CMS experiment: Higgs boson interactions with the gauge sector

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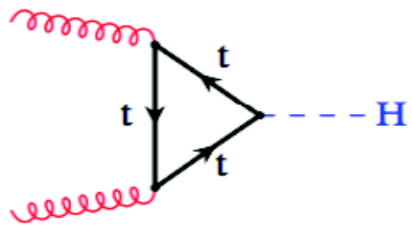
On behalf of the CMS Collaboration

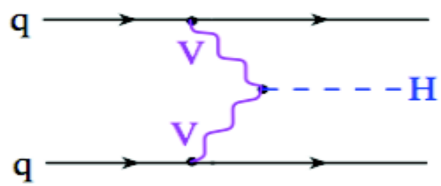
Higgs Couplings 2015 , 12-15 Oct 2015
IPPP, Durham, UK

SM H Boson Production and Decay at LHC

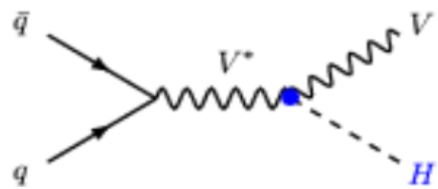
- Gluon fusion



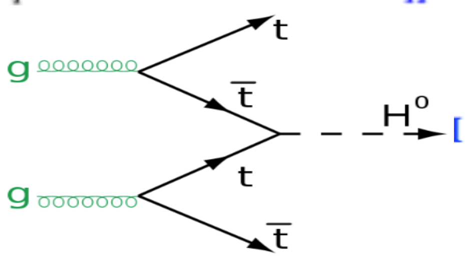
- VBF

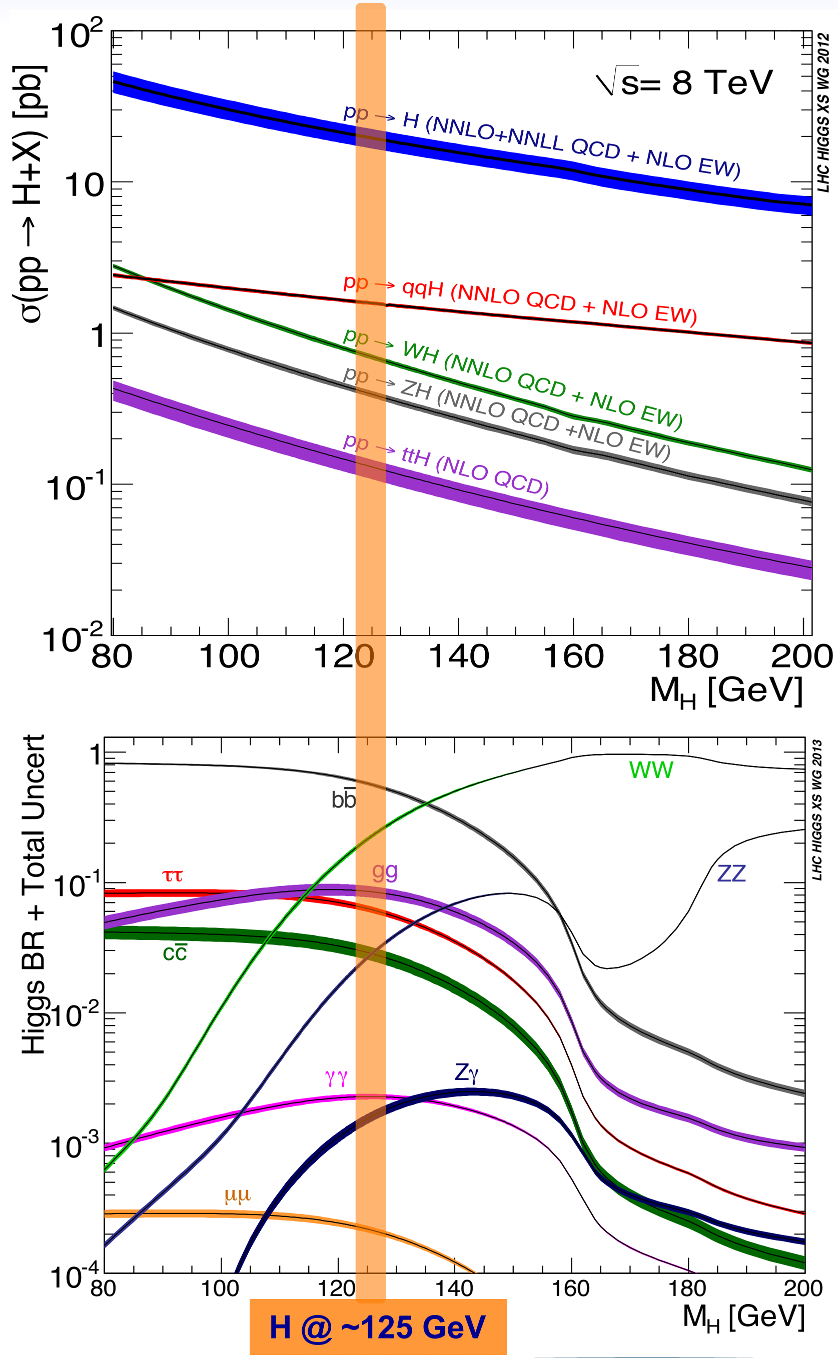


- VH



- ttH





Gluon fusion (gg→H) it the dominant production mechanism at LHC but VBF, VH and ttH allow to test H couplings/properties.

γγ, ZZ and WW decays continue to play a key role to study H@125 GeV properties/couplings

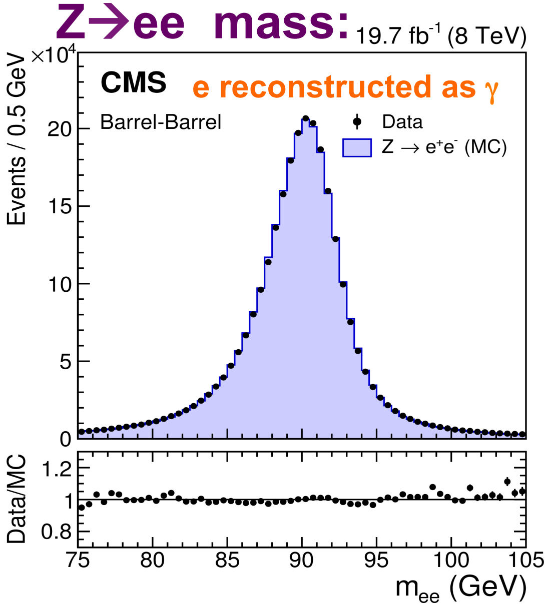
Also studying the Zγ mode.

arxiv:1407.0558

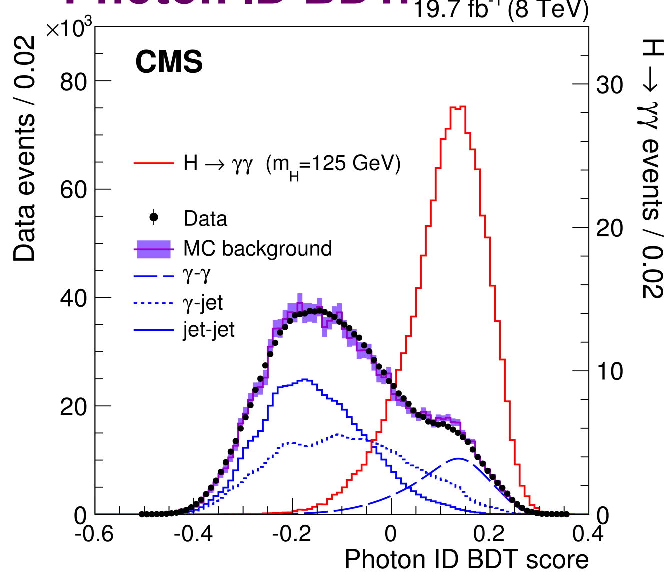
$H \rightarrow \gamma\gamma$: Overview

- Fully reconstructed decay with excellent **mass resolution (1-2%)**
- **Large** continuum background from **QCD γγ and γ+jet → Photon ID BDT to reject jet fakes**
- **Analysis separated in several di-photon categories to exploit different S/B ratio**
- **Dedicated VBF (di-jet BDT) as well as VH and ttH (event topology tags) categories**
  → In total 25 analysis categories (11 in 2011 and 14 in 2012)

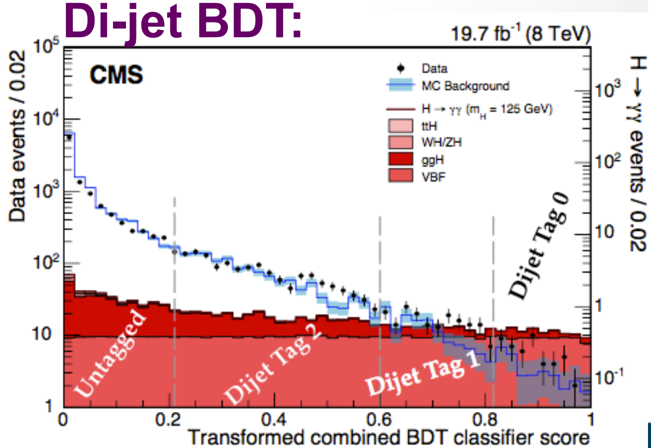
Z→ee mass:



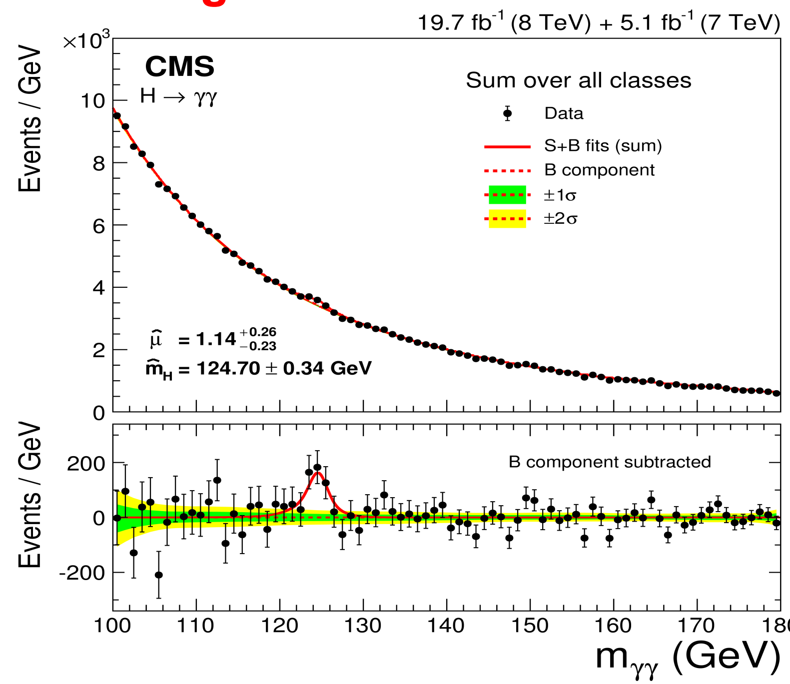
Photon ID BDT:



Di-jet BDT:



- **Background shape fitted from the data $m_{\gamma\gamma}$ invariant mass → search for narrow peak resonance on top of smooth background**

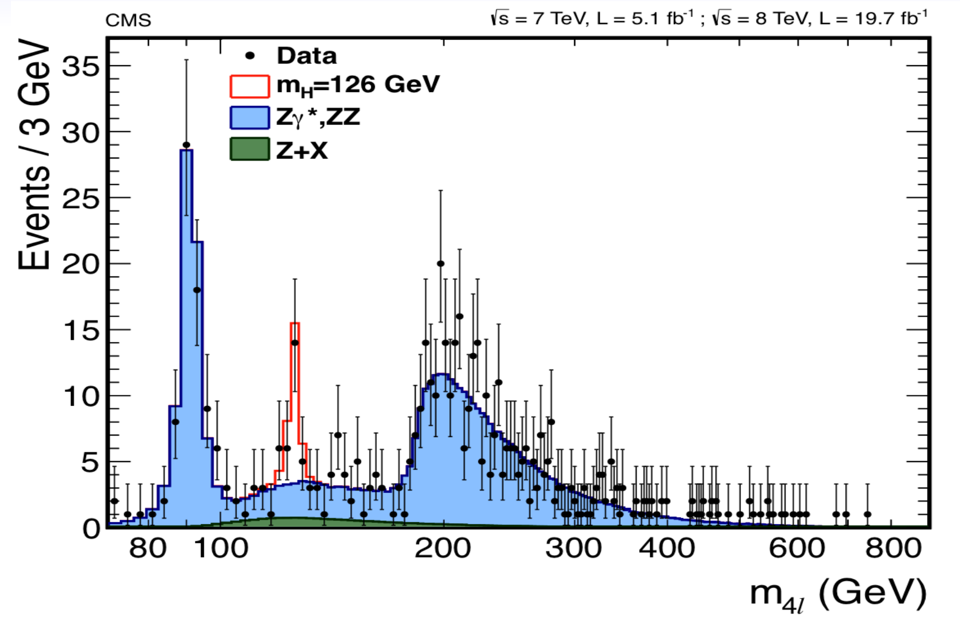


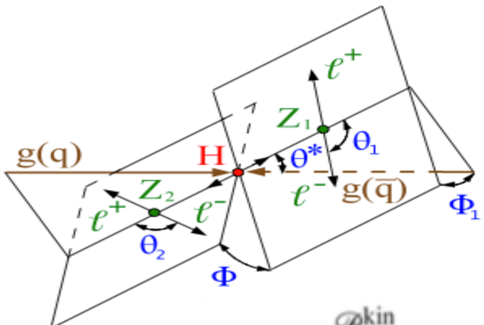
→ 5.7 σ signal around m_H = 125 GeV

Phys. Rev. D89 (2014) 092007

H→ZZ→4l : Overview

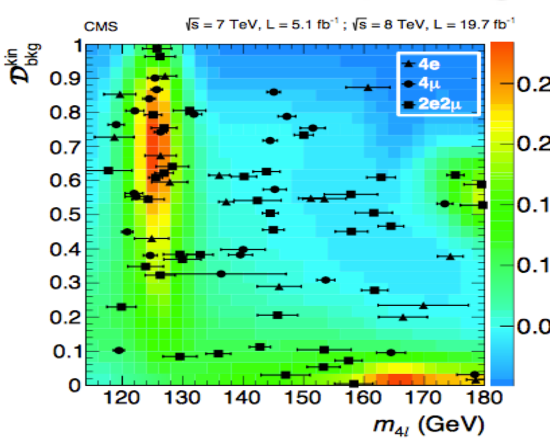
- Search for a narrow peak in 4-leptons (e,μ) invariant mass
- Backgrounds: Z, ZZ and Z+jets
- High S/B ratio
- Use kinematic discriminant and/or categorization to enhance S/B separation based on expected angular distributions
- 3D fit: m_{4l}, kinematic discriminant + p_T (0/1-jet) or LD (2-jet)

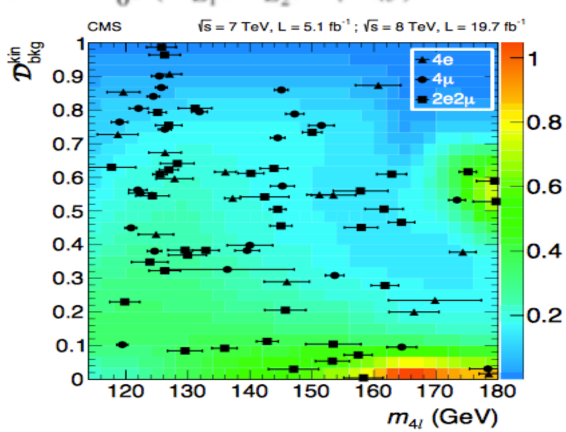


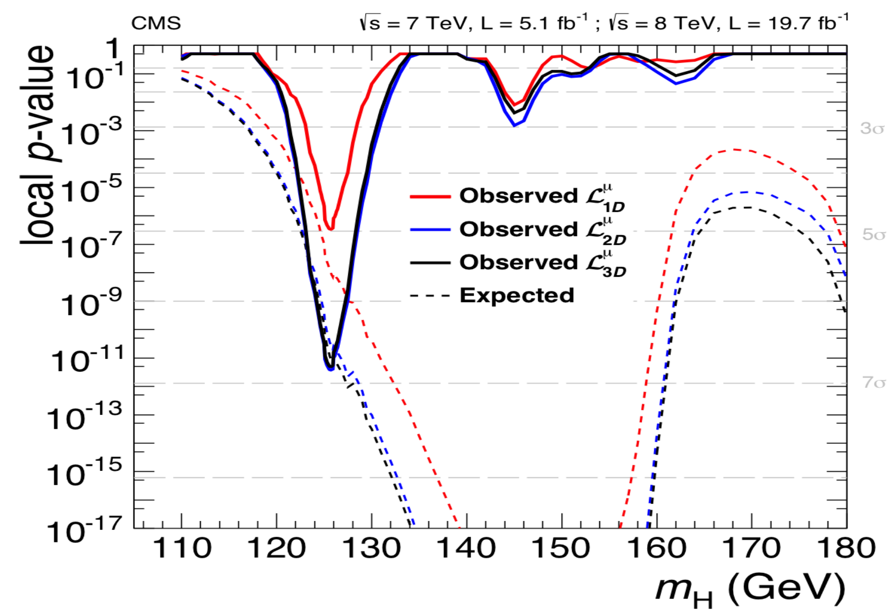


- MELA discriminant use as inputs m_{Z1}, m_{Z2} + five angles

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







→ 6.8 σ signal @ 125.6 GeV

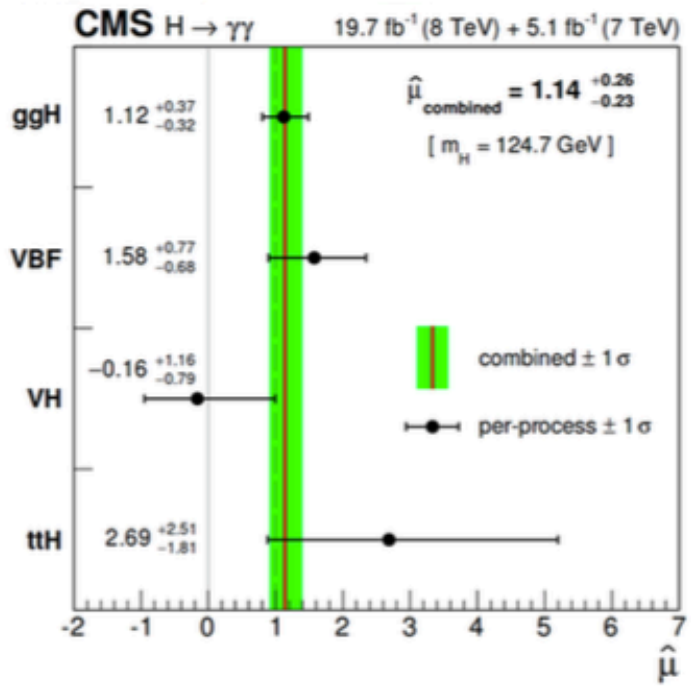
H→γγ & H→ZZ→4l: Signal strength

arxiv:1407.0558

Phys. Rev. D89 (2014) 092007

H→γγ:

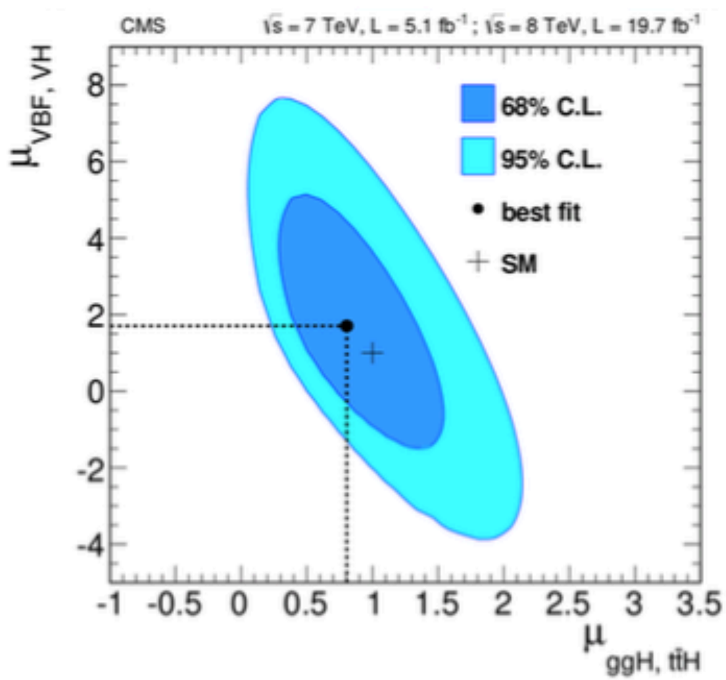
$$\sigma/\sigma_{SM} = 1.14^{+0.21}_{-0.21}(\text{stat.})^{+0.13}_{-0.09}(\text{th.})^{+0.09}_{-0.05}(\text{sys.})$$



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

H→ZZ:

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



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

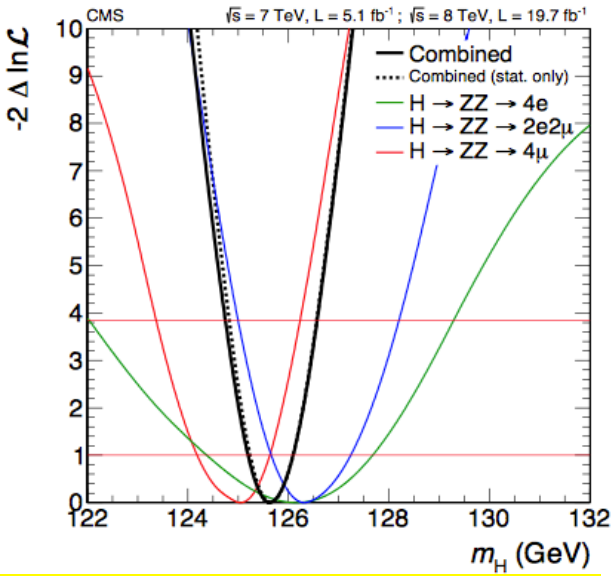
→ **Compatible with SM Higgs** **(within ~23-30% uncertainty on total signal strength)**

+ Talk on Higgs combination ATLAS+CMS this afternoon (K. Grimm)

H→γγ & H→ZZ→4l: Mass

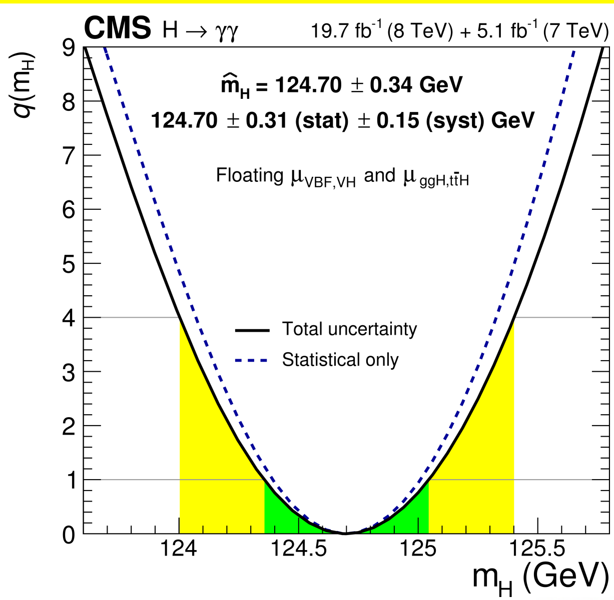
H→ZZ: m_H= 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV

Phys. Rev. D89 (2014) 092007



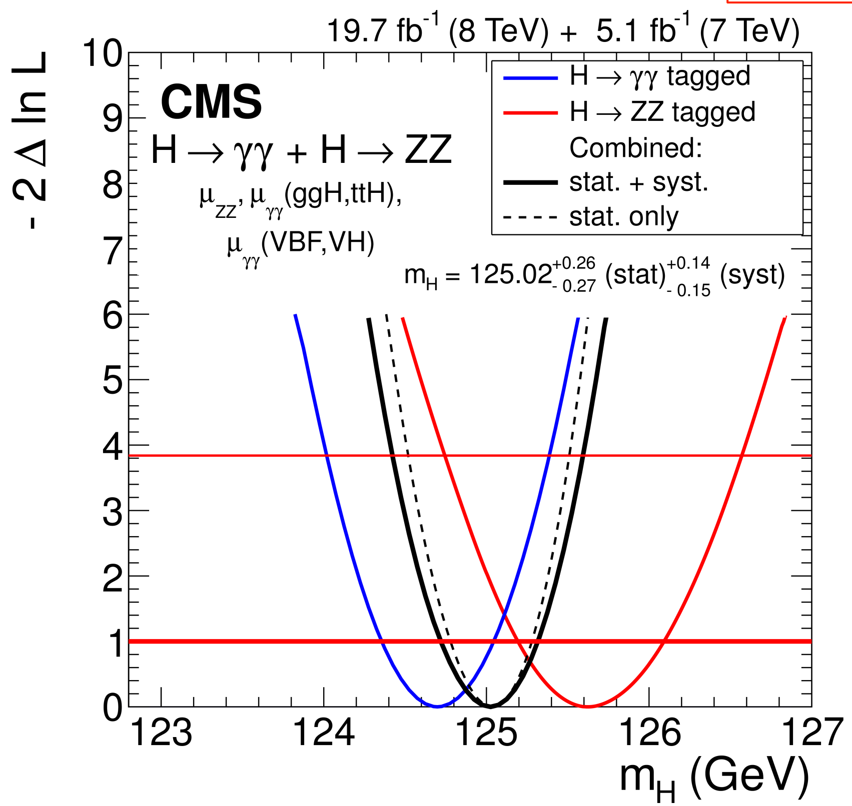
H→γγ: m_H= 124.70 ± 0.31 (stat.) ± 0.15 (syst.) GeV

arxiv:1407.0558



H→gg and H→ZZ Combination:

arxiv:1412.8662



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

$$m_H^{\gamma\gamma} - m_H^{4\ell} = -0.89^{+0.56}_{-0.57}\ \text{GeV}$$

→ Mass Measured with ~0.25% uncertainty by CMS

→ H→gg and H→>ZZ m_H compatible within 1.6 σ

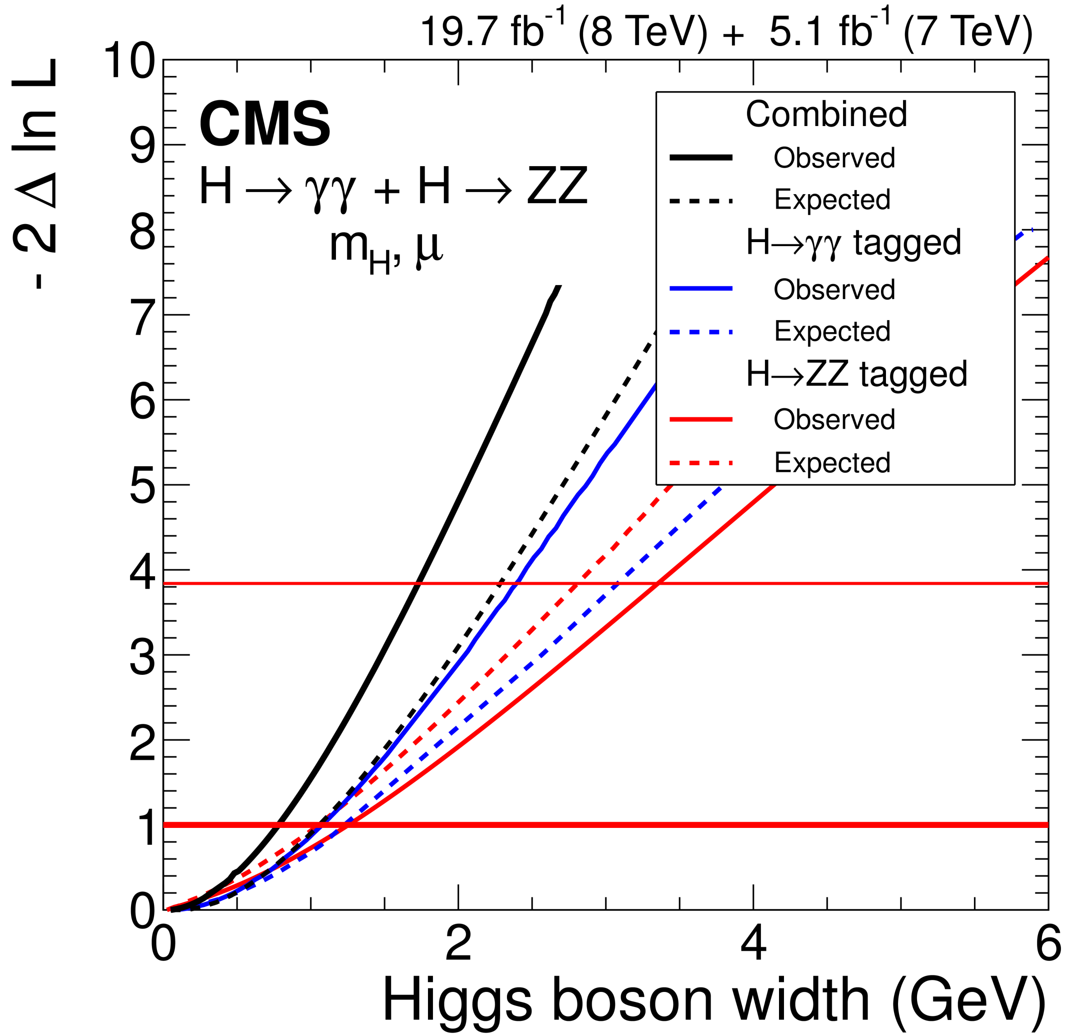
→ Direct width measurement limited by resolution

+ Talk on Mass and Width ATLAS+CMS this afternoon (I. Giotis)

Width from on-shell H→ZZ→4l and H→γγ

arXiv:1412.8662

- For m_H = 125 GeV → Γ_H ~ 4 MeV
- Higgs width from H→ZZ→4l and H→γγ resonance shapes @ ~125 GeV only with reduced precision of ~GeV due to detector resolution for e/γ/μ p_T measurements



@ m_H = 125 GeV:

H→ZZ: Γ_H < 3.4 GeV @ 95% CL
H→γγ: Γ_H < 2.4 GeV @ 95% CL

ZZ+γγ : Γ_H < 1.7 GeV @ 95% CL

>> ~4 MeV SM width theoretical

→ Measurements mostly limited already by resolution

Higgs Width from off-shell H → ZZ

Assuming Higgs boson is produced on-shell is far from real Higgs mass lineshape

→ **Competing effects from BW in high mass region and $\Gamma_{H\to 4l}$ cause plateau**

→ **~8% of total H→ZZ cross section found in $m_{ZZ} > 2m_Z$ region**

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g^2_{ggH} g^2_{HZZ} \frac{F(m_{ZZ})}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

Which gives for on-peak:

$$\sigma^{on-peak}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H},$$

and for off-peak:

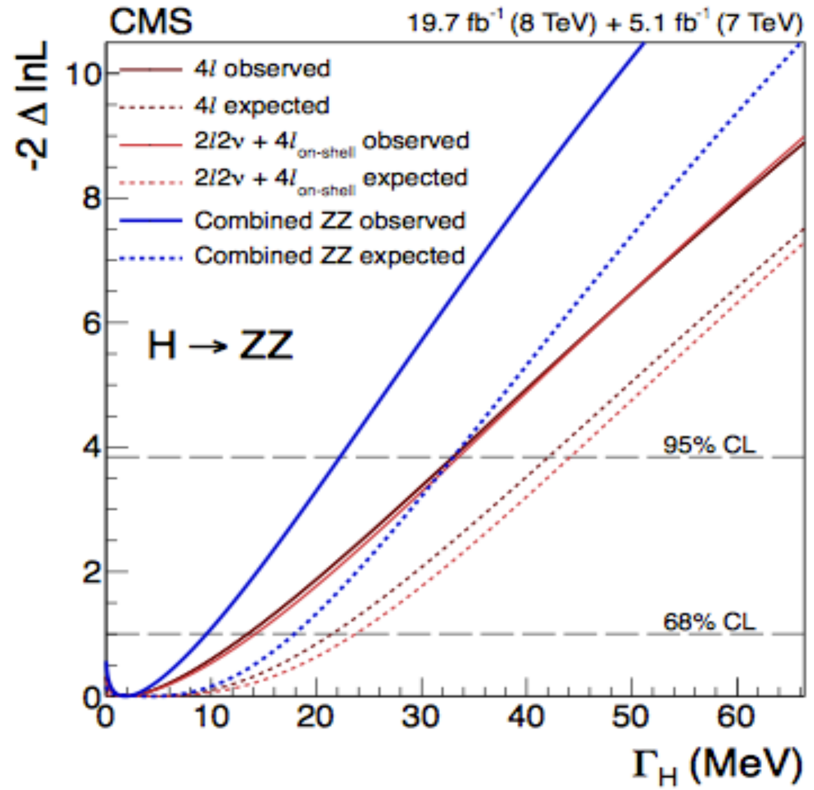
$$\sigma^{off-peak}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

→ **Off-peak to peak ratio sensitive to Γ_H:**

$$\frac{\sigma_{off-peak}}{\sigma_{peak}} \propto \Gamma_H$$

→ **Need to account for large interference with non resonant ZZ background at high m_{ZZ}**

- **H→ZZ→4l: Dedicated MELA discriminant**
- **H→ZZ→2l2v: High mT region**



→ $\Gamma_H < 5.4 \times \Gamma_{SM}$
→ $\Gamma_H \leq 22$ MeV

+ Talk on Mass and Width ATLAS+CMS this afternoon (I. Giotis)
+ Talk on H lifetime with H→ZZ→4l on Wednesday (c. You)

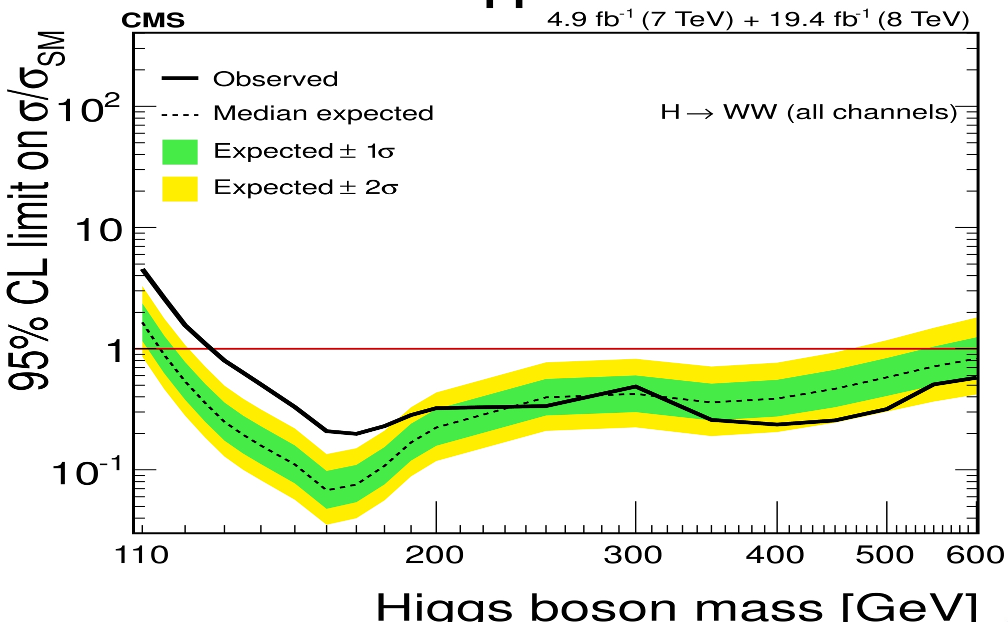
H→WW

Final states with 2 leptons:

- ❑ **2 leptons (e or μ) + MET**
- ❑ **H→WW→2l2ν + 0/1-jet**
  - → 2D Shape in m_{ll}/m_T (eμ) & cuts (ee/μμ)
- ❑ **VBF H→WW →2l2ν + 2q**
  - → $|\Delta\eta(jj)| > 3.5$ & $m_{jj} > 500$ GeV
  - → 1D Shape in m_{ll} (eμ) & cuts (ee/μμ)
- ❑ **VH→ 2l2ν + 2q**
  - → V=W/Z: $65 < m_{jj} < 105$ GeV & $|\Delta\eta(jj)| < 1.5$
  - → cut based analysis

Final states with 3 leptons:

- ❑ **WH → WWW → 3l3ν**
- ❑ **ZH → ZWW → 3lνqq**

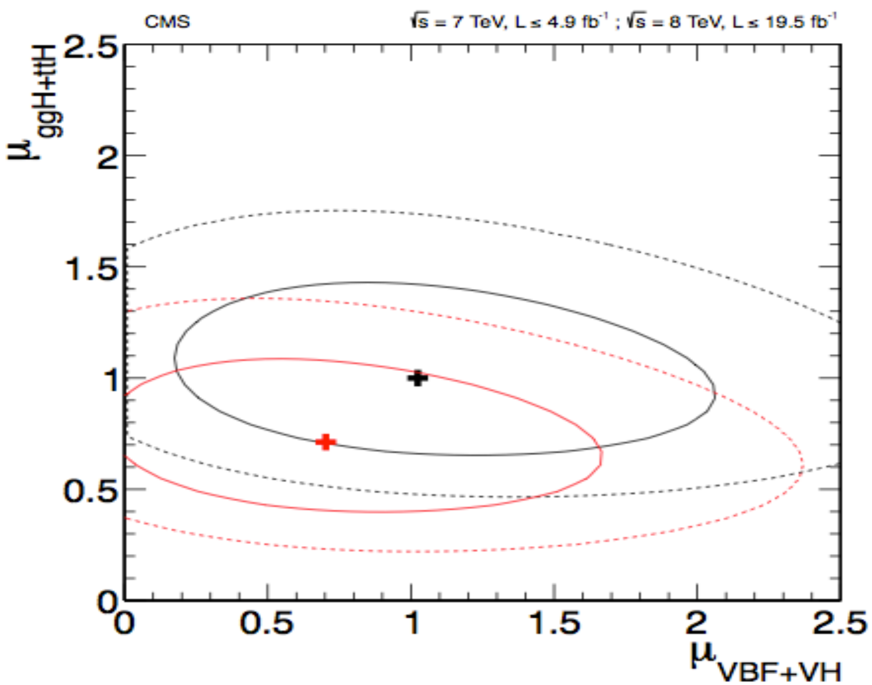


→ **Large excess at low Higgs mass**

→ **@ m_H = 125.6 GeV:**

$\mu = 0.71 \pm 0.12\ (\text{stat.}) \pm 0.14\ (\text{syst.})$
$= 0.71 \pm 0.18\ (\text{stat.+syst.})$

	Exp.	Obs.
Significance	5.8 σ	**4.3 σ**



→ **Compatible within 1 σ with SM**

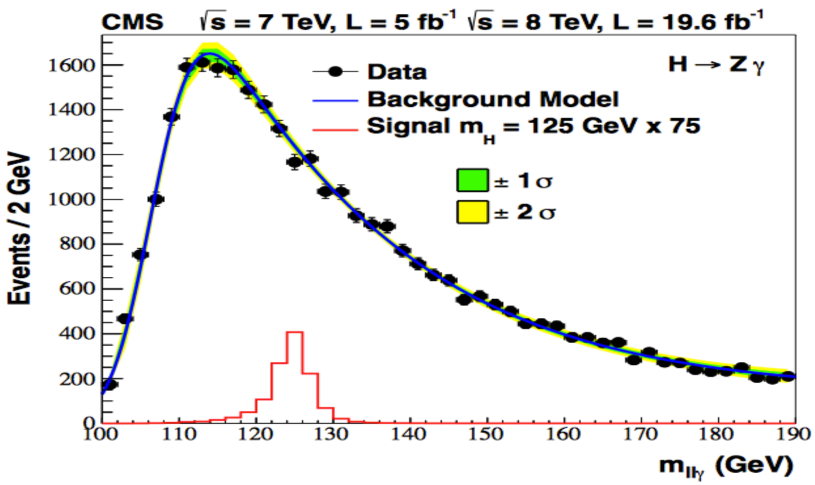
→ **Good precision on ggH**

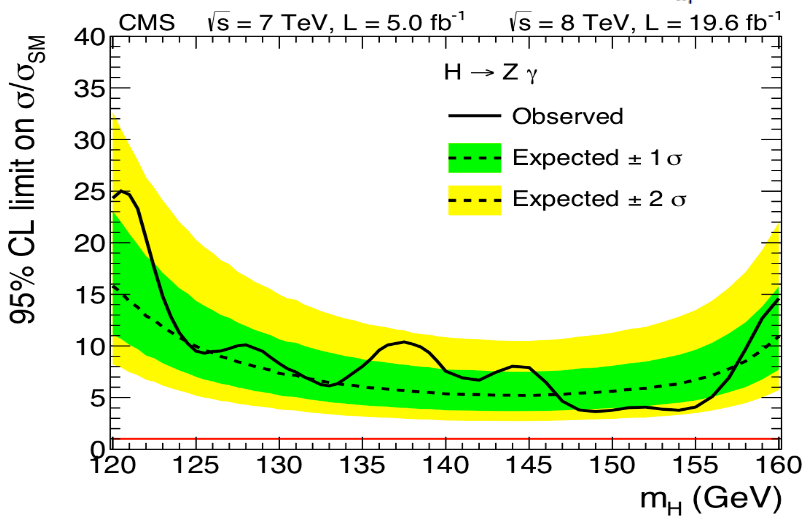
→ **Large error for VBF+VH**

H→Zγ and H→γγ*→γl+l-

H→Zγ

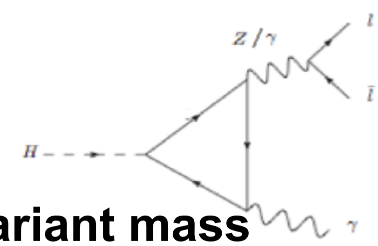
- Select e+e-γ and μ+μ−γ events with m_{ll}>50 GeV
- If more than one l+l- pair, select the one most compatible with Z mass



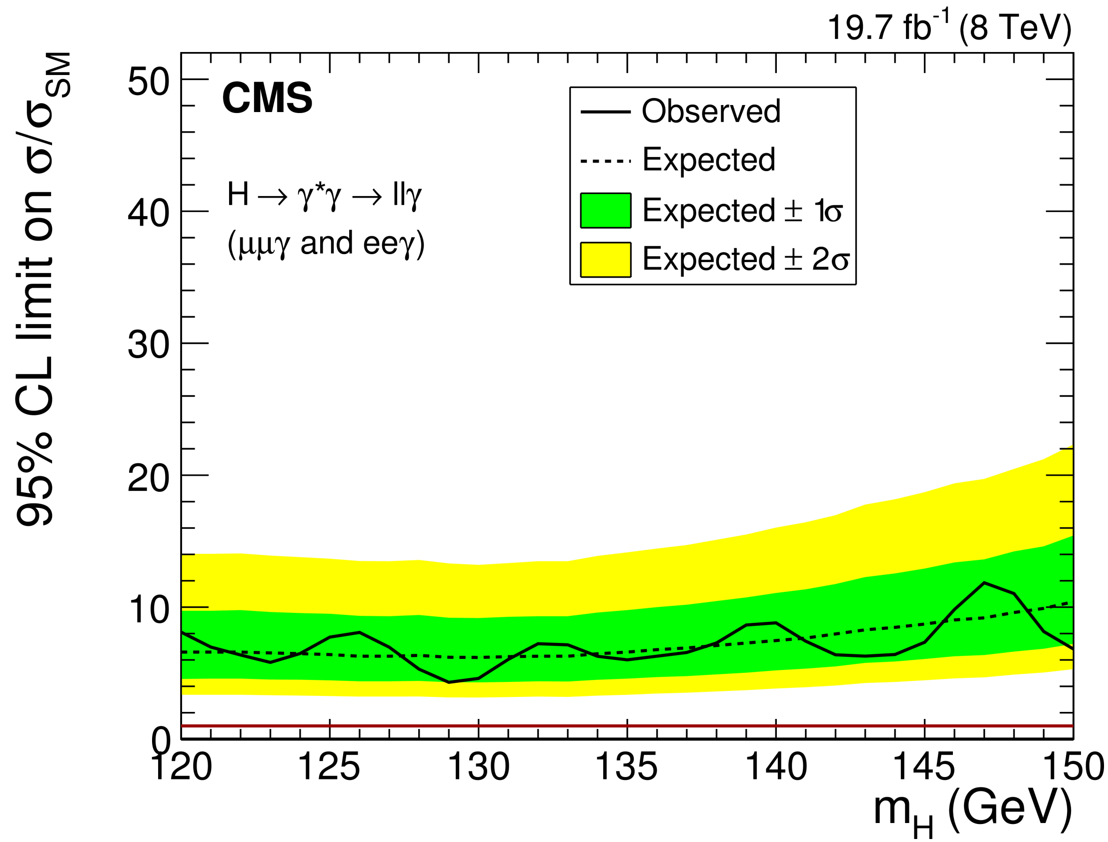


→ Sensitivity 5-16 x SM, no excess of events observed

H→γγ*→γl+l-



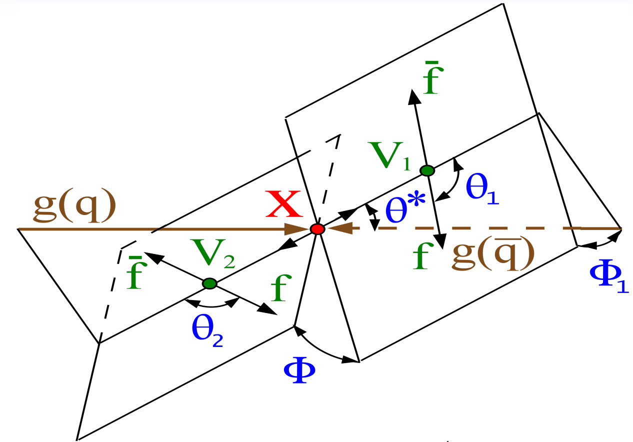
- Search for H→γγ events where one γ converts to a e or μ pair
- Isolated lepton pair at low invariant mass
- Reject known resonance (J/Ψ, Y)
- ΔR(l,γ)>1 → Suppress events with γ radiation



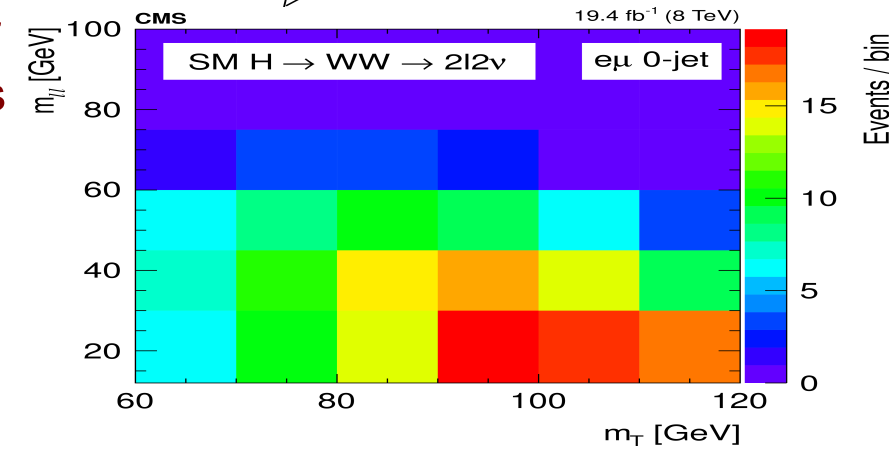
→ Sensitivity ~7 x SM, no excess of events

arXiv:1411.3441

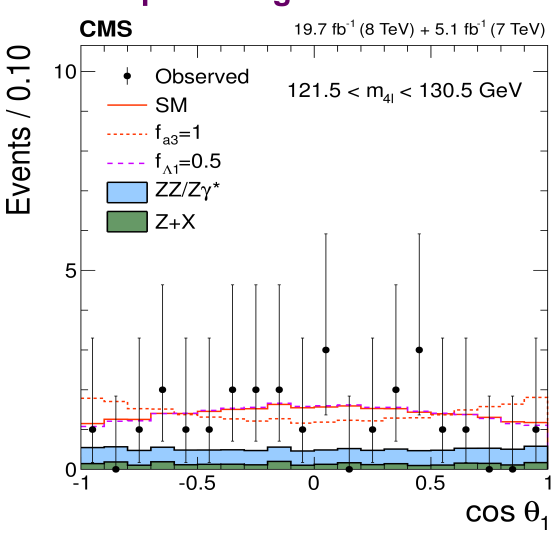
Higgs Spin and Parity

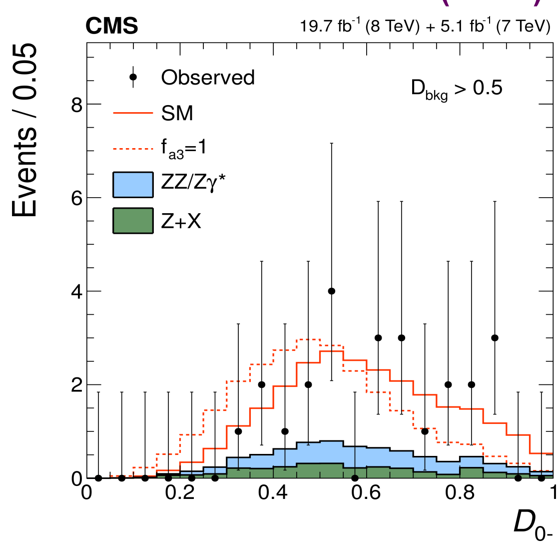


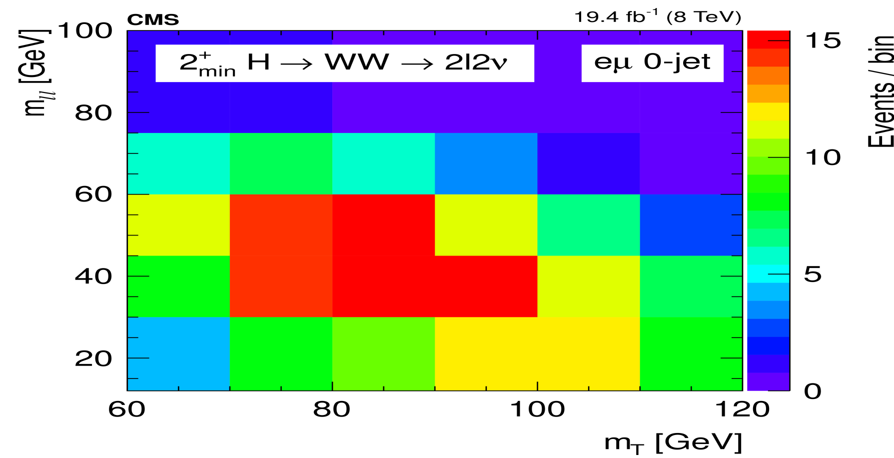
- **Study the kinematic distributions of the decay products:**
  - Two production angles: θ* and Φ1 in the X rest frame
  - Three decay angles: θ1, θ2, and Φ in the V rest frames
- **Angular distributions determined by the tensor structure of the HVV interactions**
- H→ZZ→4l: The information is condensed in a set of discriminants based on **Matrix Element** calculations
- H→WW: Reduced information available
  → 2D templates of m_{ll}, m_T in eμ channel 0/1-jet



Example of angular distribution and discriminant for SM vs. 0- (fa1=1):



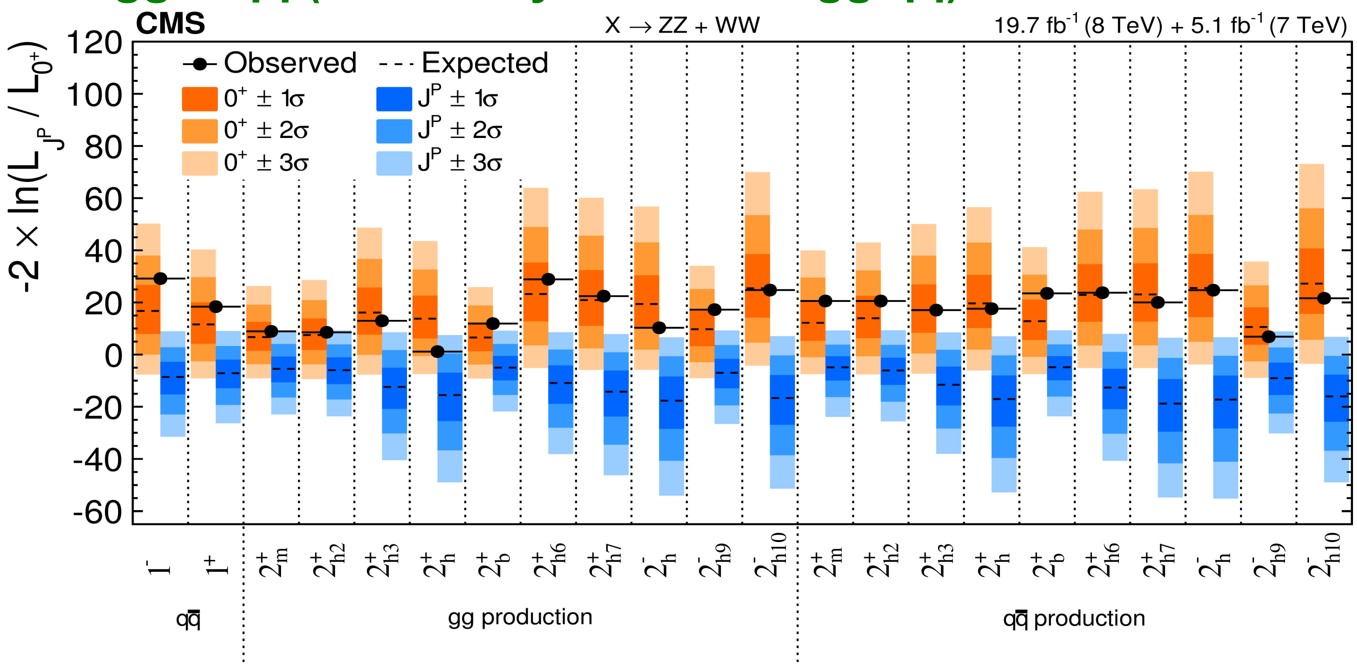




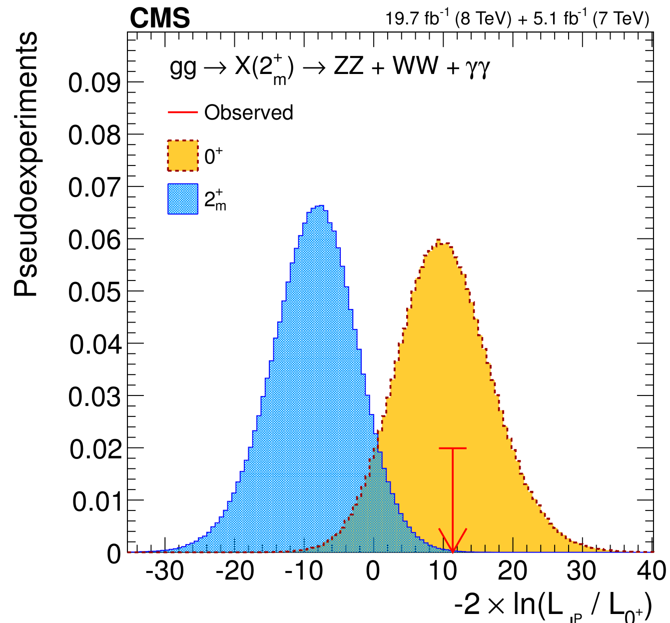
Spin 1&2

- J=1 not allowed for $X \to \gamma\gamma$ by the Landau-Yang theorem
  → Test for ZZ & WW under assumption it decouples from γγ

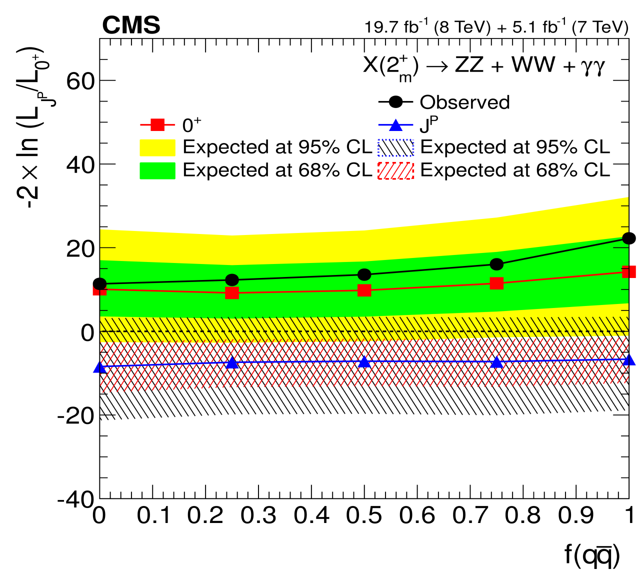
- Testing 10 models (x) 2 production modes
  gg & qq (+ arbitrary mixture of gg/qq)



Example: $gg \to 2^+_m$ with ZZ+WW+γγ



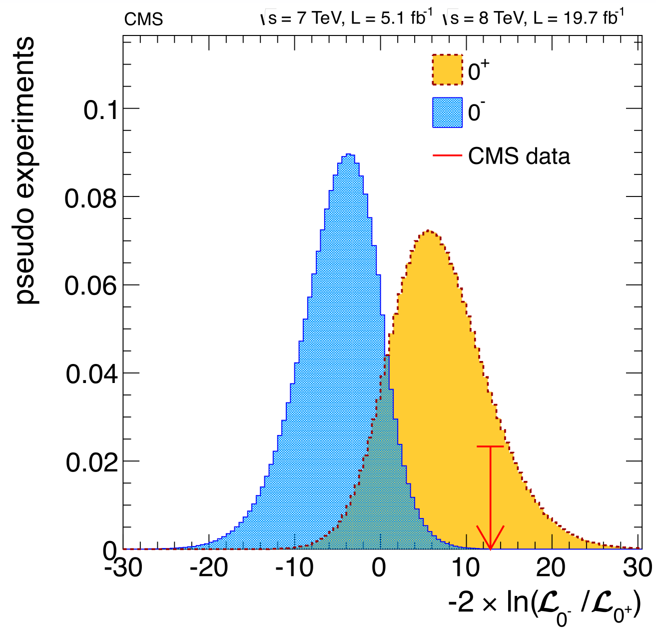
… and as function of f_{qq}



→ All spin-1 hypotheses excluded at > 99.996% CL
→ Spin-2 boson 2+m, excluded at a 99.99% CL
→ Other spin 2 excluded at > 99%
→ So it has to be spin 0 !

Spin 0 and anomalous couplings

arXiv:1411.3441

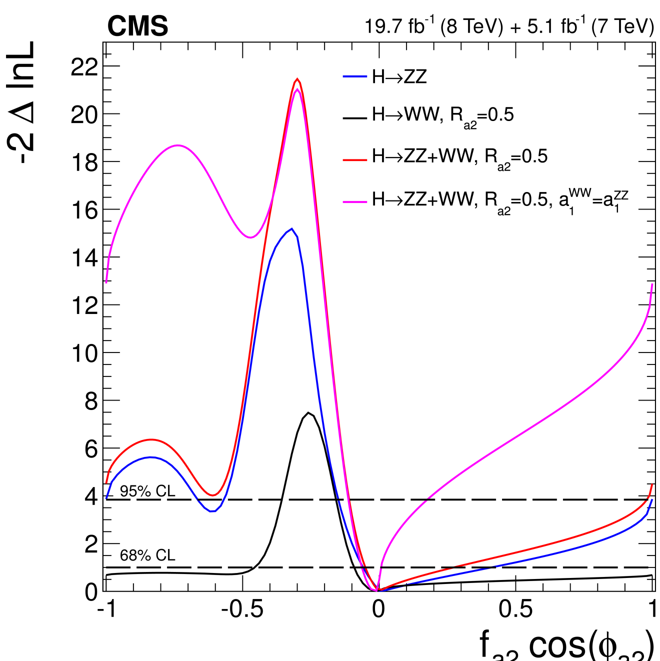


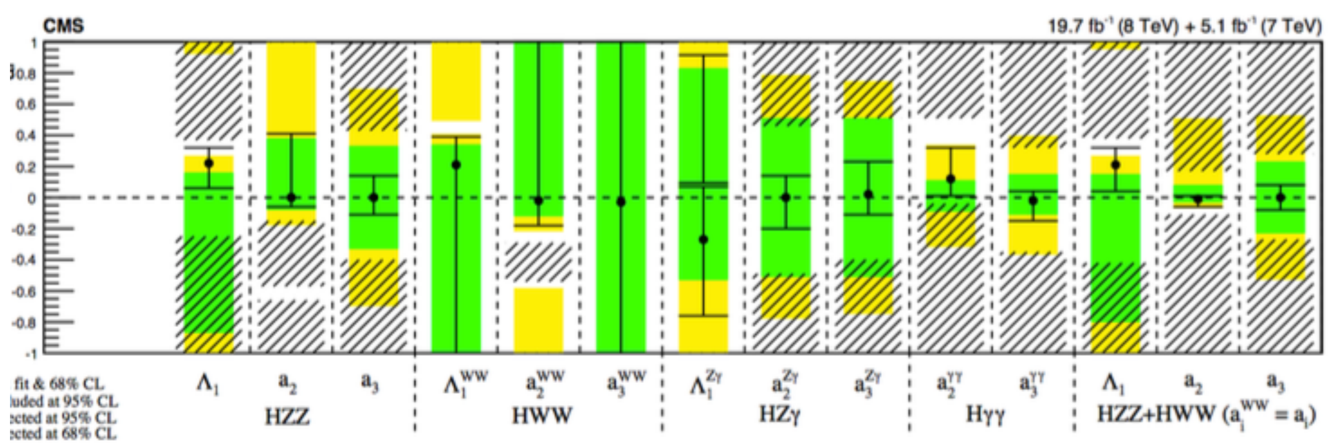
- **Pure 0^- ruled out at 99.9% CL by H→ZZ→4l alone**
- **Study small deviations of couplings to gauge bosons of the HVV spin 0 tensor:**

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V_1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V_2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2}\right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V_1}}^* \epsilon_{\mathrm{V_2}}^* + a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu} + a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}$$

Λ_1 term: leading momentum expansion
a_2 term: CP even state
a_3 term: CP odd state

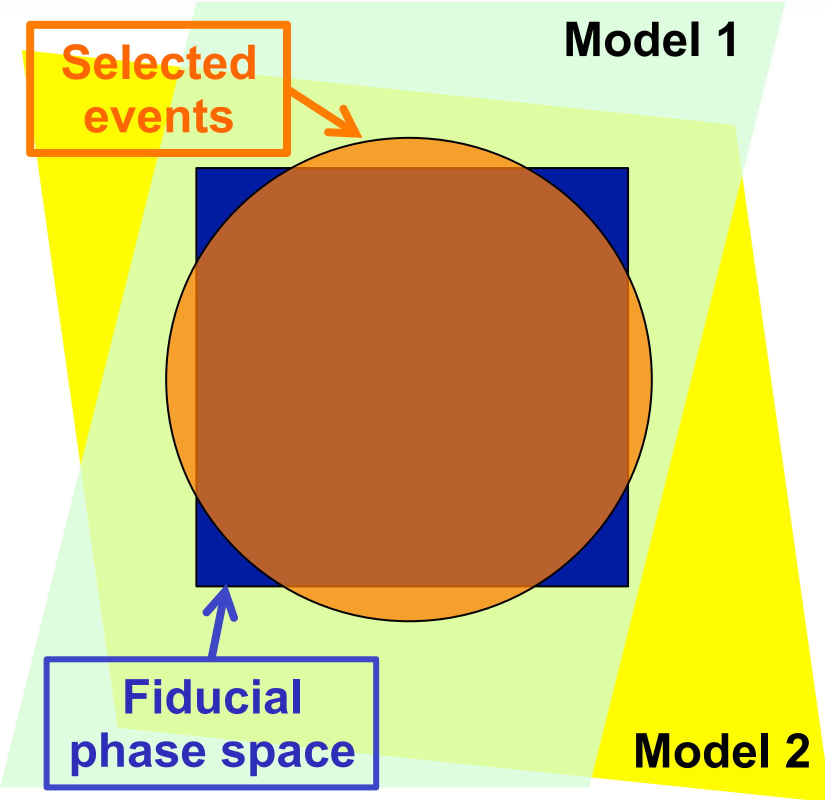
- **Use parameterization that relates cross sections fractions: f_{a2}, f_{a3}, $f_{\Lambda1}$**
- **Combine ZZ and WW w.r.t. to ratio of couplings in both channels: R_{ai}**





→ No sign of deviations to the SM but need more data to better constraints some of the couplings

Fiducial and Differential Cross-sections



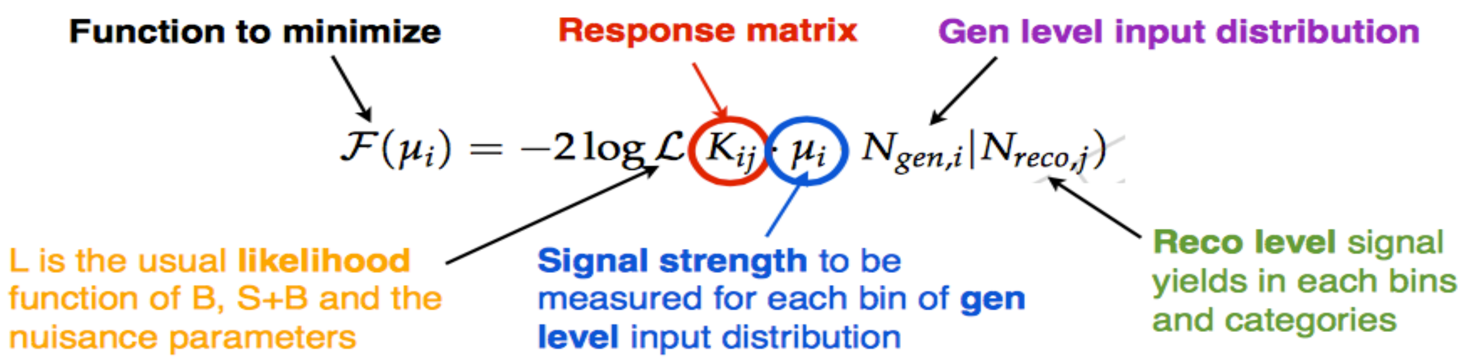
Design fiducial phase-space selection:

- ❑ **As close as possible to the reconstructed level selection**
- ❑ **Unfolding should only impact minimally the distributions: minimize extrapolation to larger phase-space**

Fiducial should minimize model dependence:

- ❑ **Try to have the acceptance similar for different "reasonable" signal models**
- ❑ **Definition should be easily implemented in different MC simulation**

- ❑ **Signal extraction: Fit mass ($m_{\gamma\gamma}$ or m_{4l}) in bins of the desired quantity (e.g. $p_{T,H}$)**
- ❑ **Unfolding: Fold in the response matrix** into the likelihood minimization



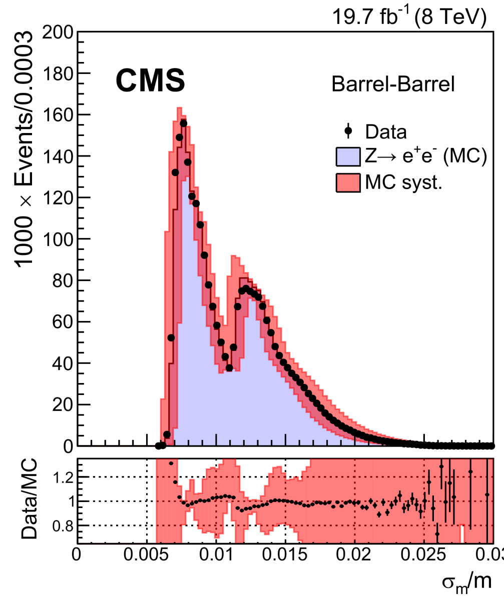
arXiv:1508.07819

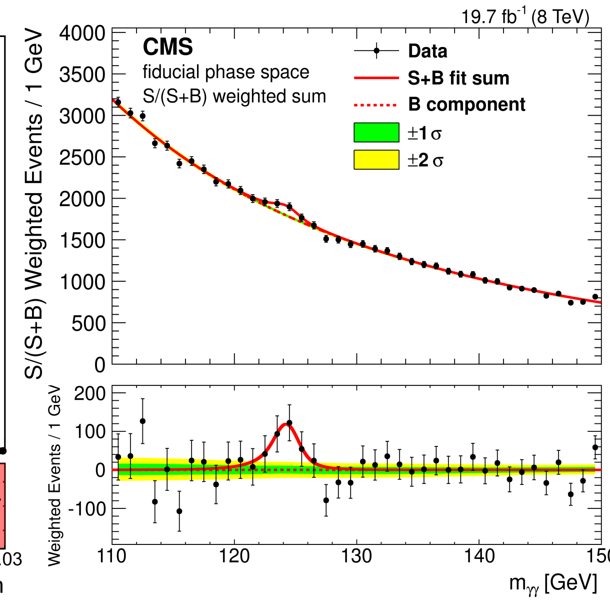
H→γγ Fiducial Cross-section

Fiducial Volume:
- $|\eta_\gamma| < 2.5$
- Isolated γ: $\sum_i E_{T,i} < 10$ GeV in a $\Delta R < 0.4$ cone around γ
- $p_T^{\gamma 1}/m_{\gamma\gamma} > 1/3$
- $p_T^{\gamma 2}/m_{\gamma\gamma} > 1/4$

→ ~60% signal efficiency

Methodology:
- Perform event classification in $\sigma(m_{\gamma\gamma})/m_{gg}$
  → Avoid kinematic correlations to observable (like in BDT)
- Fit $m_{\gamma\gamma}$ in each class in bins of the observable
- Include response matrix in LH to correct to particle level





→ Observed cross-section in fiducial volume:

$$\sigma_{\text{obs}} = 32^{+10}_{-10}\,(\text{stat})^{+3}_{-3}\,(\text{syst})\,\text{fb},$$

→ In agreement with theory predictions:

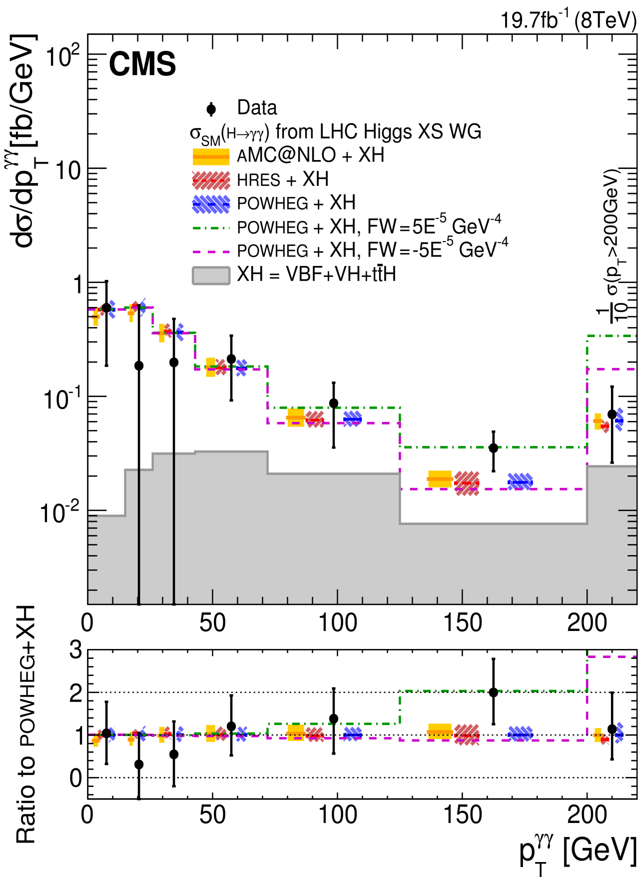
$$\sigma_{\text{HRES+XH}} = 31^{+4}_{-3}\,\text{fb},$$

$$\sigma_{\text{POWHEG+XH}} = 32^{+6}_{-5}\,\text{fb},$$

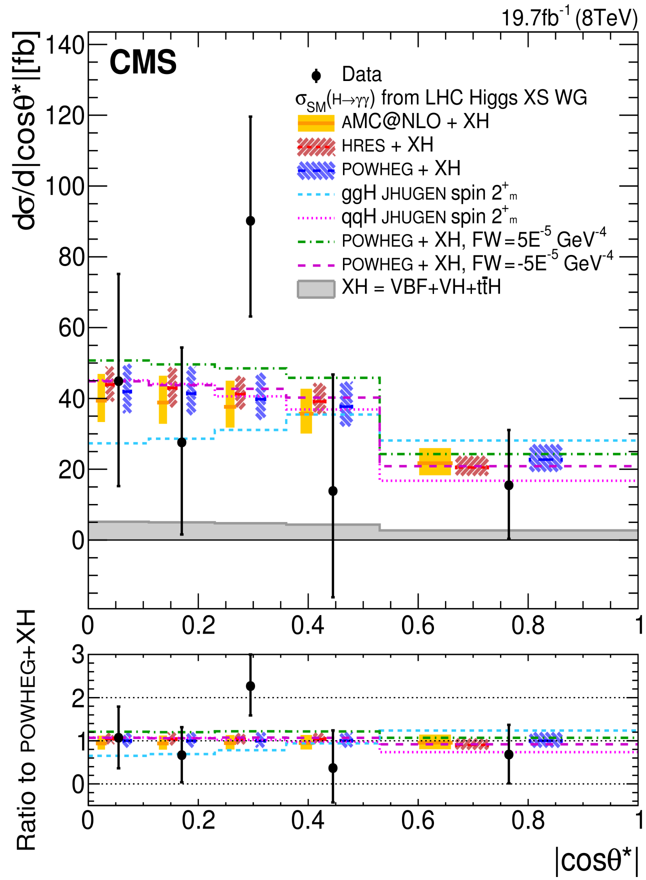
$$\sigma_{\text{MADGRAPH5\_aMC@NLO+XH}} = 30^{+6}_{-5}\,\text{fb}.$$

H→γγ Differential Cross-sections

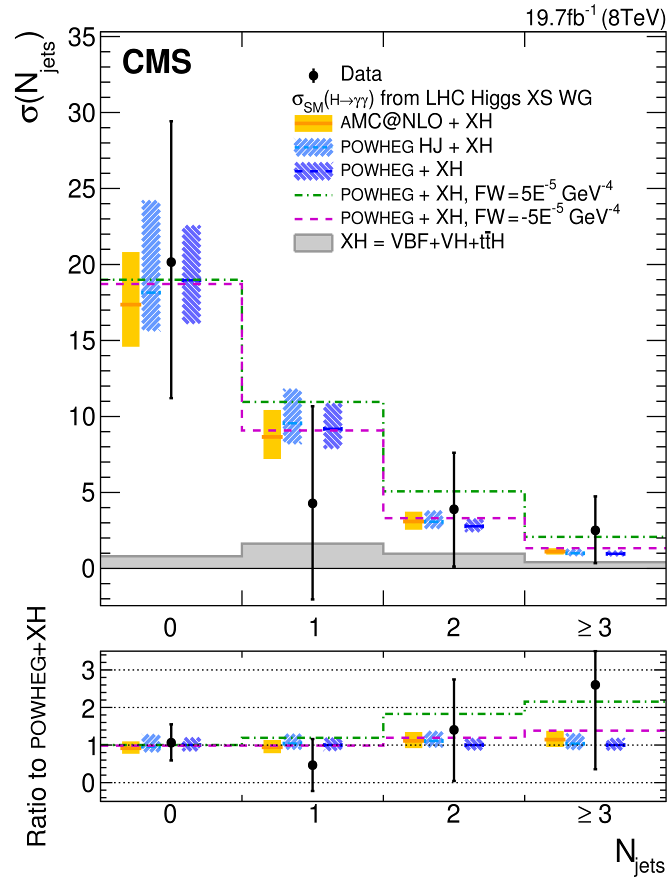
$p_{T,Higgs}$



|cos Θ* |



jets in |η|<2.5



→ **Already some good precision**
→ **Data fairly described by theory predictions**
→ **More variables in backup**

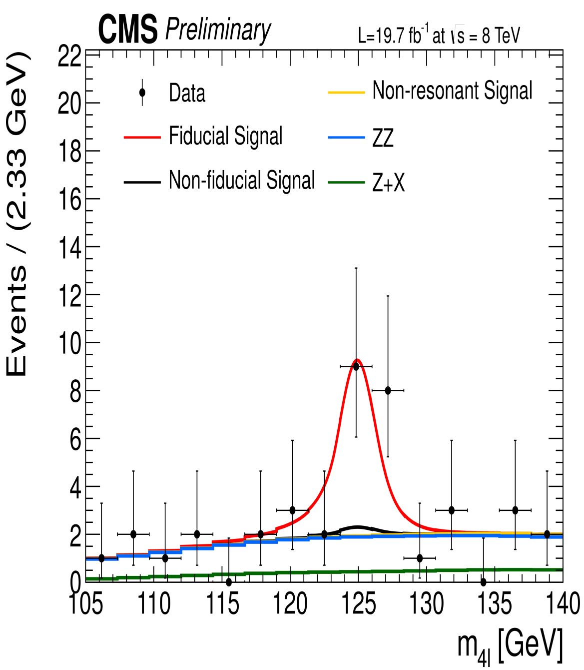
H→ZZ→4l Fiducial Cross-section

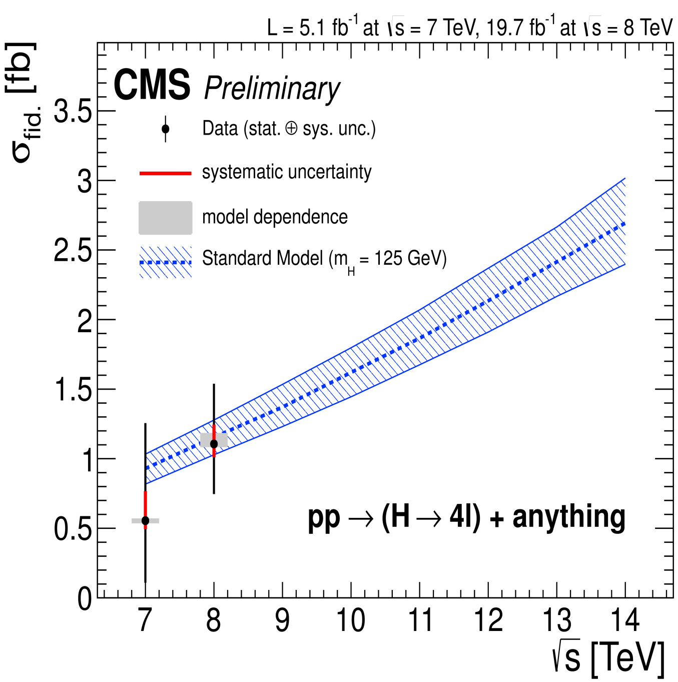
CMS-PAS-HIG-14-028

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_T	$p_T > 20$ GeV
next-to-leading lepton p_T	$p_T > 10$ GeV
additional electrons (muons) p_T	$p_T > 7(5)$ GeV
pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
p_T sum of all stable particles within $\Delta R < 0.4$ from lepton	less than $0.4 \cdot p_T$
Event topology	
existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
inv. mass of the Z_1 candidate	$40\,\text{GeV} < m(Z_1) < 120\,\text{GeV}$
inv. mass of the Z_2 candidate	$12\,\text{GeV} < m(Z_2) < 120\,\text{GeV}$
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$m(\ell^+ \ell'^-) > 4\,\text{GeV}$
inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$
the selected four leptons must originate from the $H \to 4\ell$ decay	

Methodology:

- Fit the m_{4l} in bins of the variable including:
  - backgrounds
  - fiducial signal
  - non-fiducial signal
- LH fit embedding the response matrix to correct to particle level





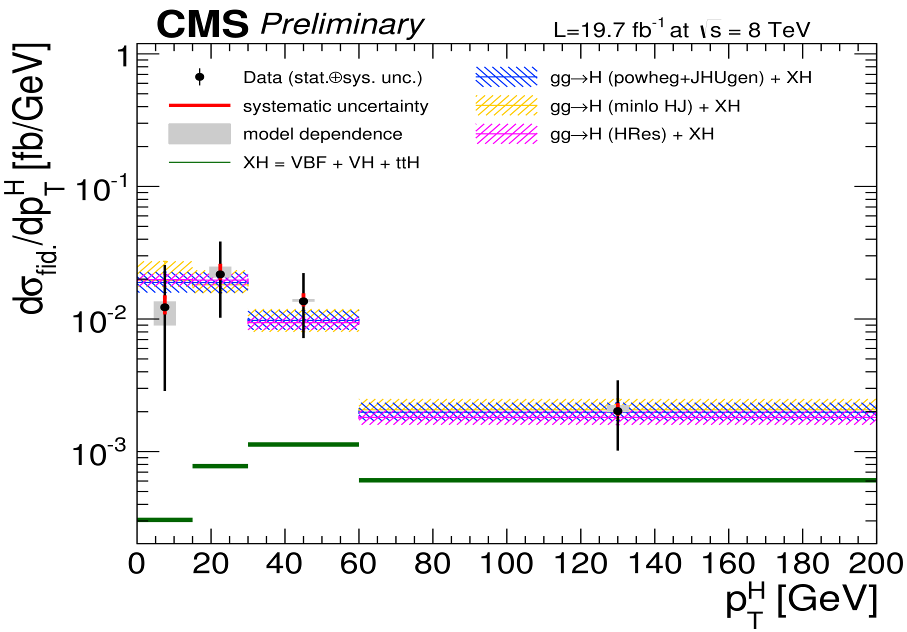
Fiducial cross section $H \to 4\ell$ at 7 TeV	
Measured	$0.56^{+0.67}_{-0.44}$ (stat.) $^{+0.21}_{-0.06}$ (sys.) $^{+0.02}_{-0.02}$ (model) fb
$gg \to H$(HRES) + XH	$0.93^{+0.10}_{-0.11}$ fb
Fiducial cross section $H \to 4\ell$ at 8 TeV	
Measured	$1.11^{+0.41}_{-0.35}$ (stat.) $^{+0.14}_{-0.10}$ (sys.)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

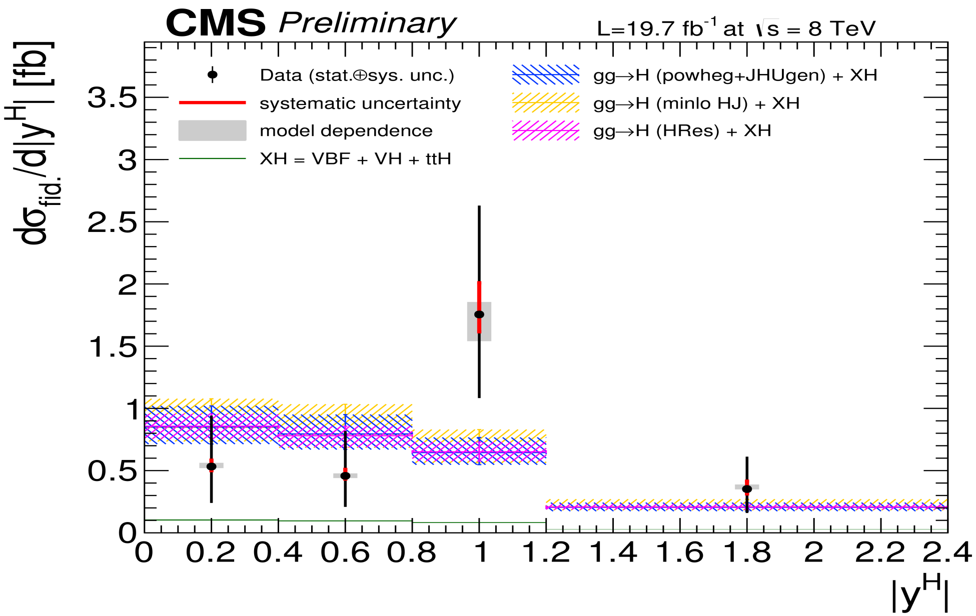
→ Good agreement with theory predictions

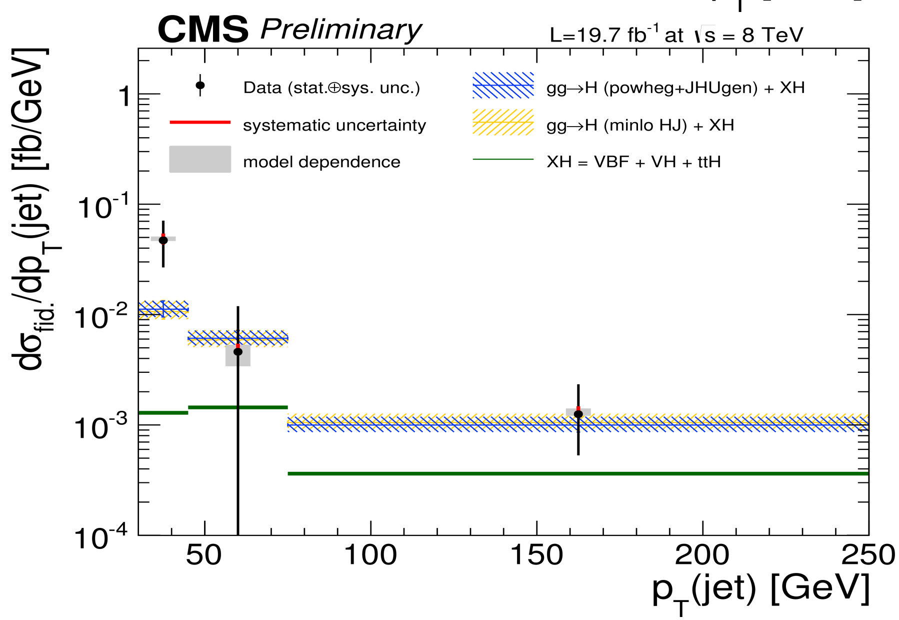
H→ZZ→4l Differential Cross-sections

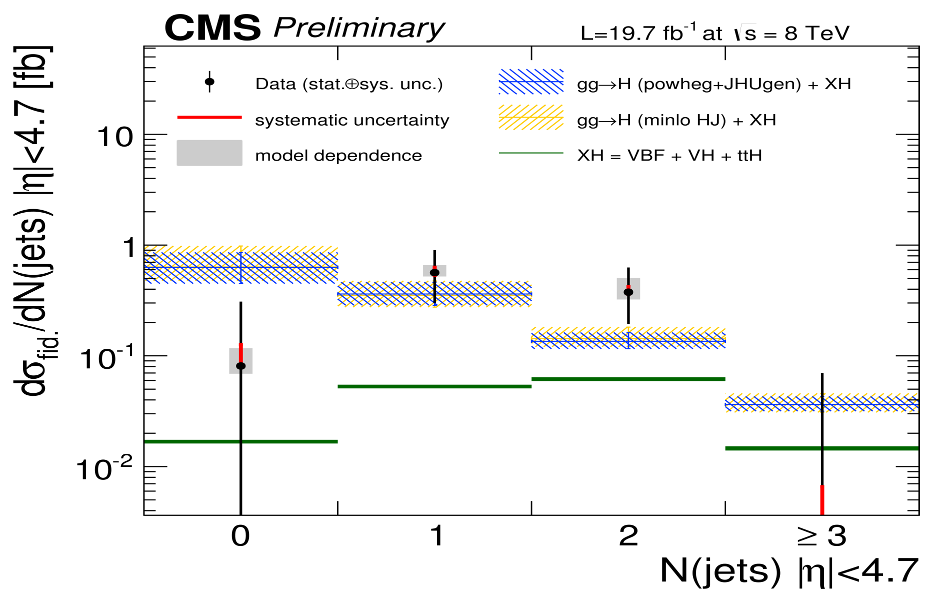
CMS-PAS-HIG-14-028

Enough data at 8 TeV to extract differential cross-sections already:









Conclusions

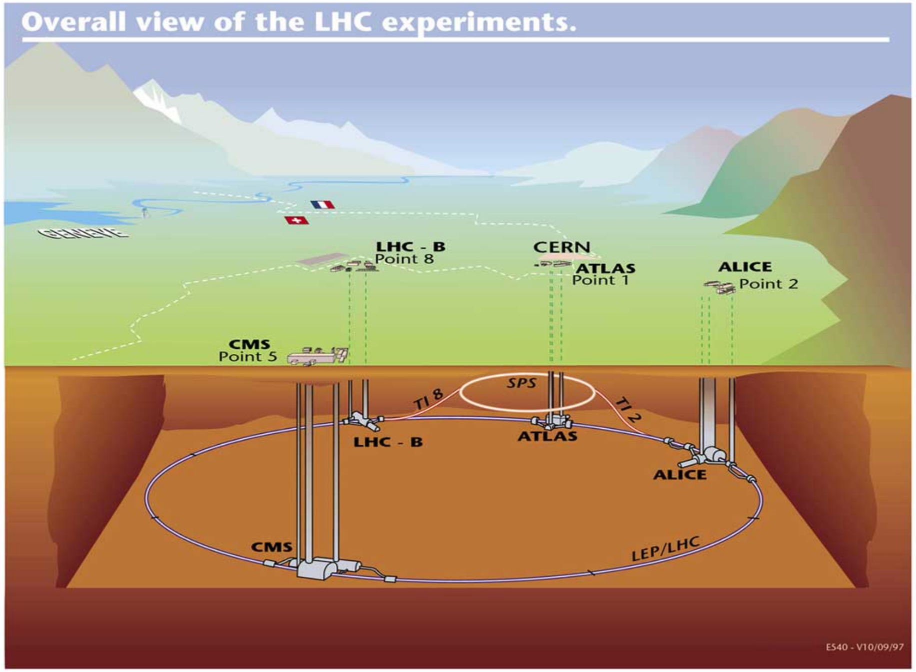
After the Higgs discovery in 2012, the CMS $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow WW \rightarrow 2l2\nu$ analysis's allowed to further measure its properties:

- **Higgs Mass** ($\gamma\gamma$+ZZ): $m_H = 125.02^{+0.26}_{-0.27}\,(\text{stat})^{+0.14}_{-0.15}\,(\text{syst})$
- **Higgs Width**:
  - Direct Measurement ($\gamma\gamma$+ZZ): $\Gamma_H < 1.7$ GeV @ 95% CL
  - Constraint from ZZ off-shell: $\Gamma_H < 22$ MeV @ 95% CL
- Precise measurements of **signal strength and couplings**:
  - $\gamma\gamma$: $\mu = 1.14 \pm 0.21\,(\text{stat.})\,^{+0.13}_{-0.09}\,(\text{th.})\,^{+0.09}_{-0.05}\,(\text{sys.})$
  - ZZ: $\mu = 0.93\,^{+0.26}_{-0.23}\,(\text{stat.})\,^{+0.13}_{-0.09}\,(\text{syst.})$
  - WW: $\mu = 0.71 \pm 0.12\,(\text{stat.}) \pm 0.14\,(\text{syst.})$
  - + contribution to global coupling fit (not shown)
- **Exclusion** of all **Spin 1&2** models
- **Exclusion of 0^-**
- **Limits on anomalous couplings for spin 0:** no deviations
- **First measurements of cross-sections in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$**

→ **Discovered Higgs Boson is SM like within uncertainties**

BACKUP SLIDES

LHC and CMS

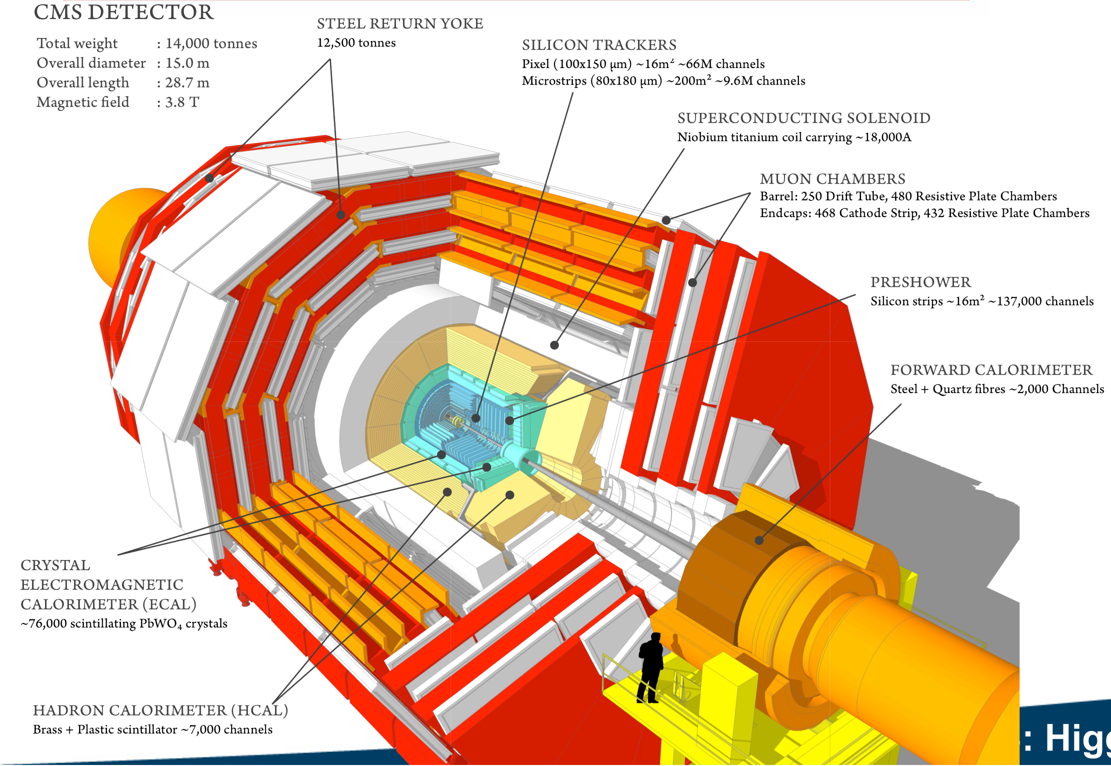


p-p collisions at center of mass energy of:

- ❑ 7 TeV : ~5 fb^{-1} in 2011
- ❑ 8 TeV : ~ 20 fb^{-1} in 2012
- ❑ 13 TeV : since restart in March 2015

→ Study Standard Model at high energy
→ Precise measurements of top quark
→ Search/study Higgs Boson
→ Search for BSM particles

+ Heavy Ions collisions: study of dense matter/medium properties



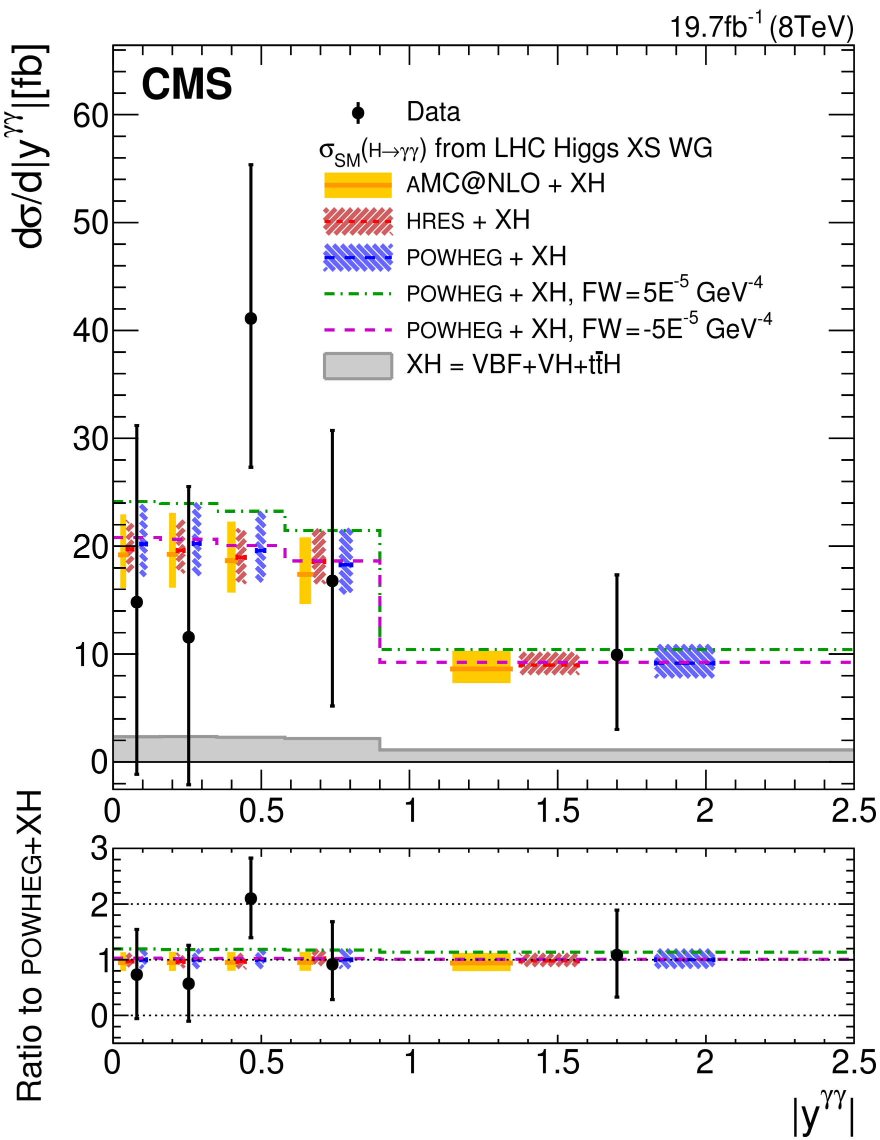
Can detect and measure momentum of:

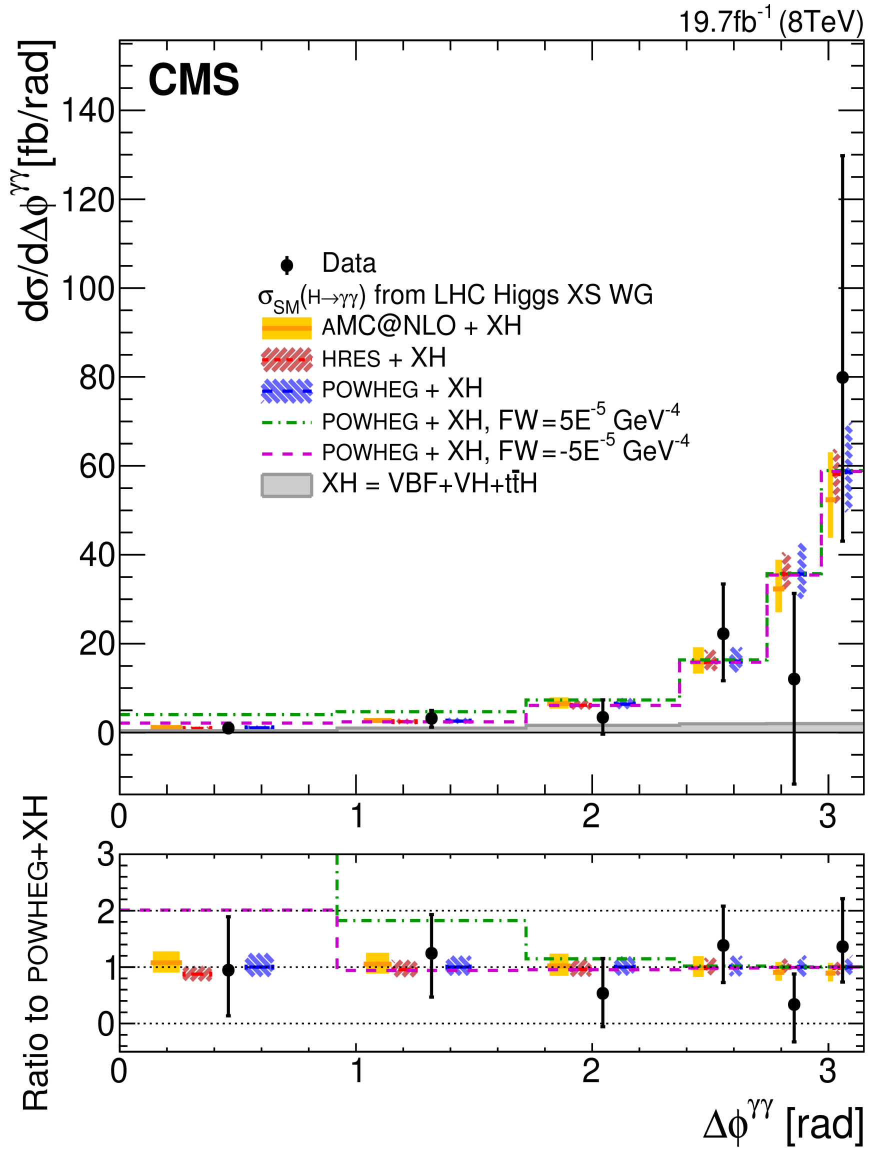
- ❑ Electrons
- ❑ Photons
- ❑ Hadrons
- ❑ Muons
- ❑ Transverse momentum of particles escaping detection (neutrinos, BSM particles, …)
  = Missing transverse energy

Cross-sections

H→γγ Differential Cross-sections

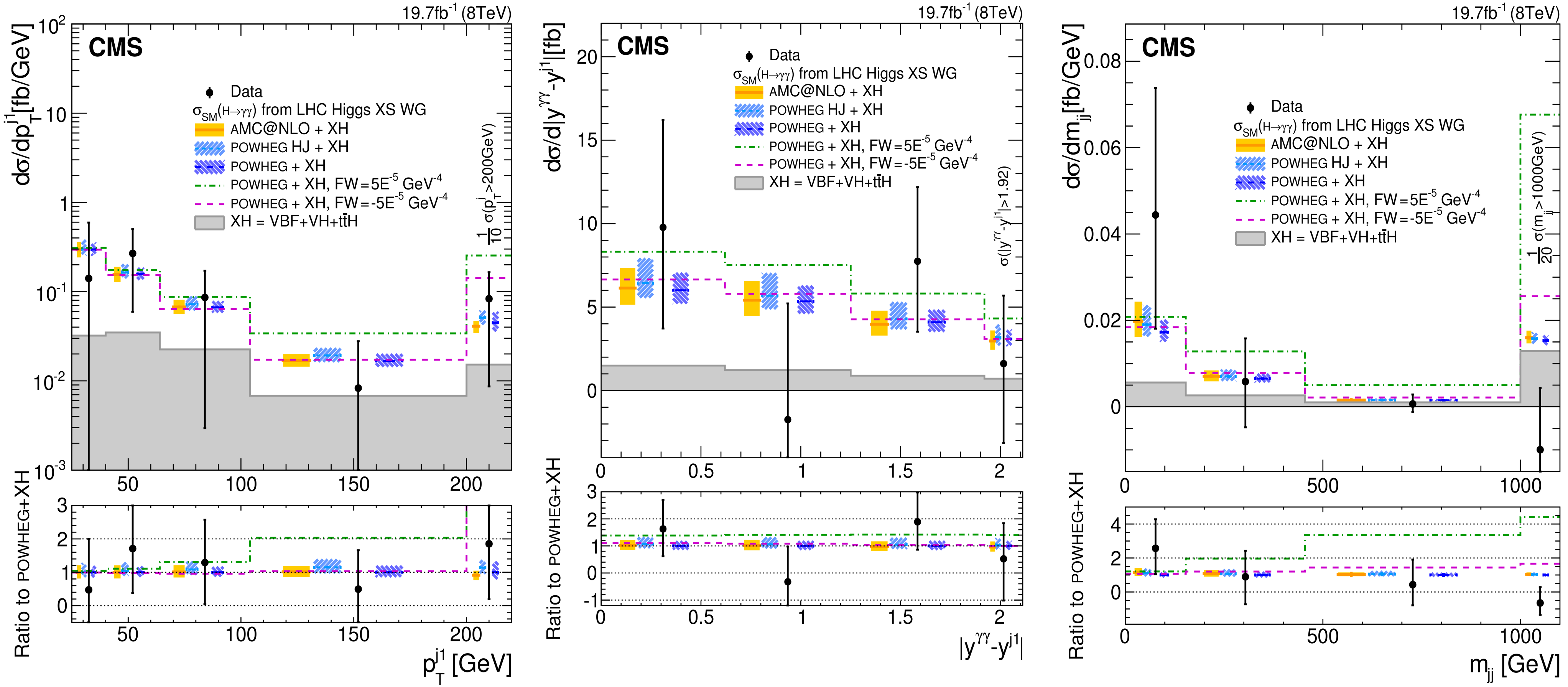
arXiv:1508.07819





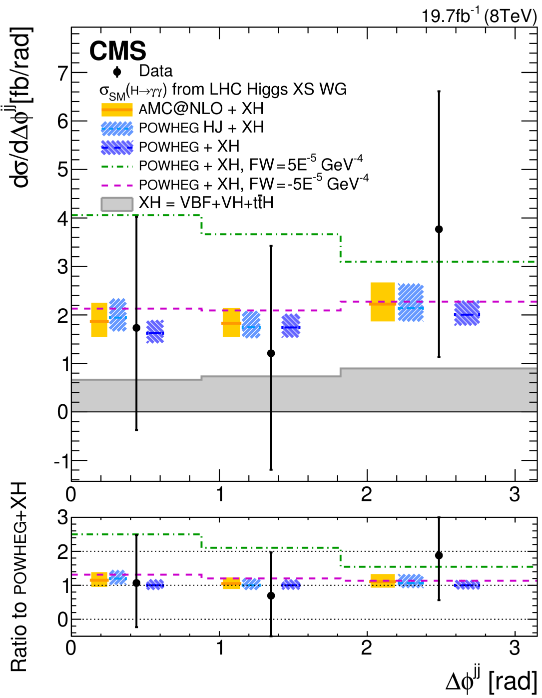
arXiv:1508.07819

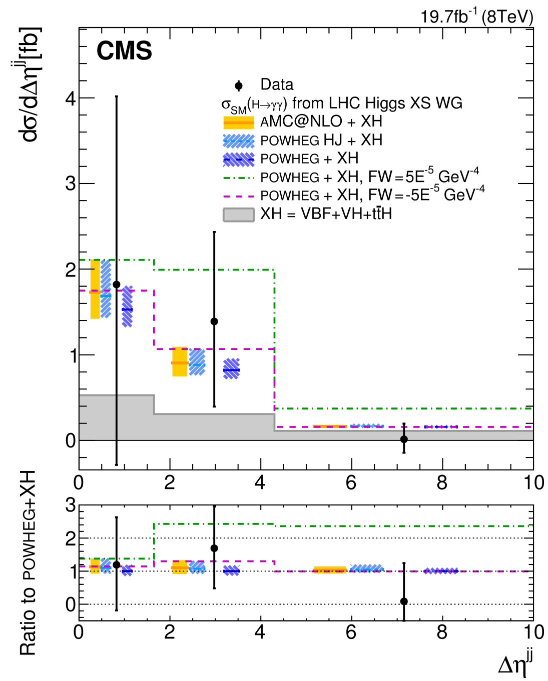
H→γγ Differential Cross-sections

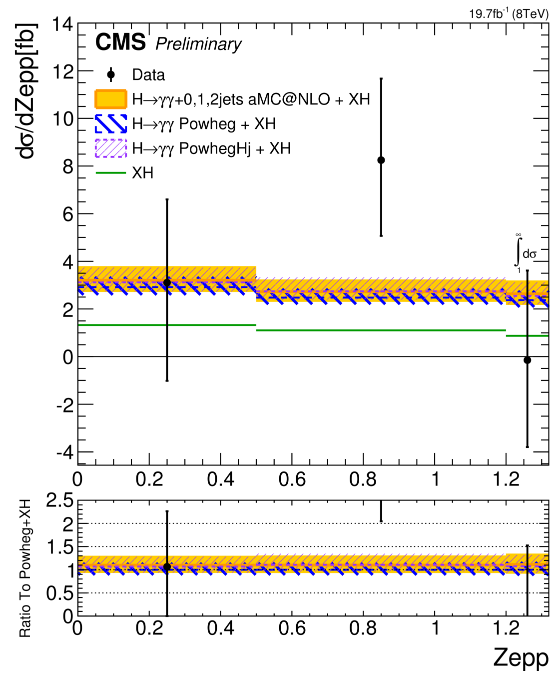


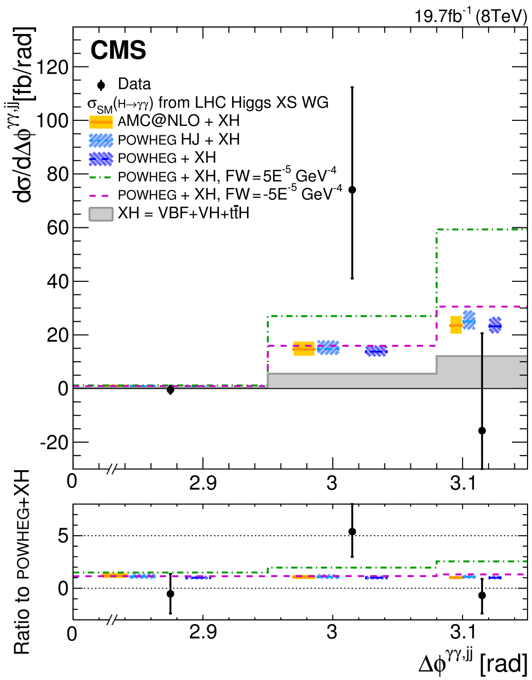
H→γγ Differential Cross-sections

arXiv:1508.07819



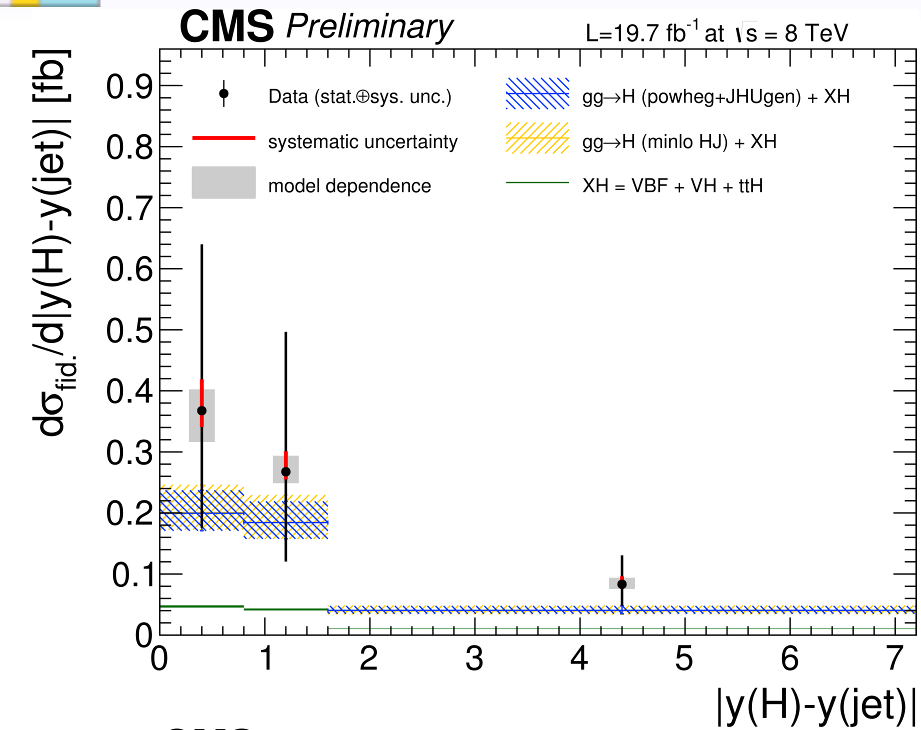


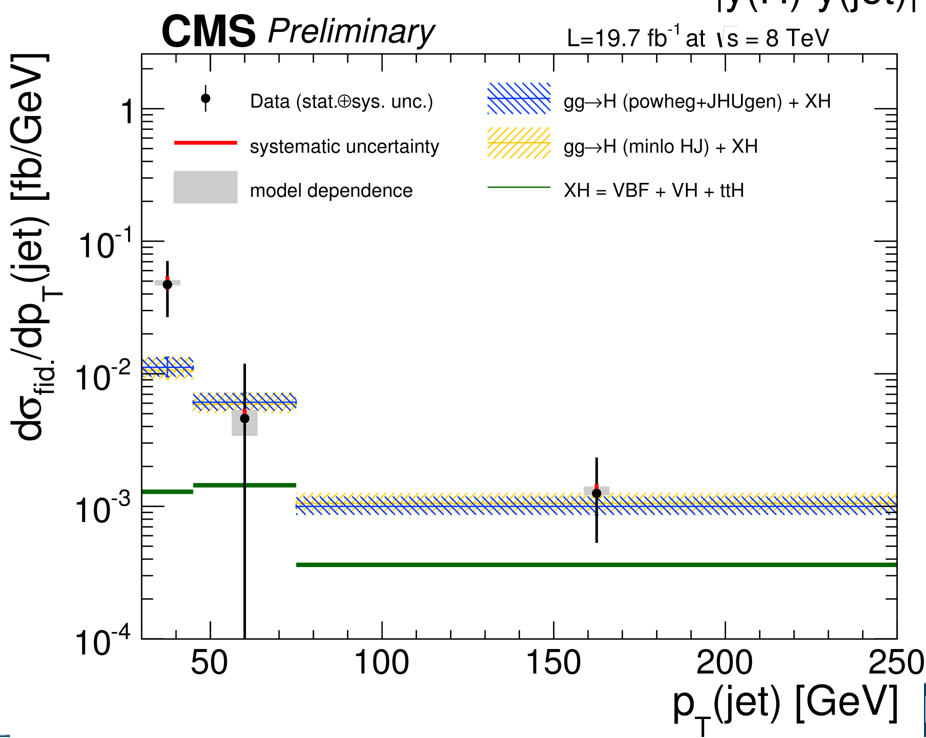


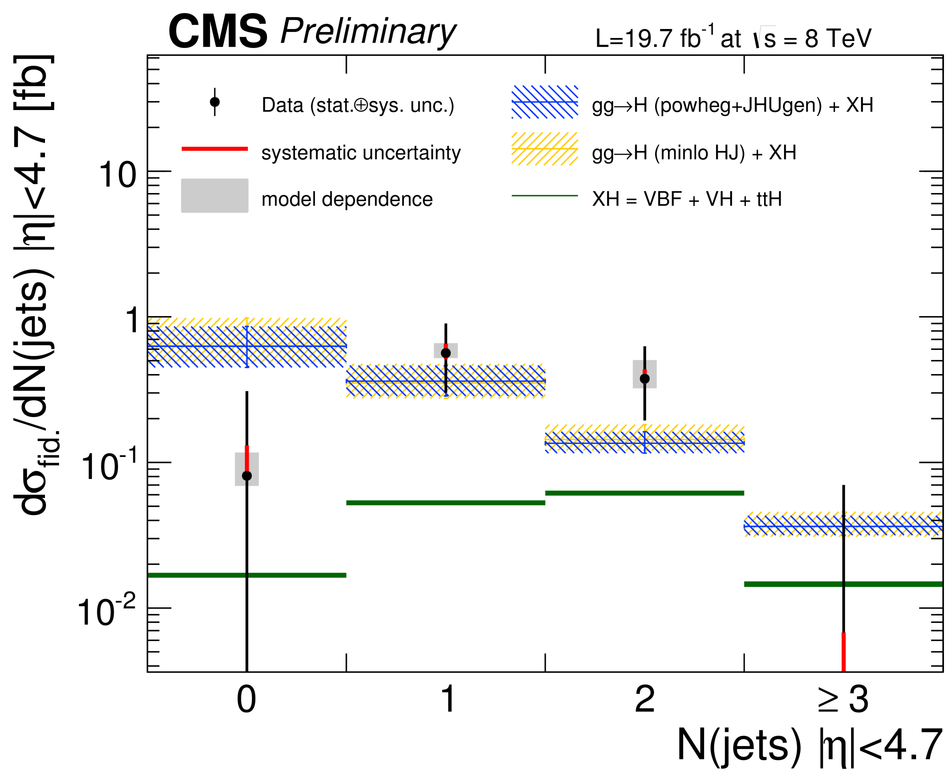


H→ZZ→4l Differential Cross-sections

CMS-PAS-HIG-14-028



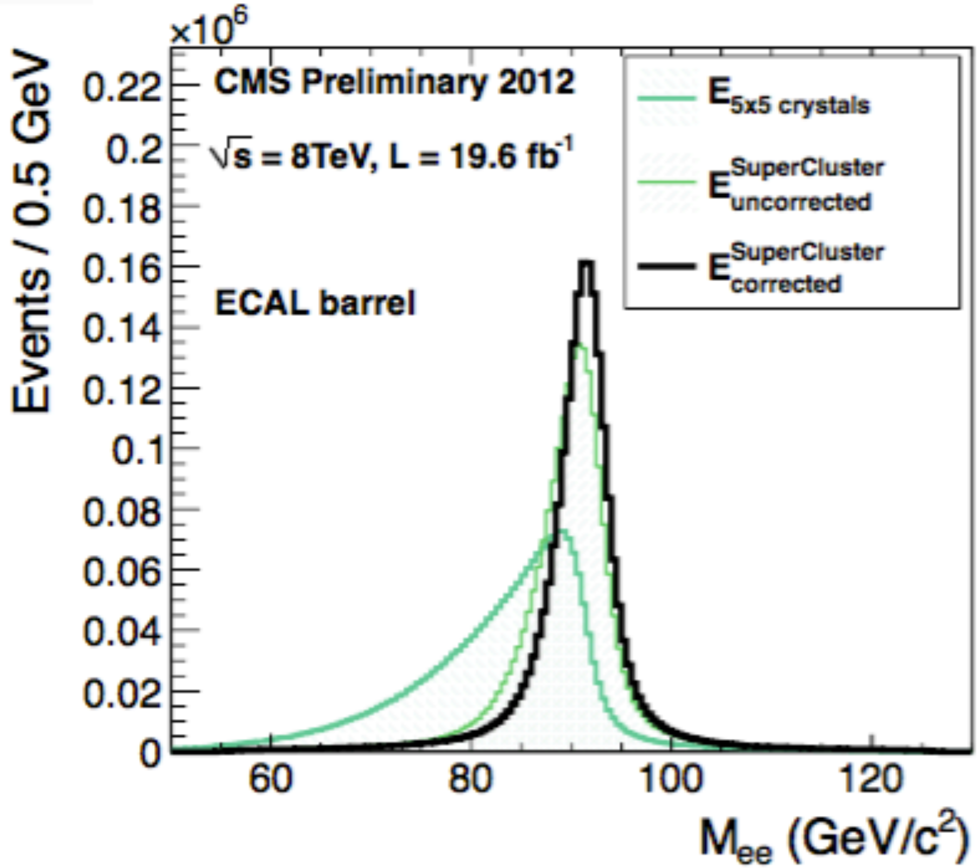


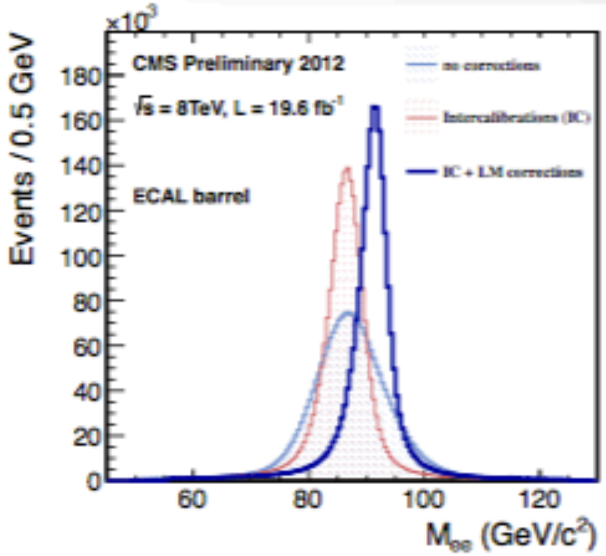


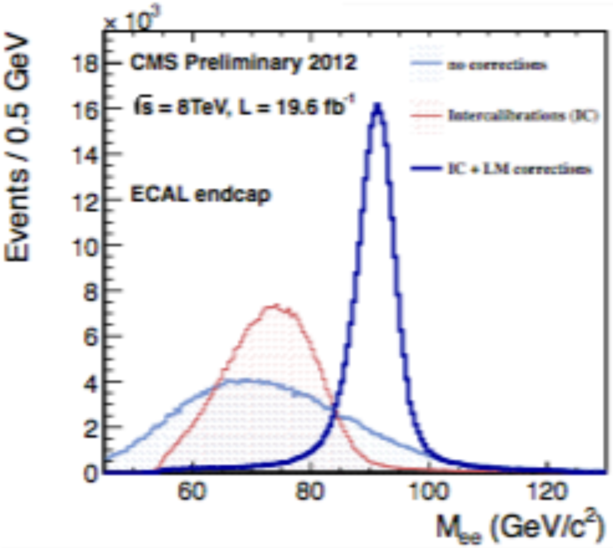
H→γγ Backups

Channel inter-calibration

- The uniformity and time stability of the single channel response affects the resolution
- Derive individual corrections *in situ* by equalising the response to diphoton resonaces (η,π^0)
  - Cross check using ϕ invariance of energy flow
  - And E/p ratio for electrons

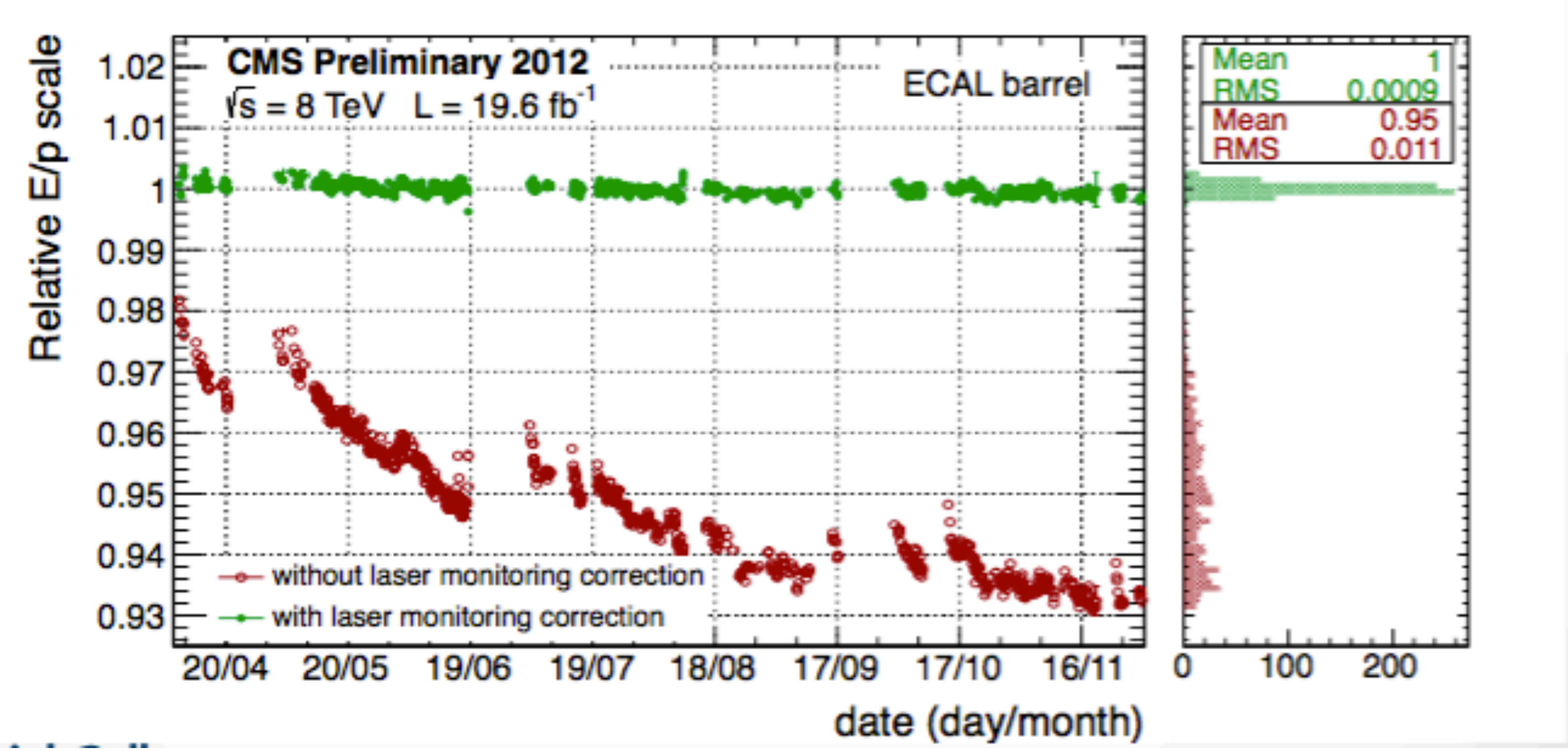






ECAL Calibrations

- Monitor crystal transparency using blue (and green) laser light
  - Construct time dependent set of corrections to give a flat response over time
- Derive inter channel calibration constants
  - The uniformity of the single channel response affects the resolution
  - Individual corrections by equalising the response to diphoton resonances (η,π^0, E/p and ϕ-symmetry
  - Zee events also used for eta and absolute scale
- Thanks to ECAL DPG for their work in calibration and simulation



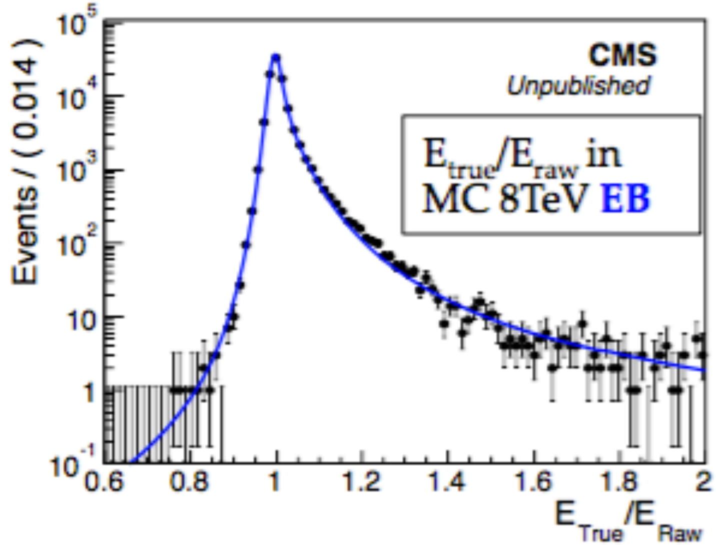
Energy regression

- Use the raw supercluster energy and several other input variables
  - to model shower shape, position etc. (label inputs as $\vec{x}$)
  - Correct for local containment of showers and bremsstrahlung losses etc.
- Now use specialised BDT (not TMVA) to predict full probability distribution for E_{true}/E_{raw}
  - Distribution is given by a double CB which has six free params (μ, σ, α_L, α_R, n_L, n_R)
  - "Regress" the non-parametric dependence of each of these variables on the BDT input variables whilst minimising the likelihood,

$$-\ln \mathcal{L} = - \sum_{MCphotons} \ln p(E_{true}/E_{raw} | \mu(\vec{x}), \sigma(\vec{x}), \alpha_L(\vec{x}), \alpha_R(\vec{x}), n_L(\vec{x}), n_R(\vec{x}))$$

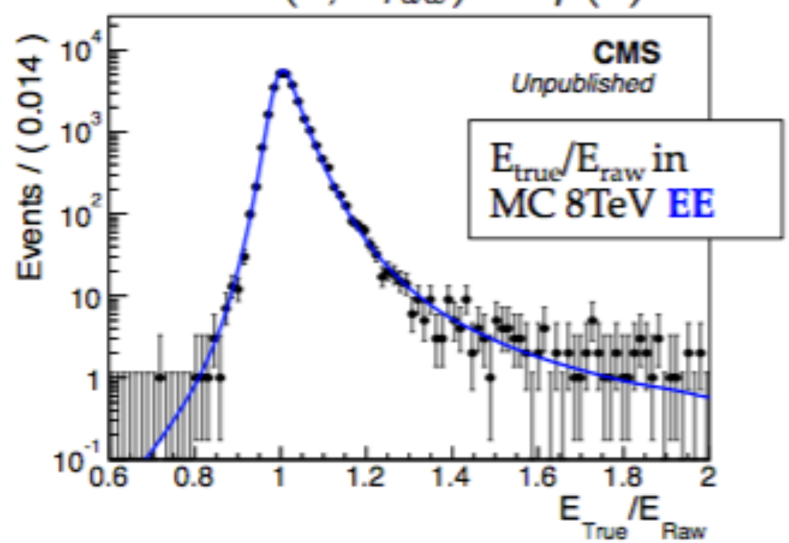
Best estimate for the true energy:

$$E(\vec{x}, E_{raw}) = \mu(\vec{x}) E_{raw}$$



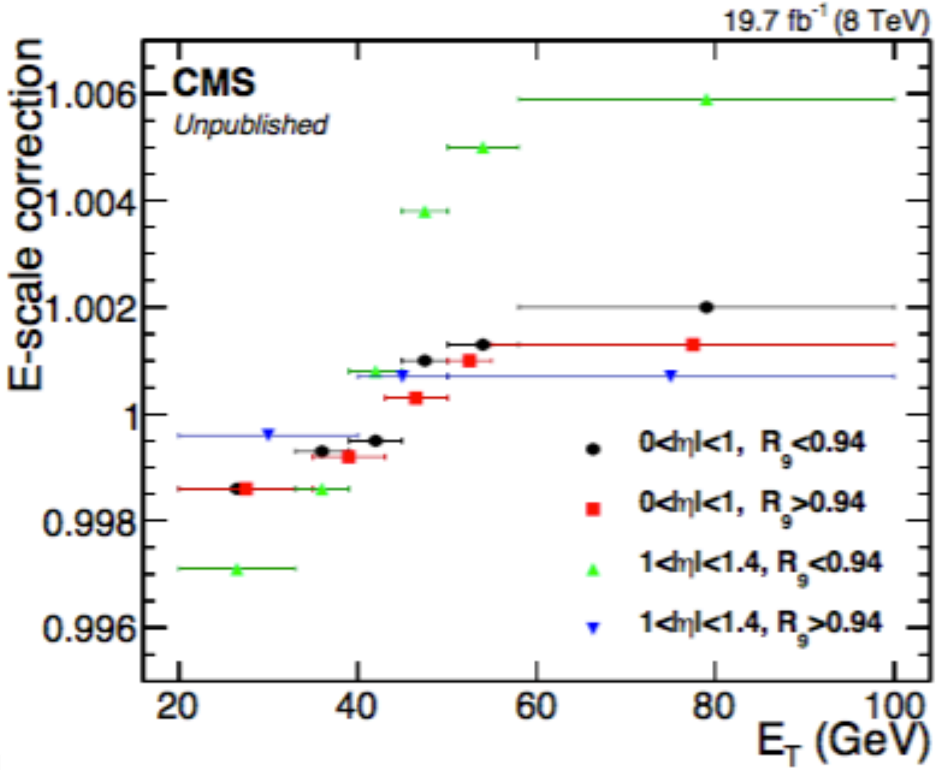
Per photon energy resolution:

$$\frac{\sigma_E(\vec{x}, E_{raw})}{E(\vec{x}, E_{raw})} = \frac{\sigma(\vec{x})}{\mu(\vec{x})}$$



Energy scale and smearing

- Apply residual scale corrections to the data and subsequent smearings to the MC
- resolve differences between data and MC from Z→ee decay (when electrons are reconstructed as photons)
- Employ a new multistep procedure
  - Split data and MC into 59 run ranges, 4 η bins and 2 R_9 bins
  - Fit Z line shape and find scale correction from data→MC in run×|η| bins
  - Simultaneously fit scale with a Gaussian smearing term for MC in $|\eta|\times R_9$
    - In the barrel (for 8 TeV) the smearing term has an energy dependence by parameterisation through: $b/\sqrt{E_T}+c$
  - Then have a further residual scale correction in $E_T\times|\eta|\times R_9$



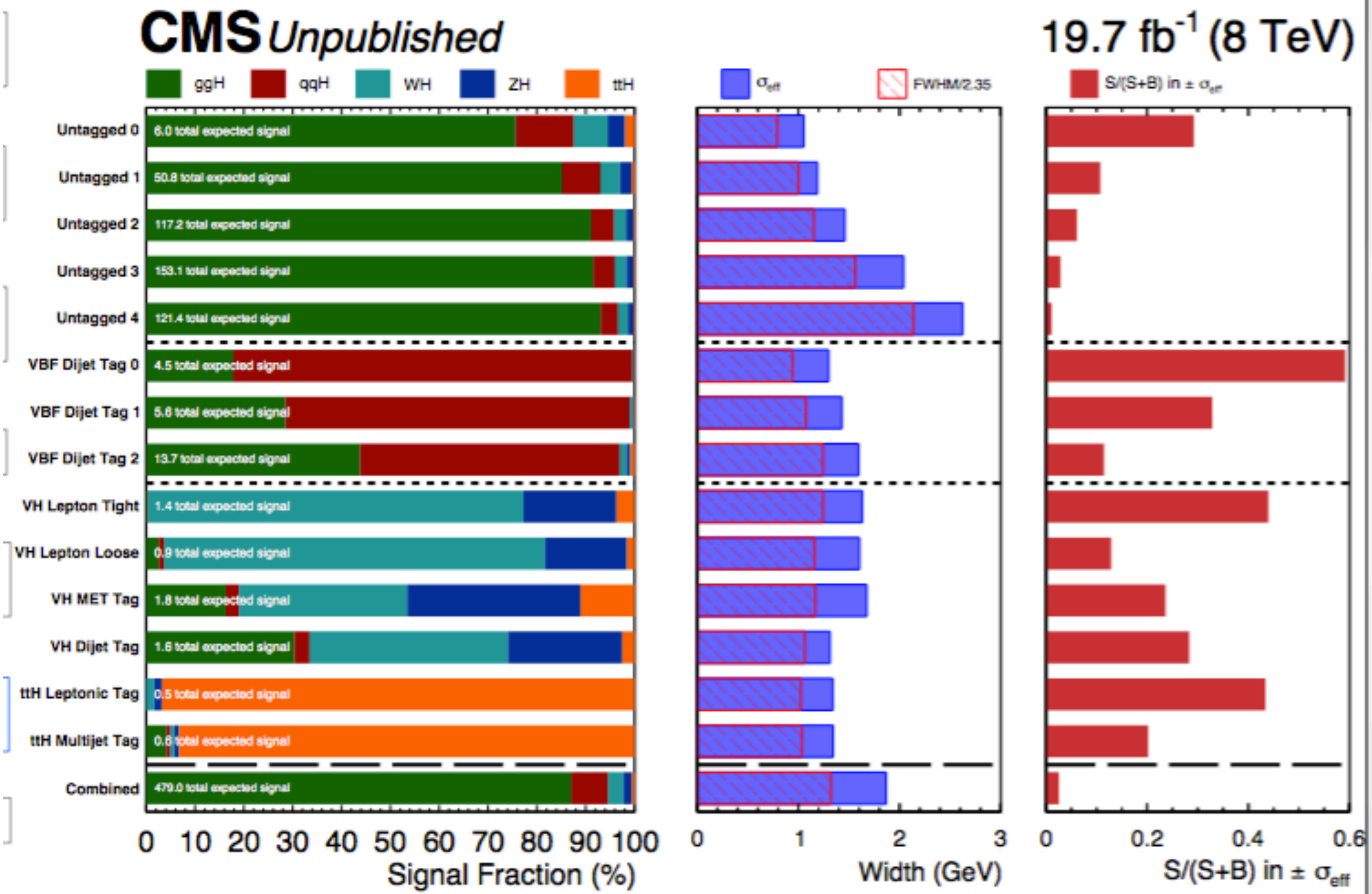
Imperial College

Event Tag Summary

Label	No. of classes 8 GeV	7 GeV	Main requirements
$t\bar{t}H$ lepton tag	1	⋆	$p_T^{\gamma}(1) > m_{\gamma\gamma}/2$ 1 b-tagged jet + 1 electron or muon
VH tight ℓ tag	1	1	$p_T^{\gamma}(1) > 3 \cdot m_{\gamma\gamma}/8$ e or μ, $p_T > 20$ GeV, and $E_T^{miss} > 45$ GeV OR 2e or 2μ, $p_T > 10$ GeV; $70 < m_{\ell\ell} < 110$ GeV
VH loose ℓ tag	1	1	$p_T^{\gamma}(1) > 3 \cdot m_{\gamma\gamma}/8$ e or μ, $p_T > 20$ GeV
VBF dijet tag 0-2	3	2	$p_T^{\gamma}(1) > m_{\gamma\gamma}/2$ 2 jets; dijet and combined diphoton-dijet BDTs used
VH E_T^{miss} tag	1	1	$p_T^{\gamma}(1) > 3 \cdot m_{\gamma\gamma}/8$ $E_T^{miss} > 70$ GeV
$t\bar{t}H$ multijet tag	1	⋆	$p_T^{\gamma}(1) > m_{\gamma\gamma}/2$ 1 b-tagged jet + 4 more jets
VH dijet tag	1	1	$p_T^{\gamma}(1) > 3 \cdot m_{\gamma\gamma}/8$ jet pair, $p_T > 40$ GeV and $60 < m_{jj} < 120$ GeV
Untagged 0-4	5	4	The remaining events, classified using diphoton BDT

⋆ For the 7 TeV dataset, events in the $t\bar{t}H$ lepton tag and multijet tag classes are selected first, and combined to form a single event class.

Signal breakdown at 8 TeV

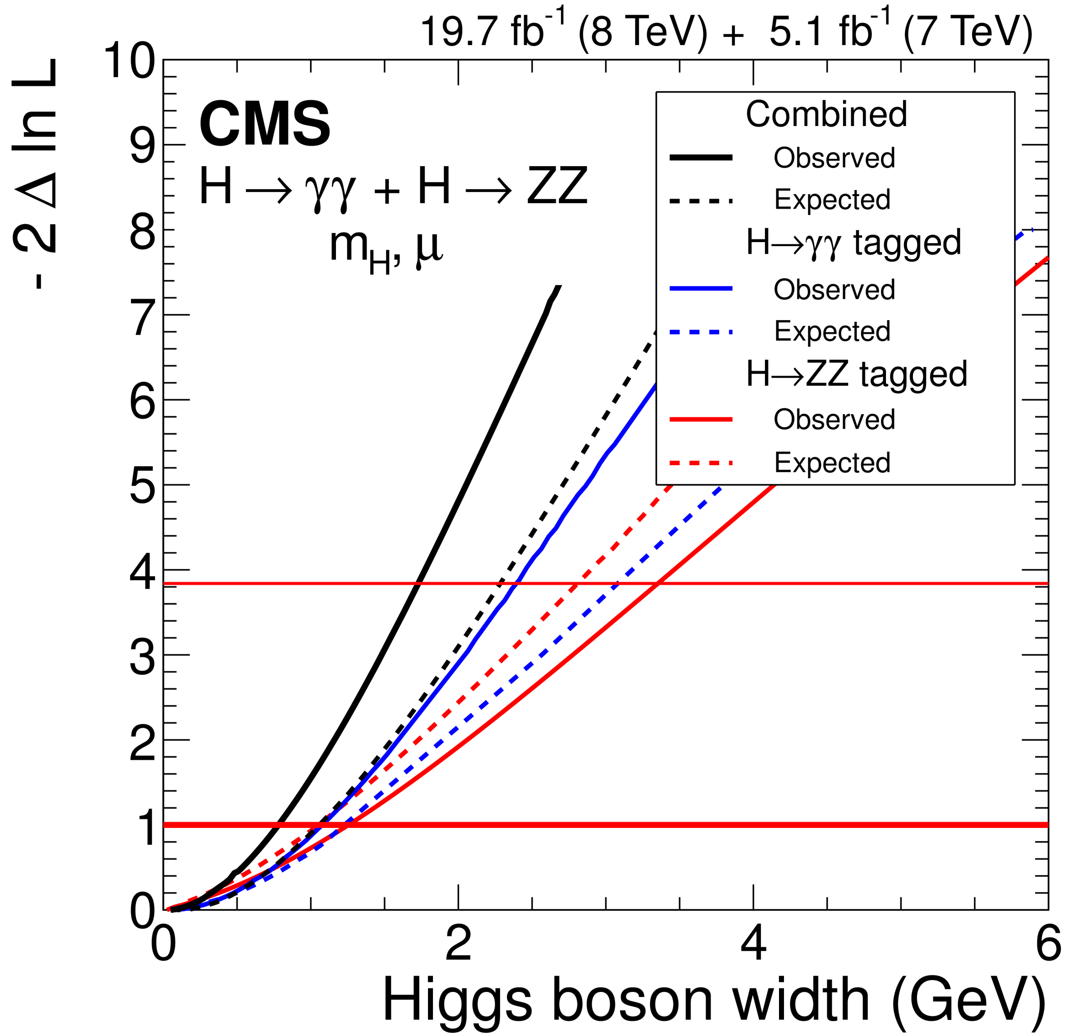


H→ZZ Width Backups

Width from on-shell H→ZZ→4l and H→γγ

arXiv:1412.8662

- For m_H = 125 GeV → Γ_H ~ 4 MeV
- Higgs width from H→ZZ→4l and H→γγ resonance shapes @ ~125 GeV only with reduced precision of ~GeV due to detector resolution for e/γ/μ p_T measurements



@ m_H = 125 GeV:

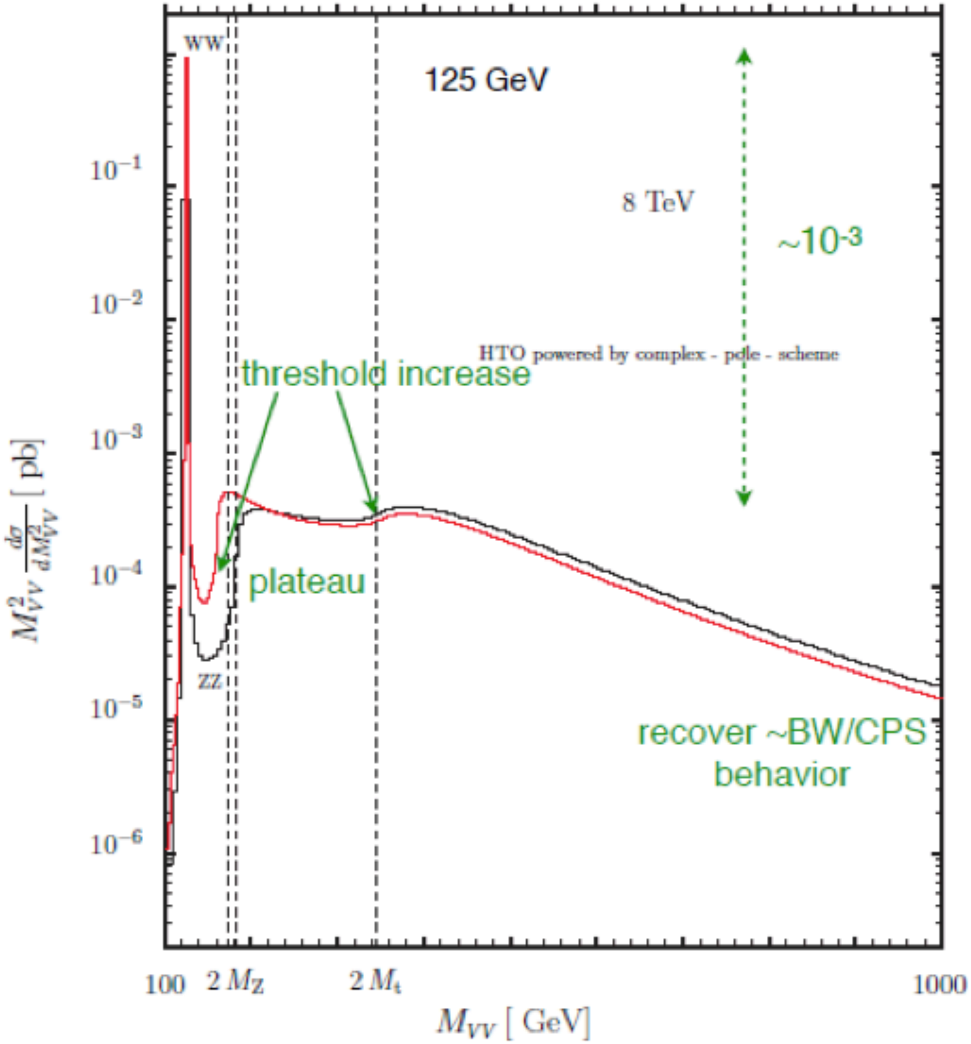
H→ZZ: Γ_H < 3.4 GeV @ 95% CL
H→γγ: Γ_H < 2.4 GeV @ 95% CL

ZZ+γγ : Γ_H < 1.7 GeV @ 95% CL

>> ~4 MeV SM width theoretical

→ Measurements mostly limited already by resolution

Constraints on Higgs Width from off-shell H → VV



	Tot[pb]	$M_{ZZ} > 2M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Kauer, Passarino (*JHEP* **08** (2012))
Campbell, Ellis, Williams: arXiv:1311.3589v1
Caola, Melnikov (*Phys Rev D* **88** (2013) 054024)

Zero Width Approximation is far from real Higgs mass

→ **Competing effects from BW in high mass region and $\Gamma_H \to 4l$ cause plateau in region**

→ **~8% of total $H \to ZZ$ cross section found in $m_{ZZ} > 2m_Z$ region**

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g^2_{ggH} g^2_{HZZ} \frac{F(m_{ZZ})}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

Which gives for on-peak:

$$\sigma^{on-peak}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H},$$

and for off-peak:

$$\sigma^{off-peak}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

→ **Off-peak to peak ratio sensitive to Γ_H:**

$$\frac{\sigma_{off-peak}}{\sigma_{peak}} \propto \Gamma_H$$

→ **Need to account for large interference with non resonant ZZ background at high m_{ZZ}**

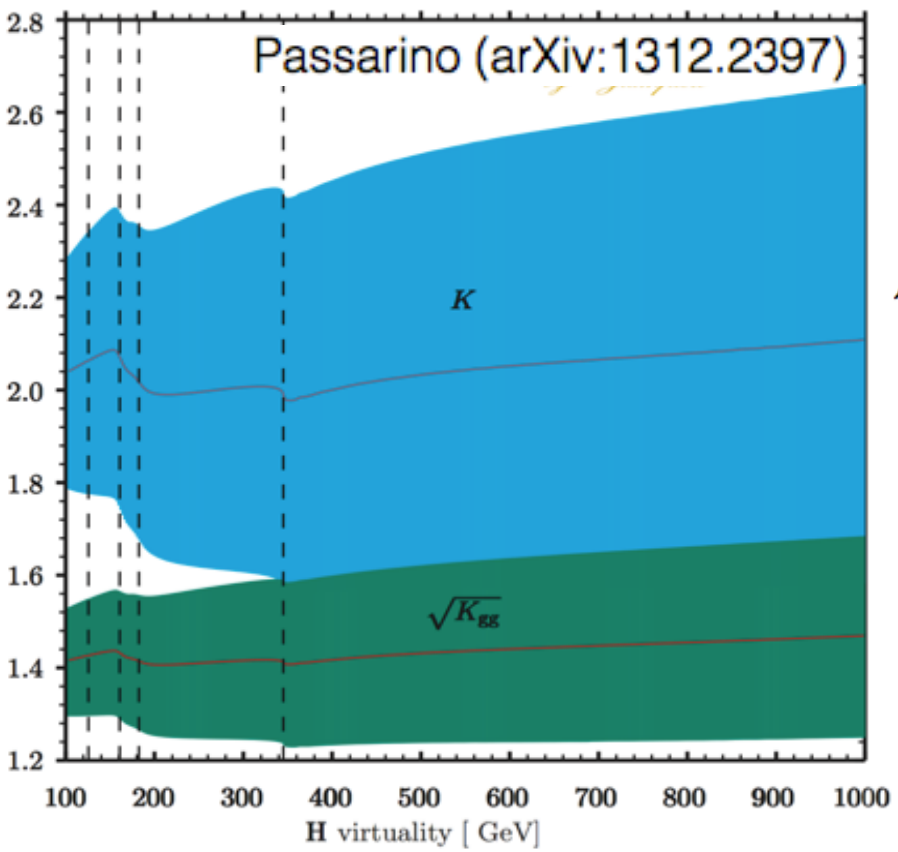
→ **Same for H→WW (Analysis ongoing)**

Higgs Width from off-shell H → ZZ

Monte Carlo simulation

- **gg→H: gg2VV LO (or MCFM) + NLO/LO m_{ZZ} dependent k-factors (same for signal and background):**

Bonvini et al. (*Phys Rev D* **88** (2013) 034032)



- **VBF: Phantom, ~7% on-peak, ~10% at high mass**
- **VH and ttH: negligible at high mass**

Statistical approach

- **Perform a maximum likelihood fit based on the probability of each selected event to be signal (ggH or VBF) or background:**

$$\mathcal{L} = N_{\mathrm{gg}\to\mathrm{ZZ}} \left[\mu_F \Gamma_H \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{\mu_F \Gamma_H} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}} \right] + N_{\mathrm{VBF}} \left[\mu_V \Gamma_H \times \mathcal{P}^{VBF}_{\mathrm{sig}} + \sqrt{\mu_V \Gamma_H} \times \mathcal{P}^{VBF}_{\mathrm{int}} + \mathcal{P}^{VBF}_{\mathrm{bkg}} \right] + N_{\mathrm{q\bar{q}}\to\mathrm{ZZ}} \mathcal{P}^{\mathrm{q\bar{q}}}_{\mathrm{bkg}} + N_{\mathrm{Z+X}} \mathcal{P}^{\mathrm{Z+X}}_{\mathrm{bkg}} + \ldots$$

- **Use signal strength from legacy analysis:**

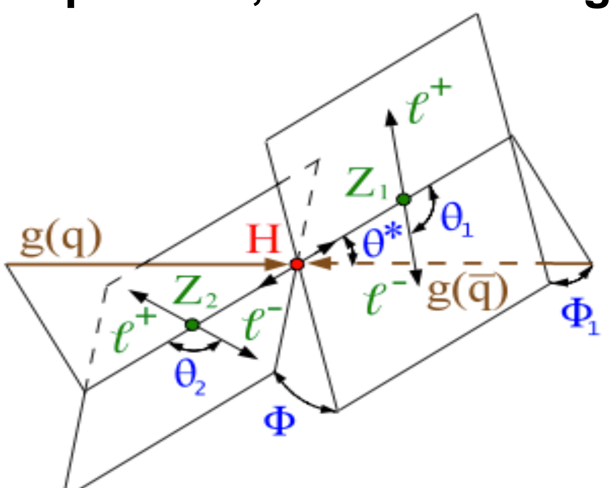
  μ = 0.93+0.26-0.24

Γ_H from off-shell H→ZZ→4l

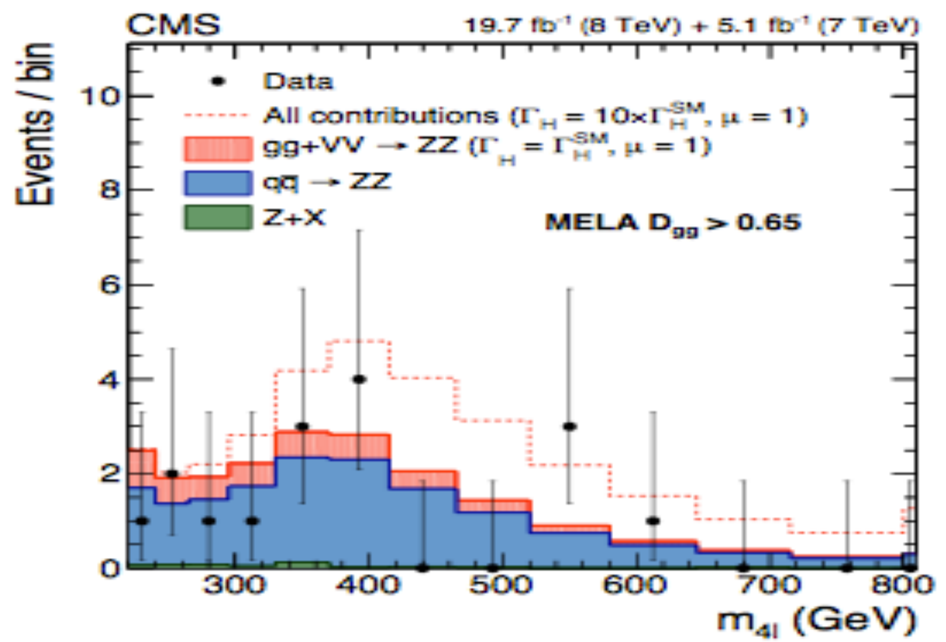
- Selection consistent with "legacy" analysis
- Build discriminant discriminant for gg→ZZ production using matrix element likelihood approach (MELA)
- Optimal separation for gg→ZZ including signal, background, and their interference with any relative signal strength:

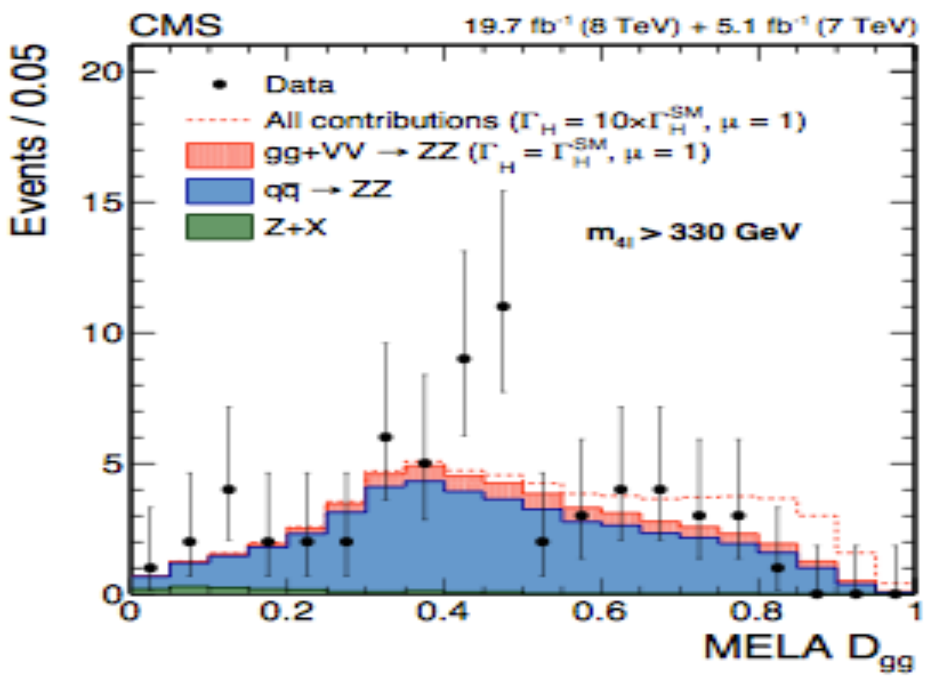
$$\mathcal{D}_{gg,a} = \frac{\mathcal{P}_{gg,a}}{\mathcal{P}_{gg,a} + \mathcal{P}_{q\bar{q}}}$$

- Use as input mZ1, mZ2 + five angles:



- Pgg(qq̄) are joint probabilities for gg→ZZ signal + background + interference (qq̄→ZZ background) from MCFM matrix elements



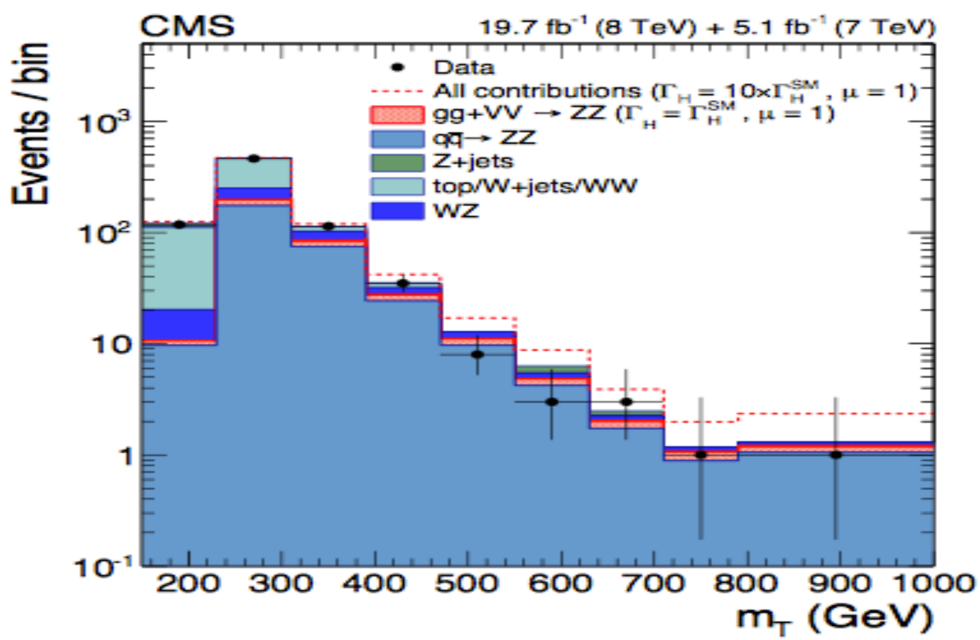


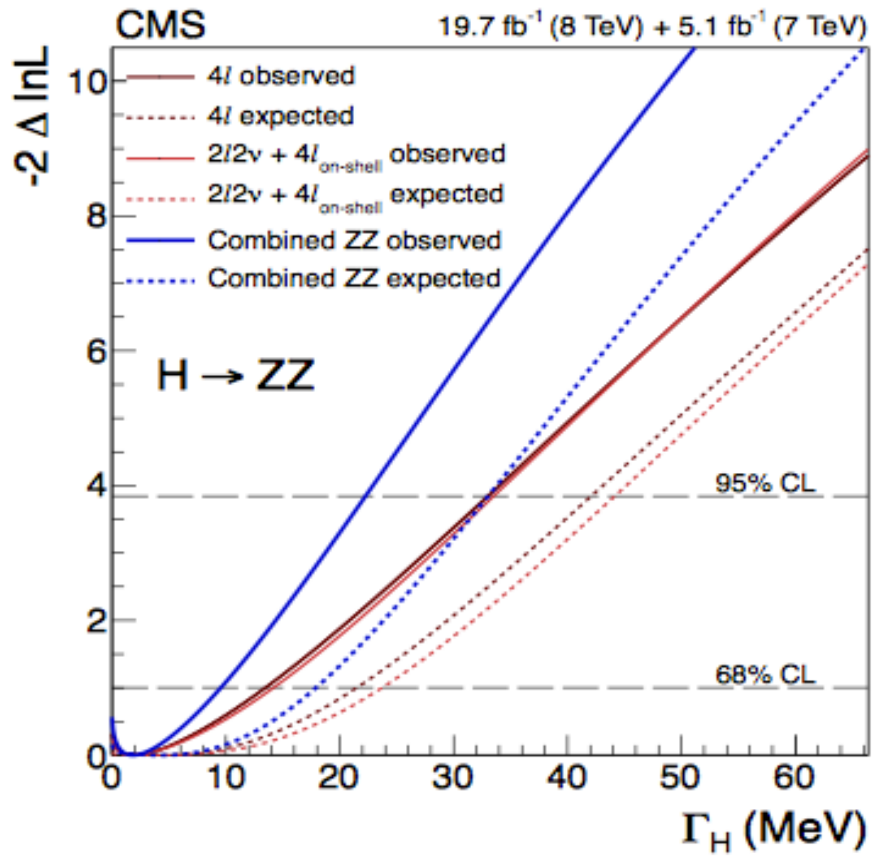
Γ_H from off-shell H → ZZ→2l2ν + Results

arXiv:1405.3455

- Two isolated leptons p_T>20 GeV, veto Z peak and b-taggged jets + $E_{T,miss}$> 80 GeV +Δφ(jet,$E_{T,miss}$)>0.5
- Data-driven estimate of reducible backgrounds (double and single top, WW, W+jets, Z+jets); qq→ZZ/WZ from MC
- Fit the transverse mass:

$$m_T^2 = \left[\sqrt{p_{T,2l}^2 + m_{2l}^2} + \sqrt{E_T^{miss\,2} + m_{2l}^2}\right]^2 - \left[\vec{p}_{T,2l} - \vec{E}_T^{miss}\right]^2$$





→ $\Gamma_H < 5.4 \times \Gamma_{SM}$
→ $\Gamma_H \leq 22$ MeV

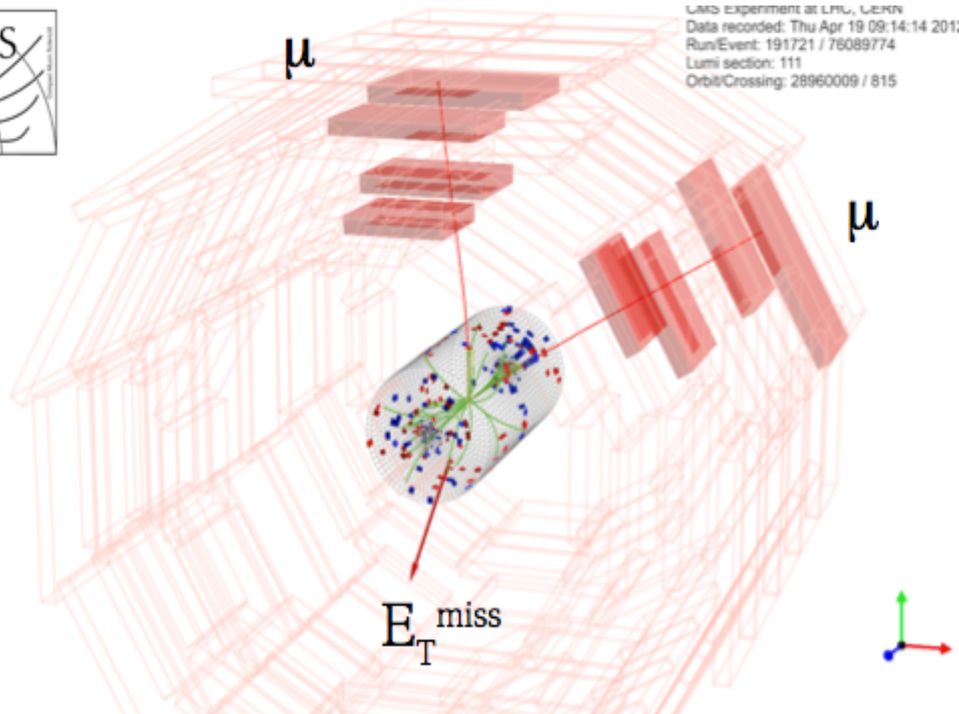
Close to 4.15 MeV SM width theoretical value for m_H = 125.6 GeV

+ Talk on Mass and Width ATLAS+CMS this afternoon (I. Giotis)
+ Talk on H lifetime with H→ZZ→4l on Wednesday (c. You)

H→WW
Final states with two leptons

arXiv:1312.1129

H→ WW: Final states with 2 leptons



Common WW→2l2ν selection:

- **Trigger: Single and double leptons**
- **2 isolated (e,μ) leptons (p$_T$ >10 ,20 GeV)**
- **Missing E$_T$ > 20 GeV**

- **Z-veto (ee/μμ):**
  - **-- $|m_{ll}-m_z|$ > 15 GeV**
  - **-- higher MET cuts or MVA**

- **Top veto: Jet b-tag + no soft μ**

- **Jet counting for $|\eta|<4.7$ and $p_T>30$ GeV**

Background from data driven techniques:

- W+jets with jet faking lepton
- Wγ /Wγ*
- DY→ee/μμ
- DY→ττ witk ττ decaying to eμ + ν' s
- Top→bWbW→bblvlv (b-jets not identified)
- WW→lvlv

Other backgrounds: ZZ/VZ/Tri-bosons
→MC predictions

Signal Extraction:

- Optimised **Cut-Based** selection for each Higgs mass hypothesis (ee/μμ)
  → **Systematic limited due to Z→ll**

- **Shape analysis (eμ)**:
  → Kinematic fit in 2D and 1D
  → **Still statistic limited**

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H → WW → 2l2ν: 0/1-jet

Selection:
- 0 or 1 jet (p_T>30 GeV)
- p_T(ll) > 30 (45) GeV shape (cut-based)

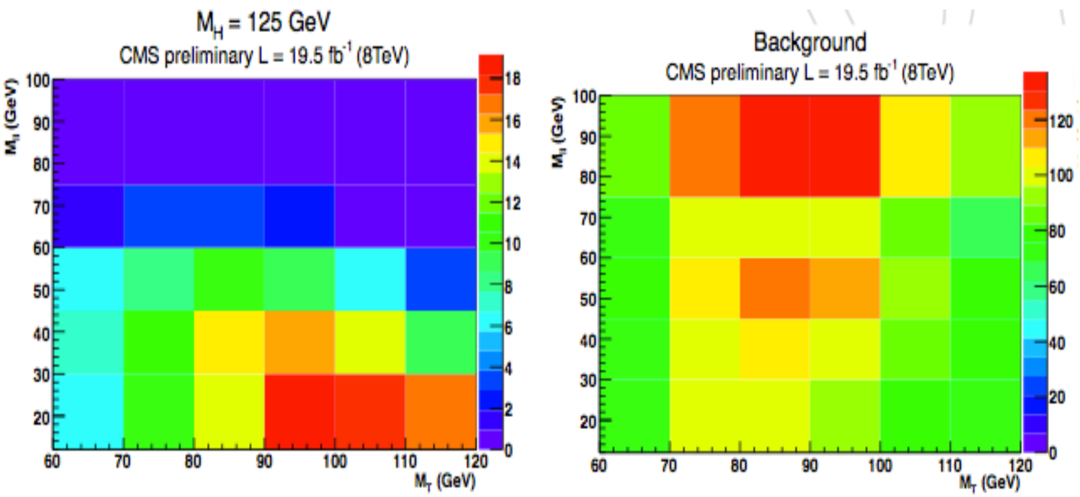
Cut-based analysis (ee/μμ + eμ as cross-check):

m_H[GeV]	$p_T^{\ell,max}$ [GeV]	$p_T^{\ell,min}$ [GeV]	$m_{\ell\ell}$ [GeV]	$\Delta\phi_{\ell\ell}$ [dg.]	$m_T^{\ell\ell E_T}$ [GeV]
	>	>	<	<	[,]
120	20	10	40	115	[80,120]
125	23	10	43	100	[80,123]
130	25	10	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
400	90	25	300	175	[120,400]
600	140	25	500	175	[120,600]

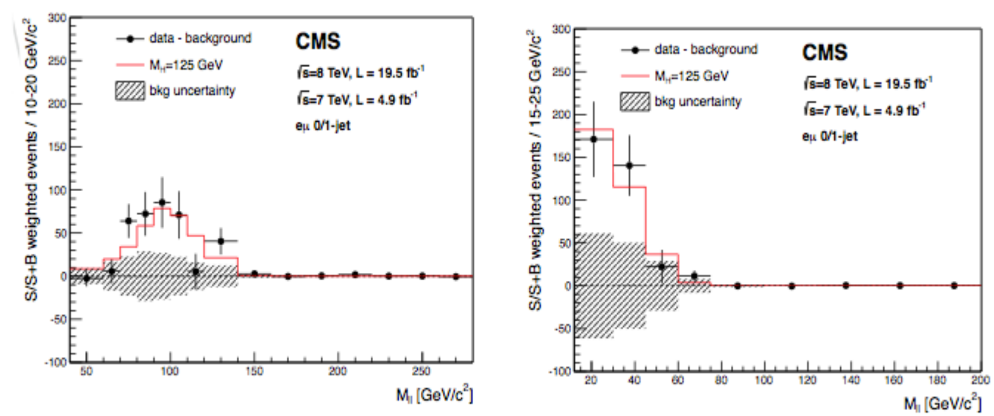
Shape analysis (eμ Only):
- 2D shapes: - m_T : higgs transverse mass
  - m_{ll} : di-lepton invariant mass
- Comparison from results for different WW MC: POWHEG, MADGRAPH, MC@NLO
- Study of compatibility between CR at high m_{ll} and high m_T (see backup)
- Dedicated plots to template validation for Top and W+jet (see backup)

→ **Default result:** shape DF+cut-based SF

2D templates in m_{ll} and $m_{T,H}$ (0 jet case):



→ post-fit data-background 1D projection from the 2D shape analysis weighted by S/(S+B):



→ **4 sigma evidence for H→ WW 0/1-jet**

→ **μ = 0.76 ± 0.21 @ m_H = 125 GeV**

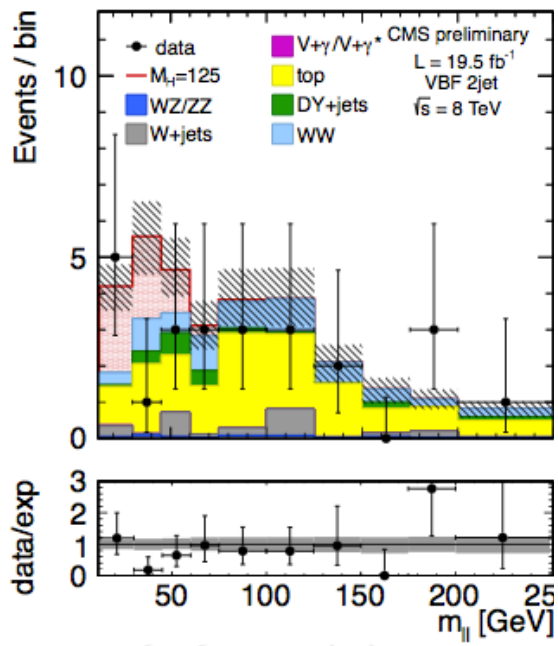
VBF H → qq+WW → qq+2l2ν

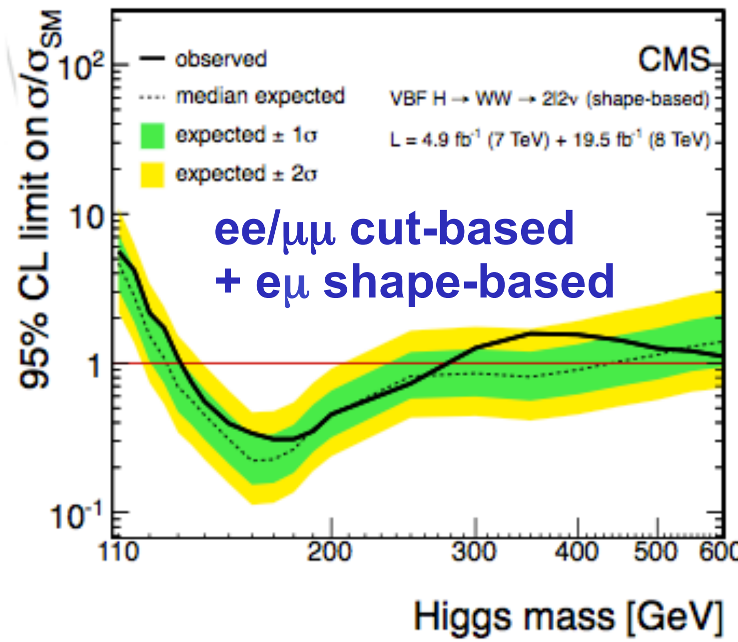
Additional Selection:
- 2 or 3 jets (p_T>30 GeV)
- $|\Delta\eta(jj)| > 3.5$
- m_{jj} > 500 GeV
- Lepton centrality w.r.t. jets

Cut-based analysis (ee/μμ/eμ):
- Same selection as 0/1-jet but m_T>30 GeV
- Tables with cut-based yields

Shape analysis (eμ Only):
- Fit to the m_{ll} distribution: 14 (10) bins at 8 (7) TeV for 12< m_{ll} < 600 GeV
- Pre-selection:
  - m_T < m_H
  - For m_H>250 GeV: leading lepton p_T >50 GeV

→ **Default result:**
shape DF+cut-based SF





VBF analysis $m_H = 125$ GeV	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
Shape-based (default)	1.1 / 1.7	2.1 / 1.3 sd	$0.62^{+0.58}_{-0.47}$
Counting analysis	1.1 / 0.9	2.0 / —	$-0.35^{+0.43}_{-0.45}$

→ **Mild excess for shape analysis:**
1.3 sigma / μ = 0.62 + 0.58 – 0.47

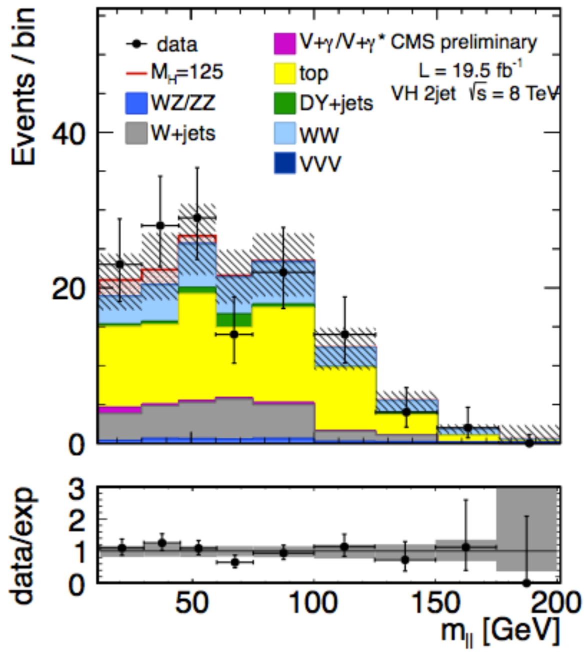
VH → VWW → 2l2νqq

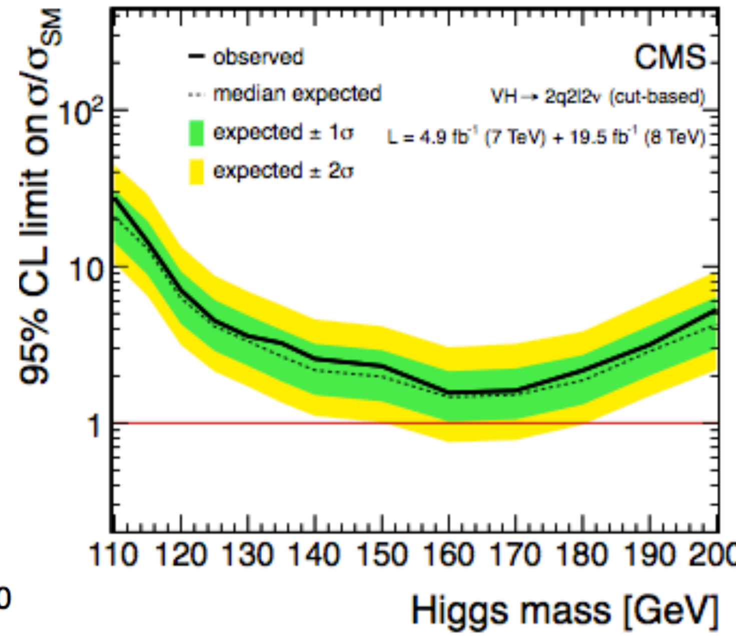
Additional Selection:
- 2 central jets: $|\eta| < 2.5$
- W/Z: - $65 < m_{jj} < 105$ GeV
  - $|\Delta\eta(jj)| < 1.5$
- H: 60 (70) $< m_T < m_H$ GeV for $m_H <$ (>) 180 GeV

Cut-based analysis (SF+DF):
- m_{ll}>20 GeV for m_H>135 GeV
- mll<60 (80) GeV for m_H <(>)180 GeV
- mH dependent cut on $|\Delta R_{ll}|$
- + 2 tables with cut-based yields

→ **Default result: Cut-based (low stat.)**

Shape analysis (DF Only):
- Method as reference for high luminosity
- Fit to the m_{ll} distribution:
- Pre-selection:
  - $m_{ll} < 200$ GeV
  - $|\Delta R_{ll}| < 2.5$





VH analysis $m_H = 125$ GeV	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
Counting analysis (default)	4.1 / 4.5	0.6 / 0.2 sd	$0.40^{+2.03}_{-1.93}$
Shape-based	4.0 / 4.7	0.6 / 0.4 sd	$0.73^{+2.04}_{-1.85}$

→ **Similar performance for cut based and shape**
→ **Still statistically limited channel**

VH→WW
Final states with three leptons

Common selection:

- 3 isolated leptons with pT > 20, 10, 10 GeV
- Total lepton charge: ±1

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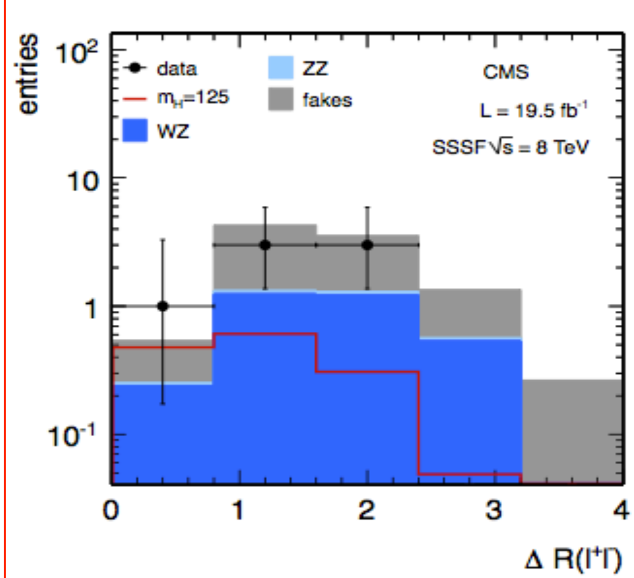
WH → WWW → 3l3ν

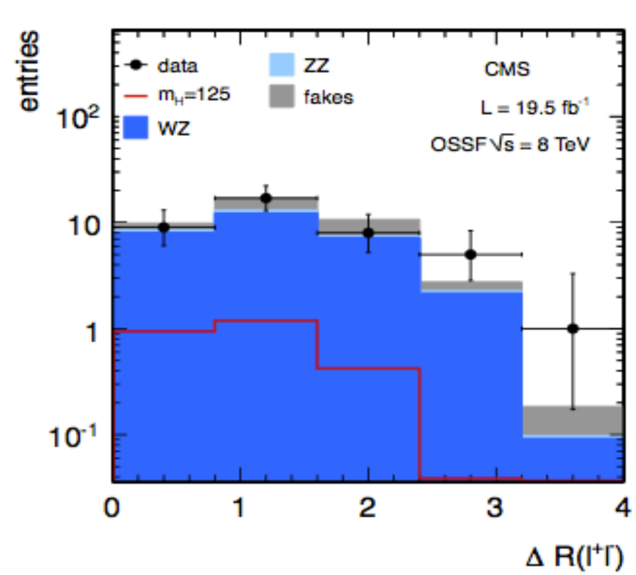
Selection:
- 2 categories: OSSF & SSSF
- Z+jets rejection:
  - min($E_{T,miss}$,track-$E_{T,miss}$) > 40(30) GeV for OSSF (SSSF)
  - No jet with E_T>40 GeV
  - OS pairs: m_{ll}>12 GeV
- Top: No b-tag
- WZ: OSSF pairs 25 GeV away from m_Z
- m_{ll} < 100 GeV
- OS pairs: $|\Delta R_{ll}|$<2

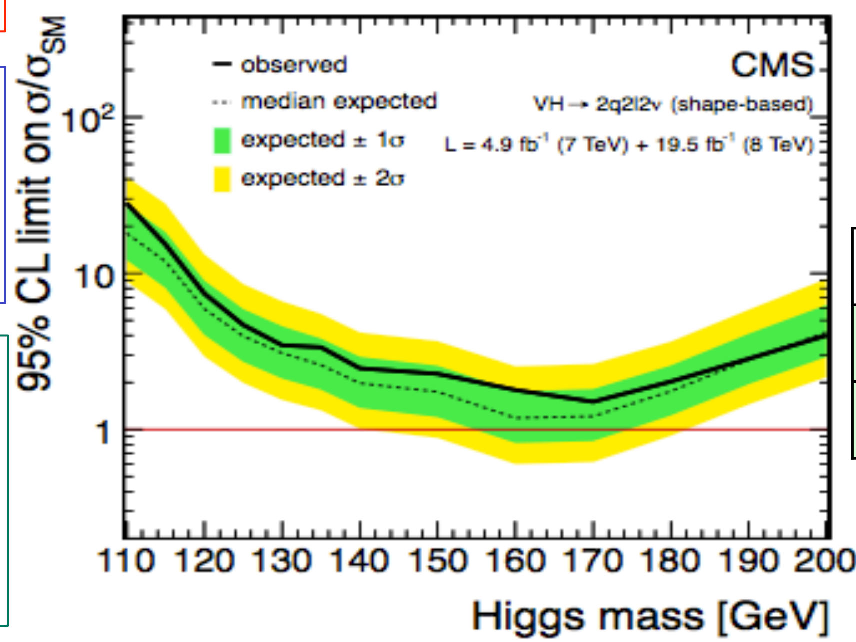
Cut-based analysis:
- Events for above selection
- Tables with yields at each cut group stage

Shape analysis:
- Fit to the $|\Delta R_{ll}|$ distributions
- Selection: all but $|\Delta R_{ll}|$ cut

→ Default result







95% CLs limits @ 125 GeV

	Exp.	Obs.
Cut	3.6	3.7
Shape	3.0	3.3

ZH → ZWW → 3lνqq

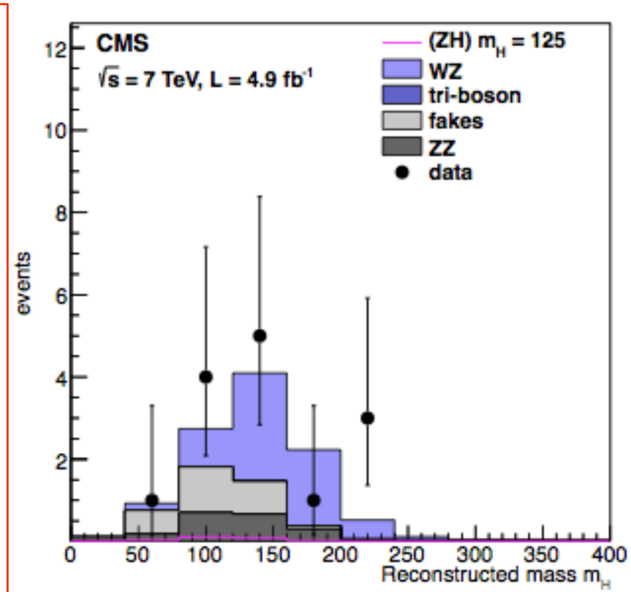
Selection:
- Z selection: $|m_{ll}-m_Z| < 15$ GeV
- V+$\gamma^{(*)}$ rej. : $m_{ll} > 12$ GeV
- Z→4l rej. : $|m_{lll}-m_Z| > 10$ GeV
- W→jj sel. :
  - #jets ≥ 2
  - $|m_{jj}-m_W| < 60$ GeV
- W→lν sel. : $m_T < 85$ GeV
- H→ WW: $|\Delta\phi(jj\text{-}lE_T)| < 1.8$ rad.
- Categories: eee/eeμ/eμμ/μμμ

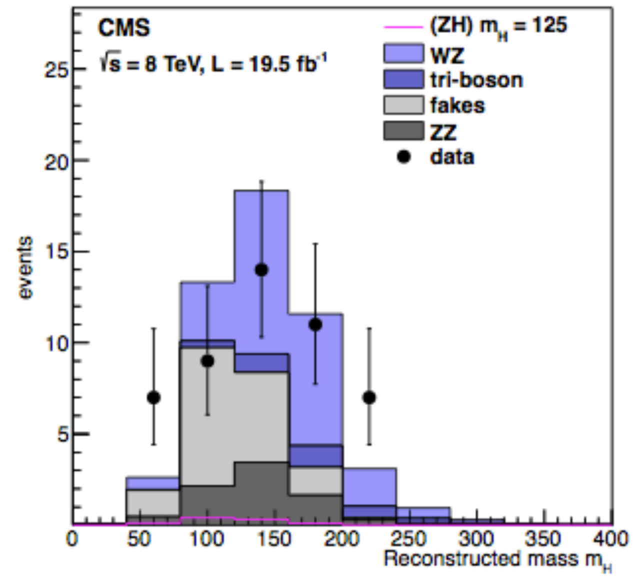
→ $m_H = \sqrt{(\sum p_T)^2 - (\sum p_x)^2 - (\sum p_y)^2},$

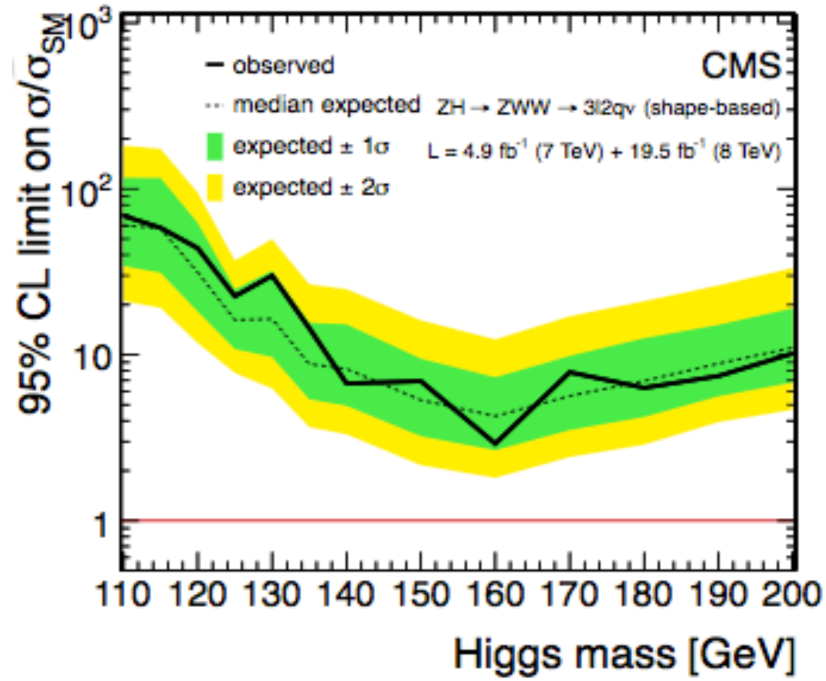
Cut-based analysis:
- Events for above selection
- Cut on reco m_H for each mass
- Tables with yields at each cut group stage

Shape analysis:
- Fit to the reco m_H distributions
- Selection as above

→ **Default result**







H→WW: Backgrounds x-checks, systematics, Mass

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H→WW Systematics

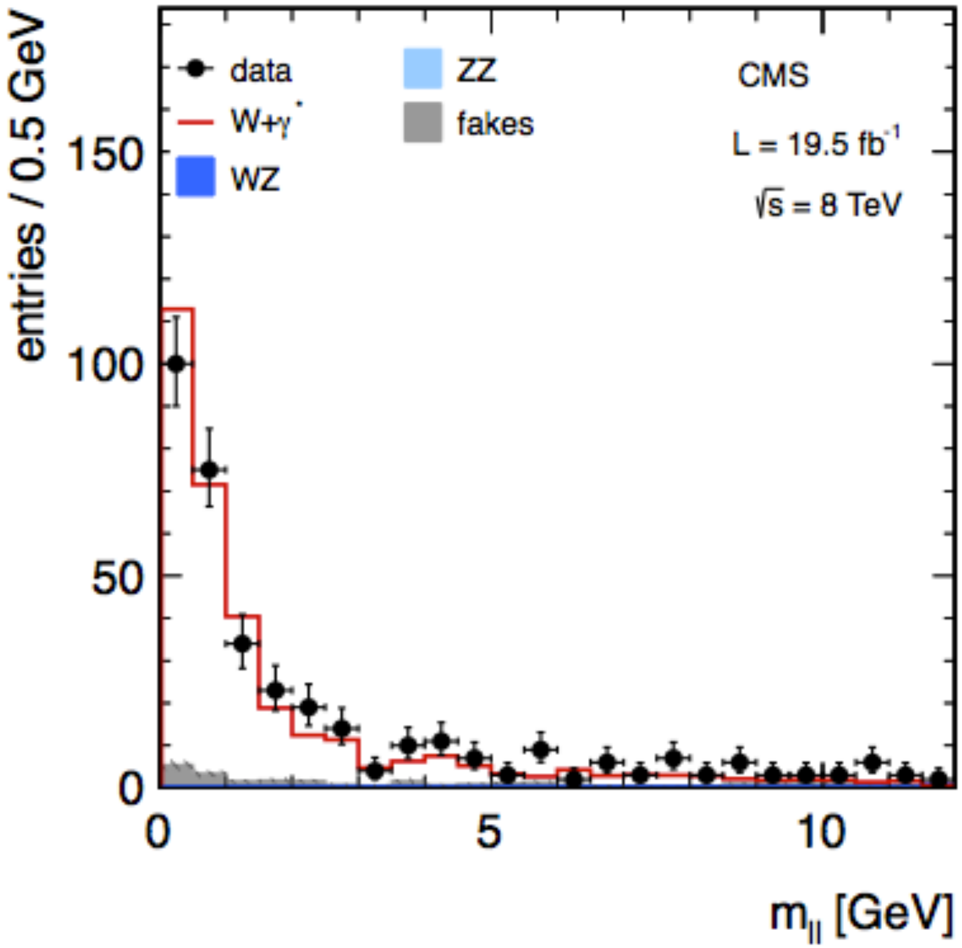
- **Sources of uncertainties**
  - Theoretical uncertainties on PDF and QCD scale and generator uncertainties : 10-50 %
  - Background normalization
    - WW and Top : 10-30 %
    - W+jets : 36 %
    - $Z / \gamma^* \rightarrow \ell\ell$: 20 % to > 100 %
    - $W+\gamma^{(*)}$, $Z/\gamma^* \rightarrow \tau\tau$: ~30 %
  - MC description of experimental measurements (eff. , energy scale and resolution) : 2-10 %
  - Luminosity : 4.4 %

- **Uncertainty variation in shape templates**
  - Vertical morphing
    - Up/Down variations at each bin as a function of a single parameter
    - Correlations between variables are preserved when alternate shapes are constructed
  - Instrumental variation
    - Lepton efficiency, lepton momentum scale/resolution, MET resolution, Jet energy resolution
  - Background shape variation
    - W+jets : different jet p_T thresholds
    - WW : QCD scale variations and different generators (Madgraph/MC@NLO)
    - Top : different generators (POWHEG / Madgraph)
  - Bin-by-bin statistical uncertainty
    - All bins up / down simultaneously
    - Consistent result with full independent bin-by-bin variation
  - WW normalization is left to float (large sideband in high m_T and high $m_{\ell\ell}$ is able to constrain it)
  - WW PDF uncertainty : threated as shape systematic now

Wγ* background estimation

Wγ$^{(*)}$ is a LO Madgraph sample with $m_{\ell\ell}$ < 12 GeV

- Measure cross-section for muons :
  - Reconstruct Wγ$^{(*)}$ → eμμ and μμμ in data using 20/10/3 lepton pt cuts allowing for $m_{\ell\ell}$ in [0,12] GeV
  - Correct MC for observed event yield in data :

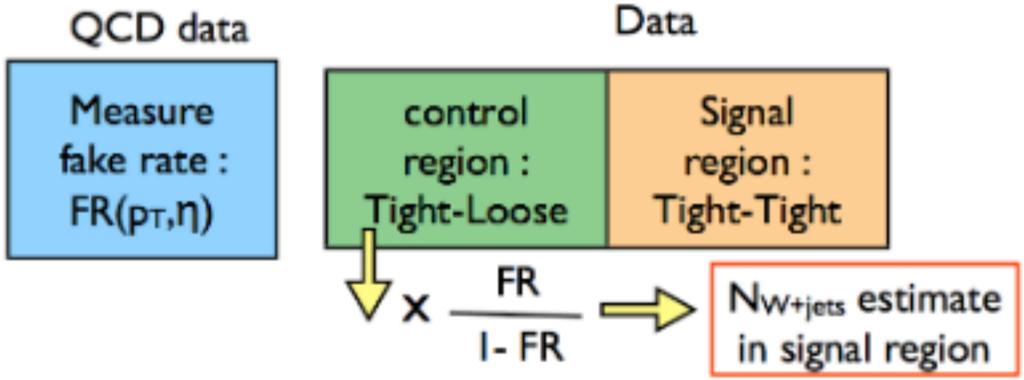


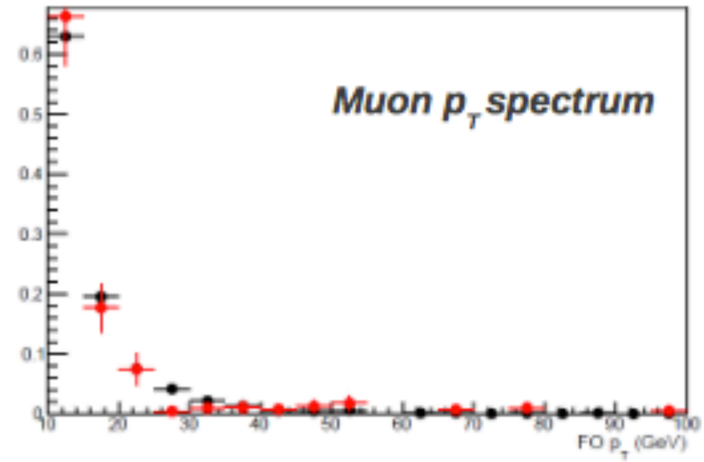
→ **"k-factor" ~ 1.5 ± 0.5**

→ **systematic from difference between channels and low/high mass**

W+Jets estimation

- **Important background in low mass region**

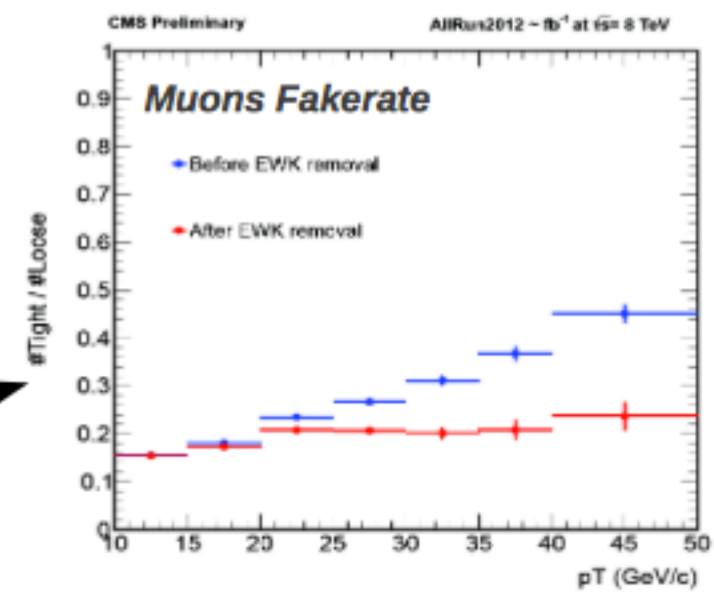




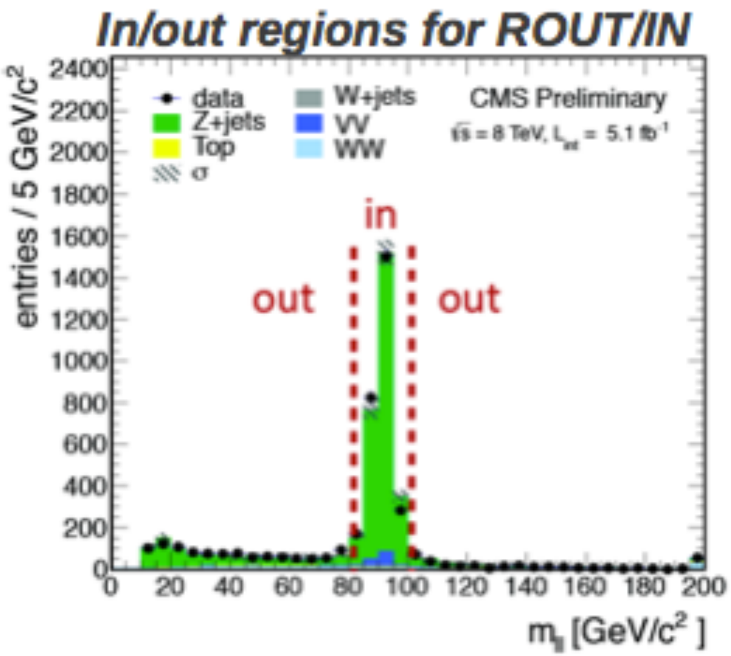
- Jet can be mis-identified as leptons
- Measure the rate for a lepton with loose selection to pass full requirement (Fake Rate) in data events dominated by dijet QCD

- Apply the « fake rate » to selected dilepton control region to estimate the fake contribution

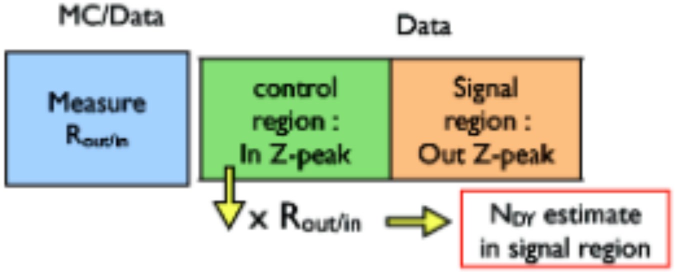
- **W and Z contamination at high p_T**
  - Removed real lepton contamination(from W and Z) in the fake rate derivation sample
  - only first 3 p_T bins are relevant due to p_T spectrum



Drell-Yan: Rin/out method



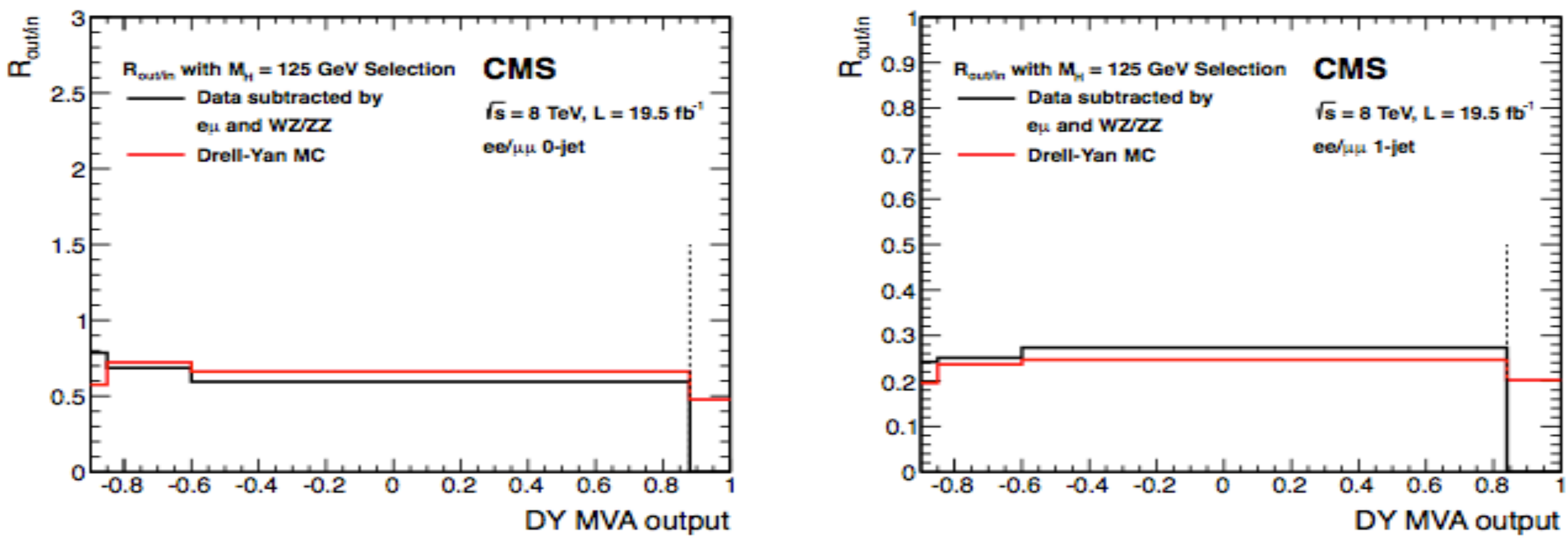
- $R_{OUT/IN}$: default uses the Z peak



$$N_{out}^{ll,exp} = R_{out/in}^{ll}(N_{in}^{ll} - 0.5N_{in}^{e\mu}k_{ll}),$$

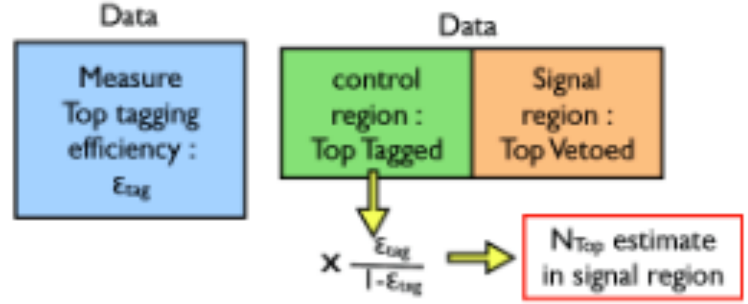
→ **Systematic from looking at Rin/out from different MET bins**

→ **Show the Rin/out MET dependence in the paper**



Top Estimation

Top background estimated from top enriched region taking in-situ b-tag efficiencies



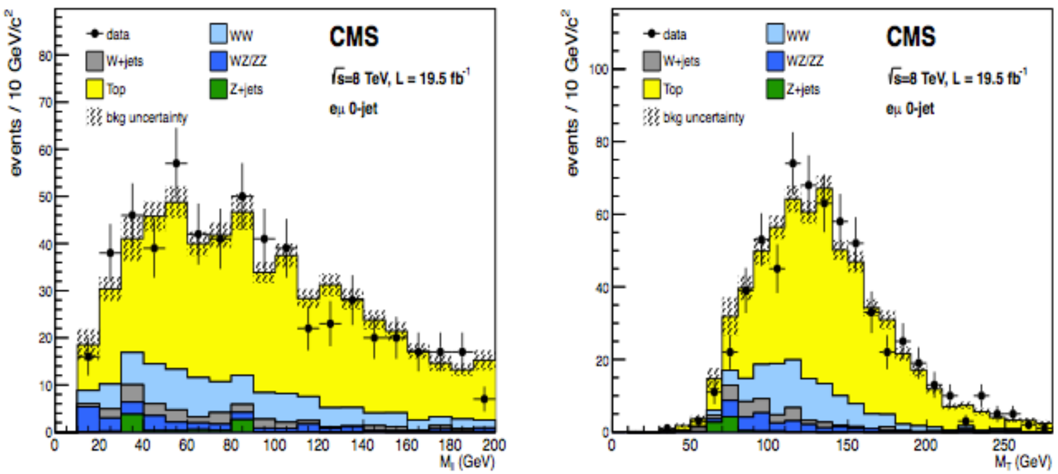


Figure 30: $m_{\ell\ell}$ (left) and $m_{\mathrm{T}}^{\ell\ell E_{\mathrm{T}}}$ (right) distributions in the 0-jet category for b different-flavor final state at the WW preselection level at $\sqrt{s} = 8$ TeV. The includes the statistical and systematic uncertainty of all background processe

← 0-jet control region

1-jet control region →

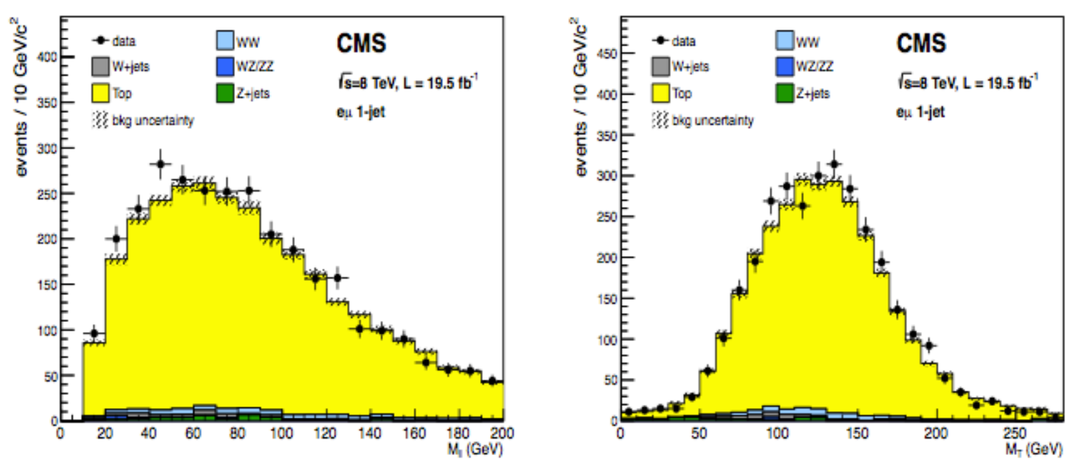
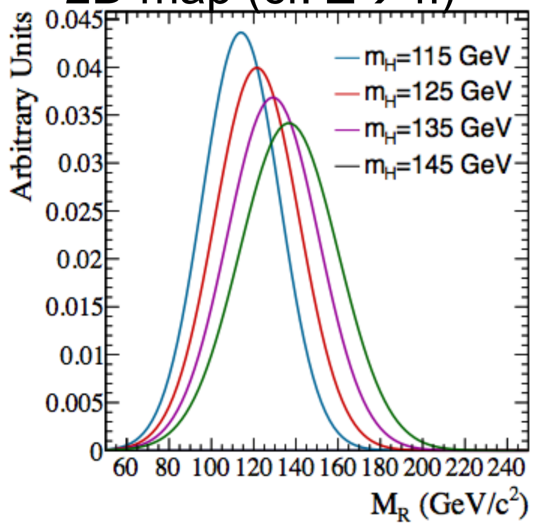


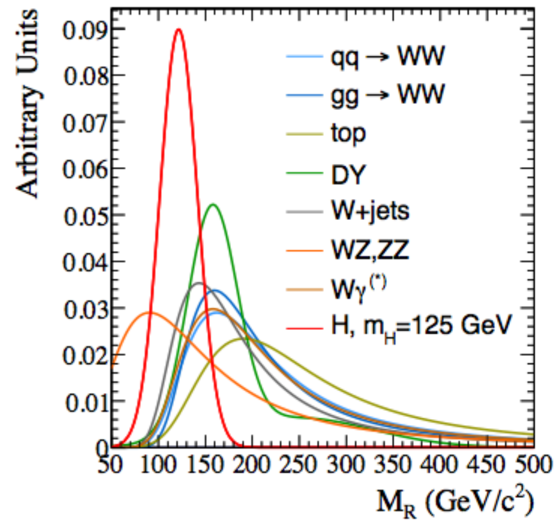
Figure 31: $m_{\ell\ell}$ (left) and $m_{\mathrm{T}}^{\ell\ell E_{\mathrm{T}}}$ (right) distributions in the 1-jet category for b-tagged events in different-flavor final state at the WW preselection level at $\sqrt{s} = 8$ TeV. The uncertainty band includes the statistical and systematic uncertainty of all background processes.

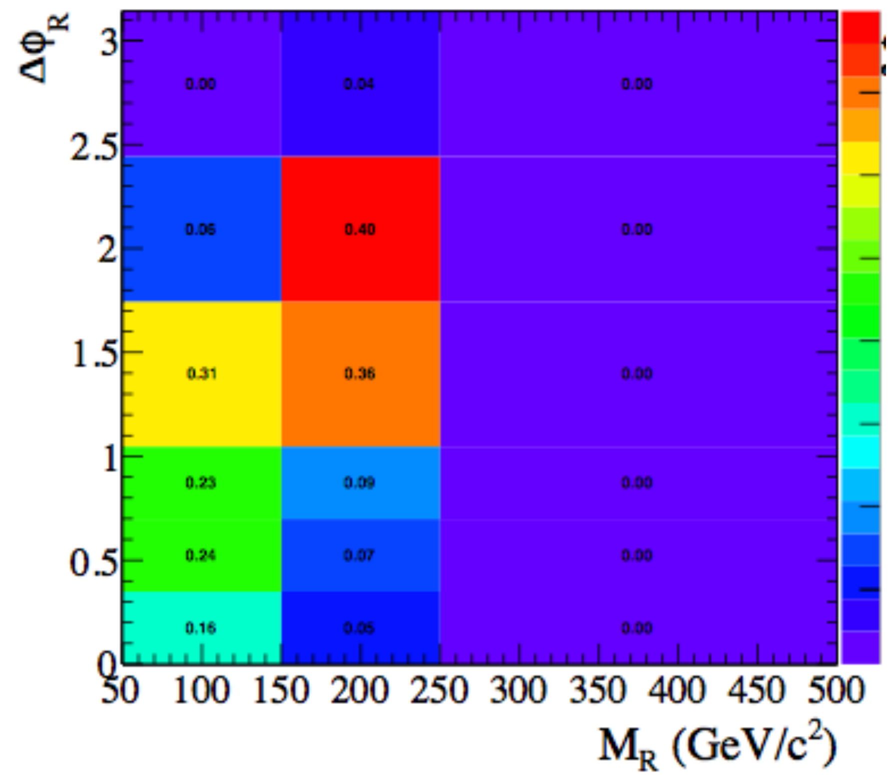
Unbinned parametric fit in H→WW→2l2ν 0/1-jet

2D fits based on the "razor" variable: M_R and $\Delta\phi_R$

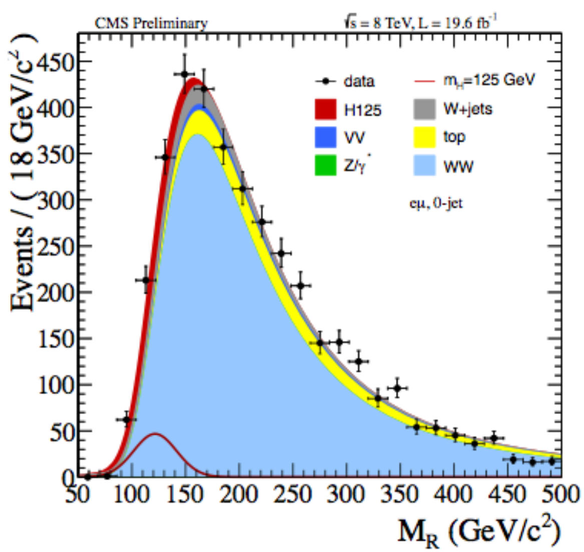
- M_R shapes are parametric
- $\Delta\phi_R$ Are taken from MC to fill an m_H independent 2D map (cf. Z→4l)

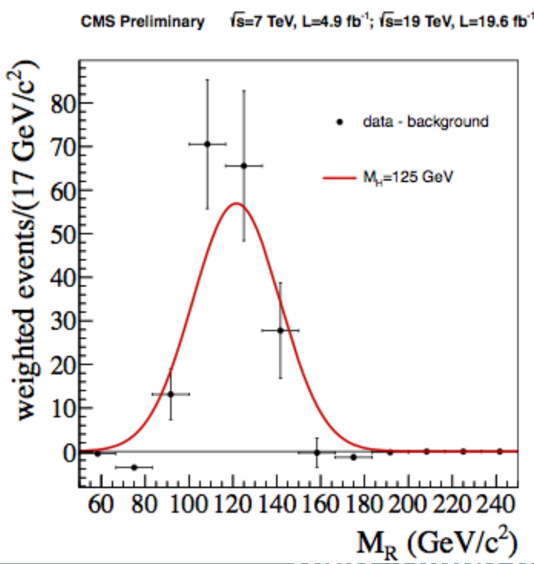






Post-fit projection on M_R @ 125 GeV



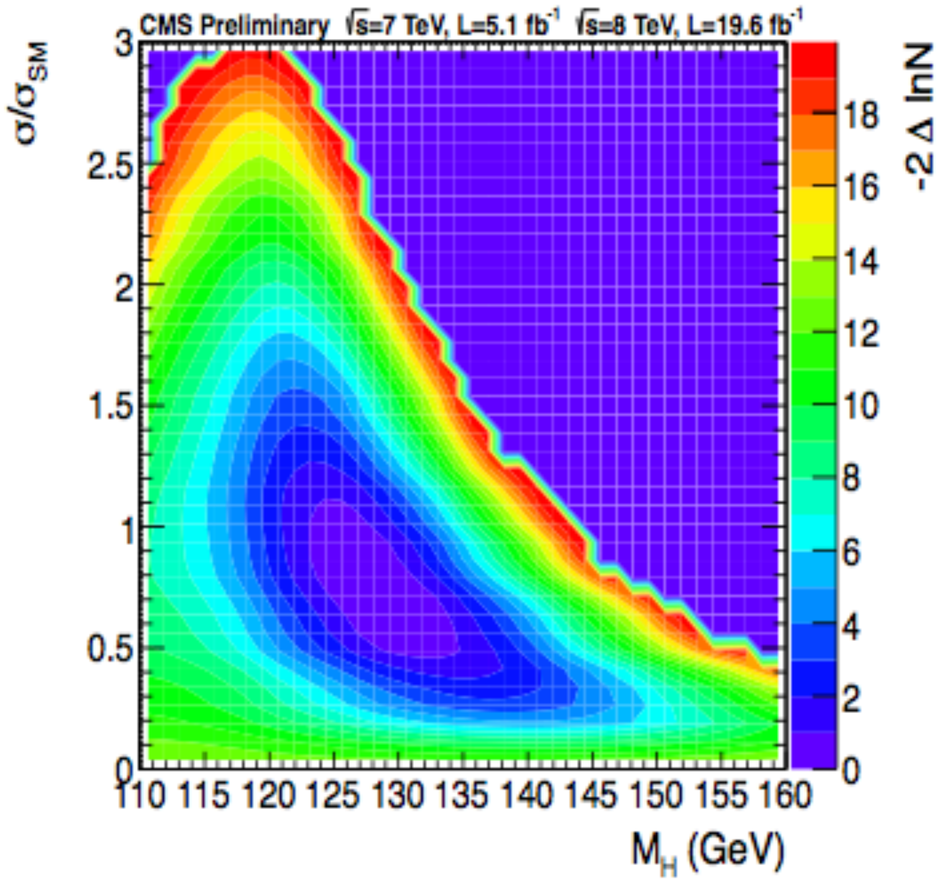


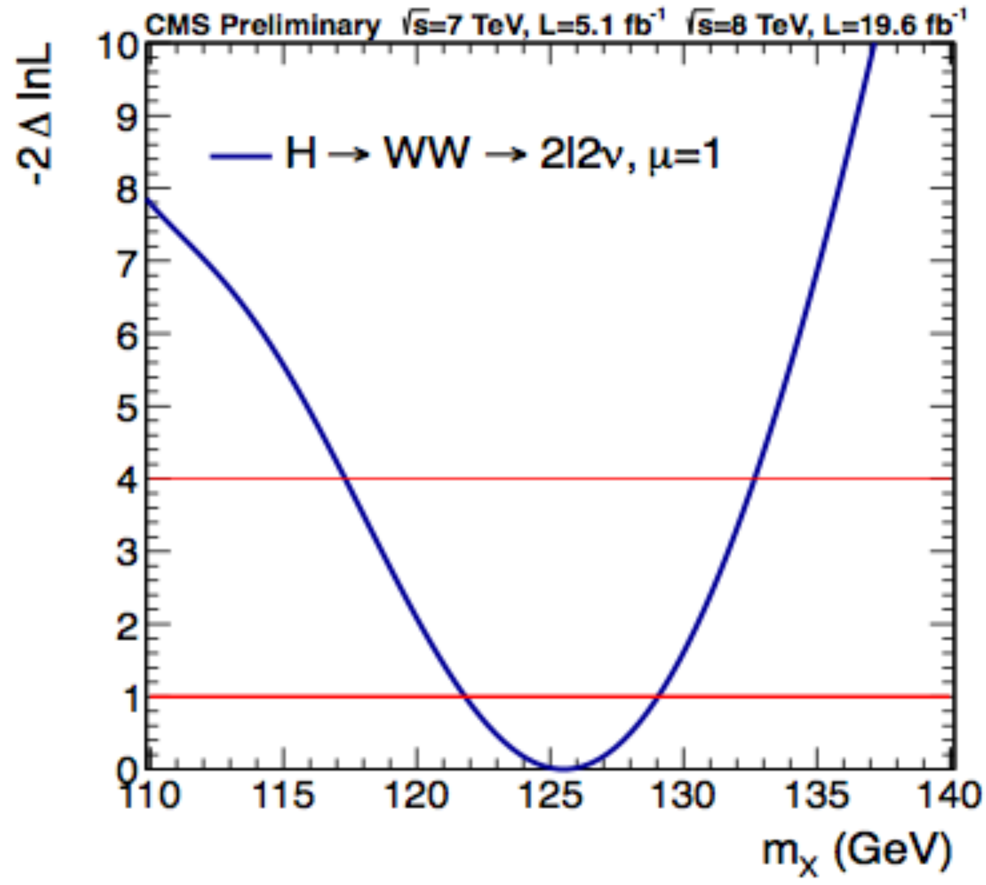
limits expected / observed	significance expected / observed	best μ observed
0.5 / 1.4	5.0 / 4.0	0.88 ± 0.25

→ Results are comparable to 2D fit in m_T-m_{ll} for 0/1-jet

Unbinned parametric fit in H→WW→2l2ν 0/1-jet

Parametric nature of the analysis allow to directly scan the (μ,m_H) plane and perform a fit of the mass for fixed value of μ:





Spin/Parity

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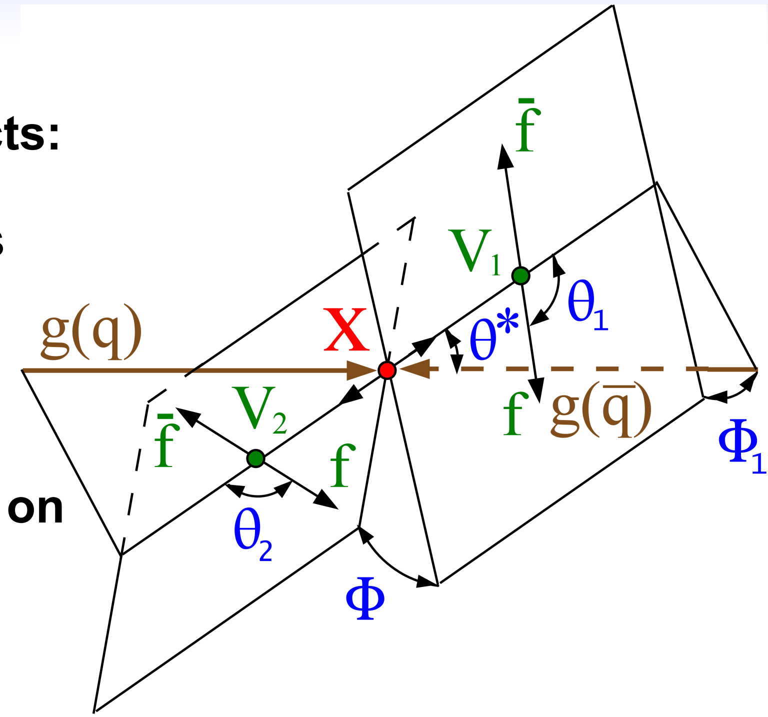
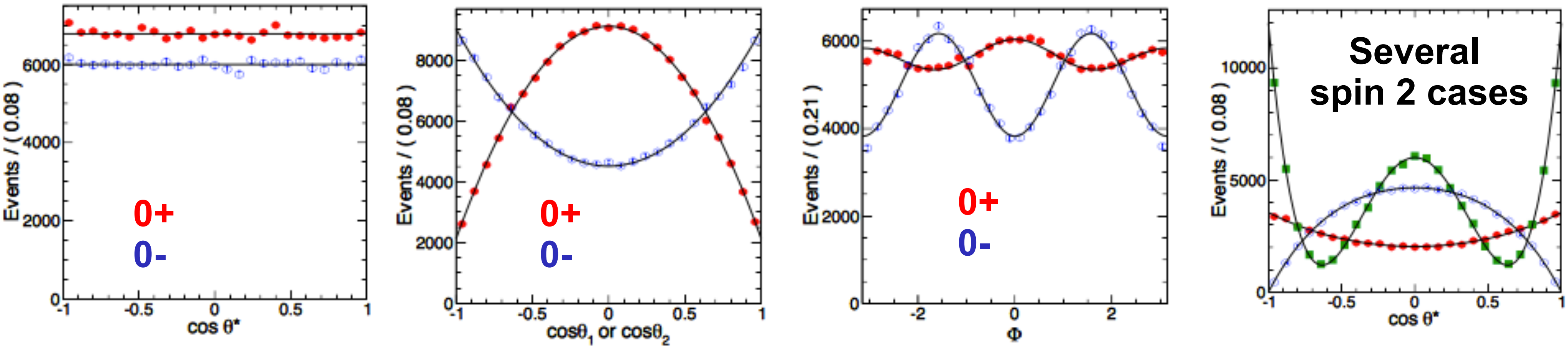
Introduction



- **Study the kinematic distributions of the decay products:**
  - Two production angles: θ* and Φ1 in the X rest frame
  - Three decay angles: θ1, θ2, and Φ in the V rest frames
- **Angular distributions determined by the tensor structure of the HVV interactions**
- **The number of kinematic variables available depends on the Higgs decay**
  → determines the strategy followed in each channel
- **Study production via gg and qq (or mix)**
- **Study decays to: ZZ→4l, WW→2l2ν and γγ**

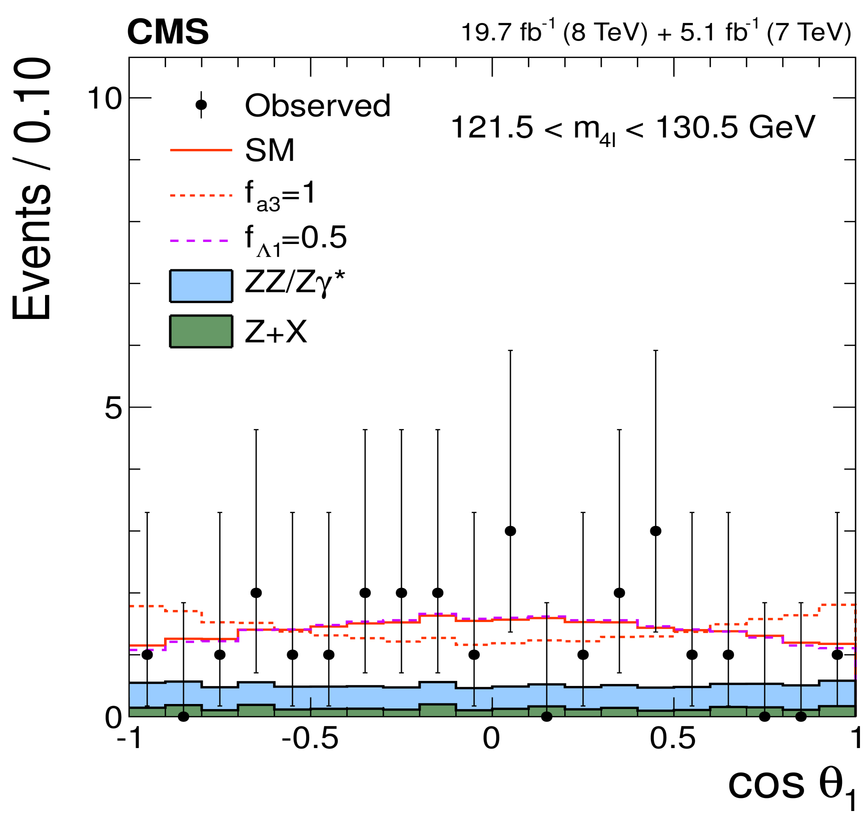


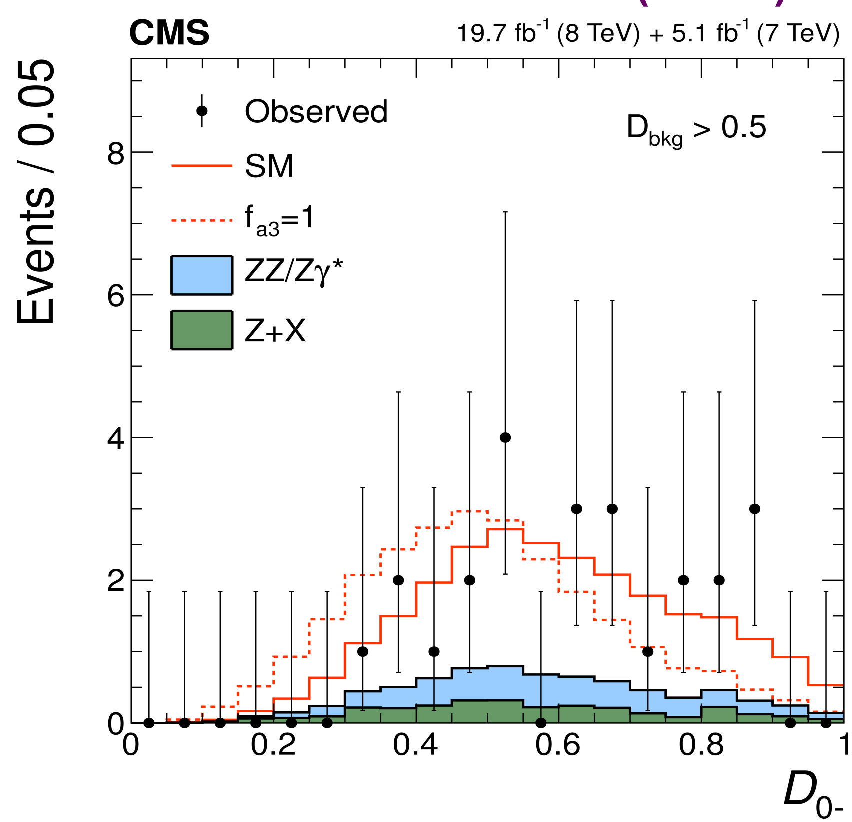
H→ZZ->4l Analysis

The complete final state can be reconstructed → Full kinematic information accessible → Best sensitivity

- **8 kinematic variables:** 5 angles : $\theta^*, \theta_1, \theta_2, \Phi, \Phi_1$; 3 masses: m_{Z1}, m_{Z2}, m_{4l}
- The information is condensed in a set of discriminants based on: **Matrix Element** calculations, such as the Matrix Element Likelihood Approach (MELA) or **BDT** discriminants trained with simulation
- Also possible to perform an 8D fit to these variables (second analysis)

Example of angular distribution and discriminant for SM vs. 0- (fa1=1):

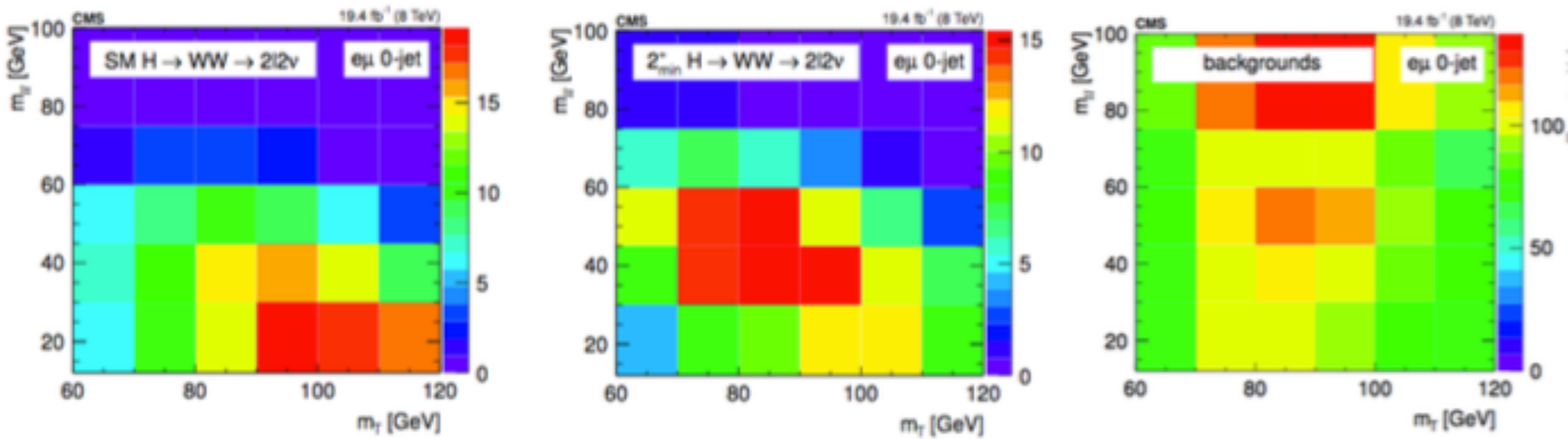




H→WW→2l2ν

Two lepton final state (eμ) + two neutrinos
→**Full final state cannot be reconstructed**
→ Rely on limited set kinematics:
2D templates of m_{ll}, m_T in eμ channel only
→**Use only 0/1-jet and same selection as legacy**

Examples of templates for SM Higgs and 2^+_{min} and backgrounds



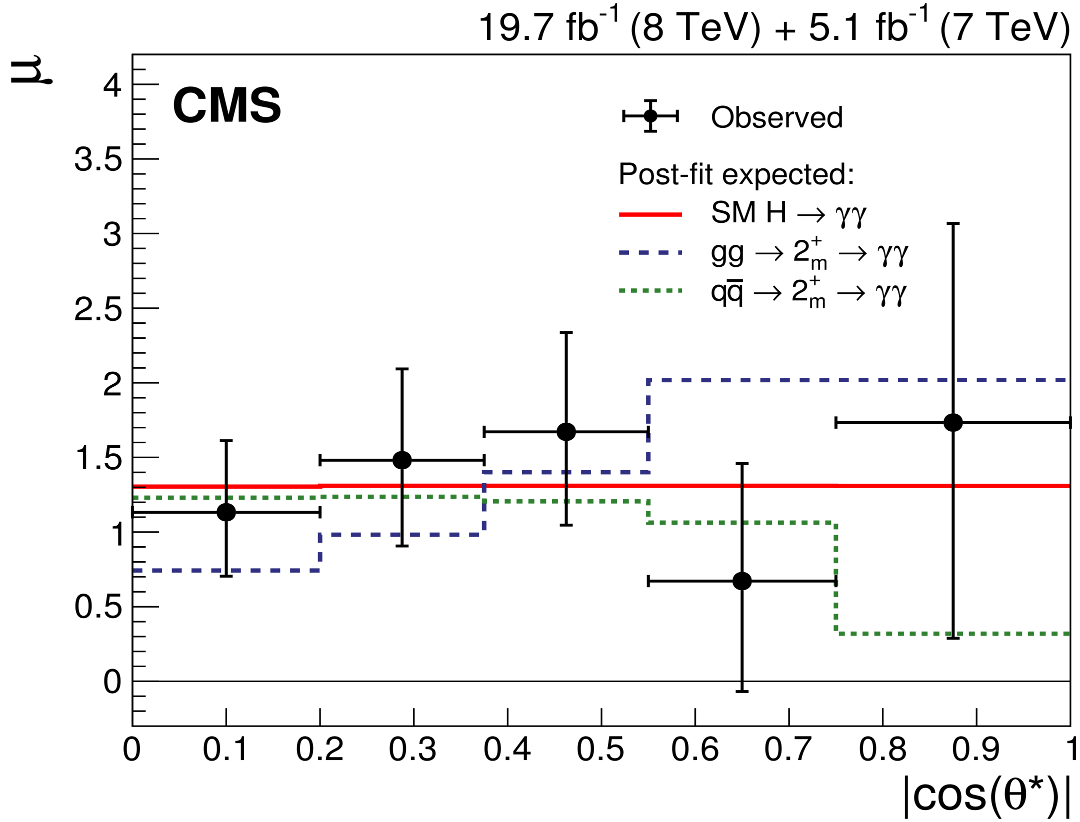
→**Sensitivity lower than H→ZZ but not for all spin hypothesis → gain in the combination as well**

H→γγ

- Only a **single kinematic variable encodes the spin information**:
  → **cosθ* :** cosine of scattering angle in the Collins-Soper frame

- CMS use that variable and follow legacy H→γγ analysis selection

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$



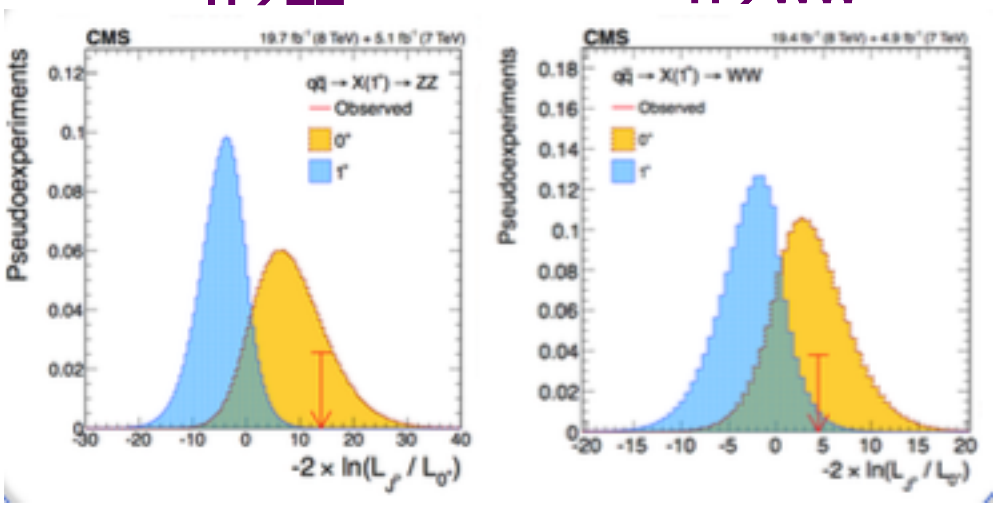
→ **Sensitivity limited → Look at separation of SM Higgs and 2^+_m only**

Spin 1

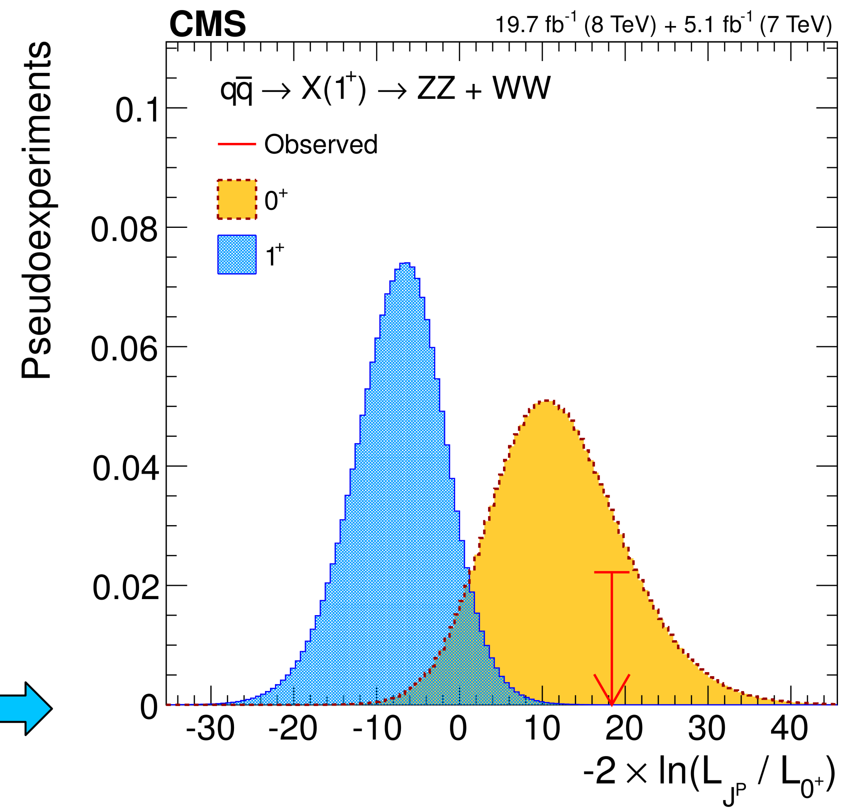
- J=1 not allowed for $X \to \gamma\gamma$ by the Landau-Yang theorem
  → Test for ZZ & WW under assumption it decouples from $\gamma\gamma$

Test Hypothesis statistics for SM vs. 1^+:

$H \to ZZ$ **$H \to WW$**



COMBIBATION



J^P Model	J^P Prod.	Expected $X \to ZZ$	Expected $X \to WW$	Expected (μ=1)	Obs. 0^+	Obs. J^P	CL_s
1^-	$q\bar{q}$	2.9σ	2.2σ	3.6σ (4.6σ)	-1.2σ	$+4.9\sigma$	<0.001%
1^+	$q\bar{q}$	2.4σ	1.8σ	3.0σ (3.8σ)	-0.8σ	$+4.3\sigma$	0.004%

→ 1+ and 1- excluded w.r.t. SM at > 99.996 % CL

Spin 2

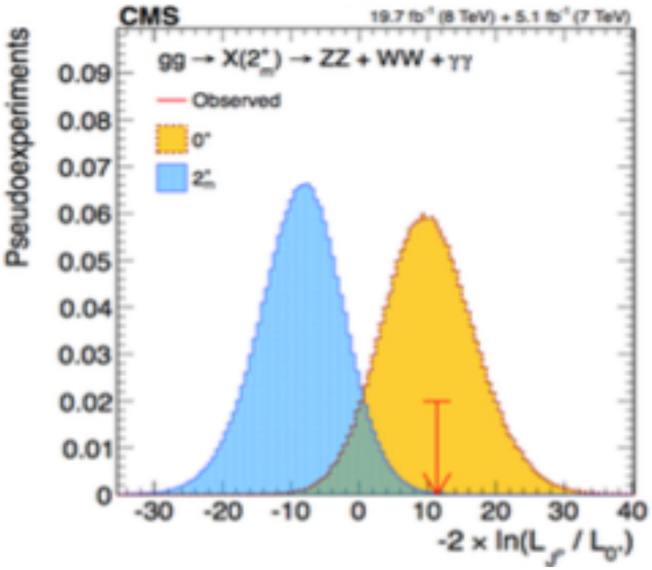
Generic Lagrangian for spin 2 is a bit more complicate than spin 1:

$$L(X_{J=2}ZZ) \sim \Lambda^{-1}\Big(-c_1 X_{\mu\nu}Z^{\mu\alpha}Z^{\nu}_{\alpha} + \frac{c_2}{\Lambda^2}\left(\partial_\alpha\partial_\beta X_{\mu\nu}\right)Z^{\mu\alpha}Z^{\nu\beta} + \frac{c_3}{\Lambda^2}X_{\beta\nu}\left[\partial^\alpha,\left[\partial^\beta,Z^{\mu\nu}\right]\right]Z_{\mu\alpha}$$
$$+\frac{c_4}{2\Lambda^2}X_{\mu\nu}\left[\partial^\mu,\left[\partial^\nu,Z^{\alpha\beta}\right]\right]Z_{\alpha\beta} + c_5 m_Z^2 X_{\mu\nu}Z^{\mu}Z^{\nu} + \frac{2c_6 m_Z^2}{\Lambda^2}\partial_\alpha X_{\mu\nu}\left[\partial^\mu,Z^\nu\right]Z^\alpha$$
$$-\frac{c_7 m_Z^2}{2\Lambda^2}X_{\mu\nu}\left[\partial^\mu,\left[\partial^\nu,Z_\alpha\right]\right]Z^\alpha + \frac{c_8}{2\Lambda^2}X_{\mu\nu}\left[\partial^\mu,\left[\partial^\nu,Z^{\alpha\beta}\right]\right]\tilde{Z}_{\alpha\beta}$$
$$-\frac{c_9 m_Z^2}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma}\partial^\sigma X^{\mu\alpha}Z_\nu\partial_\alpha Z^\rho + \frac{c_{10}m_Z^2}{\Lambda^4}\epsilon_{\mu\nu\rho\sigma}\partial^\rho\partial^\beta X^{\mu\alpha}\left[\partial^\sigma,\left[\partial_\alpha,Z^\nu\right]\right]Z_\beta\Big).$$

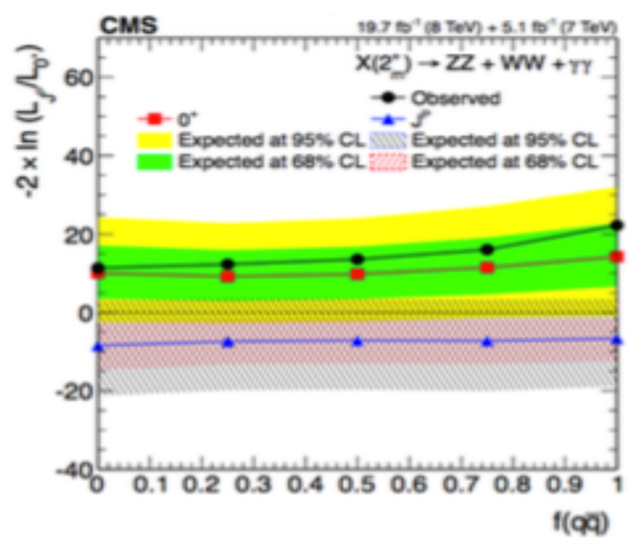
→ **Testing 10 models (x) 2 production modes: gg & qq (+ arbitrary mixture of gg/qq)**

J^P Model	$gg \to X$ Couplings	$q\bar{q} \to X$ Couplings	$X \to VV$ Couplings
2^+_m	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} = c_5^{VV} \neq 0$
2^+_{h2}	$c_2^{gg} \neq 0$	$\rho_1 \neq 0$	$c_2^{VV} \neq 0$
2^+_{h3}	$c_3^{gg} \neq 0$	$\rho_1 \neq 0$	$c_3^{VV} \neq 0$
2^+_h	$c_4^{gg} \neq 0$	$\rho_1 \neq 0$	$c_4^{VV} \neq 0$
2^+_b	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} \ll c_5^{VV} \neq 0$
2^+_{h6}	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_6^{VV} \neq 0$
2^+_{h7}	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_7^{VV} \neq 0$
2^-_h	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_8^{VV} \neq 0$
2^-_{h9}	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_9^{VV} \neq 0$
2^-_{h10}	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_{10}^{VV} \neq 0$

Example: gg→2^+_m with ZZ+WW+γγ

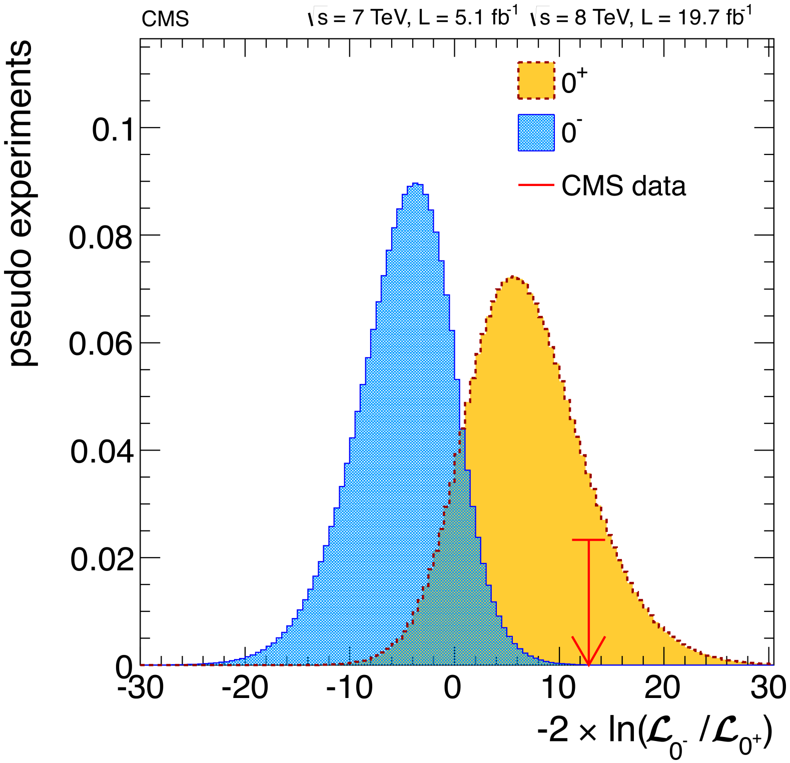


… and as function of f_{qq}



Spin 0

- **Pure 0⁻ ruled out at 99.9% CL by H→ZZ→4l alone:**



→ **Study small deviations of couplings to gauge bosons of the HVV spin 0 tensor:**

$$A(HV_1V_2) \sim \left[a_1^{V_1V_2} + \frac{\kappa_1^{V_1V_2} q_{V_1}^2 + \kappa_2^{V_1V_2} q_{V_2}^2}{\left(\Lambda_1^{V_1V_2}\right)^2} \right] m_V^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + a_2^{V_1V_2} f_{\mu\nu}^{*(V_1)} f^{*(V_2),\mu\nu} + a_3^{V_1V_2} f_{\mu\nu}^{*(V_1)} \tilde{f}^{*(V_2),\mu\nu}$$

Λ_1 term: leading momentum expansion; a_2 term: CP even state; a_3 term: CP odd state

- **Choose a parameterization that relates cross sections fractions (f_{a2}, f_{a3}, $f_{\Lambda1}$) to a_2, a_3, and Λ_1 as:**

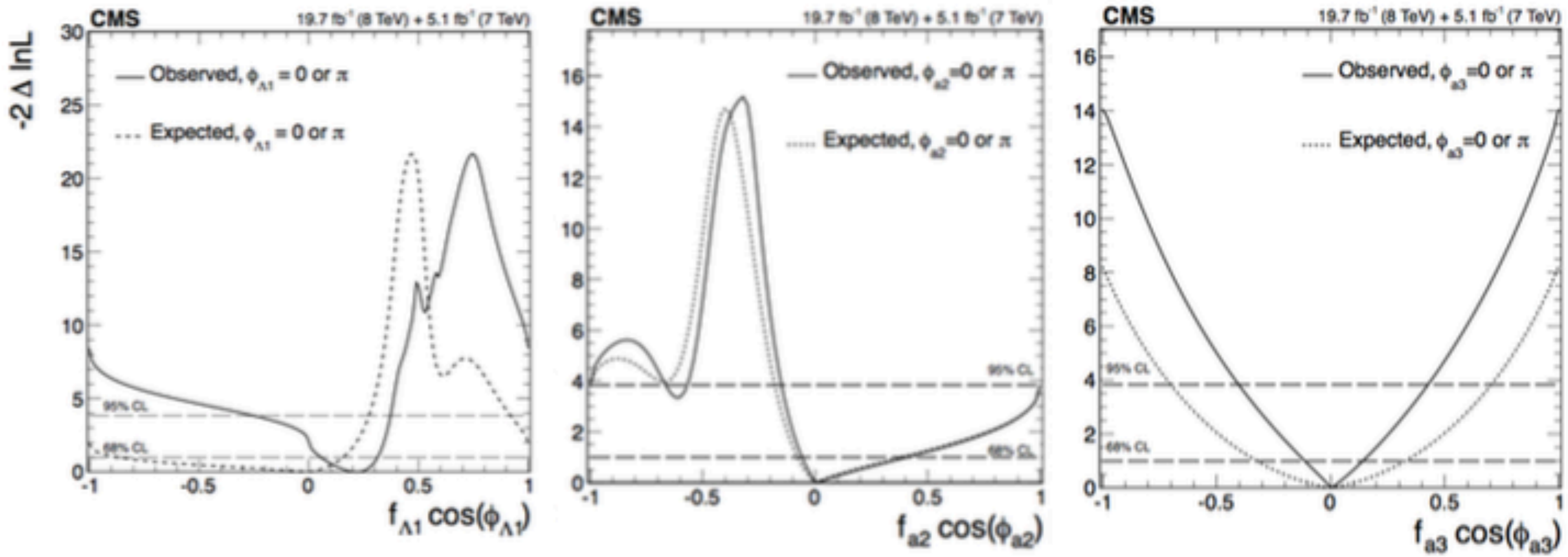
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

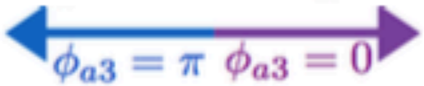
- σ_i in each case corresponds to $a_i = 1$ and $a_{j \neq i} = 0$
- **$f_{a1} = 1 - f_{a2} - f_{a3} - f_{\Lambda1}$ -...** is the SM contribution → expected to dominate
- For a **measured value of f_x** → possible to extract the ratio ai/a1

→ **Perform Likelihood scans (1D and 2D) of f_x to set limits on the anomalous couplings**

Anomalous couplings: Likelihood scans of f_x

H→ZZ: Couplings constrained to be real, other couplings fixed to the SM





Full set of scans available, e.g. allowing complex phases. fitting more than one parameter at a time …
→ all consistent with the SM

cosϕ term allows for a signed quantity
cosϕ= −1 (π) or +1 (0)

+ similar scans for H→WW with lower sensitivity than H→ZZ

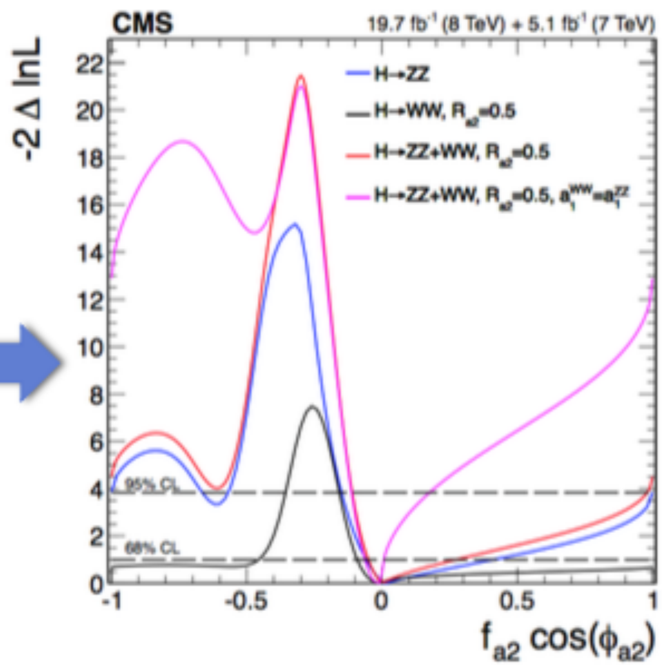
Anomalous Couplings: ZZ+WW combination

General relationship between HWW and HZZ couplings:

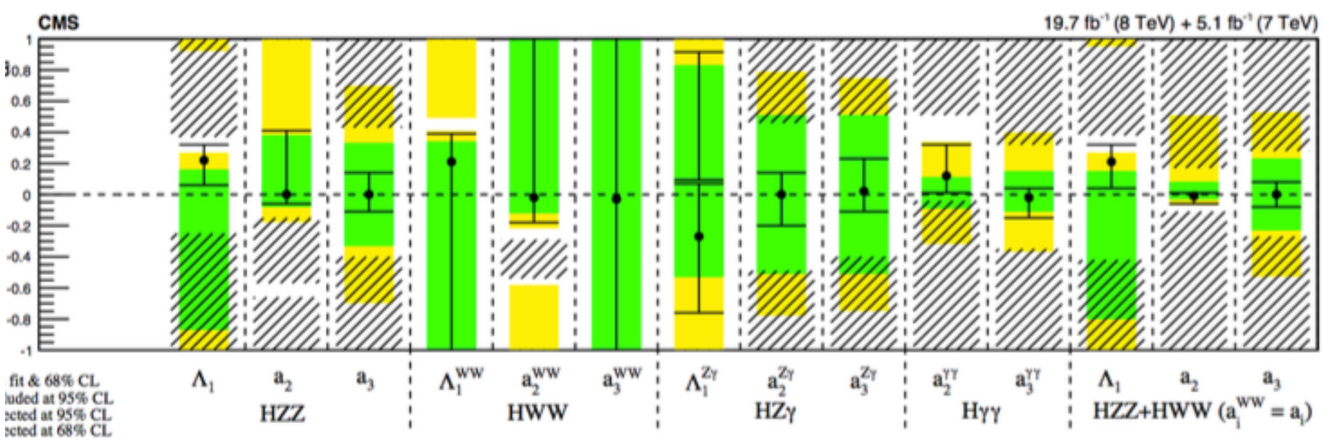
$$r_{ai} = \frac{a_i^{WW}/a_1^{WW}}{a_i/a_1} \quad r_{ai}\,[-\infty, +\infty] \longrightarrow R_{ai} = \frac{r_{ai}|r_{ai}|}{1+r_{ai}^2} \quad R_{ai}\,[-1,+1]$$

- f_{ai} can then be written as a function of f_{ai}^{WW} via R_{ai}
- Two scenarios for combination:
  - arbitrary relationship between a1 for W and Z : $a_1^{WW} \neq a_1^{ZZ}$
  - custodial symmetry: $a_1^{WW} = a_1^{ZZ}$

Example for R_{ai} = 0.5 (full 2D scan available)



→ **Summary of limits on Anomalous couplings:**



→ **No sign of deviations to the SM but need more data to better constraints some of the couplings**