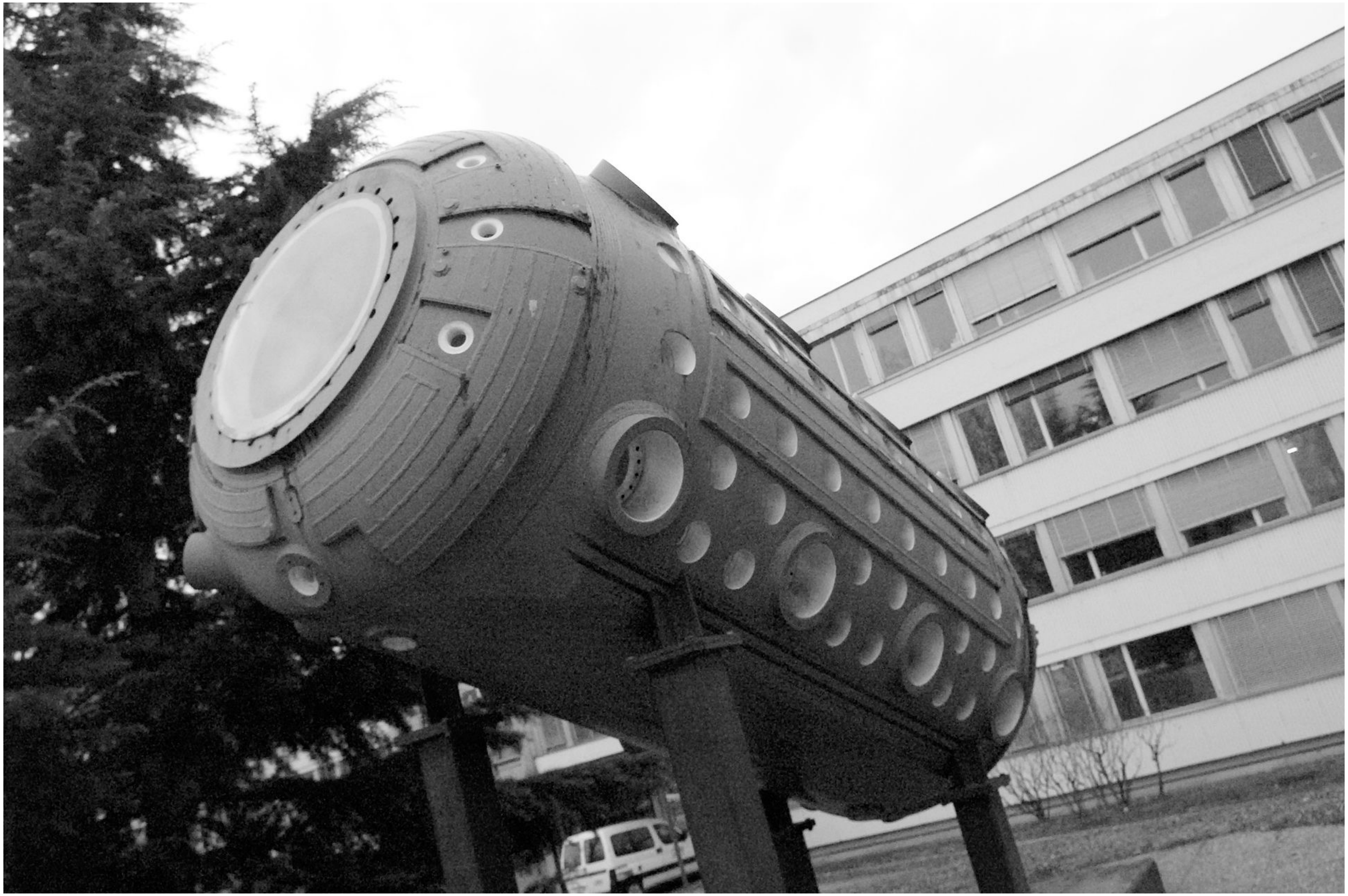
Observation of weak neutral currents

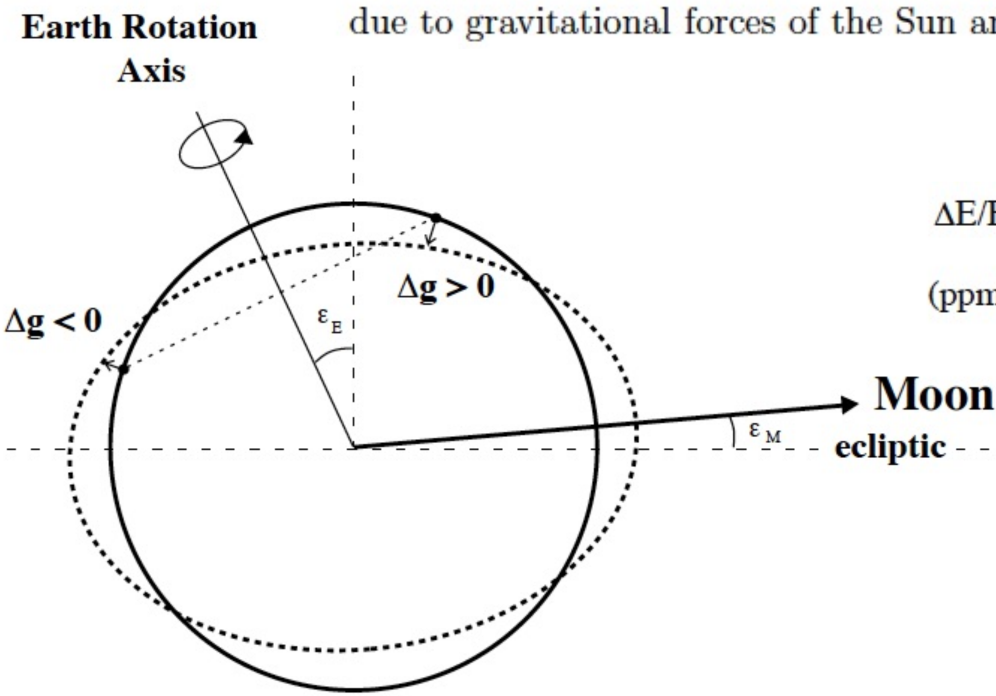
Gargamelle experiment:

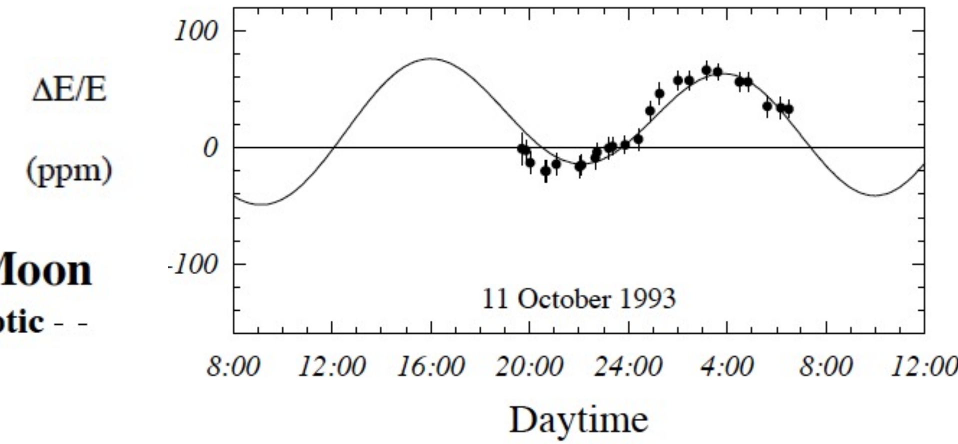


Mass of the Z Boson: $m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$

From the Particle Data Group

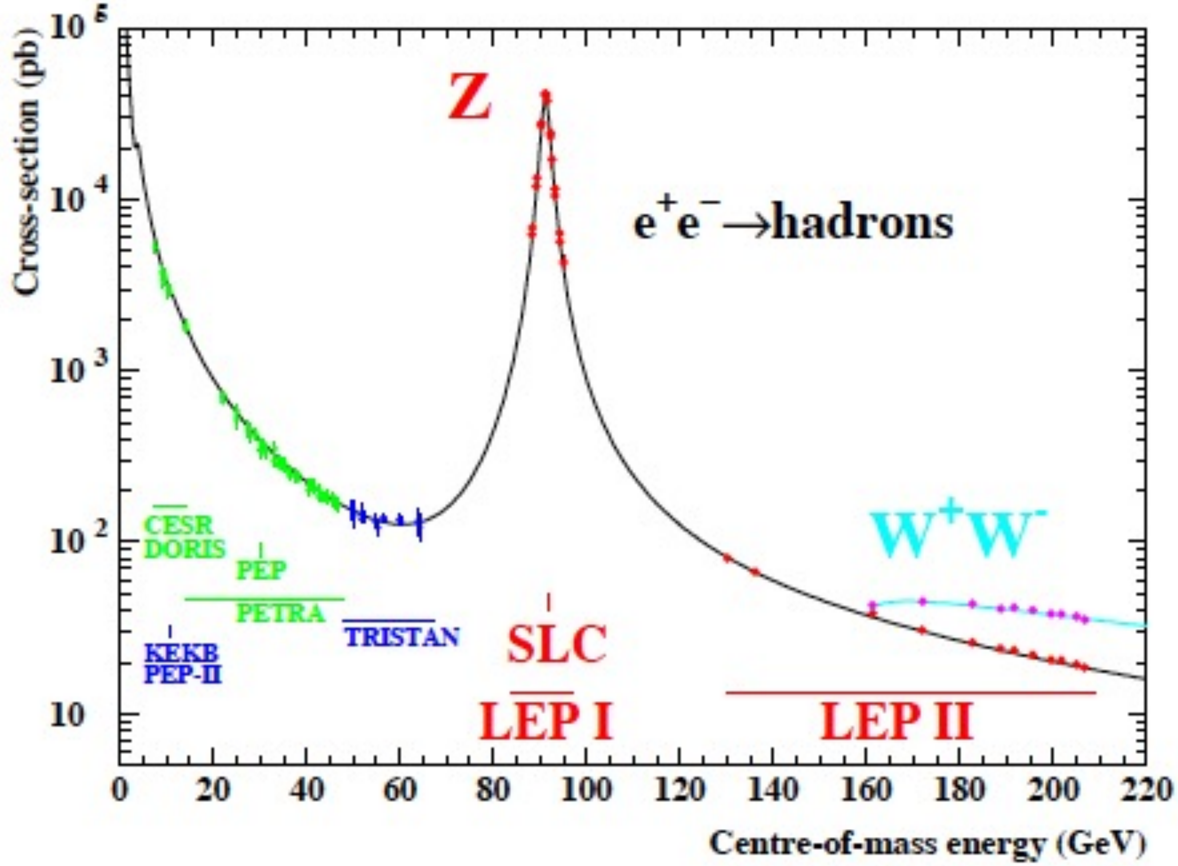
Precise energy calibration was done outside normal data-taking using the resonant depolarization technique. Run-time energies were determined every 10 minutes by measuring the relevant machine parameters and using a model which takes into account all the known effects, including leakage currents produced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



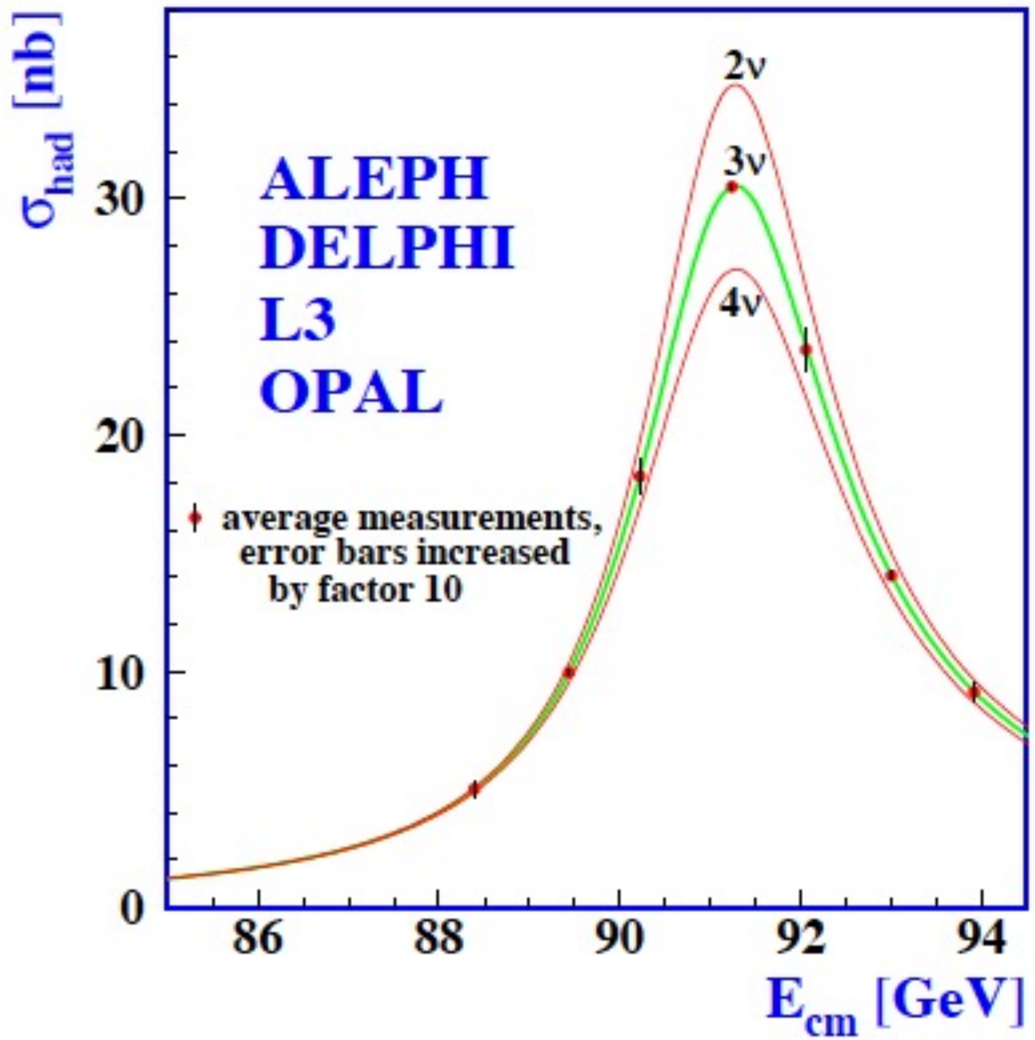


dependent gravity variation $\Delta g(t)$ is simpler to measure and to predict. Using estimates for the elastic properties of the Earth [10], the largest resulting strain is estimated to $\sim \pm 2 \cdot 10^{-8}$, which corresponds to a change of the 26.7 km LEP circumference of $\pm$ 0.5 mm. To a good

Z/γ* lineshape



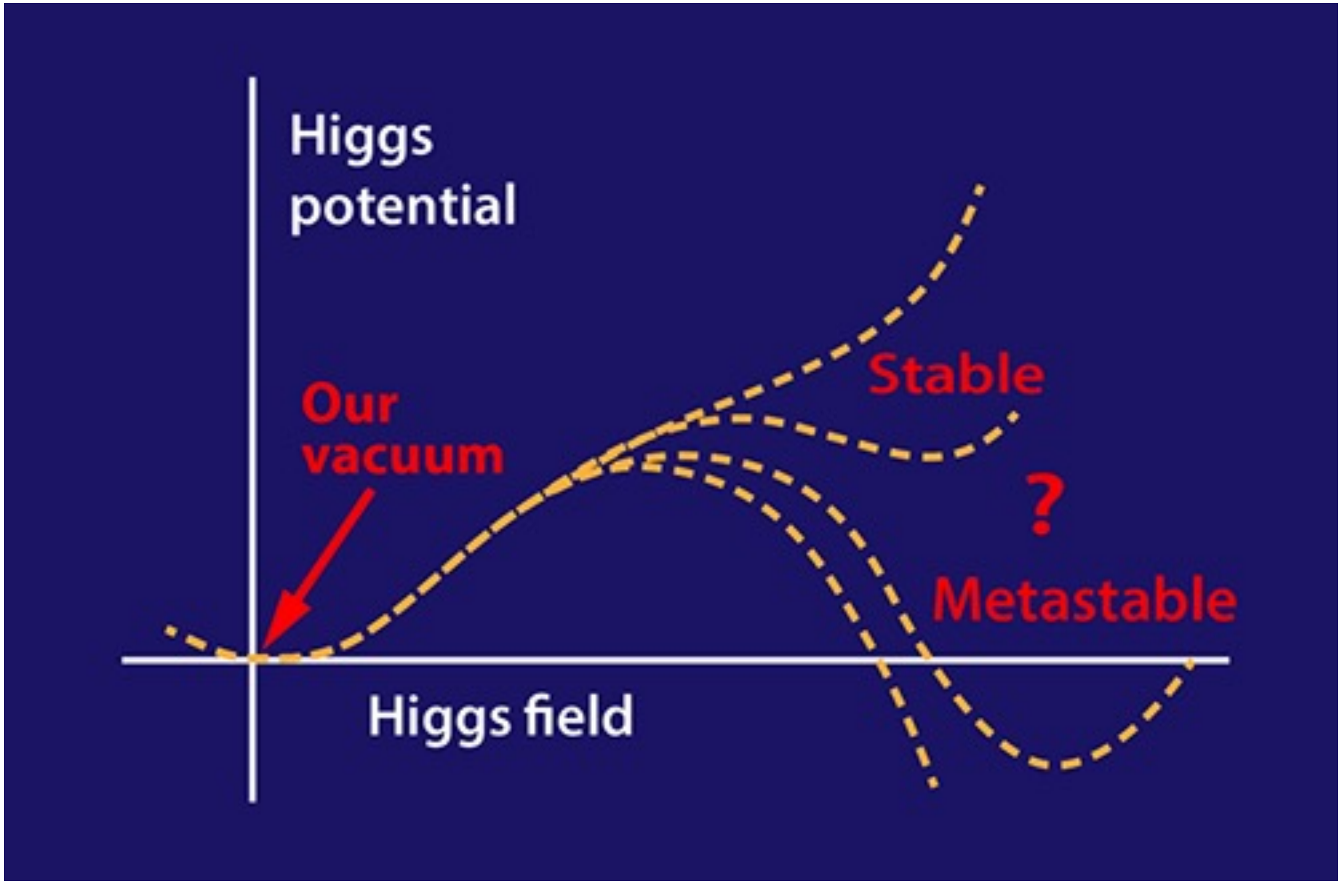
Neutrinos from Lineshape



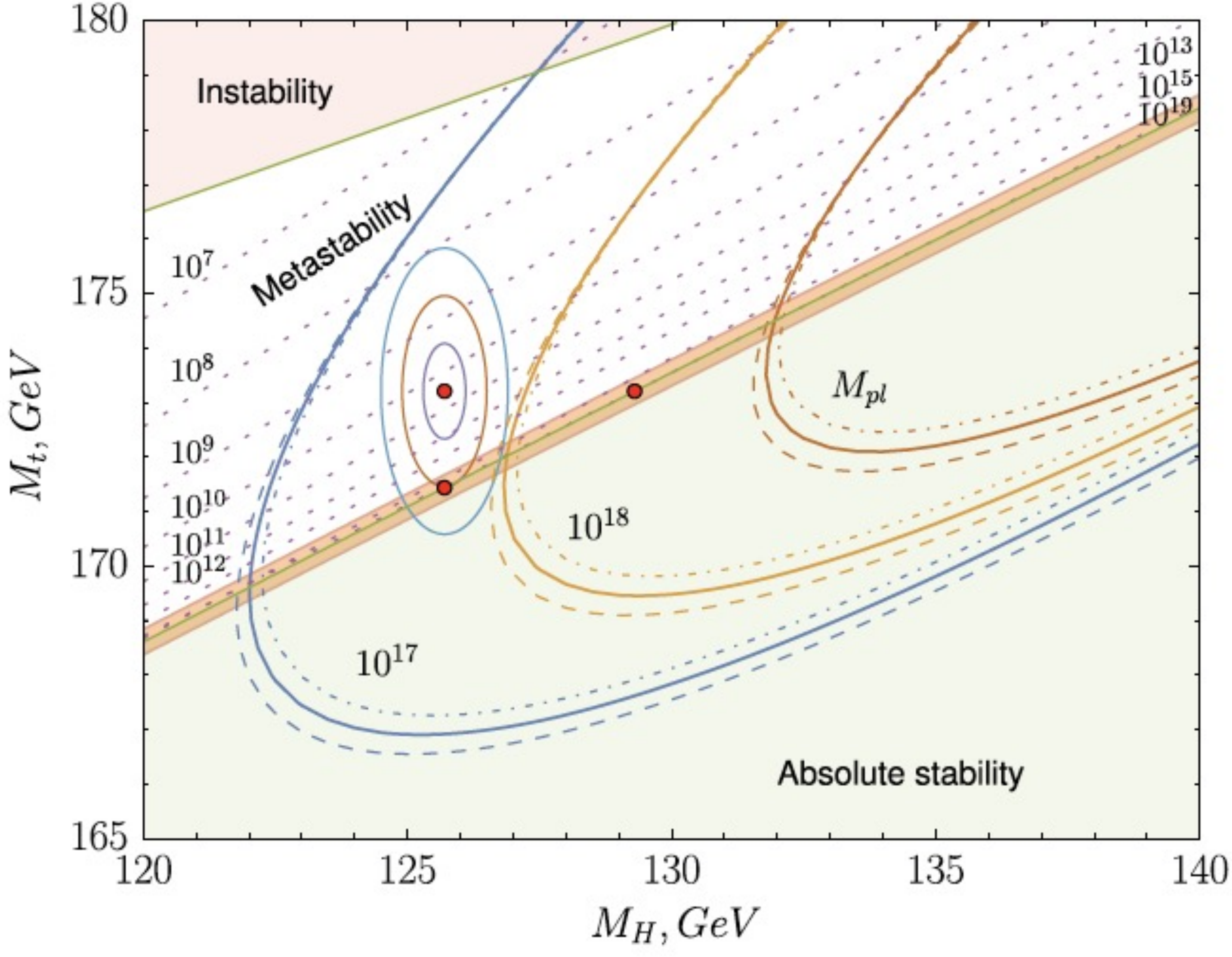
$$N_\nu = 2.9840 \pm 0.0082$$

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

Higgs and Vacuum Stability



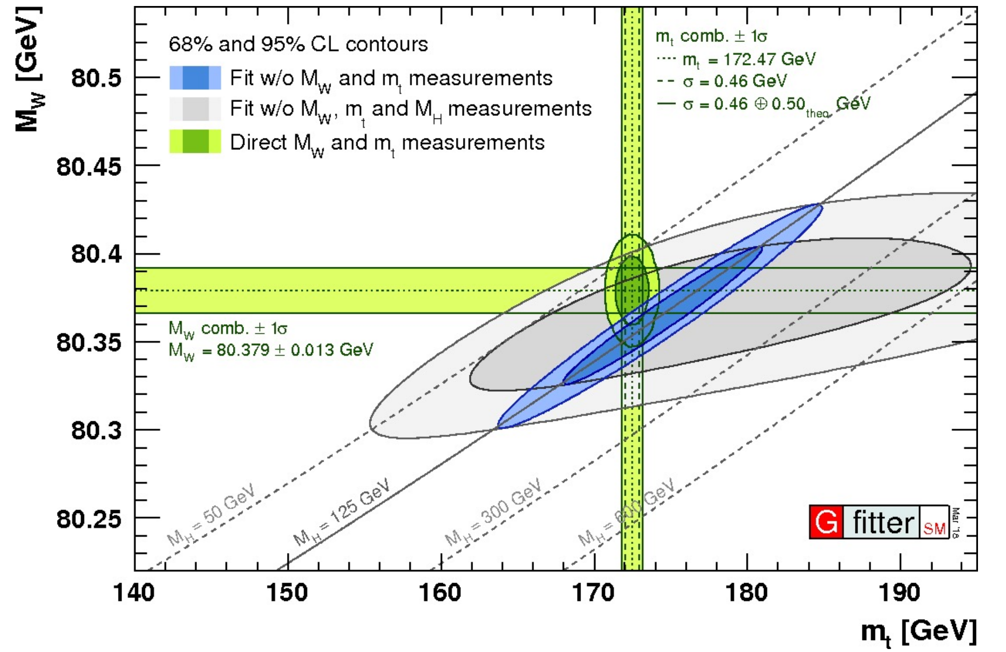
Higgs and Vacuum Stability



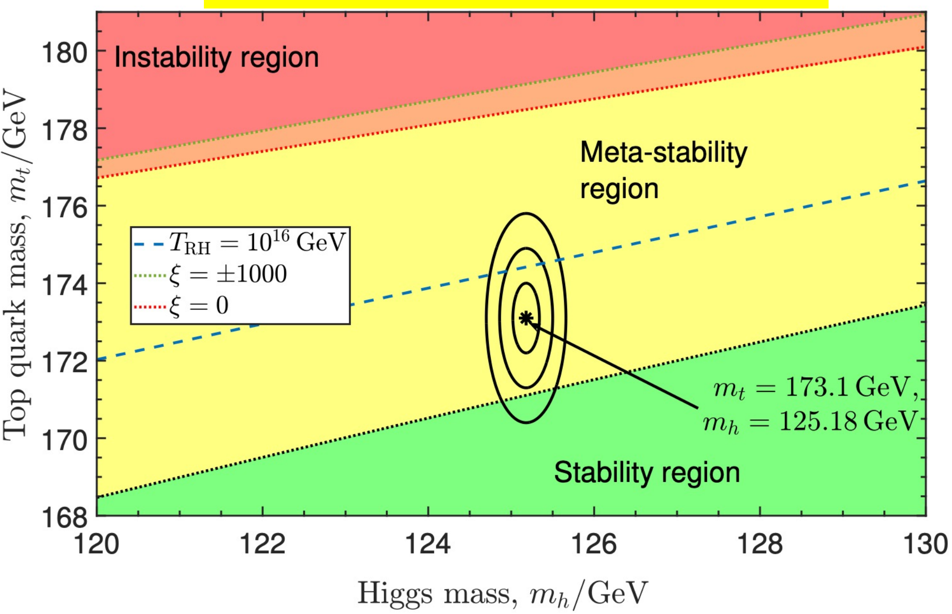
Precision Mass Measurements

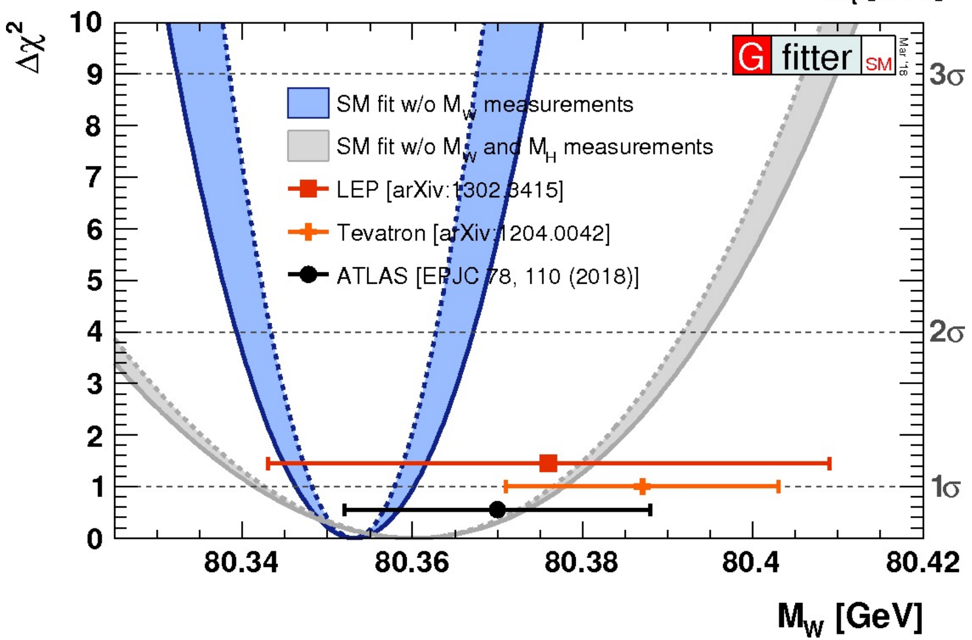
LHC experiments producing precision mass measurements of top quark, W boson, and Higgs boson

- Important self-consistency test of the Standard Model
- Contributions from BSM particles can impact SM particle masses



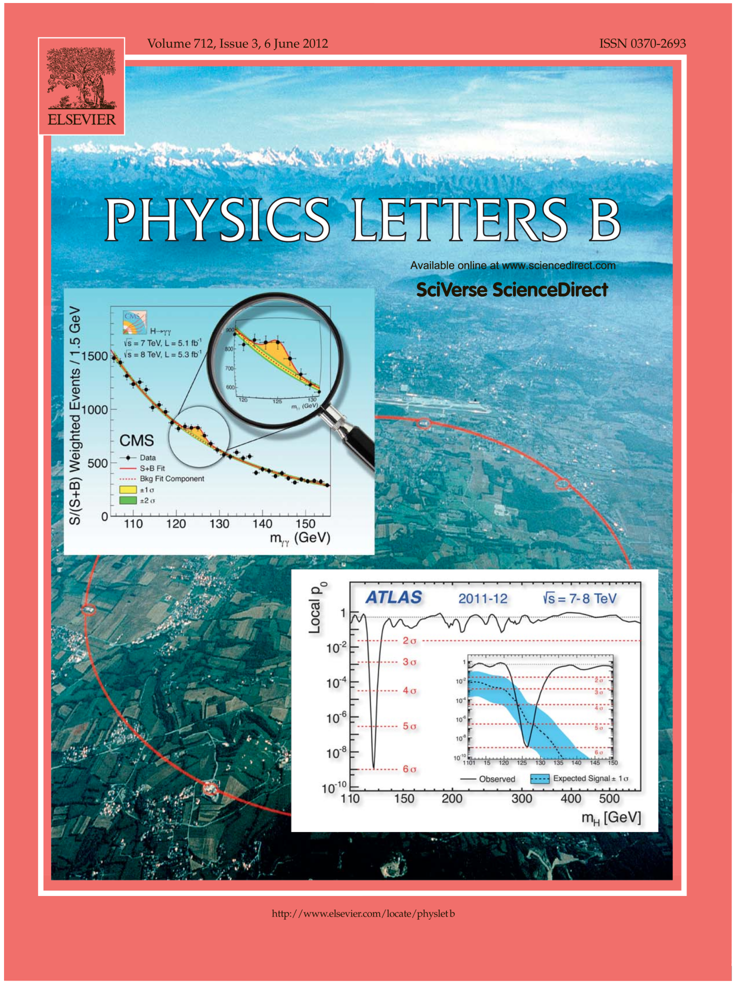
Front. Astron. Space Sci., 18 December 2018





July 2012 and July 2022

"Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC"

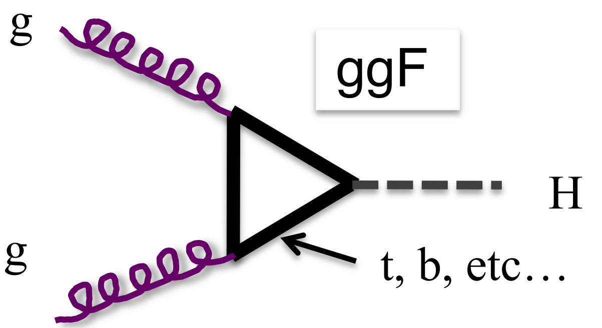


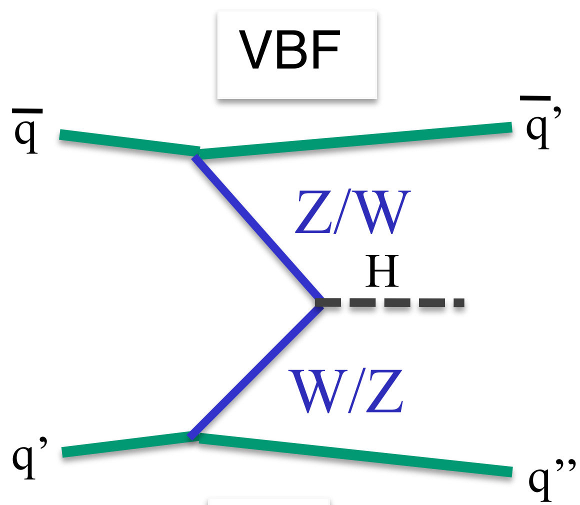
"A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery"

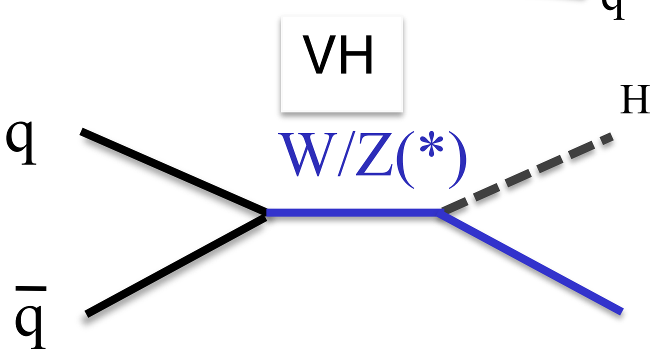
Higgs Boson Physics

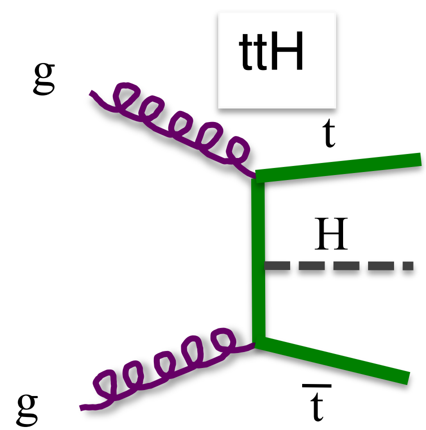
	process	8 TeV	13 TeV
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb
tH	Associated production	~20 fb	~90 fb

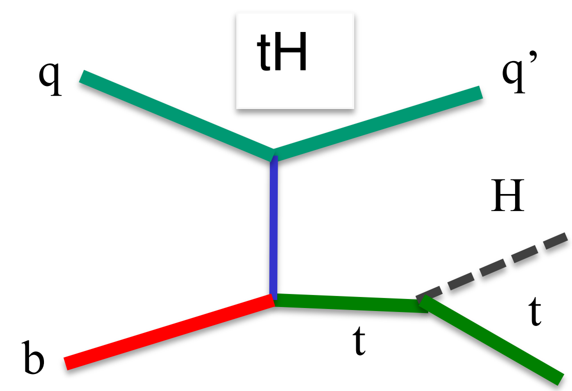
SM Production Modes
(M_H = 125 GeV)







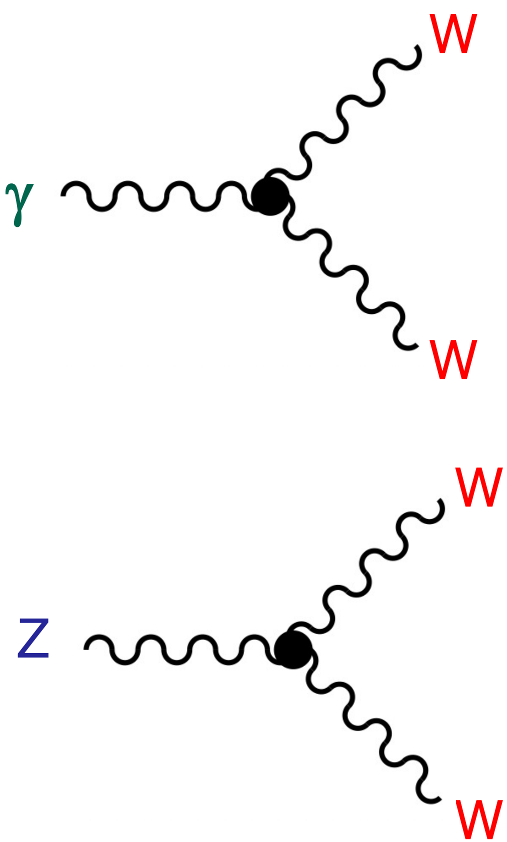




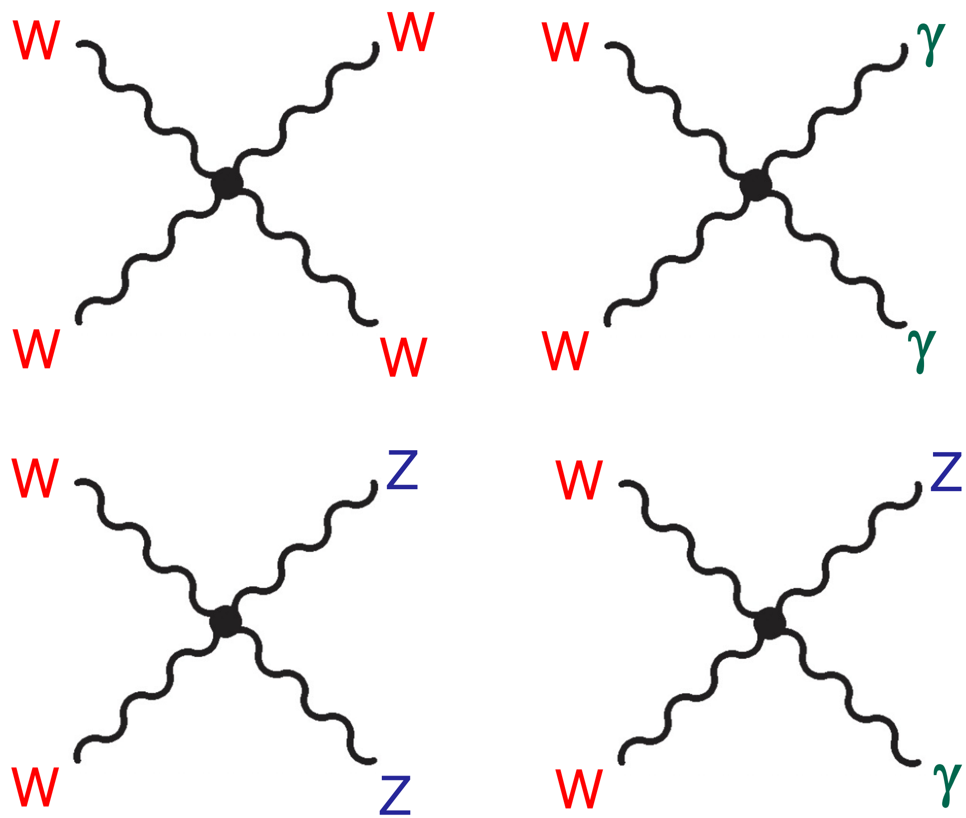
Testing the Electroweak Sector of the SM

With the Run 2 dataset, analyses can now probe final states where the electroweak quartic couplings of the SM contribute

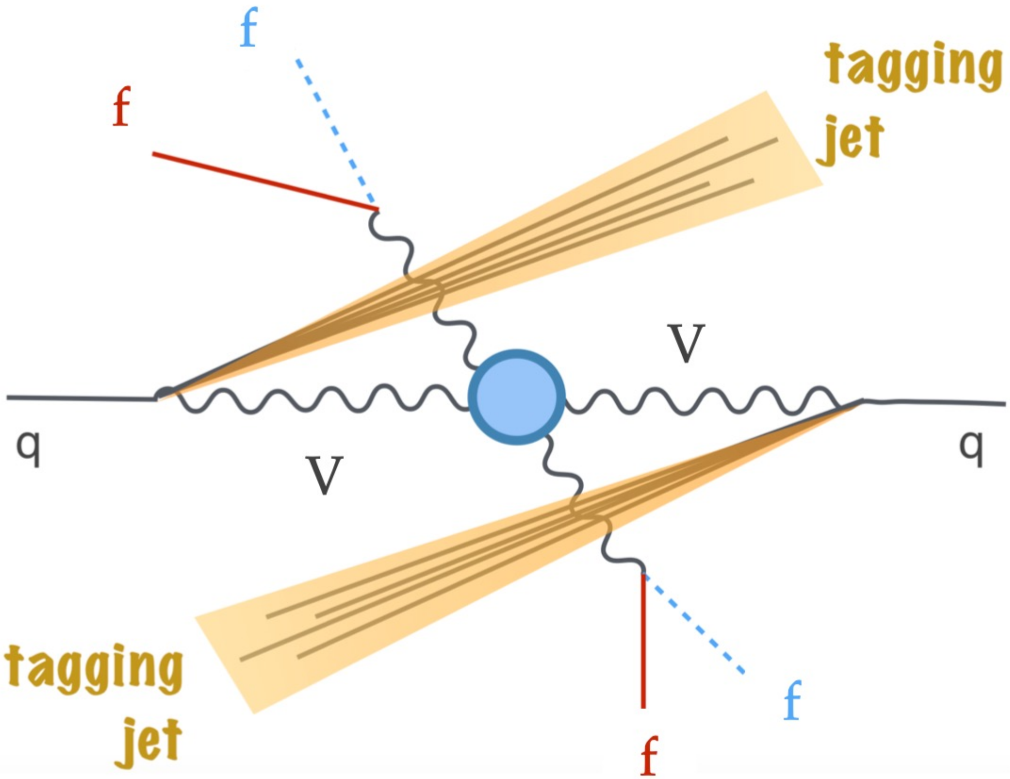
Cubic Couplings

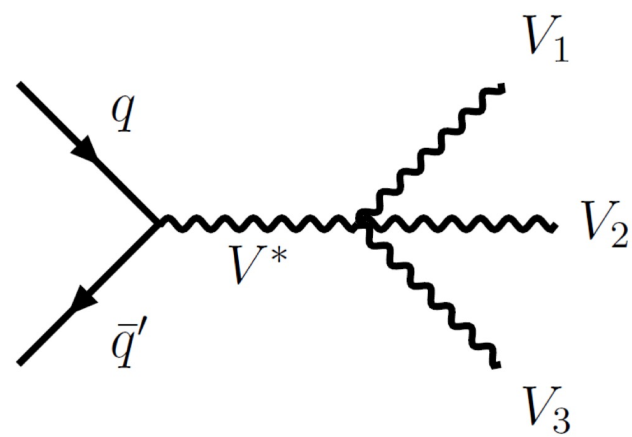


Quartic Couplings



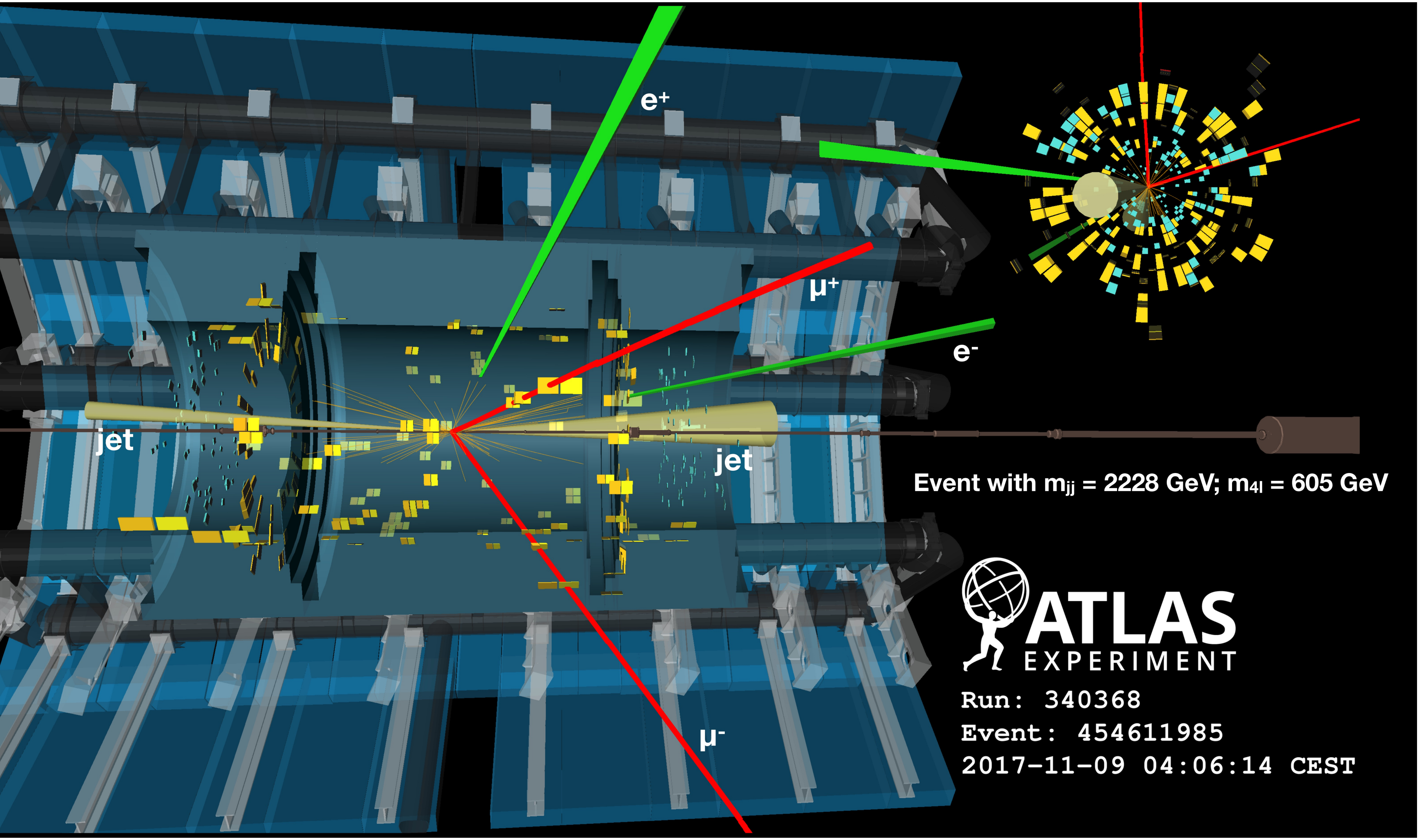
Vector Boson Scattering and Triboson Final States





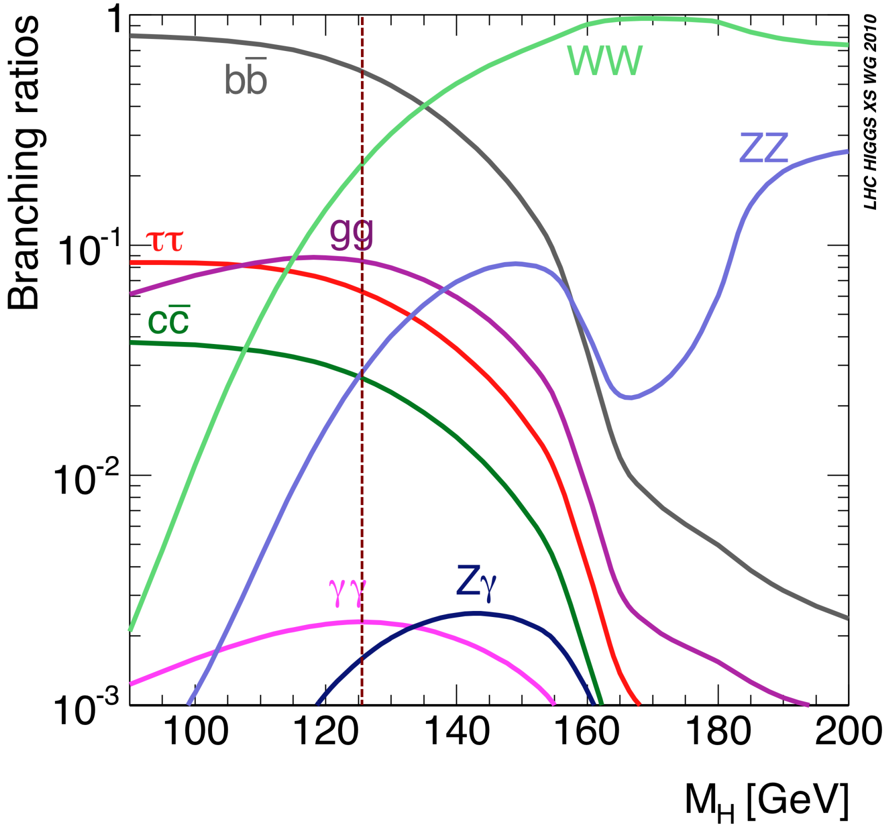
From Yee Chinn Yap

ZZjj Candidate Event



Higgs Boson Physics

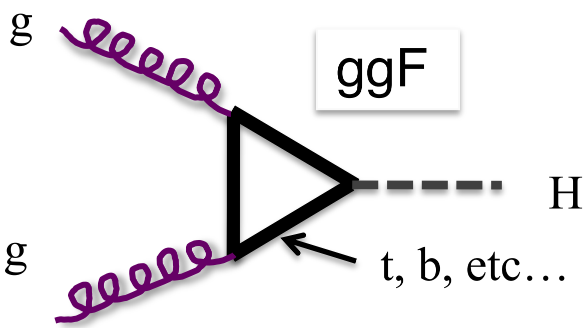
- At m_H = 125 GeV, many decay channels can be studied



SM Decay Modes
(M_H = 125.0 GeV)

Process	Br
bb	0.58
WW	0.22
ττ	0.06
ZZ	0.027
γγ	0.0023
Zγ	0.0016
μμ	0.0002

Higgs Boson Physics



	process	8 TeV	13 TeV
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VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
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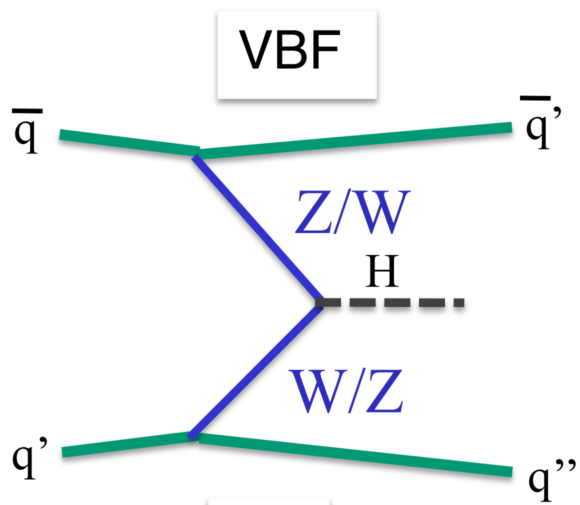
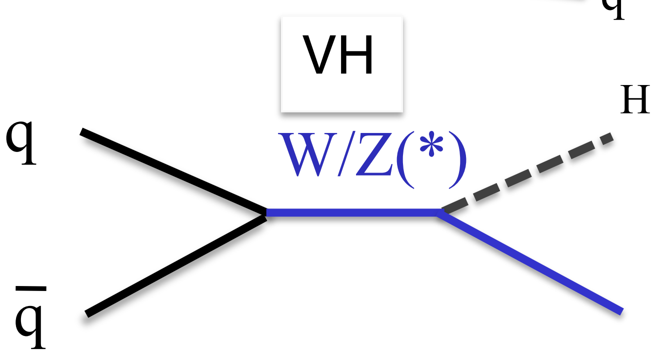
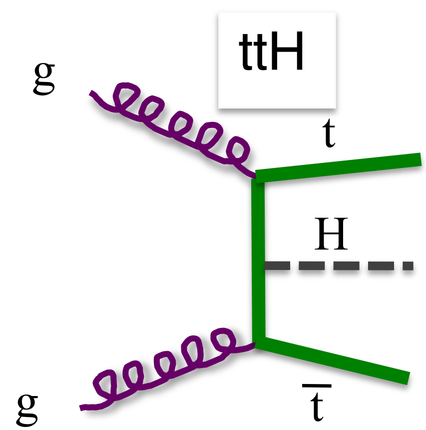
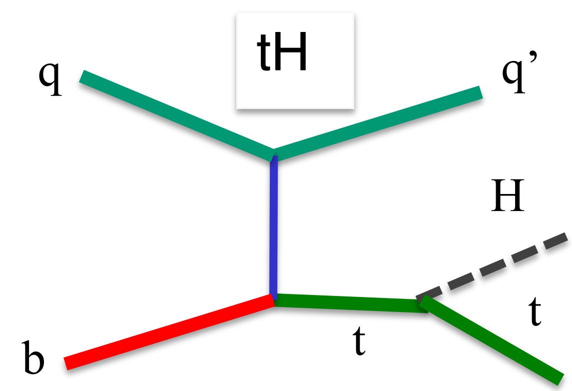
SM Production Modes
(M_H = 125 GeV)



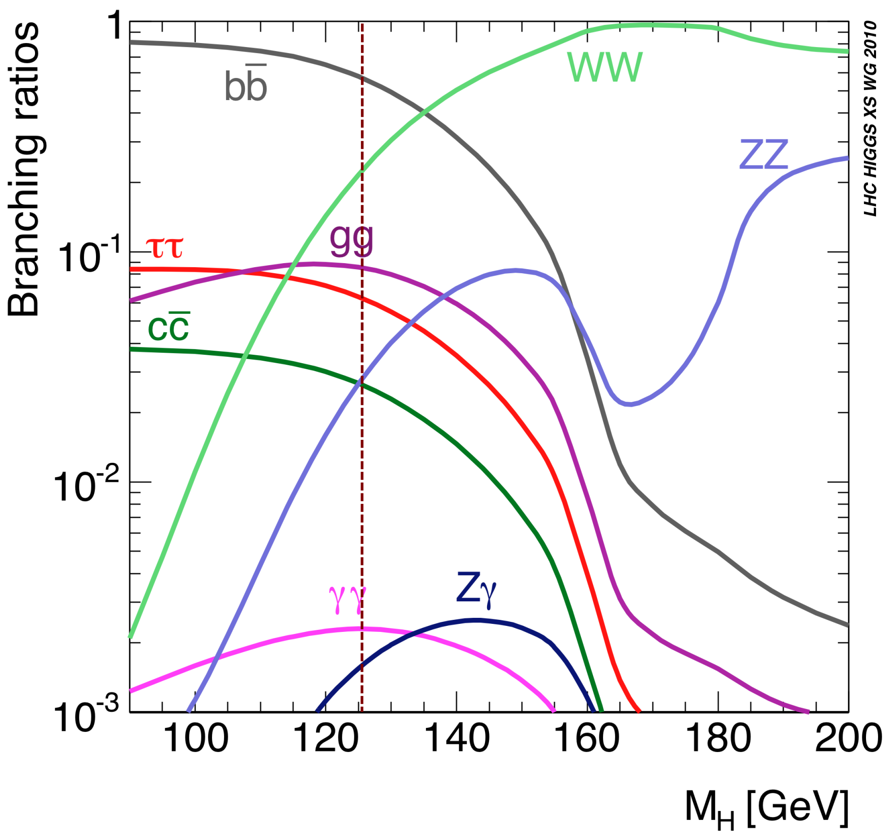






Higgs Boson Physics

- At m_H = 125 GeV, many decay channels can be studied

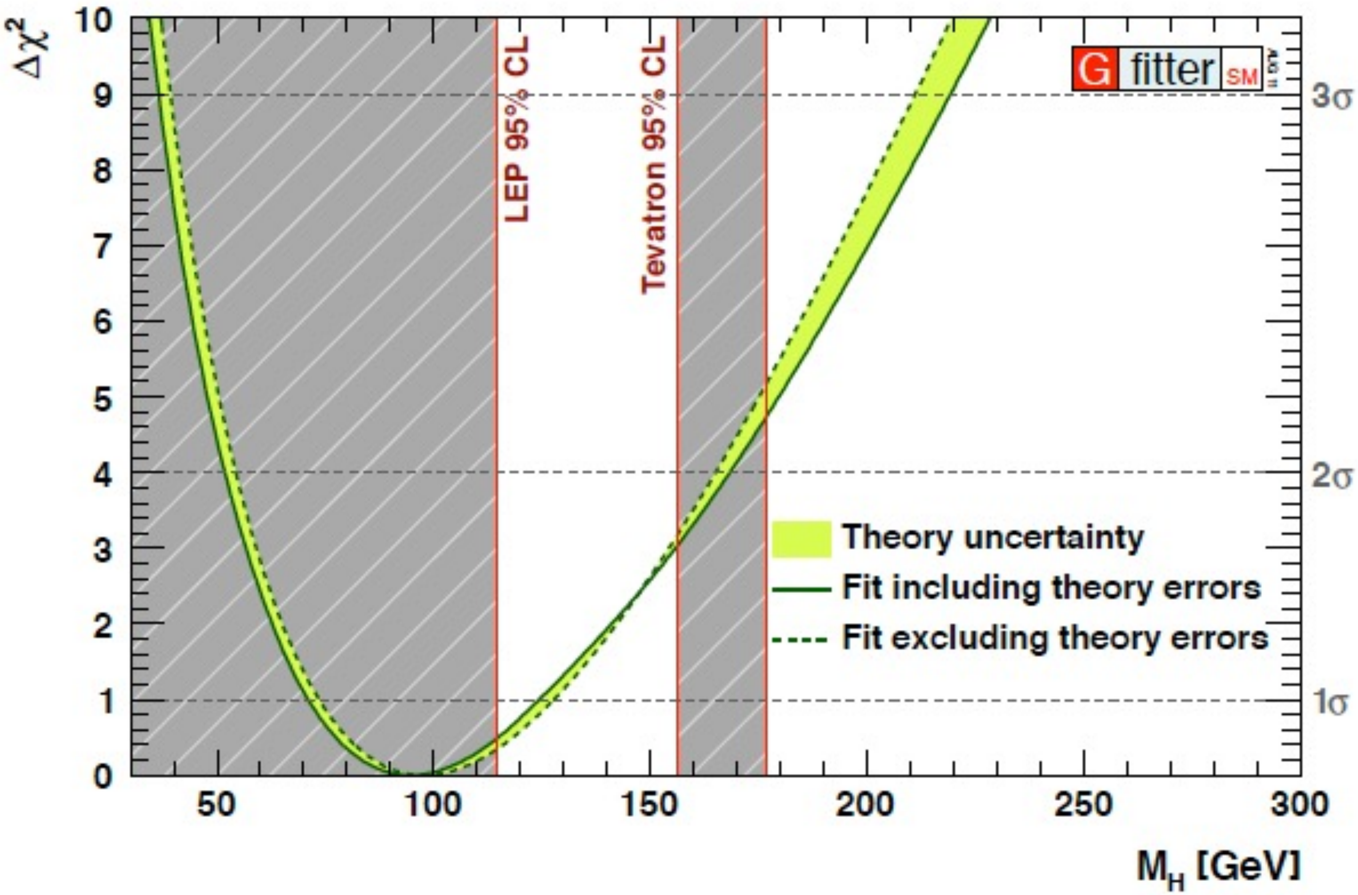


SM Decay Modes
(M_H = 125.0 GeV)

Process	**Br**
bb	0.58
WW	0.22
ττ	0.06
ZZ	0.027
γγ	0.0023
Zγ	0.0016
μμ	0.0002

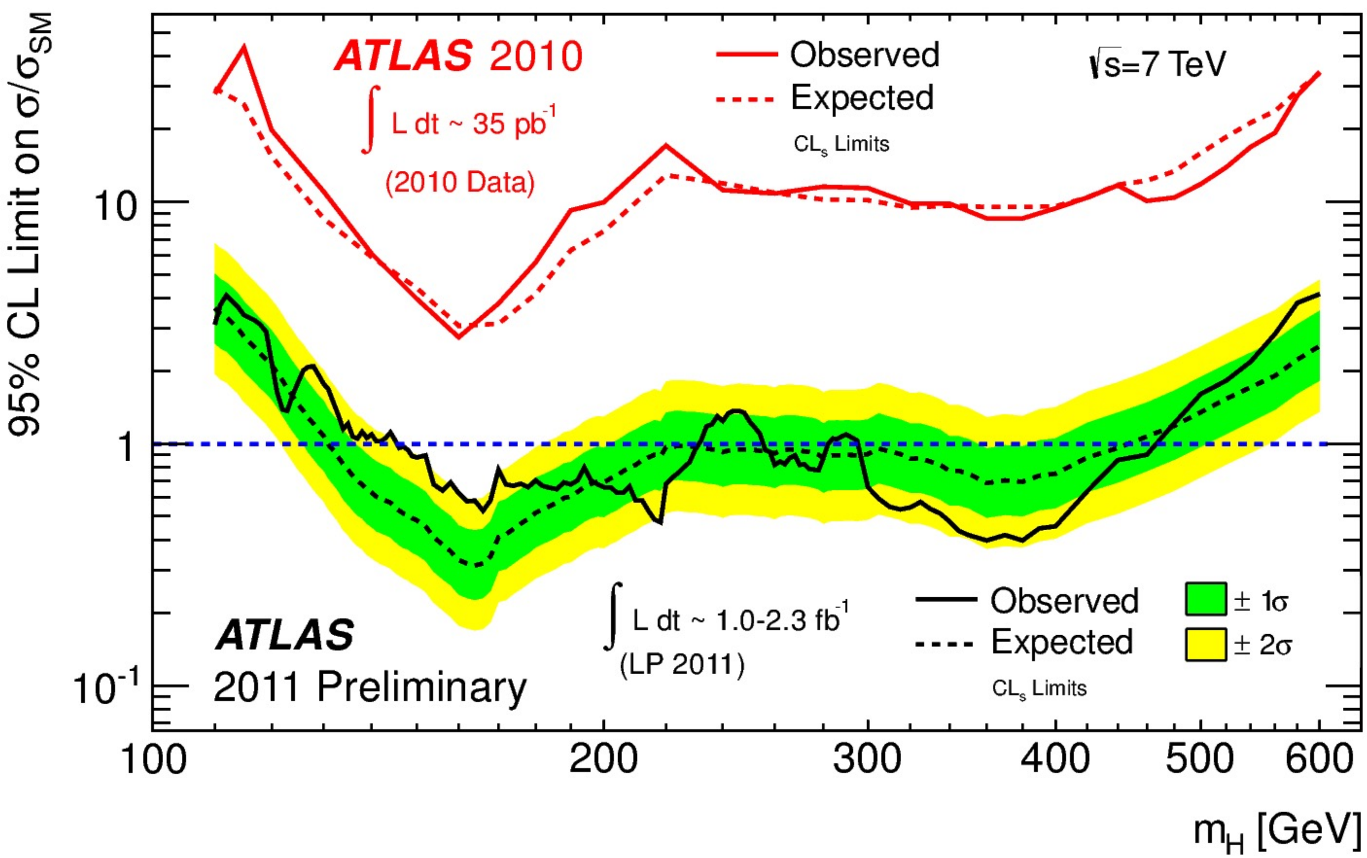
Before LHC: where to expect the Higgs?

- 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

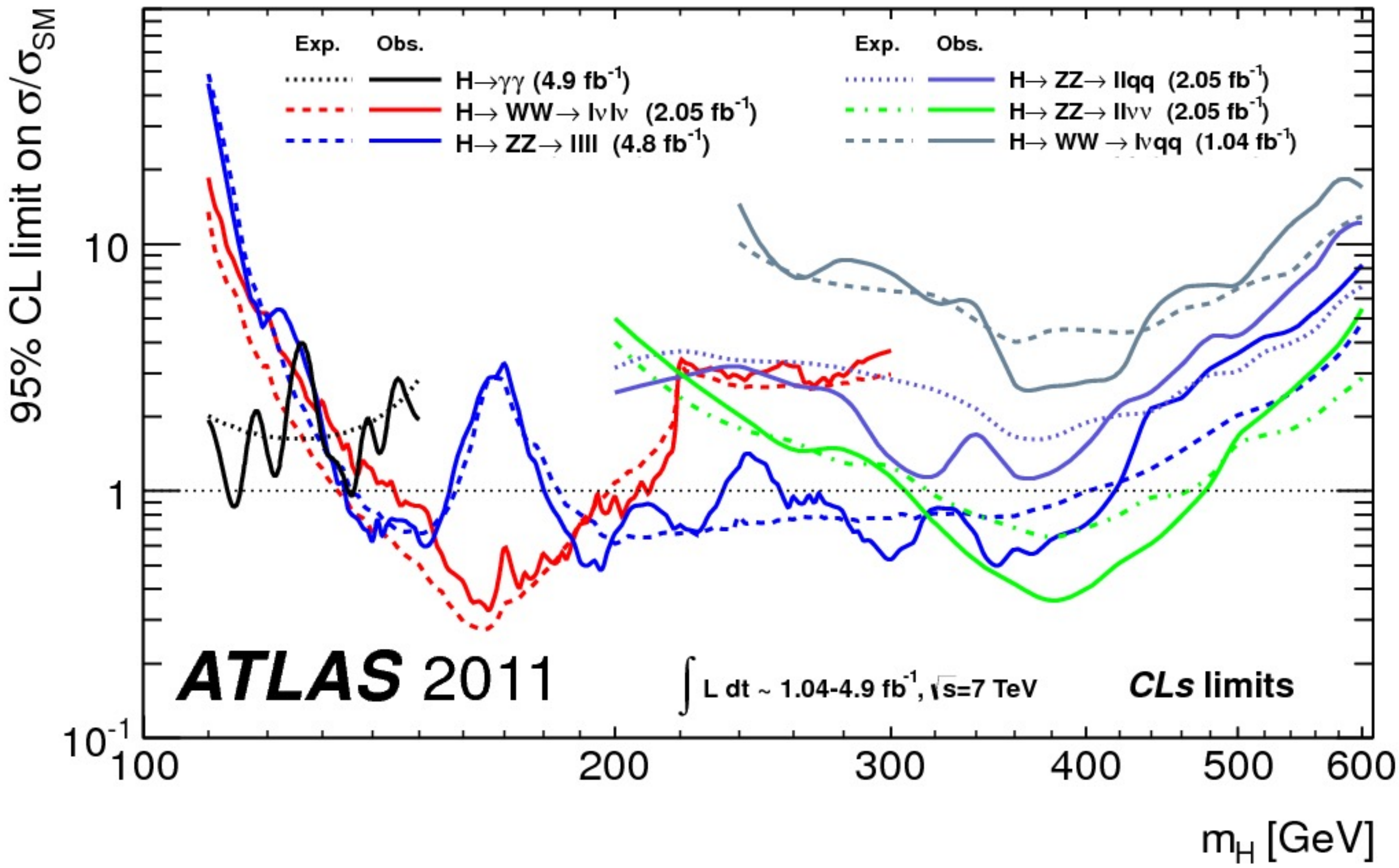


Summer 2011: Limits on Higgs Mass

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

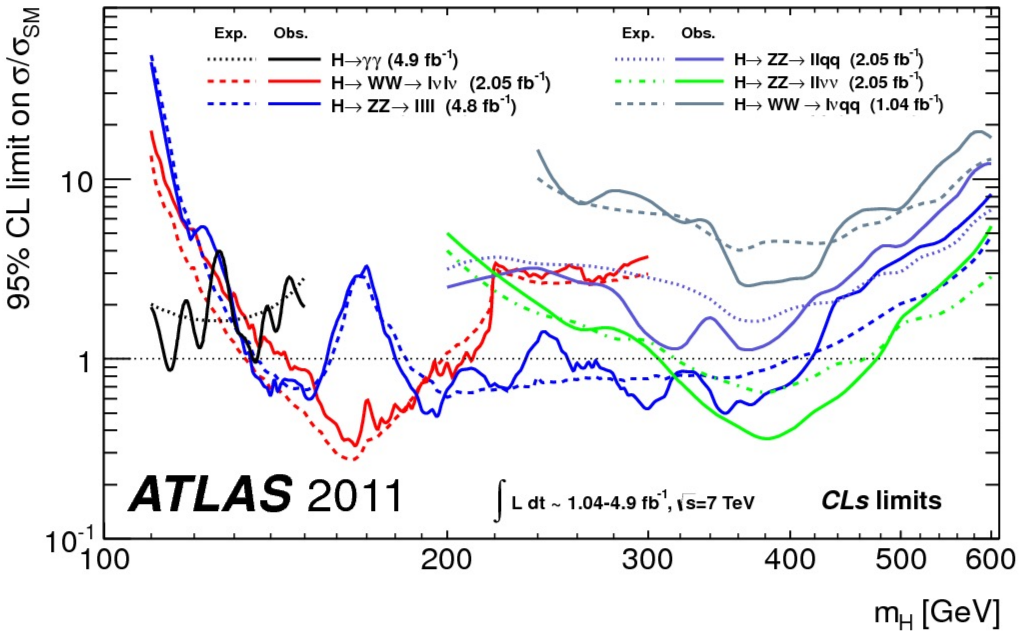


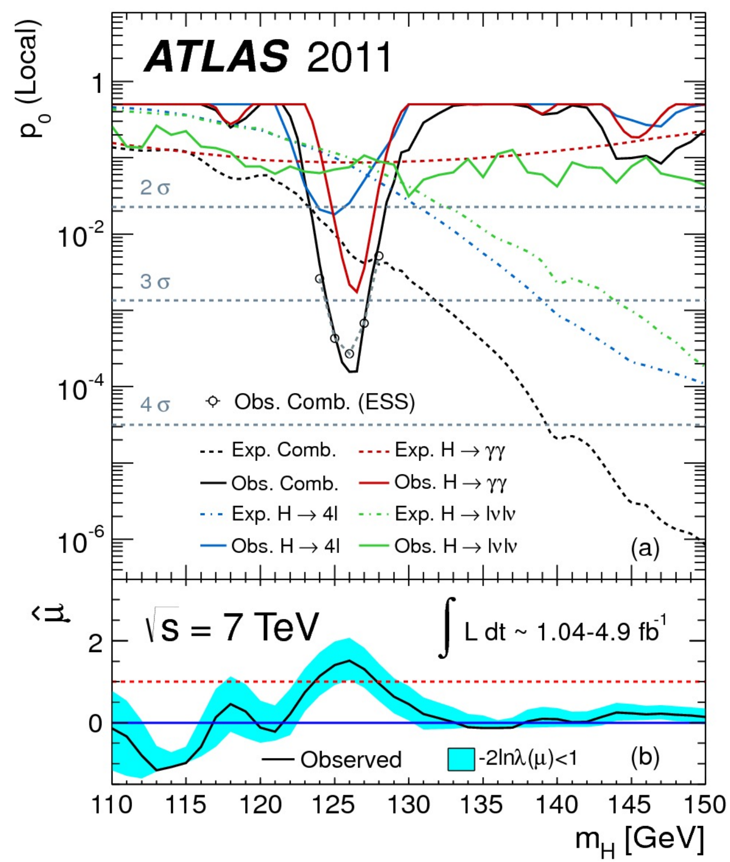
ATLAS 2011 Combination



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**

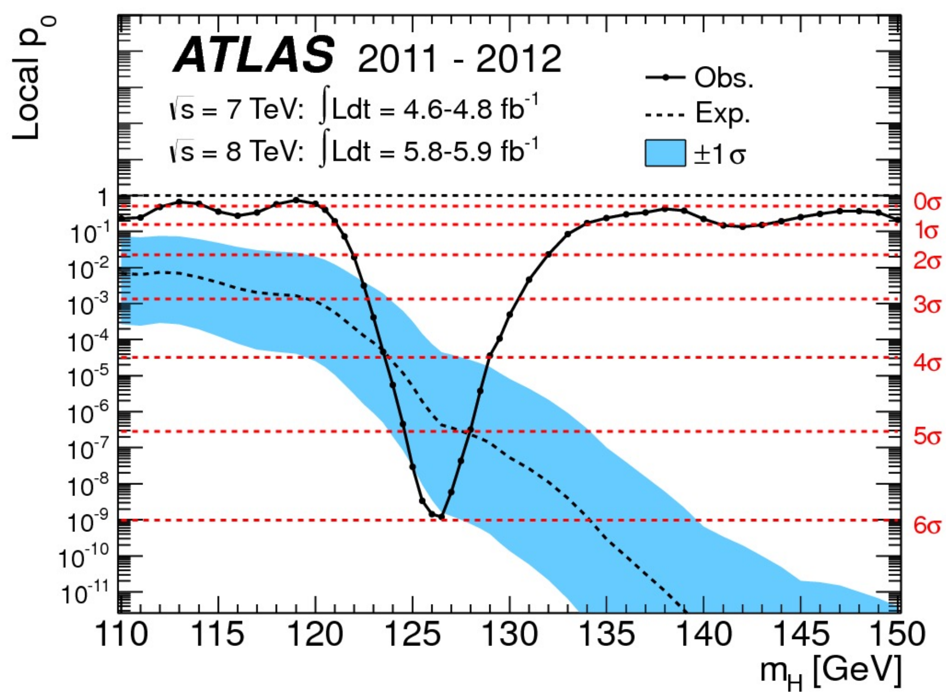


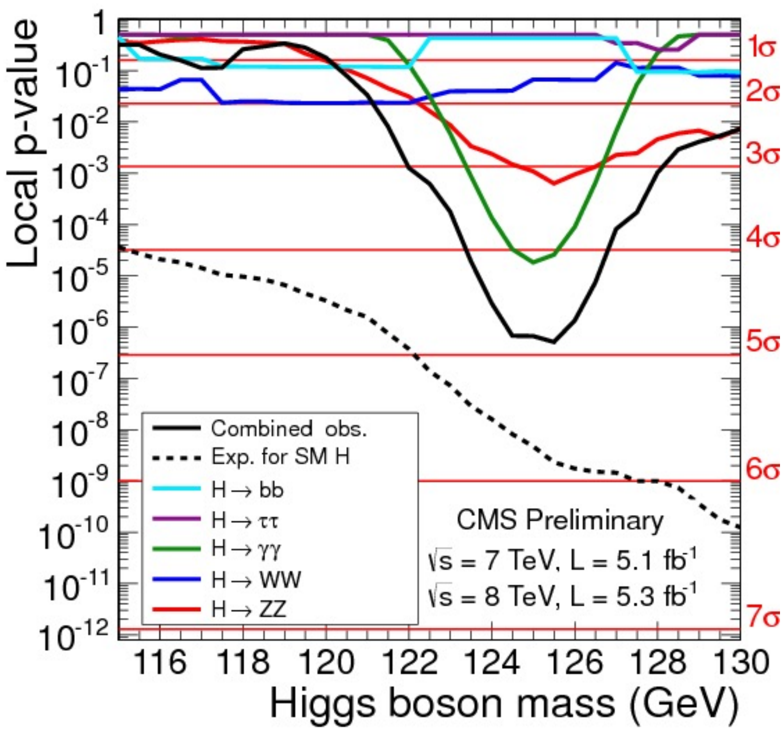


Diphoton, ZZ, WW had similar sensitivity for m_H~125 GeV

July 2012: Combination of Channels

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



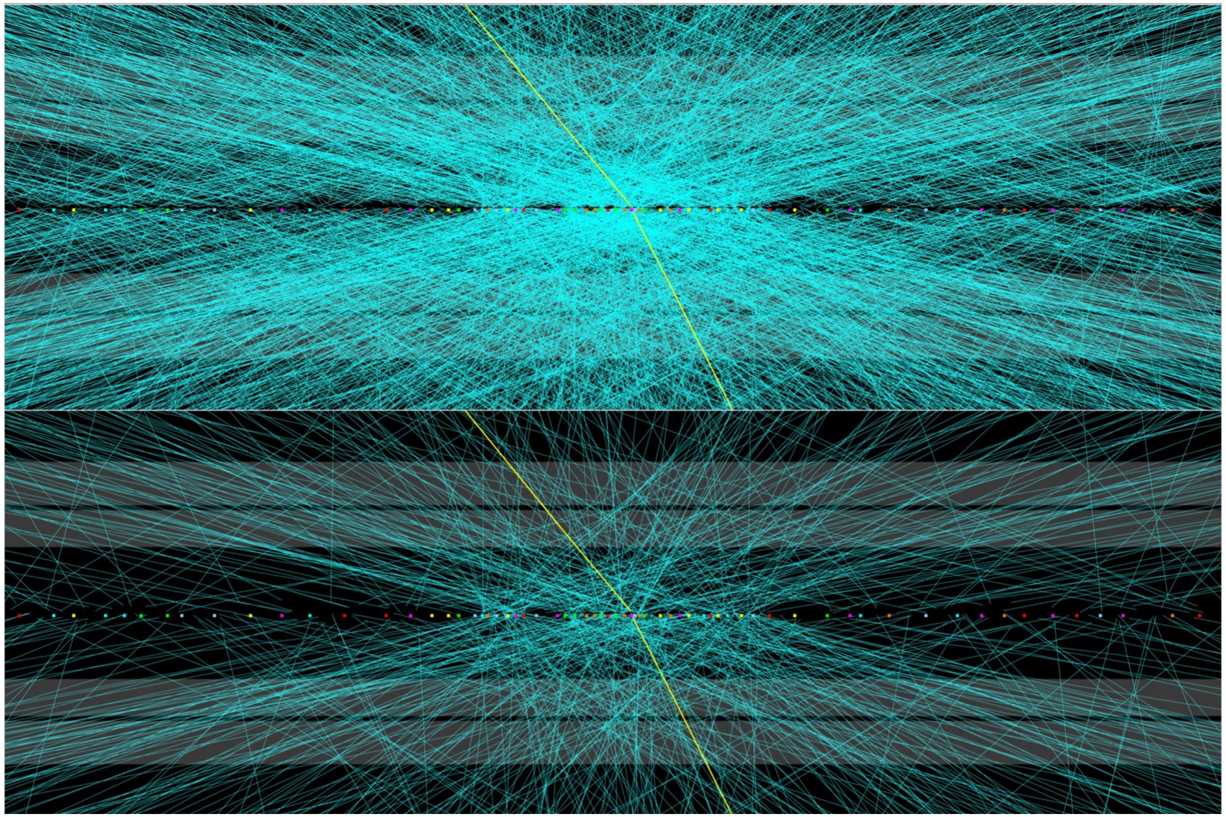


The LHC: high energy and high luminosity

During Run 2 the LHC produced 10^{16} collisions

Large samples of various particles produced:

- W bosons: 12 billion
- Z bosons: 3 billion
- Top quarks: 300 million
- Higgs bosons: 8 million



Event displays showing a Z→ll candidate produced with 65 reconstructed proton-proton collisions (top: 100 MeV tracks, bottom 1 GeV tracks)

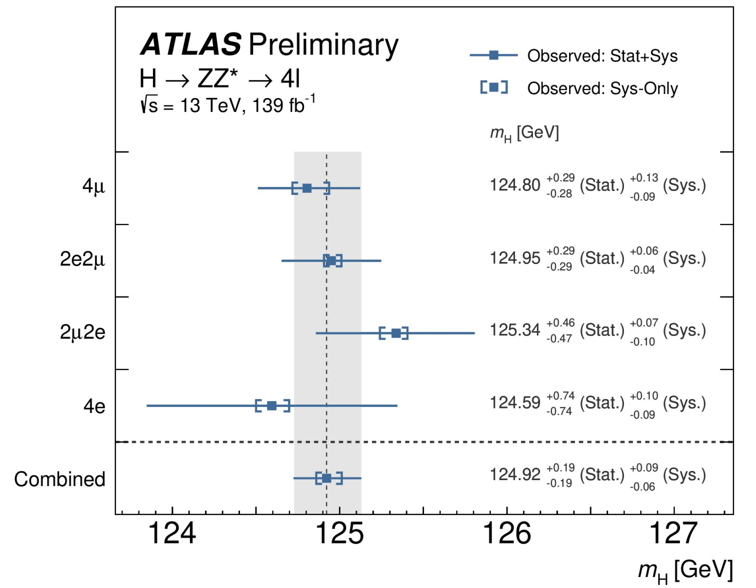
These samples allow for precision measurements of electroweak processes, for the in-depth characterization of the Higgs boson, and detailed studies of the top quark

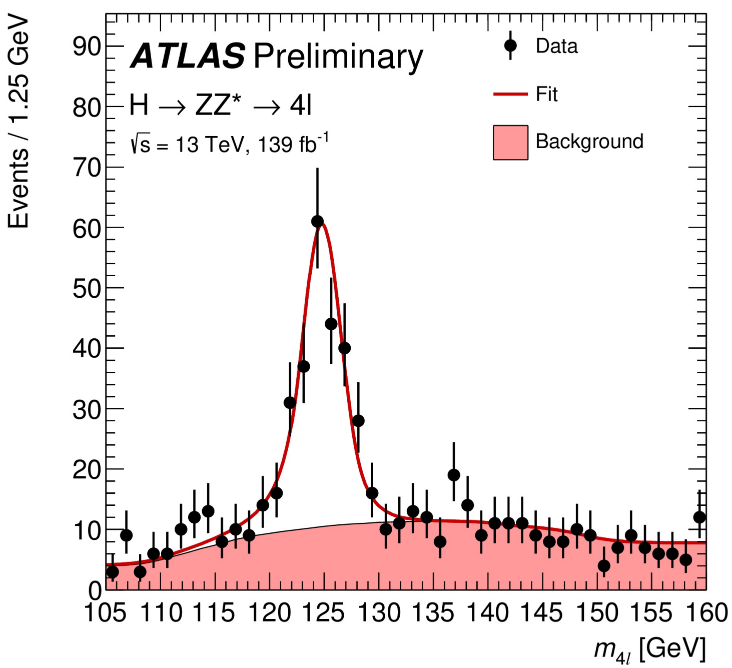
Higgs Mass Measurements

Standard Model predicts production and decay rates of the Higgs boson as a function of Higgs mass. It does not predict the Higgs mass: it must be measured.

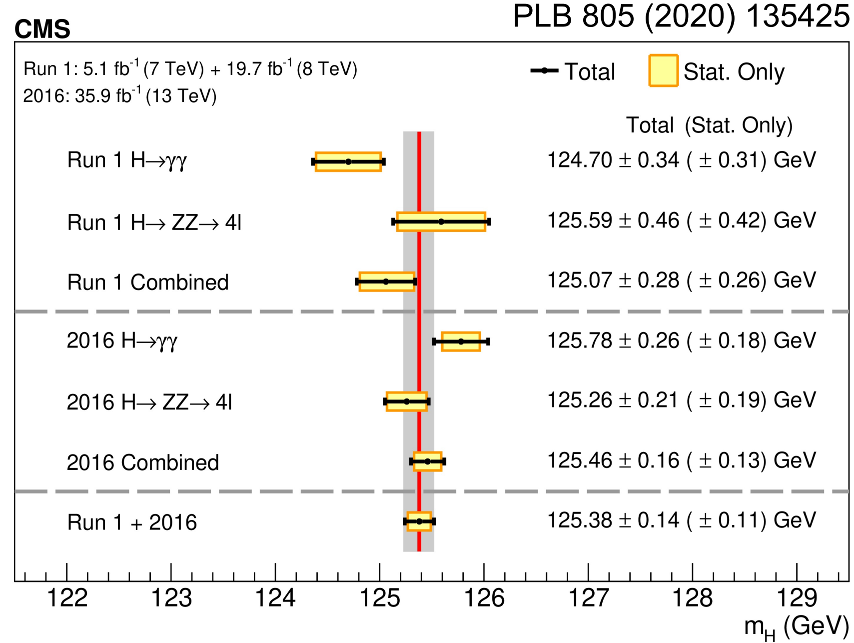
Precision on the Higgs boson mass now at the 0.1% level. Precision will improve with statistics

ATLAS-CONF-2020-005





PLB 805 (2020) 135425



Properties of SM Higgs boson

- Electric charge: 0 (easy…)
- Spin: 0
- Parity: “even” (but…)
- Lifetime/width at measured mass: 4.1 MeV
- Coupling to SM particles: all predicted
- Production and decay rates (depend on couplings above)
- Mass: not predicted, must be measured

SM Higgs boson

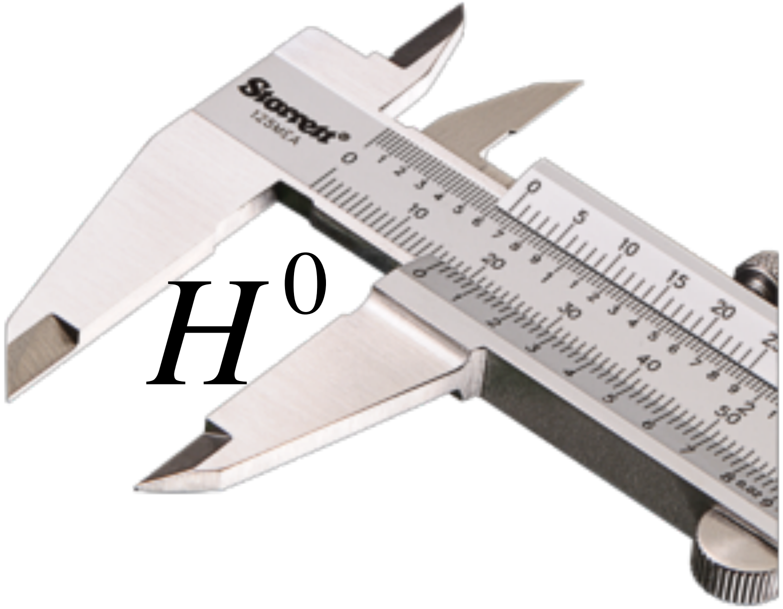
- SM couplings:

$$g_{Hf\bar{f}} = \frac{m_f}{v}, \qquad g_{HVV} = \frac{2m_V^2}{v}, \qquad g_{HHVV} = \frac{2m_V^2}{v^2}$$

$$g_{HHH} = \frac{3m_H^2}{v} \qquad g_{HHHH} = \frac{3m_H^2}{v^2}$$

- Couplings to fermions proportional to their mass
- Couplings to weak bosons proportional to mass^2
- No couplings to photon and gluon (massless particles…)

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
  - 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 Boson Physics

Large sample of ~8M Higgs bosons produced allows for precision tests of the Higgs sector of the SM:

Channel	Produced	Selected	Mass resolution
$H \to \gamma\gamma$	18,200	6,440	1–2%
$H \to ZZ^*$	210,000	($\to 4\ell$) 210	1–2%
$H \to WW^*$	1,680,000	($\to 2\ell 2\nu$) 5,880	20%
$H \to \tau\tau$	490,000	2,380	15%
$H \to bb$	4,480,000	9,240	10%

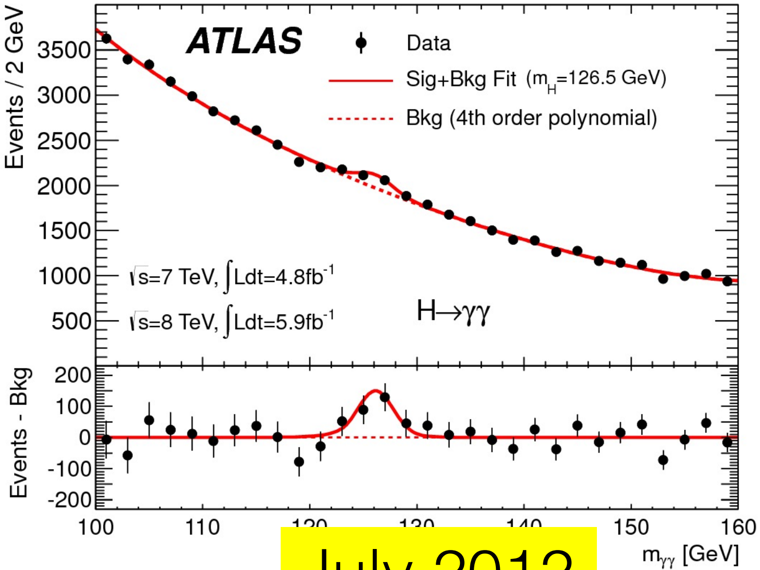
Major progress in last few years:

- Observation of H→bb decay
- Observation of ttH production
- Observation of VH production
- Evidence of $\mu\mu$ decay

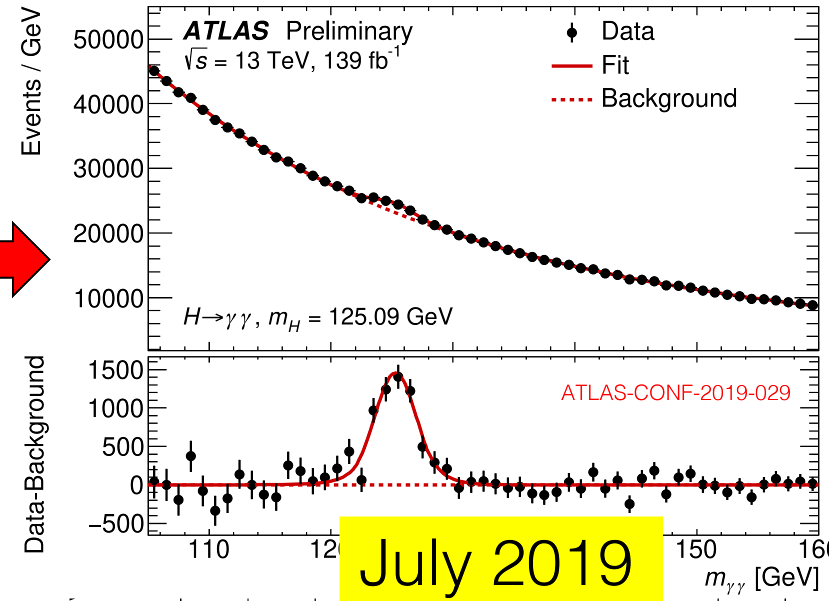
All major production and decay modes of the Higgs have now been observed

The Higgs Boson: then and now

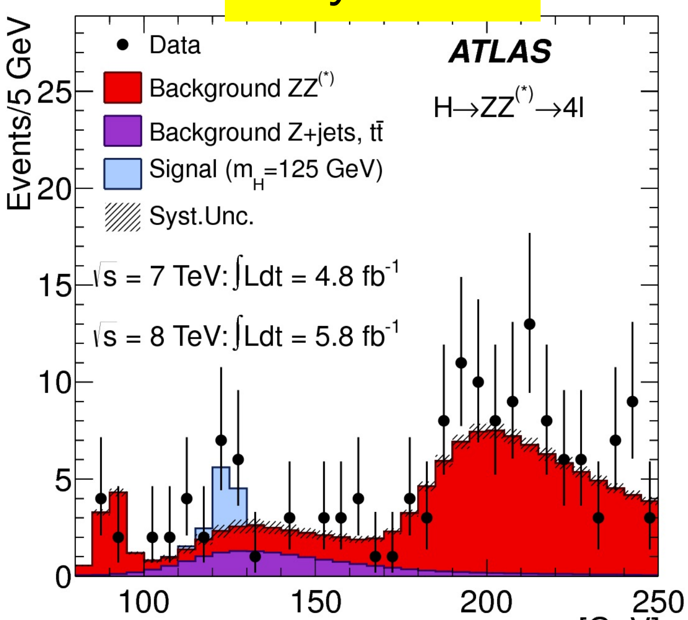
Full Run-2



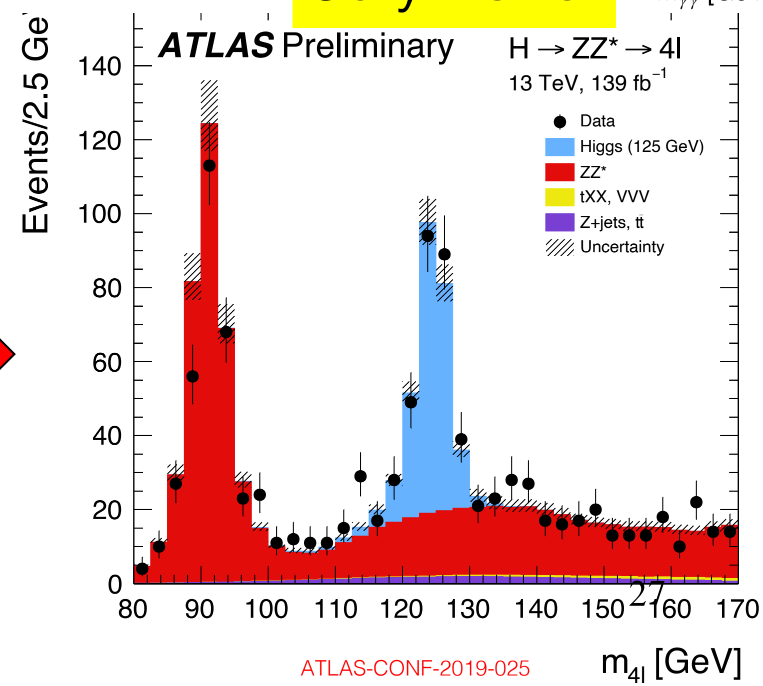
July 2012



July 2019



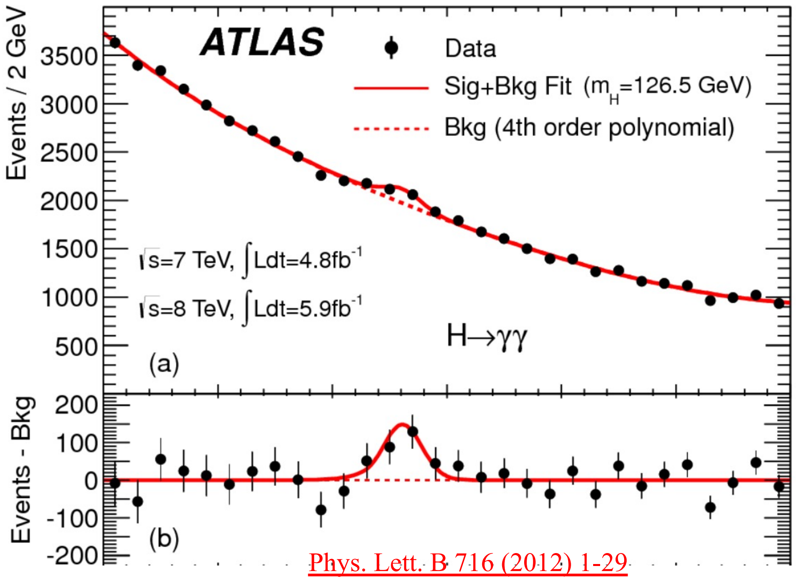
Phys. Lett. B 716 (2012) 1-29



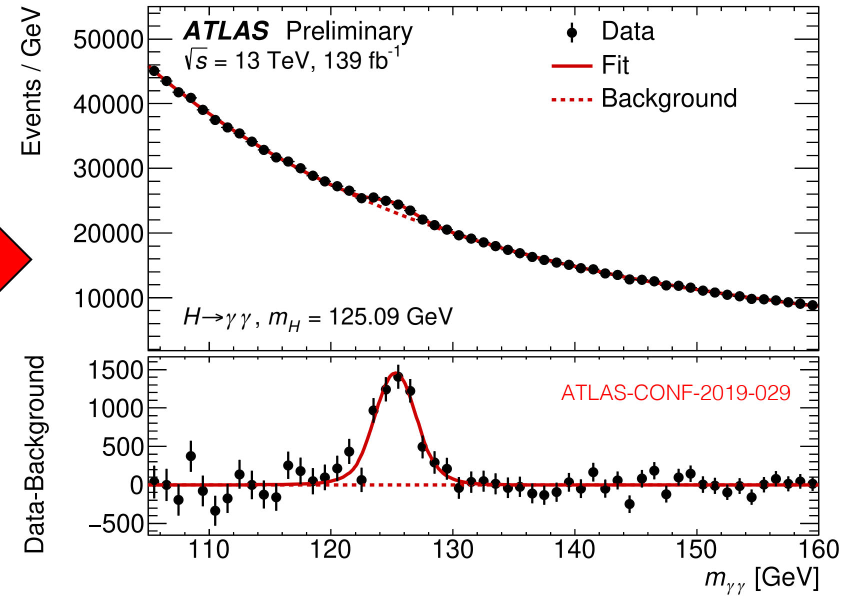
ATLAS-CONF-2019-025

The Higgs Boson: then and now

Full Run-2

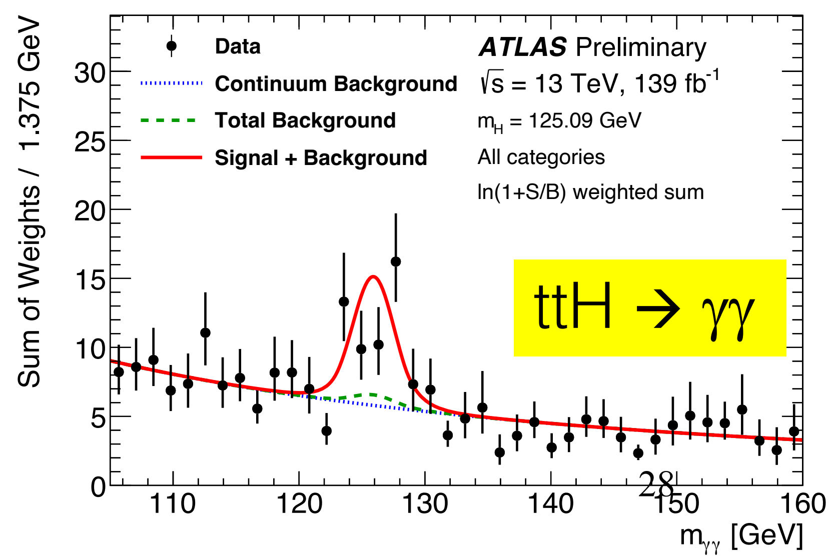


July 2012



July 2019

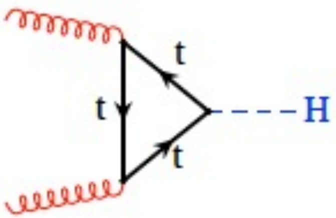
Observation of H → γγ in rare ttH production channel in 2019
ATLAS-CONF-2019-004

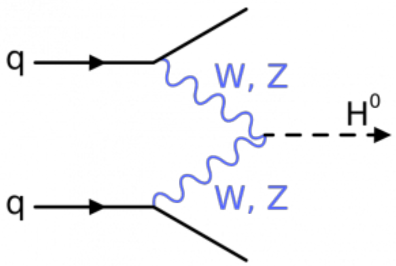


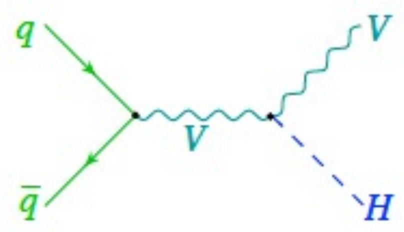
H decays to bosons
WW, ZZ, $\gamma\gamma$

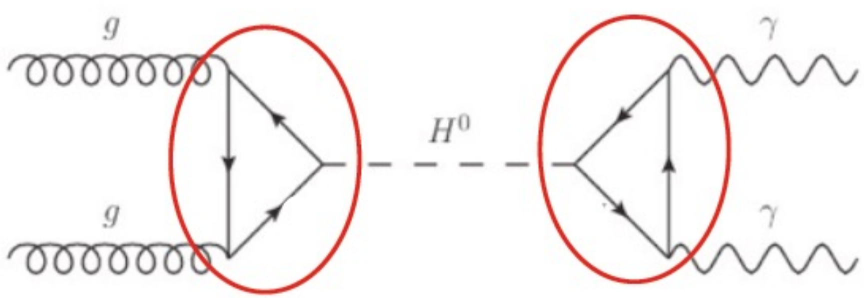
H → γγ

- 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:



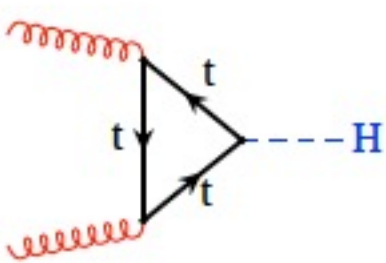


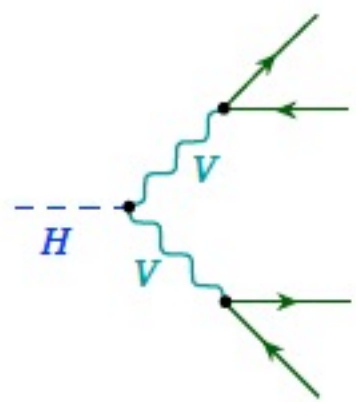




$H \rightarrow ZZ^* \rightarrow llll$

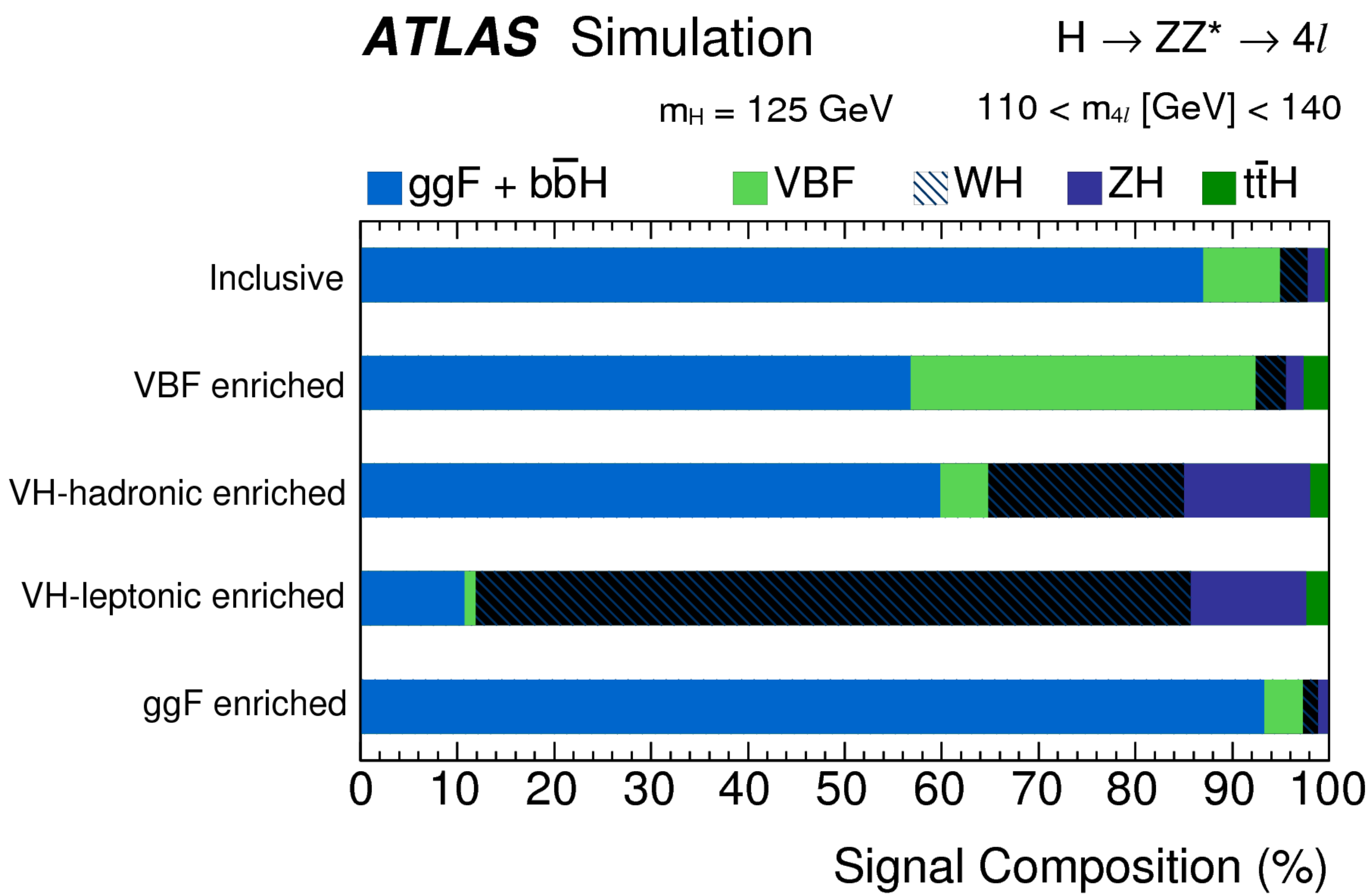
- Production depends on coupling to top quark (in SM), with small contributions from other production modes
- Decay depends on coupling to Z boson
- Small branching fraction to 4-lepton final state (need int. lumi.)
- A good discovery final state:
  - Very low backgrounds
  - Very good Higgs mass resolution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

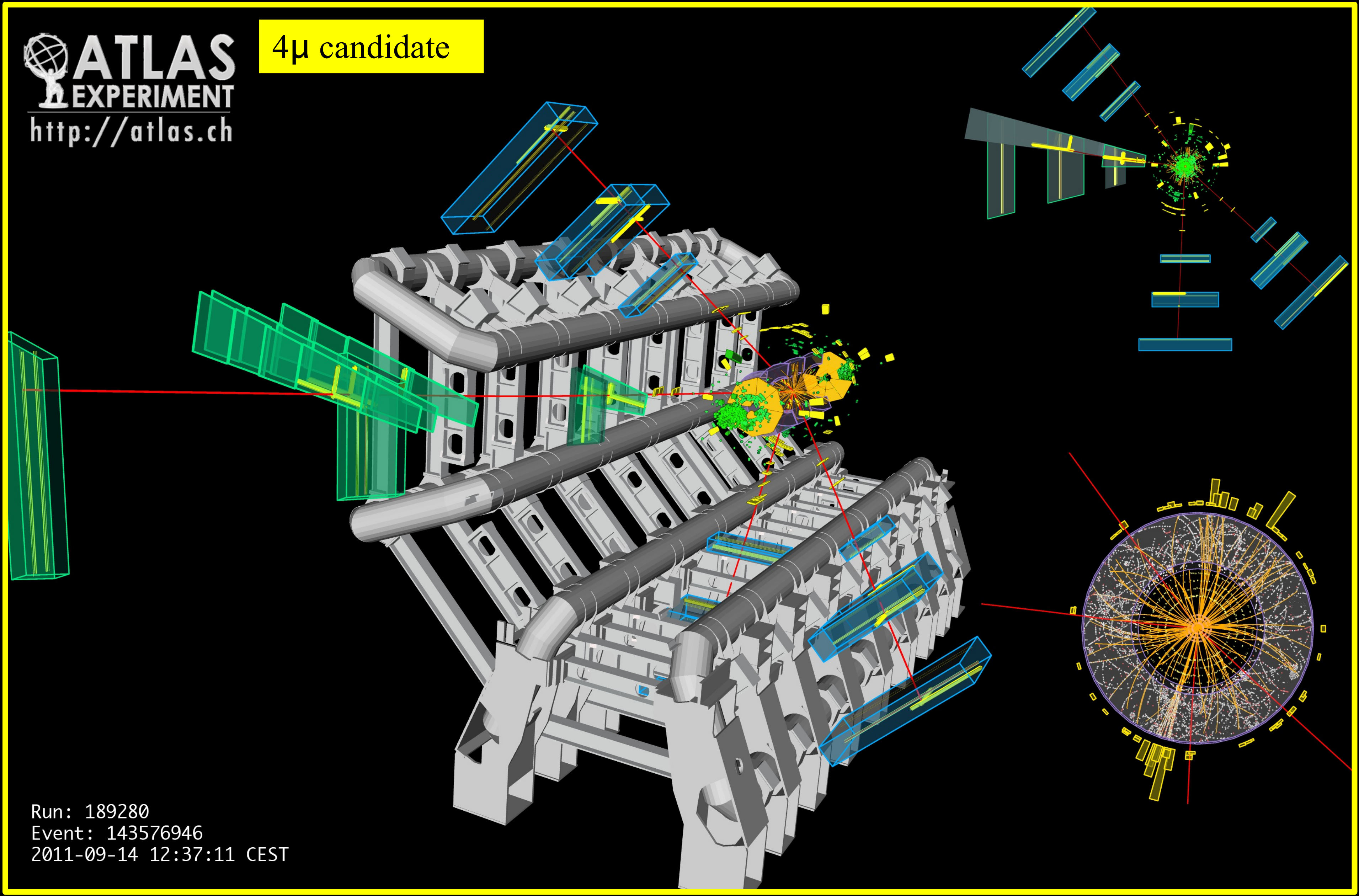




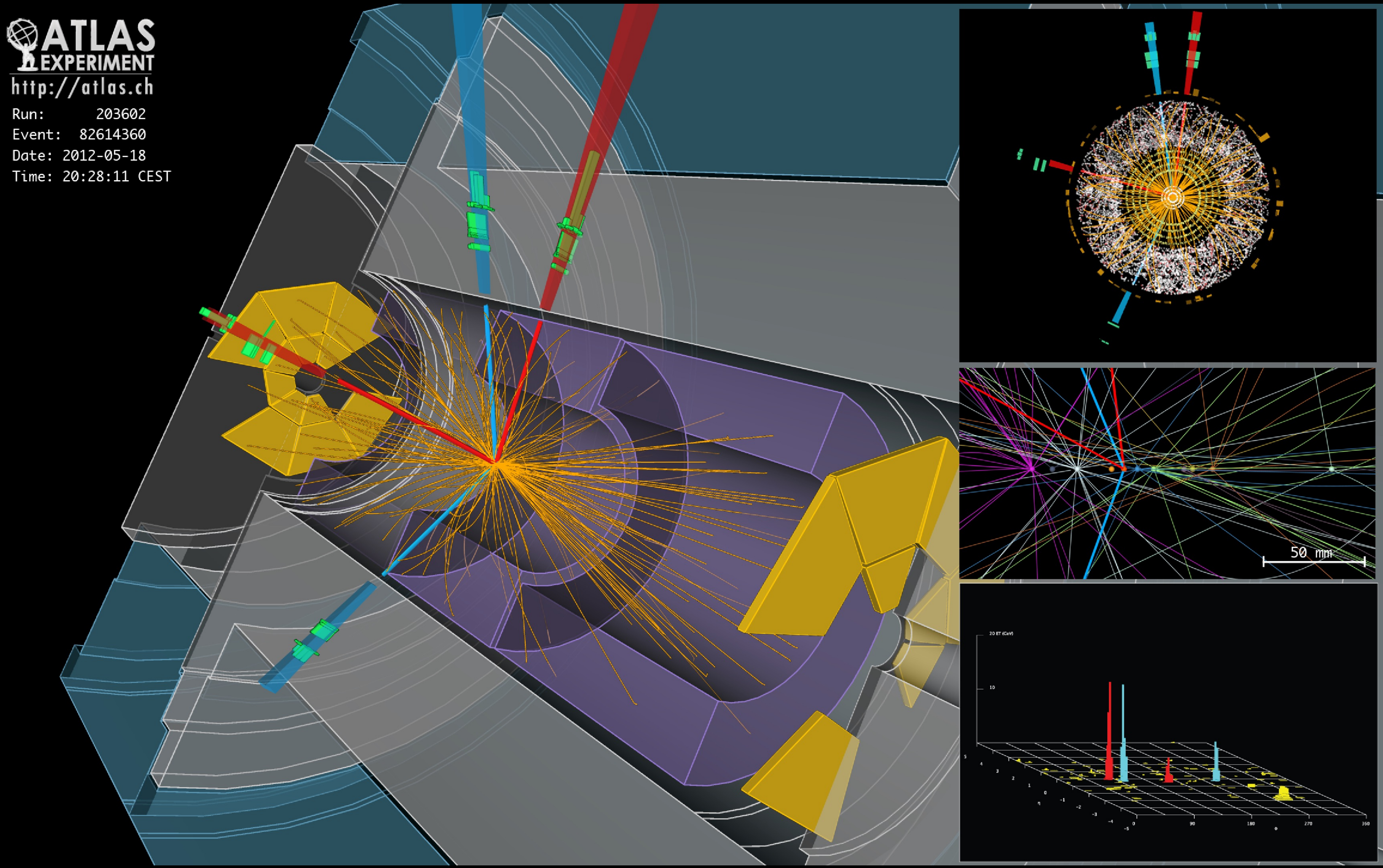
H → ZZ$^{(*)}$ → 4 LEPTONS

Estimated signal composition
in various categories

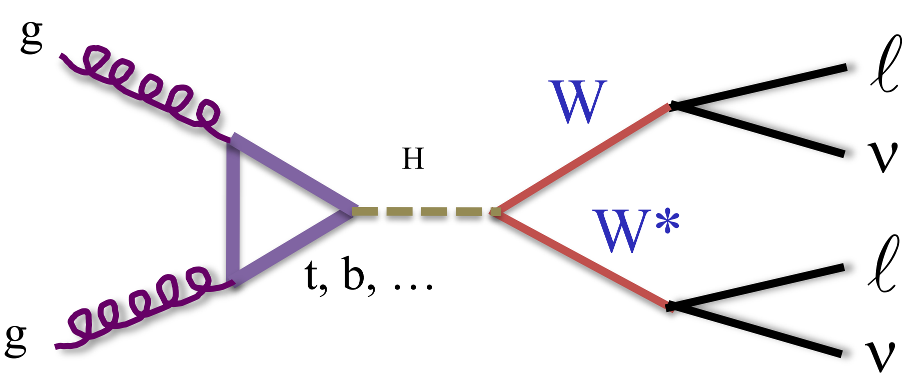



ATLAS
EXPERIMENT
http://atlas.ch
4μ candidate
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST

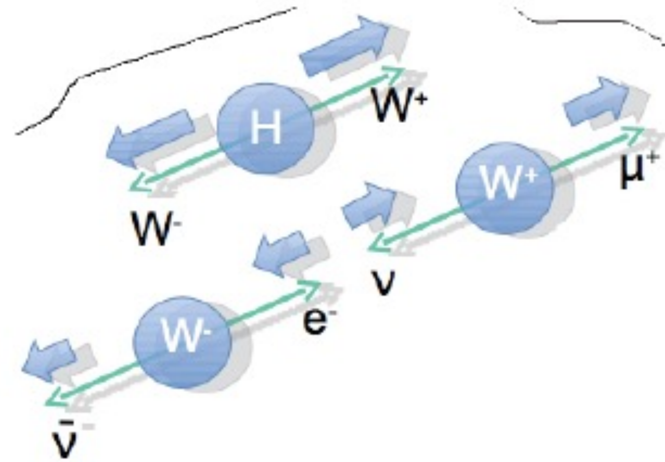
4e candidate



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



(soft



- 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

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

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

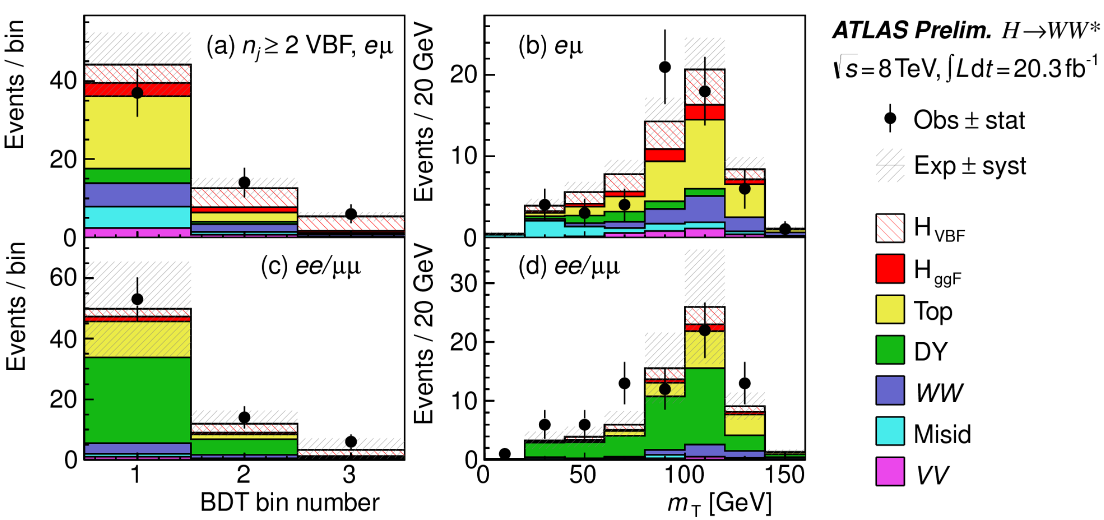
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$

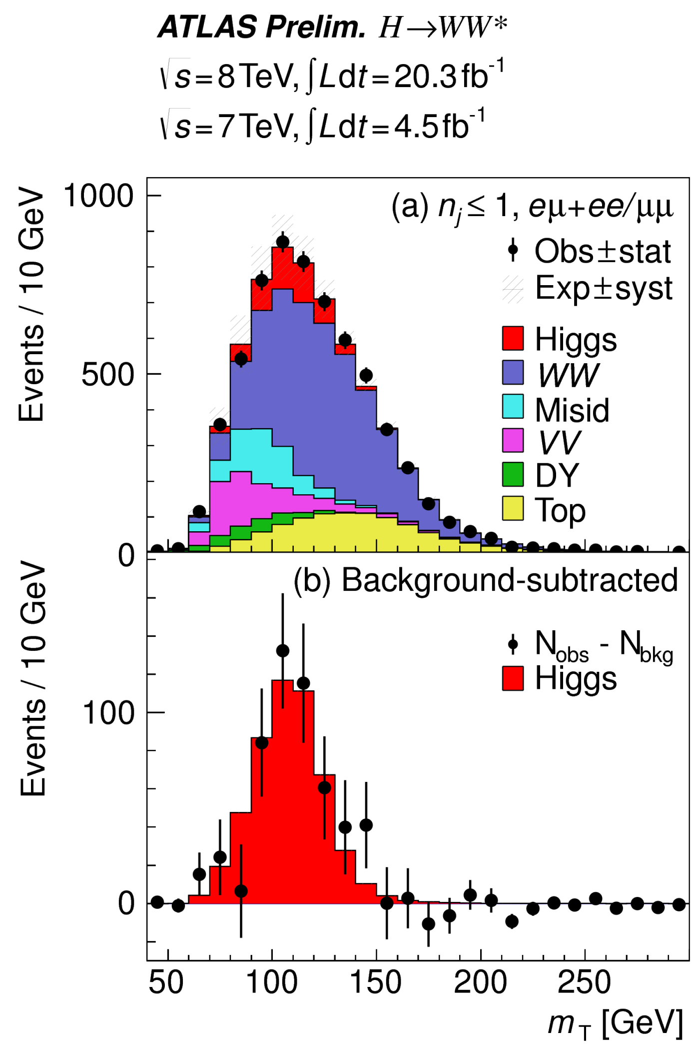
Results:

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

Combined WW → lνlν signal strength

$\mu = 1.08^{+0.16}_{-0.15}$ (stat.)$^{+0.16}_{-0.13}$ (syst.)

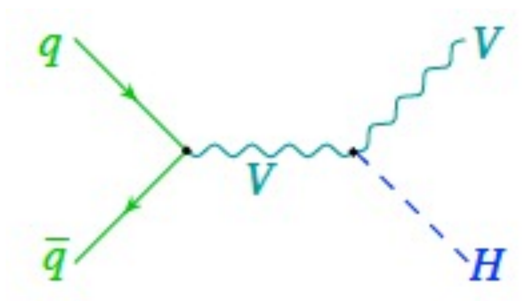


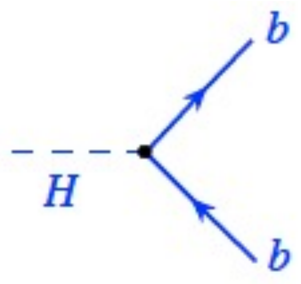


H decays to fermions
$b\bar{b}$, $\tau\bar{\tau}$

$H \rightarrow b\bar{b}$

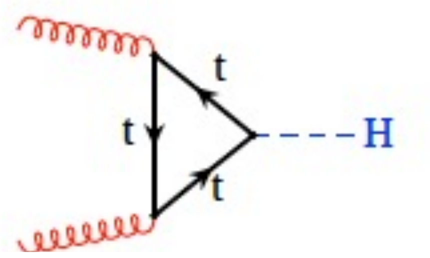
- Production depends (mainly) on coupling to W/Z bosons
- Decay depends on coupling to b quark (down-type quark coupling)
- Small production cross section (but branching ratio is the largest)
- A challenging final state:
  - Very large backgrounds (W/Z+jets)
  - Higgs mass resolution is not that good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

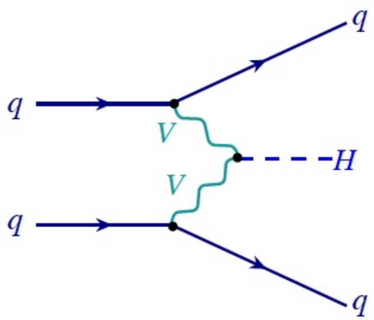


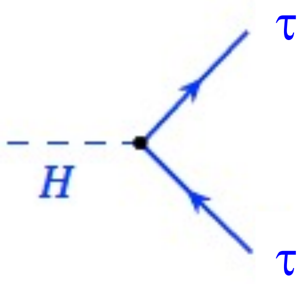


$H \rightarrow \tau\bar{\tau}$

- 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





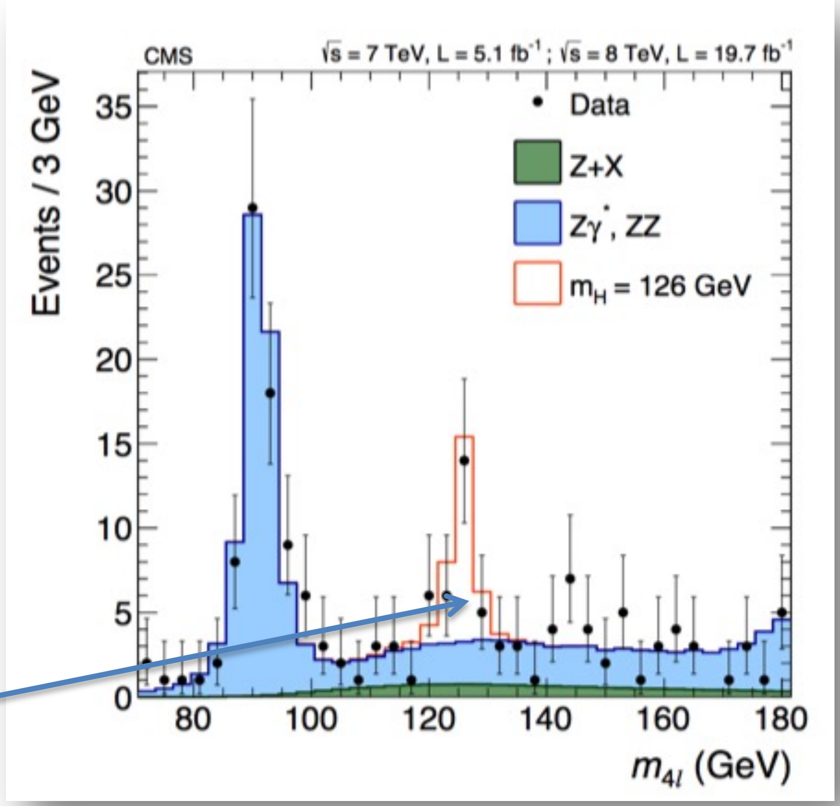


From Signal Yields to Couplings

- 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:

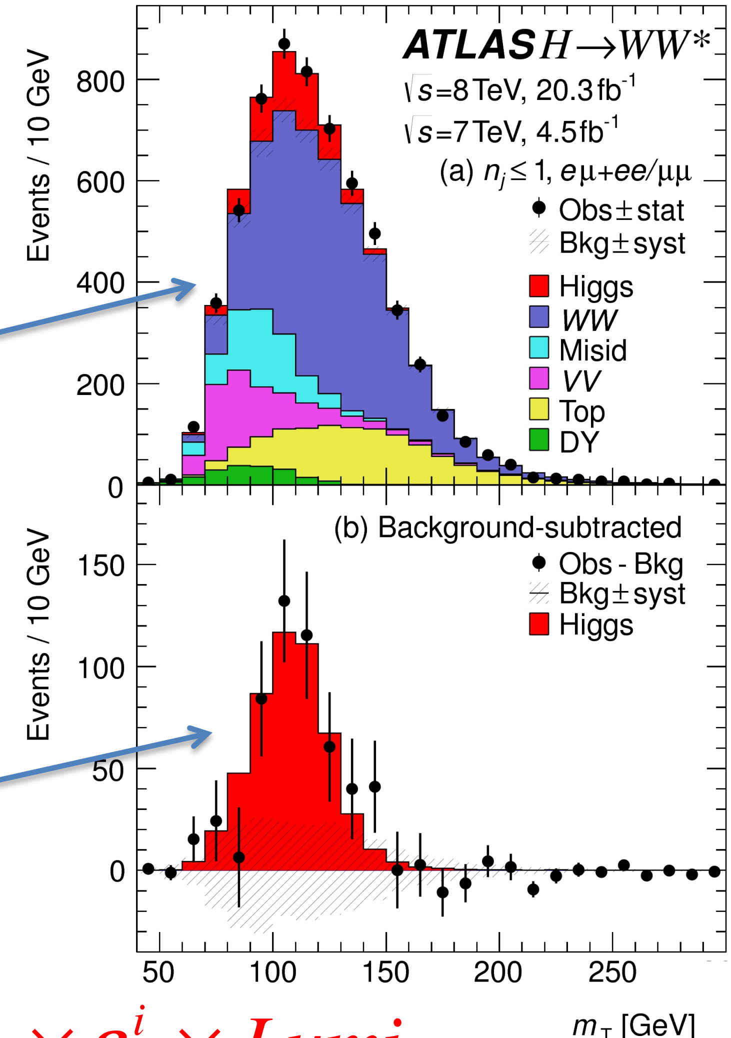


$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

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



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

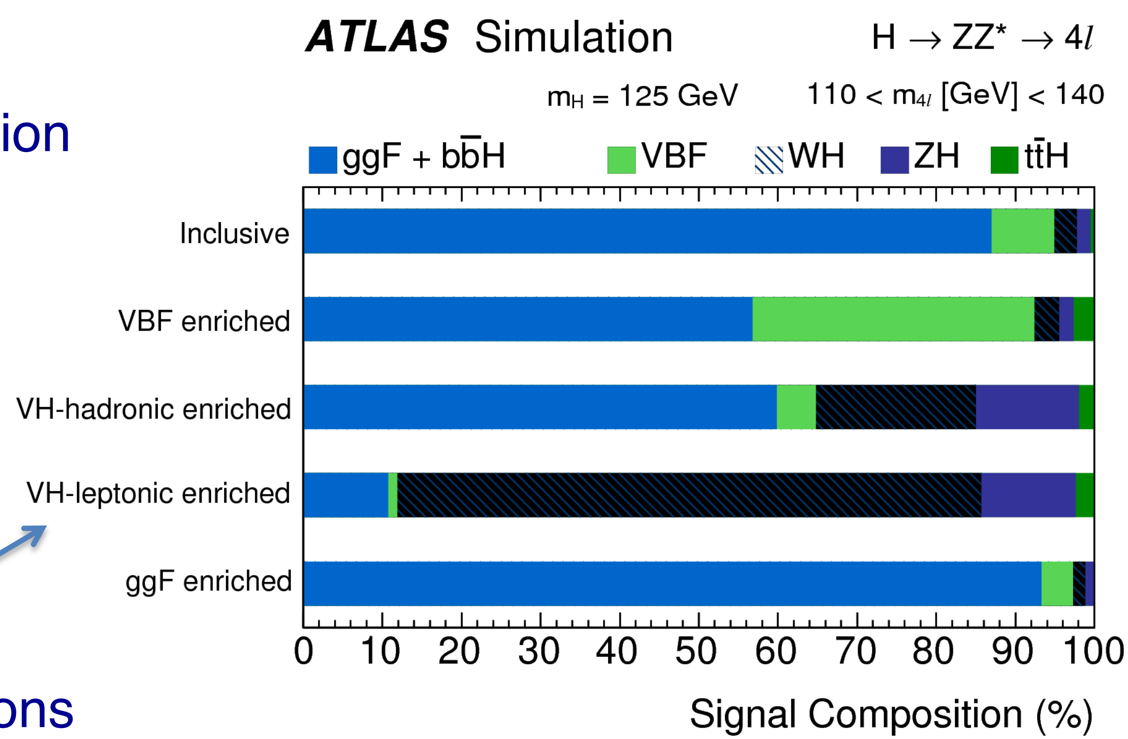
$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

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

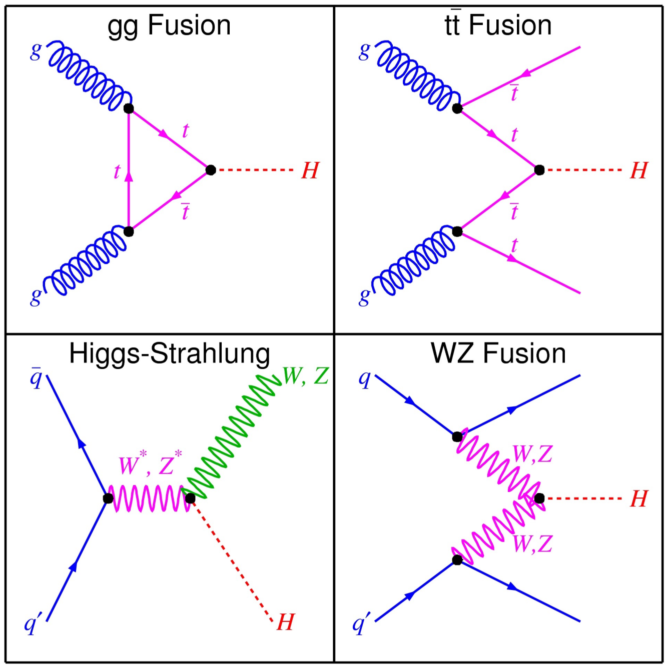


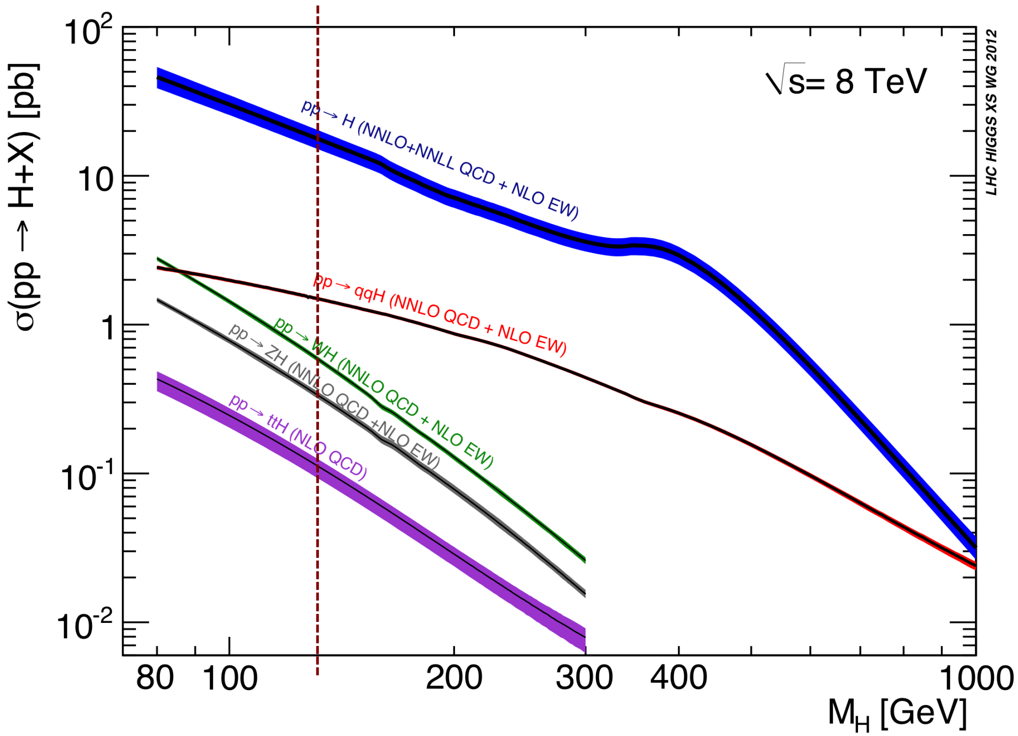
$$n_s^{c,i} = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

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

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

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

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

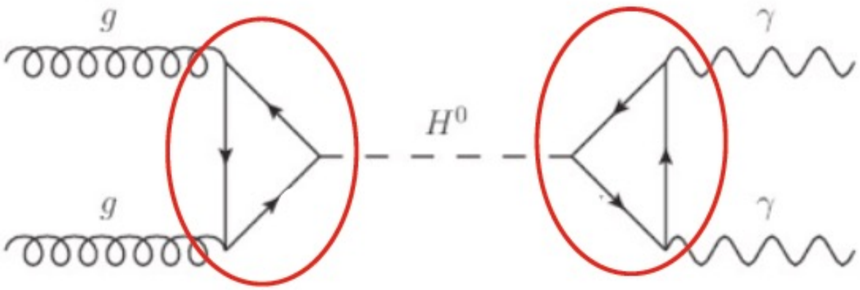
- Decay: $\Gamma_i = \kappa_i^2\ \Gamma_i^{SM}$
- Production: $\sigma_i = \kappa_i^2\ \sigma_i^{SM}$
- Width: $\Gamma_H = \Sigma_i\, \kappa_i^2\ \Gamma_i^{SM}$

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:

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

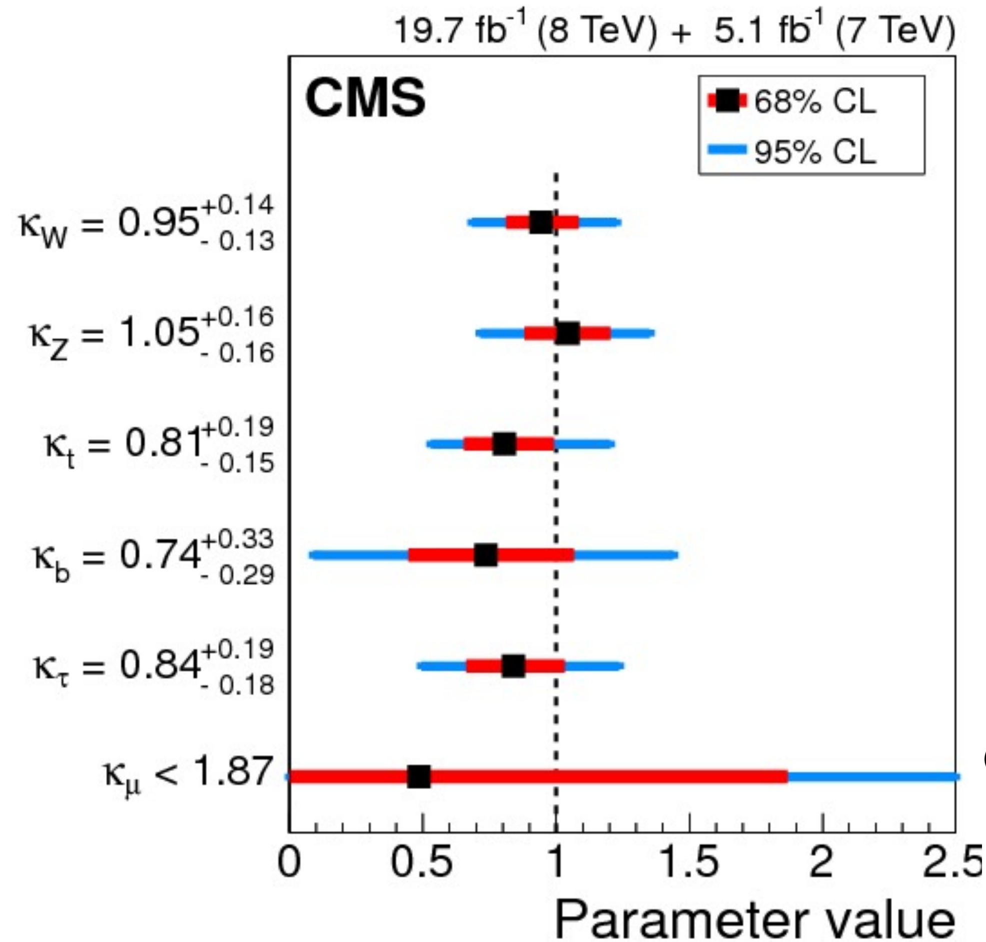
$$\kappa_\gamma^2(\kappa_F, \kappa_V) = 1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$$

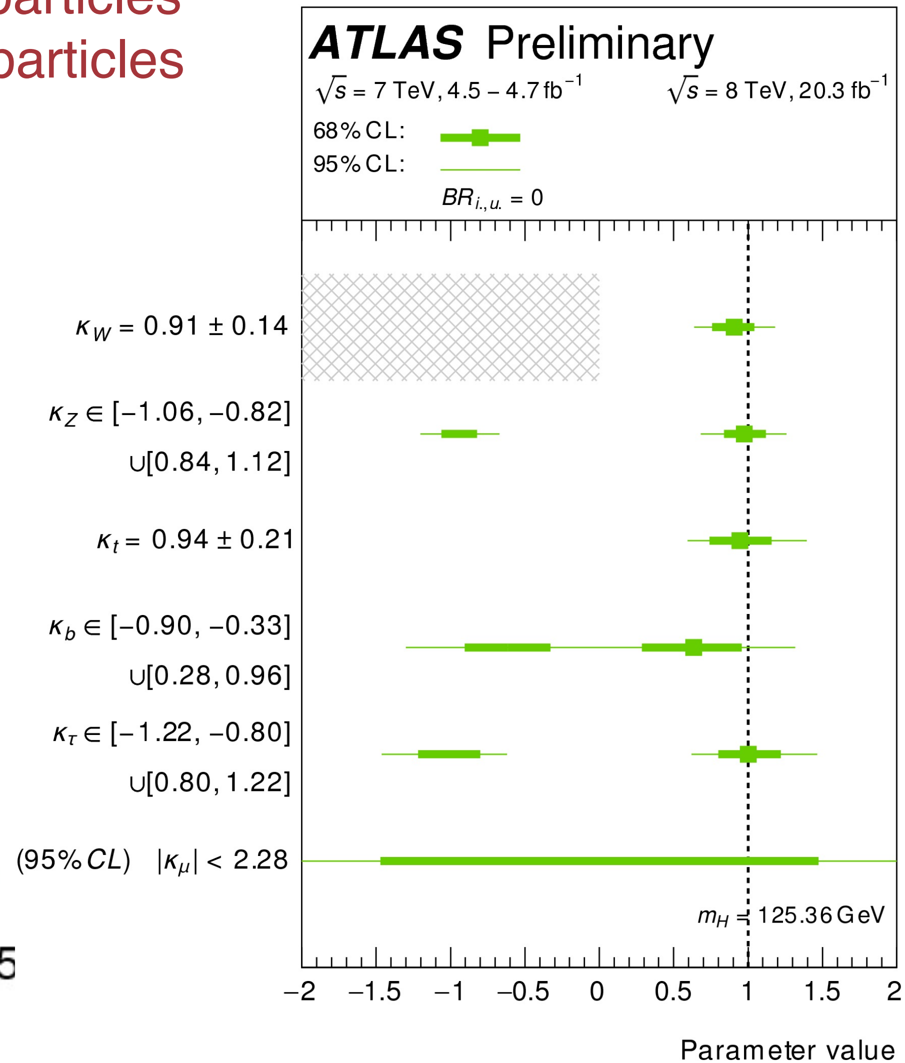
- BSM coloured or charged particles in loops could cause deviations

Couplings with SM Particle content

"Absolute couplings". Assumptions:

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





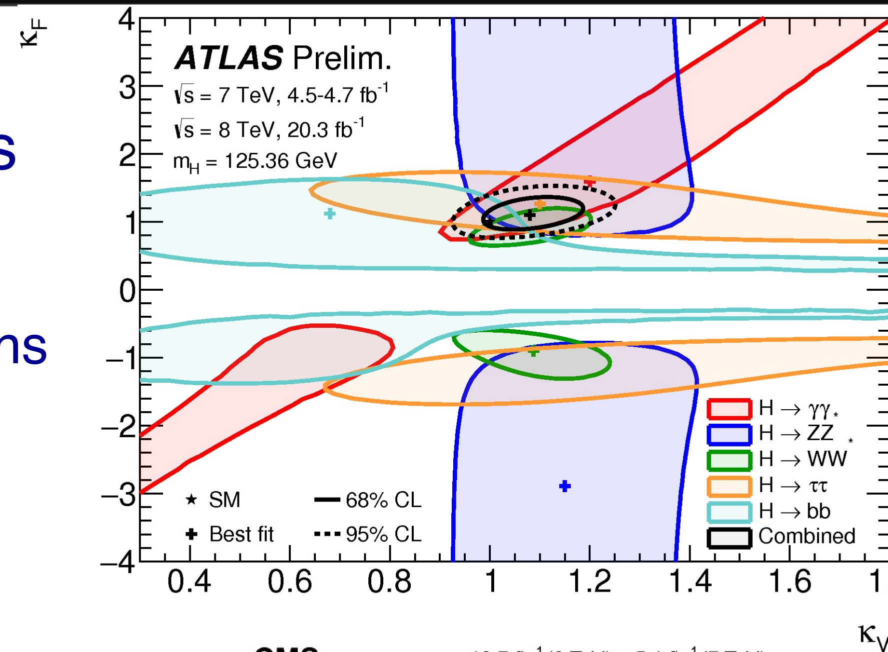
Coupling to Fermions and Bosons

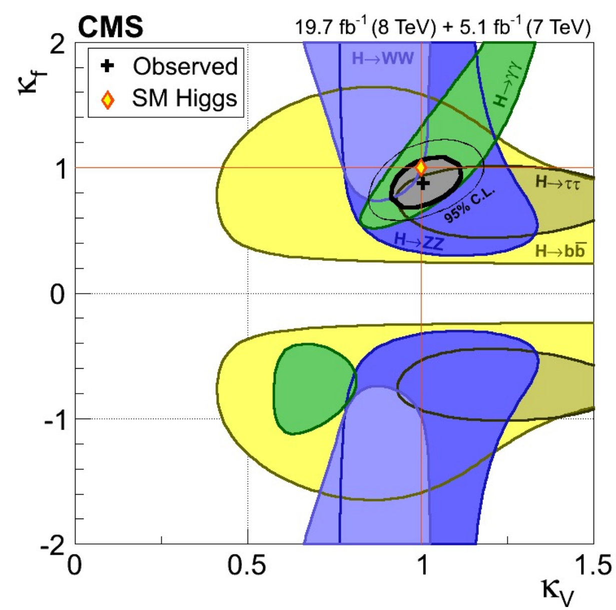
Test gauge vs Yukawa couplings

- 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





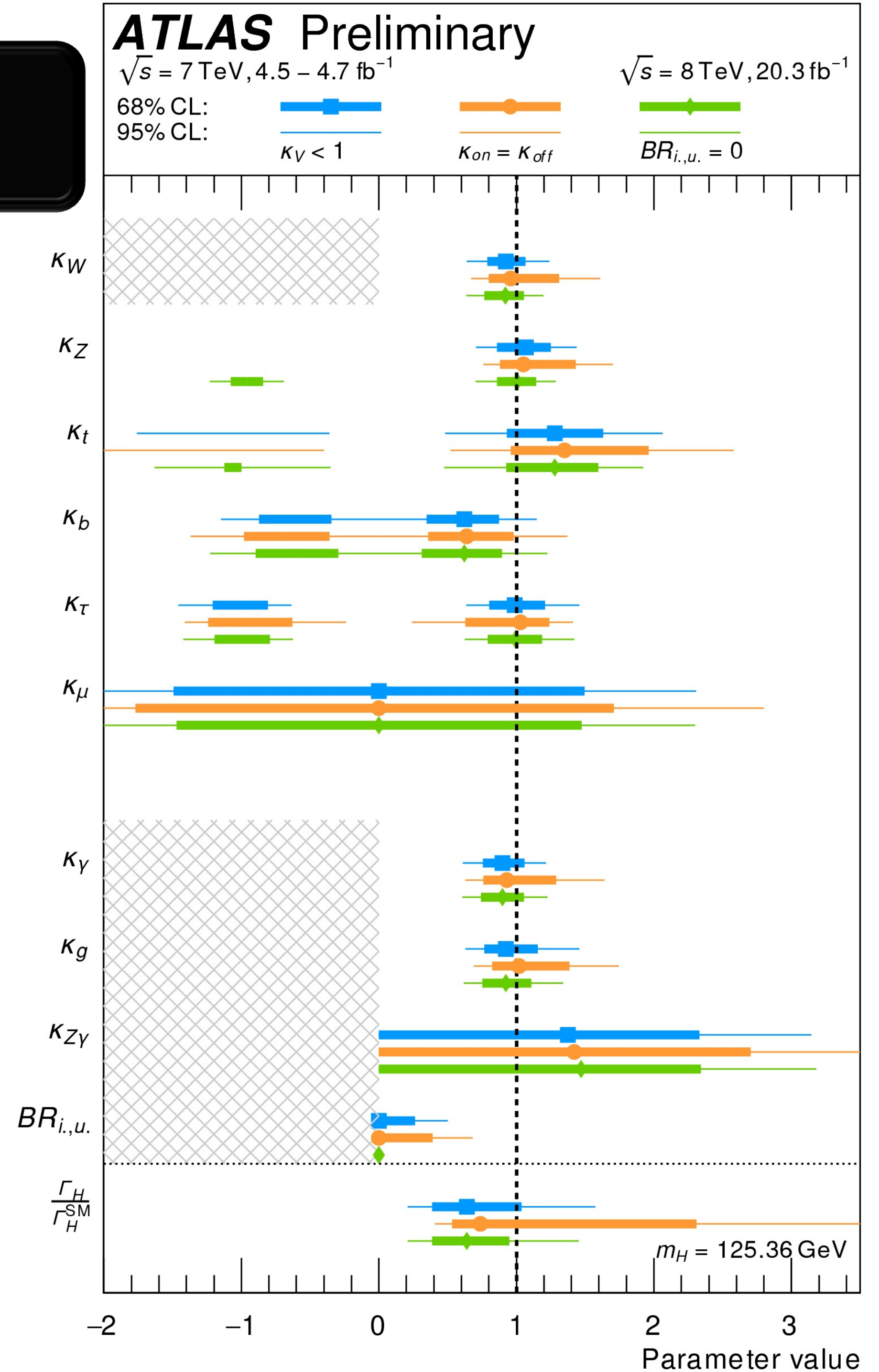
New Physics in the Loops?

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

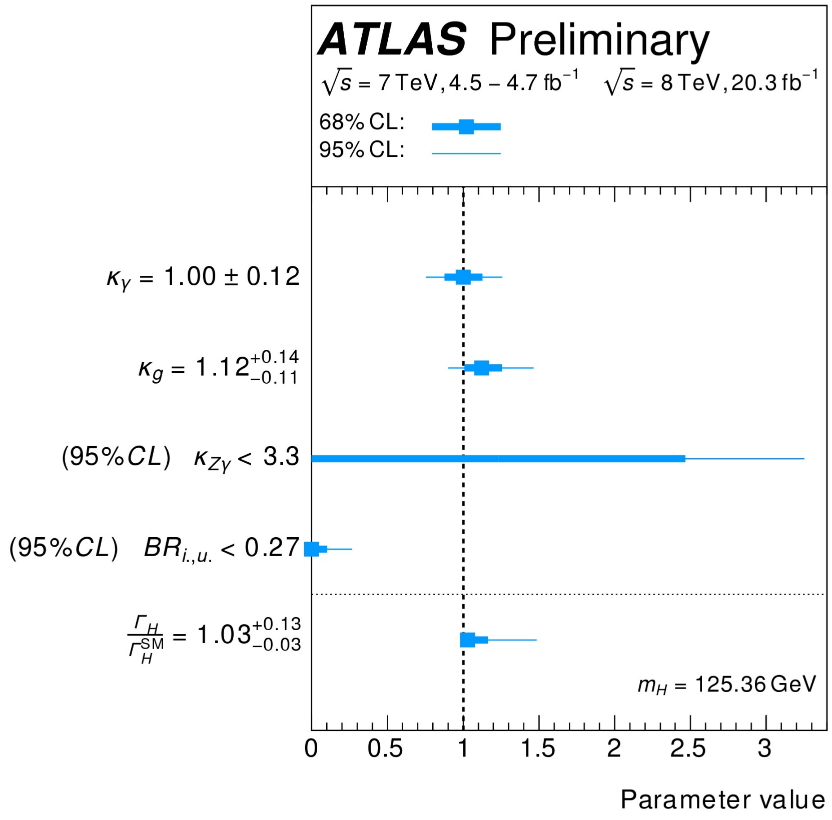
- Green diamond: impose no contributions to the width from BSM particles

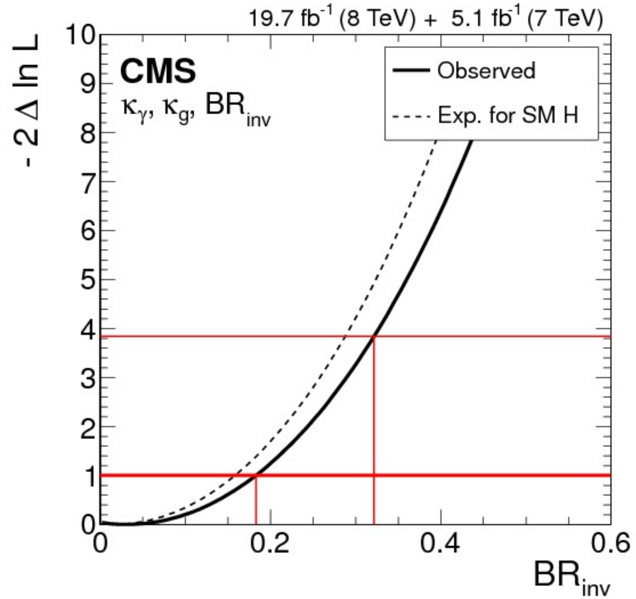


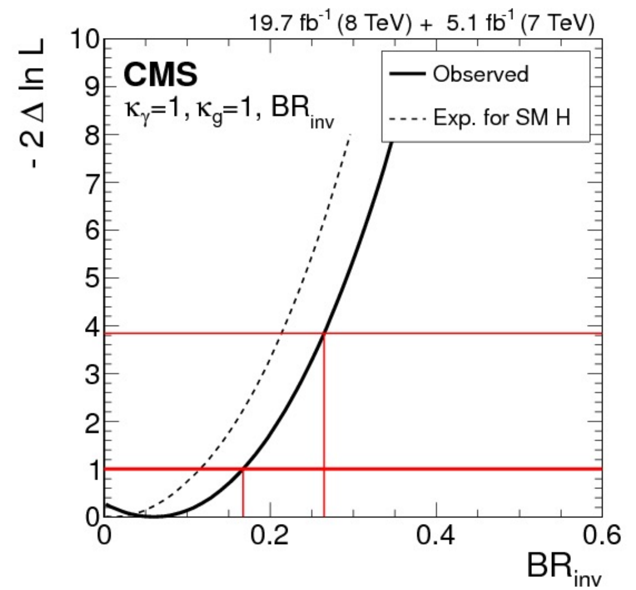
New Physics in the Loops?

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

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

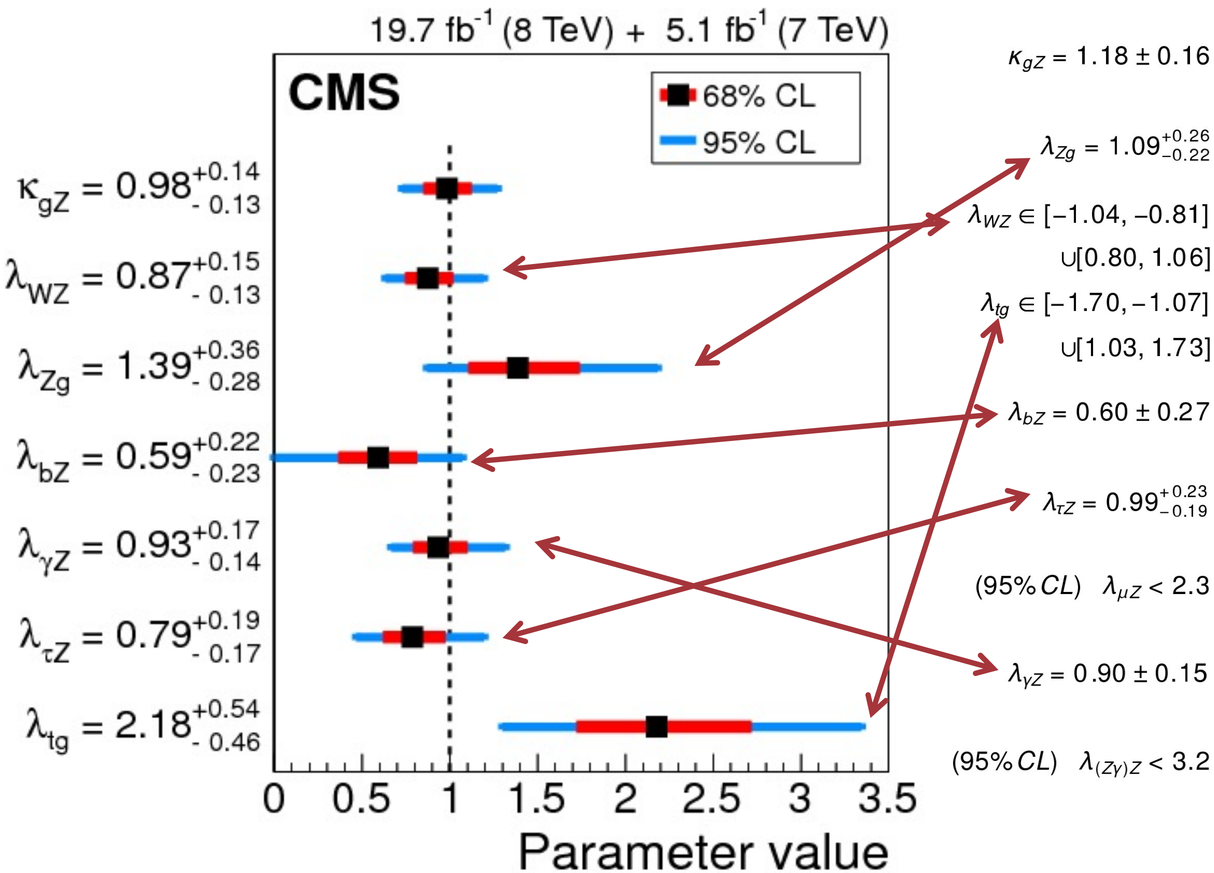


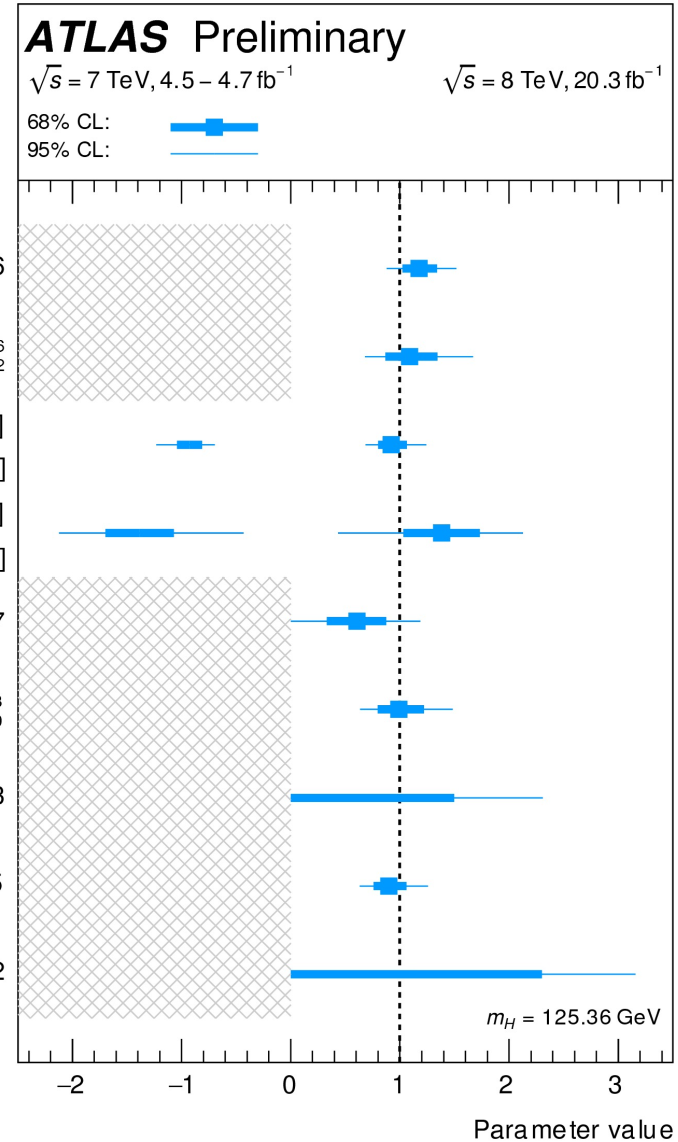




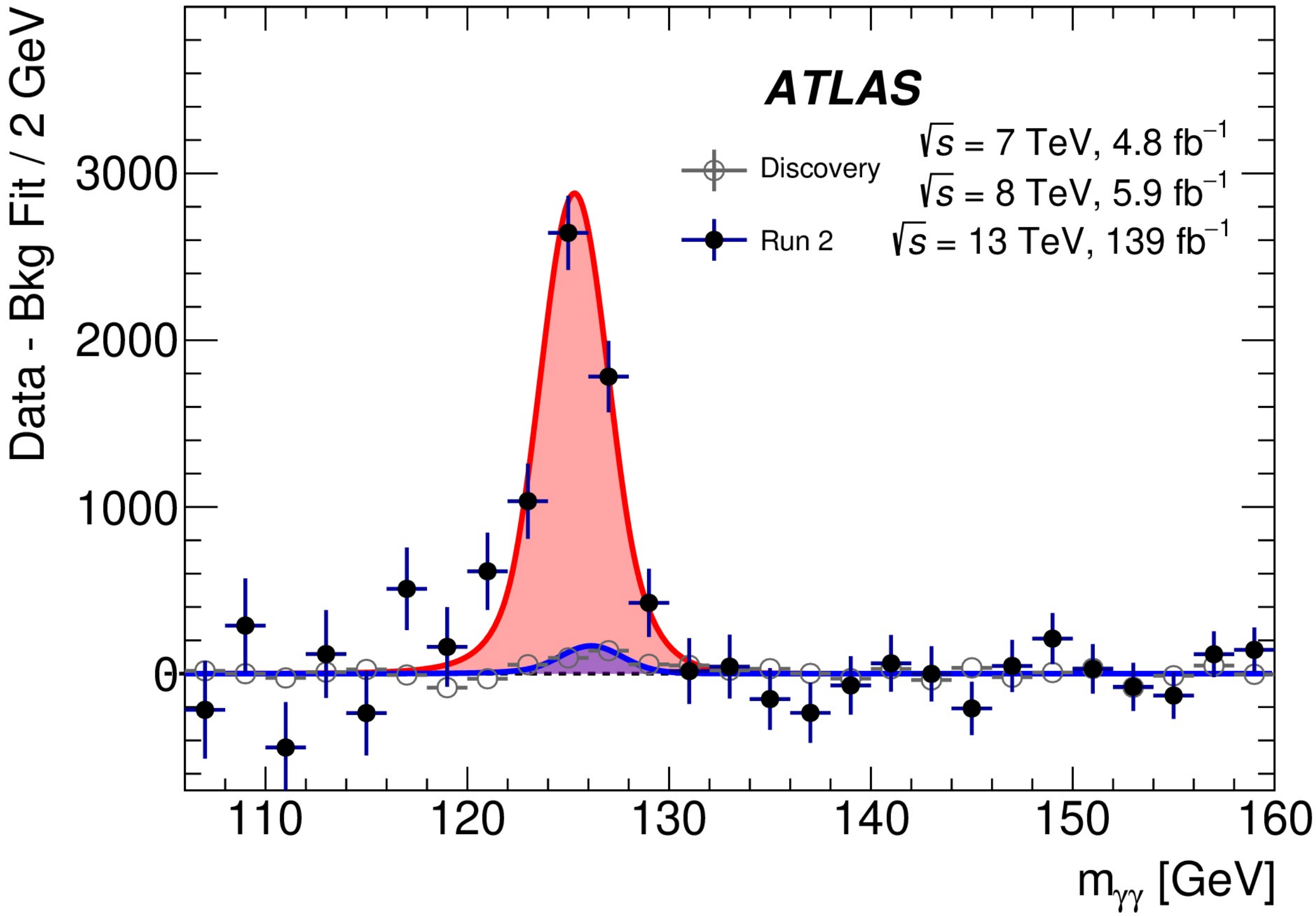
Most General Fit

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





Nature Paper



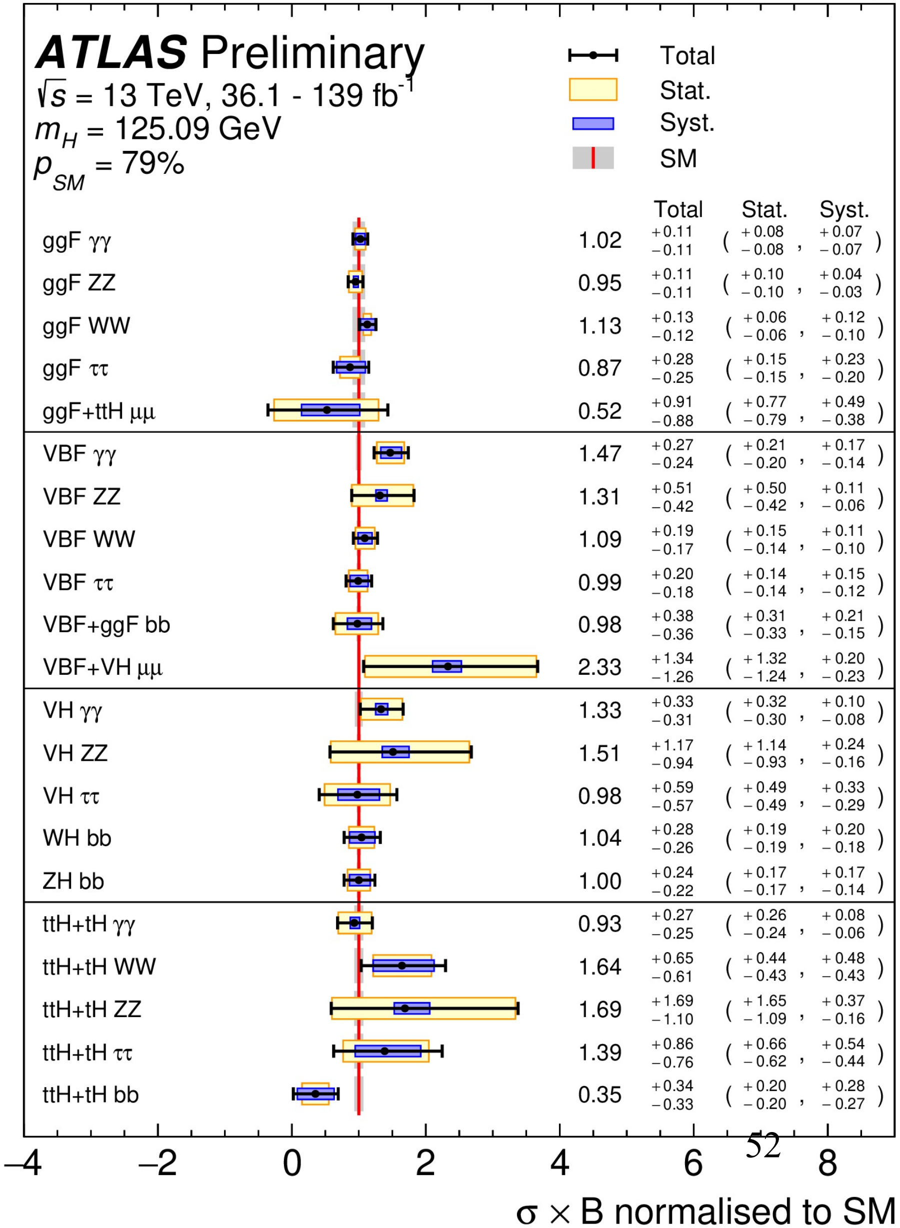
Production cross sections and branching ratios

Analyses performed by ATLAS and/or CMS have targeted the production and decay modes below:

	WW	ZZ	γγ	bb	ττ	μμ
ggH	X	X	X	X	X	X
VBF	X	X	X	X	X	X
WH	X	X	X	X	X	X
ZH	X	X	X	X	X	X
ttH	X	X	X	X	X	X

Right figure:

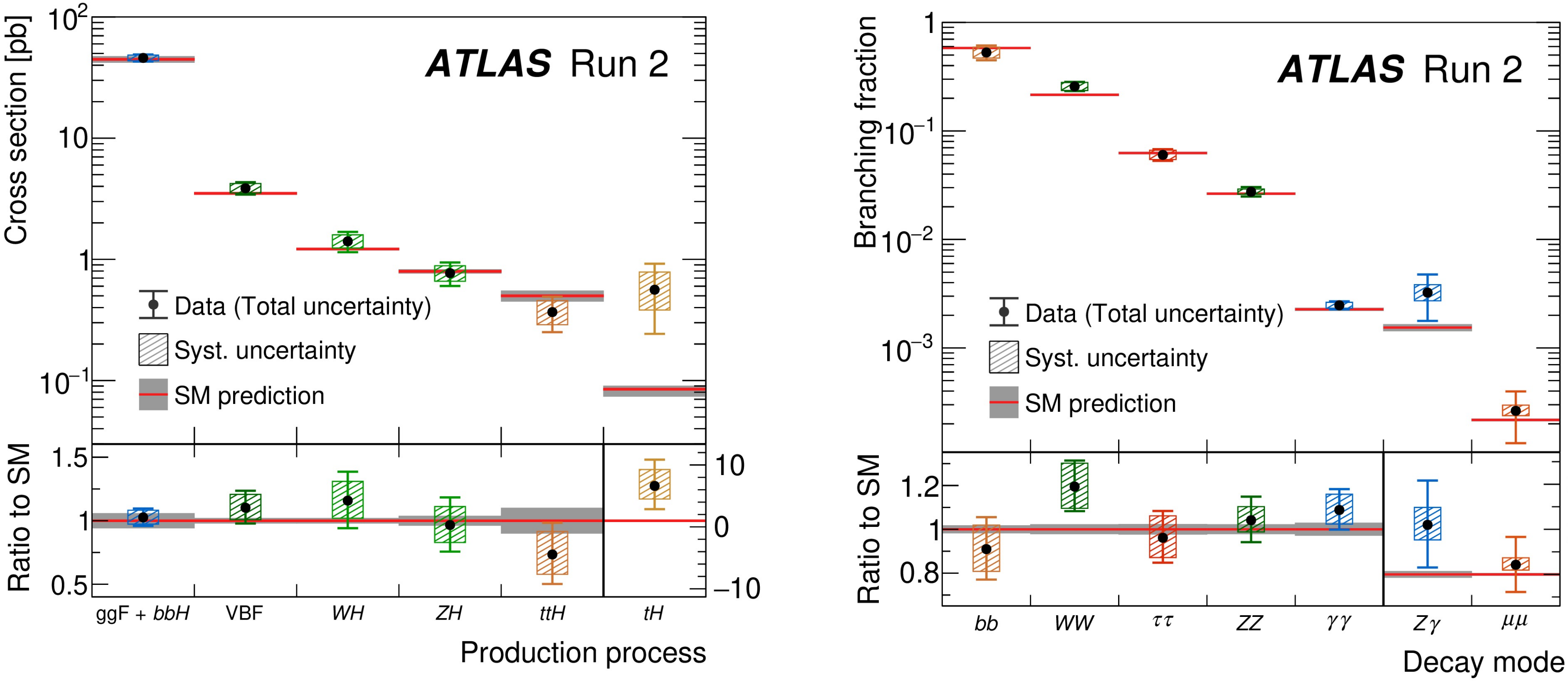
Higgs production cross sections times branching fractions normalised to Standard Model



Topics for presentation

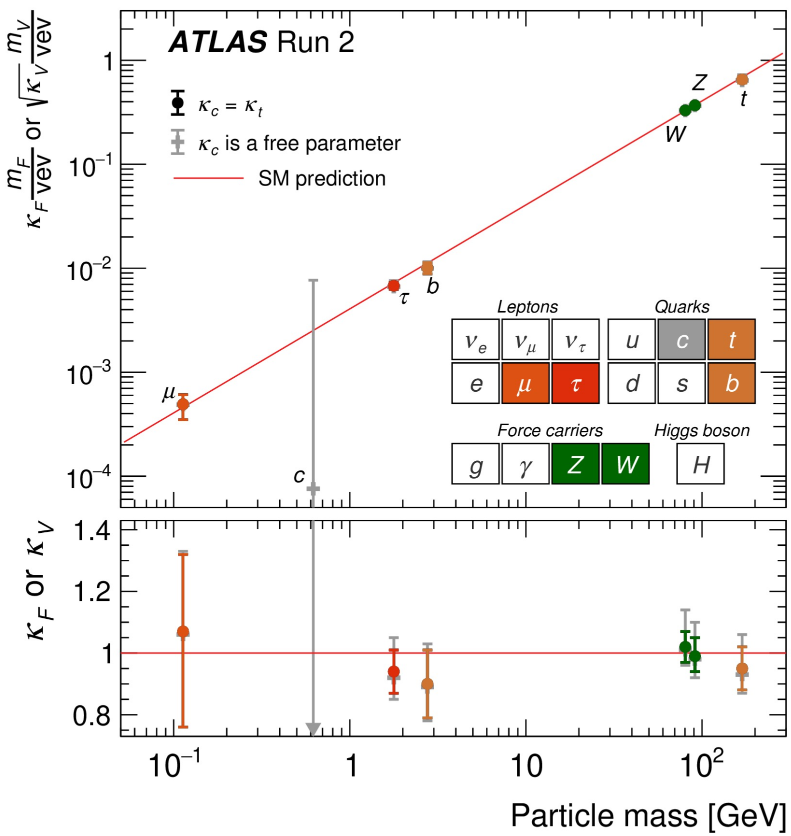
- B physics, CP
- The QCD axion
- Introduction to SCET
- Quartic Gauge boson couplings
- The Hierarchy problem: RS solutions
- Top quark pheno
- The Dirac Monopole
- Mass of the neutrinos: Majorana and/or Dirac, nu-less double beta decay
- Measuring Higgs couplings
- Neutrinos and CP violation: status
- Measuring the mass of the top quark
- What can we learn from a future e+/e- collider
- Measuring he Higgs self-coupling: prospects
- Dark Sectors
- WIMP Dark Matter summary
- The B physics anomalies —> update
- A prototype GUT: SU(5)
- The g-2 experiment and results
- IceCube: high energy neutrinos
- Hermeneutics of feline videology
- Resolving the neutrino mass hierarchy
- Neutron EDM experiments
- Introduction to supersymmetry and experimental status
- High energy cosmic rays
- Heavy ion collisions and quark-gluon plasma

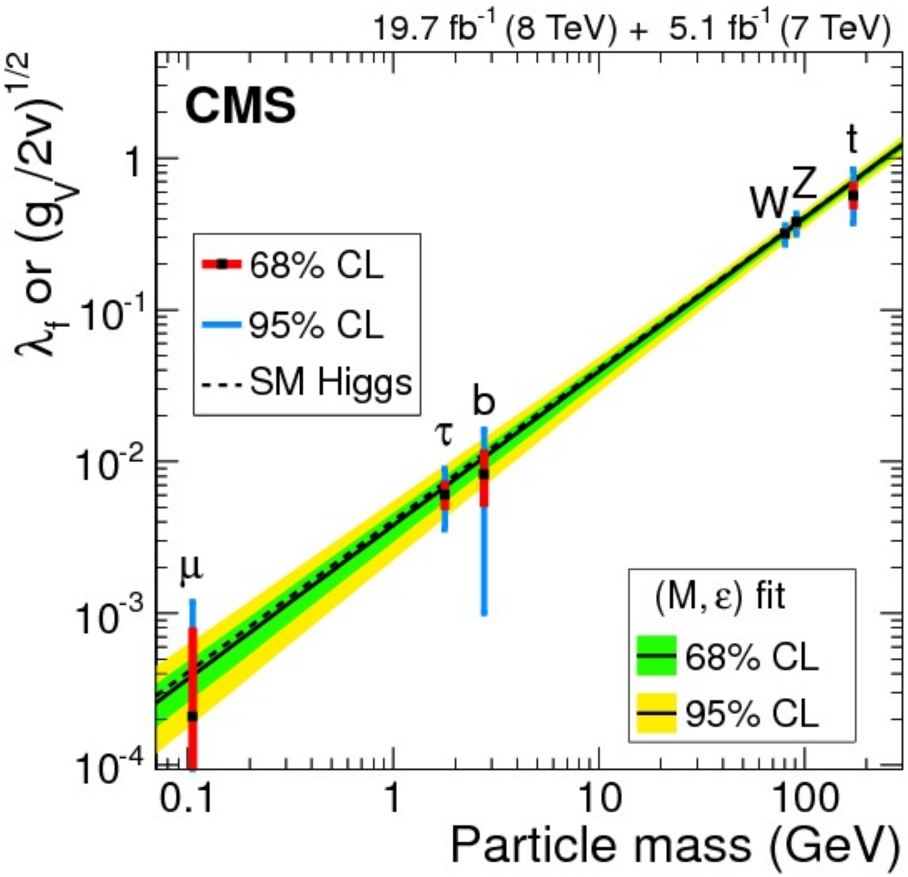
Nature Paper



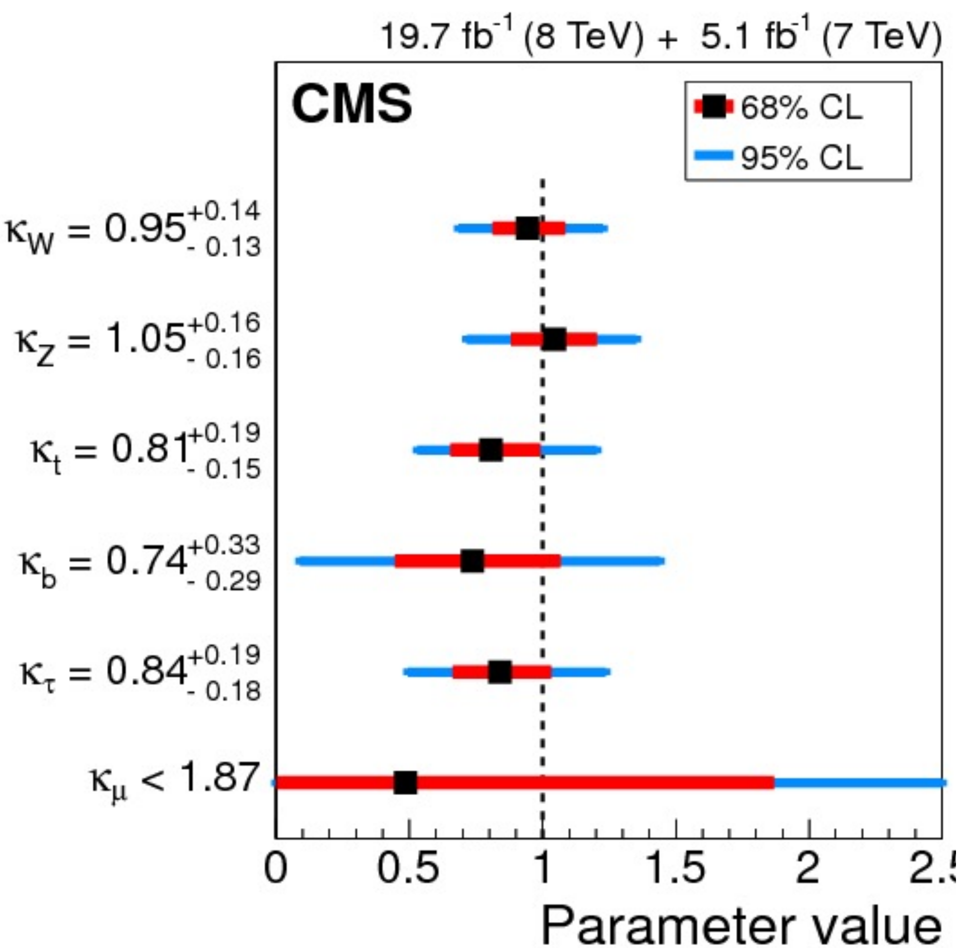
Higgs Couplings and Mass

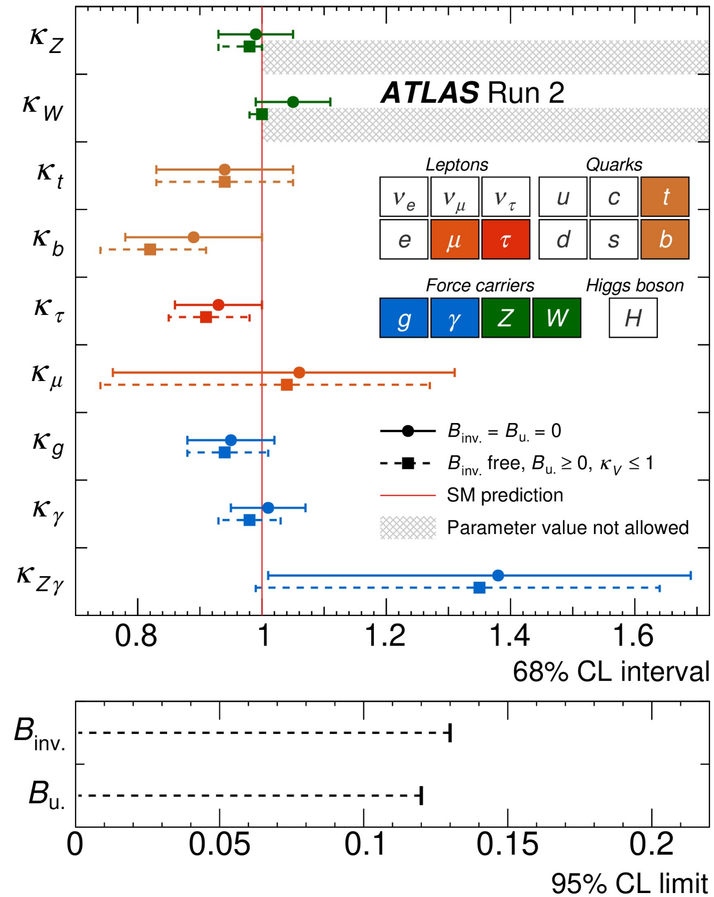
Couplings versus fermion mass or vector boson mass²





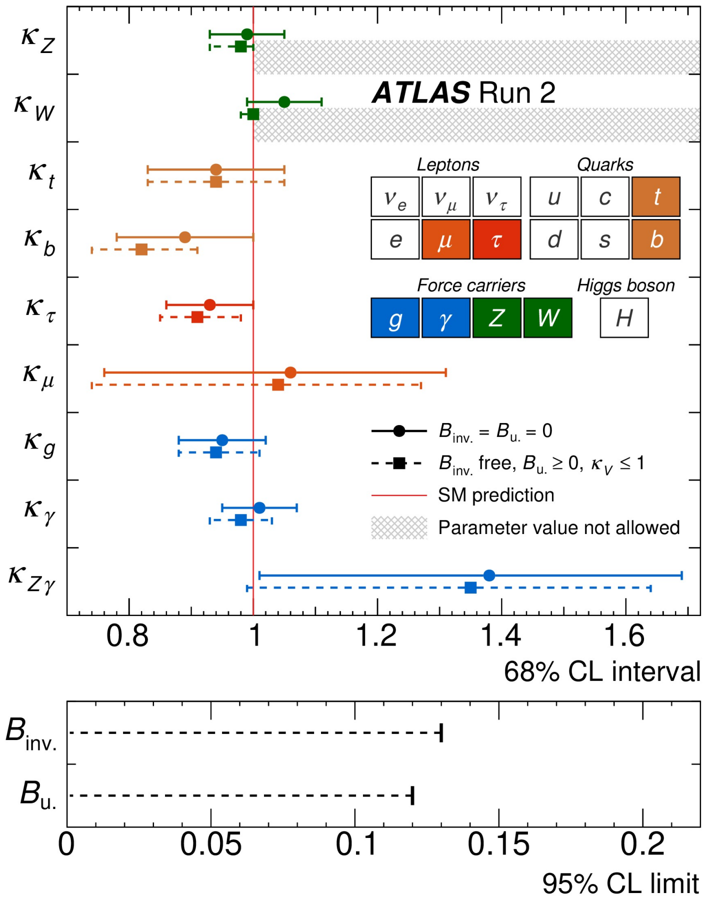
Couplings with SM Particle content



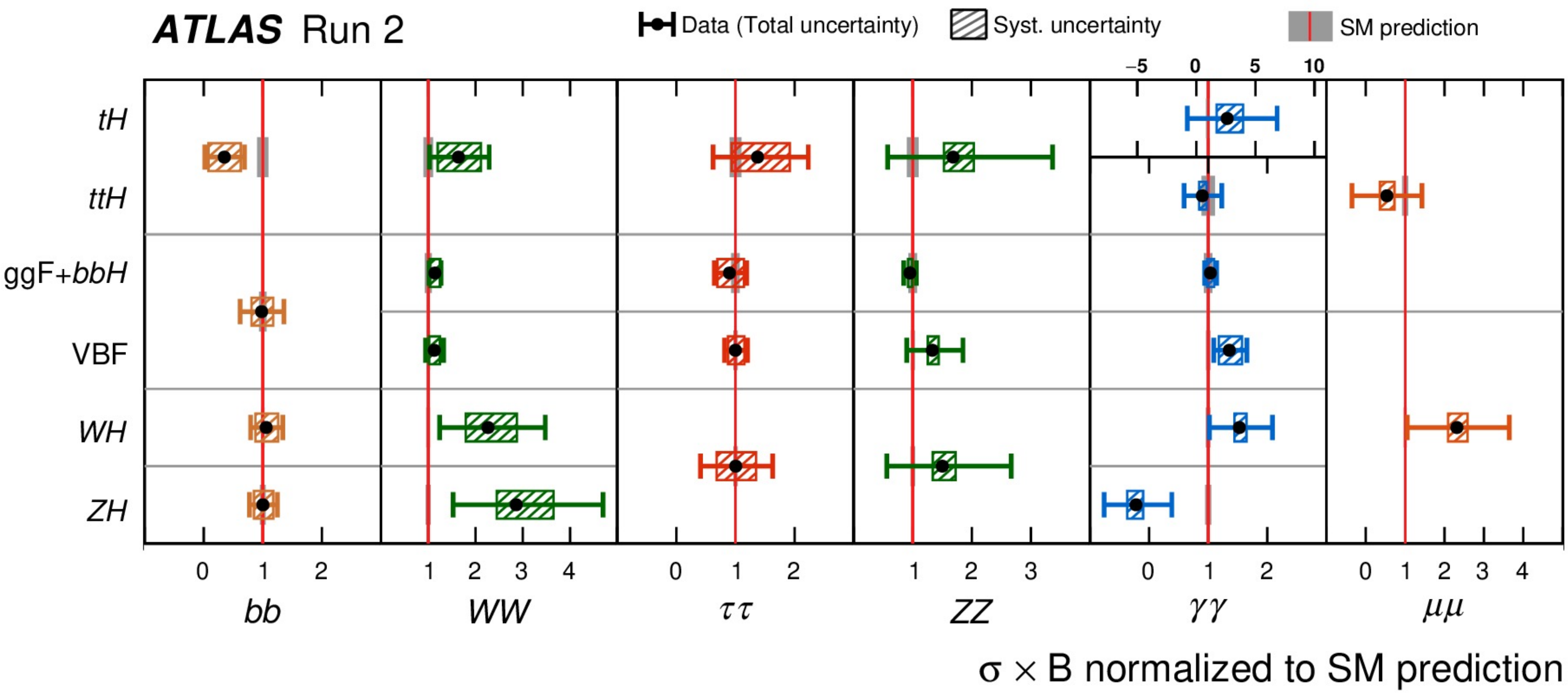


Higgs Couplings

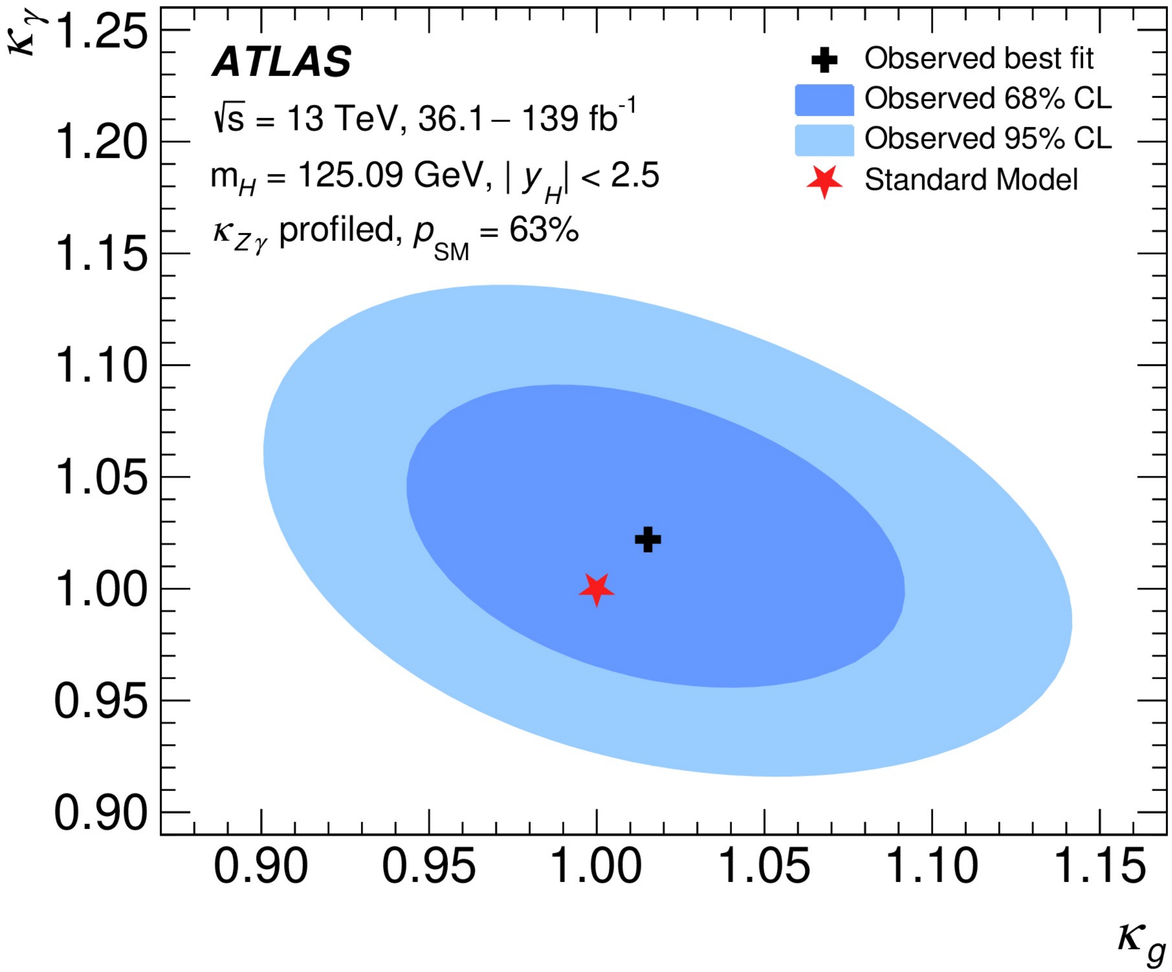
	(a) $B_{inv.} = B_{u.} = 0$	(b) $B_{inv.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	$0.99^{+0.06}_{-0.06}$	$0.98^{+0.02}_{-0.05}$
κ_W	$1.05^{+0.06}_{-0.06}$	$1.00_{-0.02}$
κ_t	$0.94^{+0.11}_{-0.11}$	$0.94^{+0.11}_{-0.11}$
κ_b	$0.89^{+0.11}_{-0.11}$	$0.82^{+0.09}_{-0.08}$
κ_τ	$0.93^{+0.07}_{-0.07}$	$0.91^{+0.07}_{-0.06}$
κ_μ	$1.06^{+0.25}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	$0.95^{+0.07}_{-0.07}$	$0.94^{+0.07}_{-0.06}$
κ_γ	$1.01^{+0.06}_{-0.06}$	$0.98^{+0.05}_{-0.05}$
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	$1.35^{+0.29}_{-0.36}$
$B_{inv.}$	-	< 0.13
$B_{u.}$	-	< 0.12



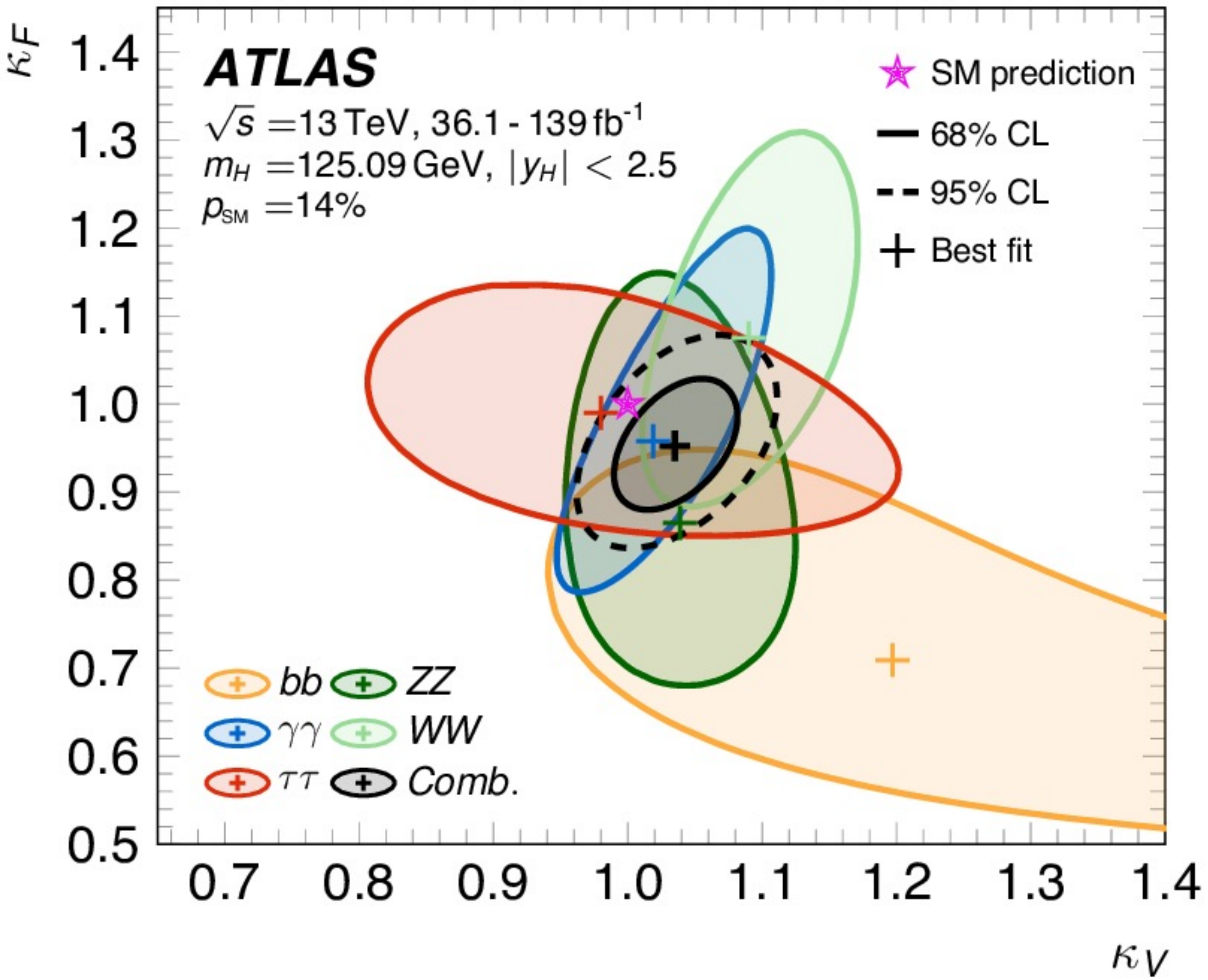
Nature Paper



Nature Paper



Nature Paper

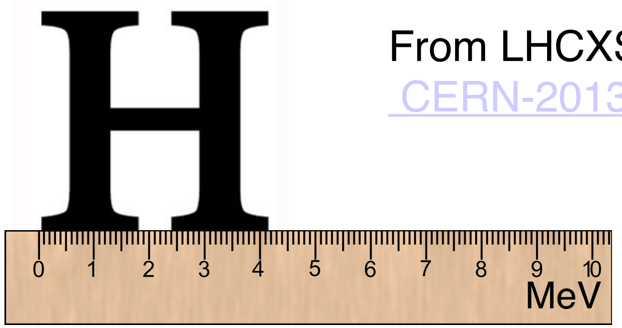


Higgs Natutal Width

Higgs width measurements at the LHC:

- Lifetime too short to measure
- Width too small to measure directly

SM width (m_H=125.1 GeV): 4.1 MeV



From LHCXSWG [CERN-2013-004]

- Indirect measurement possible:

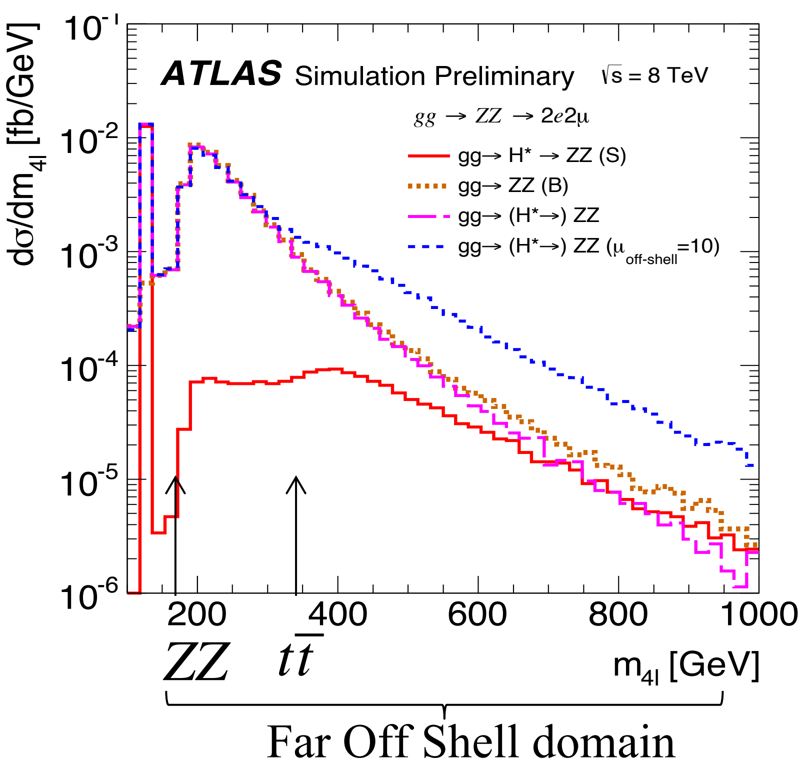
$$\sigma_{\text{on-peak}} \sim g^2_{ggH}\, g^2_{HZZ} / \Gamma^2_H$$

$$\sigma_{\text{off-peak}} \sim g^2_{ggH}\, g^2_{HZZ}$$

→ Can extract width by using ratio of on-shell to off-shell cross-sections

- Requires some assumptions e.g. off-shell and off-shell couplings are the same, no BSM backgrounds

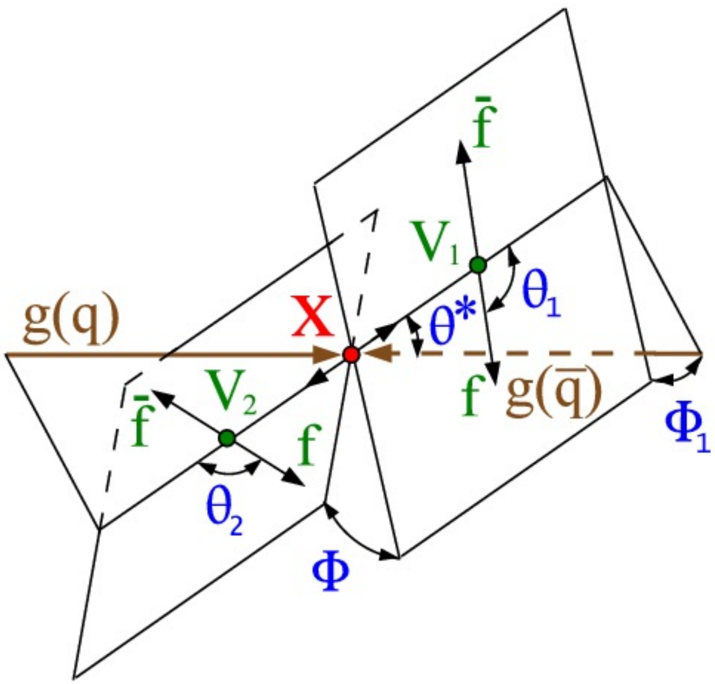
- Best results by CMS: $3.2^{+2.4}_{-1.7}$ MeV



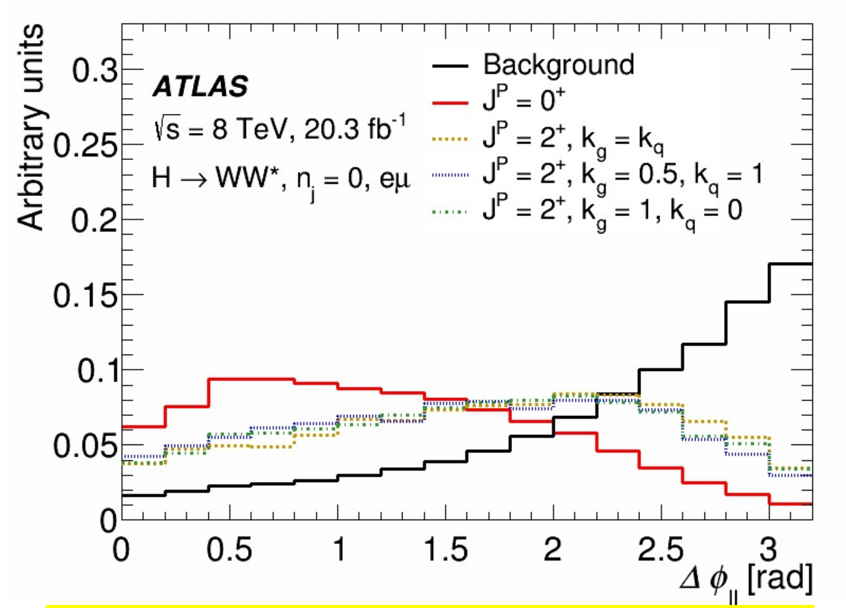
Spin/CP Hypotheses Tests

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

ZZ: full kinematic information available for spin/CP determination

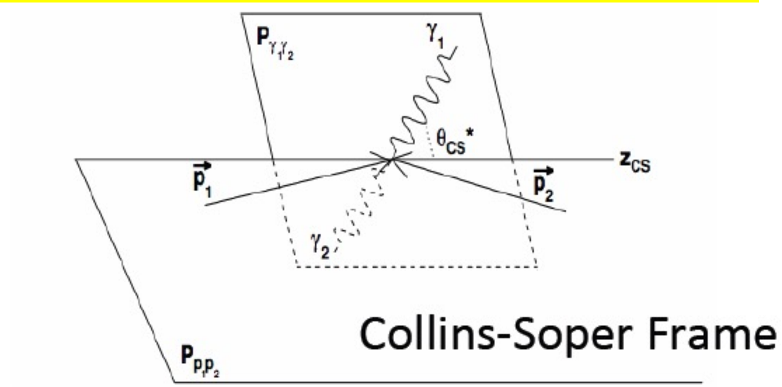


WW spin information from kinematic variables



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

$\gamma\gamma$



Fixed Spin and Parity Tests

Test alternative fixed spin and parity hypotheses relative to the SM 0^+ hypothesis

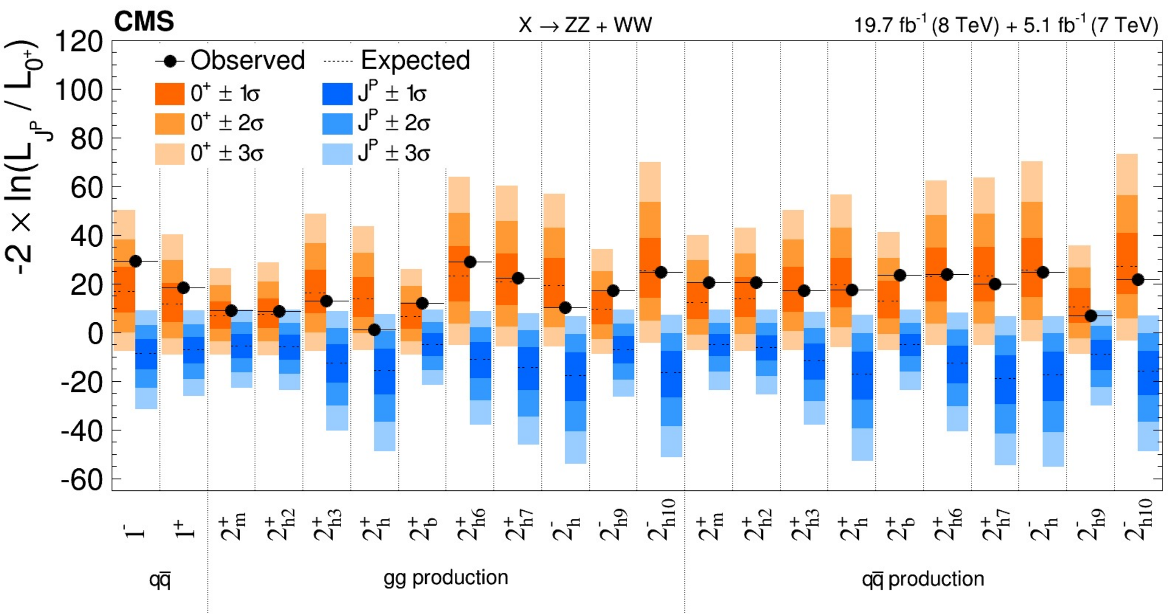
$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\mathrm{SM}}, \hat{\hat{\mu}}_{J^P_{\mathrm{SM}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{SM}}})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}$$

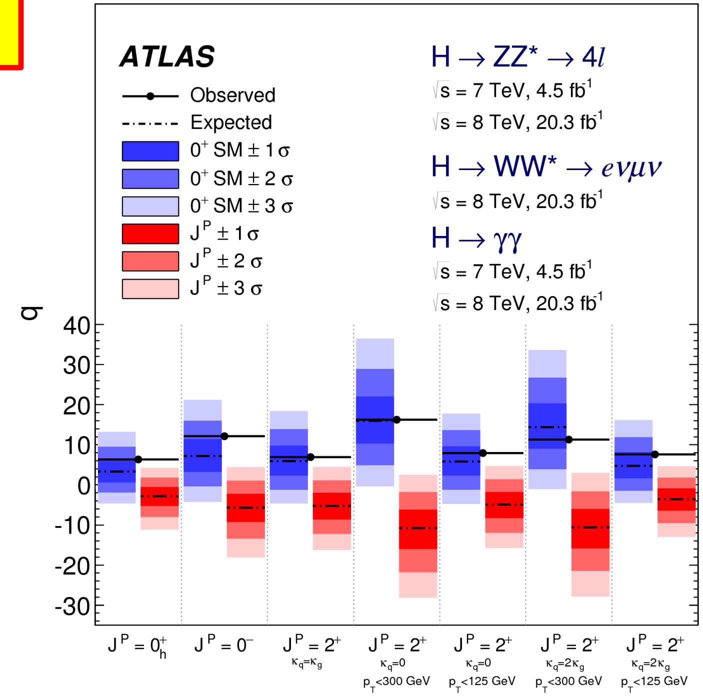
Results favour the spin 0^+ hypothesis

Alternatives: 0-, 1-, 1+, various spin 2 models are typically excluded at > 99.9% CL

Also Tevatron results: **arXiv:1502.00967**

Large anomalous couplings are excluded. Next steps: look for presence of smaller contributions



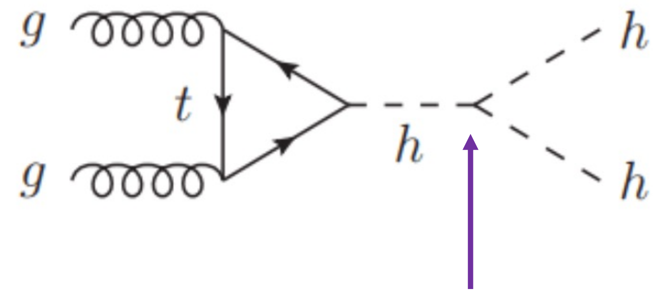


Higgs Self-Coupling

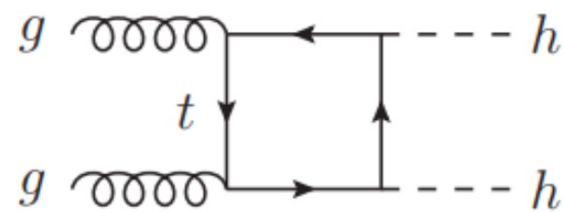
Making progress towards testing the shape of the Higgs potential through the Higgs self-coupling (λ_3)

Sensitivity to SM-strength coupling will require HL-LHC but much progress has been made in recent years

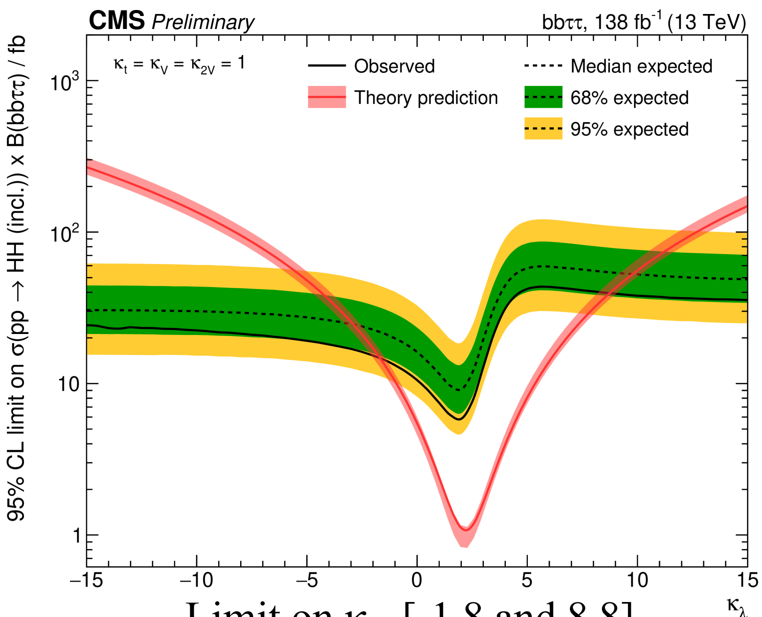
Recent $bb\tau\tau$ result from CMS (left), combination of $bb\tau\tau$ and $bb\gamma\gamma$ from ATLAS (right)



$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

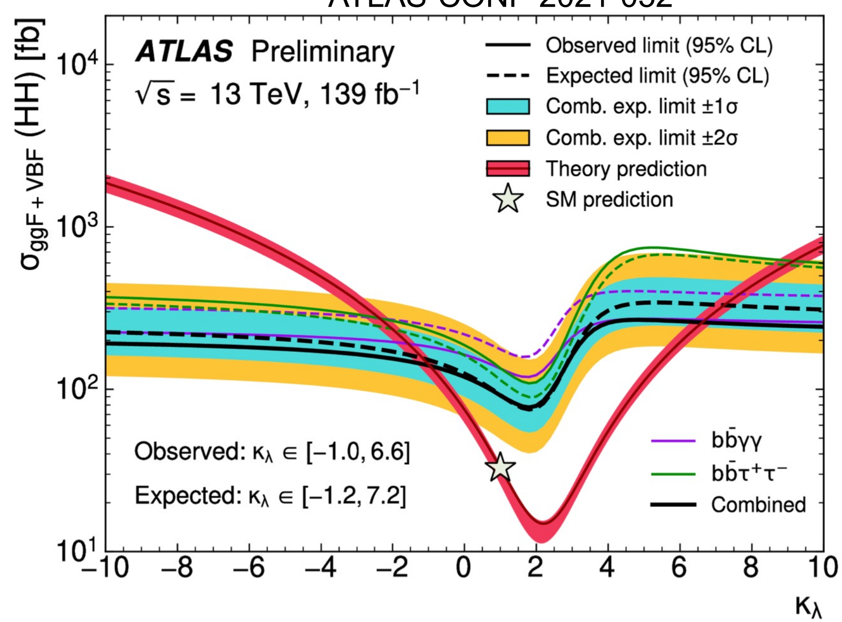


CMS-PAS-HIG-20-010



Limit on κ_λ [-1.8 and 8.8]

ATLAS-CONF-2021-052



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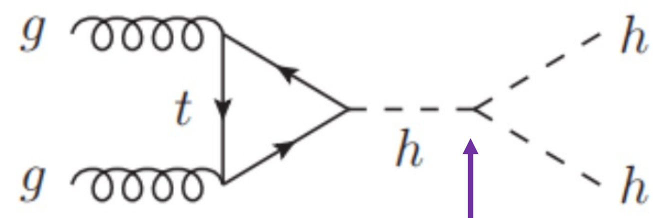
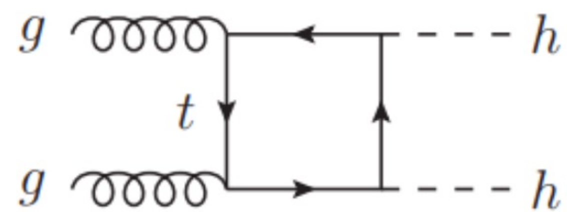


$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda v H^3 + \cdots$$



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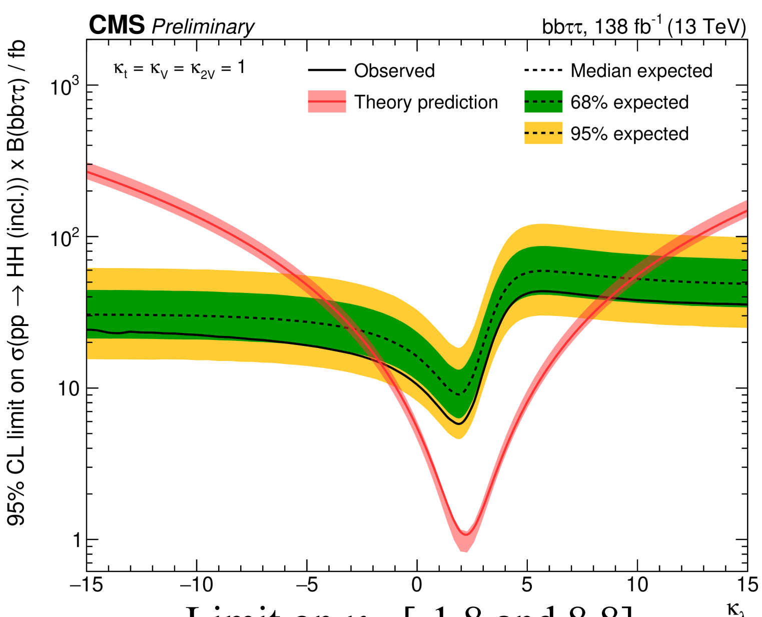

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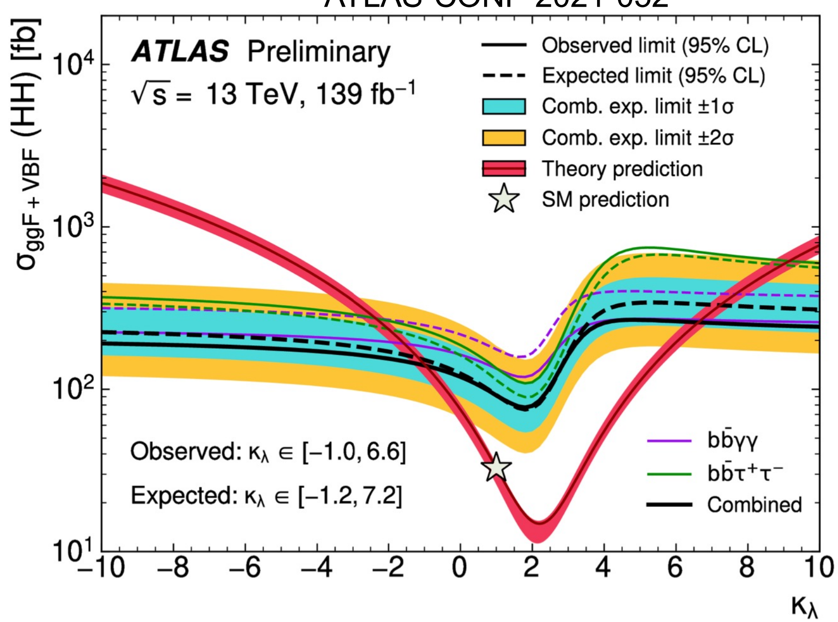
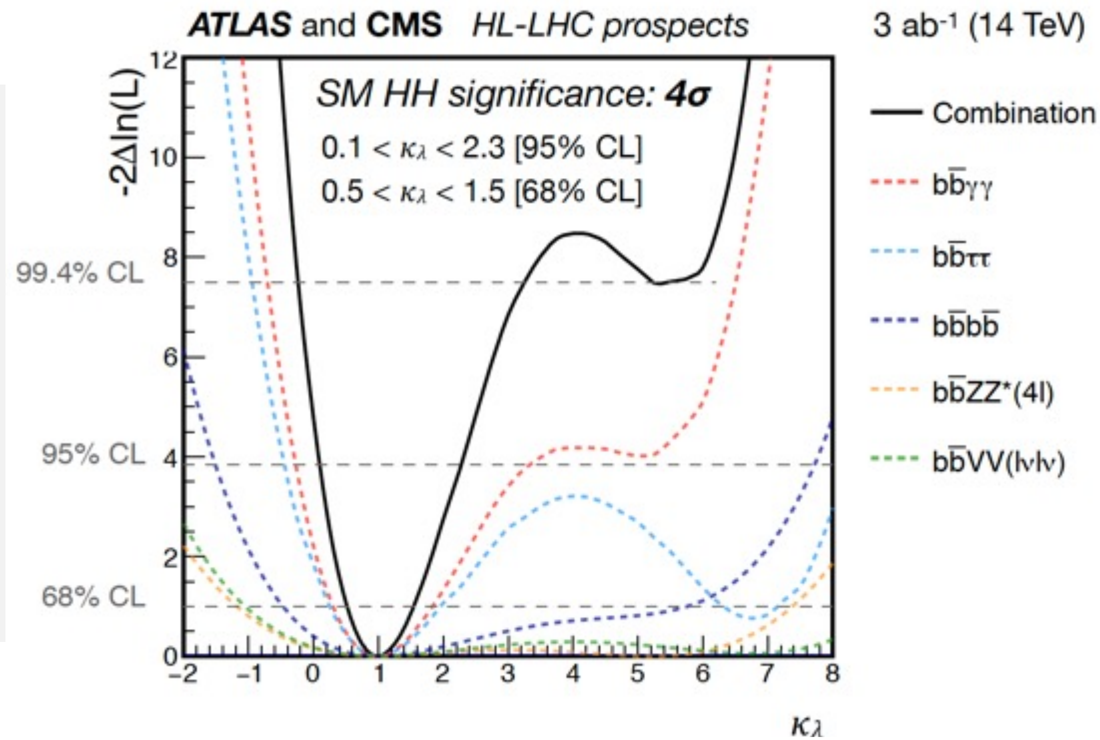


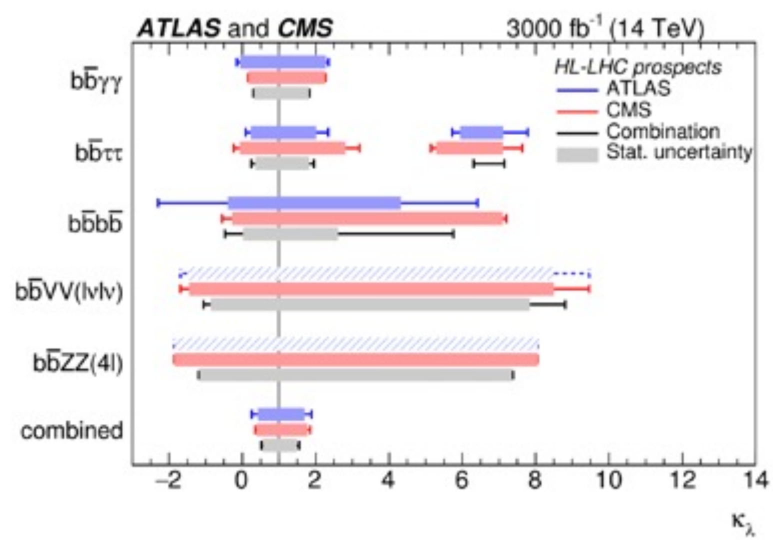
HL-LHC: Higgs Self-Coupling

CERN-LPCC-2018-04

- Significance of HH signal at the 4σ level (both exp.)
- Uncertainty on κ_λ of 50%
  - 2nd minimum excluded at > 99% CL
- Note that HH observation analysis and κ_λ analysis require different optimizations



	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

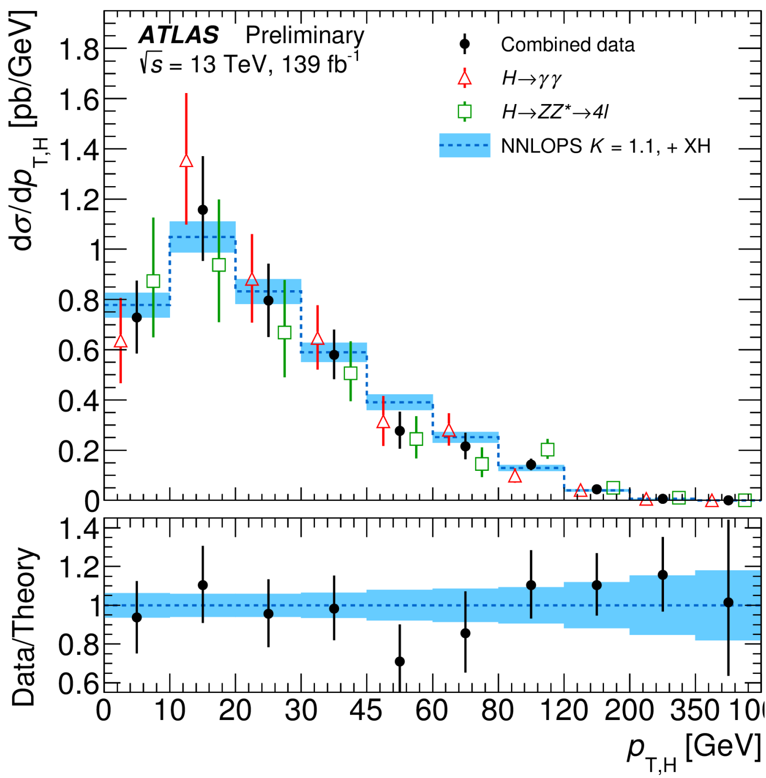


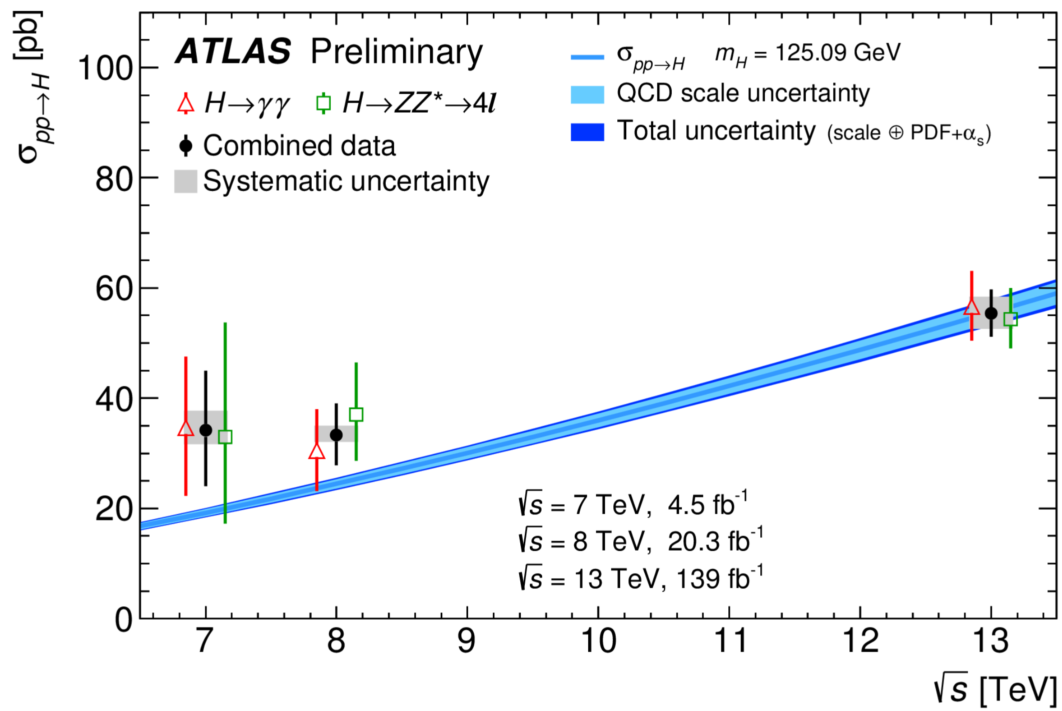
Higgs Boson Cross Sections

Full Run-2

Statistical combination for total and differential cross section measurements

ATLAS-CONF-2019-032





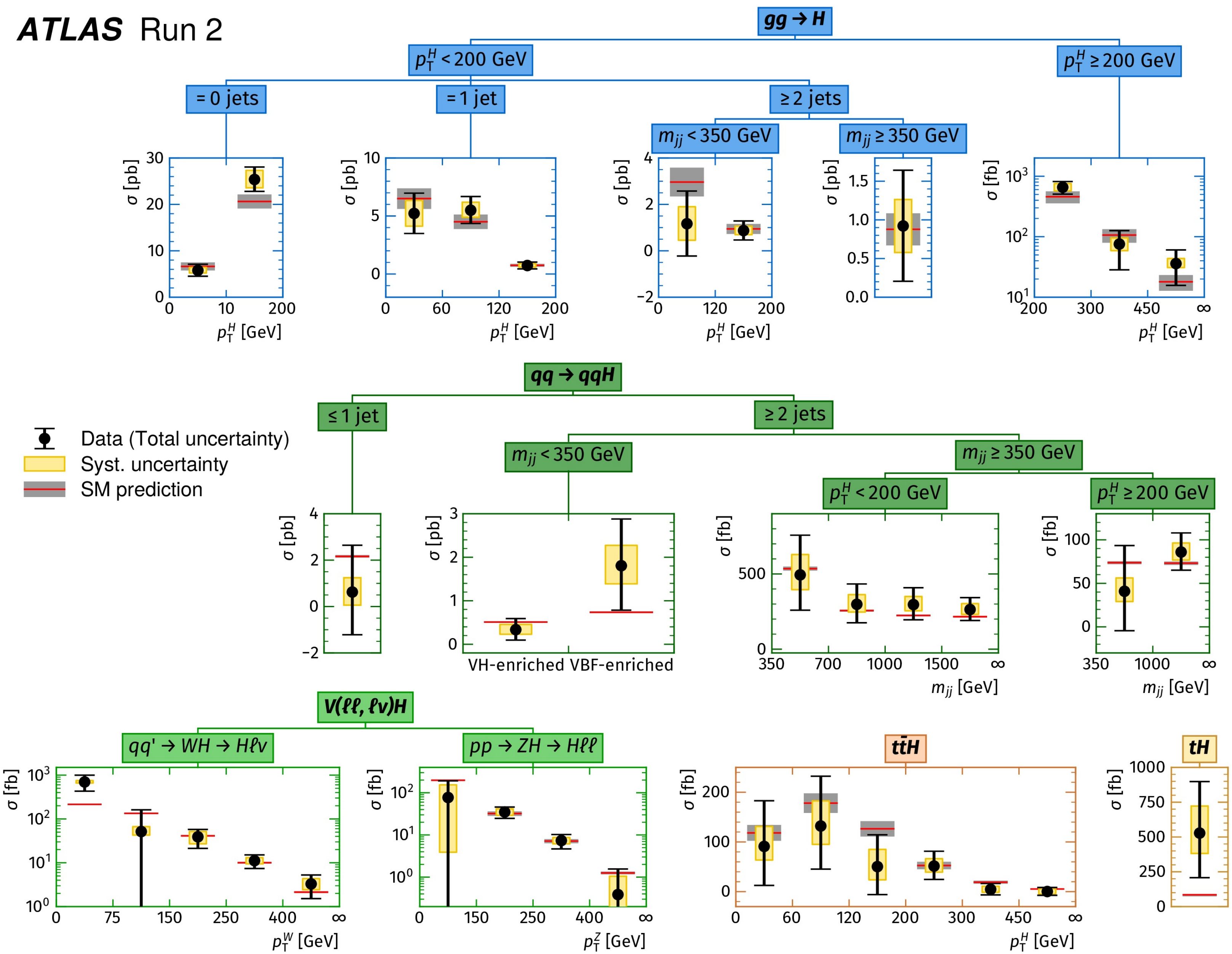
Combined inclusive pp → H + X cross section:

$$\sigma(pp \to H) = 56.7\,^{+6.4}_{-6.2}(\gamma\gamma),\ 54.4\,^{+5.6}_{-5.4}(4\ell),\ 55.4\,^{+4.3}_{-4.2}(\text{comb})\ \text{pb}$$

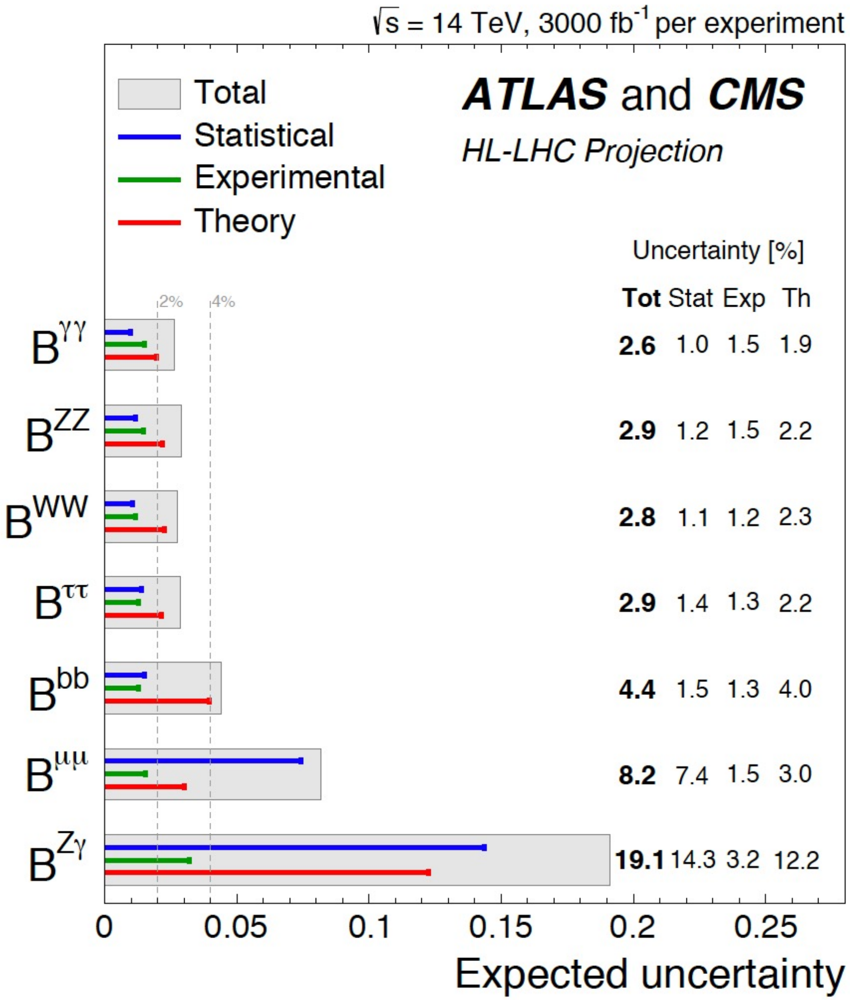
(Precision of 7.7%)

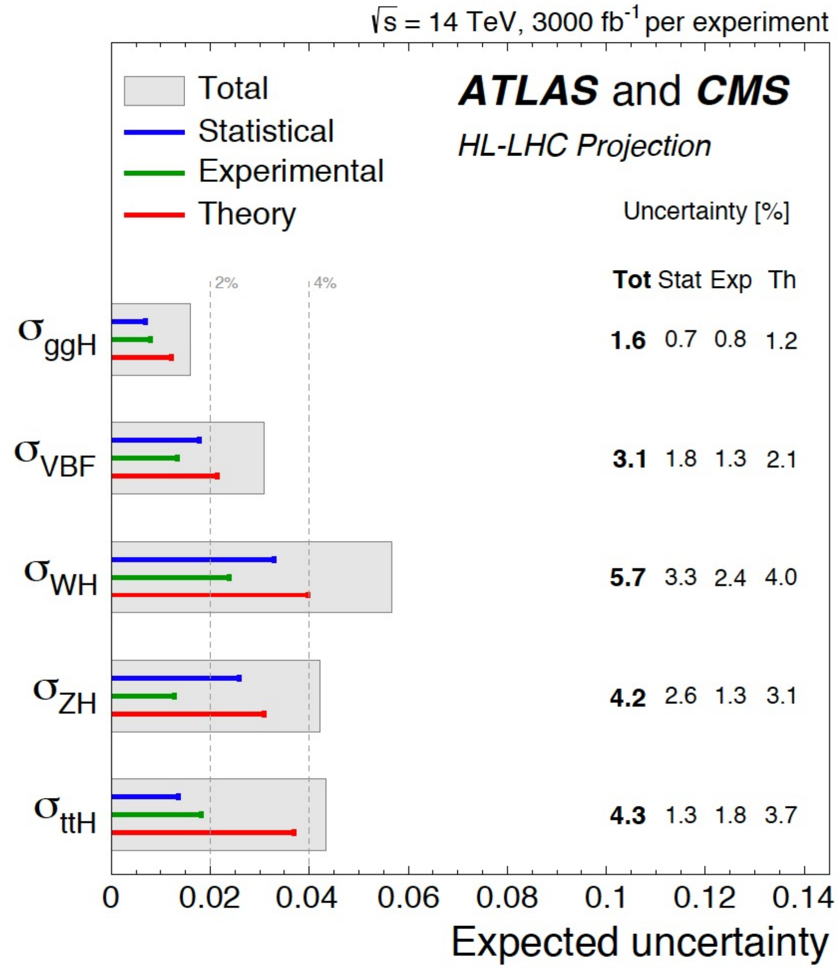
SM: 55.6 ± 2.5 pb (NLO–3NLO QCD, NLO EW)

Simplified Template Cross Sections



HL-LHC: Branching Ratios and Cross Sections

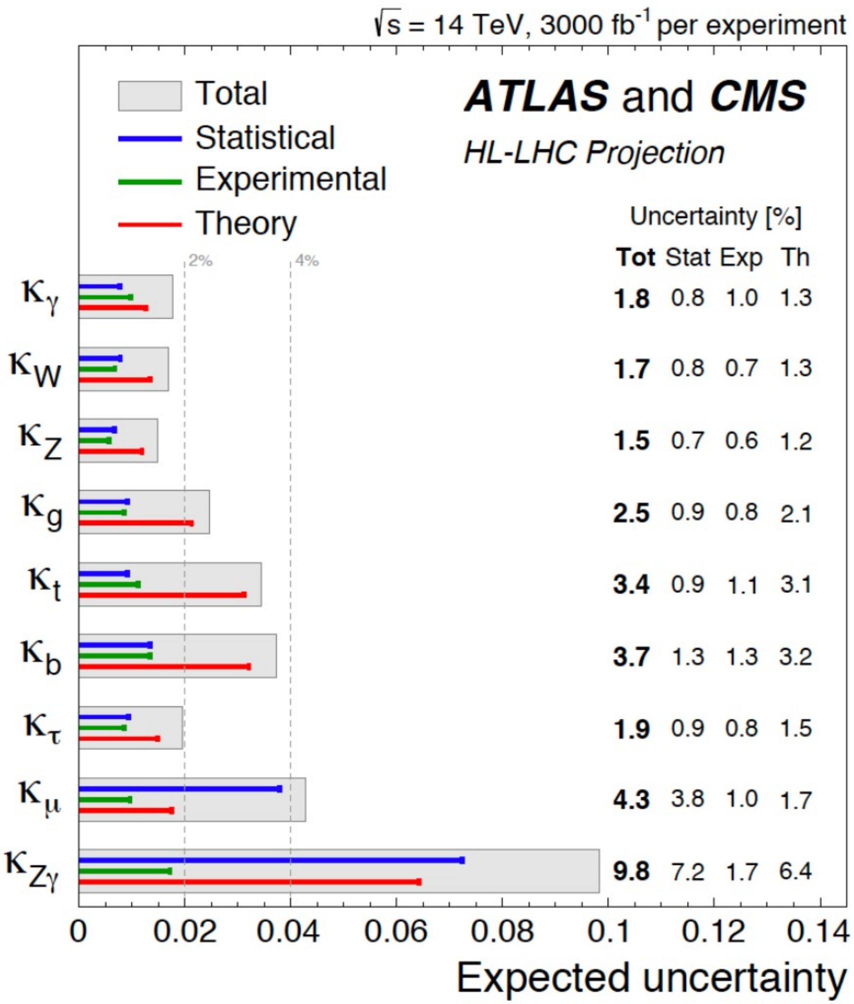


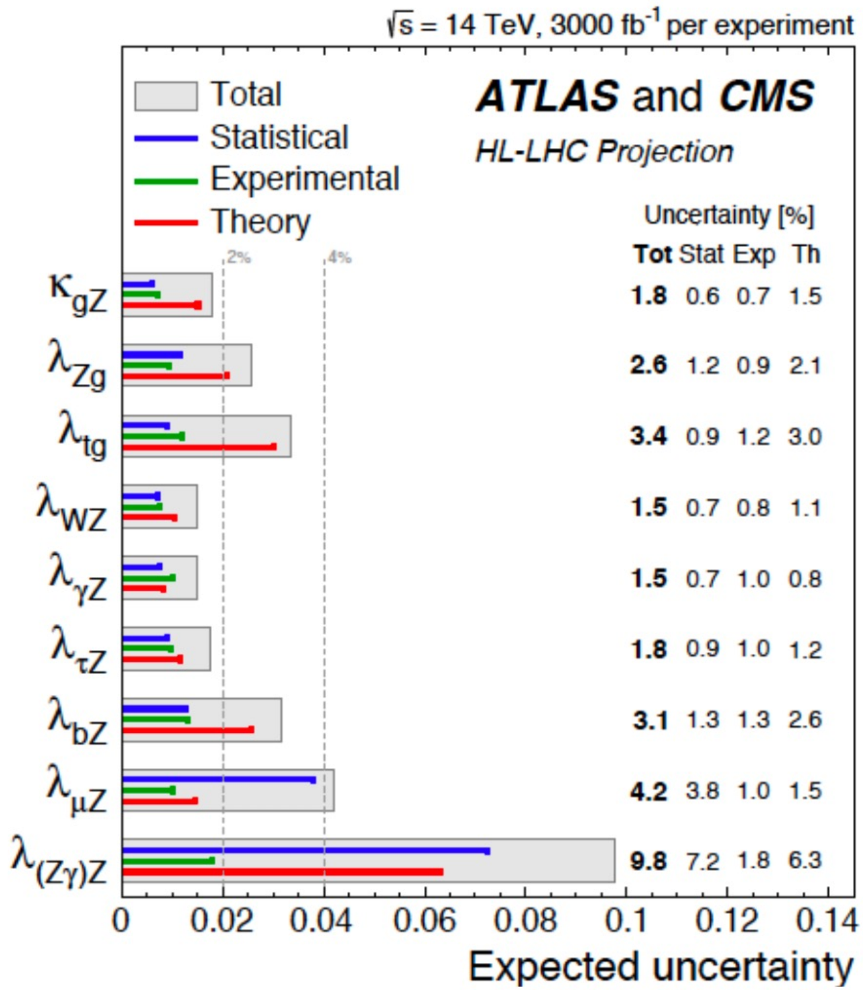


Combination of ATLAS and CMS for systematic uncertainty scenario 2

- Theory uncertainty remains the largest component for most measurements

HL-LHC: Couplings and Coupling Ratios





Combined results for ATLAS and CMS for systematic uncertainty scenario 2

- Coupling ratios on the right allow for reduced uncertainties in general

HL-LHC: Higgs Self-Coupling

CERN-LPCC-2018-04

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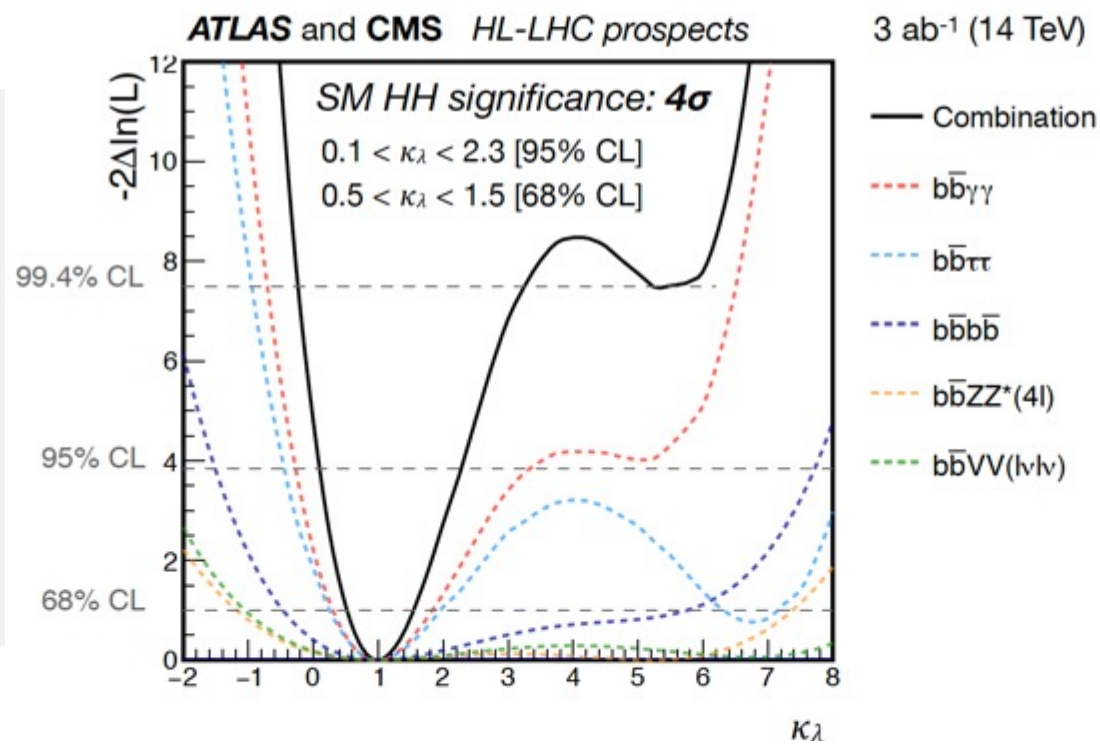

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