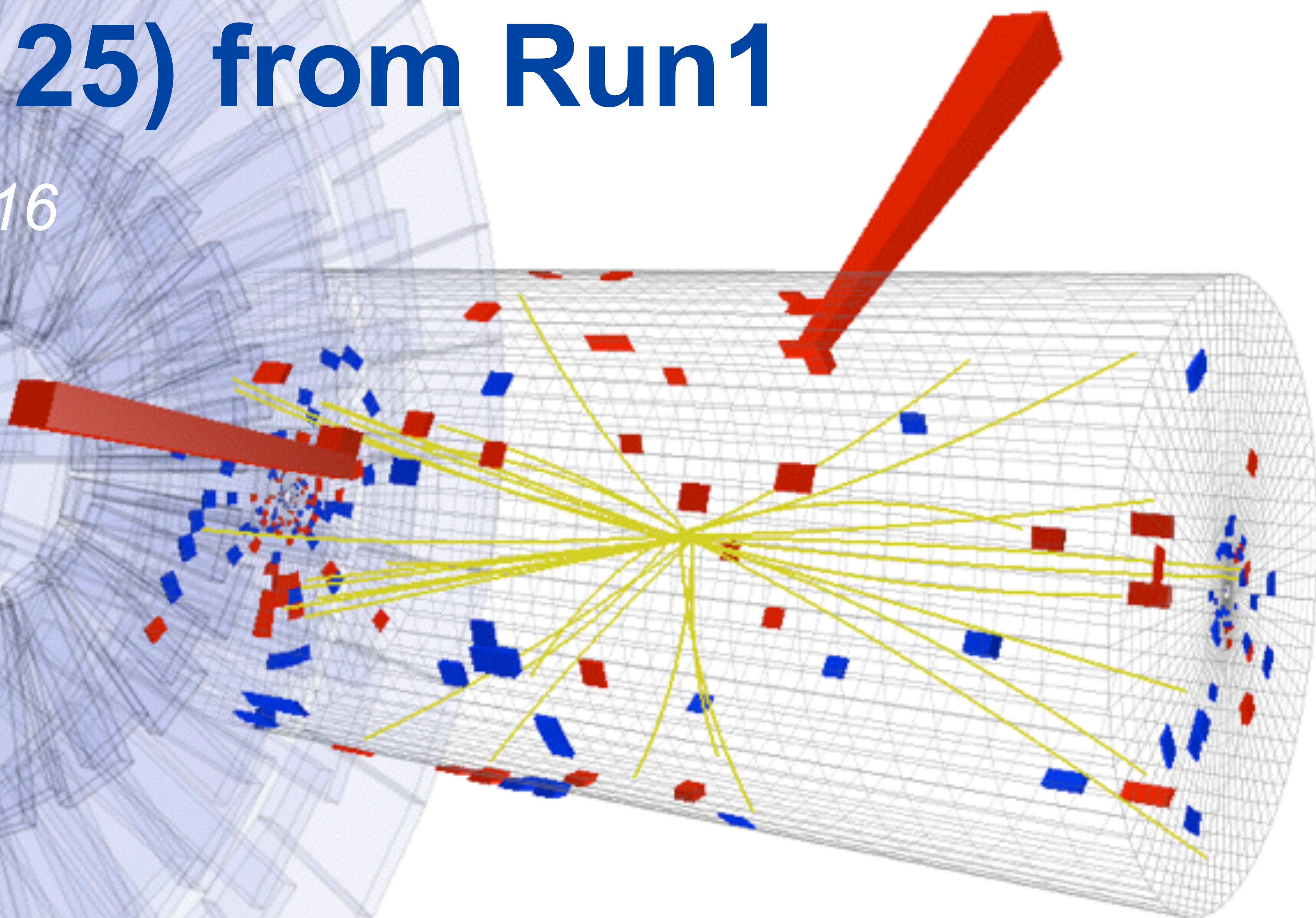
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Higgs(125) from Run1

Blois May 2016



Mauro Donegà

Outline

- Mass measurement

- Coupling measurements:
  Signal strengths
  Coupling modifiers (k-framework)

- Fiducial and Differential cross sections

All ATLAS and CMS results are based on the full Run 1 dataset:
~5 fb^{-1} at 7 TeV (2011)
~20 fb^{-1} at 8 TeV (2012)

(Reference to all presented measurements can be found at the end in the last slides)

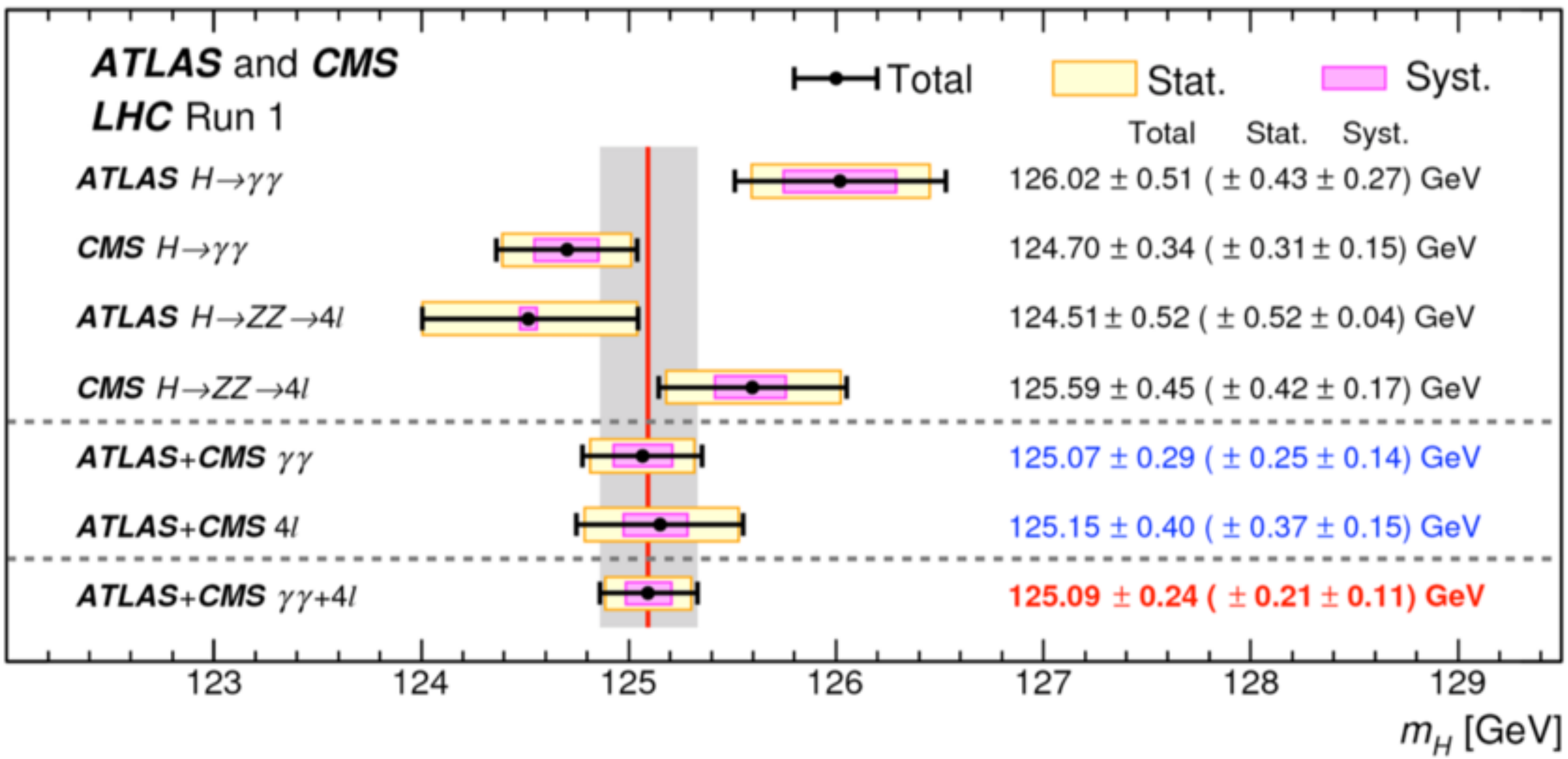
ATLAS+CMS
Combined measurements

Mass measurement

The Higgs boson mass is the (non-predicted) parameter from which the whole phenomenology of the SM-Higgs sector is derived

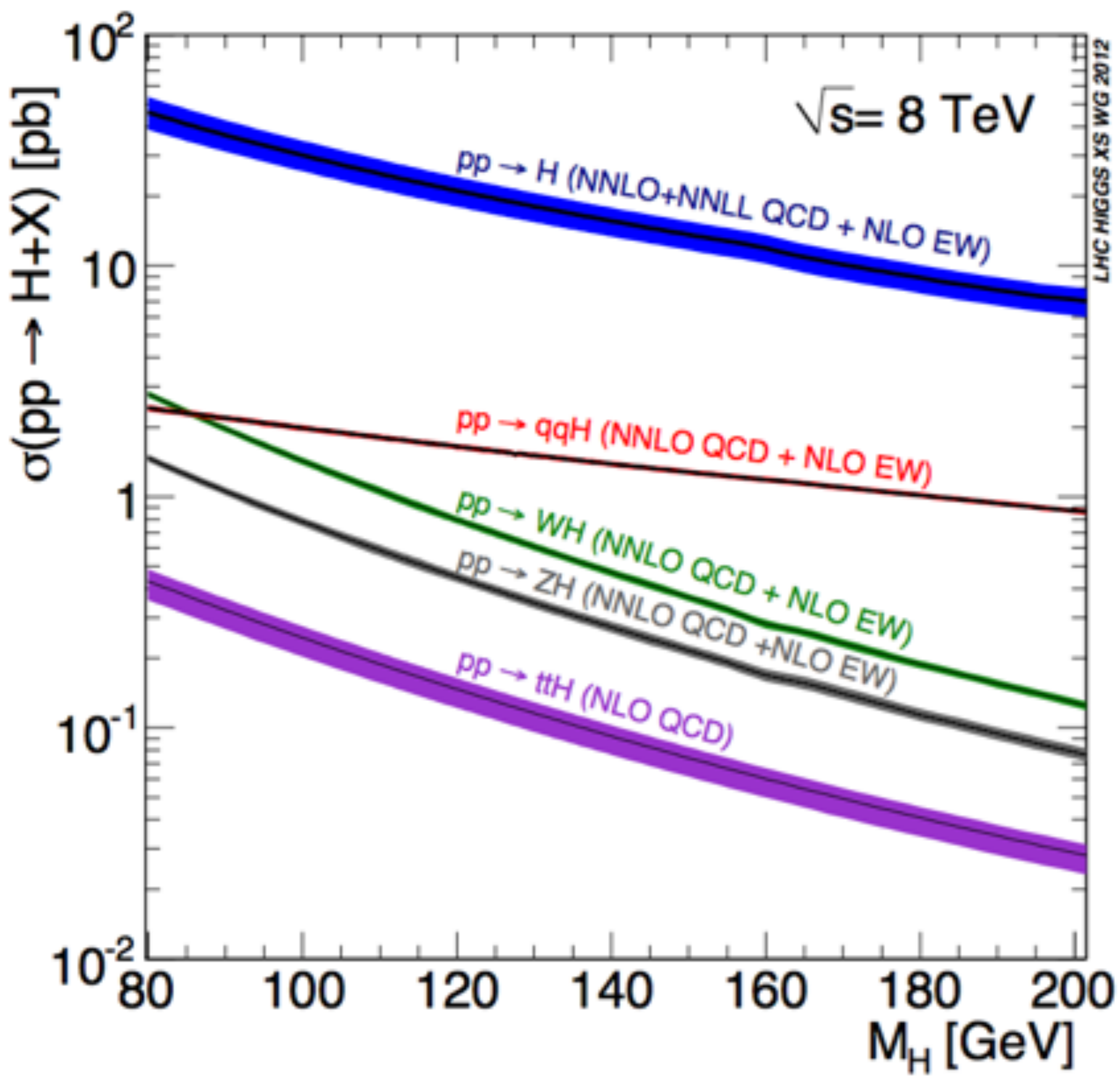
High mass resolution channels: $H \to \gamma\gamma$ and $H \to ZZ \to 4$ leptons

$M_H = 125.09 \pm 0.24$ GeV $= \pm 0.21$ (stat.) ± 0.11(syst.) GeV

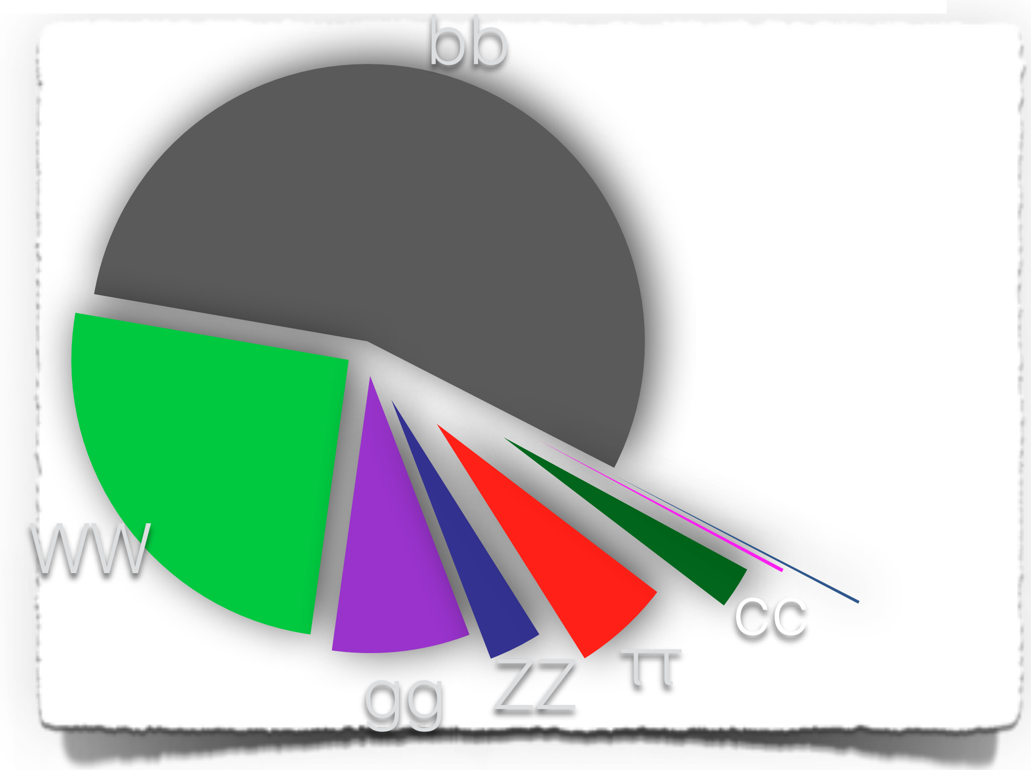


Opposite trends in $H \to \gamma\gamma$ / $H \to ZZ$ in ATLAS / CMS: p-value~10%

Production and decay



Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001



SM ggF, ttH, bbH theory uncertainty: ~10%

VBF, VH: 2-3%

BR uncertainty ~5% on leading channels

Combination framework

General assumptions:

1) the signal comes from only 1 particle
2) SM Higgs boson hypothesis 0^+ and in terms of its production and decay kinematics
3) narrow width approximation is valid (production/decay decoupled)

$$(\sigma \cdot BR)(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

i = production mode ; f = decay channel ; Γ_H = total width = sum of all partial widths

The signal yield in category k, $n_{signal}(k)$ is computed as:

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f \right\},$$

$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{ \sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_{\text{SM}}^f \right\}$$

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{\text{BR}_{\text{SM}}^f}.$$

Luminosity ($\mathcal{L}(k)$); production/decay modifiers ($\mu_i \mu^f$); Acceptance ($A_i^f(k)$); Efficiency ($\varepsilon_i^f(k)$)

Basically all experimental systematics between the experiments are assumed uncorrelated (impact tested). Main correlations through theory uncertainties on production σ and BR.
In total we combine ~100 categories per experiment with ~4200 nuisance parameters.

Signal strength measurements

We combine {ggF, VBF, VH, ttH} ⊗ {H→γγ, H→ZZ, H→WW, H→bb, H→μμ, H→ττ}

(not included ggF/VBF for H→bb and VH/ttH for H→μμ)

All remaining production ⊗ decay modes end up in other channels (e.g. tHq in ttH)

The most constrained model used is to use only one overall μ (same also for 7 and 8 TeV)

$$\mu = 1.09^{+0.11}_{-0.10} \quad = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

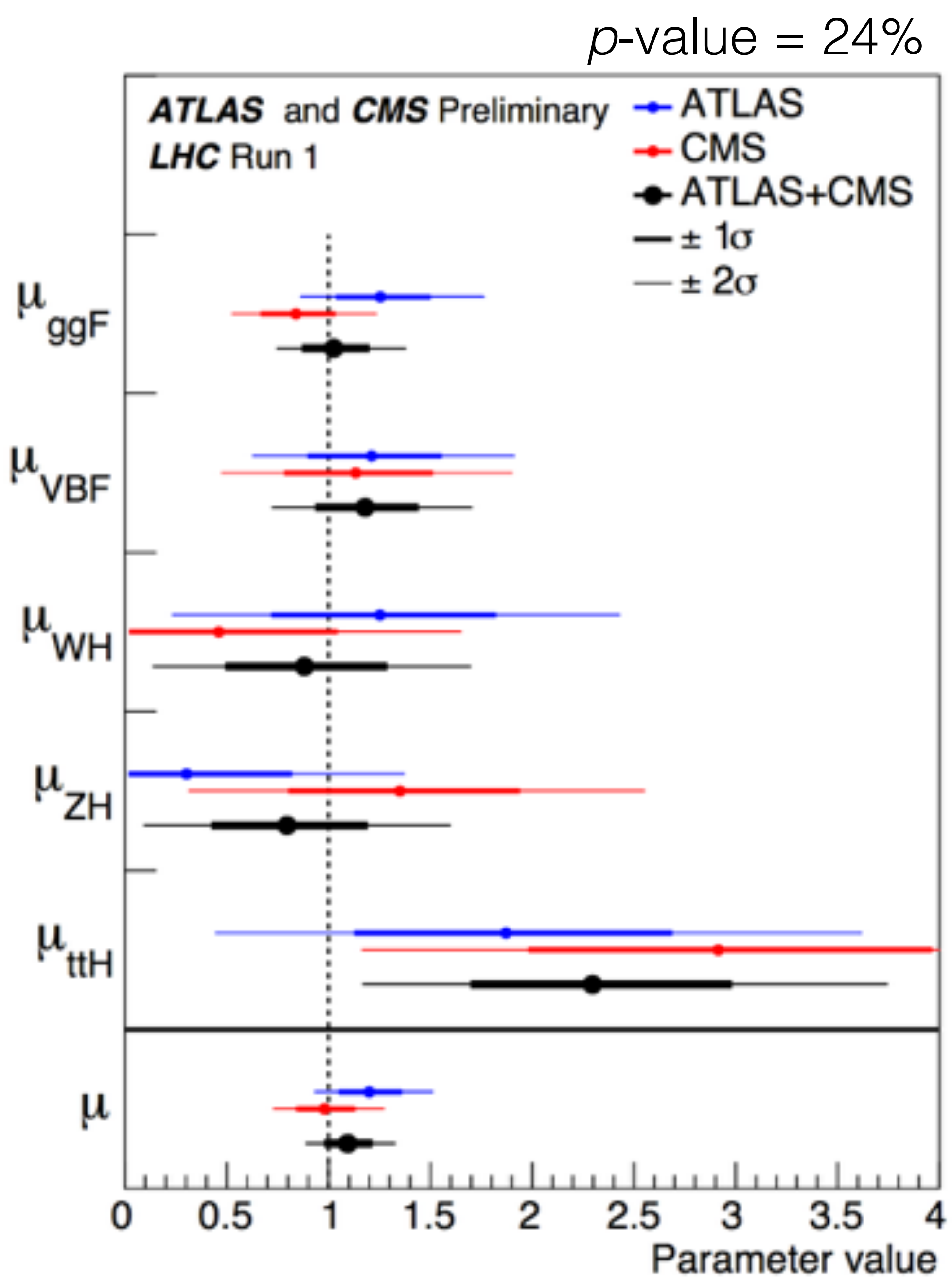
stat = statistical uncertainty
thsig = theory uncertainty on the signal model
thbgd = theory uncertainty on the background predictions
expt = all other experimental uncertainties (+finite MC statistics)

⇒ Compatible with SM : the most precise test so far o(10%)

VERY model dependent and there could be all sorts of compensations acting

Production processes

Assume all BR as in the SM ($\mu^f = 1$) and test the production mechanisms

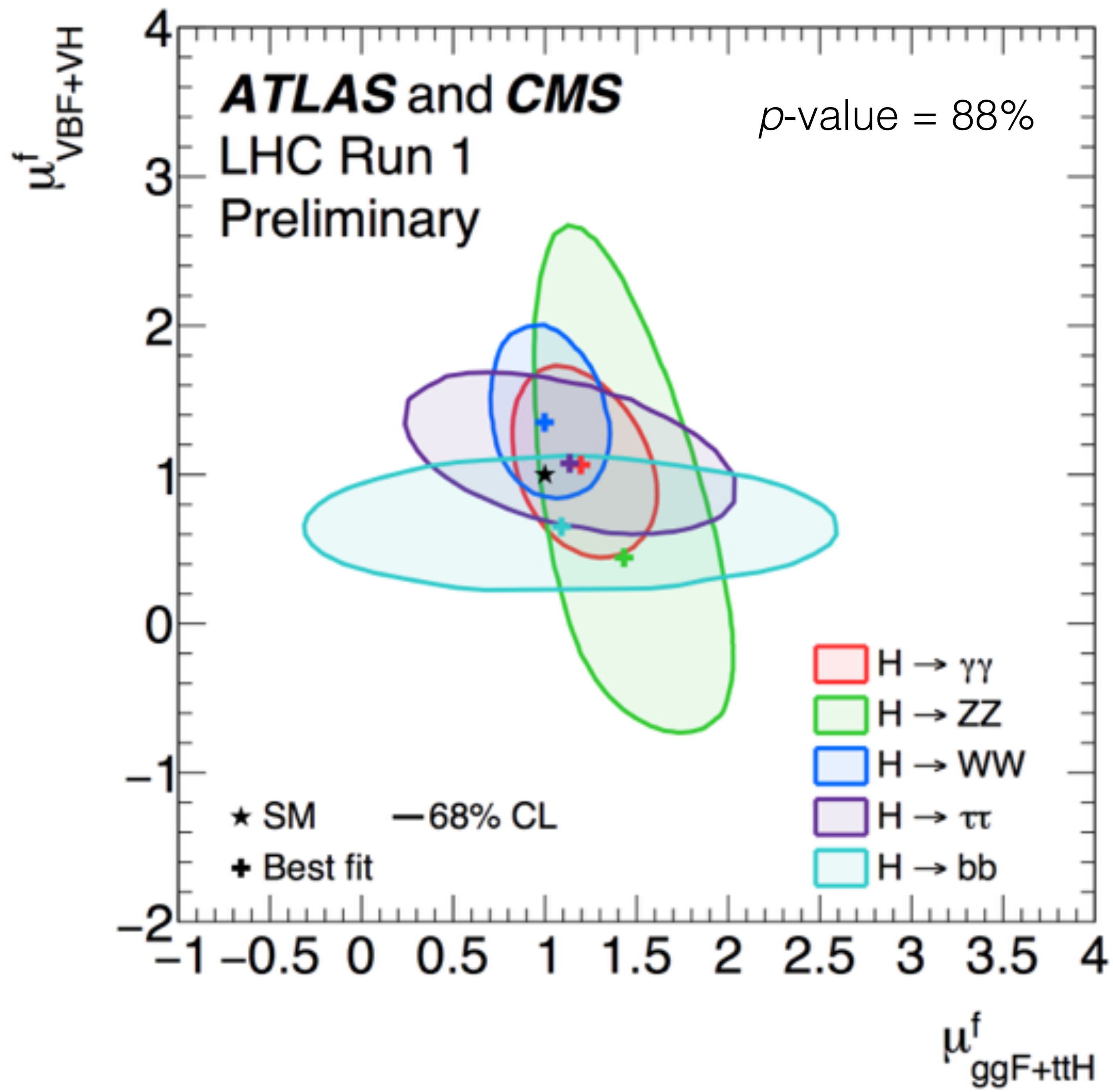


largest deviation: ttH ~2.3σ wrt SM

μ^f_{VBF+VH} coupling to bosons VBF + VH

$\mu^f_{ggF+ttH}$ coupling to fermions ggF + ttH

5 x 2 parameters (combination of contours would require additional hypothesis on BR)



k-framework

Parametrization defined by the LHC Higgs cross section working group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

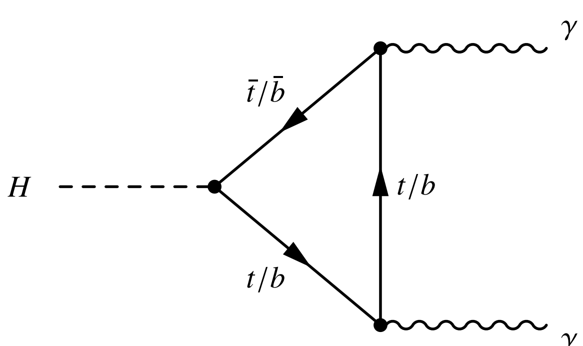
Coupling modifiers: "k-framework" (kappa-framework) = multipliers at amplitude level introduced to parametrise possible deviation from SM. They are defined as

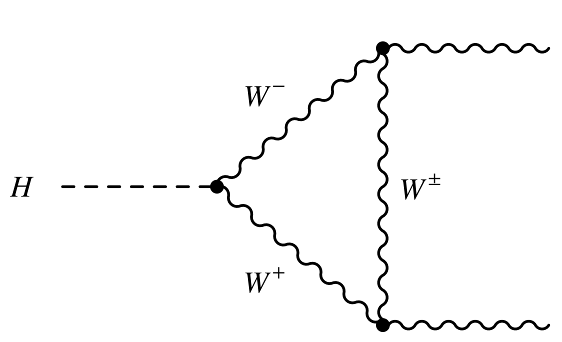
$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

$$\kappa_H^2 = \sum_j \mathrm{BR}^j_{\mathrm{SM}} \kappa_j^2 \qquad \Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

Sensitive to interference effect in loops

e.g. negative interference between:





Fermion/Vector couplings

Assume no new particles in the loops and $BR_{BSM} = 0$
(see BSM in Tatjana's talk)

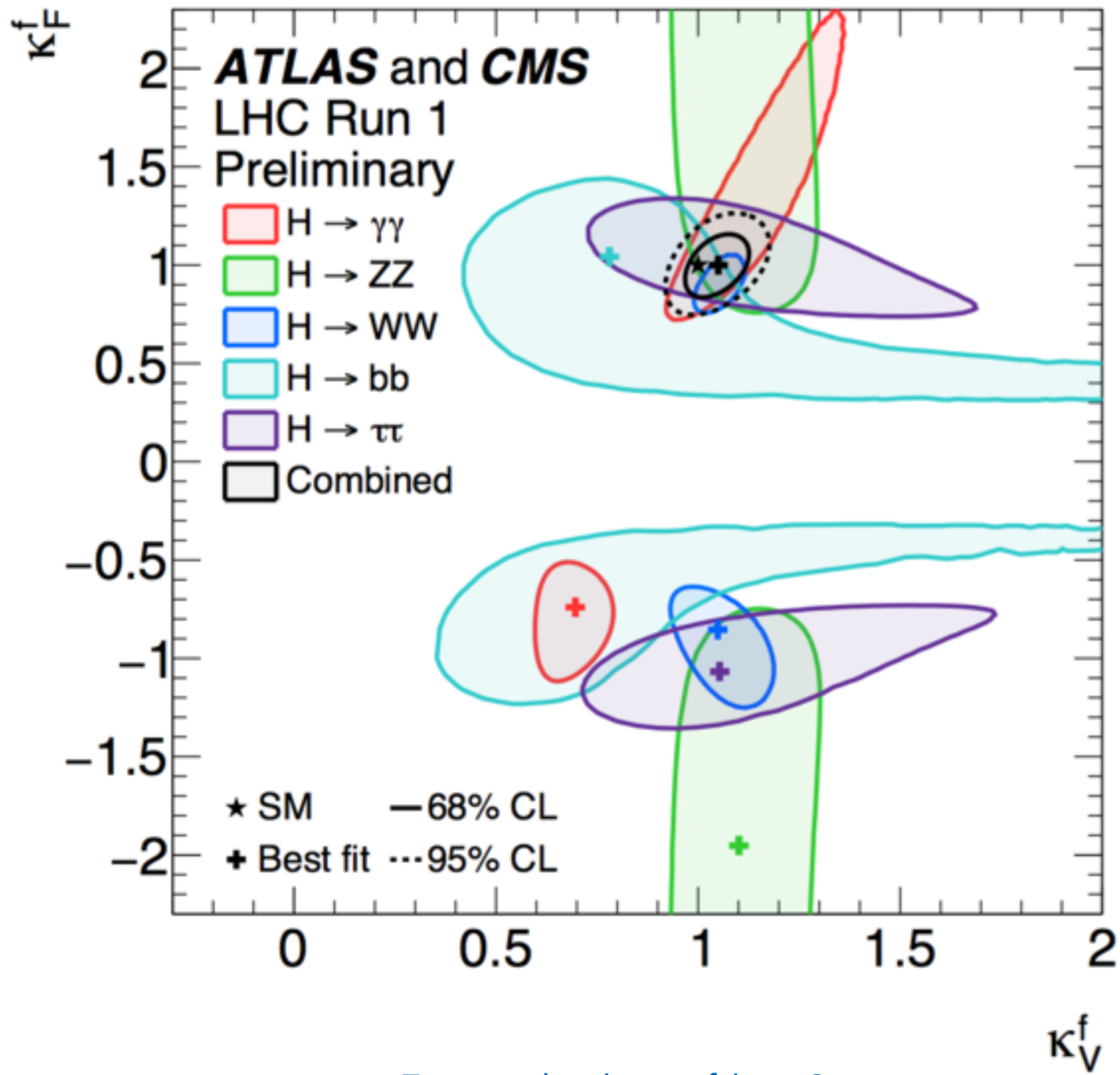
Define:

$\kappa_V = \kappa_Z = \kappa_W$

$\kappa_F = \kappa_t = \kappa_\tau = \kappa_b$

Total 2 x 5 parameters

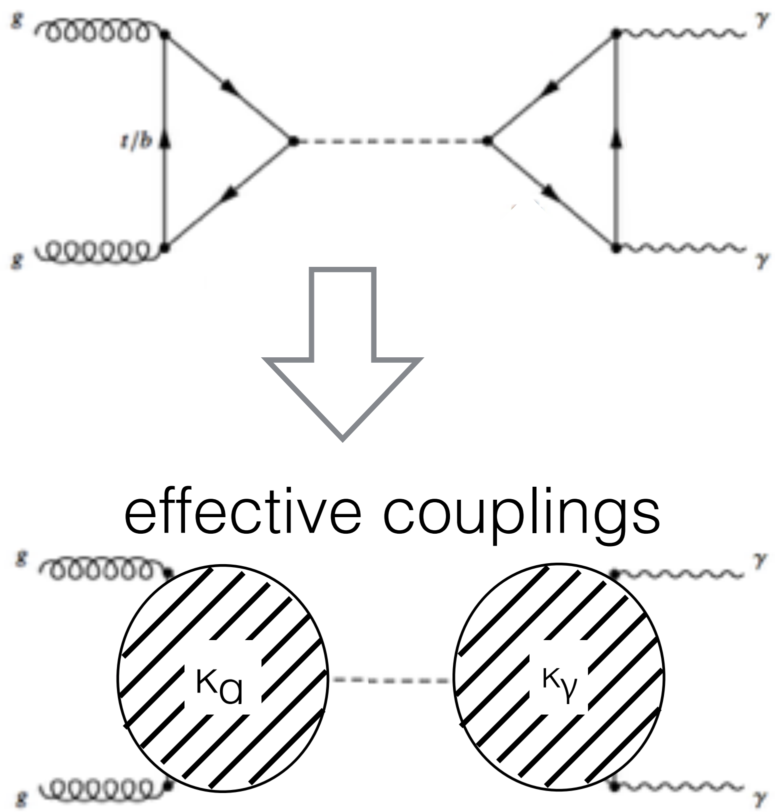
(the other two quadrants are symmetric wrt (0,0) because we're only sensitive to products of two kappas)



~5σ exclusion of $k_F<0$

k_g, k_γ

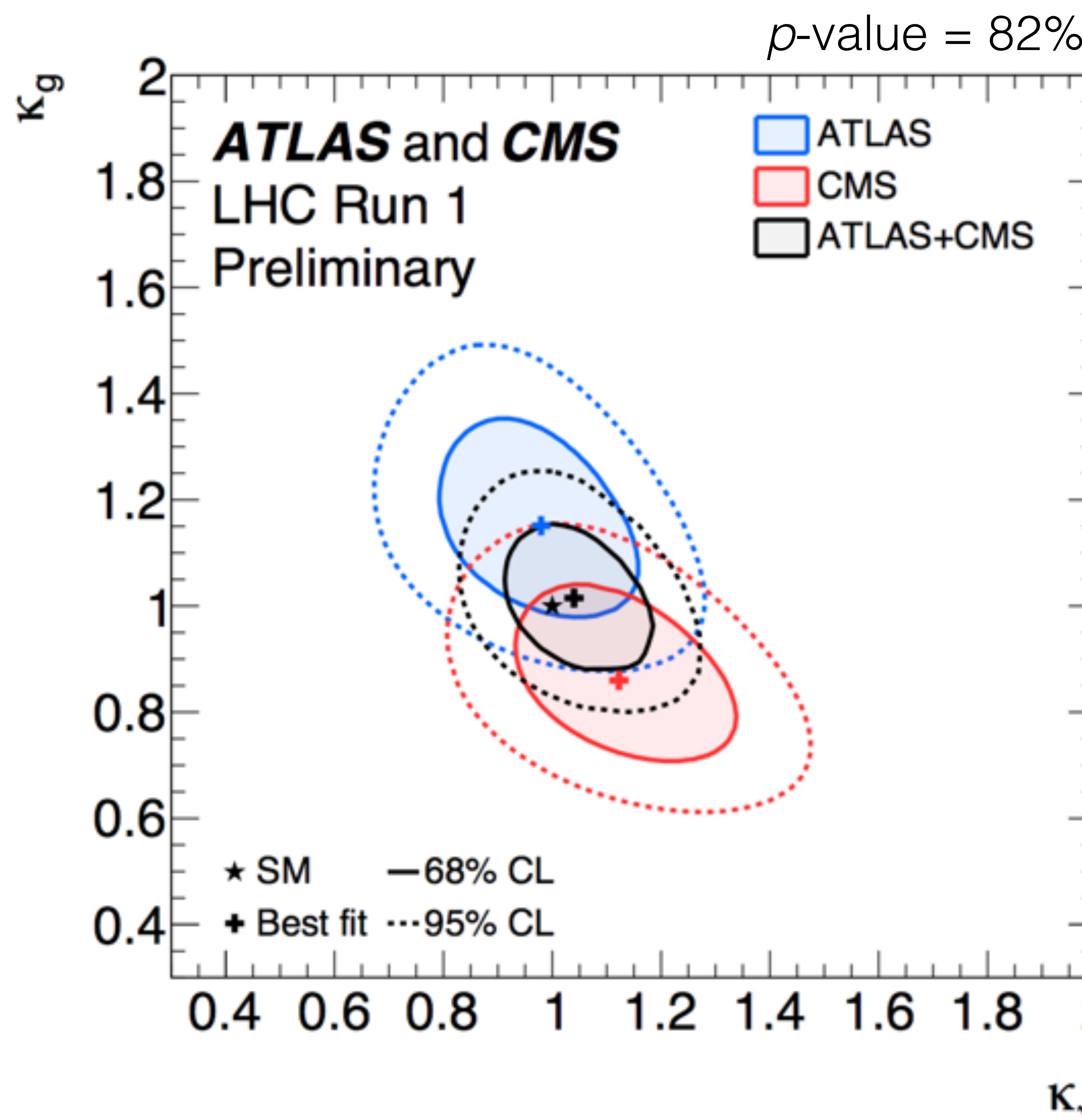
Test effective couplings for κ_γ, κ_g



Suppose all tree level decays are SM,
test BSM in production/decay "loops":

$$\kappa_W = \kappa_Z = \kappa_b = \kappa_t = \kappa_\tau = 1$$

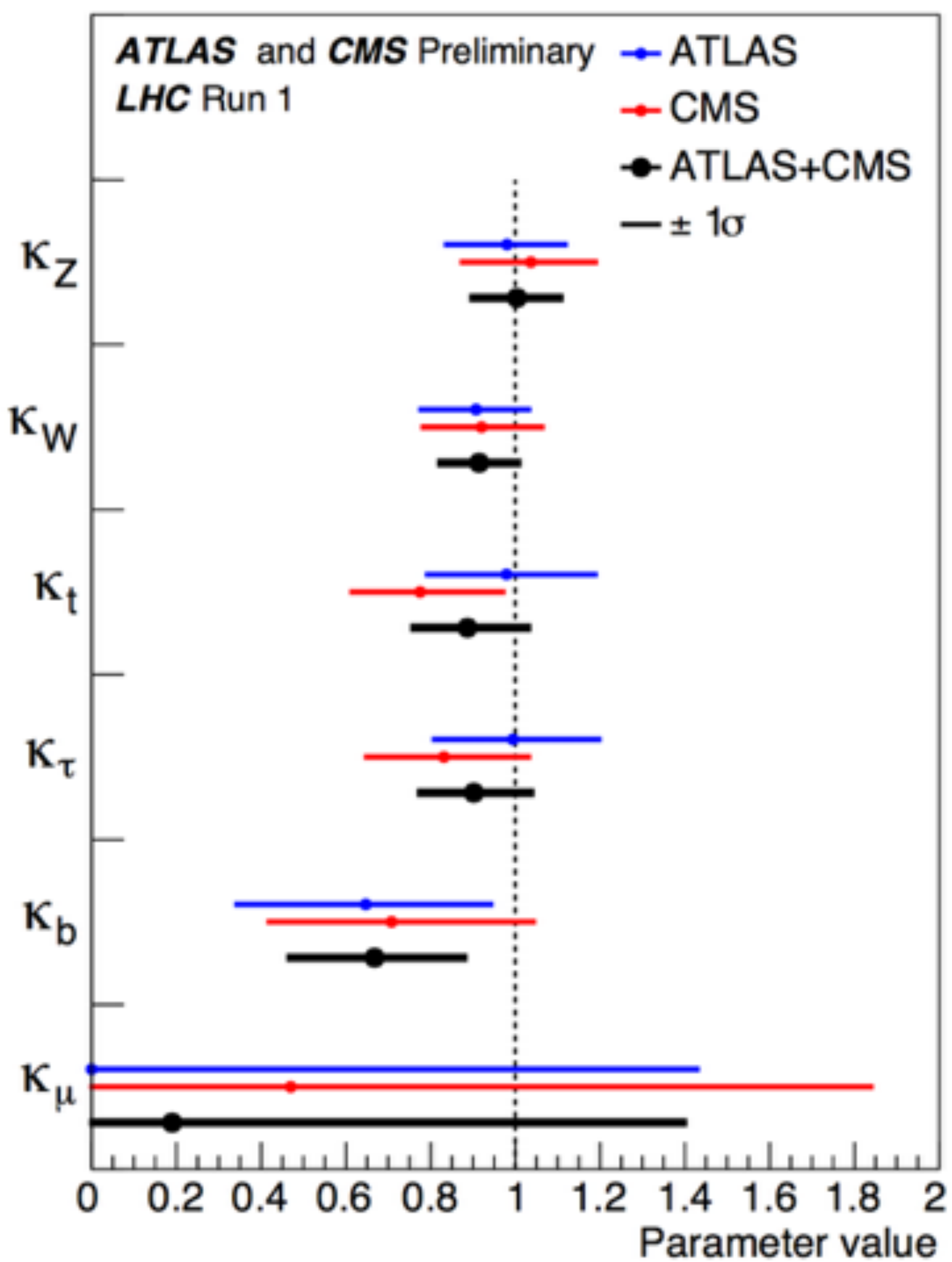
test κ_γ, κ_g



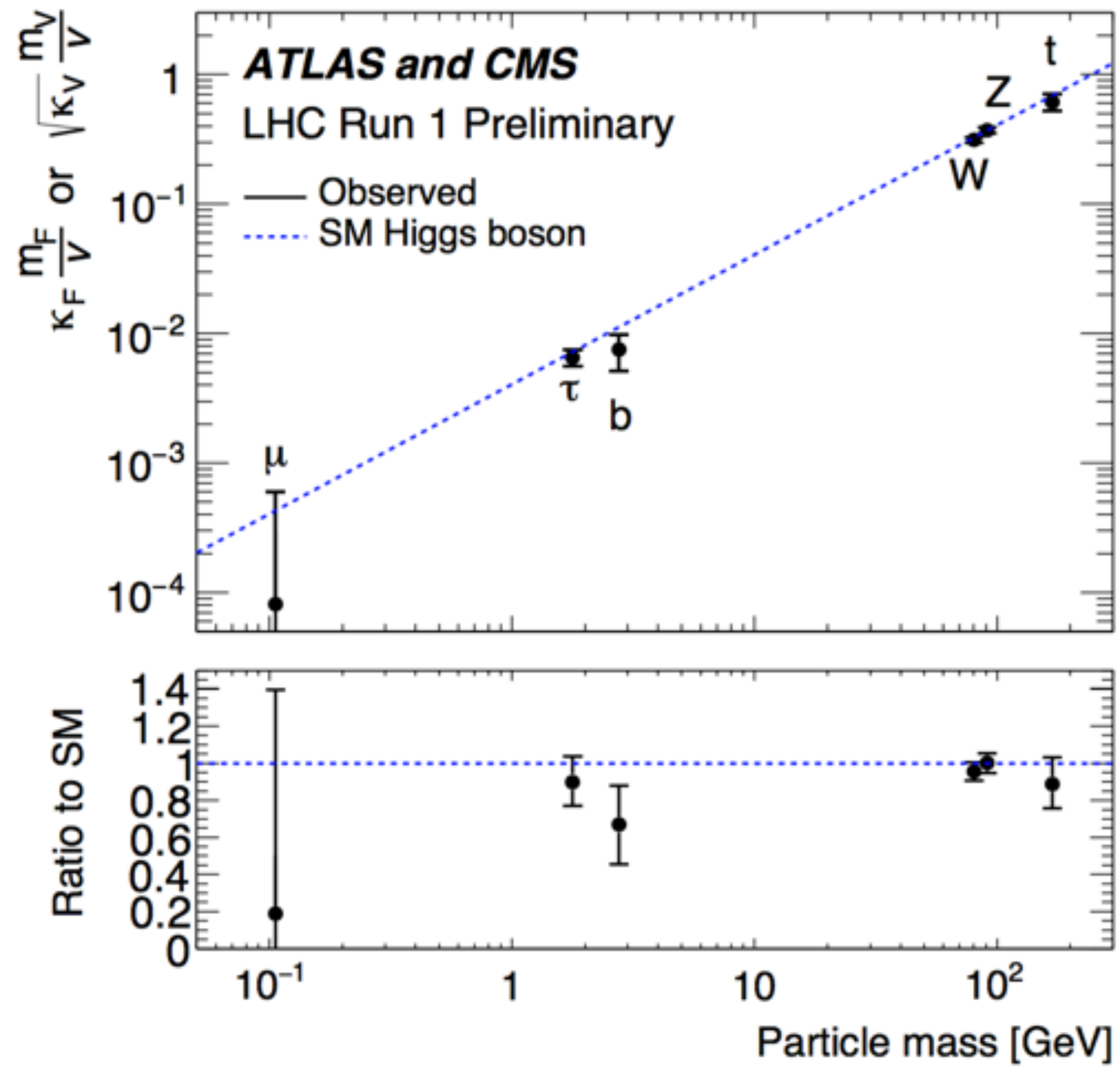
κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_μ

Because $\kappa_\gamma \sim 1$ and $\kappa_g \sim 1$, assume no BSM in loops and fit all the other coupling modifiers:

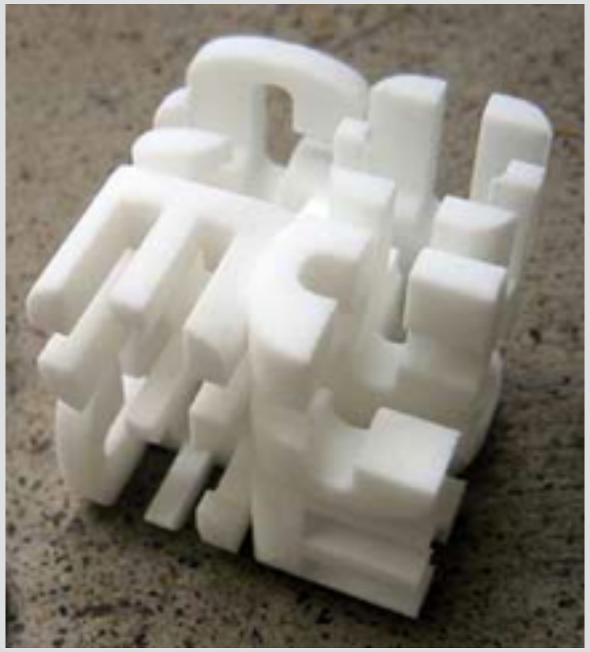
κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_μ



p-value = 65%



Both ATLAS and CMS measure a low κ_b, Γ is dominated by Γ_{bb}
and remembering that $\mu = 1.09 \pm 0.11$ pulls down all the BRs



Fiducial and Differential cross sections

Towards precision

Fiducial cross sections: reduce model dependence
(remove acceptance corrections measuring in a fiducial region)

Differential cross sections: compare differentially theoretical predictions

Measurement structure

For each differential observable:
- define a fiducial phase space at generator level to match analysis acceptance
- extract signal for each bin of the observable (repeat the analysis for each bin)
- unfold the measurement from reconstructed to generator level quantities
  (ATLAS bin-by-bin / iterative, CMS combined with the signal extraction / regularization)
- compare the SM/BSM theoretical prediction

Different observables are sensitive to different parameters of the Higgs sector, e.g.:

p_T^H, y^H	production process, QCD radiation, proton PDF
N_{jets}, p_T^j, y^j	QCD radiation
$\cos\vartheta^*$, $\Delta\phi_{jj}$	spin CP
$\Delta\phi_{\gamma\gamma,jj}$, Zeppenfeld	VBF production

Decay channels studied so far: $H\to\gamma\gamma$, $H\to ZZ\to 4$ leptons, $H\to WW$

H→ZZ→4 leptons

Low background, high mass resolution, but low statistics

Fiducial cross sections:

ATLAS acceptance = 45.7%

Fiducial region e(μ):

p_T > 20, 15, 10, 7 (6) GeV, |η| < 2.47 (2.7)

No Isolation (applied at reco level),

118 < m_{4l} < 129 GeV

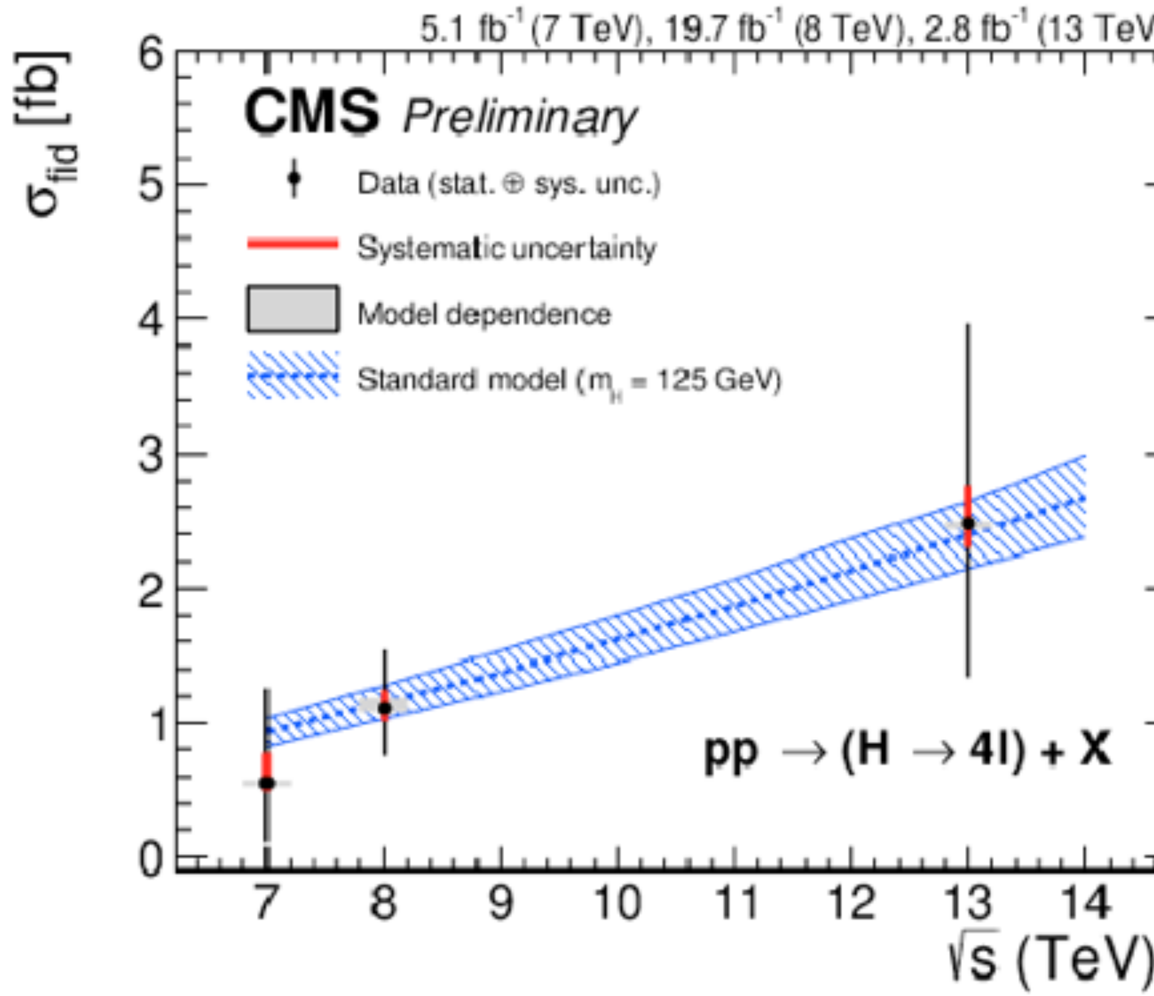
Data set [TeV]	N_s	$\sigma_{4\ell}^{\text{fid}}$ [fb]	$\sigma_{\text{theory}}^{\text{fid}}$ [fb]
7	$4.5\,^{+2.8}_{-2.2}$	$1.9\,^{+1.2}_{-0.9}$	1.03 ±0.11
8	$24.0\,^{+6.0}_{-5.3}$	2.1 ± 0.5	1.29 ±0.13
13	$1.0\,^{+2.3}_{-1.5}$	$0.6\,^{+1.3}_{-0.9}$	2.74 ±0.28

CMS acceptance = 42.2 %

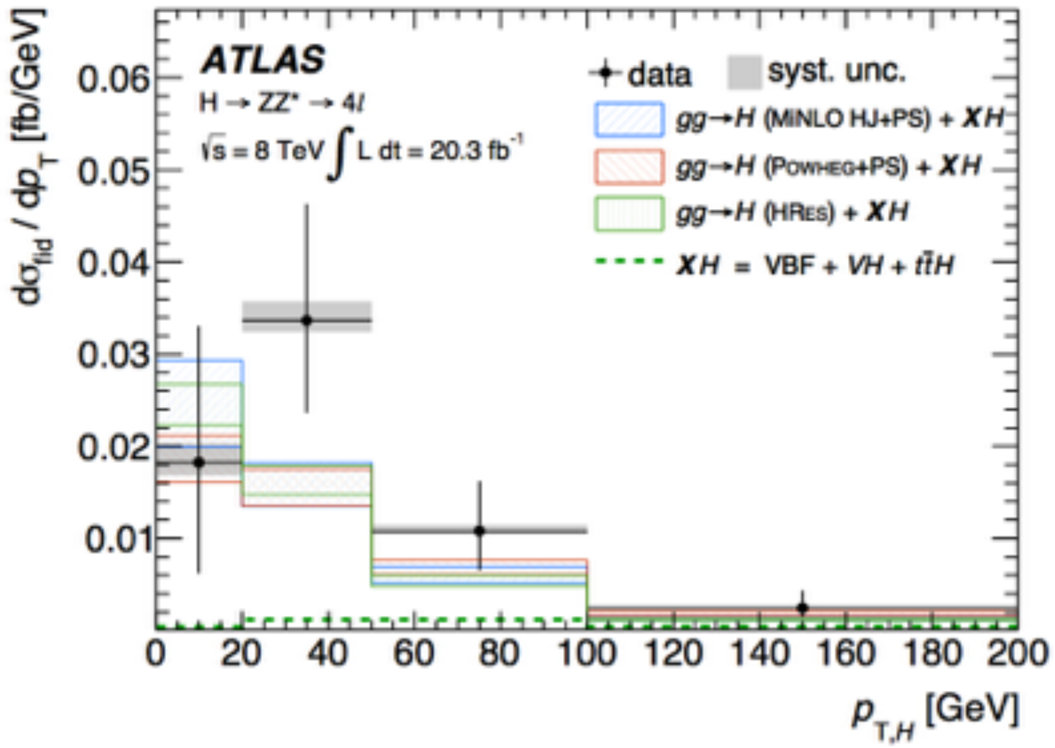
Fiducial region e(μ):

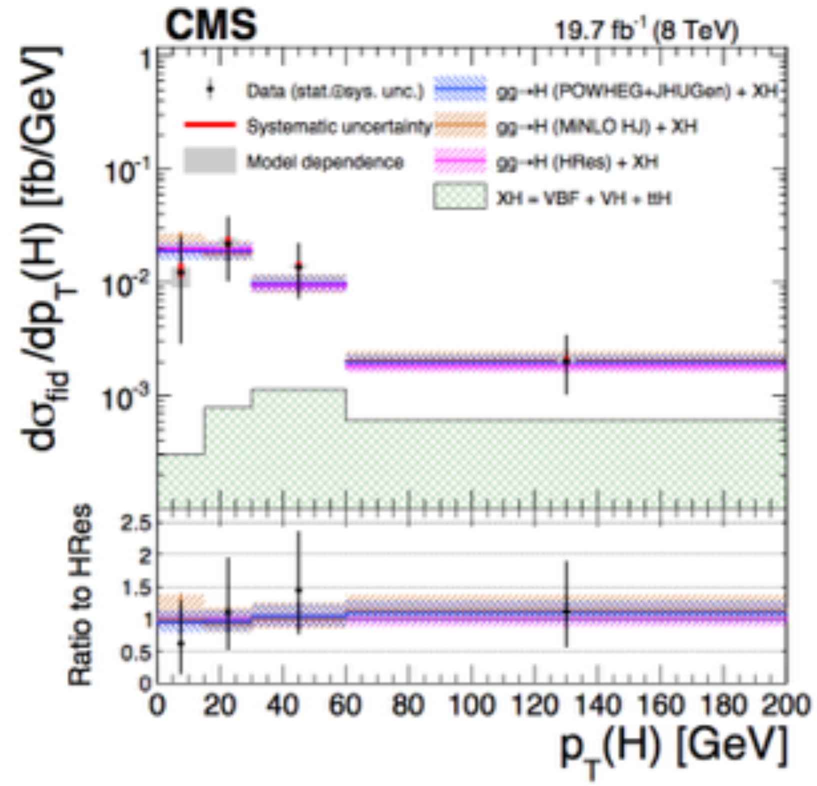
p_T> 20, 10, 5, 5,(7, 7) GeV |η| < 2.4 (2.5)

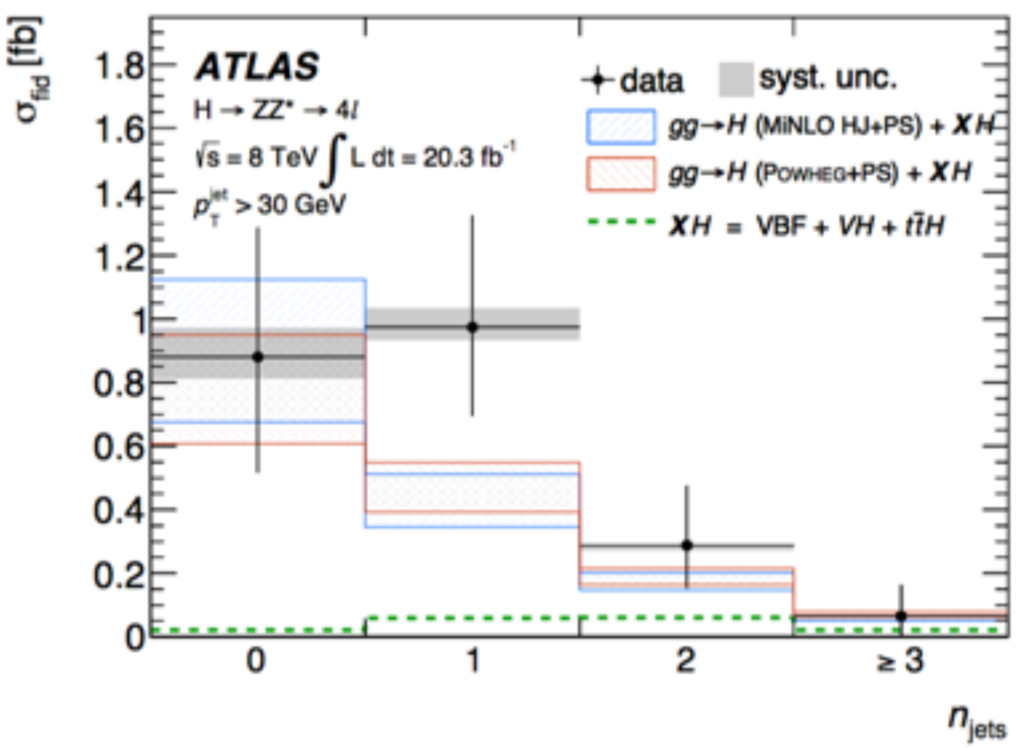
Isolation applied, 105 < m_{4l} < 140 GeV

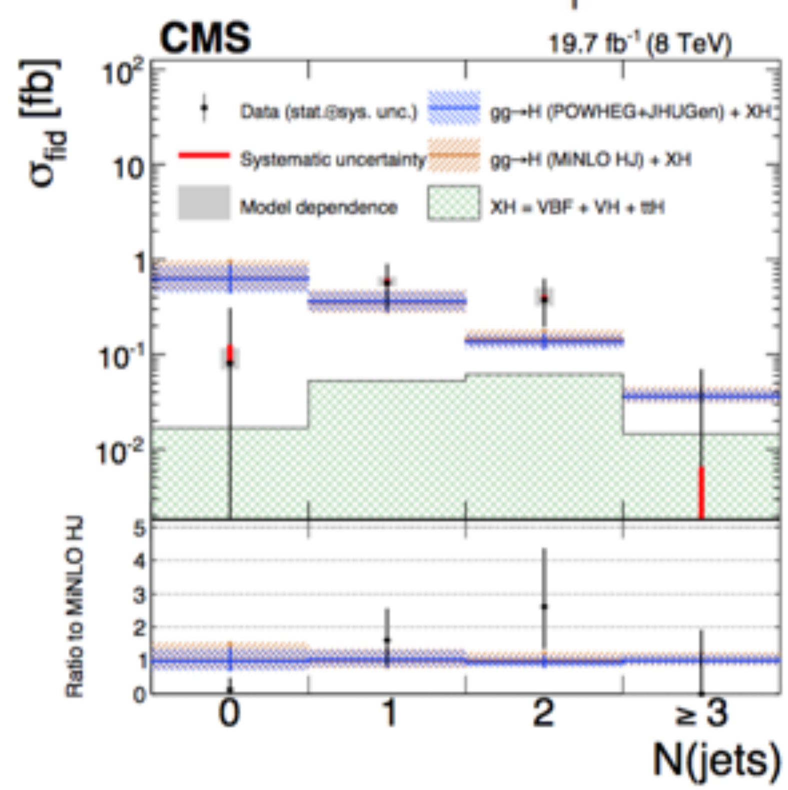


H→ZZ→4 leptons









Compatible with SM predictions but very large statistical uncertainties

H→γγ

Large background but clean signal because of high mass resolution

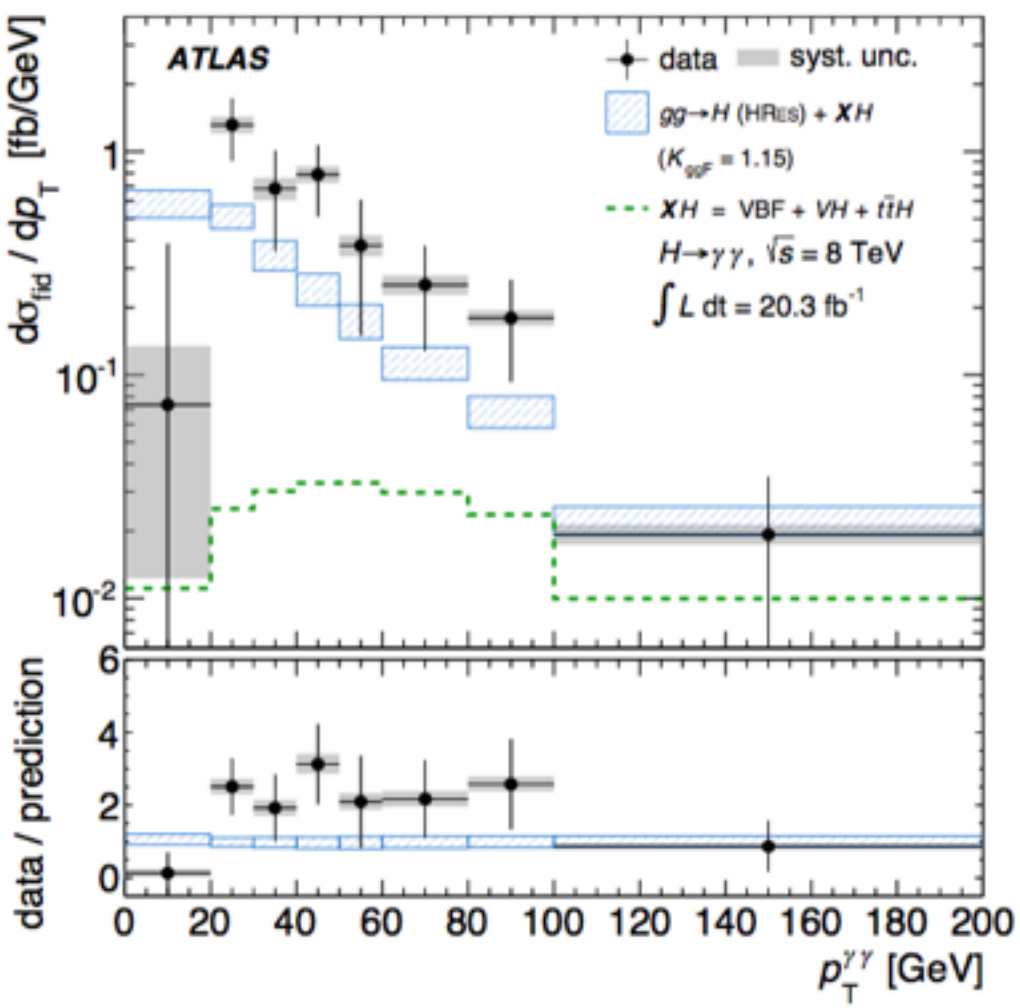
Fiducial cross sections:

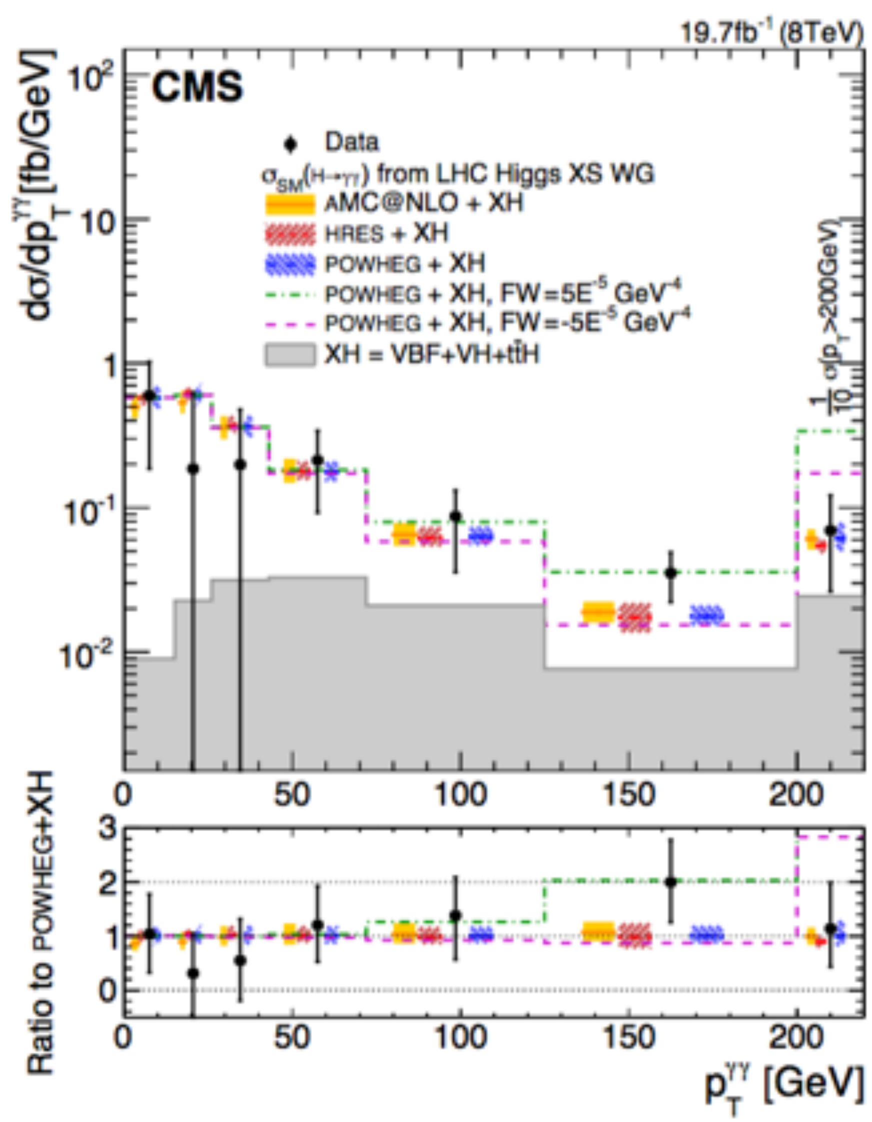
ATLAS measured: $\sigma_{\rm fid}(pp \to H \to \gamma\gamma) = 43.2 \pm 9.4\,({\rm stat.})\,^{+3.2}_{-2.9}\,({\rm syst.}) \pm 1.2\,({\rm lumi})\ {\rm fb}$

theory: $30.5 \pm 3.3\ {\rm fb}$

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

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





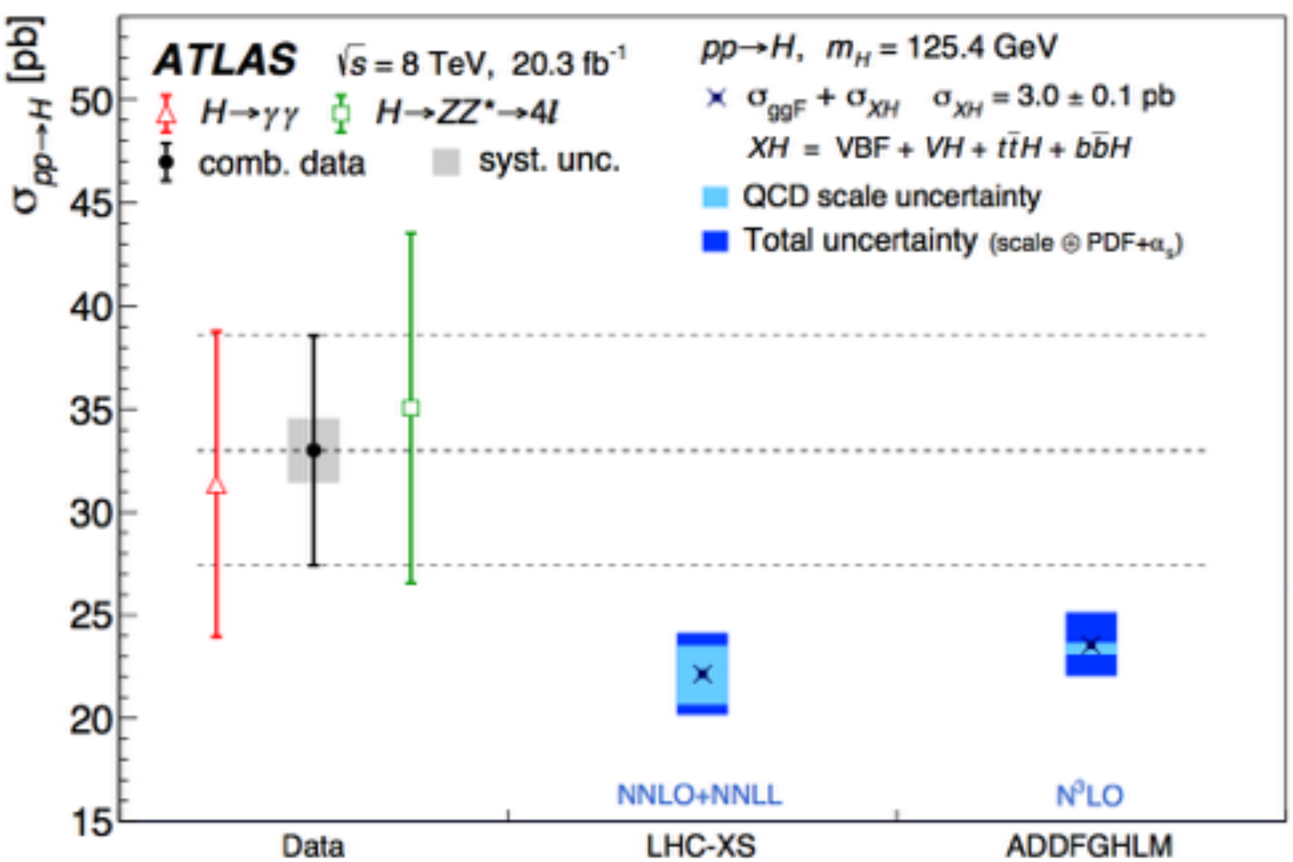
Combination H→γγ,H→ZZ

Statistical uncertainty reduced by ~30% on average

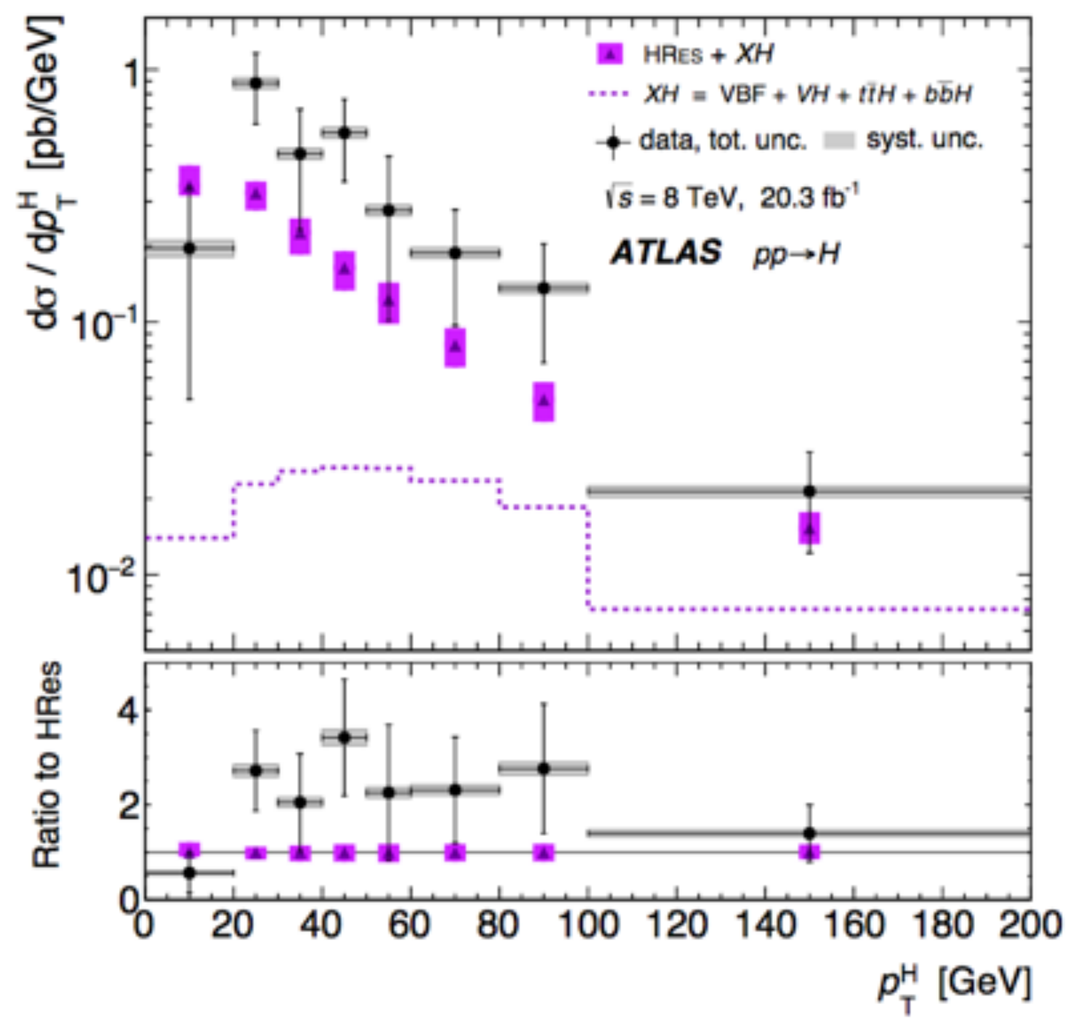
Measurements extrapolated to total cross section: acceptances

56-62% (H→γγ) 44-53% (H→ZZ*→4l)

Four variables are studied: p_T^H, y^H, N_{jets}, p_T^{j1}



p-value = 5.5%   p-value = 9%



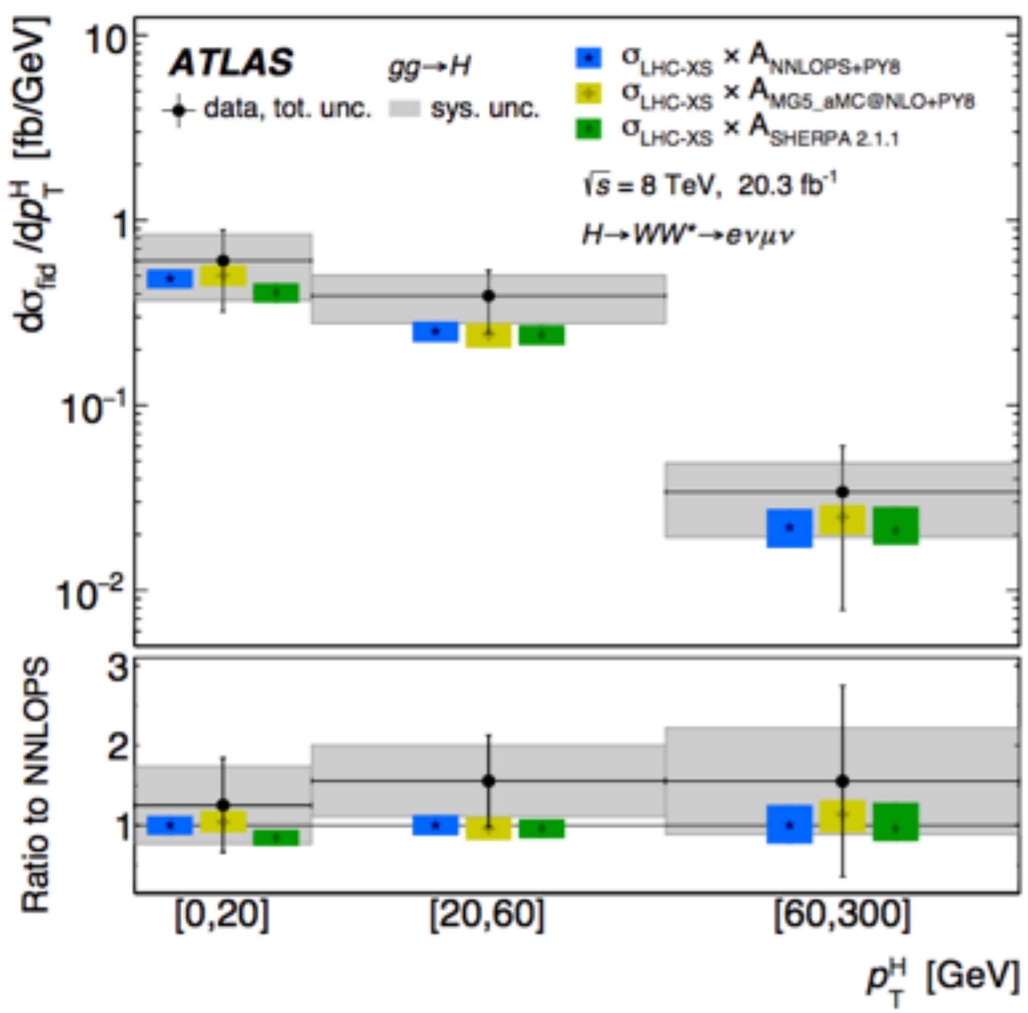
H→WW→ $\ell\nu\ \ell'\nu'$

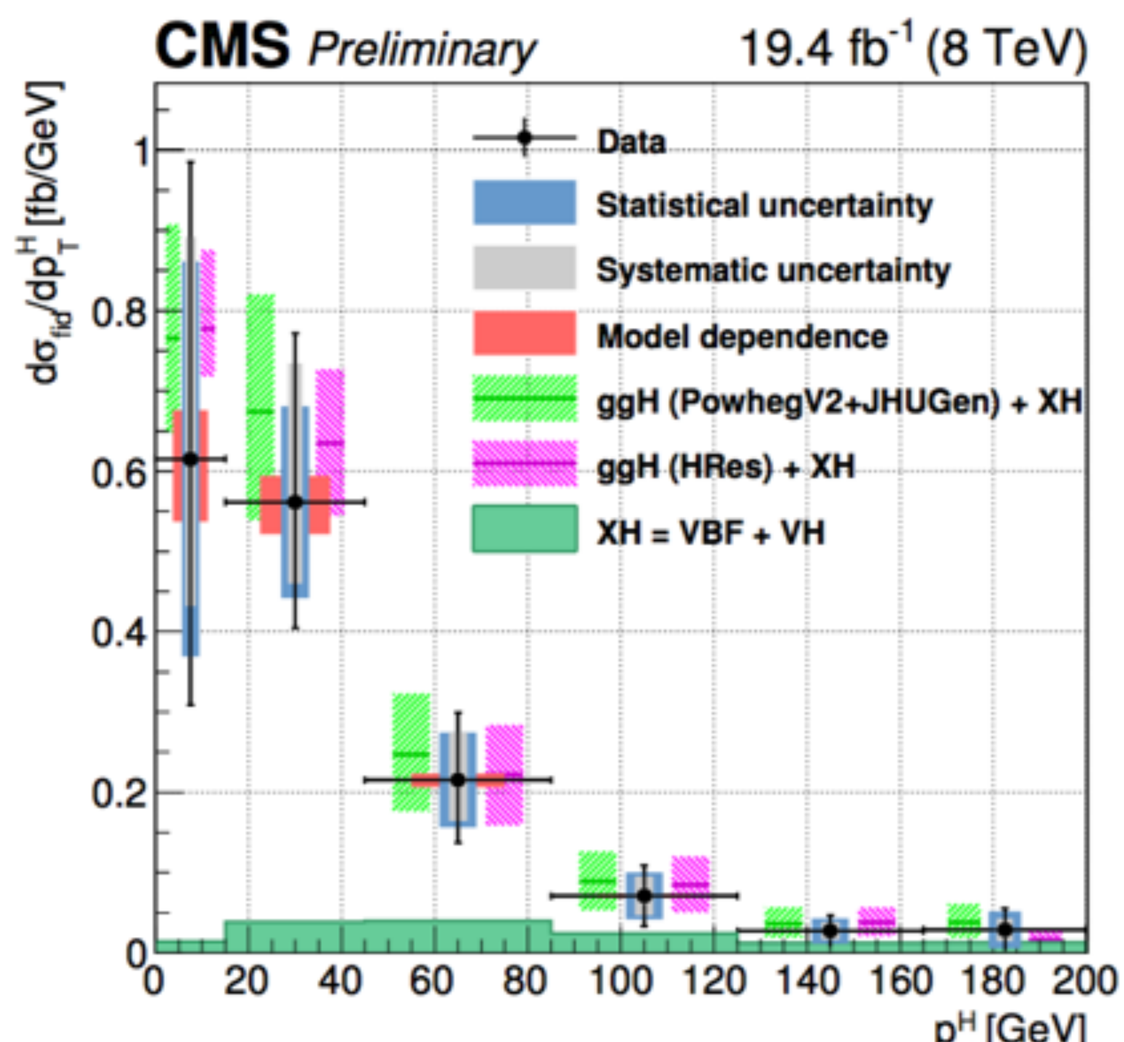
Different flavour and opposite charge. Large σxBR, but low mass (E_T^{miss}) resolution
⇒large off diagonal elements in the unfolding matrix
(ATLAS: iterative bayesian, CMS: Tikhonov regularization)

Fiducial cross sections:

ATLAS (ggF only) σ^{fid}= 36.0 ± 7.2 (stat.) ± 6.4 (syst.) ± 1.0 (lumi) fb
theory : 25.1 ± 2.6 fb

CMS σ_{fid} = 38 ± 8 (stat.) ± 9 (syst.) fb
theory : 48 ± 8 fb





Summary

ATLAS and CMS combined results allow to exploit the full LHC potential on Higgs Physics:

- $\sqrt{2}$ improvement on sensitivity from combination
- o(0.2%) mass precision $m_H = 125.09 \pm 0.24$ GeV
- o(10%) coupling precision $\mu = 1.09^{+0.11}_{-0.10}$ (most constrained model)
- In less constrained models couplings are also in agreement within SM predictions

First differential cross section measurements were performed and found in agreement with SM prediction (within the large statistical uncertainty)

The larger integrated luminosity of Run 2 will open the "precision Higgs physics era"
…because sometimes things are not what they look like !

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References

- ATLAS/CMS Combination:
- https://cds.cern.ch/record/2053103 (ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002)
- http://arxiv.org/abs/1503.07589 (Phys. Rev. Lett. 114, 191803 (2015))

- Differentials CMS:
- http://arxiv.org/abs/1508.07819 (Hgg - EPJC 76 (2016) 13)
- http://arxiv.org/abs/1512.08377 (HZZ - JHEP 04 (2016) 005)
- https://cds.cern.ch/record/2116452 (HWW - HIG-15-010)

- Differentials ATLAS:
- http://arxiv.org/abs/1407.4222 (Hgg - JHEP09(2014)112)
- http://arxiv.org/abs/1408.3226 (HZZ - Physics Letters B 738 (2014) 234-253)
- http://arxiv.org/abs/1504.05833 (combined Hgg HZZ - Phys. Rev. Lett. 115 (2015) 091801)
- http://arxiv.org/abs/1604.02997 (HWW - HIGG-2015-04 - submitted JHEP)