



# Fiducial inclusive and differential Higgs boson cross sections at CMS

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*ICHEP2018, COEX Seoul, 6 July 2018*

**ETH** zürich

IPA



- Cross sections measured inclusively and differentially in fiducial **phase spaces**:
  - **Extrapolation** to full phase space **minimized**
  - Reproducibility in calculations for **future comparisons**
- Higgs inclusive measurements approaching **precision era** in Run2 → explore Higgs production **differentially**, in order to:
  - test SM predictions for **full spectra** of observables of interest
  - probe for **BSM hints**

**NEW!**  $H \rightarrow \gamma\gamma$  *submitted to JHEP*

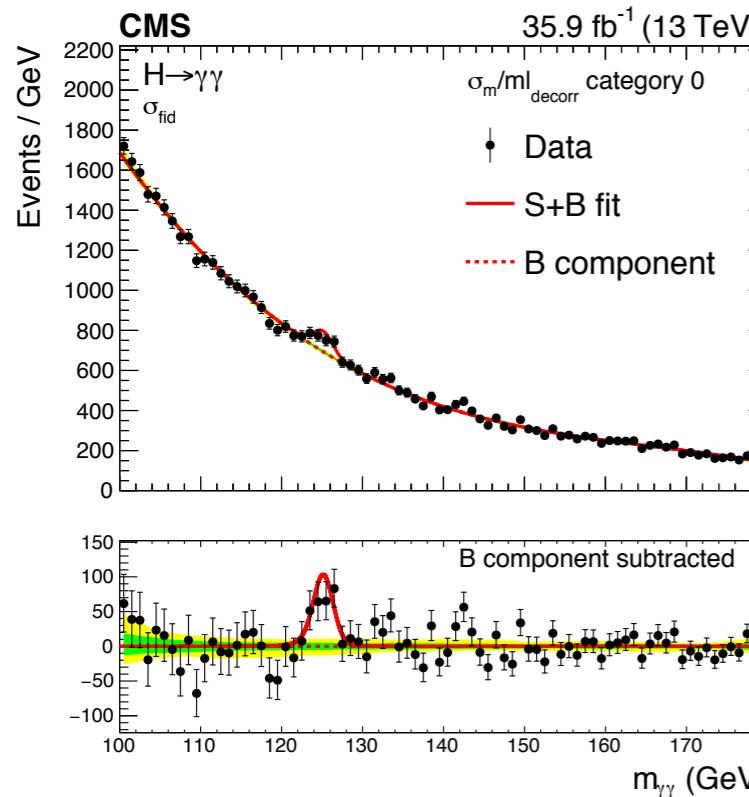
- In this talk, selected results on  $35.9\text{fb}^{-1}$  of 2016 data from:  $H \rightarrow ZZ^* \rightarrow 4\ell$  *JHEP 11 (2017) 047*
- Outline:

$H \rightarrow bb$  *PRL 120 (2018) 071802*

- Combination of channels (*HIG-17-028*) **NEW!**
- Overview of  $H \rightarrow \gamma\gamma$  results **NEW!**
- Interpretation in terms of coupling modifiers **NEW!**

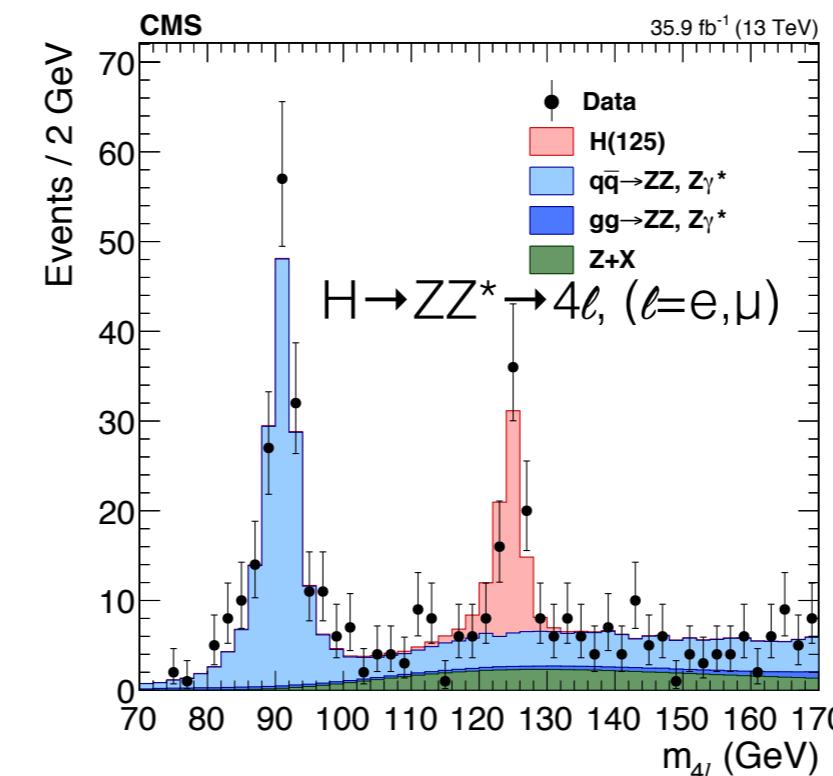
## H $\rightarrow$ $\gamma\gamma$

- Fit to diphoton invariant mass
- Categorization in mass resolution
- Most comprehensive and precise set of measurements (**>25** observables): H kinematics, jets, b-jets, leptons,  $p_T^{\text{miss}}$ , specific production modes



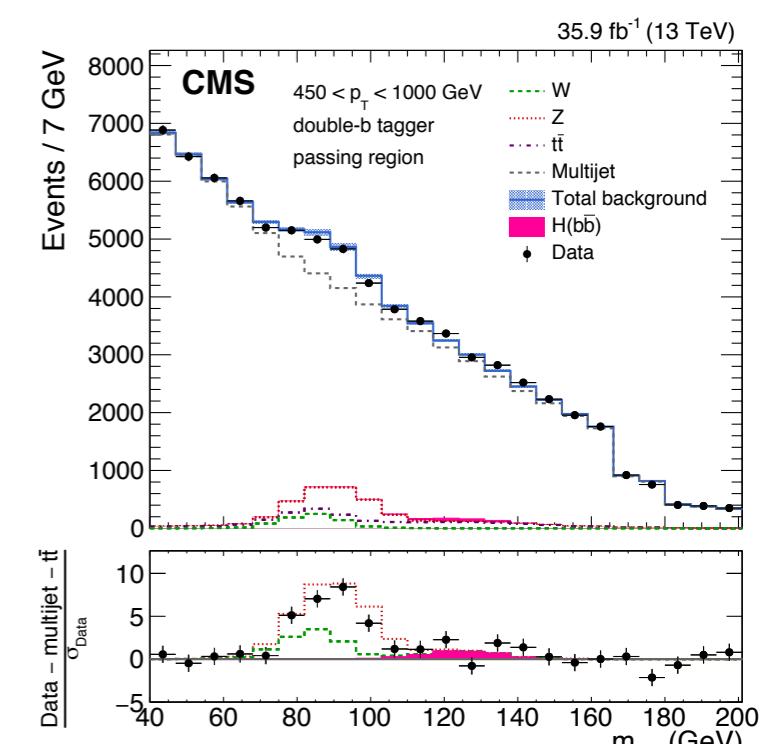
## H $\rightarrow$ ZZ\* $\rightarrow$ 4 $\ell$

- Fit to  $m_{4\ell}$  mass distribution
- Categorization in lepton flavours
- Inclusive precision close to H $\rightarrow$  $\gamma\gamma$
- Measurements as functions of 4 observables  $p_T(H)$ ,  $y(H)$ ,  $N_{\text{jets}}$ ,  $p_T(j_1)$



## H $\rightarrow$ bb

- Fit to  $m_{\text{SD}}$  mass distribution
- Measurement of boosted inclusive H production with categorization in jet substructure
- Combined in differential  $p_T(H)$  measurement



$H \rightarrow \gamma\gamma$

$p_{T,1}/m_{\gamma\gamma}$	$> 1/3$
$p_{T,2}/m_{\gamma\gamma}$	$> 1/4$
$Iso_{gen1,2}$	$< 10 \text{ GeV}$
$ \eta_{1,2} $	$< 2.5$

$H \rightarrow ZZ^* \rightarrow 4\ell$

Lepton kinematics and isolation	
Leading lepton $p_T$	$p_T > 20 \text{ GeV}$
Subleading lepton $p_T$	$p_T > 10 \text{ GeV}$
Additional electrons (muons) $p_T$	$p_T > 7(5) \text{ GeV}$
Pseudorapidity of electrons (muons)	$ \eta  < 2.5(2.4)$
Sum $p_T$ of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Invariant mass of the $Z_1$ candidate	$40 < m_{Z_1} < 120 \text{ GeV}$
Invariant mass of the $Z_2$ candidate	$12 < m_{Z_2} < 120 \text{ GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02 \text{ for any } i \neq j$
Invariant mass of any opposite-sign lepton pair	$m_{\ell^+\ell'^-} > 4 \text{ GeV}$
Invariant mass of the selected four leptons	$105 < m_{4\ell} < 140 \text{ GeV}$

- The fiducial cross section are measured to be

$$\hat{\sigma}_{\text{fid}}(H \rightarrow \gamma\gamma) =$$

$$= 84 \pm 11(\text{stat}) \pm 7(\text{syst}) \text{ fb}$$

no theory uncertainties, only experimental

$$\hat{\sigma}_{\text{fid}}(H \rightarrow 4\ell) =$$

$$= 2.90^{+0.48}_{-0.44}(\text{stat})^{+0.27}_{-0.22}(\text{syst}) \text{ fb}$$

in agreement with the theory predictions

$$\sigma_{\text{fid}}^{\text{theory}}(H \rightarrow \gamma\gamma) =$$

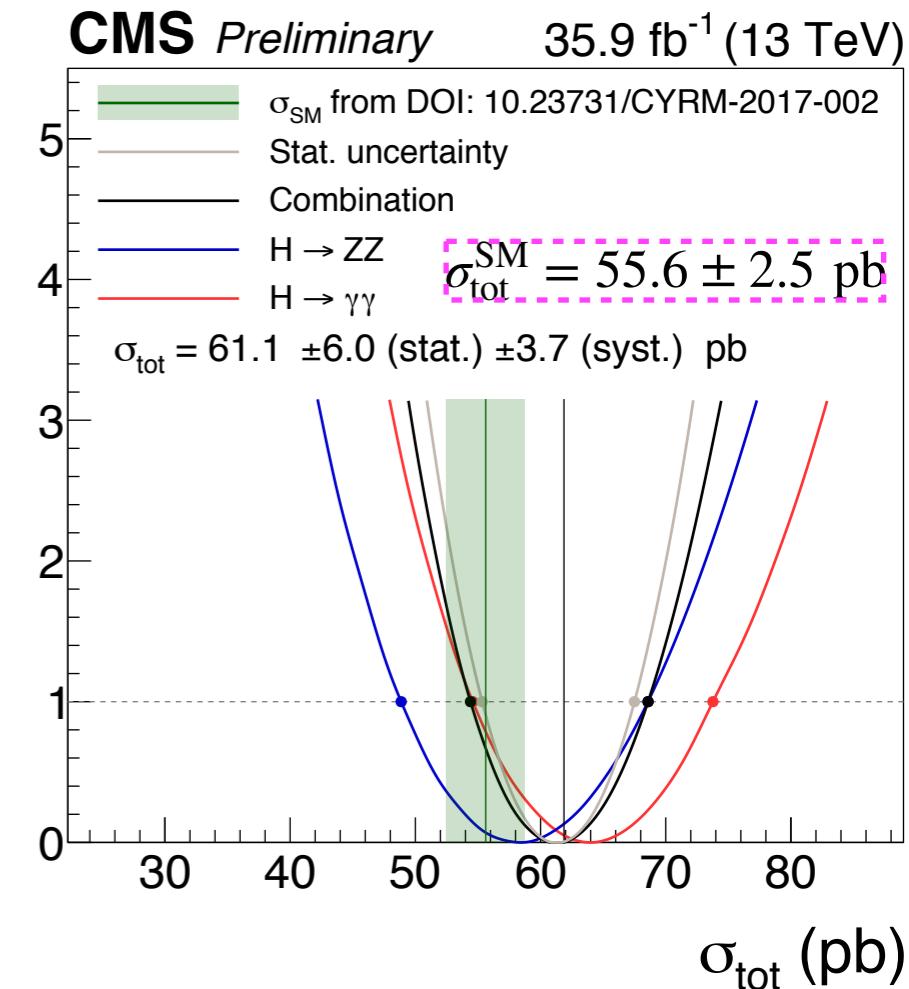
$$= 73 \pm 4 \text{ fb}$$

$$\sigma_{\text{fid}}^{\text{theory}}(H \rightarrow 4\ell) =$$

$$= 2.72 \pm 0.14 \text{ fb}$$

## Combination

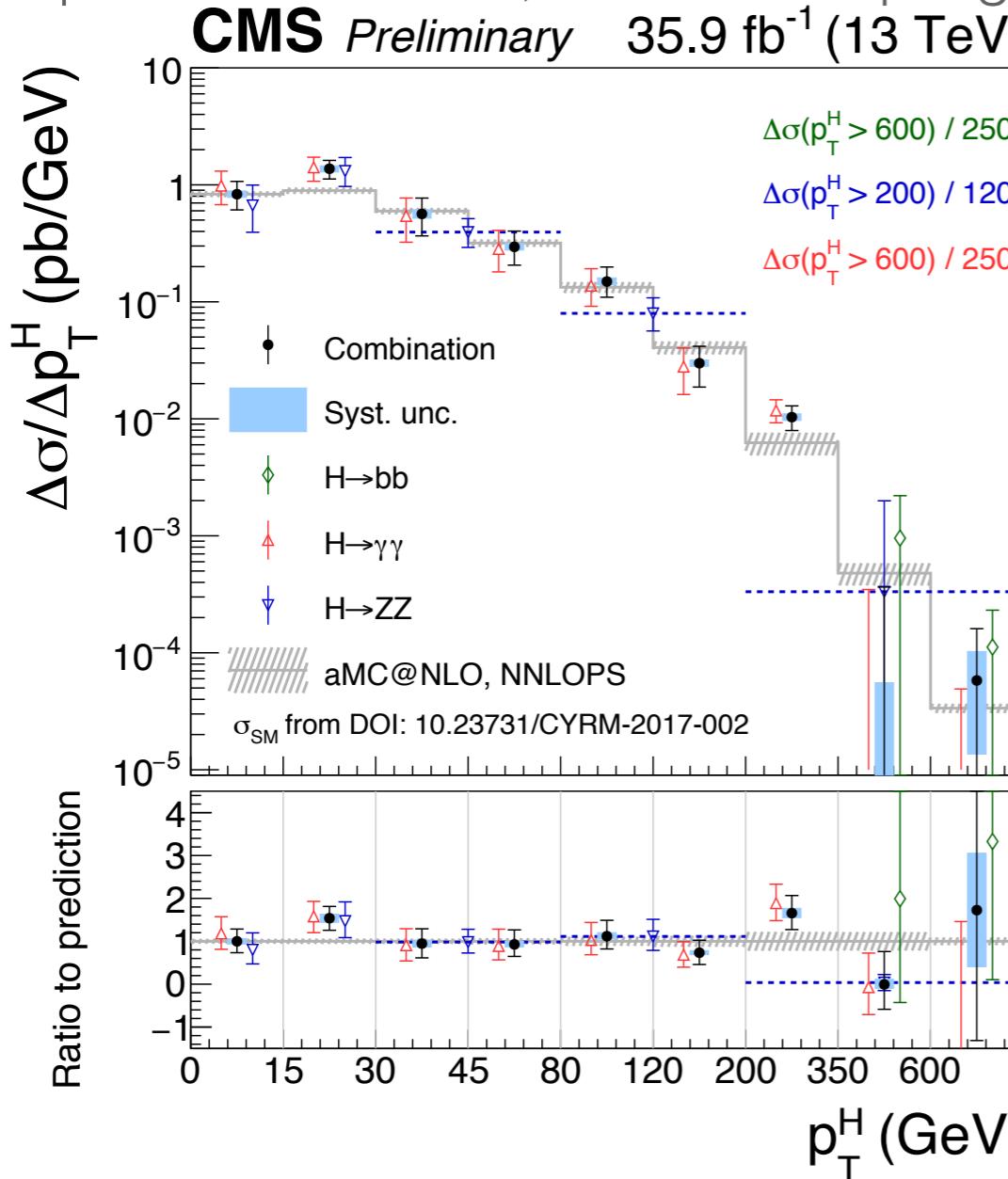
- Extrapolation to full phase space
- Total cross section measured with  $\sim 11\%$  uncertainty
- Precision still statistically limited



# Combination results: $p_T(H)$ , $y(H)$

## $p_T(H)$

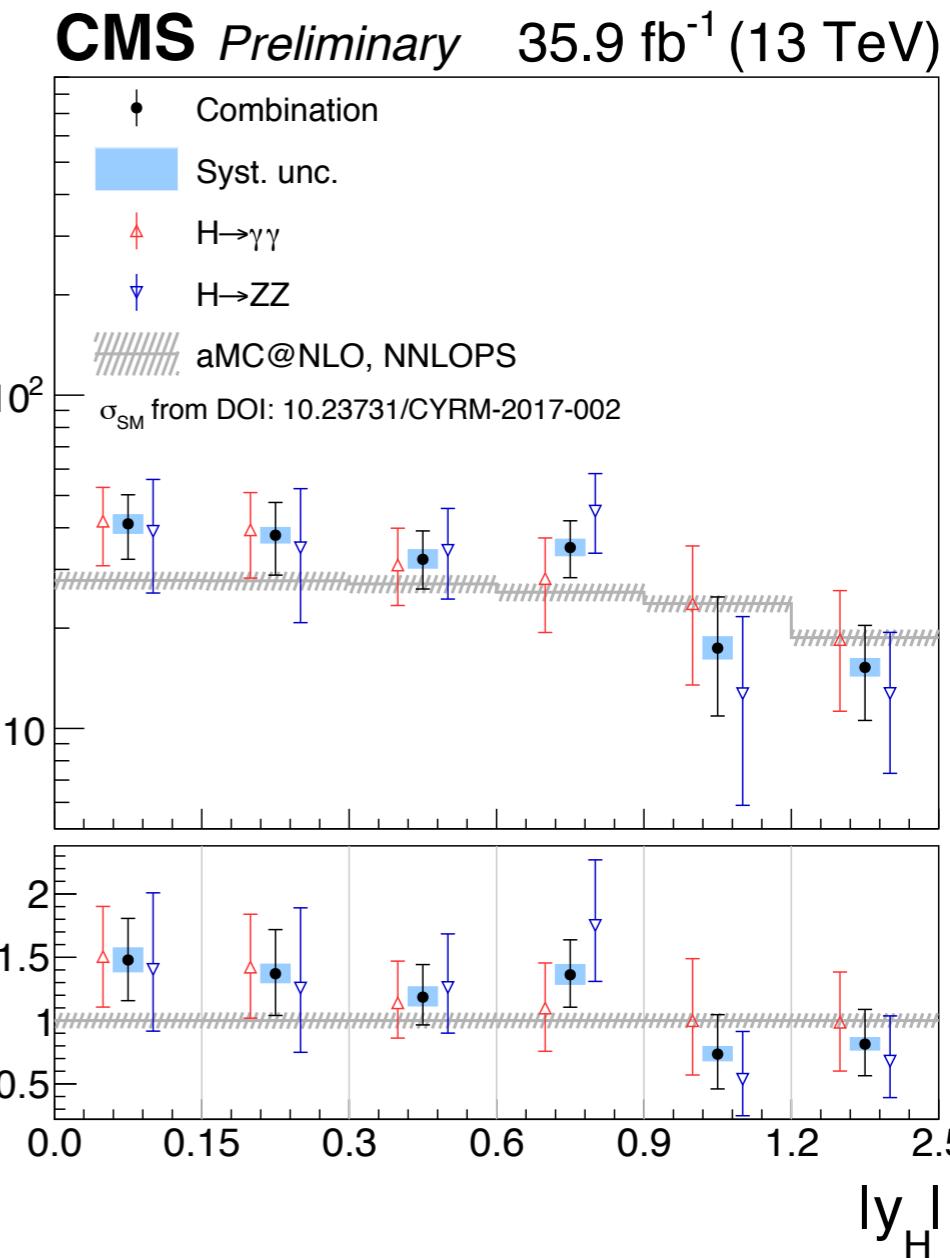
sensitive to perturbative QCD modelling,  
production mode, Yukawa couplings, ...



~10-20% improvement from combination  
 $H \rightarrow \gamma\gamma$  allows 30-40% precision up to 350 GeV,  
 $H \rightarrow bb$  contributes at high  $p_T$

## $y(H)$

probe of PDFs, production mode



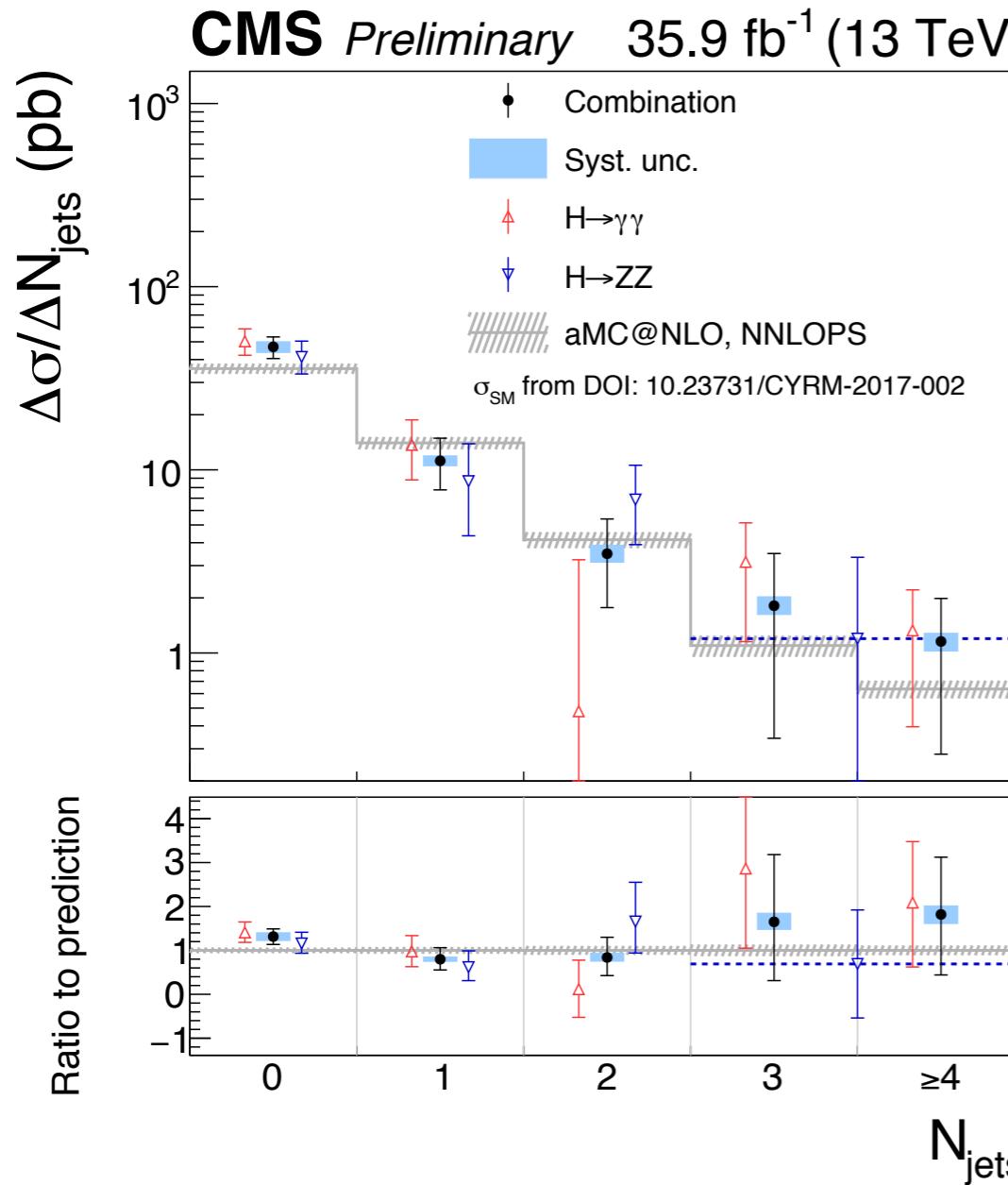
30-50% precision across the spectrum

# Combination: $N_{\text{jets}}$ , $p_T(\text{jet})$

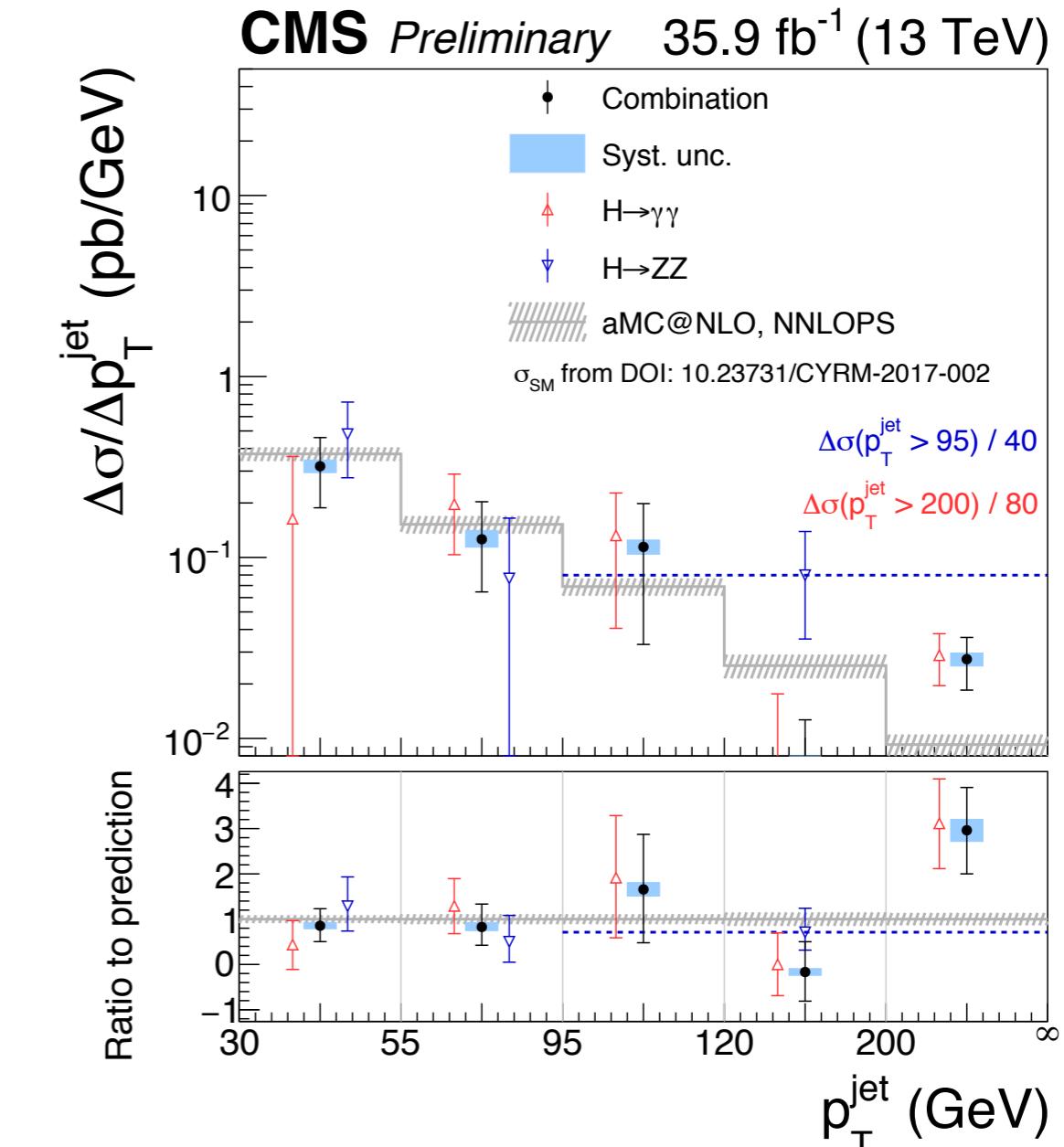
$N_{\text{jets}}$

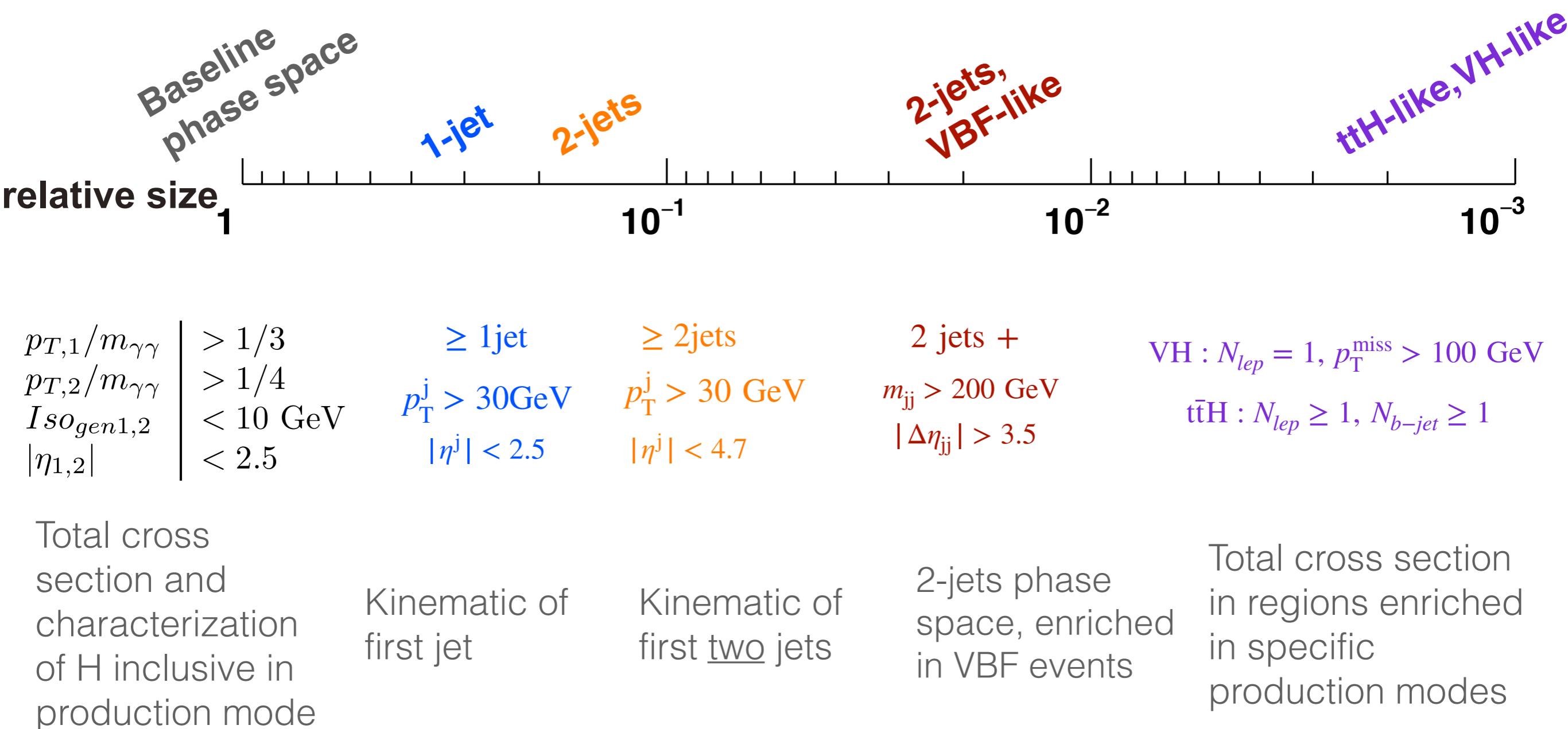
$p_T(\text{jet})$

test of modelling of QCD radiation, production mechanism



20% precision in 0-jet bin, ~100% in high multiplicity bins

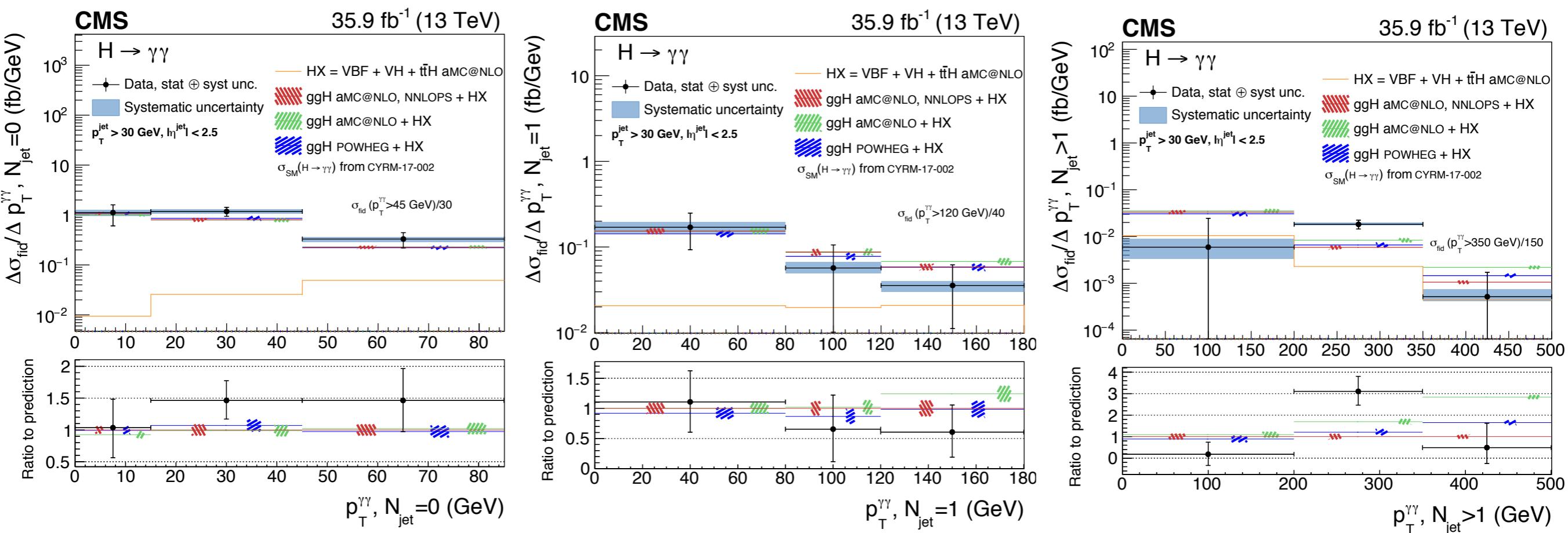




In the following, a **selection** of the vast campaign of measurements is shown

# Double-differential measurement

- Double-differential measurement as a function of  $p_T(H) \times N_{\text{jets}}$



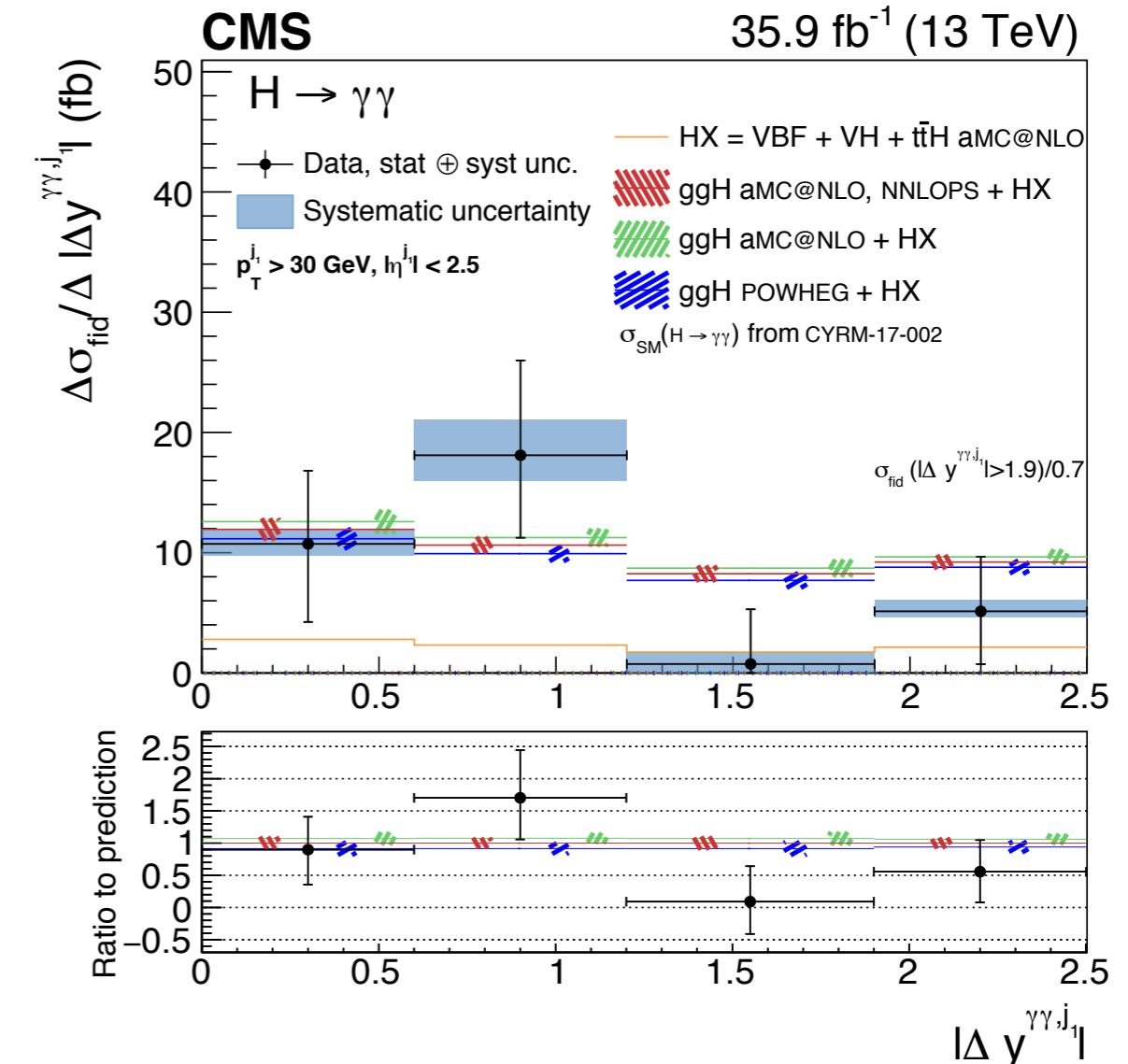
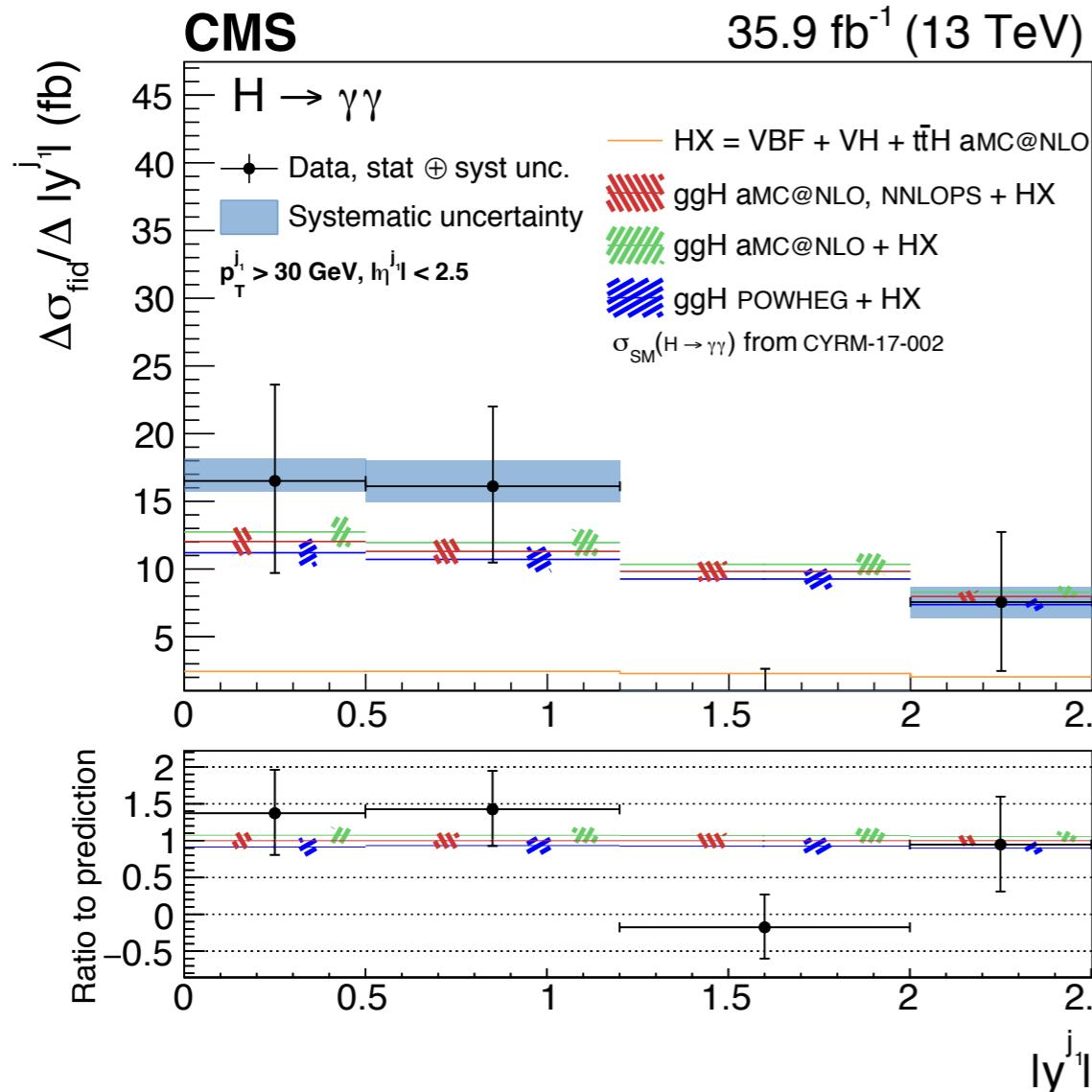
- 9 kinematic bins, with uncertainties ranging between 35% and 60%

# l-jet measurements

$\geq 1\text{jet}$

$p_T^j > 30\text{GeV}$   
 $|\eta^j| < 2.5$

- Characterization of the **highest-pT jet** produced in association with the H

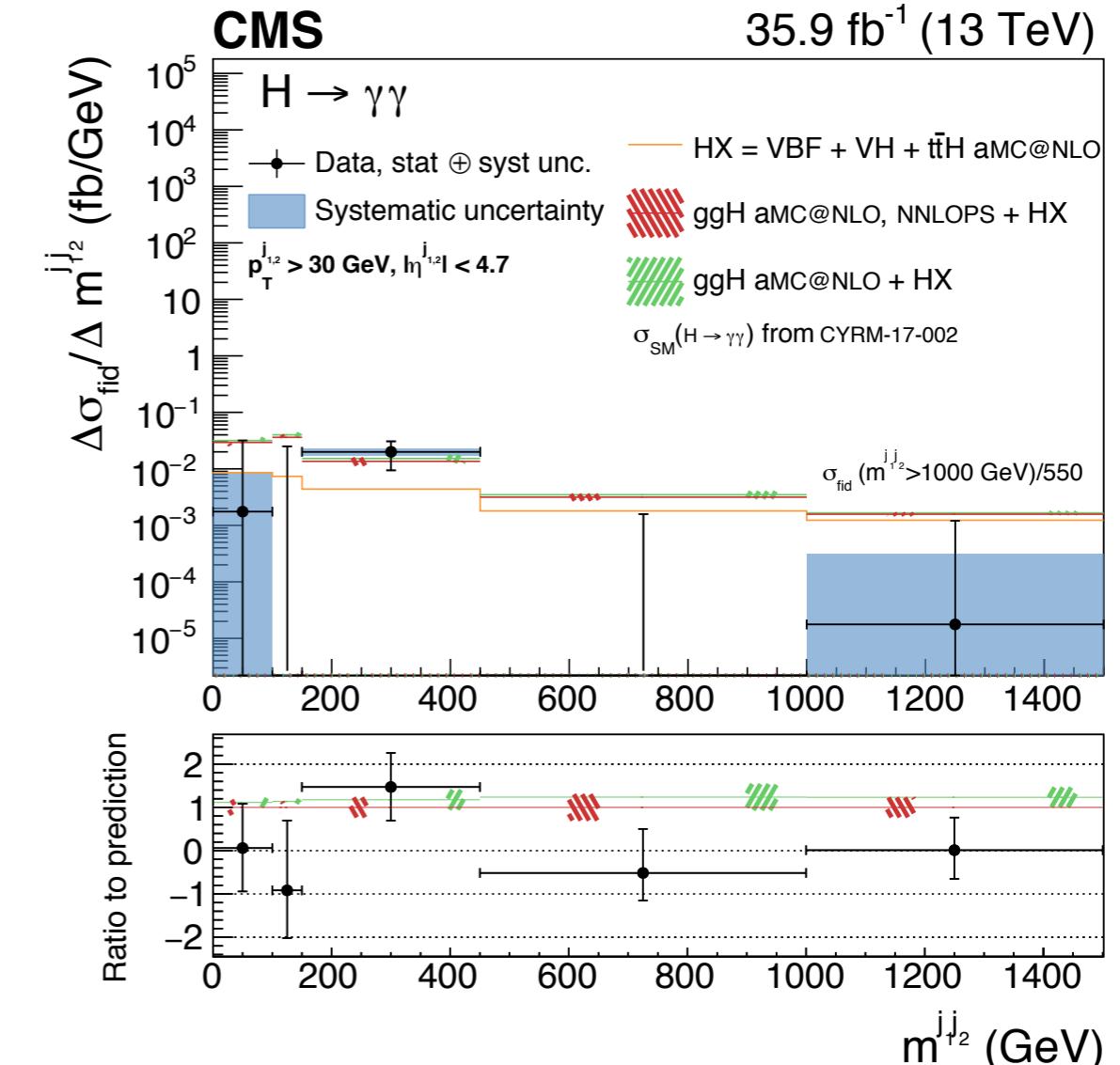
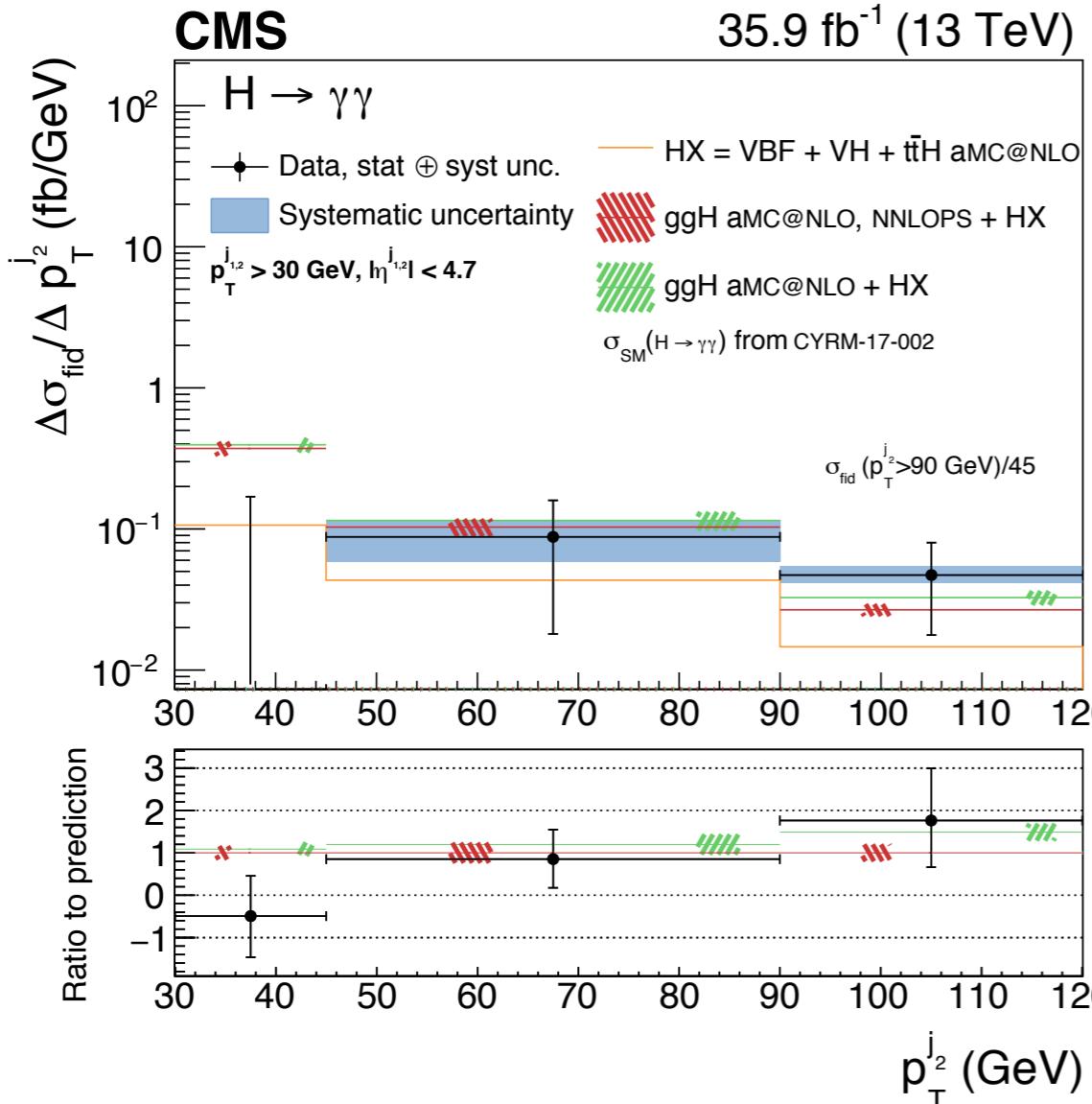


- Spectra are measured with 50-70% uncertainty

# 2-jets measurements

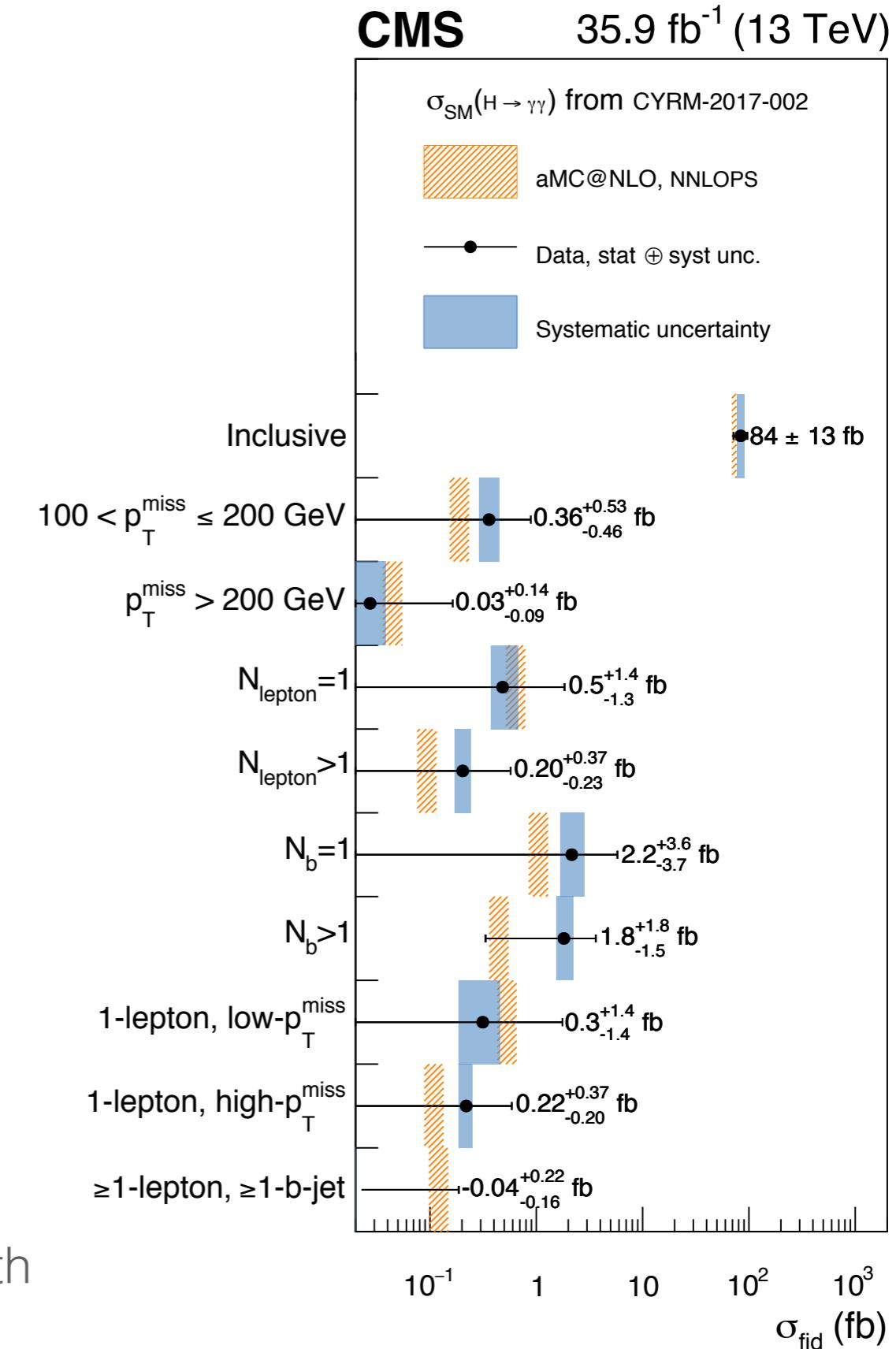
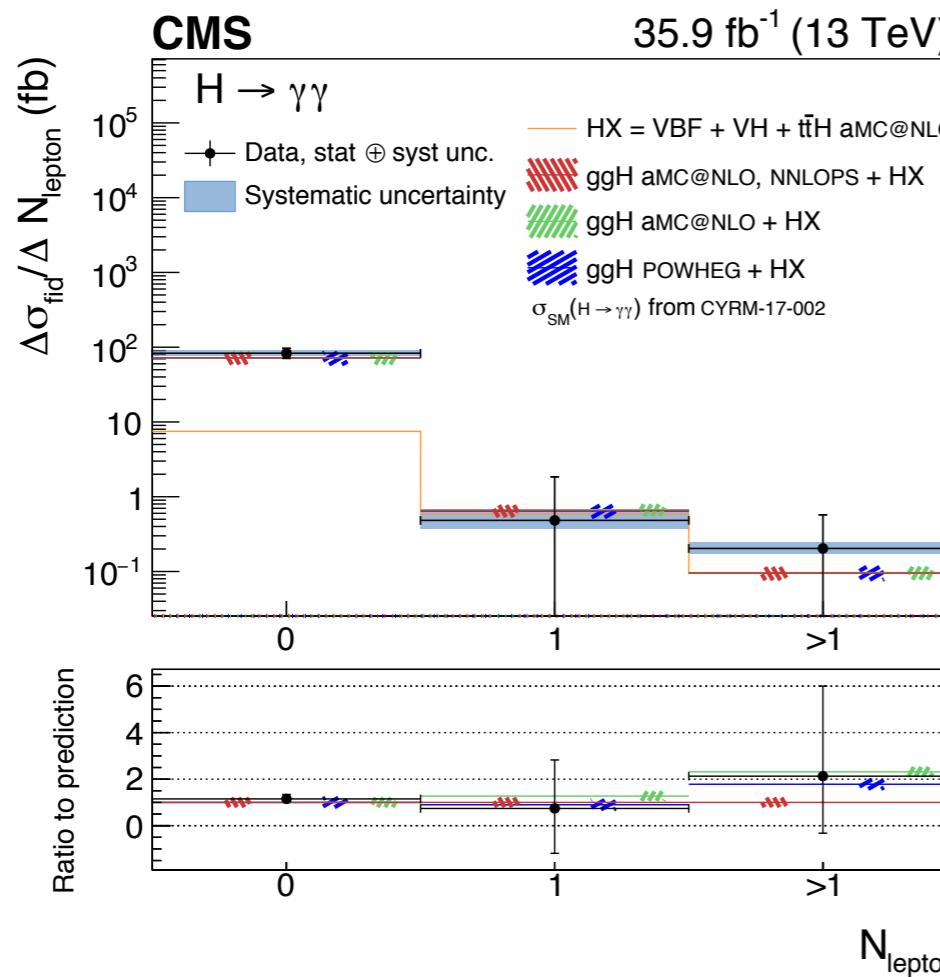
- Measurements related to the **second jet** associated with H and to the dijet system

$\geq 2\text{jets}$   
 $p_T^j > 30 \text{ GeV}$   
 $|\eta^j| < 4.7$



- Uncertainties in the range between 70 and 90%
- A set of the 2-jets observables is measured in the **VBF-like** phase space as well

# Exclusive production processes

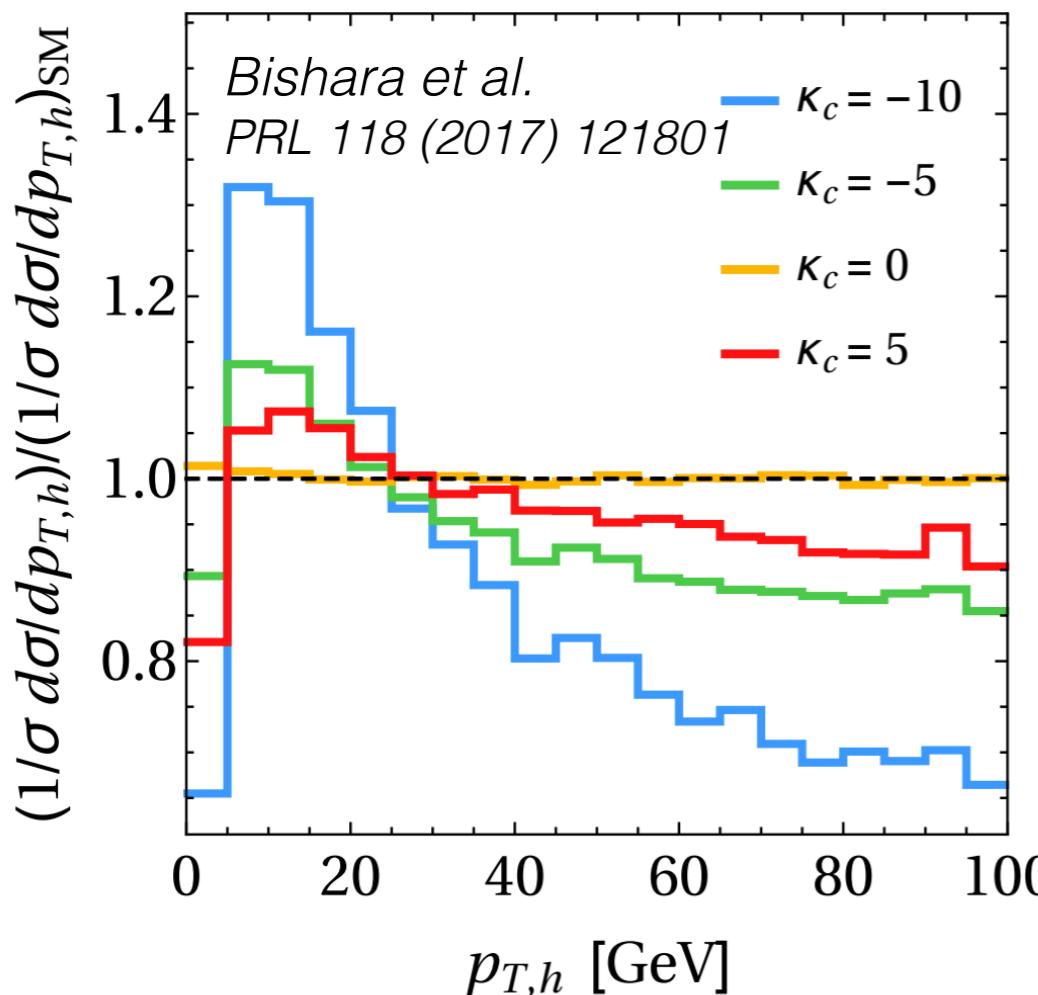


- H production is measured as a function of lepton and b-jet multiplicities and of  $p_T^{\text{miss}}$
- The total cross sections is measured for **VH- and ttH-enriched** phase spaces
  - VH** :  $N_{\text{lep}} = 1, p_T^{\text{miss}} > 100 \text{ GeV}$
  - ttH** :  $N_{\text{lep}} \geq 1, N_{\text{b-jet}} \geq 1$
- All measurements are found in agreement with the standard model predictions

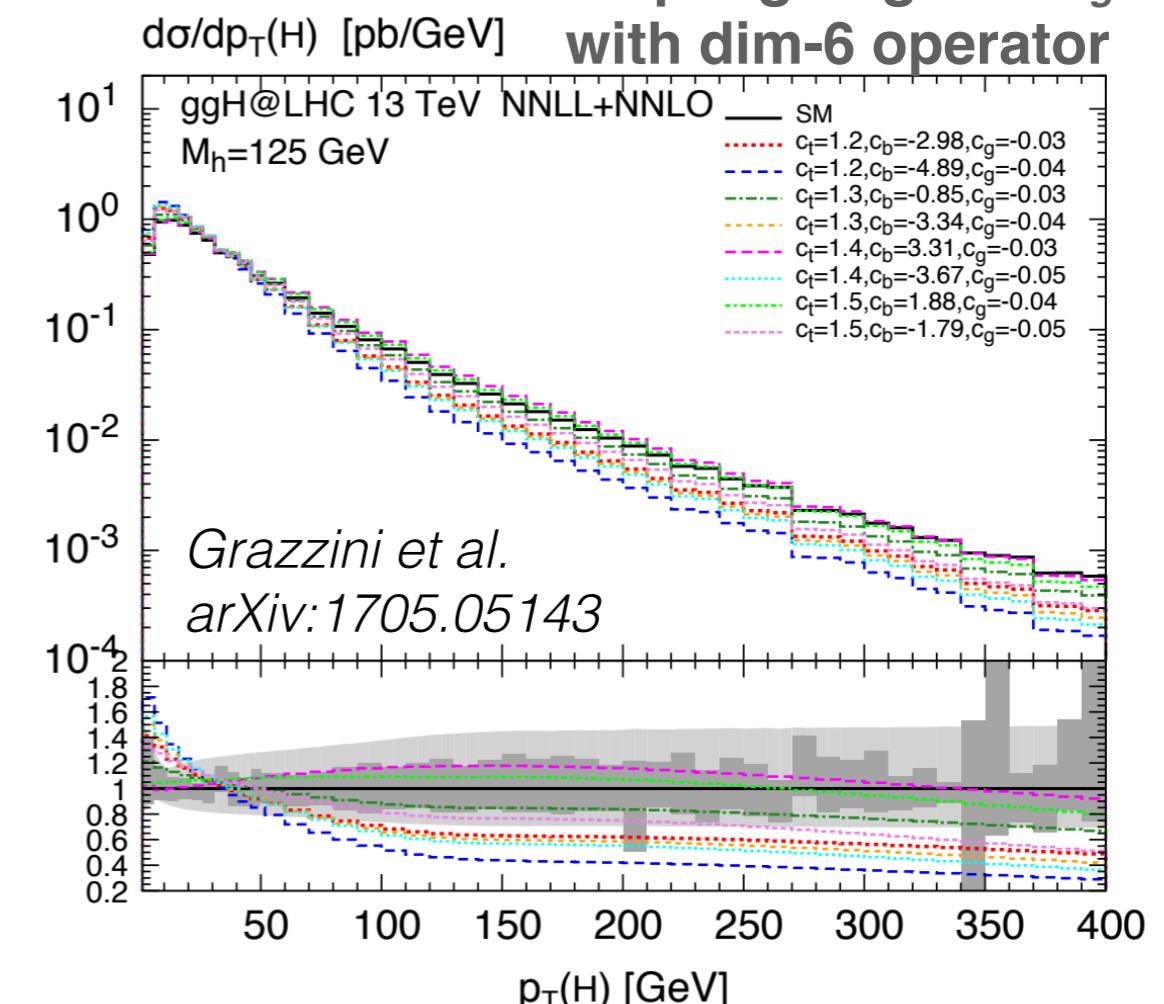
# Coupling modifiers

- Variations of couplings not only affect total cross section and BR, but they **distort the shape of  $p_T(H)$**
- Different models are provided by theorists to describe the shape distortions

**coupling to t, b, c quarks in k-framework**



**coupling to gluon  $c_g$  with dim-6 operator**

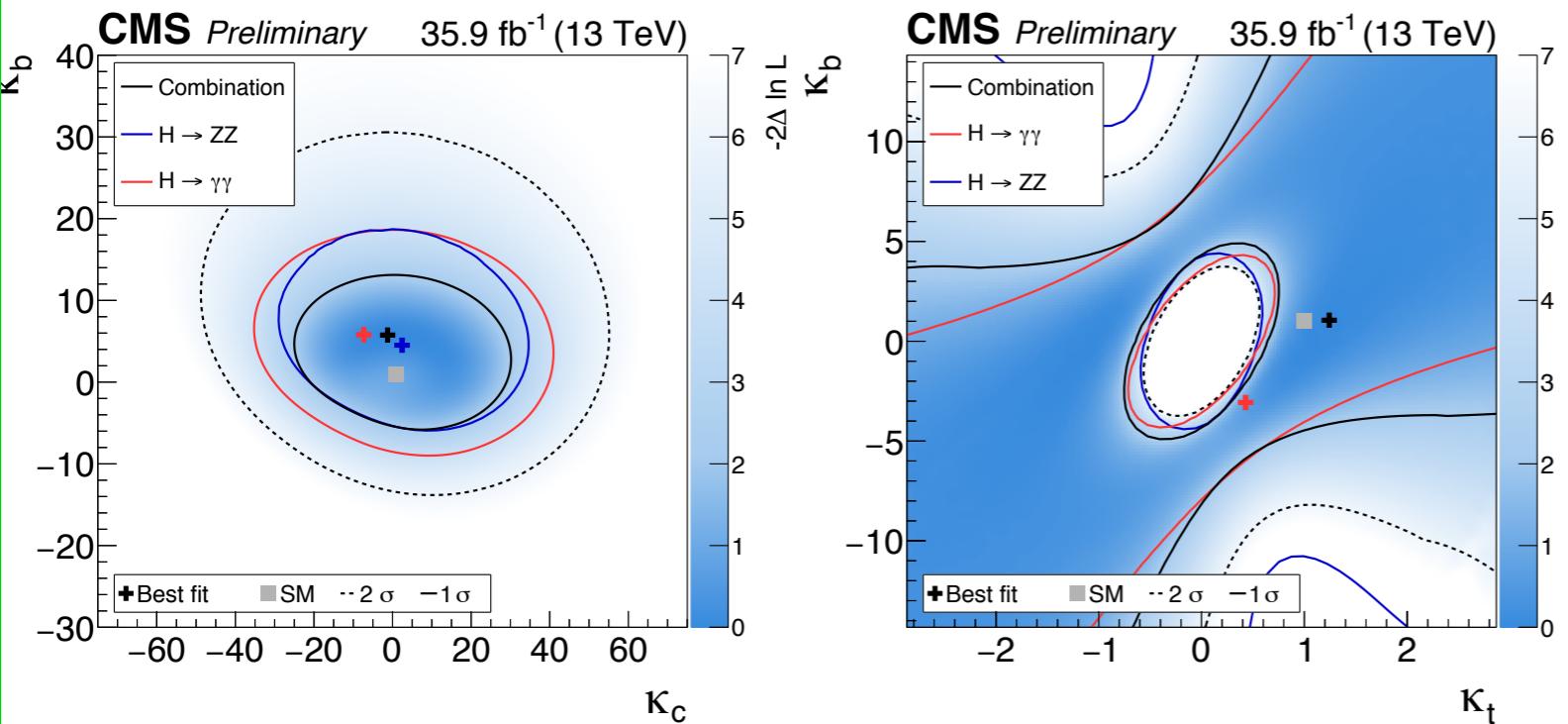


The **combined** measurement of the  $p_T(H)$  spectrum is used to set constraints on the coupling modifiers

- Results are dependent on the **assumptions** about BR under coupling variations, two scenarios studied:
  1. **BR freely floating** —> purely shape information

## Scenario 1

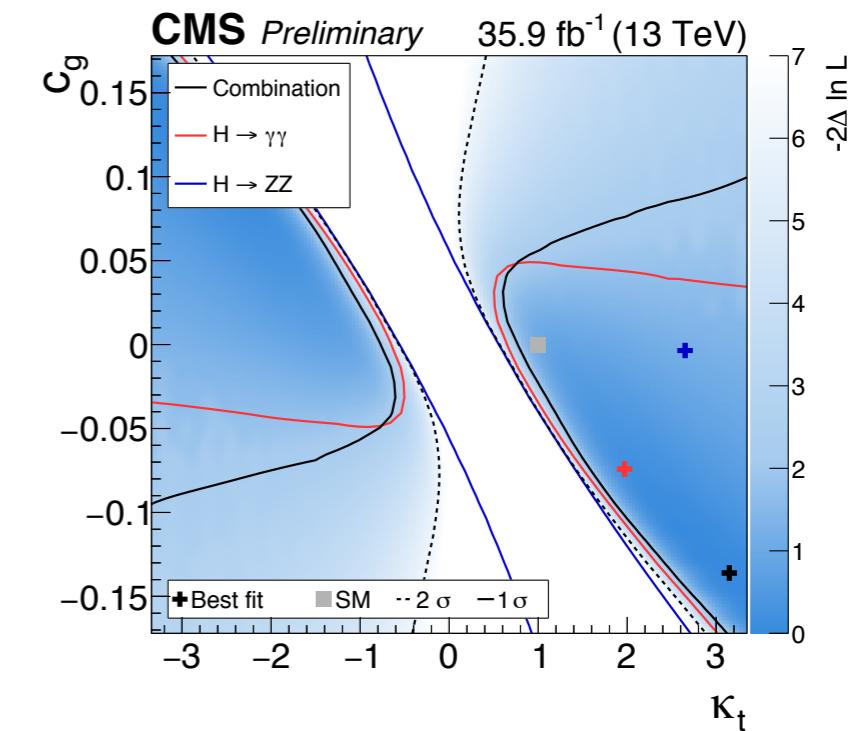
### coupling to t, b, c quarks in k-framework



$$-2.8 < k_b < 9.9 \quad (-3.7 < k_b < 7.3 \text{ expected})$$

$$-18.0 < k_c < 22.9 \quad (-15.7 < k_c < 19.3 \text{ expected})$$

### coupling to gluon $c_g$ with dim-6 operator

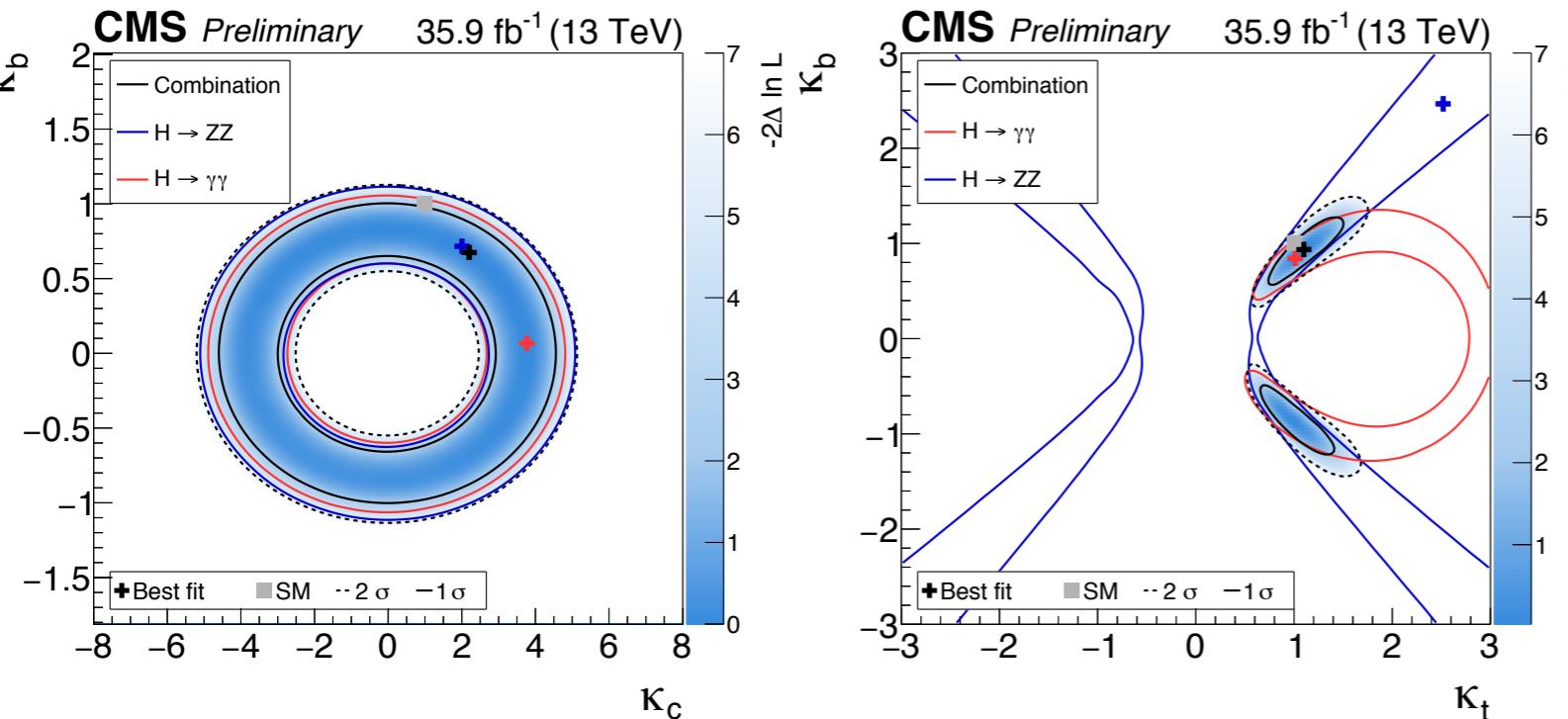


# Coupling modifiers

- Results are dependent on the **assumptions** about BR under coupling variations, two scenarios studied:
  1. **BR freely floating** —> purely shape information
  2. **BR scaling with couplings** —> full knowledge from SM of Higgs decay modes

## Scenario 2

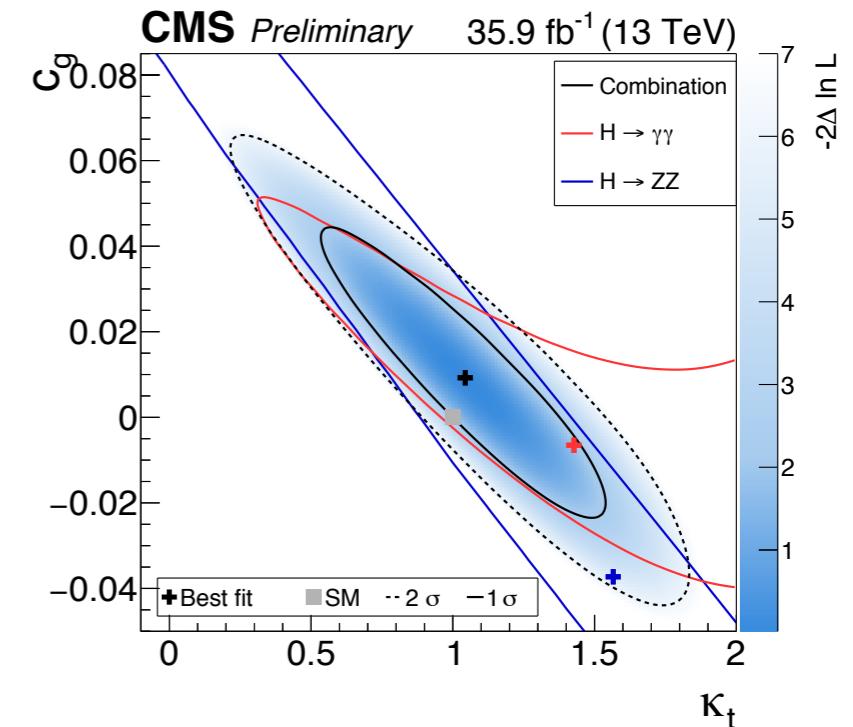
### coupling to t, b, c quarks in k-framework



$$-0.9 < k_b < 0.9 \quad (-1.2 < k_b < 1.2 \text{ expected})$$

$$-4.3 < k_c < 4.3 \quad (-5.4 < k_c < 5.3 \text{ expected})$$

### coupling to gluon $c_g$ with dim-6 operator



# Conclusions

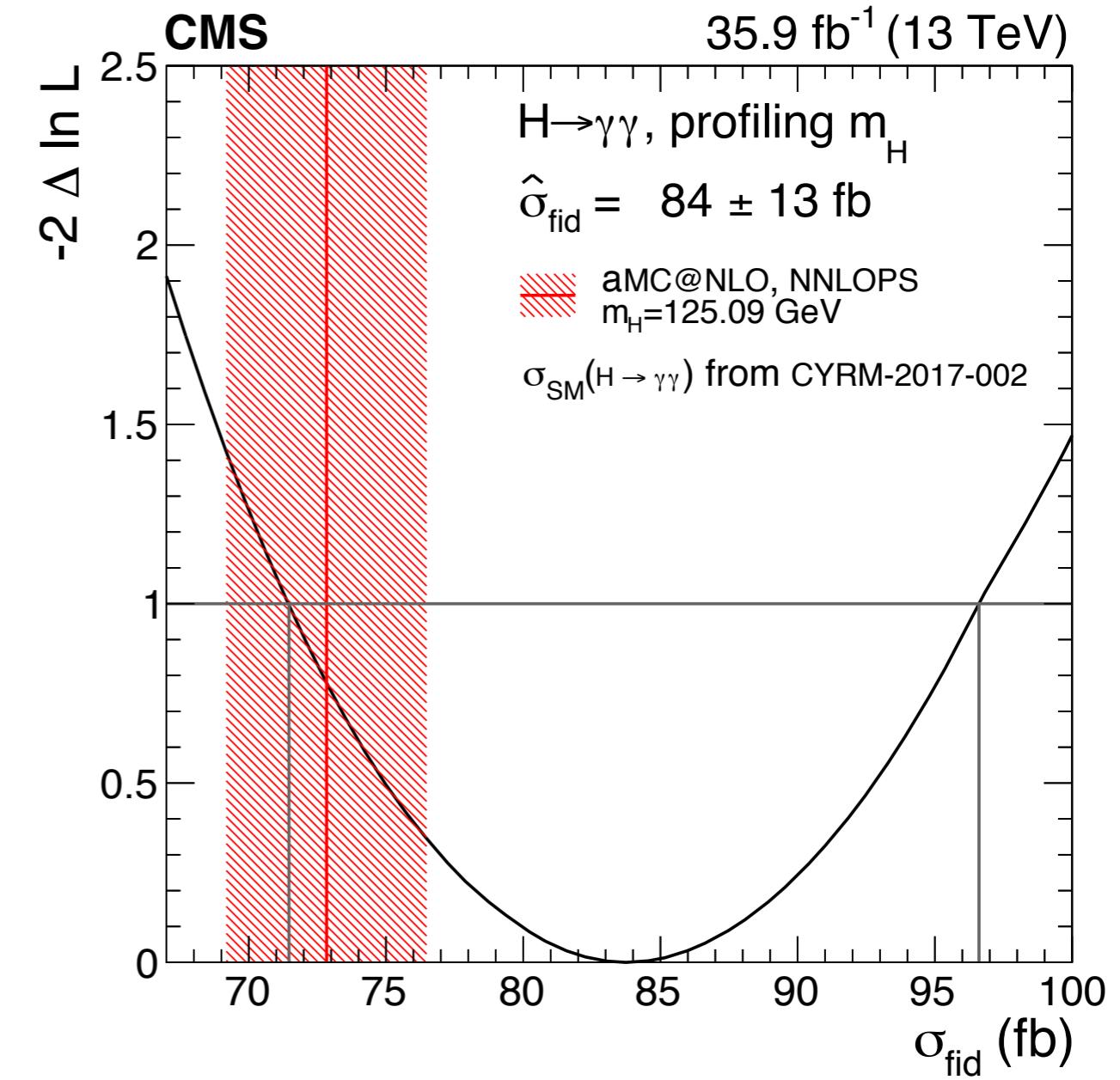
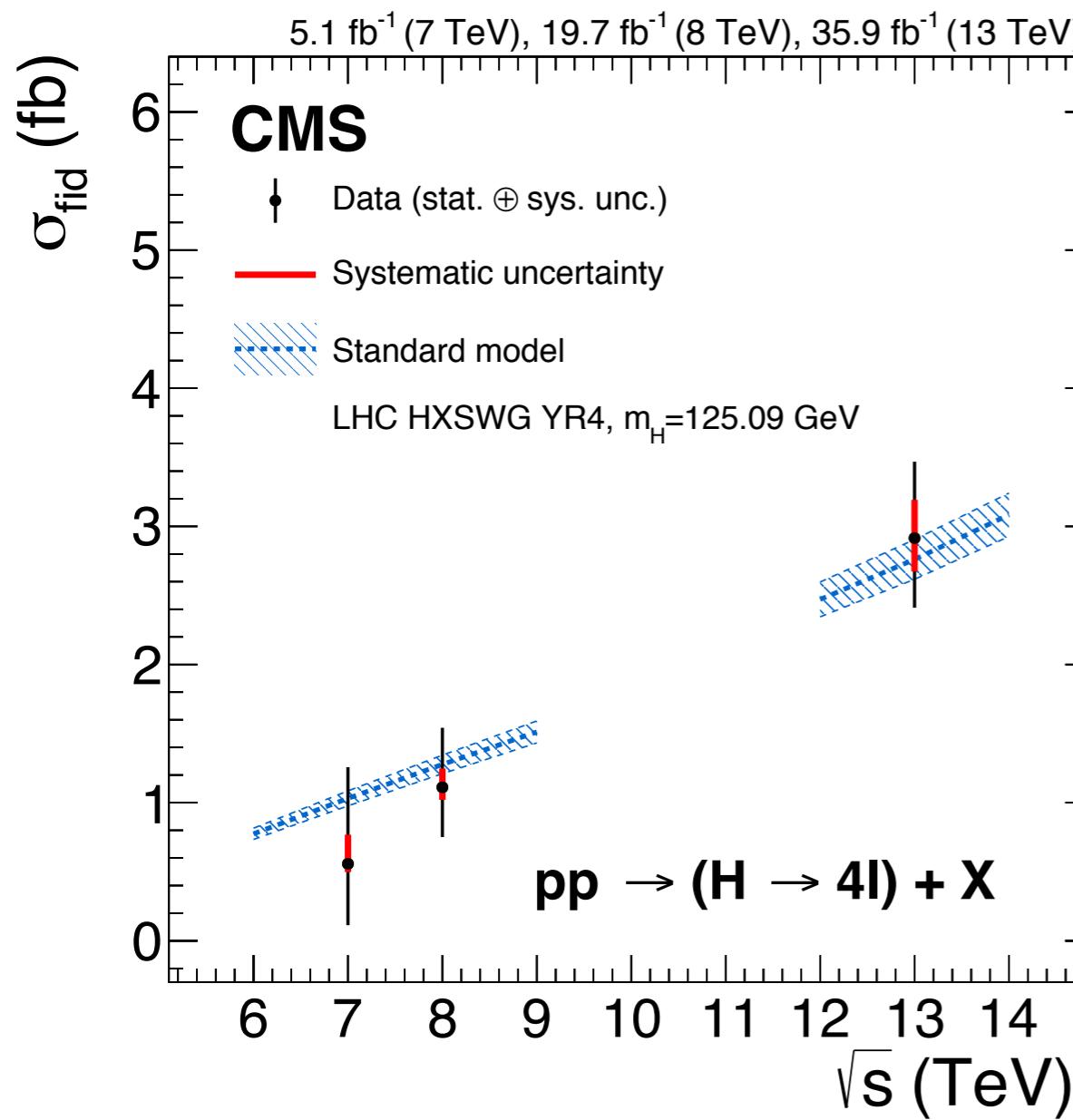
- **Run2 data sets** allow extensive study of Higgs boson cross sections **differentially** and for phase spaces enriched in specific production mechanisms
- **New** measurements are reported using the  $H \rightarrow \gamma\gamma$  channel alone and in **combination** with the  $H \rightarrow ZZ^* \rightarrow 4\ell$  and the  $H \rightarrow bb$  (high- $p_T$  only)
- $p_T(H)$  distribution provides a handle to set limits on **coupling modifiers** variations
- Precision on measurements is still largely **statistically limited** → improved results are expected from analysis of full Run2 data sets
- **No significant deviation** from SM Higgs boson is observed, inclusively and differentially

# BACKUP

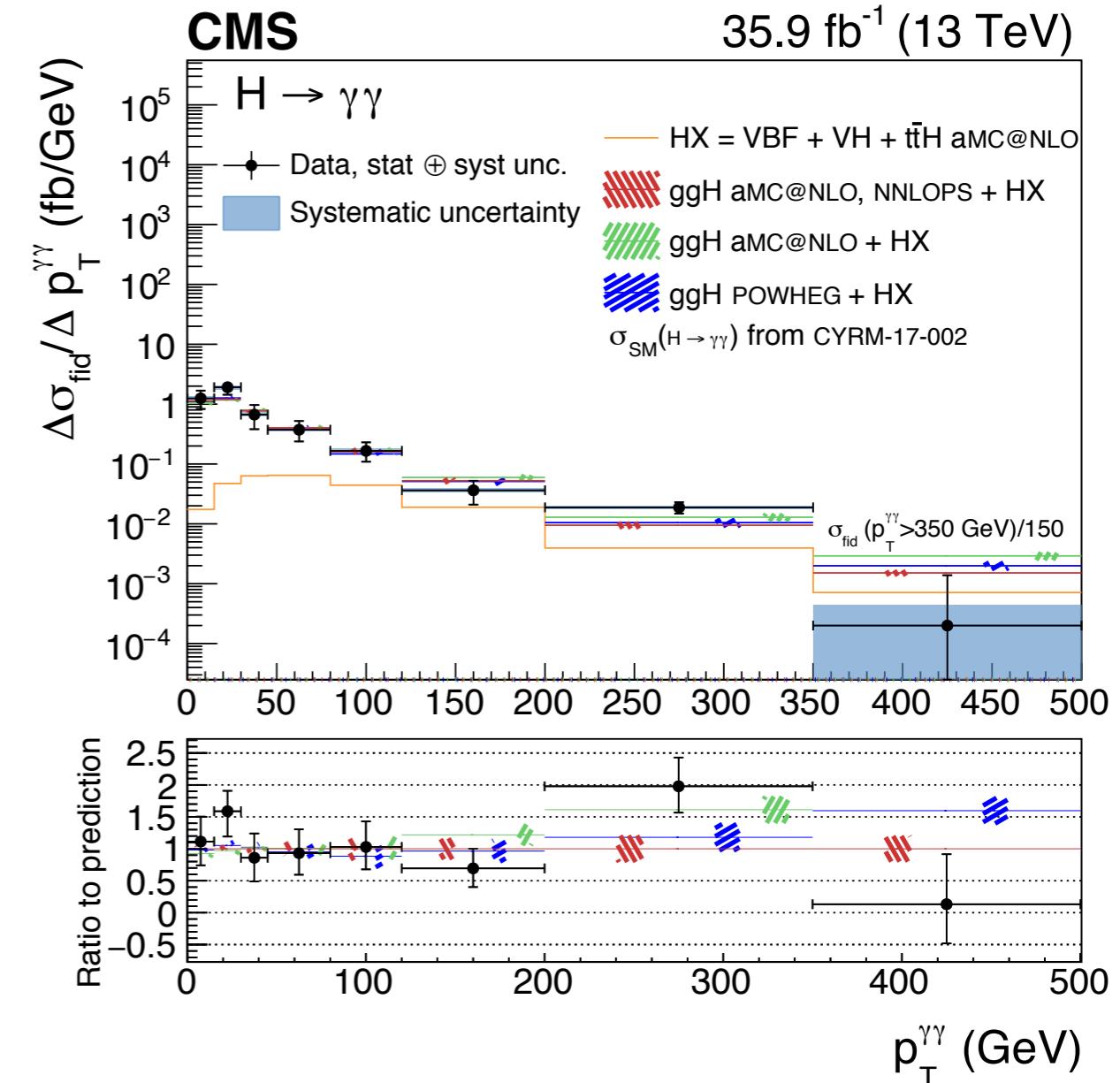
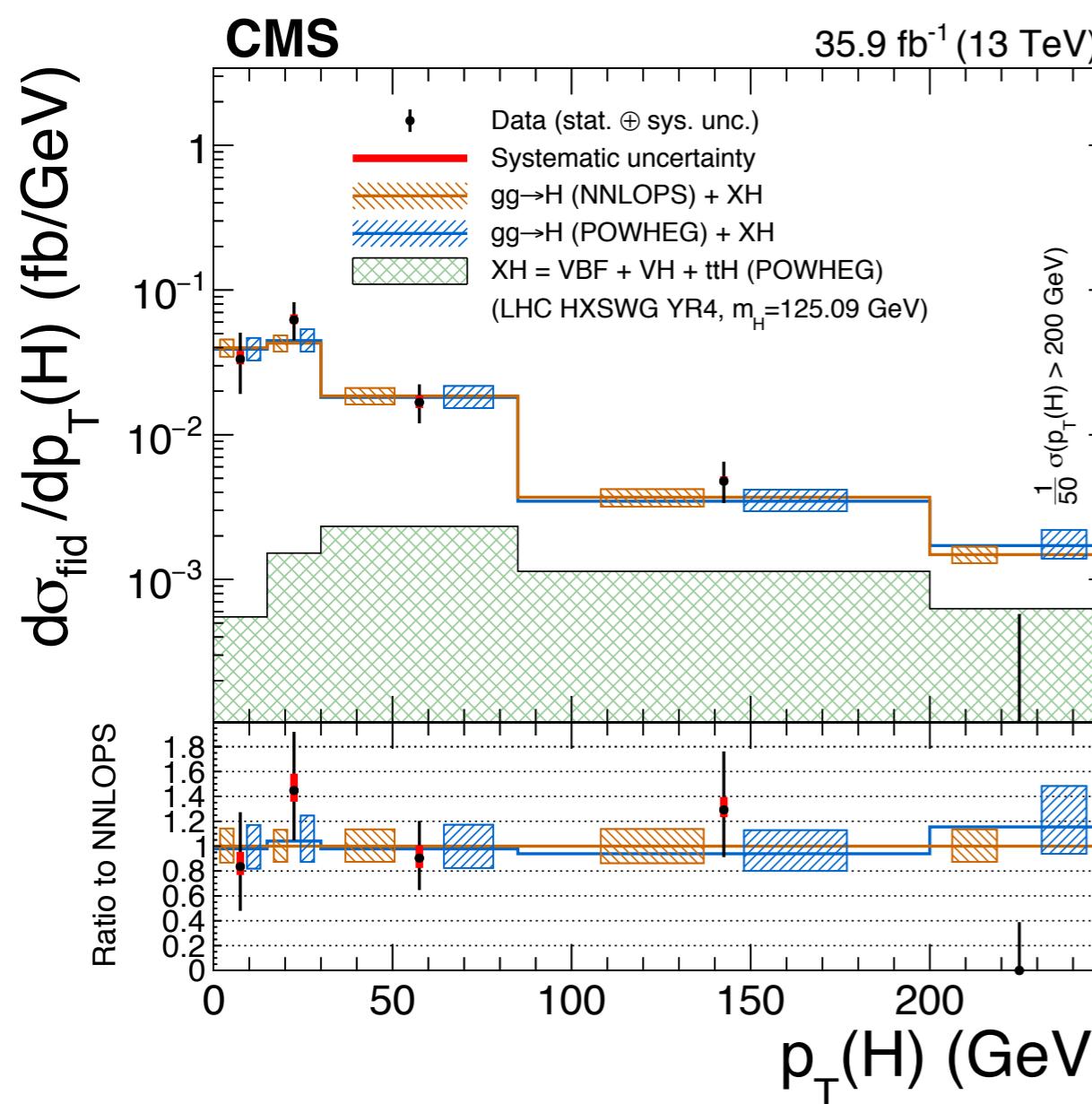
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^* \rightarrow 4\ell$	$H \rightarrow bb$
Inclusive	✓	✓	-
$p_T(H)$	✓	✓	✓
$y(H)$	✓	✓	-
$N_{\text{jets}}$	✓	✓	-
$p_T(j_1)$	✓	✓	-
kinematic $j_1$	✓	-	-
kinematic $j_2$	✓	-	-
additional objects	✓	-	-
production modes	✓	-	-

A red bracket groups the first five rows of the table, which correspond to the production modes  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ^* \rightarrow 4\ell$ , and  $H \rightarrow bb$ . A red arrow points from this group to the word "Combination".

# Inclusive fiducial cross section

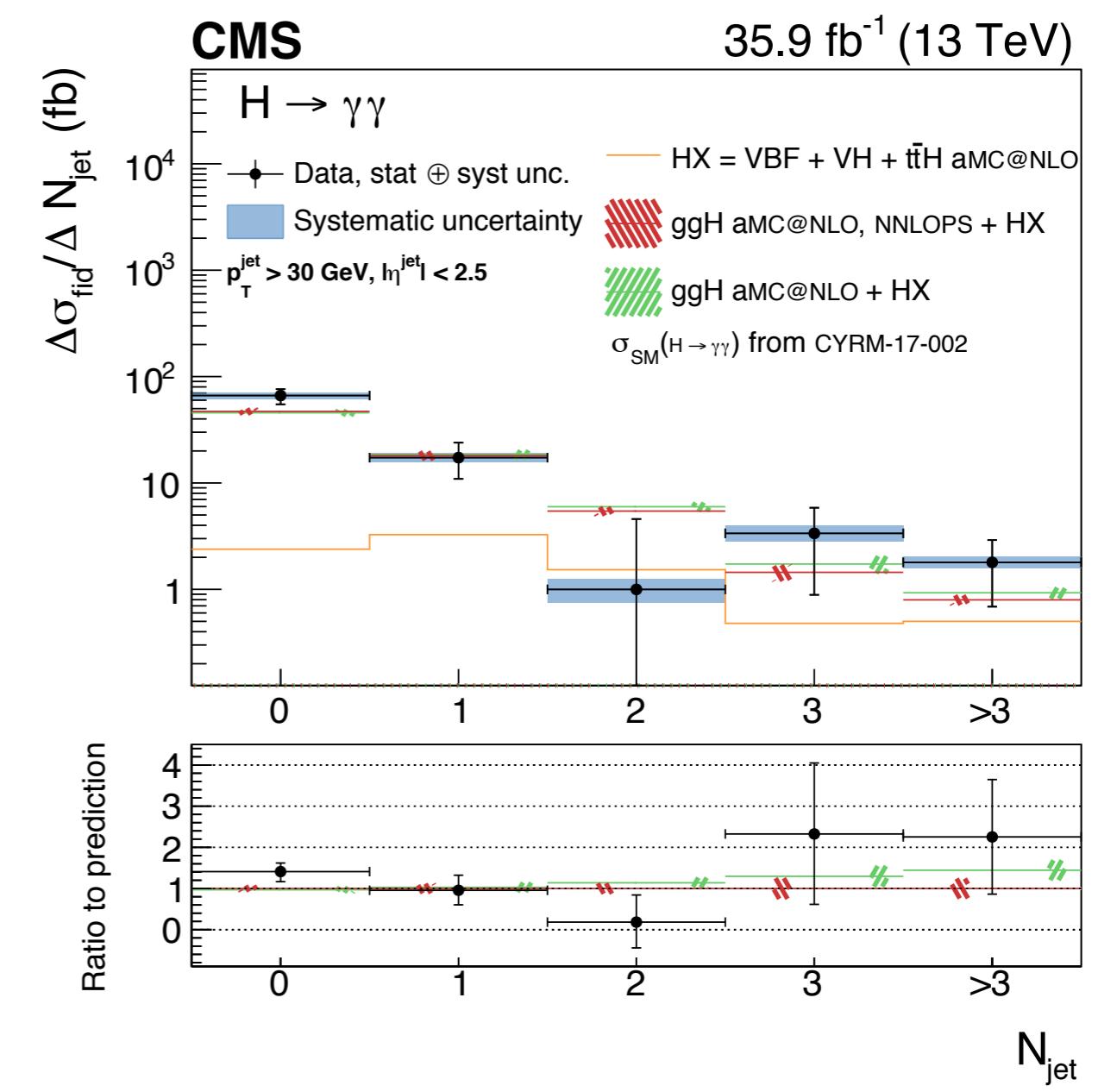
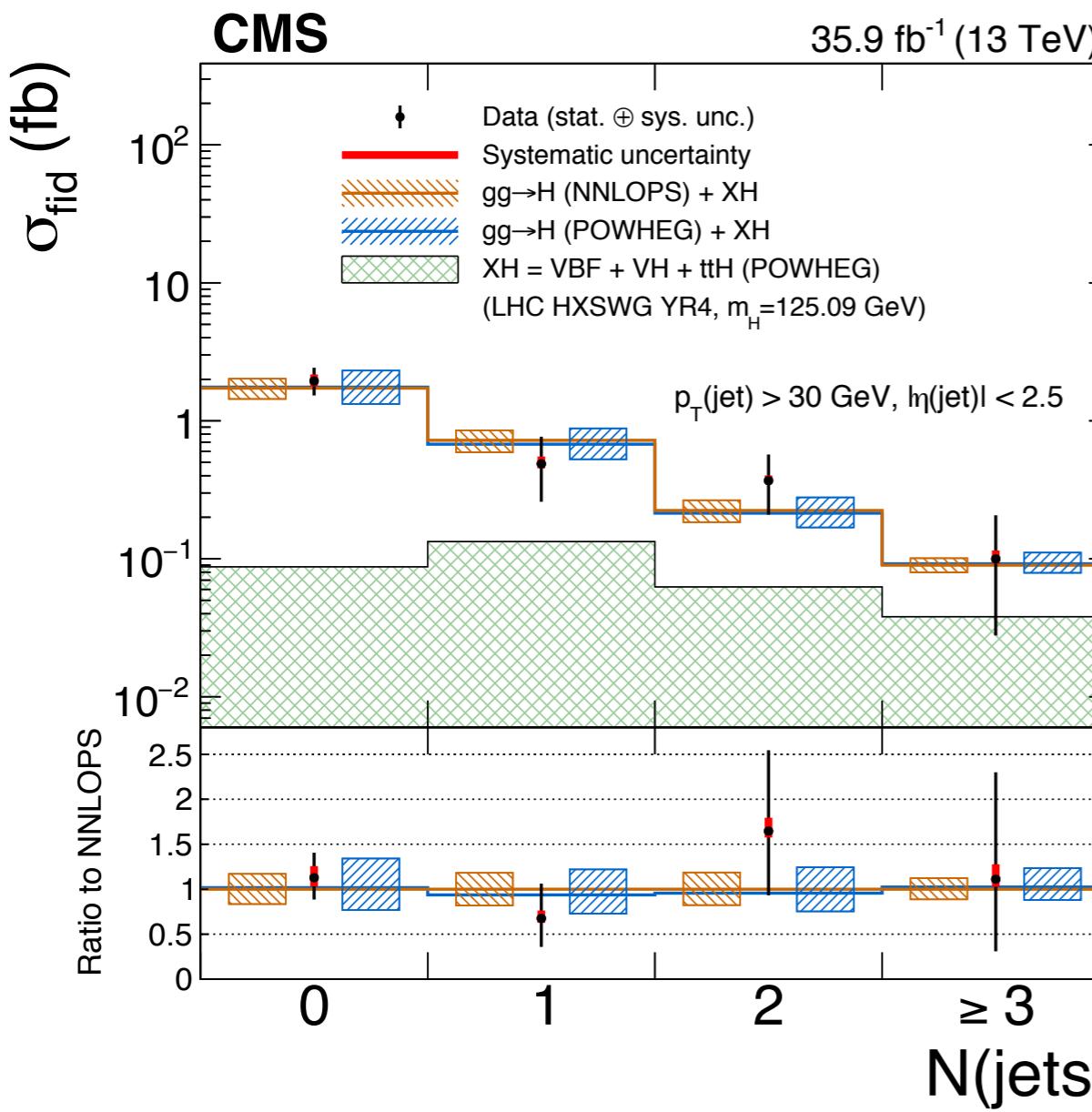


# Combination inputs: $p_T(H)$

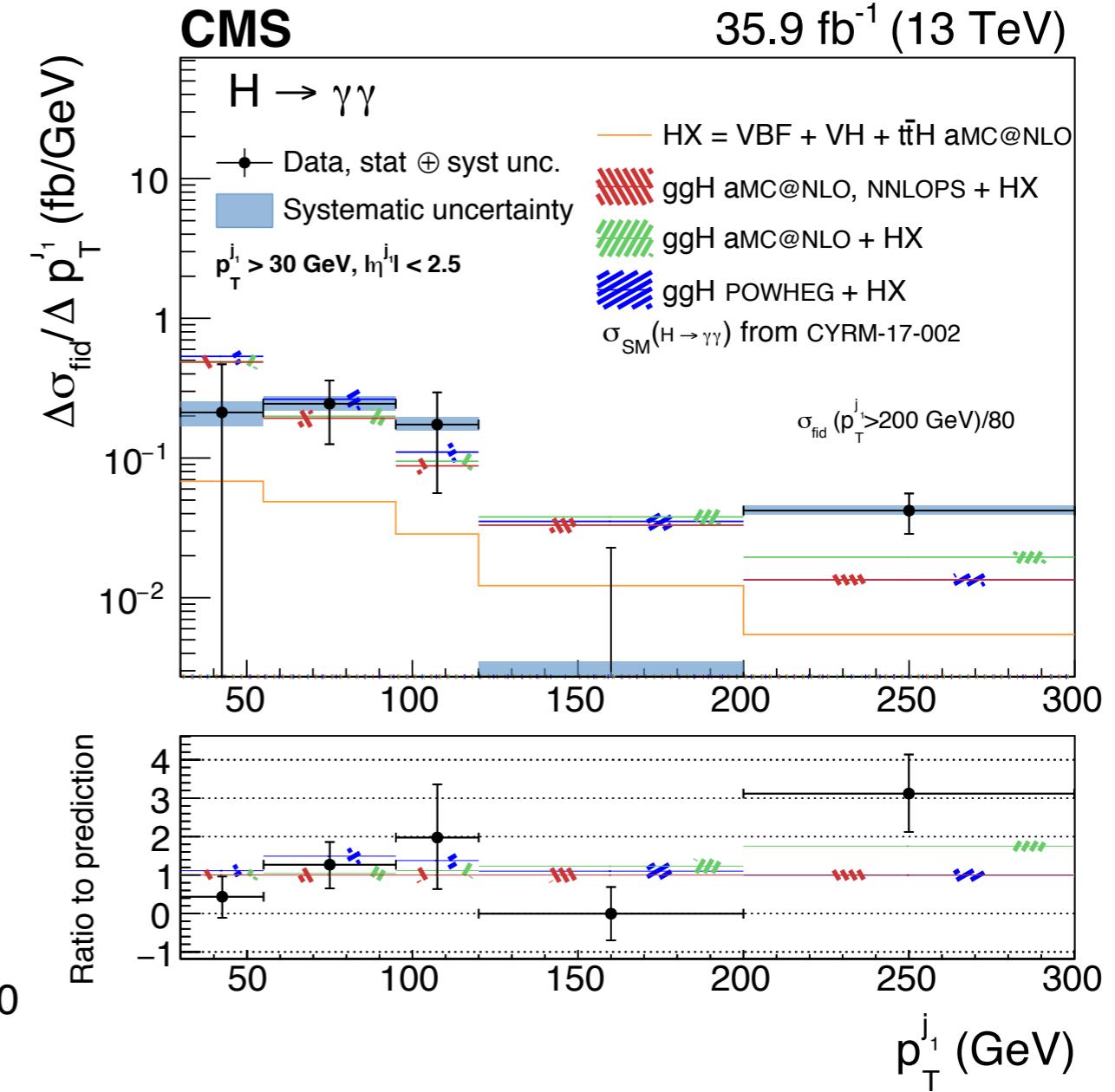
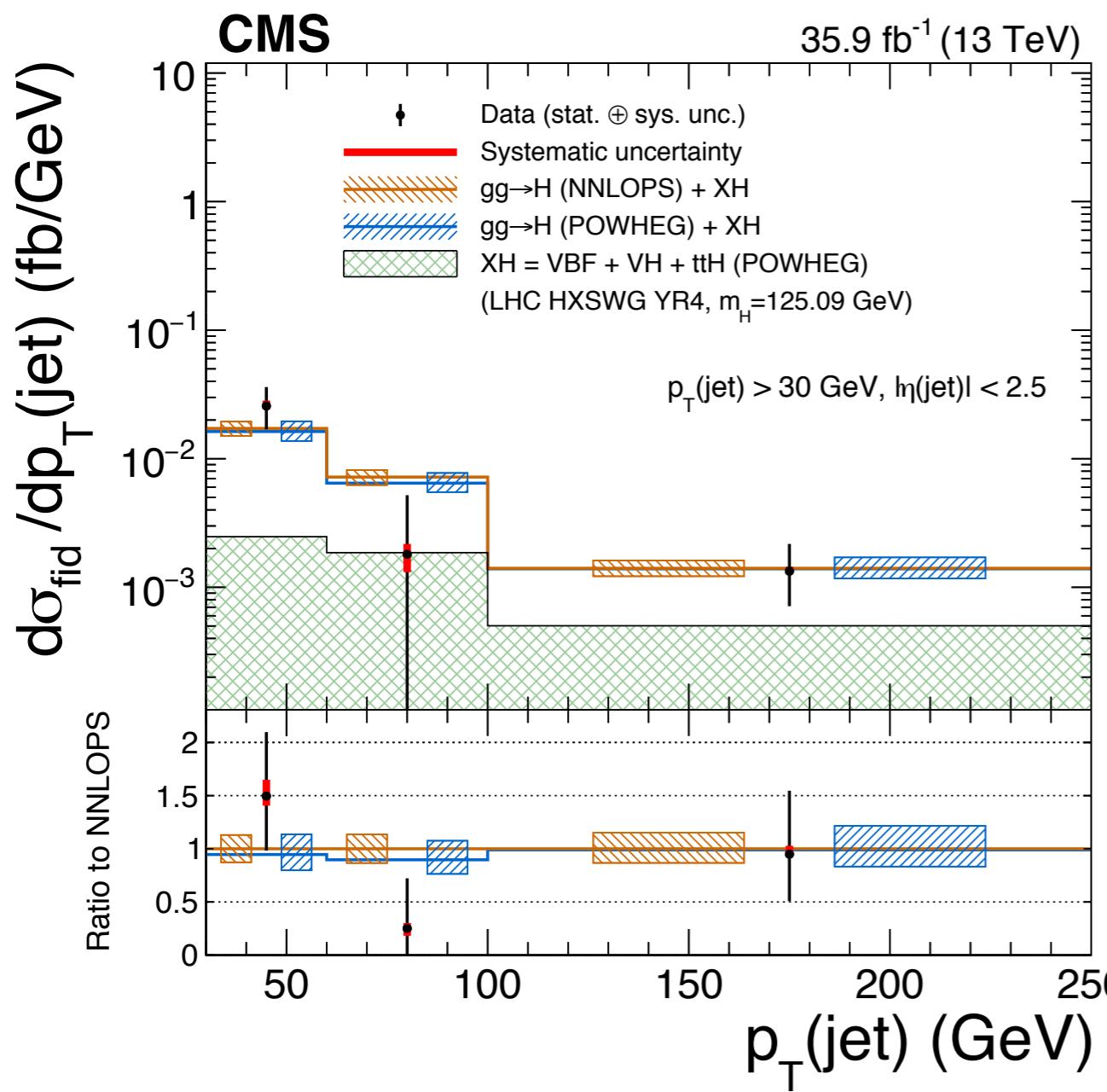


$$\hat{\sigma}_{H \rightarrow b\bar{b}}^{ggH}(p_T(H) > 450 \text{ GeV}) = 74 \pm 48(\text{stat})^{+17}_{-10}(\text{syst}) \text{ fb}$$

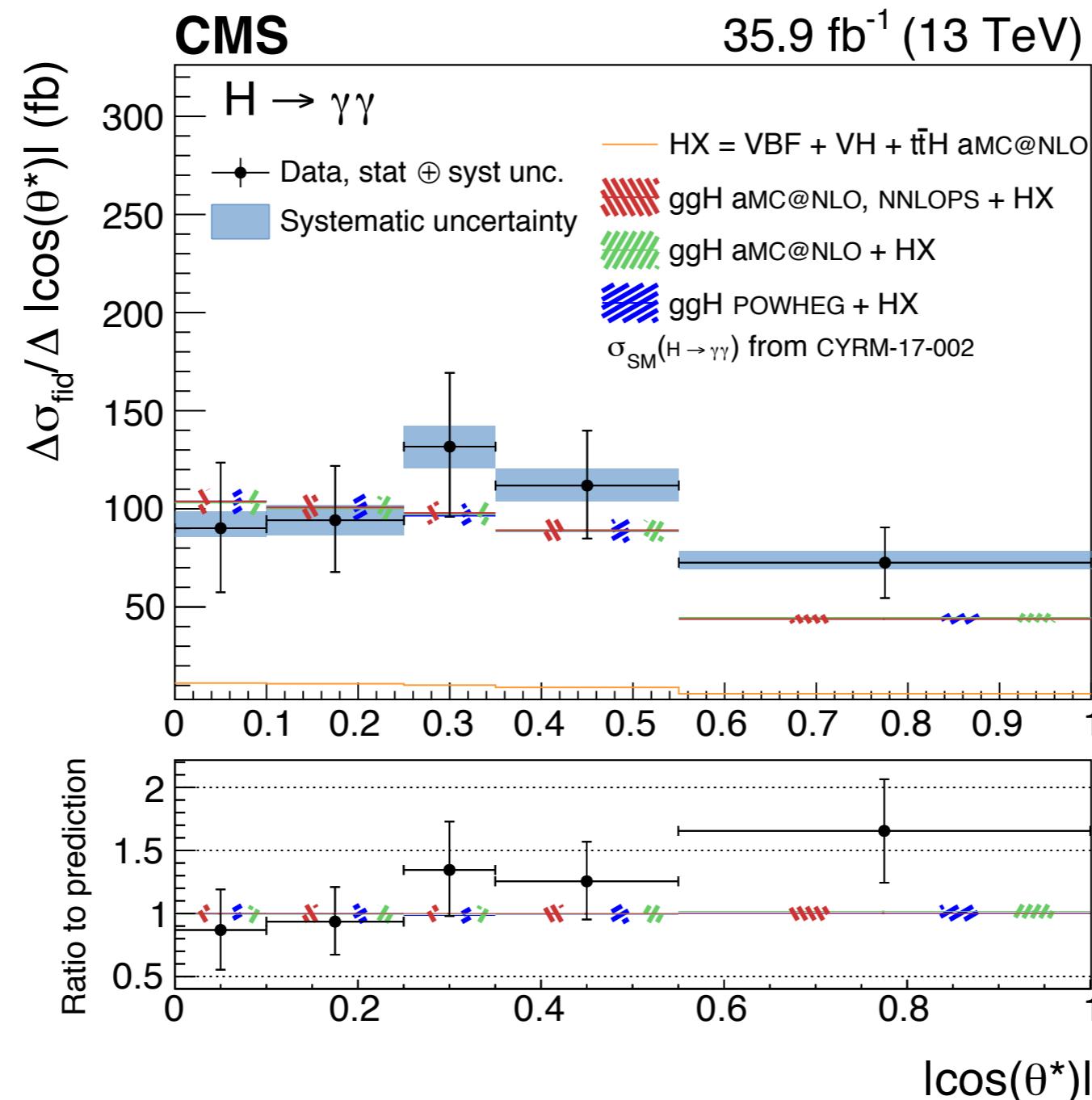
# Combination inputs: $N_{\text{jets}}$

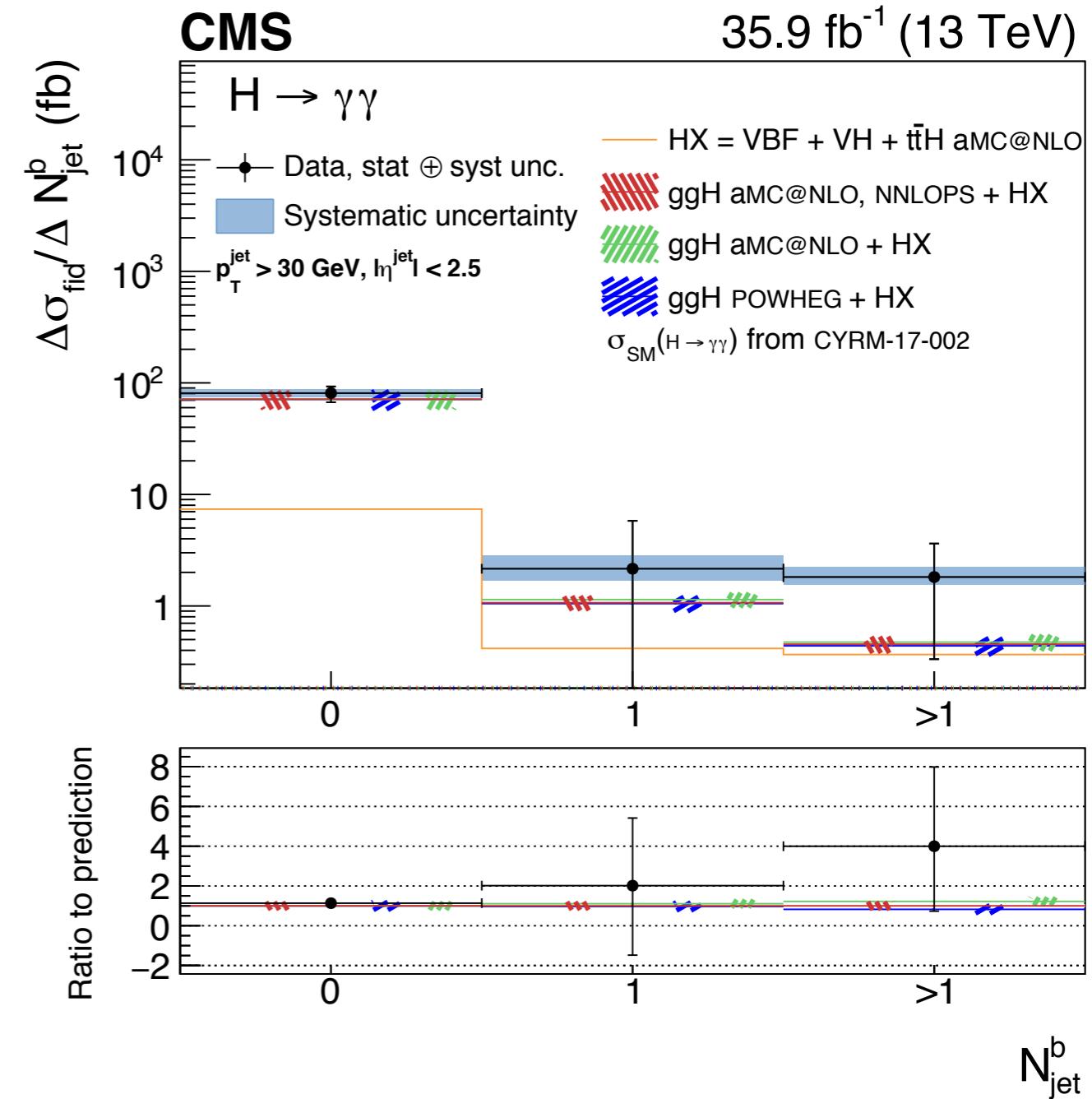
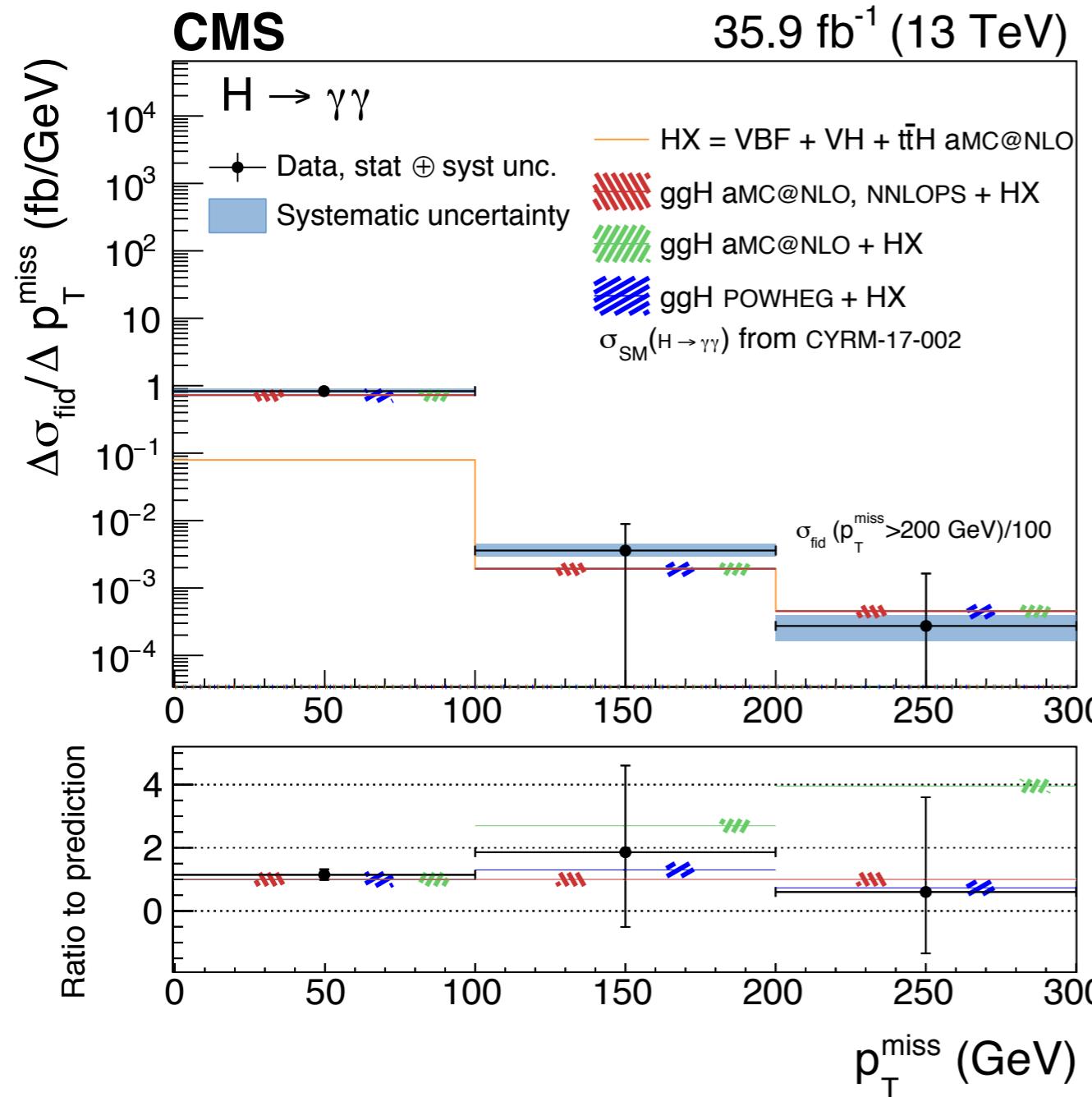


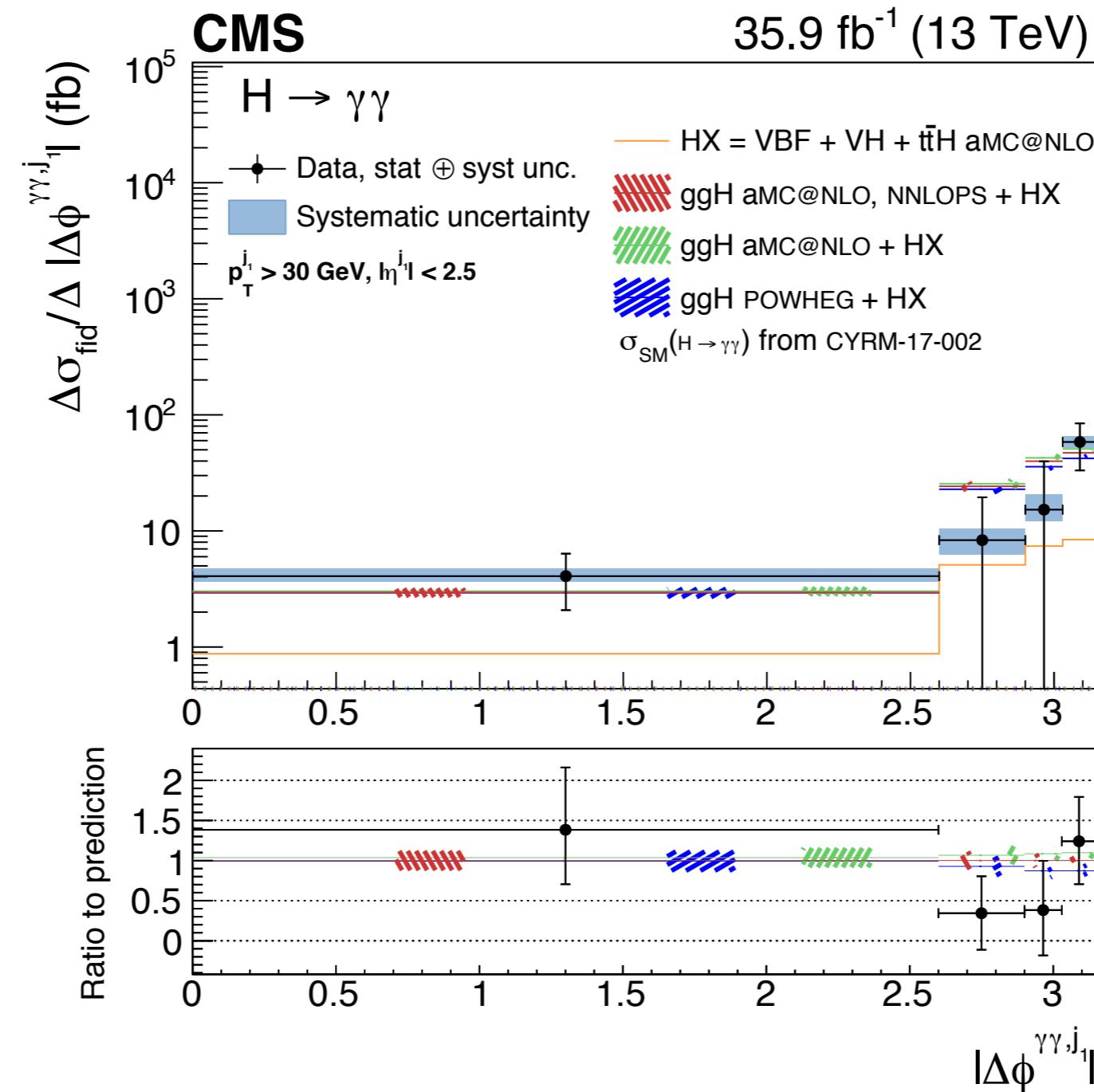
# Combination inputs: $p_T(\text{jet})$

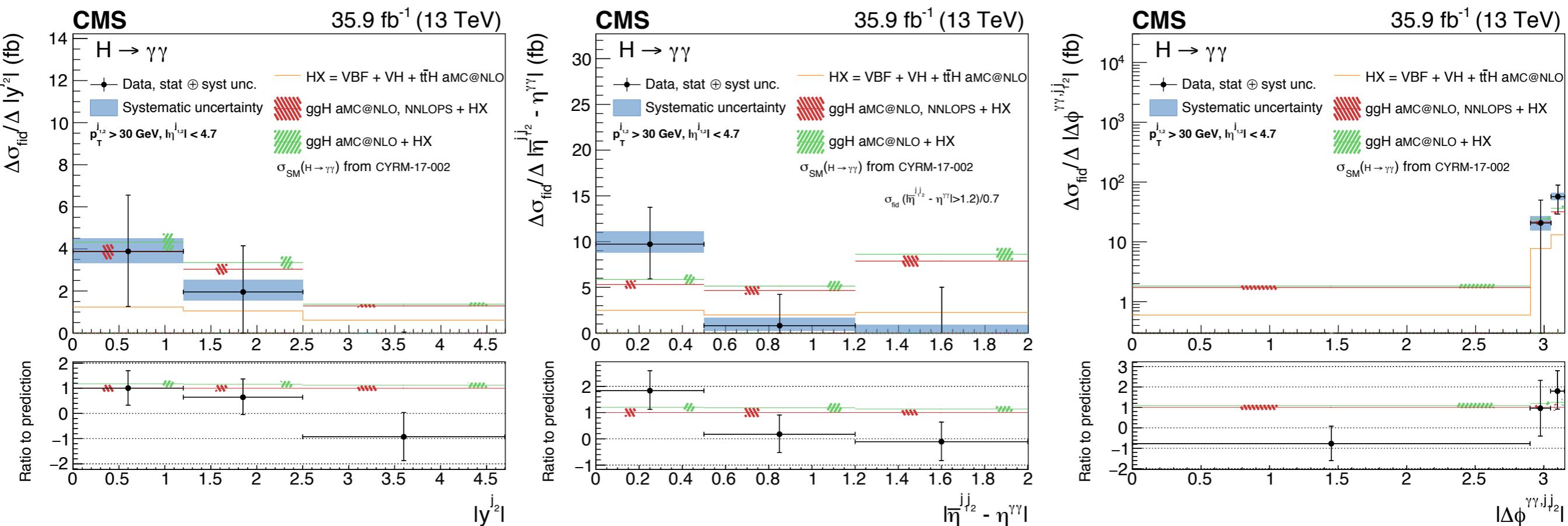


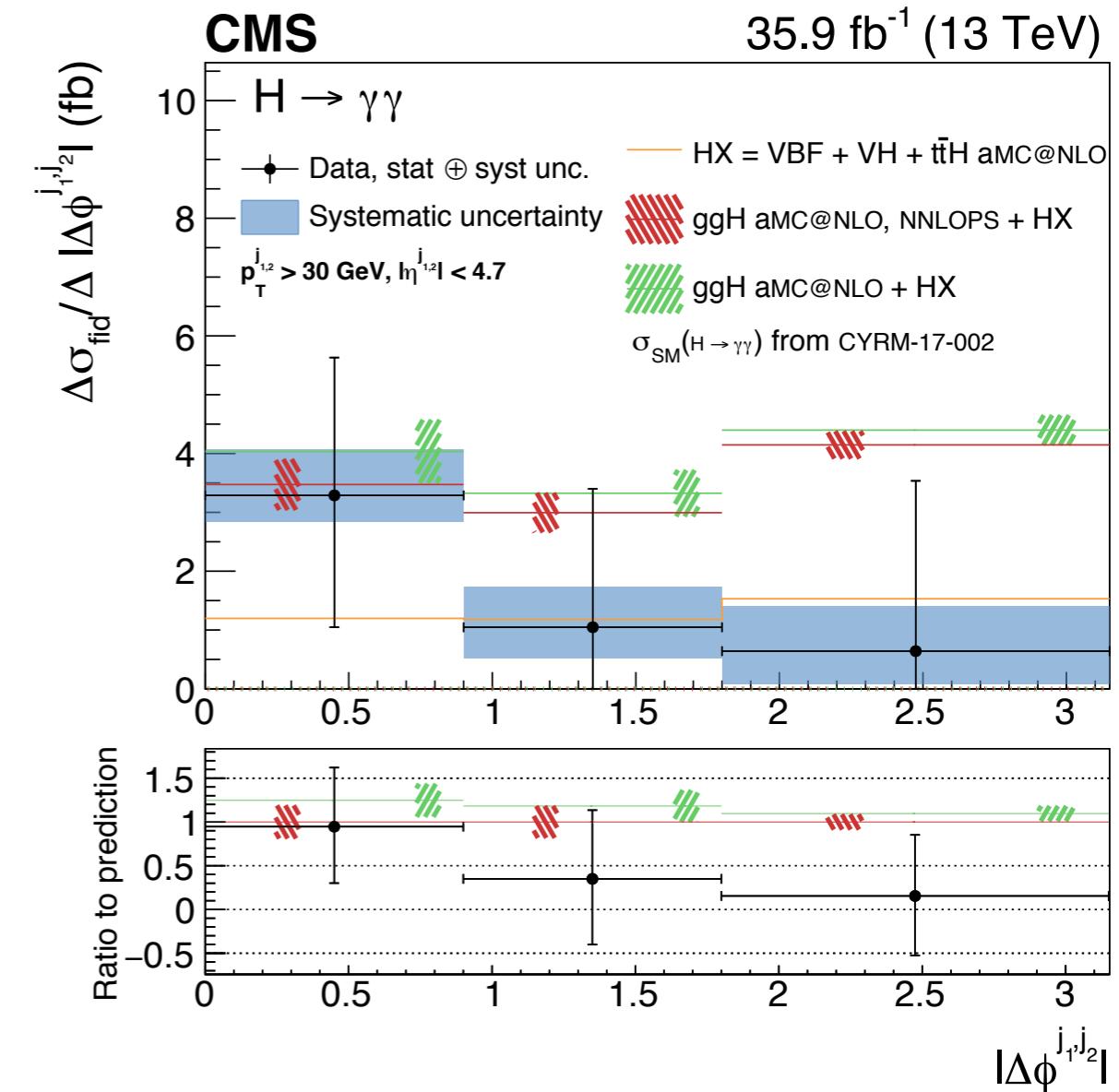
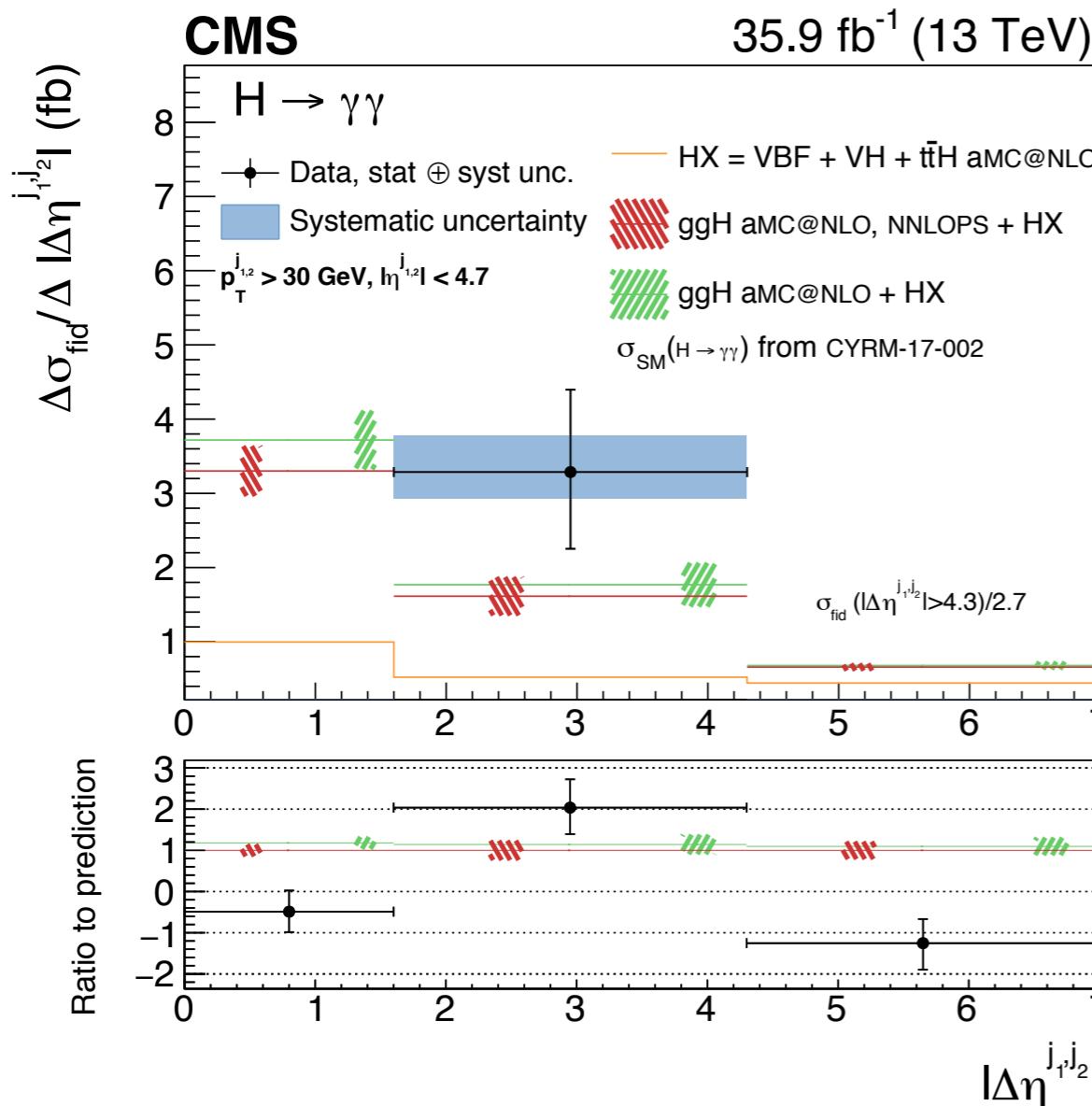
Phase space	Observable	Bin boundaries								
		0	15	30	45	80	120	200	350	$\infty$
Baseline	$p_T^{\gamma\gamma}$ (GeV)	0	15	30	45	80	120	200	350	$\infty$
	$N_{\text{jet}}$	0	1	2	3	4				$\infty$
	$ y^{\gamma\gamma} $	0	0.15	0.3	0.6	0.9				2.5
	$ \cos(\theta^*) $	0	0.1	0.25	0.35	0.55				1
$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} = 0$	0	20	60						$\infty$
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} = 1$	0	60	120						$\infty$
$ \eta^\gamma  < 2.5$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} > 1$	0	150	300						$\infty$
$\text{Iso}_{\text{gen}}^\gamma < 10 \text{ GeV}$	$N_{\text{jet}}^b$	0	1	2						$\infty$
	$N_{\text{lepton}}$	0	1	2						$\infty$
	$p_T^{\text{miss}}$ (GeV)	0	100	200						$\infty$
1-jet	$p_T^{j_1}$ (GeV)	0	45	70	110	200				$\infty$
Baseline + $\geq 1$ jet	$ y^{j_1} $	0	0.5	1.2	2	2.5				
	$ \Delta\phi^{\gamma\gamma,j_1} $	0	2.6	2.9	3.03	$\pi$				
	$ \Delta y^{\gamma\gamma,j_1} $	0	0.6	1.2	1.9	$\infty$				
2-jets	$p_T^{j_2}$ (GeV)	0	45	90		$\infty$				
Baseline + $\geq 2$ jets	$ y^{j_2} $	0	1.2	2.5	4.7					
	$ \Delta\phi^{j_1,j_2} $	0	0.9	1.8	$\pi$					
	$ \Delta\phi^{\gamma\gamma,j_1j_2} $	0	2.9	3.05	$\pi$					
$p_T^j > 30 \text{ GeV},  \eta^j  < 4.7$	$ \bar{\eta}_{j_1j_2} - \eta_{\gamma\gamma} $	0	0.5	1.2		$\infty$				
	$m^{j_1j_2}$ (GeV)	0	100	150	450	1000				$\infty$
	$ \Delta\eta^{j_1,j_2} $	0	1.6	4.3		$\infty$				
VBF-enriched	$p_T^{j_2}$ (GeV)	0	45	90		$\infty$				
2-jets + $ \Delta\eta^{j_1,j_2}  > 3.5,$	$ \Delta\phi^{j_1,j_2} $	0	0.9	1.8	$\pi$					
$m^{j_1j_2} > 200 \text{ GeV}$	$ \Delta\phi^{\gamma\gamma,j_1j_2} $	0	2.9	3.05	$\pi$					

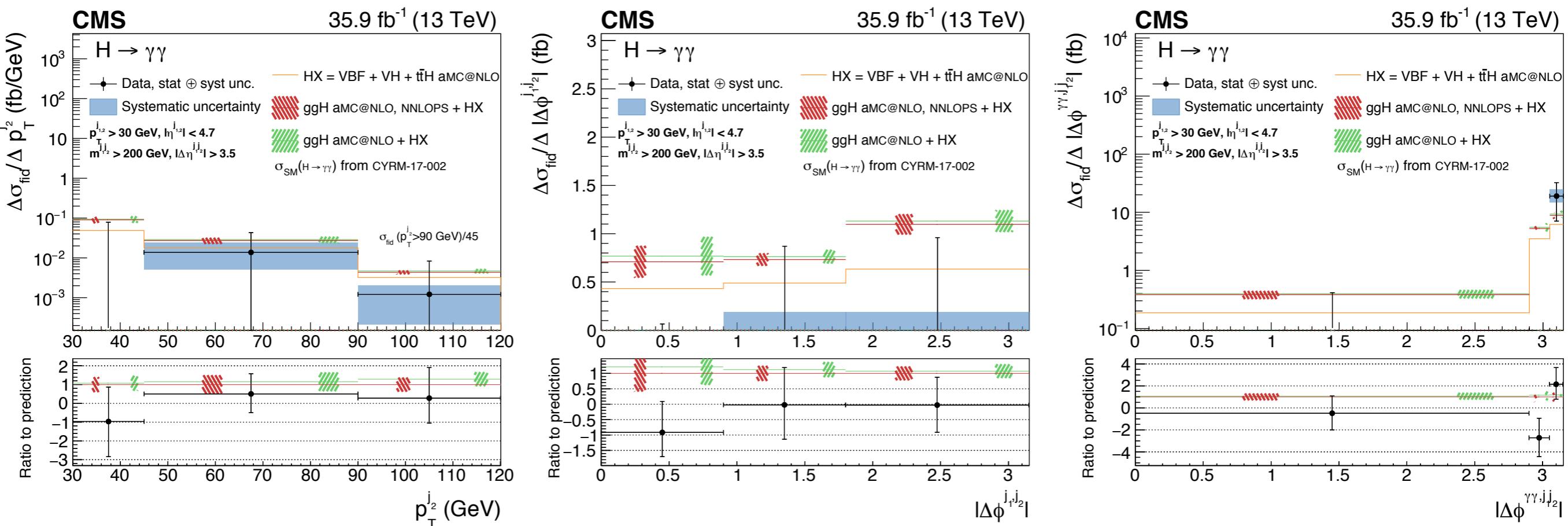




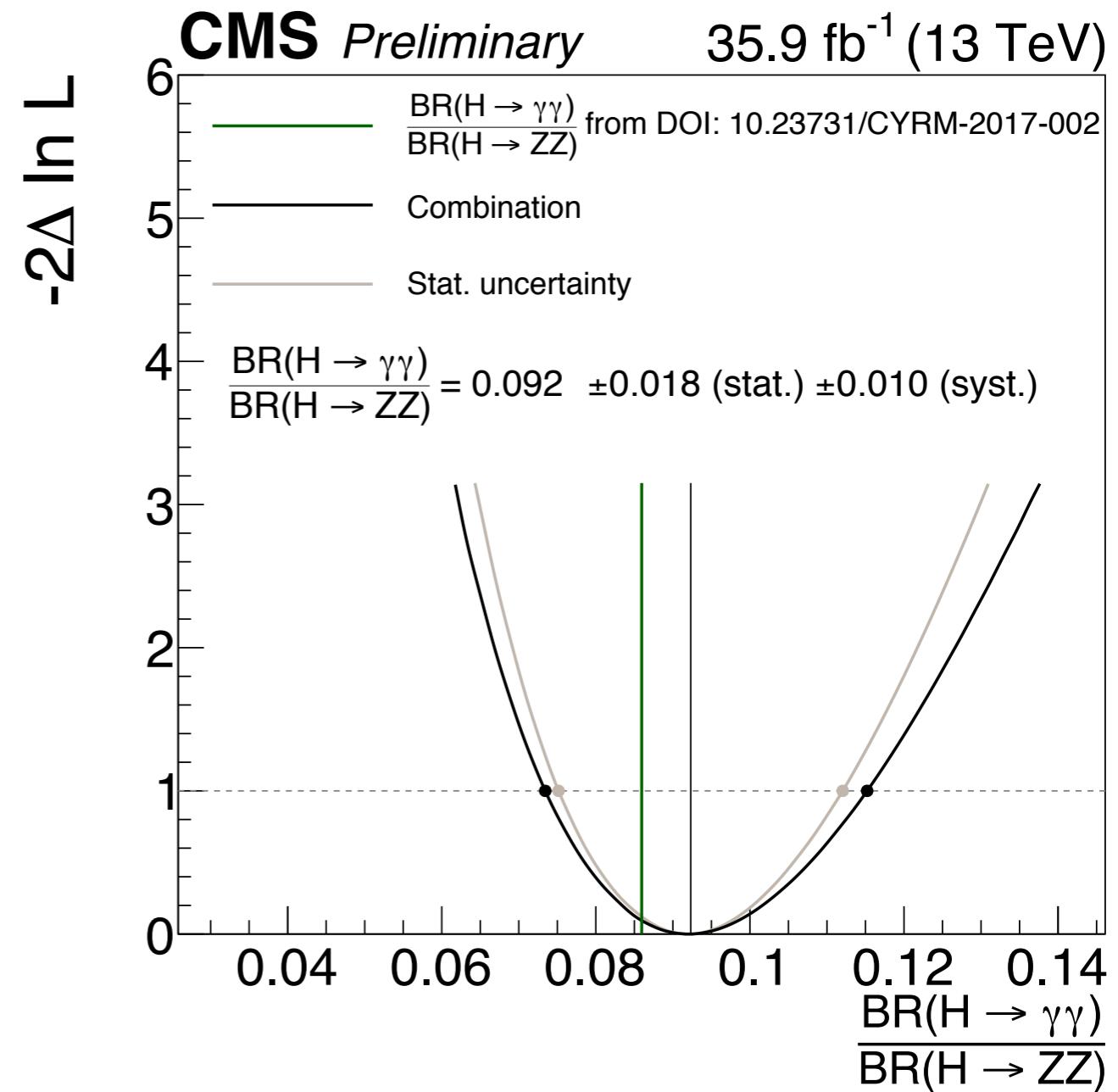
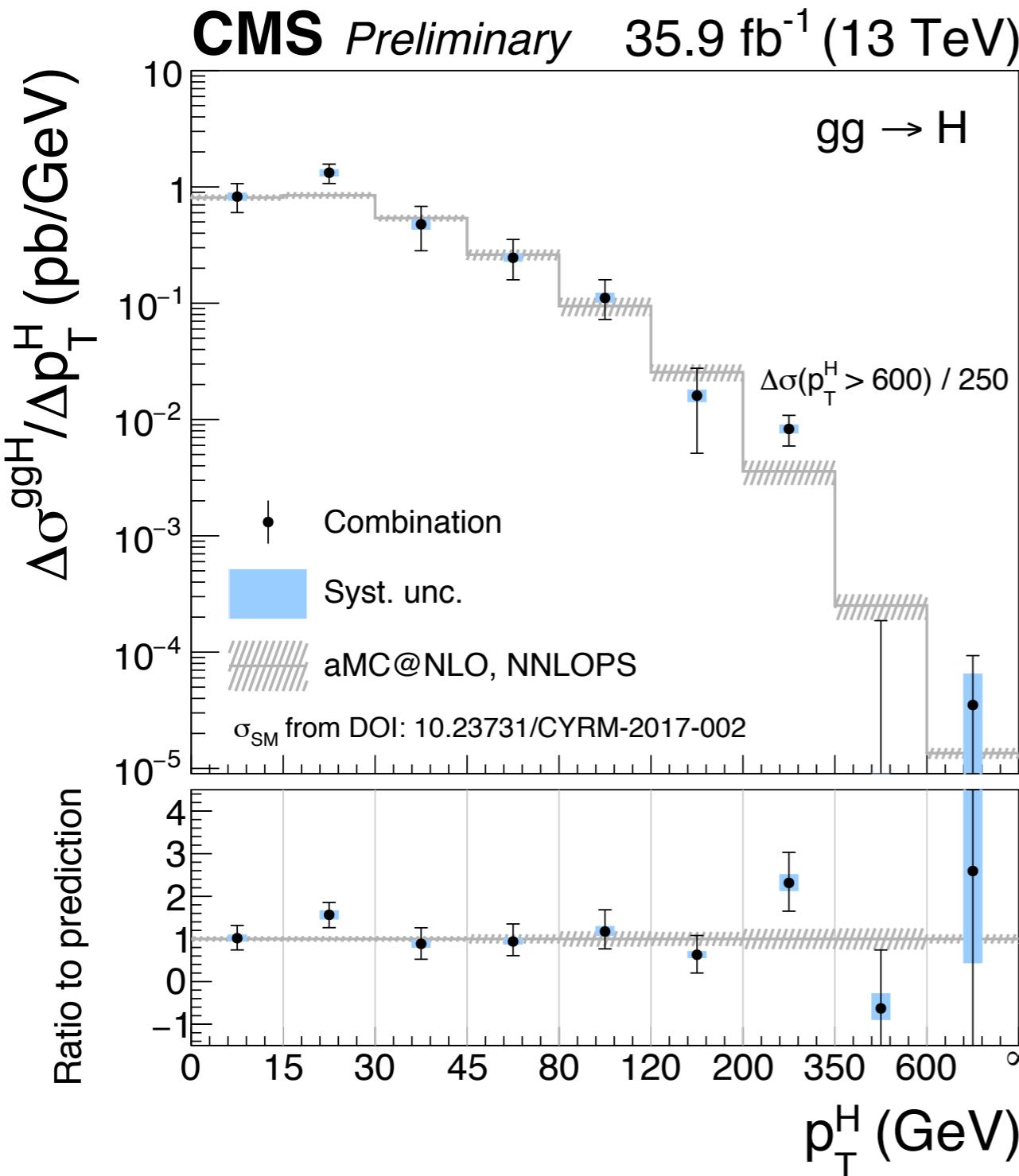




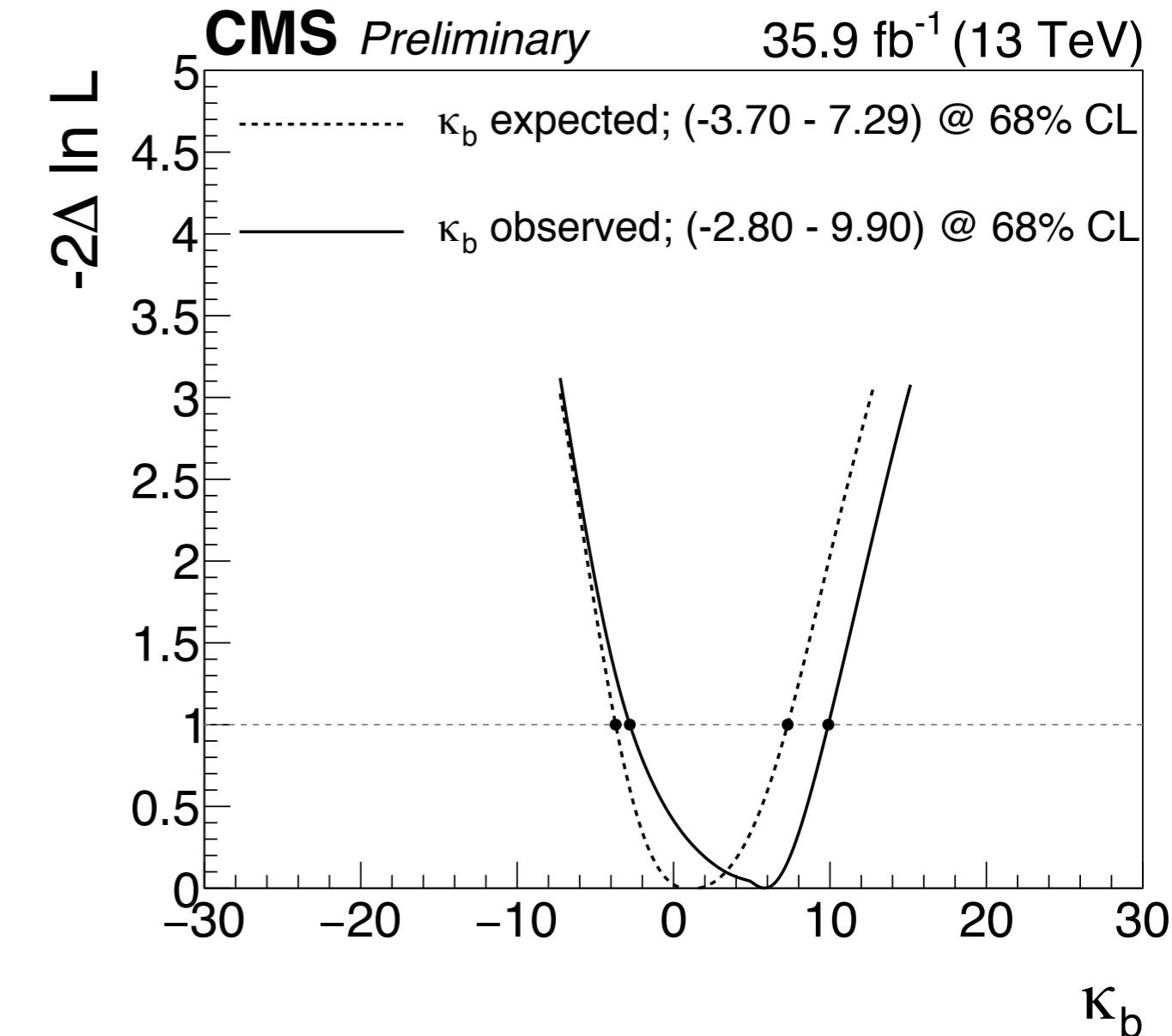
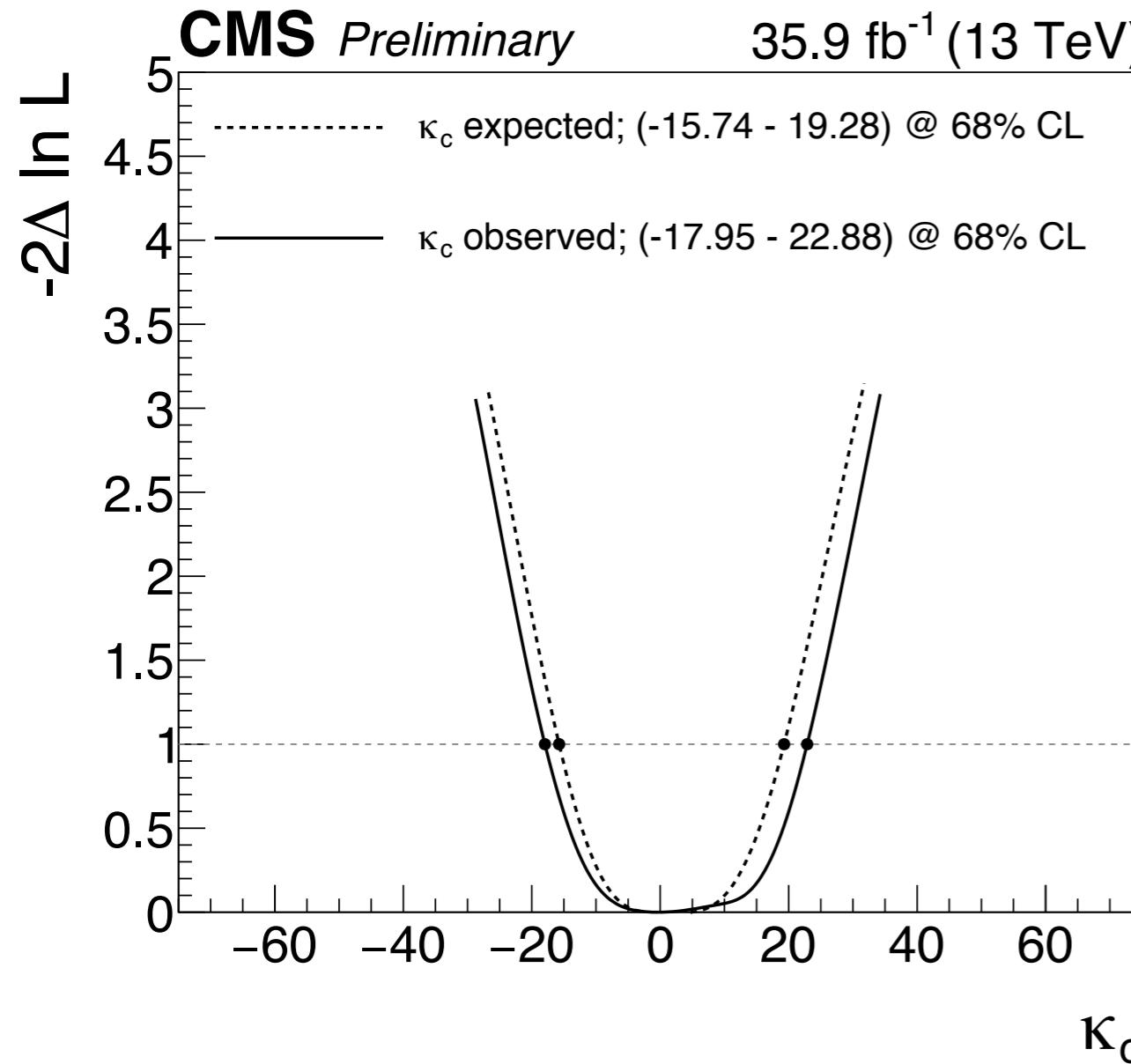




# Combination results

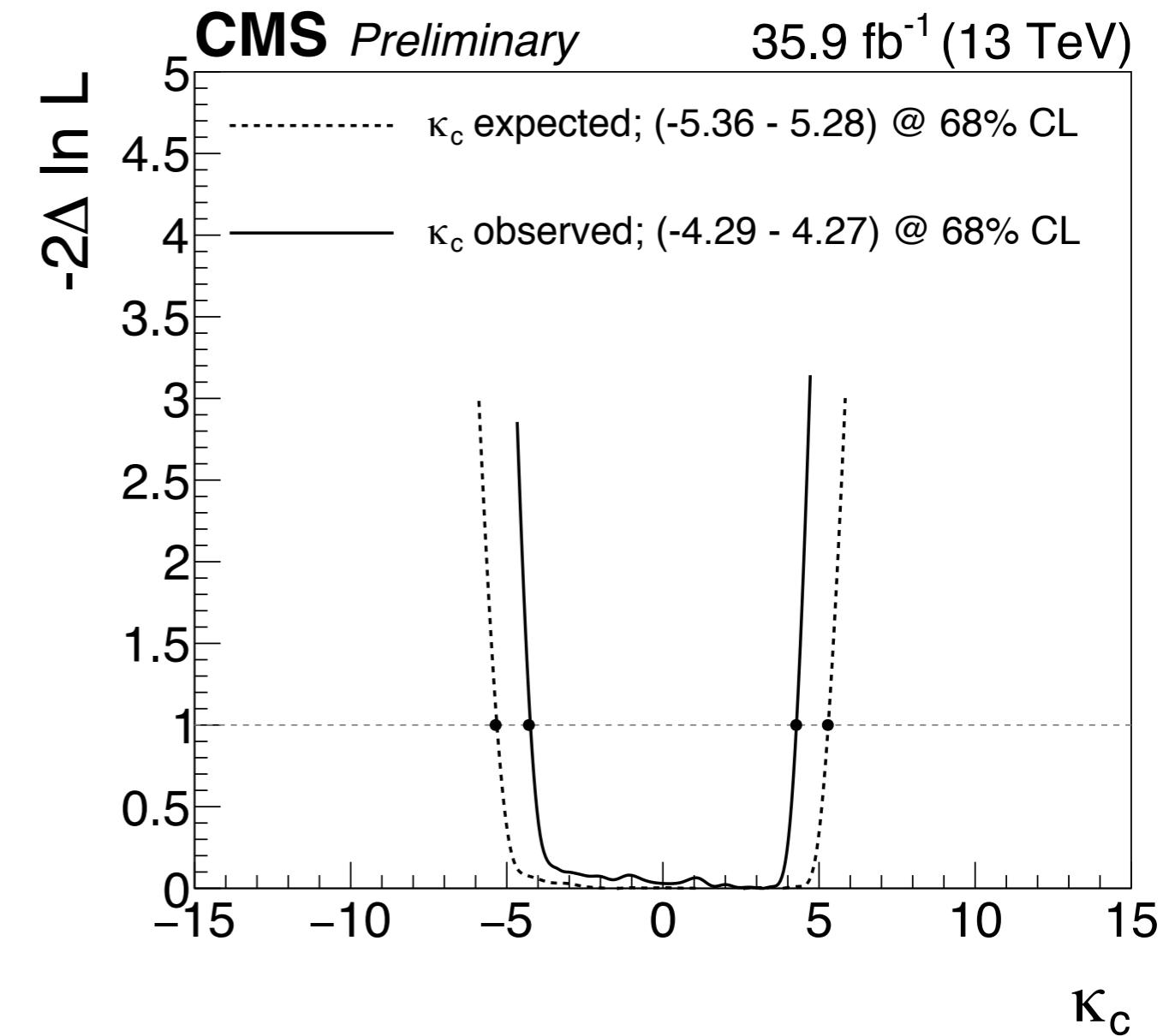
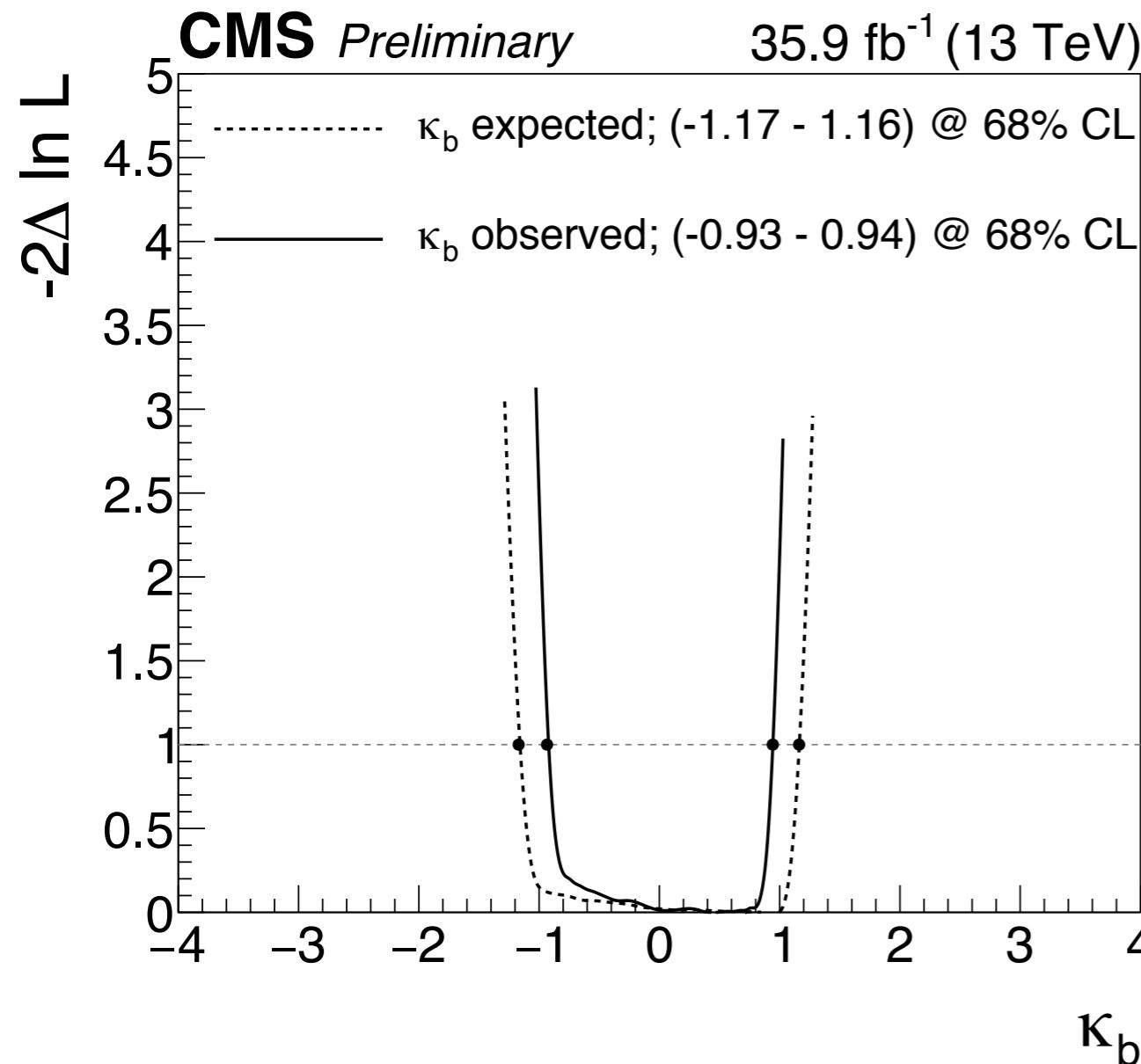


## BR freely floating



# Coupling variations (ii)

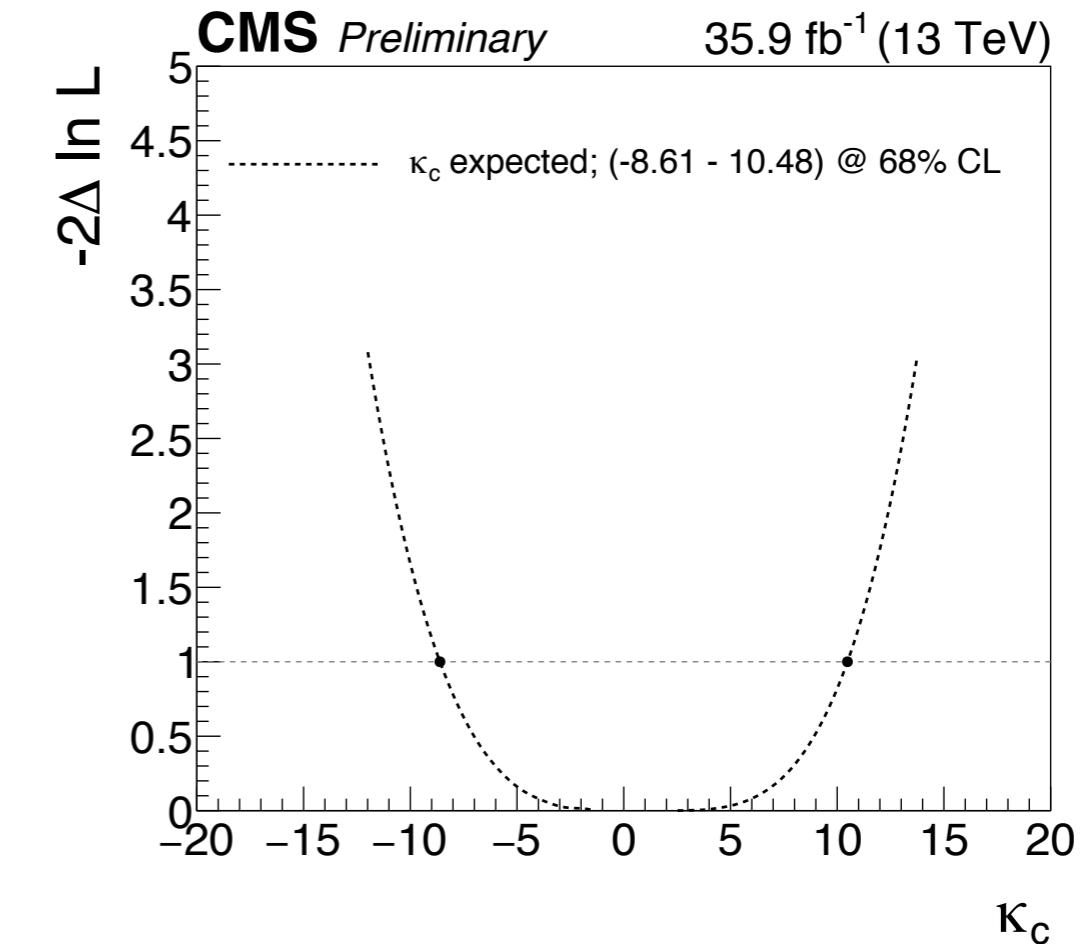
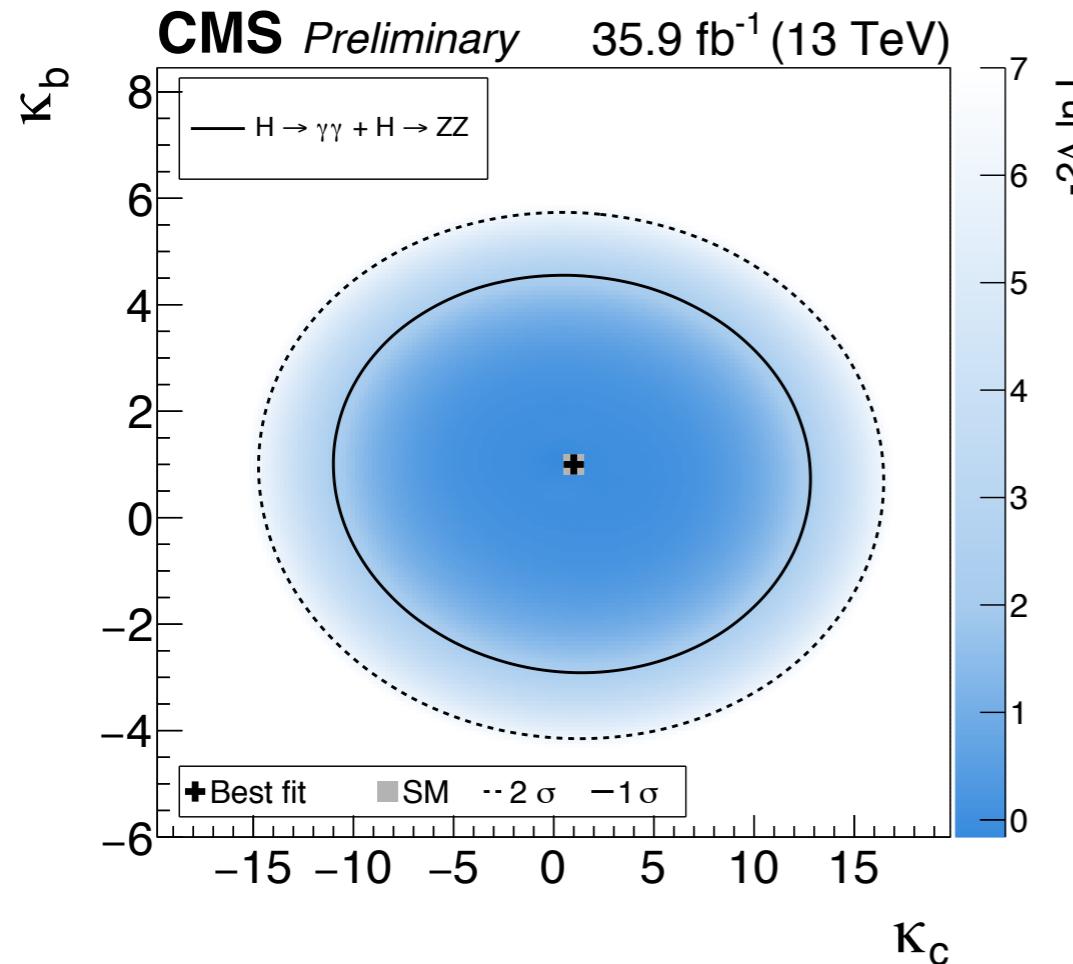
## BR scaling with couplings



# Coupling variations (i)

**Alternative scenario:** BR **fixed to SM** values (as done in Bishara et al. PRL 118 (2017) 121801)

- Expected results from Asimov fit

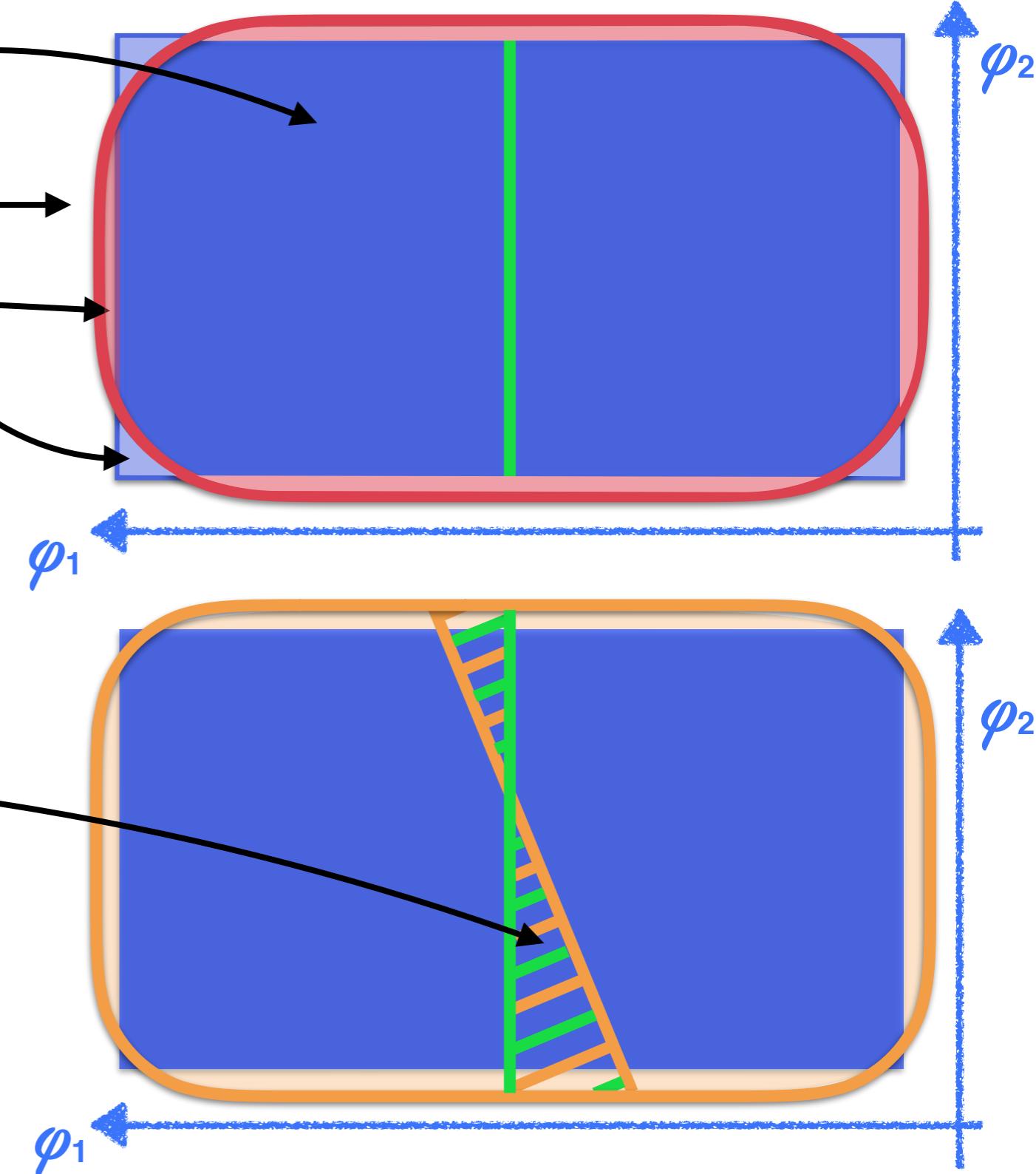


- From Bishara, limits set on  $k_c$  in  $[-16, 18]$  at 95%CL using  $20\text{fb}^{-1}$  at 8TeV from ATLAS

- **Signal strengths** provide measurements with **best sensitivity**, but short lifespan since:
  - assumptions on signal characteristics have to be made
  - non trivial (re-)interpretation as cross section due to complicate acceptance selection
- **Differential fiducial** cross sections:
  - Test SM predictions for **full spectrum of observables of interest**
  - Probe for hints of BSM physics
  - Different observables are sensitive to different Higgs properties
  - **Restriction to a phase space** as close as possible to the detector acceptance, simpler signal selection and categorization:
    - minimal theory dependence and extrapolation
    - improved longevity of the results

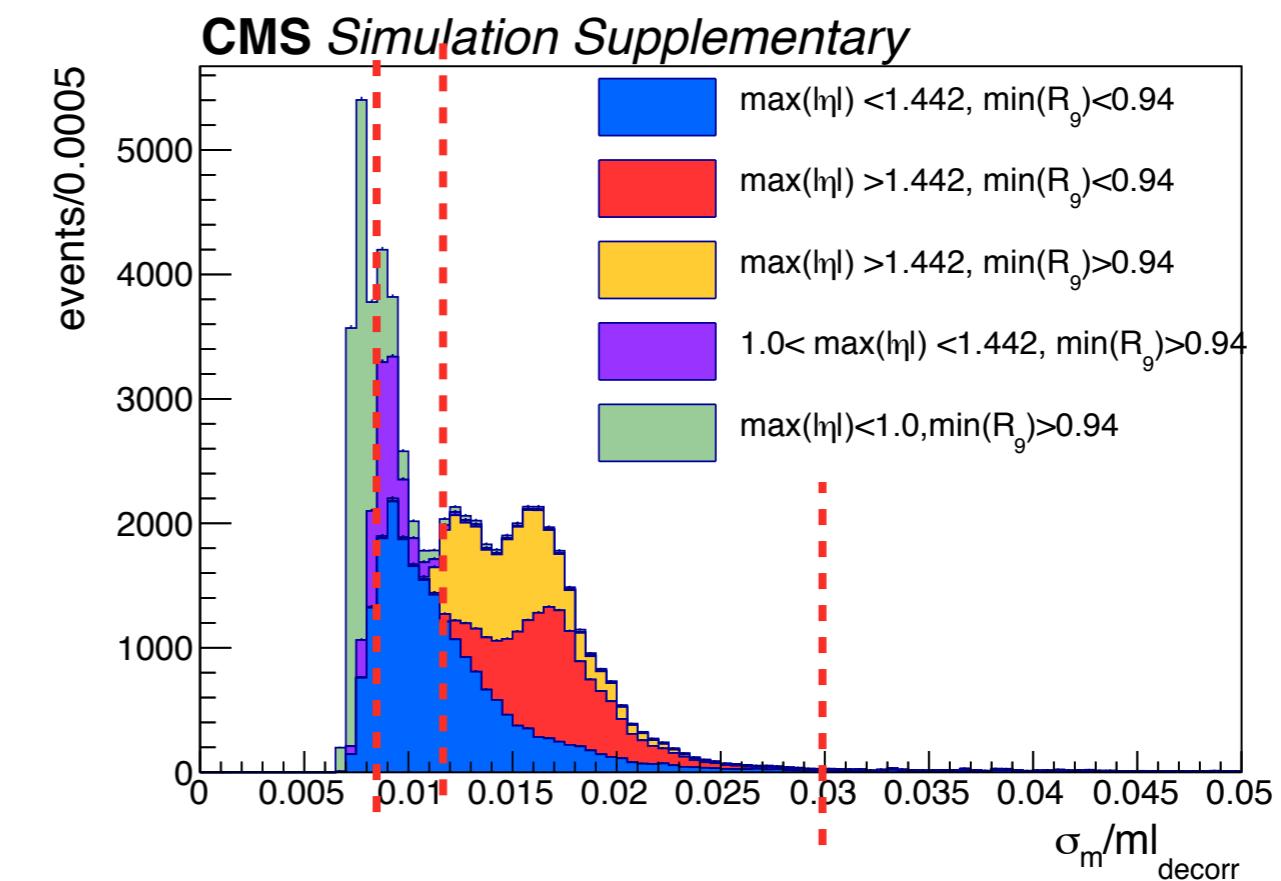
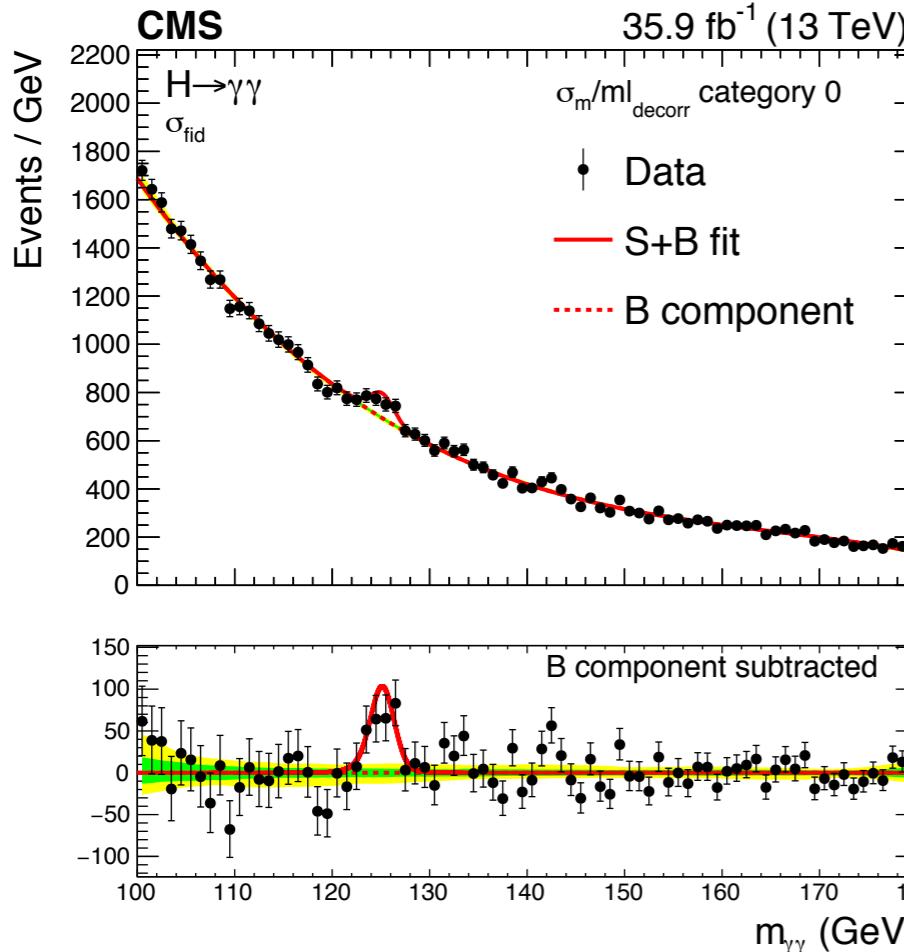
# Fiducial cross section extraction

- Definition of **fiducial phase space**, aligned to **detector acceptance**
- Migration of events from **outside to inside** (contamination) and **inside to outside** (efficiency)
- Observable **binning** at **fiducial** and **detector** level:  
**bin-to-bin migrations** → fiducial-to-reconstruction response matrix
- Unfolding to particle level
- Interpretation of the measurement

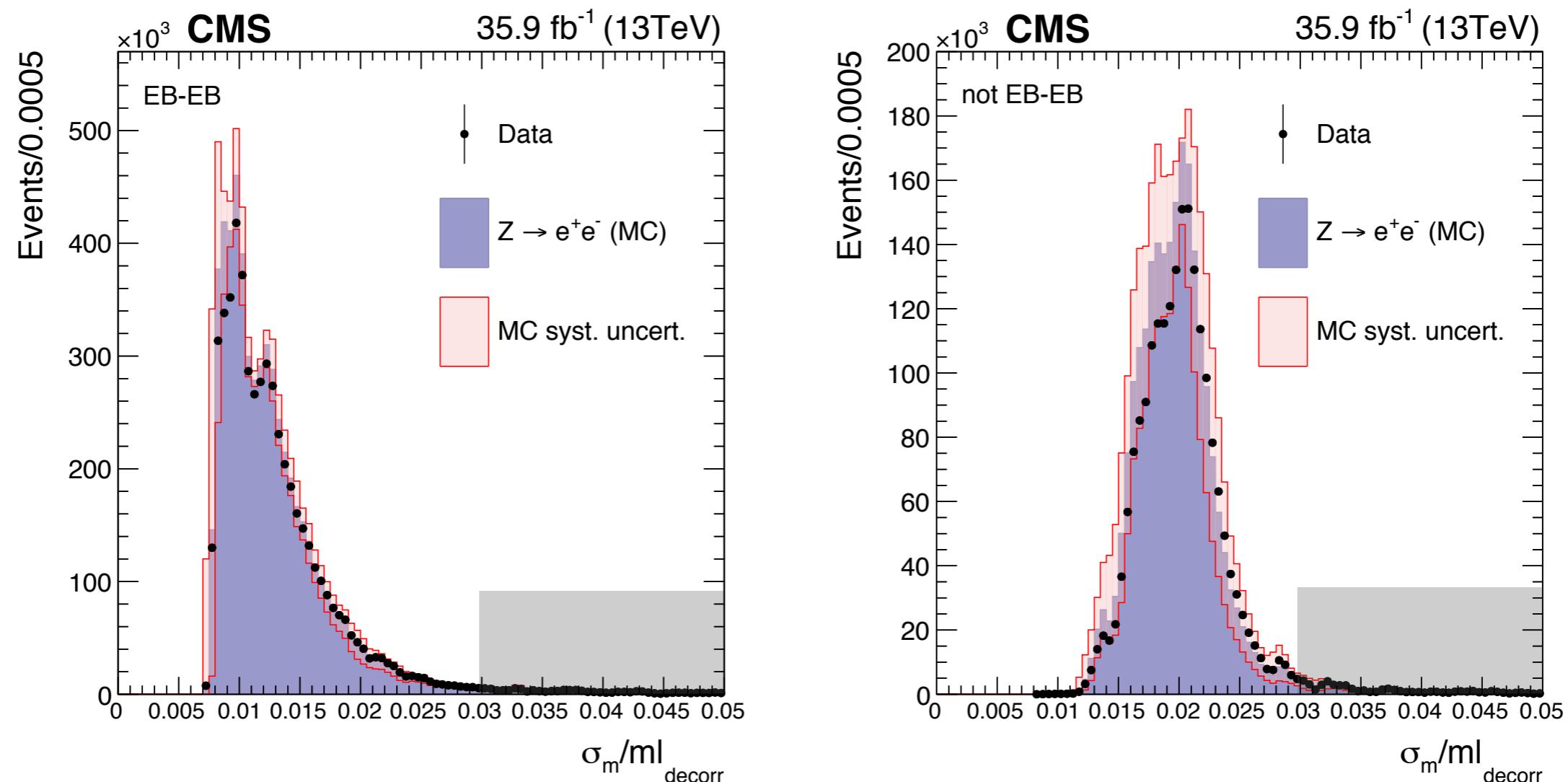


$$m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos \theta)}$$

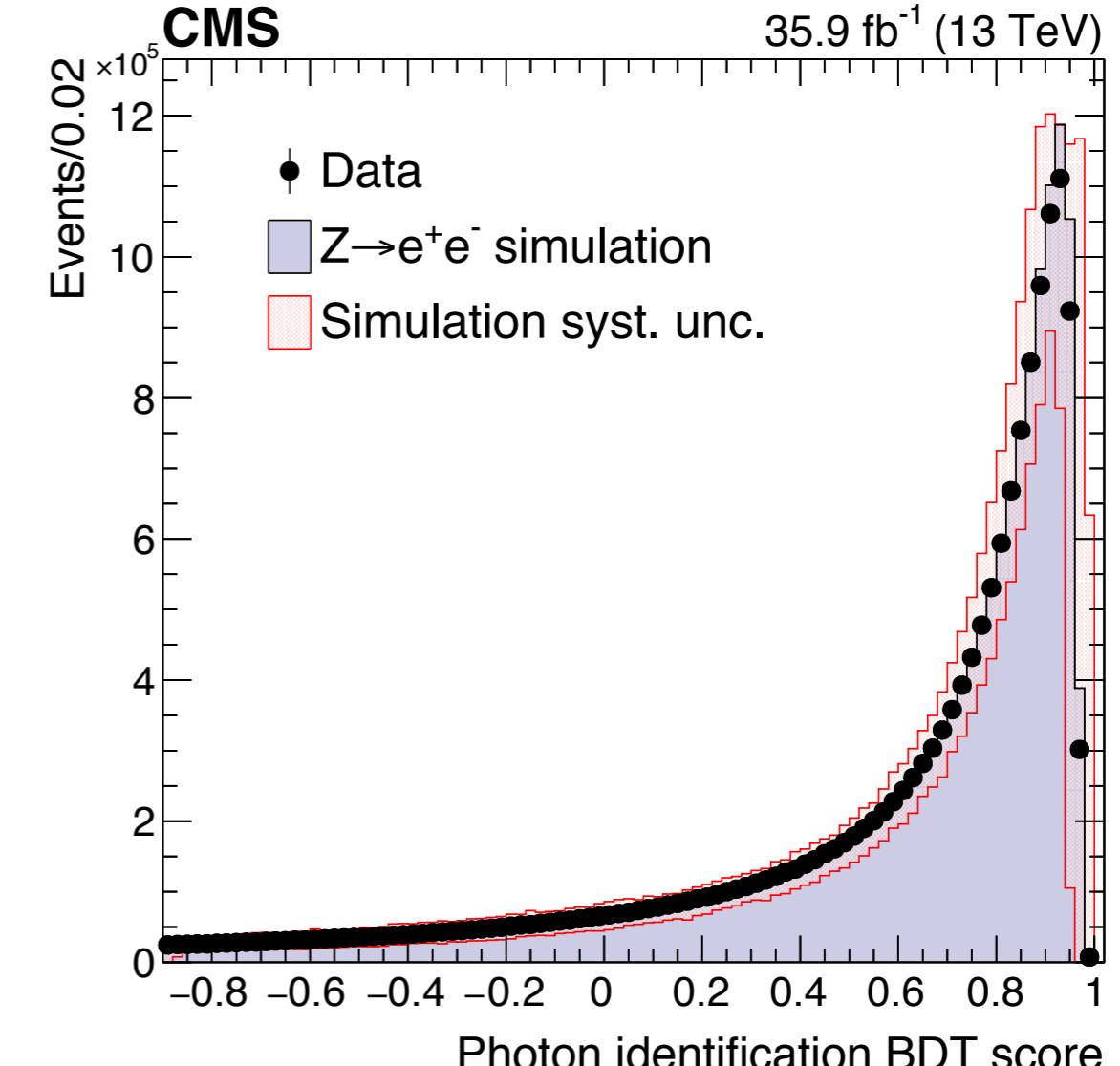
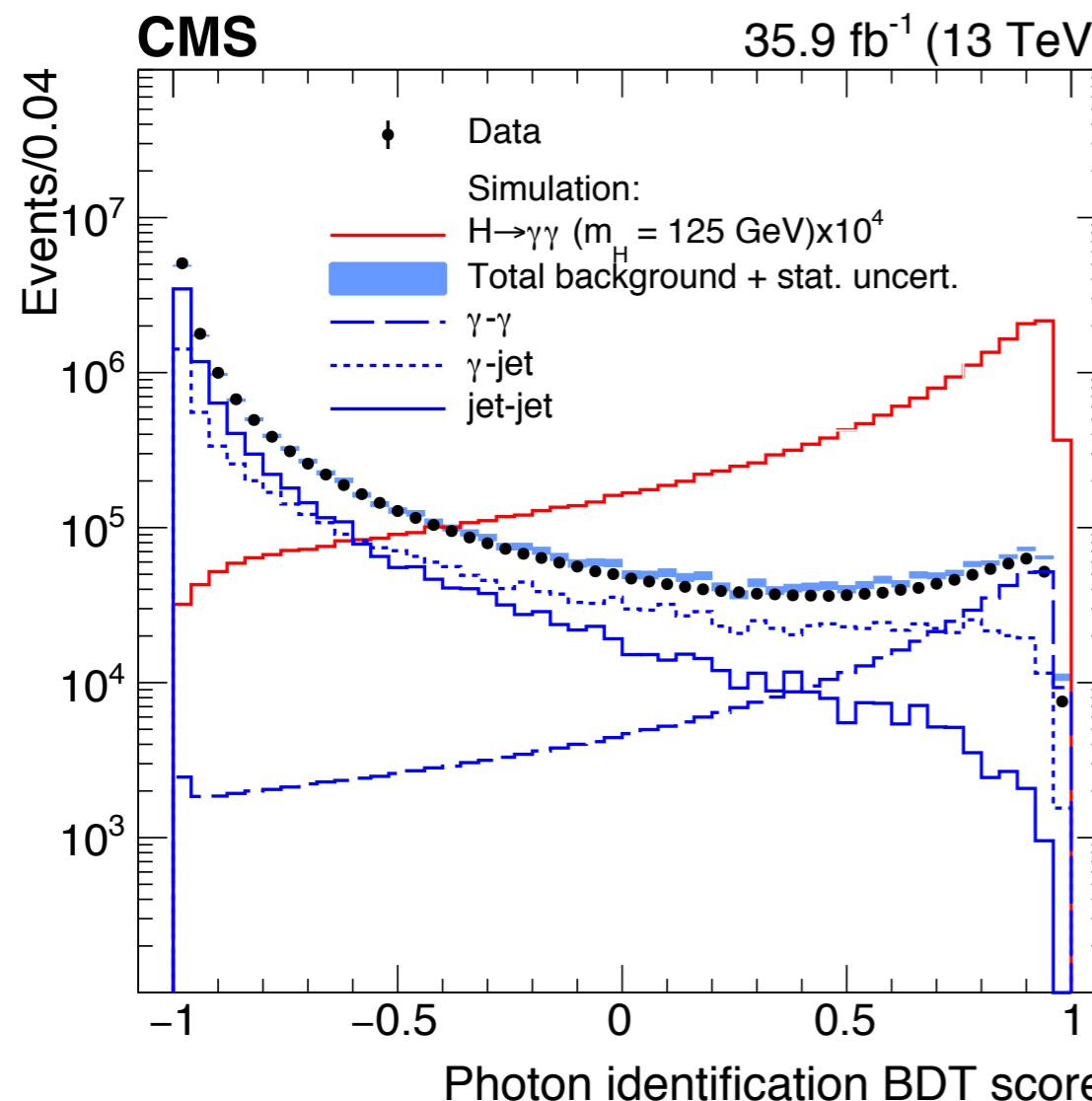
- **Calorimetric energy resolution**
- **Vertex ID**



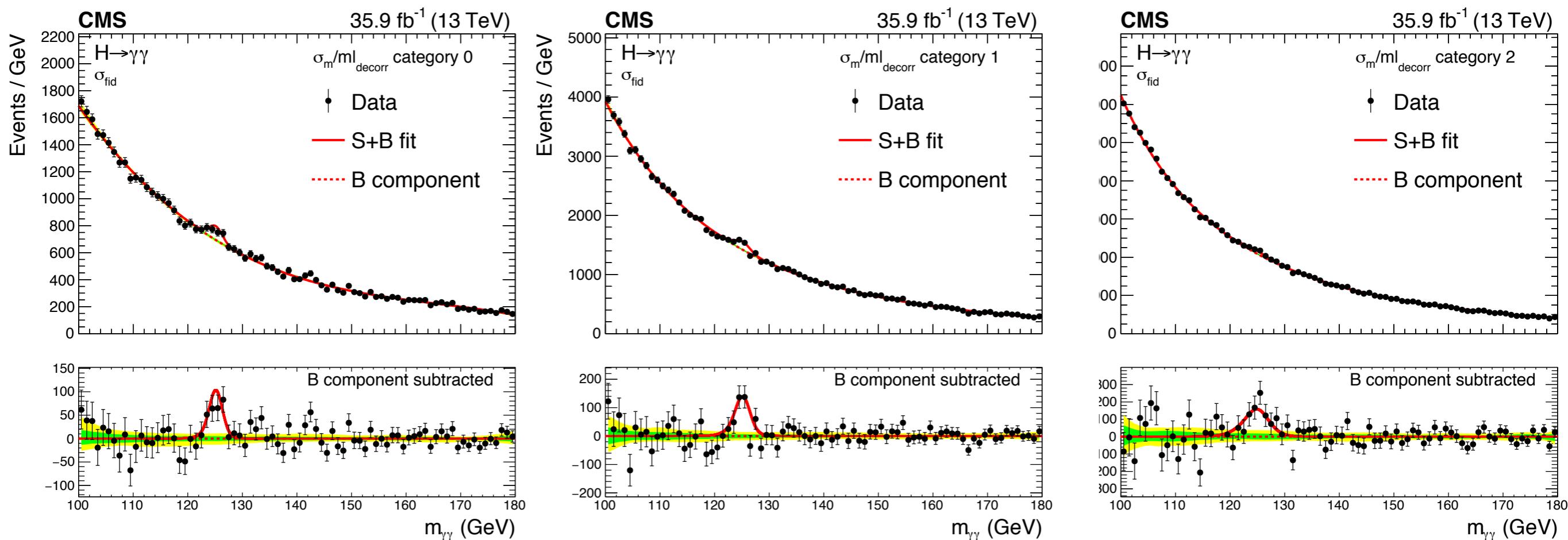
- Backgrounds: irreducible  $\gamma\gamma$ , reducible  $\gamma$ -fake and fake-fake  
 $\rightarrow$  multivariate Photon ID to reject fakes
- **3 event categories** defined using a **relative mass resolution estimator**,  
 fully **decorrelated** from the mass itself to prevent shaping of  $m_{\gamma\gamma}$  distribution



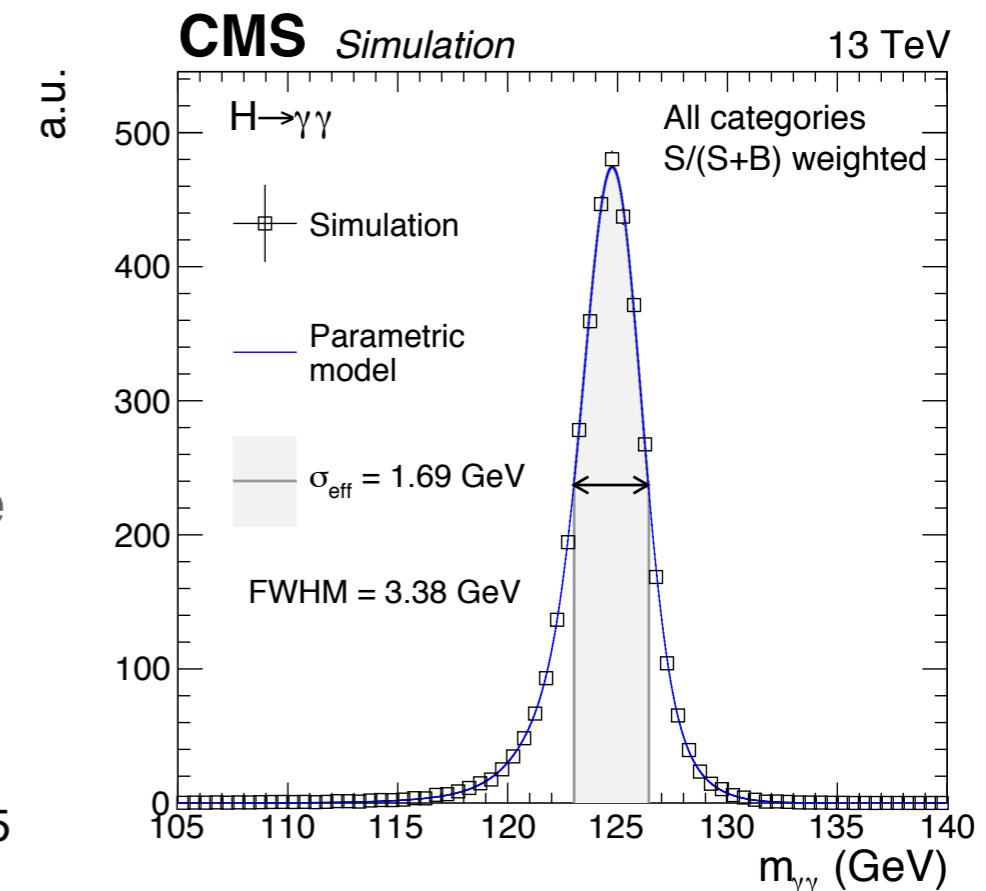
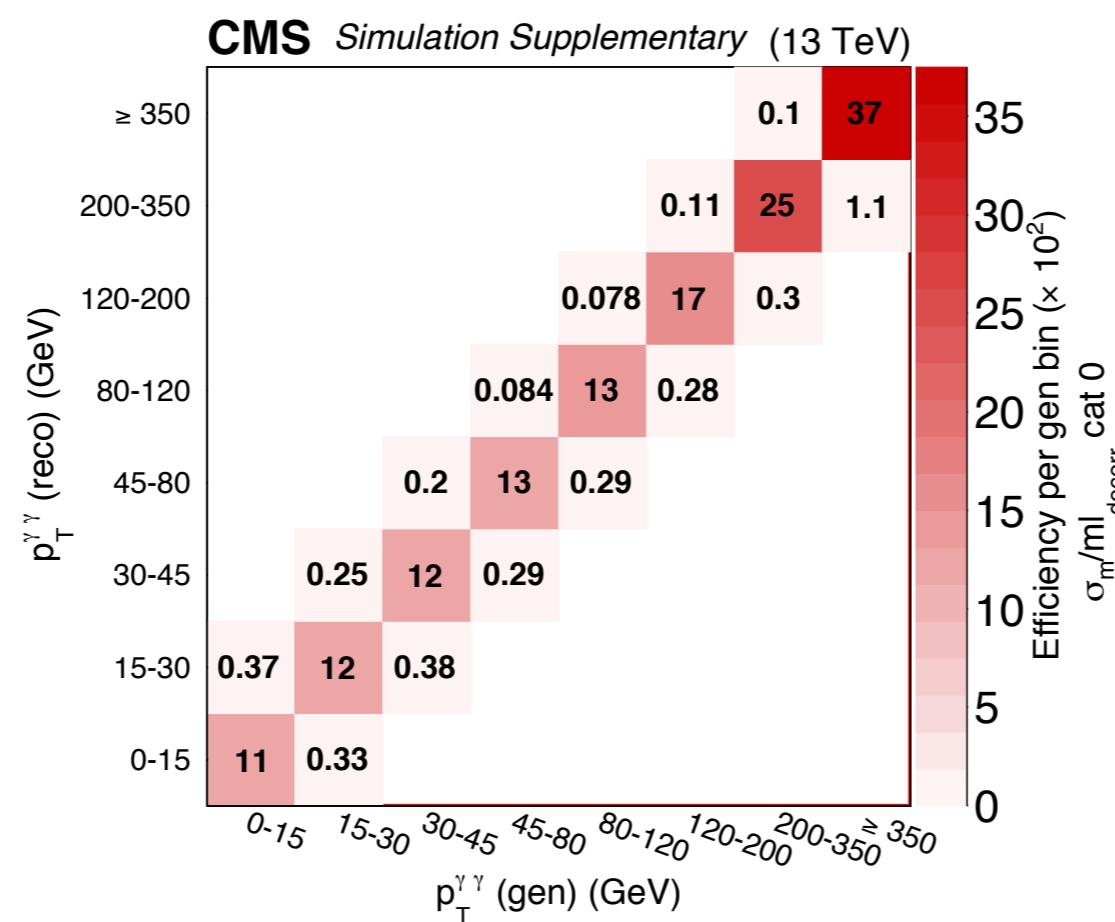
- Relative mass resolution estimator in  $Z \rightarrow ee$  events
- Sensitive to photon position in the detector and calorimetric shower shape
- The red band shows the impact of the systematic uncertainty on the photon energy resolution



- Photon identification BDT built with kinematic variables and isolations of photons as inputs

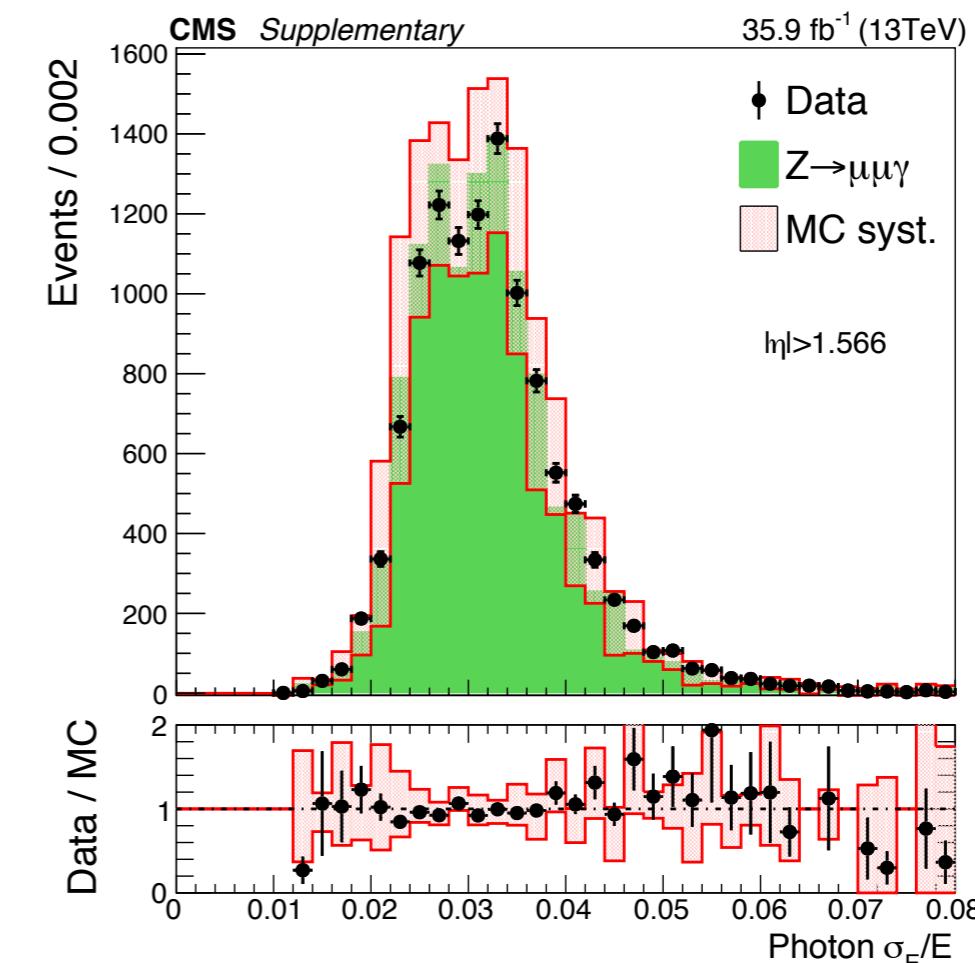
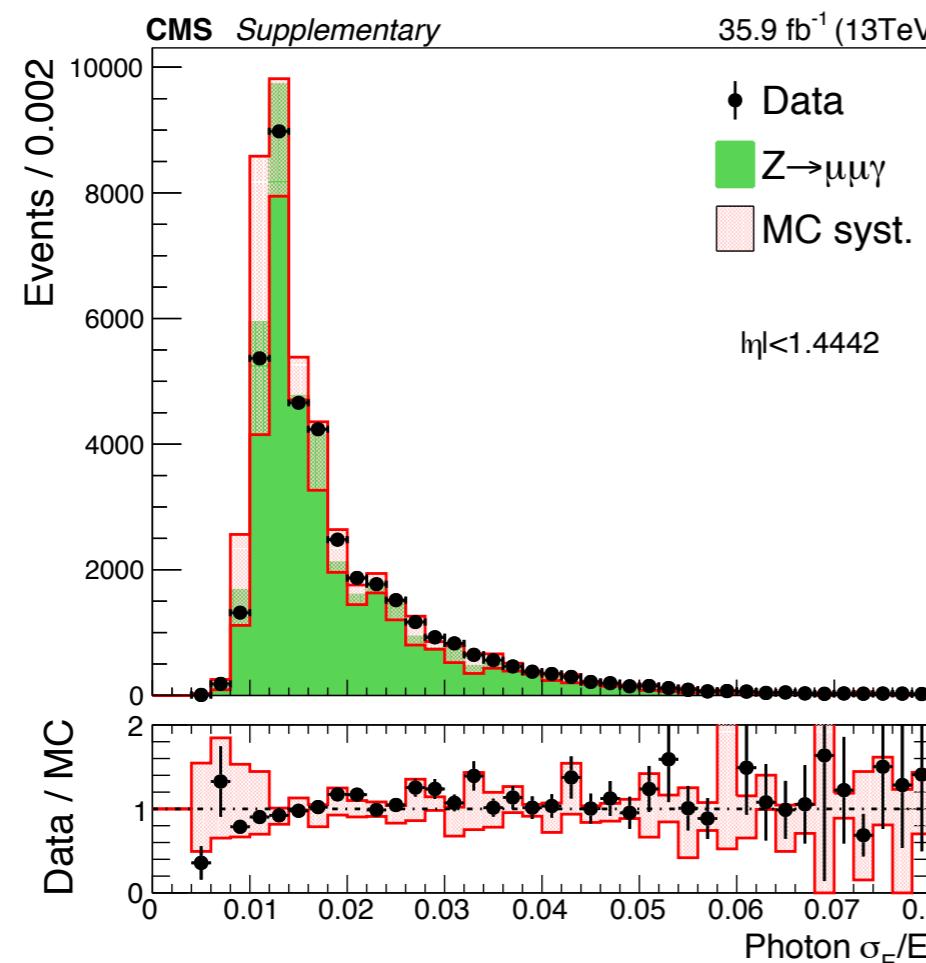


- **Fully parametric** signal model from simulation
- Background model **data driven**:
  - background functional form treated as **discrete nuisance** parameter



# $H \rightarrow \gamma\gamma$ : selection and photon ID

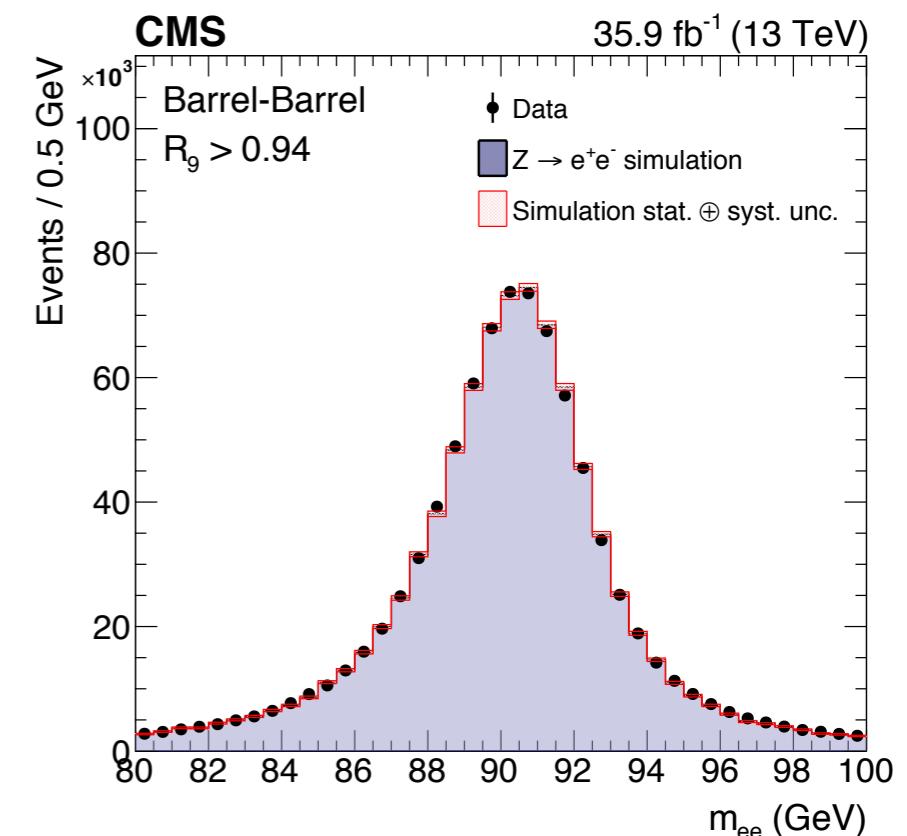
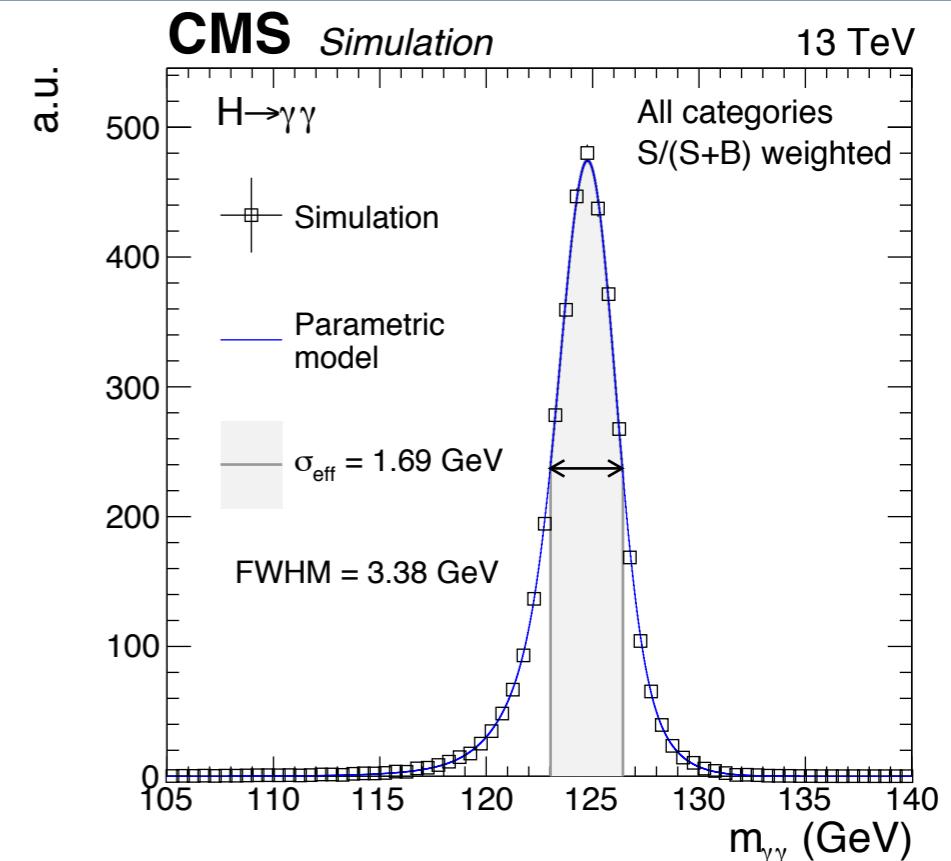
- **Double-photon trigger** selection based on transverse energy,  $m_{\gamma\gamma}$ , isolation and electromagnetic shower shapes variables
- Minimal **pre-selection**, similar to but tighter than trigger selection
- Photon ID input variables: shower shape variables, particle-flow isolations, kinematic of photon, median energy density ( $\rho$ )
- Pure sample of photons from  $Z \rightarrow \mu\mu\gamma$  used for validation of multivariate photon ID

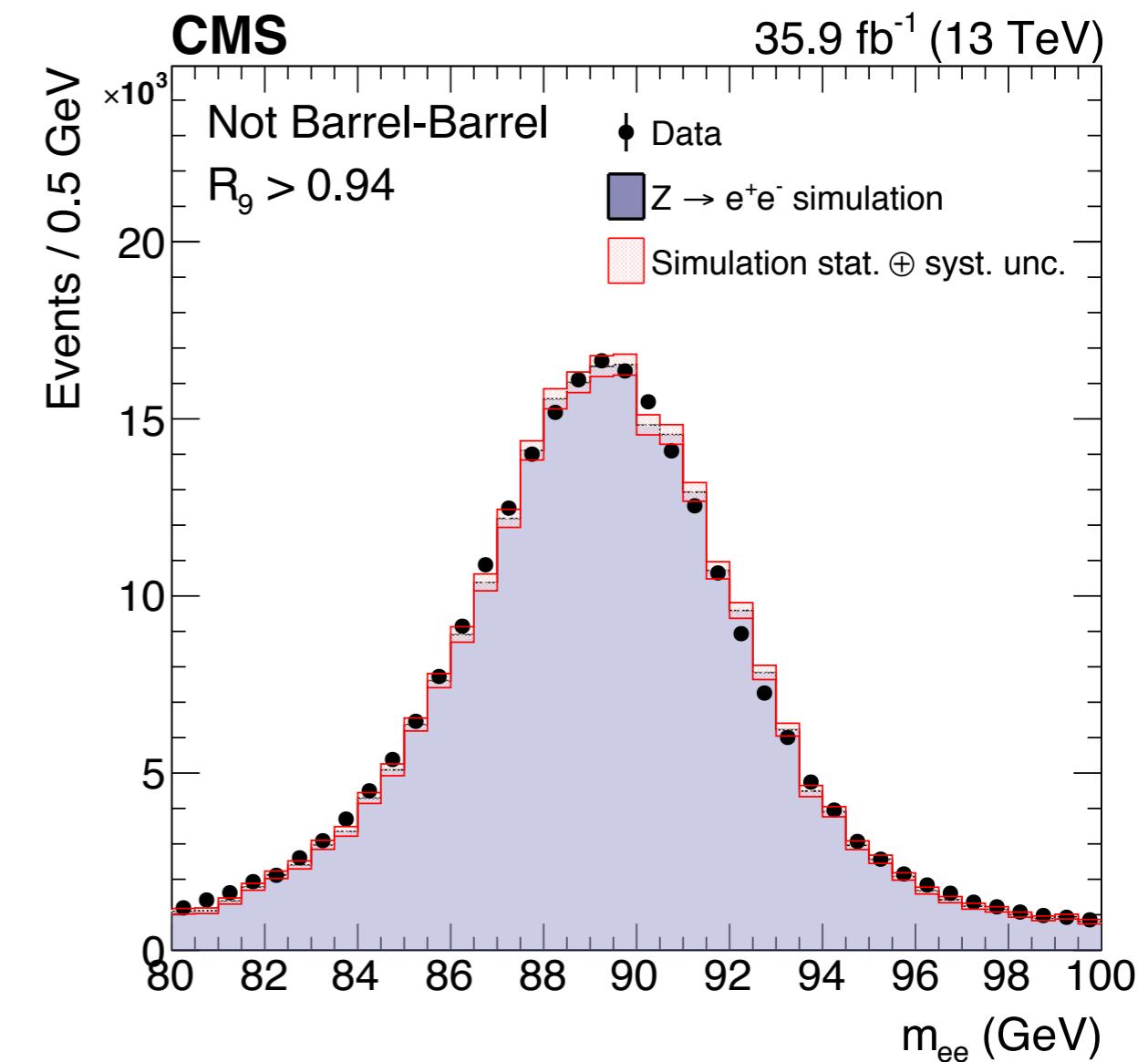
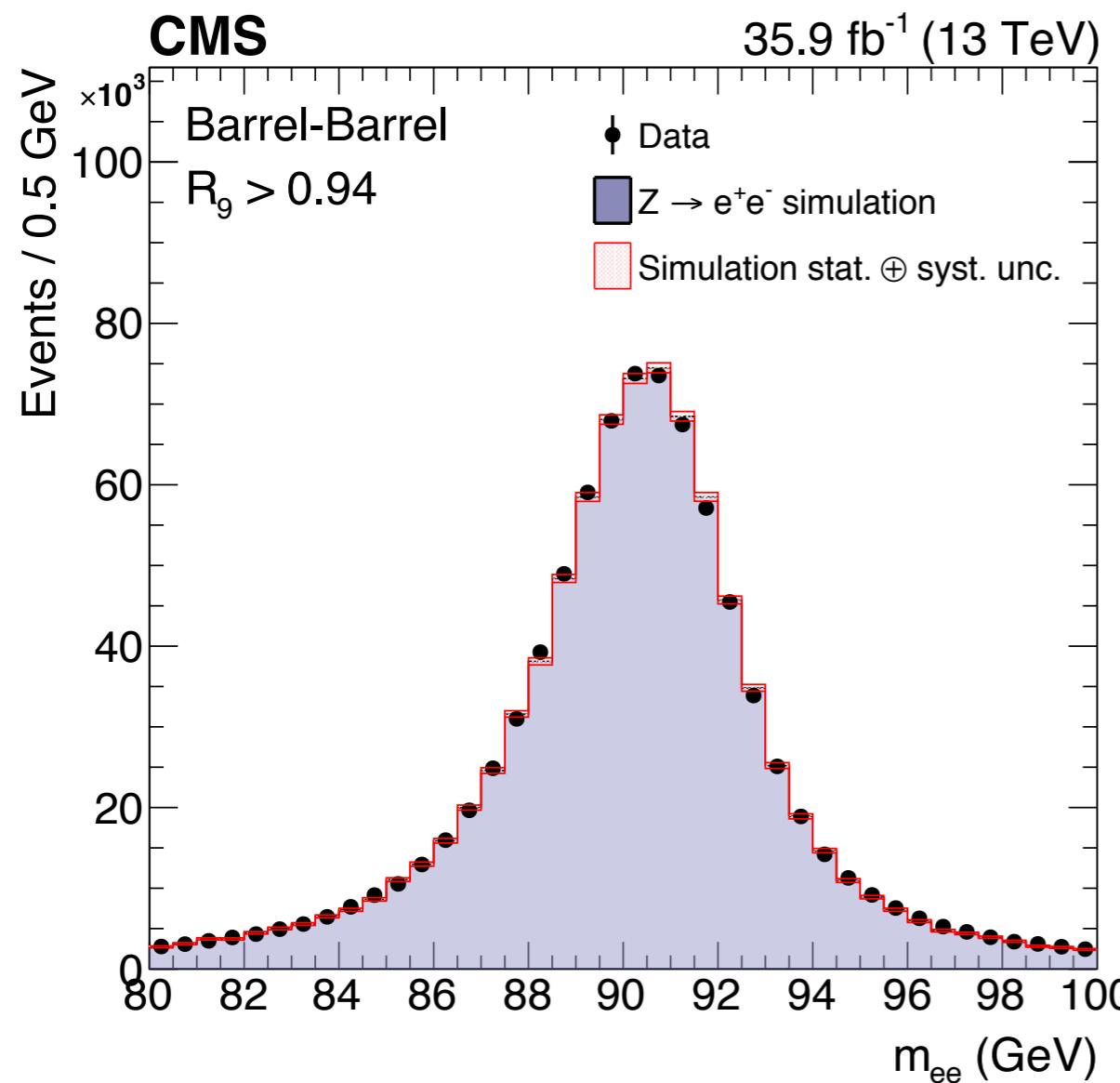


# $H \rightarrow \gamma\gamma$ : photon Energy

$$m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos \theta)}$$

- Electro-magnetic calorimeter (ECAL) response:
  - corrected for **change in time**
  - inter-calibrated to be uniform in  $\eta/\phi$
  - adjustment of **absolute scale**
  
- **Energy and its uncertainty** corrected for local and global shower containment:
  - **regression** targeting  $E_{\text{true}}/E_{\text{reco}}$
  - **Scale** vs time and **resolution** calibration:  $Z \rightarrow ee$  peak used as reference
  - **Corrected** energies and resolutions used in the analysis

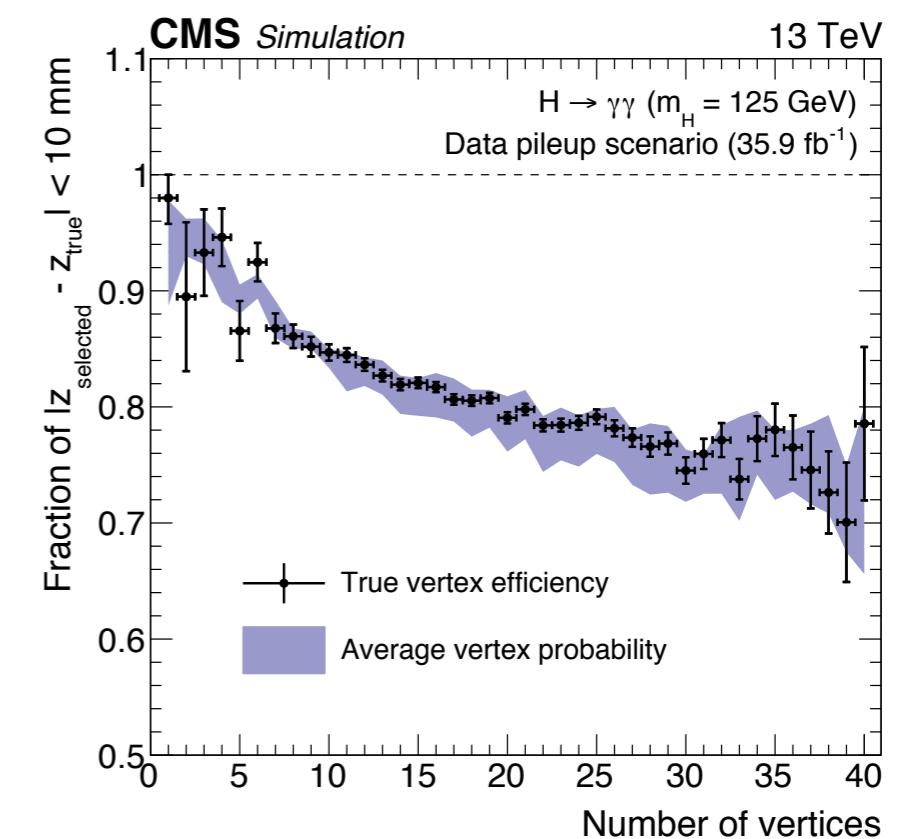
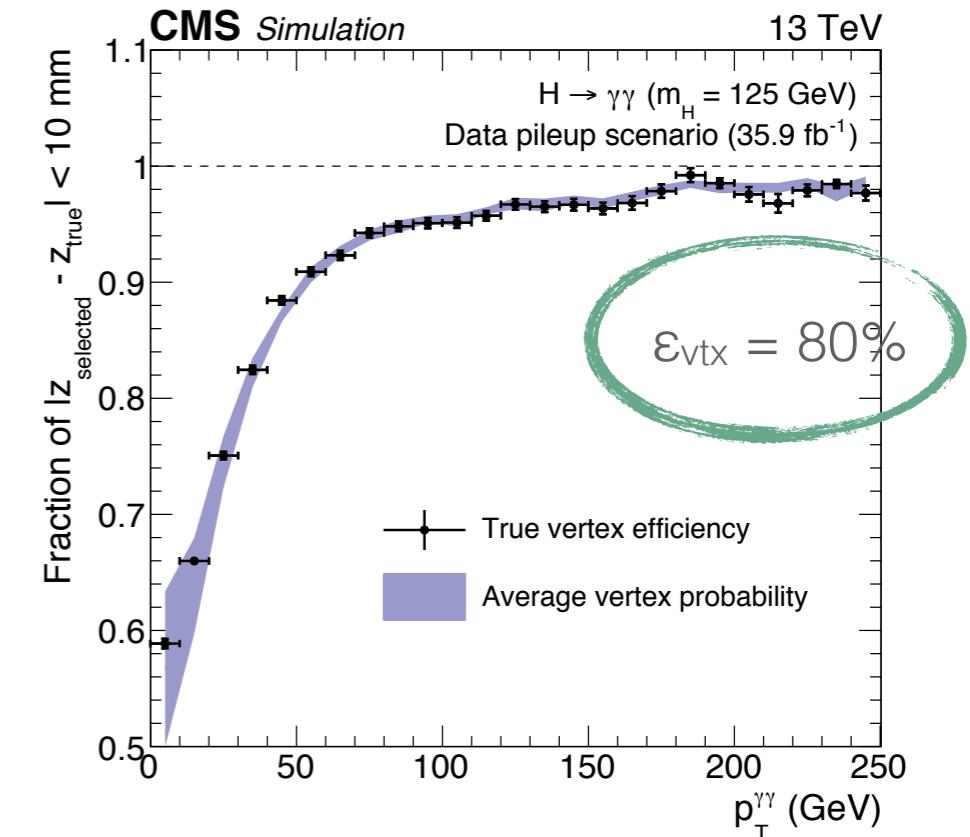




# Vertex identification

$$m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos \theta)}$$

- Vertex assignment correct within **1 cm** → **negligible** impact on mass resolution
- No ionization in the tracker for photons
- **Multi-variate approach** for vertex identification
  - exploit kinematic correlations and **track distribution imbalance**
  - direction of **conversion tracks**, when present
- Method validated on  $Z \rightarrow \mu\mu$  ( $\gamma + j$  for converted  $\gamma$ ) events, where vertex found after removing muon tracks



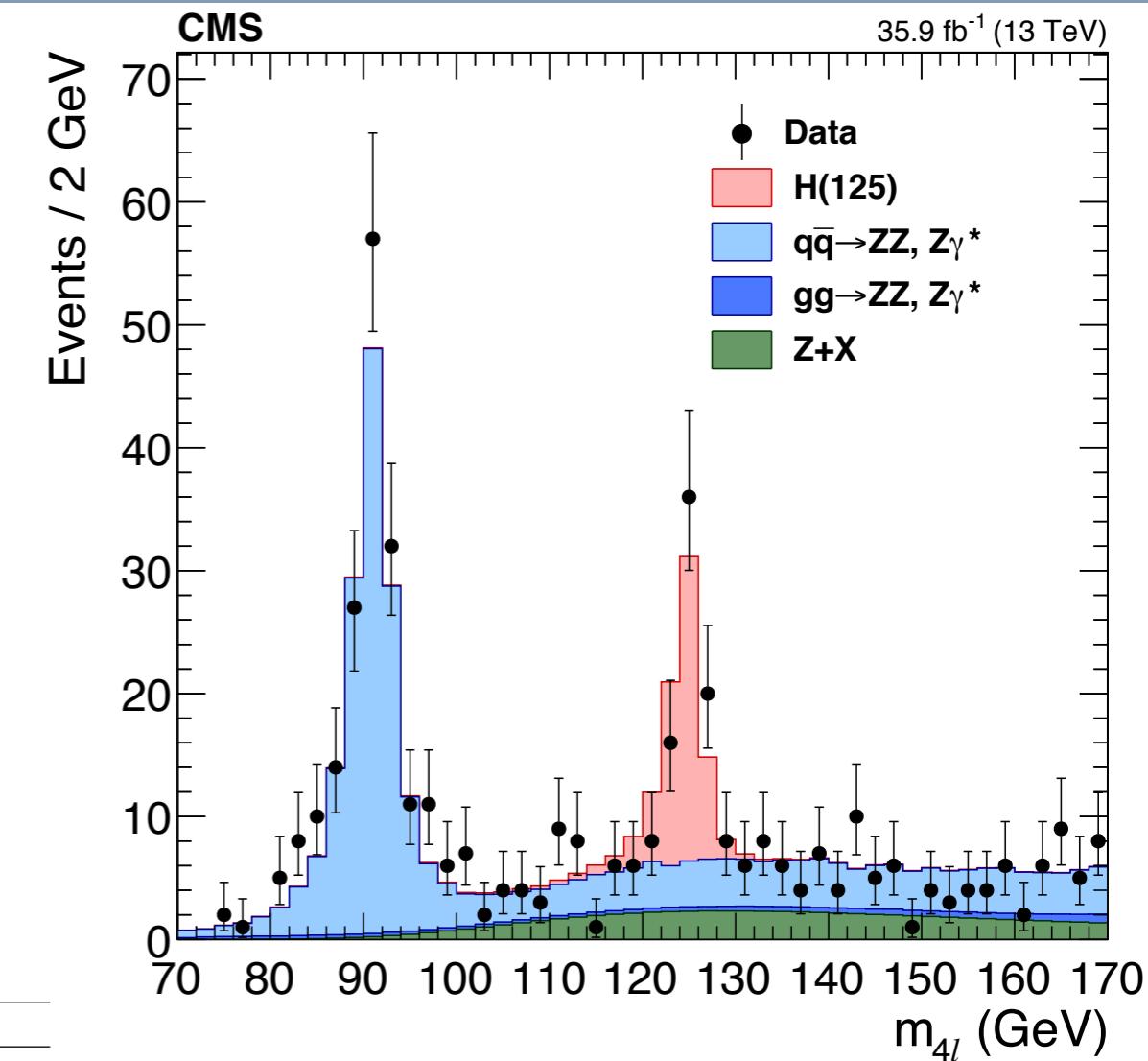
- Very small branching fraction ( $1.2 \cdot 10^{-4}$ )
- **Small background** from ZZ and (reducible) from Z+X
- Two same flavour, opposite sign lepton pairs, reconstructed with **excellent  $m_{4\ell}$  resolution**
- **No use** of matrix element discriminants, to reduce model dependence
- Signal + background fit to  $m_{4\ell}$  distribution

## Lepton kinematics and isolation

Leading lepton $p_T$	$p_T > 20 \text{ GeV}$
Subleading lepton $p_T$	$p_T > 10 \text{ GeV}$
Additional electrons (muons) $p_T$	$p_T > 7 (5) \text{ GeV}$
Pseudorapidity of electrons (muons)	$ \eta  < 2.5 (2.4)$
Sum $p_T$ of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$

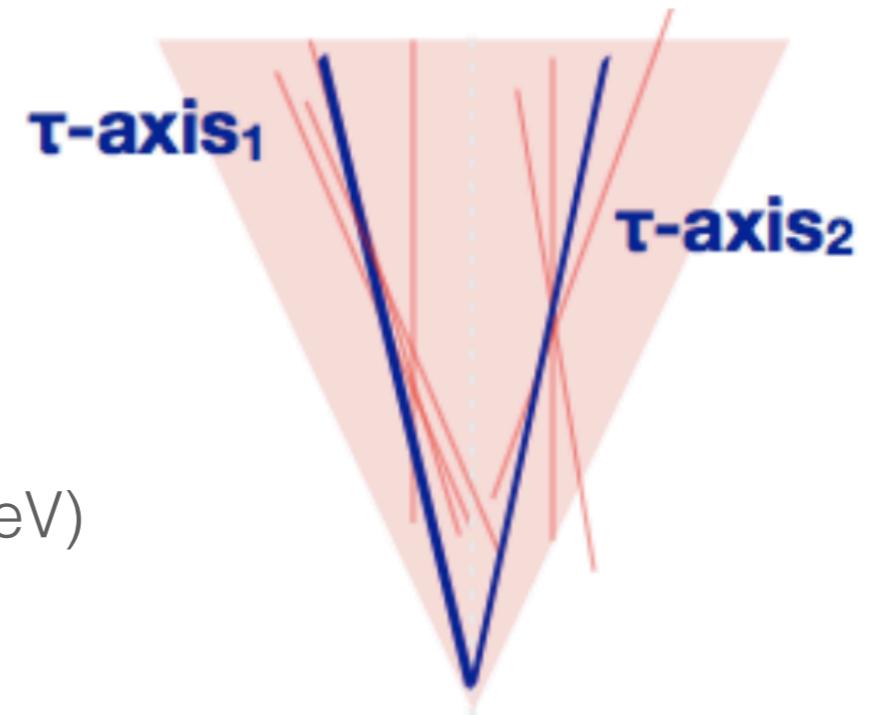
## Event topology

Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Invariant mass of the $Z_1$ candidate	$40 < m_{Z_1} < 120 \text{ GeV}$
Invariant mass of the $Z_2$ candidate	$12 < m_{Z_2} < 120 \text{ GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02 \text{ for any } i \neq j$
Invariant mass of any opposite-sign lepton pair	$m_{\ell^+\ell^-} > 4 \text{ GeV}$
Invariant mass of the selected four leptons	$105 < m_{4\ell} < 140 \text{ GeV}$



- Full response matrix in signal extraction
- More complex fiducial phase space definition

- Largest branching ratio (58%) channel
- **Overwhelming background** from QCD production of two b jets ( $10^7$ )
- **Boosted H** regime to reduce background ( $p_T > 450 \text{ GeV}$ )  
—> select **one ‘fat’ jet**, with **two-prong** structure
- Hadronic transverse energy ( $H_T$ ) or jet  $p_T$  above thresholds
- **Double-b tagger** to identify signal jet: ‘passing’ and ‘failing’ region
- **Soft-drop grooming** of jet mass removes soft and wide-angle radiation
- Z $\rightarrow$ bb as SM candle, allows validation of the measurement



# H $\rightarrow$ bb overview (ii)

- QCD background shape estimated from events failing the double-b tag requirements
- Transfer factor R as a function of  $\rho$  and  $p_T$  of the jet

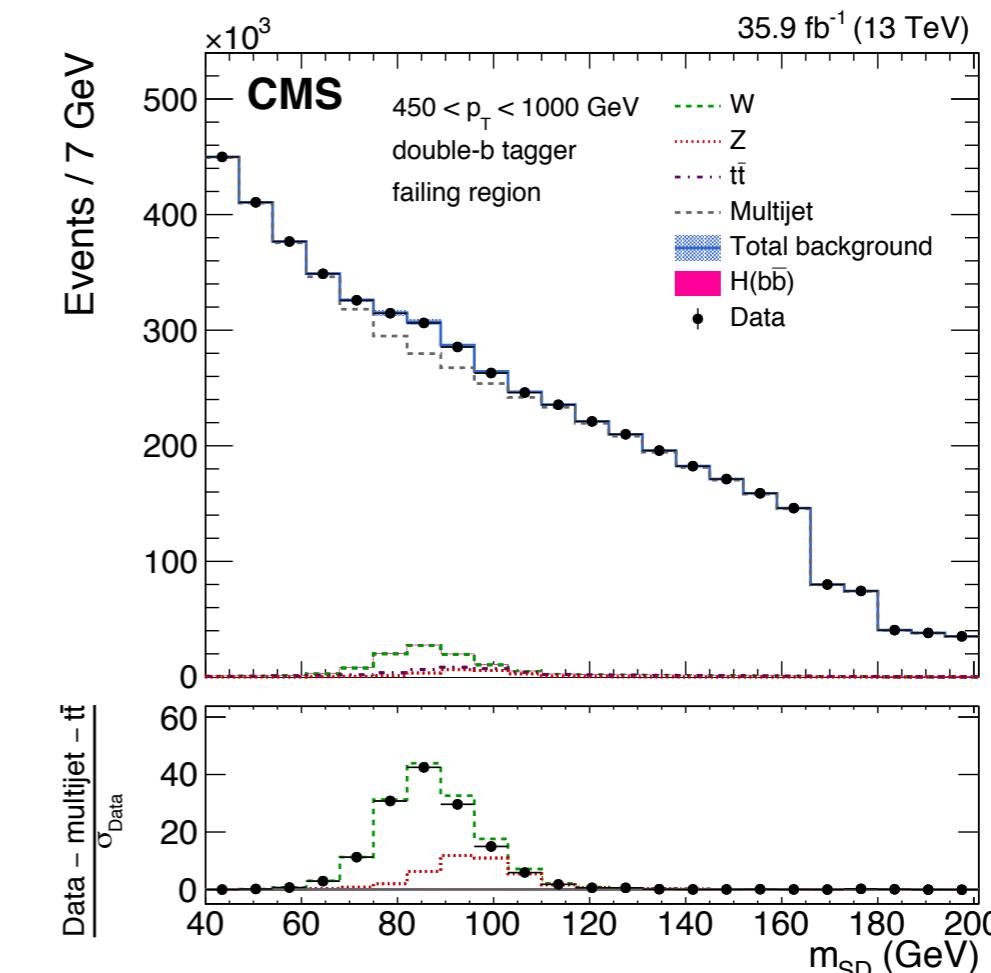
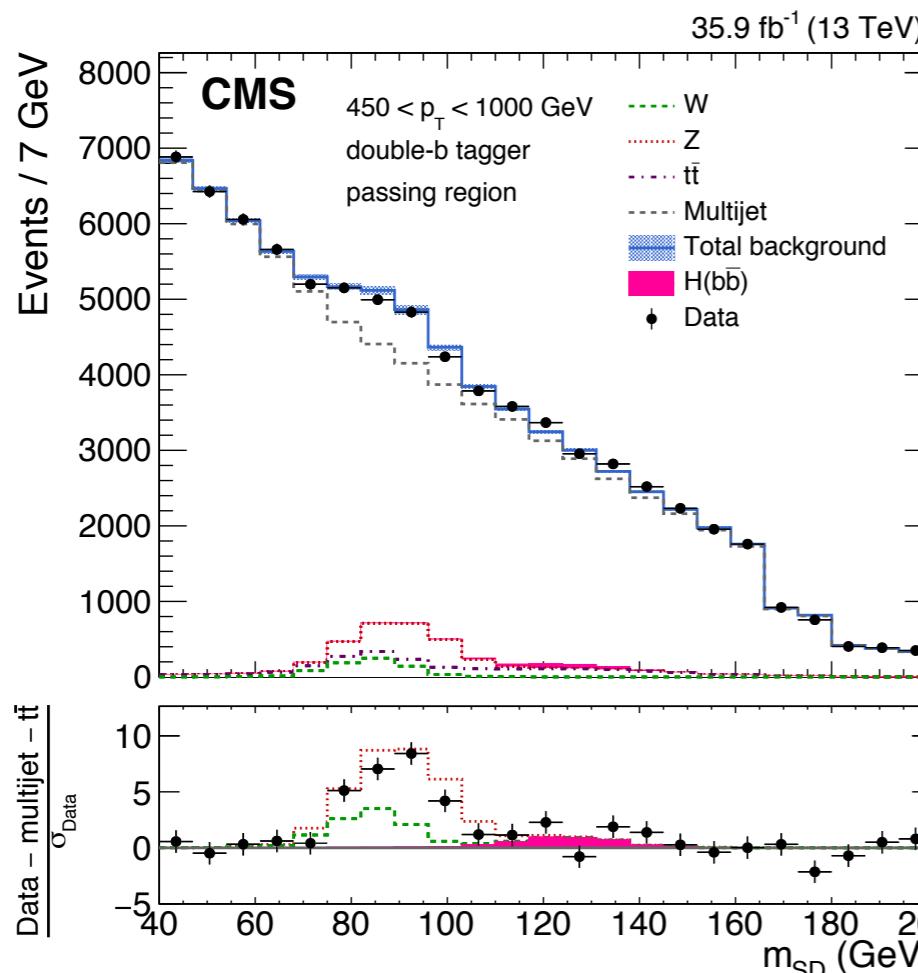
$$N_{pass}^{QCD} = R_{p/f}(\rho, p_T) N_{fail}^{QCD}$$

- R determined simultaneously with signal extraction
- Simultaneous fit of Z $\rightarrow$ bb and H $\rightarrow$ bb signal strengths

**mass scale variable**  
 $\rho = \log(m_{SD}^2/p_T^2)$

$$\mu_Z = 0.78 \pm 0.14(\text{stat})^{+0.19}_{-0.13}(\text{syst})$$

$$\mu_H = 2.3 \pm 1.5(\text{stat})^{+1.0}_{-0.4}(\text{syst})$$



# CMS detector

## CMS DETECTOR

Total weight : 14,000 tonnes  
 Overall diameter : 15.0 m  
 Overall length : 28.7 m  
 Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
 Pixel ( $100 \times 150 \mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
 Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
 Niobium titanium coil carrying  $\sim 18,000\text{A}$

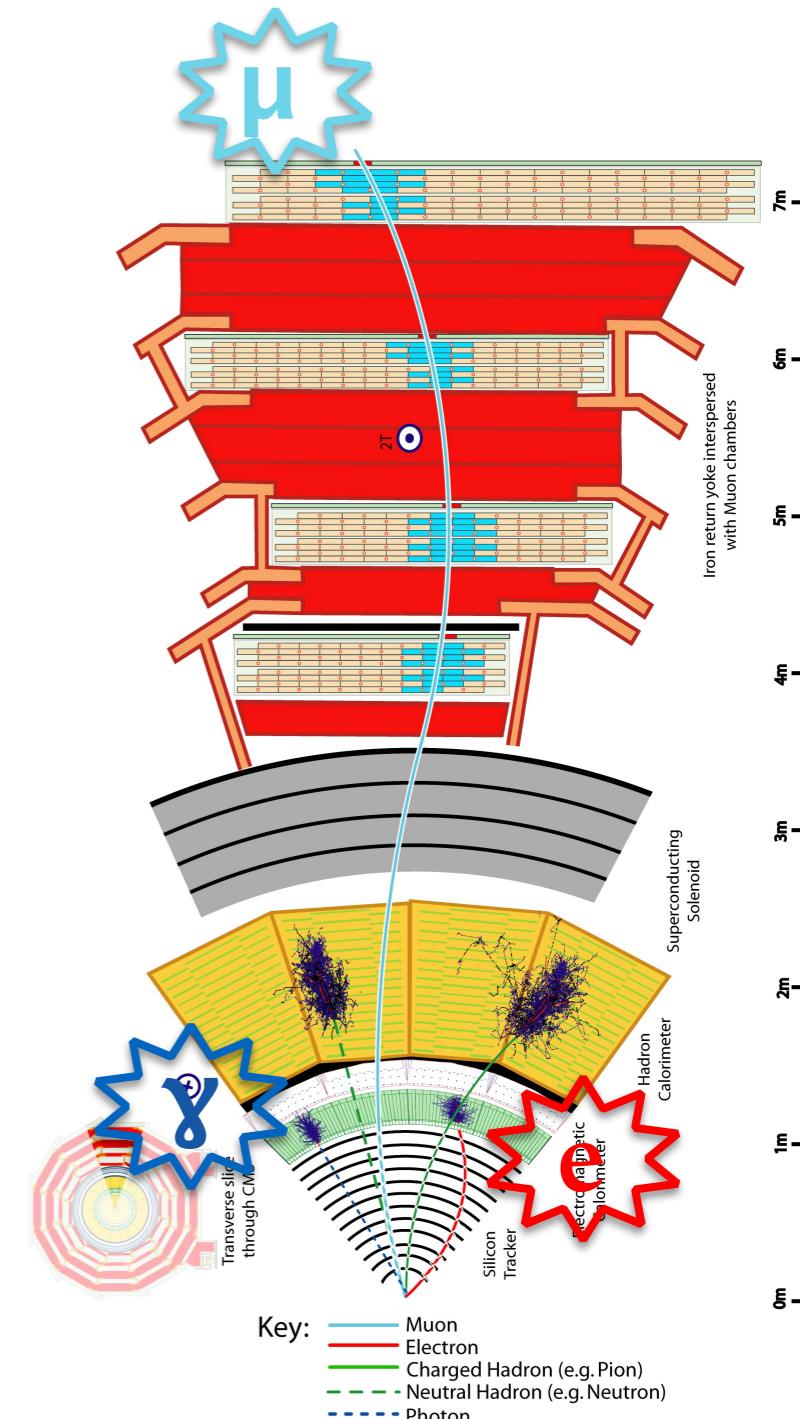
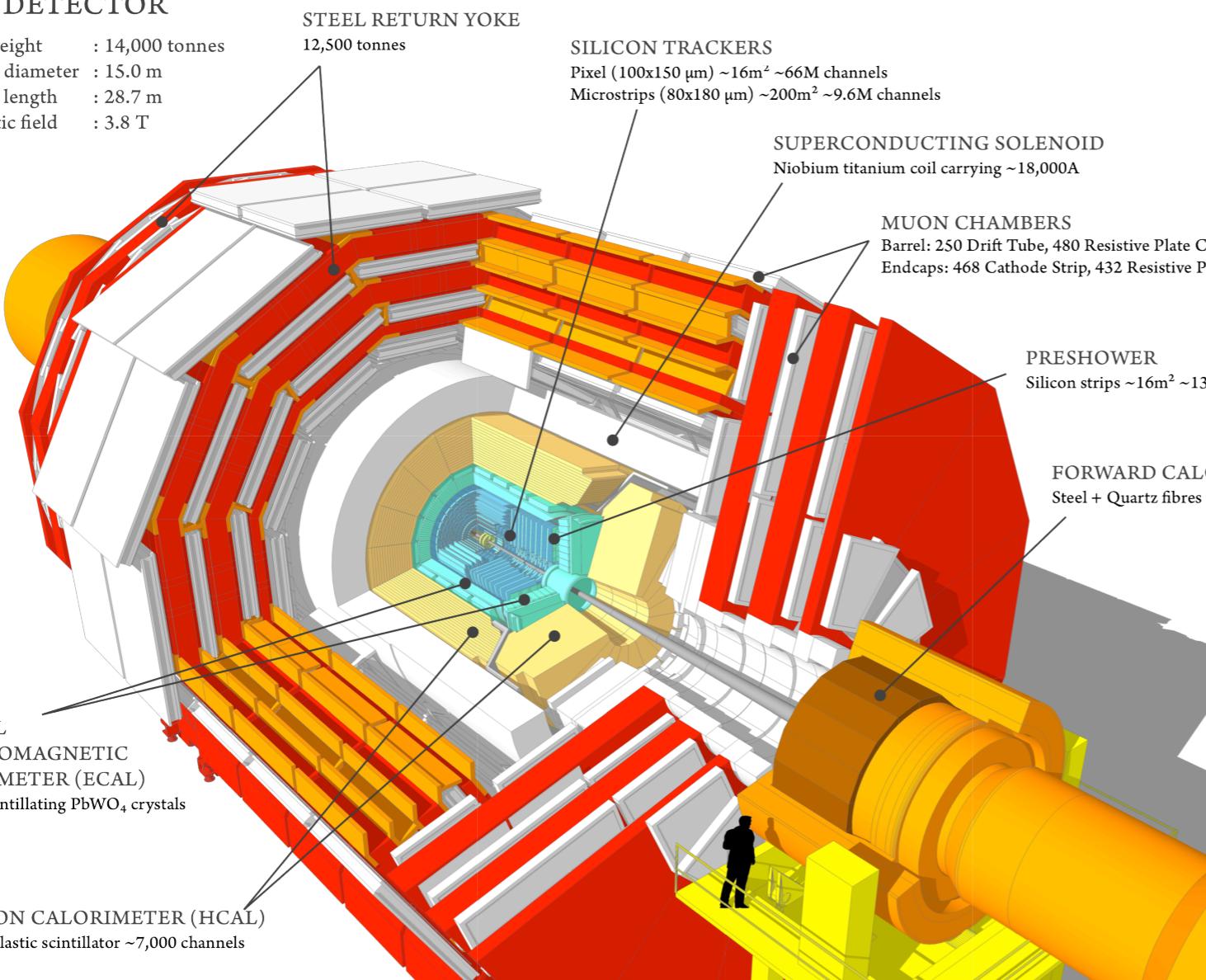
MUON CHAMBERS  
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
 Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
 Steel + Quartz fibres  $\sim 2,000$  Channels

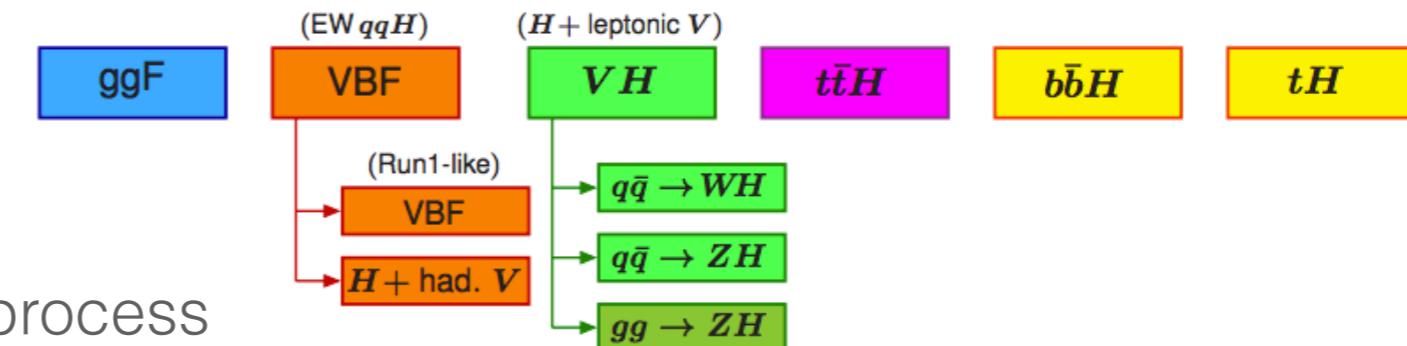
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
 Brass + Plastic scintillator  $\sim 7,000$  channels

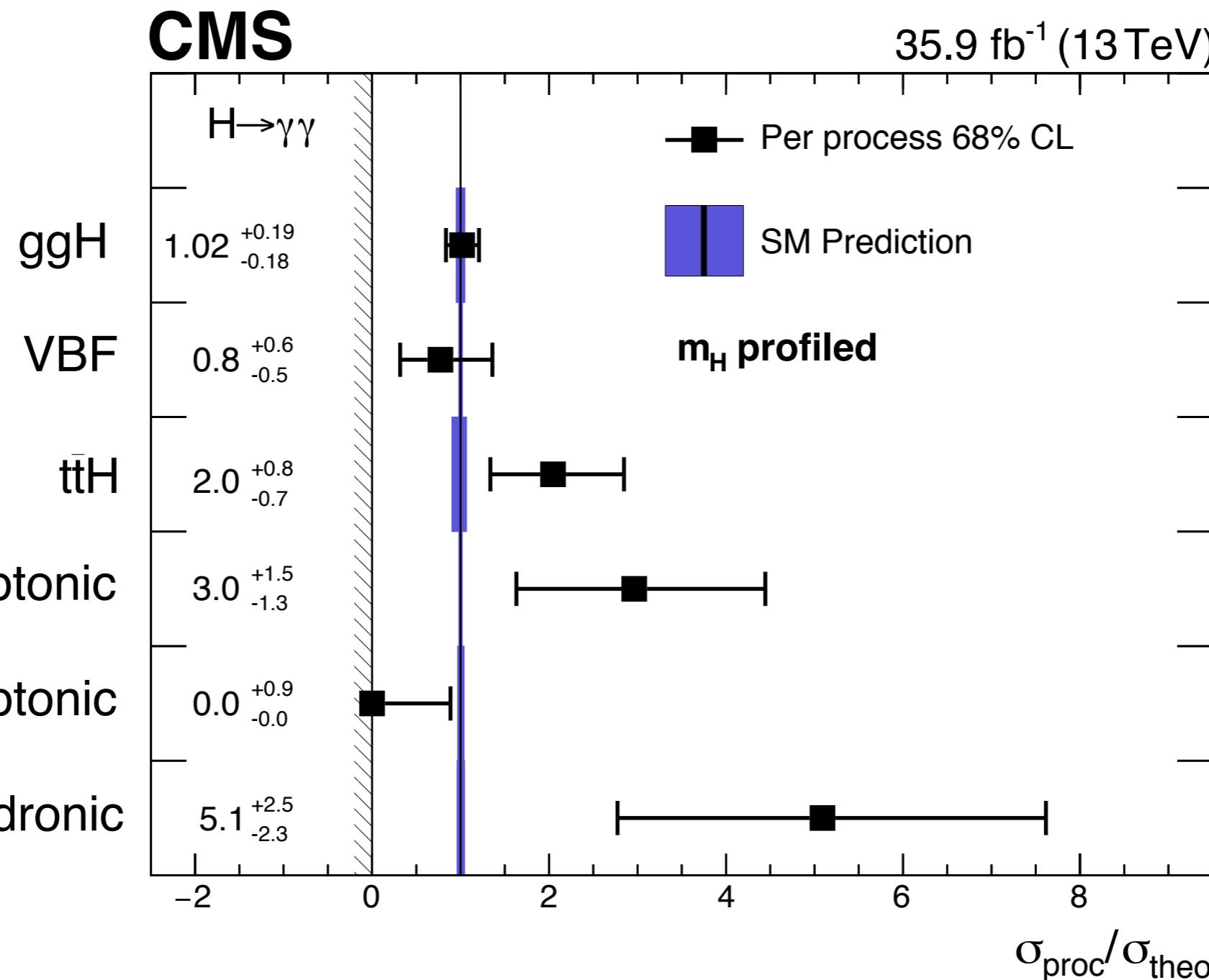


# Other approaches to Higgs physics

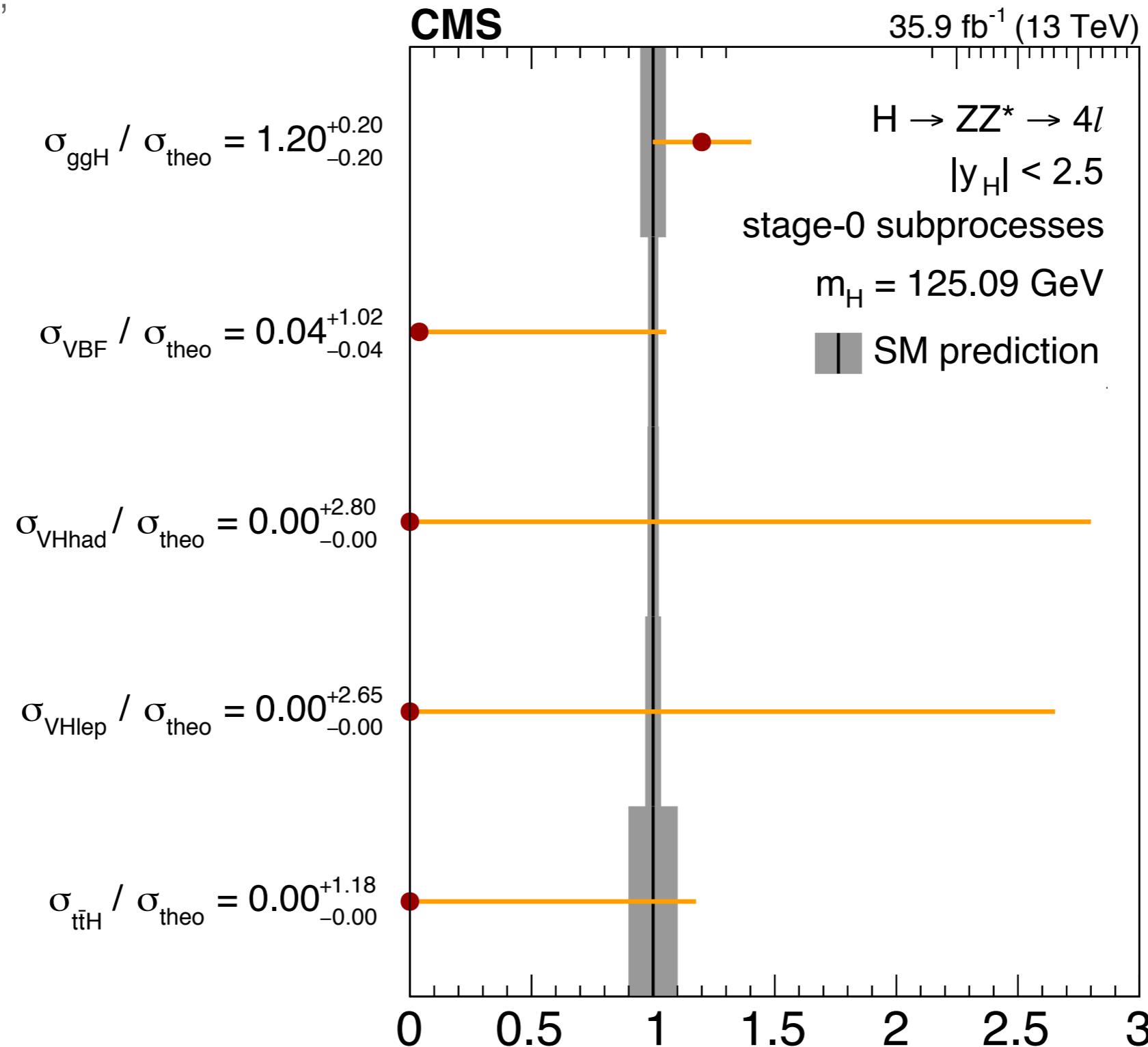
- Simplified template cross sections:
  - generalize production process to sub-process
  - measure cross sections in mutually exclusive regions of the phase space
  - several stages of partitioning, evolving with size of datasets
- Pseudo-observables:
  - On-shell amplitudes described through a momentum expansion around physical poles
- Effective Field Theories:
  - Describe deformations of SM through bases of higher dimension operators (Warsaw, BSM primary bases)



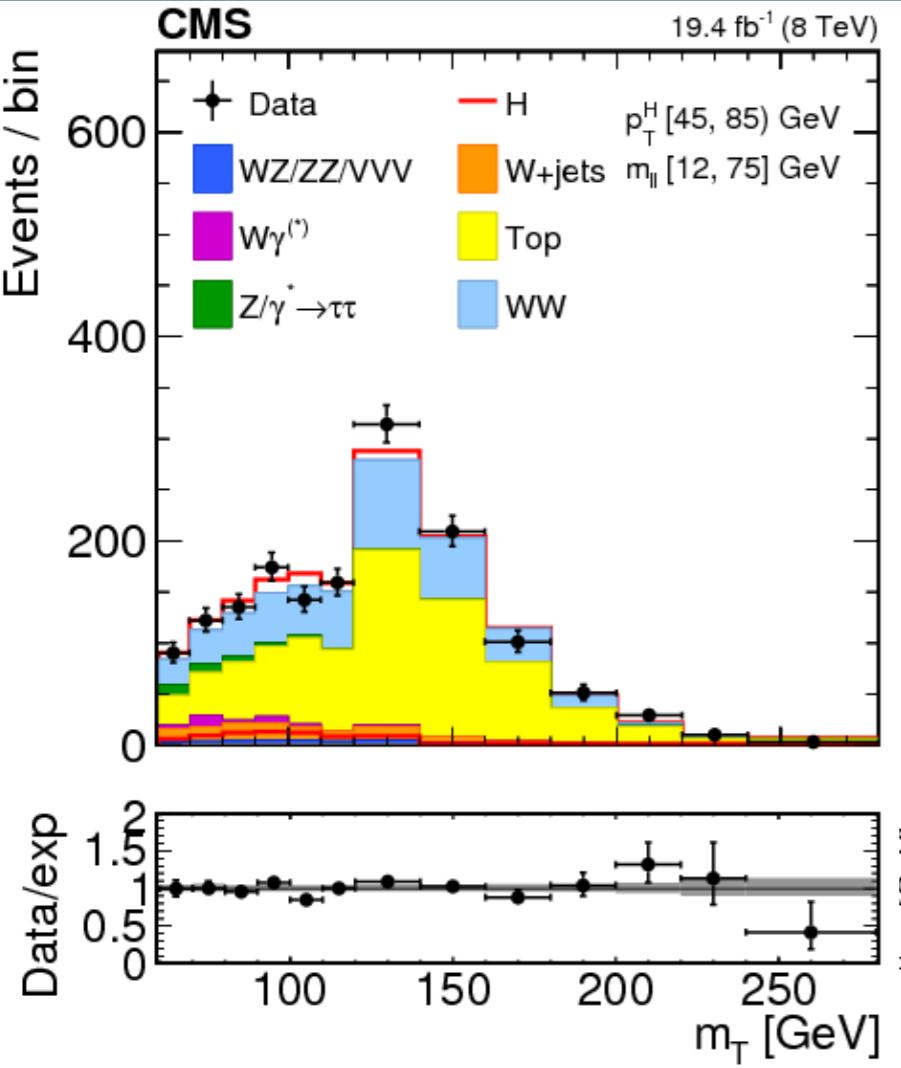
- Stage-0 cross section ratios in the Higgs Simplified Template Cross Section framework, for profiled mH . The signal strength modifiers are constrained to be non-negative.



- Stage-0 cross section ratios in the Higgs Simplified Template Cross Section framework,



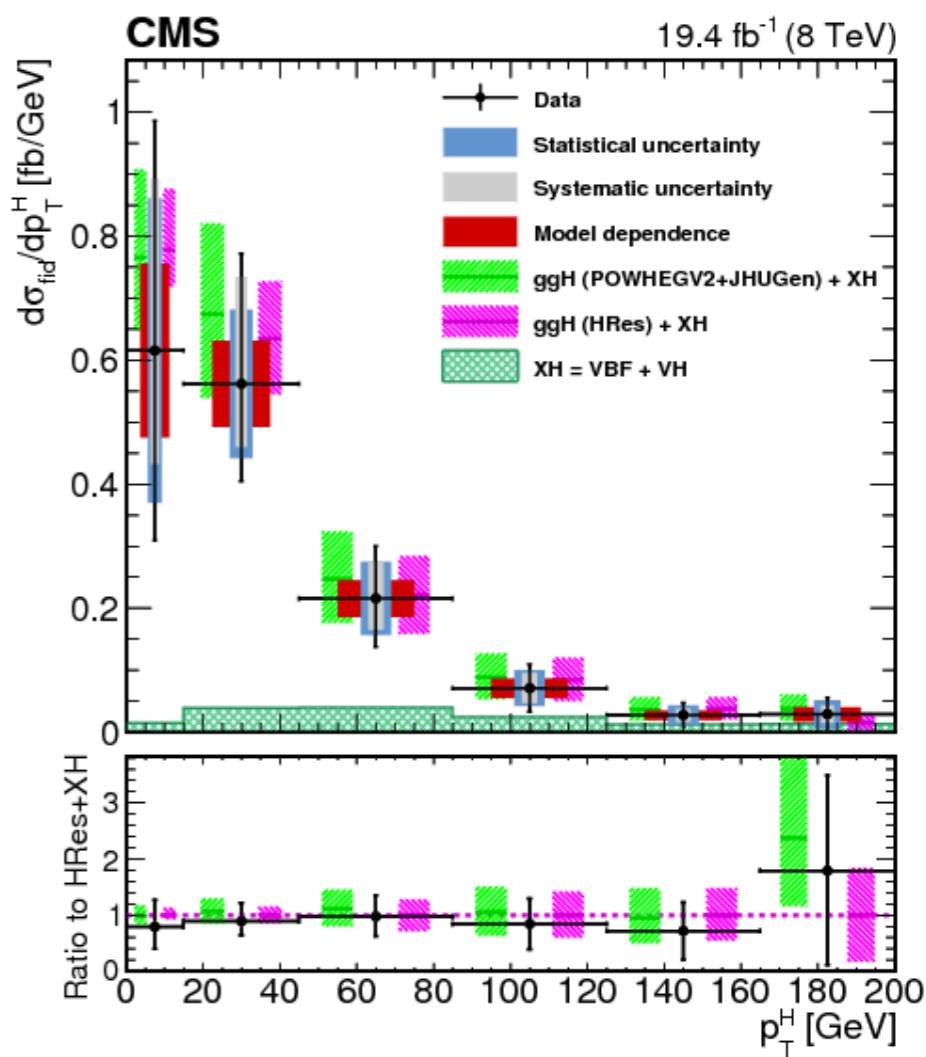
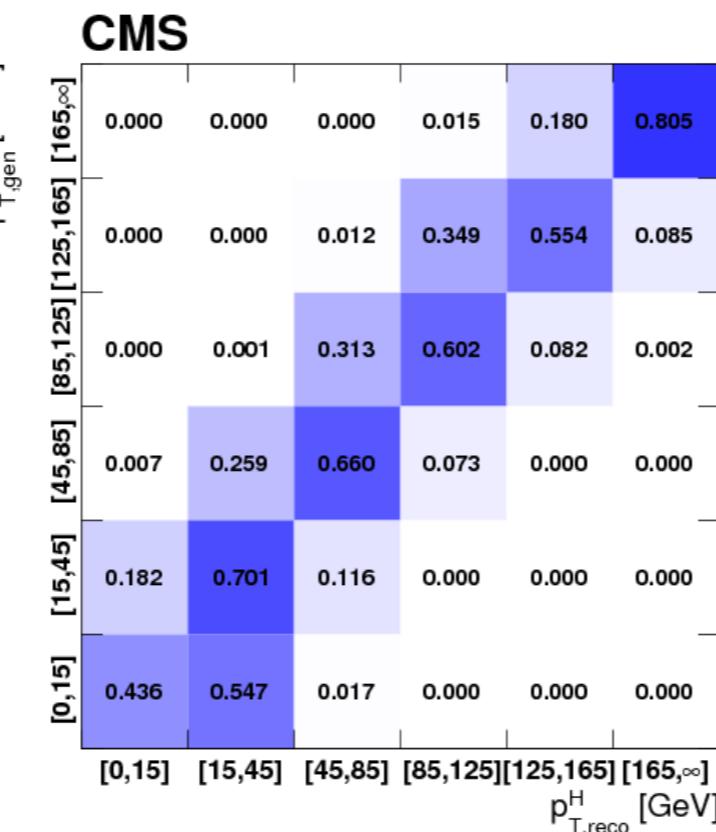
Signal process	$\mathcal{A}_{\text{fid}}$	$\epsilon$	$f_{\text{nonfid}}$	$(1 + f_{\text{nonfid}})\epsilon$
gg $\rightarrow H$ (POWHEG)	0.398	$0.592 \pm 0.001$	$0.049 \pm 0.001$	$0.621 \pm 0.001$
VBF (POWHEG)	0.445	$0.601 \pm 0.002$	$0.038 \pm 0.001$	$0.624 \pm 0.002$
WH (POWHEG MINLO)	0.314	$0.577 \pm 0.002$	$0.068 \pm 0.001$	$0.616 \pm 0.002$
ZH (POWHEG MINLO)	0.342	$0.592 \pm 0.003$	$0.071 \pm 0.002$	$0.634 \pm 0.003$
ttH (POWHEG)	0.311	$0.572 \pm 0.003$	$0.136 \pm 0.003$	$0.650 \pm 0.004$

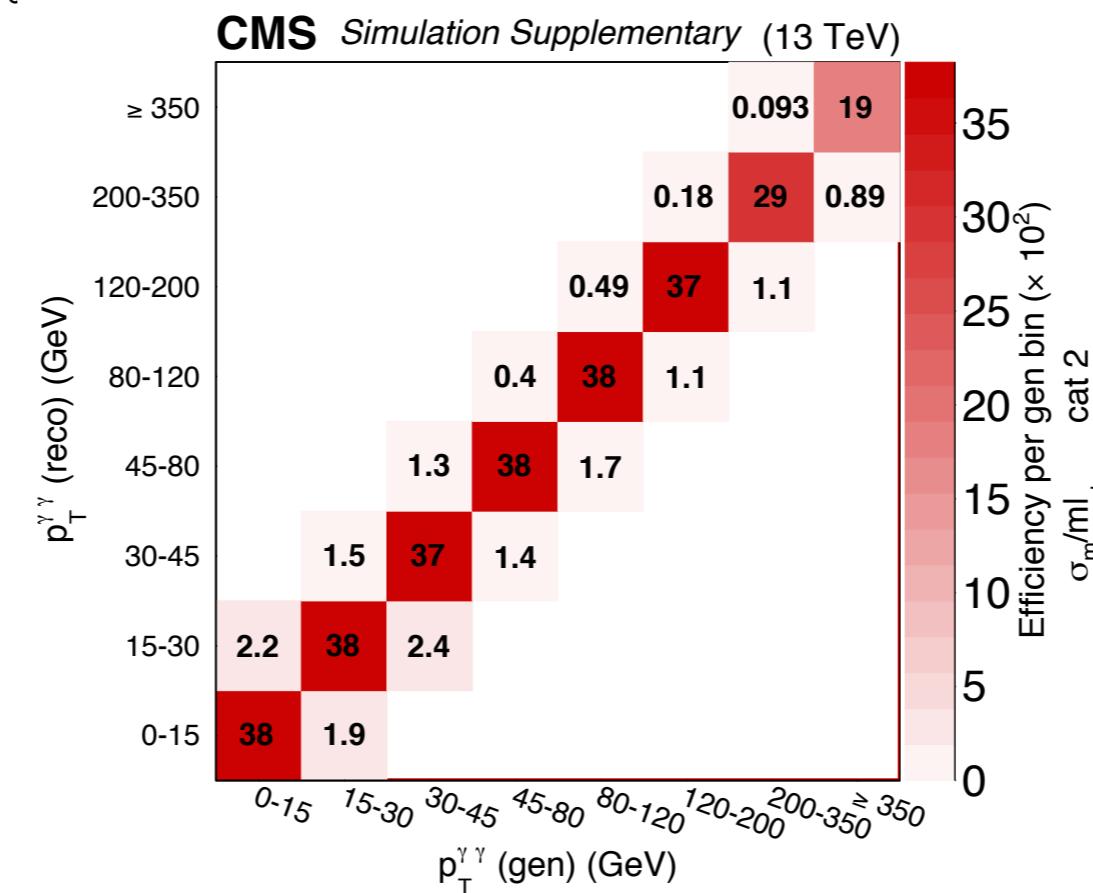
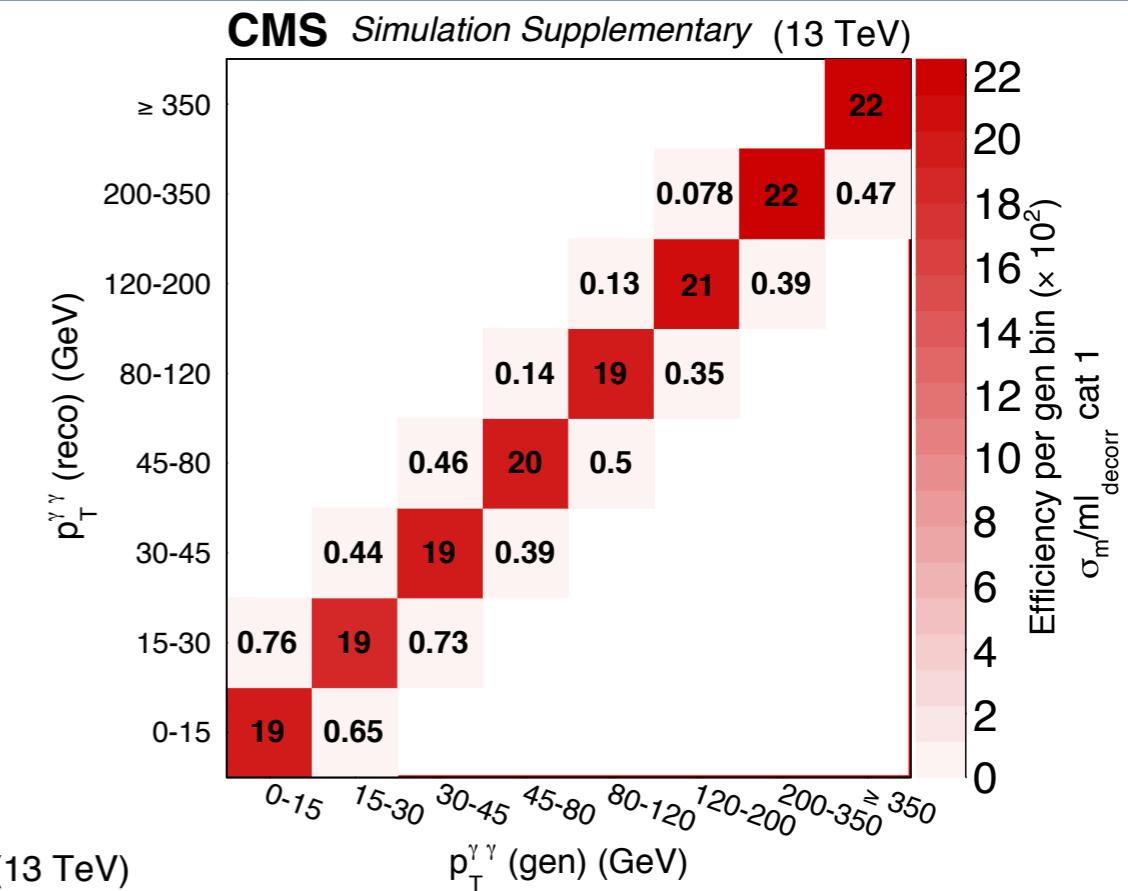
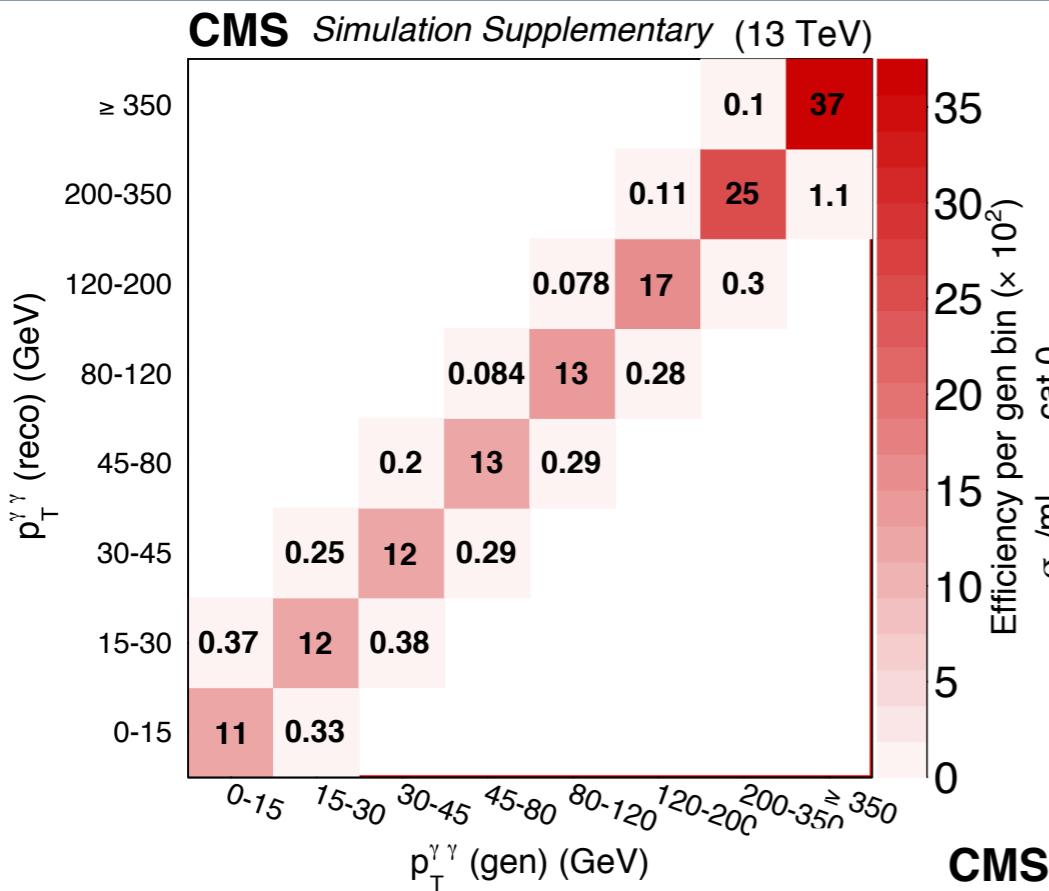


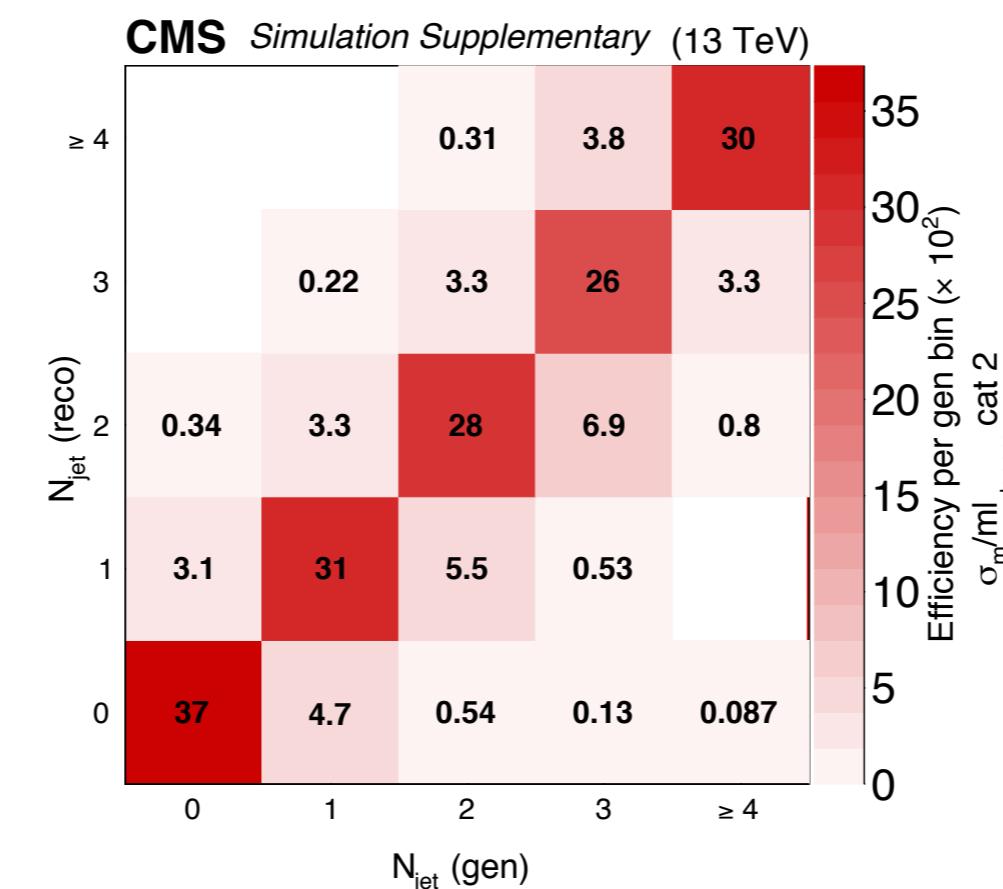
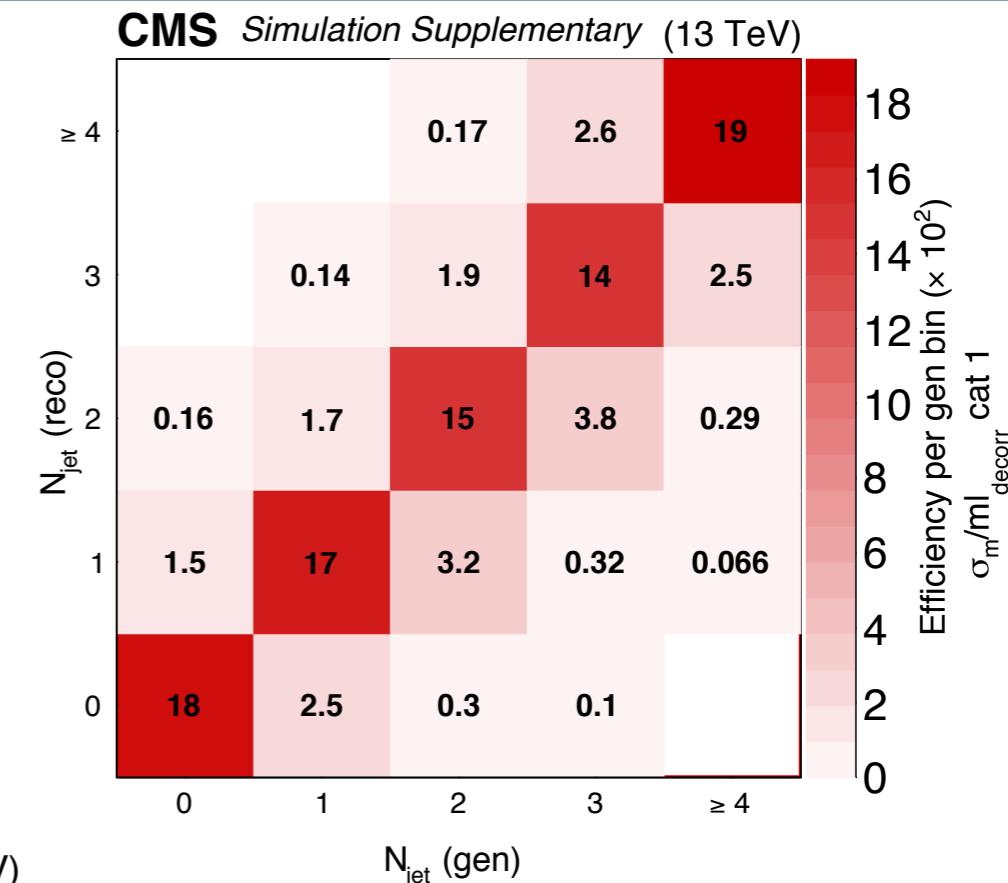
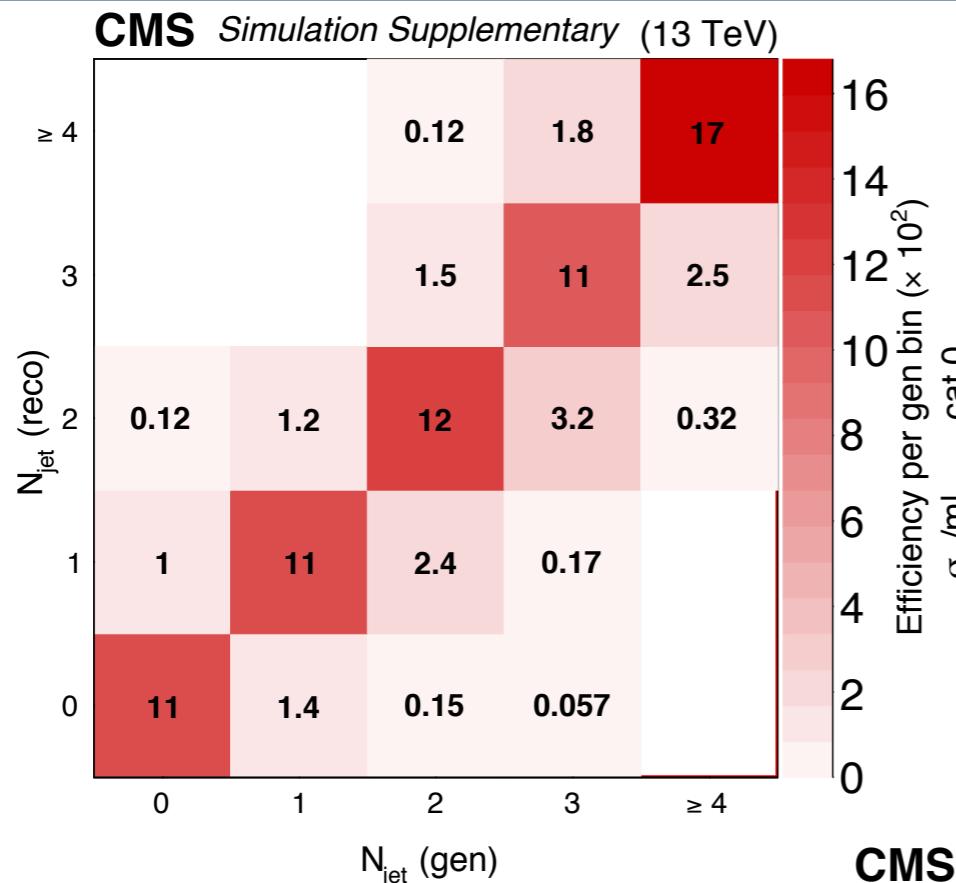
$$\hat{\sigma}_{fid} = 39 \pm 8(stat) \pm 9(syst) \text{ fb}$$

$$\sigma_{fid}^{theory} = 48 \pm 8 \text{ fb}$$

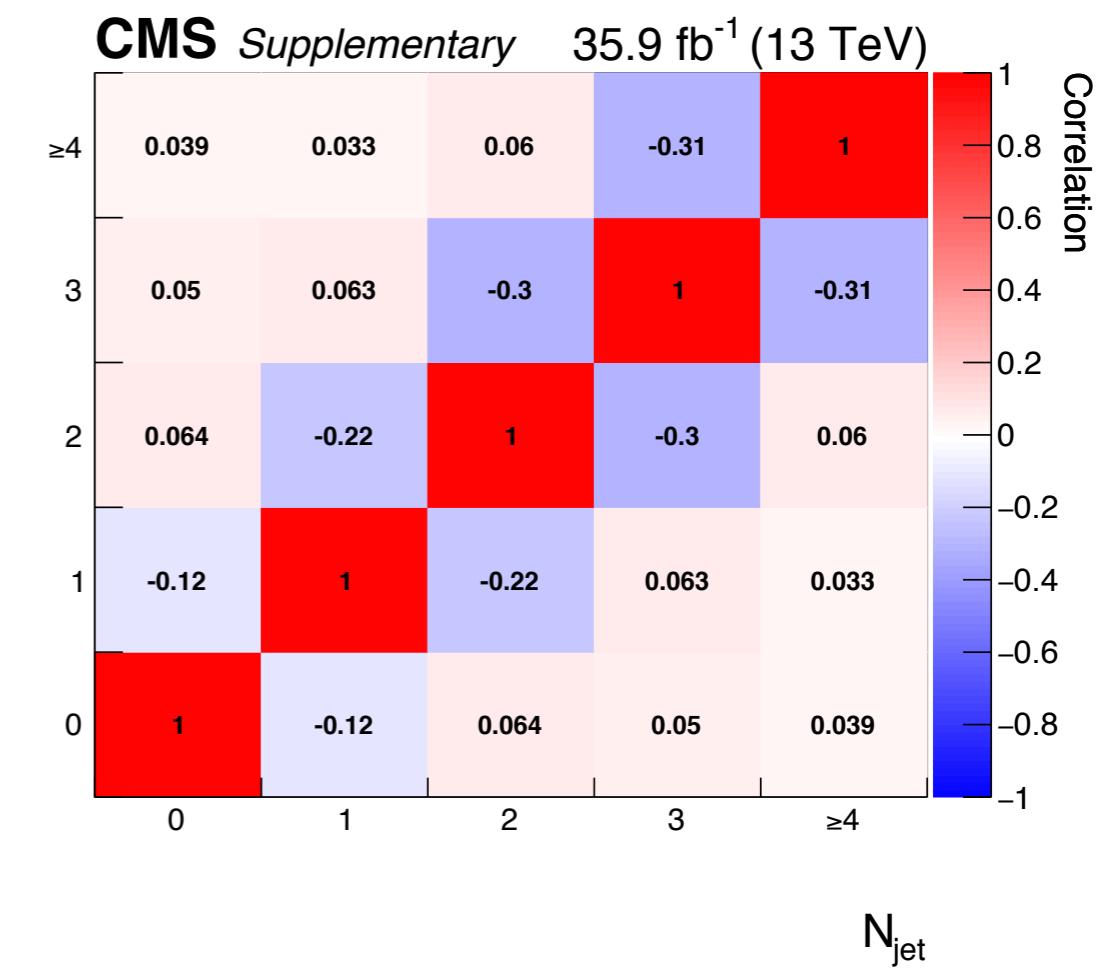
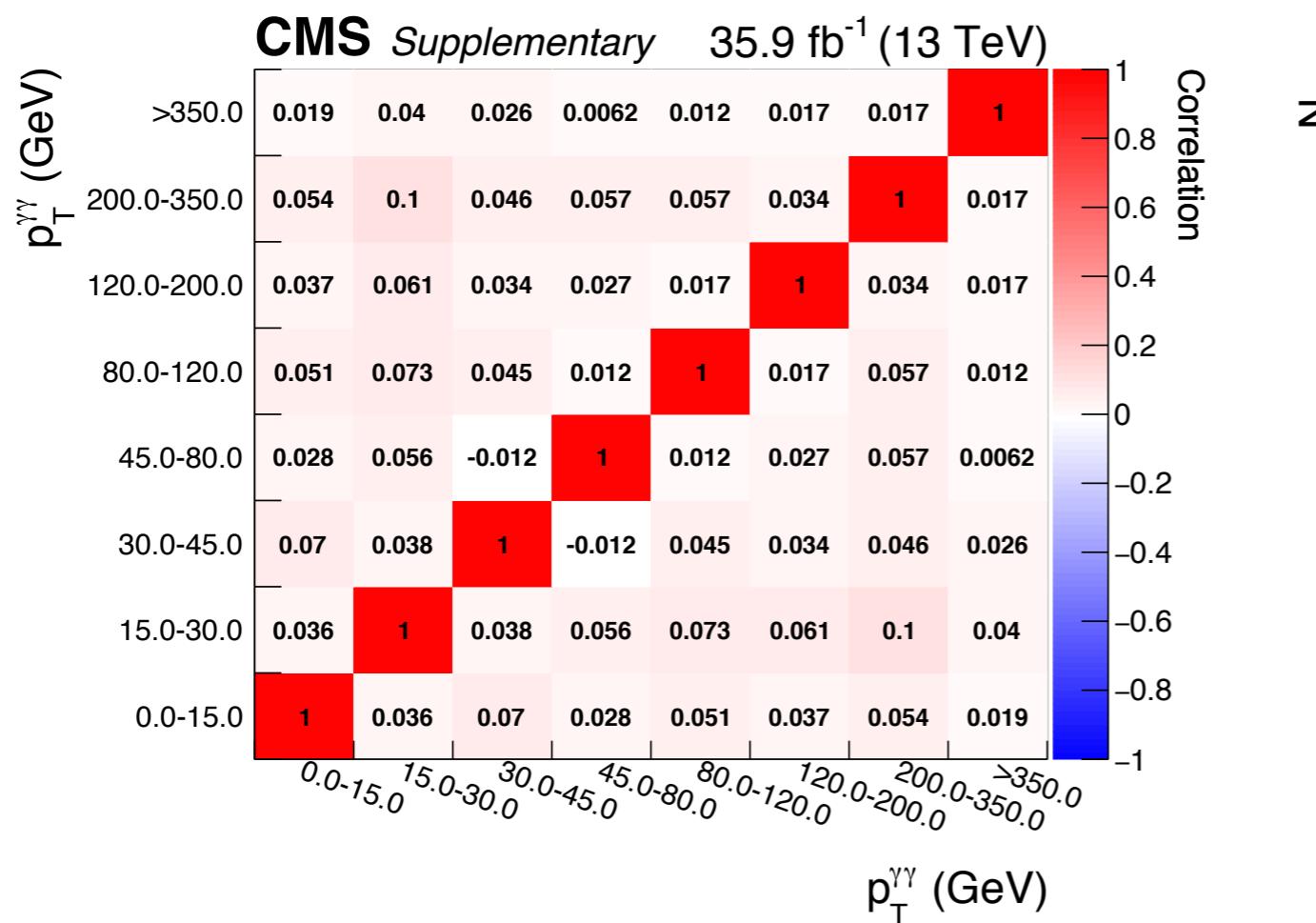
- Broad signal distribution
- Backgrounds (WW, tt) from control regions
- Large non-diagonal distribution in response matrix
- Regularised unfolding through single value decomposition







- Matrices showing the correlation between signal strengths across bins of the differential cross section measurements, for the diphoton transverse momentum (a) and the jet multiplicity (b)



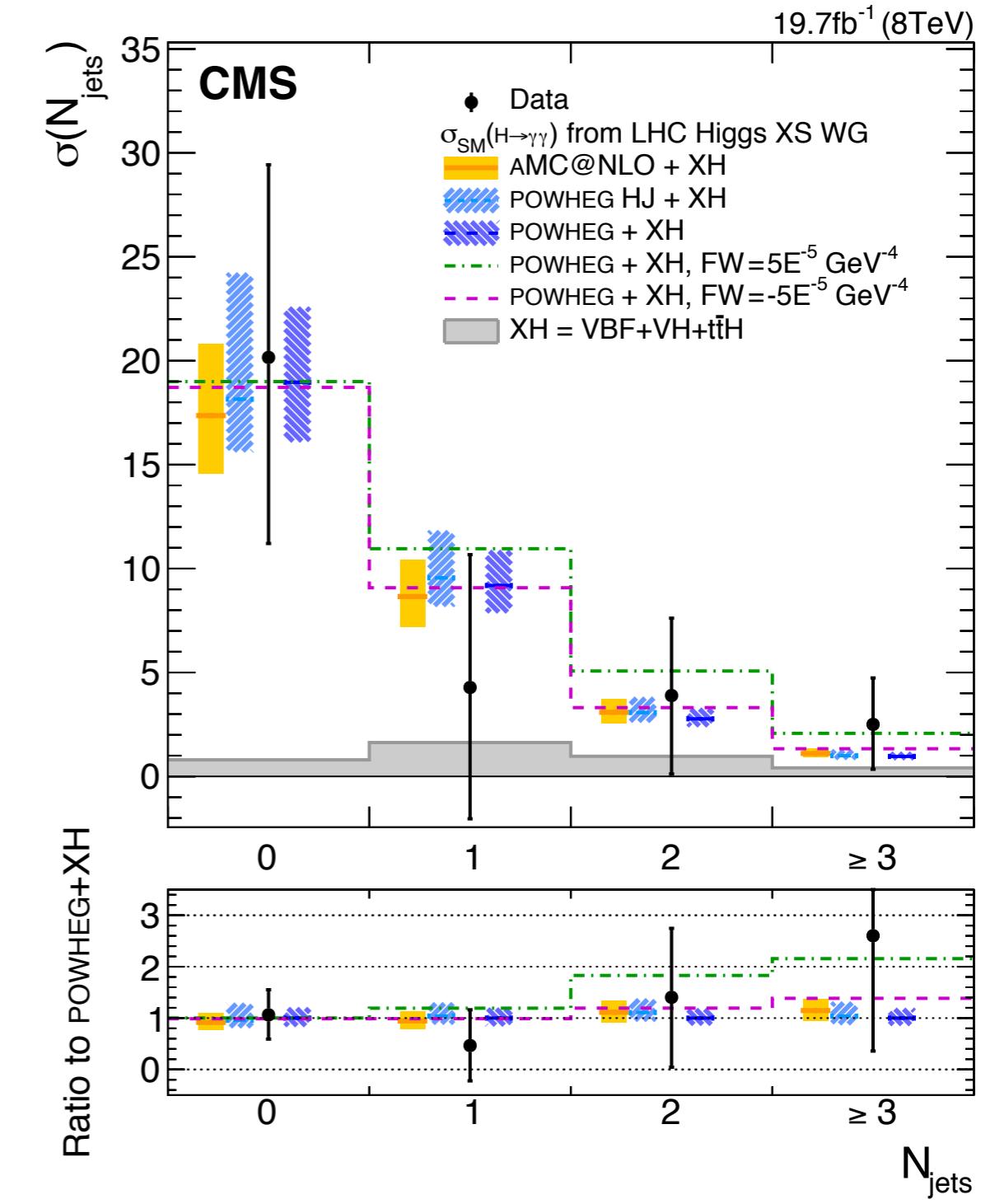
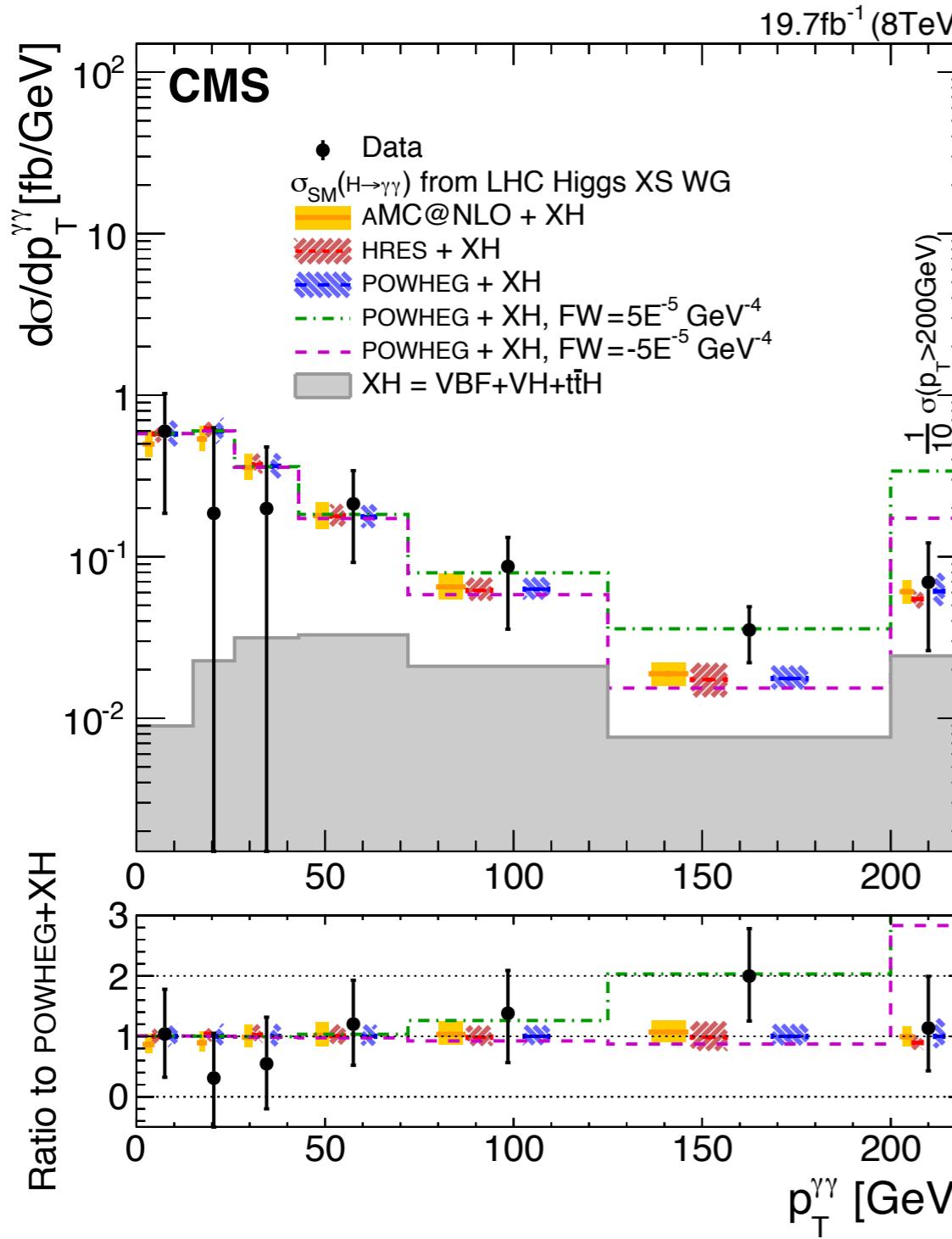
- $p_T > 30$  (20) GeV,  $p_T/m_{\gamma\gamma} > 1/3$  (1/4) for (sub)leading- $p_T$  photon
- $|\eta| < 2.5$ , removing  $1.44 < |\eta| < 1.57$ , electron veto
- either  $R_9 > 0.8$ , or charged hadron isolation  $< 20$  GeV, or charged hadron isolation relative to  $p_T < 0.3$

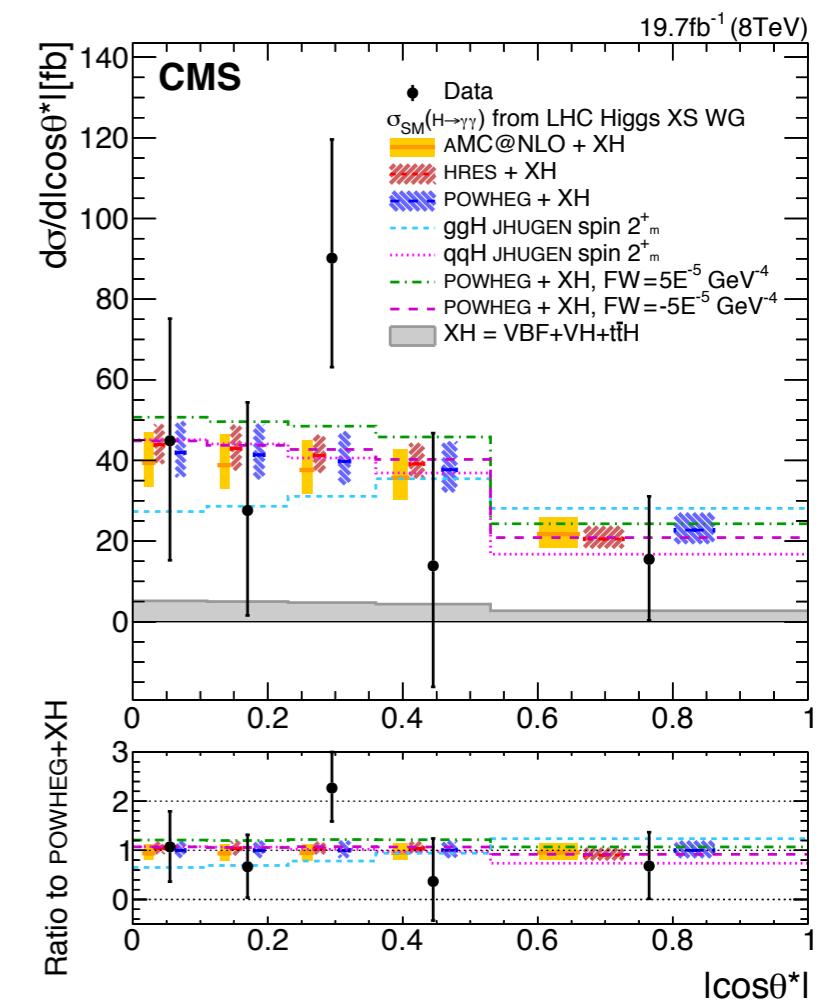
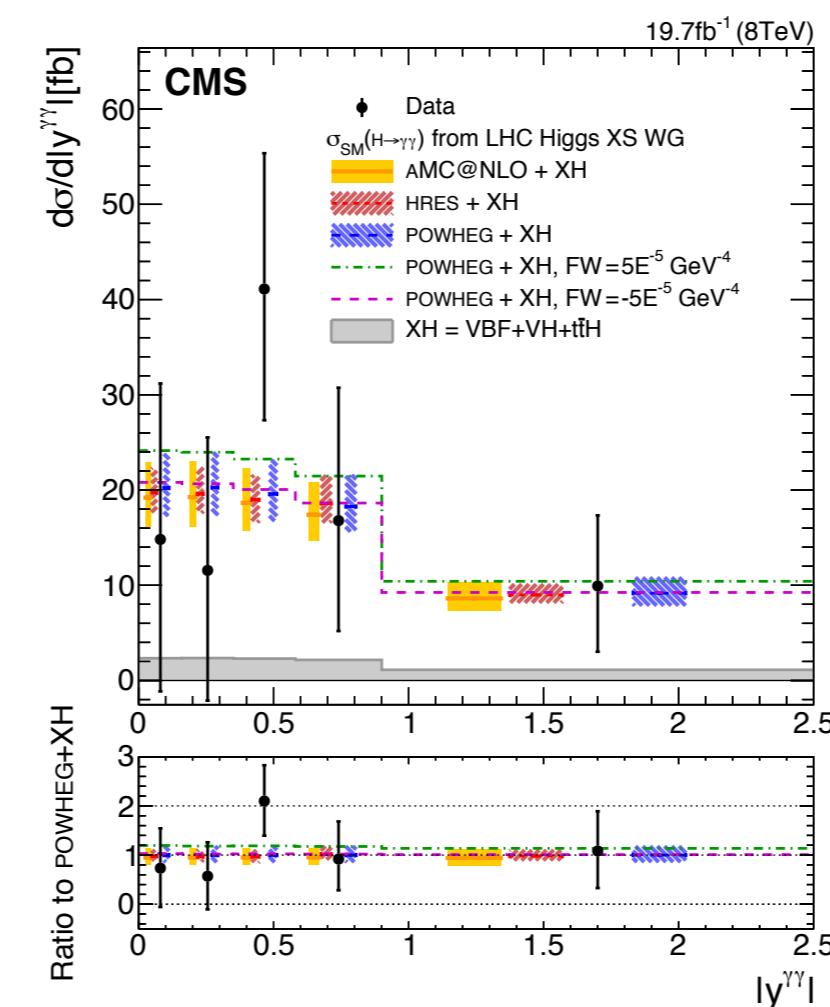
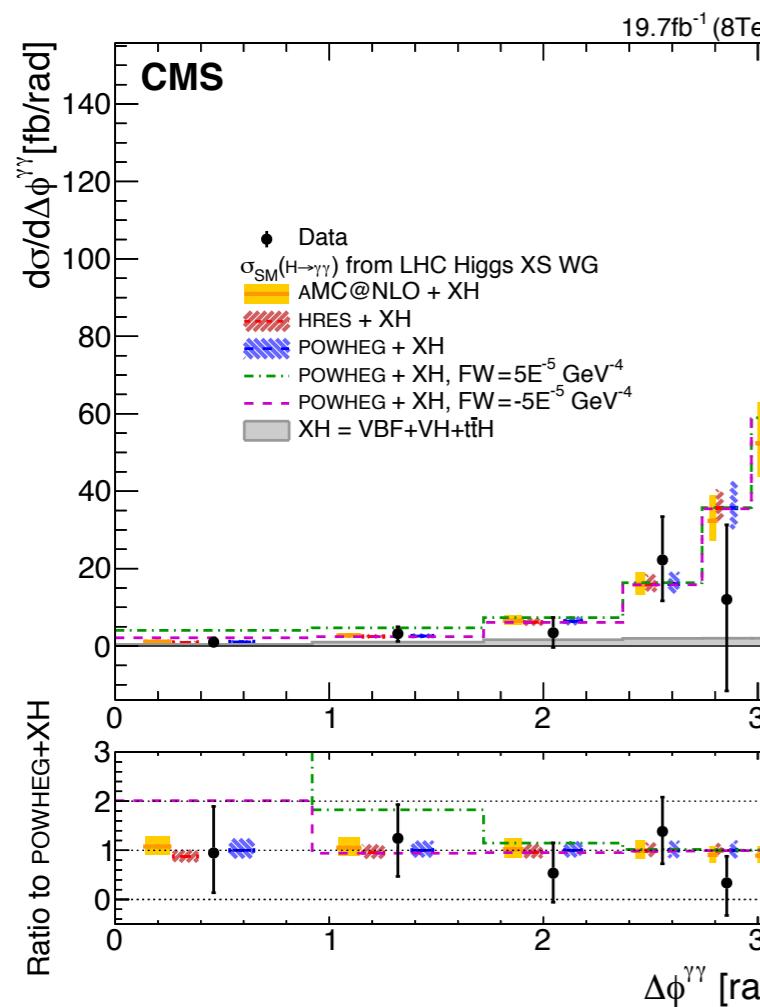
	H/E	$\sigma_{\eta\eta}$	$R_9$	photon iso.	tracker iso.
ECAL barrel; $R_9 > 0.85$	<0.08	–	>0.5	–	–
ECAL barrel; $R_9 \leq 0.85$	<0.08	<0.015	>0.5	< 4.0	< 6.0
ECAL endcaps; $R_9 > 0.90$	<0.08	–	>0.8	–	–
ECAL endcaps; $R_9 \leq 0.90$	<0.08	<0.035	>0.8	< 4.0	< 6.0

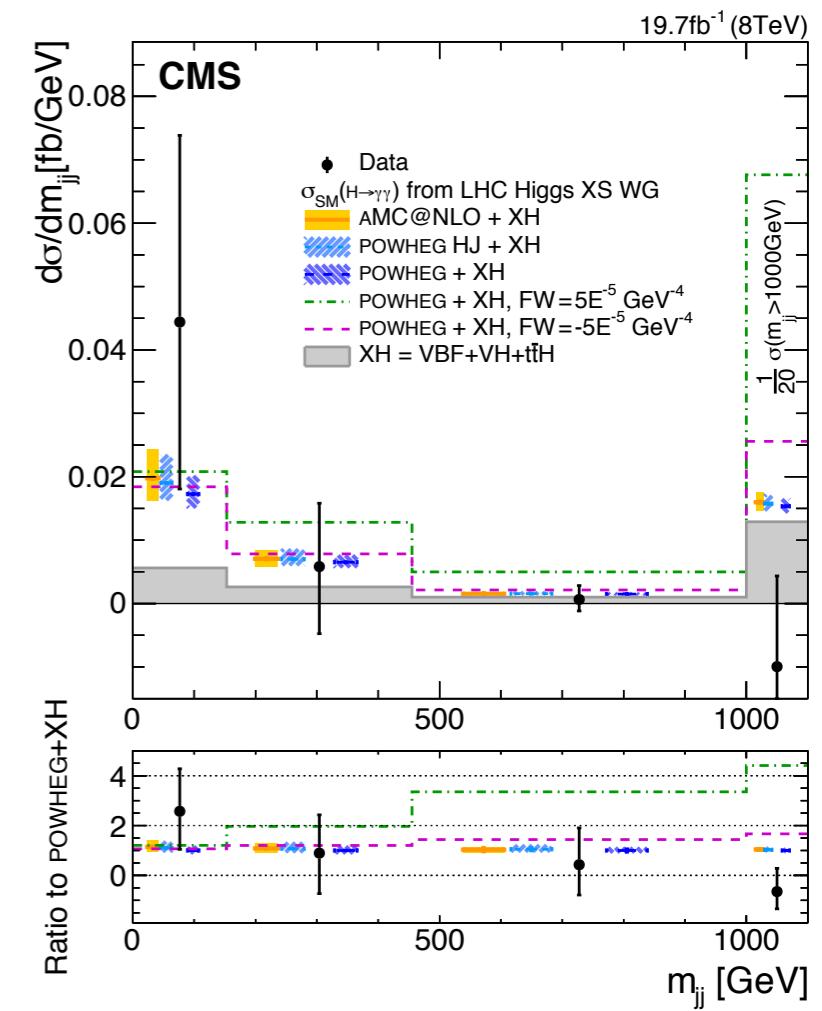
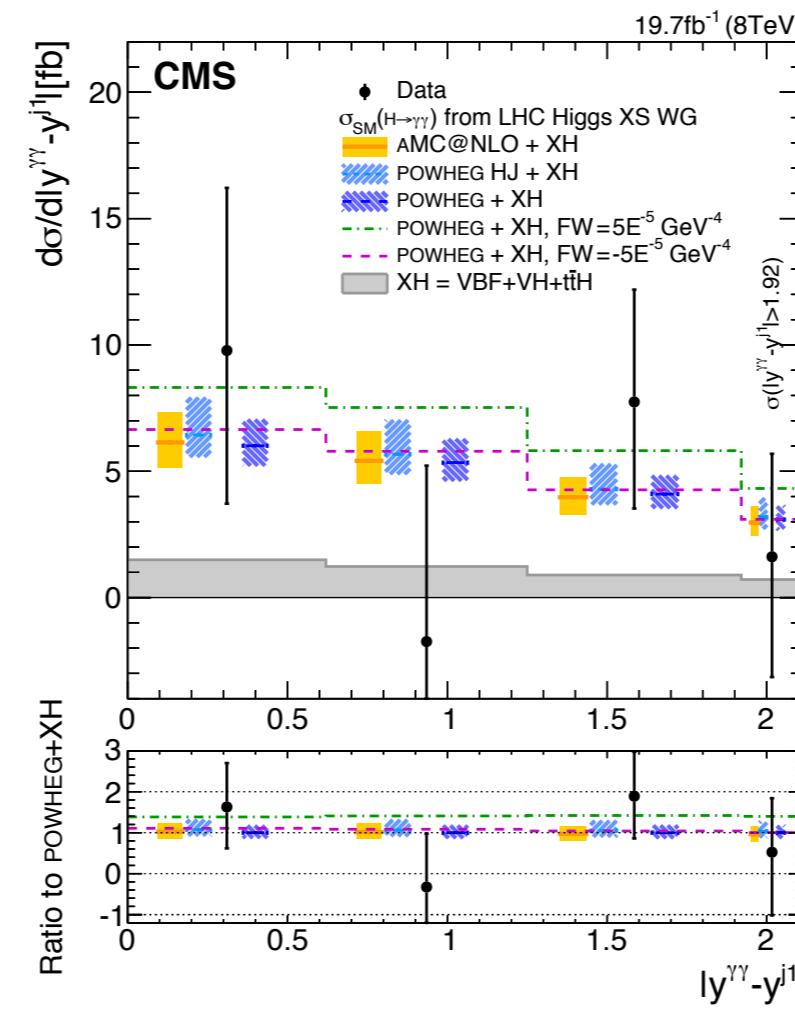
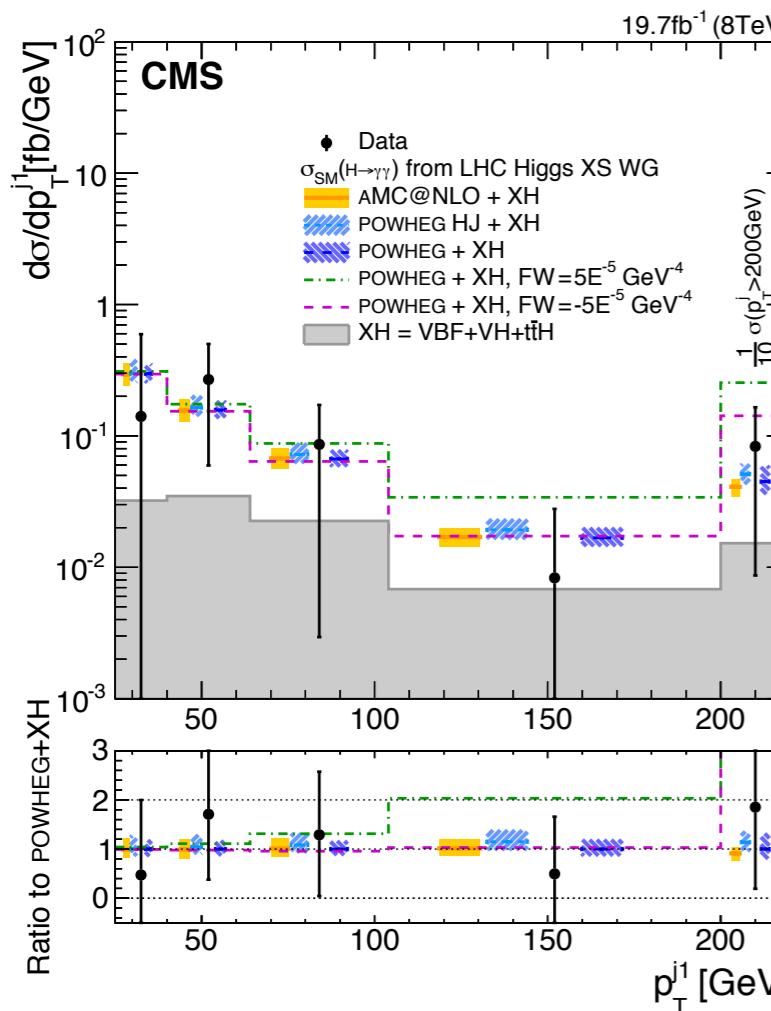
# $H \rightarrow \gamma\gamma$ results, 8 TeV data

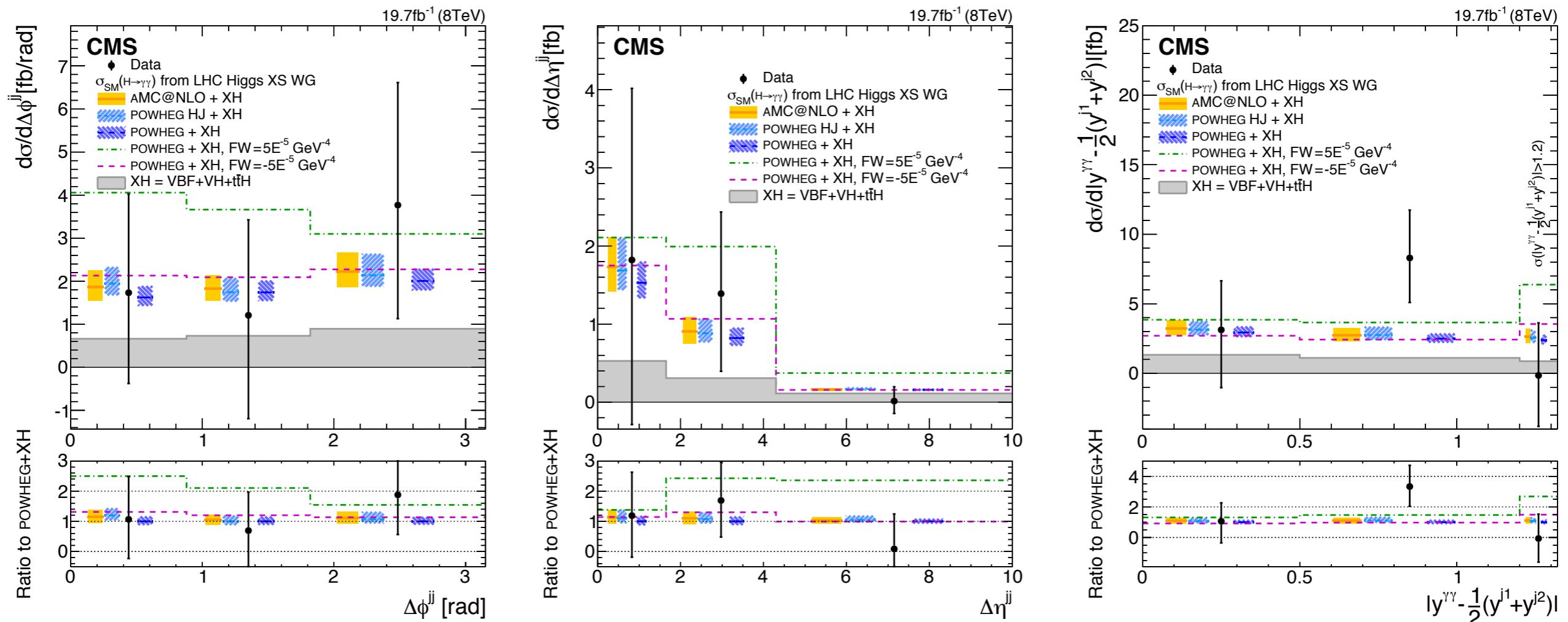
$$\hat{\sigma}_{fid} = 32 \pm 10(stat) \pm 3(syst) \text{ fb}$$

$$\sigma_{fid}^{theory} = 30^{+6}_{-5} \text{ fb}$$

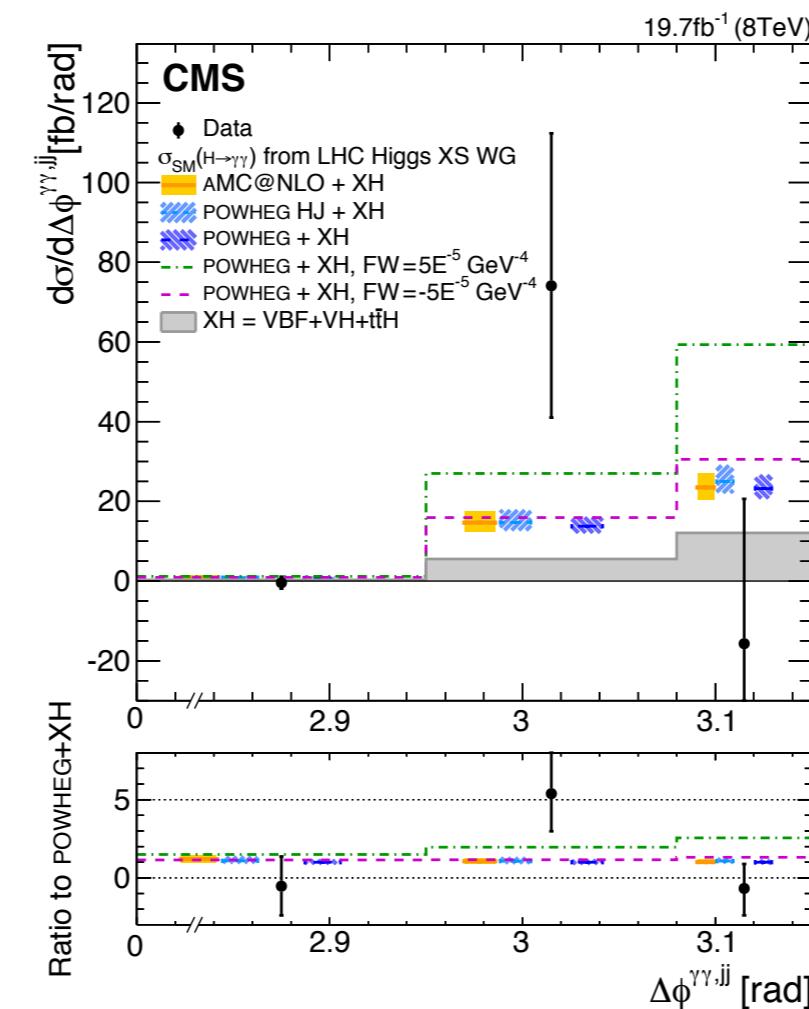








# $H \rightarrow \gamma\gamma$ results, 8 TeV data



$$\hat{\sigma}_{fid} = 1.11^{+0.41}_{-0.35}(stat)^{+0.14}_{-0.10}(syst)^{+0.08}_{-0.02}(syst) \text{ fb}$$

$$\sigma_{fid}^{theory} = 1.15^{+0.12}_{-0.13} \text{ fb}$$

