BEH Scalar to Bosons at the LHC

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On Behalf of the ATLAS and CMS Collaborations

Moriond Electroweak - La Thuile, Italy
16 March 2016

Imperial College London

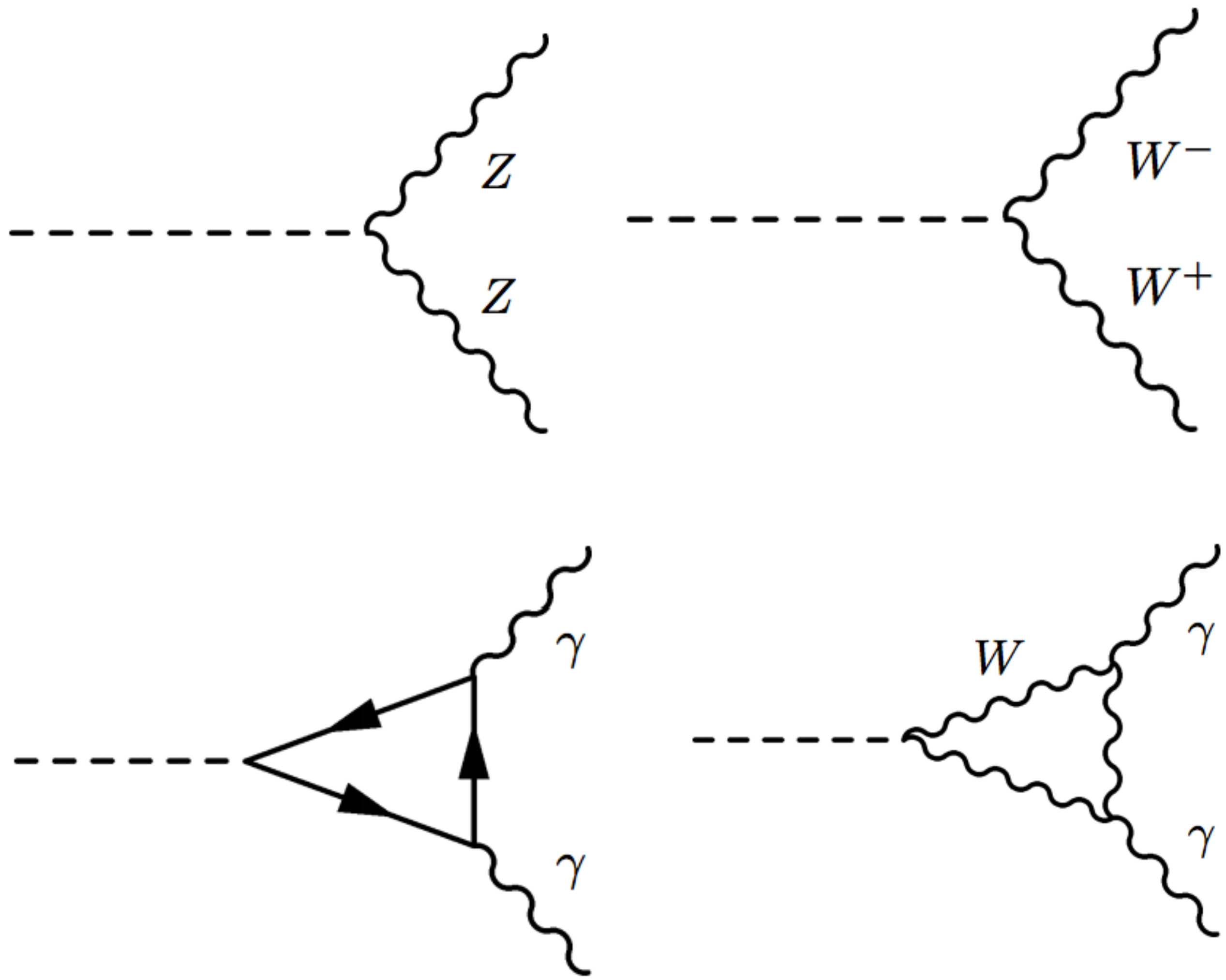
Overview

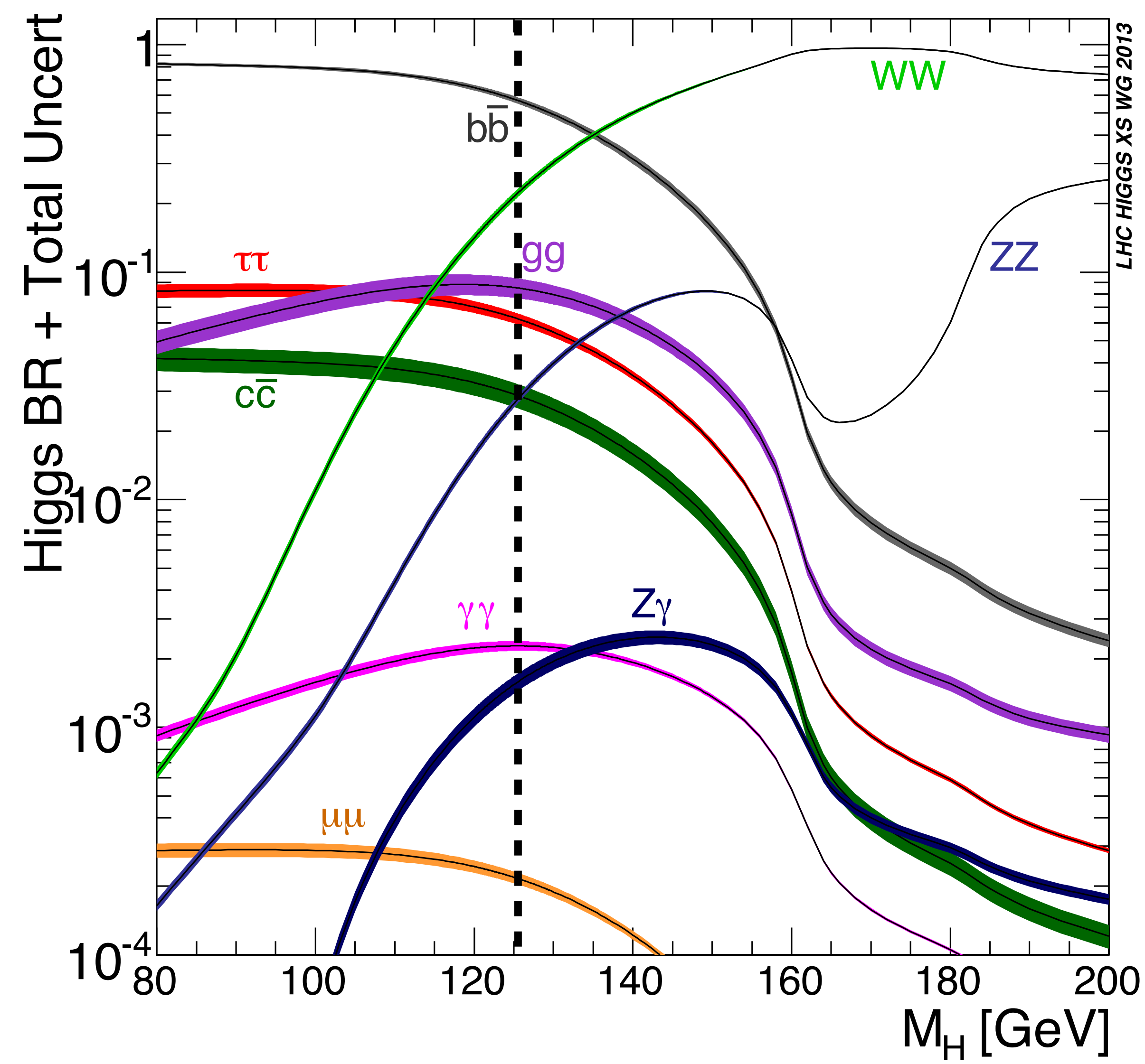
- 13 TeV Results
  - Scalar decays to: $\gamma\gamma$, ZZ → 4ℓ
  - Different choices made for low-statistics 2015 data
    - CMS: "Run 1-like" event categorization
    - ATLAS: count in single category, cross section measurements
  - $\gamma\gamma$ + MET ATLAS: CONF-2016-011
  - h* → hh → bb$\gamma\gamma$ ATLAS: CONF-2016-004
  - h* → hh → bb$\tau\tau$ CMS: HIG-15-012, HIG-15-013
- 8 TeV: WW differential measurement CMS: HIG-15-010

CMS ZZ: HIG-15-004
CMS $\gamma\gamma$: HIG-15-005
ATLAS ZZ: CONF-2015-059
ATLAS $\gamma\gamma$: CONF-2015-060
ATLAS xsec: CONF-2015-069

New today!

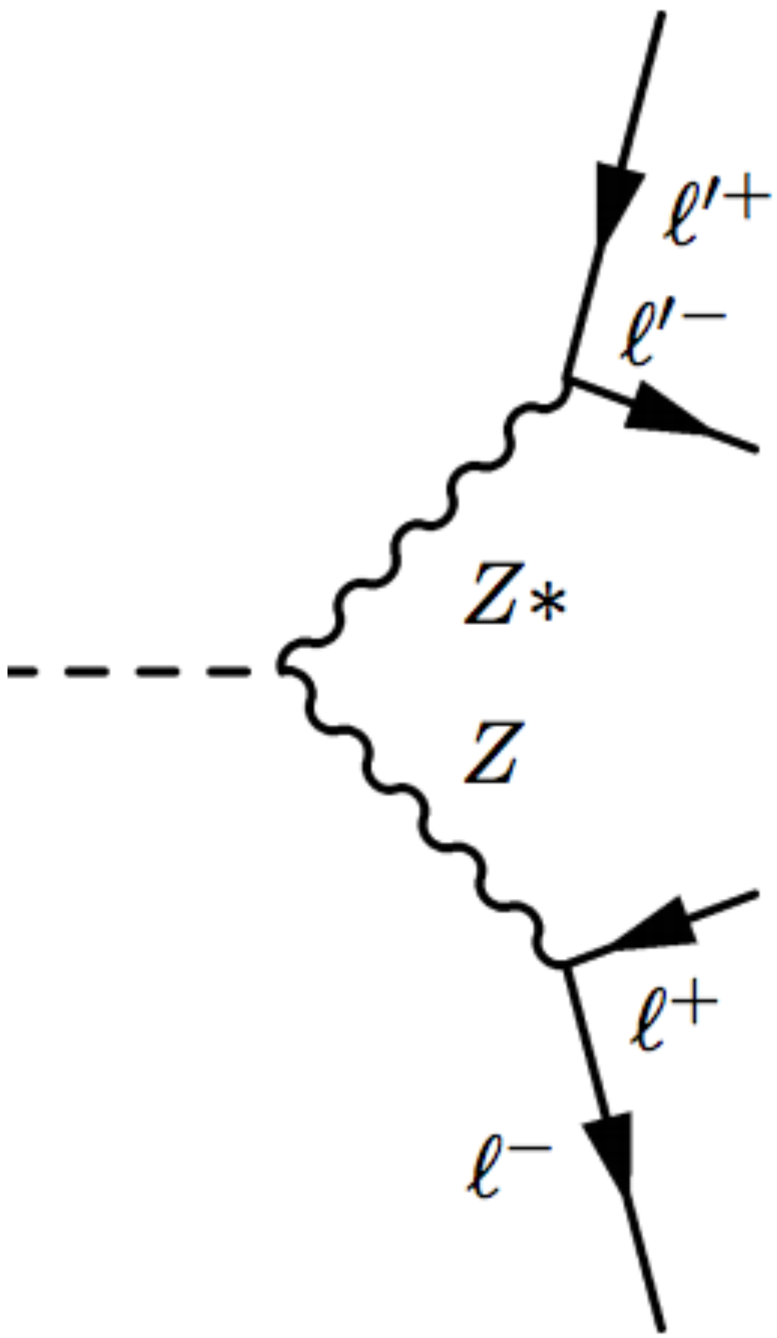
Scalar Decay to Bosons



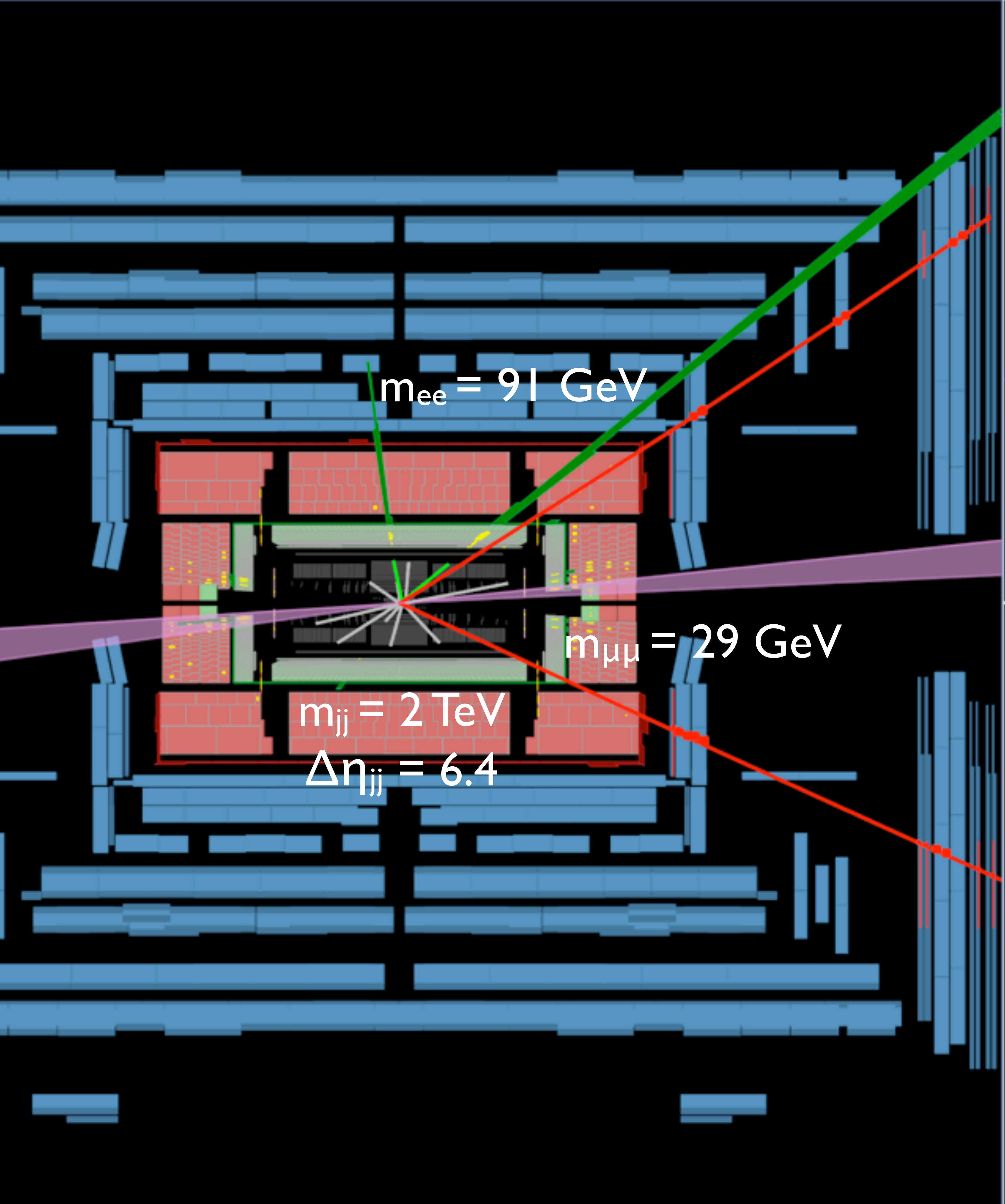


- Excellent mass resolution: $\gamma\gamma$, $ZZ \rightarrow 4\ell$
- Large cross section: WW

$ZZ^* \rightarrow 4\ell$



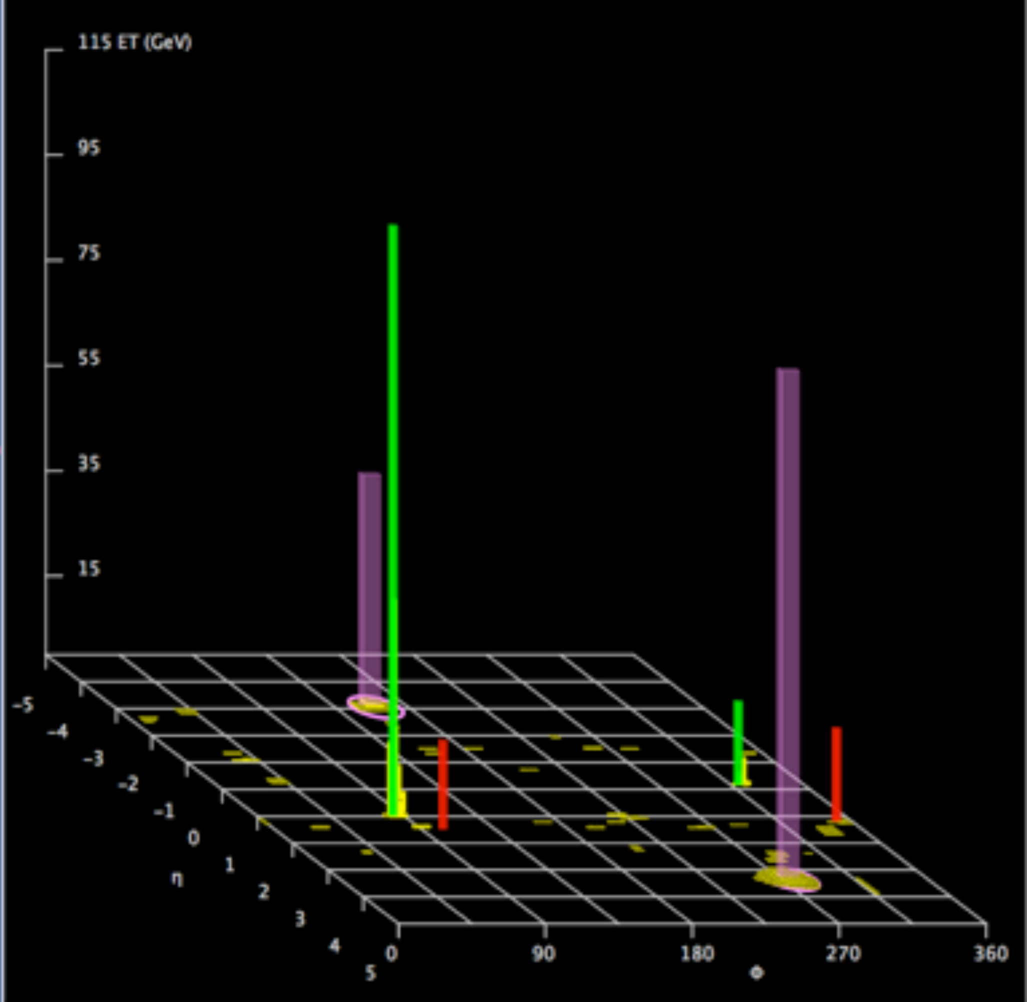
- Two same-flavor, opposite-sign lepton pairs
- ATLAS Selection
  - e (μ) p_T (E_T) > 7 (6) GeV, $|\eta| < 2.47$ (2.7)
  - Leading 3 leptons: $p_T > 20, 15, 10$GeV
  - FSR Recovery: add at most one photon to "improve" $m_{\ell\ell\gamma}$, priority to photons close to the leading dilepton
- CMS Selection
  - e (μ) $p_T > 7$ (5) GeV, $|\eta| < 2.5$ (2.4)
  - Leading 2 leptons: $p_T > 20, 10$ GeV
  - FSR Recovery: attached to closest lepton
- Signal extraction
  - ATLAS: Z mass-constrained kinematic fit, fiducial cross section for 118-129 GeV
  - CMS: kinematic discriminants (118-130 GeV)



Run Number: 280862, Event Number: 53564866

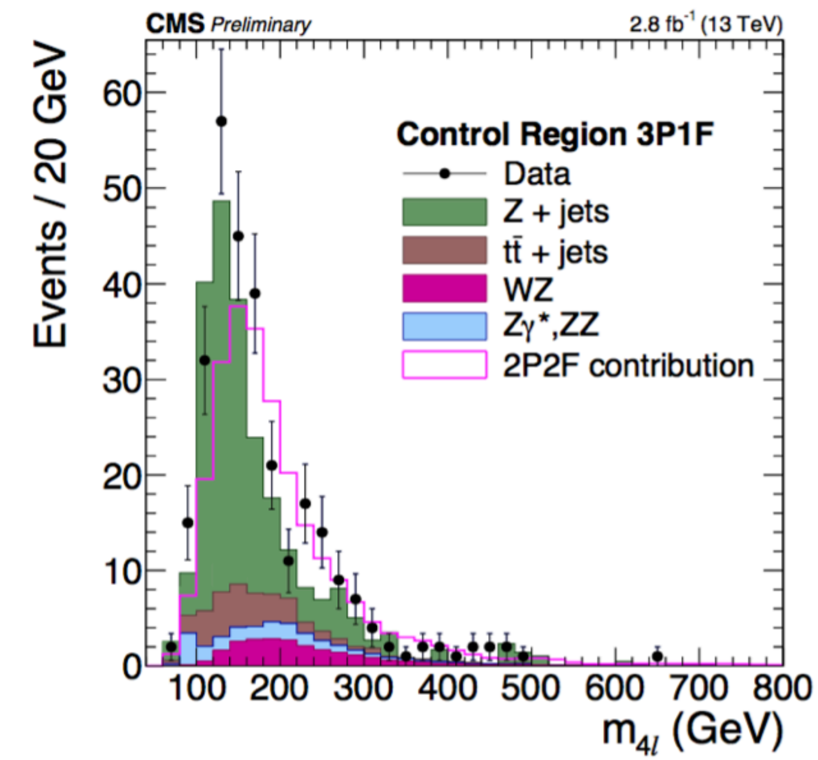
Date: 2015-10-02 16:24:44 CEST

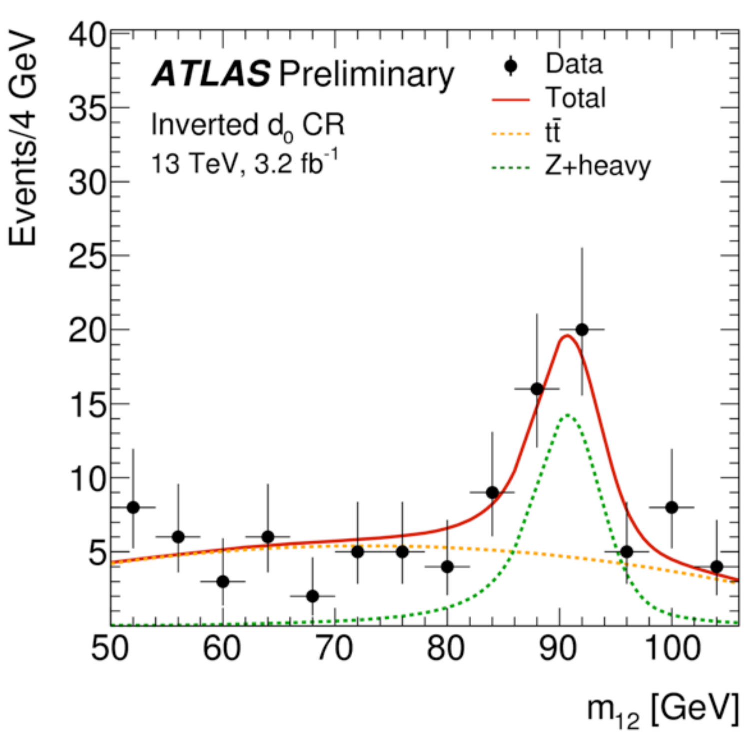
$m_{4\ell}$ = 129 GeV

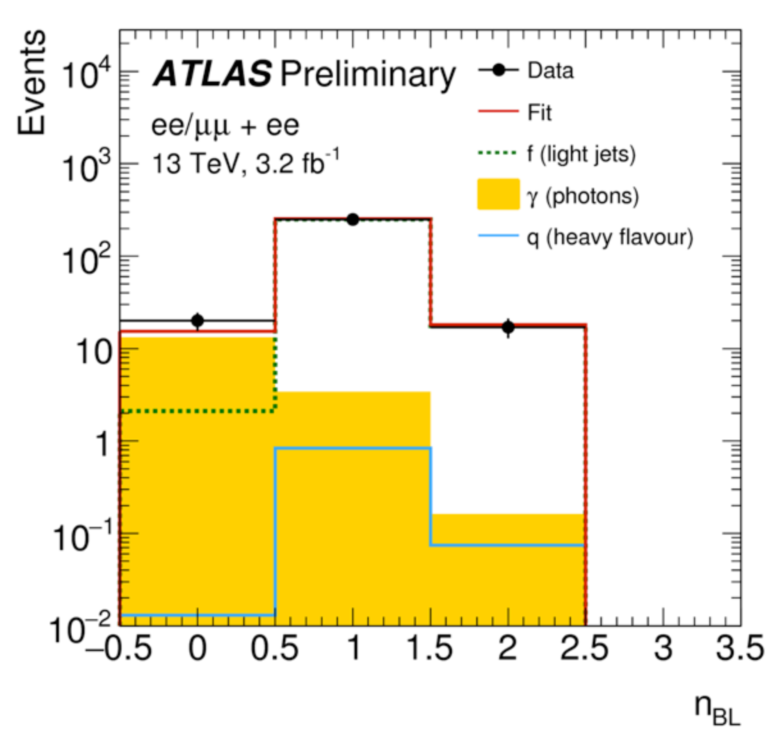


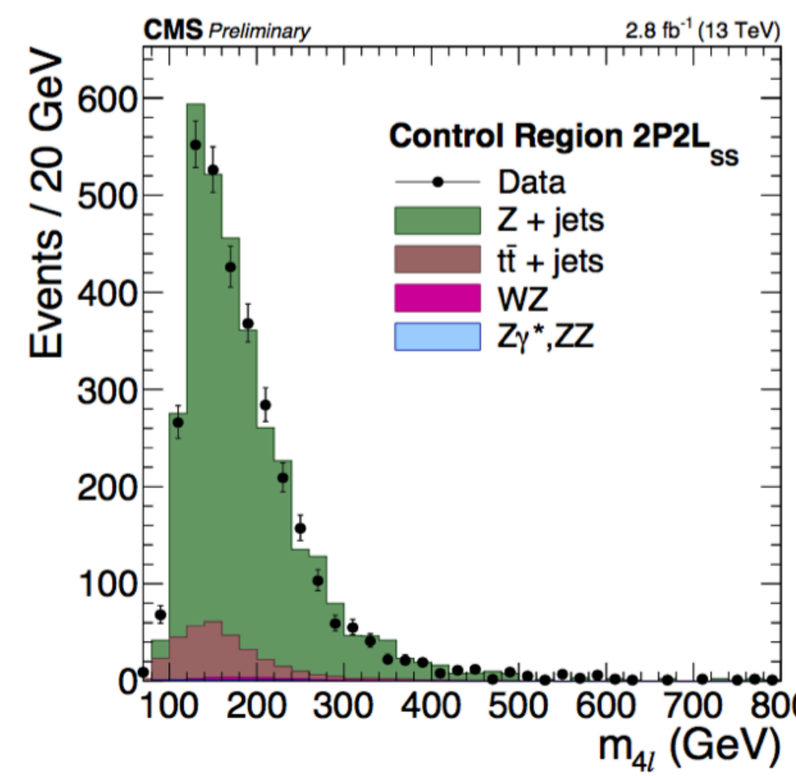
Backgrounds

- Main background: non-resonant ZZ* (irreducible)
  - Simulation shape prediction
  - Normalization checked in $m_{4\ell}$ sidebands
- Smaller reducible backgrounds: Z+jets, tt
  - Measured from control regions
  - ATLAS: inverted d_0 cut and isolation
  - CMS: 2 methods give good agreement

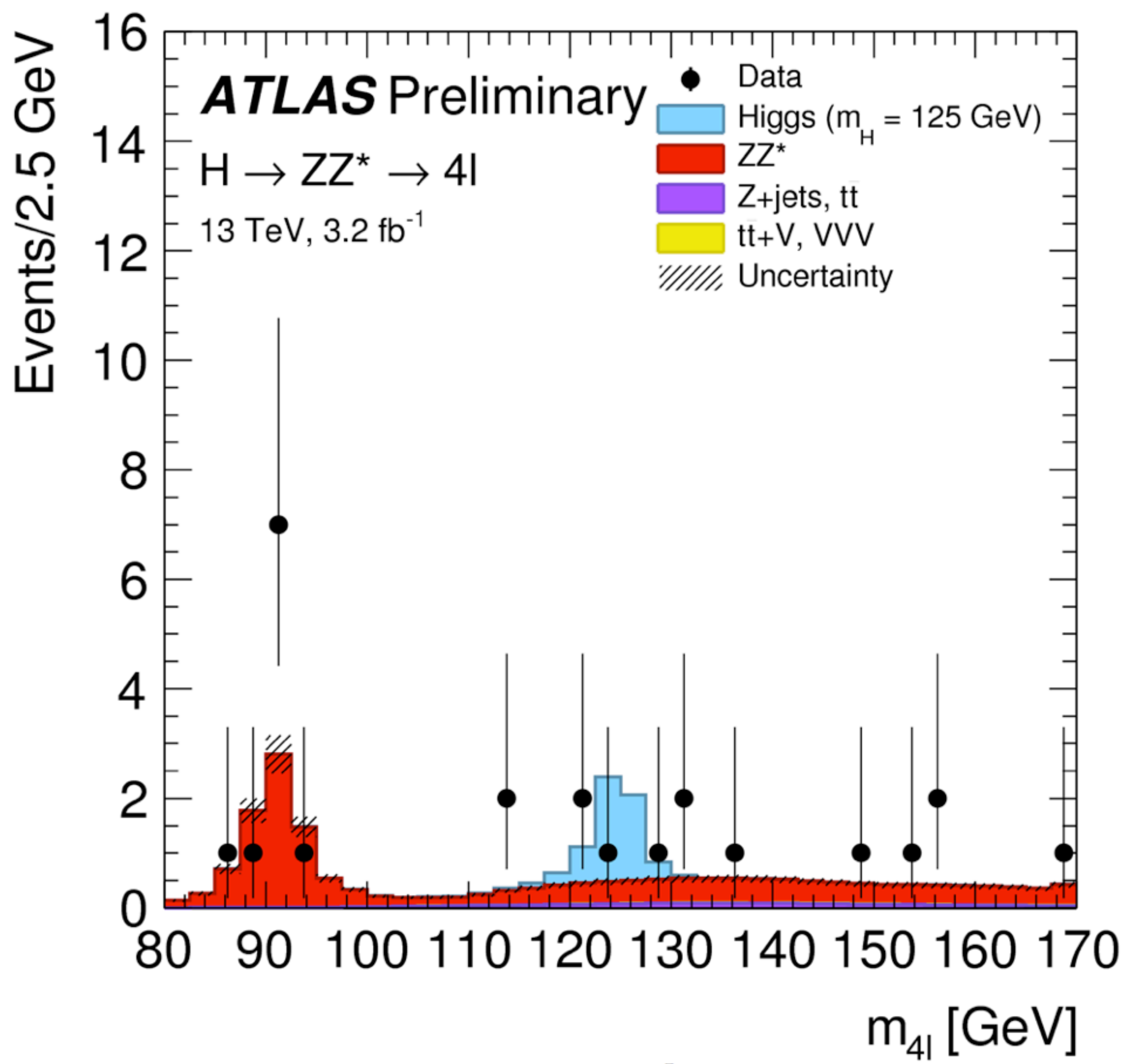


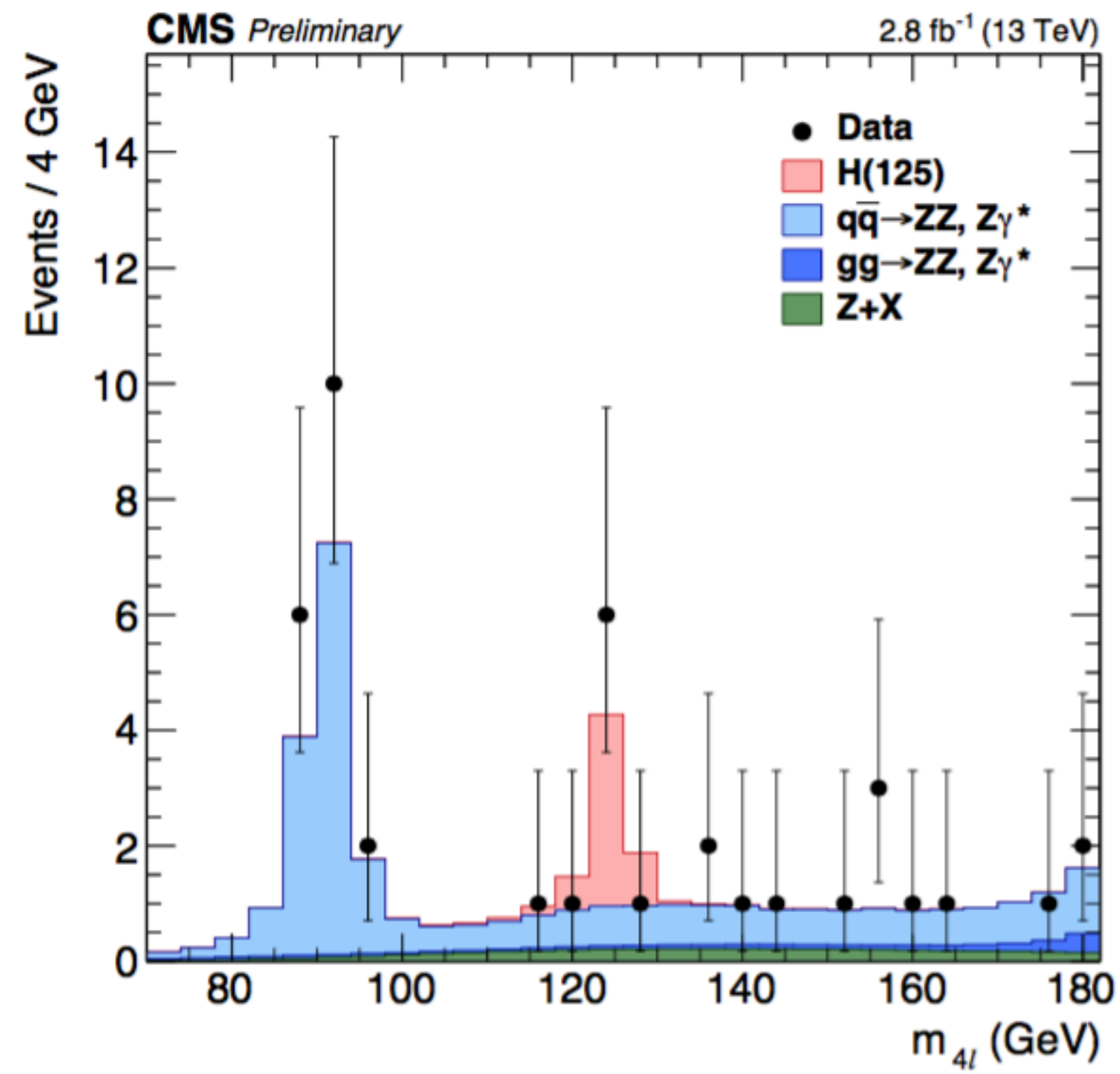






$m_{4\ell}$ Distribution



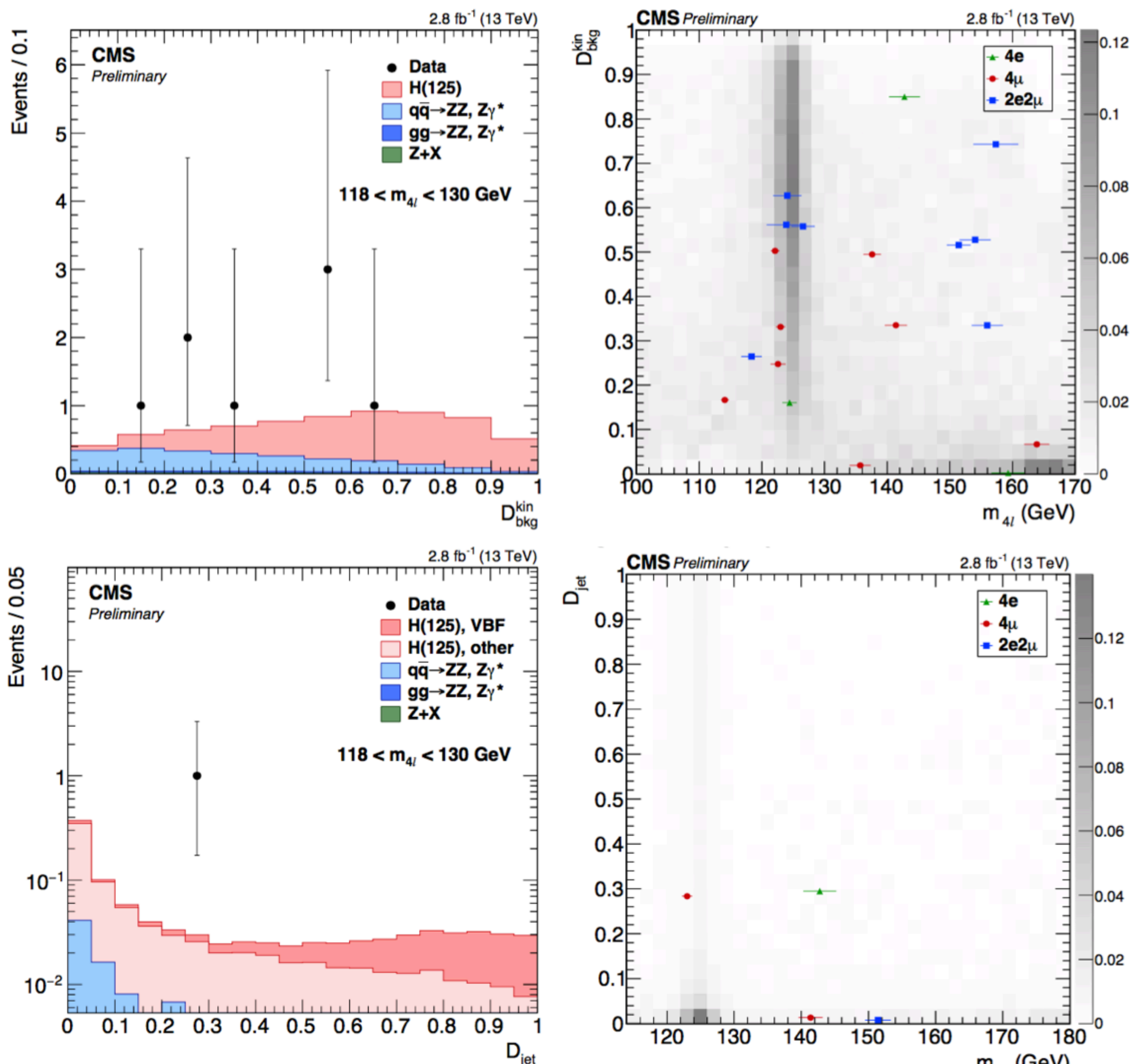


ATLAS

118-129 GeV

Final state	Signal full mass range	Signal	ZZ^*	$Z+jets$, $t\bar{t}$ $t\bar{t}V, VVV, WZ$	S/B	Expected	Observed
4μ	1.79 ± 0.21	1.67 ± 0.20	0.64 ± 0.06	0.08 ± 0.03	2.3	2.39 ± 0.21	1
$2e2\mu$	1.19 ± 0.14	1.06 ± 0.13	0.44 ± 0.04	0.07 ± 0.03	2.1	1.57 ± 0.14	1
$2\mu 2e$	1.07 ± 0.16	0.96 ± 0.15	0.34 ± 0.05	0.09 ± 0.02	2.2	1.40 ± 0.16	2
$4e$	1.01 ± 0.15	0.88 ± 0.13	0.32 ± 0.05	0.09 ± 0.02	2.1	1.30 ± 0.14	0
Total	5.06 ± 0.60	4.57 ± 0.54	1.74 ± 0.19	0.34 ± 0.06	2.2	6.65 ± 0.58	4

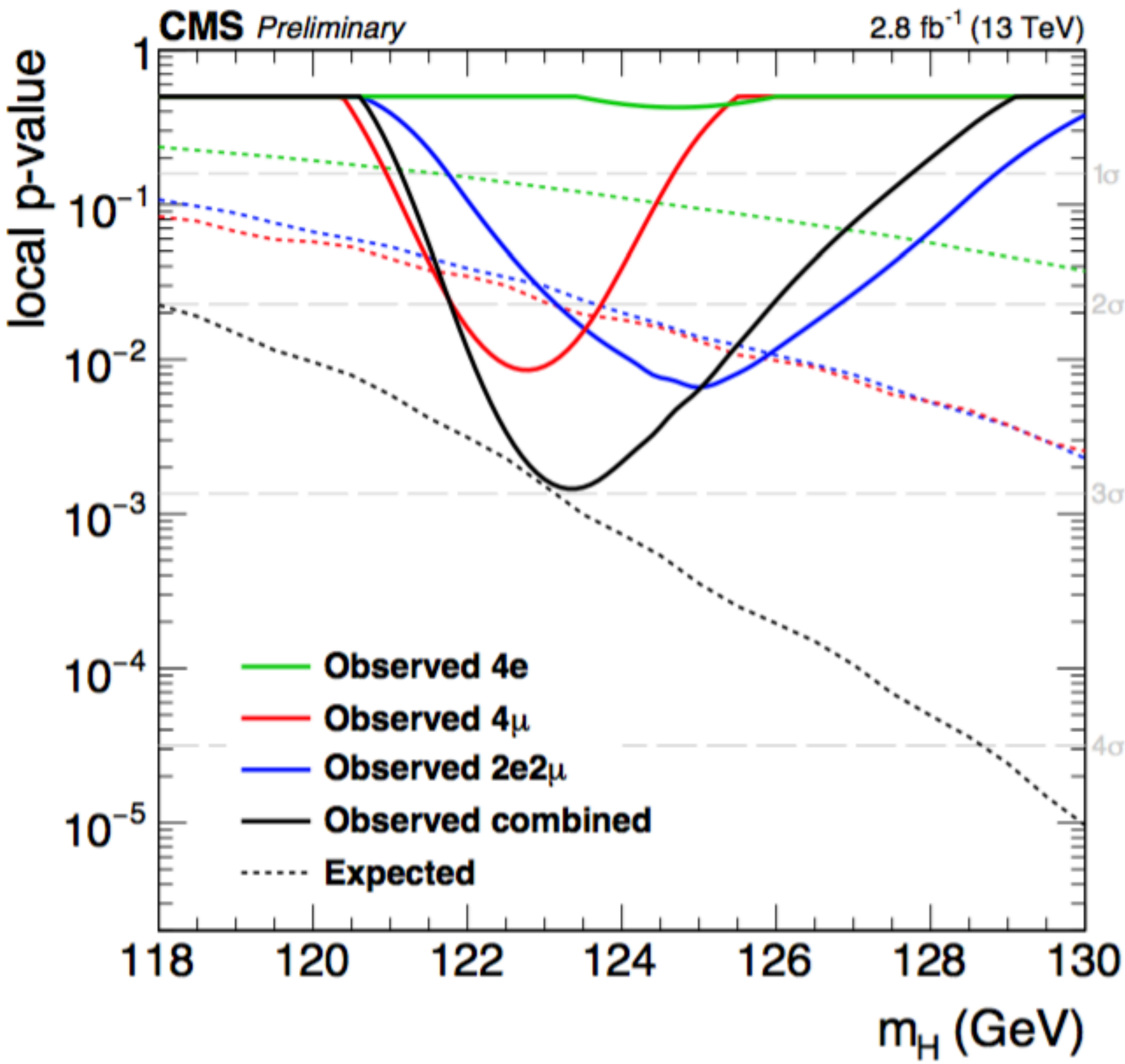
CMS: Signal extraction



- Top: kinematic discriminant between signal and background
- Bottom: kinematic discriminant to identify VBF-like events
- Define 6 channels:
  - 4e, 2e2μ, 4μ
  - VBF (D_{jet} > 0.5), untagged

$$\mathcal{L}_{2D}(m_{4l}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}}) = \mathcal{L}(m_{4l})\mathcal{L}(\mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}}|m_{4l})$$

CMS: Signal extraction



- Top: kinematic discriminant between signal and background
- Bottom: kinematic discriminant to identify VBF-like events
- Define 6 channels:
  - 4e, 2e2μ, 4μ
  - VBF (D_{jet} > 0.5), untagged
- Observed (expected) at 125.09 GeV: 2.5σ (3.4 σ)

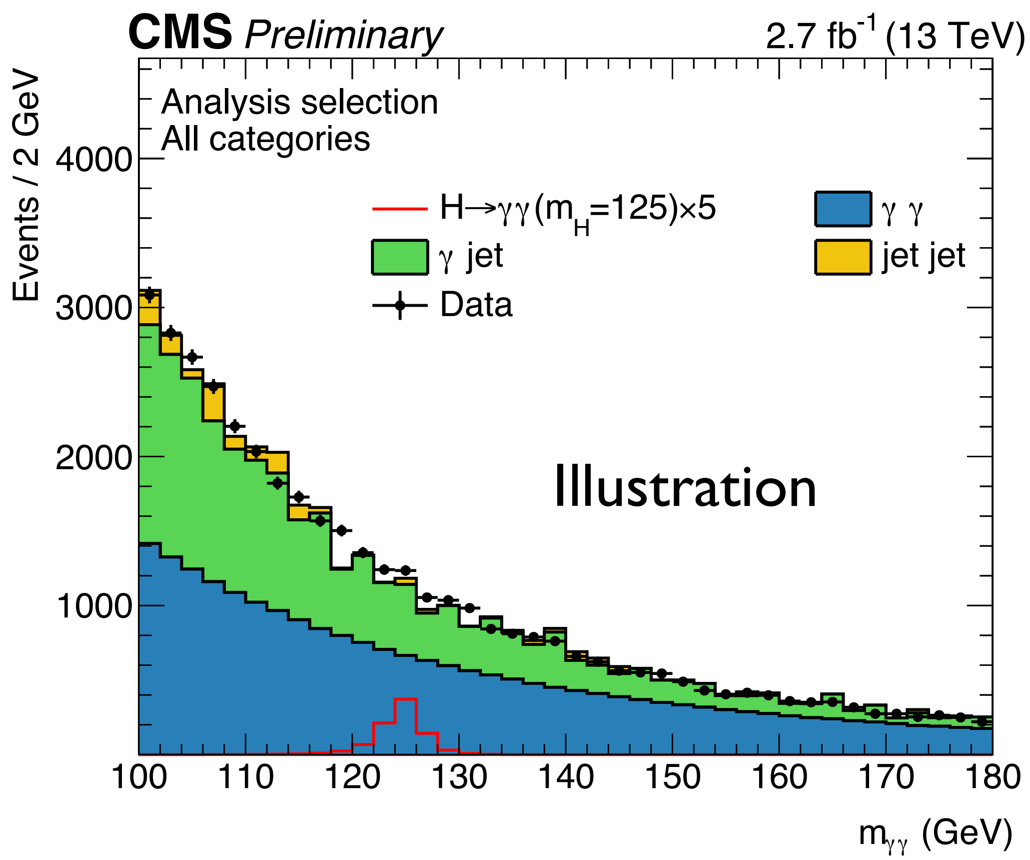
$$\mu = \sigma/\sigma_{SM} = 0.82^{+0.57}_{-0.43}$$

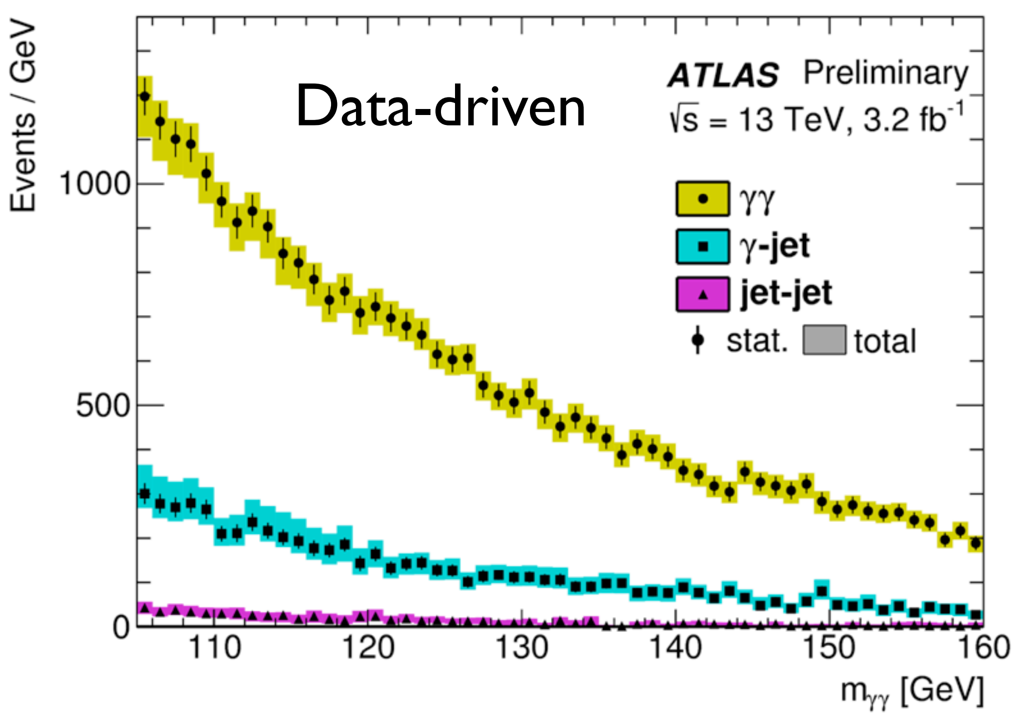
Untagged: $0.89^{+0.62}_{-0.46}$

VBF: $0.00^{+1.67}_{-0.00}$

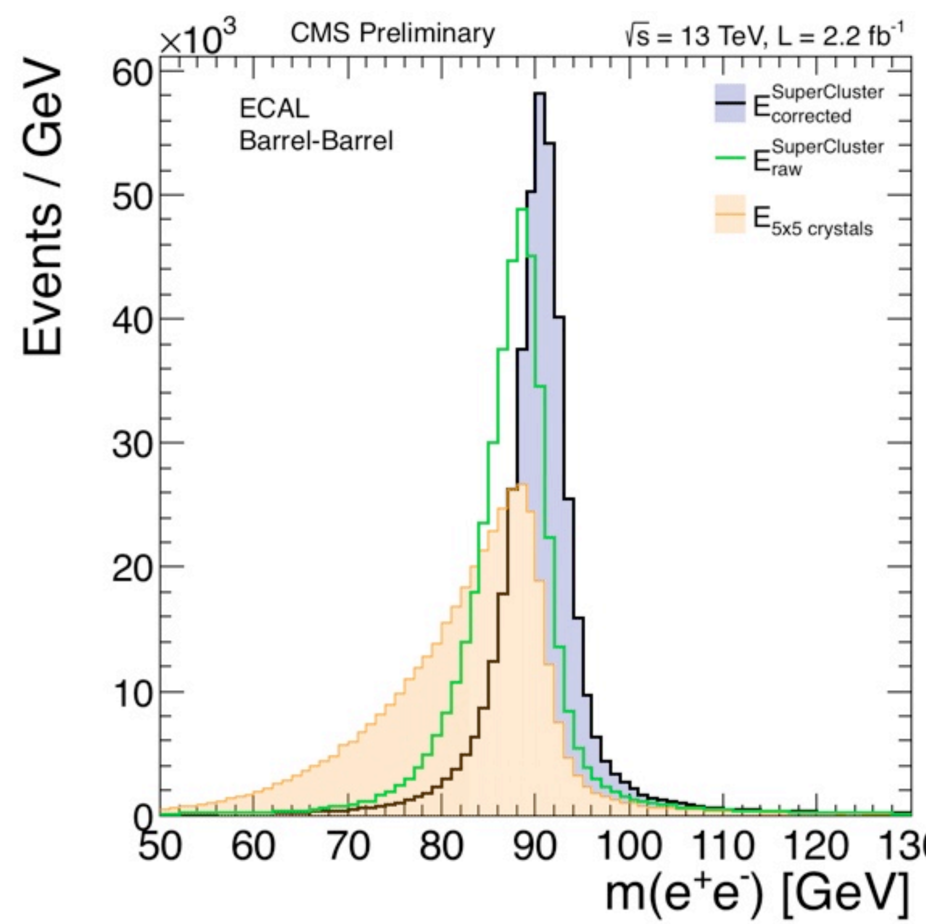
$$\mathcal{L}_{2D}(m_{4l}, \mathcal{D}^{\text{kin}}_{\text{bkg}}) = \mathcal{L}(m_{4l})\mathcal{L}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4l})$$

H → γγ



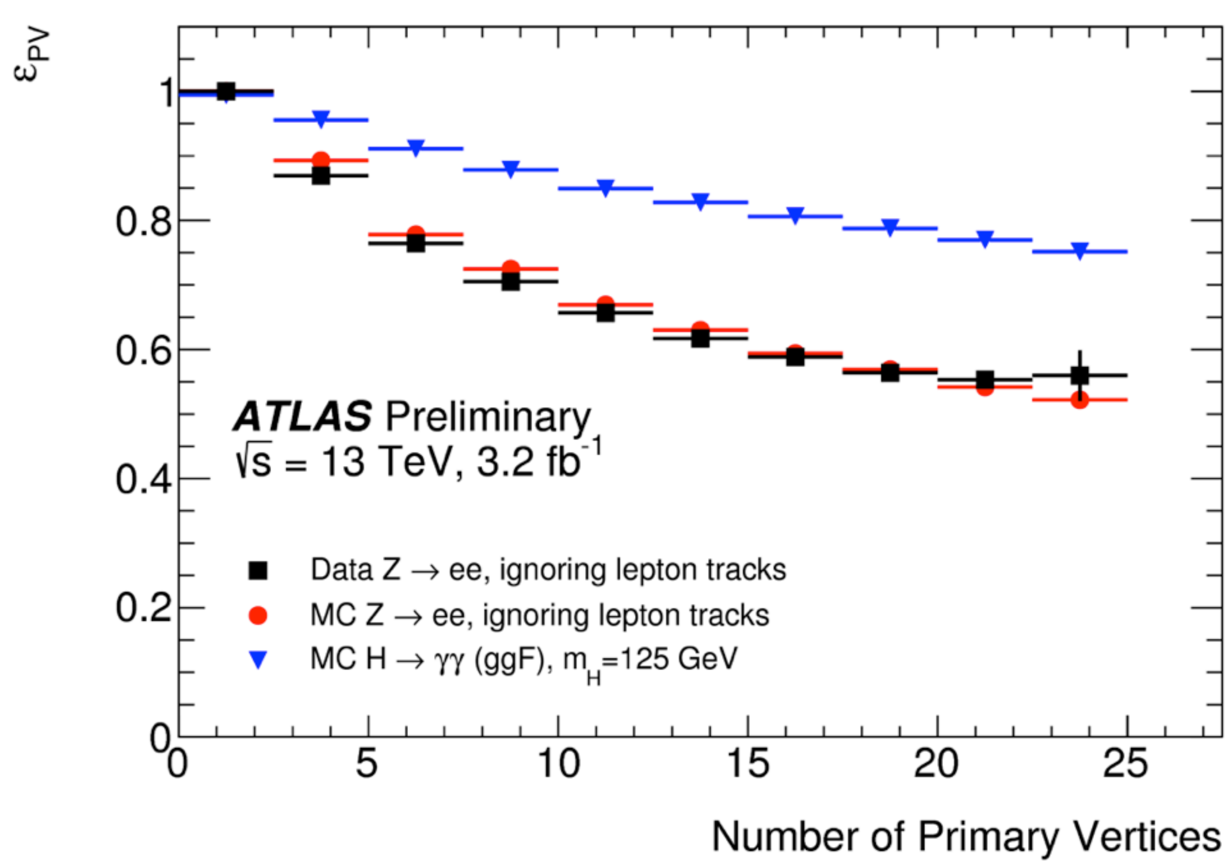


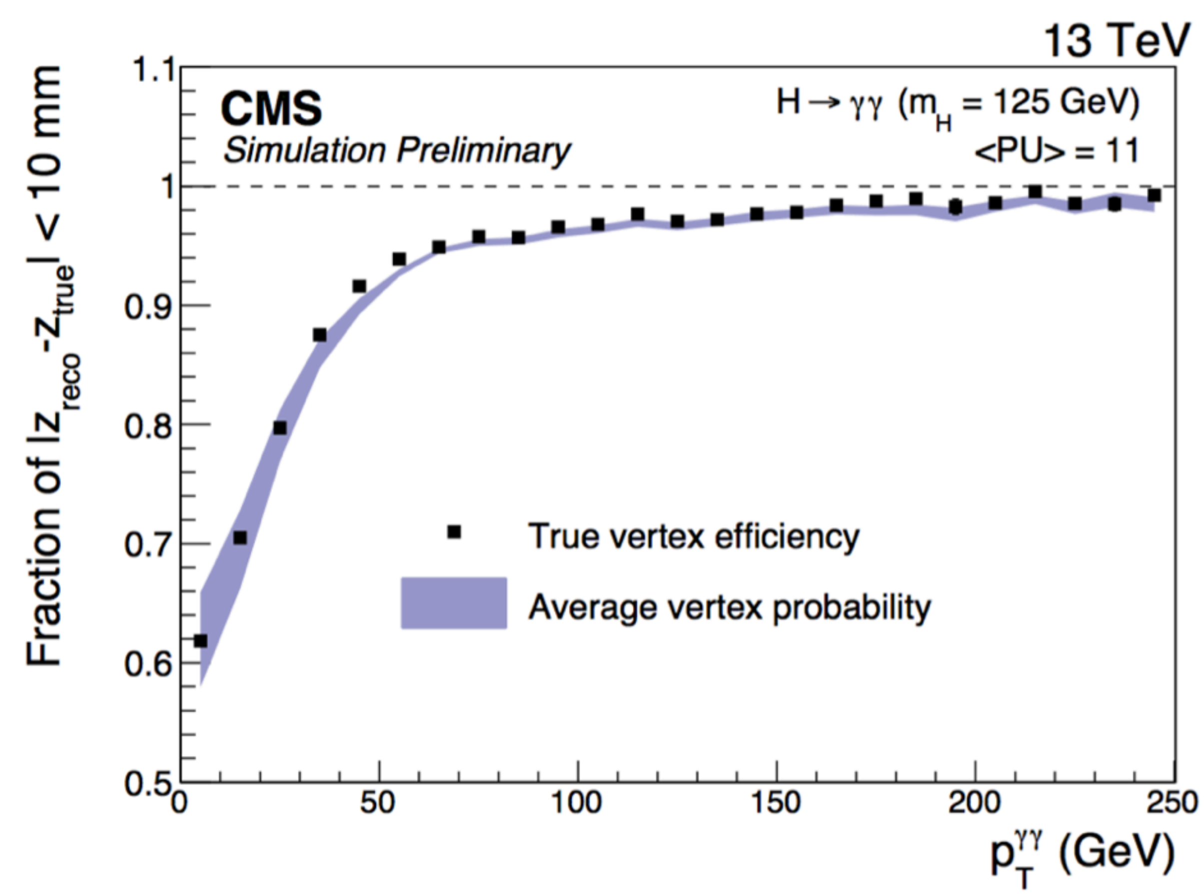
- Maximize Signal-to-Background using mass: $m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\Delta\alpha)$
  - Photon energy resolution
  - Correct vertex identification



Vertex Identification

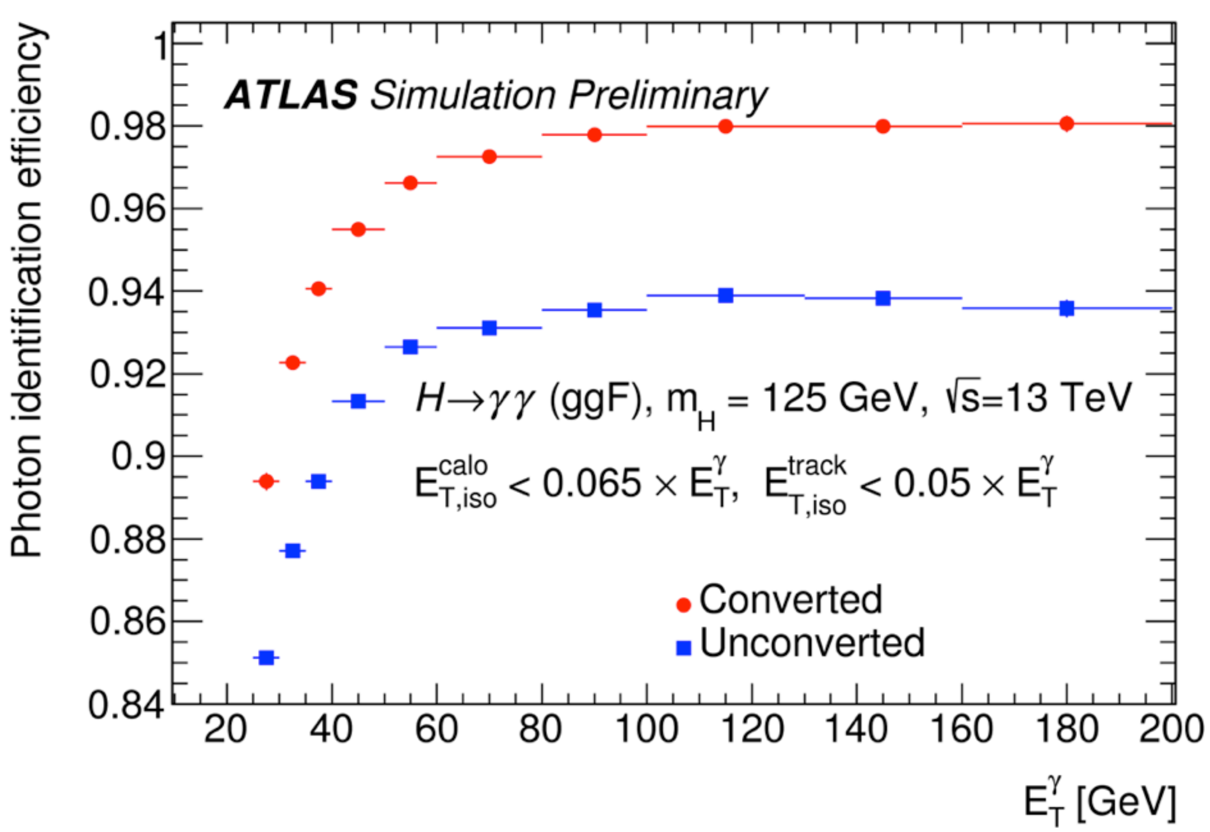
- ATLAS: MVA using Σp_T^2, Σp_T of vertex tracks, diphoton balancing with vertex tracks, trajectory from calorimeter segmentation
- CMS
  - MVA using Σp_T^2, diphoton balancing with vertex tracks
  - Estimator of correct ID probability propagated to photon categorization
  - More details: I. Kucher's YSF talk last night

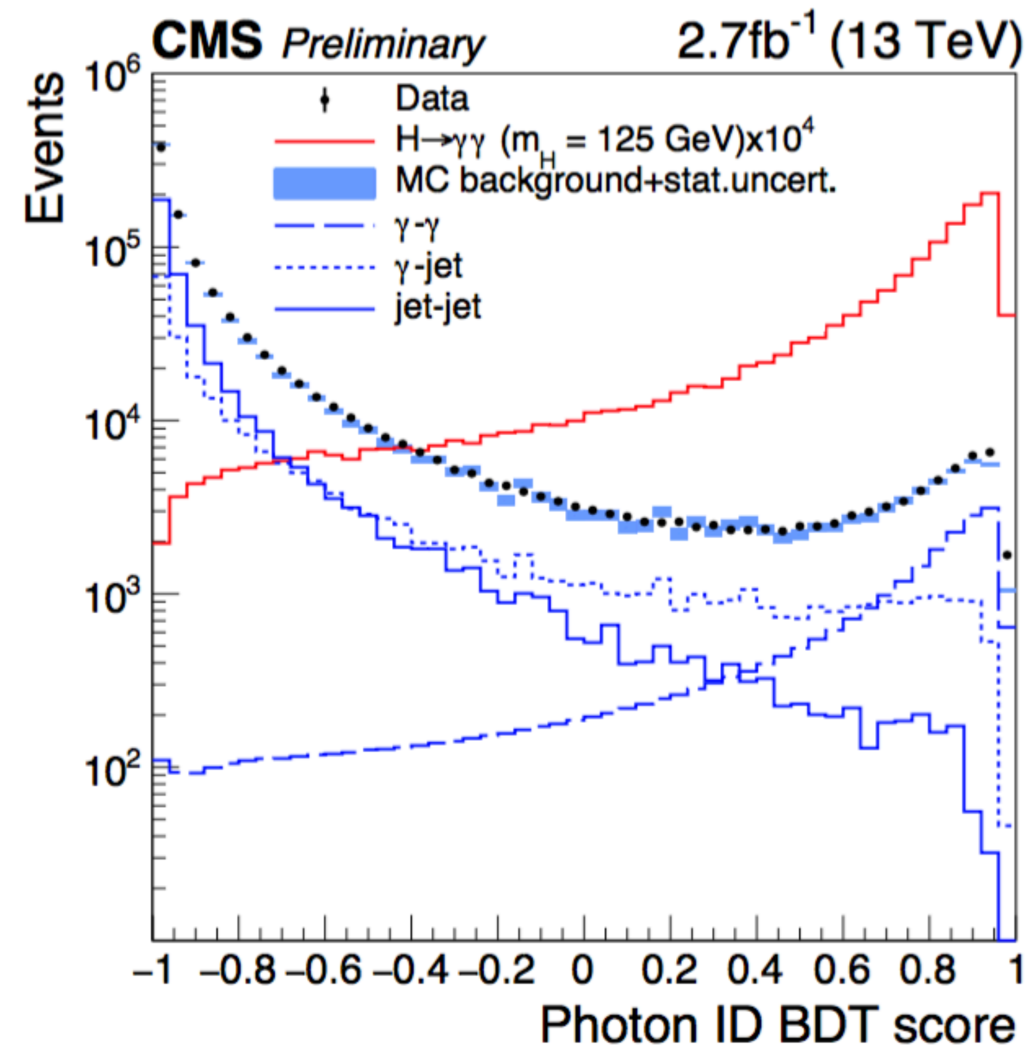




Photon Identification

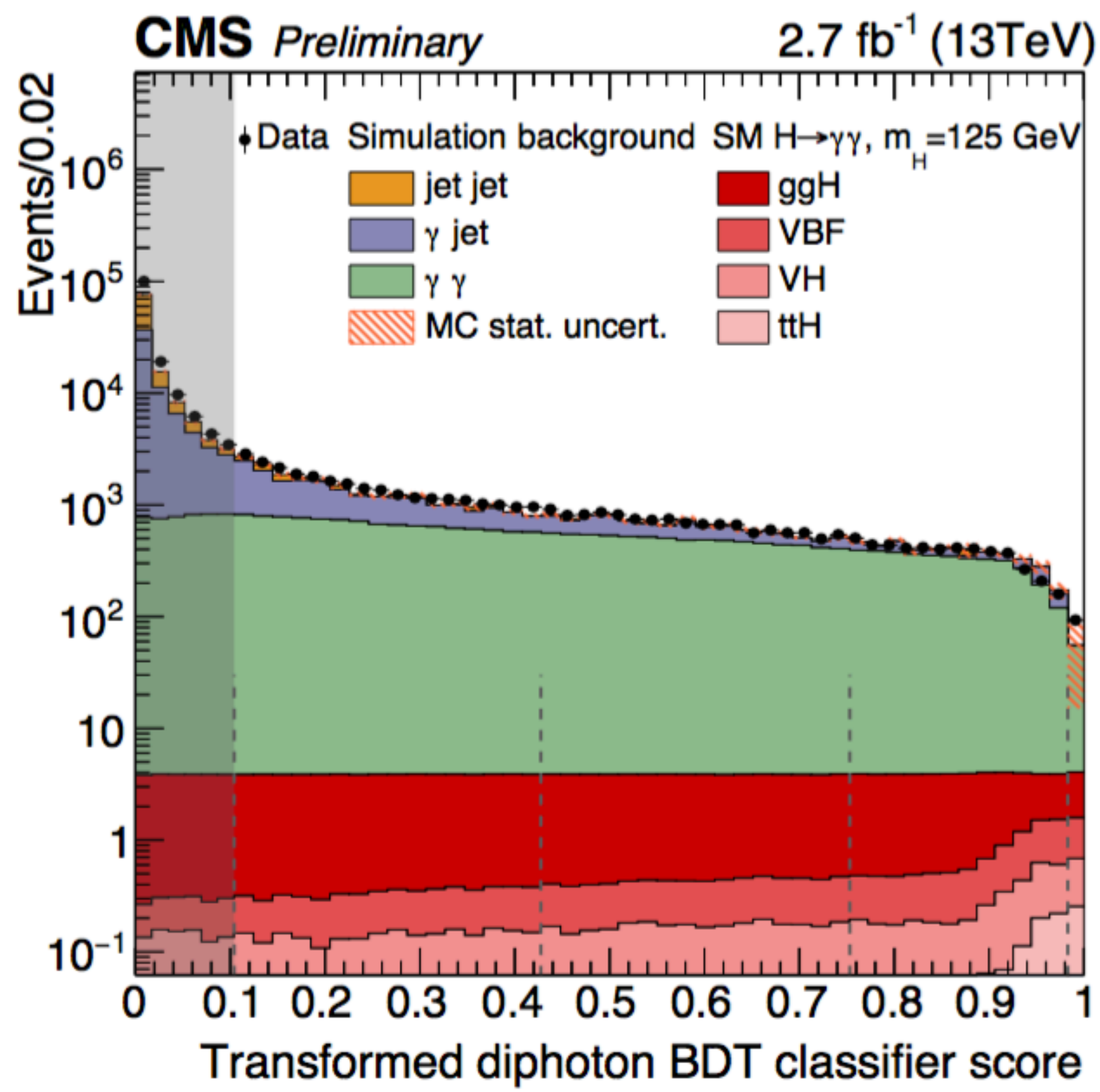
- Both experiments: set of variables reflecting the expected shower shape and containment, key variables corrected for data/MC agreement
- ATLAS: high granularity first ECAL layer for π^0 discrimination, cut-based ID
- CMS: MVA combining shower shape and isolation variables





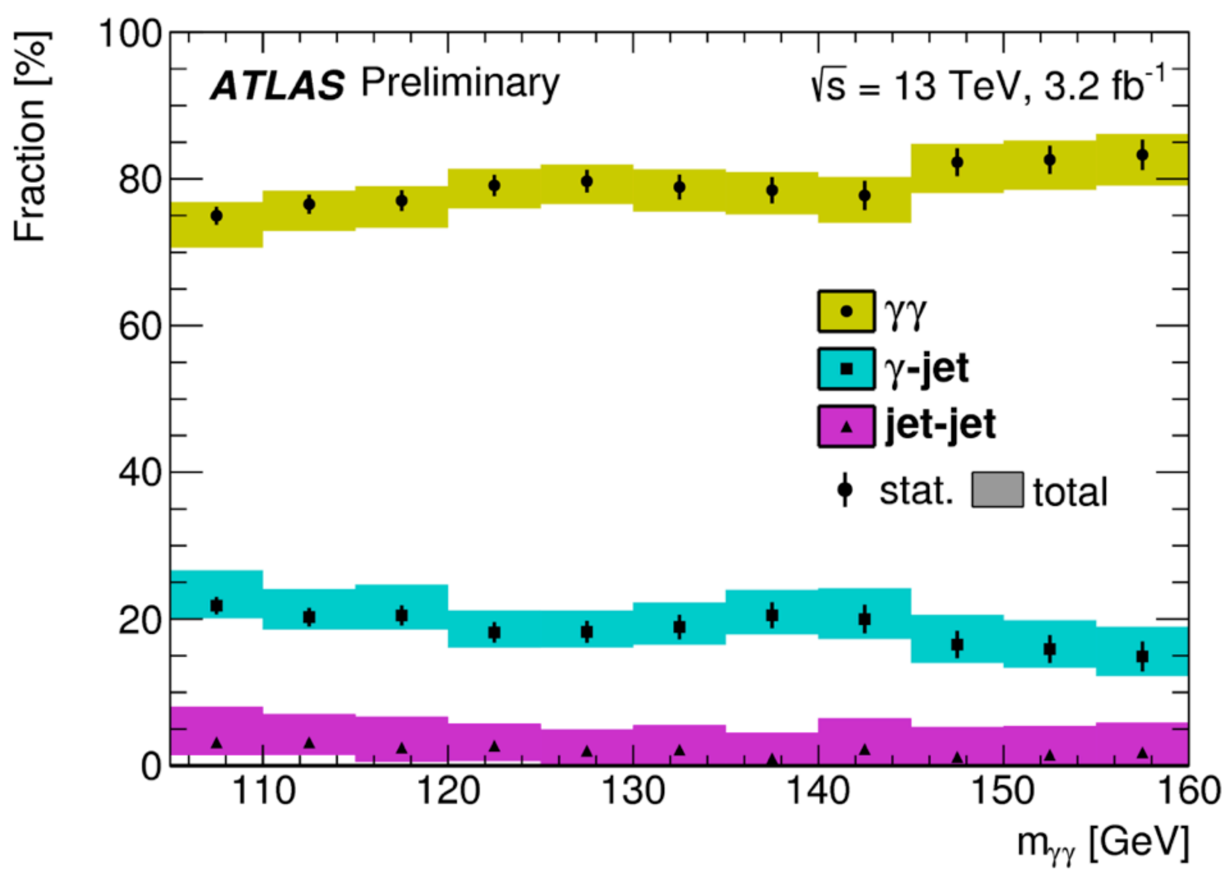
CMS: Event Categorization

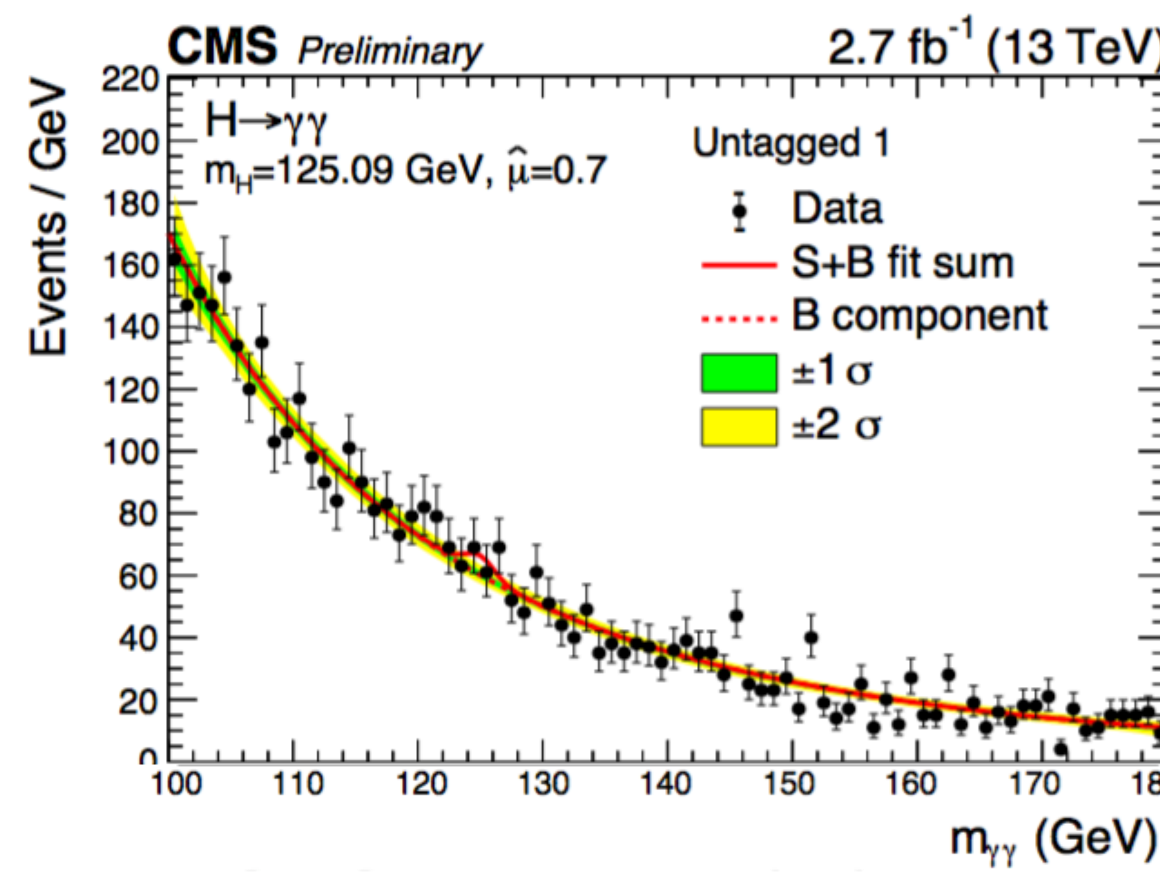
- Use vertexing, photon information, kinematics to produce classifier that indicates the expected diphoton resolution
- Divide events into 4 categories based on output of classifier
- Additional categories:
  - TTH events require a b-tag and:
    - Lepton + ≥2 jets; or
    - ≥4 jets
  - VBF events tagged additional, similar multivariate discriminator (2 categories)
- Signal model resolution: 1.25-2.63 GeV depending on category
  - Inclusive: 1.94 GeV
  - ATLAS inclusive: 1.68 GeV



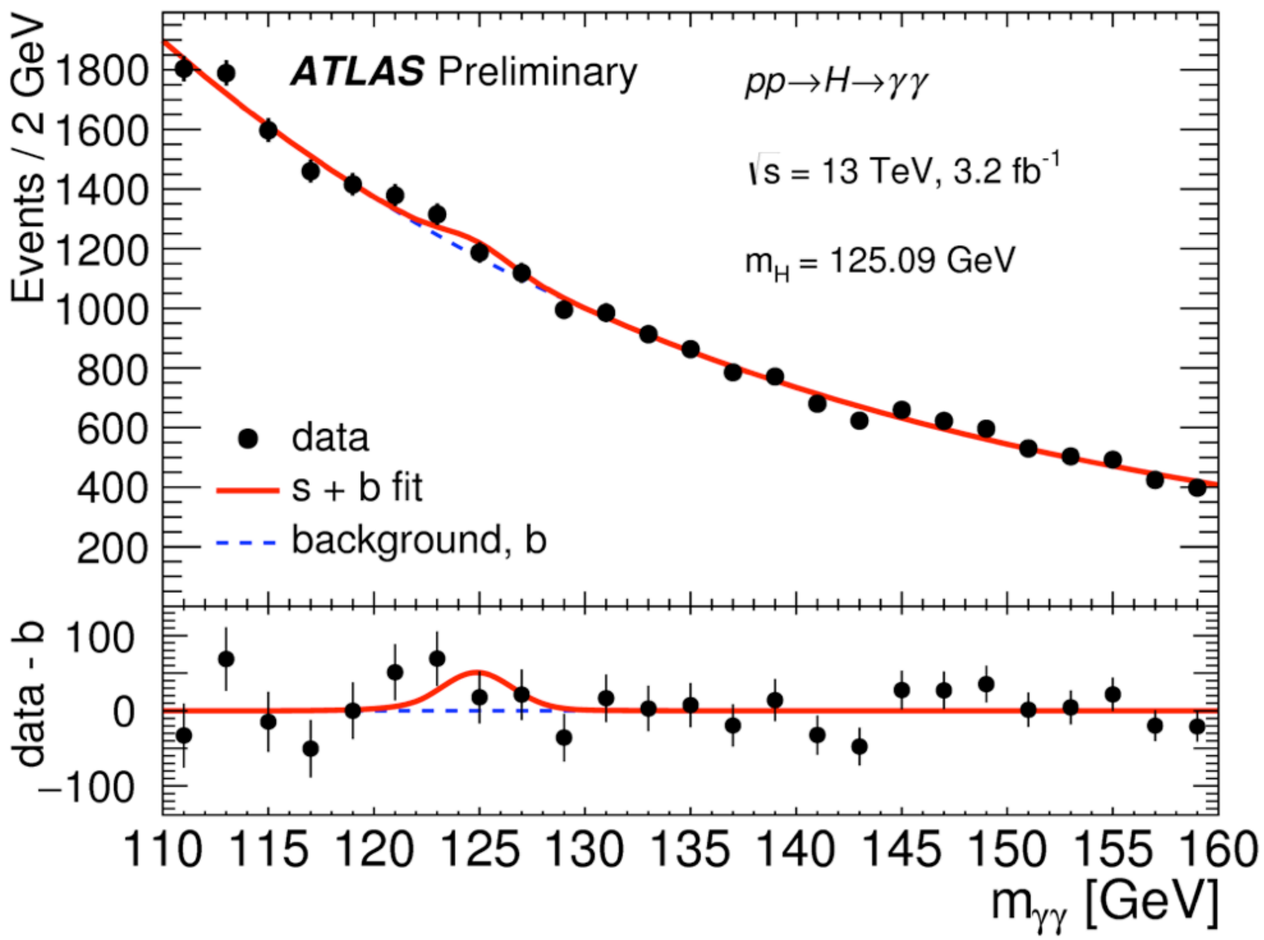
Background Model

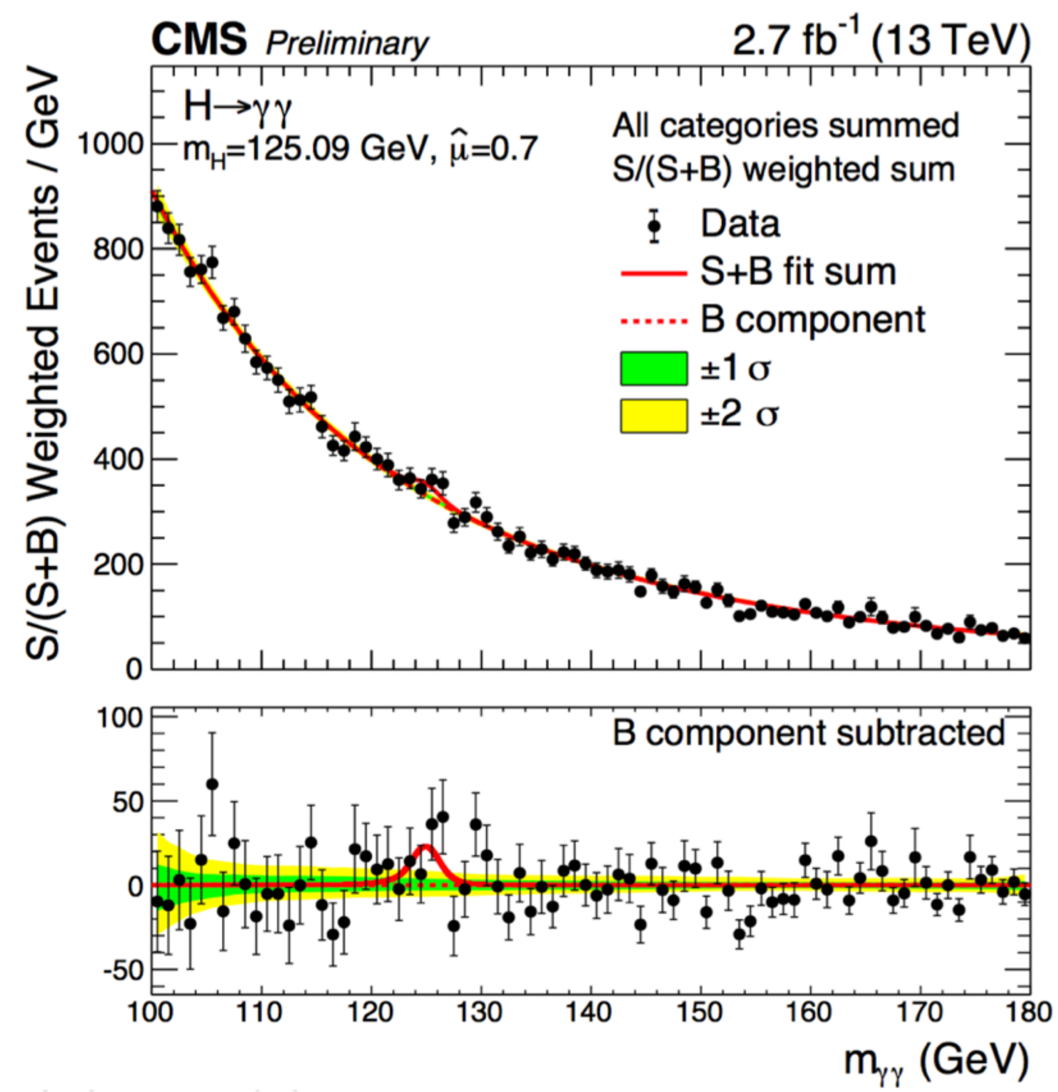
- ATLAS: templates from γγ, γ-jet, jet-jet background
  - Normalization from data-driven measurement
  - Number of signal events in fit to background-only samples used as bias estimate
- CMS: discrete profiling method
  - Range of functions considered that fit background well
  - Choice of function made by signal fit, bias accounted for by other possibilities





Inclusive $m_{\gamma\gamma}$ Distribution

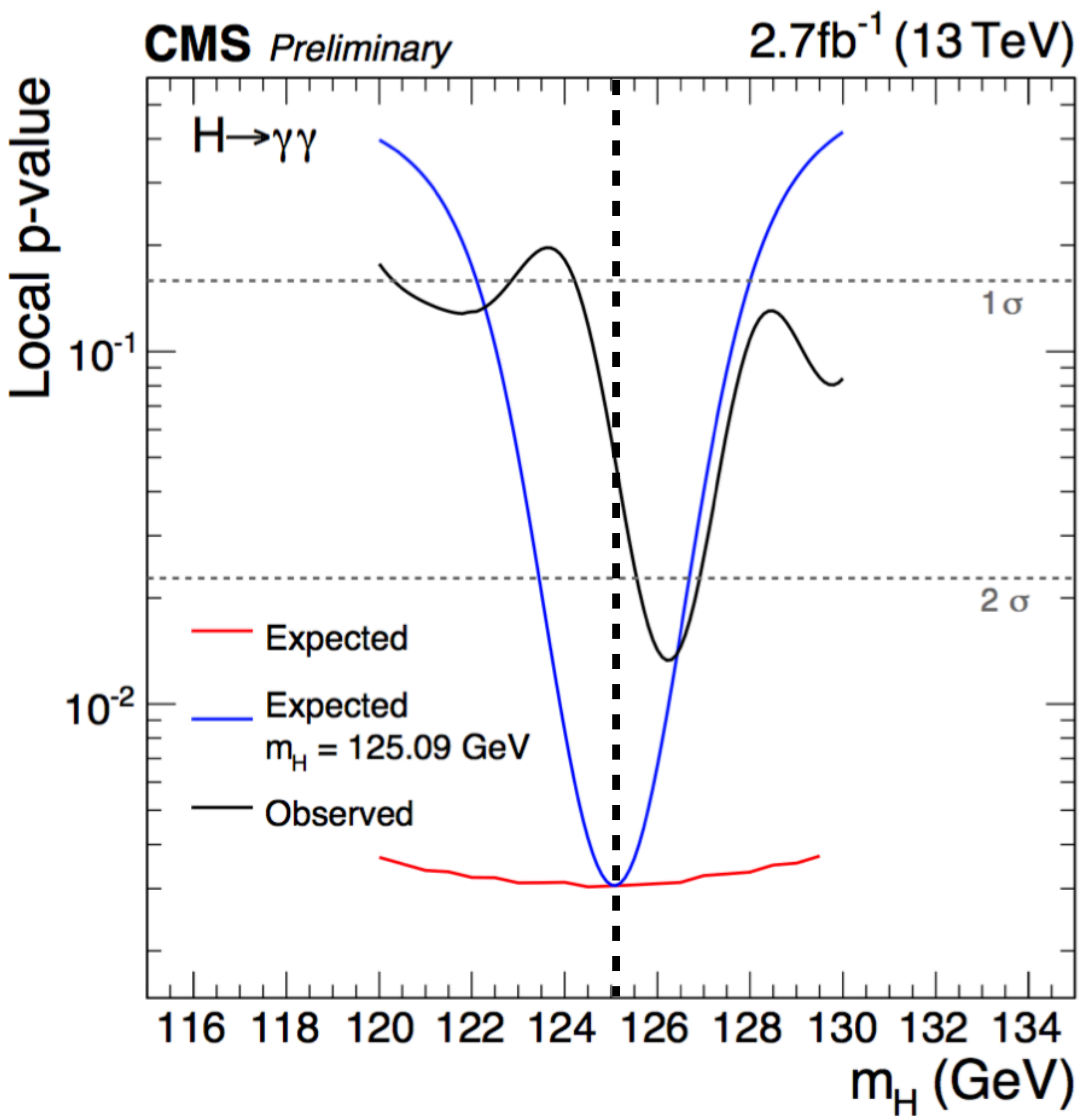


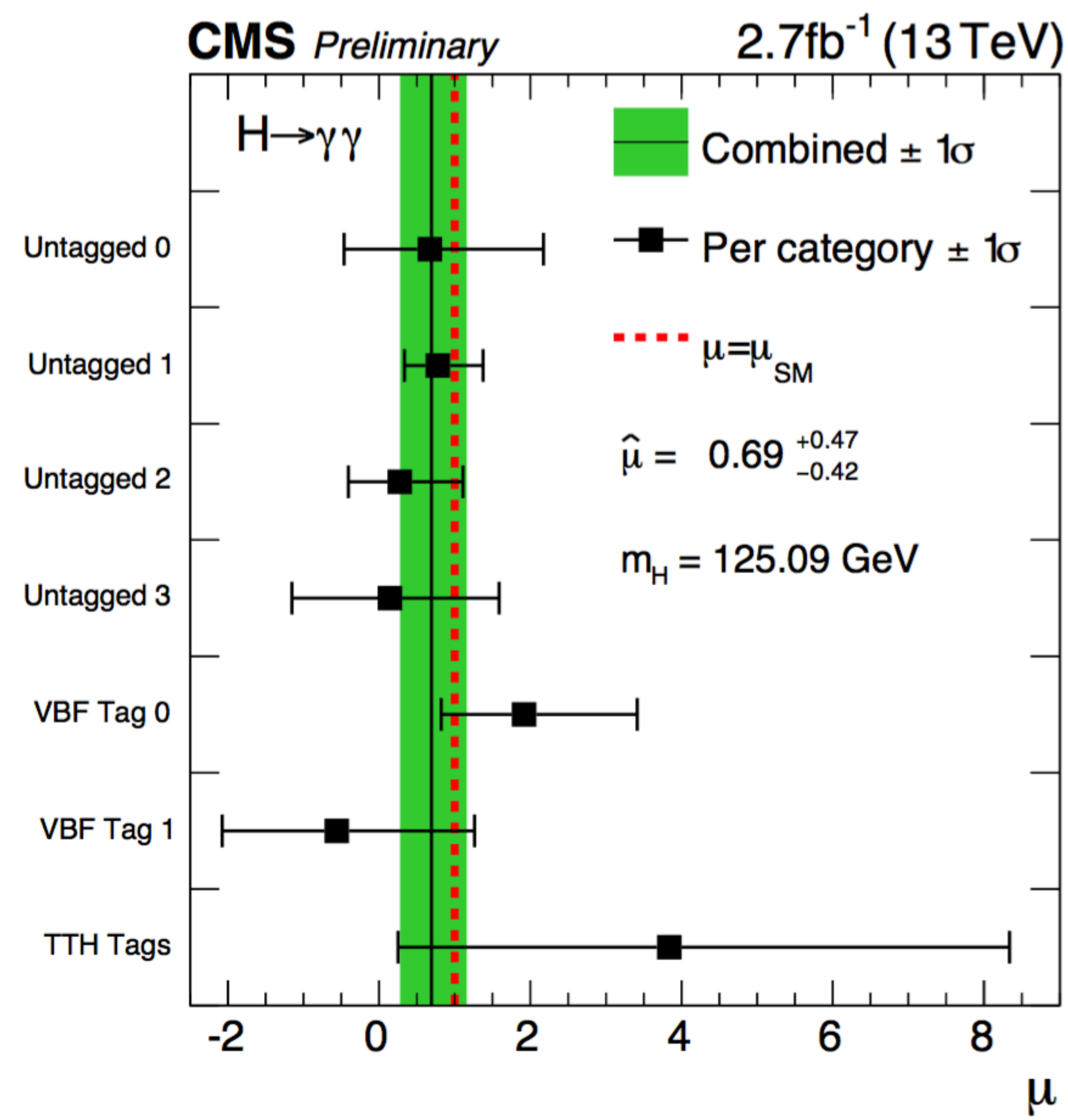


- Both experiments: fix mass to Run 1 measurement, much more precise than constraints from Run 2 data
- CMS: sum over all categories, weighted over S/(S+B)

CMS: Signal Extraction

- Profile likelihood fit yields:
  - Observed (expected significance at 125.09 GeV: 1.7σ (2.7σ)
  - $\hat{\mu} = 0.69^{+0.47}_{-0.42}$ @ fixed 125.09 GeV

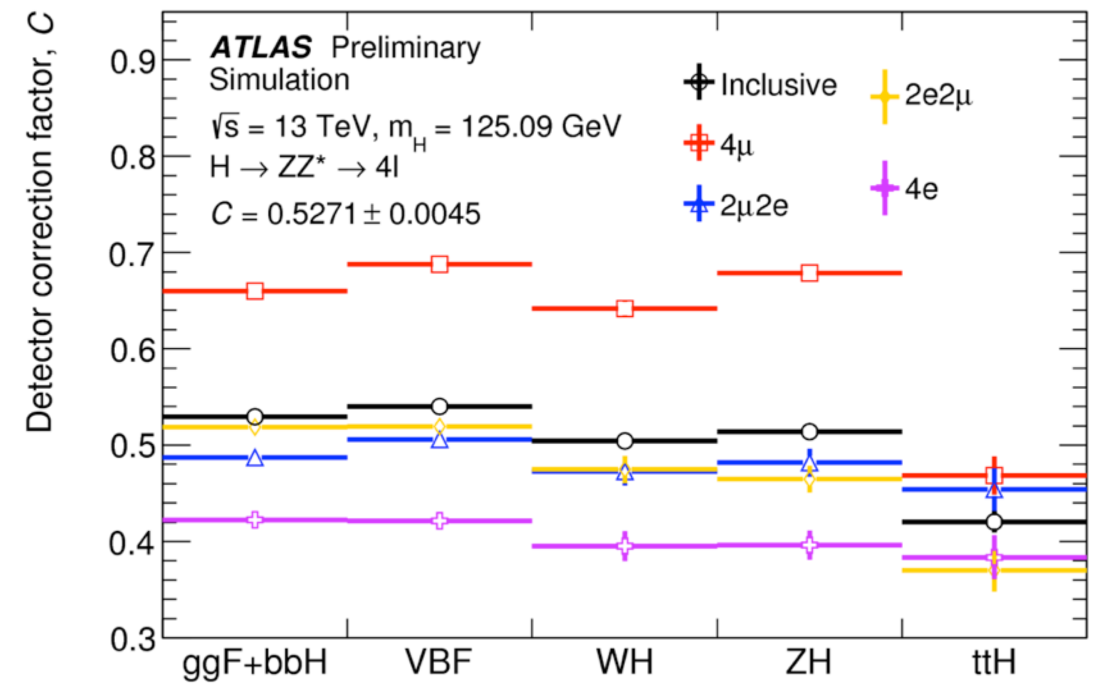




ATLAS: Cross Sections

- Fiducial cross section extracted for ATLAS γγ and ZZ
- Both measurements extrapolated to total cross section & combined

$$\sigma^{\text{tot}} = \frac{N_s}{\mathcal{A} \cdot C \cdot \mathcal{B} \cdot \mathcal{L}_{\text{int}}}, \qquad \sigma^{\text{fid}}_{4\ell} = \frac{N_s}{C \cdot \mathcal{L}_{\text{int}}},$$



	7 TeV	8 TeV	13 TeV
Acceptance factor			
$H \to \gamma\gamma$	0.620 ± 0.007	0.611 ± 0.012	0.570 ± 0.006
$H \to ZZ^* \to 4\ell$	0.467 ± 0.010	0.460 ± 0.010	0.427 ± 0.006
Fiducial cross section [fb]			
$H \to \gamma\gamma$	49 ± 18	43 ± 10	52^{+40}_{-37}
$H \to ZZ^* \to 4\ell$	$1.9^{+1.2}_{-0.9}$	2.1 ± 0.5	$0.6^{+1.3}_{-0.9}$
Total cross section [pb]			
$H \to \gamma\gamma$	35^{+13}_{-12}	$30.5^{+7.5}_{-7.4}$	40^{+31}_{-28}
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16}	37^{+9}_{-8}	12^{+25}_{-16}
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.)	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.)	24^{+20}_{-17} (stat.) $^{+7}_{-3}$ (syst.)
LHC-XS	17.5 ± 1.6	22.3 ± 2.0	$50.9^{+4.5}_{-4.4}$

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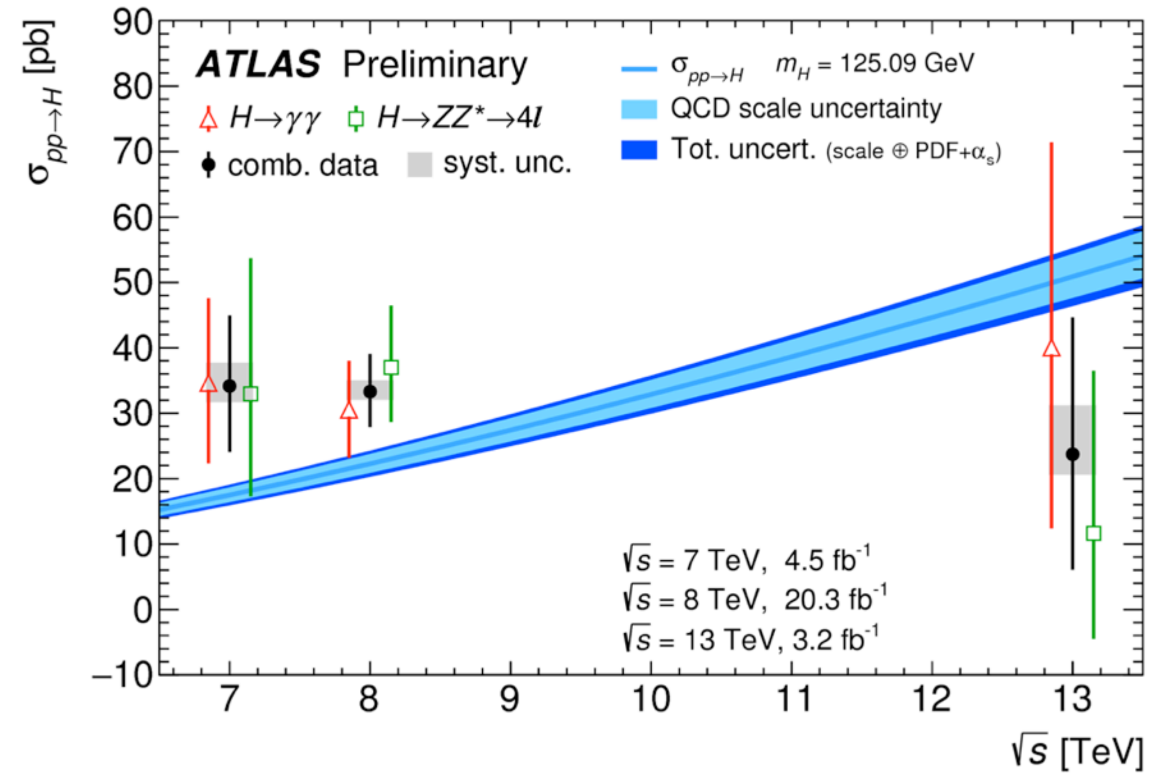

$$\sigma^{\text{tot}} = \frac{N_s}{\mathcal{A}\cdot\mathcal{C}\cdot\mathcal{B}\cdot\mathcal{L}_{\text{int}}}$$

$$\sigma^{\text{fid}}_{4\ell} = \frac{N_s}{\mathcal{C}\cdot\mathcal{L}_{\text{int}}}$$

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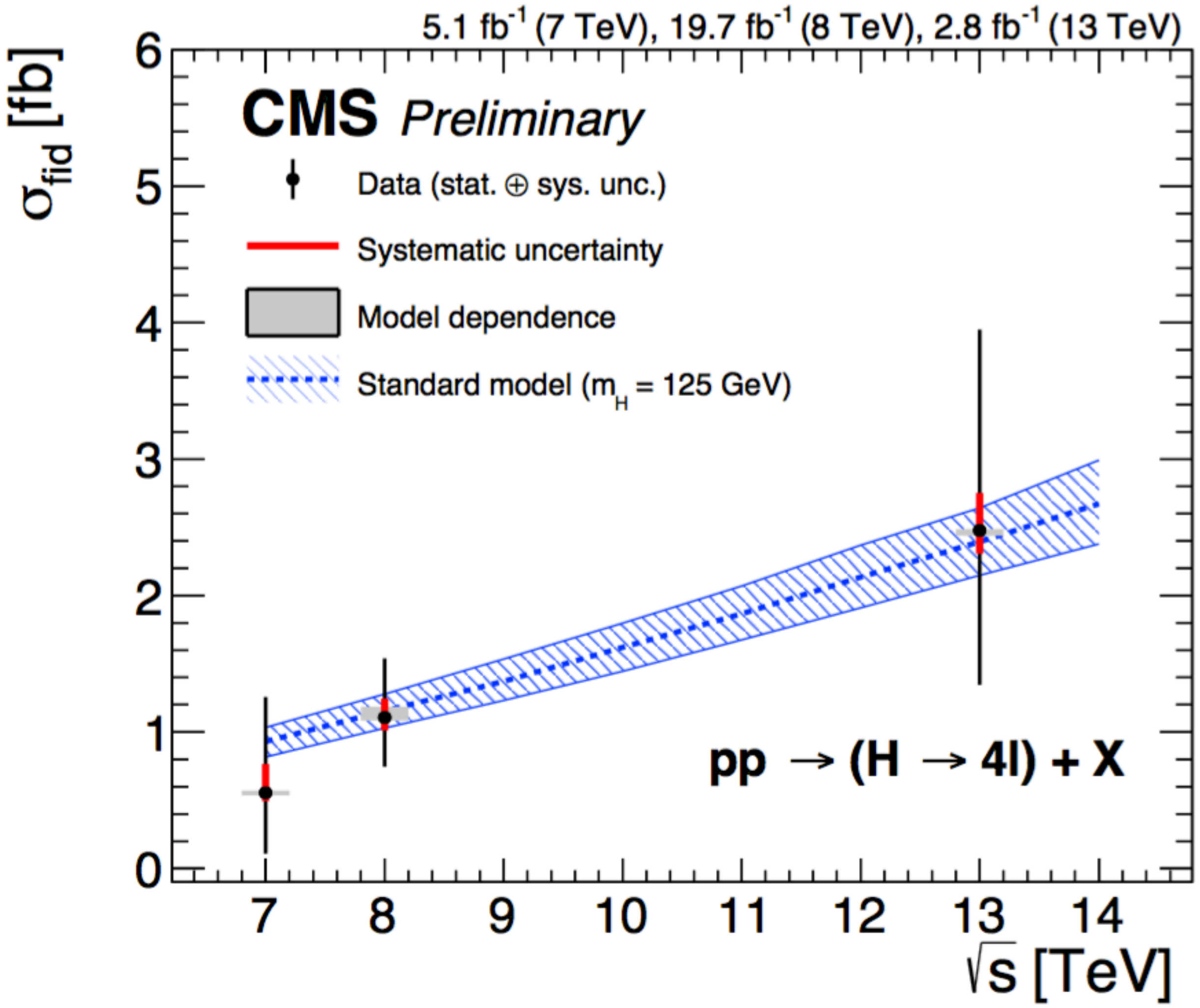
LHC-XS	17.5 ± 1.6	22.3 ± 2.0	$50.9^{+4.5}_{-4.4}$

CMS ZZ: Cross Section

$$\sigma_{\mathrm{fid.}} = 2.48^{+1.46}_{-1.13}(\mathrm{stat.})^{+0.28}_{-0.18}(\mathrm{sys.})^{+0.01}_{-0.04}(\mathrm{model\ dep.})\ \mathrm{fb}$$

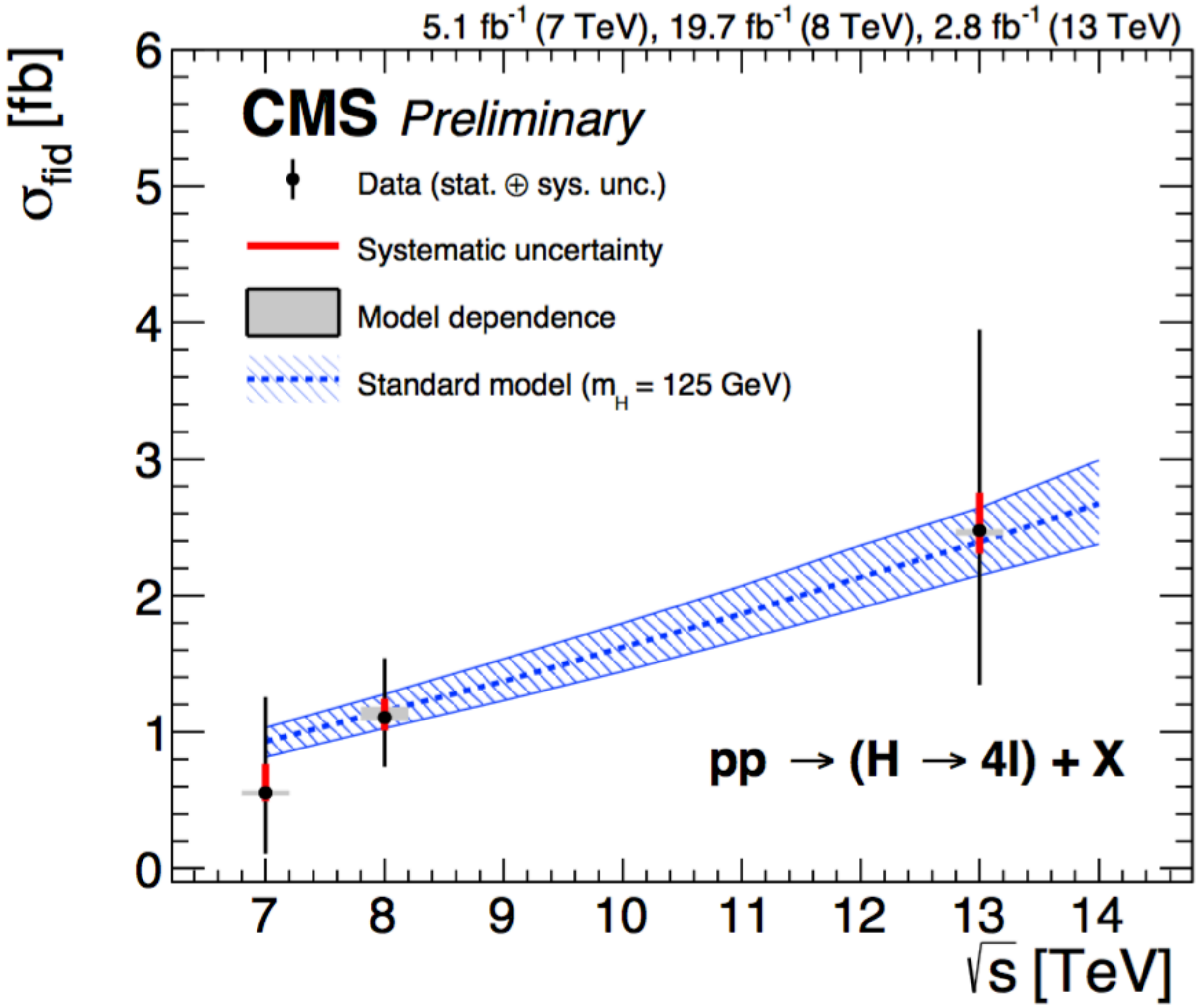
$$\sigma^{\mathrm{SM}}_{\mathrm{fid.}} = 2.39\ \mathrm{fb}$$

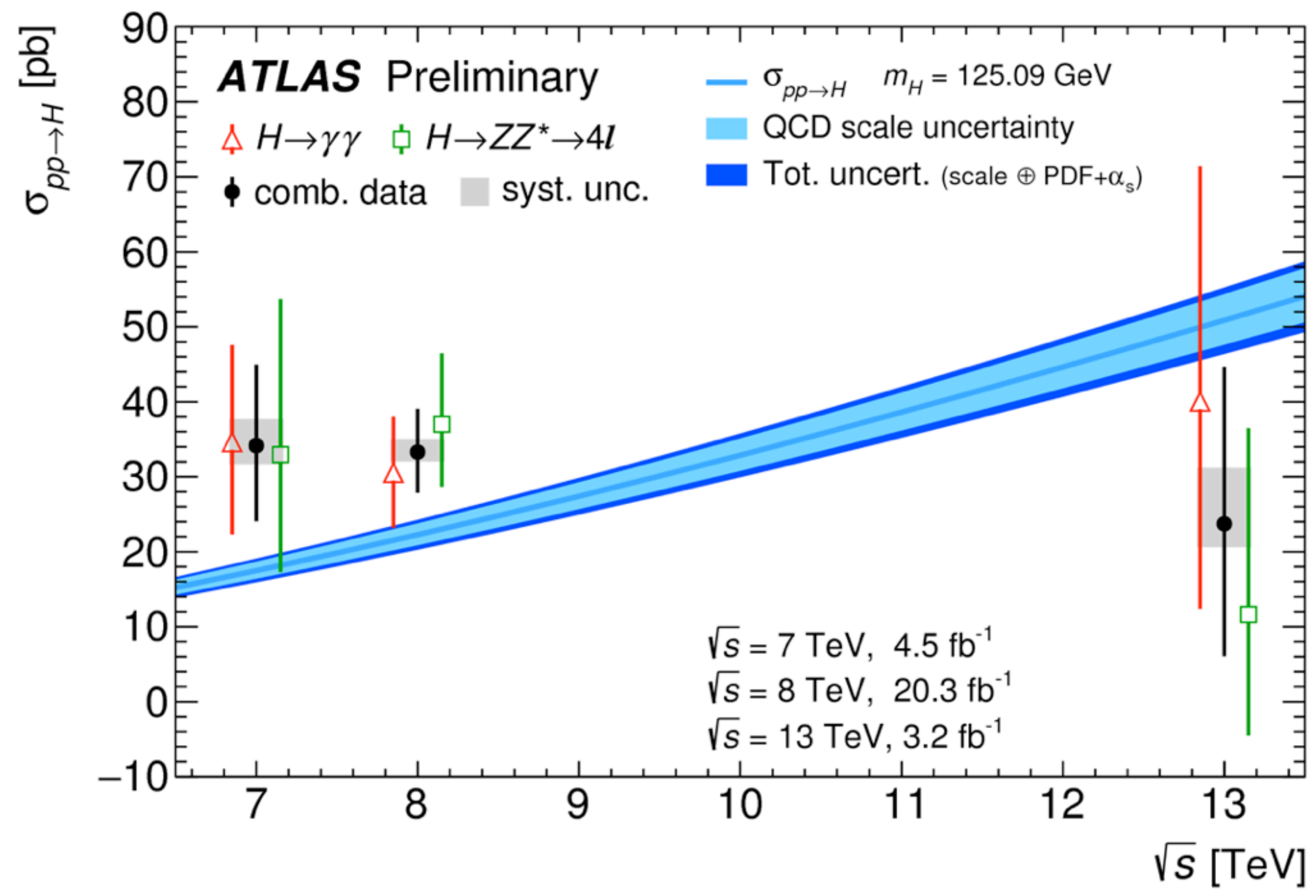


$$p_T > 20\ \mathrm{GeV}$$
$$p_T > 10\ \mathrm{GeV}$$
$$p_T > 7(5)\ \mathrm{GeV}$$
$$|\eta| < 2.5(2.4)$$
$$\text{Isolation } < 0.4 \cdot p_T$$
$$40\,\mathrm{GeV} < m(Z_1) < 120\,\mathrm{GeV}$$
$$12\,\mathrm{GeV} < m(Z_2) < 120\,\mathrm{GeV}$$
$$\Delta R(\ell_i \ell_j) > 0.02 \text{ for any } i \neq j$$
$$\mathrm{m}(\ell^+ \ell'^-) > 4\,\mathrm{GeV}$$
$$105\,\mathrm{GeV} < m_{4\ell} < 140\,\mathrm{GeV}$$

7+8 TeV: HIG-14-028 accepted for publication in JHEP

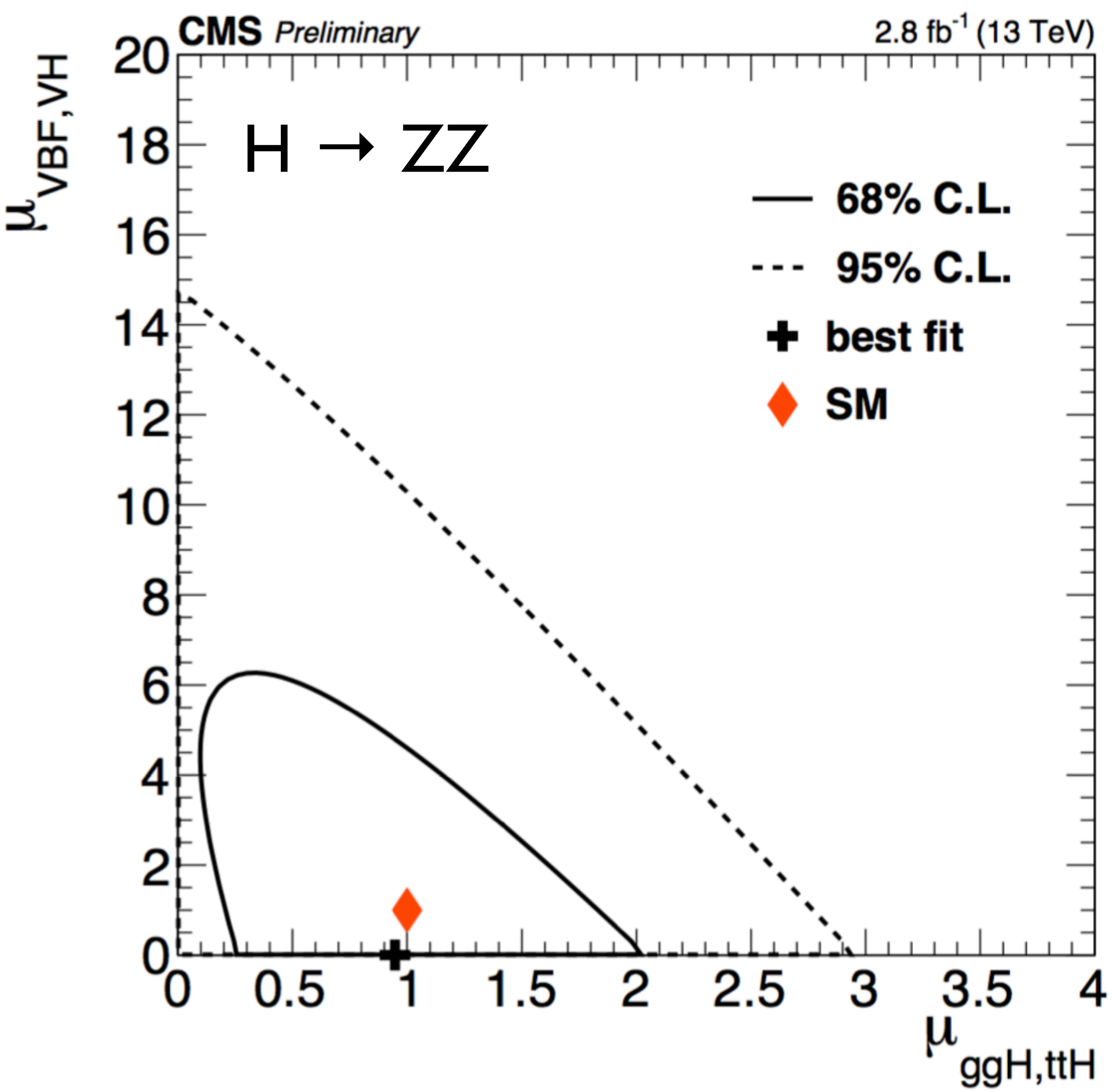
Cross Section Comparison

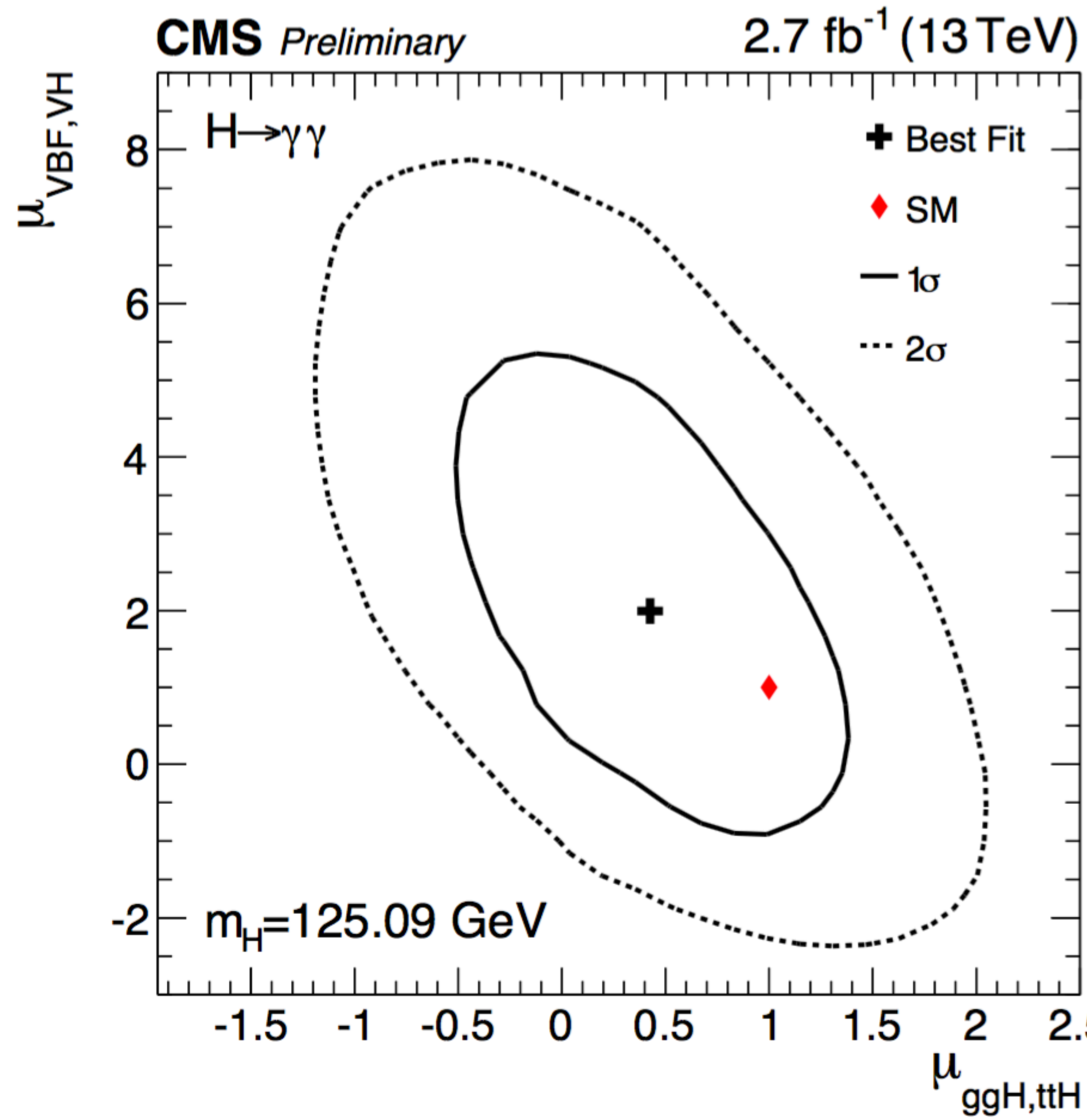




- All fully consistent with the Standard Model!

CMS: Production Modifiers

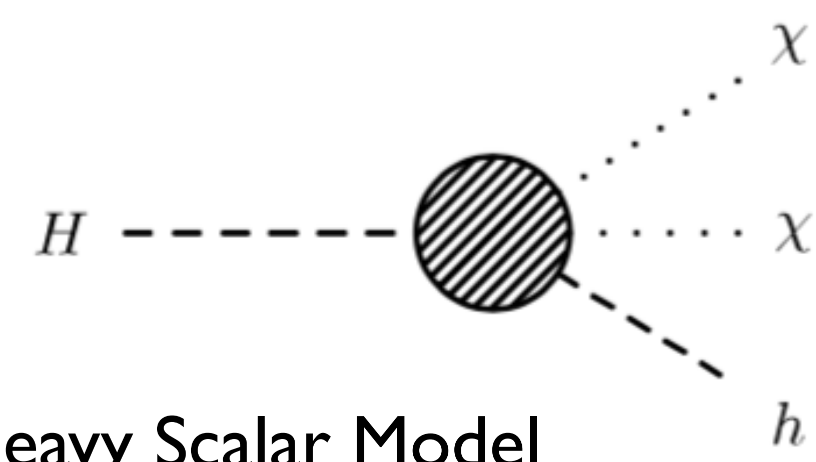




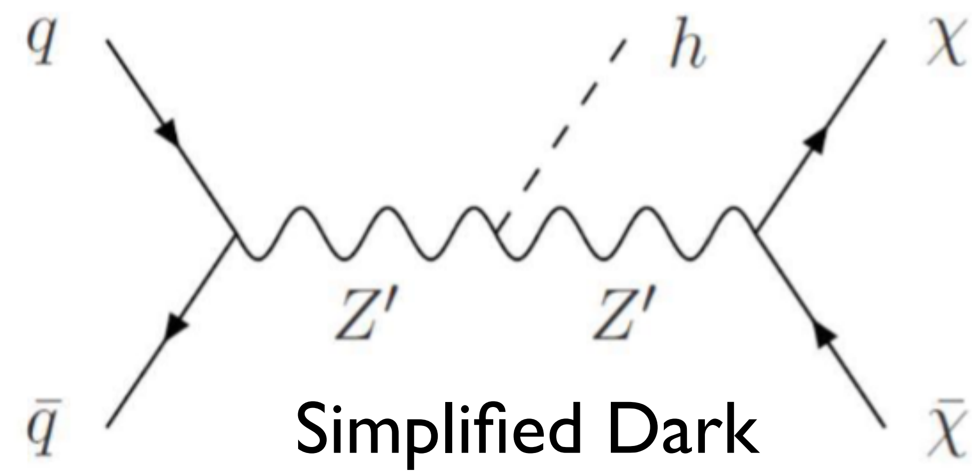
- All fully consistent with the Standard Model (as in Run 1)

ATLAS: γγ + Missing Energy

- Define signal regions with good efficiency for two benchmark models

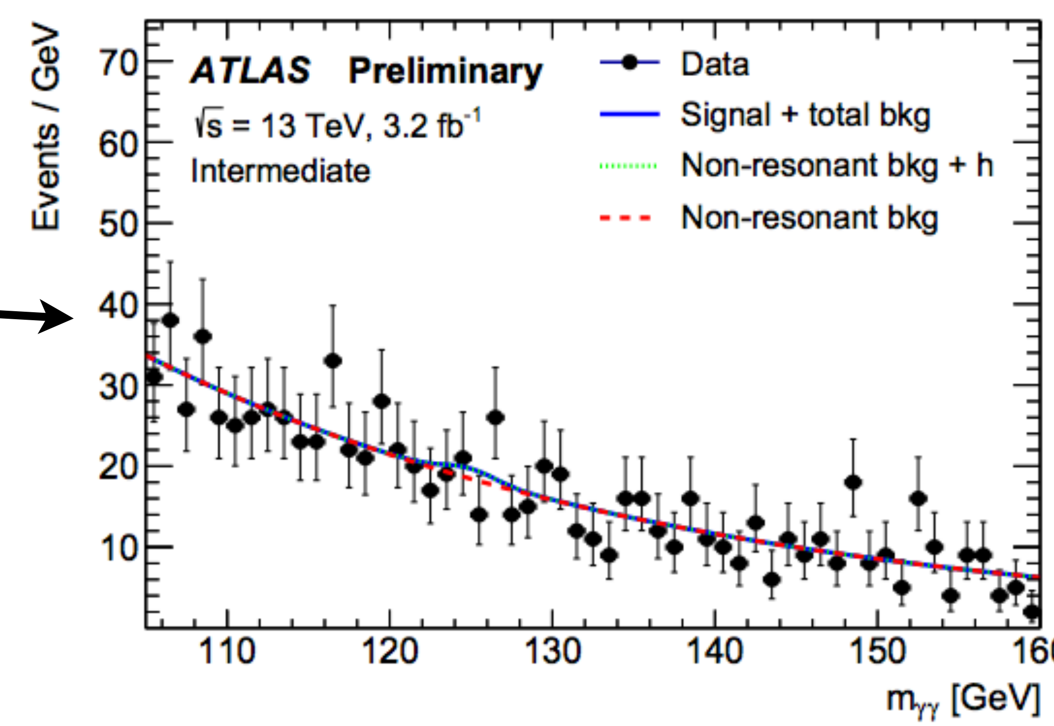


Heavy Scalar Model



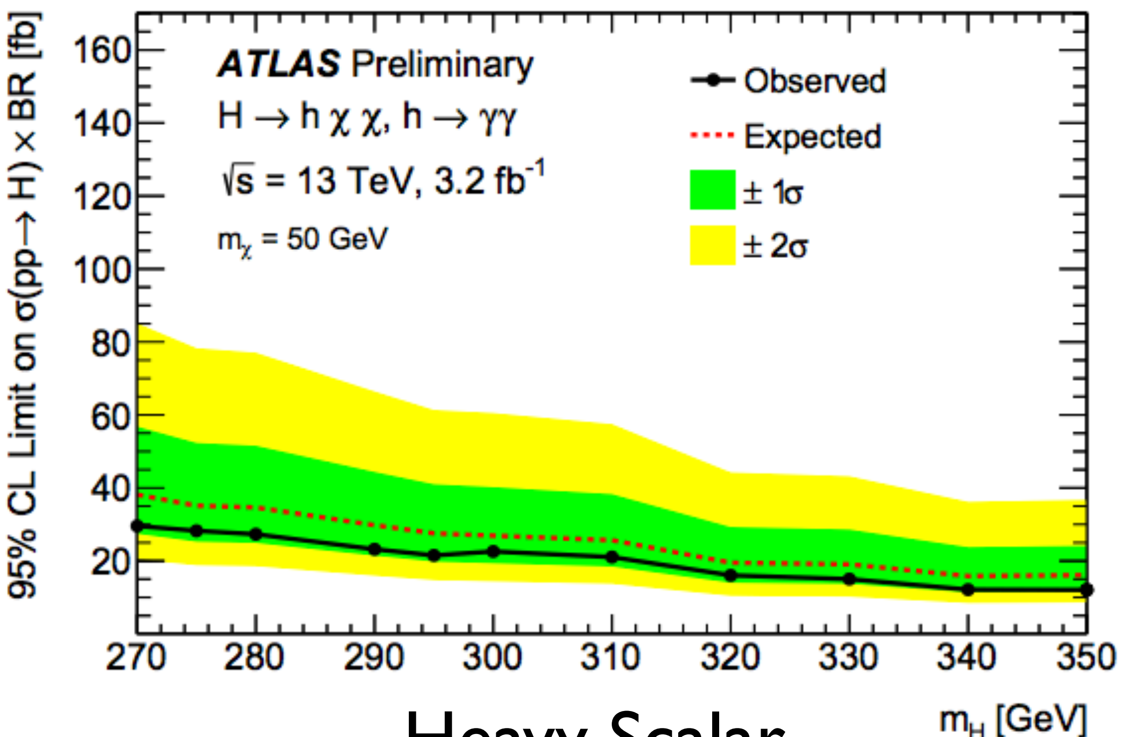
Simplified Dark Matter Model

Category	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{hard}}$ [GeV]	$p_{\mathrm{T}}^{\gamma\gamma}$ [GeV]
High $E_{\mathrm{T}}^{\mathrm{miss}}$, high $p_{\mathrm{T}}^{\gamma\gamma}$	> 100	-	> 100
High $E_{\mathrm{T}}^{\mathrm{miss}}$, low $p_{\mathrm{T}}^{\gamma\gamma}$	> 100	-	≤ 100
Intermediate $E_{\mathrm{T}}^{\mathrm{miss}}$	> 50 and ≤ 100	> 40	-
Rest	-	-	> 15

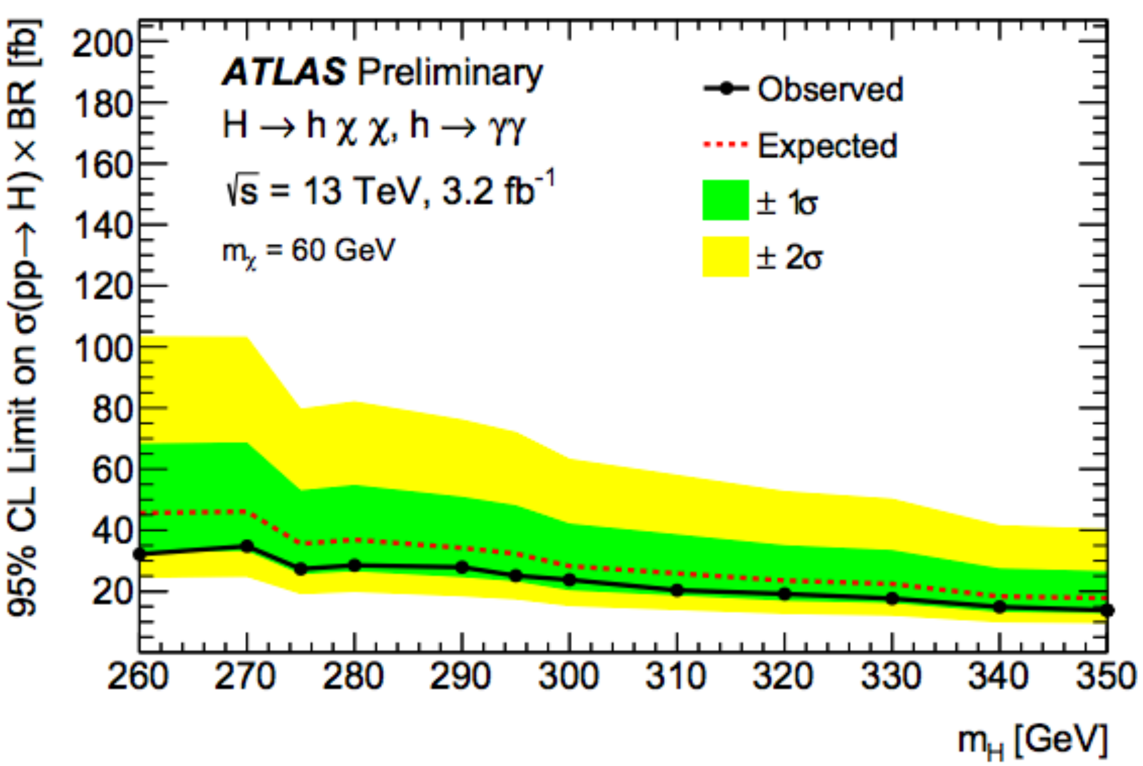


- Fit with SM scalar and new signal both modeled as double-sided Crystal Ball (shapes consistent)

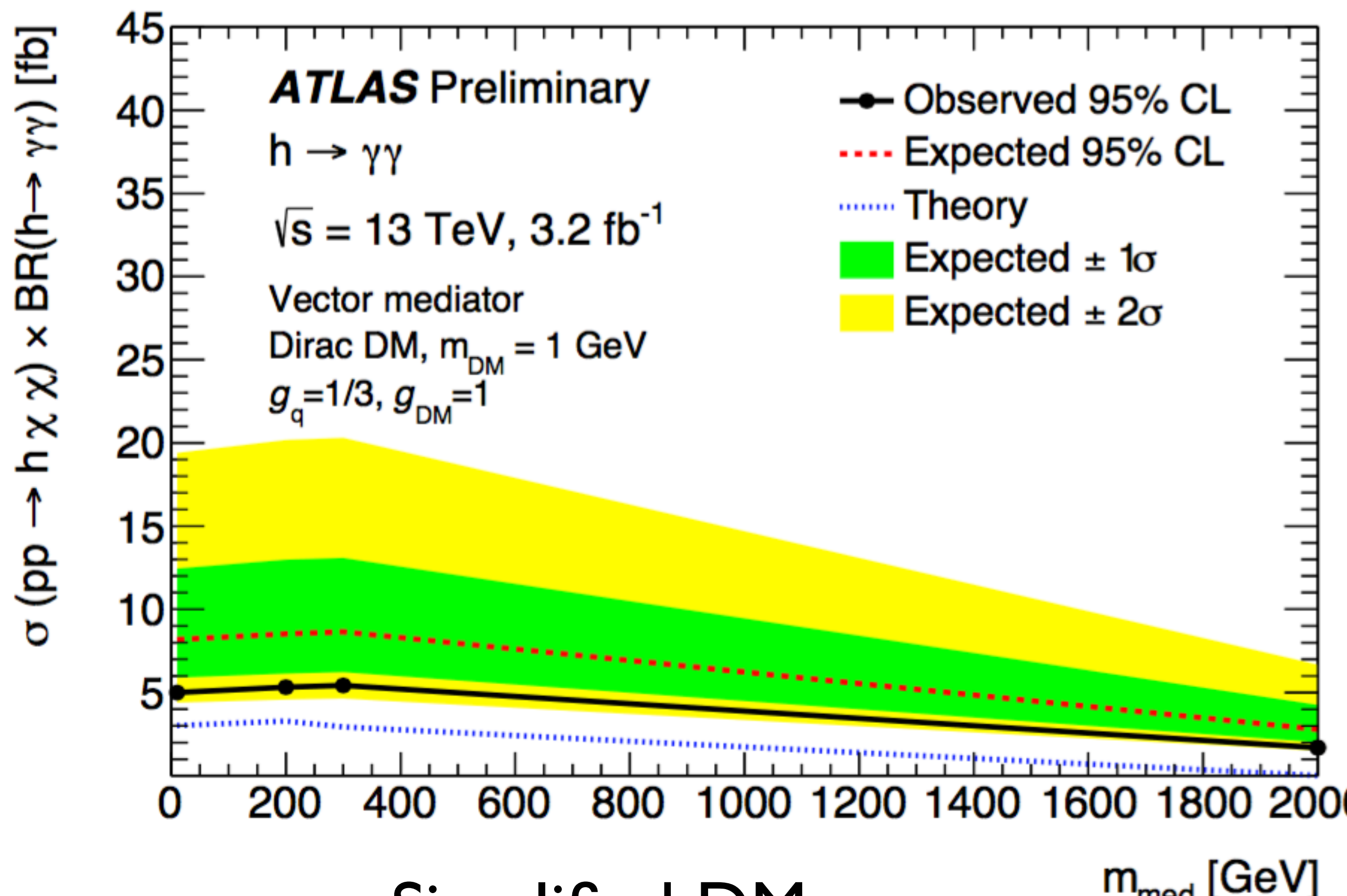
ATLAS: γγ + Missing Energy



Heavy Scalar

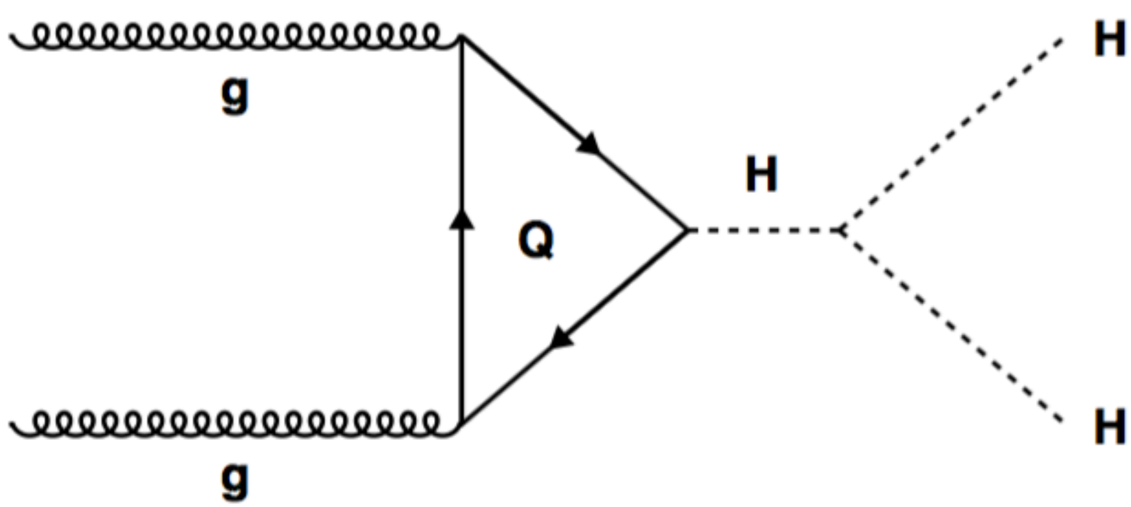


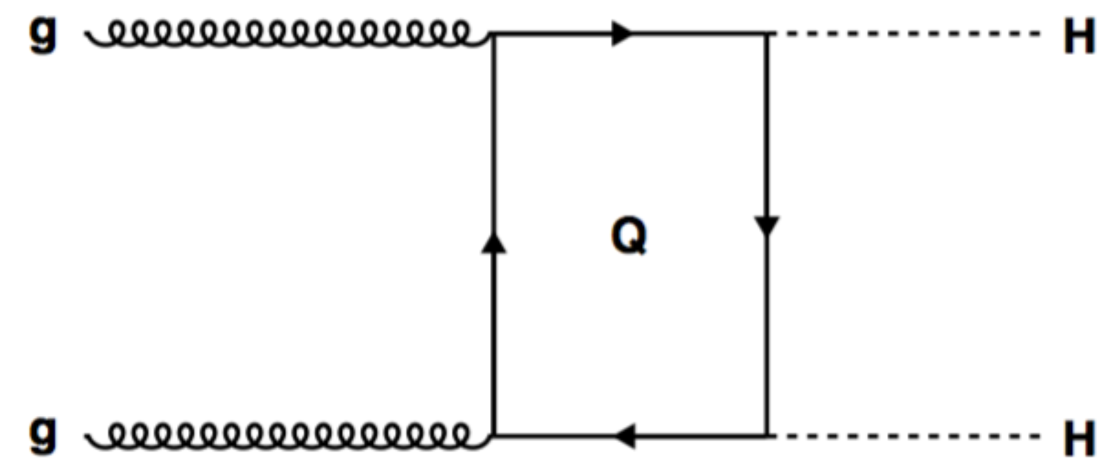
- Interpret fits in context of both models



Simplified DM

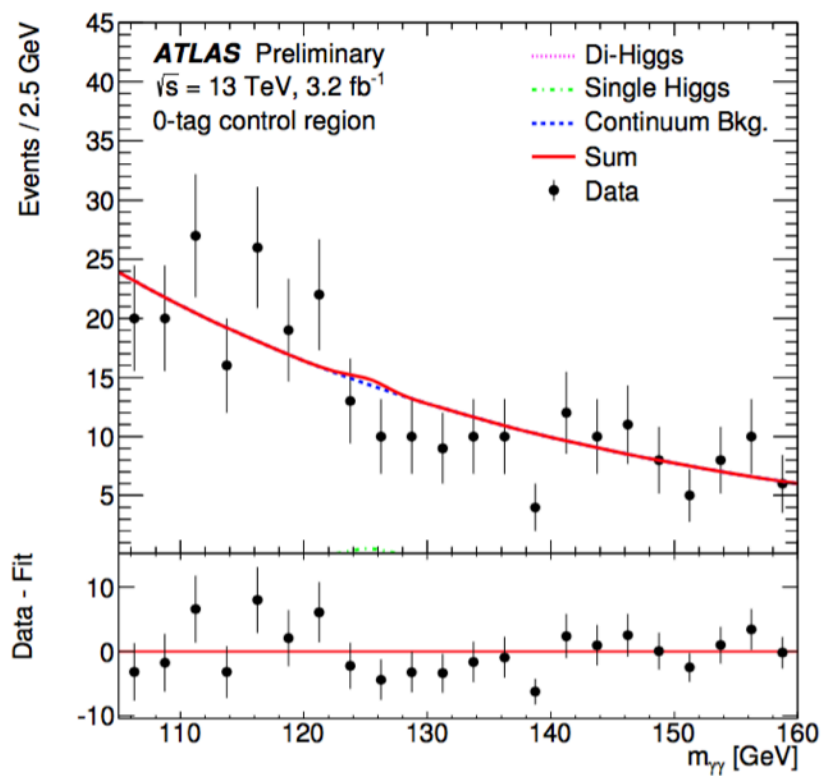
ATLAS: $h^* \rightarrow hh \rightarrow bb\gamma\gamma$

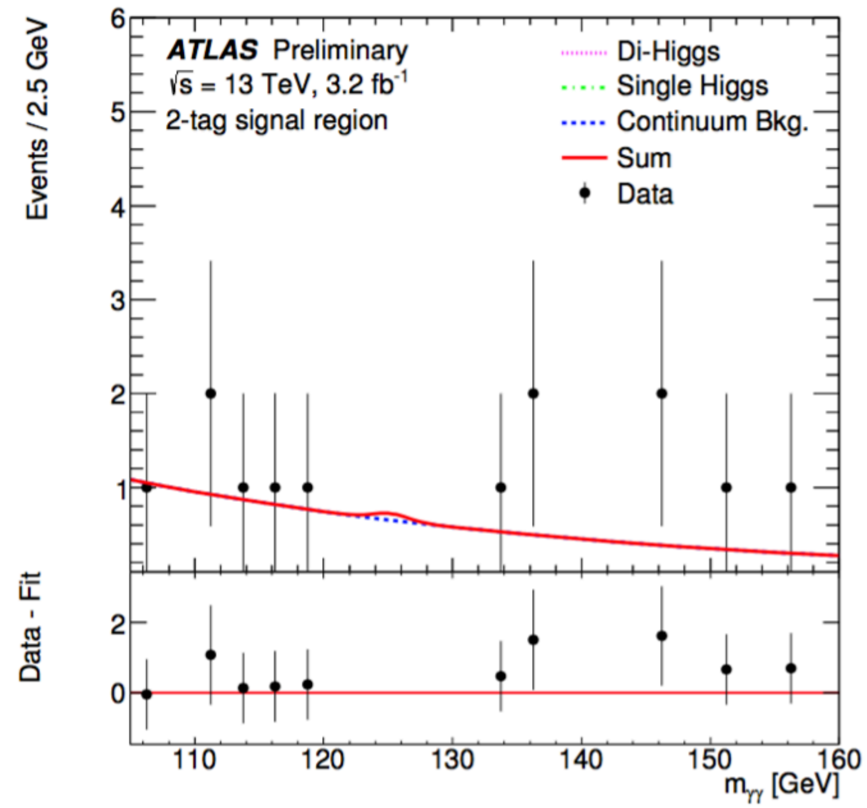




- Non-resonant hh production
  - Interference ⇒ very small SM cross section
  - Resonant: see talk from A. McCarn
- Large cross section from bb, good resolution from $\gamma\gamma$
- 2.4σ excess in Run 1 Phys. Rev. Lett. 114 (2015) 081802, arXiv: 1406.5053
- Fit to sidebands in 0-tag region to derive continuum background shape

ATLAS: $h^* \to hh \to bb\gamma\gamma$

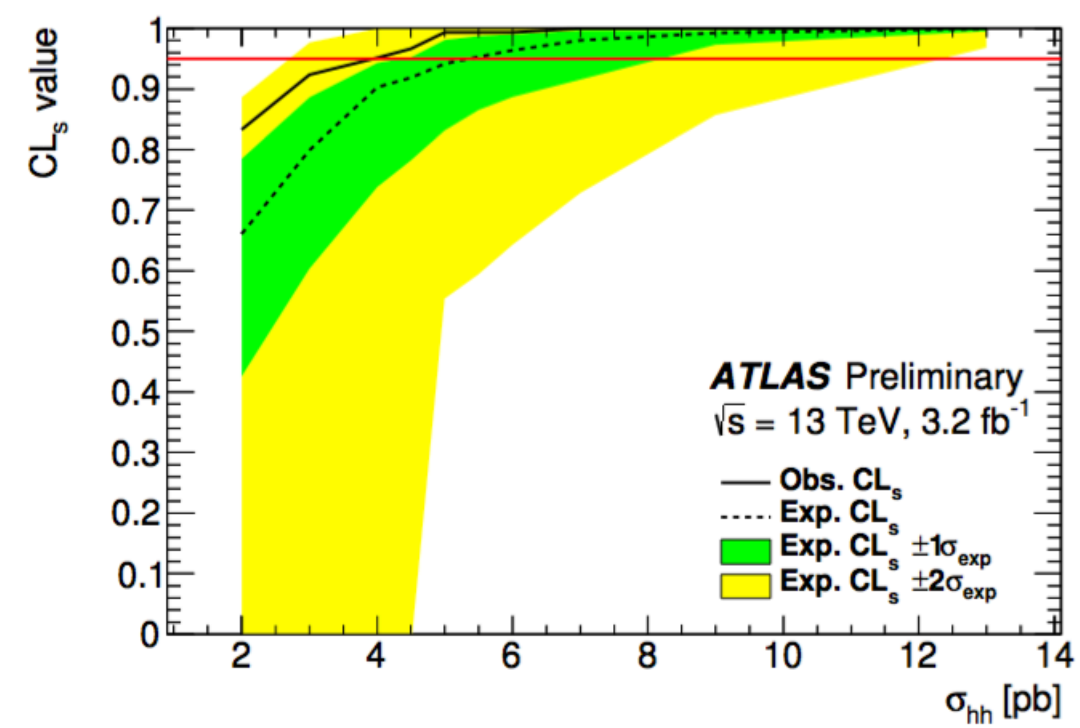




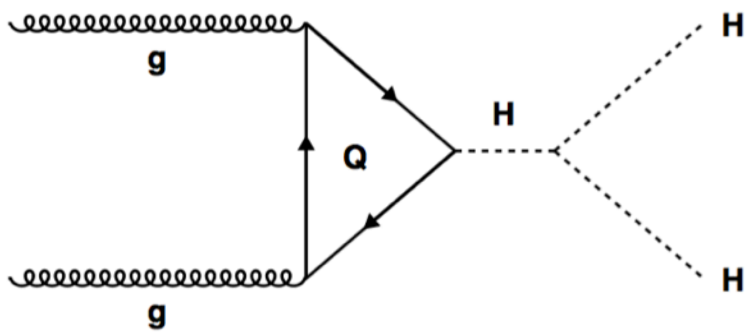
At 95% CL,
σ < 3.9 pb (obs.)
$5.4^{+2.8}_{-1.0}$ pb (exp.)

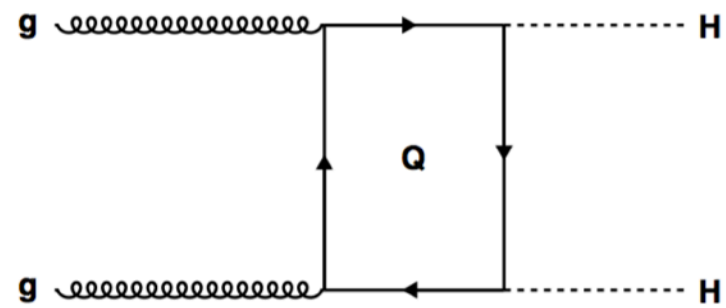
σ_{SM} = 37.9 fb

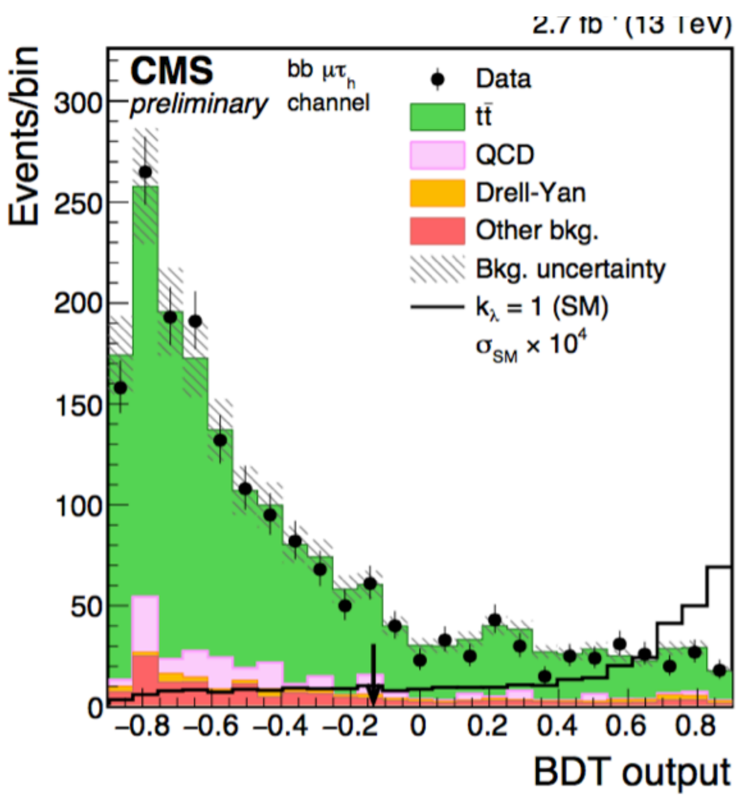
Process	0-tag	2-tag
Continuum background	35.8 ± 2.1	1.63 ± 0.30
SM single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM di-Higgs	<0.001	0.027 ± 0.006
Observed	27	0

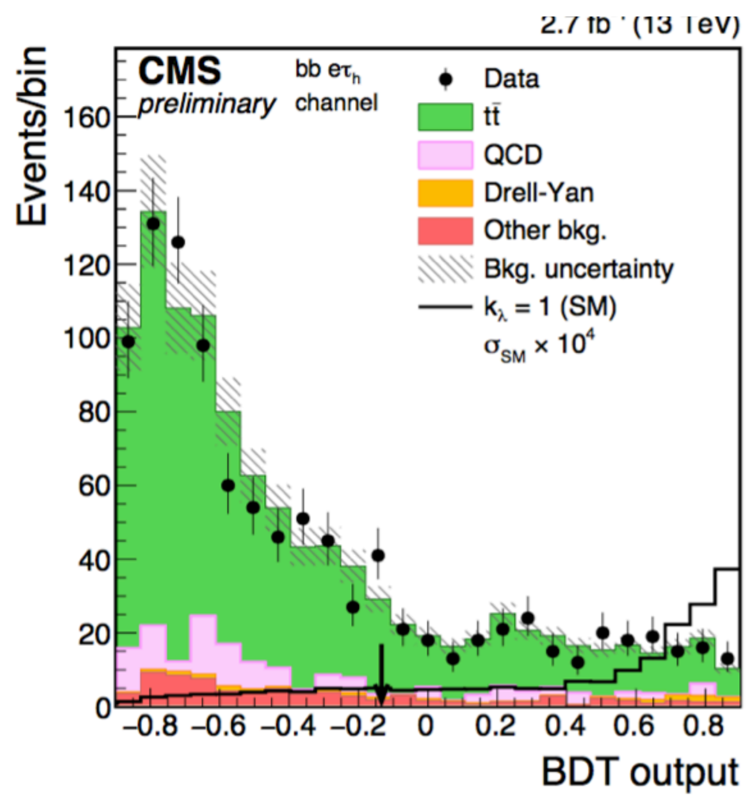


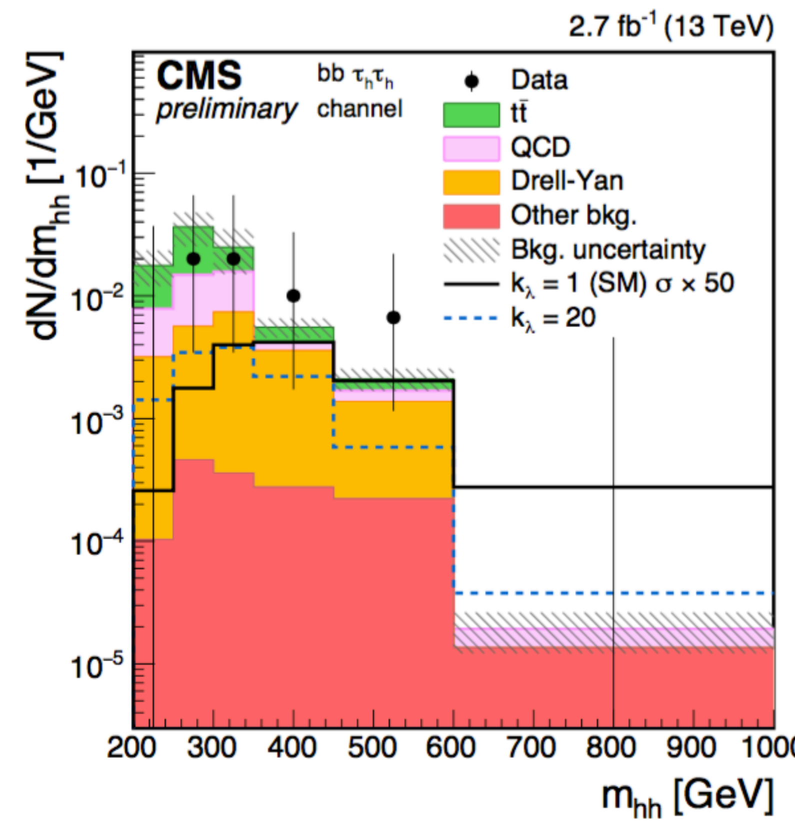
CMS: 13 TeV h* → hh → bb$\tau\tau$

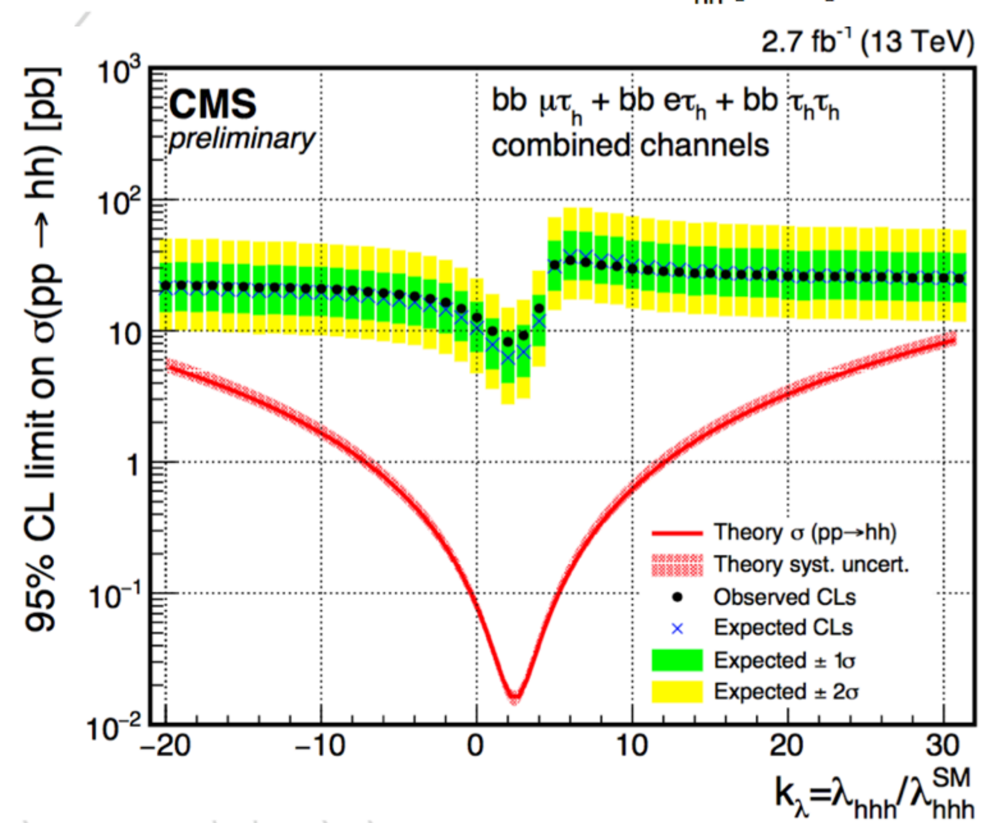






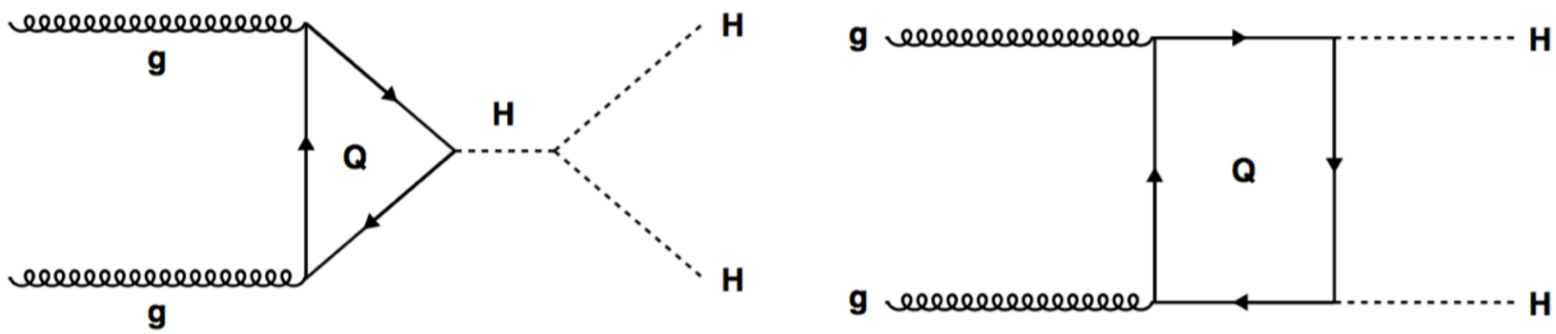




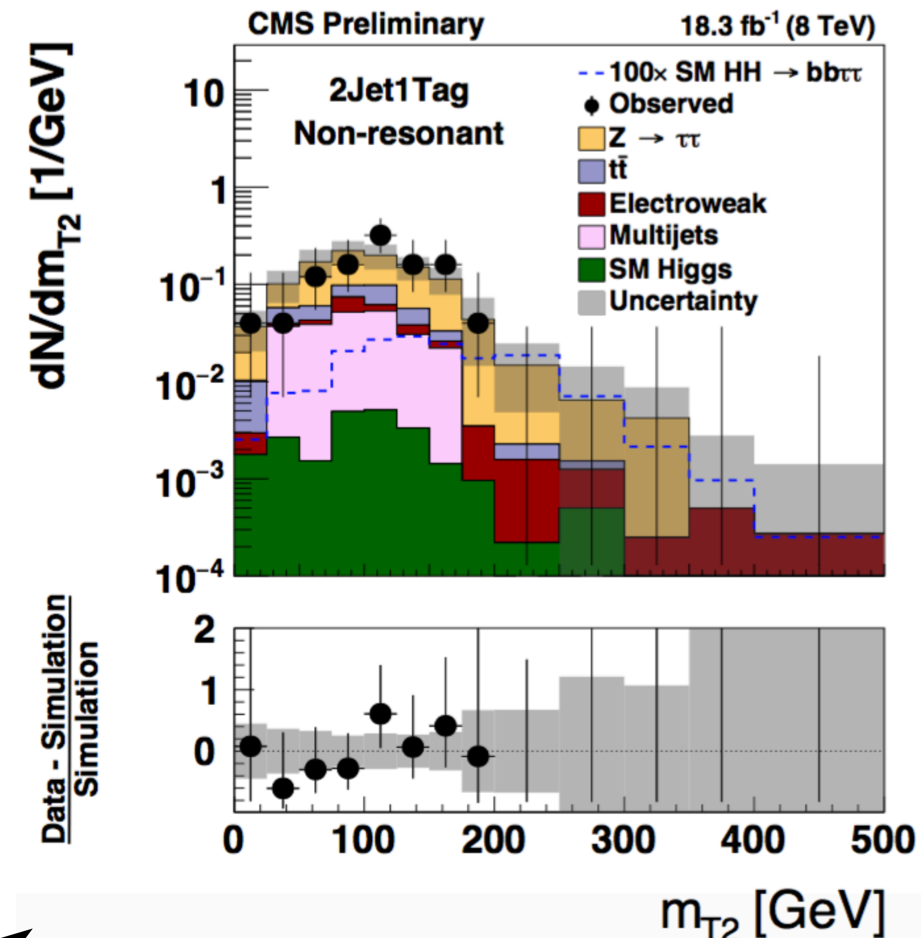


- $\Delta\varphi$ between bb, $\tau\tau$, E_T,miss; $\Delta R(\ell,\tau)$ $\Delta R(b,b)$
- Do not strongly depend on trilinear coupling λ_{hhh}
- No anomalous coupling found

CMS: 8 TeV $h^* \rightarrow hh \rightarrow bb\tau\tau$



$\mathbf{m_{T2}}$: upper kinematic bound on the mass of the di-scalar system in each event



Non-resonant analysis			
Process	2jet0tag	2jet1tag	2jet2tag
Non-resonant HH production	1.3 ± 0.2	5.1 ± 0.7	4.7 ± 0.6
$Z \rightarrow \tau\tau$	120.3 ± 11.1	17.7 ± 3.0	2.0 ± 0.8
QCD multijet	27.9 ± 2.7	5.4 ± 1.0	0.7 ± 0.2
W+jets	4.3 ± 0.8	0.4 ± 0.1	0.4 ± 0.1
Z+jets (e, μ or jet faking τ_h)	0.7 ± 0.2	< 0.1	< 0.1
$t\bar{t}$	1.3 ± 0.2	3.4 ± 0.5	1.2 ± 0.2
Di-bosons + single top	5.7 ± 1.0	1.1 ± 0.2	0.5 ± 0.1
SM Higgs	3.7 ± 1.3	0.6 ± 0.2	0.2 ± 0.1
Total expected	163.9 ± 11.4	28.6 ± 3.2	5.2 ± 1.1
Observed data	165	26	1

SM x100

Observed (Expected)
95% CL limit:

0.59 pb ($0.94\,^{+0.46}_{-0.24}$ pb)

$53\sigma_{SM}$ ($84\sigma_{SM}$)

CMS: Scalar p_T in WW decays

8 TeV

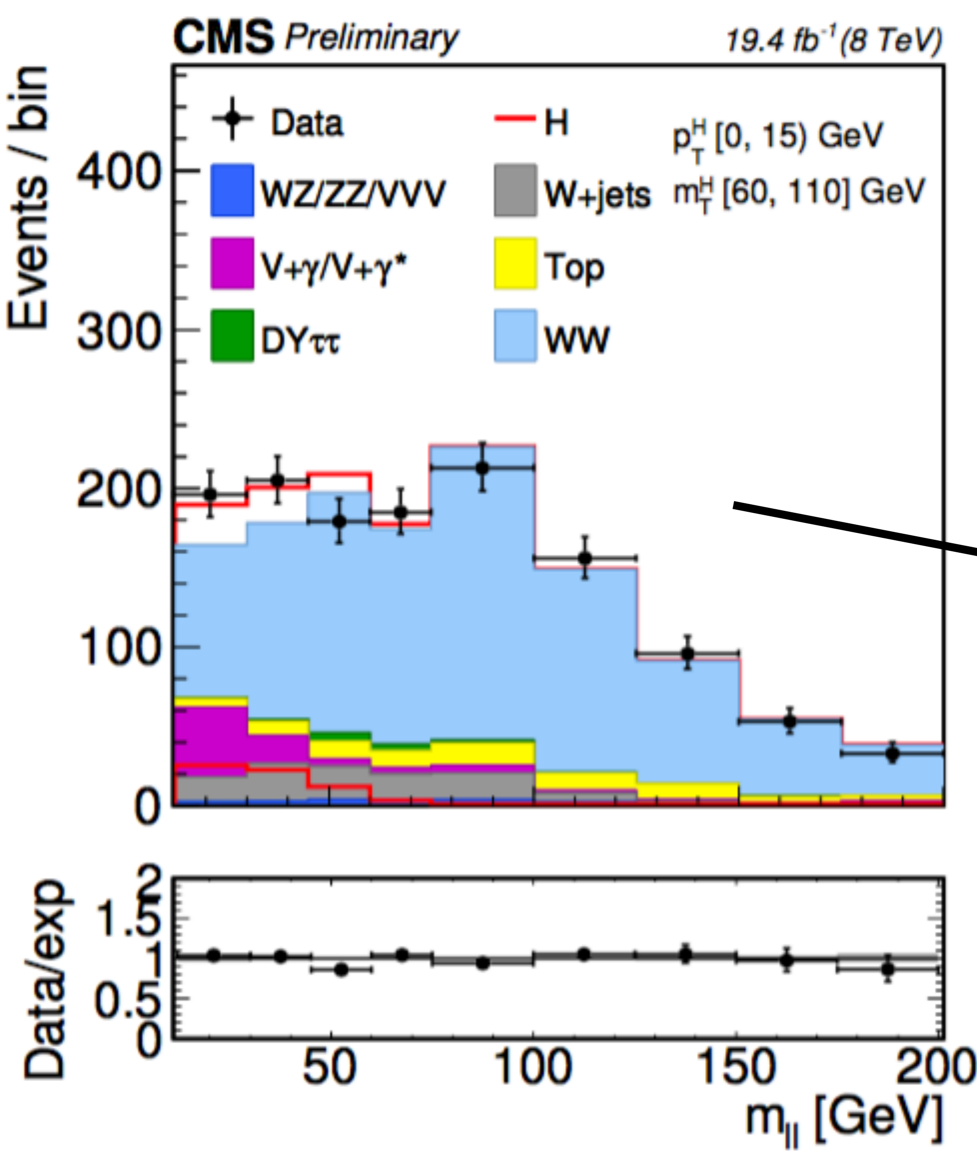
- WW → eνμν, opposite sign
- Analysis inclusive in number of jets
  - Jet multiplicity correlated with $p_{T,H}$
  - To remove top: B-tag and soft non-isolated muon veto
- Correct to fiducial phase space to measure cross section in bins of reconstruction p_T
- Unfold distribution for final $d\sigma_{fid}/dp_T$ measurement

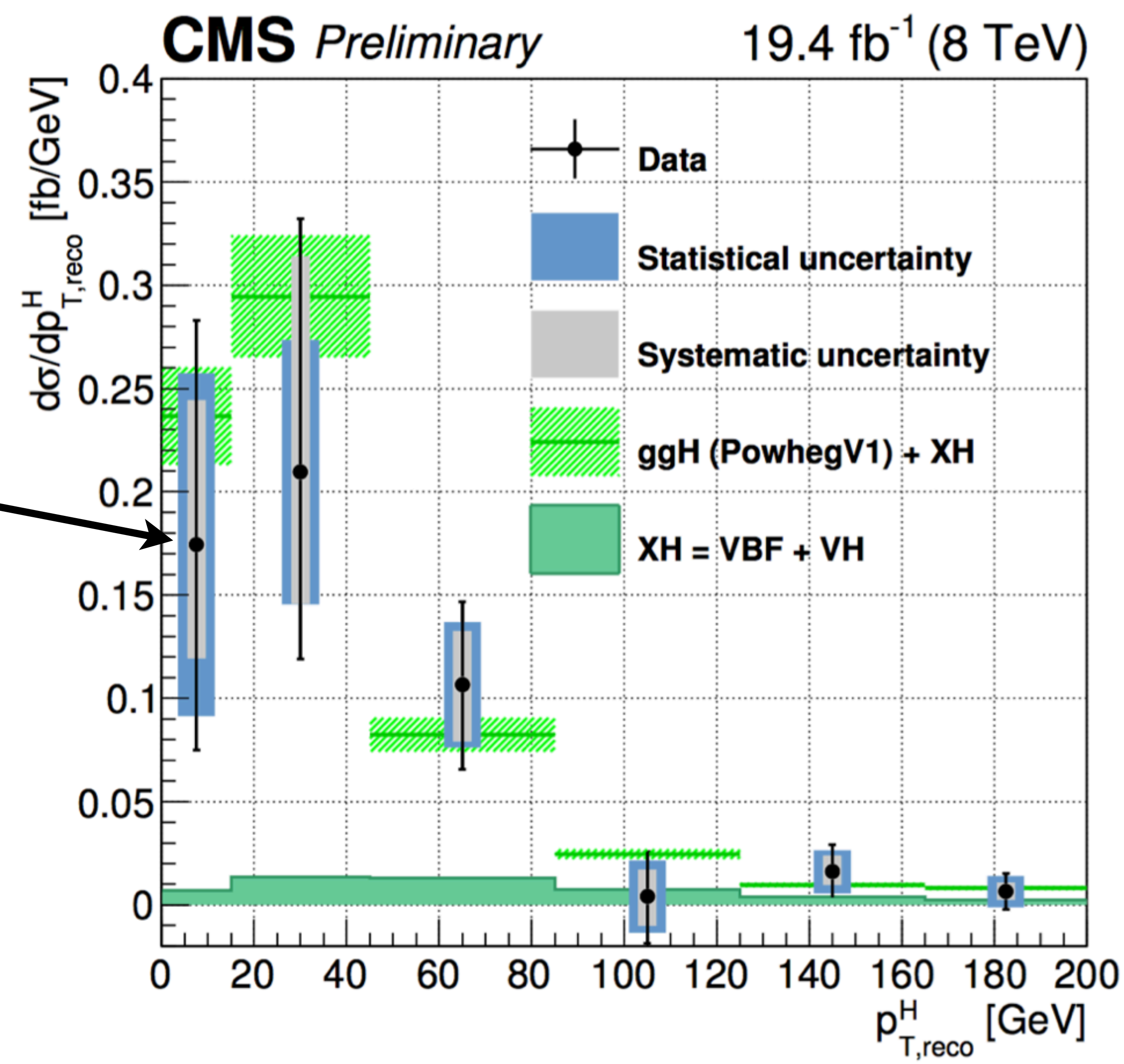
$$\vec{p}_{\mathrm{T}}^{\mathrm{H}} = \vec{p}_{\mathrm{T}}^{\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}$$

Kinematic requirements for the $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ **fiducial phase space**	
Leading lepton p_{T}	$p_{\mathrm{T}} > 20$ GeV
Sub-leading lepton p_{T}	$p_{\mathrm{T}} > 10$ GeV
Pseudorapidity of electrons and muons	$\|\eta\| < 2.5$
Invariant mass of the two leptons	$m_{\ell\ell} > 12$ GeV
Transverse momentum of the lepton pair	$p_{\mathrm{T}}^{\ell\ell} > 30$ GeV
Invariant mass of the leptonic system in the transverse plane	$m_{\mathrm{T}}^{\ell\ell E_{\mathrm{T}}^{\mathrm{miss}}} > 50$ GeV
No $E_{\mathrm{T}}^{\mathrm{miss}}$ cut applied	

Signal extraction

- For each $p_{T,H}$ bin perform 2D fit in m_T, $\Delta\varphi(\ell\ell, E_{T,miss})$



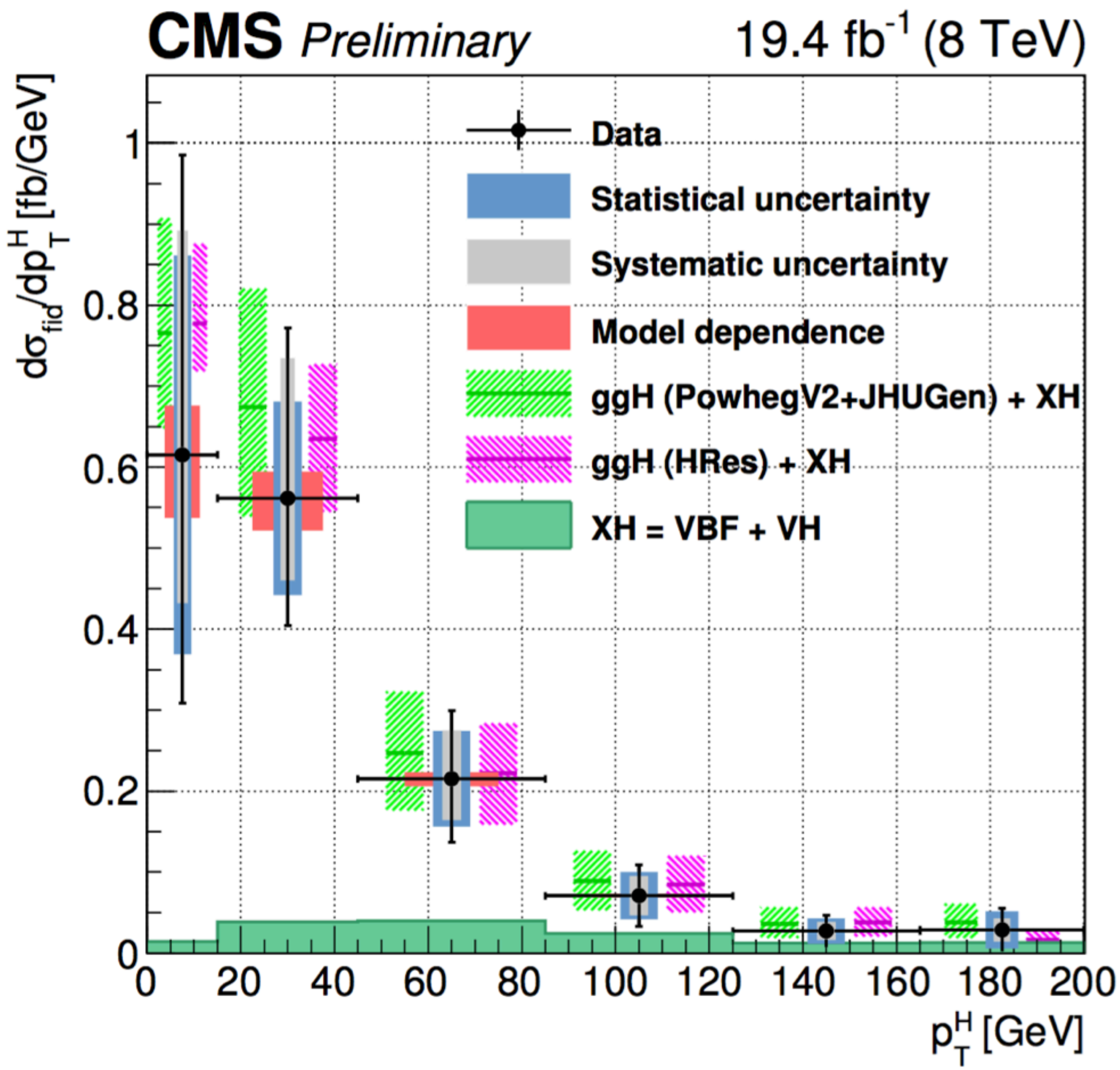


Unfolded Results

- Unfold using Singular Value Decomposition

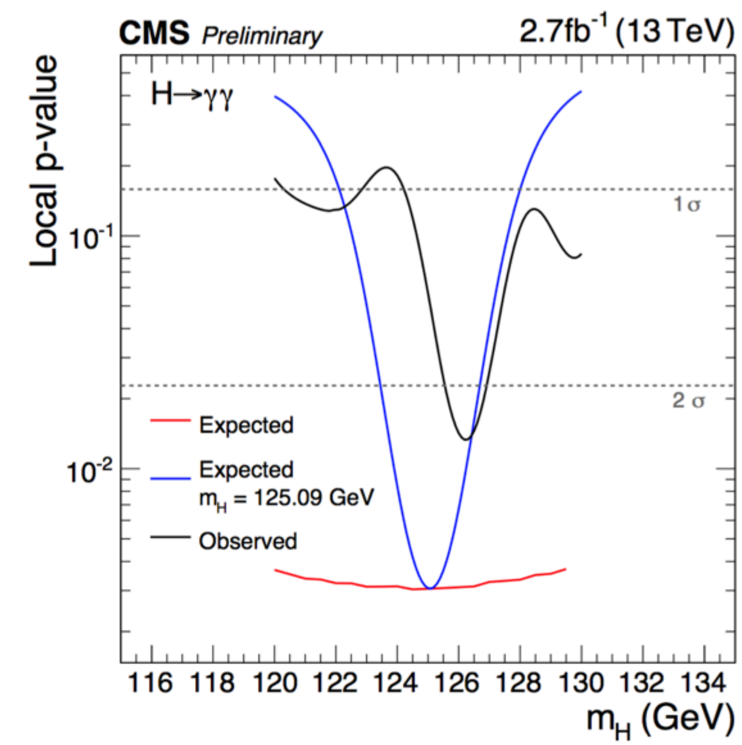
$$\sigma_{\text{fid}} = 39 \pm 8\ (\text{stat}) \pm 9\ (\text{syst})\ \text{fb}$$

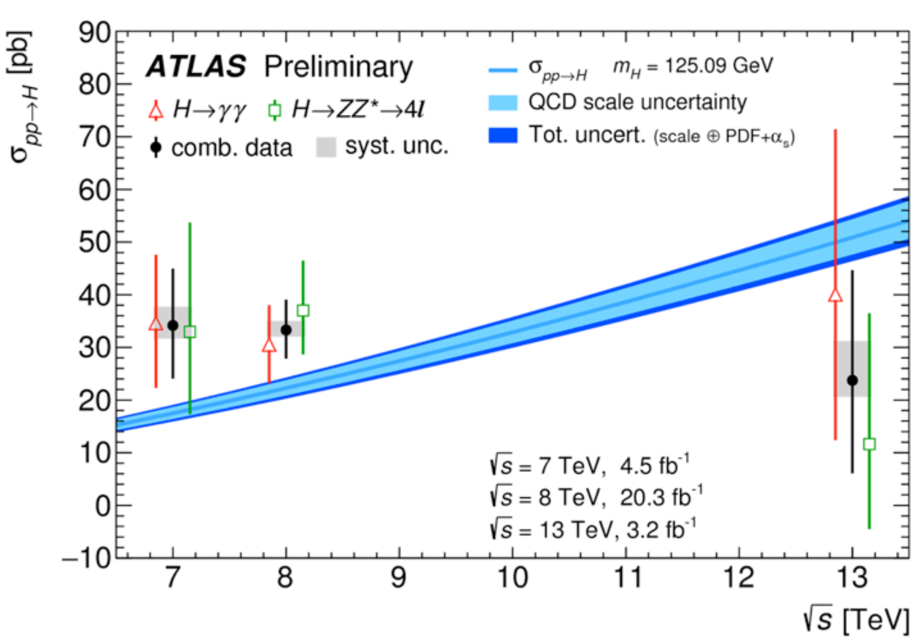
Uncertainties on backgrounds contributions	
Source	Uncertainty
$t\bar{t}$, tW	$\sim 20-50\%$
W+ jet	$\sim 40\%$
WZ, ZZ	$\sim 4\%$
$V\gamma/\gamma^*$	$\sim 30\%$
Experimental uncertainties	
Source	Uncertainty
Luminosity	2.6%
Trigger efficiency	$1-2\%$
Lepton reconstruction and ID	$3-4\%$
Lepton energy scale	$2-4\%$
E_T^{miss} modeling	2%
Jet energy scale	10%
Pileup multiplicity	2%
B-mistag modeling	$\sim 3\%$
Theoretical uncertainties	
Source	Uncertainty
b-veto jet binning	$\sim 1-2\%$
PDF	$\sim 1\%$
WW shape	$\sim 1\%$

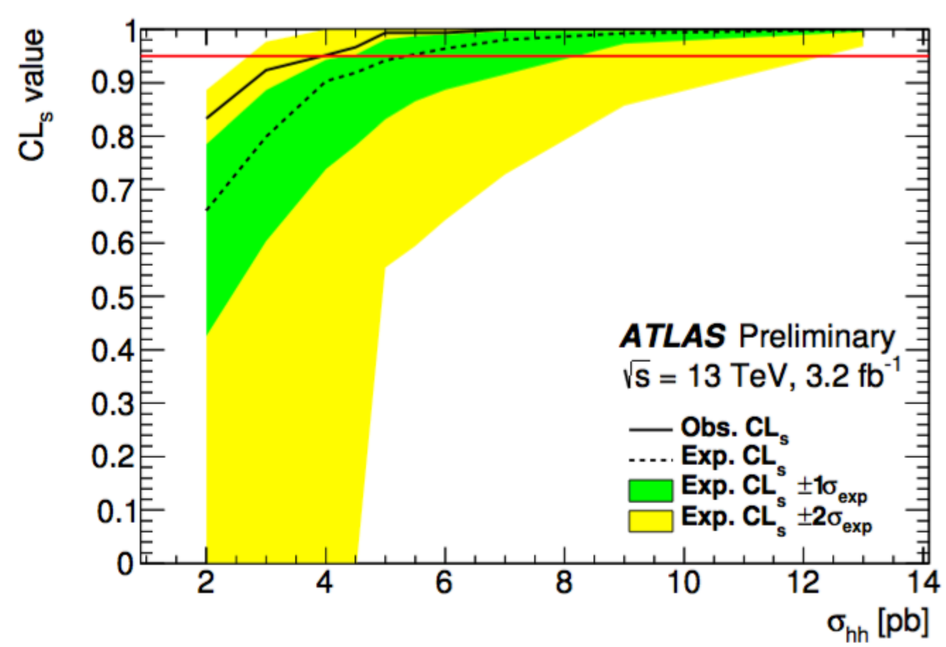


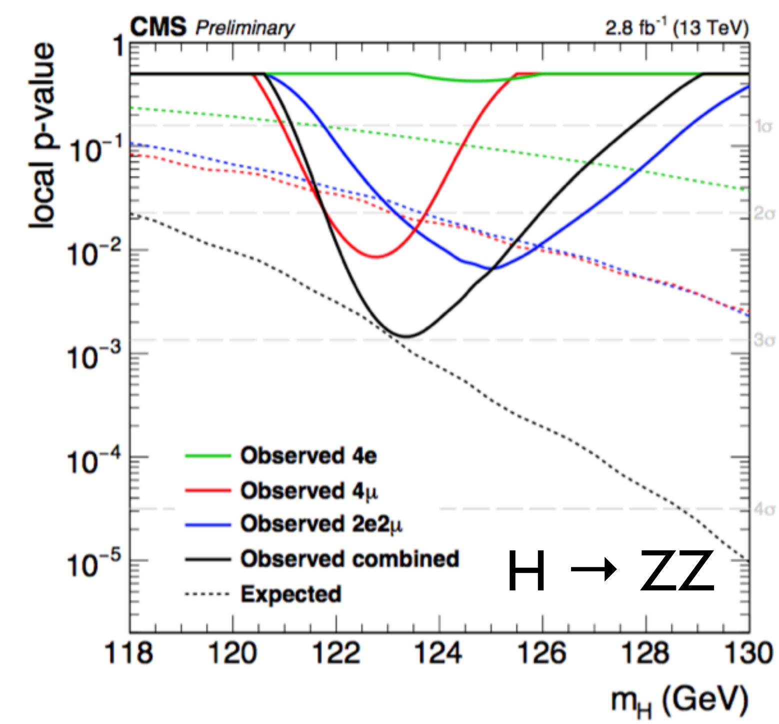
Conclusions

- First 13 TeV measurements of scalar decays to $\gamma\gamma$ and $ZZ \rightarrow 4\ell$
  - Results remain consistent with SM
  - Statistics limited in 2015 run
- LHC Run 2 will make precise measurements of scalar boson properties and search for deviations from SM
  - Differential measurements
  - Anomalous trilinear couplings
  - In association with dark matter candidates
- Stay tuned for more data!



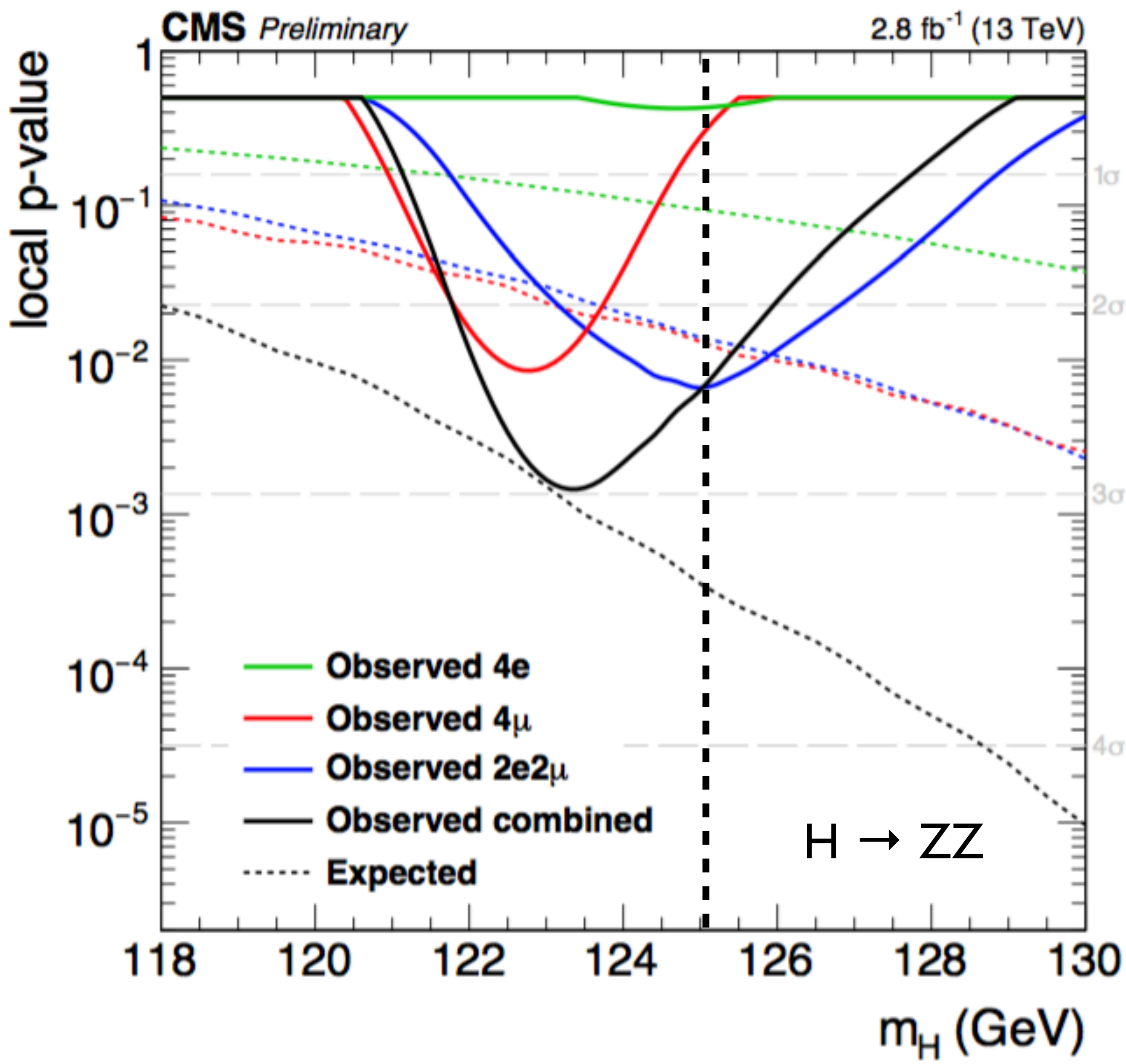


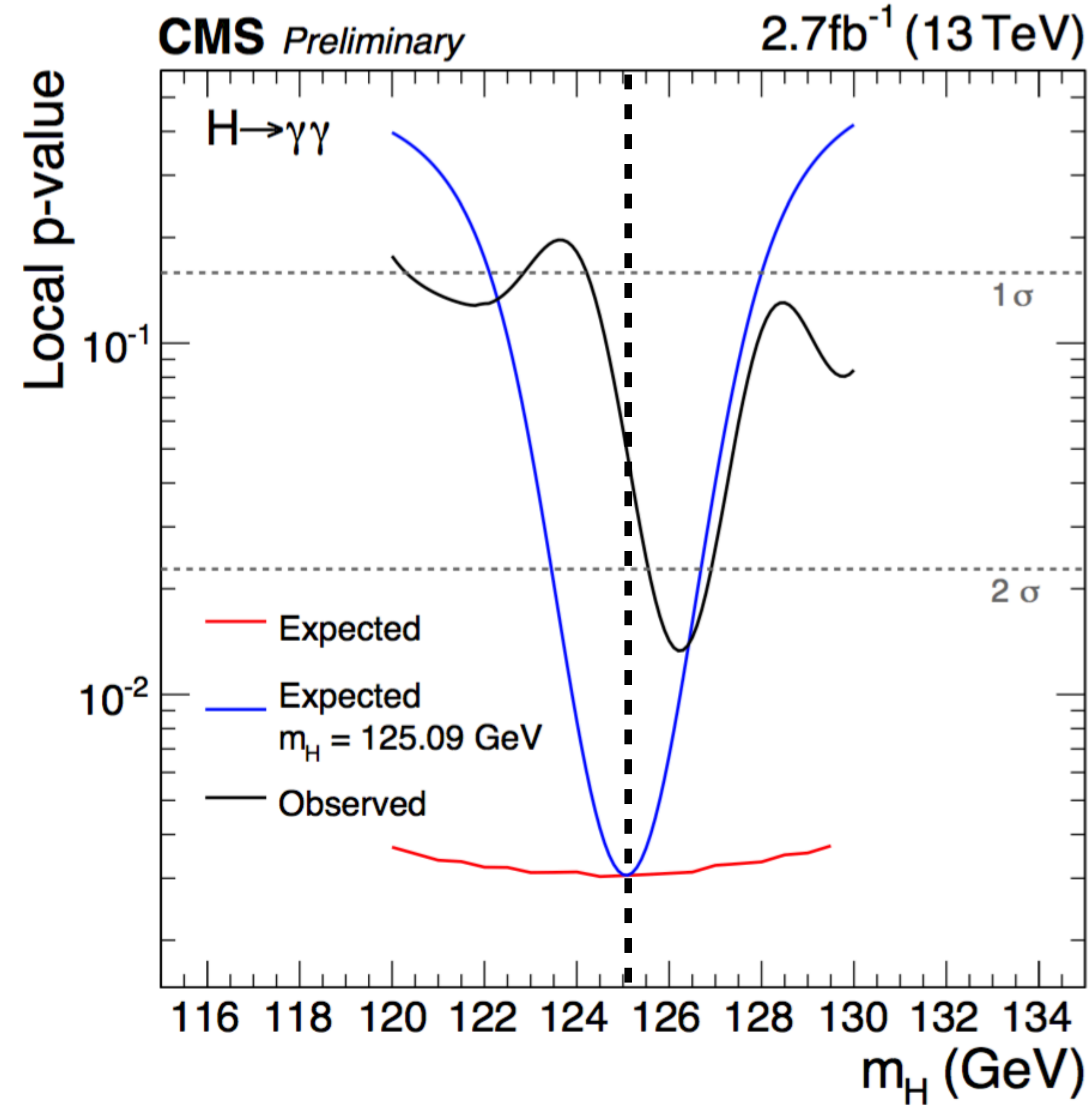




Extras

CMS ZZ and γγ Mass

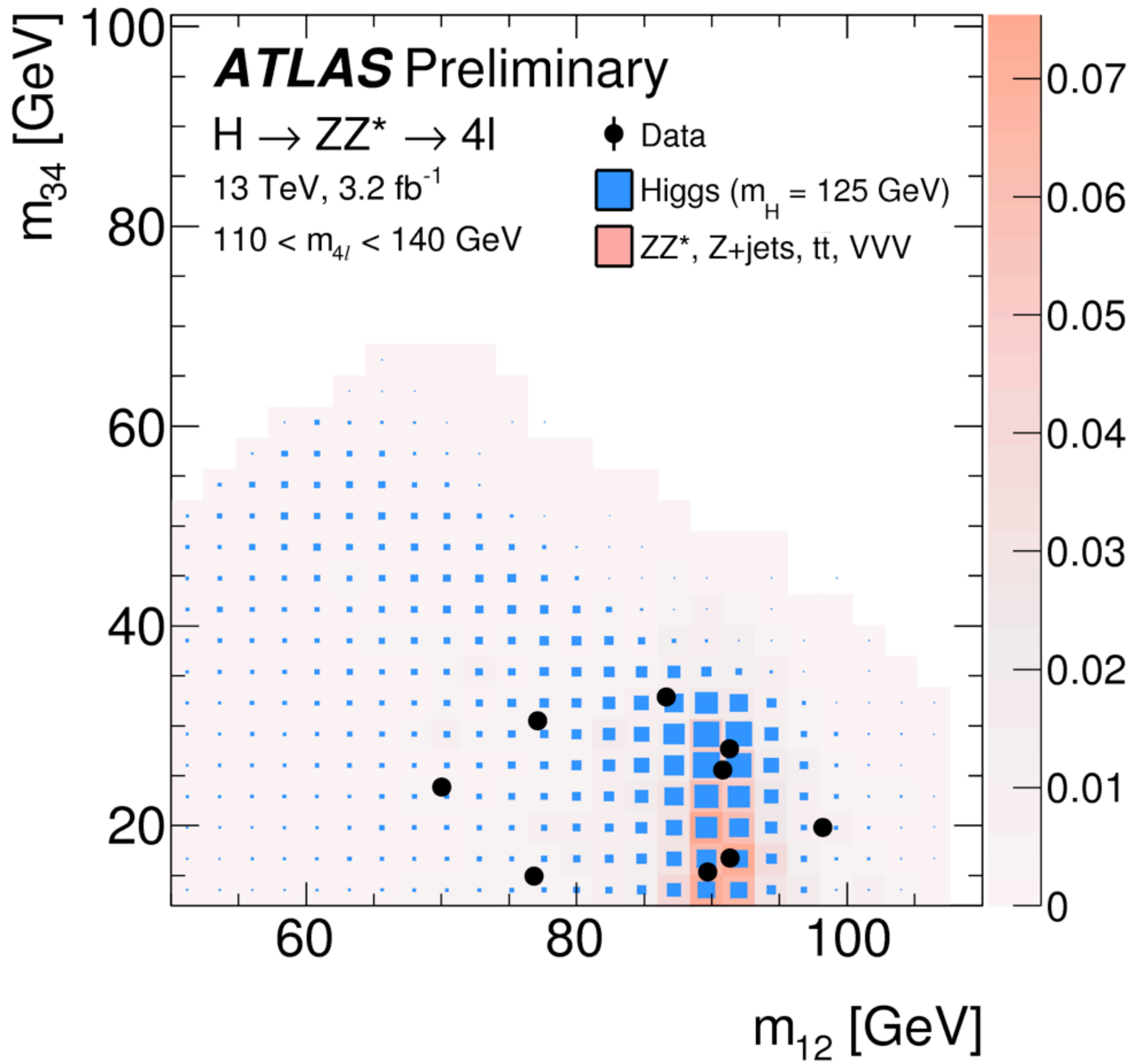


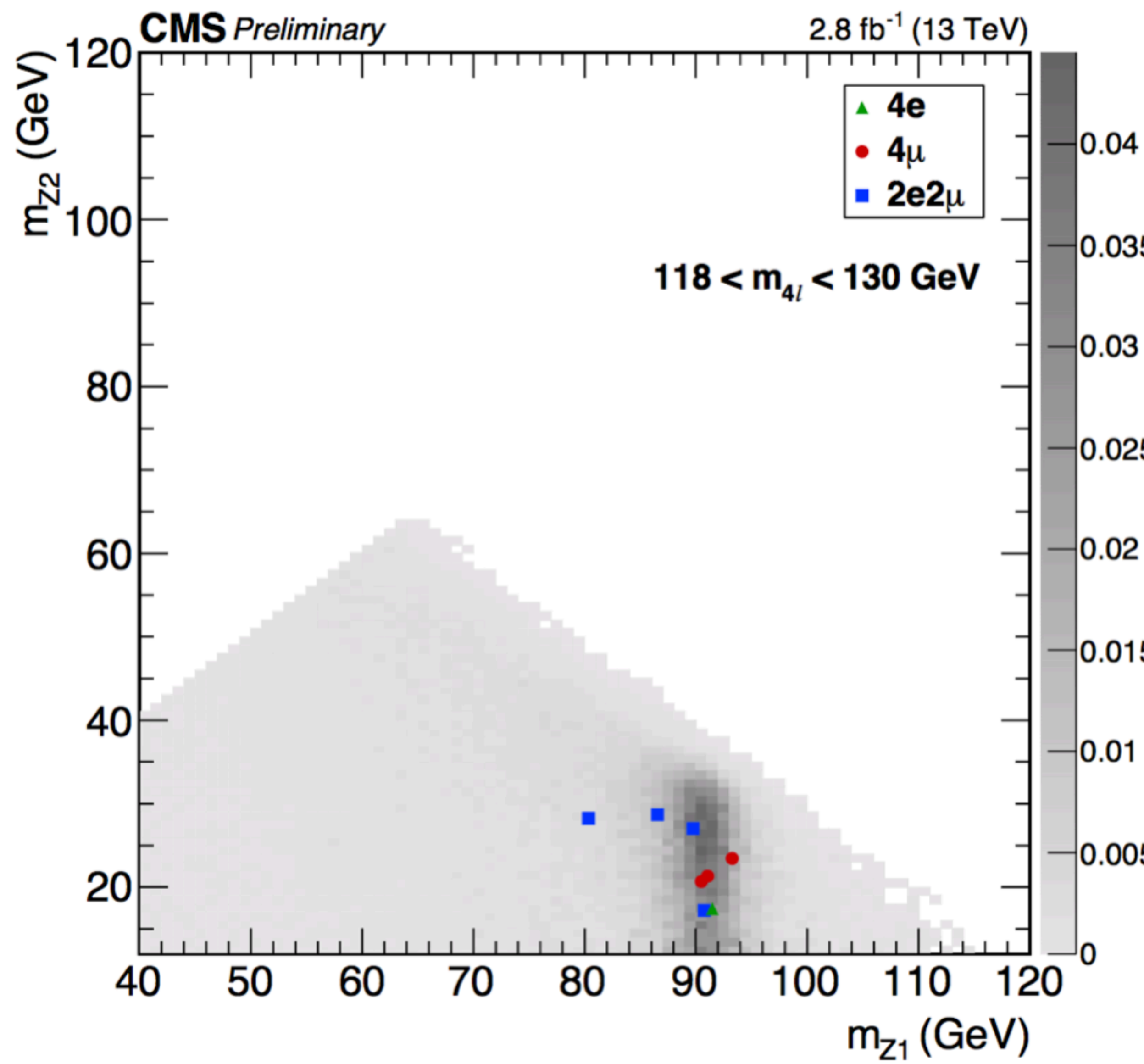


1σ uncertainty on mass: 0.7-0.9 GeV

Run 1 LHC Average: 125.09 ± 0.24 GeV

Z Candidate Masses



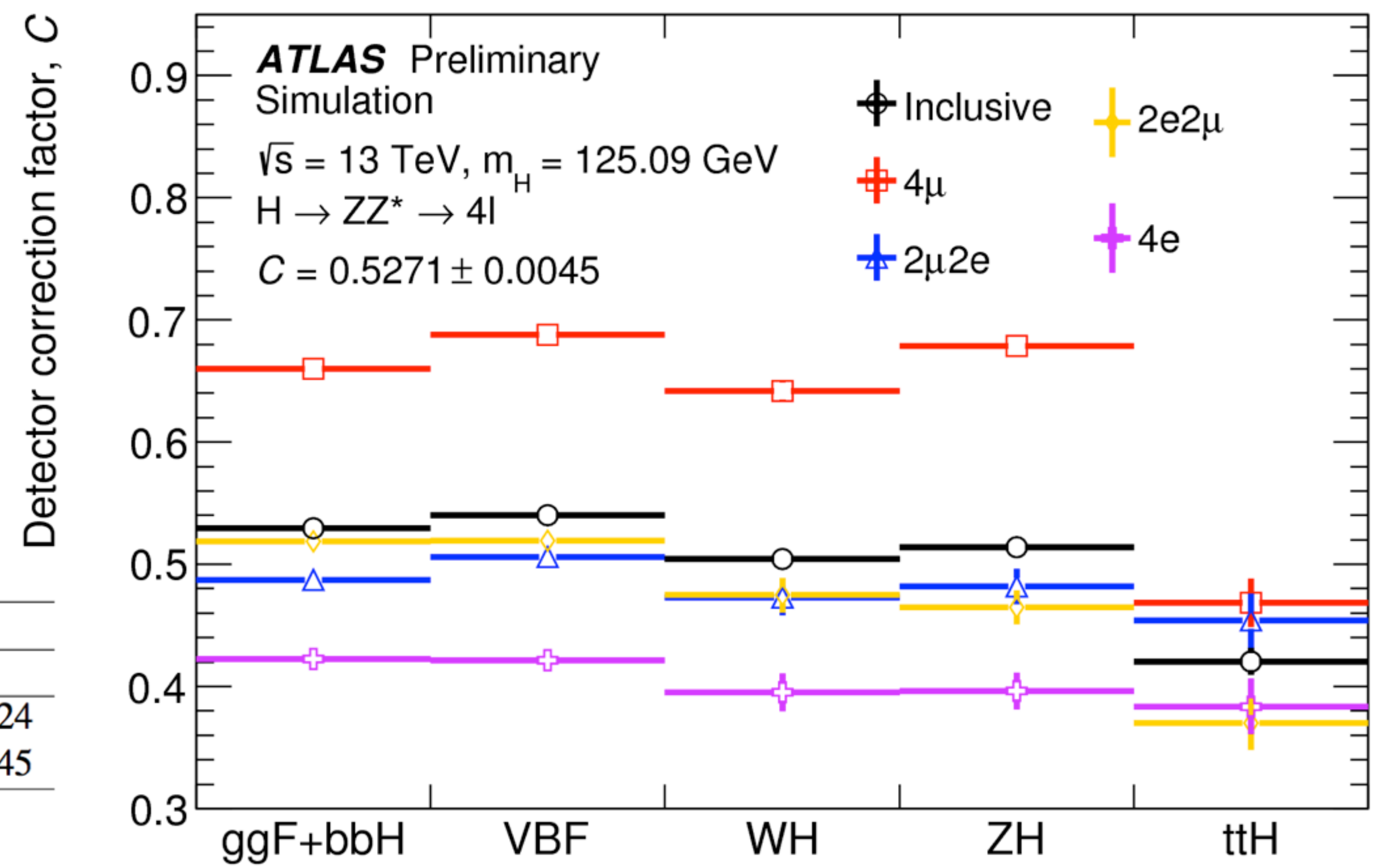


ATLAS: Fiducial Cross Section

$$\sigma^{\text{tot}} = \frac{N_s}{\mathcal{A} \cdot C \cdot \mathcal{B} \cdot \mathcal{L}_{\text{int}}}$$

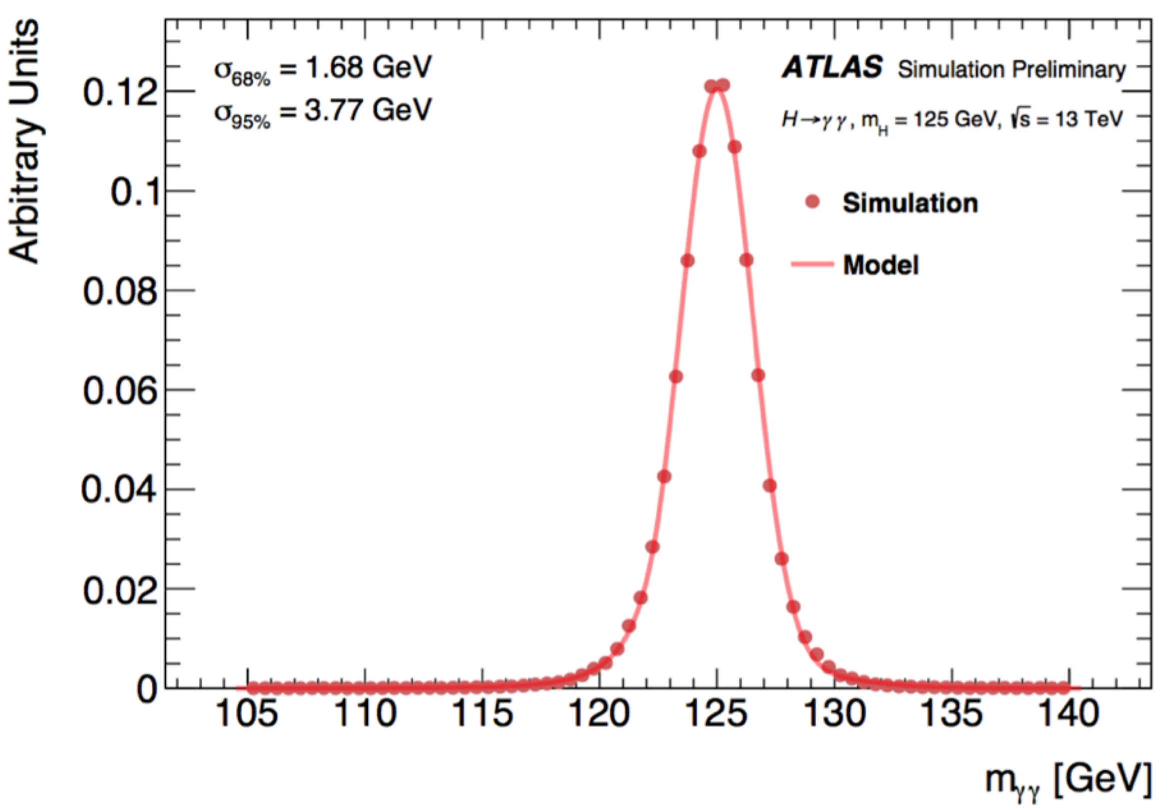
$$\sigma^{\text{fid}}_{4\ell} = \frac{N_s}{C \cdot \mathcal{L}_{\text{int}}}$$

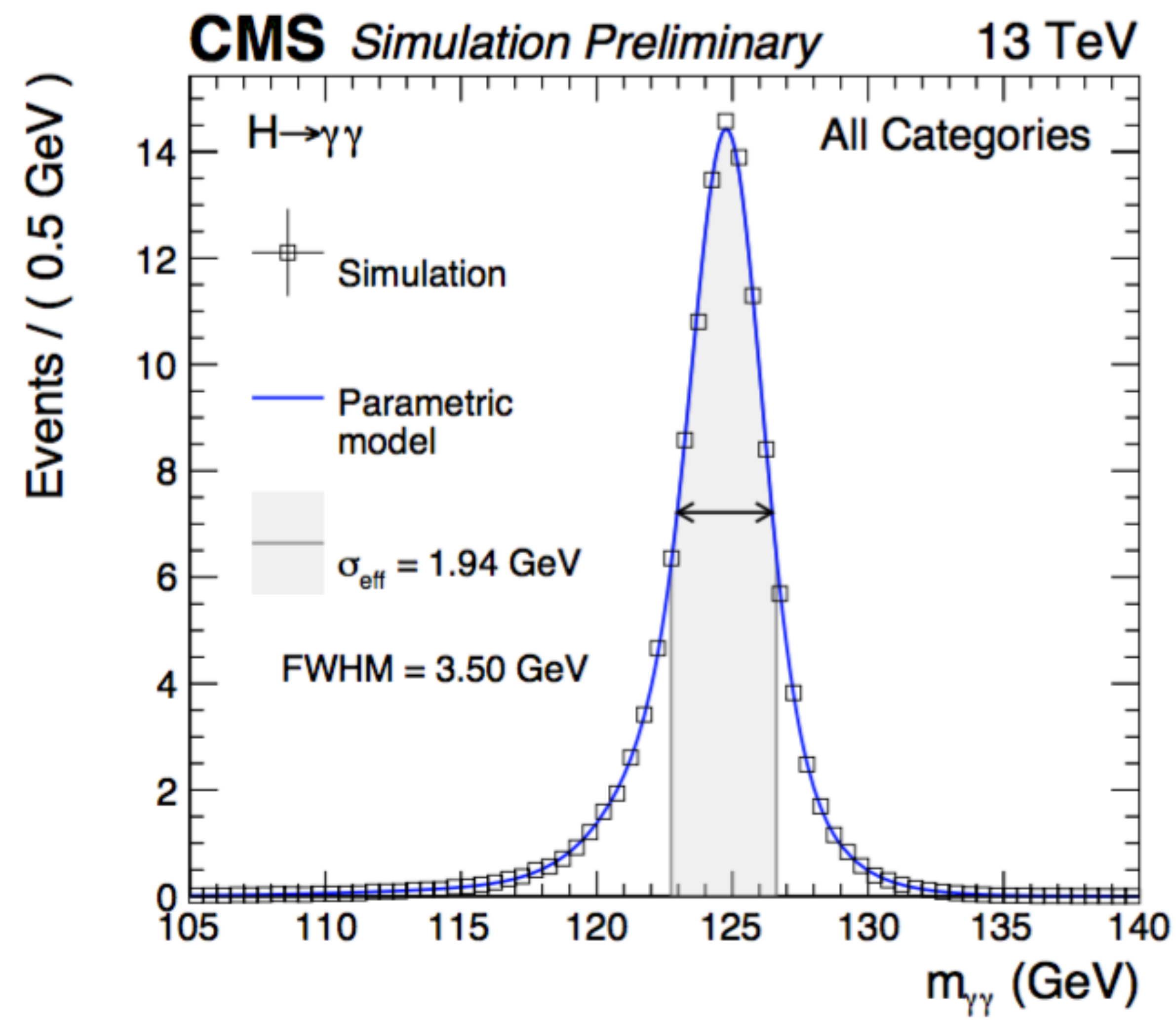
	$\sqrt{s}$ [TeV]		
	7	8	13
$\mathcal{A}$ [%]	46.67 ± 0.23	45.98 ± 0.14	42.74 ± 0.24
C [%]	51.89 ± 0.36	55.32 ± 0.24	52.71 ± 0.45



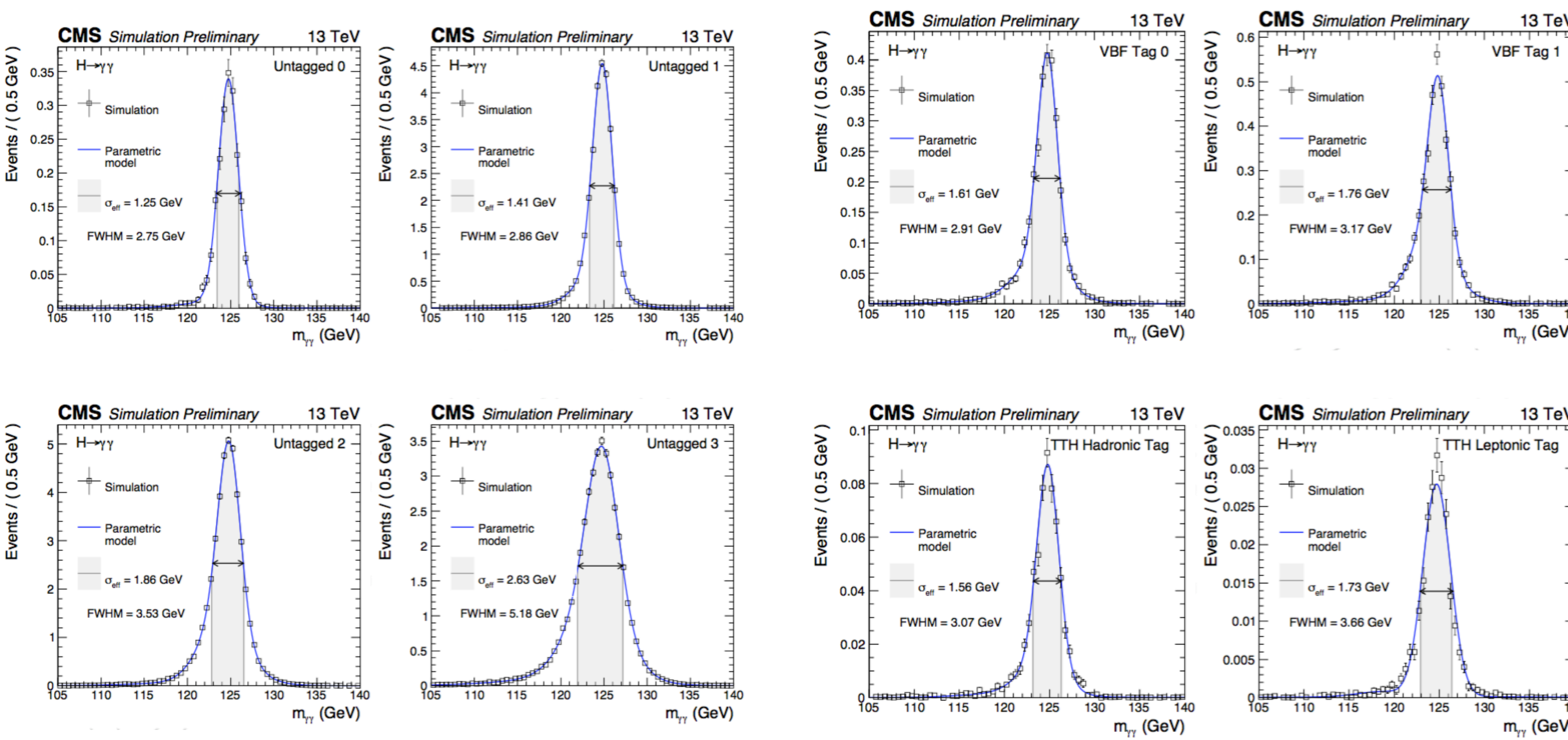
Data set [TeV]	N_s	$\sigma^{\text{fid}}_{4\ell}$ [fb]	$\sigma^{\text{fid}}_{\text{theory}}$ [fb]	σ^{tot} [pb]	$\sigma^{\text{tot}}_{\text{theory}}$ [pb]
7	$4.5^{+2.8}_{-2.2}$	$1.9^{+1.2}_{-0.9}$	1.03 ±0.11	33^{+21}_{-16}	17.5 ± 1.6
8	$24.0^{+6.0}_{-5.3}$	2.1 ± 0.5	1.29 ±0.13	37^{+9}_{-8}	22.3 ± 2.0
13	$1.0^{+2.3}_{-1.5}$	$0.6^{+1.3}_{-0.9}$	2.74 ±0.28	12^{+25}_{-16}	$50.9^{+4.5}_{-4.4}$

Signal Models

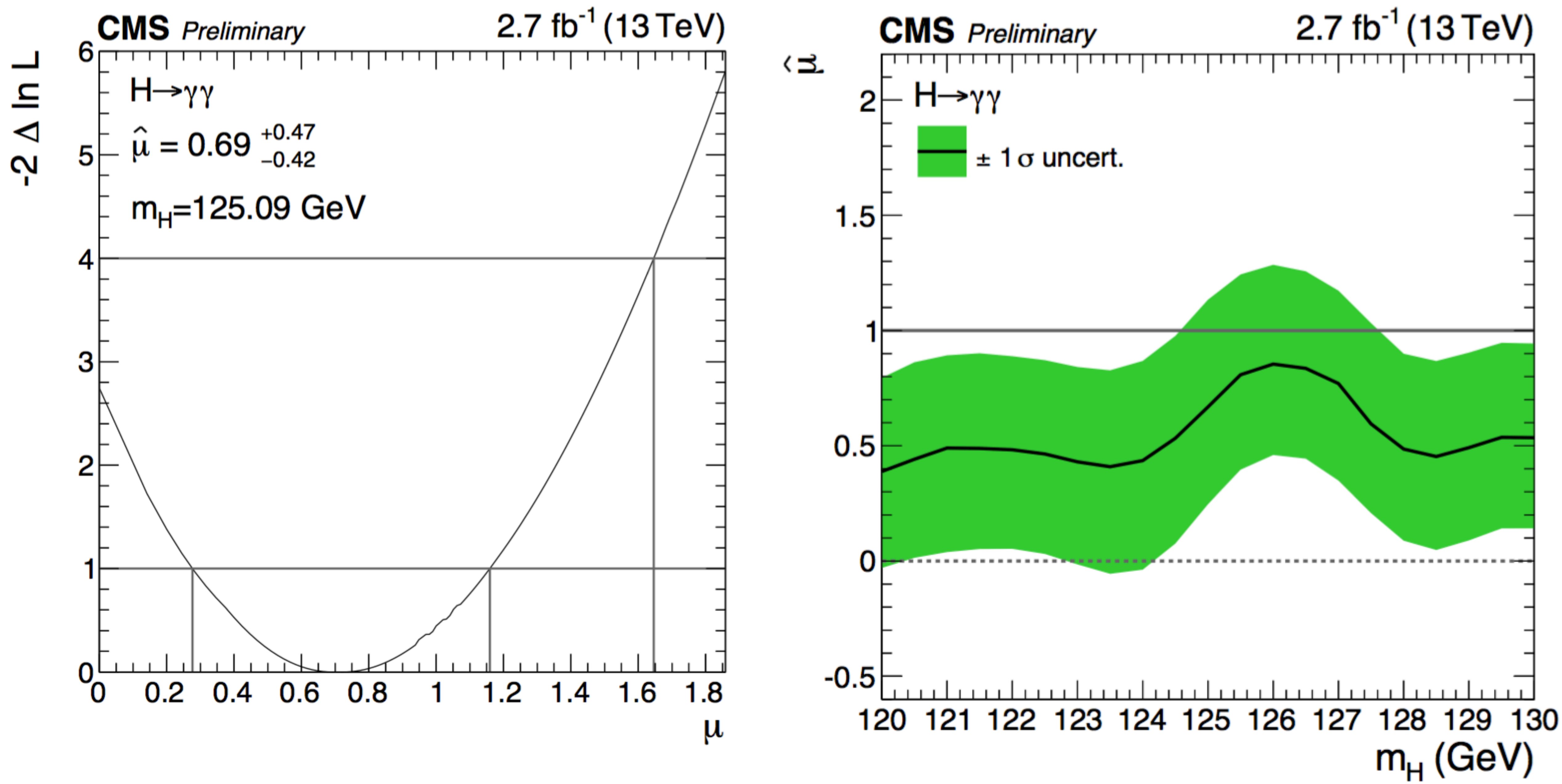




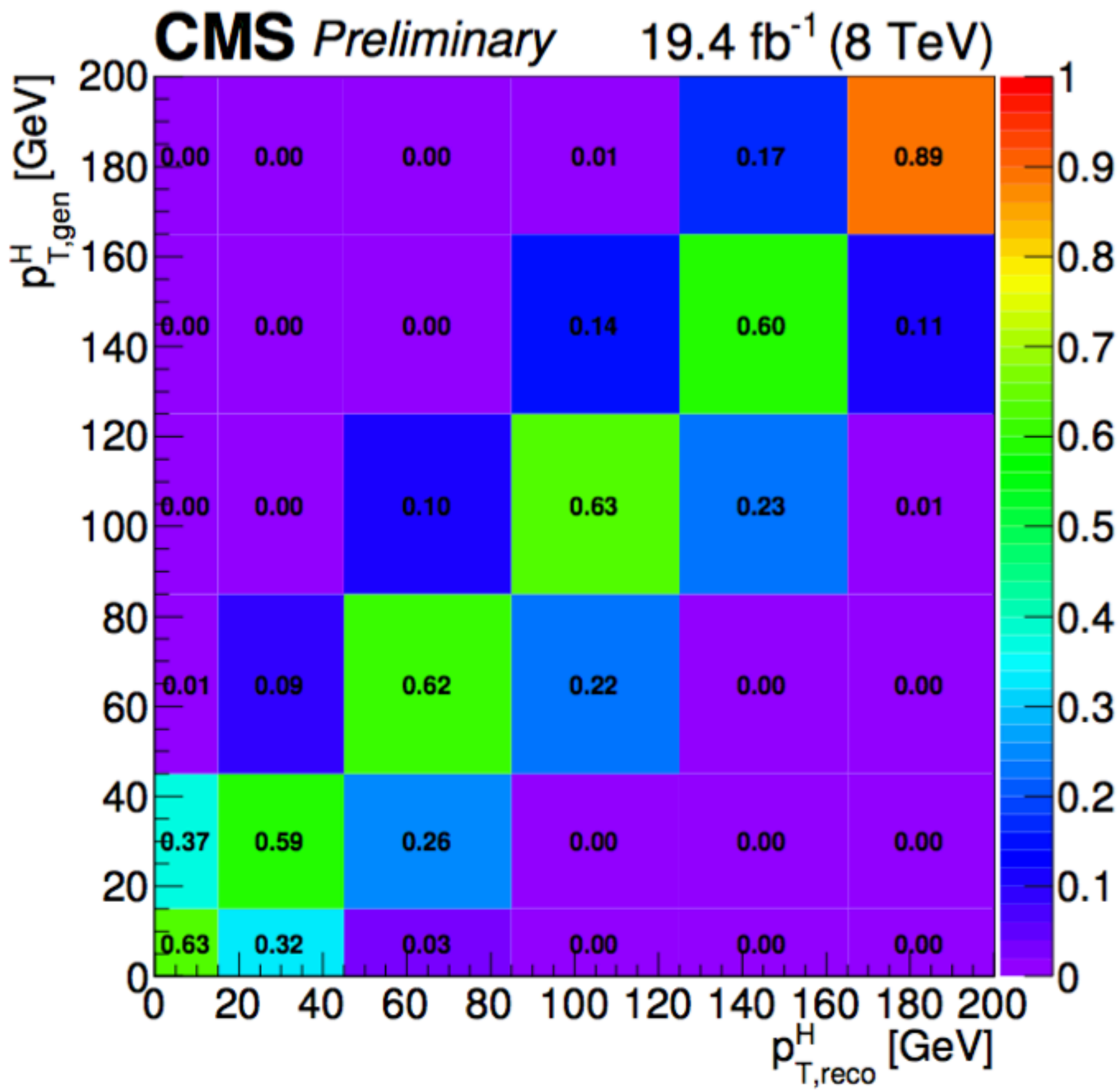
Per-Channel CMS Signal Models



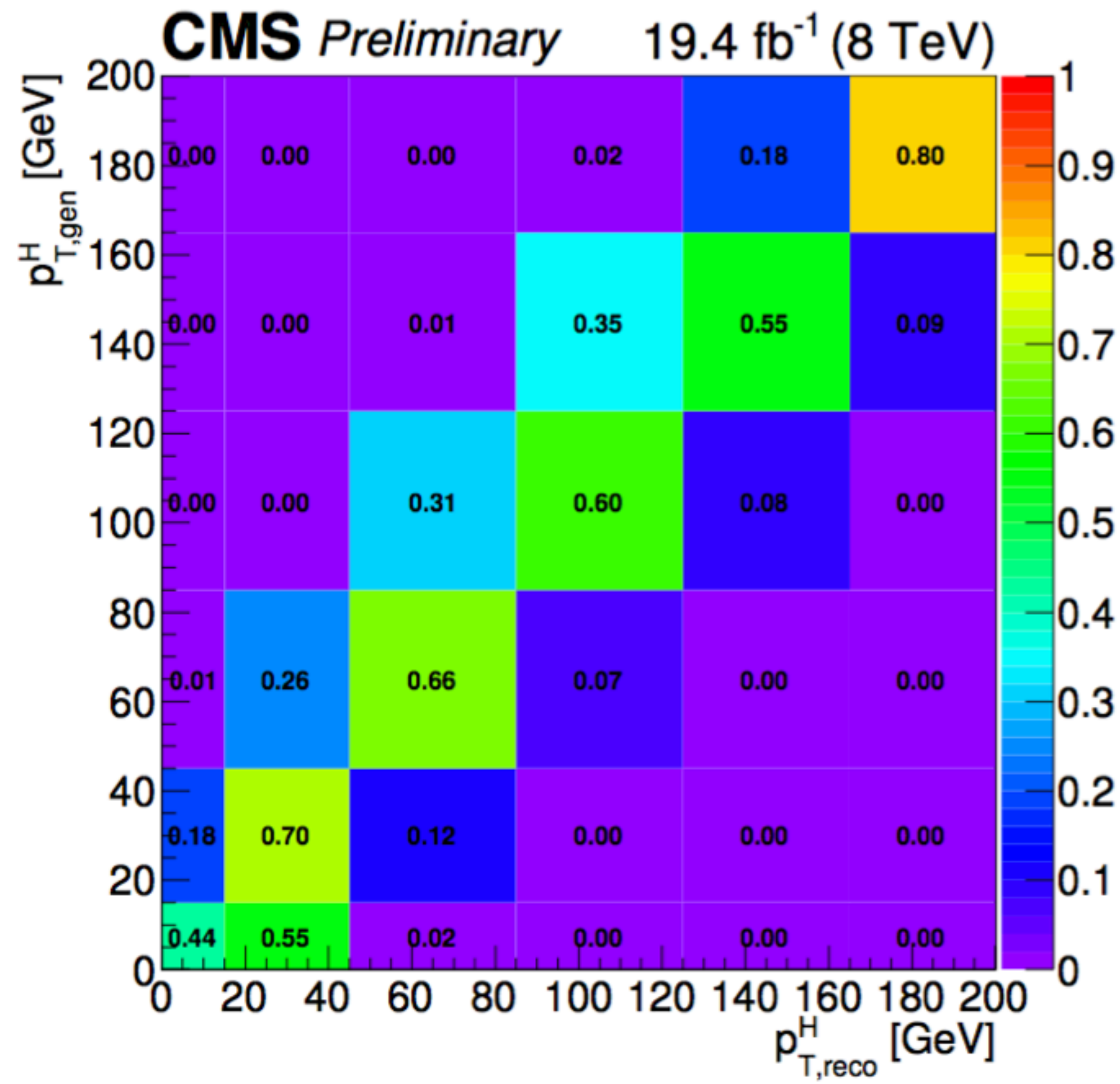
CMS: best-fit mu



- Singular Value Decomposition



(a) Deconvolution matrix



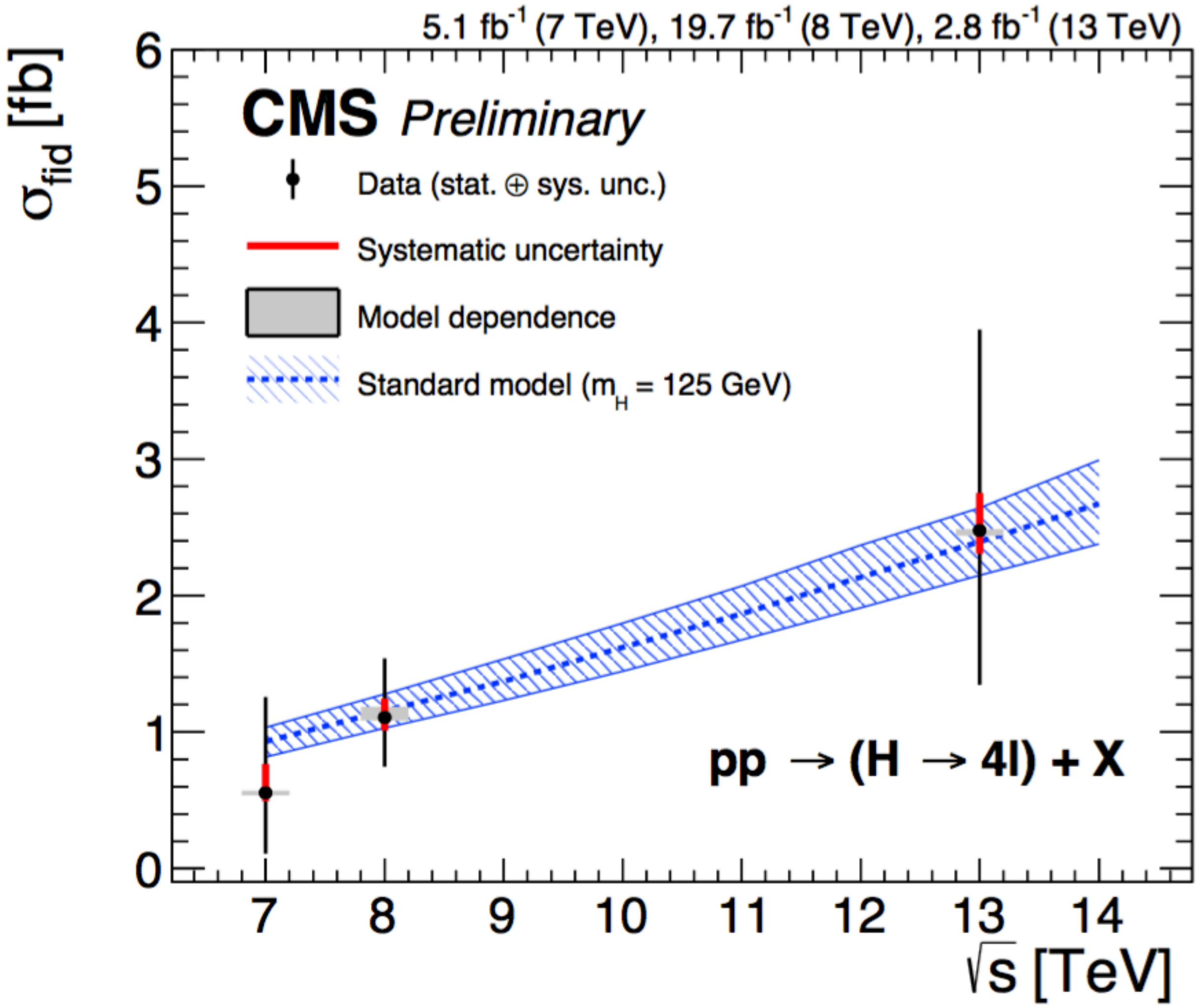
(b) Response matrix

CMS ZZ: Cross Section

$$\sigma_{\text{fid.}} = 2.48^{+1.45}_{-1.12}(\text{stat.})^{+0.28}_{-0.17}(\text{sys.})^{+0.01}_{-0.04}(\text{model dep.})\ \text{fb}$$

$$\sigma^{\text{SM}}_{\text{fid.}} = 2.39\ \text{fb}$$

Isolation ($\Delta R < 0.4$)



$p_T > 20$ GeV
$p_T > 10$ GeV
$p_T > 7(5)$ GeV
$|\eta| < 2.5(2.4)$
Isolation $< 0.4 \cdot p_T$
$40\,\text{GeV} < m(Z_1) < 120\,\text{GeV}$
$12\,\text{GeV} < m(Z_2) < 120\,\text{GeV}$
$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
$m(\ell^+ \ell'^-) > 4\,\text{GeV}$
$105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$

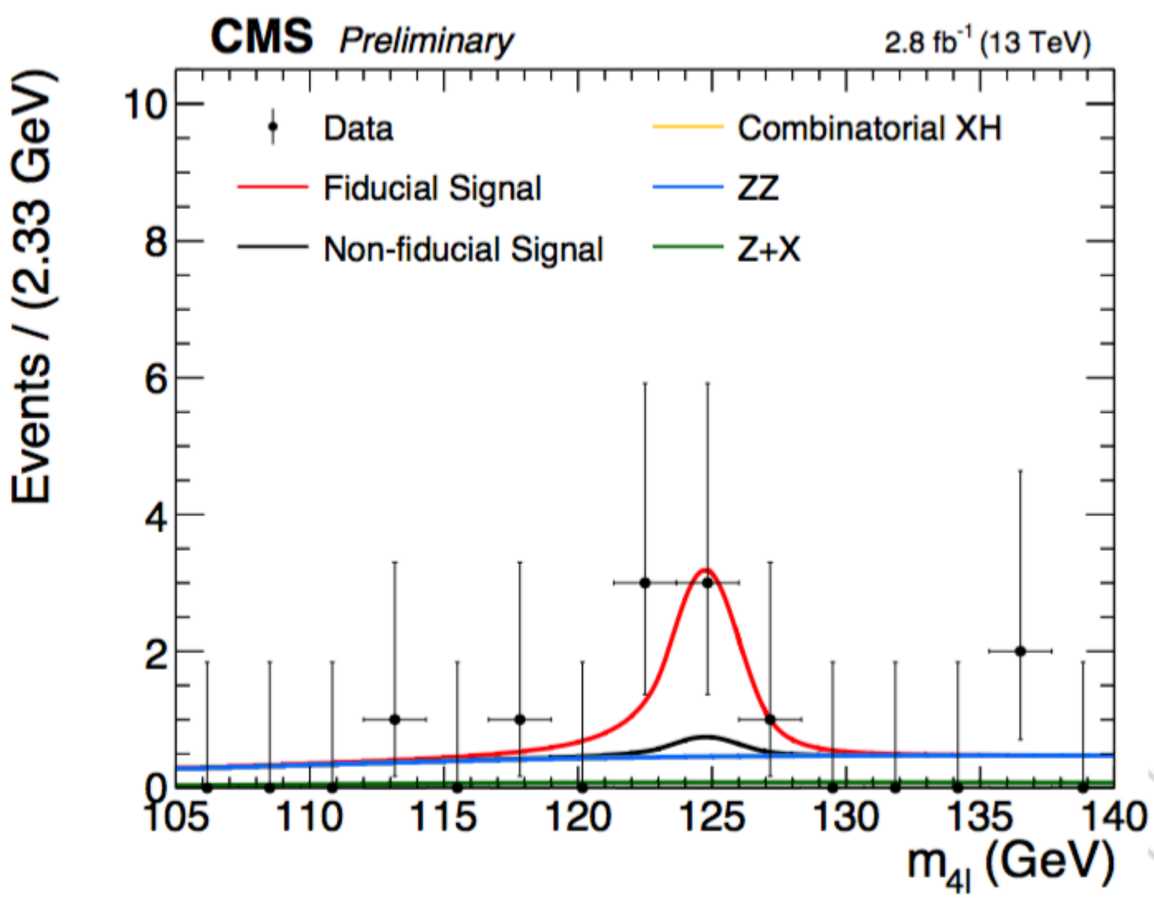
Isolation ($\Delta R < 0.3$)

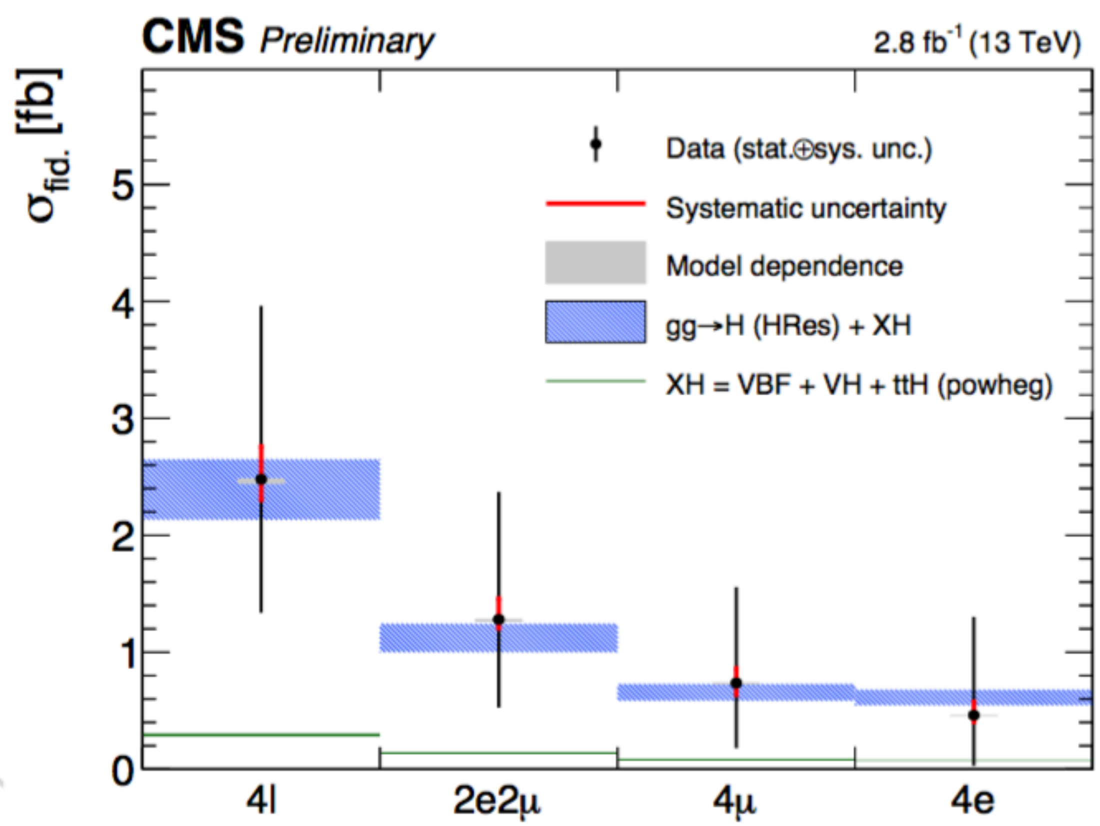
$\sigma_{\text{fid.}} = 2.66^{+1.58}_{-1.22}$ fb $\quad \sigma^{\text{SM}}_{\text{fid.}} = 2.50$ fb

Model dependence < 1%

7+8 TeV: HIG-14-028 accepted for publication in JHEP

CMS ZZ: Cross Section

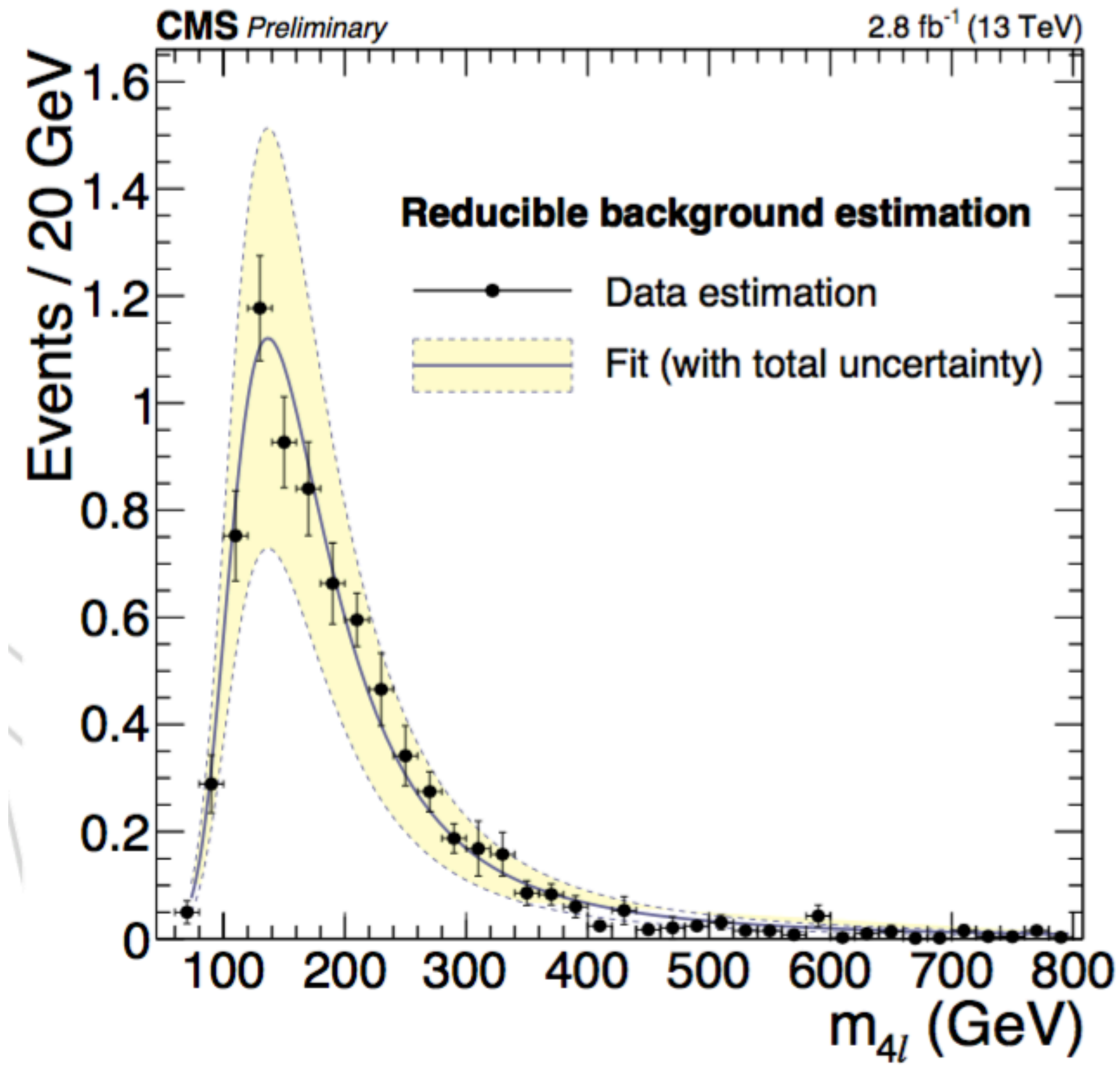




Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1+f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg→H	0.382 ± 0.001	0.697 ± 0.001	0.118 ± 0.001	0.779 ± 0.001
VBF	0.422 ± 0.001	0.707 ± 0.001	0.086 ± 0.001	0.768 ± 0.002
WH	0.277 ± 0.001	0.686 ± 0.002	0.164 ± 0.002	0.799 ± 0.003
ZH	0.302 ± 0.002	0.697 ± 0.003	0.172 ± 0.003	0.817 ± 0.004
$t\bar{t}$H	0.239 ± 0.001	0.687 ± 0.003	0.419 ± 0.007	0.975 ± 0.006

CMS: ZZ Uncertainties

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.7 %
Lepton identification/reconstruction efficiencies	4 – 9 %
Background related uncertainties	
QCD scale ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 10 %
PDF set ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 5 %
Electroweak corrections ($q\bar{q} \to ZZ$)	1 – 15 %
$gg \to ZZ$ K factor	10 %
Reducible background (Z+X)	40 – 90 %
VBF tagging efficiency (experimental)	7 – 14 %
VBF tagging efficiency (theoretical)	15 – 25 %
Signal related uncertainties	
QCD scale ($q\bar{q} \to$ VBF/VH, $gg \to H/t\bar{t}H$)	3 – 10 %
PDF set ($q\bar{q} \to$ VBF/VH, $gg \to H/t\bar{t}H$)	3 – 4 %
Acceptance	2 %
BR($H \to ZZ \to 4\ell$)	2 %
Lepton energy scale	0.04 – 0.3 %
Lepton energy resolution	20 %
VBF tagging efficiency (experimental)	2 – 7 %
VBF tagging efficiency (theoretical)	5 – 15 %



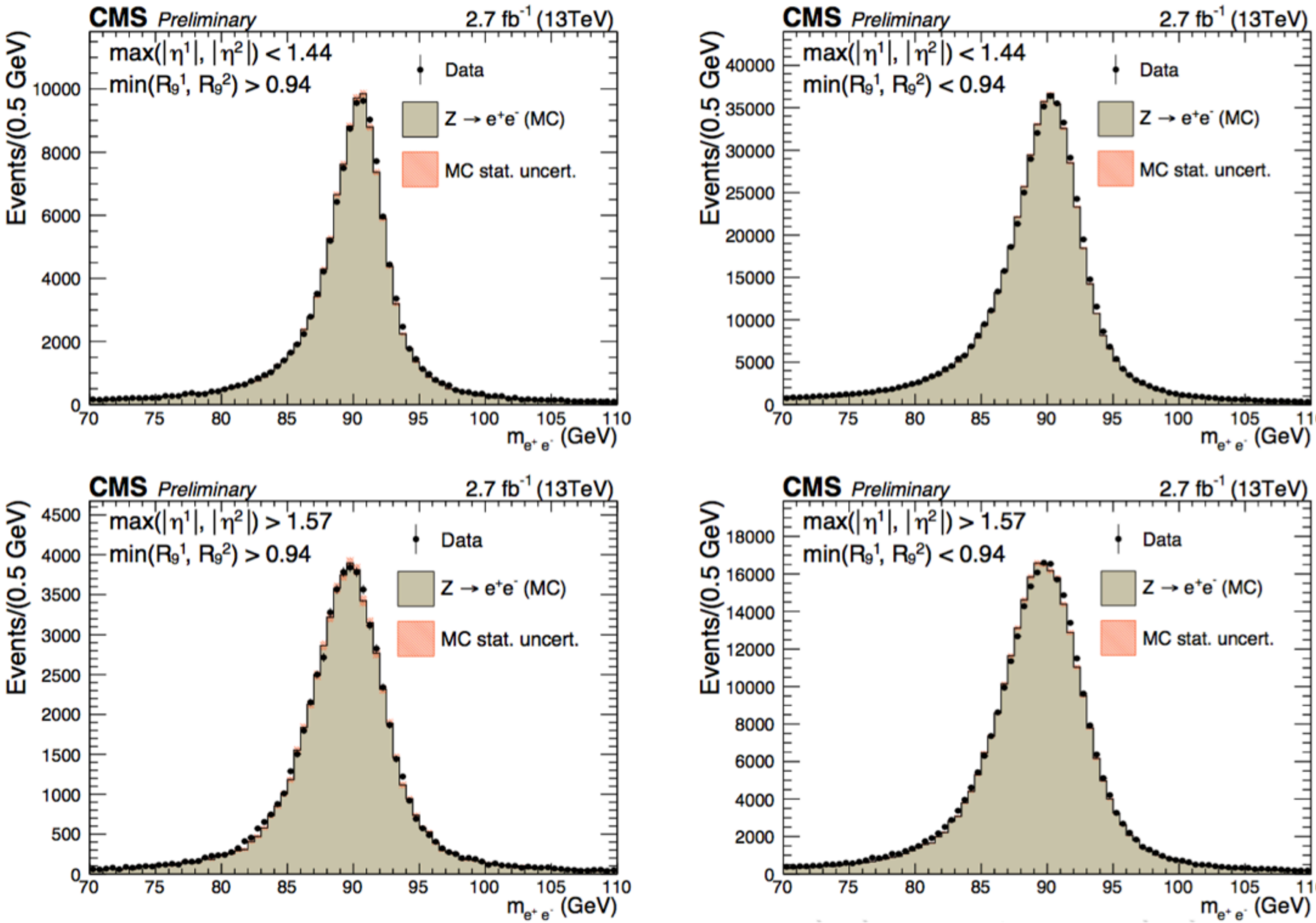
CMS ZZ Yields

118-130 GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \rightarrow ZZ$	0.33 ± 0.03	0.75 ± 0.05	0.92 ± 0.07	2.00 ± 0.14
$gg \rightarrow ZZ$	0.04 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	$0.18^{+0.03}_{-0.02}$
Z+X	$0.17^{+0.15}_{-0.09}$	0.19 ± 0.08	0.26 ± 0.10	$0.62^{+0.20}_{-0.16}$
Sum of backgrounds	$0.54^{+0.16}_{-0.10}$	1.02 ± 0.09	1.25 ± 0.13	$2.80^{+0.25}_{-0.22}$
Signal ($m_H = 125$ GeV)	$0.91^{+0.11}_{-0.10}$	1.70 ± 0.15	2.21 ± 0.22	$4.82^{+0.44}_{-0.45}$
Total expected	$1.45^{+0.21}_{-0.16}$	2.72 ± 0.20	3.45 ± 0.29	$7.62^{+0.58}_{-0.56}$
Observed	1	3	4	8

>70 GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \rightarrow ZZ$	$18.3^{+1.9}_{-1.8}$	31.1 ± 2.0	$42.6^{+3.5}_{-3.3}$	$92.0^{+6.7}_{-6.4}$
$gg \rightarrow ZZ$	3.9 ± 0.6	5.9 ± 0.8	9.0 ± 1.3	$18.8^{+2.6}_{-2.5}$
Z+X	$2.2^{+2.0}_{-1.2}$	2.1 ± 0.9	3.2 ± 1.3	$7.5^{+2.5}_{-2.0}$
Sum of backgrounds	$24.4^{+3.0}_{-2.4}$	39.1 ± 2.5	$54.8^{+4.4}_{-4.2}$	$118.3^{+8.3}_{-7.8}$
Signal ($m_H = 125$ GeV)	1.1 ± 0.1	1.9 ± 0.2	2.5 ± 0.2	5.5 ± 0.5
Total expected	$25.5^{+3.1}_{-2.5}$	$40.9^{+2.6}_{-2.5}$	$57.3^{+4.5}_{-4.4}$	$123.7^{+8.6}_{-8.2}$
Observed	17	49	43	109



CMS Preliminary
2.7 fb-1 (13TeV)
max(|η1|, |η2|) < 1.44
min(R91, R92) > 0.94
Data
Z → e+e- (MC)
MC stat. uncert.
Events/(0.5 GeV)
me+e- (GeV)
CMS Preliminary
2.7 fb-1 (13TeV)
max(|η1|, |η2|) < 1.44
min(R91, R92) < 0.94
Data
Z → e+e- (MC)
MC stat. uncert.
Events/(0.5 GeV)
me+e- (GeV)
CMS Preliminary
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max(|η1|, |η2|) > 1.57
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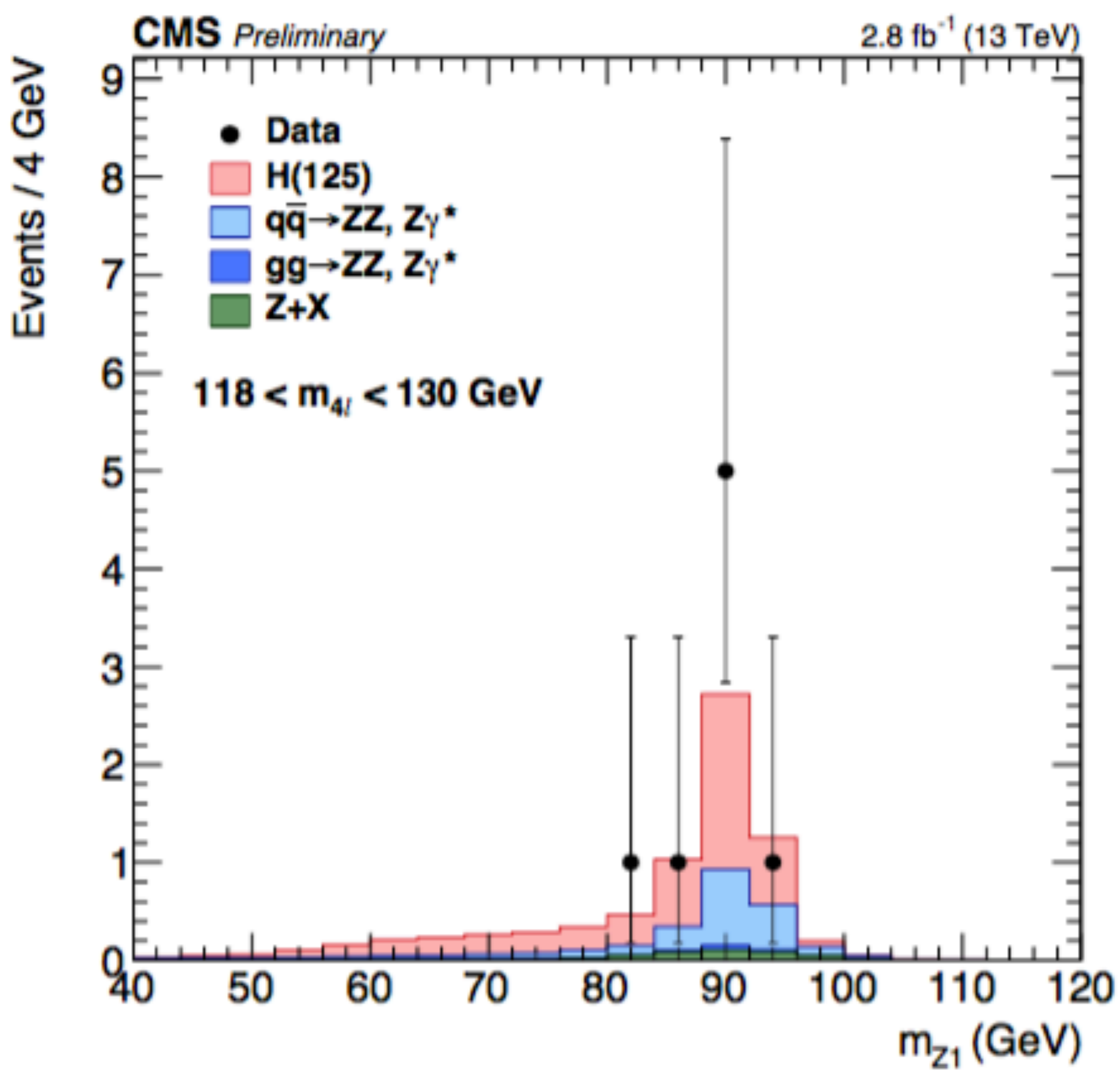
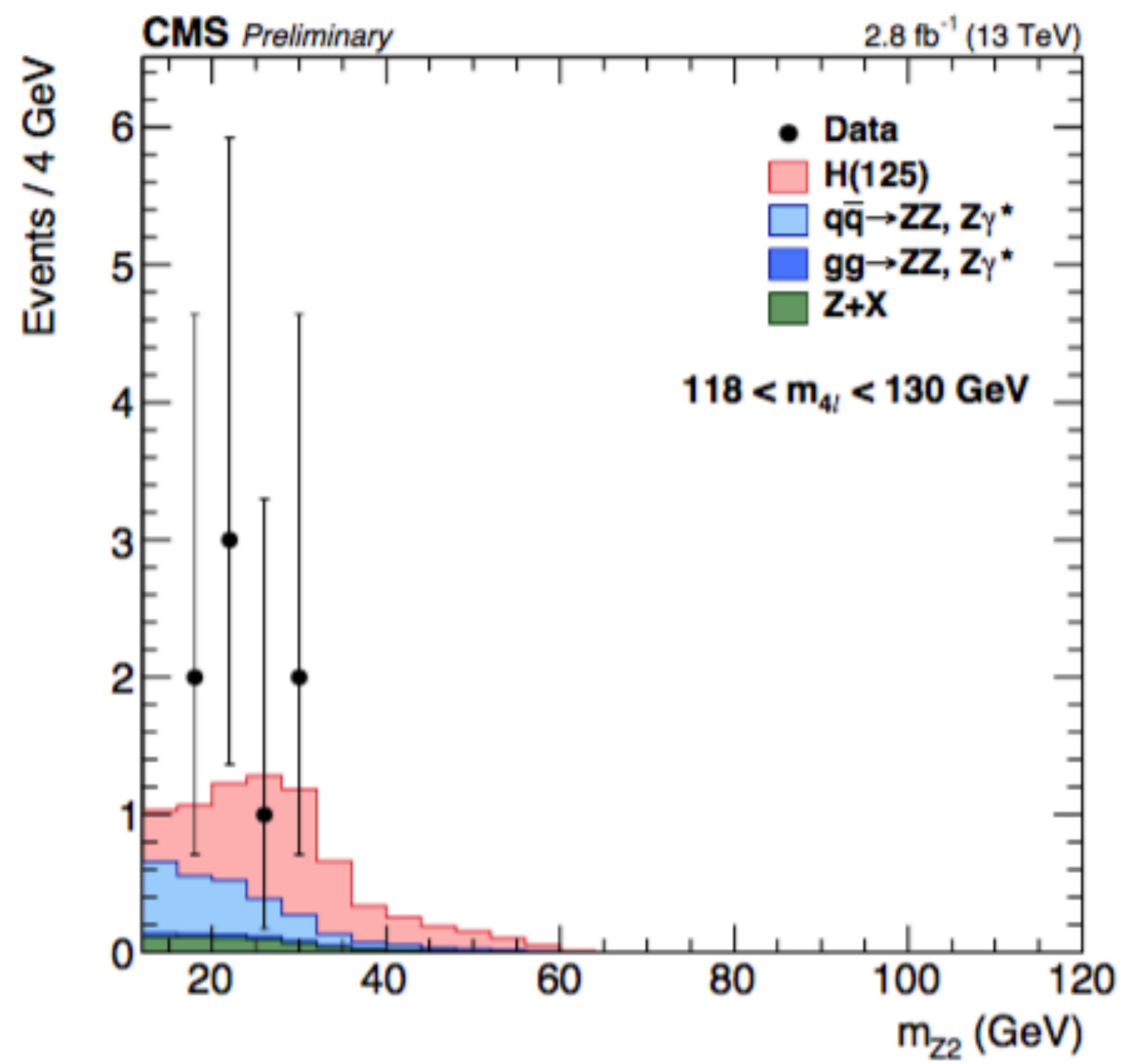
Z → e+e- (MC)
MC stat. uncert.
Events/(0.5 GeV)
me+e- (GeV)



CMS Preliminary
2.8 fb-1 (13 TeV)
Events / 4 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
118 < m4l < 130 GeV
mZ1 (GeV)



CMS Preliminary
2.8 fb-1 (13 TeV)
Events / 4 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
118 < m4l < 130 GeV
mZ2 (GeV)