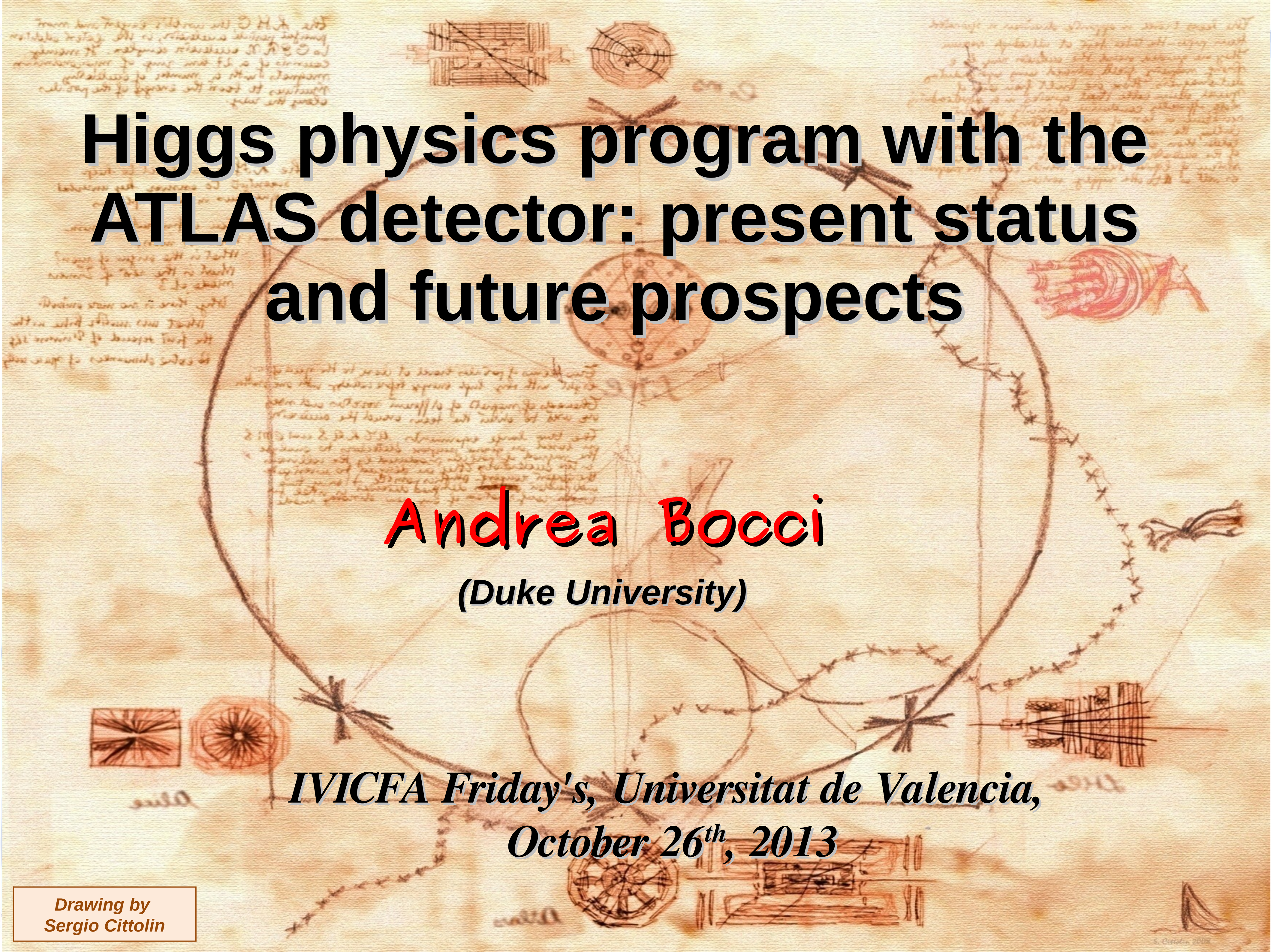
Higgs physics program with the ATLAS detector: present status and future prospects

Andrea Bocci

(Duke University)

IVICFA Friday's, Universitat de Valencia, October 26th, 2013



Drawing by Sergio Cittolin

July 4th ,2012

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

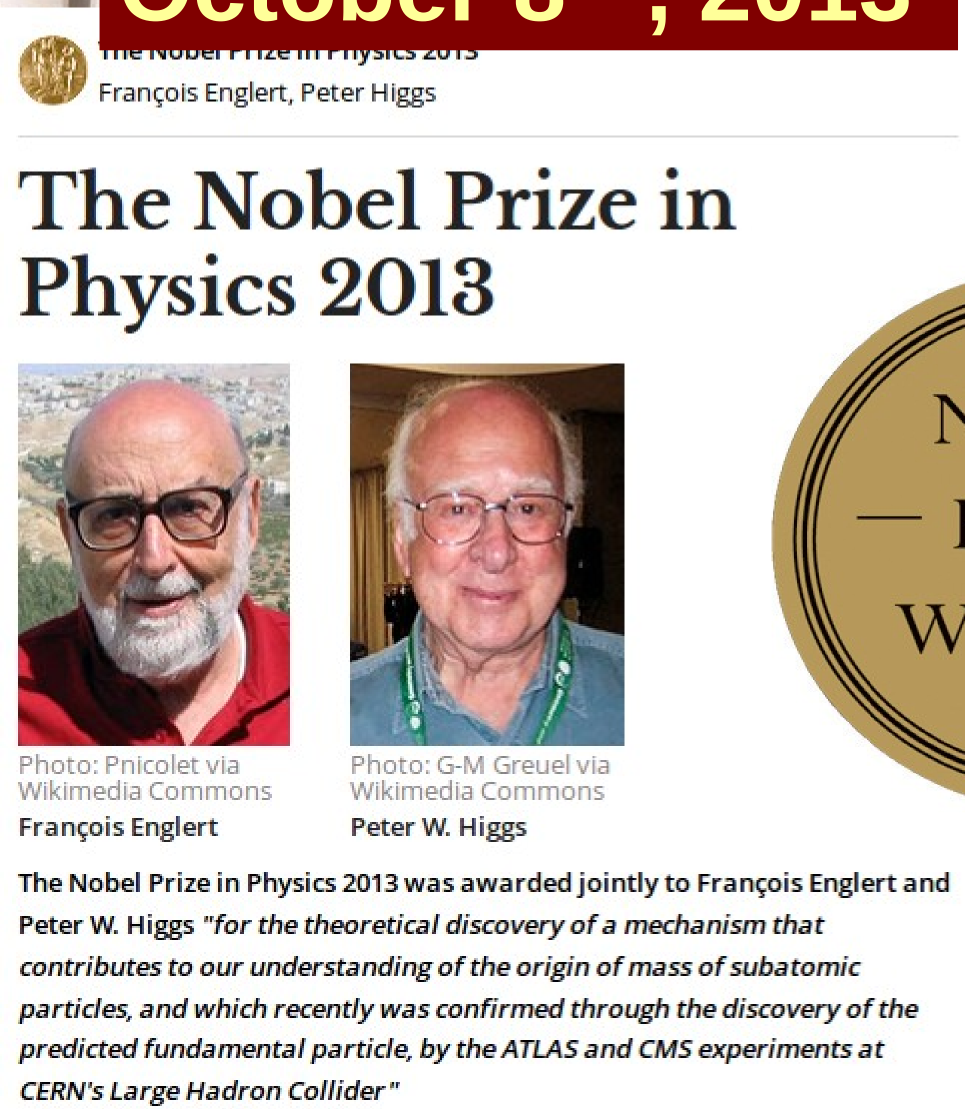
July 4th ,2012

Scientists in Geneva o
subatomic particle tha

July 4th ,2012

March 14th , 2013

October 8th , 2013


The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Outline

- **Why the discovery of ~~the~~ a Higgs boson is important**
- **Tools for the discovery: LHC and the ATLAS detectors**
- **Why we can call the new boson a “Higgs” boson (with high CL)**
- **Future prospects for investigating the Higgs sector with the ALTAS detector**

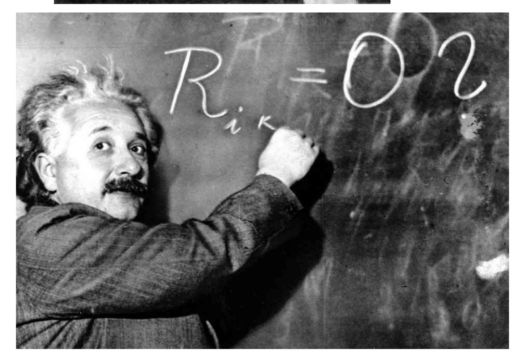
Why do Things Weight?

Newton:

Weight proportional to mass

Einstein:

Energy related to mass



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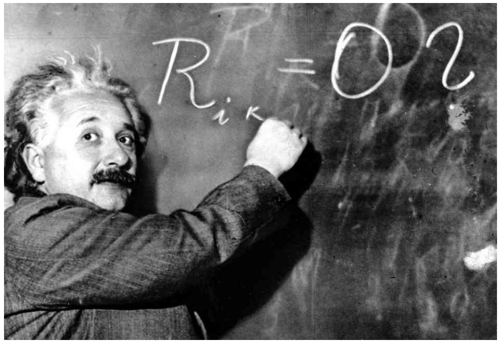
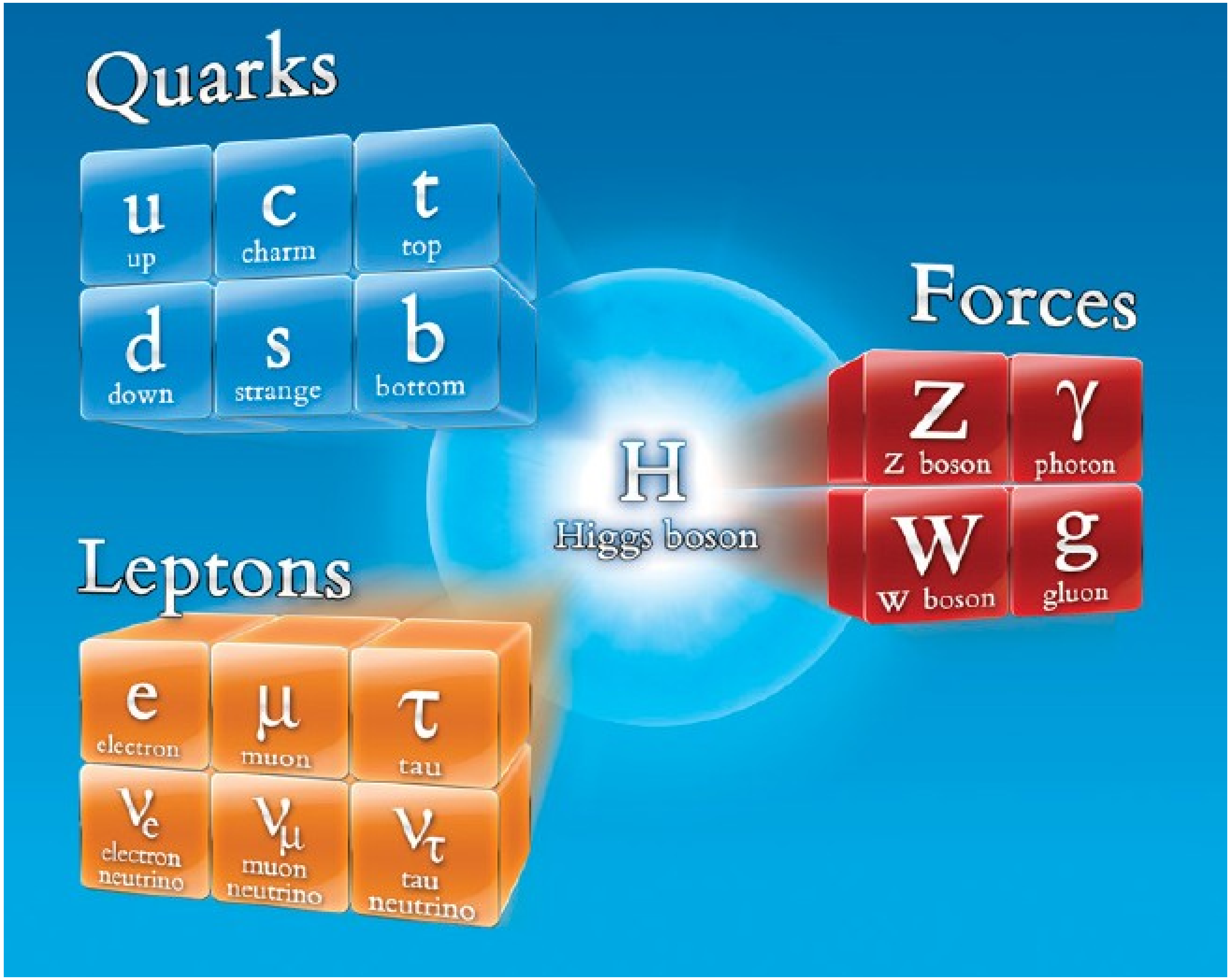


Neither explained origin of Mass

A Short History...



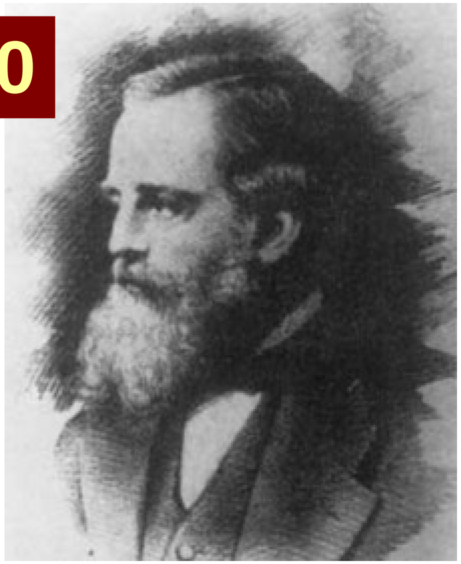
The Electromagnetic Interaction

Complete electromagnetic field equations by Maxwell:

$$\vec{\nabla} \bullet \vec{B} = 0 \qquad \vec{\nabla} \bullet \vec{E} = \frac{\rho_{in}}{}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla} \times \vec{B} = \mu_o \vec{J} + \mu_o \varepsilon_o \frac{\partial \vec{E}}{\partial t}$$

1860



The Electromagnetic Interaction

Complete electromagnetic field equations by Maxwell:

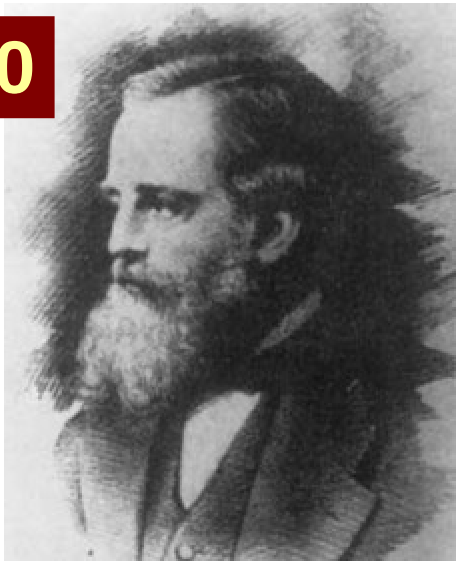
$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

Messenger for the EM interaction is the photon, a massless spin 1 boson
(EM waves at speed of light)

Today we understand why M_A=0 with symmetry principles: a mass term for A would break the U(1) local gauge invariance

1860



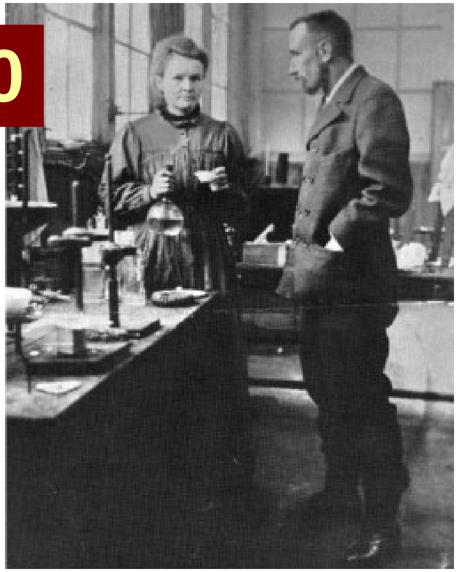
Gauge invariance is a guiding principle

Discovery of the Weak Interaction

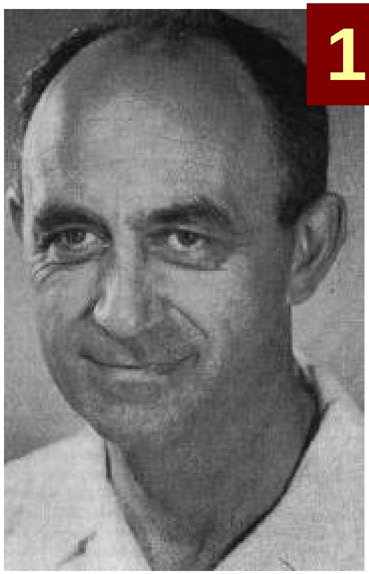
At beginning of the 20th century the discovery of the natural radioactivity as the first observation of forces beyond gravitational and electromagnetism

→Weak Interaction

1900



1933



Original explanation from Fermi worked quite well for low energies

In the early 1960's gauge invariance principles used to understand the character of weak interaction, introducing invariance under 3-dimensional rotation in (weak) isospin space

→3 messenger particles: W^+, W^+, Z

Pulling it all together: the Electroweak Theory

1968

Electromagnetic and weak interaction were unified by Glashow, Salam and Weinberg under a gauge invariant theory with 4 messenger particles (the photon, W^+, W^+, and Z) :

→Electroweak Theory

As for electromagnetism, an exact symmetry requires all messenger particles to be massless: however, because the weak interaction is short range it requires ***massive messenger particles***!
(direct measurement in 1983 at CERN, W/Z masses 80-90 GeV)

A mechanism had to be introduced to break the electroweak symmetry

The Higgs Mechanism

In 1964 four seminal papers discussed a mechanism to spontaneously break a gauge symmetry

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

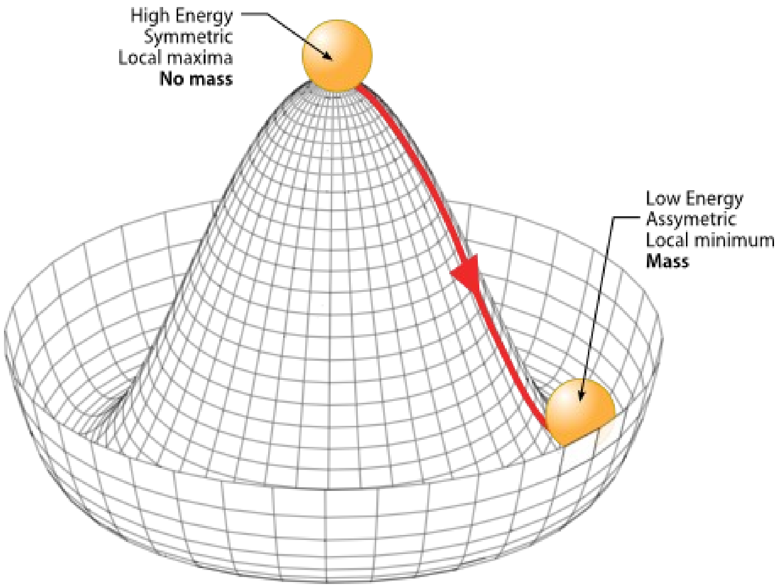
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The Higgs Mechanism

In 1964 four seminal papers discussed a mechanism to spontaneously break a gauge symmetry

- Introducing an **additional scalar field,** additional term in mass appear
- Particles move through field which gives them **mass proportional to the coupling strength**
- Minimum of "mexican hat" potential not at zero (symmetry breaking)
- Self-coupling responsible for a **physical Higgs particle**
- **Give mass** to W^+, W^+, and Z, and keep the photon mass-less



Lagrangian is symmetric, ground state is not
→*spontaneous symmetry breaking*

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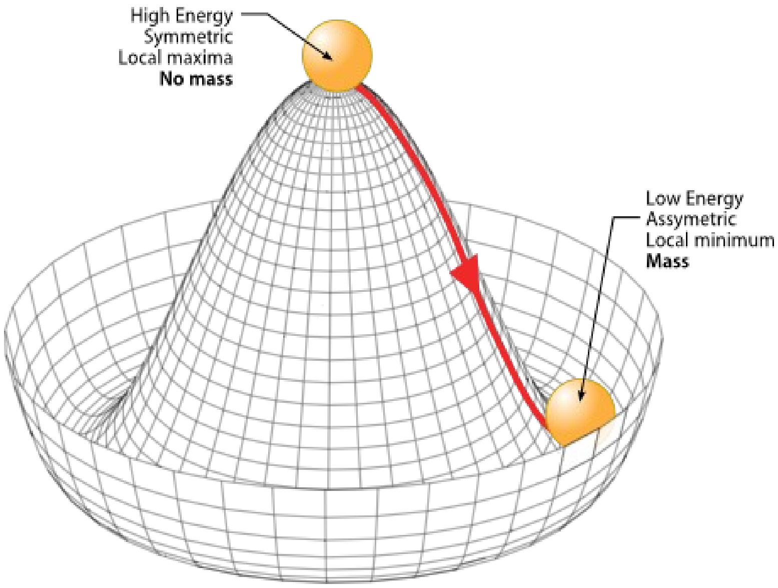
- **Give mass** to W^+, W^+, and Z, and keep the photon mass-less
- **Model makes very precise predictions: decay kinematics, couplings, cross section, cross section ratio, etc...**
- **Only parameter free is the Higgs mass**



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Beautiful and very economic theory (just one particle and one free parameter).

It surely would have deserved a Nobel Prize right away!

But there was one thing missing...

photon mass-less

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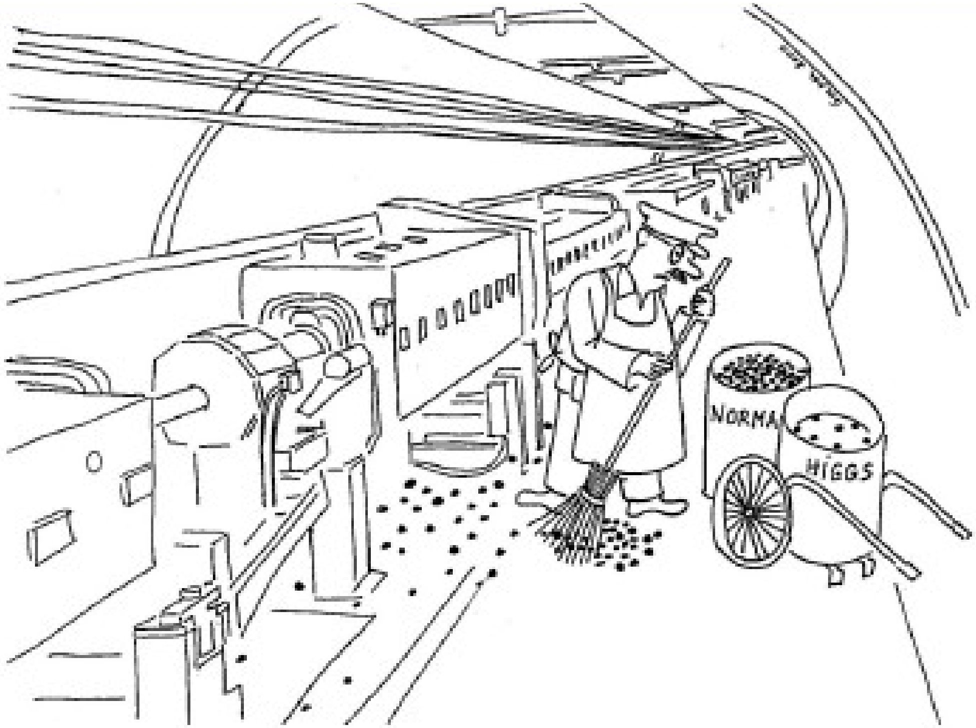
Experimental evidence !!

Searches for The Higgs Boson



Higgs Hunting in the Early 1970's

Prog. Theor. Phys. Vol. 54 (1975), Nov.

Higgs Meson Emission from a Star and a Constraint on Its Mass

Katsuhiko SATO and Humitaka SATO

Research Institute for Fundamental Physics Kyoto University, Kyoto

July 3, 1975

Pre-collider era Higgs exclusion summary plot!

(Nucl. Phys. B106 (1976) 292-340)

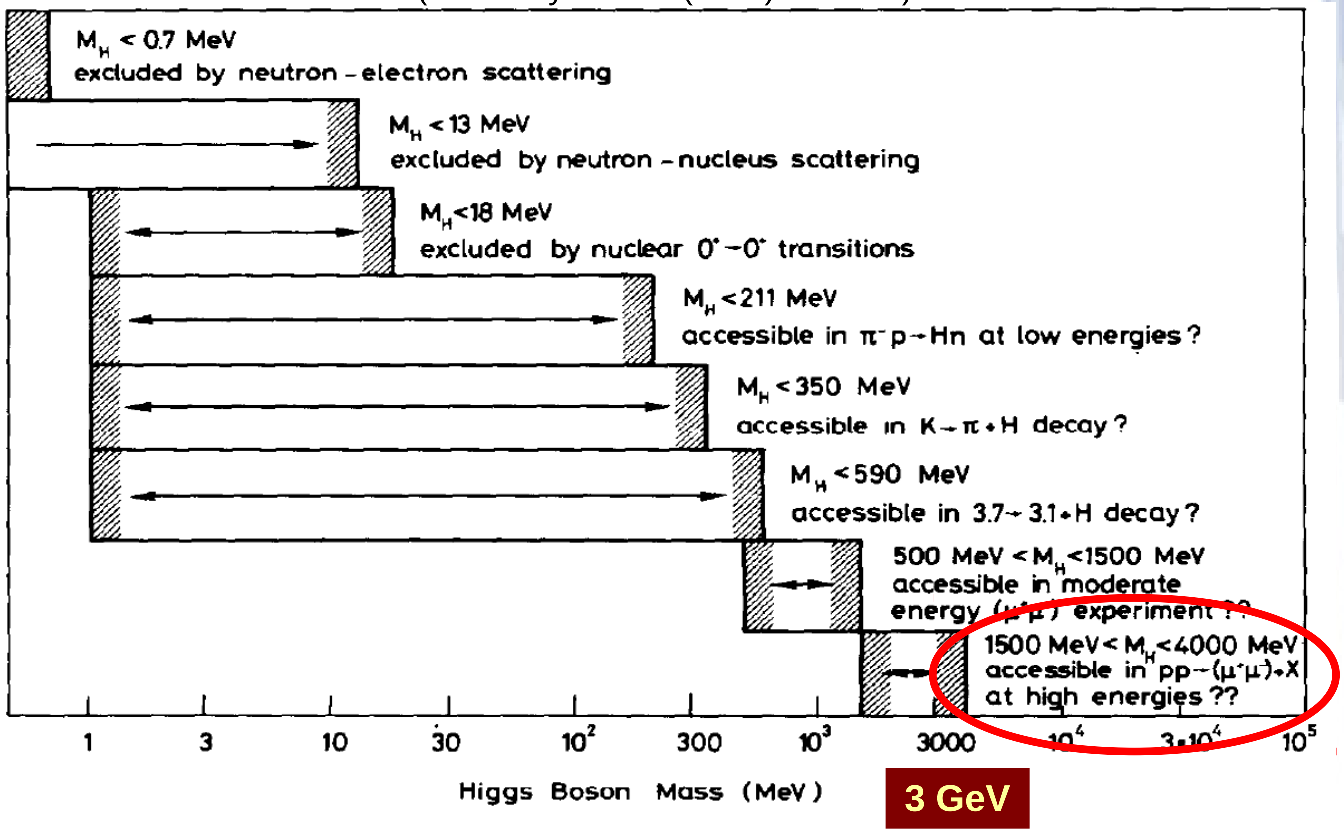


Fig. 3. Present and possible future limits on the Higgs boson mass.

Higgs Hunt in the Early 1970's

Pre-collider era Higgs exclusion summary plot!
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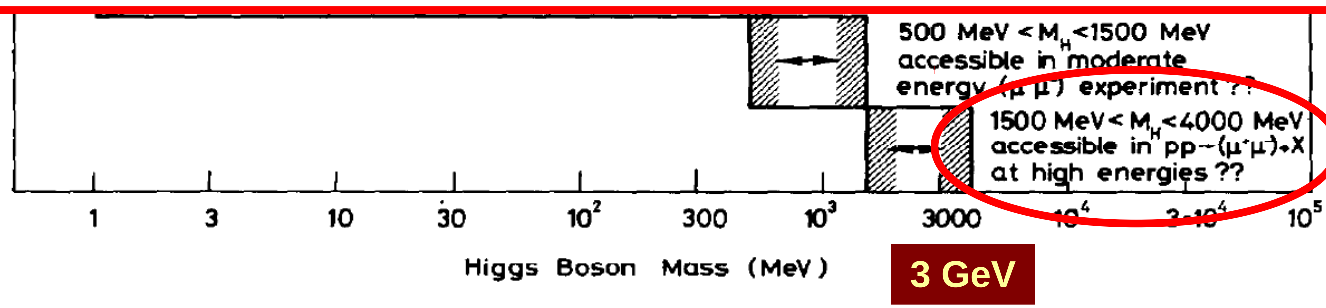
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



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perim… case v… …ept that t… …e big ex… …ng
experiments vulnerable to the Higgs boson should know how it may turn up.

Despite the warning, a three decade-long race started to build accelerators and detectors powerful enough to find experimental evidence of the existence of the Higgs boson

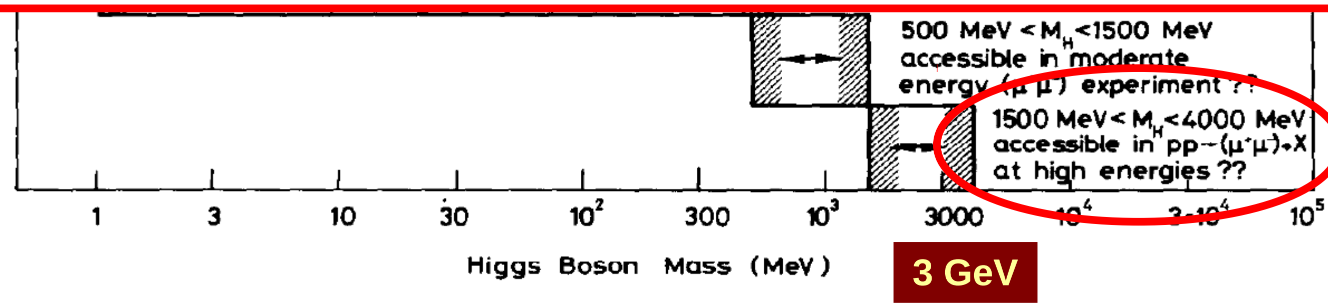
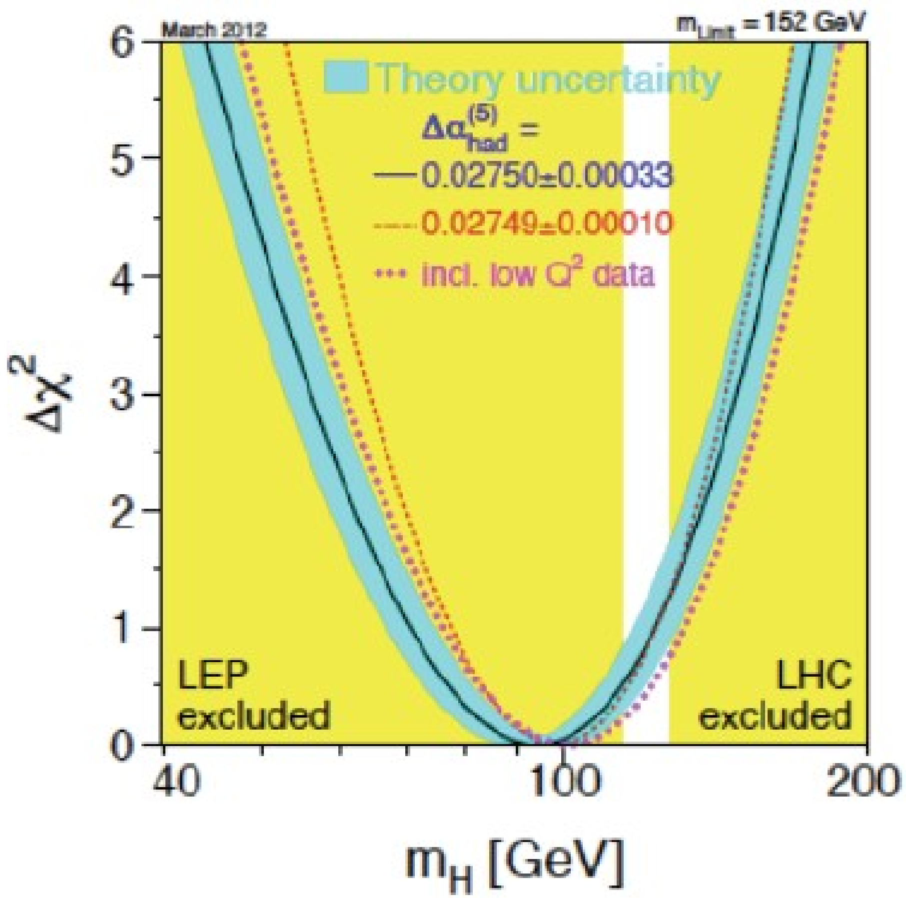
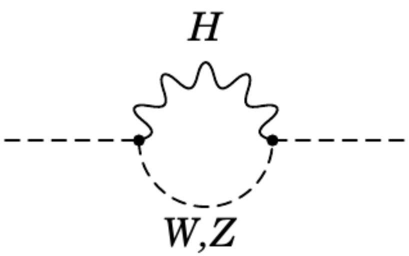


Fig. 3. Present and possible future limits on the Higgs boson mass.

Indirect Searches Before LHC

Higgs boson leaves a "trace" in measurements of W and Z properties through its virtual presence in quantum loop





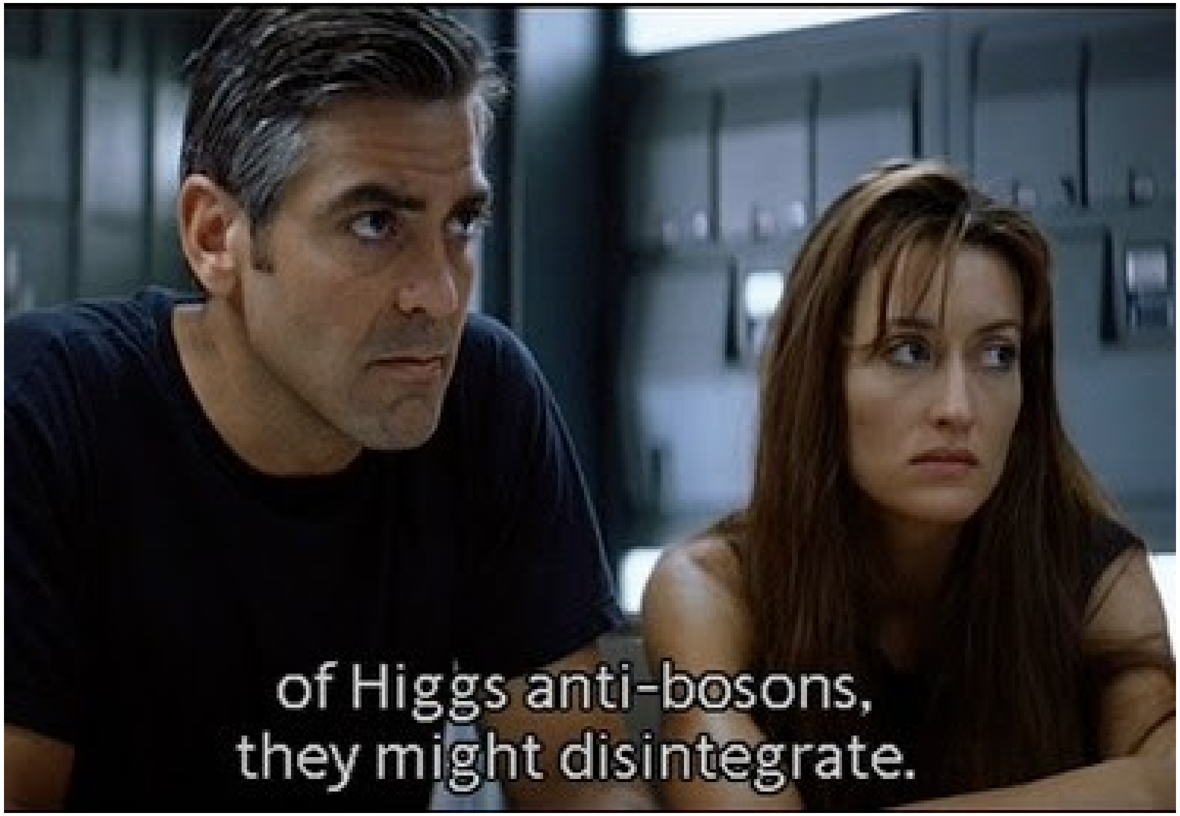
Use precise measurements to constrain the SM parameters

EW Fits favor a light Higgs:

$M_H = 94^{+29}_{-24}$ GeV

Producing and Detecting the Higgs: LHC and the ATLAS Detector

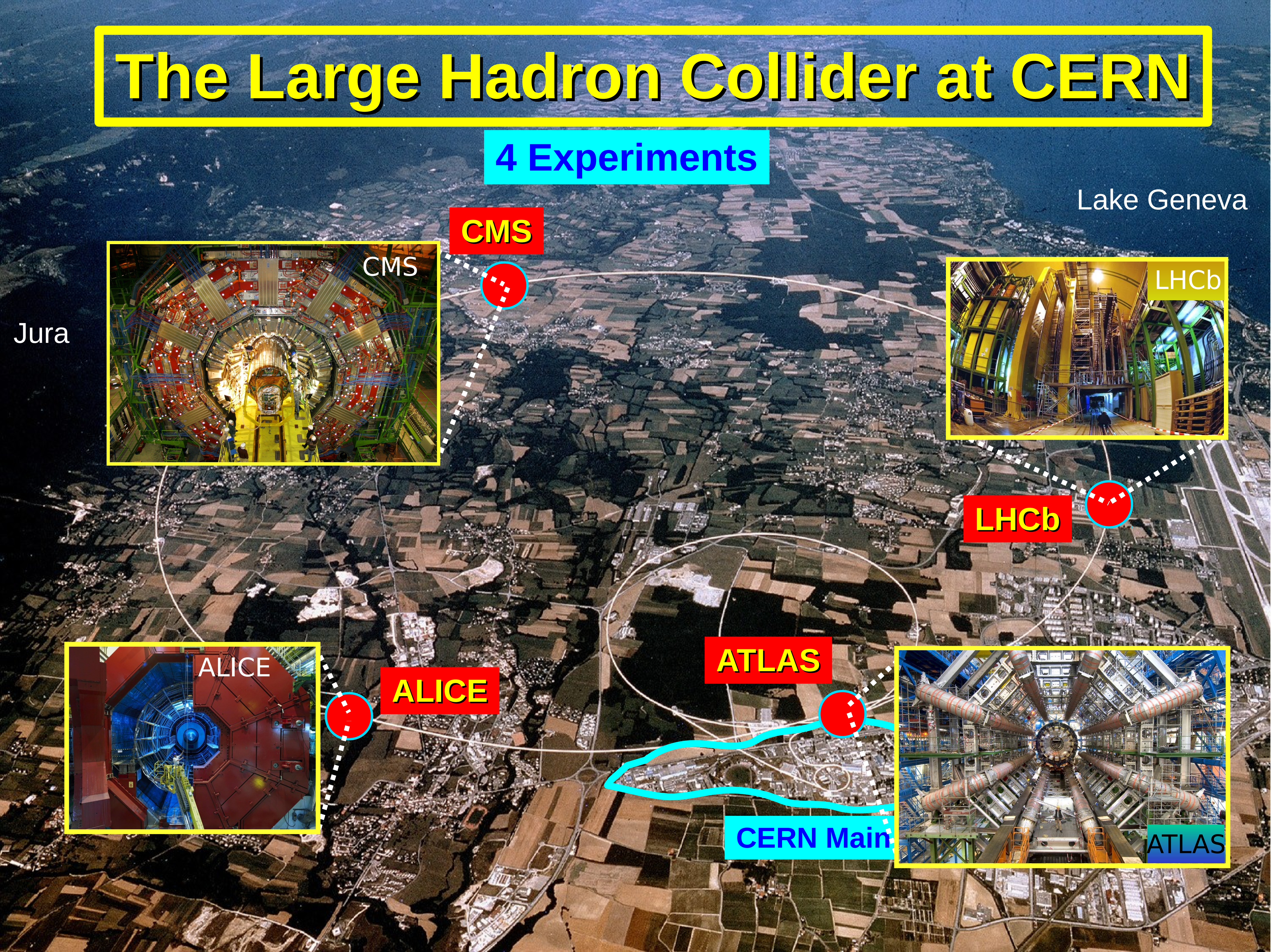
Producing and Detecting the Higgs: LHC and the ATLAS Detector



"So, if we created a negative Higgs field, and bombarded them with a stream of Higgs anti-bosons, they might disintegrate."

The Large Hadron Collider at CERN

The Large Hadron Collider at CERN



LHC Performance

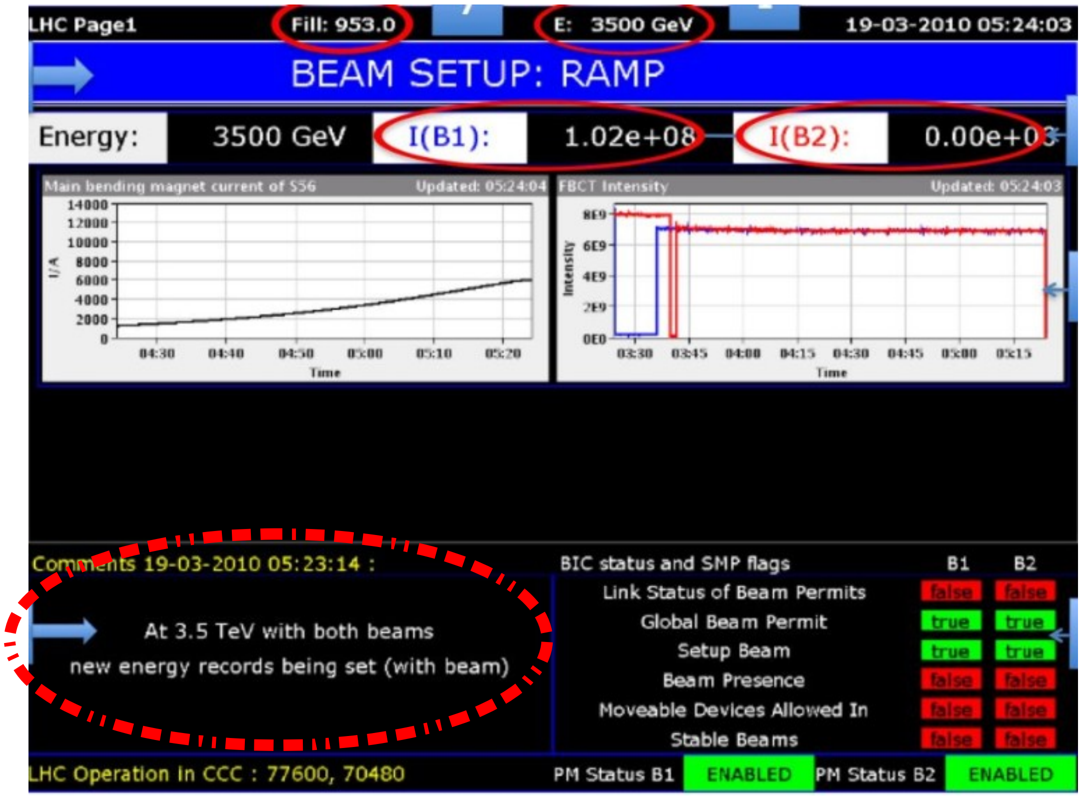
LHC: proton-proton collider (mainly):

- Center of mass energy
  - 7 TeV in 2010-2011
  - 8 TeV in 2012
- Bunch intensity: $N_p \sim 10^{11}$
- Number of bunches: B=1400
- Luminosity:
  - Instantaneous: $L \approx \dfrac{N^2 f B \gamma}{4\pi \varepsilon_n \beta^*}$
  - Integrated: measured in fb^{-1} ($1\ b = 10^{-24}\ cm^2$)

$$N = \sigma \cdot \int L dt$$

Note: LHC operating so far at about "half" its potential

LHC Operation Page on March 19, 2010



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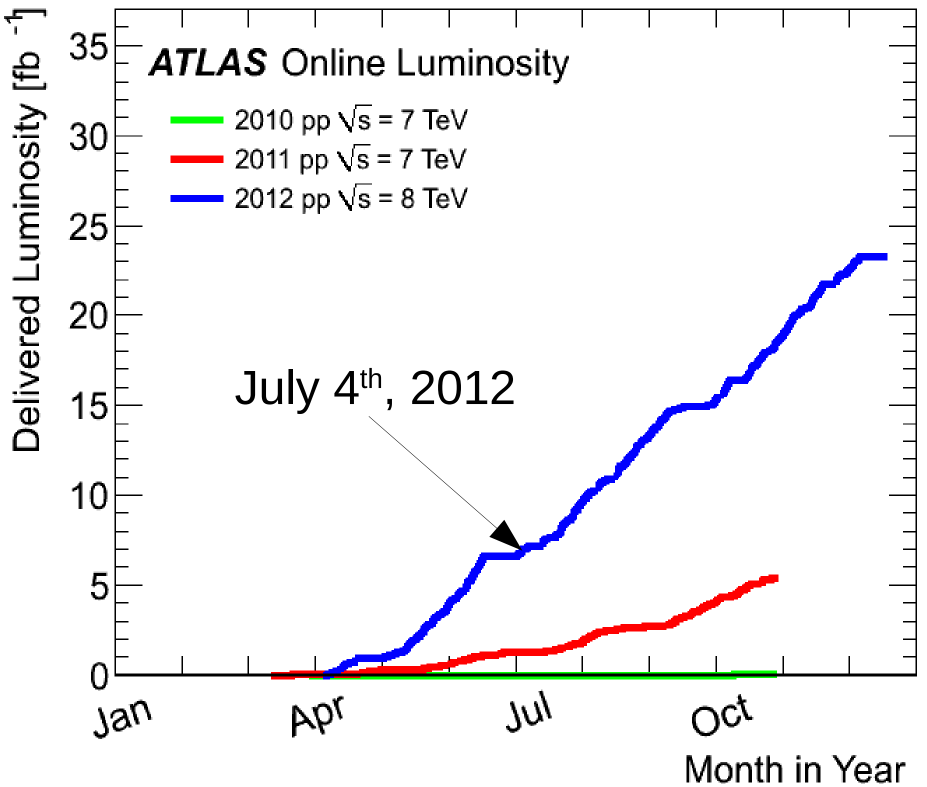
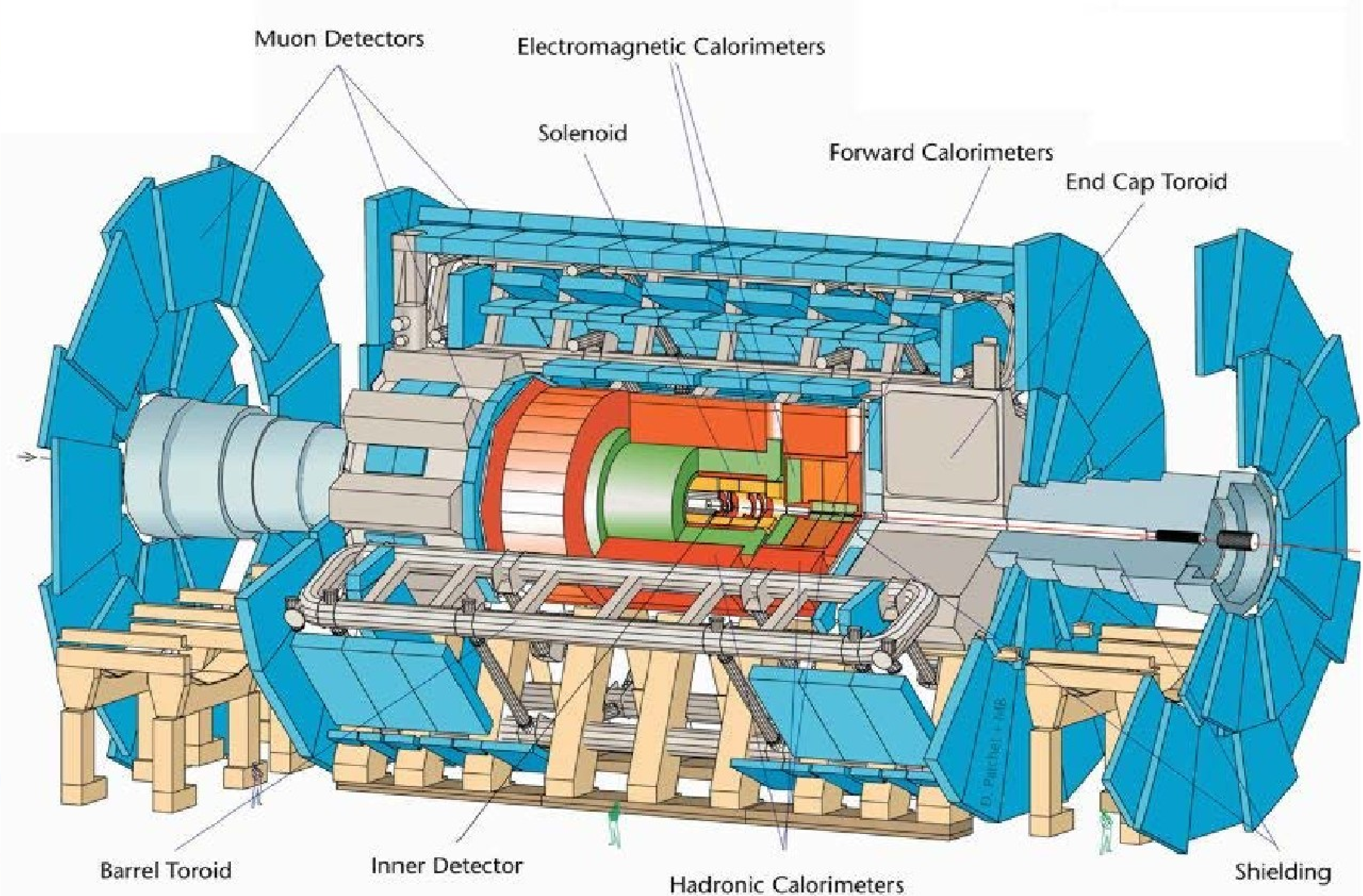
Run I (2010-2012) Summary



Amount of (usable) data collected by ATLAS

- 5 fb^{-1} in 2011
- 21 fb^{-1} in 2012

The ATLAS Detector



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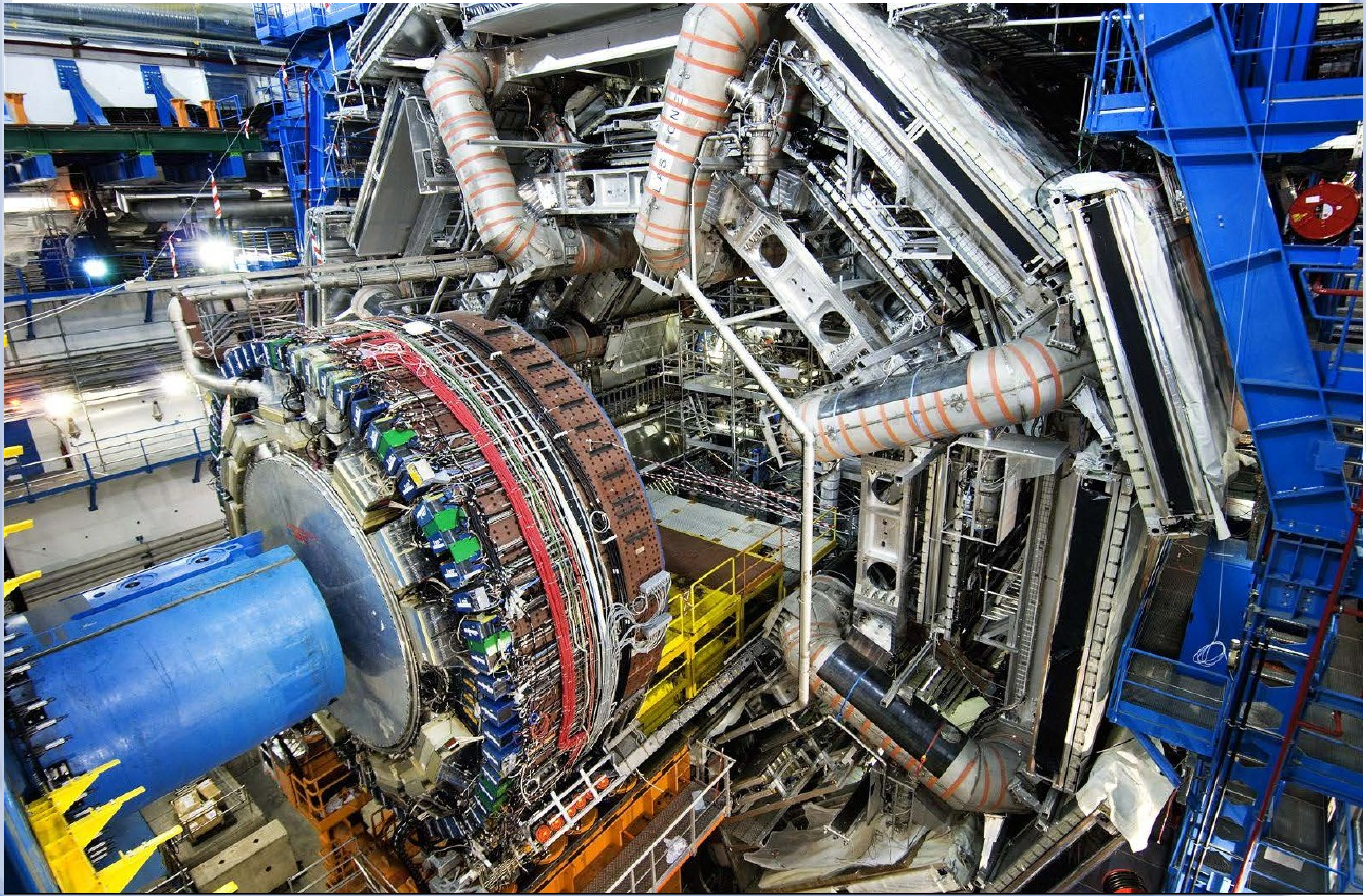
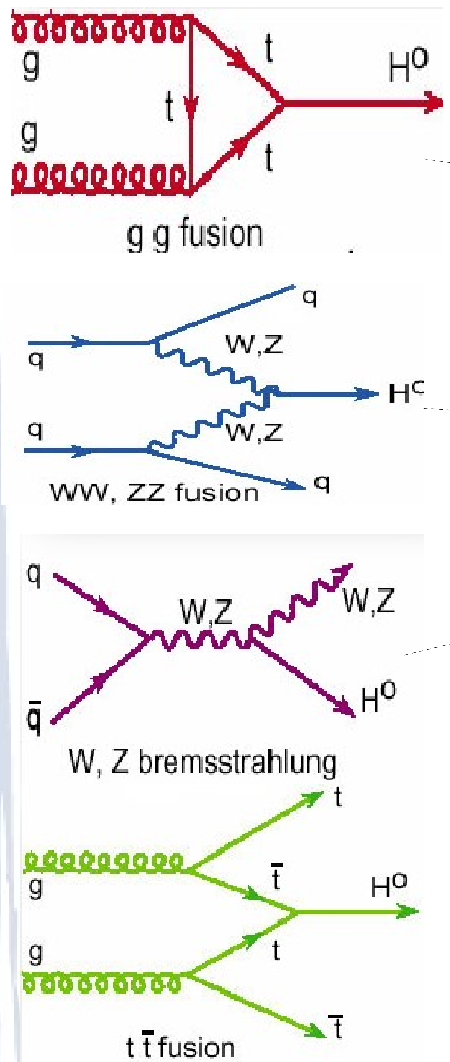


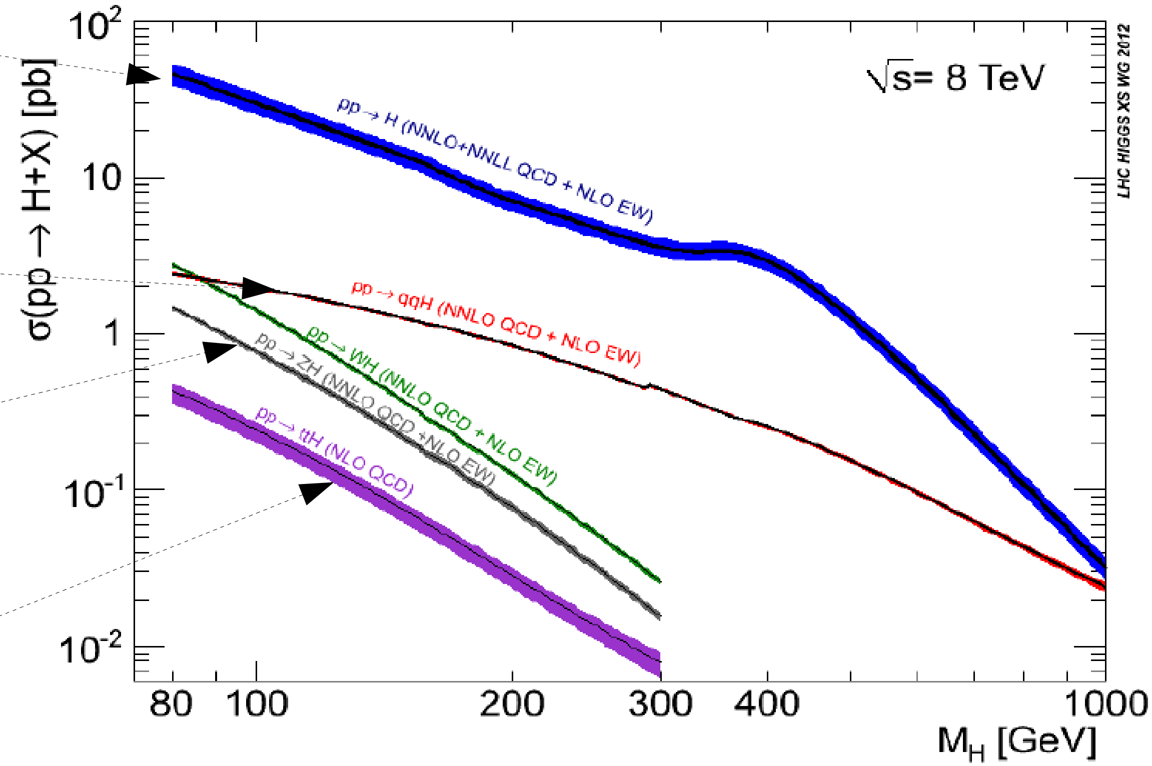
How to Plan a Discovery?

- Lay down the needed experimental ingredients...
  - Produce as much Higgs as possible → excellent performance of the accelerator
  - Detect and reconstruct the Higgs decay product → excellent performance of the detector
  - Suppress the huge background to make the Higgs signal visible → excellent calorimeter performance
- ...Knowing what to search for
  - Design and build the detector with the stringent quality and performance to make the discovery possible

How Higgs is produced



LHC is a Higgs Factory:
~10 SM Higgs @125 GeV/minute
(at LHC peak luminosity for 2012)



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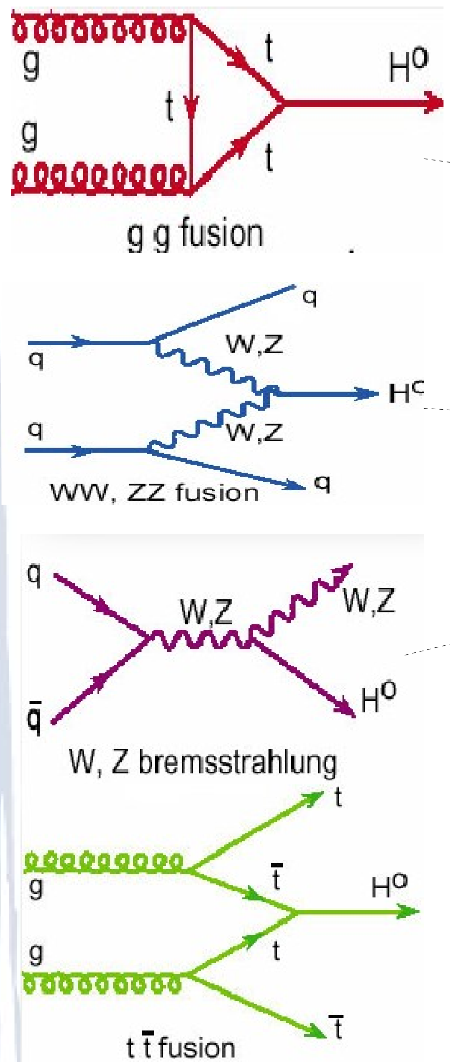

gg F

VB F

VH

ttH

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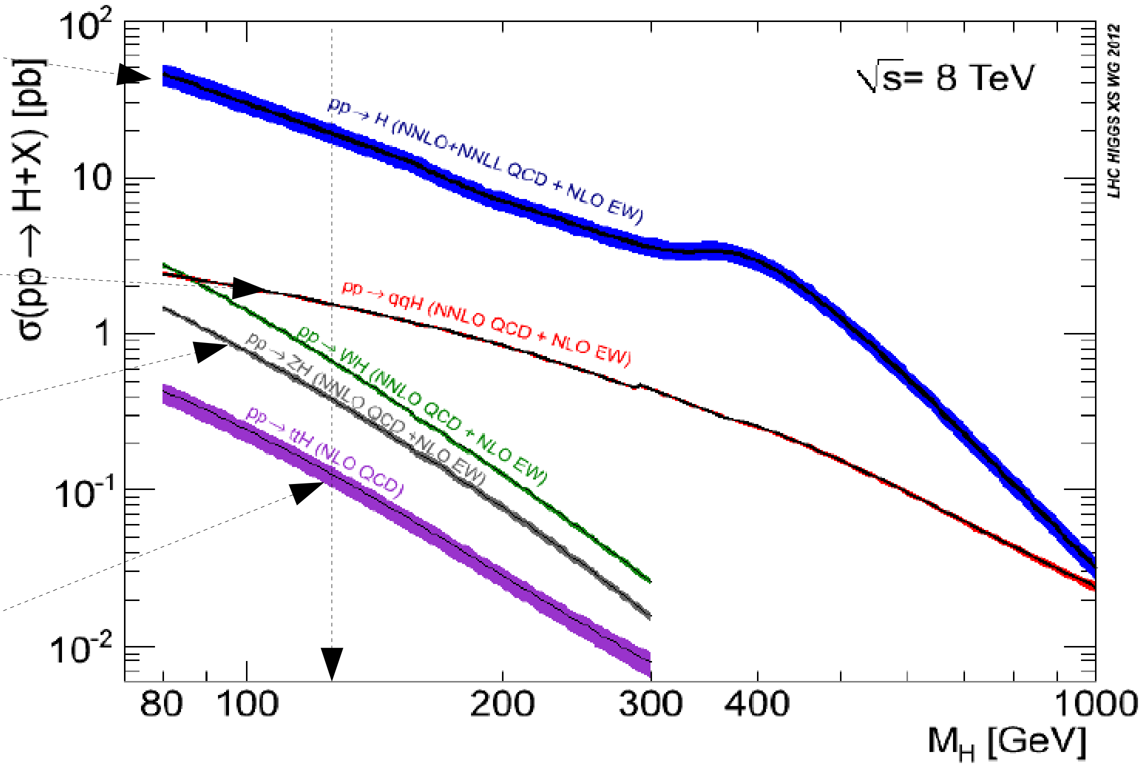

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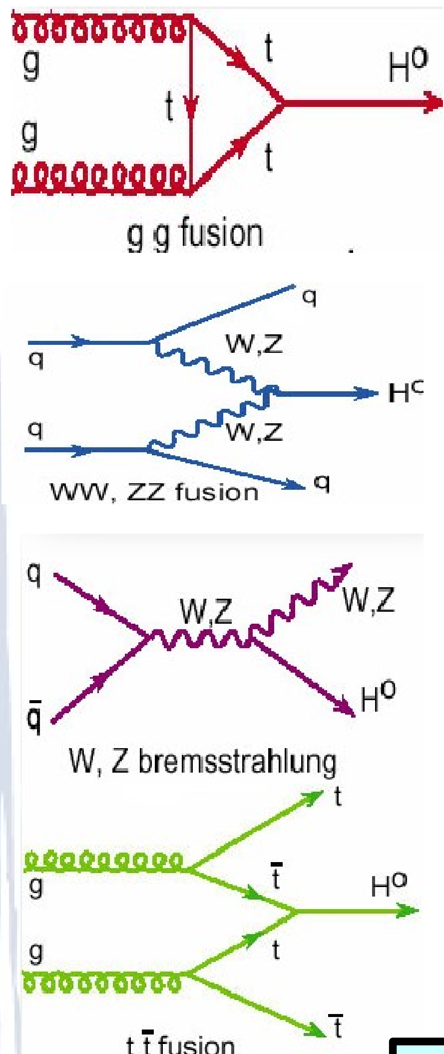

g g fusion	**19.5 pb** (87%)	**Fermion Coupling**
WW, ZZ fusion	**1.6 pb** (7%)	**Boson Coupling**
W, Z bremsstrahlung	**1.1 pb** (5%)	**Boson Coupling**
t t̄ fusion	**0.1 pb** (1%)	**Fermion Coupling**

σ(pb) @125 GeV
pp √s=7 TeV

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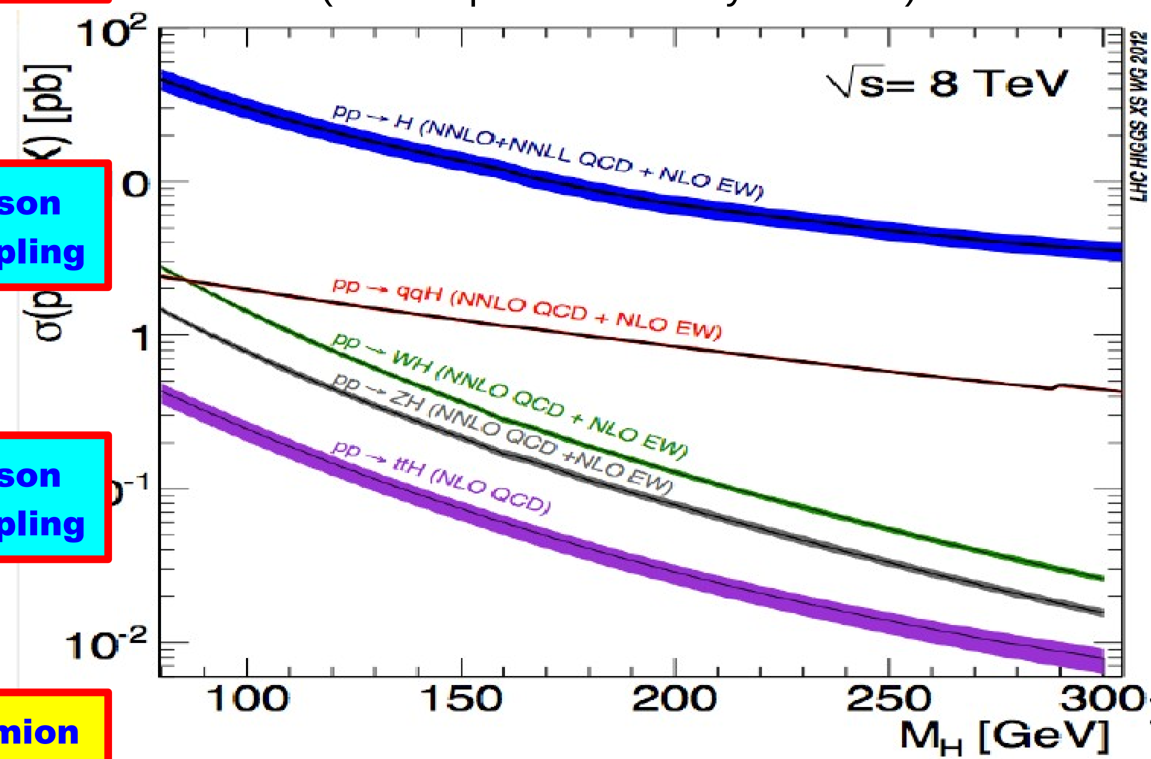
(at LHC peak luminosity for 2012)

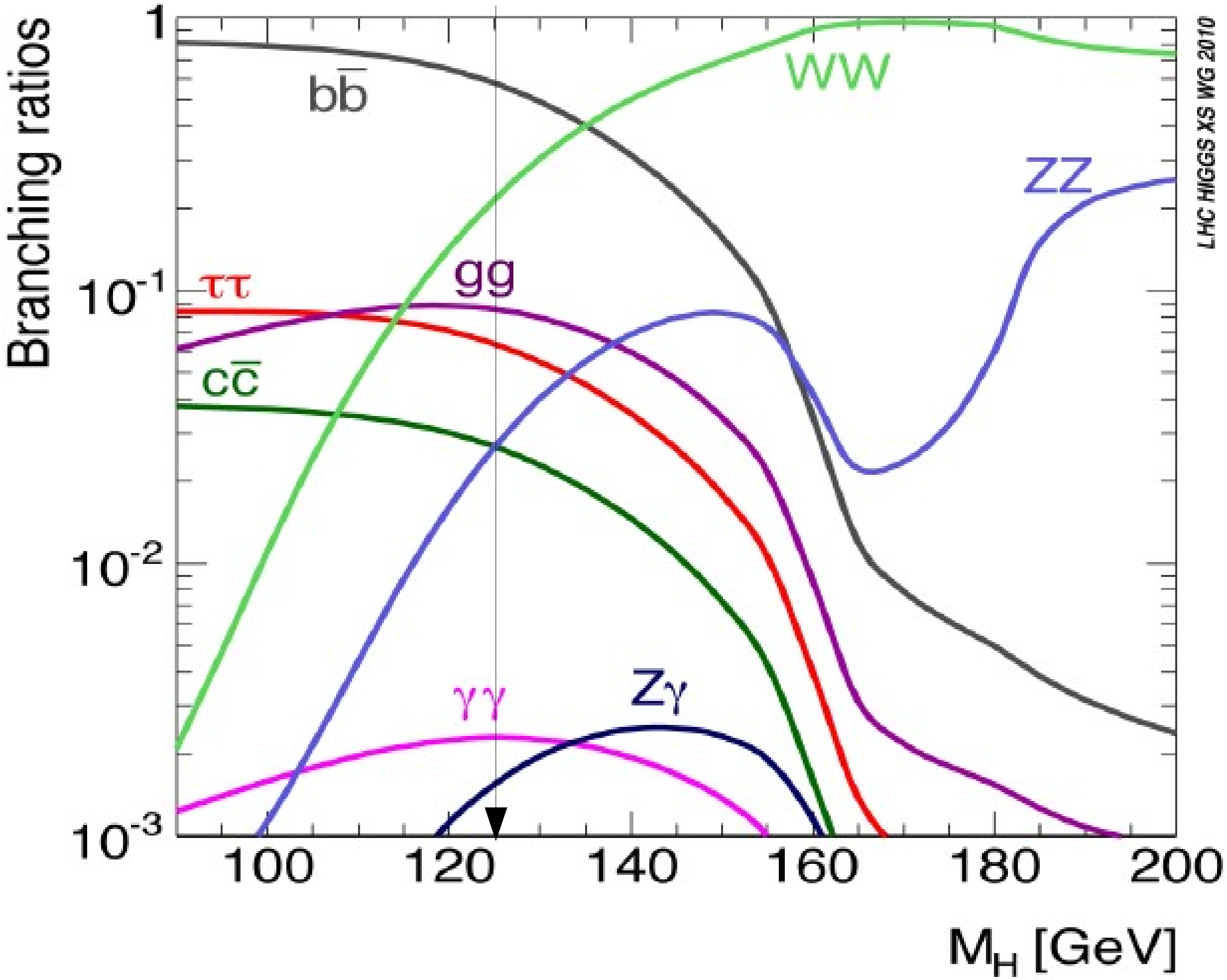


Very important to probe all the production processes to extract experimentally the maximum amount of information

How Higgs Decay

SM Higgs couples with mass

$$\Gamma_{Hff} \sim m_f^2$$
$$\Gamma_{HVV} \sim m_V^4$$



How Higgs Decay

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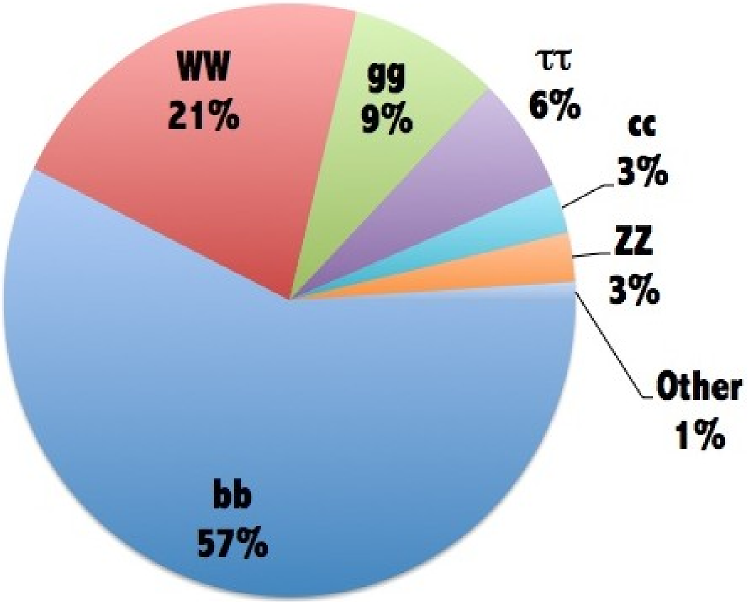
The "Big Five"

Golden Channels:
- ➔ $H \rightarrow \gamma\gamma$
- ➔ $H \rightarrow ZZ \rightarrow 4\ l$ (l=e,μ)

Most Sensitive Channel:
- ➔ $H \rightarrow WW \rightarrow l\nu l\nu$ (l=e,μ)

Fermionic Channels:
- ➔ $H \rightarrow \tau\tau$
- ➔ $VH \rightarrow Vbb$

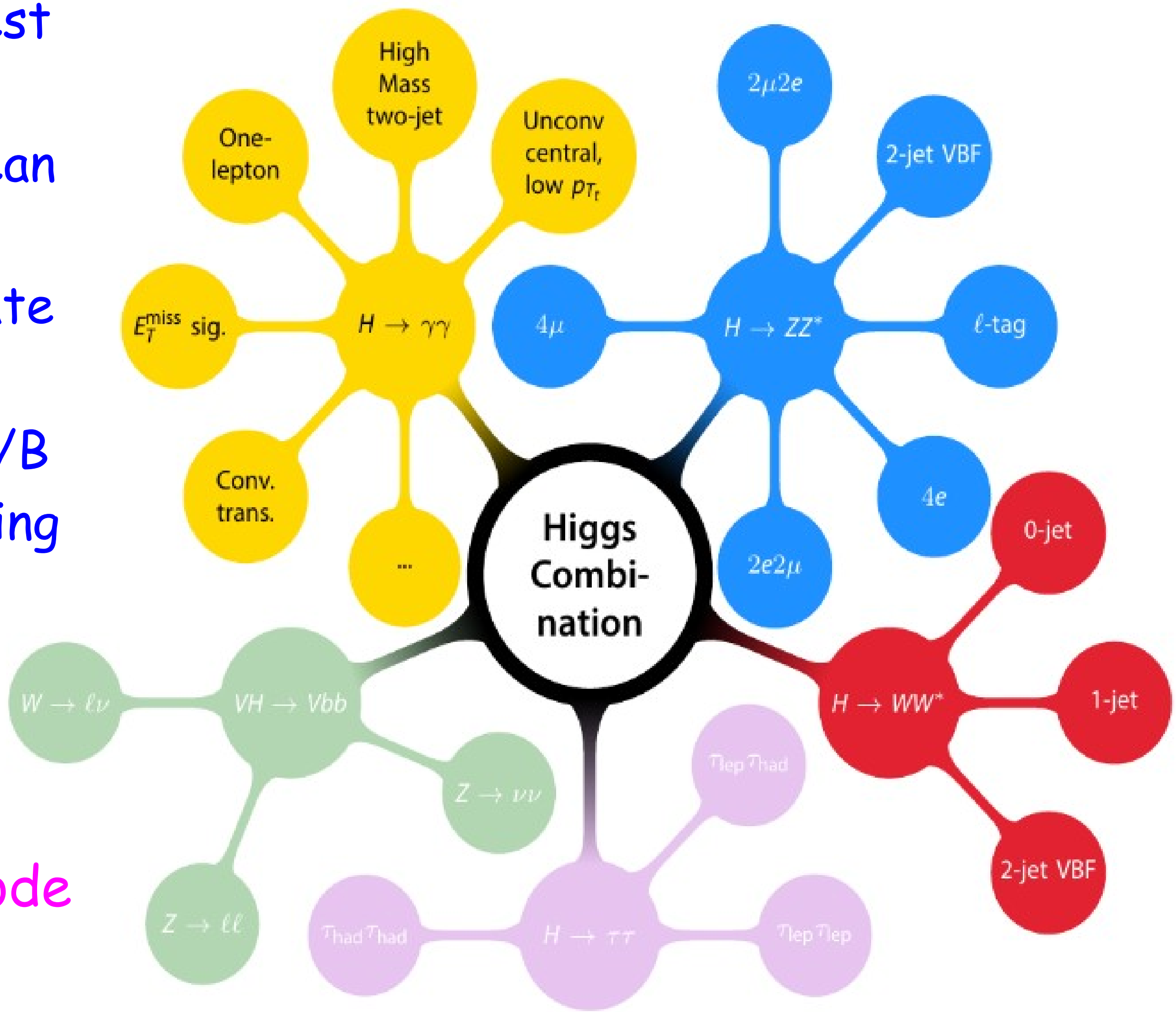
Higgs decays at m_H=125GeV



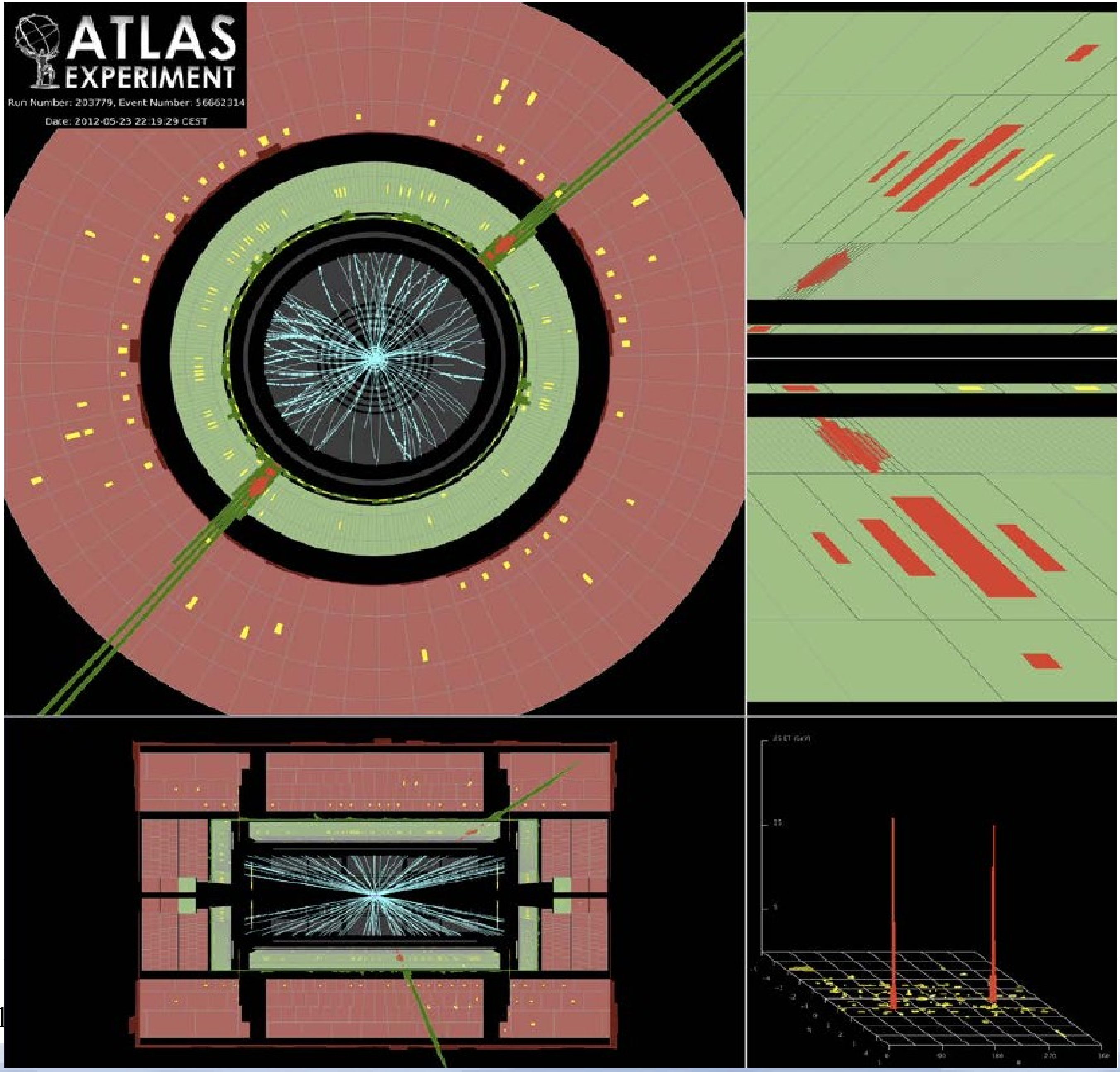
Analysis of the "Big Five"

- **H → γγ:** very rare, but best for mass measurement
- **H→ZZ→4l:** extremely clean (~ no bkg)
- **H->WW →lνlν**: highest rate
- **H →ττ**: Direct lepton coupling, rare with good S/B
- **VH → Vbb**: Fermion coupling + associate production

- Event categorization to maximize sensitivity to different production mode



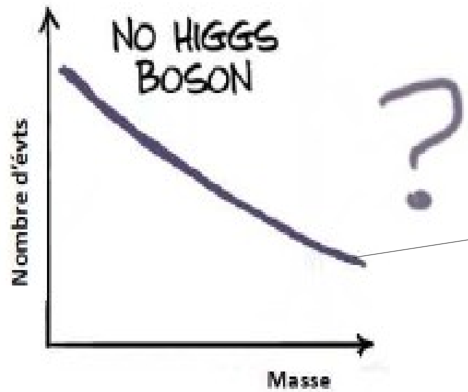
$H \to \gamma\gamma$ Channel



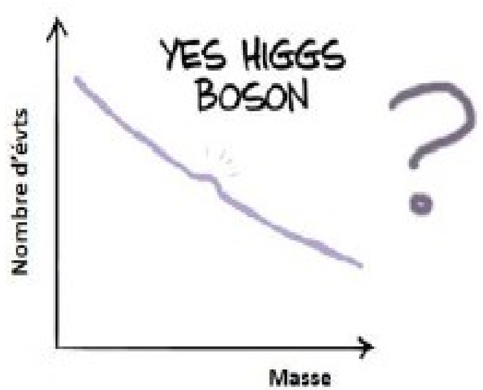
$\mathcal{H}\rightarrow\gamma\gamma$: Overview

Relatively simple selection: **two isolated, high quality reconstructed photons**

But very low S/B (~3%): **detector requirement and performance essential !**



$$m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$$

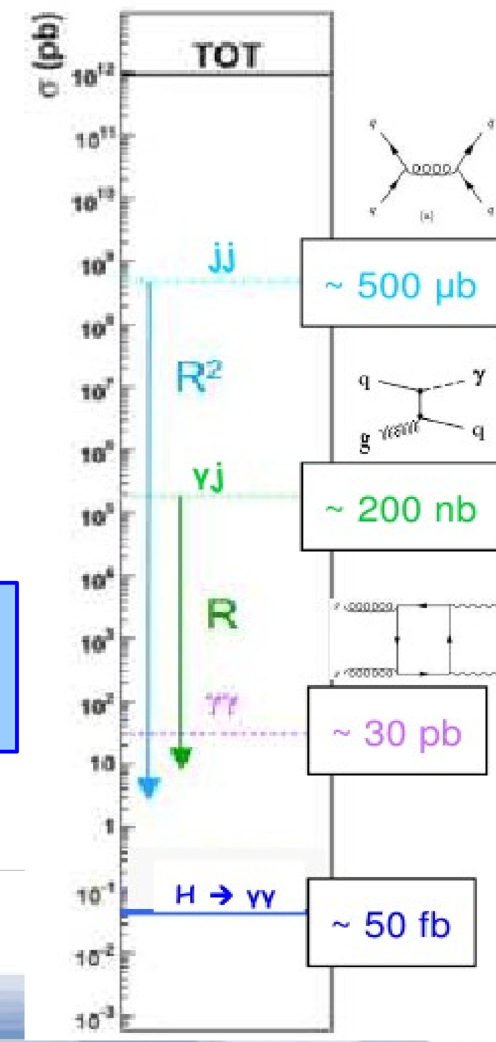


M$\gamma\gamma$-background from:

- $\gamma\gamma$ continuum
- jγ
- jj

with jet are reconstructed as photons (mainly $\pi^0/\eta^0 \rightarrow \gamma\gamma$)

Need a detector (calorimeter) able to perform a photon identification with a π^0/γ rejection power of O(10^4)!



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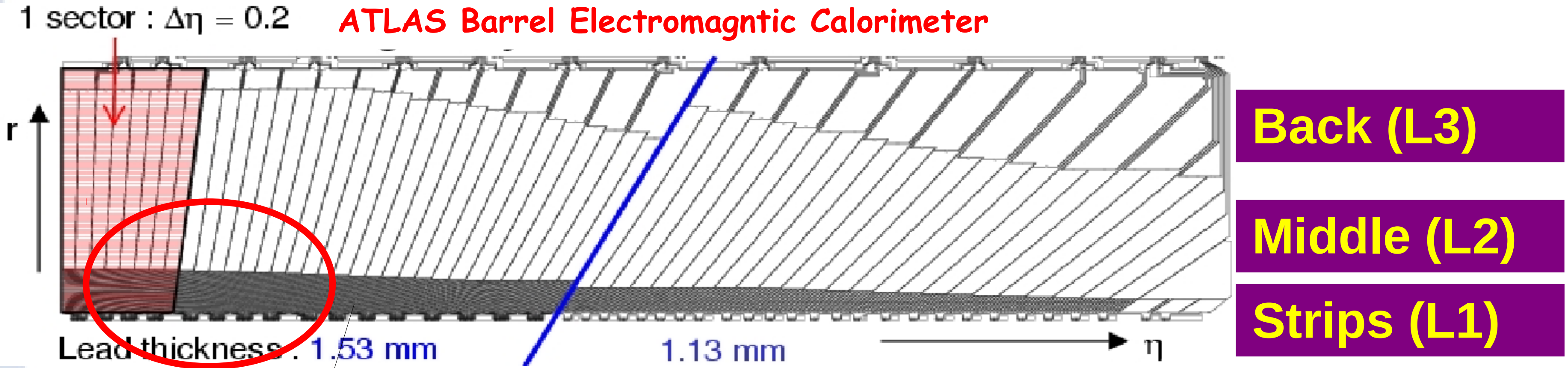
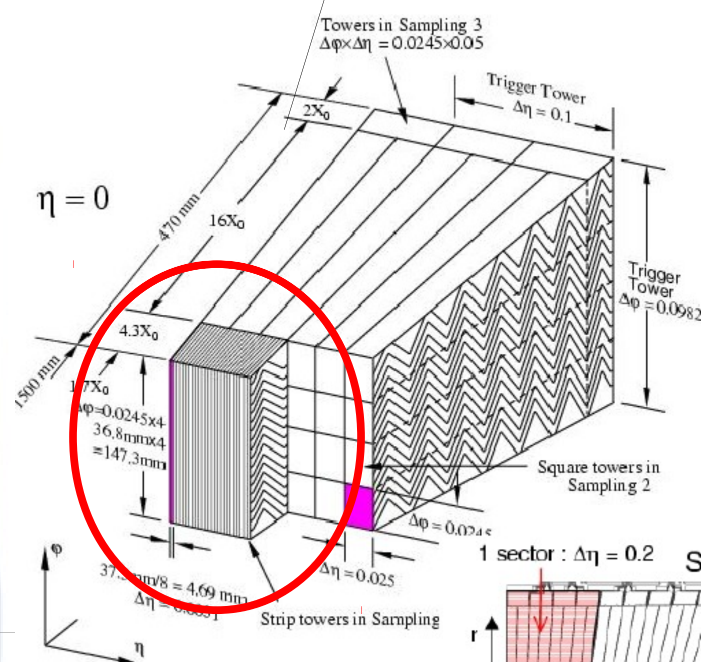
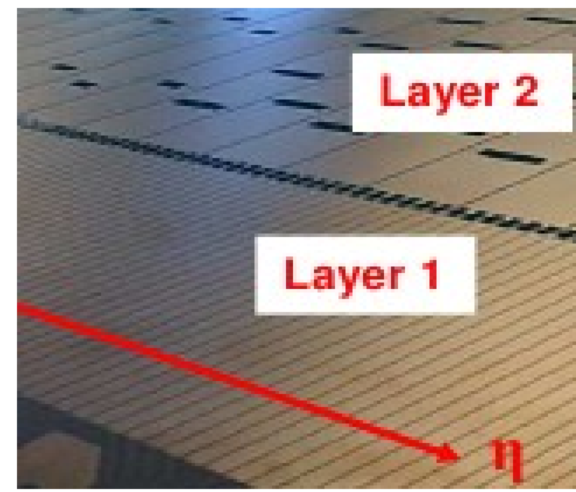




Fine granularity
for the strips key
for bkg rejection



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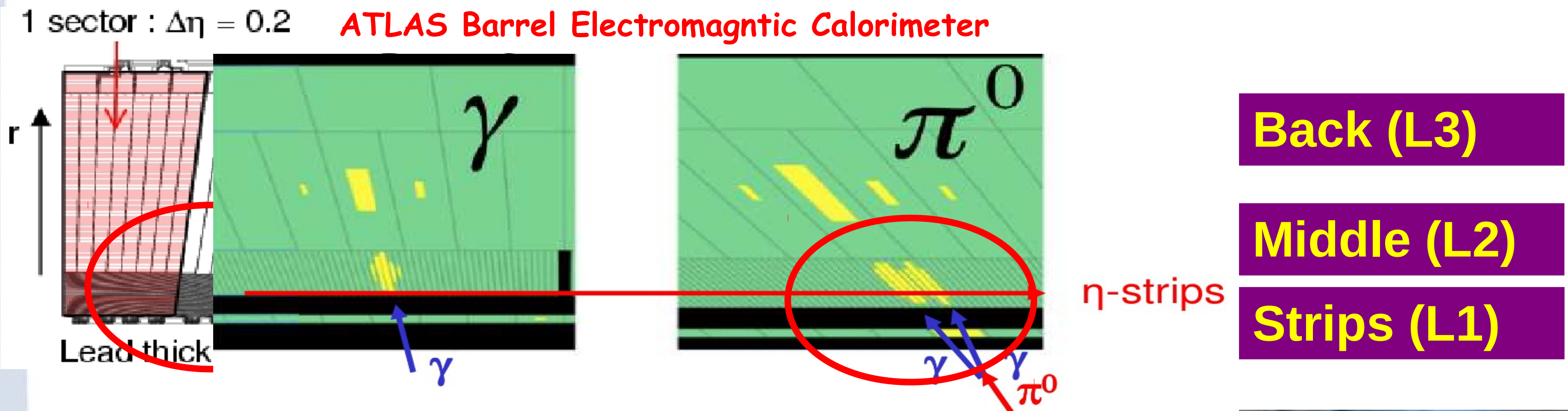

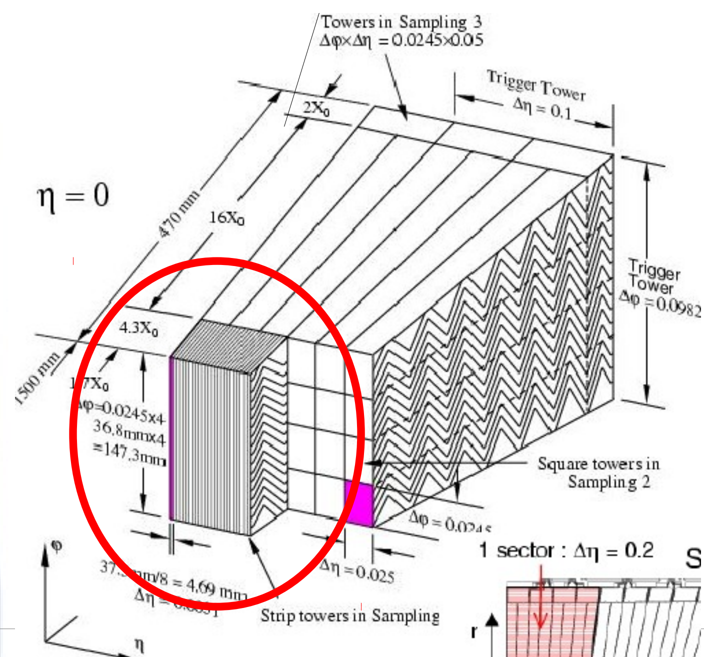

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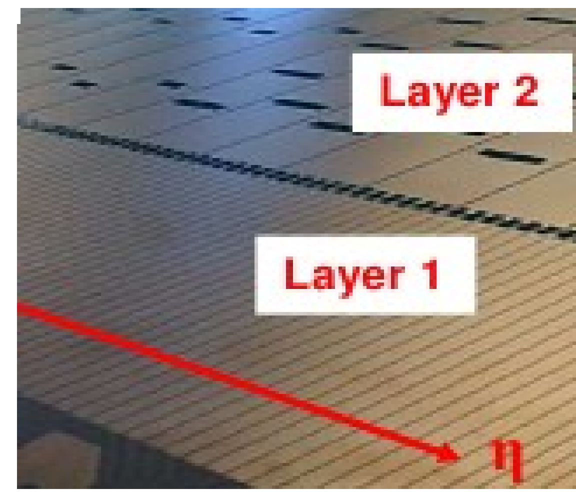

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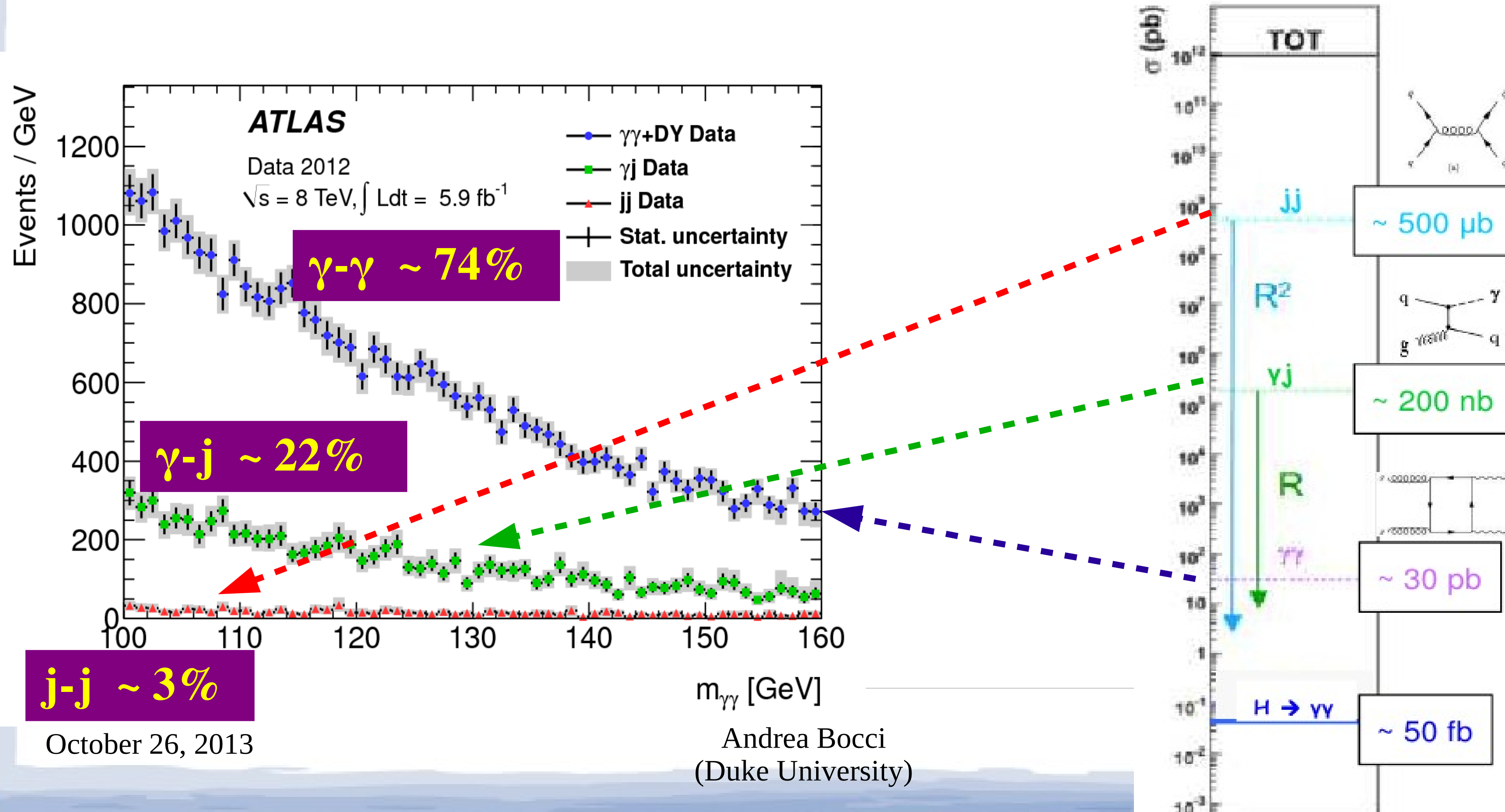
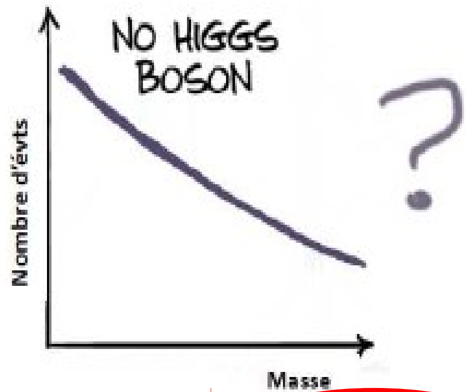


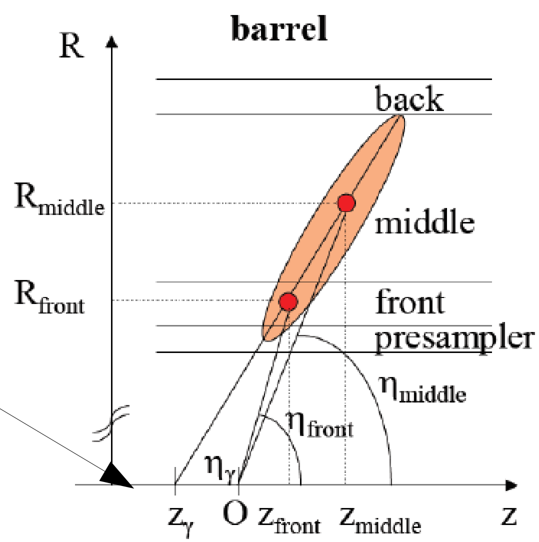
$\mathcal{H}\rightarrow\gamma\gamma$: Overview

Relatively simple selection: **two isolated, high quality reconstructed photons**

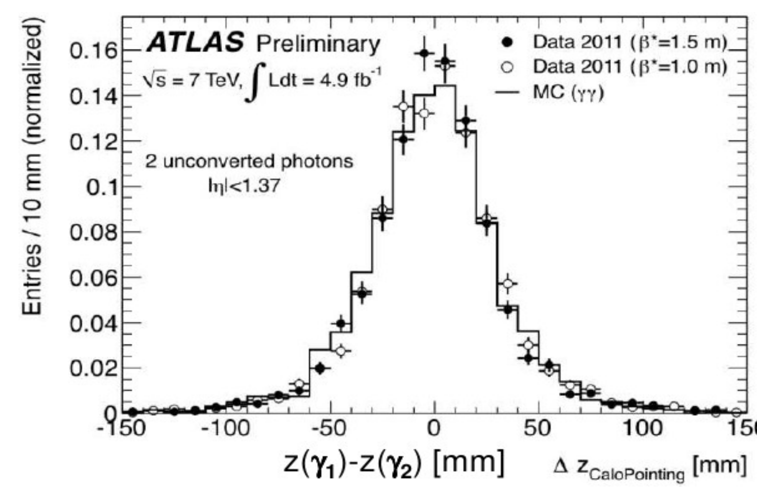
But very low S/B (~3%): **detector requirement and performance essential !**

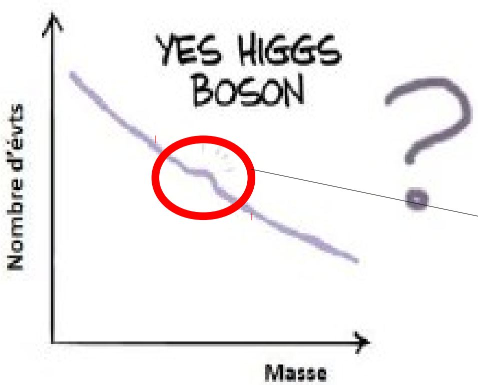


$$m_{\gamma\gamma} = \sqrt{E_1^{\gamma} E_2^{\gamma}(1-\cos\alpha_{12})}$$



Vertex position resolution with calo only ~ 1.5 cm



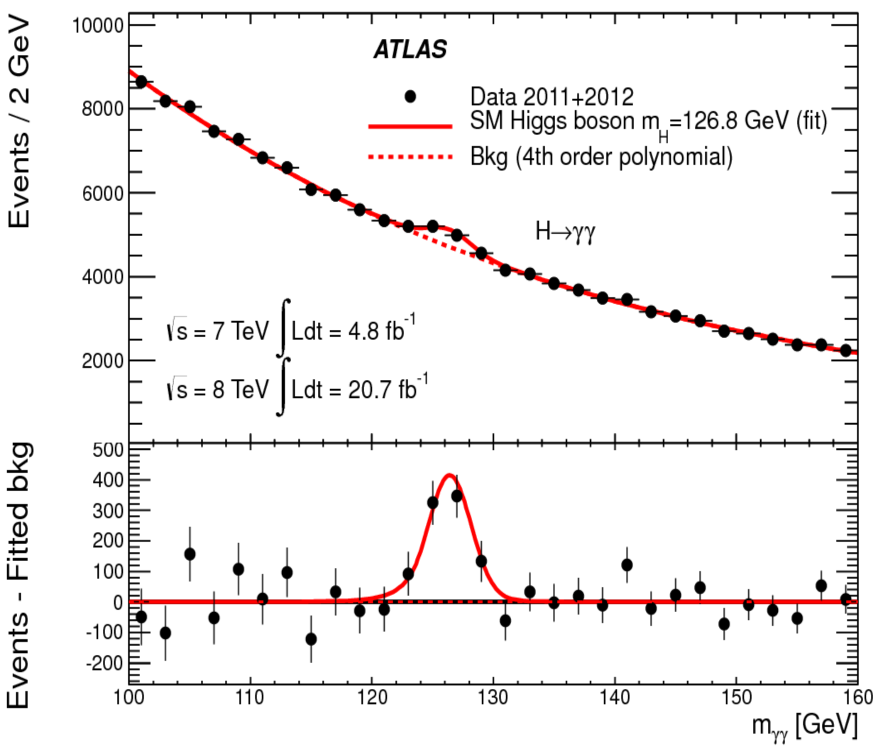


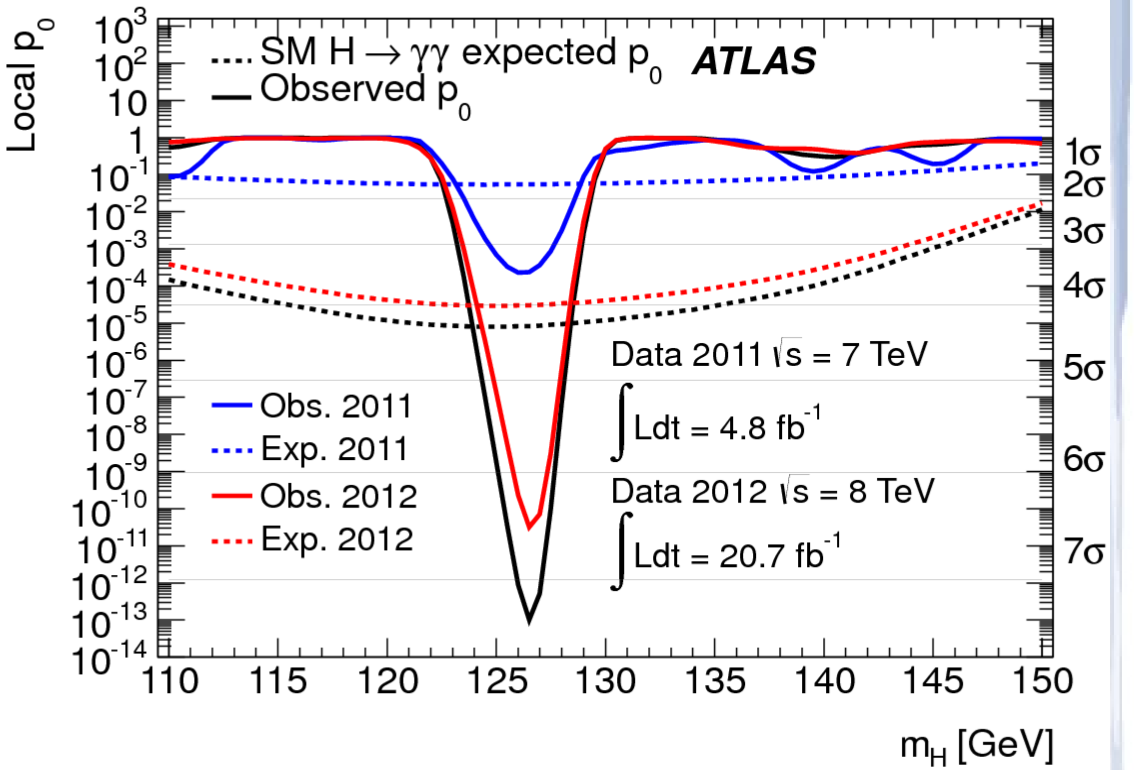
Mγγ resolution also important to have a small bump to emerge

$H\to\gamma\gamma$: Results

$$m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$$

Local p_0: probability for the background to produce a fluctuation at least as large as the one observed in the data

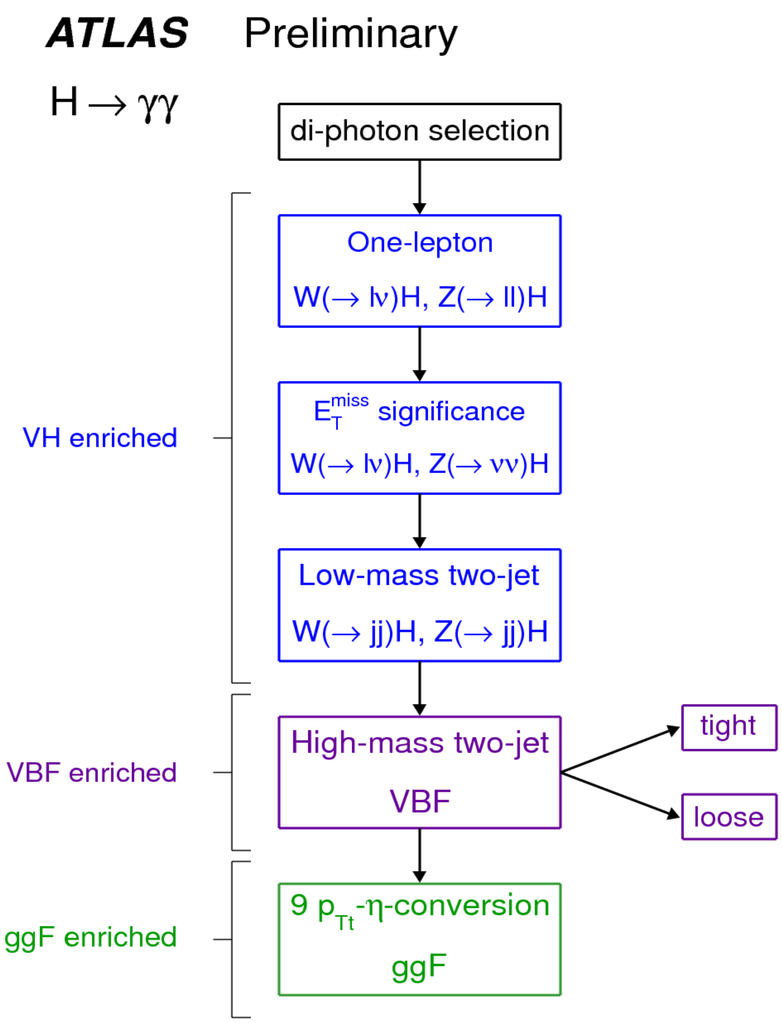


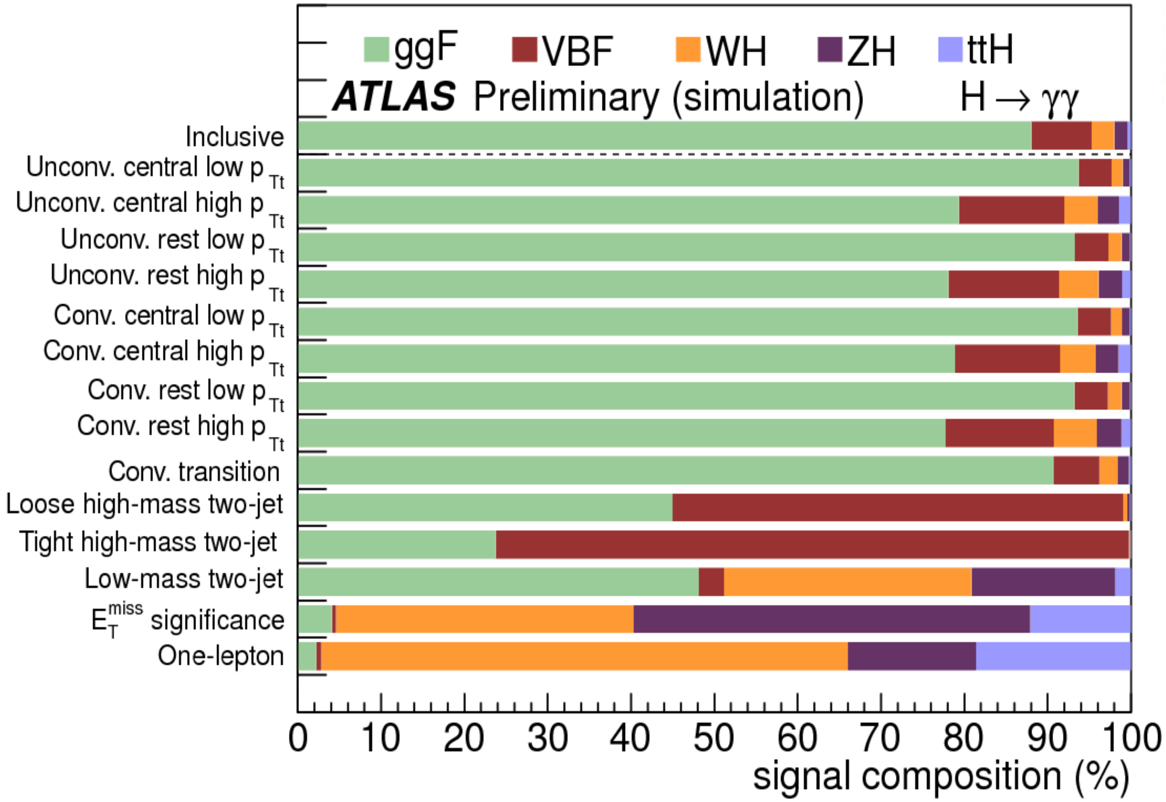


Observed local significance to the excess: 7.4 σ
"Single" channel discovery!

$H \to \gamma\gamma$: Results

Events divided in not-overlapping sets to maximize sensitivity to signal yield and different couplings





$\mathcal{H}\rightarrow\gamma\gamma$: Results

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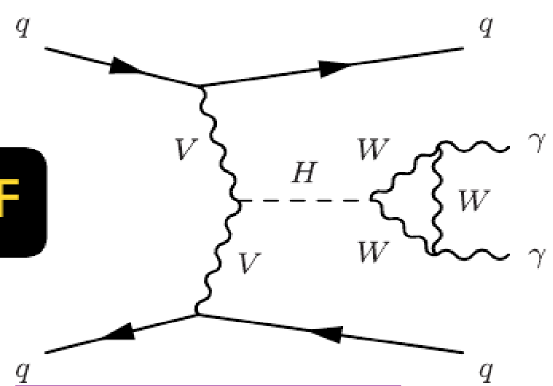
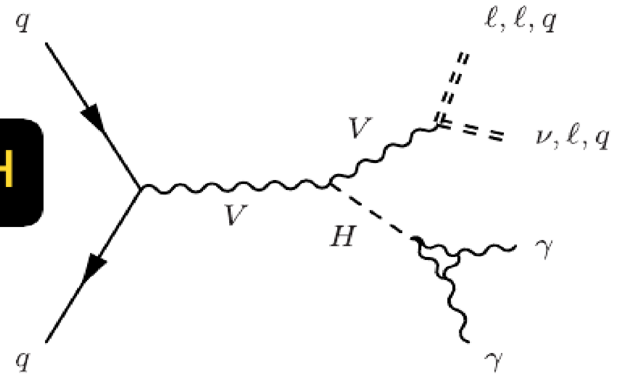
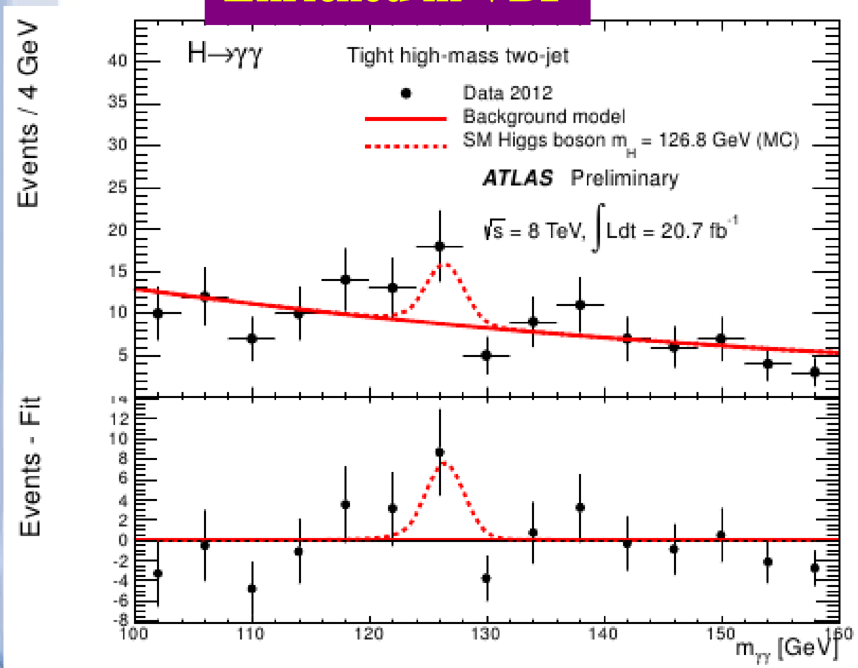
VBF



VH



Enriched in VBF



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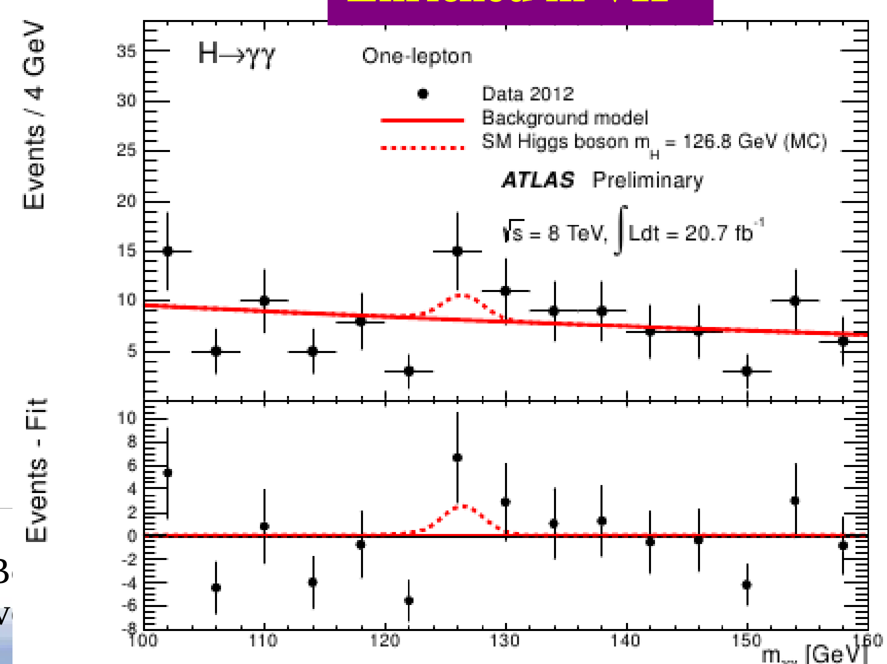
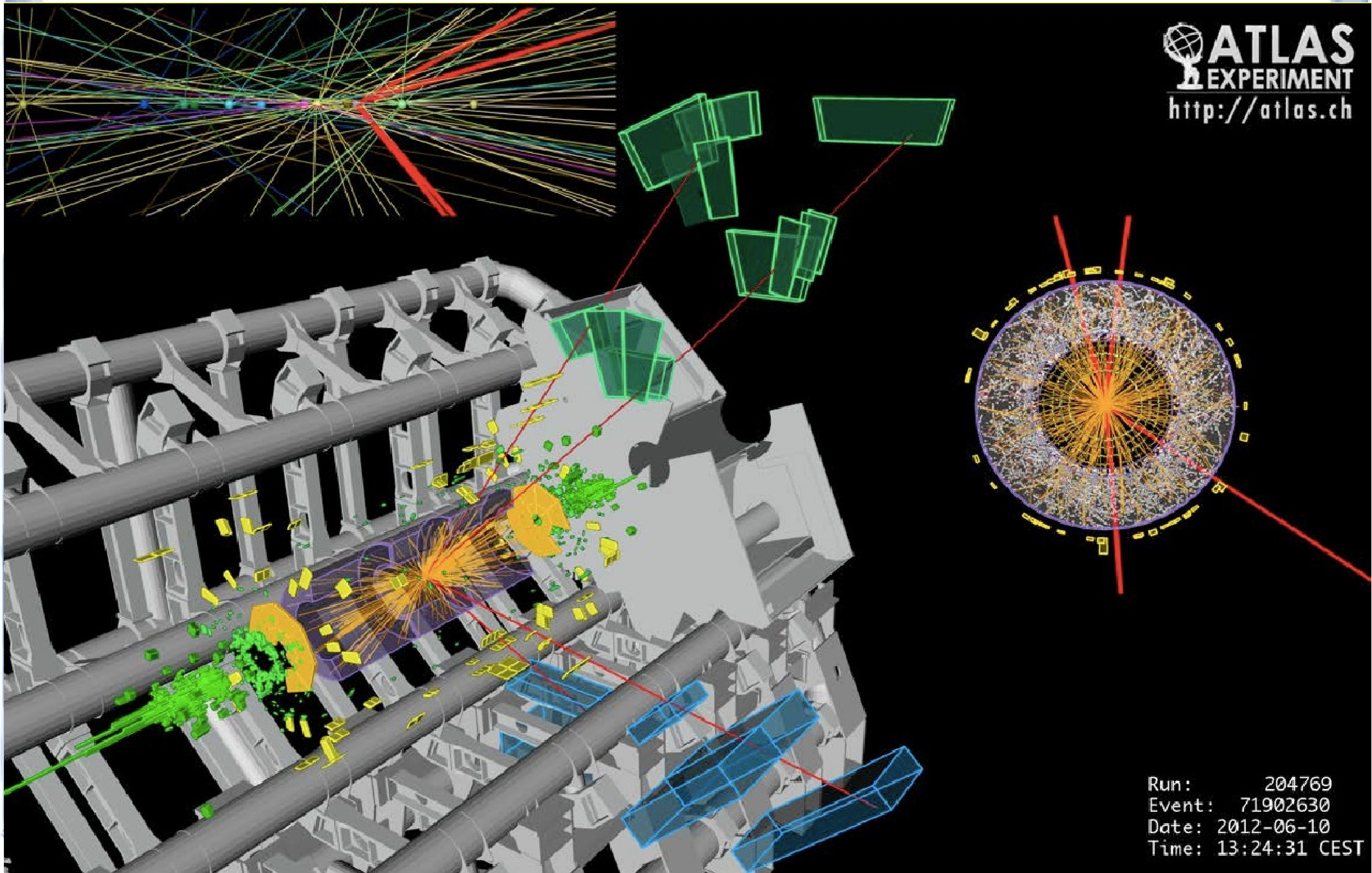


$\mathcal{H}\to ZZ$ Channel



H->ZZ: Overview

The Good: well measured objects, good mass resolution, clean (high S/B), spin measurement

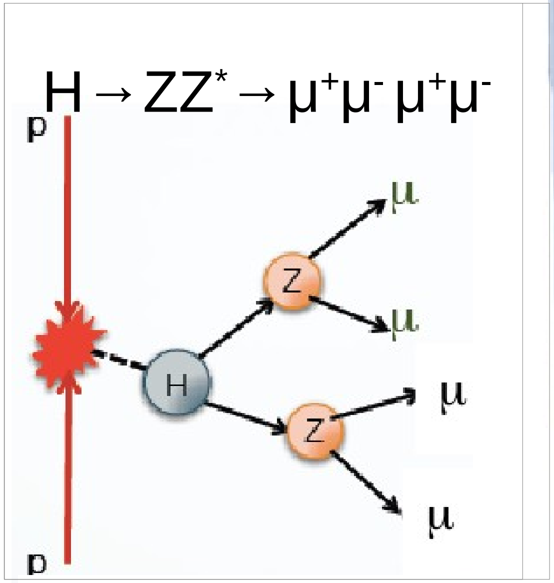
The Bad: at M_H~125 GeV one Z off-shell, low rate

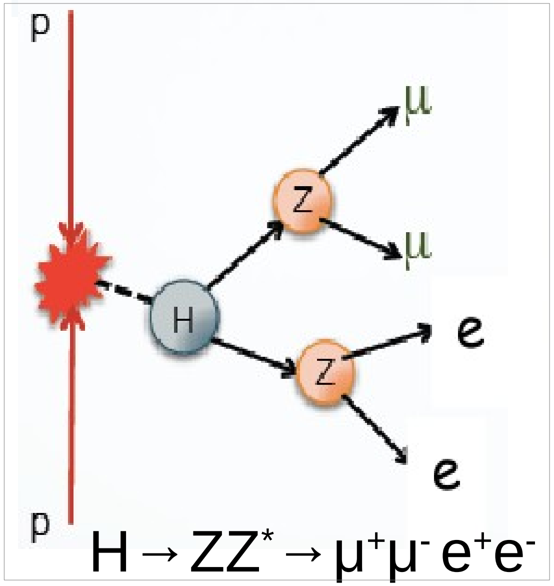
The Ugly: background from SM ZZ also rare, Poisson stat. with small sample

M_{4l} = Invariant mass of two pairs of opposite-sign same-flavor isolated leptons

Electron (muons) with energy (momentum) down to 7 GeV (6 GeV)

Crucial aspects:
- very tiny rate → maximize acceptance and efficiency
- 4 object mass reconstruction → good energy/momentum scale/resolution
- Background at low Et → good rejection capability





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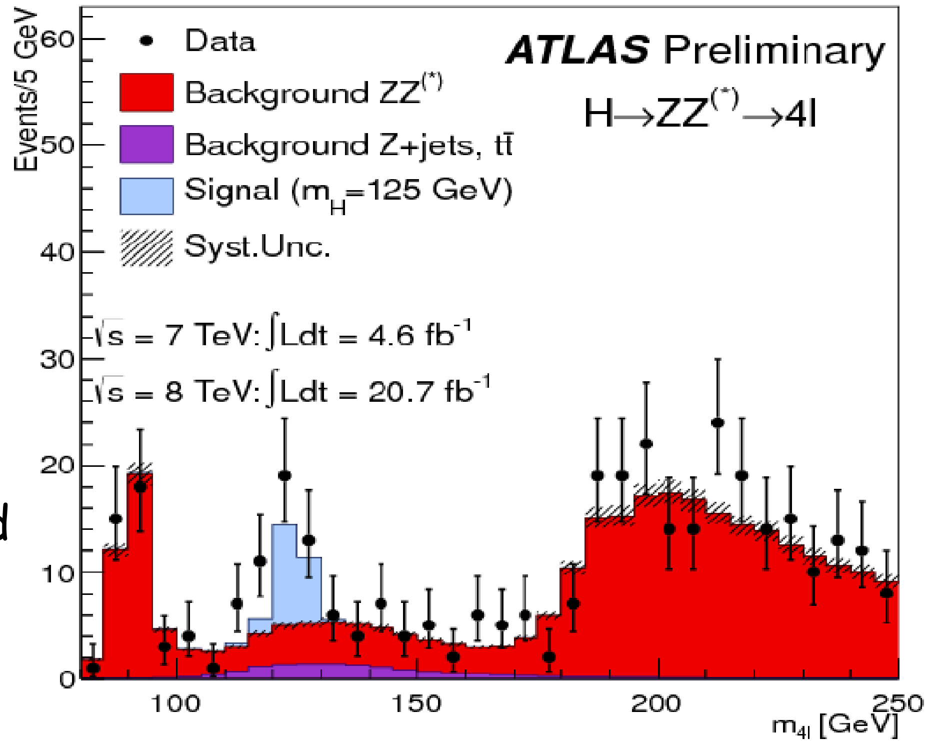
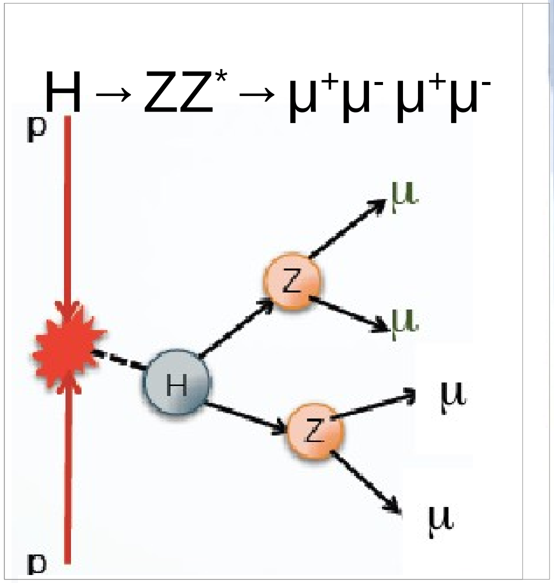
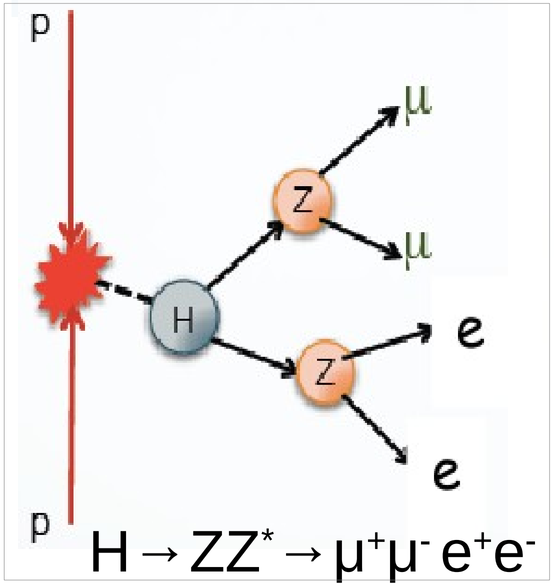


Only 32 candidates in 120-130 GeV





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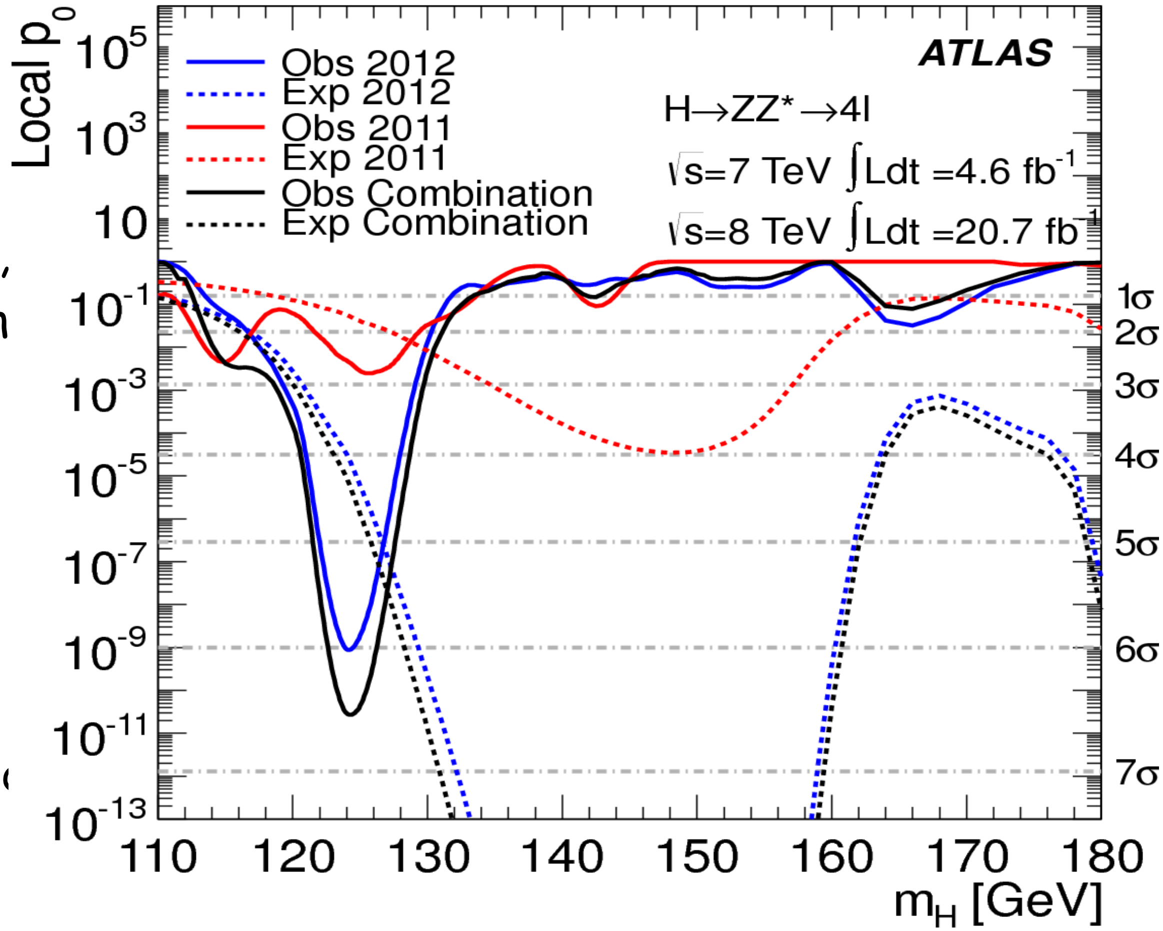
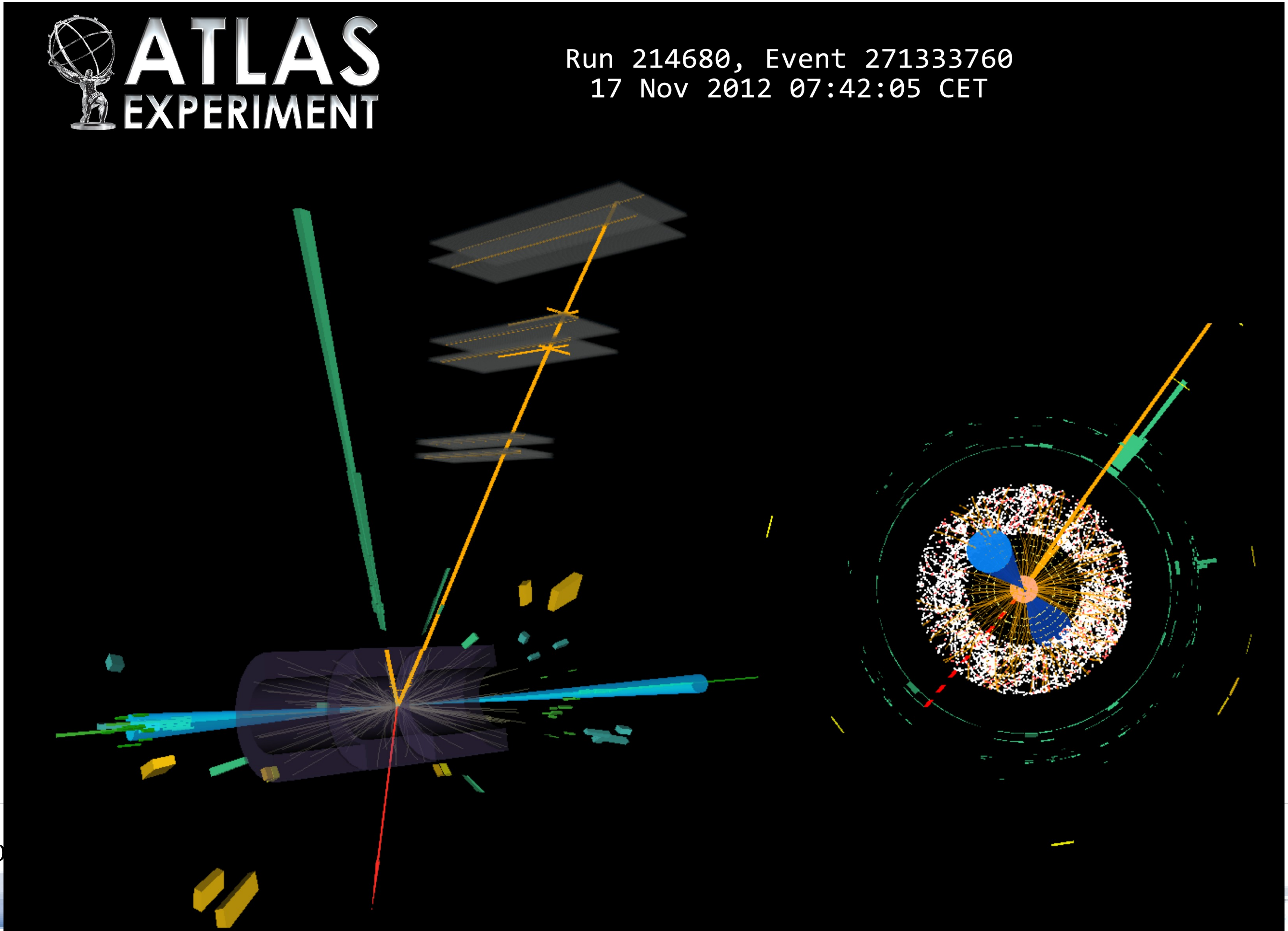


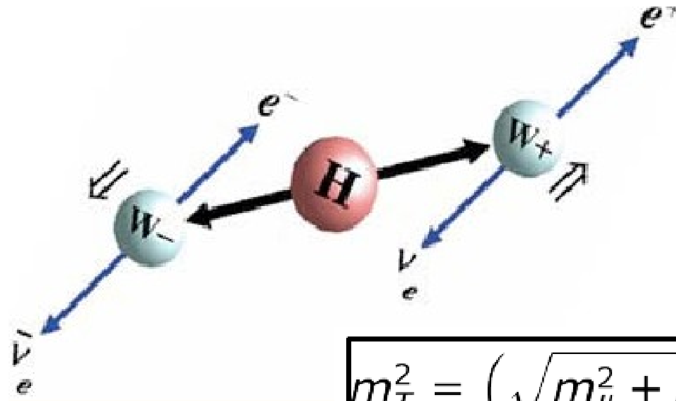
Observed local significance to the excess: 6.6σ
"Single" channel discovery!

$\mathcal{H} \rightarrow WW$



H->WW: Overview

The Good: The most sensitive channel in $130<M_H<200$ GeV



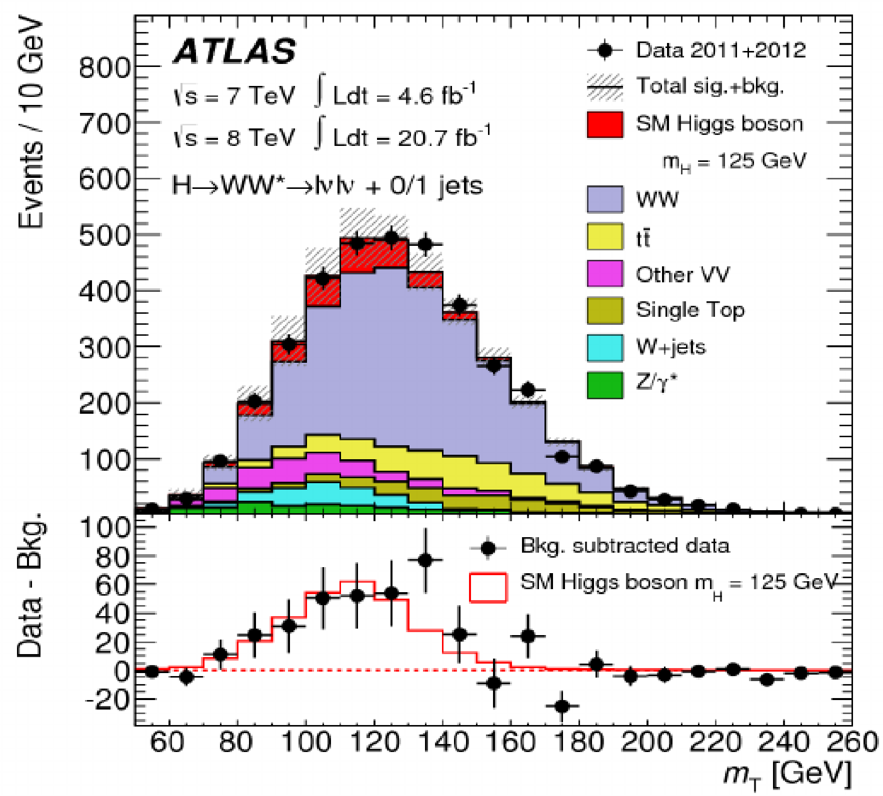
Selection optimized based on the assumption of a spin-0 resonance

(lepton/neutrino more collinear)

The Bad: Mass reconstruction not possible because of missing energy

$$m_T^2 = \left(\sqrt{m_{ll}^2 + p_{T_{ll}}^2} + E_T^{miss}\right)^2 - \left(p_{T_{ll}} + E_T^{miss}\right)^2$$

The Ugly: irreducible background from WW SM process, plus more from top (tt and single top) and Drell Yan



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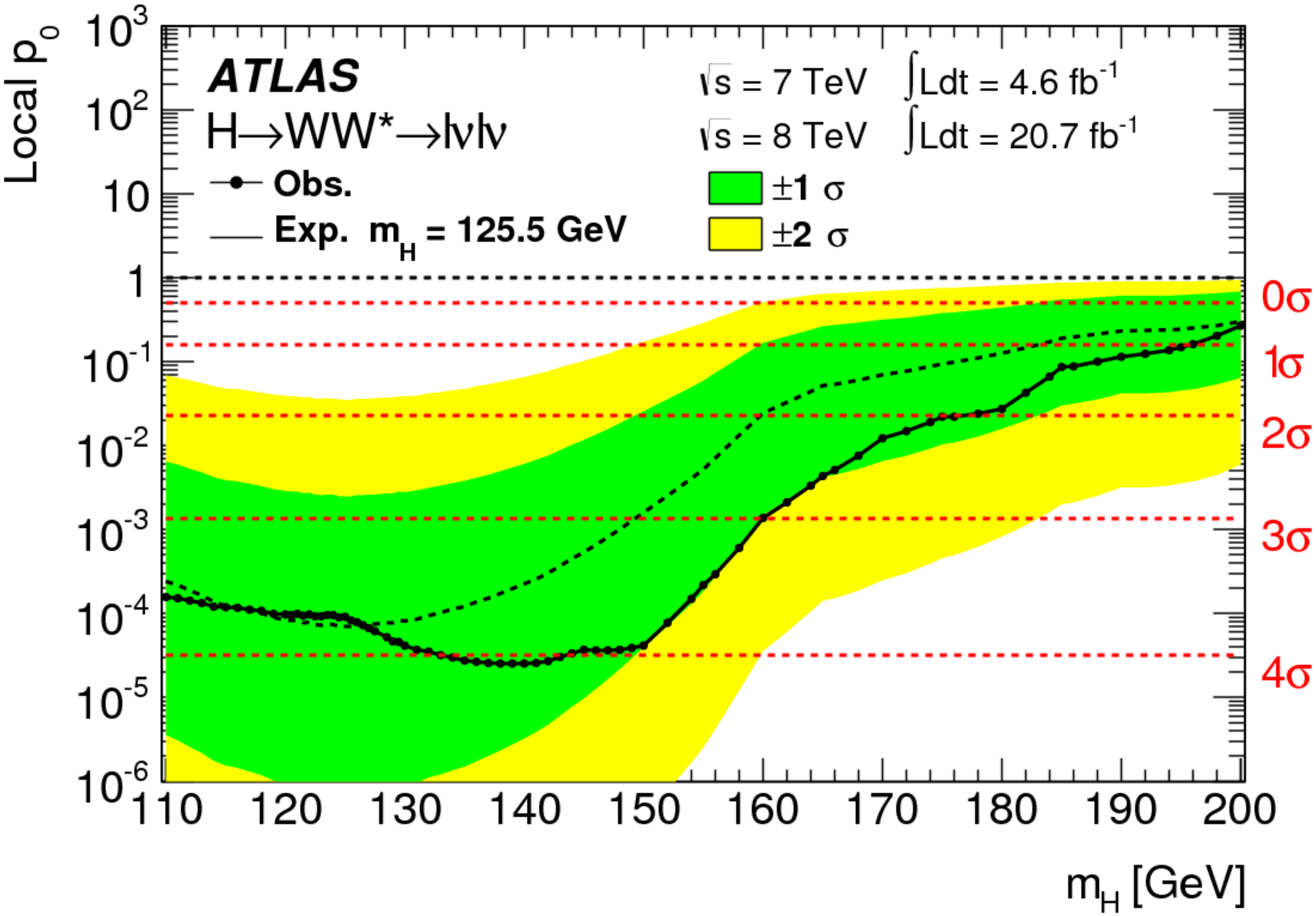

Observed local significance at 125 GeV: 3.8σ
(max. deviation of 4.1σ at m_H=140 GeV)

$\mathcal{H} \rightarrow \tau\tau / bb$

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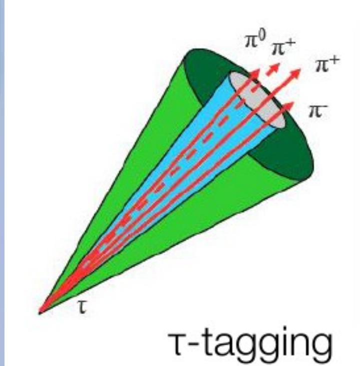
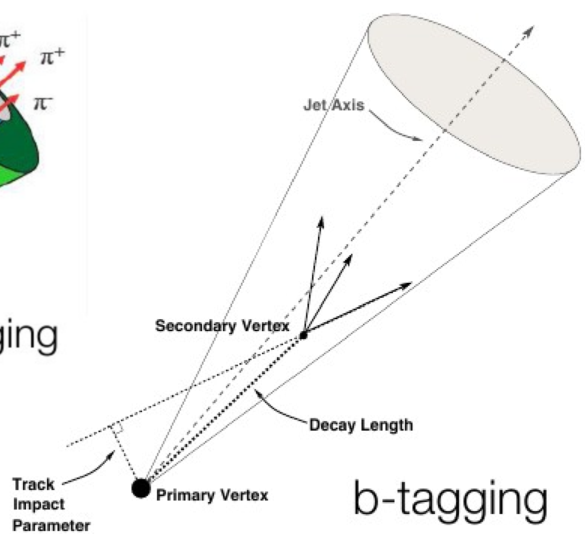
[direct measurement of fermionic coupling]

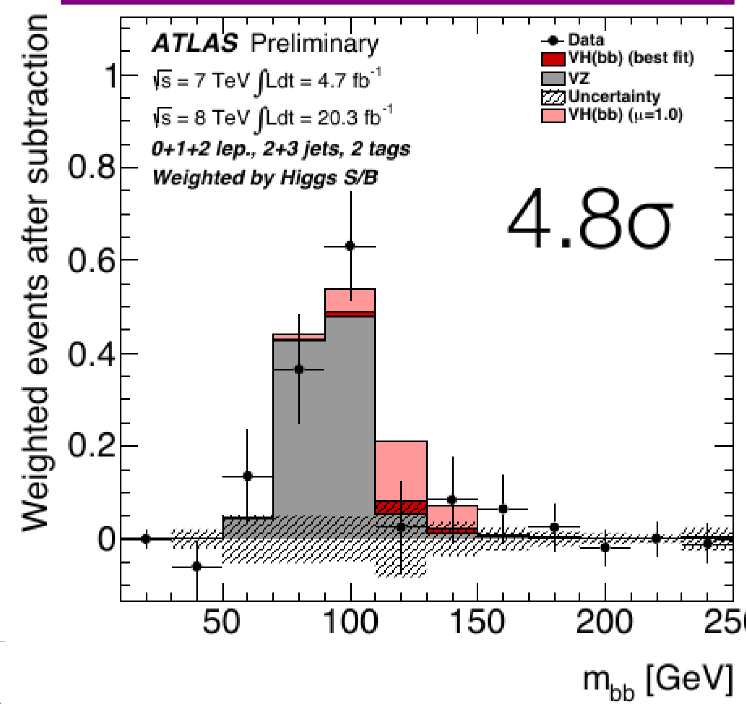
Reconstruction of τ's and b-jets:

- Complex (MVA) identification algorithms
- B-tagging mainly exploit b-quark lifetime
- Hadronic taus identified by decay of 1 or 3 charged hadrons





Validation with SM Candles (WZ/ZZ, Z → bb)



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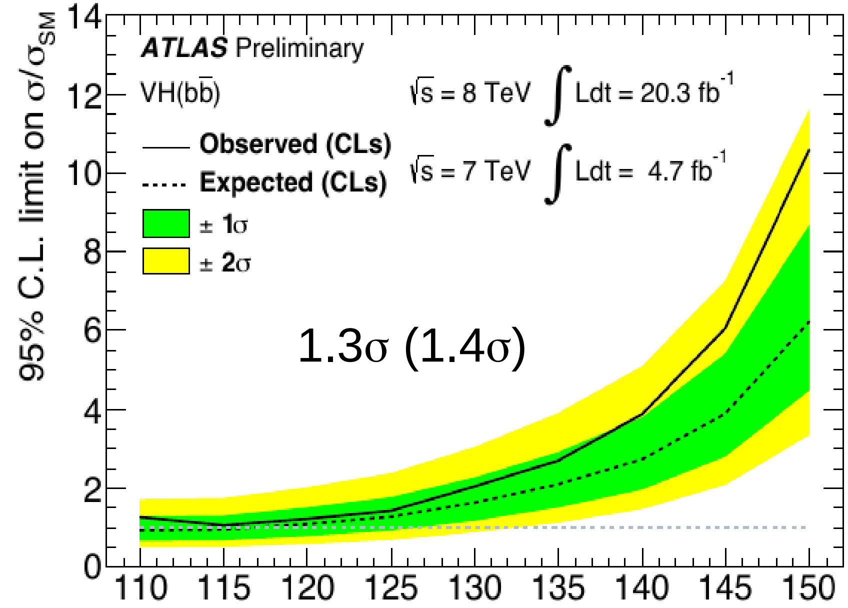

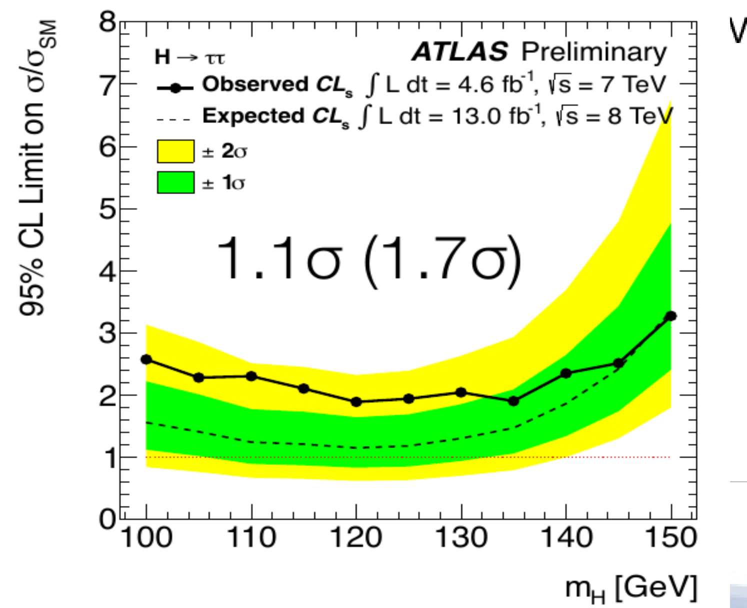

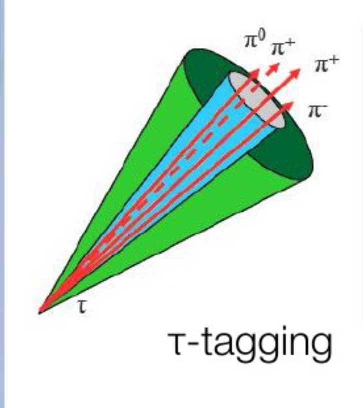

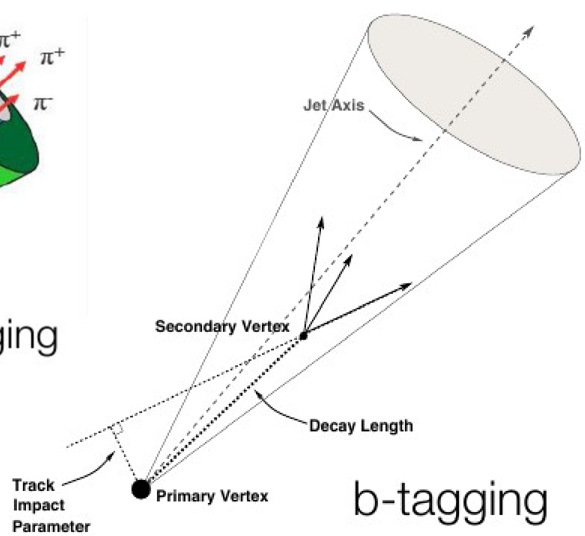

Historic Moment for Particle Physics

New data consolidated the discovery of the new particle, even in few individual channels alone

End of a long journey started in the 1970's, after 4 generations of accelerators built in two continents, a dozen of giant multipurpose detectors, and thousands of physicists, engineers, students, etc.. working to operate the detectors and analyze the data collected with them

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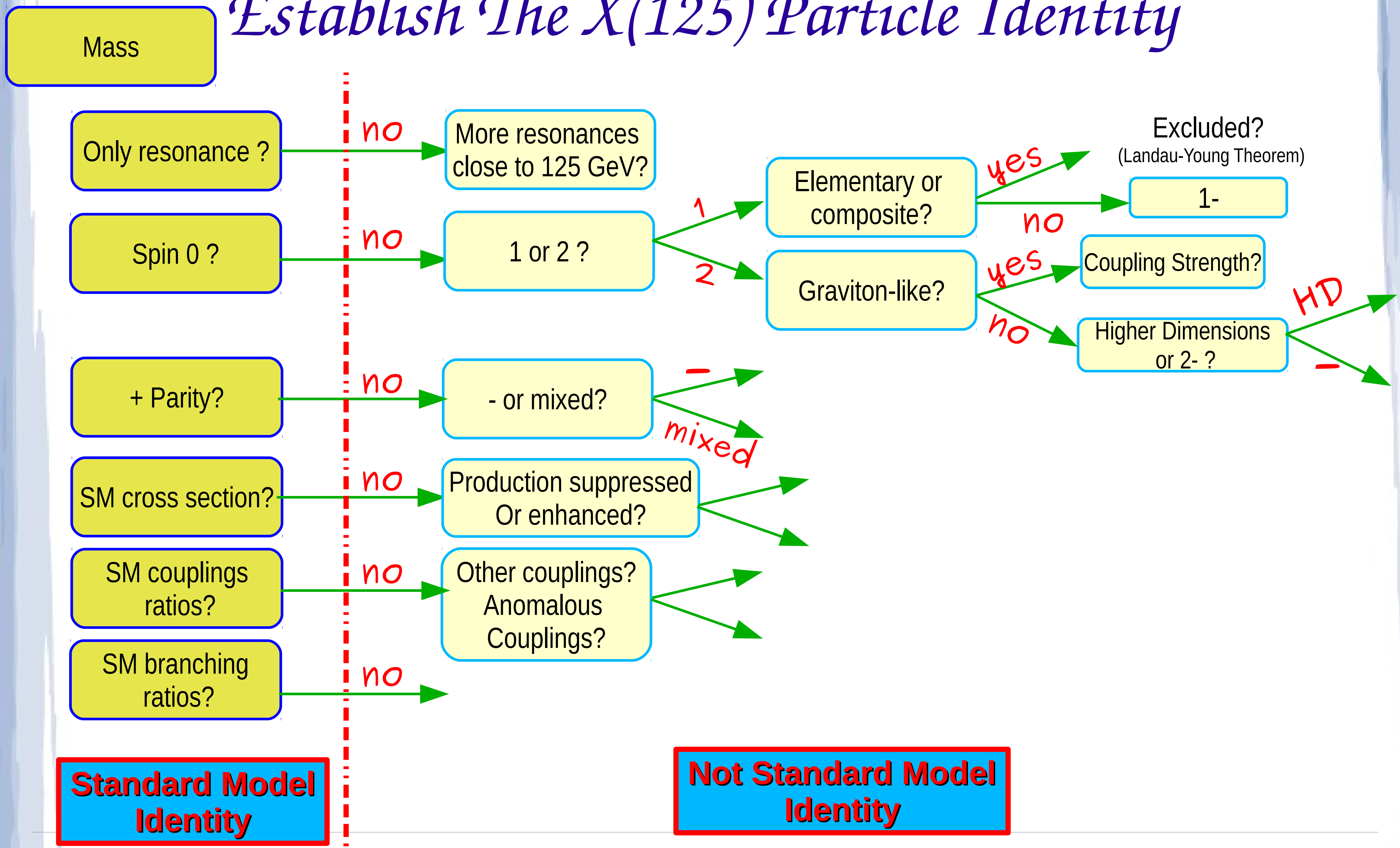
One (big) question remains: What have we found?

Establish The X(125) Particle Identity

Standard Model Identity

Not Standard Model Identity

Establish The X(125) Particle Identity



First Steps on The Higgs Sector Land...

Recent ATLAS Results

Measurements of new boson identity done with full ~26 fb^{-1} of Run 1 data!on:

- **Mass**
- **Cross section**
- **Coupling**
- **Spin**
- Parity
- Custodial symmetry
- Coupling Ratio

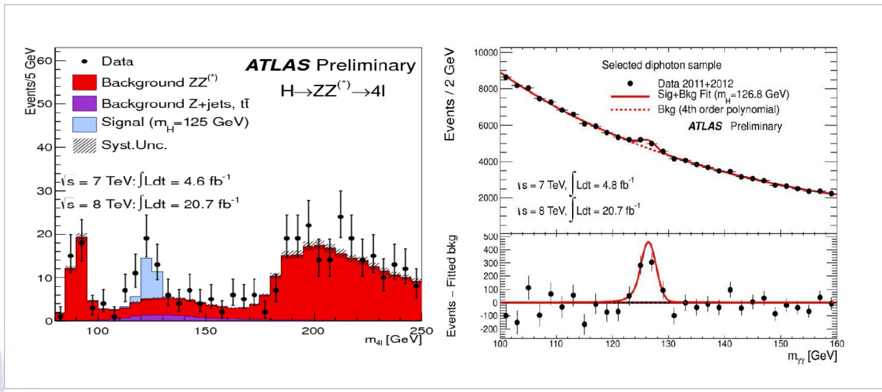
Measurements done for each individual channel and then combined

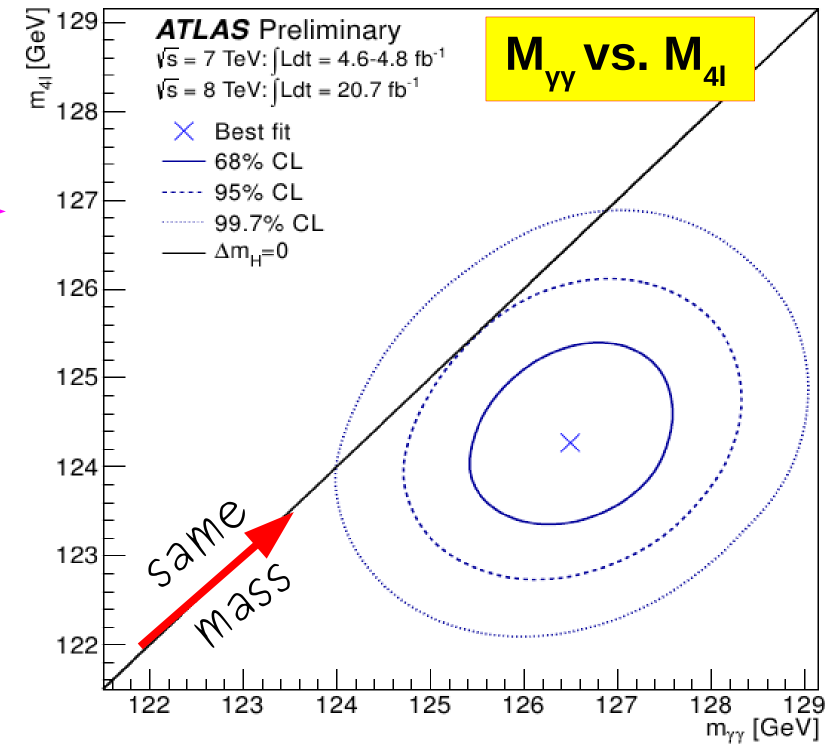
Only an highlight of (some) results shown here...

Mass And Signal Yield

Mass Measurement

[only missing parameter in the SM Higgs Sector]





Precise m_H measurement from

$H\to\gamma\gamma$ and $H\to ZZ\to 4l$

$$\mathbf{m_{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(sys.)}$$

$$\mathbf{m_{4l} = 124.3^{+0.6}_{-0.5}(stat) \pm^{+0.5}_{-0.3}(sys)}$$

$$\mathbf{m_H = 125.5 \pm 0.2(stat) \pm^{+0.5}_{-0.6}(sys)}$$

Consistency with same mass hypothesis: **2.4σ (1.5%)**

$M_{\gamma\gamma}$ systematics fully dominated by the photon energy scale

M_{4l} systematics mainly from muon momentum scale

Signal Strength

[correlated with mass measurement]

Signal strength μ defined as observed event yield normalized to expected SM yield

$$\mu = \frac{\sigma \cdot \mathcal{BR}}{(\sigma \cdot \mathcal{BR})_{\mathrm{SM}}}$$

No Higgs: μ = 0
SM Higgs: μ = 1

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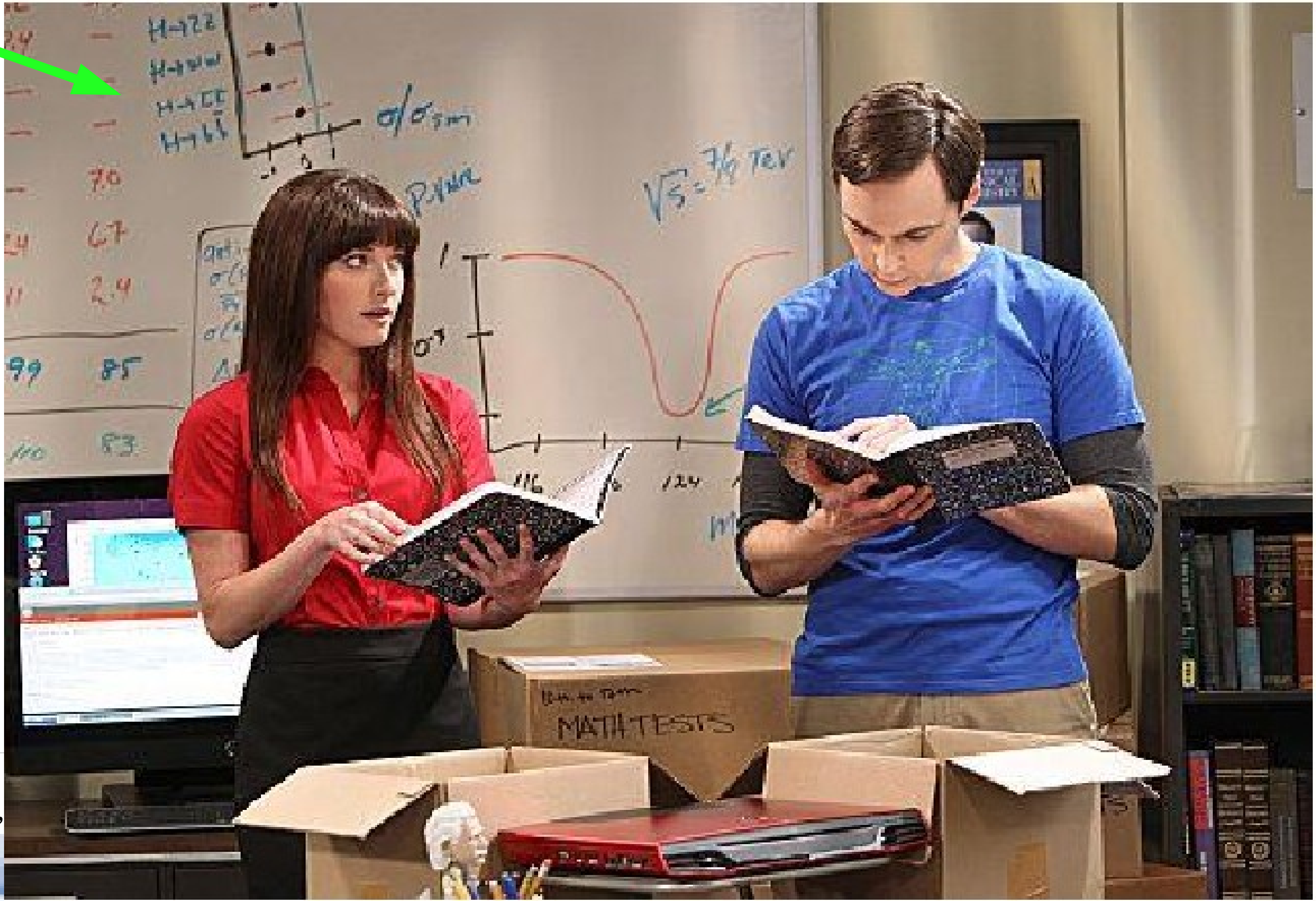

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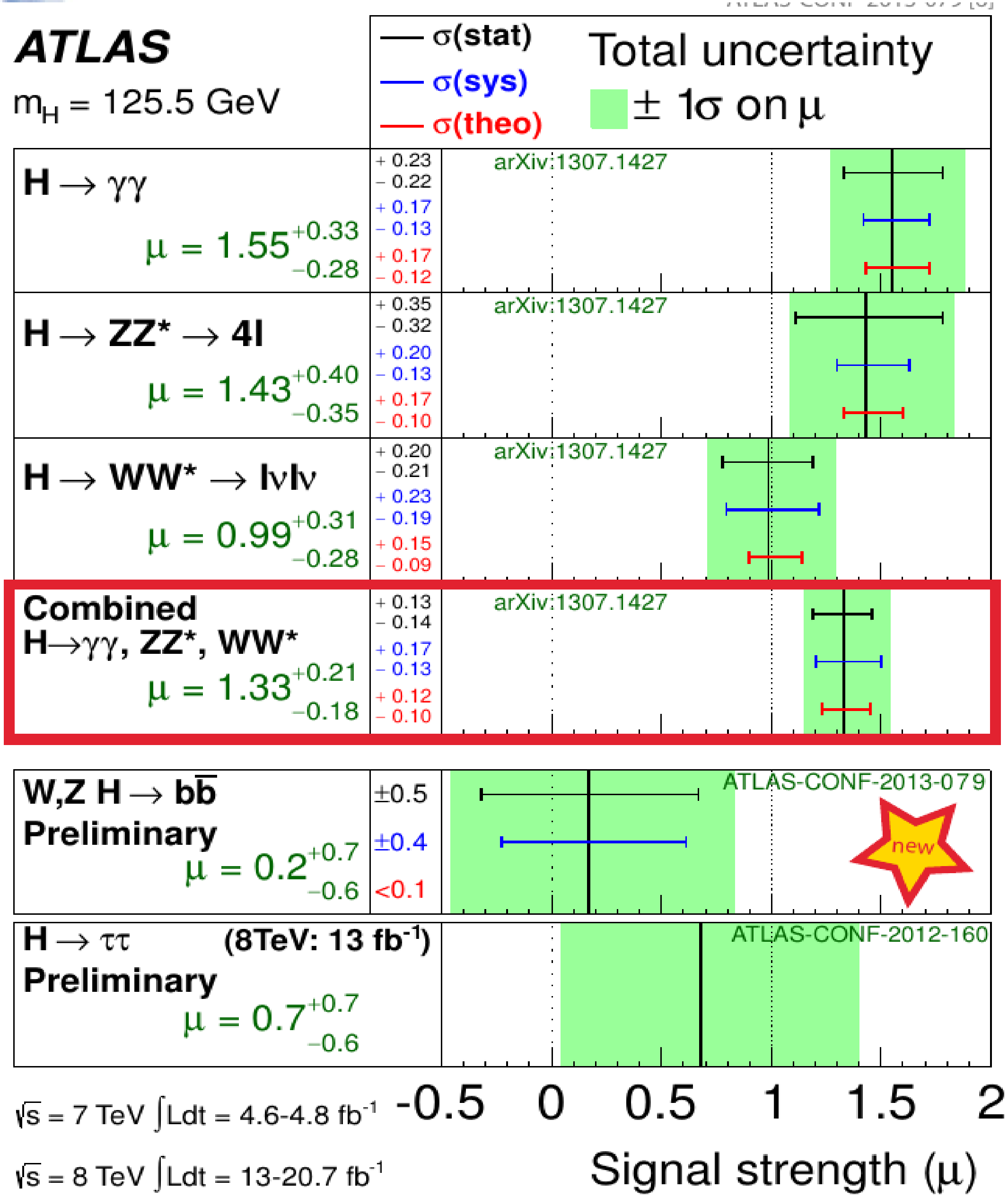

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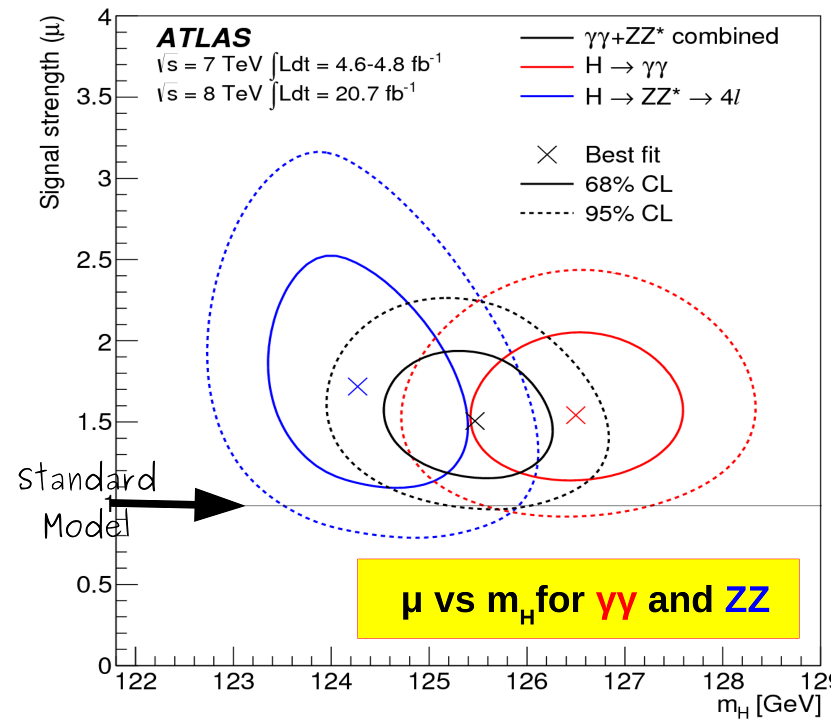
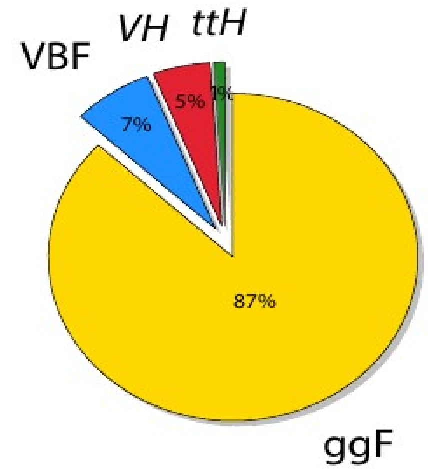


Consistency of combined μ with SM at about 14%

Higgs Production Modes

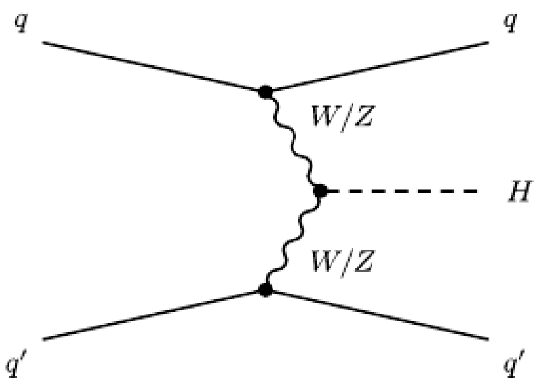
Higgs Production Modes

Signal strength relies on the SM assumptions about relative contribution of the production modes

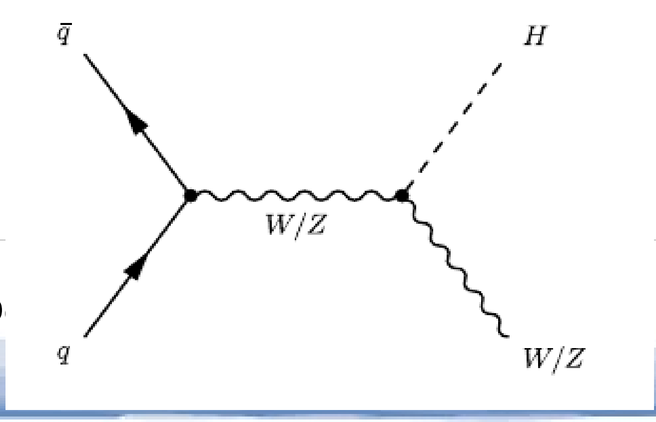


Disentangle vector-boson mediated and gluon or fermion-initiated production mechanisms (SM μ=1):

μ_{VBF+VH} vs. $\mu_{ggF+ttH}$

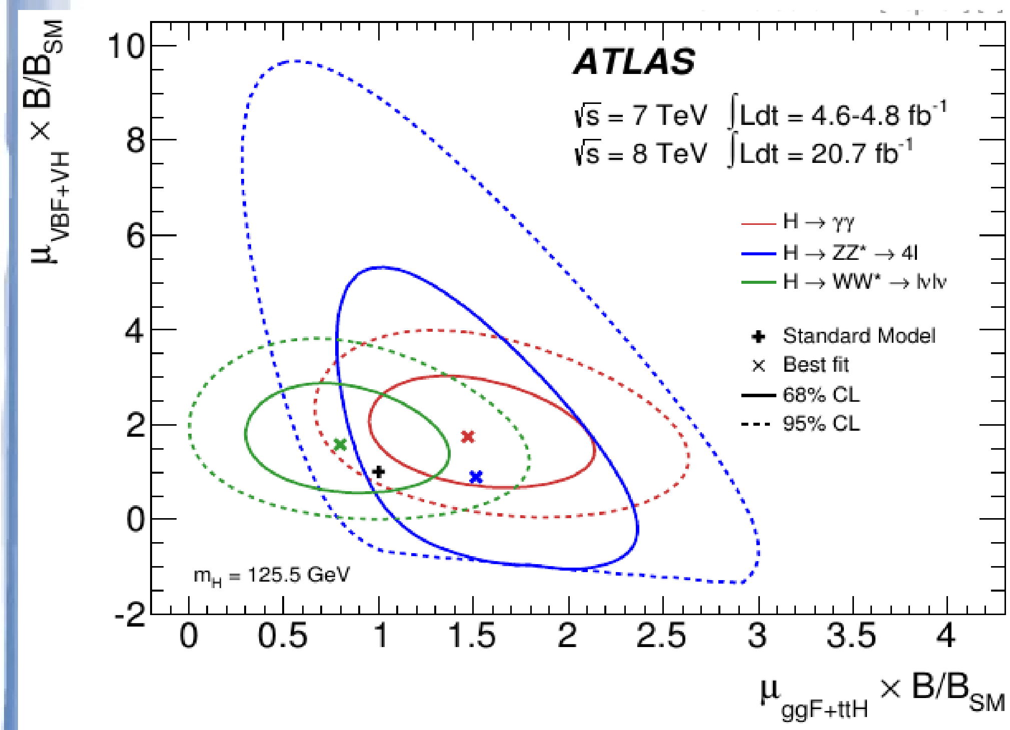


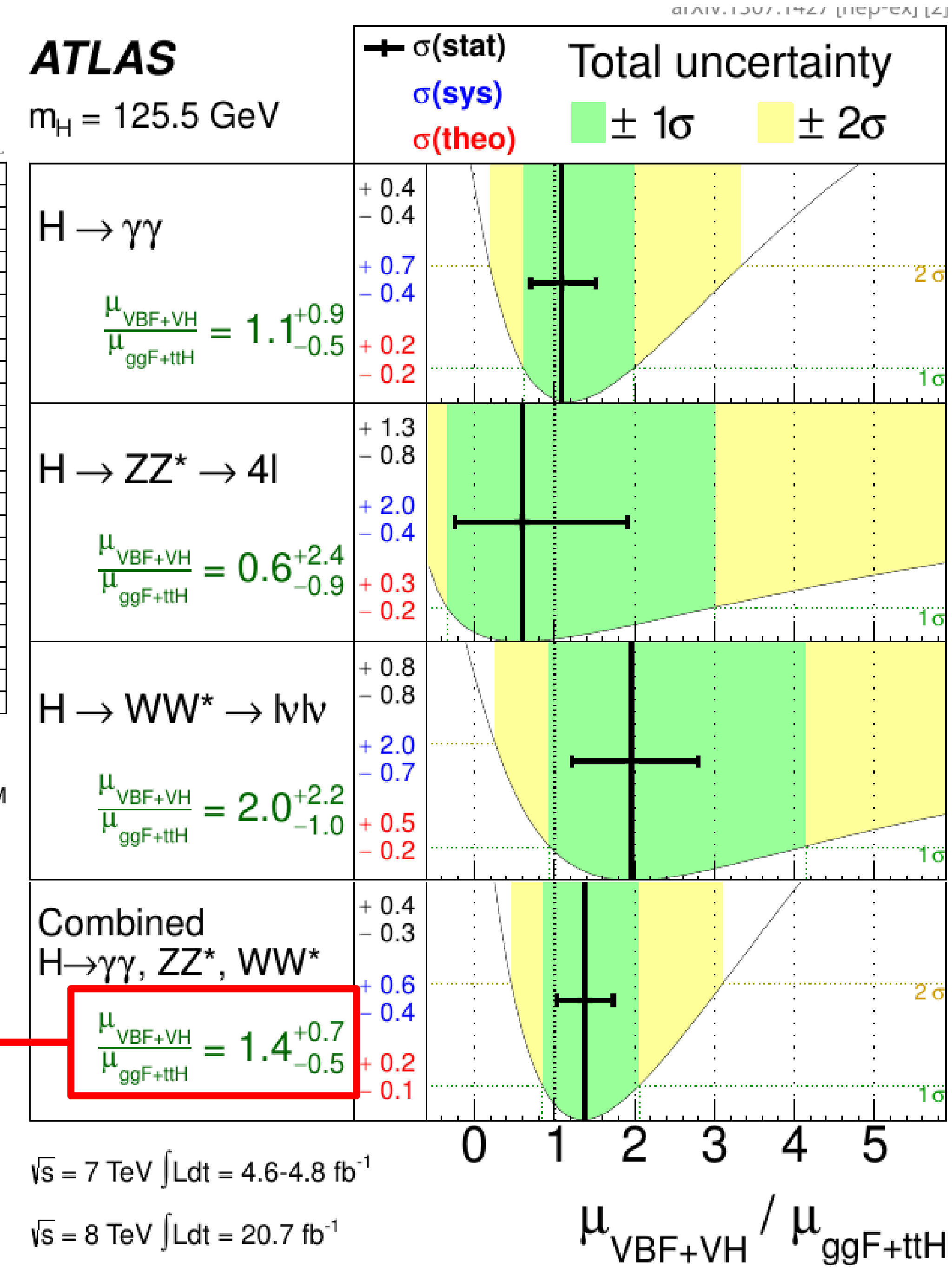
VBF: two forward jets, with little hadronic activities between them, large separation in pseudo-rapidity, high invariant mass



VH: Associated production with a W/Z, i.e. 2 leptons, or 1 lepton + missEt

Higgs Production Modes

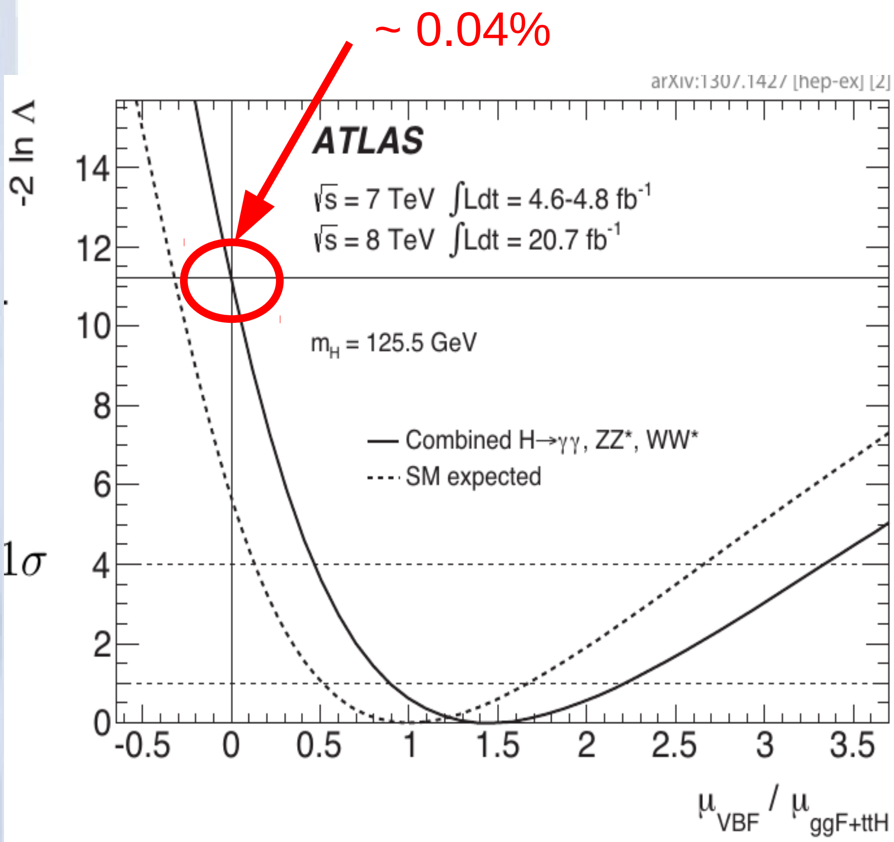


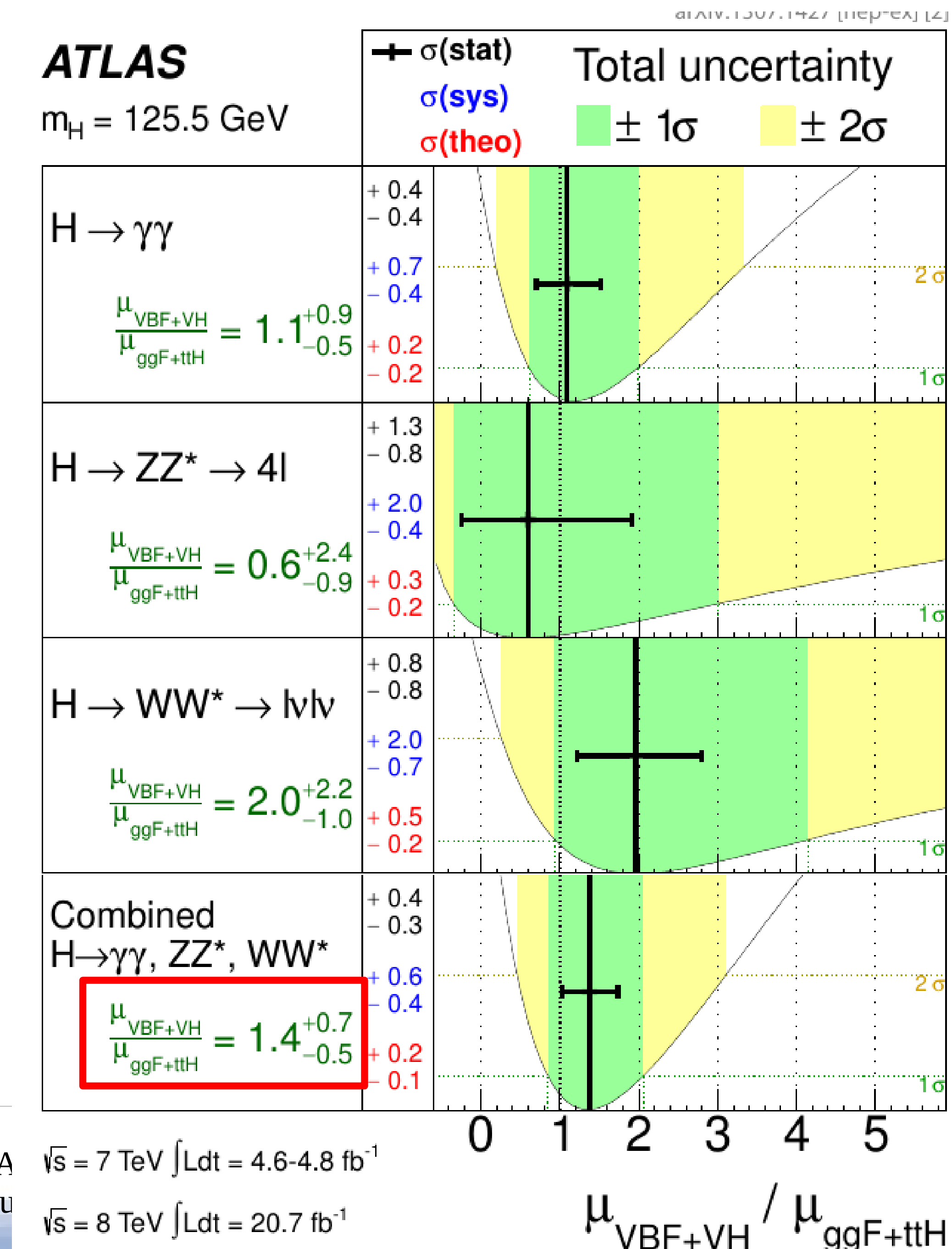


The ratio μ probes production only (BR cancel out)

Possible to isolate single processes by "profiling"

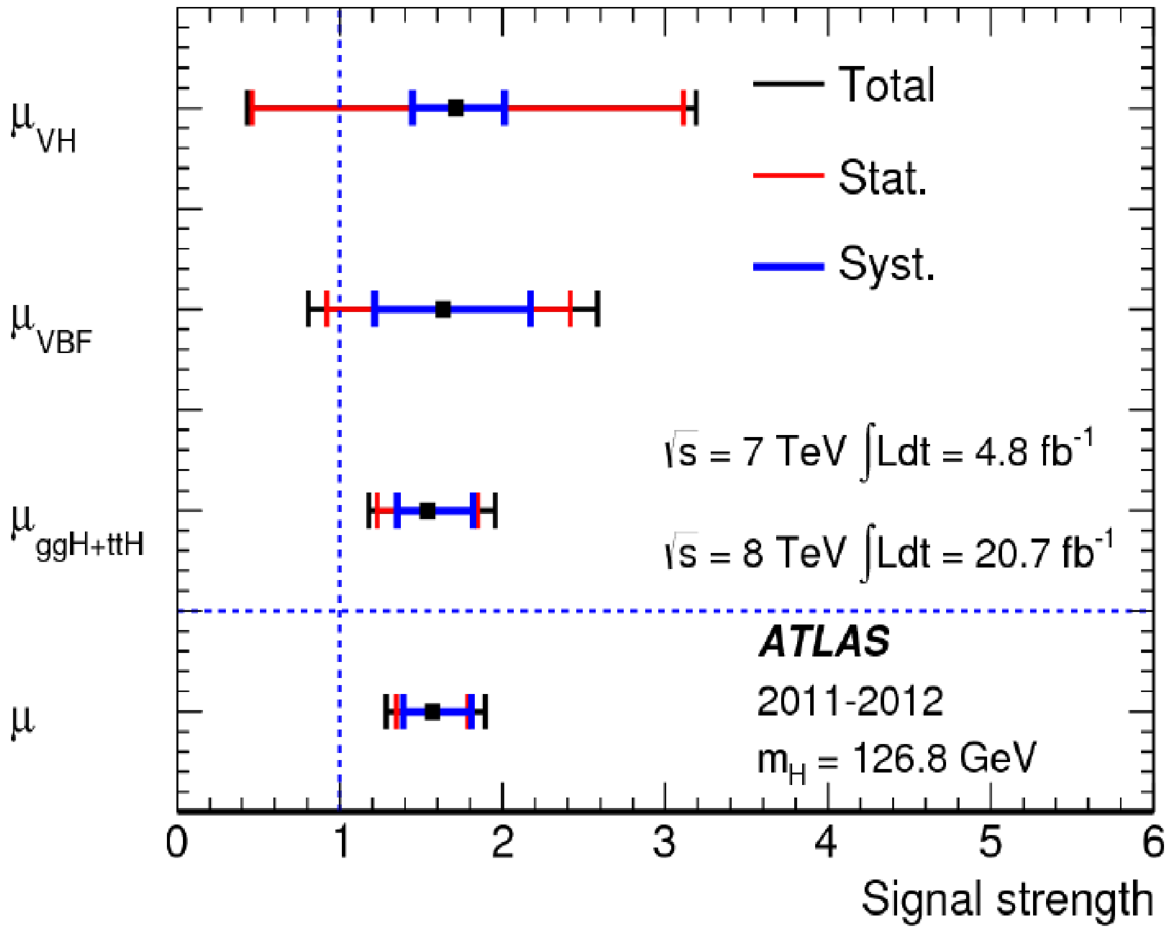
Higgs Production Modes





3.3σ evidence for VBF production

Higgs Production Modes



Status:

- ggF well established
- Evidence for VBF
- Indication for VH
- Not yet sensitive to ttH

Spin and Parity

Spin and Parity

- What are the quantum numbers of observed state X ?
  - J^{PC}: J=spin, P=parity, C=charge conjugation
- Spin0: Standard Model Higgs boson
  - The Standard Model Higgs boson is scalar particle (0^+).
  - CP-mixing/violation in spin-0 can exist but small in many BSM models.
- Spin1: Landau-Yang theorem
  - Landau-Yang theorem forbids the direct decay of an on-shell spin-1 particle into a pair of massless particles.
  - Observation of $H\to\gamma\gamma$ rules out the possibility that the new resonance has spin 1, and fixes C=1 (barring C violating effects in the Higgs sector).
  - This theorem strictly applies to an on-shell resonance (*i.e.* small width hypothesis).
- Spin2: graviton
  - Theoretically difficult. Velo-Zwanziger problem with U(1) gauge field.
  - Who will be responsible for electroweak symmetry breaking?
  - Why haven't we observed analogous KK excitations of SM gauge bosons?

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- Spin1: Landau-Yang theorem
  - particle

Now can get answers directly from Nature looking at experimental data !

  - Observation of H→γγ rules out the possibility that the new resonance has spin 1, and fixes *C*=1 (barring *C* violating effects in the Higgs sector).
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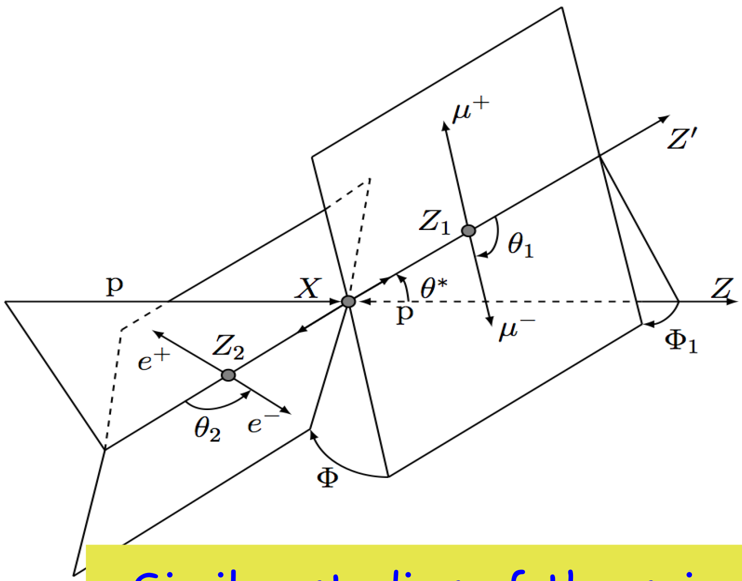
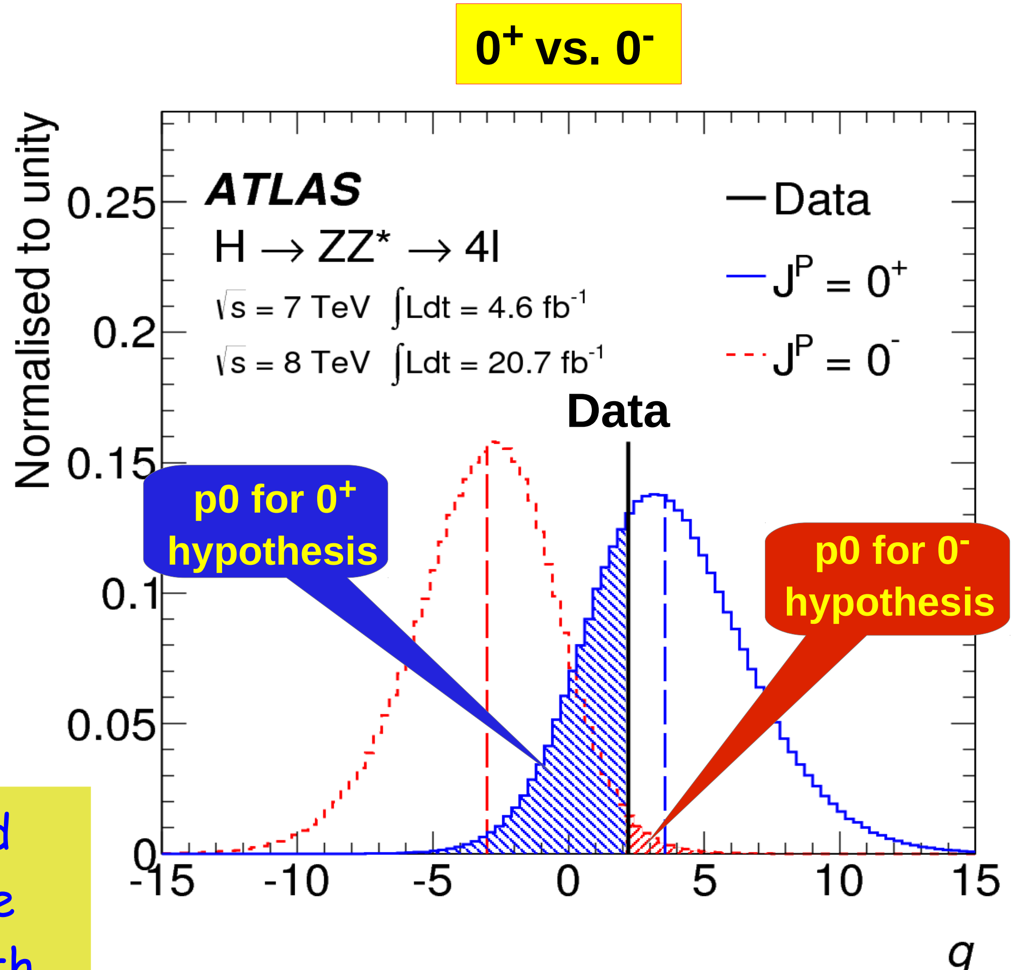
Example: J^P Measurement with H->ZZ(*)->4l

Kinematic of production and decay of H→ZZ→4 l channel (5 angles, Z mass) sensitive to spin and parity of the new boson



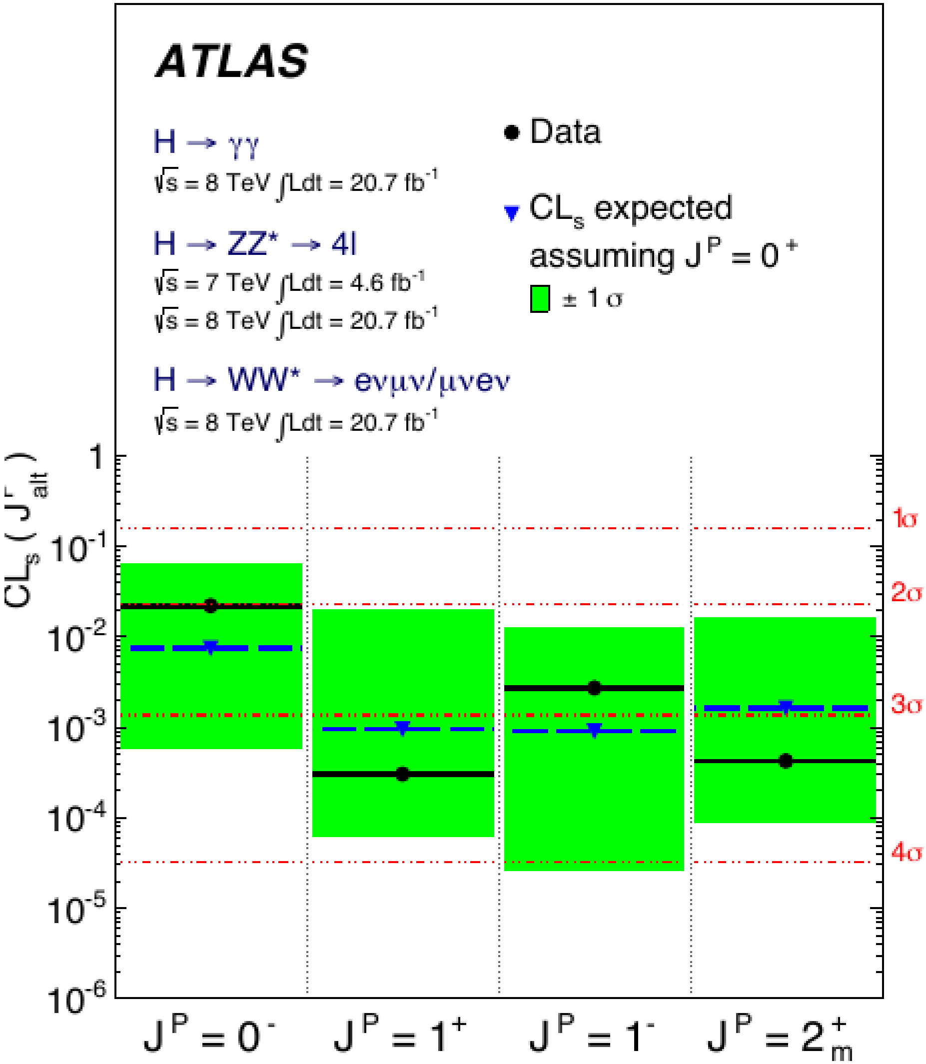


Similar studies of the spin and parity quantum numbers of the Higgs boson performed also with H → γγ and H → WW

Spin Measurement Summary

CERN-PH-EP-2013-102

J^P	production	particle	ATLAS CLs
0^-	gg→X	pseudoscalar	2.2% (H→ZZ*)
1^+	qq→X	exotic pseudovector	0.030% (H→ZZ*,WW*)
1^-	qq→X	exotic vector	0.27% (H→ZZ*,WW*)
2^+	gg/qq→X	graviton minimal couplings	0.042% (gg) (H→γγ,ZZ*,WW*)



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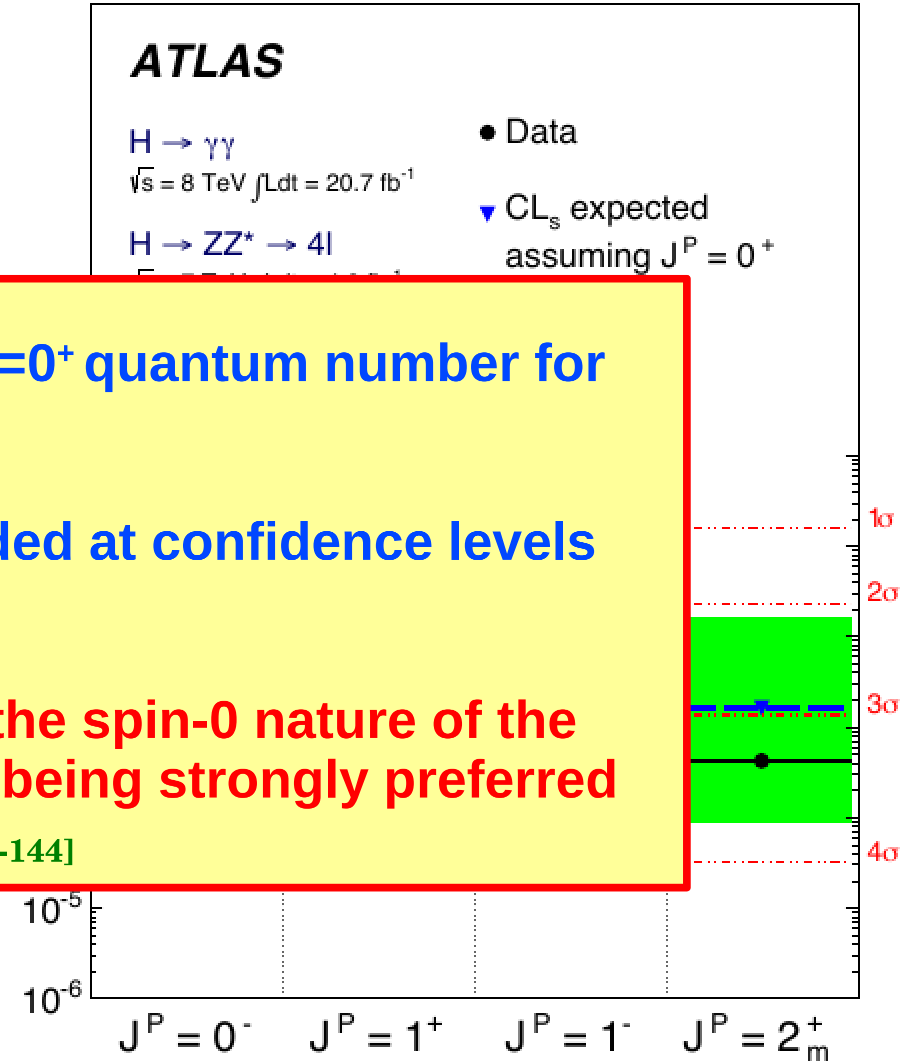
1^-			
2^+			



- **Data compatible with the SM $J^P=0^+$ quantum number for the Higgs Boson**
- **$J^P=0^-, 1^+, 1^-, 2^+$ models are excluded at confidence levels above 97.8%**

Data thus provide evidence for the spin-0 nature of the Higgs boson, with positive parity being strongly preferred

[PLB 726 (2013) 120-144]

Higgs Couplings

A Coherent Framework For Couplings Determinations

Signal strength mixes different production processes and potentially obscure new physics

Using scale parameter **κ**'s (κ=1 SM) to parametrize the deviations from SM Higgs coupling to fermions and vector bosons

Fermions: $g_F = \sqrt{2} m_F / v$, Gauge bosons: $g_V = 2 m_V^2 / v$

$$\kappa_i = g_i / g_{SM}$$

$$\sigma \cdot B \, (i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

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SM Modifiers

Production

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

Decay

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

Total Width

$$\kappa_H^2 = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

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Small Print:

- **Assume CP-even scalar**
- **One single resonance**
- **Narrow Width approximation**

SM Modifiers

Production

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

Decay

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

Total Width

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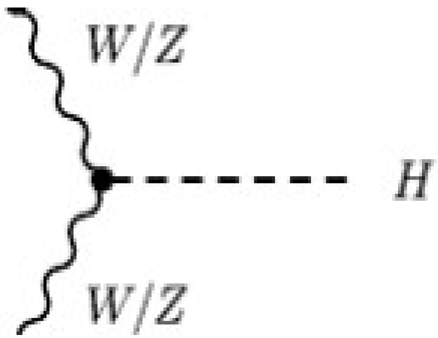

$\kappa_{W/Z}$

A Coherent Framework For Couplings Determinations

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Higgs coupling to fermions and vector bosons

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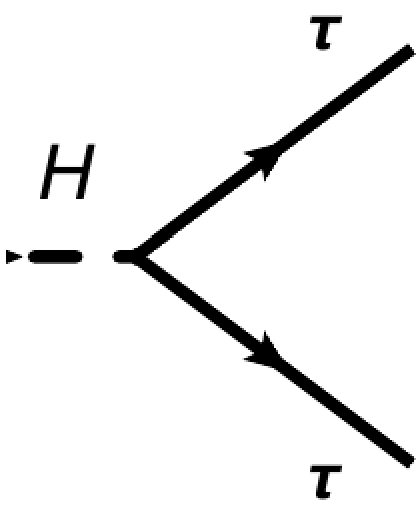

κ_τ

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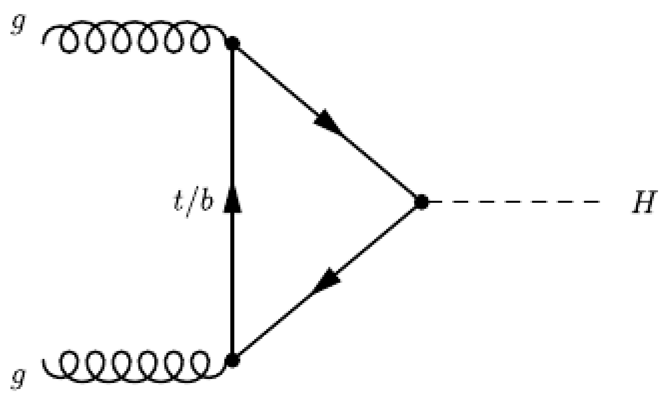

$$\sigma(gg \to H) \propto \kappa_g^2 \simeq 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t\kappa_b$$

A Coherent Framework For Couplings Determinations

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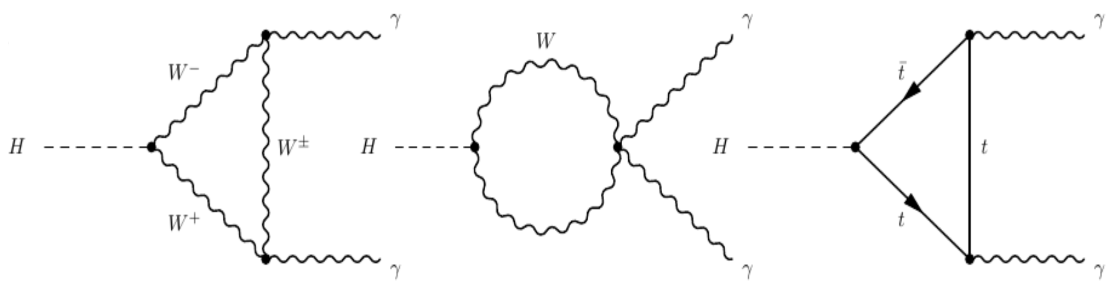

$$\Gamma(H \to \gamma\gamma) \propto \kappa_\gamma^2 \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

A Coherent Framework For Couplings Determinations

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Using scale parameter κ's (κ=1 SM) to parametrize the deviations from SM
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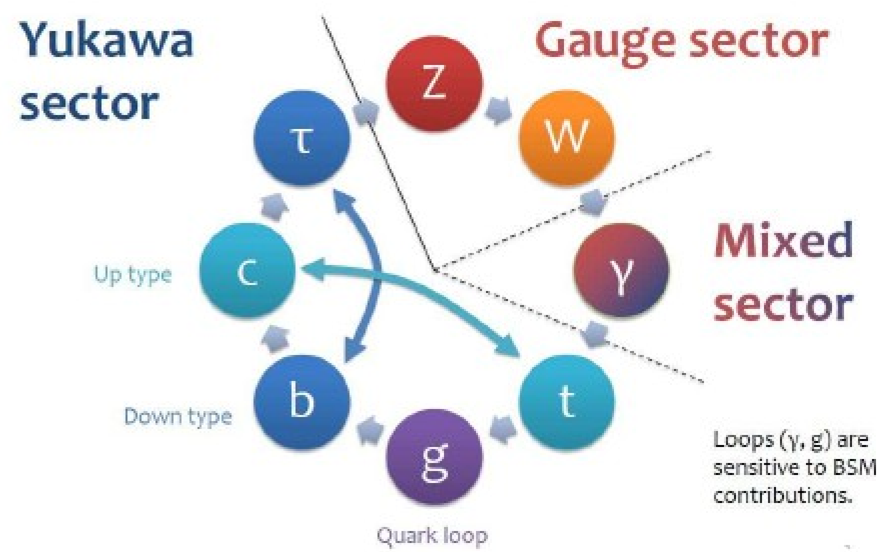
$$\kappa_i = g_i / g_{SM}$$

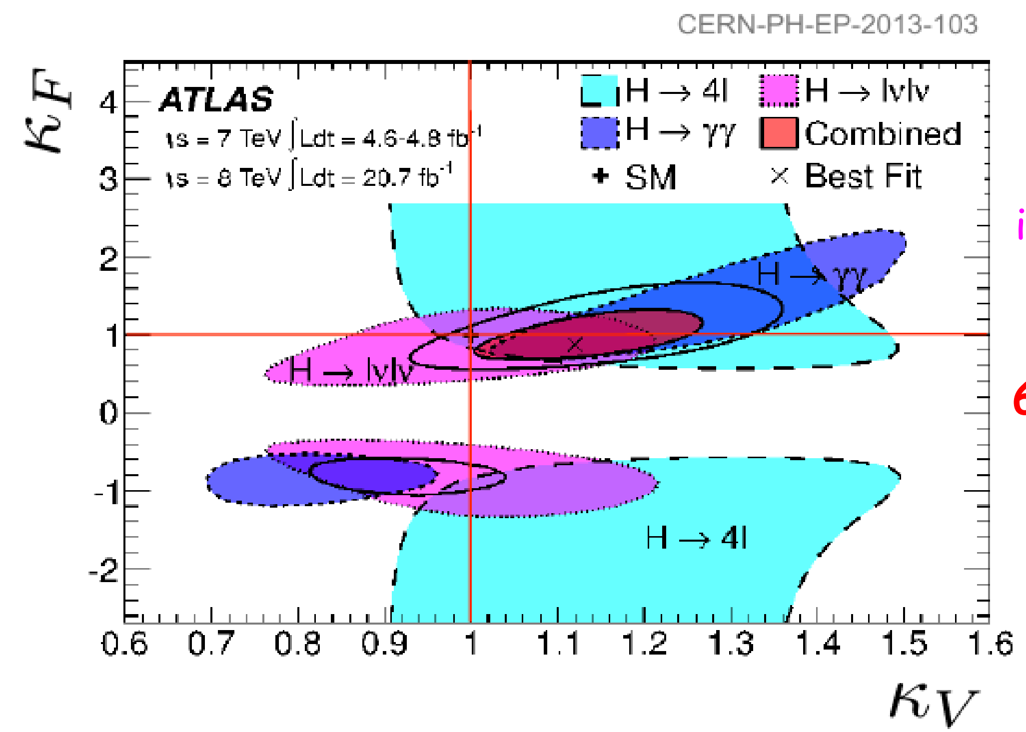
$$\sigma \cdot \mathcal{BR}(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathcal{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Gauge vs. Yukawa Sector

Test fundamental difference between
couplings to fermions and vector bosons



Assume same scale k_F for all fermions and
same scale k_V for all bosons.
Tree level couplings for k_g and k_γ

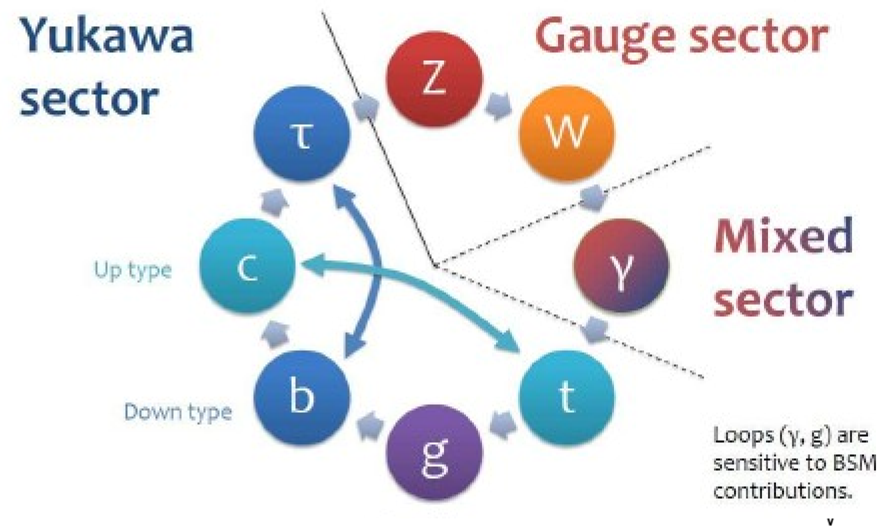


Sensitive to relative sign of k_F and k_V from interference between W-loop and t-loop in $H \rightarrow \gamma\gamma$

68% CL Interval: $k_F \in [0.76,\ 1.18]$
$K_V \in [1.05,\ 1.22]$

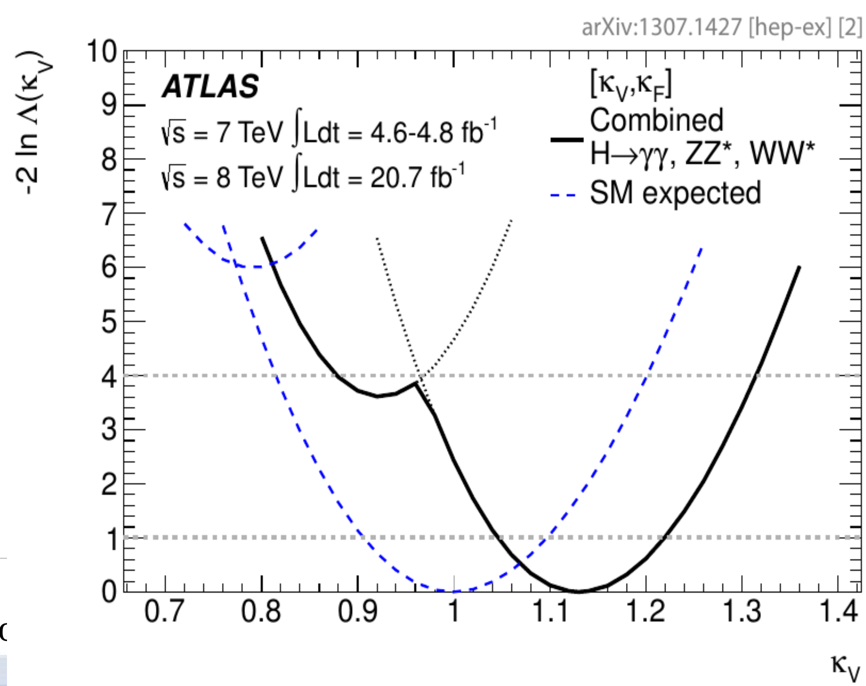
Gauge vs. Yukawa Sector

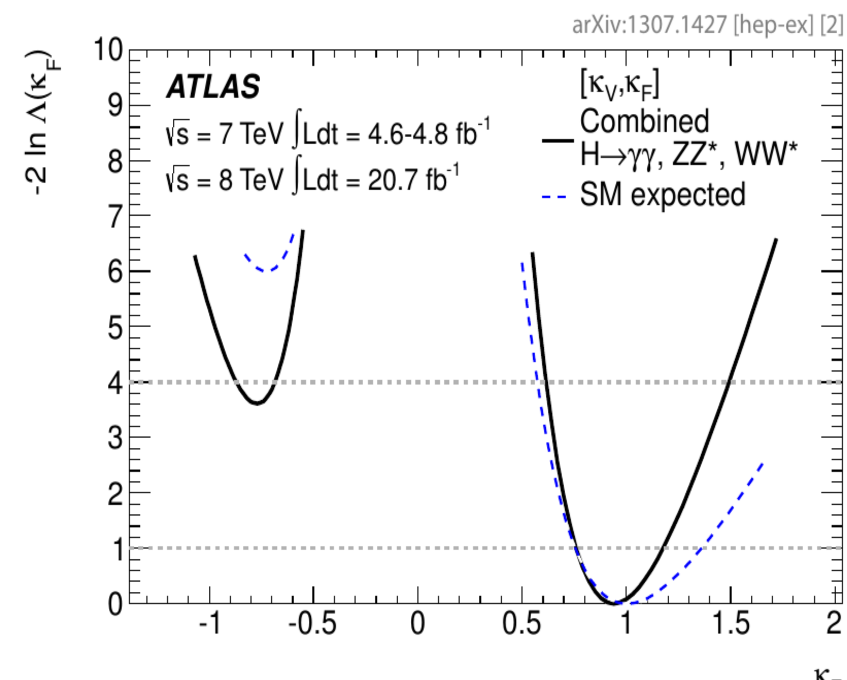
Test fundamental difference between couplings to fermions and vector bosons



Assume same scale k_F for all fermions and same scale k_V for all bosons.

Tree level couplings for k_g and k_γ





Gauge vs. Yukawa Sector

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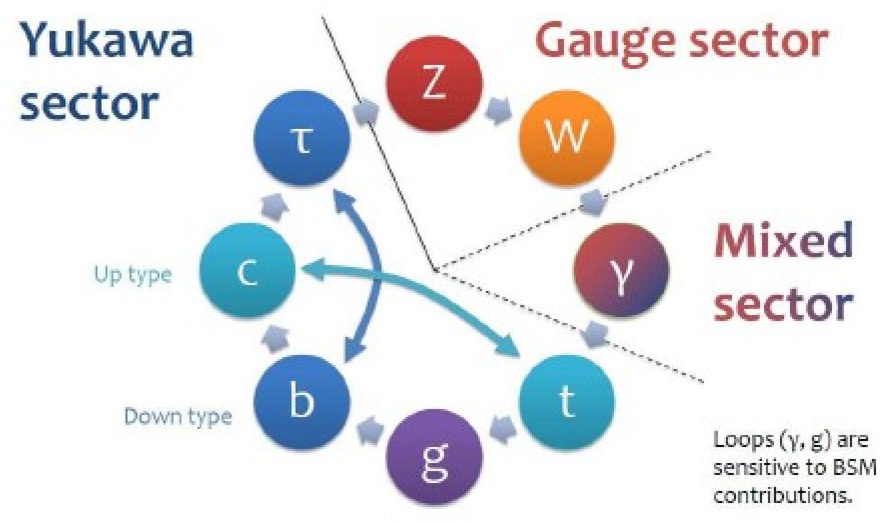

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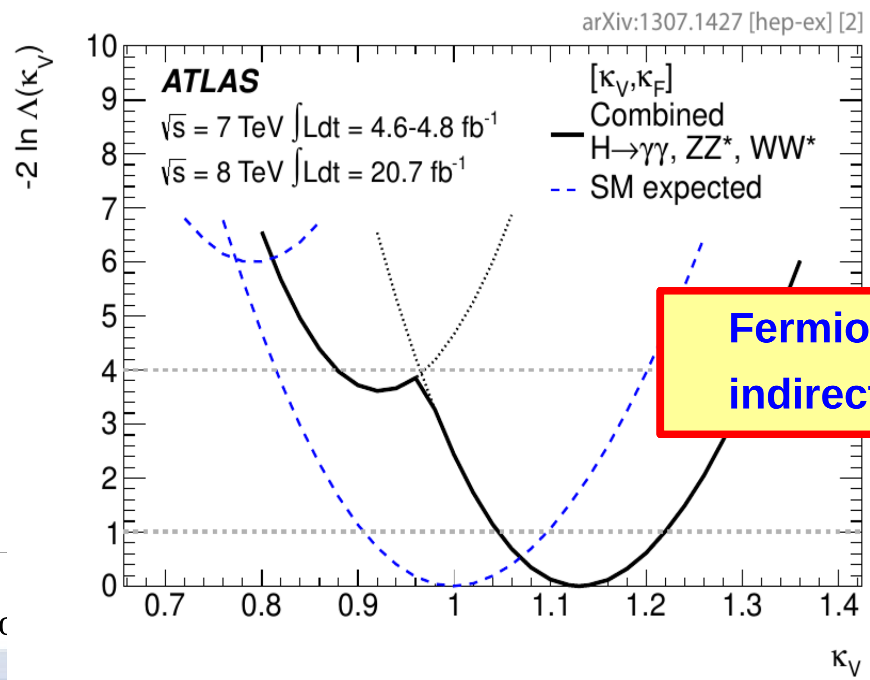
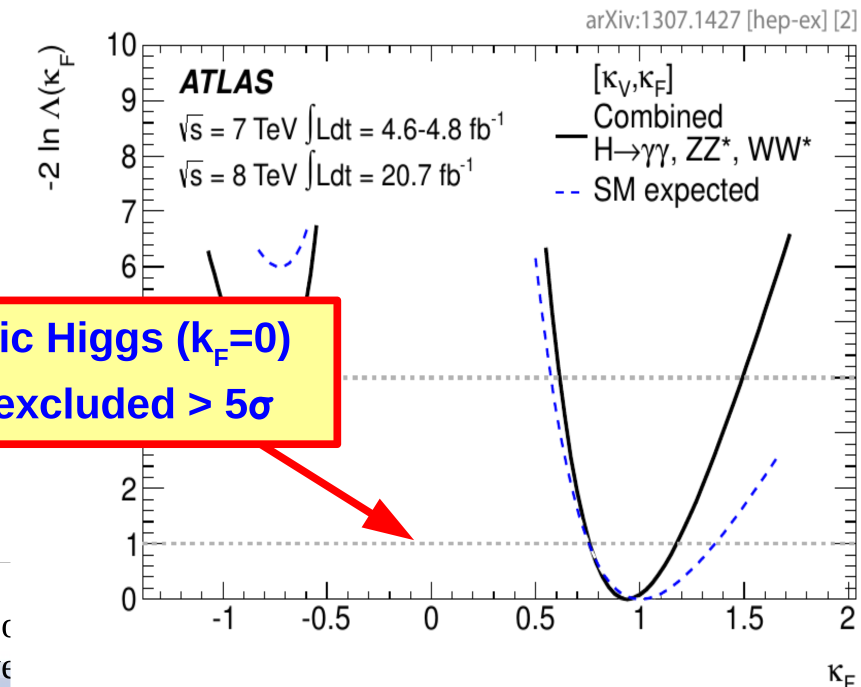
Tree level couplings for k_g and k_γ



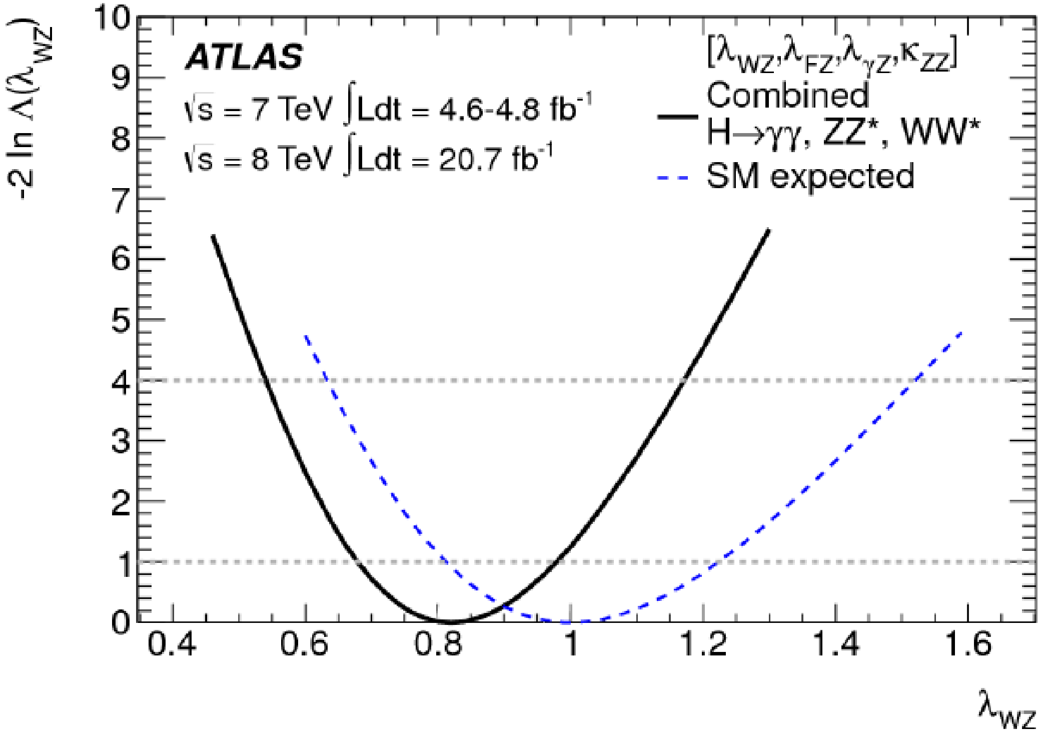


Fermiofobic Higgs (k_F=0) indirectly excluded > 5σ

Custodial, weak-isospin symmetries, etc...

Ratio of parameters λ $\lambda_{FV} = \frac{\kappa_F}{\kappa_V}, \quad \kappa_{VV} = \frac{\kappa_V^2}{\kappa_H^2}$, etc....

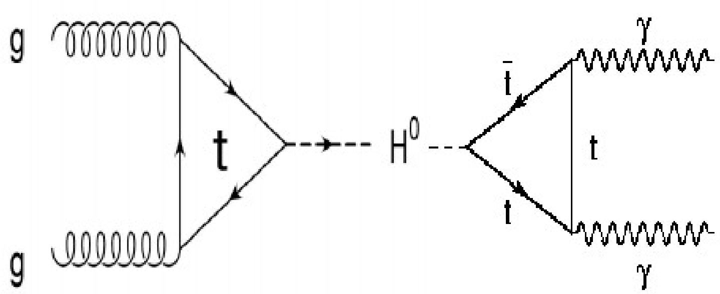
→ Custodial symmetry: $k_W = k_Z$?

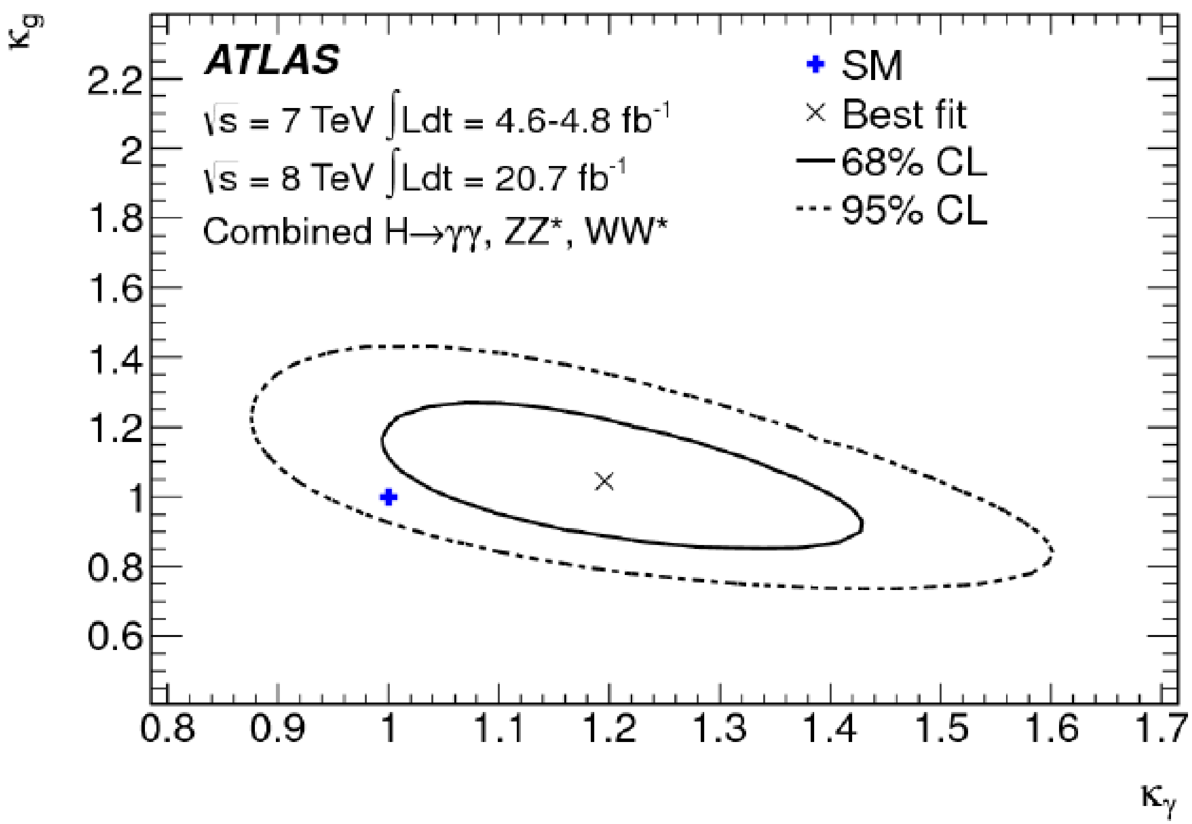


Custodial, weak-isospin symmetries, etc...

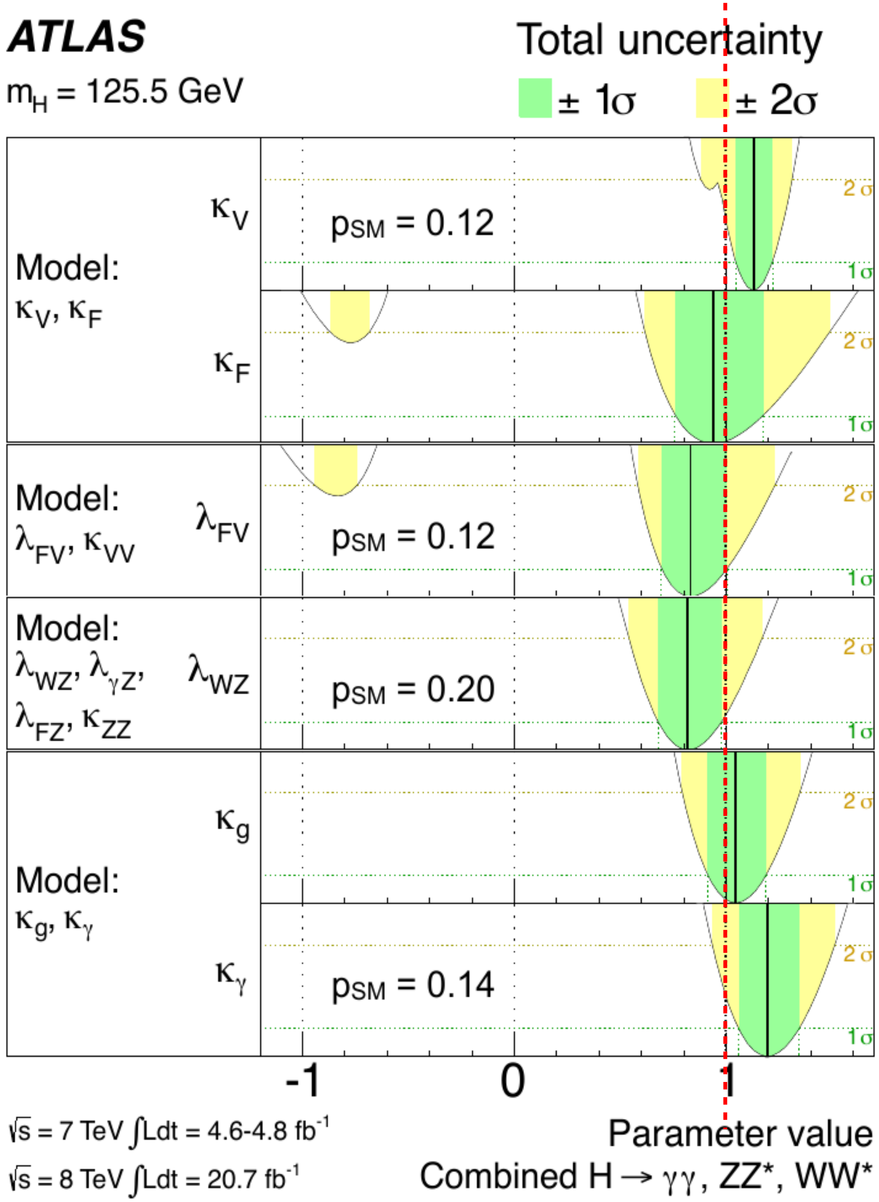
Ratio of parameters λ $\lambda_{FV} = \frac{\kappa_F}{\kappa_V}, \quad \kappa_{VV} = \frac{\kappa_V^2}{\kappa_H^2}$, etc....

→ Probing vertex loop k_g and k_γ
(for BSM contributions)





Properties Summary



Couplings parameters are determined at ~10% level

The bottom line is that with current data the consistency of the Higgs sector with the SM expectation is at 10% level

Higgs potential – Higgs Self Coupling remains as an important experimental probe to be explored in HL-LHC

What's Next?

LHC Program Timeline

LS = Long Shutdown

Integrated Luminosity

			Integrated Luminosity
2009		LHC start up, $\sqrt{s}$ = 900 GeV	
2010	RUN 1		
2011		$\sqrt{s}$ = 7-8 TeV , L = 6 to 8·10^{33} $cm^{-2}s^{-1}$, bunch spacing **50 ns**	
2012			~25 fb^{-1}
2013	LS1	Go to [We are here] ergy, nominal luminosity	
2014			
2015		$\sqrt{s}$ = 13-14 TeV, L = 1•10^{34} $cm^{-2}s^{-1}$, bunch spacing **25 ns**	
2016		**(likely to be more)**	
2017			~50 fb^{-1}
2018	LS2	Injector & LHC Phase I upgrade to full design luminosity	
2019			
2020		$\sqrt{s}$ = 14 TeV, L = 2•10^{34} $cm^{-2}s^{-1}$, bunch spacing **25 ns**	
2021		**(likely to be more)**	~300 fb^{-1}
2022	LS3	HL-LHC Phase-2 upgrade, crab cavities?, IR	
2023		$\sqrt{s}$ = 14 TeV, L = 5•10^{34} $cm^{-2}s^{-1}$, bunch spacing **25 ns**	~3000 fb^{-1}
2030?		**Plan for 50% more**	

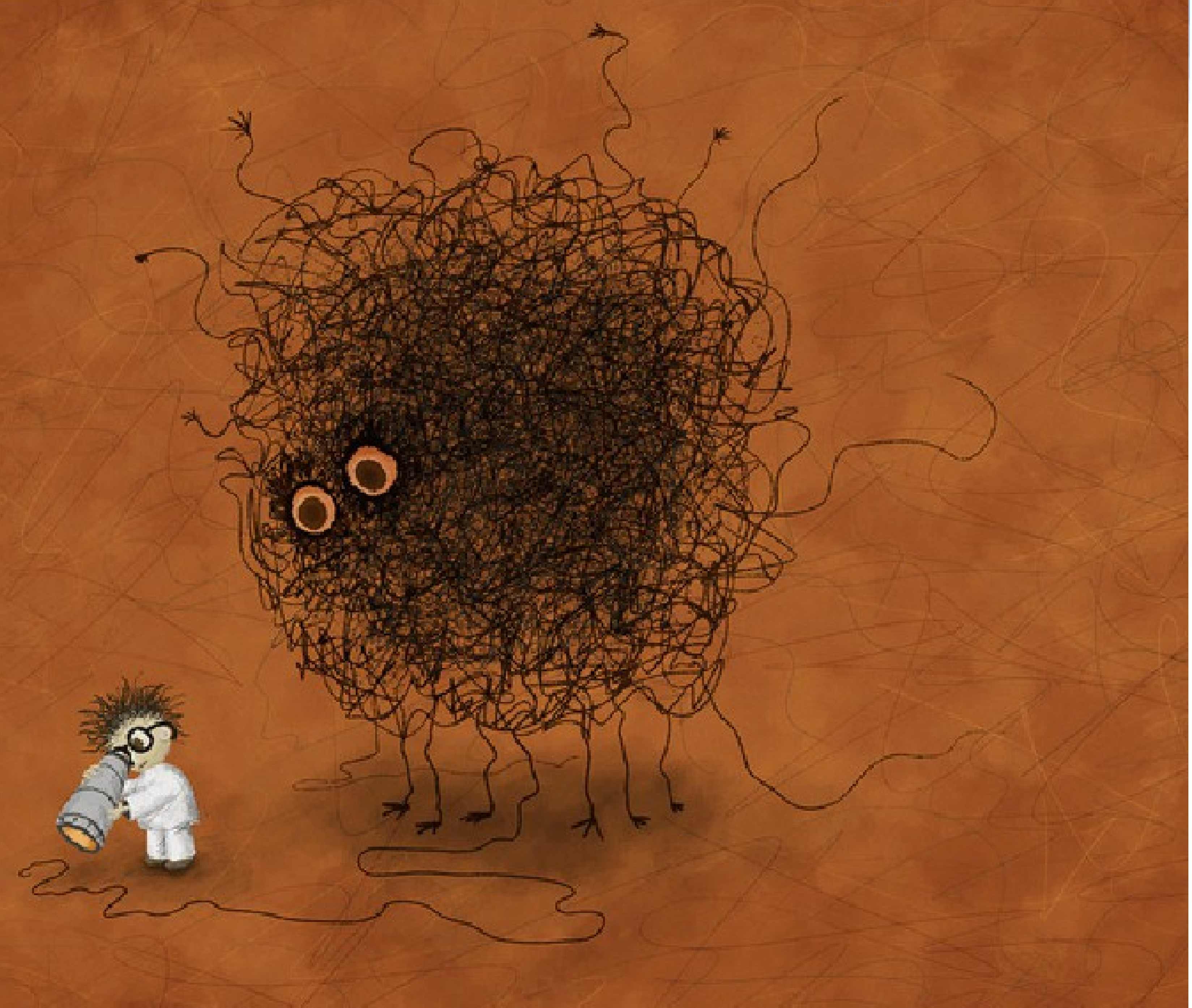
Conclusions

- The analysis of the full Run I data confirmed that the new discovered particle is the first spin-0 elementary particle ever observed, with properties compatible with the ones of the Standard Model Higgs (within current sensitivity)
- The Higgs sector exploration opened by this new discovery provides unprecedented ways to test the predictions of the Standard Model, and maybe will disclose the path to new physics
- Direct measurements of the new boson properties provide also stringent constraints on theories beyond the standard model (i.e. supersimmetry, Technicolor, etc..) helping excluding those that do not describe a world with a scalar boson with M~125 GeV: our world.
- The experimental exploration of the Higgs Sector has and will have also consequences on our understanding of the universe, i.e. meta-stability, etc...
- This is probably one of the best time in recent history to be an experimentalist in our field, with the challenge to keep the experiments up with the expectations of more and more precise measurements in the Higgs sector

We are entering the precision measurement era for the Higgs sector

But keep looking for BSM, never know what Nature can reserve us....

Standard Model Higgs... or New Physics?



(taken from Alexey Drozdetskiy's talk at HCP2012)

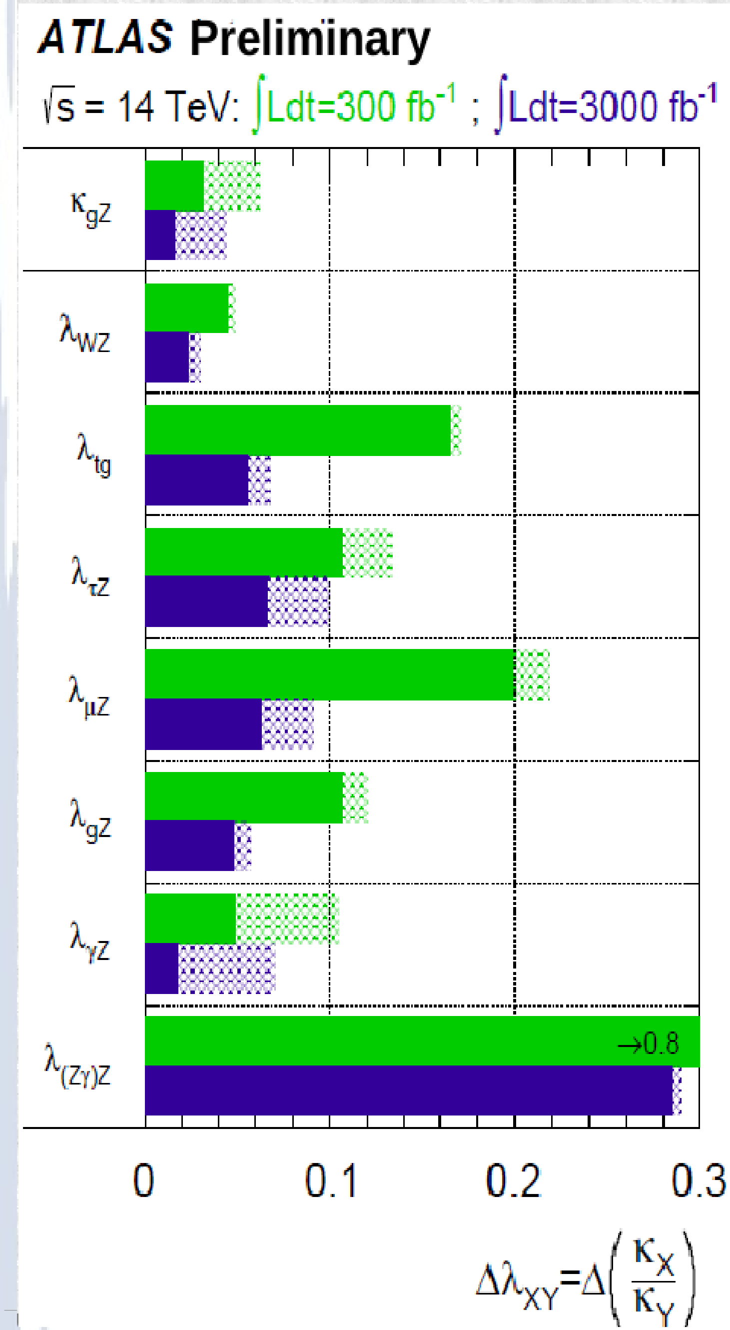
“New directions in science are launched by new tools much more often than by new concepts.

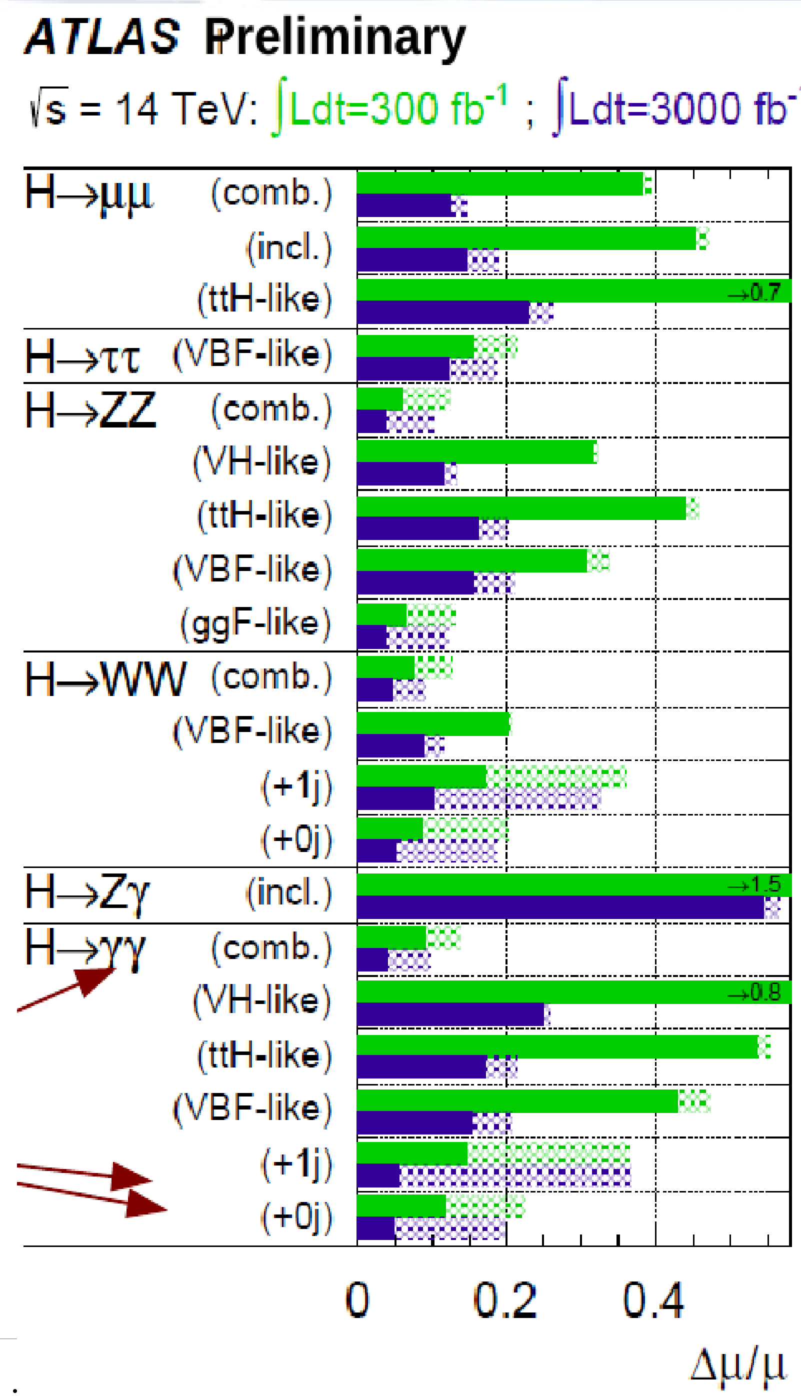
The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained”

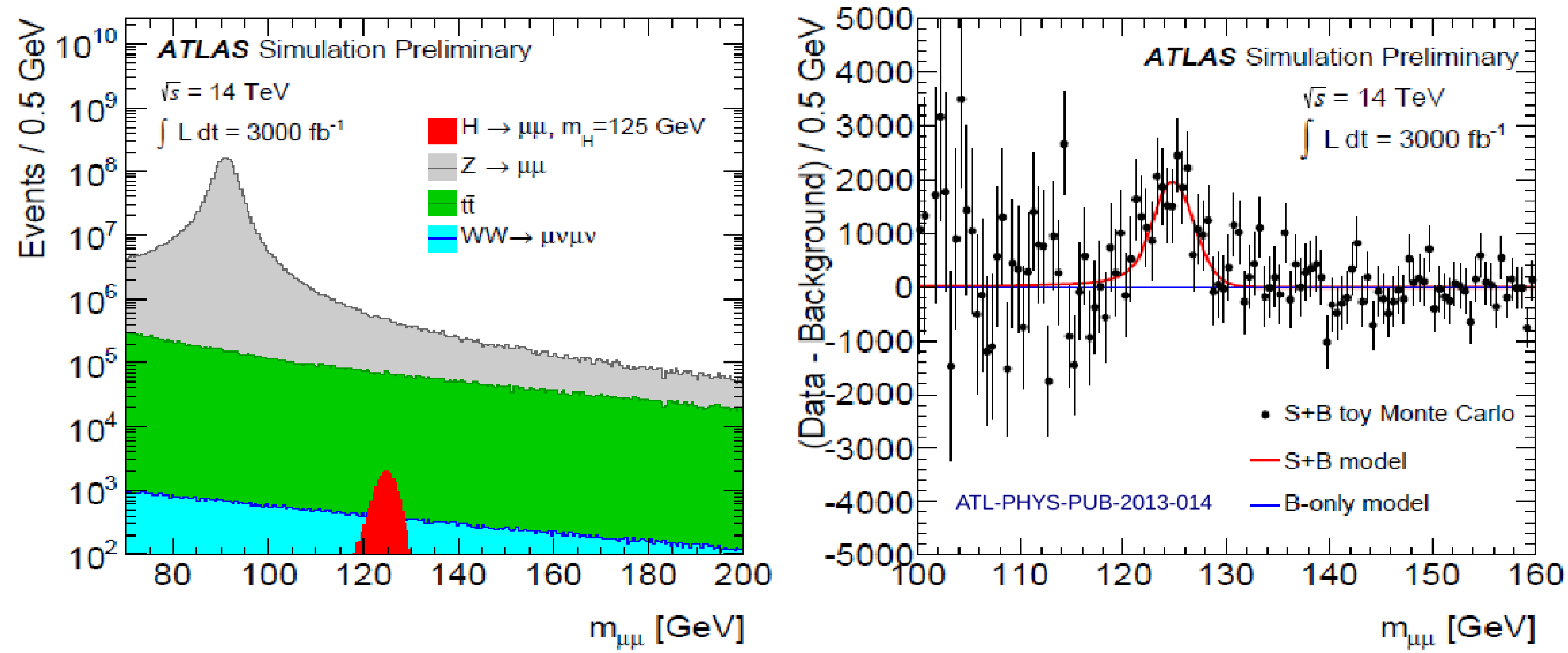
Freeman Dyson

Backup

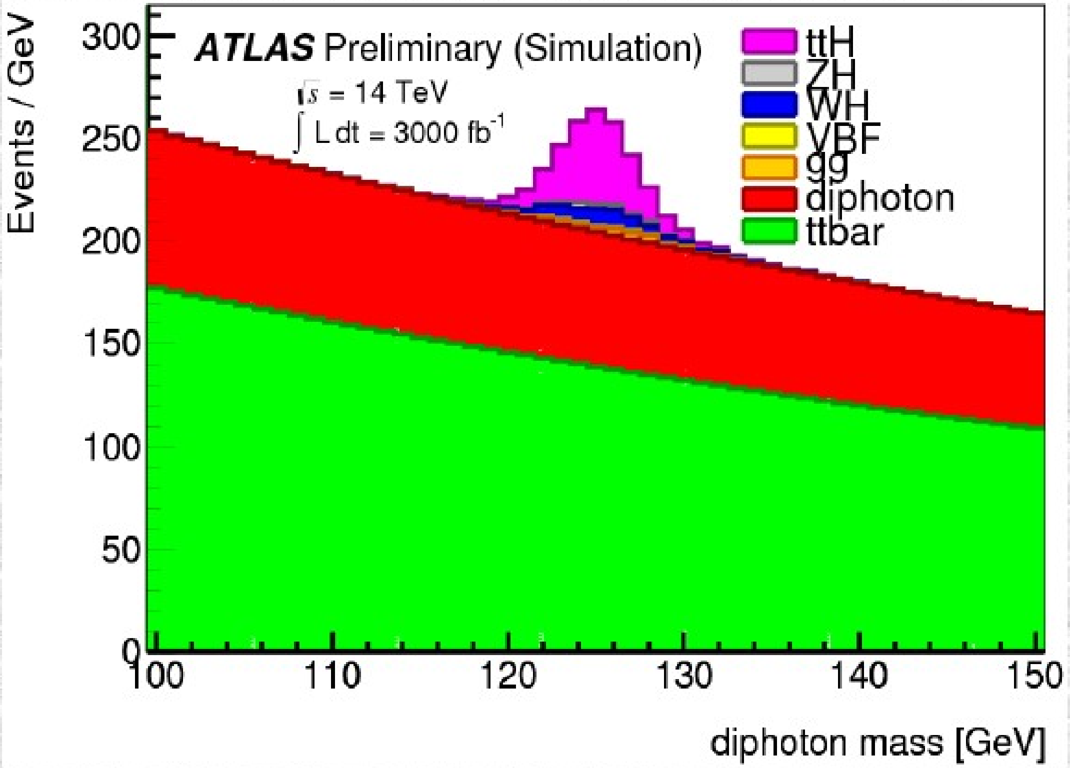

ATLAS Preliminary
√s = 14 TeV: ∫Ldt=300 fb-1 ; ∫Ldt=3000 fb-1
κgZ
λWZ
λtg
λτZ
λμZ
λgZ
λγZ
λ(Zγ)Z
→0.8
0
0.1
0.2
0.3
ΔλXY=Δ(κX/κY)


ATLAS Preliminary
√s = 14 TeV: ∫Ldt=300 fb-1 ; ∫Ldt=3000 fb-1
H→μμ (comb.)
(incl.)
(ttH-like)
→0.7
H→ττ (VBF-like)
H→ZZ (comb.)
(VH-like)
(ttH-like)
(VBF-like)
(ggF-like)
H→WW (comb.)
(VBF-like)
(+1j)
(+0j)
H→Zγ (incl.)
→1.5
H→γγ (comb.)
(VH-like)
→0.8
(ttH-like)
(VBF-like)
(+1j)
(+0j)
0
0.2
0.4
Δμ/μ

$3000 fb^{-1}$ at 14TeV offers new possibilities



3000fb^{-1} at 14TeV offers new possibilities



ATL-PHYS-PUB-2013-007