Ecole de Gif - 2015

Quel futur pour le Modèle Standard après la découverte du Higgs ?

This course:

Higgs Boson and Electroweak Physics

I Origin and Discovery
Stand-alone results from ATLAS and CMS

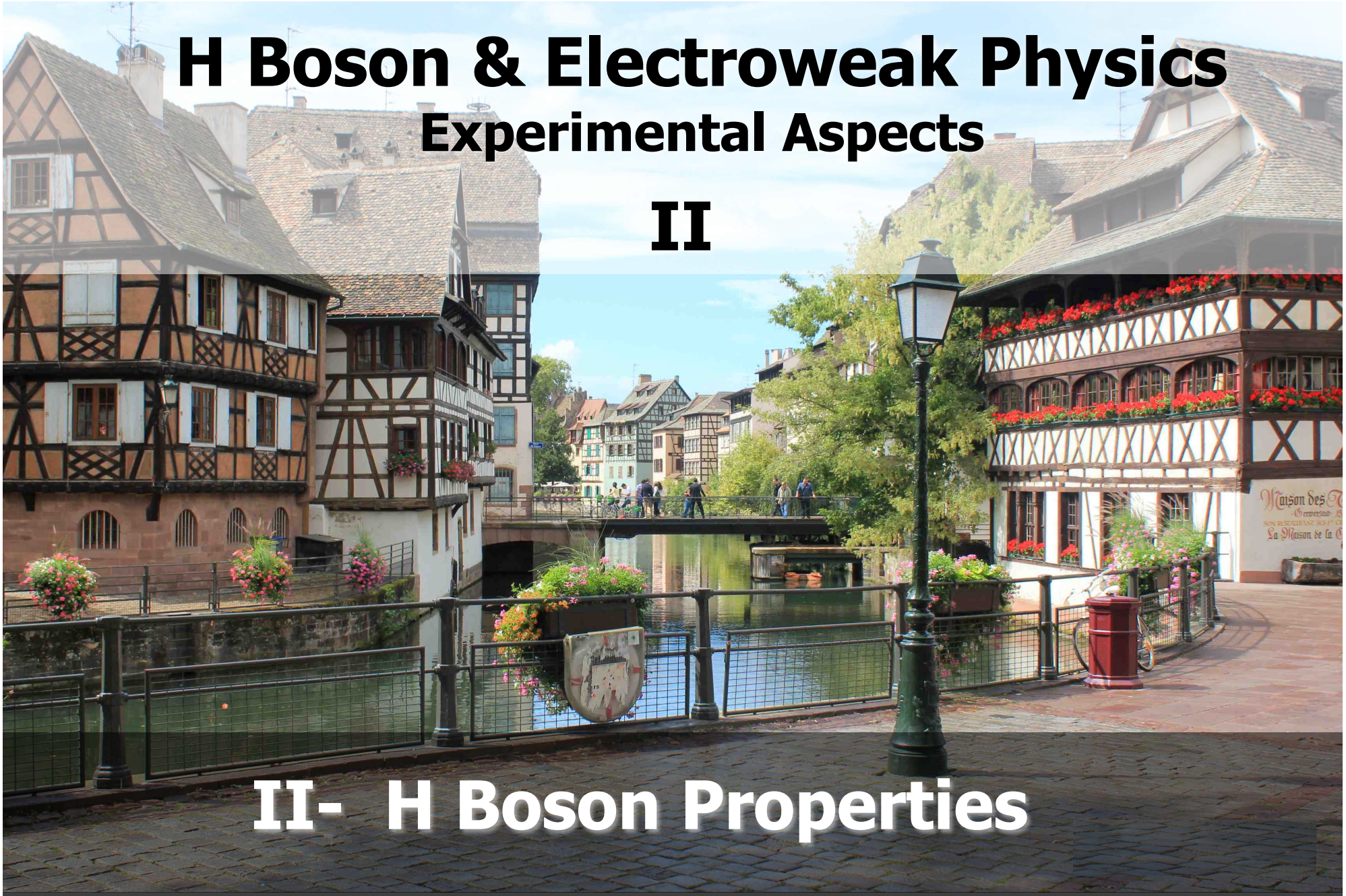
II H Boson Properties ... and beyond
Full combination of ATLAS and CMS (september 2015)

III H Boson Aftermath
Next steps and extension of the scalar sector

H Boson & Electroweak Physics

Experimental Aspects

II



II- H Boson Properties

Ecole de Gif, September 2015

Yves Sirois
Ecole Polytechnique
CNRS

Reminder from yesterday

Summary (I)

- Theoretical motivations for the BEH Mechanism and the H boson reviewed together theory and with pre-LHC constraints
- Discovery in July 2012 at a very special "mass value" of the H boson by ATLAS and CMS experiments at LHC exploiting mainly di-boson channels

ATLAS and CMS Strategies and stand-alone results were presented:

- The mass of new H boson ($\gamma\gamma$ and 4l) is measured at ~ 125 GeV
- The spin-parity of the H boson is consistent with a pure CP-even state (0^{++}) as expected from the Brout-Englert-Higgs EWK symmetry breaking mechanism
- The intrinsic width is consistent with the SM expectation
- Signal rate in all 5 main decays have been measured with 20-40% precision
- Couplings to fermions and bosons are measured at the 10-20% precision

BACCALAURÉAT GÉNÉRAL

SESSION 2015

Boson de Higgs … et au-delà: les grandes questions

- Peut-on éviter l'arbitraire pour masse du boson de Higgs et/ou contraindre le secteur scalaire ? Déduire le boson de symétries géométriques ? Faire émerger l'auto-couplage à partir des couplages de jauge ?
- Le secteur scalaire « Higgs » est-il relié à l'inflation et/ou à l'énergie noire ?
- Le secteur scalaire de « Higgs » déstabilise-t'il le vide ?
- Le secteur scalaire de « Higgs » est-il un portail vers la matière noire ?
- Le secteur scalaire de « Higgs » est-il responsable de la baryogénèse ?
- Le secteur scalaire permet (est à l'origine ?) de distinguer les familles de fermions … mais comment générer la structure ?
- Le secteur scalaire de « Higgs » parle-t-il aux neutrinos ($\nu_L \leftrightarrow \nu_R$) ?

DURÉE DE L'ÉPREUVE : 10-30 ans – COEFIFICIENT 6
L'usage de collisionneurs est permis

New Challenges

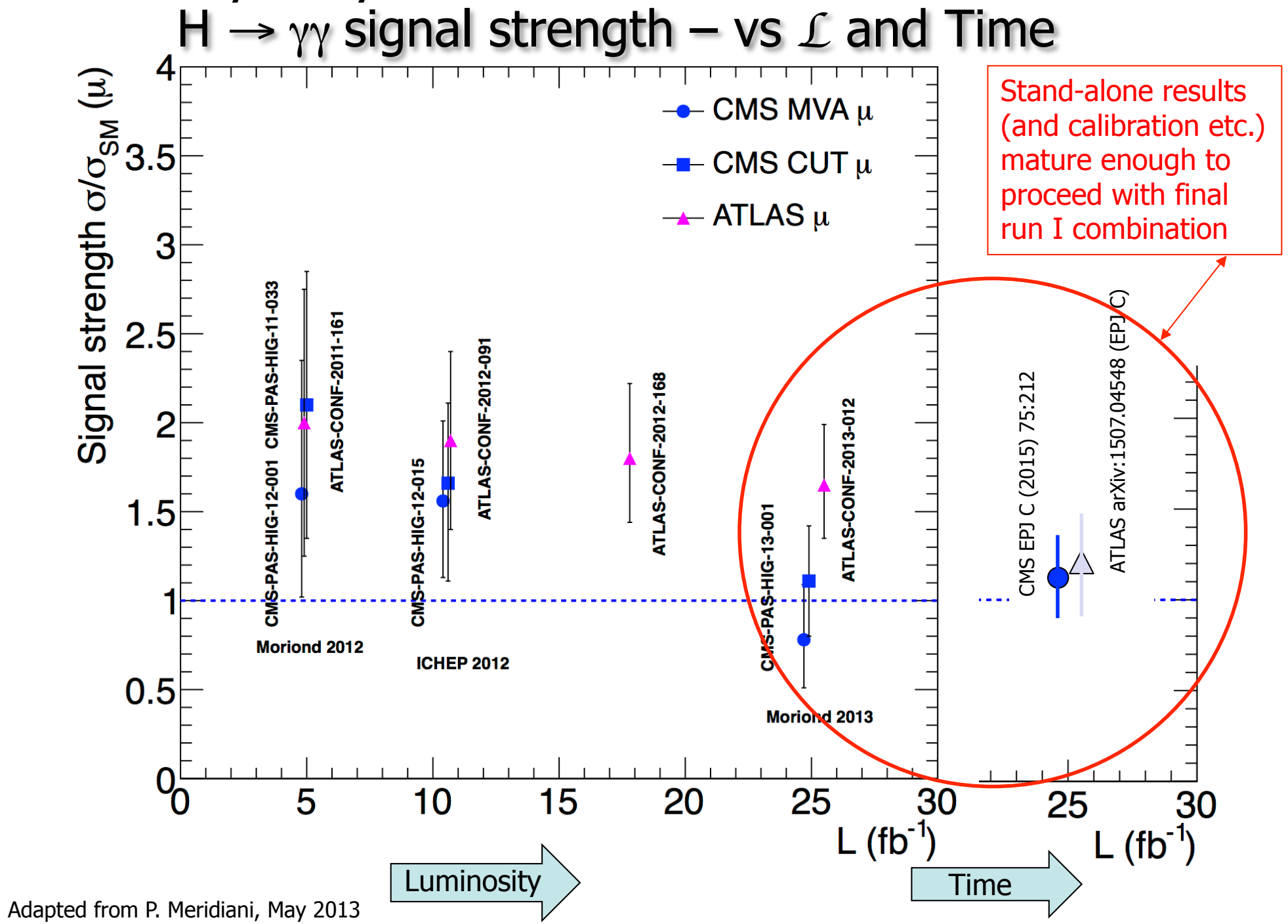
In addition to all the great SM precision measurements with Z, W and the top quarks, HI Physics, flavour physics etc. …

Driven by the new physics (i.e. the scalar sector) Discovered during run I

- Complete precision measurements of the Higgs boson
- Observe Di-Higgs production and access the self-coupling
- Measure trilinear and quartic couplings of weak bosons
- Measure rare decays and search for forbidden H decays
- Search for an extended scalar sector

- Search for extra-structure, supersymmetric matter, Exotica, …

Reminder from yesterday

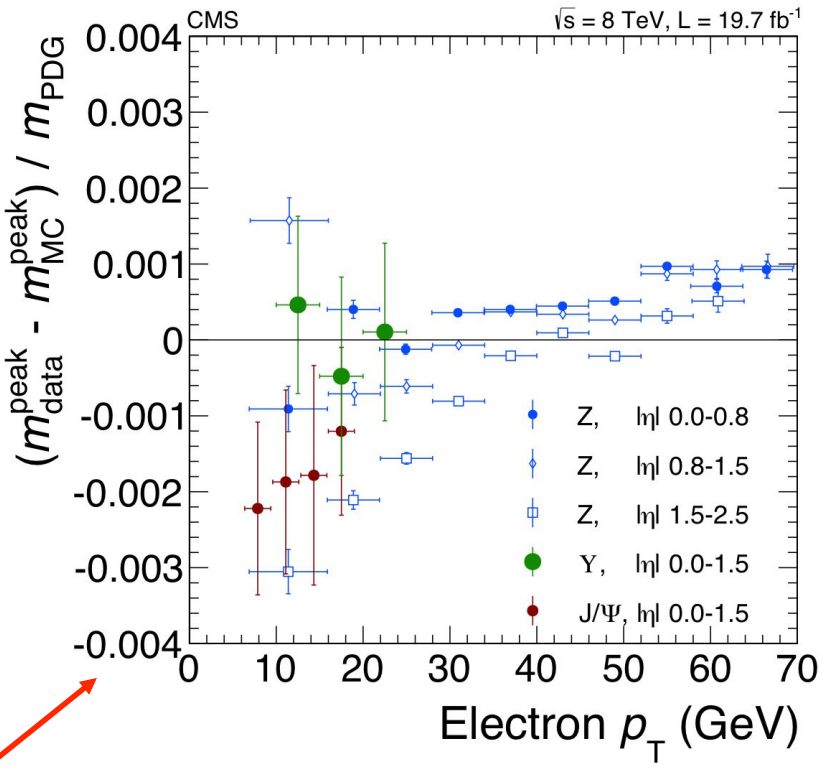


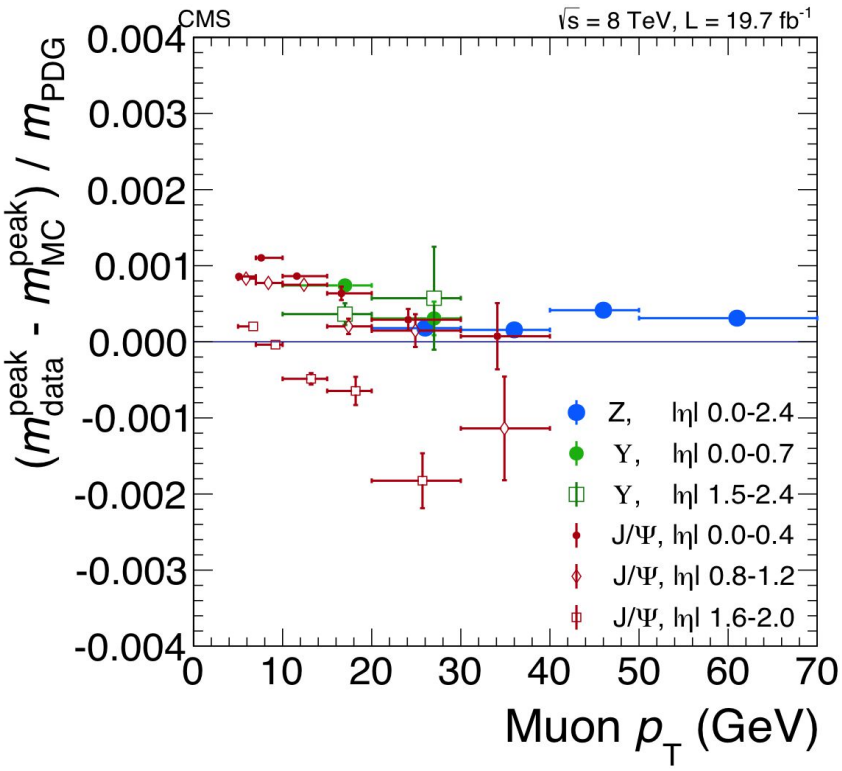
Adapted from P. Meridiani, May 2013

The LHC Mass Measurement for the H_{125}

Precision Calibration (e)

- Each experiment relies on final (« legacy ») e/γ calibrations
- e/γ energies corrected for detector effects using regression techniques based on collection of shower shape variables
- Use Z → ee, μμ for the absolute energy scale
- For H → 4l, control systematics at low P_T with J/ψ and Υ

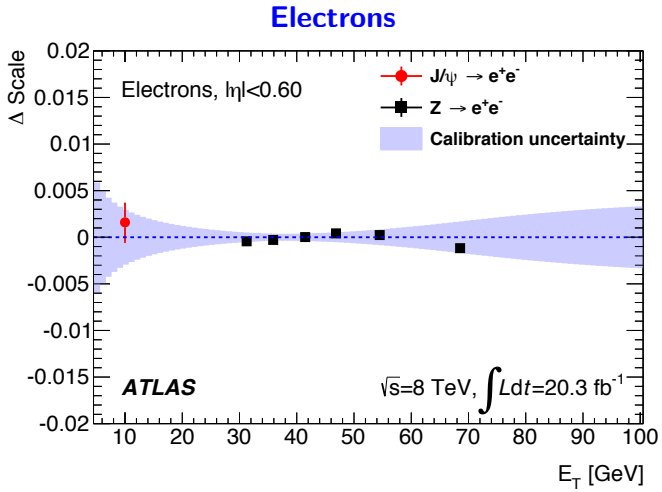




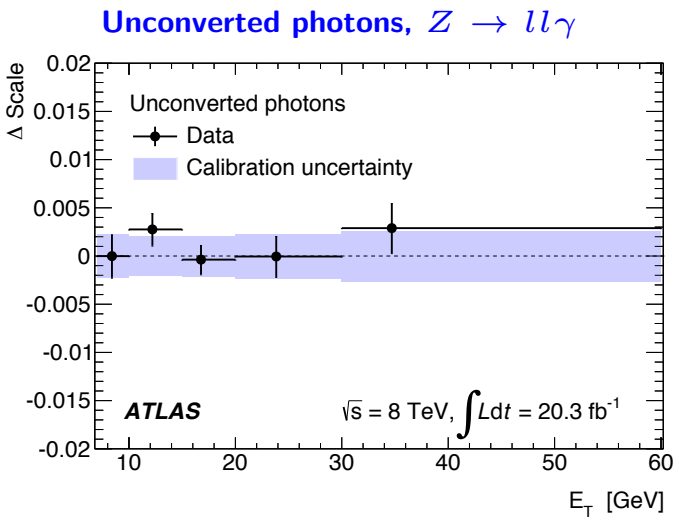
Combine ECAL E and tracker P exploiting their relative uncertainties, the E/P ratio, the amount of bremsstrahlung in tracker material along e track

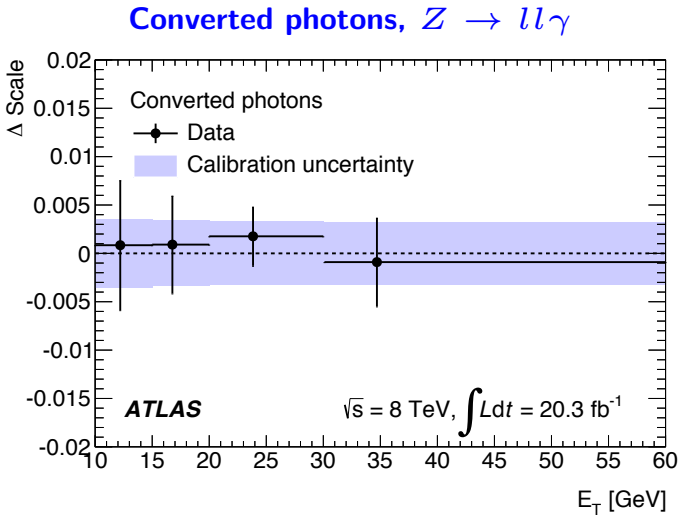
Precision Calibration (γ)

- Each experiment relies on final (« legacy ») e/γ calibrations
- e/γ energies corrected for detector effects using regression techniques based on collection of shower shape variables
- Use Z → ee, $\mu\mu$ for the absolute energy scale
- For H → 2γ :
  - correct e from Z → ee to get γ absolute scale,
  - control the extrapolation to γ harder P_T spectrum with MC data



Independent control via Z → $\ell\ell$ g





Why Energy Regression ? (1)

Reminder:

The energy calibration typically requires 2 main steps

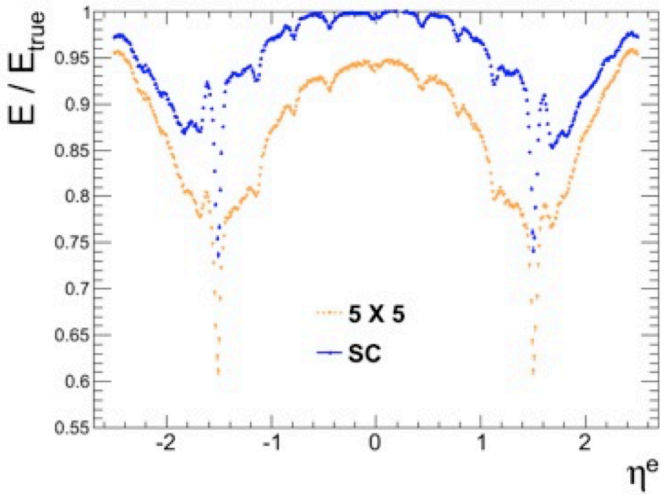
1) Calibration of individual cells
e.g. in CMS these are individual $PbWO_4$ crystals]

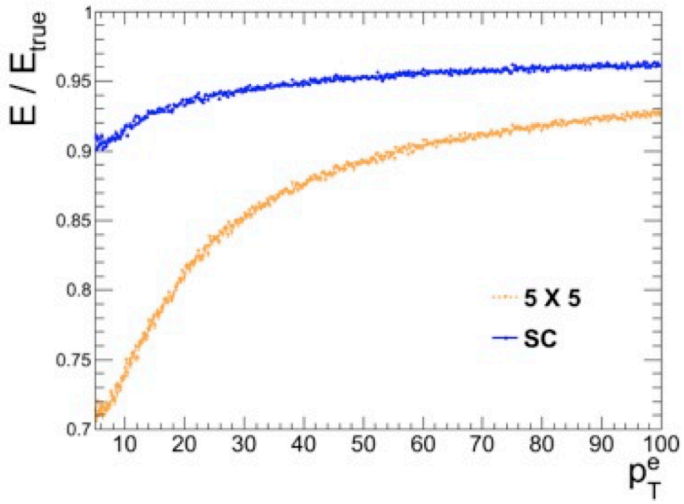
2) Calibration of the shower Cluster (per event)
e.g. contains the most significant for of e.m. shower

2') Calibration of the E-P combination
e.g. in CMS for low PT electrons and further correct for bremss in the tracker layer

Initially, the step 2 (and 2') was done with simple parameterized functions to correct for leading effects from η (bremss) dependent E losses

$$F_{e,\gamma} = f(\sigma_\phi/\sigma_\eta) \cdot F(E_T, \eta)$$





CMS uses:

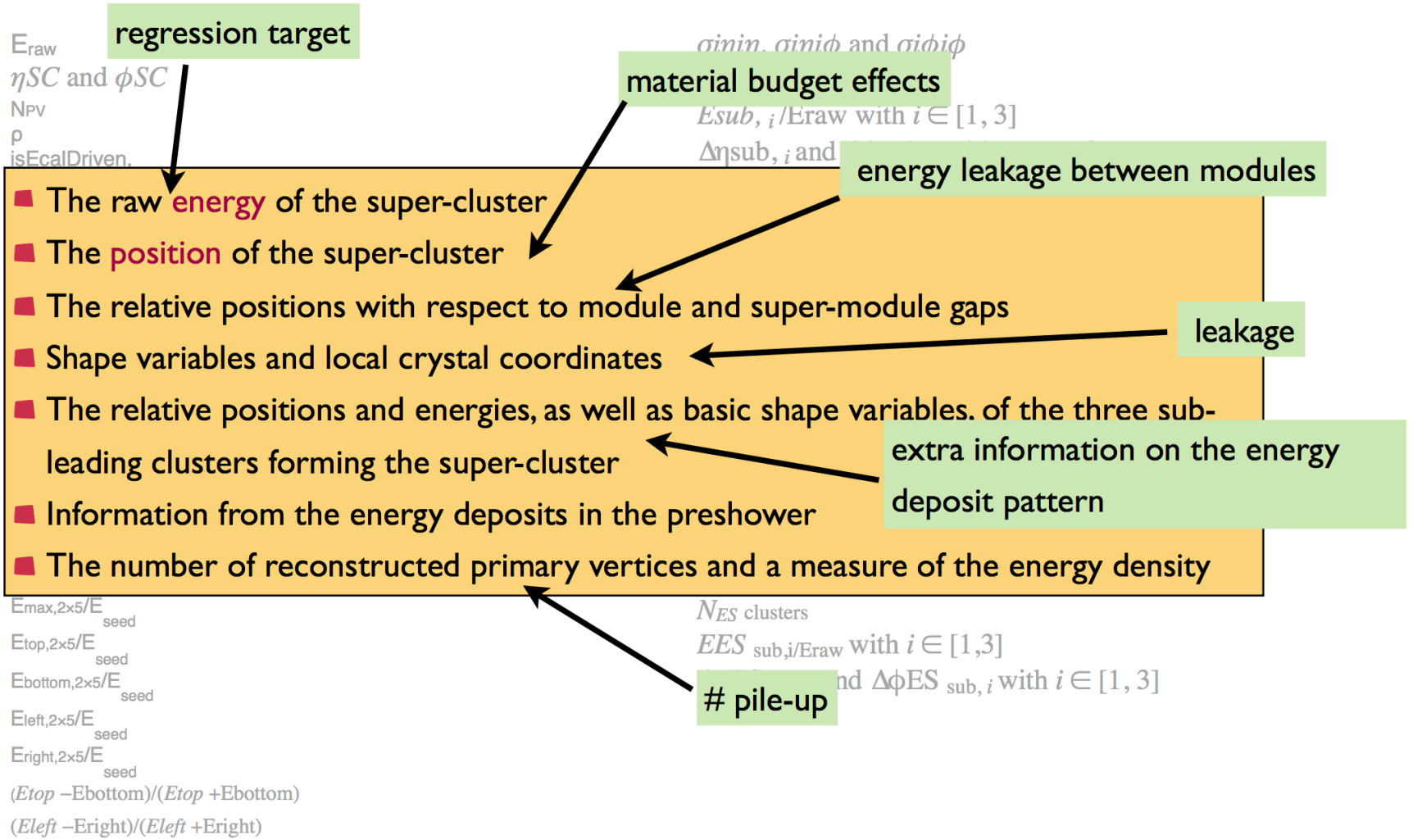
γ 5×5
e Supercluster (SC)

Why Energy Regression ? (2)

ECAL

- The « regression » replaces the per-event cluster E calibration with corrections mostly targeting energy containment
- It relies in CMS on a MVA (Boosted Decision Tree) targeting $E_{true}/E_{SC\ trained}$ trained on MC data

Variables used for 4ℓ or γγ



Why Energy Regression ? (3)

E-P

- A regression is also used at the E-P matching step
- The target of the BDT regression here is α in:

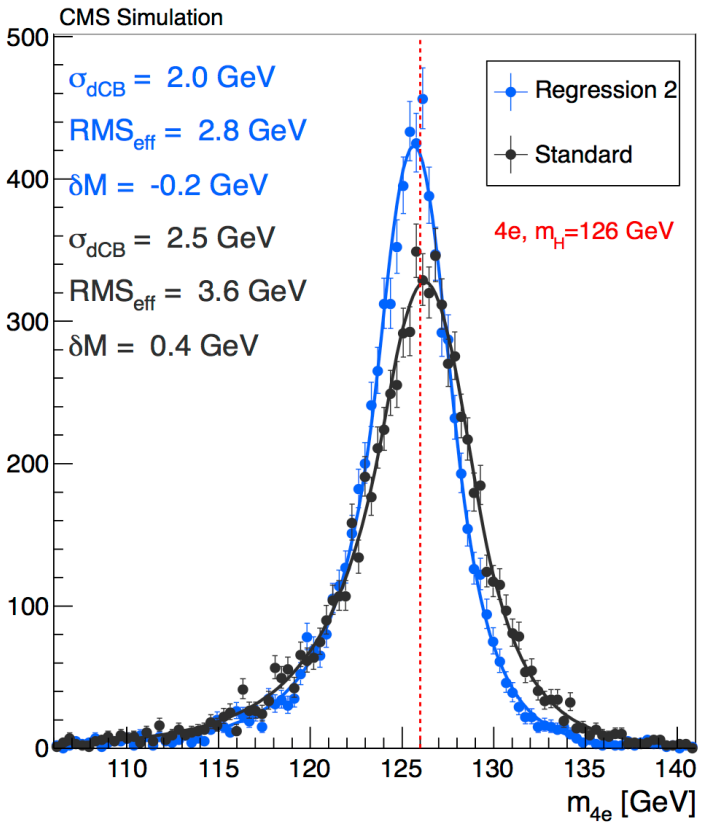
$$p_{\text{truth}} = \alpha \times p_{\text{track}} + (1 - \alpha) \times E_{\text{ECAL}}^{\text{corr}}$$

Variables used:

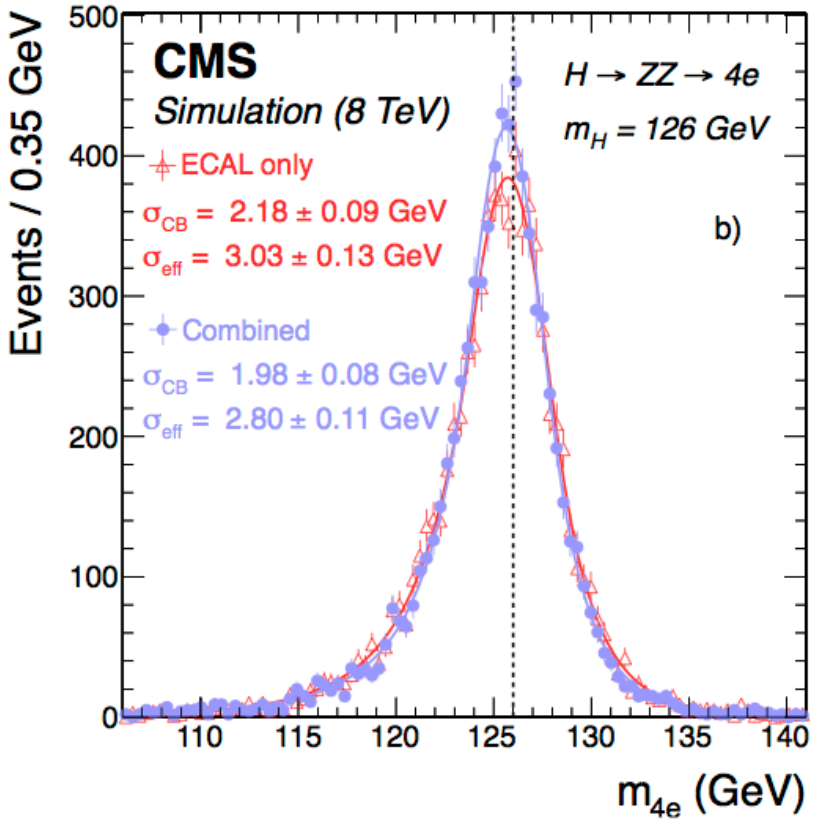
Corrected ECAL energy and its relative error
Track momentum and its relative error
$E_{ECAL}^{corr}/p_T^{GSF}$ ratio and the error on this ratio
Ratio of the two relative errors
The electron category
Two flags for ECAL driven and tracker driven electrons
Barrel/endcap flag

Why Energy Regression ? (3)

Cluster regression



E-P regression



25% improvement on the ECAL resolution is obtained with respect to original corrections

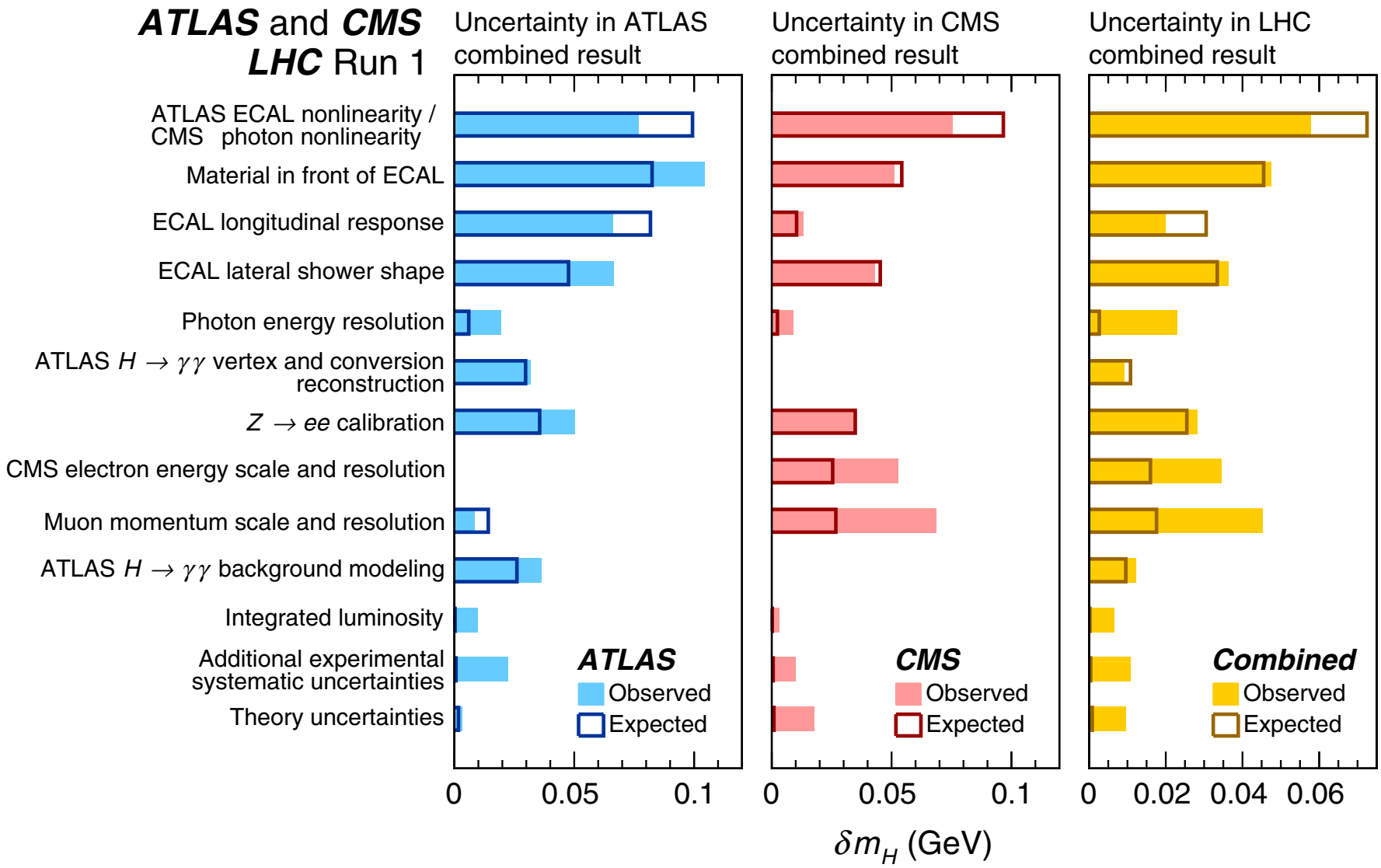
7% improvement on the effective resolution after E-P matching (9% improvement on Gaussian core)

Bias is also reduced (vs pile-up)

Systematic Uncertainties on δm_H

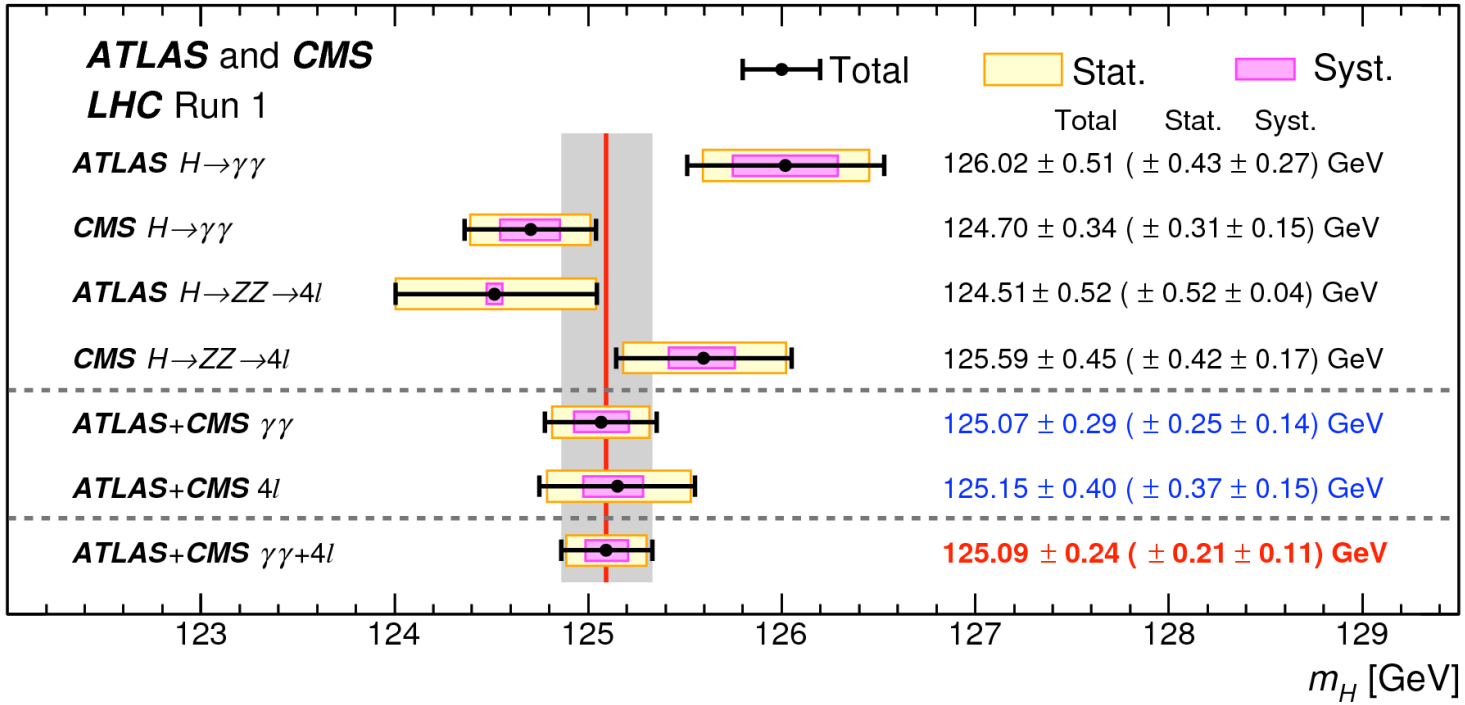
	Uncertainty in ATLAS results (GeV): observed (expected)		Uncertainty in CMS results (GeV): observed (expected)		Uncertainty in combined result (GeV): observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL nonlinearity or CMS photon nonlinearity	0.14 (0.16)	···	0.10 (0.13)	···	0.02 (0.04)	0.05 (0.06)
Material in front of ECAL	0.15 (0.13)	···	0.07 (0.07)	···	0.03 (0.03)	0.04 (0.03)
ECAL longitudinal response	0.12 (0.13)	···	0.02 (0.01)	···	0.02 (0.03)	0.01 (0.01)
ECAL lateral shower shape	0.09 (0.08)	···	0.06 (0.06)	···	0.02 (0.02)	0.03 (0.03)
Photon energy resolution	0.03 (0.01)	···	0.01 (<0.01)	···	0.02 (<0.01)	<0.01 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex and conversion reconstruction	0.05 (0.05)	···	···	···	0.01 (0.01)	···
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	···	0.02 (0.01)	0.02 (0.02)
CMS electron energy scale and resolution	···	···	···	0.12 (0.09)	···	0.03 (0.02)
Muon momentum scale and resolution	···	0.03 (0.04)	···	0.11 (0.10)	<0.01 (0.01)	0.05 (0.02)
Other uncertainties:						
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	···	···	···	0.01 (0.01)	···
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties:	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	< 0.01 (<0.01)	0.01 (<0.01)	
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)	0.11 (0.10)	
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)	0.11 (0.10)	
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)	0.21 (0.22)	
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)	0.24 (0.24)	
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)	···	

Impact on δm_H Uncertainties



H boson Mass – LHC Combination

- Mass measured with high precision in $\gamma\gamma$ and ZZ $\rightarrow 4\ell$ channels



- Some tension but opposite for $\gamma\gamma$ and 4ℓ between ATLAS and CMS; (p-value ~10%) for the four measurements
- Very good agreement in the central values

$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV}$$
$$= 125.07 \pm 0.25\,(\text{stat.}) \pm 0.14\,(\text{syst.}) \text{ GeV}$$

$$m_H^{4\ell} = 125.15 \pm 0.40 \text{ GeV}$$
$$= 125.15 \pm 0.37\,(\text{stat.}) \pm 0.15\,(\text{syst.}) \text{ GeV}$$

M_H = 125.09, narrow width, pure CP even state (0^+)

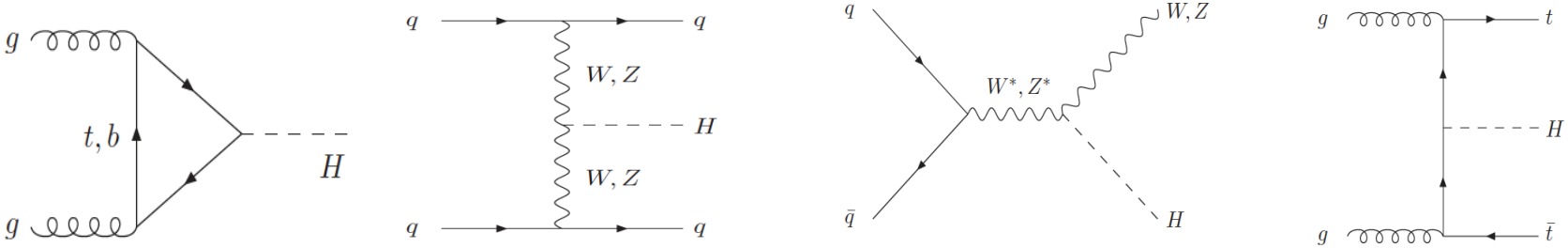
The LHC H_{125} Coupling Measurements

Assuming M_H = 125.09, narrow width, pure CP even state (0^+)

Theoretical Inputs

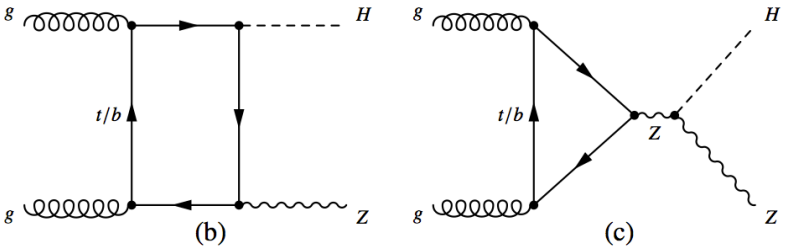
H Production Processes

Main: ggH VBF VH ttH



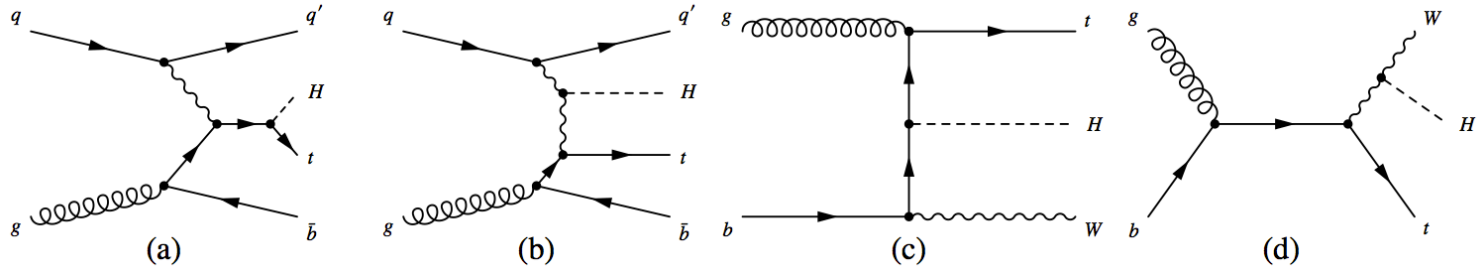
Others:

ggZH



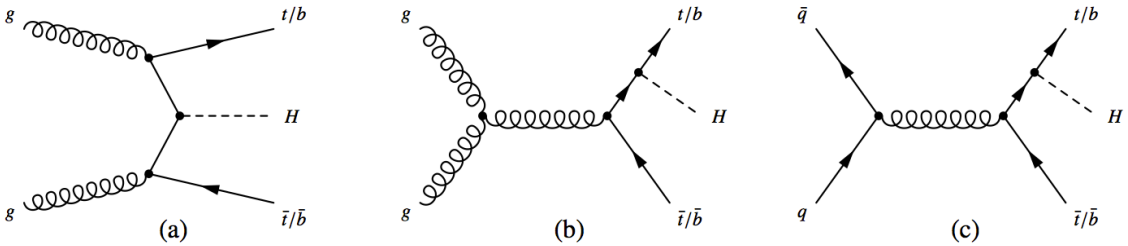
O(10%) effect on VHbb in SM, higher p_T than qqZH

tHq + tHW



Not really sensitive but has larger effects for negative couplings

bbH



Similar to ttH and almost indistinguishable from ggH production

Production Cross Sections (with theory uncertainties)

ATLAS-HIGG-205/CMS PAS HIG-15-002

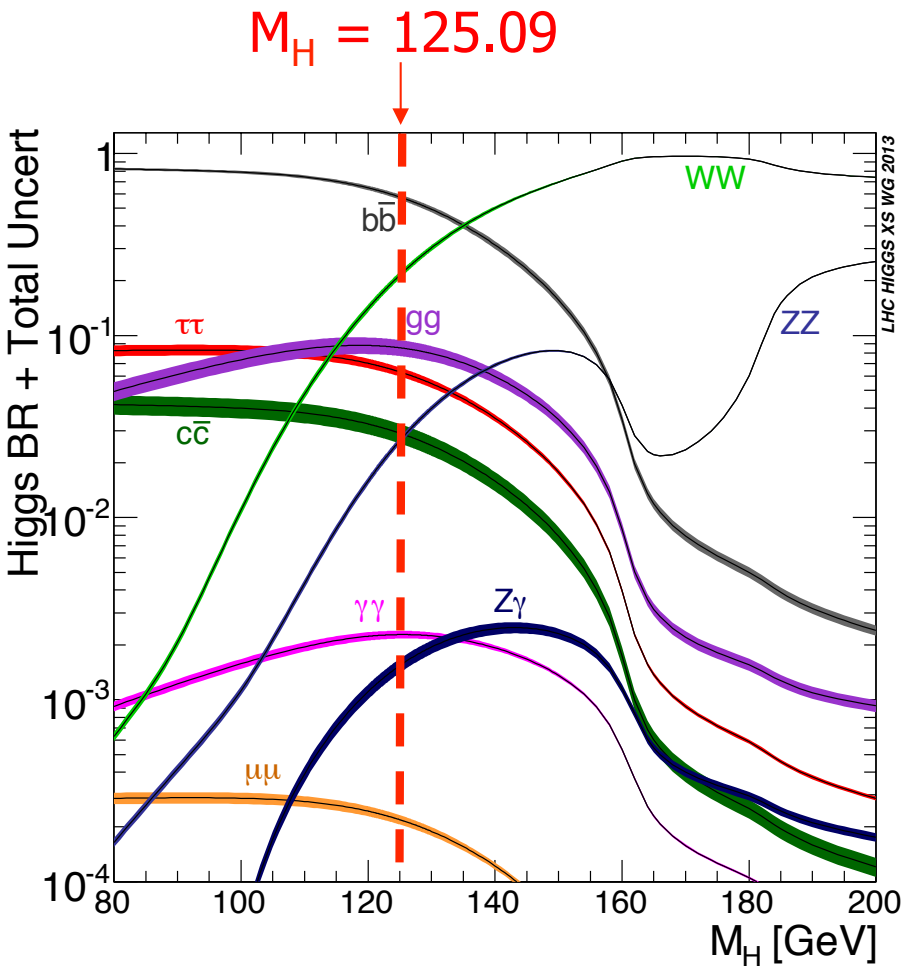
Production Process	Cross section (pb) $\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	Order of theory calculation QCD	EWK	Event generators ATLAS	CMS
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO	NLO	POWHEG	POWHEG
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO	~NNLO	POWHEG	POWHEG
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO	NLO	PYTHIA8	PYTHIA6.4
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO	NLO		
qq→ZH			LO		PYTHIA8	PYTHIA6.4
gg→ZH					POWHEG	PYTHIA6.4*
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO	4FS NLO	PYTHIA8	PYTHIA6 aMC@NLO
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO		POWHEL	PYTHIA6.4
tH	0.012 ± 0.001	0.018 ± 0.001	NLO			
qb→tHq'					MADGRAPH	aMC@NLO
gb→WtH					aMC@NLO	aMC@NLO

SM theory uncertainties: ggF, ttH, bbH ~10%
VBF, VH, ZH: 2-3%

M_H = 125.09 GeV

* = reweighted

Decay Branching ratios



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 theory uncertainties on the branching ratios (BR) at the level of 2-5% for the most important ones
- The natural width of the Higgs boson is expected to be very small (4.1 MeV in the SM)

Channels used for the LHC Combination

Production: / Decay H →:	Untagged (mostly ggH)	VBF	VH	ttH
$\gamma\gamma$	✓	✓	✓	✓
$ZZ \rightarrow 4l$	✓	✓	✓	✓
$WW \rightarrow 2\ell\, 2\nu$	✓	✓	✓	✓
bb	✗	✗	✓	✓
tt	✓	✓	✓	✓
$\mu\mu$	✓	✓	✗	✗

✔ = Entering the LHC combination
✗ = Not-entering the LHC combination

- Other production modes are not specifically tagged by the ATLAS and CMS analyses but enter via one of the above
  e.g. The tHq and tHW events are selected by the ttH analyses
- All main production channels are sensitive
  directly to the couplings H to W, Z, γ bosons and H to τ, b, t fermions,
  & indirectly to gluons and t-quarks

Statistical Treatment

- Profile likelihood ratio test statistics:

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

  - Likelihood built from product of signal and background pdf's
  - for each likelihood evaluation, all systematic uncertainties (**nuisances**) are varied to maximize the profile likelihood (**profiled**)

- ~4200 nuisances $\vec{\theta}$ in the combined fits
  - A large part related to the finite MC statistics
  - Signal theory normalization uncertainties
  - BG theory uncertainties (for BGs not using the data)
  - Other experimental uncertainties

- Most experimental uncertainties are assumed uncorrelated between the two experiments and many tests have been carried out to check the possible impact that was found negligible

- Main correlated systematic uncertainties are the cross sections and BRs between ATLAS and CMS: QCD scale uncertainties and PDF
  - Theory cross sections and BR, Higgs p_T, … state-of-the art calculations in common between the two experiments for this analysis

Signal strengths

- **LHC Results per Decay-Experiment and the Combination**

Signal Strengths / Stand-Alone

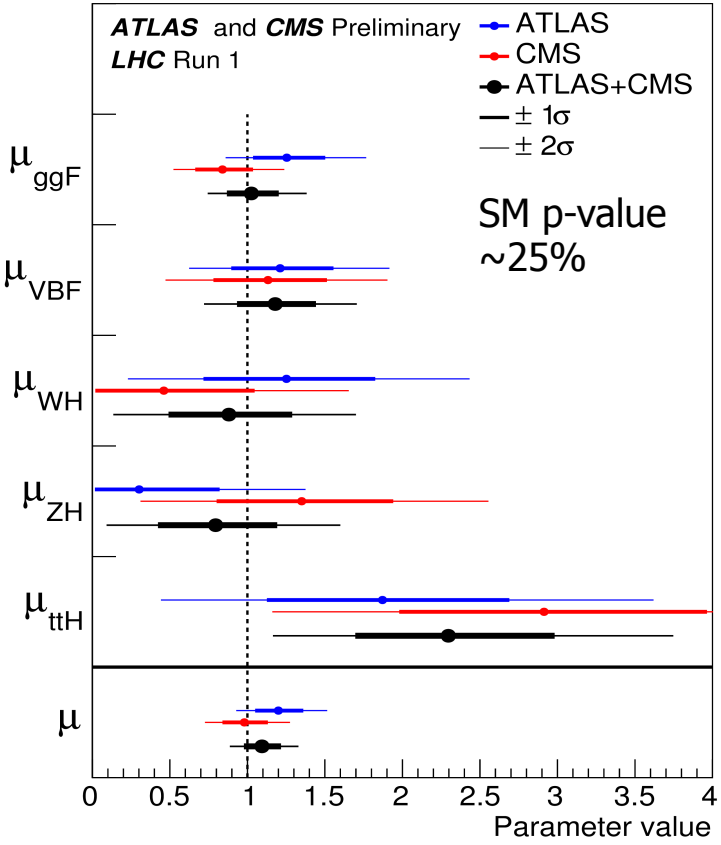
- Consistently obtained here for the LHC mass M_H = 125.09 GeV
- Some values differ slightly from those of earlier publications

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[27]	[50]	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6 ← Measured
			$(^{+0.26}_{-0.24})$	$(^{+0.24}_{-0.22})$	(4.6)	(5.1) ← (expected)
$H \to ZZ \to 4\ell$	[51]	[52]	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
			$(^{+0.33}_{-0.27})$	$(^{+0.31}_{-0.26})$	(5.5)	(6.8)
$H \to WW$	[53, 54]	[55]	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
			$(^{+0.21}_{-0.20})$	$(^{+0.23}_{-0.20})$	(5.8)	(5.6)
$H \to \tau\tau$	[56]	[57]	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
			$(^{+0.37}_{-0.33})$	$(^{+0.31}_{-0.29})$	(3.3)	(3.7)
$H \to bb$	[37]	[38]	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
			$(^{+0.39}_{-0.37})$	$(^{+0.45}_{-0.43})$	(2.7)	(2.5)
$H \to \mu\mu$	[58]	[59]	-0.7 ± 3.6	0.8 ± 3.5		
			(± 3.6)	(± 3.5)		
ttH production	[60–62]	[64]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$(^{+0.72}_{-0.66})$	$(^{+0.88}_{-0.80})$	(1.6)	(1.3)

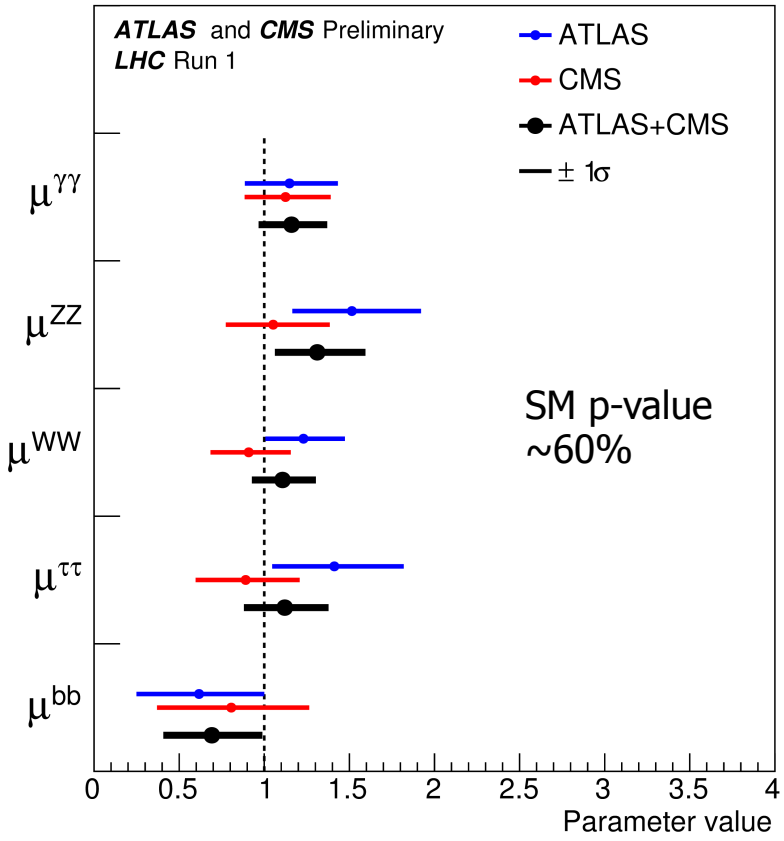
Slight ttH prod. excess … and slight H → bb decay deficit

Signal Strength μ: Production and Decay (1)

Production:
SM branching ratios assumed

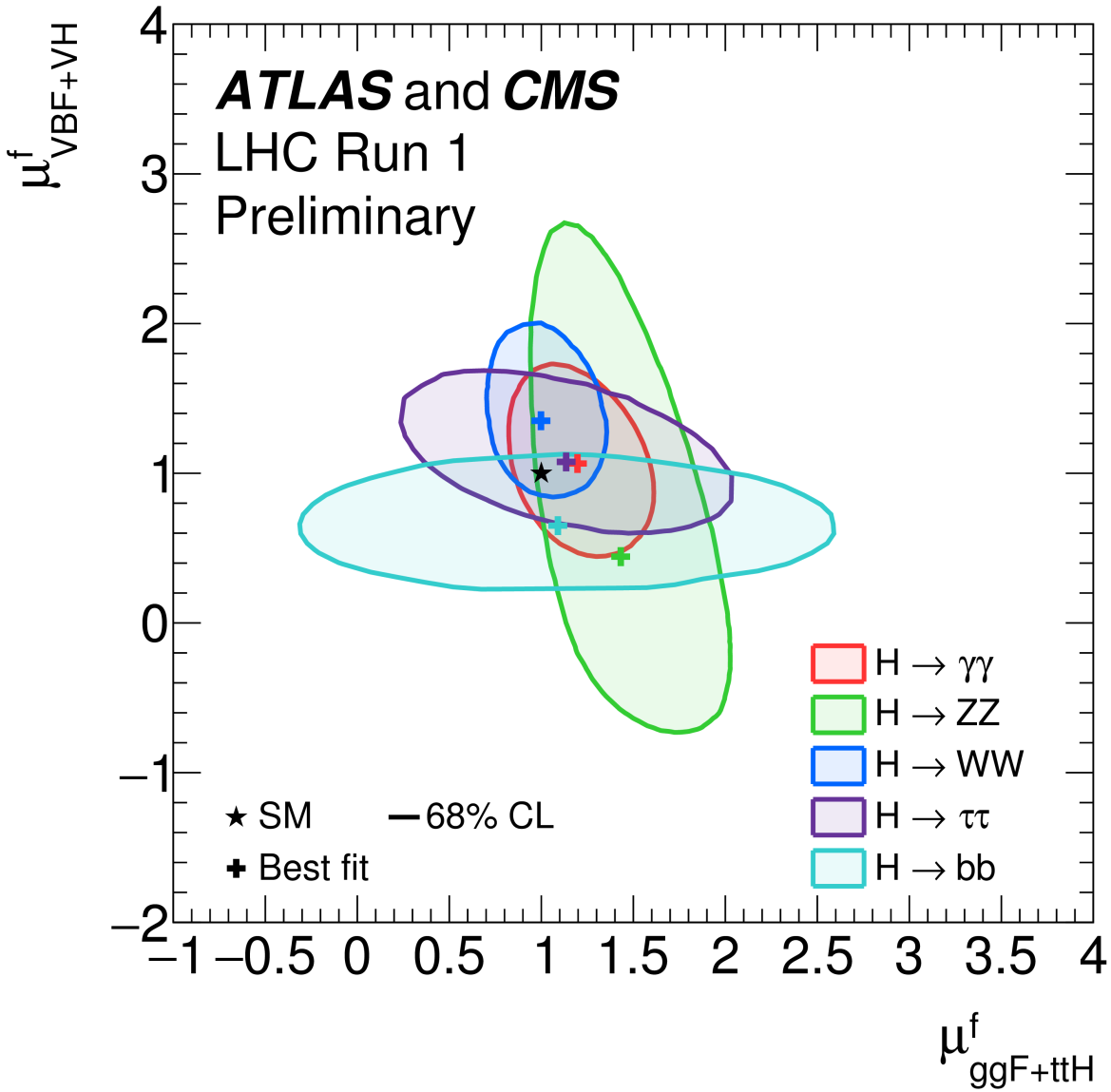


Decay:
SM production X-sections assumed



- Signal strengths in different channels are consistent with 1 (SM)
- Largest difference in ttH: 2.3 σ excess with respect to SM
  (also small deficit in decays into $\overline{bb}$)

Signal Strength μ: Production and Decay (2)



- Assume that μ_F^f and m_V^f are the same for $\sqrt{s}$ = 7 and 8 TeV
- 10-parameter fit of μ_F^f and m_V^f for each of the 5 decay channels

p-value of 88% for the compatibility with SM expectation !!

Signal Strength μ: Production and Decay (3)

Production: SM branching ratios assumed

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}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

Decays: SM production x-sections assumed

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}	$0.69^{+0.29}_{-0.27}$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$

Assuming prod./decay scaling by a global μ gives:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}(stat)^{+0.04}_{-0.04}(\exp t)^{+0.08}_{-0.07}(theo)$$

Significance for the Observations per Channel

- ggH production as well a di-bosons decays (gg, ZZ, WW) each already observed with significance > 5σ by both ATLAS and CMS
- Combining (statistics x 2) the results brings additional sensitivity:

Production process	Observed 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	
Decay channel			
H → ττ	**5.5**	**5.0**	←
H → bb	2.6	3.7	

VBF and H → ττ now established at LHC at more than 5σ !!
TeVatron still pertinent for H → bb !

Coupling Constraints

- κ-Framework and Generic Models
- Interpretation of Combined Results
- Best Fit Values
- Couplings to Fermions and bosons

Testing Couplings: the κ-Framework

- The production × decay are always sensitive at LO to a linear combination of products of two couplings ⇔ model assumptions required to disentangle

  e.g. Prescription from HXSWG in arXiv:1209.0040

  Consider a narrow width approximation $\sigma \times \beta_i = \frac{\sigma_i \times \Gamma_i}{\Gamma_H}$

  Introduce SM modifiers for production $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$ and decay $\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$

  And $\kappa_H^2 = \frac{\sum \kappa_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$

- Define benchmark scenarios:

  - Test custodial symmetry : $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$ ($\lambda_{WZ} = 1$ in SM)

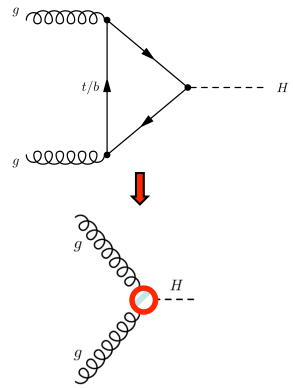
  - Test bosonic & fermionic couplings: consider $\kappa_V (= \kappa_W = \kappa_Z)$ & $\kappa_f (= \kappa_l = \kappa_q)$

  - Assume either only SM particles in the loops,
    or
    "new physics" in width or loops (allowing or not invisible decay)

κ Definitions

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06\cdot\kappa_t^2 + 0.01\cdot\kappa_b^2 - 0.07\cdot\kappa_t\kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74\cdot\kappa_W^2 + 0.26\cdot\kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27\cdot\kappa_Z^2 + 0.37\cdot\kappa_t^2 - 1.64\cdot\kappa_Z\kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84\cdot\kappa_t^2 + 1.57\cdot\kappa_W^2 - 2.41\cdot\kappa_t\kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4\cdot\kappa_t^2 + 3.56\cdot\kappa_W^2 - 5.96\cdot\kappa_t\kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59\cdot\kappa_W^2 + 0.07\cdot\kappa_t^2 - 0.66\cdot\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57\cdot\kappa_b^2 + 0.22\cdot\kappa_W^2 + 0.09\cdot\kappa_g^2 + 0.06\cdot\kappa_\tau^2 + 0.03\cdot\kappa_Z^2 + 0.03\cdot\kappa_c^2 + 0.0023\cdot\kappa_\gamma^2 + 0.0016\cdot\kappa_{Z\gamma}^2 + 0.0001\cdot\kappa_s^2 + 0.00022\cdot\kappa_\mu^2$

Loop parametrized with effective κ e.g. κ_t



- Includes higher-order QCD and EW corrections to inclusive x-sections
- No specific couplings for ggZH and tH given lack of sensitivity
- Unmeasured κ factors taken from related: $\kappa_c = \kappa_t$, $\kappa_\mu = \kappa_\tau$, $\kappa_s = \kappa_b$

κ Generic "Ratio" Parametrisations

Cannot disentangle production x-section from BR in a model-independent way

- The gg → H → ZZ channel is chosen as a reference
- All measurements expressed in either « ratio of cross sections or branching ratios » or « ratio of coupling modifiers »

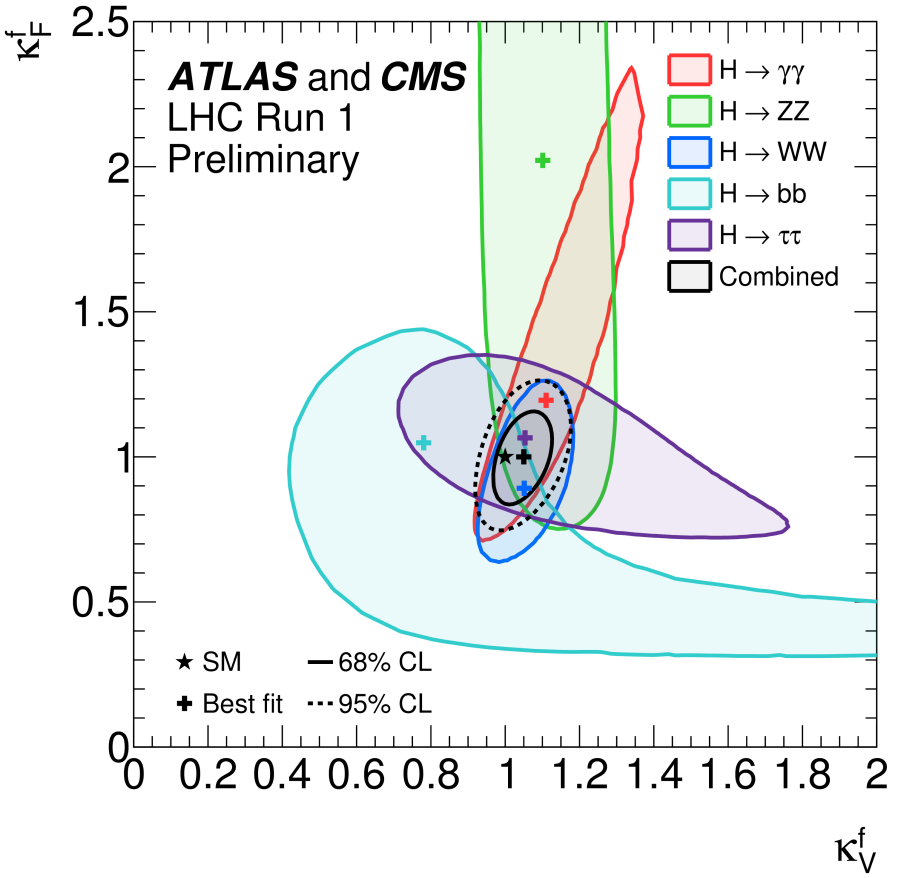
σ and BR ratio model
$\sigma(gg \to H \to ZZ)$
$\sigma_{VBF}/\sigma_{ggF}$
σ_{WH}/σ_{ggF}
σ_{ZH}/σ_{ggF}
$\sigma_{ttH}/\sigma_{ggF}$
BR^{WW}/BR^{ZZ}
$BR^{\gamma\gamma}/BR^{ZZ}$
$BR^{\tau\tau}/BR^{ZZ}$
BR^{bb}/BR^{ZZ}

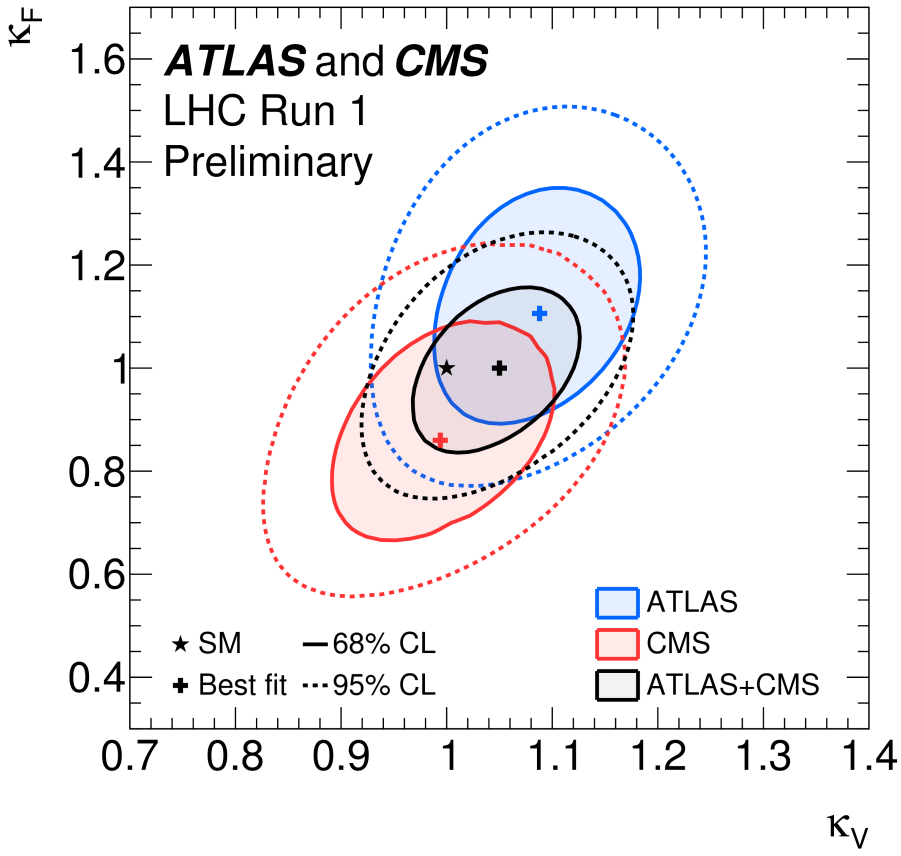
Coupling-strength ratio model
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$
$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\lambda_{tg} = \kappa_t/\kappa_g$
$\lambda_{WZ} = \kappa_W/\kappa_Z$
$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
$\lambda_{bZ} = \kappa_b/\kappa_Z$

In this parameterization BR^{ZZ}, BR^{WW}, σ_{WH} , σ_{WH} and σ_{VBF} are function of $\varkappa_Z$ and $\varkappa_W$ e.g. for example $\sigma_{WH}/\sigma_{ggF} \sim (\lambda_{WZ}/\lambda_{zg})^2$

κ_V κ_F Contours (1)

All vector and fermion couplings are scaled by κ_V and κ_F

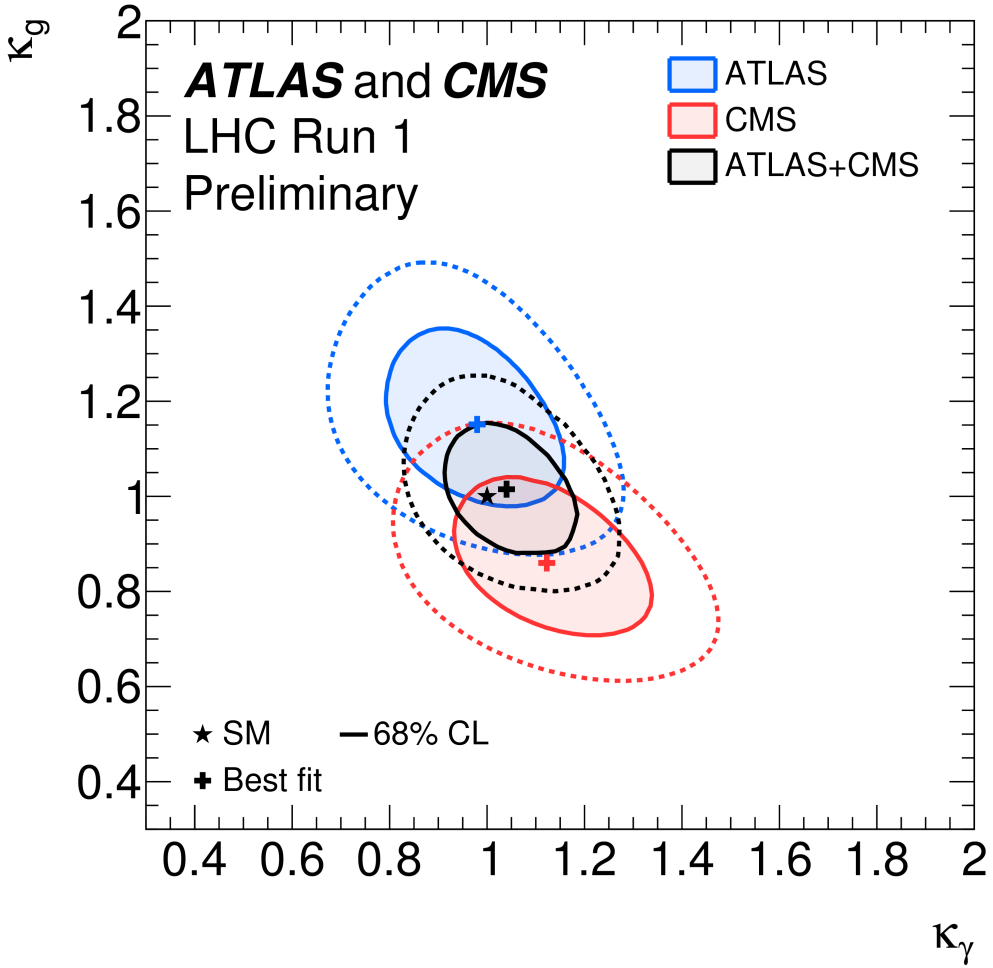


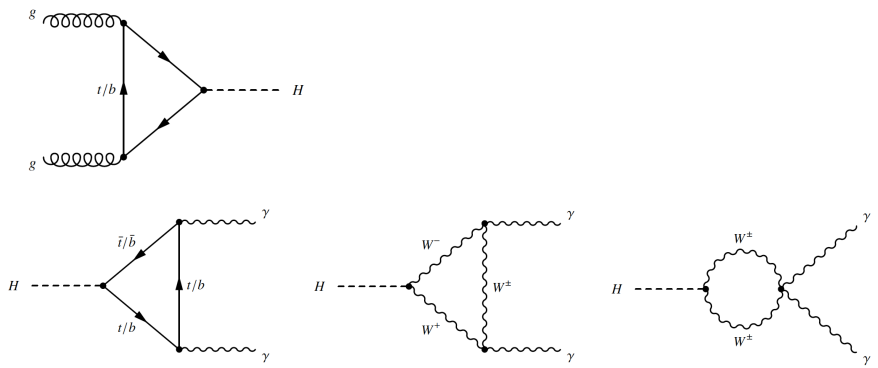


All results in agreement with SM ($\kappa_V = \kappa_f = 1$) within 1σ

Constraints on the H couplings via Loops

All κ modifiers set to SM values (=1) except effective couplings κ_γ and κ_g



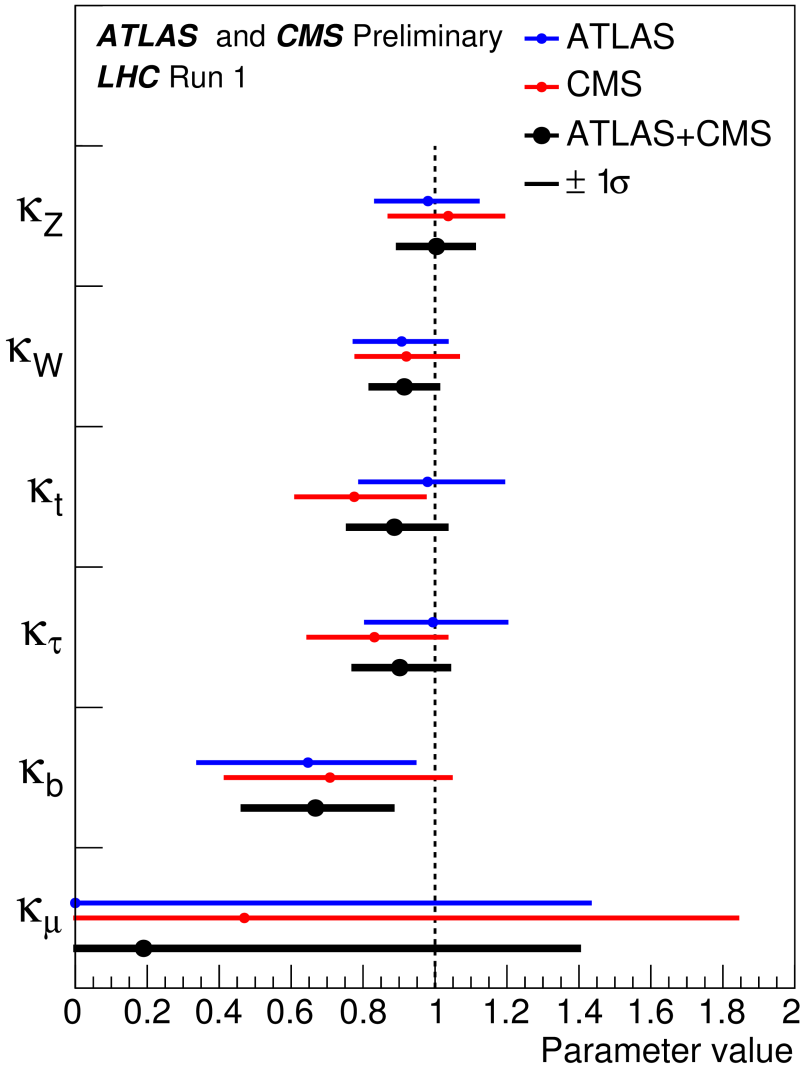


- The point $\kappa_\gamma = \kappa_g = 1$ lies well within the 68% contour
- The *p*-value of the compatibility between the data and the SM predictions is 82%

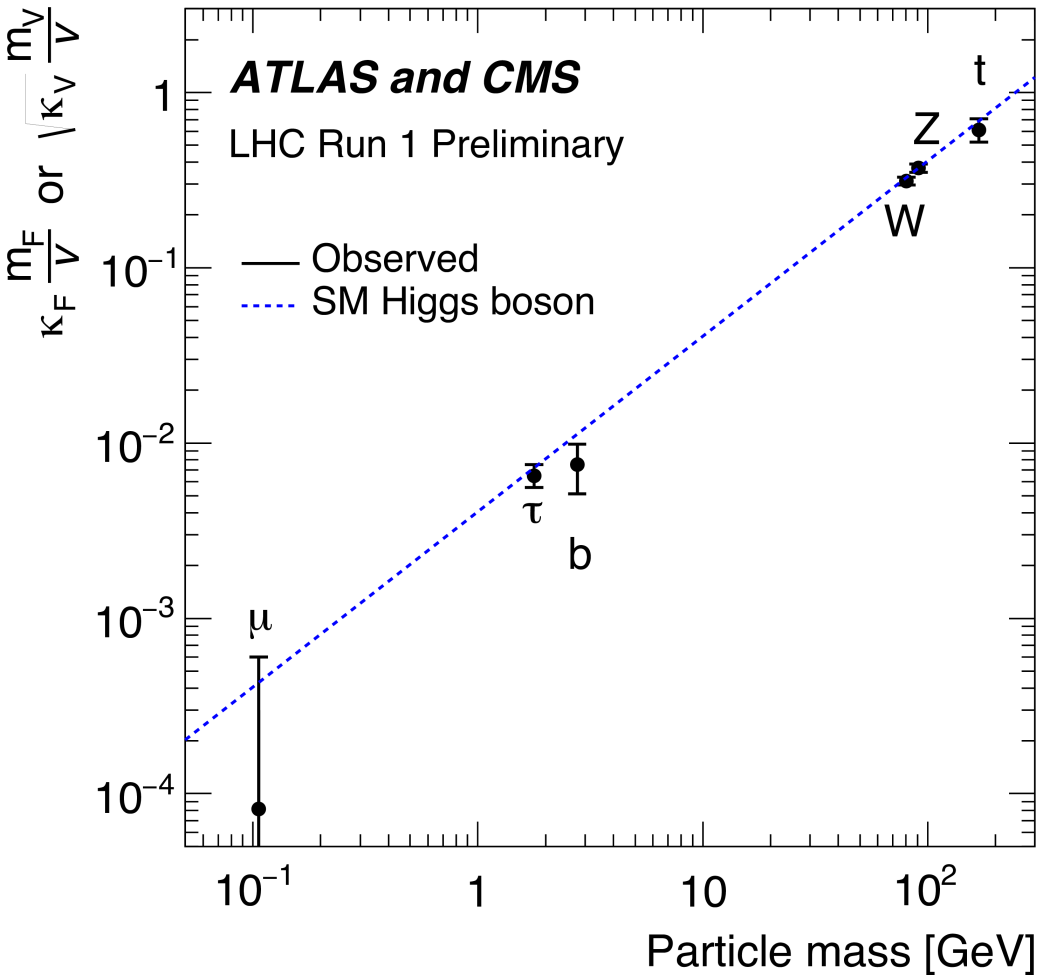
⇒ One can assume that there is no BSM particles in the loops … this justifies next slide's fit for the fermion and boson SM couplings

Test SM Couplings to Fermions and Bosons

Assuming no BSM in the loops: i.e. assume SM for κ_γ and κ_g



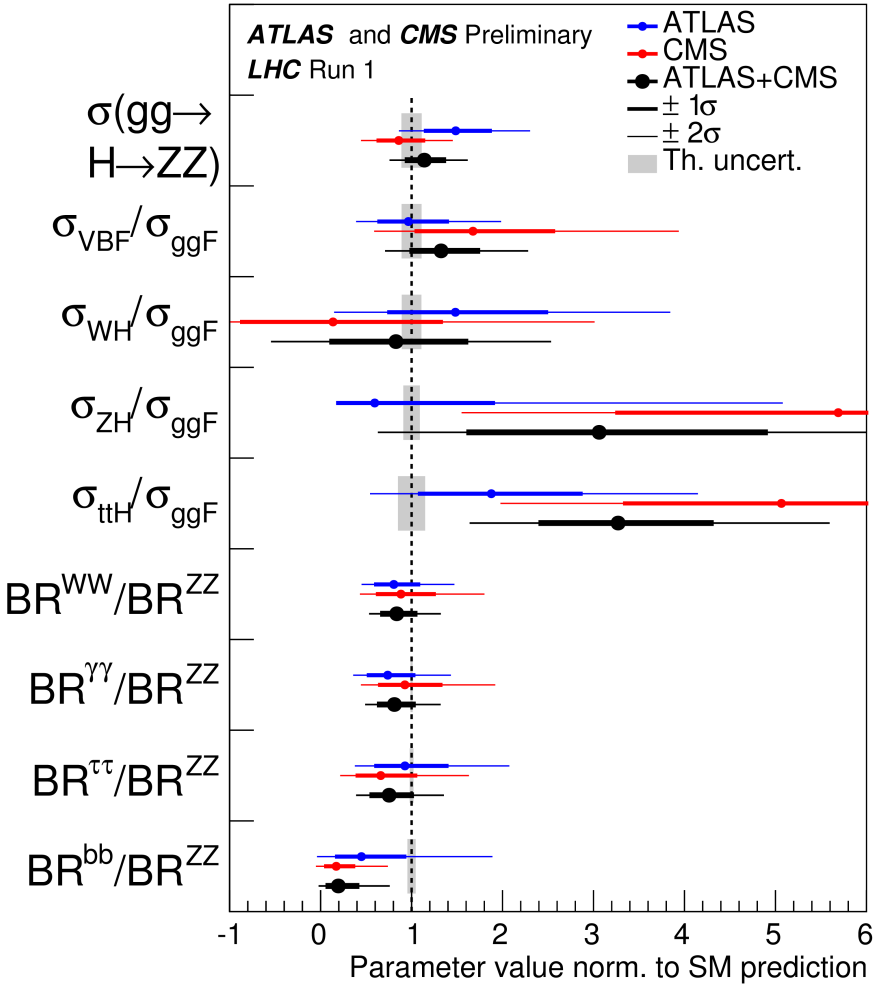
Fit parametrization with 6 free κ parameters: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ

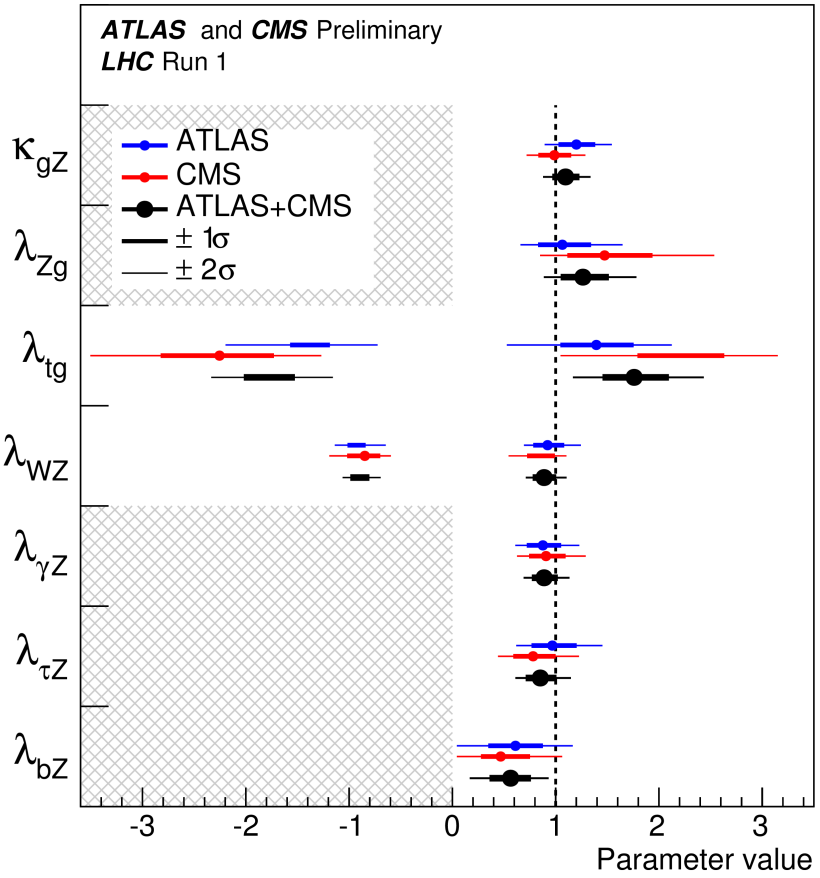


The Higgs boson couplings scale with particle masses as expected
From the BEH EW symmetry breaking mechanism

Ratio Parametrizations

- Parameterization of ratio of observables allows for minimal dependence on theory model assumptions





- Results in general agreement with the SM expectation
- A tension at the level of 2.4σ is seen in BR^{bb}/BR^{ZZ}

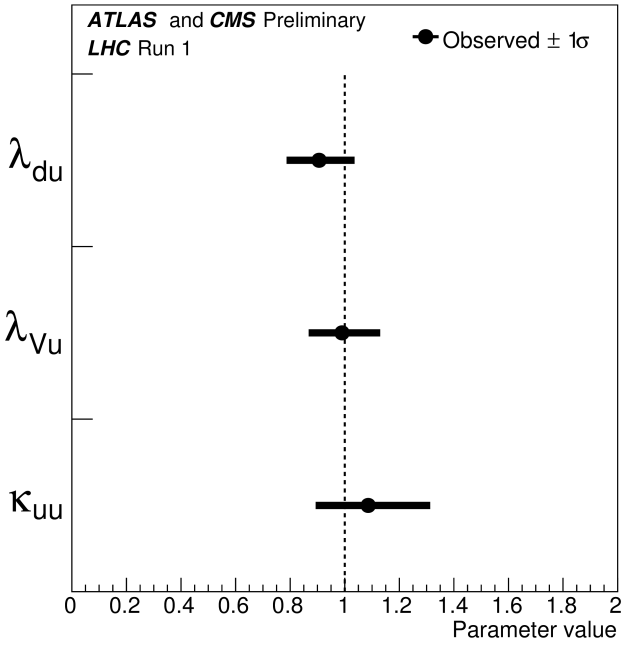
Effect mainly coming from large ZH and ttH (both have $\sigma_i / \sigma_{ggF} \sim 3$)

Fermion Symmetries

Probing up-down symmetry; 3 free parameters:

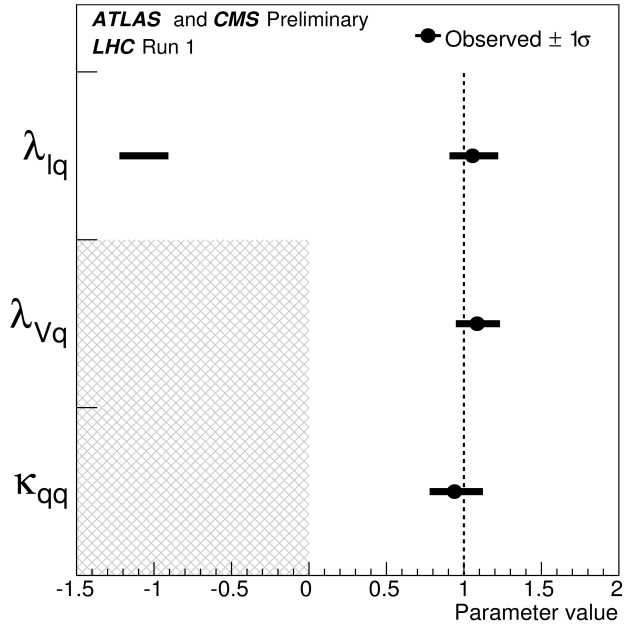
$\lambda_{du} = \kappa_d/\kappa_u \quad \lambda_{Vu} = \kappa_V/\kappa_u \quad \kappa_{uu} = \kappa_u\kappa_u/\kappa_H$

Parameter	ATLAS+CMS	
	Measured	Expected uncertainty
λ_{du}	$0.91^{+0.12}_{-0.11}$	$[-1.21, -0.92] \cup [0.87, 1.14]$
λ_{Vu}	$0.99^{+0.13}_{-0.12}$	$^{+0.20}_{-0.12}$
κ_{uu}	$1.09^{+0.22}_{-0.19}$	$^{+0.20}_{-0.27}$
$\lvert\lambda_{lq}\rvert$	$1.06^{+0.15}_{-0.14}$	$^{+0.16}_{-0.14}$
λ_{Vq}	$1.09^{+0.14}_{-0.13}$	$^{+0.13}_{-0.11}$
κ_{qq}	$0.94^{+0.17}_{-0.15}$	$^{+0.18}_{-0.16}$



Probing lepton-quark symmetry; 3 free parameters:

$\lambda_{lq} = \kappa_l/\kappa_q \quad \lambda_{Vq} = \kappa_V/\kappa_{uq} \quad \kappa_{qq} = \kappa_q\kappa_q/\kappa_H$

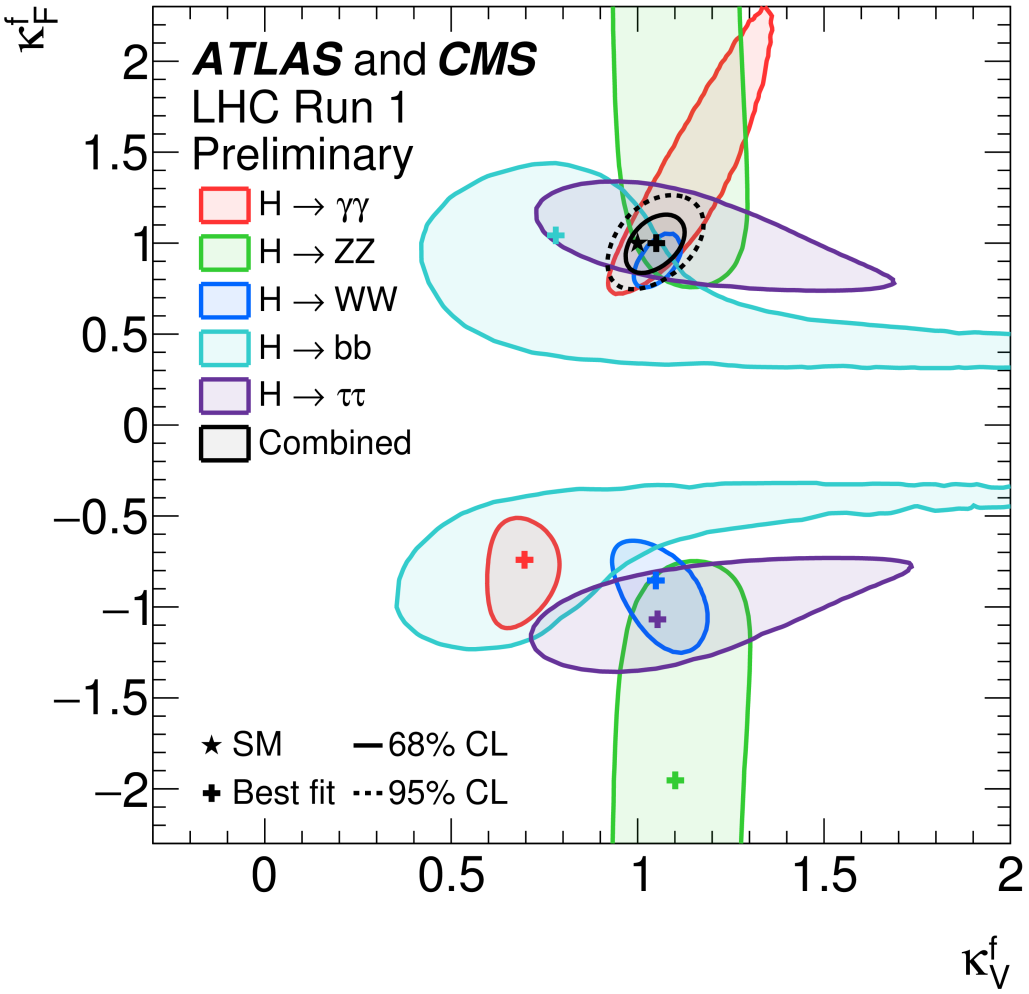


p-values of 67% (ud) and 78% (lq)

Constraints with BSM Physics

κ_V κ_F Contours (2)

Allow for negative κ_F (which changes the sign of t-W loop interference)



- Almost 5s exclusion of $k_F < 0$!!!
- Some decays in least significant production channels pulled towards inverted interference

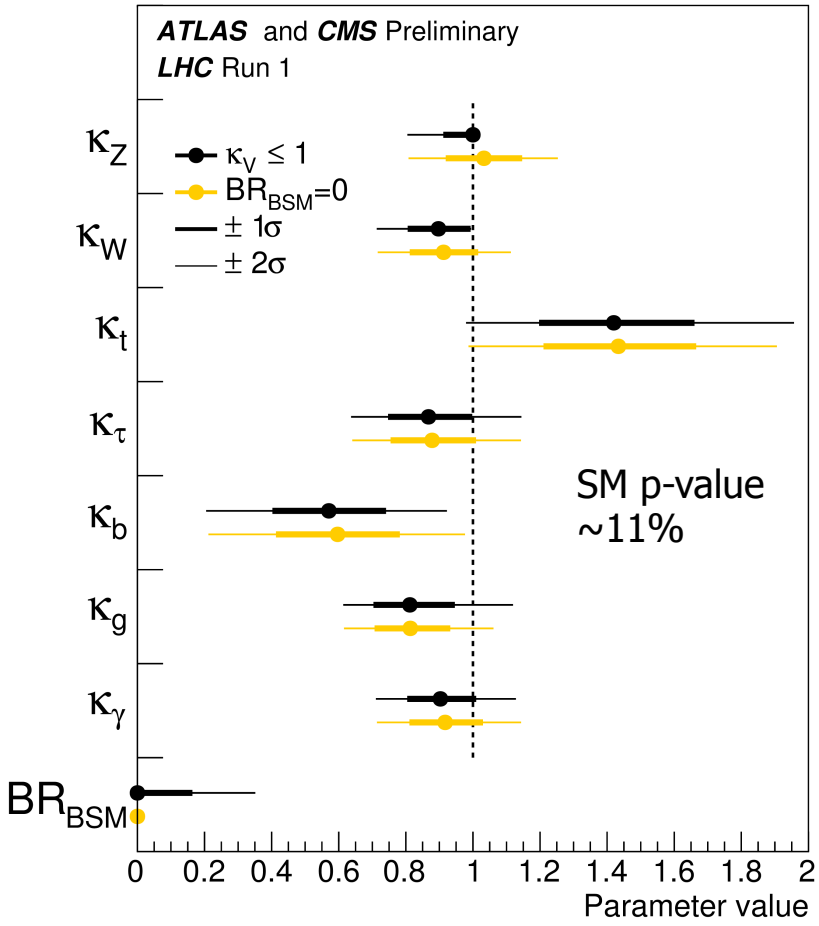
Note: all physical quantities depend on a product of two κ's ⇔ other two quadrants are symmetric with respect to (0,0)

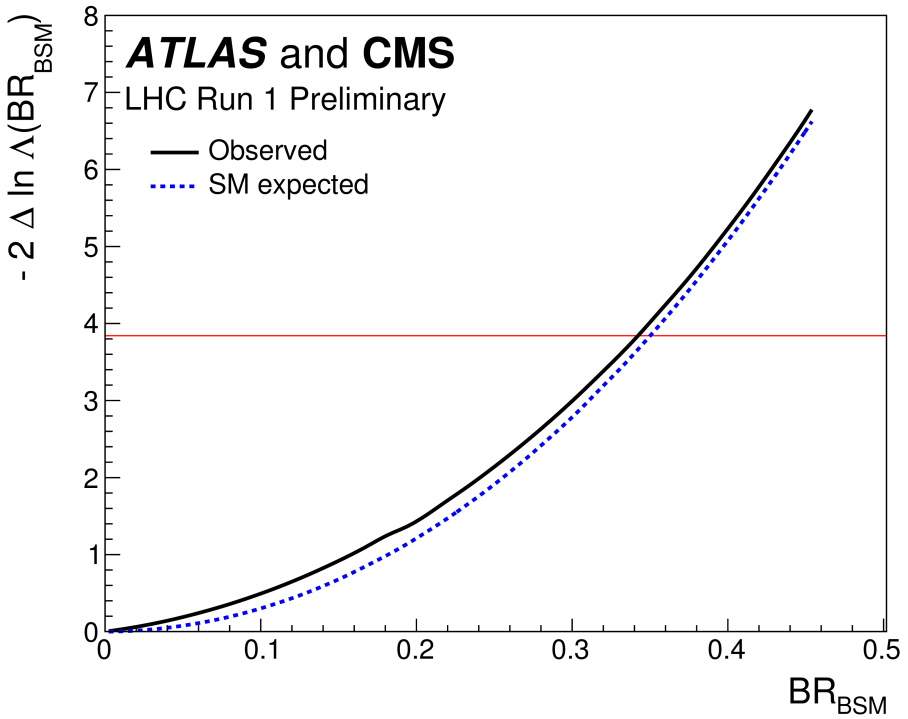
Test SM Couplings to Fermions and Bosons

Allowing for BSM in the loops: i.e. allow effective couplings for κ_γ and κ_g

- Only "σ x Branching Ratios" can be measured at the LHC
  $\Leftrightarrow$ need further assumptions on the H width;
- take $\kappa_V \leq 1 \Rightarrow BR_{BSM}$ can be constrained

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$



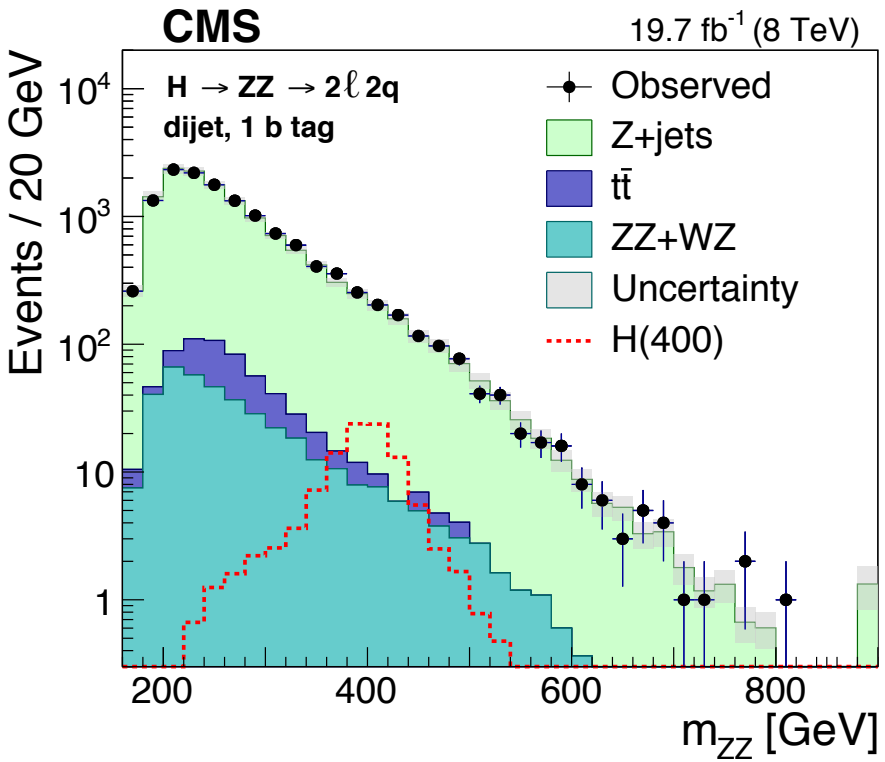


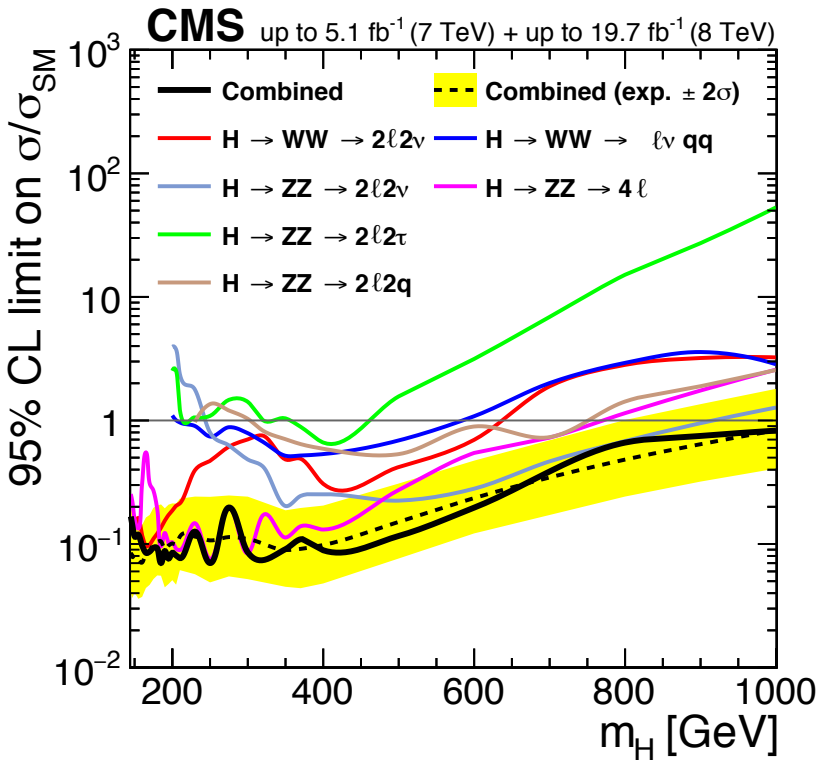
BR_{BSM} < 0.34 at 95% C.L. (assuming $\kappa_V \leq 1$)
where
BR_{BSM} includes all possible non standard decays, visible or invisible

Search for another SM-Like Higgs Boson

Search for (another) SM-Like H Boson

- Explore the possibility of the presence of yet another SM-like H boson in the observable mass range [motivated experimentally … hardly justified on a theory basis]
- Such resonance in di-boson decay modes may appear in exotic theories (e.g. Radions in theories with large extra-dimensions)





Higgs boson with standard model-like couplings and decays in the Range 145 < M_H < 1000 GeV excluded at better than 95% level.

CMS arXiv:1504.00936

Search for (another) SM-Like H Boson

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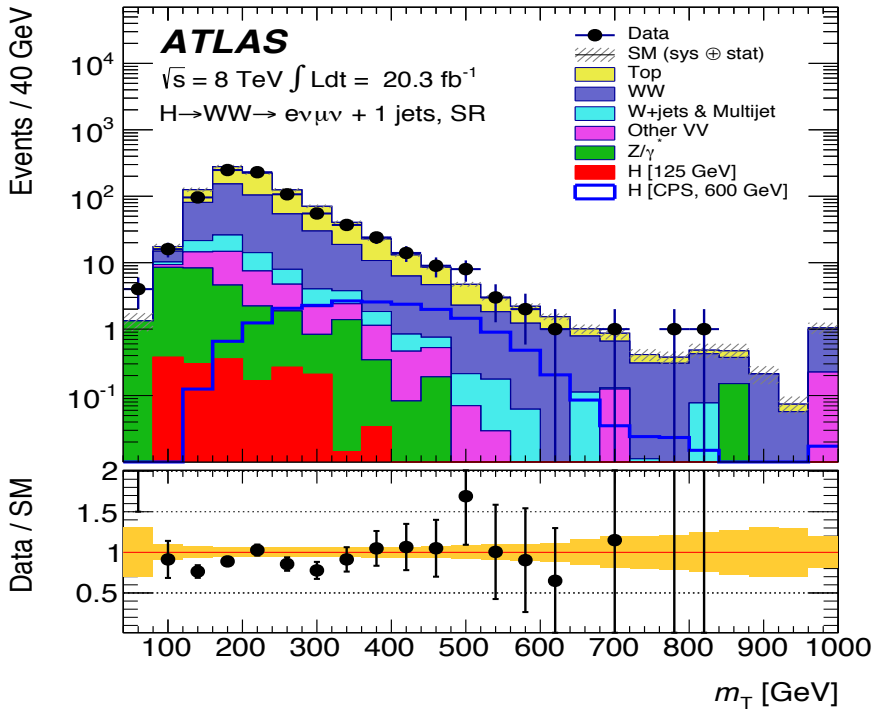
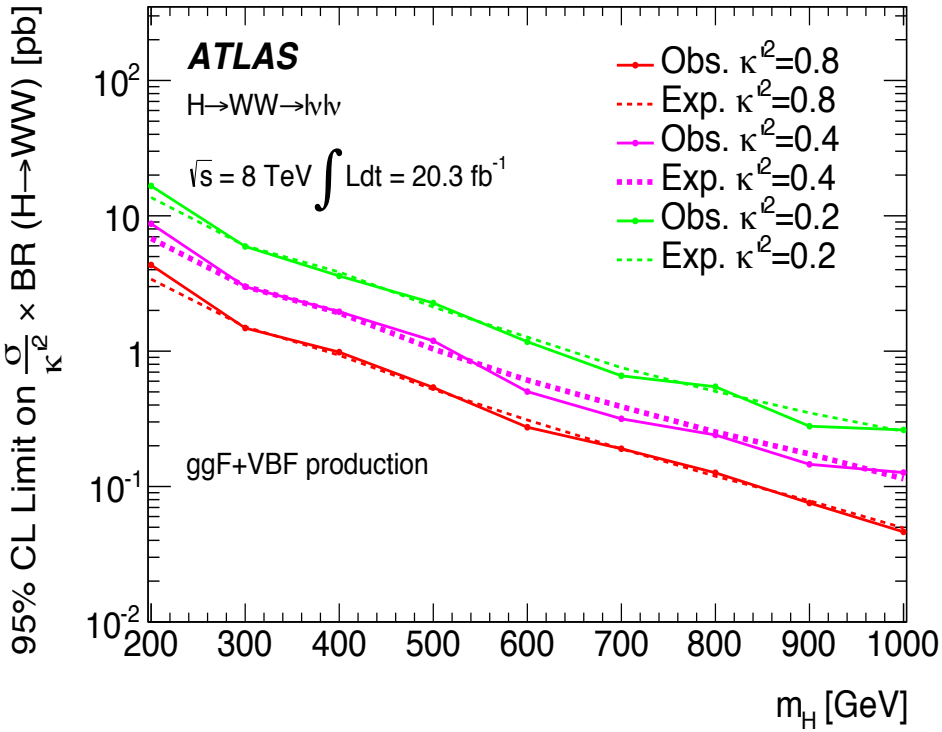
- Such resonance in di-boson decay modes may appear in exotic theories (e.g. Radions in theories with large extra-dimensions)





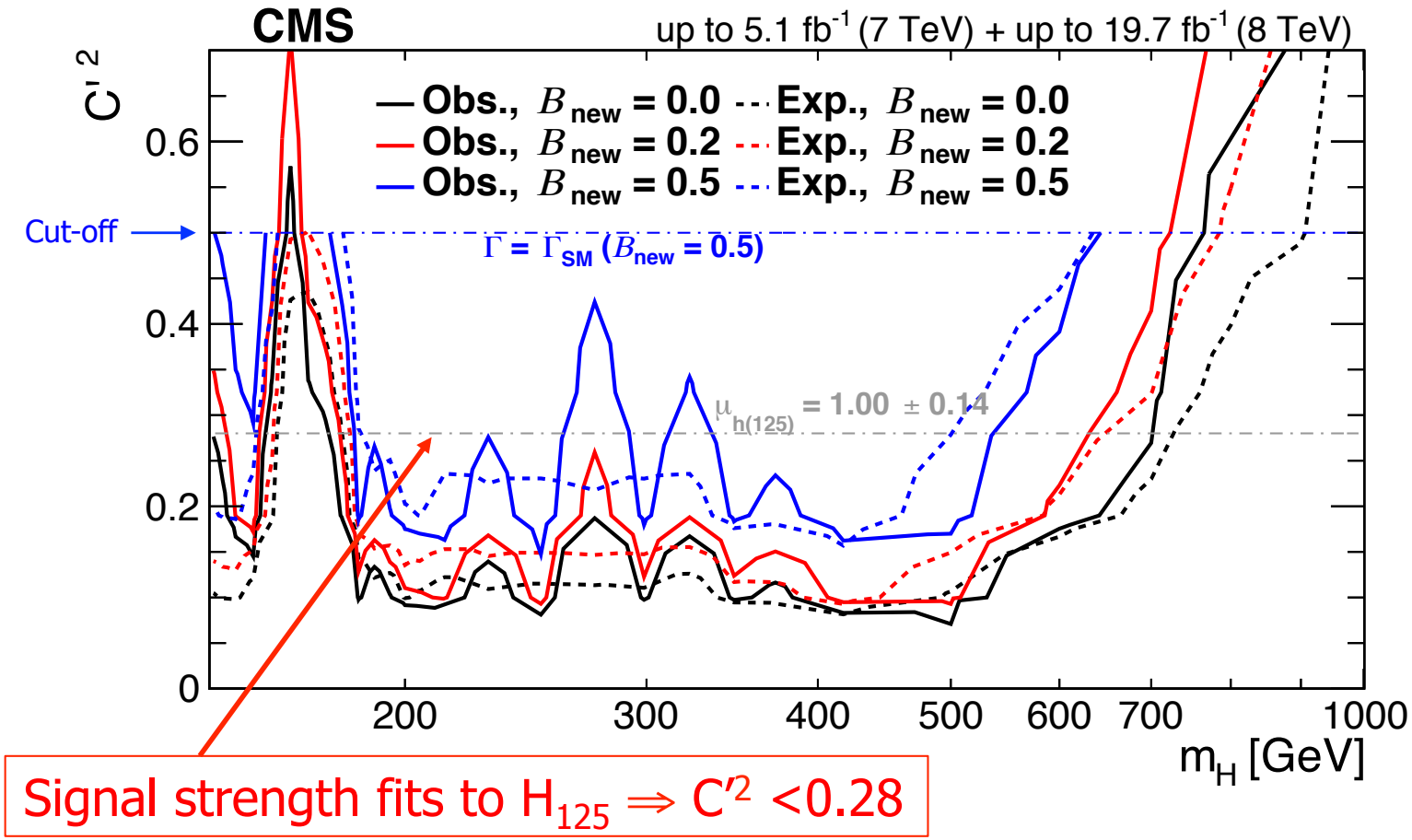
$$\sigma_H = \kappa'^2 \times \sigma_{H,\mathrm{SM}}$$
$$\Gamma_H = \kappa'^2 \times \Gamma_{H,\mathrm{SM}}$$
$$\mathrm{BR}_i = \mathrm{BR}_{\mathrm{SM},i}.$$

Upper limits for a heavy scalar resonance width in the range $0.2\ \Gamma_{H,SM} < \Gamma_H < 0.8\ \Gamma_{H,SM}$

ATLAS arXiv:1509.00389

Search for an EW Singlet Extension of the SM

- Interpret high mass SM-like decay searches results in EW singlet extension of SM
- Motivated by shortcomings of the SM for cosmology (e.g. DM)
- Could generate deviations in SM decay rates for the H_{125} boson via mxing



Signal strength fits to $H_{125} \Rightarrow C'^2 < 0.28$

$$\Gamma' = \Gamma_{SM} \frac{C'^2}{1 - \mathcal{B}_{new}}$$

C' is a scale factor for the coupling with respect to SM

β_{new} is the branching fraction of the EW singlet to non-SM decay modes

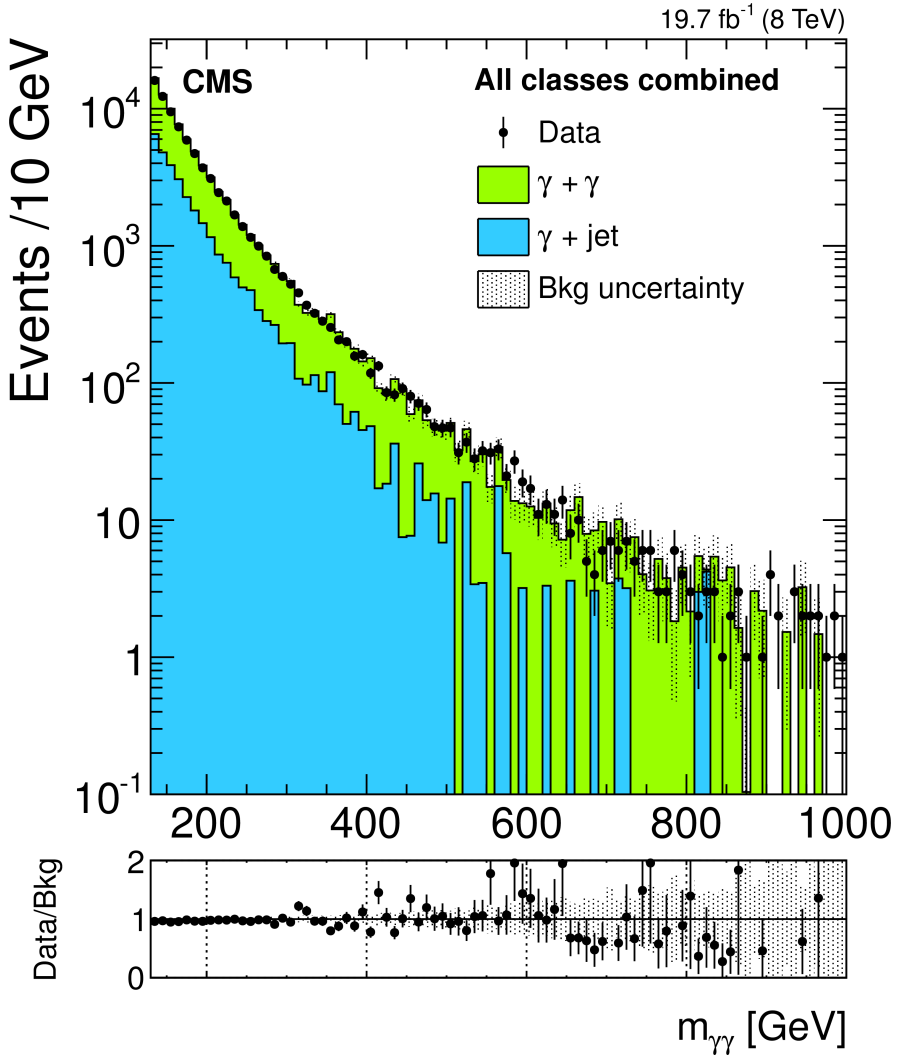
Focus on $C'^2 < (1 - \beta_{new})$

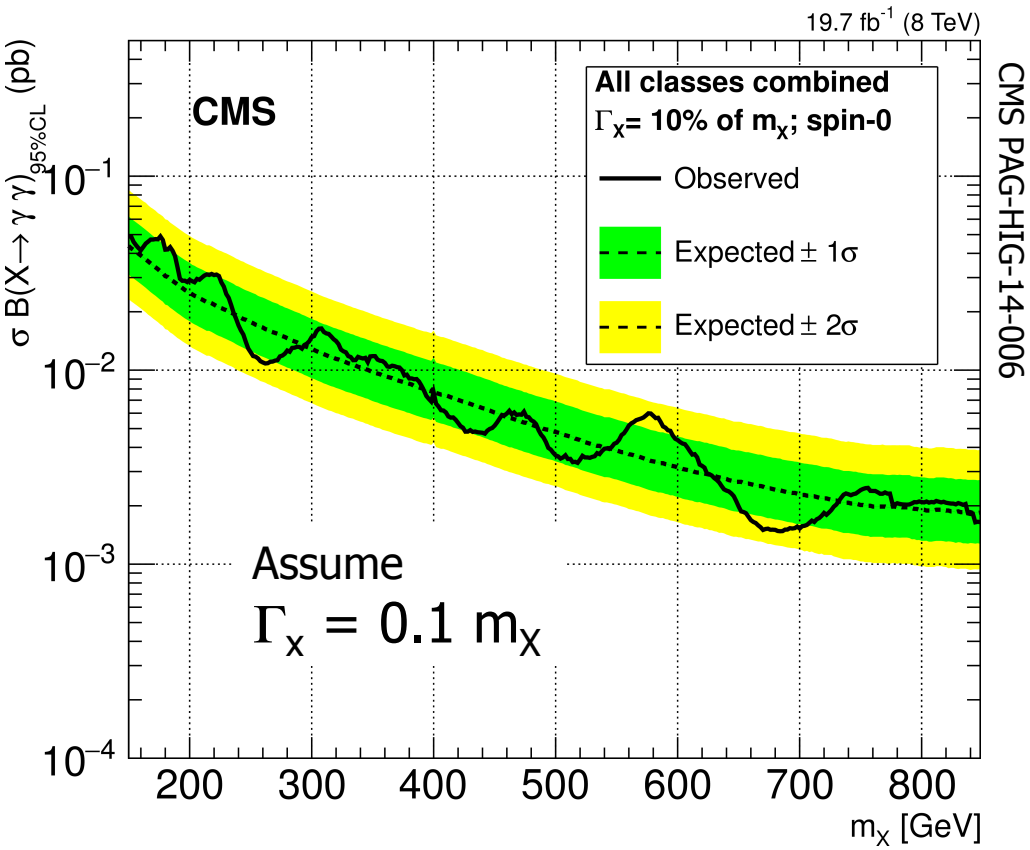
The direct extend beyond the indirect constraints

CMS arXiv:1504.00936

Search for X → γγ at High Mass

- Use analysis techniques developed for the H analysis at M_H = 125 GeV for the interpretation





- Set limits on spin 0 and spin 2 resonances with various assumptions on the width

Also set constraints on effective for A/H in 2HDM in « alignment limit » (H → VV , H → hh, A → Zh suppressed)

Great and Malicious H

Reminder from yesterday

The H Boson discovery is now firmly established

- ✓ $M_H \sim 125$ GeV
- ✓ Couplings to fermions and to weak bosons (verified to ~10-30% precision) consistent with the minimal scalar sector required for the BEH mechanism
- ✓ Custodial symmetry verified (~ 15% precision) and the existence of a boson with non-universal family couplings established ($\tau\tau$ evidence + no $\mu\mu$ signal)

A truly astonishing achievement !

- Culmination of a reductionism strategy evolving from the question of the *structure of matter* to that of the *very origin of interactions (local gauge symmetries) and matter (interactions with Higgs field)*
- We understand the **origin of mass** (i.e. scalar field, BEH mechanism) for particles in a quantum field theory with local (i.e. point like) gauge interactions
- Ignoring gravitation, we have for the first time in the history of science a theory which is at least in principle complete, consistent, and coherent at all scales … (up to the Planck scale ?)

… but it is not over

The Scalar Sector & the Malicious H Boson (1)

- The H boson is not a gauge boson
  (its mass is not protected by symmetries of the theory)
- Scalar fields "qualitatively" changes the nature of the vacuum

Cosmological problem:

Quantum fluctuations at Planck scale involves Planckian energies (space-time distorted)
→ contribute to a vacuum energy density disagreeing with our universe by 10^{120} orders
→ the principle of locality (a pillar of quantum field theory) breaks down at Planck scale !

Hierarchy problem:

Fine tuning by 10^{30} orders needed to cancel the scalar field coupling to quantum fluctuations of space-time at the Planck scale

- The complexity of the Standard Model is encoded a scalar sector

$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs\ (Symm.\ Break.)}(\phi, A_a, \psi_i)$$

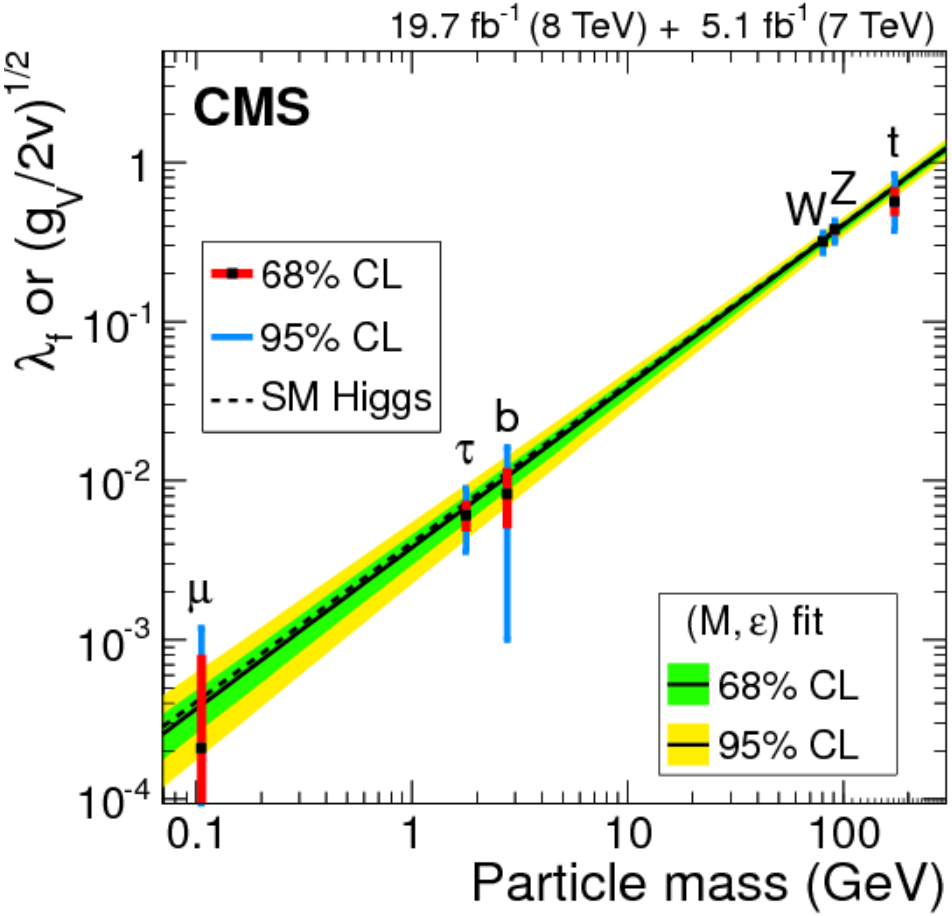
Natural
verified with high precision; stable with respect to quantum corrections; highly symmetric
(gauge and flavour symmetries)

Ad hoc
but necessary (other mass terms forbidden by EWK gauge symmetries); unstable with respect to quantum corrections; possibly at the origin of flavour structure and all other problems of the SM

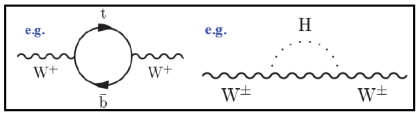
State of the Art

State of the Art (1)

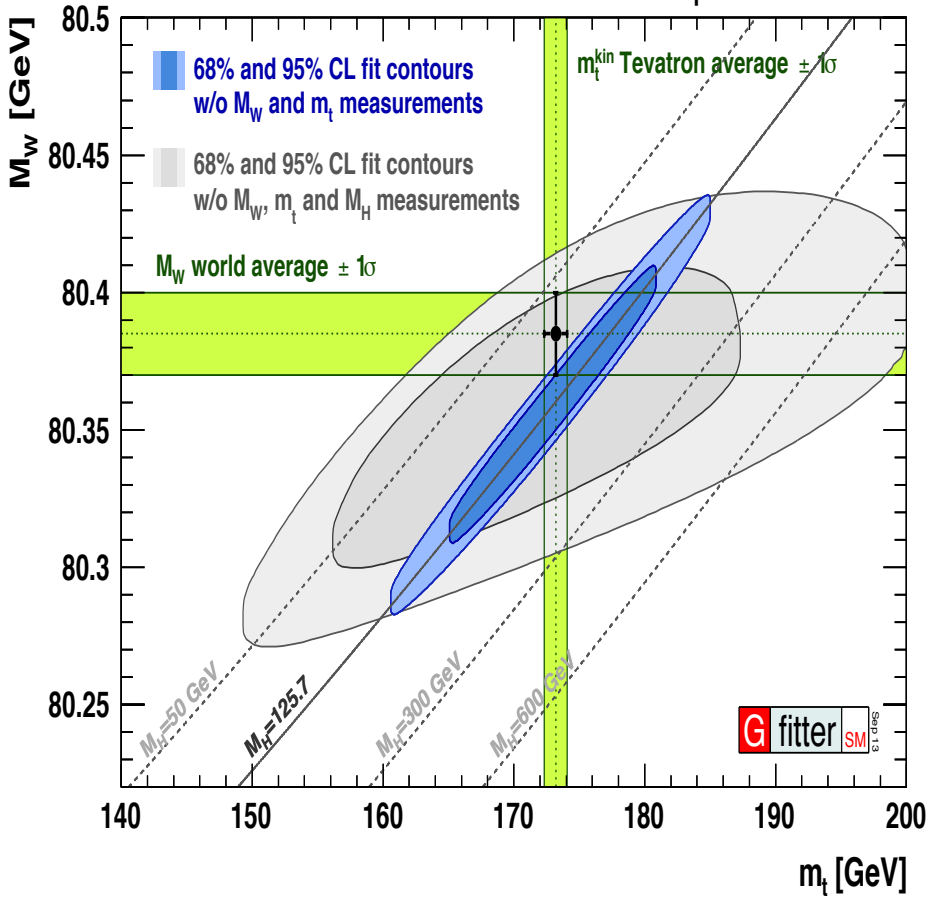
Couplings to fermions and to weak bosons
(verified to ~10-30% precision)



Rad. corrections:



W, Z meas. sensitive to M_{top} M_H



- SM-like Higgs at ~125 GeV is compatible with global EWK data at 1.3σ (p = 0.18)
- Indirect constraints now superior to some precise direct W, Z measurements

Indirect (EWK fit): $M_W = 80.359 \pm 0.011$
Direct (World average): $M_W = 80.385 \pm 0.015$

State of the Art (2)

Flavour anomalies ?

- The BEH mechanisms introduces masses in a gauge-invariant way

but

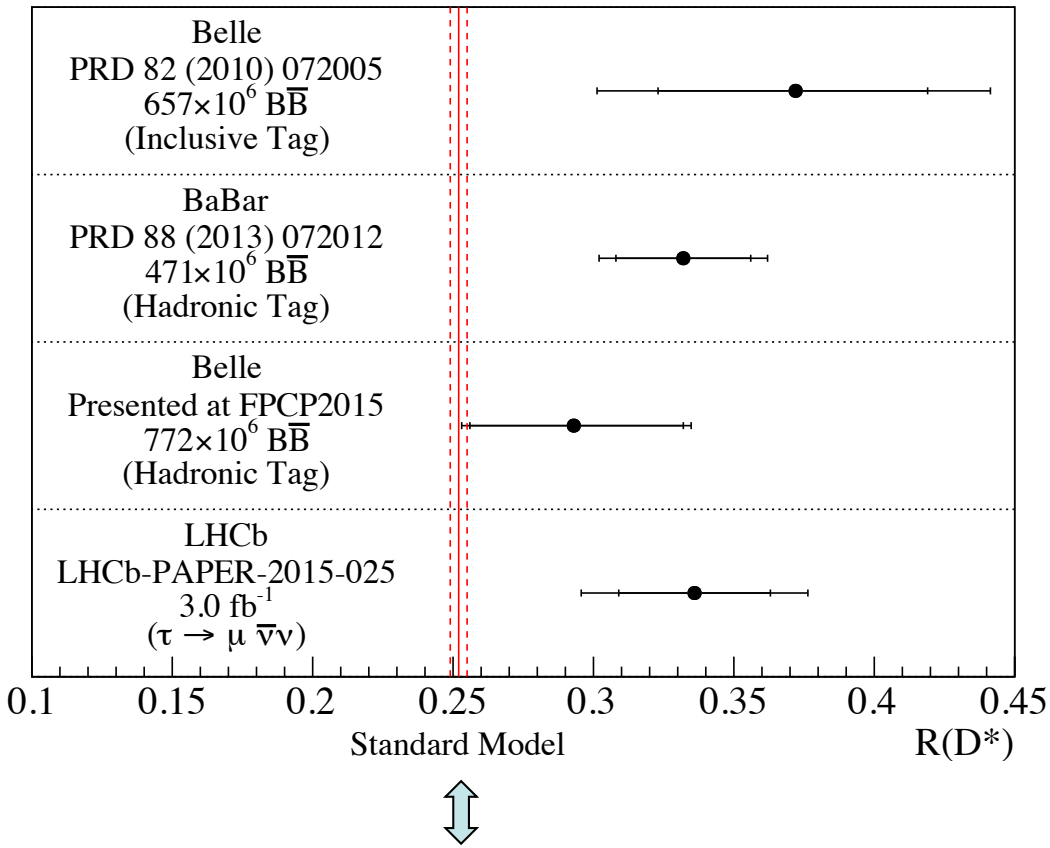
- The fermions masses and mixing depend on arbitrary matrices in flavour space

- Indirect measurements could provide sensitivity to sources of flavour symmetry breaking beyond the standard model

- A new result from LHC B confirms the anomaly previously seen in BABAR and BELLE in ratios R(D*) of $\bar{B} \to D^* + l^- + \bar{\nu}_l$ for $l = e, \mu, \tau$

3-4 σ deviation from SM expectation !

EPS HEP 2015



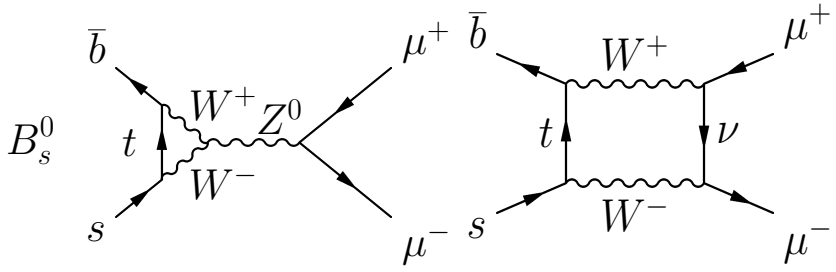
SM expectation from S. Fajfer et al. PRD 85 (2012) 094025

- Also, puzzling discrepancy between inclusive and exclusive (selecting a particular charmless) final state from $\bar{B} \to X_u + l^- + \bar{\nu}_l$ to measure $|V_{ub}|$

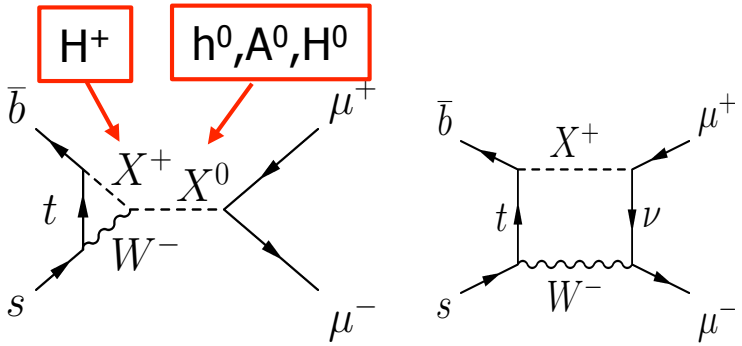
State of the Art (3)

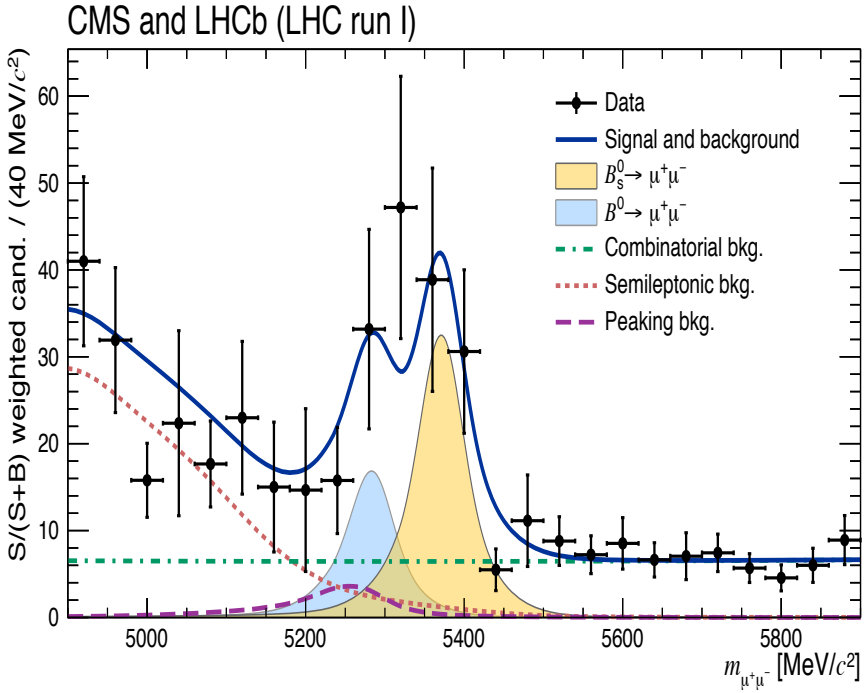
- Flavour physics benefits from large cross-sections at the LHC
- $B_s^0 \to \mu\mu$ decays are FCNC highly suppressed: proceed through quantum loops

SM Helicity-suppressed by $(M_\mu / M_B)^2$
CKM-suppressed $| V_{ts(td)} |^2$



BSM Sensitive to NP in the loops





Observation:

Signif.:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad 6.2\,\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad 3.0\,\sigma$$

Relative to expectation:

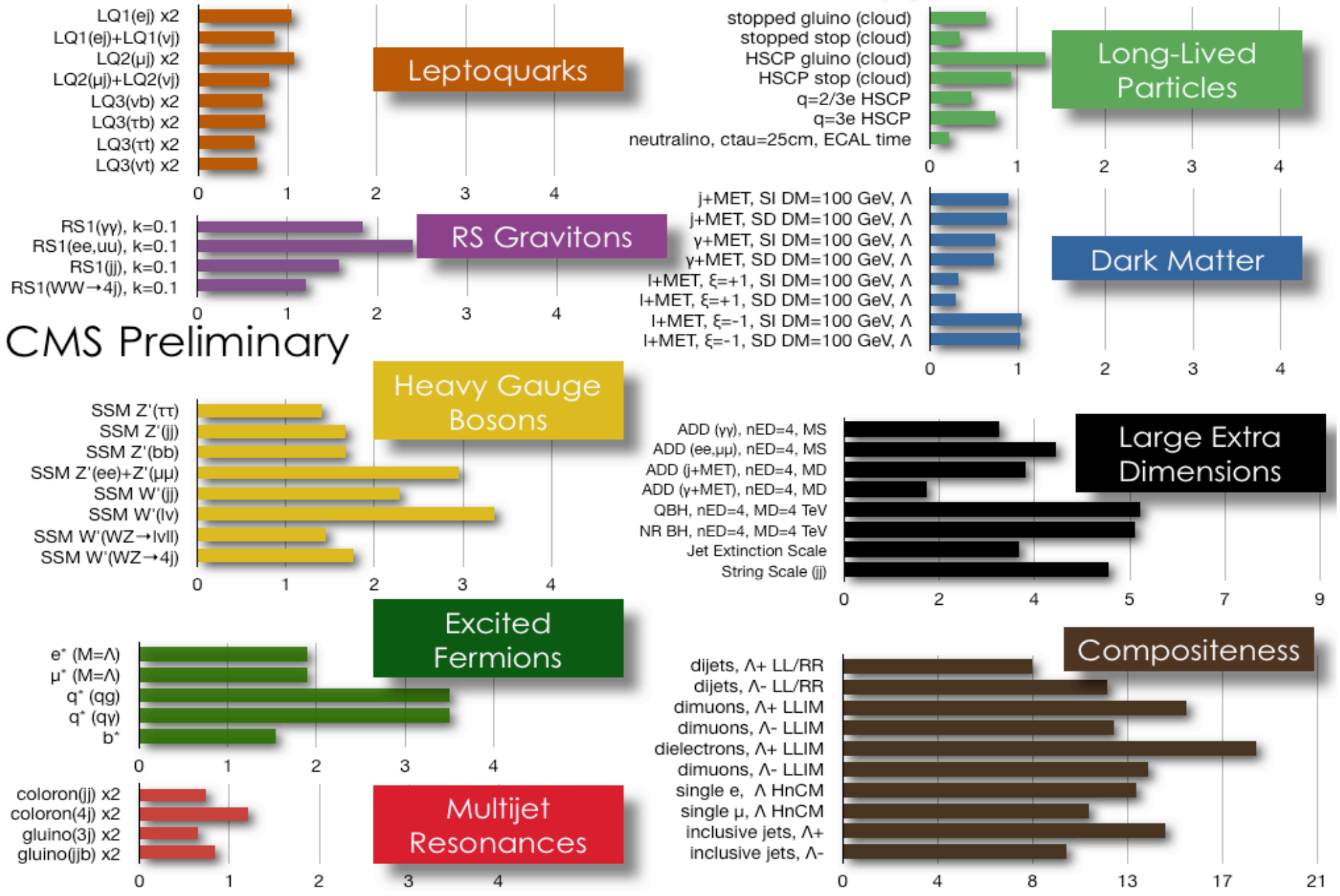
$$\mathcal{S}^{B_s^0}_{\rm SM} = 0.76\,^{+0.20}_{-0.18} \text{ and } \mathcal{S}^{B^0}_{\rm SM} = 3.7\,^{+1.6}_{-1.4}$$

Ratio: $$R \equiv \frac{\mathbf{B}(B^0 \to \mu^+\mu^-)}{\mathbf{B}(B_s^0 \to \mu^+\mu^-)} = (0.14^{+0.08}_{-0.06})$$

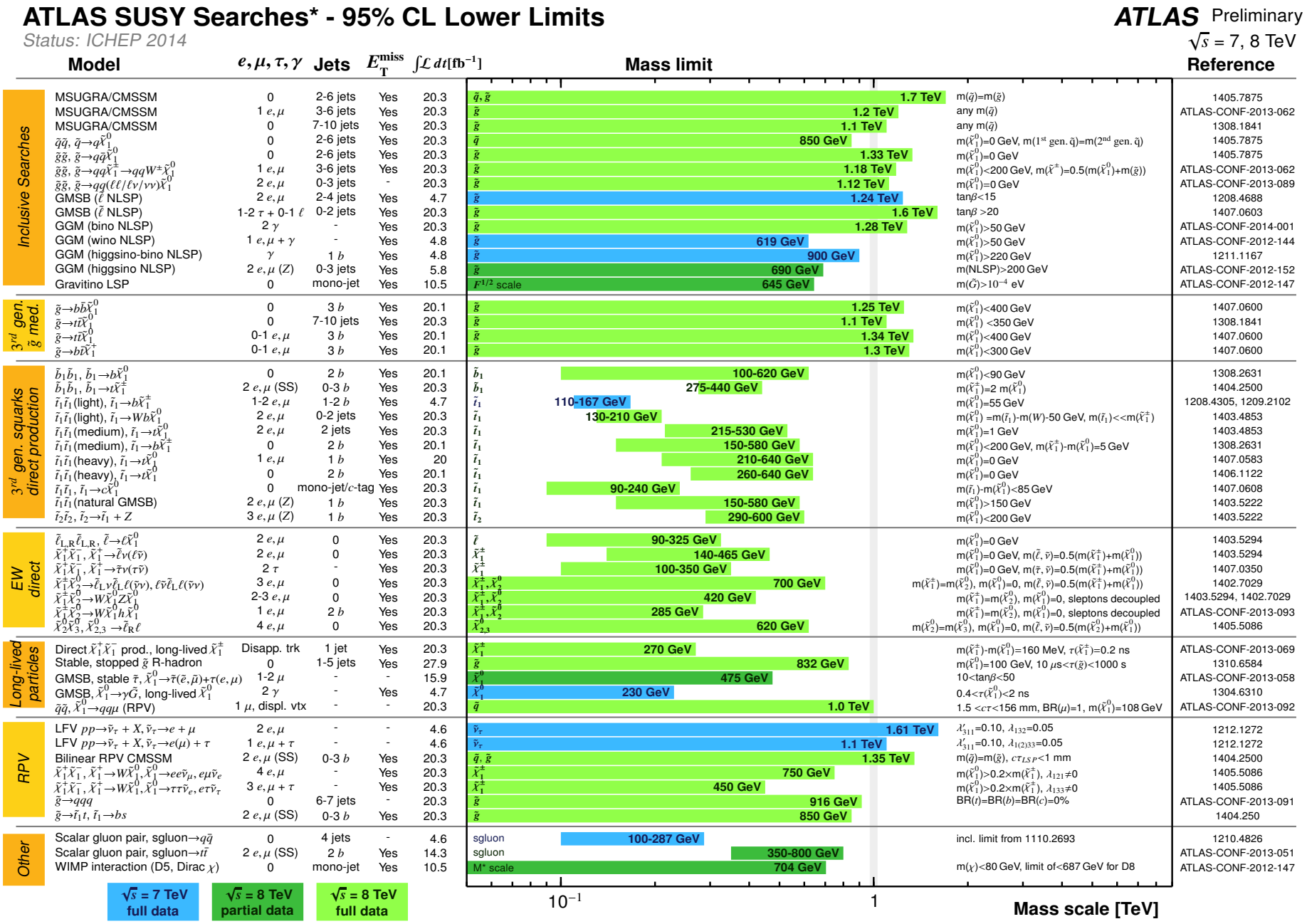
LHC B PRL 110 (2013) 021801
LHC B + CMS arXiv:1411.4413 (Nov. 2014) … Nature

$B_s^0 \to \mu\mu$ agree with SM; expect improvement of x 2 on the precision for R with 300 fb-1

State of the Art (4)



State of the Art (5)



*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

No "Exotic" Discovery at the TeV Scale

- A considerable amount of "exotic" models have been tested at the LHC up to the ~ TeV range
- Only very few of the models tested so far really address more than one of many problems of the theory !!!

Arbitrariness of the Higgs potential after EWSB
(arbitrary Higgs boson mass, of the self-coupling and sign of μ ...)

Origin of the flavour structure of the theory
(three families of fermions, flavour mixing parameters, matter-antimatter asymmetry in the Universe … Scalar sector and the origin of families ($H \to \mu\mu$, $H \to \tau\tau$)

Origin of the specific gauge symmetry / set of conserved charges
(cancelation of triangle anomalies, gauge unification ? Scalar sector talking to ν's ($\nu_L \leftrightarrow \nu_R$) ?)

Hierarchy between EWK and the Planck scale (and GUT scale ?)
(metastability of the EWK vacuum, problem of quantum gravity etc.)

- The rise of $\sqrt{s}$ in coming runs at LHC gives access to new territory for the search of the unexpected …
- It is useful to consider how the discovery of the H boson in Run I could serve a a guide towards BSM physics

Summary (II)

- The LHC run I "legacy" combination results have been published by the ATLAS and CMS Collaboration last week and were reviewed
- The convergence of the results between the experiments is globally excellent and in agreement with the expectation from the SM for the CP-even H boson measured at 125.09 GeV
- No additional SM-Like H boson has been found

- Some small tension remains with an excess of ttH production and a deficit of $H \rightarrow bb$ decays
- VBF Production and the $H \rightarrow \tau\tau$ decay have been observed ($> 5\sigma$)

- The Run I at the LHC has produced a remarkable set of results consistent with the SM with a minimal scalar sector

But the mass MH = 125 GeV is very special … and new questions will be raised in tomorrow 3rd and last course