SM Higgs Physics at the LHC

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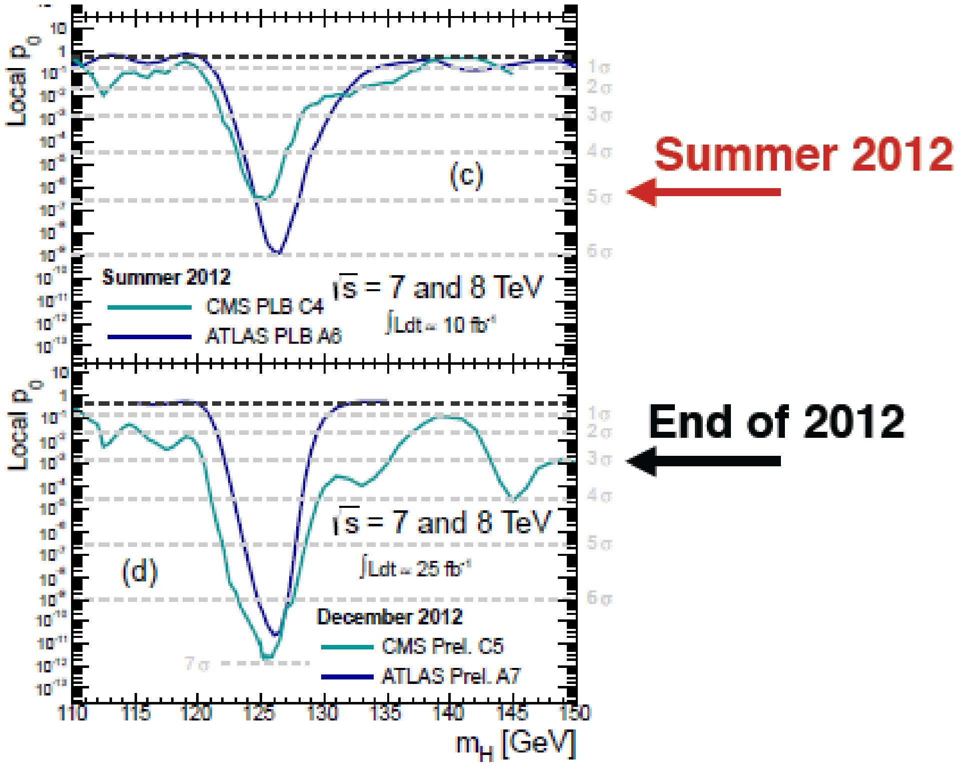
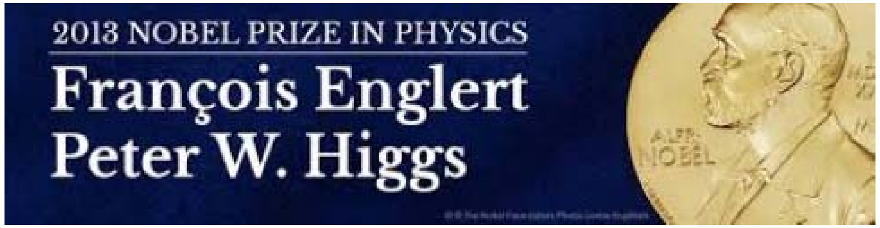
Higgs Boson Discovery at LHC

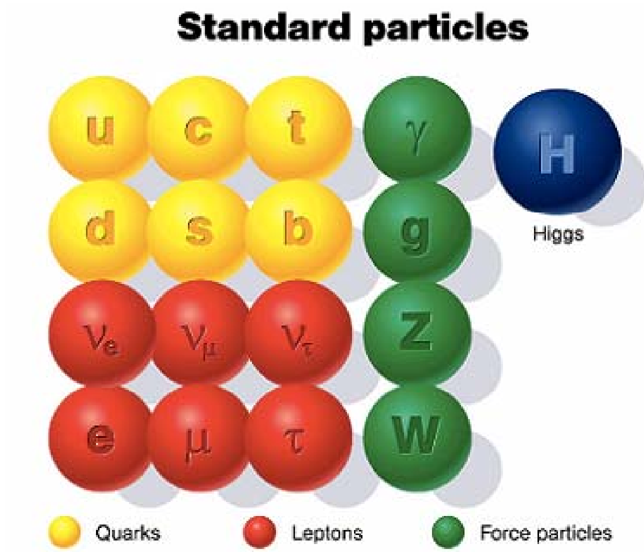
- **On 4th July 2012, Higgs discovered by ATLAS and CMS at the LHC**



PDG review, Chin. Phys. C, 38, 090001 (2014)



- **With the discovery of Higgs, the Standard Model has been completed**

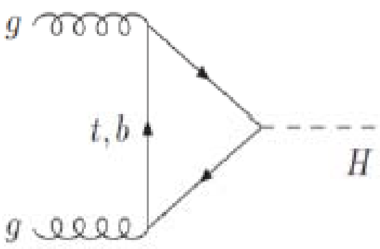


- **To explore the properties of the 125 GeV Higgs more precisely**

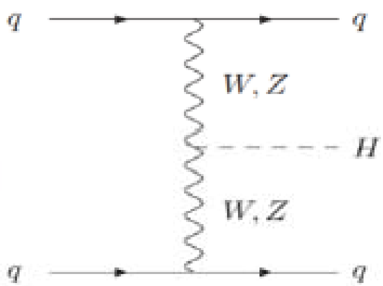
Mass, width, lifetime, signal strengths, couplings, cross section and differential cross sections, Spin/Parity , CP mixing …

SM Higgs production at LHC

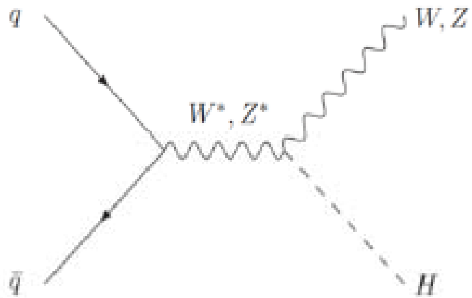
ggH



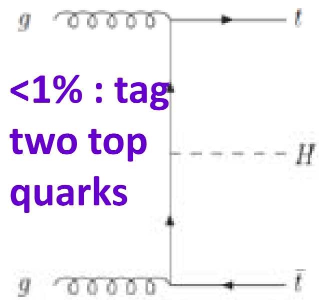
VBF



VH



ttH



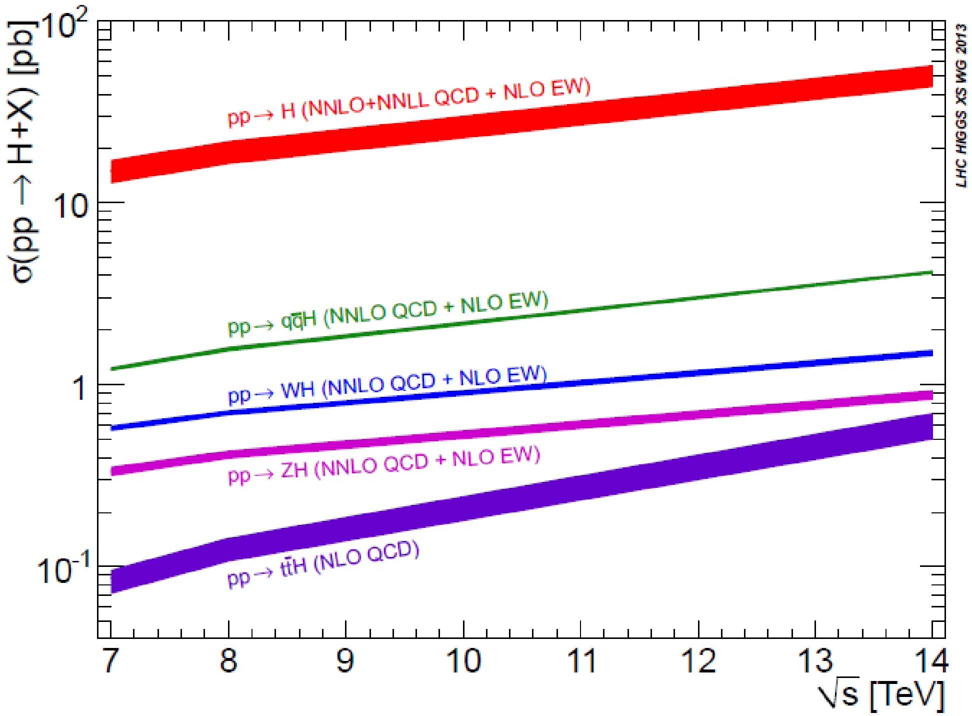
<1% : tag two top quarks

87% : Dominant mode (typically no extra high-pT object)

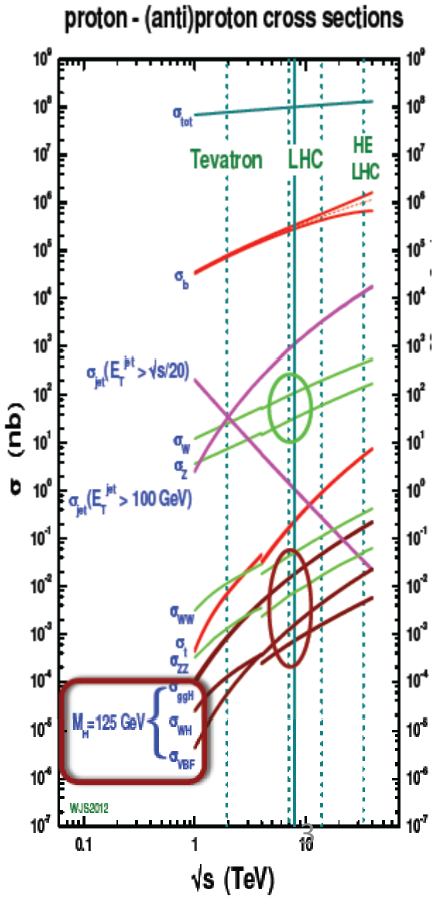
7%: tag two forward jets

5% : tag Z and W decays (leptonic or hadronic)

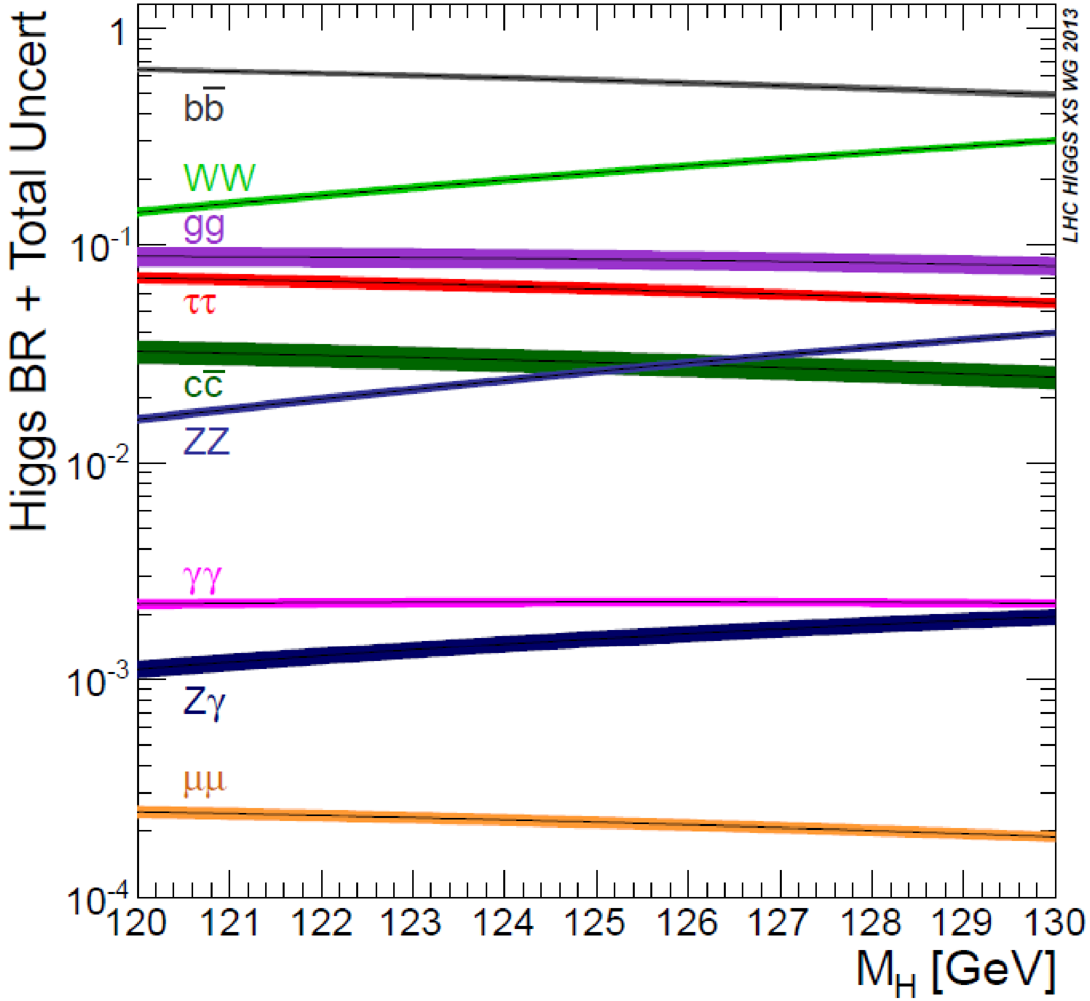
σ_{total} = 22 pb @ √s = 8 TeV, m_H = 125 GeV



Exp. challenges: select rare signal from huge background



Higgs decays



- **BR @ mH=125GeV**

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

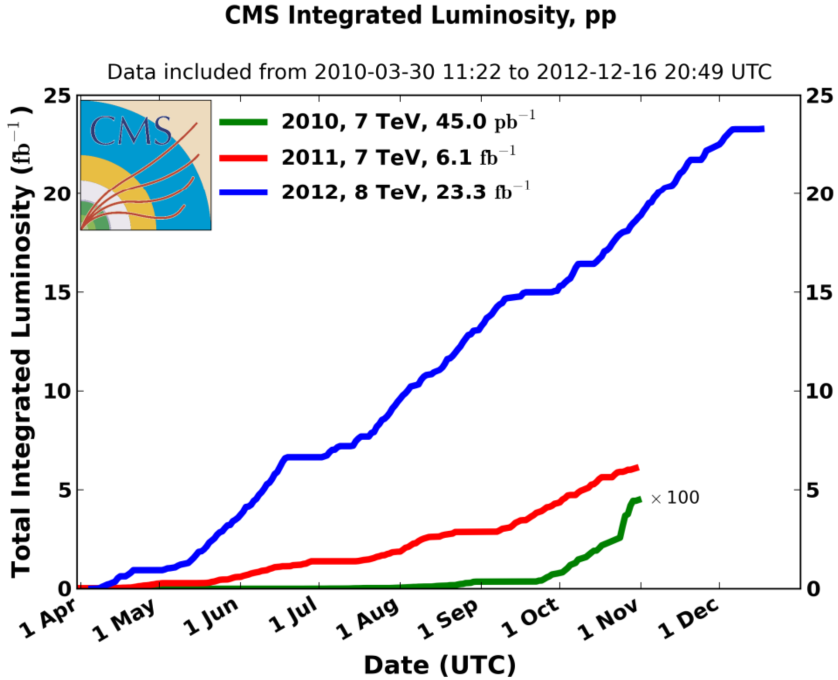
- **Five sensitive channels** for low mass SM Higgs boson searches **at the LHC**

Decay channel	Mass resolution
$H \to \gamma\gamma$	1-2%
$H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	1-2%
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$	20%
$H \to b\bar{b}$	10%
$H \to \tau^+\tau^-$	15%

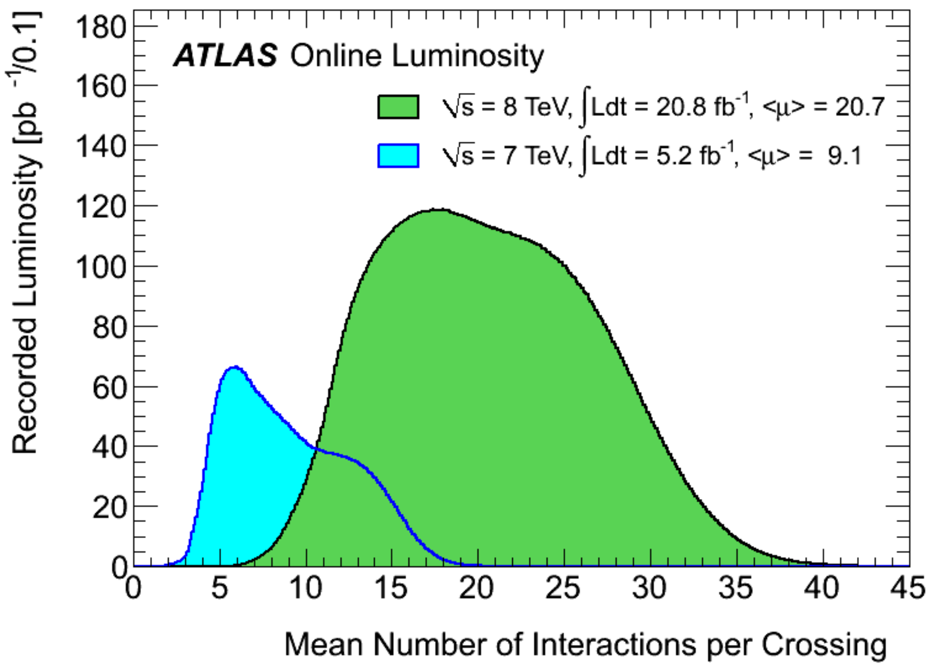
LHC Run 1

Successful operations in both LHC and Experiments

- LHC was in good condition during Run-1 (2010-2012)
- ATLAS and CMS collected good fraction of data (>95%) throughout Run-1
- 8 (7) TeV collisions
  ~20 (5) fb^{-1} good data for physics



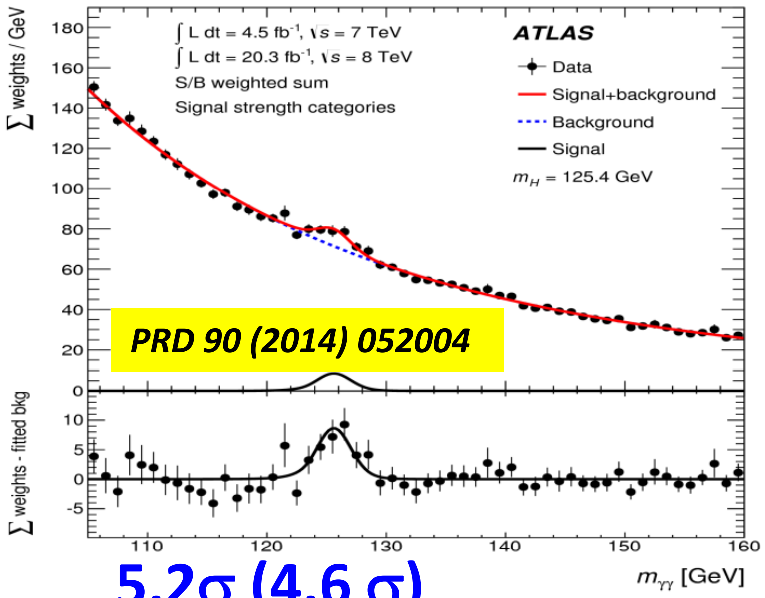
Challenging pile-up conditions



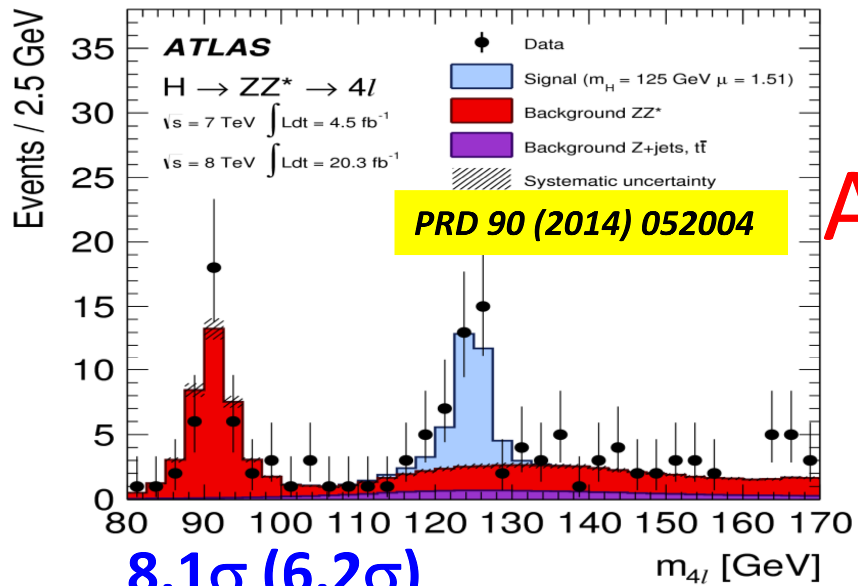
Channels explored

	WW	ZZ	γγ	bb	ττ
ggH	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS
VBF	ATLAS CMS	ATLAS CMS	ATLAS CMS	**CMS**	ATLAS CMS
WH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	CMS
ZH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	CMS
ttH	**ATLAS** CMS	**ATLAS** CMS	ATLAS CMS	ATLAS CMS	**ATLAS** CMS

Observing the Higgs: $\gamma\gamma$ and ZZ



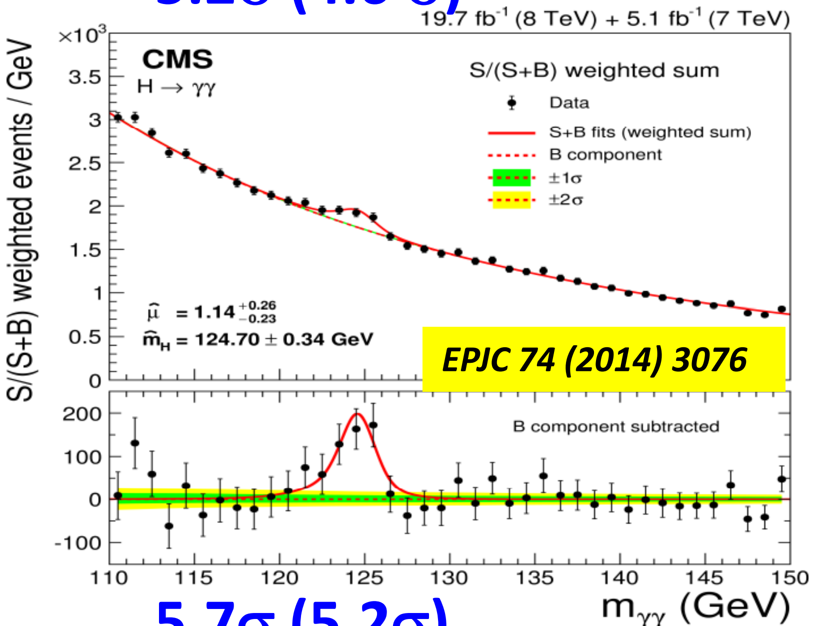
5.2σ (4.6 σ)



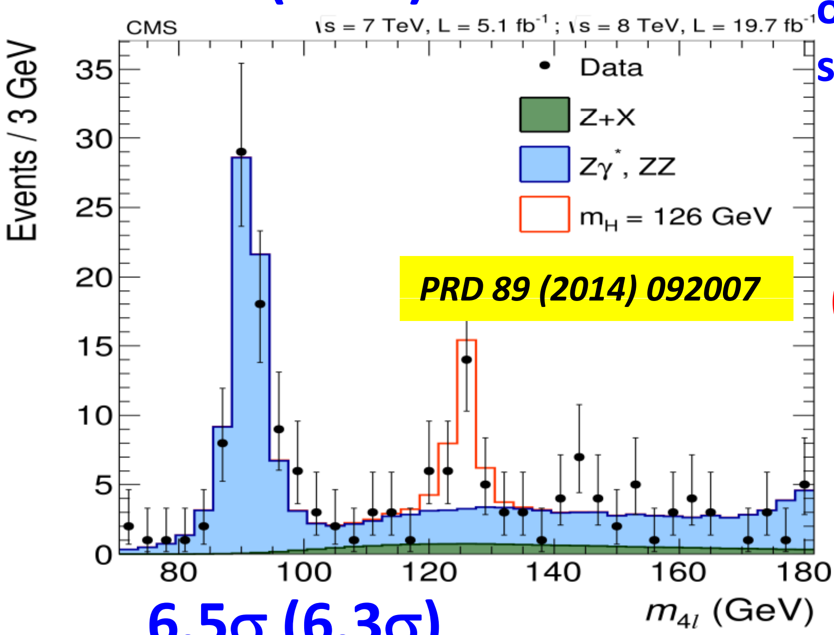
8.1σ (6.2σ)

ATLAS

obs(expected) significance



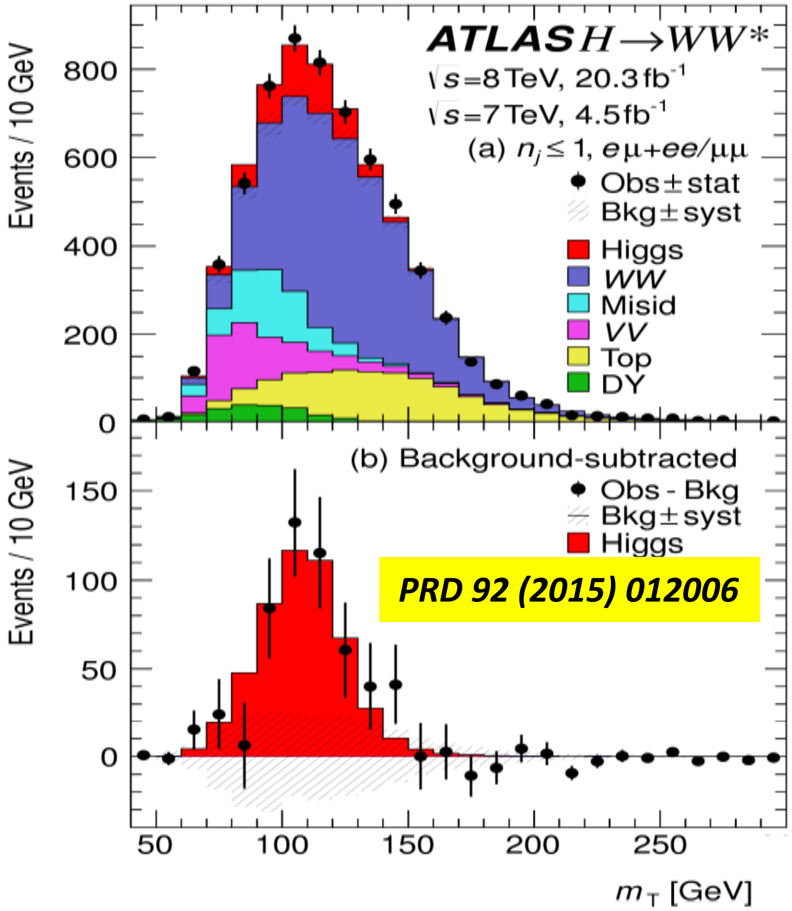
5.7σ (5.2σ)

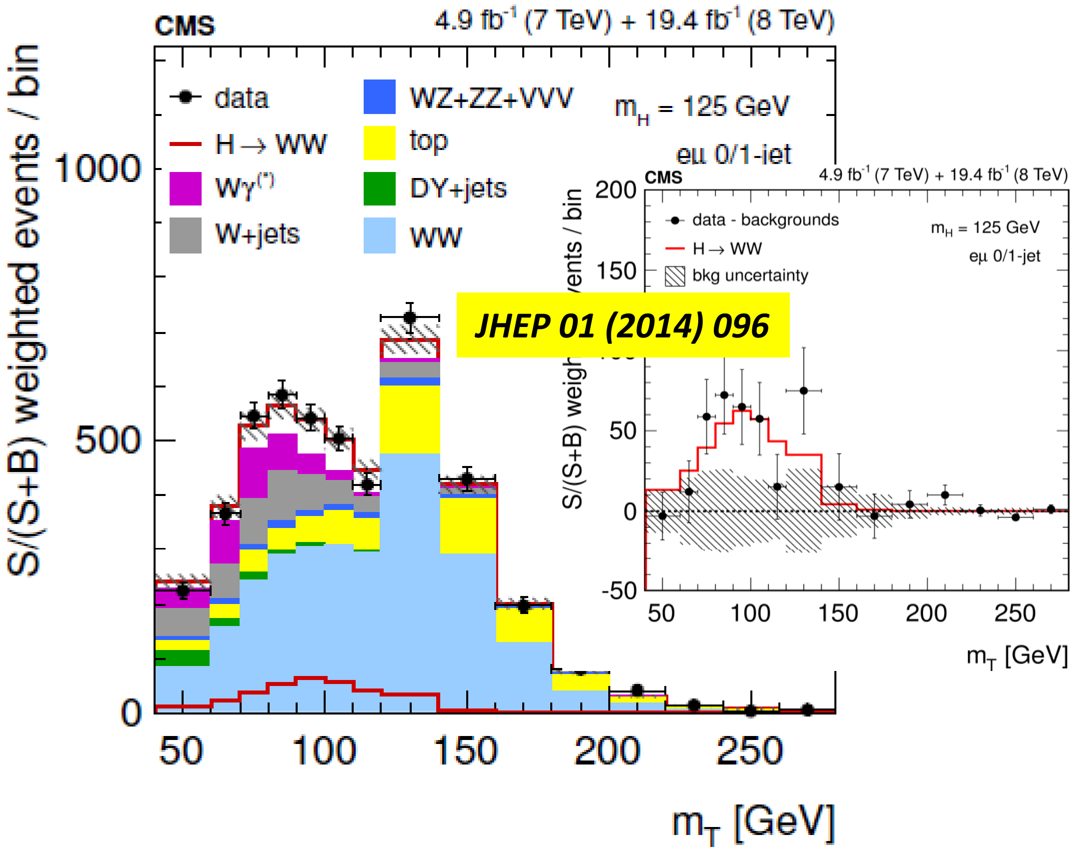


6.5σ (6.3σ)

CMS

Higgs Decaying to WW





Observed 6.5σ (expected 5.9σ)

Observed 4.7σ (expected 5.4σ)

ATLAS

CMS

Higgs Decaying to ττ

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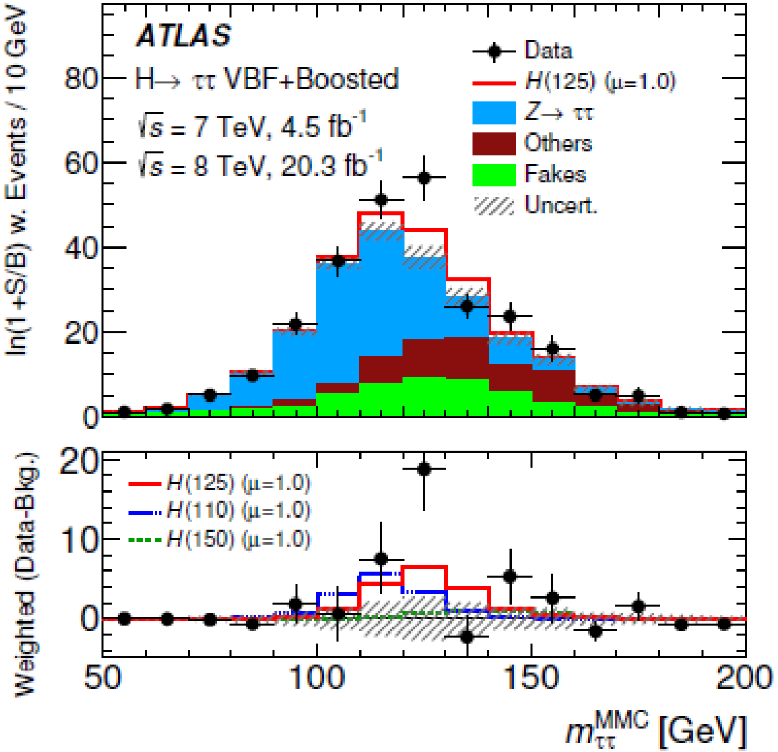

Observed 4.5σ (expected 3.4σ)

ATLAS

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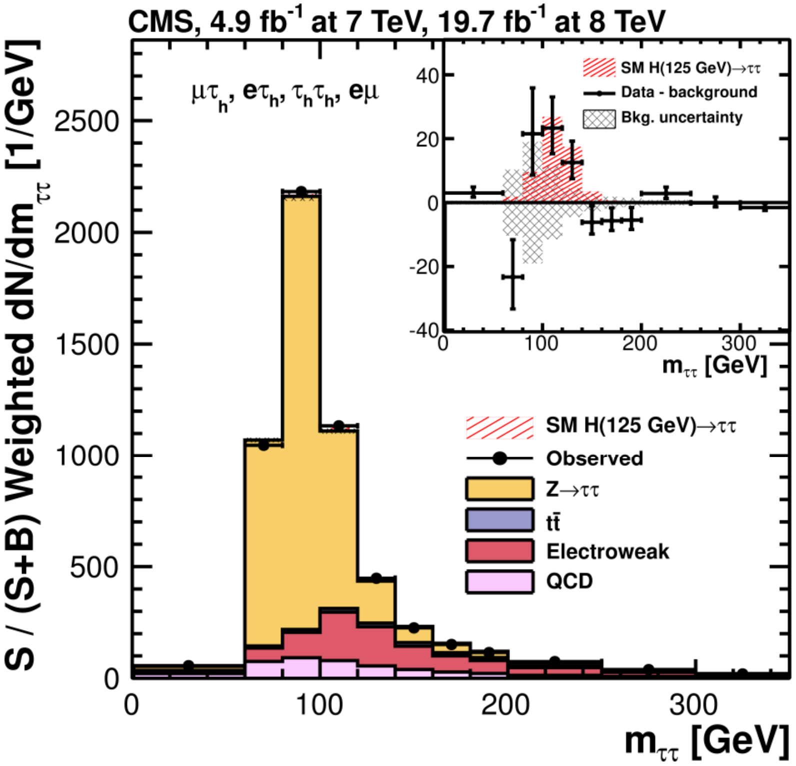


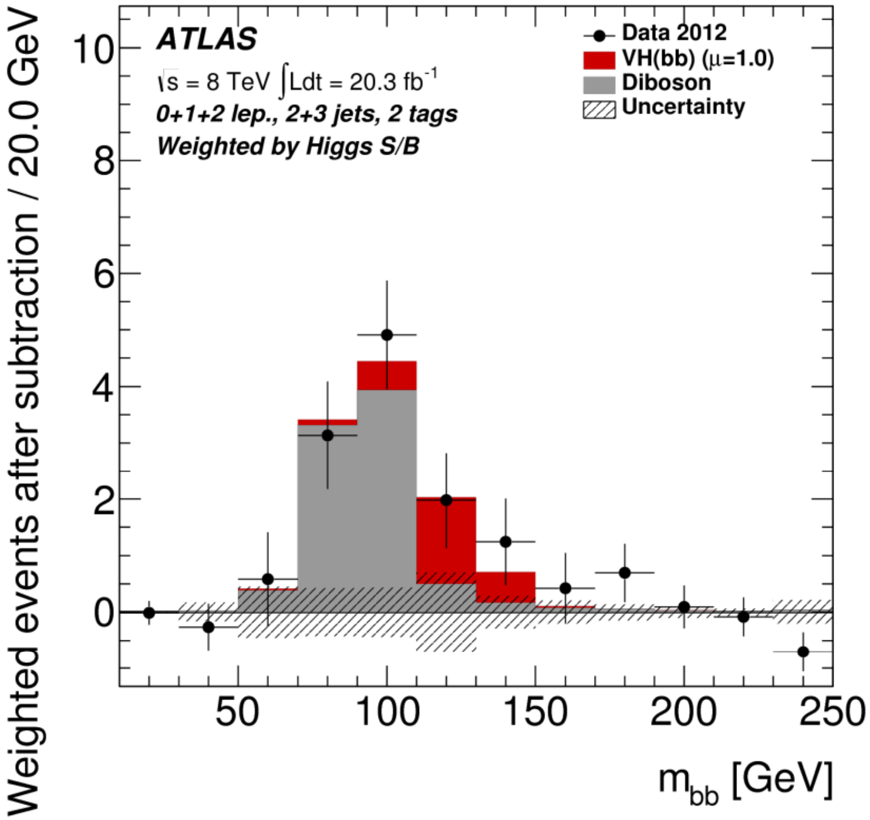
Observed 3.2σ (expected 3.7σ)

CMS

ATLAS and CMS combined: 5.5σ (5.0σ)

Higgs Decaying to bb

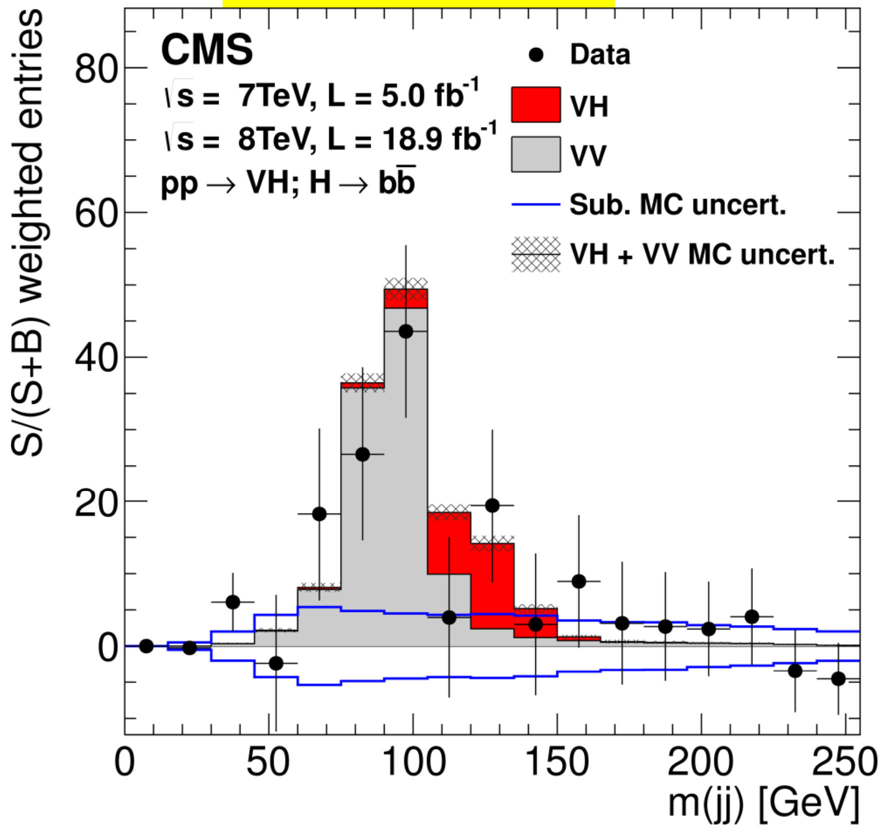
JHEP 01 (2015) 069



Observed 1.8σ (expected 2.8σ)

ATLAS

PRD 89 (2014) 012003



Observed 2.6σ (expected 2.7σ)

CMS

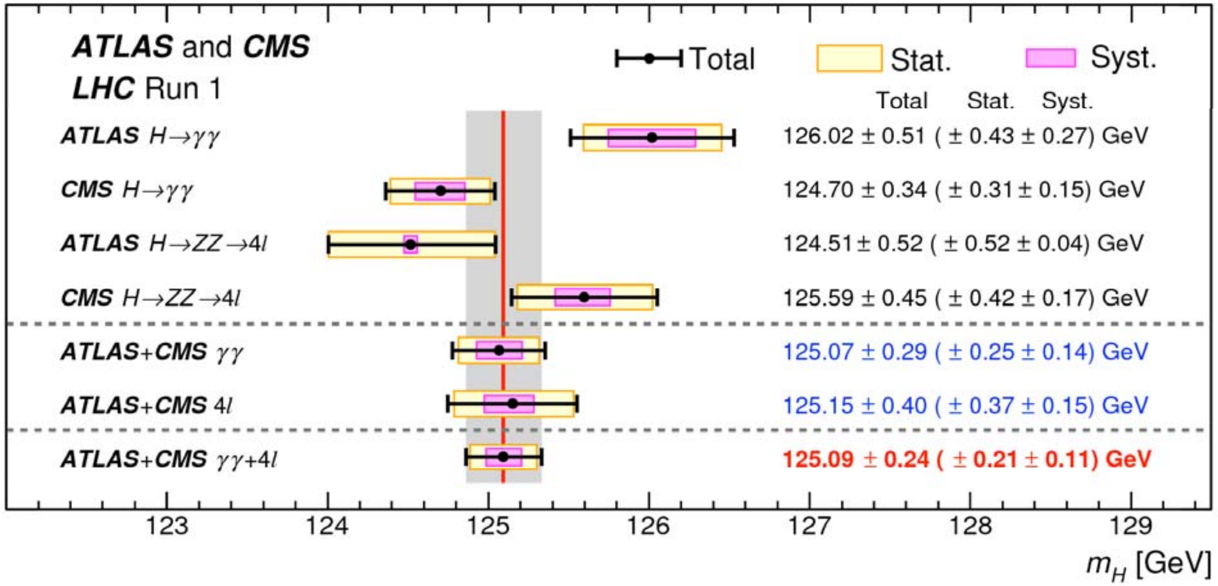
Mass, width, lifetime

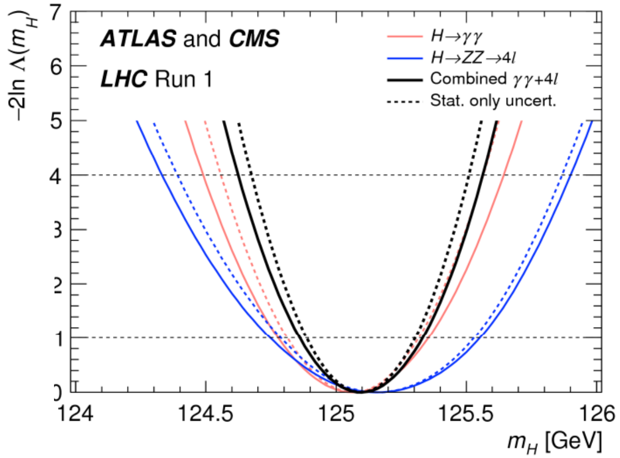
Higgs mass

Measured from the global fit to data of high precision channels $H \to \gamma\gamma$ and $H \to ZZ \to 4l$

PRL 114 (2015) 191803

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21 \,(\text{stat}) \pm 0.11 \,(\text{syst}) \text{ GeV}$$



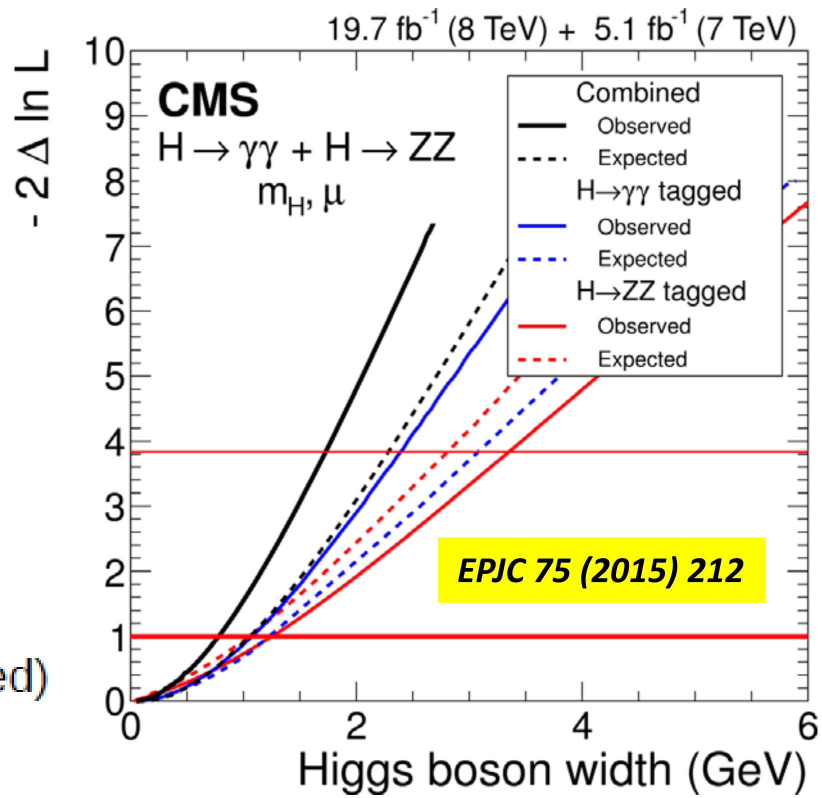


Some tension between the four measurements (p-value ~10%) and opposite in ATLAS and CMS - very good agreement in the central values

Higgs total width： direct limit

4 MeV predicted in SM, direct measurement from peak width limited by detector resolution (~1.5 GeV)

- **CMS** results;
  2 decay modes combined resulting in;
  Γ_H < 1.7 GeV observed @ 95% CL (2.3 expected)

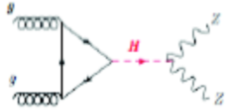


- **ATLAS** results;
  – H → γγ; **Γ_H < 5.0 GeV** obs. @ 95% CL (6.2 exp.)
  – H → ZZ → 4l; **Γ_H < 2.6 GeV** obs. @ 95% CL (6.2 exp.)

Higgs total width: on/off shell

Breit-Wigner production gg→H→ZZ:

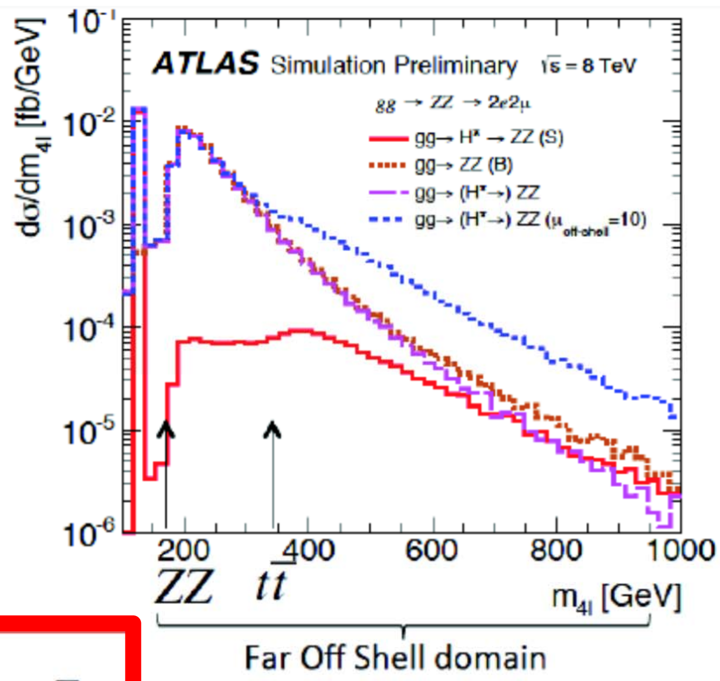
$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$



<u>On-peak</u> and <u>off-peak</u> cross sections:

$$\sigma^{on-shell} = \int_{|m-m_H| \leq n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}$$

$$\sigma^{off-shell} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2$$



<u>Off-peak to on-peak ratio</u> is proportional to Γ_H

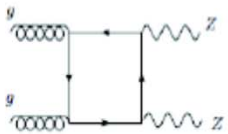
$$\frac{\sigma^{off-shell}}{\sigma^{on-shell}} \sim \Gamma_H$$

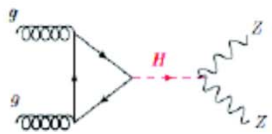
CAVEATS (model-dependent assumptions):

- assume that gg → H is the dominant production mechanisms (e.g., not qq → H)
- evolution of $g_{ggH}(m_{H*})$ depends on what is in the loop: assume top-loop dominance
- off-peak production depends strongly on tensor structure of H→ZZ: assume SM-like 0^+

Technical, but very important, detail:

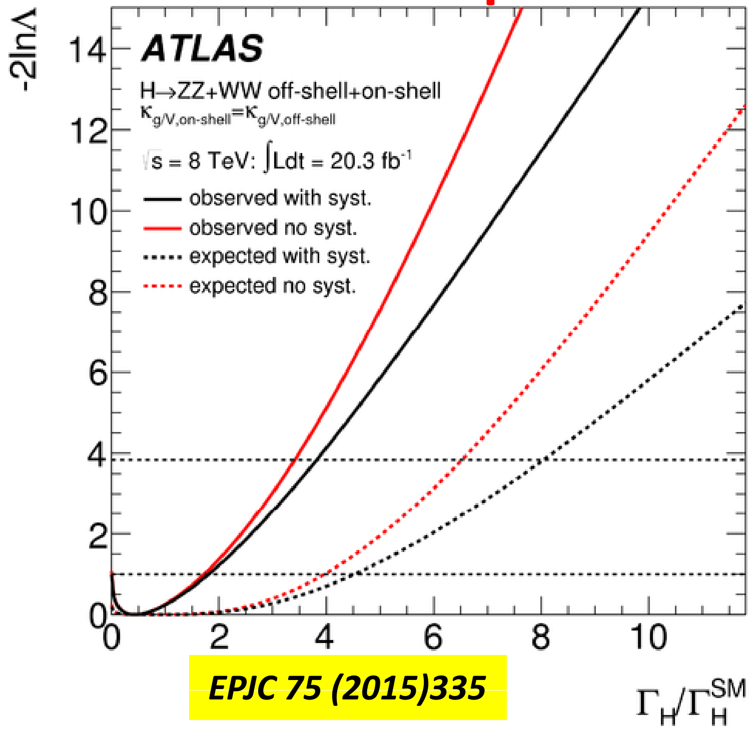
- must include negative interference between gg→H*→ZZ and gg→(box)→ZZ
- off-shell production: $\sigma_{gg\to H^*\to ZZ} + \sigma_{gg\to(box)\to ZZ} + \sigma_{interference}$
- K-factor on gg→(box)→ZZ is large and not well known



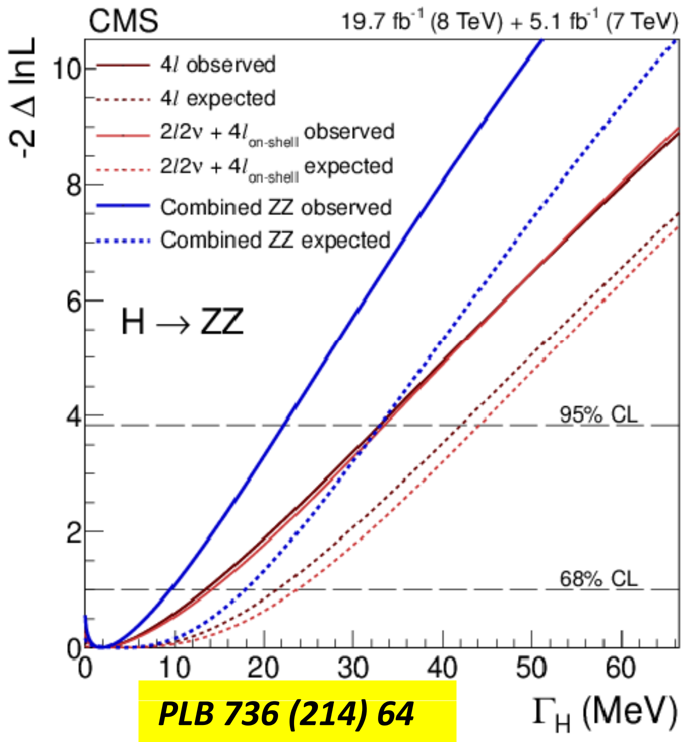


Higgs total width: on/off shell

- **ATLAS combined ZZ (4l, 2l2ν) and WW (eνμν) channels**
- **CMS include both ZZ→4l and ZZ→2l2ν final states, ZZ+WW combination will be public soon**



EPJC 75 (2015)335



PLB 736 (214) 64

ATLAS:

Γ_H<23 MeV

Expected :33 MeV

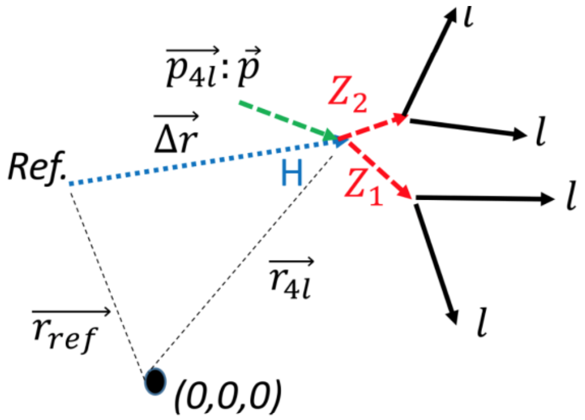
CMS:

Γ_H<22 MeV

Expected : 33 MeV

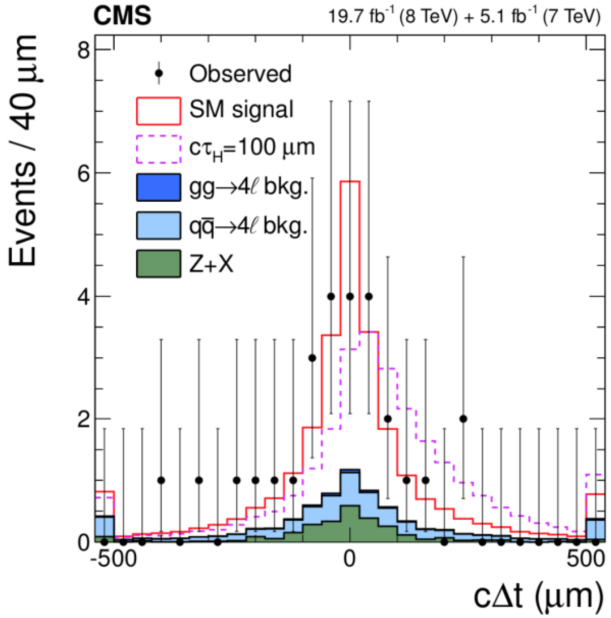
lifetime

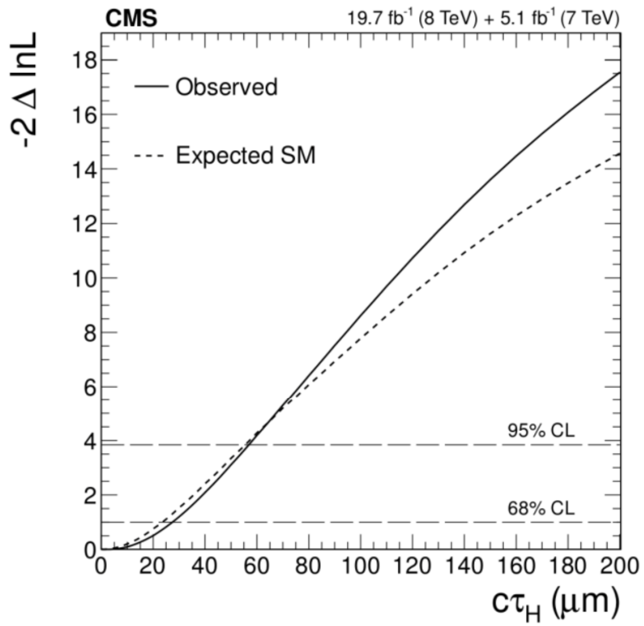
- $c\tau_H^{SM} \approx 4.8 \times 10^{-8} \mu m$ (well beyond experimental sensitivity)
- H→ZZ→4l channel is used to measure lifetime
- p_T-spectrum dependence of vertex resolution taken into account



$$\Delta t = \frac{m_{4\ell}}{p_T}\left(\Delta\vec{r}_T \cdot \hat{p}_T\right)$$

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





First ever constraint on the Higgs boson lifetime!

$c\tau_H$ < 57 µm observed @ 95% CL (56 µm expected)

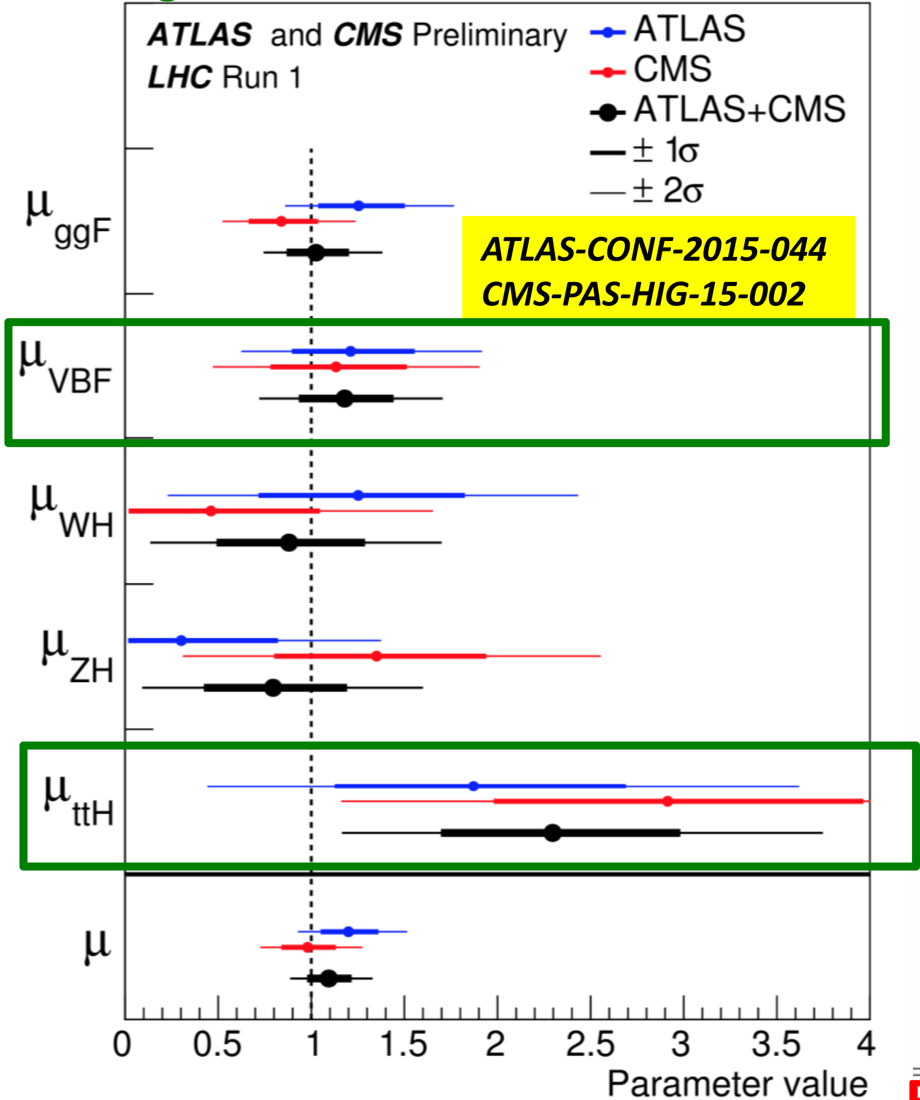
$\Gamma_H > 3.5 \times 10^{-9}$ MeV observed @ 95% CL (3.6×10^{-9} MeV expected)

Signal strengths, couplings

- ATLAS and CMS results are combined for the measurement of the Higgs boson production and decay rates and tests of its couplings
- Gain a factor $\sqrt{2}$ in precision (still statistics limited, including many syst. uncertainties)
- All results are compared to the Standard Model (SM) predictions

Signal strength of Higgs Productions

$\mu=\sigma_{measured}/\sigma_{SM}$ Assuming **only one SM-Higgs boson** and **SM decay**, and **strength for 7TeV and 8TeV are the same**



ATLAS+CMS combination provides 5.4σ (4.7σ expected) significance for VBF production

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0

Largest difference in ttH: 2.3σ excess with respect to SM

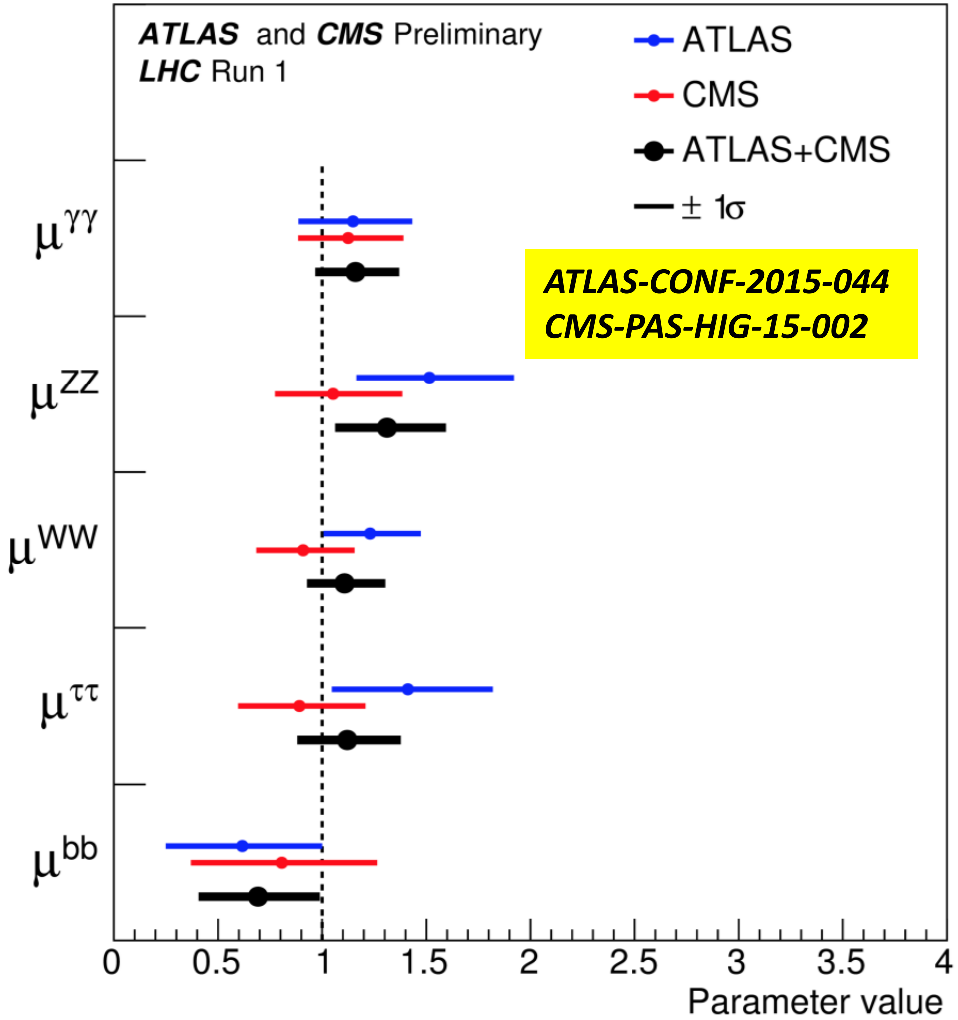
Overall $\mu = 1.09^{+0.11}_{-0.10}$

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

Relative error is about 15% -50%

Signal strength of Higgs Decays

Assuming SM production

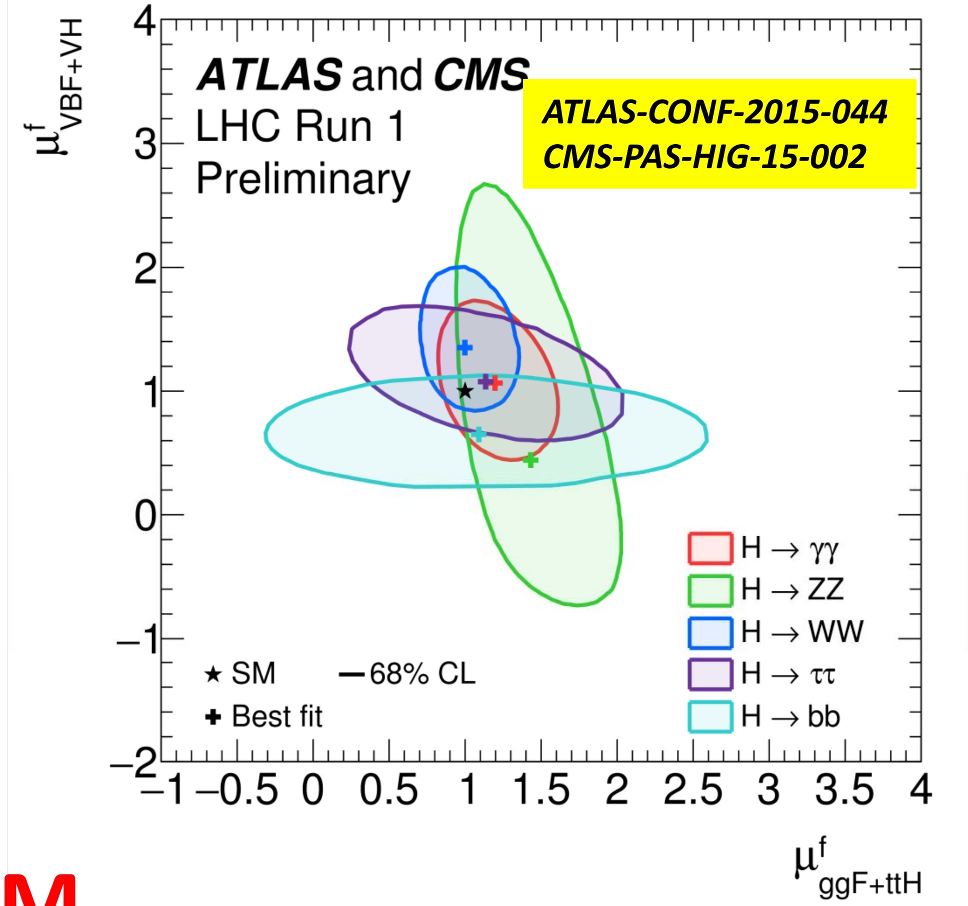


Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$

Signal strengths in different channels are consistent with SM in 1σ

Fermionic & Bosonic production

- **Fit the bosonic and fermionic productions separately per decay**
- $\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$
- No assumption on the BRs is needed in the combination of the $\mu_{VBF+VH} / \mu_{ggF+ttH}$ ratio (benefit of the ratio)



In agreement with SM

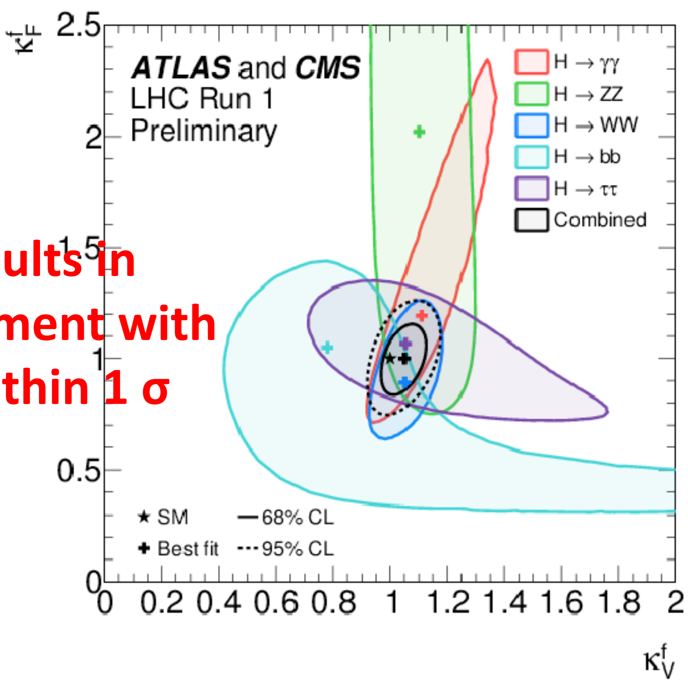
Coupling: κ

- **"κ-framework" by LHC Higgs cross-section working group:** simplest parametrization of Higgs-couplings deviations from SM values

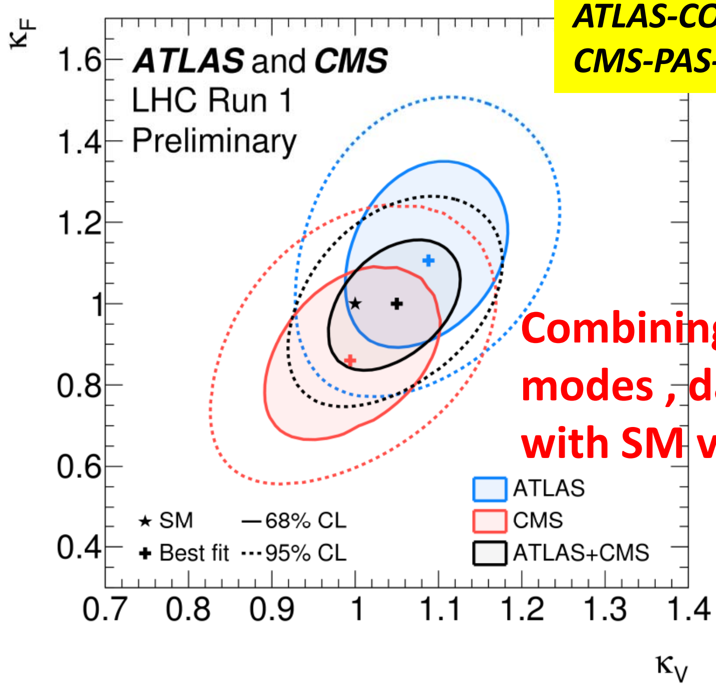
$$\kappa_i \equiv g_i / g_i^{SM}$$

- **Minimal model**
  - All fermion couplings scale the same way: $\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$
  - All boson couplings scale the same way: $\kappa_V \equiv \kappa_W = \kappa_Z$
  - No new physics beyond the SM

All results in agreement with SM within 1 σ

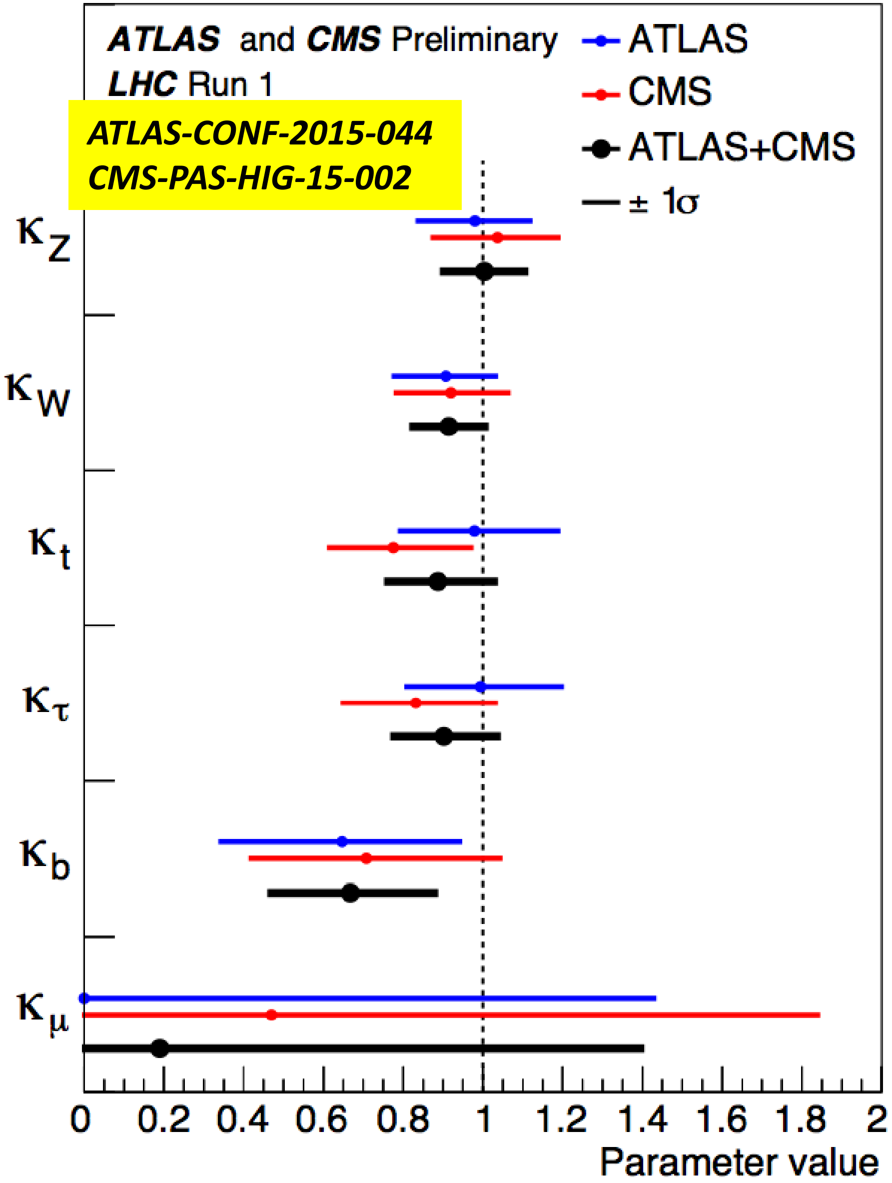


ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002



Combining 5 decay modes , data agree with SM very well

Individual coupling modifiers



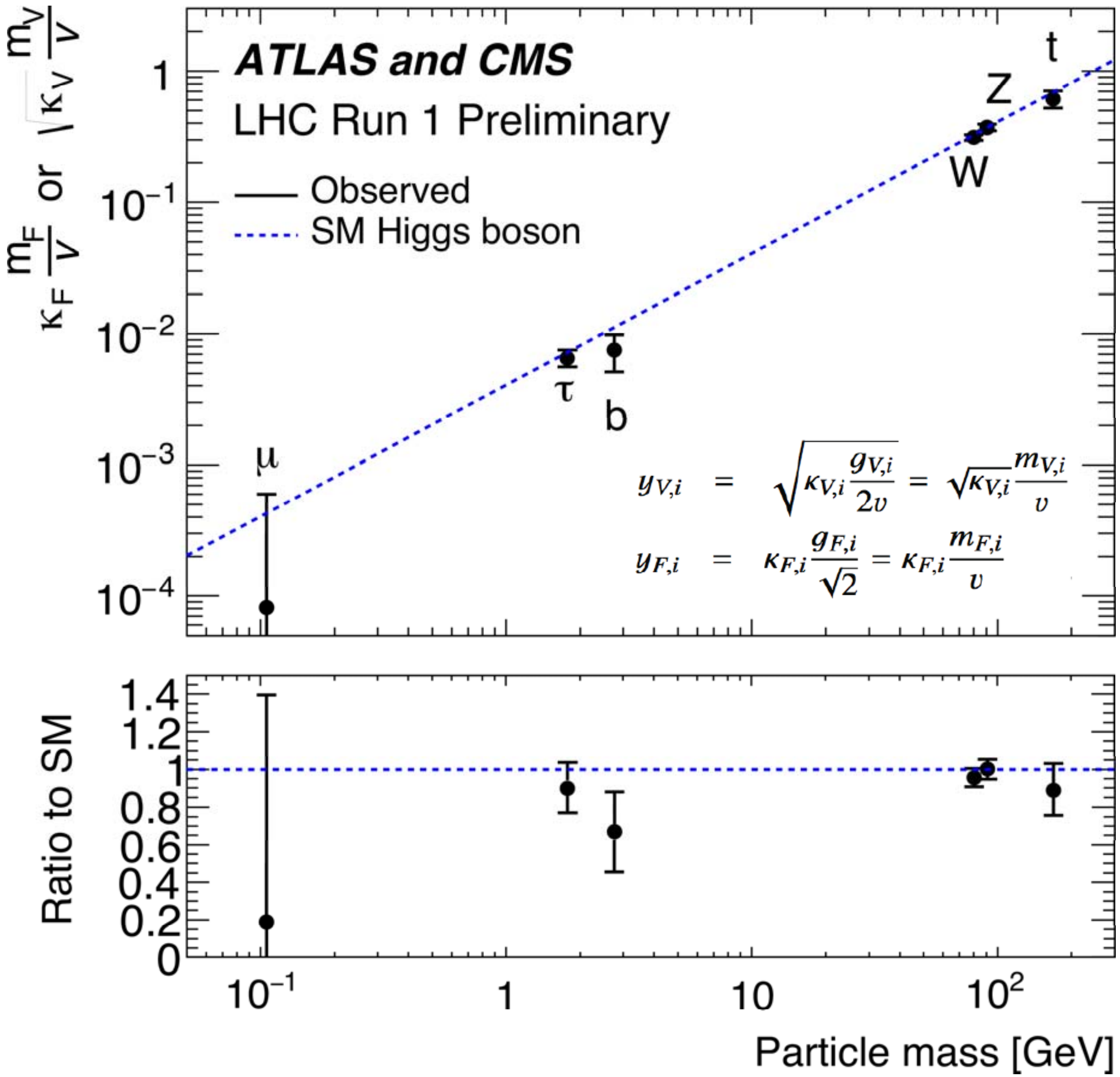
Assuming :

- no BSM particles in the loops
- BR_{BSM}=0
- K_j>=0

K_b is lower than SM more than 1σ

The measurement of κ_μ is very poor

Coupling modifiers vs Particle Mass



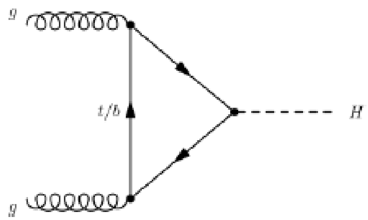
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Within current precision Higgs couplings scale with particle masses

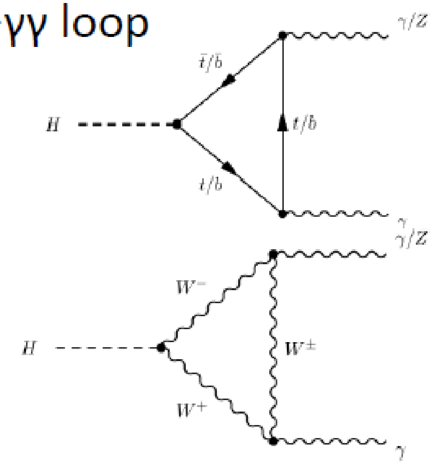
Coupling modifiers : κ_γ vs κ_g

- We can also set effective couplings κ_g and κ_γ
- Assuming tree level couplings as in the SM and BR_{BSM}=0
- Not unit κ_g and κ_γ means additional particles enter the loops

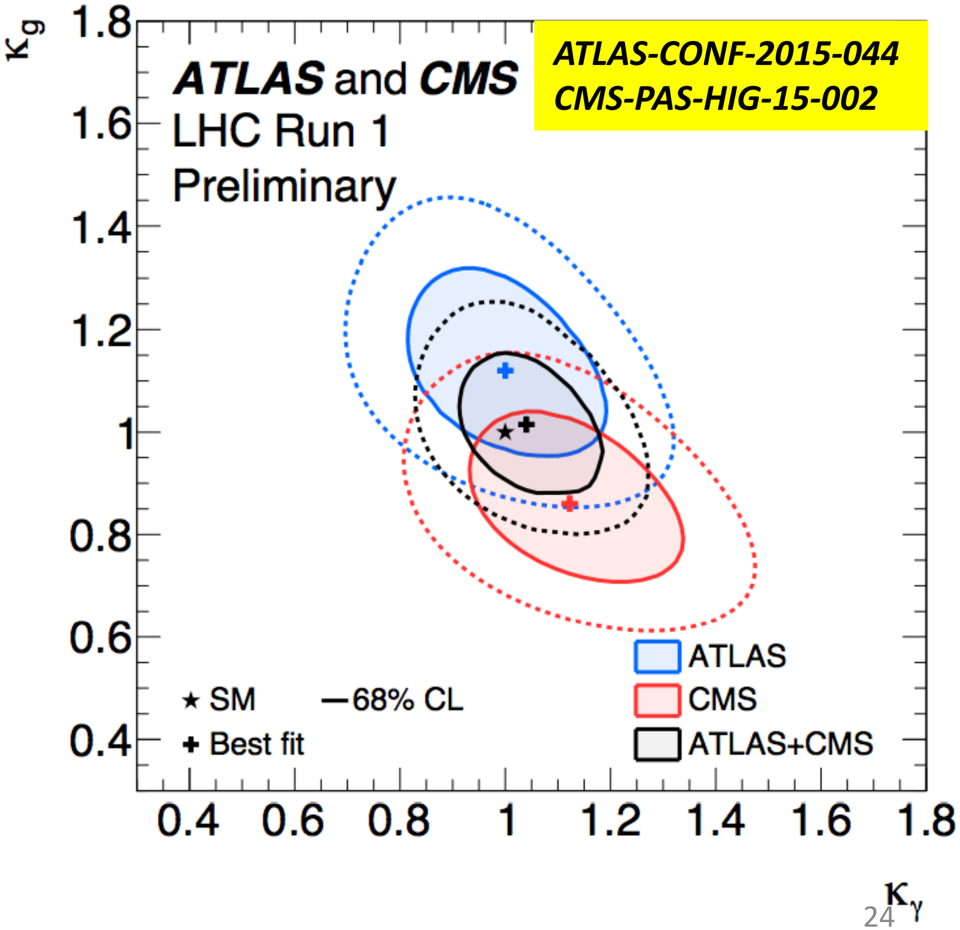
ggF loop



H→γγ loop

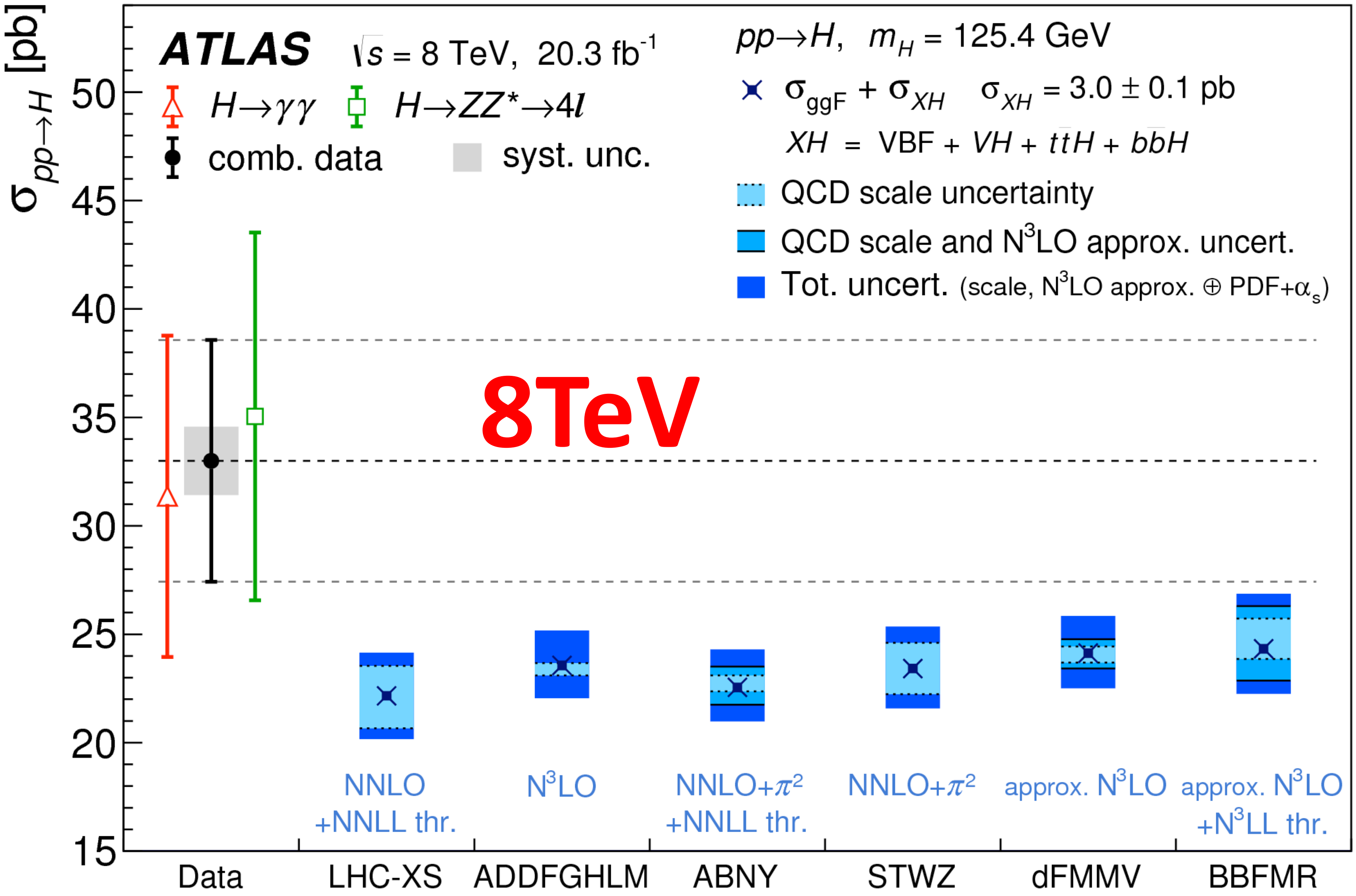


Additional heavy fermions or charged Higgs boson would modify the effective couplings



cross section

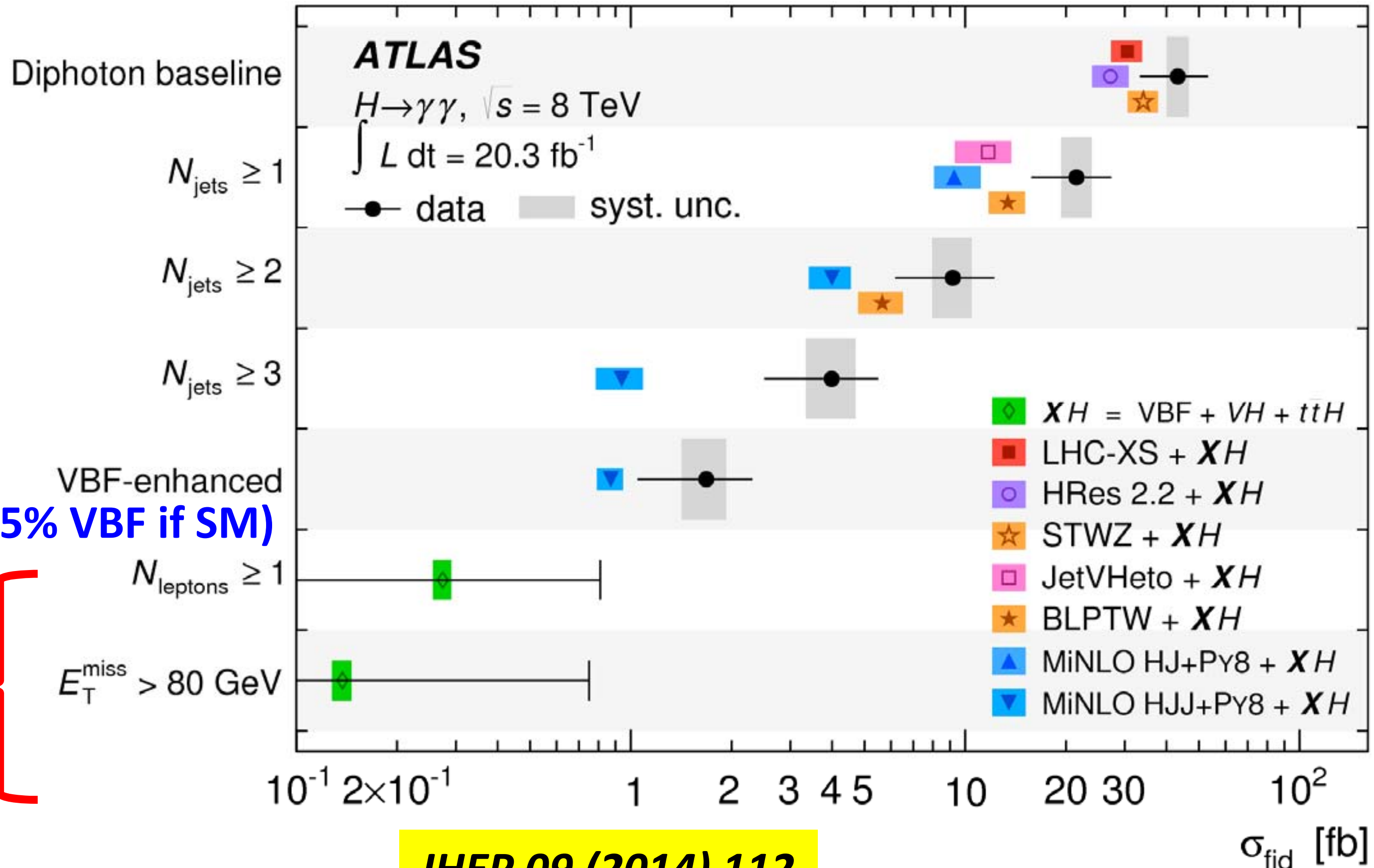
Total cross section



PRL 114 (2015) 191803

Fiducial Cross-sections

- Fiducial region definition motivated by **experimental cuts**
- **Model-independent** measurement of production and decay kinematics
- **Allows comparison** with **precision calculations**, alternative models
- Test **theoretical modelling** of **different Higgs boson production mechanisms**
- **Sensitive to BSM physics**

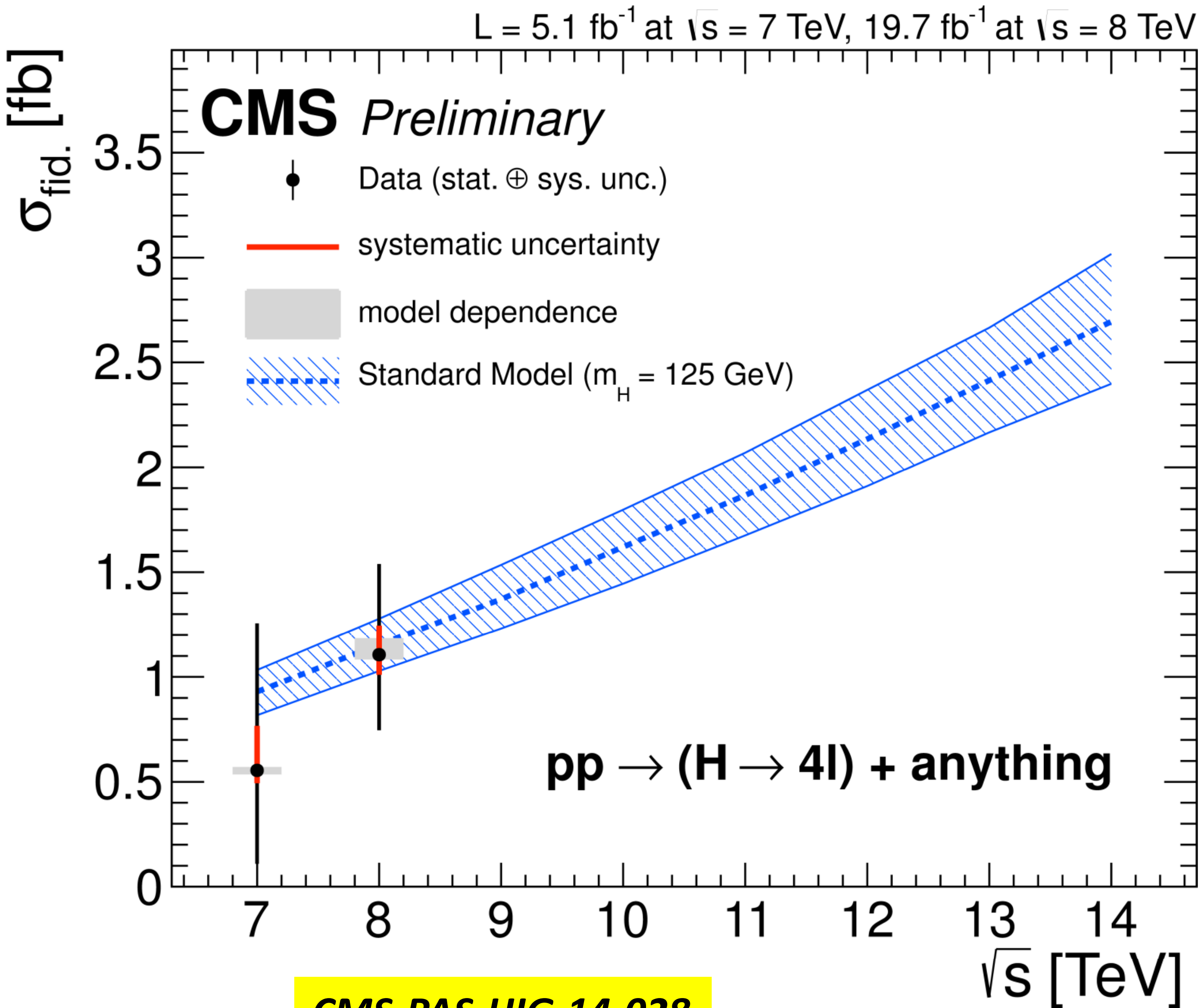


(~75% VBF if SM)

VH+ttH if SM
Constrains e.g. H+dark matter production

JHEP 09 (2014) 112

Fiducial Cross-sections



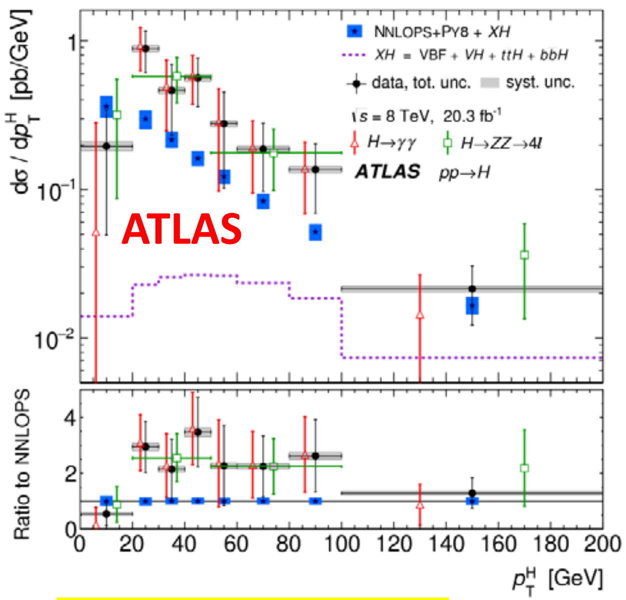
consistent with SM in 1σ

CMS-PAS-HIG-14-028

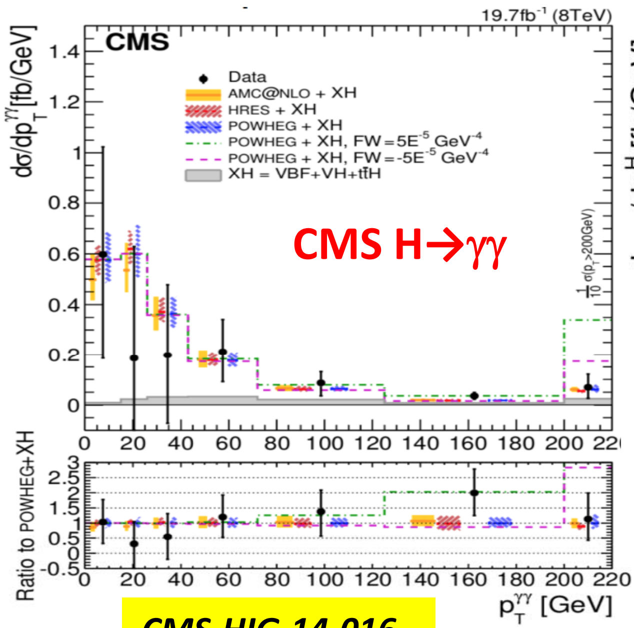
Fiducial Cross-sections vs p_T^H

Measurements designed as model independent as possible

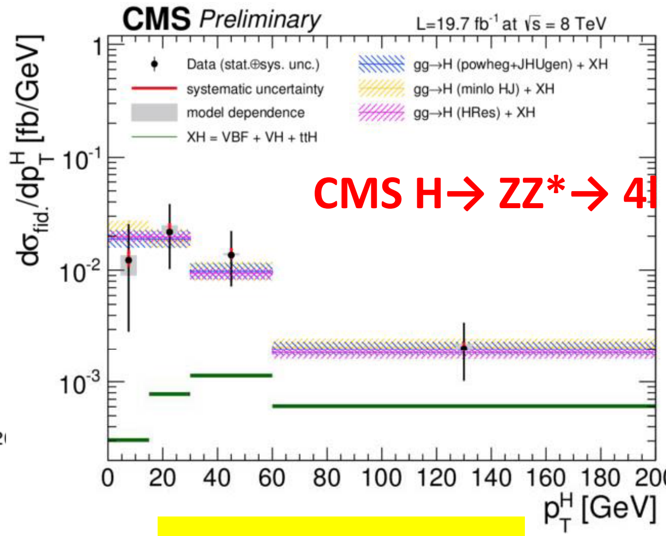
Higgs p_T distributions are sensitive to new physics in loops



PRL 115 (2015) 091801



CMS-HIG-14-016
arXiv:1508.07819

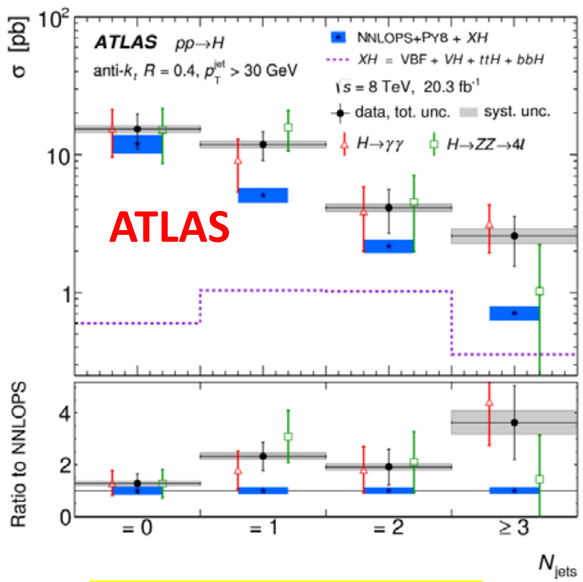


CMS-PAS-HIG-14-028

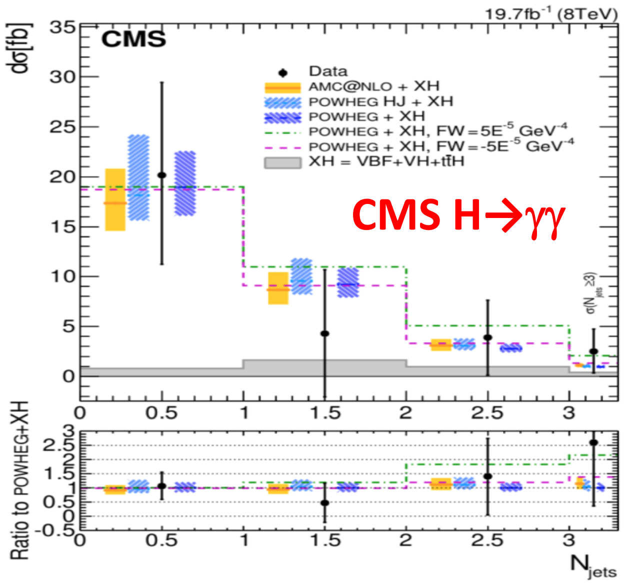
ATLAS see ~2σ trend of more boosted Higgs boson, not seen by CMS

Fiducial Cross-sections vs N_{jets}

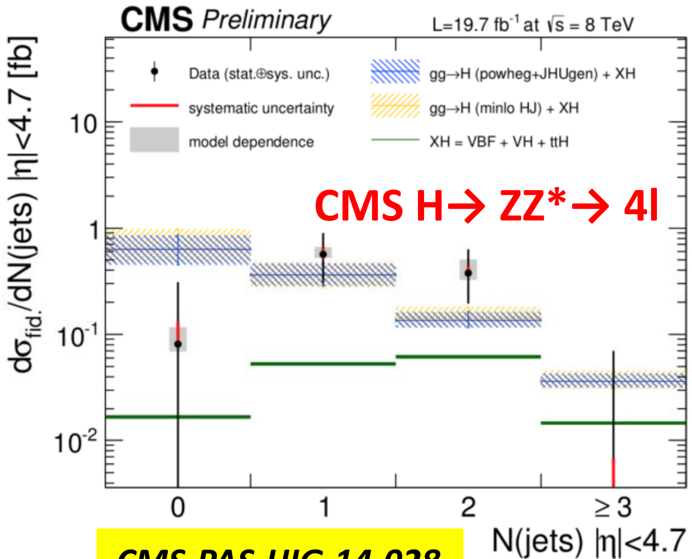
Measurements designed as model independent as possible



PRL 115 (2015) 091801



CMS-HIG-14-016
arXiv:1508.07819

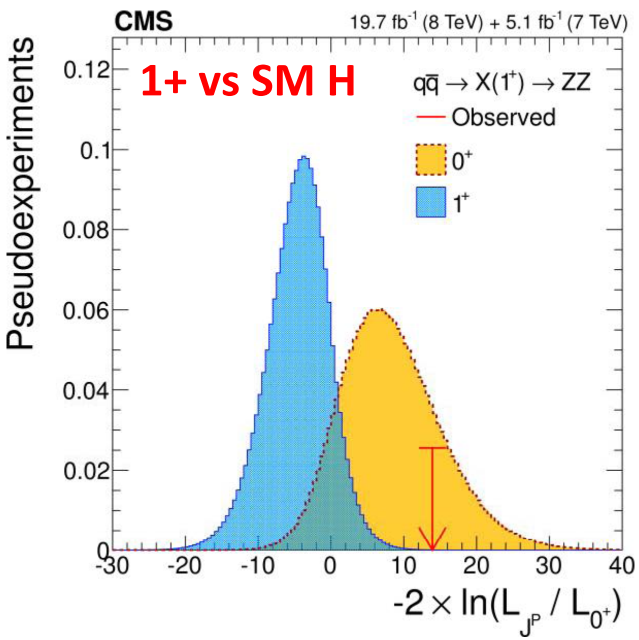


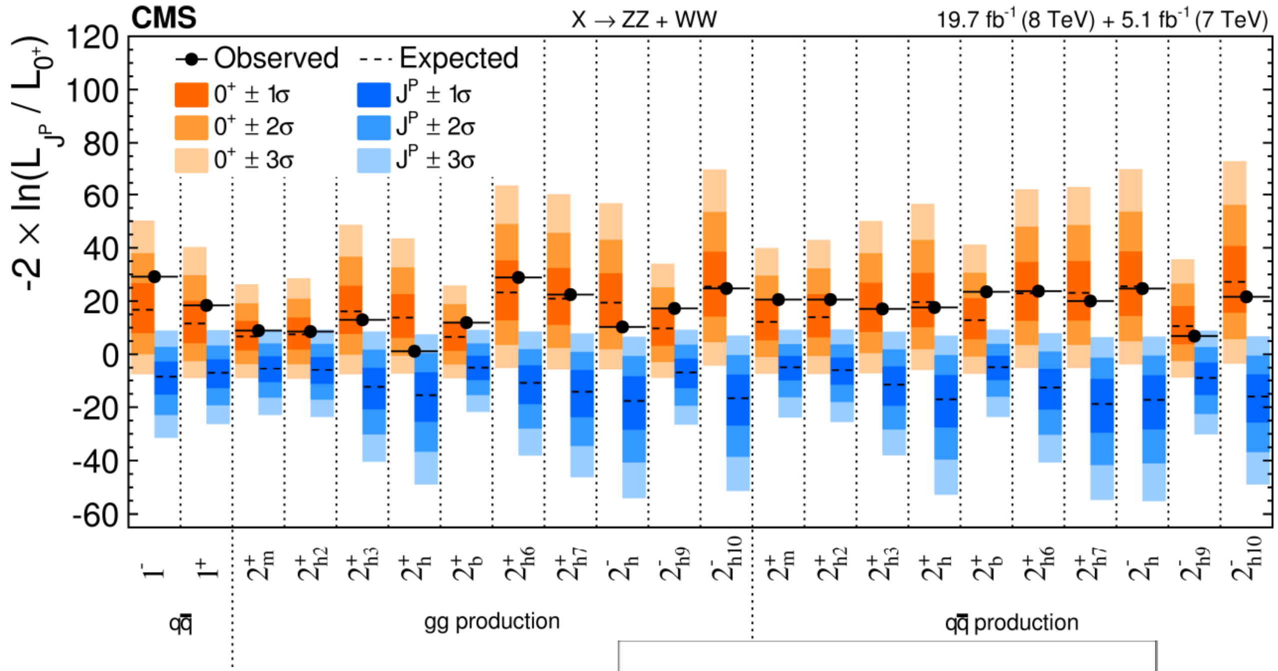
CMS-PAS-HIG-14-028

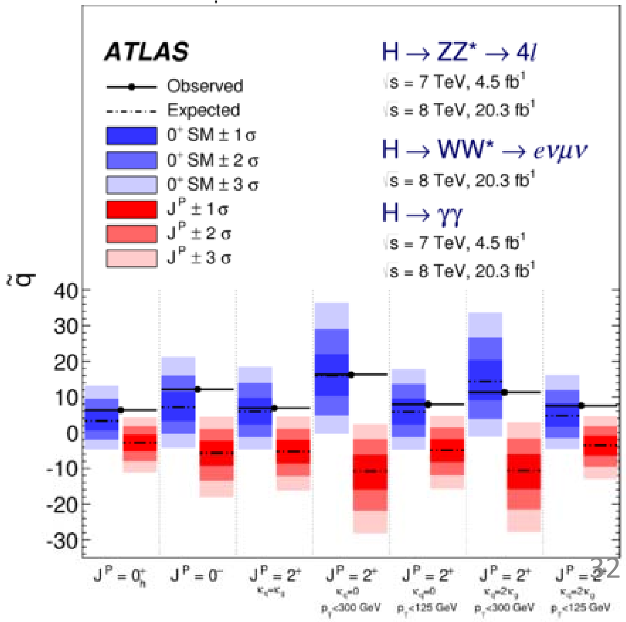
ATLAS see slightly more associated jets, not seen by CMS

Spin/Parity, CP mixing

Spin-Parity Results: X(JP) vs. H(0+)







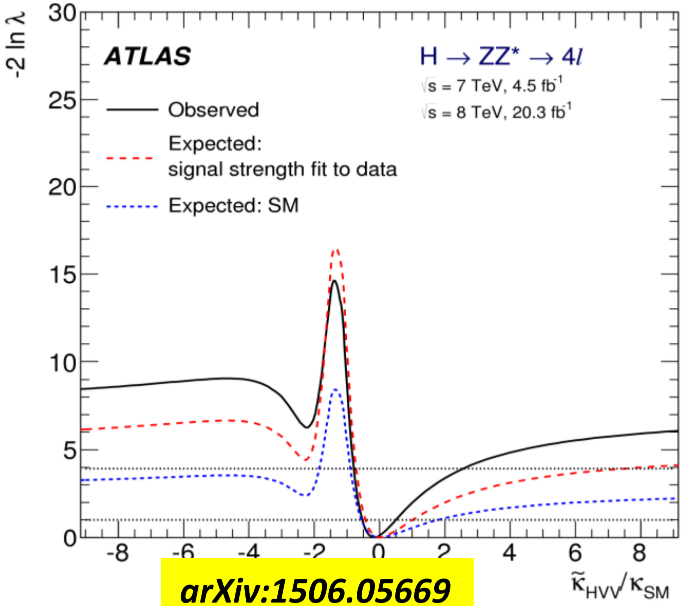
- ➢ Both experiments tested quite **a lot alternative hypothesis** against SM prediction.
- ➢ **In general data favors SM 0+ hypothesis**
- ➢ **Alternative tested pure states typically excluded at >99% CL**

CP Mixing

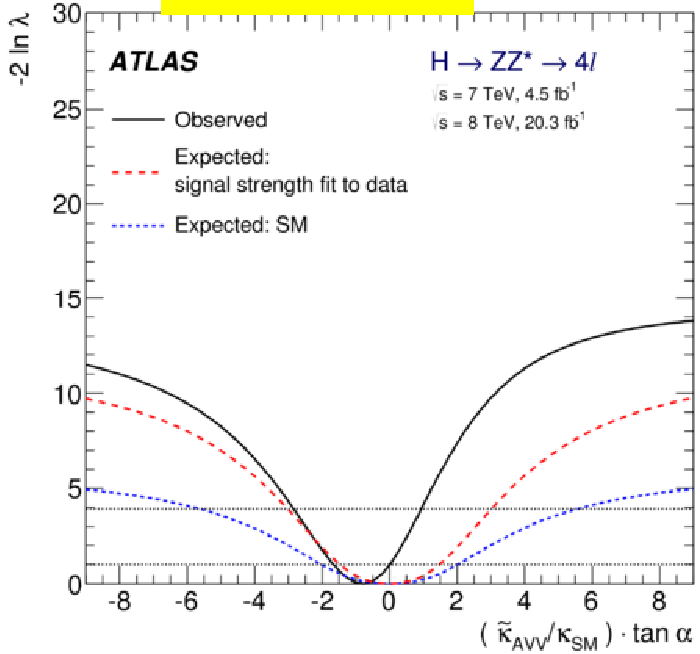
Higgs coupling could have CP-mixing and alternative tensor structure

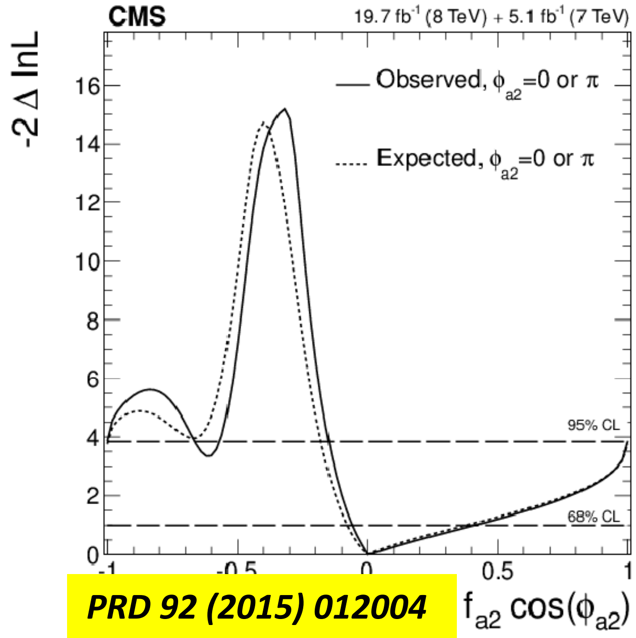
Test coupling and mixing angle in CP even and CP odd hypotheses

No evidence of CP violation observed

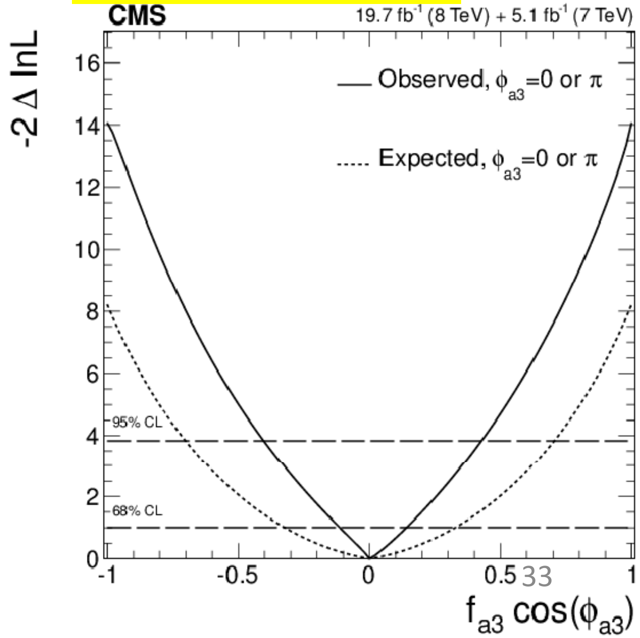


arXiv:1506.05669





PRD 92 (2015) 012004



Higgs boson pair production

X → HH

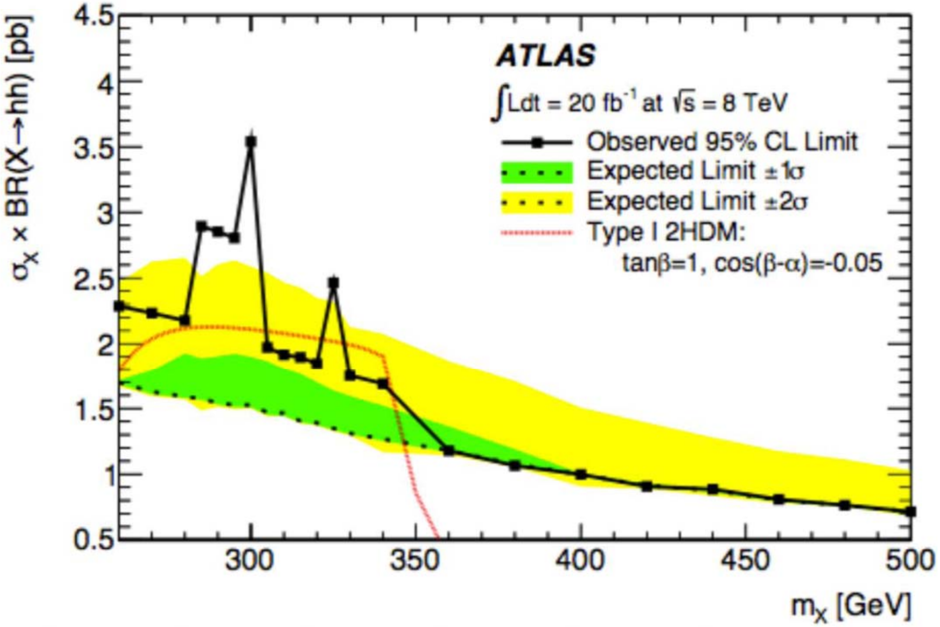
➢ Prepare for long-term SM HH @ HL-LHC: test self coupling

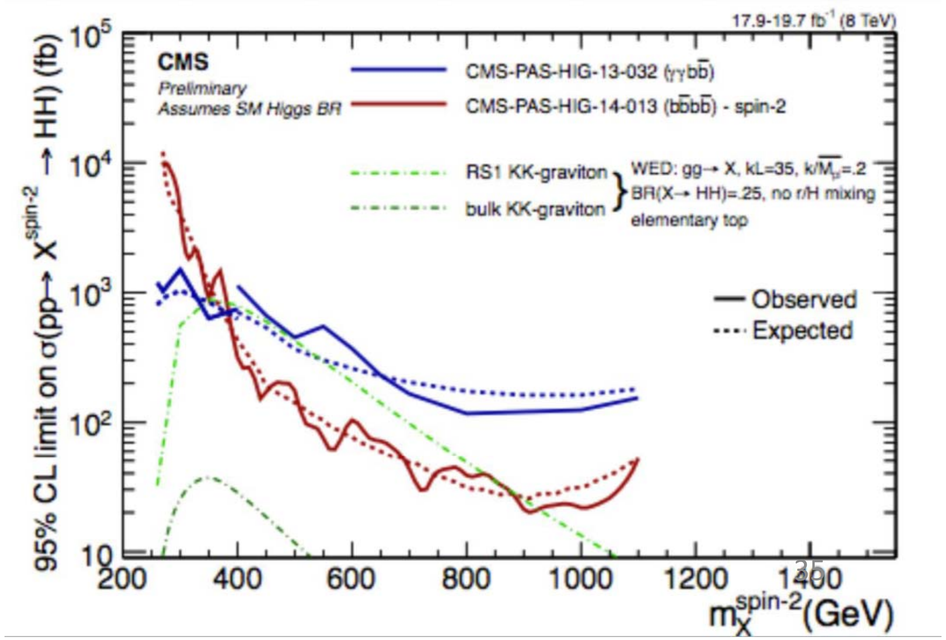
➢ Now: X→HH resonances

- bbγγ, bbττ, bbbb, multilepton results

➢ Results

- ATLAS excess 2.4σ [global]
- CMS does not see





First results with 2015 13TeV data

ATLAS and CMS physics results from Run 2

Tuesday, 15 December 2015 from **15:00** to **17:00** (Europe/Zurich)

CERN (500-1-001 - Main Auditorium)

Organised by M. Mangano, C. Lourenco, G. Unal........................ **Tea and Coffee will be served at 14h30**

Webcast There is a live webcast for this event Watch

Tuesday, 15 December 2015

15:00 - 15:40 CMS results *40'*

Speaker: Jim Olsen (Princeton University (US))

CMS_13_TeV_resul...

15:40 - 16:20 ATLAS results *40'*

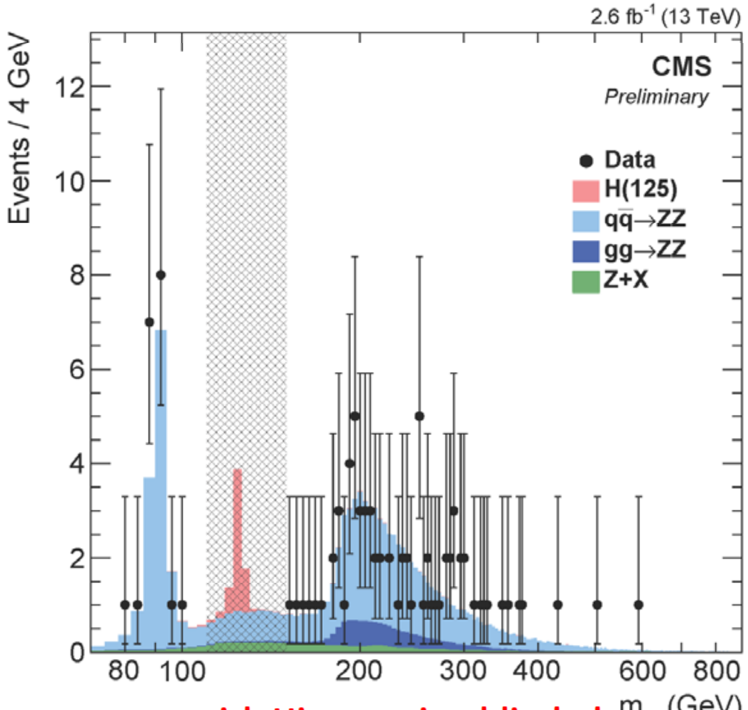
Speaker: Marumi Kado (Laboratoire de l'Accelerateur Lineaire (FR))

CERN-Council2015...

LHC Seminar https://indico.cern.ch/event/442432/

First look at the Higgs boson at Run2

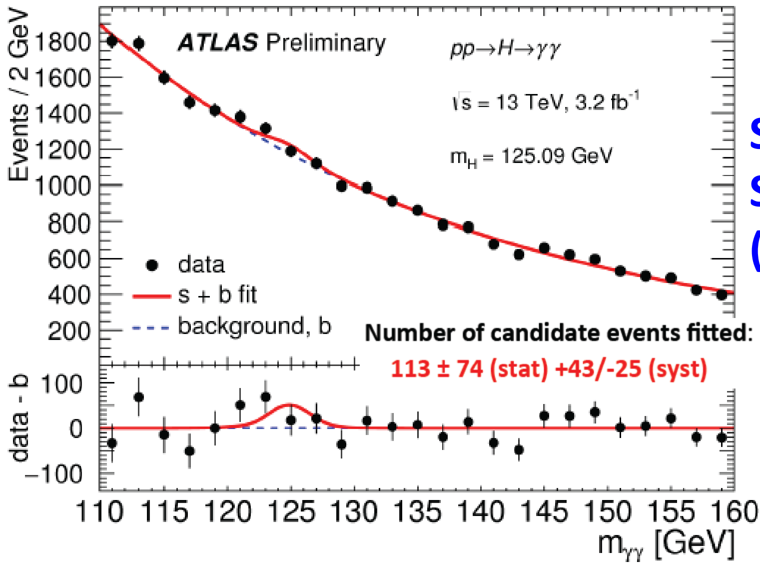
All CMS Higgs analyses remain blind



m_{4l} mass with Higgs region blinded

CMS 2.6 fb^{-1}

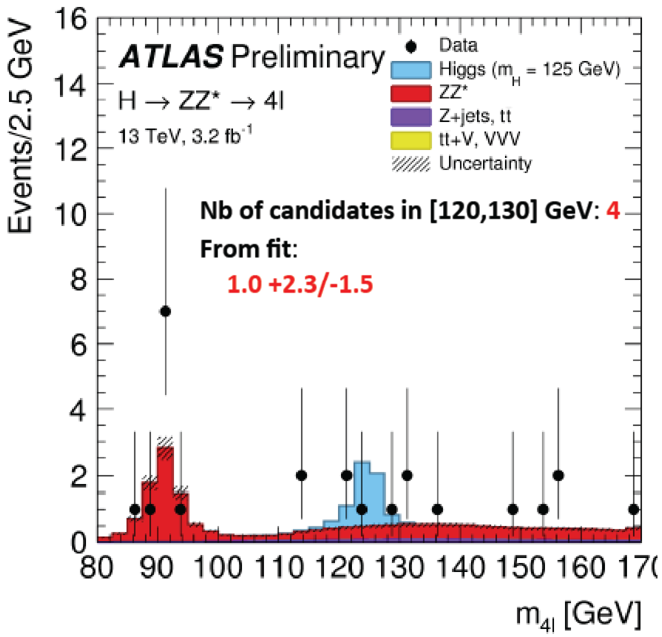
ATLAS-CONF-2015-060



Sensitivity to SM Higgs: 1.9σ (Observed 1.5σ)

ATLAS 3.2 fb^{-1}

ATLAS-CONF-2015-059



Sensitivity to SM Higgs: 2.8σ (Observed 0.7σ)

Summary

- **LHC entered Higgs boson precision era : Run 1 measurements still statistics dominated**

- **The 125GeV Higgs is very SM-like, but there are still rooms for BSM (see next presentation by Yaquan or other parallel presentations later)**

- **First results from Run2 with increased energy of √s=13 TeV and higher luminosity**

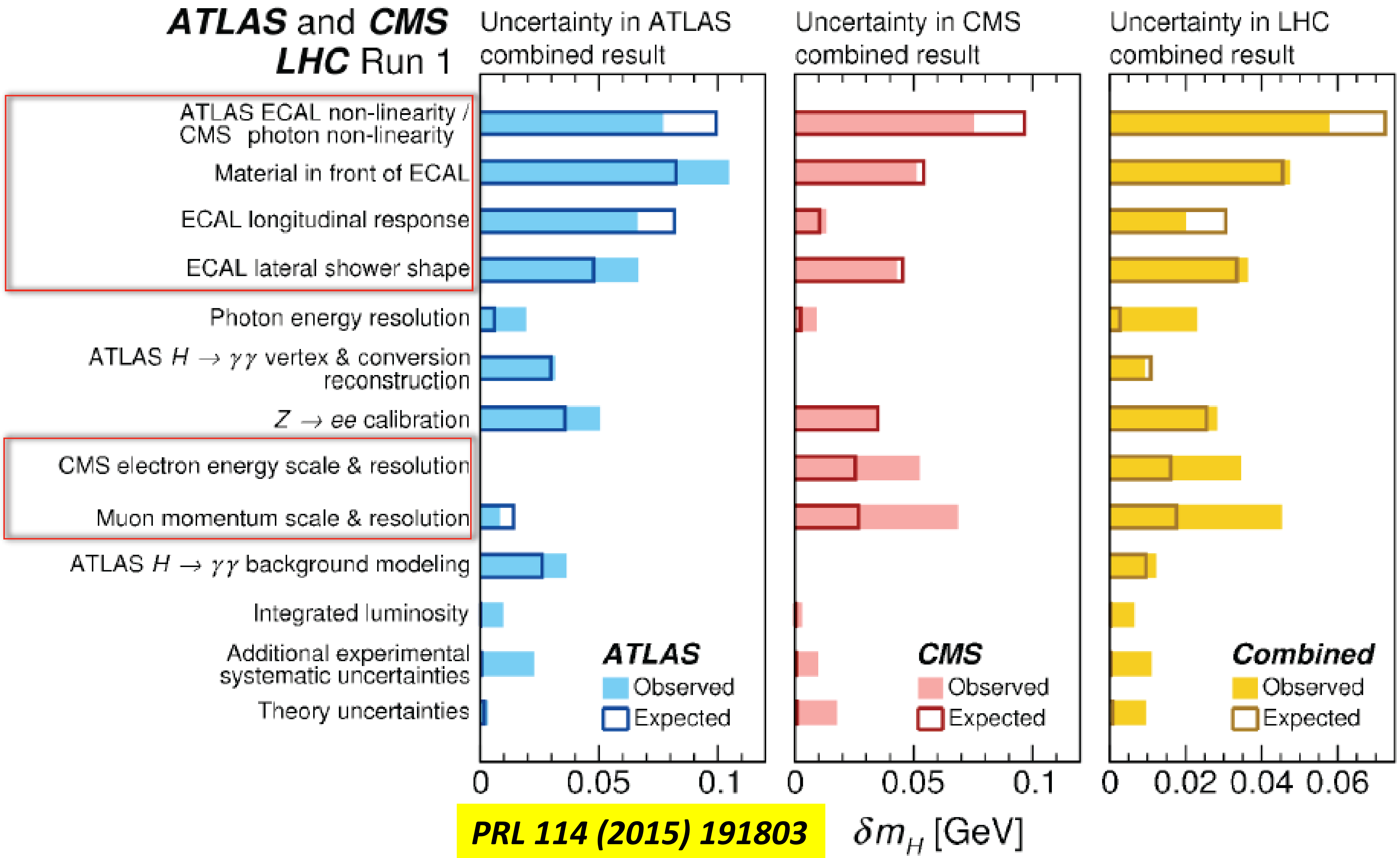
- **Eagerly awaiting the updated results and a much larger haul of data in 2016!**

The end

Many thanks for your attention and the organizers

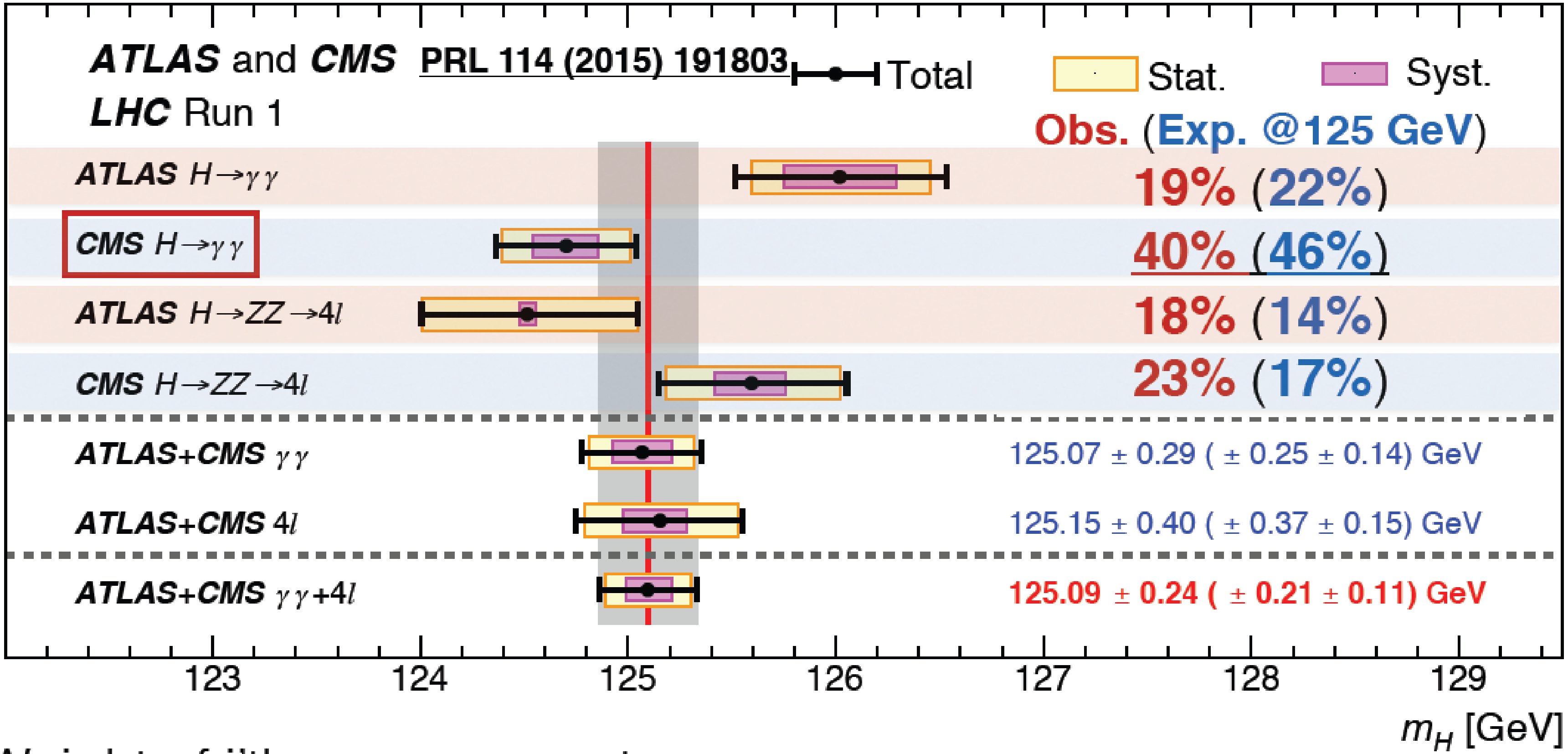
Backup

Higgs mass uncertainties



PRL 114 (2015) 191803

Weight of each measurement



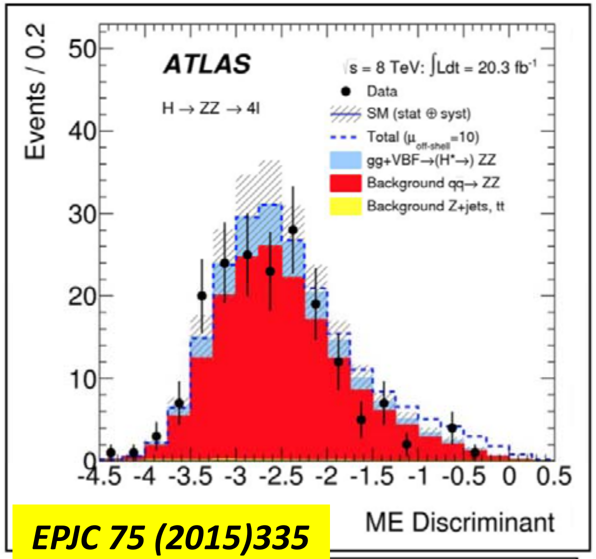
- Weight of i'th measurement

$$w^i=1/(\delta m_H^i)^2/\Sigma_j 1/(\delta m_H^j)^2$$

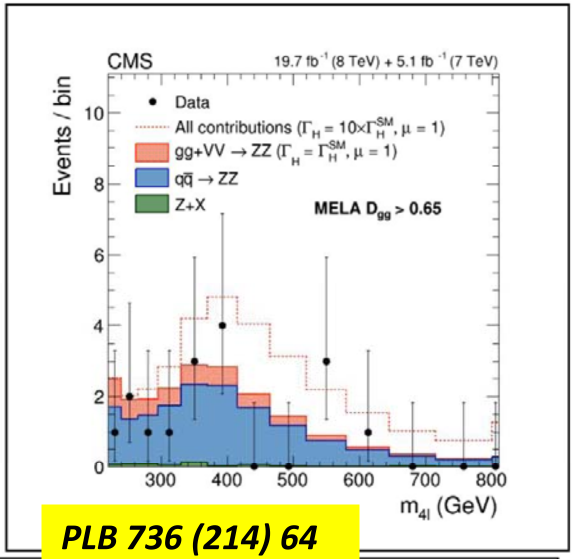
- ATLAS combined measurement weight 35% (36%); CMS 65% (64%)

Higgs total width： on/off shell

➢ **ATLAS use a multivariate discriminant to enhance sensitivity**



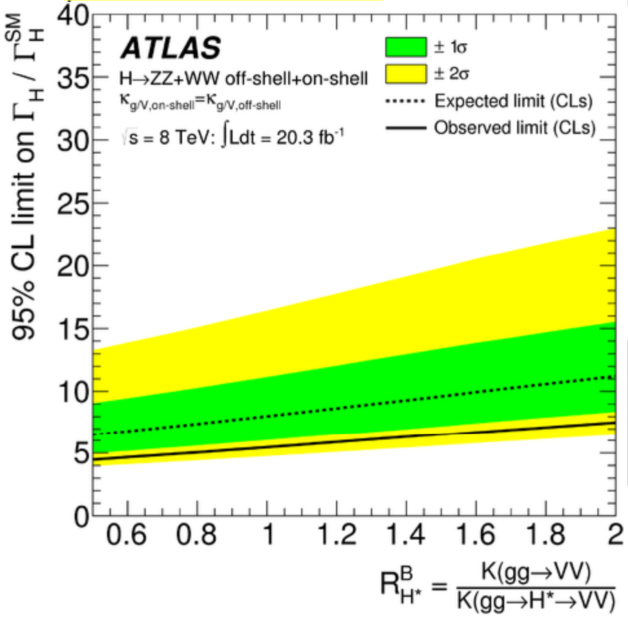
EPJC 75 (2015)335



PLB 736 (214) 64

ATLAS:
Γ_H<23 MeV
Expected :33 MeV

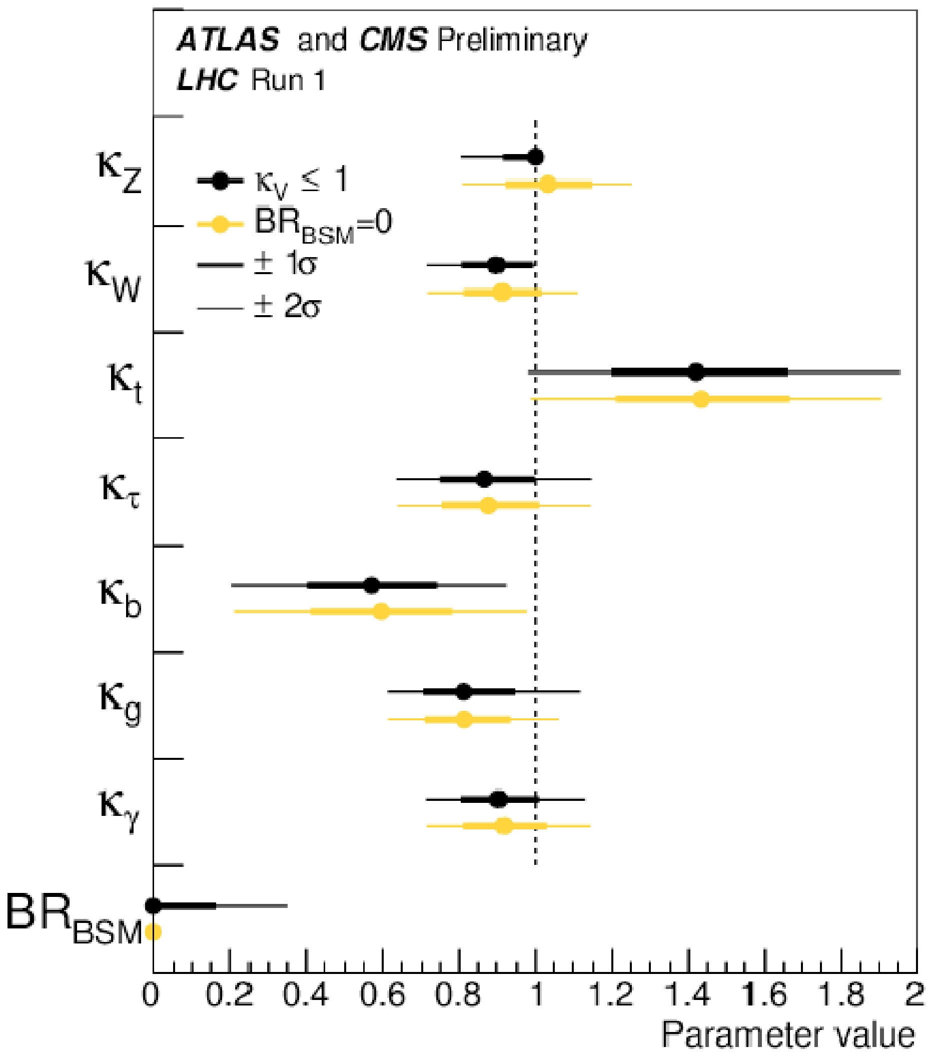
CMS:
Γ_H<22 MeV
Expected : 33 MeV



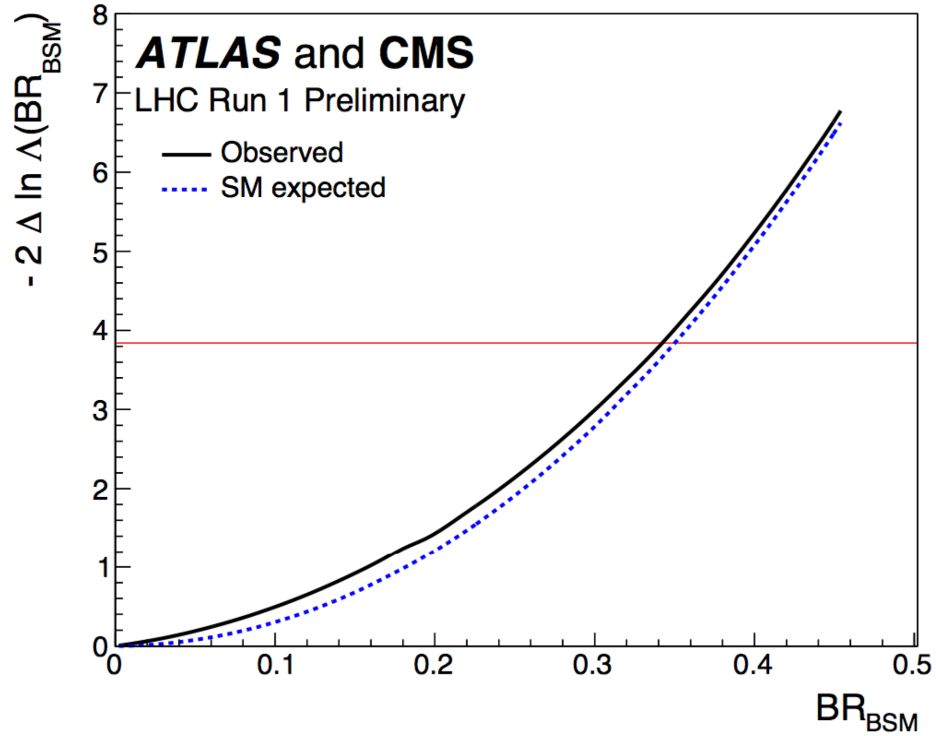
$R^B_{H^*}$	Observed 0.5	Observed **1.0**	Observed 2.0	Median expected 0.5	Median expected **1.0**	Median expected 2.0	Assumption
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2	$\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}},\ \Gamma_H/\Gamma_H^{SM}=1$

BSM decays

Generic models allowing physics beyond the SM



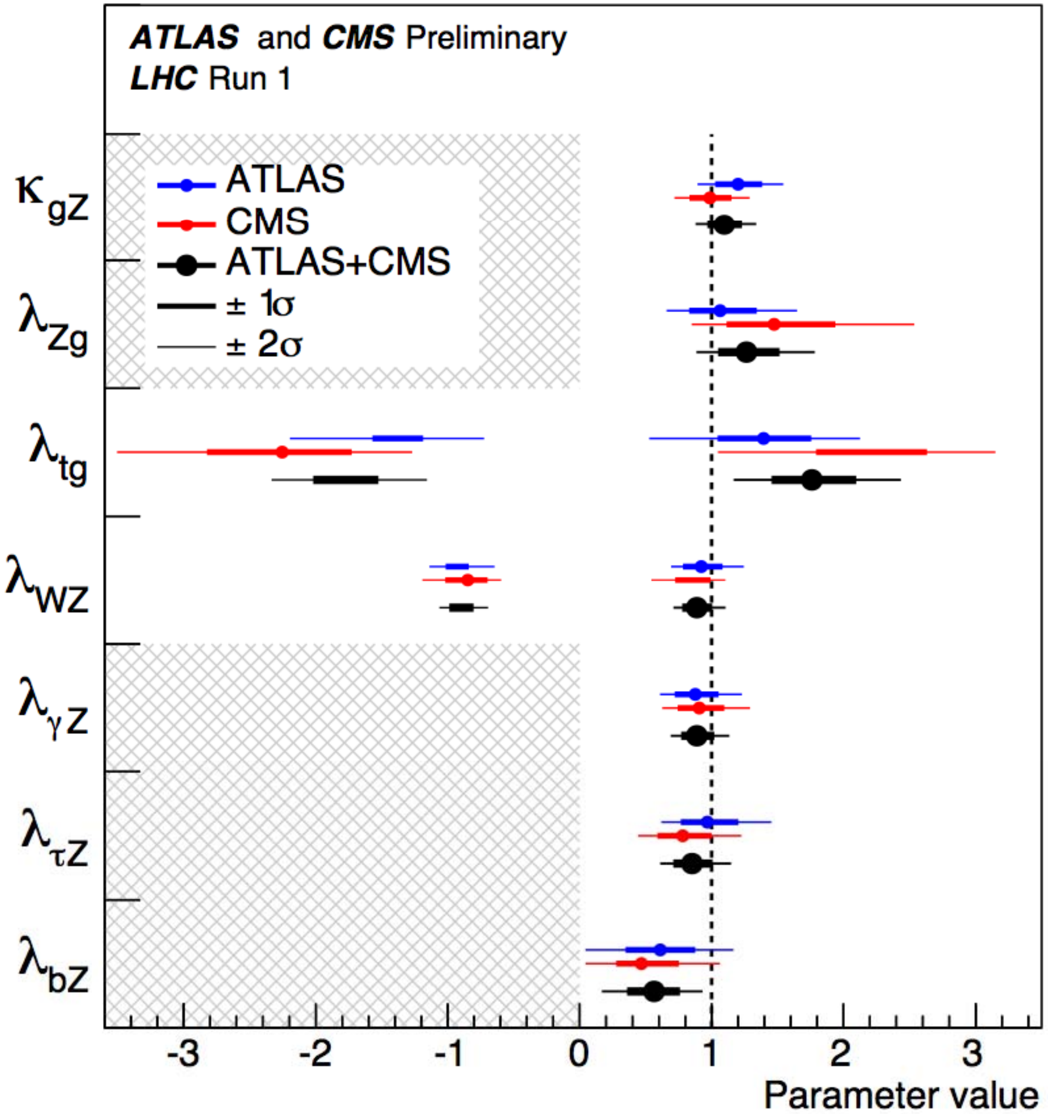
Assume $k_V \leq 1$ (as in 2HDM) - BR_{BSM} can be measured



From the combined fitting, we set the limit: $BR_{BSM} < 0.34$ at 95% C.L. (with $\kappa_V \leq 1$)

Ratios of κ's

Again, results in agreement with SM



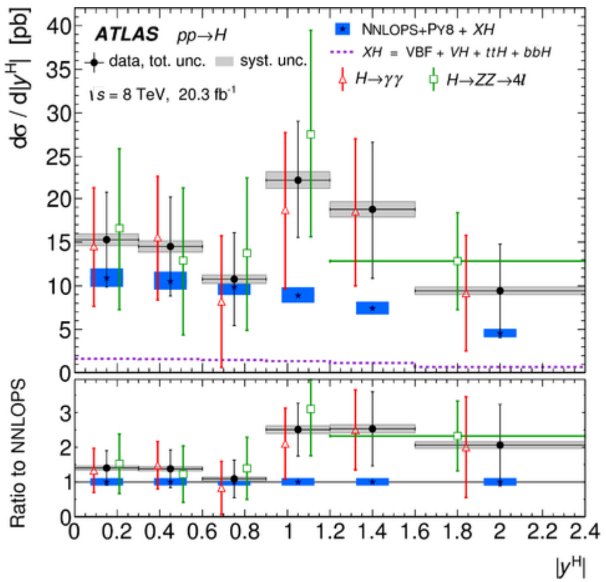
Measure ratios of cross sections and BR or ratios of μ's

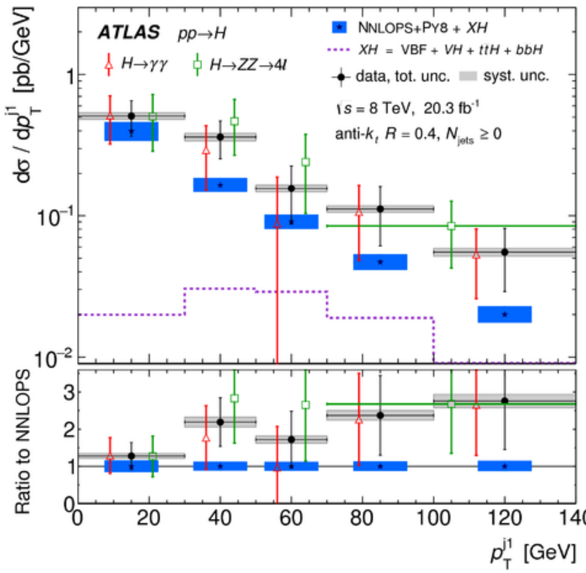
σ and BRs ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$
BR^{WW}/BR^{ZZ}	$\lambda_{WZ} = \kappa_W/\kappa_Z$
$BR^{\gamma\gamma}/BR^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$BR^{\tau\tau}/BR^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
BR^{bb}/BR^{ZZ}	$\lambda_{bZ} = \kappa_b/\kappa_Z$

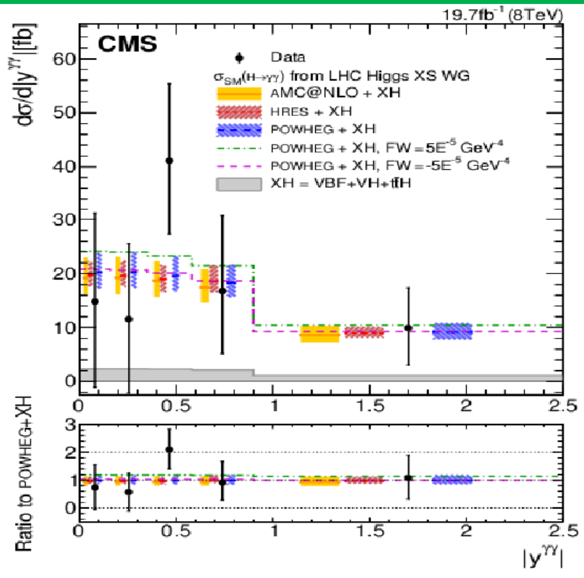
ggF, gg→H→ ZZ is the cleanest channel and less affected by systematic uncertainties

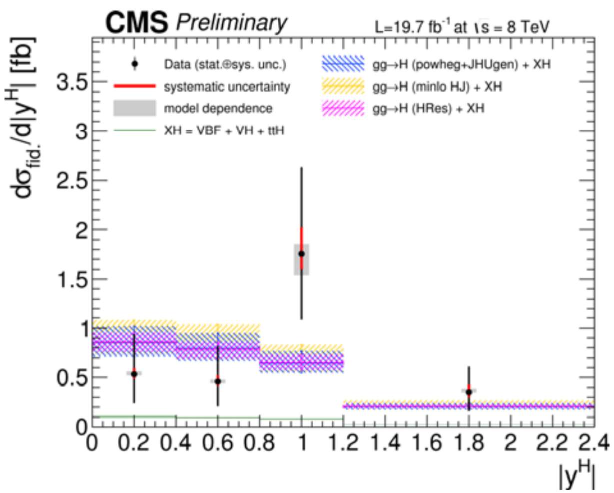
In the ratios, systematic of the same source will be canceled

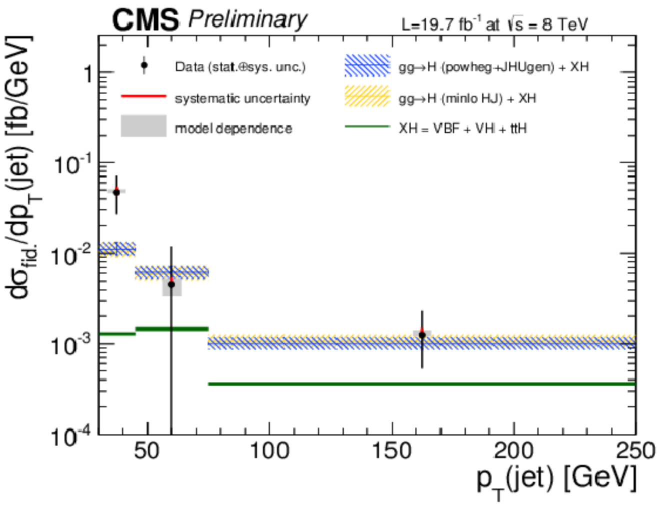
Fiducial Cross-sections

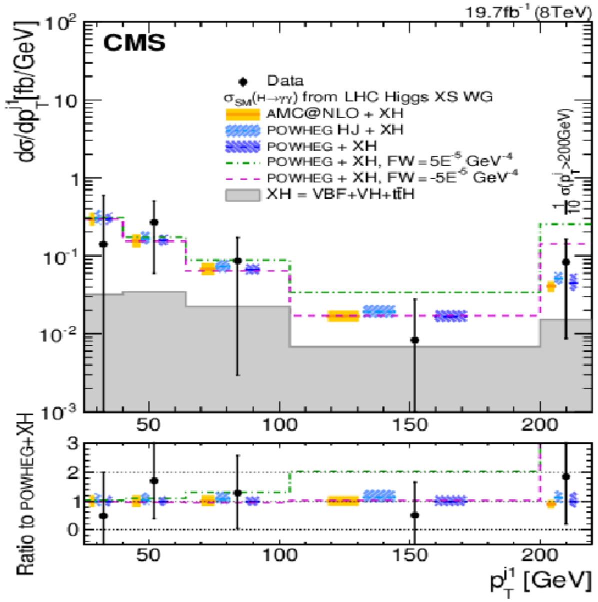










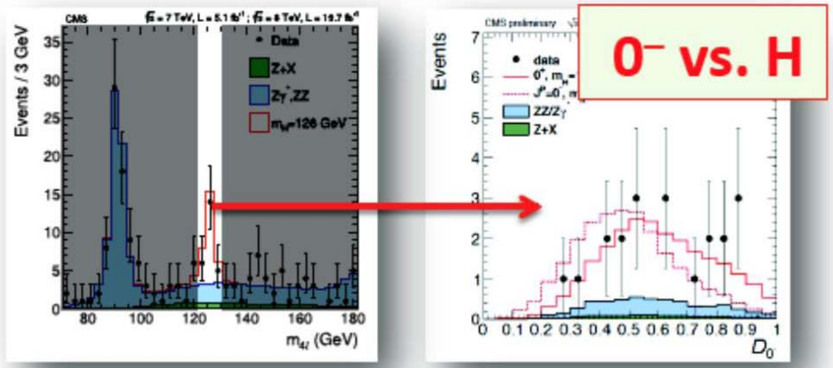


Spin-Parity Test: X(JP) vs. H(0+)

H→ZZ→4l

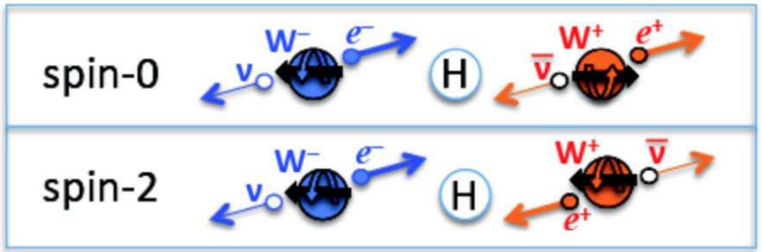
- 4l system is fully reconstructed
- use ME-based discriminator

$$d = \frac{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4 \middle| \mathrm{H}\right)\right|^2}{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4 \middle| J^P\right)\right|^2}$$



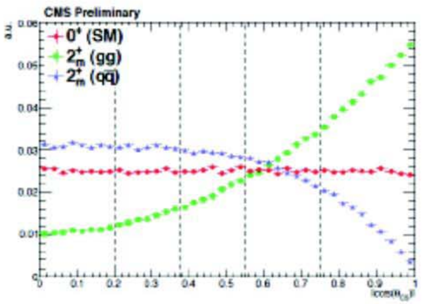
H→WW→lνlν

- di-lepton angle and mass are sensitive to the spin of the decaying $X(J^P)$



H→γγ

- J=1 forbidden (Landau-Yang theorem)
- cosθ* is the only variable sensitive to J^P information at leading order



- shown: before acceptance and reconstruction
- after acc x reco, discrim. power lessens
- poor S:B makes measurements difficult

CP Mixing and Tensor Structure

- **Higgs coupling could have CP-mixing and alternative tensor structure**

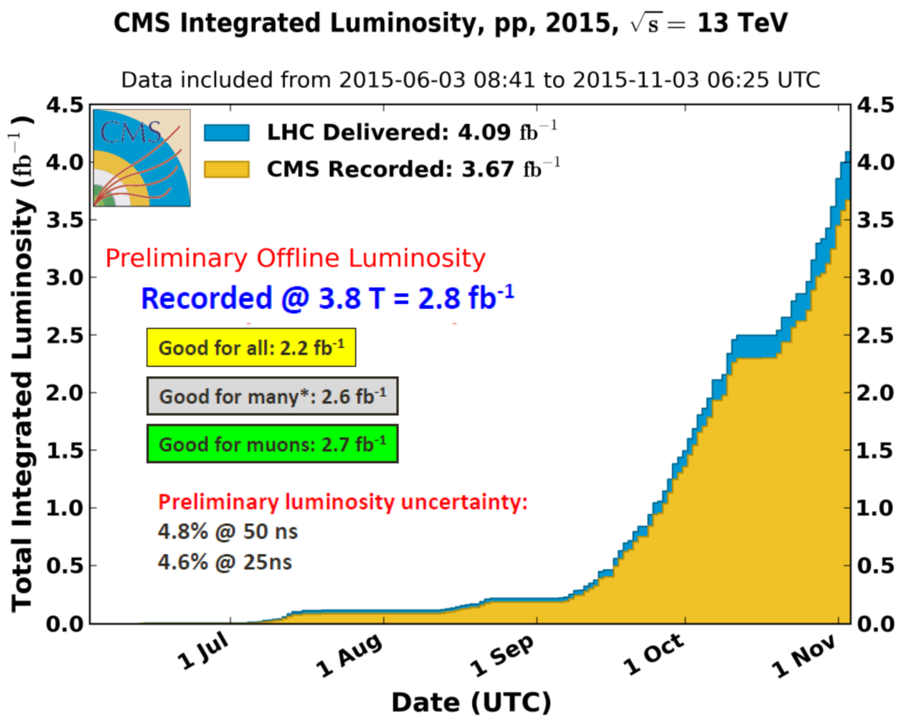
- ATLAS: Effective field theory; fit a general Lagrangian compatible with Lorentz invariance

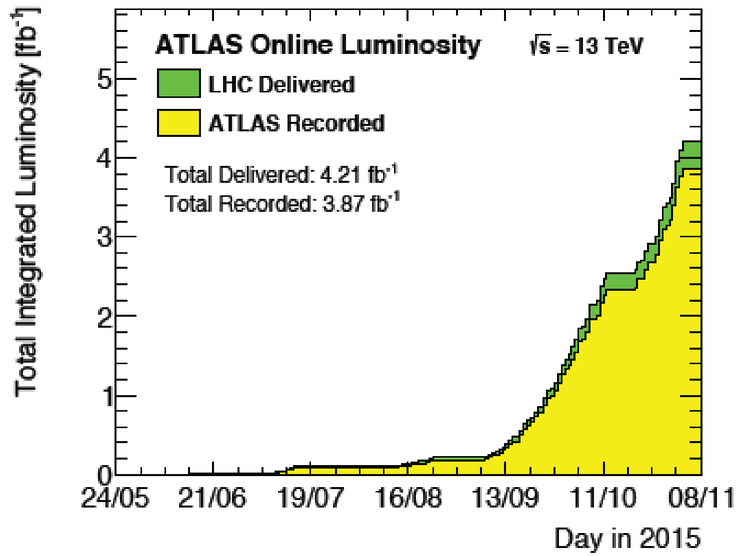
- CMS: Anomalous couplings; fit a generic amplitude compatible with Lorentz and gauge invariance

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

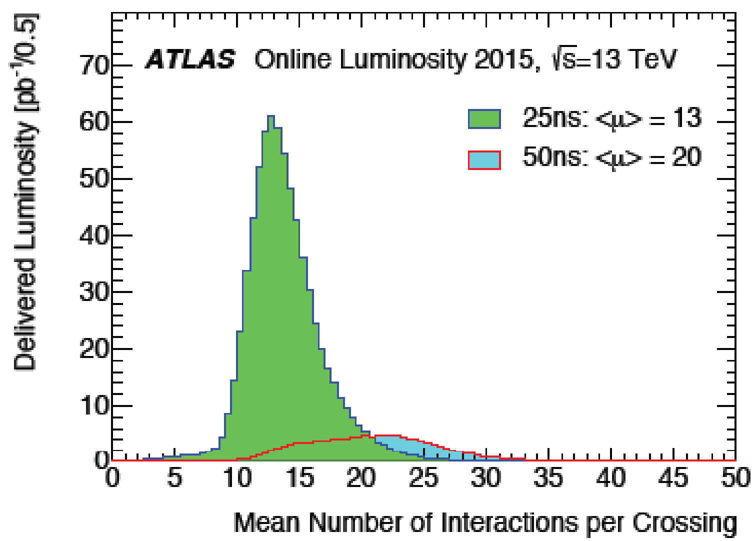
SM — BSM CP-even — BSM CP-odd

13 TeV dataset



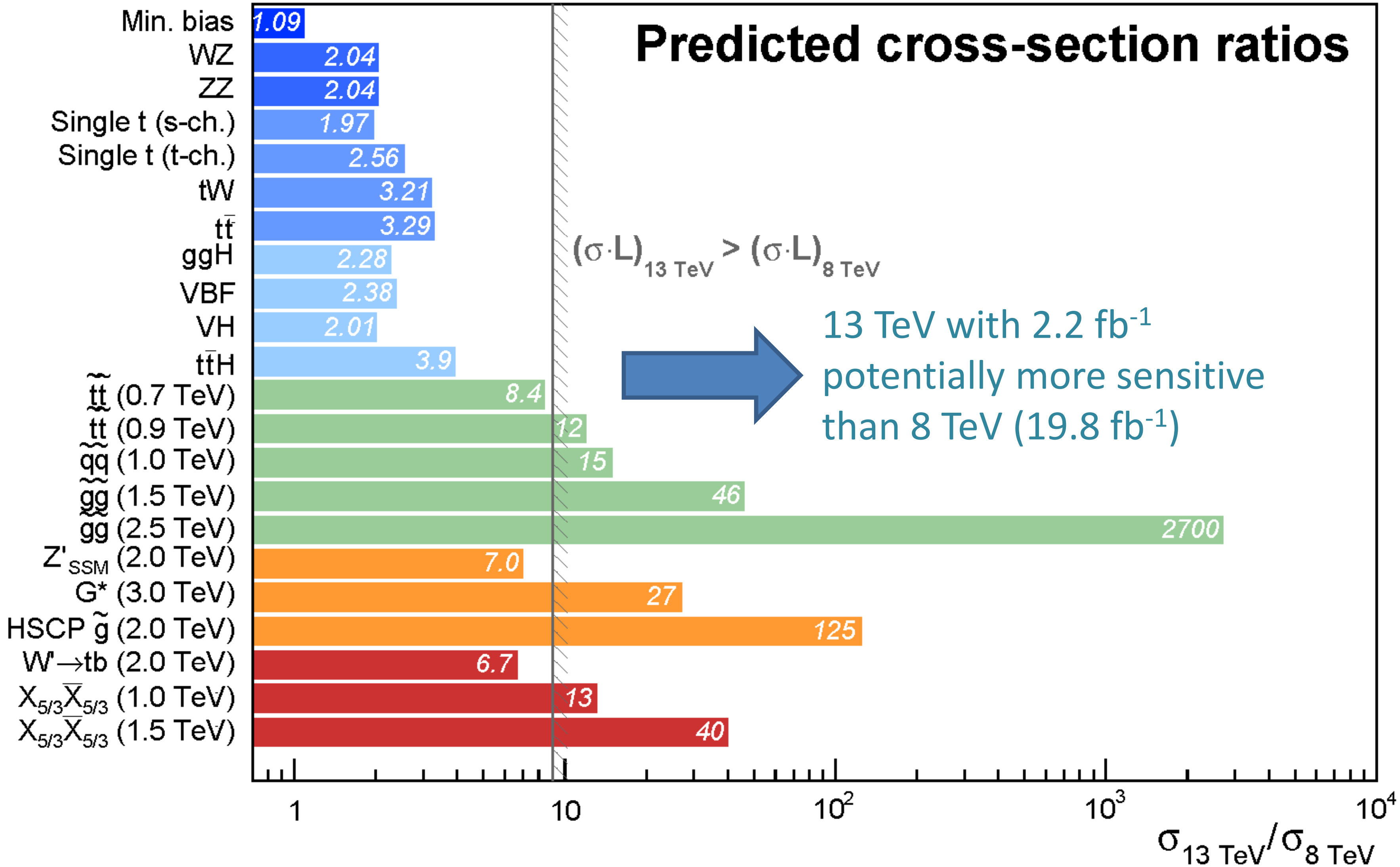


Data taking efficiency of 92%



***Run 1**: 8 TeV (mu~21) and 7 TeV (mu~9)*

Reminder: increased reach @ 13 TeV



13 TeV with 2.2 fb^{-1} potentially more sensitive than 8 TeV (19.8 fb^{-1})

Summary of Run-2 Total Cross Section Measurements