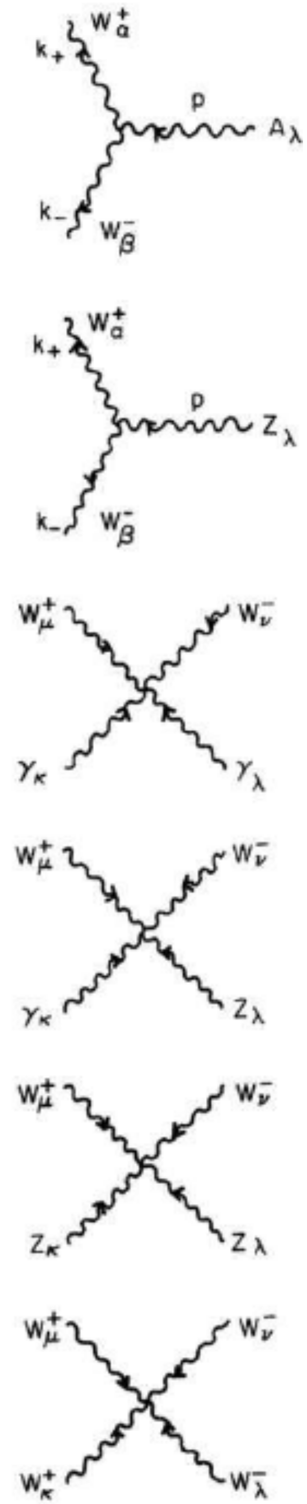
Assignment 3



Kinetic terms for gauge fields:

$$\mathcal{L}_G = -\frac{1}{4} W^i_{\mu\nu} W^{\mu\nu i} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

with

$$W^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g\epsilon_{ijk} W^j_\mu W^k_\nu$$
$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$$

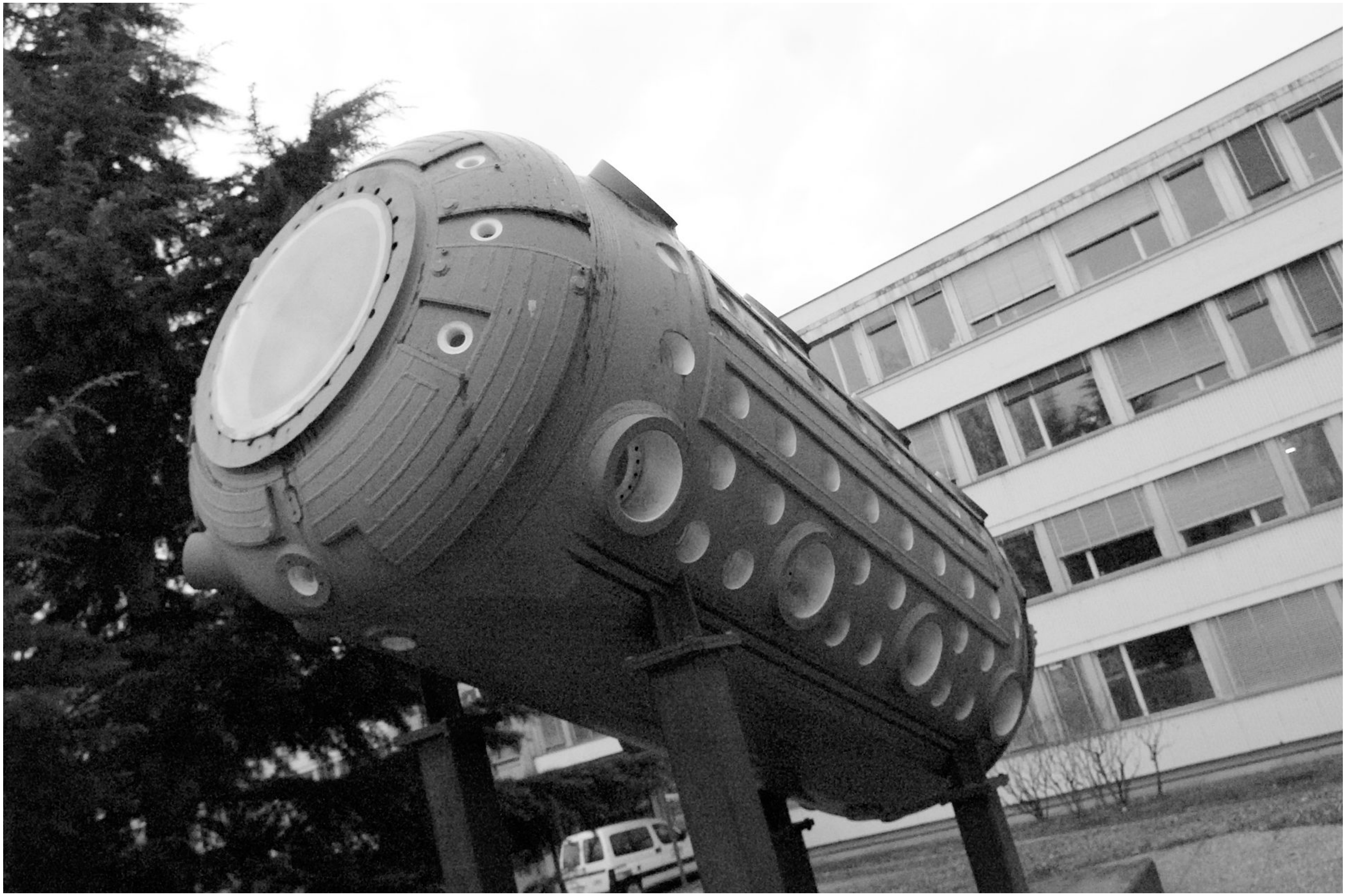
After writing in terms of physical fields $W^{+/-}$, Z and A one finds trilinear and quartic couplings: $W^+ W^- Z$, $W^+ W^- A$, $W^+ W^- W^+ W^-$, $W^+ W^- ZZ$, $W^+ W^- ZA$, $W^+ W^- AA$.

Assignment: show that these are the allowed trilinear and quartic couplings of the SM

Due Friday 14th of February

Observation of weak neutral currents

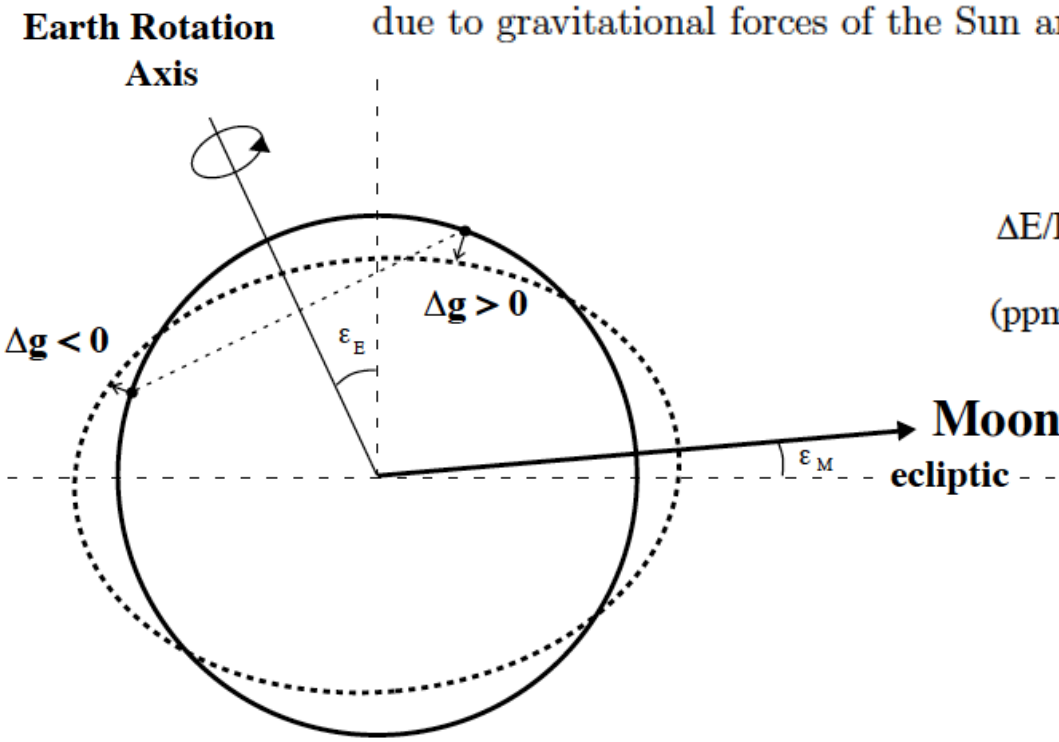
Gargamelle experiment:

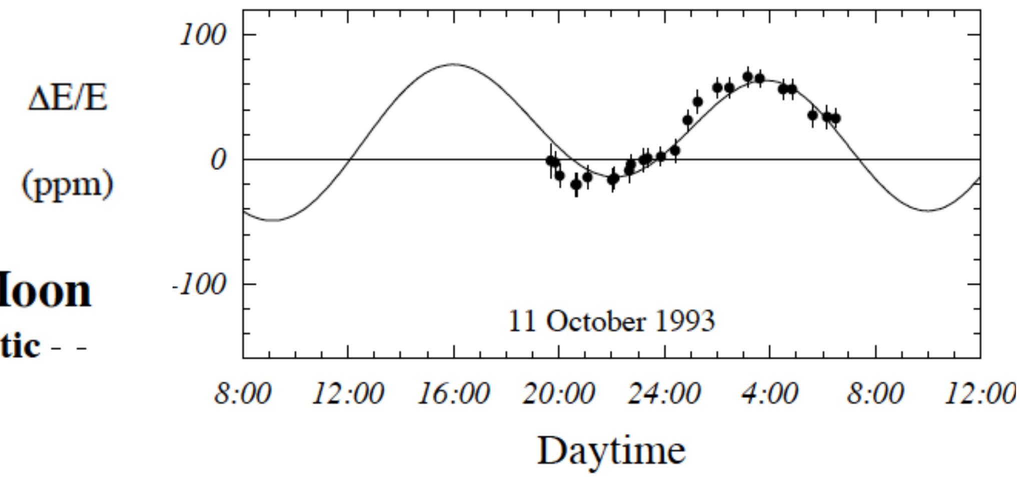


Mass of the Z Boson: $m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$

From the Particle Data Group

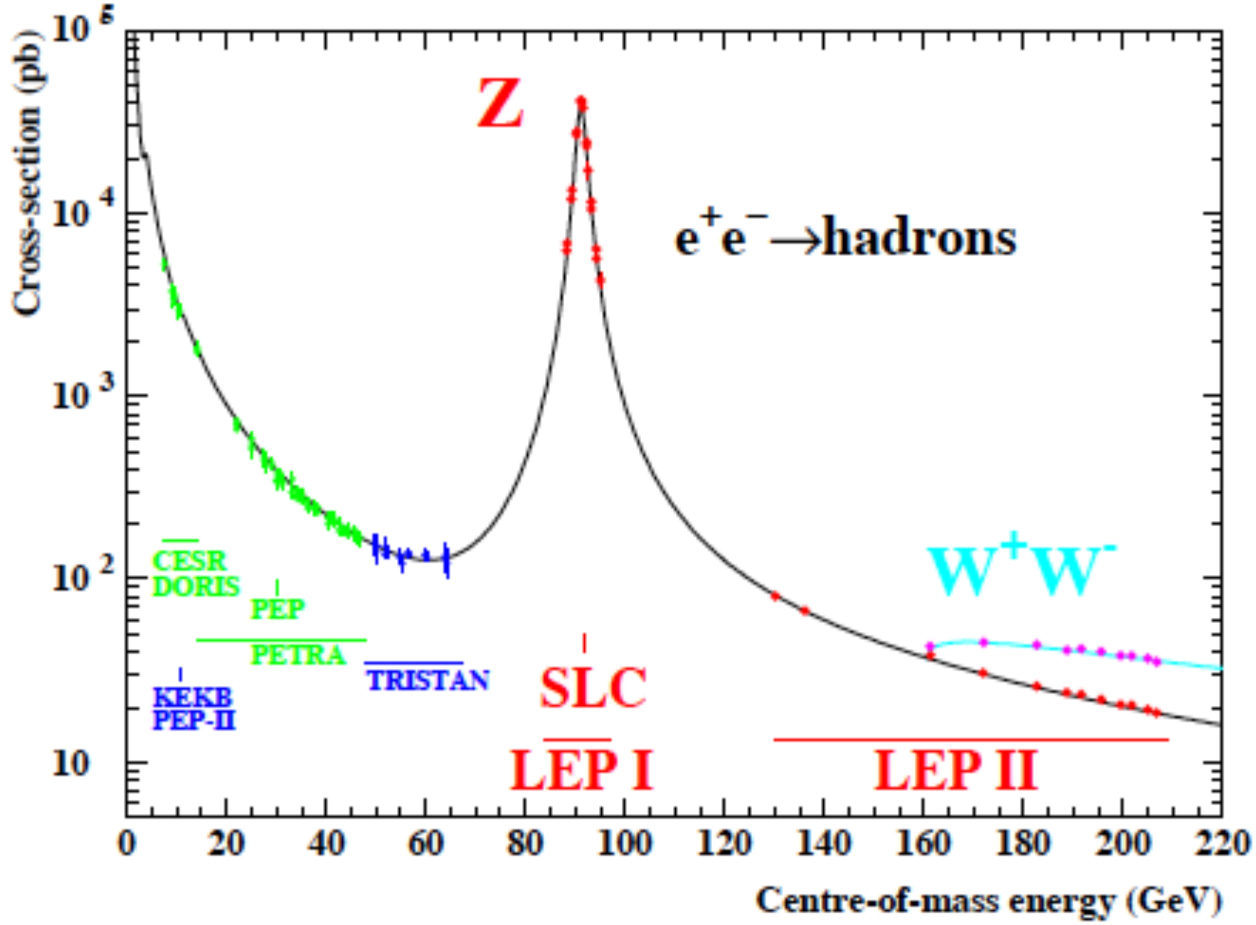
Precise energy calibration was done outside normal data-taking using the resonant depolarization technique. Run-time energies were determined every 10 minutes by measuring the relevant machine parameters and using a model which takes into account all the known effects, including leakage currents produced by trains in the Geneva area and the tidal effects due to gravitational forces of the Sun and the Moon. The LEP



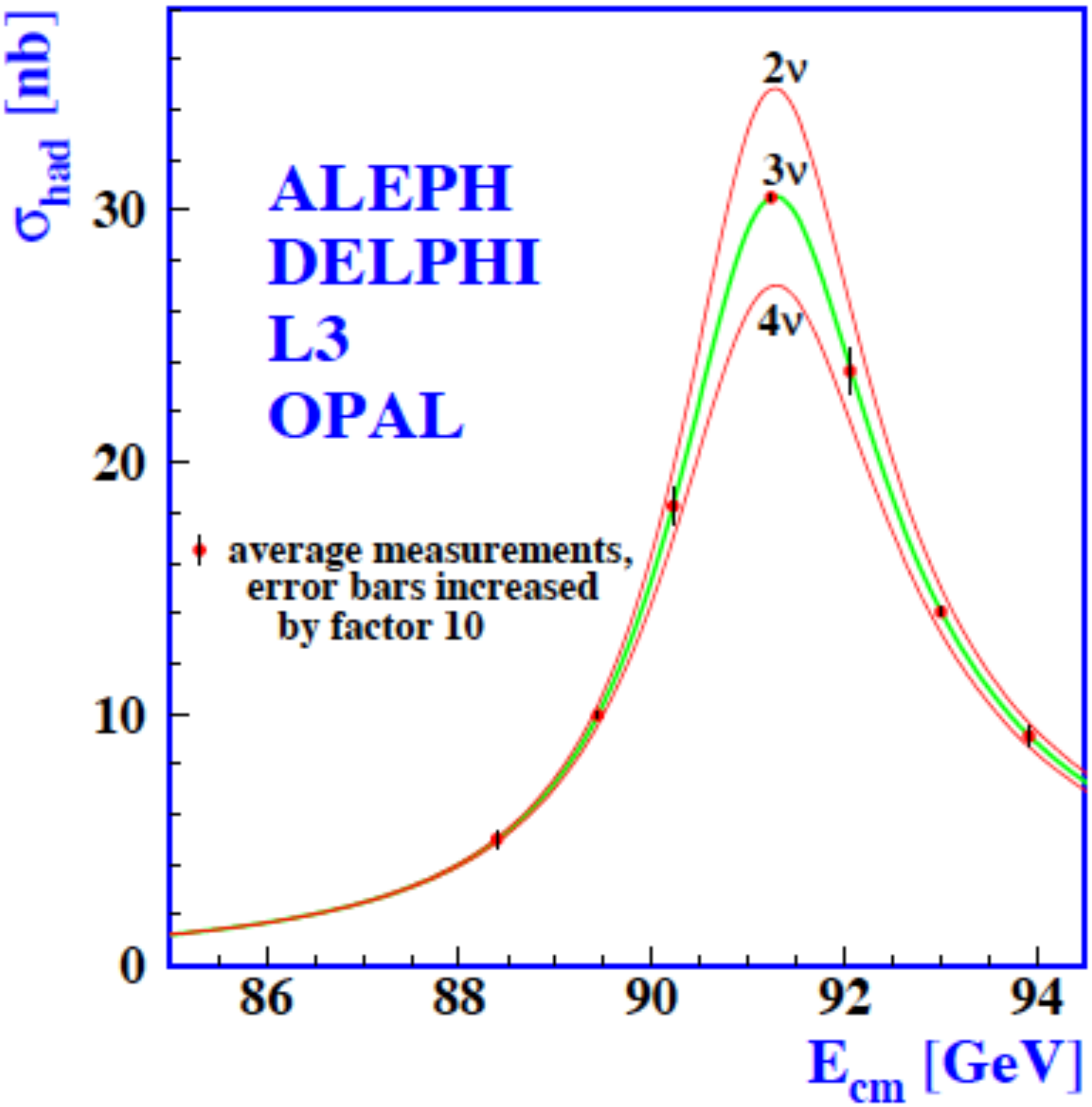


dependent gravity variation $\Delta g(t)$ is simpler to measure and to predict. Using estimates for the elastic properties of the Earth [10], the largest resulting strain is estimated to $\sim \pm\, 2 \cdot 10^{-8}$, which corresponds to a change of the 26.7 km LEP circumference of $\pm$ 0.5 mm. To a good

Z/γ* lineshape



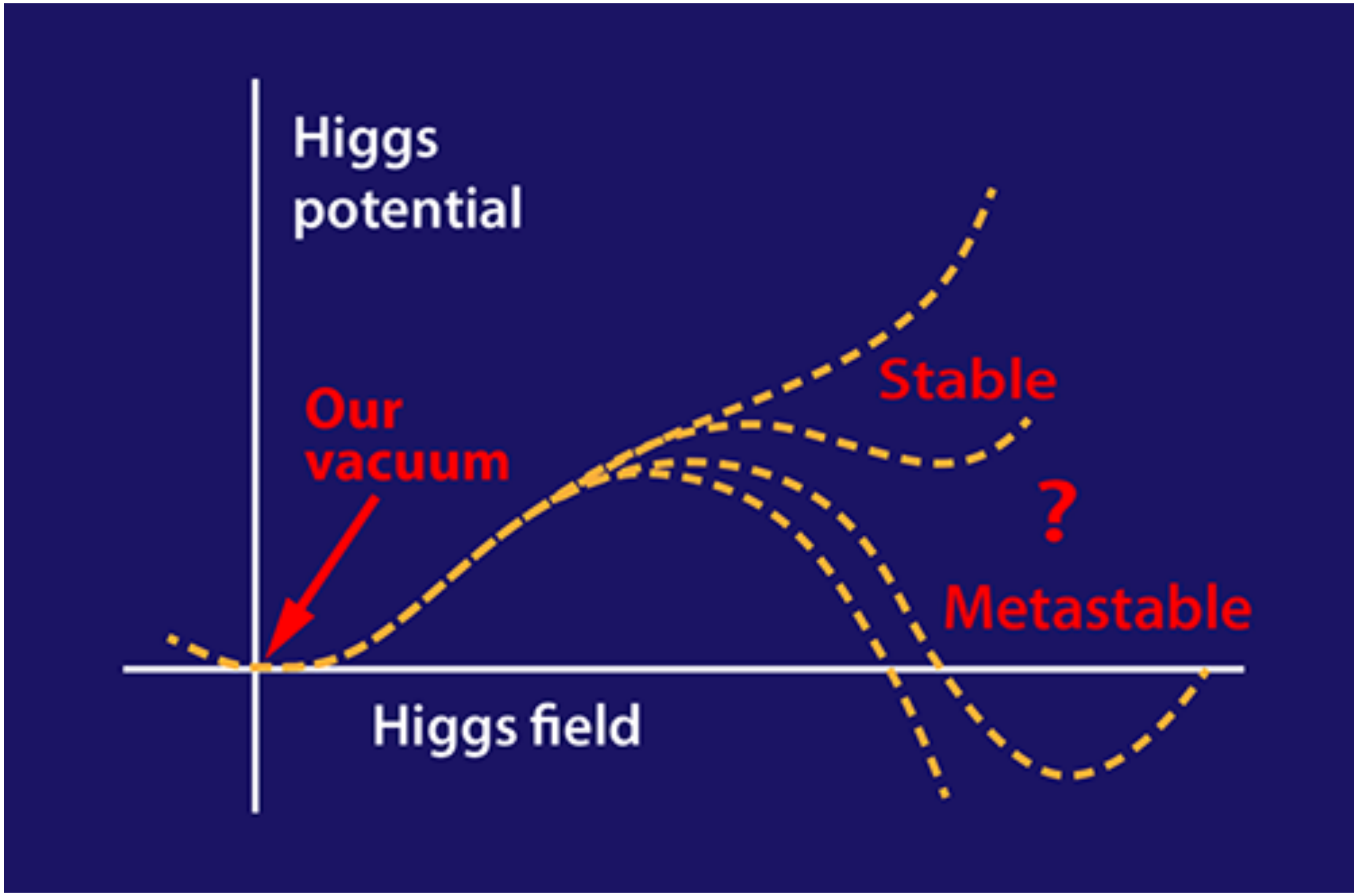
Neutrinos from Lineshape



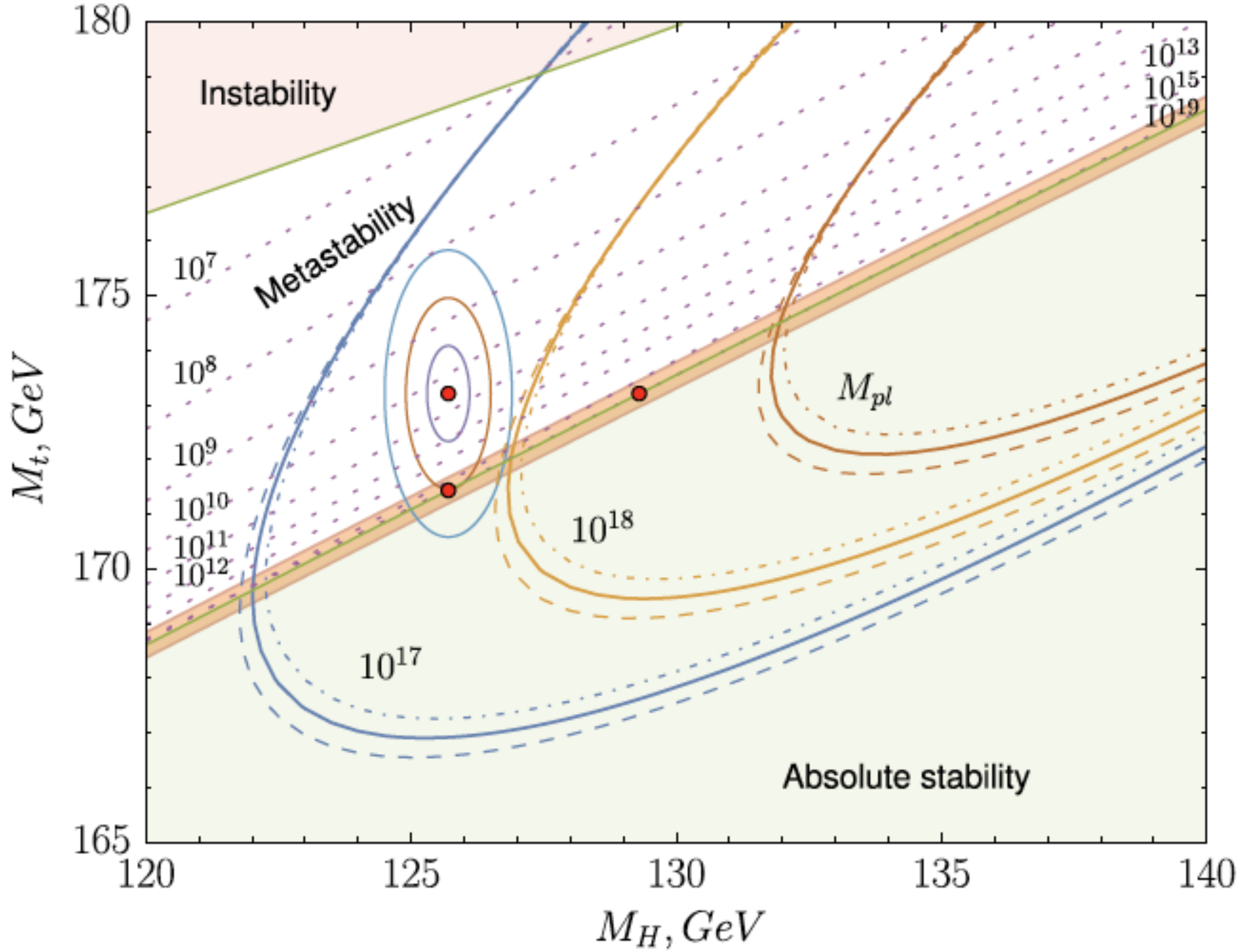
$$N_\nu = 2.9840 \pm 0.0082$$

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\nu_1\nu_1} + \Gamma_{\nu_2\nu_2} + \Gamma_{\nu_3\nu_3} + ?$$

Higgs and Vacuum Stability

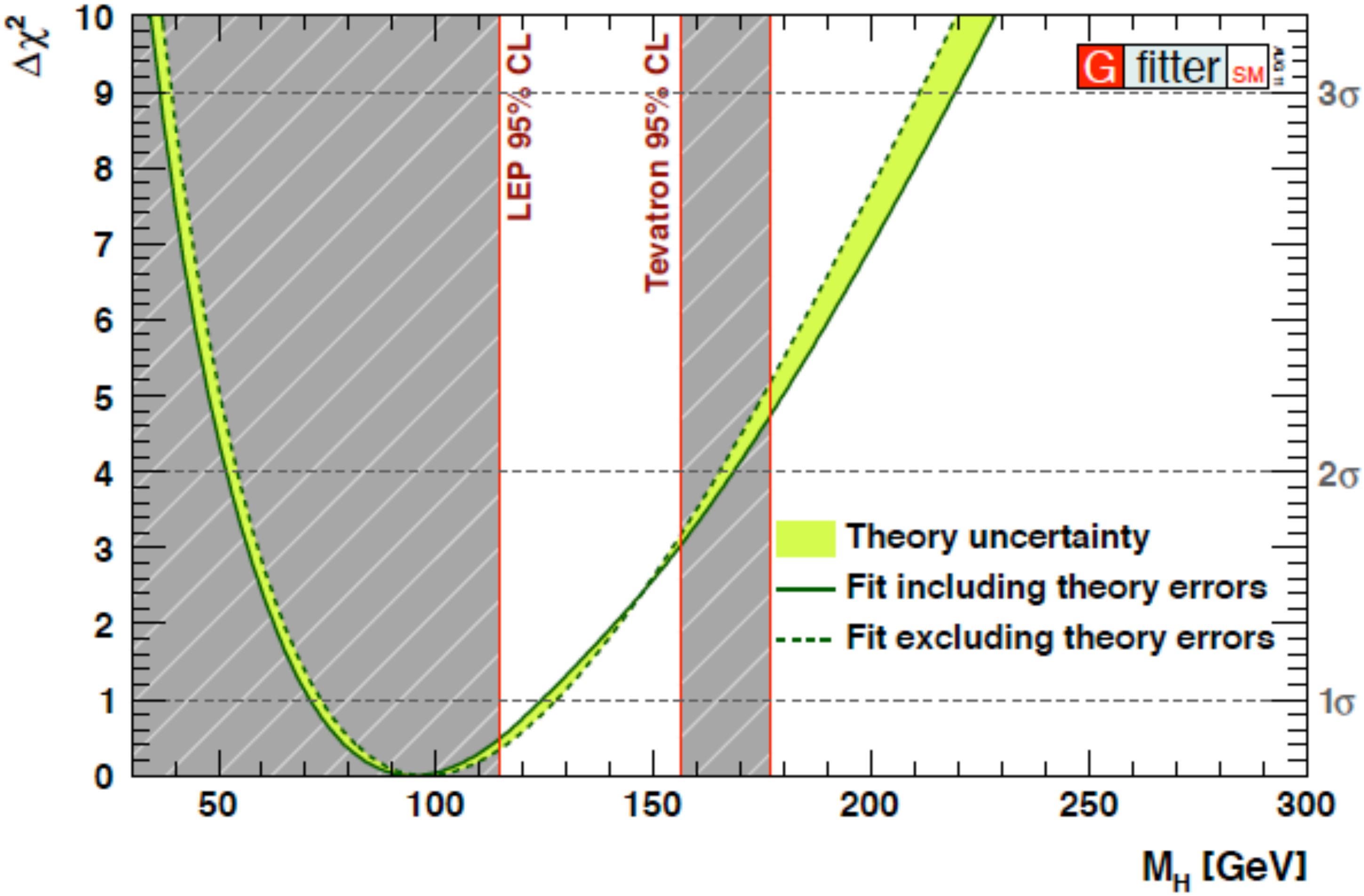


Higgs and Vacuum Stability



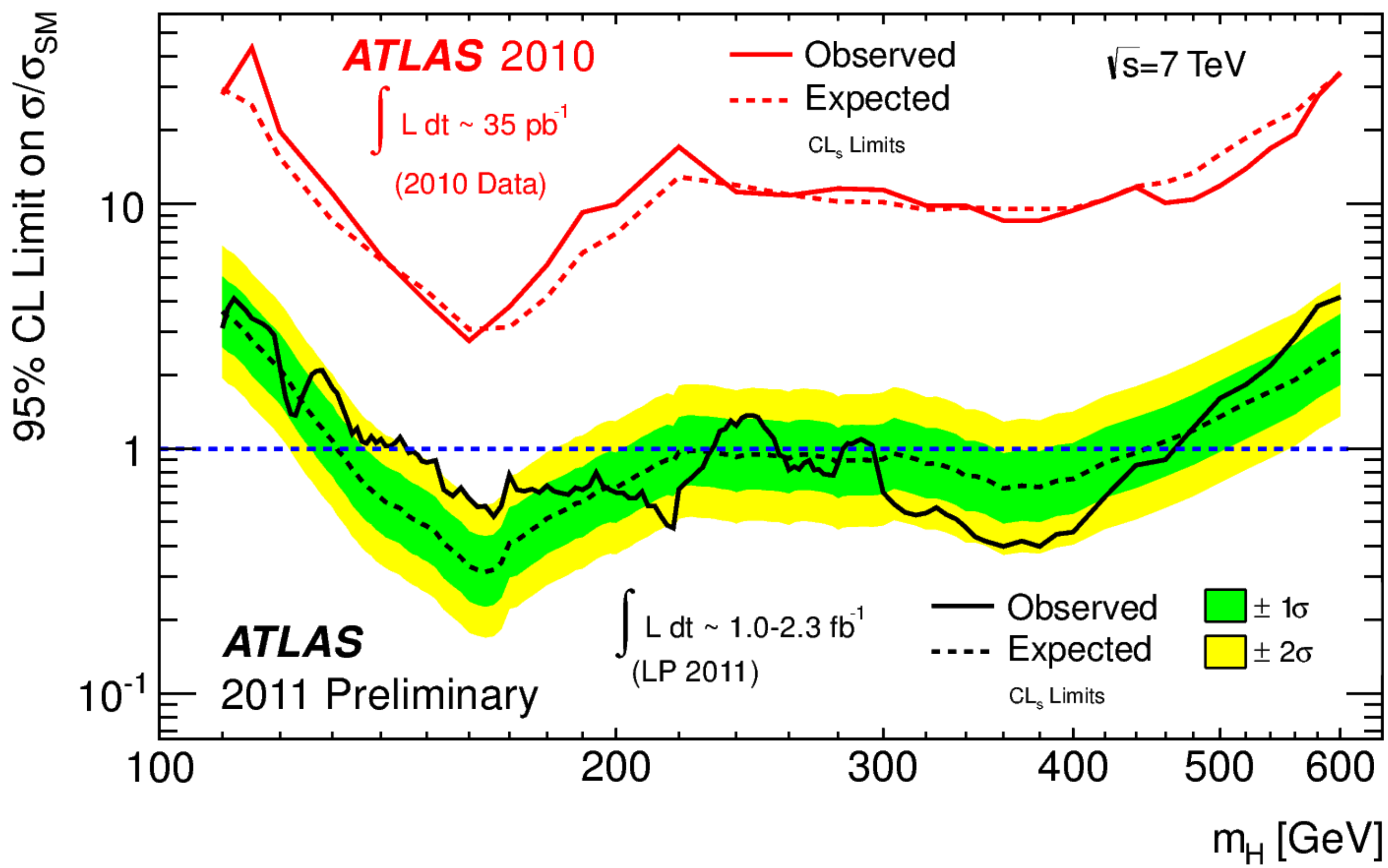
Before LHC: where to expect the Higgs?

- Fits to Standard Model data favors a "light" Higgs Boson
- After 2010, at 95% CL, a 40 GeV window was left for the SM Higgs

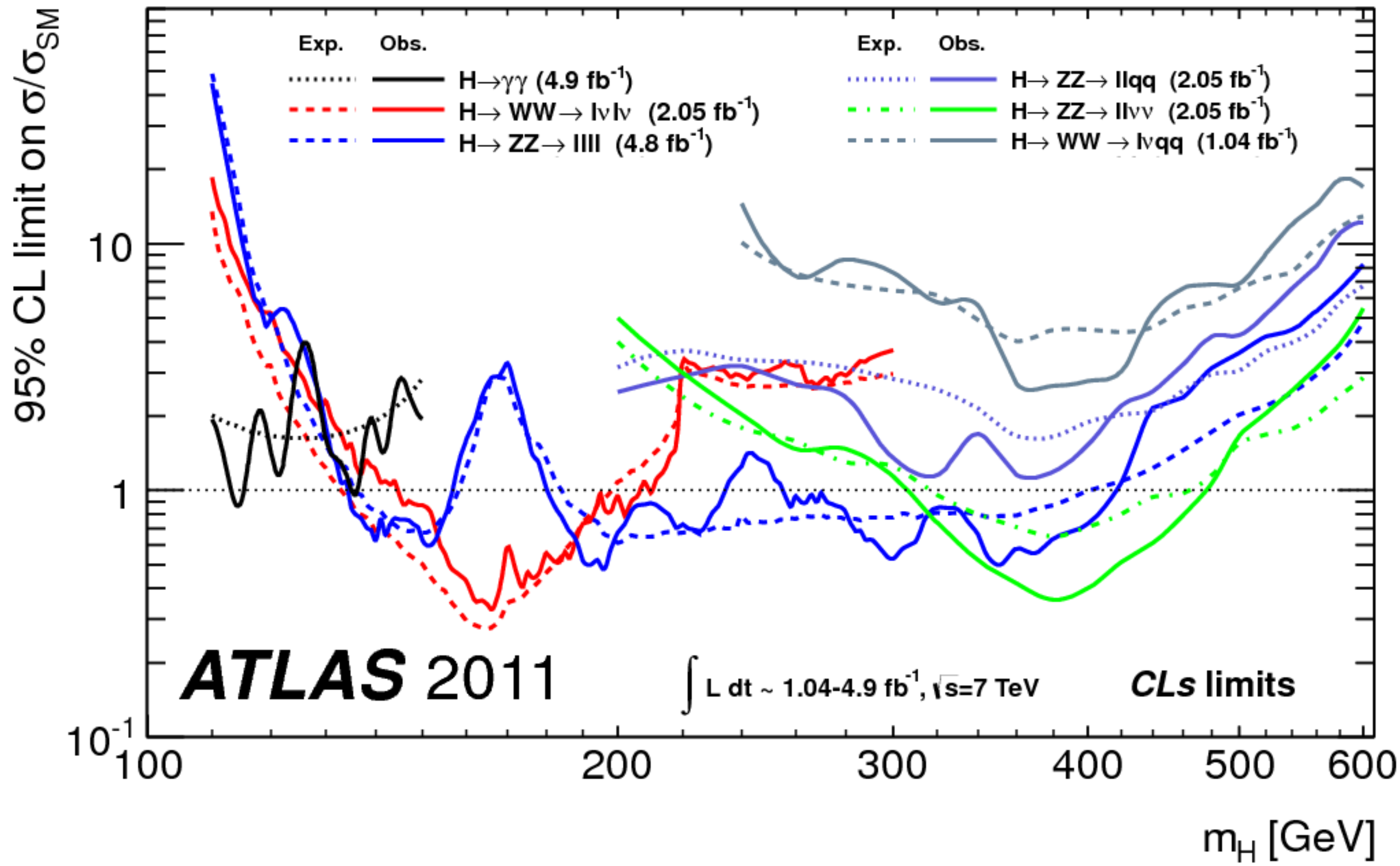


Summer 2011: Limits on Higgs Mass

- Results from 2010 and up to Summer 2011: a lot of progress!
- In low mass range: excluded 146-242 GeV (131 GeV expected)

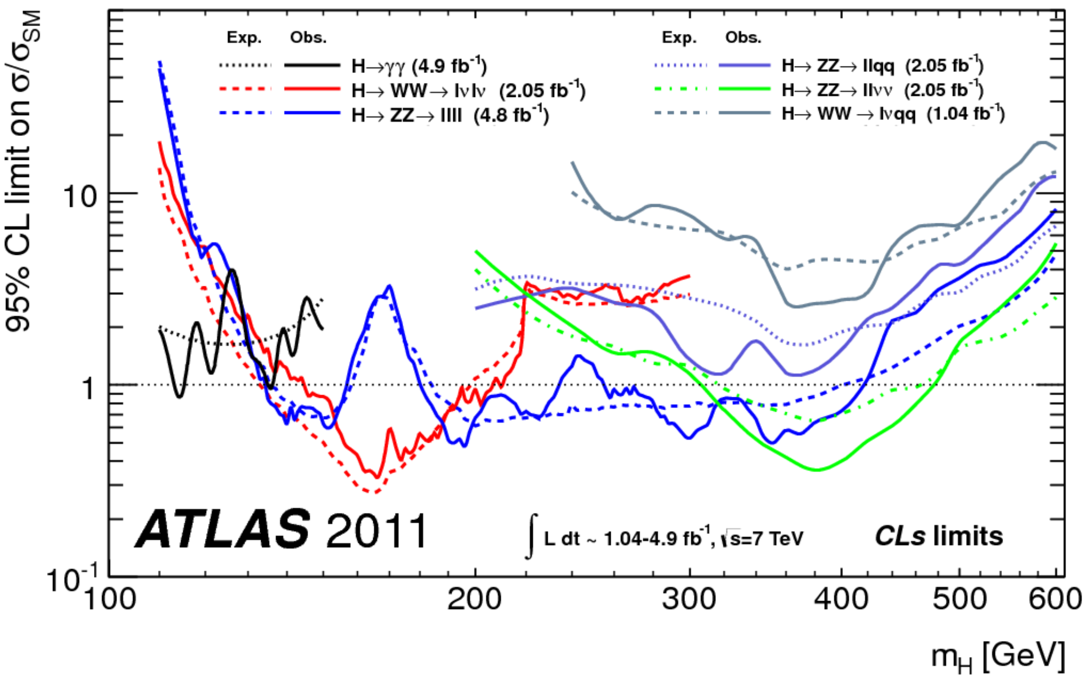


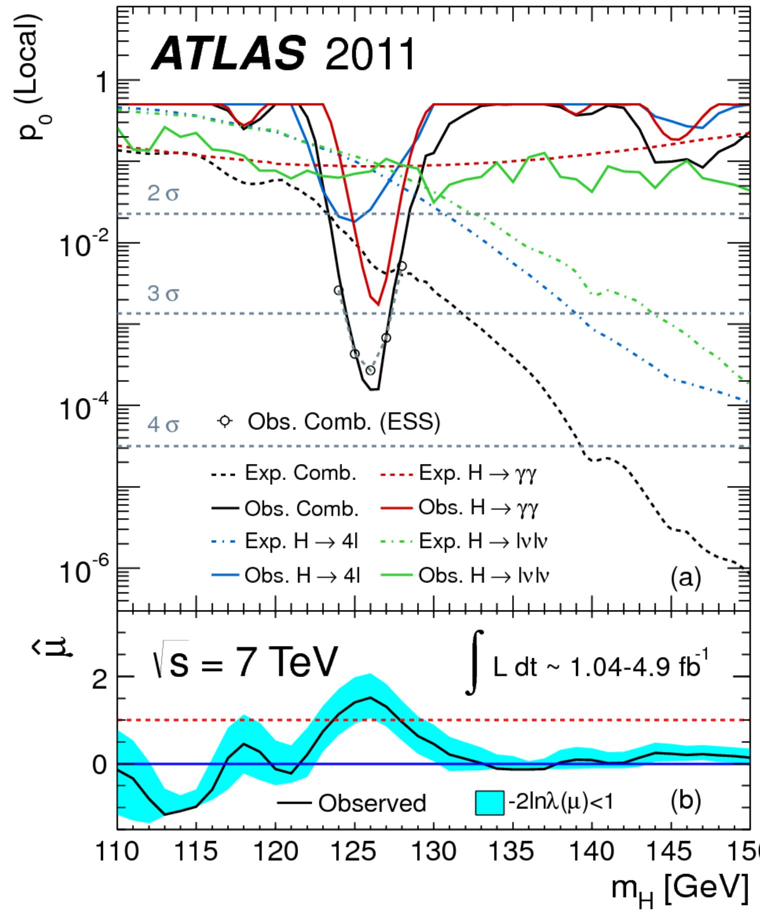
ATLAS 2011 Combination



ATLAS 2011 Combination

- At 126 GeV local signif.: 3.5σ (p_0: 2.7x 10^{-4})
- Accounting for Look Elsewhere Effect (LEE)::
  - Global p_0~0.6% (2.5 σ) for 114-146 GeV (HCP mass range)
  - Global p_0~1.4% (2.2 σ) for full mass range 110-600 GeV

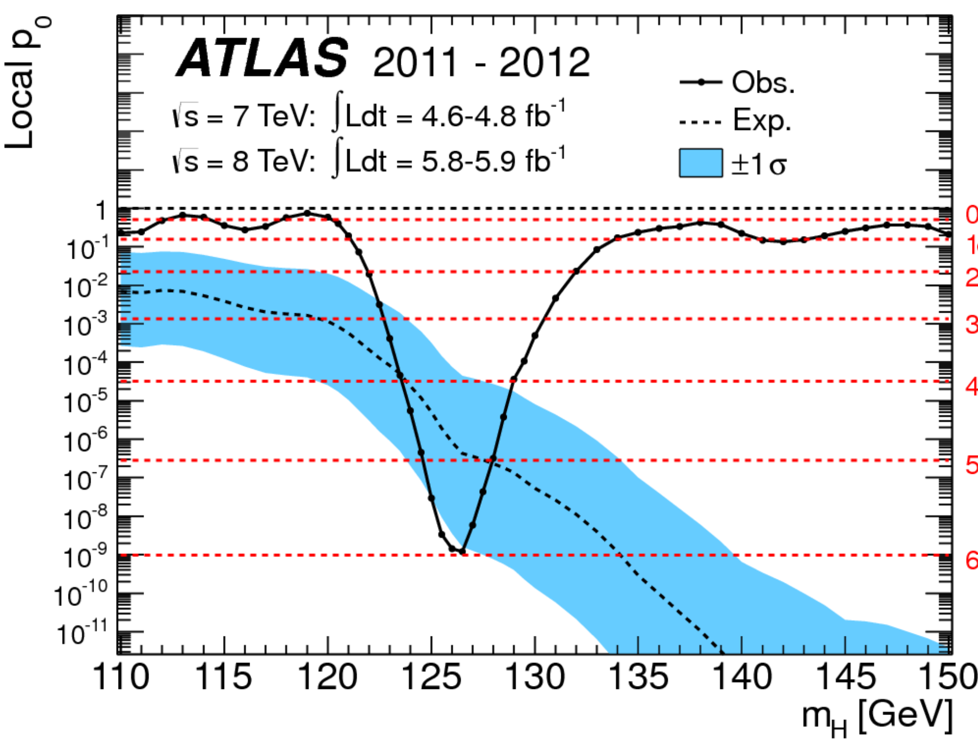


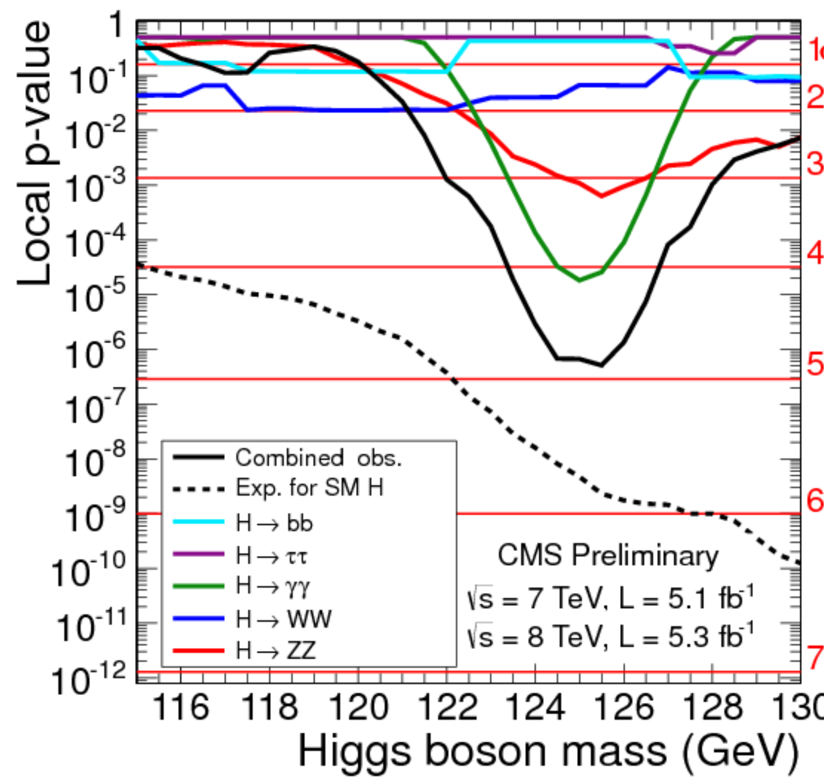


Diphoton, ZZ, WW had similar sensitivity for m_H~125 GeV

July 2012: Combination of Channels

- Probability that the background fluctuated to produce the distributions that we observe
  - ATLAS left, CMS right

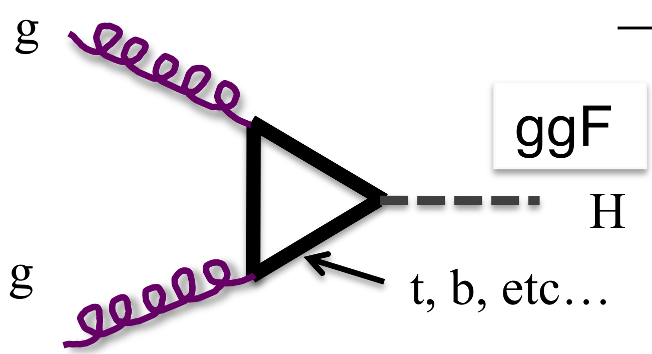


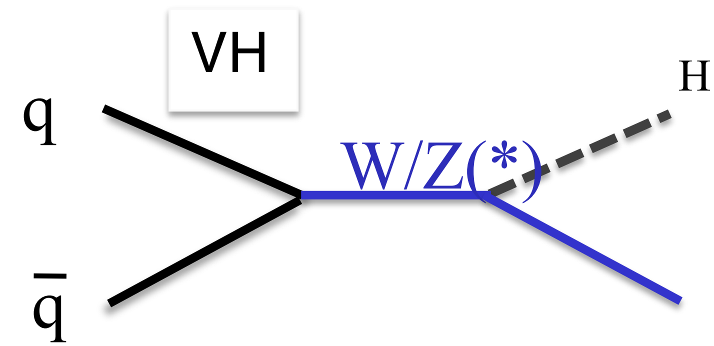


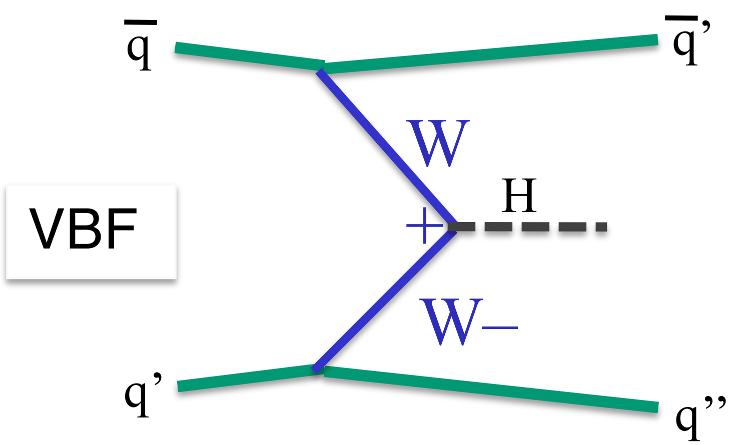
Higgs Production

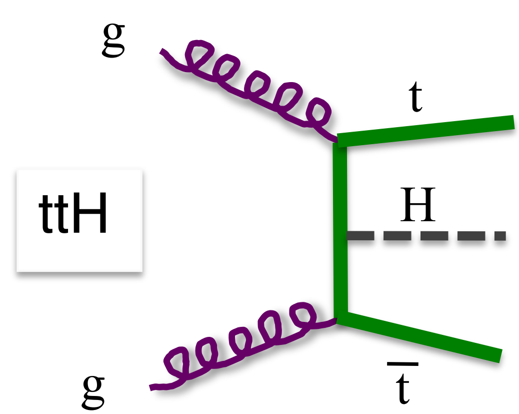
Cross sections for m_H=125 GeV:

	process	**8 TeV**	**13 TeV**
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb







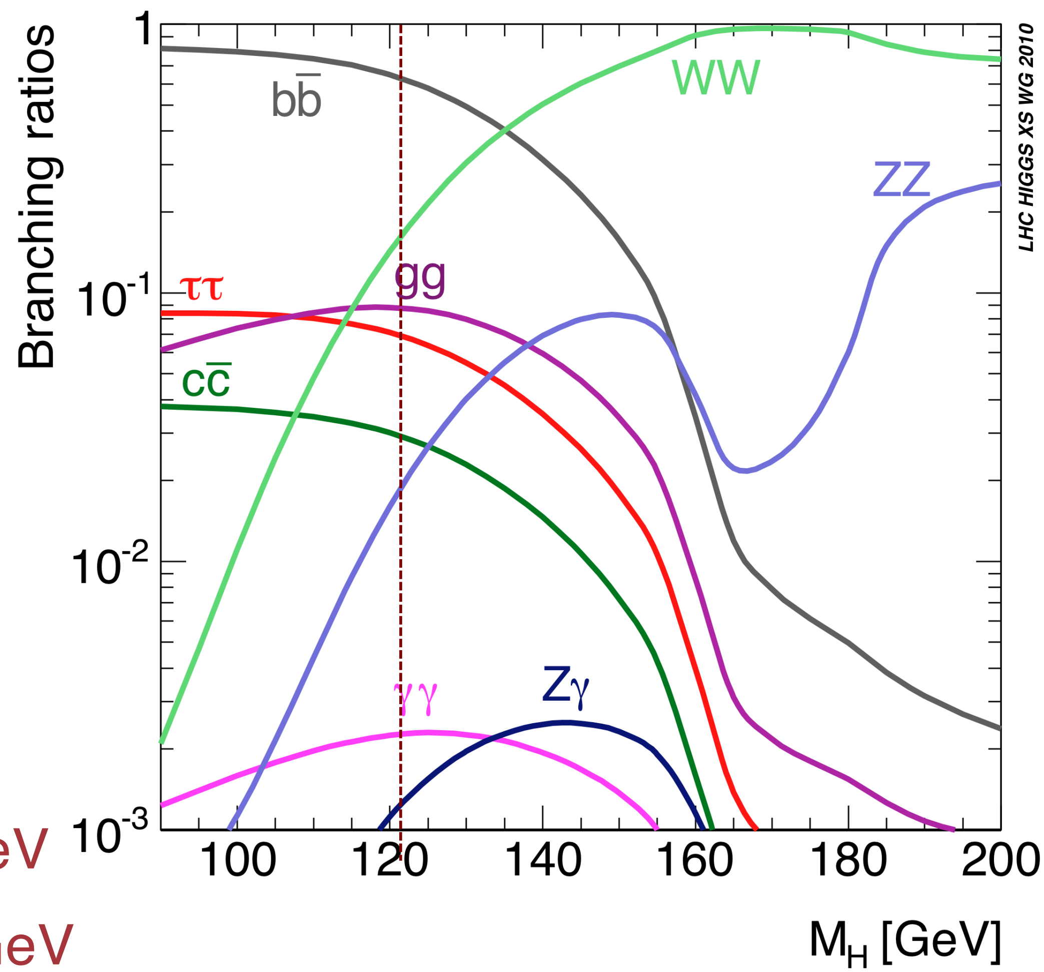


Input Parameter: Higgs boson mass

- The SM does not predict the Higgs boson mass: we need to measure it

- Given a mass, we can make predictions for the production cross section and decay rates

- Around a mass of 125 GeV:
  - ggH xs changes by ~1.5% per GeV
  - WW BR changes by ~7.5% per GeV
  - ZZ BR changes by ~9.5 per GeV



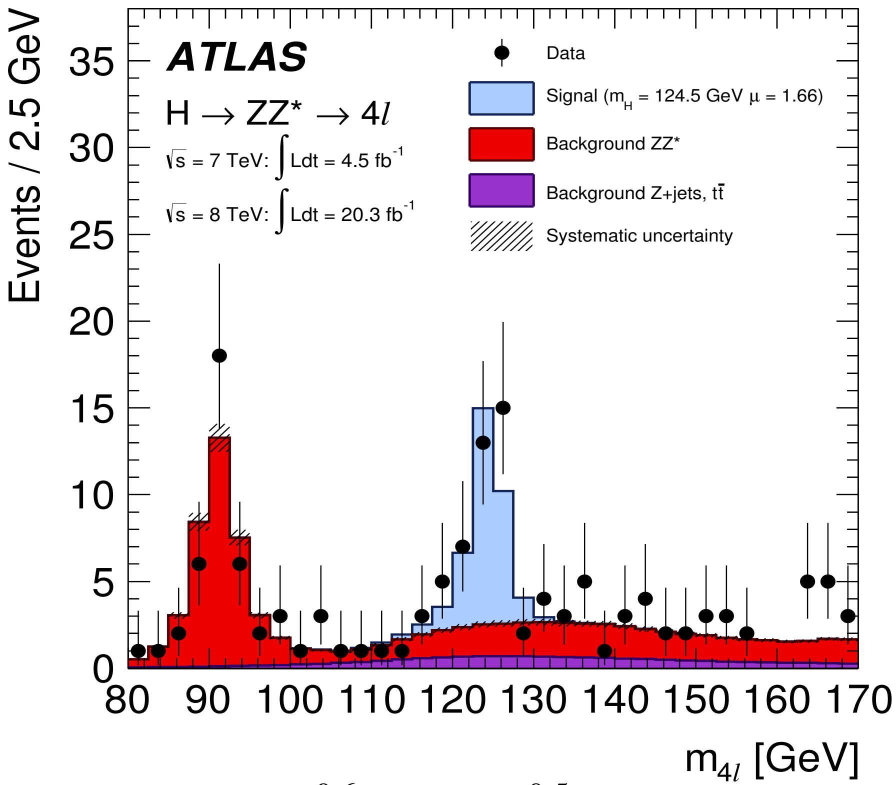
Higgs mass measurements (GeV):

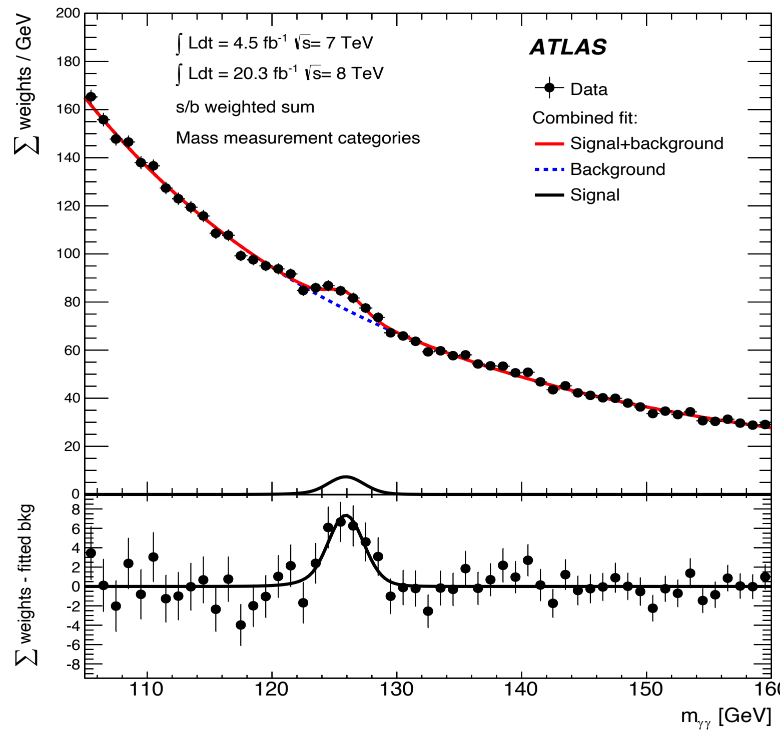
ATLAS: 125.36 ± 0.37 (stat) ± 0.18 (sys

CMS: 125.02 ± 0.27 (stat) ± 0.15 (sys

ATLAS Mass Measurement

Published in PRD arXiv:1406.3827





Old: $124.3\,^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

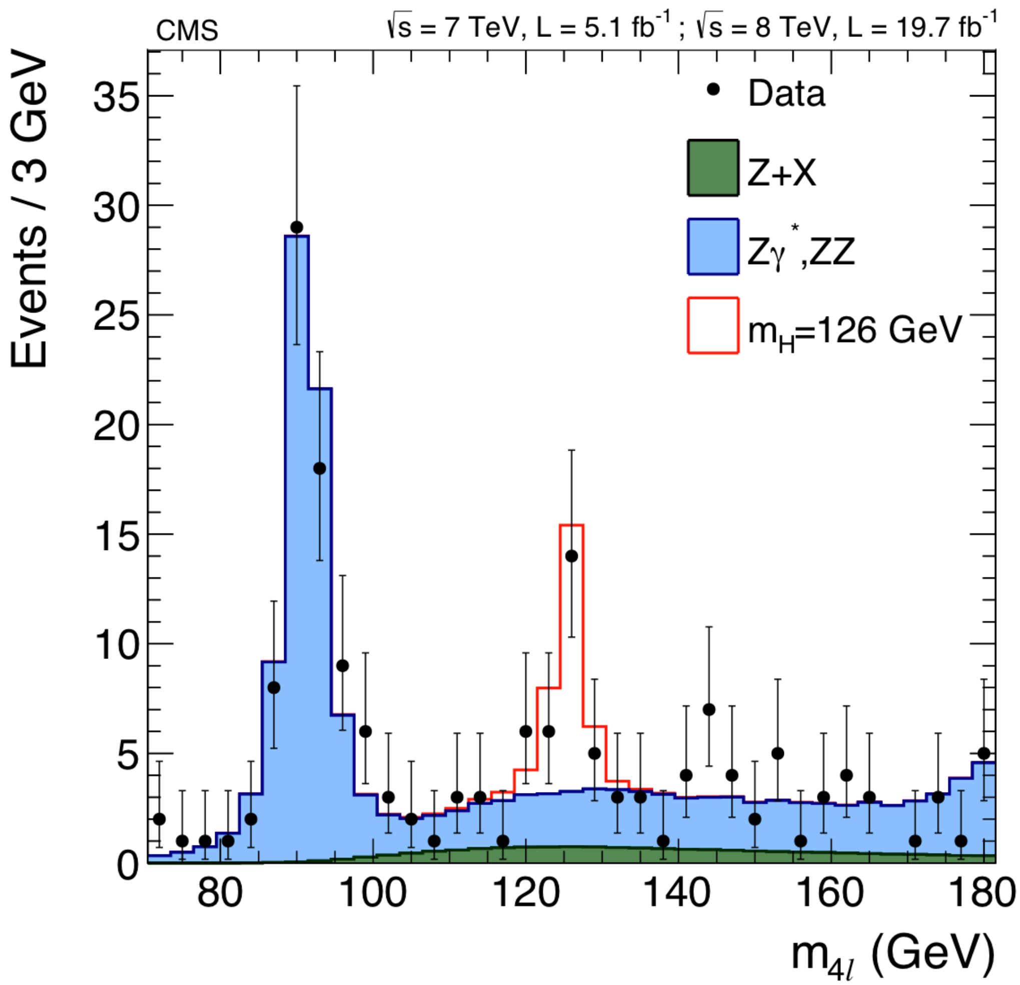
Expected mass shift -450 +/- 350 MeV

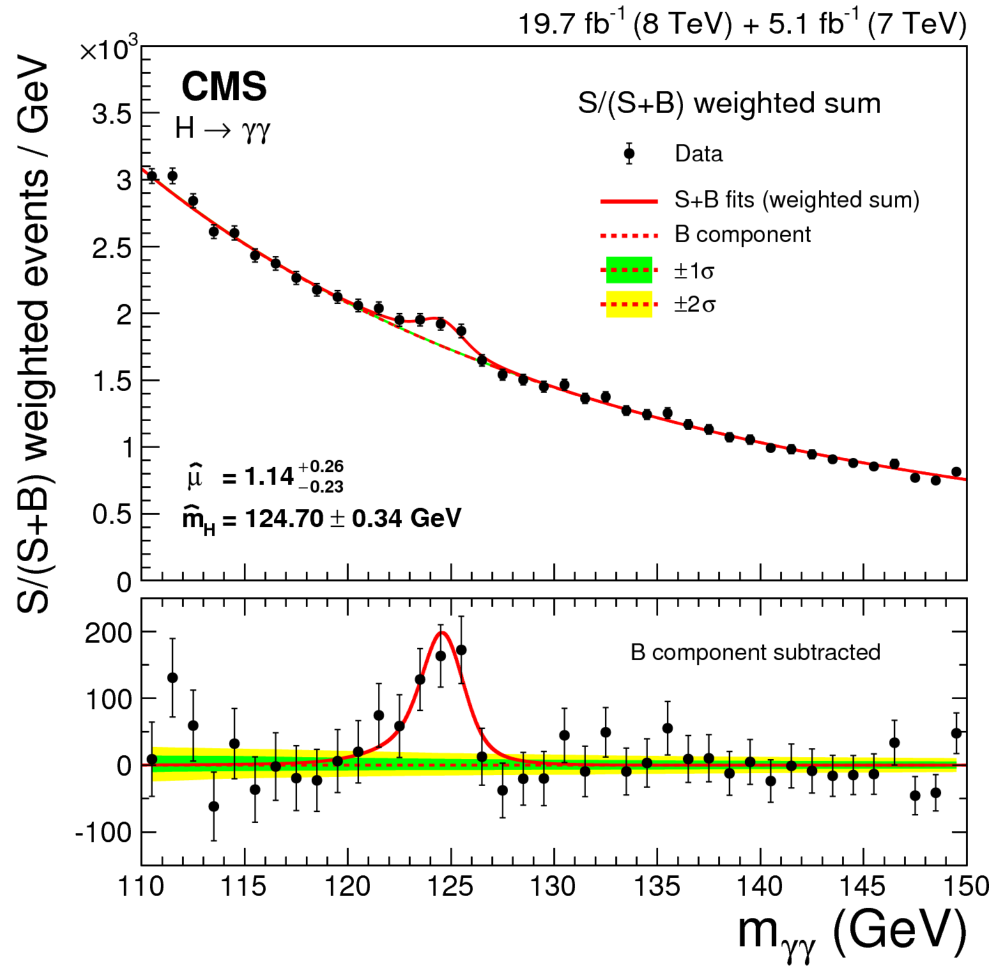
New: 124.51 ± 0.52 (stat) ± 0.06 (syst) GeV

125.98 ± 0.42 (stat) ± 0.28 (syst) GeV

Systematics greatly reduced

CMS Mass Measurement

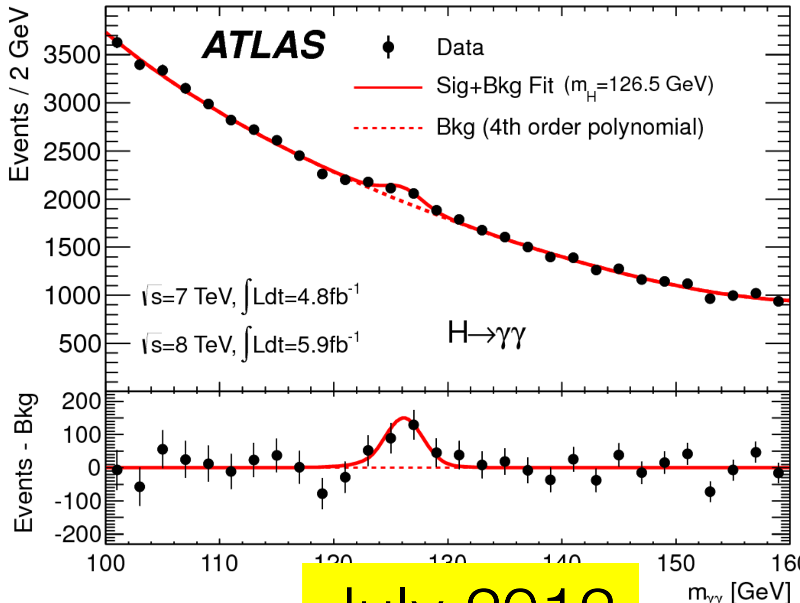




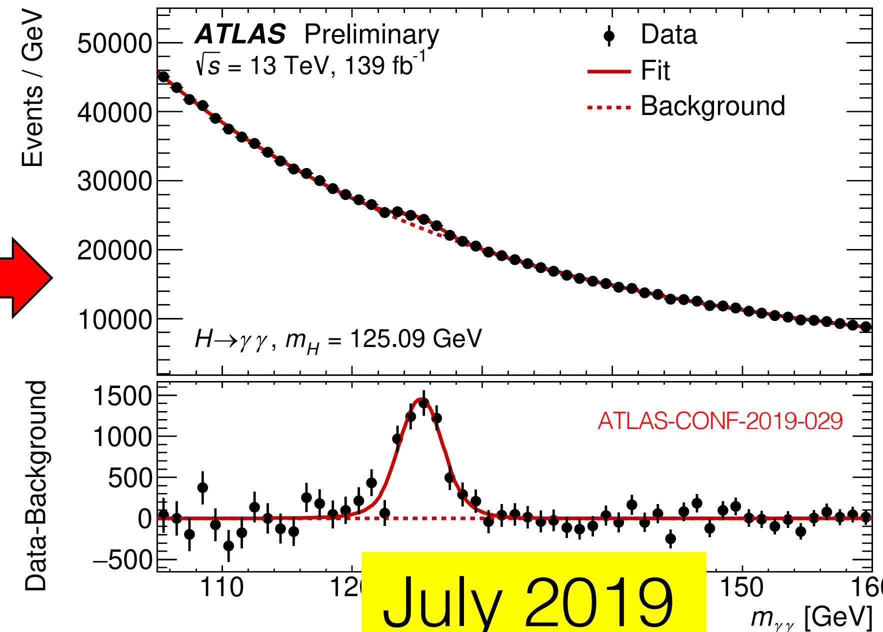
CMS combined mass result: 125.02 ± 0.27 (stat) ± 0.15 (syst) G

The Higgs Boson: then and now

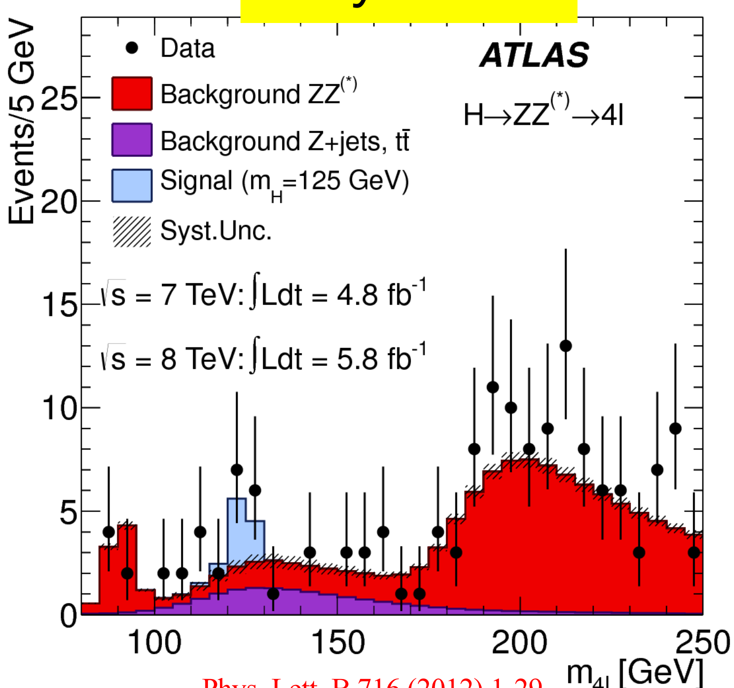
Full Run-2



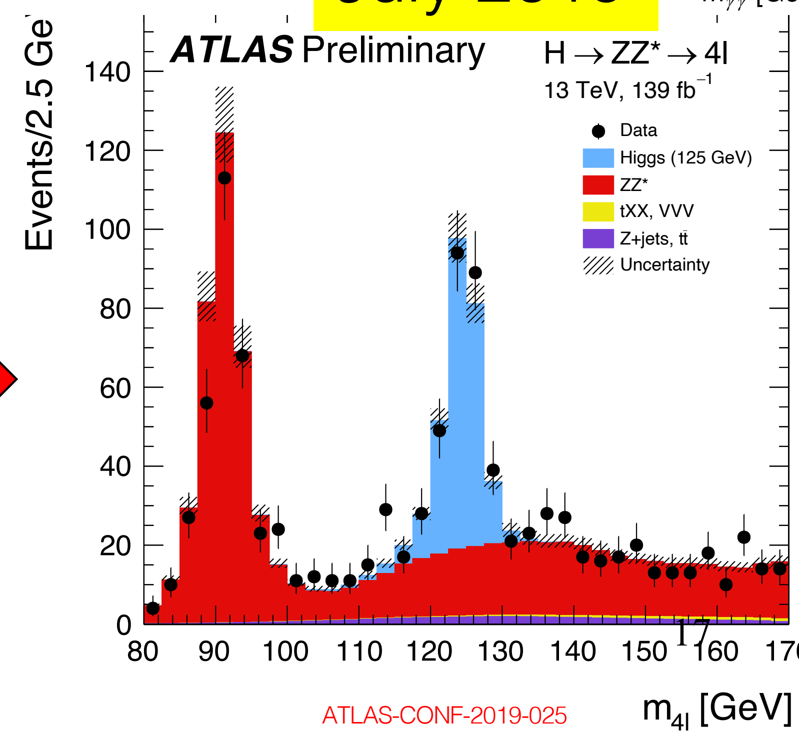
July 2012



July 2019



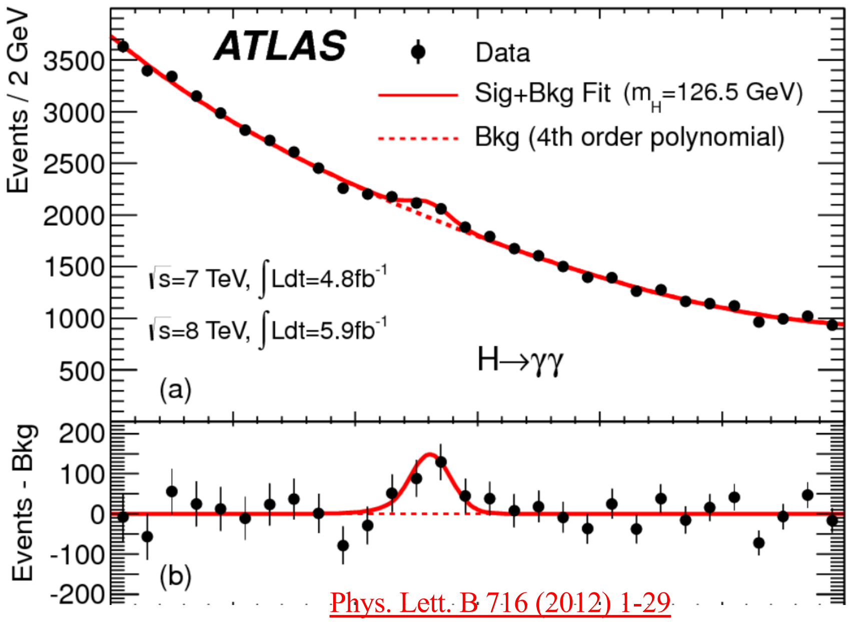
Phys. Lett. B 716 (2012) 1-29



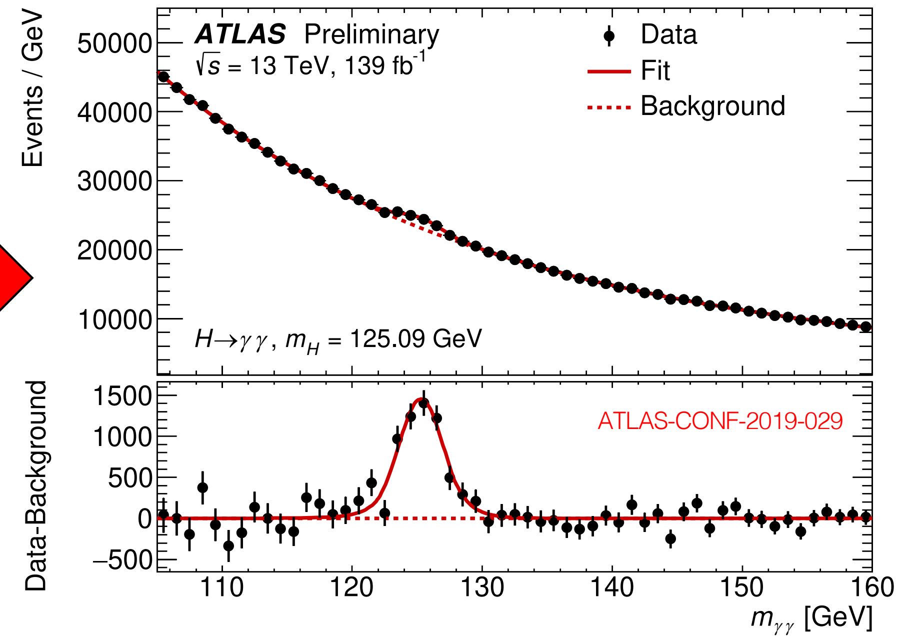
ATLAS-CONF-2019-025

The Higgs Boson: then and now

Full Run-2

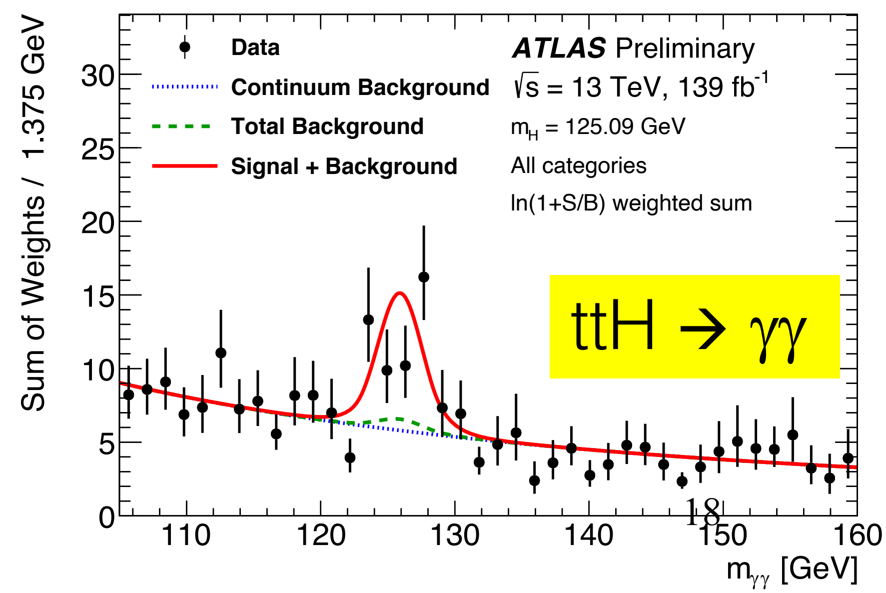


July 2012

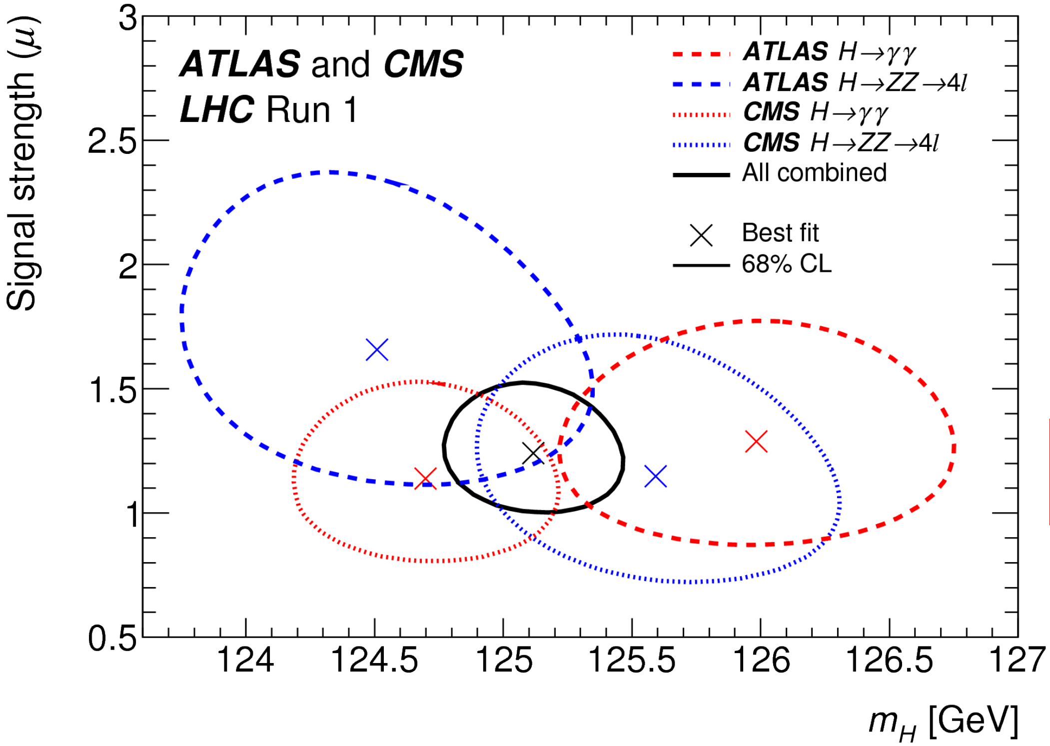


July 2019

Observation of H → γγ in rare ttH production channel in 2019
ATLAS-CONF-2019-004

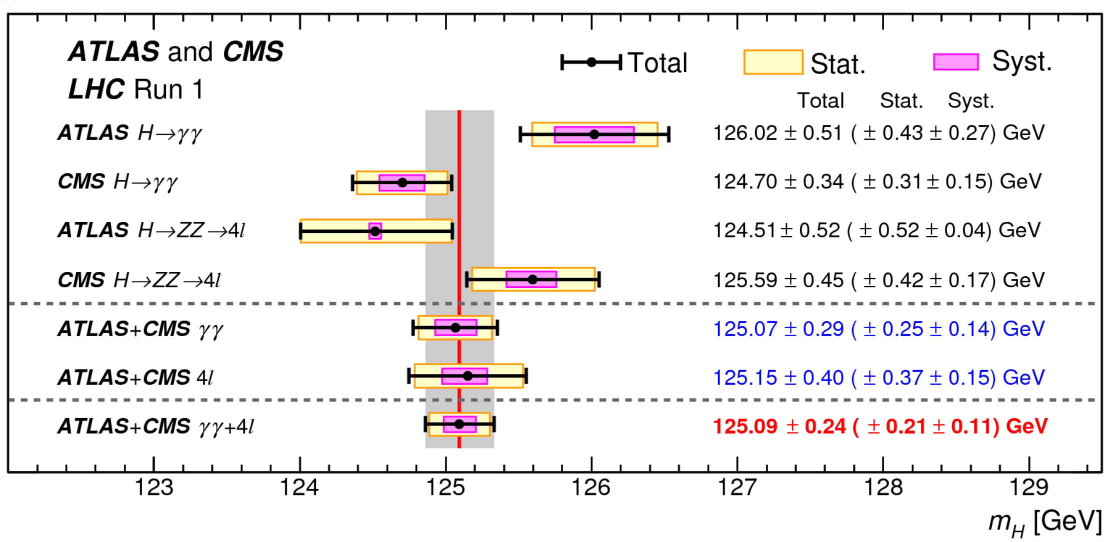


Higgs Mass Measurement



Combined ATLAS/CMS Mass:

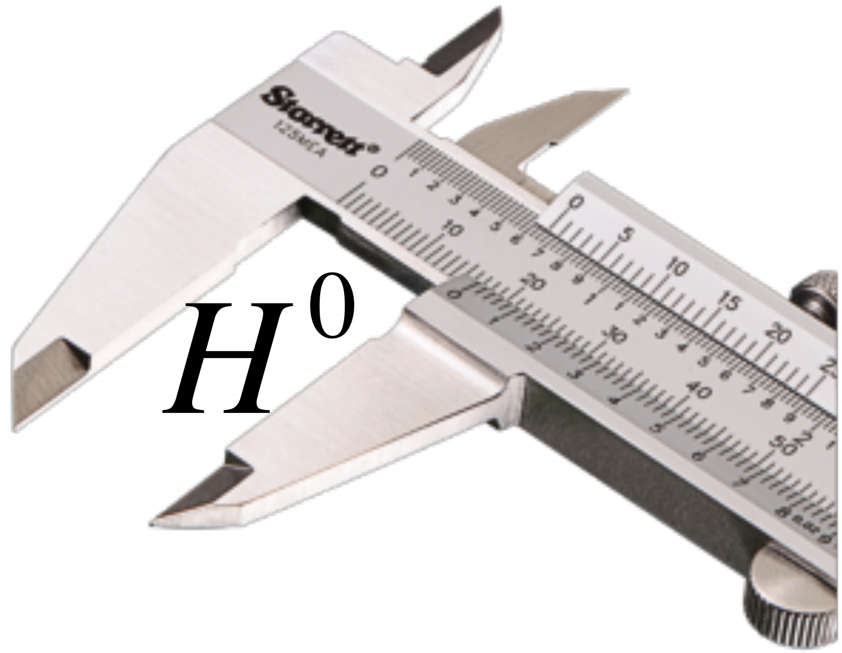
125.09 ± 0.21 (stat) ± 0.11 (syst) G



0.2% precision measurement. Statistical uncertainty is the dominant uncertainty

SM Higgs boson Physics

- A comprehensive program to test the SM Higgs hypothesis:
  - Precision mass measurements
  - Measurement of couplings
    - Production modes
      - ggH, WH, ZH, VBF, ttH
    - Decay modes:
      - $\gamma\gamma$, WW, ZZ, tt, bb
    - Off-shell measurements
  - Rare Decay modes:
    - $\mu\mu$, $Z\gamma$, $J/\psi\ \gamma$
  - Quantum numbers: Spin and CP
  - Fiducial and differential measurements
  - Width
    - Direct, off-shell, interference



Higgs Bosons — H^0 and $H^\pm$

H^0 Mass $m = 125.9 \pm 0.4$ GeV

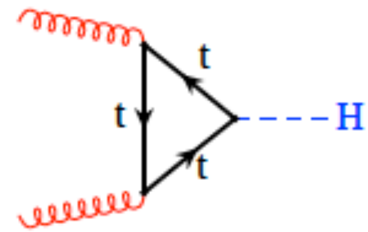
H^0 signal strengths in different channels [n]

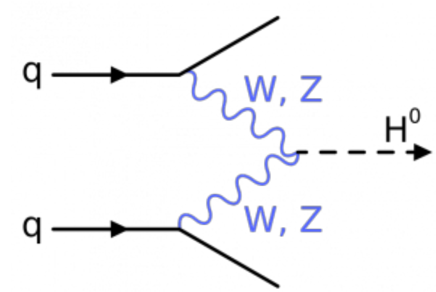
Combined Final States $= 1.07 \pm 0.26$ $(S = 1.4)$
WW^* Final State $= 0.88 \pm 0.33$ $(S = 1.1)$
ZZ^* Final State $= 0.89^{+0.30}_{-0.25}$
$\gamma\gamma$ Final State $= 1.65 \pm 0.33$
$b\bar{b}$ Final State $= 0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State $= 0.1 \pm 0.7$

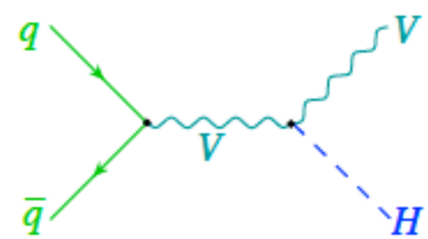
H decays to bosons
WW, ZZ, $\gamma\gamma$

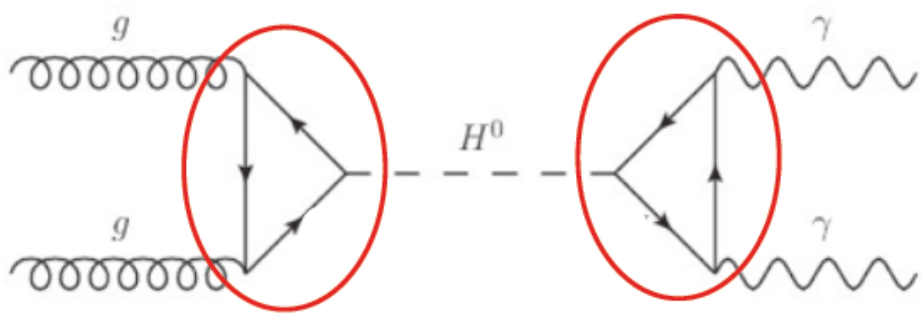
H → γγ

- Main production depends on coupling to top quark (in SM), with smaller contribution from VBF (and VH) which depends on coupling to W/Z bosons
- Decay depends on coupling to top and W boson (in SM)
- Large backgrounds: need good photon identification
  - ATLAS EM calorimeter designed with this signal in mind
- Small branching ratio, need integrated luminosity
- A good discovery final state:
  - Excellent Higgs mass resolution
  - Looking for a resonance on top of smooth background
  - Probes new physics in loops:



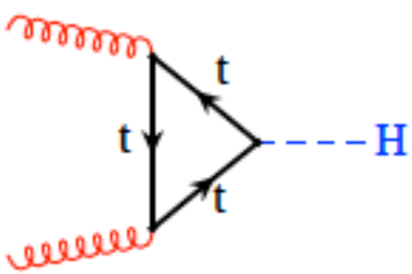


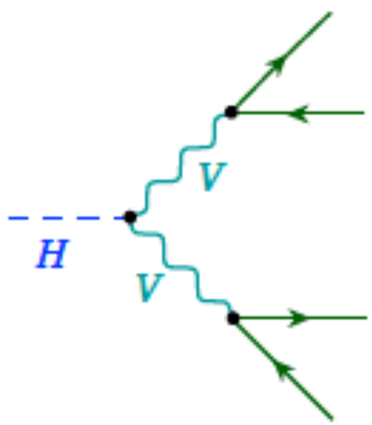




$H \rightarrow ZZ^* \rightarrow llll$

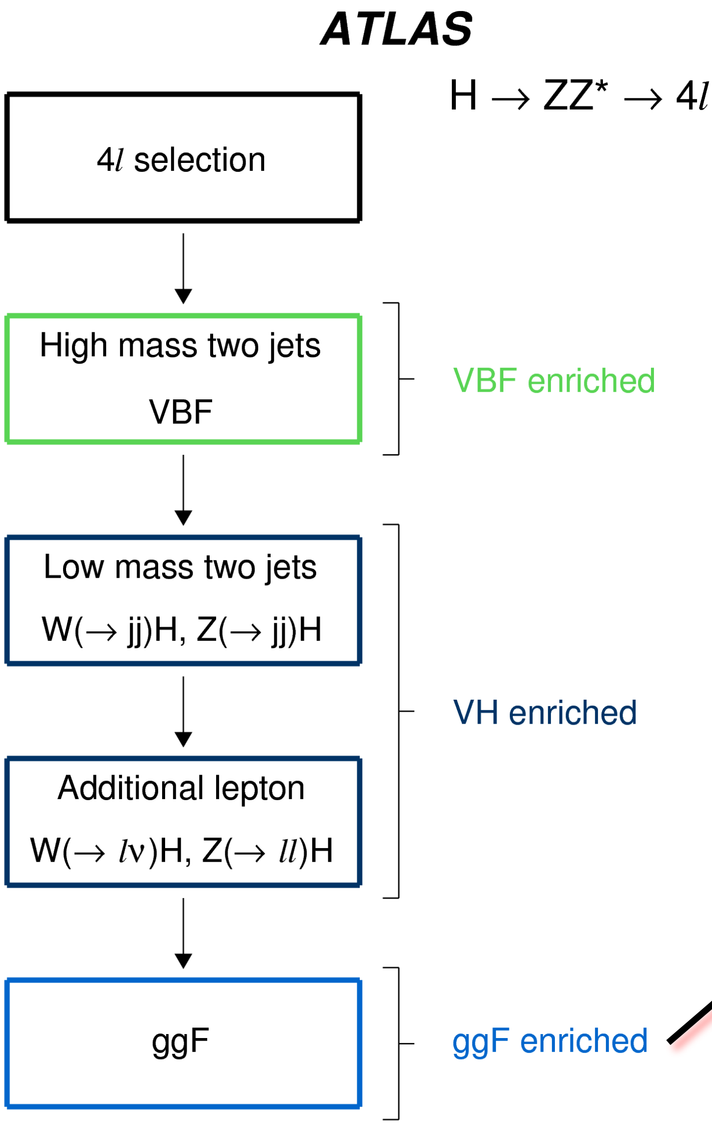
- Production depends on coupling to top quark (in SM), with small contributions from other production modes
- Decay depends on coupling to Z boson
- Small branching fraction to 4-lepton final state (need int. lumi.)
- A good discovery final state:
  - Very low backgrounds
  - Very good Higgs mass resolution
  - Requires good lepton reconstruction efficiencies
    - Can cope with high pileup environment
  - Clear/robust signal of coupling of Higgs to



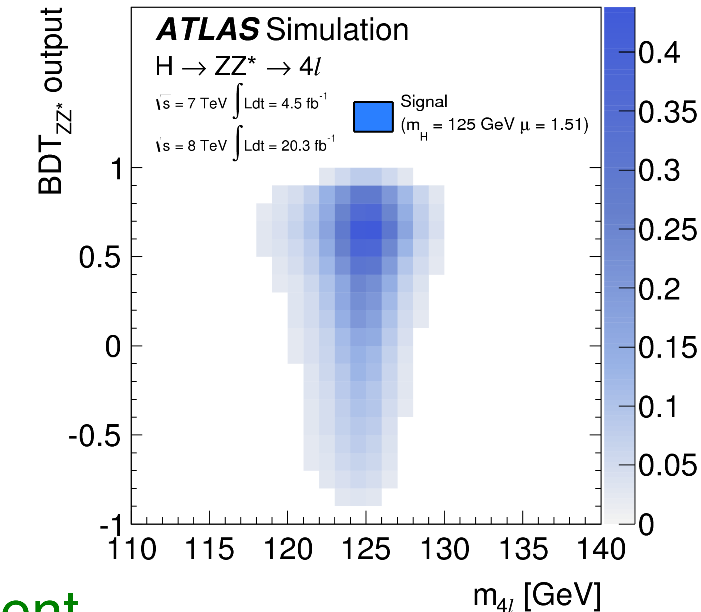


H → ZZ$^{(*)}$ → 4 LEPTONS

Event categorization:

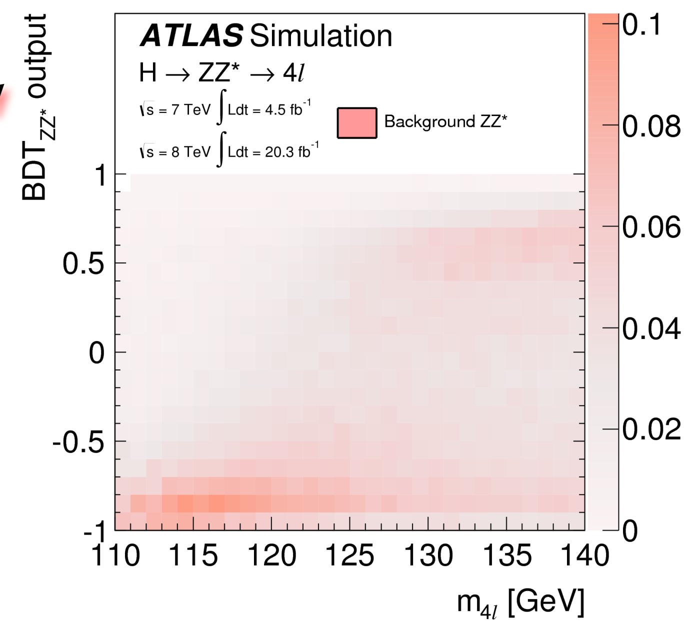


BDT vs mass



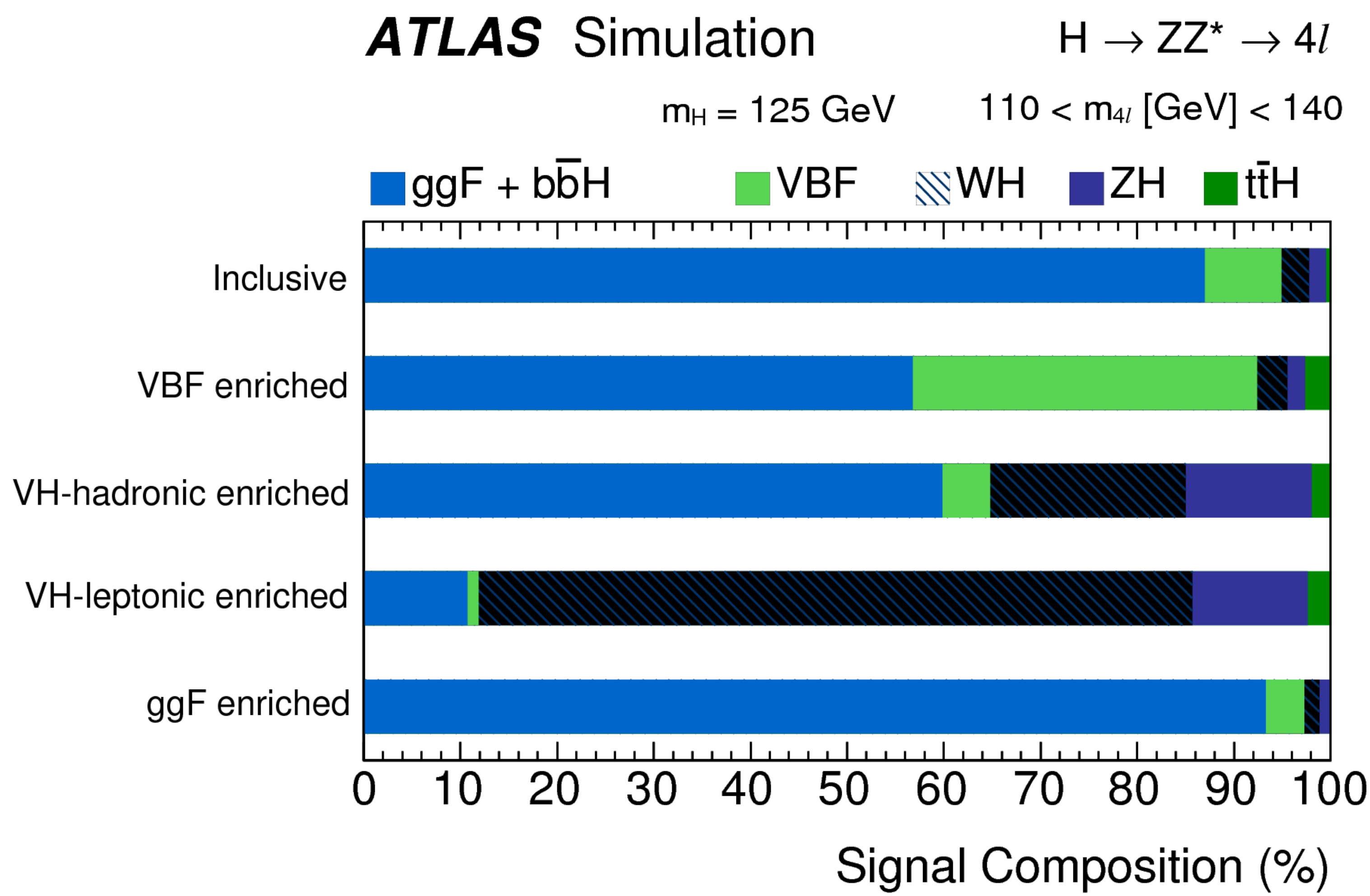
BDT variables:

- $P_T(4l)$
- $\eta(4l)$
- Matrix Element Discriminant



$H \rightarrow ZZ^{(*)} \rightarrow$ 4 LEPTONS

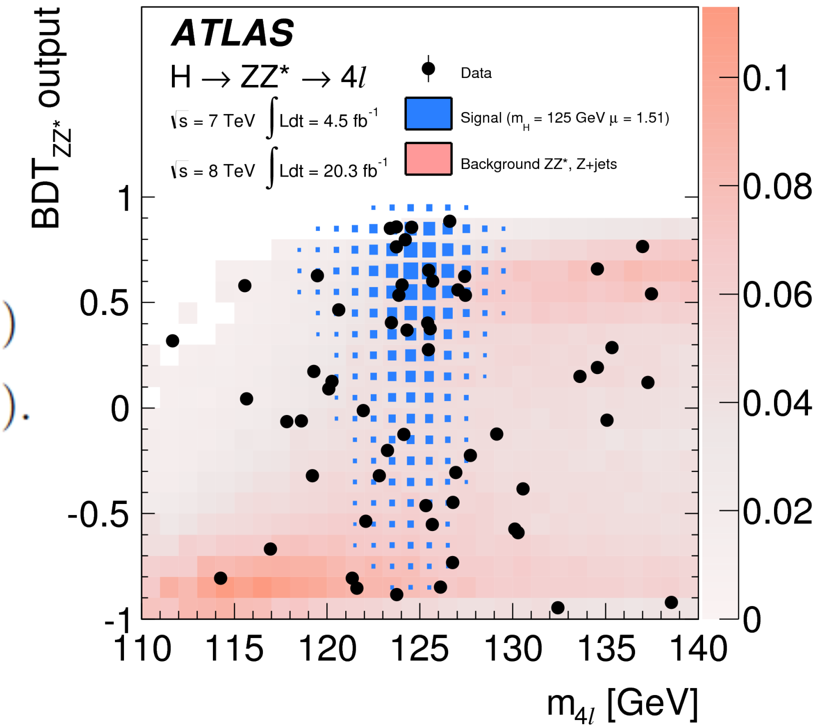
Estimated signal composition
in various categories

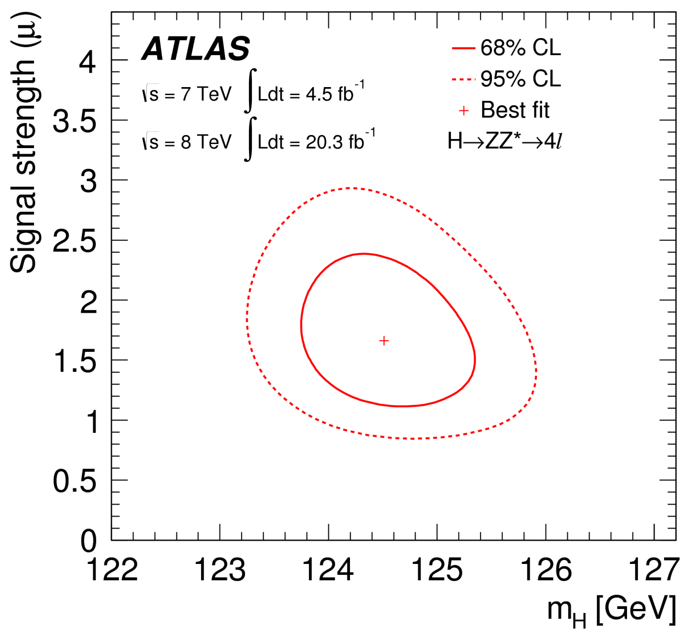


$H \rightarrow ZZ^{(*)} \rightarrow$ 4 LEPTONS

Results for $M_H = 125.4$

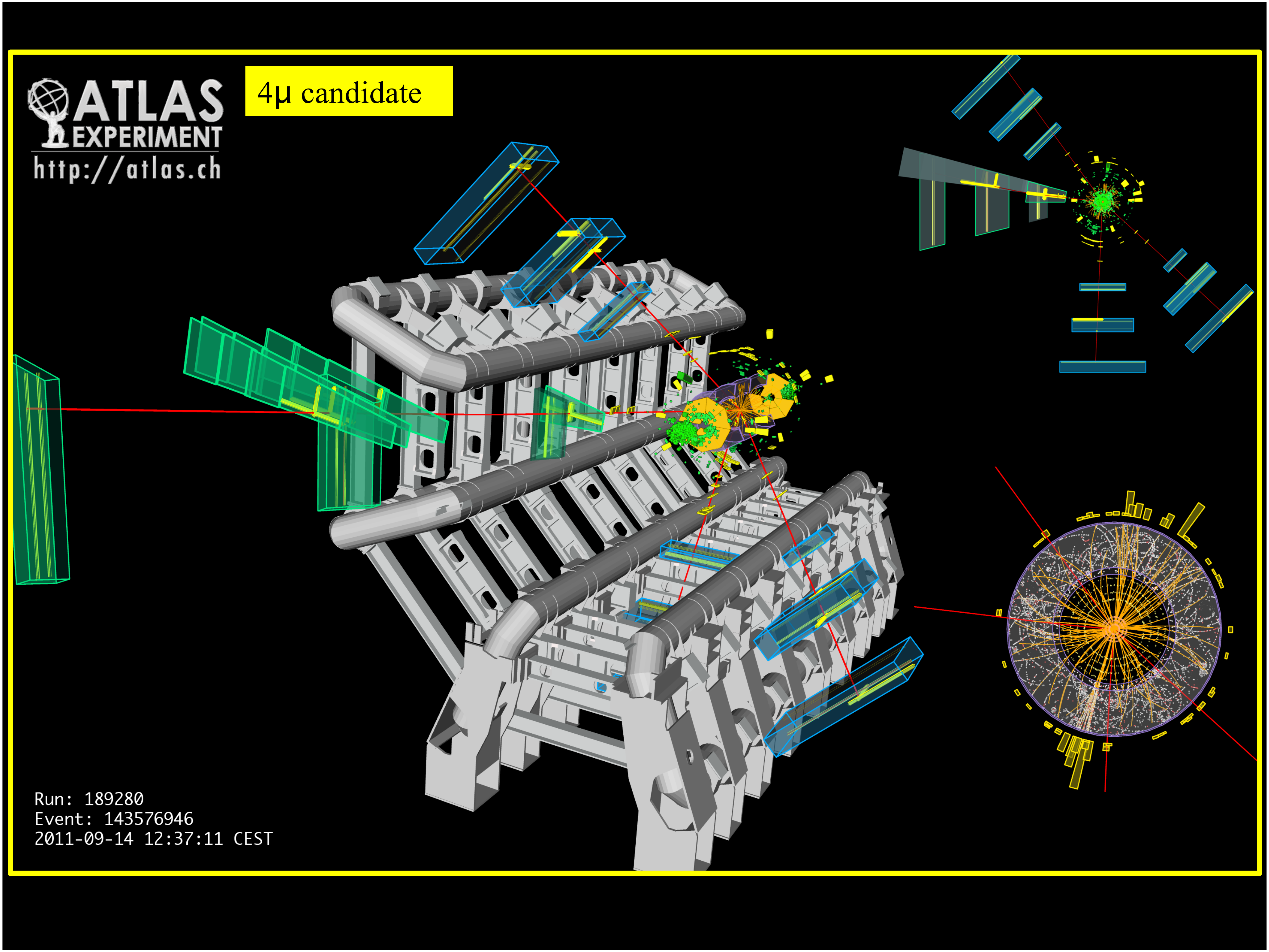
$$\mu_{ggF+b\bar{b}H+t\bar{t}H} \times B/B_{SM} = 1.66 \, ^{+0.45}_{-0.41} \, (\text{stat}) \, ^{+0.25}_{-0.15} \, (\text{syst})$$
$$\mu_{VBF+VH} \times B/B_{SM} = 0.26 \, ^{+1.60}_{-0.91} \, (\text{stat}) \, ^{+0.36}_{-0.23} \, (\text{syst}).$$



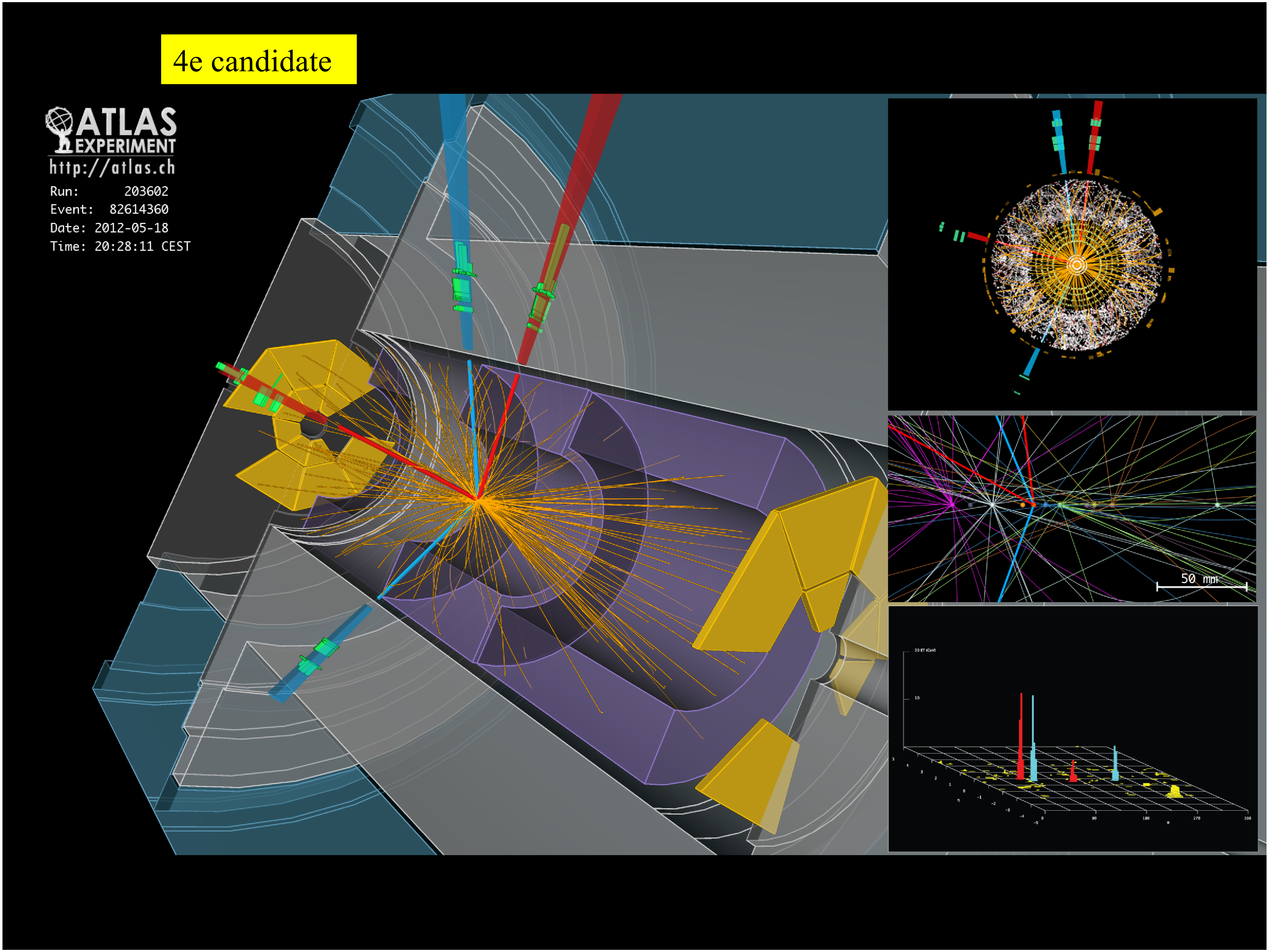


Combined result:

$$1.44 \, ^{+0.34}_{-0.31} \, (\text{stat}) \, ^{+0.21}_{-0.11} \, (\text{syst})$$

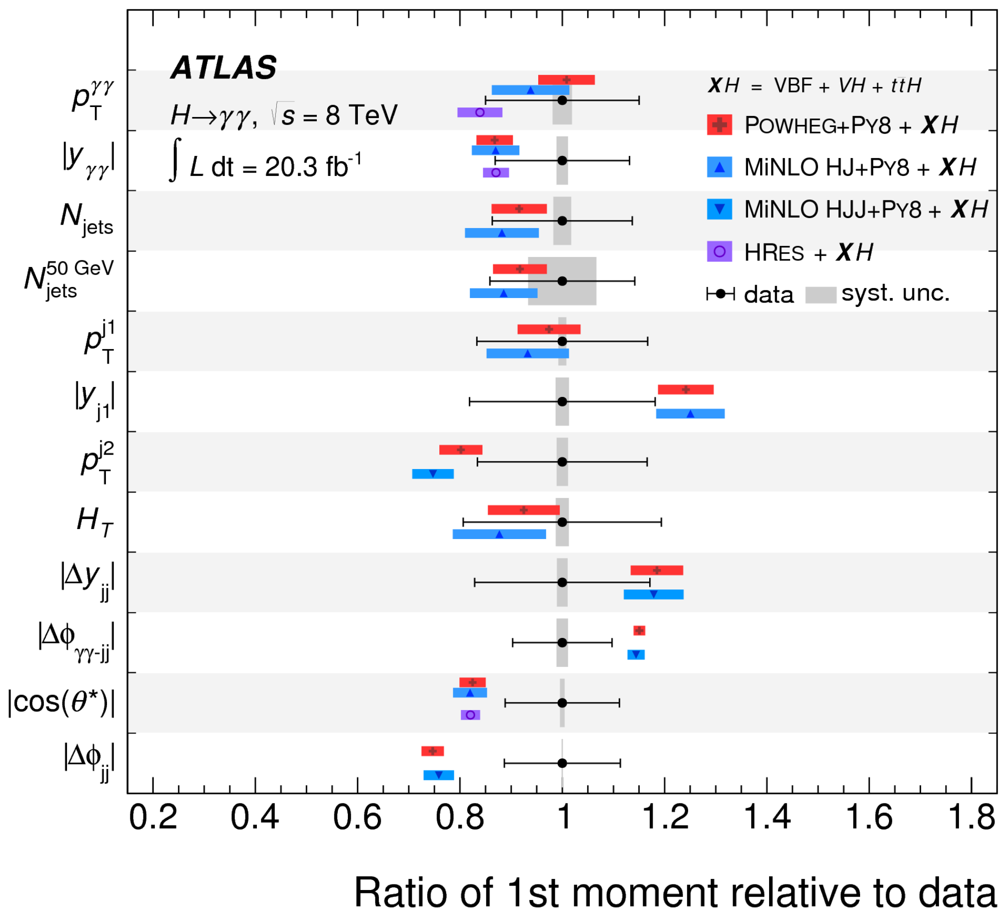


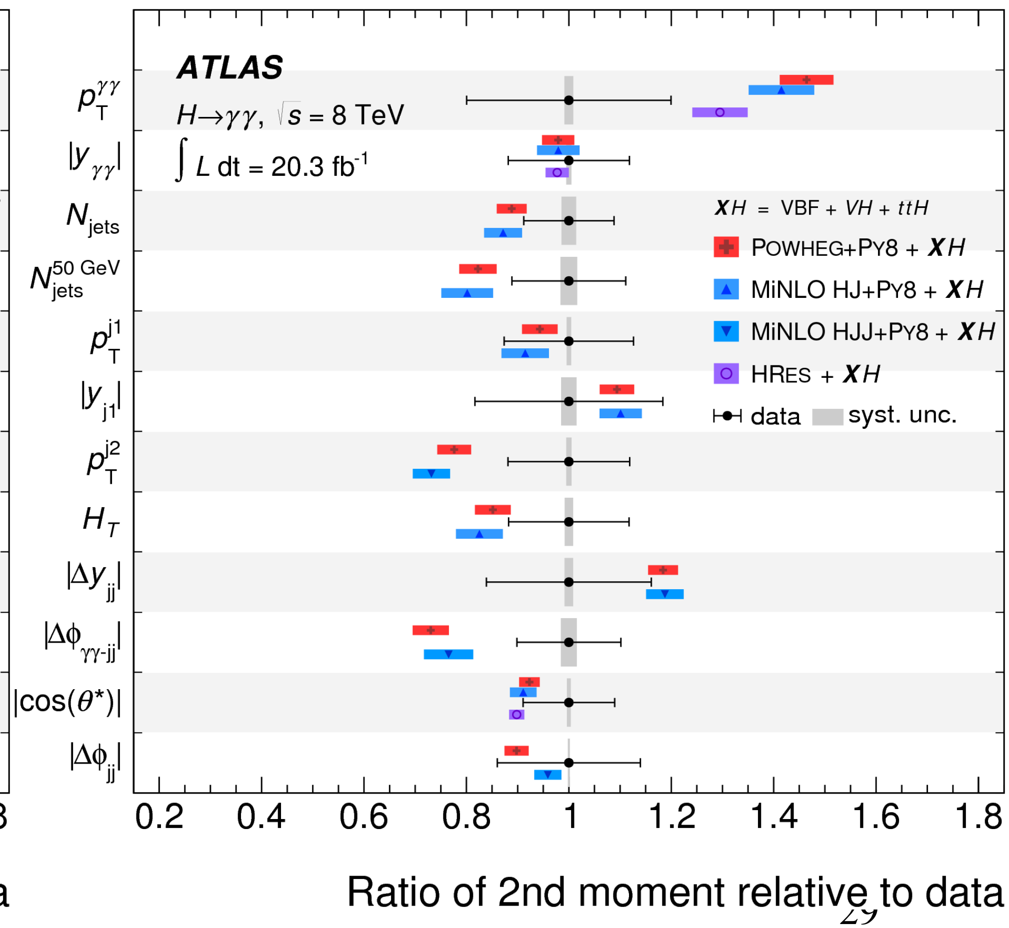
ATLAS EXPERIMENT
http://atlas.ch
4μ candidate
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST


4e candidate
ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm

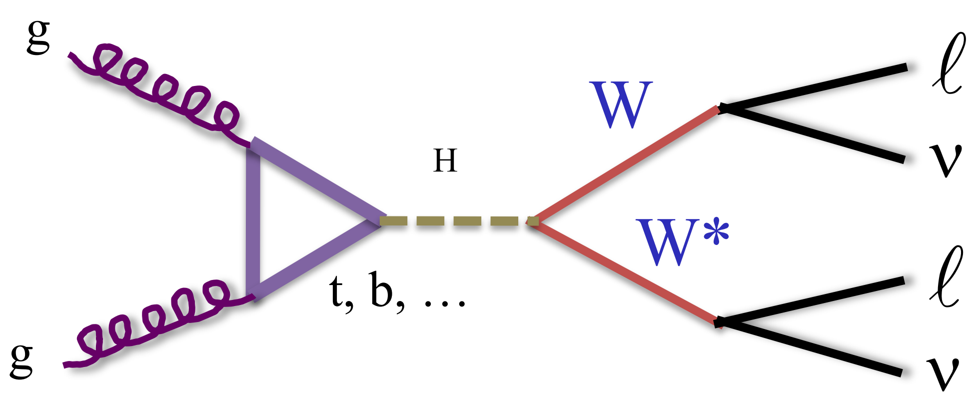
Differential Cross Sections

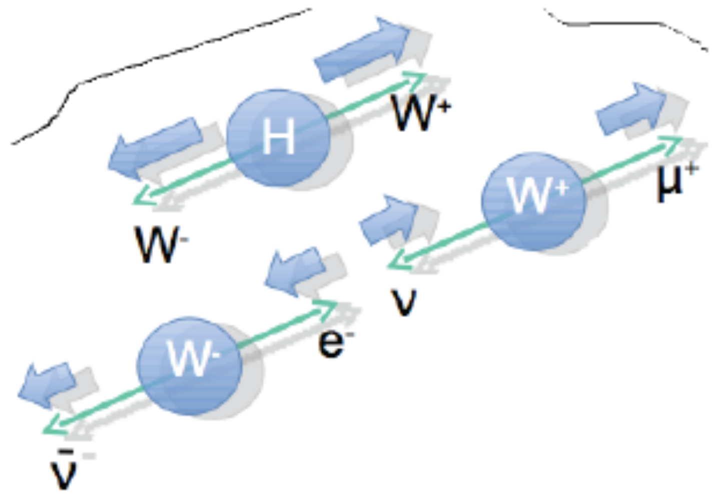
- $\gamma\gamma$ summary of measured variables:
  - Left: 1st moment of the distributions (Mean)
  - Right: 2nd moment of the distributions (RMS)





$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$





- Large Br to WW:
  - many signal events
  - But final state features low pt lepton and neutrinos
- Can't fully reconstruct final state because of neutrinos
  - Missing Et reconstruction is important (and challenging in presence of pileup)

- Exploit spin 0 kinematics
- Use transverse mass as main discriminating variable

$$M_T^2 = (E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}})^2$$

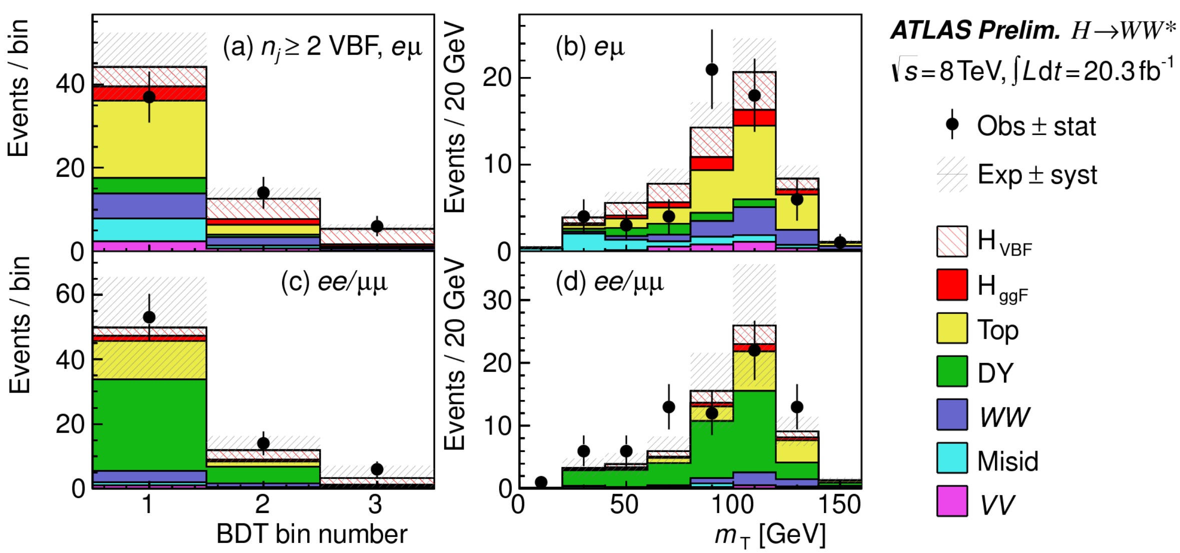
$$(E_T^{\ell\ell})^2 = (\vec{p}_T^{\ell\ell})^2 + (m_{\ell\ell})^2$$

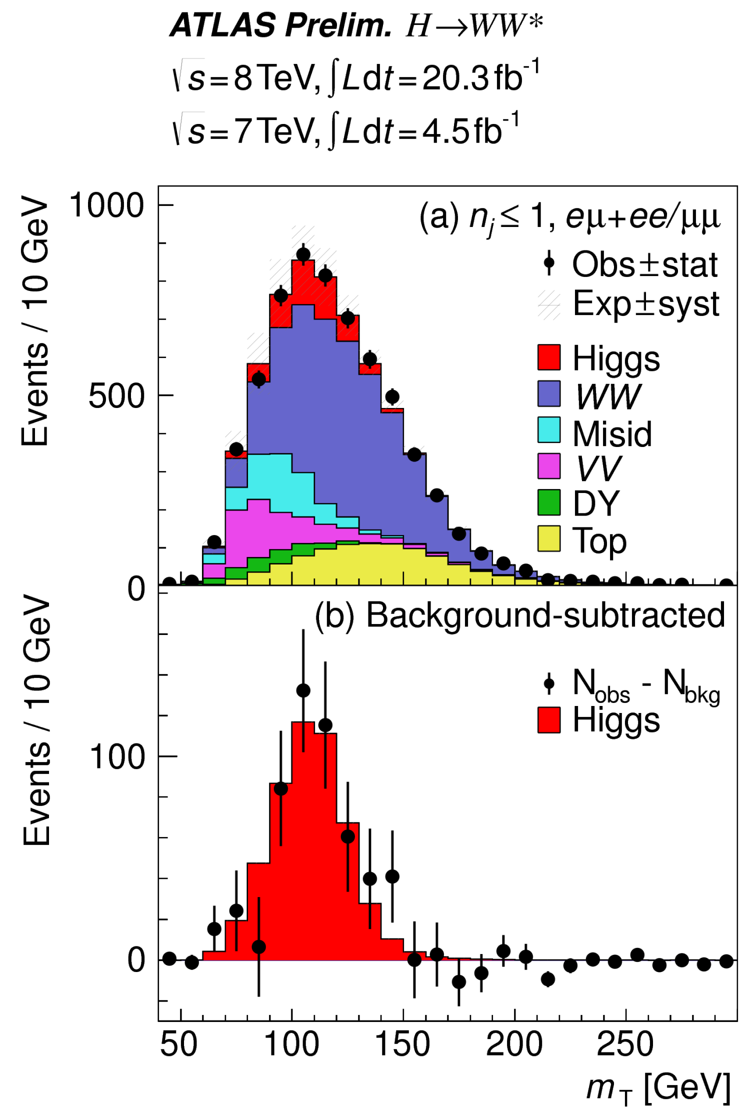
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

Results:

- Observed (expected) significance: 6.1σ (5.8σ)
- Observed (expected) significance for VBF: 3.2σ (2.7σ)

Combined WW → lνlν signal strength
$\mu = 1.08^{+0.16}_{-0.15}\,(\text{stat.})^{+0.16}_{-0.13}\,(\text{syst.})$

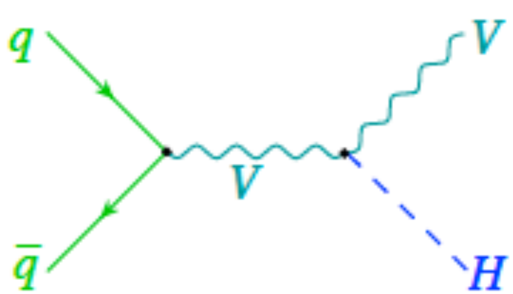


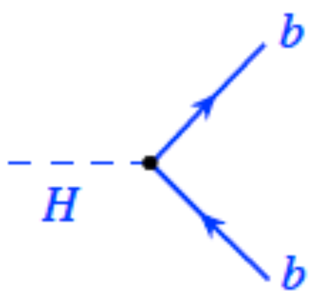


H decays to fermions
$b\bar{b}$, $\tau\bar{\tau}$

H → $b\bar{b}$

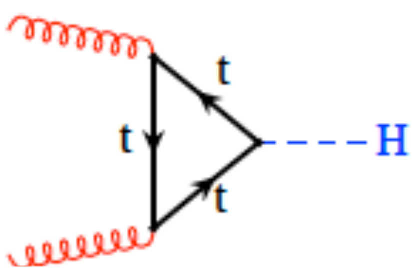
- Production depends (mainly) on coupling to W/Z bosons
- Decay depends on coupling to b quark (down-type quark coupling)
- Small production cross section (but branching ratio is the largest)
- A challenging final state:
  - Very large backgrounds (W/Z+jets)
  - Higgs mass resolution is not that good (two jets compared to two photons)
  - Requires good b-tagging efficiency and fake rejection

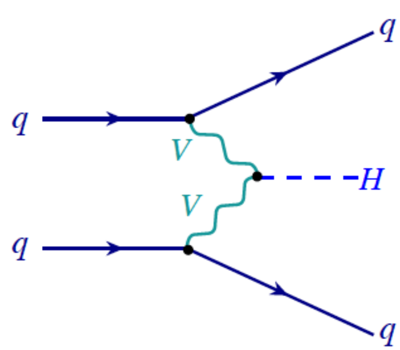


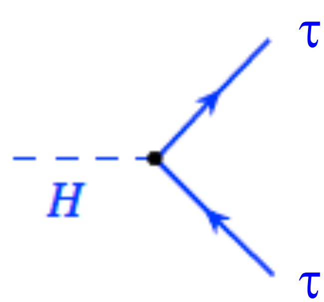


$H \rightarrow \tau\bar{\tau}$

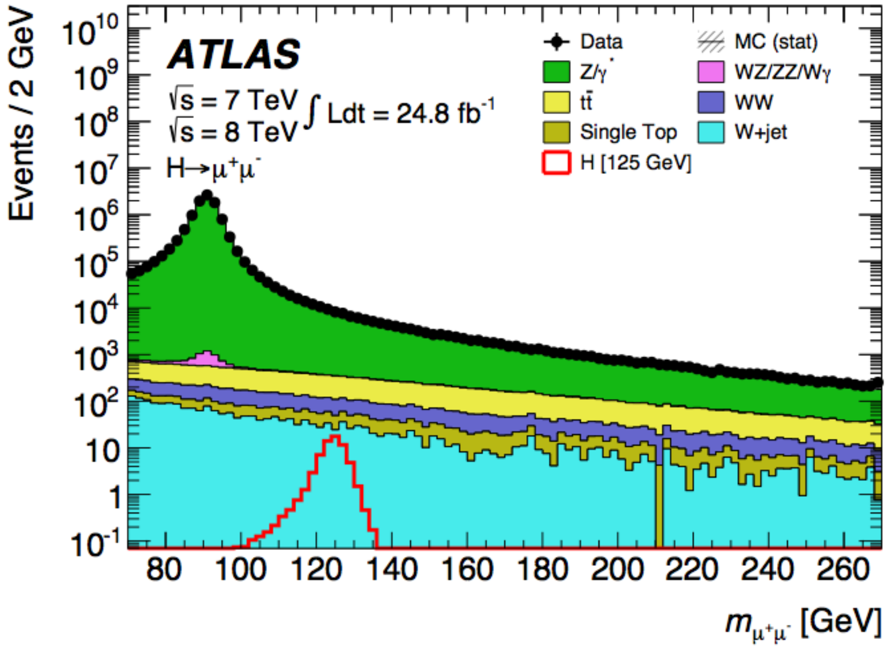
- Production depends on coupling to top quark (in SM) and WBF+ VH production (coupling to Z/W bosons)
- Decay depends on coupling to taus (coupling to leptons)
- Cross section times branching ratio is relatively high
- Challenging final state:
  - Large backgrounds
  - Sensitive to pileup, was an extra challenge in 2012







Rare Decays



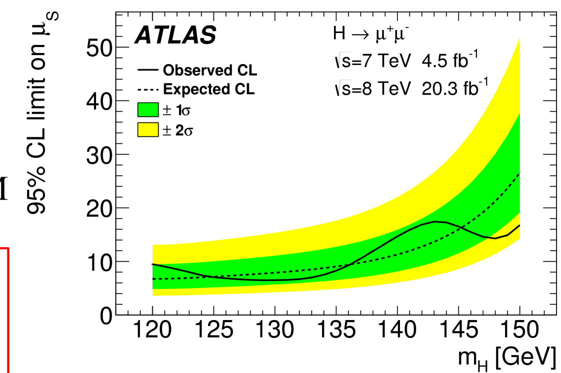
$\mu^+\mu^-$ Analysis strategy

- 2 analysis channels (ggF and VBF)
- Analytic background model (similarly to γγ)

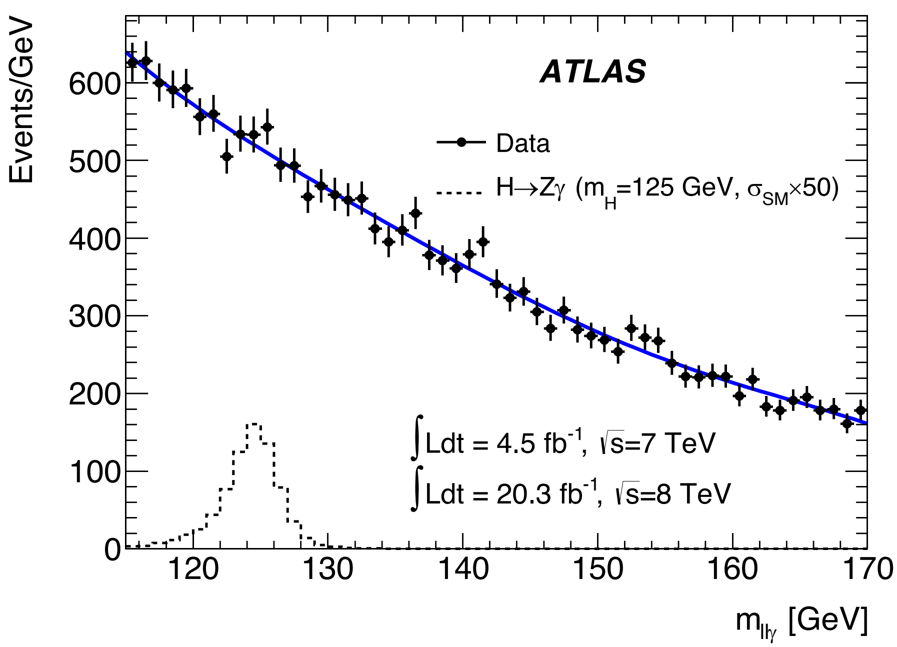
Results at 95% CL:

$\sigma.Br < 7.0\ (7.2)(\sigma.Br)_{SM}$

Universal couplings
~260 times SM



Accepted by PLB



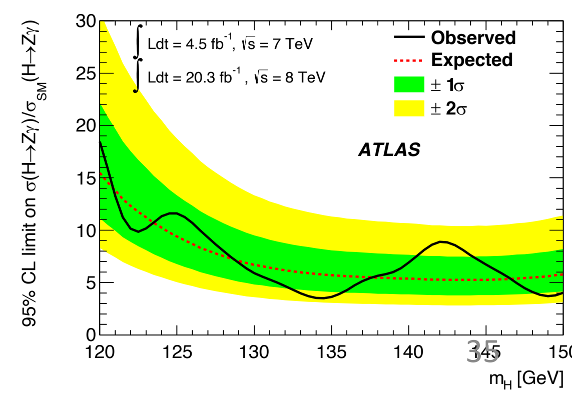
$Z\gamma$ Analysis strategy

PLB 732 (2014)

- Detector and pT Categories
- Analytic background model (similarly to γγ)

Results at 95% CL:

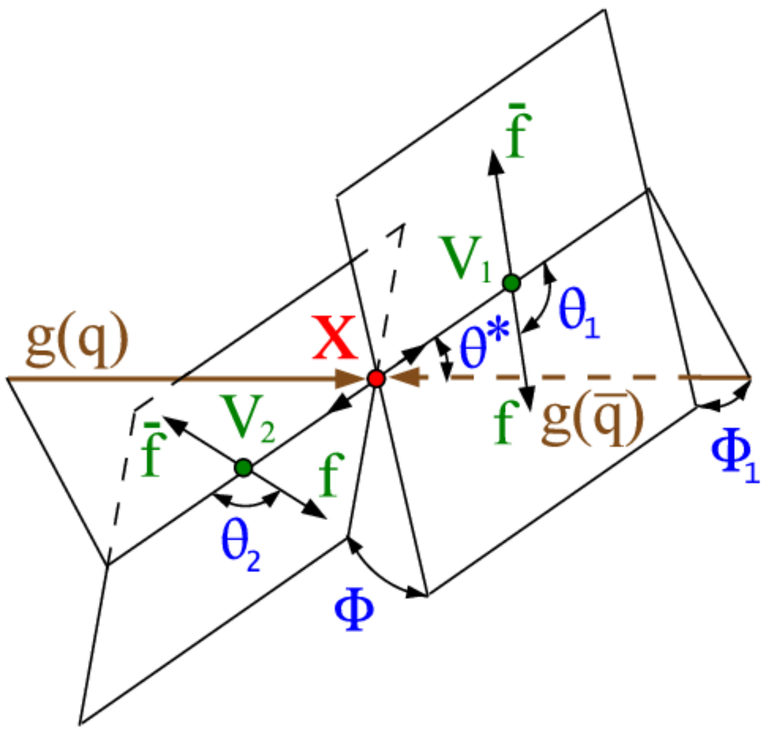
$\sigma.Br < 11\ (9)(\sigma.Br)_{SM}$



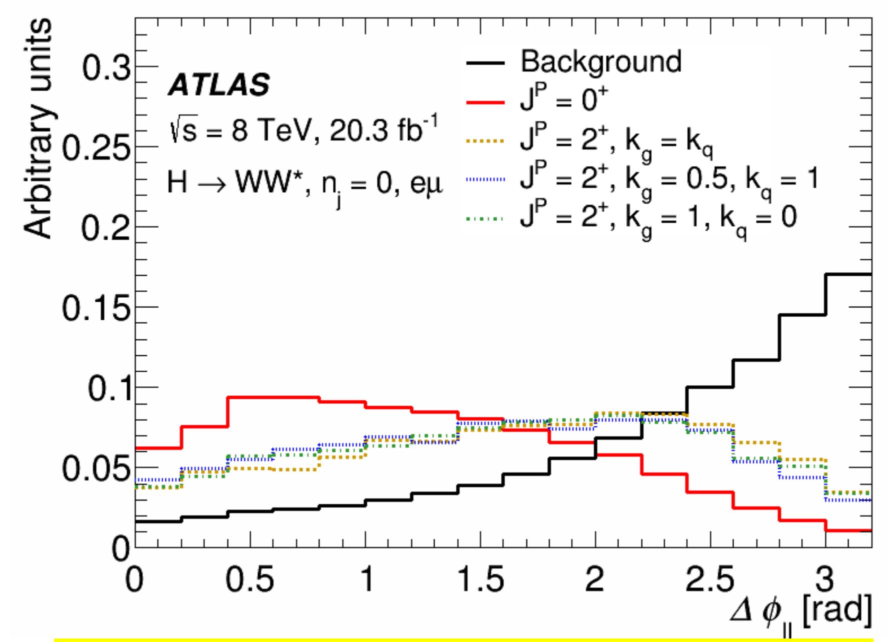
Spin/CP Hypotheses Tests

Tests of spin/CP properties performed in ZZ, $\gamma\gamma$, WW channels

ZZ: full kinematic information available for spin/CP determination

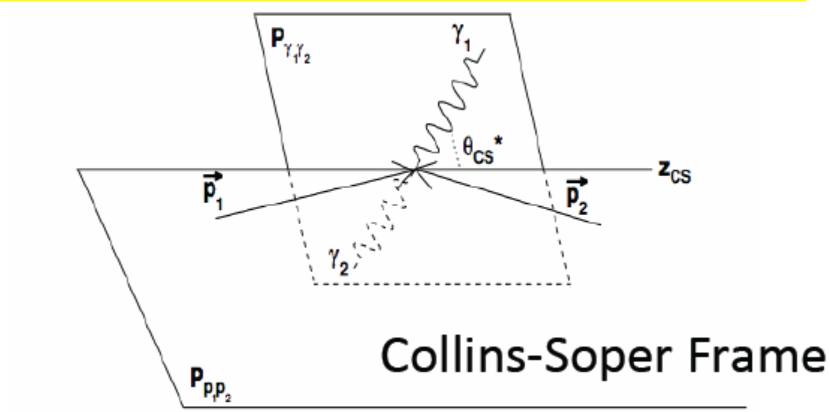


WW spin information from kinematic variables



$\gamma\gamma$: use $\cos(\theta^*)$ in Collins-Soper frame

$\gamma\gamma$



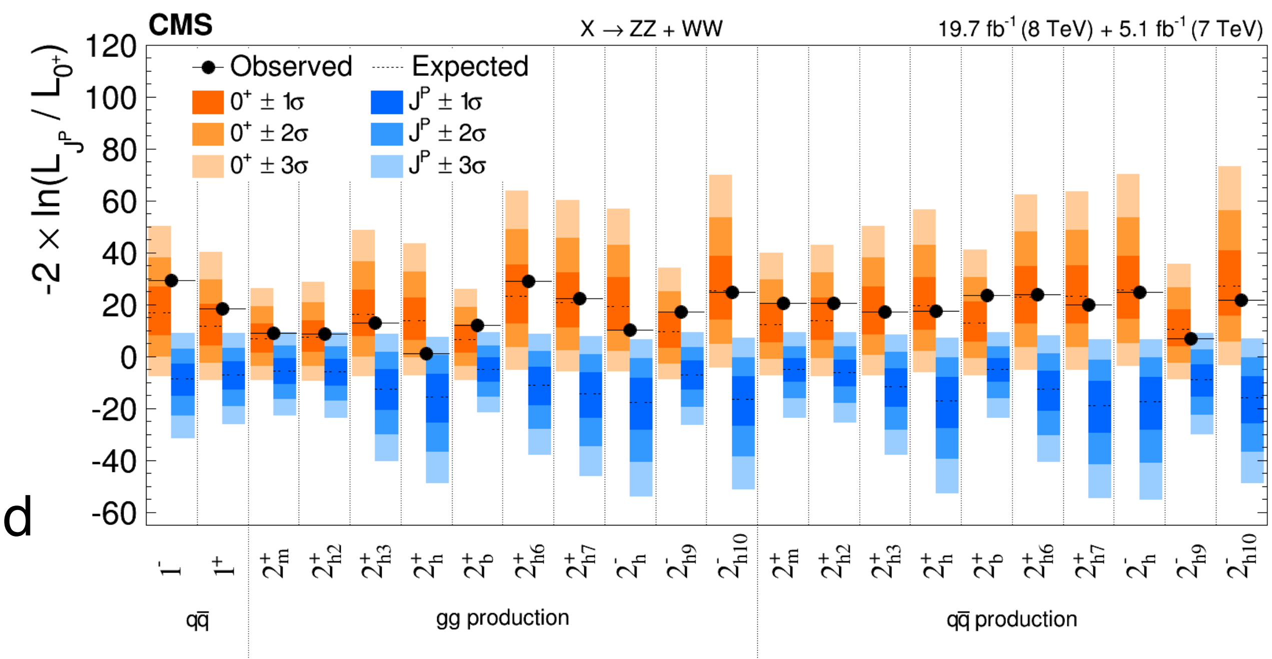
Spin and Parity Tests

- Probe deviations from SM of decay kinematics

- Results favour the spin 0^+ hypothesis and almost all spin 1 and 2 variants excluded at > 95%

- 0^- hypothesis also excluded at > 95% CL by both experiments

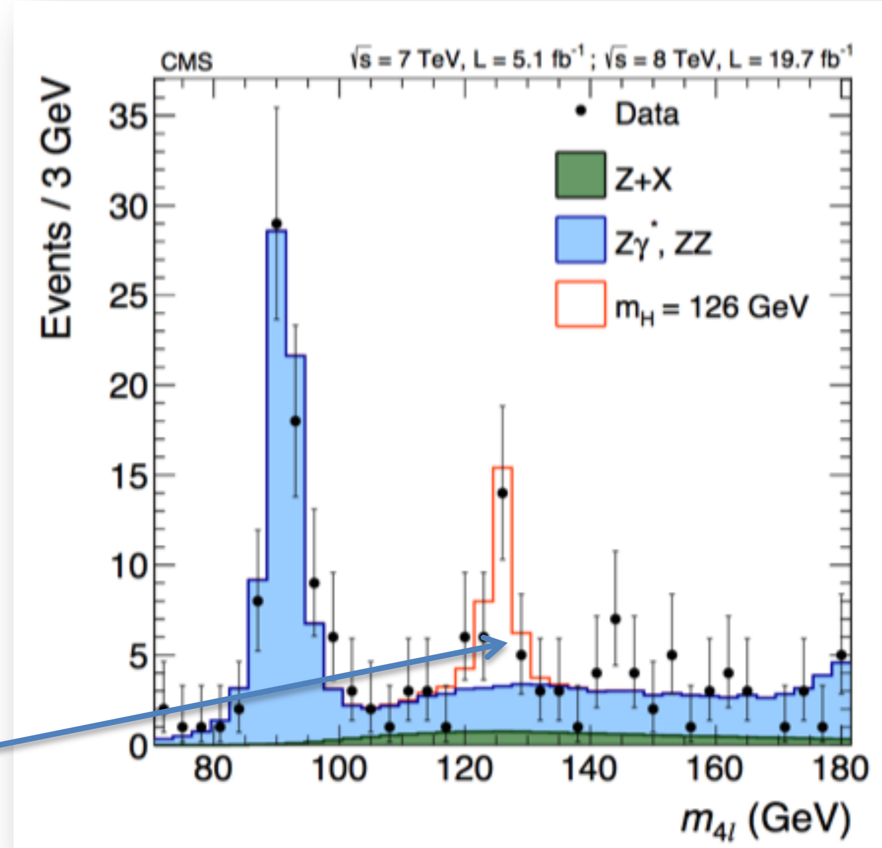
Also Tevatron results: **arXiv:1502.00967**



Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

From Signal Yields to Couplings

- We measure event yields n_{evt}
- We need to extract signal yields
  - Need to evaluate and subtract backgrounds $n_s = n_{evt} - n_{bkg}$
- We can extract the signal strength μ corresponding to the ratio of the observed yield to the SM prediction:

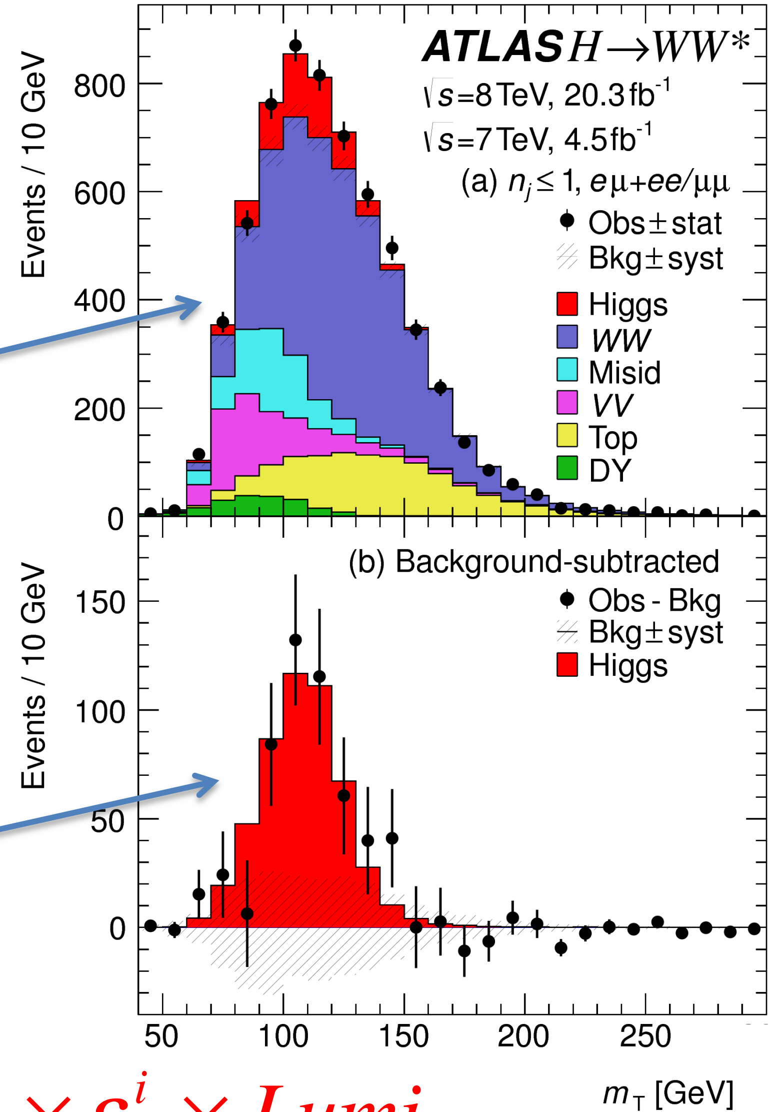


$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \qquad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

From Signal Yields to Couplings

- We measure event yields n_{evt}
- We need to extract signal yields
  - Need to evaluate and subtract backgrounds $n_s = n_{evt} - n_{bkg}$
  - Assume only SM backgrounds
- We can extract the signal strength μ corresponding to the ratio of the observed yield to the SM prediction



$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

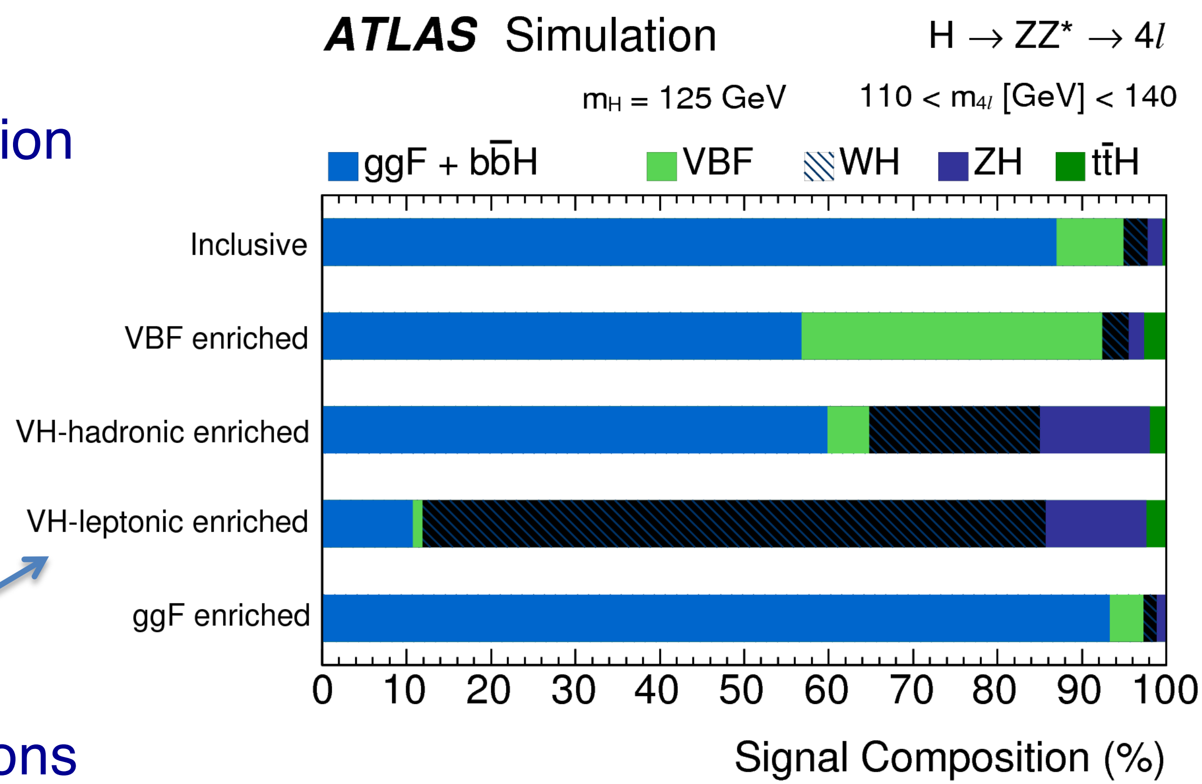
$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

From Signal Yields to Couplings

- We measure the signal strength using selections aimed at “tagging” production modes

- These tags or categories are contaminated by other production processes

- Global fit to all categories can take into account all contributions and correlations

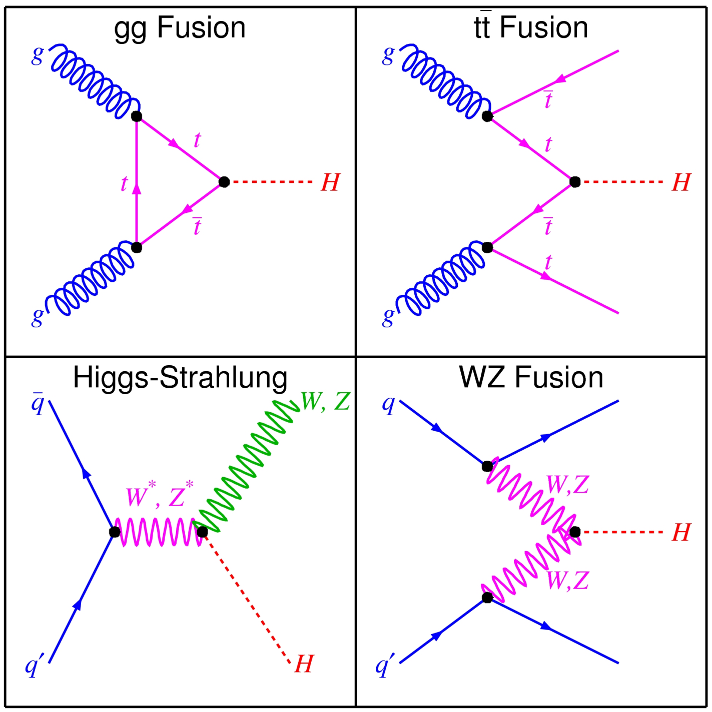


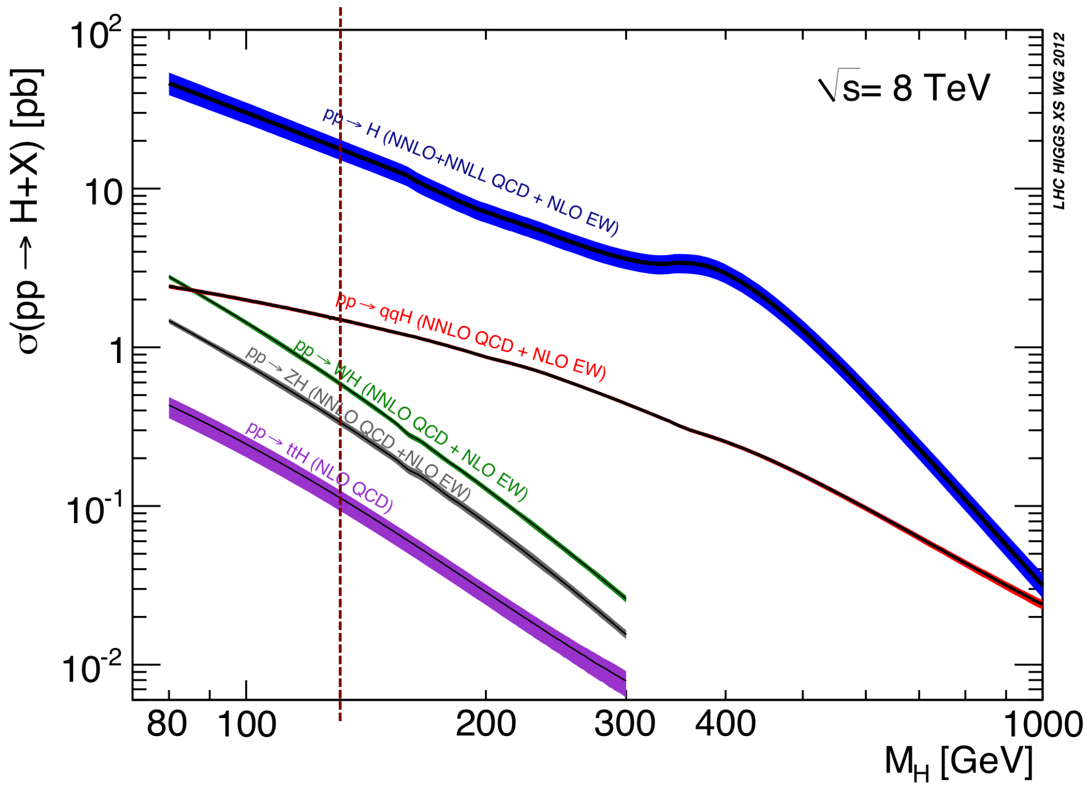
$$n_s^{c,i} = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

SM Higgs Producton

Analyses target the main 5 production modes in various final states





$$n_s^{c,i} = \sum_p \left[\mu^p \mu_{BR}^i\right] \times (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

Note that we fit to the product of production and decay signal strengths

Couplings Framework

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\overline{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\overline{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\overline{f} \right) H$$

•"κ framework": signal strength parameters (μ_p, μ^i_{BR}) are further interpreted in terms of modifiers to the SM couplings:

•Decay: $\Gamma_i = \kappa_i^2\ \Gamma_i^{SM}$

•Production: $\sigma_i = \kappa_i^2\ \sigma_i^{SM}$

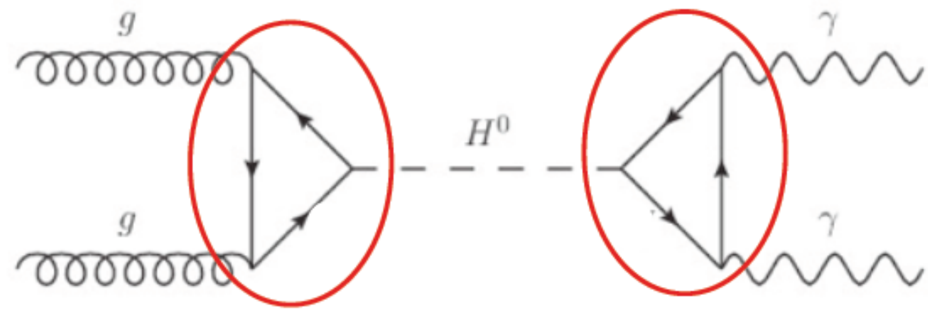
•Width: $\Gamma_H = \Sigma_i\, \kappa_i^2\ \Gamma_i^{SM}$

Assumptions (see LHCXSWG YR3):

- Only one Higgs
- SM production and decay kinematics
  - Tensor structure is that of SM
  - 0+ scalar
- Narrow resonance

Couplings Framework

- Loops and interference:



- Encoded in effective couplings κ_γ, κ_g

Example: gg -> H -> γγ

$$\frac{(\sigma \cdot \mathrm{BR})(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- In terms of SM coupling modifiers:

$$\kappa_g^2(\kappa_t, \kappa_b) = 1.06 \cdot \kappa_t^2 - 0.07 \cdot \kappa_t \kappa_b + 0.01 \cdot \kappa_b^2$$

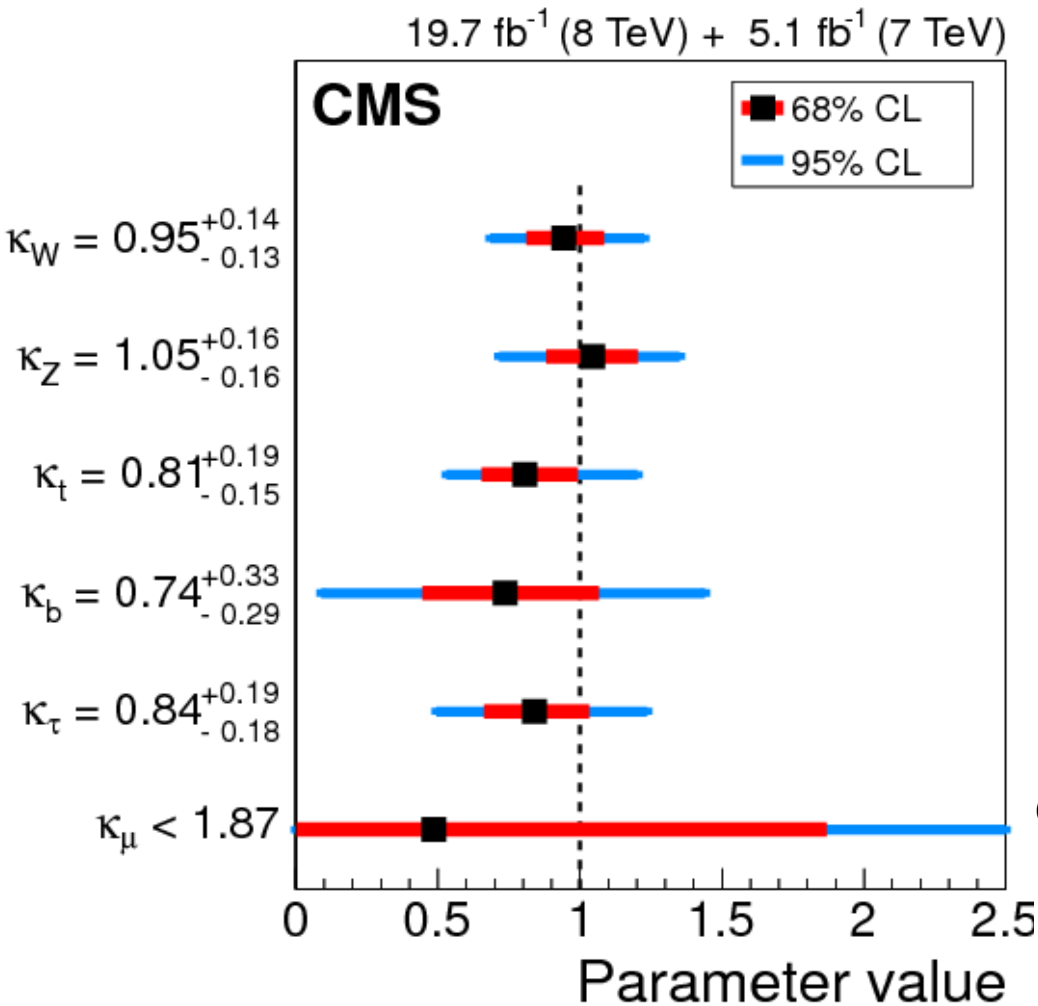
$$\kappa_\gamma^2(\kappa_F, \kappa_V) = 1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$$

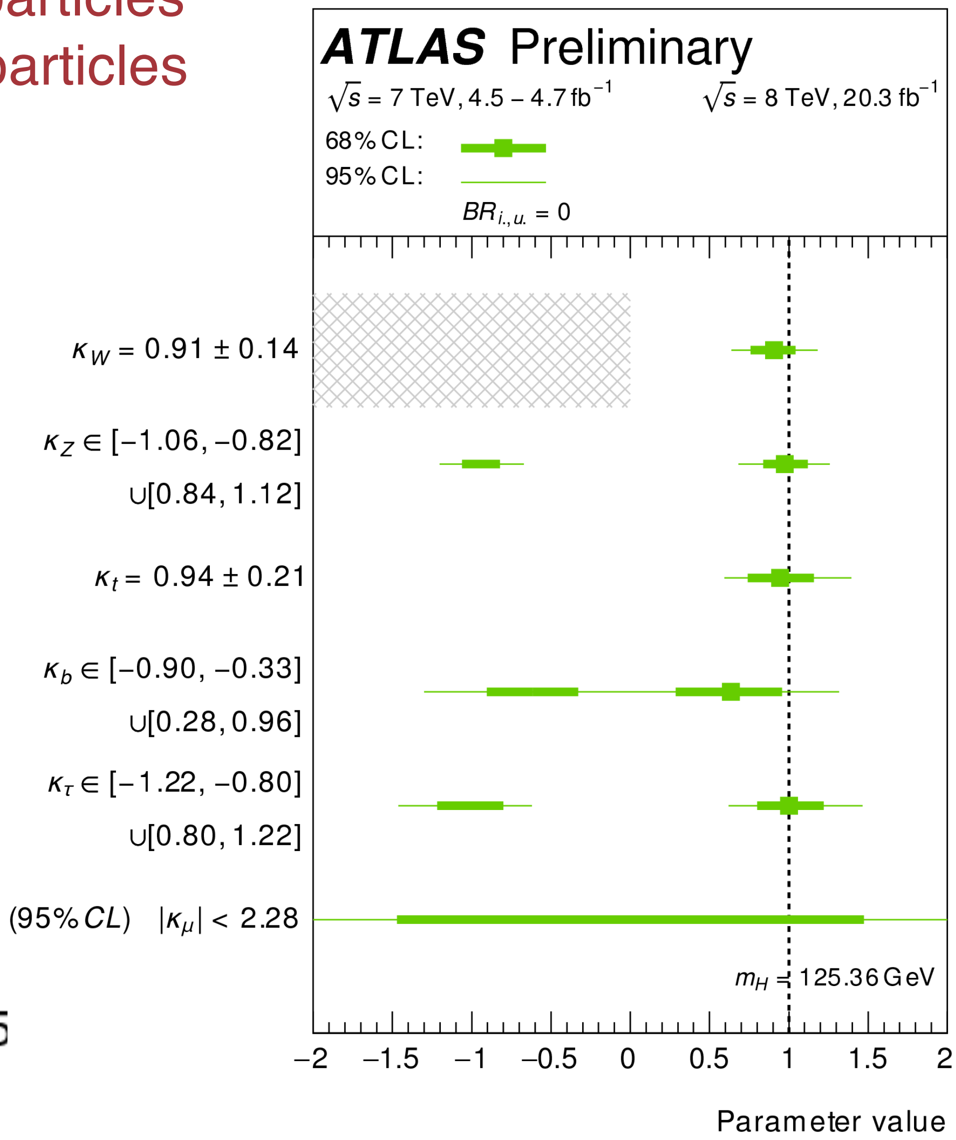
- BSM coloured or charged particles in loops could cause deviations

Couplings with SM Particle content

"Absolute couplings". Assumptions:

- No contributions to width from BSM particles
- No contributions to loops from BSM particles

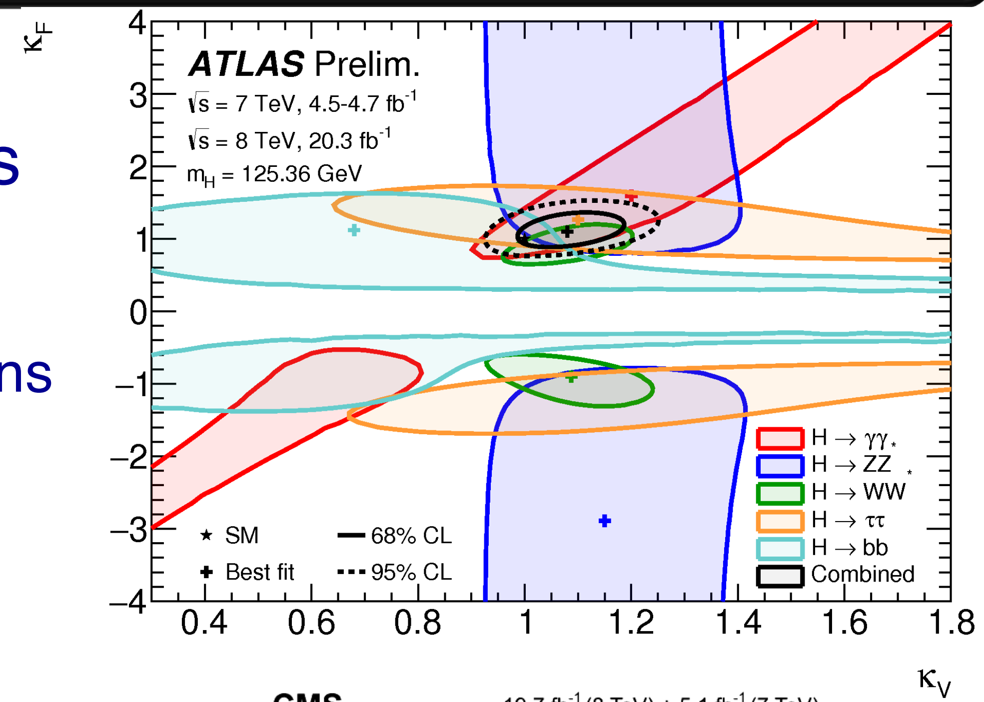


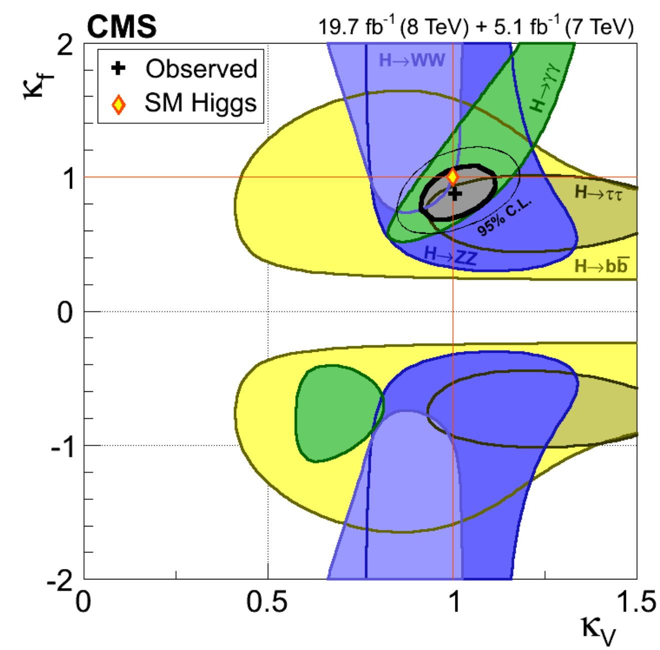


Coupling to Fermions and Bosons

Test gauge vs Yukawa couplings

- Assumptions:
  - Common scaling factor for fermions and gauge bosons:
    - κ_F and κ_V
  - No BSM contributions to width
  - No BSM contributions to loops
- Interference in gg, tH, gg->ZH can resolve relative sign between κ_F and κ_V
- Results compatible with SM





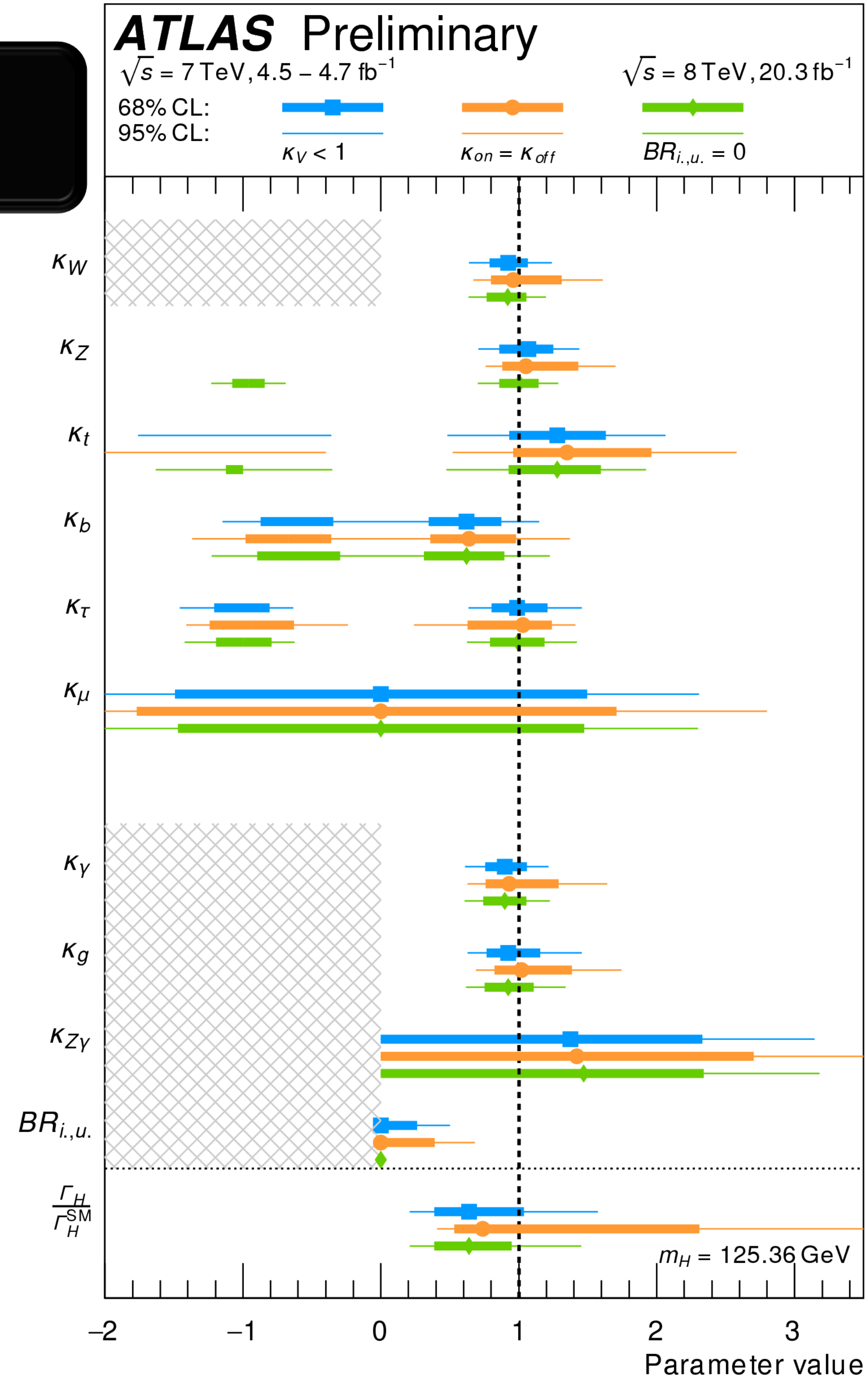
New Physics in the Loops?

Relax assumptions on SM couplings of known particles and consider various scenarios:

- •Blue squares: models with Higgs singlets or doublets κ_V <=1. Impose this constraint on gauge couplings in the fit

- •Orange circles: add off-shell measurements assuming on-shell couplings equal to off-shell couplings

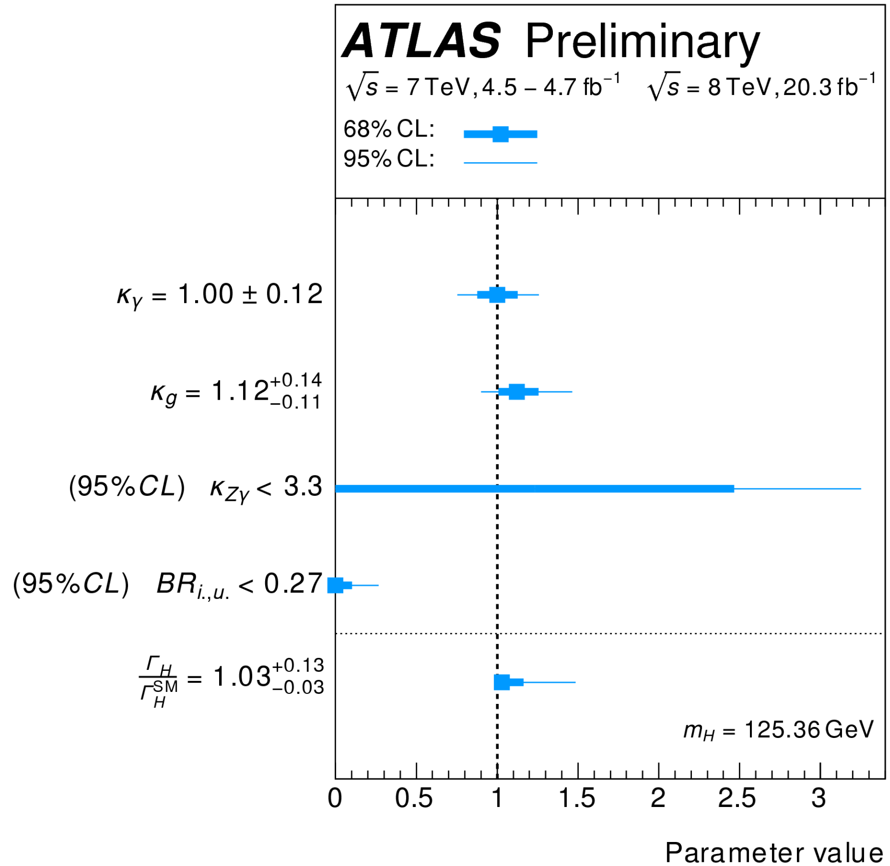
- •Green diamond: impose no contributions to the width from BSM particles

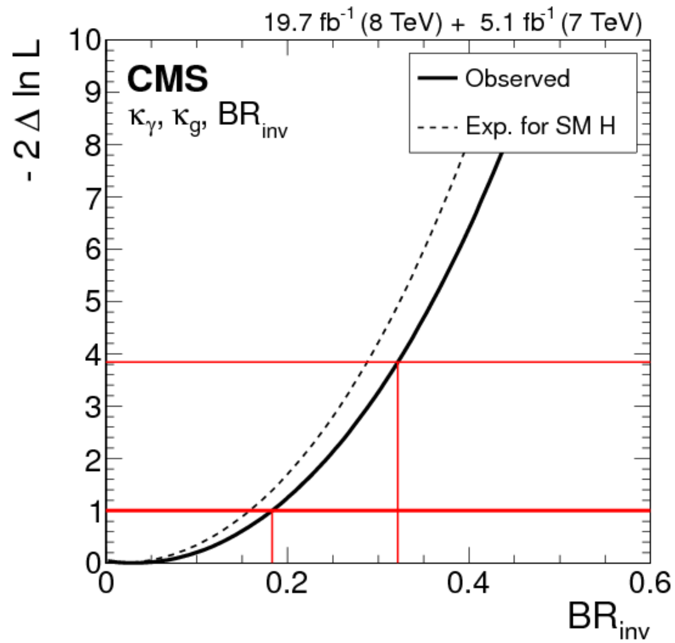


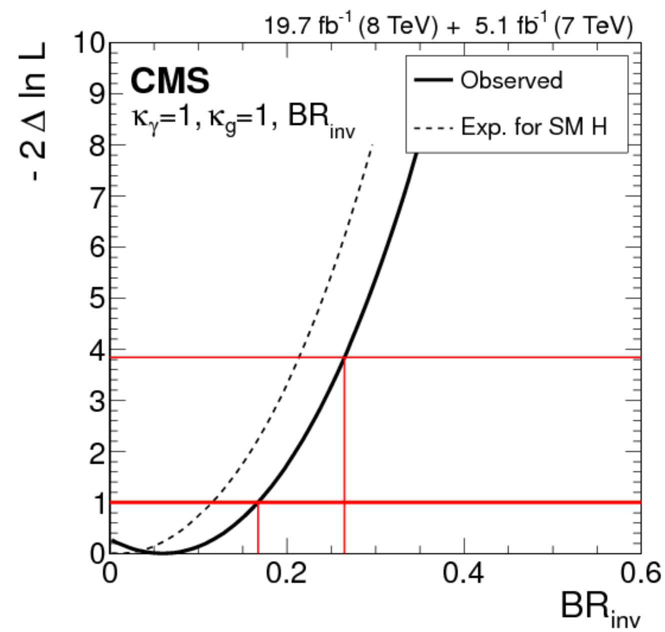
New Physics in the Loops?

Allow for contributions from BSM particles with mass < $m_H/2$

- Relax assumption on the width
- Bottom right: include direct limits

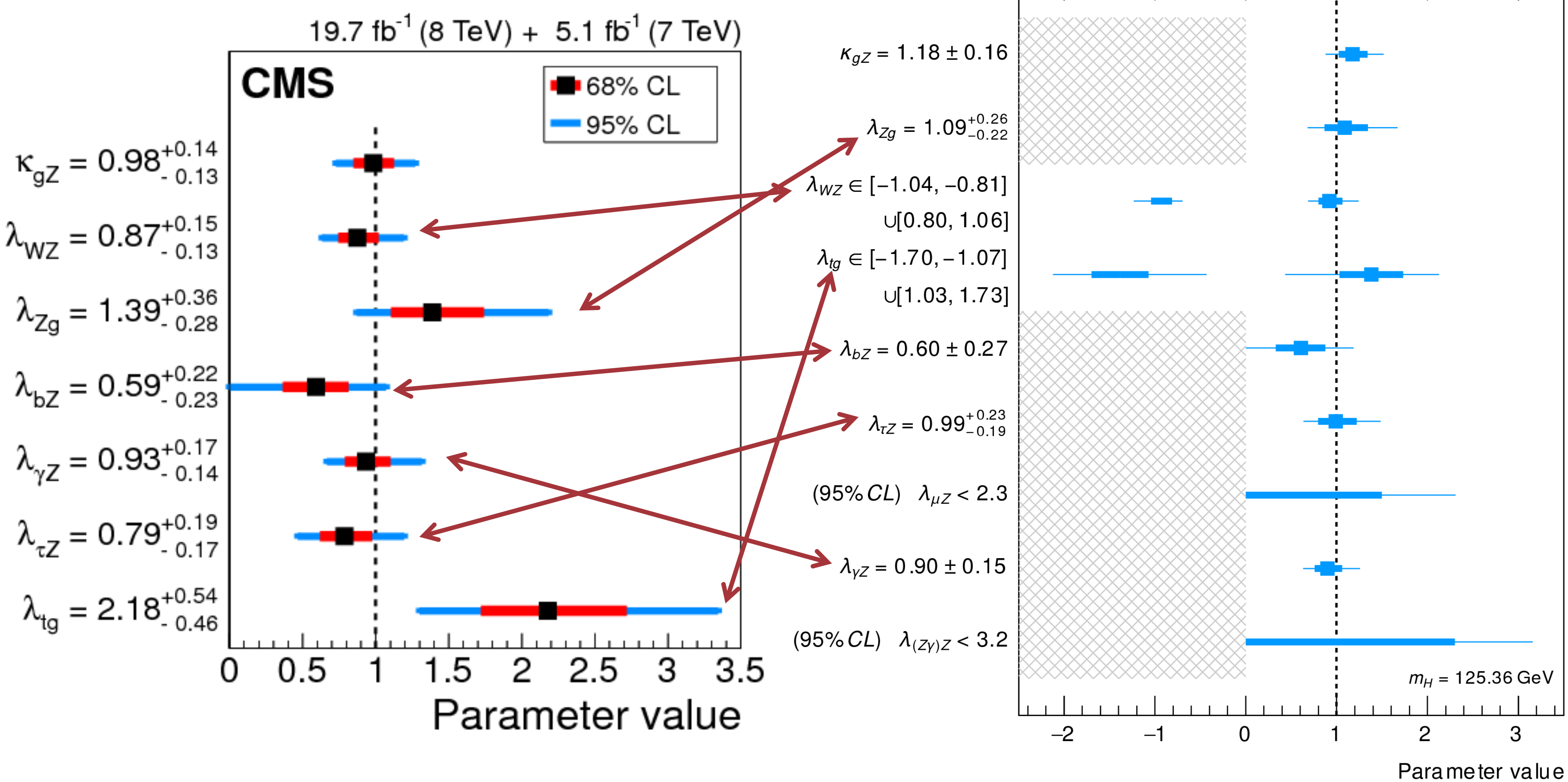






Most General Fit

- No assumptions on particle content in loops
- No assumptions on BSM decay or Higgs width
    - Drawback: can only fit ratios



Higgs Couplings and Mass

Couplings versus fermion mass or vector boson mass[2]