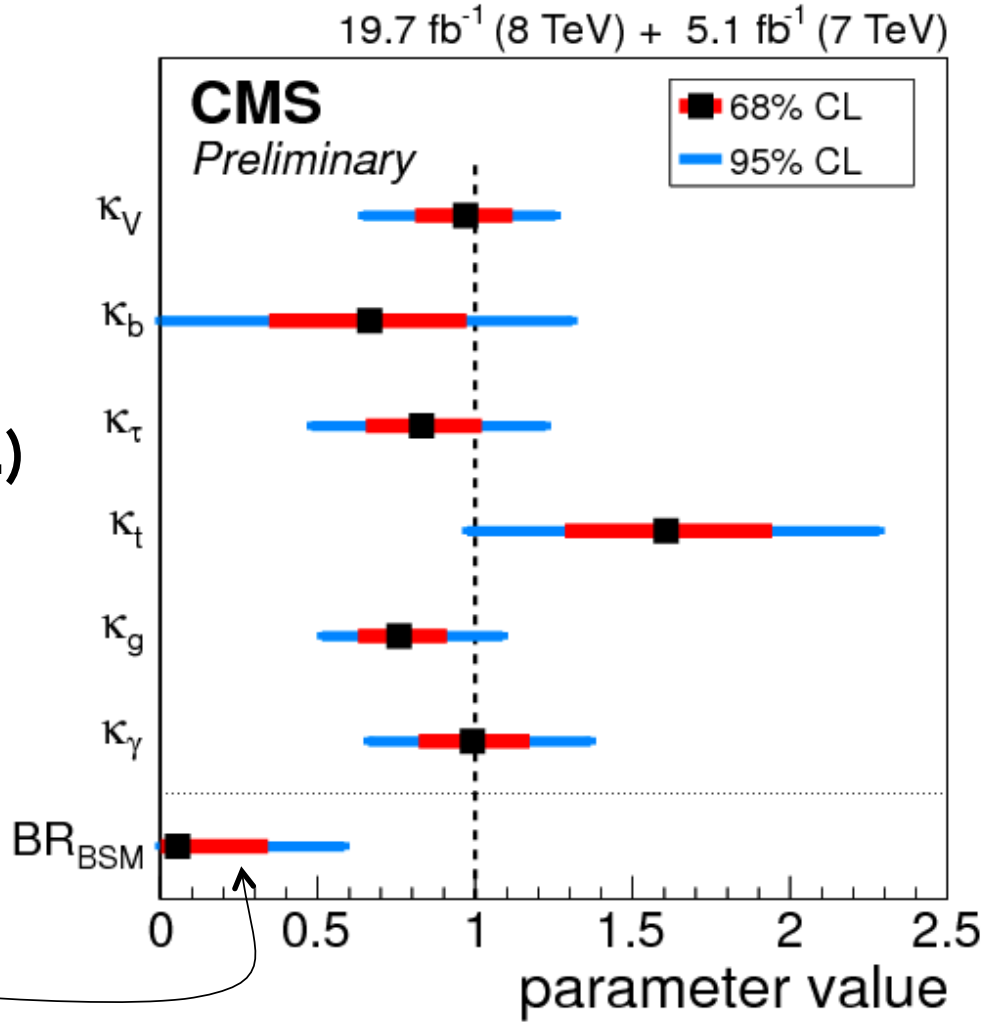


Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

- 6 or 7 parameter fits with effective loops.
- BR_{BSM} measured assuming $\kappa_V \leq 1$:
  - **BR_{BSM} < 0.34 (95% CL)**





Coupling deviations

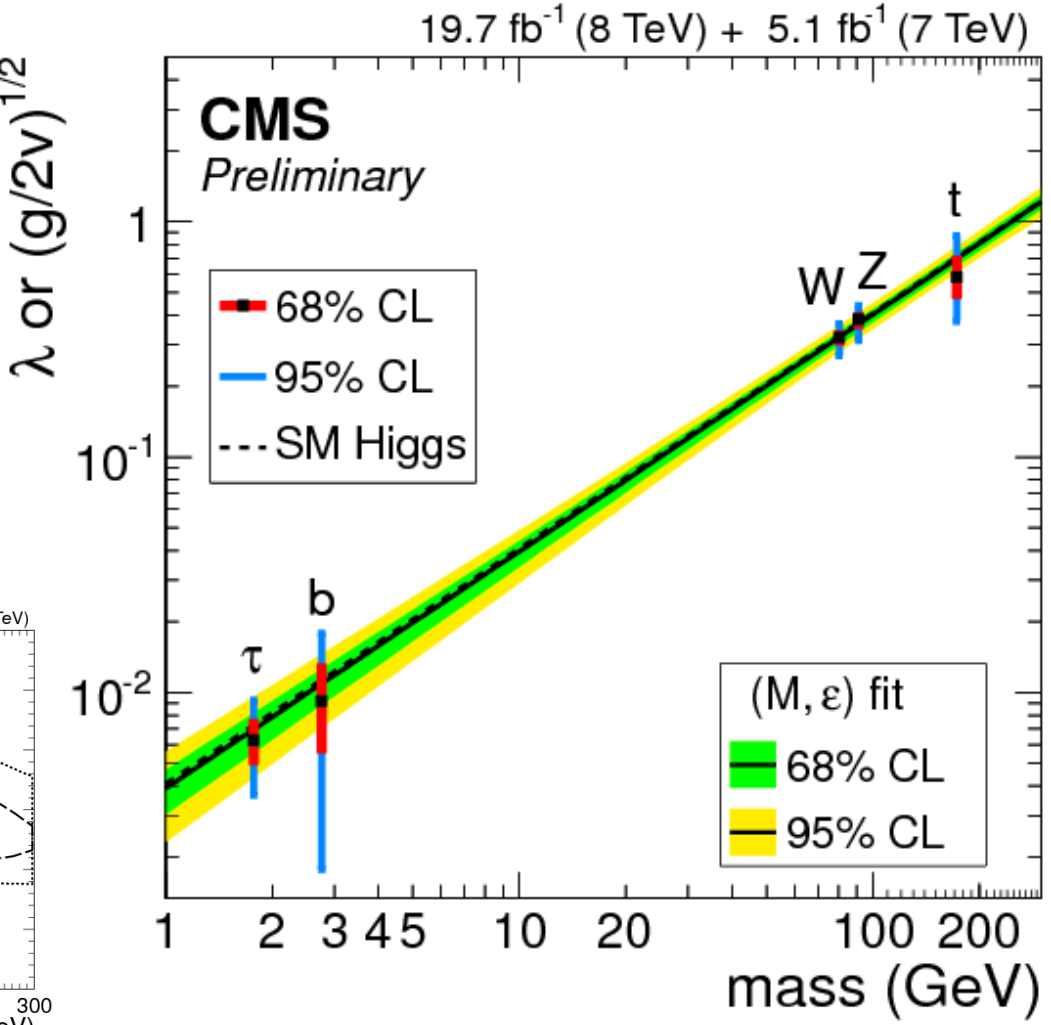
[CMS-PAS-HIG-14-009] [arXiv:1307.1347]

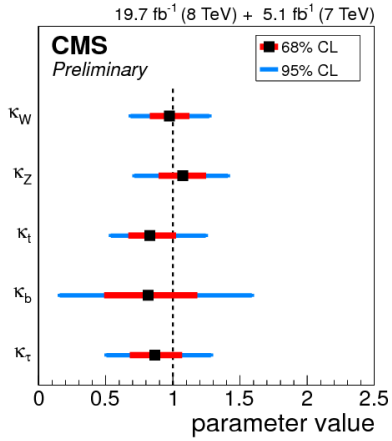
Model Parameters	Table in Ref. [27]	Best-fit result Parameter	68% CL	95% CL	Comment
κ_Z, λ_{WZ} (κ_f =1)	-	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	[0.61,1.45]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ using ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.91^{+0.14}_{-0.12}$	[0.70,1.22]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	[0.88,1.15]	κ_V scales couplings to W and Z bosons.
		κ_f	$0.89^{+0.14}_{-0.13}$	[0.64,1.16]	κ_f scales couplings to all fermions.
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.10}_{-0.10}$	[0.69,1.10]	Effective couplings to gluons (g) and photons (γ).
		κ_γ	$1.15^{+0.13}_{-0.13}$	[0.89,1.42]	
$\kappa_g, \kappa_\gamma, BR_{BSM}$	48 (middle)	BR_{BSM}	≤ 0.13	[0.00,0.32]	Branching fraction for BSM decays.
$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$1.01^{+0.20}_{-0.19}$	[0.66,1.43]	$\lambda_{du} = \kappa_u/\kappa_d$, relating up-type and down-type fermions.
$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.02^{+0.22}_{-0.21}$	[0.61,1.49]	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relating leptons and quarks.
$\kappa_g, \kappa_\gamma, \kappa_V, \kappa_b, \kappa_\tau, \kappa_t$	Similar to 50 (top)	κ_g	$0.76^{+0.15}_{-0.13}$	[0.51,1.09]	
		κ_γ	$0.99^{+0.18}_{-0.17}$	[0.66,1.37]	
		κ_V	$0.97^{+0.15}_{-0.16}$	[0.64,1.26]	
		κ_b	$0.67^{+0.31}_{-0.32}$	[0.00,1.31]	Down-type quarks (via b).
		κ_τ	$0.83^{+0.19}_{-0.18}$	[0.48,1.22]	Charged leptons (via τ).
		κ_t	$1.61^{+0.33}_{-0.32}$	[0.97,2.28]	Up-type quarks (via t).
as above plus BR_{BSM} and $\kappa_V \leq 1$	-	BR_{BSM}	≤ 0.34	[0.00,0.58]	

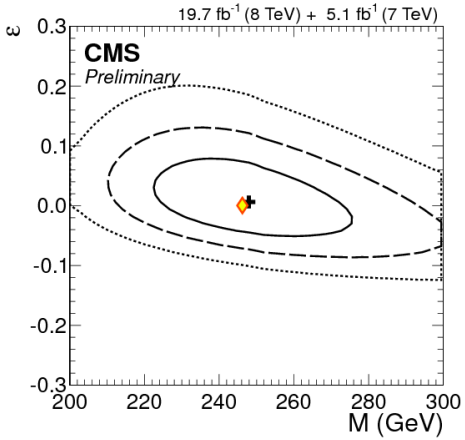
Coupling deviations summaries

[CMS-PAS-HIG-14-009] [arxiv:1207.1693] [arxiv:1303.3570]

- Assuming no BSM particles.







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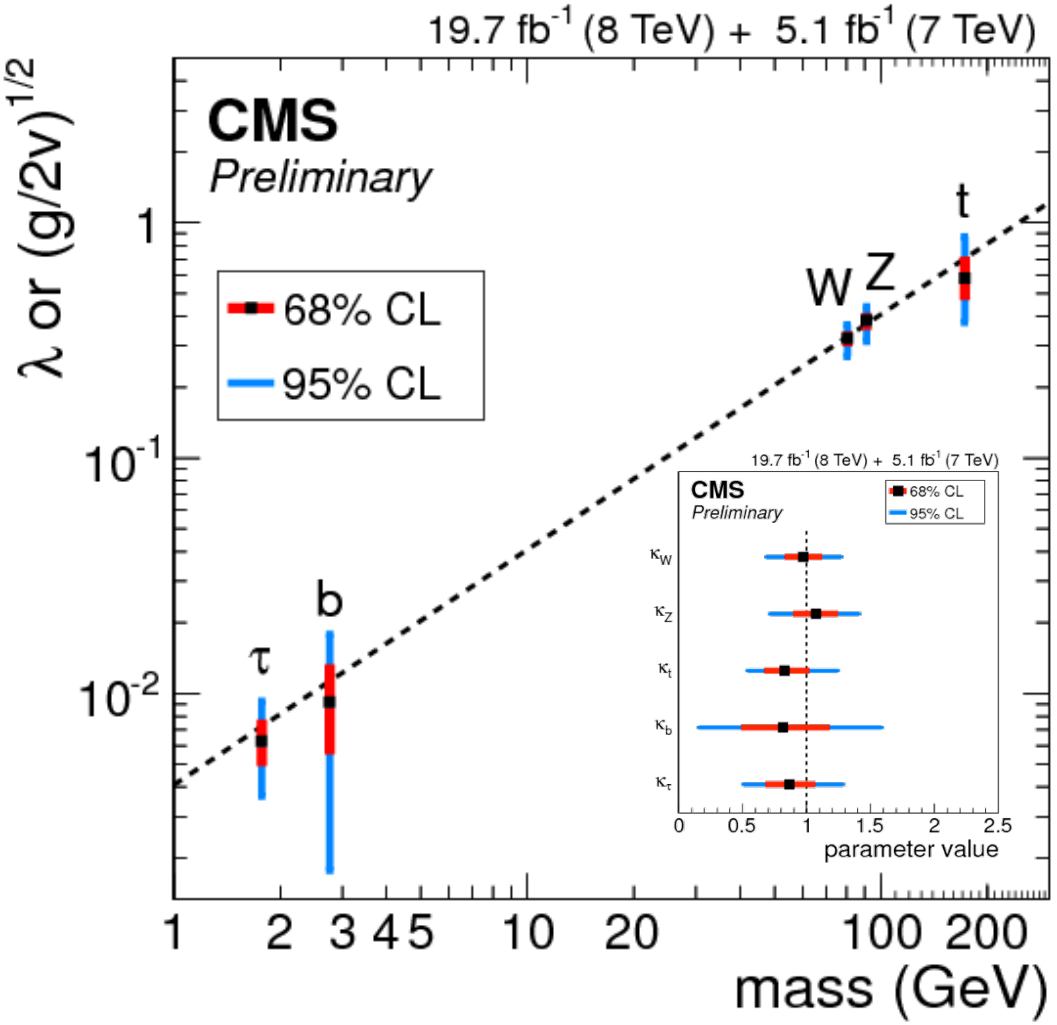
Resolving SM contributions

[CMS-PAS-HIG-14-009] [arxiv:1303.3570]

- Individual coupling scaling factors:
  - κ_W, κ_Z, κ_b, κ_t, κ_τ.
  - All loops resolved:
    - $\kappa_\gamma(\kappa_W, \kappa_t)$
    - $\kappa_g(\kappa_t, \kappa_b)$
  - SMH width scaled.

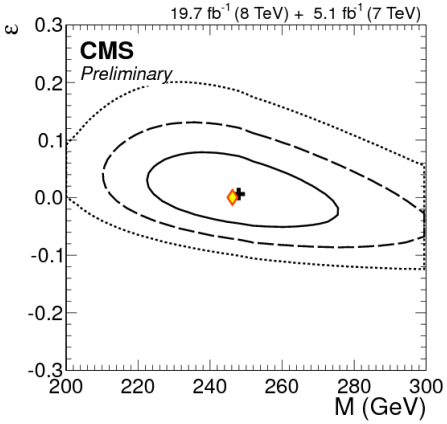
- "Reduced" couplings as function of "mass":
  - $\lambda_f = \kappa_f\ (m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{1/2}\ (m_V/vev)$

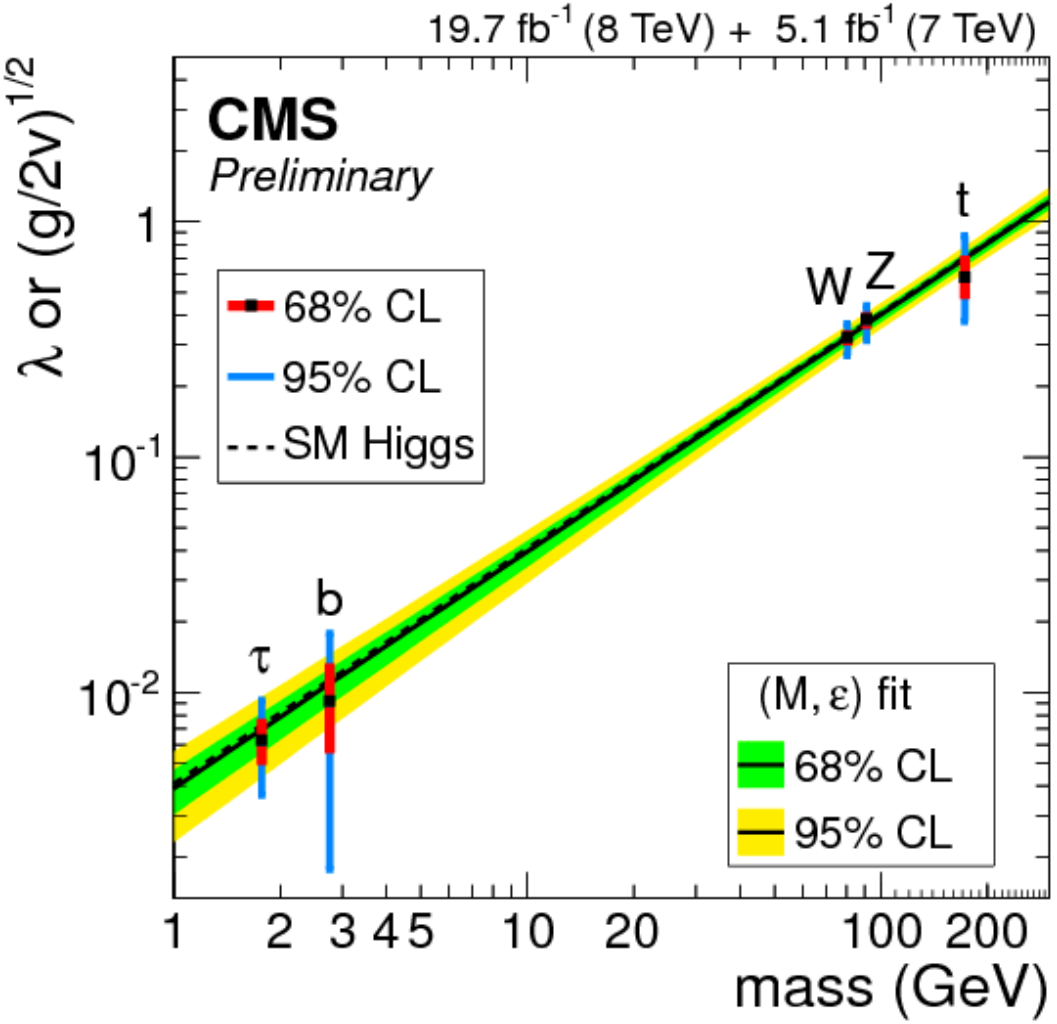


Mass power parametrization

[CMS-PAS-HIG-14-009] [arxiv:1207.1693]

- *Vev* modifier and power of coupling to mass:
  - Gauge bosons: $\kappa_V = vev \times m_V^{2\varepsilon} / M^{1+2\varepsilon}$
  - Fermions: $\kappa_f = vev \times m_f^{\varepsilon} / M^{1+\varepsilon}$
- For SMH, M = *vev* = 246.22 GeV and ε = 0.





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Spin zero amplitude in H→VV

[CMS-PAS-HIG-14-014]

- Parameterization in terms of cross-section fractions:

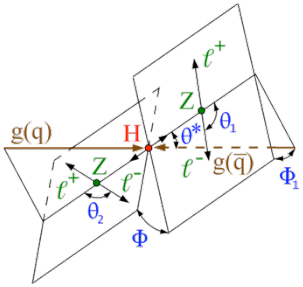
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4} \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

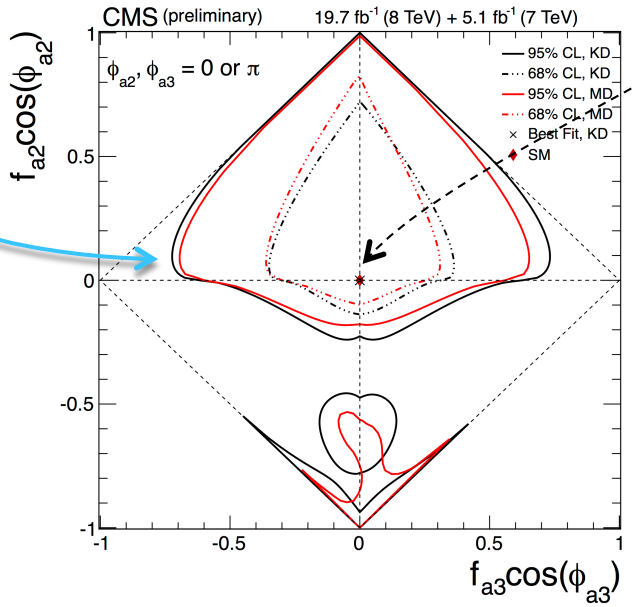
$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4} \qquad \phi_{\Lambda 1},$$

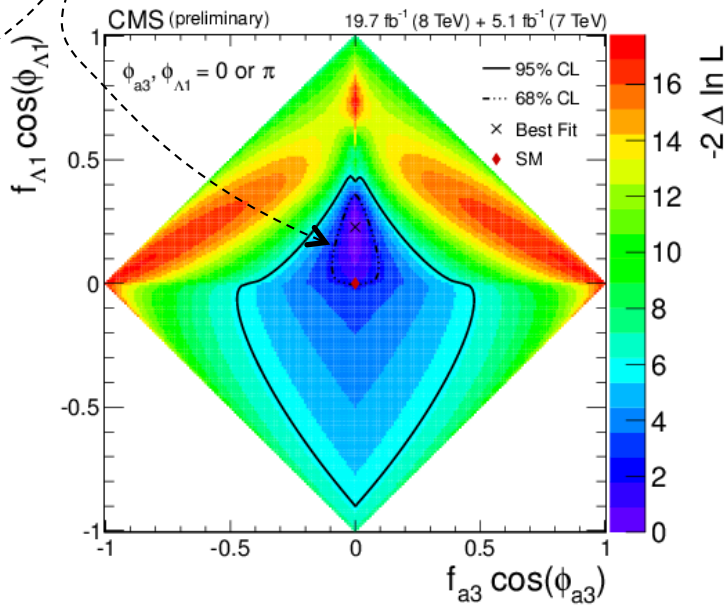
Spin zero amplitude in H→ZZ→4ℓ

[CMS-PAS-HIG-14-014]



- Full final state available:
  - **Kinematic discriminants** reducing to 2D or 3D.
  - **8D likelihood** fit.
- 2D scans of anomalous coupling fractions (real phases).
  - But also done profiling over the phases.
- **No significant deviations from SM found.**

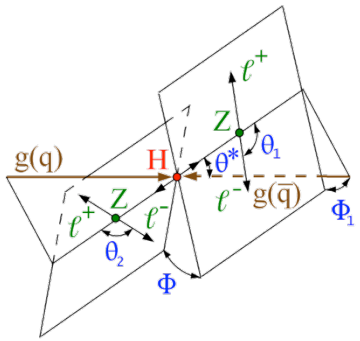


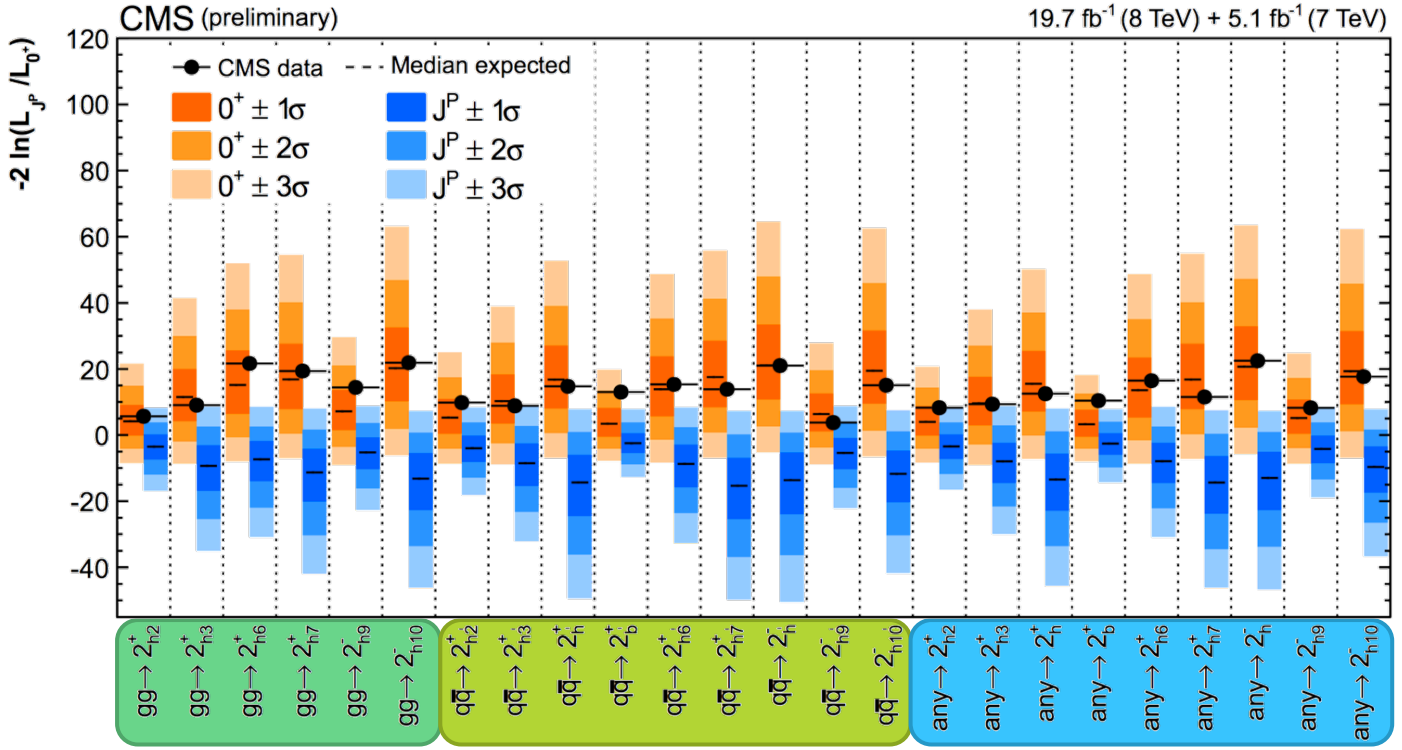


H→ZZ→4ℓ – J=2 states

[CMS-PAS-HIG-14-014]

- Broad range of hypothesis tests based on the observables optimized for each case.

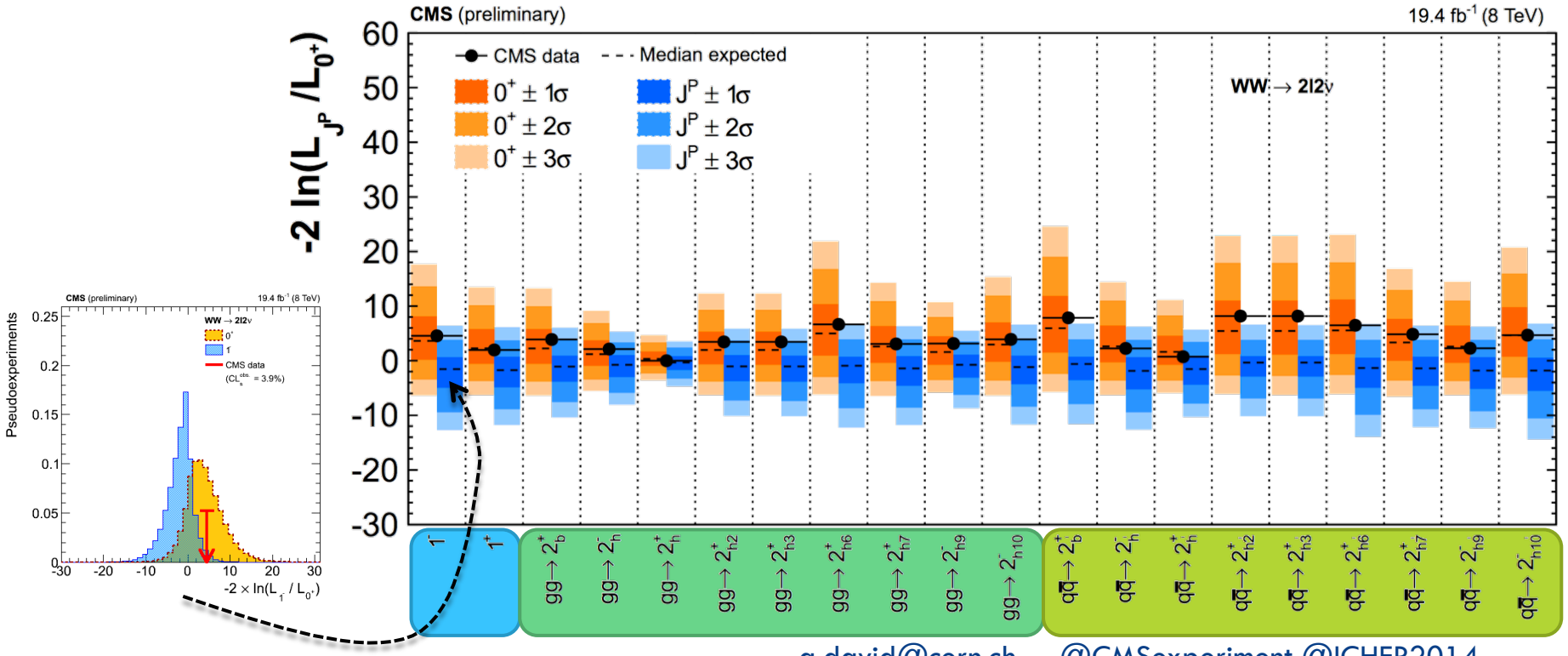




H→WW→2ℓ2ν – J>0 states

[CMS-PAS-HIG-14-012]

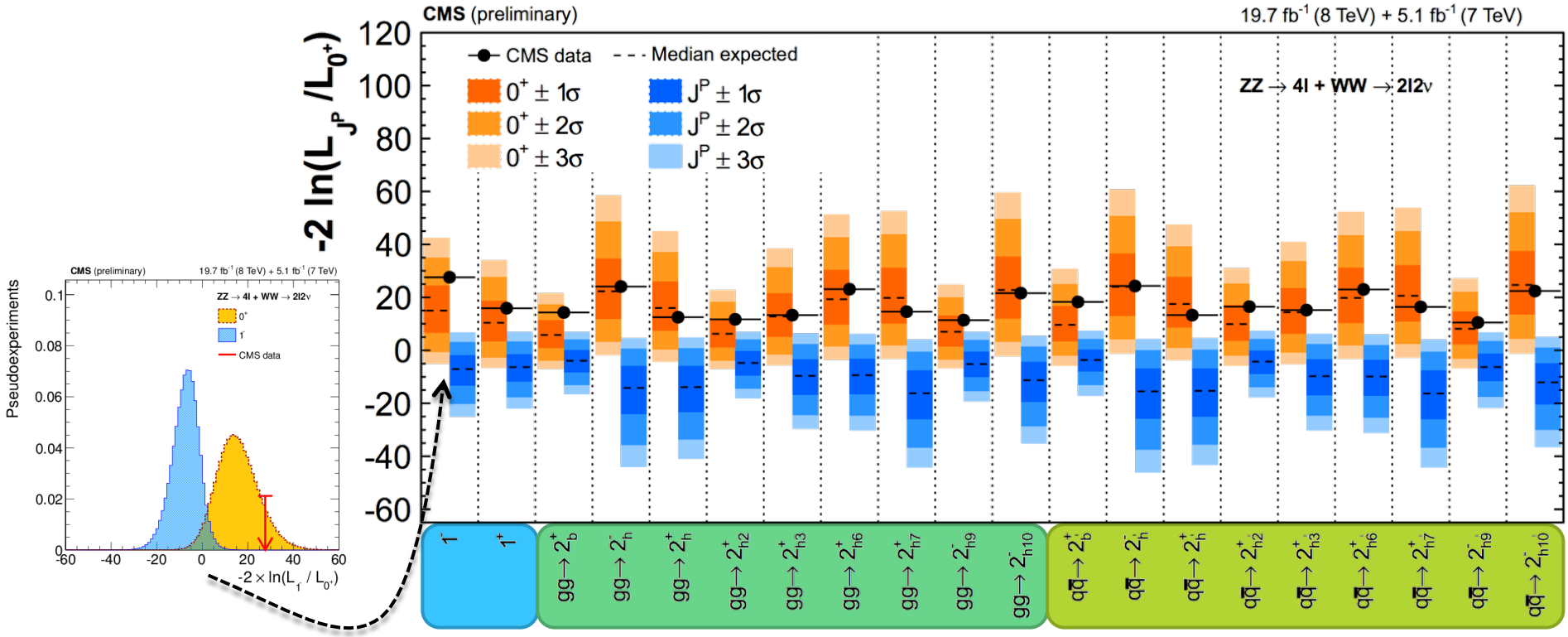
- Broad range of hypothesis tests based on the observables used for the SM measurements.



H→VV combination on J>0 states

[CMS-PAS-HIG-14-012] [CMS-PAS-HIG-14-014]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CL_S.



a.david@cern.ch

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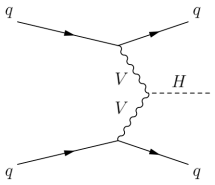
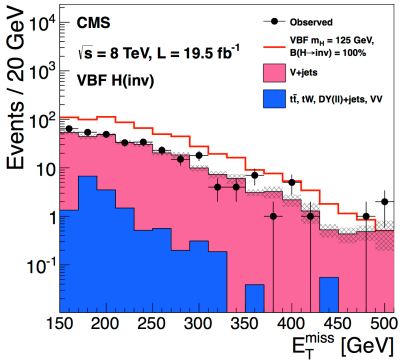
Direct searches

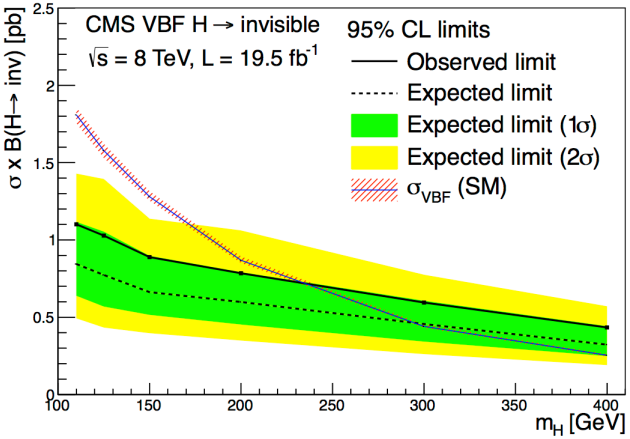
Invisible Higgs search combination

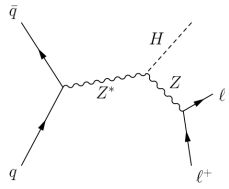
[arXiv:1404.1344, submitted to EPJC]

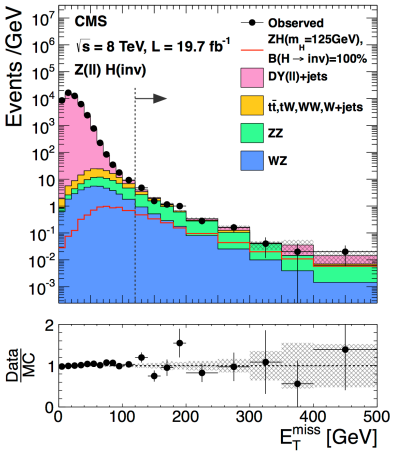
- VBF and ZH topologies combined; $Z \to \ell\ell$ and $Z \to b\bar{b}$.
- **BR(H→inv.) < 0.58 (0.44 exp.) at 95% CL**

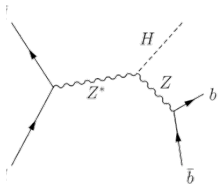


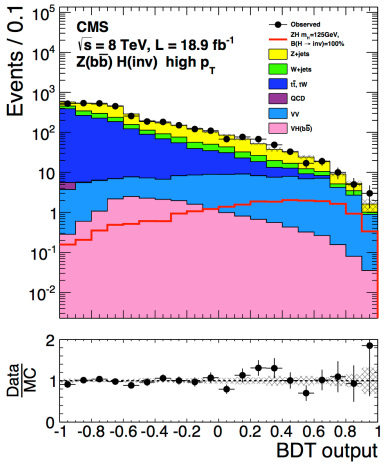


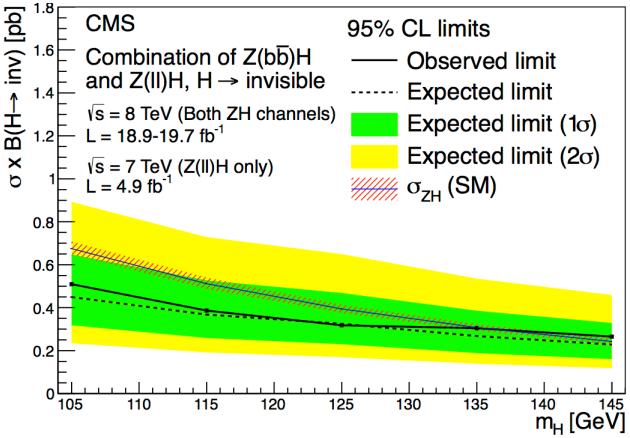






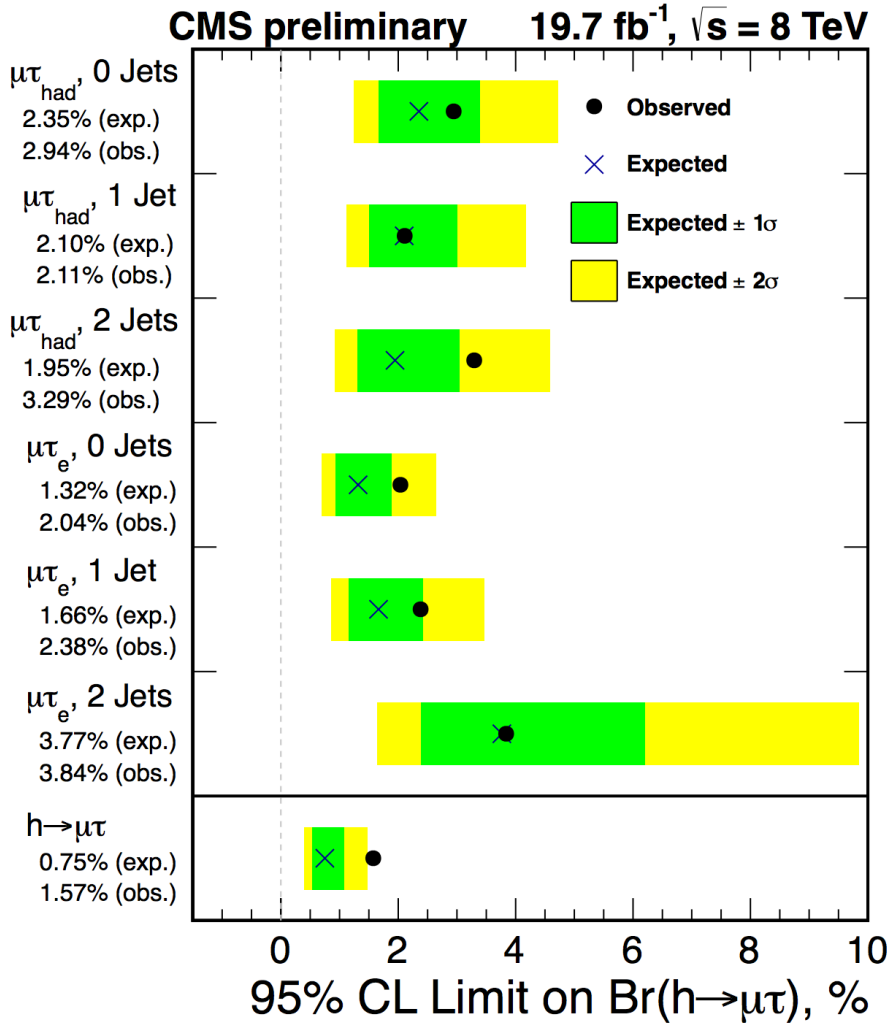


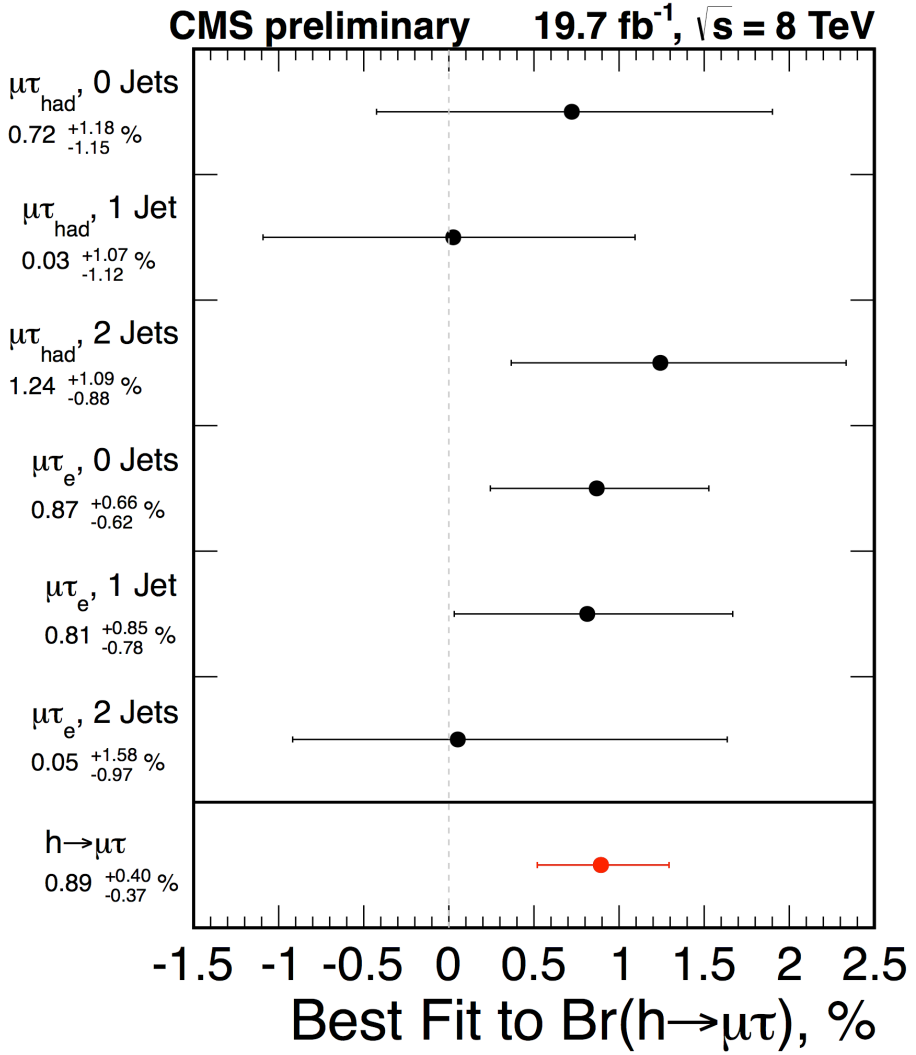




Search for H→μτ

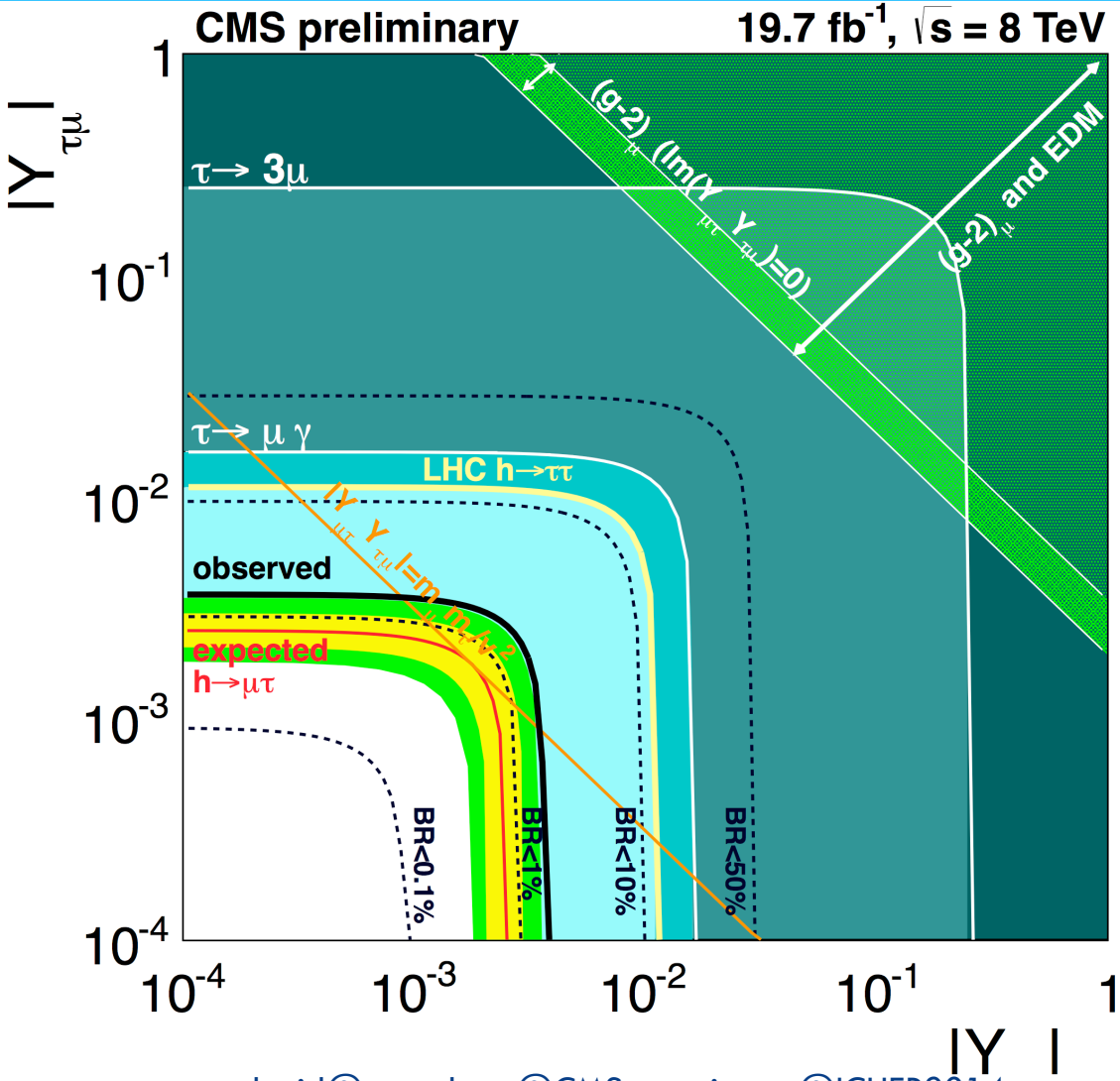
[CMS-PAS-HIG-14-005]





Search for H→μτ

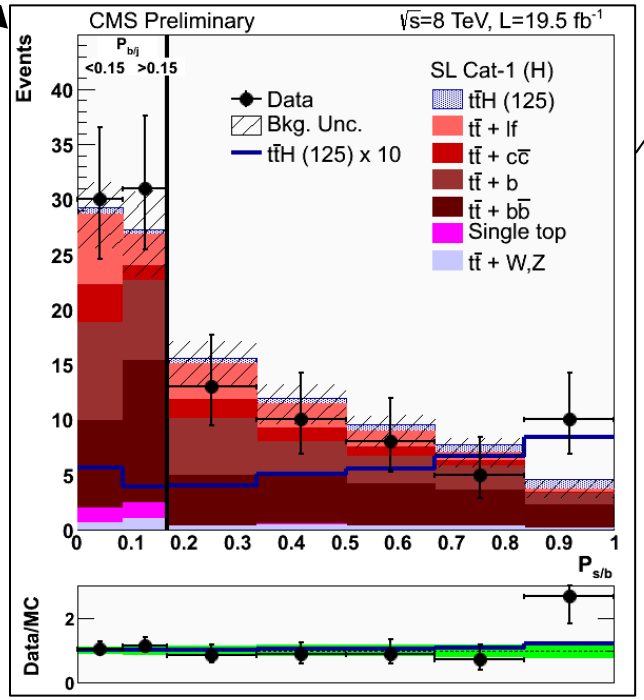
[CMS-PAS-HIG-14-005]

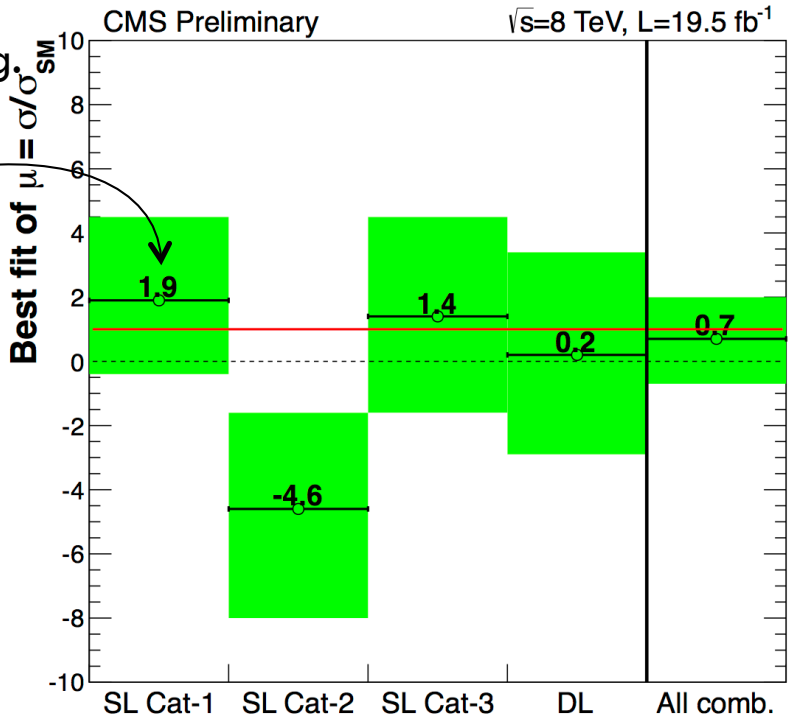


New search for ttH with H→bb̄

[CMS-PAS-HIG-14-010]

- Improved performance:
  - Event probability ($P_{s/b}$) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified W→jj (**SL Cat-1**).
  - Reduced dependency on tt+HF modeling.
- **Clearly a hot topic for Run 2.**





$$P_{s/b} = \frac{\mathcal{P}_{S(bbbb)}}{\mathcal{P}_{S(bbbb)} + \lambda \mathcal{P}_{B(bbbb)} + (1-\lambda)\mathcal{P}_{B(bbjj)}}$$

Statistics

Statistics interlude

[ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005]

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\tilde{\theta})}{\mathcal{L}(data\|0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|0,\hat{\theta}_0)}$	yes	Bayesian-frequentist hybrid
LHC	$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|\hat{\mu},\hat{\theta})}$	yes $(0 \leq \hat{\mu} \leq \mu)$	frequentist

- **LEP**: nuisances parameters (θ) kept at nominal values (~).
- **Tevatron**: maximise likelihood against nuisances (^).
  - Denominator considers **background-only hypothesis** (μ=0).
- **LHC**: frequentist profiled likelihood.
  - Denominator considers **global best-fit likelihood** with **floating signal strength**.
  - **Nice asymptotic properties, savings in computational power.**

Breaking down uncertainties

- Nuisances grouped into **stat, theo, other.**
  - **stat** includes H→γγ background parameters.
  - **theo** includes QCD scales, PDF+α_s, UEPS, and BR.
  - **syst** = **theo** ∪ **other.**
- Procedures:
  - For (**stat**)+(**syst**):
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{syst} = \sigma_{all} \ominus \sigma_{stat}$.
  - For (**stat**)+(**theo**)+(**other**)
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{stat+other}$ from scan floating **stat** and **other.**
    - $\sigma_{theo} = \sigma_{all} \ominus \sigma_{stat+other}$.
    - $\sigma_{other} = \sigma_{all} \ominus \sigma_{stat} \ominus \sigma_{theo}$.

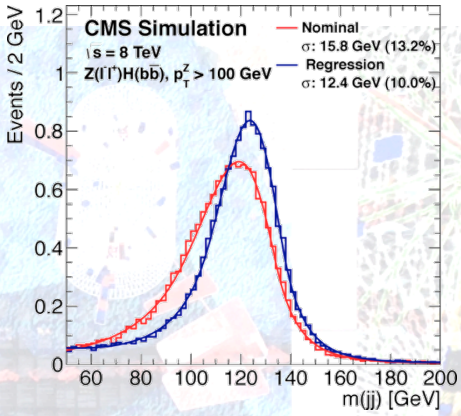
Vignettes

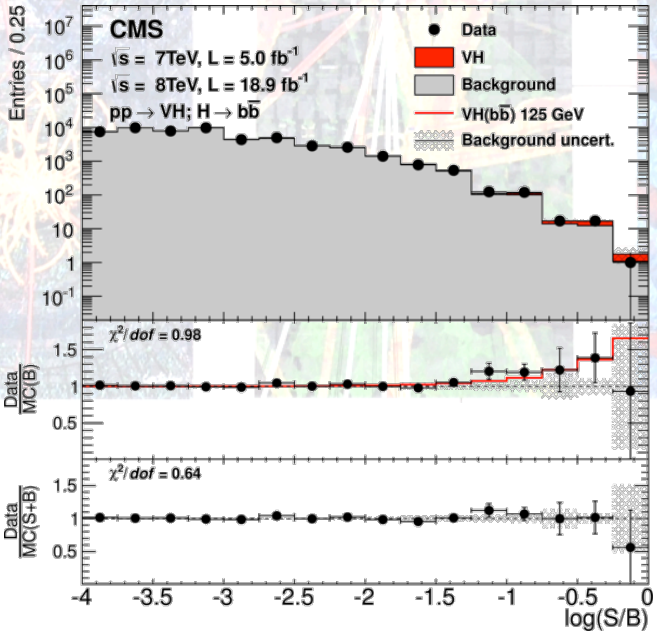
VH, H→$b\bar{b}$ vignettes

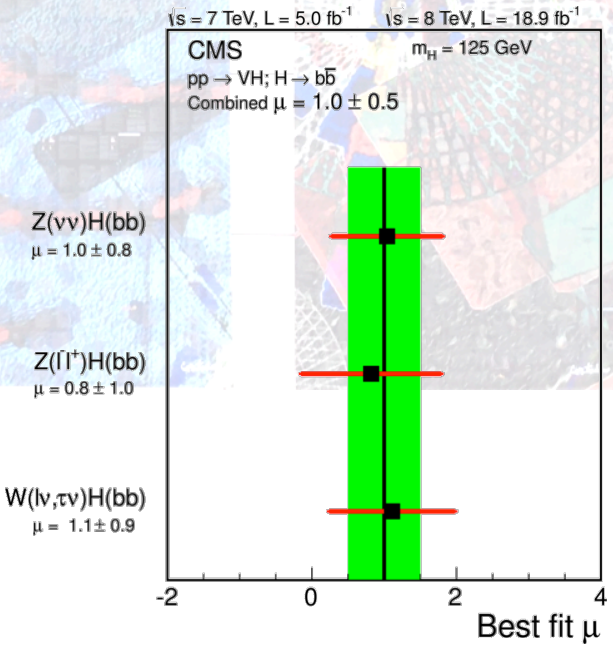
[PRD 89 (2014) 012003]

PRD 89 (2014) 012003

- 2.1σ (2.3σ exp.)
- $\sigma/\sigma_{SM} = 1.0 \pm 0.5$

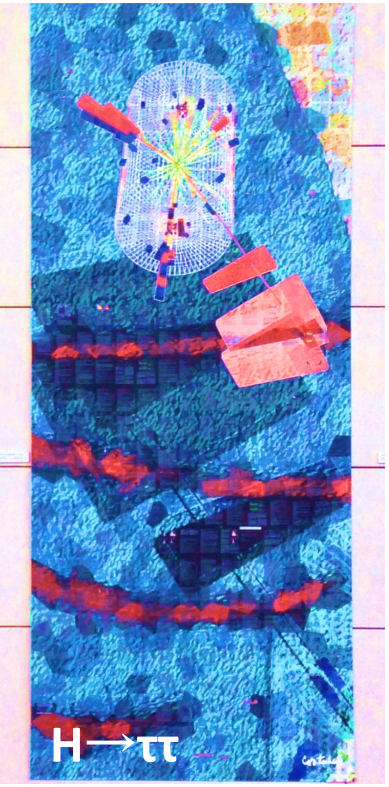






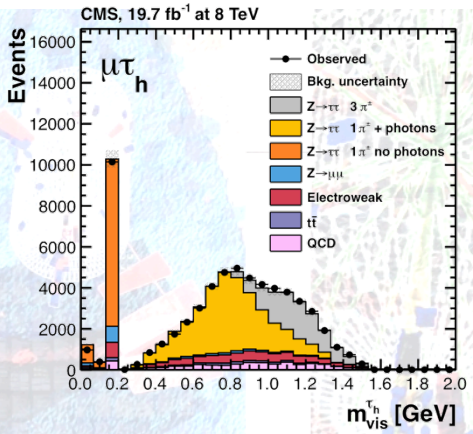
H→ττ vignettes

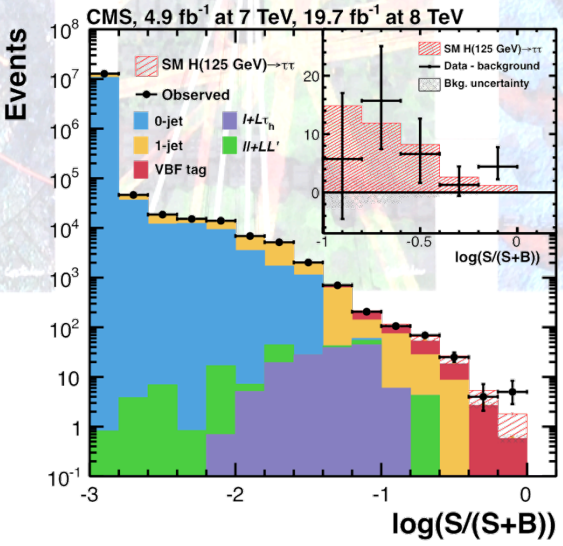
[JHEP 05 (2014) 104]

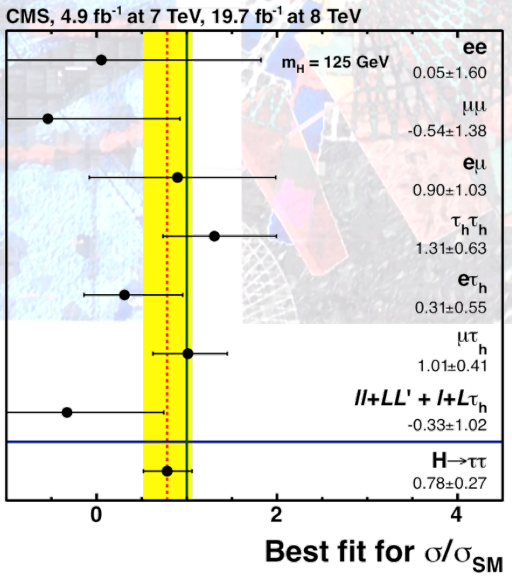


JHEP 05 (2014) 104

- 3.2σ (3.7σ exp.)
- $\sigma/\sigma_{SM} = 0.78 \pm 0.27$

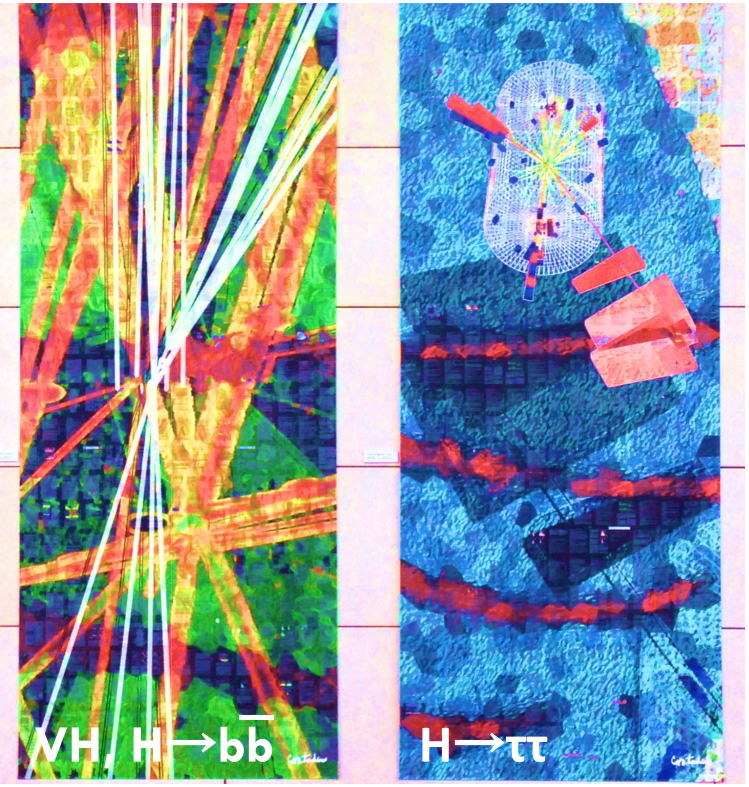






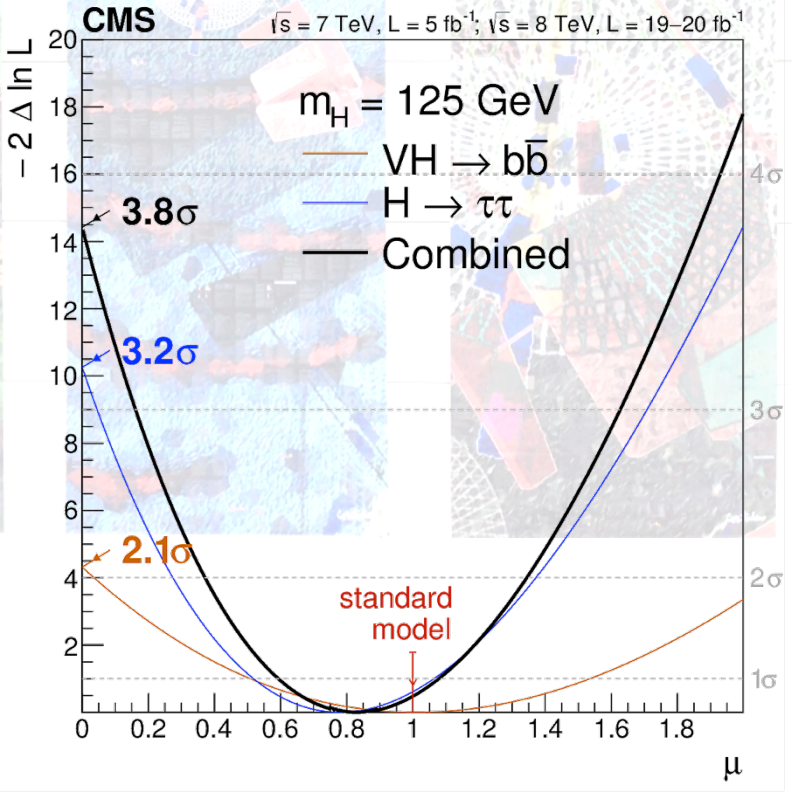
Fermion decay combination vignette

[Nature Physics, doi:10/1038/nphys3005]



PRD 89 (2014) 012003 JHEP 05 (2014) 104

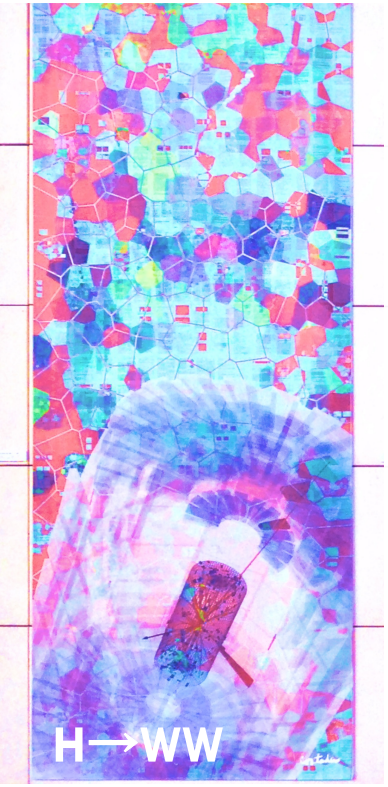
- 3.8σ (4.4σ exp.)
- $\sigma/\sigma_{SM} = 0.83 \pm 0.24$



Fermion decay combination
3.8σ obs. (4.4σ exp.)
Nature Physics, doi:10.1038/nphys3005

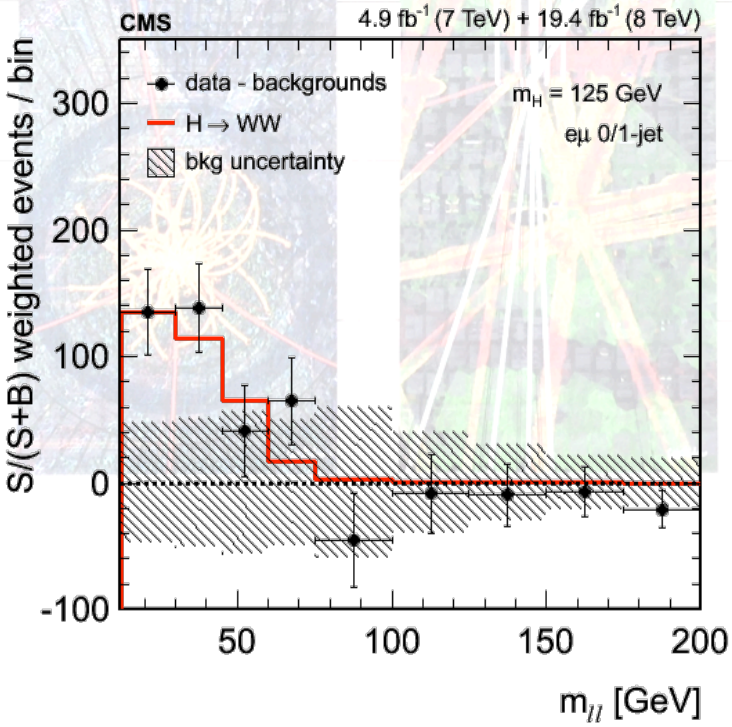
H→WW vignettes

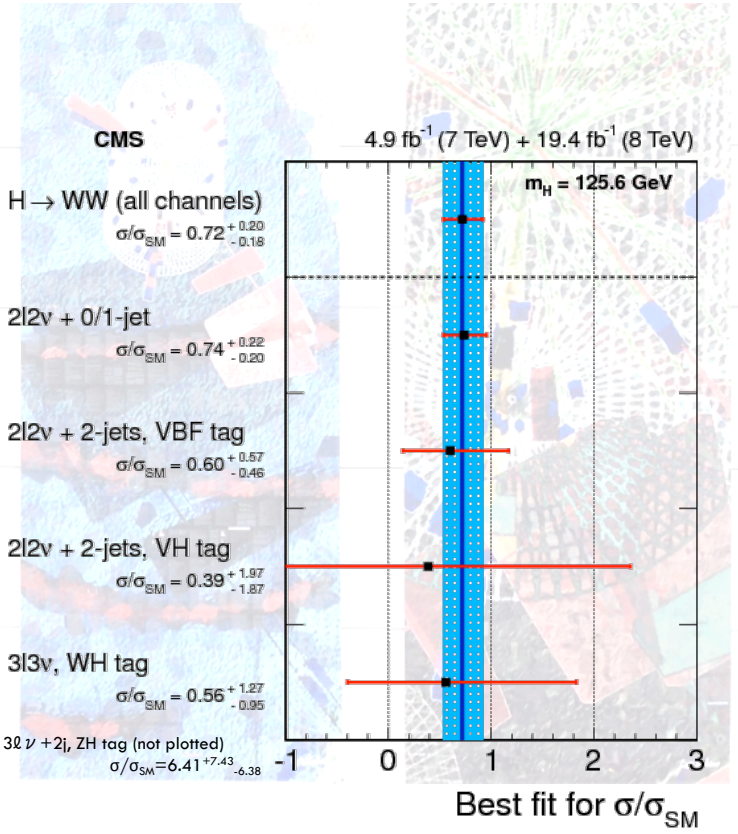
[JHEP 01 (2014) 096]



JHEP 01 (2014) 096

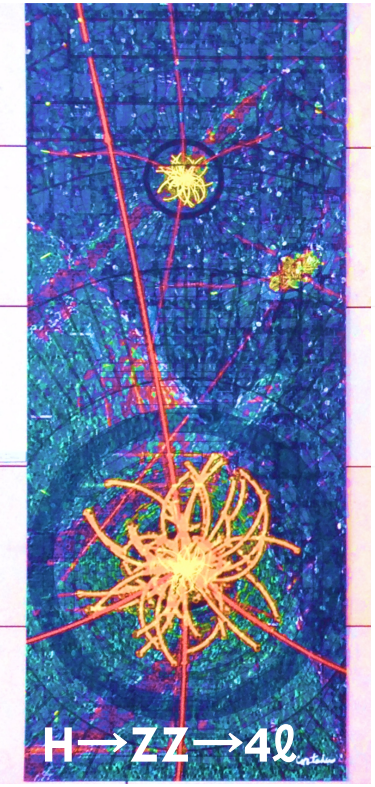
- 4.3σ (5.8σ exp.)
- $\sigma/\sigma_{SM} = 0.72 \pm 0.19$





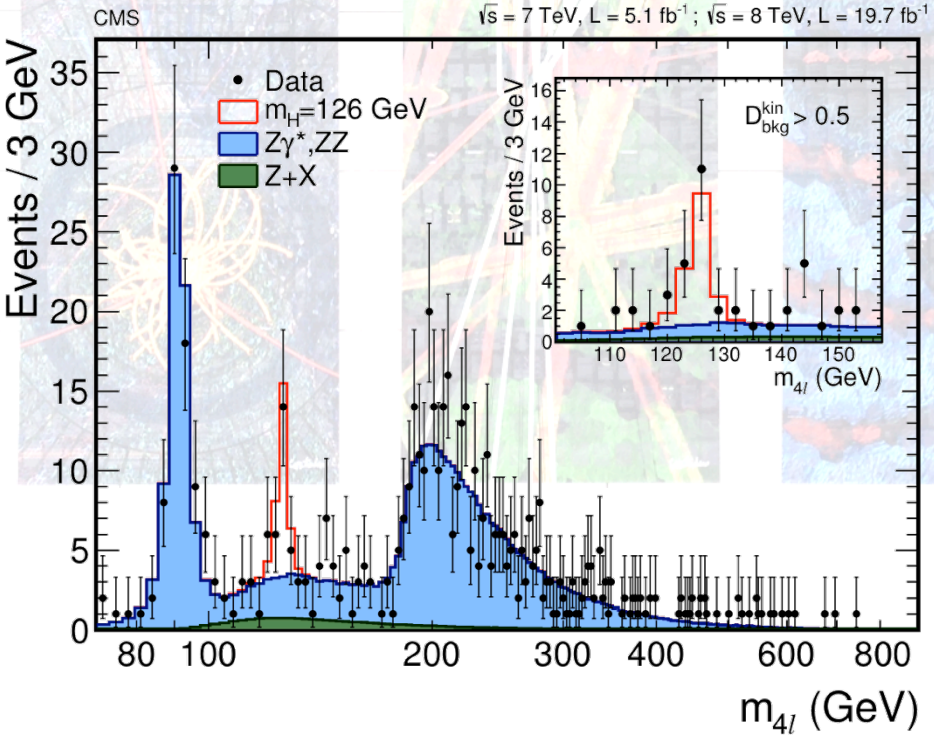
H→ZZ→4ℓ vignettes

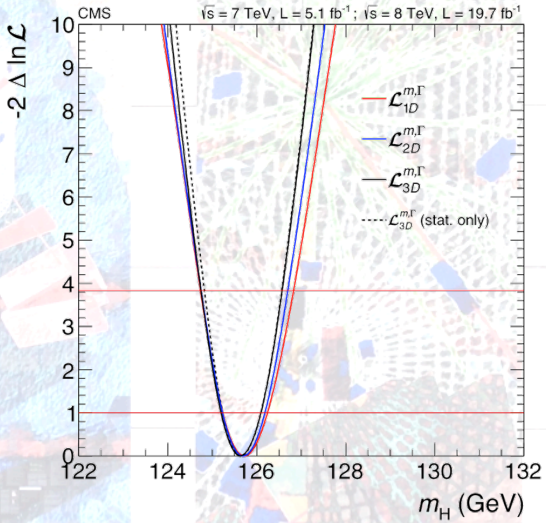
[PRD 89 (2014) 092007]

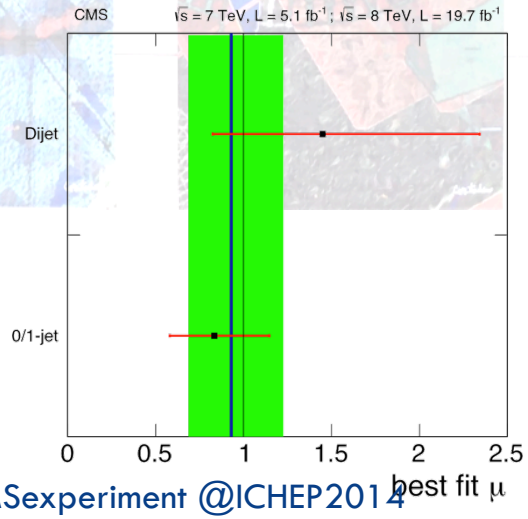


PRD 89 (2014) 092007

- 6.8σ (6.7σ exp.)
- m_H= 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV
- σ/σ_{SM} = 0.93 ±0.25 (stat.) ±0.13 (syst.)

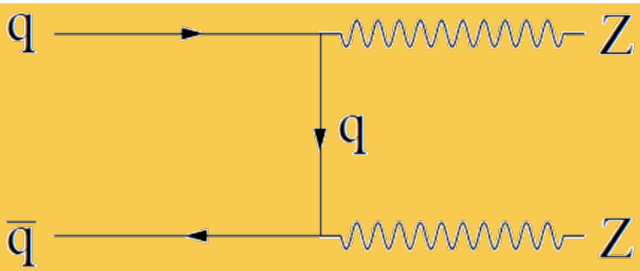




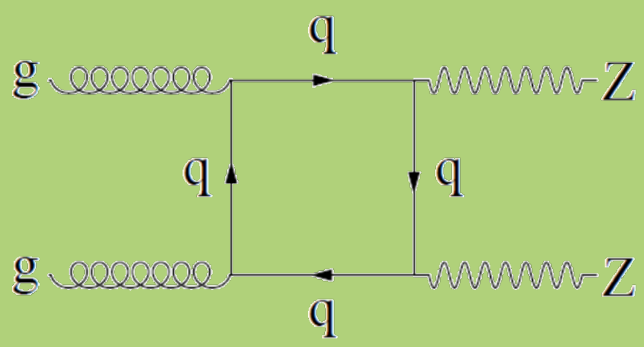


Odds and ends

Off-shell – involved processes

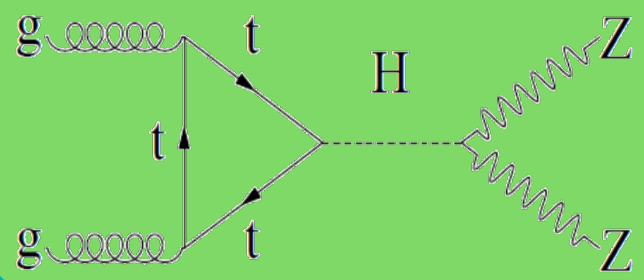


Backgrounds



Strong interference

NNLO/LO k-factors depend on m_{ZZ}
[G. Passarino, arXiv:1312.2397]
Use the same k-factors for signal and gg continuum
[M. Bonvini et al., PRD 88 2013]



Signal

H* – off-shell

[arXiv:1405.3455, accepted by PLB] [JHEP 08 (2012) 116] [Phys. Rev. D88 2013] [arXiv:1311.3589]

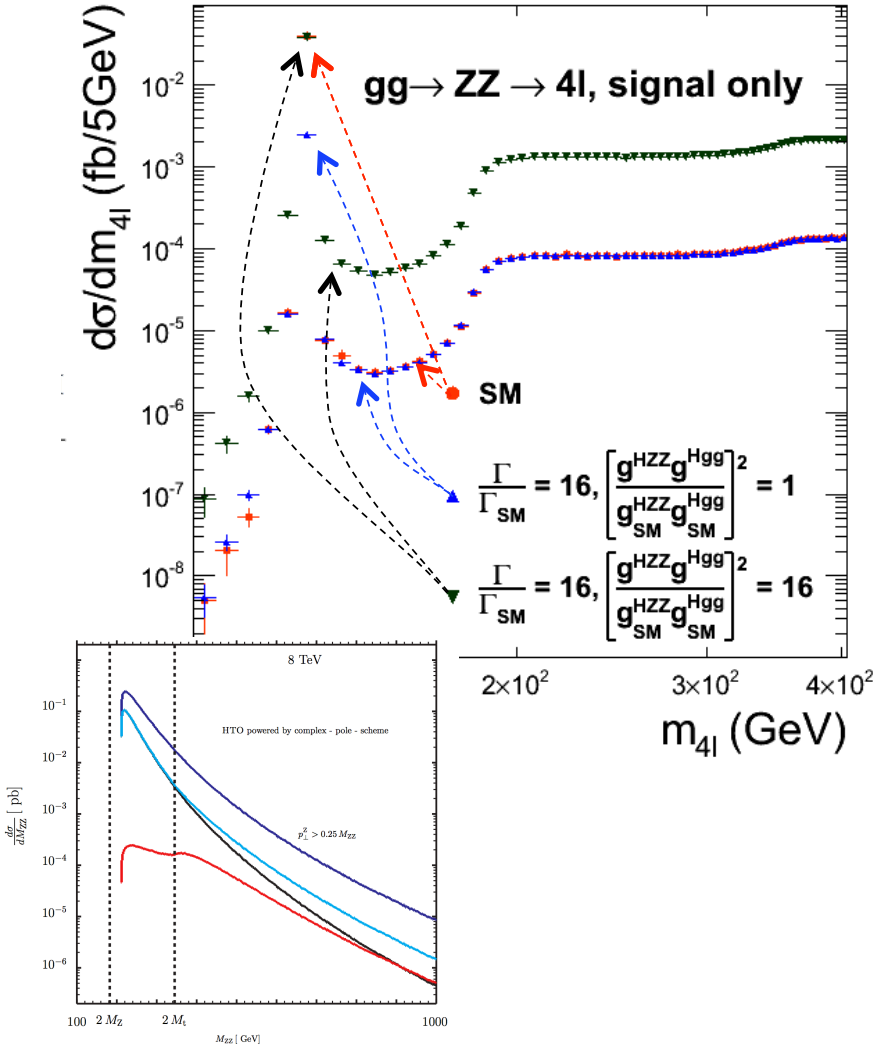
- Define $r = \Gamma_H / \Gamma_H^{SM}$
- On-mass-shell we have

$$\sigma^{on-peak}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot\mathcal{B})_{SM}$$

- Off-mass-shell there is no ***r***:

$$\frac{d\sigma^{off-peak}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2 \cdot \frac{d\sigma^{off-peak,SM}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

- Can make inference on ***r*** from on- **and** off-shell **assuming:**
  - $\mu_{on\text{-}shell} = \mu_{off\text{-}shell}$
  - Only SM processes → ZZ:
    - gg→H*
    - **gg** = |gg→H* + gg→non-H|²
    - |gg→H*|² + |gg→non-H|²
    - **Total** = **gg** + $q\bar{q}$



A 2012 hit

186 [http://goo.gl/ShJJG]

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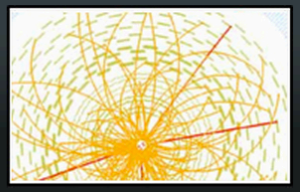
Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



FREE ACCESS

The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

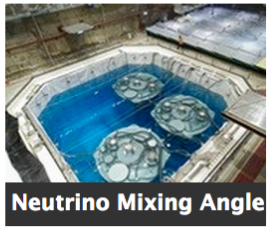
Read more about the Higgs boson from the research teams at CERN.

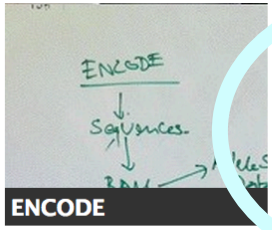
Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.


Denisovan Genome

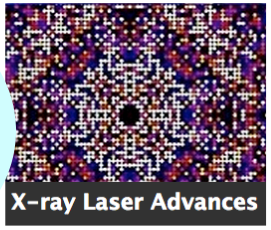

Genome Engineering


Neutrino Mixing Angle

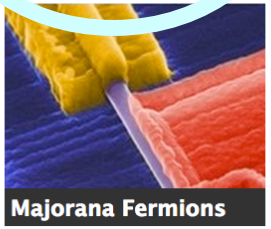


ENCODE


Curiosity Landing


X-ray Laser Advances


Controlling Bionics


Majorana Fermions


Eggs from Stem Cells