Combined Measurement of the Higgs Boson Mass in pp Collisions at √s = 7 and 8 TeV at the LHC

Higgs Hunting 2015

July 31st, 2015

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on behalf of the ATLAS and CMS collaborations

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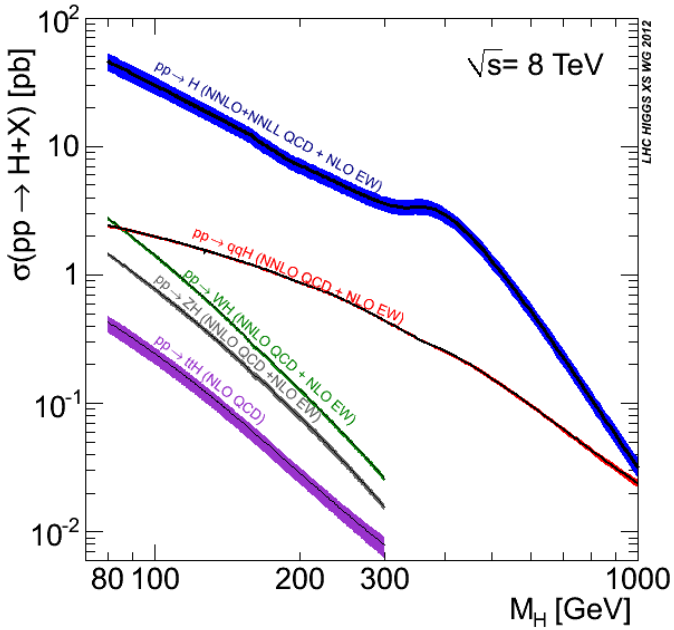
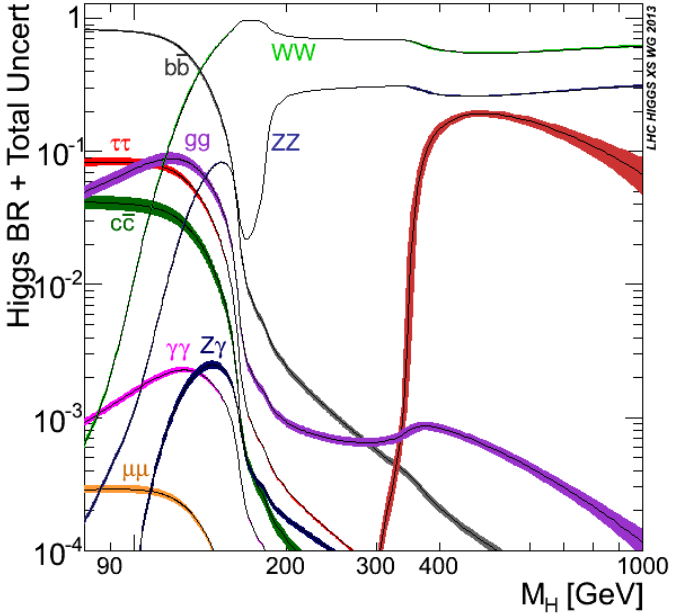
Significance of the Higgs boson mass

- The mass of the Higgs boson is **not predicted**, it is a **free parameter** in Standard Model.
- Once the mass is known, all the properties of the Standard Model Higgs are known, such as production cross section, decay branching ratios.

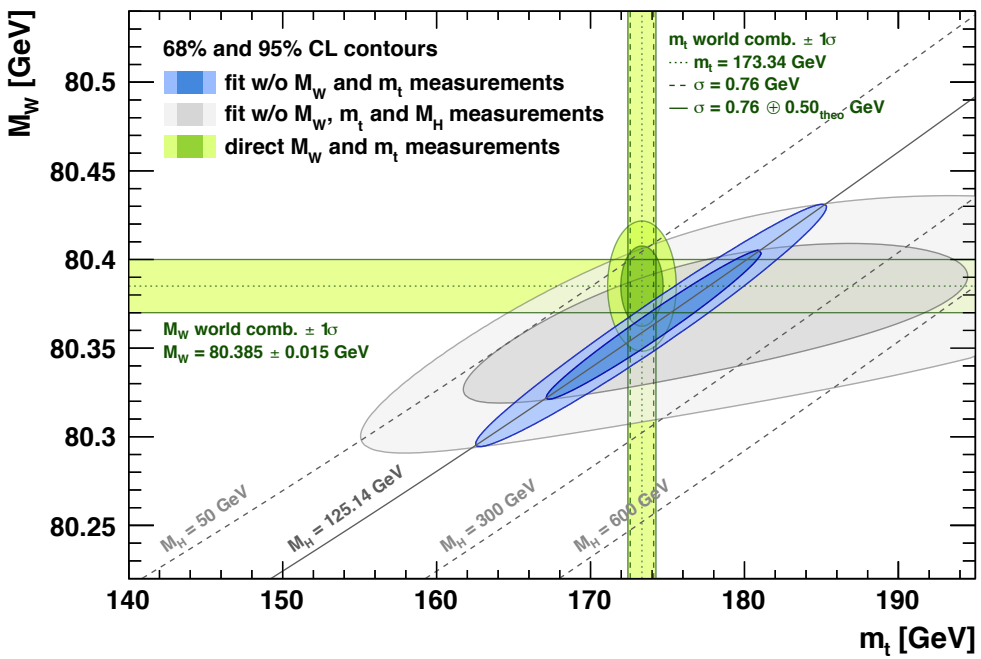




Once the mass is known

- Consistency tests of Standard Model parameters
- Recent results from Gfitter by R.Kogler tomorrow

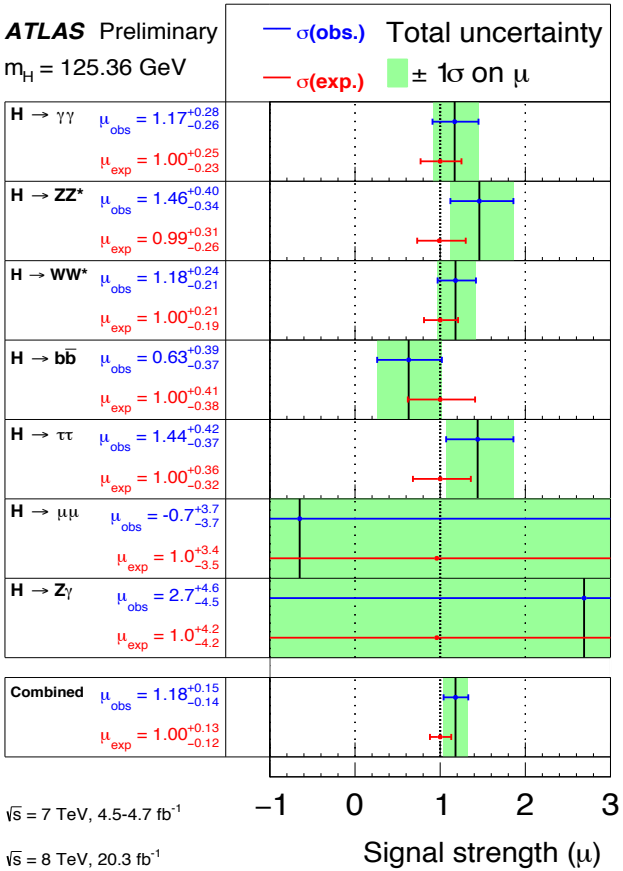
arXiv:1407.3792v1
The global electroweak fit at NNLO and prospects for the LHC and ILC



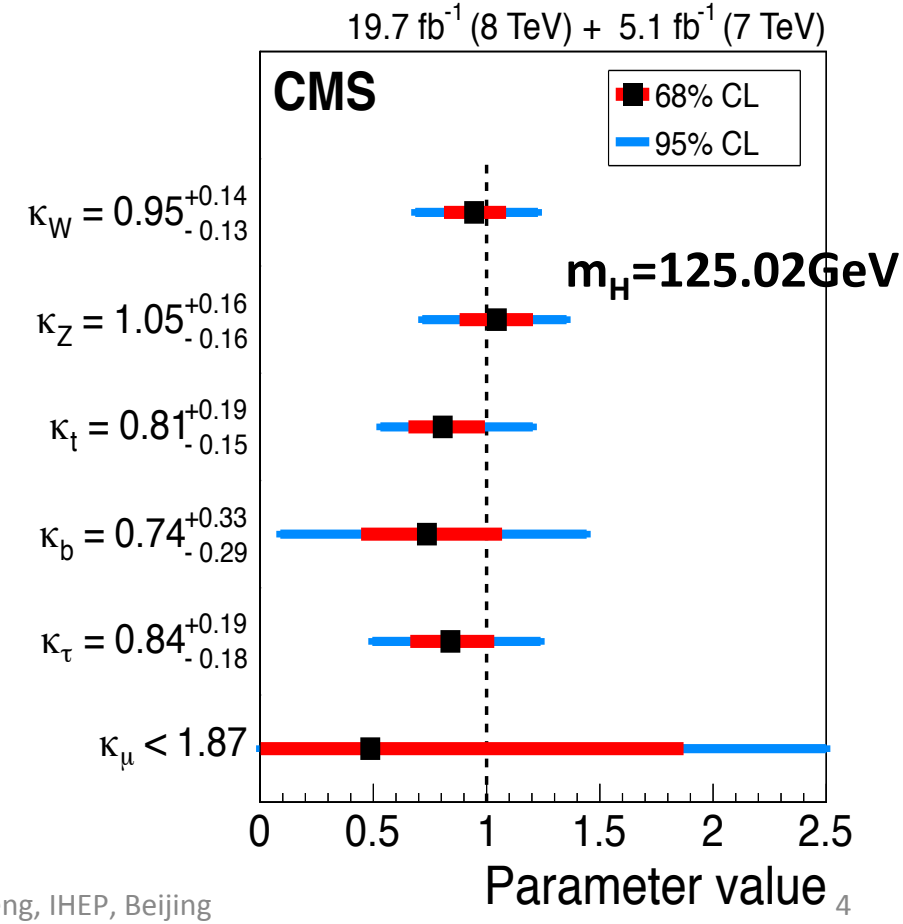
Once the mass is known

- Studies of deviation w.r.t. Standard Model

ATLAS-CONF-2015-007



Eur. Phys. J. C (2015) 75(212)



Since discovery of the Higgs boson

- July 4th 2012, ATLAS and CMS announced the discovery of Higgs boson at ICHEP.

- Synergy between ATLAS and CMS from 2014

  on Higgs combination of the two experiments
  - First published results on Higgs mass in 2015 using **γγ** and **4l** channels (most sensitive channels in mass measurement)

Stay tuned for more combined results!

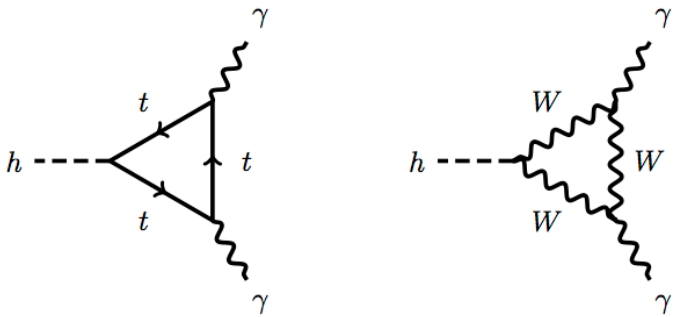
Mass measurement sensitivity

Channel	Branching ratio (m_H=125GeV)	(Relative) mass resolution
H->bb	**57.7%**	**10%**
H->WW->2l2v	**0.756%**	**20%**
H->ττ	**6.32%**	**10-20%**
H->Zγ->llγ (l = e, μ)	**0.01%**	**1-2%**
H->μμ	**0.0219%**	**1-2%**
H->γγ	**0.228%**	**1-2%**
H->ZZ->4l (l = e, μ)	**0.0276%**	**1-2%**

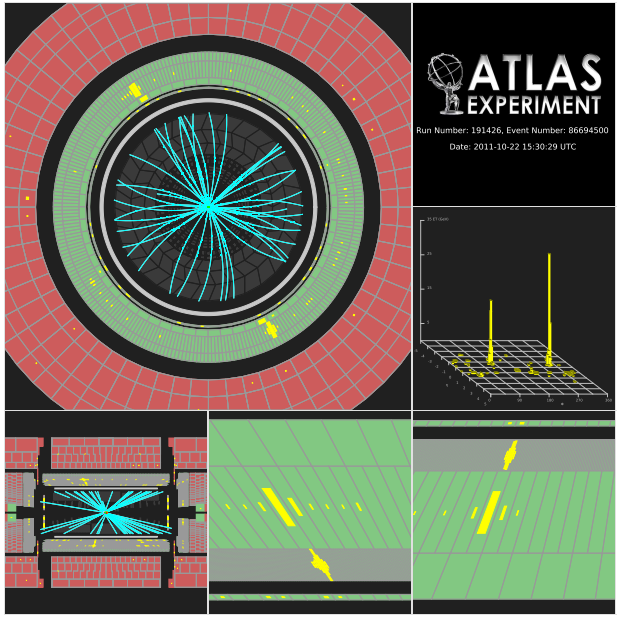
Limited by mass resolution

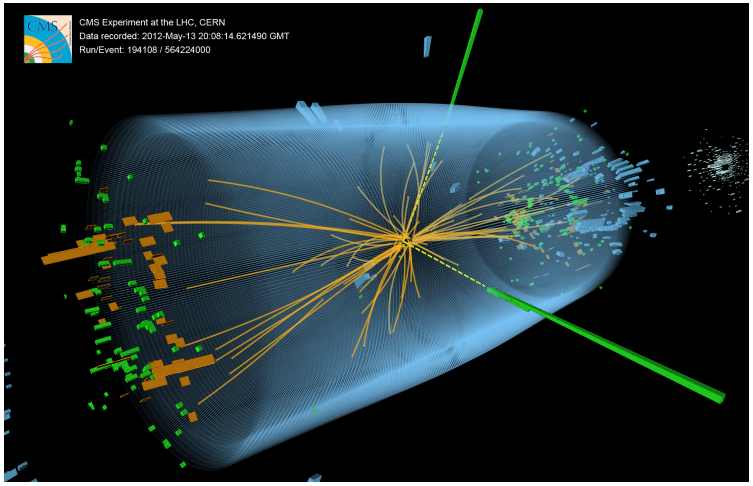
Limited by low S/B w.r.t. 4l channel

Higgs to γγ



More information can be found at talks by E.Mountricha, D.Sperka and B.Courbon

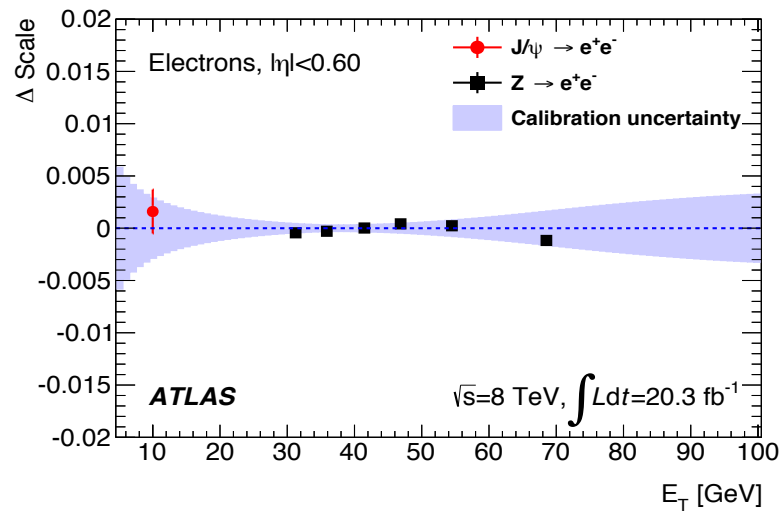


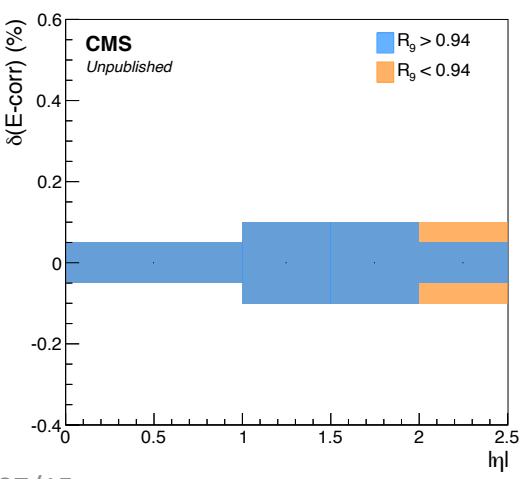


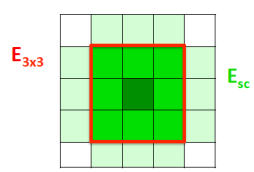
Photon energy scale

Calibration using Z->ee and validation using **Z->μμγ**

- **ATLAS**
  - Uncertainties from
    - non-linearity at cell level,
    - relative calibration for different layers,
    - material description before ECAL,
    - reconstruction of photon conversion,
    - modeling lateral shower shape

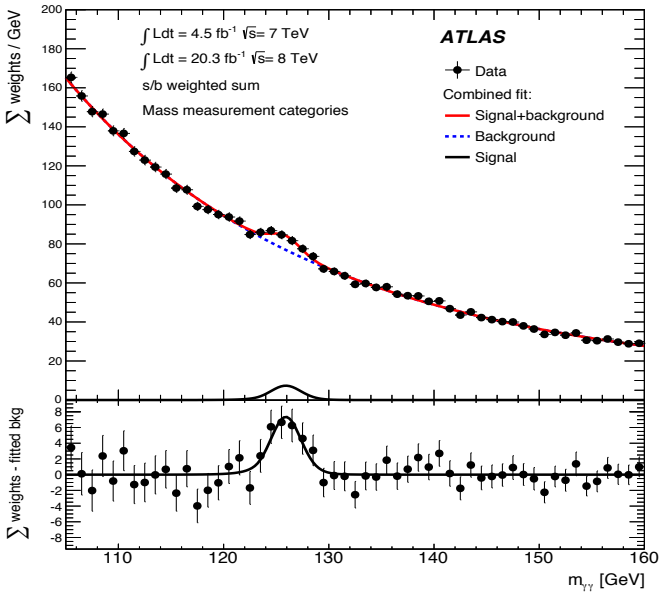






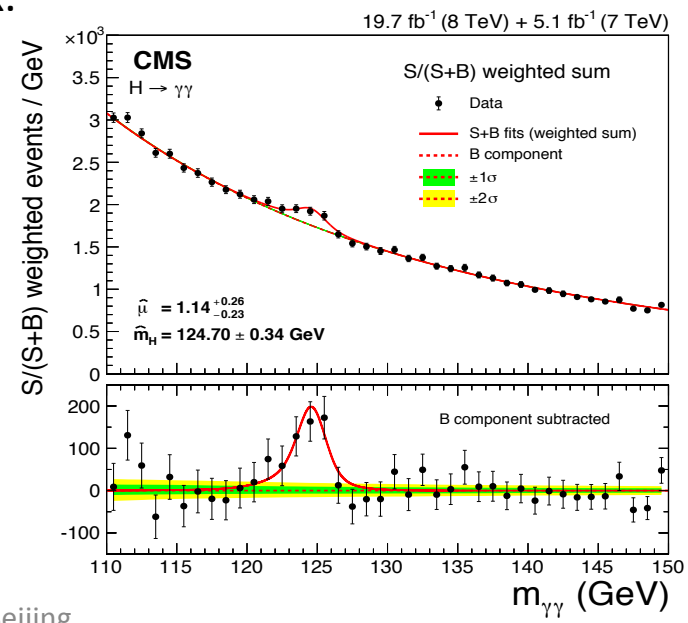
- **CMS**
  - Calibration determined as a function of E_T for barrel/ endcap, low R_9/high R_9
  - Uncertainties from
    - difference in electron and photon
    - and material knowledge

Analysis strategy



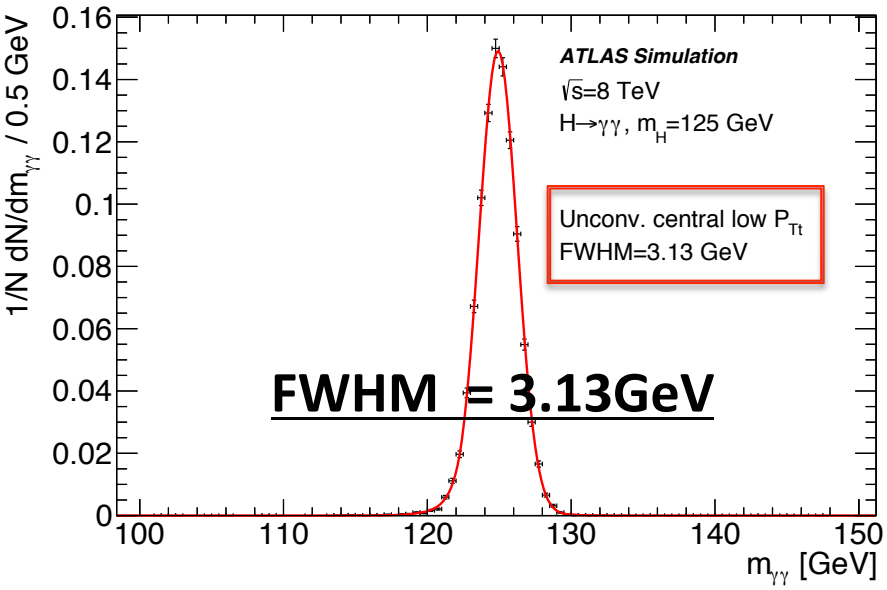
- **ATLAS**
  - Dedicated analysis optimized for mass measurement
  - 10 categories based on
    - Unconverted/converted photon
    - |η| of photon
    - Di photon momentum transverse to thrust
  - Neural network using photon pointing +tracks+ recoil info to select most probable primary vertex.

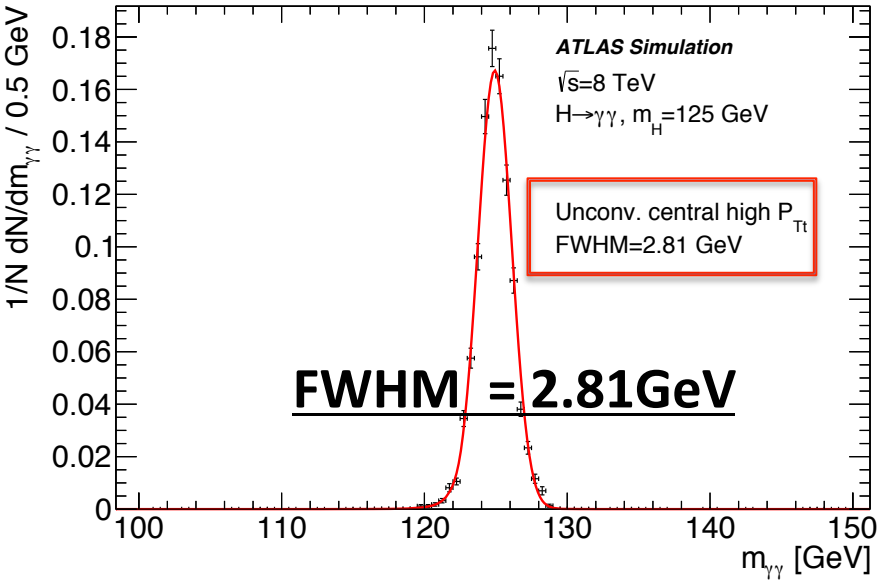
- CMS
  - Events are classified to tag different production modes
  - Untagged events are classified according to MVA (BDT) categorization based on photon kinematics, quality, shower shape and mass resolution
  - Vertex selected using BDT trained with tracks + recoil info + photon pointing (converted photon)



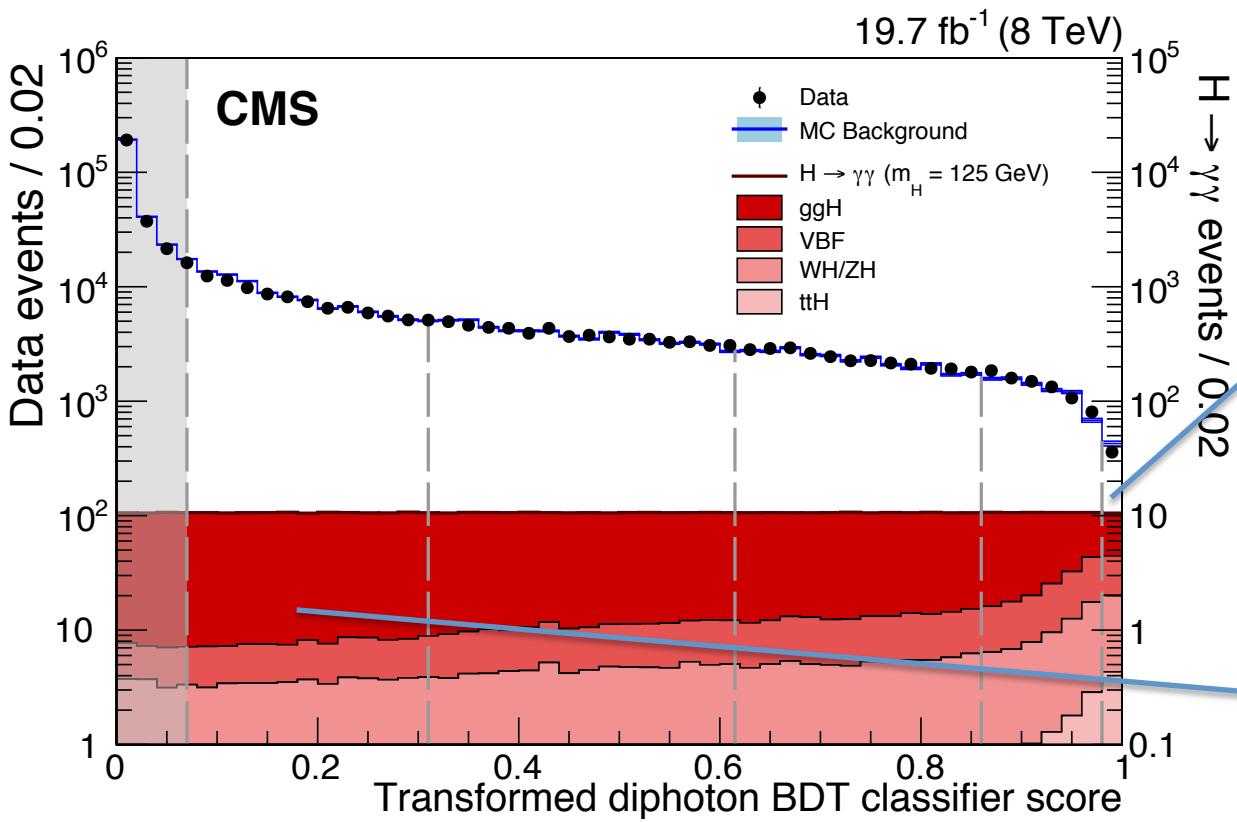
Analysis strategy

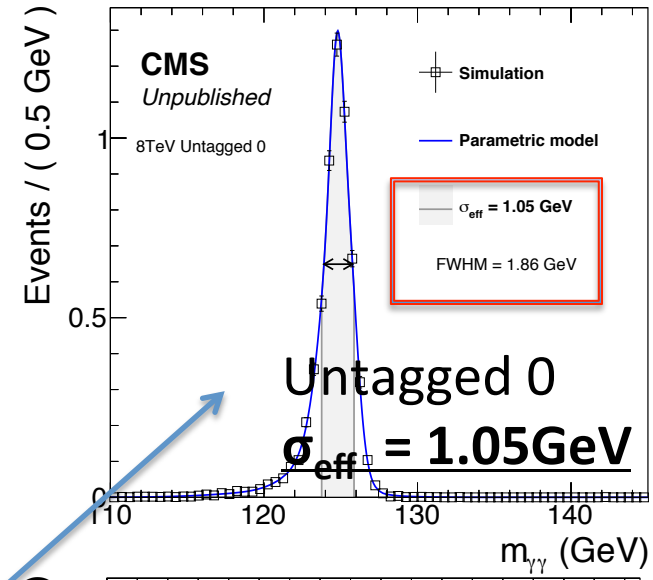
Different categories have **difference S/B, different mass resolutions**

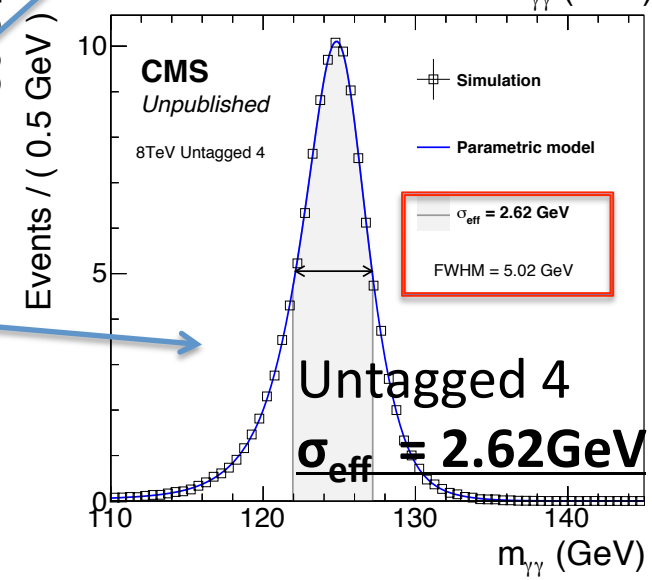




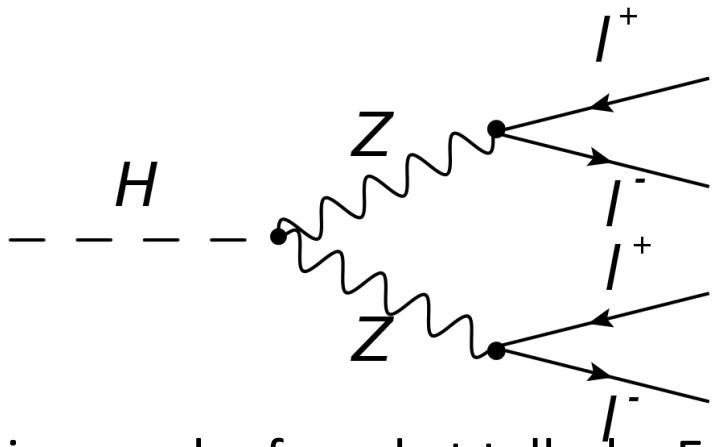
Analysis strategy : BDT classifier







Higgs to ZZ to four leptons



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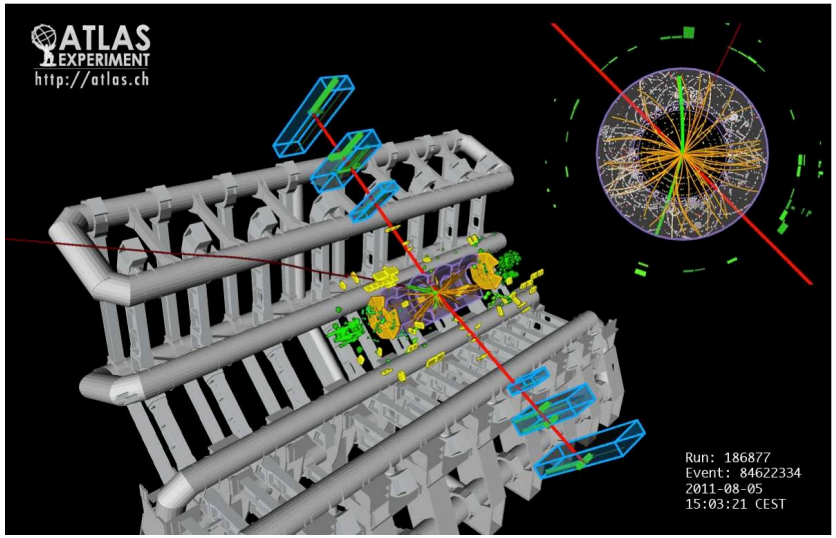
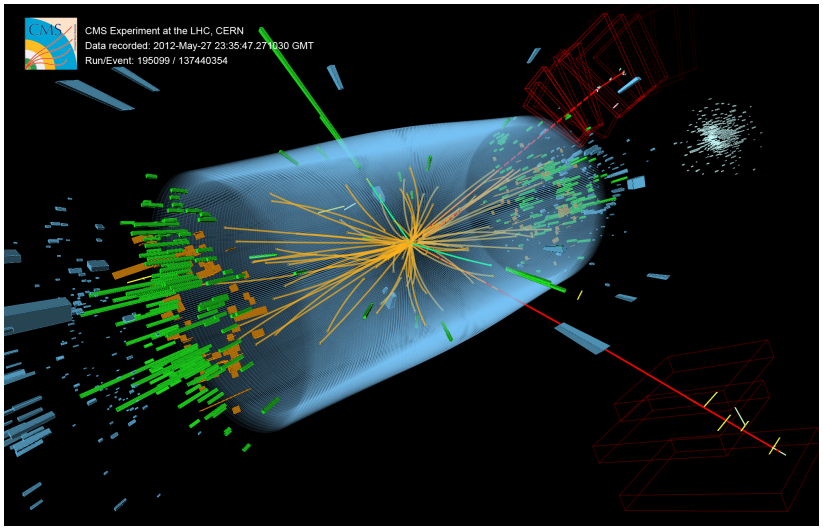
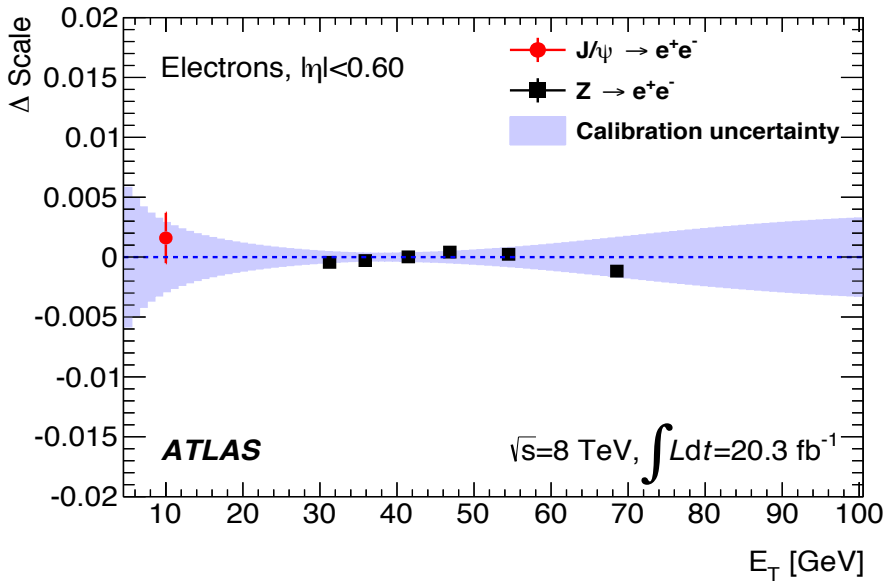
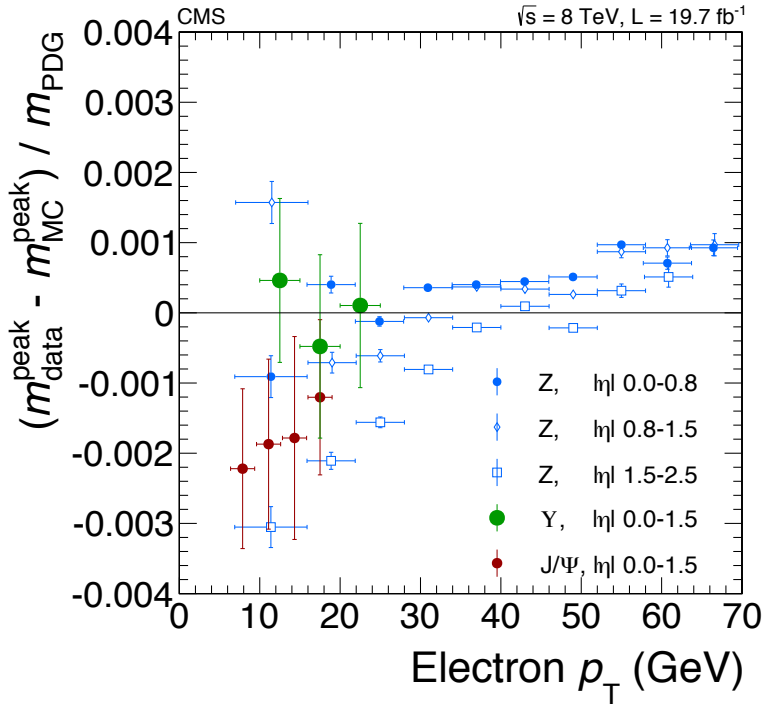




Electron/muon energy scale

- **Electron**
  - using Z->ee resonance and verified using **J/ψ , Υ->ee**

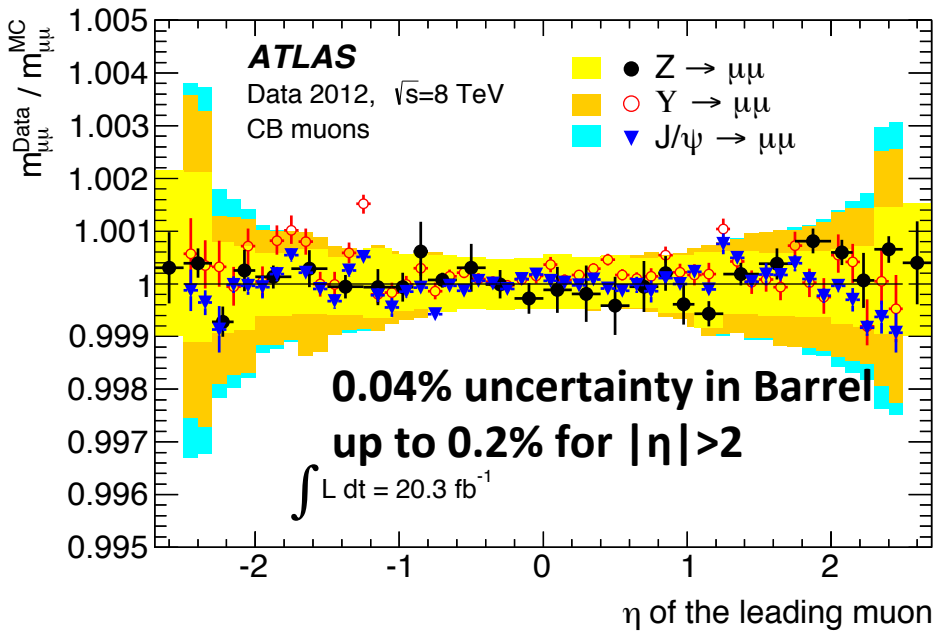


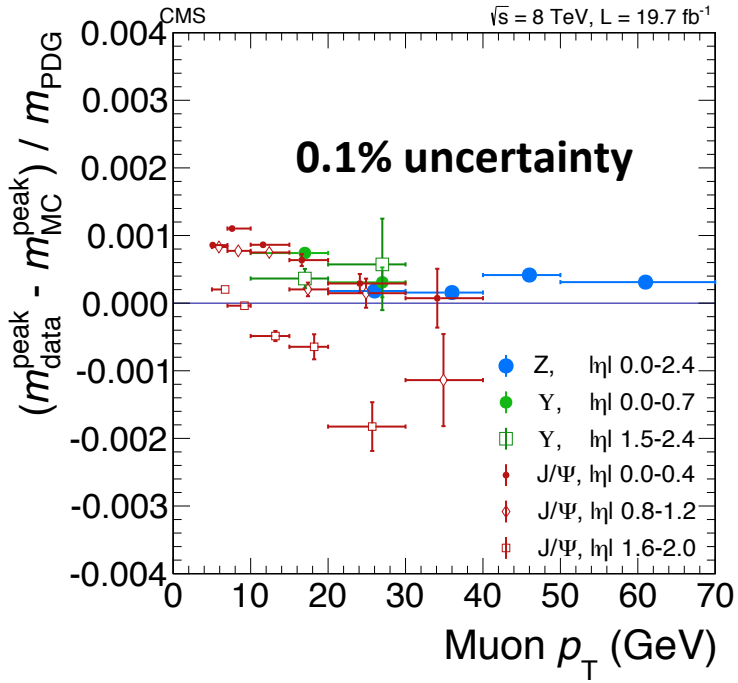


Systematic on m_{4l} peak :
0.3% in 4e and 0.1% in 2e2mu

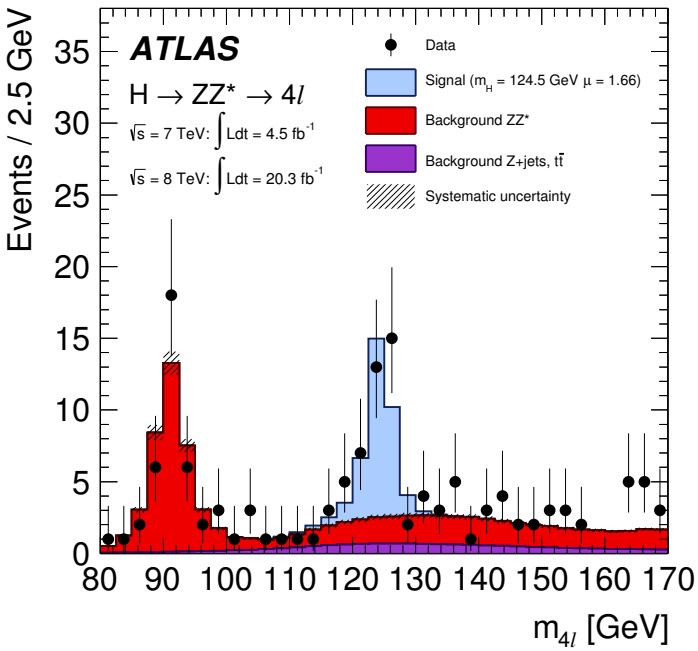
Electron/muon energy scale

- **Muon**
  - using Z->μμ resonance
  - ATLAS uses **J/ψ->μμ** to improve scale uncertainty for low momentum muon (relevant to Higgs mass measurement)



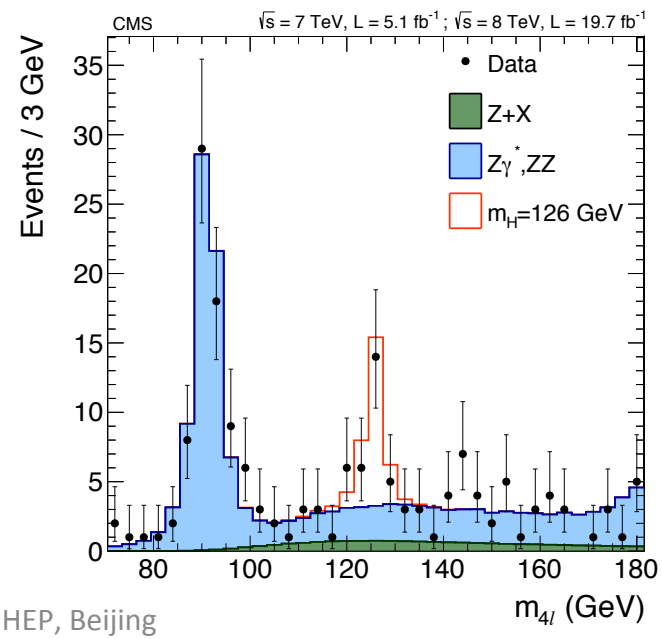


Analysis strategy



ATLAS

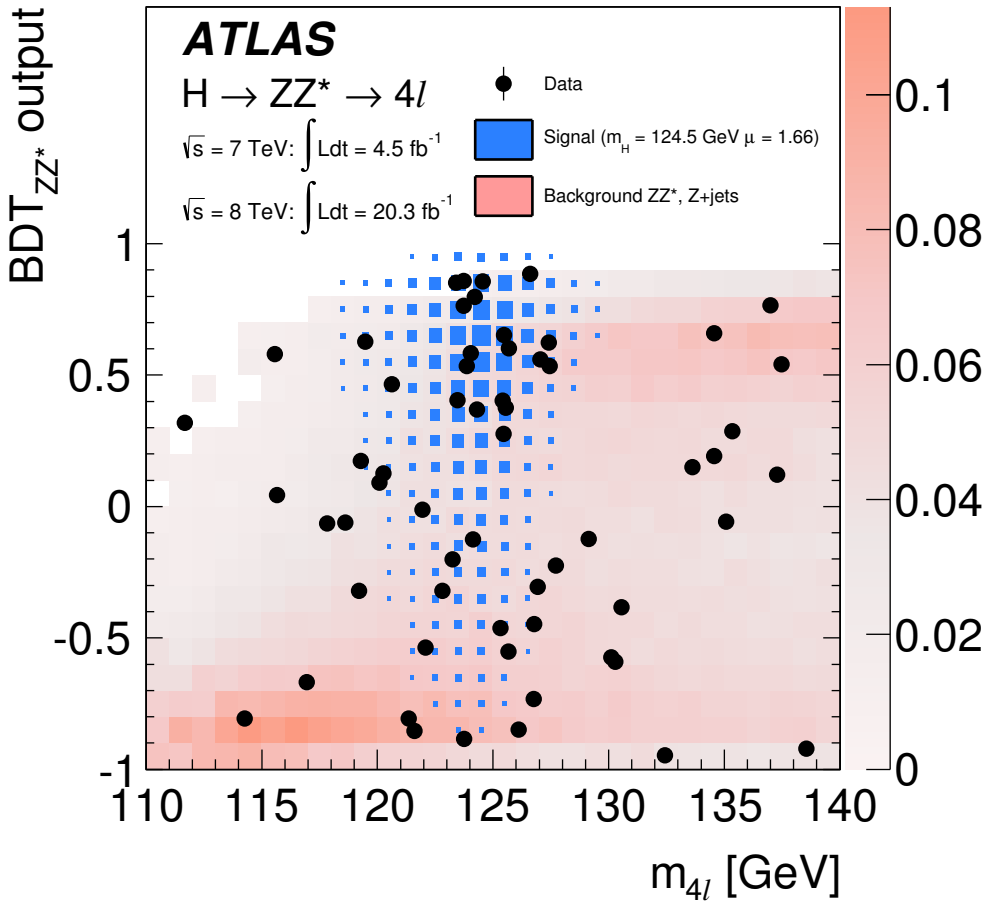
- Four isolated leptons grouped into **<u>2e2μ, 2μ2e</u>**, 4e and 4μ final states
- Using **Z mass constraint kinematic** fit on leading di-lepton mass with 15% improvement
- BDT using LO matrix element, η and P_T of 4l system
- Include FSR photon recovery



CMS

- One category **includes 2e2μ, 2μ2e**
- Kinematic discriminator based on LO matrix elements

Mass measurement

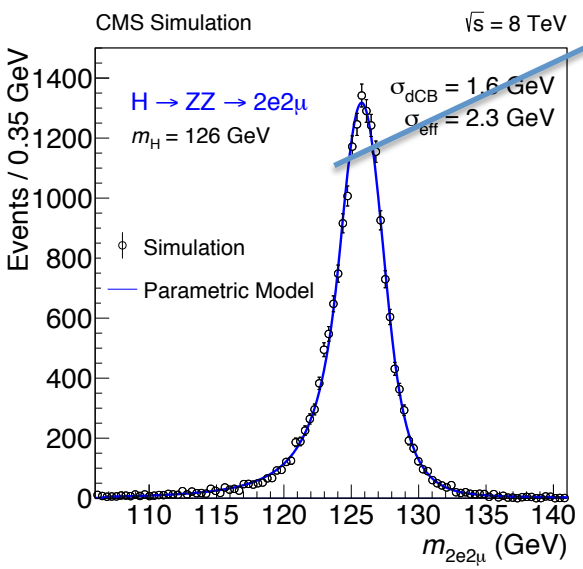


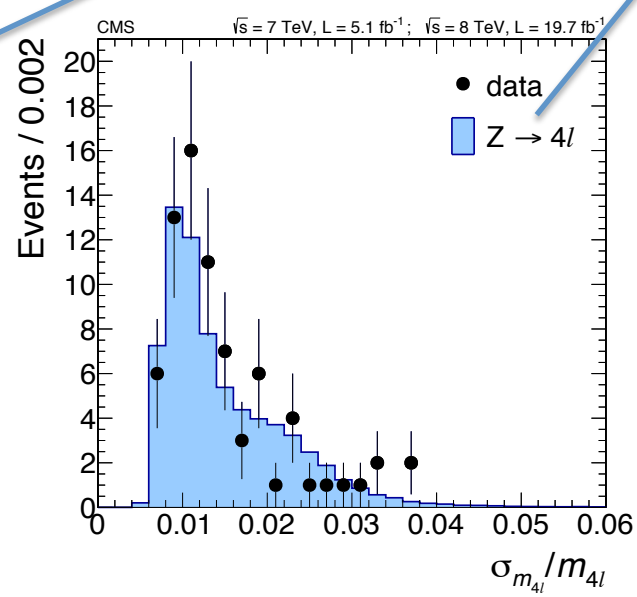
- 2D distribution based on BDT and m_{4l} is used to extracted m_H.
- 8% improvement using 2D-fit for mass measurement

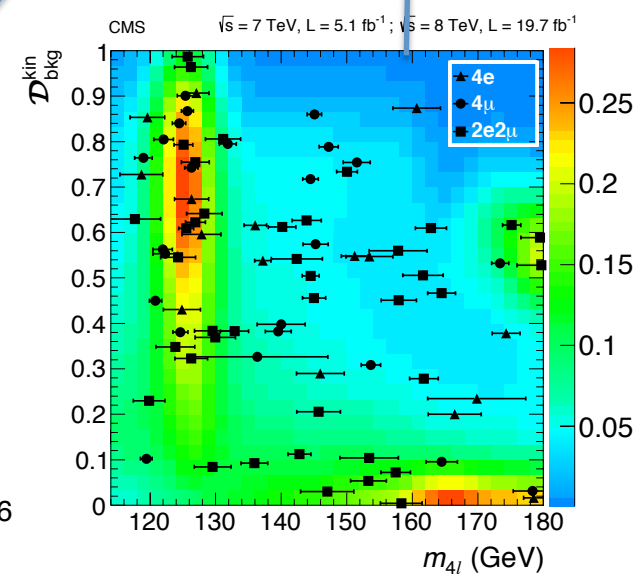
Mass measurement

- 3D fit for mass measurement including m_{4l}, D^{kin}_{bkg} and per-event mass resolution σ_{m4l} **(8% expected gain in sensitivity).**

$$\mathcal{L}_{3D}^{m,\Gamma} \equiv \mathcal{L}_{3D}^{m,\Gamma}(m_{4\ell}, \mathcal{D}_{\rm m}, \mathcal{D}_{\rm bkg}^{\rm kin}) = \mathcal{P}(m_{4\ell}|m_{\rm H}, \Gamma, \mathcal{D}_{\rm m})\mathcal{P}(\mathcal{D}_{\rm m}|m_{4\ell}) \times \mathcal{P}(\mathcal{D}_{\rm bkg}^{\rm kin}|m_{4\ell})$$







Mass measurement from ATLAS+CMS Higgs combination

Likelihood model

- Higgs mass m_H is determined by maximizing the **profiled likelihood** ratio

$$\Lambda(m_H) = \frac{L\left(m_H\,,\,\hat{\hat{\mu}}^{\gamma\gamma}_{gg\mathrm{F}+t\bar{t}H}(m_H)\,,\,\hat{\hat{\mu}}^{\gamma\gamma}_{\mathrm{VBF}+VH}(m_H)\,,\,\hat{\hat{\mu}}^{4\ell}(m_H)\,,\,\hat{\hat{\boldsymbol{\theta}}}(m_H)\right)}{L(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{gg\mathrm{F}+t\bar{t}H}, \hat{\mu}^{\gamma\gamma}_{\mathrm{VBF}+VH}, \hat{\mu}^{4\ell}, \hat{\boldsymbol{\theta}})}$$

- **Θ** : nuisance parameters (systematic uncertainties)
- **Three signal strengths** are included to reduce model-dependence, assuming to be the same between ATLAS and CMS
  - $\mu^{\gamma\gamma}_{\mathrm{ggF+ggH}}$: scaling for gluon fusion an ttH production for γγ channel
  - $\mu^{\gamma\gamma}_{\mathrm{VBF+VH}}$: scaling for VBF and associated production for γγ channel
  - μ^{4l} : scaling for 4l channel

Results

- Higgs mass is
  - $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV
  - with three signal strengths

$$\mu^{\gamma\gamma}_{ggF+ttH} = 1.15^{+0.28}_{-0.25} \quad \mu^{\gamma\gamma}_{VBF+VH} = 1.17^{+0.58}_{-0.53}$$

$$\mu^{4l} = 1.40^{+0.30}_{-0.25}$$

compare with expectation with 125GeV **Standard Model** Higgs :

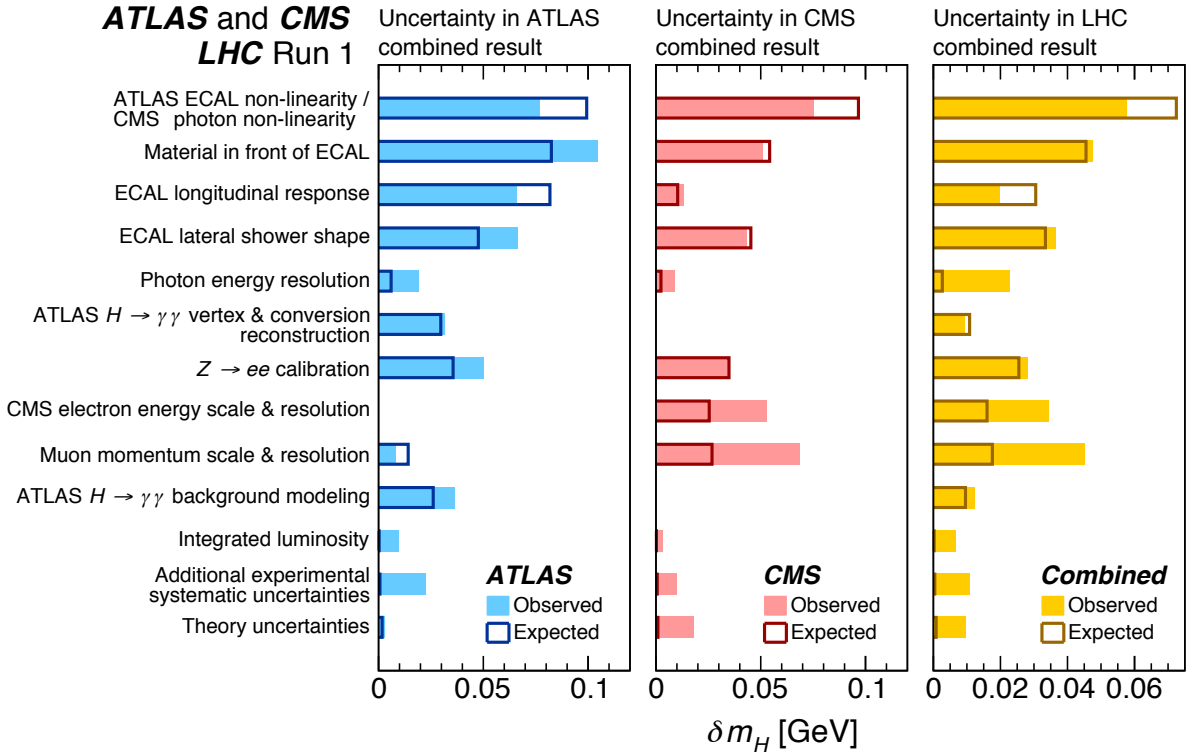
for prefit $\delta\, m_{H\ prefit} = \pm 0.24\text{GeV} = \pm 0.22(\text{stat.}) \pm 0.10(\text{syst.})$ GeV

for post-fit $\delta\, m_{H\ prefit} = \pm 0.22\text{GeV} = \pm 0.19(\text{stat.}) \pm 0.10(\text{syst.})$ GeV

Results：ranking systematic uncertainties

The mass shift δm_H :

difference in m_H when re-evaluating the profile-likelihood ratio after **fixing the nuisance parameter in question to its best-fit value increased or decreased by 1σ**

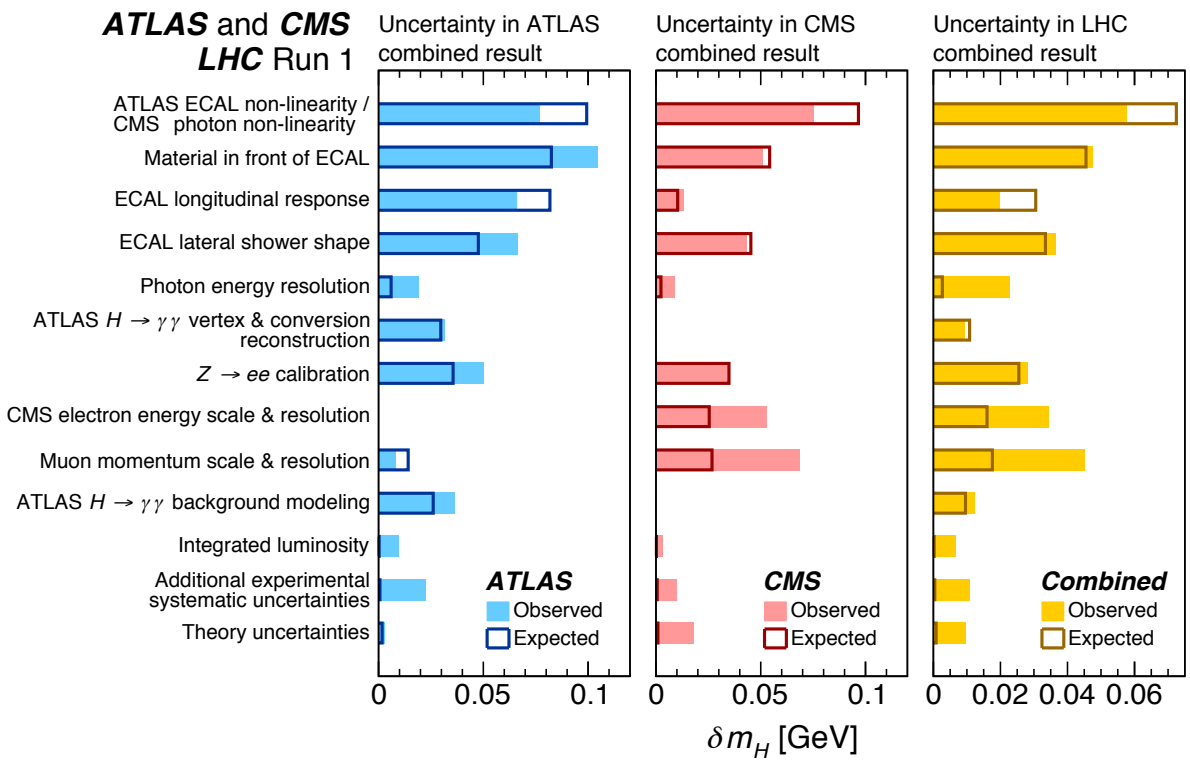


Results：ranking systematic uncertainties

Energy scale/resolution is the dominant effect,

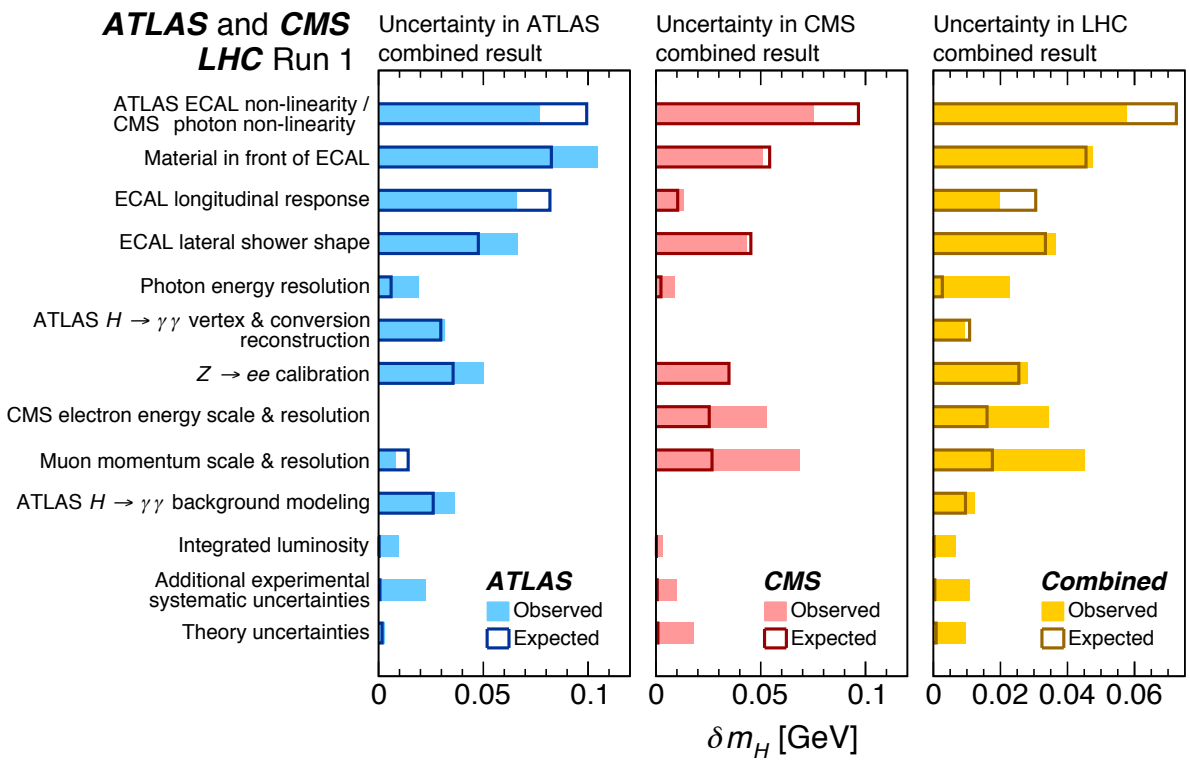
coming from e/γ/μ calibration and resolution,

γγ vertex and conversion reconstruction



Results：ranking systematic uncertainties

Other comes from other experimental uncertainties such as efficiency, jet energy scale (uncorrelated between the two experiments), luminosity (partially correlated)…….

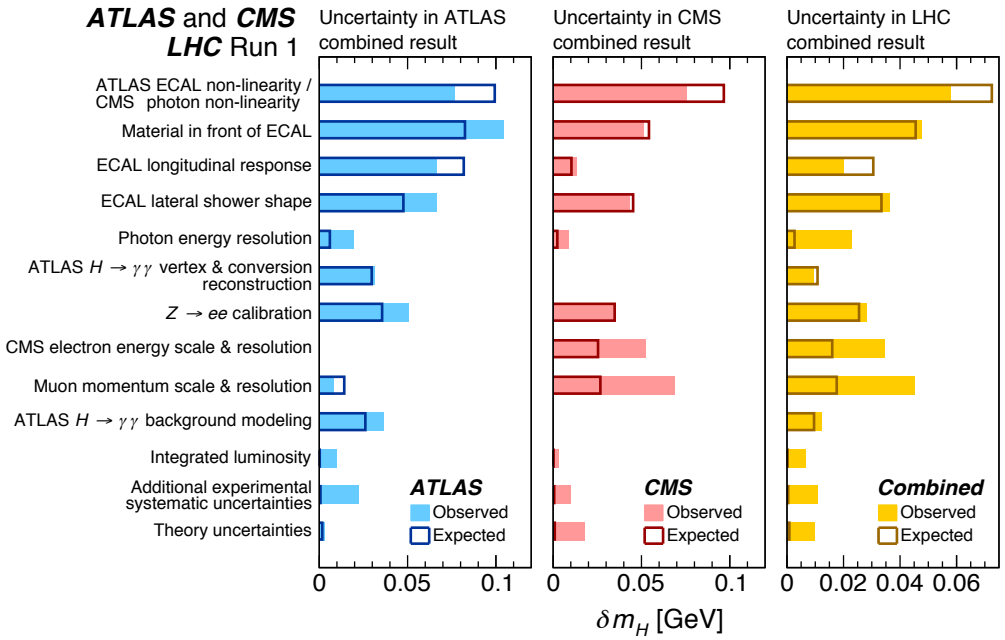


Results：ranking systematic uncertainties

Theoretical uncertainties (QCD scales, PDF, BR…) are treated 100% correlated between the two experiments.

Almost no impact on mass measurement.

(Mass shift due to signal-background interference is not taken into account for individual analysis and combination.)



Results : summary of systematic uncertainties

	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)		Uncertainty in combined result [GeV]: observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ$llll	$H \to \gamma\gamma$	$H \to ZZ$llll	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL non-linearity / CMS photon non-linearity	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 & 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 & resolution	–	–	–	0.12 (0.09)	–	0.03 (0.02)
Muon momentum scale & 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%)	–	

Results：decompose systematic uncertainty

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{scale})\ \text{GeV}$$

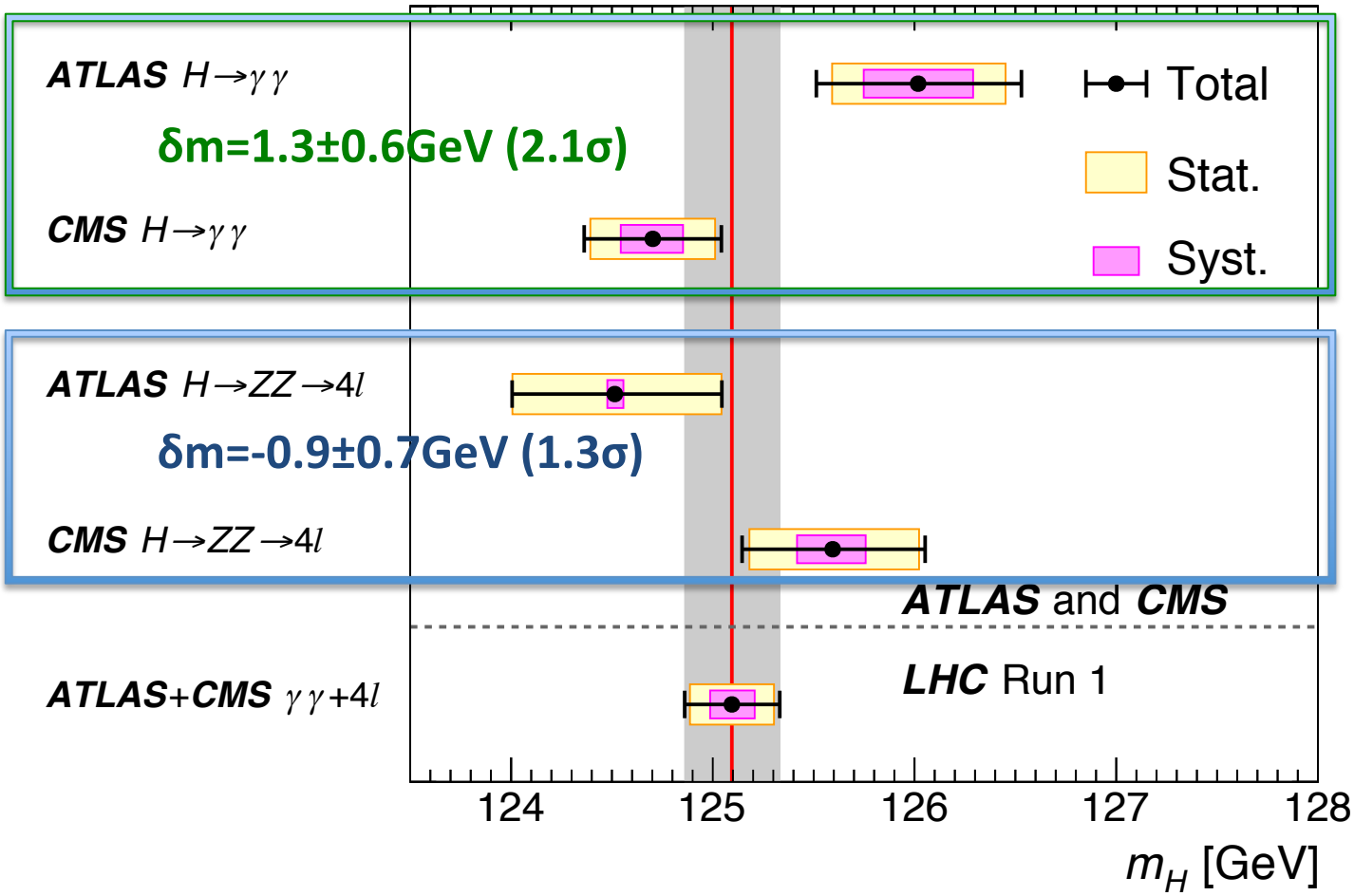
$$= 125.09 \pm 0.21(\text{stat.})$$

$$\pm 0.11(\text{scale})$$

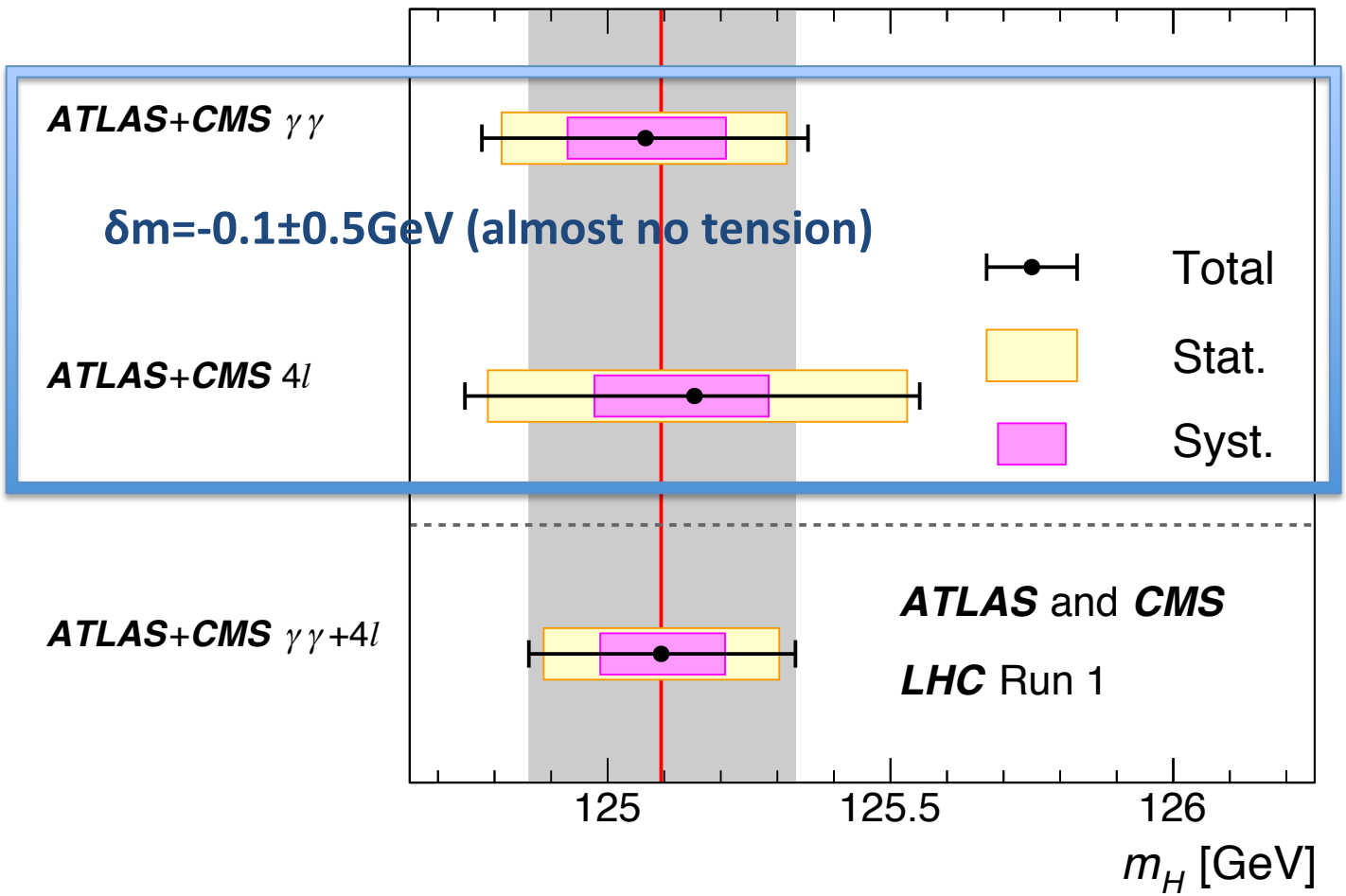
$$\pm 0.02(\text{other})$$

$$\pm 0.01(\text{theory})\ \text{GeV}$$

Compatibility tests :
tension between ATLAS and CMS



Compatibility tests :
tension between **γγ** and **four-lepton** channels



Compatibility test : signal strengths

- Compatibility of the signal strengths from ATLAS and CMS:
  - $\lambda^{expt} = \mu(ATLAS) / \mu(CMS)$
  - $\lambda_F^{expt} = \mu^{\gamma\gamma}_{ggF+ttH}(ATLAS) / \mu^{\gamma\gamma}_{ggF+ttH}(CMS)$
  - $\lambda_{4l}^{expt} = \mu^{\gamma\gamma}_{4l}(ATLAS) / \mu^{\gamma\gamma}_{4l}(CMS)$
- $\lambda^{expt} = 1.21^{+0.30}_{-0.24}$

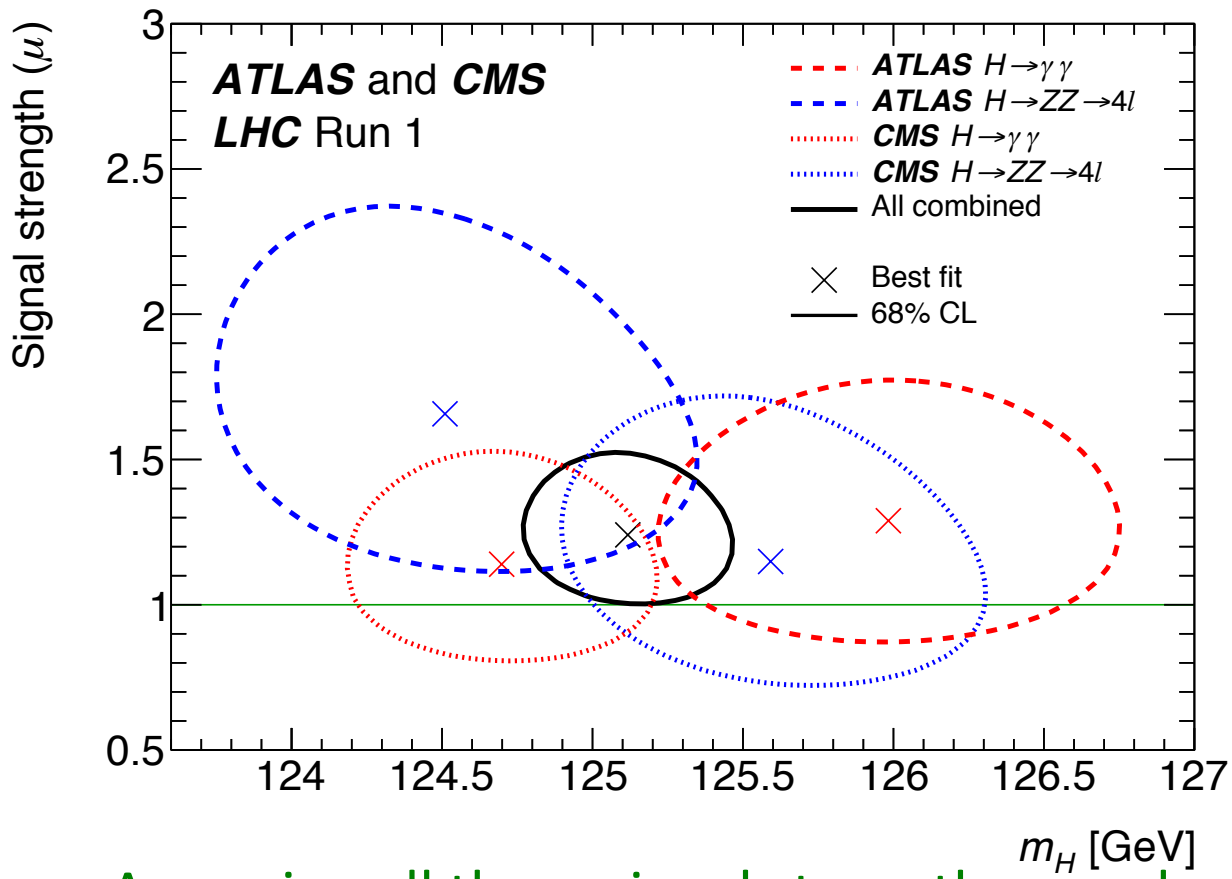
  $\lambda_F^{expt} = 1.30^{+0.80}_{-0.50}$

  $\lambda_{4l}^{expt} = 1.30^{+0.50}_{-0.40}$

Tension within 1σ.

Allowing the ATLAS and CMS signal strengths to vary independently yields a result with 40MeV higher in m_H

Compatibility test : one signal strength

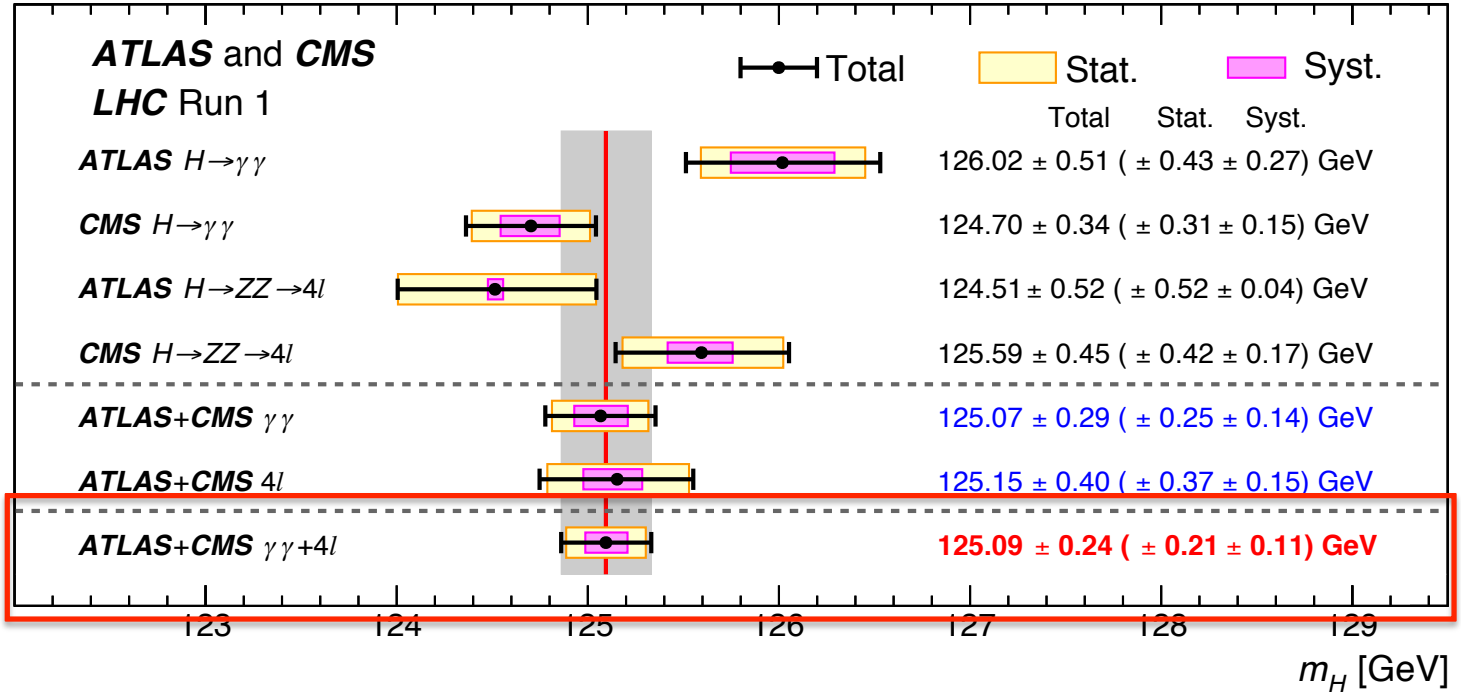


Standard Model

Assuming all three signal strengths equal one leads to 70MeV higher m_H

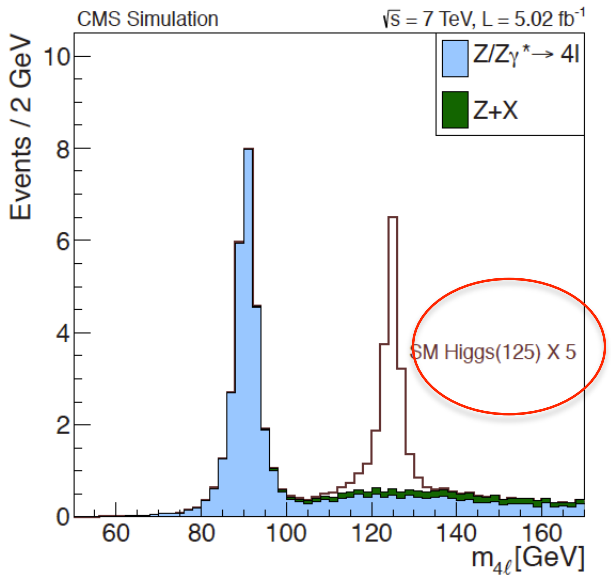
Summary

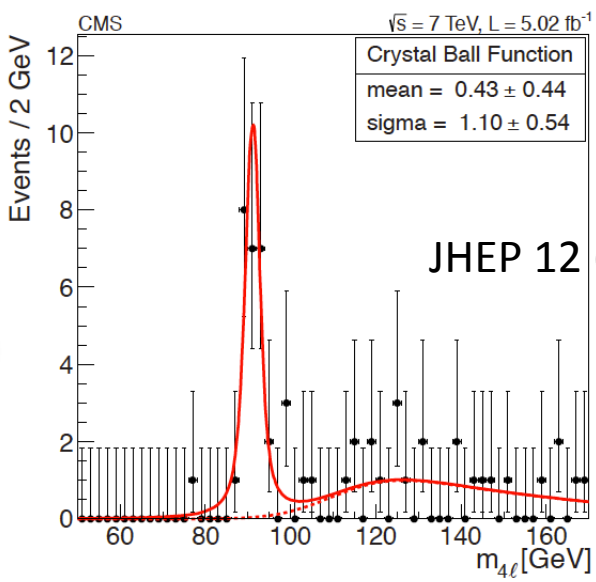
- ATLAS and CMS combined measurement of the Higgs boson mass is published in PRL
- The precision is <0.2% using Run-I data



Perspective on mass measurement

- Systematic uncertainty will become **more important** as more data come in Run-II of the LHC.
  Systematic uncertainty is driven by **scale uncertainty**
  - **room for improvement**
- Exploit standard candle(s) : Z->4l and H->ZZ->4l
  - 2011 first observation of Z->4l peak at the LHC

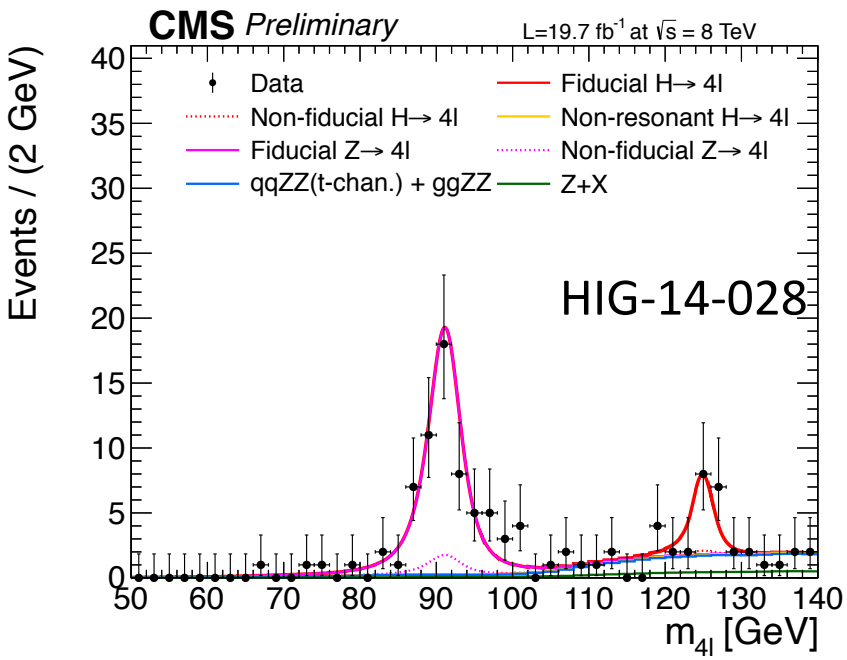




JHEP 12 (2012) 034

Perspective on mass measurement

- Exploit standard candle(s) :
  - Z->4l as a standard candle for H->ZZ->4l : energy scale (mass) and efficiency (cross section)
  - **Simultaneous** Z->4l and H->ZZ->4l peak fit in CMS H->ZZ->4l fiducial cross section paper



Back up

Reference

- Combined Measurement of the Higgs Boson Mass in pp Collisions at √s = 7 and 8TeV with the ATLAS and CMS Experiments, Phys. Rev. Lett. 114, 191803 (2015)

- Measurement of the Higgs boson mass from the H->γ γ and H-> ZZ->4l channels with the ATLAS detector at the LHC, Phys. Rev. D. 90, 052004 (2014)

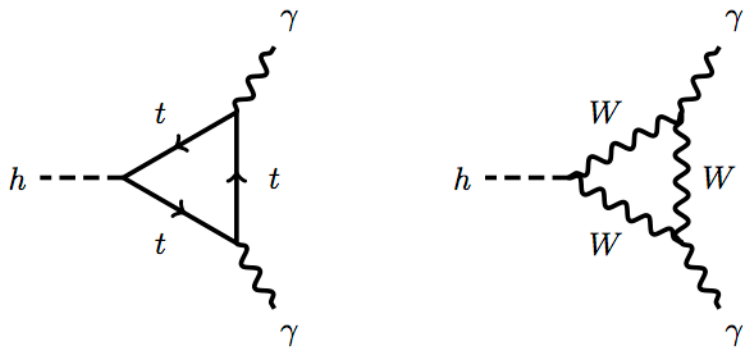
- Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, Phys. Rev. D 91, 012006 (2015)

- Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV, Eur. Phys. J. C 75 (2015) 212

- Measurement of the properties of a Higgs boson in the four-lepton final state, Phys. Rev. D 89 (2014) 092007

- Observation of the diphoton decay of the Higgs boson and measurement of its properties, Eur. Phys. J. C 74 (2014) 3076

Higgs to γγ



Event categorizations

Category	n_{sig}	FWHM [GeV]	σ_{eff} [GeV]	b in $\pm\sigma_{\mathrm{eff90}}$	s/b [%]	$s/\sqrt{b}$
		$\sqrt{s}$=8 TeV				
Inclusive	402.	3.69	1.67	10670	3.39	3.50
Unconverted central low p_{Tt}	59.3	3.13	1.35	801	6.66	1.88
Unconverted central high p_{Tt}	7.1	2.81	1.21	26.0	24.6	1.26
Unconverted rest low p_{Tt}	96.2	3.49	1.53	2624	3.30	1.69
Unconverted rest high p_{Tt}	10.4	3.11	1.36	93.9	9.95	0.96
Unconverted transition	26.0	4.24	1.86	910	2.57	0.78
Converted central low p_{Tt}	37.2	3.47	1.52	589	5.69	1.38
Converted central high p_{Tt}	4.5	3.07	1.35	20.9	19.4	0.88
Converted rest low p_{Tt}	107.2	4.23	1.88	3834	2.52	1.56
Converted rest high p_{Tt}	11.9	3.71	1.64	144.2	7.44	0.89
Converted transition	42.1	5.31	2.41	1977	1.92	0.85
		$\sqrt{s}$=7 TeV				
Inclusive	73.9	3.38	1.54	1752	3.80	1.59
Unconverted central low p_{Tt}	10.8	2.89	1.24	128	7.55	0.85
Unconverted central high p_{Tt}	1.2	2.59	1.11	3.7	30.0	0.58
Unconverted rest low p_{Tt}	16.5	3.09	1.35	363	4.08	0.78
Unconverted rest high p_{Tt}	1.8	2.78	1.21	13.6	11.6	0.43
Unconverted transition	4.5	3.65	1.61	125	3.21	0.36
Converted central low p_{Tt}	7.1	3.28	1.44	105	6.06	0.62
Converted central high p_{Tt}	0.8	2.87	1.25	3.5	21.6	0.40
Converted rest low p_{Tt}	21.0	3.93	1.75	695	2.72	0.72
Converted rest high p_{Tt}	2.2	3.43	1.51	24.7	7.98	0.40
Converted transition	8.1	4.81	2.23	365	2.00	0.38

Systematic uncertainties

	Unconverted					Converted				
	Central		Rest		Transition	Central		Rest		Transition
Class	low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}		low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}	
$Z \to e^+e^-$ calibration	0.02	0.03	0.04	0.04	0.11	0.02	0.02	0.05	0.05	0.11
LAr cell nonlinearity	0.12	0.19	0.09	0.16	0.39	0.09	0.19	0.06	0.14	0.29
Layer calibration	0.13	0.16	0.11	0.13	0.13	0.07	0.10	0.05	0.07	0.07
ID material	0.06	0.06	0.08	0.08	0.10	0.05	0.05	0.06	0.06	0.06
Other material	0.07	0.08	0.14	0.15	0.35	0.04	0.04	0.07	0.08	0.20
Conversion reconstruction	0.02	0.02	0.03	0.03	0.05	0.03	0.02	0.05	0.04	0.06
Lateral shower shape	0.04	0.04	0.07	0.07	0.06	0.09	0.09	0.18	0.19	0.16
Background modeling	0.10	0.06	0.05	0.11	0.16	0.13	0.06	0.14	0.18	0.20
Vertex measurement	0.03									
Total	0.23	0.28	0.24	0.30	0.59	0.21	0.25	0.27	0.33	0.47

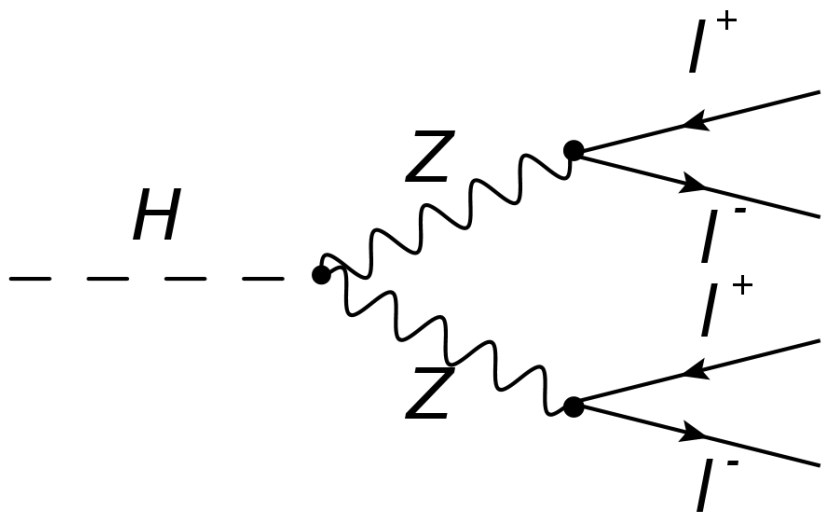
Event categorizations

Event classes		Expected SM Higgs boson signal yield (m_H=125 GeV)								Bkg. (GeV^{-1})
		Total	ggH	VBF	WH	ZH	$t\bar{t}H$	σ_{eff} (GeV)	σ_{HM} (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	5.8	**79.8%**	9.9%	6.0%	3.5%	0.8%	1.11	0.98	11.0
	Untagged 1	22.7	**91.9%**	4.2%	2.4%	1.3%	0.2%	1.27	1.09	69.5
	Untagged 2	27.1	**91.9%**	4.1%	2.4%	1.4%	0.2%	1.78	1.40	135.
	Untagged 3	34.1	**92.1%**	4.0%	2.4%	1.3%	0.2%	2.36	2.01	312.
	VBF dijet 0	1.6	19.3%	**80.1%**	0.3%	0.2%	0.1%	1.41	1.17	0.5
	VBF dijet 1	3.0	38.1%	**59.5%**	1.2%	0.7%	0.4%	1.65	1.32	3.5
	VH tight ℓ	0.3	—	—	**77.2%**	20.6%	2.2%	1.61	1.31	0.1
	VH loose ℓ	0.2	3.6%	1.1%	**79.1%**	15.2%	1.0%	1.63	1.32	0.2
	VH E_T^{miss}	0.3	4.5%	1.1%	41.5%	**44.6%**	8.2%	1.60	1.14	0.2
	VH dijet	0.4	27.1%	2.8%	**43.7%**	24.3%	2.1%	1.54	1.24	0.5
	$t\bar{t}H$ tags	0.2	3.1%	1.1%	2.2%	1.3%	**92.3%**	1.40	1.13	0.2
8 TeV 19.7 fb^{-1}	Untagged 0	6.0	**75.7%**	11.9%	6.9%	3.6%	1.9%	1.05	0.79	4.7
	Untagged 1	50.8	**85.2%**	7.9%	4.0%	2.4%	0.6%	1.19	1.00	120.
	Untagged 2	117.	**91.1%**	4.7%	2.5%	1.4%	0.3%	1.46	1.15	418.
	Untagged 3	153.	**91.6%**	4.4%	2.4%	1.4%	0.3%	2.04	1.56	870.
	Untagged 4	121.	**93.1%**	3.6%	2.0%	1.1%	0.2%	2.62	2.14	1400.
	VBF dijet 0	4.5	17.8%	**81.8%**	0.2%	0.1%	0.1%	1.30	0.94	0.8
	VBF dijet 1	5.6	28.5%	**70.5%**	0.6%	0.2%	0.2%	1.43	1.07	2.7
	VBF dijet 2	13.7	43.8%	**53.2%**	1.4%	0.8%	0.8%	1.59	1.24	22.1
	VH tight ℓ	1.4	0.2%	0.2%	**76.9%**	19.0%	3.7%	1.63	1.24	0.4
	VH loose ℓ	0.9	2.6%	1.1%	**77.9%**	16.8%	1.5%	1.60	1.16	1.2
	VH E_T^{miss}	1.8	16.3%	2.7%	34.4%	**35.4%**	11.1%	1.68	1.17	1.3
	VH dijet	1.6	30.3%	3.1%	**40.6%**	23.4%	2.6%	1.31	1.06	1.0
	$t\bar{t}H$ lepton	0.5	—	—	1.6%	1.6%	**96.8%**	1.34	1.03	0.2
	$t\bar{t}H$ multijet	0.6	4.1%	0.9%	0.8%	0.9%	**93.3%**	1.34	1.03	0.6

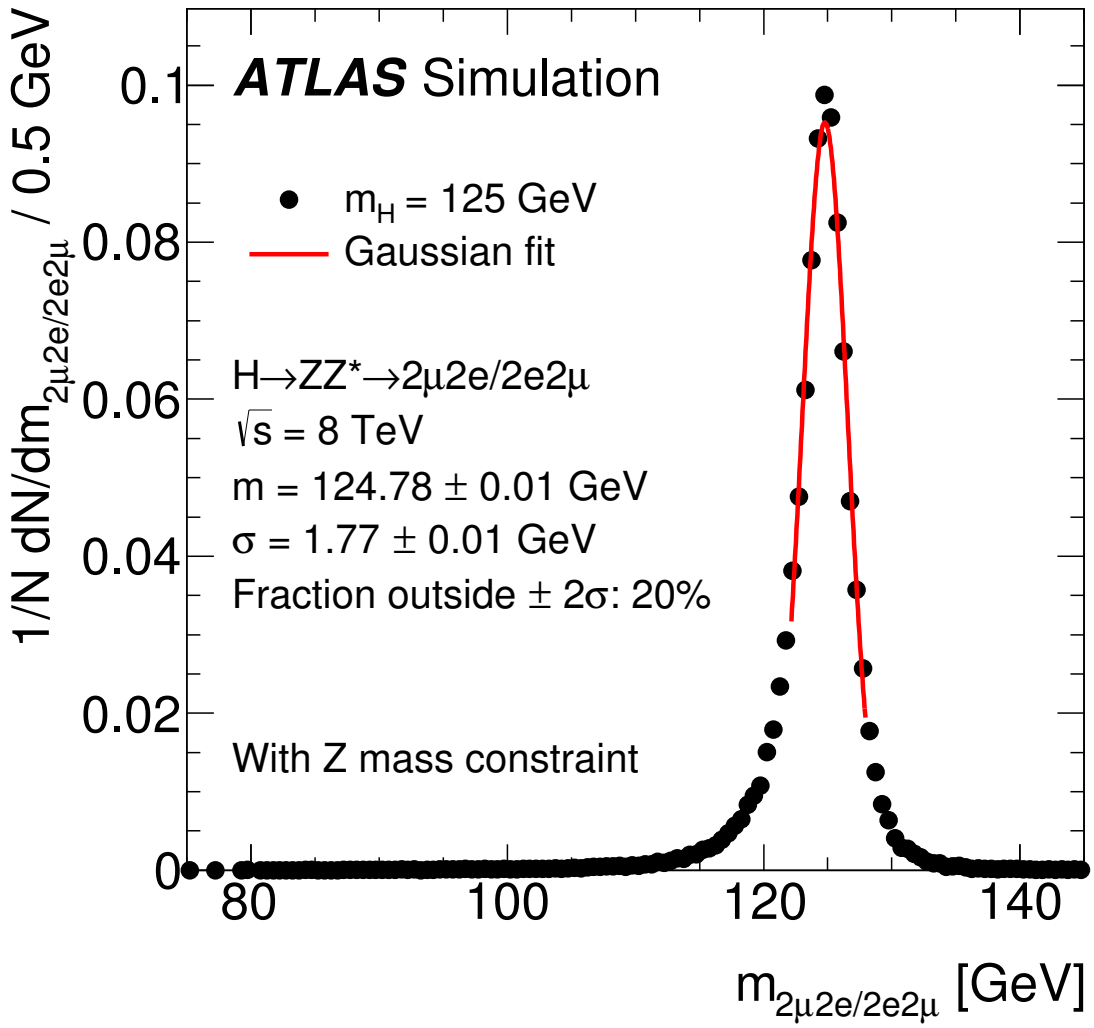
Systematic uncertainties

Source of uncertainty	Uncertainty in $\hat{m}_{\mathrm{H}}$ (GeV)	
Imperfect simulation of electron-photon differences	0.10	
Linearity of the energy scale	0.10	
Energy scale calibration and resolution	0.05	
Other	0.04	
All systematic uncertainties in the signal model	0.15	
Statistical		0.31
Total		0.35

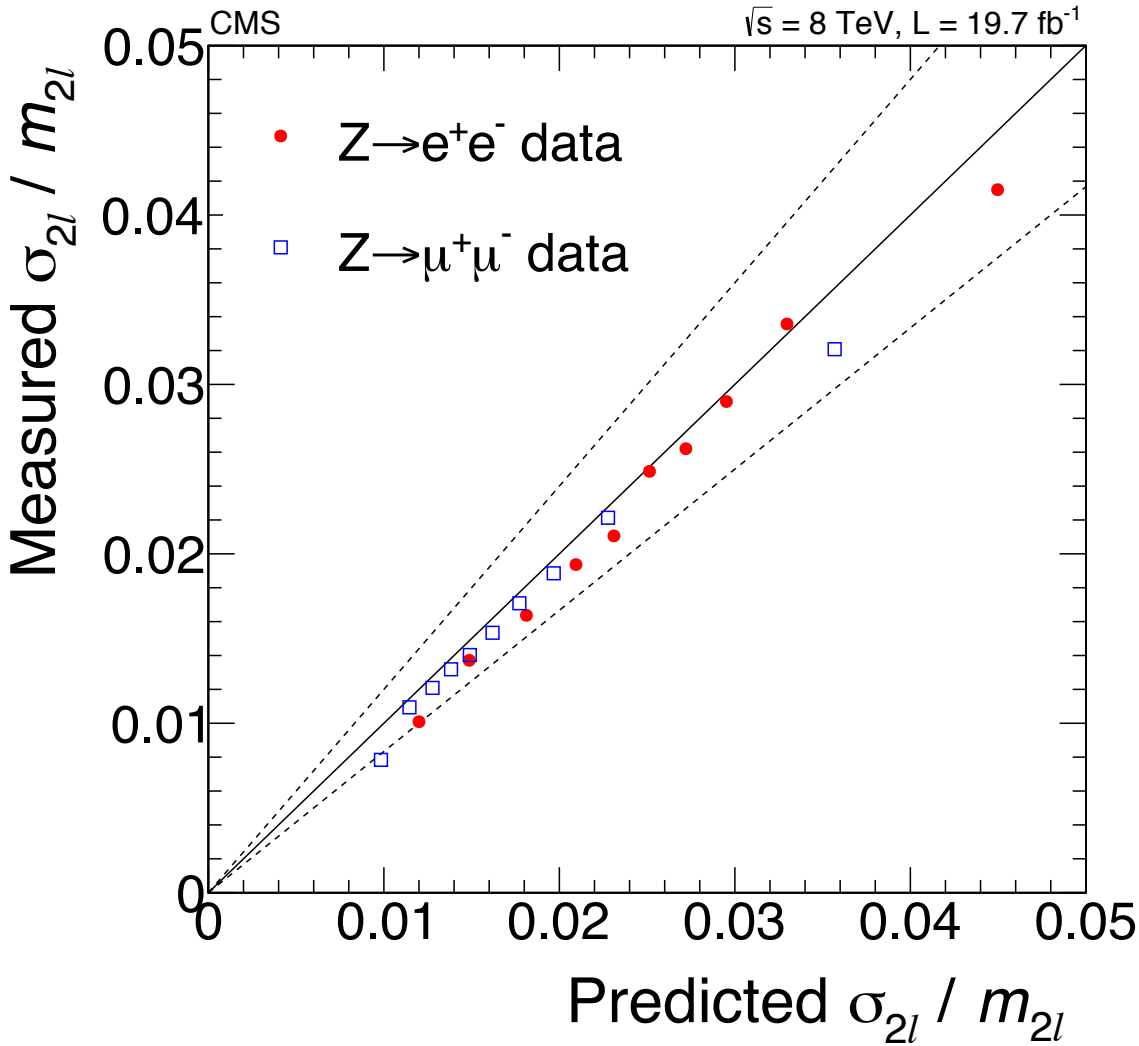
Higgs to ZZ to four leptons



Fit the signal shape

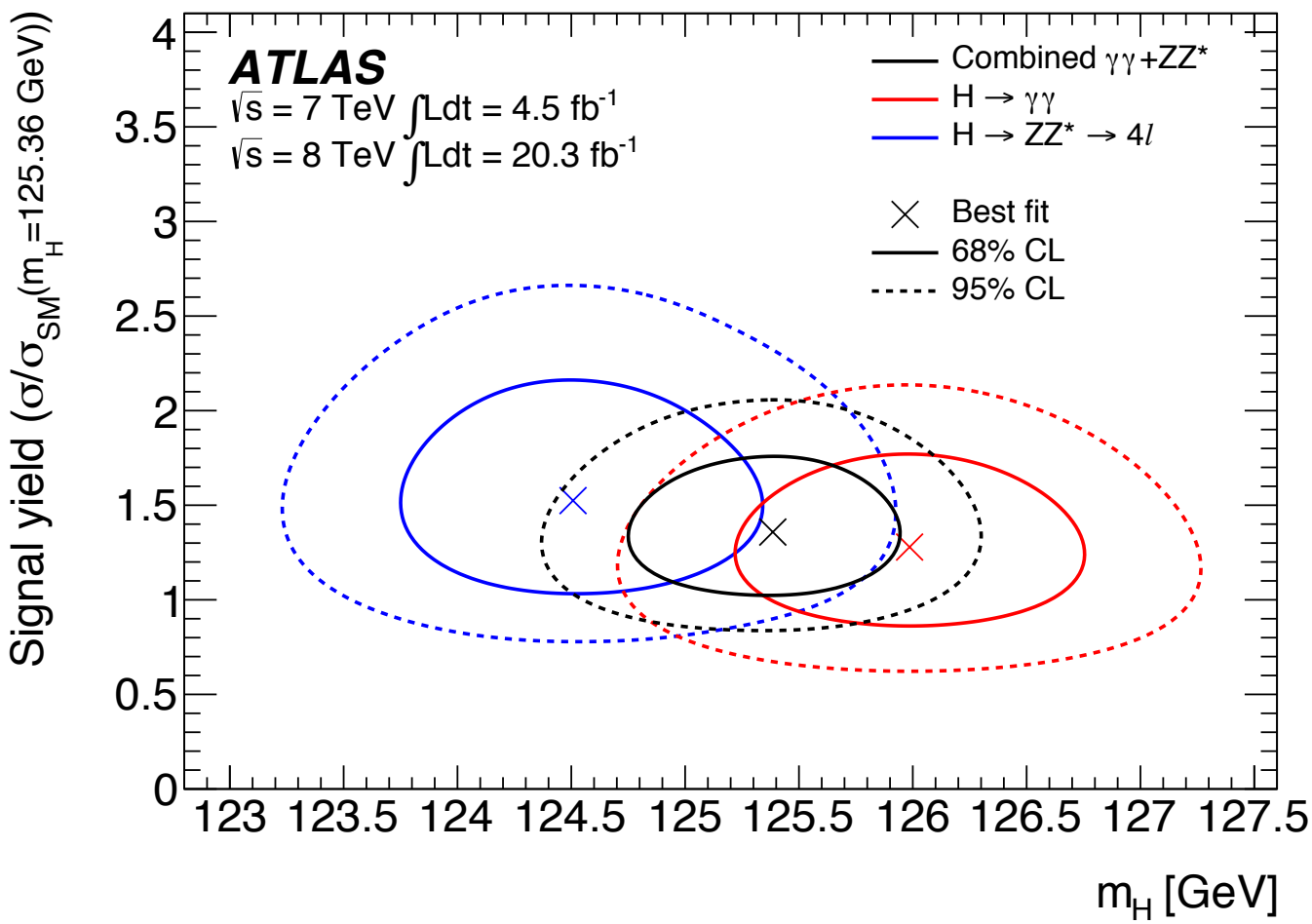


Validation of per-event mass resolution

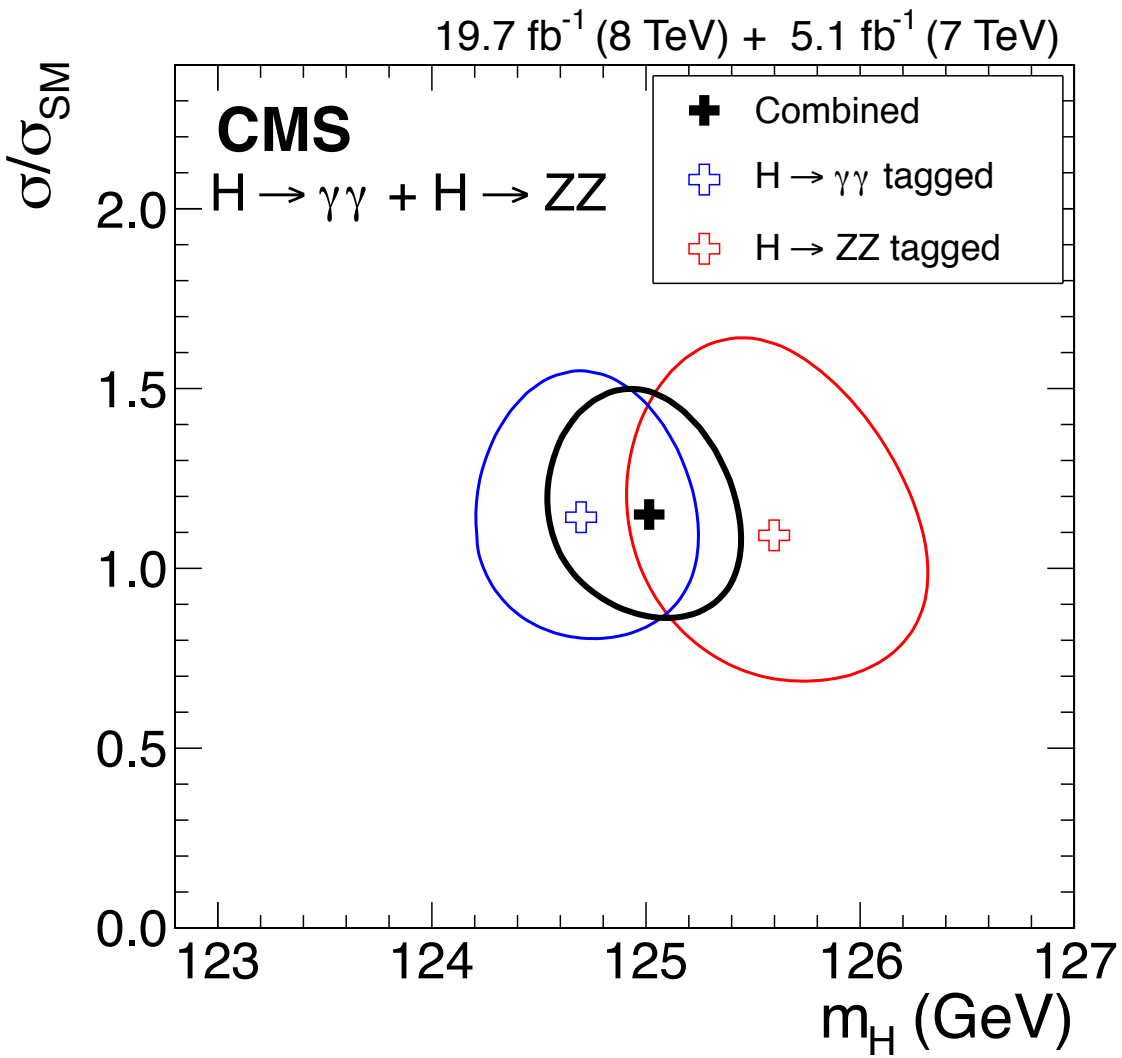


Mass measurement from ATLAS+CMS Higgs combination

γγ+4l


ATLAS
√s = 7 TeV ∫Ldt = 4.5 fb-1
√s = 8 TeV ∫Ldt = 20.3 fb-1
Combined γγ+ZZ*
H → γγ
H → ZZ* → 4l
Best fit
68% CL
95% CL
Signal yield (σ/σSM(mH=125.36 GeV))
mH [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
123
123.5
124
124.5
125
125.5
126
126.5
127
127.5

γγ+4l


19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
CMS
H → γγ + H → ZZ
Combined
H → γγ tagged
H → ZZ tagged
σ/σ$_{SM}$
2.0
1.5
1.0
0.5
0.0
123
124
125
126
127
m$_H$ (GeV)

Compatibility test :
mutual compatibility of m_H

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

Nominal combination:
1 m_H, three μ

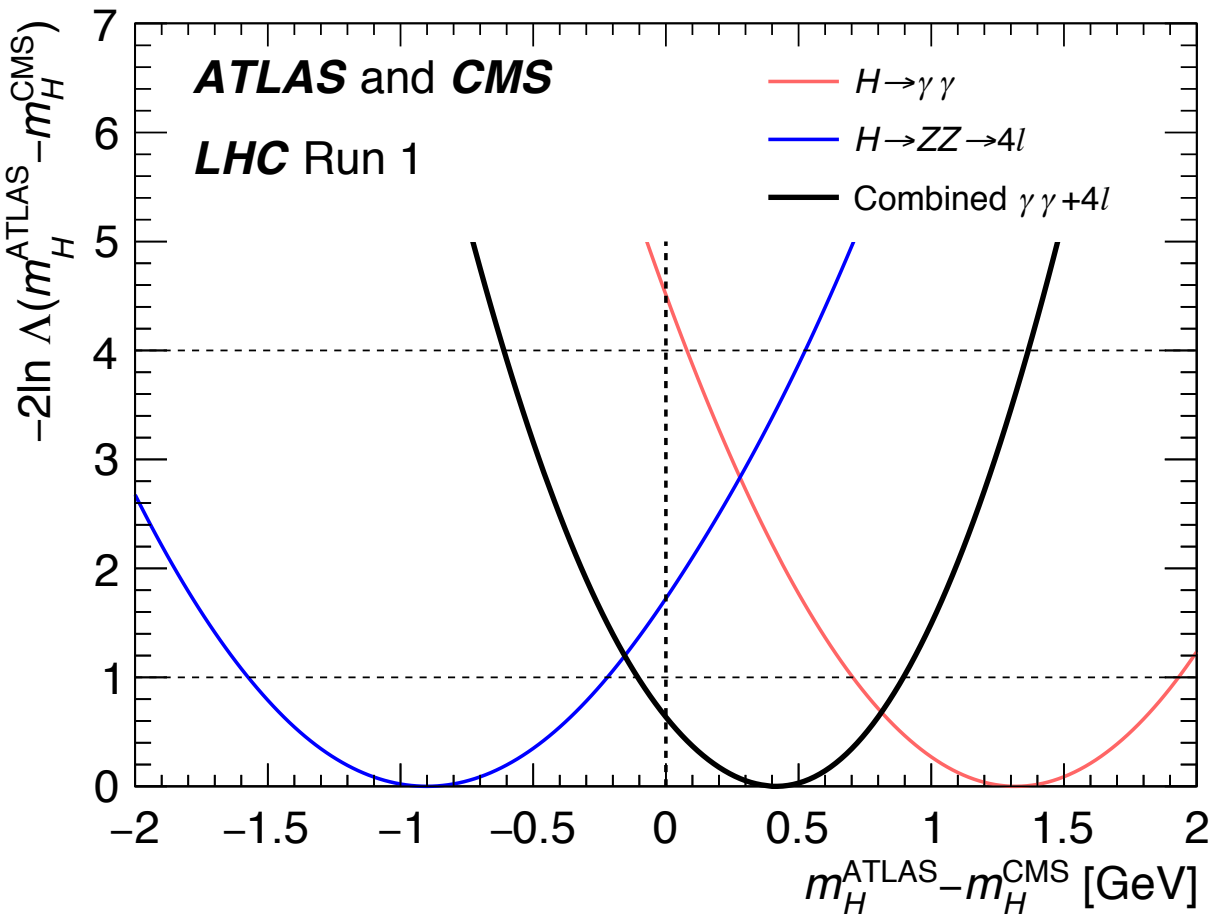
10 % compatibility

4 m_H (m_H from 4l, γγ from CMS and ATLAS), three μ

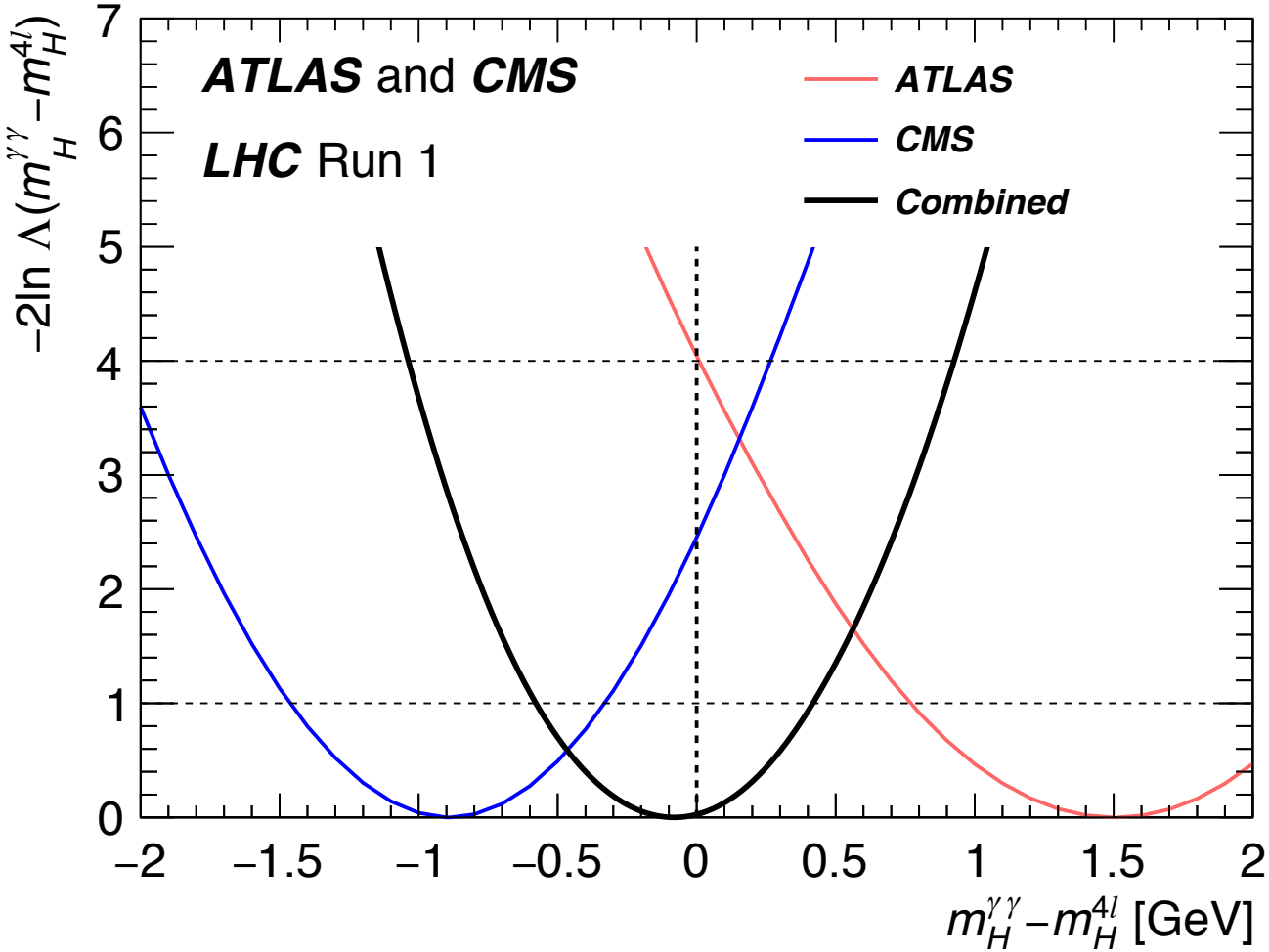
7 % compatibility

4 m_H (m_H from 4l, γγ from CMS and ATLAS), six μ (μ from CMS and ATLAS vary independently)

Compatibility test : between two channels



Compatibility test : between two experiments



Compatibility test : tension correlation