SM Higgs Boson Properties

16/9/2015 - PIC2015, Warwick

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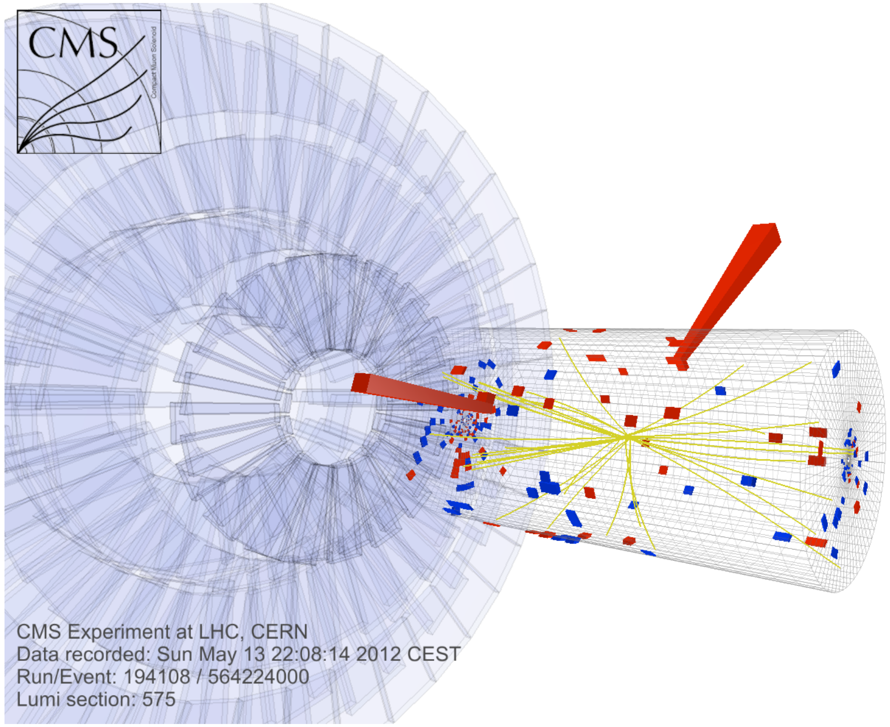
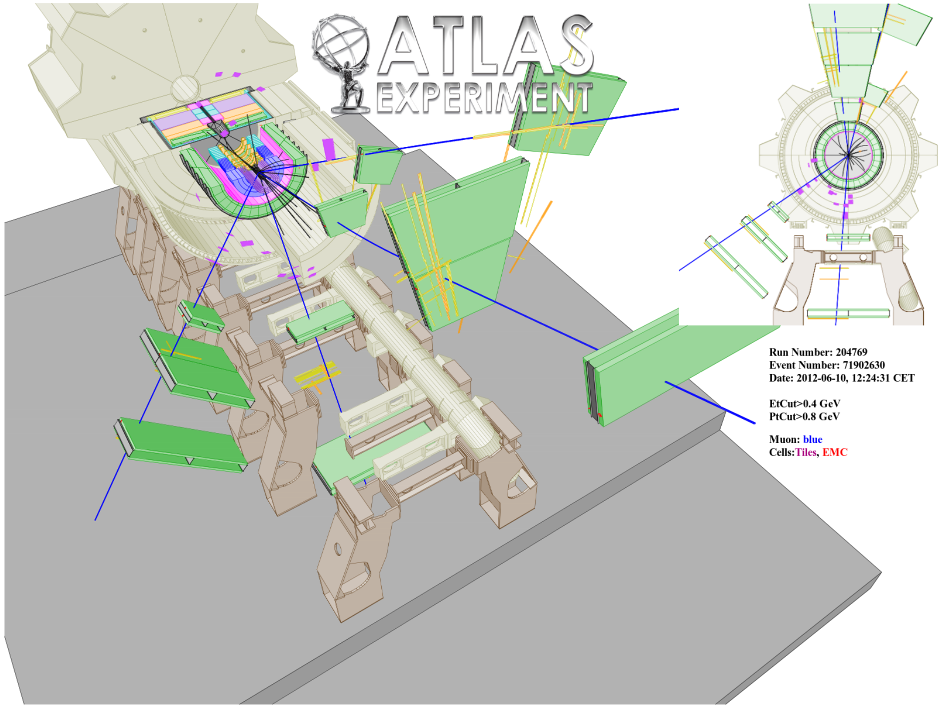
for the ATLAS and CMS Collaborations





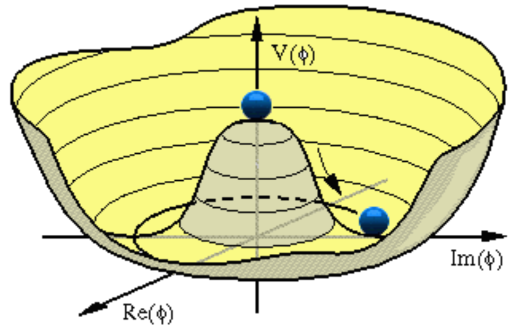
Outline

Introduction
- The Higgs boson in the SM
- Analysis methods

Properties
- Mass, width, lifetime
- Spin/CP
- Differential cross sections
- Anomalous Higgs couplings

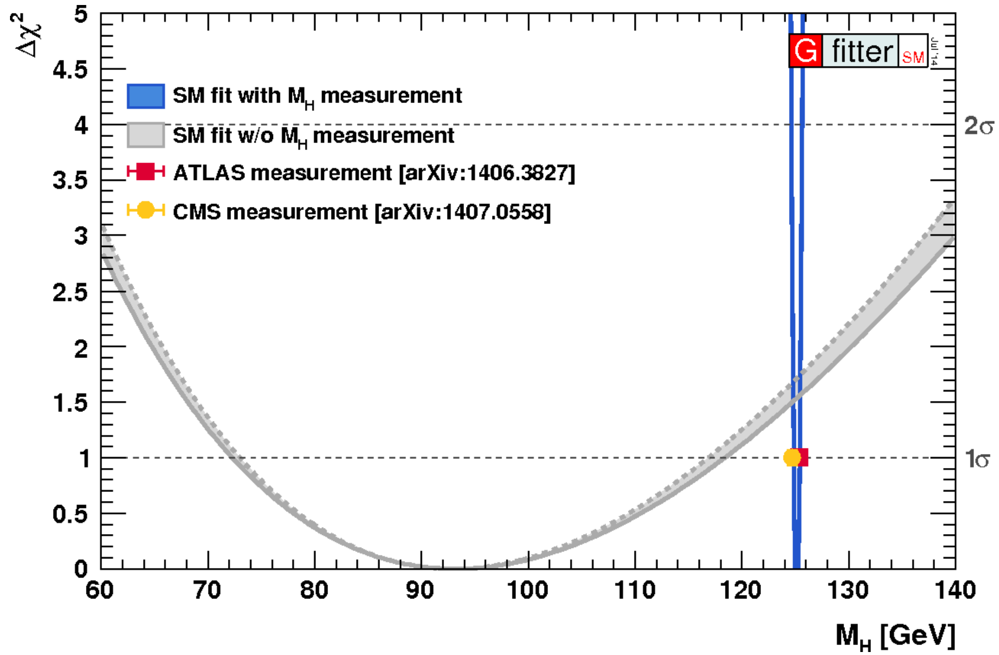
Higgs boson: standard model

Standard model (SM) of electro-weak interaction [Glashow, Weinberg, Salam], **Higgs mechanism:**
- **Scalar field** breaking spontaneously the **electro-weak symmetry**
- **Longitudinal degrees of freedom** absorbed in $W^{\pm}$ and Z^0 gauge bosons
- Higgs boson gives masses to leptons and quarks through **Yukawa couplings**



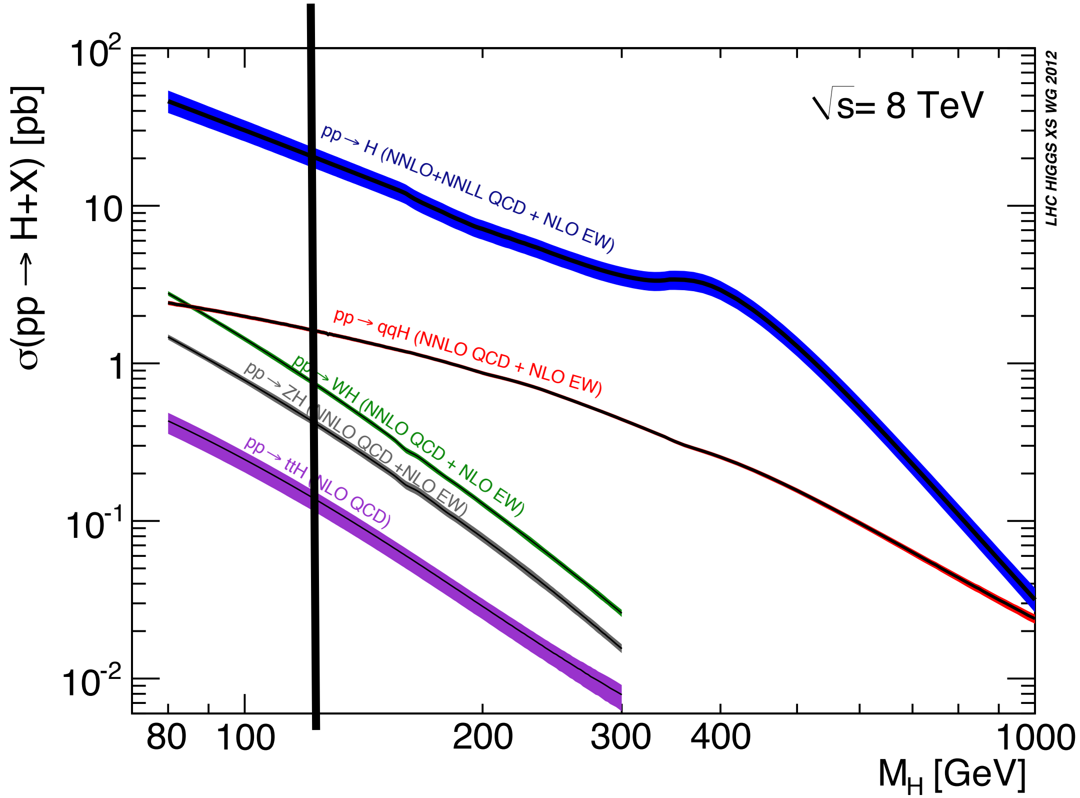
$$\hat{\mathscr{L}}_\phi = (\hat{D}_\mu\phi)^\dagger(\hat{D}^\mu\phi) + \mu^2\phi^\dagger\phi - \frac{\lambda}{4}(\phi^\dagger\phi)^2$$

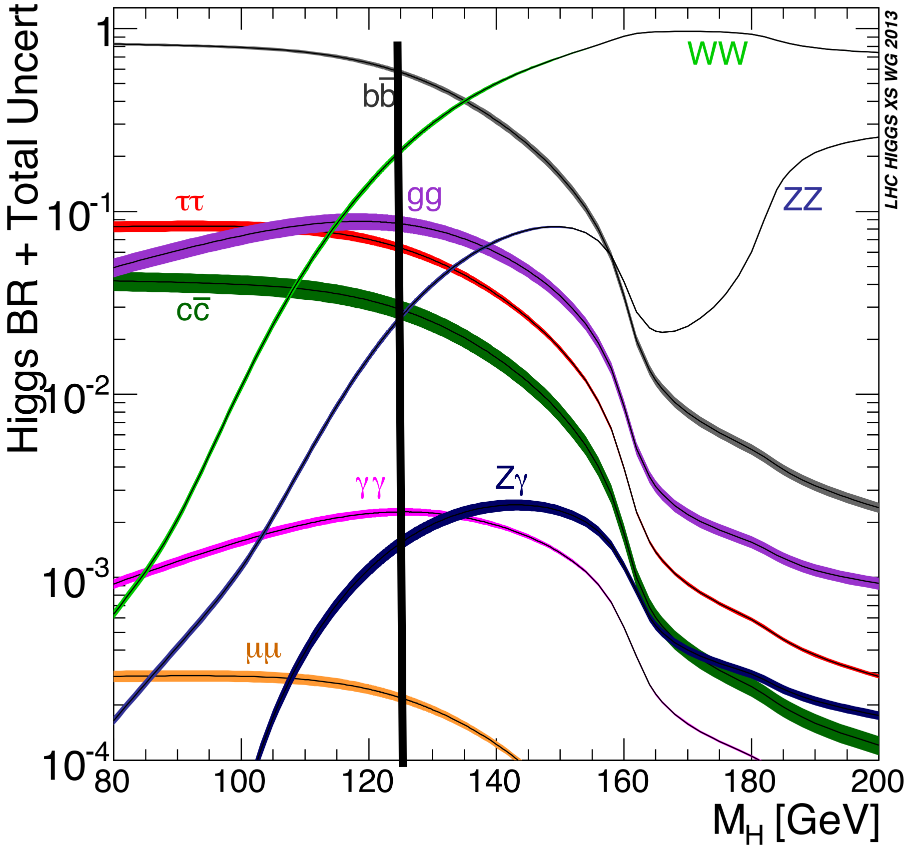
SM predictions:
- **Mass :** unpredicted
- **Width at 125 GeV:** ~4 MeV (dominated by Higgs coupling to b-quark)
- **Spin/CP:** Scalar field => spin 0, CP even

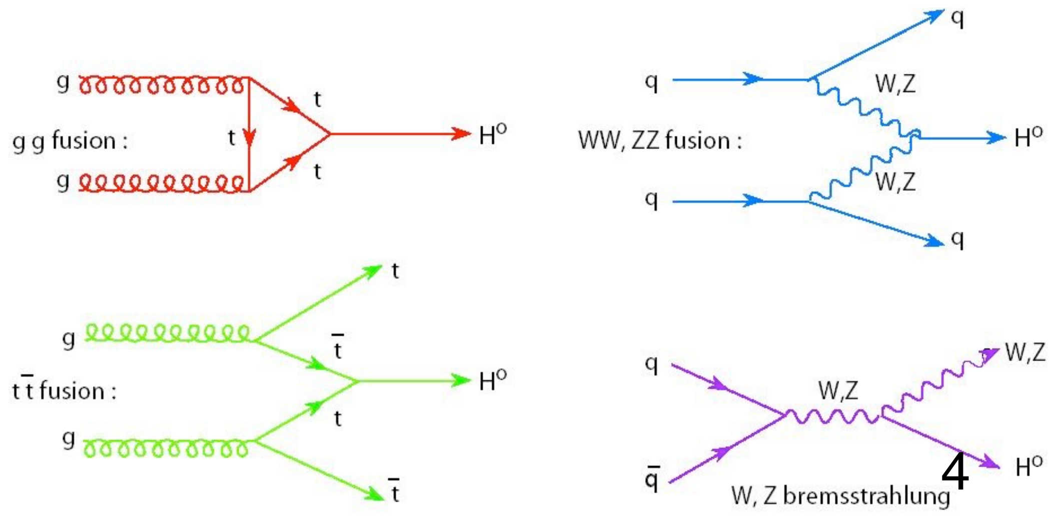


Higgs boson channels at the LHC

- At the LHC, the main **Higgs production** mechanism in the SM is **gluon fusion** followed by **VBF** and associated production with W,Z or tt
- **Essential to probe both boson and fermion decay**



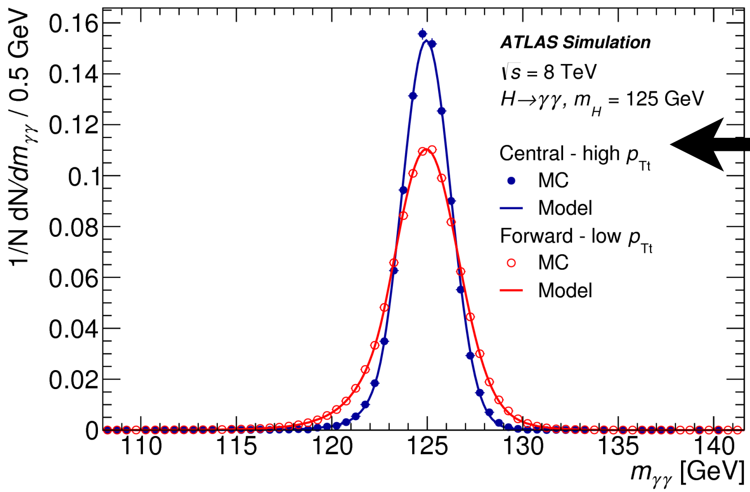




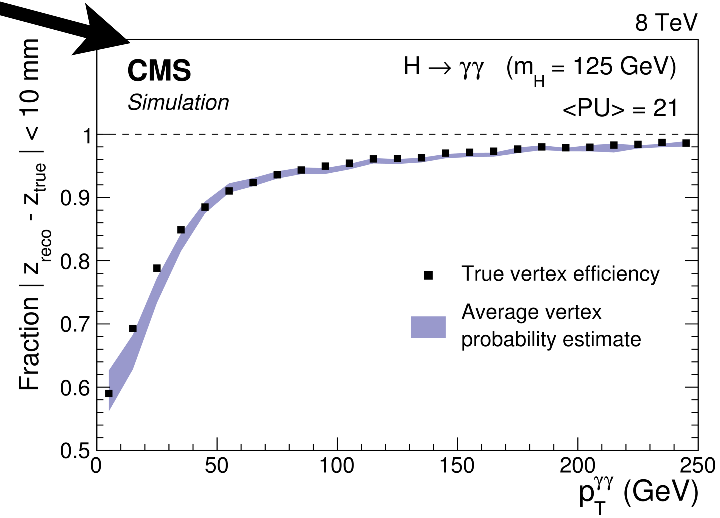
Analysis methods

H→γγ analysis

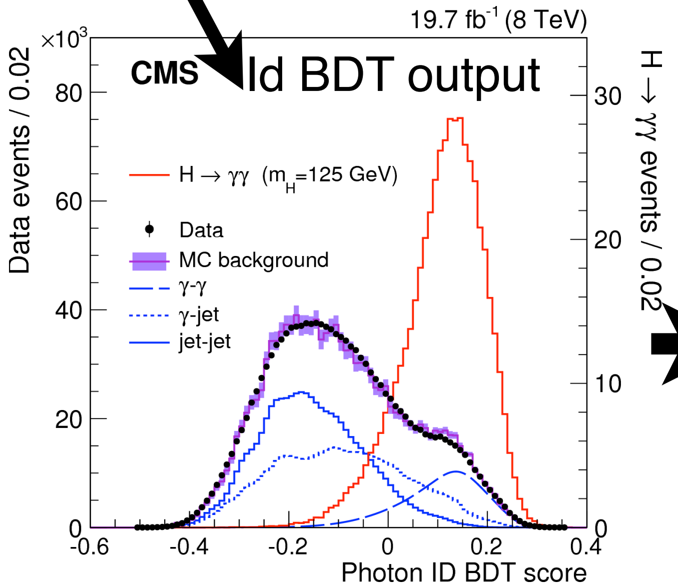
CMS - EPJC 74 (2014) 3076, ATLAS - PRD 90 (2014) 112015

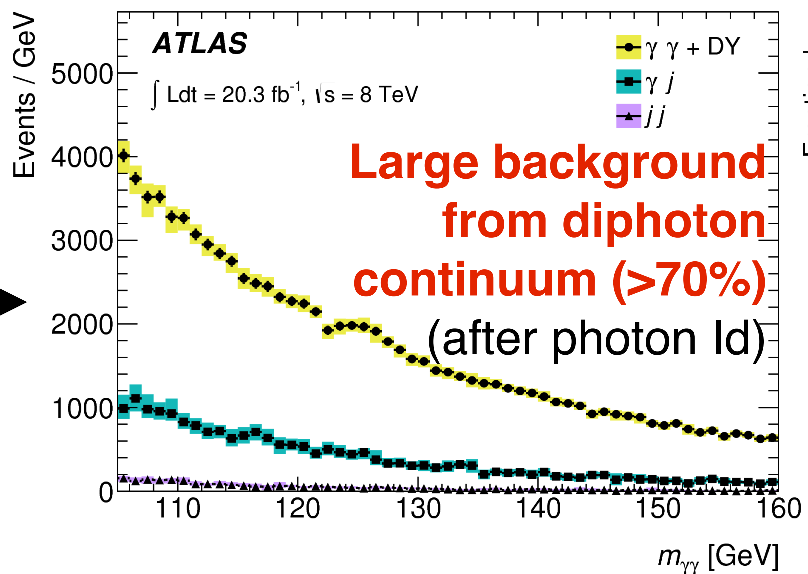


- Look for **small signal peak (BR~0.2%) over large background**
- **Photon energy resolution** 1-2 GeV depending on categories: calibration is crucial
- **Vertex finding** among pileup vertices helps improving identification and resolution



- **Photon identification:** reject jets faking photons with shower shape and isolation using cuts (ATLAS) or BDT (CMS)

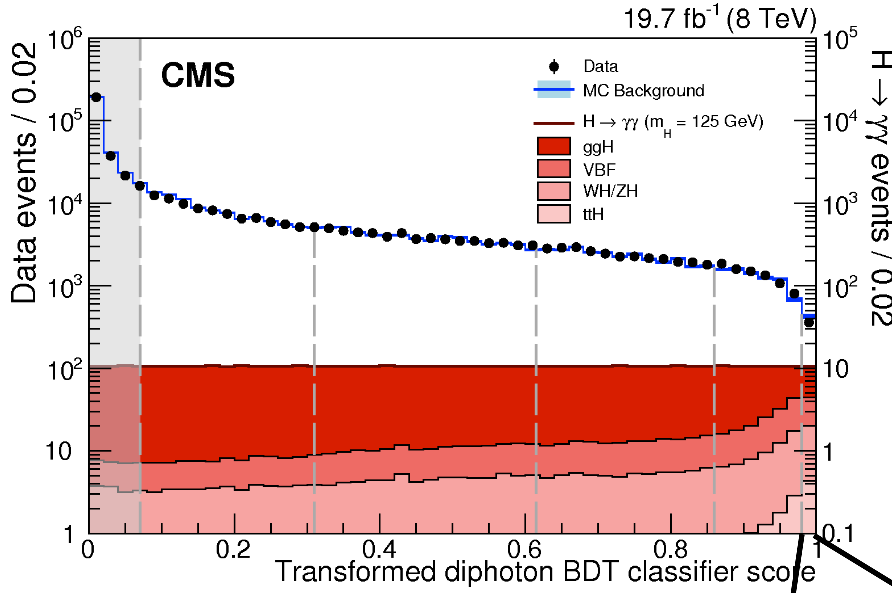




H→γγ: inclusive categories

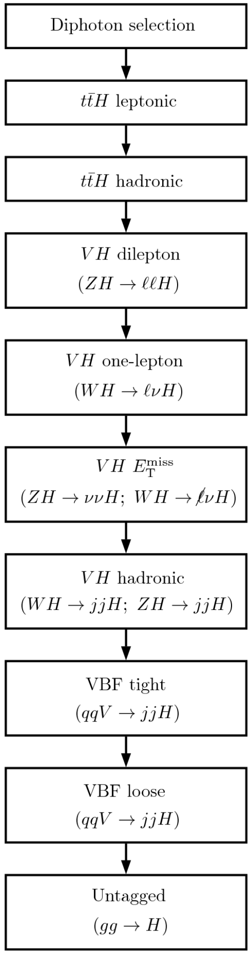
CMS - EPJC 74 (2014) 3076, ATLAS - PRD 90 (2014) 112015

Sensitivity from mass fit

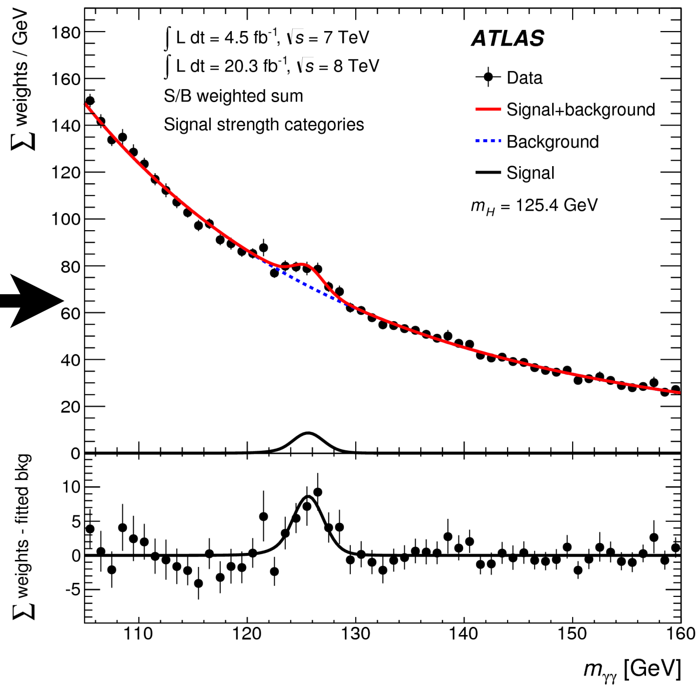


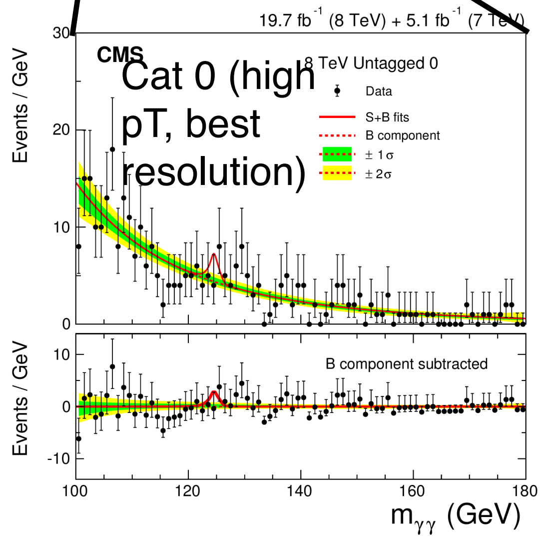
CMS categorizes with **Diphoton BDT:**
- Mass independant
- Kinematics, vertexing, PhotonId output, energy resolution variables

ATLAS: mainly cut-based categories:



All categories merged





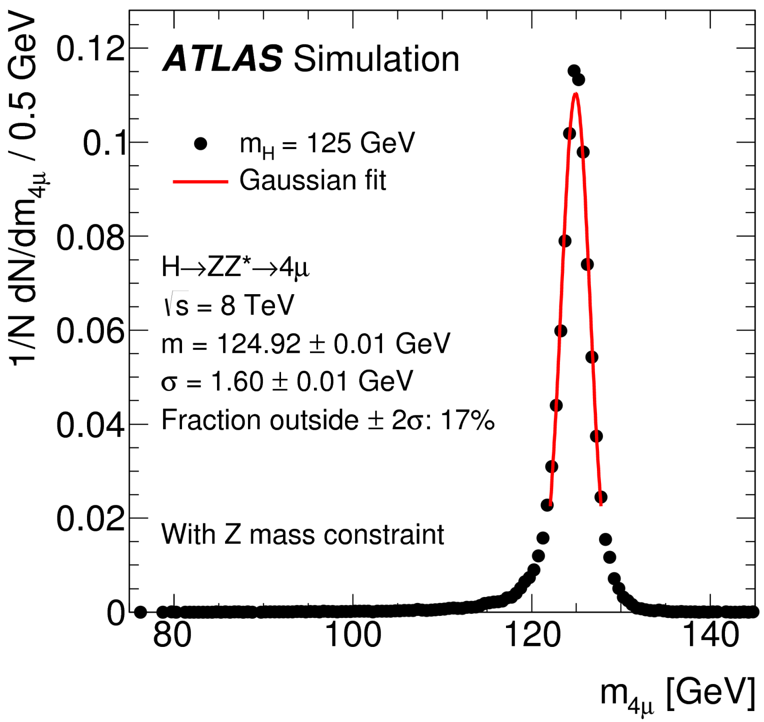
Cat 0 (high pT, best resolution)

$H \to ZZ^{(*)} \to 4l$

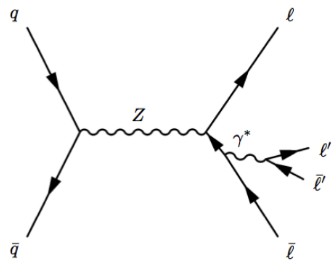
ATLAS PRD 90 (2014) 052004, CMS - PRD 89 (2014) 092007

Signature:

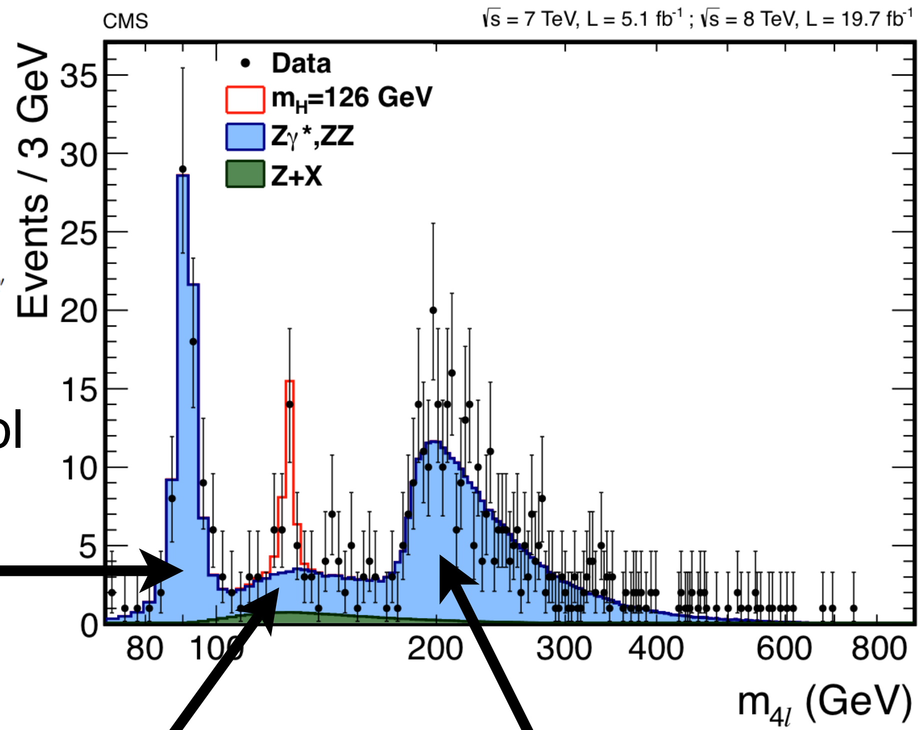
- 2 pair of opposite sign isolated leptons (4e, 2e2μ, 4μ) consistent with the same vertex
- Need **momentum** as **low** as pT>7 GeV (electrons) and pT>5-6 GeV (muons) to not loose too much **efficiency** missing the 4th lepton
- **Main backgrounds**: ZZ continuum, Z+jets, ttbar



The 4 muons channel has the best mass resolution



$Z \to 4l$: control region



$H \to ZZ^* \to 4l$:
- **Very good s/b~2**
- **2D/3D analysis**

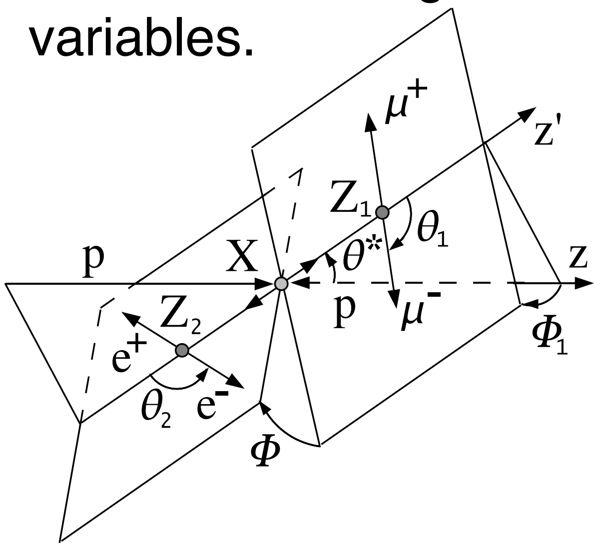
- **$ZZ \to 4l$ region**: used to constrain higgs boson width

H→ZZ$^{(*)}$→4l analysis

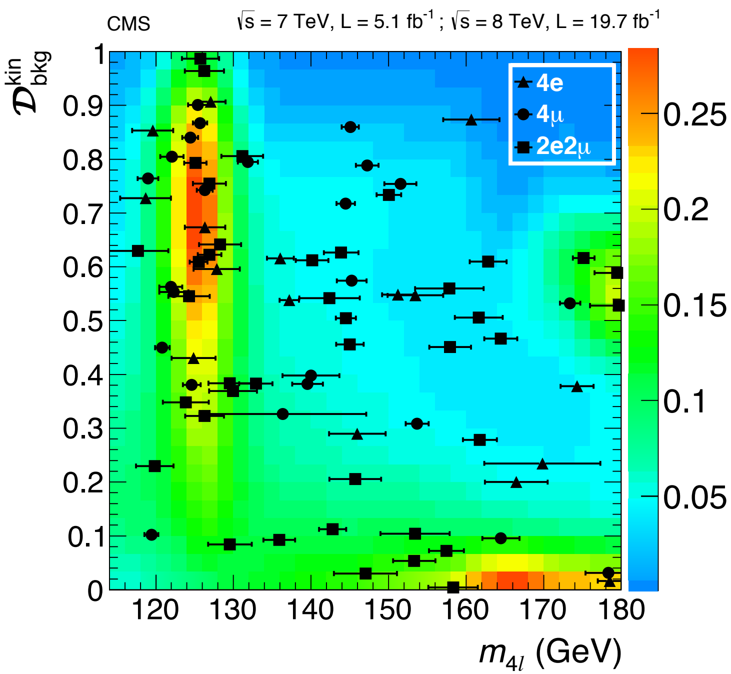
ATLAS PRD 90 (2014) 052004, CMS - PRD 89 (2014) 092007

- **Mass measurement: 2D analysis** in (m4l, BDT) in **ATLAS**, **3D analysis** (m4l, KD, Resolution) in **CMS**
- For spin and width measurement resolution is not as crucial as for the mass measurement. Adapt KD to each signal.

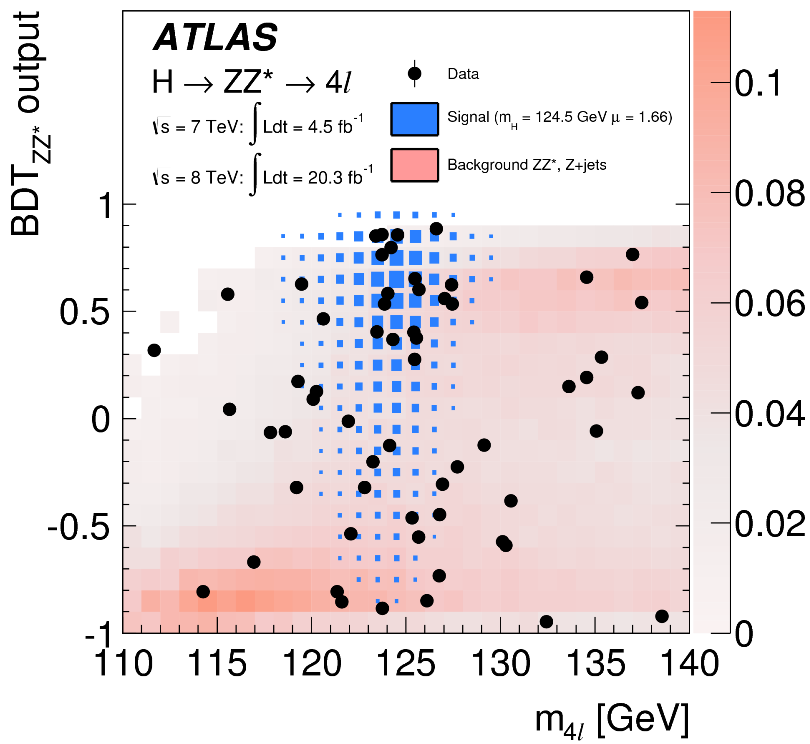
4l decay kinematics: can be fully reconstructed. Most of the information in invariant mass of Z1 and Z2 and 5 angular variables.



CMS: 0,1jet Kinematic discriminant (**KD**): Matrix element based discriminant



ATLAS: BDT using a KD as input



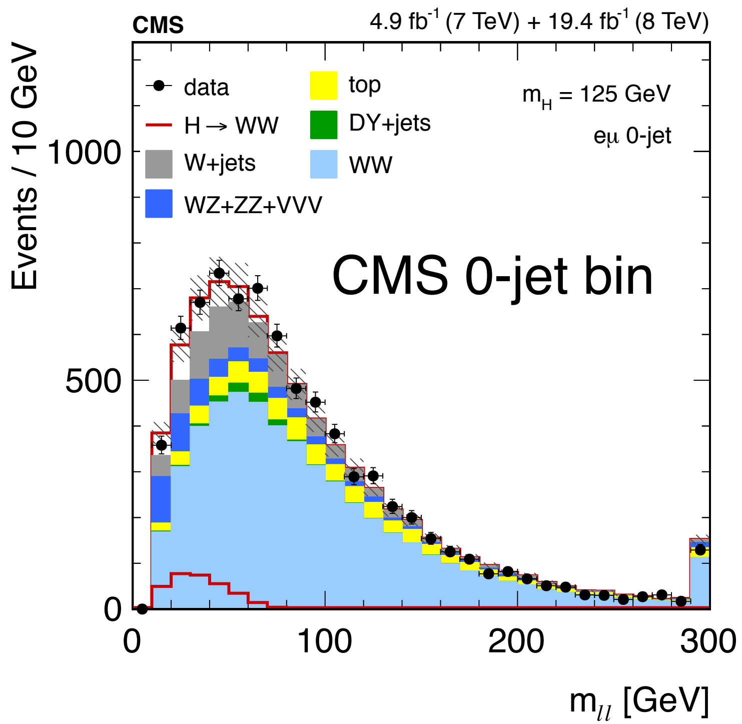
H→W⁺W⁻ analysis

CMS - JHEP 01 (2014) 096, ATLAS - PRD 92 (2015) 012006

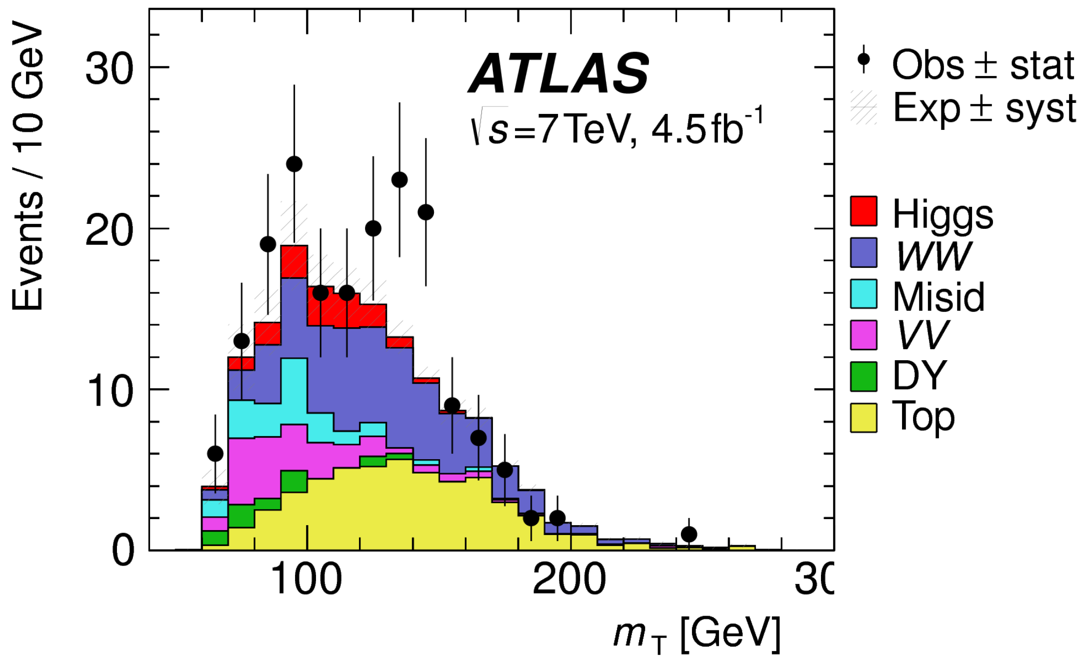
H→WW→2l2ν analysis:

- High BR, but no mass peak (resolution is ~20%): **not used for the mass measurement**
- Categories: **0-jet, 1-jet, 2-jet bins** (w/o VBF cuts), then **ee,μμ,eμ** with opposite charge
- **Main backgrounds**: WW, top (1,2jet bins), W+jets (estimated from control regions in data)

CMS: 2D analysis in **(m_T, m_{ll})** for the opposite flavor 0-jet and 1-jet bins, used for spin/CP



ATLAS: m_T used for the ggH categories, BDT used for VBF. Use **BDT** for spin/CP, cut-and-count for width.

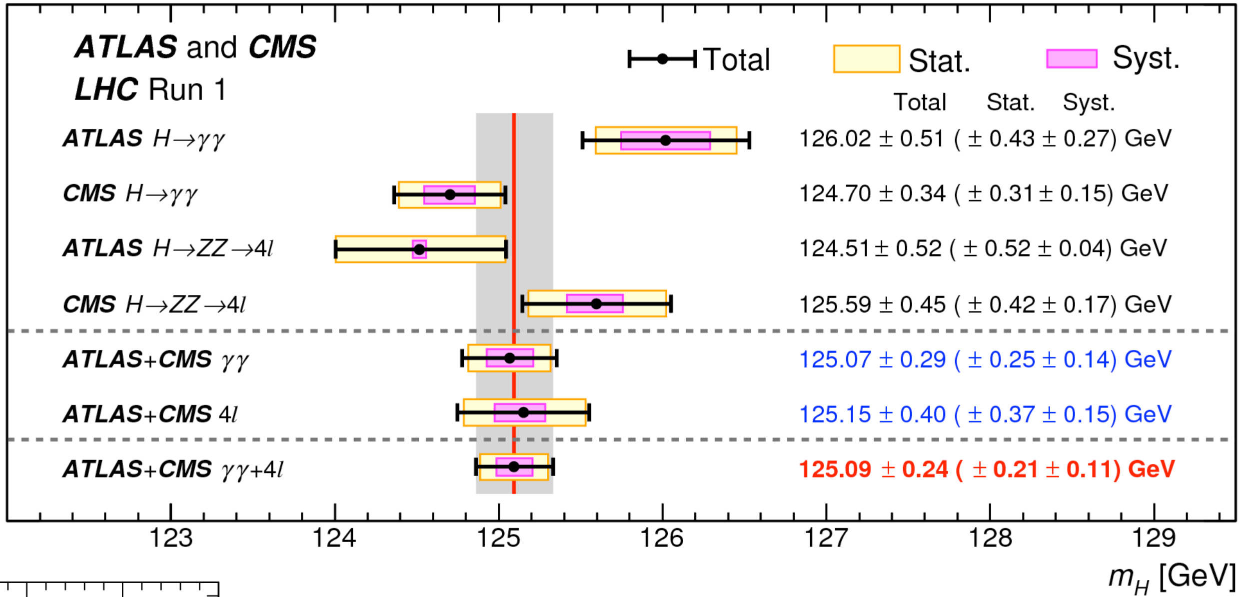


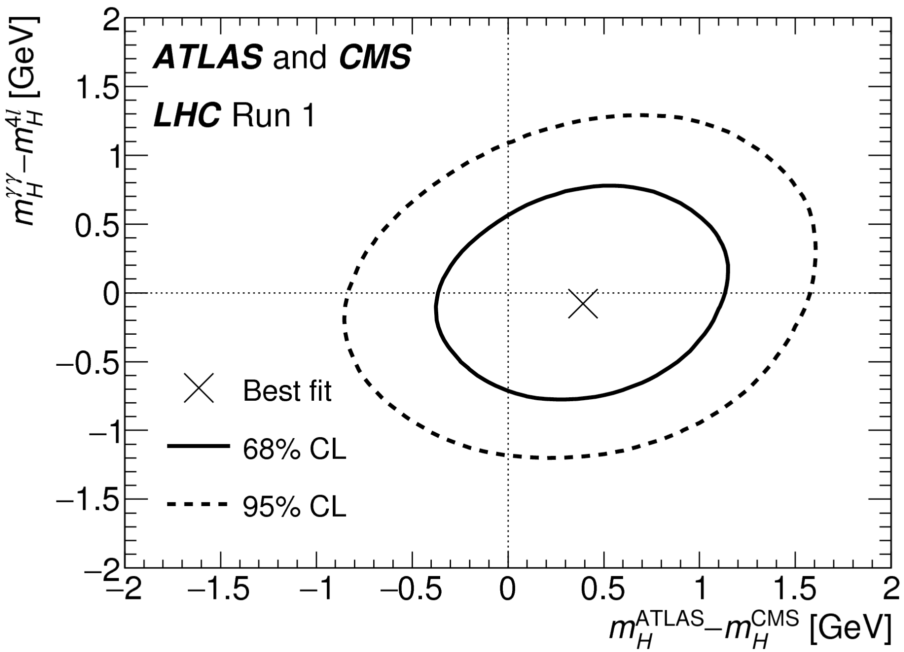
Higgs boson properties

Mass measurement in Run I

ATLAS+CMS - PRL 114 (2015) 191803

- The mass of the Higgs boson is not predicted by the SM: **free parameter**
- Combined masses from H→γγ and H→ZZ in CMS and in ATLAS in Run I





- H→γγ: 2.1σ tension
- H→ZZ: 1.3σ tension

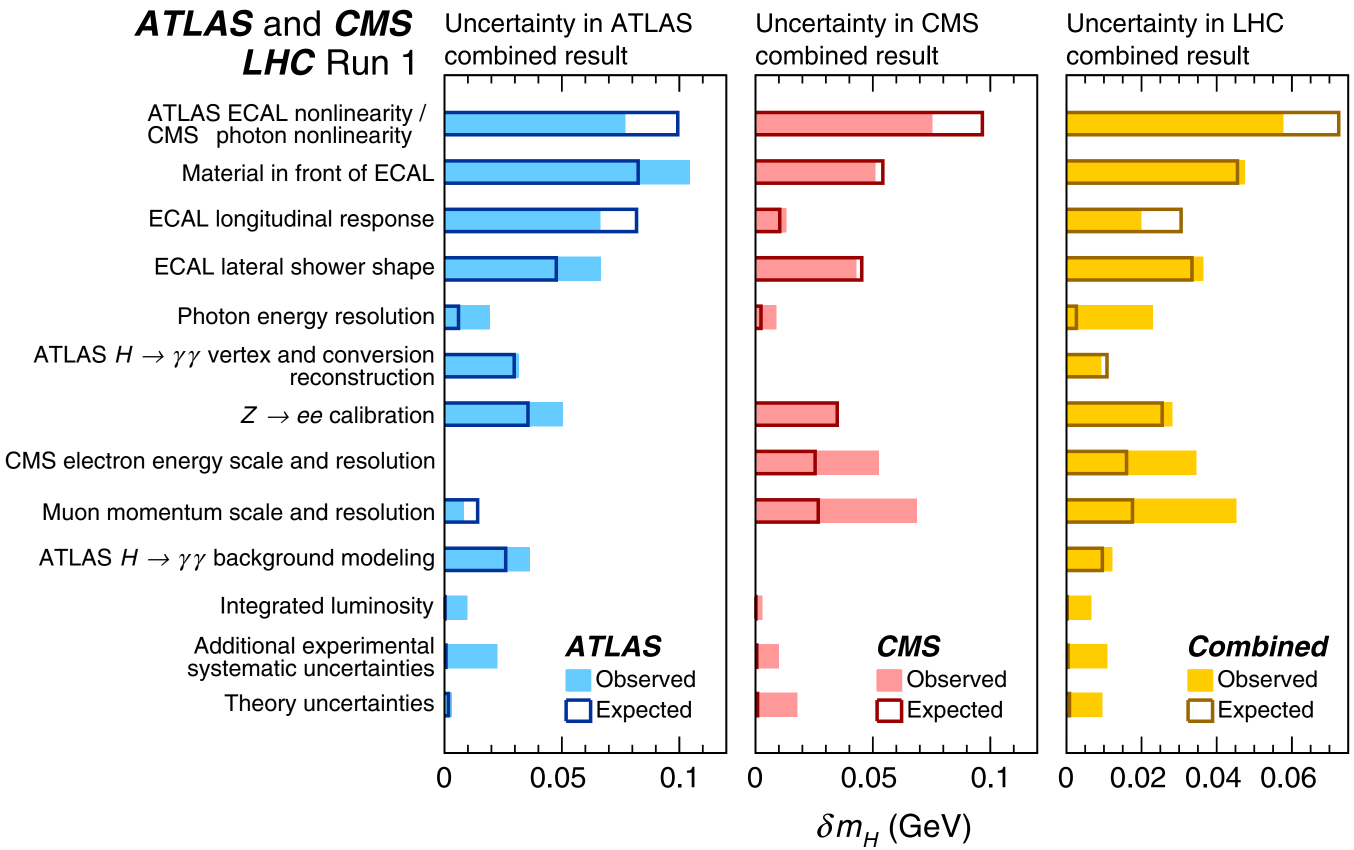
- Combination $\mathbf{m_H}$ **= 125.09 ± 0.24 GeV**

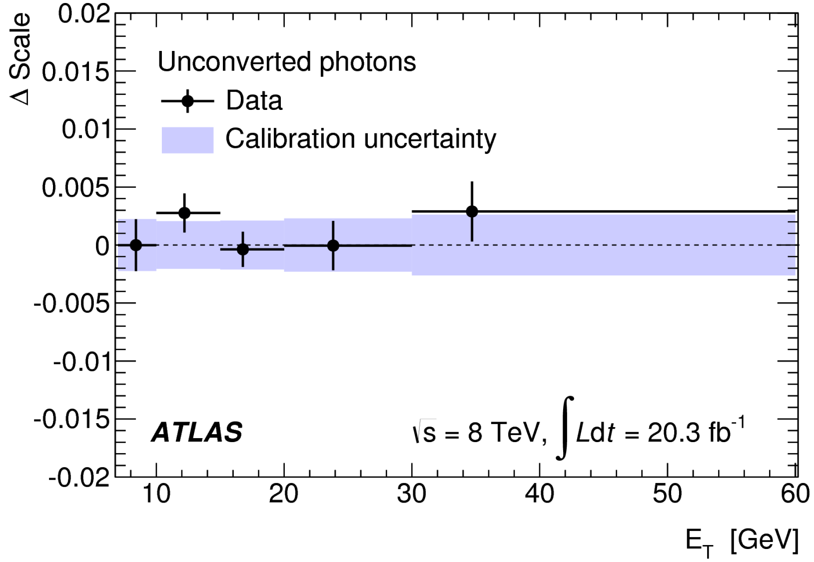
Mass measurement: systematics

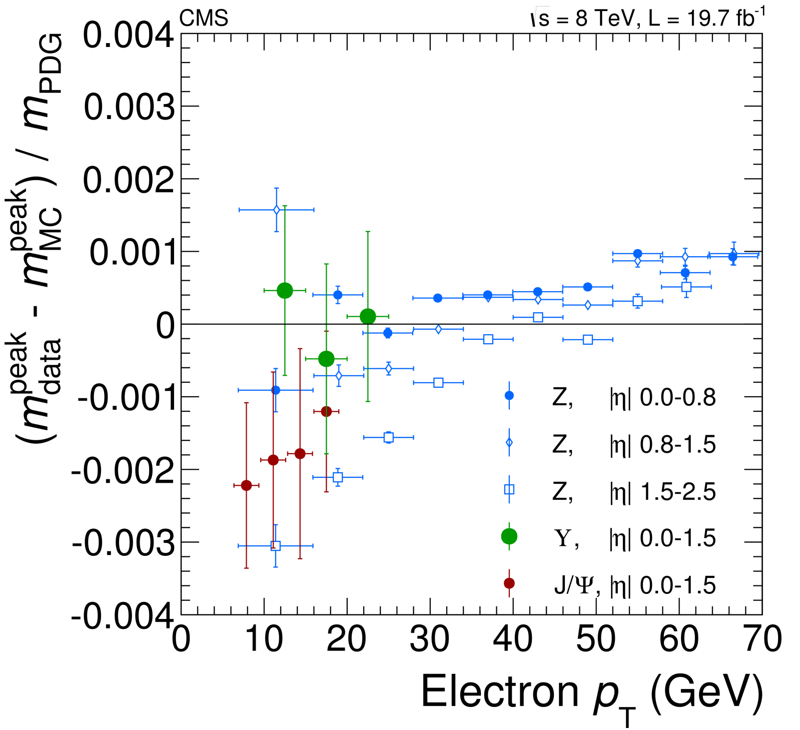
ATLAS+CMS - PRL 114 (2015) 191803

Main systematic uncertainties:

- ECAL non-linearity
- Material in front of the ECAL
- ECAL longitudinal response and lateral shower shape
- Zee energy calibration







Signal strengths

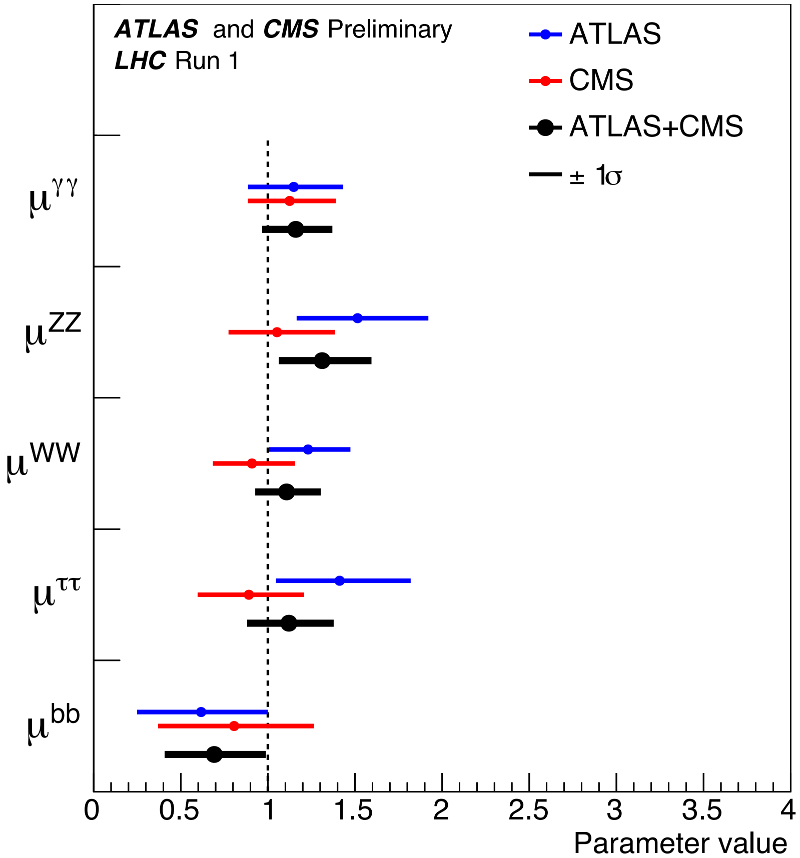
NEW

ATLAS-CONF-2015-044, CMS-PAS-HIG-002 (to appear soon)

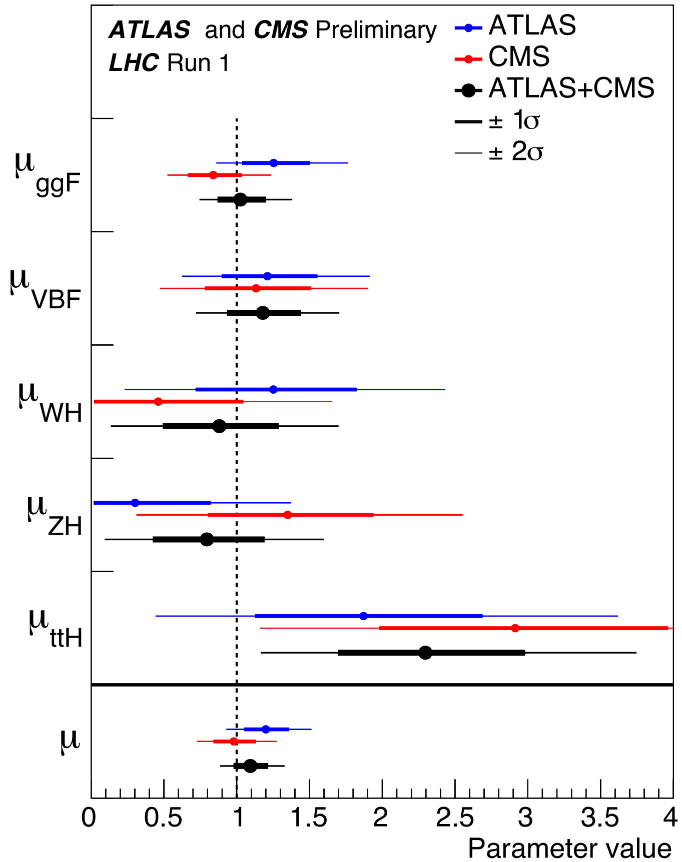
- Entering in precise measurement era
- **ATLAS+CMS Combined best fit μ=1.09±0.11:** Cross section measured is in very good agreement with the SM
- Less known production mechanism ttH, and decay H→bb

Higgs boson signal strength $\mu=\sigma/\sigma_{SM}$

by final state tag



by production mechanism

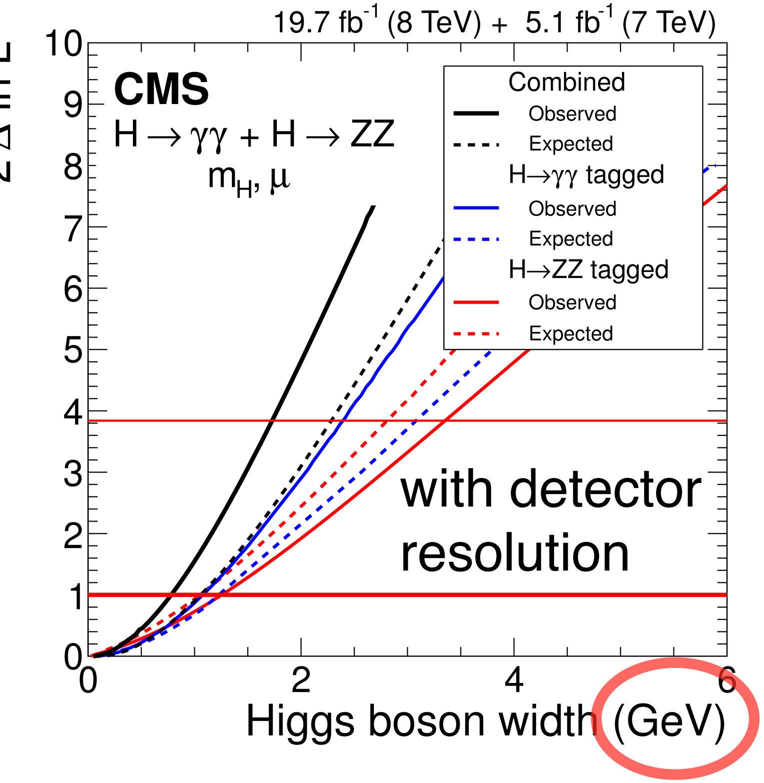


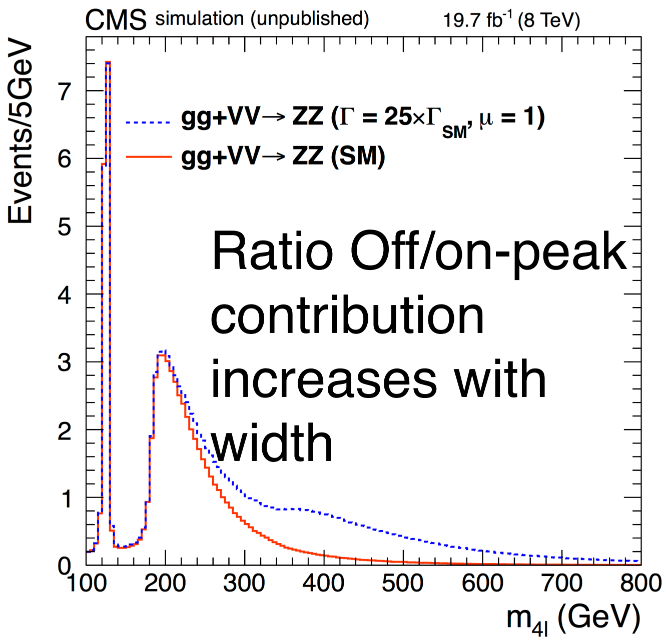
Higgs boson width (CMS)

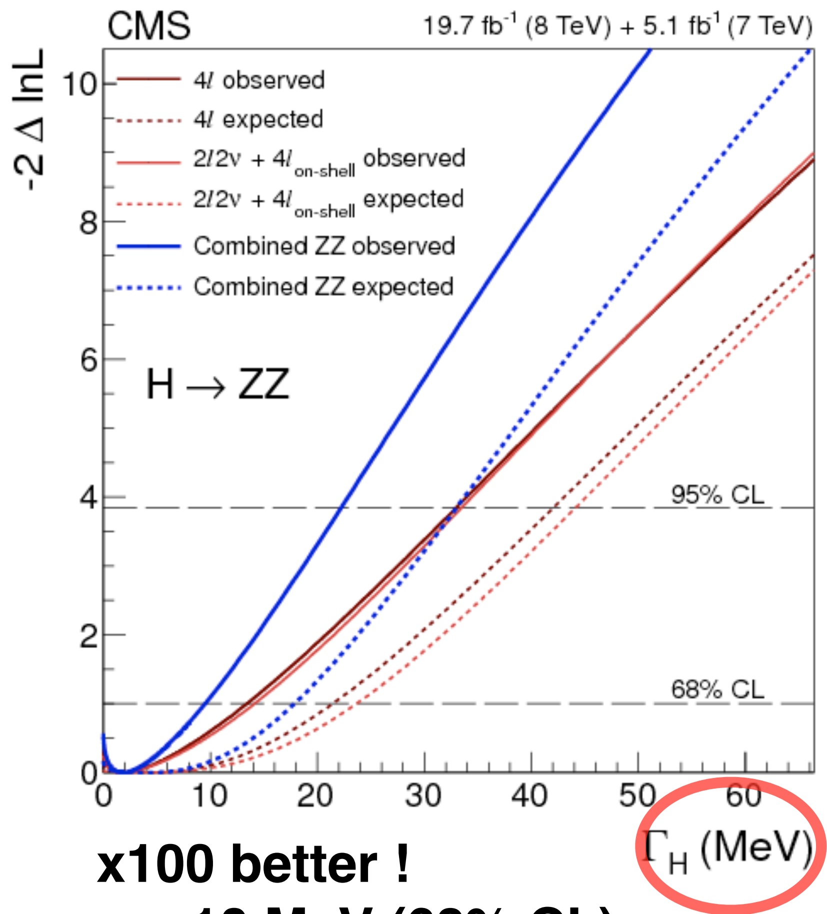
CMS - Phys. Lett. B 736 (2014) 64

- In the SM, Higgs total width is ~4 MeV, but direct measurement from peak width is limited by detector resolution (~1 GeV)
- **Solution: interferometry,** use off/on-shell mass ratio (see for instance arxiv:1311.3589)
- **Caveat**: although quite generic assumptions, still model-dependent

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







x100 better !

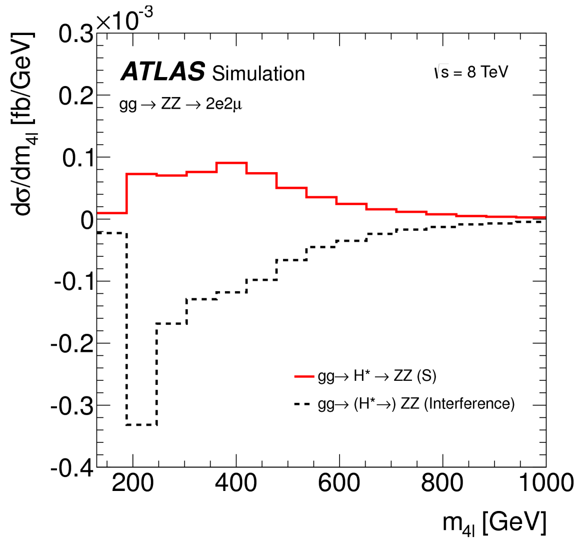
σ < 10 MeV (68% CL)

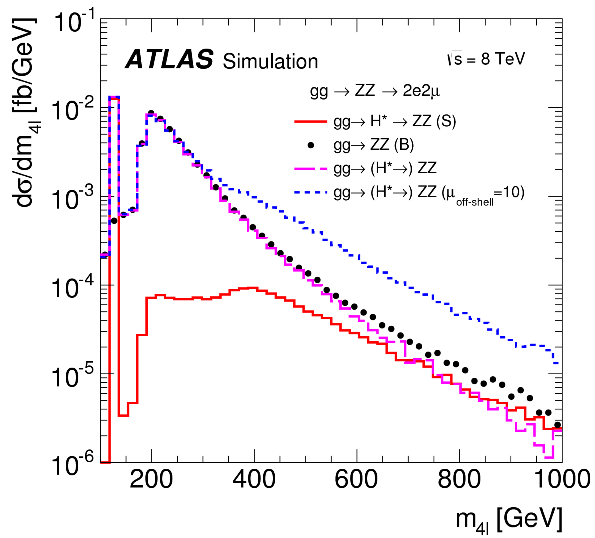
Higgs boson width (ATLAS)

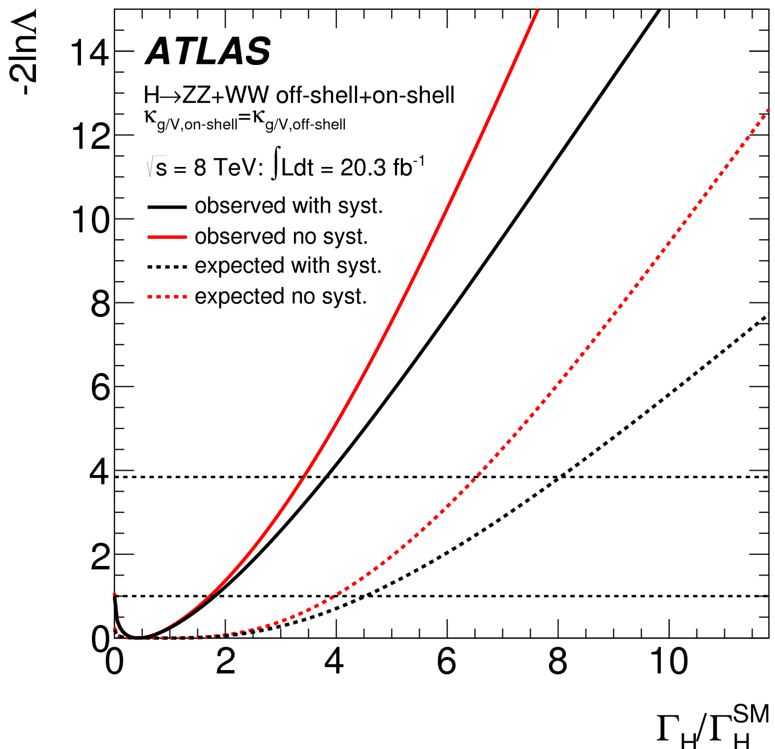
ATLAS - EPJC 71 (2015) 335

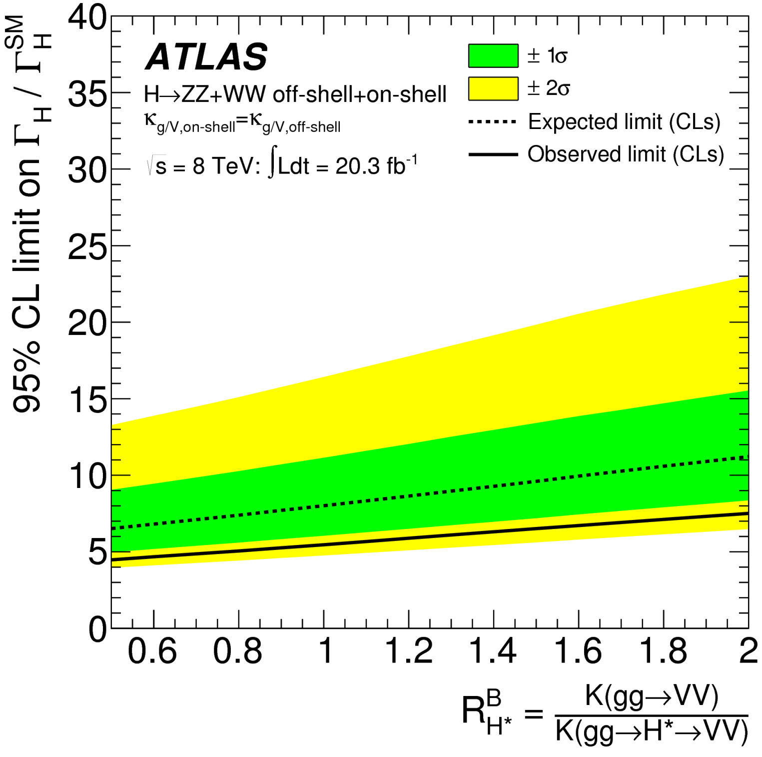
- ATLAS uses H→ZZ→4l (BDT), H→ZZ→2l2v (mT) and H→WW->evμv (cut and count)
- **Interference gg→H→ZZ/gg→ZZ**

$$
\begin{aligned}
\sigma_{gg\to(H^*\to)VV}(\mu_{\text{off-shell}}, m_{VV}) \\
&= \mathrm{K}^{H^*}(m_{VV})\cdot\mu_{\text{off-shell}}\cdot\sigma^{\text{SM}}_{gg\to H^*\to VV}(m_{VV}) \\
&+\sqrt{\mathrm{K}^{H^*}_{gg}(m_{VV})\cdot\mathrm{K}^{\mathrm{B}}(m_{VV})\cdot\mu_{\text{off-shell}}}\cdot\sigma^{\text{SM}}_{gg\to VV,\,\text{Interference}}(m_{VV}) \\
&+\mathrm{K}^{\mathrm{B}}(m_{VV})\cdot\sigma_{gg\to VV,\,\text{cont}}(m_{VV}).
\end{aligned}
\tag{5}
$$









- Provides result as the ratio of signal/background: limit is ~5x SM

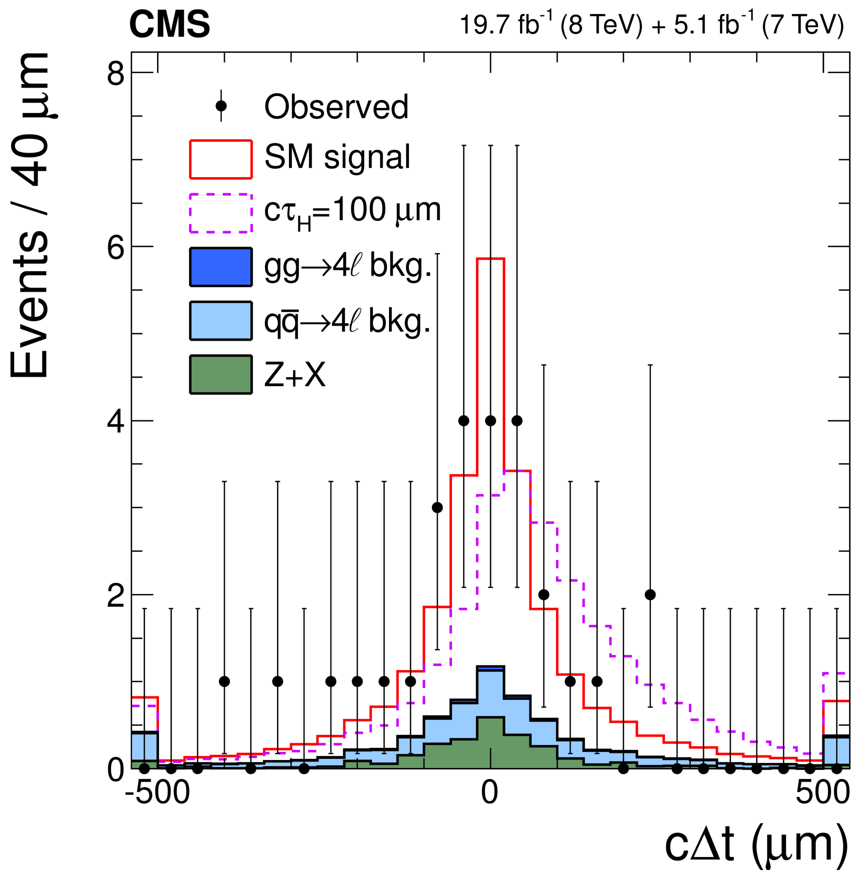
Higgs boson life-time (CMS)

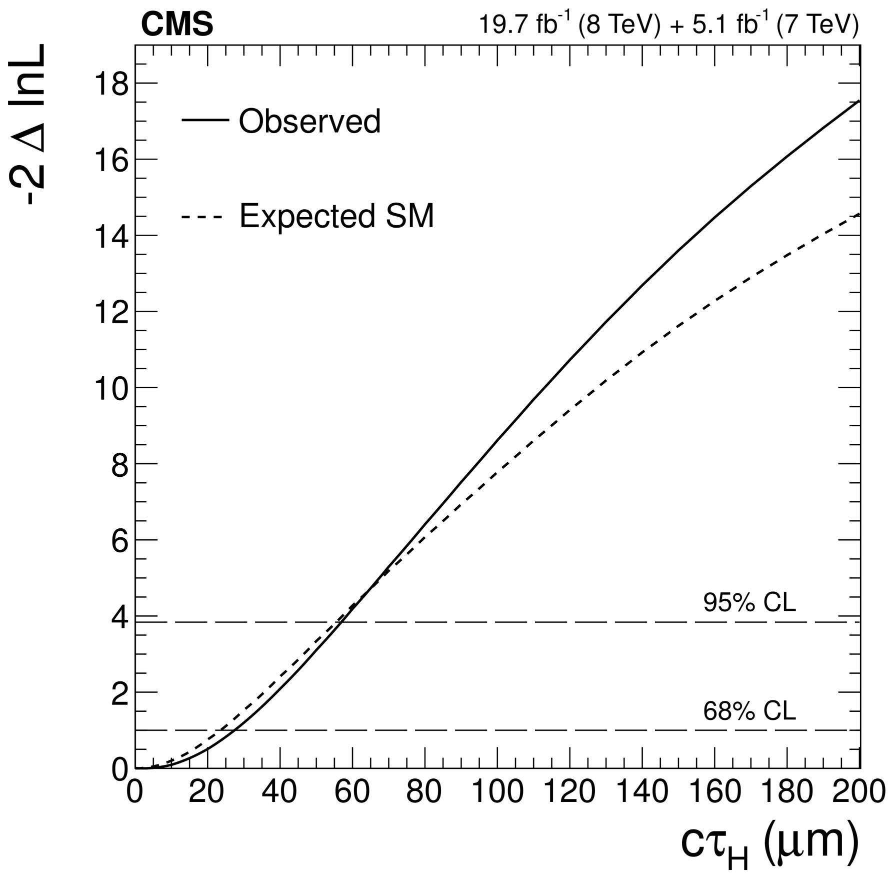
CMS - NEW arxiv:1507.06656 (submitted to PRD)

- Measure **Higgs boson time of flight** using 4l consistent with a displaced vertex:

$$\Delta t = \frac{m_{4\ell}}{p_T}(\Delta \vec{r}_T \cdot \hat{p}_T) \qquad \langle \Delta t \rangle = \tau_H = \frac{\hbar}{\Gamma_H}$$

- SM predictions are beyond experimental direct detection:
  $\tau_H \approx 48\,\mathrm{fm/c} \quad (16 \times 10^{-8}\,\mathrm{fs})$
- **Result:** $c\tau_H < 57\,(56)\,\mu\mathrm{m}\ (\tau_H < 190\,\mathrm{fs}$
  $\Gamma_H > 3.5 \times 10^{-9}\,\mathrm{MeV}$

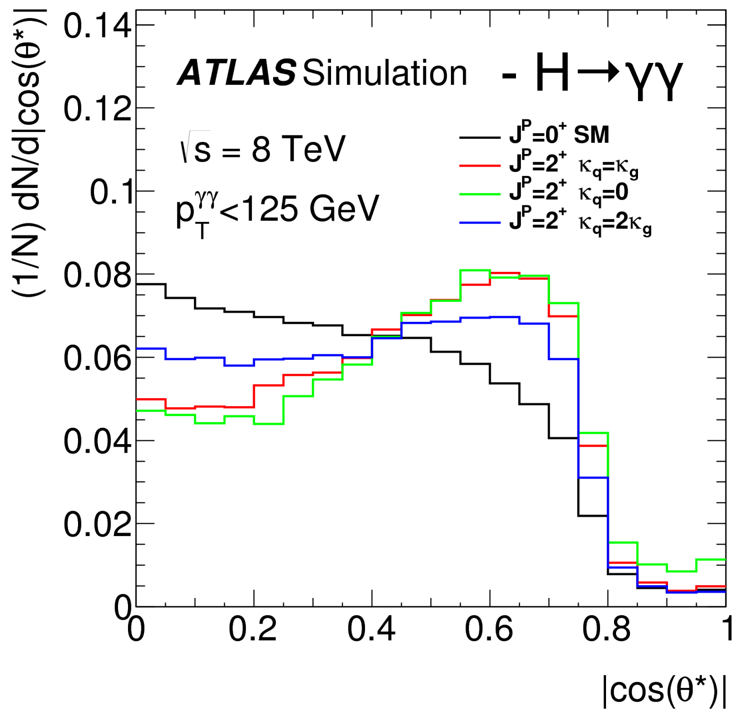


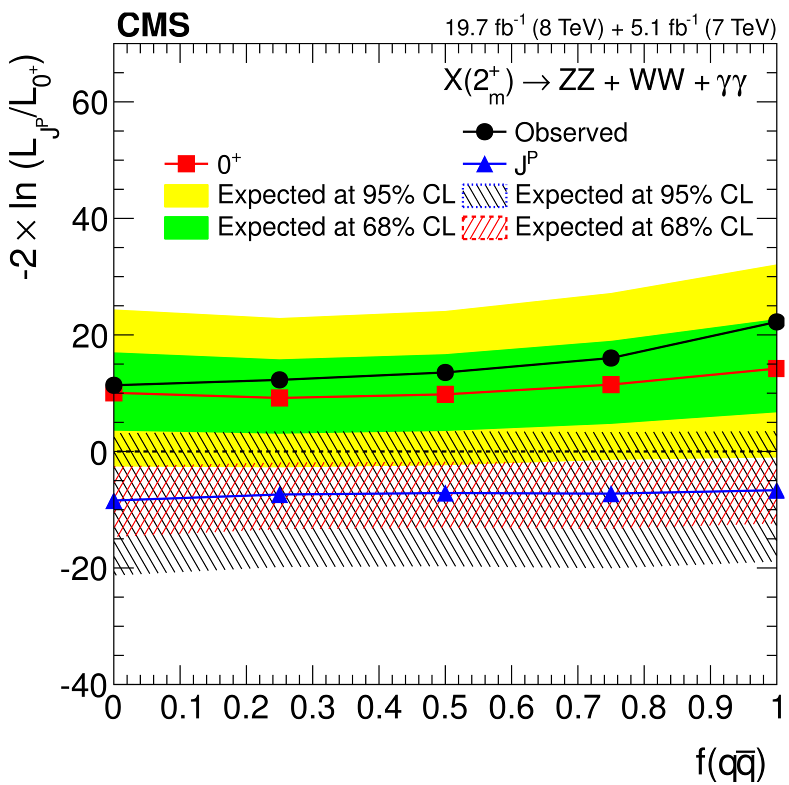


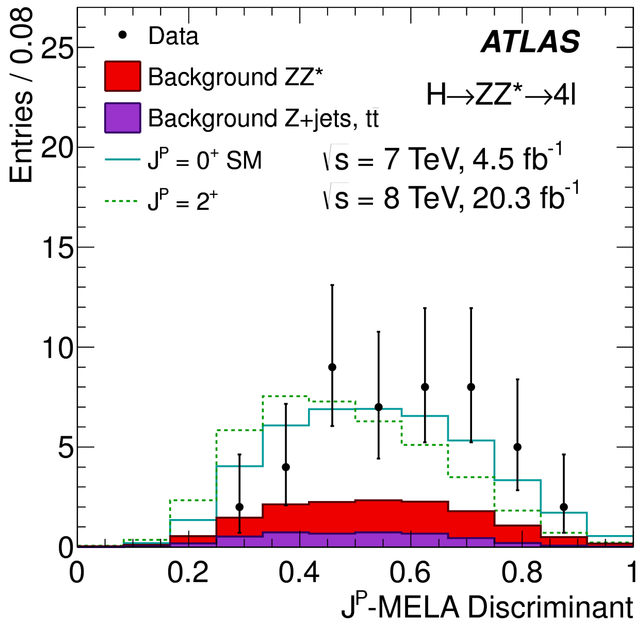
Spin/Parity measurement

CMS - PRD 92 (2015) 012004, ATLAS - arxiv:1506.05669 (submitted to EPJC)

- Need to test some reasonable **benchmark models for alternative J^{CP} hypotheses**
- Use mainly **angular distributions**:
  - Collins-Soper cosθ* in $H \to \gamma\gamma$
  - Matrix element discriminant and BDT in $H \to ZZ^* \to 4l$
  - Kinematic BDT in $H \to WW^* \to e\nu\mu\nu$







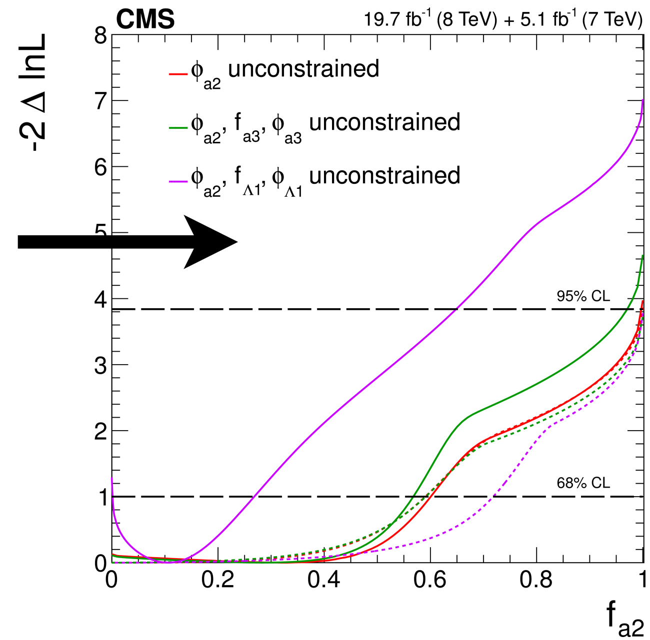
- Testing production mechanisms via gluon fusion and qqbar
- Minimal graviton couplings **2^+** is disfavoured by data

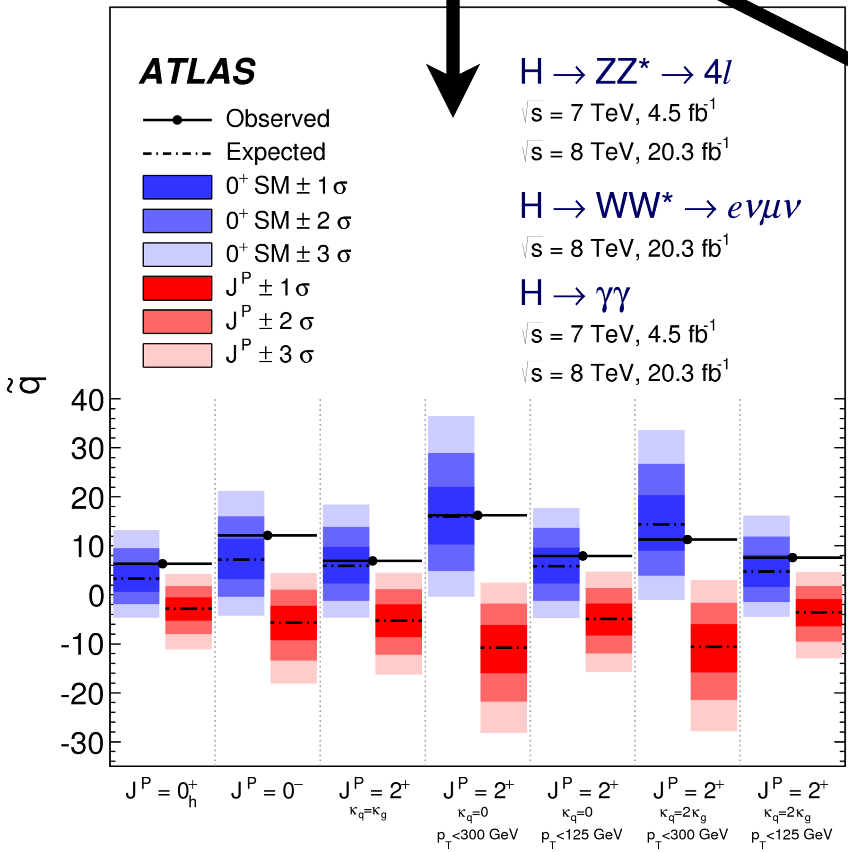
Spin/Parity measurement

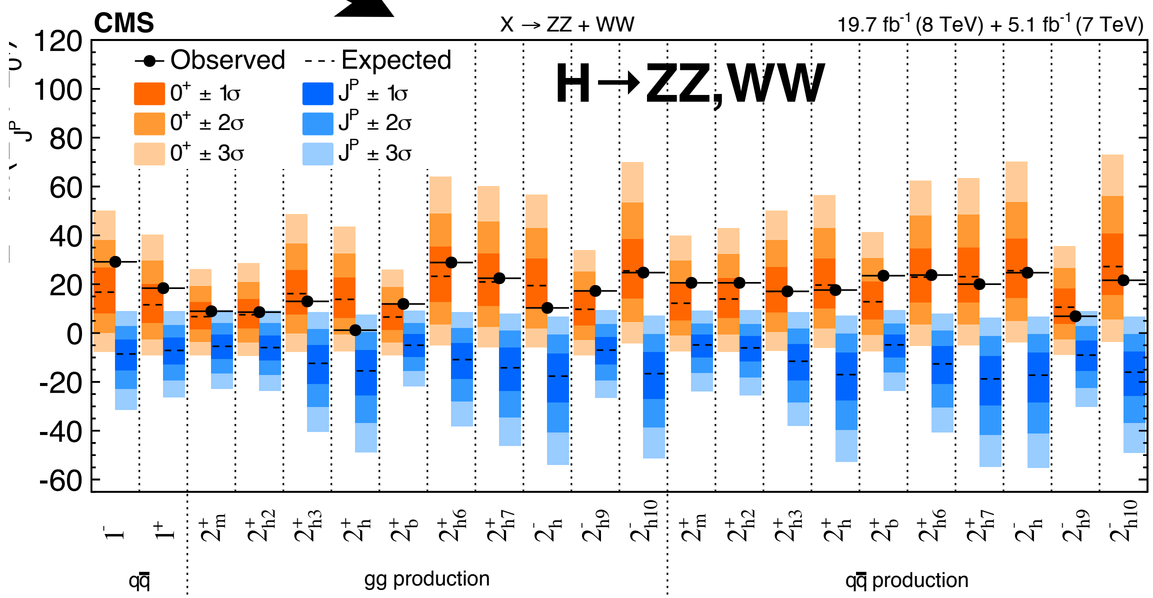
CMS - PRD 92 (2015) 012004, ATLAS - arxiv:1506.05669 (submitted to EPJC)

- **In general data favours 0+ hypothesis**
  - Testing as well **higher dimension tensor structure**

- Testing **mixture of 0-/0+** hypothesis (fraction of CP odd/even)







Higgs anomalous couplings

CMS - PRD 92 (2015) 012004, ATLAS - arxiv:1506.05669 (submitted to EPJC)

- Extension from spin hypothesis testing to **anomalous parameter measurement**
- Testing Higgs to diboson coupling in **H→WW,ZZ,Zγ,γγ→4l**
- Parametrization on **anomalous vertices** (CMS) or **Effective Field Theory** (ATLAS)

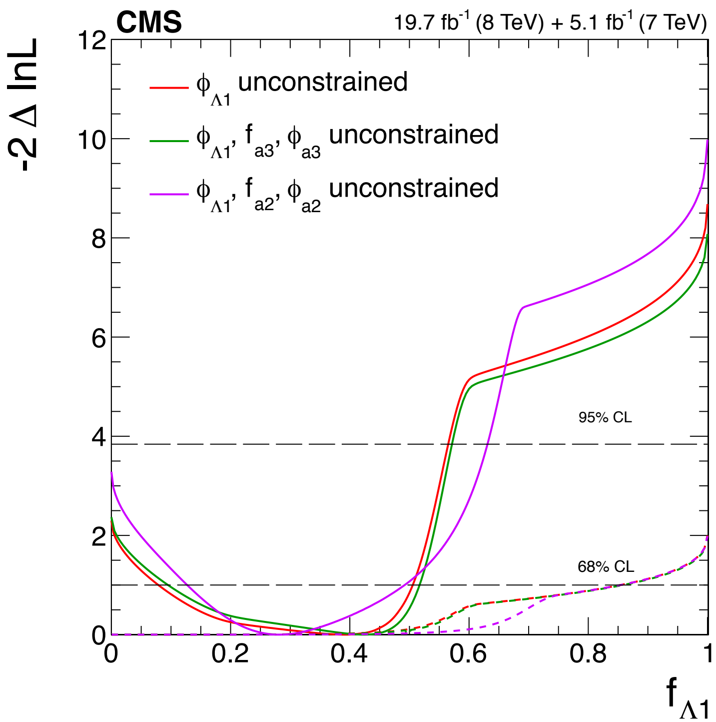
(spin 0)

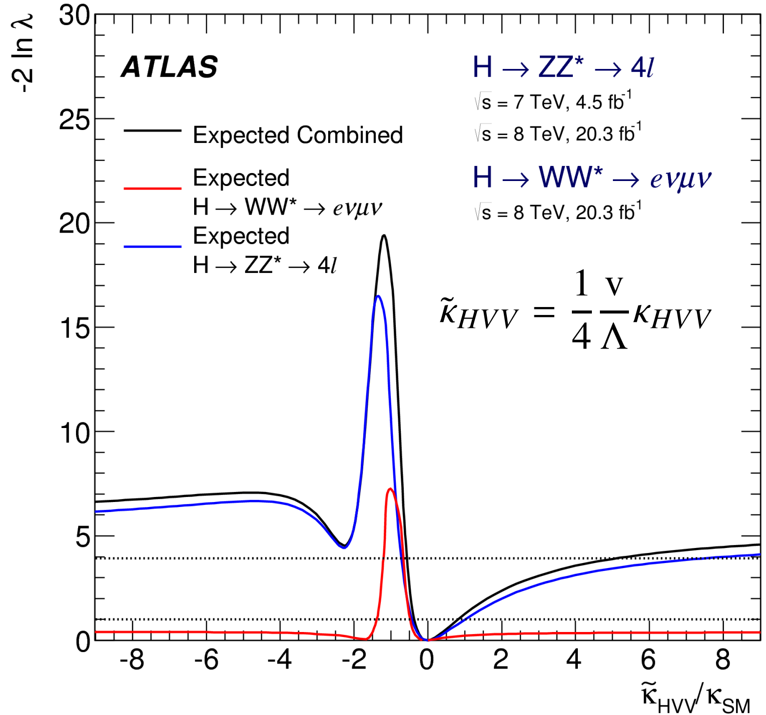
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

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

spin 0 higher dimension

$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{\mathrm{SM}}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\} X_0$$





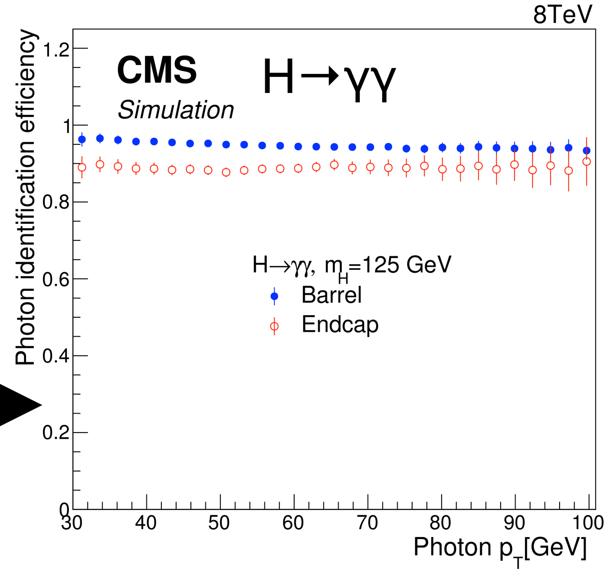
Differential cross sections

ATLAS - PRL 115 (2015) 091801, NEW CMS arxiv:1508.07819 (submitted to EPJC), NEW HIG-14-028

Analysis methods

- Extract signal strength with a **simultaneous mass fit** on all bins of a given distribution

- Design **model-independent analysis** as much as possible:
    - Do not use MVA nor p_T-dependent categories for extracting signal strength, to not bias the kinematics
    - Design fiducial phase-space close to reconstructed phase-space (isolation included in the fiducial phase-space definition)

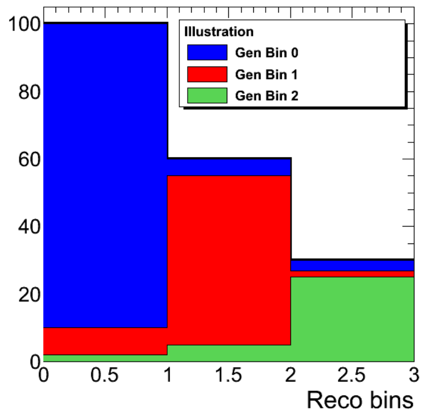


Photon identification via pT- and η-independent BDT cut improves model independence

- **Unfold detector effects** to **fiducial phase-space**:
    - bin-by-bin correction (ATLAS),
    - folding of the response matrix in the fit (CMS)

$$c_i = \frac{N_i^{\mathrm{reco}}}{N_i^{\mathrm{fid}}}$$

$$\mathcal{F}(\vec{\mu}) = -2\sum_j \log\mathcal{L}\left(\sum_i K_{ij}\mu_i N_i^{\mathrm{gen}} | N_j^{\mathrm{reco}}\right)$$



Fiducial cross sections

ATLAS - PRL 115 (2015) 091801, NEW CMS arxiv:1508.07819 (submitted to EPJC), NEW HIG-14-028

H→γγ Fiducial phase space

- CMS: $p_{T1}/m_{\gamma\gamma}>1/3$, $p_{T2}/m_{\gamma\gamma}>1/4$ within $|\eta|<2.5$
- ATLAS $p_{T1}/m_{\gamma\gamma}>0.35$, $p_{T2}/m_{\gamma\gamma}>0.25$ within $|\eta|<2.37$
- Isolation: $\sum E_T < 10$ GeV (CMS), 14 GeV (ATLAS) for stable generator level particles in $\Delta R<0.4$.

H→4l Fiducial phase space

- CMS $p_T>20,10,7(5)$ GeV within $|\eta|<2.5$ (2.4) for e (μ)
- ATLAS $p_T>25,15,10,7(6)$ GeV within $|\eta|<2.7$ (2.47) for e (μ)
- Isolation: $\sum E_T < 0.4 \cdot p_T$ GeV (CMS), no (ATLAS)
- Z1 and Z2 mass windows requirement

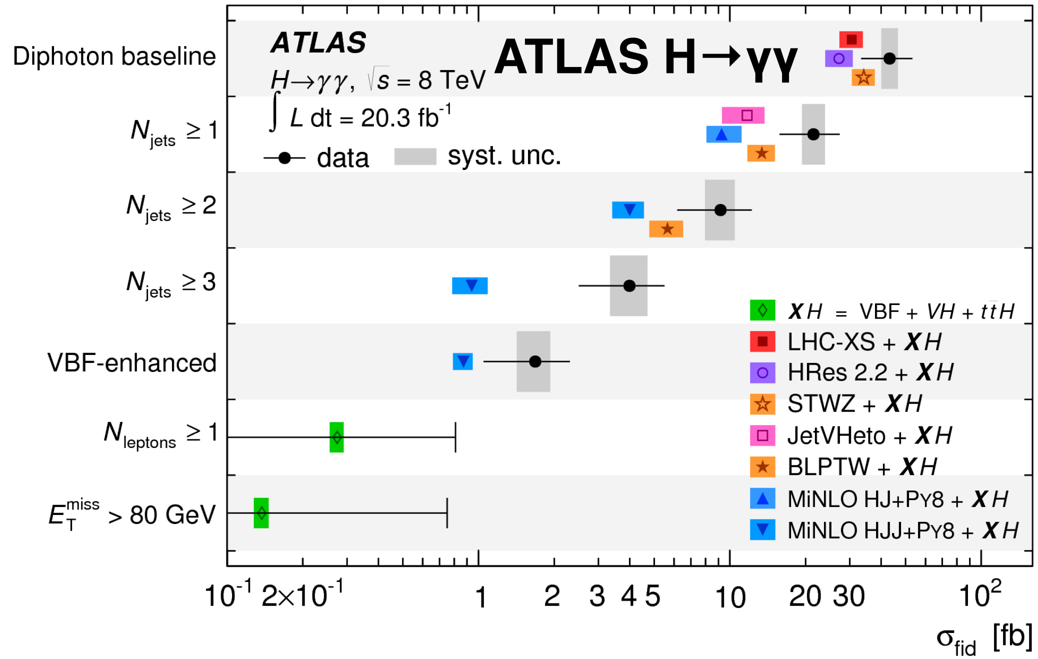
CMS H→γγ

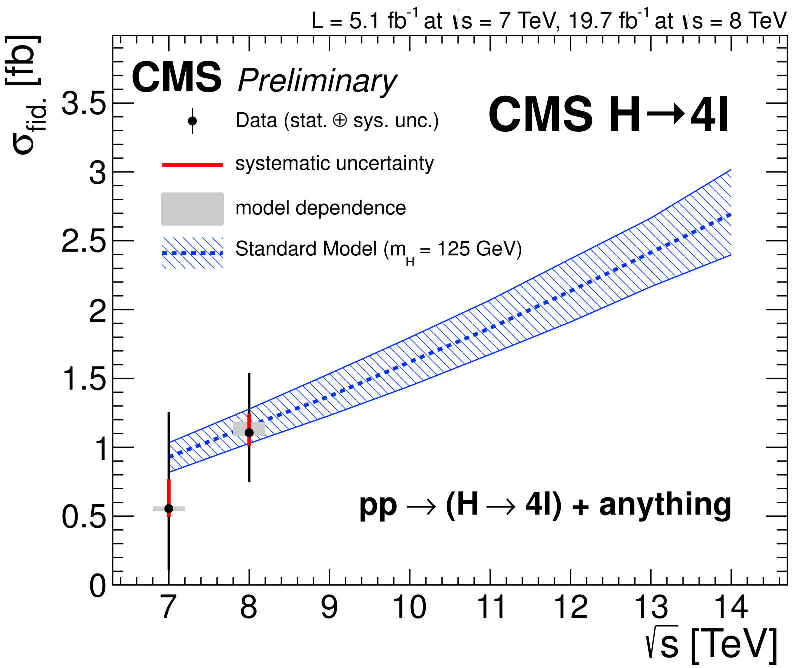
$$\sigma_{\text{obs}} = 32^{+10}_{-10}\,(\text{stat})^{+3}_{-3}\,(\text{syst})\ \text{fb},$$
$$\sigma_{\text{HRES+XH}} = 31^{+4}_{-3}\ \text{fb},$$
$$\sigma_{\text{POWHEG+XH}} = 32^{+6}_{-5}\ \text{fb},$$
$$\sigma_{\text{MADGRAPH5\_aMC@NLO+XH}} = 30^{+6}_{-5}\ \text{fb}.$$

ATLAS H→4l

$$\sigma^{\text{fid}}_{\text{tot}} = 2.11^{+0.53}_{-0.47}(\text{stat.}) \pm 0.08(\text{syst.})\ \text{fb}.$$

SM predictions 1.30 ± 0.13 fb

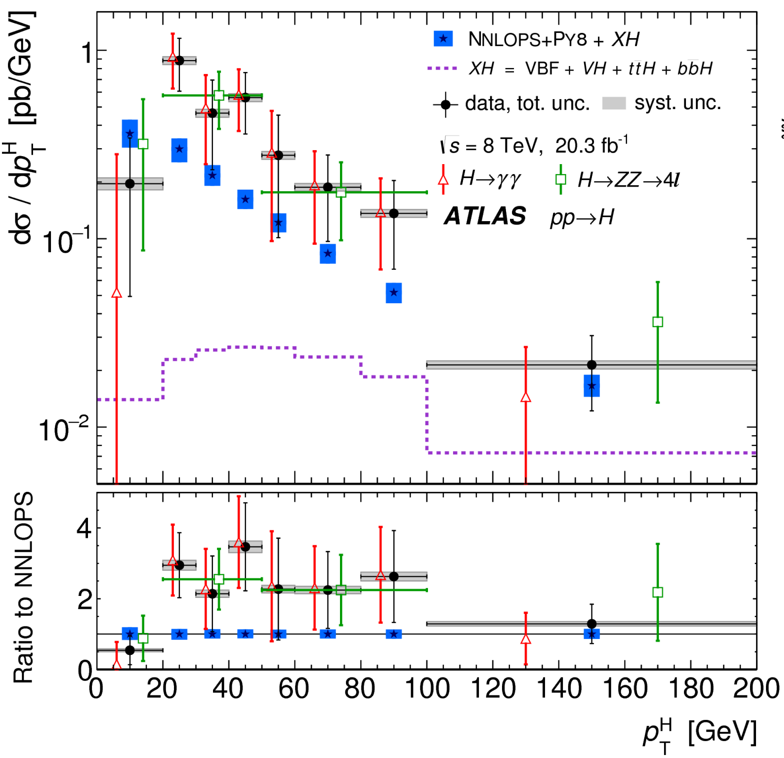


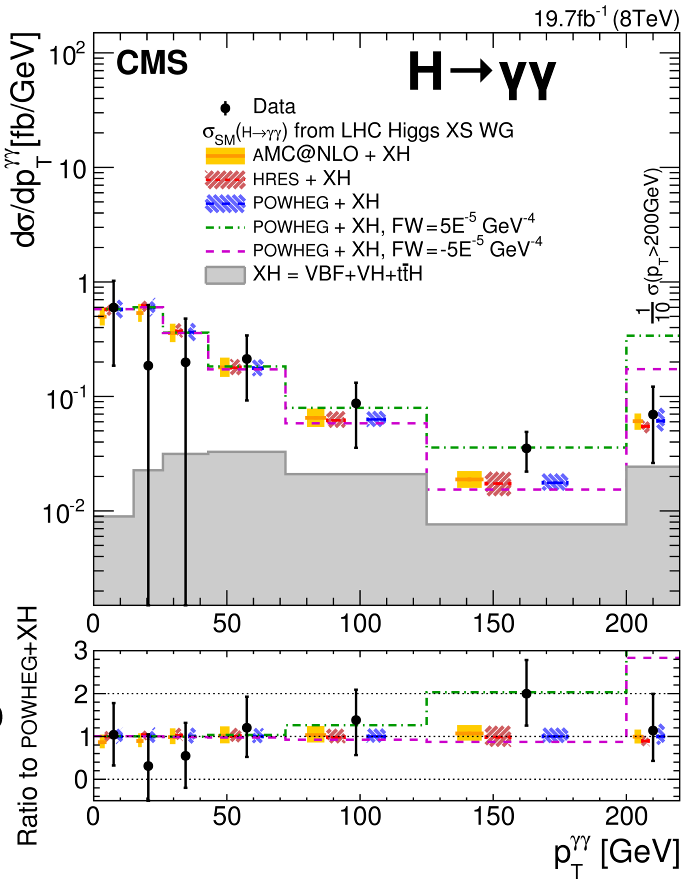


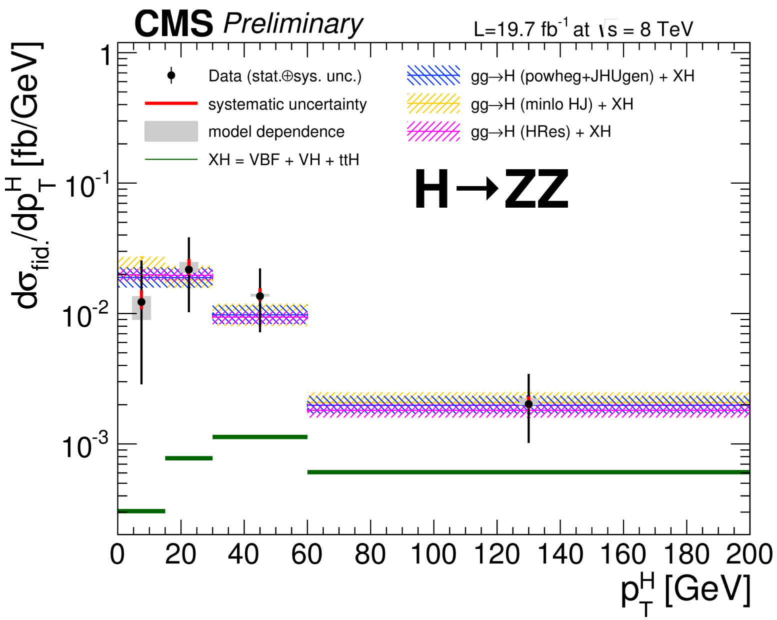
Higgs boson p_T

ATLAS - PRL 115 (2015) 091801, NEW CMS arxiv:1508.07819 (submitted to EPJC), NEW HIG-14-028

- ATLAS combines $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ$ after extrapolating to common phase-space, while CMS shows separately (will be done in Run II)
- XH = VBF + WH + ZH + ttH +bbH(ATLAS only)
- Higgs pT is sensitive to new contribution in the ggH loop
- No evidence of significant deviation from SM predictions



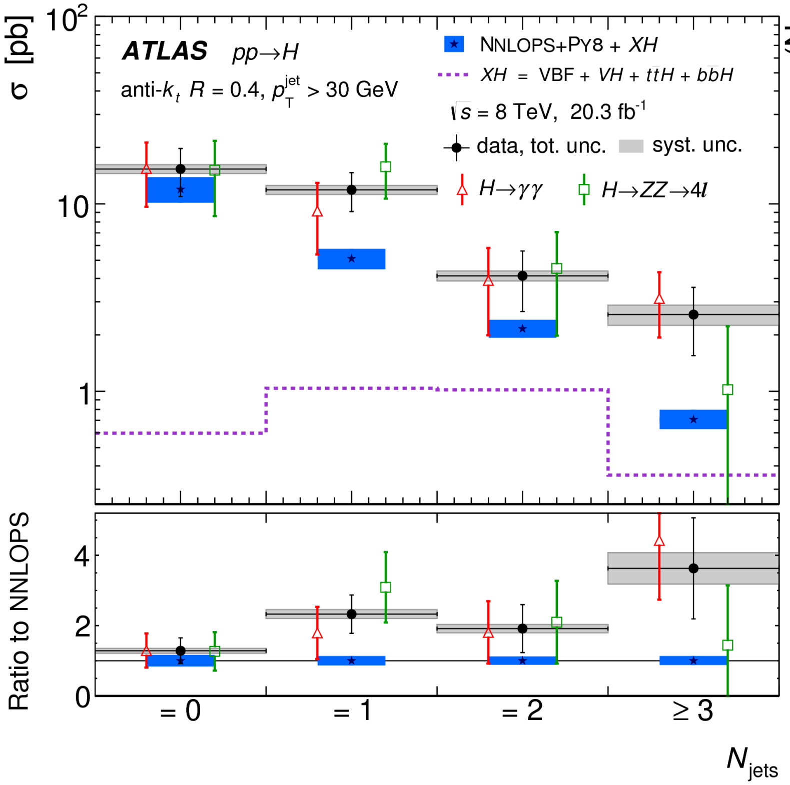


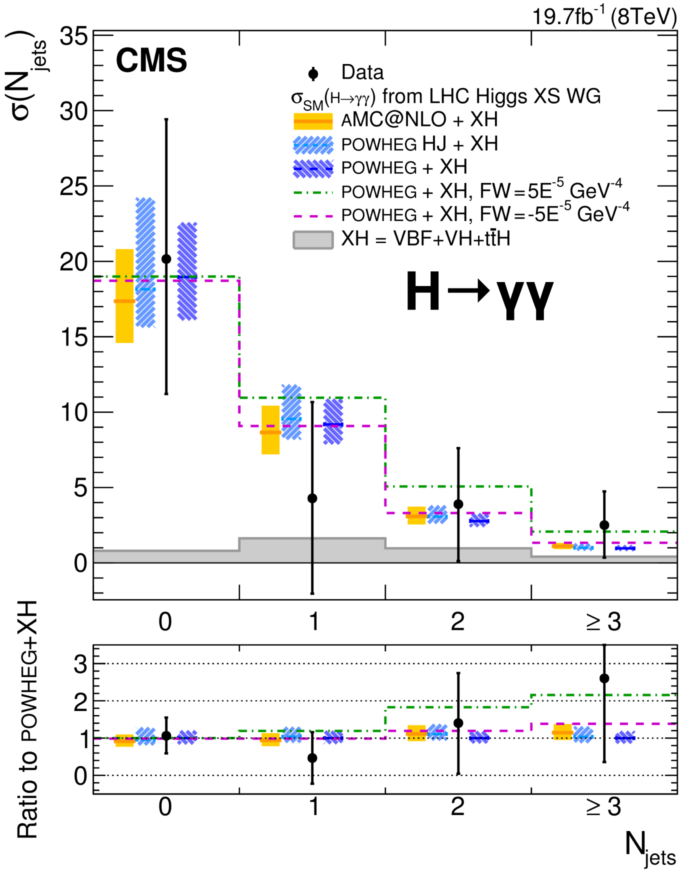


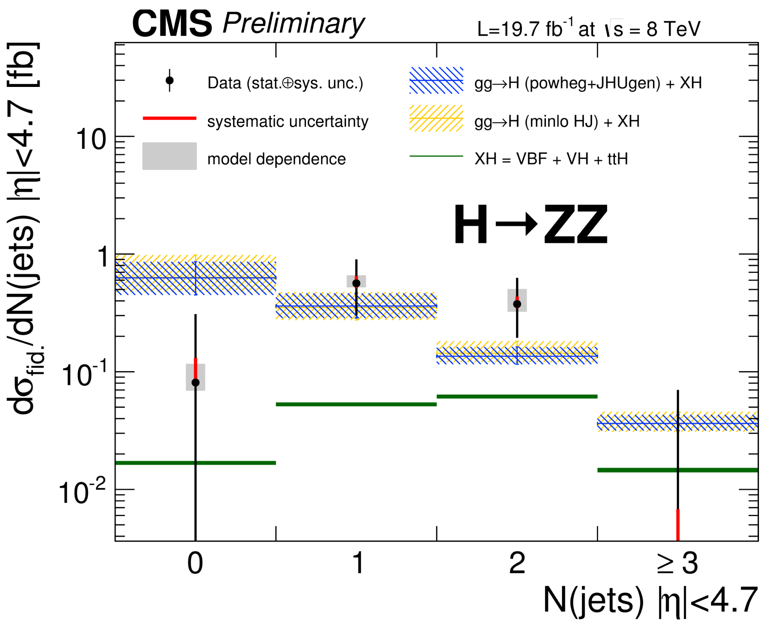
Jet multiplicity in Higgs events

ATLAS - PRL 115 (2015) 091801, NEW CMS arxiv:1508.07819 (submitted to EPJC), NEW HIG-14-028

- 0-jet and 1-jet are dominated by gluon fusion
- Associated production (XH=VBF,VH,ttH) populates higher jet multiplicity bins: about 40% for 2 or more jets



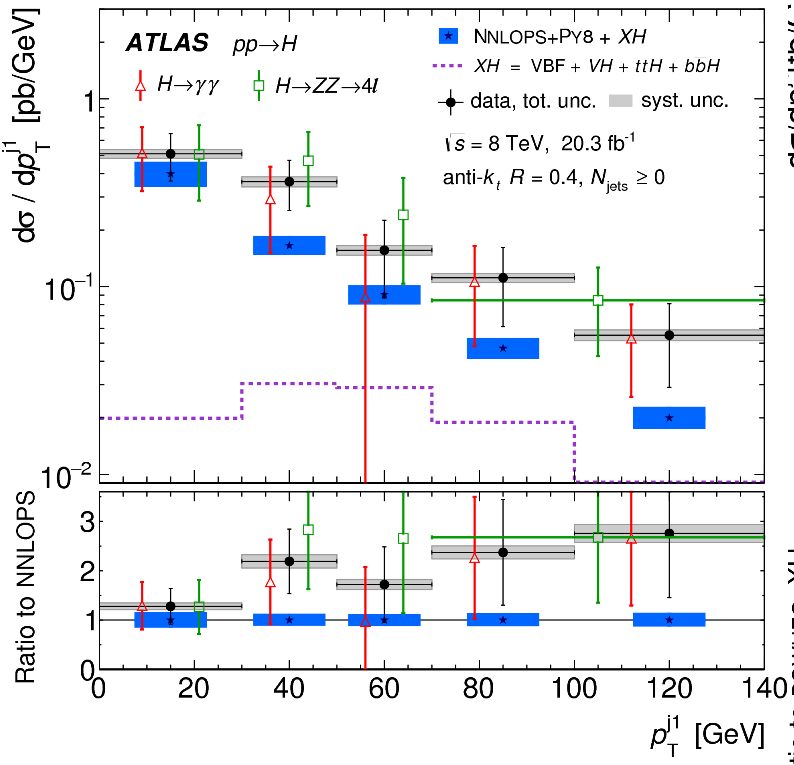


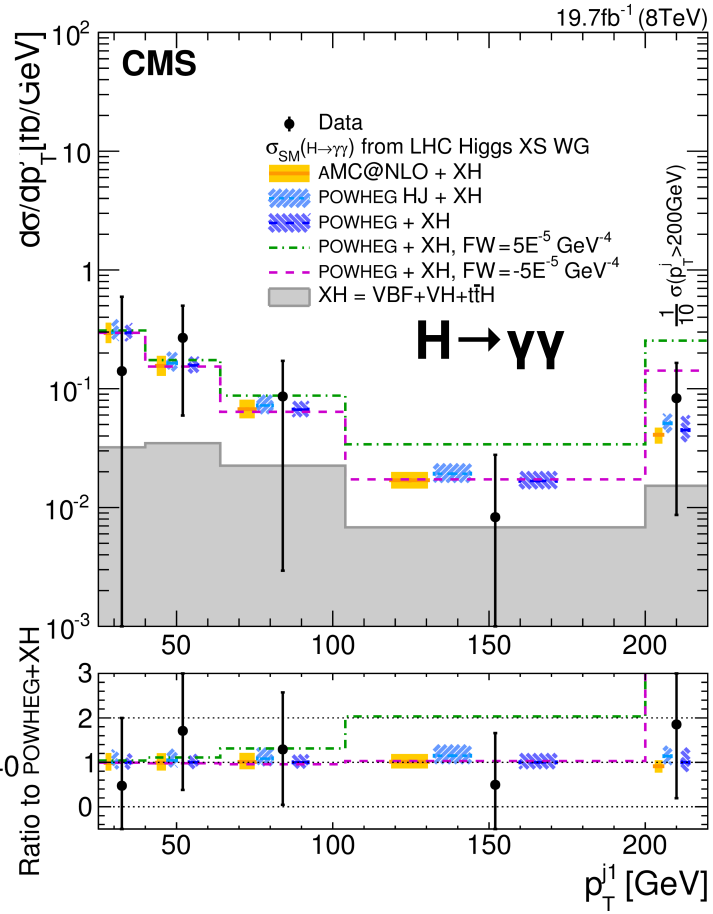


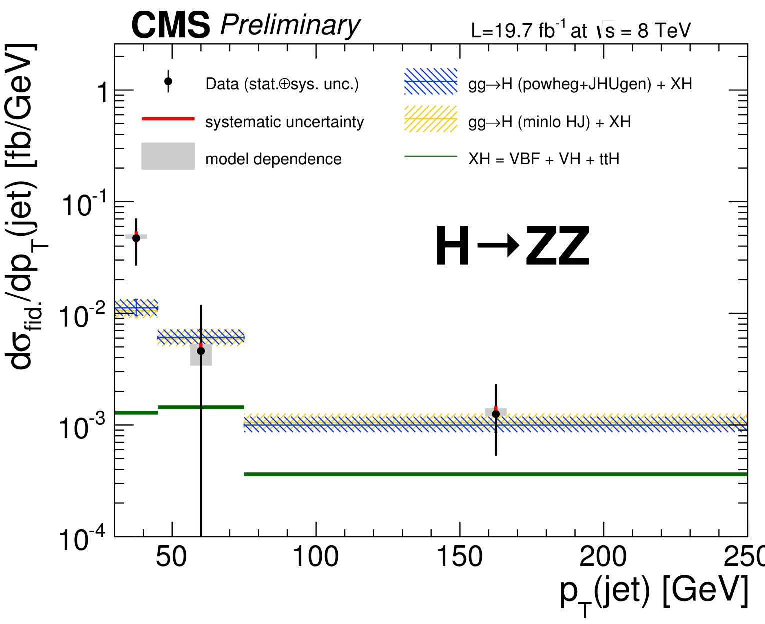
Leading jet p_T in Higgs events

ATLAS - PRL 115 (2015) 091801, NEW CMS arxiv:1508.07819 (submitted to EPJC), NEW HIG-14-028

- 0-jet and 1-jet are dominated by gluon fusion: probes new contribution in the loop
- Also sensitive to enhancement of the coupling to bosons (if one jet is missed)



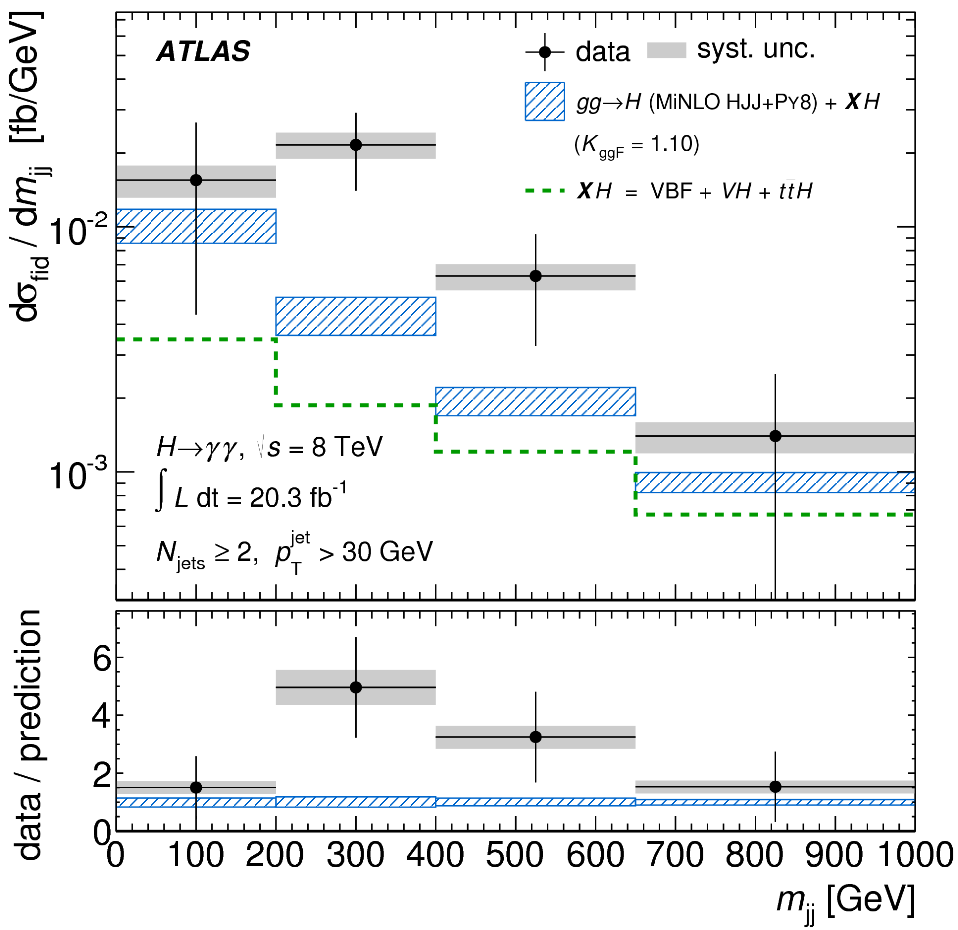


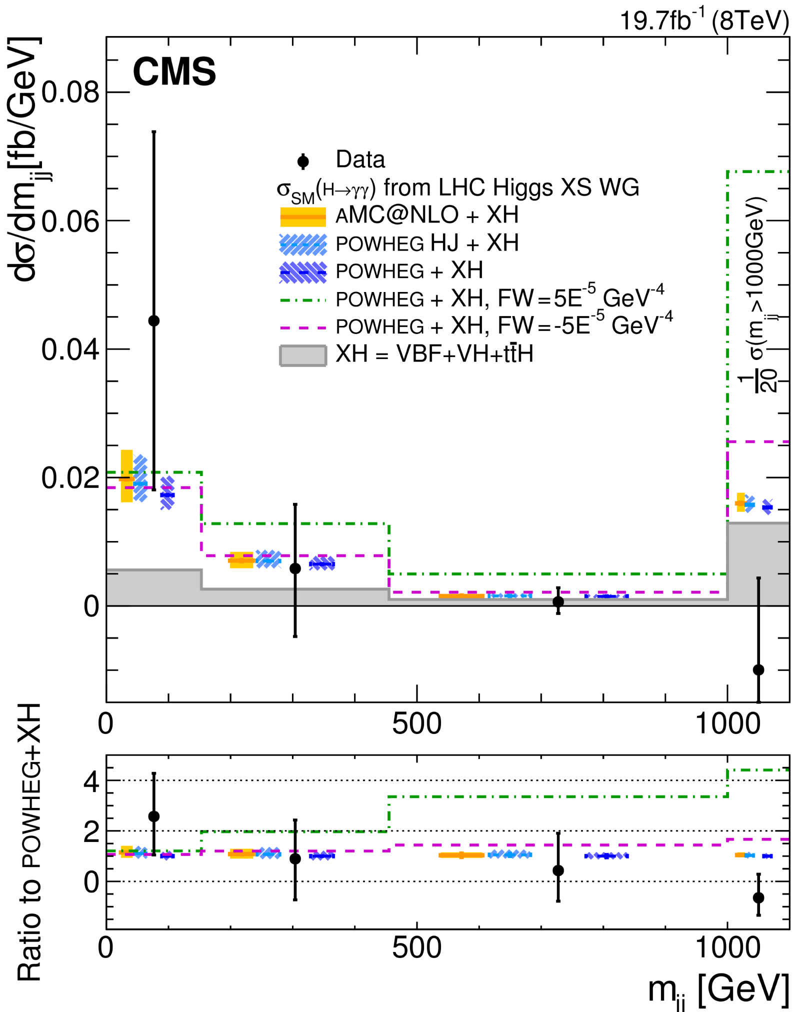


Dijet mass in H→γγ events

ATLAS - JHEP 09 (2014) 112, NEW CMS - arxiv:1508.07819 (submitted to EPJC)

- Statistics is still poor in 4l events to measure 2-jets observables, look only at H→γγ
- Mjj distribution is used to discriminate gluon fusion from VBF
- Mjj is sensitive to the Higgs coupling to vector boson, tails can be enhanced

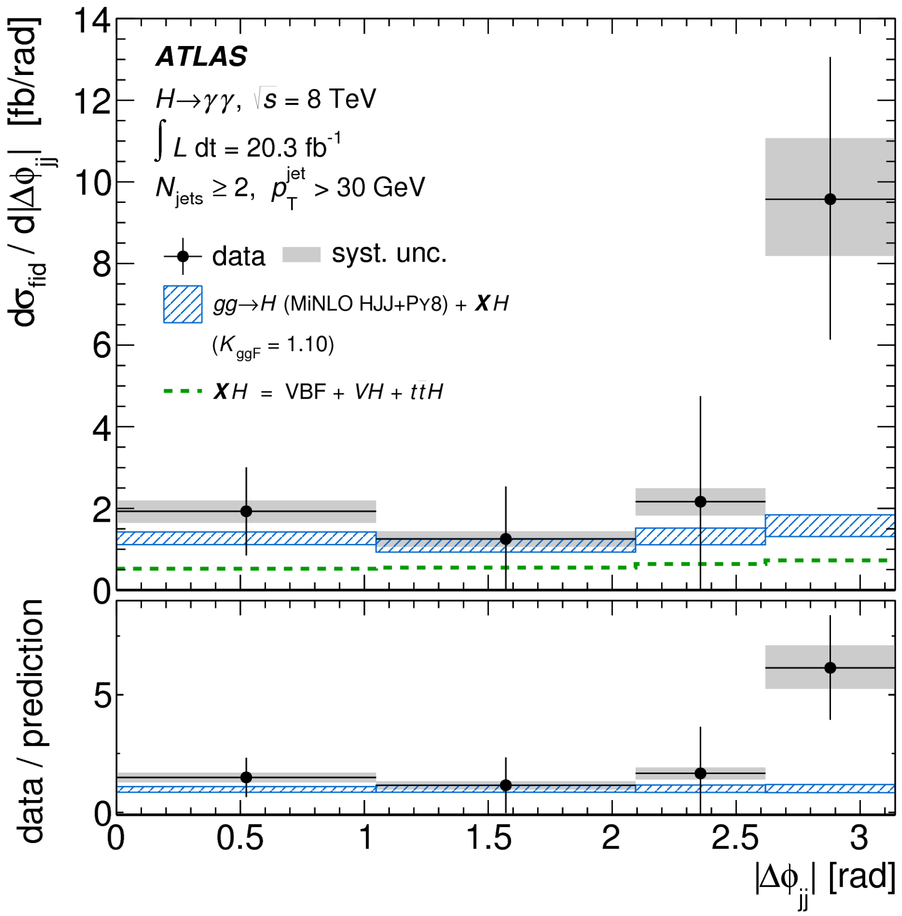


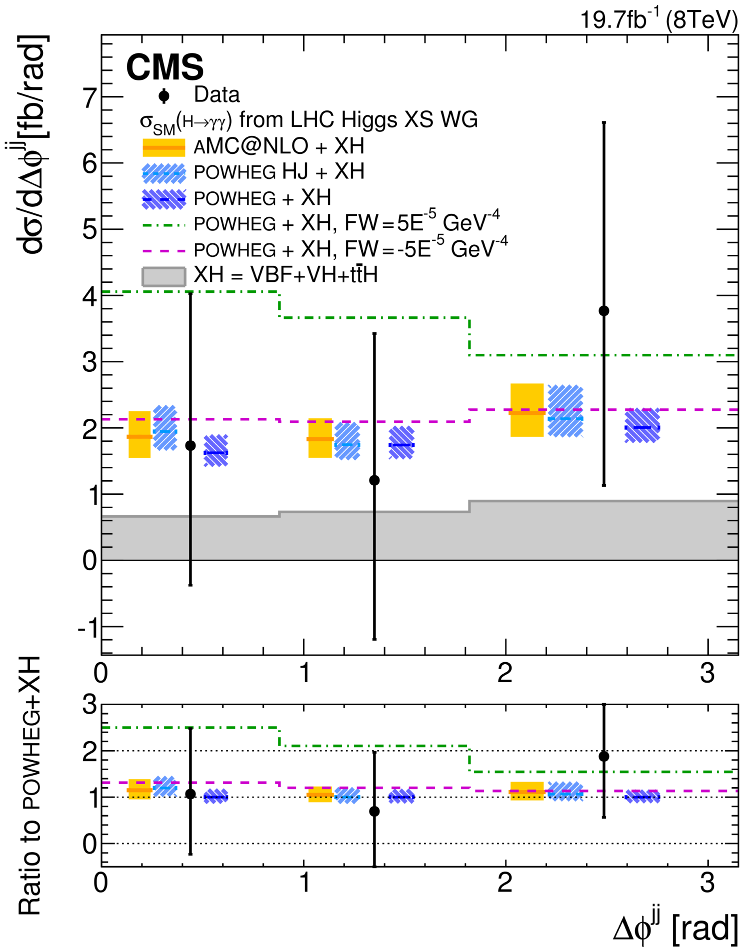


Δϕ(j1,j2) in H→γγ events

ATLAS - JHEP 09 (2014) 112, NEW CMS - arxiv:1508.07819 (submitted to EPJC)

- Δϕ(j1,j2) distribution is used to discriminate gluon fusion from VBF
- Anomalous Higgs coupling to vector boson would enhance low values of Δϕ(j1,j2)





Higgs anomalous couplings

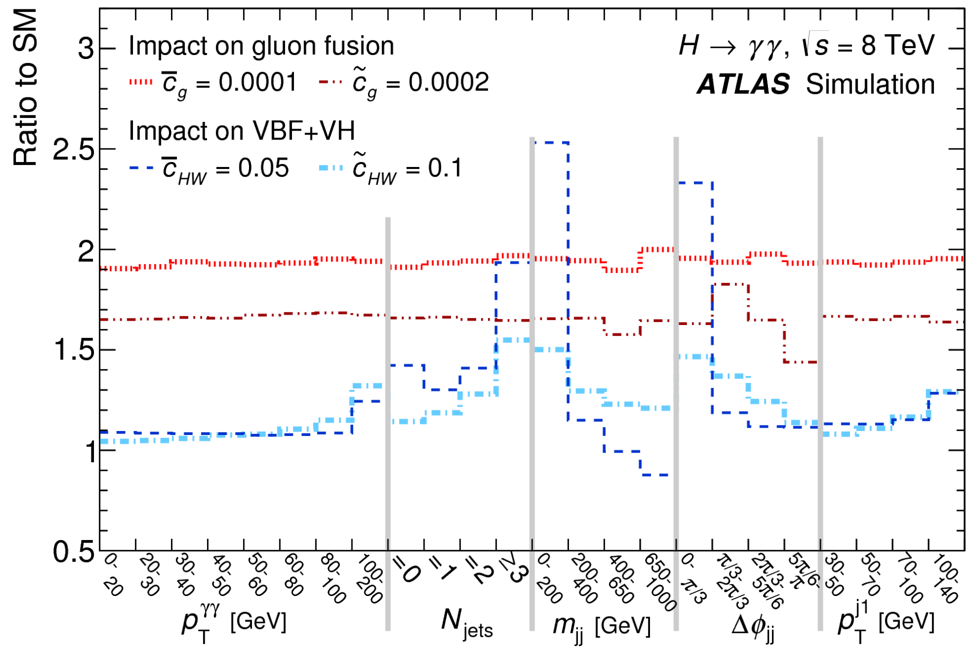
ATLAS - arxiv:1508.02507 (submitted to PLB)

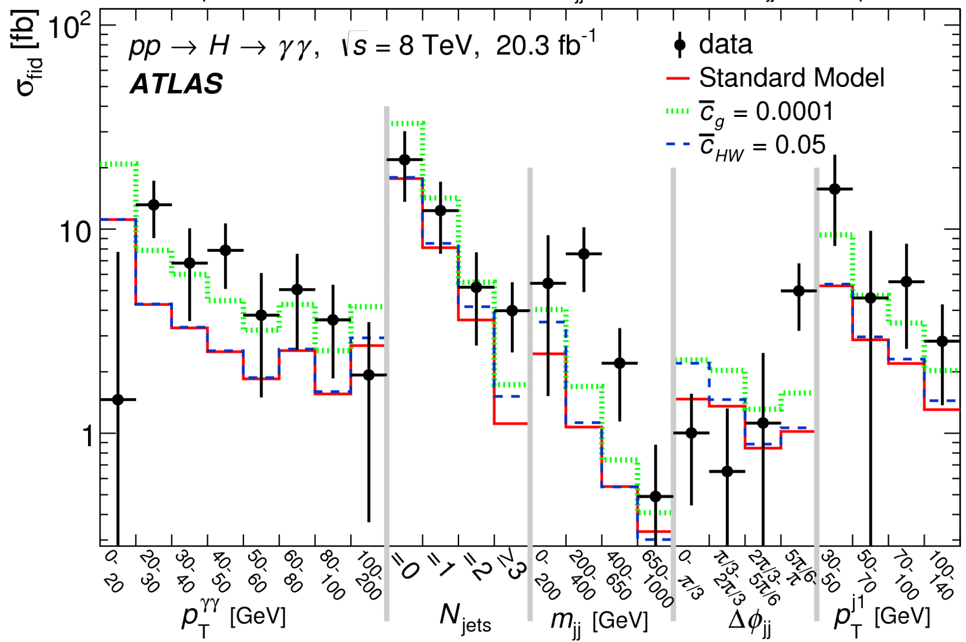
NEW

- **Interpret ATLAS H→γγ differential cross sections** in term of **Higgs anomalous couplings**
- Use **5 differential measurement**, take into account **correlations** in the likelihood
- Interpretation with the **Effective Lagrangian** framework
- Probe Higgs anomalous coupling to gluons, photons and vector bosons, CP conserving or violating

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

Coefficient	95% $1 - CL$ limit
$\bar{c}_\gamma$	$[-7.4, 5.7]\times10^{-4} \cup [3.8, 5.1]\times10^{-3}$
$\tilde{c}_\gamma$	$[-1.8, 1.8]\times10^{-3}$
$\bar{c}_g$	$[-0.7, 1.3]\times10^{-4} \cup [-5.8, -3.8]\times10^{-4}$
$\tilde{c}_g$	$[-2.4, 2.4]\times10^{-4}$
$\bar{c}_{HW}$	$[-8.6, 9.2]\times10^{-2}$
$\tilde{c}_{HW}$	$[-0.23, 0.23]$





Conclusions

Mass
- ATLAS+CMS $H \to \gamma\gamma$ and $H \to ZZ$, **m_H = 125.09 ± 0.24 GeV (precision ~0.2%)**

Width
- Constrained via $H \to ZZ$ and $H \to WW$ off-peak distribution: **< 22 MeV** at 95% CL (SM ~4 MeV)

Spin/parity
- $H \to ZZ$, $H \to WW$ and $H \to \gamma\gamma$: **Data is favouring 0^+** hypothesis.

Differential cross sections
- Differential distributions in $H \to ZZ$ and $H \to \gamma\gamma$ are **in agreement with SM predictions**, and do not allow yet to favour some of the SM Monte-Carlo simulations

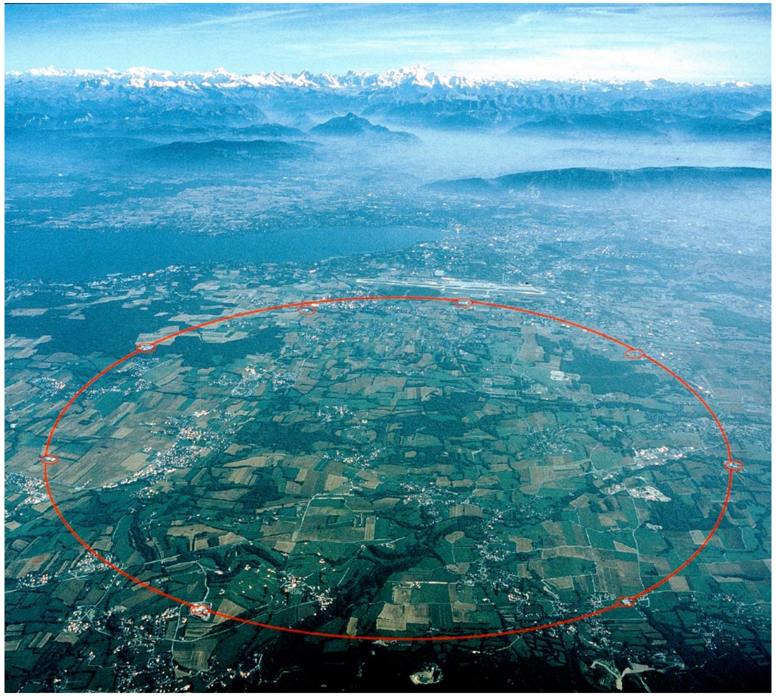
Anomalous couplings / Effective Lagrangian
- Moving toward quantifying differences in kinematics due to anomalous couplings: **no significant deviation from the SM is observed**

LHC Run II will allow to probe further Higgs boson properties, and maybe find some hints for new physics beyond standard model!

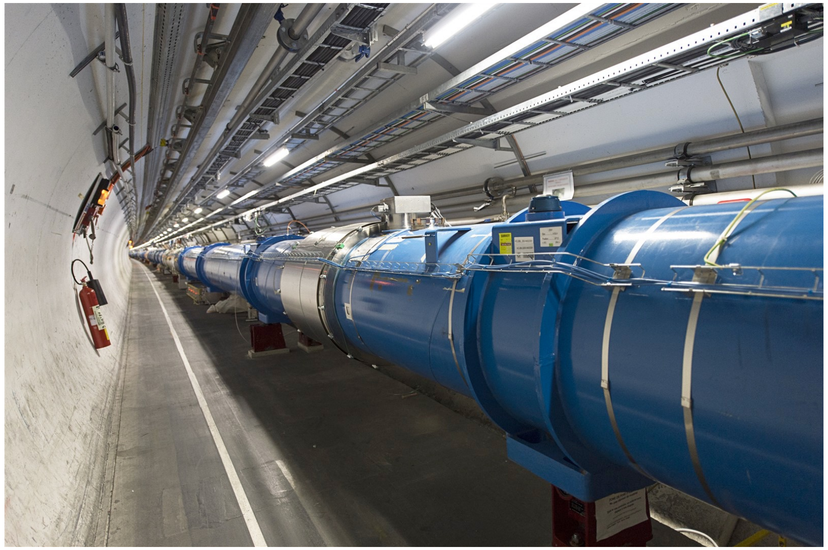
Thank you!

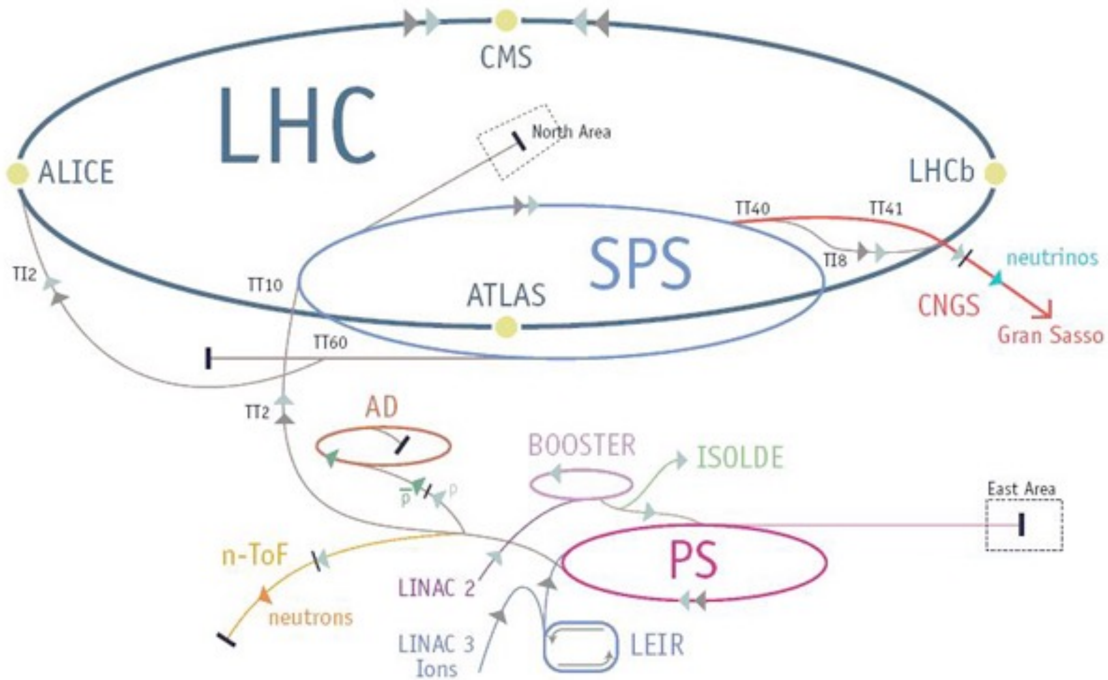
BACK-UP SLIDES

Large Hadron Collider (LHC)

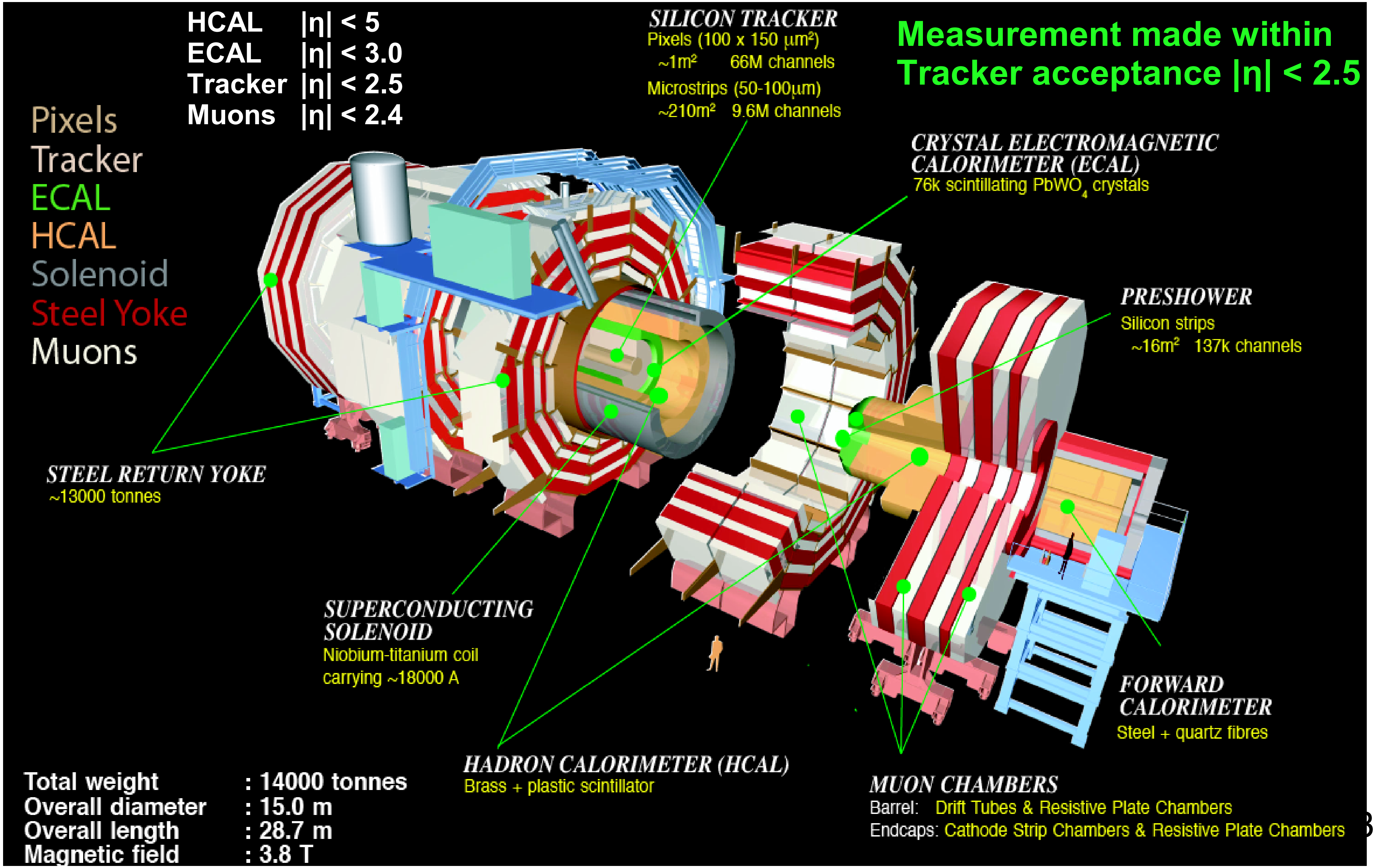


- **Proton-proton** collider at **CERN**, Geneva
- 27 km circumference, fully supra-conducting magnets at 100m depth
- 7 TeV center of mass energy in 2010 and 2011, 8 TeV in 2012
- Instantaneous luminosity: reached peak 7.7x10^{33} cm^{-2}s^{-1}

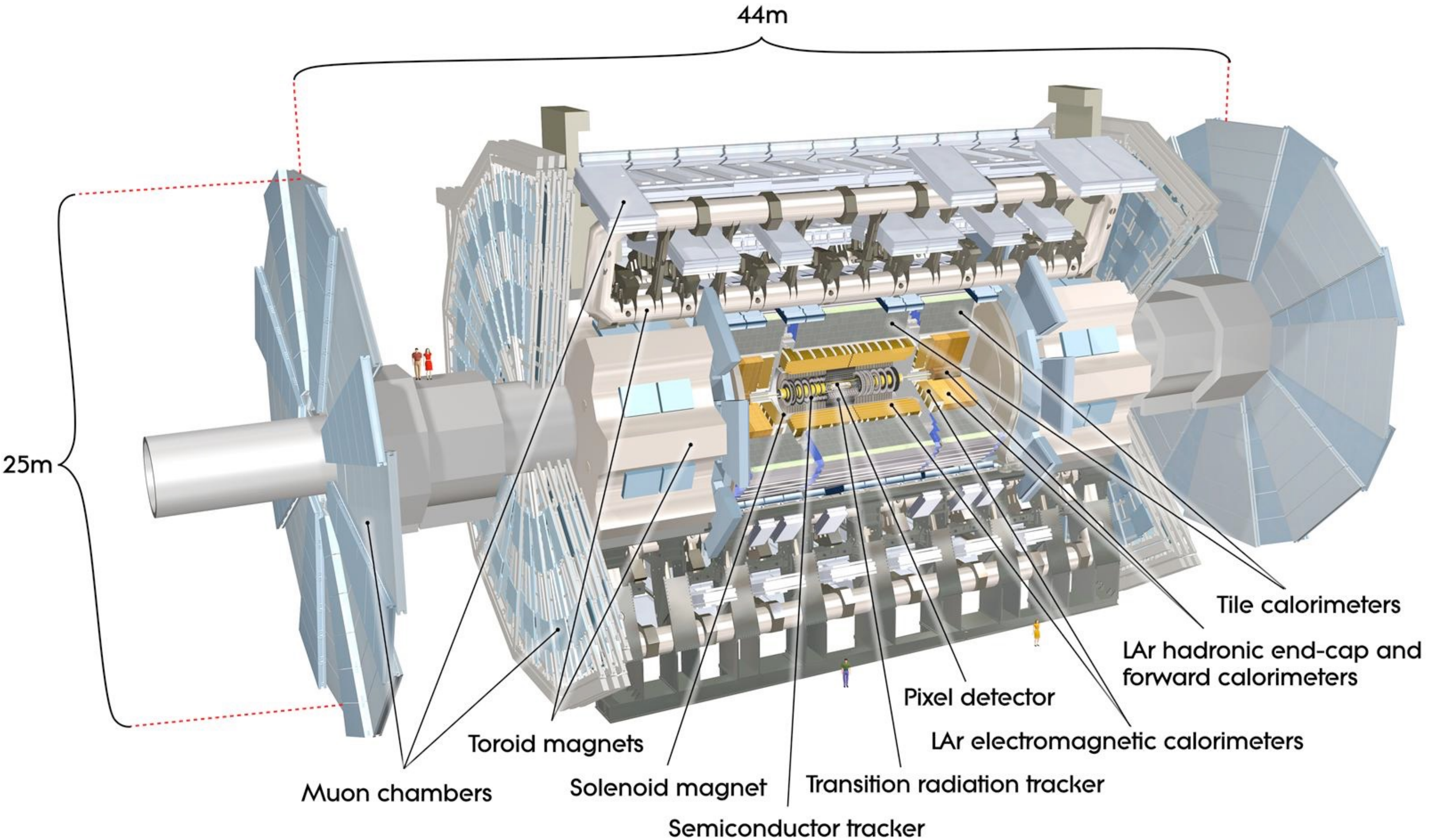




CMS detector



ATLAS detector



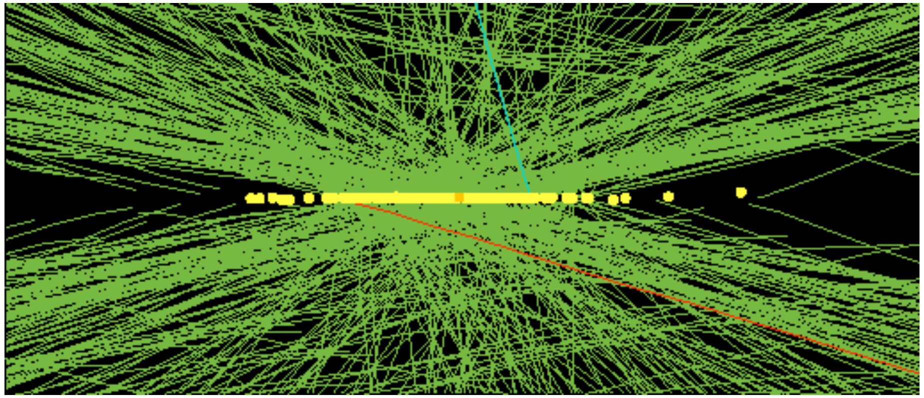
Luminosity conditions

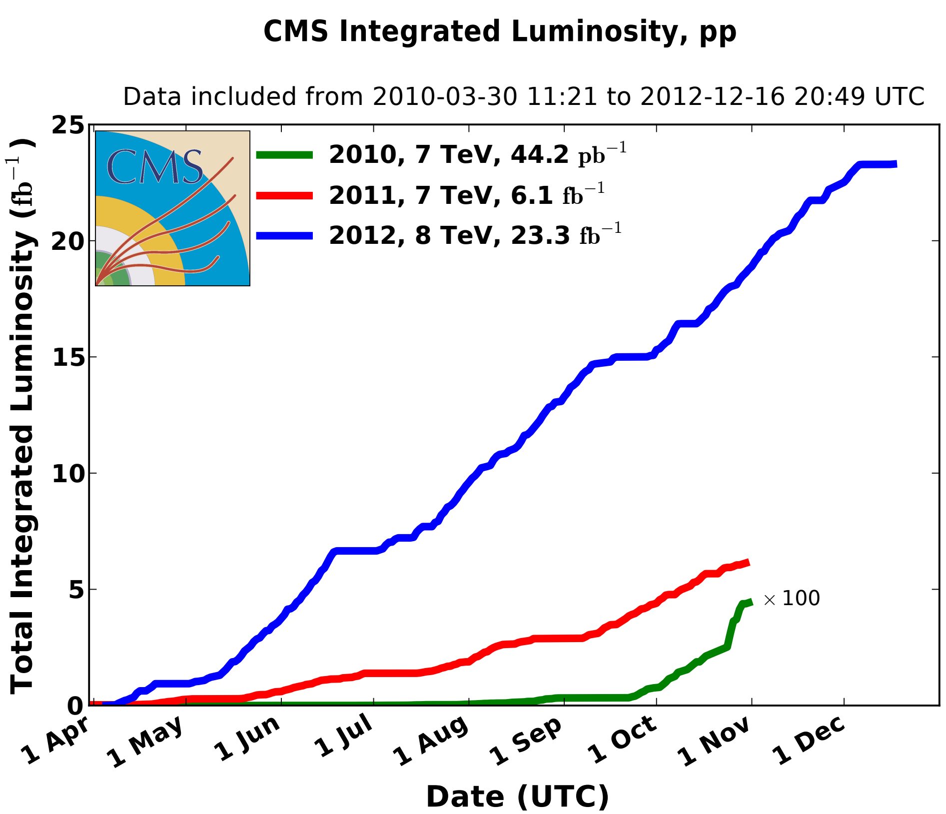
Analyses presented in this talk are using:

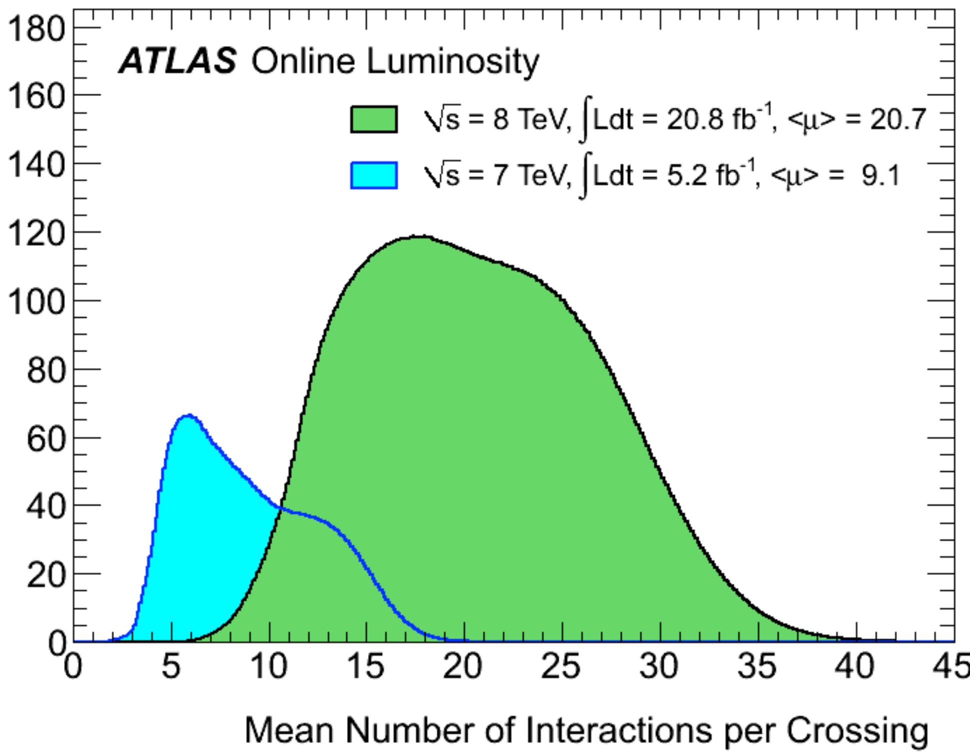
- **5.1 fb-1 of 7 TeV data** in 2011
- **Up to 19.6 fb-1 of 8 TeV data** in 2012

Pileup mean interaction ~21 in 2012 (~10 in 2011)

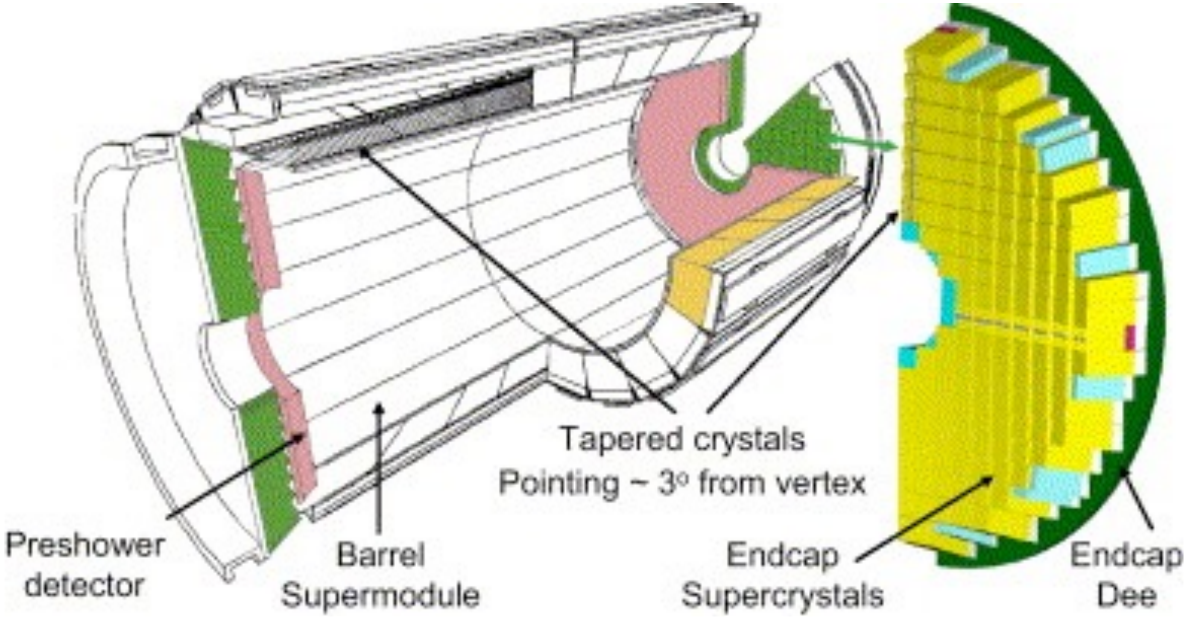
Event with 70 reconstructed vertices (special run)







CMS electromagnetic calorimeter(ECAL)



CMS Electromagnetic calorimeter(ECAL) :

- 75848 $PbWO_4$ crystals
- **Excellent** energy resolution (design: 1% for H→γγ barrel photons)

The **ECAL** is made of scintillating crystals of PbWO4 :

-**Barrel** : 36 “supermodules” with 1700 crystals each (coverage |η|<1.48)

-**Endcaps** : 268 “supercrystals” with 25 crystals each (coverage 1.48<|η|<3.0)

A **preshower** made of silicon strip sensors is located in front of the endcaps (1.65<|η|<2.6)

Energy resolution (measured in electron test beam) :

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus \frac{b}{E(GeV)} \oplus c$$

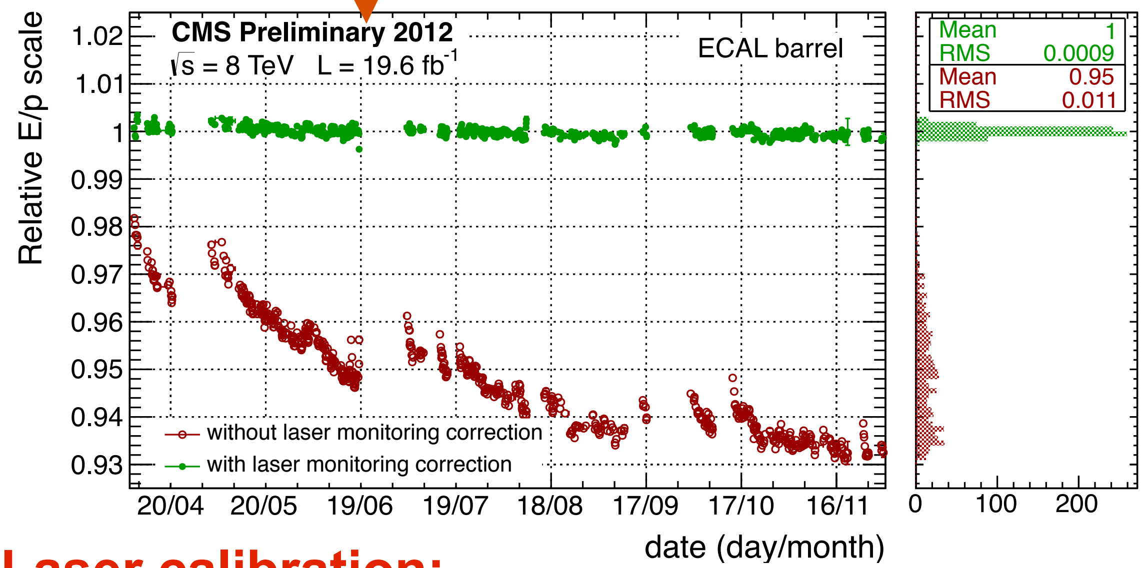
a = 2.8% stochastic term

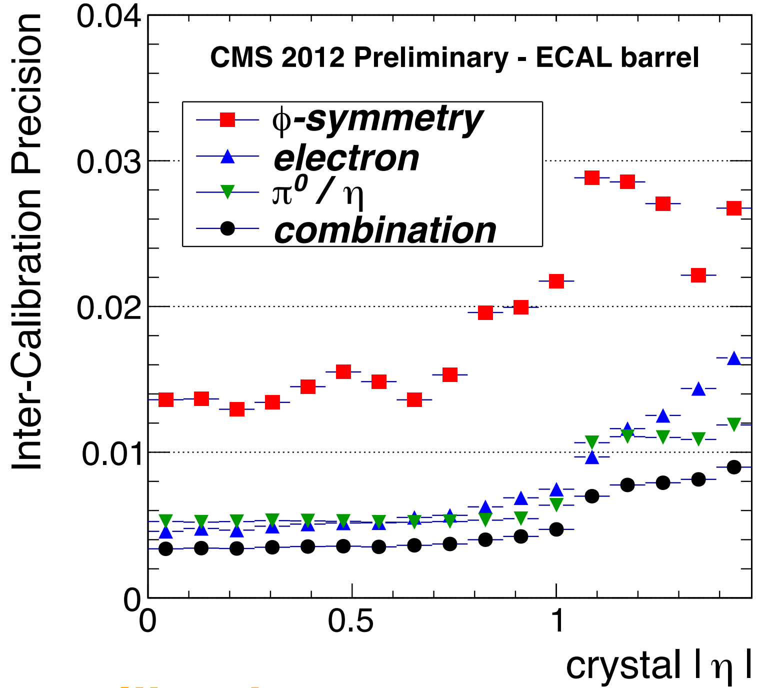
b = 12% noise term

c = 0.3% constant tern

CMS ECAL Calibration

Laser monitoring → **Crystal Intercalibration ($\pi^0 \rightarrow \gamma\gamma$)** → **Cluster energy correction (MC)** → **Energy scale ($Z \rightarrow ee$)**





Laser calibration:

- Correct for ECAL crystals **transparency loss due to electromagnetic damage**
- RMS stability after corrections 0.09% (barrel), 0.28% (Endcap)

Inter-calibrations

- Correct for response non-uniformity
- Use π^0 and η (mass), **ϕ-symmetry** (minimum bias), **W→eν** (E/p)
- **Precision**: better than **0.5% in central barrel**

CMS H→γγ mass resolution

HIG-13-001

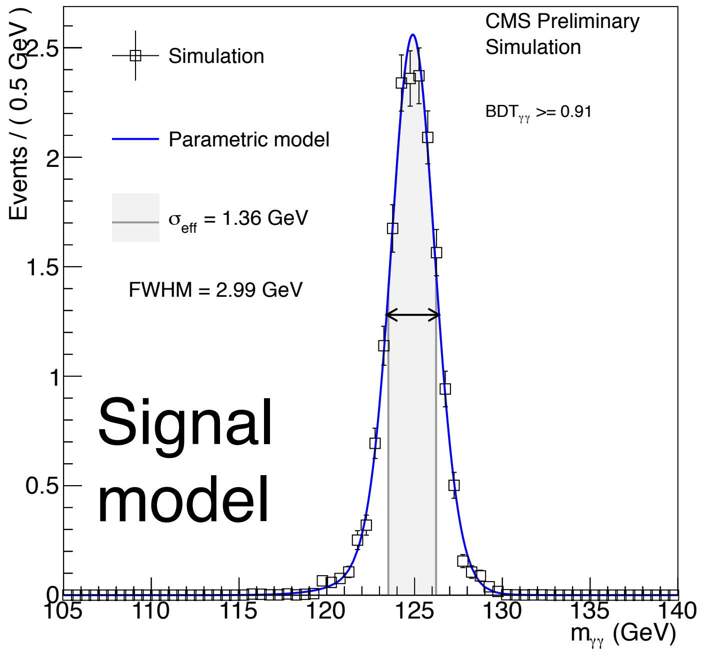
Laser monitoring → Crystal Intercalibration ($\pi^0 \to \gamma\gamma$) → Cluster energy correction (MC) → Energy scale ($Z \to ee$)

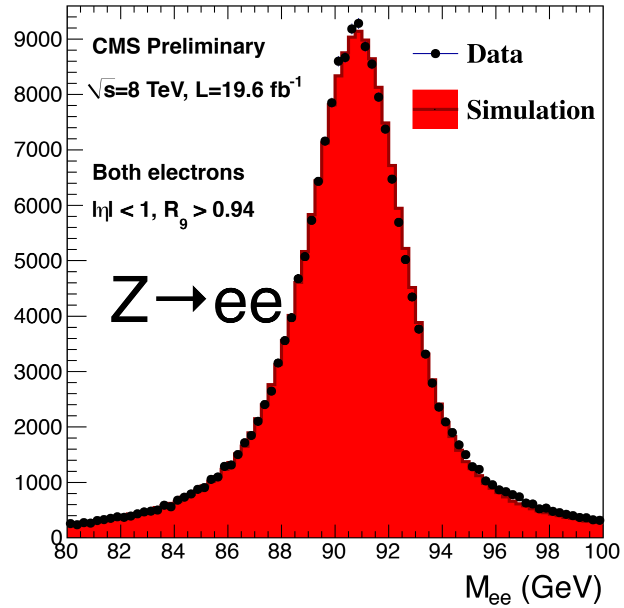
Cluster energy corrections

- Correct for **energy loss** in the **material** upstream ECAL and in ECAL cracks
- Use **geometry**, **shower profile**, energy in **preshower**
- **Energy regression: 1-2% mass resolution**
- **Best untagged category**: 1.36 GeV effective sigma (narrow shower shape in barrel or high diphoton p_T events)

Energy scale:

- Correct for data/MC residual differences in scale and resolution using Z mass shape
- Stable along data-taking period





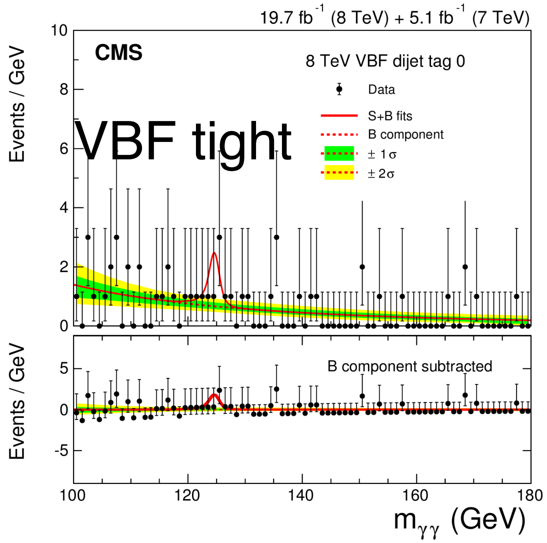
CMS H→γγ: other categories

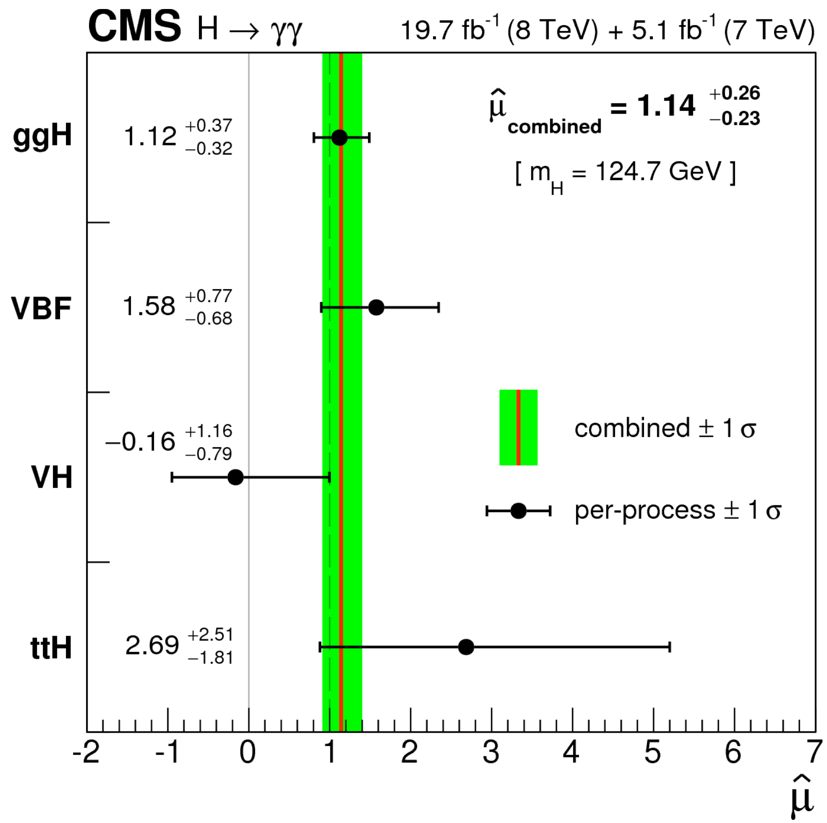
EPJC 74 (2014) 3076

VBF tags:

- VBF is higher γγ p_T, two forward jets
- **Dijet BDT** using γγ, jets kinematics
- Define two categories: s/b~0.5 and s/b~0.2

Gluon-gluon fusion contamination in VBF categories ~20-50%



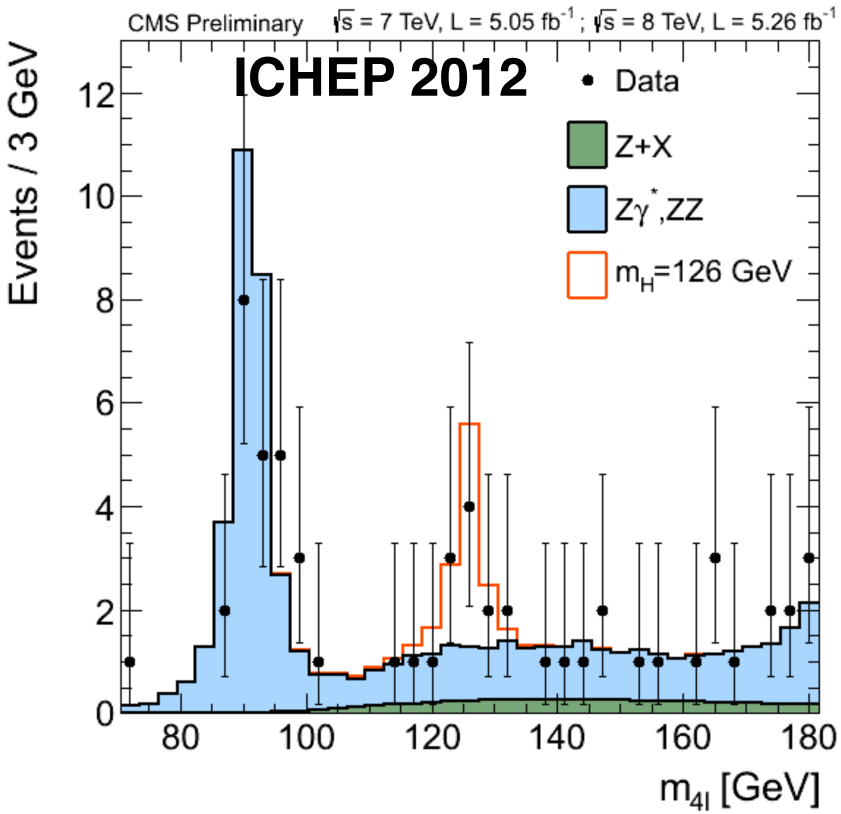


Categories:

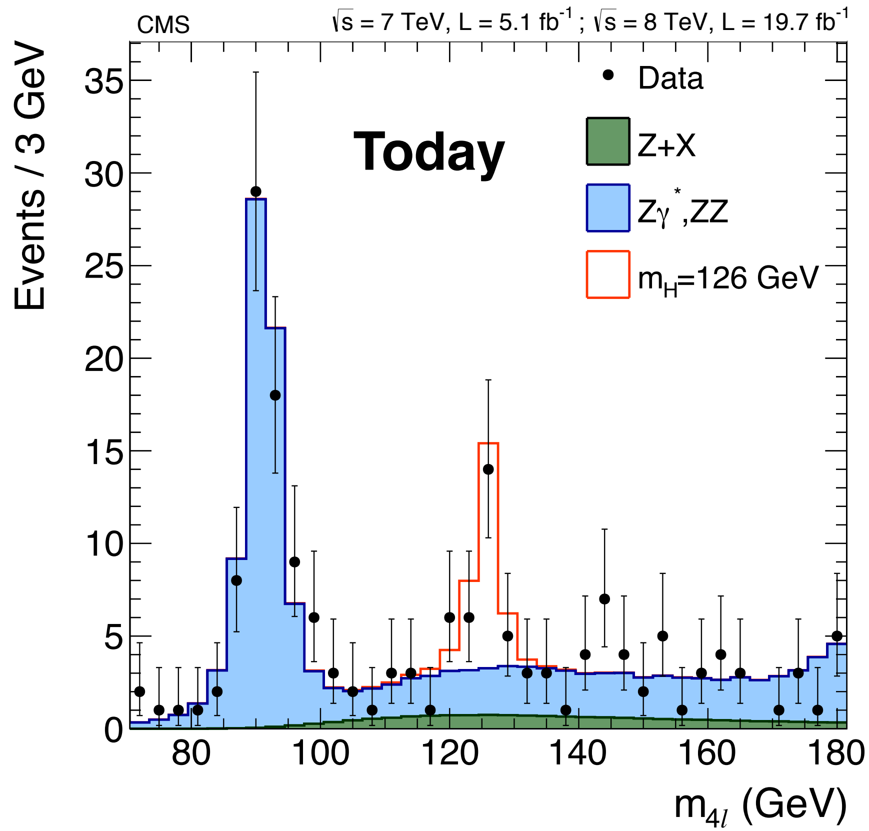
- Defined with s/b and resolution level
- 5 **untagged**, 3 **VBF categories,** 3 VH cat, 2 ttH

CMS H→ZZ→4l analysis

arxiv:1312.5353



Note the scale!

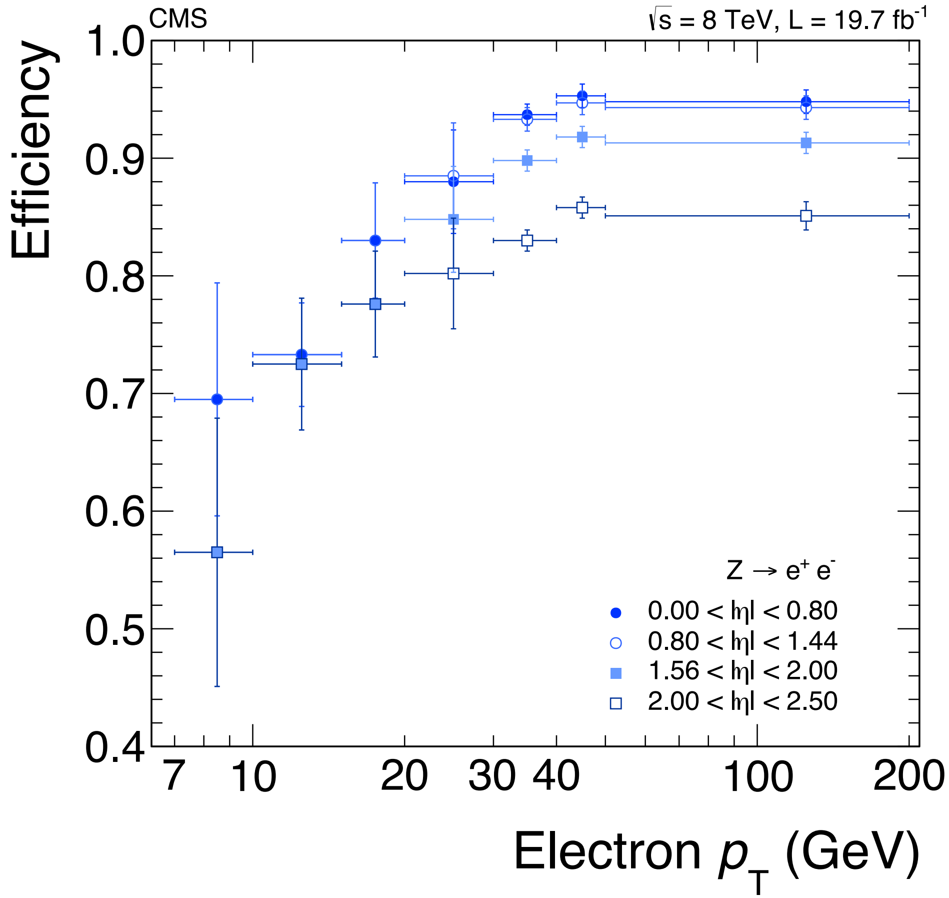


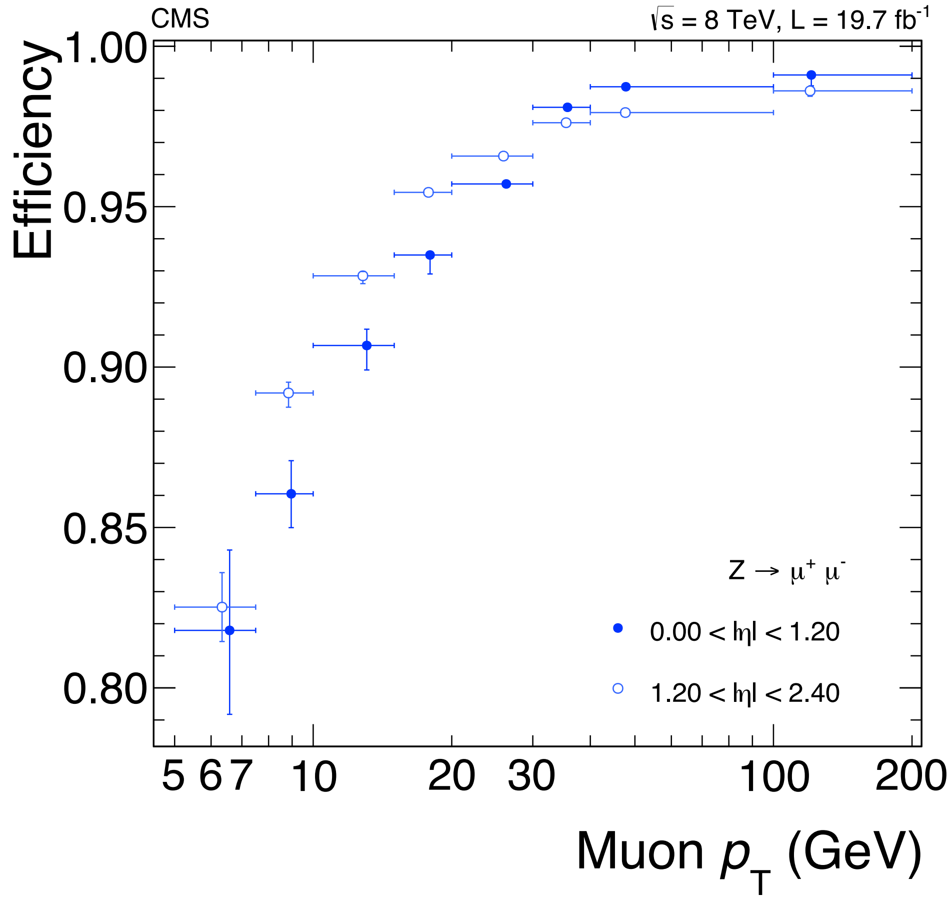
- **Small background (s/b~2), almost flat around 125 GeV**
- **Clear excess observed**

Mass range 121.5 - 130.5 GeV:

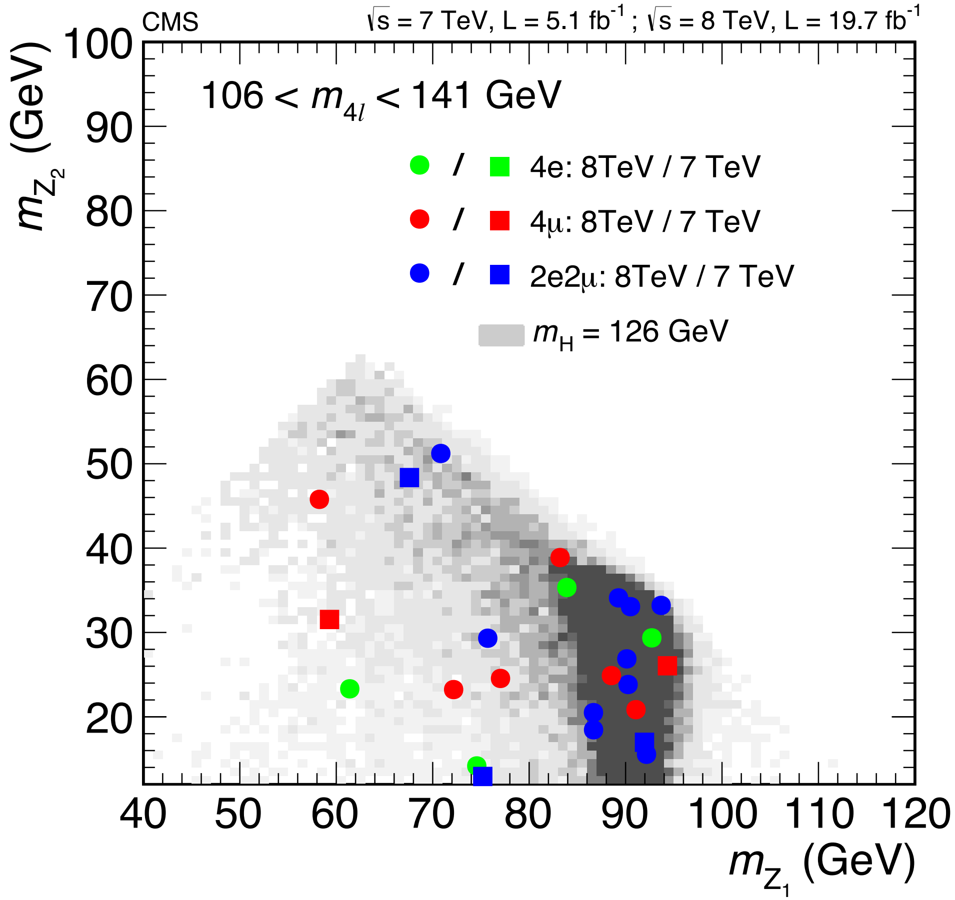
Channel	4e	2e2μ	4μ	4ℓ
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
$m_H = 125$ GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
$m_H = 126$ GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

CMS H→ZZ: lepton efficiency

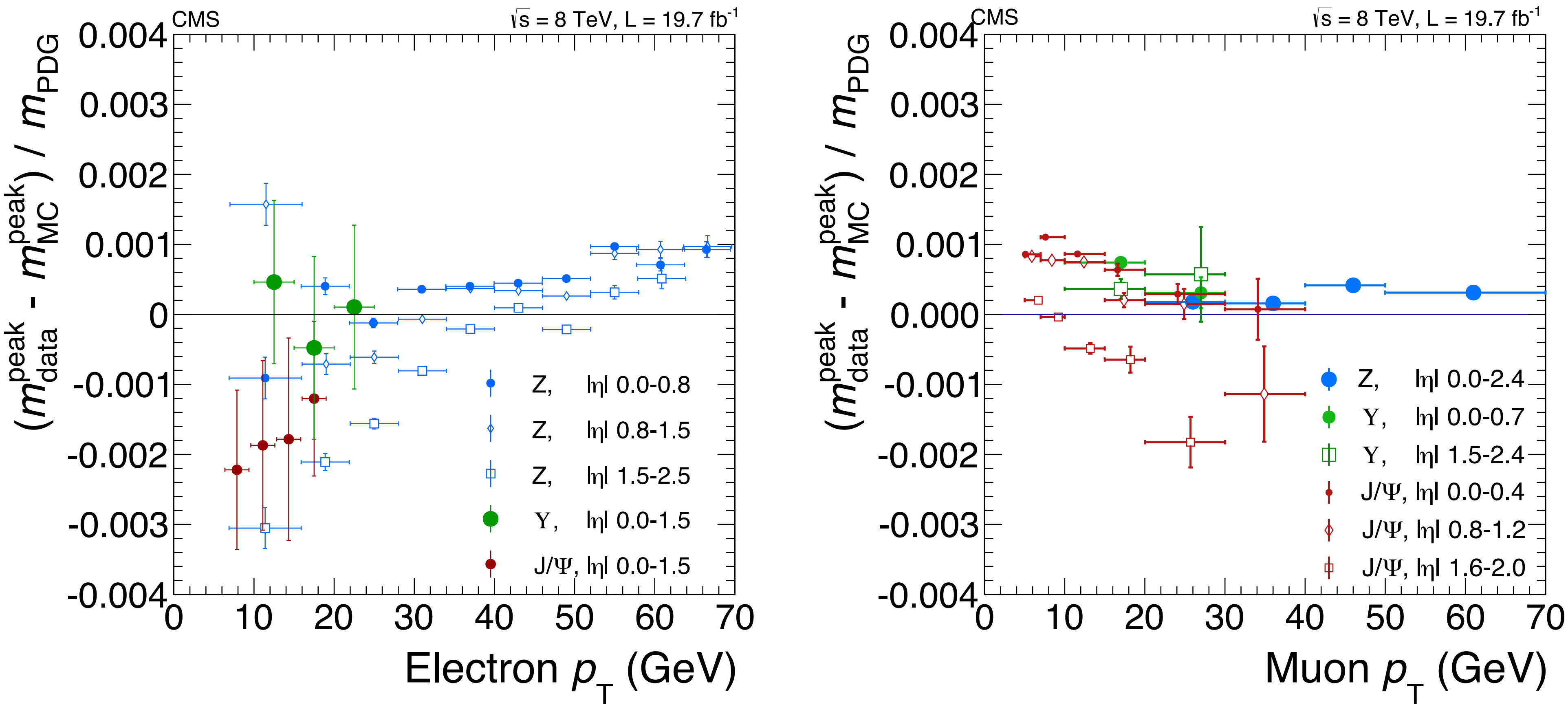




CMS H→ZZ: Z1 and Z2 masses



H→ZZ: mass scale



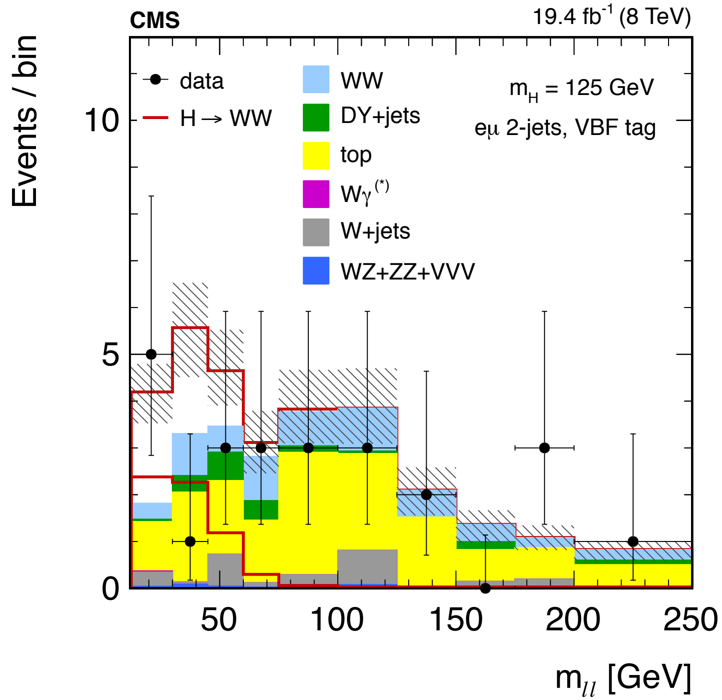
CMS H→W^+W^- dijet and results

JHEP 01 (2014) 096

VBF tag

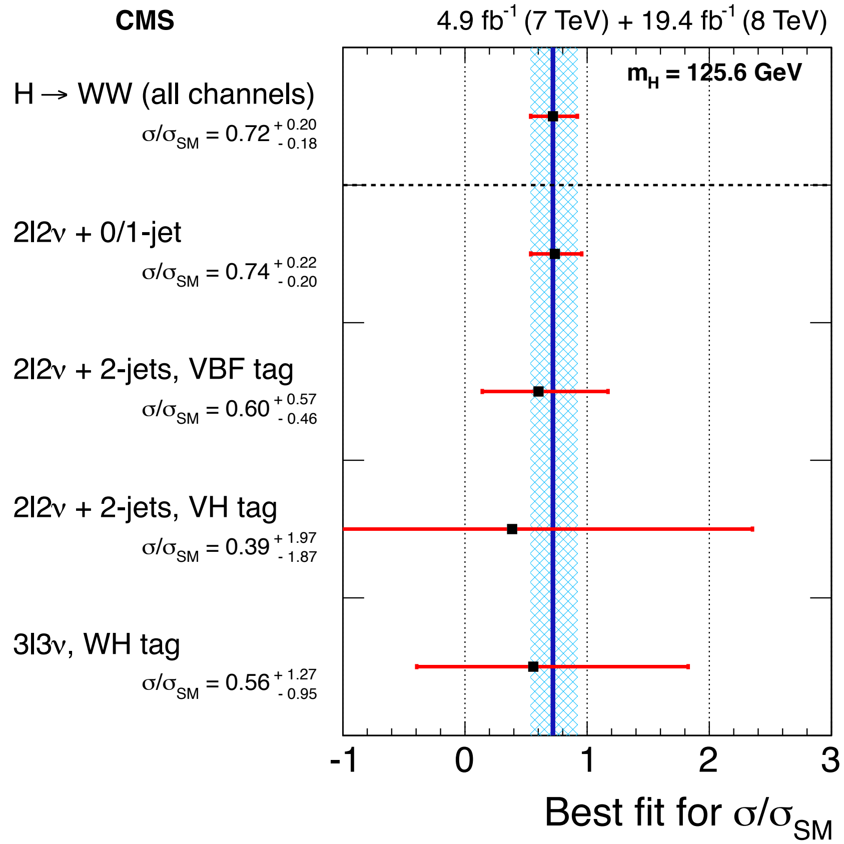
$$|\Delta\eta_{jj}| > 3.5$$

$$m_{jj} > 500\,\mathrm{GeV}$$



- **2jets**: **VBF-tag and VH tag** use a fit to mll distribution

- Trilepton final state also used: WH→3l3ν, ZH→3lν+2jets



- **Best fit** signal strength **$\mu=0.72^{+0.20}_{-0.18}$ at 125.6 GeV**
- **Local significance: expected 5.8σ, observed 4.3σ**

Parameterizing deviations with EFT

Effective Field Theory for anomalous couplings:

- Look for manifestation of **higher scale physics** to the electroweak scale
- Construct all **operators** involving electroweak fields with new interactions in the gauge sector, respecting gauge invariance
- Non-linear realization (without Higgs) or more recent linear realization (with Higgs):

$$L = L_{SM} + \sum_i \frac{a_i}{\Lambda^2} O_i + \sum_j \frac{b_i}{\Lambda^4} O_j + \dots$$

Dimension 6 operators are involving **charged aTGC and Higgs couplings**

Dimension 8 involves **aQGC, neutral TGC, higher order Higgs couplings**

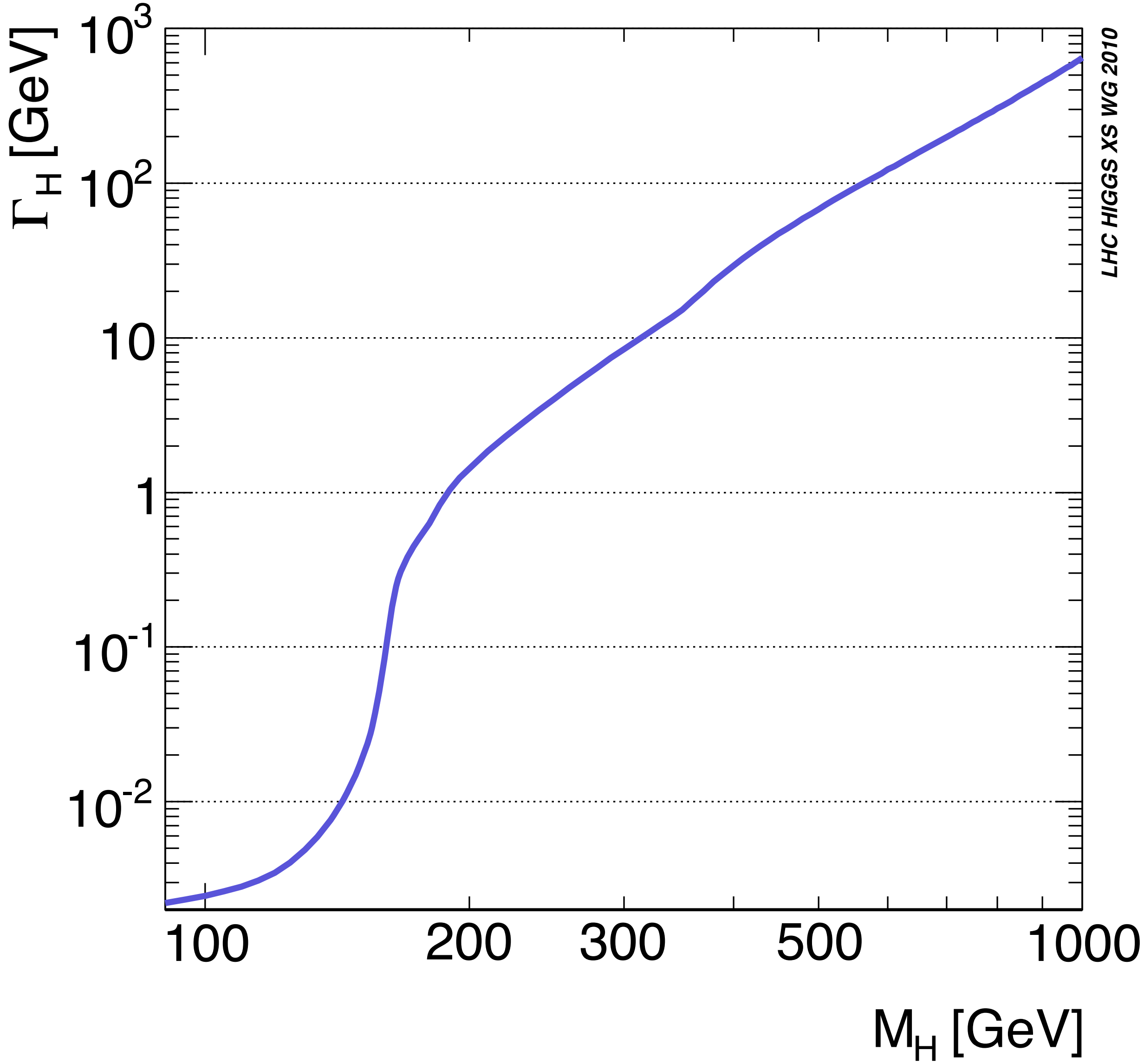
Building blocks: $D_\mu \Phi = (\partial_\mu - igW^j_\mu \frac{\sigma^j}{2} - ig' B_\mu \frac{1}{2})\Phi$

$$\hat{W}_{\mu\nu} \equiv \sum_j W^j_{\mu\nu} \frac{\sigma^j}{2}$$

$$B_{\mu\nu}$$

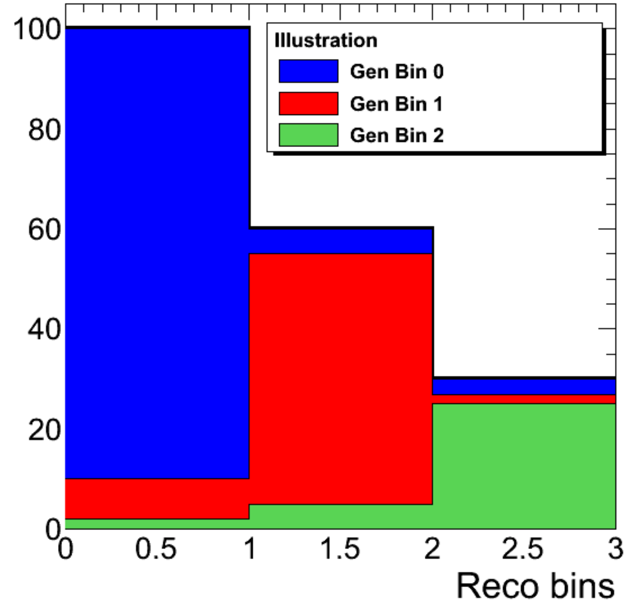
- **Enhances total cross-section, enhances (Higgs) boson pT** (depends on $U(1)_Y$ and SU(2) field strength and derivative of the scalar field)

SM Higgs total width



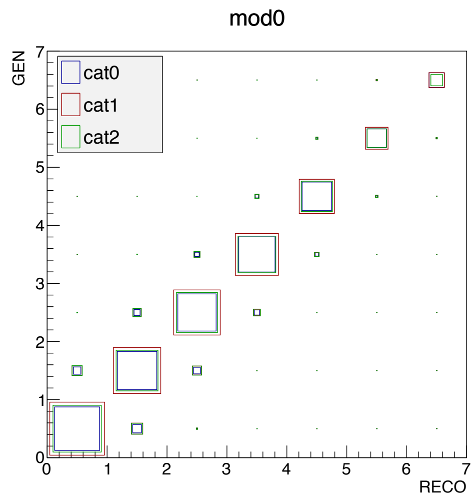
Unfolding procedure: response matrix

See also A. Marini's talk on Wed.



Why unfolding ?

- Unfolding is needed to **undo detector effects**
- There are bin by bin **migrations** between generator level and reconstructed level
- This needs to be corrected: use a **response matrix** to propagate the statistical uncertainty in each bin
- Selected events **falling out of acceptance** at generator level are collected in a special bin



The proposed method:

- **Fold in the response matrix** into the likelihood (perform measurement and unfolding at the same time)
- **Each cell** of the response matrix contains **normalization** (efficiency) and **signal model** for a given set of (gen, reco) **bin and analysis category**

Unfolding procedure (cont.)

Function to minimize

Response matrix

Gen level input distribution

$$\mathcal{F}(\mu_i) = -2\log\mathcal{L}(K_{ij}\cdot\mu_i\; N_{gen,i}|N_{reco,j})$$

L is the usual **likelihood** function of B, S+B and the nuisance parameters

Signal strength to be measured for each bin of **gen level** input distribution

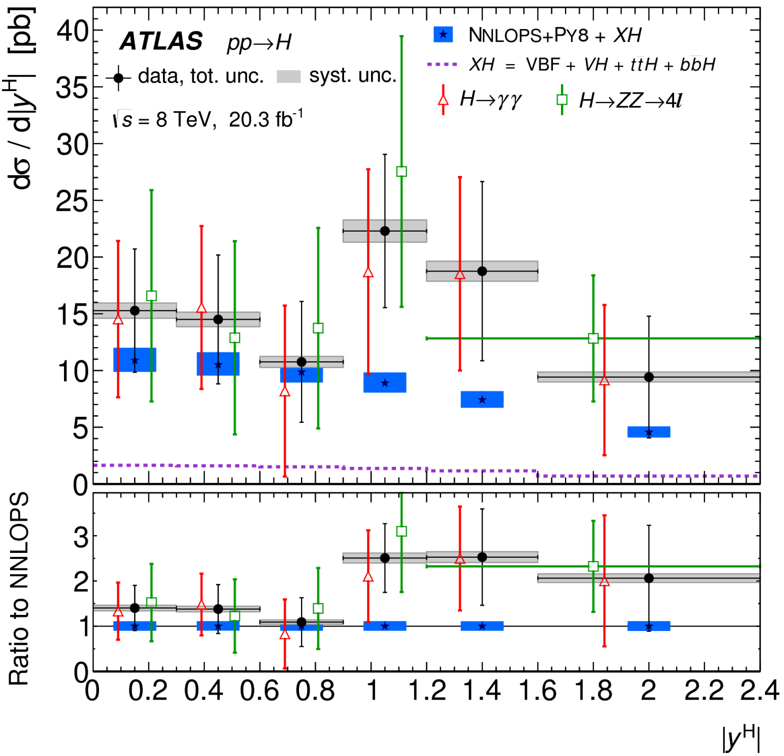
Reco level signal yields in each bins and categories

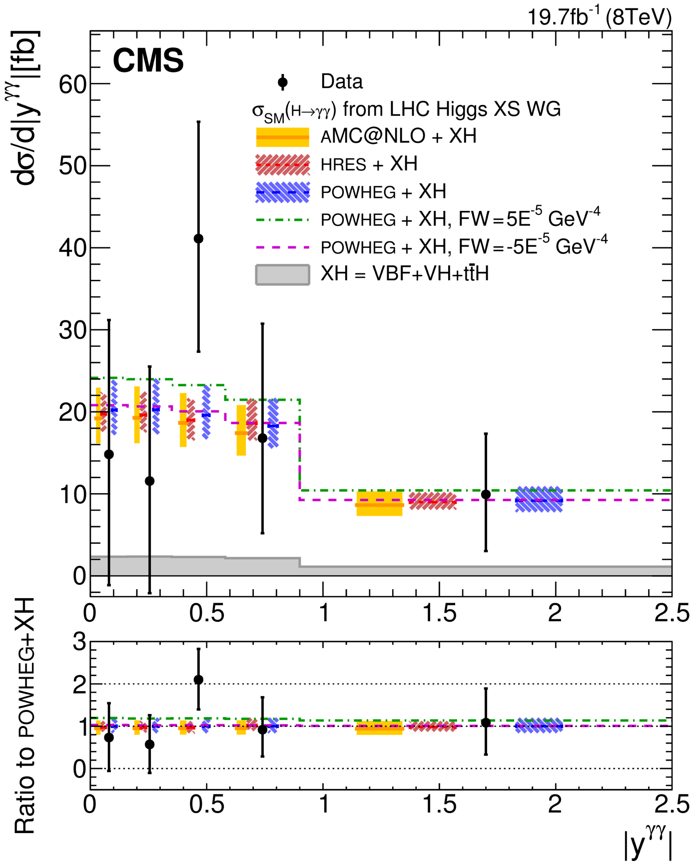
- **Same procedure is already used** e.g. for unfolding from μ in untagged and dijet-tagged categories to μ_{GGH}, μ_{VBF}
- This is **similar to response matrix inversion**, but:
- Usual method of estimating uncertainties (covariance matrix applied after μ measurement) is approximate (in particular for low statistics categories),
- Advantage: use the full likelihood including nuisance parameters

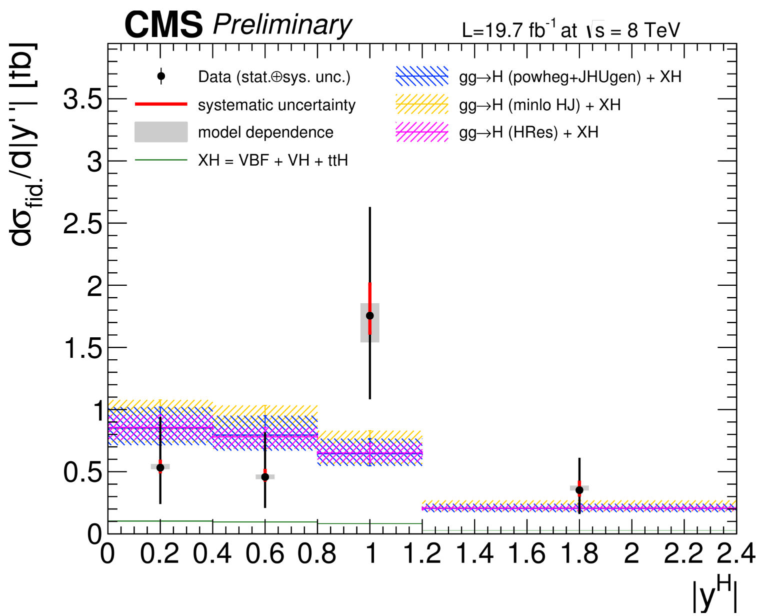
Higgs boson rapidity

ATLAS - PRL 115 (2015) 091801, CMS arxiv:1508.07819 (submitted to EPJC), HIG-14-028

- Higgs rapidity is sensitive to pdf in the proton
- Agreement with the SM predictions





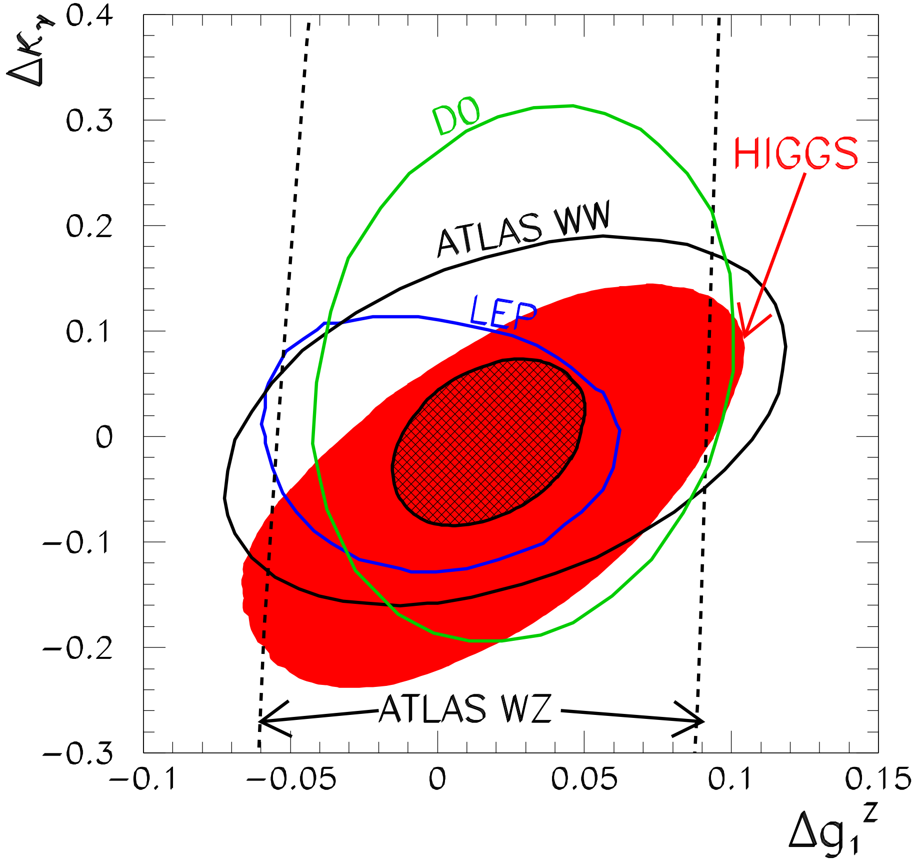


Example of Electroweak / Higgs combination with EFT

$$\Delta\kappa_\gamma = \frac{g^2 v^2}{8\Lambda^2}\left(f_W + f_B\right),$$

$$\Delta g_1^Z = \frac{g^2 v^2}{8c^2\Lambda^2} f_W\,, \quad \Delta\kappa_Z = \frac{g^2 v^2}{8c^2\Lambda^2}\left(c^2 f_W - s^2 f_B\right)$$

arxiv:1411.5364



Higgs anomalous couplings

ATLAS - arxiv:1508.02507 (submitted to PLB)

Correlation matrix

(example)