Mass, spin and width of the Higgs boson

XLIX Rencontres de Moriond,
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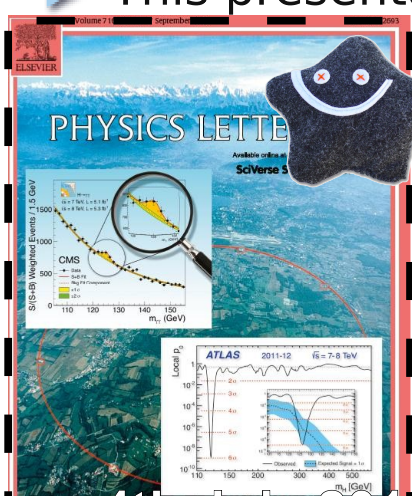
Pasquale Musella (CERN)

on behalf of the CMS and ATLAS collaborations

Recent history

- A new boson, compatible with the Higgs particle discovered at the LHC in 2012.
  - Fundamental Physics Prize 2012 assigned to ATLAS, CMS and LHC and EPS 2013 prize to CMS and ATLAS.
  - Nobel prize in Physics assigned to profs. Englert and Higgs in 2013.
- New window on the study of the Electroweak symmetry breaking opened.
- Measuring the properties of the new boson very important test of SM predictions.
  - Scalar couplings: presented by E. Gross.
  - This presentation: mass, spin width and invisible BR.



4th July 2014

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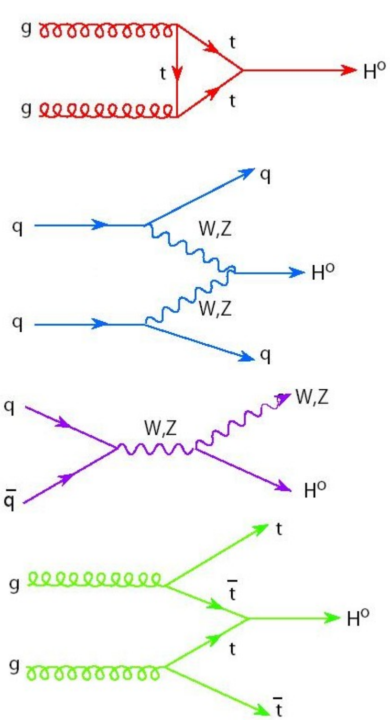
8th October 2013

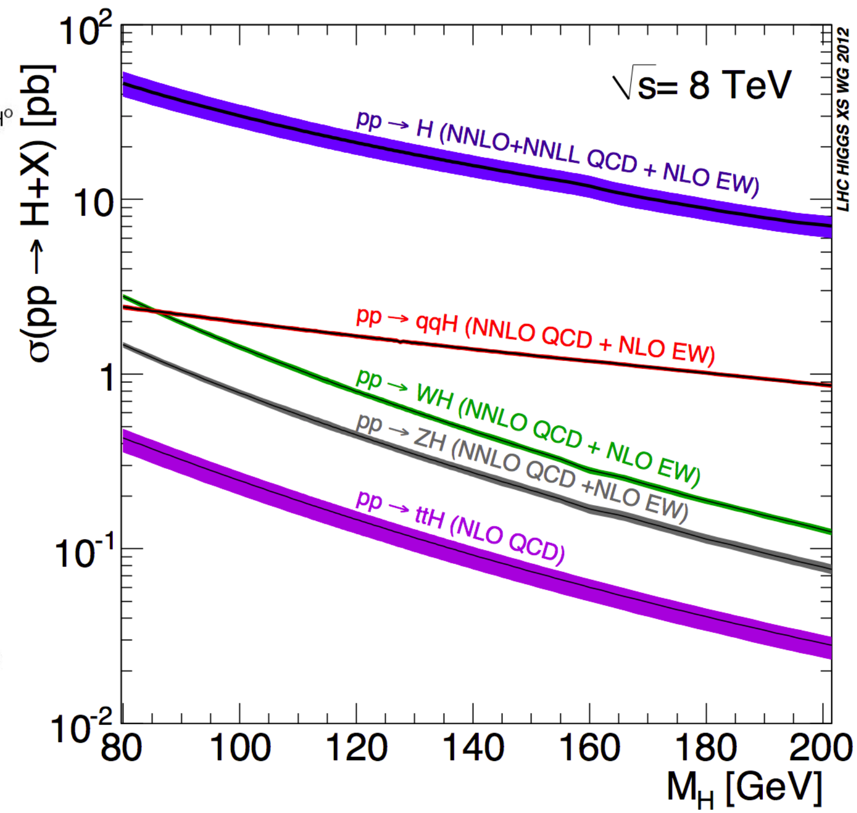
Coming years....

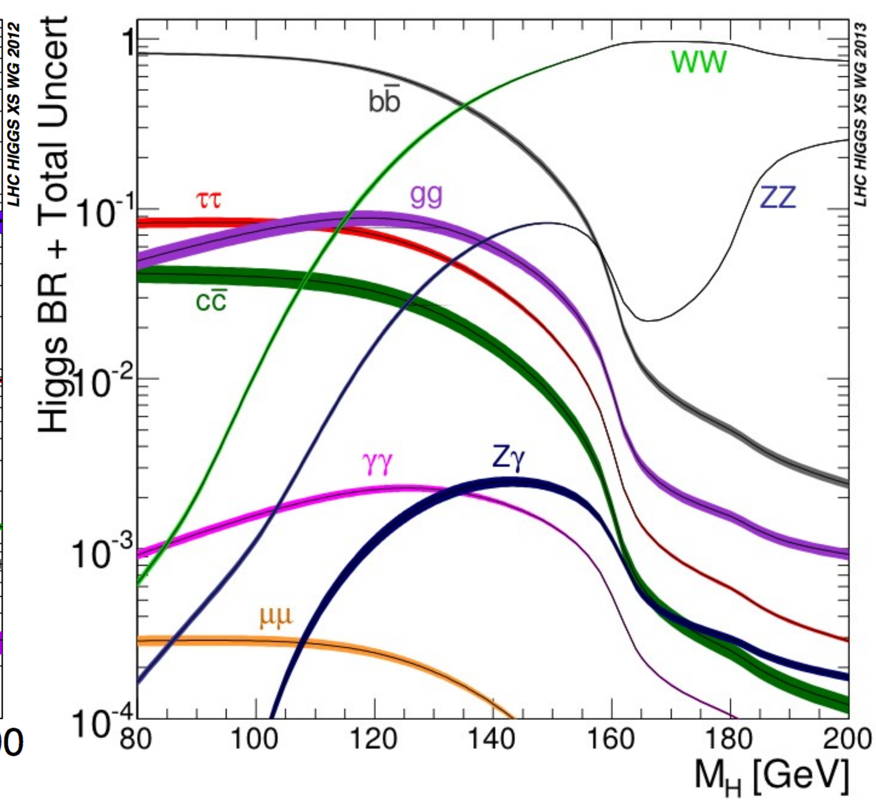
* http://www.particlezoo.net

Production and decay modes

- Production cross section and branching fraction of Higgs boson are a function of its mass.
- At the LHC, search conducted in both fermionic (ττ,bb) and bosonic(γγ,WW,ZZ) final states.







Production and decay modes

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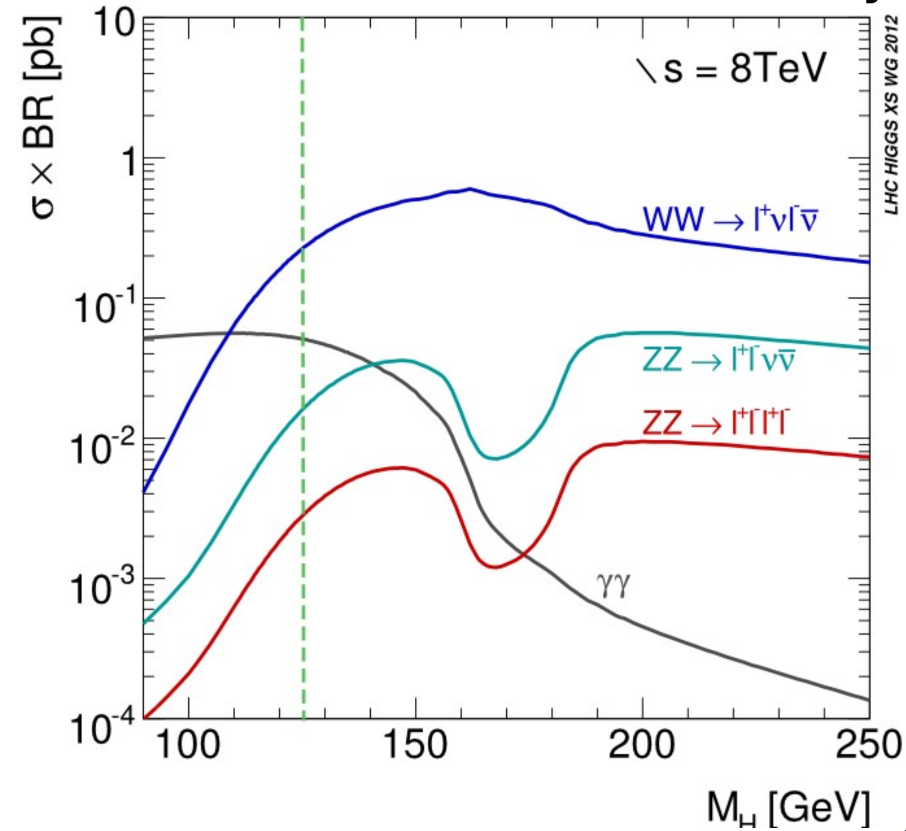
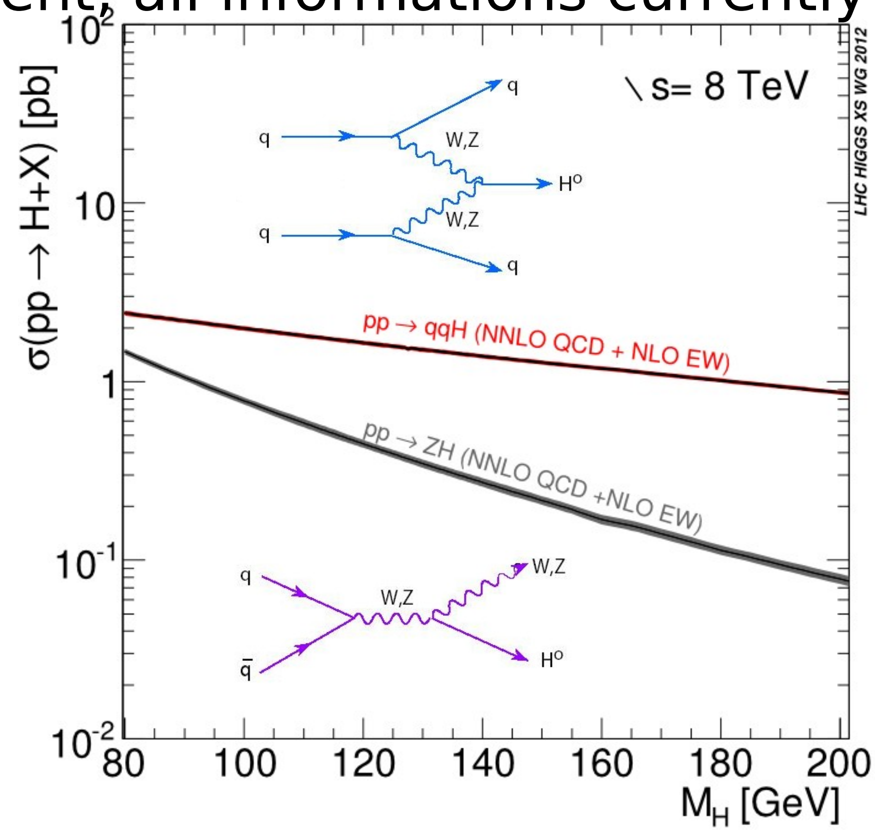
- For **mass**, **spin and width** measurement, all informations currently coming from **bosonic** decay channels.



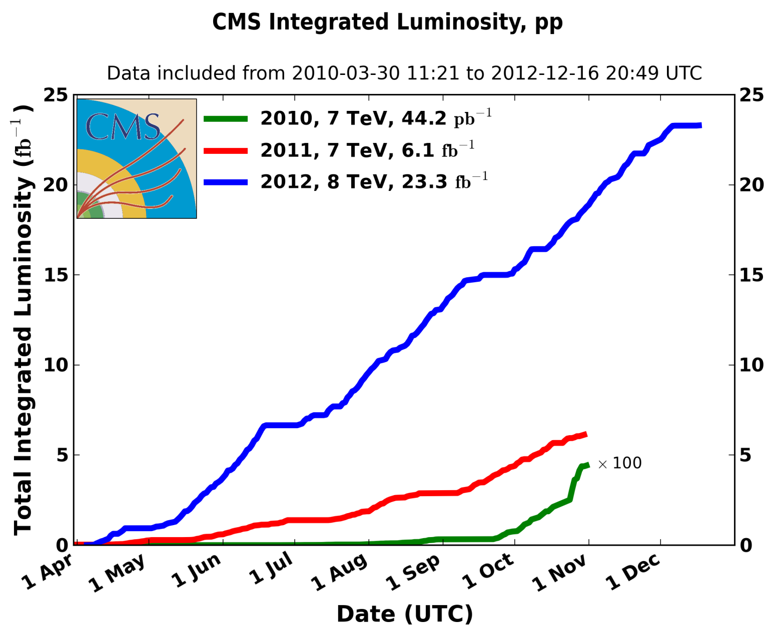
Production and decay modes

- Production cross section and branching fraction of Higgs boson are a function of its mass.
- At the LHC, search conducted in both fermionic ($\tau\tau$,bb) and bosonic($\gamma\gamma$,WW,ZZ) final states.
- For mass, **spin and width** measurement, all informations currently coming from **bosonic** decay channels.
- Search for **invisible decays** performed using **VBF** production and **associated** production with a **Z** boson.

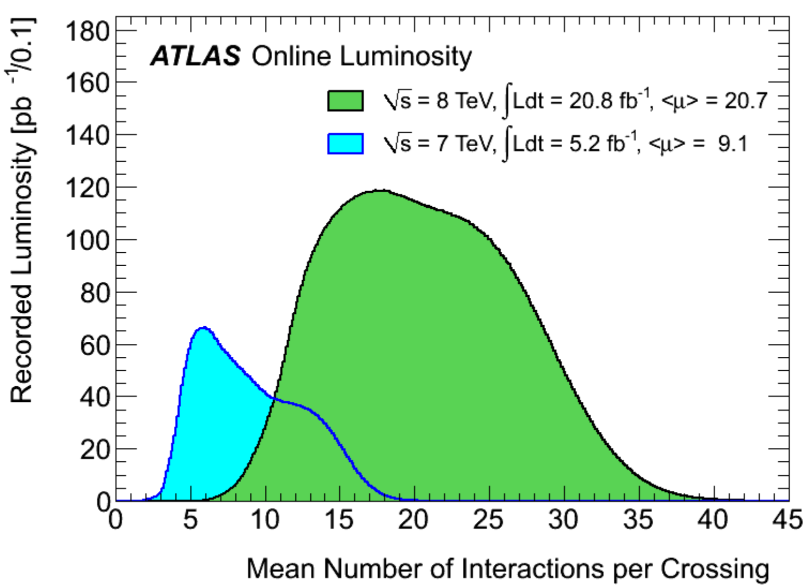


LHC Run 1 dataset

- Excellent performance of the LHC machine throughout the Run 1.
- Also excellent performance of the CMS and ATLAS detectors
  - ~90% of the delivered data available for offline analysis.



- Available dataset:
  - ~5fb^{-1} $\sqrt{s}$=7TeV + ~20fb^{-1} $\sqrt{s}$=8TeV



- Challenging pile-up conditions.
  - Up to 30 average interactions per bunch-crossing.
  - Ingenious ideas needed to keep detector performances.

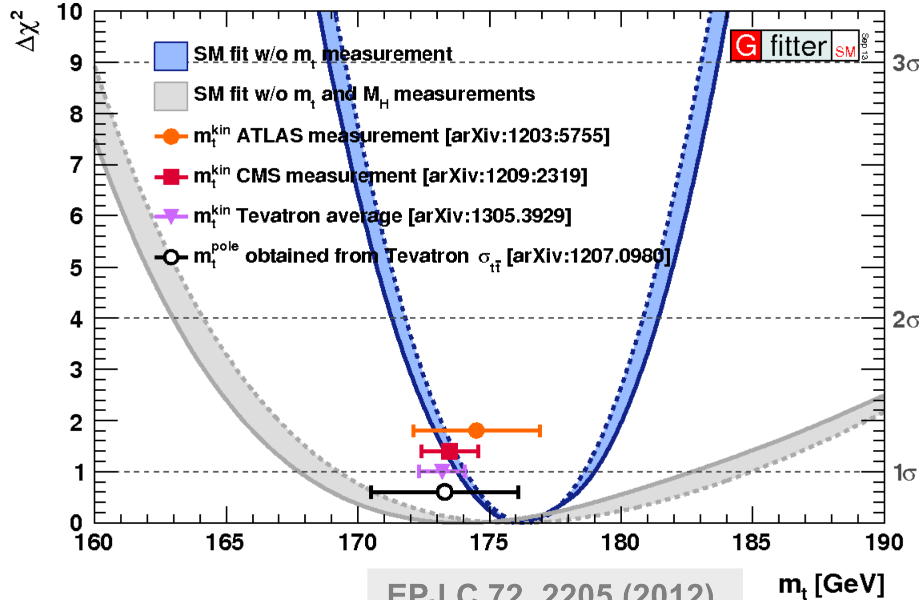
References

Channel		Ref
ATLAS	Mass & couplings	[PLB 726 (2013), pp. 88-119]
	Spin/parity	[PLB 726 (2013), pp. 120-144]
	Invisible decays	[arXiv:1402.3244, ATLAS-CONF-2014-011] New
	$H \to \gamma\gamma$ width from interferometry (projections)	[ATL-PHYS-PUB-2013-014]
CMS	$H \to WW(l\nu l\nu)$	[JHEP 01 (2014) 096] New
	$H \to ZZ(4l)$	[arXiv:1312.5353] (accepted by PRD) New
	$H \to \gamma\gamma$ spin and width	[CMS-PAS-HIG-13-016]
	Mass & couplings	[CMS-PAS-HIG-13-005]
	Invisible decays	[CMS-PAS-HIG-13-018,CMS-PAS-HIG-13-013, CMS-PAS-HIG-13-028]
	$H \to ZZ$ width from interferometry	[CMS-PAS-HIG-14-002] New

Mass

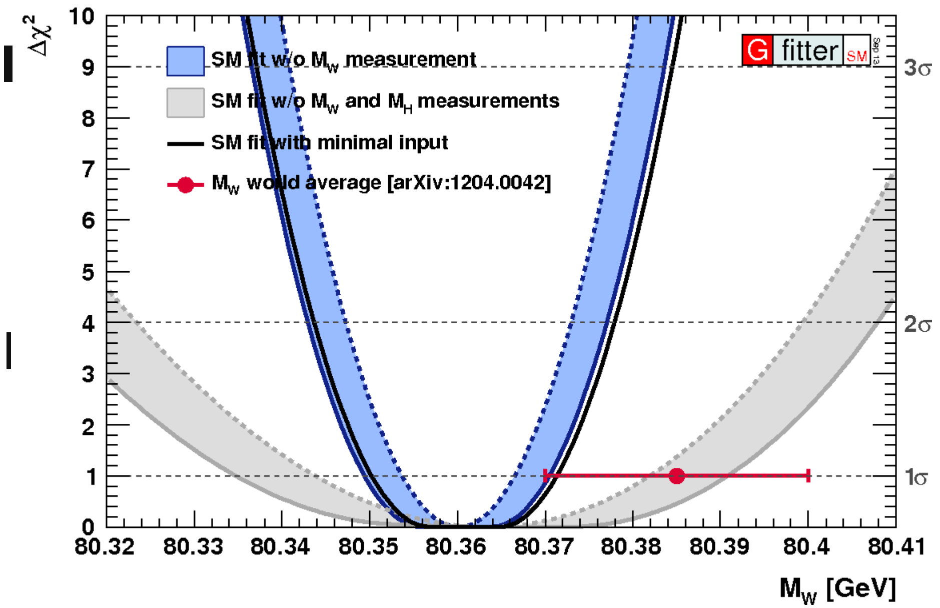
Higgs mass measurement at the LHC

- Fundamental parameter to measure.
  - Not given by theory.
  - SM predictions fully determined once the mass of the boson has been measured.
  - Over-constrain electroweak fit.



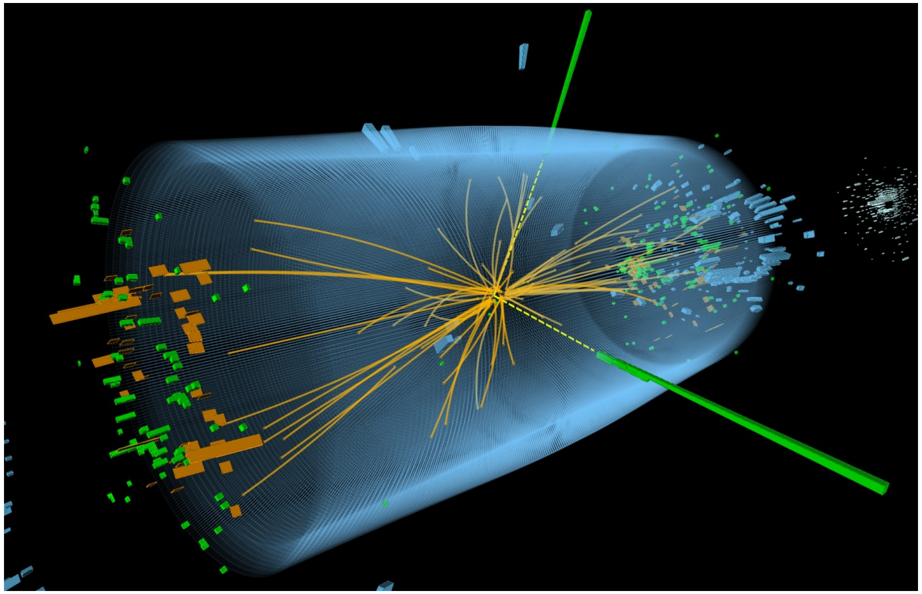
EPJ C 72, 2205 (2012)

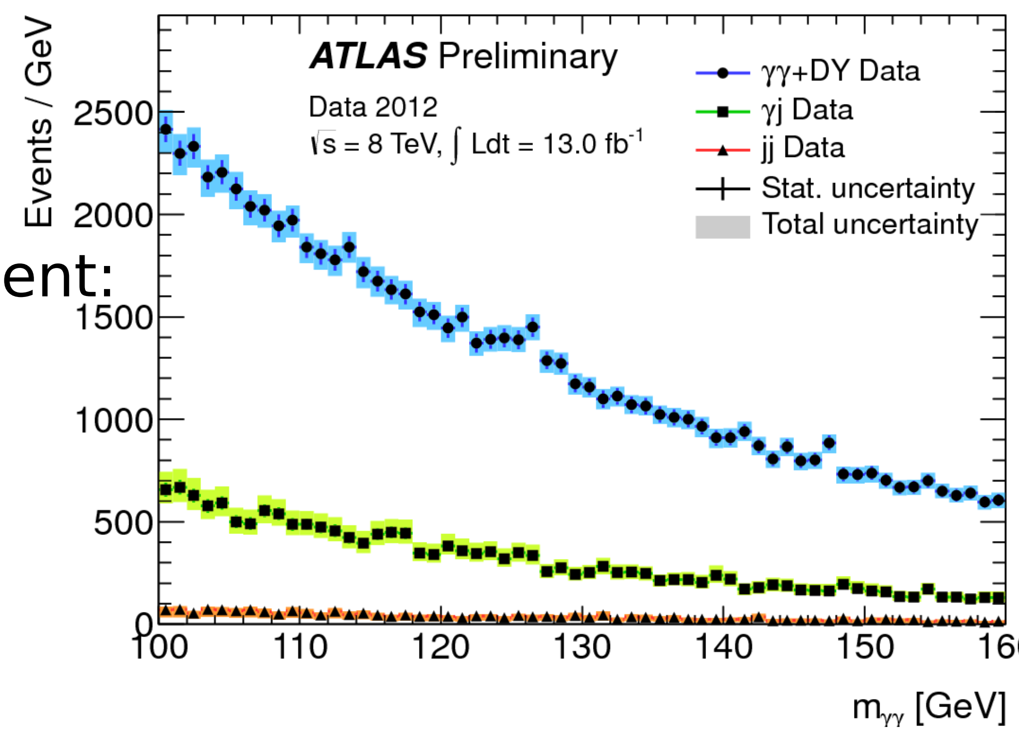
- How (well) can we measure it at the LHC?
  - Using high resolution channels: **γγ** and **4l** final states.
  - Current uncertainty ~0.3-0.4% per experiment.
  - Expect to measure it at **<0.2%** with final analysis of **Run 1** data.
  - The **first precision measurement** of the properties of the new boson.



Di-photon decay channel

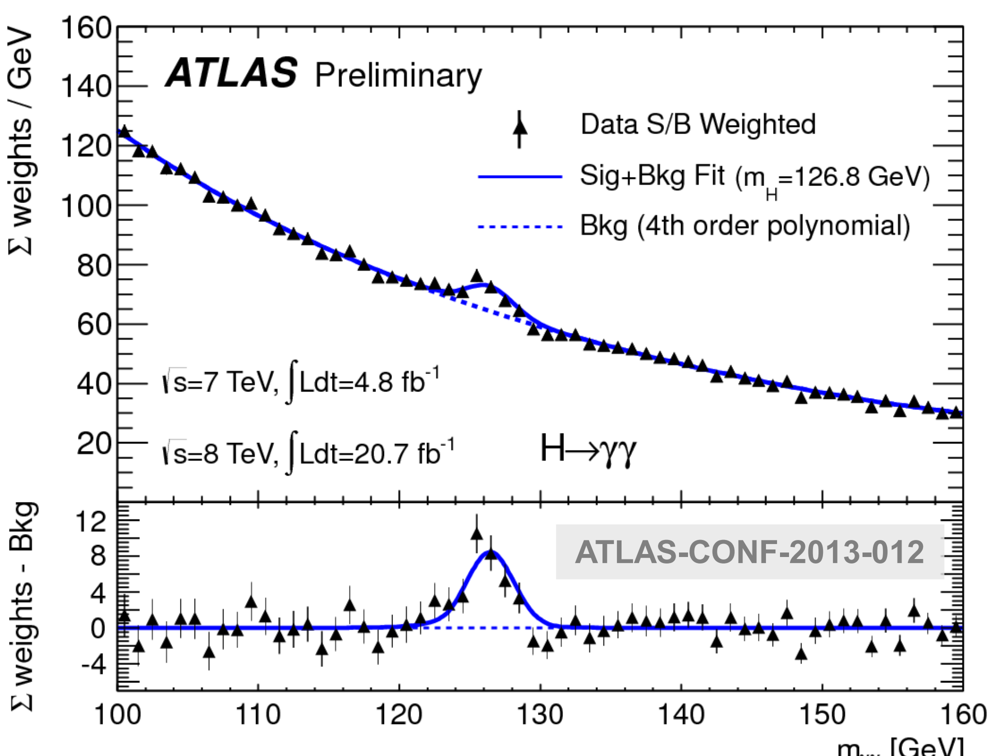
- Clean signature:
  - Two isolated, high p_T photons.
- Modest branching-fraction:
  - ~0.2%.
- Excellent mass resolution:
  - 1-2%.
- Large background from QCD processes:
  - S/B ~ 1/1 ÷ 1/20
- **Challenges** for mass measurement:
  - Maintain good mass-resolution in high-pile-up environment (for both energy and angle).
  - Understand **electron/photon extrapolation** for E-scale (material, shower description, etc.).

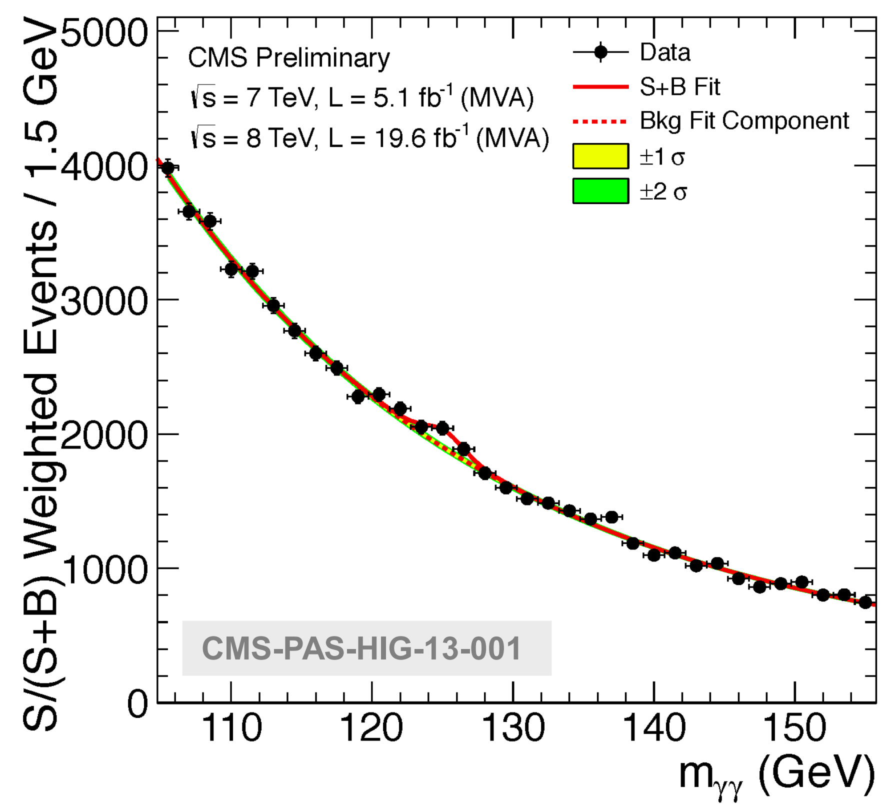




Di-photon decay channel (2)

- Similar analysis strategy for both CMS and ATLAS.
  - Events categorized according to photon resolution and kinematics.
  - Additional exclusive channels targeting VBF and associated production.
  - Signal extracted from simultaneous S+B fit to all categories.
  - Background modeled with polynomials or falling power-law or exponentials.
  - Analytic signal model accounting for data/MC corrections and associated uncertainties.





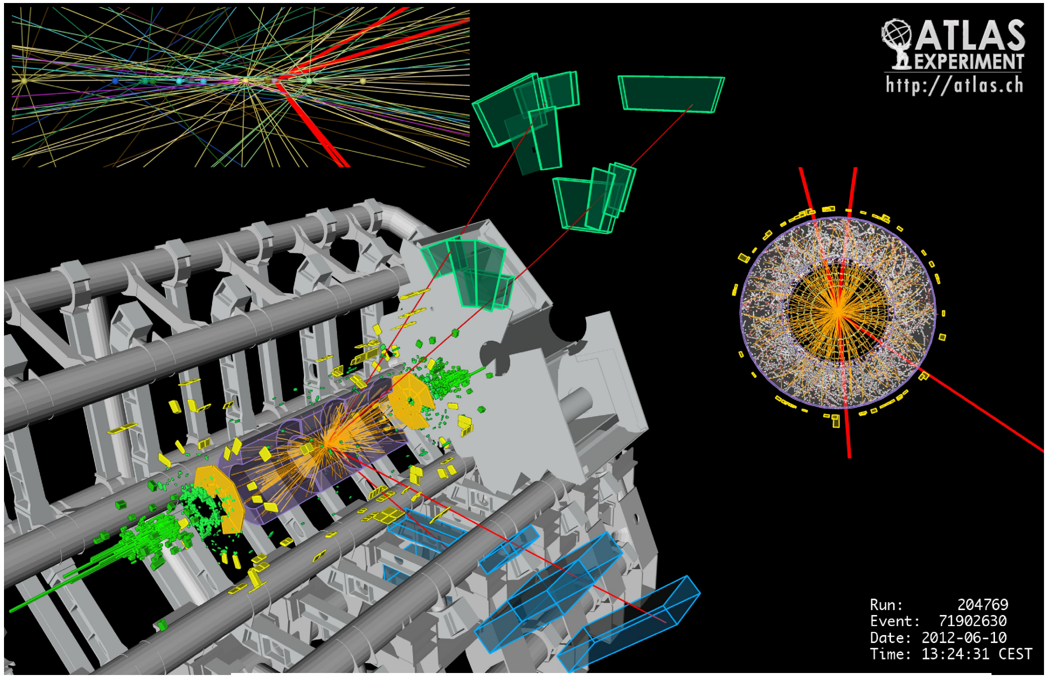
Di-photon decay channel (3)

- Energy measurement:
  - MC-based corrections:
    - ATLAS: weighted sum of energy deposits in the different calorimeter layers.
    - CMS: multi-variate regression (BDT-based) tuning energy corrections as a function of the photon cluster shape.
  - In-situ corrections:
    - Use Z → ee decays and isolated electrons from W → eν to derive E-scale adjustment for data and correct E-resolution in MC.
- Systematic uncertainty on mass scale currently ~0.5%.
  - Expected to improve considerably for legacy Run 1 results.

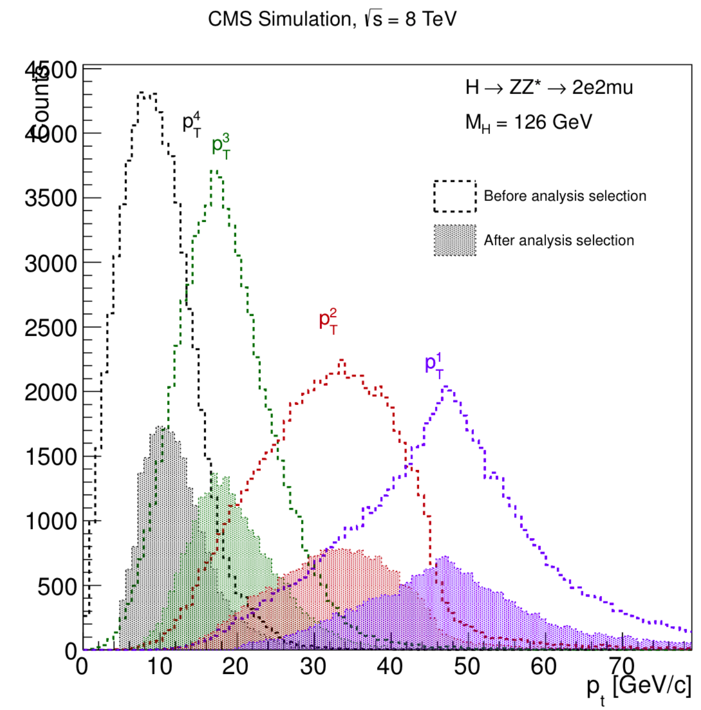
	ATLAS		CMS	
Measured mass	**126.8 +- 0.2(stat) +- 0.7(syst) GeV**		**125.4 +- 0.5(stat) +- 0.6(syst) GeV**	
Syst unc.	Z → ee E-scale	0.3%	Residual non-linearity from Z → ee to H → γγ	0.4%
	Material knowledge	0.3%	Material knowlegde	0.25%
	Pre-sampler E-scale	0.1%		
	Other	0.3%		
	Total	0.55%	Total	0.47%

ZZ(4l) decay channel

- Golden channel:
  - Four isolated leptons.
- Very small branching fraction:
  - $\sim 10^{-4}$
- Extremely pure:
  - S/B ~ 2

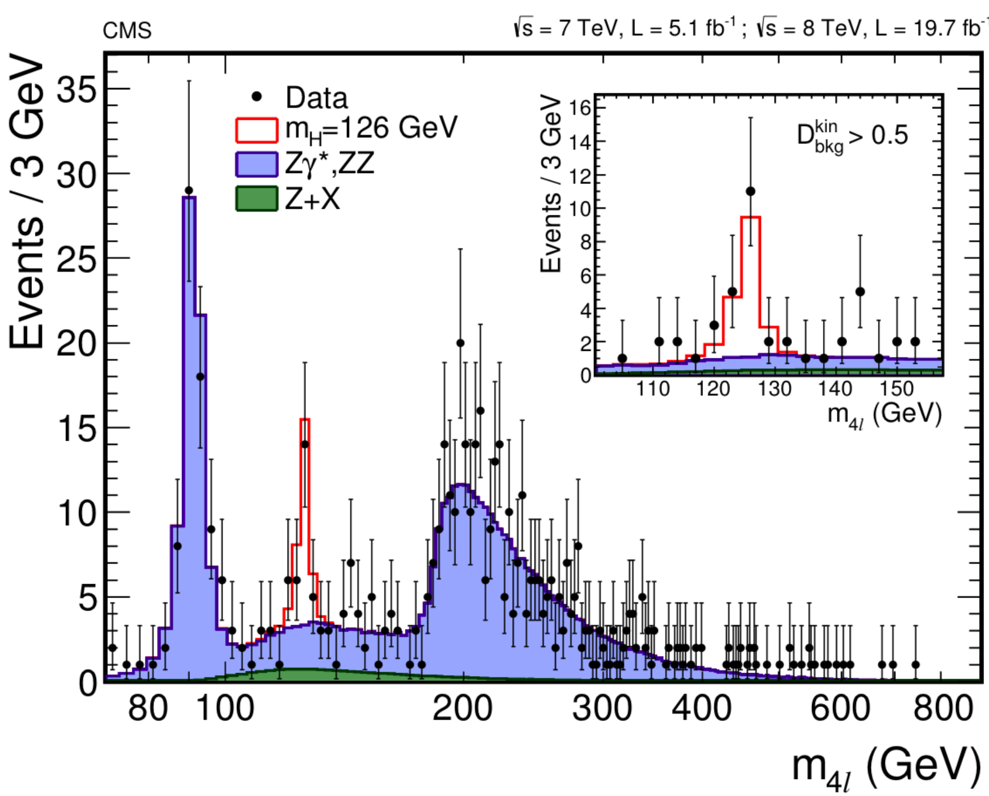


- **Challenges** for mass measurement:
  - Efficiency and resolution of low-p_T leptons
  - Energy and momentum scale linearity at **low** $\mathbf{p_T}$

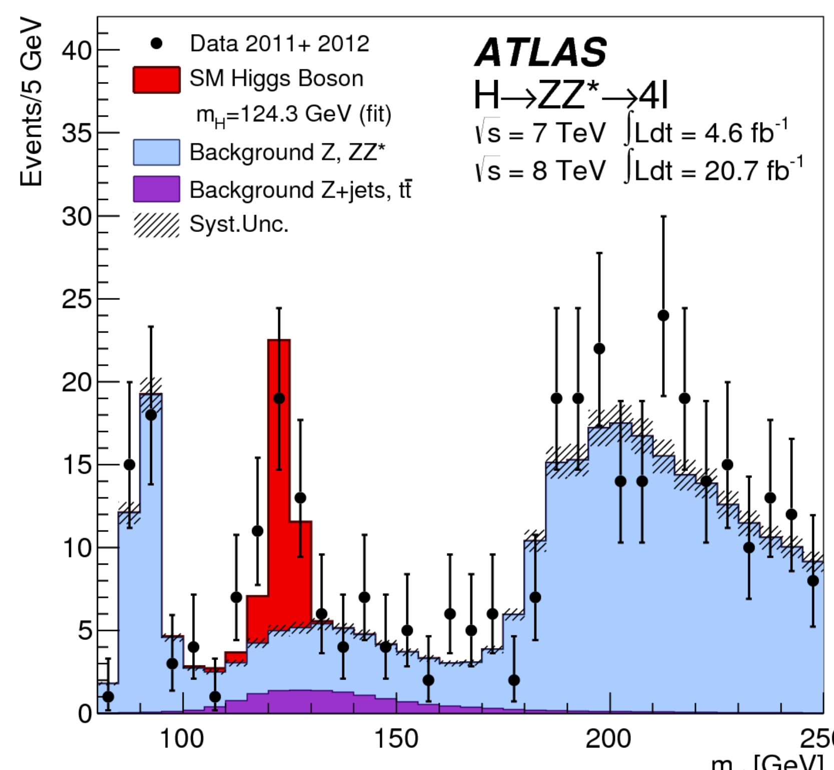


ZZ(4l) decay channel (2)

- Analysis strategy:
  - Maximize acceptance for low pT leptons
  - CMS: use m4l vs kin. Discriminant (KD) for S/B separation.
    Only lepton flavor categorization used for mass measurement.
    Use information on event-by-event mass resolution.
  - ATLAS: use m4l for S/B separation.
    Categorize events into VBF-like, VH-like and untagged.



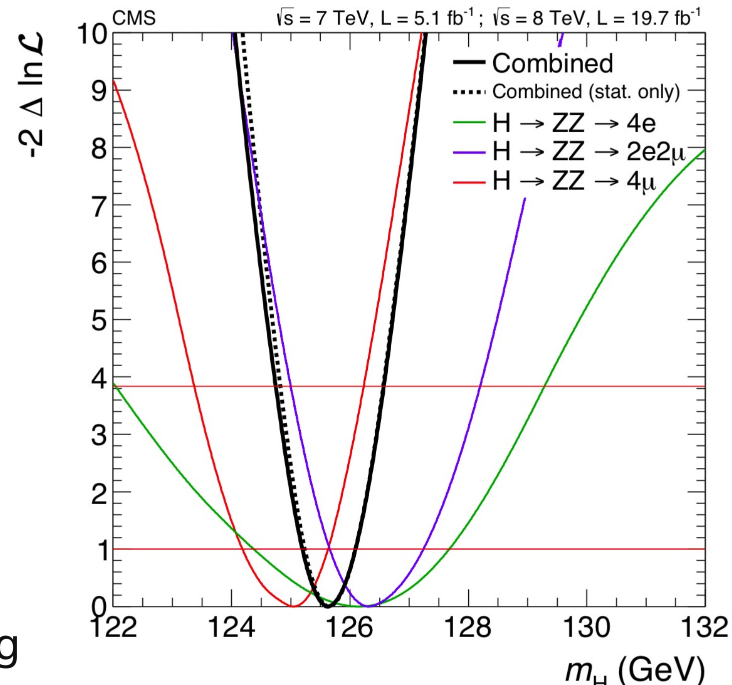
arXiv:1312.5353

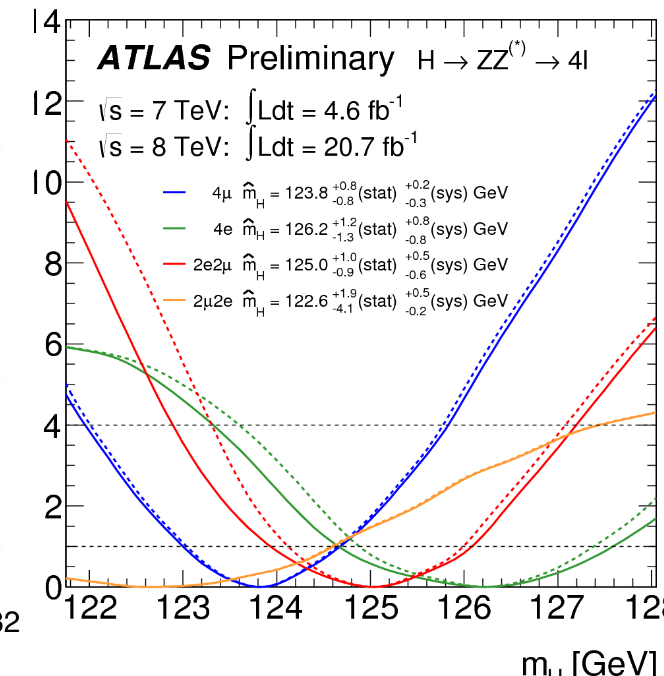


PLB 726 (2013), 88-119

ZZ(4l) decay channel (3)

- Electron energy corrections.
  - MC driven correction using multivariate regression (CMS) or weighted sum of energy deposits.
  - Data/MC corrections derived on Z → ee and checked with Z → ee and low-mass resonances.
- Muon momentum scale corrections.
  - Data/MC corrections from Z → μμ + check w/ low-mass resonances.
- Mass fit:
  - CMS: 3D fit to m_{4l}, KD and σ_{m4l}/m
  - ATLAS: 1D fit to m_{4l}. Using kinematic constraint to Z_1 canditate.

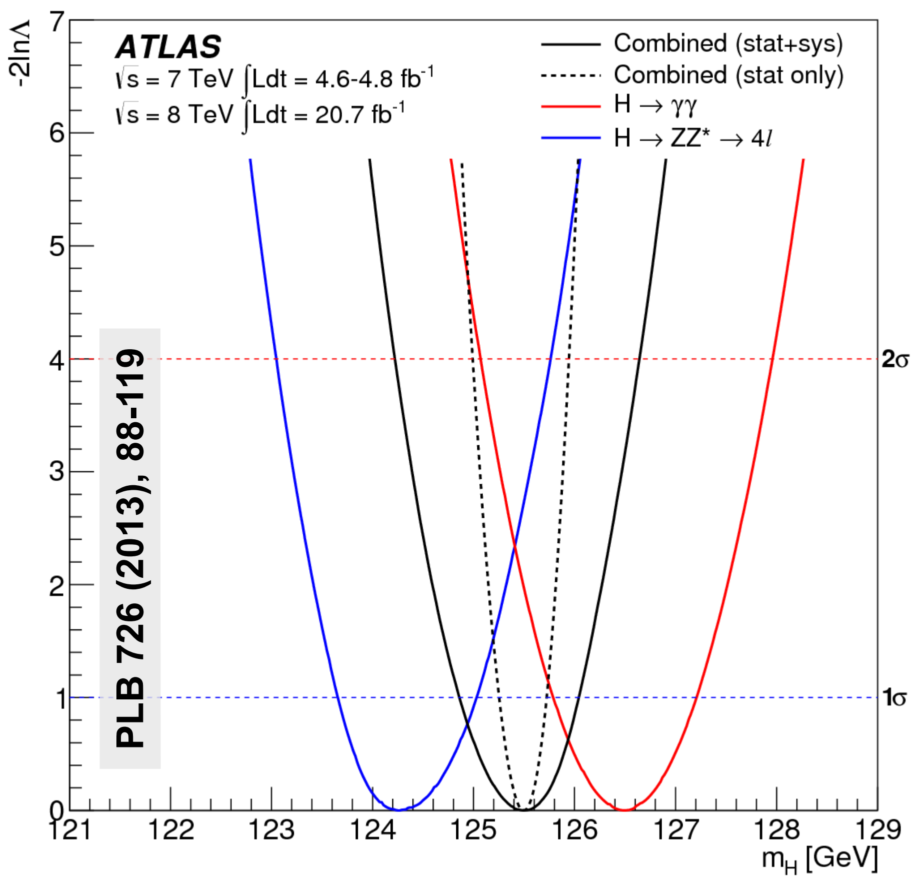


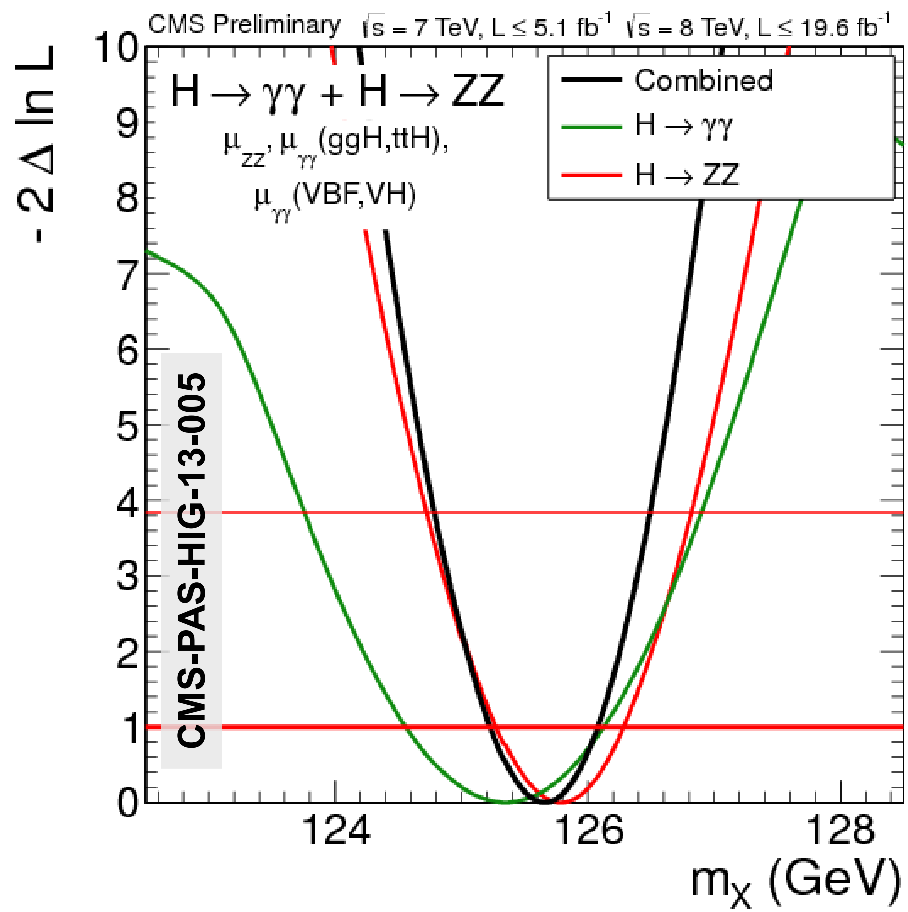


	ATLAS	PLB 726 (2013), 88-119	CMS	arXiv:1312.5353 New
Measured mass	**$124.3\ ^{+0.6}_{-0.5}$(stat) $^{+0.5}_{-0.3}$(syst) GeV**		**125.6 +- 0.4(stat) +- 0.2(syst) GeV**	
Syst unc.	Electron e/p-scale	0.2%-0.4%	Electron e/p-scale	0.1-0.3%
	Muon p-scale	0.1%-0.2%	Muon p-scale	0.1%

Combination

- Measurements obtained in the di-photon and four-lepton channels can be combined (under the hypothesis that the same state decays in both modes).





ATLAS	CMS (new ZZ(4l) not used)
125.5 +-0.2 (stat) $^{+0.5}_{-0.6}$(syst) GeV	125.7 +- 0.3(stat) +- 0.3(syst) GeV

Expected Run 1 precision

- Rough combination of available measurements yields a **total** uncertainty of **0.25%**

- Precision still expected to improve.
  - CMS di-photon channel still preliminary.
  - ATLAS measurement expected to be updated.
  - Both experiment will use updated calibrations and improved understanding of energy/momentum scale uncertainties.

- LHC **combination** expected to take place **later this year**.
  - **Ultimate** Run 1 precision expected to be **below 0.2%**.
  - Stay tuned!

Spin/parity

Spin/parity of the new boson

- Clear prediction of the Standard Model: Higgs boson is a 0^+ state.
  - Very important to test such basic prediction experimentally.

- Most general form of spin-(1)2 state scattering amplitude has large number of free parameters.
  - We are not really *measuring* the spin of the new boson yet.
  - Rather **testing** alternative **hypotheses**.

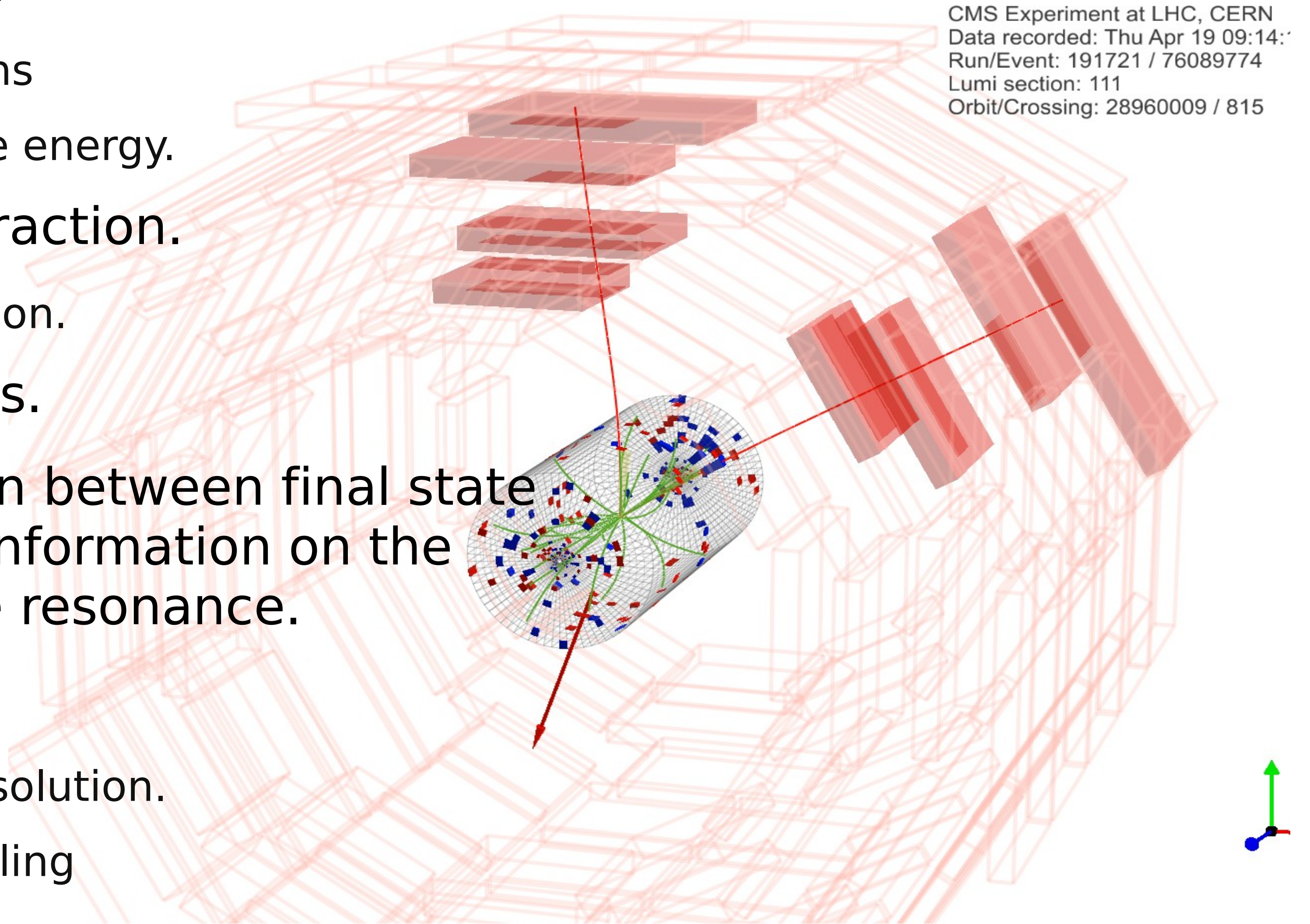
- Test statistics:

$$q=-2\ln\frac{L\left(B+\widehat{\mu_{SM}}\,S_{SM};\widehat{\theta_{SM}}\right)}{L\left(B+\widehat{\mu_{ALT}}\,S_{ALT};\widehat{\theta_{ALT}}\right)}$$

- Most sensitive channels.
  - $H \rightarrow ZZ(4l)$
  - $H \rightarrow WW(2l2\nu)$
  - $H \rightarrow \gamma\gamma$

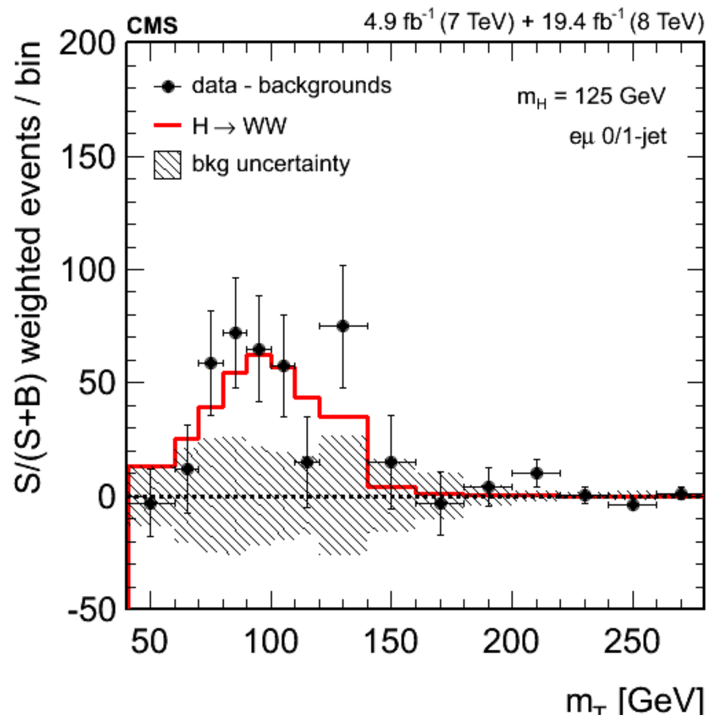
WW(2l2ν) decay channel

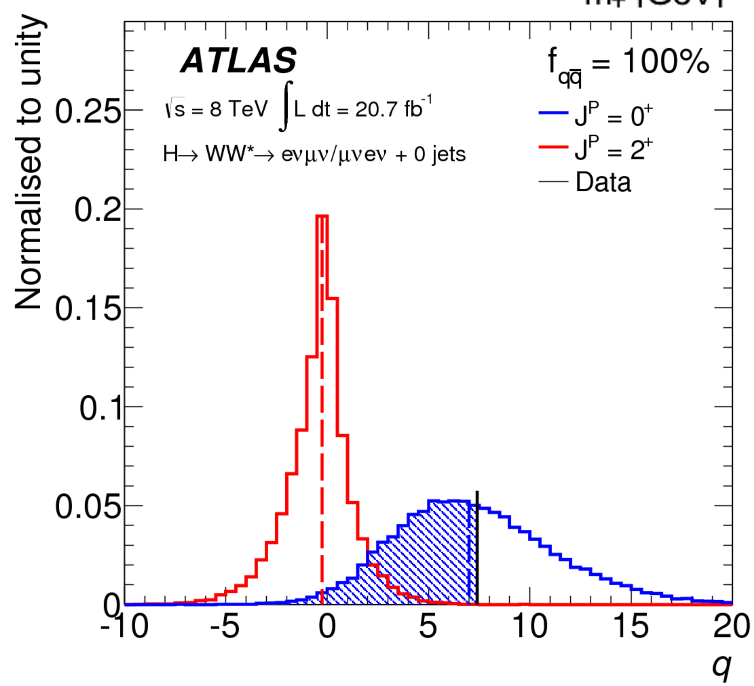
- Distinct signature:
  - Two high pT leptons
  - Missing transverse energy.
- Large branching fraction.
  - Poor mass resolution.
- Large backgrounds.
- Angular correlation between final state leptons provides information on the polarization of the resonance.
- **Challenges**:
  - Missing energy resolution.
  - Background modeling



WW(2l2ν) decay channel (2)

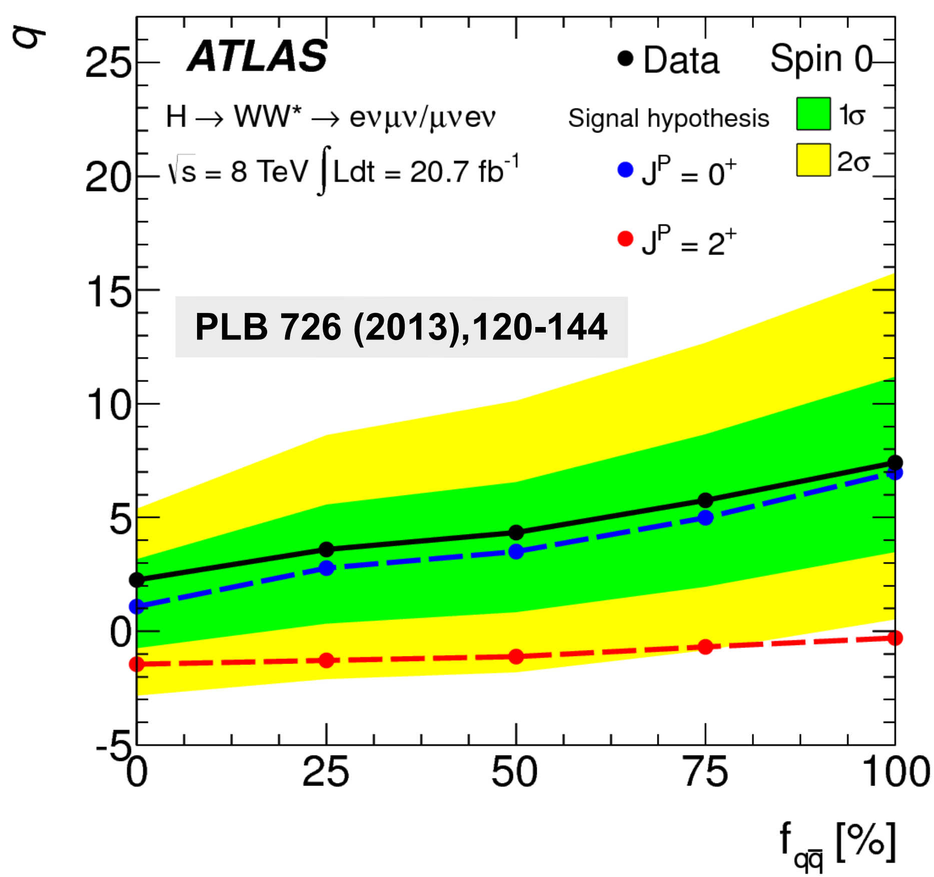
- Analysis strategy:
  - Select two high p_T, different flavor leptons plus missing E_T.
  - CMS: categorize events in 0,1jet bins
  - ATLAS: no categorization in number of jets.
- Hypothesis test from 2D template fit to data:
  - CMS: m_{ll} vs m_T
  - ATLAS: use two BDT discriminants ($\Delta\phi_{ll}$, m_{ll}, m_T)
    BDT0 (discriminate SM from background)
    BDTalt (discriminate alternative hyp from background).
- Tested alternative models:
  - CMS: 2^+_m “graviton-like” and 0^-.
  - ATLAS: 2^+_m “graviton-like”.
  - For 2^+_m model both qq, gg production modes (and mixtures) are considered.

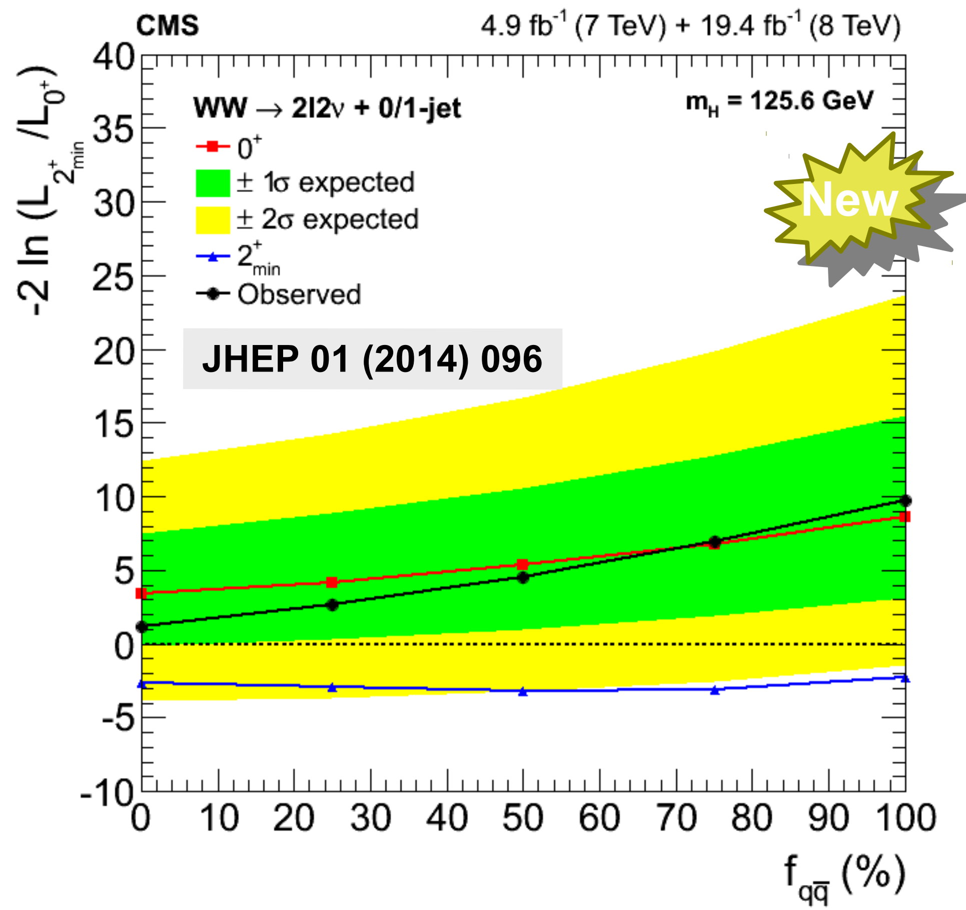




WW(2l2ν) decay channel (3)

- Expected (post-fit) exclusion for 2^+_m model 1-CLs > 0.94.
  - In CMS, 0^- expected (post-fit) exclusion 1-CLs = 0.72.
- Observed results favor SM hypothesis.





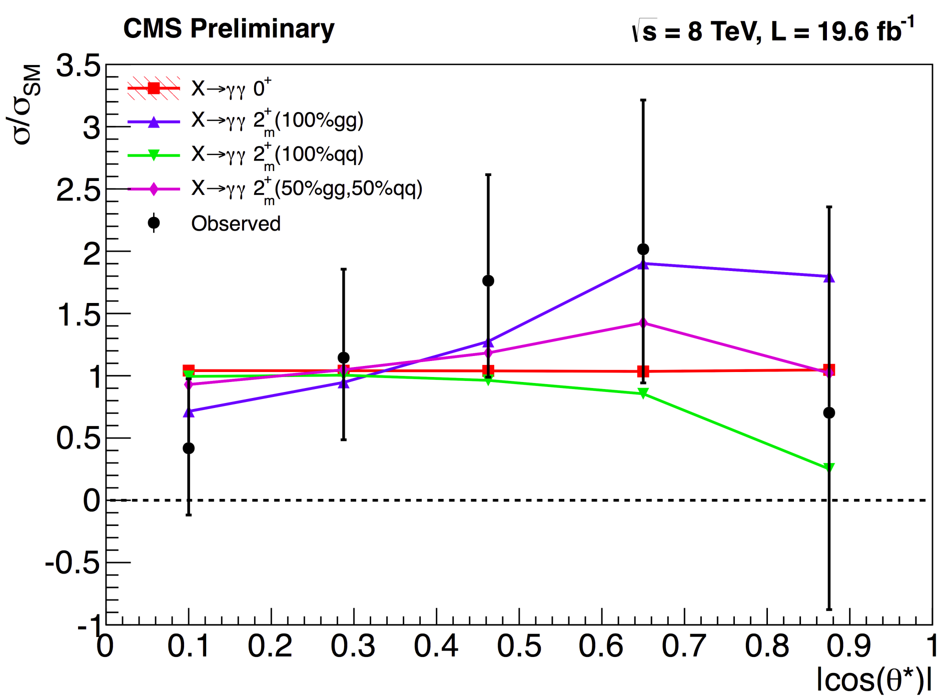
Di-photon channel

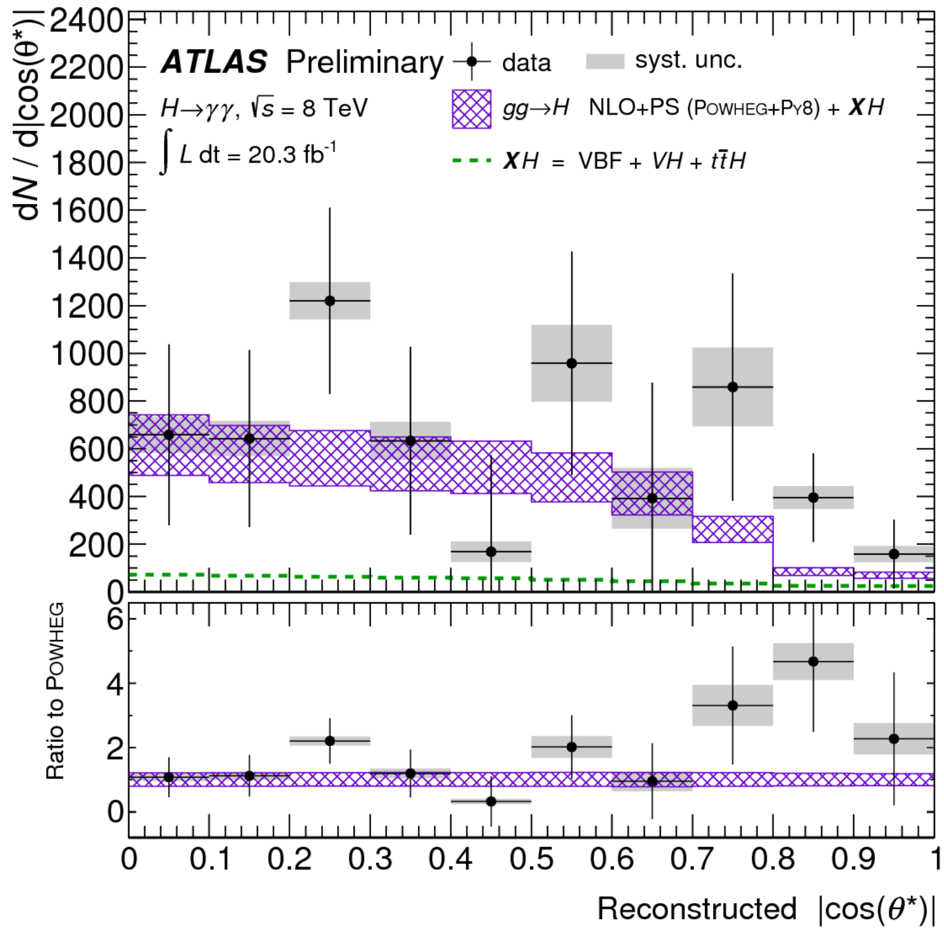
- Distribution of production angle sensitive to spin/parity.

  Event selection similar to mass analysis.

$$\cos(\theta^*) = 2\frac{E_2 p_{z1} - E_1 p_{z2}}{m_{\gamma\gamma}\sqrt{m_{\gamma\gamma}^2 + p_{T\gamma\gamma}^2}}$$

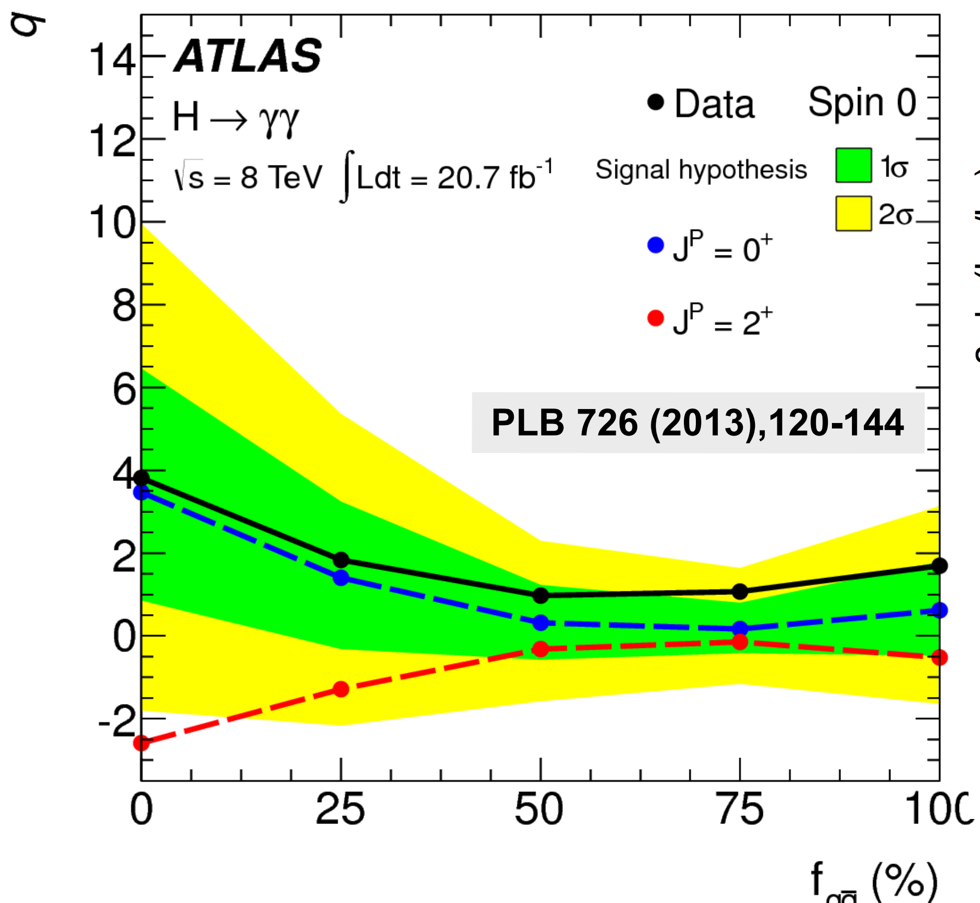
  - ATLAS: no categorization in photon kin. or resolution
  - CMS: simple 4 categories cut-based categorization
- Hypotesis test:
  - ATLAS: 2D fit of $\cos(\theta^*)$ vs $m_{\gamma\gamma}$
  - CMS: simultaneous fit to $m_{\gamma\gamma}$ in 5 $\cos(\theta^*)$ bins

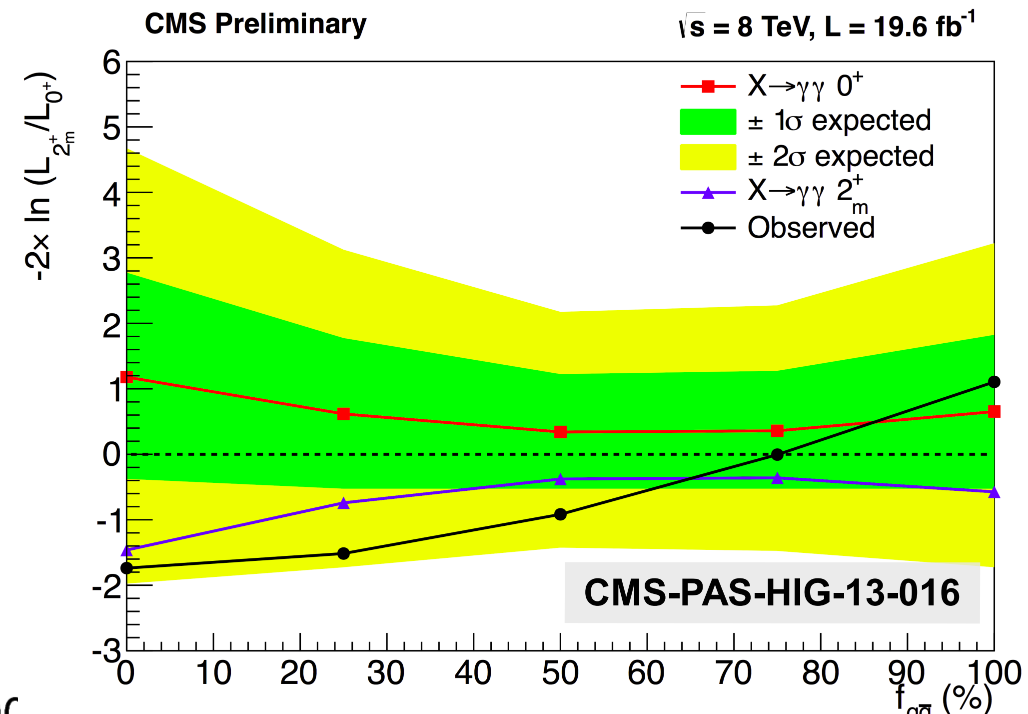




Di-photon channel (2)

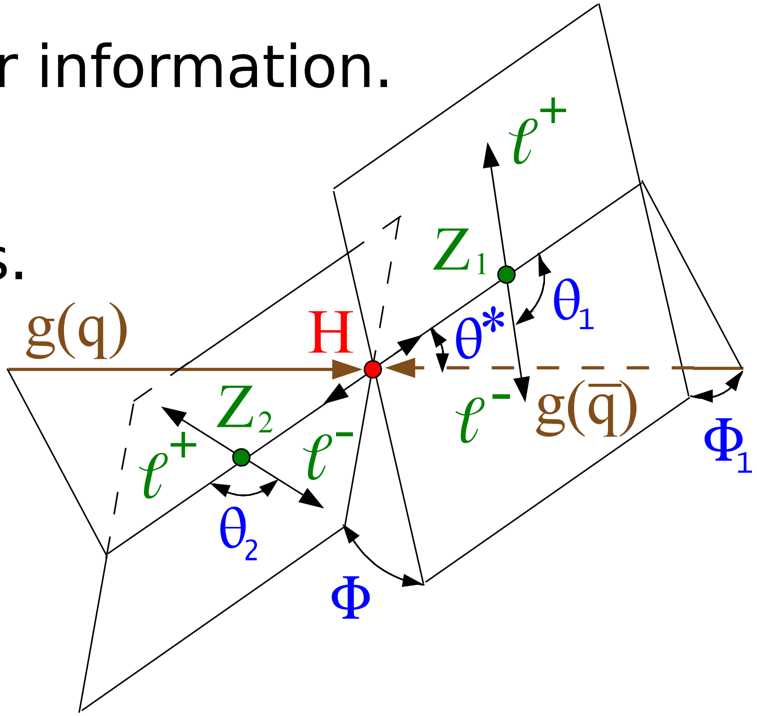
- (Post-fit) Expected separation: 1-CLs > 17(55)-60(99)% for CMS (ATLAS).
  - Better sensitivity for ATLAS analysis partially driven by higher observed excess.
- SM hypothesis generally favored in data.





ZZ(4l) decay mode

- Extremely rich channel in terms of angular information.
  - Best suited to study spin and parity.
- Same event selection as for mass analysis.



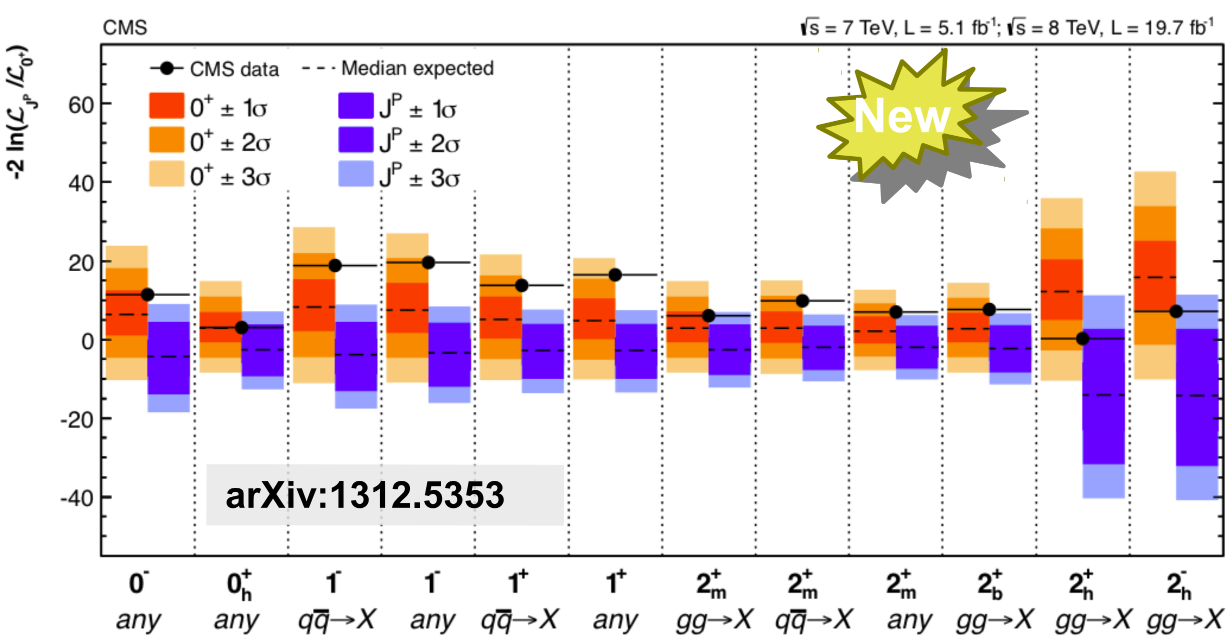
- Spin/parity hypotheses separated using angular correlation between leptons.
  - CMS: build ME kinematic discriminant for SM vs ALT hypotesis.
  - ATLAS: use BDT based discriminant.

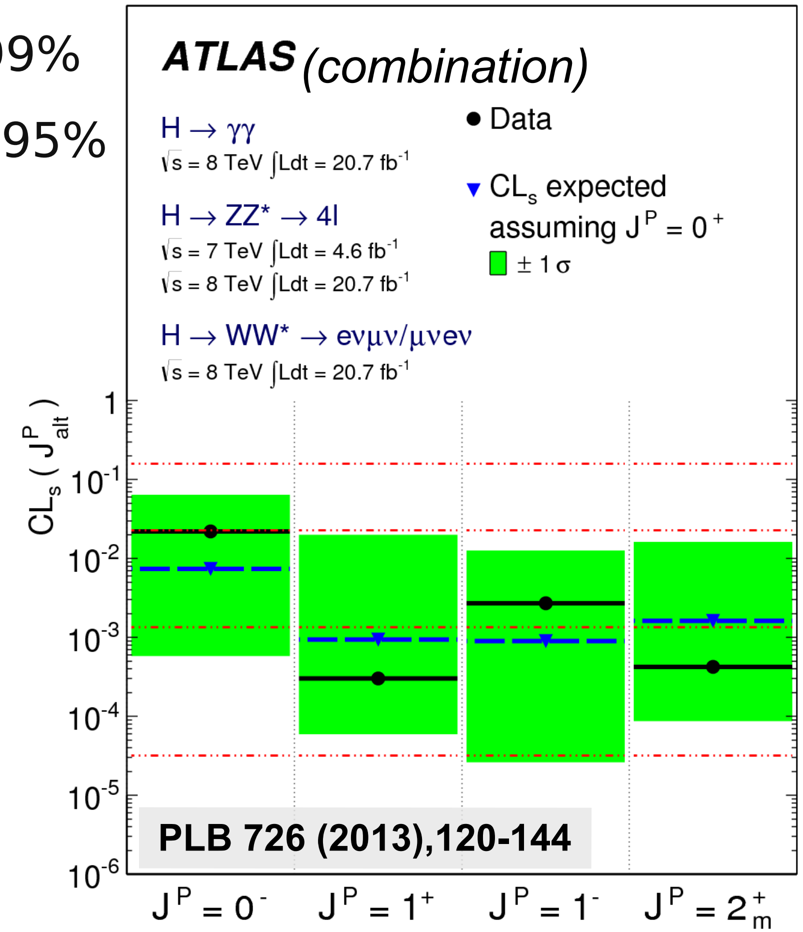
$$\mathcal{D}_{J^P} = \left[1 + \frac{\mathcal{P}^{\mathrm{kin}}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}{\mathcal{P}^{\mathrm{kin}}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})} \right]^{-1}$$

- Hypothesis test:
  - CMS: 2D fit of superKD(m_{4l}xKD) vs KD(J^P)
  - ATLAS: template fit of BDT score distribution.

ZZ(4l) decay mode

- CMS: 8 alternative JCP hypotheses tested, for spin 0,1 and 2, including **production-independent analysis**.
- ATLAS: 4 alternative JCP hypoteses tested for spin 0,1 and 2, considering qq, gg initiated productions (and mixtures).
- Data favors SM hypothesis.
  - Tested spin-1 and O^- excluded with 1-CLs>0.99%
  - Tested Spin-2 models excluded with 1-CLs>0.95%





Beyonds hypothesis tests

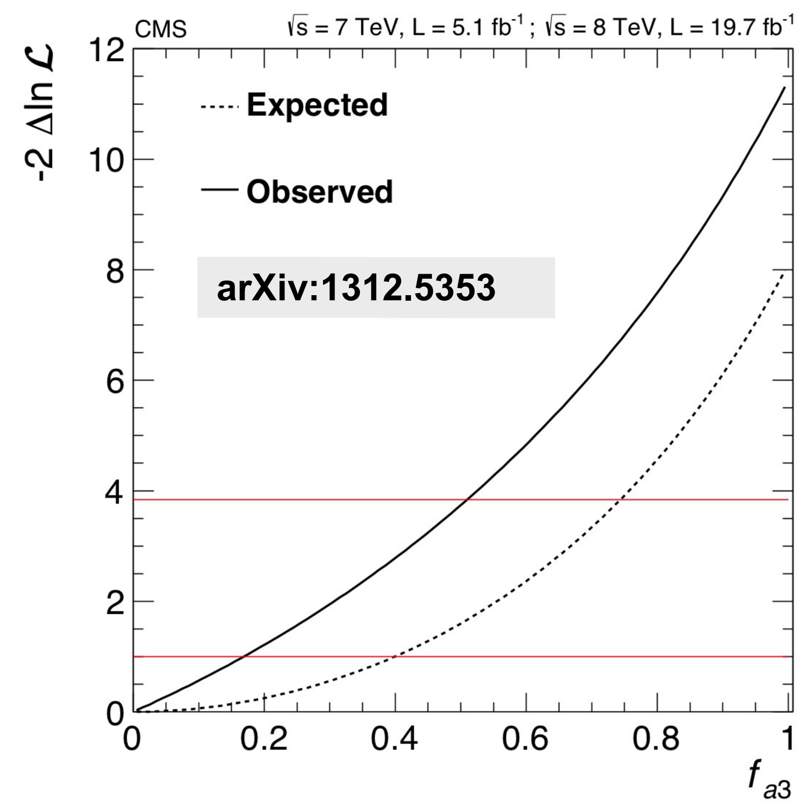
- Natural evolution of spin/parity studies will be towards constraining anomalous coupling parameters in the Higgs sector.
- First such example, in the CMS ZZ(4l) analysis.

$$A(\mathrm{H} \to \mathrm{ZZ}) = v^{-1}\left(\underbrace{a_1 m_Z^2 \epsilon_1^* \epsilon_2^*}_{\text{SM}} + \underbrace{a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{aCP even}} + \underbrace{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{aCP odd}}\right)$$

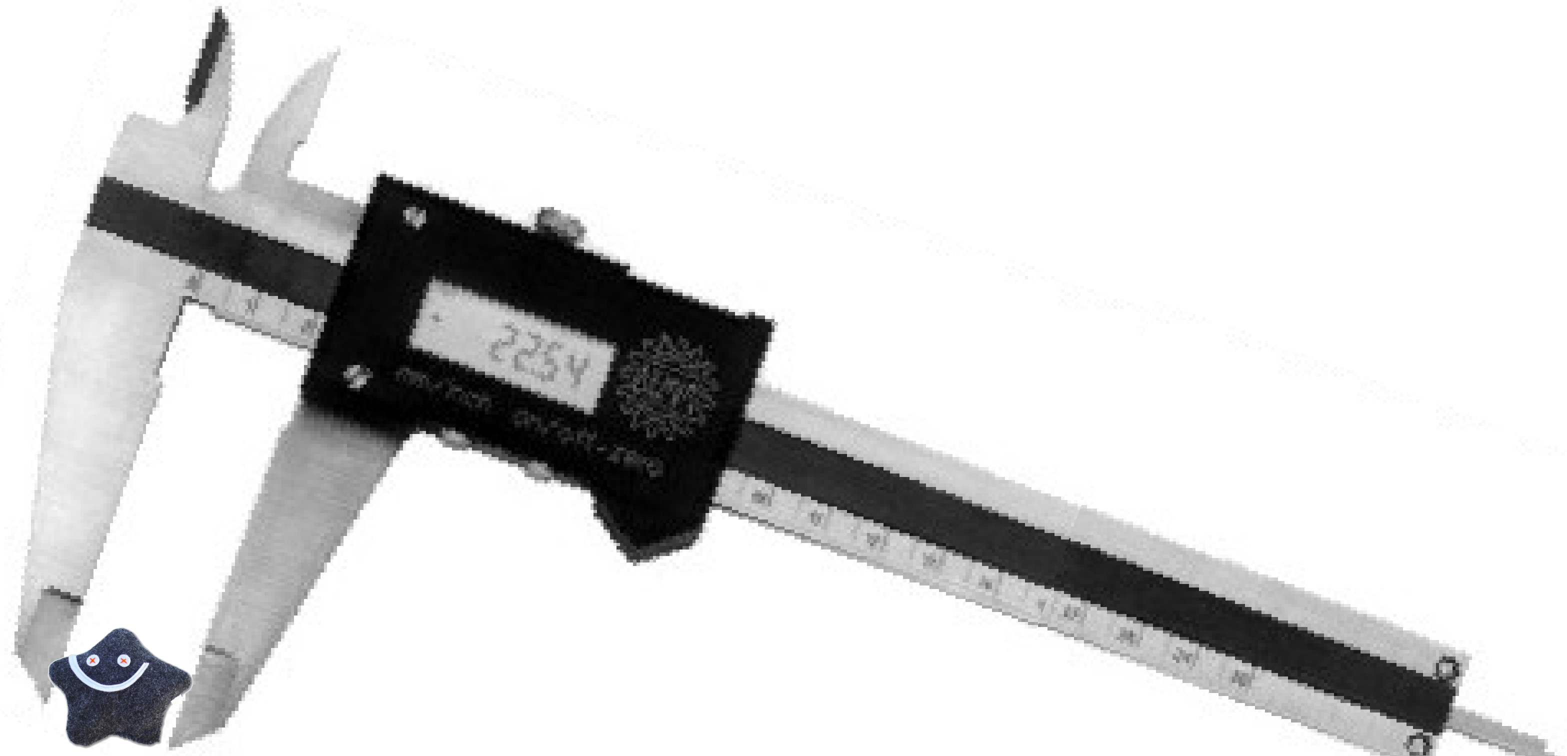
- Effective CP odd fraction extracted from data, re-parameterizing the likelihood fit used in the 0+ vs 0- test as a function of:

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3}$$

- Observed(expected) 95% C.L. Bound: $f_{a3} < 0.5(0.7)$.

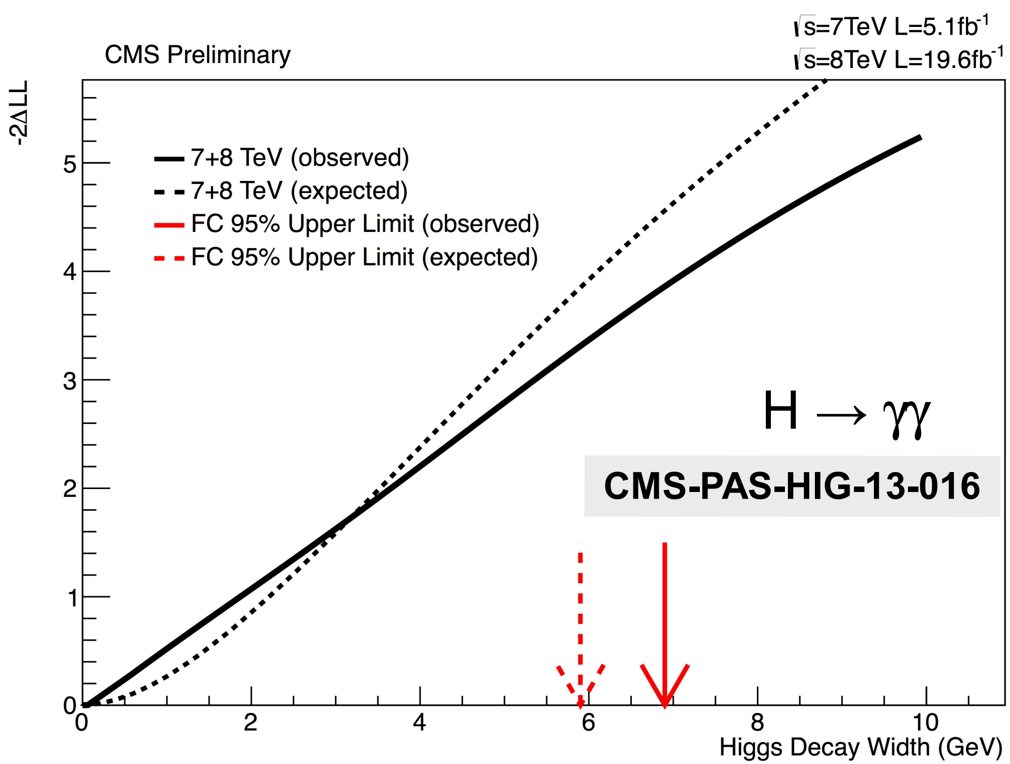


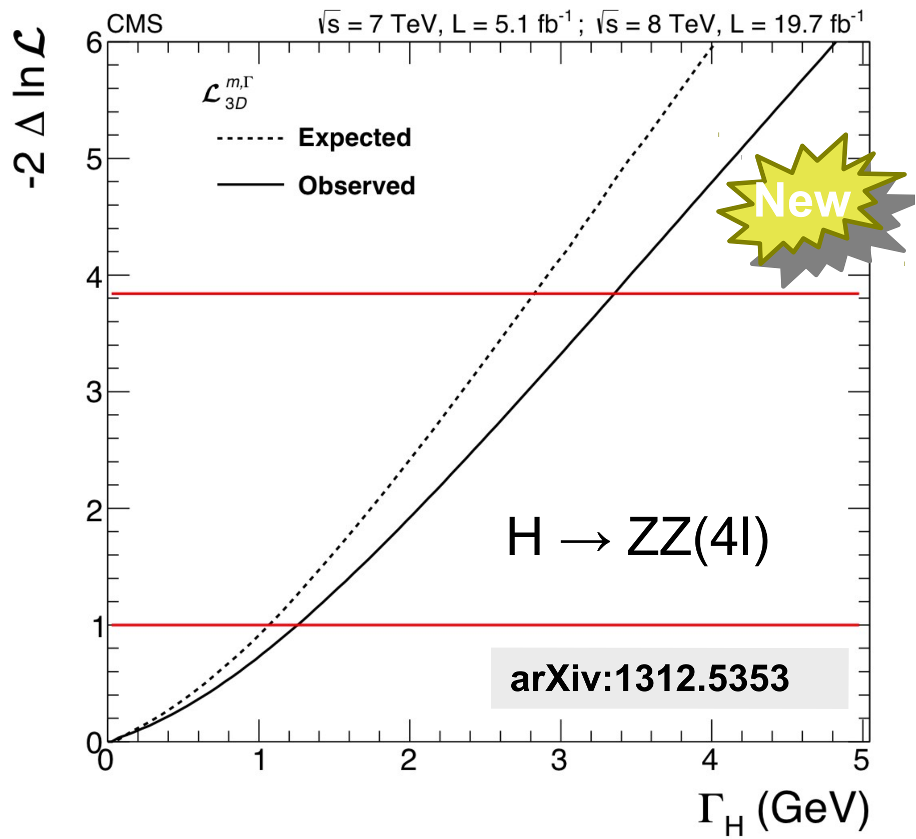
Width



Direct constraint on the Higgs boson width

- Standard model prediction: $\Gamma_H \sim 4$MeV.
  - Direct measurement heavily limited by experimental resolution.
  - Current upper limits 3.4(7)GeV from 4l($\gamma\gamma$) decay modes.





Interferometry - ZZ(4l,2l2ν)

New

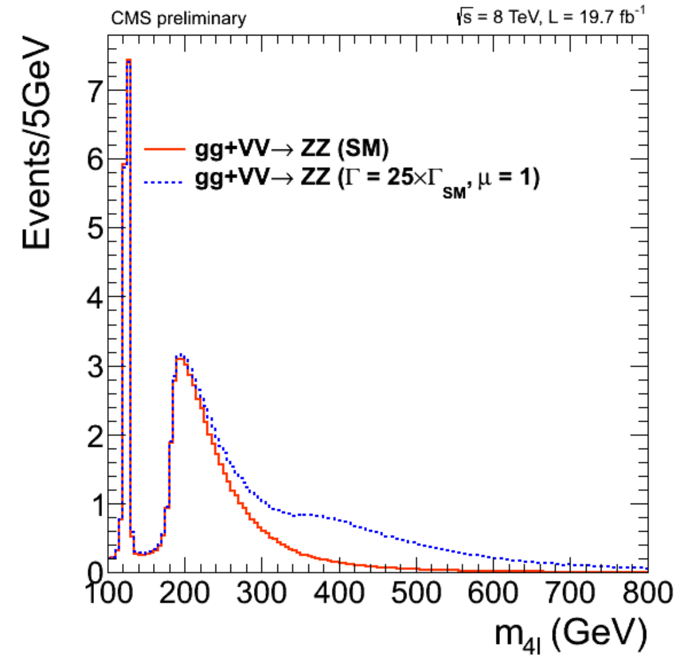
- Constraint on total width can come from measurement of H* contribution to high mass pp → ZZ production.

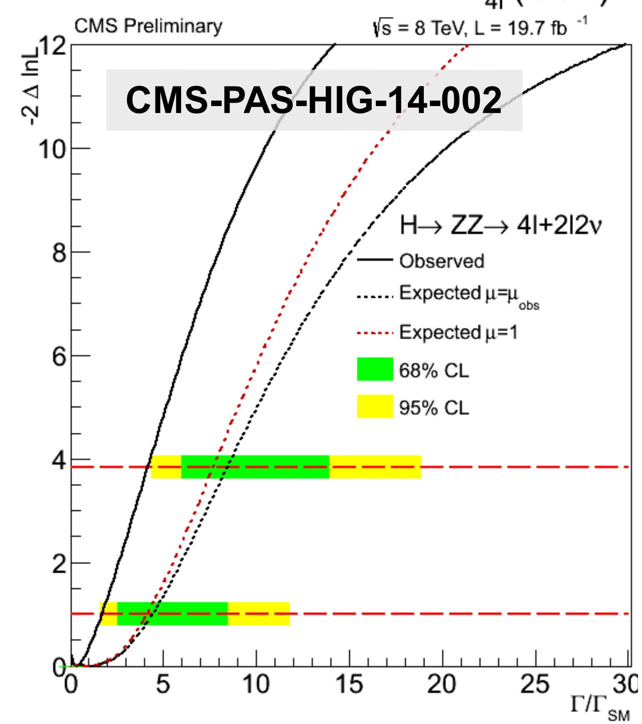
$$\sigma^{\mathrm{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot \mathrm{BR})_{\mathrm{SM}} \equiv \mu(\sigma\cdot \mathrm{BR})_{\mathrm{SM}}$$

$$\frac{d\sigma^{\mathrm{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

- Challenge: understand (destructive) interference with gg → ZZ continuum
  - Combine 4l and 2l2n decay channels.
  - **Observed (expected)** 95%CL limits: **Γ < 8.5(4.2) x Γ_{SM}**.
- See R. Covarelli talk for details.

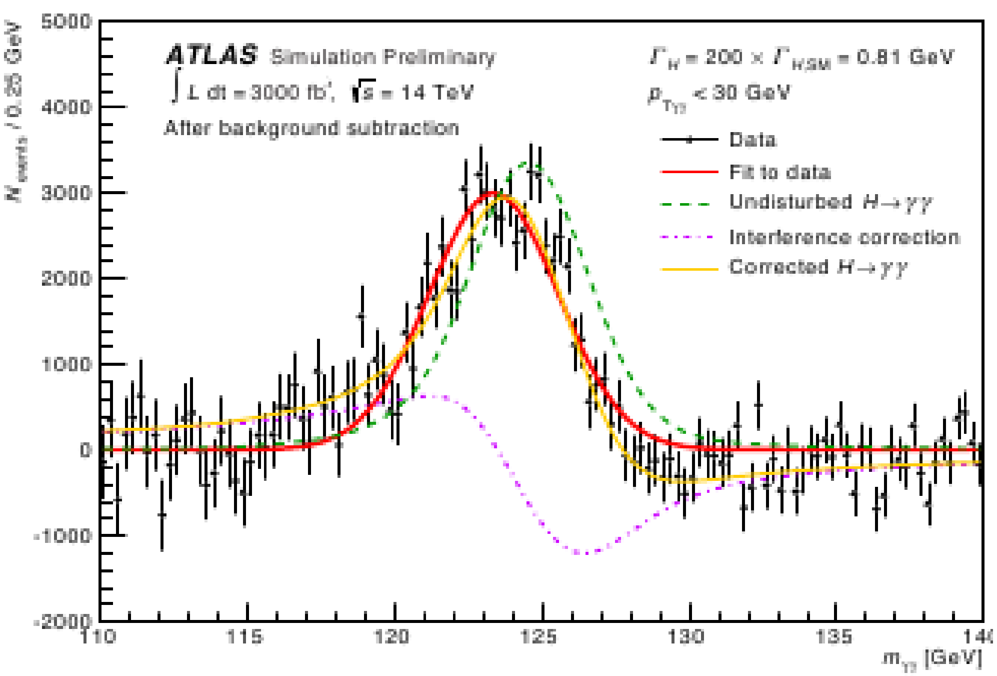
	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H (MeV)	27.4	26.6	17.4

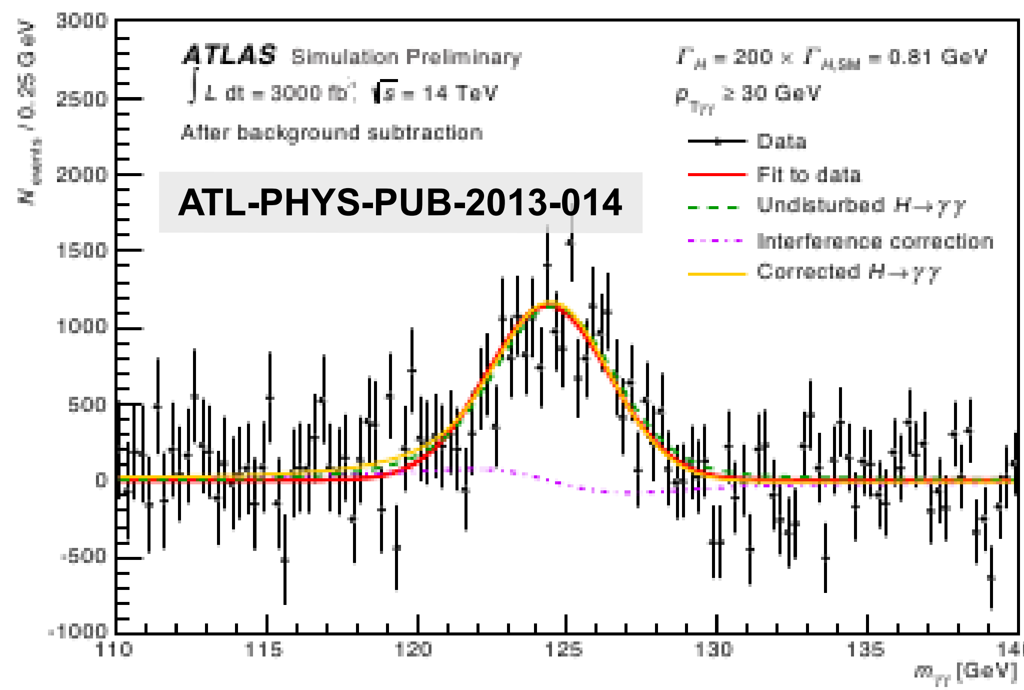




Interferometry - di-photon

- Can also exploit destructive interference between gg → γγ and gg → H → γγ.
  - Generate effective mass shift, which magnitude varies as a function of the boson p_T.
  - Constraint of the width from measurement of m_H vs p_{TH}.
  - Projected sensitivity for $3ab^{-1}$ $\Gamma < 30\ \Gamma_{SM}$ (95% CL).

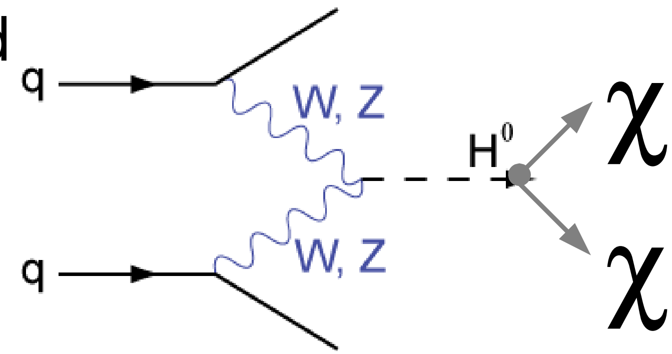




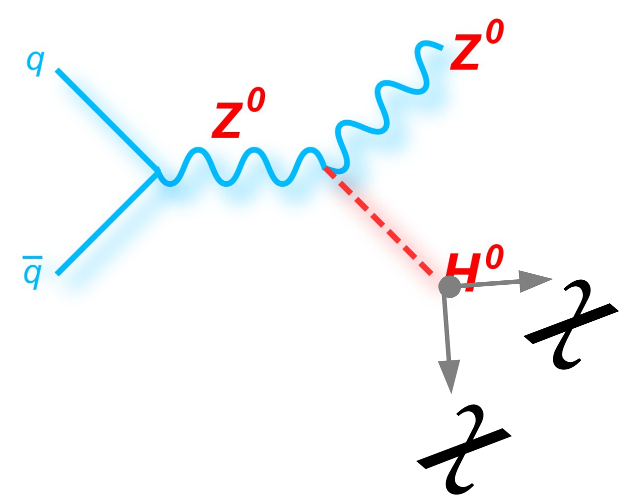
Invisible decays

Search for invisible decays of the Higgs boson

- While all properties of Higgs boson measured so far agree with SM expectation, still quite some room for exotic decay modes.



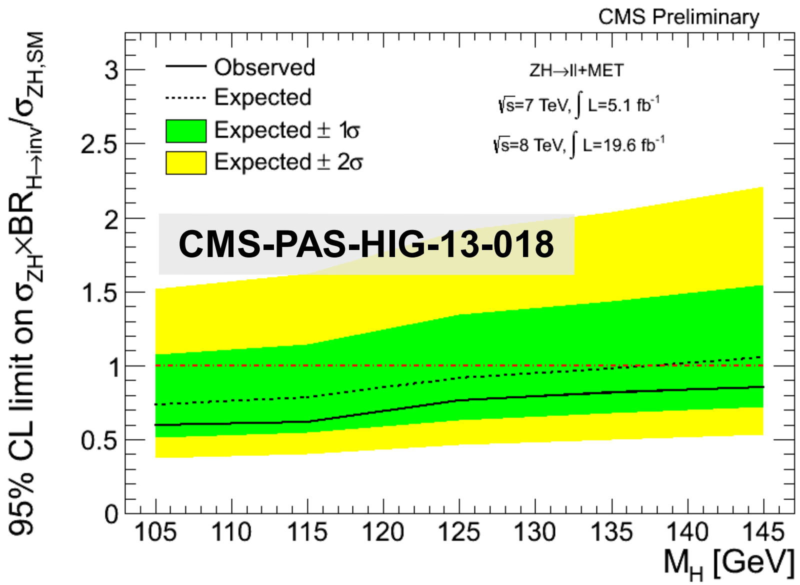
- Can look for decays of Higgs boson to weekly interacting particles using VBF and ZH production.
  - Complementary to direct searches for dark matter.

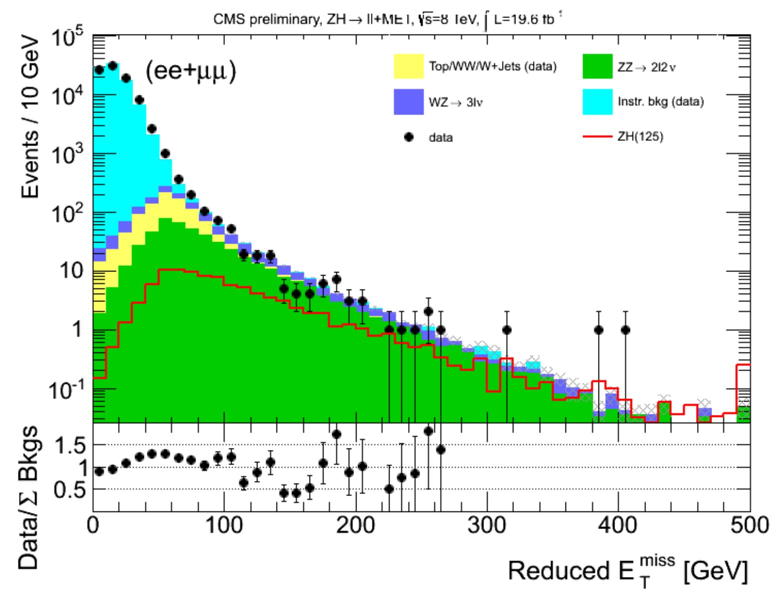


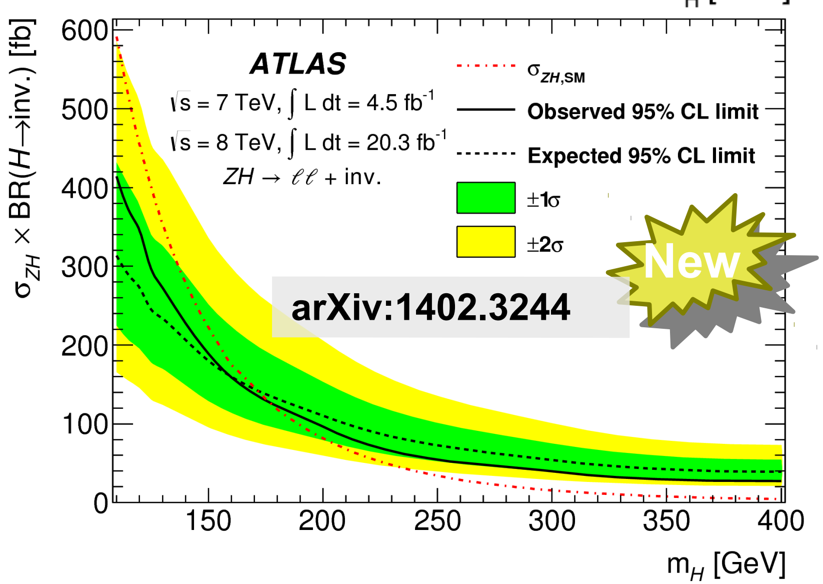
- Exploited channels:
  - ATLAS: Z(ll) + MET
  - CMS: Z(ll,bb) + MET, VBF + MET

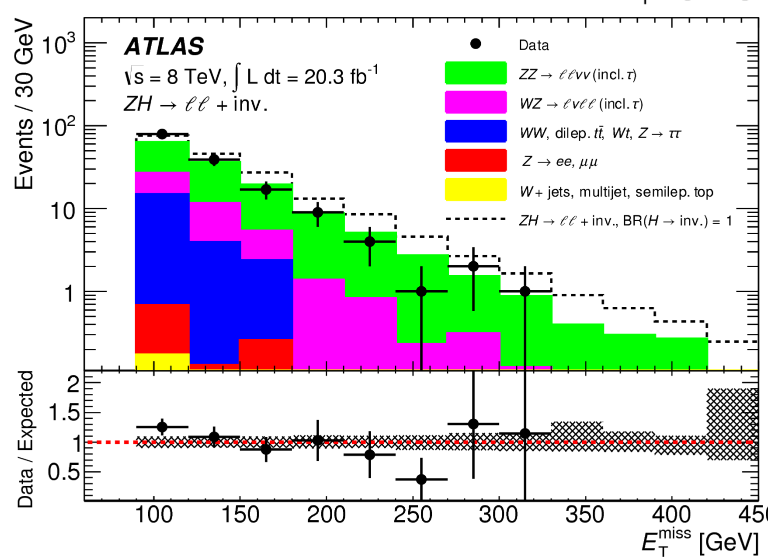
Z + MET channel

- Expected sensitivity to σ x BR / σ_{SM} < 0.6 (ATLAS) 0.75(CMS) 95%CLs.
- Observed limit σ x BR / σ_{SM} < 0.75.





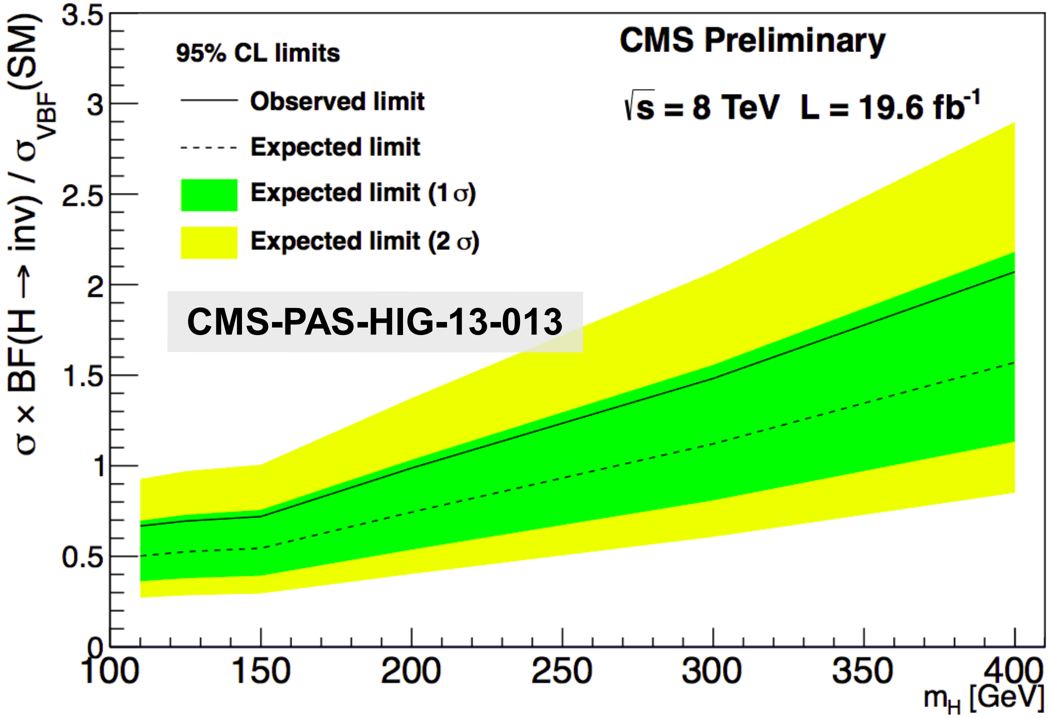




VBF + MET channel

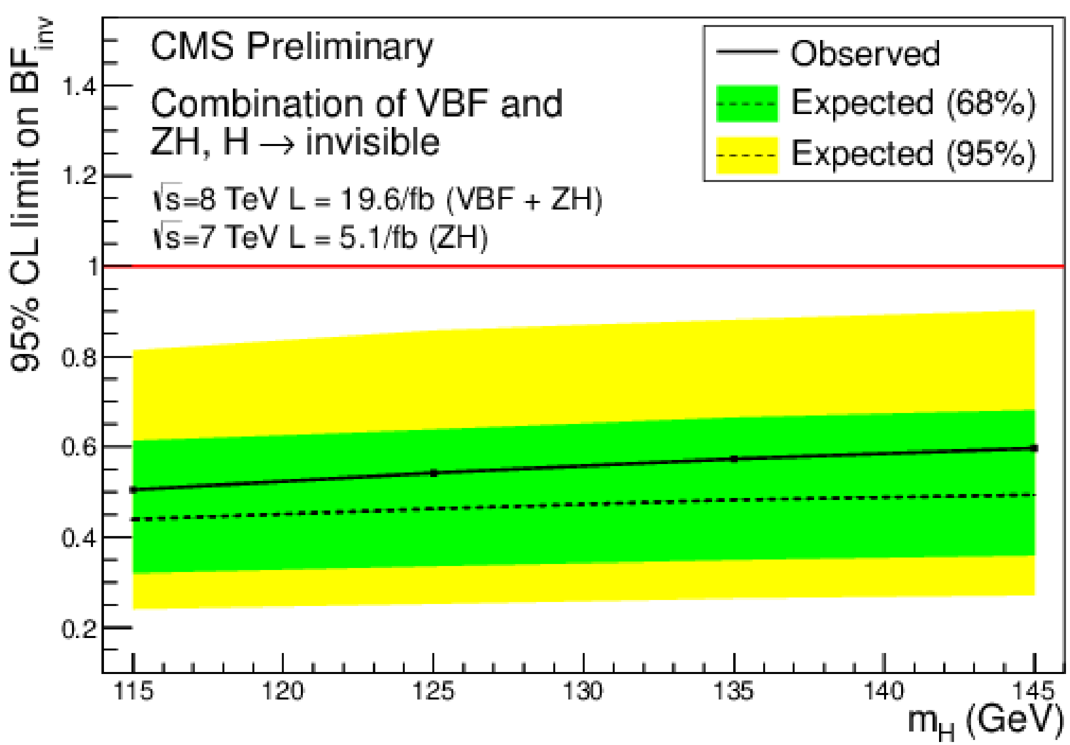
- Expected (observed) sensitivity on σ x BR / σ_{SM} < 0.5(0.7) 95%CLs

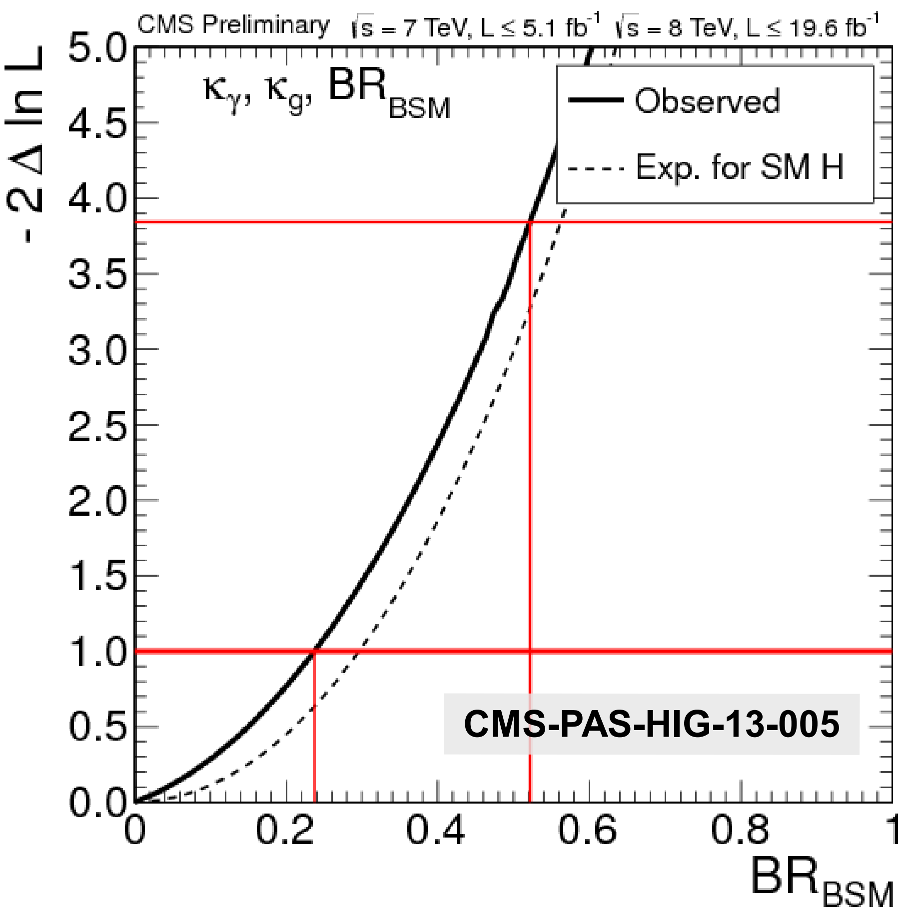
Background	N_{est}
$Z \to \nu\nu$	$102 \pm 30\,(\text{stat.}) \pm 26\,(\text{syst.})$
$W \to \mu\nu$	$67.2 \pm 5.0\,(\text{stat.}) \pm 15.1\,(\text{syst.})$
$W \to rmev$	$68.2 \pm 9.2\,(\text{stat.}) \pm 18.1\,(\text{syst.})$
$W \to \tau\nu$	$54 \pm 16\,(\text{stat.}) \pm 18\,(\text{syst.})$
QCD multijet	$36.8 \pm 5.6\,(\text{stat.}) \pm 30.6\,(\text{syst.})$
Other SM	$10.4 \pm 3.1\,(\text{syst.})$
Total background	$339 \pm 36\,(\text{stat.}) \pm 50\,(\text{syst.})$
Observed	390



Direct vs indirect constraint

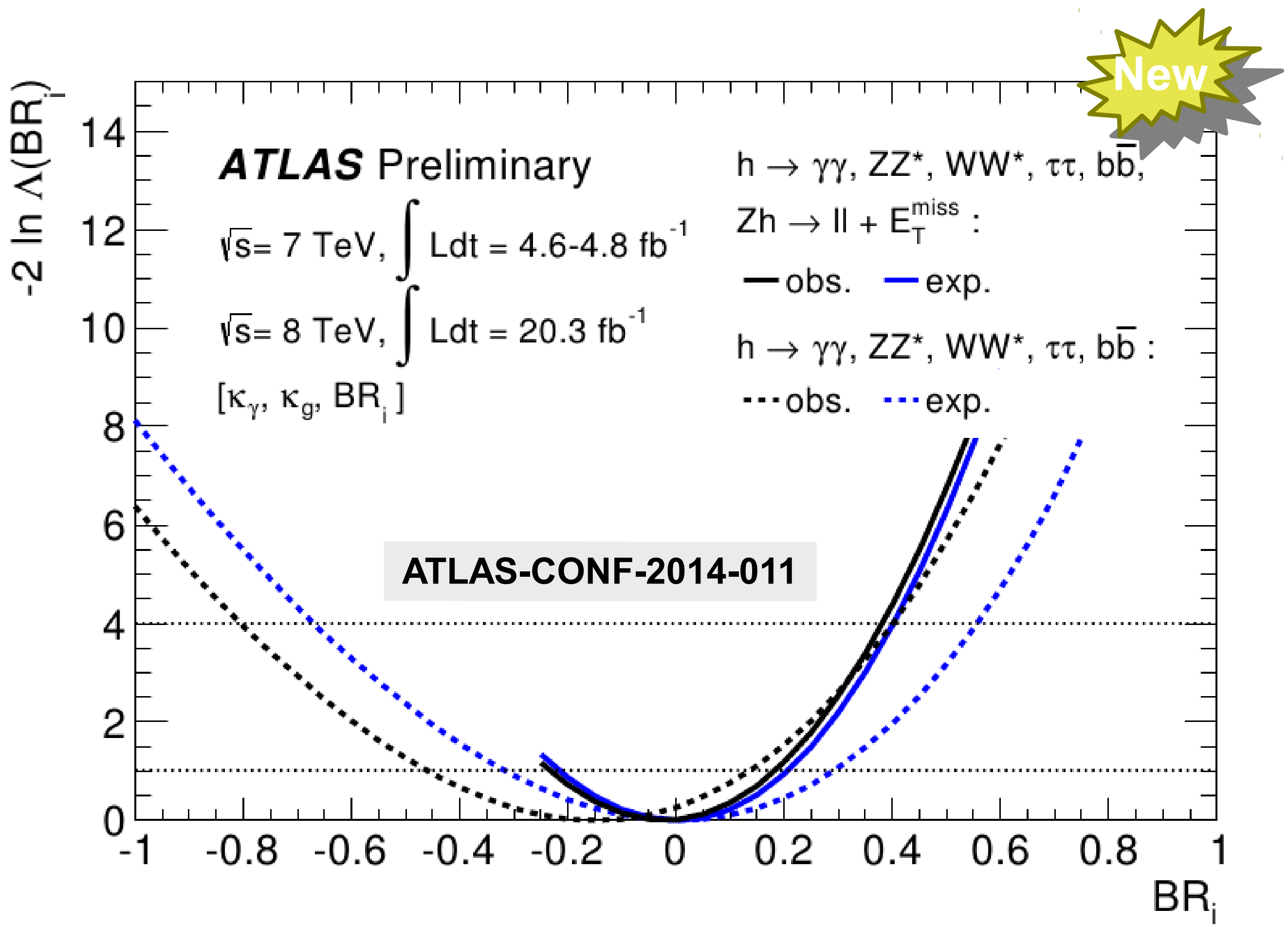
- Indirect constraint on BR_{inv} can also be obtained from global fit of measured decay modes.
  - Fixing unmeasured modes to SM predictions and assuming k_V<1.
- Direct and indirect limits have comparable magnitudes.





... and combination

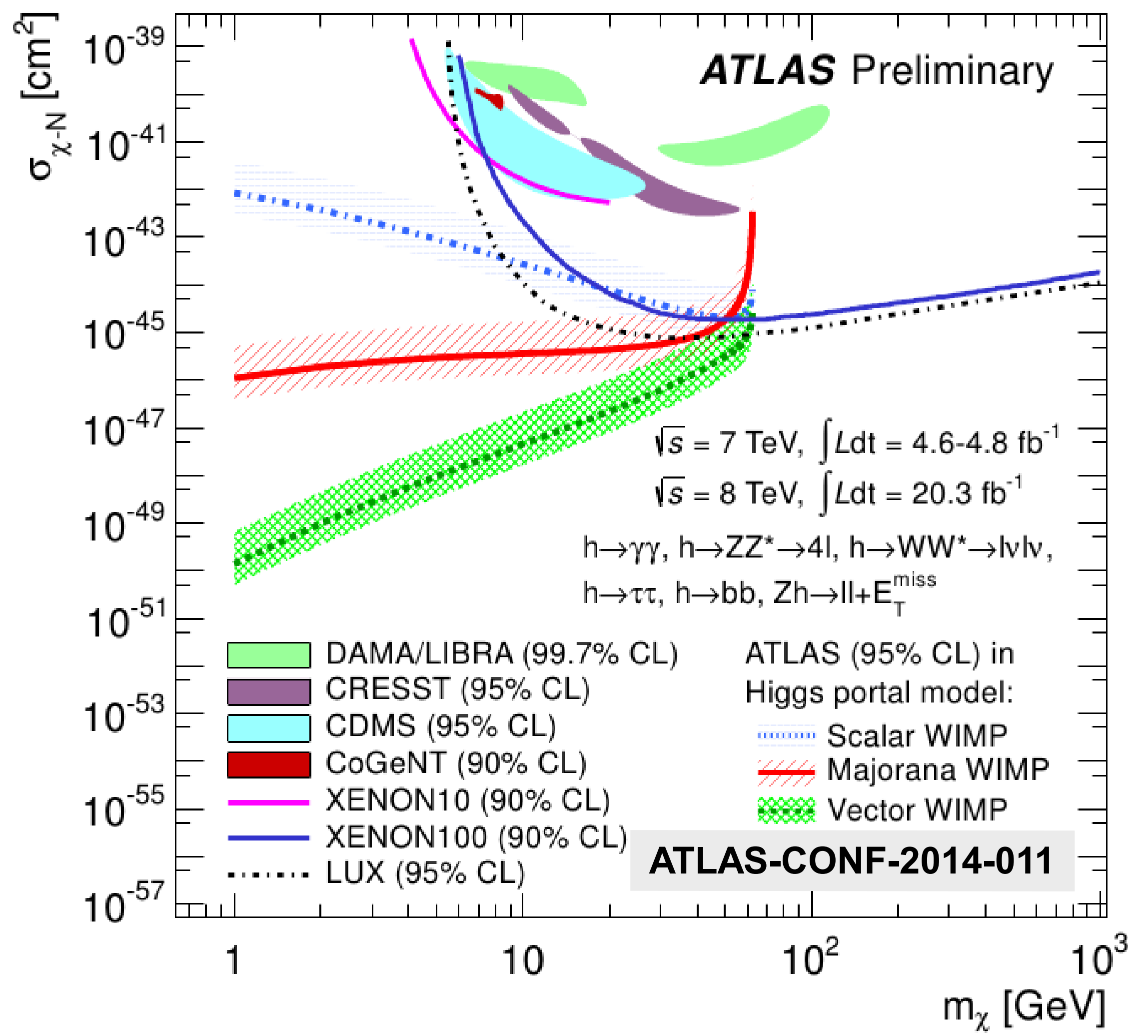
- Can combine results of direct and indirect constraints in BRinv.
  - ATLAS Observed (expected) limit BRinv<0.41(0.55)



From Higgs to dark matter

New

- Can interpret limit on invisible BR as limit on DM candidates coupling to Higgs boson.
- Interpretation in Higgs-portal model:
  - DM sector decoupled from SM, except for Higgs-mediated interactions.
- In this framework, gives complementary information to direct DM searches.

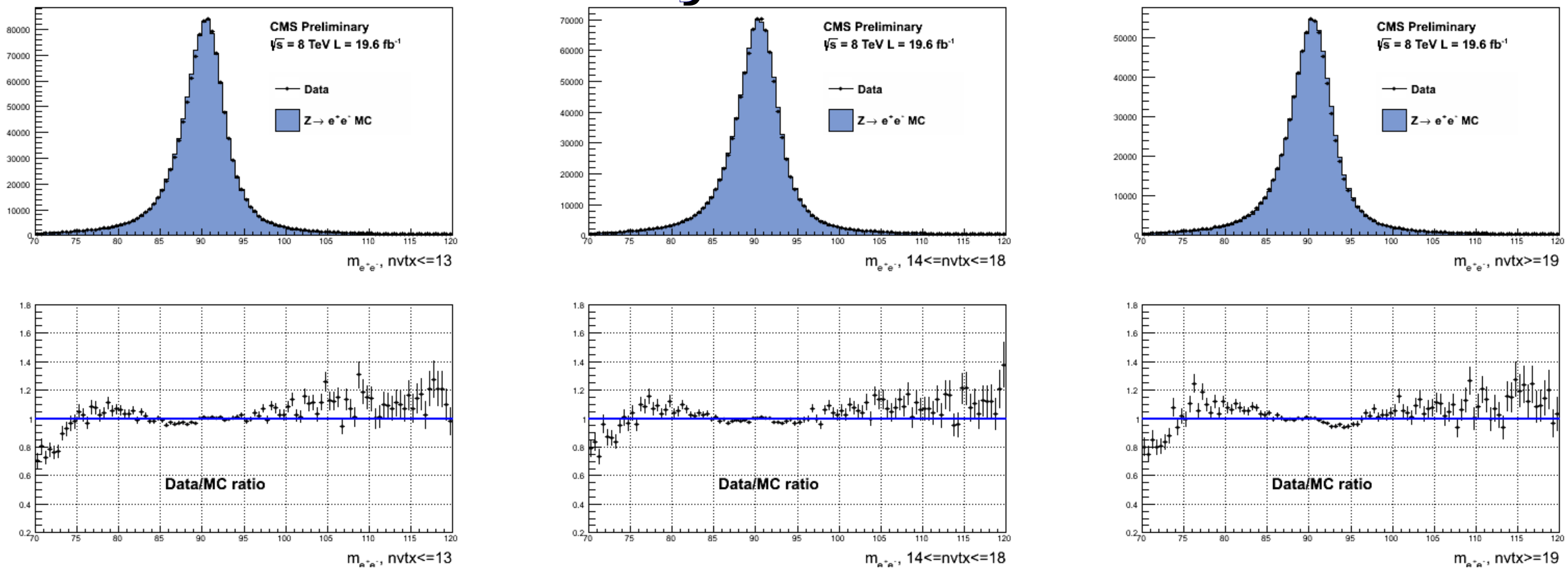


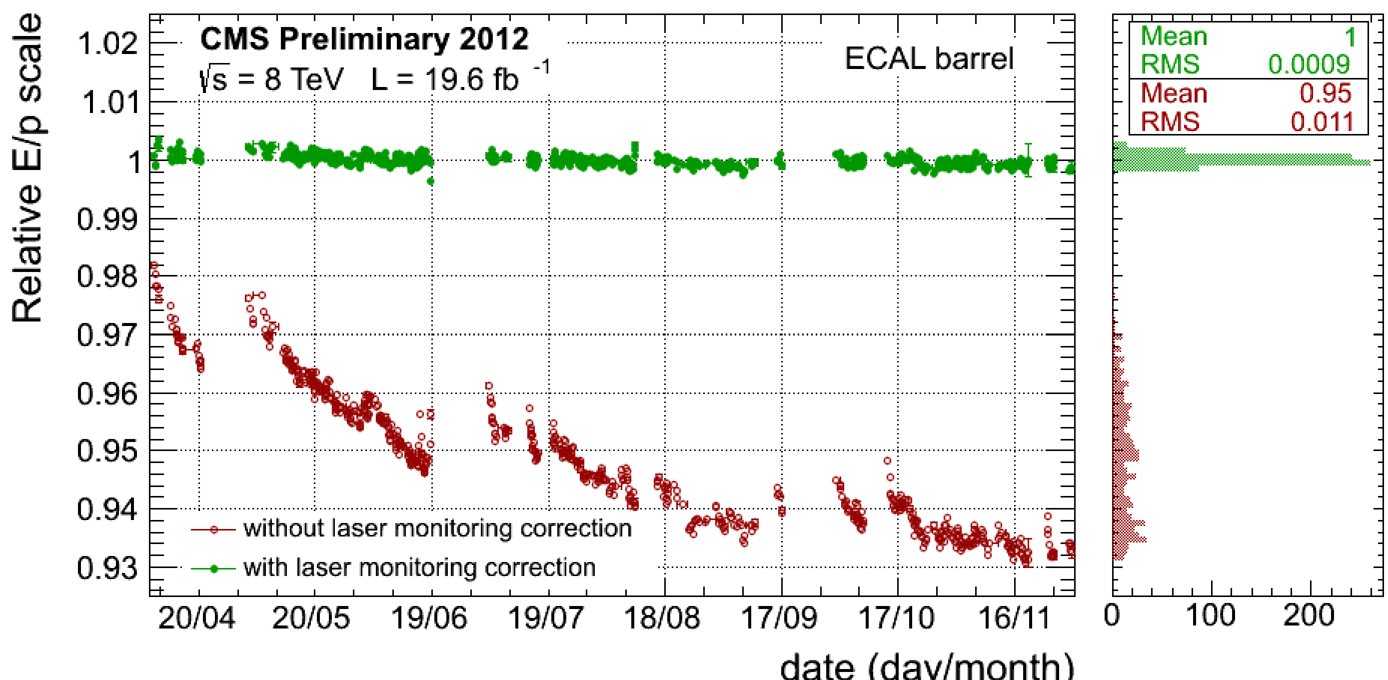
Summary

- Presented **results** on **mass, spin/parity, width and invisible decays** of the Higgs boson discovered at the LHC.
    - **Beginning of a long program** of SM prediction tests.
    - **Uncertainties** still large and mostly dominated by **statistics**.
    - Much **more to come** in the next years.
- **First precision measurement** in Higgs sector is $\mathbf{m_H}$.
    - Allows to over-constraint SM electroweak prediction.
    - **Expect** precision better **than 0.2%** for LHC Run 1 combination.
- **Spin/parity** of new boson **consistent** with $\mathbf{0^+}$.
    - Quite a few alternative models have been tested.
    - Moving **towards anomalous couplings** fits.
- New technique to constrain the Higgs boson **width** from **non-resonant ZZ** production.
    - **Major breakthrough** for Higgs physics at the LHC.
- Branching fraction to weakly interacting constraints at 0.5 per experiment.

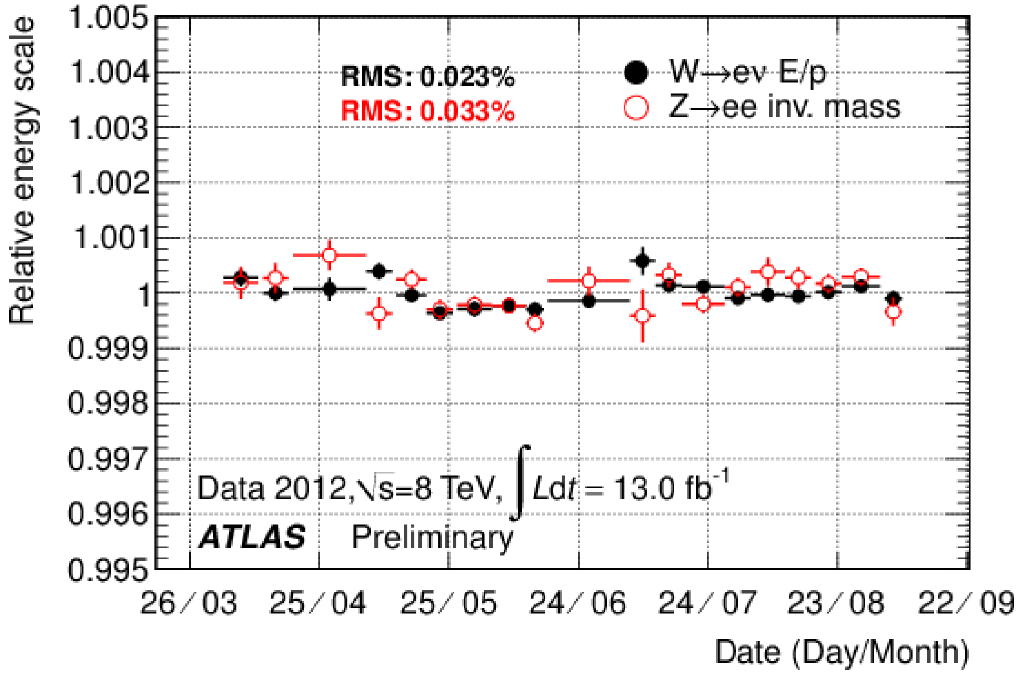
Additional material

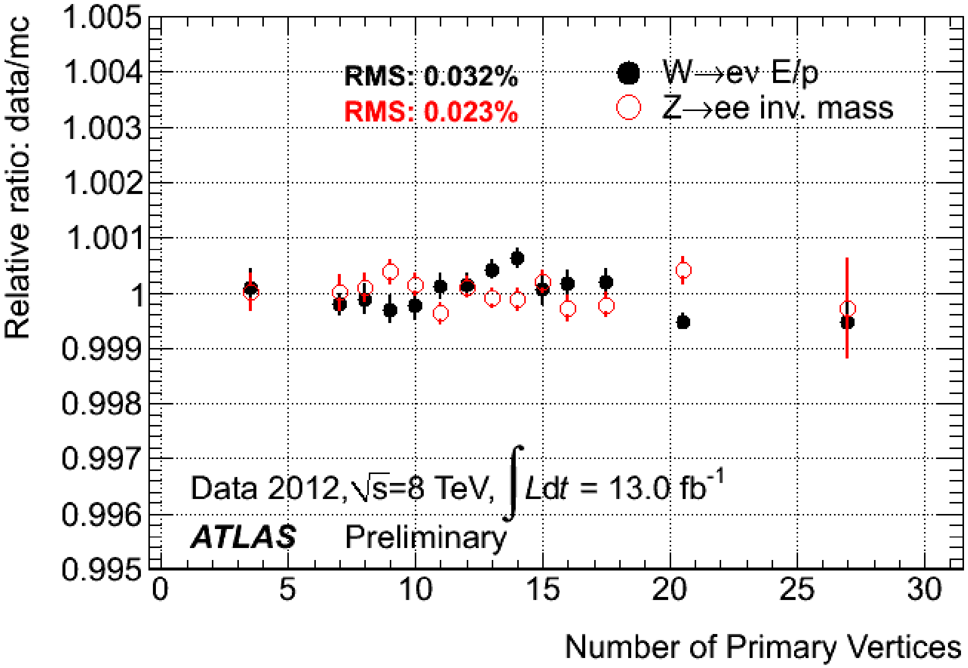
CMS: electron/photon energy reconstruction stability



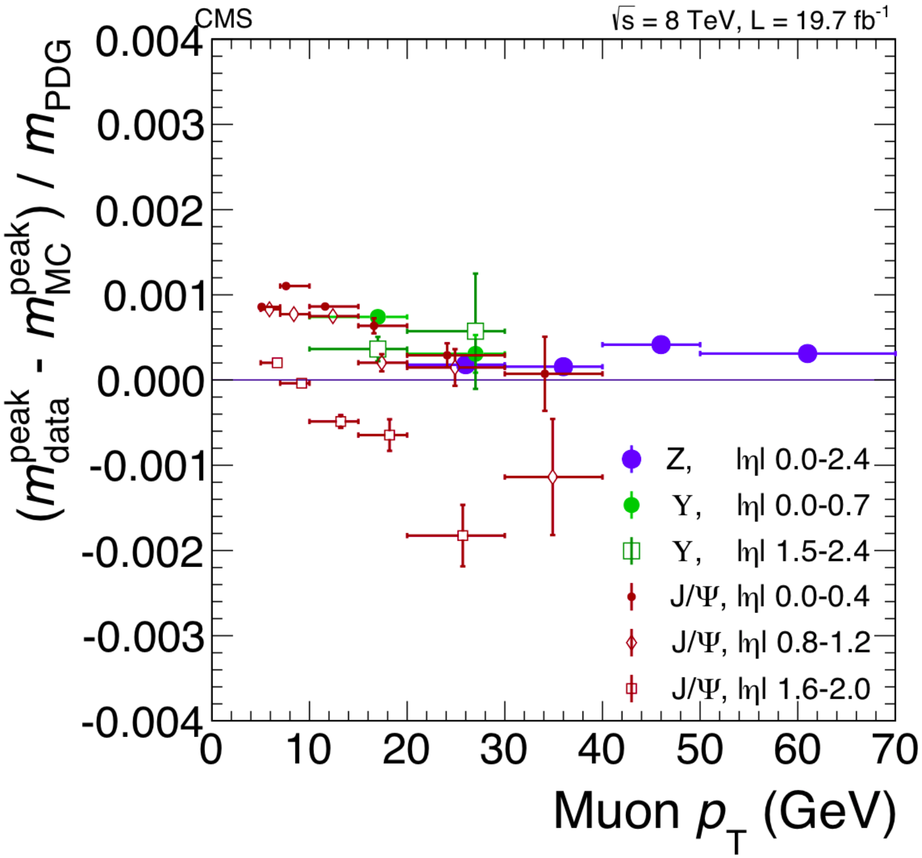


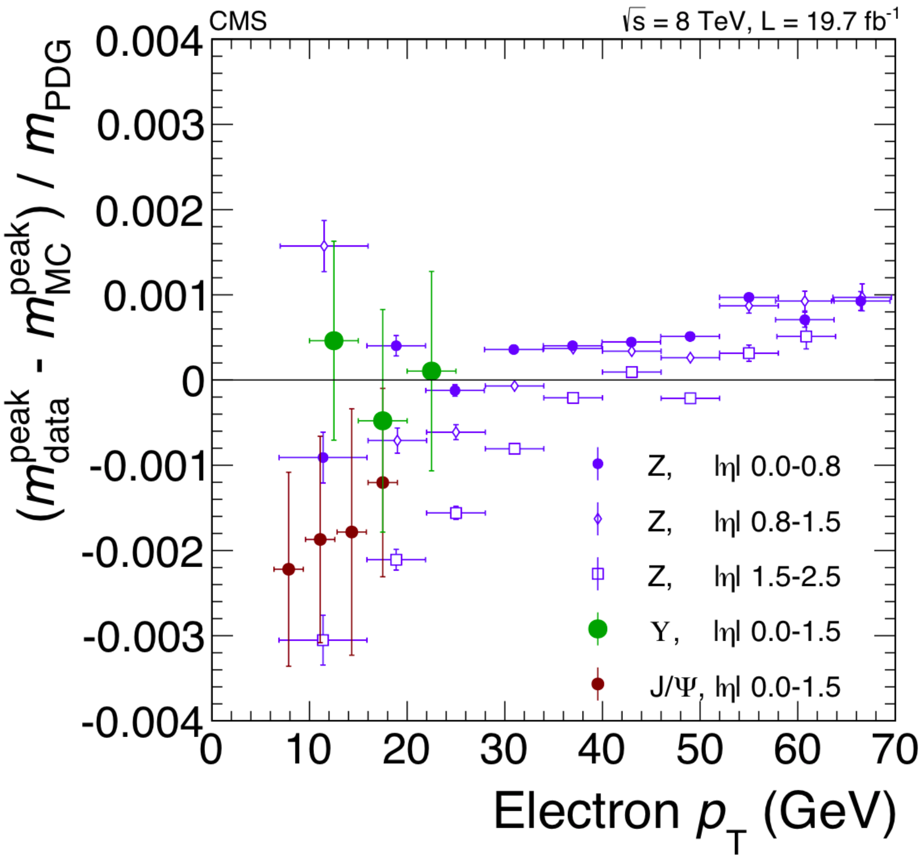
ATLAS: electron/photon energy reconstruction stability



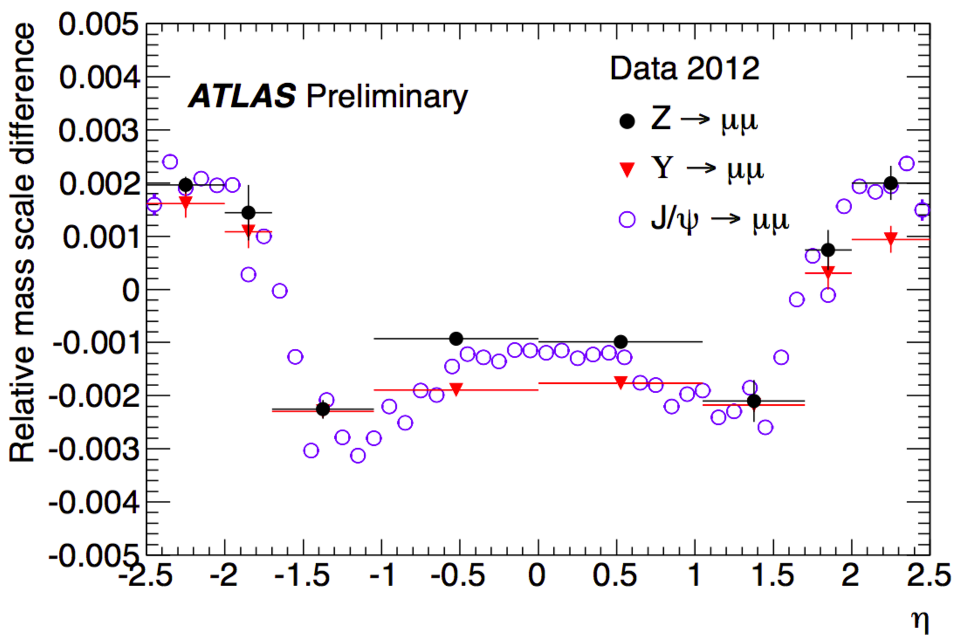


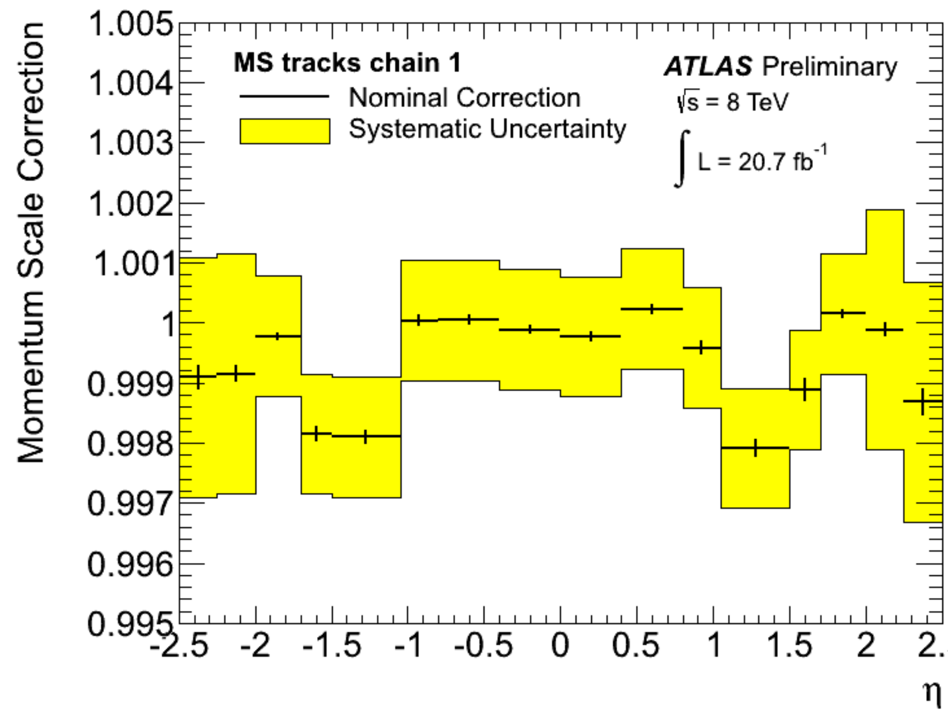
CMS: lepton momentum scale





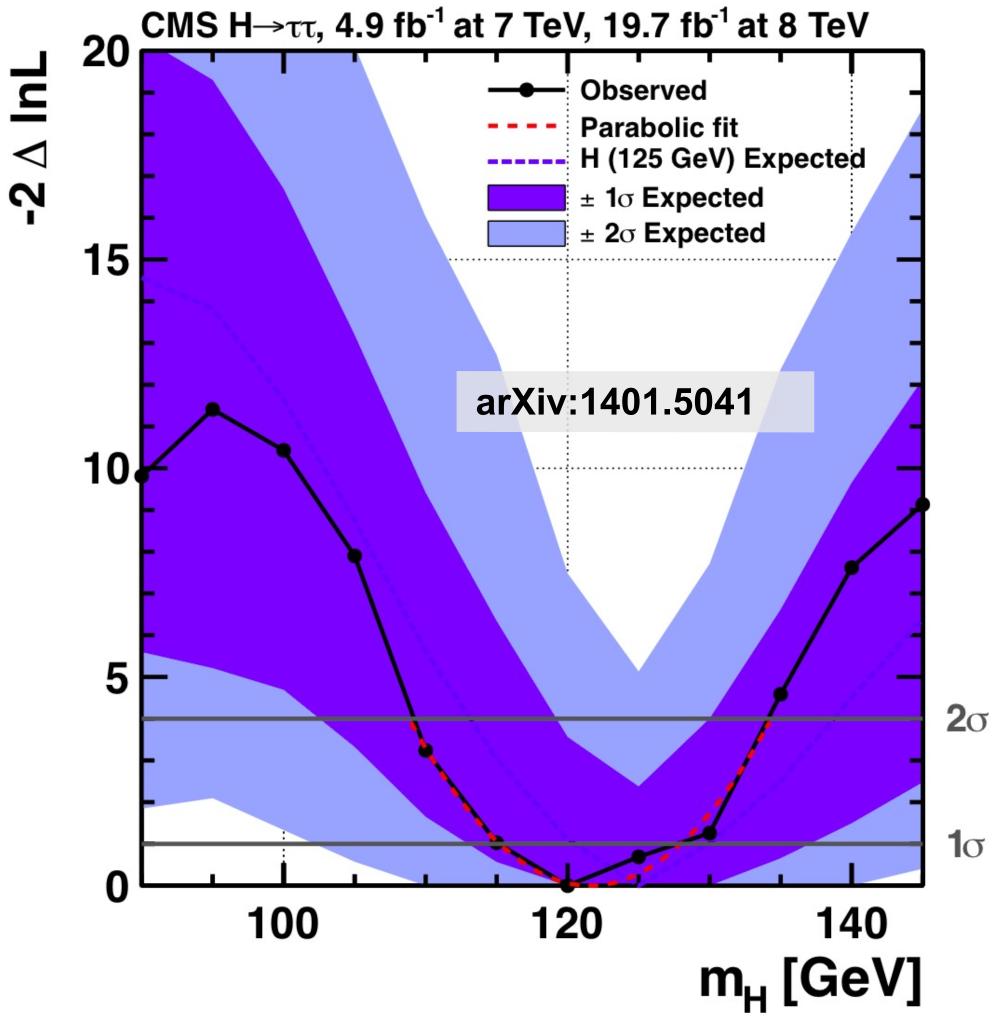
ATLAS: muon momentum scale





Mass "measurement" from ττ channel

- Details of the analysis can be found on arXiv:1401.5041.
- Several production mechanisms and τ decays employed.
- Mass measured from simultaneous fit to all channels.
    - MH = 122 +- 7 GeV

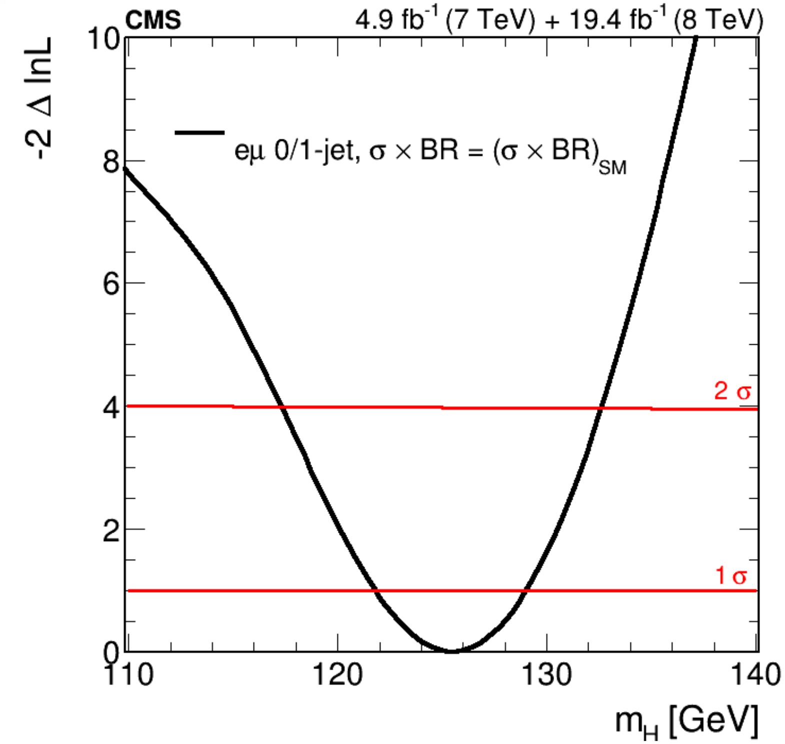


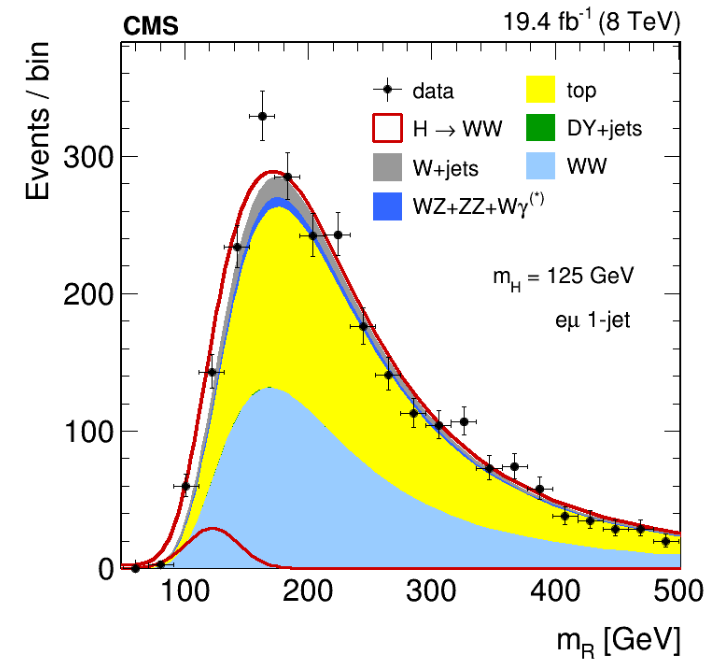
Indirect mass using WW channel

- Details of the analysis in JHEP 01 (2014) 096.

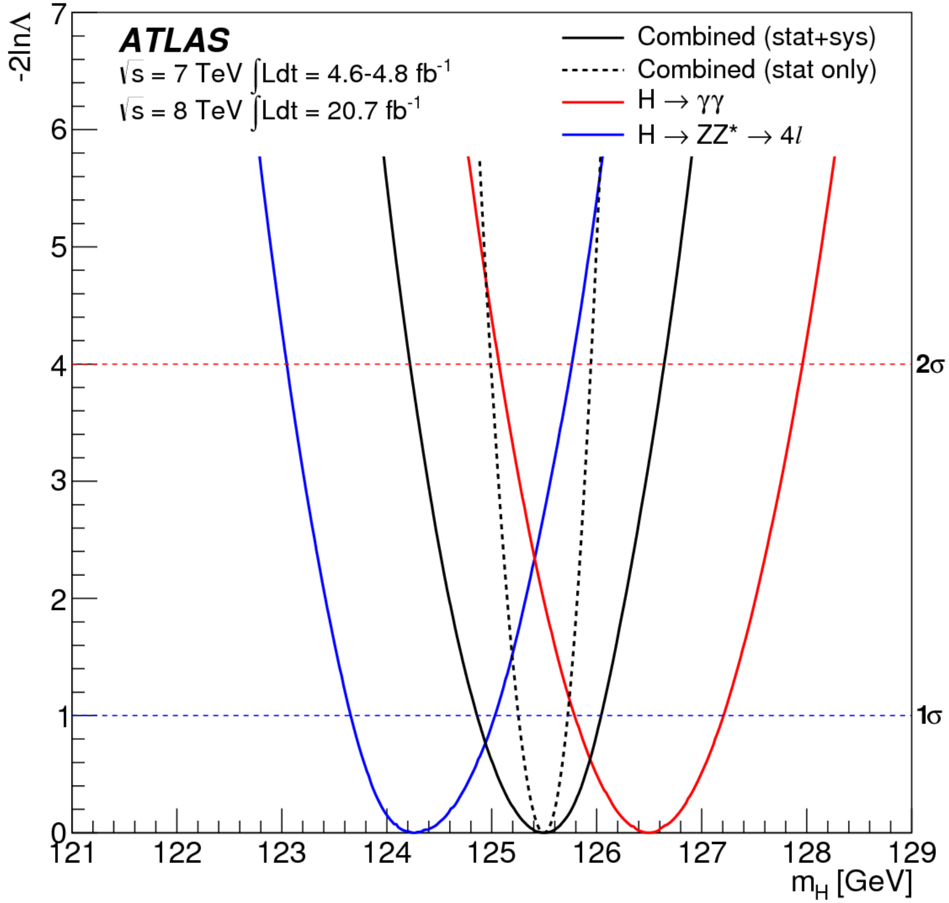
- Two kind of determinations
  - Direct fit (using MR vs $\Delta\phi_{ll}$)
    $m_H = 128.2\ ^{+6.6}_{-5.3}$ GeV
  - Indirect fit exploiting σ x BR mass dependence, assuming the SM predictions.
    $m_H = 125.5 \pm 3.7$GeV

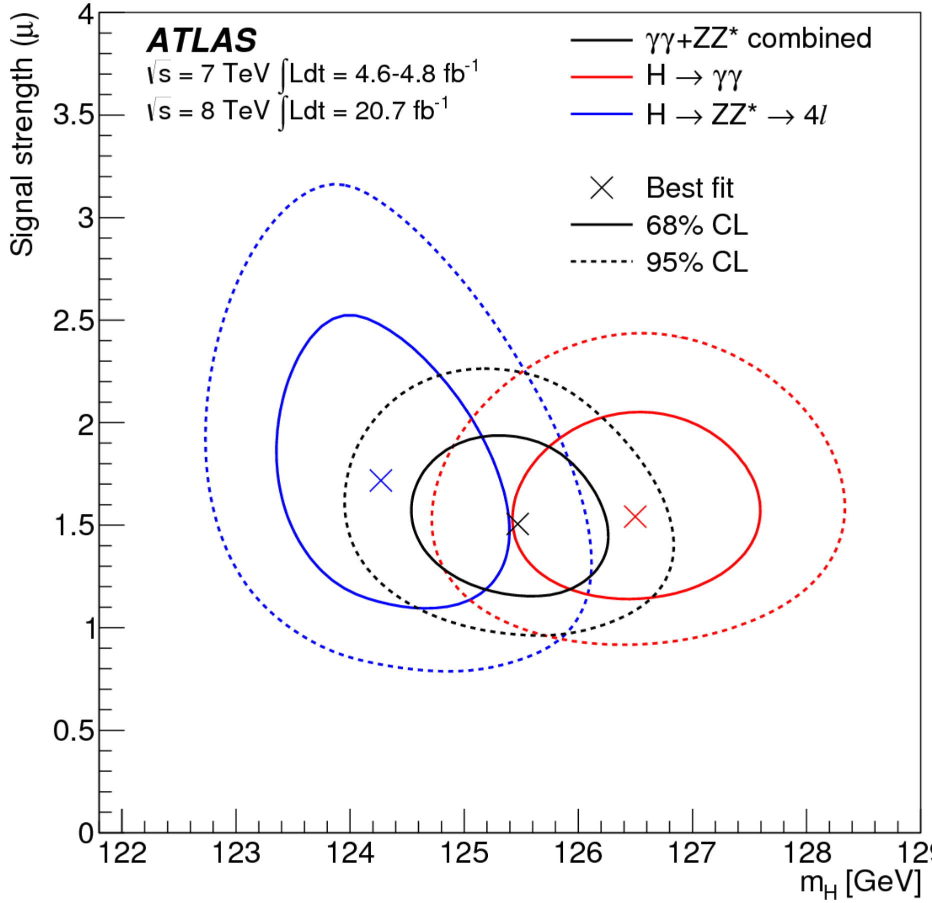
$$m_R = \sqrt{\frac{1}{2}\left[m_{\ell\ell}^2 - \vec{E}_T^{\mathrm{miss}} \cdot \vec{p}_T^{\,\ell\ell} + \sqrt{(m_{\ell\ell}^2 + (p_T^{\ell\ell})^2)(m_{\ell\ell}^2 + (E_T^{\mathrm{miss}})^2)}\right]}$$



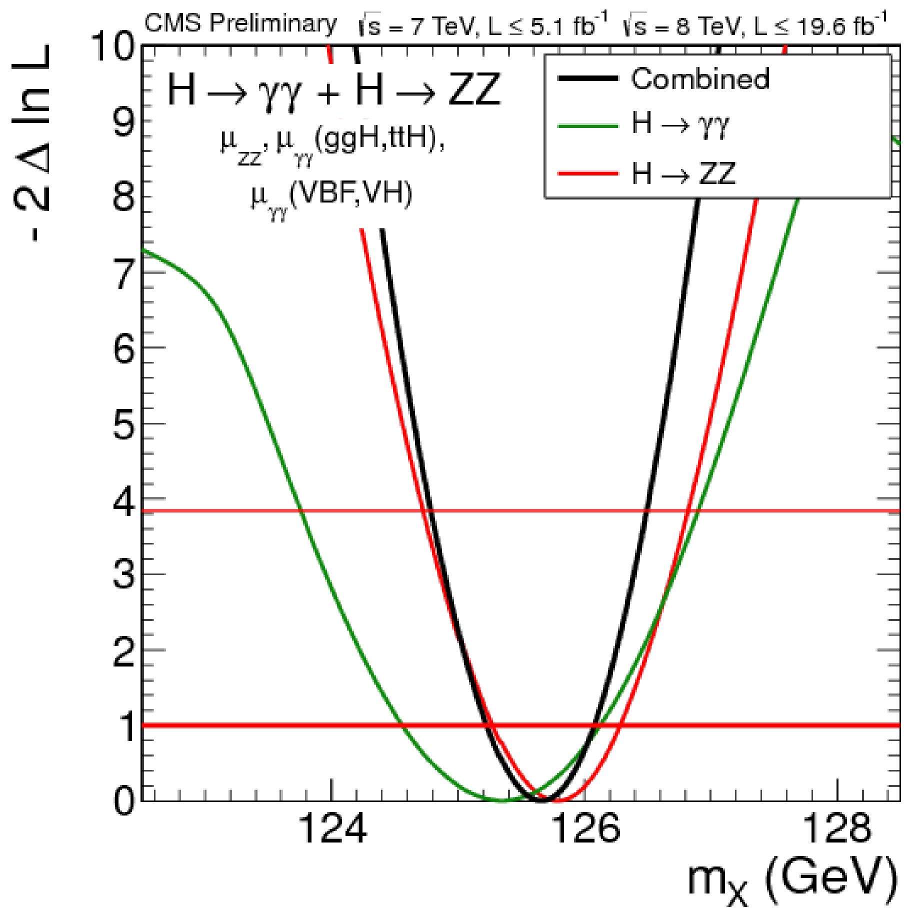


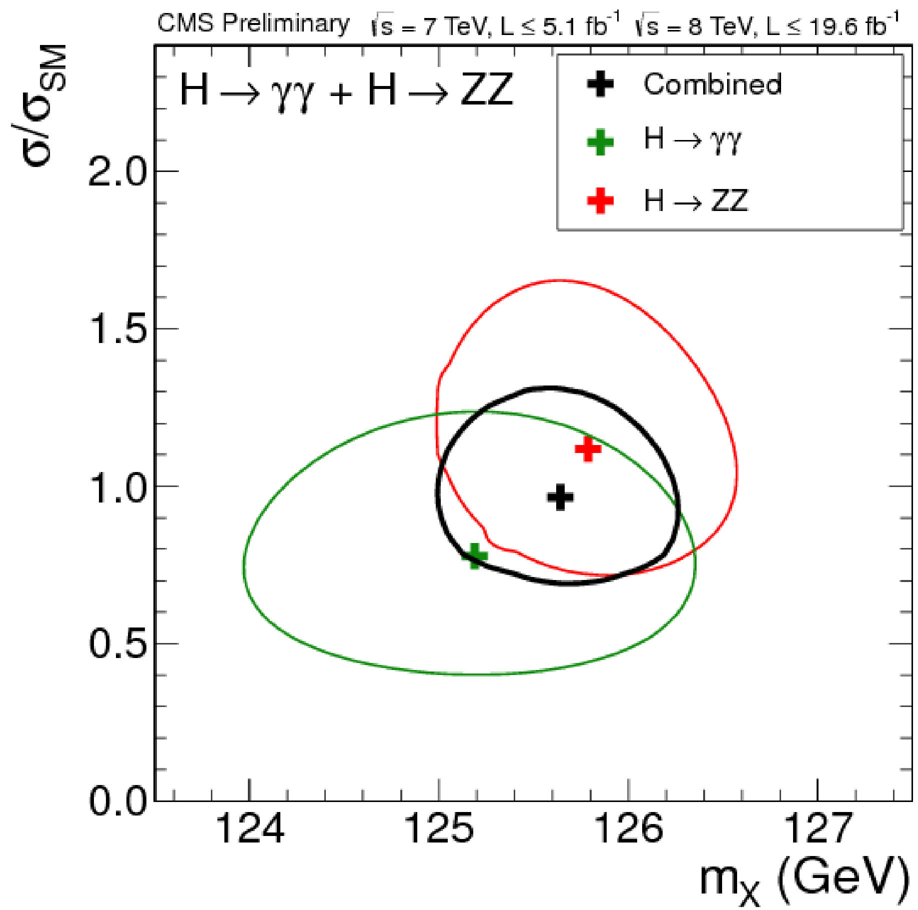
ATLAS mass combination



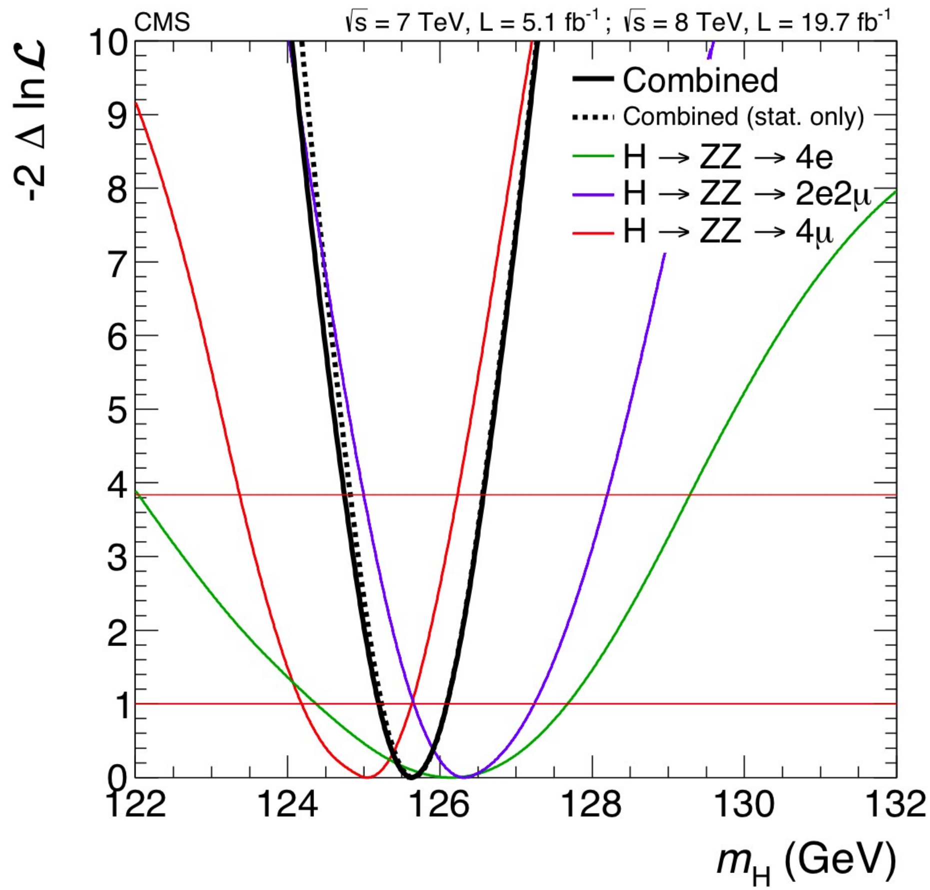


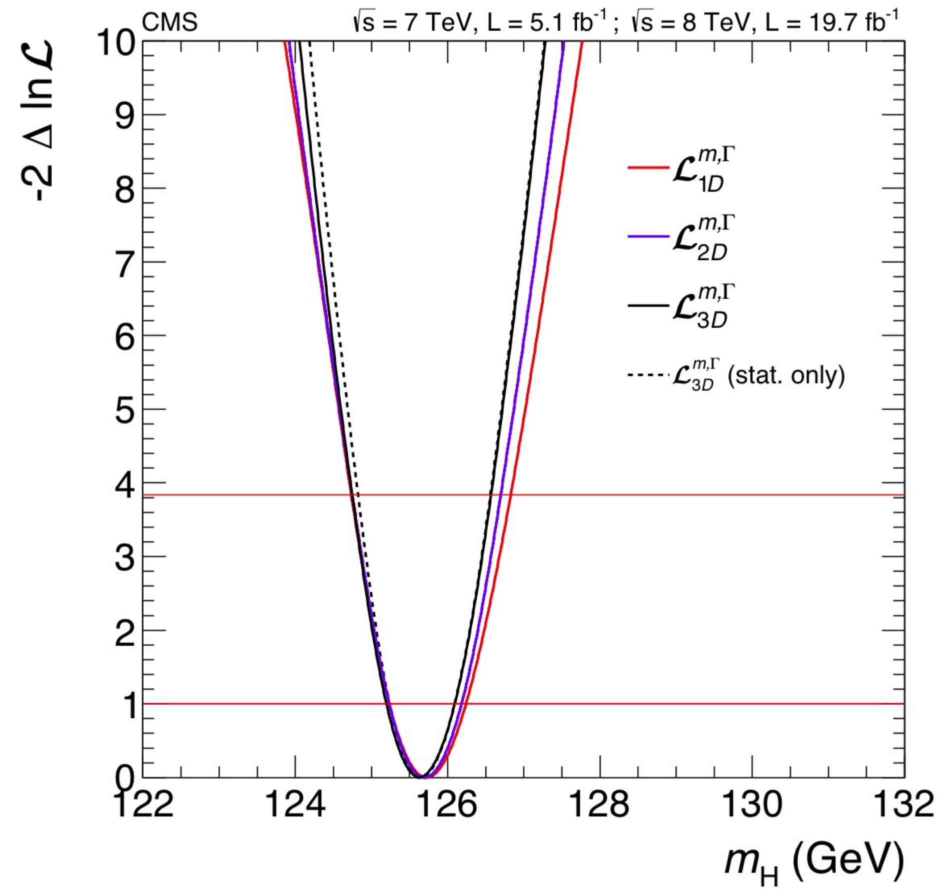
CMS mass combination





Mass: CMS H → ZZ(4l)





ATLAS: Hγγ vs H4l compatibility

- Mass difference: mγγ – m4l:
  - test assumption that both come from a common mass
  - parameter of interest: $\Delta mH = m_{\gamma\gamma} - m_{4l}$
  - $\Delta mH = 2.3 ^{+0.6}_{-0.7}$ (stat) ± 0.6 (sys) GeV
- Consistency of ΔmH = 0:
  - 2.4 σ away from ΔmH = 0 (p-value = 1.5%)
  - increases to 8% (<1.5 σ) using conservative treatment of the uncertainties by fixing the three main sources contributing to the e/γ energy scale uncertainty to their ±1σ values
    - material
    - presampler energy scale
    - calibration procedure