CYCU HEP Seminar

CYCU
Chungli, Taiwan
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Our understanding of the 125 GeV Nobel-prized boson, 1189 days after its discovery

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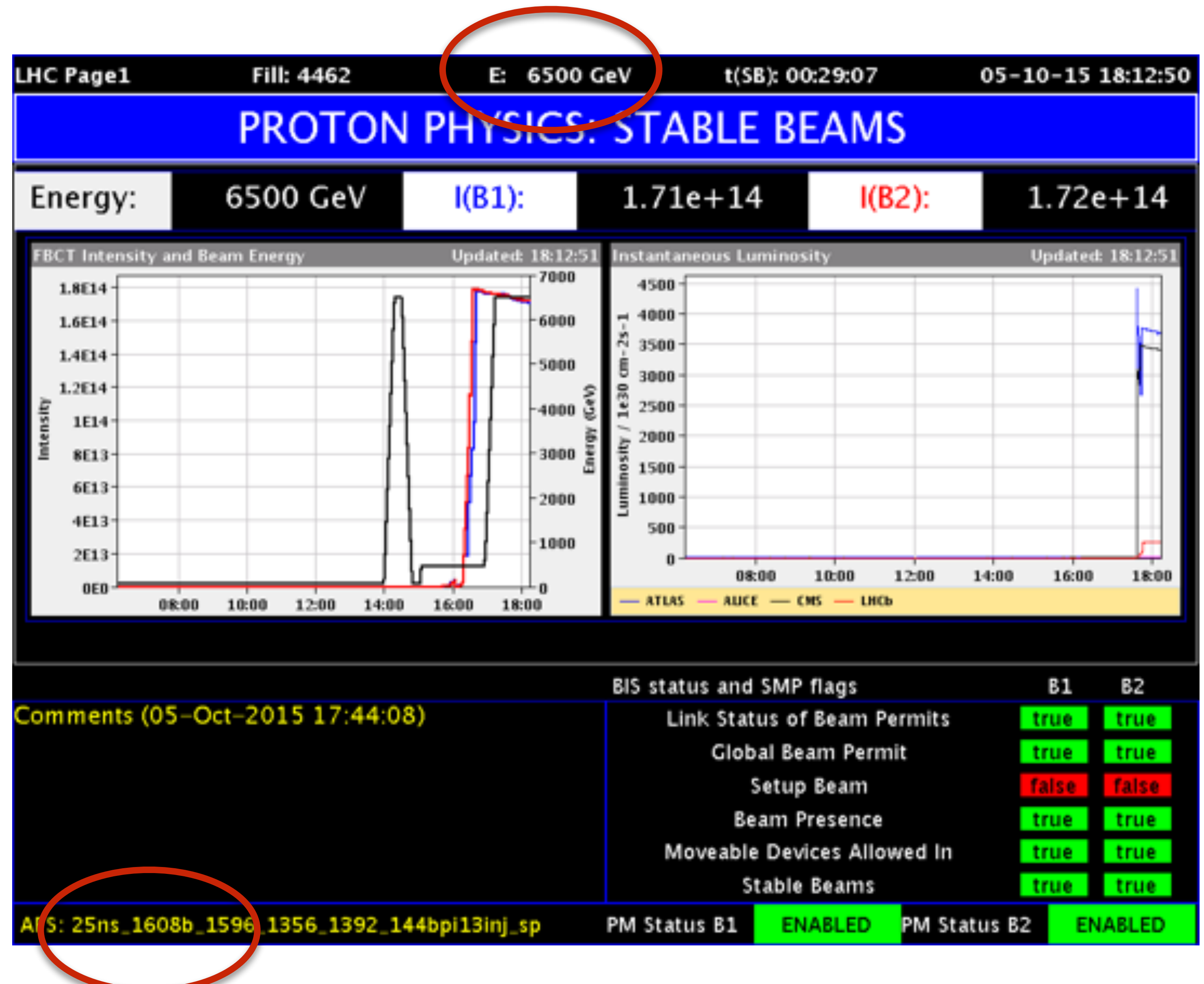
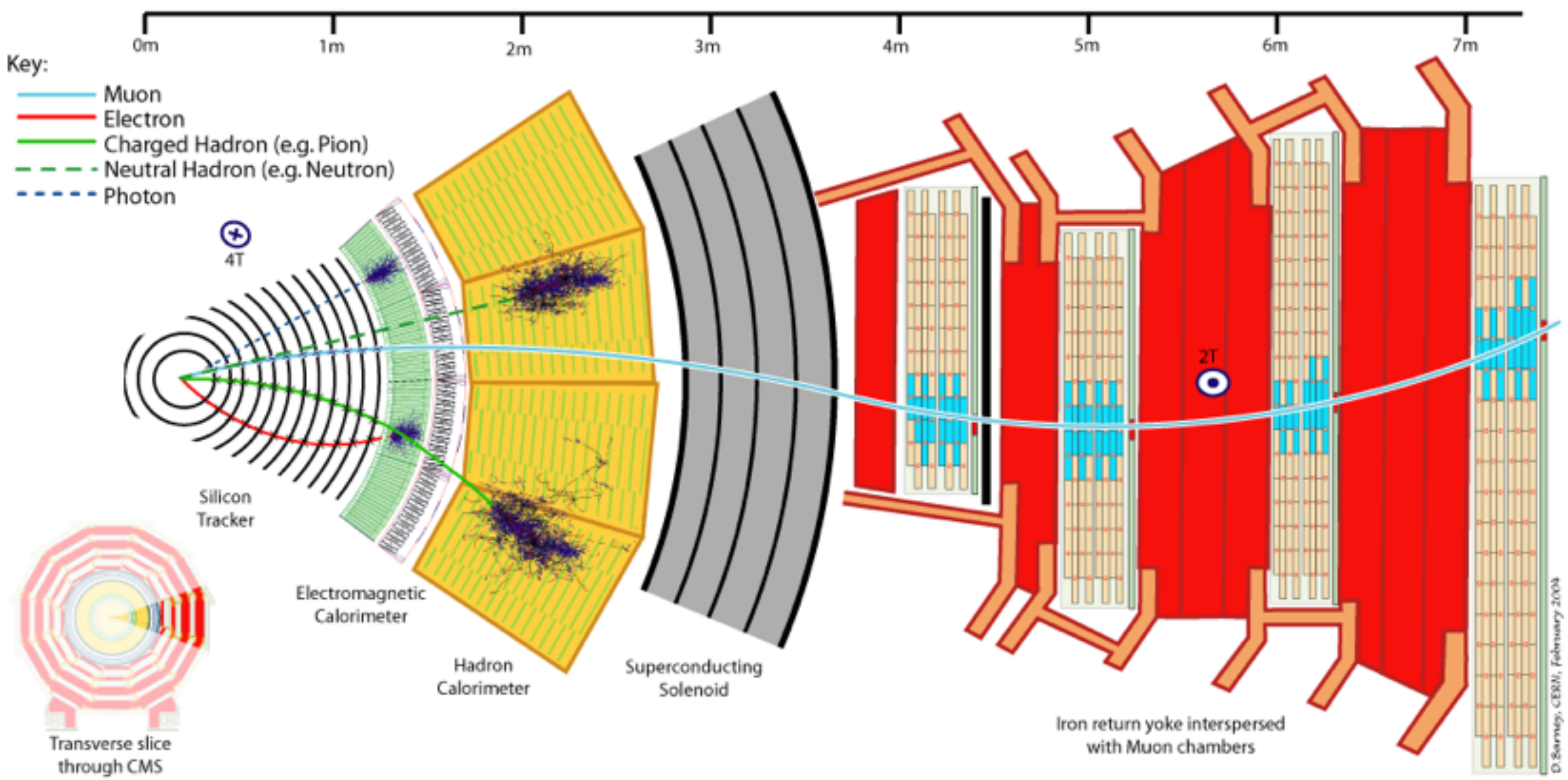
Large Hadron Collider

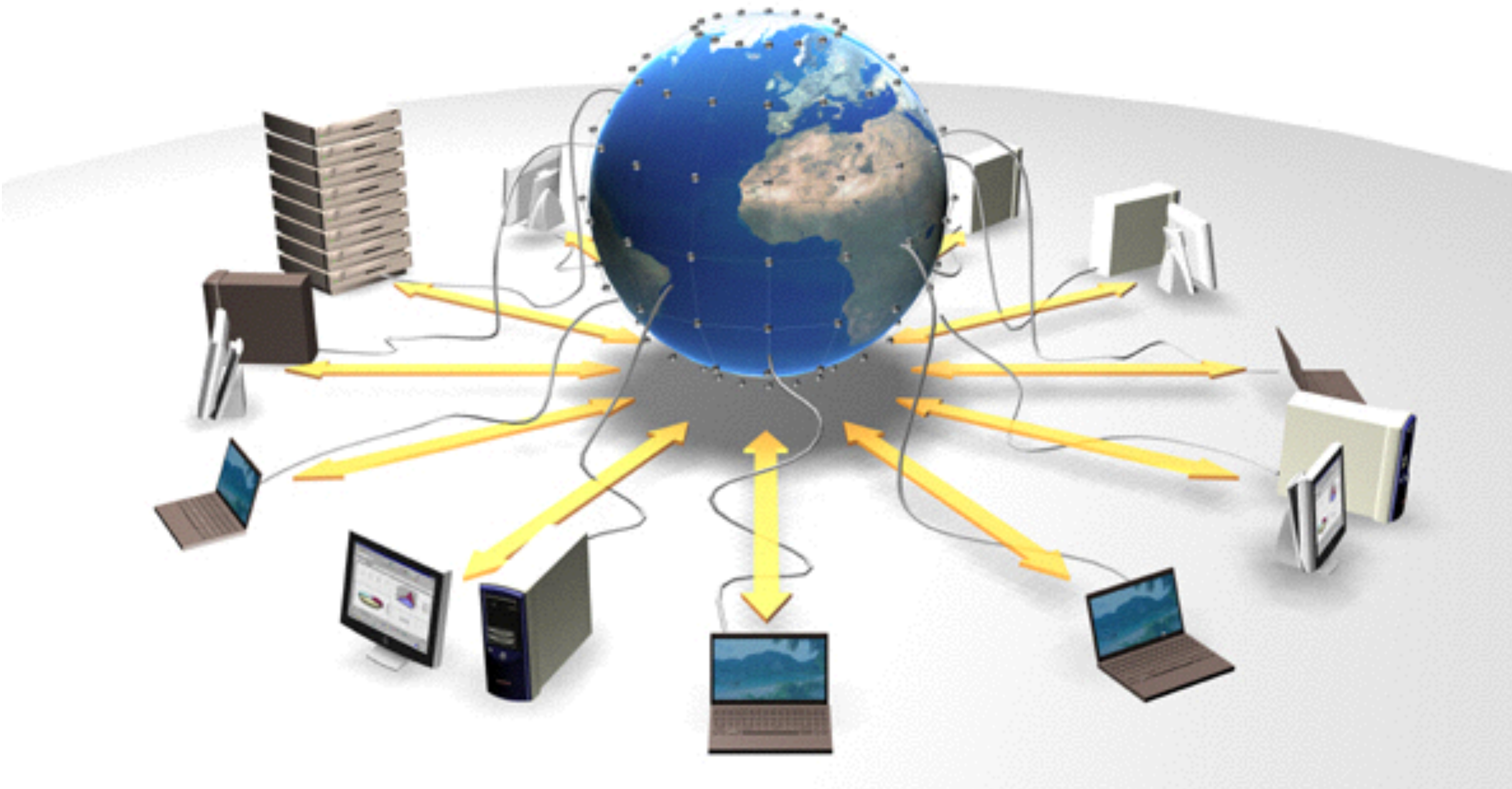


CMS detector



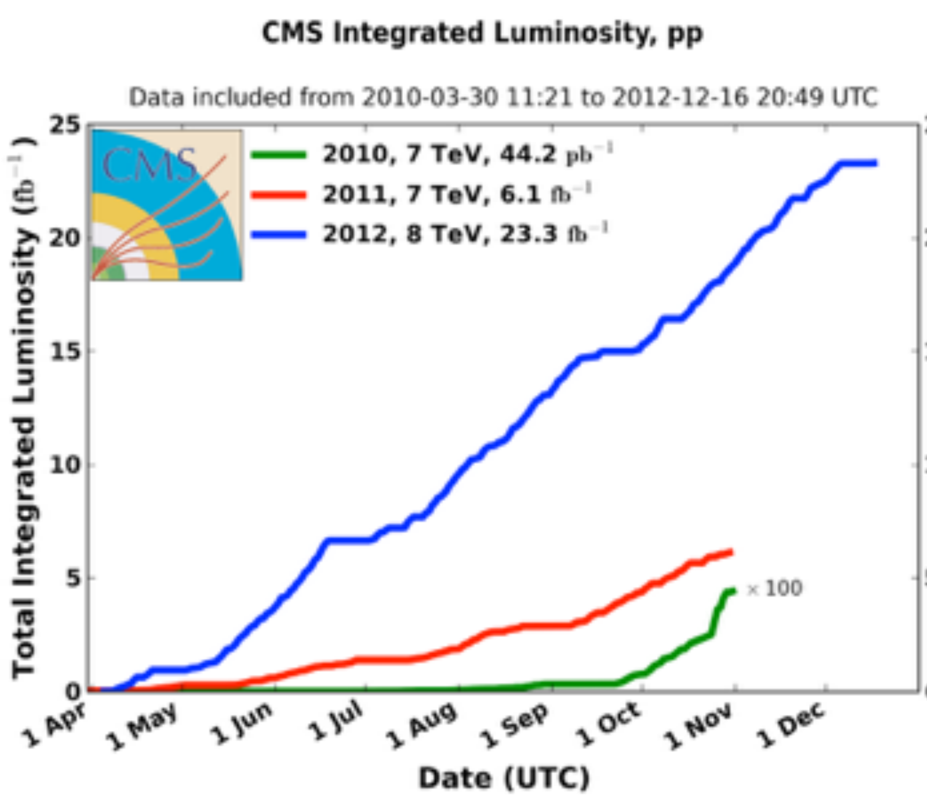
People

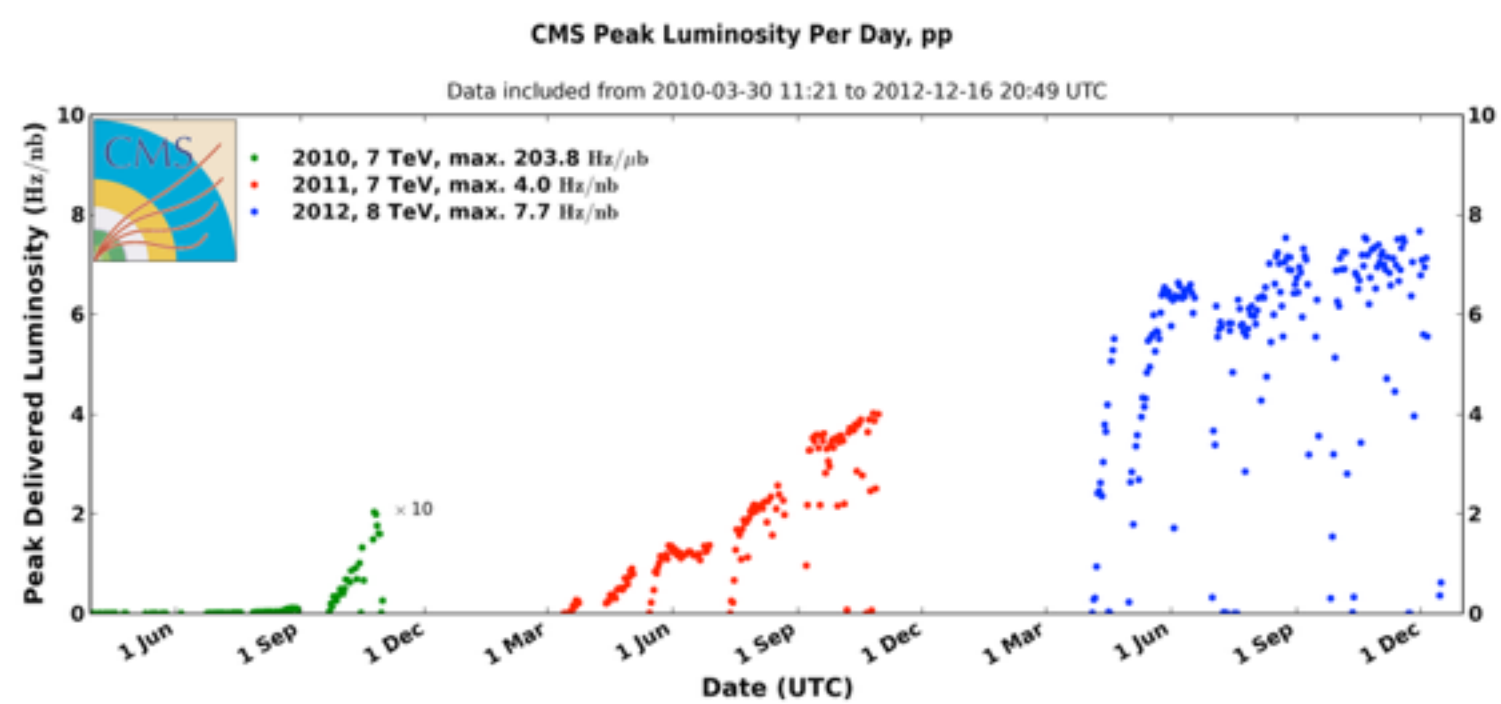
Grid computing



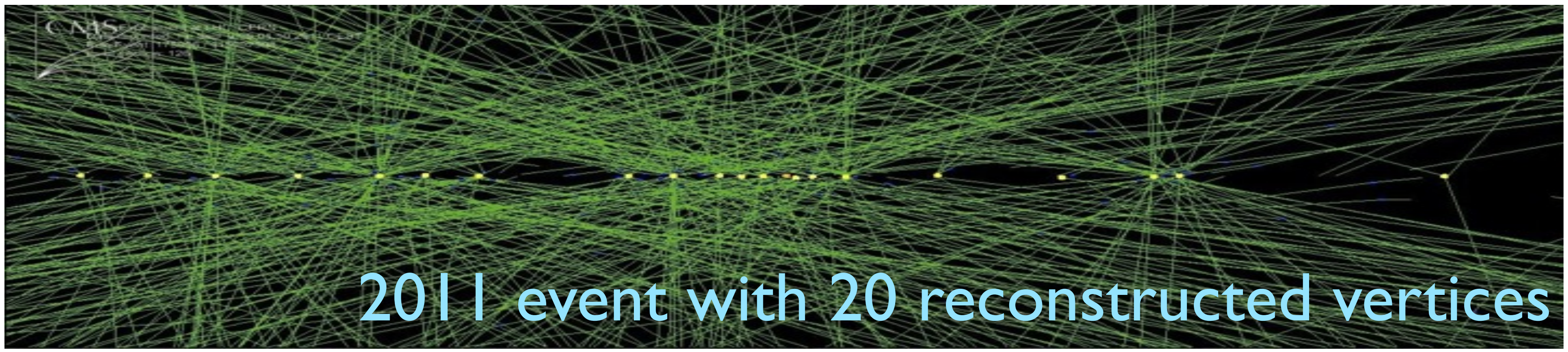
Luminosity from 2010 to 2012

- CMS performance
  - Overall data taking efficiency ~91%
  - Average fraction of operation channel per subsystem > 98.5%

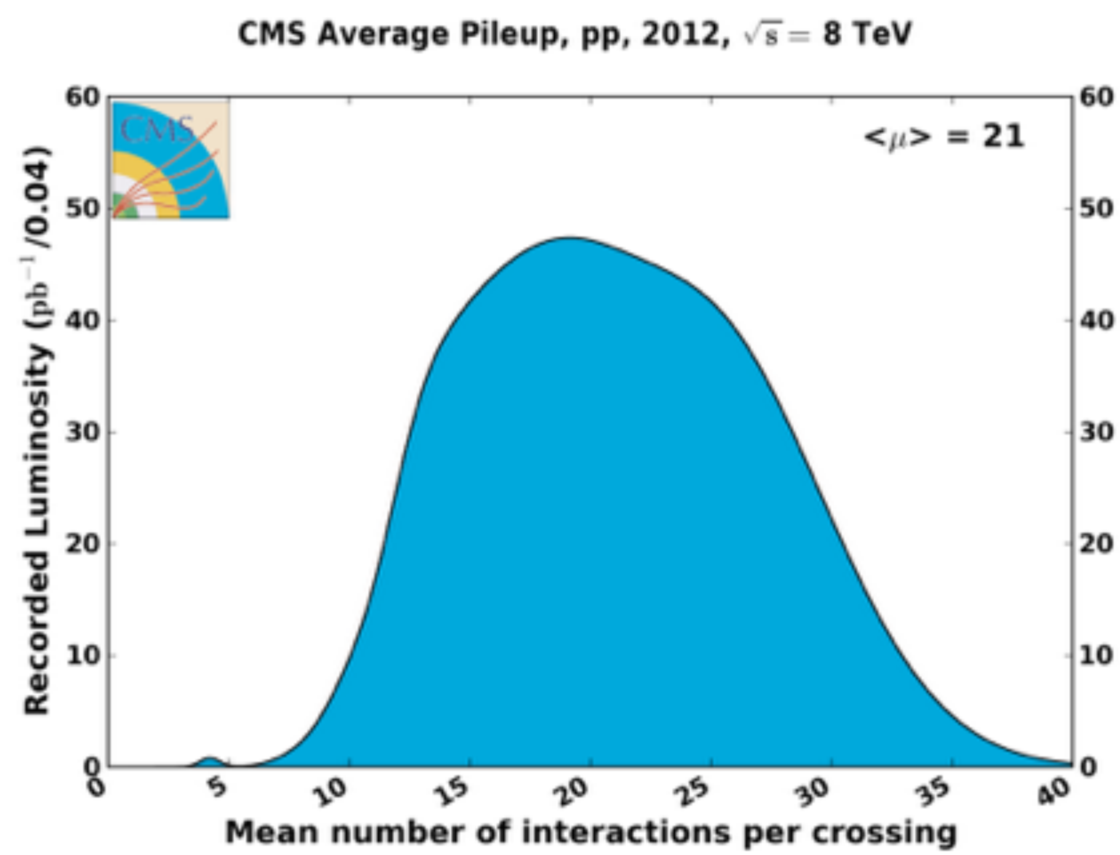




The challenge : Pile-Up

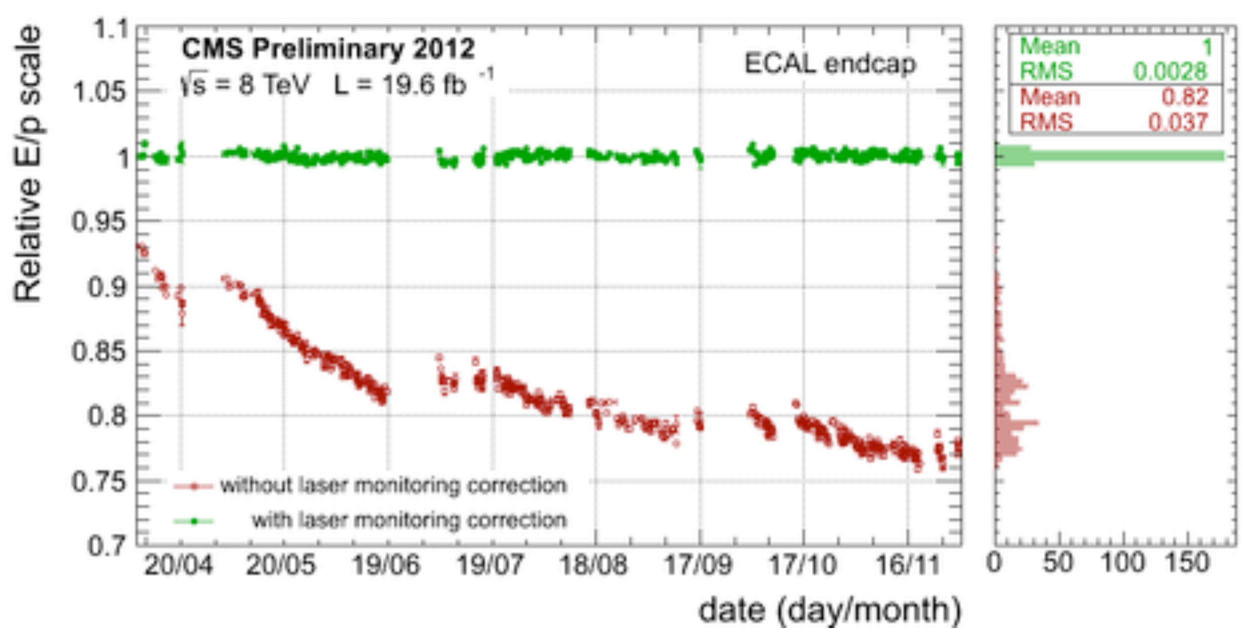


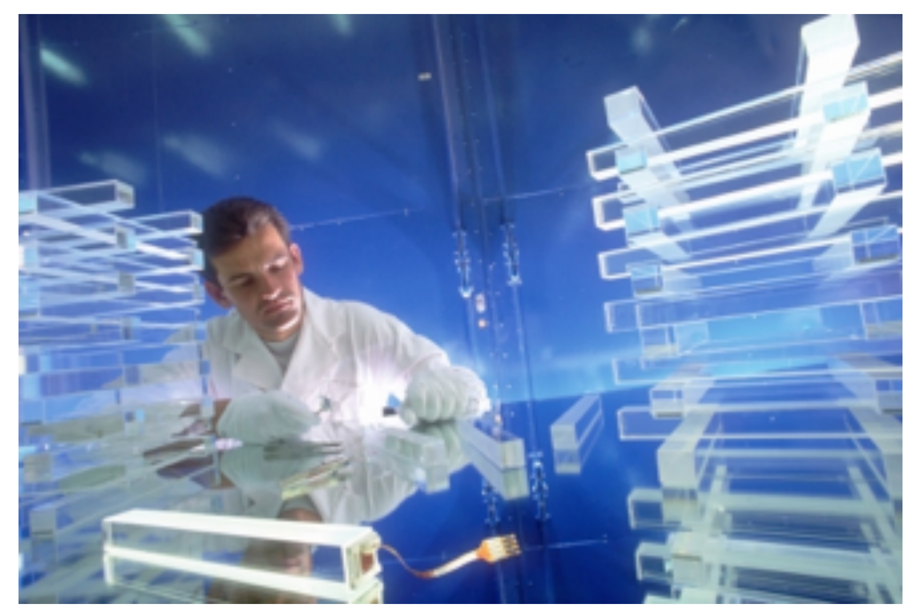
- A ZZ event can be a fake one due to pile-up
- Spoil the "isolation" and MET resolution
- Additional challenge for H→γγ channel, where the hard-scattering vertex is often not known well
  - picking a wrong vertex would make the mass resolution worse



The CMS electromagnetic calorimeter

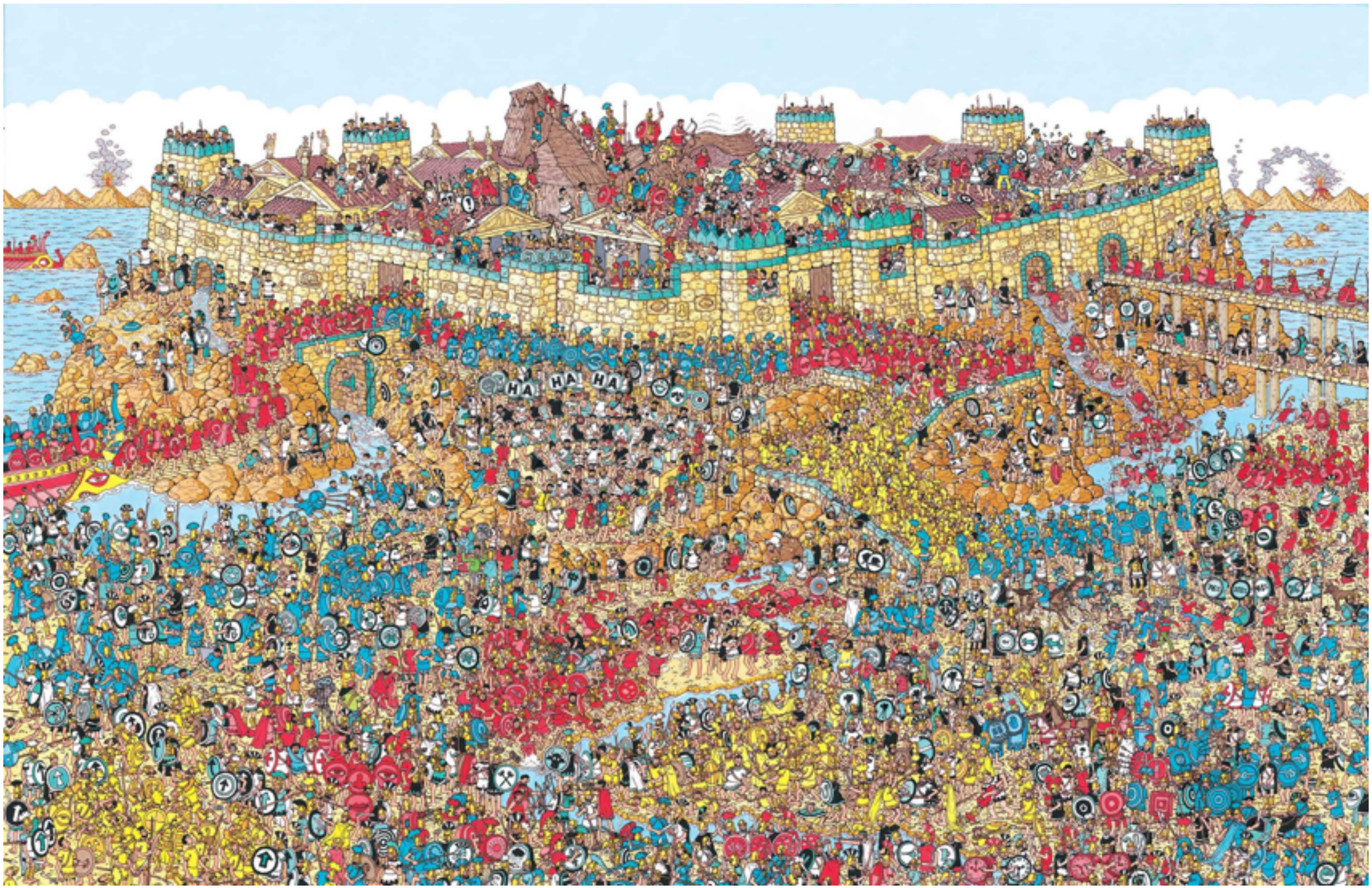
- Discovery potential depends on the di-photon invariant mass resolution
    - excellent performance of the electromagnetic crystal calorimeter needed
- Design energy resolution : ~0.5% for $E_\gamma > 100$ GeV for unconverted photons in the ECAL barrel
- Crucial aspect: precise calibration
    - in-situ energy calibration using $\pi^\circ \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $W \rightarrow e\nu$ E/p, $Z \rightarrow ee$
    - monitoring of transparency losses due to radiation damage with laser system





76K $PbWO_4$ crystals organized in barrel ($|\eta| < 1.48$) and endcap ($1.48 < |\eta| < 3$)
A Pb-Si Preshower in endcap

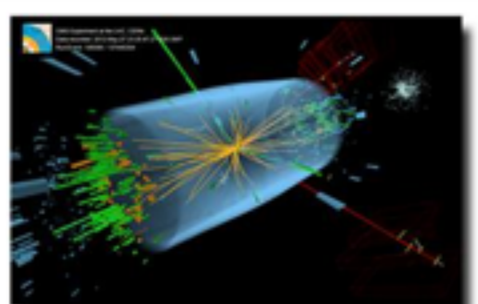
Kids : Where is Wally ?
Particle Physicists : Where is the Higgs boson of the SM ?

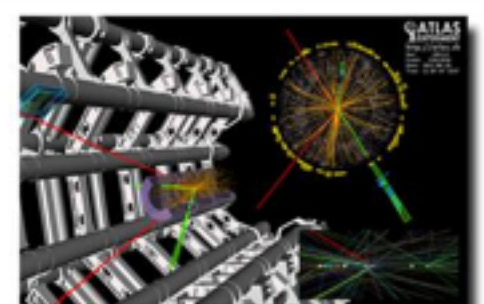


47 years, 8 months, 15 days

1189 days ago …..

461 days after it stood out





- for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider

Questions to answer after the discovery

- Is this the Higgs boson of the SM ?
  - Are the signal strengths at the correct SM levels ?
  - Where is it observed ?
  - Is the new boson a scalar, and not a pseudo-scalar or a tensor ?
  - Does it couple to itself ?
- Are there any other Higgs bosons to observe ?
- Is this Higgs boson a window to new physics ?

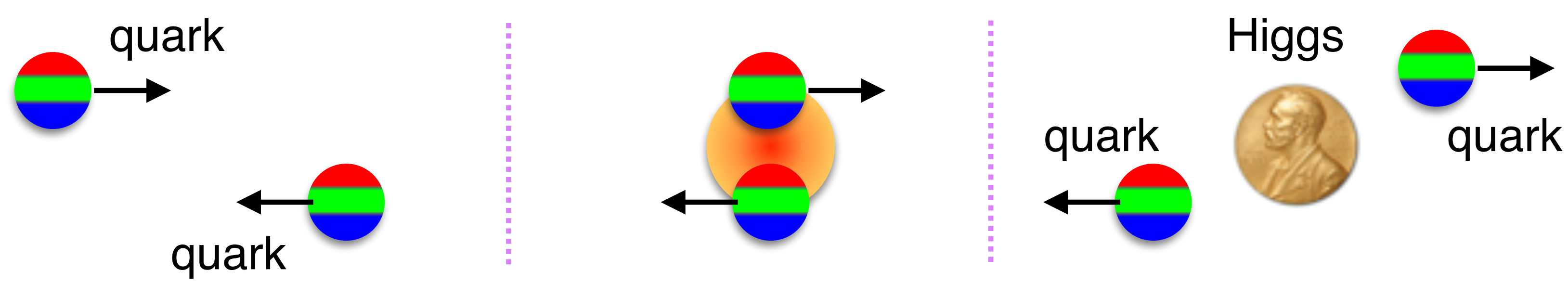
over the last 1189 days

SM Higgs boson production

pp → H
86%

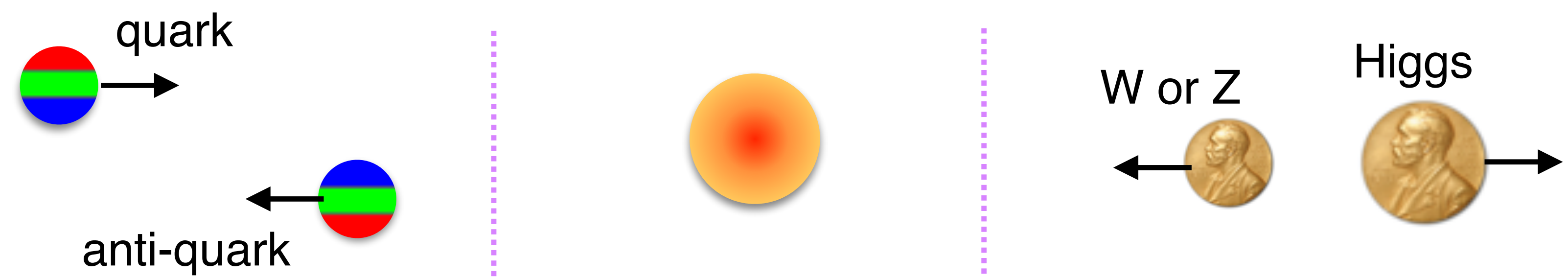
top loop dominant

pp → qqH
7%



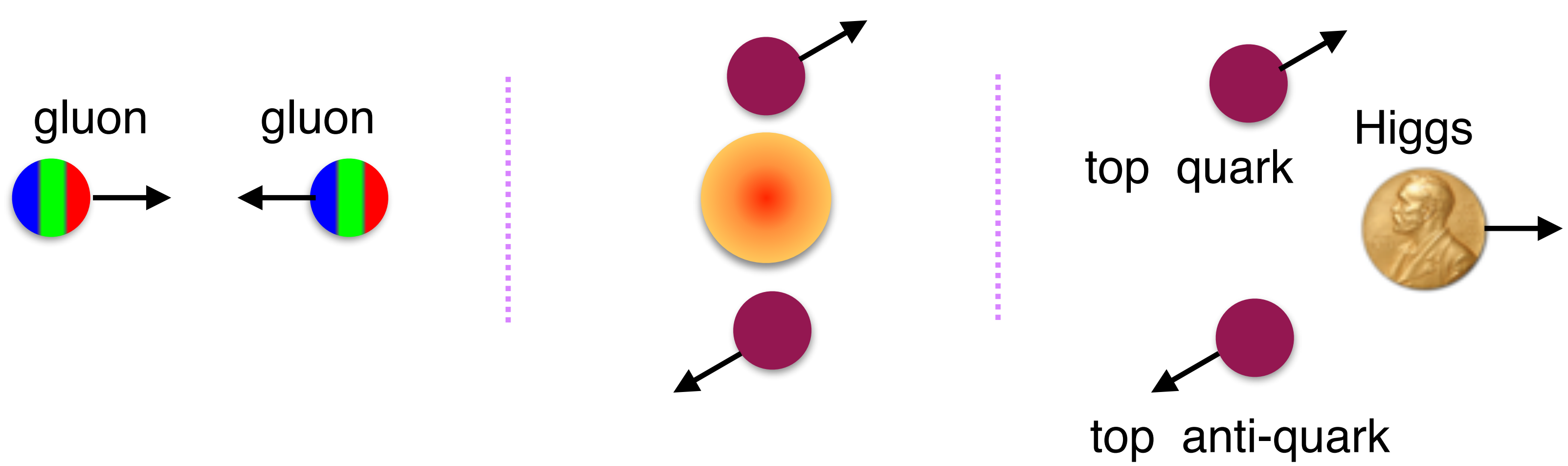
distinct signature, access to W/Z Higgs couplings

pp → WH, ZH
5%



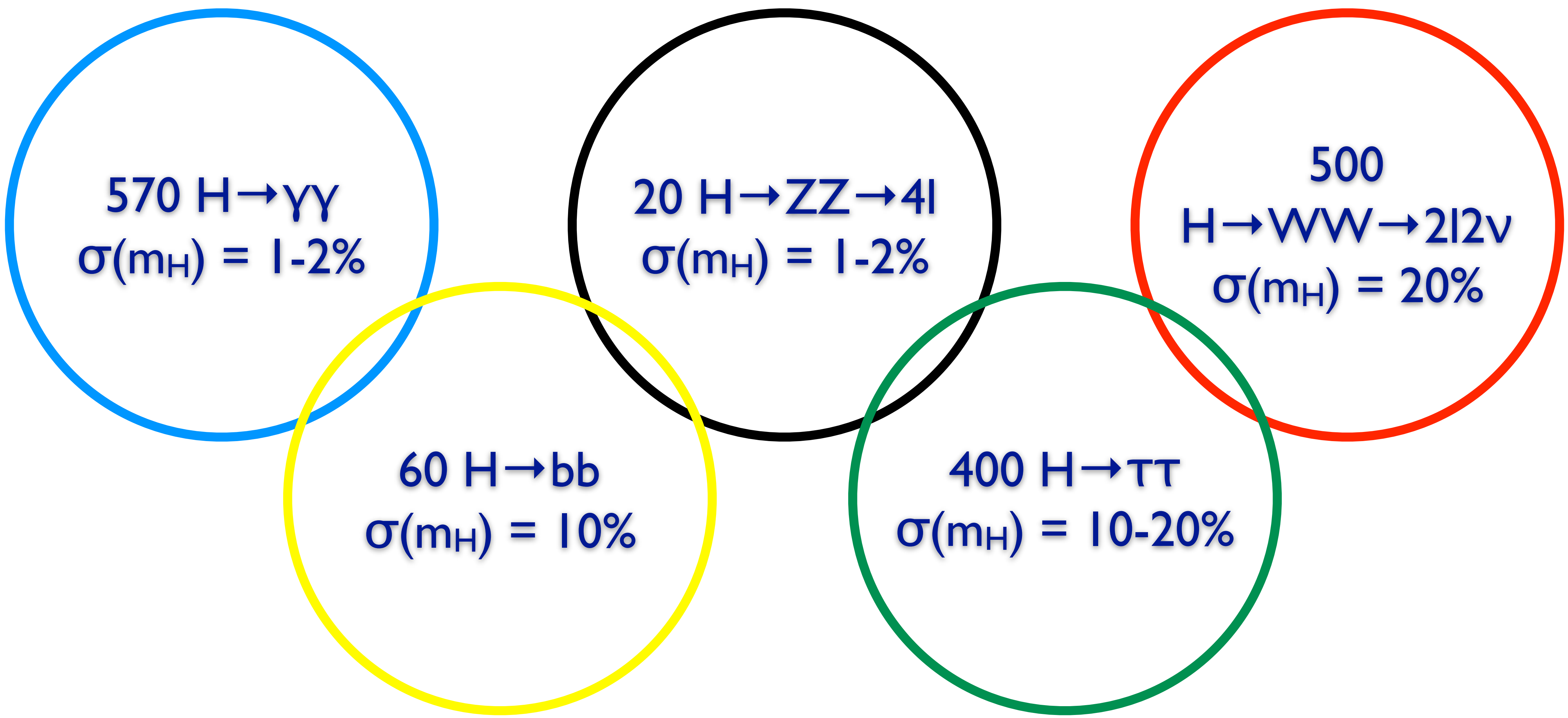
clean signature with leptons, access to H→bb and W/Z Higgs couplings

pp → ttH
0.6%



direct coupling of top and Higgs

Higgs decays



Higgs decays

570 $H \to \gamma\gamma$
$\sigma(m_H)$ = 1-2%

20 $H \to ZZ \to 4l$
$\sigma(m_H)$ = 1-2%

500
$H \to WW \to 2l2\nu$
$\sigma(m_H)$ = 20%

plays a role in electroweak symmetry breaking

Higgs decays

Higgs field serves as the source of mass generation in the fermion sector, through a Yukawa interaction

60 $H \rightarrow bb$
$\sigma(m_H)$ = 10%

400 $H \rightarrow \tau\tau$
$\sigma(m_H)$ = 10-20%

Higgs decays

570 H→γγ
$\sigma(m_H)$ = 1-2%

20 H→ZZ→4l
$\sigma(m_H)$ = 1-2%

Higgs decays

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60 $H \rightarrow bb$
$\sigma(m_H)$ = 10%

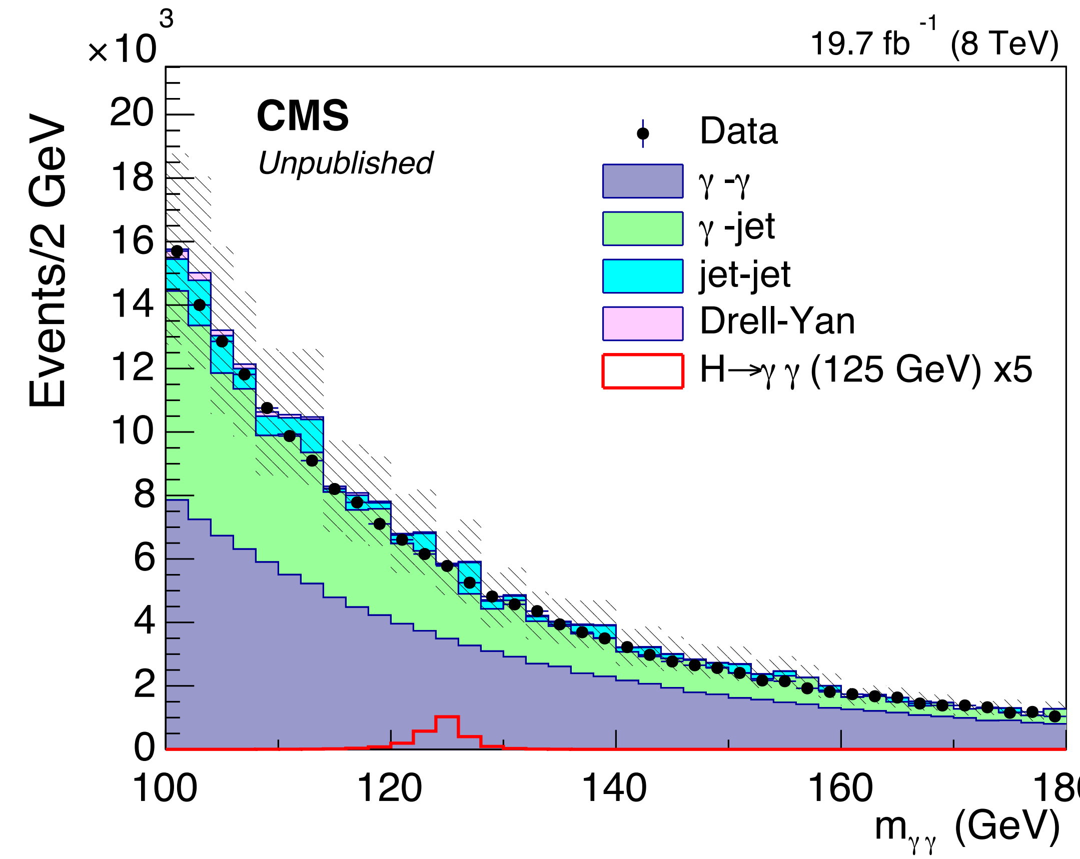
signal strength, properties

Five major channels

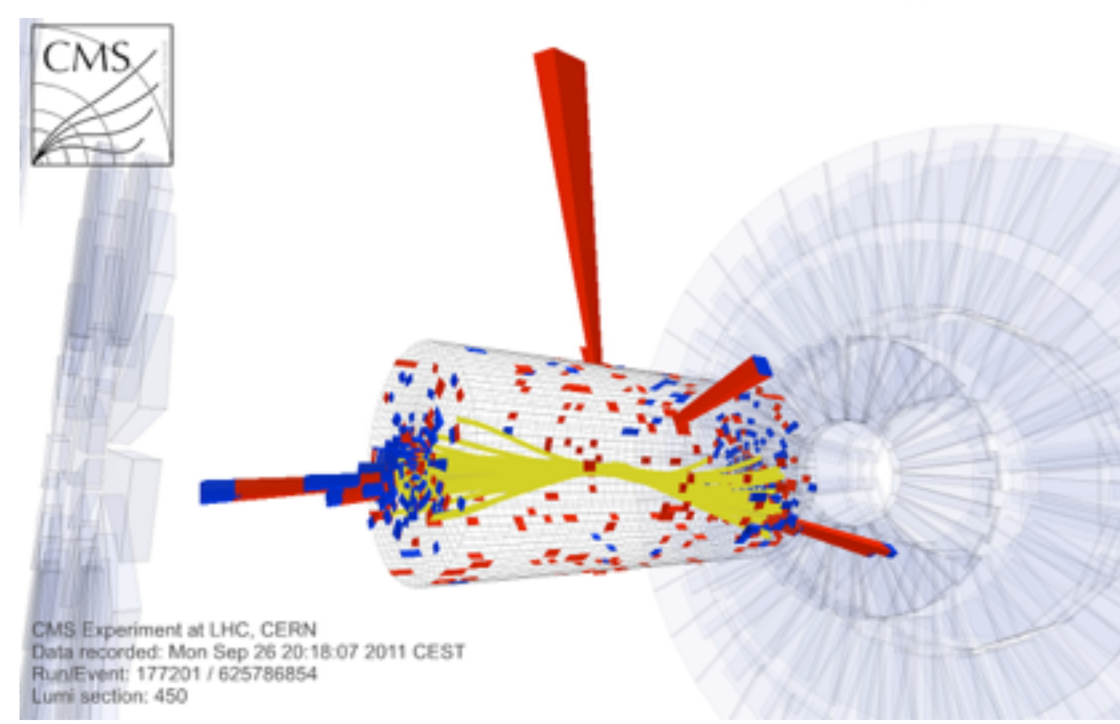
$H \rightarrow \gamma\gamma$

BR = 2.3×10^{-3}
S/B = 1:20

ATLAS : PRD 90 (2014) 112015
CMS : EPJC 74 (2014) 3076



- excellent mass resolution : 1-2%
- select two isolated high p_T photons
- dedicated vertex finding algorithm
- sophisticated energy calibration
- split events into exclusive categories
- Background estimated by fitting to $m_{\gamma\gamma}$



$H\rightarrow\gamma\gamma$

BR = 2.3×10^{-3}

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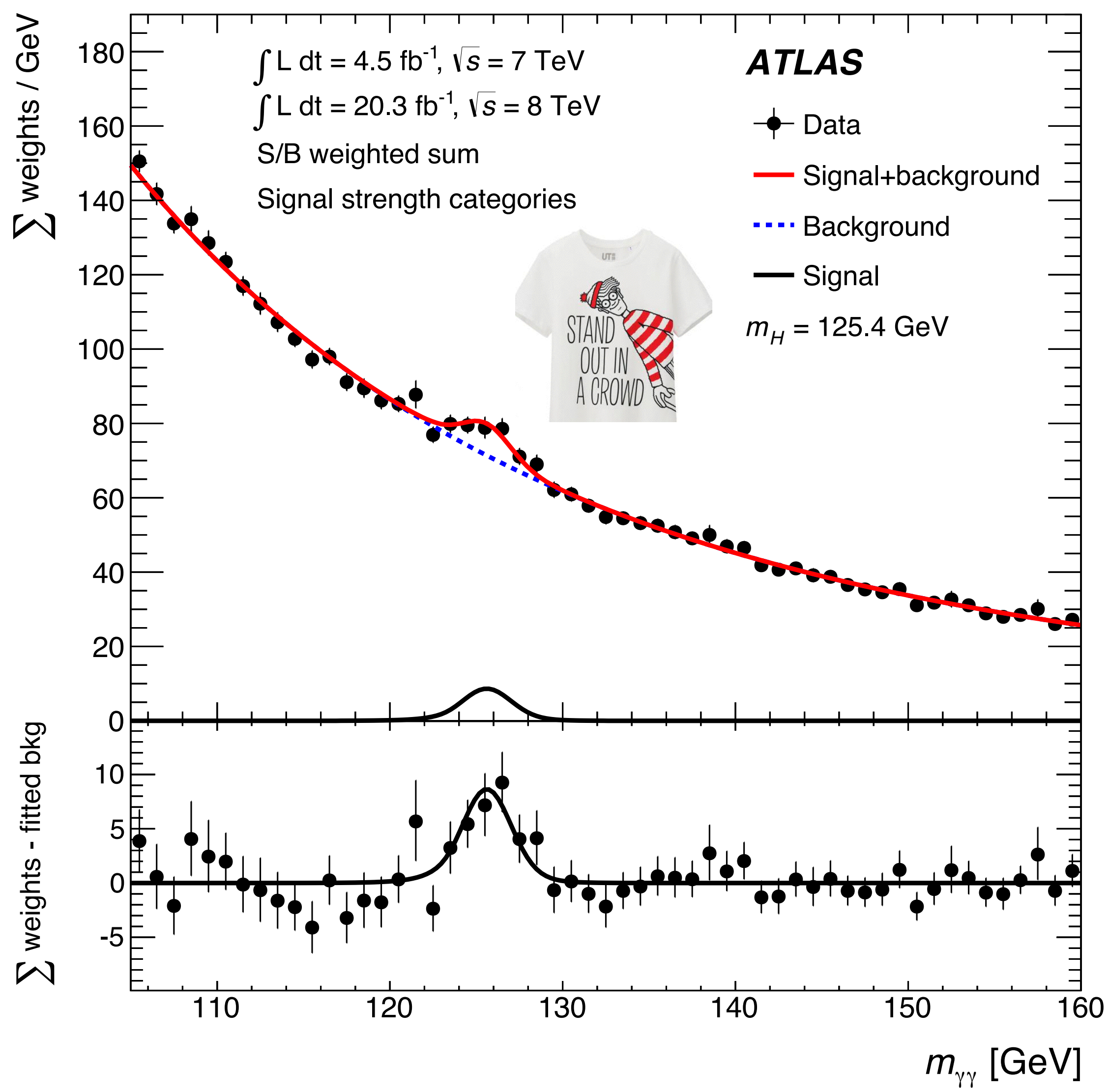
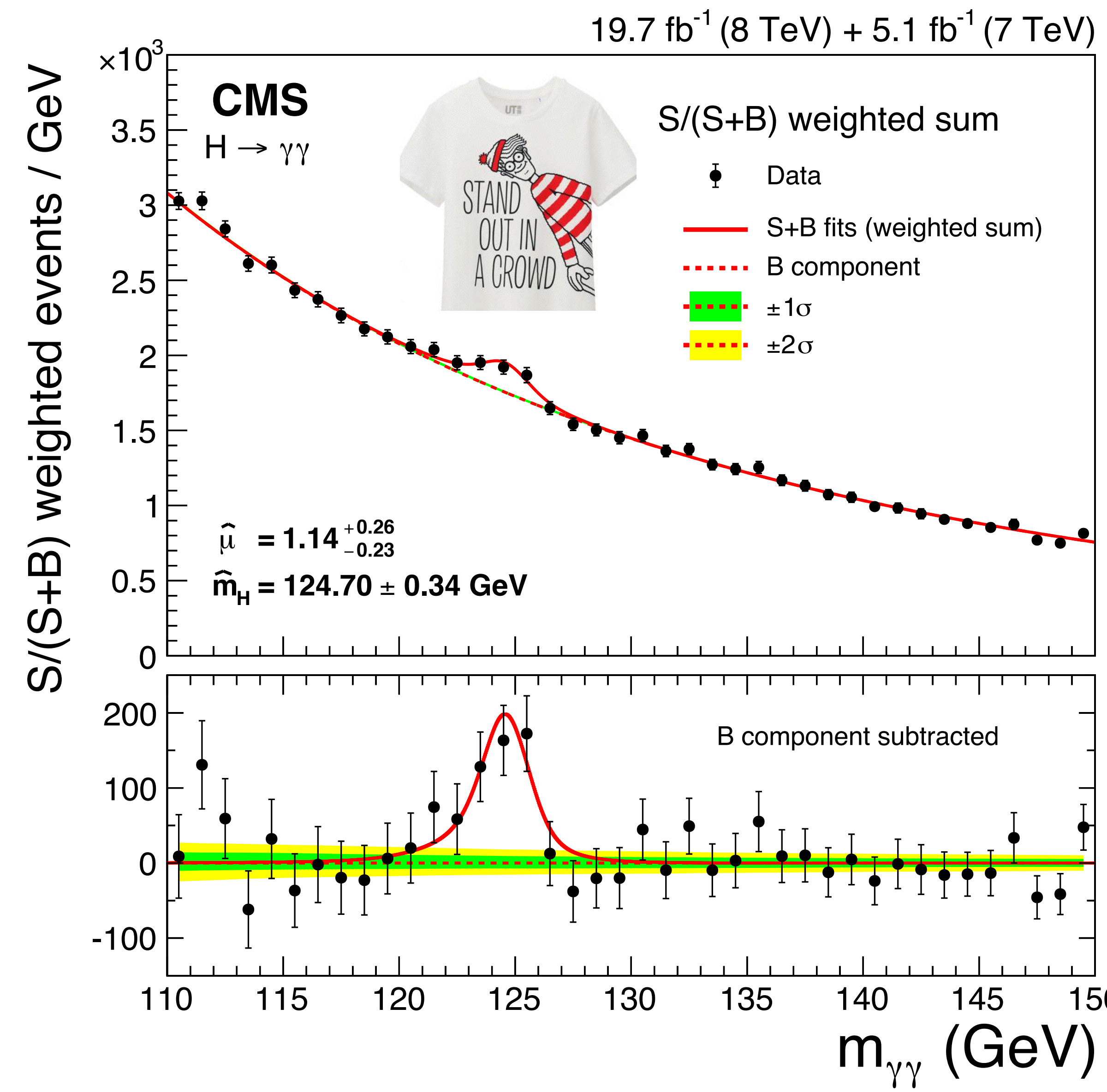
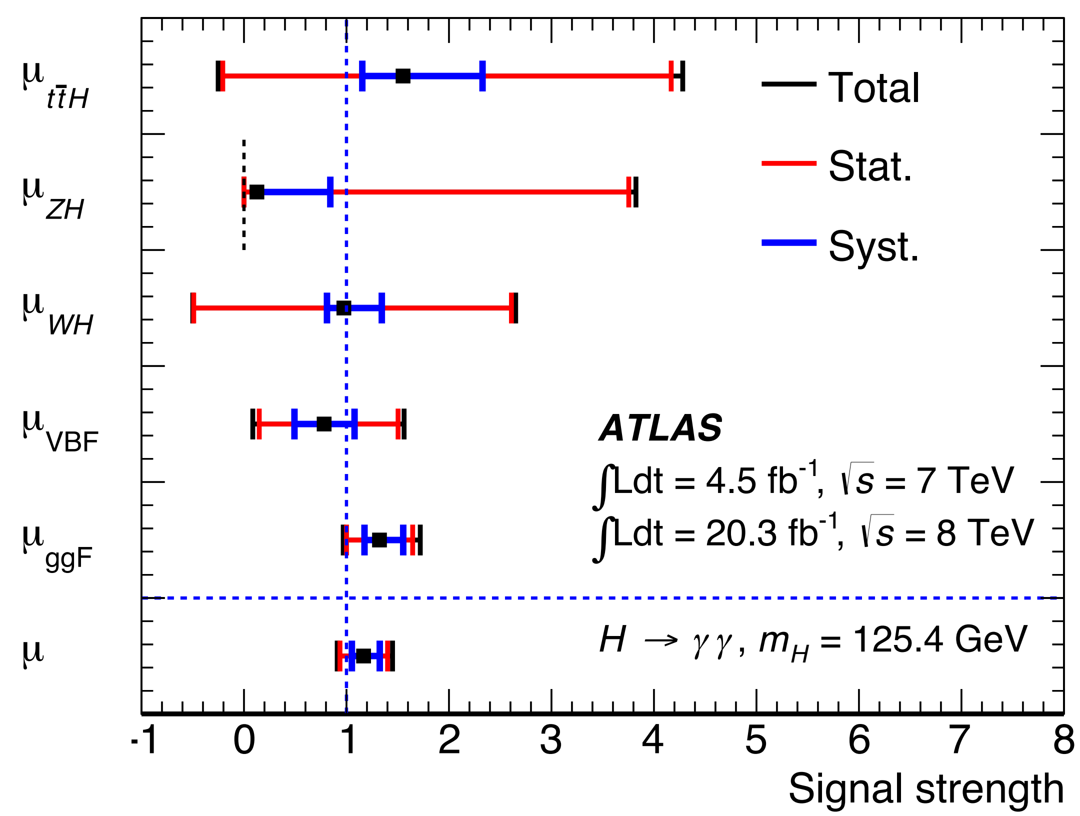
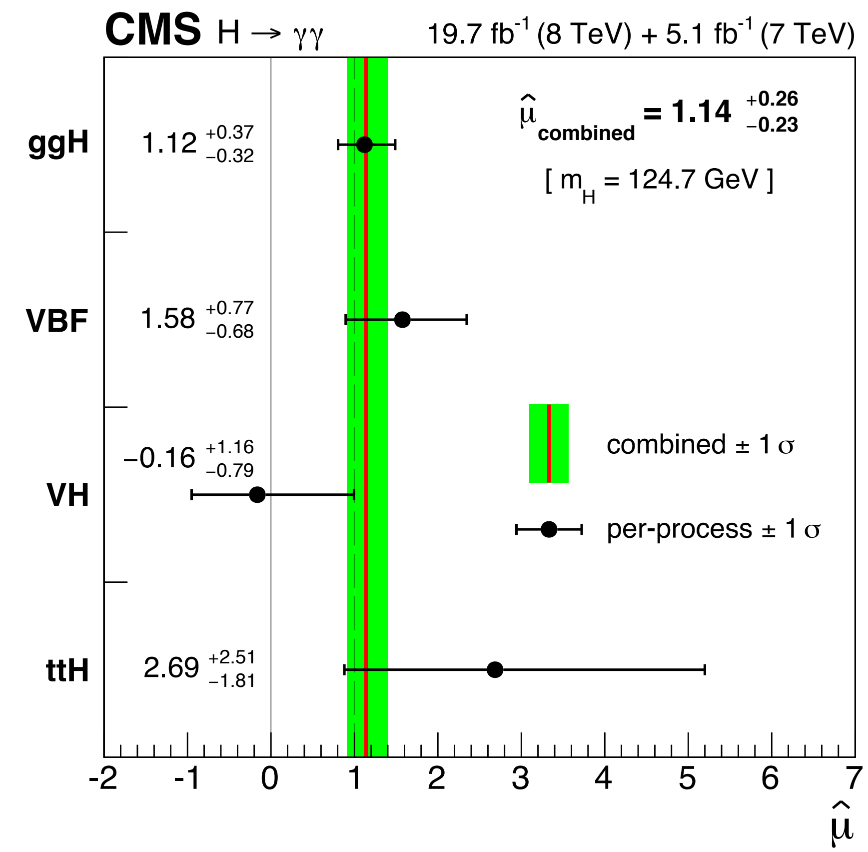




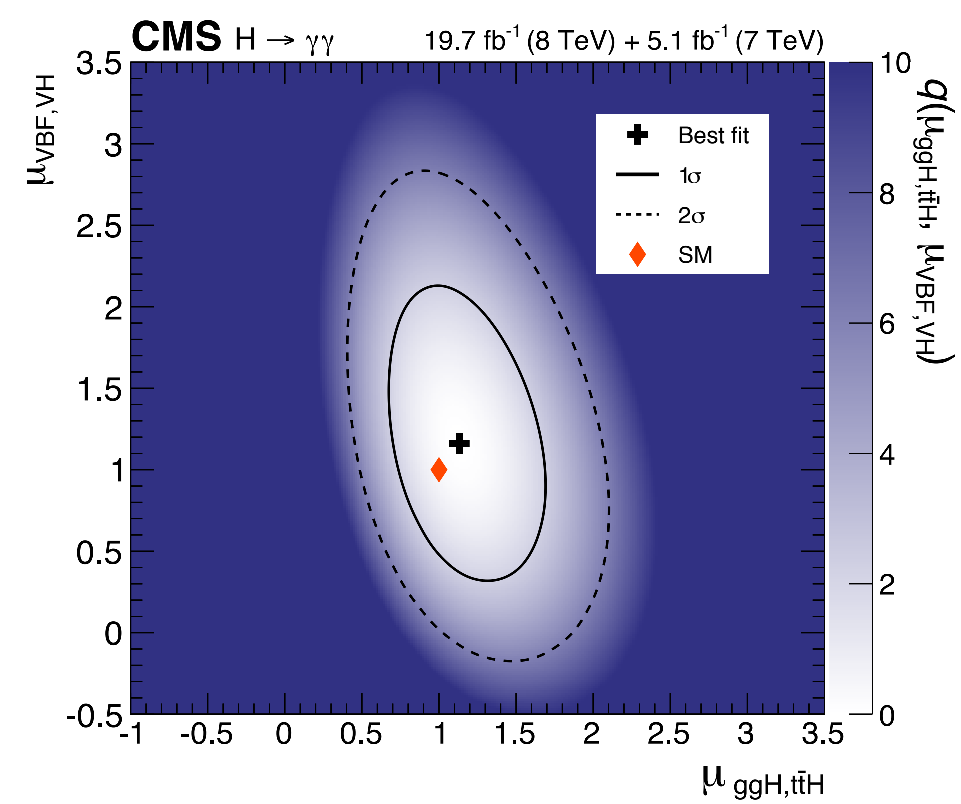
	Datasets	obs. (exp.) local significance
Atlas	**7+8 TeV**	**5.2σ (4.6σ)**
CMS	**7+8 TeV**	**5.7σ (5.2σ)**

$H \to \gamma\gamma$ signal strength





	Datasets	best-fit $\mu = \sigma/\sigma_{SM}$
Atlas	**7+8 TeV**	**1.17 ± 0.27**
CMS	**7+8 TeV**	**$1.14^{+0.26}_{-0.23}$**

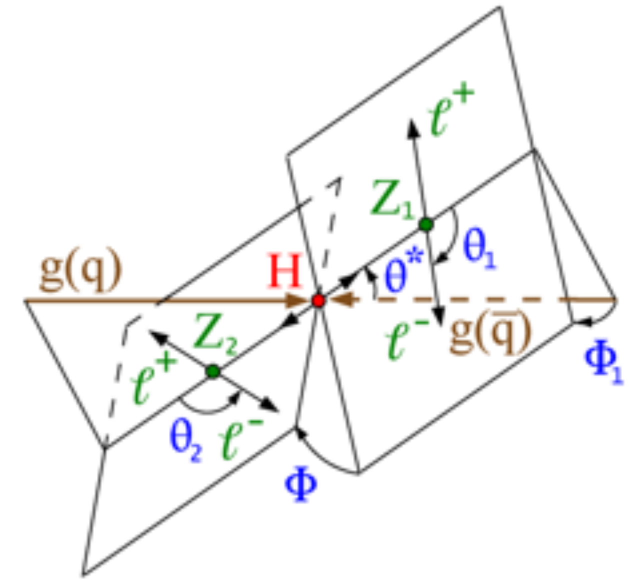


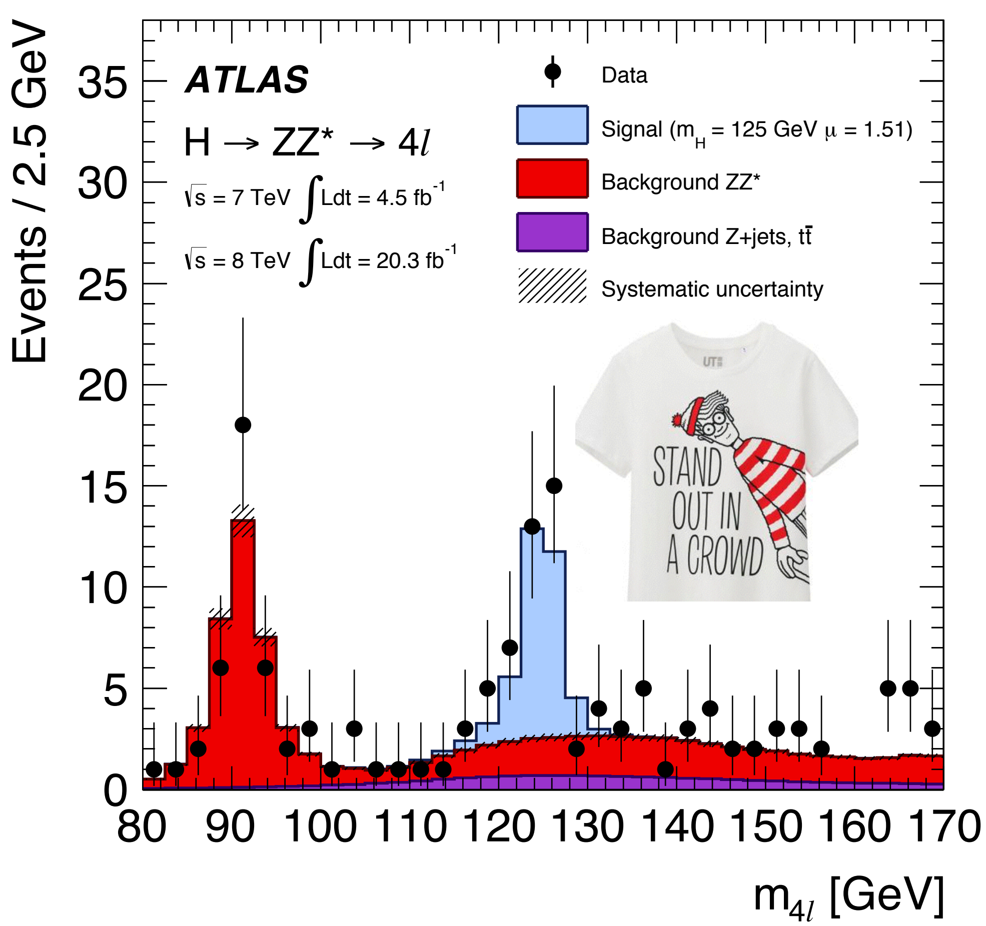
$H \rightarrow ZZ \rightarrow 4l$

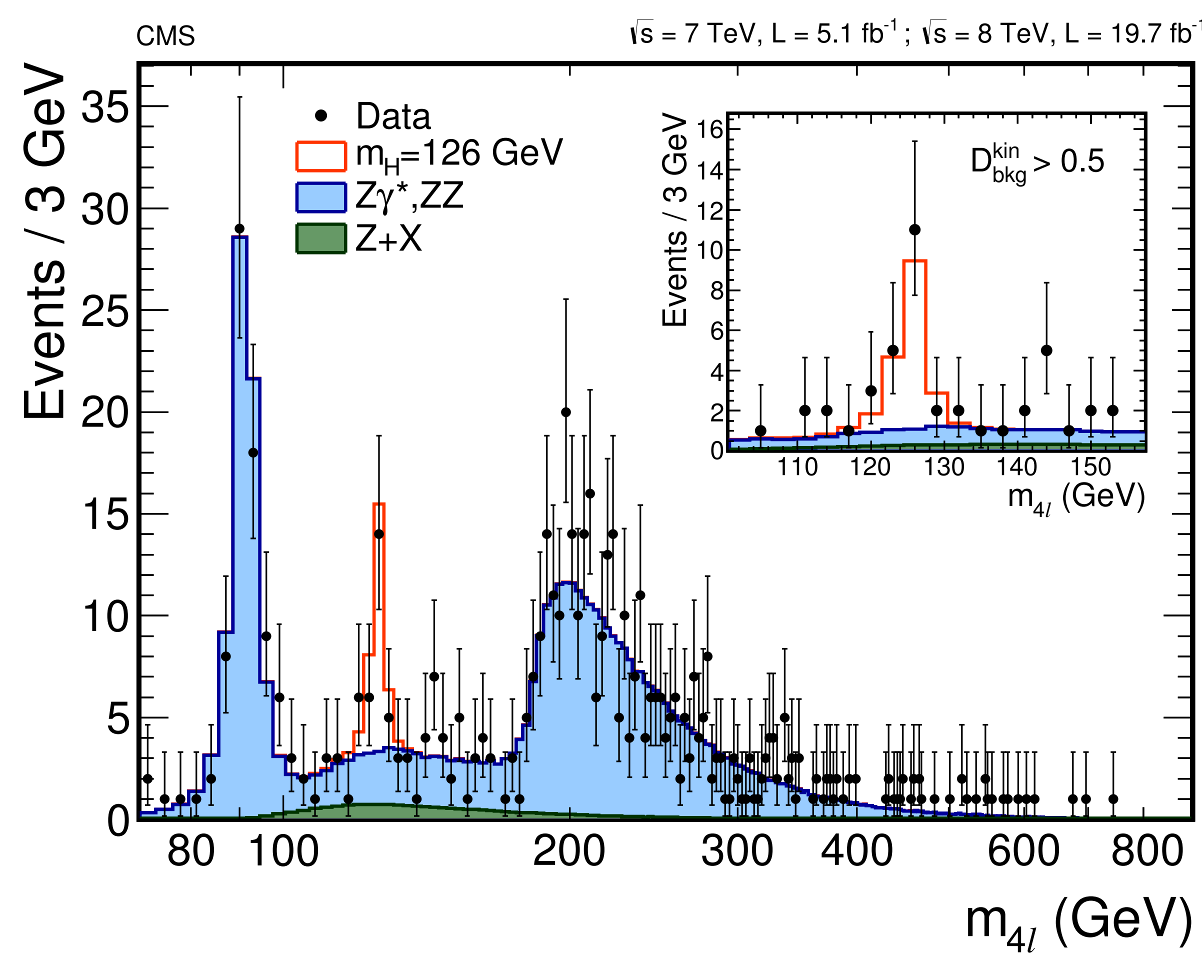
BR = 1.3×10^{-4}
l = e,μ (S:B = 2:1)

ATLAS : PRD 91 (2015) 012006
CMS : PRD 89 (2014) 092007

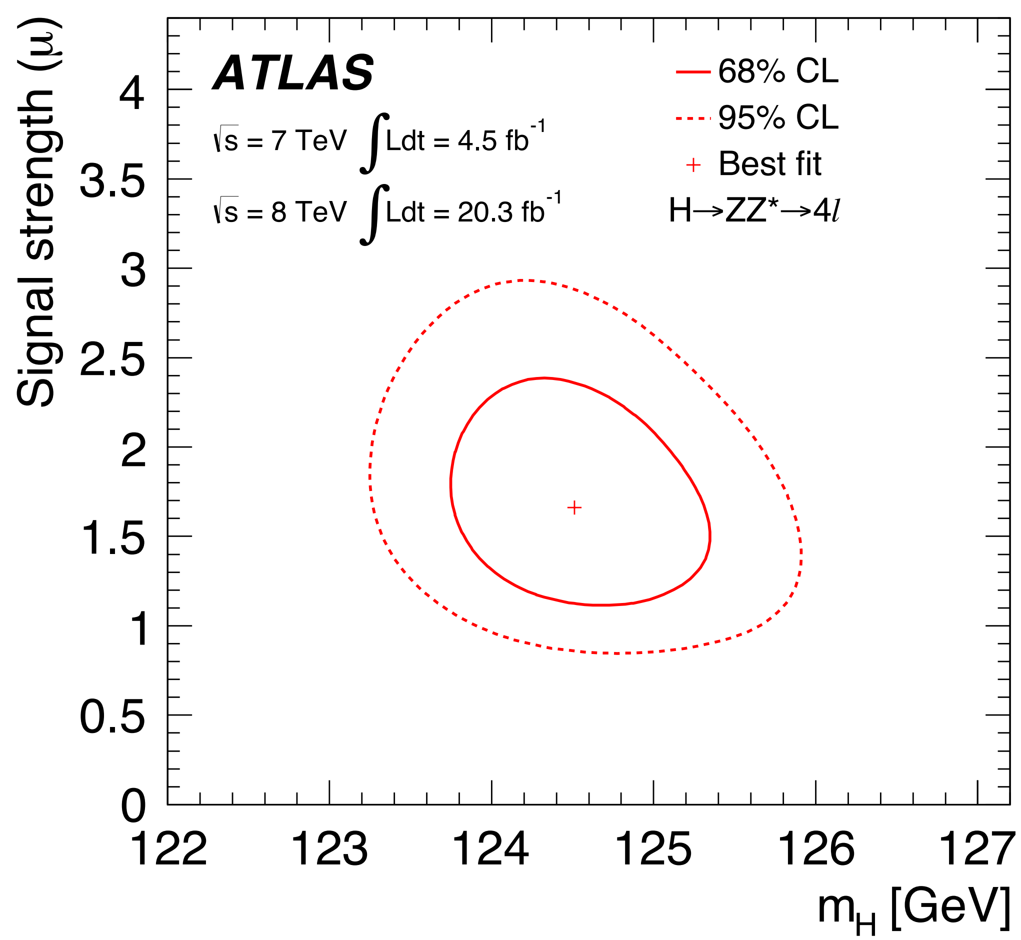
- excellent mass resolution : 1-2%
- select four isolated leptons (low p_T is important)
- split events into exclusive categories
- Fold angular information in a kinematic discriminant to separate signal and background

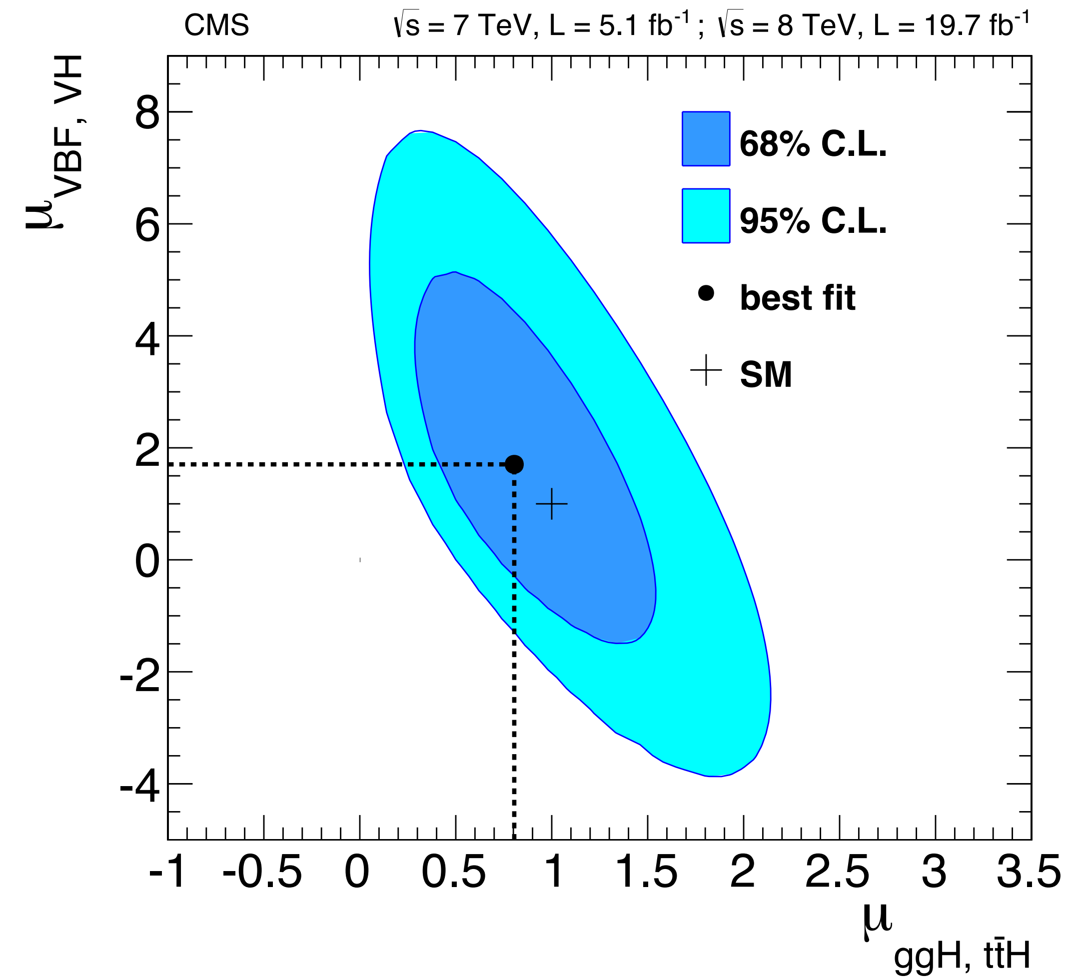






$H \to ZZ \to 4l$



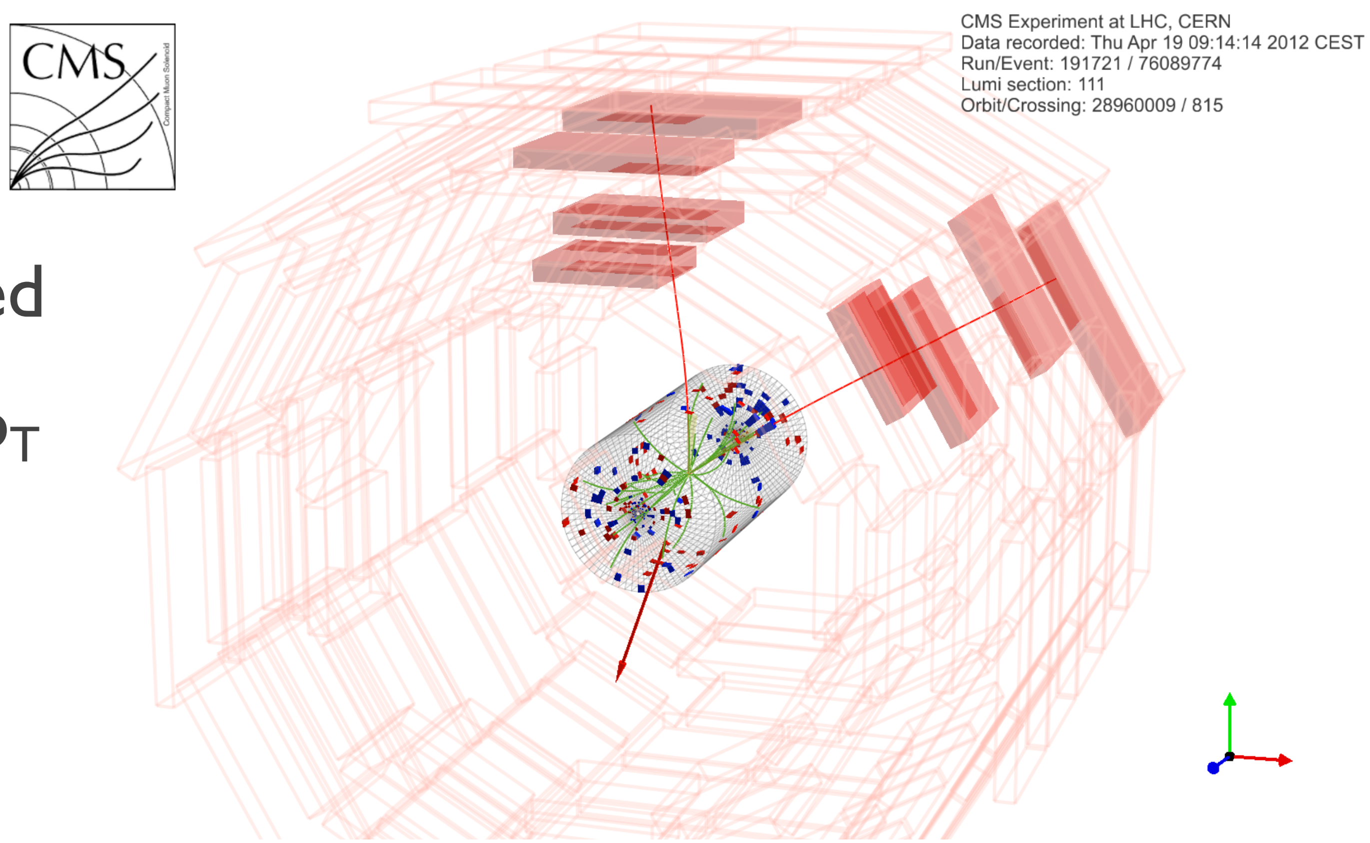


	Datasets	best-fit $\mu = \sigma/\sigma_{SM}$	obs.(exp.) local significance
Atlas	**7+8 TeV**	**$1.66^{+0.39}_{-0.34}$(stat.)$^{+0.21}_{-0.14}$(syst.) @ 124.5 GeV**	**8.2σ (5.8σ)**
CMS	**7+8 TeV**	**$0.93^{+0.26}_{-0.23}$(stat.)$^{+0.13}_{-0.09}$(syst.) @ 125.6 GeV**	**6.8σ (6.7σ)**

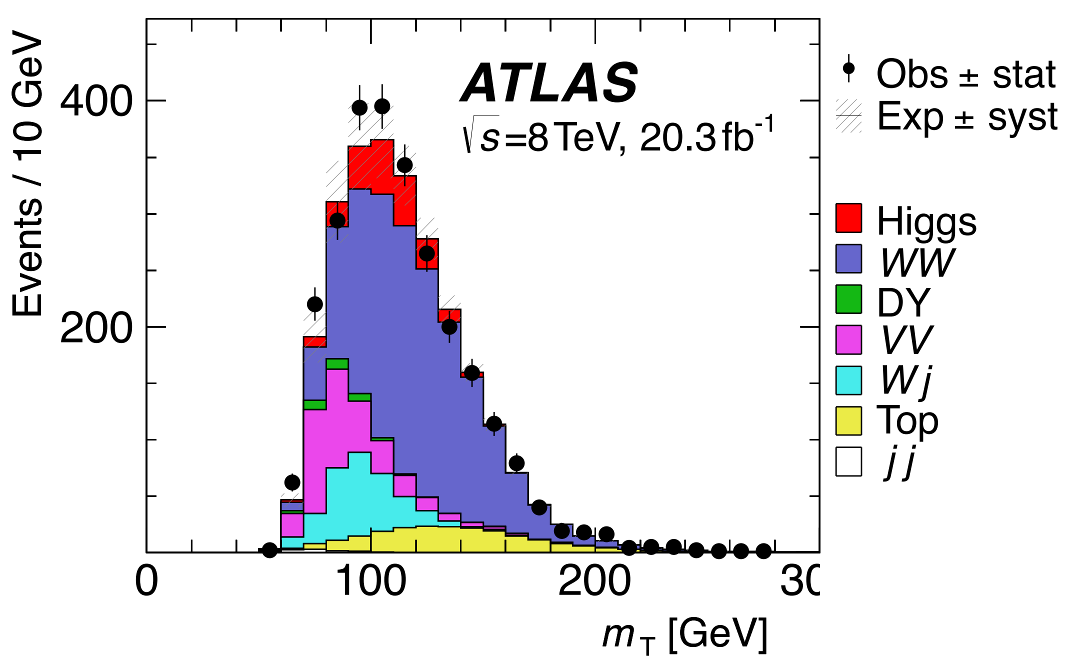
$H\to WW\to 2l2\nu$

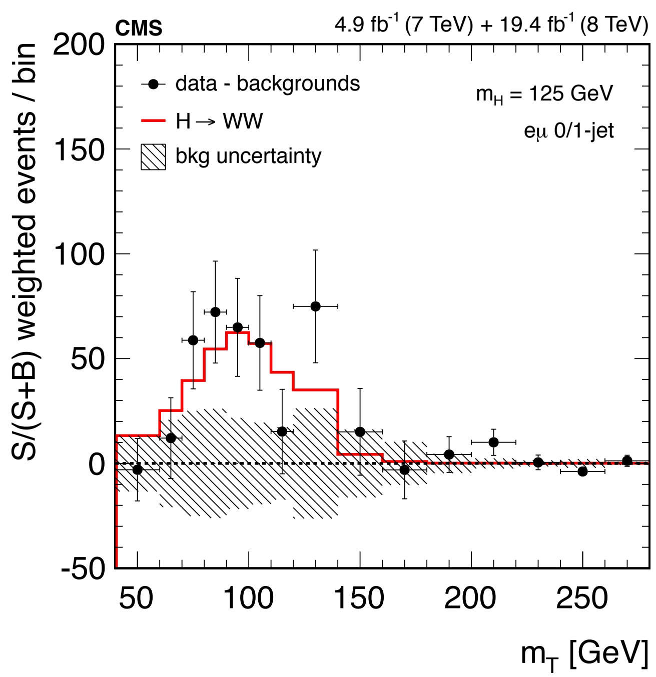
BR = 1.1×10^{-2}
l = e,μ (S:B = 1:10)

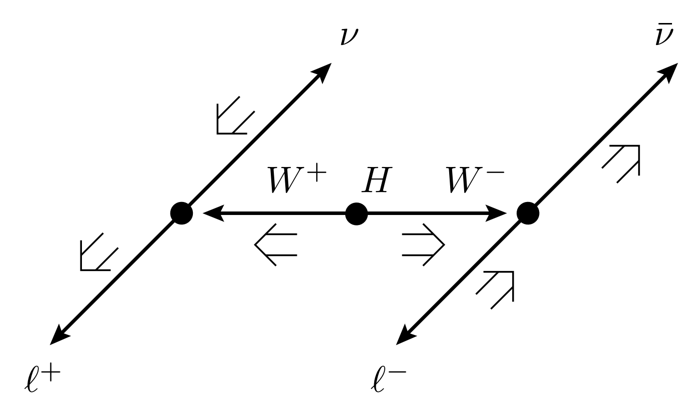
ATLAS : PRD 92 (2015) 012006
CMS : JHEP 1401 (2014) 096



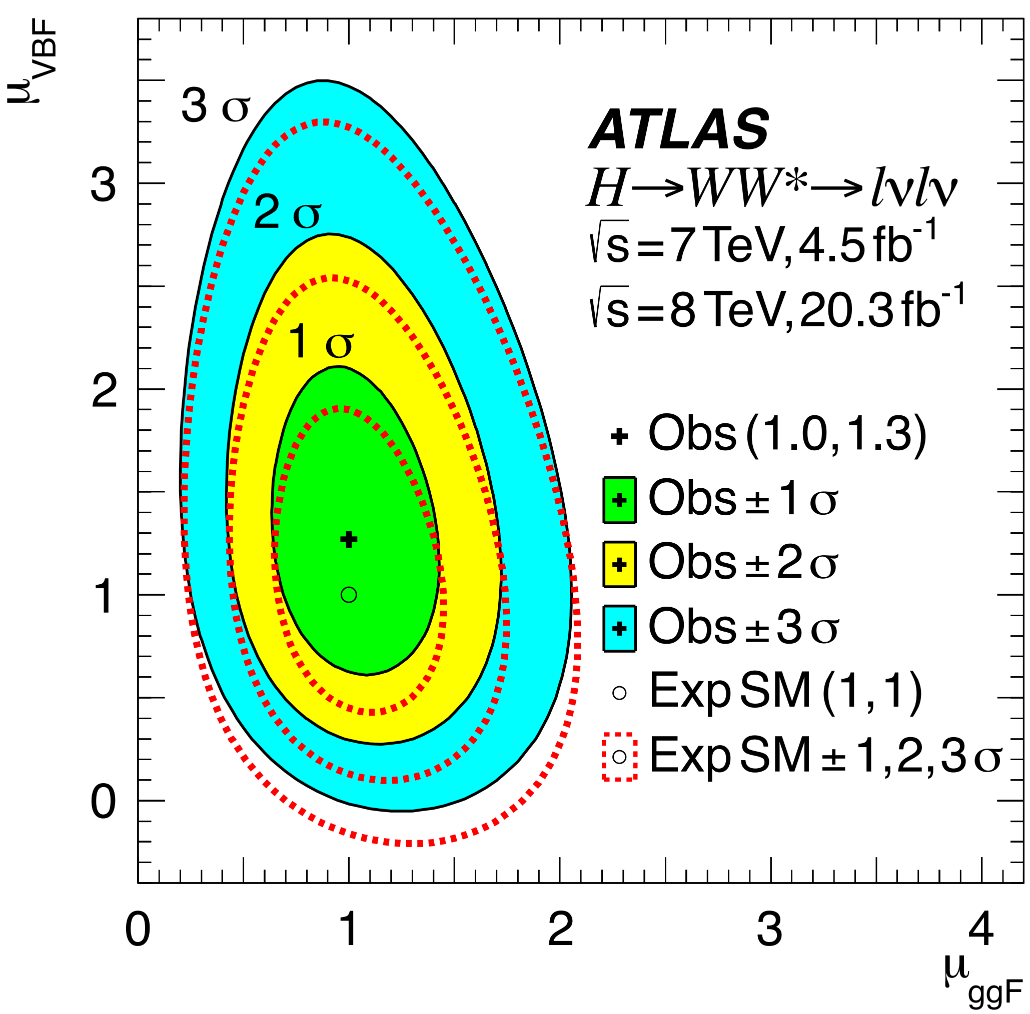
- mass resolution : 20%
- Final state cannot be fully reconstructed
    - main observable : m_T, m_{ll}, lepton p_T
- analysis performed in categories
- Angular correlations used to reject background

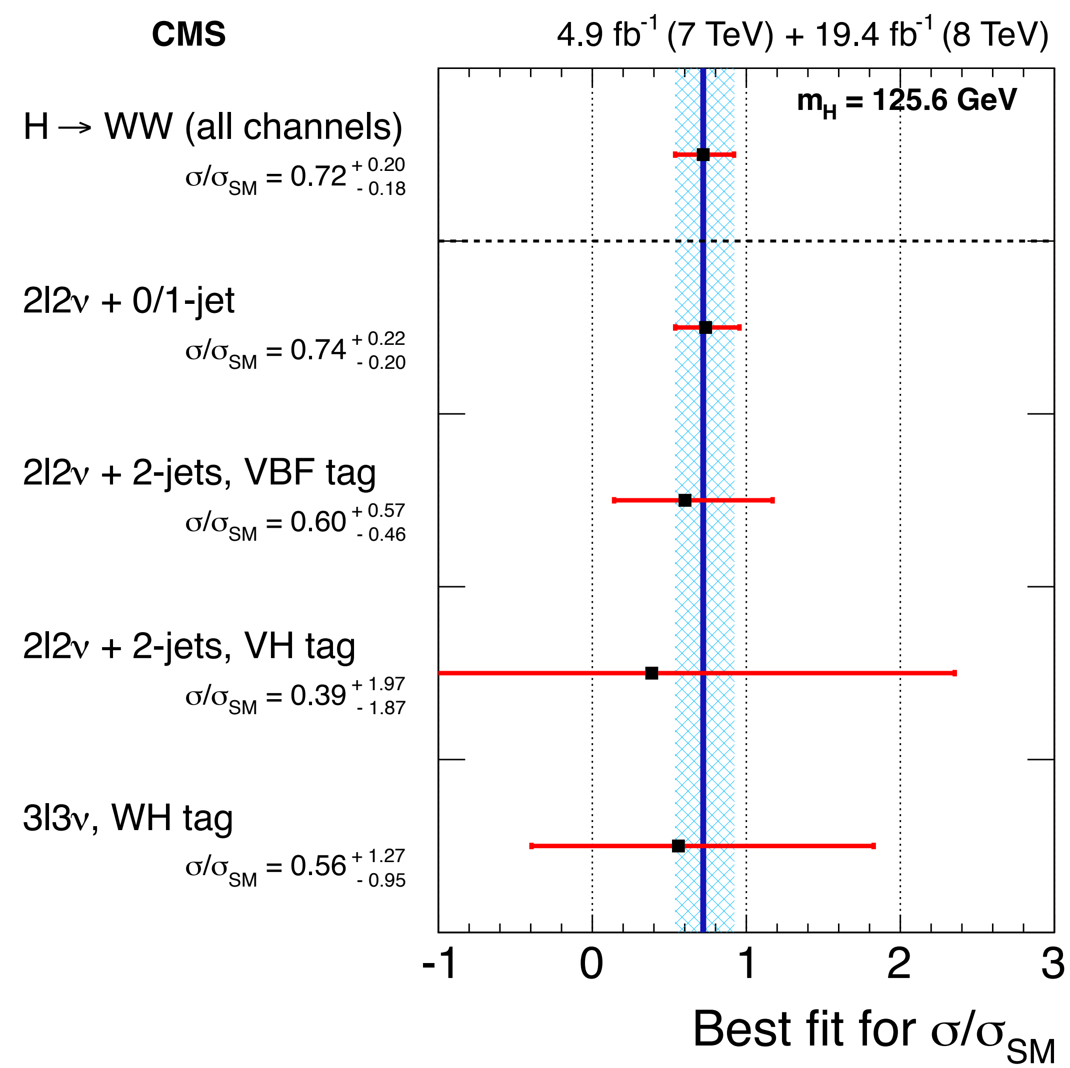






$H \rightarrow WW \rightarrow 2l2\nu$





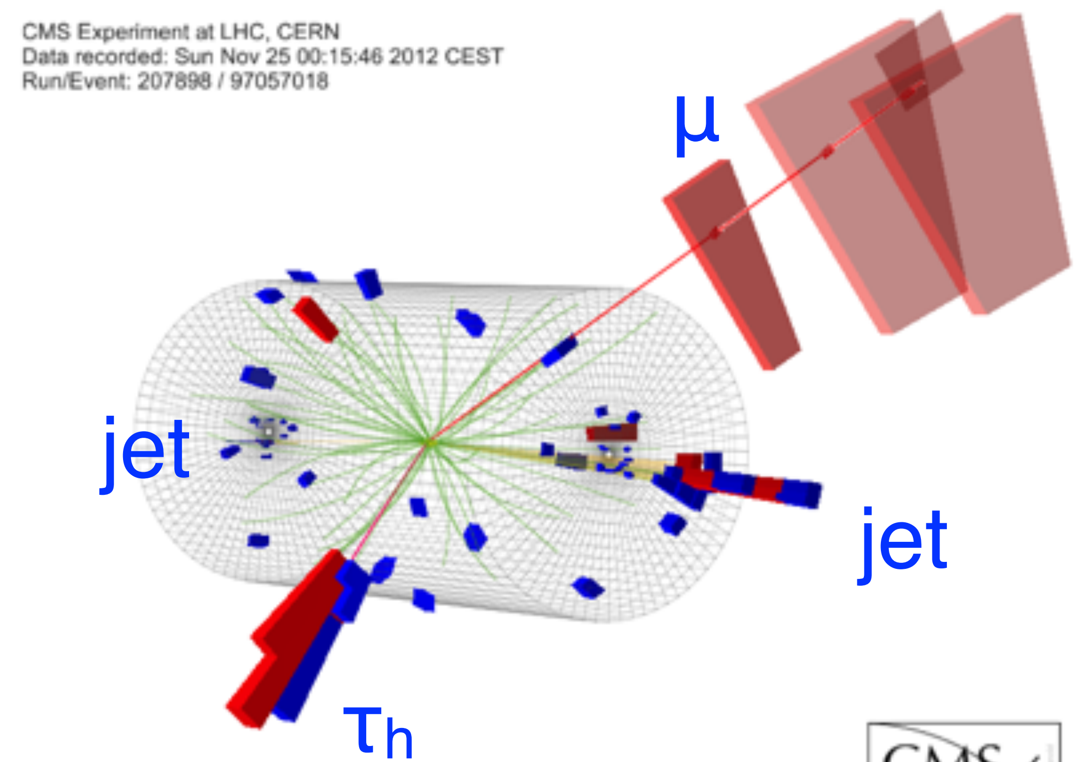
	Datasets	best-fit $\mu = \sigma/\sigma_{SM}$	obs.(exp.) local significance
Atlas	**7+8 TeV**	**$1.09^{+0.23}_{-0.21}$ @ 125.4 GeV**	**6.1σ (5.8σ)**
CMS	**7+8 TeV**	**$0.72^{+0.20}_{-0.18}$ @ 125.6 GeV**	**4.3σ (5.8σ)**

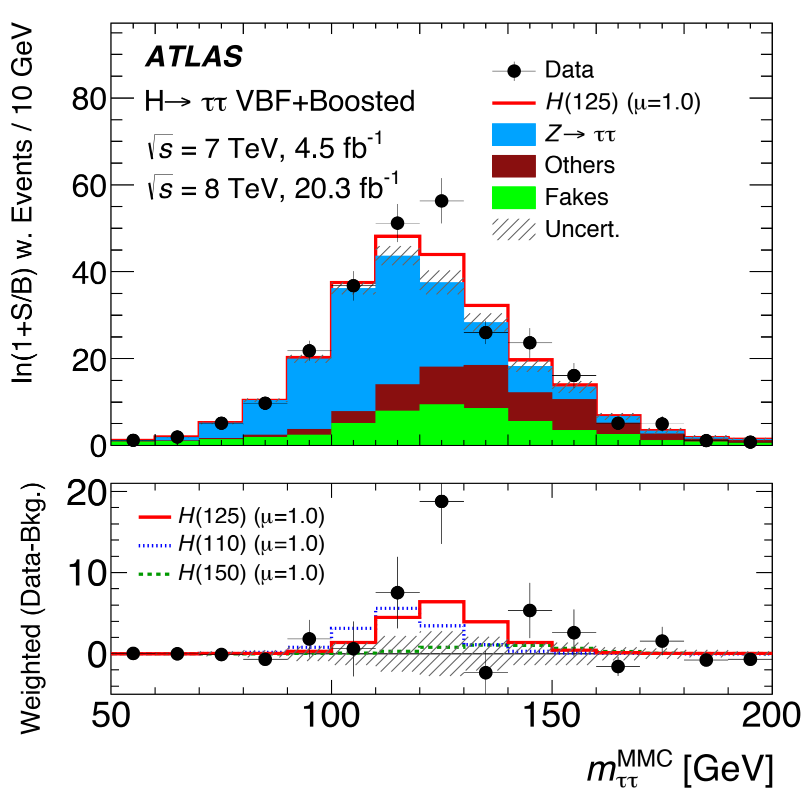
$H \to \tau\tau$

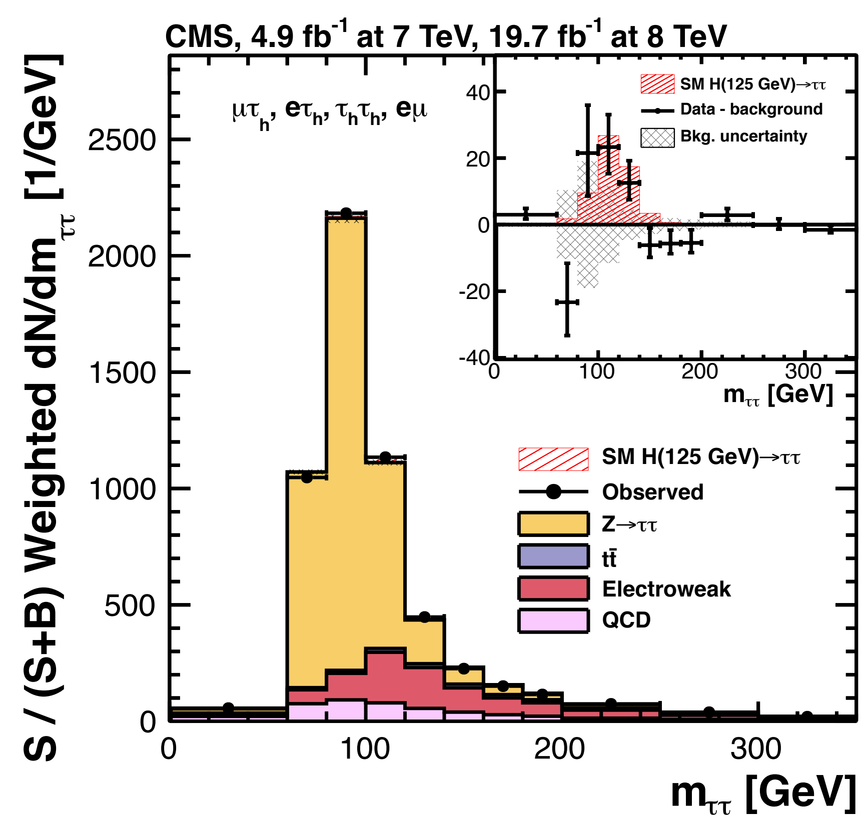
BR = 6.3×10^{-2}
(S:B = 1:50)

ATLAS : JHEP 04 (2015) 117
CMS : JHEP 05 (2014) 104

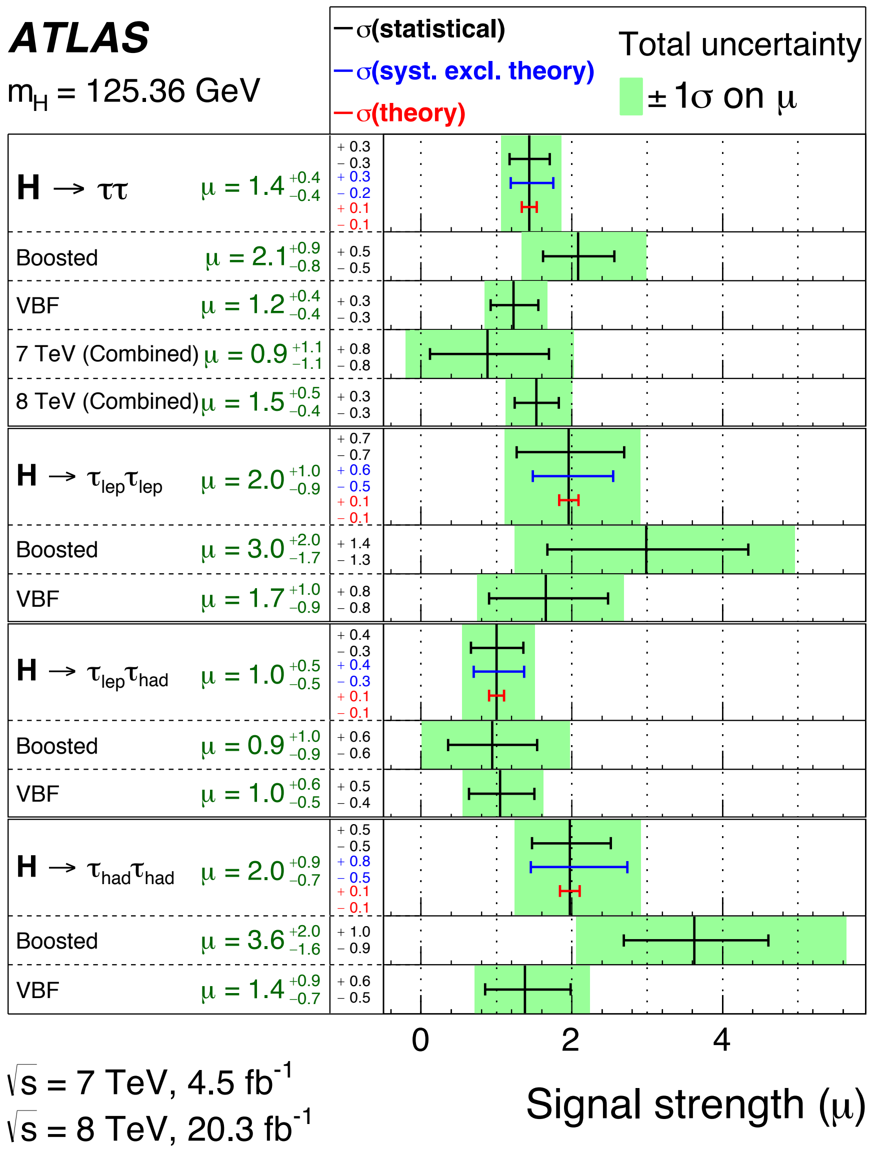
- look into $e\tau_h$, $e\tau_h$, ee, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- mass resolution : 10-20%
- experimental challenges : hadronic τ ID, $m_{\tau\tau}$ reconstruction
- categories motivated by production
  - sensitivity mainly driven by VBF

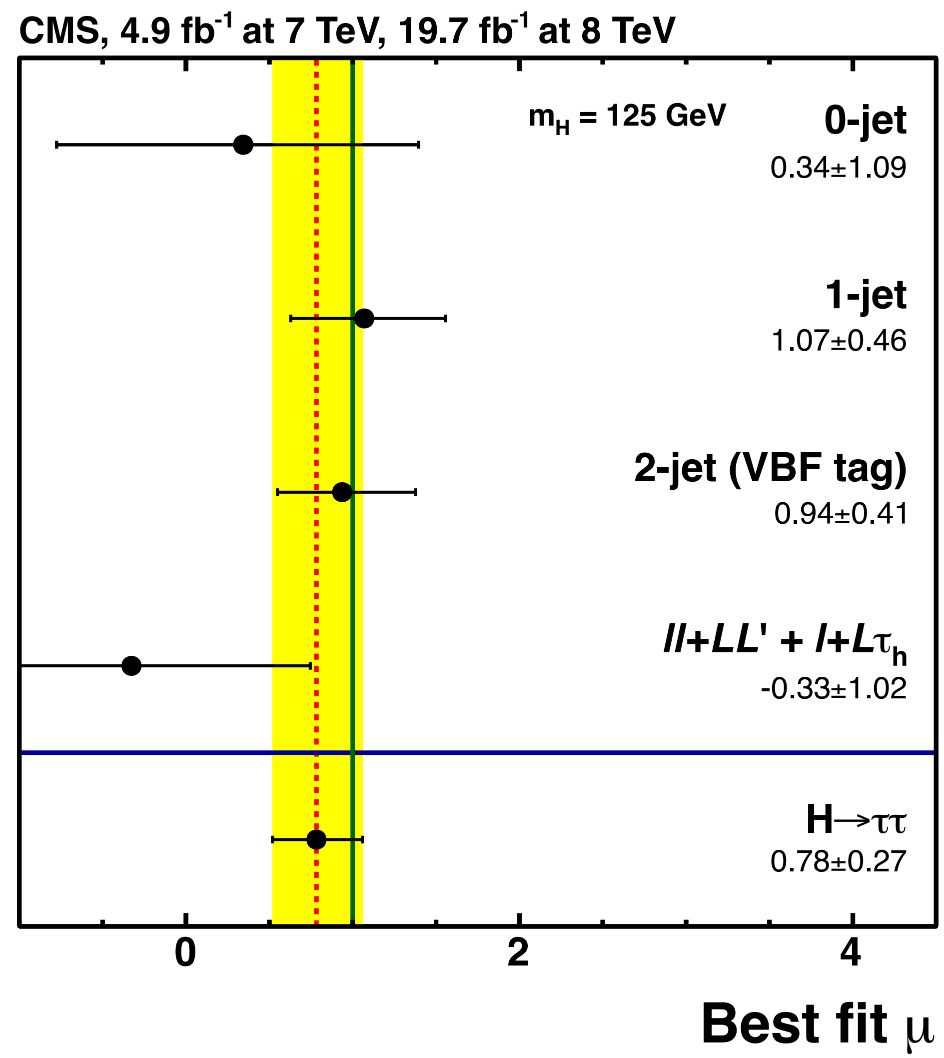






$H \to \tau\tau$





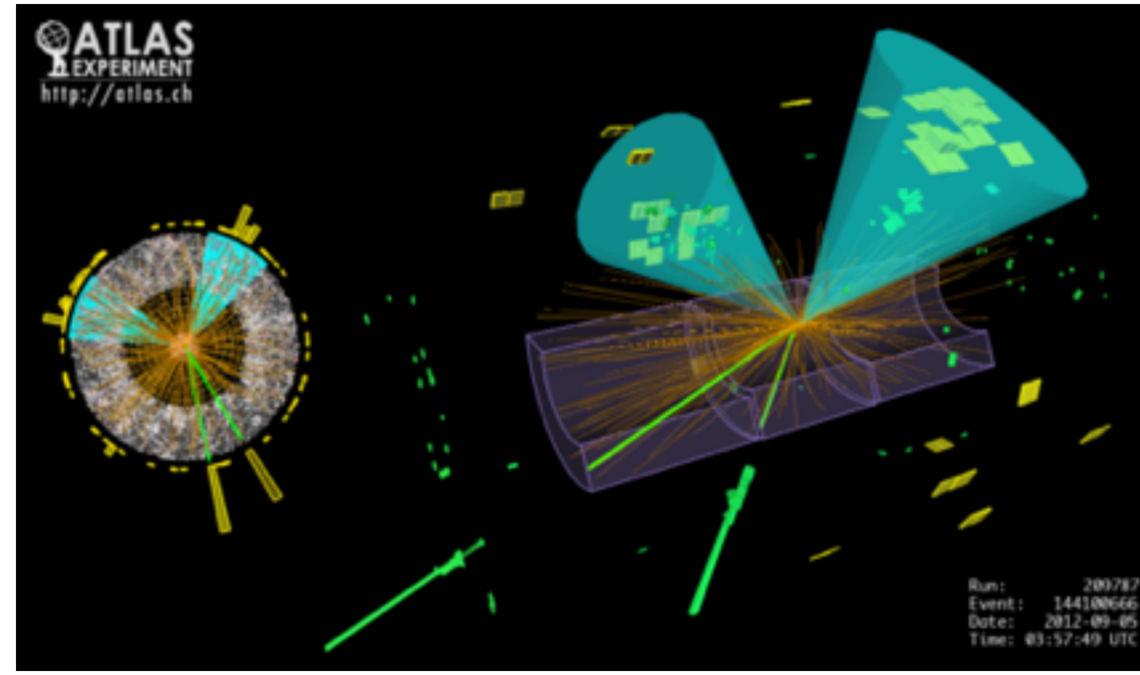
	Datasets	best-fit $\mu = \sigma/\sigma_{SM}$	obs.(exp.) local significance
Atlas	**7+8 TeV**	**$1.43^{+0.43}_{-0.37}$@ 125.4 GeV**	**4.5σ (3.4σ)**
CMS	**7+8 TeV**	**0.86 ± 0.29 @ 125.0 GeV**	**3.4σ (3.6σ)**

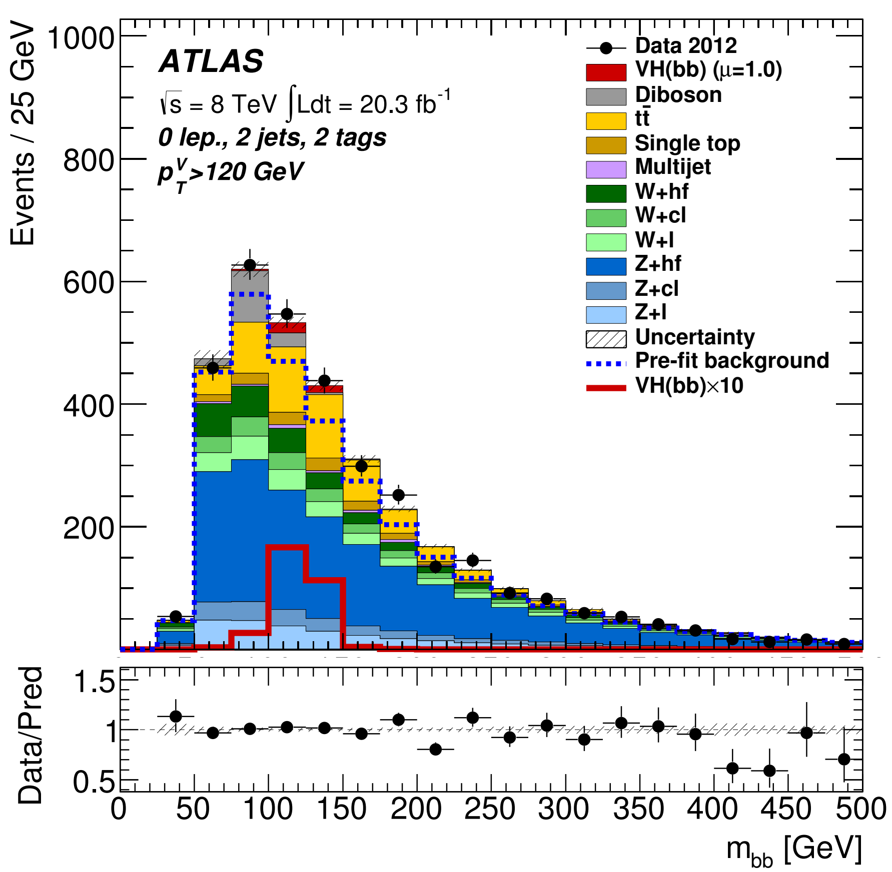
H→bb

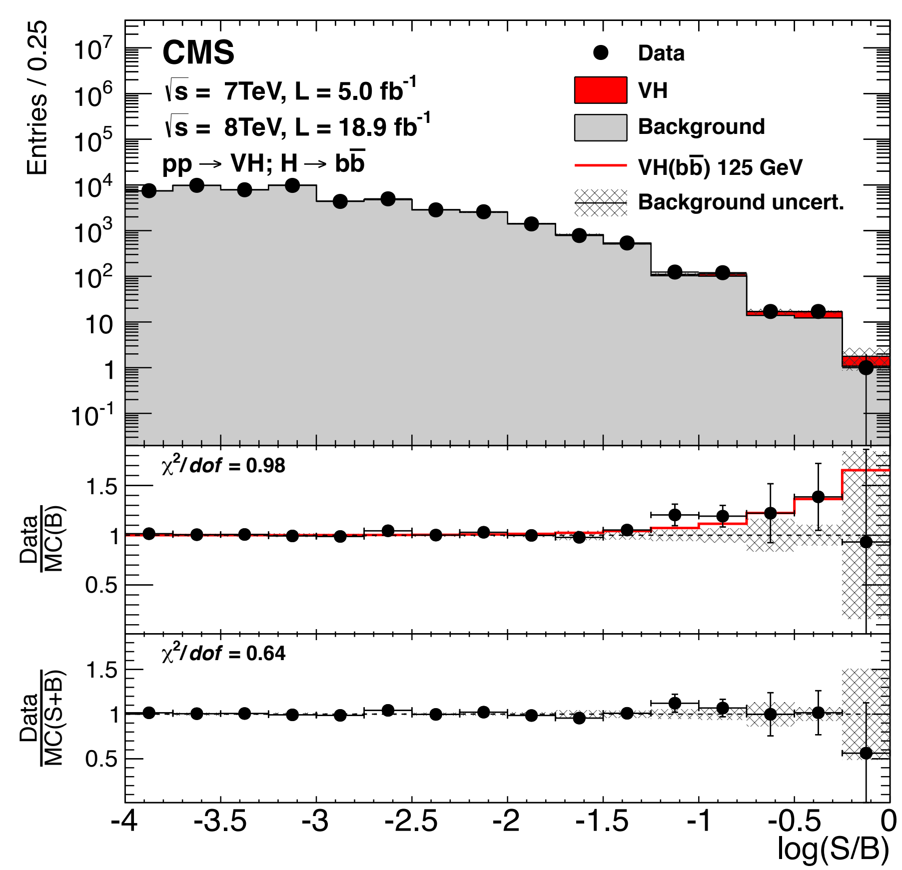
BR = 0.58
(S:B = 1:20)

ATLAS : JHEP 01 (2015) 069
CMS : PRD 89 (2014) 012003
PAS HIG-13-011

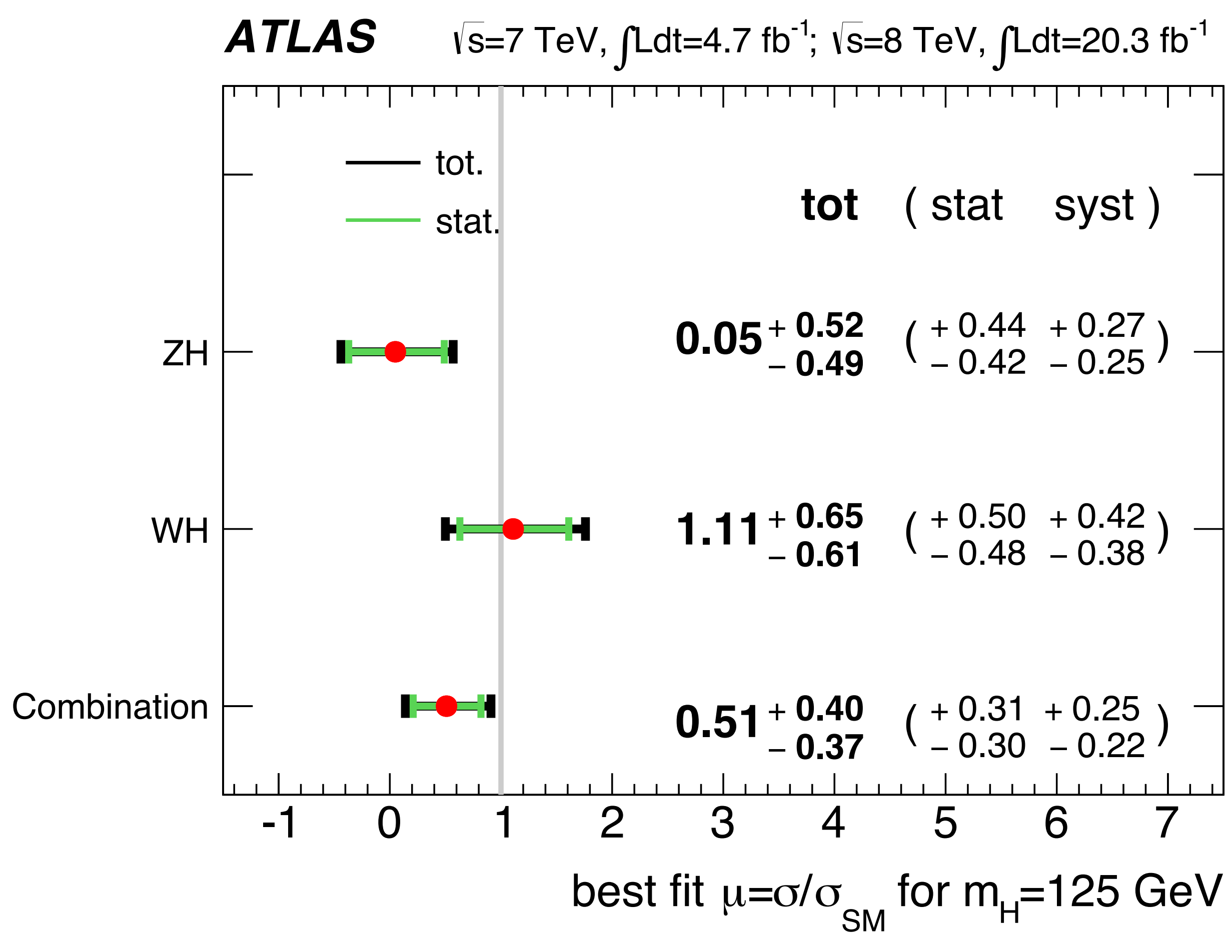
- mass resolution : 10%
- two b-tagged jets (very challenging at hadron collider)
- look into VH (and ttH)

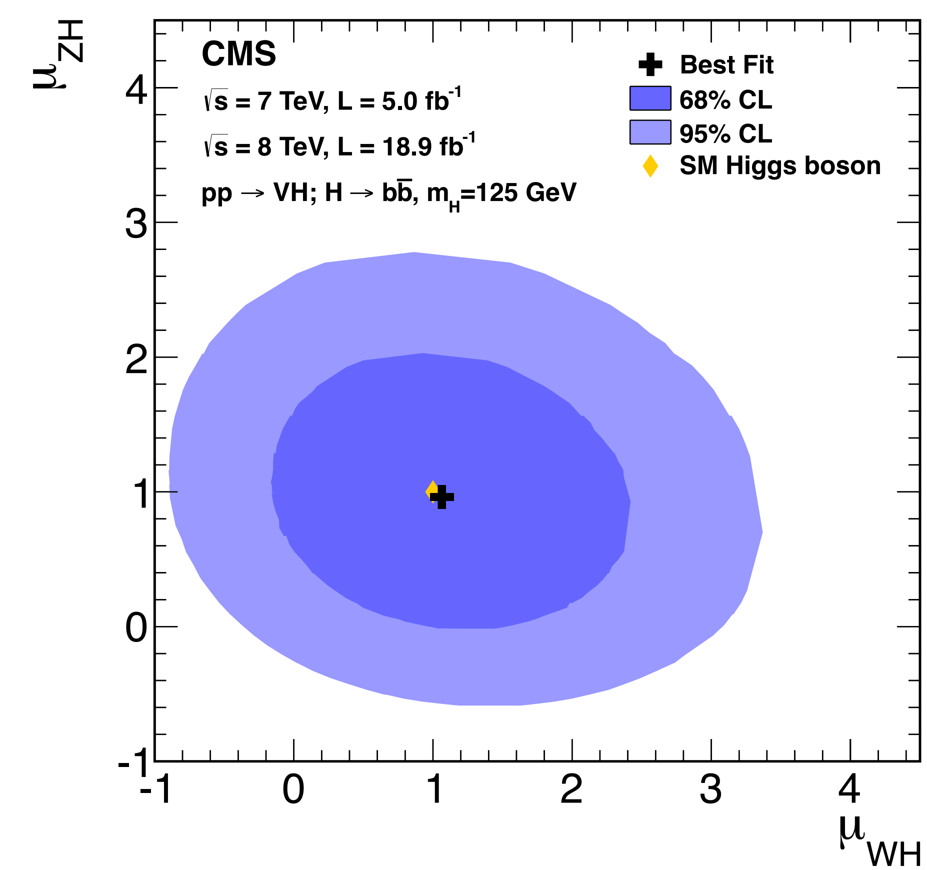






$H \to bb$

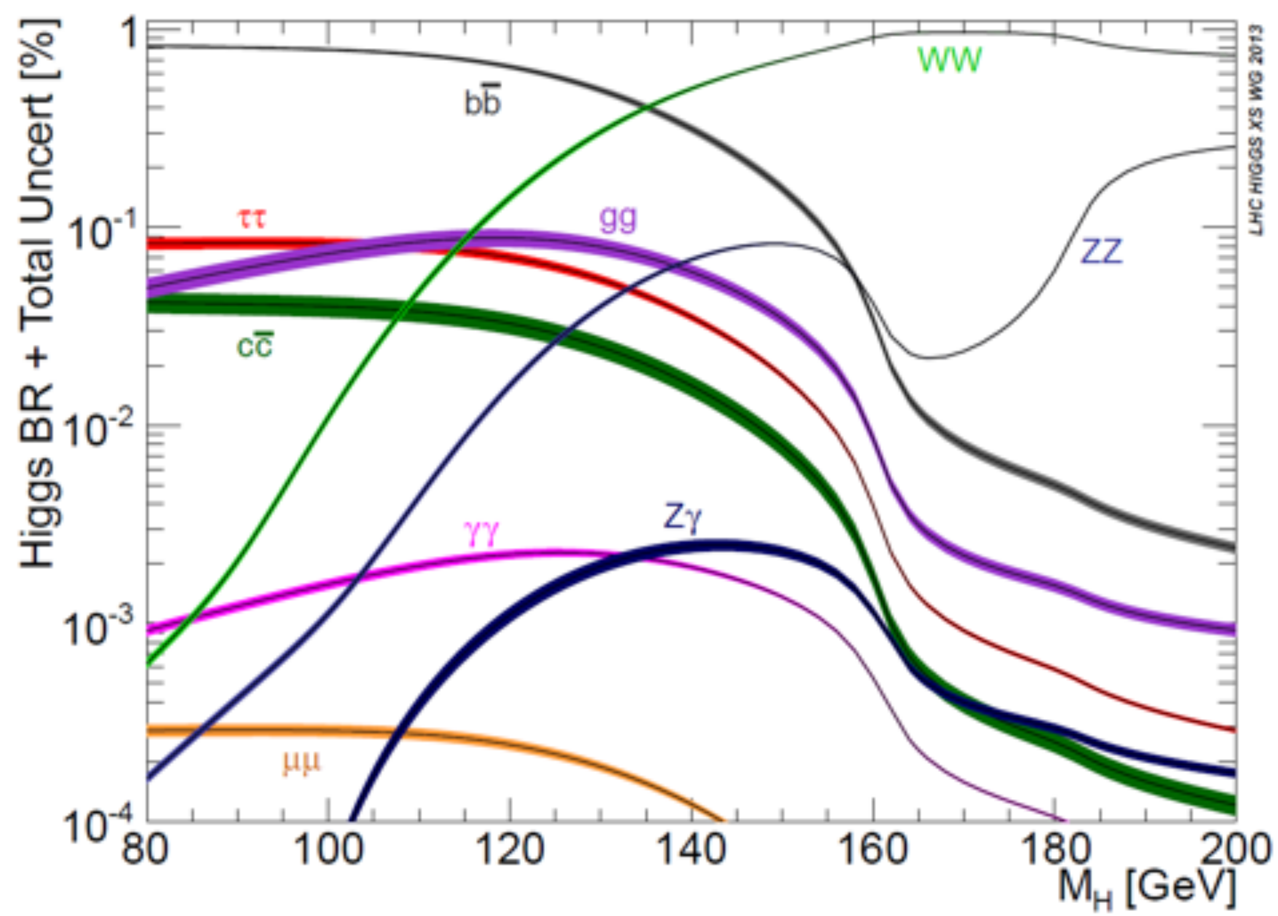




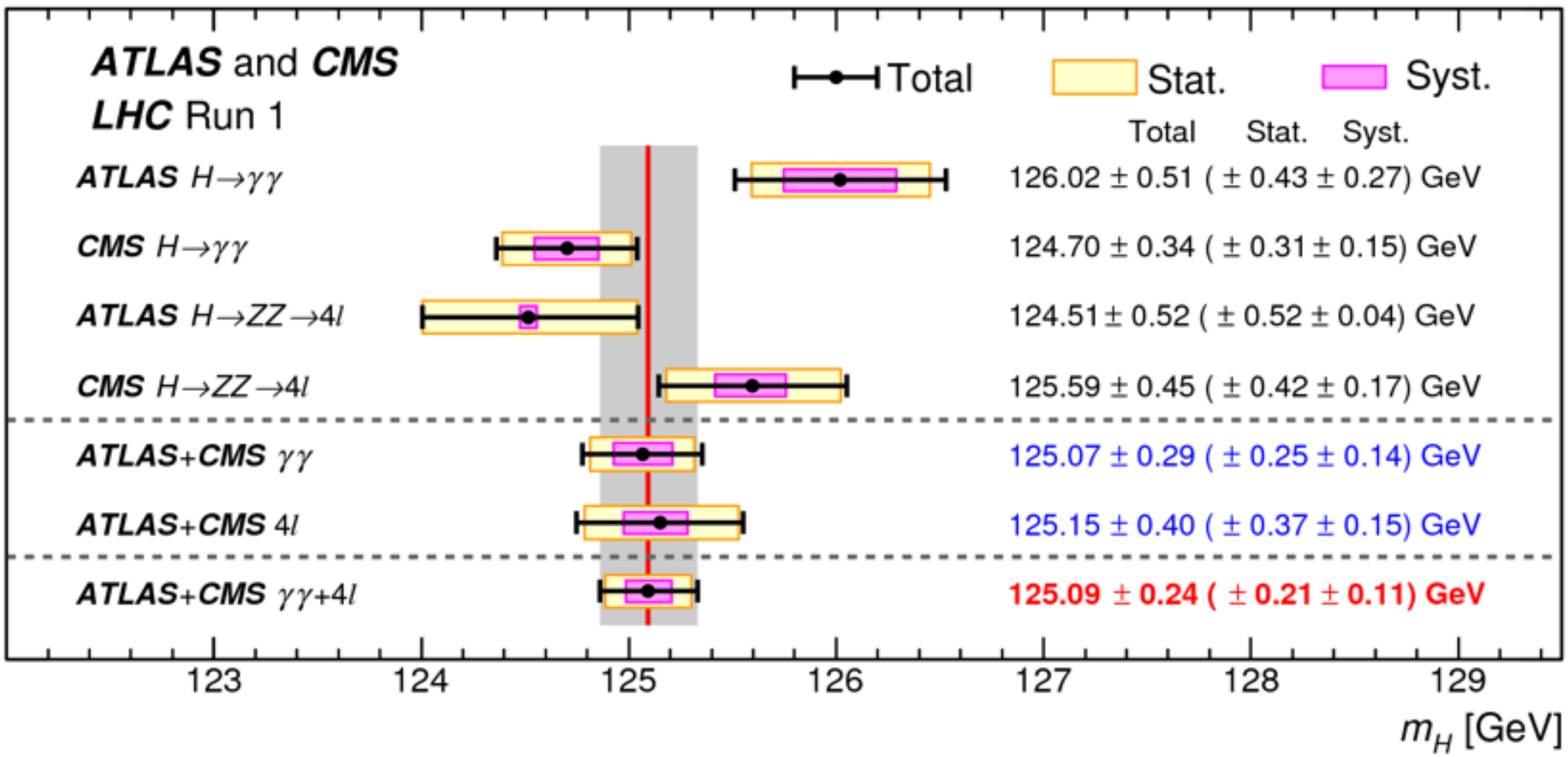
	Datasets	best-fit $\mu = \sigma/\sigma_{SM}$	obs.(exp.) local significance
Atlas	**7+8 TeV**	**0.5 ± 0.4 @ 125.4 GeV**	**1.4σ (2.6σ)**
CMS	**7+8 TeV**	**1.0 ± 0.5 @ 125.0 GeV**	**2.1σ (2.1σ)**

Higgs mass

- The mass of the Higgs boson is not predicted
  - It is a free parameter of the SM
  - Once we know the mass, all Higgs couplings (production and decay) within the SM are known



Combined Measurement of m_H

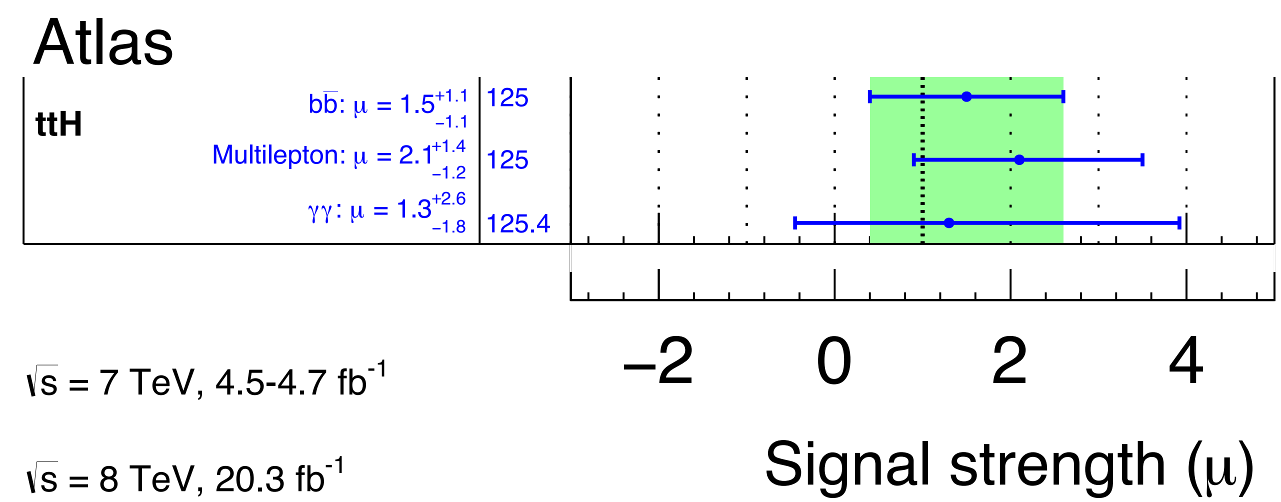


Rare productions and decays

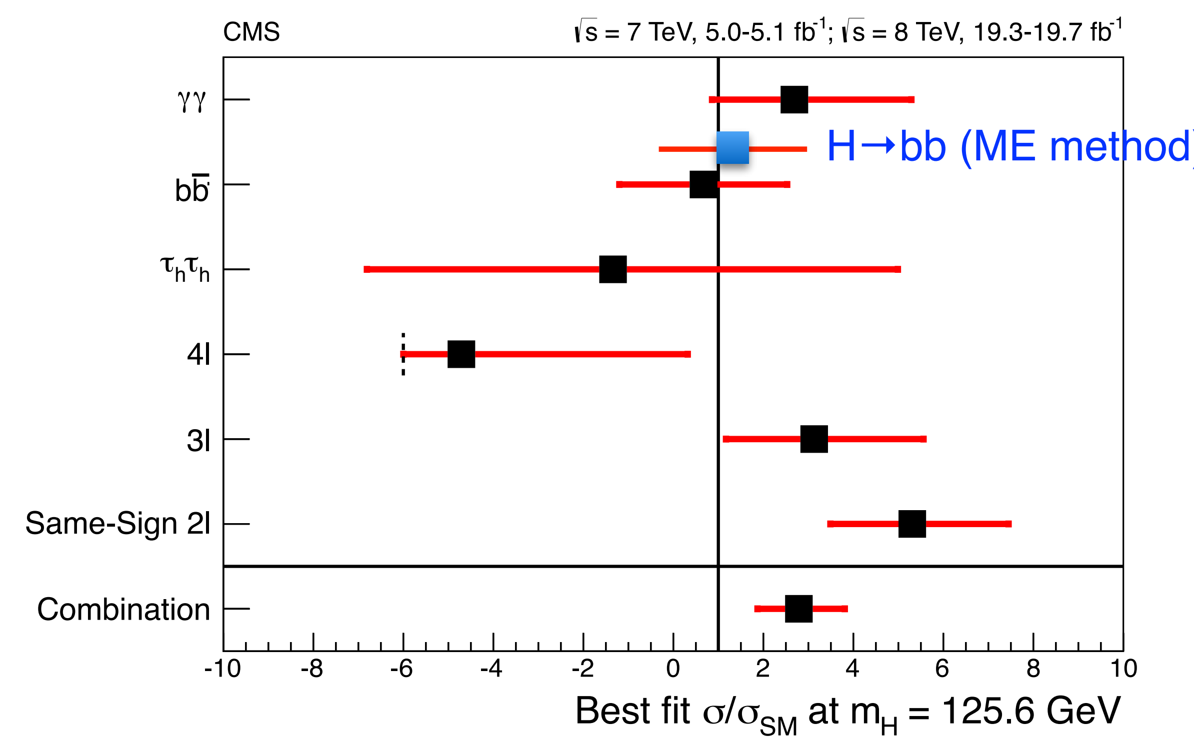
Rare production : ttH

ATLAS : CONF-2015-006
EPJC 75 (2015) 349
PLB 740 (2015) 222
CMS : JHEP 09 (2014) 087
EPJC 75 (2015) 251

- very low rate : 3000 events without acceptance cut and selections
- large tt background (ttH : tt ~ 1 : 2000)
- was thought to be feasible with a lot of luminosity before LHC started



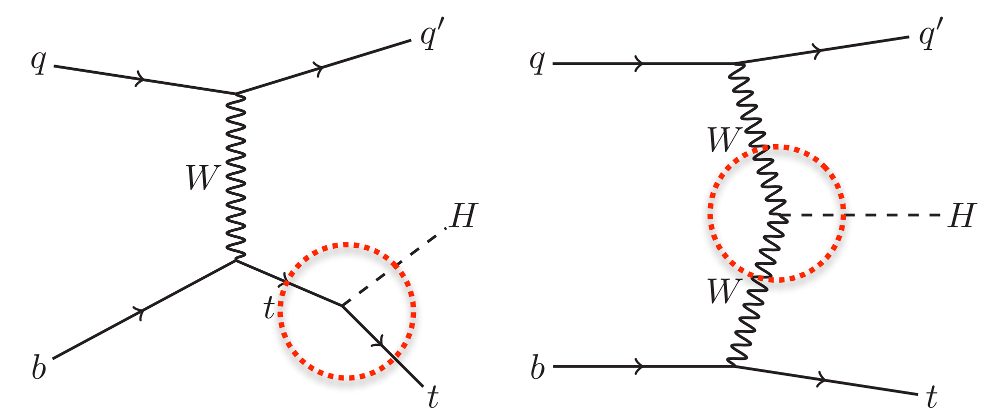
	Datasets	best-fit $\mu = \sigma/\sigma_{SM}$	exclusion limit @ 95% C.L.
Atlas H→bb	**7+8 TeV**	**1.5 ± 1.1 @ 125.0 GeV**	**<3.4(2.2)SM**
			obs.(exp.) local significance
CMS	**7+8 TeV**	**2.8 ± 1.0 @ 125.6 GeV**	**3.4σ (1.2σ)**



Rare production : tHq

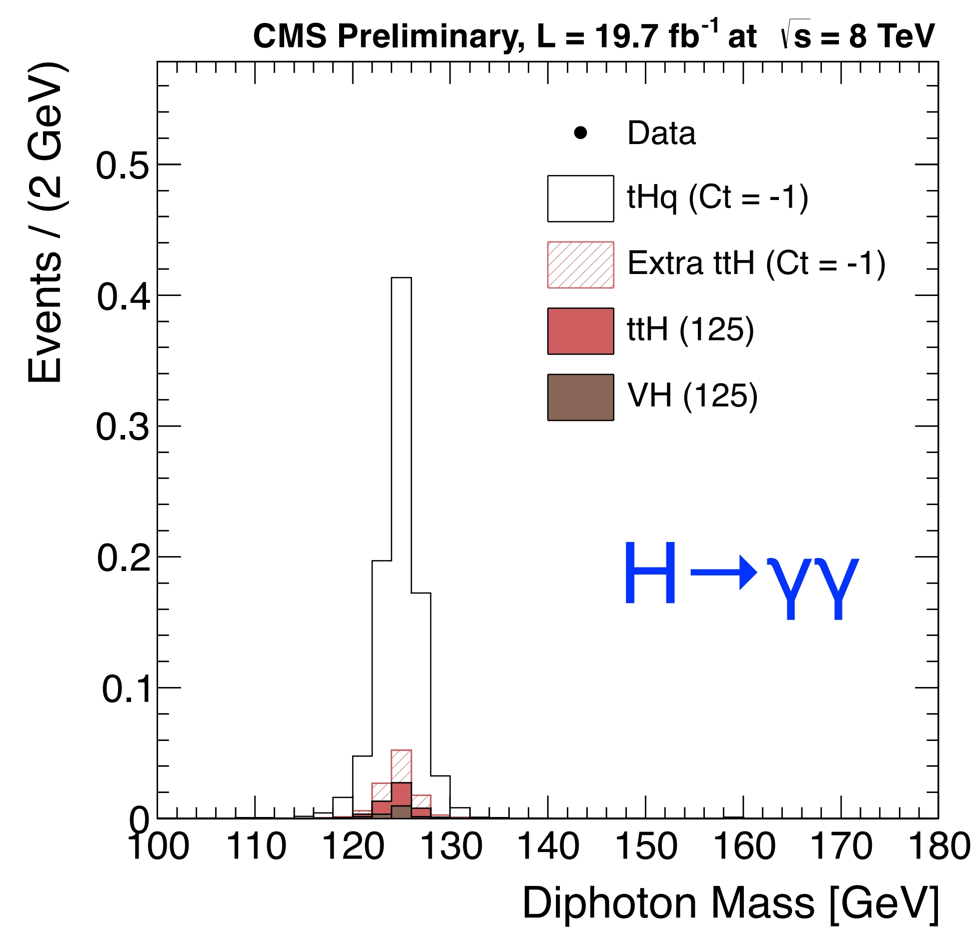
CMS : HIG-14-001, HIG-14-015
HIG-14-026

- very challenging search
- very very low rate : ~1/10 of ttH
  - $H \to \gamma\gamma$: 0.2 events
  - $H \to bb$: 60 events
- If the sign of t-H is flipped, σ is x15 σ_{SM}



Opposite sign for t-H and W-H coupling in SM → destructive interference

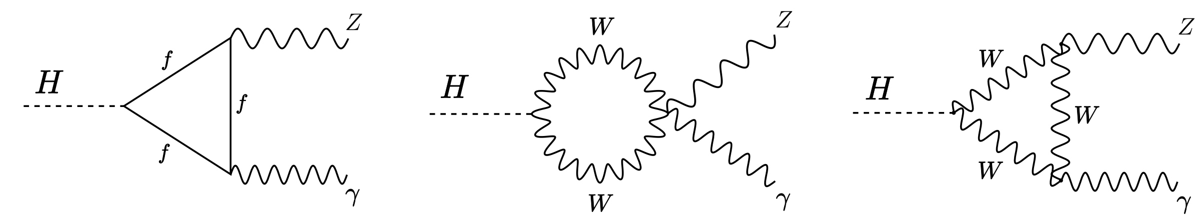
CMS	obs. (exp.) $\mu = \sigma/\sigma_{SM}$ at 95% C.L.
tHq→blν + γγ + q	**< 4.1 (4.1) x 15 = 61.5 (61.5)**
tHq→blν + bb + q	**< 7.6 (5.2) x 15 = 114.0 (78.0)**
tHq→blν + leptons + q	**< 6.7 (5.0) x 15 = 100.5 (75.0)**



$H \rightarrow Z\gamma$

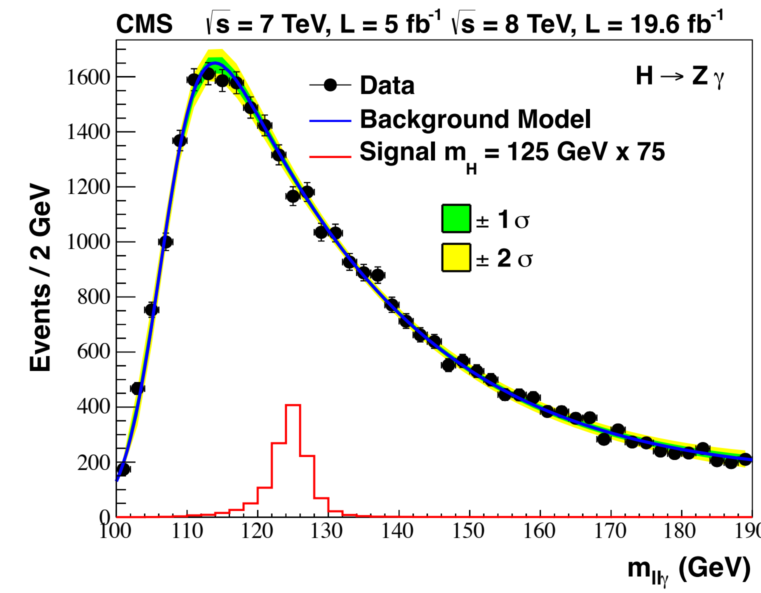
$BR(H \rightarrow Z\gamma) = 1.6 \times 10^{-3}$

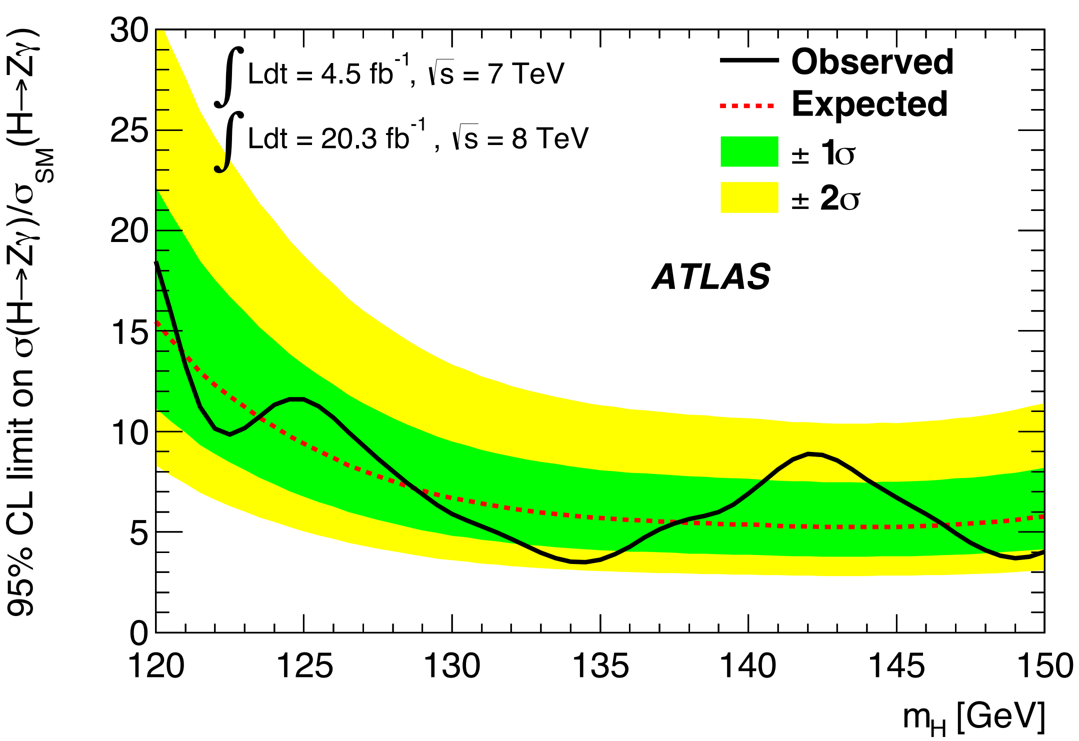
ATLAS : PLB 732 (2014) 8
CMS : PLB 726 (2013) 587

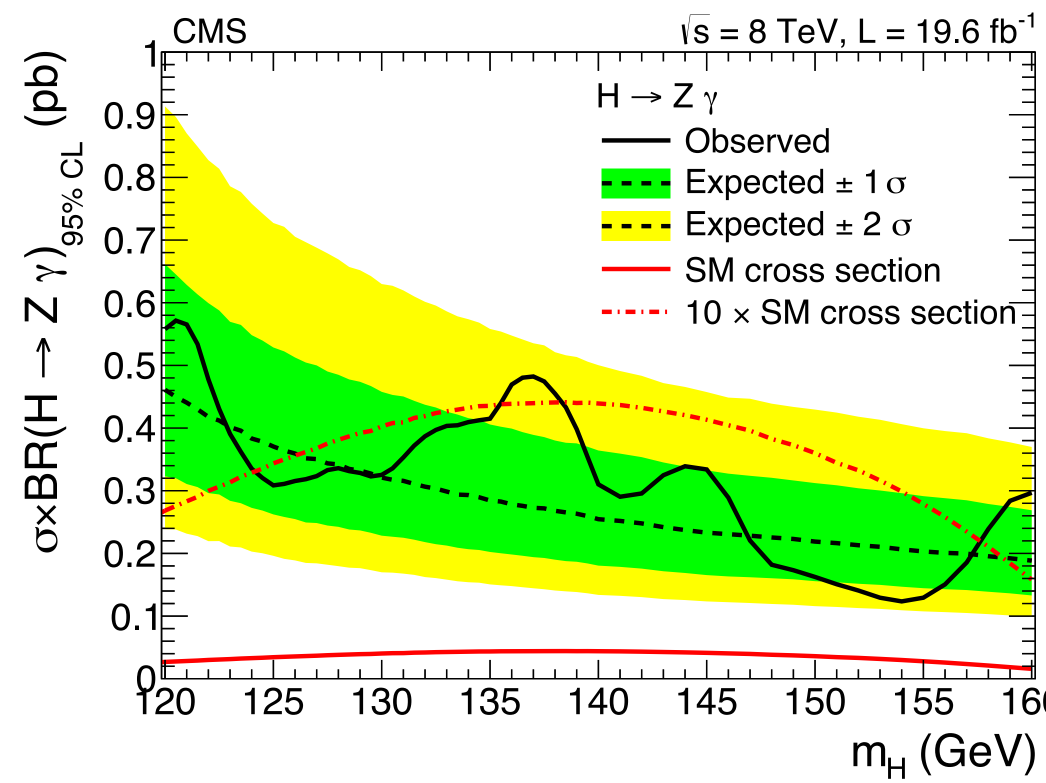


- Signal yield is similar to $H \rightarrow ZZ \rightarrow 4l$ but suffers from large background
- Future sensitivity of ATLAS : 2.3σ (300/fb), 3.9σ (3000/fb) [ATL-PHYS-PUB-2014-006]

	Datasets	obs. (exp.) 95% C.L. limit on σ/σ_{SM}
Atlas	**7+8 TeV**	**11(9) @ 125.5 GeV**
CMS	**7+8 TeV**	**9.5(10) @ 125 GeV**







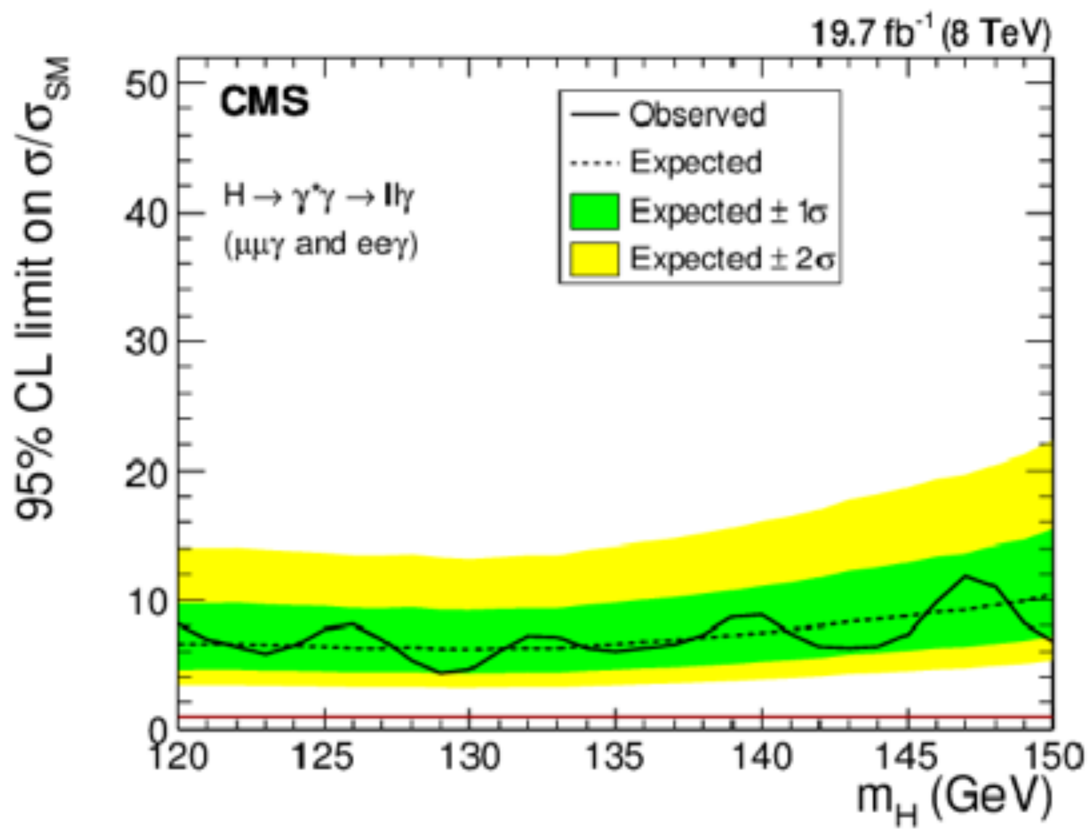
$H \to \gamma^*\gamma$

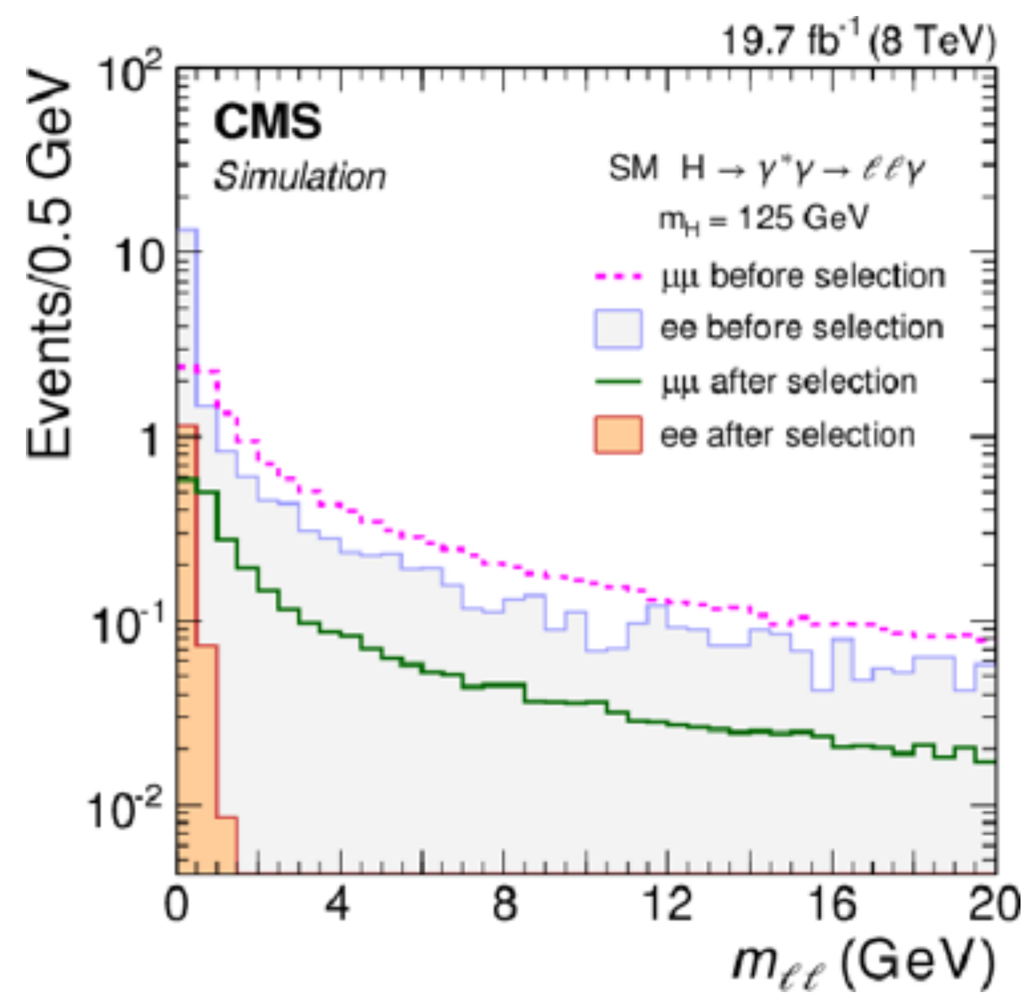
BR($H \to \gamma^*\gamma \to \mu\mu\gamma$) = 3.3 x 10^{-5}

CMS : arXiv:1507.03031

- sensitive to new physics via loops
- two collimated leptons from γ^* decay
- $m_{\mu\mu} < 20$ GeV, $m_{ee} < 1.5$ GeV
- Reject J/ψ+γ and ϒ+γ with $m_{\mu\mu}$
- Similar sensitivity as in $H \to Z(ee+\mu\mu)\gamma$

	Datasets	obs. (exp.) 95% C.L. limit on σ/σ_{SM}
CMS	**8 TeV**	**7.7(6.4) @ 125 GeV**





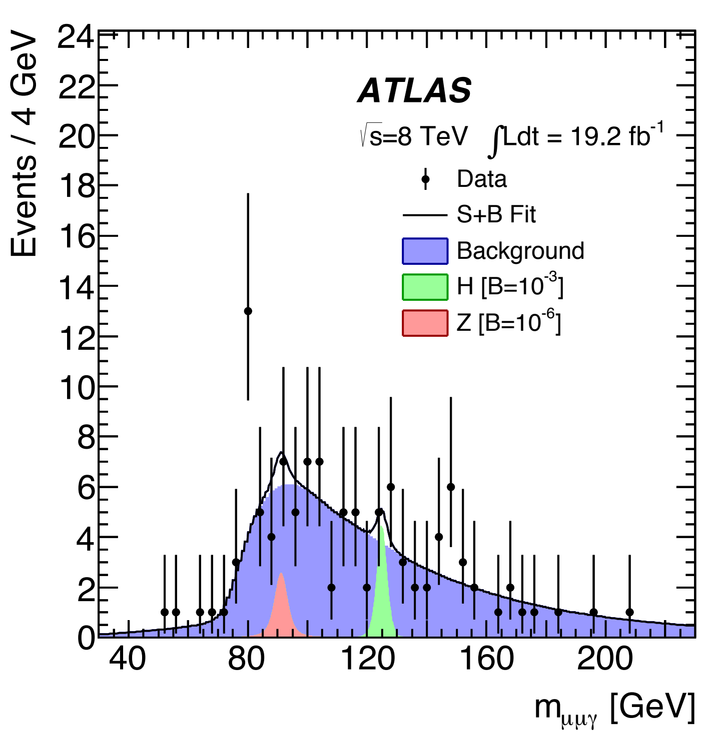
$H \rightarrow$ Quarkonium + γ

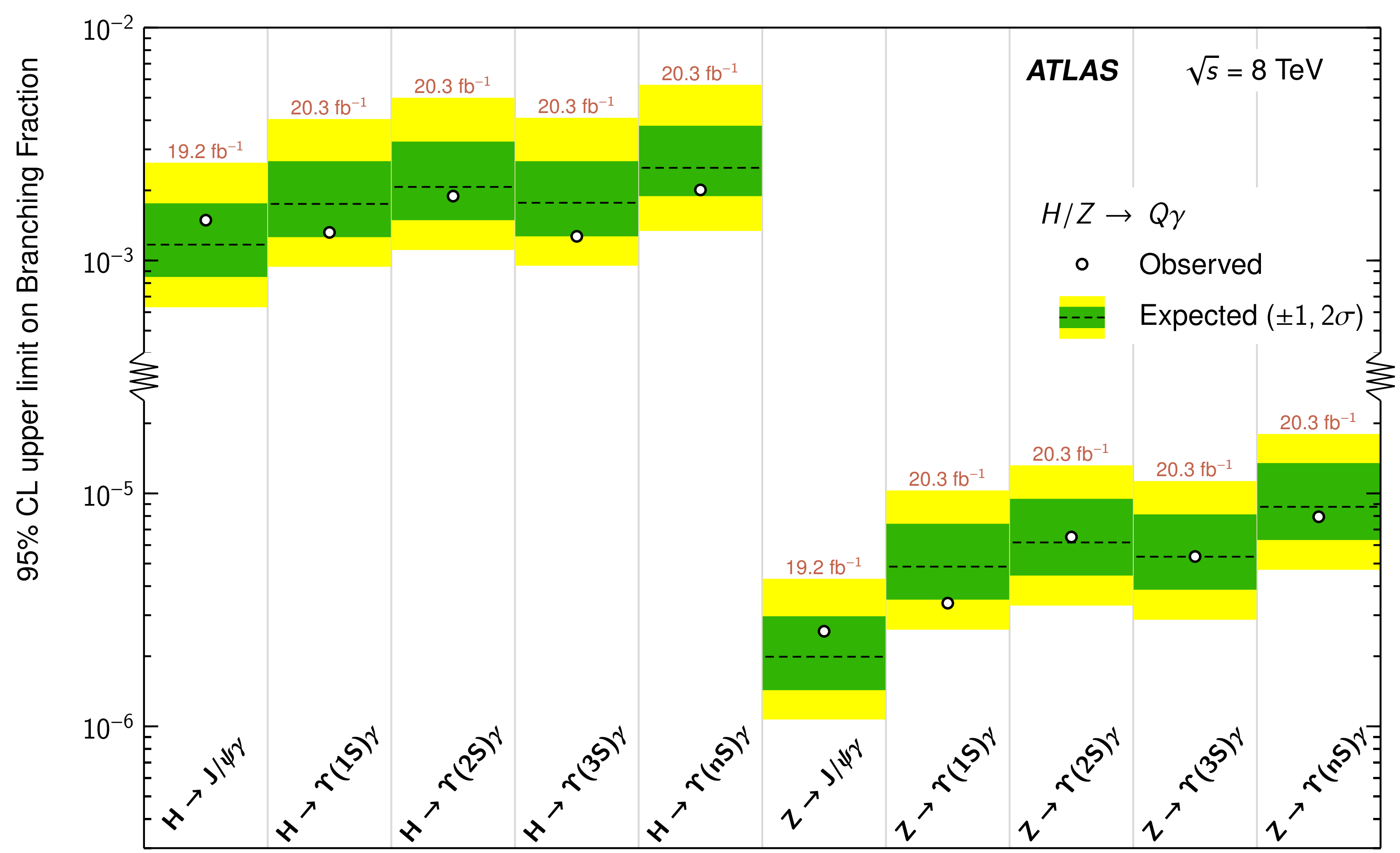
ATLAS : PRL 114 (2015) 121801

$BR(H \rightarrow J/\Psi+\gamma) = 2.8 \times 10^{-6}$
$BR(H \rightarrow Y(nS)+\gamma) = 2.0\text{-}6.1 \times 10^{-10}$

- Search for $H/Z \rightarrow J/\psi+\gamma$ and $\Upsilon(nS)+\gamma$
  - $H \rightarrow J/\psi+\gamma$ is sensitive to the Higgs-charm coupling
- Very challenging even for HL-LHC

	Datasets	obs. (exp.) 95% C.L. limit on $BR(H \rightarrow J/\Psi+\gamma)$
ATLAS	**8 TeV**	**1.5×10^{-3} (1.2×10^{-3})**





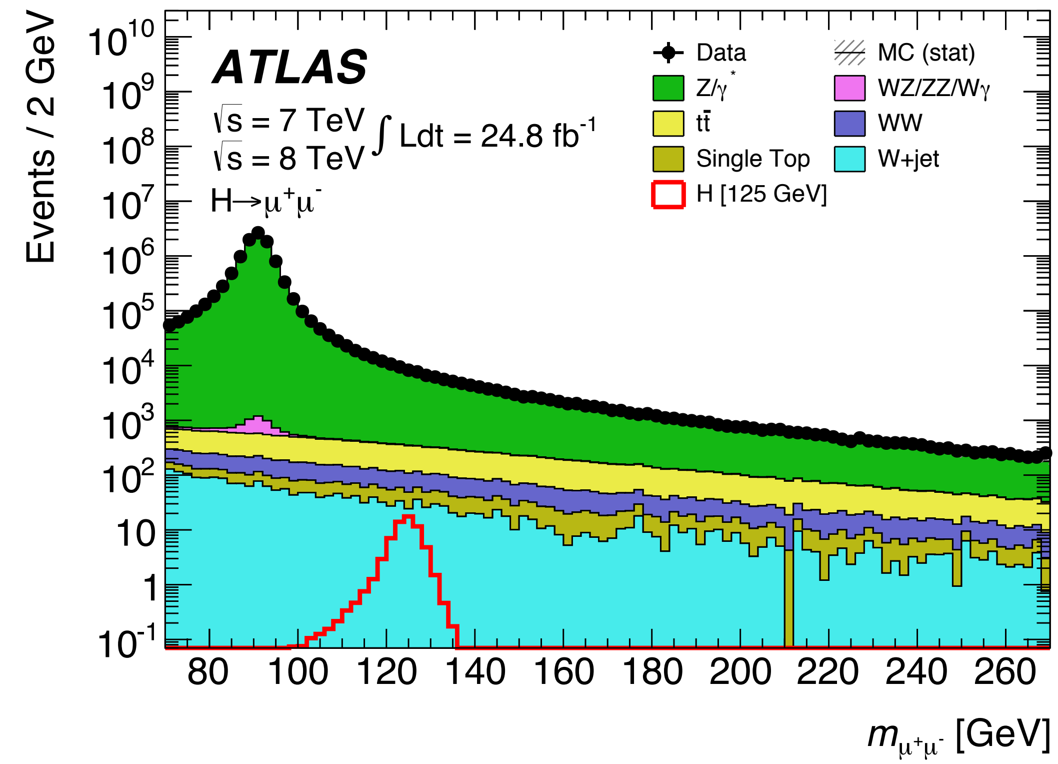
$H \rightarrow \mu\mu$

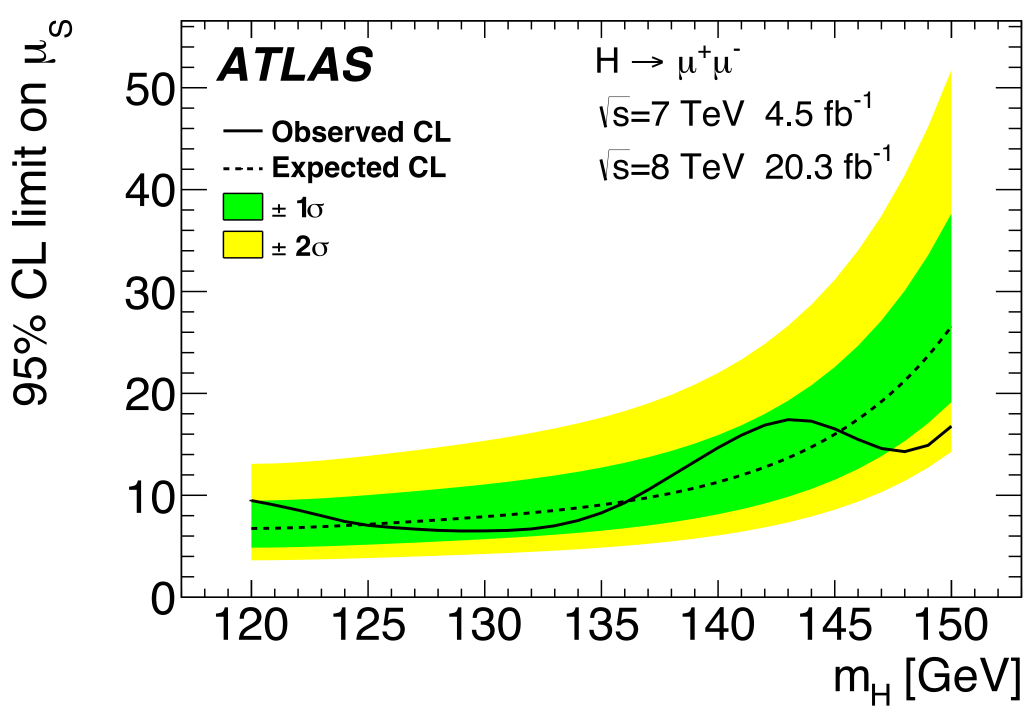
$BR(H \rightarrow \mu\mu) = 2.2 \times 10^{-4}$

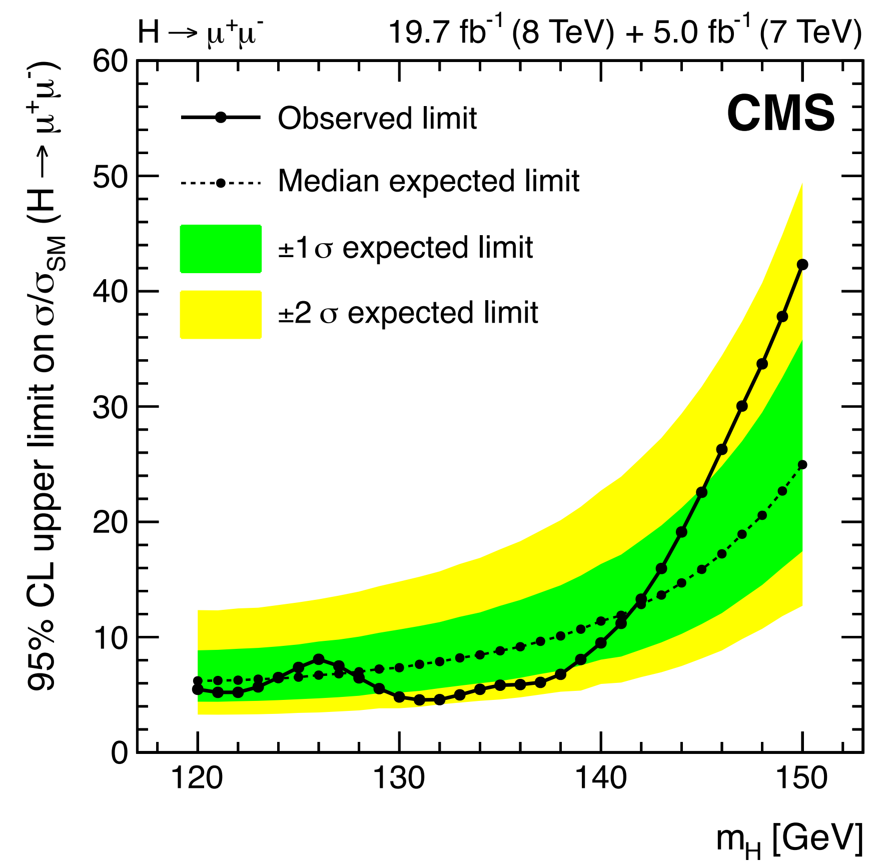
ATLAS : PLB 738 (2014) 68
CMS : PLB 744 (2015) 184

- Only accessible channel to test Higgs couplings to second generation fermions at LHC
- Future sensitivity of ATLAS : 2.3σ (300/fb), 7.0σ (3000/fb) [ATL-PHYS-PUB-2013-014]

	Datasets	obs. (exp.) 95% C.L. limit on σ/σ_{SM}
Atlas	**7+8 TeV**	**7.0(7.2) @ 125.5 GeV**
CMS	**7+8 TeV**	**7.4(6.5) @ 125 GeV**







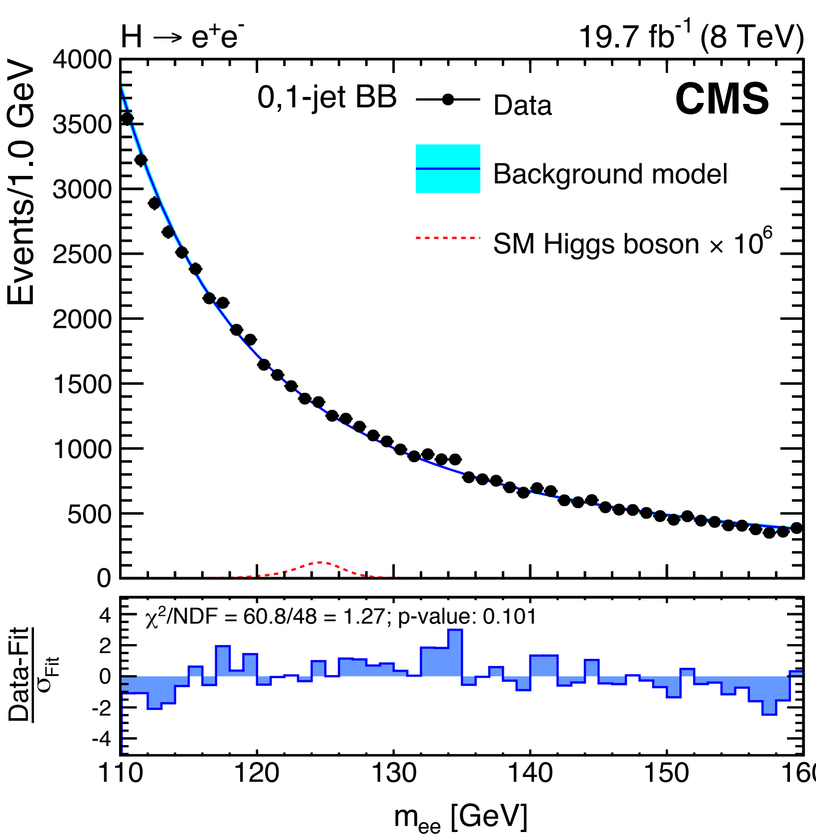
$H \rightarrow ee$

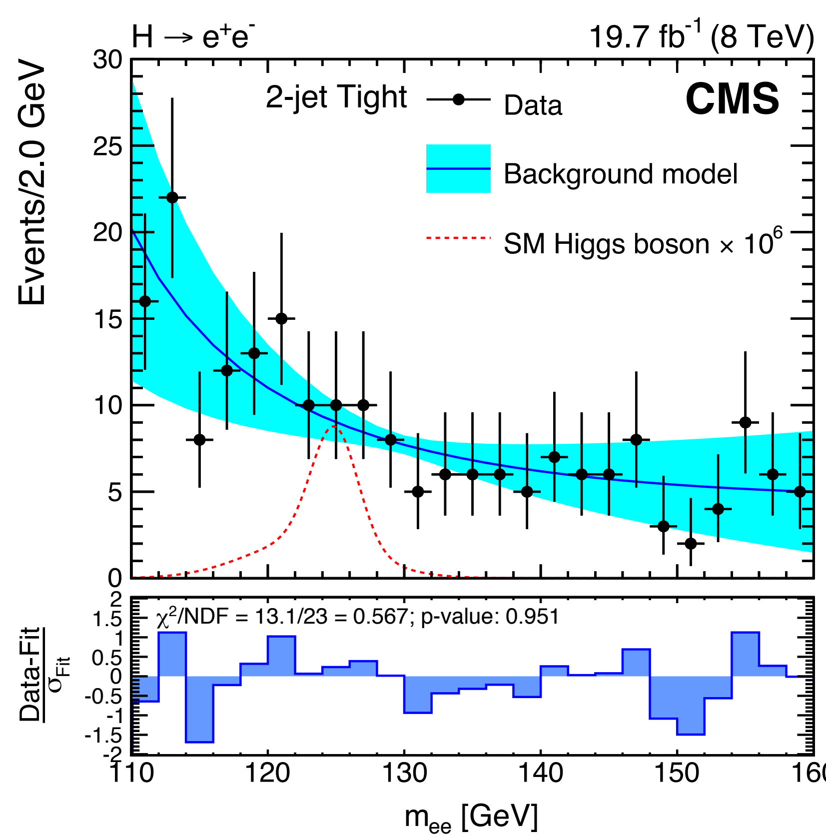
BR(H→ee) = 5 x 10^{-9}

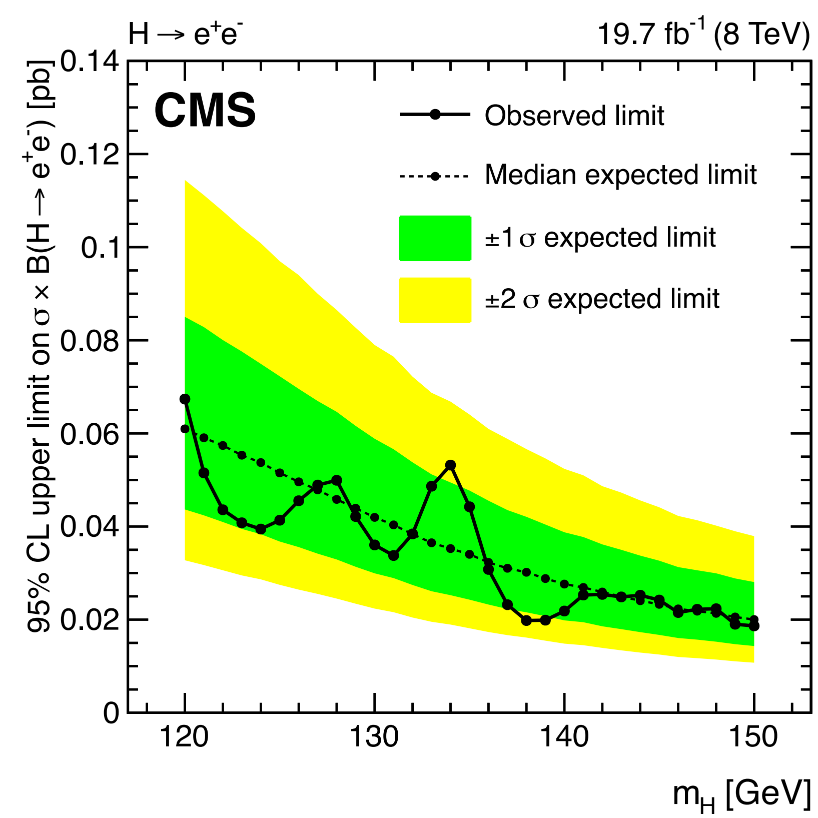
CMS : PLB 744 (2015) 184

- probe coupling dependence on lepton-flavor
- very very challenging for HL-LHC due to its nature of small BR

	Datasets	obs. 95% C.L. limit on BR(H→ee)
CMS	**7+8 TeV**	**1.9 x 10^{-3} @ 125 GeV**







$H \rightarrow invisible$

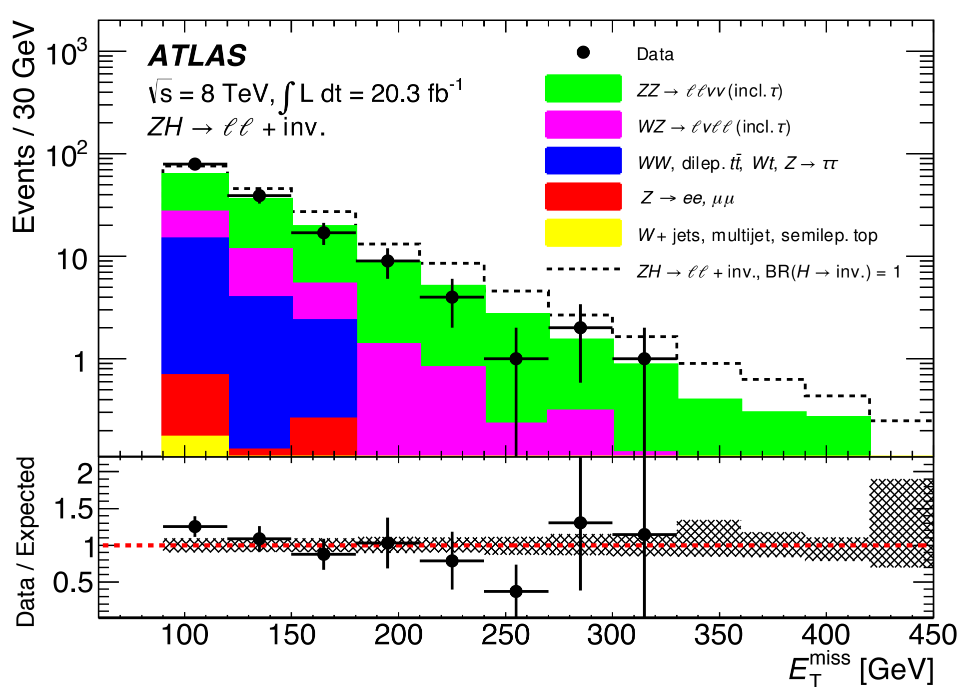
ATLAS : CONF-2015-004
PRL 112 (2014) 201802
EPJC 75 (2015) 337

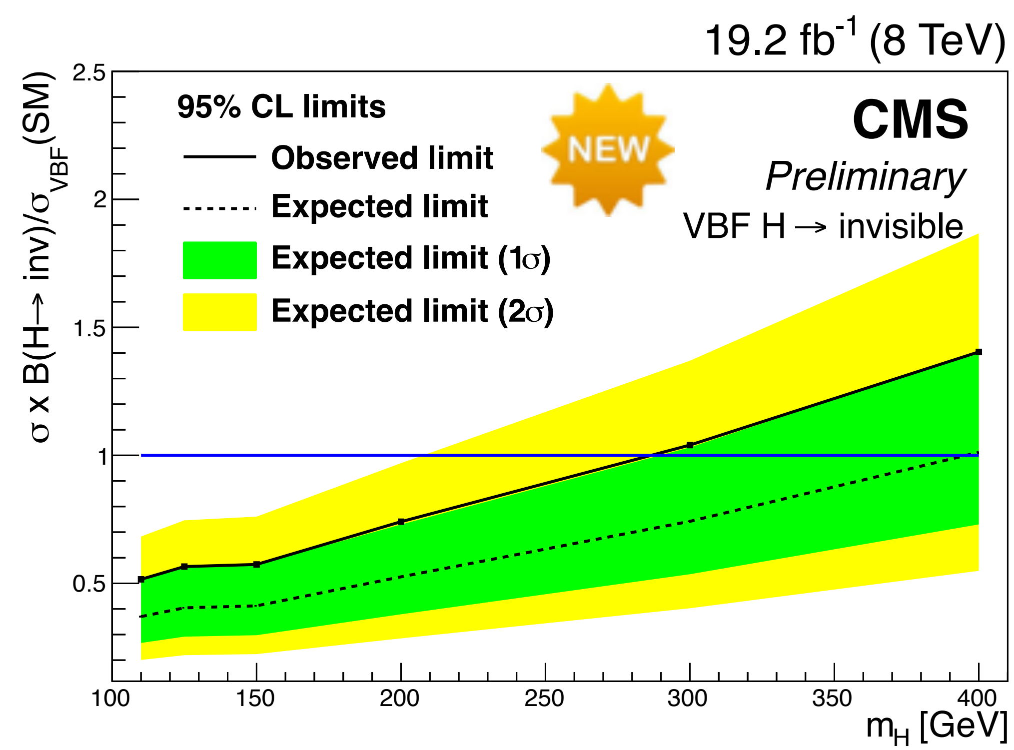
CMS : EPJC 74 (2014) 2980
HIG-14-038

- ATLAS : VBF and Z(ll,jj)H
- CMS : VBF and Z(ll,bb)H
- Future sensitivity of ATLAS : BR < 0.23 (300/fb), BR < 0.08 (3000/fb) [ATL-PHYS-PUB-2013-014]
- interesting connection to BSM searches
    - interaction between Higgs and DM would introduce invisible decays

BR(H→ZZ→4ν) = 1.2 x 10^{-3}

	Datasets	obs. (exp.) 95% C.L. limit on BR(H→inv)
ATLAS (Z→llH)	**7+8 TeV**	**0.75(0.62)**
ATLAS (VBF)	**8 TeV**	**0.29(0.35)**
ATLAS (Z→jjH) NEW	**8 TeV**	**0.78(0.86)**
CMS (comb.) NEW	**7+8 TeV**	**0.47(0.35)**

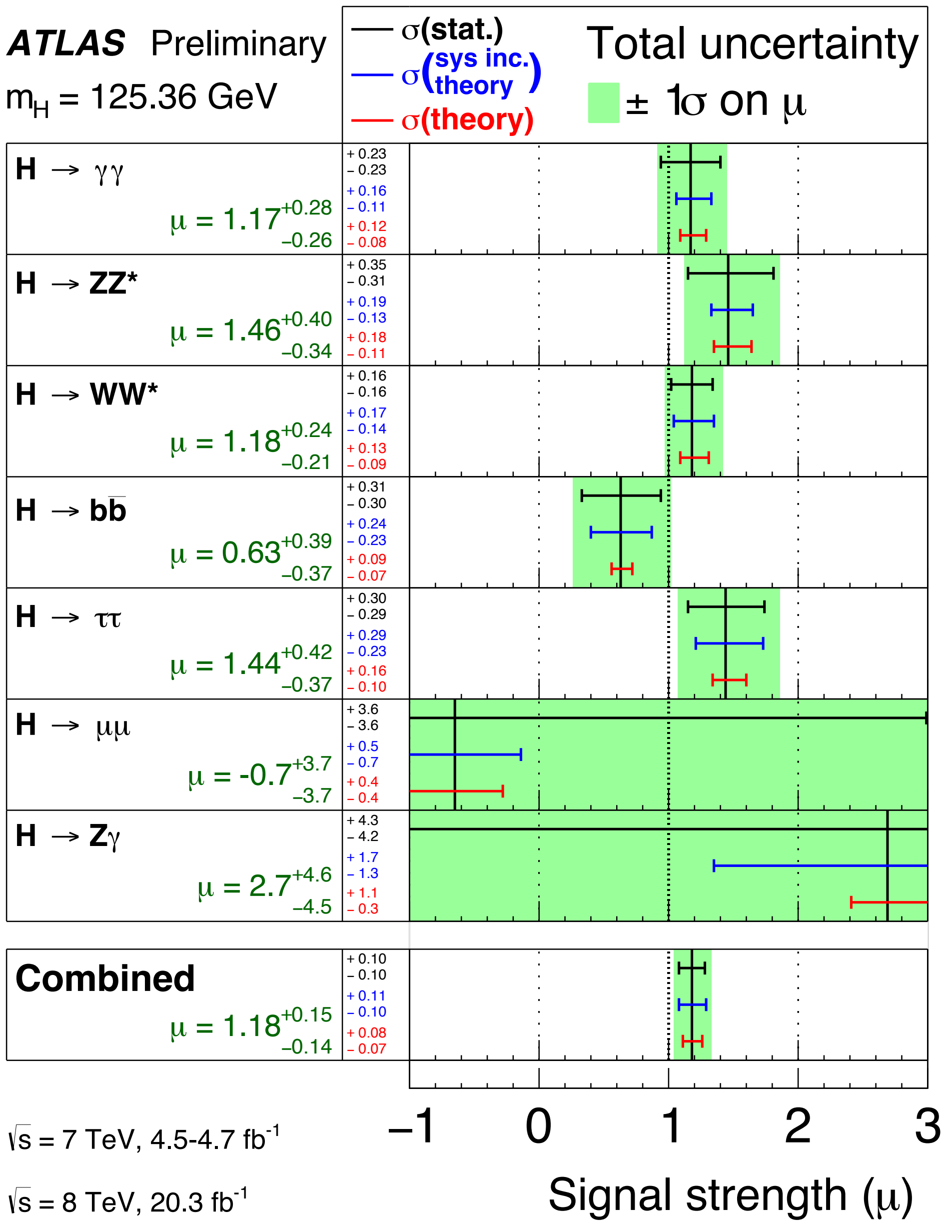


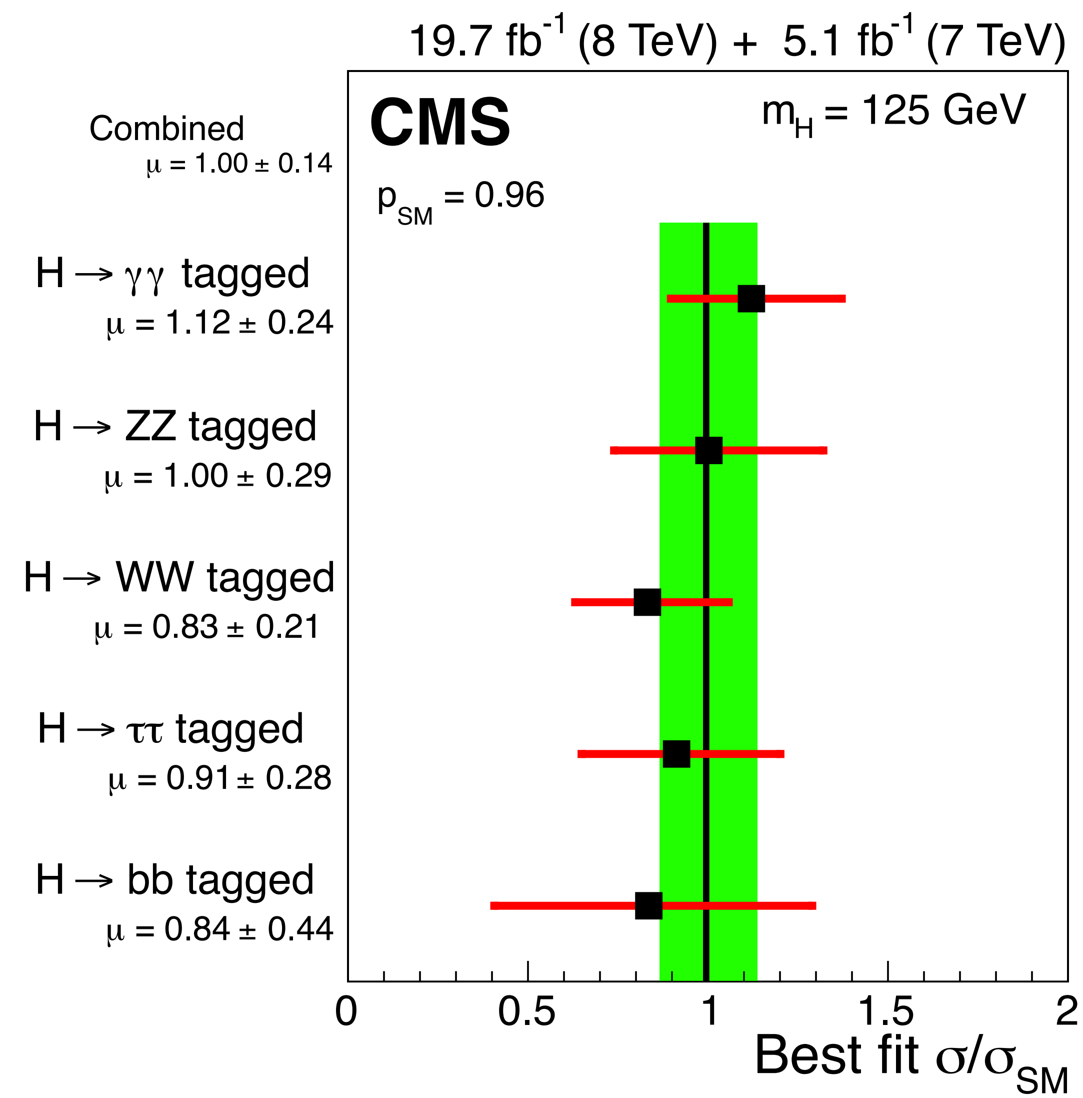


Combinations

Combination : decay modes

ATLAS : CONF-2015-007
CONF-2015-044
CMS : EPJC 75 (2015) 212
HIG-15-002

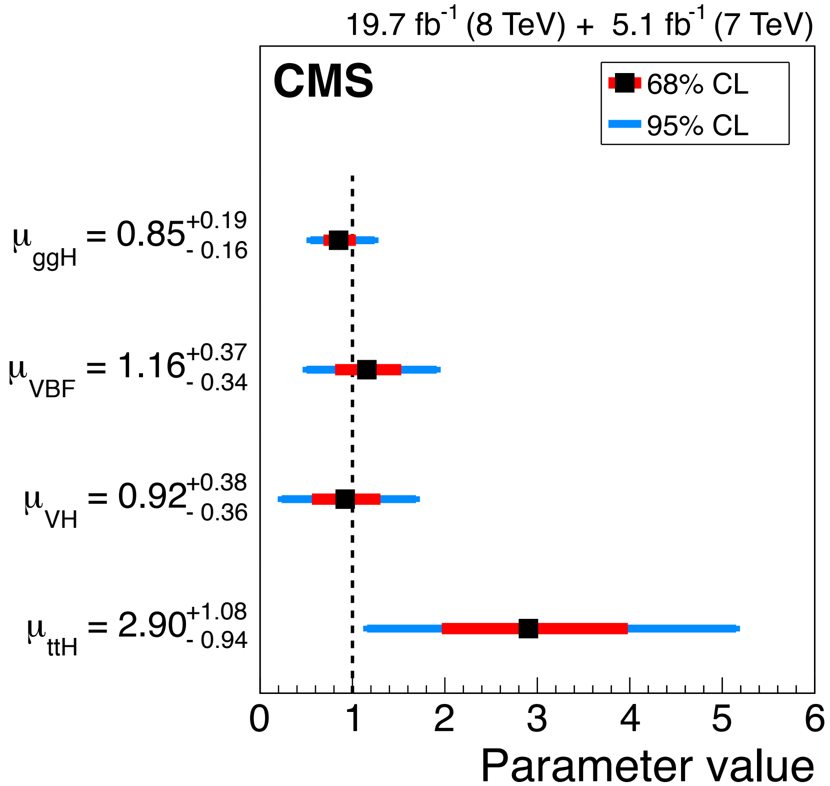


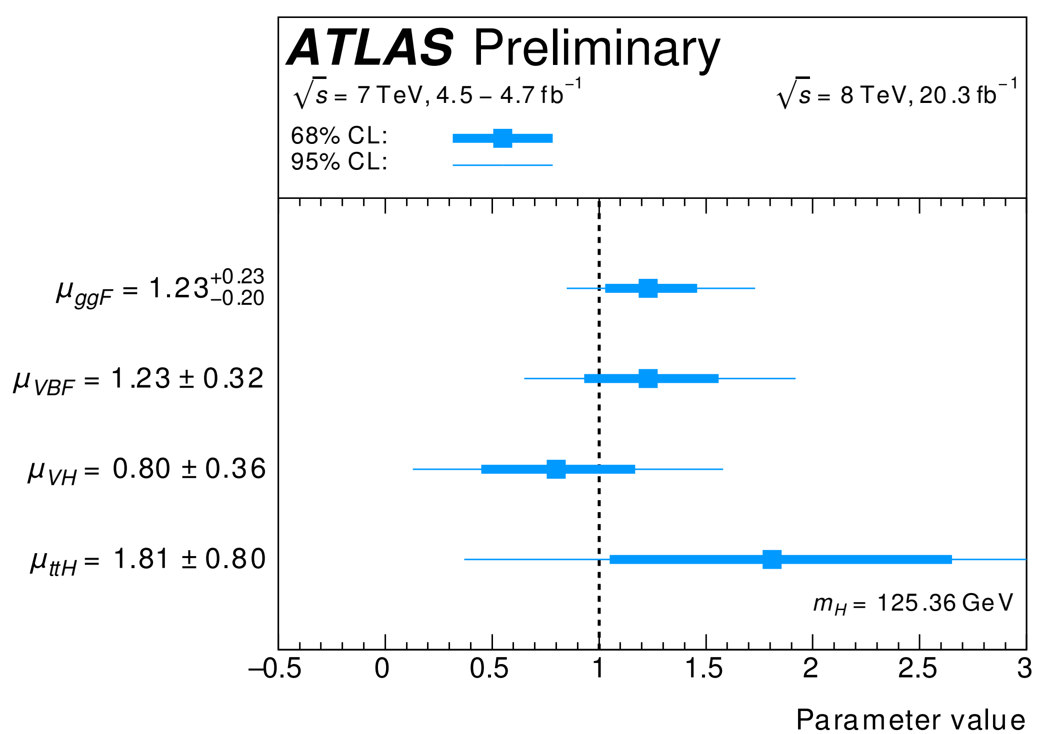


Atlas	**1.18 ± 0.10 (stat) ± 0.07 (syst) $^{+0.08}_{-0.07}$ (theory)**
CMS	**1.00 ± 0.09 (stat) ± 0.07 (syst) $^{+0.08}_{-0.07}$ (theory)**
Atlas + CMS	**1.09 $^{+0.11}_{-0.10}$**

Combination : production modes

ATLAS : CONF-2015-007
CMS : EPJC 75 (2015) 212





CMS	Significance (σ) Observed	Significance (σ) Expected	Pull to SM (σ)
μ_{ggH}	6.6	7.4	-0.8
μ_{VBF}	3.7	3.3	+0.4
μ_{VH}	2.7	2.9	-0.2
μ_{ttH}	3.5	1.2	+2.2

Branching ratios are assumed to be the predictions of the SM

Exploring the couplings

- Assumptions [*]
  - Single resonance and zero width approximation
  - No modification to kinematics (tensor structure of the interaction as in the SM)

$$\sigma \times B\,(xx \to H \to yy) = \frac{\sigma_{xx}\,\Gamma_{yy}}{\Gamma_{tot}}$$

$\Gamma_{WW} \to \kappa_W$

$\Gamma_{ZZ} \to \kappa_Z$

$\Gamma_{tt} \to \kappa_t$

$\Gamma_{bb} \to \kappa_b$

$\Gamma_{\tau\tau} \to \kappa_\tau$

$\Gamma_{\mu\mu} \to \kappa_\mu$

$\Gamma_{\gamma\gamma} \to \kappa_W, \kappa_t$ (loop induced)

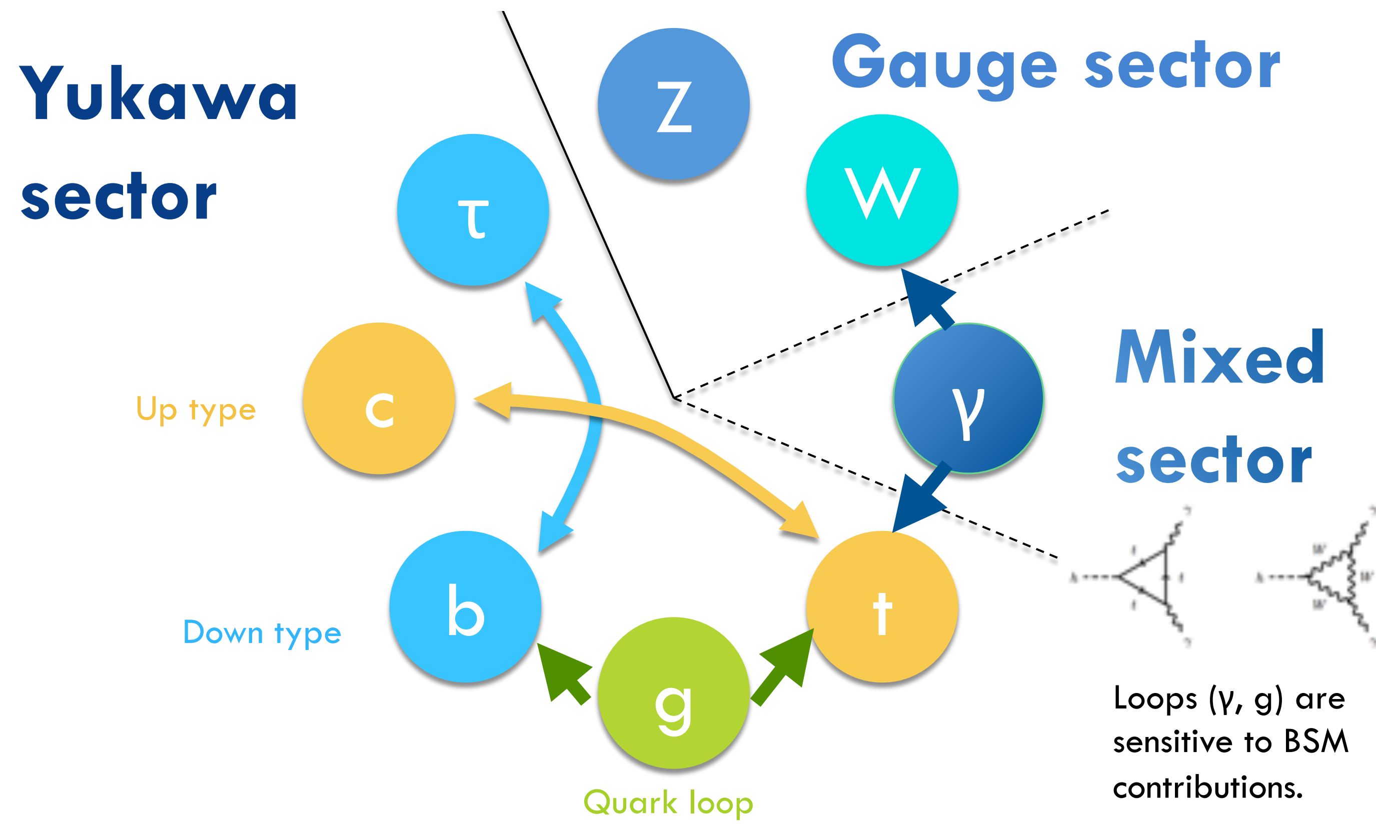
$\Gamma_{gg} \to \kappa_t, \kappa_b$ (loop induced)

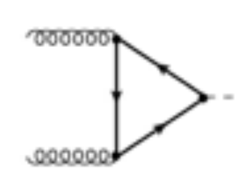
$\Gamma_{tot} \to \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{tt} + \ldots + \Gamma_{BSM}$

$\kappa_i^2 = \sigma_i / \sigma_i^{SM}$

$\kappa_i^2 = \Gamma_{ii} / \Gamma_{ii}^{SM}$

κ_i deviates from unity → imply NP beyond SM

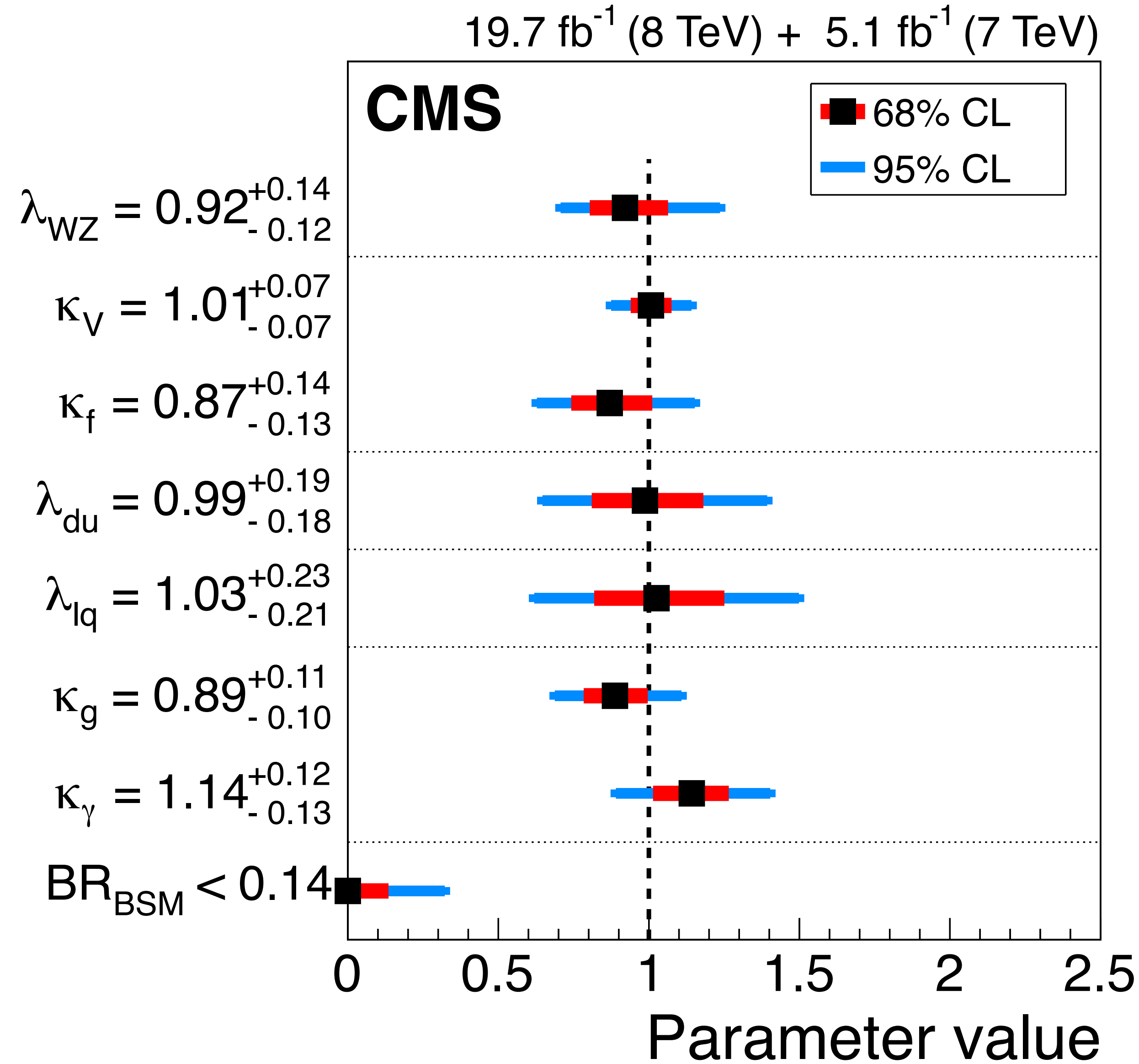




[*] LHC Higgs Cross Section Working Group arXiv:1307.1347

Couplings with different simple models

- the size of current dataset has yet to allow the determination of all the coupling modifiers (κ_i) → perform the following (simplified) fits
  - κ_W vs κ_Z (custodial symmetry)
  - κ_V vs κ_F (universal scale for bosons and for fermions)
  - κ_u vs κ_d (up/down fermion coupling ratio)
  - κ_q vs κ_l (lepton/quark coupling ratio)
  - κ_g vs κ_γ (BSM contribution to 1-loop coupling)
  - BR_{BSM} (extra width)
- No significant deviations from SM (precision : 20-30%)

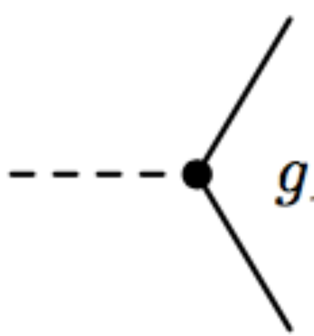


$\lambda_{XY} = \kappa_X/\kappa_Y$

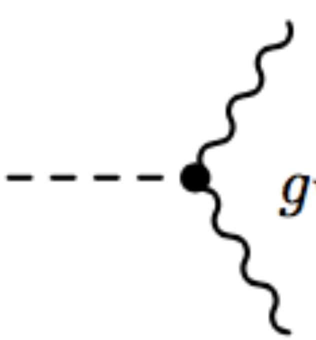
Test the scaling of couplings with mass

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

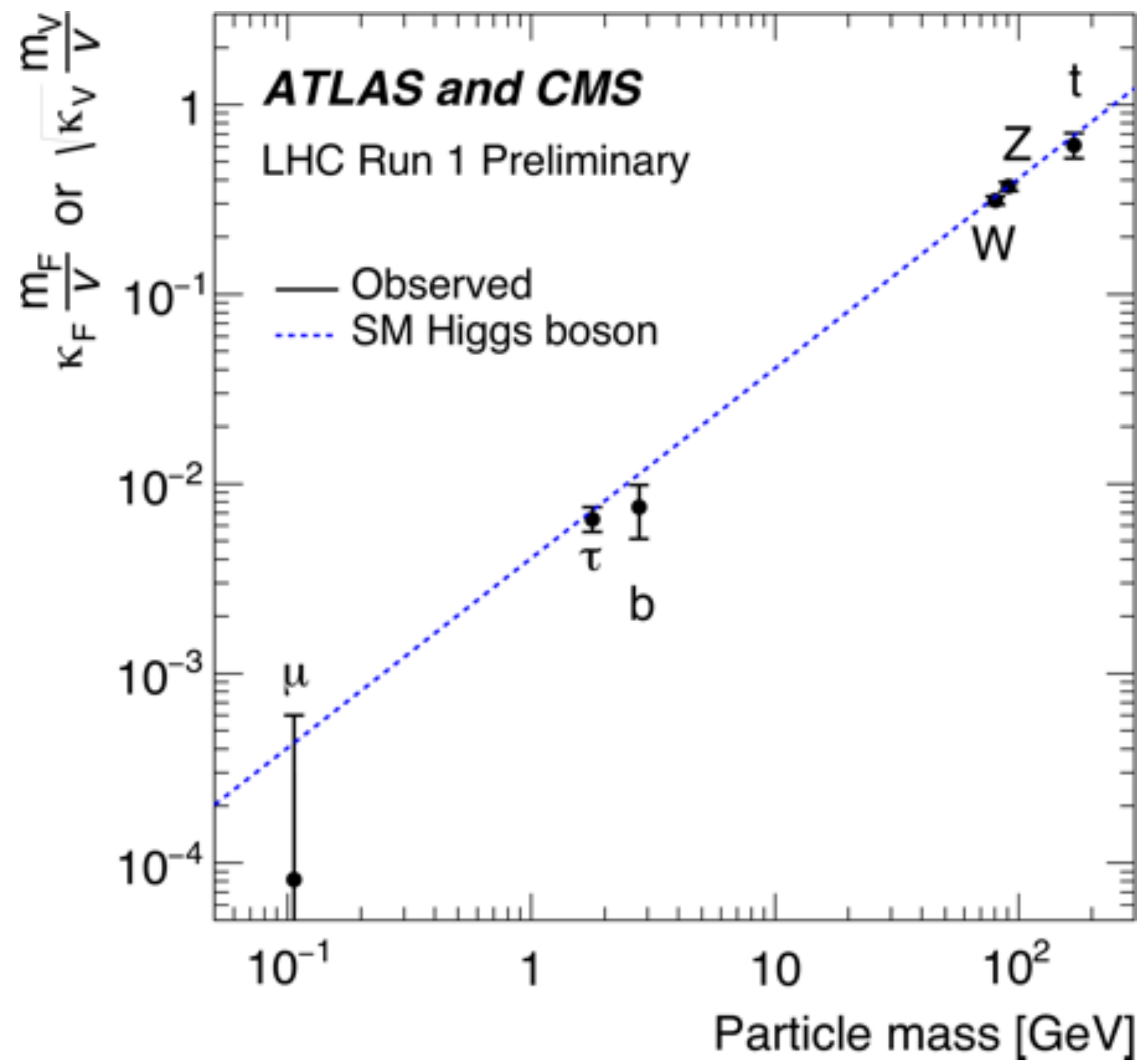
- assumption : no interactions of the Higgs boson to non-SM particles



$$g_F = \sqrt{2}\frac{m_f}{v}$$



$$g_V = 2\frac{m_V^2}{v}$$

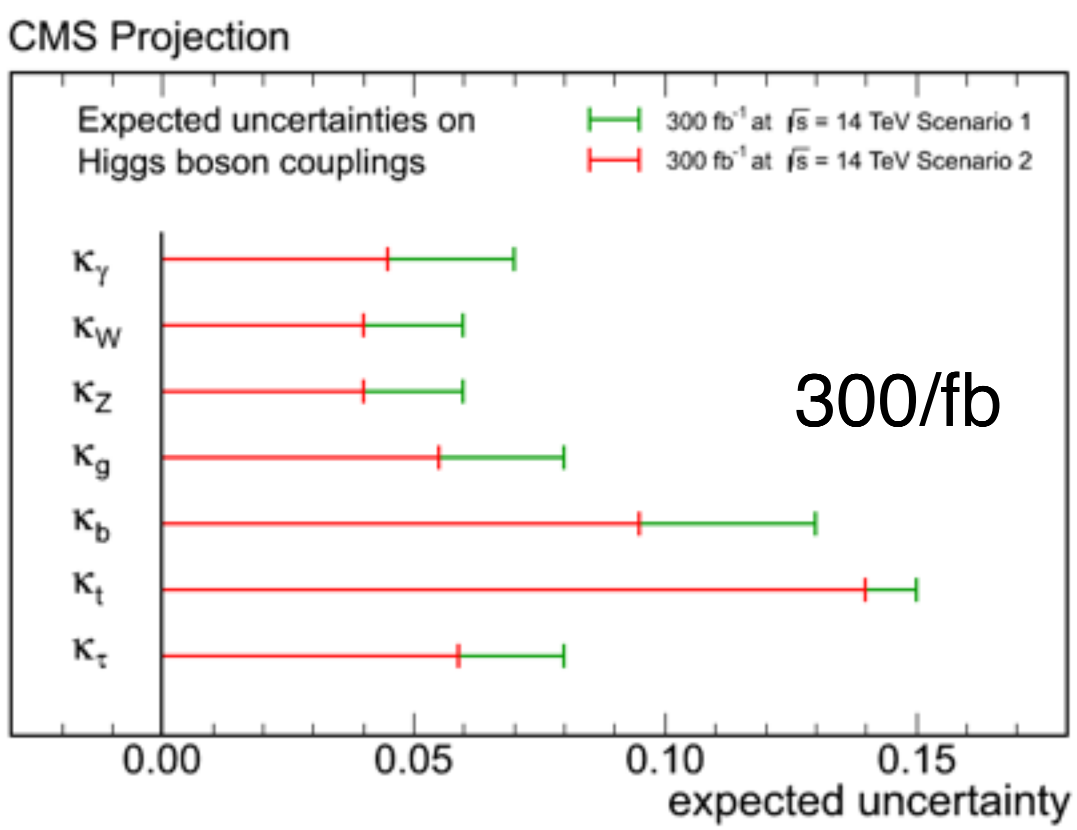


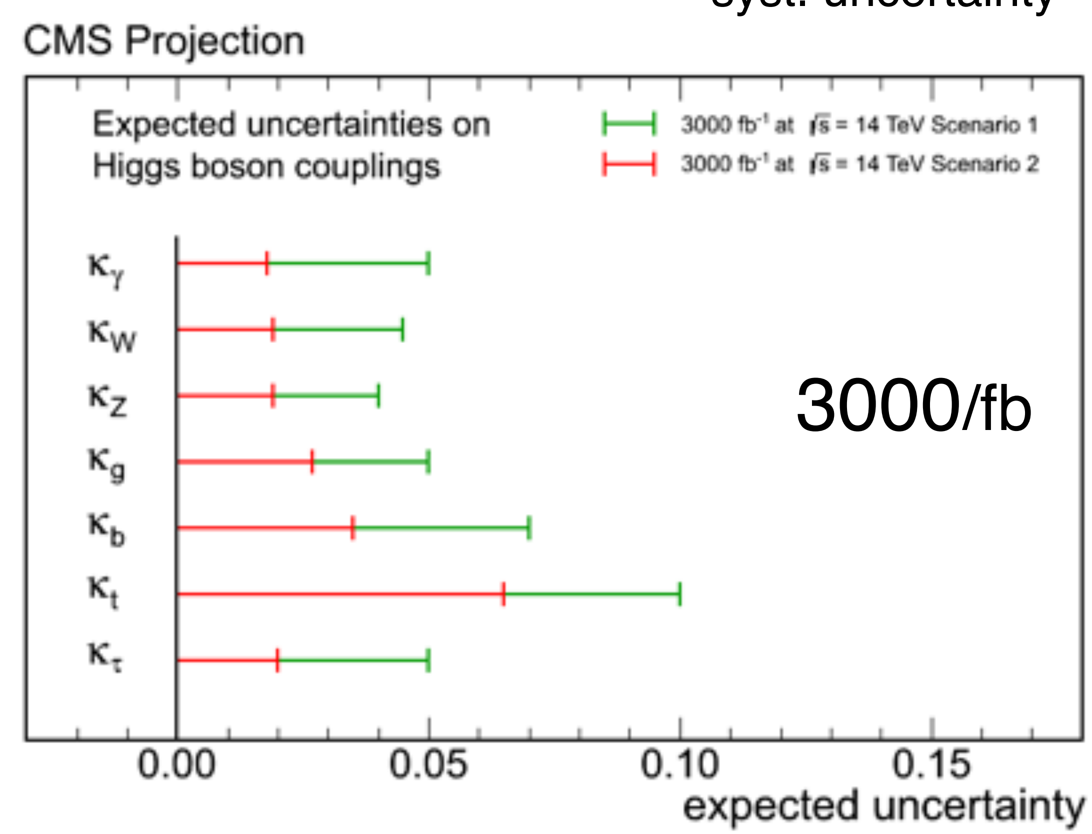
Perspective

ATLAS : PHYS-PUB-2014-016
CMS : NOTE-2013-002

Observable number of Higgs events per LHC experiment				
	2013	~2018	~2023	~2035
H→ZZ→4l	20	120	4,000	40,000
H→γγ	570	6,500	25,000	240,000
VBF H→ττ	50	700	2,600	20,000

Scenario 1 : current syst. uncertainty
Scenario 2 : 1/2 theoretical uncertainty
syst. uncertainty ～ 1/√L



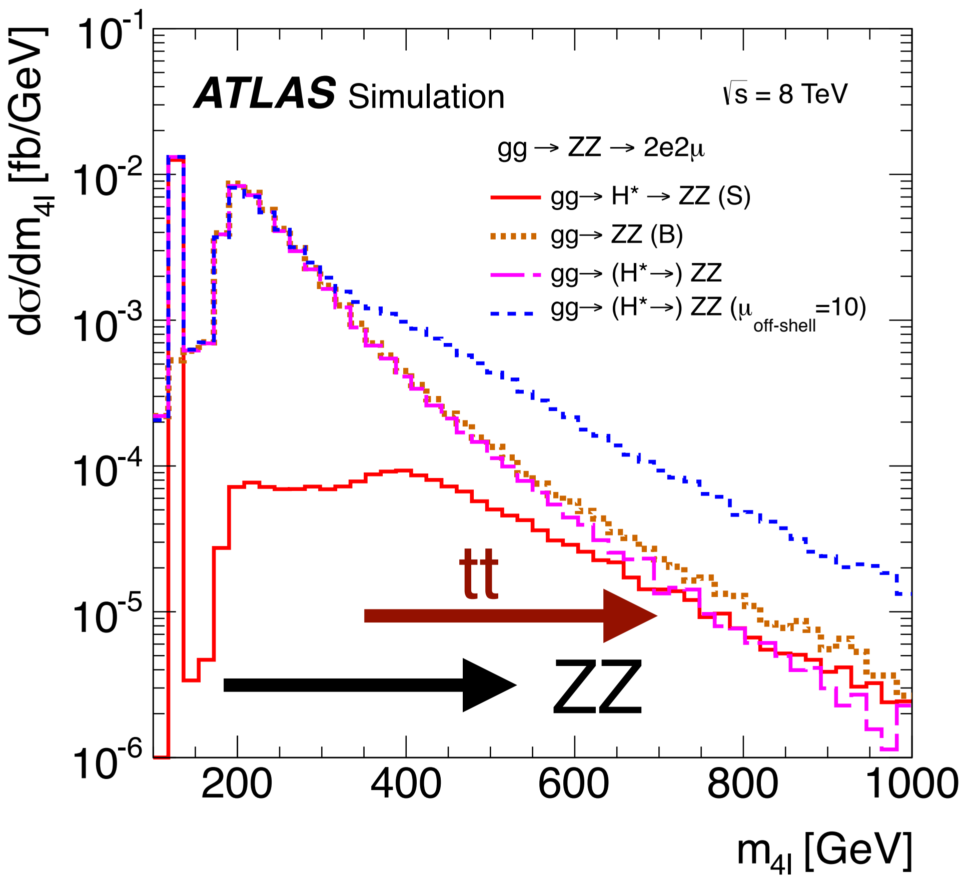


HL-LHC 3000/fb : most couplings with 2-8%
→ x3 improvement from 300/fb LHC results

Off-shell production

ATLAS : EPJC 75 (2015) 335
CMS : PLB 736 (2014) 64

- total width is measured directly by H→γγ and H→ZZ but limited by the experimental resolution (CMS : 2.4 GeV with H→γγ)
- expected width ~4 MeV for the SM Higgs boson
- indirect information (using H*→ZZ and H*→WW) on total width : $\sigma_{\text{off-shell}}$ / $\sigma_{\text{on-shell}}$ if couplings (g-H, Z-H) remain unchanged
  - assume ggH dominated by top loop and no new physics



	obs. (exp.) 95% C.L. limit on Γ_H/Γ_H^{SM}
Atlas	**< 5.5 (8.0)**
CMS	**< 5.4 (8.0)**

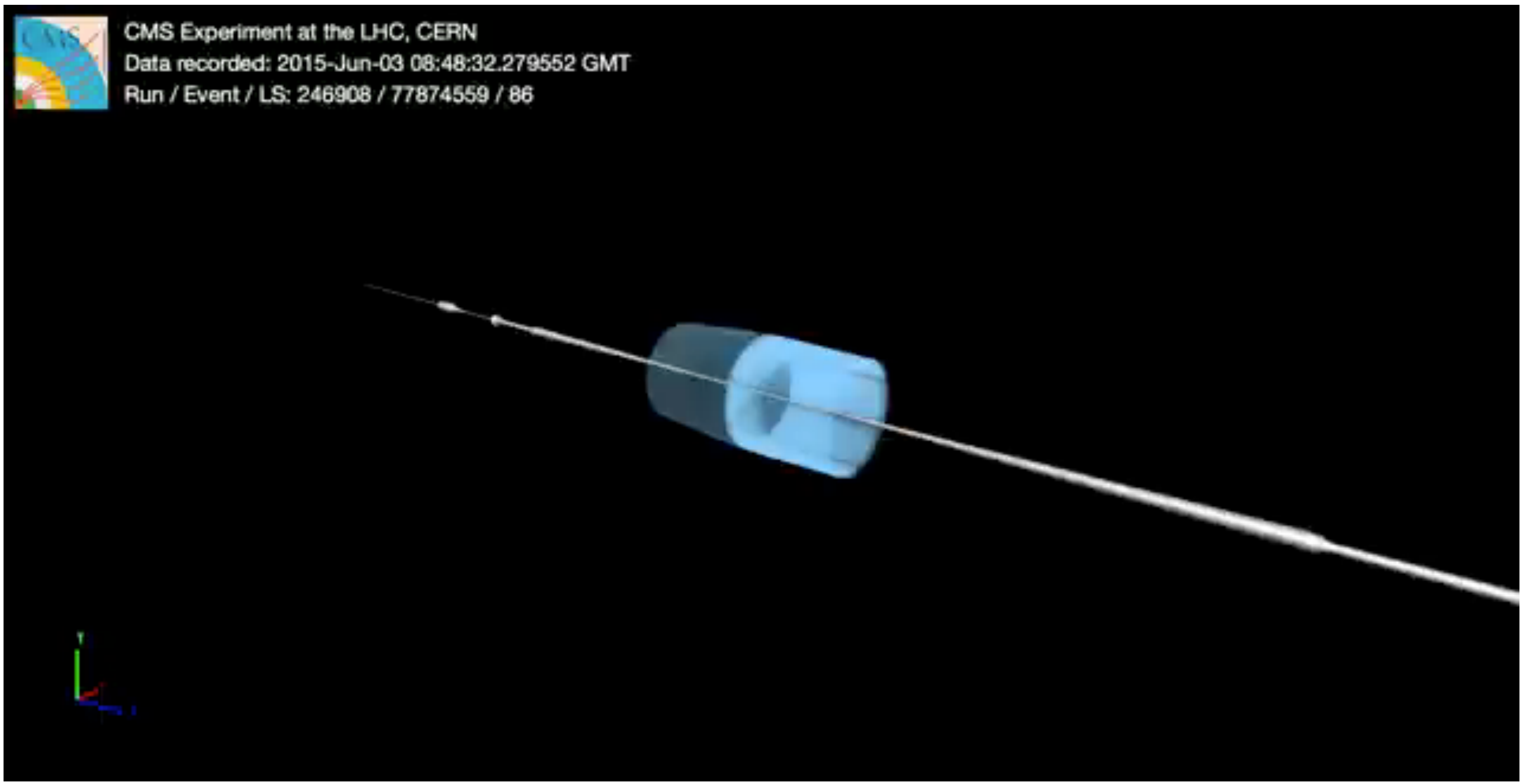
Atlas	obs. (exp.) 95% C.L. limit on $\mu_{\text{off-shell}}$
$\mathbf{R^B_{H^*} = 0.5}$	**< 5.1 (6.7)**
$\mathbf{R^B_{H^*} = 1.0}$	**< 6.2 (8.1)**
$\mathbf{R^B_{H^*} = 2.0}$	**< 8.6 (11.0)**

$R^B_{H^*} = K(gg\to VV) / K(gg\to H^*\to VV)$

Summary

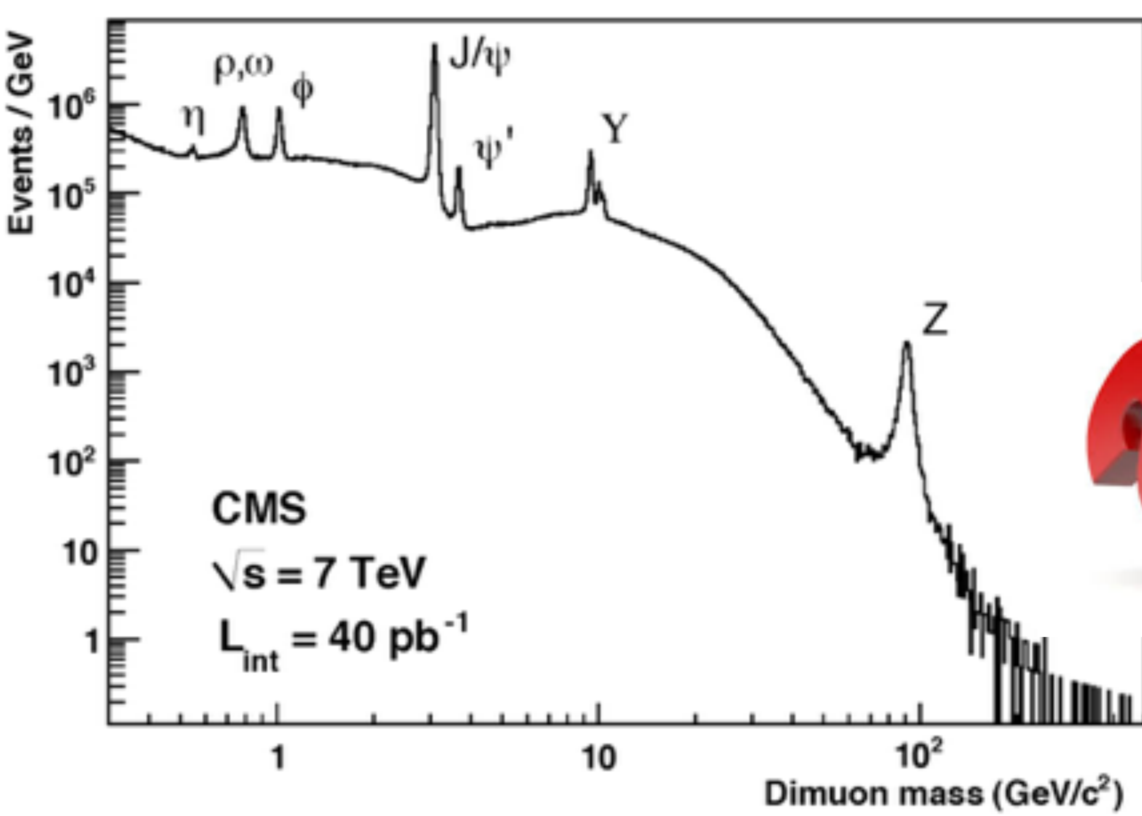
- the new boson found 1189 days ago looks just like the SM Higgs boson
- ATLAS and CMS measure m_H =125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV
- $H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$: observation
- $H\to\tau\tau$: evidence, $H\to bb$: ~2σ
- gg fusion : observation
- VBF : evidence, VH : ~evidence, ttH : 1-2 σ higher than expected
- no exotic decays are seen
- signal strengths of all production and decay modes are consistent with SM Higgs boson
- couplings to W, Z, t, b, τ are within 20-30% and agree with SM Higgs boson
- $\Gamma < 5.4\Gamma_{SM}$ (from off-shell analysis)

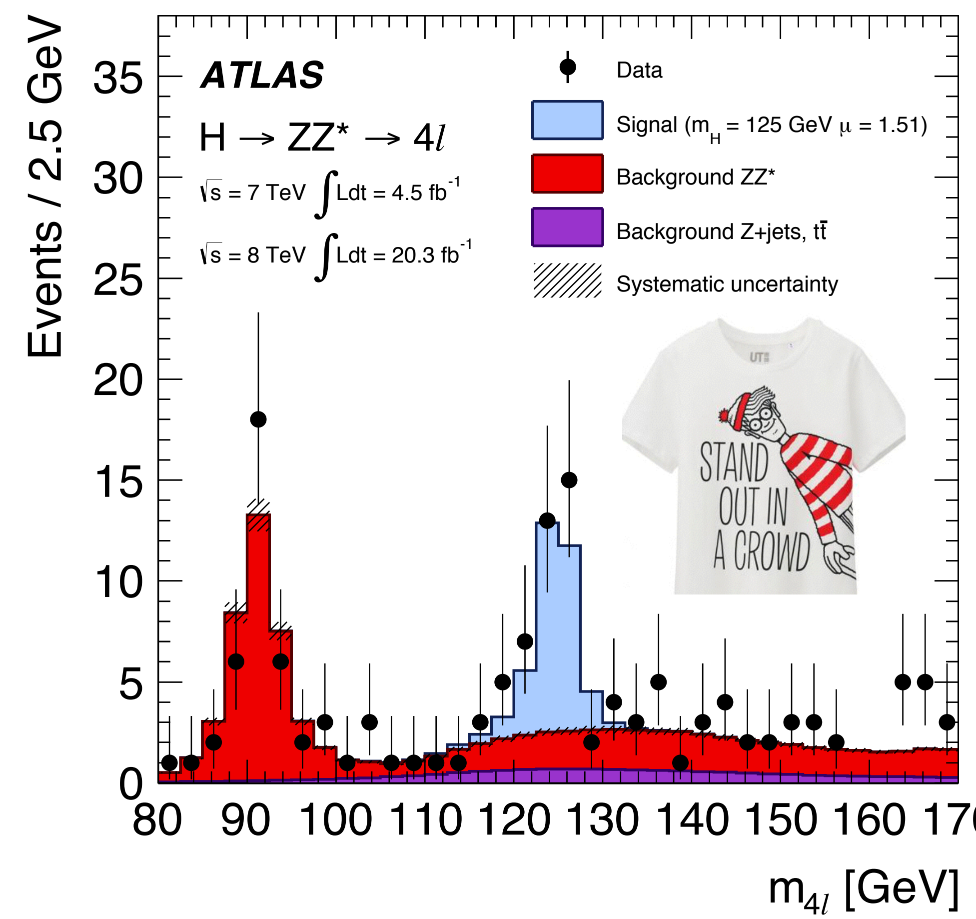
4 months ago … the start of a new era




WHERE'S WILMA?


WHERE'S WALLY?


Events / GeV
η
ρ,ω
φ
J/ψ
ψ'
Υ
Z
CMS
√s = 7 TeV
L_int = 40 pb⁻¹
Dimuon mass (GeV/c²)


ATLAS
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
Data
Signal (m_H = 125 GeV μ = 1.51)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
STAND OUT IN A CROWD
Events / 2.5 GeV
m_4l [GeV]

LHC future plan