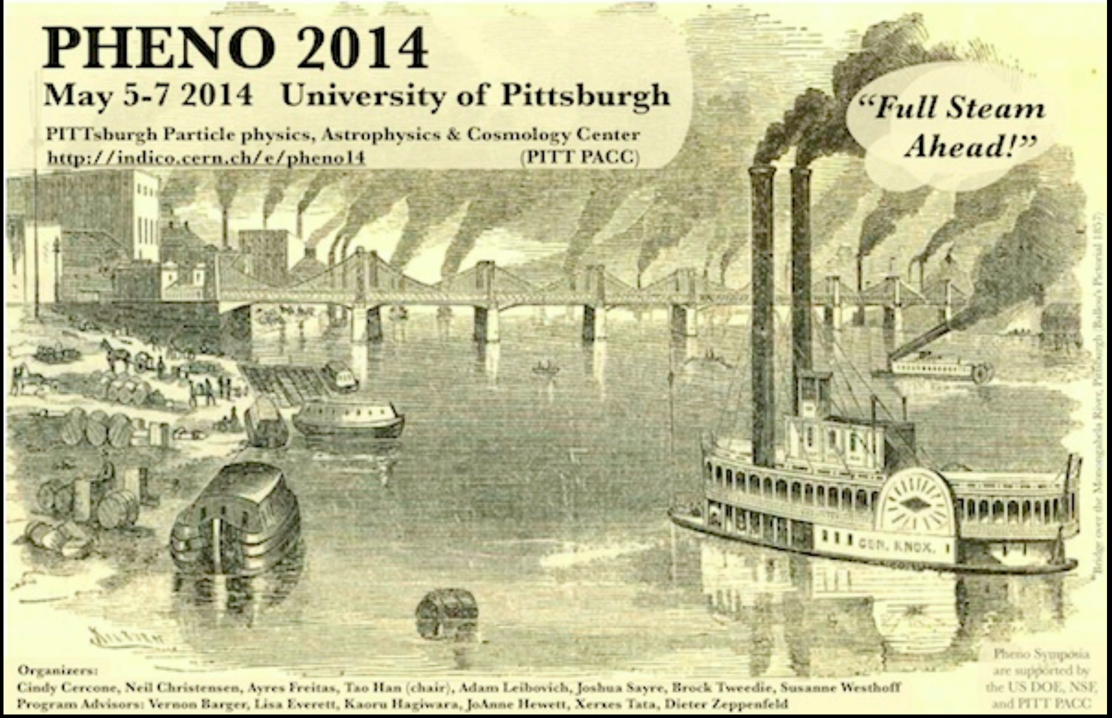
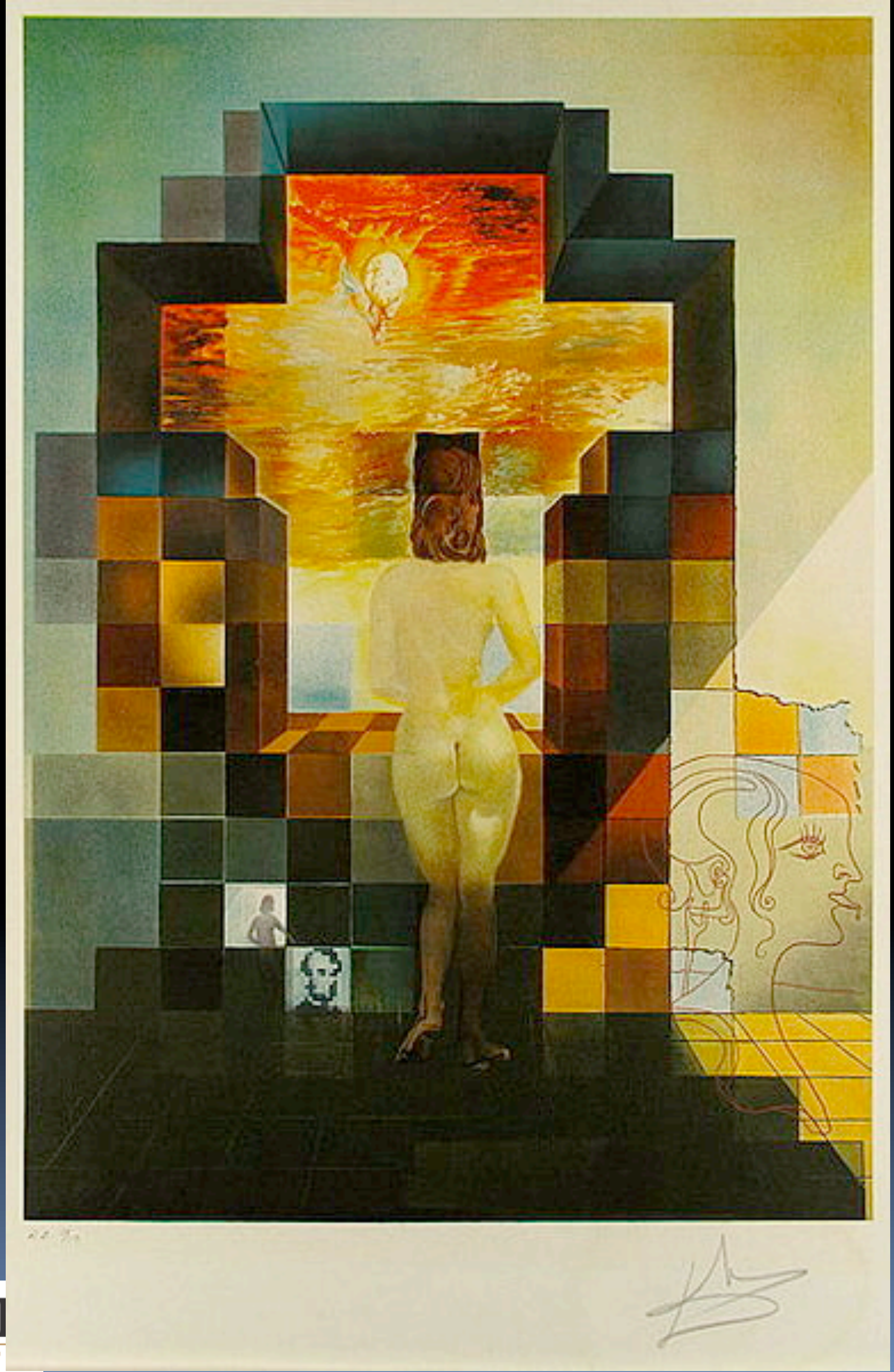
More info in the SM parallel session this afternoon



THE HIGGS BOSON THE MEASUREMENT OF ITS MASS, WIDTH, AND SPIN

D. Bortoletto
Purdue University & University of Oxford
Representing the CMS and ATLAS collaborations



Is it really Lincoln?

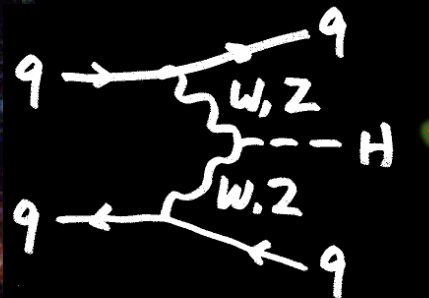
Can the study of the properties of the Higgs boson reveal cracks in the SM?

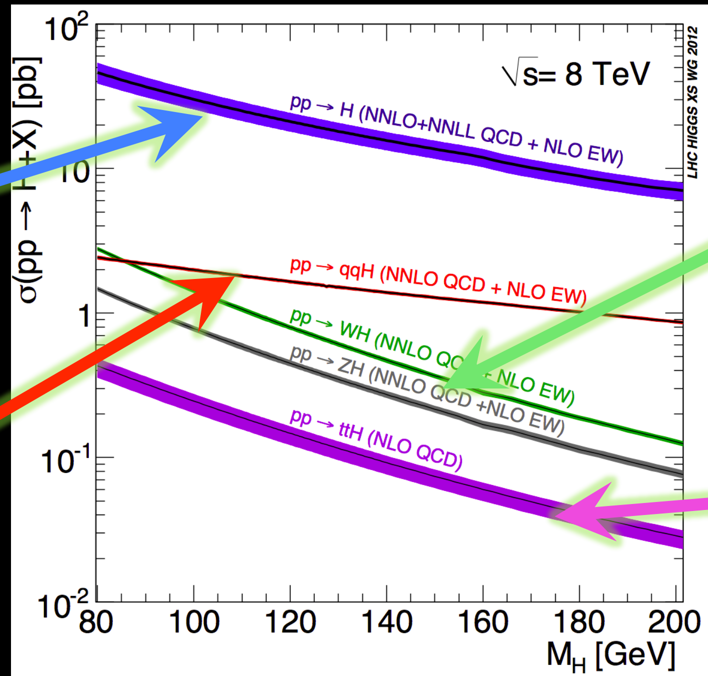
Higgs boson mass, width, and spin

Higgs Production and decay

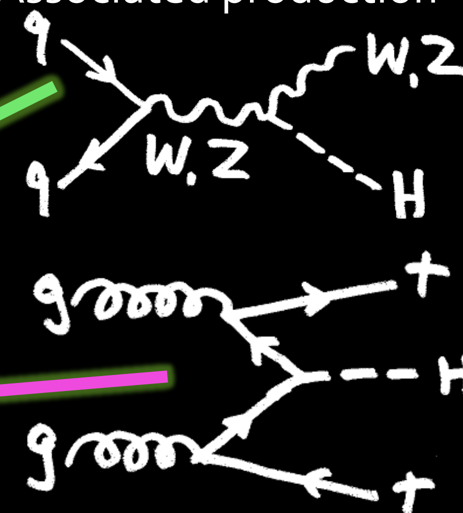
Gluon fusion

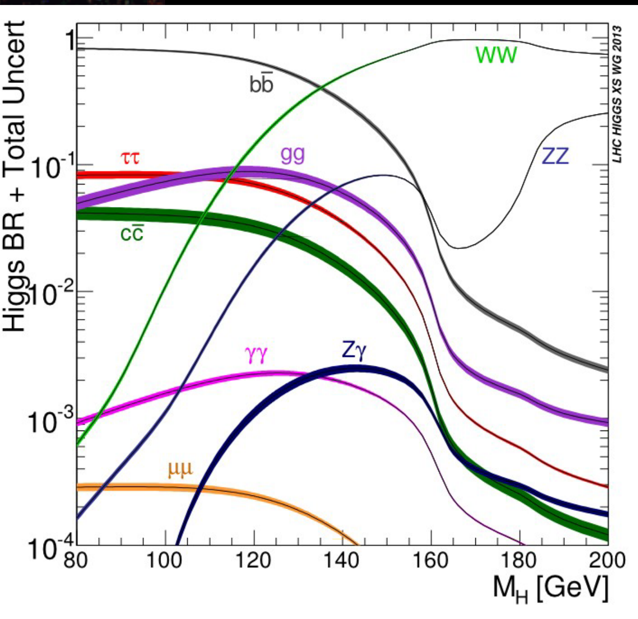
Vector Boson Fusion



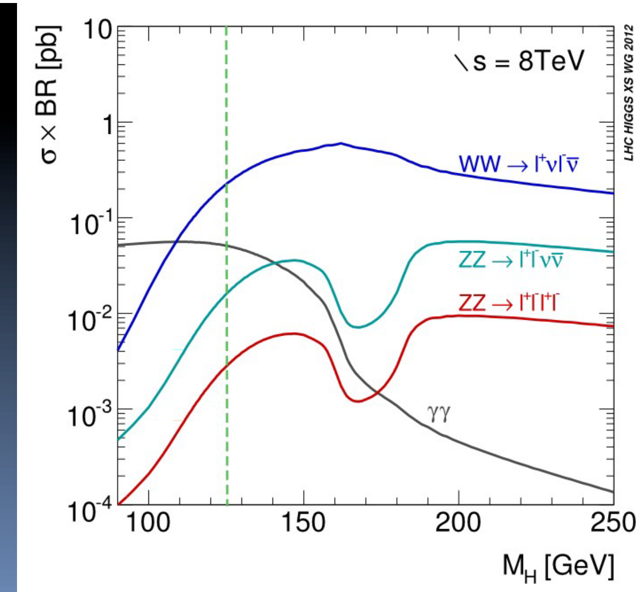


Associated production





- The LHC has measured both fermionic (ττ,bb) and bosonic (γγ, WW, ZZ) Higgs final states.
- Bosonic final states are currently providing mass, spin and width measurements



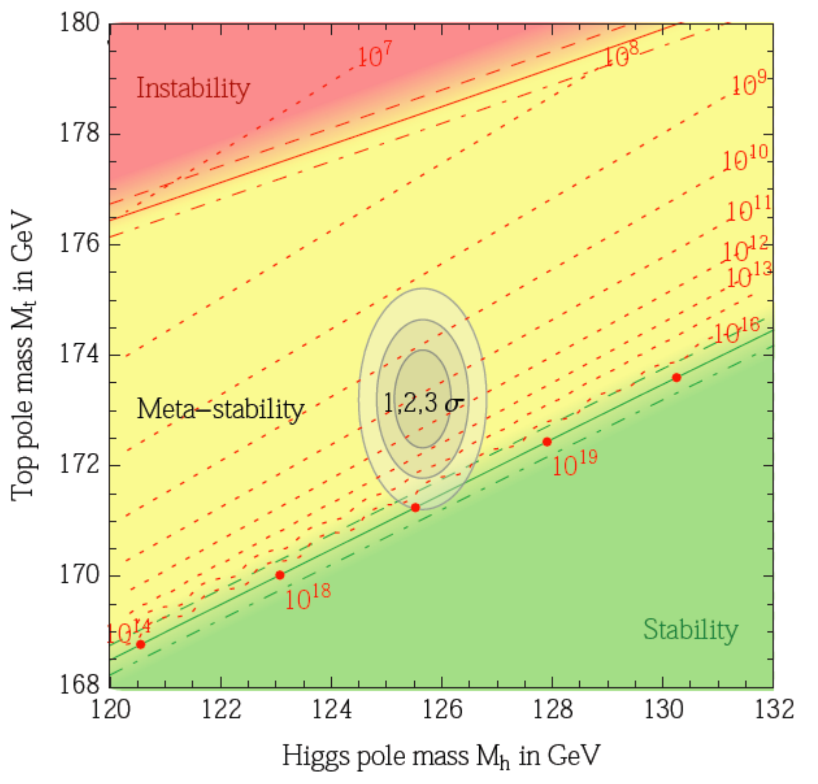
Higgs mass measurement

- M_H is a fundamental parameter not predicted by the SM
- Precision measurements of the Higgs mass provide important constraints.
- In the SM

$$\mathbf{M}^2_H = 2\lambda_{SM}\mathbf{v}^2$$

We must check this relation by measuring LHS and RHS independently

- Implication on the stability of the Higgs potential



Buttazzo, Degrassi, Giardino, Giudice, Salab, Salvio, Strumia

Higgs mass measurement

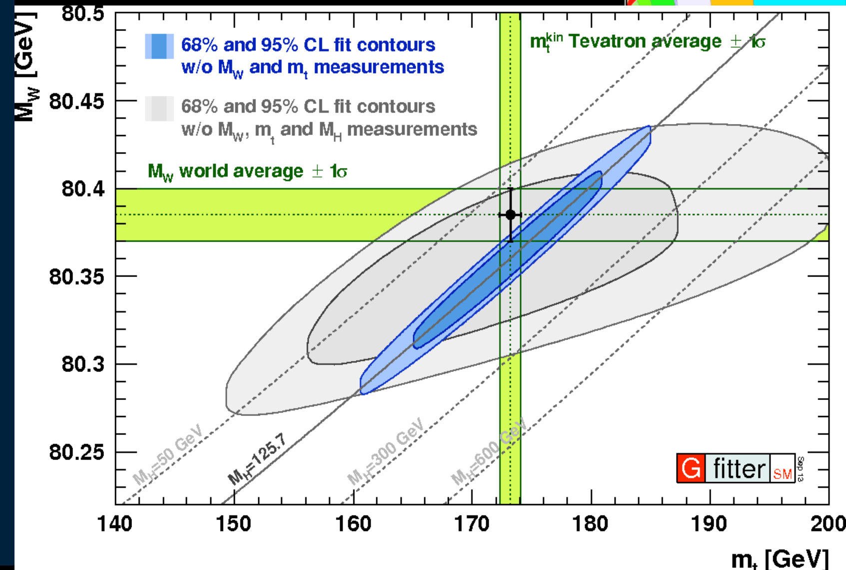
- M_H is a fundamental parameter not predicted by the SM
- Precision measurements of the Higgs mass provide important constraints.
- In the SM

$$M^2_H = 2\lambda_{SM} v^2$$

We must check this relation by measuring LHS and RHS independently

- Implication on the stability of the Higgs potential
- Over constraining the EW fits
- In SUSY

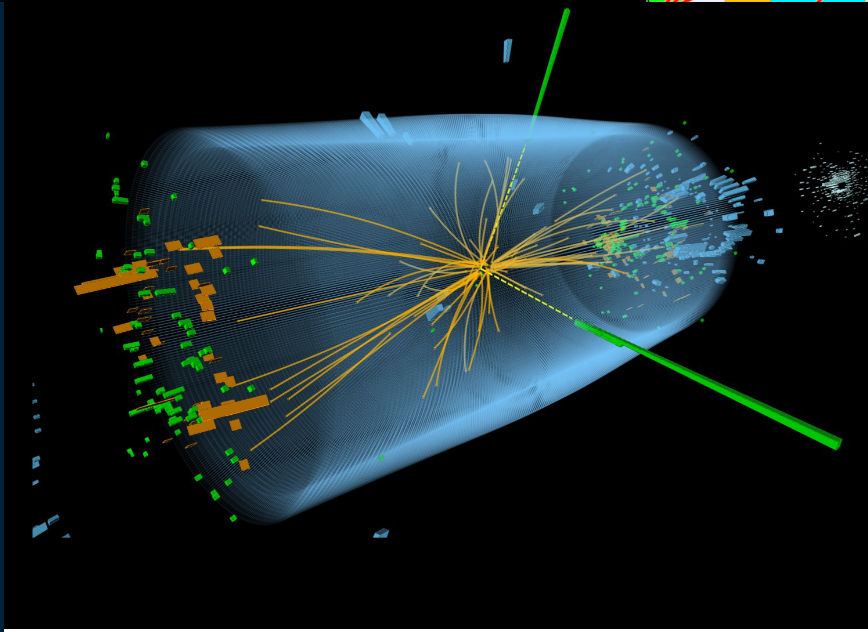
$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{\Delta_S^2}{m_t^2},$$

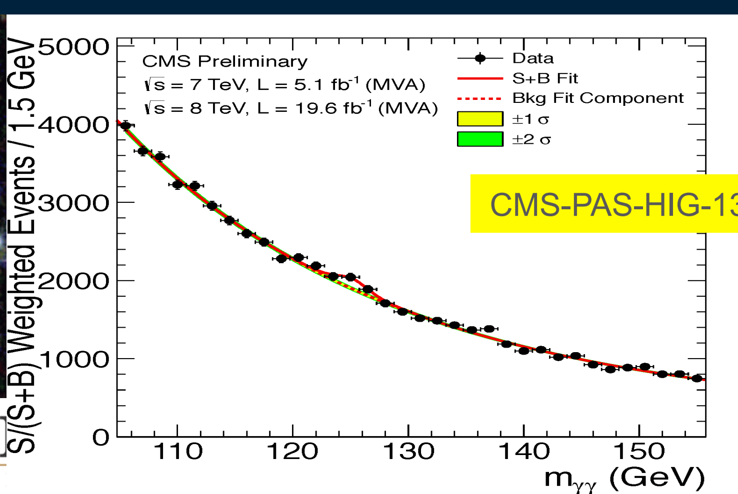


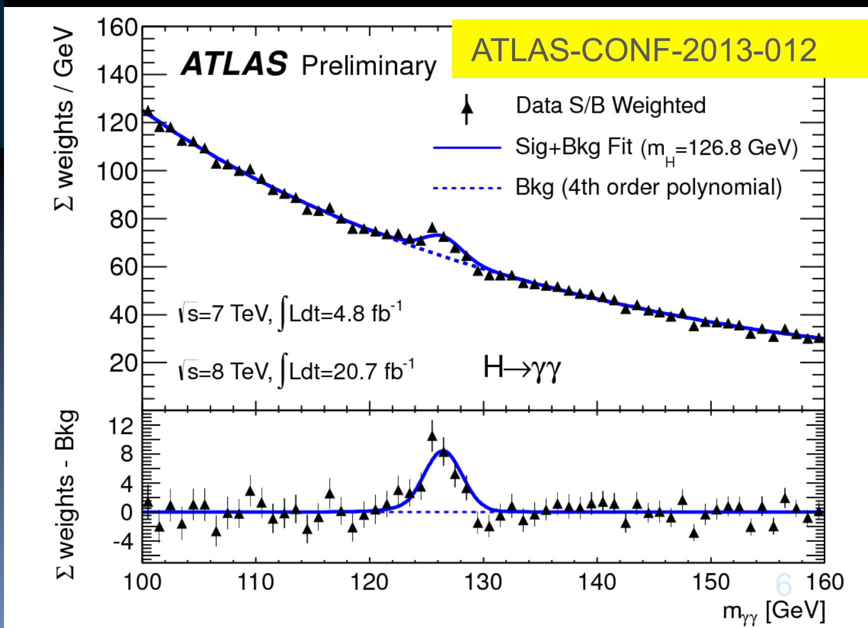
- LHC Measurement strategy
  - Use high resolution channels: H→γγ and H→4l which have a mass resolution of few %
- Challenges :
  - Maintain excellent mass-resolution in high-pile-up environment

H→γγ Mass Measurement

- Clean signature:
  - Two isolated, high p_T photons.
  - Small branching-fraction: ~0.2%.
  - Excellent mass resolution: 1-2%.
  - Large background from QCD processes: S/B ~ 1/1 ÷ 1/20
- Strategy for analysis
  - Events categorized according to photon resolution and kinematics.
  - Exclusive channels targeting VBF and associated production.
  - Background modeled with polynomials or falling power-law or exponentials







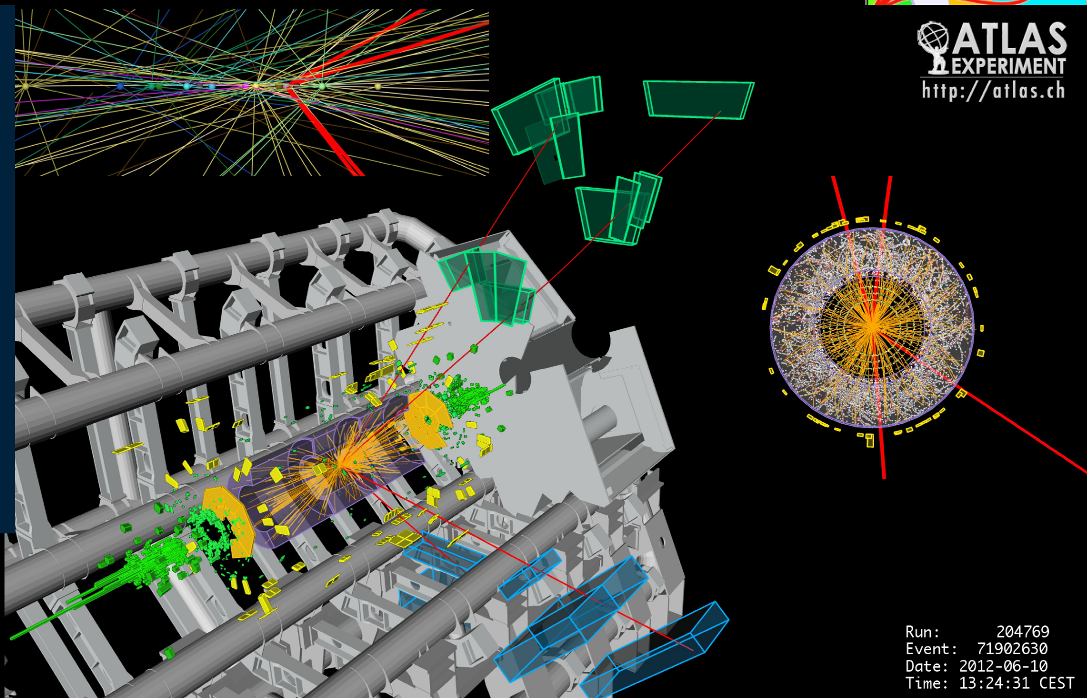
H→γγ Mass Measurement

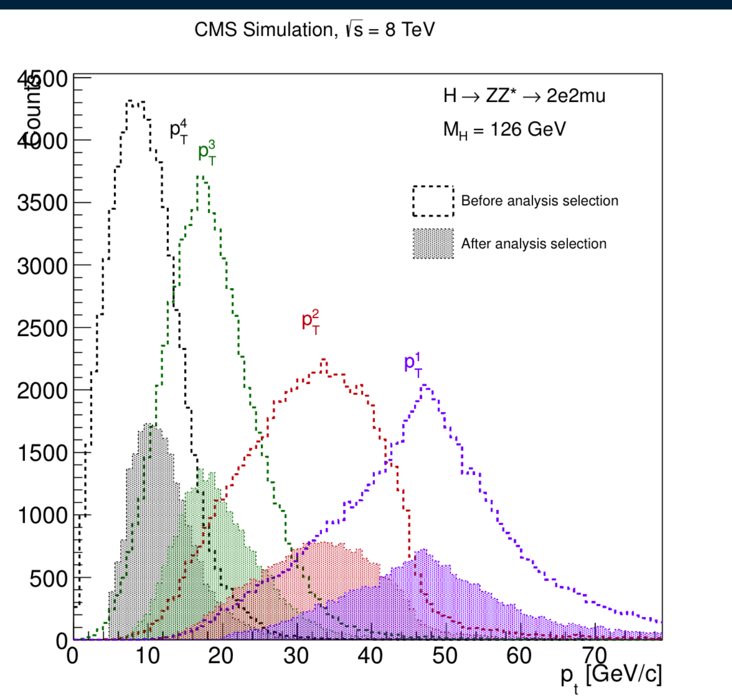
- Energy measurement:
  - CMS: **e/γ** energy estimated using multivariate regression
  - ATLAS: weighted sum of energy deposits in the different calorimeter layer
  - Energy scale and resolution validated with Z → ee, W → eν, **J**/ψ, and Upsilon resonances and corrected with MC input for e/γ differences
  - Additional smearing applied to MC to match the resolution in data
- Systematic uncertainty on mass scale currently ~0.5% but expected to improve considerably for legacy Run 1 results.

	ATLAS		**CMS**	
Mass [GeV]	$126.8 \pm 0.2(stat) \pm 0.7(sys)$		$125.4 \pm 0.5(stat) \pm 0.6(sys)$	
	Z→ee E-scale	0.3%	Residual non-linearity from Z → ee to H → γγ	0.4%
	Material modeling	0.3%	Material modeling	0.24%
	Pre-sampler scale	0.1%		
	Other	0.32%		
	Total	0.55%		0.47%

H→4l Mass Measurement

- Golden channel:
  - Four isolated leptons.
  - Small branching fraction: ~10^{-4}
- Extremely pure: S/B ~ 2:1
- Challenges :
  - Maximize acceptance for low p_T leptons
- Precise calibration of lepton p_T scale

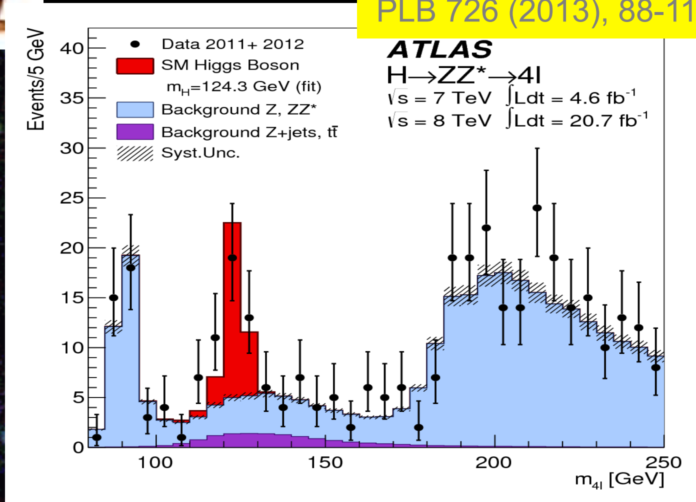


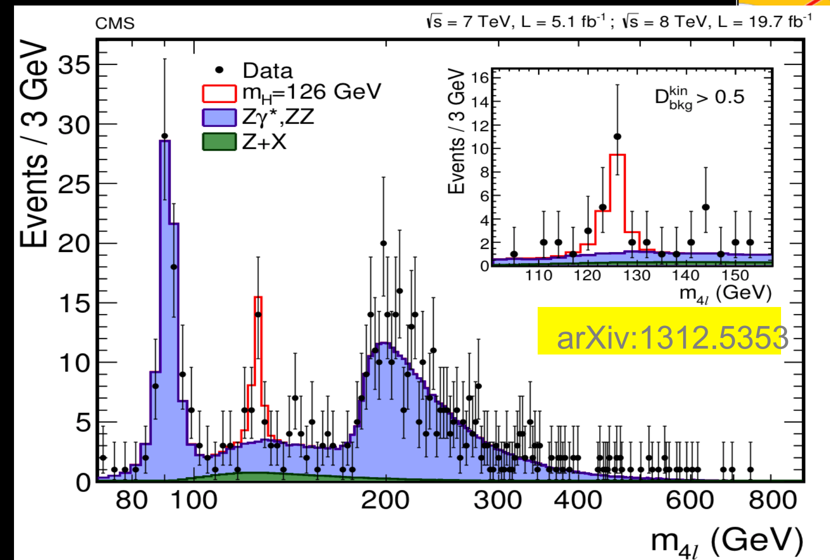


- Analysis strategy:
  - CMS
    - Use m(4l)vs kin. discriminant (KD) for S/B separation and event-by-event mass errors (estimated from lepton momentum errors)
  - ATLAS:
    - Use m(4l)for S/B separation and categorize events into VBF-like, VH-like, and untagged

H→4l Mass Measurement

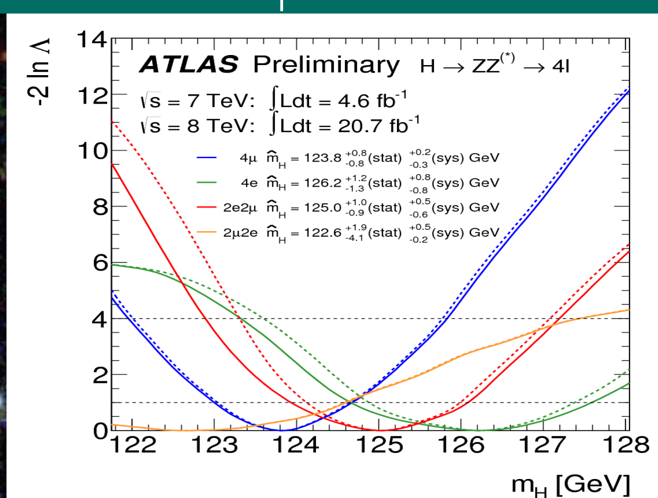
PLB 726 (2013), 88-119



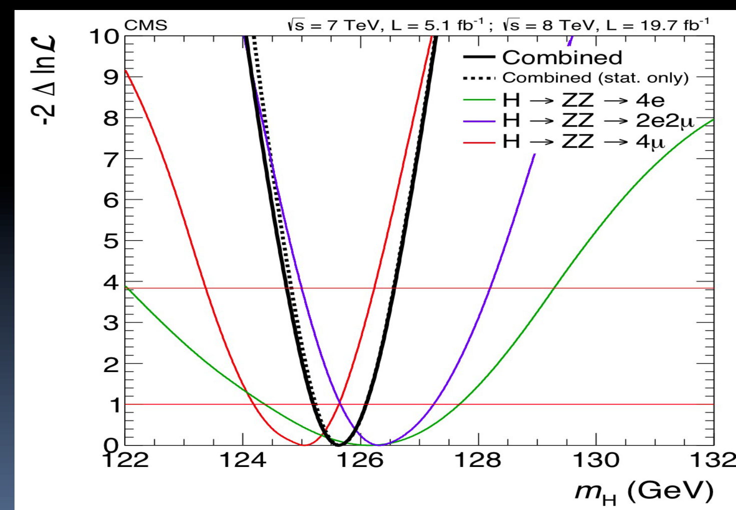


arXiv:1312.5353

- ATLAS:1D fit to m4l. Using kinematic constraint to Z_1 candidate.
- CMS: 3D fit to m4l, KD, and σ(m4l)/m



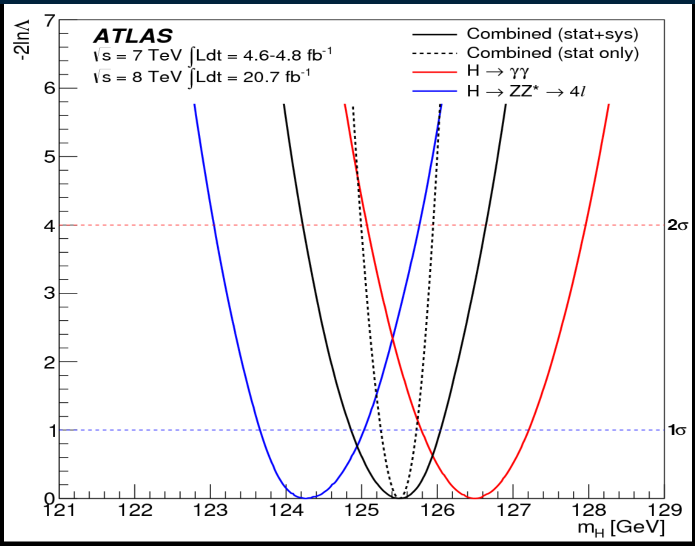
$$124.3^{+0.6}_{-0.5}(stat) \pm 0.7^{+0.5}_{-0.3}(sys)$$

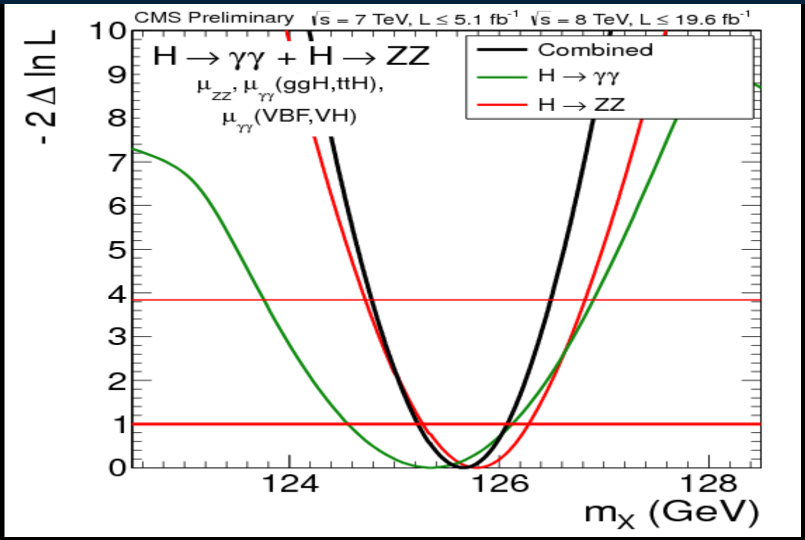


$$125.6 \pm 0.4(stat) \pm 0.2(sys)$$

Mass Measurement: Combination

- Mass measurements $\gamma\gamma$ and 4l channels can be combined (under the hypothesis that the same state decays in both modes).





	ATLAS	**CMS** (new 4l measurement not used)
Mass [GeV]	$125.5 \pm 0.2(stat) \pm^{+0.5}_{-0.6}(sys)$	$125.6 \pm 0.3(stat) \pm 0.3(sys)$

- Precision expected to improve since both CMS&ATLAS will use updated calibrations and improved understanding of energy/momentum scale uncertainties for Run 1 legacy papers
- LHC combination expected later this year with precision possibly reaching ≈ 0.2%.

Spin and Parity

- In the Standard Model the Higgs boson is a 0^+ state.
  - This must be verified experimentally
- Most general form of spin 1 and 2 scattering amplitudes have many terms

$$A(X \to V_1 V_2) = \Lambda^{-1} \Big[2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right)$$
$$+ g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big] , \quad (18)$$

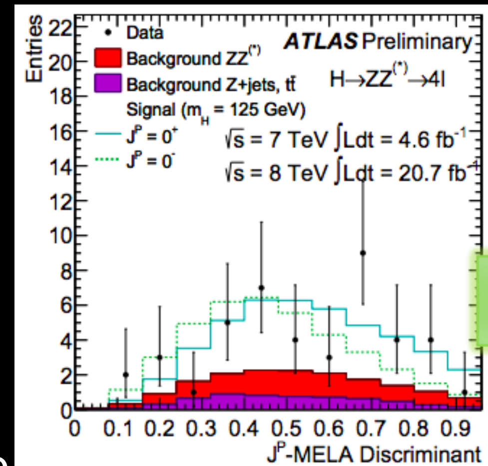
- Until there is enough data, ATLAS and CMS are testing alternative hypothesis against SMH (0^+).
- Keep only dim-4 terms ($g_1 = g_5 \neq 0$): Graviton-like "couplings" (2^+m).
- Most sensitive channels:
  - $H \to ZZ \to 4l$, $H \to WW \to 2l2\nu$ and $H \to \gamma\gamma$
- $H \to ZZ \to 4l$ Extremely rich channel in terms of angular information.
  - Best suited to study spin and parity

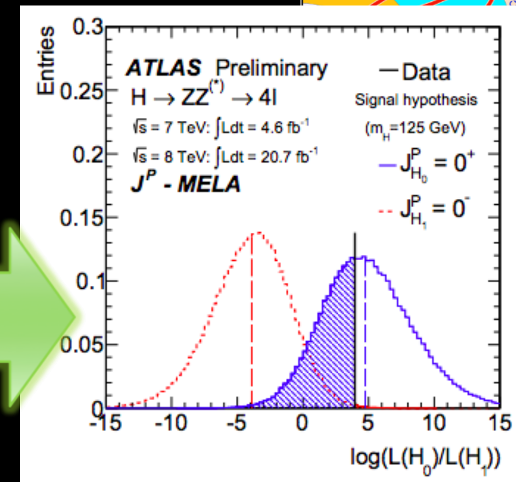
J^P in H→ZZ→4l

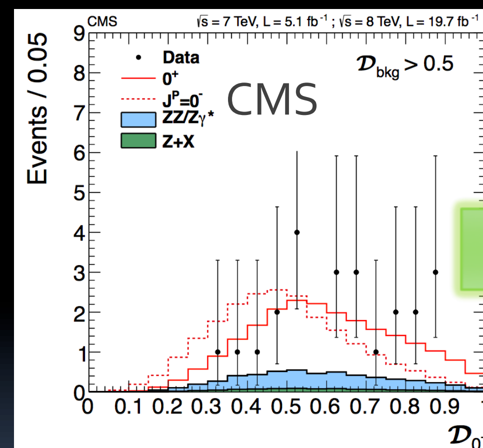
- Use discriminants from decay angles and invariant masses

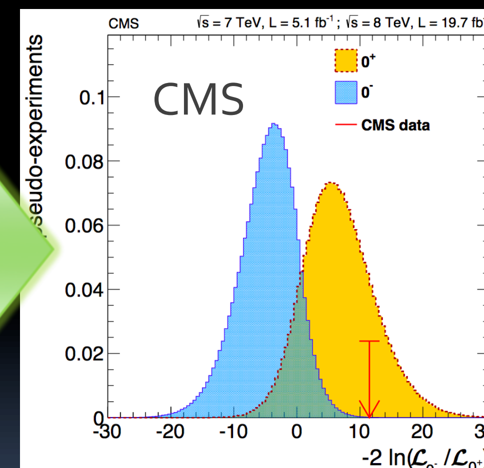
$$\mathcal{D}_{J^P} = \left[1 + \frac{\mathcal{P}^{\text{kin}}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}{\mathcal{P}^{\text{kin}}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$

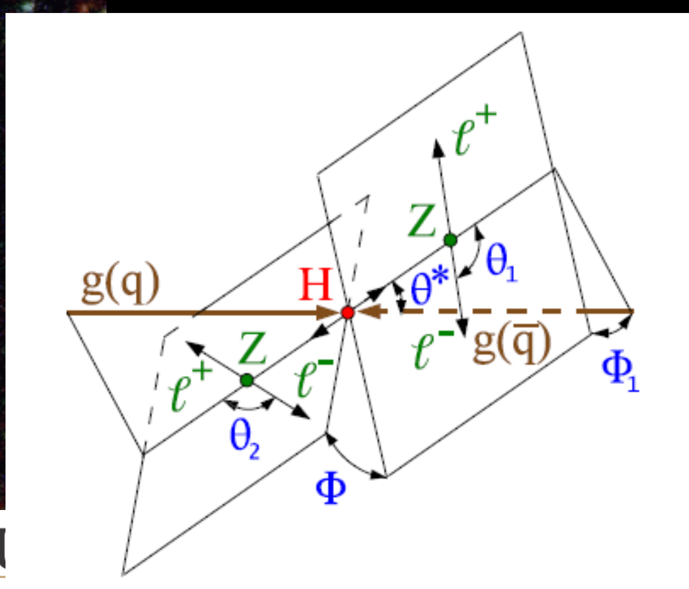
- Profiled likelihood ratio test statistic.
  - ATLAS: template fit of BDT score distribution.
  - CMS: 2D fit of superKD(m4lxKD) vs KD(JP)









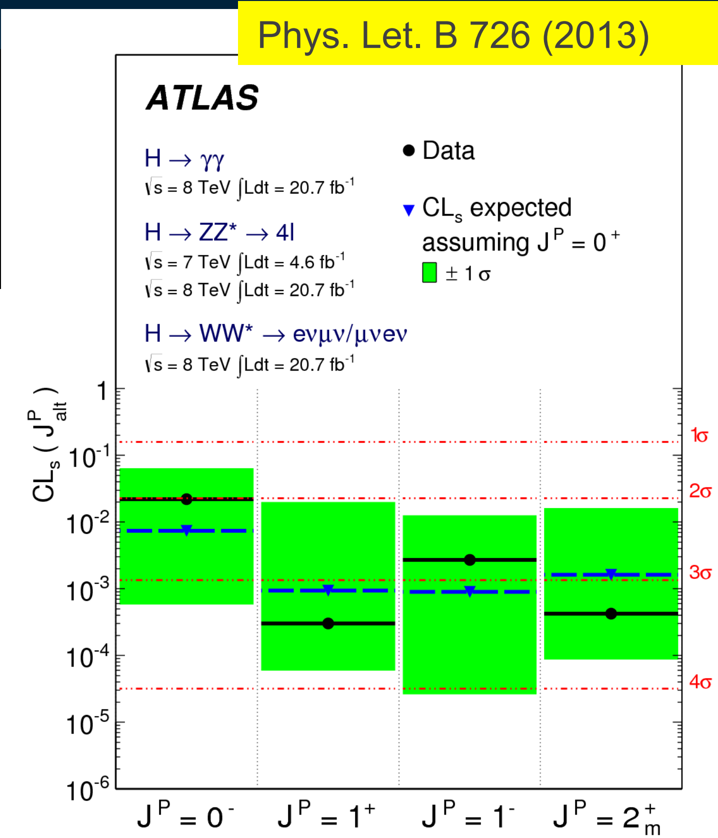


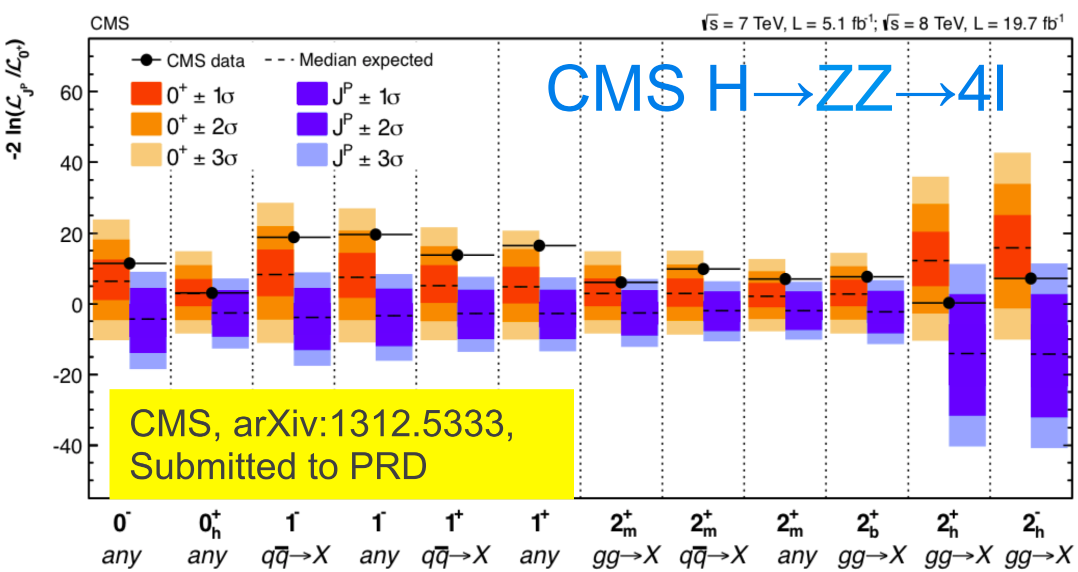
	ATLAS	CMS
CL_s	0.37%	0.09%
$P(0^+)$	0.2σ	-0.9σ
$P(0^-)$	2.8σ	3.6σ

$$CL_s(J^P_{\text{alt}}) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$

Summary J^{PC} measurements

- CMS: 8 alternative J^{CP} hypotheses tested, for spin 0,1 and 2, including production-independent analysis.
- ATLAS: 4 alternative J^{CP} hypotheses tested for spin 0,1 and 2, considering qq, gg initiated productions (and mixtures).
- Data favors SM hypothesis.
  - Exclusion of spin 1 and graviton like resonance at >3σ
  - 0^- excluded at > 2σ level





J^P in H→ZZ→4l

- Spin/parity studies will eventually constrain anomalous coupling parameters in the Higgs sector.
- First example, in the CMS H→ZZ→4l analysis.

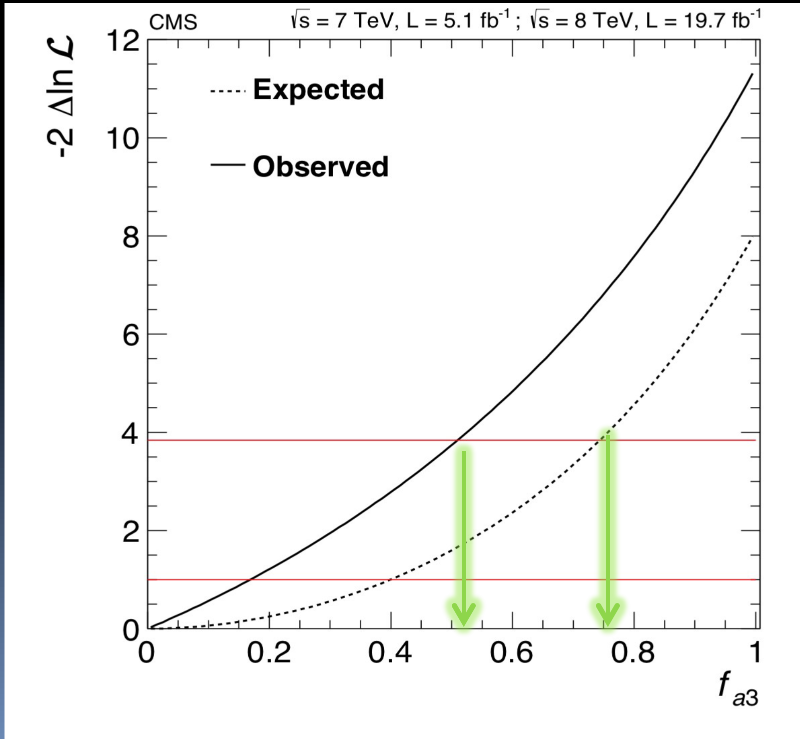
$$A(\mathrm{H} \to \mathrm{ZZ}) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

SM — A-CP even — A-CP odd

- 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).

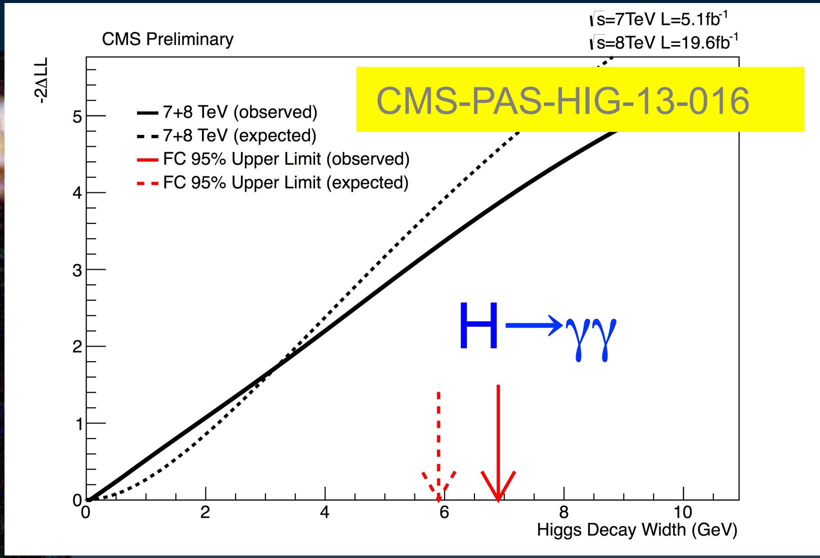


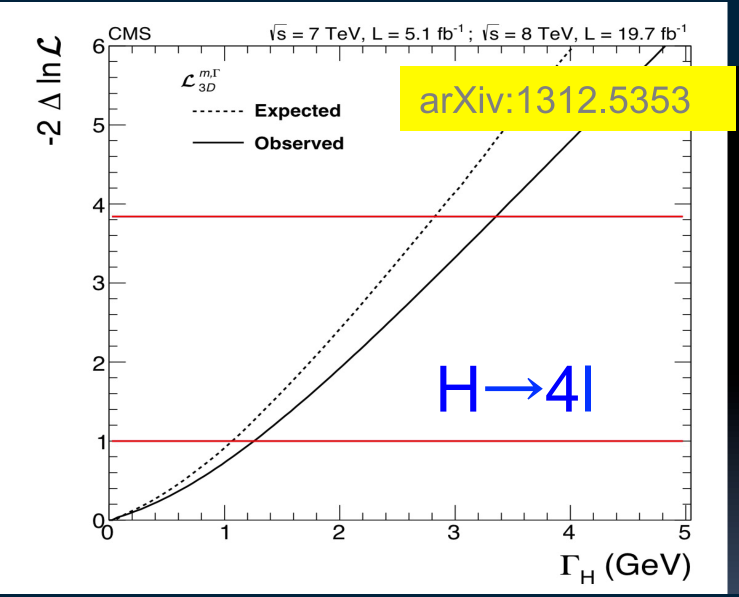
Higgs boson width

- Lack of knowledge of Γ_H introduces degeneracy in the knowledge of the Higgs couplings

$$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

- In the SM Γ_H (125 GeV)~ 4MeV
- Direct measurements limited by experimental resolution (≈ GeV).
  - Current upper limits 3.4(7) GeV from 4l (γγ) decay modes.





- New: Use interference between Higgs resonance in gluon fusion and the continuum back-ground to measure the Higgs width
  - Complements more direct measurements possible at lepton colliders

Total width: interferometry

- Off-shell $H^* \to VV$ (V = W, Z) enhances the H(126) cross-section at high mass [~8% of $\sigma(H\to ZZ)$ found in $m_{ZZ} > 2m_Z$]

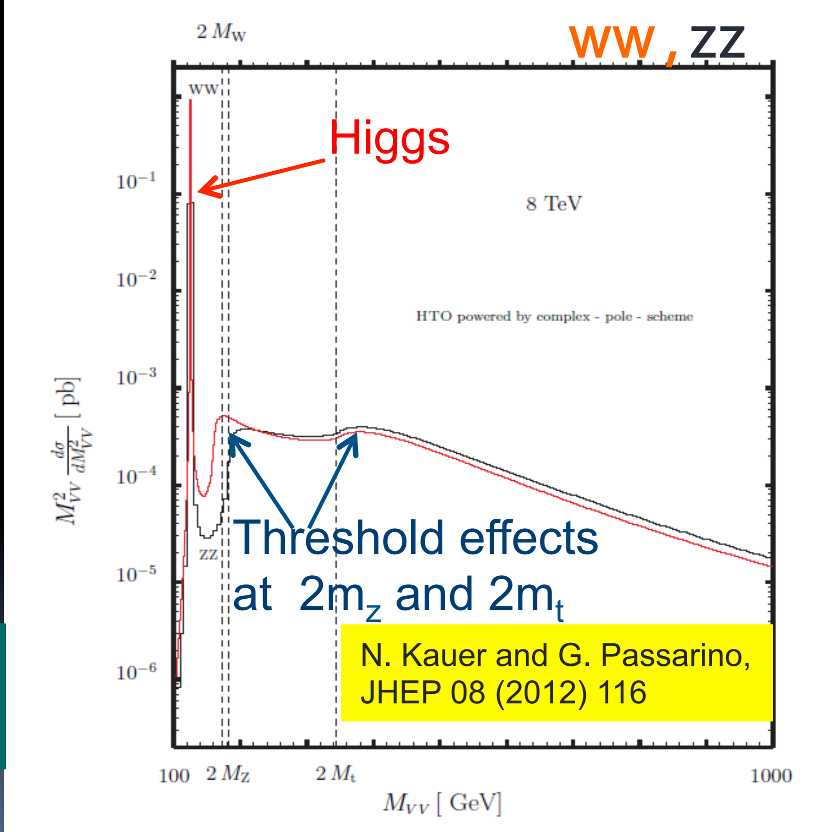
$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

$$\sigma_{gg\to ZZ}^{\text{on-peak}} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma}$$

$$\sigma_{gg\to ZZ}^{\text{off-peak}} \propto g_{ggH}^2 g_{HZZ}^2$$

- Measuring $\dfrac{\sigma_{gg\to H\to ZZ}^{on-peak}}{\sigma_{gg\to H\to ZZ}^{off-peak}}$ contrains Γ_H

gluon-gluon fusion production



N. Kauer and G. Passarino, JHEP 08 (2012) 116

F. Caola, K. Melnikov, Phys. Rev. D88 (2013) 054024
J. Campbell et al. arXiv:1311.3589

More details in Anderson's talk

Total width: interferometry

- Define $\kappa_g = g_{ggH}/g_{ggH}^{SM}$ $\kappa_Z = g_{HZZ}/g_{HZZ}^{SM}$

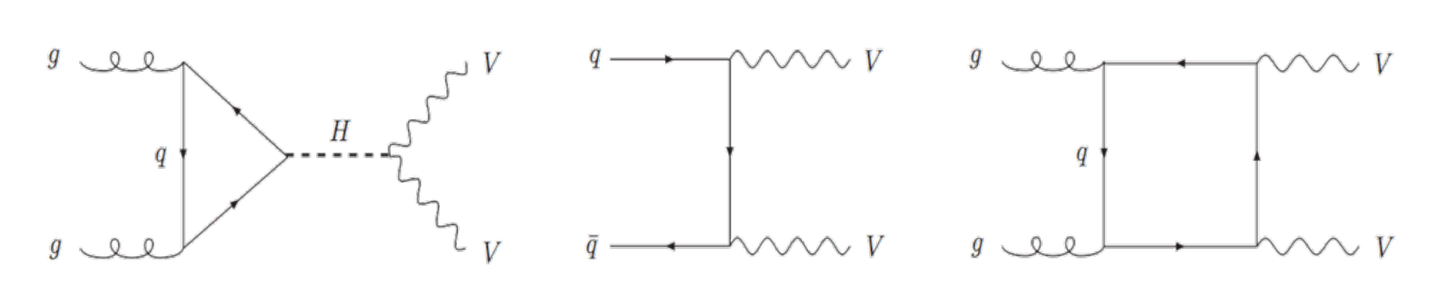
$$r = \Gamma_H / \Gamma_H^{SM}$$

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

$$\frac{d\sigma_{gg\to H\to ZZ}^{off-peak}}{dm_{ZZ}} = \kappa_g^2 \kappa_Z^2 \cdot \frac{d\sigma_{gg\to H\to ZZ}^{off-peak,SM}}{dm_{ZZ}} = \mu r \frac{d\sigma_{gg\to H\to ZZ}^{off-peak,SM}}{dm_{ZZ}}$$

- If μ is known r can be determined. Use μ from H → ZZ →4l
- Expected $\mu = 1.00^{+0.27}_{-0.24}$
- Observed $\mu = 0.93^{+0.26}_{-0.24}$

- Challenges: Interference gg → ZZ (gg2VV/MCFM)



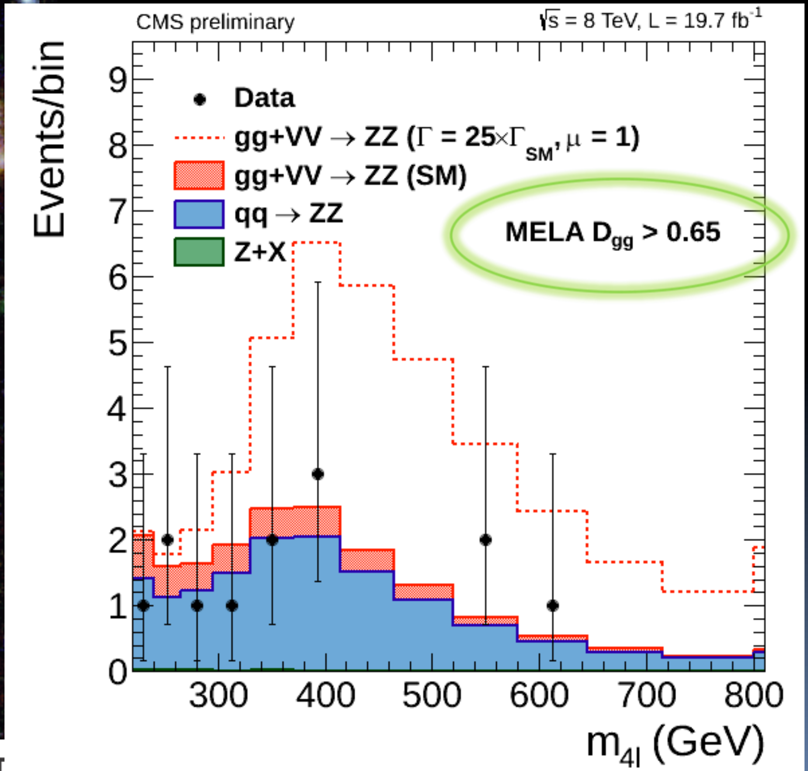
- Effect in VBF ≈10% at high mass (assume $\mu_F=\mu_V$, PHANTOM)
- Fit $P_{tot} = \mu r P_{sig} + \sqrt{\mu r} P_{int} + P_{bkg}$ where P are MC- or data-derived templates

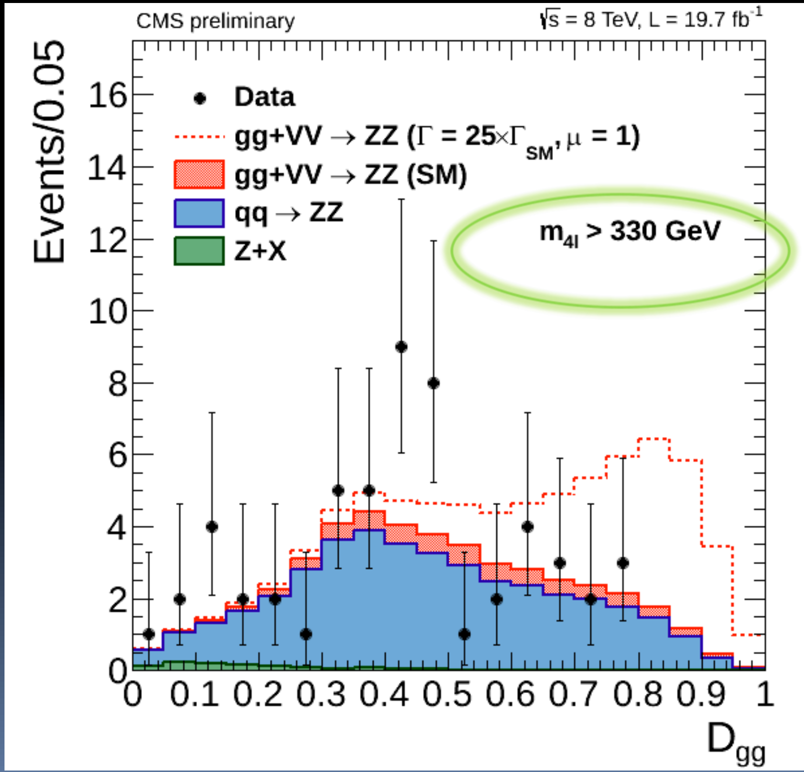
Width in H→ZZ→4l

- H→ZZ→4l analysis (arXiv:1312.5333)
  - Require m(4l) >220GeV
  - Develop NEW MELA discriminant using with 7 kinematics variables (m_{Z1}, m_{Z2}, five angles) to distinguish between gg → ZZ production (signal background and interference) vs qq → ZZ

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

a=10 [a=1 for SM]



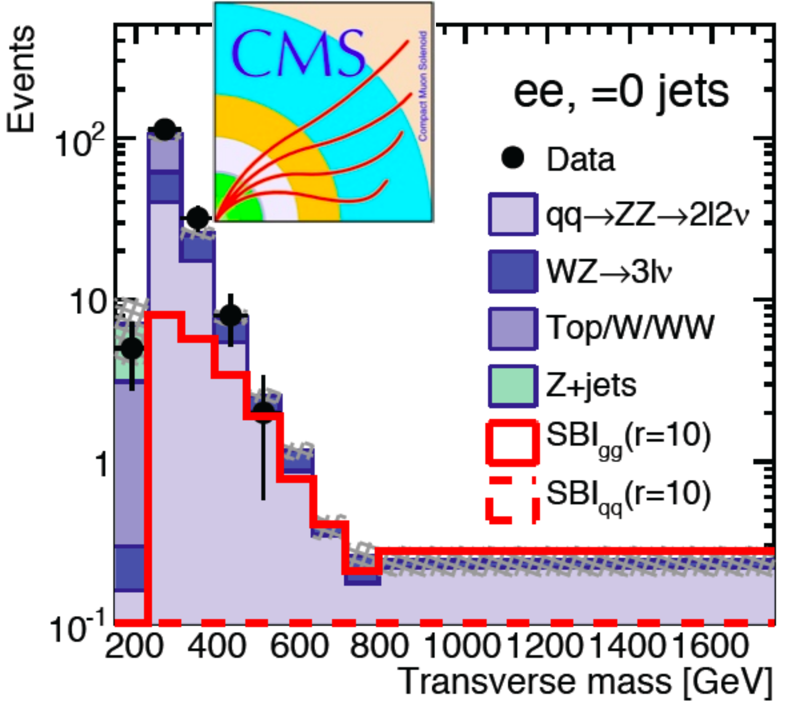


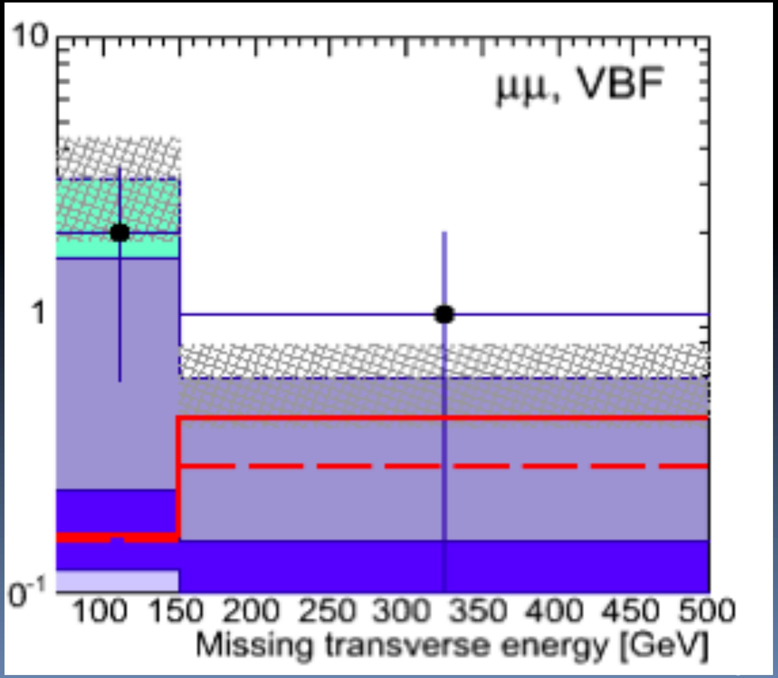
Width H→ZZ→2l2ν

- H→ZZ→2l2ν analysis as described in Eur. Phys. J. C (2013) and CMS PAS-HIG-13-014
  - Require large $p_T(Z)$ and $E_{T,miss}$ (boosted)
  - Veto 3rd lepton and b-tagged jets
  - Split events in 3 categories according to number no. jets (p_T>30GeV and $|\eta|$<4.7)
    - VBF-like: two jet with m_{JJ}>500GeV and $|\Delta\eta_{JJ}| > 4$
    - >=1 jets: excluding VBF-like category
    - 0 jets
  - discriminating variables:
    - m_T for 0 and 1-jet category:

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

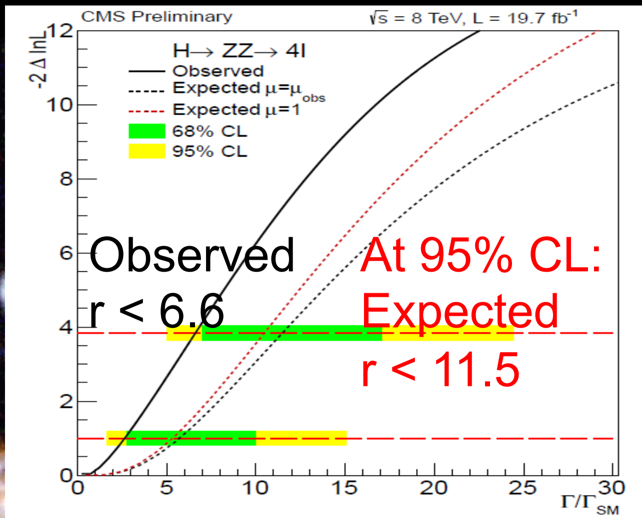
    - $E_{T,miss}$ for VBF-like category



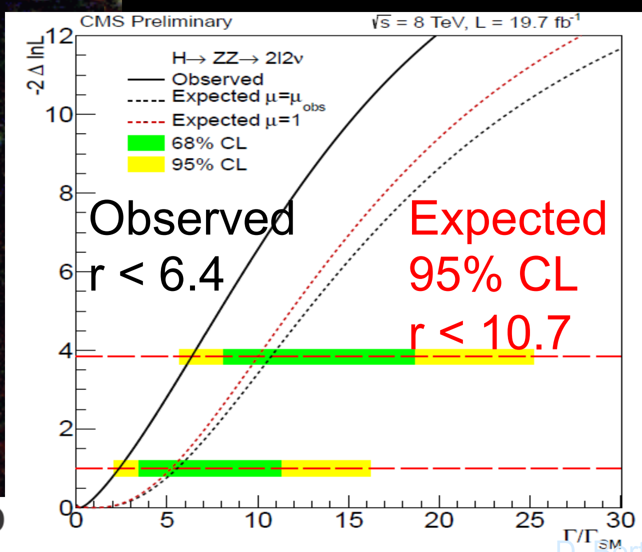


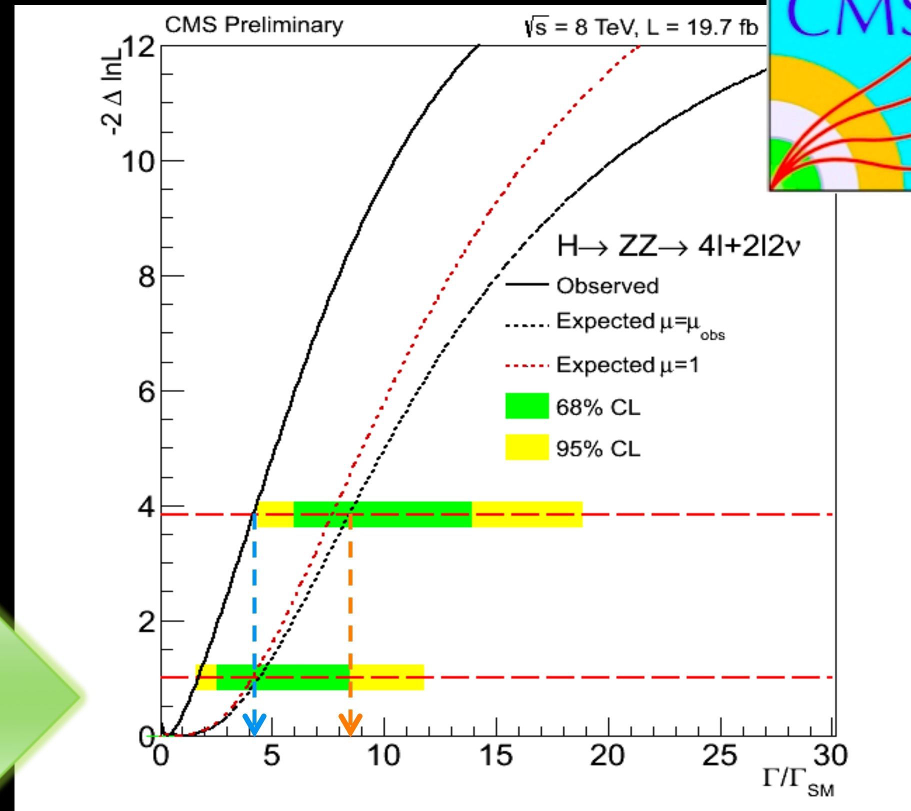
Width $H \to ZZ$

4l : 2D likelihood in m_{4l} and D_{gg}



2l2v : 1D likelihood with m_T or E_{tmiss}





- Combined observed (expected) values
  - $r = \Gamma/\Gamma_{SM} < 4.2$ (8.5) @ 95% CL (p-value = 0.02)
  - $r = \Gamma/\Gamma_{SM} = 0.3+1.5-0.3$
- equivalent to:
  - < 17.4 (35.3) MeV @ 95% CL

= (1.4+6.1-1.4) MeV

Conclusions

- Run1 of the LHC has brought the discovery of the new boson and the first measurements of its properties
  - Expect precision measurements of Higgs boson mass to ≈ 0.2% from LHC Run 1 combination.
  - Spin/parity of new boson consistent with 0^+.
  - A few alternative models have been tested and experiments are moving towards setting limits on anomalous couplings.
  - A new technique to constrain the Higgs boson width from non-resonant ZZ production has emerged
- The large luminosity of the HL-LHC upgrades will eventually
  - Allow the transition into precision Higgs physics More fully test the consistency of the new particle with the SM Higgs boson.
  - Measurements of rare Higgs boson decays
  - Study of the Higgs self coupling
- Work will be required to bring down the theory uncertainties as well

Conclusions

- Run ... the new
  bos ... ties
  - Ex ... ass to ≈
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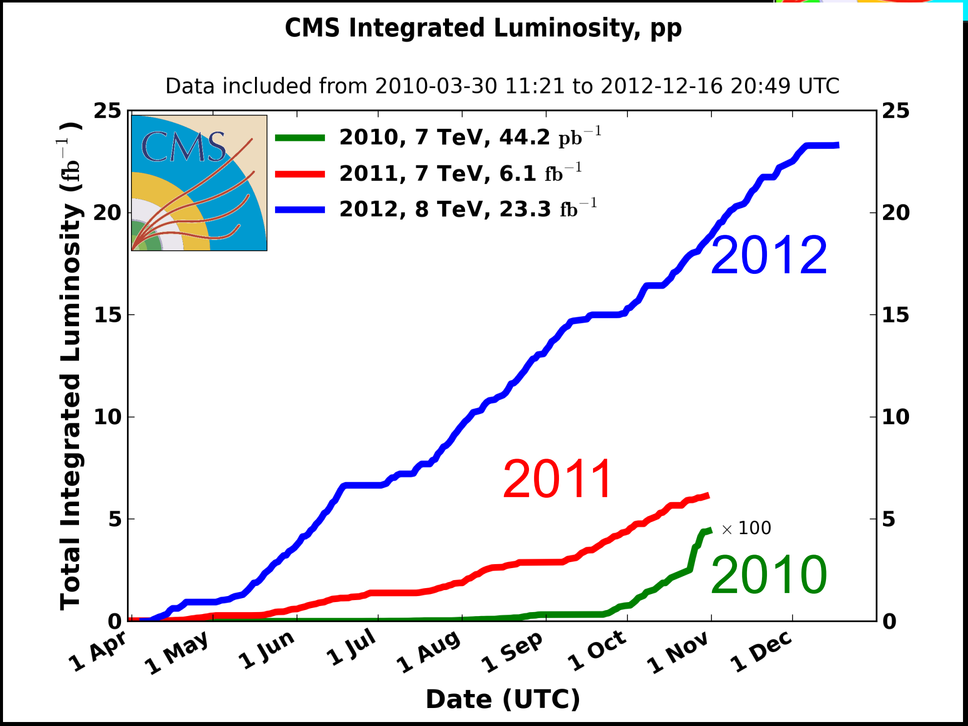
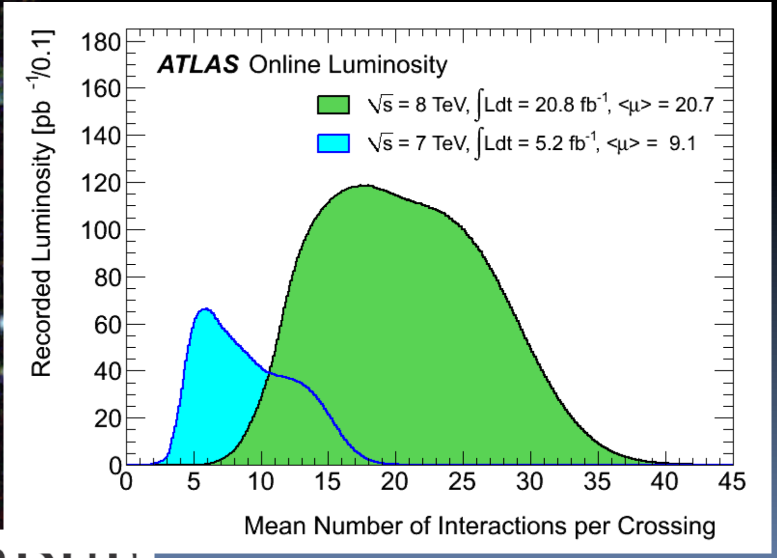
BACKUP

LHC Run 1 data set

- Spectacular performance of the machine and the detectors
- ~90% of the delivered data available for offline analysis.
- Available dataset: ~5fb^{-1} $\sqrt{s}$ = 7TeV + ~20fb^{-1} $\sqrt{s}$ = 8TeV

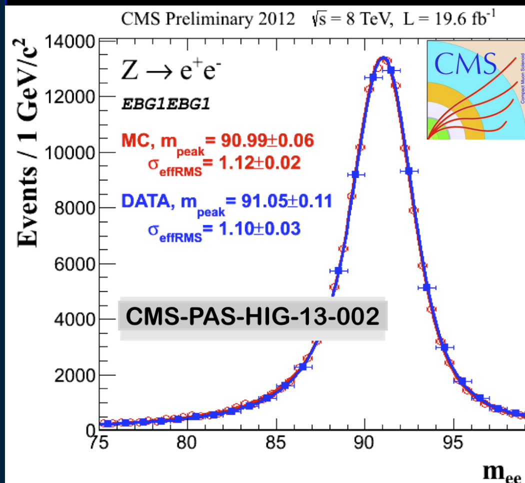


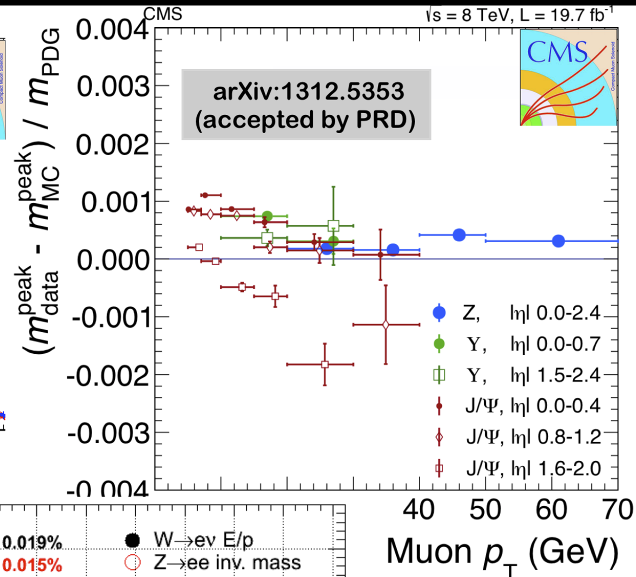


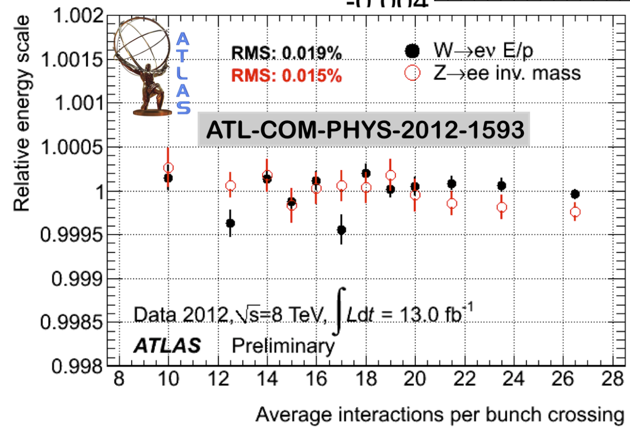
- Challenging pile-up conditions.
  - Up to 30 average interactions per bunch-crossing.
  - Development of pile-up safe analysis techniques

Mass resolution and scale uncertainties

- CMS: **e/γ** energy estimated using multivariate regression
- ATLAS: weighted sum of energy deposits in the different calorimeter layers
- Scale and resolution is obtained from **W; Z; J/psi** and Upsilon resonances
- Additional smearing is applied to MC to match the resolution in data
- Resulting systematic uncertainty on mass measurements is 0.5% per channel (H →γγ and H→ 4**l**)







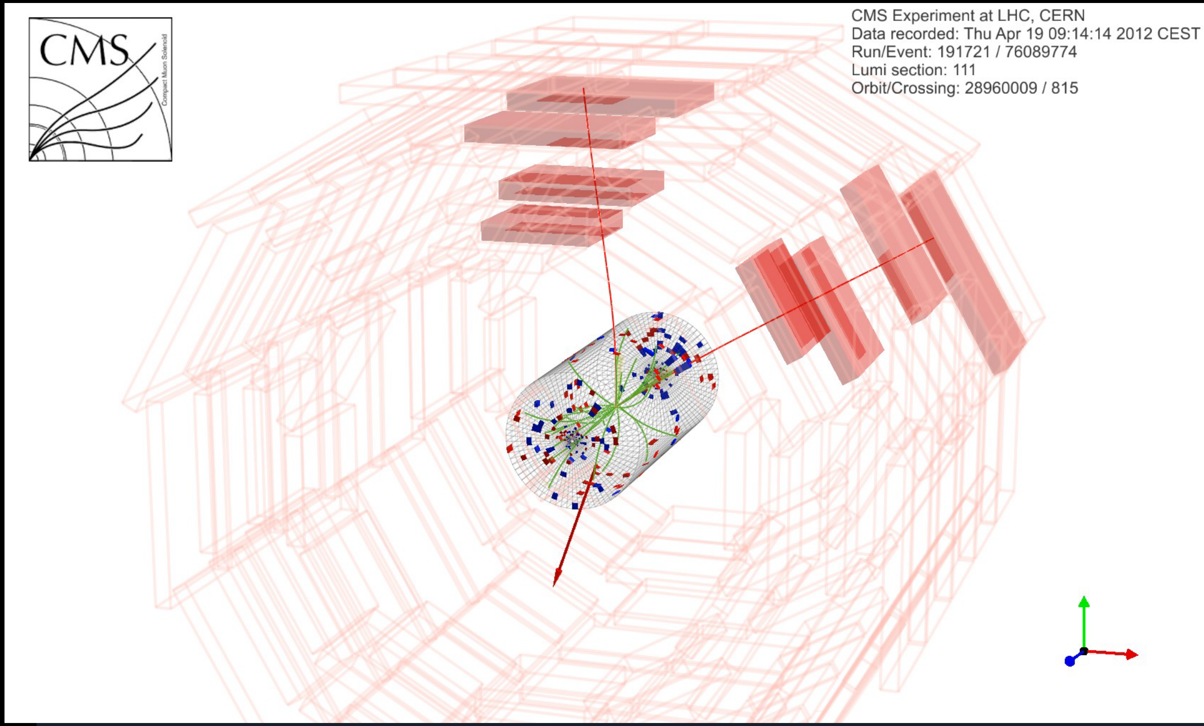
H→4l Mass Measurement

- Systematics
  - Electron energy corrections.
    - MC 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.

	ATLAS PLB 726 (2013), 88-119		**CMS** arXiv:1312.5353	
Mass [GeV]	$124.3^{+0.6}_{-0.5}(stat) \pm 0.7^{+0.5}_{-0.3}(sys)$		$125.6 \pm 0.4(stat) \pm 0.2(sys)$	
Sys. Uncertainty	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%

J^P in $H \rightarrow WW \rightarrow l\nu l\nu$

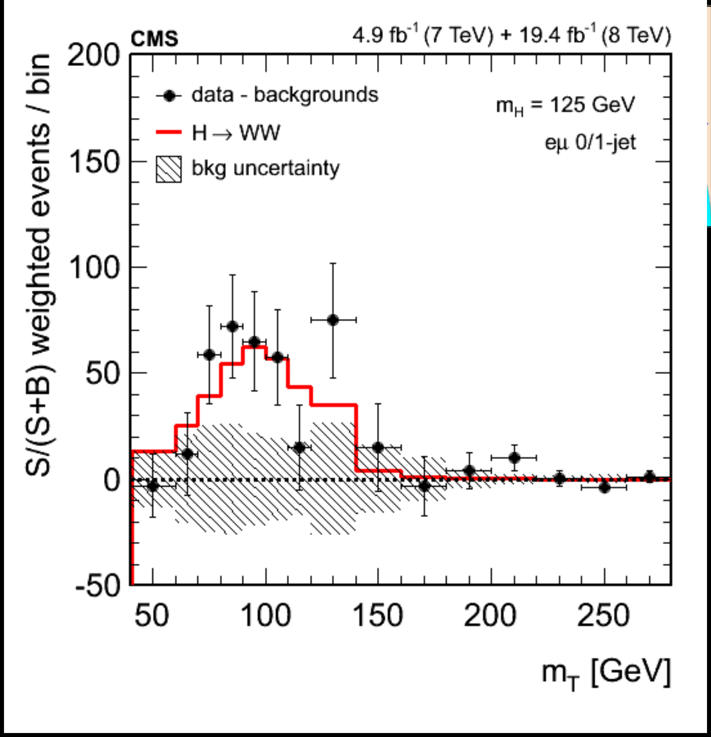
- Distinct signature:
  - Two high p_T leptons
  - Missing transverse energy.
- Large branching fraction.
- Poor mass resolution.
- Large backgrounds.
- Angular correlation between final state leptons provides information on the polarization of the resonance.

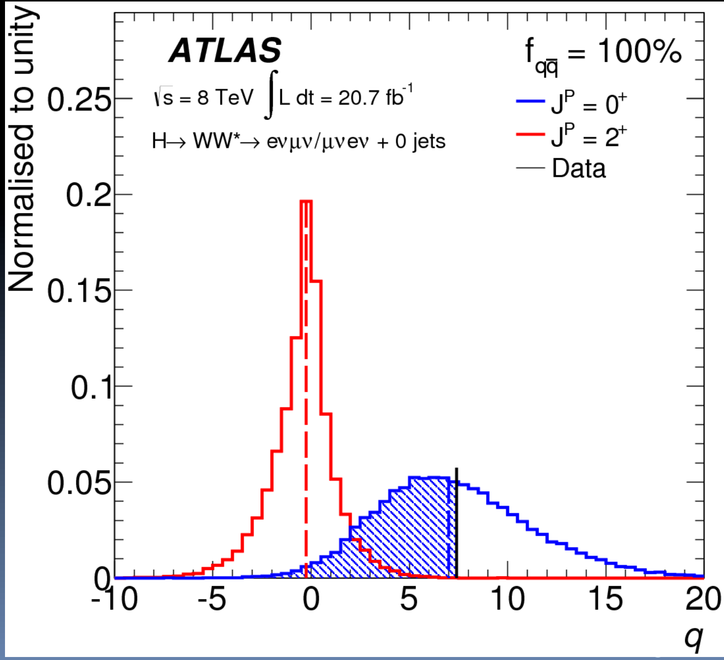


- Challenges:
  - Missing energy resolution.
  - Background modeling

J^P in $H \rightarrow WW \rightarrow l\nu l\nu$

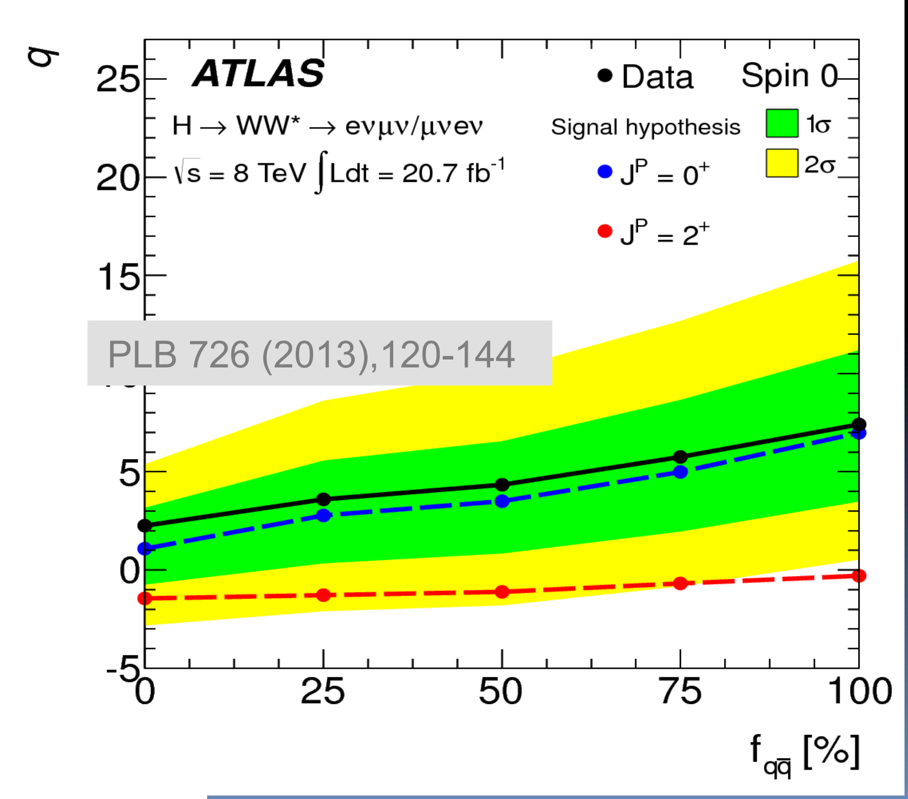
- Analysis strategy:
- Select two high p_T, different flavor leptons plus missing E_T.
  - CMS: categorize events in 0 and 1 jet bins
  - ATLAS: no categorization in number of jets.
- Hypothesis test from 2D template fit to data:
- CMS: m_{ll} vs m_T
- ATLAS: use two BDT discriminants ($\Delta\phi_{ll}$, m_{ll}, m_T)
  - DT0 (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.

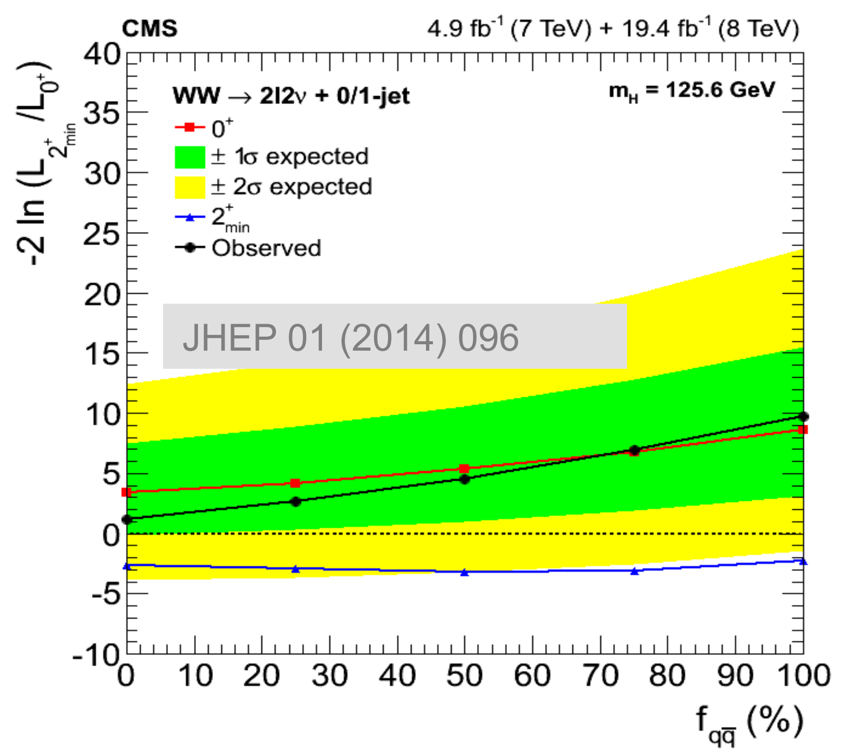




J^P in H→WW→lνlν

- 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.





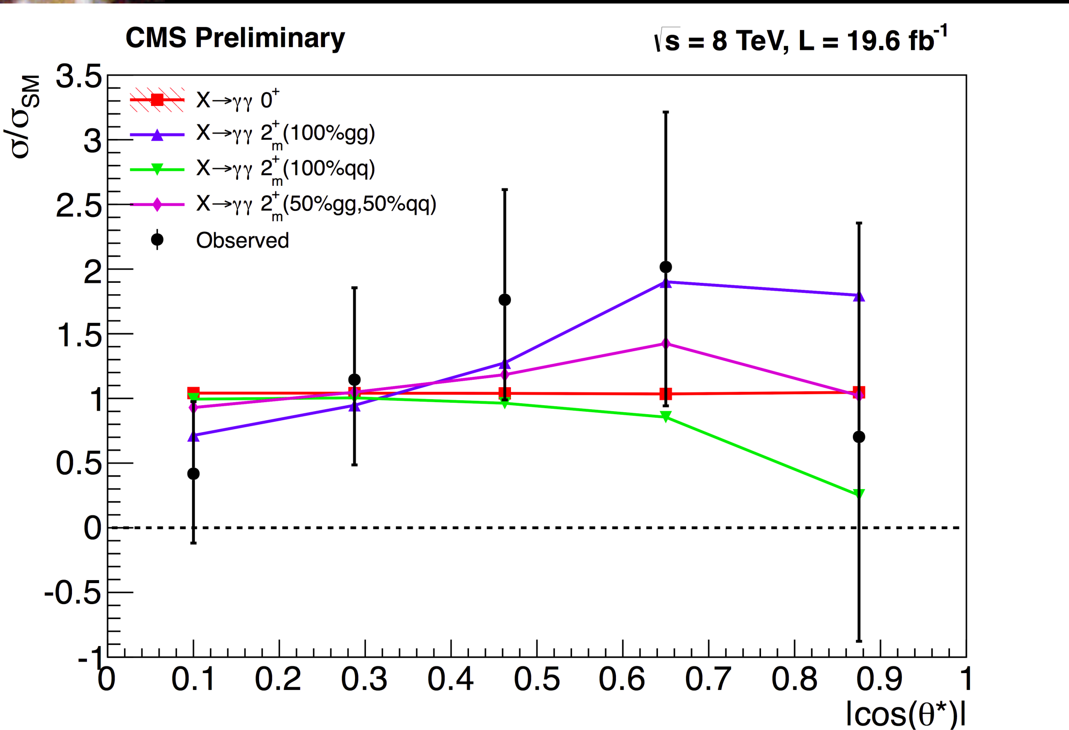
J^P in $H \rightarrow \gamma\gamma$

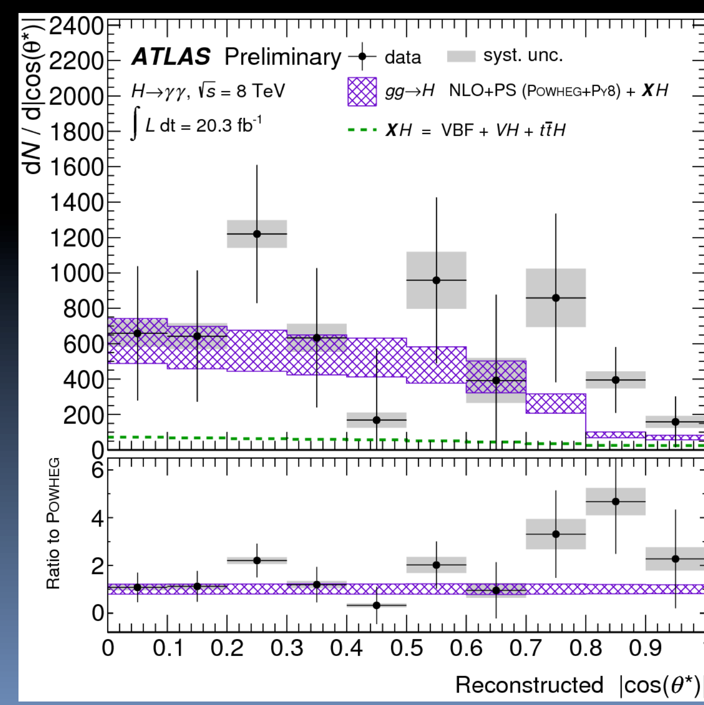
- Distribution of production angle sensitive to spin/parity.
- Event selection similar to mass analysis.
- ATLAS: no categorization in photon kin. or resolution
- CMS: simple 4 categories cut-based categorization
- Hypothesis test:

$$\cos\theta^* = 2\frac{E_2 p_{z_1} - E_1 p_{z_2}}{m_{\gamma\gamma}\sqrt{m_{\gamma\gamma}^2 + p_{T\gamma\gamma}^2}}$$

- CMS: simultaneous fit to $m_{\gamma\gamma}$ in 5 $\cos(\theta^*)$ bins

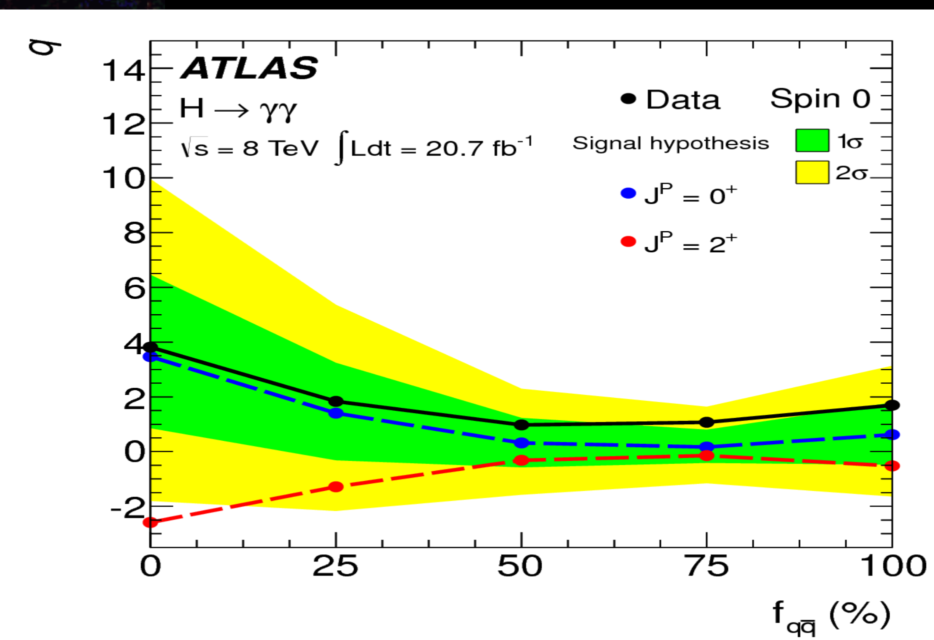
- ATLAS: 2D fit of $\cos(\theta^*)$ vs $m_{\gamma\gamma}$

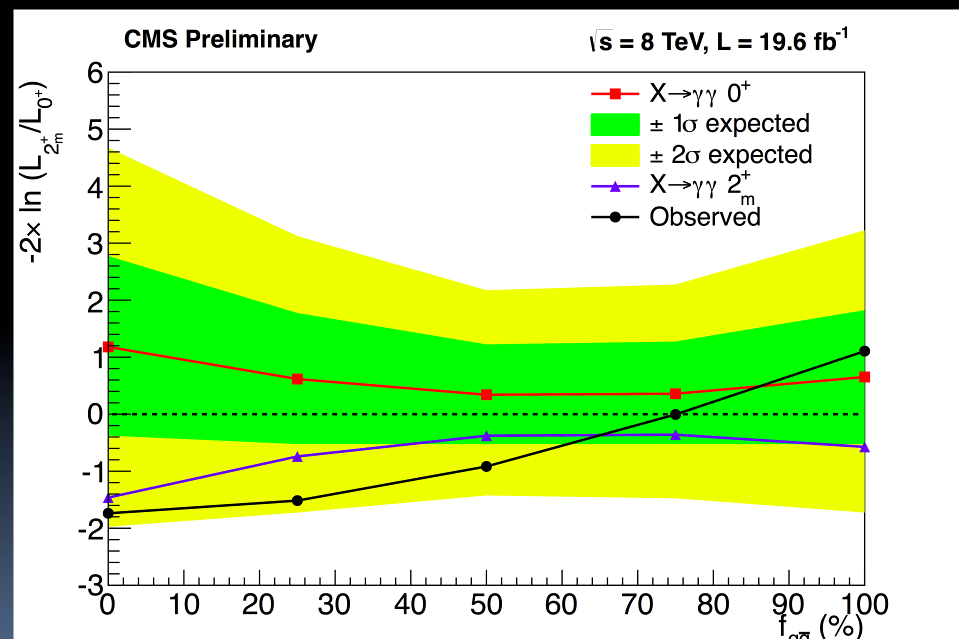




J^P in $H\to\gamma\gamma$

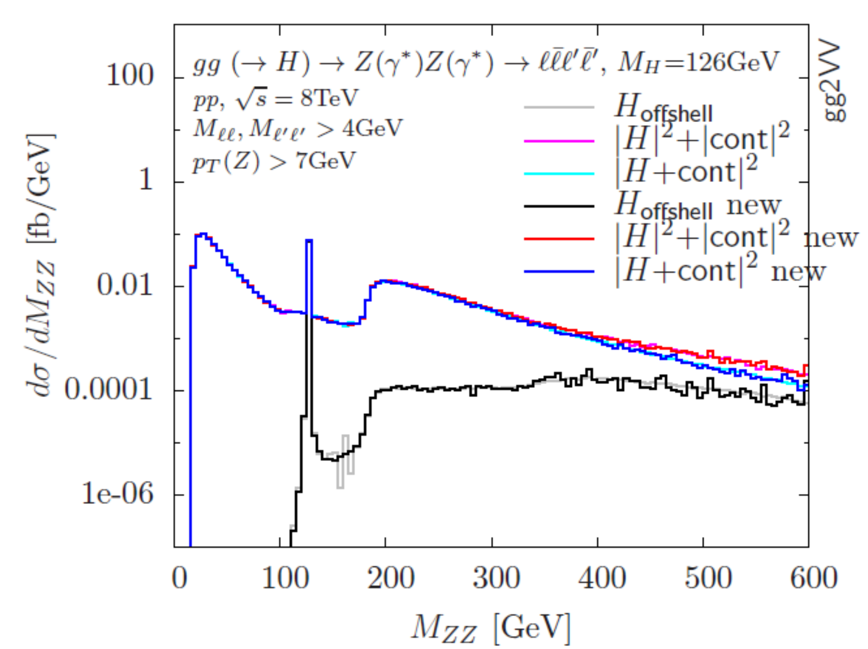
- Post-fit) Expected separation: 1-CLs > 17(55)-60(99)% for CMS
- (ATLAS).
- Better sensitivity for ATLAS analysis partially driven by higher observed excess.
- SM hypothesis generally favored in data.

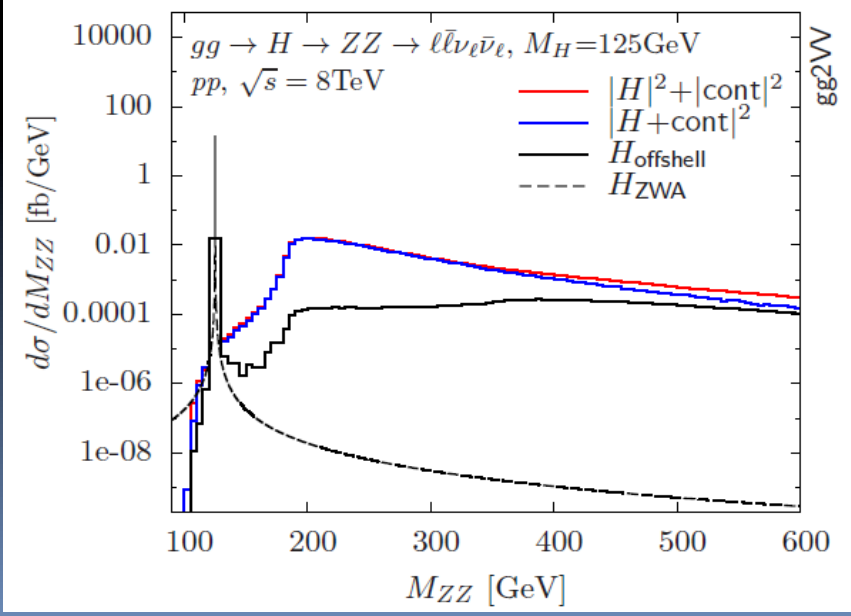




The 4l and 2l2ν final states

- 4l final state (l = e, μ)
  - At high mass, basically only background is qq → ZZ (known at NLO, QCD uncertainties at the level of %)
  - Fully reconstructed state →can use matrix element probabilities of lepton 4-vectors to distinguish between gg and qq production
- 2l2ν final state (l = e, μ)
  - Much larger BR (x6) but smaller acceptance (tight p_T selection)
  - Rely on transverse mass distributions



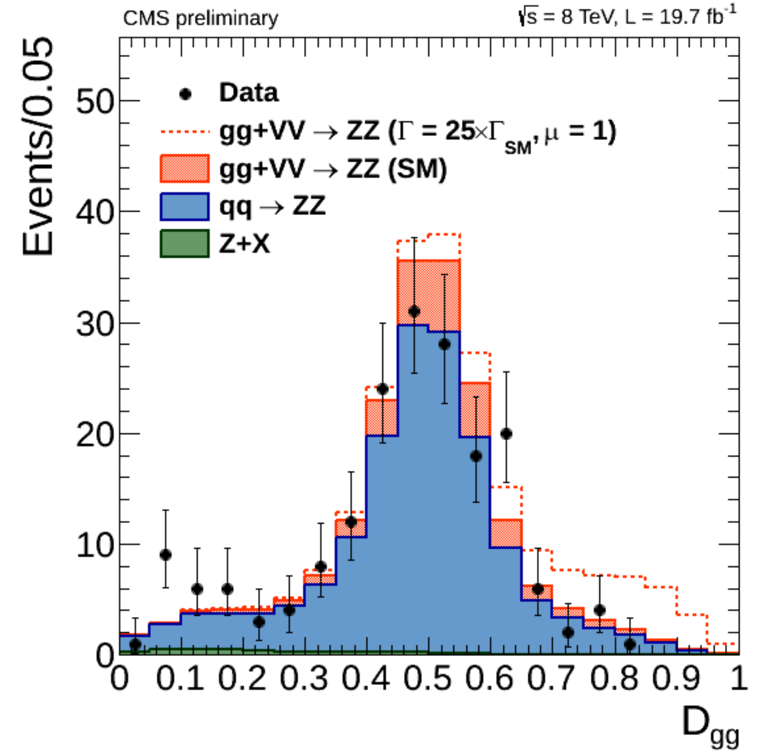


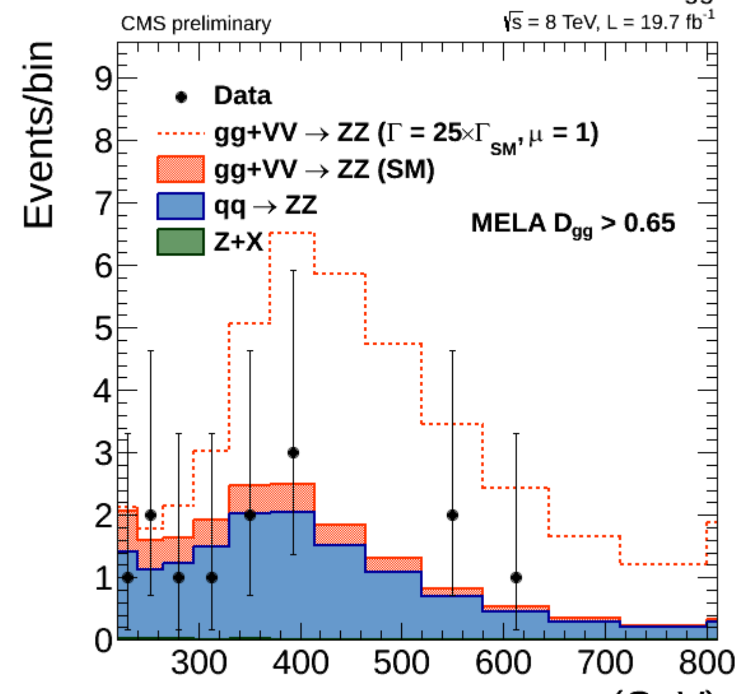
Width 4l analysis

- No changes in selection w.r.t. CMS collab. , arXiv:1312.5353
- Lepton p_T cuts, Z invariant masses, impact parameter significance, loose isolation
- In the matrix element likelihood approach (MELA), design a specific discriminant for gg → ZZ production:

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

- Built with 7 variables completely describing kinematics (m_{Z1}, m_{Z2}, five angles)
- $P_{gg,(qq)}$ are joint probabilities for gg → ZZ, signal + background + interference (qq → ZZ) from MCFM matrix elements

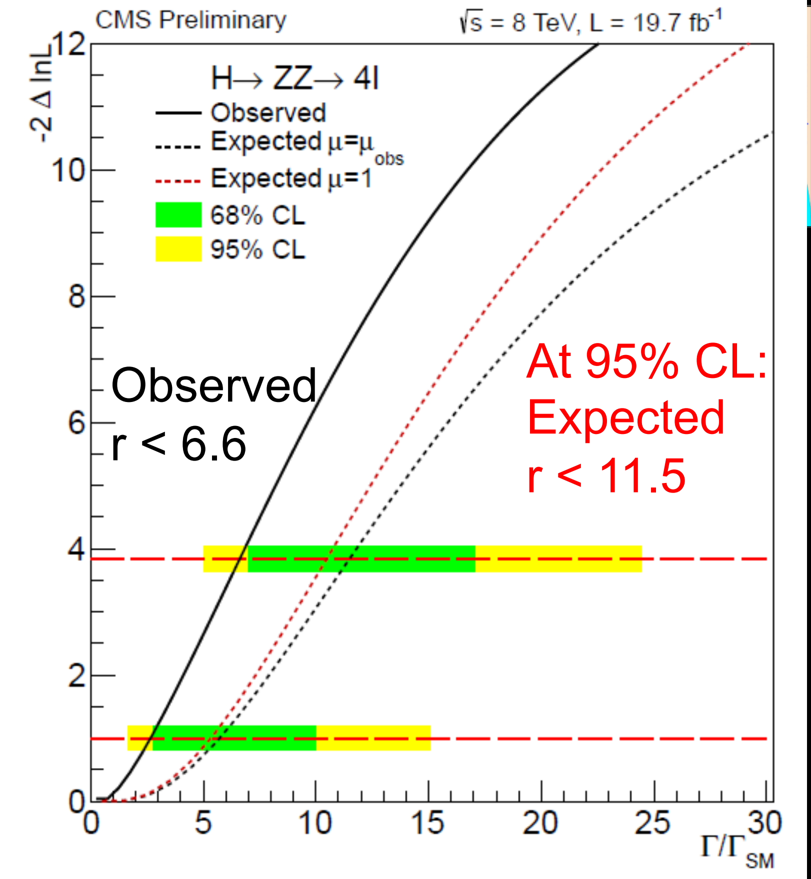




Width H→ZZ→4l

Main systematic uncertainties:

- QCD scale and PDFs for qq → ZZ and gg →ZZ
- μ uncertainties 4l low-mass paper
- Uncertainty on k-factor approximation for gg → ZZ continuum
- Experimental uncertainties (lepton trigger/reconstruction efficiencies etc.)



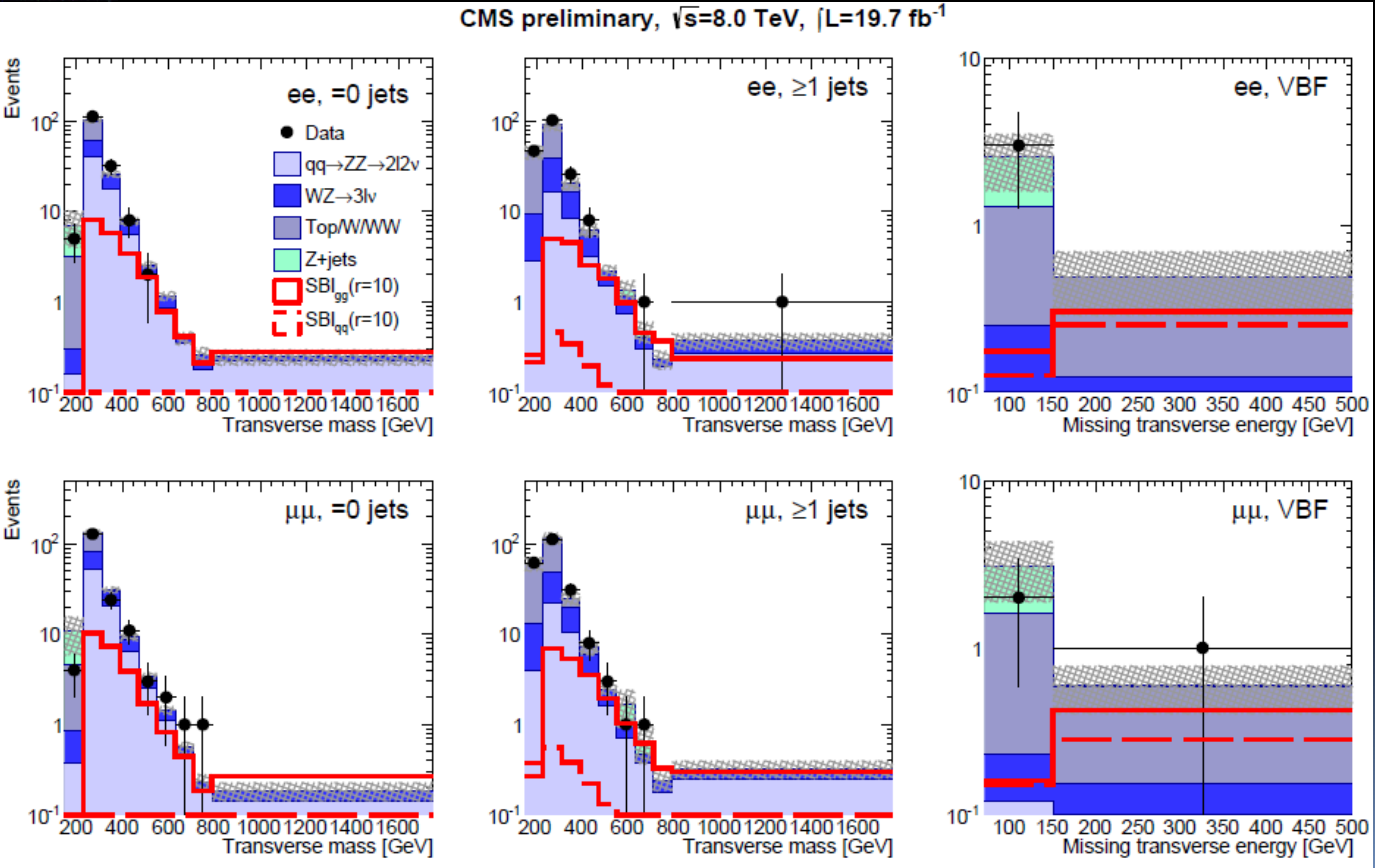
		Full region	Signal-enriched region
	$gg + VBF \to 4\ell$ (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	$2.22^{+0.15}_{-0.17}$	$1.20^{+0.08}_{-0.09}$
	$gg + VBF \to 4\ell$ (background)	$31.1^{+3.0}_{-3.1}$	2.12 ± 0.21
(a)	$gg + VBF \to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	$29.6^{+2.8}_{-2.9}$	$1.73^{+0.16}_{-0.17}$
	$gg + VBF \to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 15$)	$51.8^{+4.9}_{-5.0}$	13.1 ± 1.1
(b)	$q\bar{q}$	154.7 ± 7.4	8.6 ± 0.4
(c)	Reducible background	3.7 ± 0.6	0.44 ± 0.08
(a+b+c)	Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)	188.0 ± 7.9	10.8 ± 0.4
	Observed	183	8

Width $H \to ZZ \to 2l2\nu$

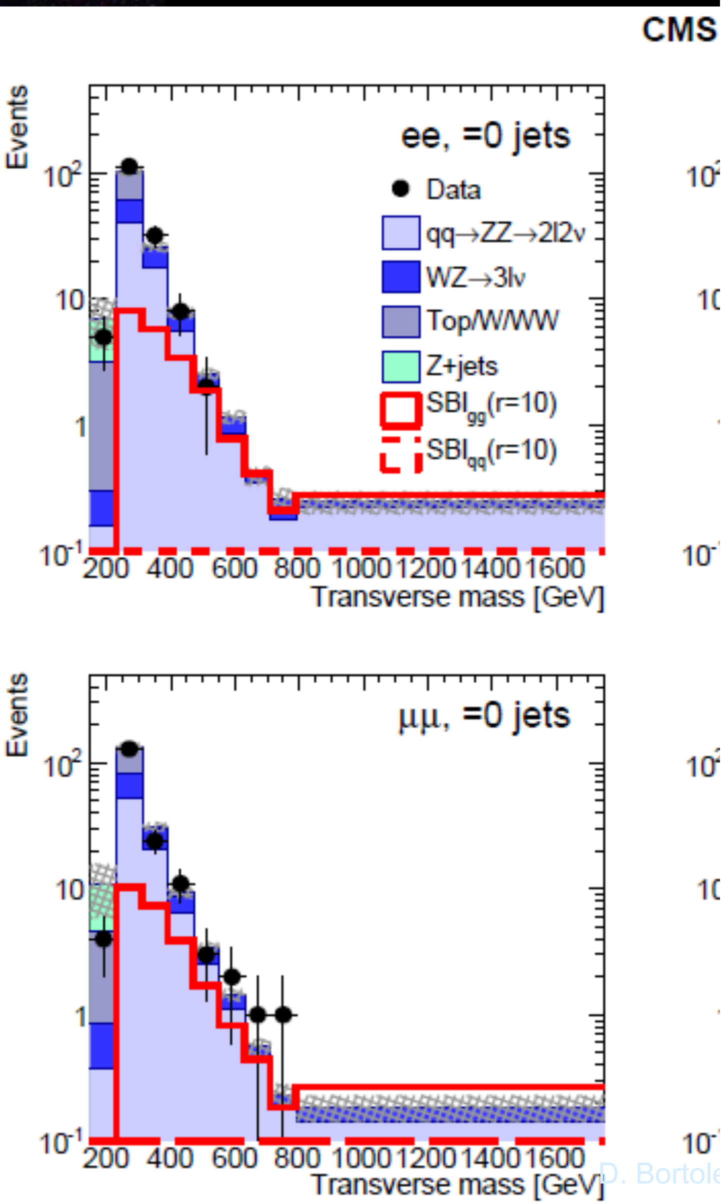
- No changes in selection to CMS PAS-HIG-13-014
  - Large $p_T(Z)$ and $E_{T,miss}$
  - Vetoing 3rd lepton and b-tagged jets (removing Z+heavy-flavor jets)
  - Events split in three purity categories according to number of selected jets ($p_T > 30$ GeV and $|\eta| < 4.7$)
    - VBF-like: two jets with $m_{JJ} > 500$ GeV and $|\Delta\eta_{JJ}| > 4$
    - >=1 jets: excluding events in VBF-like category
    - 0 jets
  - Data-derived estimation of reducible backgrounds (double and single top, WW, W+jets, Z+jets), $qq \to ZZ$ and WZ from MC
  - Fit the distribution of the transverse mass for 0 and 1-jet category

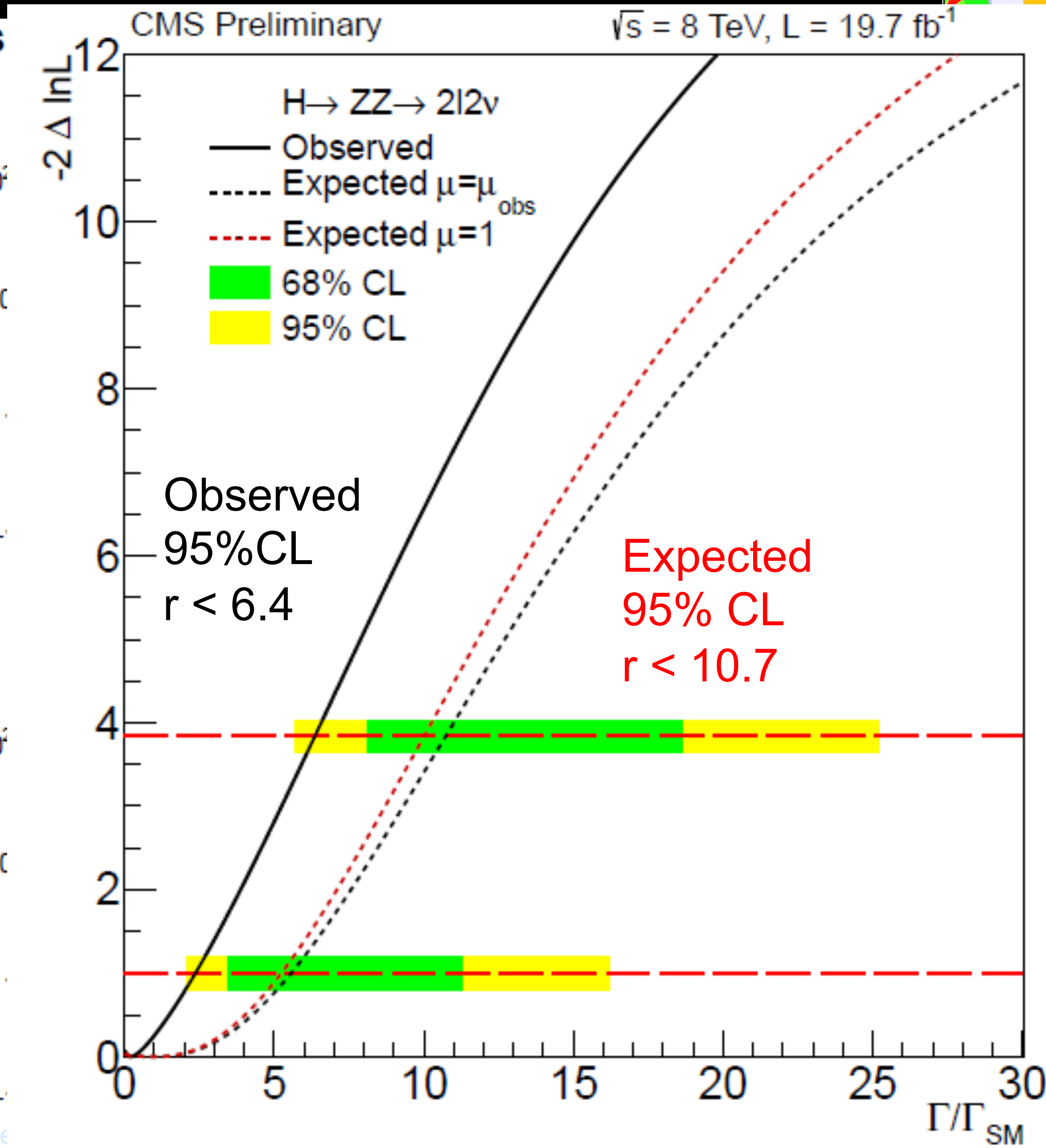
$$m_{\mathrm{T}}^2 = \left[\sqrt{p_{\mathrm{T},\ell\ell}{}^2 + m_{\ell\ell}{}^2} + \sqrt{E_{\mathrm{T}}^{\mathrm{miss}\,2} + m_{\ell\ell}{}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\mathrm{miss}}\right]^2$$

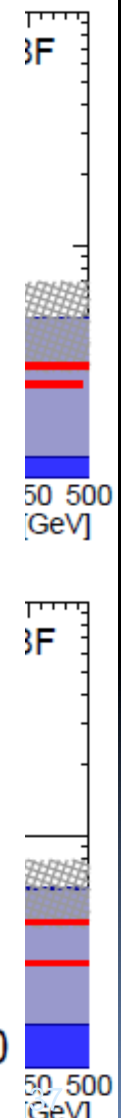
Width H→ZZ→2l2ν



Width $H \rightarrow ZZ \rightarrow 2l2\nu$

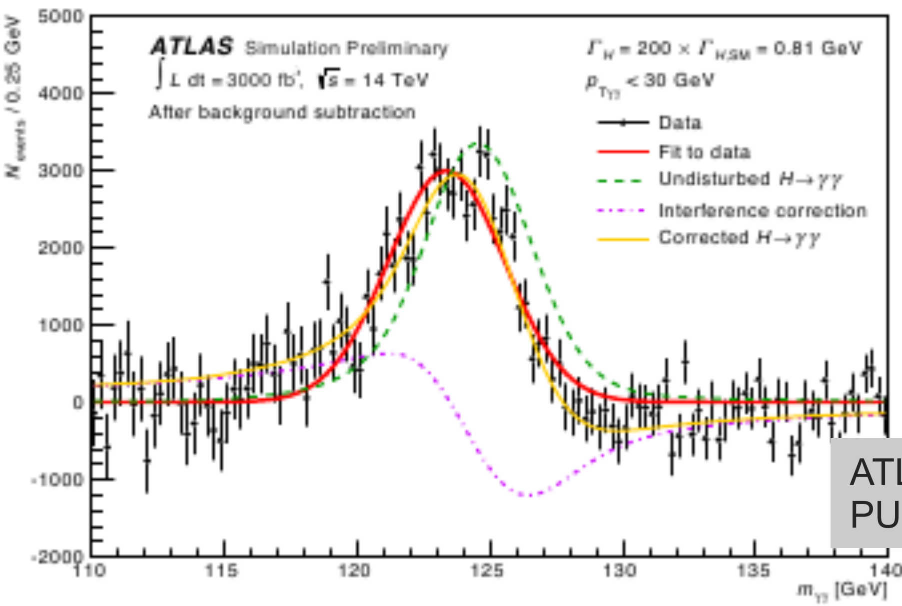


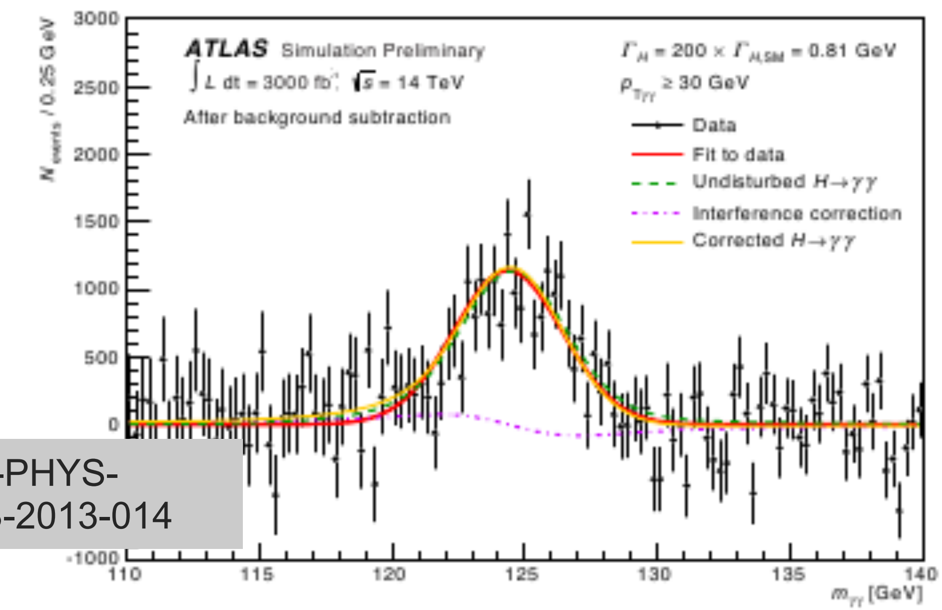




Interferometry - di-photon

- Can also exploit destructive interference between $gg \rightarrow \gamma\gamma$ and $gg \rightarrow H \rightarrow \gamma\gamma$.
- 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).

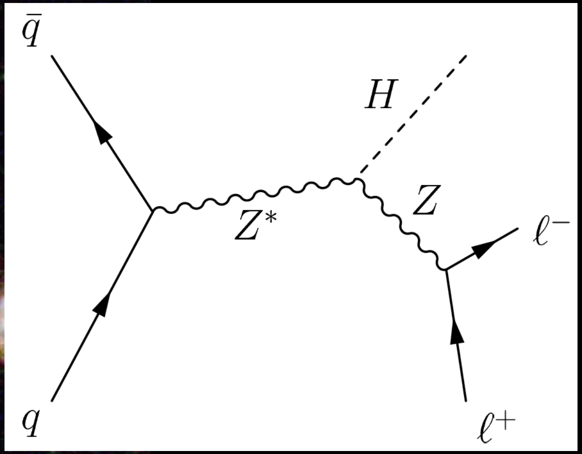


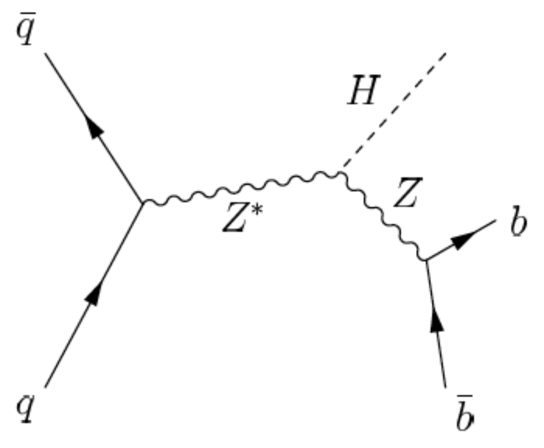


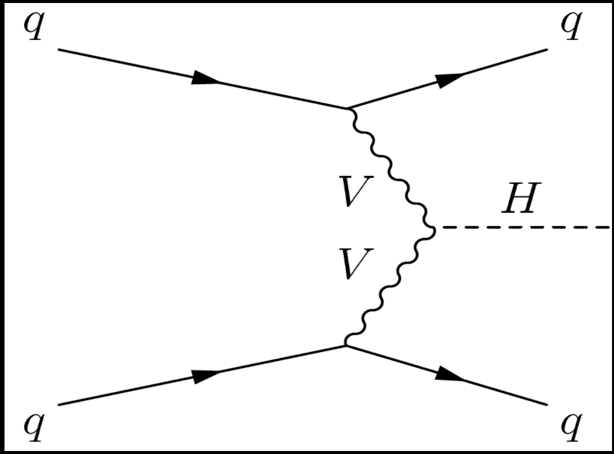
ATL-PHYS-PUB-2013-014

Invisible Higgs decays

- Look for decays of Higgs boson to weakly interacting particles B(H→inv) using VBF and ZH production.



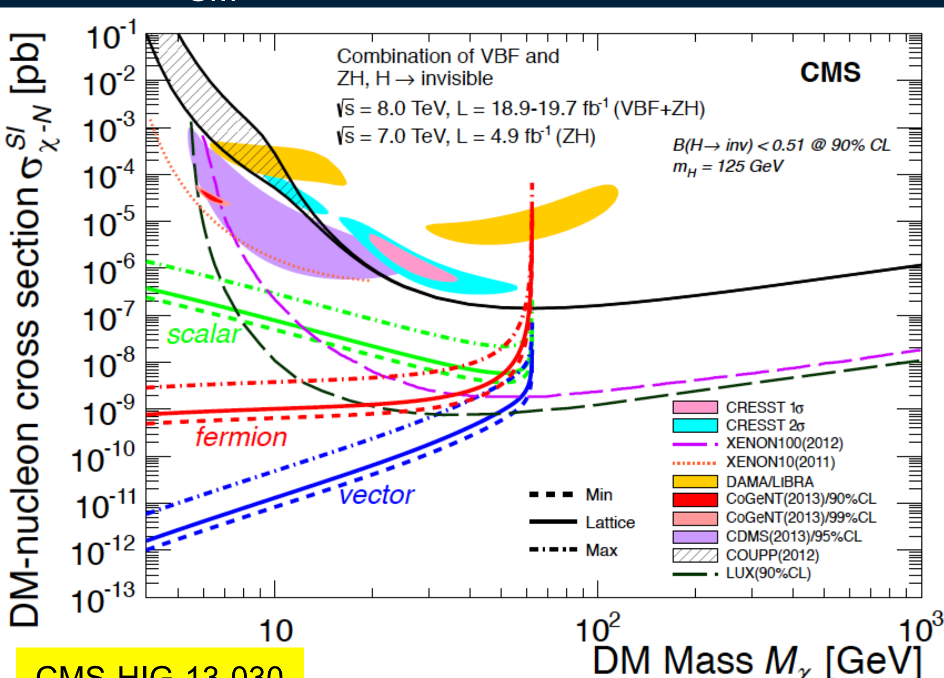




- Complementary to direct searches for dark matter.
  - Exploited channels:
    - ATLAS: Z(ll) + MET
    - CMS: Z(ll,bb) + MET, VBF + MET
- Direct constraint on B(H→inv) can also be obtained from global fit of measured decay modes

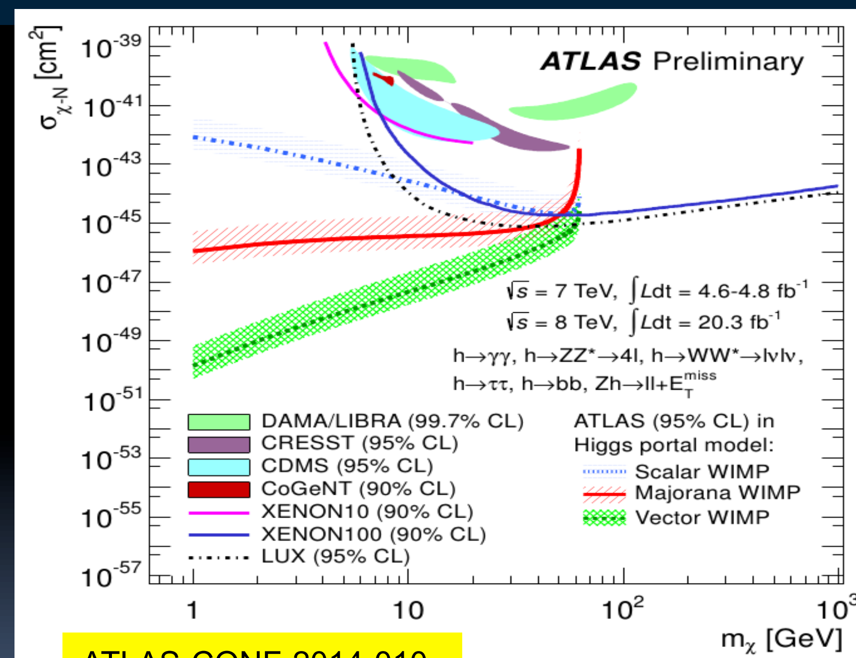
Invisible Higgs Decay

- CMS:
  - combination of Z(ll)+ MET, Z(bb) +MET and VBF + MET searches yields
  - Observed (expected) **B(H→inv)/**σ_{SM} <0.58 (< 0.44) @ 95% CL



CMS-HIG-13-030

- ATLAS:
  - Combination of direct and indirect results
  - Observed (expected) limit B(H→inv) <0.41(0.55) at 95% CL



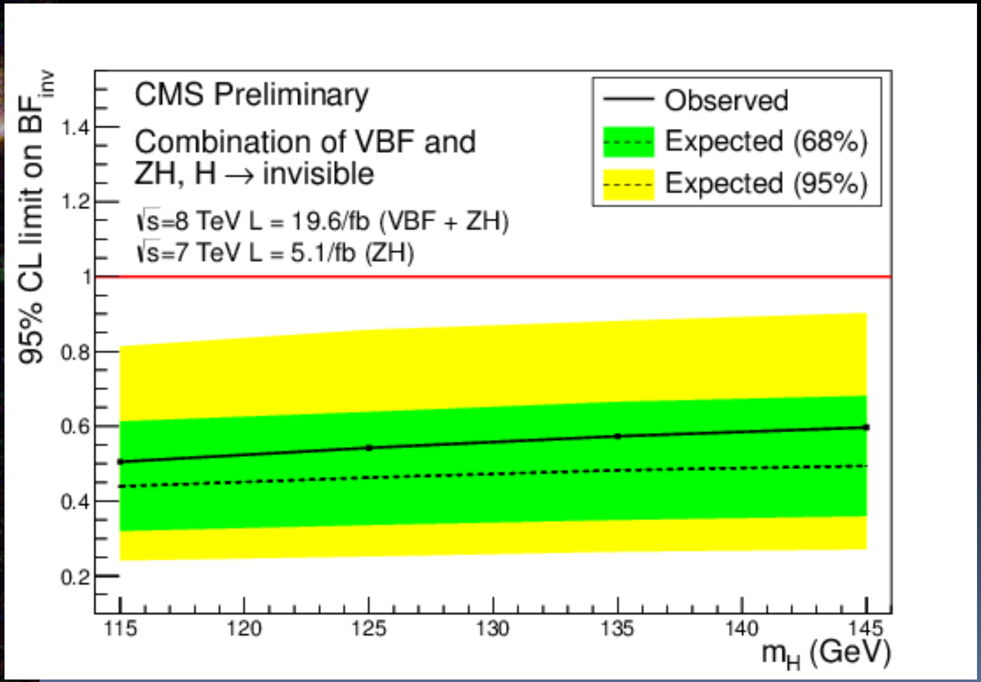
ATLAS-CONF-2014-010

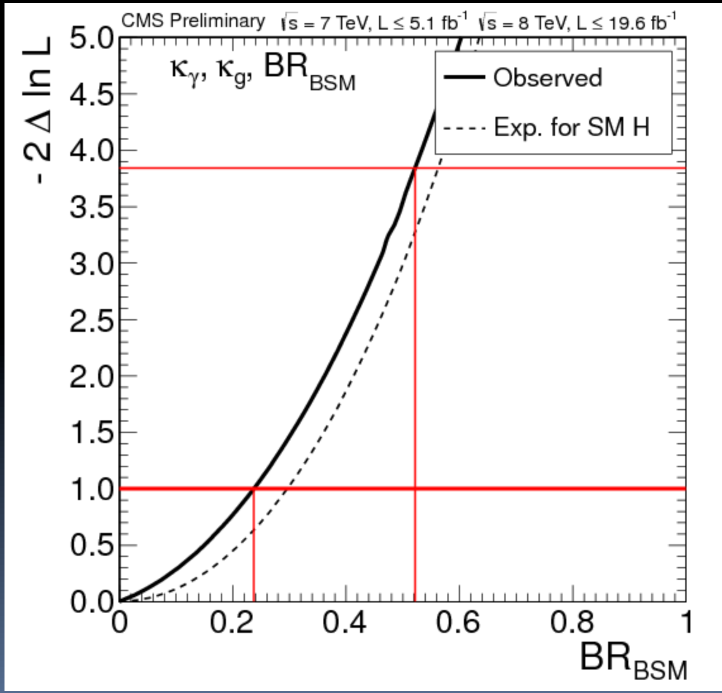
- Re-Interpret B(H→inv) limit in Higgs-portal model:
  - DM sector decoupled from SM, except for Higgs-mediated interactions with $m\chi < m_{H/2}$

- Djouadi, A. Falkowski, Y. Mambrini, and J. Quevillon
- B. Patt and F. Wilczek

Direct and indirect constraints

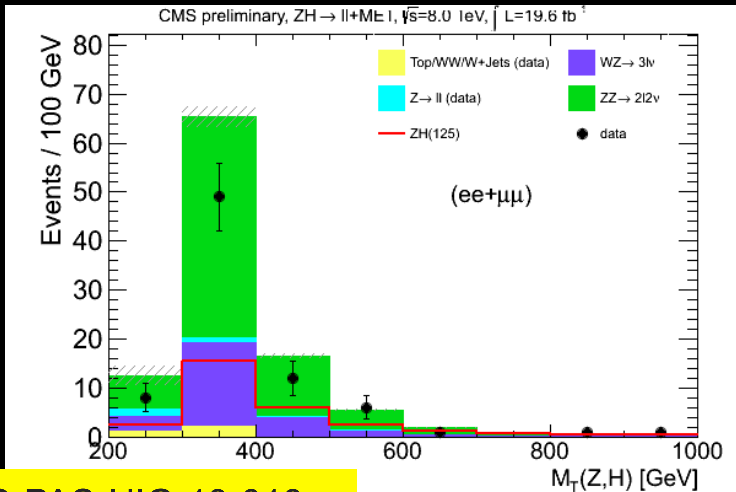
- Indirect constraint on BRinv can also be obtained from global fit of measured decay modes.
- Fixing unmeasured modes to SM predictions and assuming k_V<1.
- Direct and indirect limits have comparable magnitudes

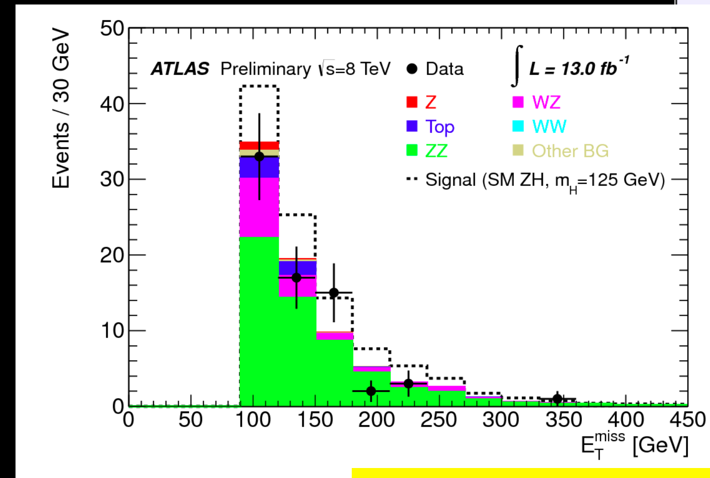




CMS-PAS-HIG-13-005

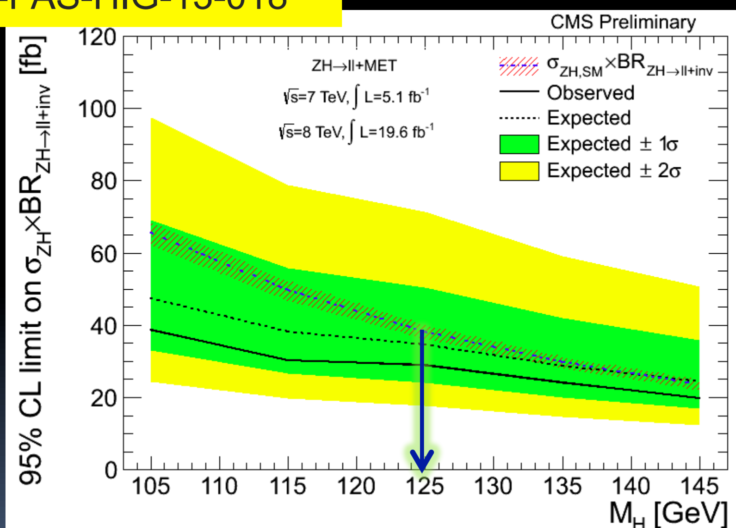
ZH →ll+invisible

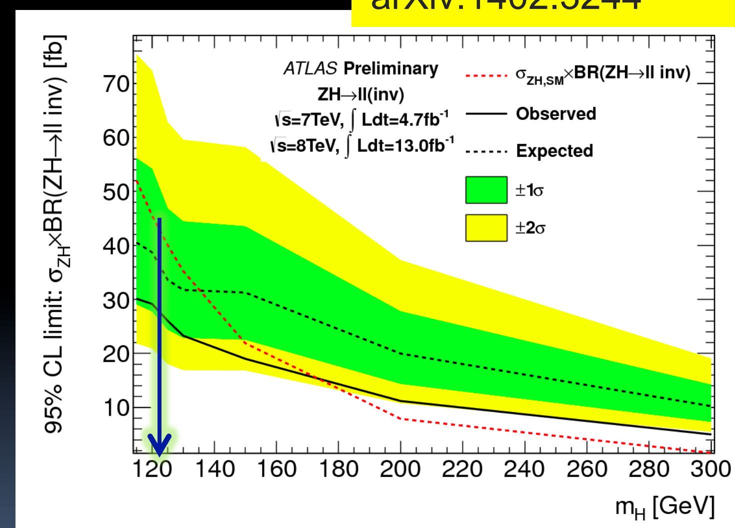




CMS-PAS-HIG-13-018

arXiv:1402.3244

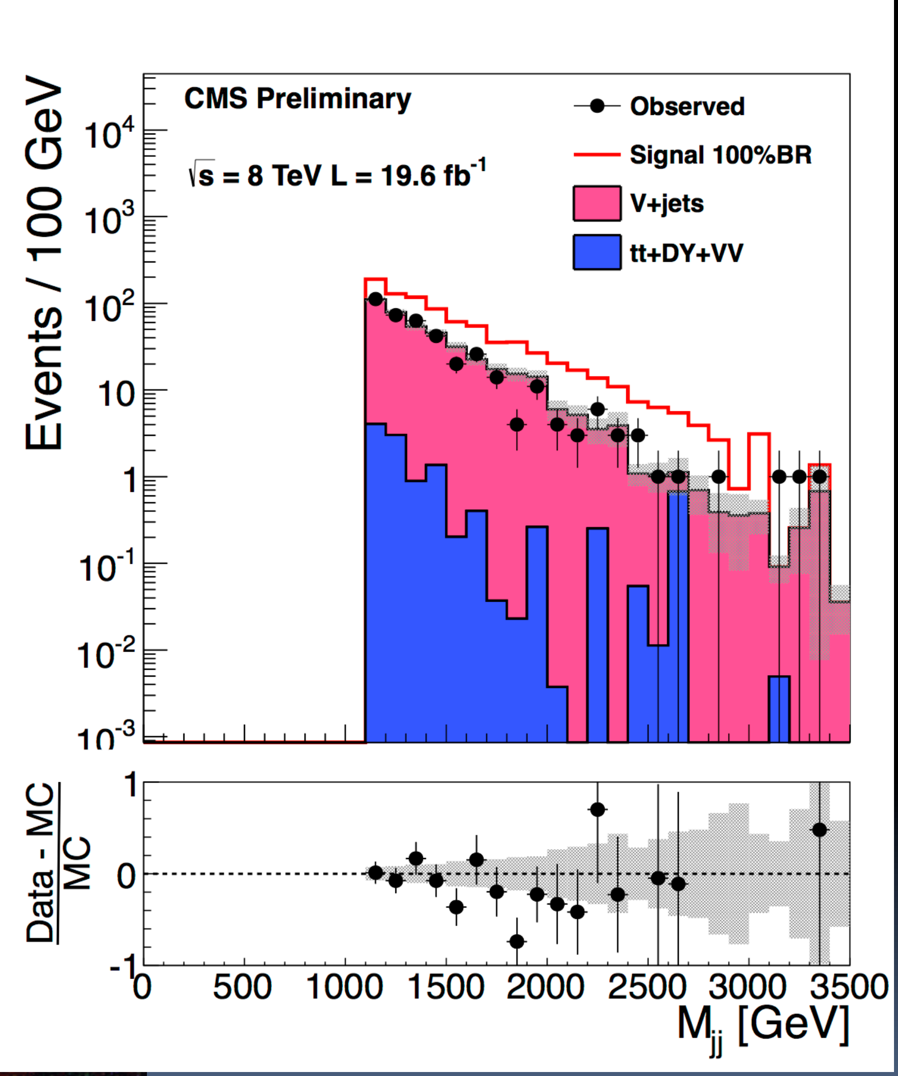


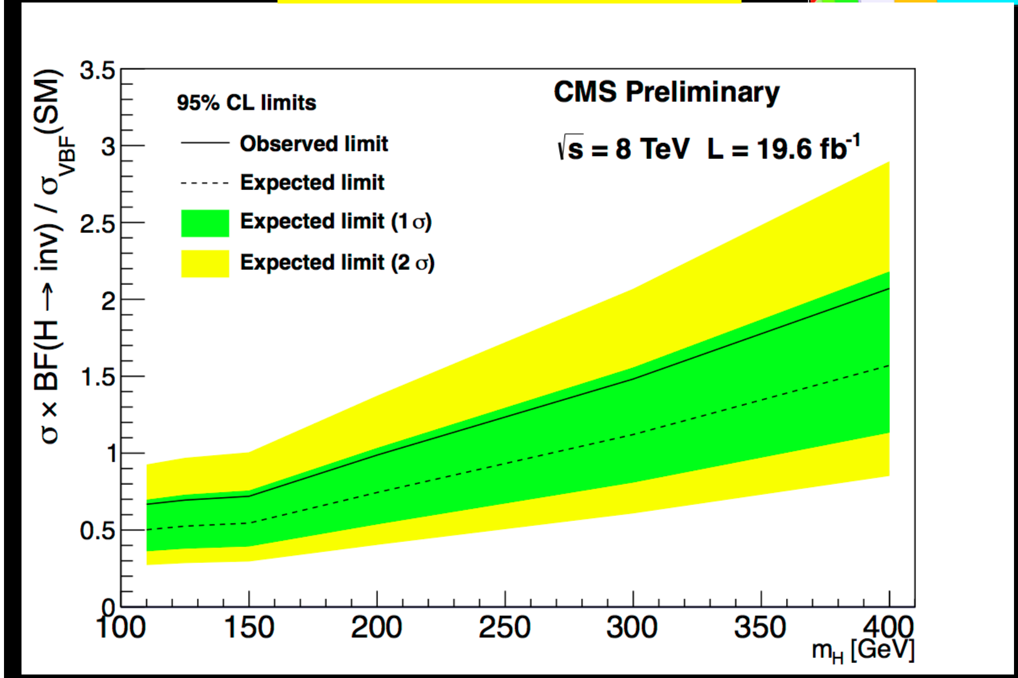


Observed (expected)	CMS	ATLAS
B(H→inv) at 125 GeV @95% CL	< 0.75 (0.91)	< 0.65 (0.84)

VBF H →Invisible

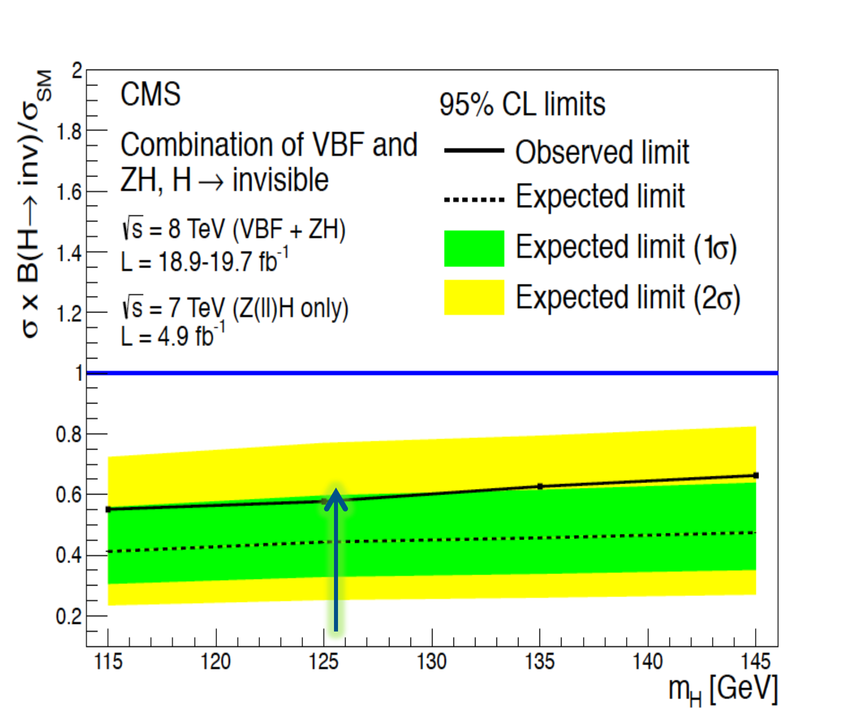
CMS-PAS-HIG-13-013



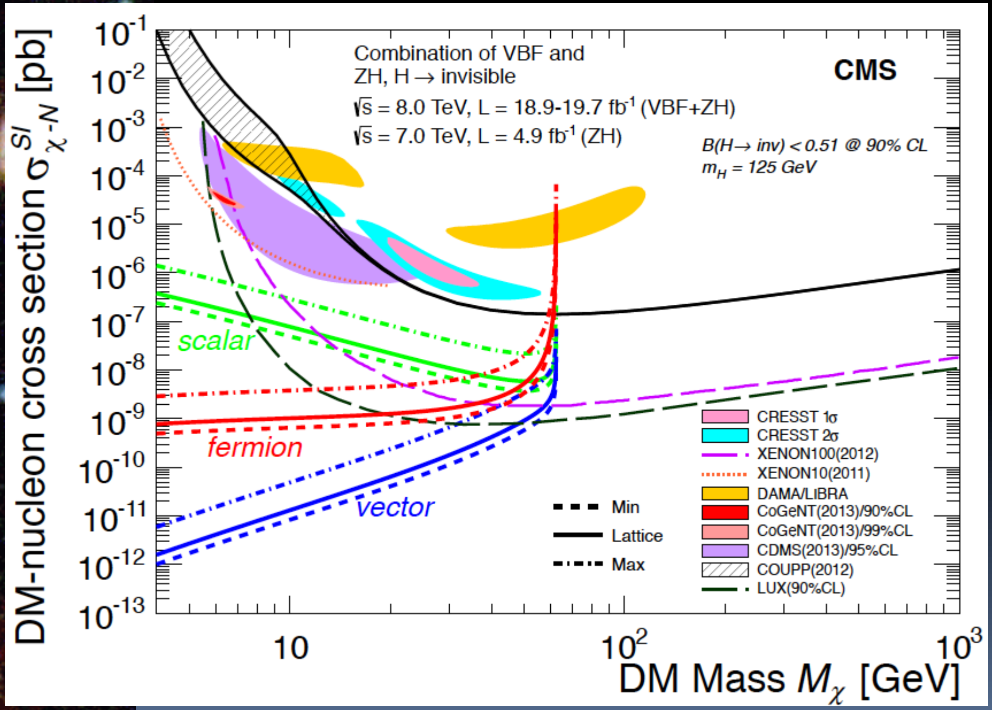


- At m_H=125 GeV observed (expected) limits at 95% CL on $\sigma \times \mathbf{B}(H\to inv) / \sigma_{SM} < 0.69$ (0.53) at 95%CLs

CMS combination



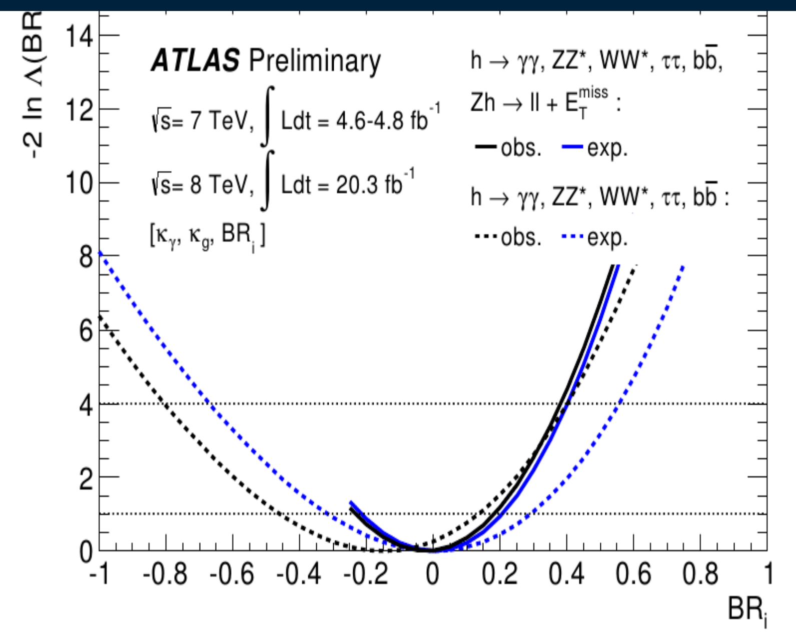
- Three individuals CMS searches combined assuming the SM production cross section and acceptance
- **B**(H→inv)/ σ_{SM} <0.58 (< 0.44) observed (expected) @ 95% CL



- **B**(H→inv) for $\mathbf{m_H}$ = 125 GeV used to obtain upper limits at 90% CL on the DM-nucleon cross section as a function of the DM mass in Higgs-portal models of DM interactions
  - Djouadi, A. Falkowski, Y. Mambrini, and J. Quevillon
  - B. Patt and F. Wilczek

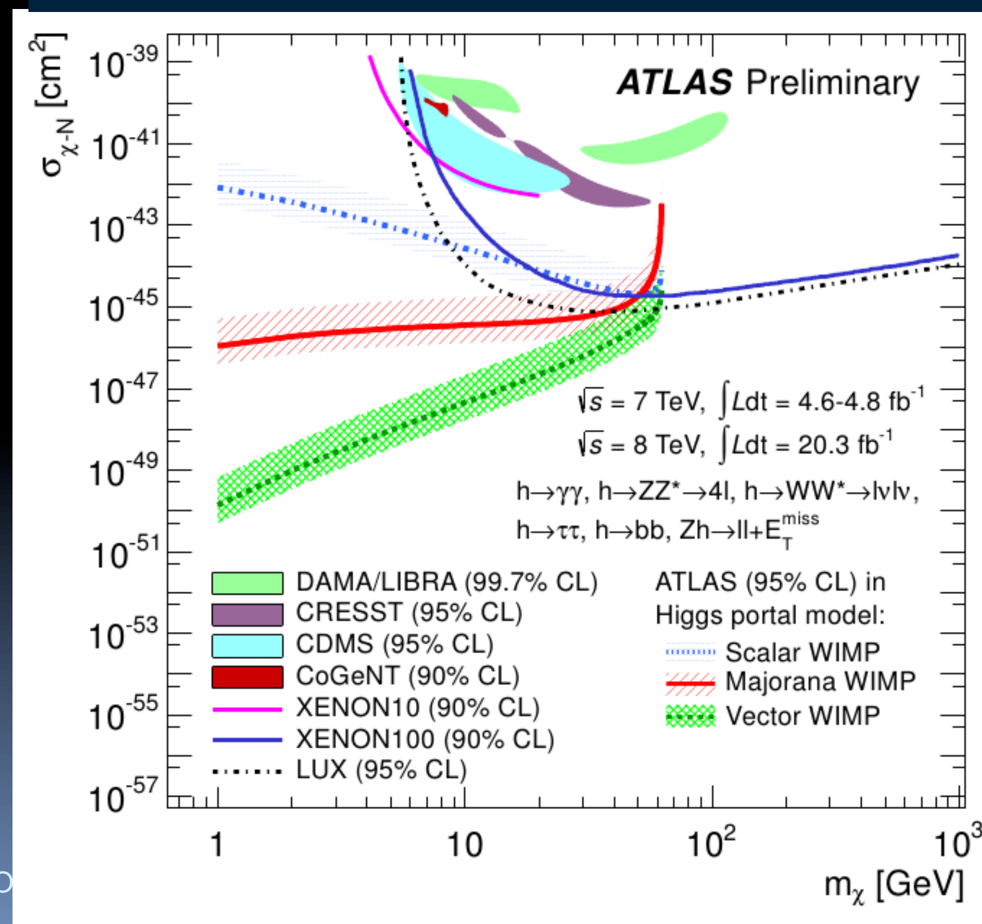
Invisible decays and dark matter

- Indirect constraint on B(H→inv) can also be obtained from global fit of measured decay modes.
- Combination of direct and indirect results
- Observed (expected) limit B(H→inv) <0.41(0.55) at 95% CL



ATLAS-CONF-2014-011

- Interpret limit on B(H→inv) as direct bounds on massive dark particles with $m_\chi < m_{H/2}$ coupling to the Higgs
- Interpretation in Higgs-portal model:
  - DM sector decoupled from SM, except for Higgs-mediated interactions



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