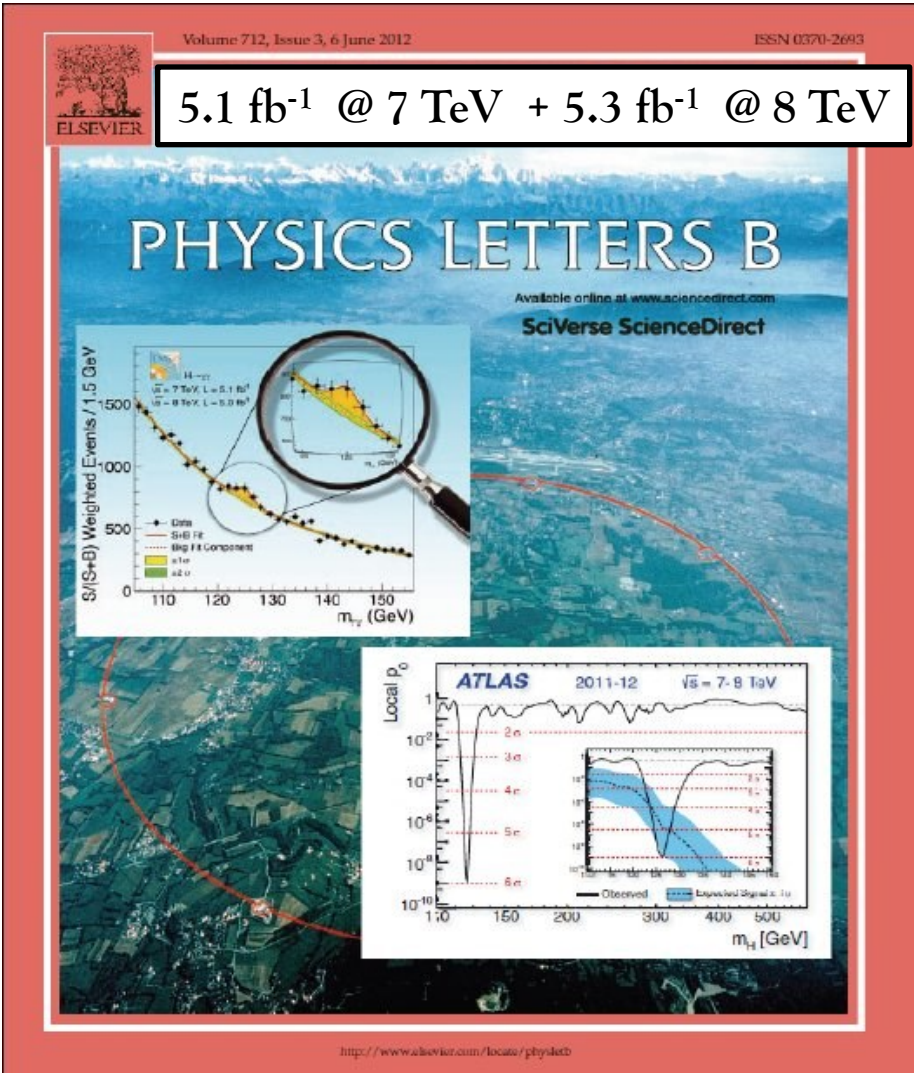
Measurements of the Higgs Boson at the LHC and Tevatron

Somnath Choudhury

(for the ATLAS, CMS, DØ and CDF collaborations)

44th International Symposium on Multiparticle Dynamics

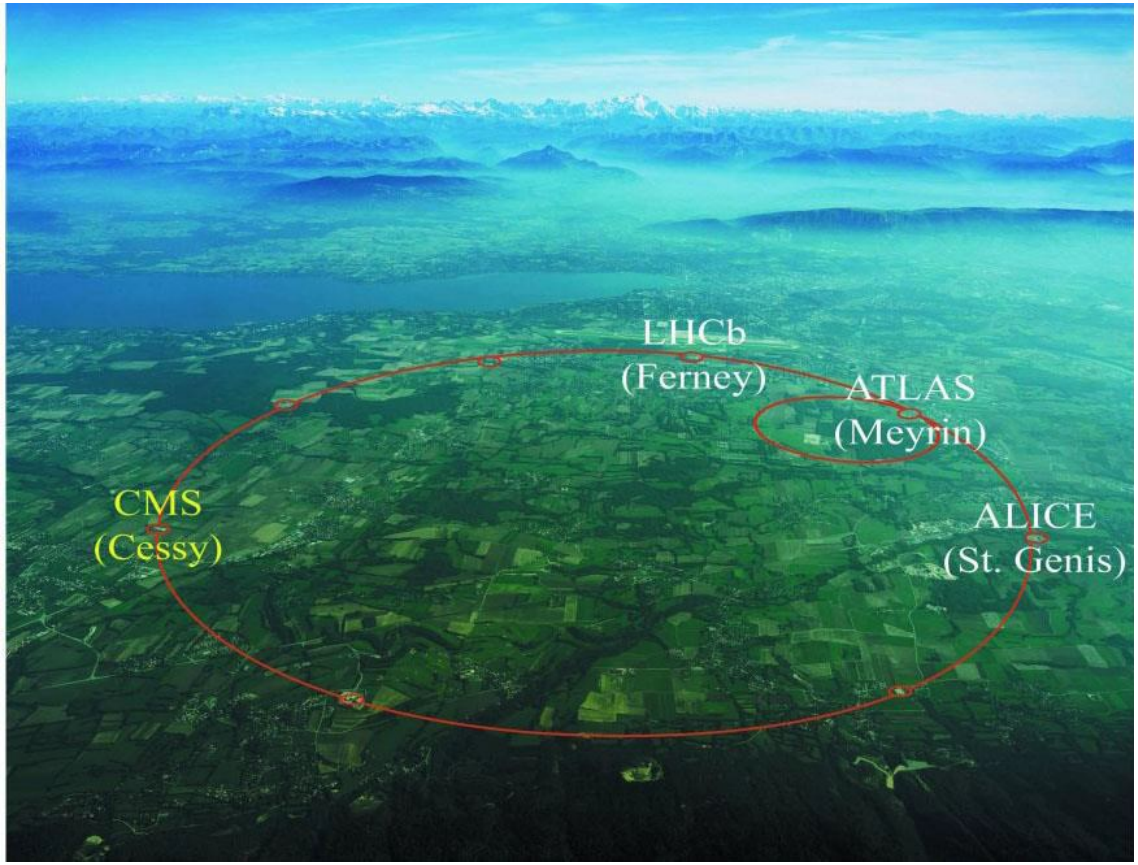
8 – 12 September 2014, Bologna (Italy)

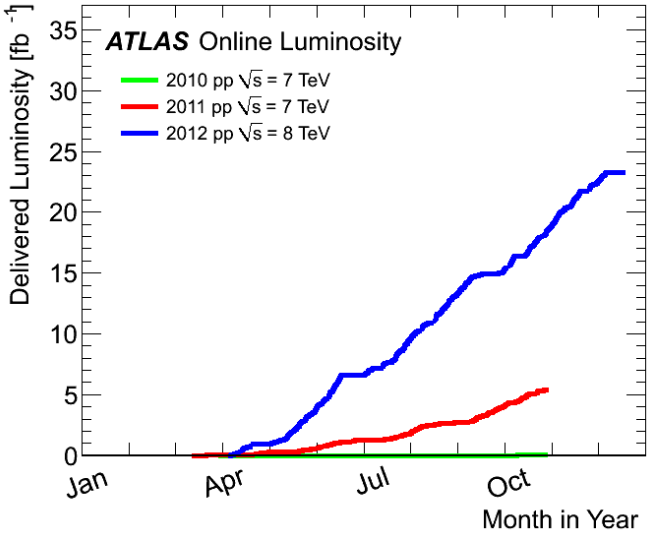


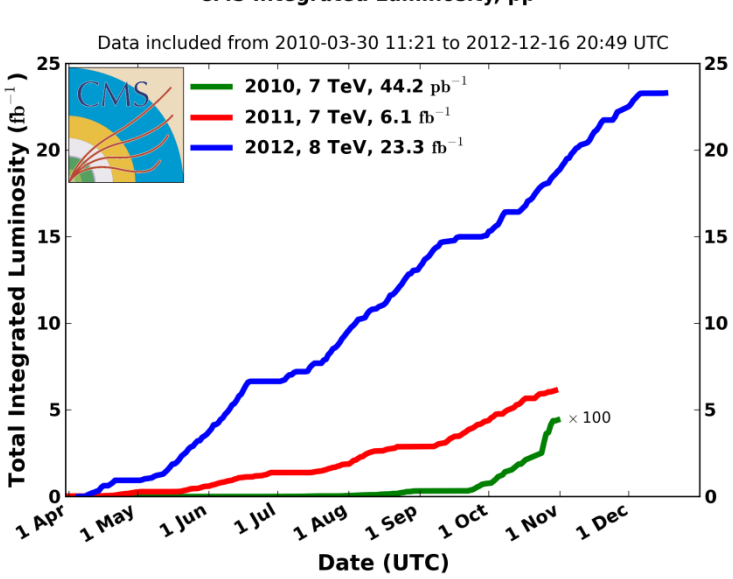
Outline

- LHC, Tevatron & Detectors
- Higgs Observation in Boson and Fermion decay
- Higgs Combination
- Higgs Measurements – Mass, Coupling, Spin/Parity Width, Cross-section
- Summary - LHC, Tevatron

The LHC







Overall data taking efficiency ~ 90% by both detectors

Mean pileup 21 interactions/bunch crossing recorded

A major challenge overcome by both ATLAS and CMS

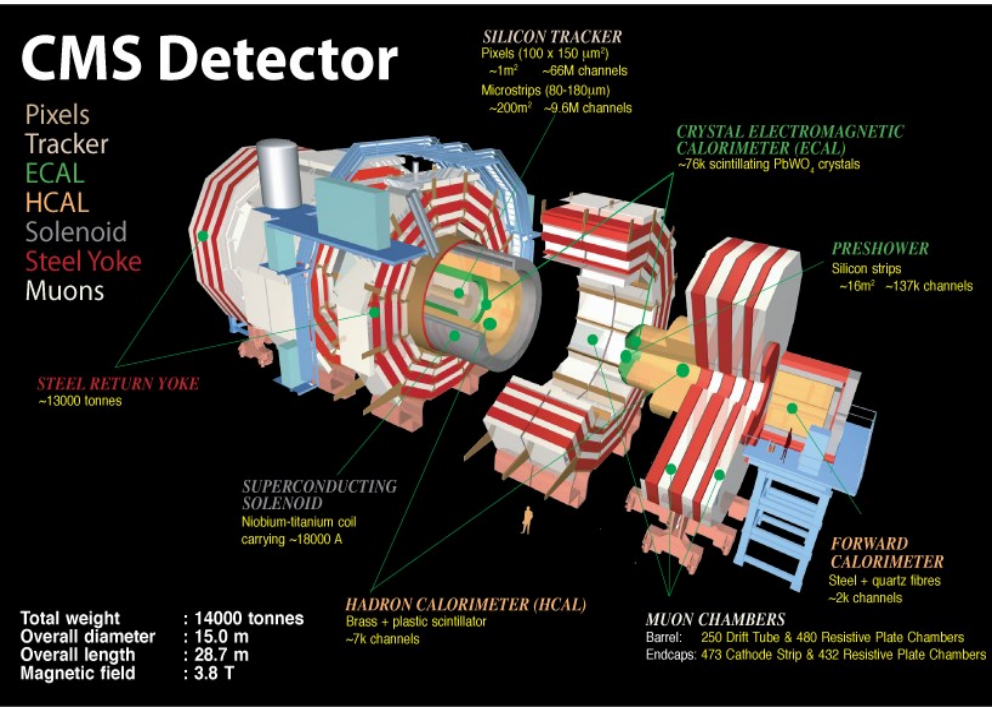
The Tevatron

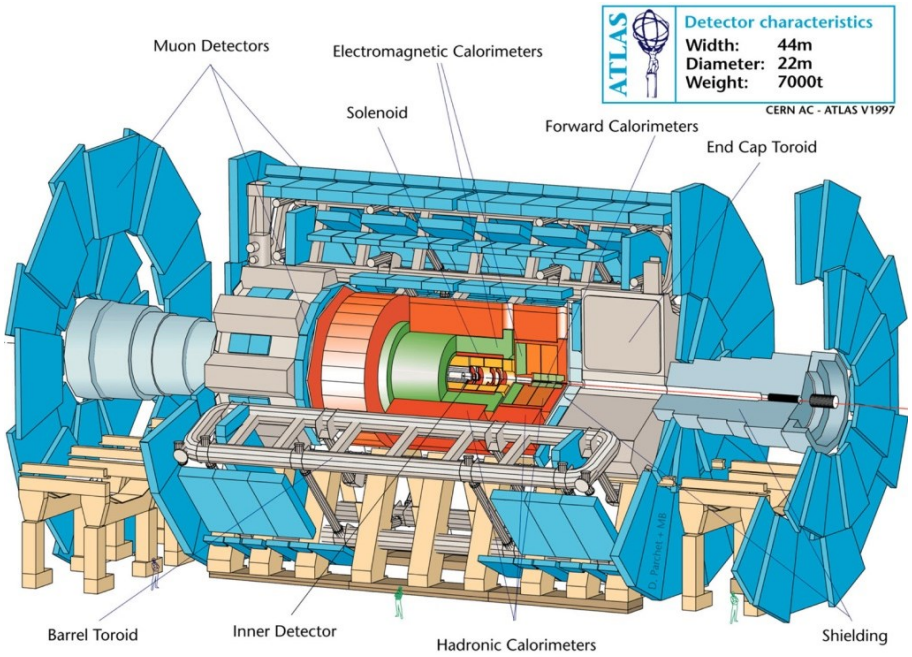
The Tevatron accelerator

Beam tunnel of Tevatron ring

Proton-Antiproton collider Tevatron Run II: (2002-2011), $\sqrt{s}$ = 1.96 TeV
A decade of successful running delivered ~10 fb^{-1} of luminosity for physics to CDF and DØ, shut down September 2011

CMS & ATLAS detector





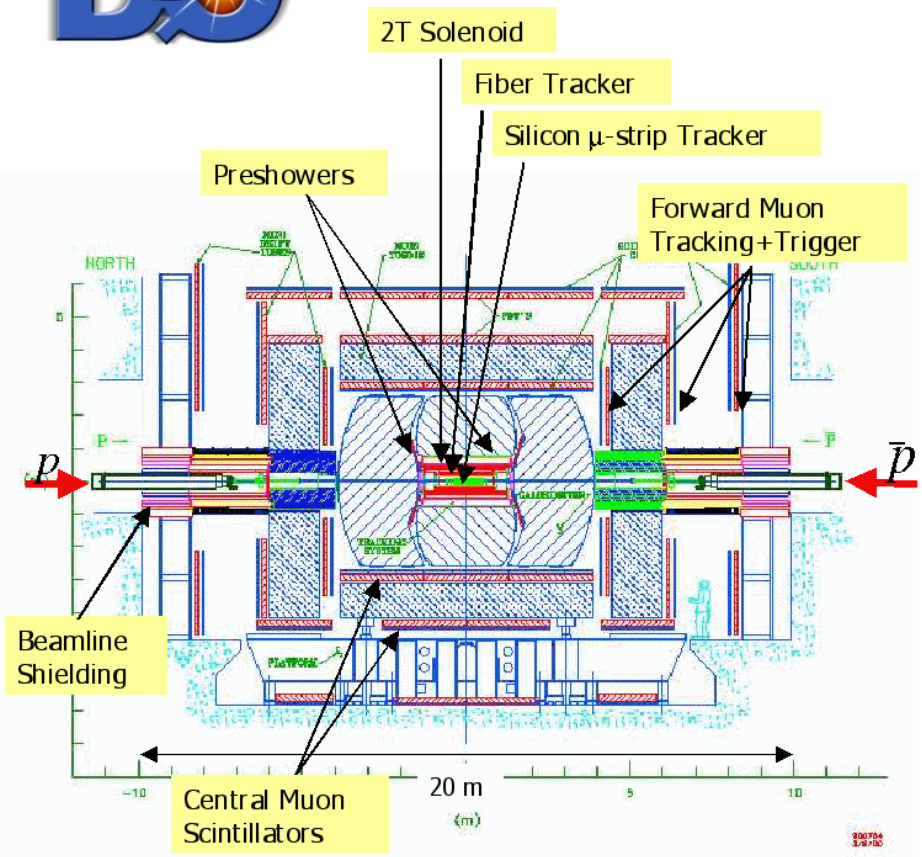
Detector subsystems

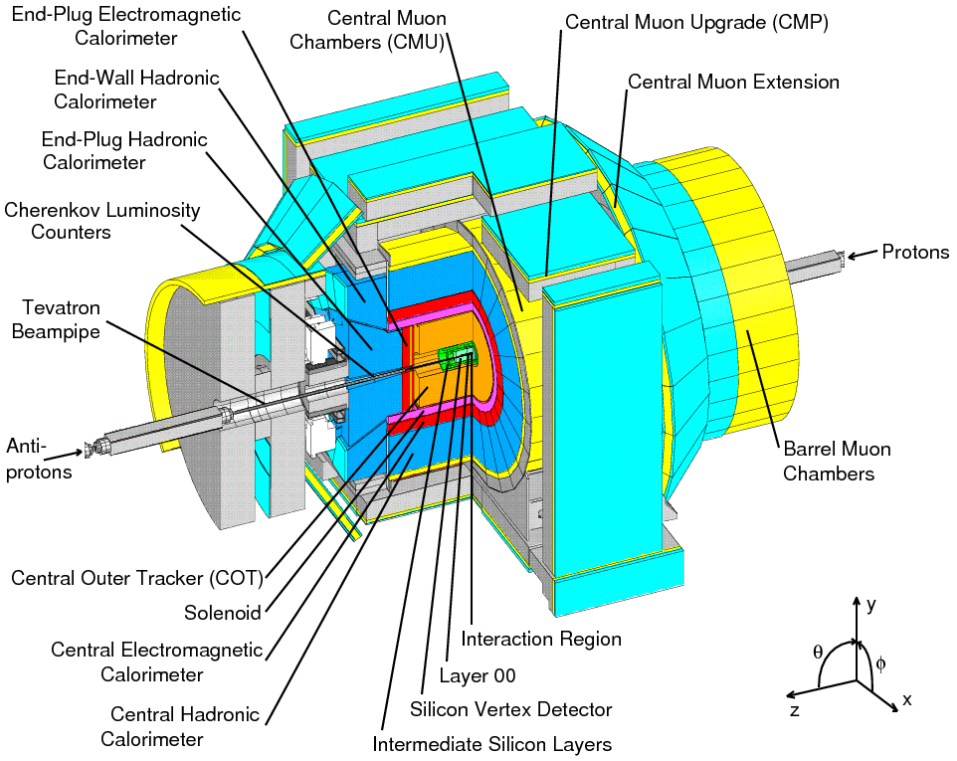
Vertex Detector
Silicon Tracker

Electromagnetic Calorimeter
Hadronic Calorimeter

Muon System

DØ & CDF detector





CERN
Higgs search
update 04.07.2012
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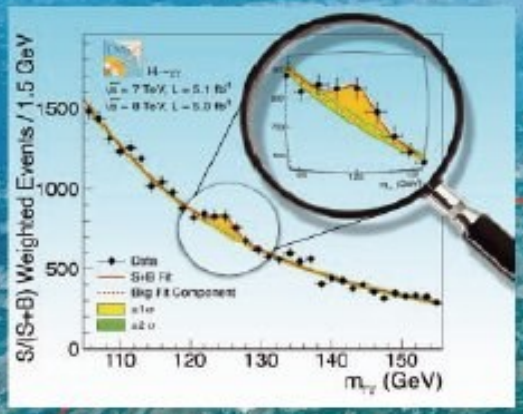

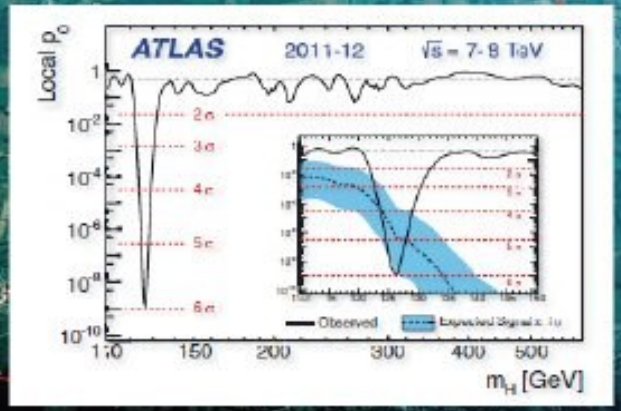

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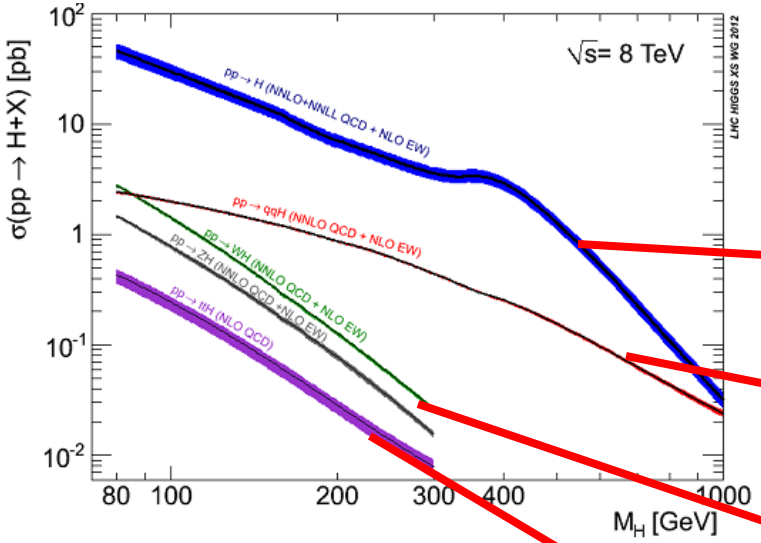
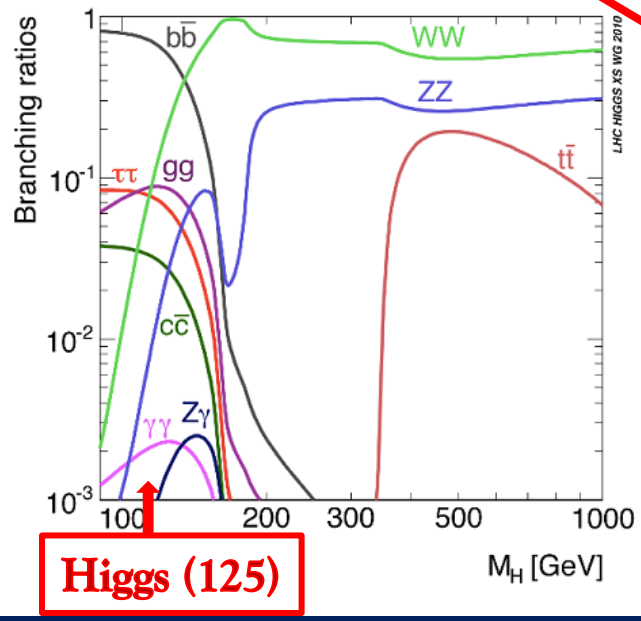
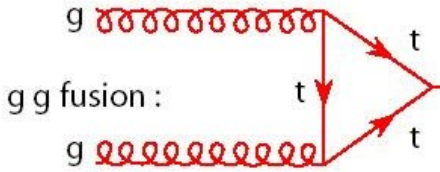
SM Higgs Sector @ LHC

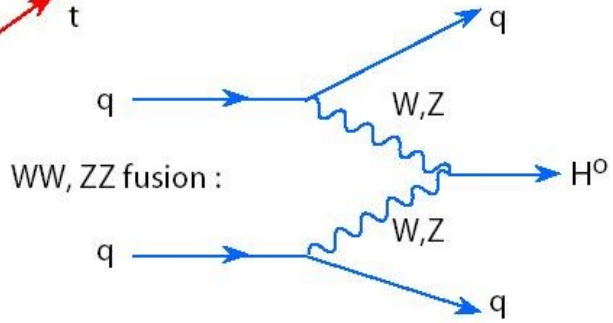
Great achievement to four decade long quest
A Higgs-like state pinned down at 125 GeV

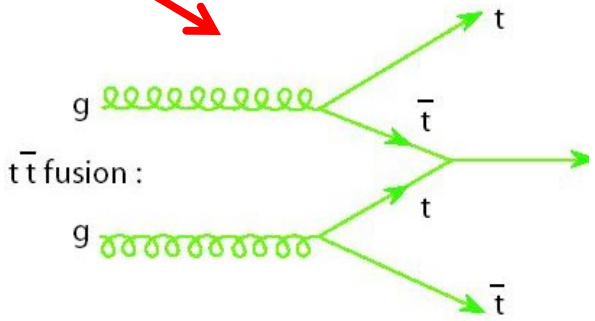


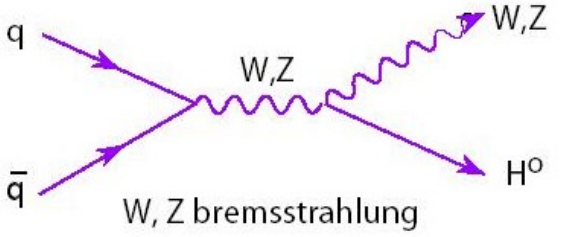


Higgs (125)

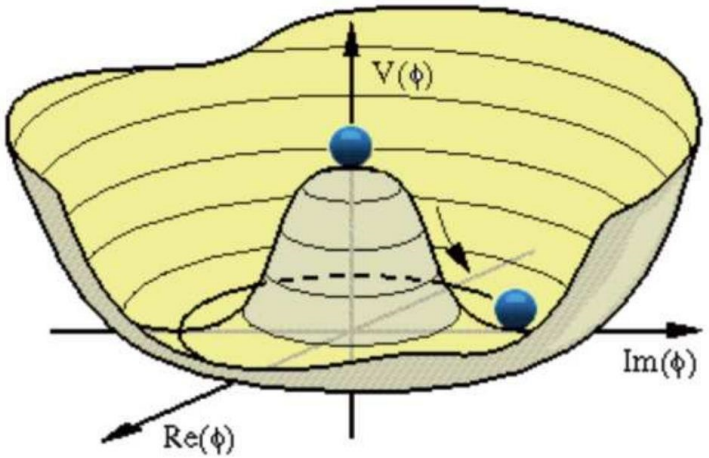






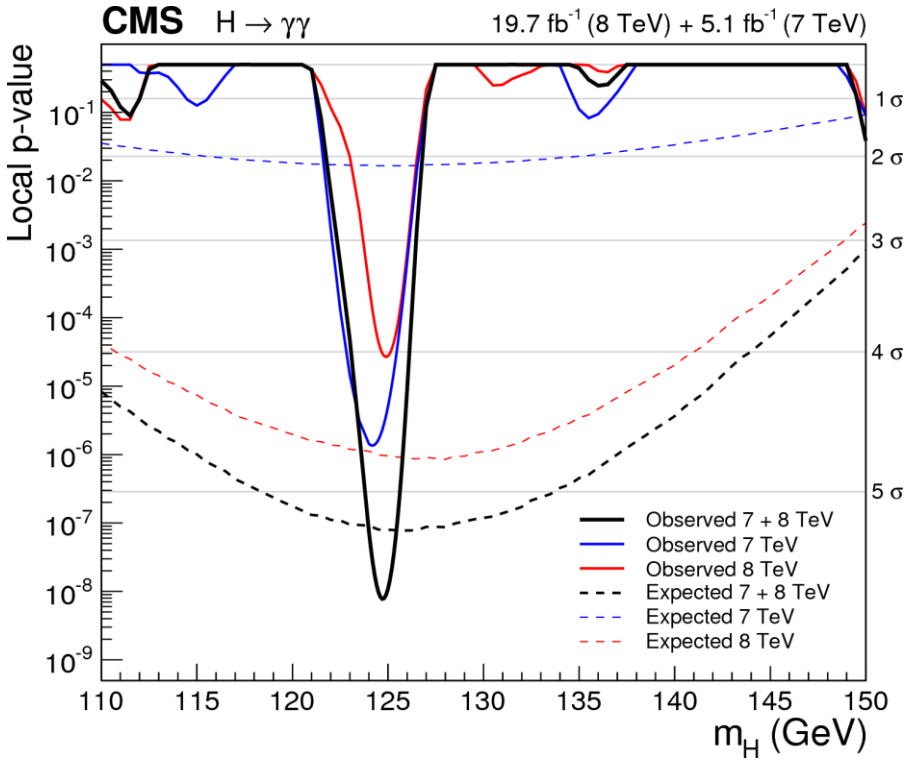


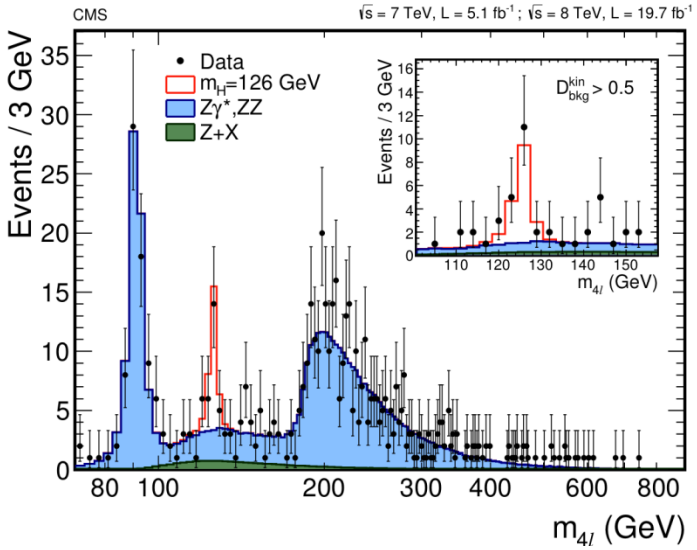
Higgs Boson
@ LHC & Tevatron

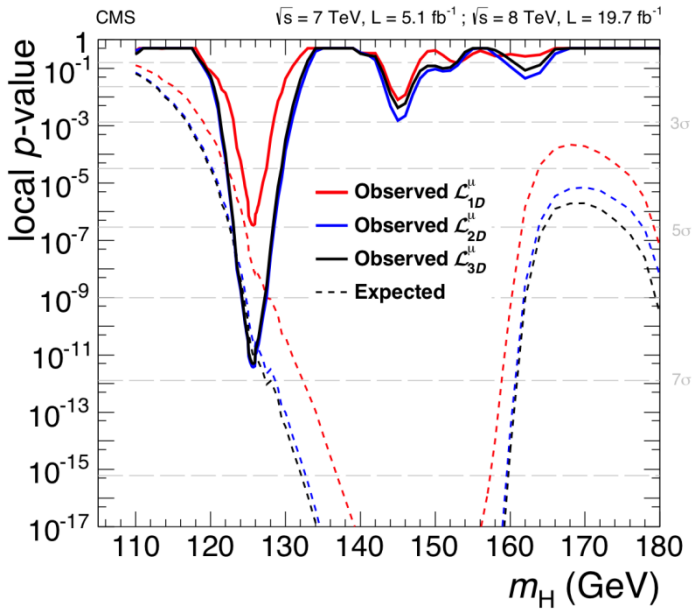


Higgs Boson @ CMS

arXiv:1407.0558 [hep-ex]

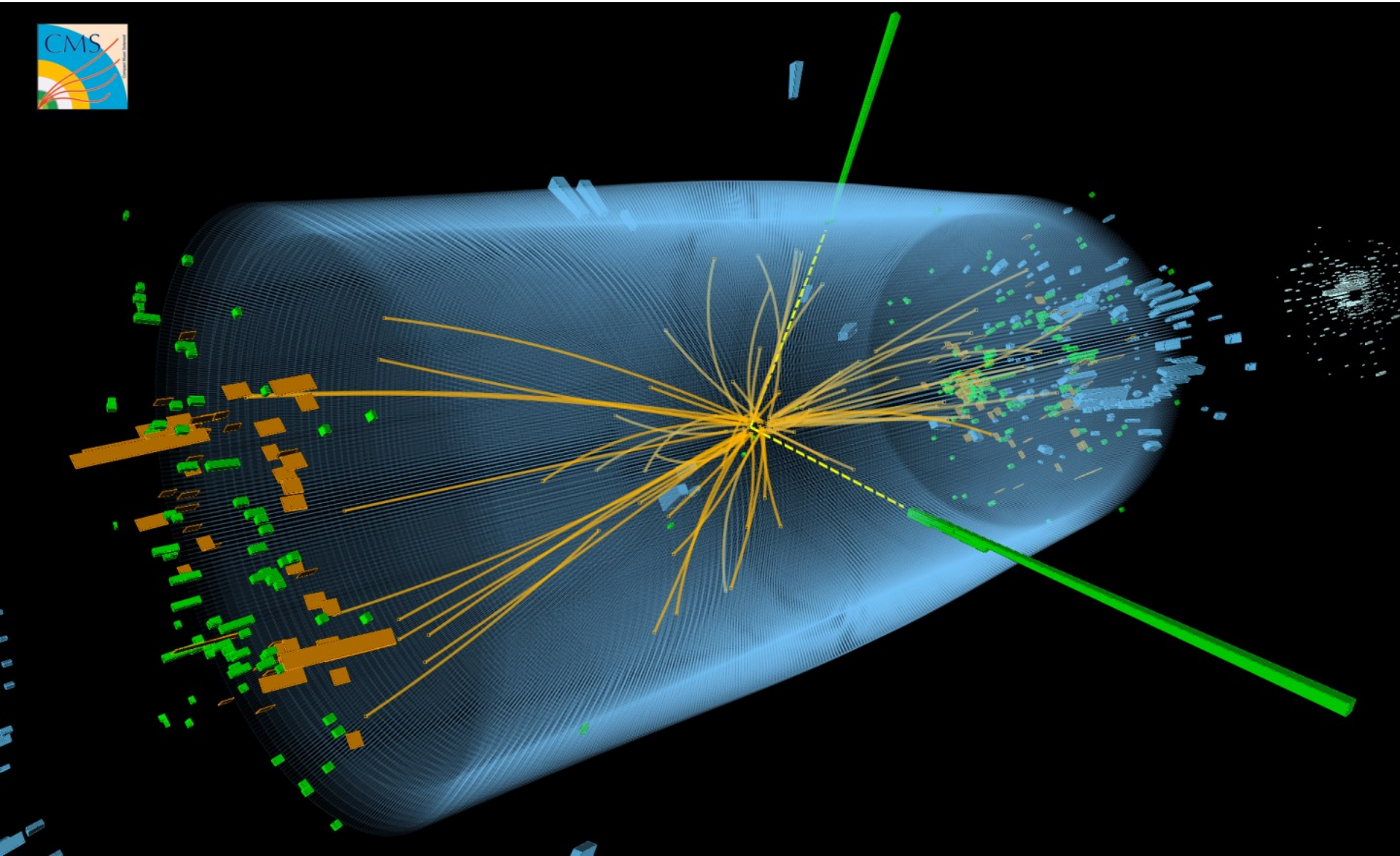




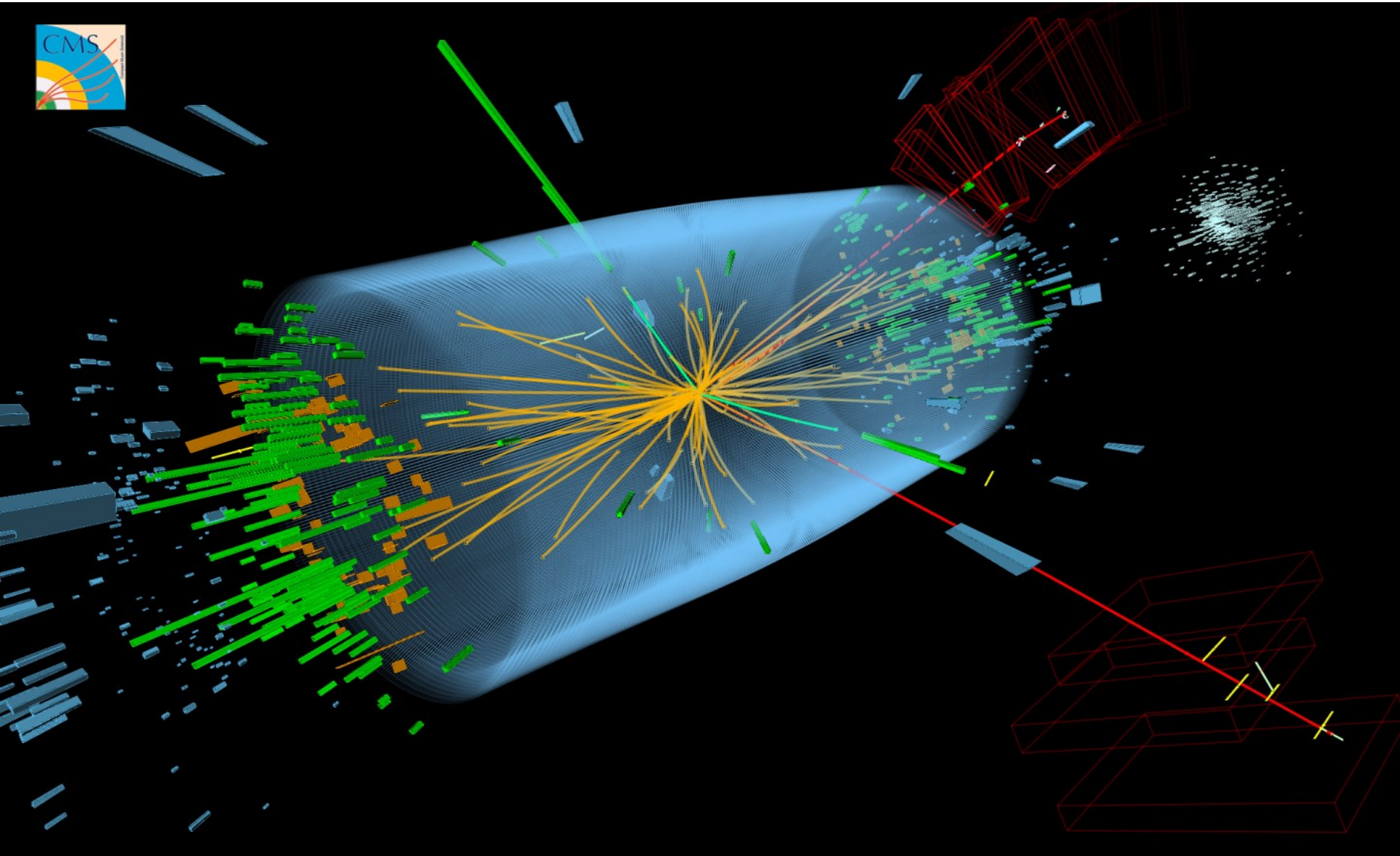


- The signal @125 GeV with significance > 5σ observed in γγ decay mode
- 6.7σ significance @125 GeV observed in H→ZZ*→4l golden decay mode

$H \rightarrow \gamma\gamma$

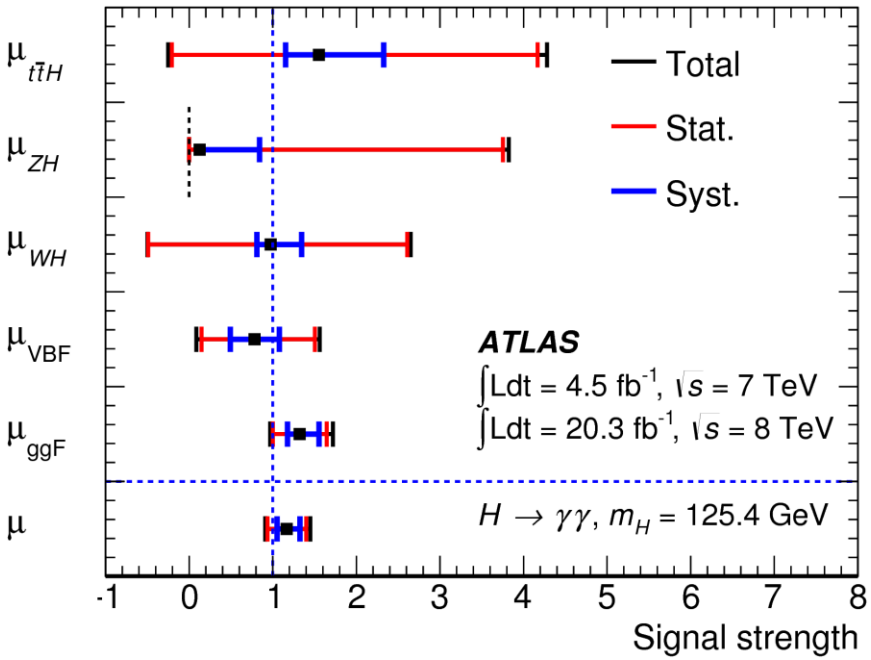


$H \rightarrow ZZ^* \rightarrow 2e2\mu$

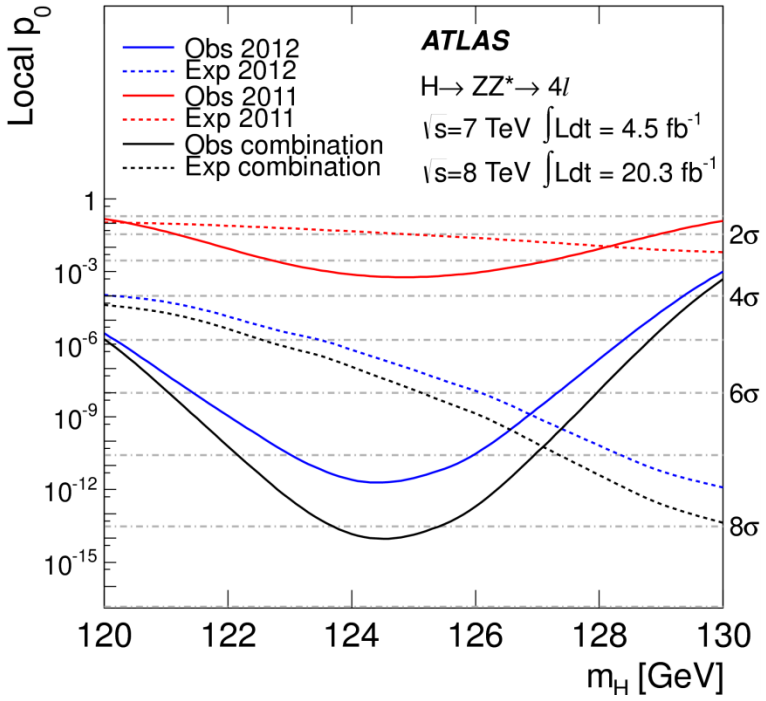


Observation of Higgs Boson in γγ and ZZ*→4l decay channels at ATLAS

arXiv:1408.7084 [hep-ex]

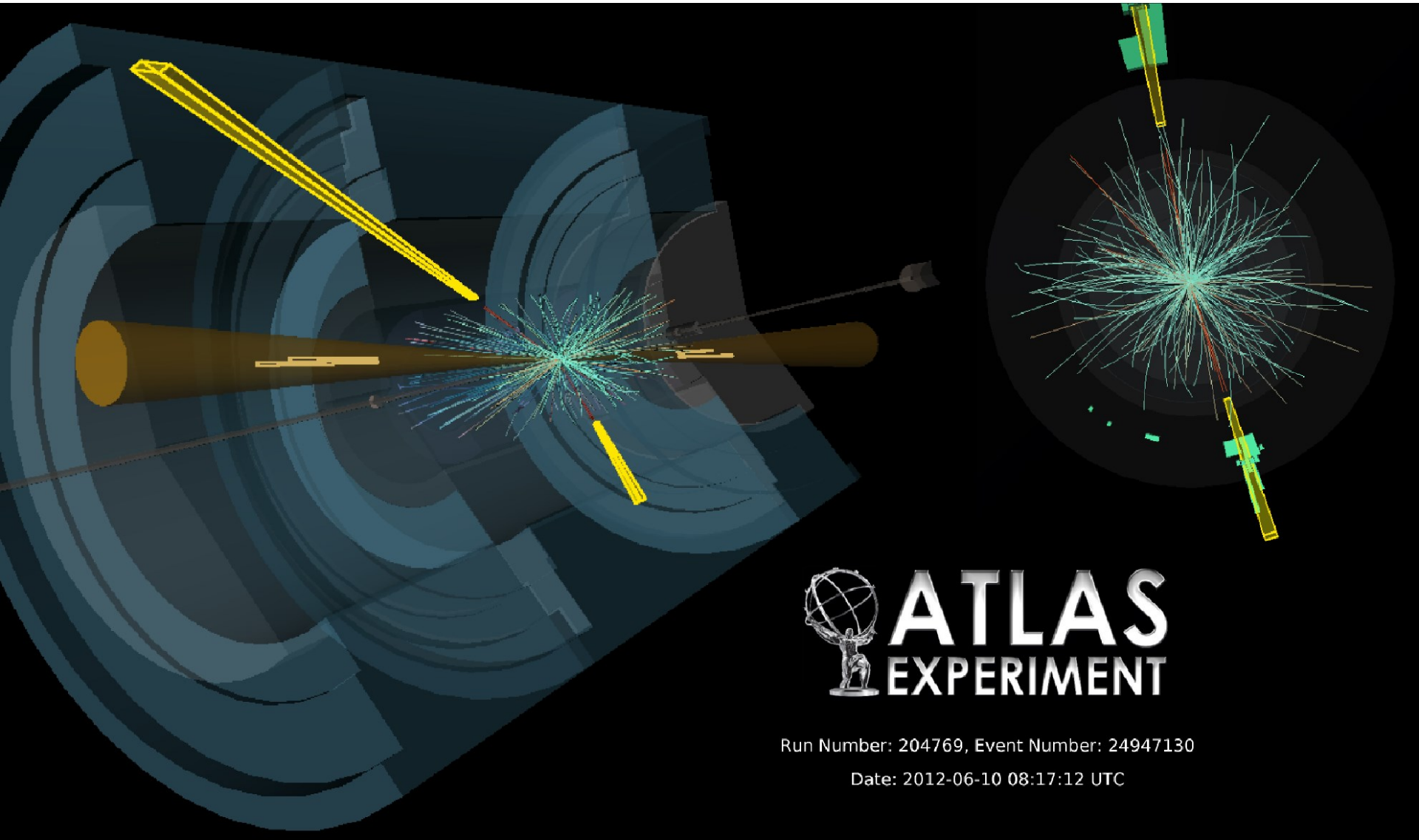


arXiv:1408.5191 [hep-ex]

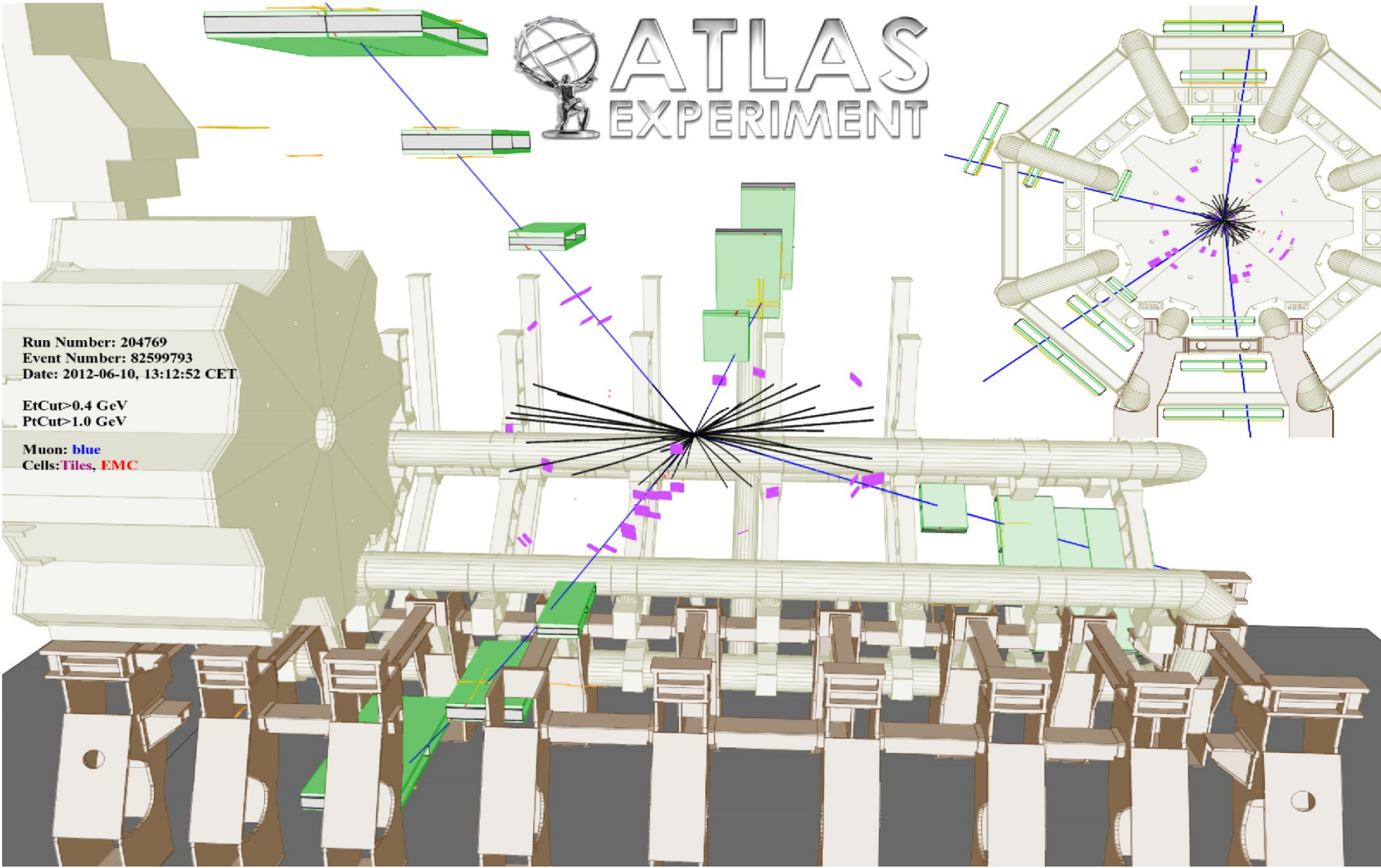


- H→ZZ*→4ℓ signal observed with a significance of 8.1σ at m_H = 125.36 GeV
- Measured signal strength μ=1.44 $^{+0.40}_{-0.33}$ in ZZ*→4ℓ and 1.17±0.27 in γγ mode

$H \rightarrow \gamma\gamma$

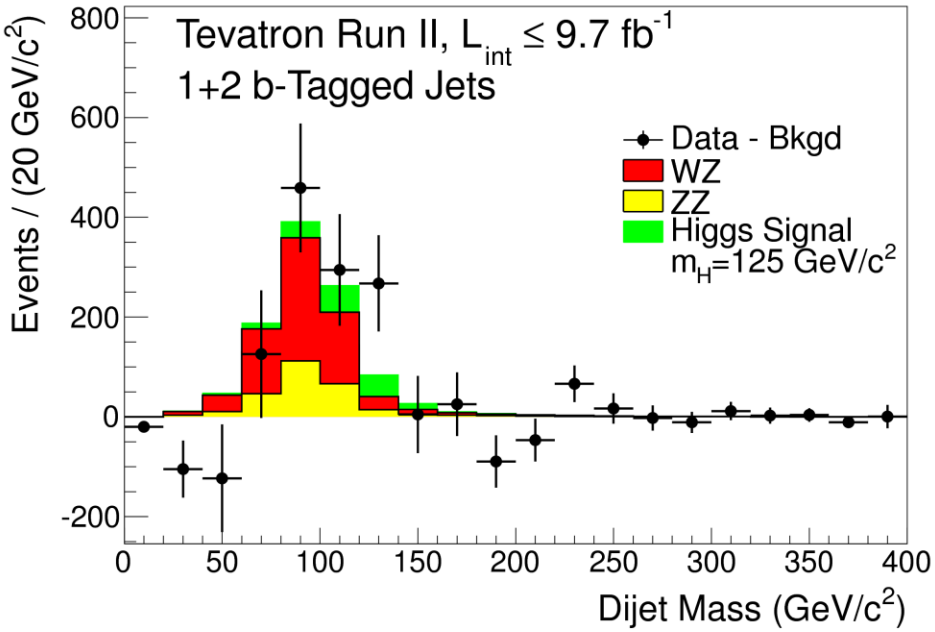


$H \rightarrow ZZ^* \rightarrow 4\mu$

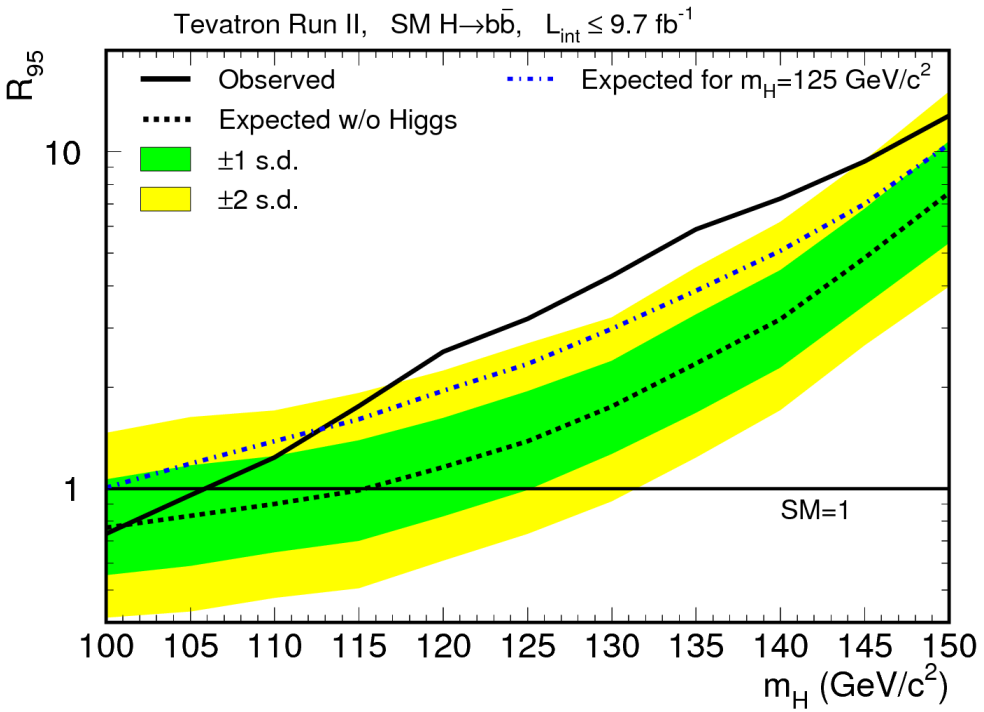


Higgs Boson @ Tevatron

Phys. Rev. Lett. 109, 071804 (2012)



Combined searches for WH→lνbb, ZH→llbb, and WH+ZH→METbb using full 9.7 fb^{-1} Tevatron dataset



Excess of data over the background seen with most significance in the mass range

$120 \leq m_H \leq 135$ GeV

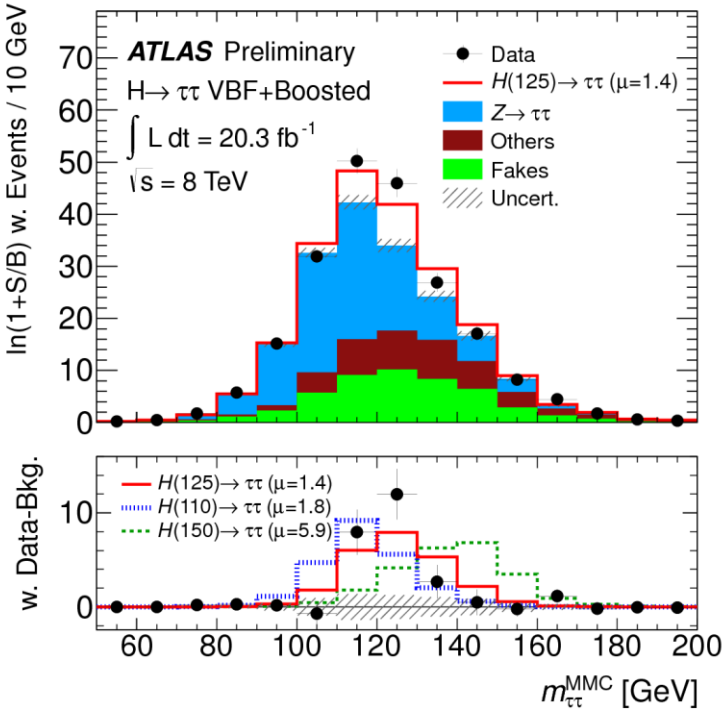
Evidence of Higgs: Direct Indication of Higgs coupling to Fermions

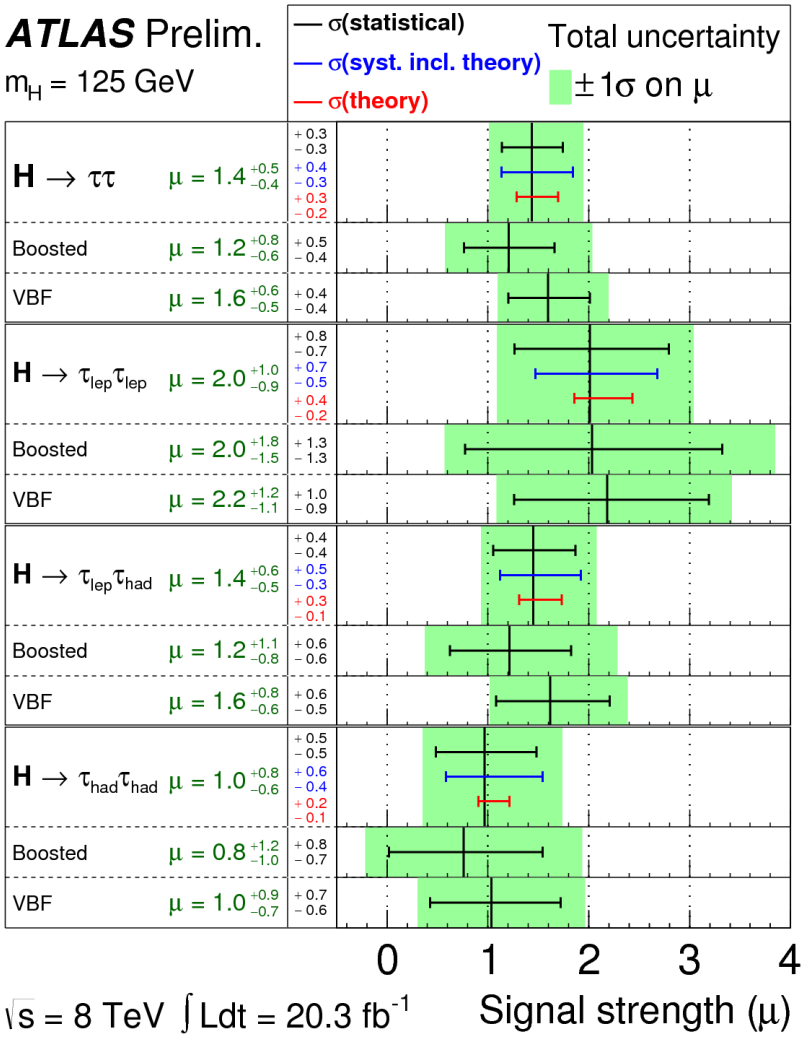
2.8σ significance at m_H=125 GeV

Higgs - Lepton Coupling @ ATLAS

ATLAS-CONF-2013-108

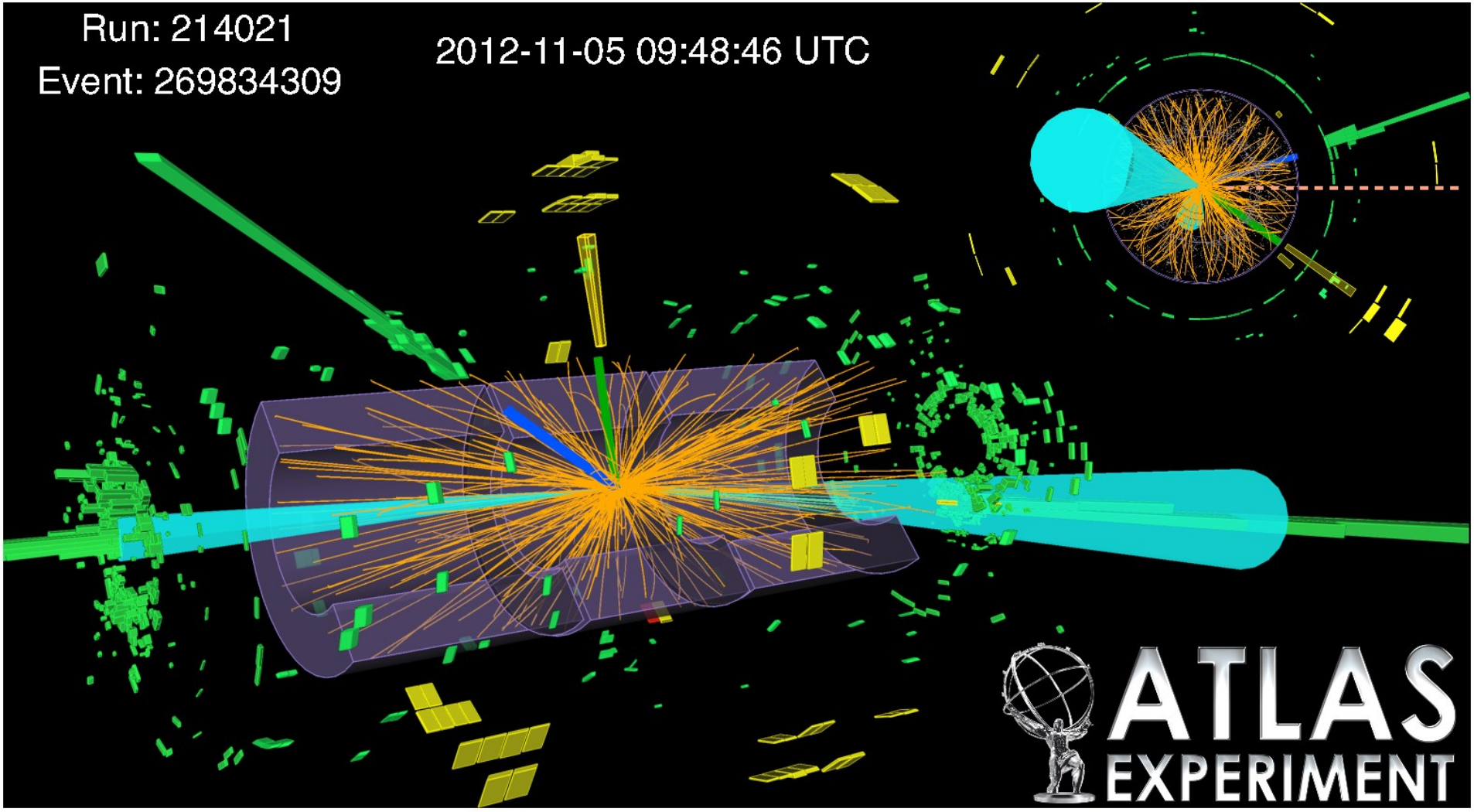
Evidence for Higgs – Lepton Coupling



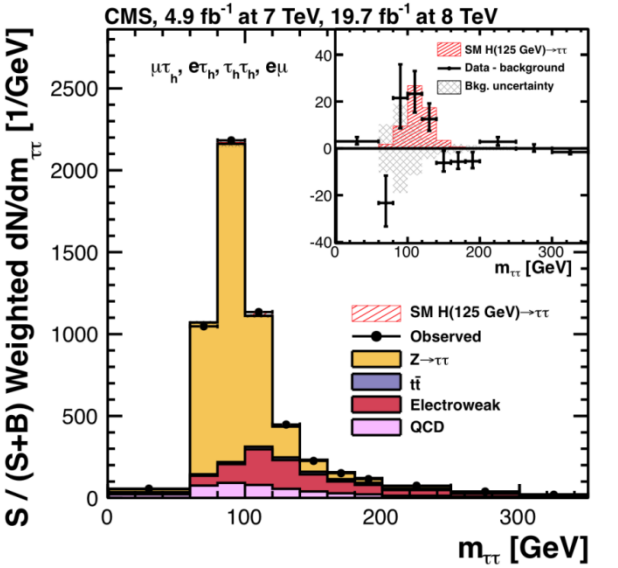


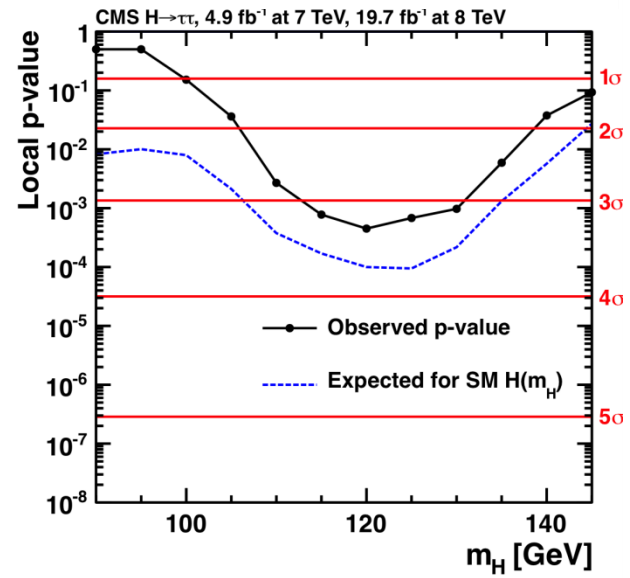
- Excess > 4σ observed over m_H 110 –130 GeV
- Best fit signal strength $1.4\ ^{+0.5}_{-0.4}$ for m_H=125 GeV
- Observed Significance 4.1σ for m_H=125 GeV
- A clear indication of Higgs – Lepton coupling

$H \rightarrow \tau\tau$



Higgs - Lepton Coupling @ CMS

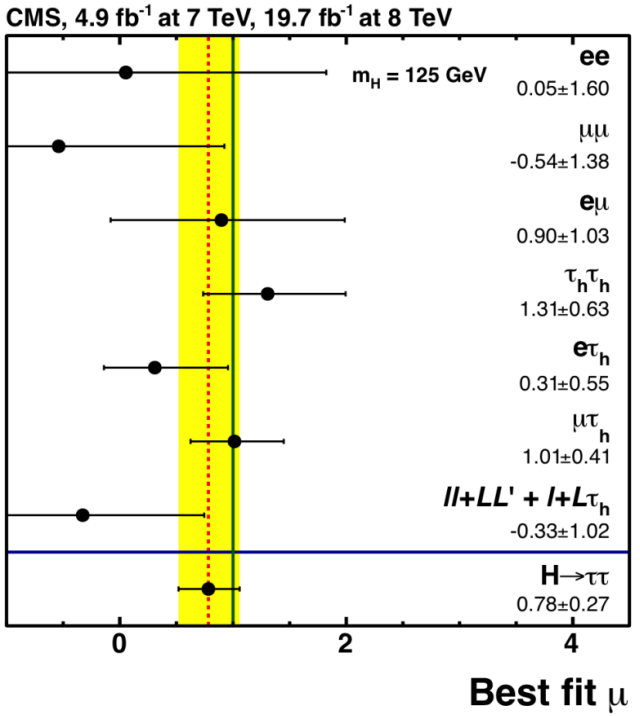




Evidence for Higgs – Lepton Coupling

JHEP 05 (2014) 104

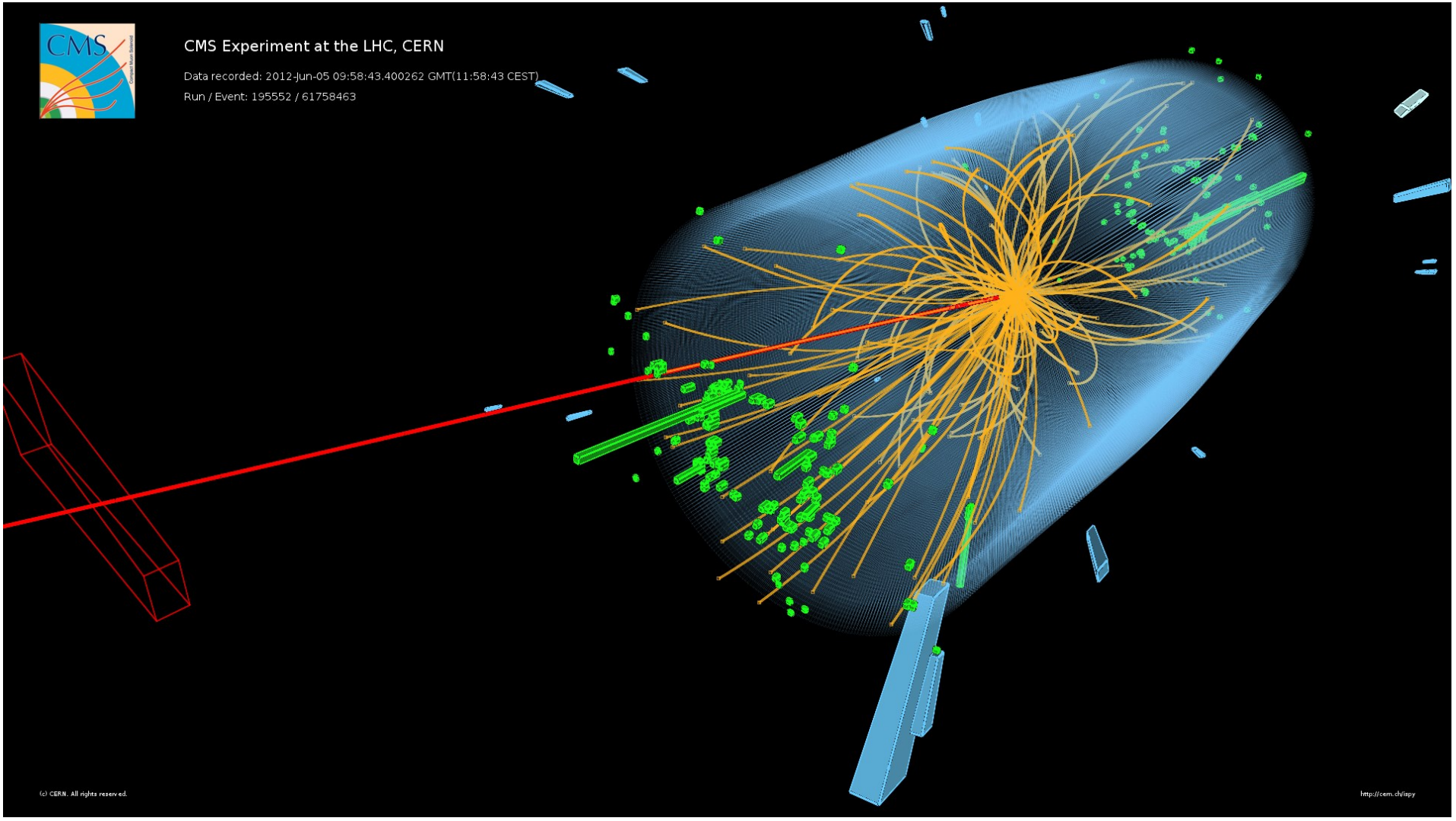
- Excess >3σ observed over m_H 110 –130 GeV
- $H \rightarrow \tau\tau$ best fit signal strength 0.78 ± 0.27 for m_H = 125 GeV
- Observed (expected) Significance 3.2σ (3.7σ) for m_H = 125 GeV
- Strong affirmation on Higgs-Fermion coupling, a clear indication of Higgs–Lepton coupling



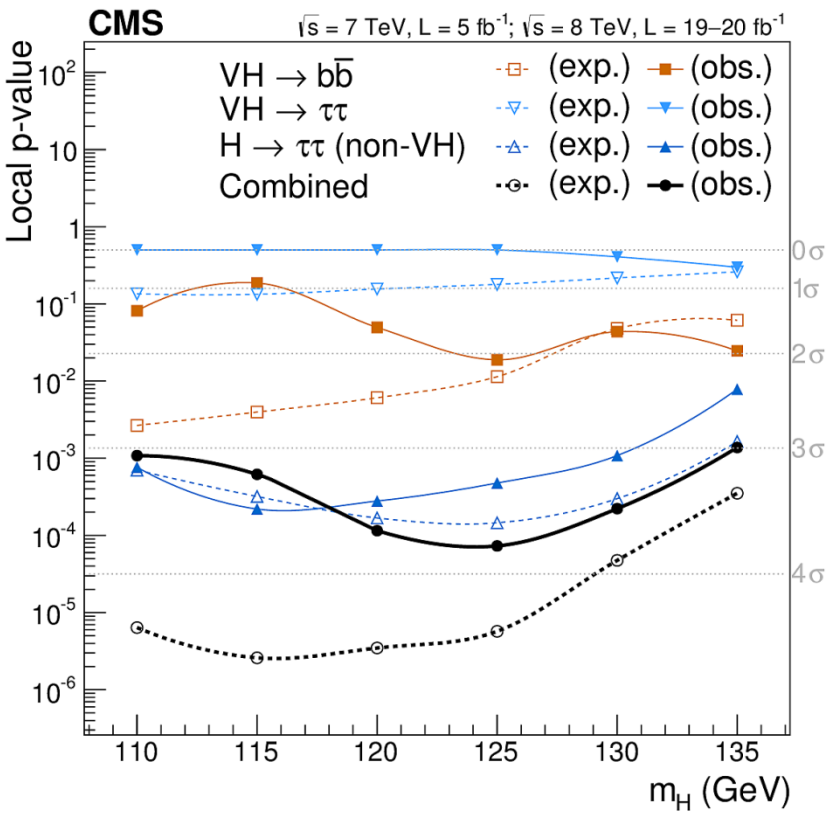
Signal strength μ compared to SM

μ = 0.78 ± 0.27

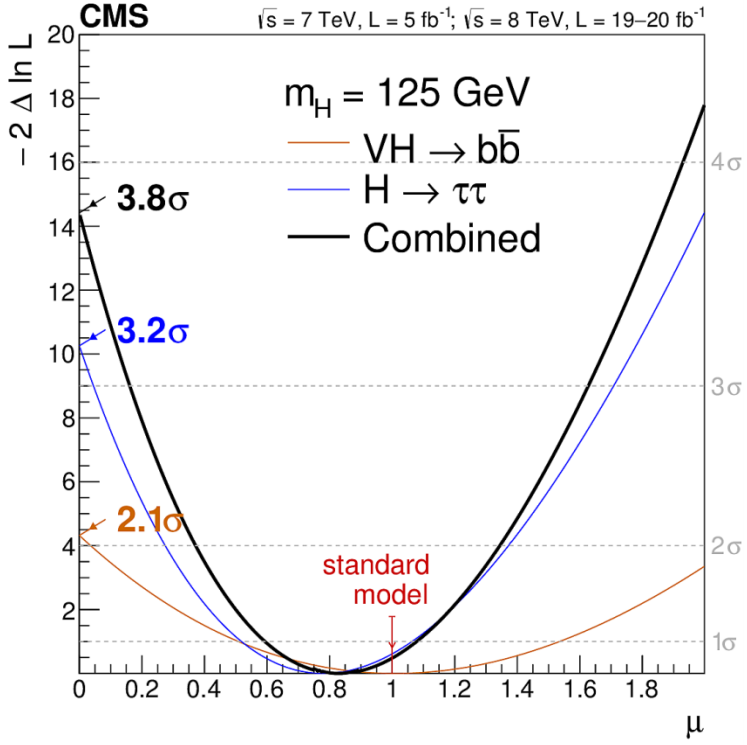
$H \rightarrow \tau\tau$



Nature Physics 10, 557 (2014)



Channel ($m_H = 125\,GeV$)	Significance (σ)		Best-fit
	Expected	Observed	μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

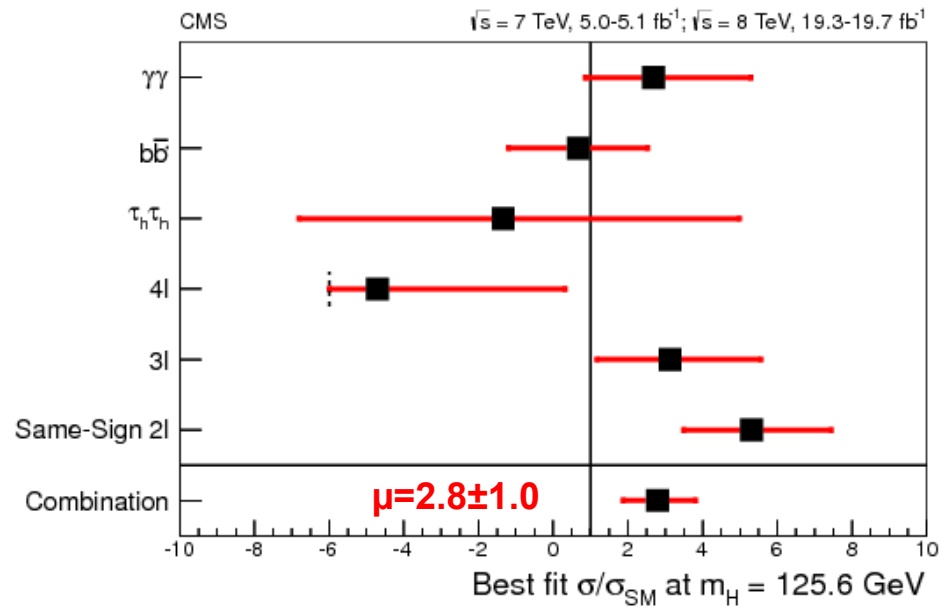


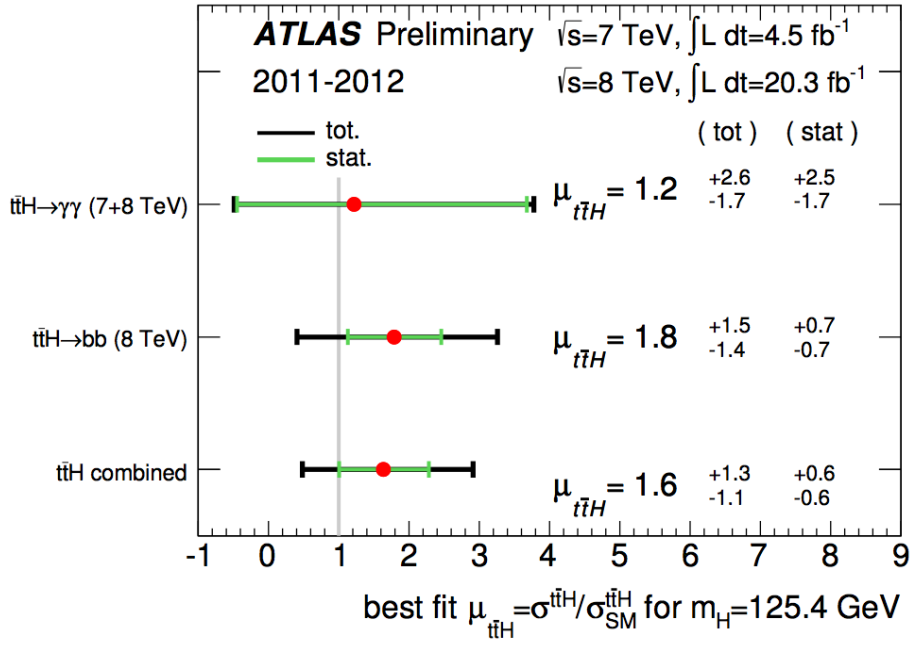
Strong evidence for the direct coupling of the 125 GeV Higgs boson to fermions, with an observed (expected) significance of 3.8σ (4.4σ)

- ttH important to **probe directly** top-Higgs Yukawa coupling
- Interested in ttH, H to anything with large enough BR
  H→bb is the most attractive here for SM m_H = 125 GeV
- Categories events based on number of jets and b-tagged jets

arXiv:1408.1682 [hep-ex]

ATLAS-CONF-2014-043



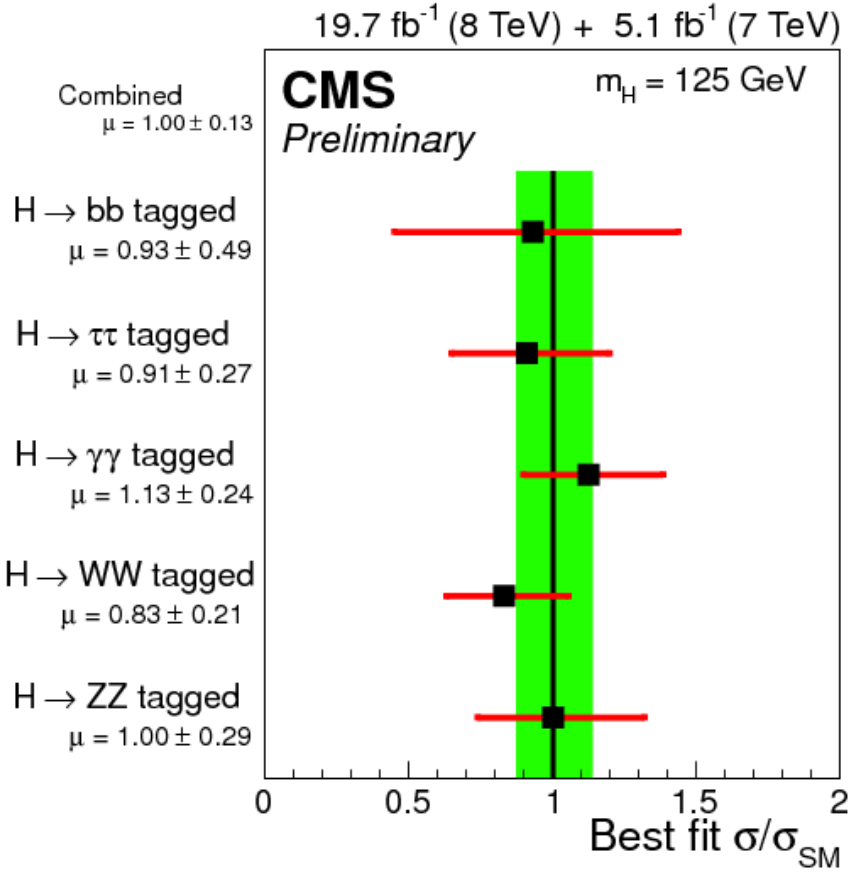


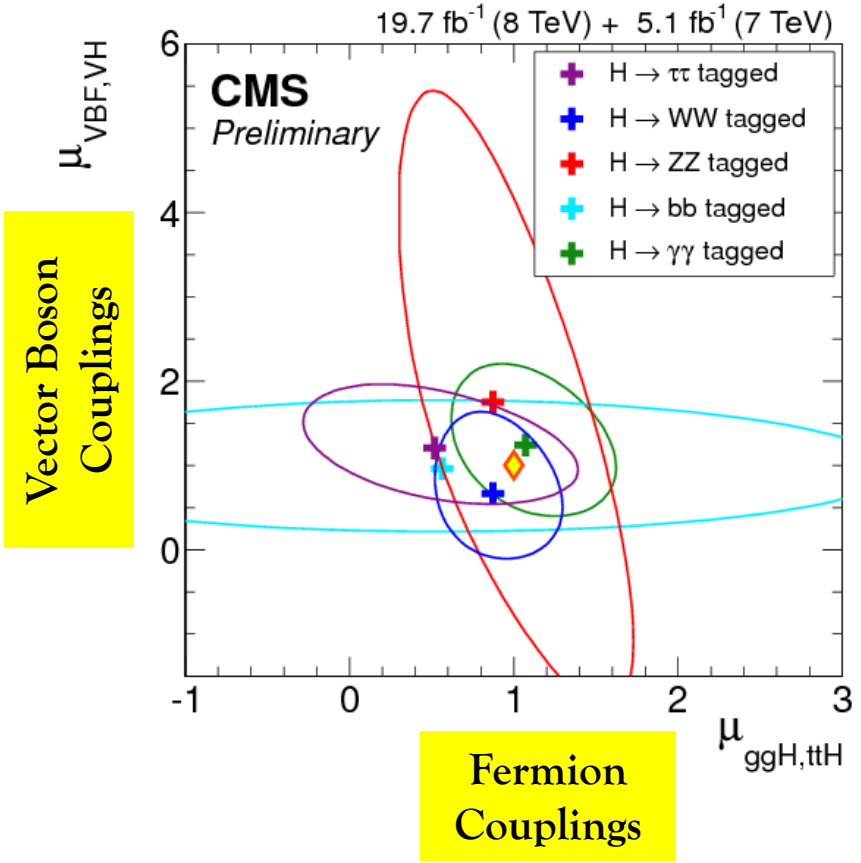
Higgs Combination

Higgs Combination @ CMS

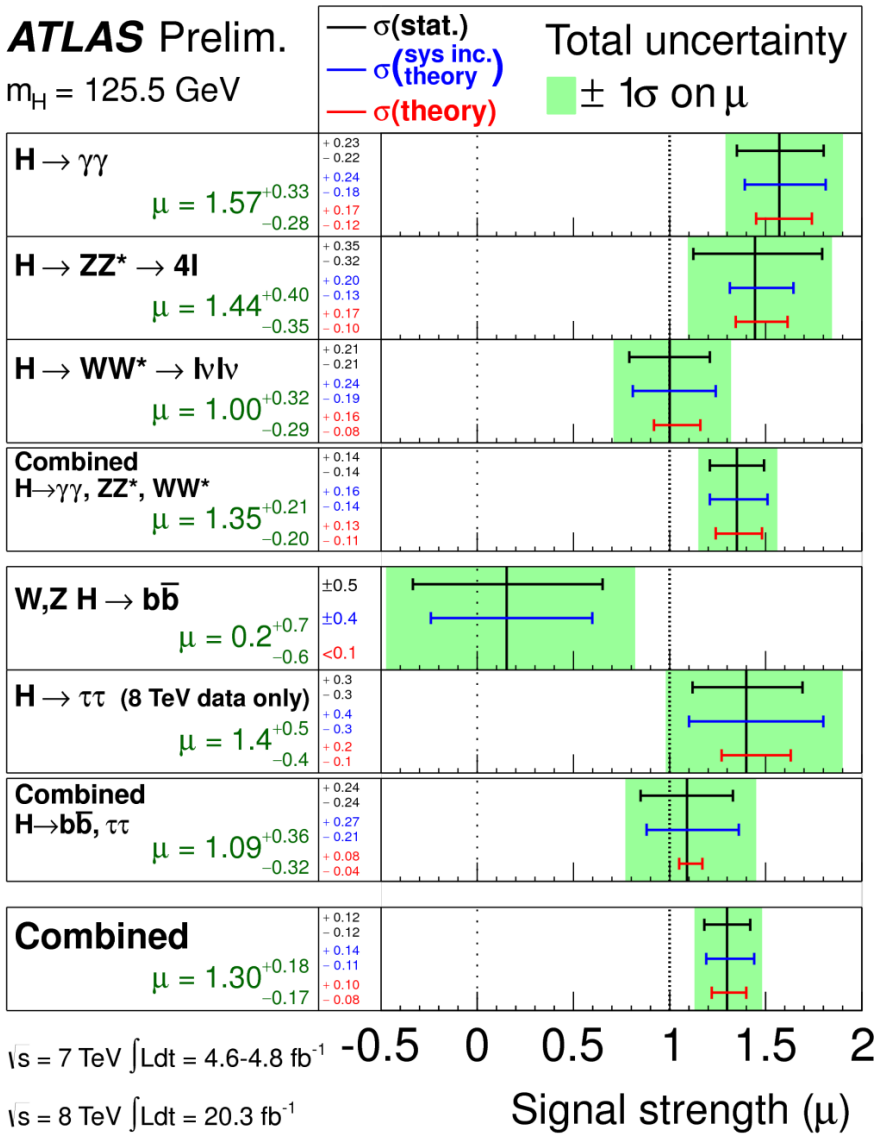
CMS-PAS-HIG-14-009

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$



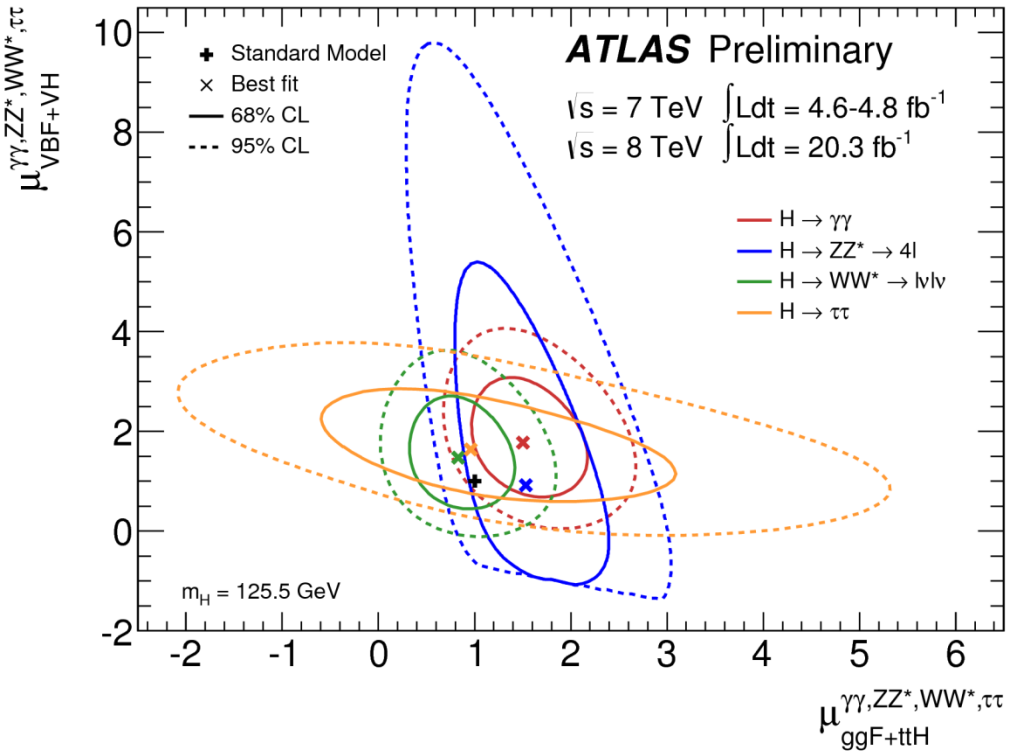


Higgs Combination @ ATLAS



ATLAS-CONF-2014-009

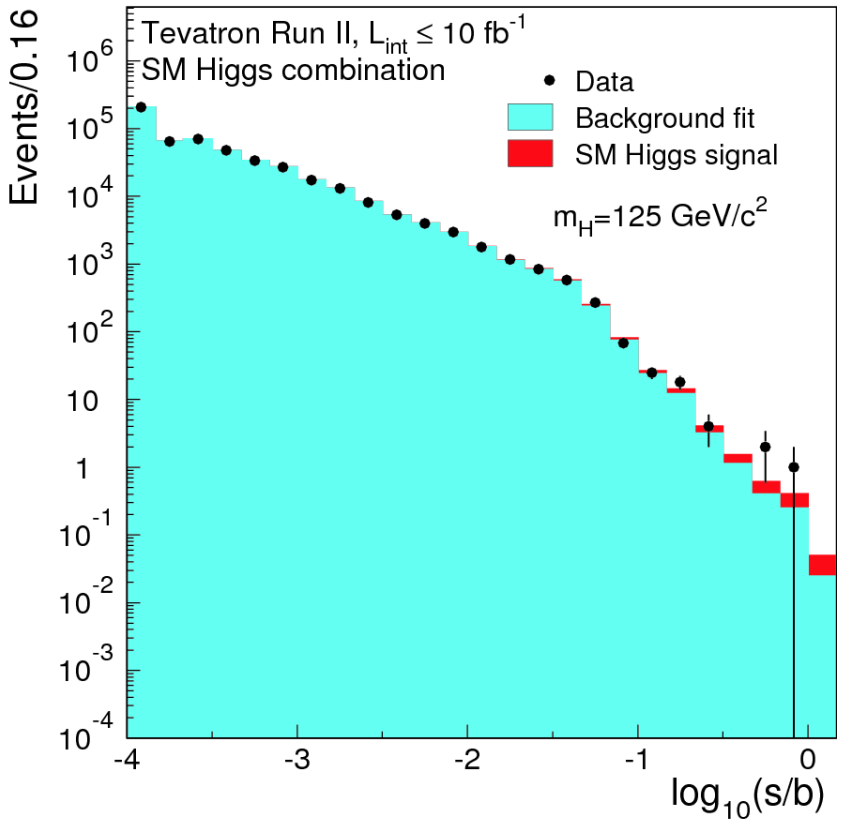
$\mu = 1.30 \pm 0.12\,(\text{stat})\,^{+0.14}_{-0.11}\,(\text{sys})$ @ m_H=125.5 GeV



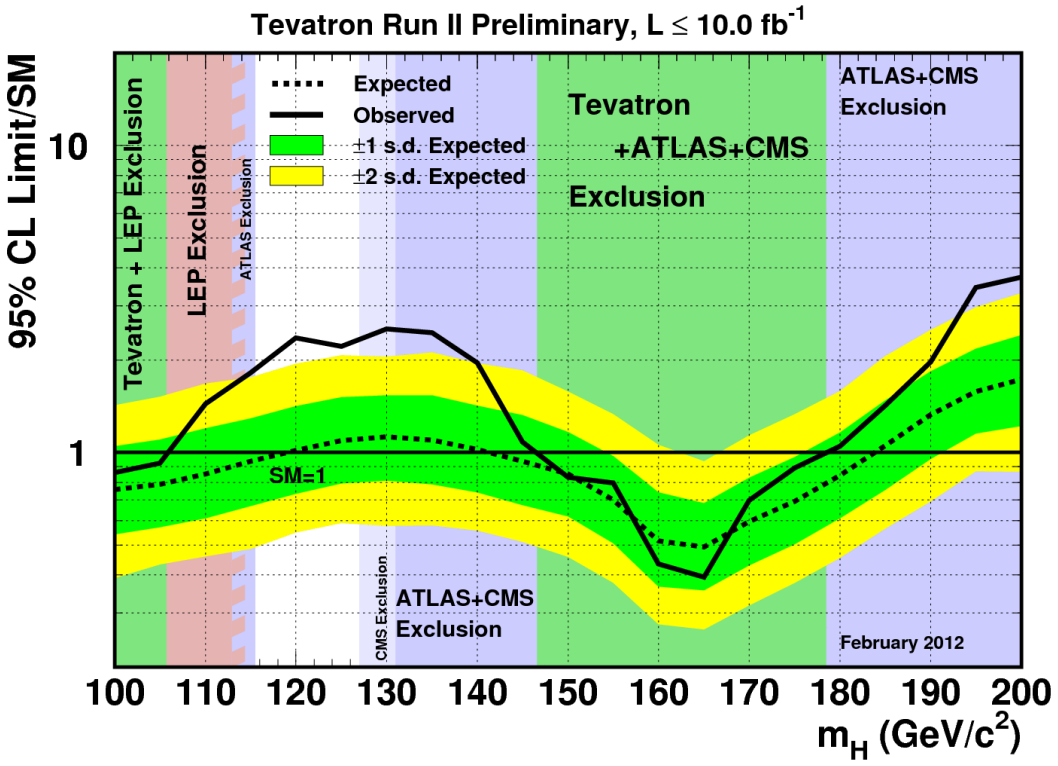
Observation in good agreement with the Standard Model Higgs boson hypothesis

Higgs Combination @ Tevatron

Phys. Rev. D 88, 052014 (2013)



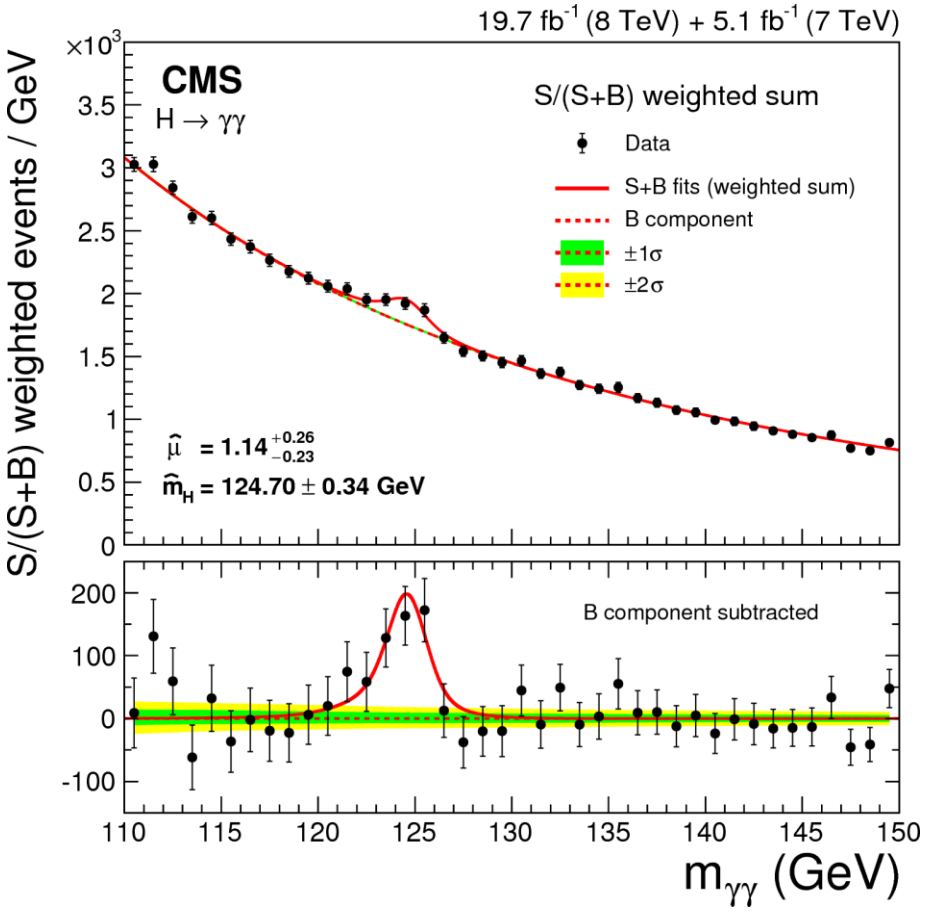
arXiv:1203.3774 [hep-ex]

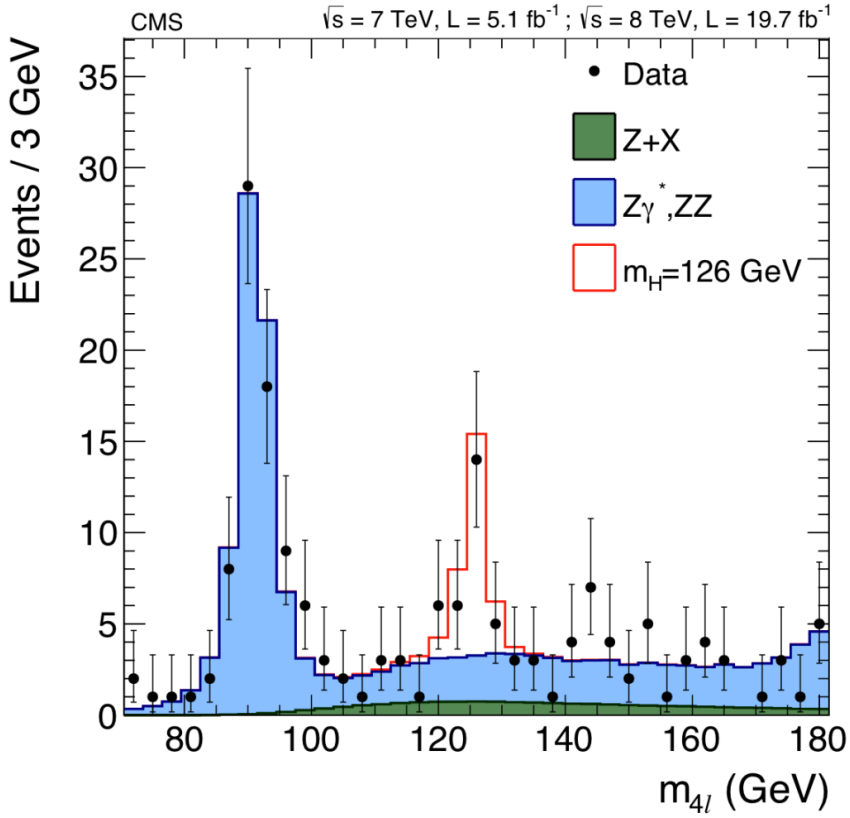


- Combined searches by CDF and DØ for the SM Higgs boson in the mass range 100–200 GeV for bb, ττ, γγ, ZZ and WW modes
- A significant excess of events observed in the mass range between 115 and 140 GeV with local significance at m_H=125 GeV corresponding to 3.0σ

Higgs Mass

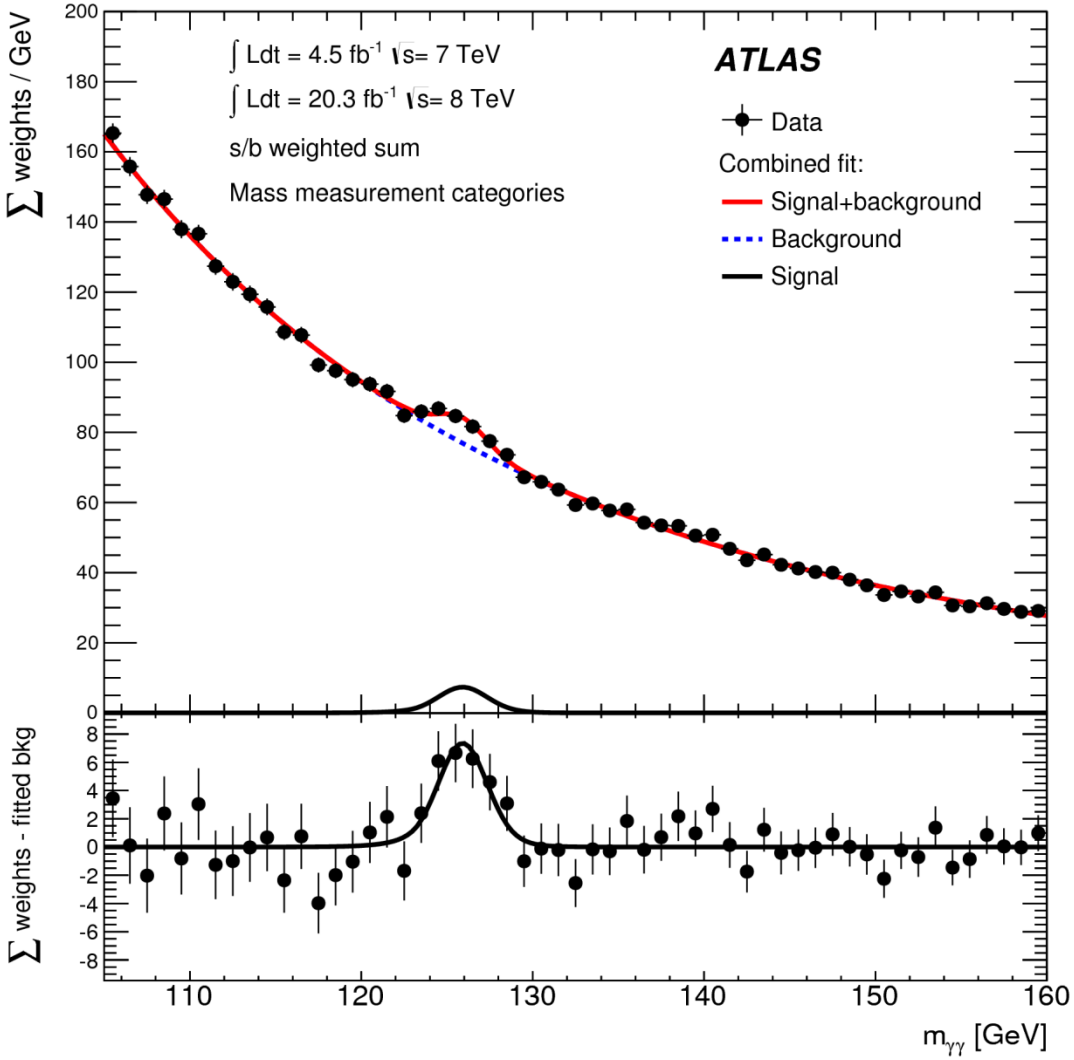
High Resolution Mass Spectrum @ CMS

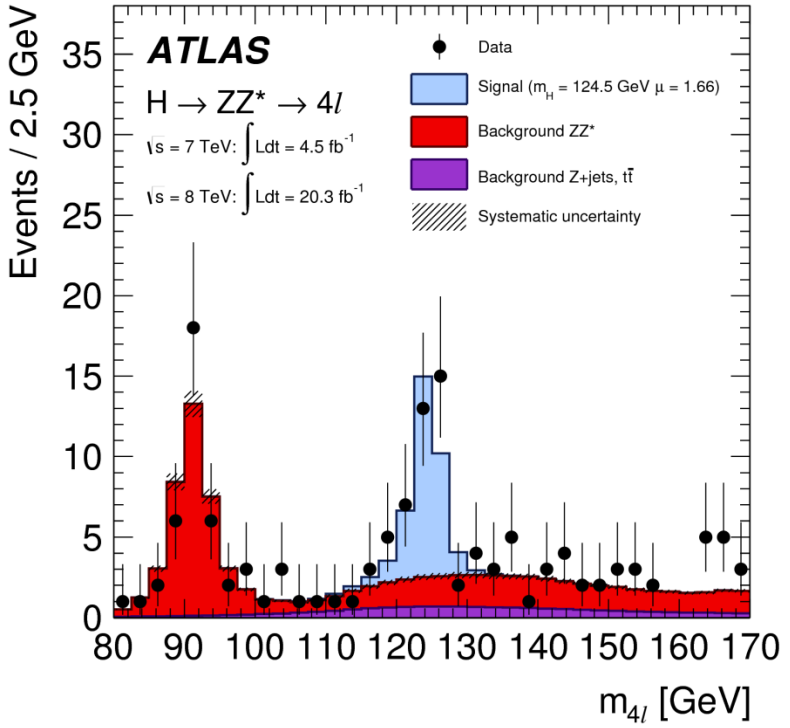




H→γγ and H→ZZ*→4l invariant mass distribution at CMS

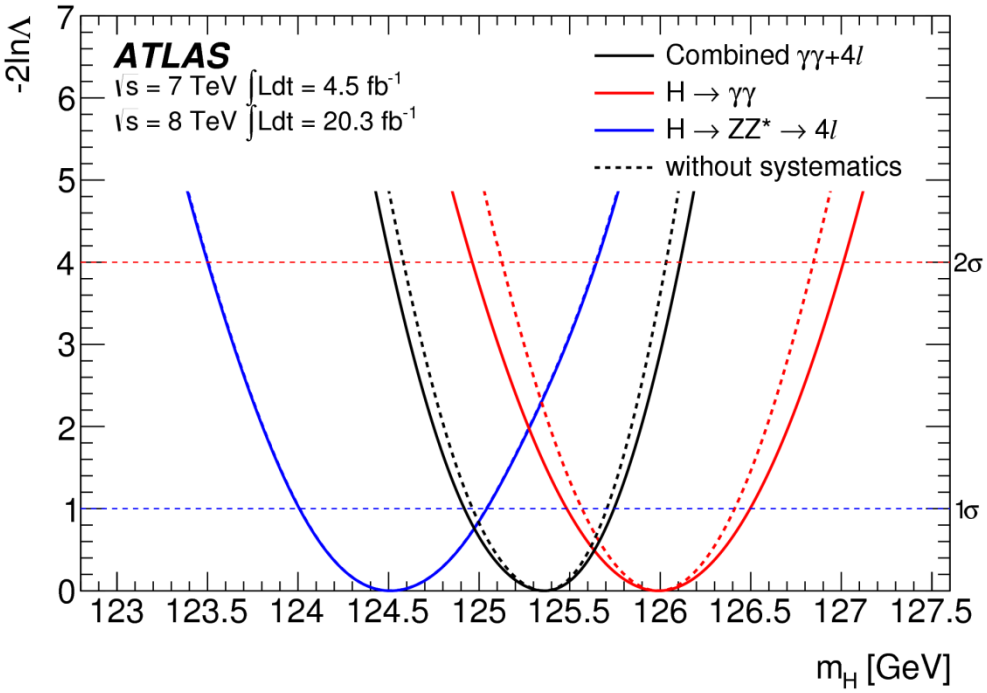
High Resolution Mass Spectrum @ ATLAS

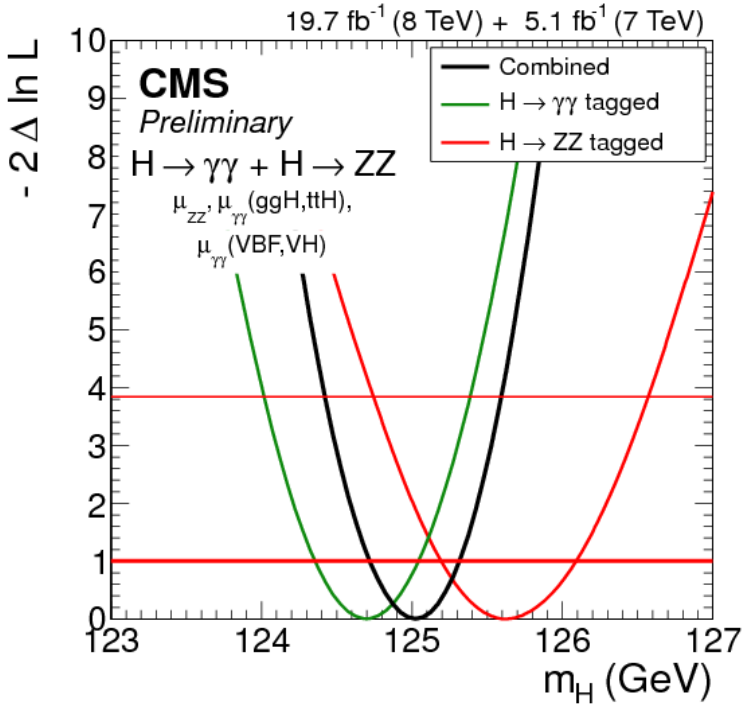




H→γγ and H→ZZ*→4l
invariant mass at ATLAS

Higgs Mass





H→γγ and H→ZZ*→4l combined mass measurement

$m_H(\text{ATLAS}) = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})$

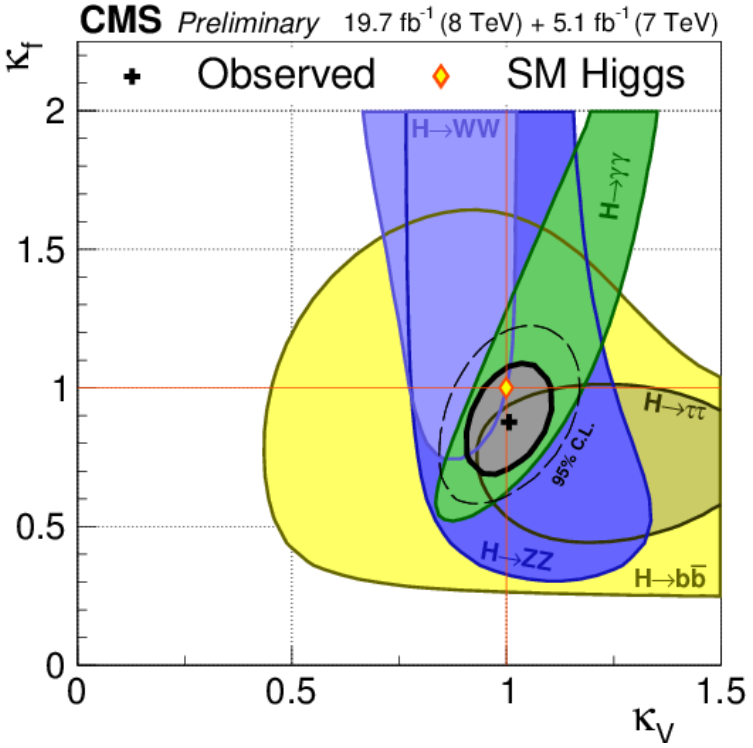
$m_H(\text{CMS}) = 125.03\ ^{+0.26}_{-0.27}\ (\text{stat})\ ^{+0.13}_{-0.15}\ (\text{syst})$

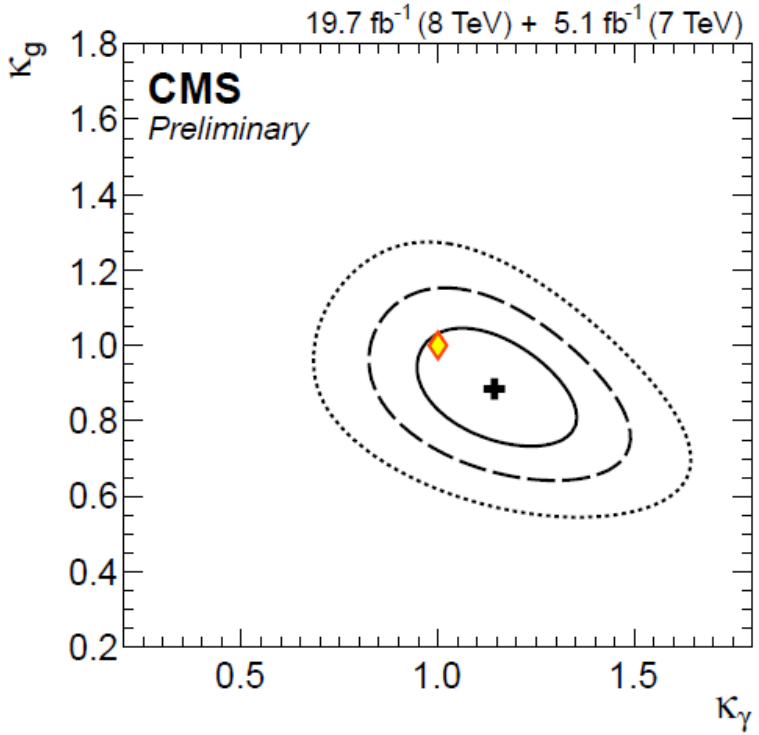
Higgs Coupling

Higgs Coupling @ CMS

CMS-PAS-HIG-14-009

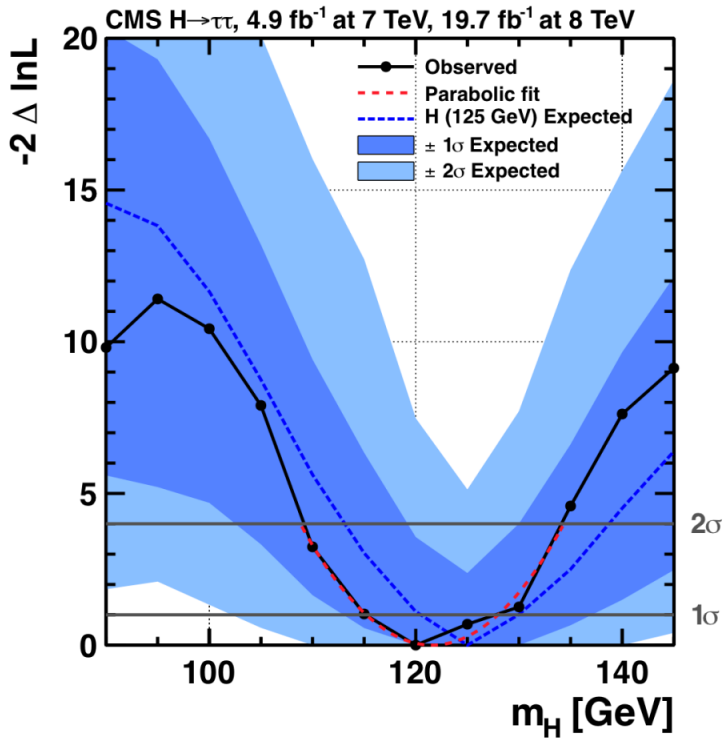
2D likelihood scan for κ_g and κ_γ parameters assuming that $\Gamma_{BSM}=0$





Results within 1σ of Standard Model prediction

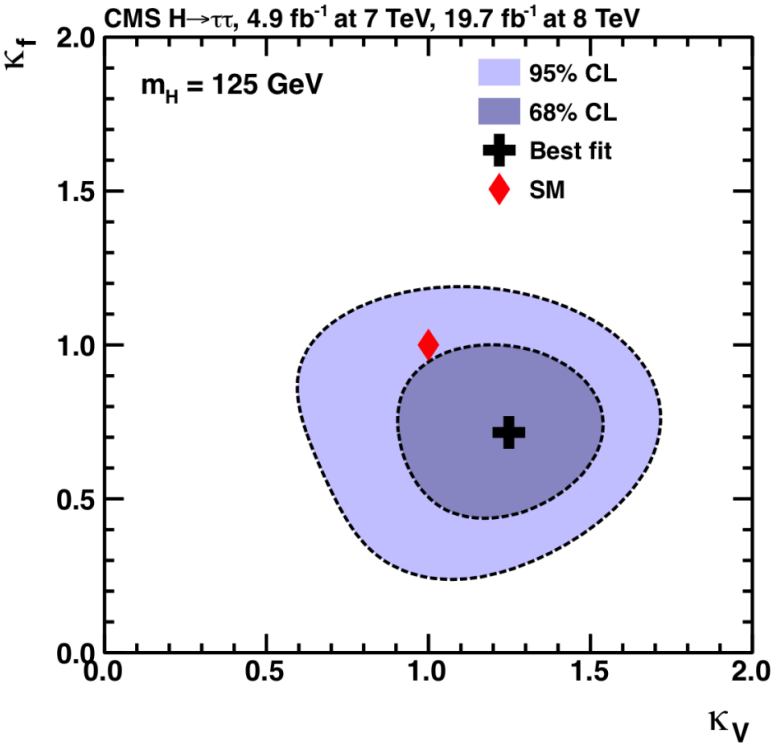
Mass & Coupling with H→ττ



Scan of $-2\Delta\ln L$, as function of m_H

background-only hypothesis includes the pp→ H(125 GeV)→WW process

M_H=122±7 GeV

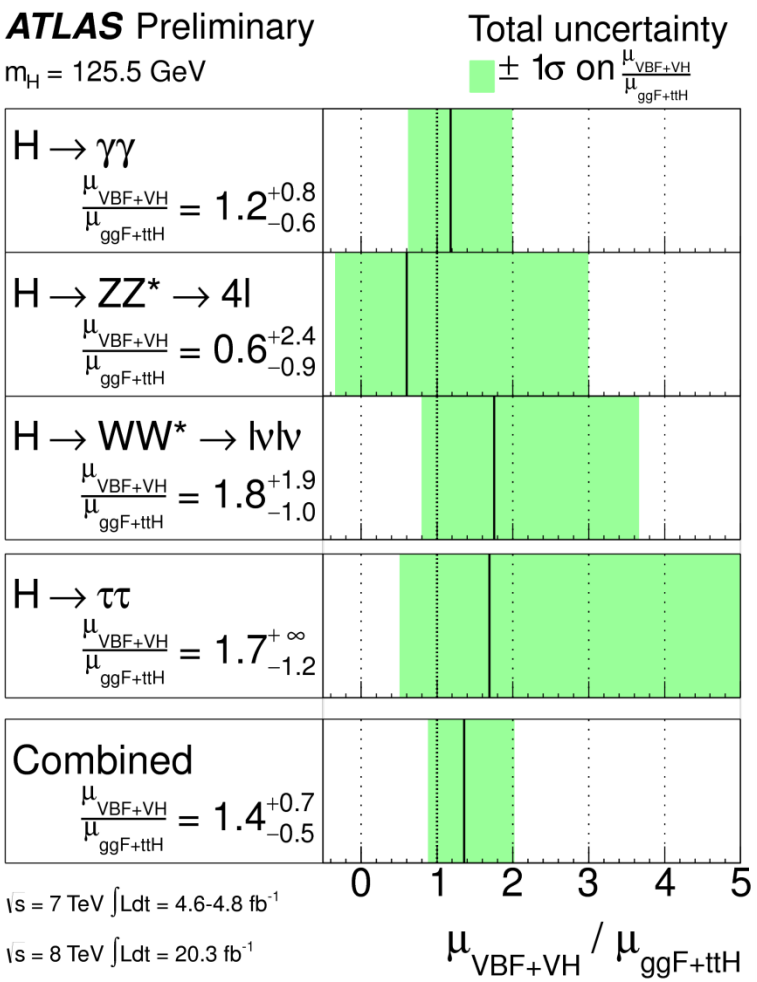


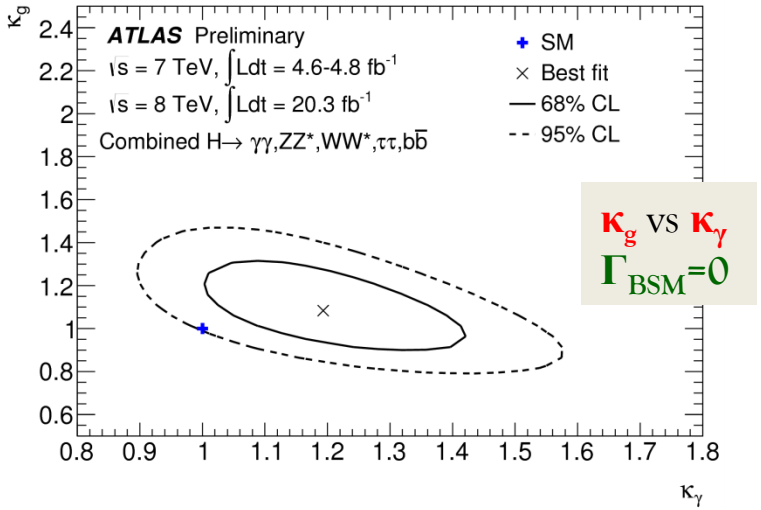
Likelihood scan as a function of κ_V and κ_f
All nuisance parm. profiled for each point

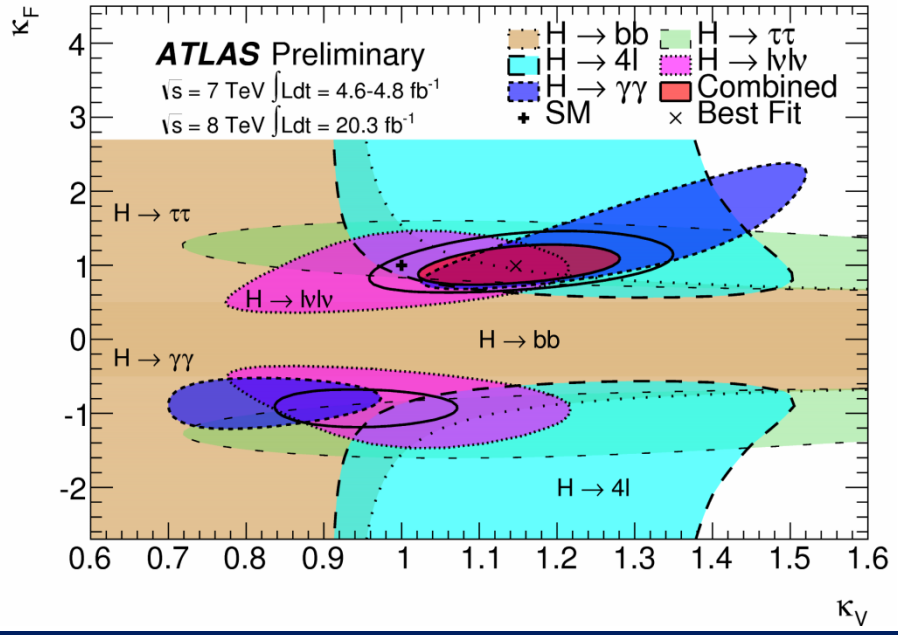
pp→ H(125 GeV)→WW process added as a signal for vector boson coupling sensitivity

Higgs Coupling @ ATLAS

ATLAS-CONF-2014-009

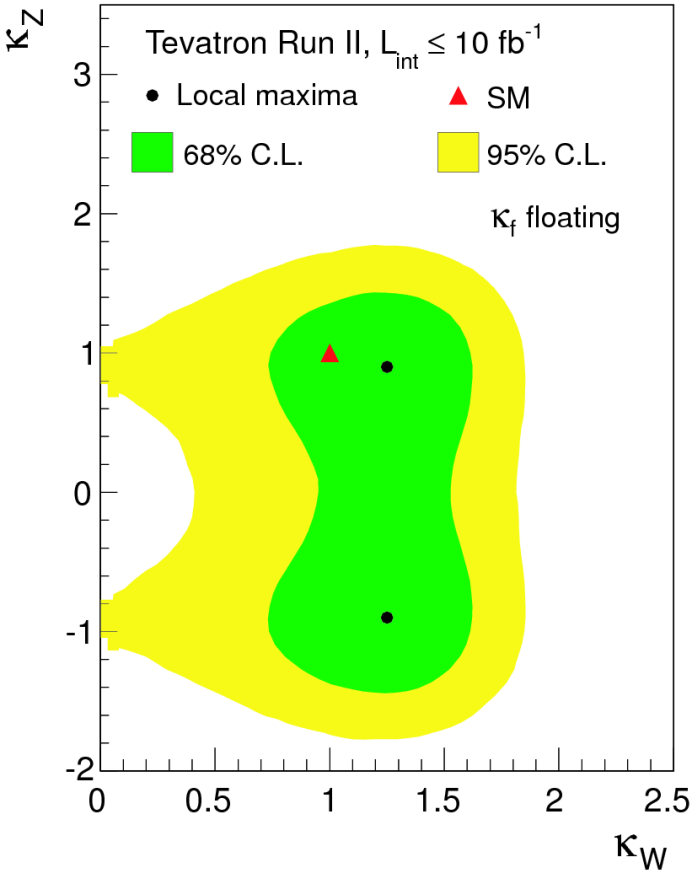






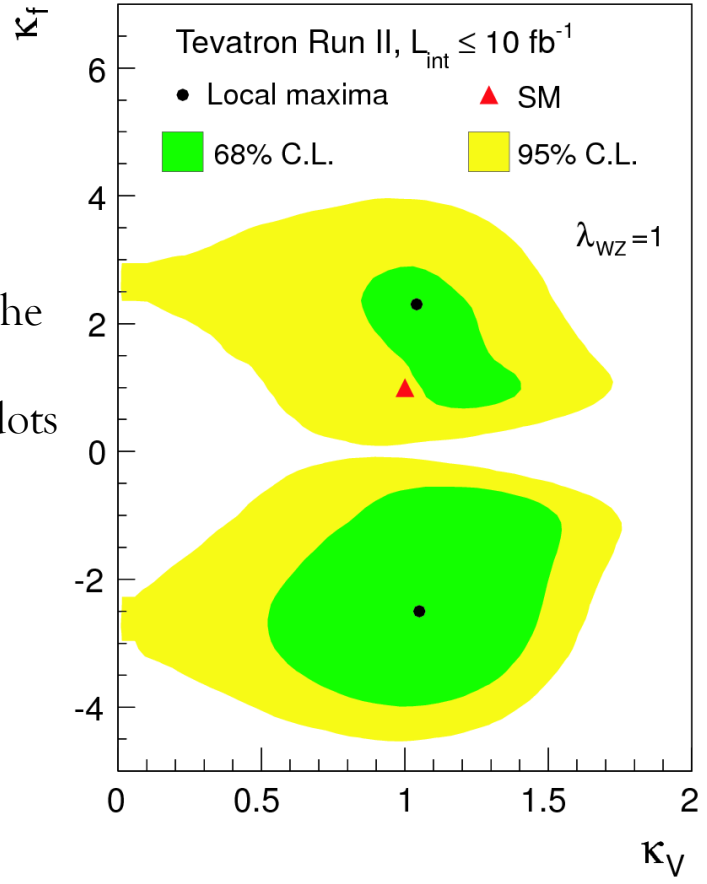
Higgs Coupling @ Tevatron

Phys. Rev. D 88, 052014 (2013)



2D constraints in (κ_W,κ_Z) plane for m_H=125 GeV allowing **κ_f to float**

The points that maximize the local posterior probability densities are marked with dots



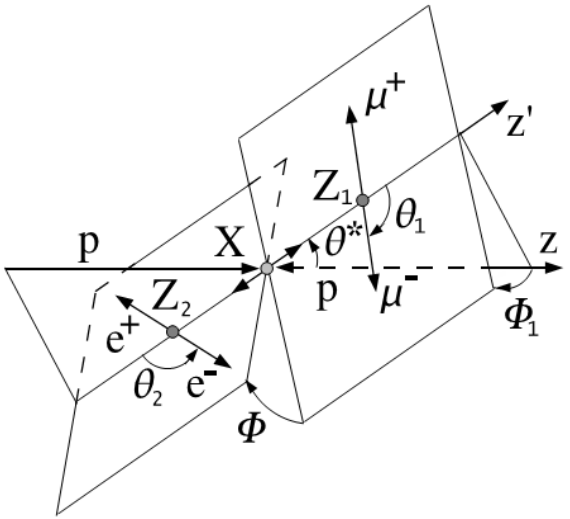
2D constraints in the (κ_V,κ_f) plane assuming **Custodial symmetry (λ_{WZ}= 1)**

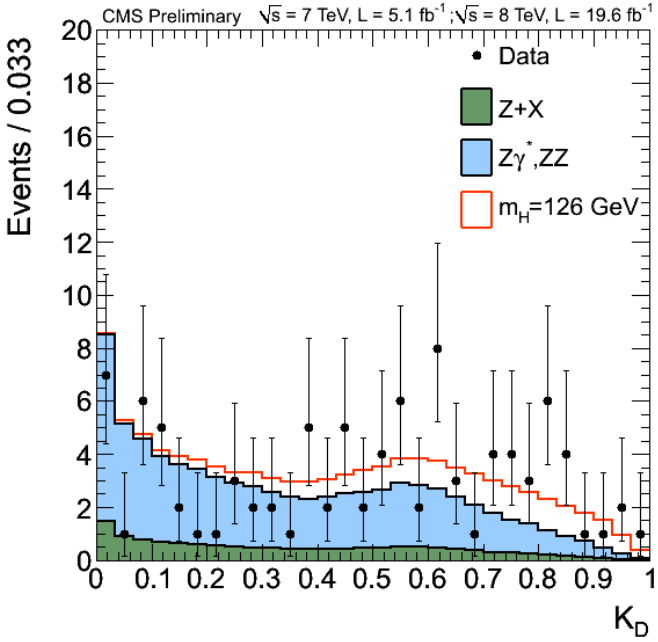
Higgs Spin / Parity

Matrix Element Likelihood Analysis

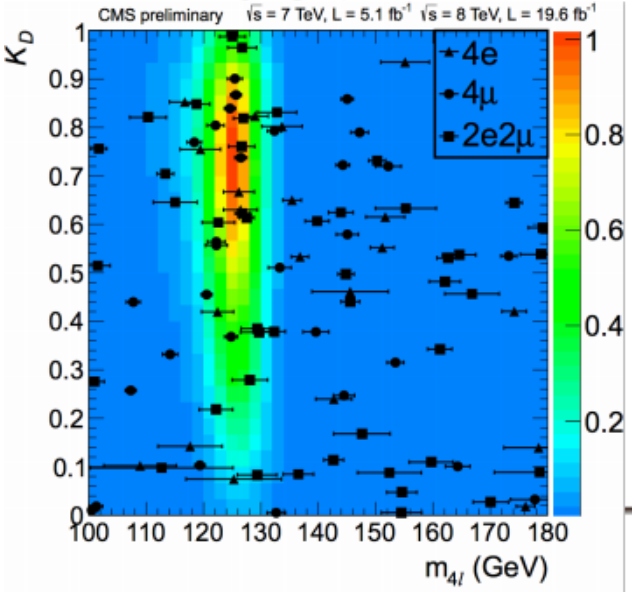
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

Masses of dilepton pairs and five angles fully defining a four-lepton configuration in their centre-of-mass frame

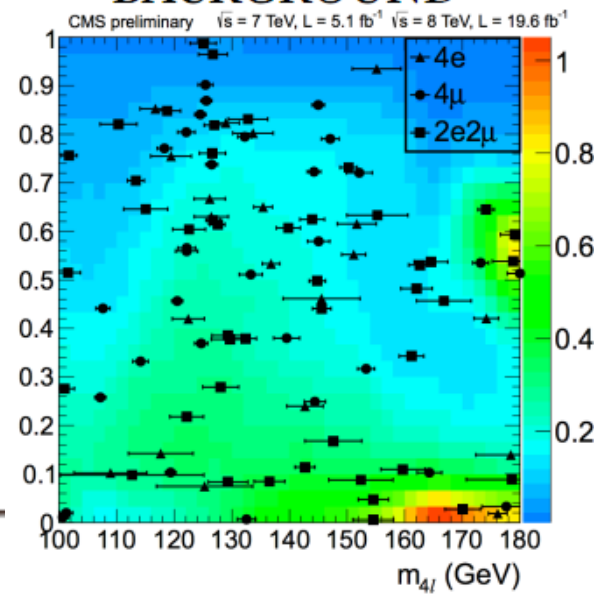




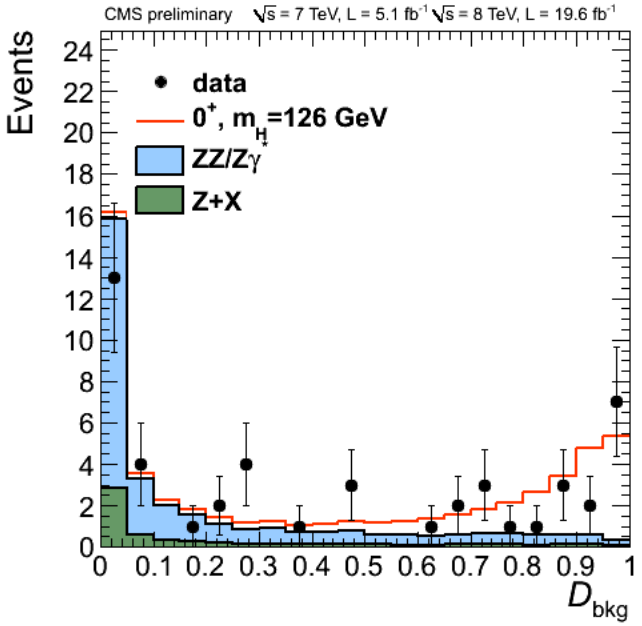
SIGNAL

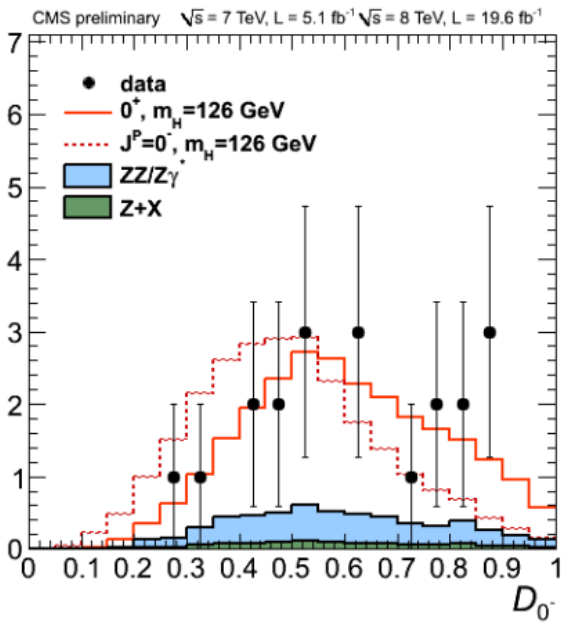


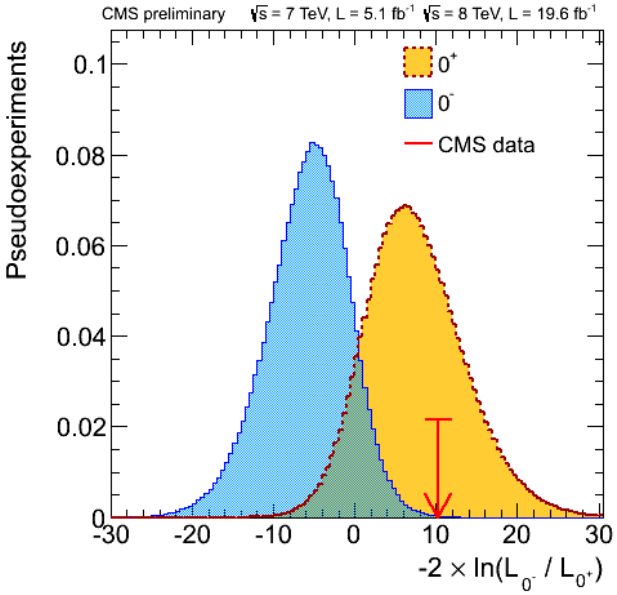
BACKGROUND



Discriminant for production and decay of different Higgs J^P state







$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{SM}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

Statistically equivalent to the 2D analysis of m_{4l} and K_D

$$\mathcal{D}_{\mathrm{bkg}} = \mathcal{P}_{\mathrm{sig}} / (\mathcal{P}_{\mathrm{sig}} + \mathcal{P}_{\mathrm{bkg}})$$

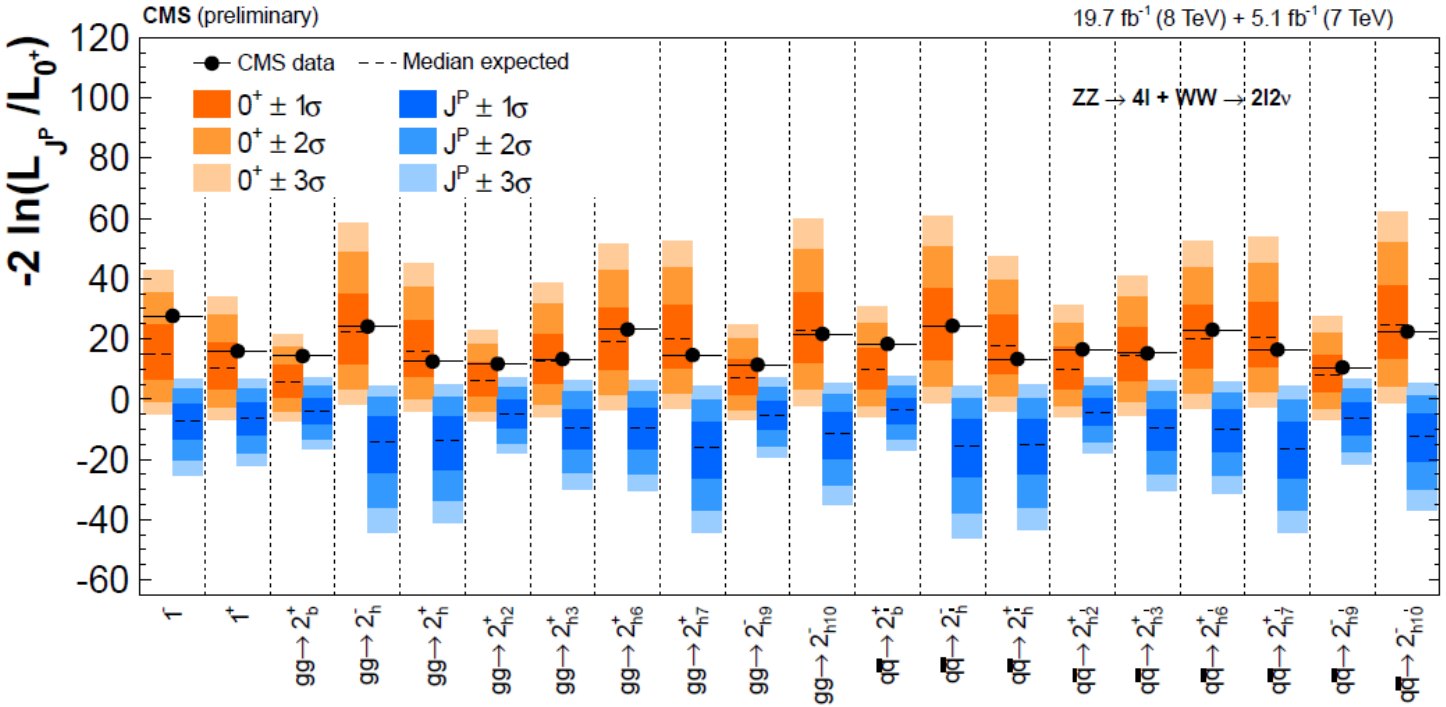
Hypotheses of a pseudoscalar and all tested spin-1 boson hypotheses excluded at 99% CL or higher

Consistency with SM scalar boson

CMS-PAS-HIG-14-014

Using full angular information defining 4 lepton system

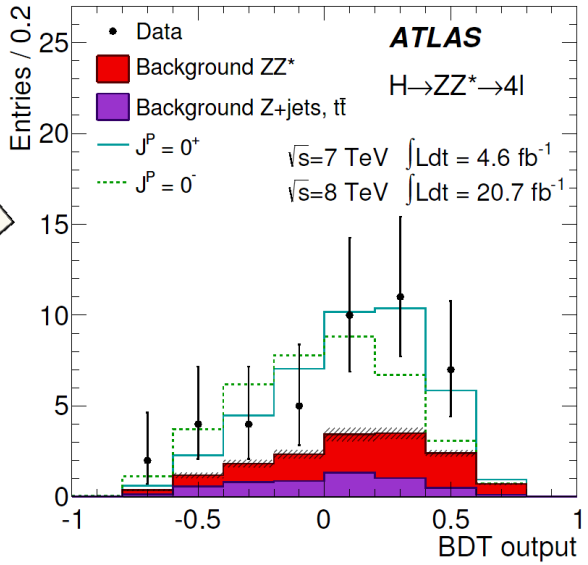
- For each hypothesis create kinematic discriminant for SM vs alternative hypothesis
- Perform 2D fit of hypothesis discriminant versus background discriminant and perform hypothesis test

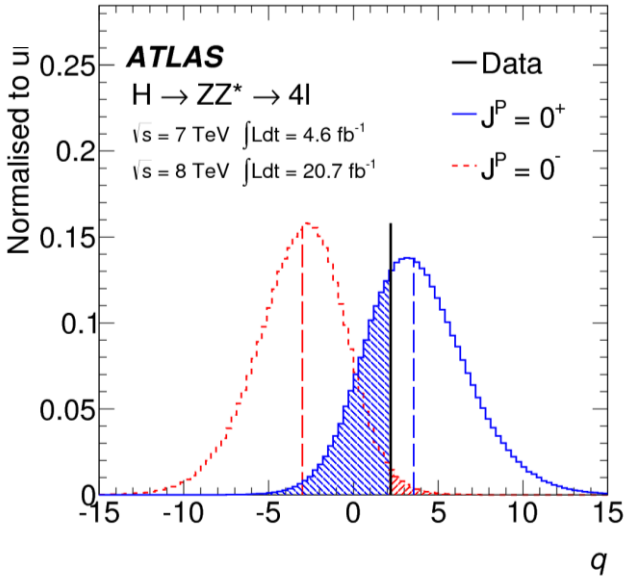


Several J^P hypotheses have been tested Consistency with the SM scalar boson

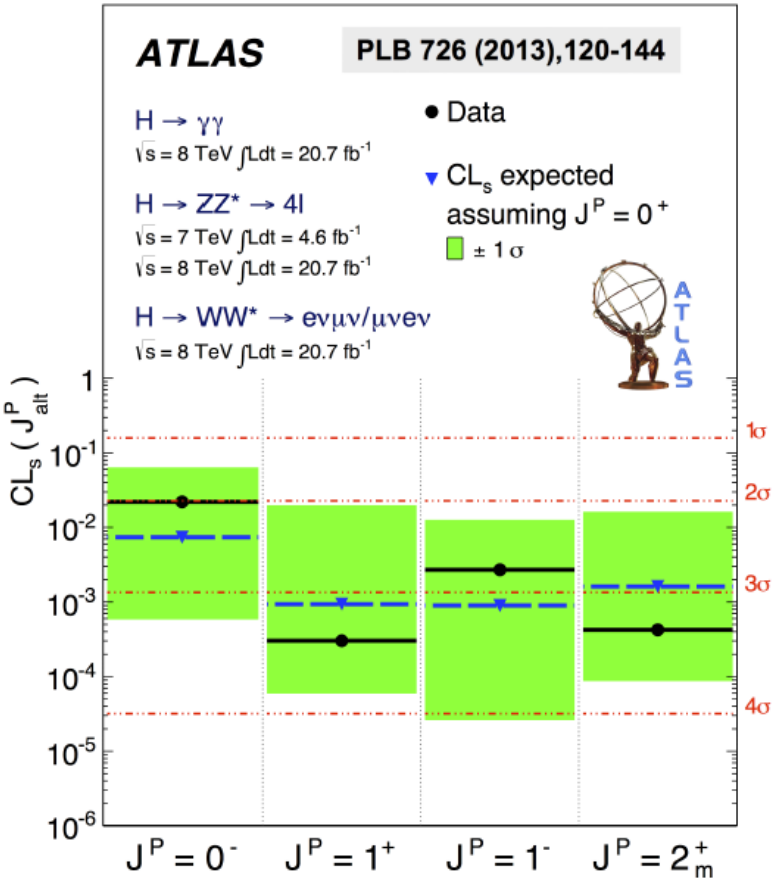
Higgs Spin & Parity @ ATLAS

Phys. Lett. B 726, 120 (2013)

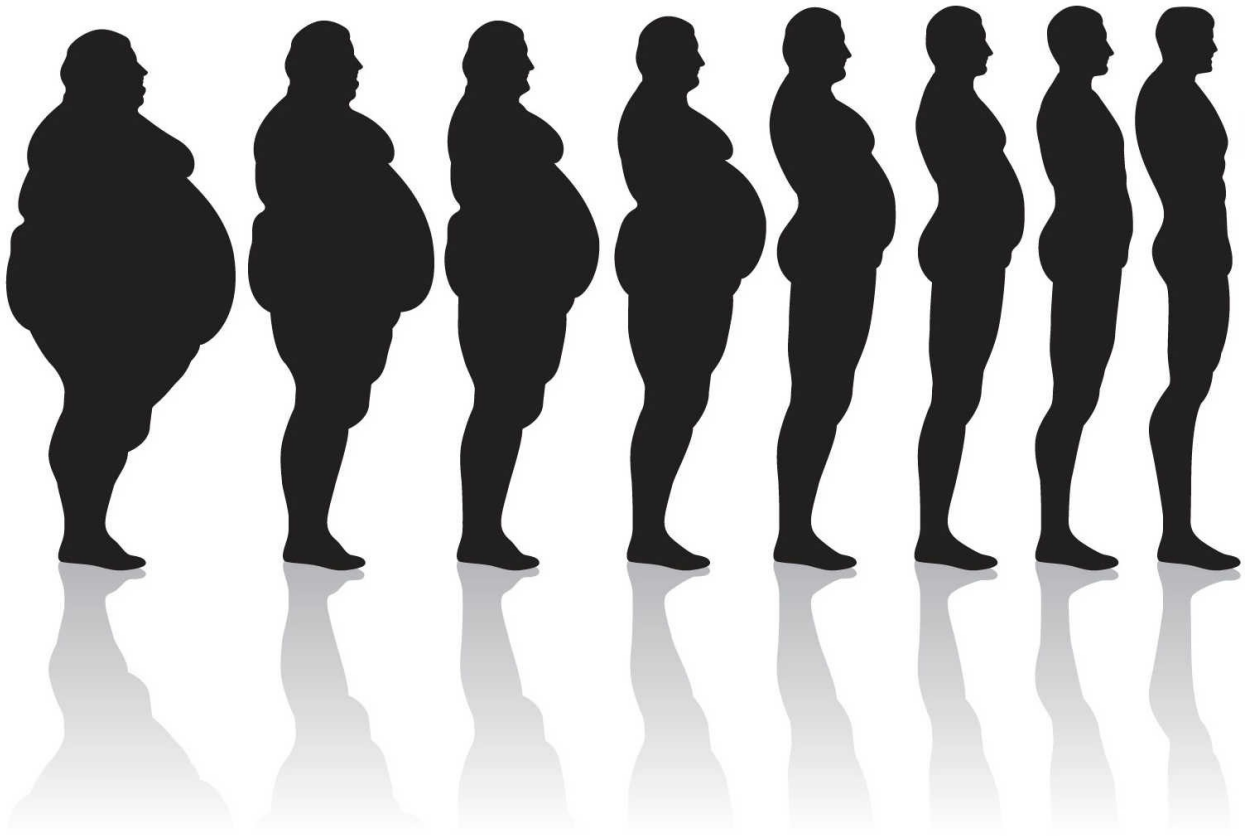




Hypotheses of a pseudoscalar state as well as spin-1 and spin-2 hypotheses disfavoured over a SM scalar boson



Higgs Width



Higgs Width @ CMS

Off-shell Higgs production sizeable at high ZZ mass

- ~7.6% of the total cross-section for $m_{ZZ} > 2M_Z$
- Destructive interference between $gg \to H \to ZZ$ and $gg \to ZZ$

Proposed by
F. Caola, K. Melnikov, PRD 88 (2013) 054024
N. Kauer, G. Passarino, JHEP 08 (2012) 116
J. Campbell et al. (arXiv:1311.3589)

Ratio of **on-shell** and **off-shell** production cross-section gives a direct handle to constrain the total width (taking into account interference)

On shell and off shell production in ZZ:

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

On-shell and off-shell cross-section expressed as a function of signal strength by scaling the couplings

- **On-shell**

cross section constrained by $H \to ZZ \to 4l$ search
$\mu = \sigma/\sigma_{SM} = 0.93^{+0.26}_{-0.24}$ (Expectation of $1.0^{+0.27}_{-0.24}$)

- **Off-shell**

cross section is constrained by $H \to ZZ \to 4l$ and $H \to ZZ \to 2l2\nu$ final states

Higgs Width @ CMS

4l final state

Using the baseline H → ZZ selection strategy

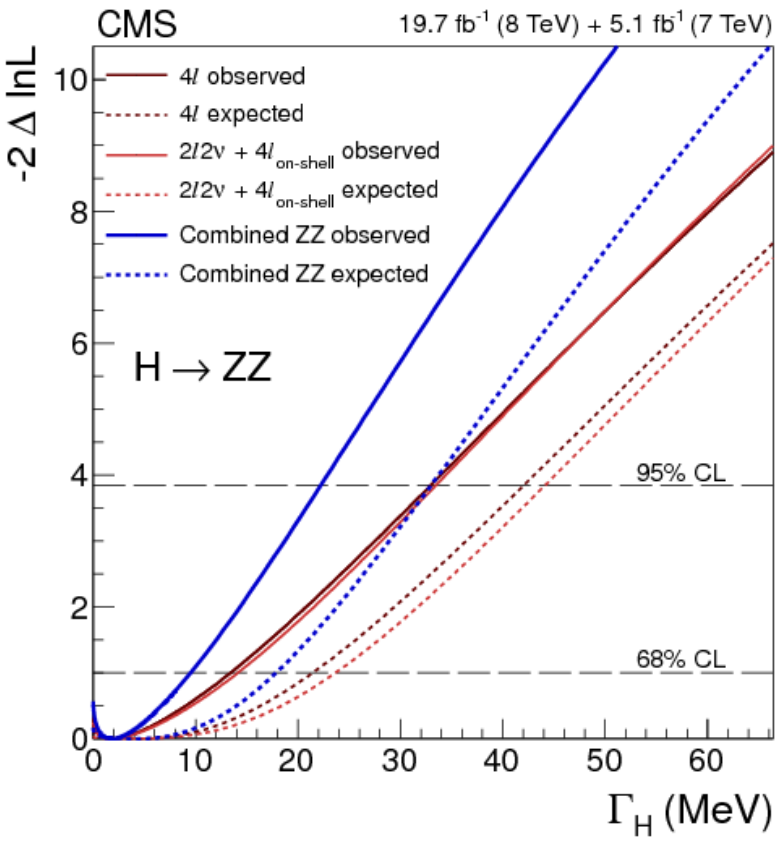
- Exploiting full reconstructed final state to separate gg→ZZ from qq→ZZ at high mass
- Using angular discriminant as in the 4l baseline search
- Signal extracted by 2D fit in the mass and kinematic discriminant

2l2ν final state

Requiring a di-lepton and high missing E_T

- Mass shape fit in different jet categories

Physics Letters B 736, 64 (2014)

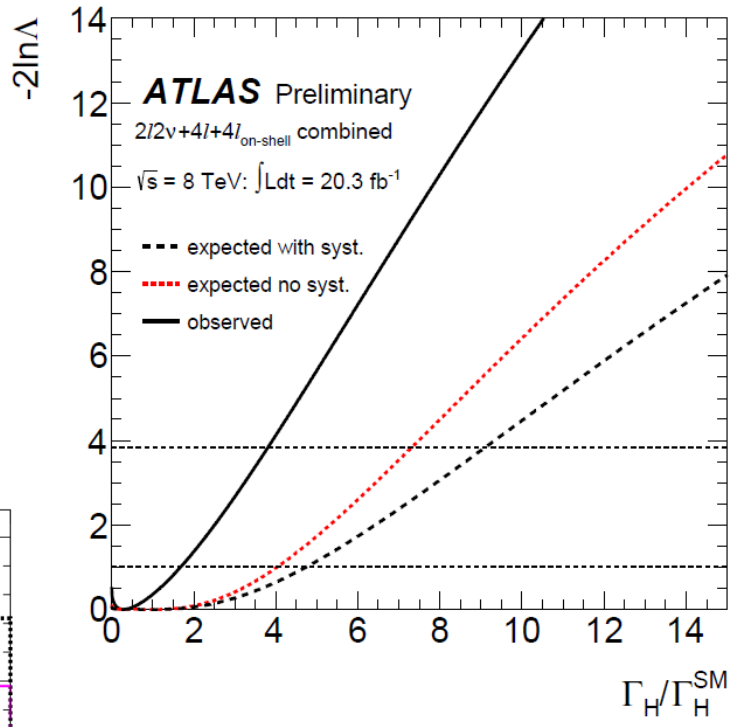


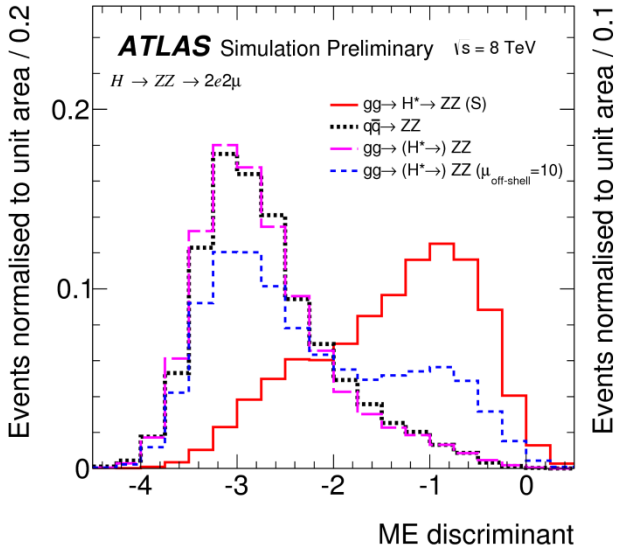
- Observed limit of 5.4 x SM corresponding to ~ 22 MeV @ 95% CL
- Sensitivity exceeds all expectations enhancing the LHC role of a Higgs factory in next years

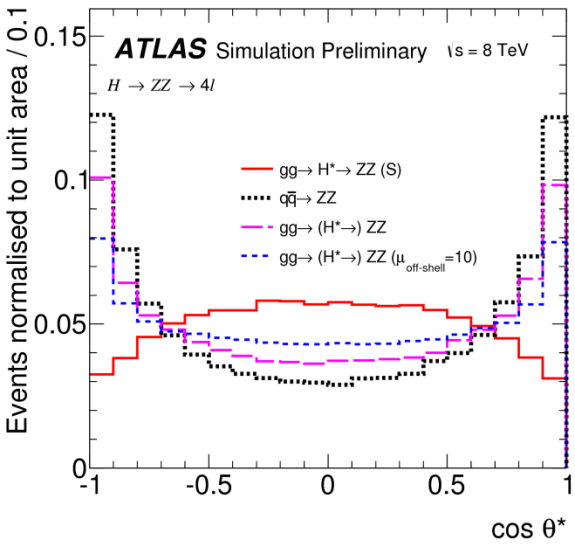
Higgs Width @ ATLAS

- Analysis in the 4l channel uses a likelihood fit to the distribution of a matrix element discriminant
- Analysis in the 2l2ν channel counts events in a $H^* \rightarrow ZZ$ enriched signal region with high E_T and high transverse mass
- Separate $gg \rightarrow ZZ$ from $qq \rightarrow ZZ$ at high mass

ATLAS-CONF-2014-042







Γ/Γ_H^{SM} observed limit 5.7 x SM @95% CL
(gg→ZZ background K-factor from higher-order QCD corrections is equal to the known signal K-factor)

Higgs Cross-section

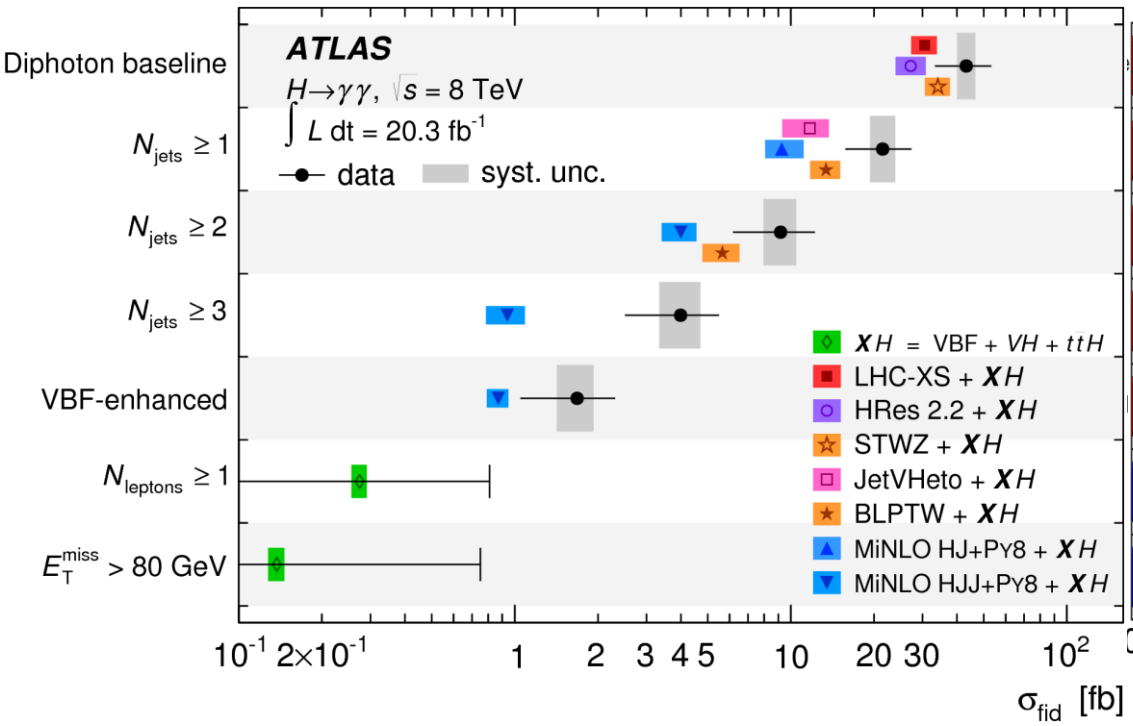
Higgs Inclusive Cross-section @ LHC

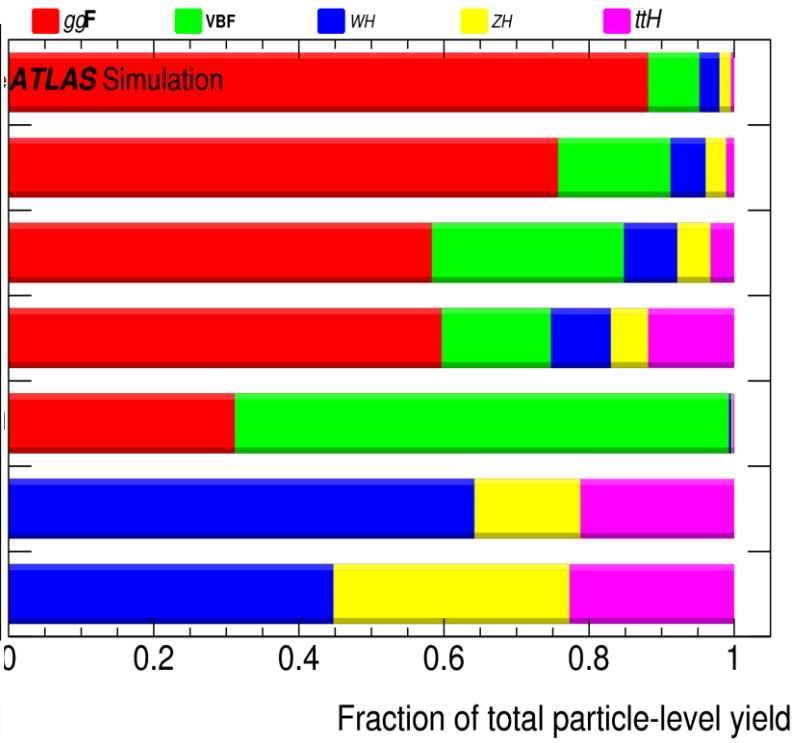
arXiv:1407.4222 [hep-ex]

H→γγ

Measured cross sections and cross-section limits for pp→H→γγ in seven fiducial regions

Data compared to state-of-the-art theoretical predictions, regions include SM prediction arising from VBF, VH and ttH labelled as *X*H





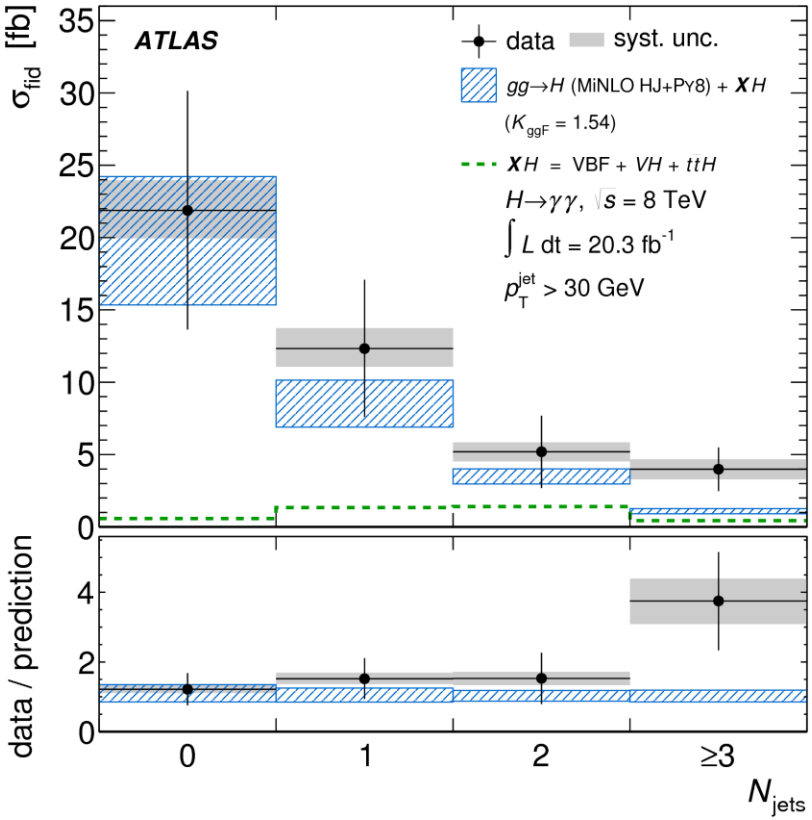
Higgs Differential Cross-section @ LHC

arXiv:1407.4222 [hep-ex]

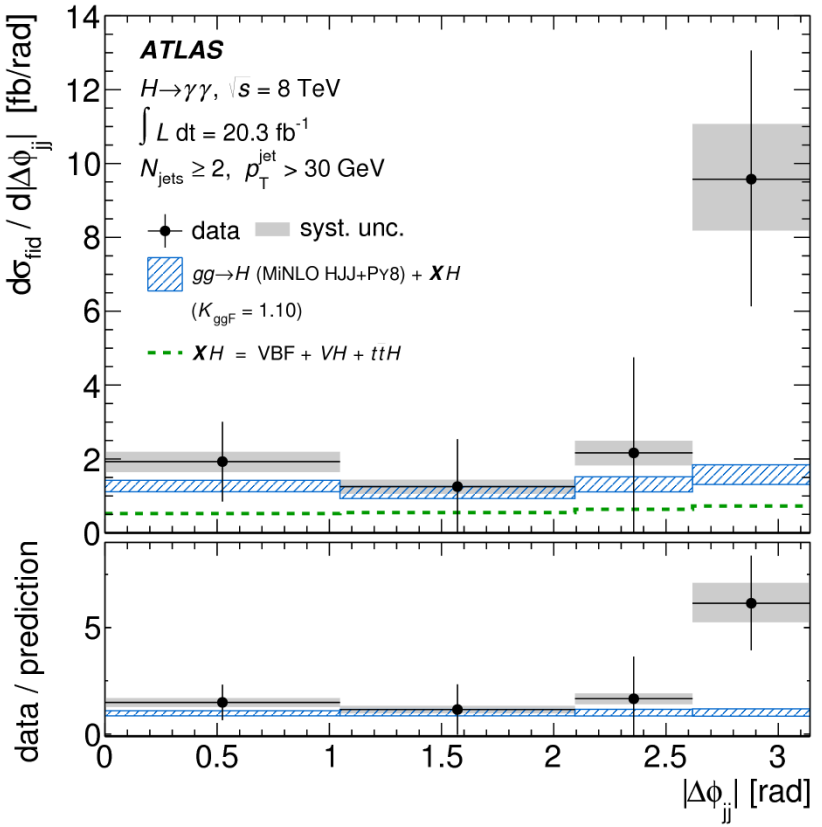
Sensitive to new physics in the context of production loop and properties

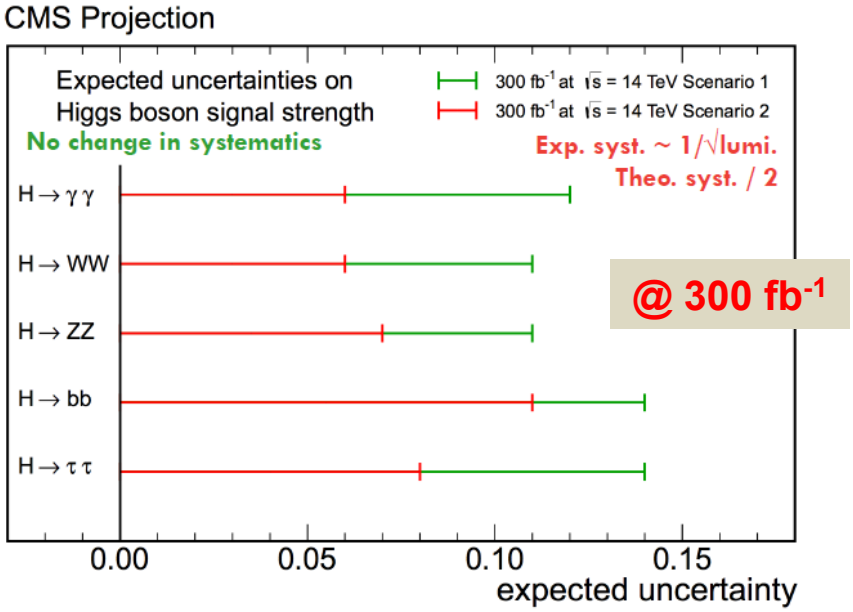
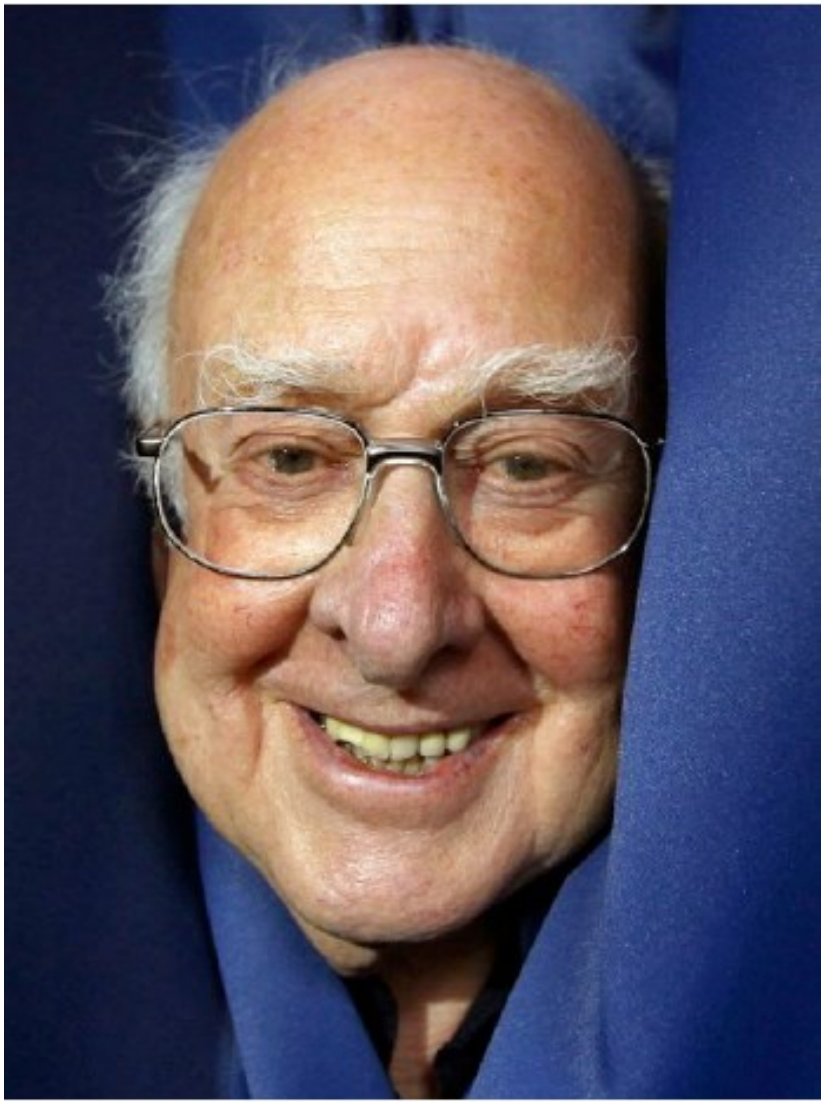
Jet multiplicity: sensitive to relative rates of **production modes** (ggH, VBF/VH/ZH, ttH)

$\Delta\varphi_{jj}$: for ggH and VBF, sensitive to the **Higgs boson spin and CP**



H→γγ



Summary & Outlook

- Higgs boson observed @ 125 GeV at the LHC and observation at Tevatron show consistency
- Di-Tau Higgs decay at LHC– First Indication of Higgs coupling to Leptons
- Coupling and Spin/Parity properties measured show consistency with SM expectations
- Continue the robust Higgs Physics programme at LHC Run 2 starting 2015