Searches for production of **two** Higgs bosons using the CMS detector

a.k.a 'More Higgses, more fun'

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on behalf of the CMS collaboration

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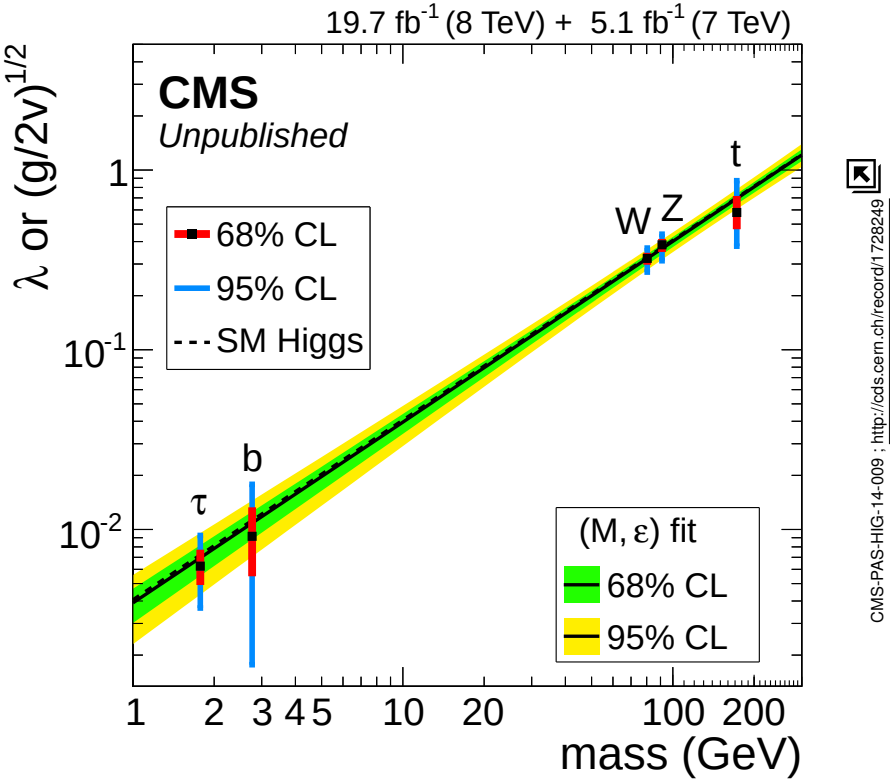
Why bother: we have found *a* Higgs boson

- Observed by ATLAS & CMS in July 2012, **VERY** SM-like:
  - Mass in the expected range
  - Couplings match SM predictions, spin-parity favors 0^+
- **It is a Higgs boson**, SM looks complete, so **what now?**

Moving forward: Higgses in the final state

- **Non-minimal Higgs sector**: 2HDM (e.g. MSSM)
- **Connection between the new boson and BSM physics** (e.g. WED)
- Handle on the last predicted couplings: HHH, WWHH



Extended Higgs sector (I): Two Higgs Doublet Model

Two Higgs Doublet Model (2HDM)

- Simplest extension compatible with gauge invariance of the minimal Higgs sector
- 5 physical Higgs bosons:
  - 2 neutral CP-even scalars h and H
  - one neutral CP-odd pseudo-scalar A
  - 2 charged scalars $H^{\pm}$

HIG-13-025: Search for $H \to hh$ and $A \to Zh$

- **Generic search with $h(125)$**: leptons and photons in the final state
- H in the range $[260, 360]$ GeV

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to bb$	$h \to \gamma\gamma$
$h \to WW^*$	☑	☑	☑	☐	☑
$h \to ZZ^*$	-	☑	☑	☑	☑
$h \to \tau\tau$	-	-	☑	☐	☑
$h \to bb$	-	-	-	☐	☐
$h \to \gamma\gamma$	-	-	-	-	☐

Extended Higgs sector (II): search strategy

- **Cut and count search** based on dilepton and diphoton triggers
- Classification by N_l / OSSF pairs / off-on Z, N_τ, N_b, $\not{E}_T$
- **Very diverse background composition**

Leptons	Photons	OSSF pairs	Hadronic τ	b-tag
4	0	0, 1 or 2	0 or 1	0 or 1
3	0	0 or 1	0 or 1	0 or 1
2	2	0 or 1	0	-
1	2	-	0	-
1	2	-	1	-
0	2	-	1 or 2	-

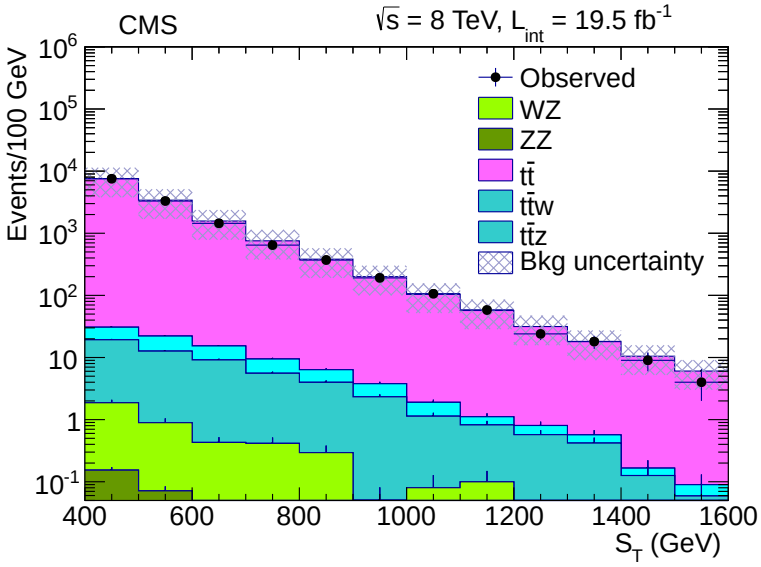
hh final state	Search channels
WW^*WW^* $WW^*\tau\tau$ $\tau\tau\tau\tau$ $ZZ^*\tau\tau$ ZZ^*bb	$3-4$ leptons ($\leq 1\tau_h$), OSSF pair off-Z or no OSSF pair in bins of $\not{E}_T$ and b-tag
$\gamma\gamma WW^*$ $\gamma\gamma ZZ^*$ $\gamma\gamma\tau\tau$	2γ ($M_{\gamma\gamma}$ within higgs bin) + $\geq$ 1 leptons($\leq 2\ \tau_h$),in bins of $\not{E}_T$

- Sensitivity comes mostly from decays of h to W bosons and taus:
  - Channels without OSSF pair (reduces DY)
  - Channels with OSSF pair but the invariant mass of the pair is off-Z
  - Channels with SS pairs (very low SM bkg)

Extended Higgs sector (III): background estimation

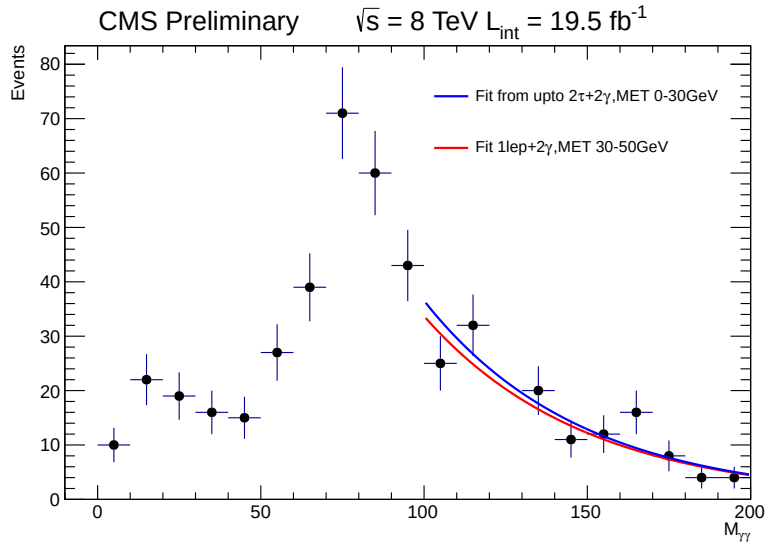
Multileptons final states

- Main backgrounds from Z+jets, VV+jets, tt, QCD, ...:
  - Non-prompt 3^{rd} lepton in $Z+$ jets, $WW+$ jets : data control sample
  - $t\bar{t}$, diboson backgounds : (validated) MC simulation
  - Asymmetric γ conversions : data control sample



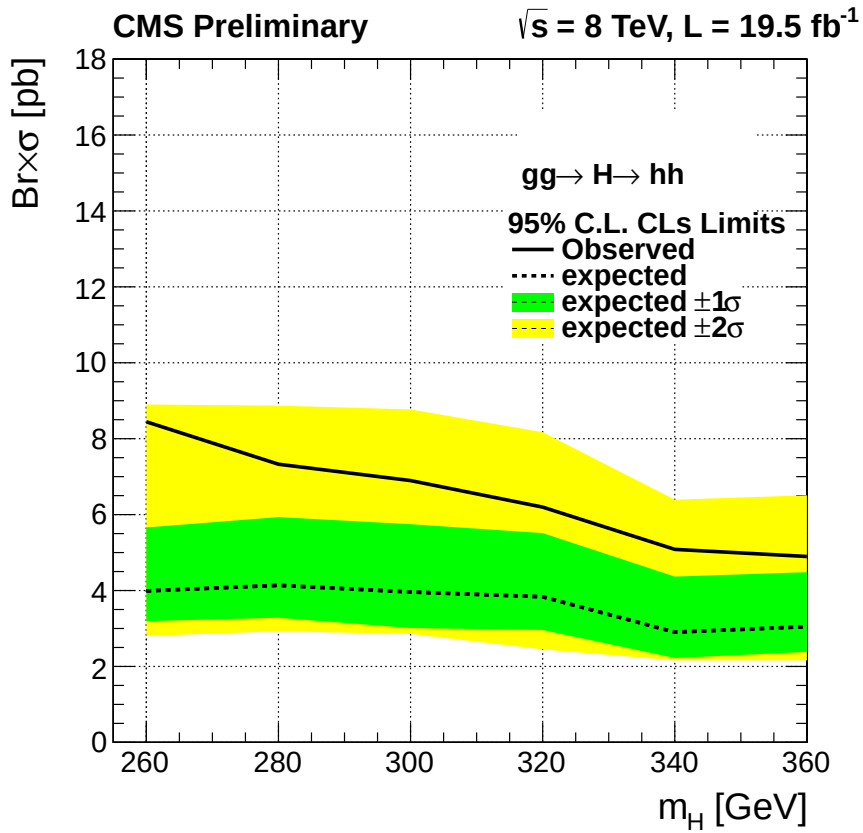
Diphoton final states

- Background evaluated in $m_{\gamma\gamma}$ sidebands ($\notin [120, 130]$ GeV) in $1 - 2\tau_h$, 2γ and $\not{E}_T < 30$ GeV



Extended Higgs sector (IV): model-independent limits

- Limits combining lepton and photon channels
- Excess in $3(e/\mu) + \tau_h$ off-Z channels with no b-tags:
  - obs. (exp.) [3 $\not{E}_T$ bins]
    - $11(5.1 \pm 1.7)$
    - $4(2.4 \pm 0.5)$
    - $5(2.6 \pm 0.6)$
- p-values:
  - local $= 1.5\ \%$
  - global, sum of $\not{E}_T$ bins: $46\ \%$
  - global, all three $\not{E}_T$ bins: $5\ \%$

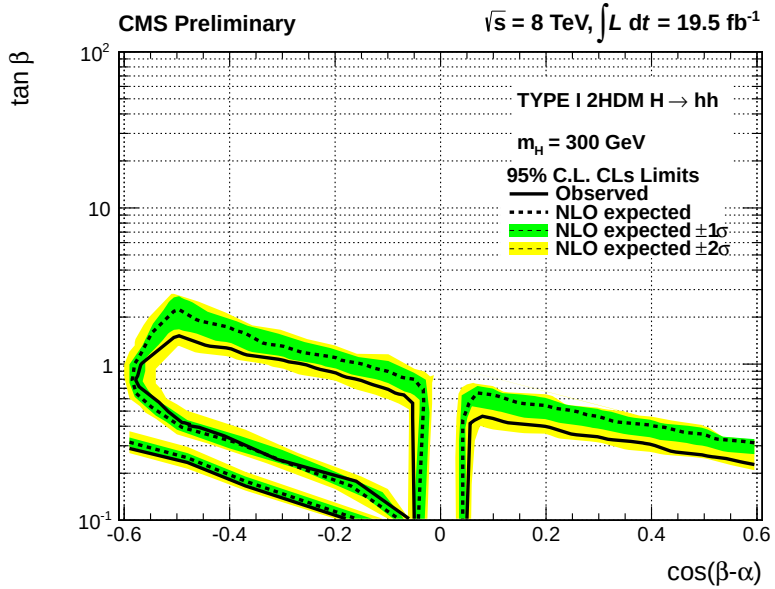


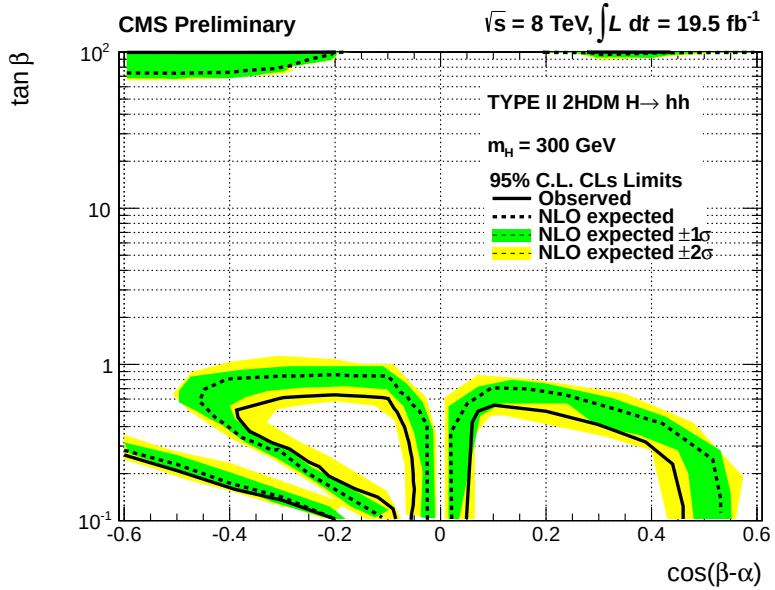
No significant deviation from expectations

Extended Higgs sector (V): limits in 2HDM space

- Recast $\sigma \times BR$ limits in 2HDM Type I and Type II parameter space:
  - α (mixing $H - h$)
  - β (relative contribution of each doublet to EWSB)

1	2HDM I	2HDM II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\ \alpha/\sin\ \beta$	$\cos\ \alpha/\sin\ \beta$
hQd	$\cos\ \alpha/\sin\ \beta$	$-\sin\ \alpha/\cos\ \beta$
hLe	$\cos\ \alpha \sin\ \beta$	$\sin\ \alpha \cos\ \beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\ \alpha \sin\ \beta$	$\sin\ \alpha \sin\ \beta$
HQd	$\sin\ \alpha \sin\ \beta$	$\cos\ \alpha \sin\ \beta$
HLe	$\sin\ \alpha \sin\ \beta$	$\cos\ \alpha \sin\ \beta$
AVV	0	0
AQu	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$

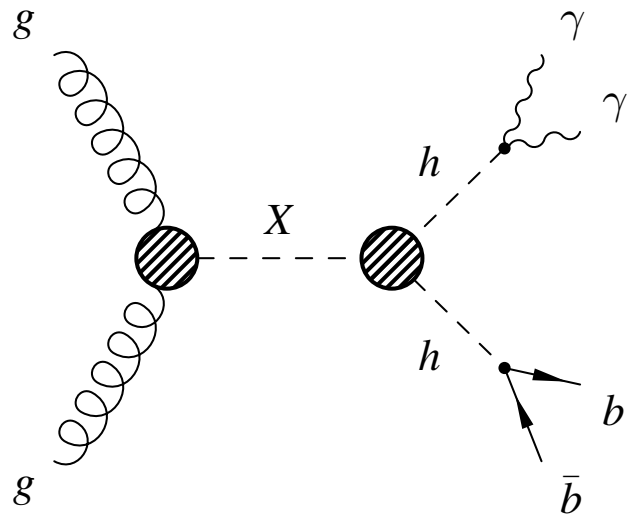




Warped Extra Dimensions (I) : motivation

Benchmark model

- **WED models**: radion and (kk)graviton
  - These radion and graviton couple to h
  - σ depend on the scale Λ_R
  - Radion mass depends on ED stabilization mechanism (= model)
  - Graviton mass depends on the geometry of the ED
- Consider only **non-boosted regime** $m_X \in [270, 1100]$ **GeV**



HIG-13-032: dedicated resonant HH search

- **Gluon-fusion** production of a massive object X
- Object X decaying to a **pair of $h(125)$**
- hh (SM) decay to $b\bar{b}\gamma\gamma$:
  - Low BR ($0.26\,\%$) - clean final state - low bkg - reconstruction of X

Warped Extra Dimensions (II) : object selection

Photons

- $L = 19.7\,\text{fb}^{-1}$, $\sqrt{s_{pp}} = 8\,\text{TeV}$
- **Inspired from $H \to \gamma\gamma$**
  - Diphoton trigger, cut based photon ID, ...
- Standard CMS vertex $\sum p_T^2$

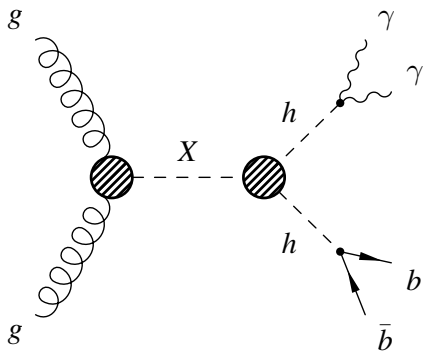
Jets

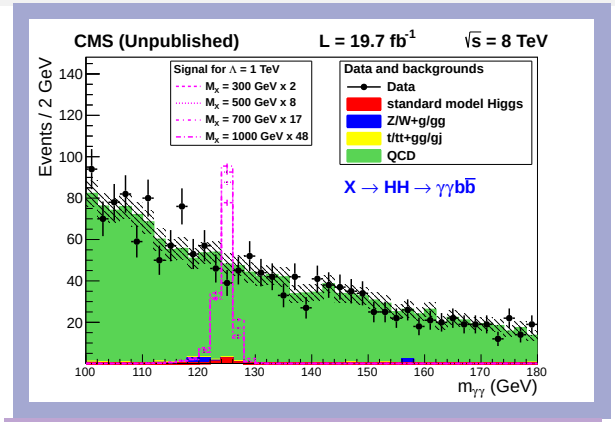
- Loose jet ID, PU rejection
- At least one b-tagged jet (CSV Medium WP, 60-70% efficiency)
- Hbb candidate : prefer b-tagged jets, max(p_T^{jj}) pair

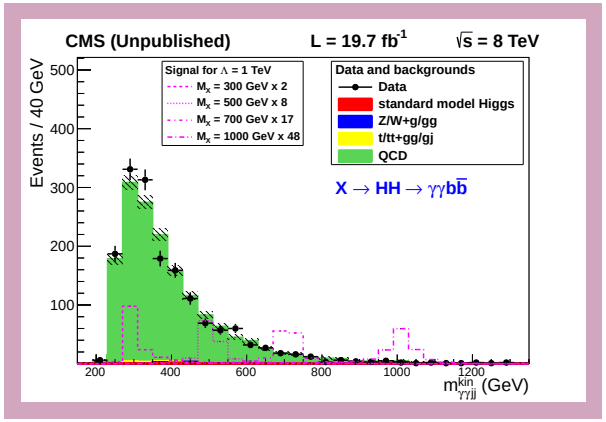
Photons	Jets	Events classification
tight photon identification	loose jet identification	
$p_{T\gamma_1}/M_{\gamma\gamma} > 1/3$	pileup rejection	
$p_{T\gamma_2}/M_{\gamma\gamma} > 1/4$	$p_{Tj} > 25$ GeV	
$\lvert\eta_\gamma\rvert < 2.5$	$\lvert\eta_j\rvert < 2.5$	$\geq$2 b–tagged jets
$100 < M_{\gamma\gamma} < 180$ GeV	at least 1 b–tagged jet	exactly 1 b–tagged jet

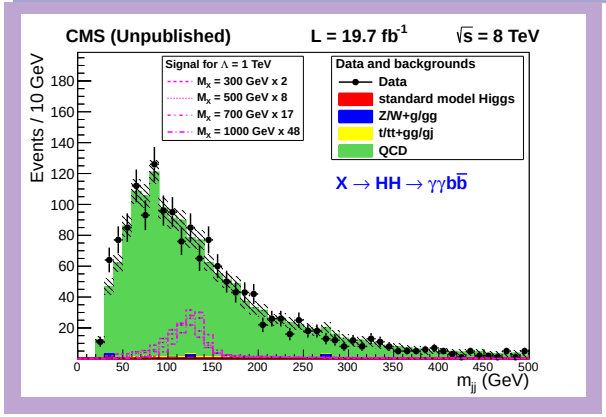
- Dominant background : QCD production of $\gamma\gamma jj$
  - **2 b-tagged jets : high-purity**
  - **1 b-tagged jet: medium purity**

Warped Extra Dimensions (III) : signal extraction









Strategy: three invariant mass handles $m_{\gamma\gamma}$, m_{jj}, $m_{\gamma\gamma\mathrm{jj}}$

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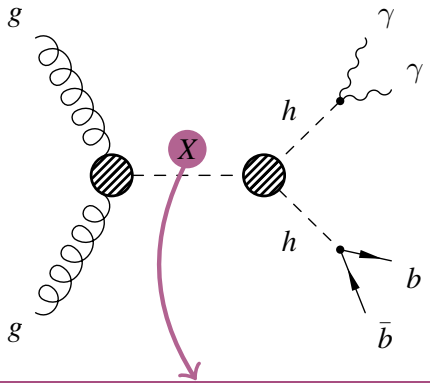

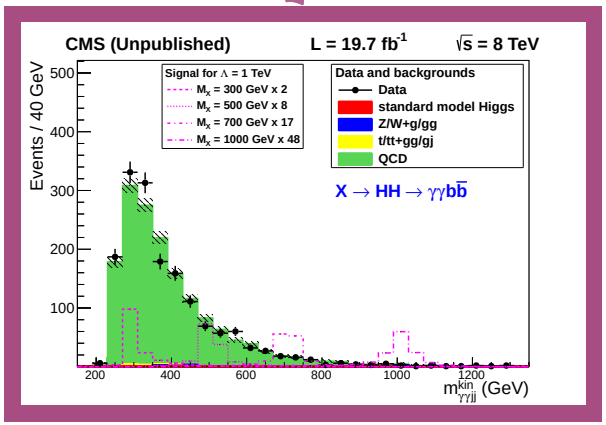

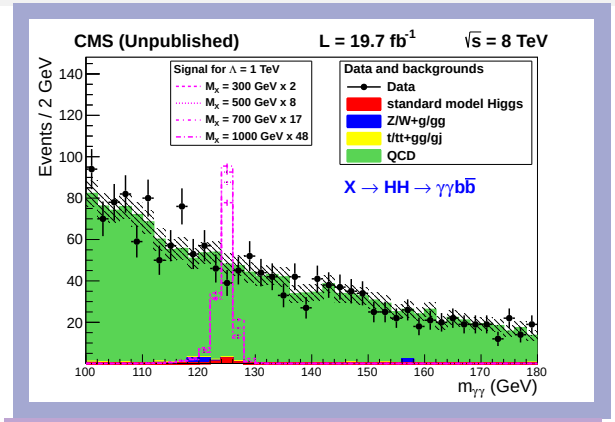

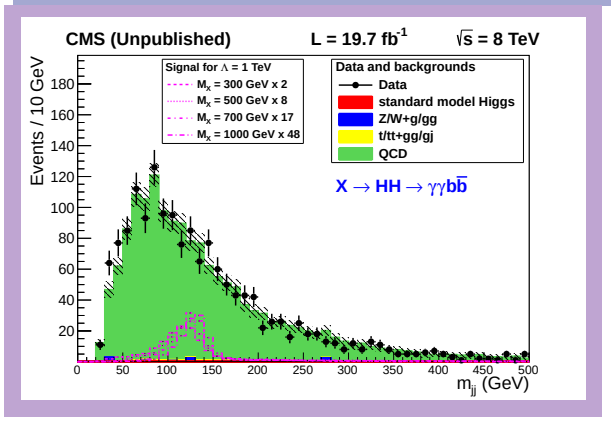

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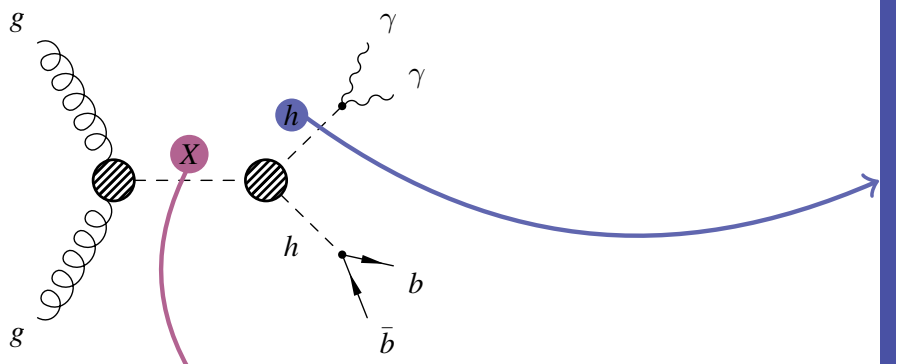

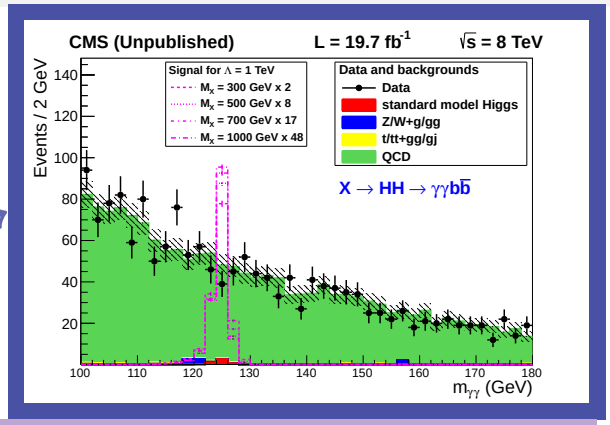

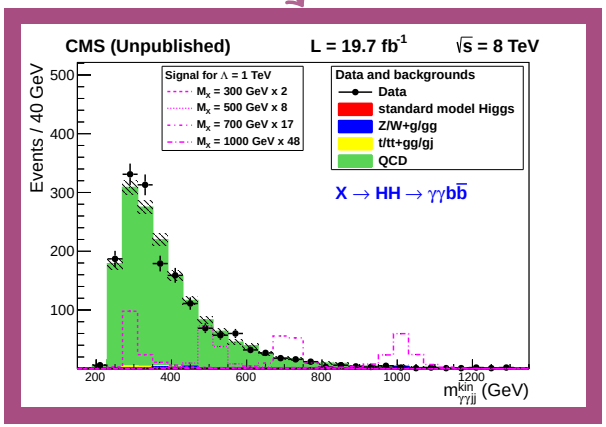

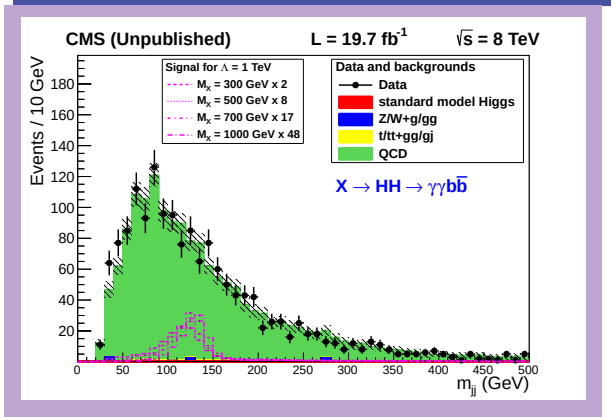

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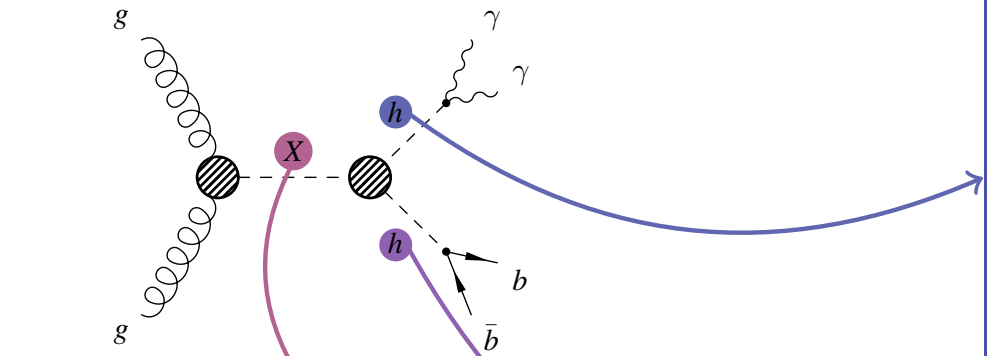

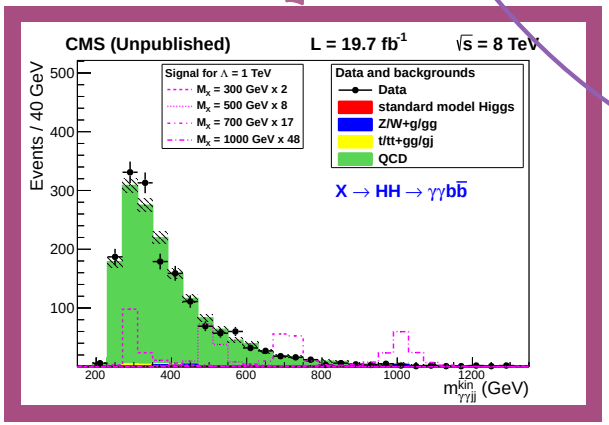

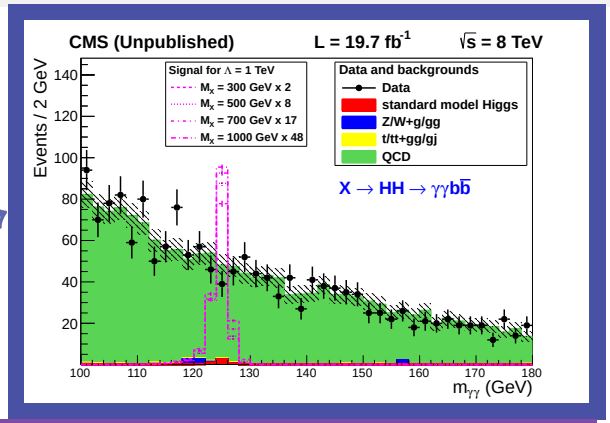

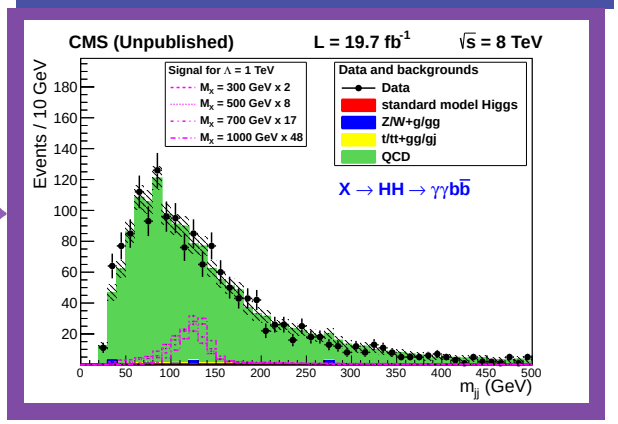

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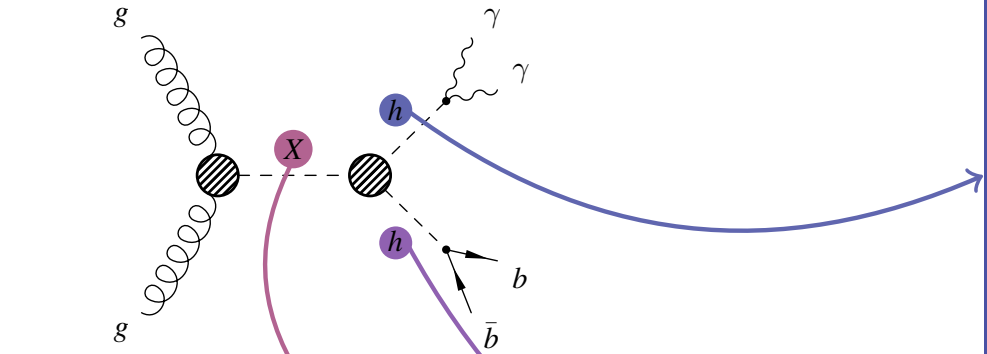

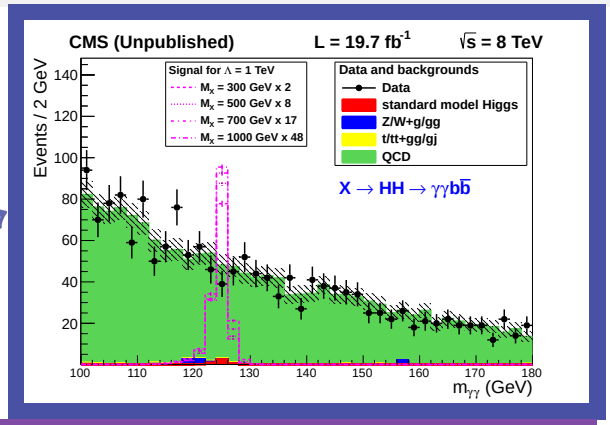

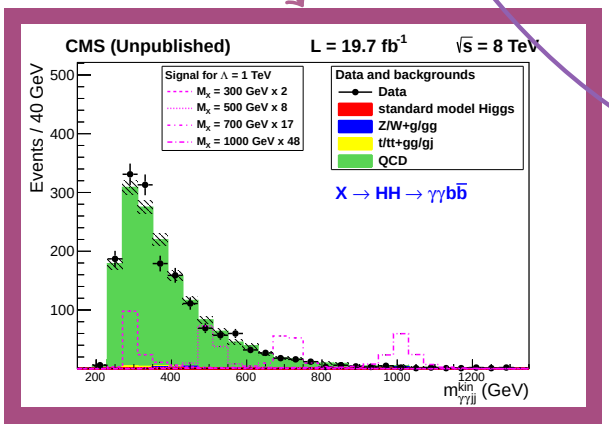

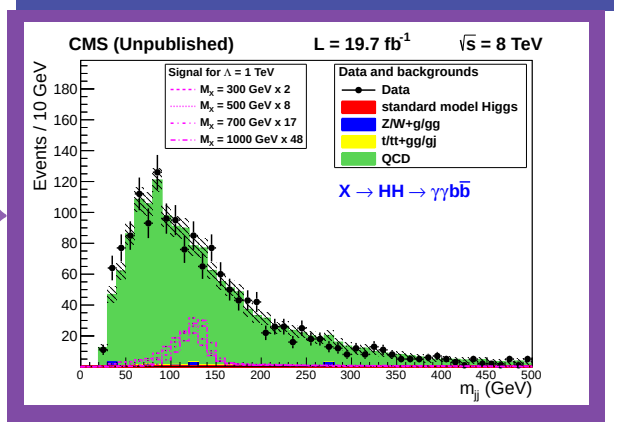

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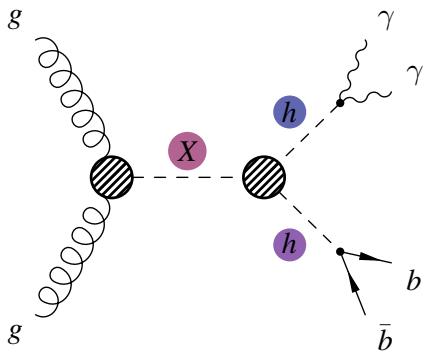
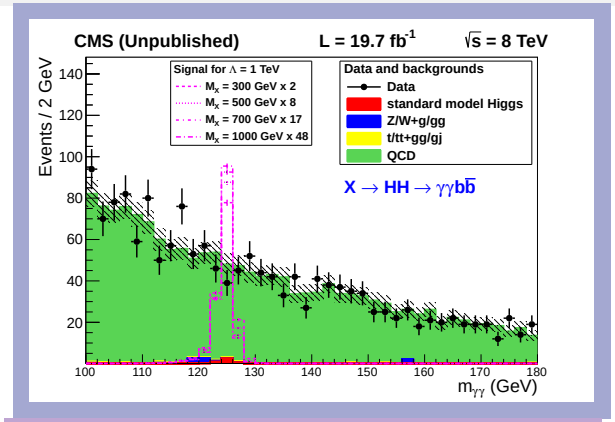
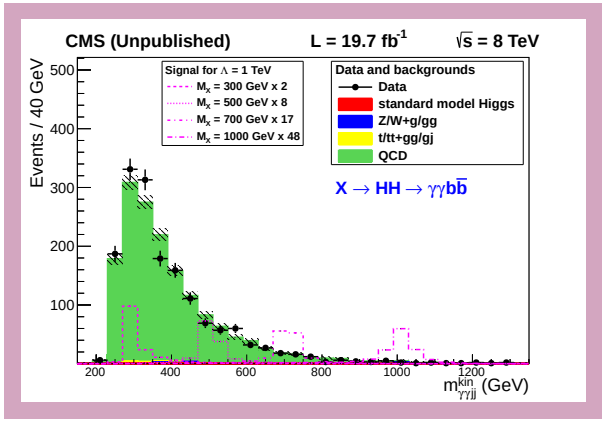
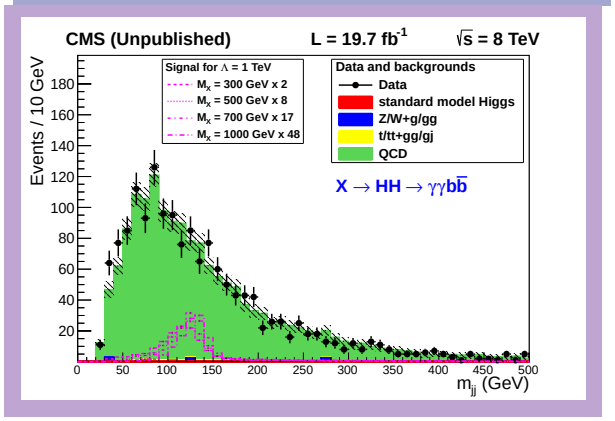
- $m_{\gamma\gamma\mathrm{jj}}$ ideal for limit extraction (direct handle on X)

Warped Extra Dimensions (III) : signal extraction









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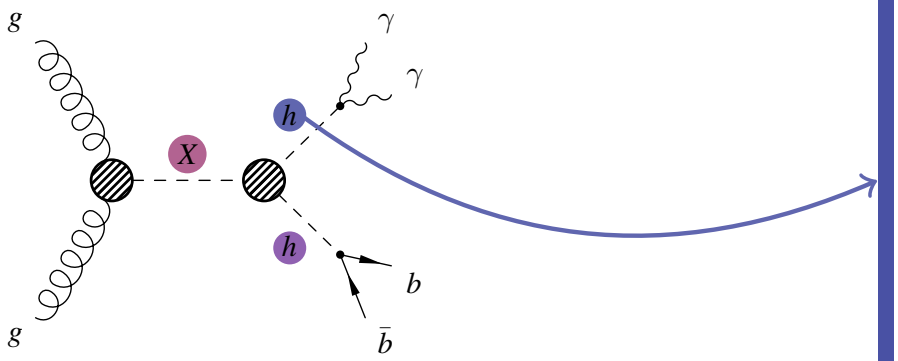
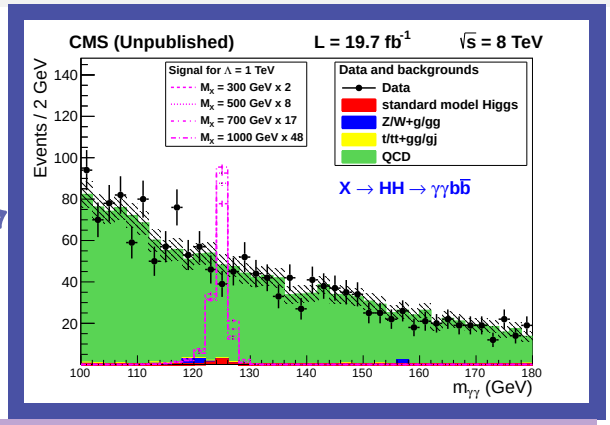
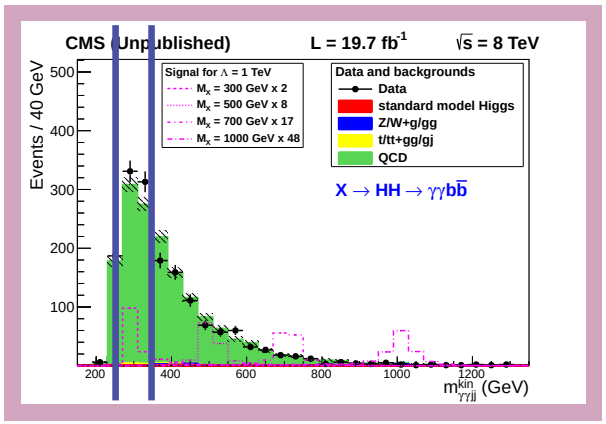
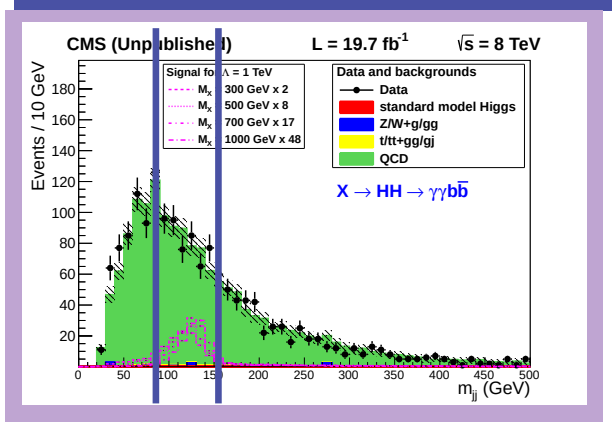
- $m_{\gamma\gamma\mathrm{jj}}$ ~~ideal~~ for limit extraction (direct handle on X) **kin. peak** (≈ 300 GeV)
- Split in **two regimes** for signal extraction:

Warped Extra Dimensions (III) : signal extraction









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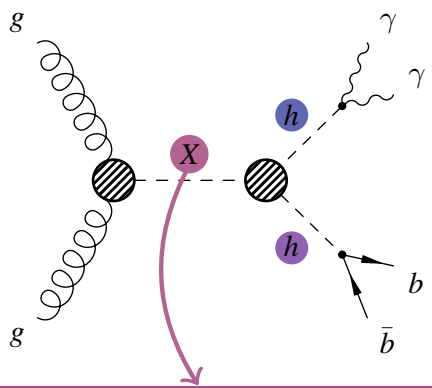

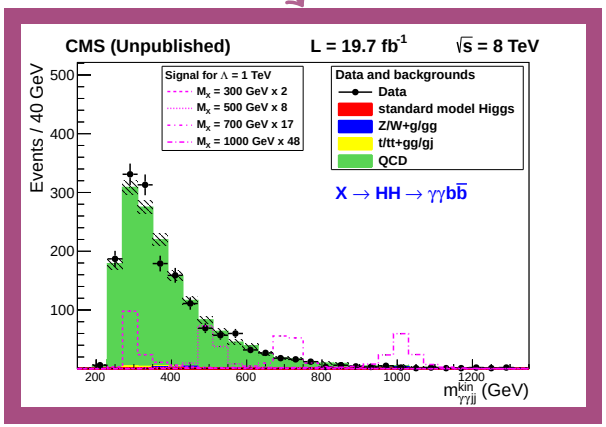

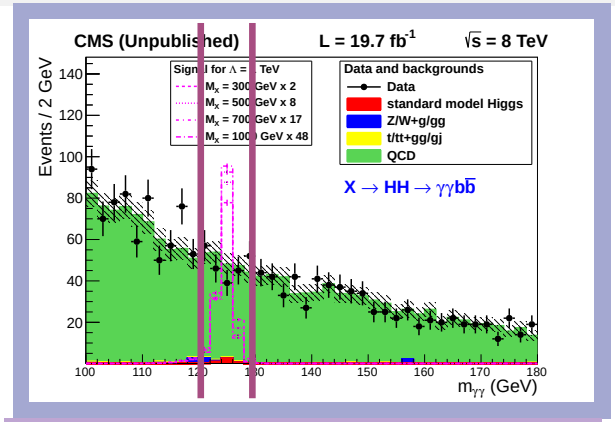

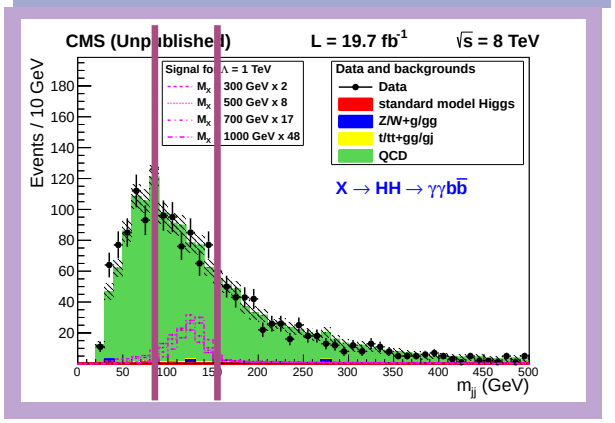

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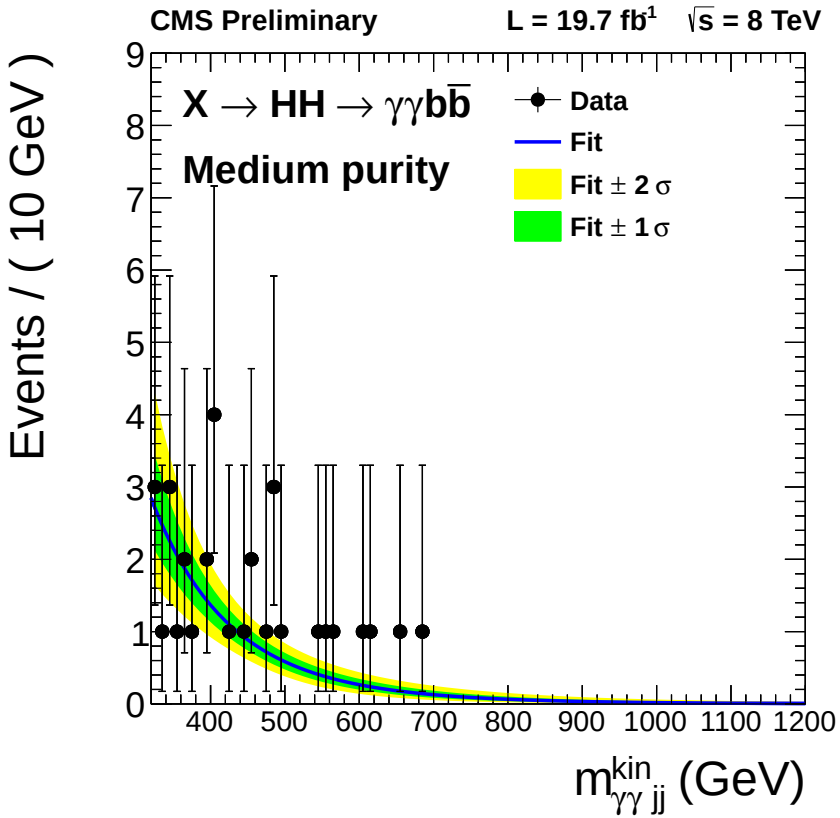
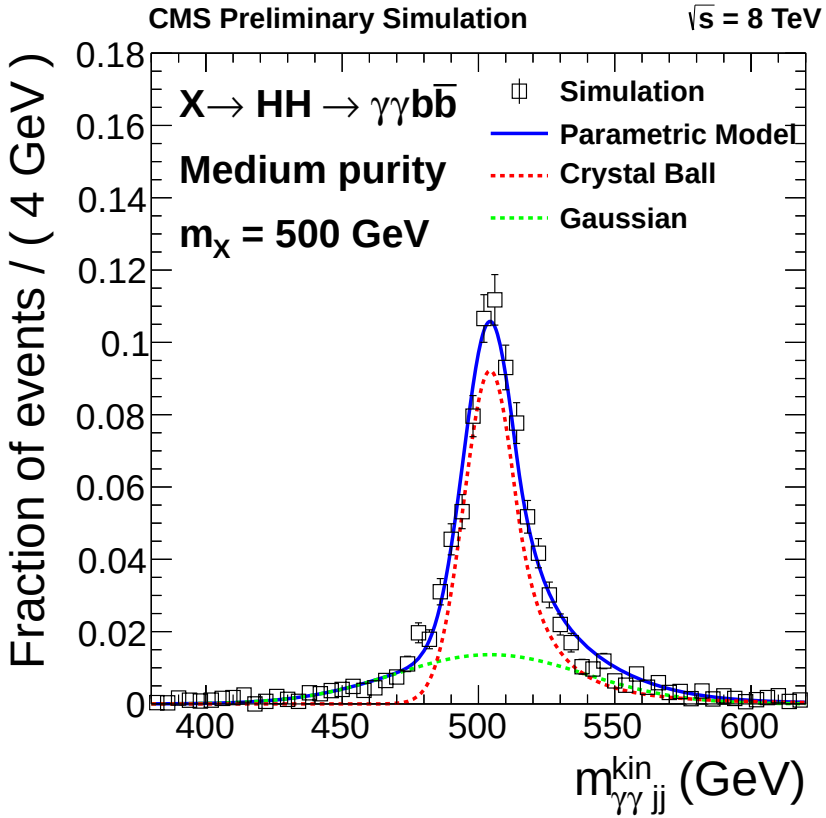
- Split in **two regimes** for signal extraction:
  - **Low mass** ($m_X \leq 400$ GeV): cut $m_{\gamma\gamma\mathrm{jj}}$ and m_{jj}, **fit** $m_{\gamma\gamma}$
  - **High mass** ($m_X \geq 400$ GeV): cut $m_{\gamma\gamma}$ and m_{jj}, **fit** $m^{\mathrm{kin.}}_{\gamma\gamma\mathrm{jj}}$ (after kin. fit)

Warped Extra Dimensions (IV): bkg & signal modeling

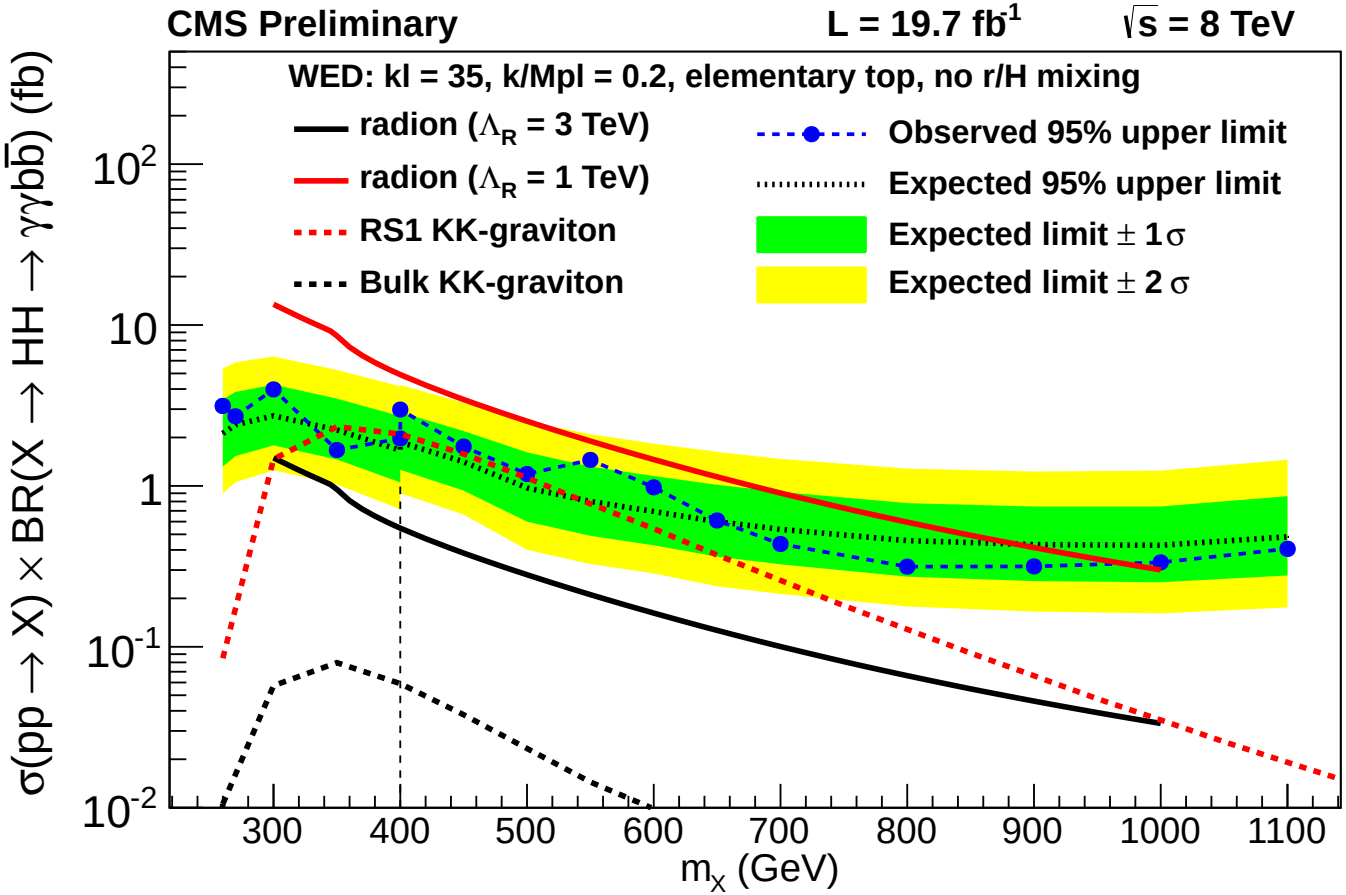




Bias studies

- Function choice for background estimation :
  - **Negligible bias on signal strength** for a variety of 'truth' background functional shapes
  - Power-law for both low and high mass

Warped Extra Dimensions (V): limits

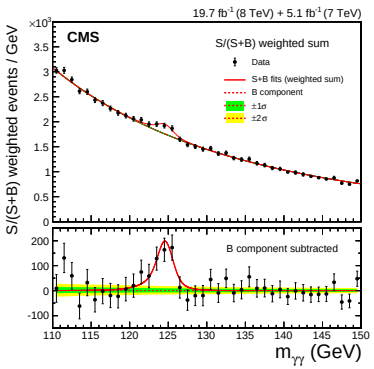


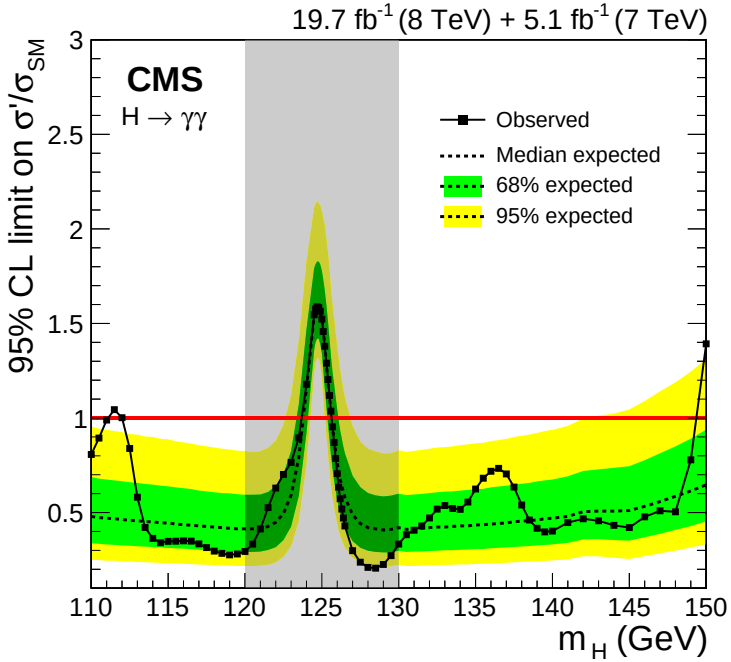
No significant deviation from expectations

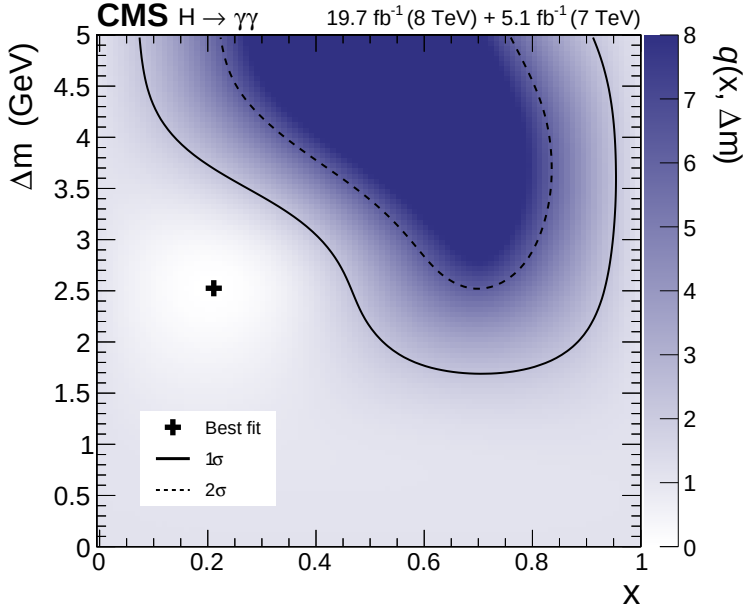
- The analysis is observed to be statistics-limited
- The systematic uncertainties worsen exp. limits by 1.7% at most

Additional Higgs-boson-like states in $h \to \gamma\gamma$ search

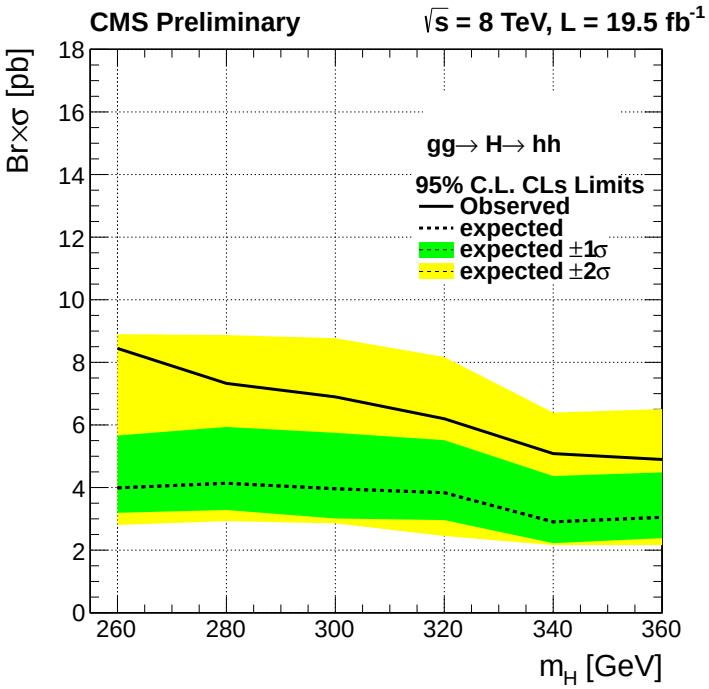
- Ancillary result from SM $H \to \gamma\gamma$ search hep-ex/1407.0558 : **substract the observed state**
  - Search for **additional $H \to \gamma\gamma$ states** in $[110, 150] \setminus [120, 130]$ GeV
  - Search for near and mass degenerate states in $[120, 130]$ GeV ($m_H + \Delta m_H$ with μx and $\mu(1-x)$ strength)

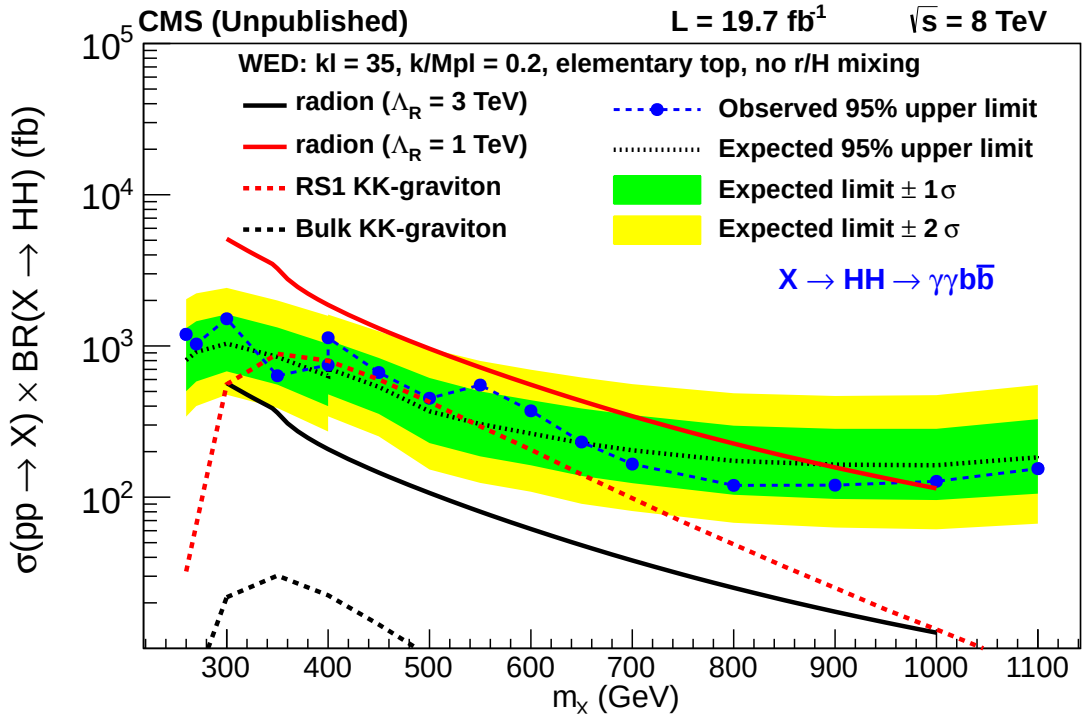






Conclusion

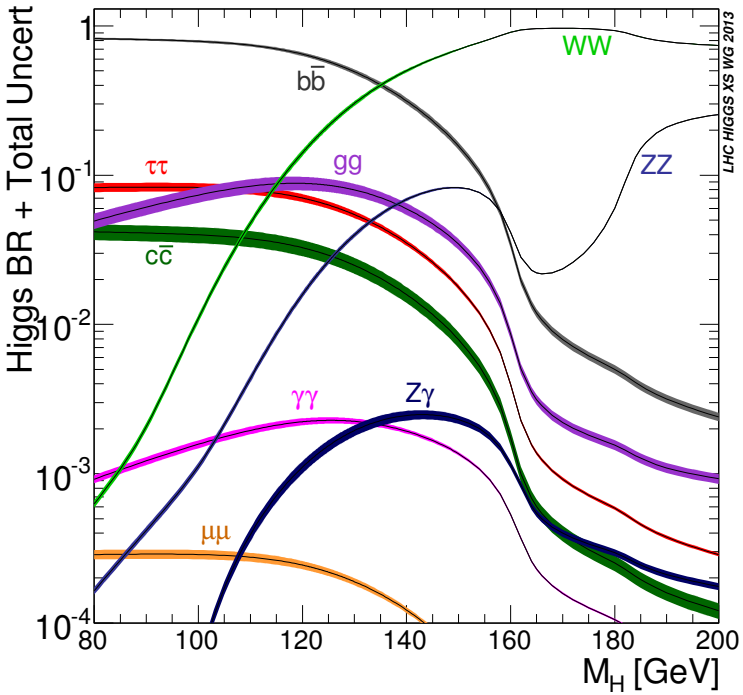




- Searches for two Higgs bosons are gearing up
  - **Resonant searches constraining 2HDM, WED**, ...
  - Non-resonant searches prospecting for HHH in preparation
- Looking forward to more data during LHC Run II

BACKUP

Comments on other channels



channel	frequency(%)
$h(b\bar{b}, c\bar{c}, gg)h(b\bar{b}, c\bar{c}, gg)$	47.86
$h(b\bar{b})h(b\bar{b})$	33.30
$h(b\bar{b}, c\bar{c}, gg)h(VV^*)$	33.40
$h(b\bar{b})h(\tau^+\tau^-)$	7.29
$h(VV^*)h(VV^*)$	5.83
$h(l^+l^-)h(VV^*)$	3.06
$h(l^+l^-)h(l^+l^-)$	0.40
$h(b\bar{b}, c\bar{c}, gg)h(\gamma\gamma)$	0.32
$h(b\bar{b})h(\gamma\gamma)$	0.26
$h(b\bar{b}, c\bar{c}, gg)h(\mu^+\mu^-)$	0.03
$h(l^+l^-)h(\gamma\gamma)$	0.03

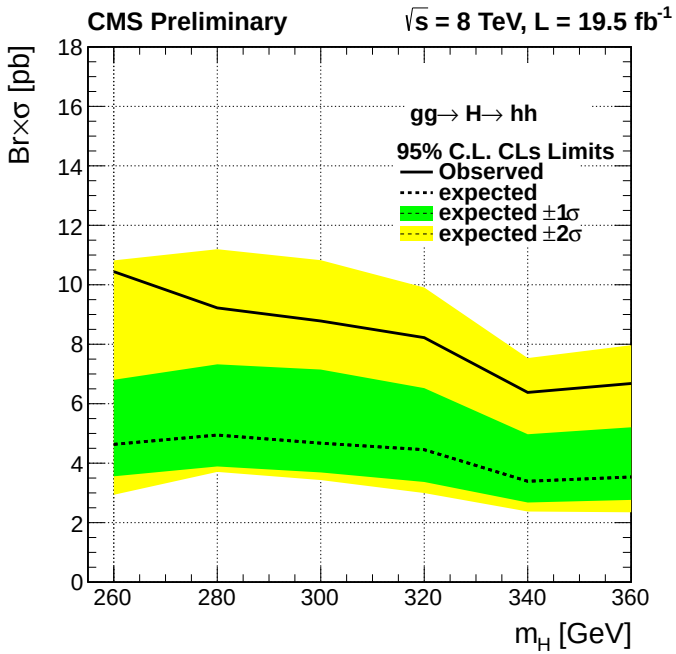
For HL-LHC ($\sqrt{s} = 14$ TeV, $\int L = 3000$ fb^{-1})

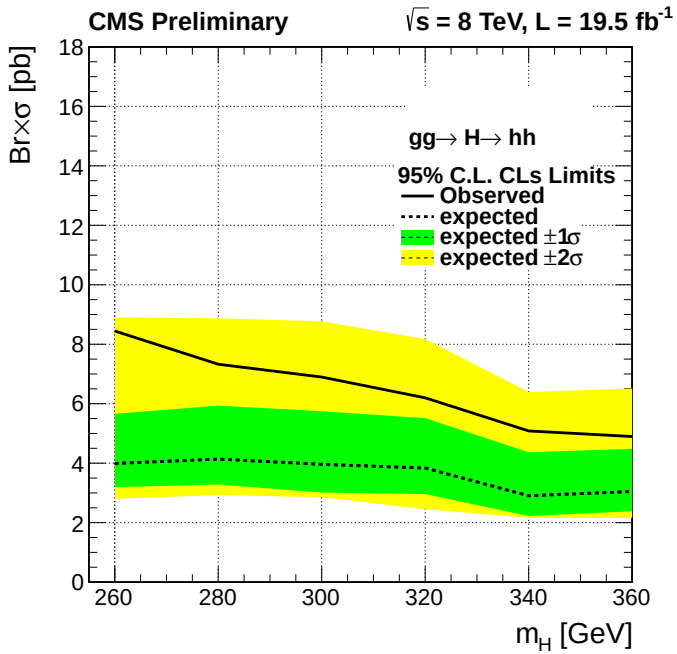
- $\sigma(pp \to HH) = 33.86$ fb:
  ≈ 100 k events produced

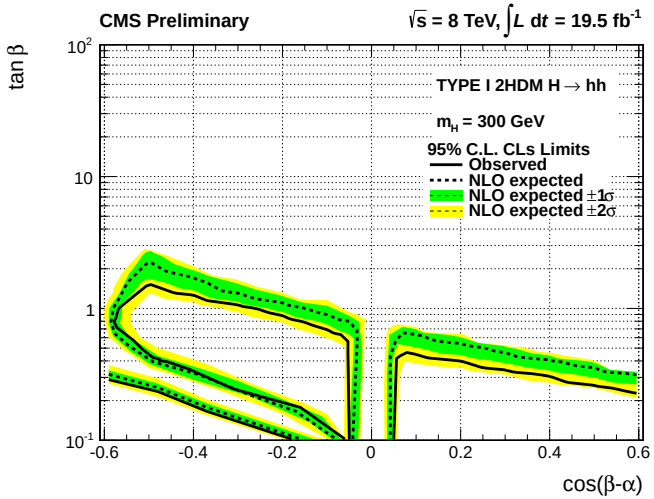
channel	Nevents
$b\bar{b}b\bar{b}$	$\approx$ 34 000
$jjVV$	$\approx$ 34 000
$b\bar{b}\tau\tau$	$\approx$ 7 400
$b\bar{b}\gamma\gamma$	$\approx$ 260

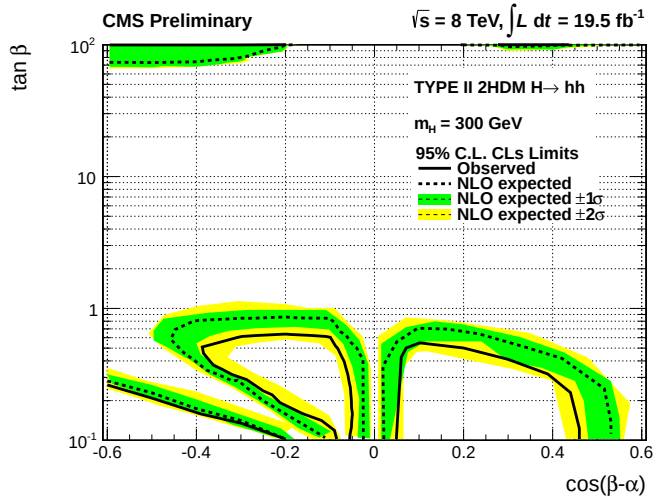
Extended Higgs sector
$HH \rightarrow$ multileptons and diphotons HIG-13-025

H > hh limits

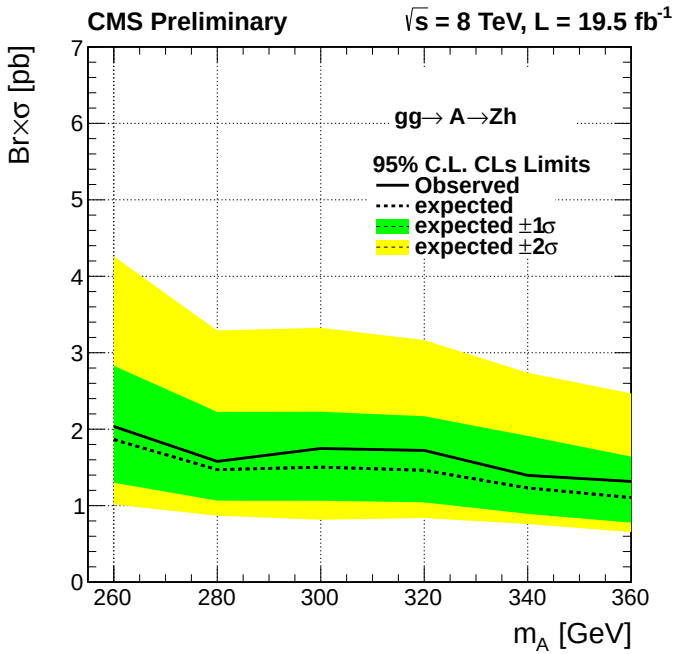

CMS Preliminary
√s = 8 TeV, L = 19.5 fb-1
Br×σ [pb]
gg→ H→ hh
95% C.L. CLs Limits
Observed
expected
expected ±1σ
expected ±2σ
mH [GHz]

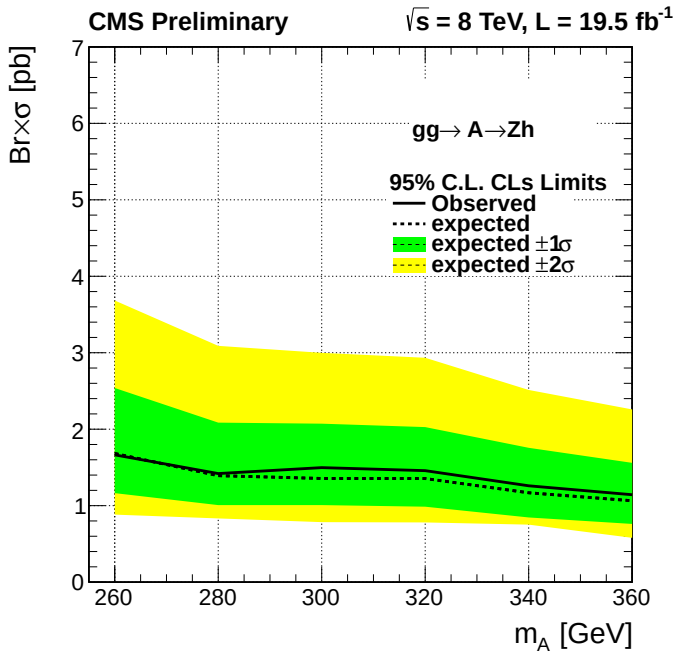

CMS Preliminary
√s = 8 TeV, L = 19.5 fb-1
Br×σ [pb]
gg→ H→ hh
95% C.L. CLs Limits
Observed
expected
expected ±1σ
expected ±2σ
mH [GeV]

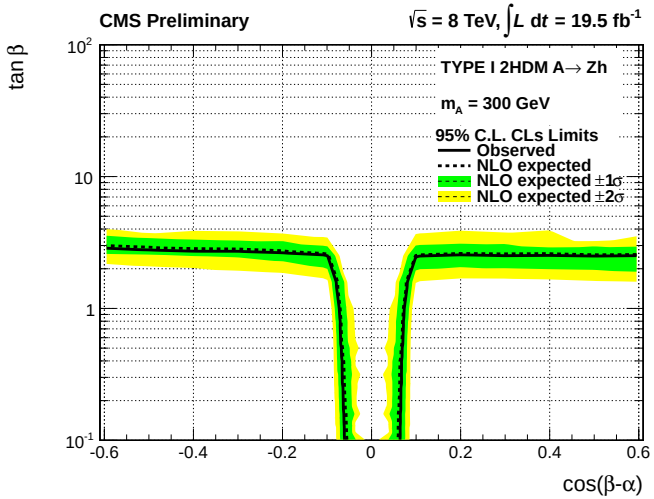

CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb-1
tan β
TYPE I 2HDM H→ hh
mH = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
cos(β-α)

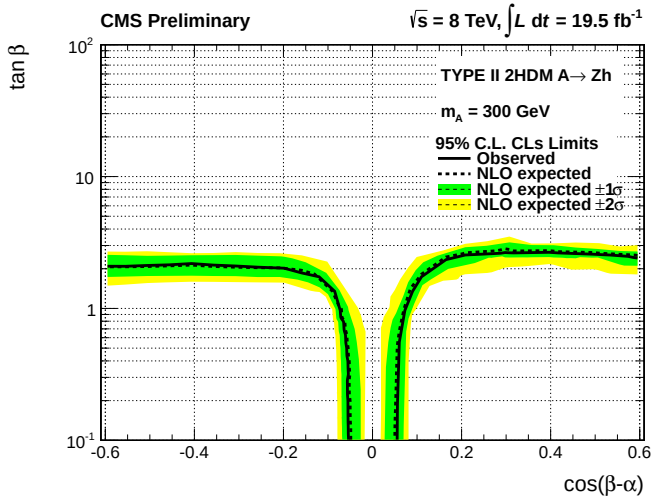

CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb-1
tan β
TYPE II 2HDM H→ hh
mH = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
cos(β-α)

A > Zh

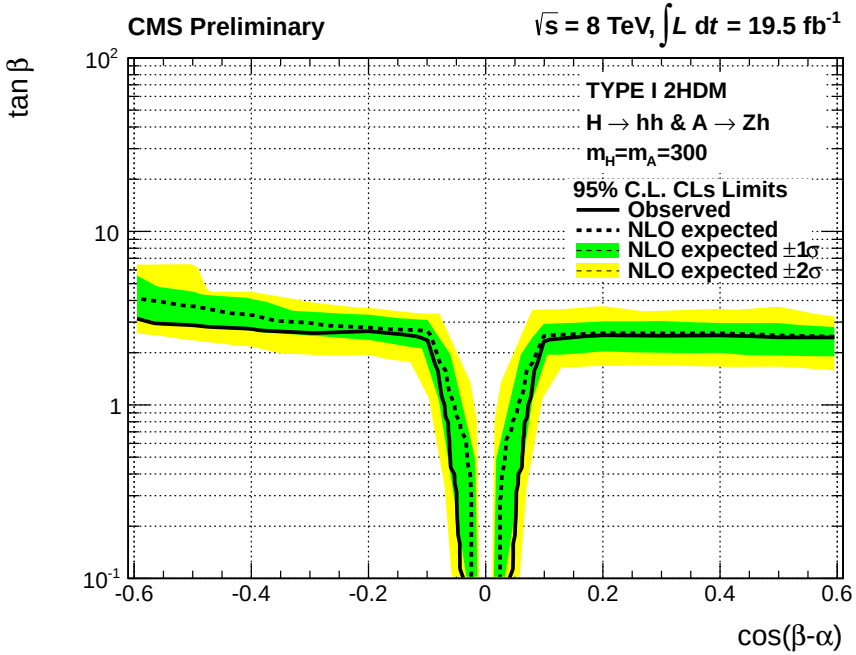

CMS Preliminary
√s = 8 TeV, L = 19.5 fb-1
Br×σ [pb]
gg→ A→Zh
95% C.L. CLs Limits
Observed
expected
expected ±1σ
expected ±2σ
mA [GHz]

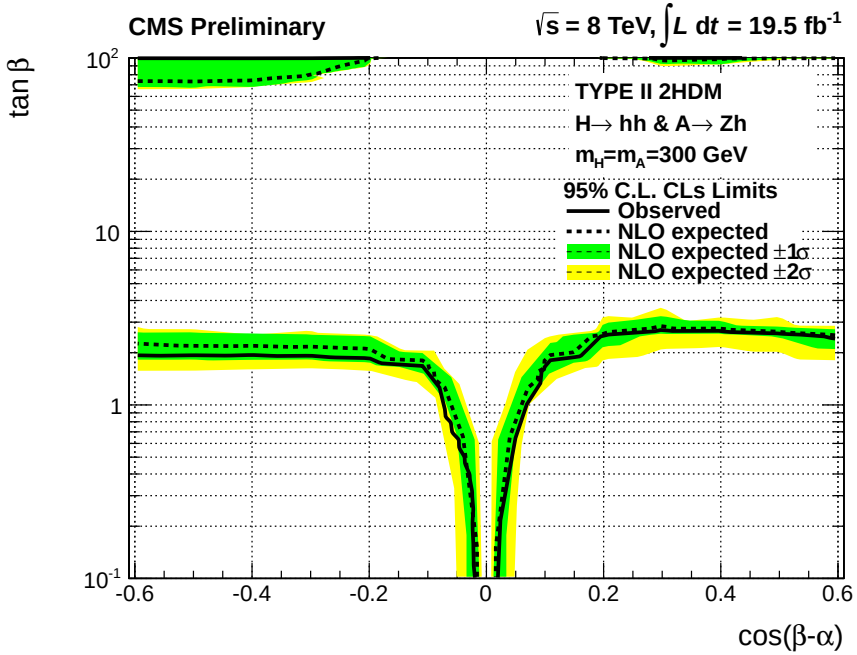

CMS Preliminary
√s = 8 TeV, L = 19.5 fb-1
Br×σ [pb]
gg→ A→Zh
95% C.L. CLs Limits
Observed
expected
expected ±1σ
expected ±2σ
mA [GeV]


CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb-1
tan β
TYPE I 2HDM A→ Zh
mA = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
cos(β-α)

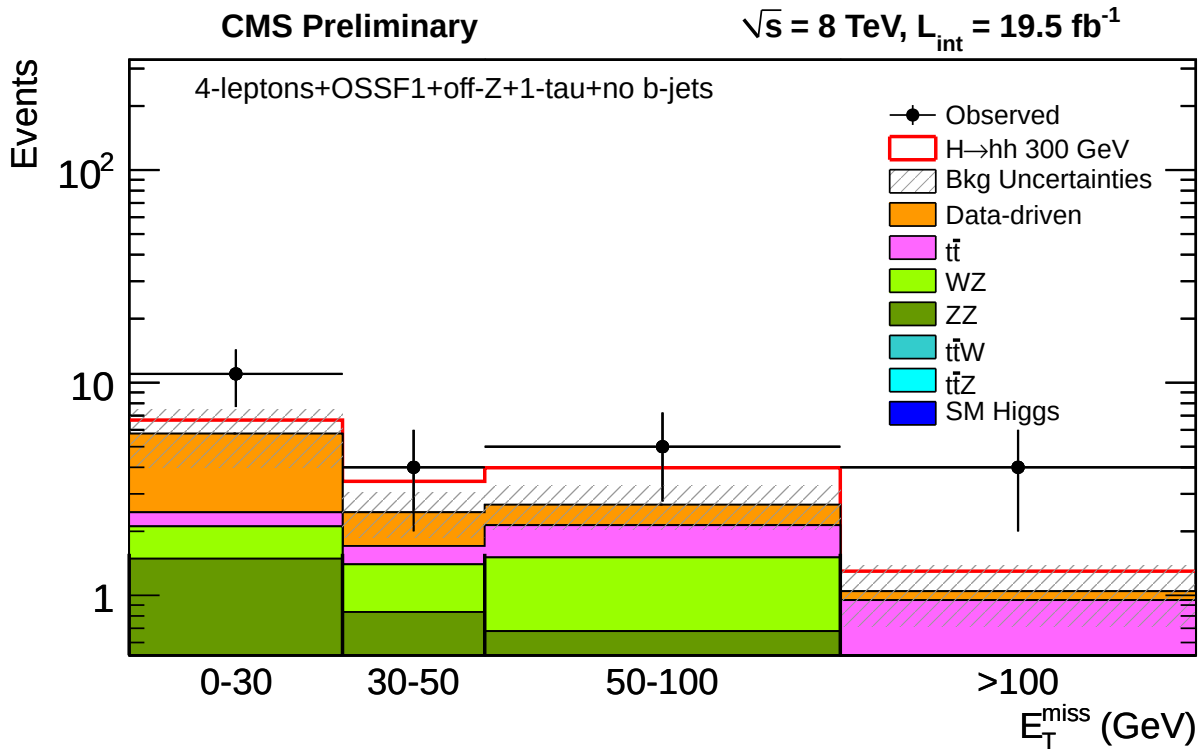

CMS Preliminary
√s = 8 TeV, ∫L dt = 19.5 fb-1
tan β
TYPE II 2HDM A→ Zh
mA = 300 GeV
95% C.L. CLs Limits
Observed
NLO expected
NLO expected ±1σ
NLO expected ±2σ
cos(β-α)

Combined limits





The excess



- Excess in $3(e/\mu) + \tau_h$ off-Z channels with no b-tags:
  - obs. (exp.) $11(5.1 \pm 1.7)$, $4(2.4 \pm 0.5)$, $5(2.6 \pm 0.6)$ for the 3 $\not{E}_T$ bins
- p-value: local $= 1.5\,\%$, global (40 channels): sum of $\not{E}_T$ bins $= 46\,\%$, all three $\not{E}_T$ bins $= 5\,\%$

Channels breakdown (I)

4 Lepton Results										
Selection	on- or off-Z	E_T^{miss}	N_τ=0, N_{b-Jet}=0		N_τ=1, N_{b-Jet}=0		N_τ=0, N_{b-Jet} ≥1		N_τ=1, N_{b-Jet} ≥1	
			obs	expect	obs	expect	obs	expect	obs	expect
OSSF0	NA	(100,∞)	0	0.07 ± 0.07	0	0.18 ± 0.09	0	0.05 ± 0.05	0	0.16 ± 0.1
OSSF0	NA	(50,100)	0	0.07 ± 0.06	2	0.8 ± 0.35	0	0 ± 0.03	0	0.43 ± 0.22
OSSF0	NA	(30,50)	0	0.001 ± 0.02	0	0.47 ± 0.24	0	0 ± 0.02	0	0.11 ± 0.09
OSSF0	NA	(0,30)	0	0.007 ± 0.02	1	0.4 ± 0.16	0	0.001 ± 0.02	0	0.02 ± 0.04
OSSF1	off-Z	(100,∞)	0	0.07 ± 0.04	4	1 ± 0.33	0	0.14 ± 0.09	0	0.46 ± 0.2
OSSF1	on-Z	(100,∞)	2	0.6 ± 0.2	2	3.4 ± 0.8	1	0.8 ± 0.41	0	0.6 ± 0.26
OSSF1	off-Z	(50,100)	0	0.21 ± 0.09	5	2.6 ± 0.6	0	0.21 ± 0.11	1	0.7 ± 0.32
OSSF1	on-Z	(50,100)	2	1.3 ± 0.39	10	12 ± 2.5	2	0.6 ± 0.33	1	0.8 ± 0.3
OSSF1	off-Z	(30,50)	1	0.16 ± 0.07	4	2.4 ± 0.5	0	0.06 ± 0.06	0	0.47 ± 0.21
OSSF1	on-Z	(30,50)	3	1.2 ± 0.35	11	14 ± 3.1	0	0.22 ± 0.12	0	0.8 ± 0.31
OSSF1	off-Z	(0,30)	1	0.38 ± 0.18	11	5.7 ± 1.7	0	0.05 ± 0.04	0	0.5 ± 0.26
OSSF1	on-Z	(0,30)	1	2 ± 0.5	32	30 ± 9.2	1	0.19 ± 0.11	3	1.3 ± 0.42
OSSF2	TwoZ	(100,∞)	0	0.02 ± 0.15	–	–	0	0.21 ± 0.13	–	–
OSSF2	OneZ	(100,∞)	1	0.43 ± 0.15	–	–	0	0.5 ± 0.29	–	–
OSSF2	off-Z	(100,∞)	0	0.06 ± 0.03	–	–	0	0.09 ± 0.07	–	–
OSSF2	TwoZ	(50,100)	3	2.8 ± 2.1	–	–	0	0.33 ± 0.11	–	–
OSSF2	OneZ	(50,100)	1	2 ± 0.7	–	–	1	0.5 ± 0.28	–	–
OSSF2	off-Z	(50,100)	2	0.2 ± 0.14	–	–	0	0.12 ± 0.1	–	–
OSSF2	TwoZ	(30,50)	19	22 ± 9	–	–	2	0.7 ± 0.24	–	–
OSSF2	OneZ	(30,50)	6	6.5 ± 2.4	–	–	0	0.32 ± 0.12	–	–
OSSF2	off-Z	(30,50)	3	1.4 ± 0.6	–	–	1	0.15 ± 0.08	–	–
OSSF2	TwoZ	(0,30)	118	109 ± 28	–	–	3	2 ± 0.5	–	–
OSSF2	OneZ	(0,30)	24	29 ± 7.6	–	–	1	0.6 ± 0.17	–	–
OSSF2	off-Z	(0,30)	5	7.8 ± 2.3	–	–	0	0.18 ± 0.06	–	–

Channels breakdown (II)

1 Lepton, 1 Hadronic Tau and 2 Photon Results		
E_T^{miss}	obs	expect
(50,∞)	0	0.16±0.66
(30,50)	0	0.5± 0.57
(0,30)	0	0.76±0.6

1 Lepton and 2 Photon Results		
E_T^{miss}	obs	expect
(50,∞)	9	14.3±7.15
(30,50)	31	22.1± 11.05
(0,30)	74	79.1±39.55

2 Lepton and 2 Photon Results				
Selection		E_T^{miss}	obs	expect
OSSF1	off-Z	(50,∞)	0	0.19±0.25
OSSF1	on-Z	(50,∞)	0	0.1± 0.17
OSSF1	off-Z	(30,50)	1	0.17± 0.25
OSSF1	on-Z	(30,50)	1	0.33± 0.28
OSSF1	off-Z	(0,30)	1	1.2± 0.74
OSSF1	on-Z	(0,30)	0	1.01± 0.55
OSSF0	NA	(0,∞)	0	0± 0.17

Upto 2 Hadronic Tau and 2 Photon Results		
E_T^{miss}	obs	expect
(50,∞)	16	11.39±5.6
(30,50)	73	69.1± 34.6
(0,30)	235	241.4±120.7

Channels breakdown (III)

3 Lepton Results									
Selection		E_T^{miss}	N(τ)=0, NbJet=0		N(τ)=1, NbJet=0		N(τ)=0, NbJet≥1		N(τ)=1, NbJet≥1	
			obs	expect	obs	expect	obs	expect	obs	expect
OSSF0(SS)		(200,∞)	1	1.3 ± 0.6	2	1.4 ± 0.5	0	0.7 ± 0.36	0	0.7 ± 0.5
OSSF0(SS)		(150,200)	2	2.1 ± 0.9	0	3 ± 1.1	1	2.1 ± 1	0	1.5 ± 0.6
OSSF0(SS)		(100,150)	9	10 ± 4.9	4	9.9 ± 3	12	12 ± 5.9	4	6.3 ± 2.8
OSSF0(SS)		(50,100)	34	37 ± 15	54	66 ± 14	32	32 ± 15	24	22 ± 10
OSSF0(SS)		(0,50)	47	46 ± 11	196	221 ± 51	28	24 ± 11	21	31 ± 9.6
OSSF0		(200,,∞)	–	–	5	4.8 ± 2.4	–	–	6	5.9 ± 3.1
OSSF0		(150,200)	–	–	12	18 ± 9.1	–	–	21	20 ± 10
OSSF0		(100,150)	–	–	94	96 ± 47	–	–	91	121 ± 61
OSSF0		(50,100)	–	–	351	329 ± 173	–	–	300	322 ± 163
OSSF0		(0to50)	–	–	682	767 ± 207	–	–	230	232 ± 118
OSSF1	below-Z	(200,∞)	2	2.5 ± 0.9	4	2.1 ± 1	1	1.9 ± 0.7	2	2.4 ± 1.2
OSSF1	on-Z	(200,∞)	17	19 ± 6.3	4	5.6 ± 1.9	1	2.4 ± 0.8	3	2.1 ± 0.9
OSSF1	below-Z	(150,200)	7	4.4 ± 1.7	11	9.3 ± 4.6	3	4.7 ± 2.1	7	11 ± 5.9
OSSF1	on-Z	(150,200)	38	32 ± 8.5	10	11 ± 3.6	4	5.4 ± 1.7	2	5.7 ± 2.7
OSSF1	below-Z	(100,150)	21	26 ± 9.9	45	56 ± 27	20	23 ± 11	56	66 ± 33
OSSF1	on-Z	(100,150)	134	129 ± 29	43	51 ± 16	20	18 ± 6	24	28 ± 14
OSSF1	below-Z	(50,100)	157	129 ± 30	383	380 ± 104	58	60 ± 28	166	173 ± 87
OSSF1	on-Z	(50,100)	862	732 ± 141	1363	1227 ± 323	80	62 ± 17	117	101 ± 48
OSSF1	below-Z	(0,50)	543	559 ± 93	10186	9171 ± 2714	40	52 ± 14	257	256 ± 79
OSSF1	on-Z	(0,50)	4041	4061 ± 691	51361	51369 ± 15340	181	181 ± 28	1003	1012 ± 286

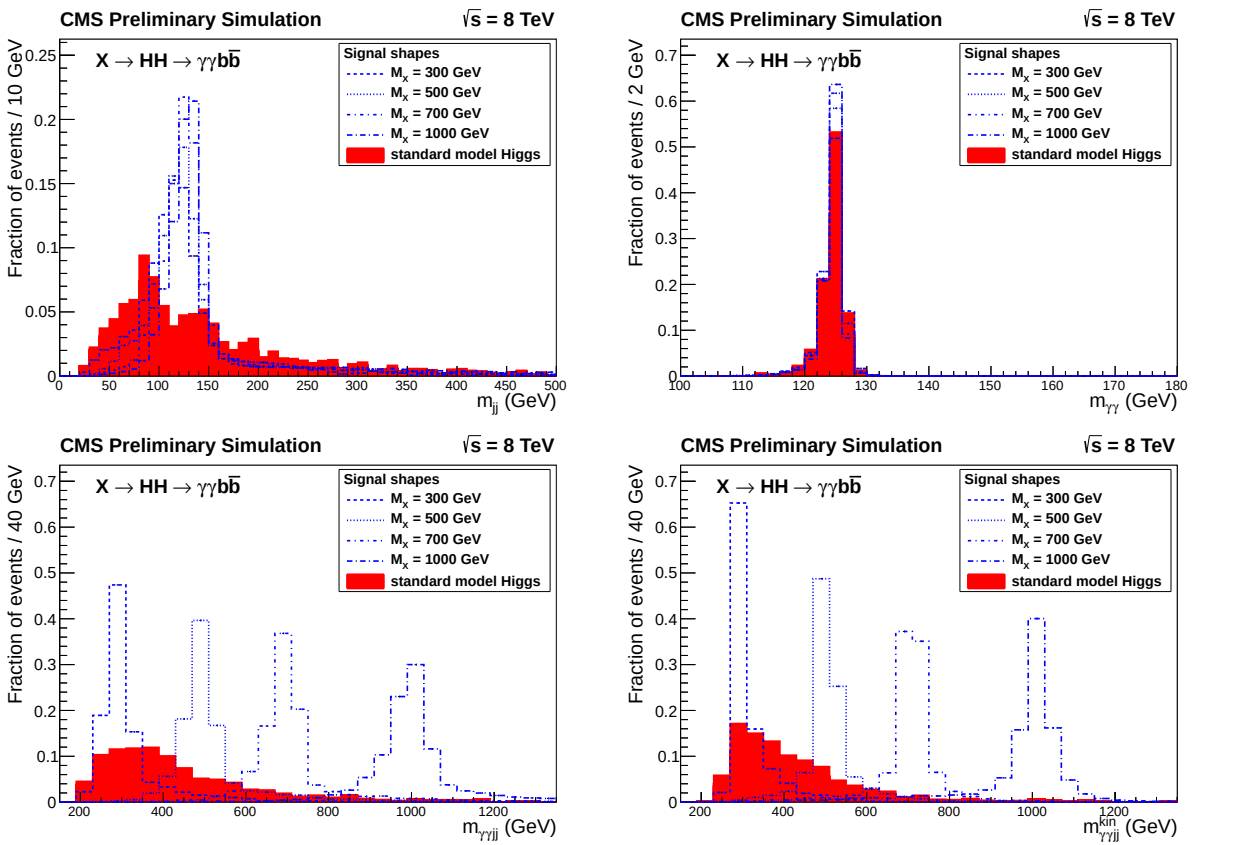
Systematic uncertainties

Source of Uncertainty	Uncertainty
Luminosity	2.6%
PDF	10%
E_T^{miss} Resolution/Smearing: 0-50 GeV, 50-100 GeV, > 100 GeV	(-3%, +4%, +4%)
Jet Energy Scale	0.5%
B-Tag scale factor	0.1% (WZ), 6% ($t\bar{t}$)
Muon ID/Isolation at 30 GeV	0.2%
Electron ID/Isolation at 30 GeV	0.6%
Trigger Efficiency	5%
$t\bar{t}$ xsec	10%
$t\bar{t}$ fake rate contribution	50%
WZ cross-section	15%
ZZ cross-section	15%

Warped Extra Dimensions

$HH \to b\bar{b}\gamma\gamma$ HIG-13-032

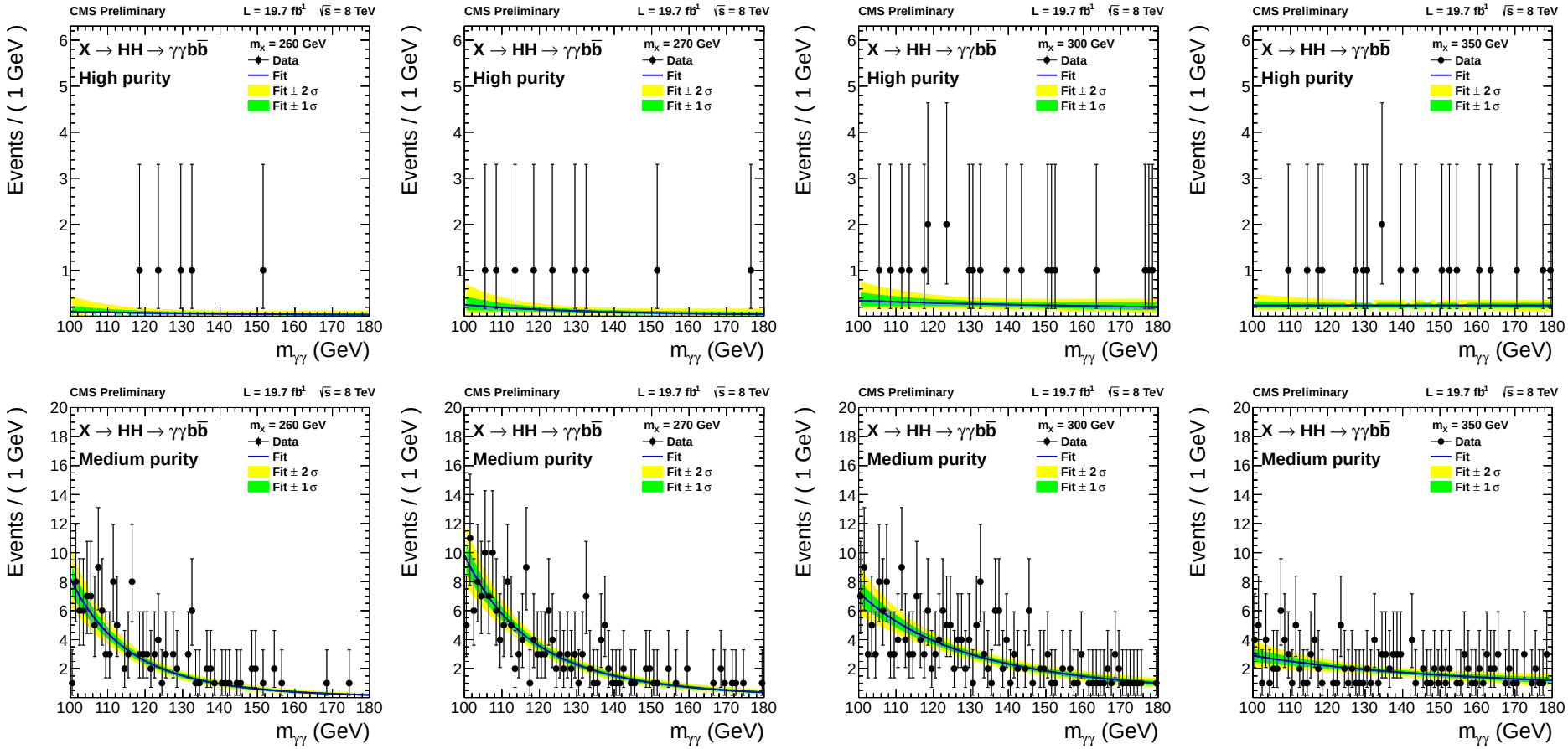
Signal shapes



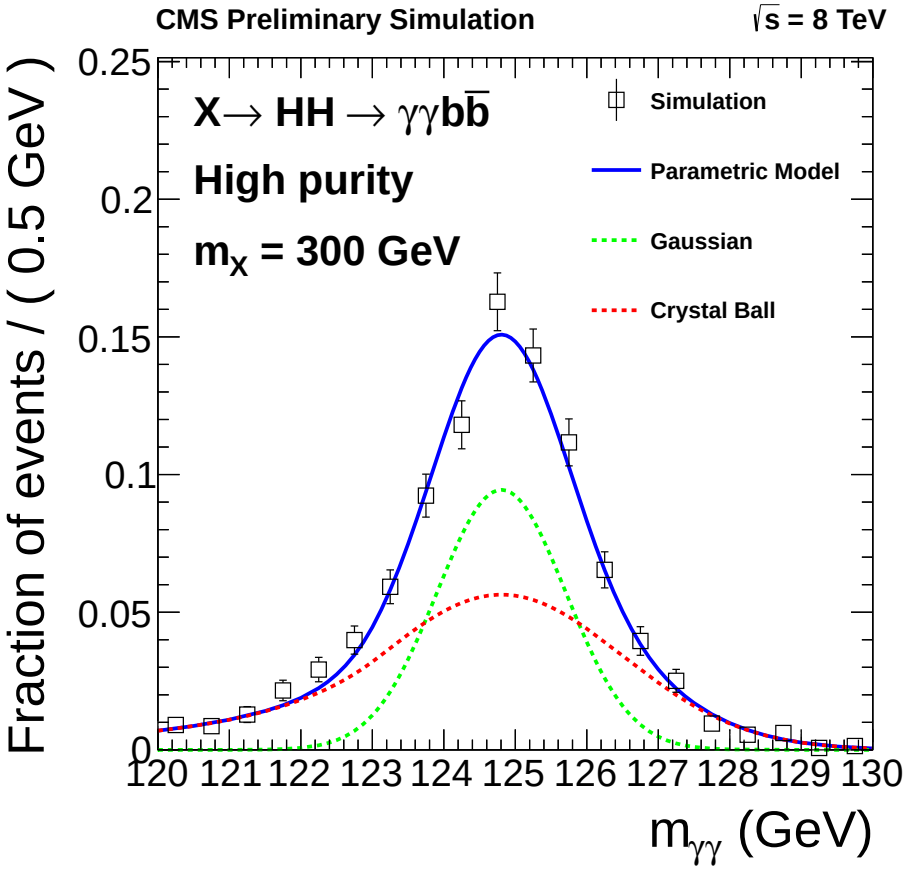
Kinematic fit

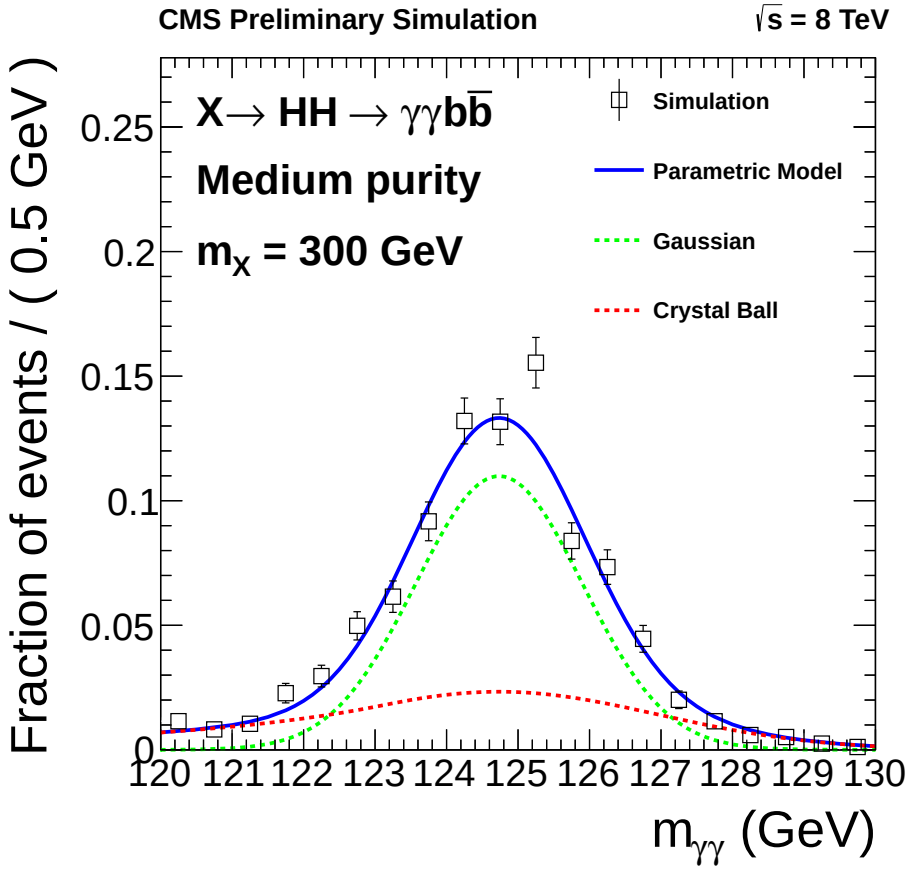
- Once the jj system is selected, constraint that m_{jj} compatible with $m_H = 125$ GeV
- This constraint takes into account the experimental jet resolutions
- Improves notably the 4-body mass spectrum resolution for signal
- Shuffle events around for background

Signal and background fits (I)

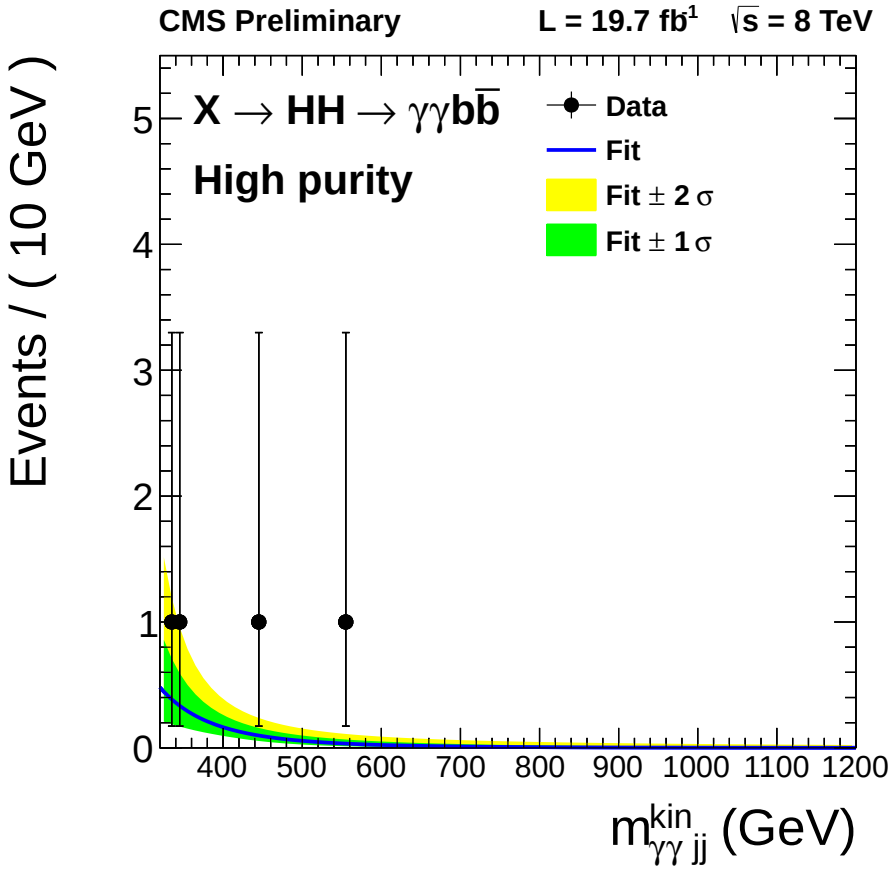


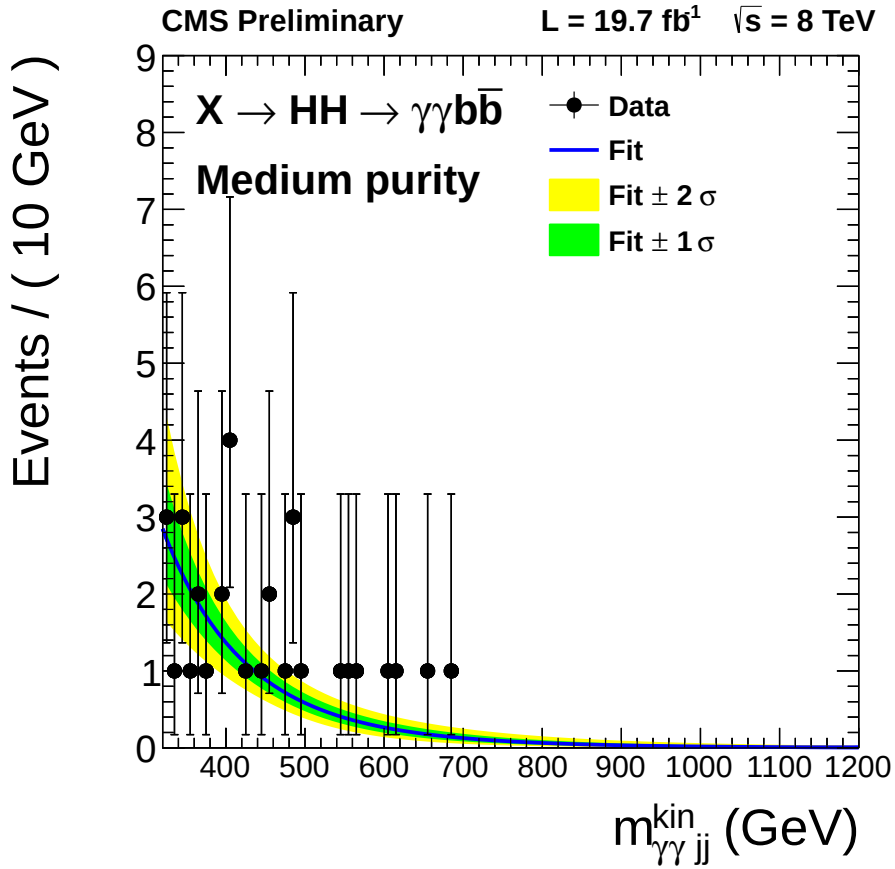
Signal and background fits (II)



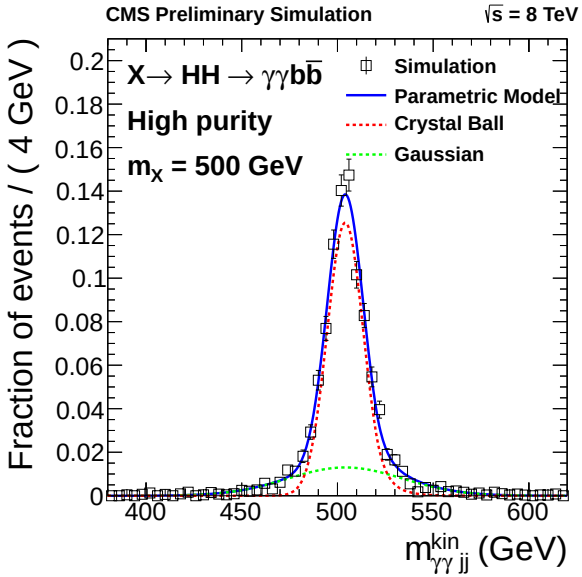


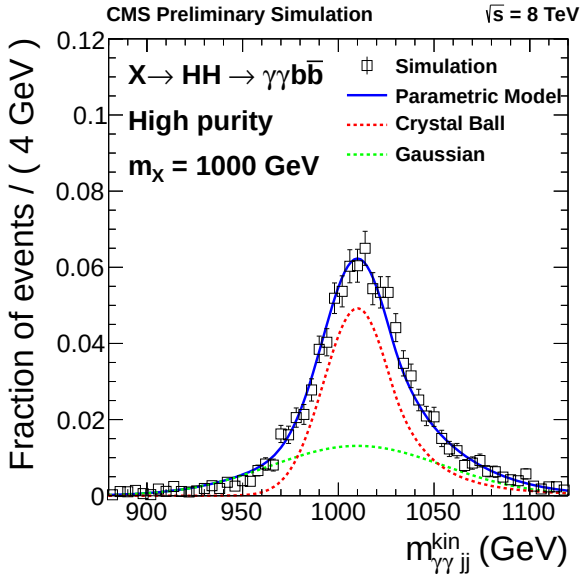
Signal and background fits (III)

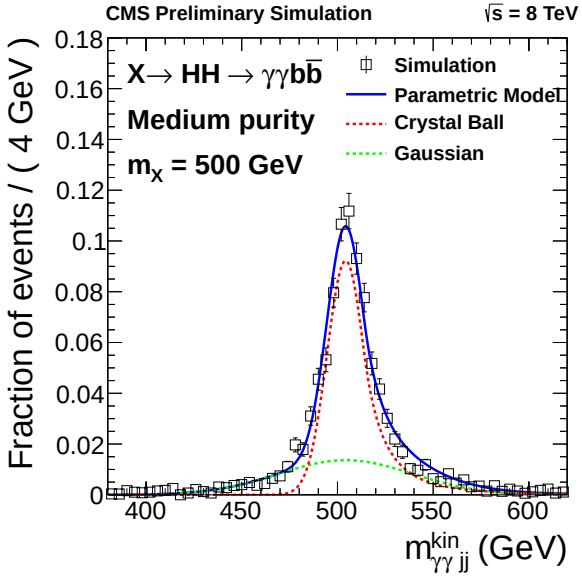


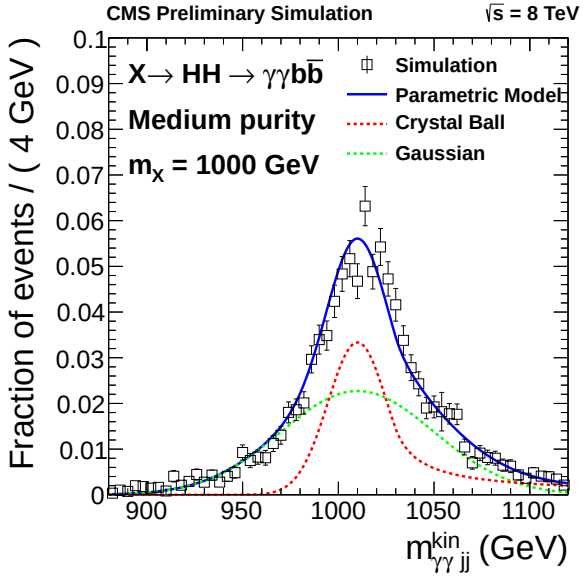


Signal and background fits (IV)





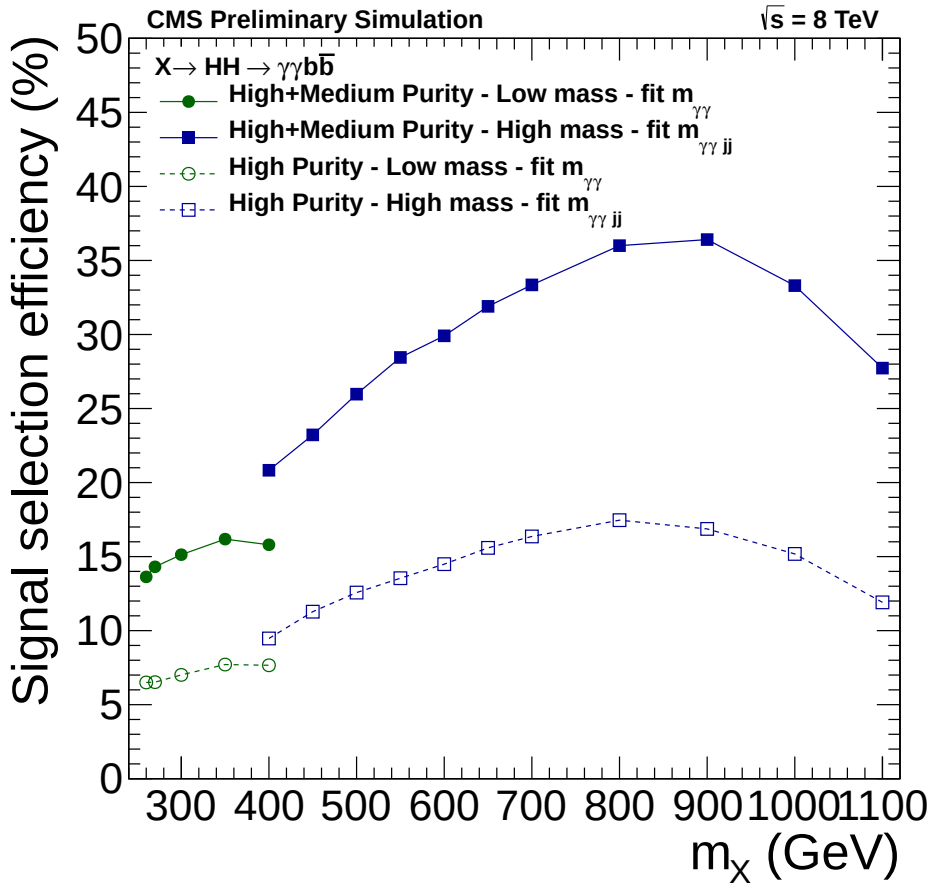




Selection cuts, efficiency and yields

m_X	$M_{\gamma\gamma jj}$ selection
260	$[225, 280]$
270	$[225, 295]$
300	$[255, 330]$
350	$[310, 395]$
400	$[370, 440]$
	M_{jj} selection
all masses	$[85, 155]$

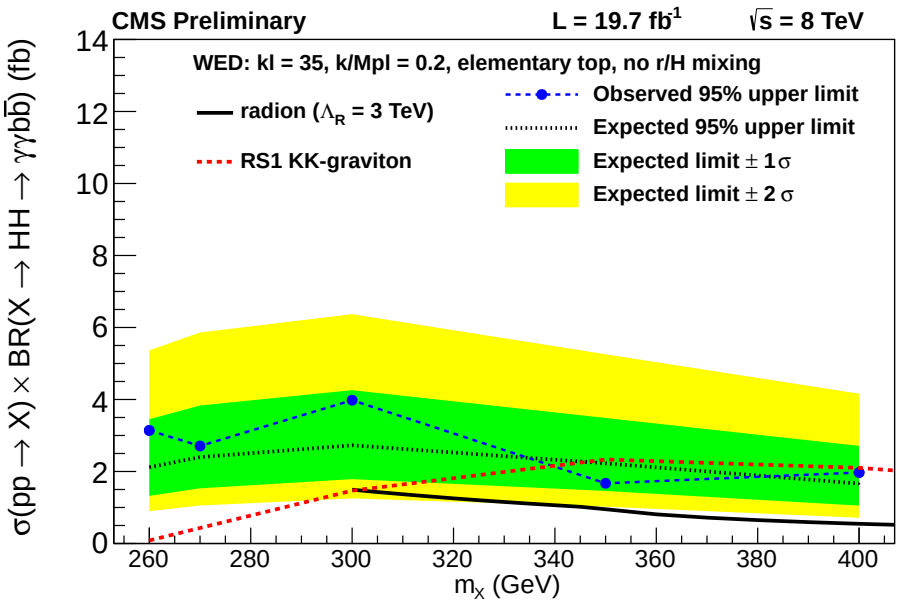
Sample	High-purity	Medium-purity
di-Higgs resonance (300 GeV, Λ_R=1 TeV)	18.73	21.66
$ggH(\to \gamma\gamma)$	0.02	0.19
VBF ($H \to \gamma\gamma$)	0.00	0.04
$VH(\to \gamma\gamma)$	0.01	0.08
$t\bar{t}H \to \gamma\gamma$	0.10	0.15
data	21	230

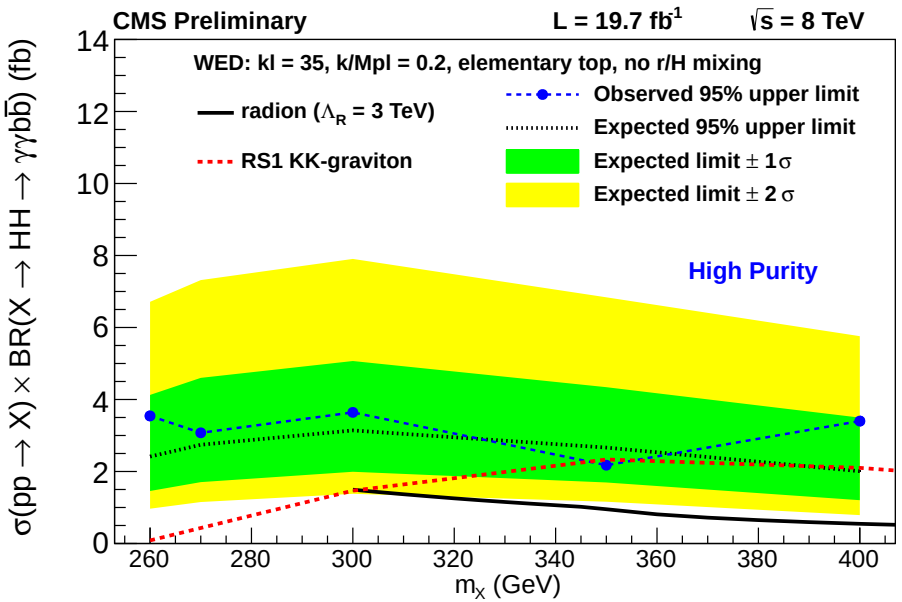


Warped Extra Dimensions: systematic uncertainties

Common normalization uncertainties	
Luminosity	2.6%
Diphoton trigger acceptance	1.0%
Low mass analysis: fit to $M_{\gamma\gamma}$	
Normalization uncertainties	
Photons selection acceptance	1.0%
"b-tag" eff. uncertainty 2 btag cat	4.6%
"b-tag" eff. uncertainty 1 btag cat	-1.2%
m_{jj} and $p_{T,j}$ cut acceptance (JES & JER)	1.5%
$m_{\gamma\gamma\mathrm{jj}}$ cut acceptance (PES $\oplus$ JES & PER $\oplus$ JER)	2%
Shape uncertainties	
Parametric scale shift (PES$\oplus$M(H) uncertainty)	$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = 0.45 \oplus 0.35\%$
Parametric resolution shift (RES)	$\frac{\Delta\sigma}{m_{\gamma\gamma}} = 0.25\%$ $\frac{\Delta\sigma}{\sigma_{\gamma\gamma}} = 22\%$
High mass analysis: fit to $M_{\gamma\gamma\mathrm{jj,kin}}$	
Normalization uncertainties	
Photons selection acceptance	1.0%
"b-tag" eff. uncertainty 2 btag cat	5.3%
"b-tag" eff. uncertainty 1 btag cat	-1.8%
m_{jj} and $p_{T,j}$ cut acceptance (JES & JER)	1.5%
$m_{\gamma\gamma}$ cut acceptance (PES & PER)	0.5%
Extra High pt norm. uncertainty	5.0%
Shape uncertainties	
Parametric abs. shift (PES $\oplus$ JES)	$\frac{\Delta m_{\gamma\gamma\mathrm{jj}}}{m_{\gamma\gamma\mathrm{jj}}} = 0.45 \oplus (0.8 \oplus 1.0) = 1.4\%$
Parametric shift (PER $\oplus$ JER)	$\frac{\Delta\sigma}{\sigma_{\gamma\gamma\mathrm{jj}}} = 10\%$

Low mass limits

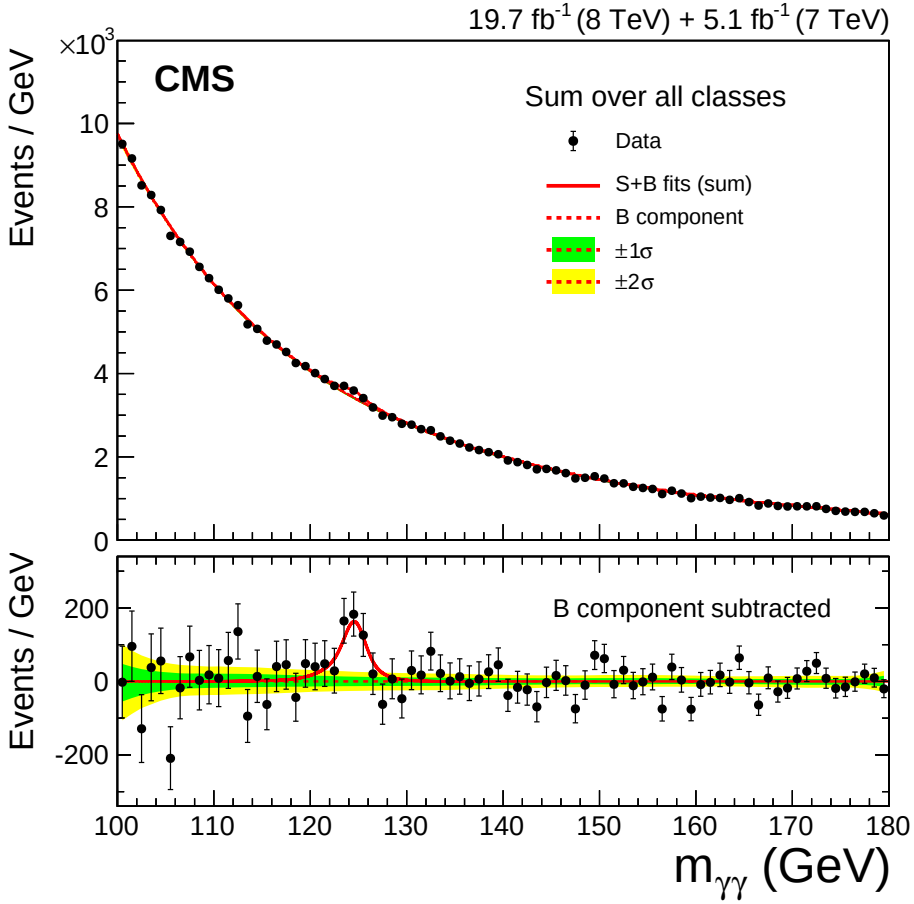


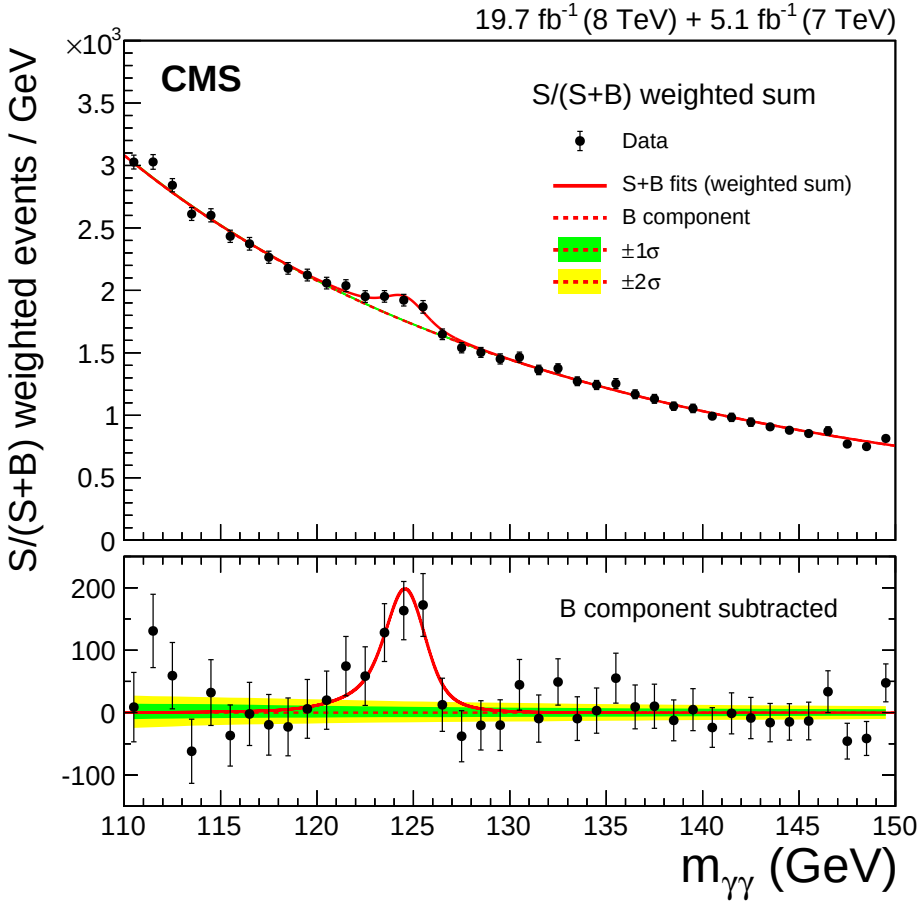


Search for additional Higgs-boson-like states

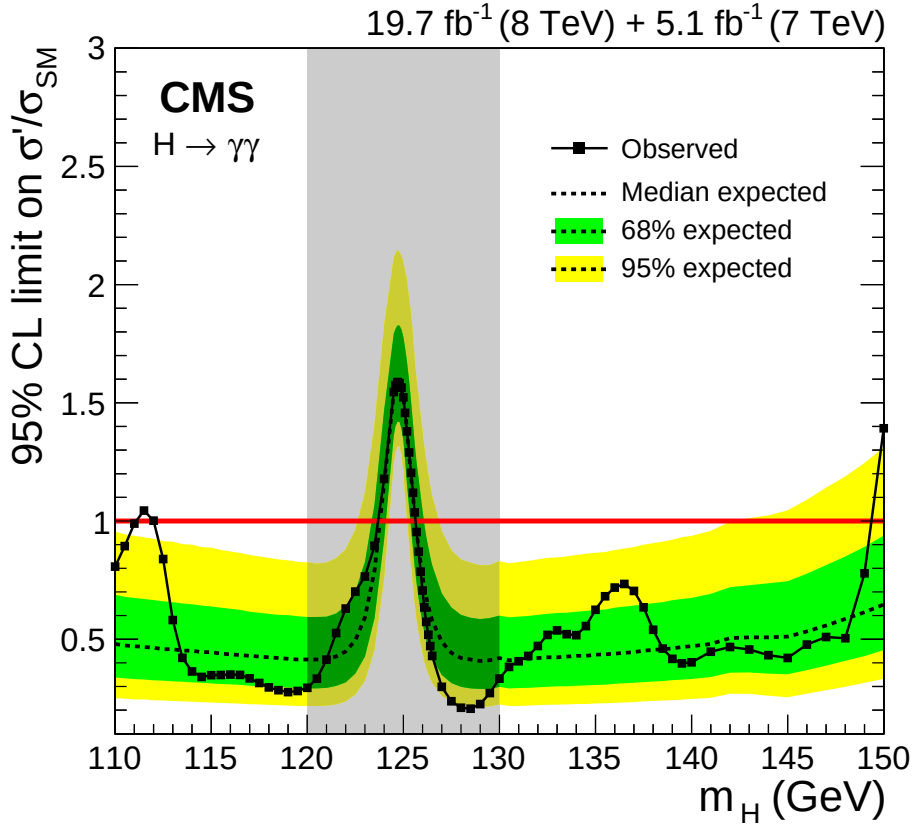
$HH \rightarrow \gamma\gamma\gamma\gamma$ hep-ex/1407.0558

Diphoton mass spectrum fits

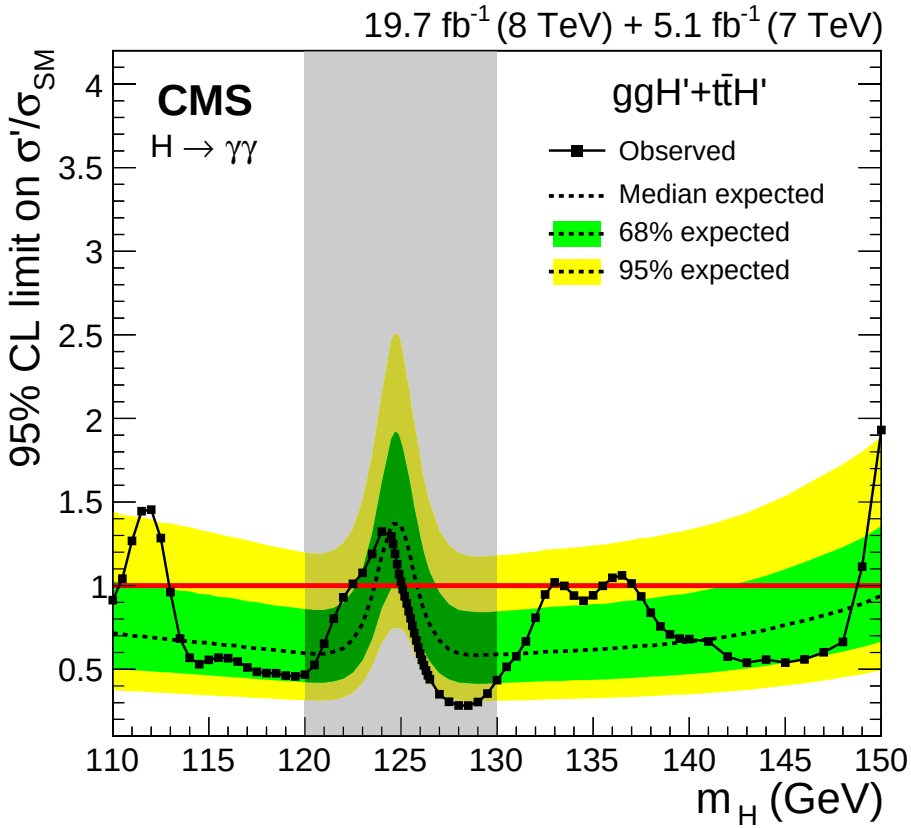


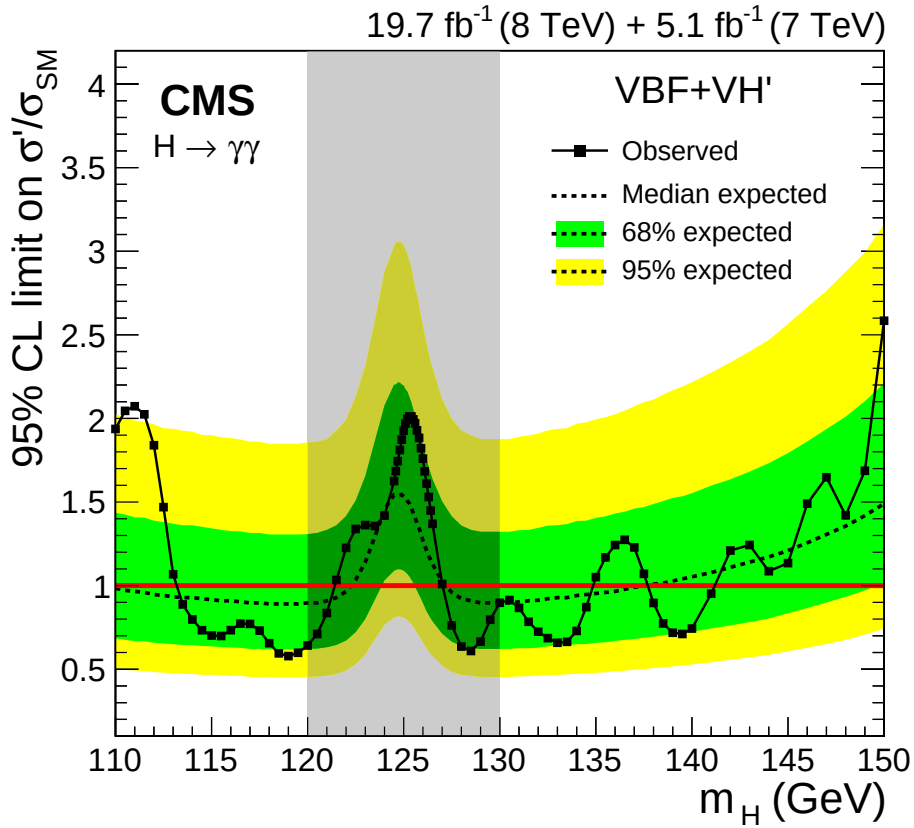


Assuming SM Higgs production rate

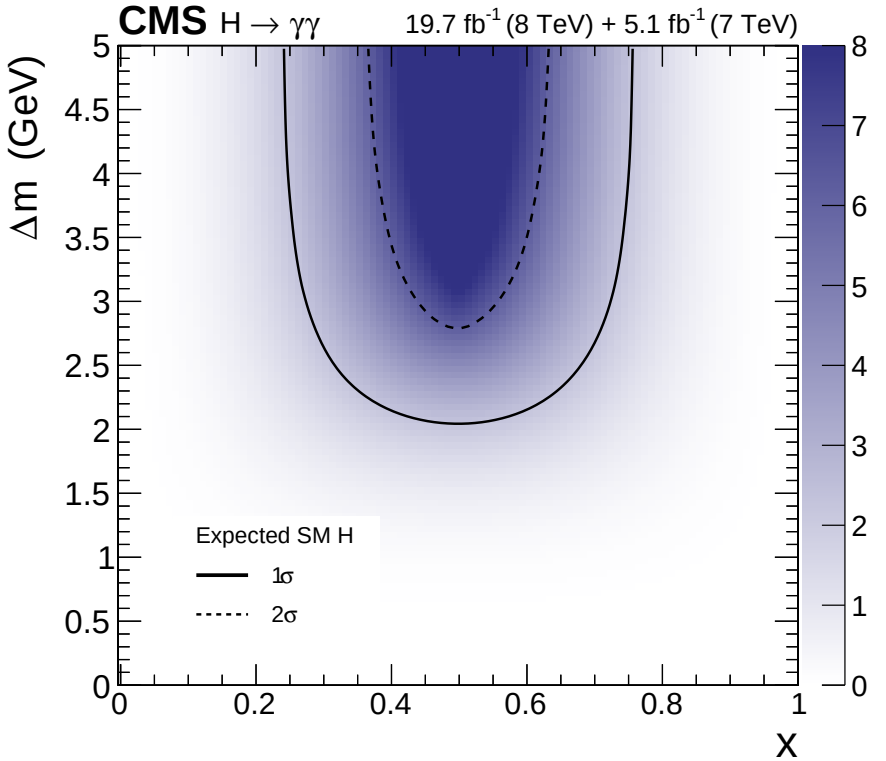


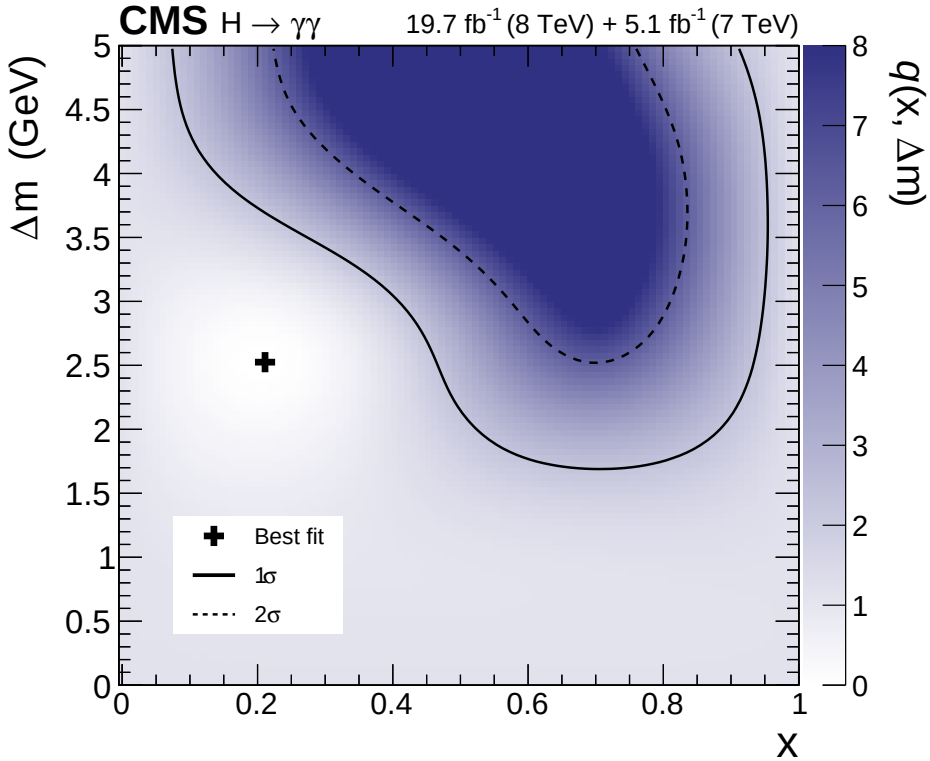
Assuming the second state couples only to fermions/bosons





Mass-degenerate states





High-mass search

Search for new resonances in the diphoton final state
in the range between 150 and 850 GeV in pp collisions at $\sqrt{(s)}$ = 8 TeV
(CMS-PAS-HIG-14-006)