CMS Diboson Results

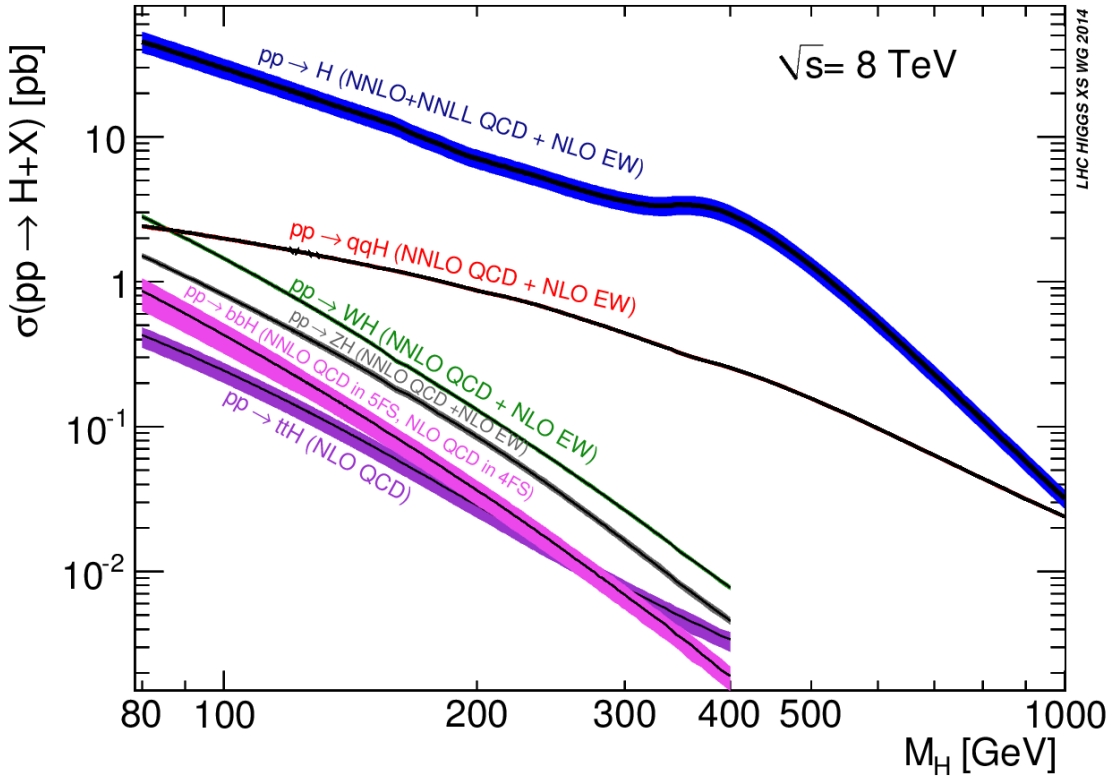
Higgs Hunting 2015
30 July 2015

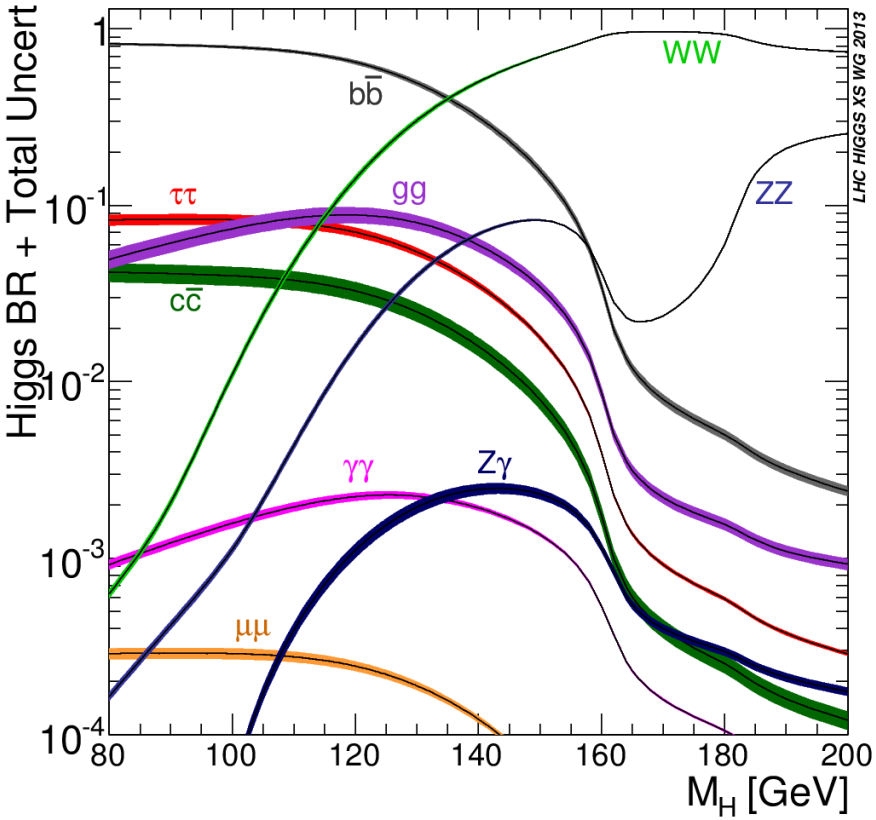
David Sperka
University of Florida

On Behalf of the CMS Collaboration

Higgs at the LHC

- The CMS experiment has entered the precision measurement era for the properties of the 125 GeV Higgs Boson
- Diboson processes continue to play a key role:
  → Large branching fraction in case of WW
  → Excellent mass resolution in case of ZZ→4ℓ, γγ

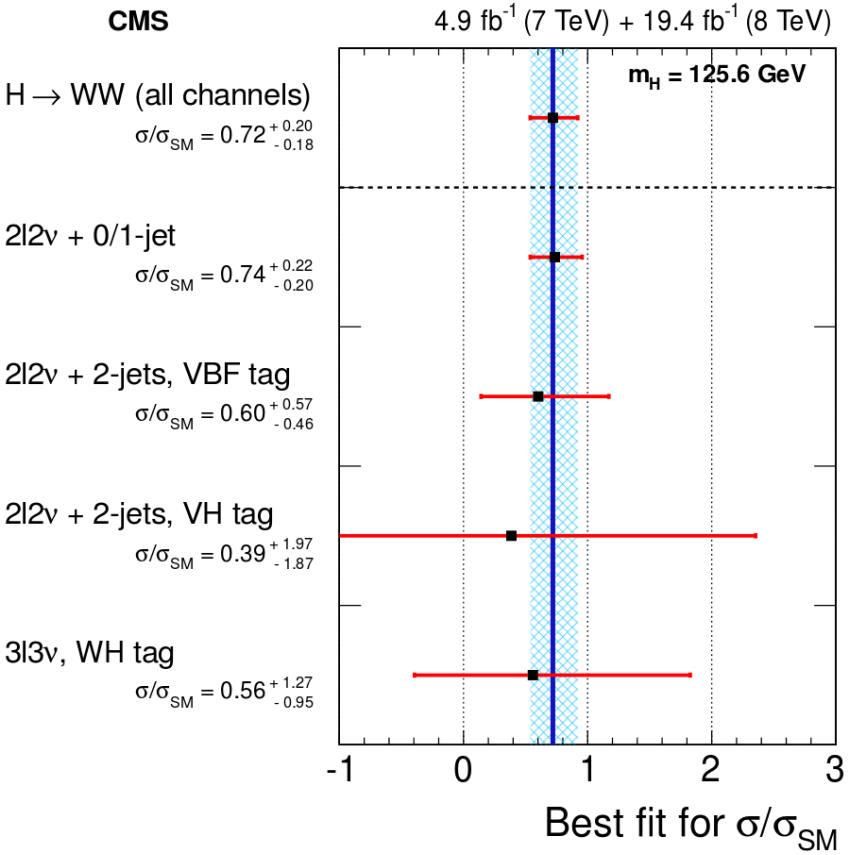


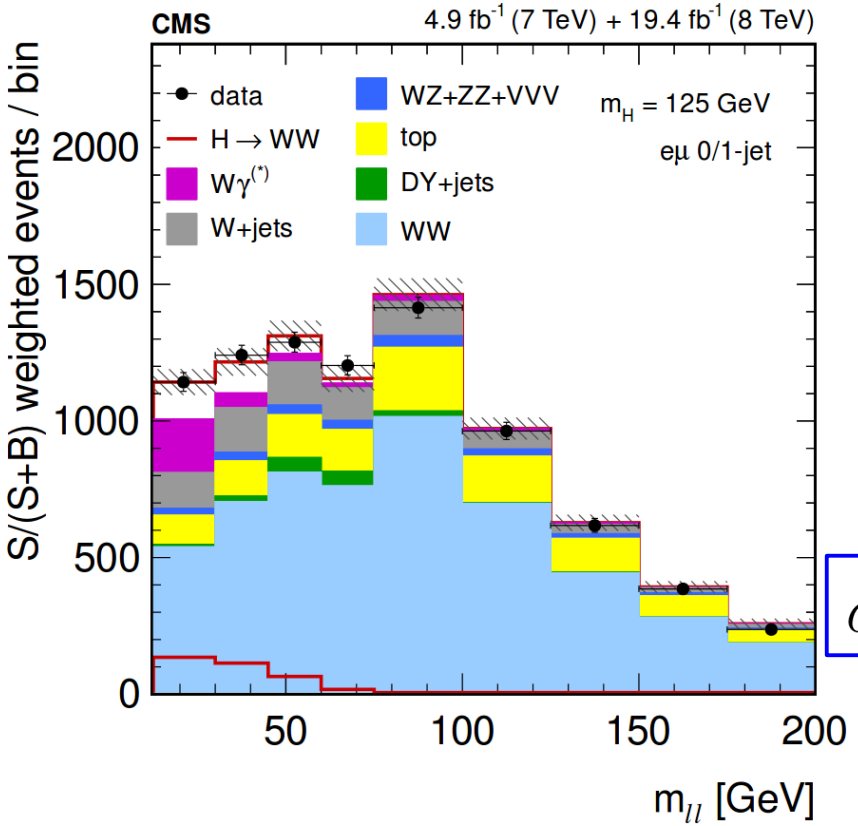


H→WW: Overview

- Large Branching Fraction
  → 0.215 @ m_H=125.0 GeV
- Not fully reconstructible due to neutrinos
  → Use observables $m_{\ell\ell}$, $\Delta\varphi_{\ell\ell}$, and m_T
- Main backgrounds: WW, W+jets and top
- 5 exclusive event categories targeting all production modes

JHEP01 (2014) 096





Broad excess observed compatible with the expected mass resolution:

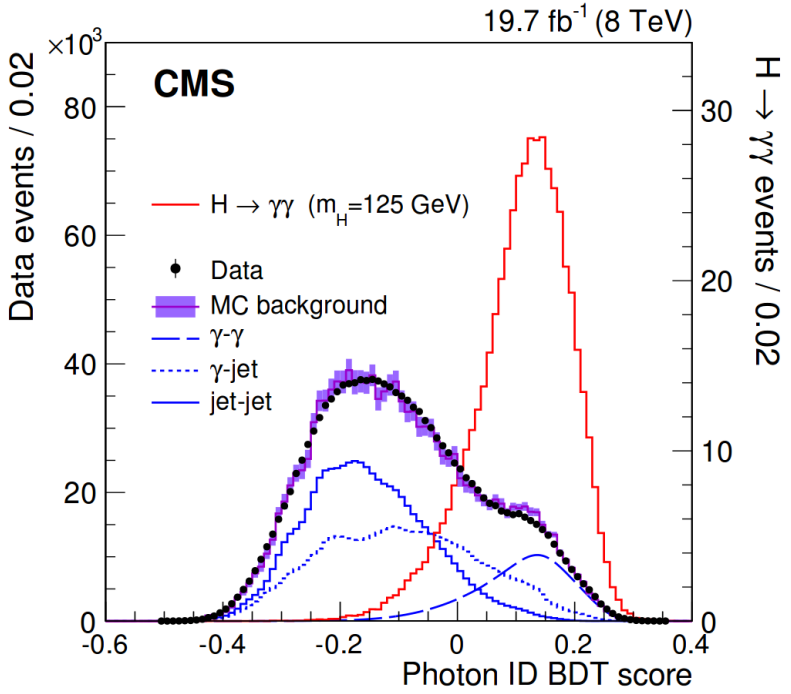
$$\sigma/\sigma_{\mathrm{SM}} = 0.72^{+0.12}_{-0.12}(\mathrm{stat.})^{+0.12}_{-0.10}(\mathrm{th.})^{+0.10}_{-0.10}(\mathrm{sys.})$$

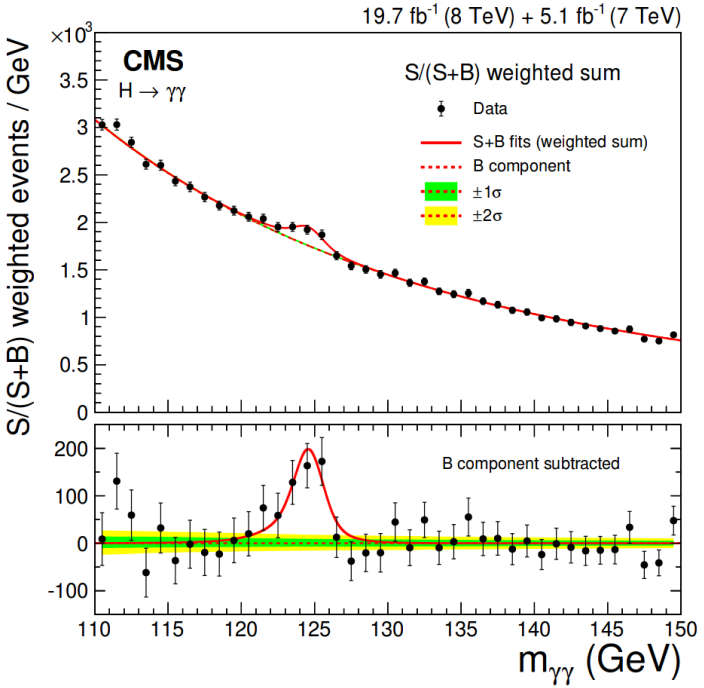
$$m_{\mathrm{H}} = 125.5^{+3.6}_{-3.8}\mathrm{GeV} \quad (\sigma = \sigma_{\mathrm{SM}})$$

H→γγ: Overview

Eur. Phys. J. C (2014) 74:3076

- Small Branching Fraction
  → 2.28 x 10^{-3} @ m_H=125.0 GeV
- Fully reconstructible decay with excellent mass resolution (1-2%)
- Large continuum background from QCD γγ and γ+jet
  → Photon ID BDT used to reject jet fakes
- Many event categories targeting all production modes





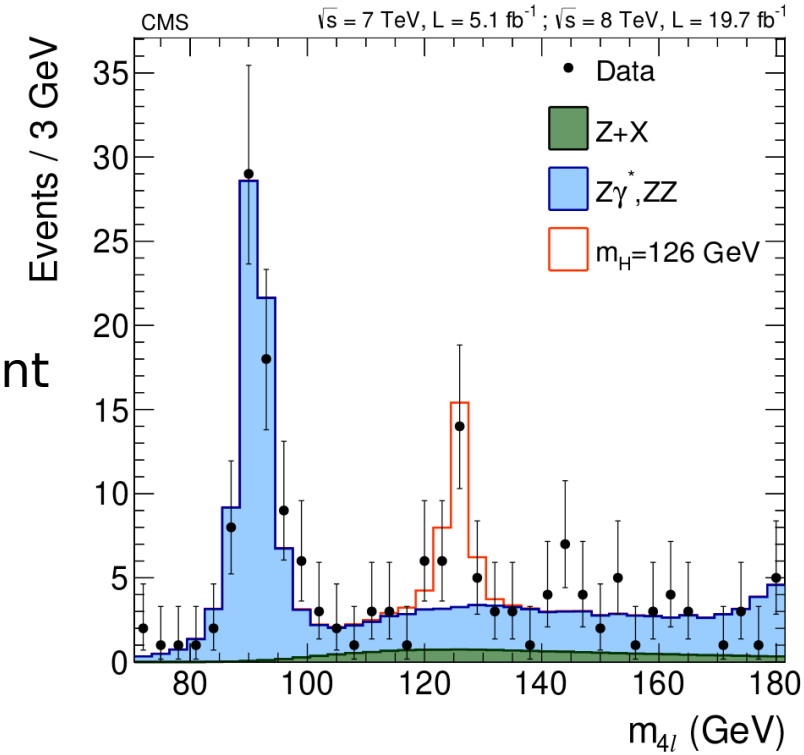
More details in talk by Benoit Courbon: "Observation and properties of a Higgs Boson in the Two-Photon Decay Channel with CMS"

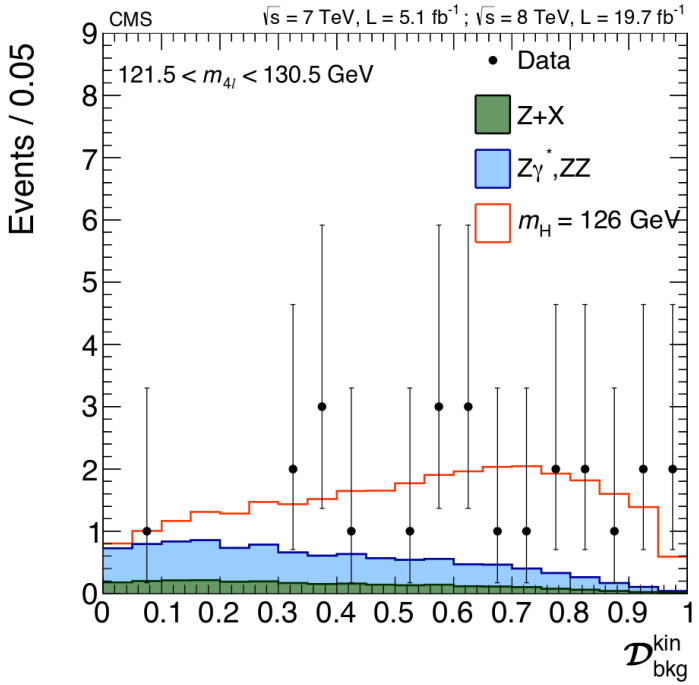
H→ZZ→4ℓ: Overview

PHYS. REV. D 89, 092007 (2014)

- Tiny Branching Fraction to 4ℓ (ℓ=e,μ)
  → 1.25 x 10^{-4} @ m_H=125.0 GeV
- Fully reconstructible decay
  → Excellent mass resolution (~1-3%)
- Very small background from irreducible ZZ and reducible Z+X
- Background further reduced using matrix element likelihood discriminant

$$\mathscr{D}^{\text{kin}}_{\text{bkg}} = \frac{\mathscr{P}^{\text{kin}}_{0^+}}{\mathscr{P}^{\text{kin}}_{0^+} + \mathscr{P}^{\text{kin}}_{\text{bkg}}} = \left[1 + \frac{\mathscr{P}^{\text{kin}}_{\text{bkg}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathscr{P}^{\text{kin}}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$





- 3D likelihood in 0/1 jet [$p_T(4\ell)$] and dijet [D_{jet}=linear discriminant using m(jj) and |Δη(jj)|] categories

$$\mathscr{L}^{\mu,0/1\text{-jet}}_{3D}\left(m_{4\ell}, \mathscr{D}^{\text{kin}}_{\text{bkg}}, p_{\text{T}}^{4\ell}\right)$$

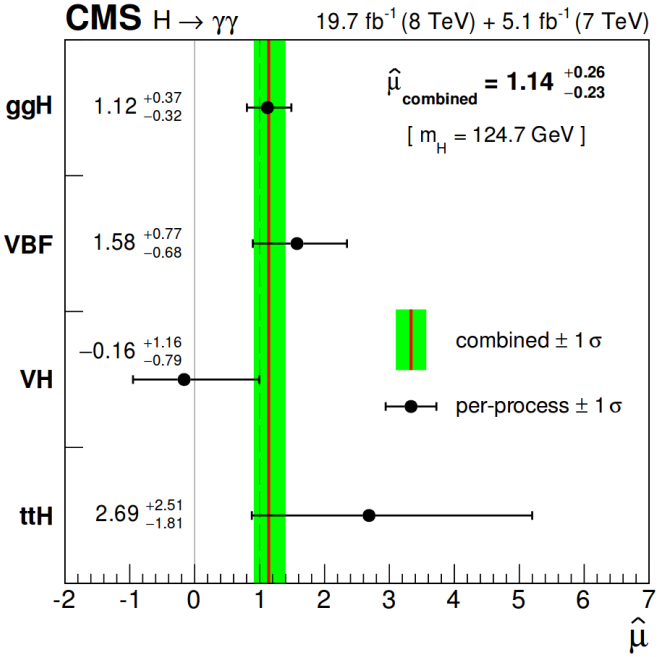
$$\mathscr{L}^{\mu,\text{dijet}}_{3D}\left(m_{4\ell}, \mathscr{D}^{\text{kin}}_{\text{bkg}}, \mathscr{D}_{\text{jet}}\right)$$

H→γγ and H→ZZ: Signal Strength

Compatible with SM Higgs (~23-30% uncertainty on total signal strength)

H→γγ:

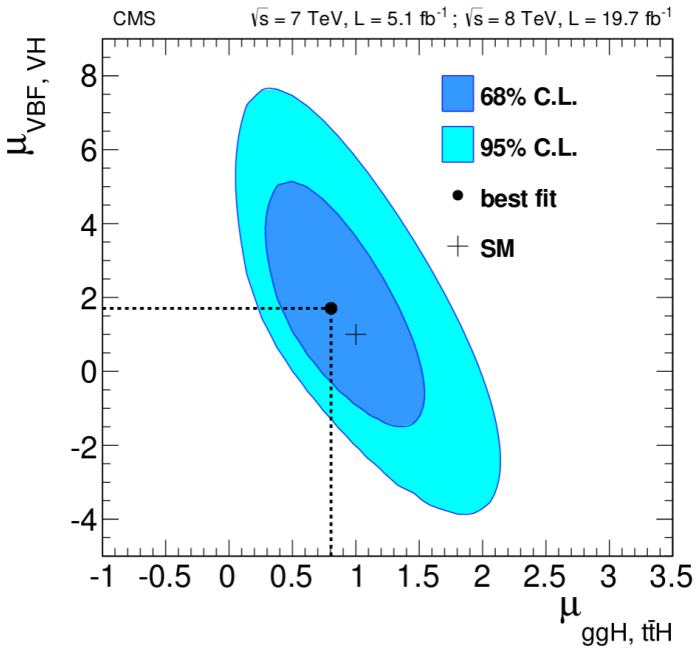
$$\sigma/\sigma_{\mathrm{SM}} = 1.14^{+0.21}_{-0.21}(\mathrm{stat.})^{+0.13}_{-0.09}(\mathrm{th.})^{+0.09}_{-0.05}(\mathrm{sys.})$$



$$\mu_{\mathrm{ggH,ttH}} = 1.13^{+0.37}_{-0.31}$$
$$\mu_{\mathrm{VBF,VH}} = 1.16^{+0.63}_{-0.58}$$

H→ZZ:

$$\sigma/\sigma_{\mathrm{SM}} = 0.93^{+0.26}_{-0.23}(\mathrm{stat.})^{+0.13}_{-0.09}(\mathrm{sys.})$$



$$\mu_{\mathrm{ggH,ttH}} = 0.80^{+0.46}_{-0.36}$$
$$\mu_{\mathrm{VBF,VH}} = 1.7^{+2.2}_{-2.1}$$

See talk by Ben Kreis for CMS Combination for couplings, spin/parity

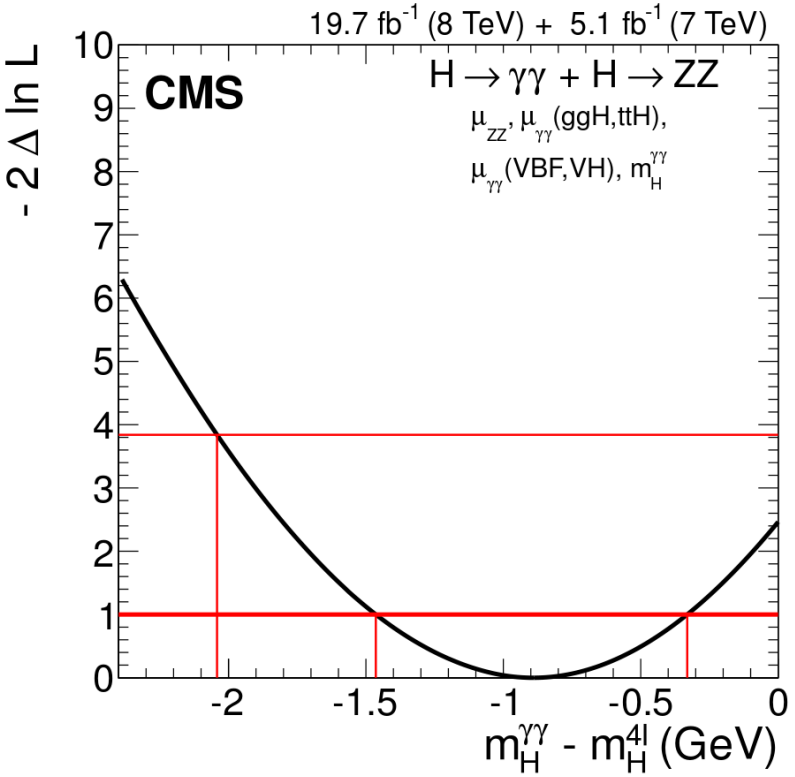
H→γγ and H→ZZ Mass Combination

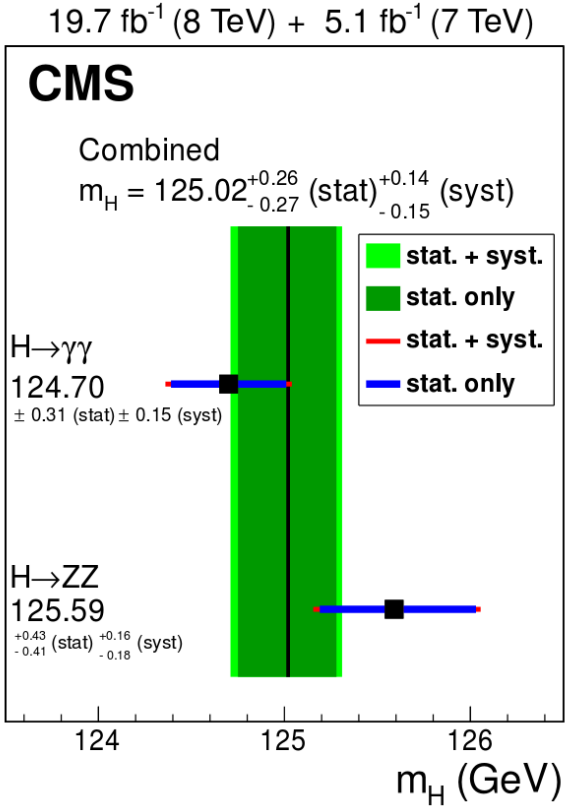
Eur. Phys. J. C (2015) 75:212

Mass Measured with ~0.25% uncertainty

$$m_{\mathrm{H}} = 125.02^{+0.26}_{-0.27}(\mathrm{stat.})^{+0.14}_{-0.15}(\mathrm{sys.})\ \mathrm{GeV}$$

$$m_{\mathrm{H}}^{\gamma\gamma} - m_{\mathrm{H}}^{4\ell} = -0.89^{+0.56}_{-0.57}\ \mathrm{GeV}$$





See talk by Tongguang Cheng for ATLAS+CMS mass combination

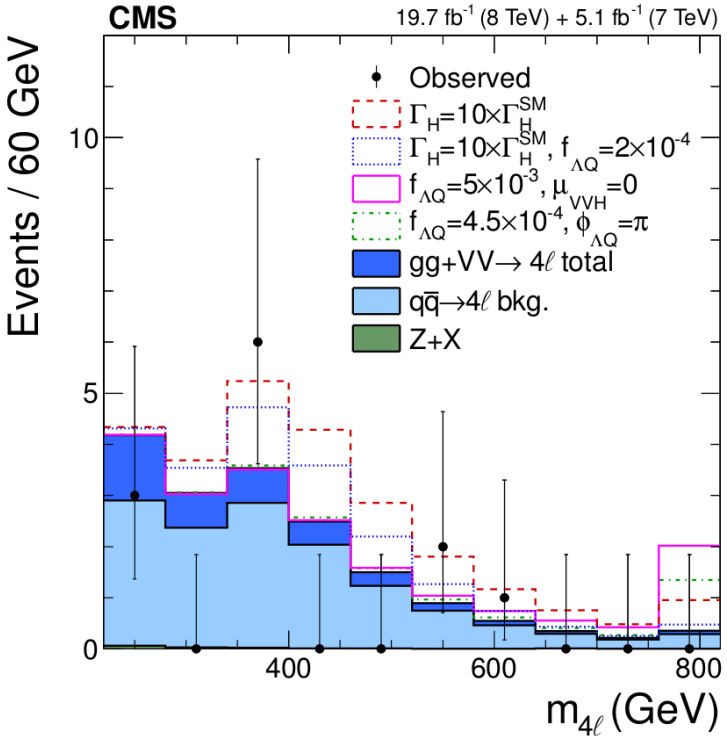
H→ZZ→4ℓ: Updated Width Analysis

- Width from off-shell production in 4ℓ channel updated with several improvements:
  - → Dijet discriminant updated to use matrix element approach
  - → Jet categories added to off-shell region (in addition to on shell region)
- Allows for presence of a mass-dependent anomalous coupling Λ_Q
  - → Previously untested, can only be probed in the off-shell region
  - → Interpretation in models with an anomalous coupling

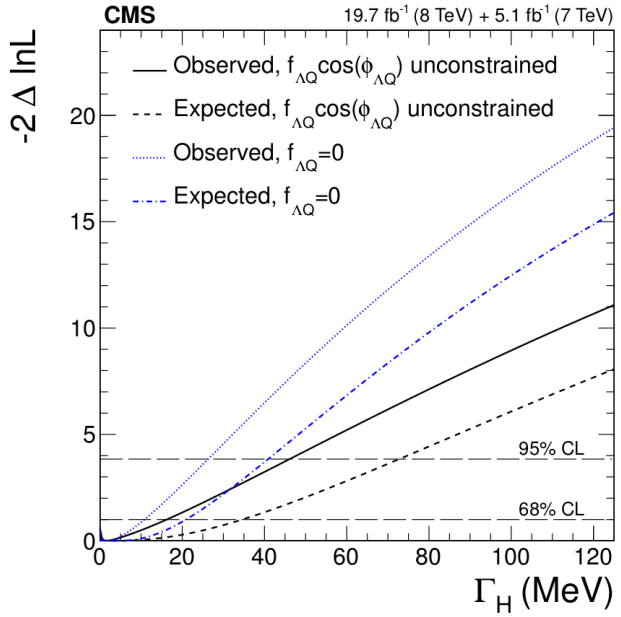
NEW!

HIG-14-036
Submitted to arxiv and Phys. Rev. D

$$A(\mathrm{HVV}) \propto \left[a_1 - \frac{e^{i\phi_{\Lambda Q}} (q_{\mathrm{V}1} + q_{\mathrm{V}2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q^2_{\mathrm{V}1} + q^2_{\mathrm{V}2})}{(\Lambda_1)^2} \right] m^2_{\mathrm{V}} \epsilon^*_{\mathrm{V}1} \epsilon^*_{\mathrm{V}2} + a_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}$$



Off-shell 0/1 jet category



$$\Gamma_H < 26\ \mathrm{MeV}\ \ 95\%\mathrm{CL}\ \ (\mathrm{f}_{\Lambda_Q} = 0)$$
$$\Gamma_H < 46\ \mathrm{MeV}\ \ 95\%\mathrm{CL}\ \ (\mathrm{f}_{\Lambda_Q}\ \mathrm{unconstrained})$$

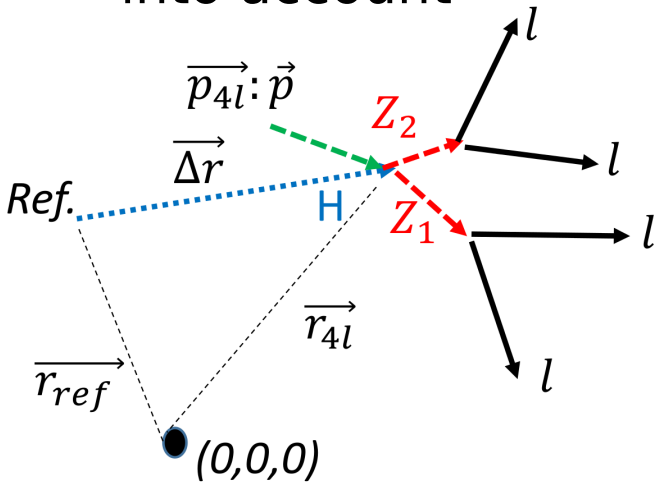
See talk by Ben Kreis for constraints on Λ_Q

H→ZZ→4ℓ: Lower Bound on Γ_H

- Obtained by setting an upper bound on the Higgs Boson lifetime
  → $c\tau_H^{\mathrm{SM}} \approx 4.8 \times 10^{-8} \mu\mathrm{m}$ (well beyond experimental sensitivity)
  → Selection updated to be unbiased w.r.t. lifetime
  → p_T-spectrum dependence of vertex resolution taken into account

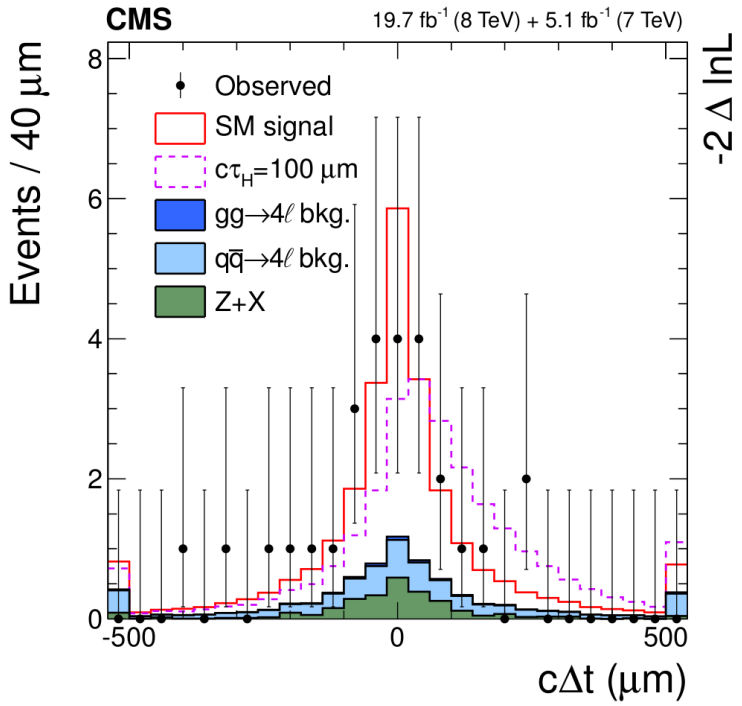
NEW!

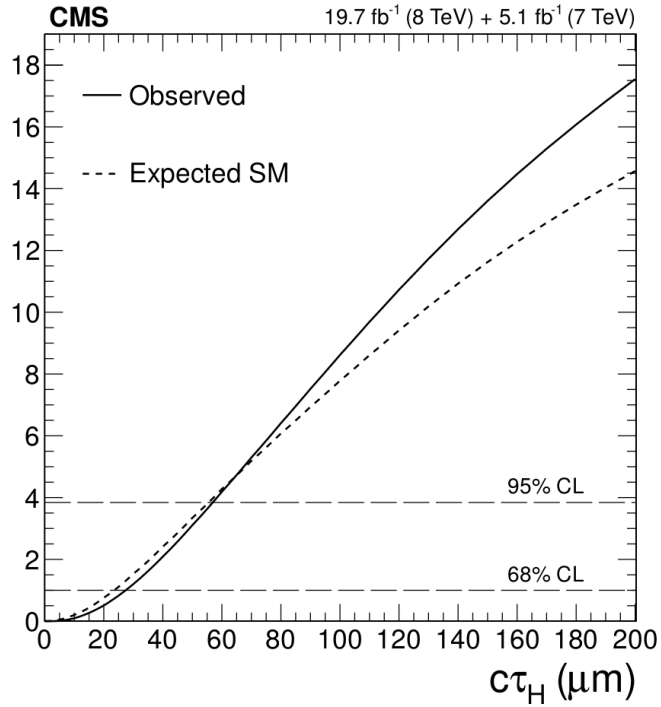
HIG-14-036
Submitted to arxiv and Phys. Rev. D



$$\Delta t = \frac{m_{4\ell}}{p_{\mathrm{T}}} \left(\Delta \vec{r}_{\mathrm{T}} \cdot \hat{p}_{\mathrm{T}}\right)$$

$$\langle \Delta t \rangle = \tau_H = \frac{\hbar}{\Gamma_H}$$





First ever constraint on the Higgs boson lifetime!

$$c\tau_{\mathrm{H}} < 57\ \mu\mathrm{m}\ , \quad \Gamma_{\mathrm{H}} > 3.5 \times 10^{-9}\ \mathrm{MeV}\ \ 95\%\mathrm{CL}$$

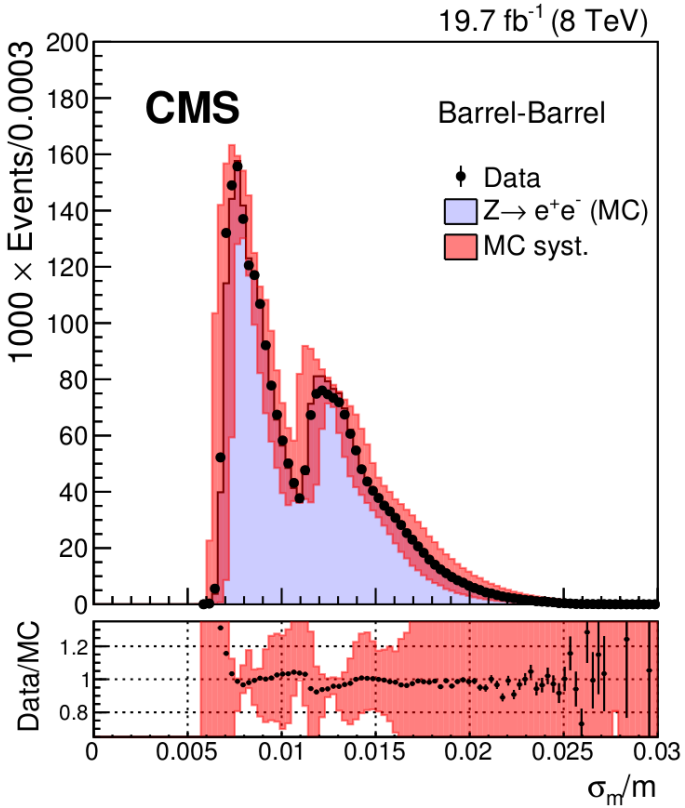
H→γγ: Fiducial Cross Section

HIG-14-016
To be submitted to arxiv and EPJC

NEW!

- Measured in fiducial phase space closely matching experimental acceptance

- Event categorization method updated:
  → Uses mass resolution estimator fully decorrelated from the mass
  → Improves sensitivity by 10% while maintaining a smooth background shape



- Background subtraction and unfolding to particle level done simultaneously by minimizing a function $\mathcal{F}$ which includes usual likelihood and detector response K_j
  → Correlation of nuisance parameters
  → K_j determined from simulation

$$\mathcal{F}\left(\mu\right) = -2\sum_{j}\log\mathcal{L}\left(K_j\mu N^{\mathrm{gen}}|N_j^{\mathrm{reco}}\right)$$

μ = Inclusive Fiducial signal strength

j = Number of reconstruction level observables $(= 3)$

Inclusive $\sigma_{\mathrm{fid.}}$ at $\sqrt{s} = 8$ TeV

$$\sigma_{\mathrm{fid.}} = 32^{+10}_{-10}\ \mathrm{fb}$$

$$\sigma^{\mathrm{SM}}_{\mathrm{fid.}} = 31^{+4}_{-3}\ \mathrm{fb}$$

H→γγ: Differential Cross Section

HIG-14-016
To be submitted to arxiv and EPJC

NEW!

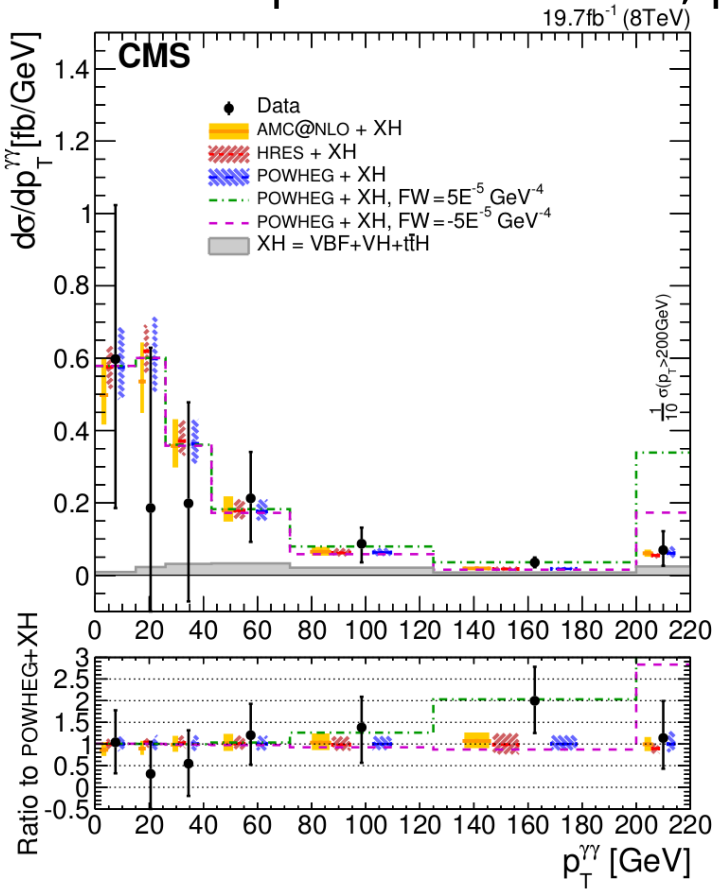
- Differential cross sections measured for several observables:

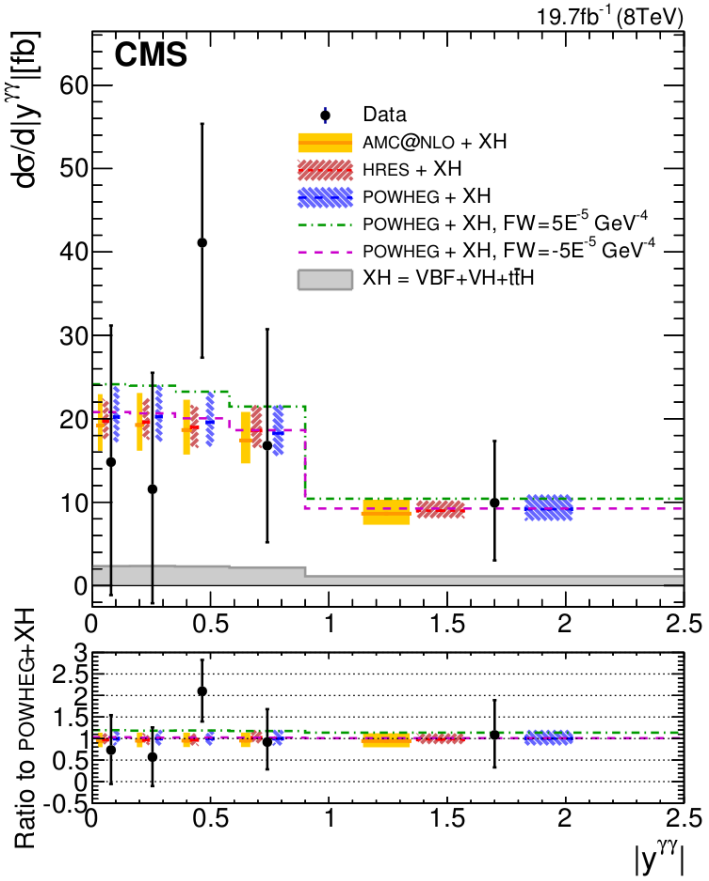
$$\mathcal{F}\Big((\mu_i)_{i=0\ldots N}\Big) = -2\sum_j \log\mathcal{L}\Big(\sum_i K_{ij}\mu_i N_i^{\text{gen}}|N_j^{\text{reco}}\Big)$$

$(\mu_i)_{i=0\ldots N} = N$ Fiducial signal strengths of interest j = Number of reconstruction level observables $(= 3\cdot N)$

→ **p_T^H:** sensitive to production mode, new physics in ggH loop

→ **$|y^H|$:** sensitive to production mode, parton distribution functions





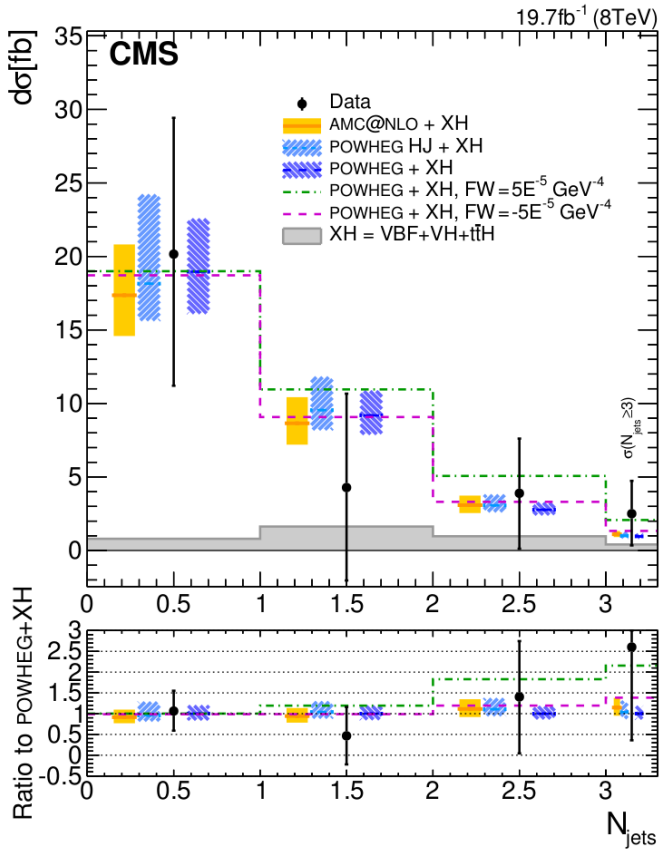
H→γγ: Differential Cross Section

HIG-14-016
To be submitted to arxiv and EPJC

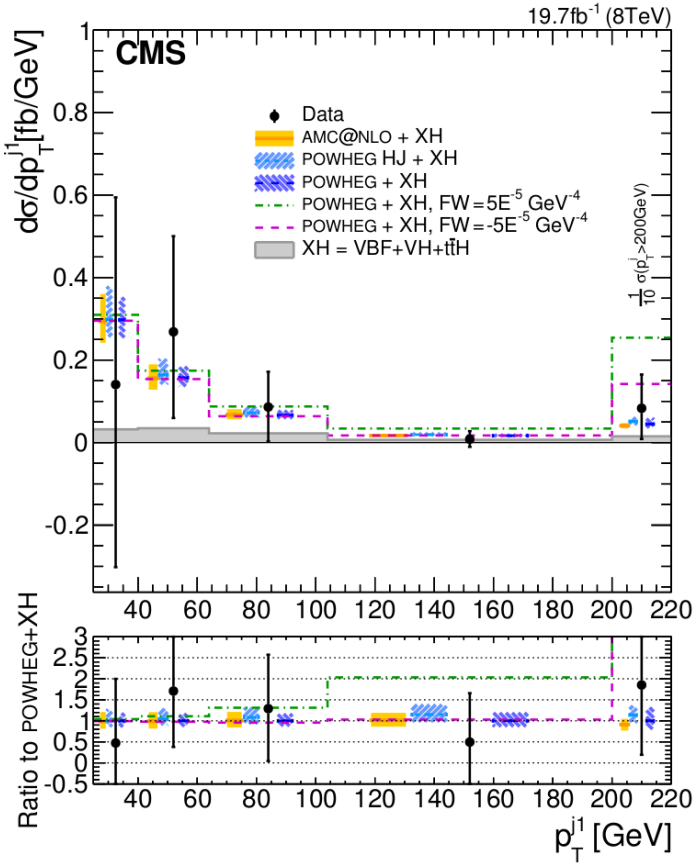
NEW!

- Jet related observables also studied
- Sensitive to production modes, modeling of hard quark/gluon radiation, BSM physics effects

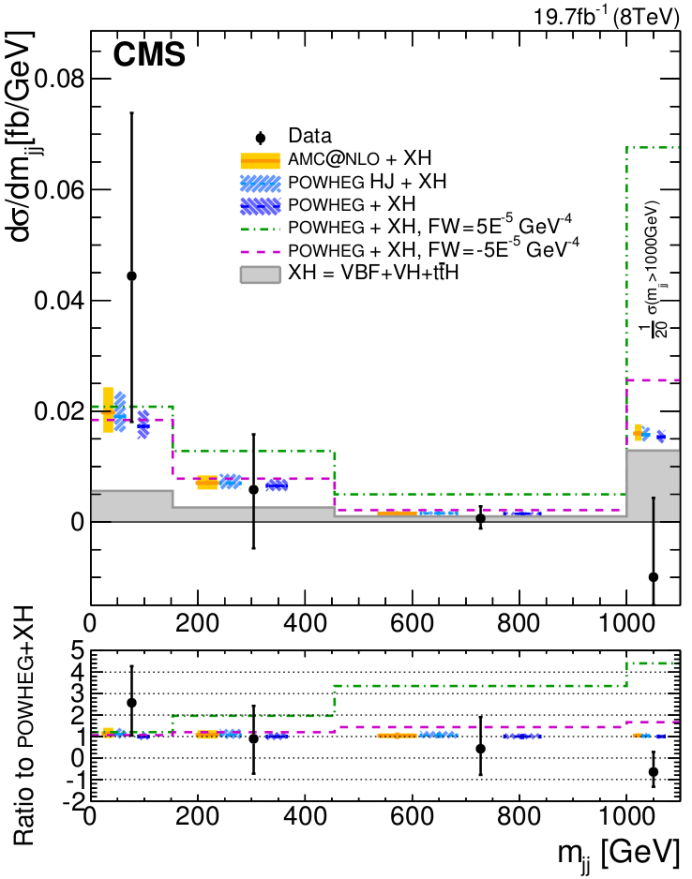
N(jets)



p_T(jet)



m(jj)

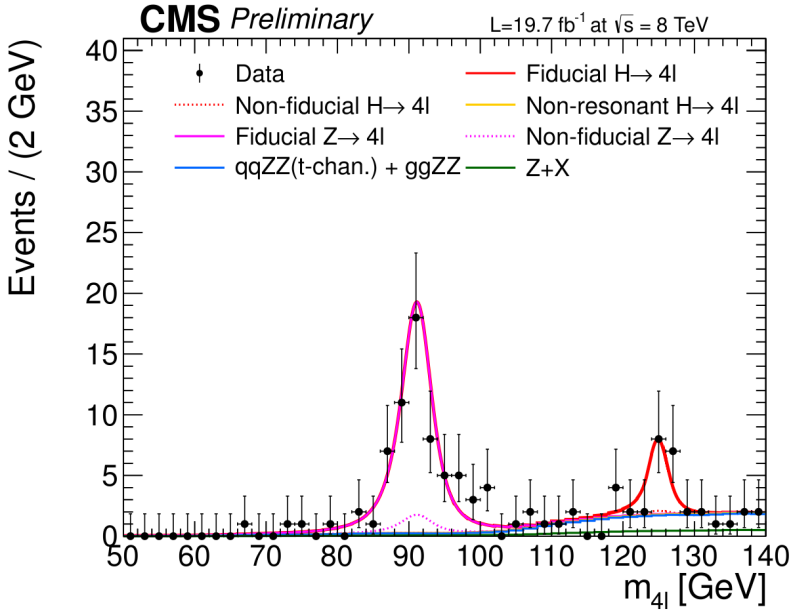


H→4ℓ: Fiducial Cross Section

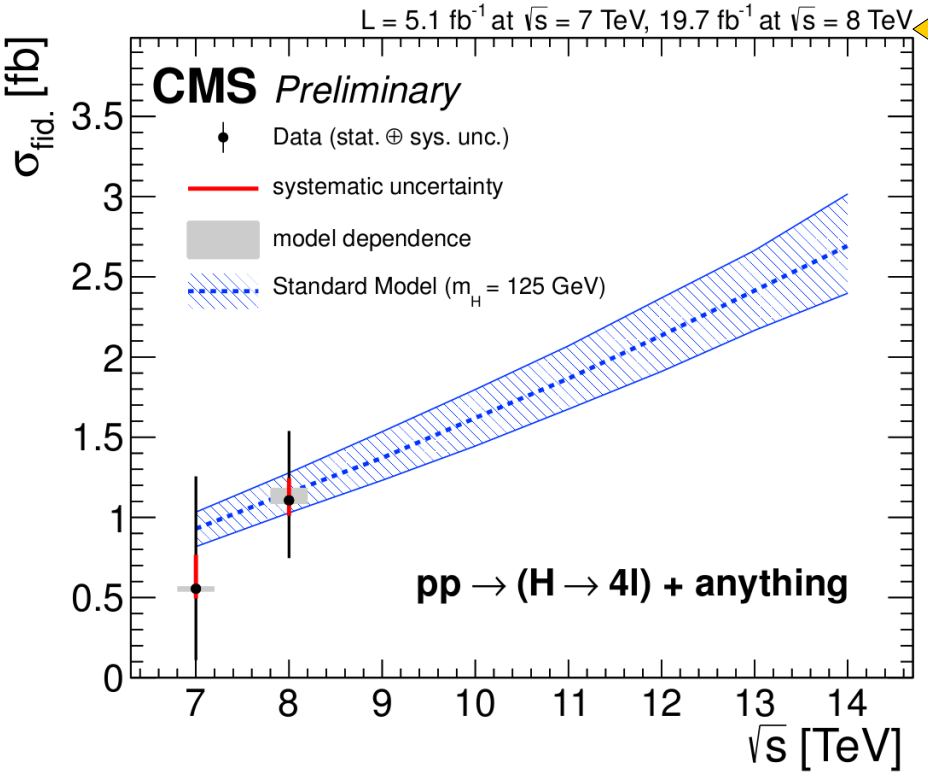
HIG-14-028

NEW!

- Measurement done at 7 and 8 TeV
- Model Dependence estimated from wide range of SM and exotic Higgs models
  → ***Full Model dependence ~7%*** for the inclusive cross section
  → <1% using experimental constraints
  → Z→4ℓ resonance used as validation
  → Several ratios also measured



$$\sigma_{\text{fid.}}(Z \to 4\ell) = 4.81^{+0.69}_{-0.63}(\text{stat.})^{+0.18}_{-0.19}(\text{sys.})\ \text{fb}$$
$$\sigma^{\text{SM}}_{\text{fid.}}(Z \to 4\ell) = 4.56^{+0.19}_{-0.19}\ \text{fb}$$



$$\text{Inclusive } \sigma_{\text{fid.}} \text{ at } \sqrt{s} = 8\ \text{TeV}$$
$$\sigma_{\text{fid.}} = 1.11^{+0.41}_{-0.35}\,(\text{stat.})\,^{+0.14}_{-0.10}\,(\text{sys.})\,^{+0.08}_{-0.02}\,(\text{model})\,\text{fb}$$
$$\sigma^{\text{SM}}_{\text{fid.}} = 1.15^{+0.12}_{-0.13}\ \text{fb}$$

$$\text{Inclusive } \sigma_{\text{fid.}} \text{ at } \sqrt{s} = 7\ \text{TeV}$$
$$\sigma_{\text{fid.}} = 0.56^{+0.67}_{-0.44}\,(\text{stat.})\,^{+0.21}_{-0.06}\,(\text{sys.})\,^{+0.02}_{-0.02}\,(\text{model})\,\text{fb}$$
$$\sigma^{\text{SM}}_{\text{fid.}} = 0.93^{+0.10}_{-0.11}\ \text{fb}$$

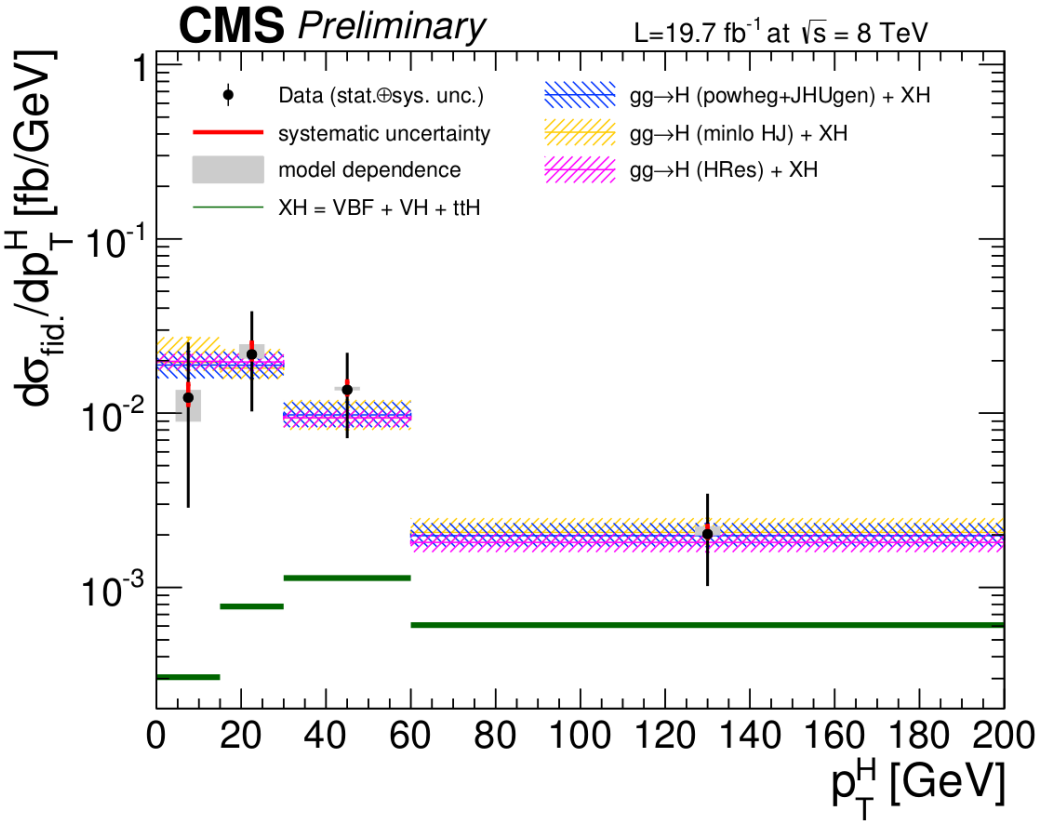
H→4ℓ: Differential Cross Section

HIG-14-028

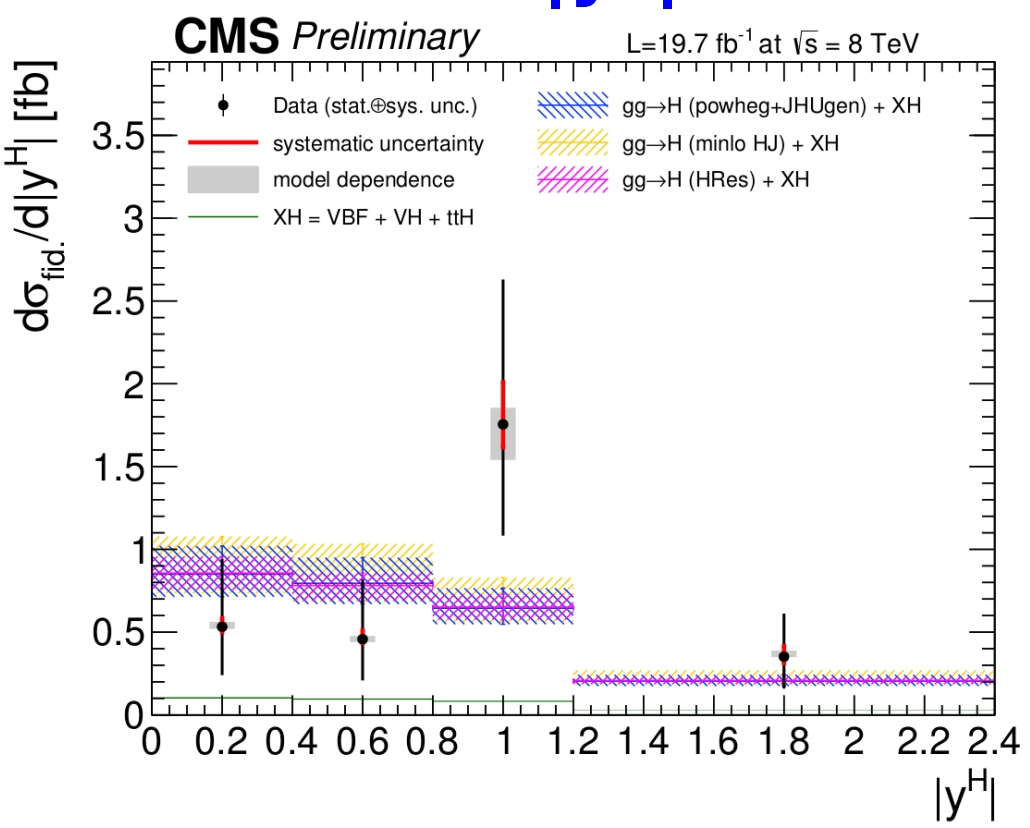
NEW!

- Several differential observables also studied with H→4ℓ
  - → Similar measurement strategy as H→γγ
  - → In agreement with SM predictions
  - → Still small model dependence

p_T^H



$|y^H|$



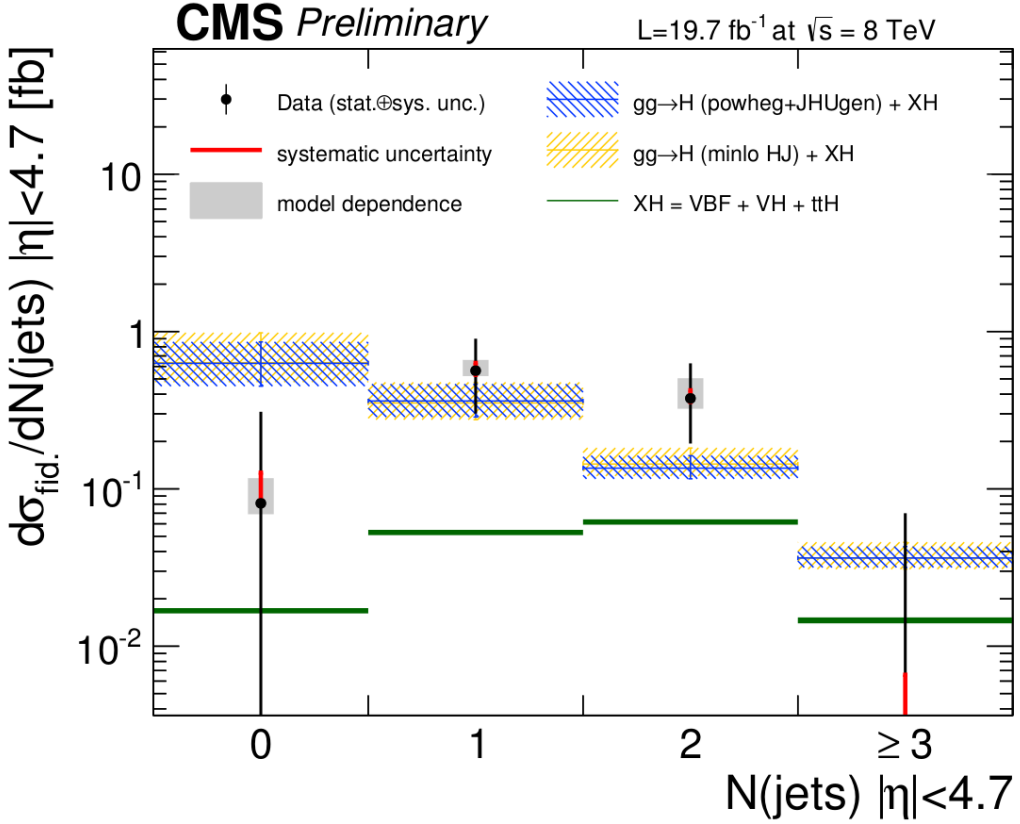
H→4ℓ: Differential Cross Section

HIG-14-028

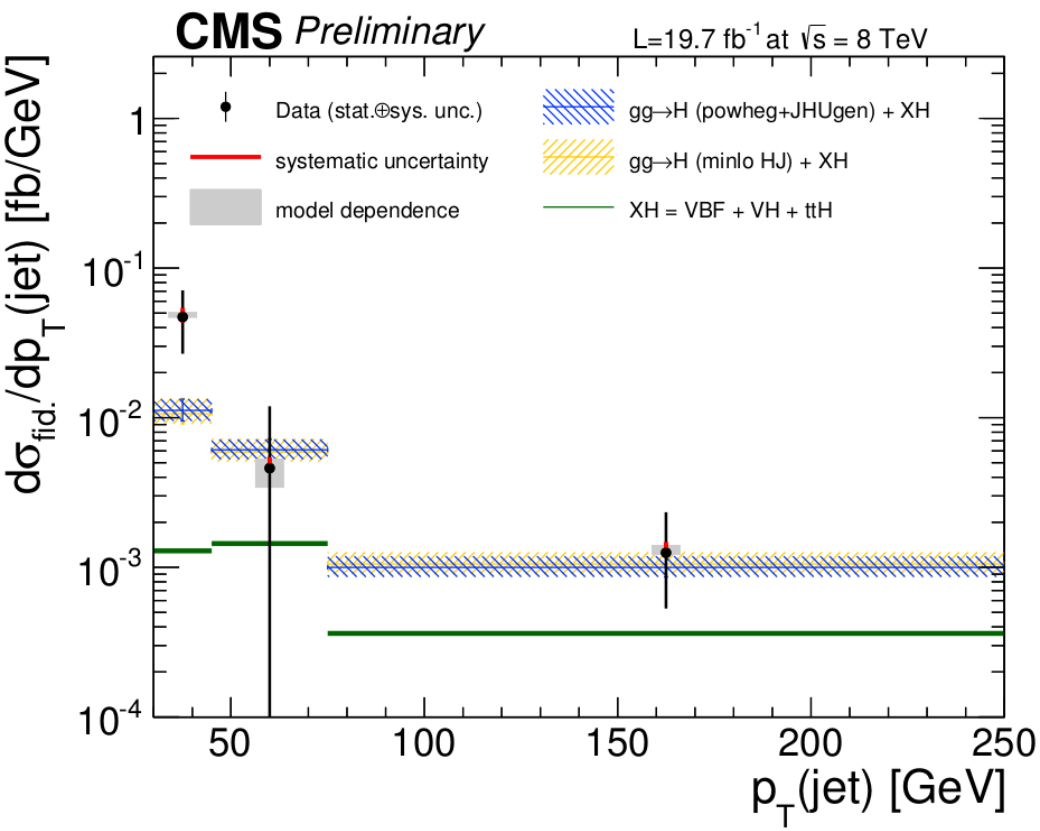
NEW!

- Jet related observables also studied in H→4ℓ:
  → N(jets), p_T(jet)
- More jets but softer p_T(jet) than SM predictions
  → p=0.13 for N(jets) distribution

N(jets)

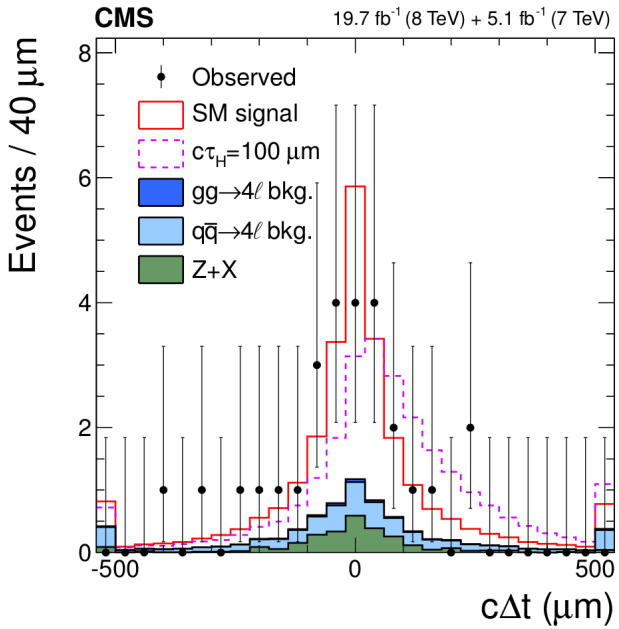


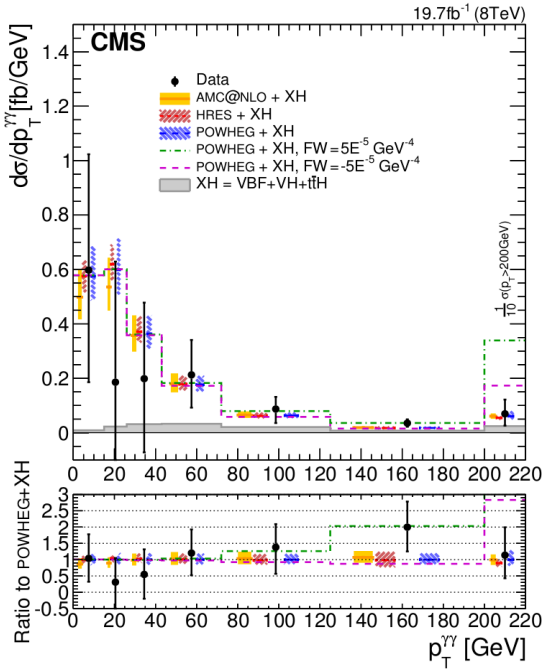
p_T(jet)

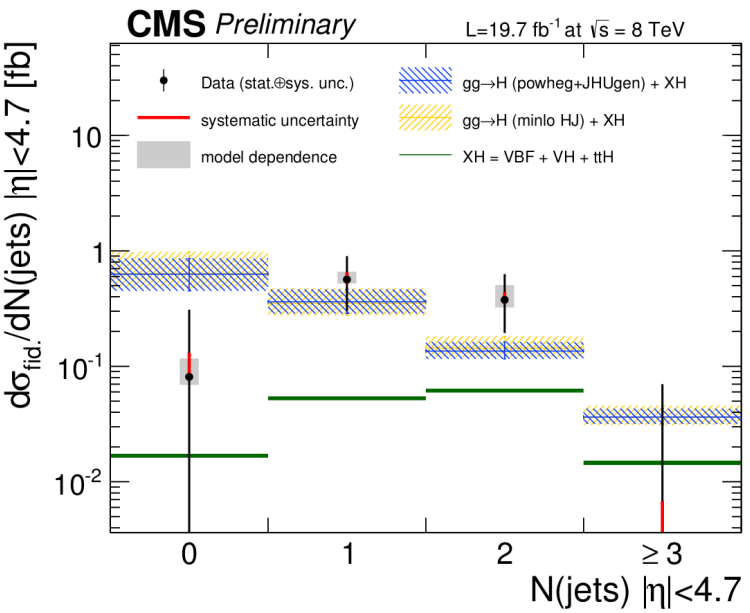


Conclusions

- Diboson processes extensively used to study properties of the 125 GeV Higgs Boson







- More recent CMS diboson results in other talks:

  → **Combined CMS results (couplings, spin/parity):** Ben Kreis

  → **ATLAS+CMS Combination (mass):** Tongguang Cheng

- Looking forward to Higgs physics at 13 TeV!

Additional Material

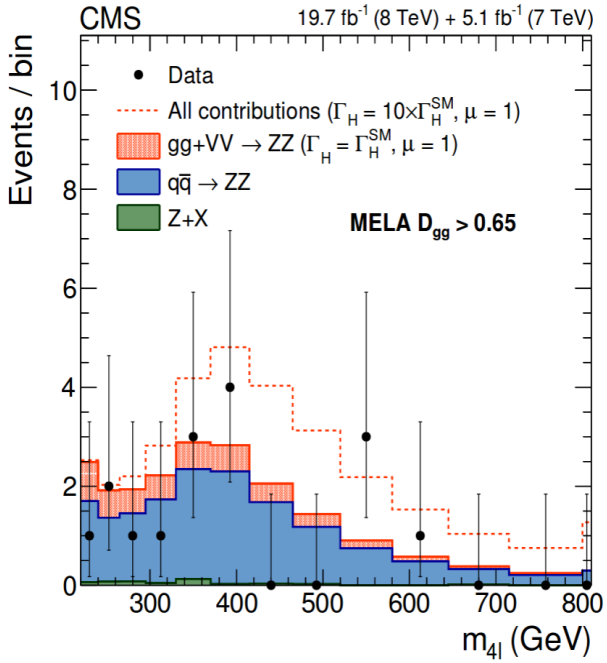
Original Width Analysis

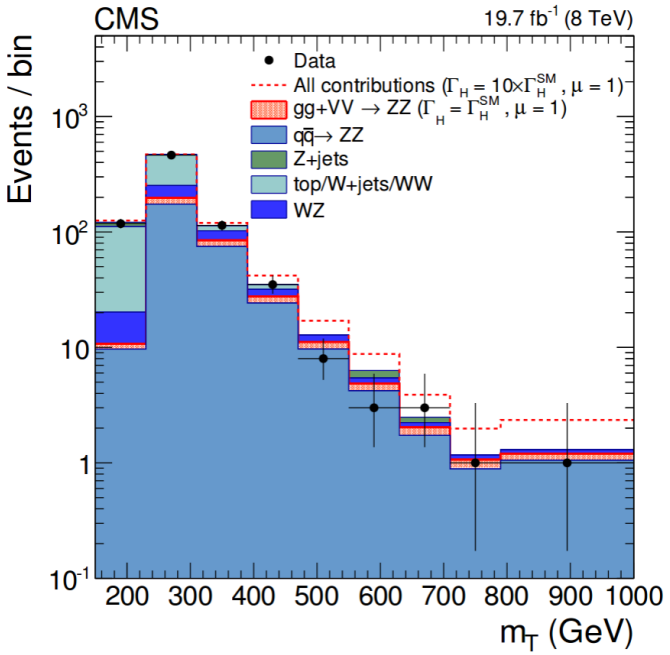
Phys. Lett. B 736 (2014) 64

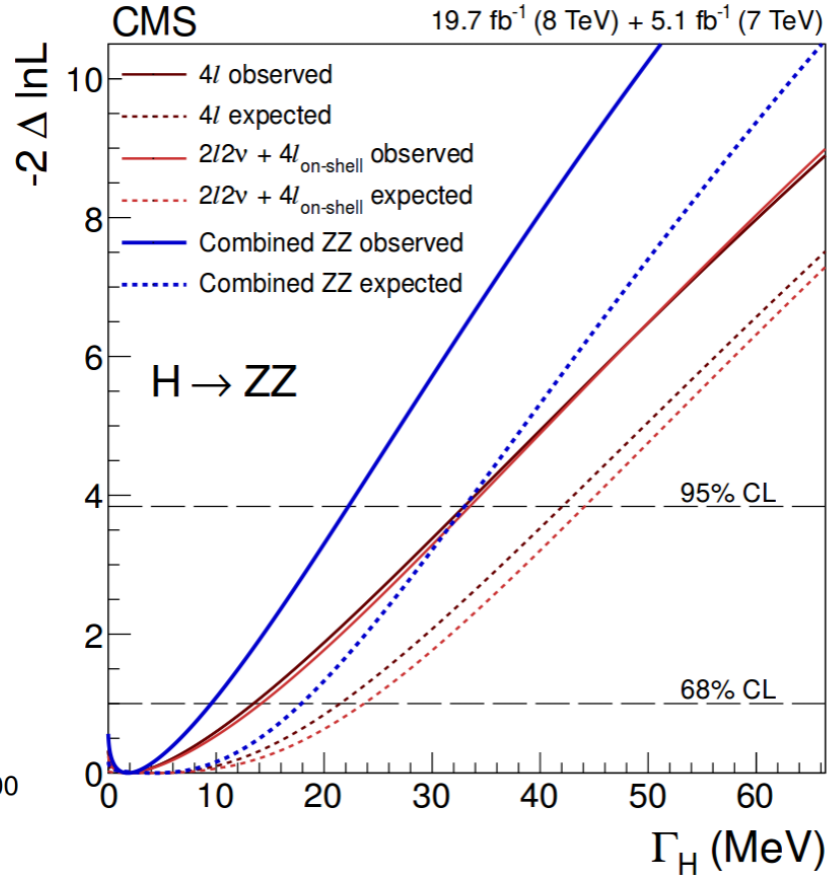
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

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

Final State	Observed	Expected
4ℓ	$\Gamma_H < 33$ MeV	$\Gamma_H < 42$ MeV
$2\ell 2\nu + 4\ell$ on-shell	$\Gamma_H < 33$ MeV	$\Gamma_H < 44$ MeV
combined	$\Gamma_H < 22$ MeV	$\Gamma_H < 33$ MeV





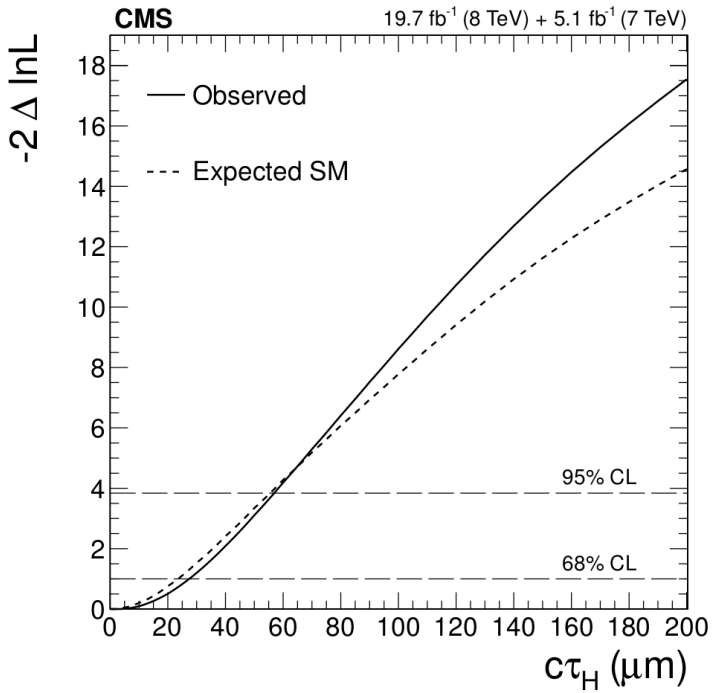


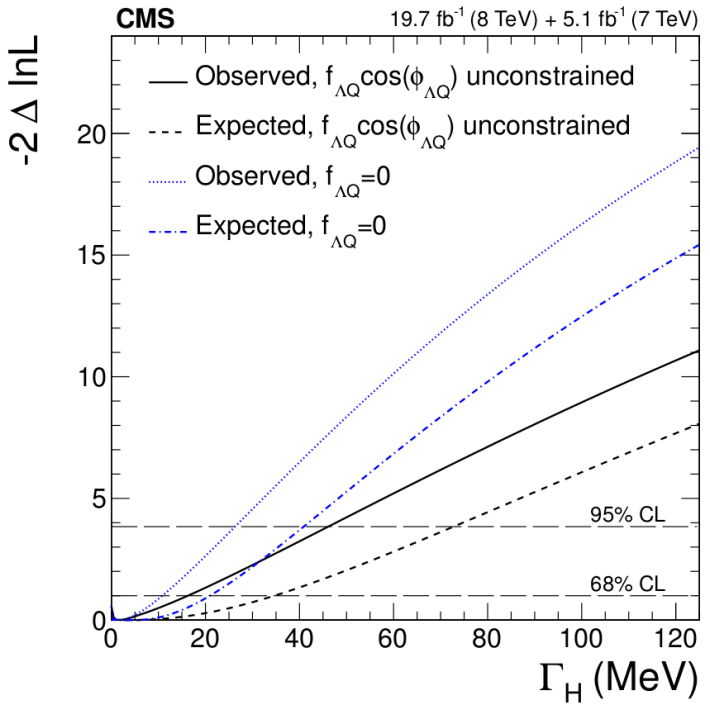
Updated Width Results

HIG-14-036

Submitted to arxiv and Phys. Rev. D

Parameter	$f_{\Lambda Q} = 0$		$f_{\Lambda Q}$ unconstrained, $\phi_{\Lambda Q} = 0$ or π	
	Observed	Expected	Observed	Expected
τ_H (fs)	$[2.5 \times 10^{-8},\ 190]$	$[1.6 \times 10^{-8},\ 190]$	$[1.4 \times 10^{-8},\ 190]$	$[9 \times 10^{-9},\ 190]$
Γ_H (MeV)	$[3.5 \times 10^{-9},\ 26]$	$[3.6 \times 10^{-9},\ 41]$	$[3.5 \times 10^{-9},\ 46]$	$[3.6 \times 10^{-9},\ 73]$





$c\tau_H < 57\ \mu\text{m}$ 95%CL

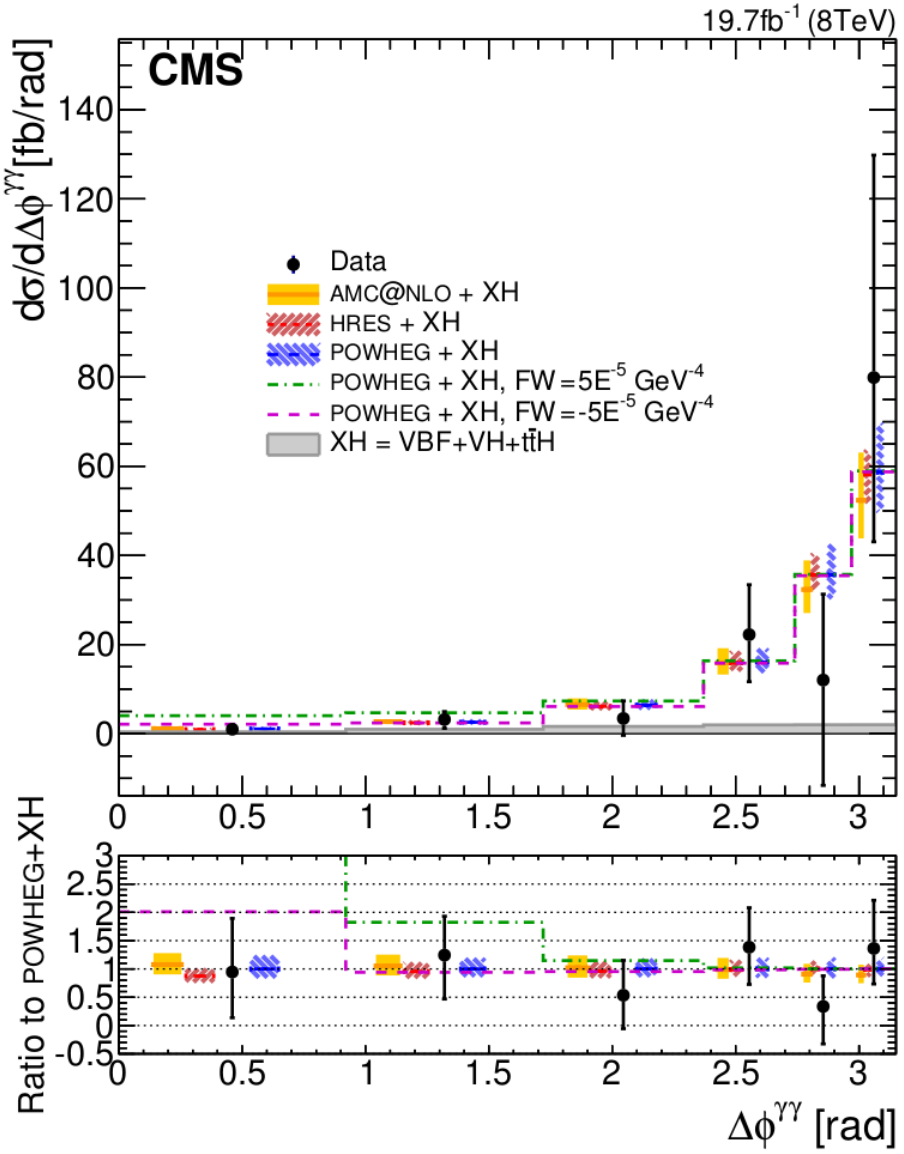
$\Gamma_H < 26$ MeV 95%CL ($f_{\Lambda_Q} = 0$)

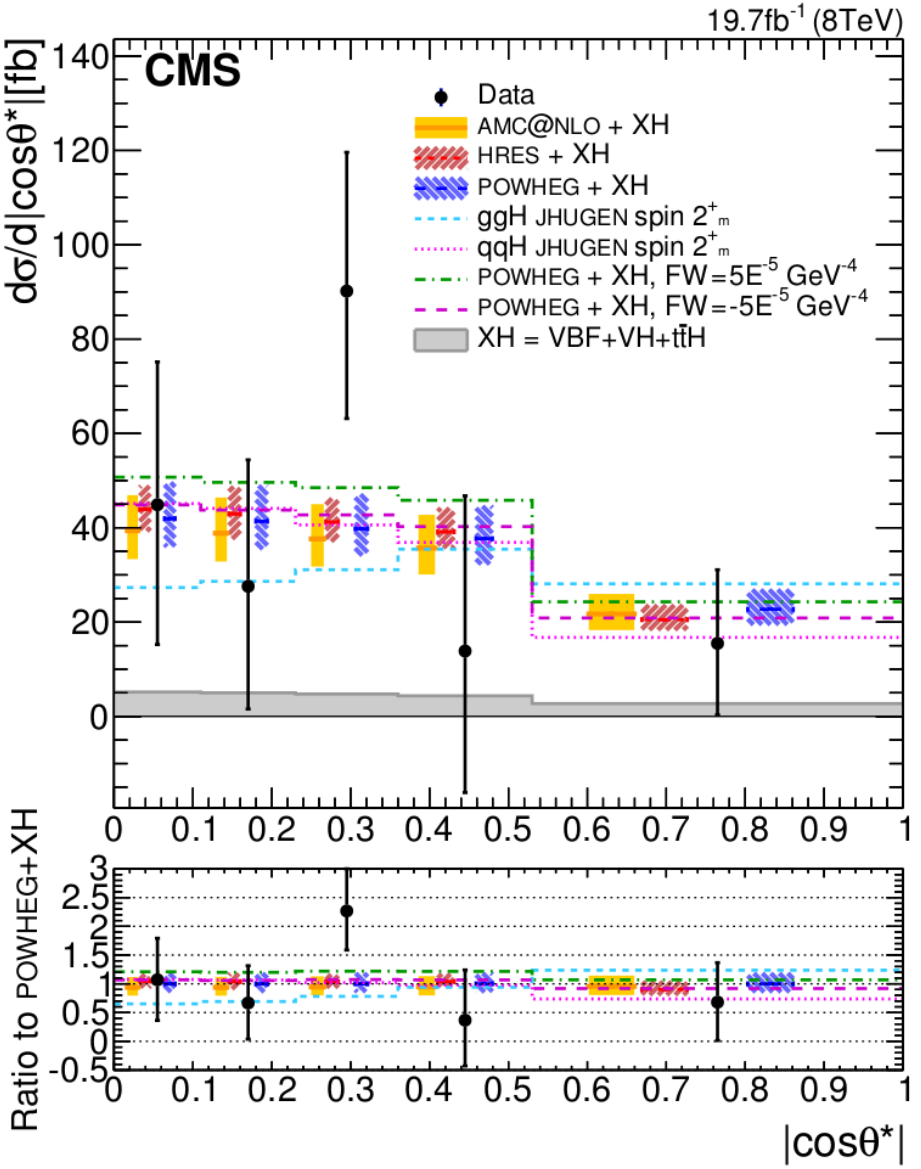
$\Gamma_H < 46$ MeV 95%CL (f_{Λ_Q} unconstrained)

H→γγ: Differential Cross Sections

HIG-14-016

To be submitted to arxiv and EPJC

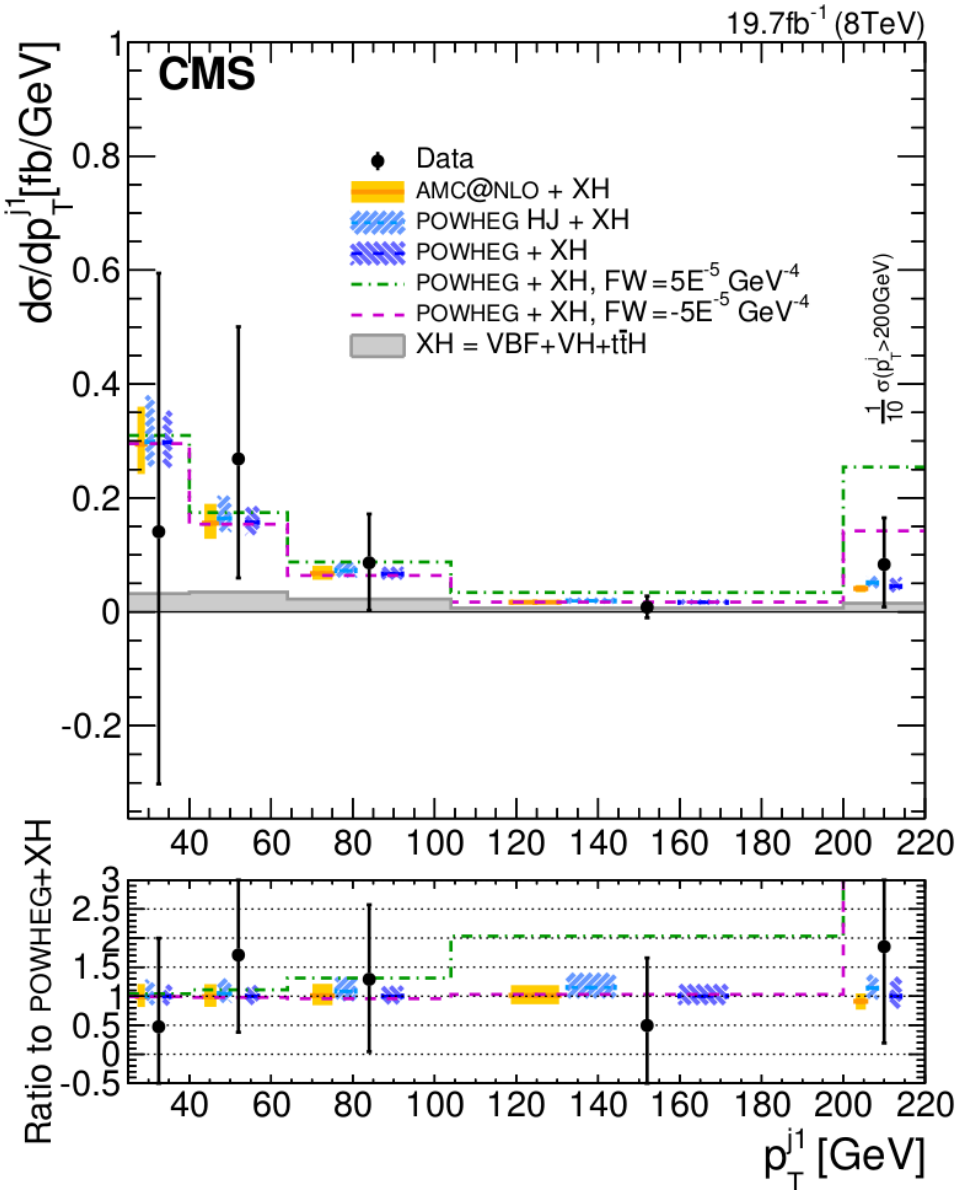


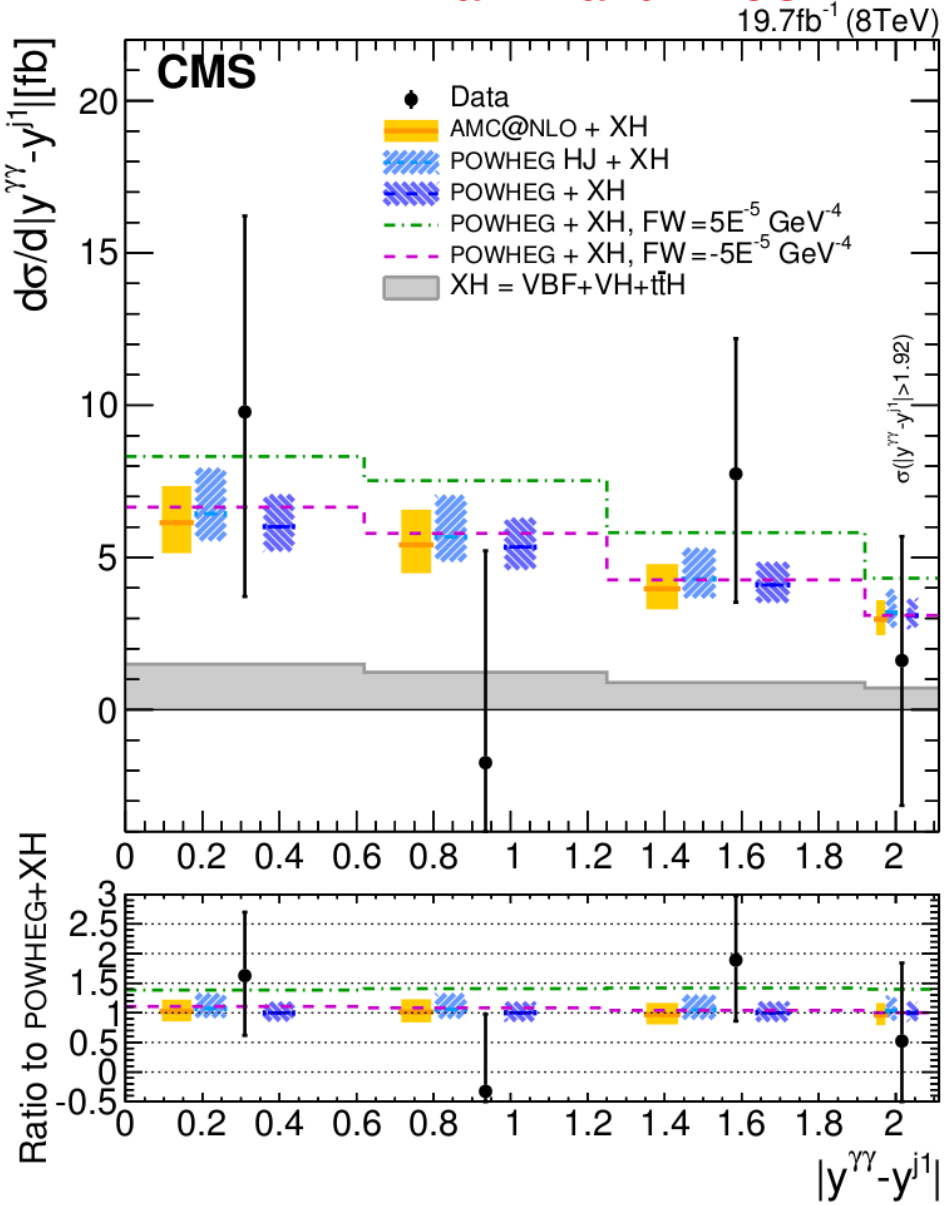


H→γγ: Differential Cross Sections

HIG-14-016

To be submitted to arxiv and EPJC

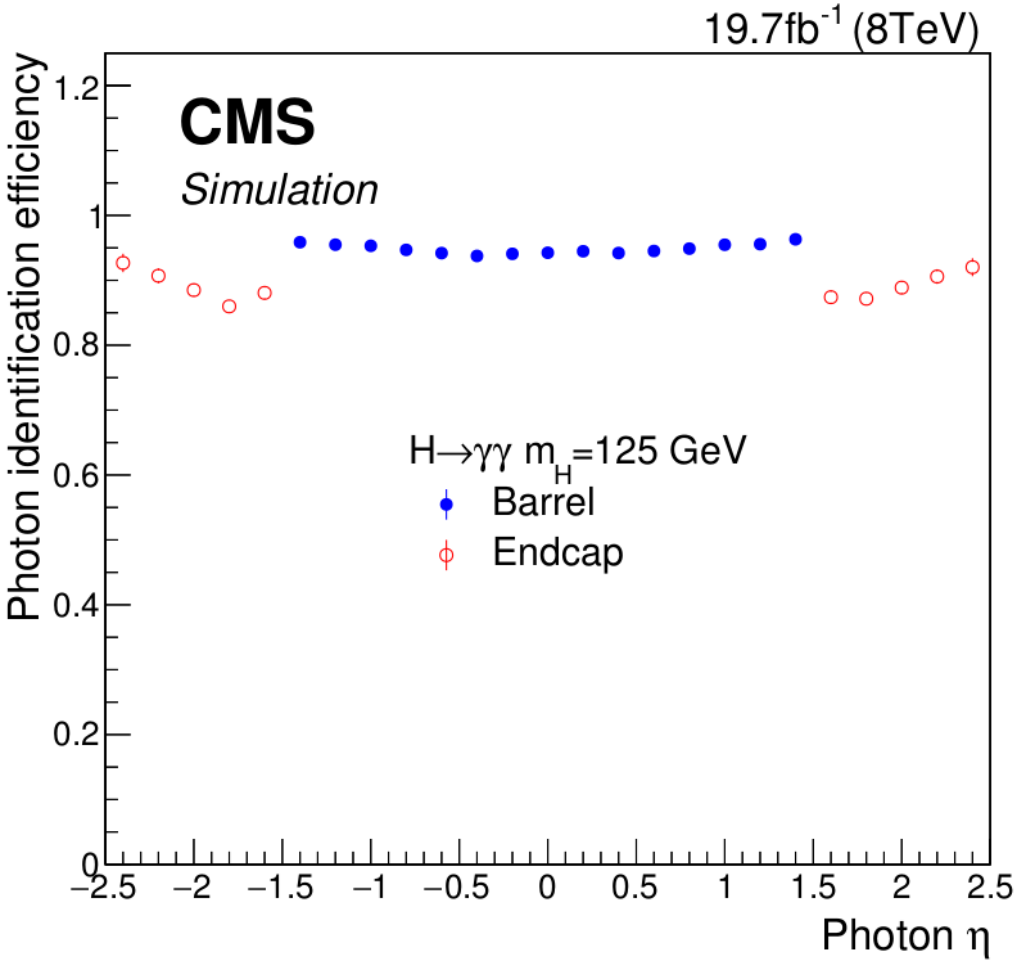


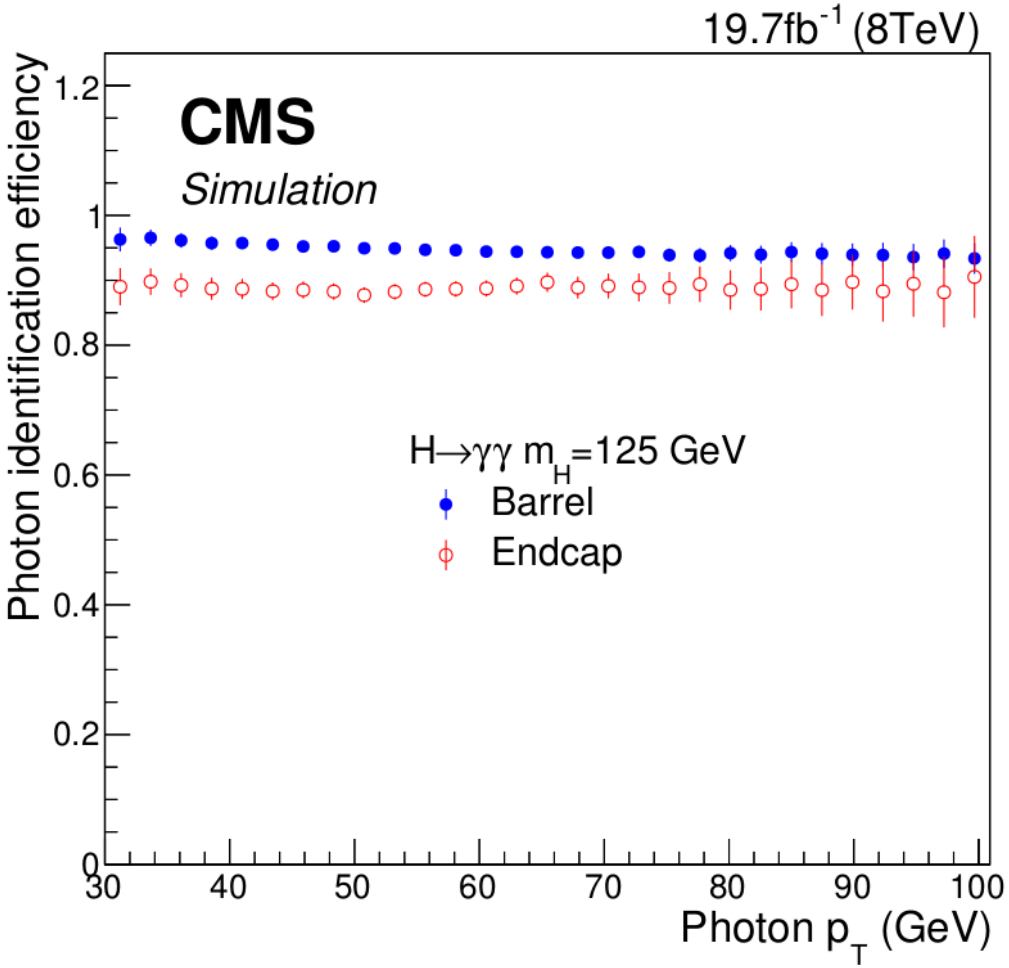


H→γγ: Photon ID Efficiencies

HIG-14-016

To be submitted to arxiv and EPJC





H→4ℓ: Inclusive Cross Sections

HIG-14-028

Fiducial cross section $H \to 4\ell$ at 7 TeV	
Measured	$0.56^{+0.67}_{-0.44}\,(\text{stat.})\,^{+0.21}_{-0.06}\,(\text{sys.})\,^{+0.02}_{-0.02}\,(\text{model})$ fb
$gg \to H(\text{HRES}) + XH$	$0.93^{+0.10}_{-0.11}$ fb
Fiducial cross section $H \to 4\ell$ at 8 TeV	
Measured	$1.11^{+0.41}_{-0.35}\,(\text{stat.})\,^{+0.14}_{-0.10}\,(\text{sys.})\,^{+0.08}_{-0.02}\,(\text{model})$ fb
$gg \to H(\text{HRES}) + XH$	$1.15^{+0.12}_{-0.13}$ fb
Ratio of fiducial cross sections of $H \to 4\ell$ at 7 and 8 TeV	
Measured	$0.51^{+0.71}_{-0.40}\,(\text{stat.})\,^{+0.13}_{-0.05}\,(\text{sys.})\,^{+0.00}_{-0.03}\,(\text{model})$
$gg \to H(\text{HRES}) + XH$	$0.805^{+0.003}_{-0.010}$

Fiducial cross section $Z \to 4\ell$ at 8 TeV ($50\ \text{GeV} < m_{4\ell} < 105\ \text{GeV}$)	
Measured	$4.81^{+0.69}_{-0.63}(\text{stat.})^{+0.18}_{-0.19}(\text{sys.})$ fb
POWHEG	$4.56^{+0.19}_{-0.19}$ fb
Ratio of fiducial cross sections of $H \to 4\ell$ and $Z \to 4\ell$ at 8 TeV ($50\ \text{GeV} < m_{4\ell} < 140\ \text{GeV}$)	
Measured	$0.21^{+0.09}_{-0.07}(\text{stat.})^{+0.01}_{-0.01}(\text{sys.})$
$gg \to H(\text{HRES}) + XH$ and $Z \to 4\ell$ (POWHEG)	$0.25^{+0.04}_{-0.04}$

H→4ℓ: Cross Section Inputs

HIG-14-028

Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1+f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
$gg \to H$ (POWHEG+JHUGEN)	0.422 ± 0.001	0.647 ± 0.002	0.053 ± 0.001	0.681 ± 0.002
VBF (POWHEG)	0.476 ± 0.003	0.652 ± 0.005	0.040 ± 0.002	0.678 ± 0.005
WH (PYTHIA)	0.342 ± 0.002	0.627 ± 0.003	0.072 ± 0.002	0.672 ± 0.003
ZH (PYTHIA)	0.348 ± 0.003	0.634 ± 0.004	0.072 ± 0.003	0.679 ± 0.005
$t\bar{t}H$ (PYTHIA)	0.250 ± 0.003	0.601 ± 0.008	0.139 ± 0.008	0.685 ± 0.010
Some characteristic models of Higgs-like boson with exotic decays and properties				
$q\bar{q} \to H(J^{CP}=1^-)$ (JHUGEN)	0.238 ± 0.001	0.609 ± 0.002	0.054 ± 0.001	0.642 ± 0.002
$q\bar{q} \to H(J^{CP}=1^+)$ (JHUGEN)	0.283 ± 0.001	0.619 ± 0.002	0.051 ± 0.001	0.651 ± 0.002
$gg \to H \to Z\gamma^*$ (JHUGEN)	0.156 ± 0.001	0.622 ± 0.002	0.073 ± 0.001	0.667 ± 0.002
$gg \to H \to \gamma^*\gamma^*$ (JHUGEN)	0.188 ± 0.001	0.629 ± 0.002	0.066 ± 0.001	0.671 ± 0.002

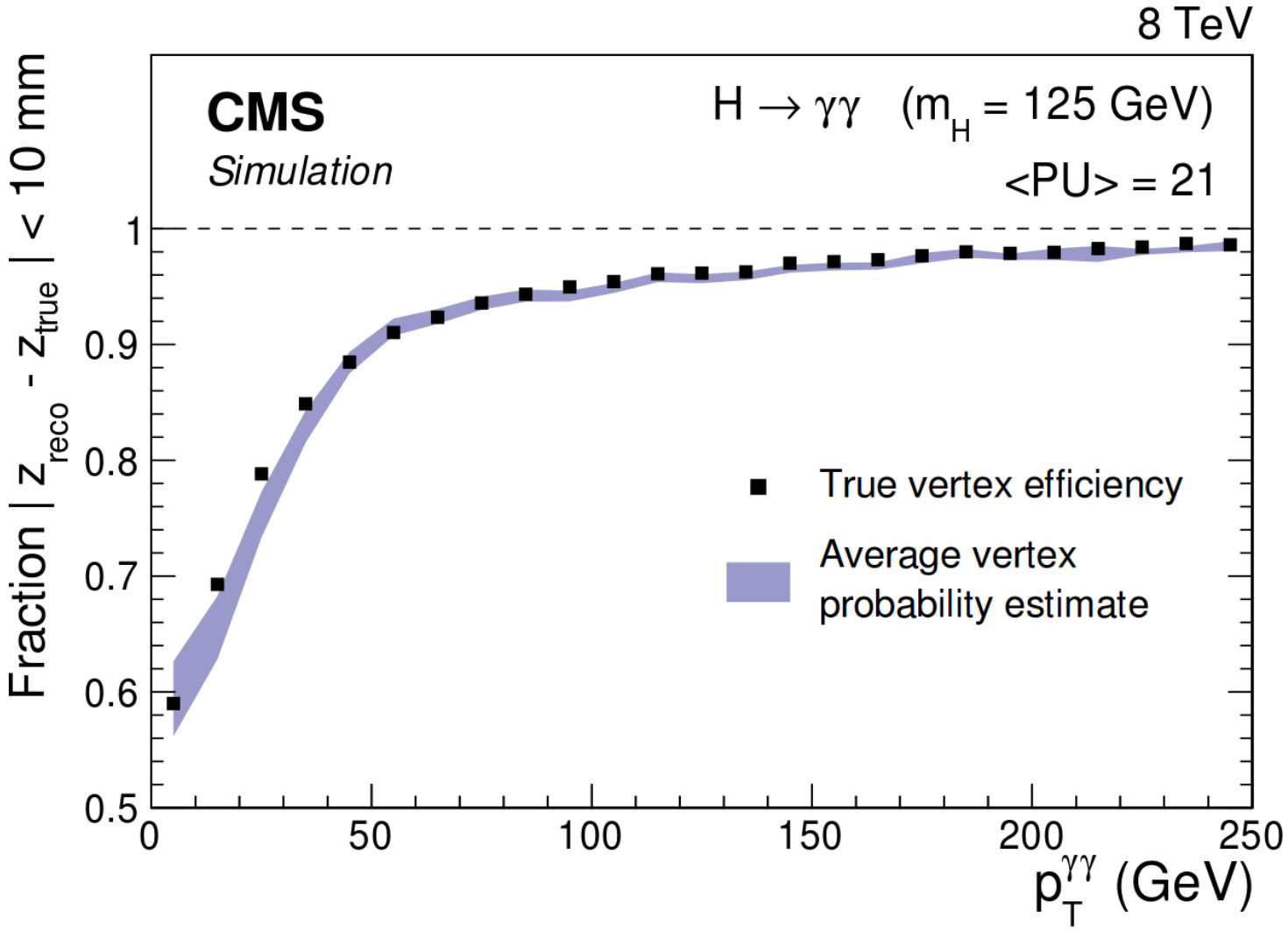
$$N^{\mathrm{f},i}_{\mathrm{obs}}(m_{4\ell}) = N^{\mathrm{f},i}_{\mathrm{fid}}(m_{4\ell}) + N^{\mathrm{f},i}_{\mathrm{nonfid}}(m_{4\ell}) + N^{\mathrm{f},i}_{\mathrm{nonres}}(m_{4\ell}) + N^{\mathrm{f},i}_{\mathrm{bkg}}(m_{4\ell})$$

$$= \epsilon^{\mathrm{f}}_{i,j} \cdot \left(1 + f^{\mathrm{f},i}_{\mathrm{nonfid}}\right) \cdot \sigma^{\mathrm{f},j}_{\mathrm{fid}} \cdot \mathcal{L} \cdot \mathcal{P}_{\mathrm{res}}(m_{4\ell})$$

$$+ N^{\mathrm{f},i}_{\mathrm{nonres}} \cdot \mathcal{P}_{\mathrm{nonres}}(m_{4\ell}) + N^{\mathrm{f},i}_{\mathrm{bkg}} \cdot \mathcal{P}_{\mathrm{bkg}}(m_{4\ell})$$

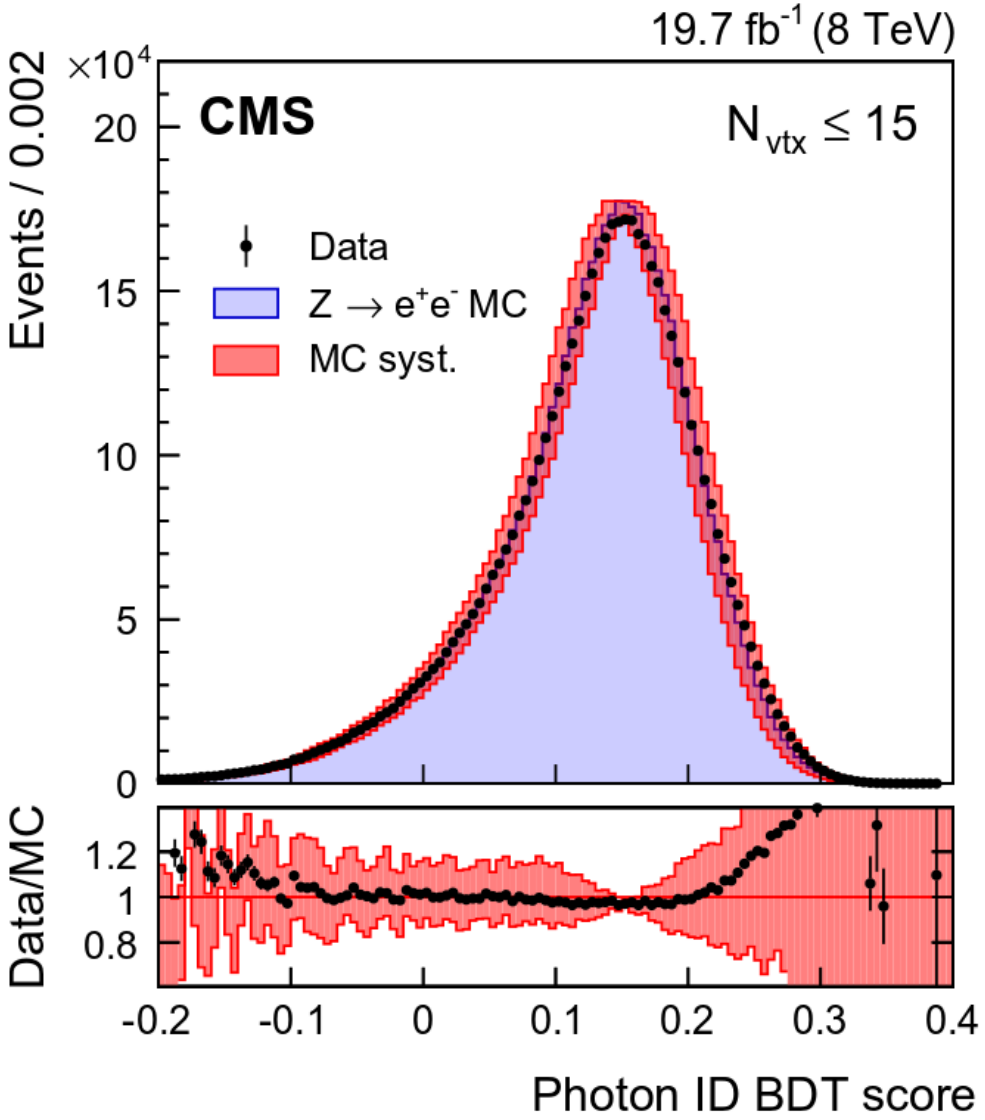
Photon Vertex Efficiency

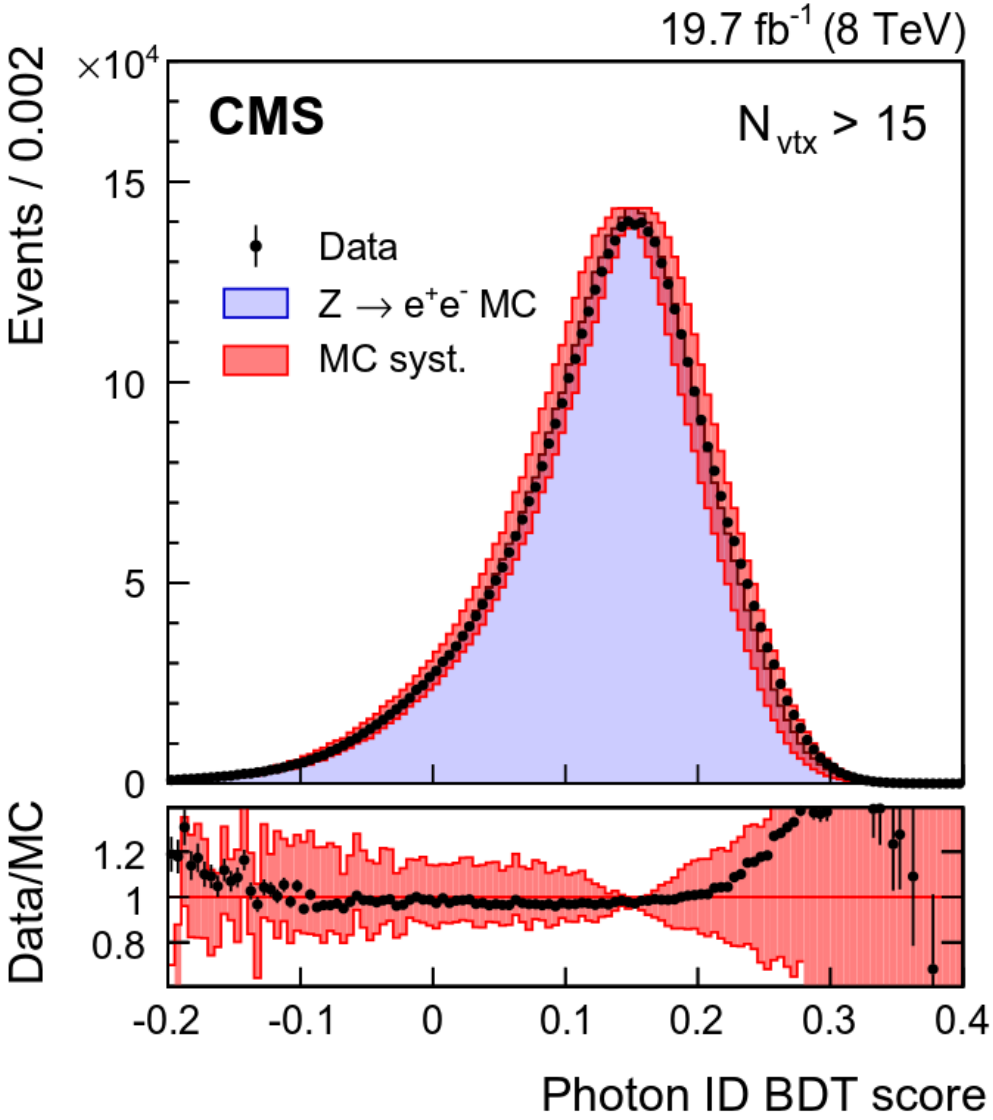
Eur. Phys. J. C (2014) 74:3076



Photon ID Validation

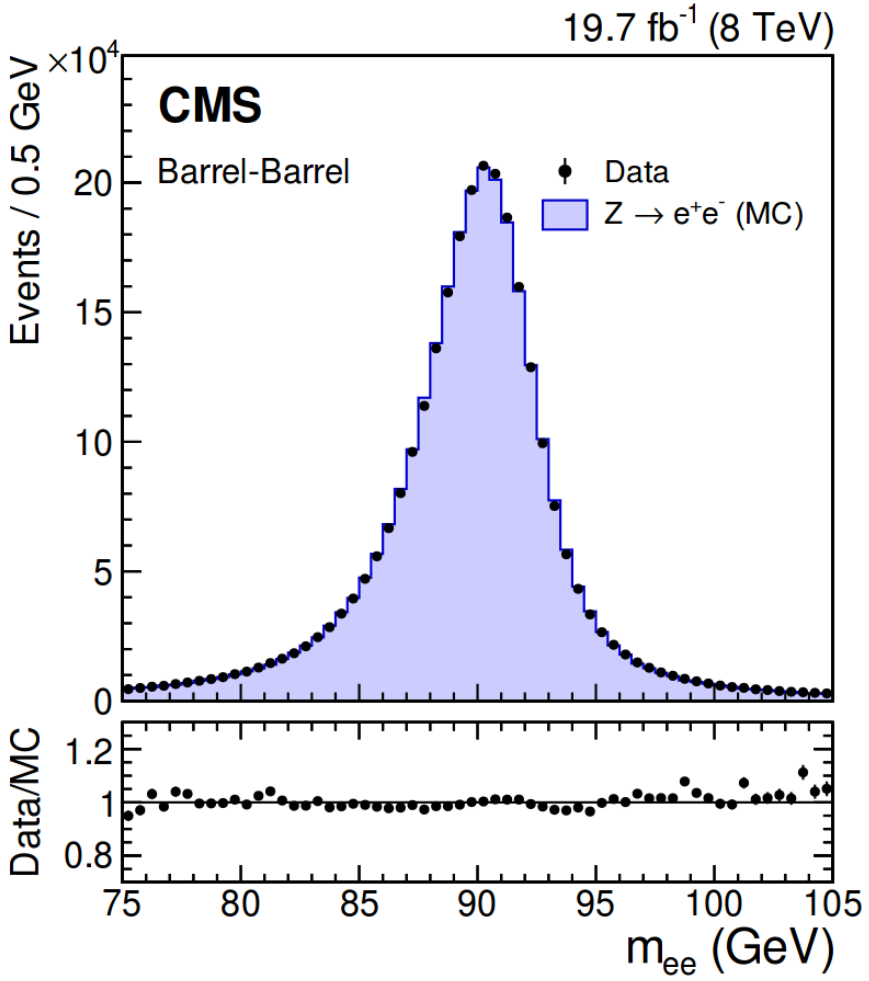
Eur. Phys. J. C (2014) 74:3076

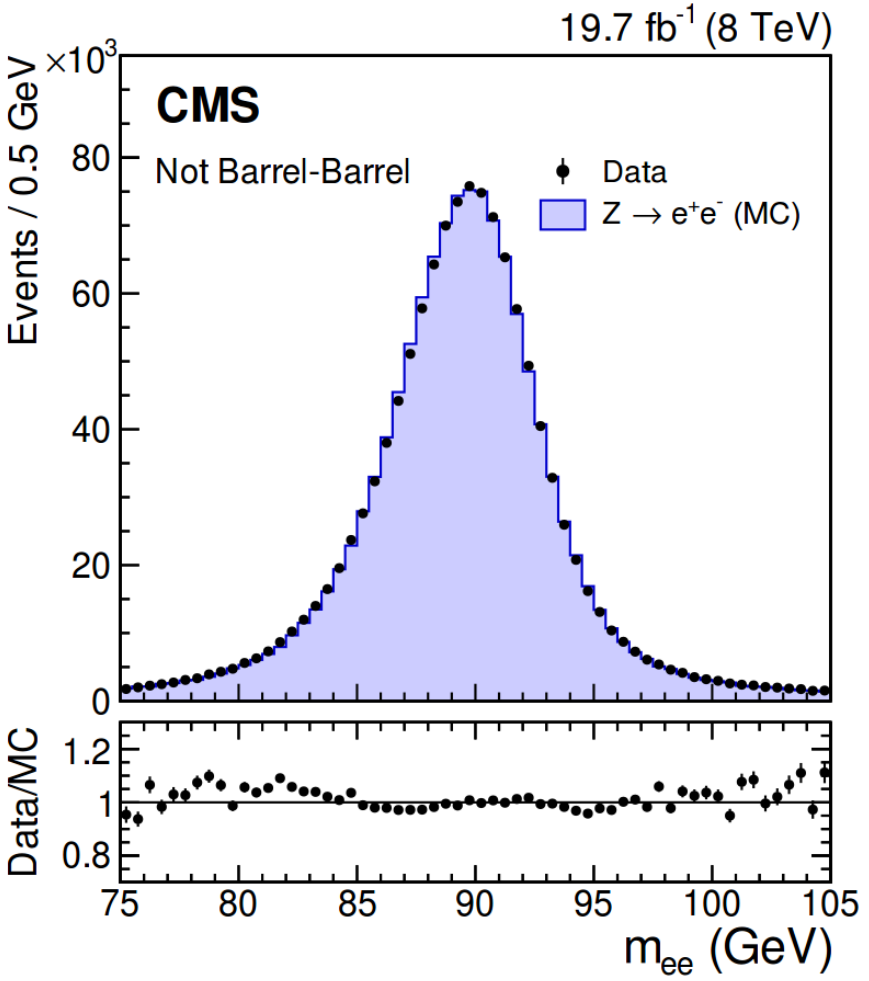




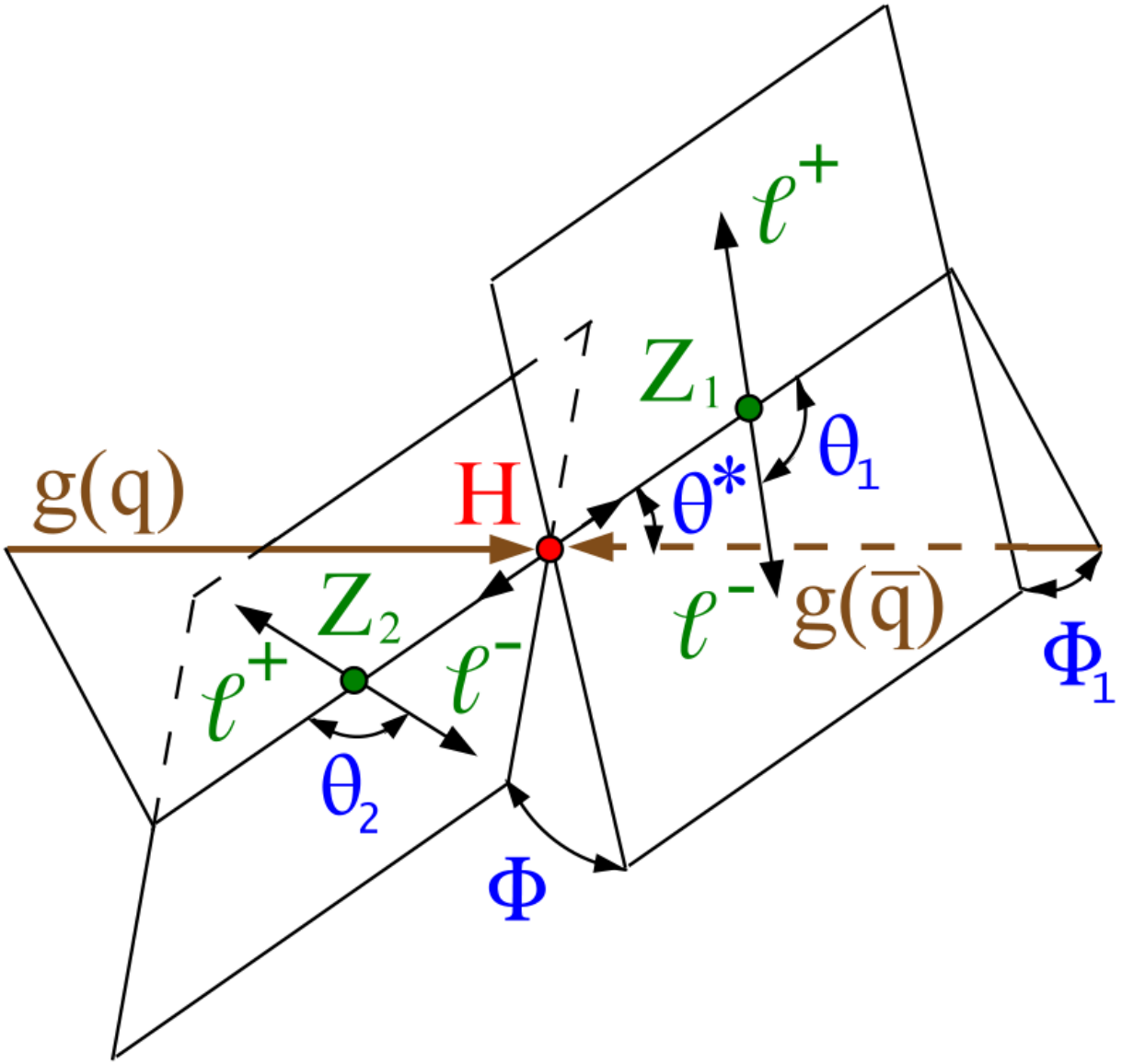
Photon Energy Scale/Resolution

Eur. Phys. J. C (2014) 74:3076



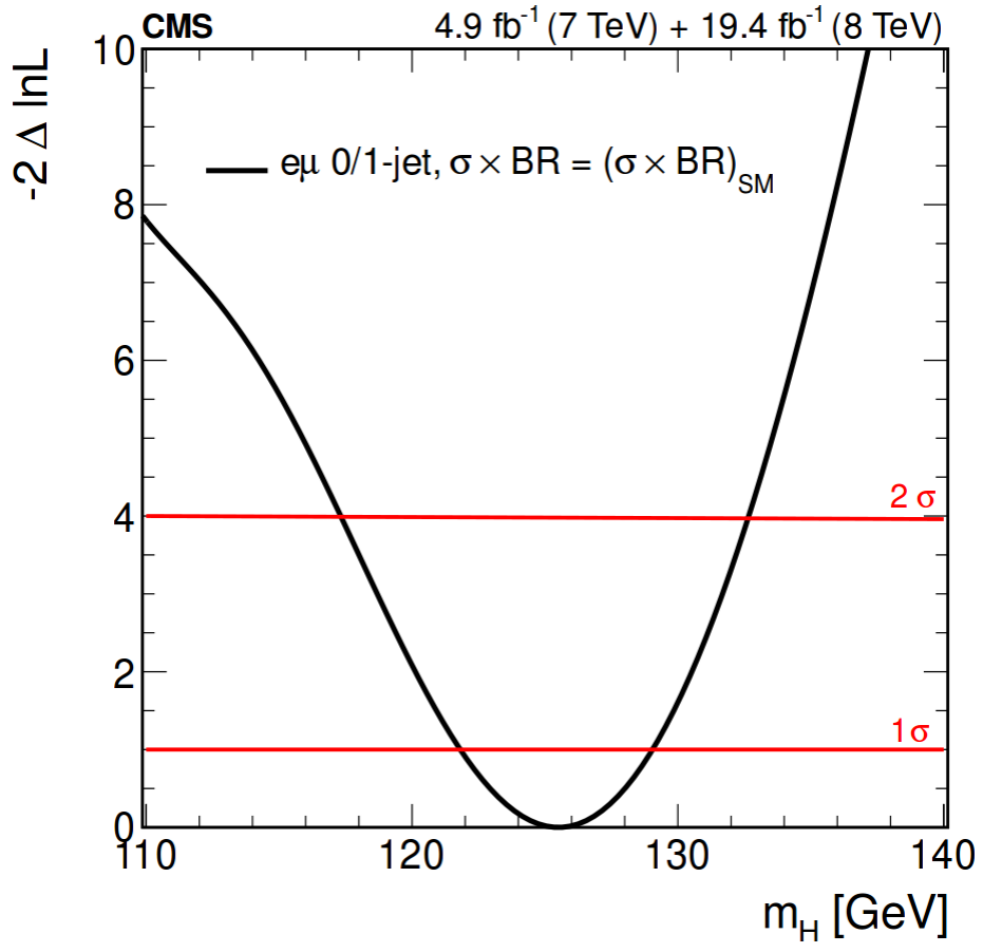


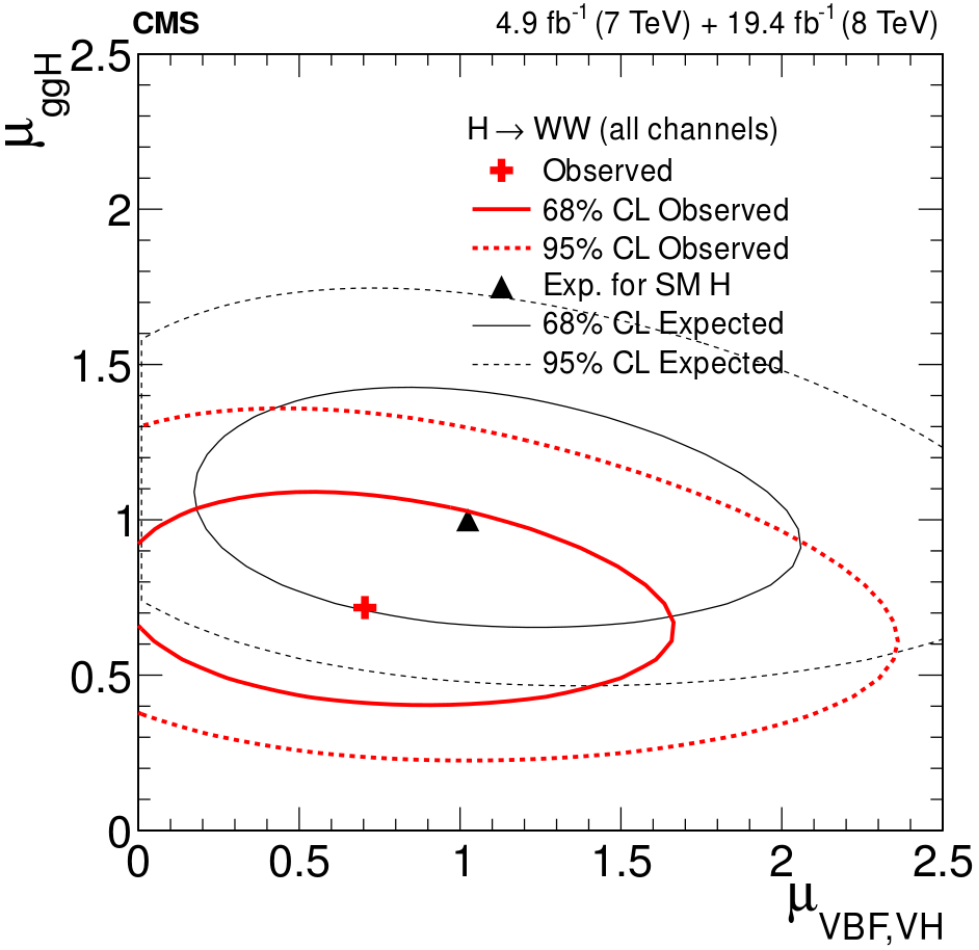
H → 4ℓ: Kinematics



H→WW: Mass and Couplings

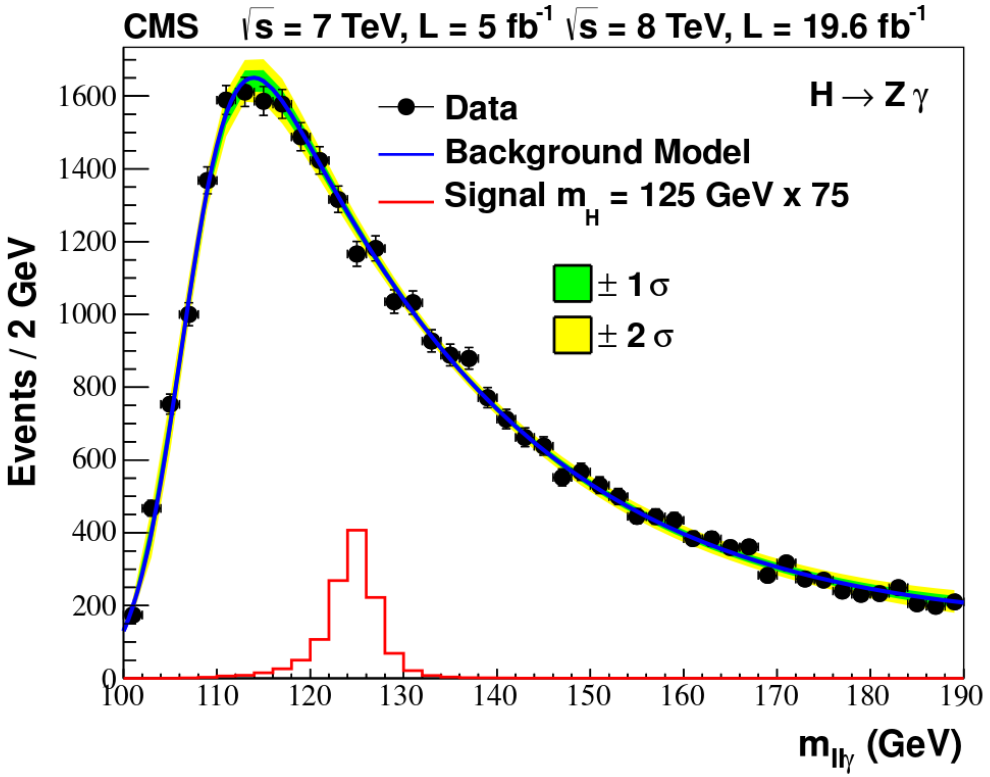
JHEP01 (2014) 096

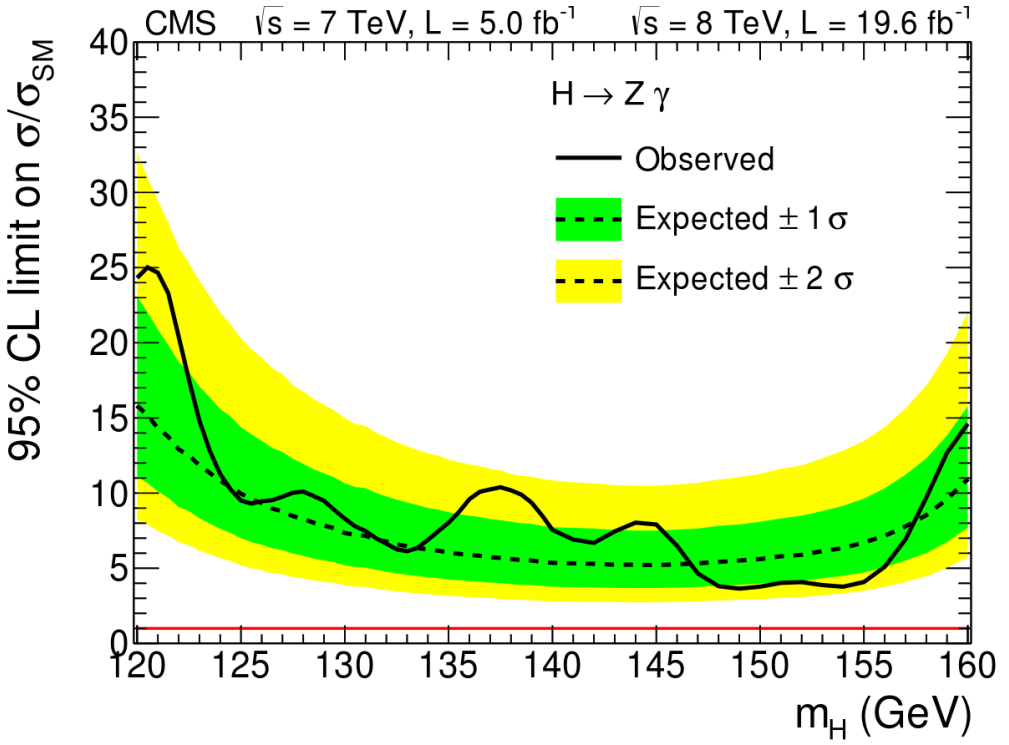




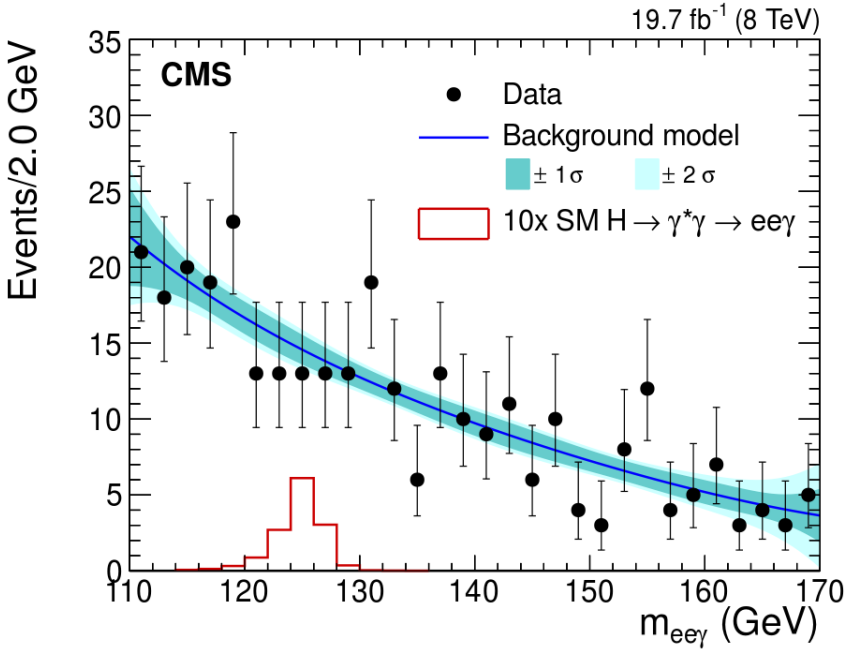
H→Zγ

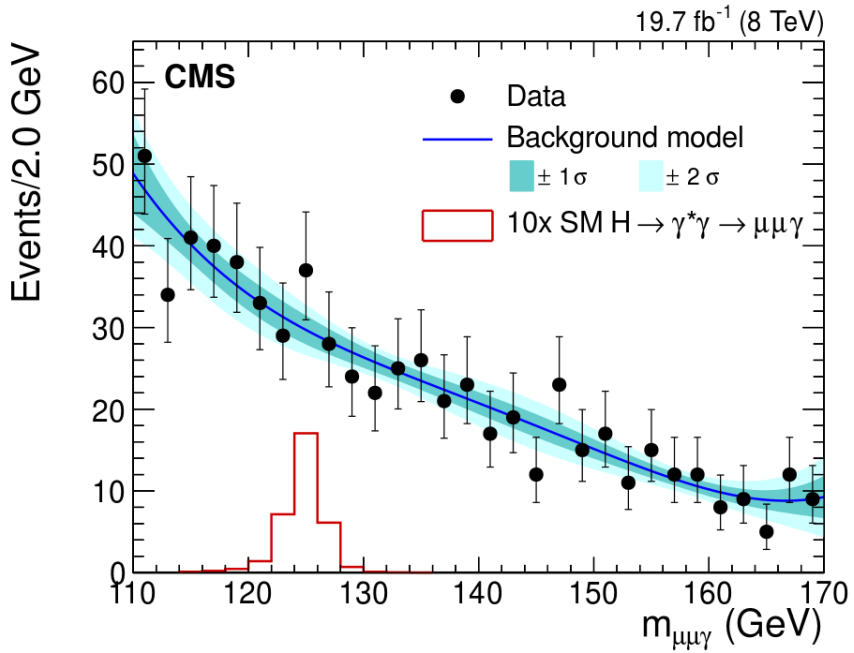
Phys. Lett. B 726 (2013) 587



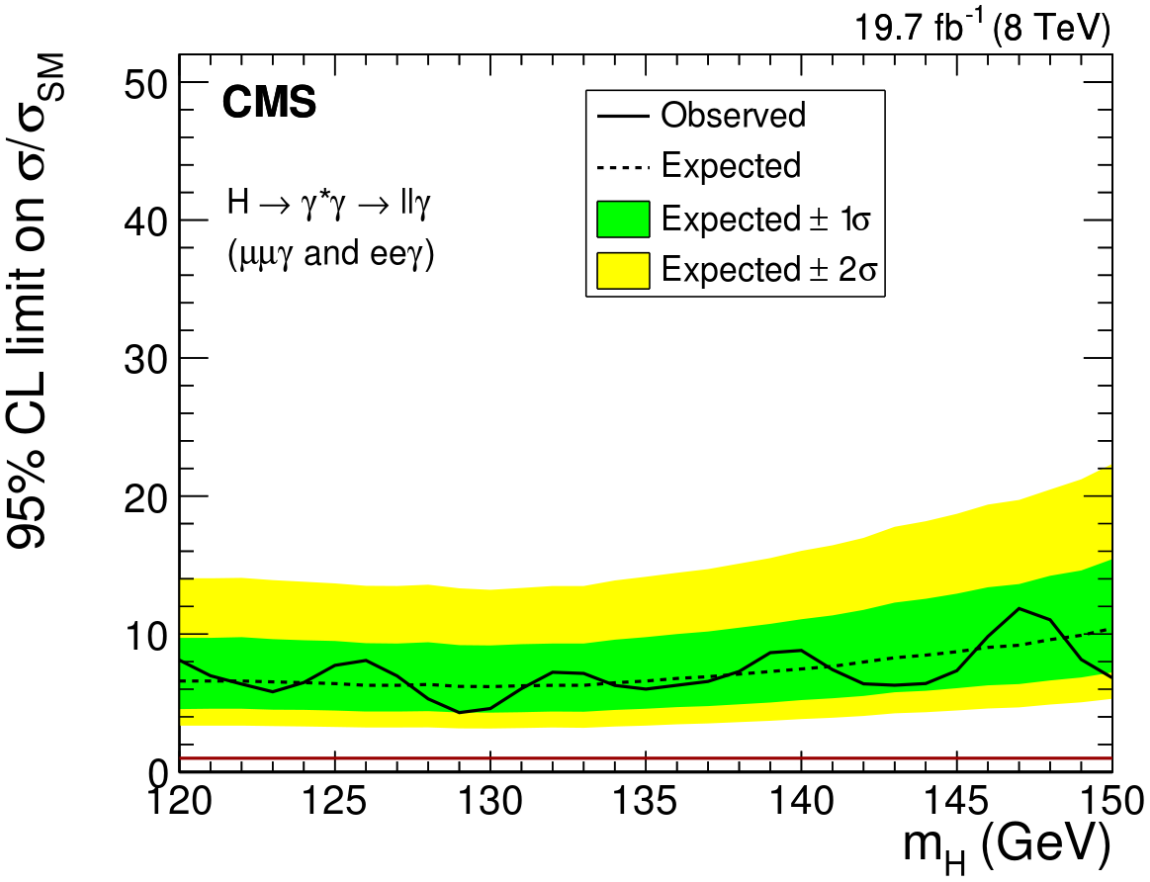


$H \to \gamma^* \gamma \to \mu^+ \mu^- \gamma$





arxiv:1507.03031



$\sigma/\sigma_{SM} < 7.7$ (95% CL)

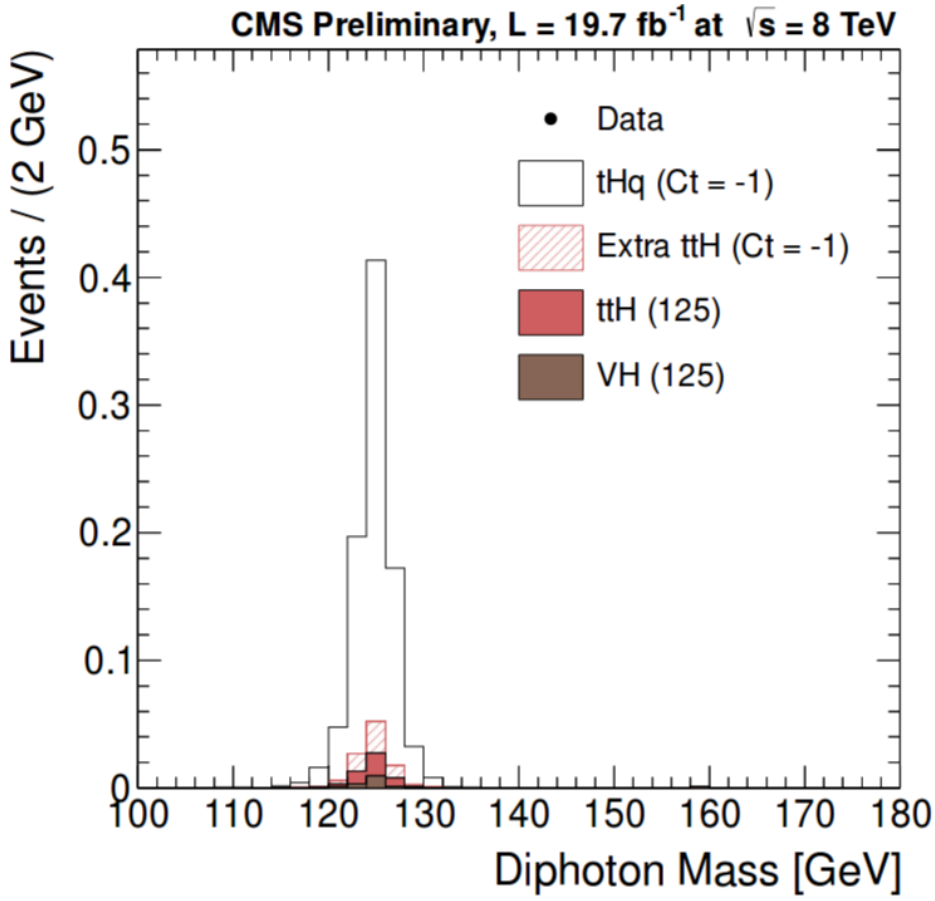
$B(H \to J/\psi\, \gamma) < 1.5 \times 10^{-3}$ (95% CL)

tHq, H→γγ

HIG-14-001

$\sigma/\sigma_{Ct=-1} < 4.1$ (95% CL)

Process	Yield
$tHq\ (C_t = -1)$	0.67
$t\bar{t}H$	$0.03 + 0.05^{\dagger}$
VH	$0.01 + 0.01^{\dagger}$
other H	0



tHq, H→WW

HIG-14-026

$\sigma/\sigma_{Ct=-1} < 6.7$ (95% CL)