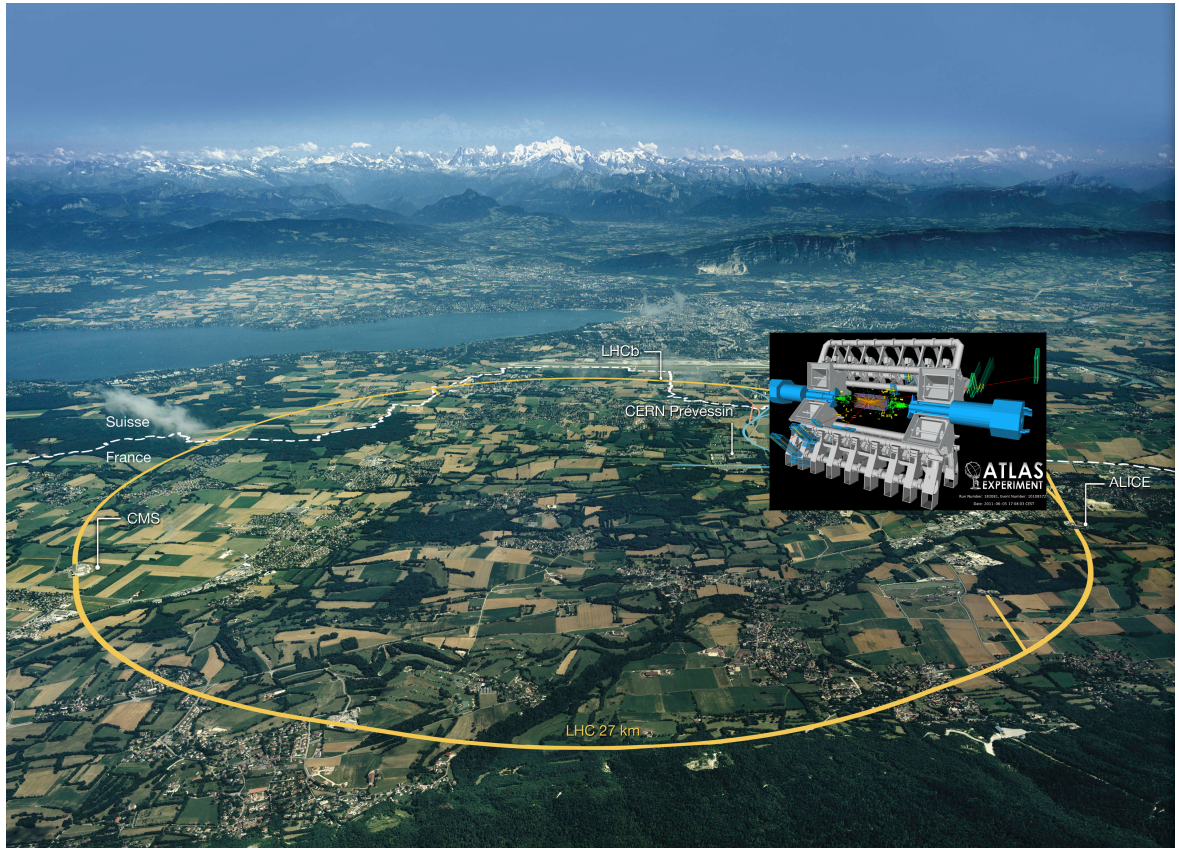
Probing fermion flavour structure with rare and exotic Higgs boson processes



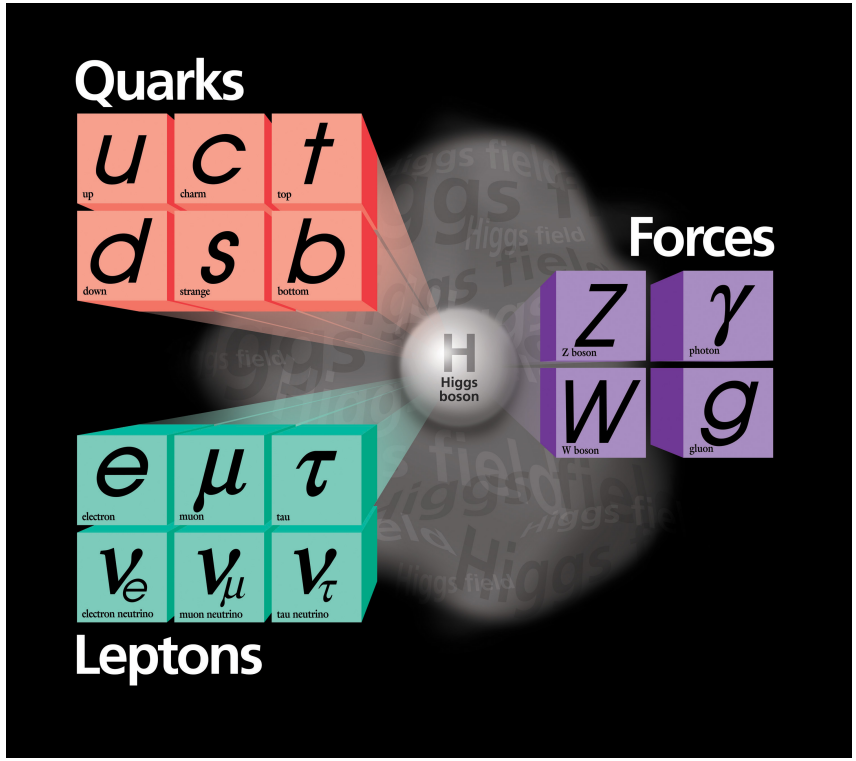
Rustem Ospanov for the ATLAS collaboration

University of Manchester

Saclay, November 21st, 2016

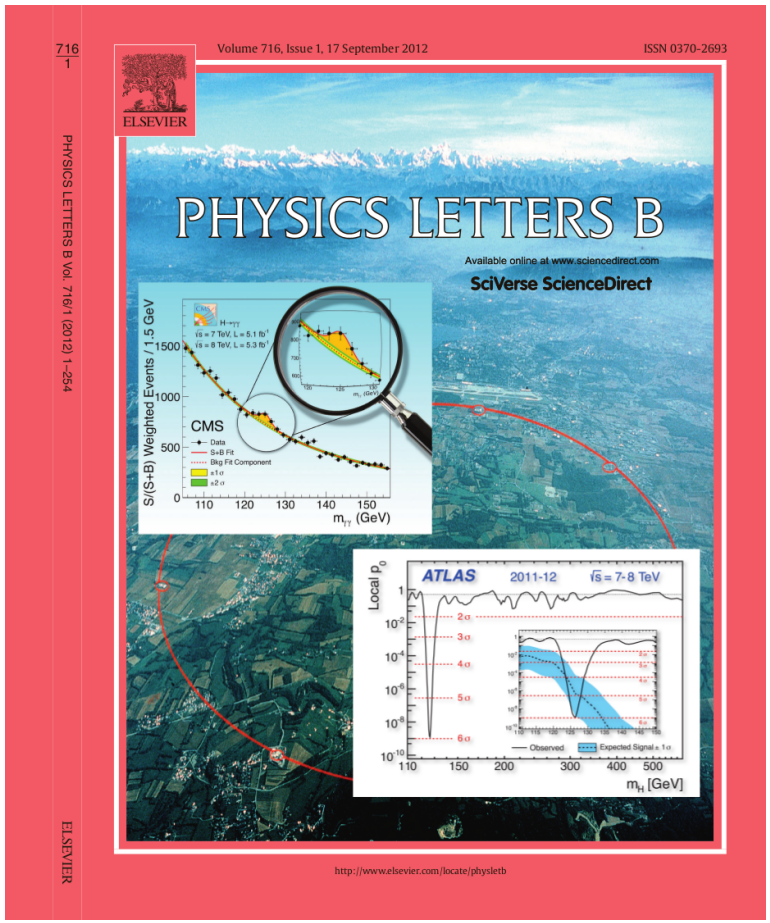
Standard Model

- Standard Model (SM) is a renormalizable quantum field theory of 12 fermions with 3 forces mediated by spin-1 gauge bosons
- Electroweak gauge symmetry is spontaneously broken by Brout-Englert-Higgs mechanism
- Predicts neutral scalar particle



"[The Higgs boson is] a particle needed for theories to work" - Gerard 't Hooft

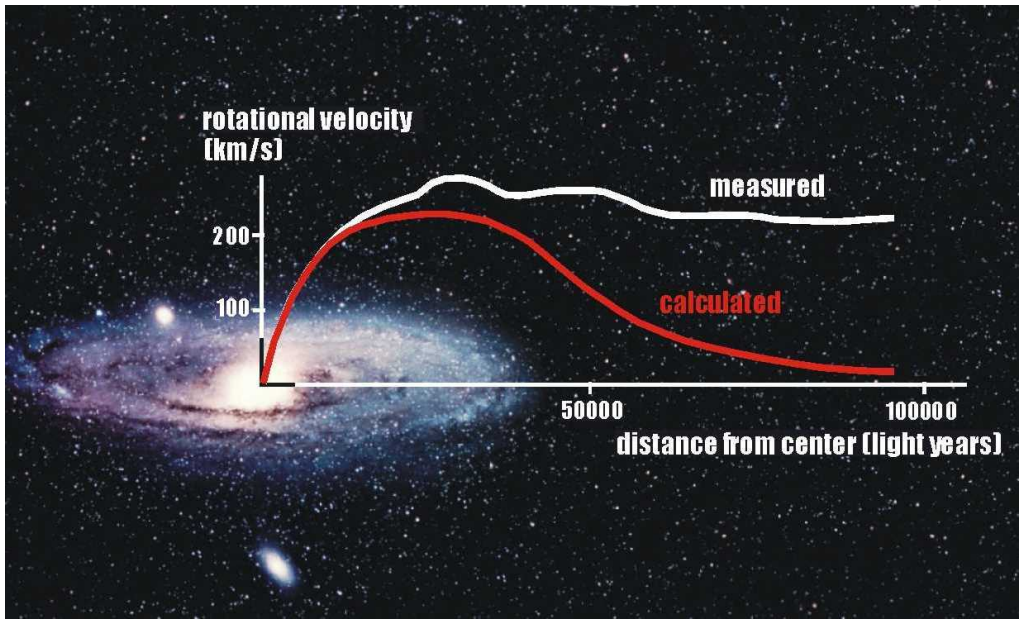
The Higgs boson discovery at the LHC in 2012



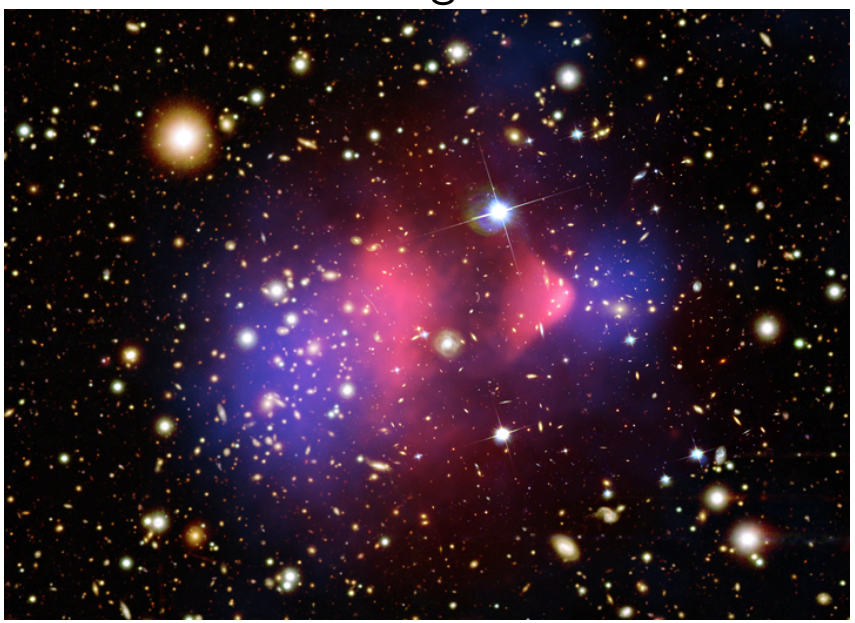
2013 Nobel Physics Prize to François Englert and Peter Higgs

The Higgs boson discovery completes the SM, making it self-consistent up to the Planck energy scale

Rotation curves of the Andromeda Galaxy



Gravitational lensing - "bullet cluster"



What is the origin of the dark matter?

What is the origin of the fermion mass hierarchy?

Why do neutrinos have mass?

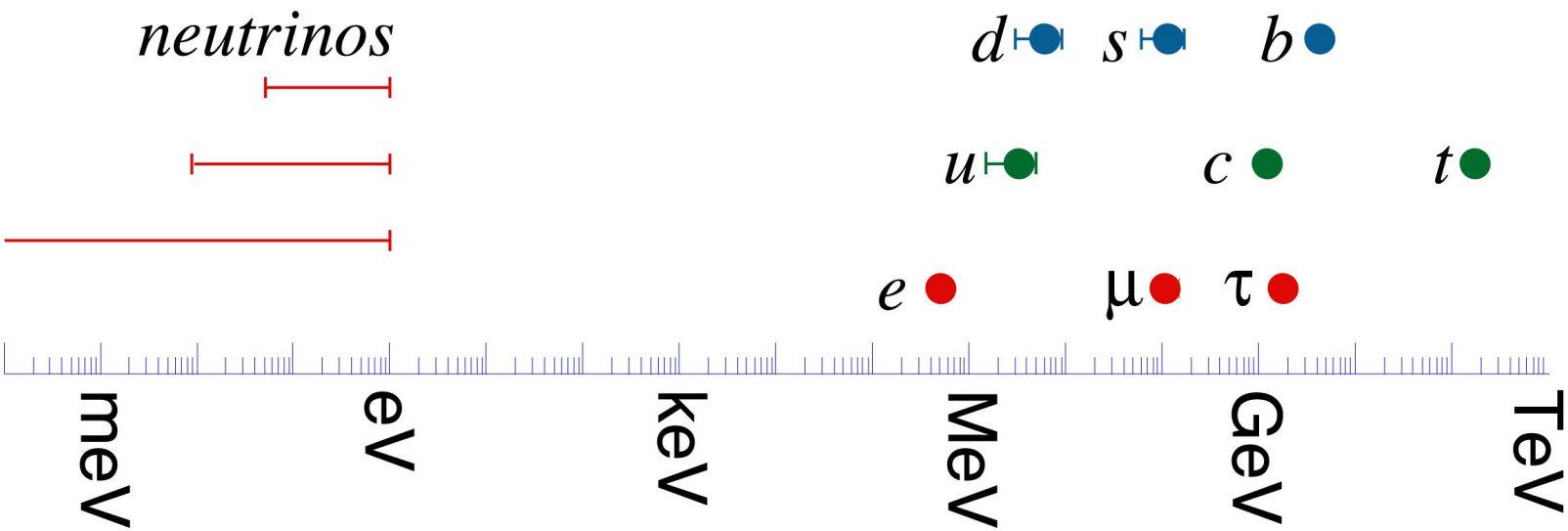
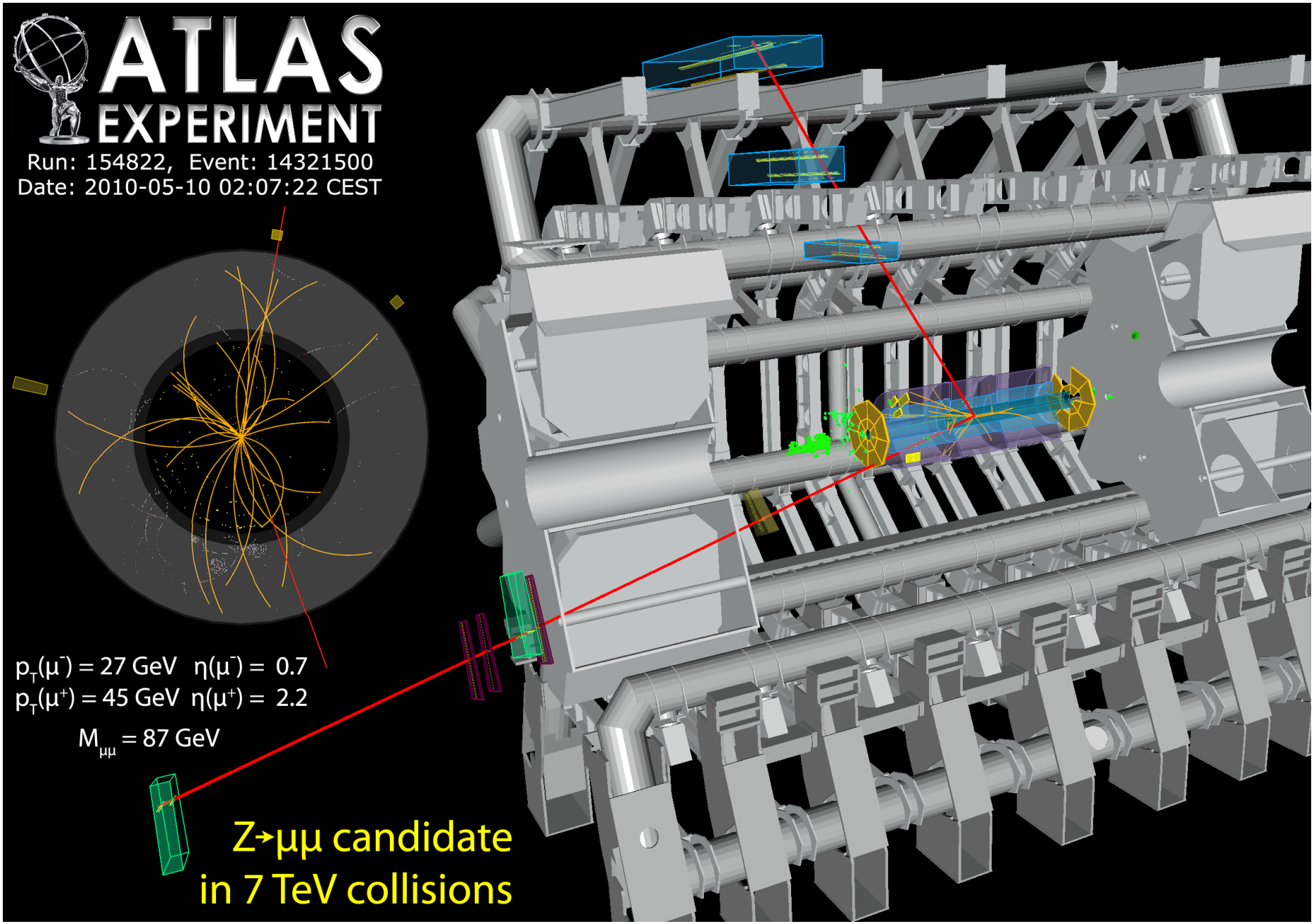


Figure by Hitoshi Murayama

Outline of this presentation

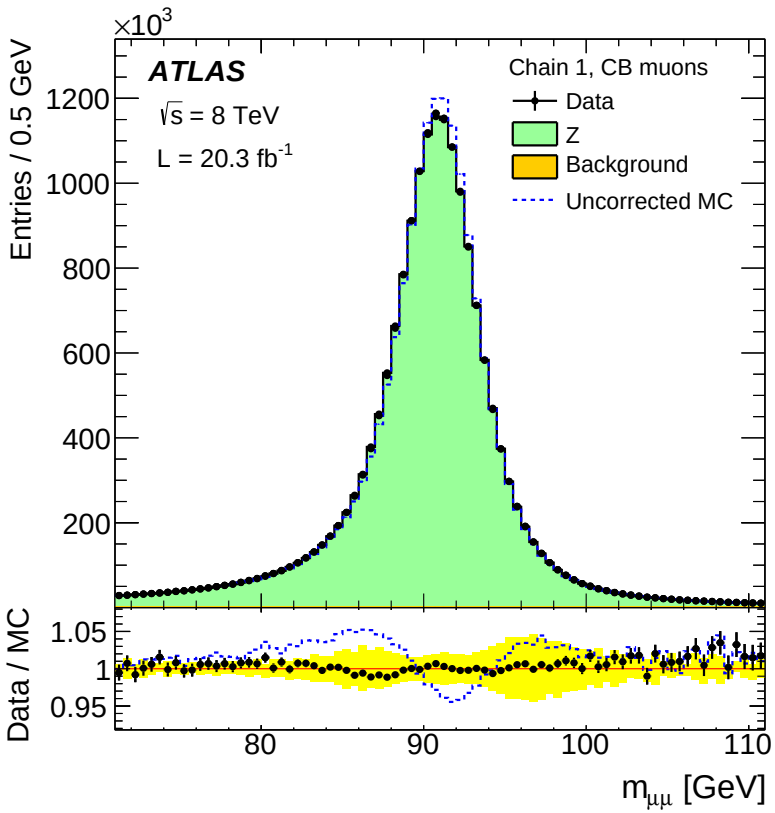
- Higgs boson mass
- Higgs boson phenomenology at LHC
- Searches for $H \to \mu\mu$ decays
- Searches for flavour violating $H \to \mu\tau$ decays
- Searches for $t\bar{t}H$ production
- Searches for flavour violating top-Higgs coupling


ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

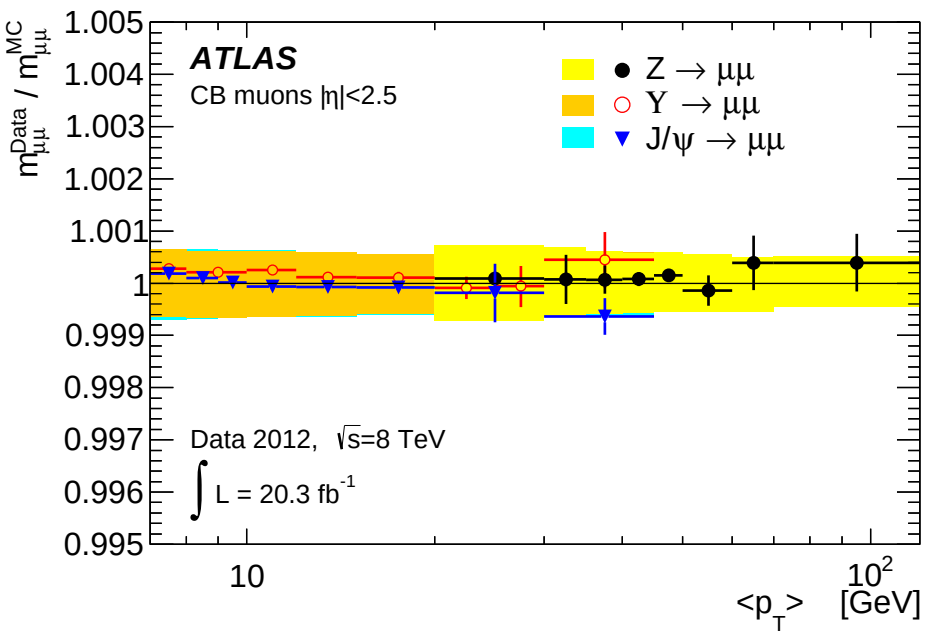
Standard Model with ATLAS detector

- SM provides excellent description of experimental data
- Main reference processes for detector calibration: Z, J/ψ, Υ
- LEP: $m_Z = 91.1876 \pm 0.0021$ GeV

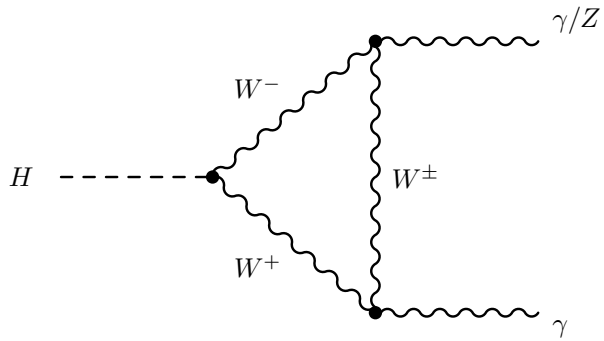
$Z \to \mu\mu$



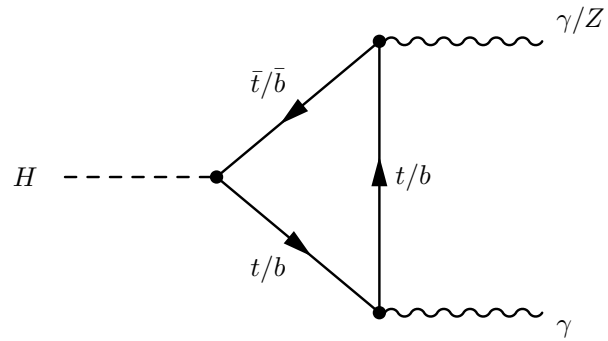
Muon momentum scale uncertainty



$H \to \gamma\gamma$: discovery channel



κ_W - H to W coupling



κ_t - H to top quark coupling

- For the mass measurement, categorise events by photon conversion status and photon η
- Fit $f(m_{\gamma\gamma})$ to measure m_H:

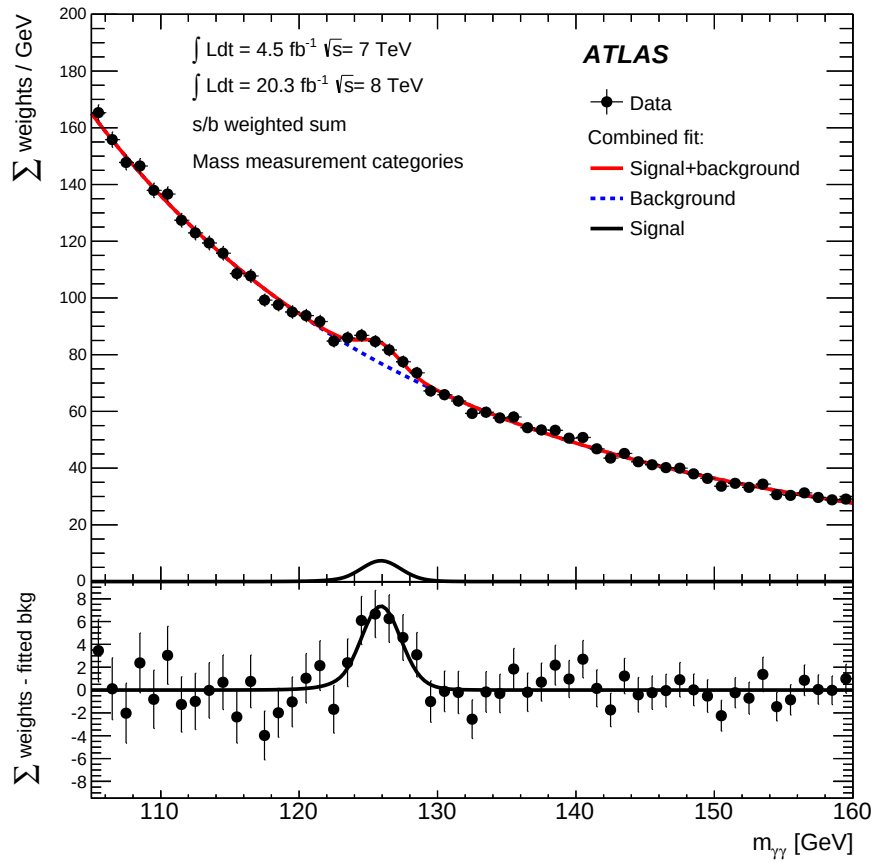
  $f(m_{\gamma\gamma}) = B(p) + \mu \times S(m_H, \theta_{\text{syst}})$

  B - background shape

  $B \sim e^{p_1 \cdot m_{\gamma\gamma} + p_2 \cdot m^2_{\gamma\gamma}}$

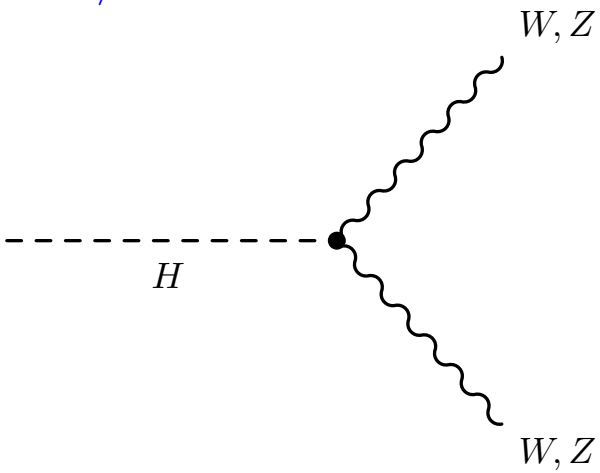
  μ - signal strength (SM $\mu = 1$)

  θ_{syst} - systematic uncertainty



$H \to ZZ^* \to 4l$: discovery channel

$\kappa_{W/Z}$ - H to W/Z coupling

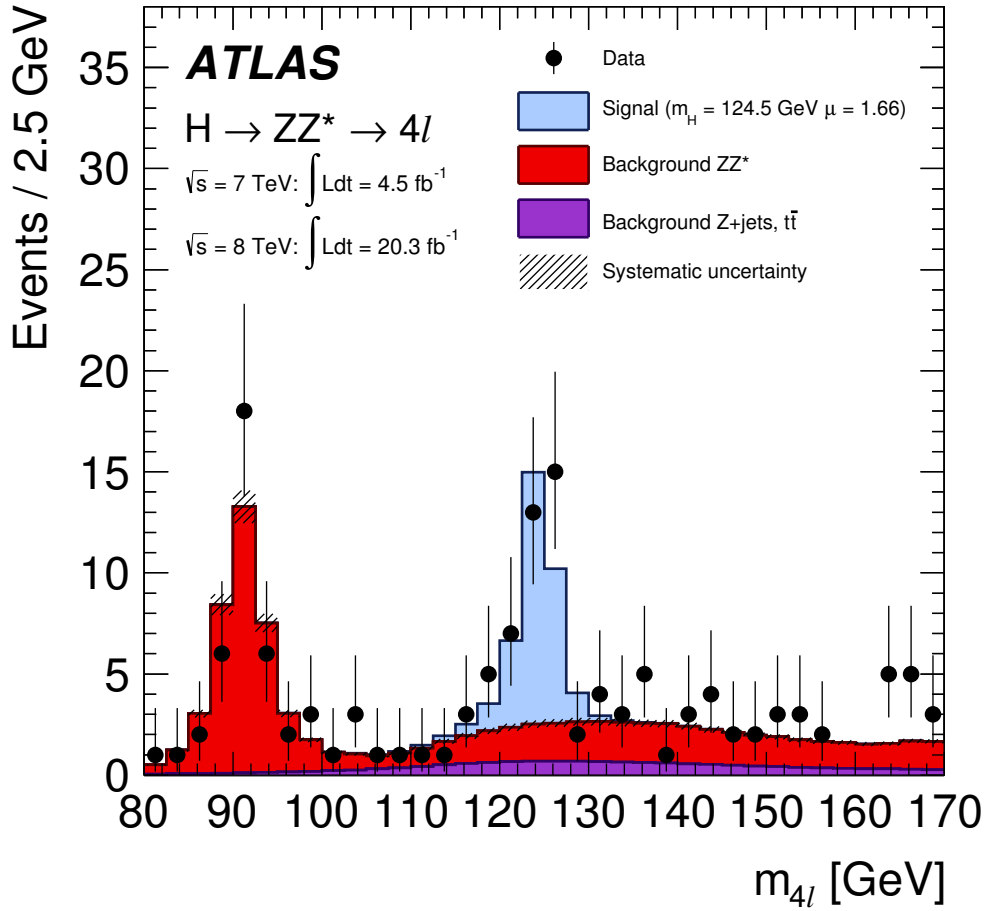


$f(m_{4l}, O_{\text{BDT}}) =$
$B(\theta_{\text{syst}}) + \mu \times S(m_H, \theta_{\text{syst}})$

B - simulated background shape

μ - signal strength (SM $\mu = 1$)

Fit $f(m_{4l}, O_{\text{BDT}})$ to measure m_H



Higgs boson mass: ATLAS

$$\Lambda(m_H) = \frac{\mathcal{L}(m_H,\ \hat{\hat{\theta}}(m_H))}{\mathcal{L}(\hat{m}_H,\ \hat{\theta})}$$

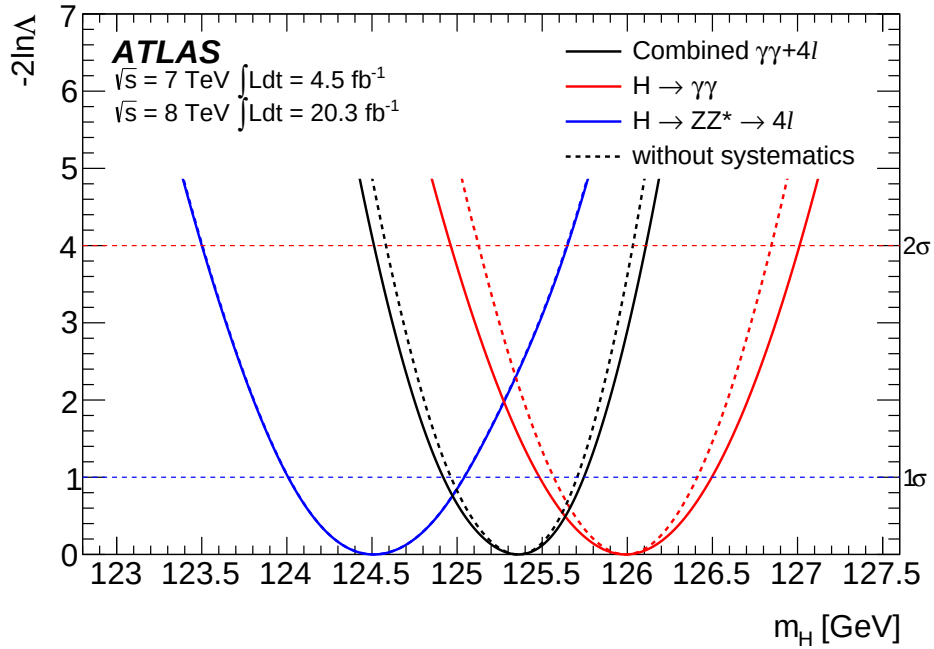
$\mathcal{L} = P(\text{model}|\text{data})$

$\mathcal{L}(m_H,\ \hat{\hat{\theta}})$ - m_H fixed

$\mathcal{L}(\hat{m}_H,\ \hat{\theta})$ - m_H and θ free

μ - free parameter

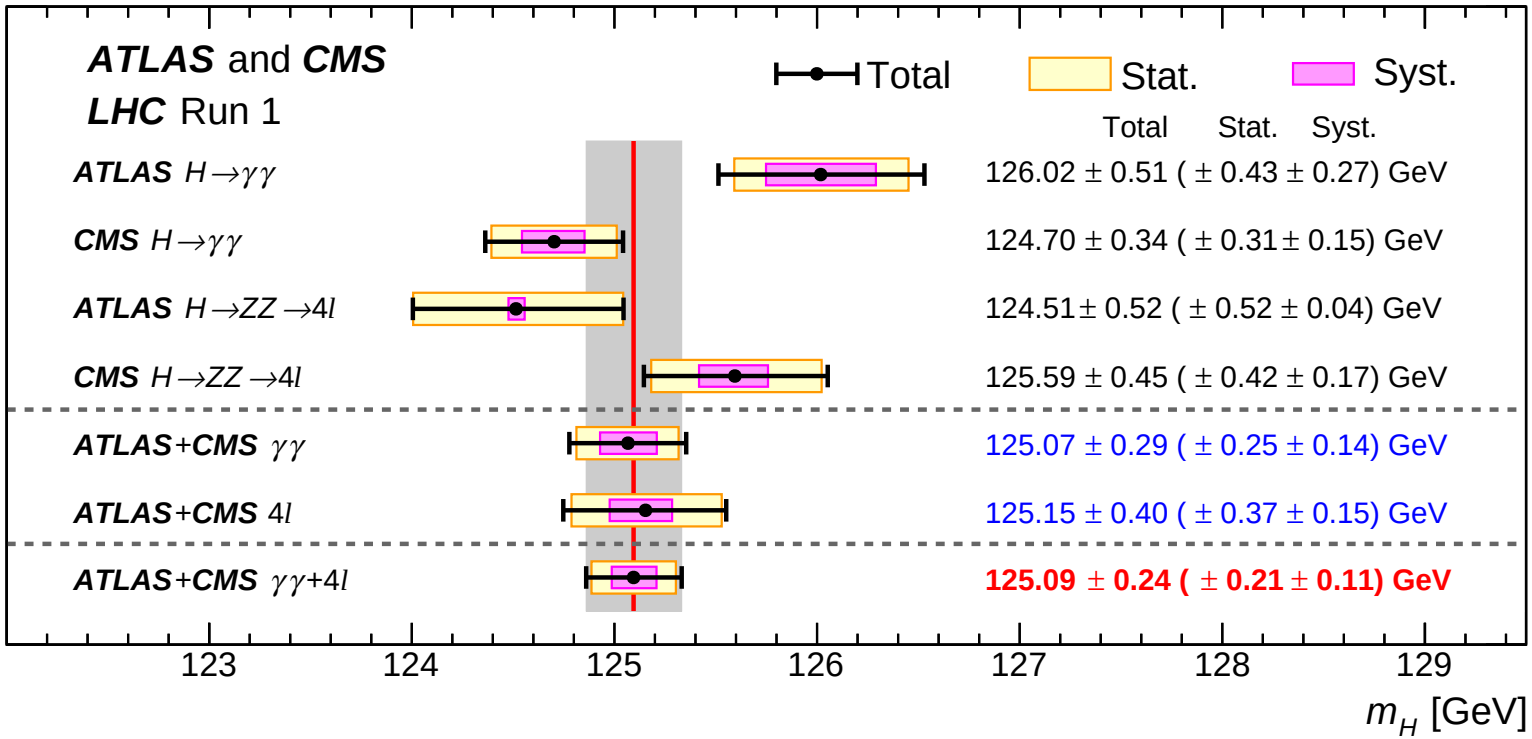
Profile likelihood ratio



Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ\text{llll}$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

m_H^{4l} and $m_H^{\gamma\gamma}$ are compatible at 4.9%

Higgs boson mass: ATLAS and CMS combination



ATLAS: $\Delta_{\text{syst}}(m_H^{4\mu}) \approx 10$ MeV

LEP: $m_Z = 91.1876 \pm 0.0021$ GeV

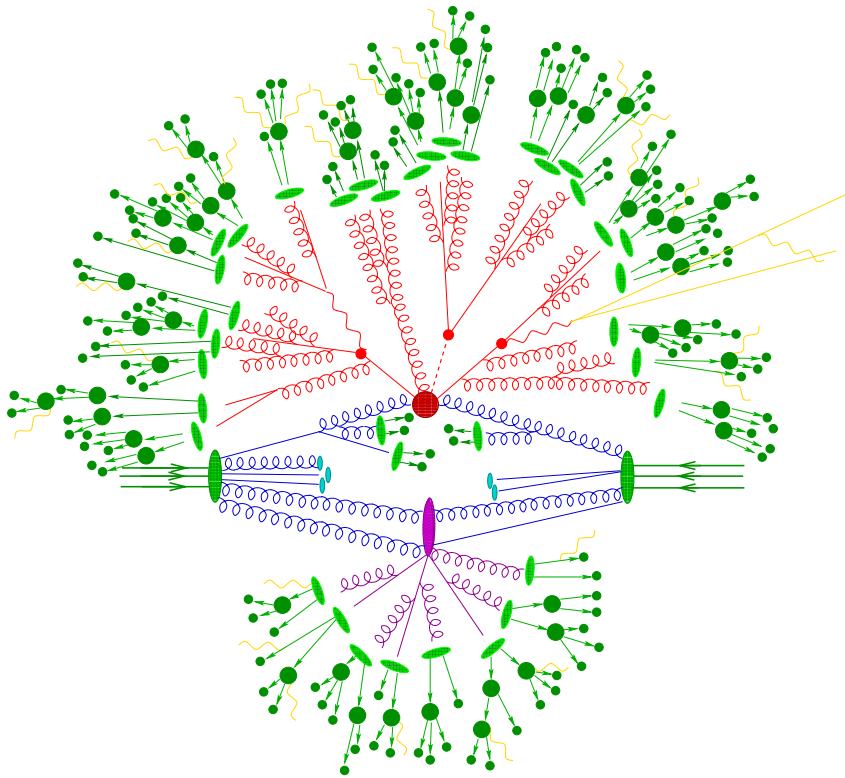
- Higgs boson mass is a free parameter of SM

  LHC: $m_H = 125.09 \pm 0.24$ GeV

- All other Higgs boson properties are predicted by SM
  - Width, spin and parity
  - Couplings to gauge bosons and fermions
  - Production cross-sections and decay branching ratios
  - Perturbative corrections to SM parameters up to the Planck energy scale

- SM is self-consistent but not complete (and perhaps not natural)
  - Gravity
  - Dark matter and dark energy
  - Baryon asymmetry
  - Neutrino masses

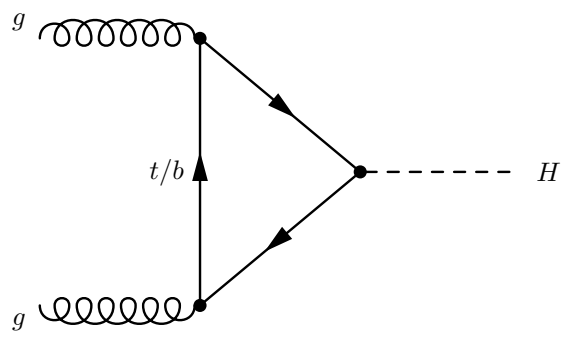
Rich LHC programme to measure Higgs boson properties and to search for new phenomena in Higgs sector



pp collision by Sherpa

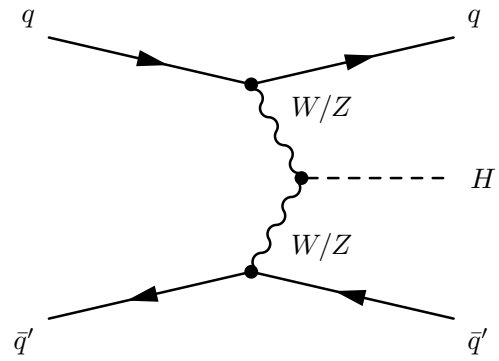
Higgs boson production at LHC

Gluon fusion (ggF) $\sim 88\%$
N^{3}LO(QCD $\sim 10^5$ diagrams) + NLO(EW)
$\sigma_{\text{theory}} \sim 7\%$



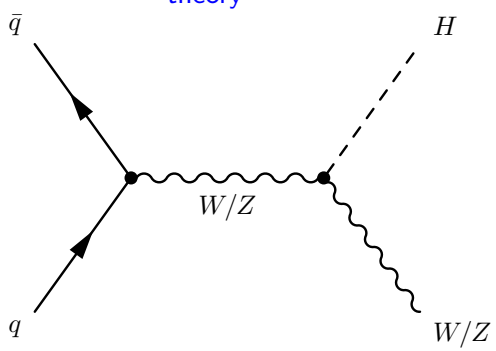
$\propto \kappa_t$

Vector boson fusion (VBF) $\sim 7\%$
NLO(QCD+EW)
$\sigma_{\text{PDF}} \sim 2\%$



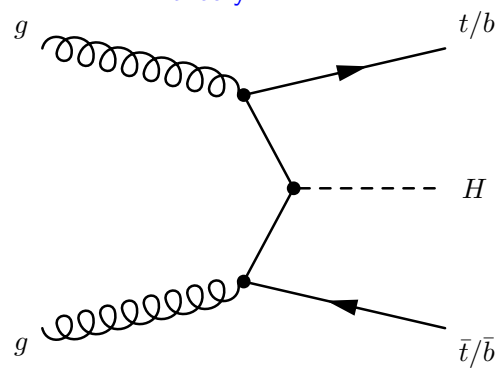
$\propto \kappa_V$

W/Z associated production (VH) $\sim 4\%$
NNLO(QCD) + NLO(EW)
$\sigma_{\text{theory}} \sim 4\%$



$\propto \kappa_V$

$t\bar{t}$ associated production ($t\bar{t}H$) $\sim 0.9\%$
NLO(QCD)
$\sigma_{\text{theory}} \sim 9\%$



$\propto \kappa_t$

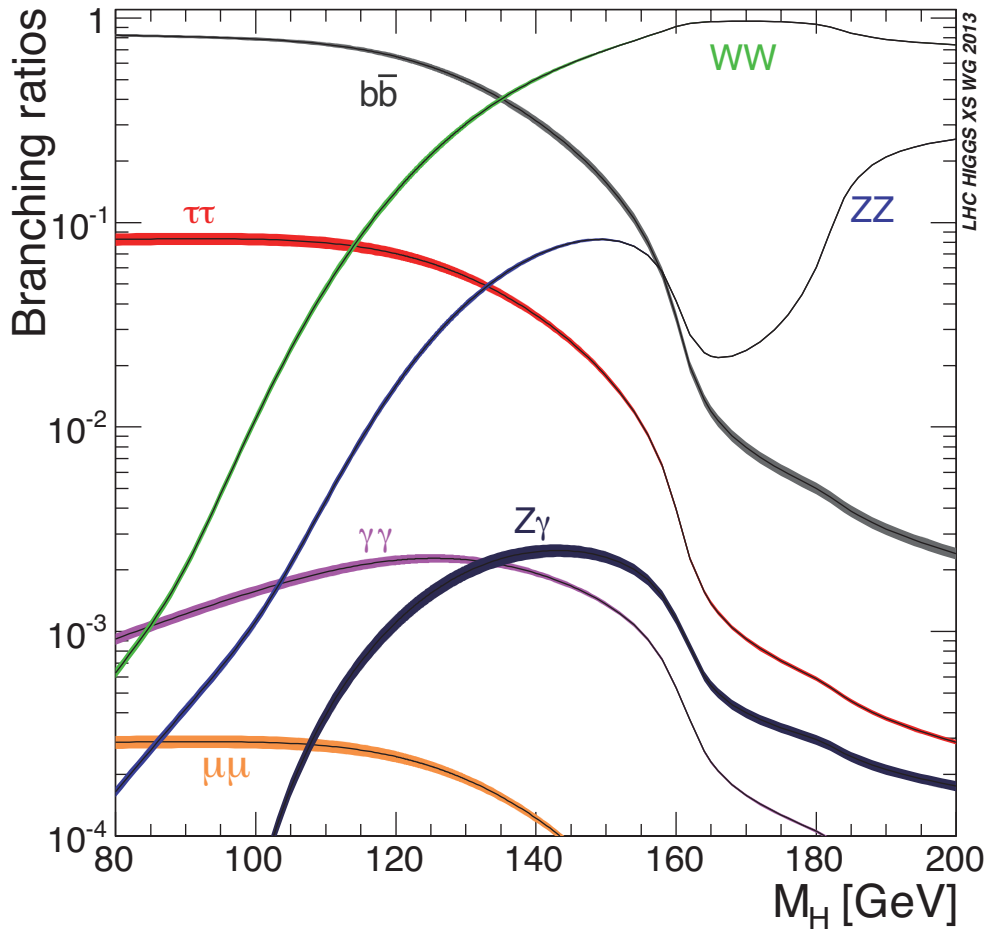
Standard Model Higgs boson decays

- $\mathcal{B}_f = \frac{\Gamma_f}{\Gamma_H}$, $\Gamma_H^{SM} = 4.1$ MeV
- 7 accessible channels for $m_H = 125.09$ GeV:

Branching ratio	[%]
$H \to bb$	58.1 ± 1.9
$H \to WW$	21.5 ± 0.9
$H \to \tau\tau$	6.26 ± 0.35
$H \to ZZ$	2.73 ± 0.11
$H \to \gamma\gamma$	0.227 ± 0.011
$H \to Z\gamma$	0.154 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001
$H \to ee$	$\sim 5 \cdot 10^{-7}$

Couplings to fermions: $\kappa_f \propto \frac{m_f}{VEV}$

Couplings to W and Z: $\kappa_V \propto \frac{m_V^2}{VEV}$



- Narrow width approximation:

$$\sigma(i \to H \to f) = \sigma_i \times \mathcal{B}_f = \sigma_i \times \frac{\Gamma_f}{\Gamma_H}$$

- Experiments observe events:

$$N_{\text{expected}} = \mathcal{L} \cdot A \cdot \epsilon_{exp} \cdot \sigma_i \cdot \mathcal{B}_f$$

$\mathcal{L}$ - integrated LHC luminosity

A - detector acceptance

ϵ_{exp} - detector efficiency

- Measure signal strengths - observed rates normalised by SM prediction:

$$\mu_i \times \mu^f = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \times \frac{\mathcal{B}_f}{\mathcal{B}_f^{\text{SM}}}$$

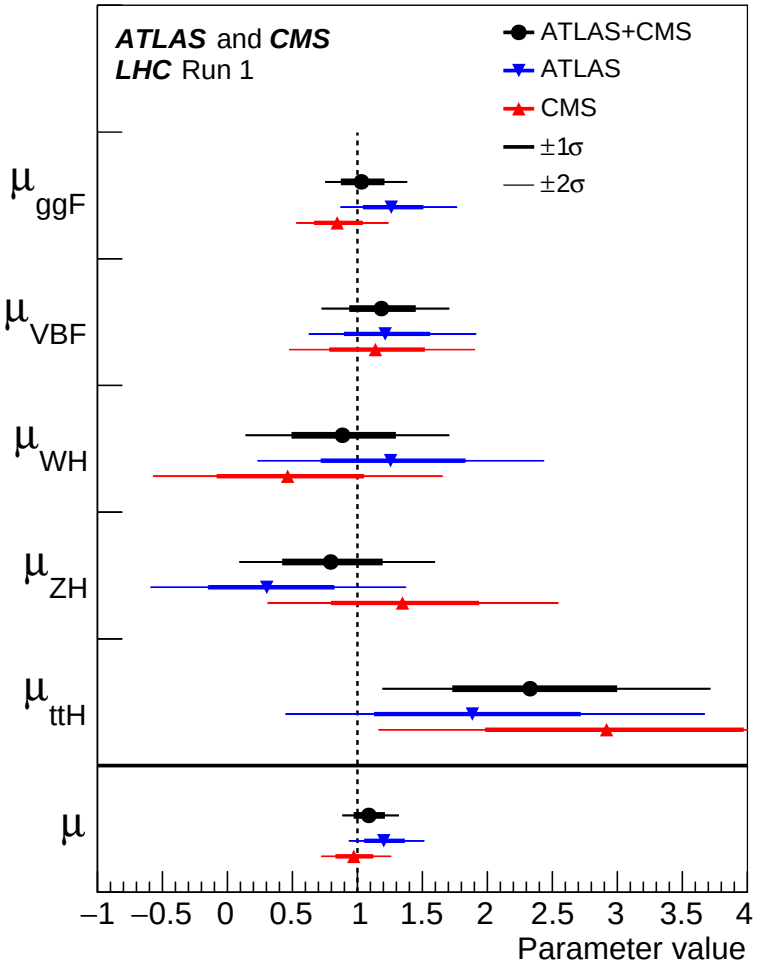
Higgs boson production and decay measurements

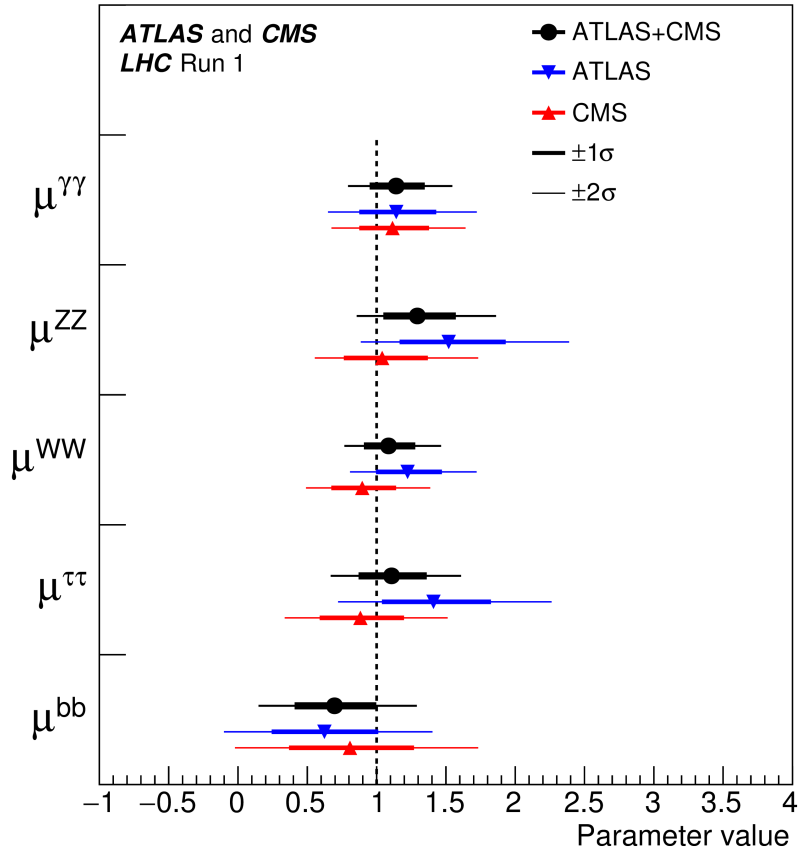
$\mathcal{B}_f/\sigma_i$	ggF	VBF	VH	$t\bar{t}H$
$H \to bb$		✓	✓	✓
$H \to WW$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to ZZ$	✓	✓	✓	✓
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to Z\gamma$	✓	✓	✓	✓
$H \to \mu\mu$	✓	✓		
$H \to \mu\tau$	✓			

✓ - current measurement

✓ - current search

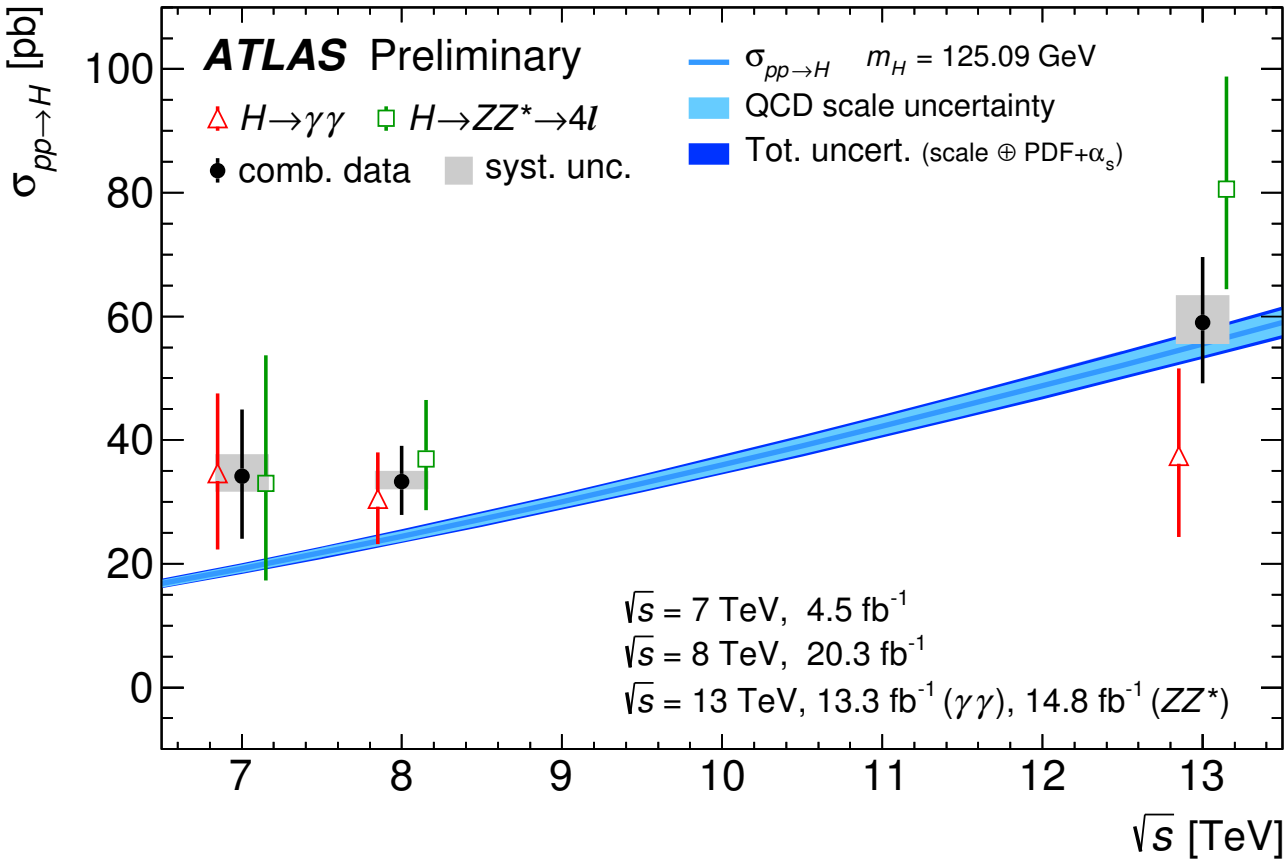
Higgs boson production and decays with LHC Run 1





- Combined signal yield: $1.09 \pm 0.07(\text{stat}) \pm 0.08(\text{syst})$
- Measured VBF significance: 5.4σ
- Measured $H \to \tau\tau$ significance: 5.5σ

Higgs boson production cross-section

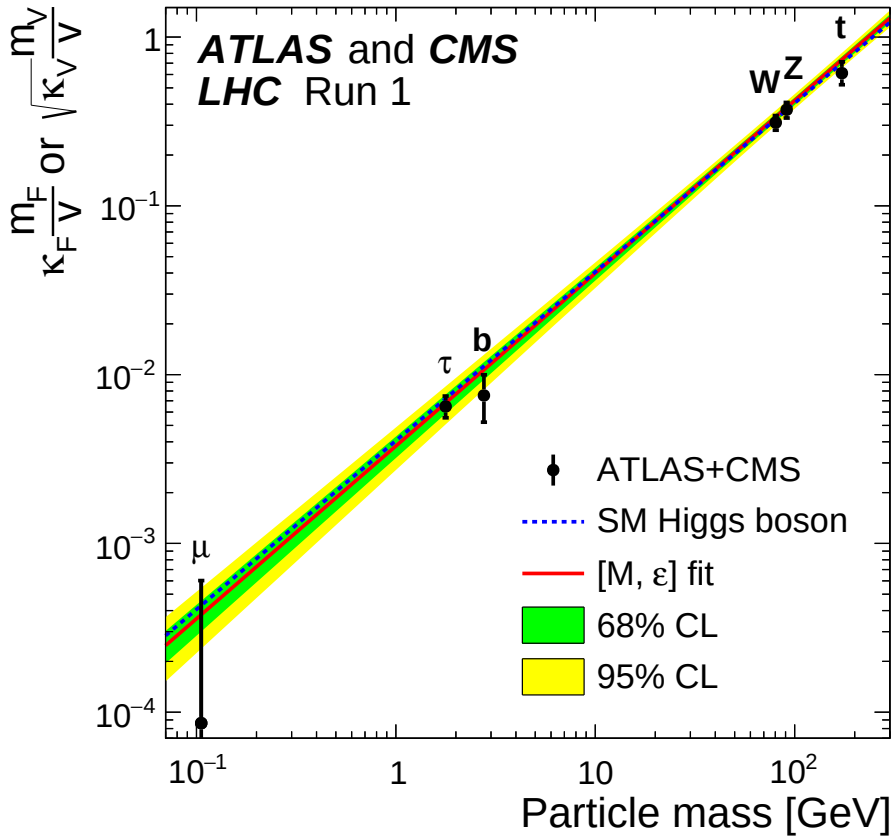


Decay channel	Total cross section ($pp \to H + X$)		
	$\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

Particle masses and Higgs boson

$$\kappa_f \propto \frac{m_f}{VEV}, \sqrt{\kappa_V} \propto \frac{m_V}{\sqrt{VEV}}$$

- Higgs boson couplings determine the mass hierarchy of charged fermions
- Search for rare Higgs boson processes to measure flavour structure of SM
- Search for exotic Higgs boson decays to probe for BSM physics

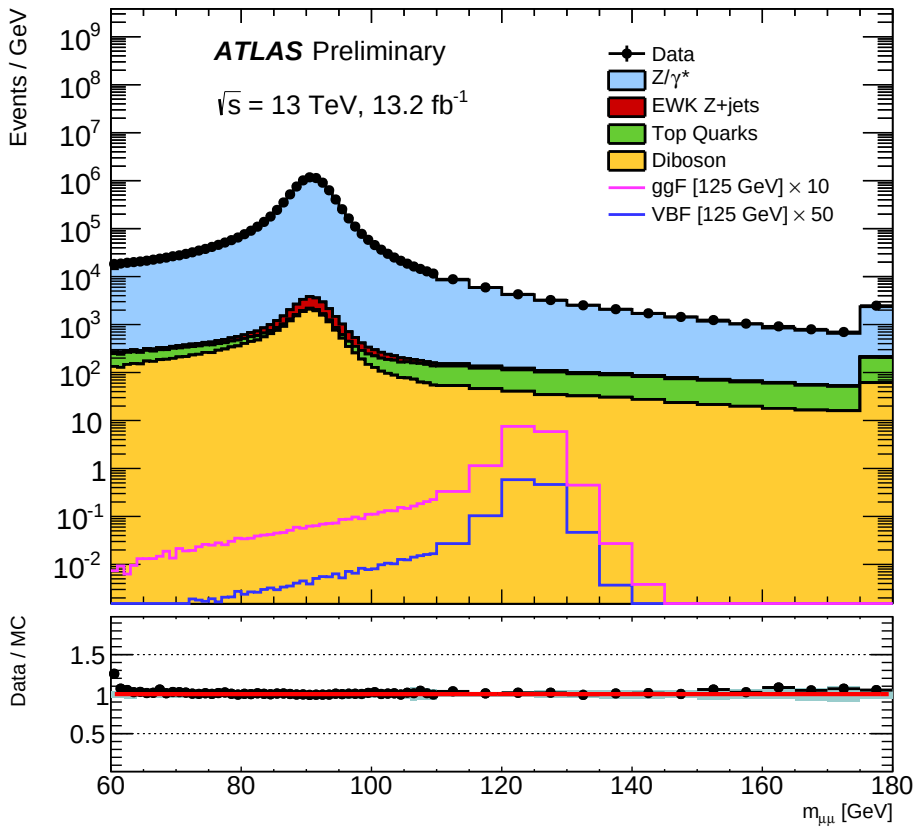


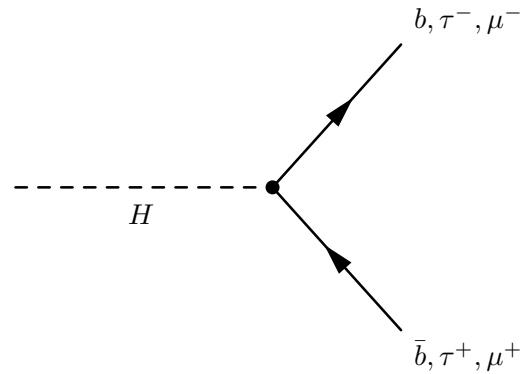
"Evidently the Higgs system knows something that we do not know: the difference between the generations" - Martinus Veltman.

Outline of this presentation

- Higgs boson mass
- Higgs boson phenomenology at LHC
- Searches for $H \to \mu\mu$ decays
- Searches for flavour violating $H \to \mu\tau$ decays
- Searches for $t\bar{t}H$ production
- Searches for flavour violating top-Higgs coupling

Search for $H \to \mu\mu$





- Search for narrow $\mu^{\pm}\mu^{\mp}$ resonance:
  $f(m_{\mu\mu}) = B(p) + \mu \times S(m_H, \theta)$
- Irreducible Z/γ^* background
  - Z resonance, continuous γ^*, plus interference terms
  - PDF and NLO - no analytic form
- Empirical background function is fitted in sidebands
- Subdominant $t\bar{t}$ and di-bosons backgrounds suppressed with $\not{E}_T$ and b-jet vetos

Background model:

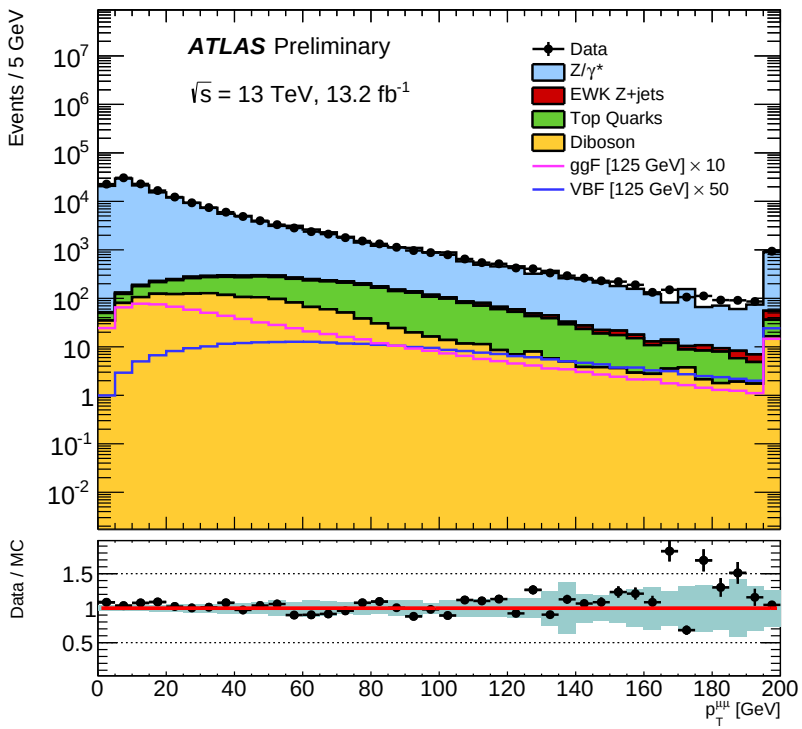
$$B = f \cdot (BW * GS) + (1 - f) \cdot C \cdot \frac{e^{-A \cdot m_{\mu\mu}}}{m^3_{\mu\mu}}$$

BW = Breit-Wigner PDF, GS = Gaussian

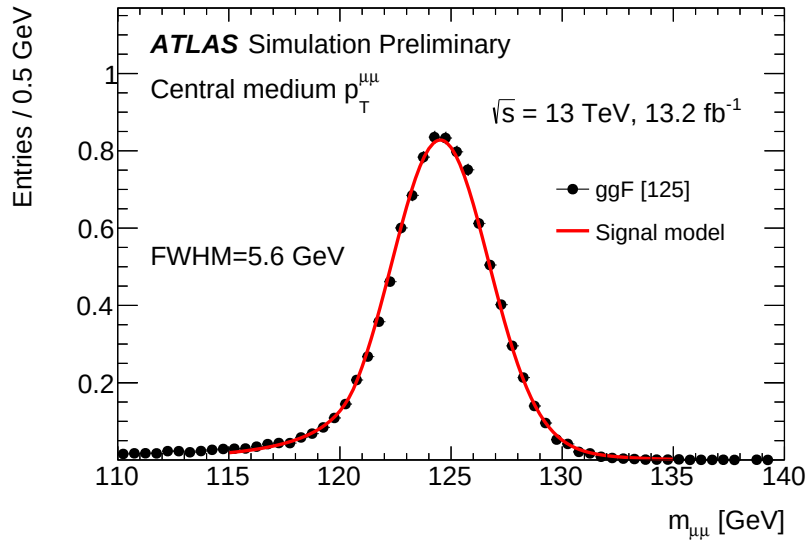
Search for $H \to \mu\mu$

7 event categories:

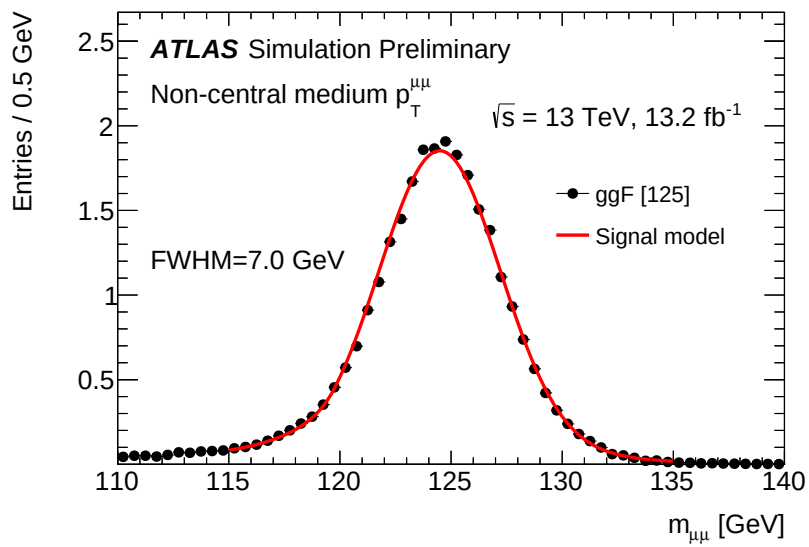
- Di-muon $p_T^{\mu\mu}$ ($p_T^H > p_T^{Z/\gamma^*}$)
- Muon η (motivated by p_T^μ resolution)
- VBF production



$|\eta_\mu| < 1$ for both muons

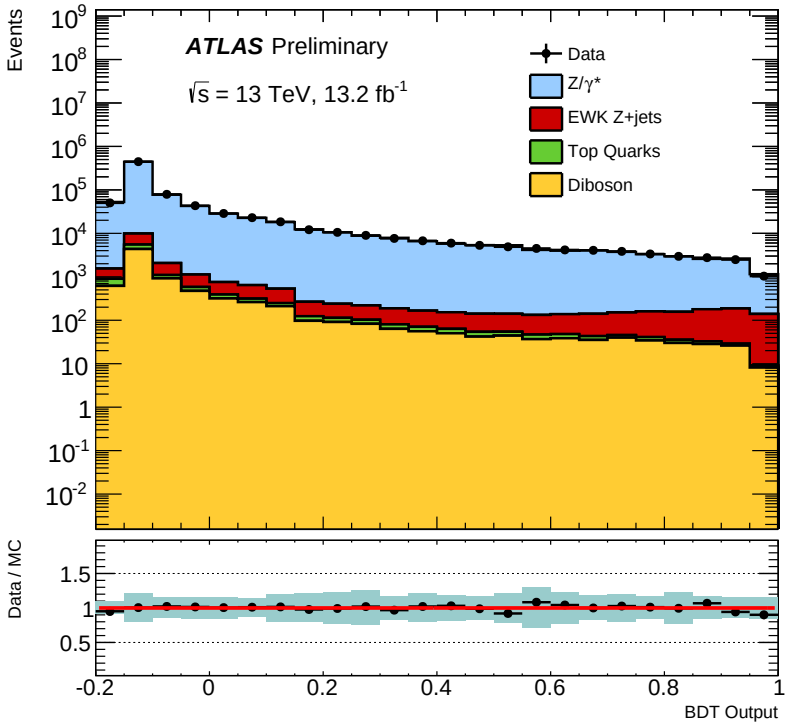


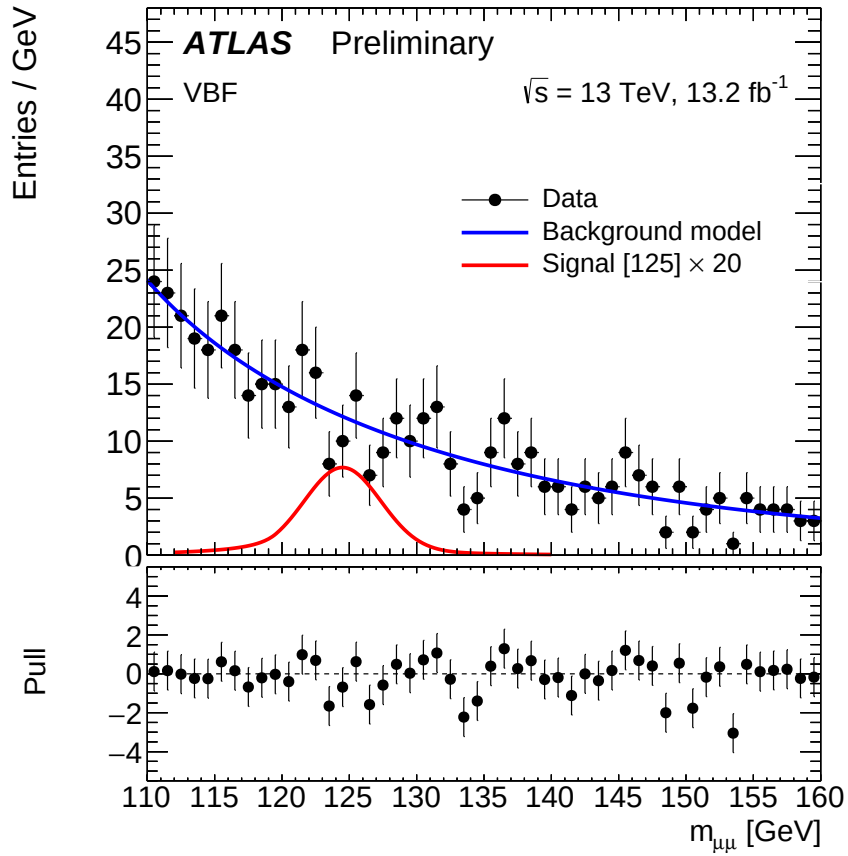
$|\eta_\mu| > 1$ for at least one muon



Search for $H \to \mu\mu$: ATLAS VBF category

BDT output for 76 GeV $< m_{\mu\mu} <$ 106 GeV

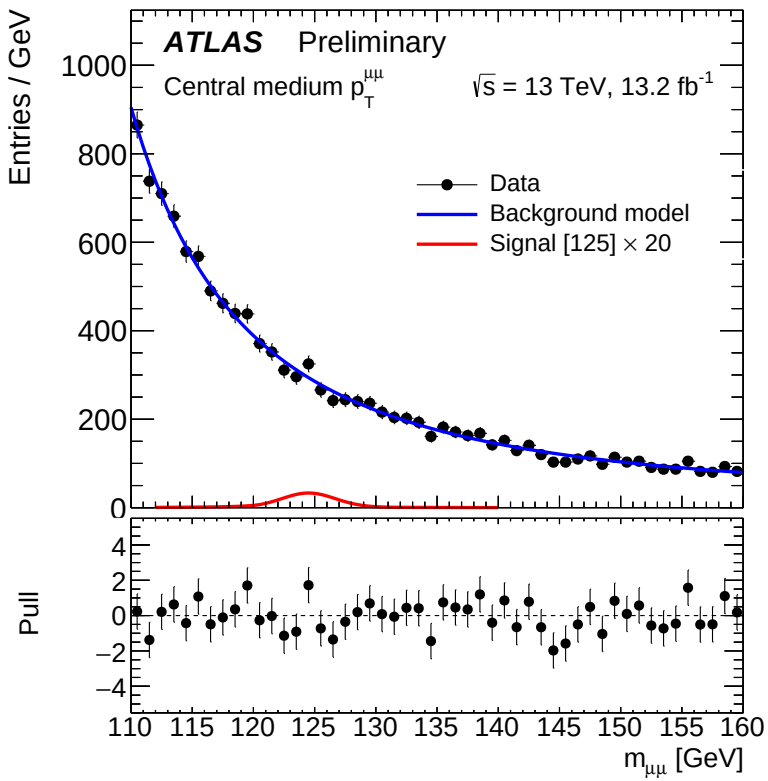




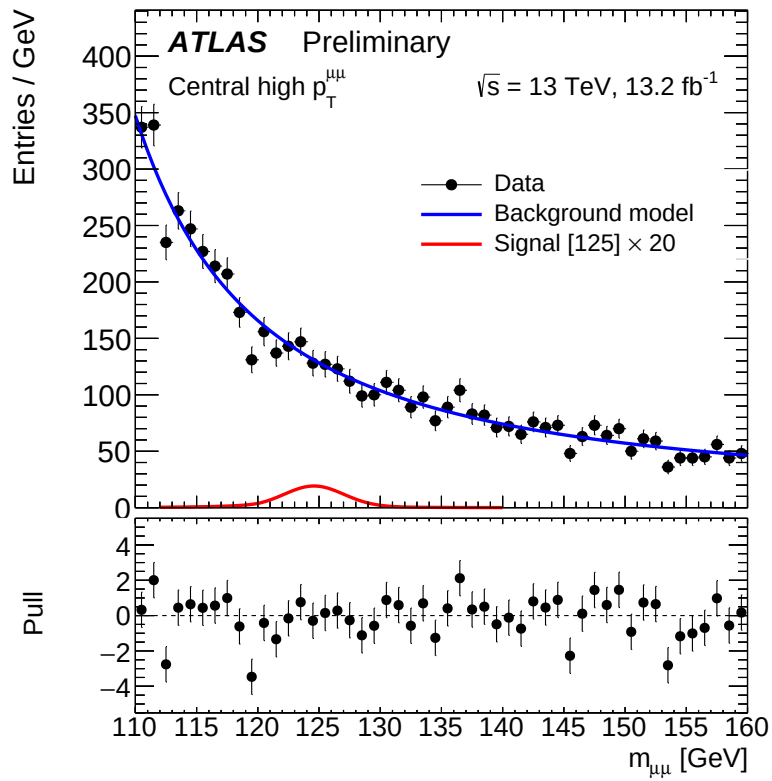
- 14 input variables using muons, MET, HT and di-jet information
- $BDT > 0.7$ results in 51.3 (2.4)% efficiency for VBF signal (total background)
- 38% ggF contamination
- Use simplified background function

Search for $H \to \mu\mu$

Central medium p_T



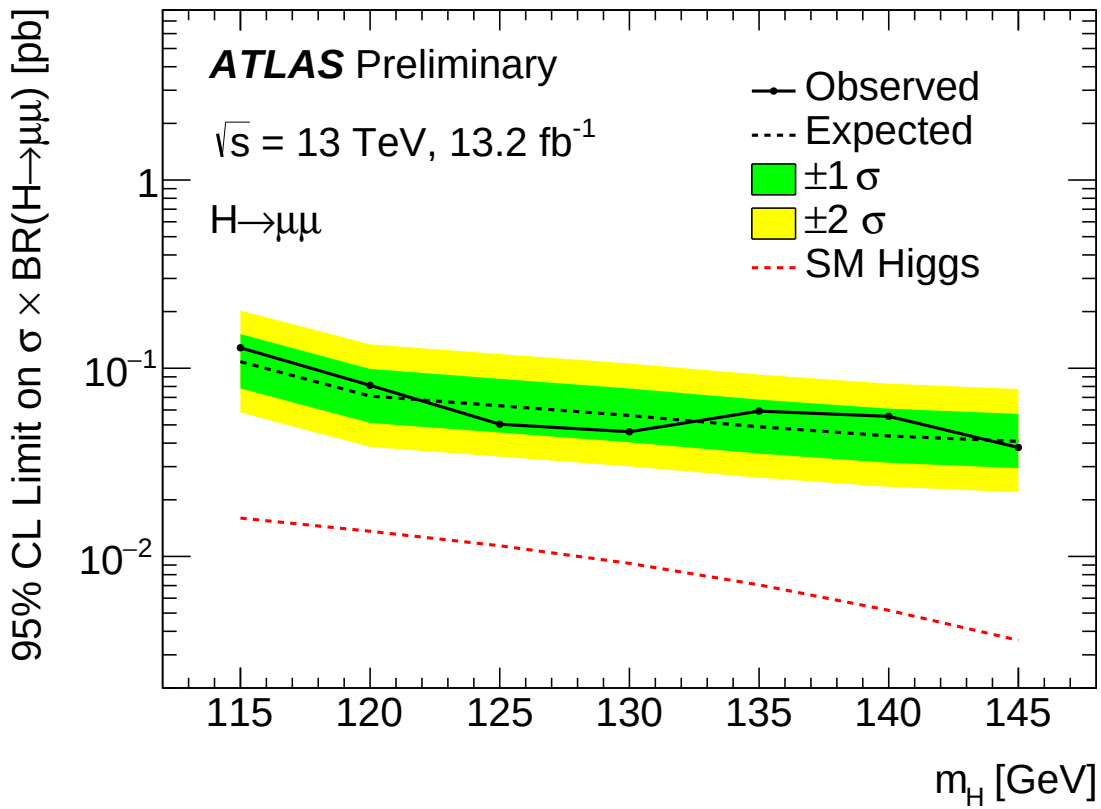
Non-central high p_T



Event yields for $120 < m_{\mu\mu} < 130$ GeV

	Signal[125]	Z+jets	Top	Di-boson	Total background	S/$\sqrt{B}$	Data
Central, low $p_T^{\mu\mu}$	4.0	3404	6	10	3419	0.07	3552
Non-central, low $p_T^{\mu\mu}$	10.8	13184	23	45	13252	0.09	14262
Central, medium $p_T^{\mu\mu}$	9.0	2872	49	31	2952	0.17	2883
Non-central, medium $p_T^{\mu\mu}$	23.9	10255	177	157	10590	0.23	11269
Central, high $p_T^{\mu\mu}$	6.6	1128	106	27	1261	0.19	1272
Non-central, high $p_T^{\mu\mu}$	15.4	3939	334	106	4379	0.23	4264
VBF	2.5	78	7	1	85	0.28	117

Search for $H \to \mu\mu$



- $H \to \mu\mu$ decay for $m_H = 125.09$ GeV is excluded at 95% CL:
  - ATLAS observed (expected): 4.4 (5.5)×SM with 13 TeV data
  - ATLAS observed (expected): 3.5 (4.3)×SM with 7+8+13 TeV data
  - Sensitivity is dominated by statistical uncertainty on measured background

Outline of this presentation

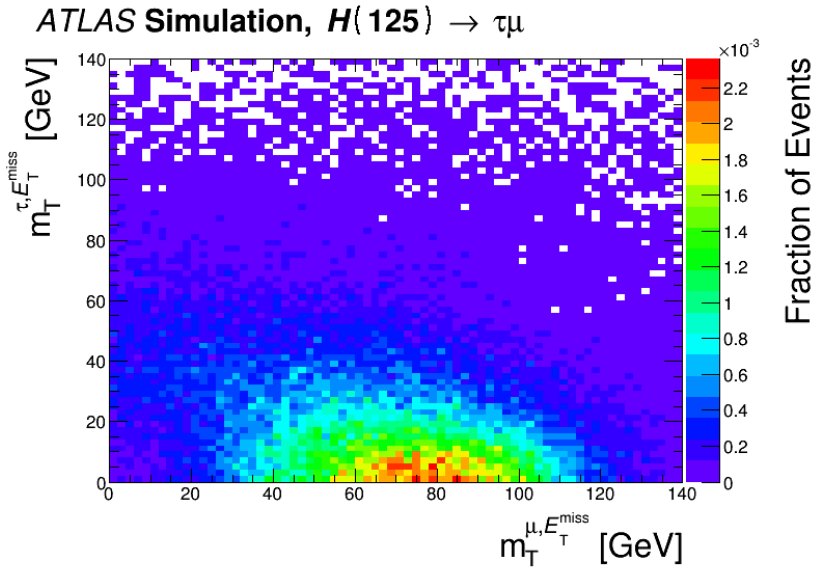
- Higgs boson mass
- Higgs boson phenomenology at LHC
- Searches for $H \to \mu\mu$ decays
- Searches for flavour violating $H \to \mu\tau$ decays
- Searches for $t\bar{t}H$ production
- Searches for flavour violating top-Higgs coupling

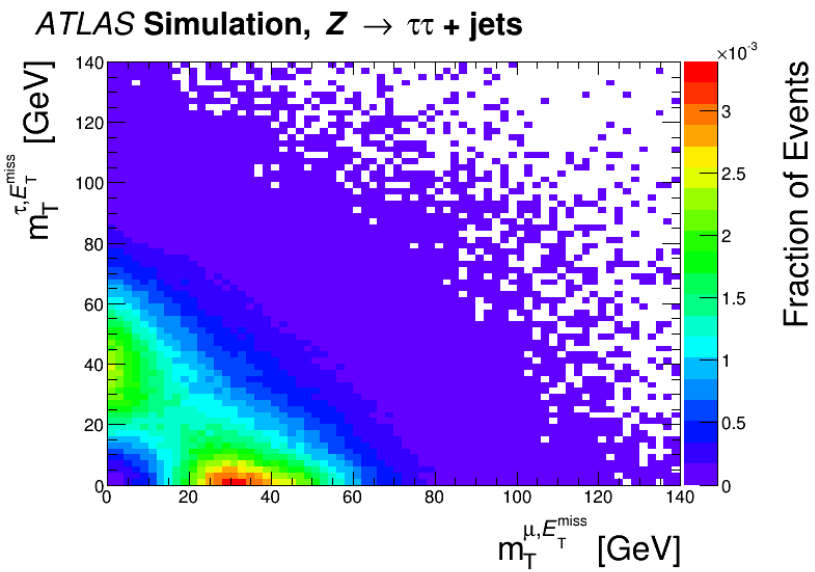
Charged Lepton Flavour Violation

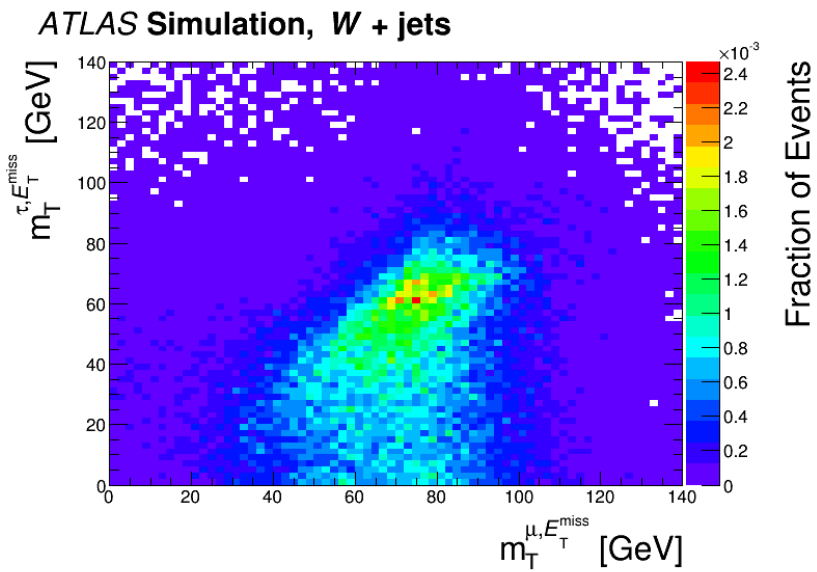
- Charged Lepton Flavour Violating (CLFV) Higgs boson couplings:
  - μ–e, τ–μ and τ–e
- CLFV couplings are negligible in SM but present in many BSM models
- $\mathcal{B}(H \to \mu e) < \mathrm{O}(10^{-8})$ - constrained by null results for $\mu \to e\gamma$ search
- $\mathcal{B}(H \to \mu\tau) < \mathrm{O}(0.1)$ - constrained by $\tau \to \mu\gamma, e\gamma$ (and other results)
- LHC is sensitive to $H \to \mu\tau$ and $H \to e\tau$ decays at percent level
  - In Run 1 CMS observed 2.4σ excess with best fit $\mathcal{B}(H \to \mu\tau) = 0.84^{+0.39}_{-0.37}\%$

Search for $H \to \mu\tau$

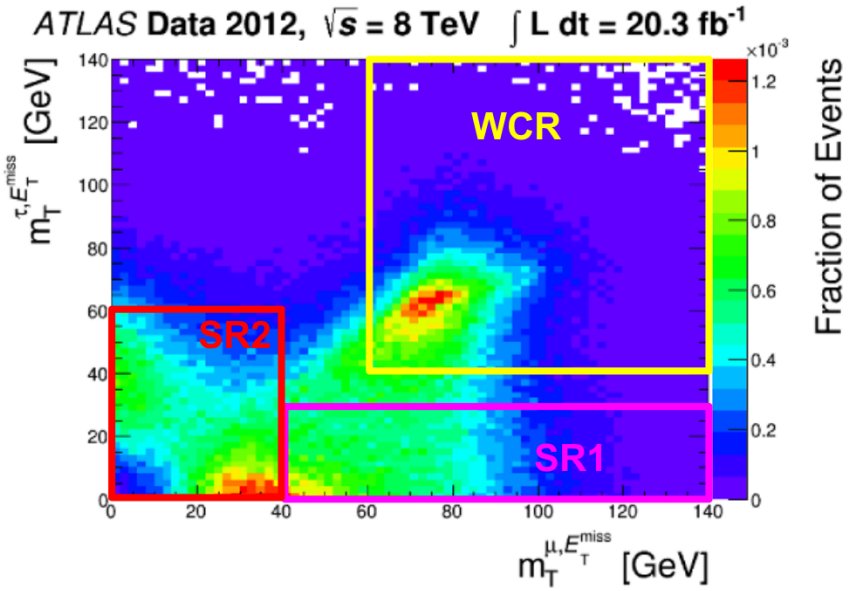
- Split by visible decays of τ lepton into hadrons (τ_h) or electron (τ_e)
  - $H \to \mu\tau_h\nu$
  - $H \to \mu e\nu$
- Signal categories by background type

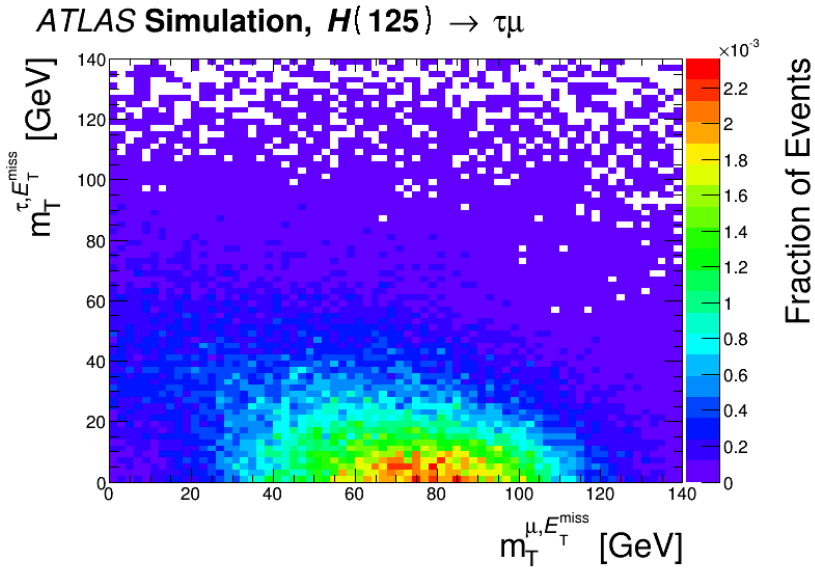


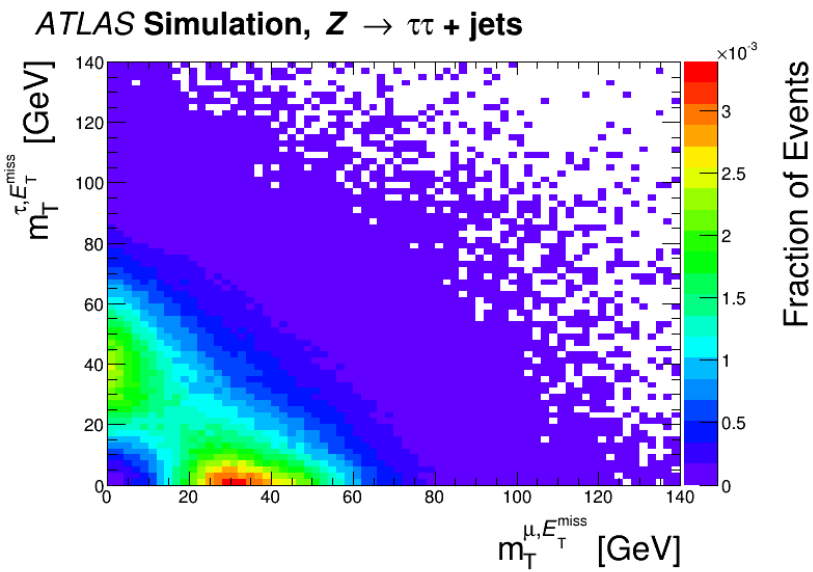


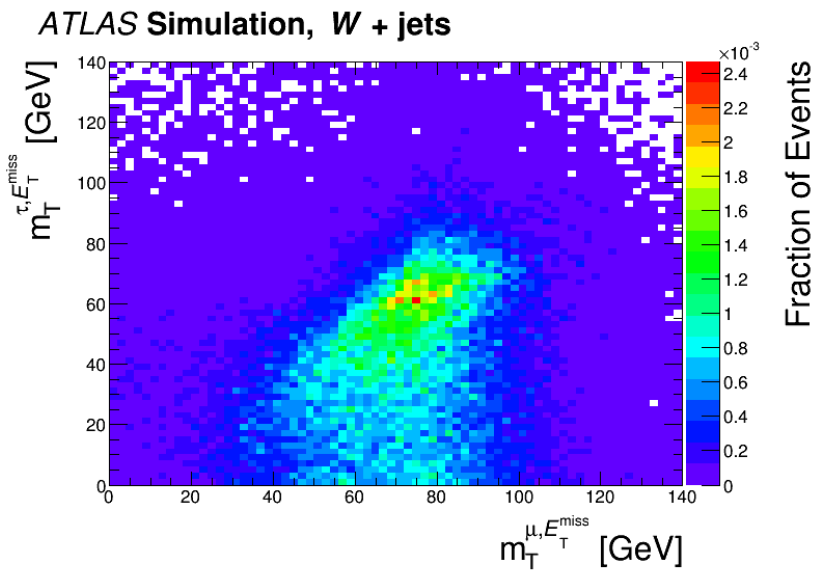


Search for $H \to \mu\tau$





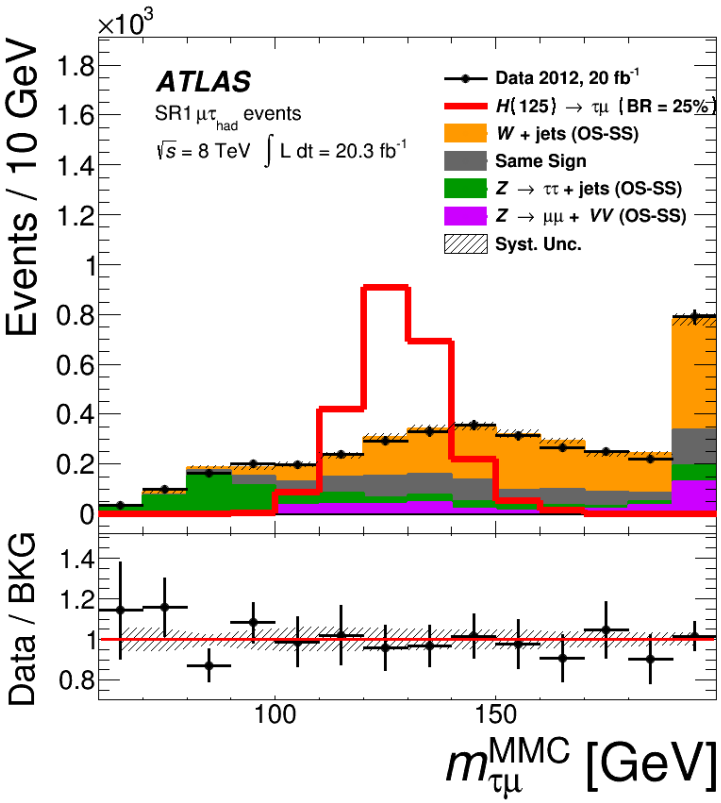




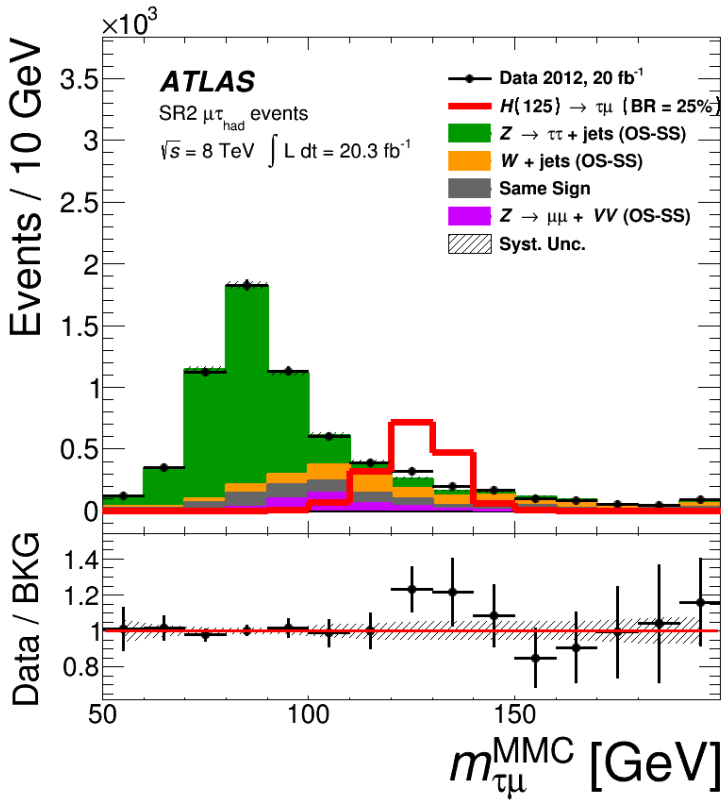
Search for $H \to \mu\tau$

- Search for broad $m_{\mu\tau}$ resonance with (fine tuned) cut-based analyses
- Reconstruct $m_{\mu\tau}$ using Missing Mass Calculator

SR1 for $H \to \mu\tau_h\nu$
dominated by W+jet



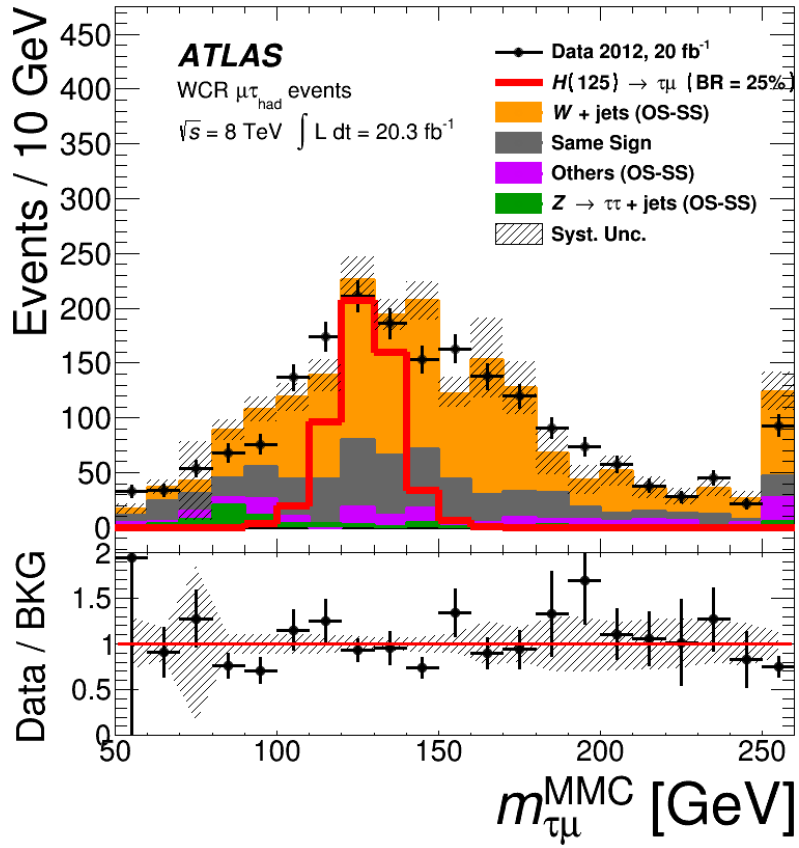
SR2 for $H \to \mu\tau_h\nu$
dominated by $Z \to \tau\tau$



Search for $H \to \mu\tau$: backgrounds

- Mis-id leptons from multi-jet and W+jet backgrounds measured from data:
  - Multi-jet from same sign events
  - W+jet from dedicated control region
- Irreducible $Z/\gamma^* \to \tau\tau$
  - τ_h embedding with $Z \to \mu\mu$
- Di-boson and $t\bar{t}$ from simulation

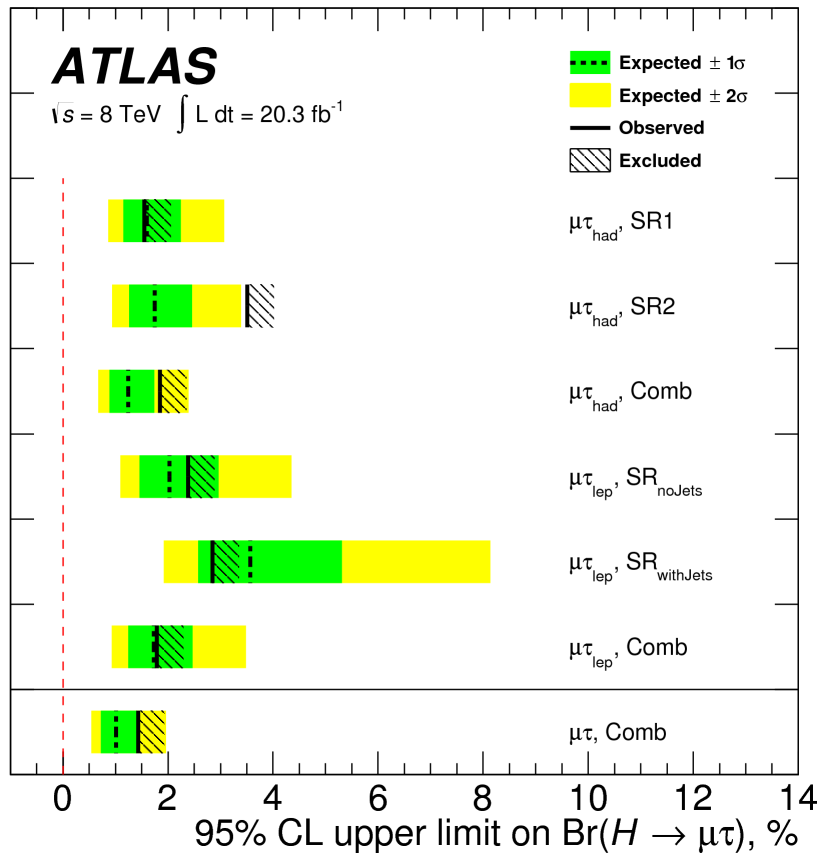
W+jet control region for fake τ_h



Search for $H \to \mu\tau$: results

			Obs. (%)	Exp. (%)	Best fit (%)
ATLAS	8 TeV	$\mathcal{B}(H \to \mu\tau)$	< 1.43	< 1.01	$0.53^{+0.51}_{-0.51}$
CMS	13 TeV	$\mathcal{B}(H \to \mu\tau)$	< 1.20	< 1.62	$-0.76^{+0.81}_{-0.84}$
CMS	8 TeV	$\mathcal{B}(H \to \mu\tau)$	< 1.51	< 0.75	$0.84^{+0.39}_{-0.37}$

CMS 13 TeV and ATLAS 8 TeV results neither rule out nor confirm 8 TeV CMS excess



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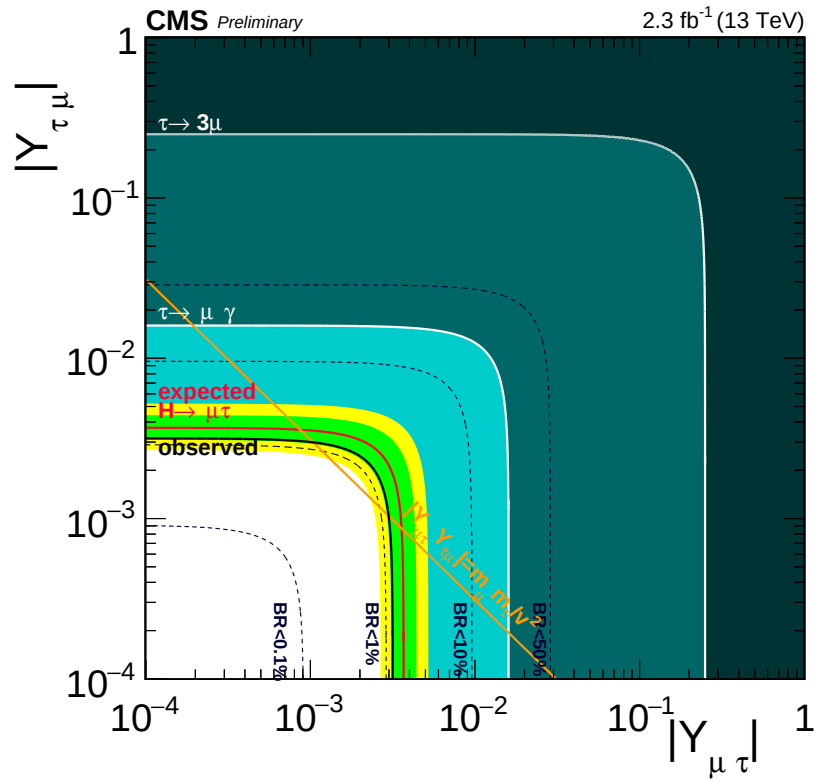
CMS 13 TeV and ATLAS 8 TeV results neither rule out nor confirm 8 TeV CMS excess

$$\Gamma(H \to \mu\tau) = \frac{m_H}{8\pi}(|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2)$$

$$\mathcal{B}(H \to \mu\tau) = \frac{\Gamma(H \to \mu\tau)}{\Gamma(H \to \mu\tau) + \Gamma_{SM}}$$

CMS at 13 TeV:

$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$



Outline of this presentation

- Higgs boson mass
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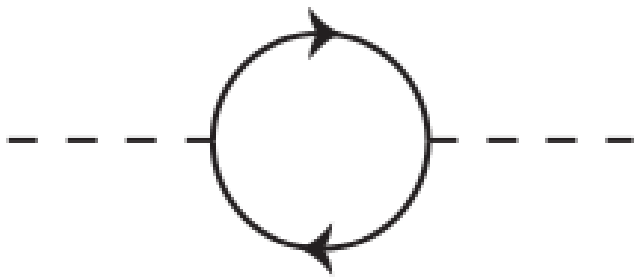
Is the electroweak vacuum stable?



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\rm UV}^2 + ...].$$

Perturbative contributions
to the Higgs boson mass

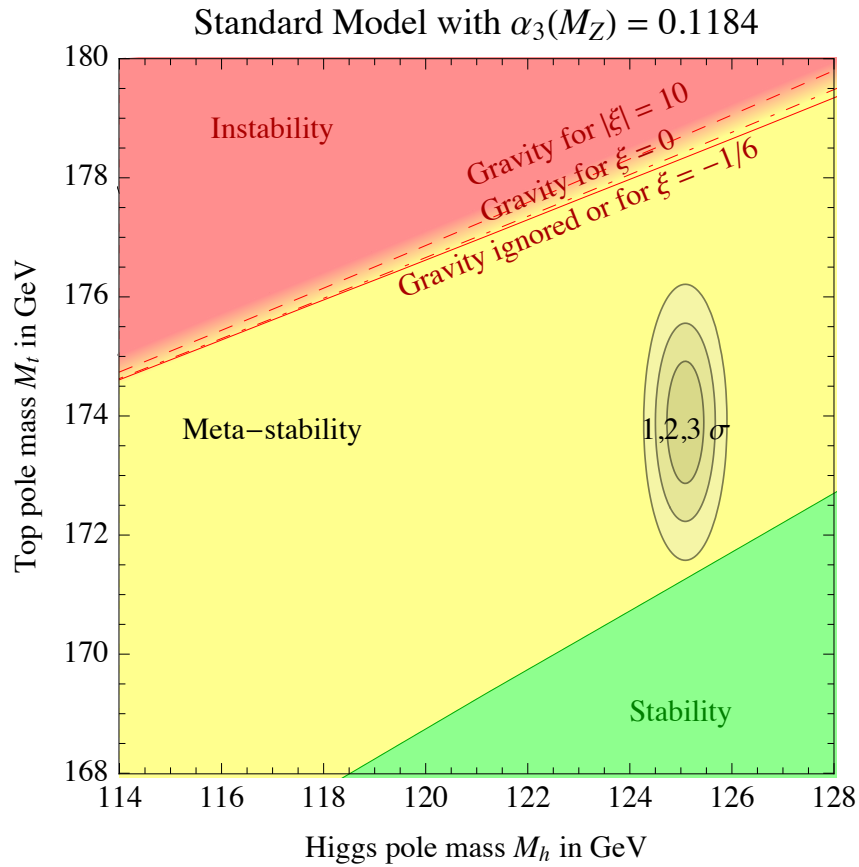
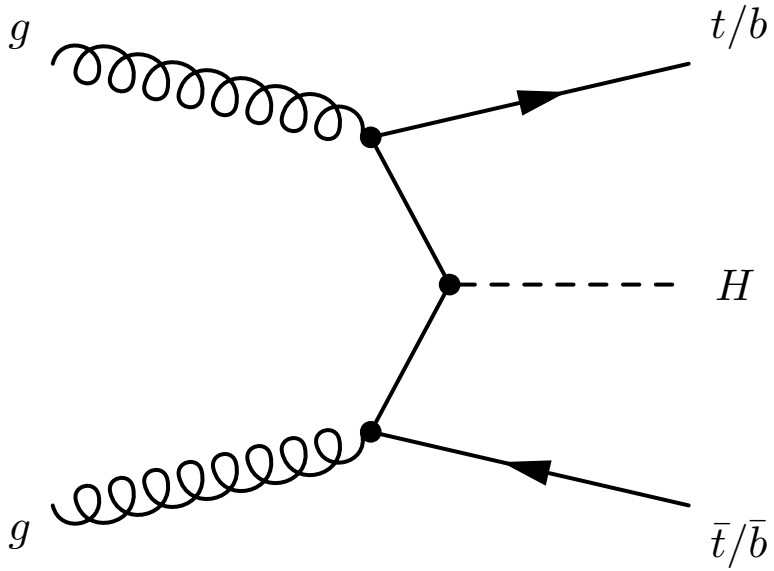


Figure from arXiv:1608.02555

Search for $t\bar{t}H$ production at 13 TeV



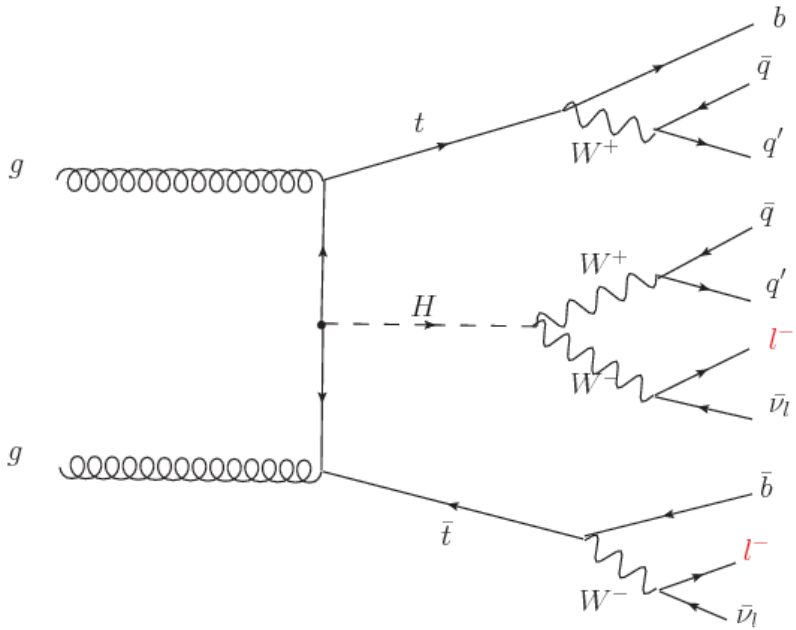
- Measure directly magnitude and phase of the top quark Yukawa coupling
  - Non-zero phase implies CP violation
- 3 $t\bar{t}H$ analyses:
  - $H \to bb$
  - $H \to WW, \tau\tau, ZZ$
  - $H \to \gamma\gamma$

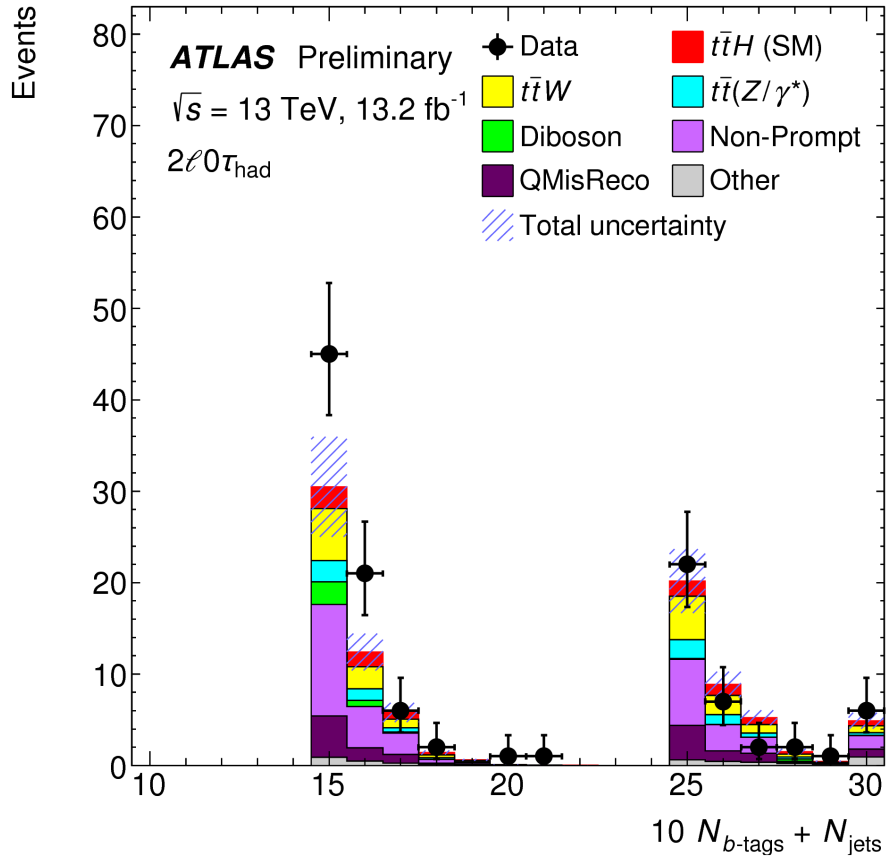
Search for $t\bar{t}H$ in multi-lepton final states at 13 TeV

- Search for $t\bar{t}H$ with $H \to WW, \tau\tau, ZZ$ decays
- 4 analysis channels selected by number of leptons and jets

	Higgs boson decay mode				$A \times \epsilon$
Category	WW^*	$\tau\tau$	ZZ^*	Other	$(\times 10^{-4})$
$2\ell 0\tau_{\text{had}}$	77%	17%	3%	3%	14
$2\ell 1\tau_{\text{had}}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

Search for $t\bar{t}H$ in multi-lepton final states at 13 TeV



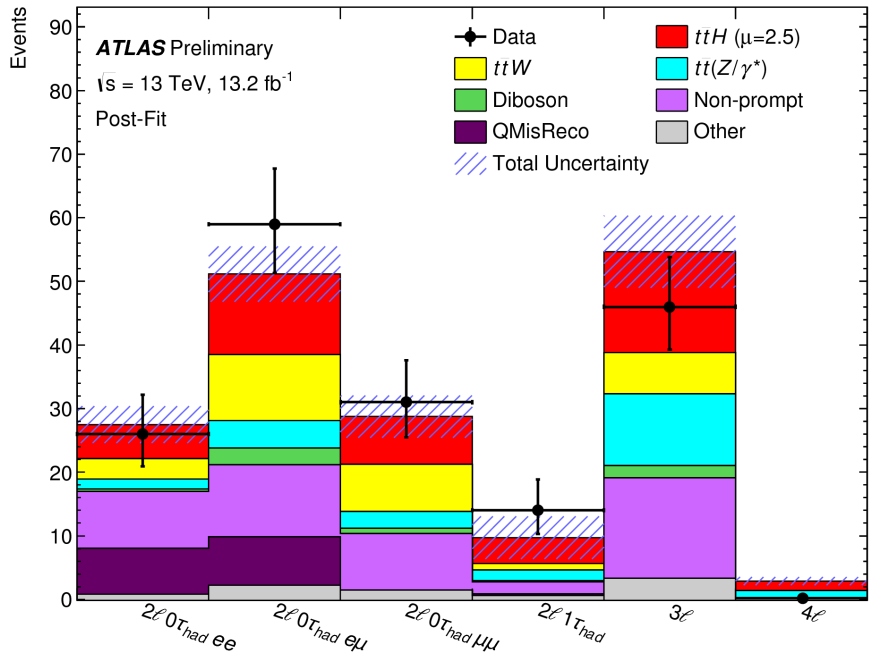


- 2 same sign electron or muon with $\geq$ 1 b-tagged jets and $\geq$ 5 jets

Search for $t\bar{t}H$ in multi-lepton final states at 13 TeV

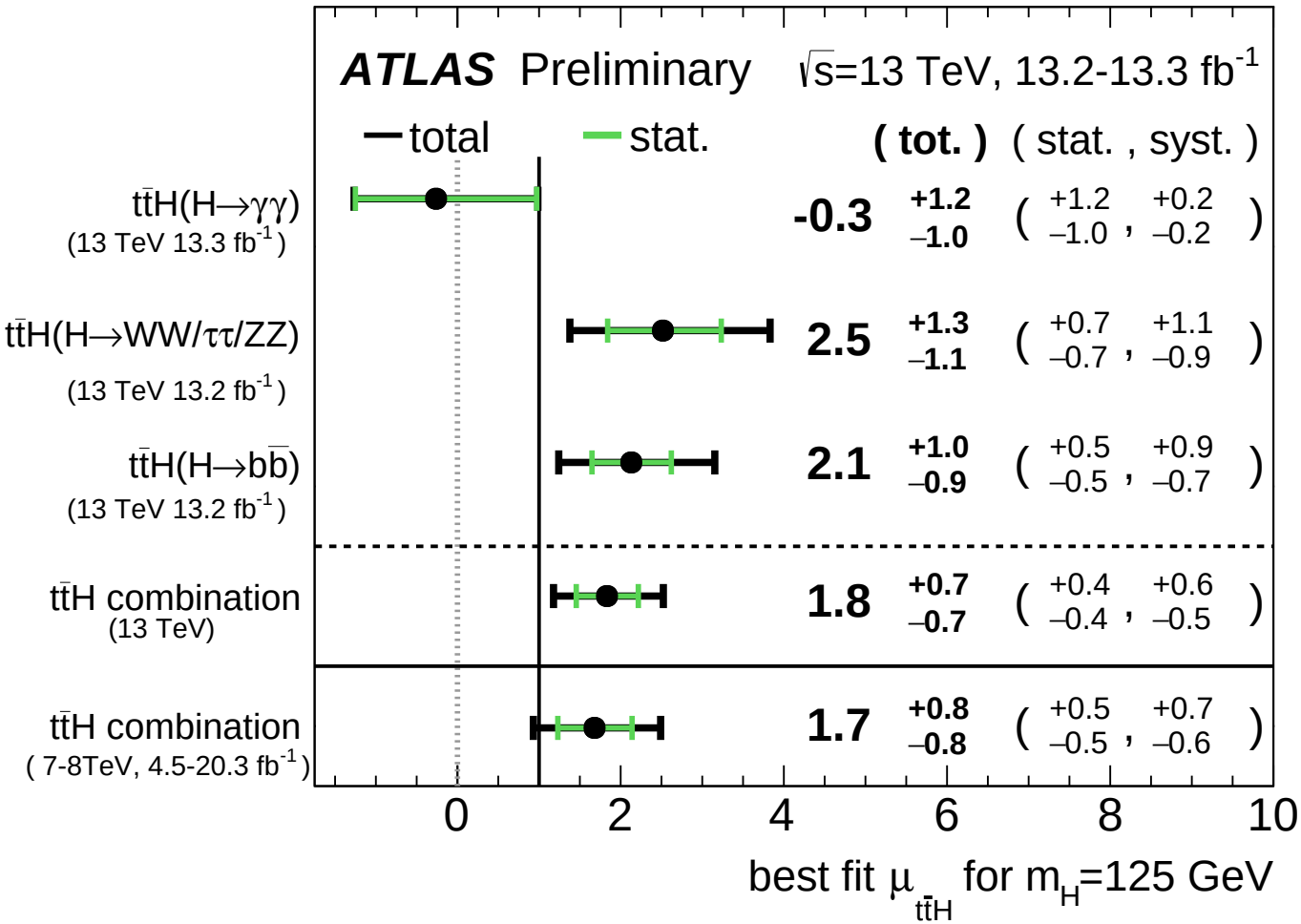
- Main irreducible backgrounds estimated from MC: $t\bar{t}W$, $t\bar{t}Z$
- Main detector background estimated from data:
  - Non-prompt electrons and muons from B hadron decays
  - Wrong sign electrons

Post-fit event yields



	$2\ell 0\tau_{\text{had}}$ ee	$2\ell 0\tau_{\text{had}}$ $e\mu$	$2\ell 0\tau_{\text{had}}$ $\mu\mu$	$2\ell 1\tau_{\text{had}}$	3ℓ	4ℓ
$t\bar{t}W$	3.2 ± 0.9	10.4 ± 2.9	7.4 ± 1.8	1.0 ± 0.5	6.5 ± 1.5	—
$t\bar{t}(Z/\gamma^*)$	1.53 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.7 ± 0.4	11.3 ± 1.9	1.08 ± 0.20
Diboson	0.40 ± 0.26	2.6 ± 1.5	0.8 ± 0.5	0.21 ± 0.15	1.9 ± 1.0	0.04 ± 0.04
Non-prompt leptons	9 ± 4	11 ± 4	8.9 ± 3.3	1.9 ± 1.6	15 ± 4	0.17 ± 0.10
Charge misreconstruction	7.2 ± 1.4	7.6 ± 1.8	—	0.25 ± 0.03	—	—
Other	0.83 ± 0.16	2.3 ± 0.6	1.5 ± 0.4	0.66 ± 0.16	3.4 ± 0.8	0.12 ± 0.05
Total background	22.2 ± 3.4	39 ± 5	21 ± 4	5.7 ± 1.7	39 ± 5	1.42 ± 0.24
$t\bar{t}H$ ($2.5 \times$ SM)	5.3 ± 1.8	13 ± 4	7.6 ± 2.5	4.0 ± 1.2	16 ± 5	1.5 ± 0.5
Data	26	59	31	14	46	0

Combined search for $t\bar{t}H$ at 13 TeV



- Combined $t\bar{t}H$ significance is 2.8σ relative to the background only hypothesis

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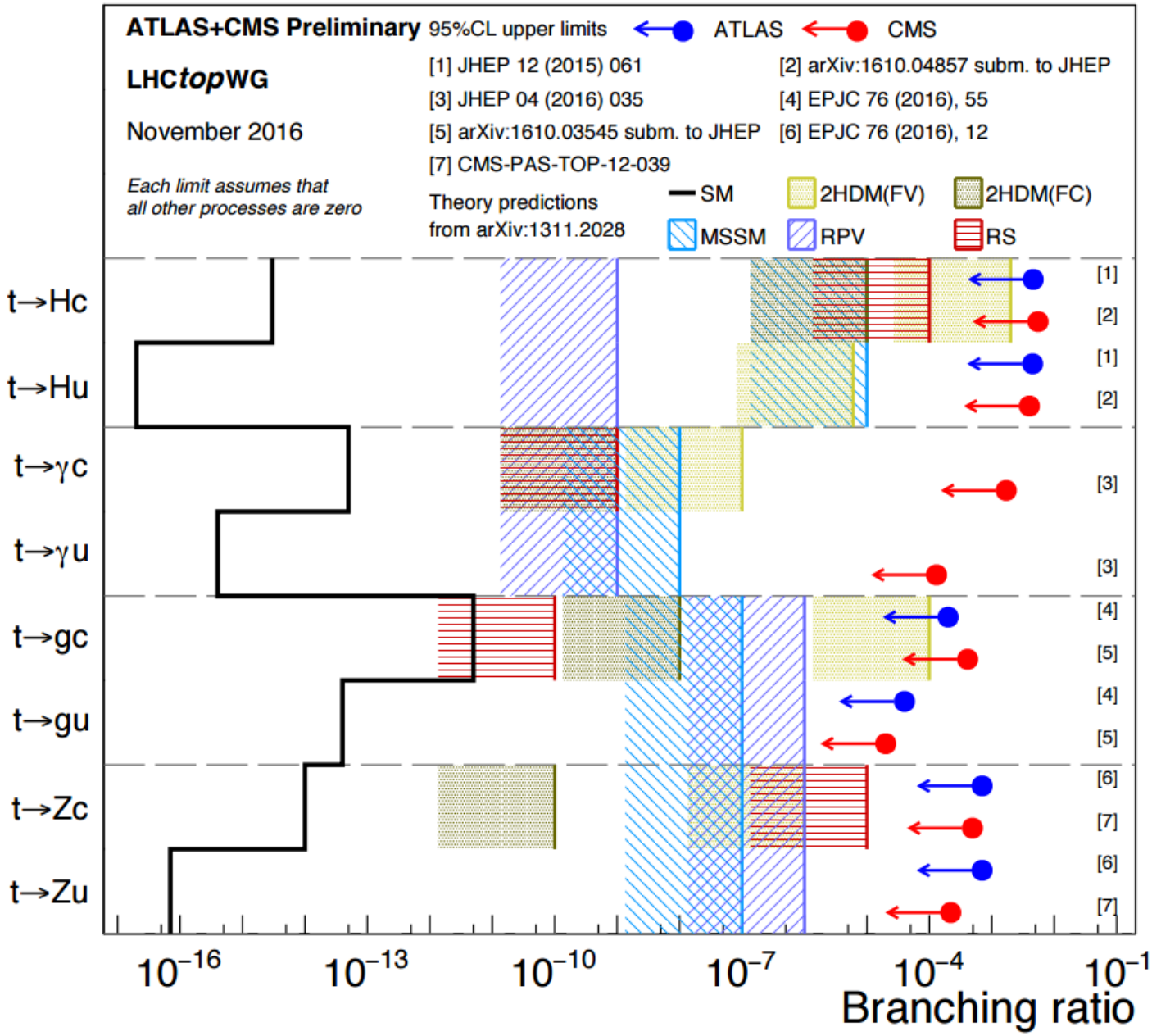
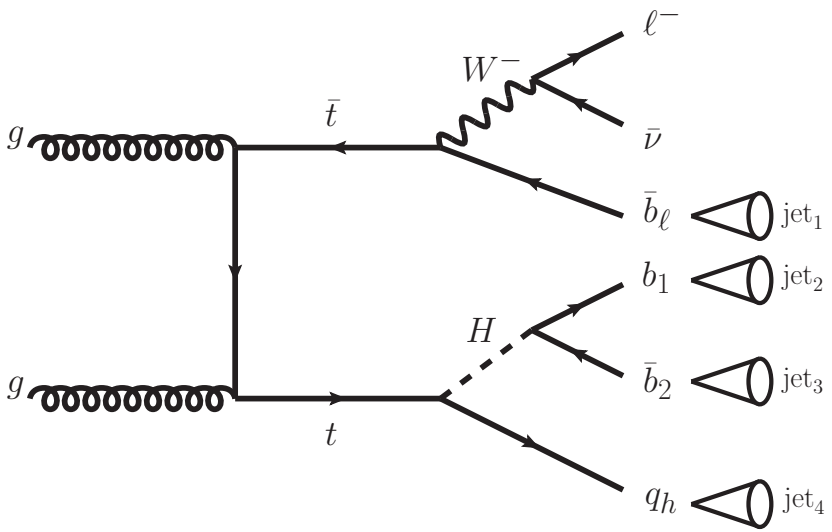
Flavour Changing Neutral Currents in top quark sector

- Flavour Changing Neutral Currents (FCNC) processes in the top quark sector are suppressed in the SM but may be enhanced in some models
- Generic searches for top FCNC processes at HERA, LEP, Tevatron and LHC:
  - Limits on $\mathcal{B}(t \to qX)$ with $X = \gamma, Z, H$
  - Limits on production, for example: $qg \to t$
- Here, focus on searches for top-Higgs FCNC decays via:
  - $t\bar{t} \to tqH \to Wb + u(c)H$
- Study clean or high rate Higgs boson decay modes:
  - $H \to \gamma\gamma$
  - $H \to bb$
  - $H \to WW, ZZ, \tau\tau \to$ multi-leptons

Flavour Changing Neutral Currents in top quark sector

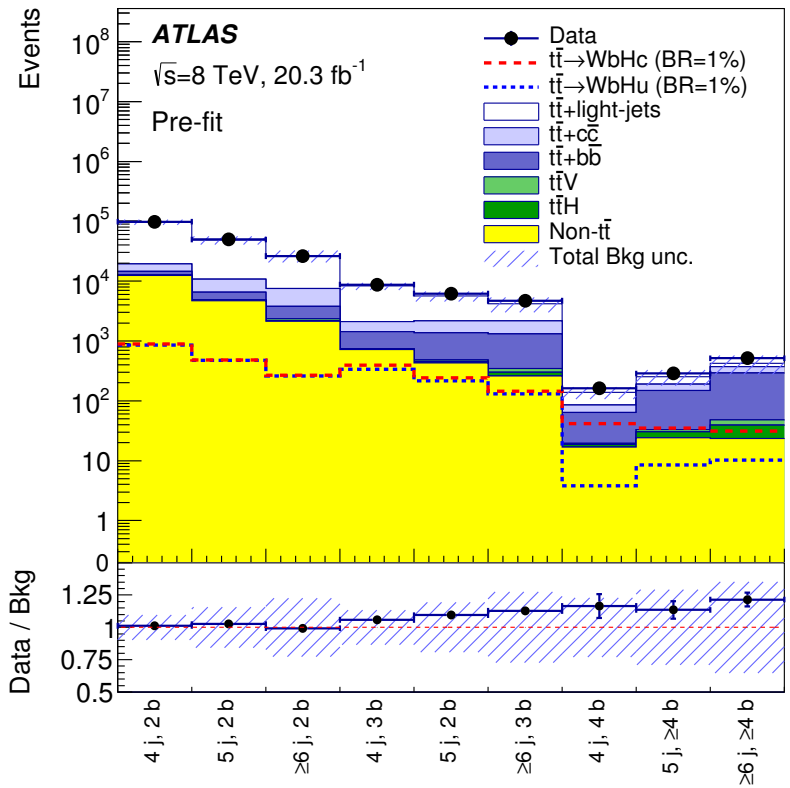


Search for $t \to qH$: $H \to bb$



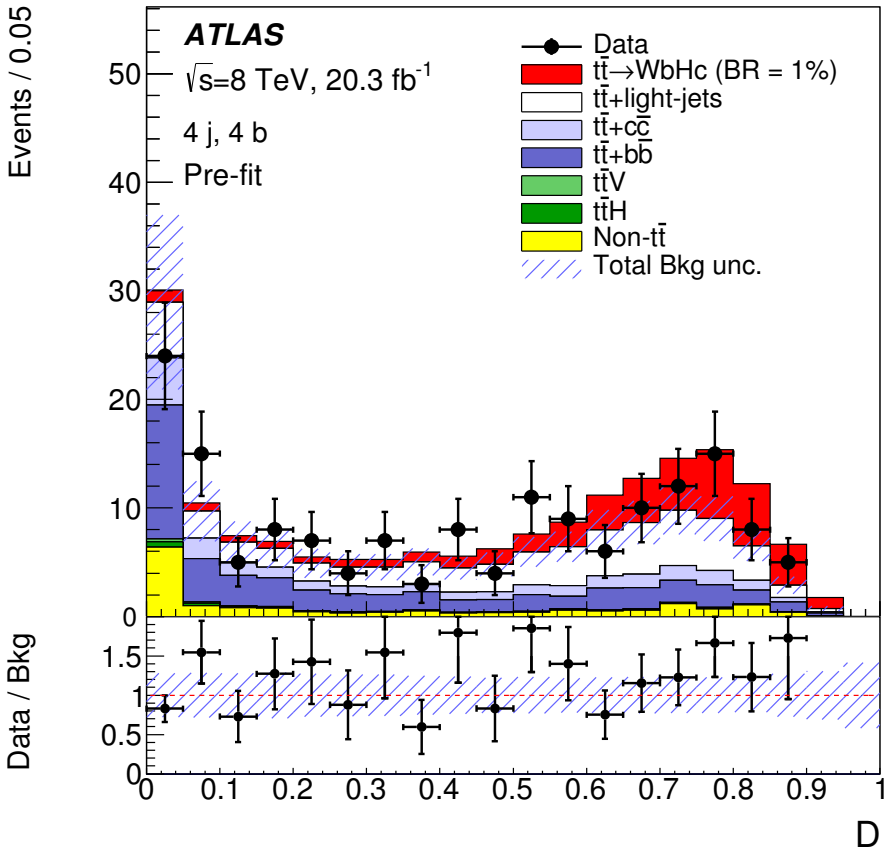
- ATLAS uses 9 categories for jets and b-jets
  - $t\bar{t} \to Wb + uH$
    most sensitive ch.: 4 jets, 3 b-jets
  - $t\bar{t} \to Wb + cH$
    most sensitive ch.: 4 jets, 4 b-jets
- Construct signal and background probabilities computed using reconstructed top and Higgs boson masses, and b-tagging weights

9 categories for jet and b-jet multiplicity

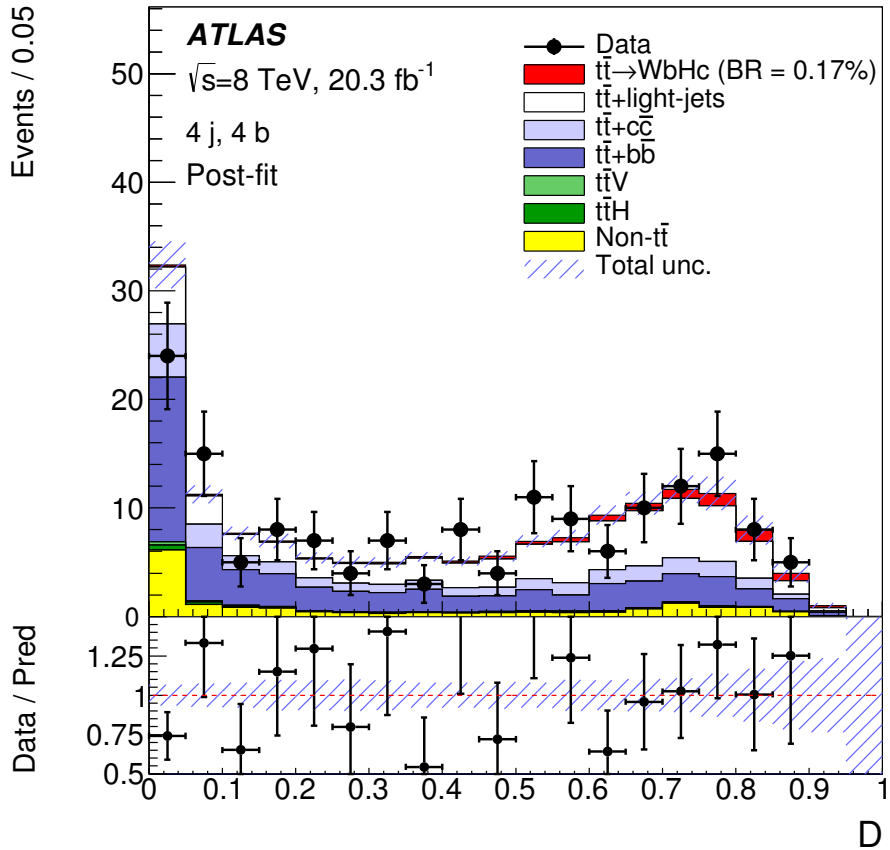


ATLAS search for $t \to qH$: $H \to bb$

4 jet, 4 b-jet pre-fit



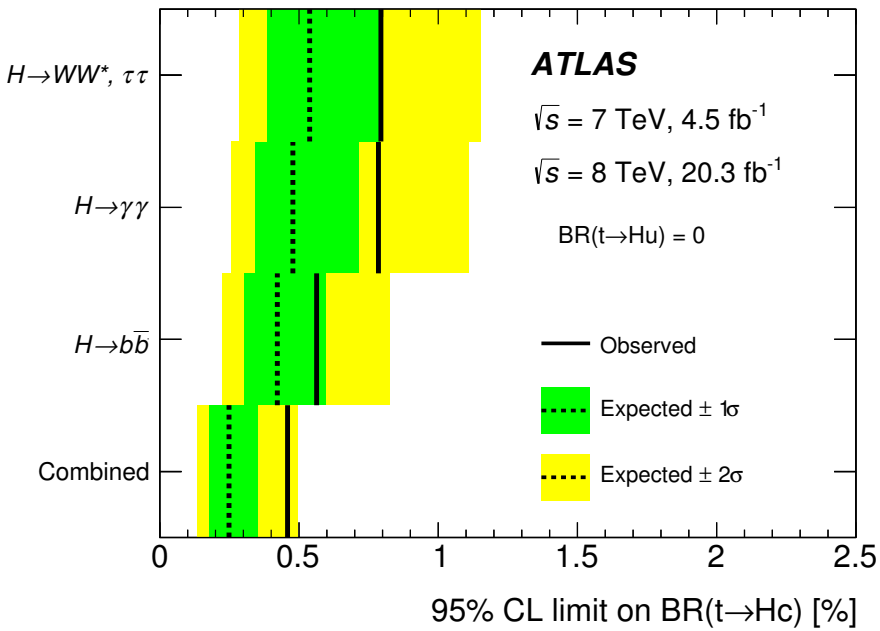
4 jet, 4 b-jet post-fit



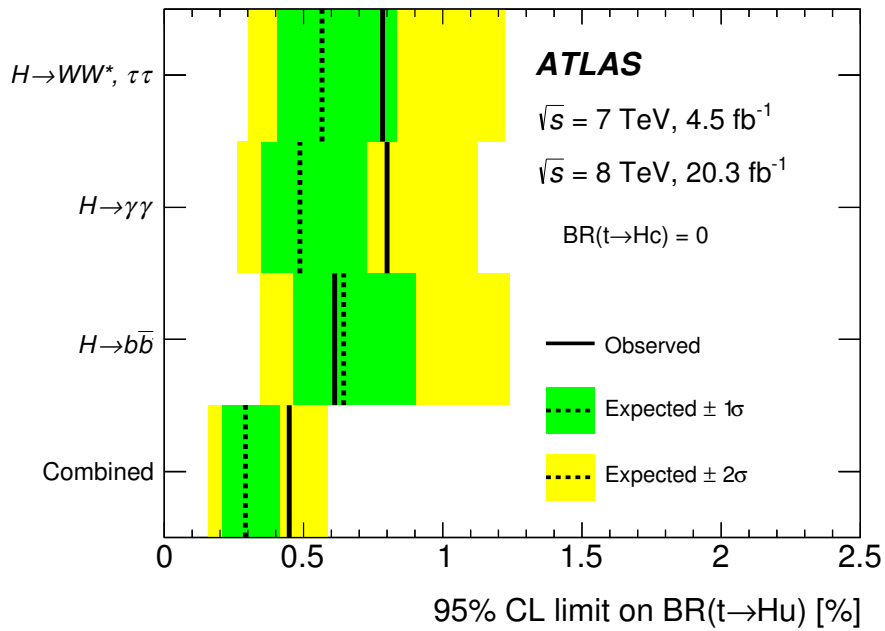
- Signal and background probabilities computed using reconstructed top and Higgs boson masses, and b-tagging weights

Search for $t \to cH$ and $t \to uH$: results

$t \to uH$



$t \to cH$



- $H \to \gamma\gamma$ sensitivity is dominated by statistical uncertainty
- Systematic uncertainties are important for $H \to WW^*$ and $H \to bb$

Search for $t \to qH$: results

			Obs. (%)	Exp. (%)
CMS	8 TeV	$\mathcal{B}(t \to cH)$	< 0.40	< 0.43
ATLAS	8 TeV	$\mathcal{B}(t \to cH)$	< 0.46	< 0.25
CMS	8 TeV	$\mathcal{B}(t \to uH)$	< 0.55	< 0.40
ATLAS	8 TeV	$\mathcal{B}(t \to uH)$	< 0.45	< 0.29

- $\mathcal{L}_{FCNC} = \lambda_{tcH}\bar{t}Hc + \lambda_{tuH}\bar{t}Hu + h.c.$

  $\mathcal{B}(t \to qH) = (\lambda_{tcH}^2 + \lambda_{tuH}^2)/(g^2 \cdot |V_{tb}|^2 \cdot \chi^2)$
  $g = 2m_W/\nu$, $x =$ kinematic factor,

  ATLAS: $|\lambda_{tqH}| = (1.92 \pm 0.02)\sqrt{\mathcal{B}(t \to qH)}$

- ATLAS observed: $|\lambda_{tcH}| < 0.13$ and $|\lambda_{tuH}| < 0.13$

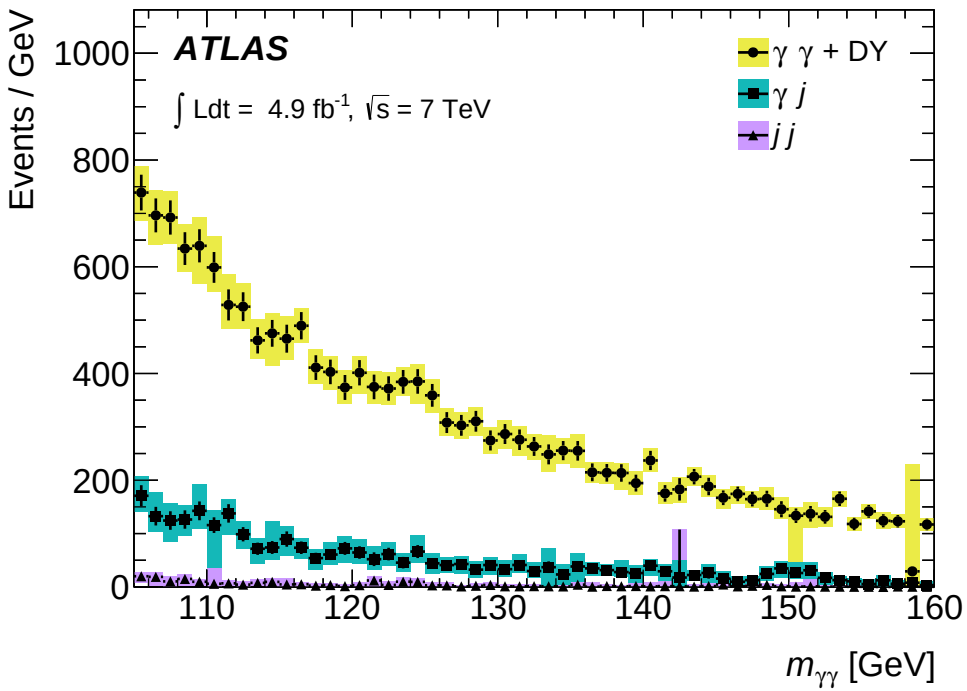
Summary and outlook

- LHC experiments have performed extensive searches for rare and flavour violating Higgs boson processes
- $\mathcal{B}(H \to \mu\mu) < 3.5 \times$ SM - already rule out universal Higgs boson couplings to the leptons
- CMS observes a mild excess in $H \to \mu\tau$ search with 8 TeV data - not yet ruled out or confirmed by new 13 TeV data
- $\mathcal{B}(t \to qH) \lesssim 0.5\%$ - strict limits on top-Higgs FCNC processes
- ATLAS approaches SM sensitivity for $t\bar{t}H$ production
- New 13 TeV results are becoming available - expect significant improvements with forthcoming Run 2 results

Thank you!

BACKUP

$H \to \gamma\gamma$



$$f(m_{\gamma\gamma}) = B(p) + \mu \times S(m_H, \theta_{\text{syst}})$$

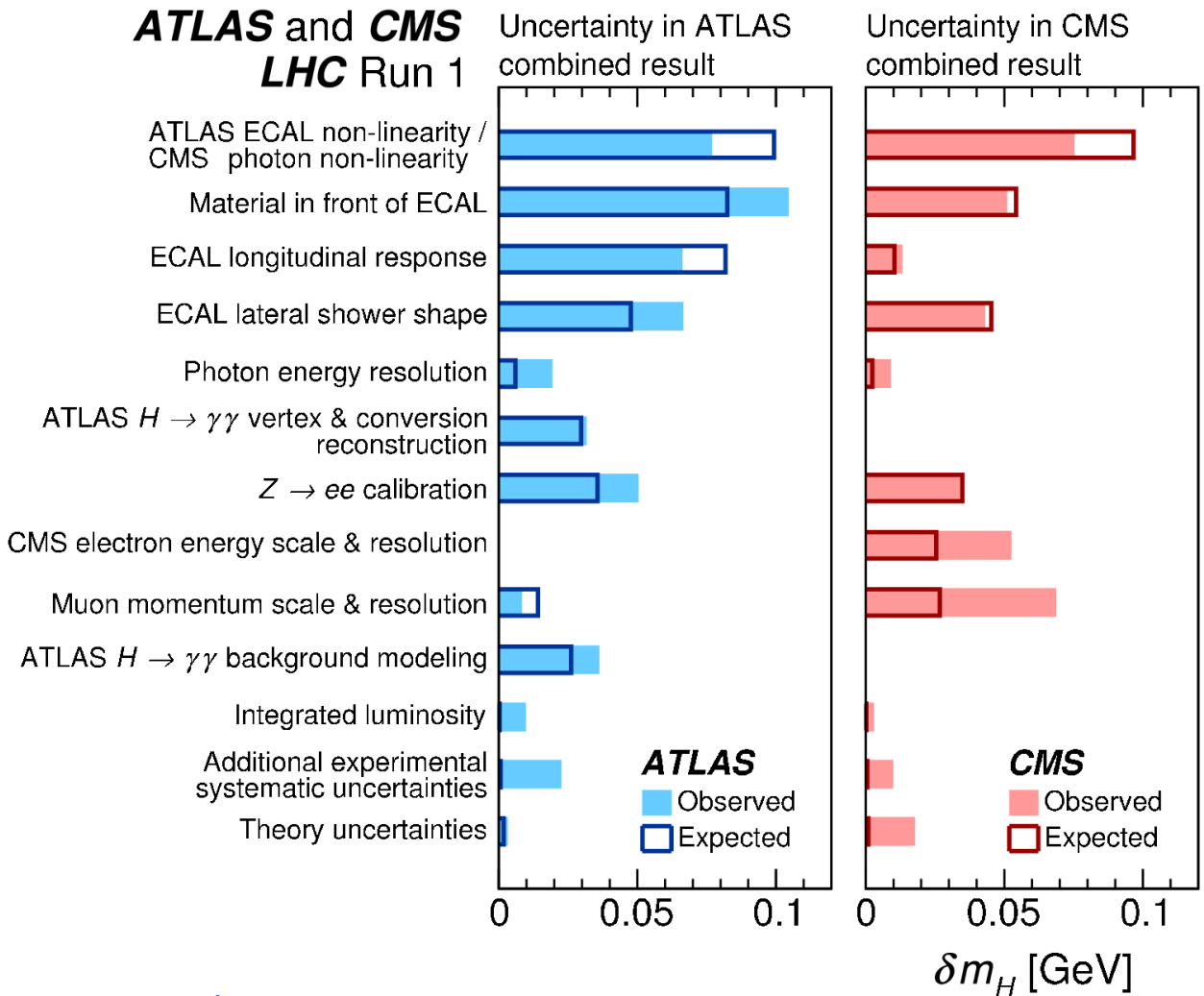
B - background shape

$B \sim e^{p_1 \cdot m_{\gamma\gamma} + p_2 \cdot m^2_{\gamma\gamma}}$

μ - signal strength (SM $\mu = 1$)

Fit $f(m_{\gamma\gamma})$ to measure m_H

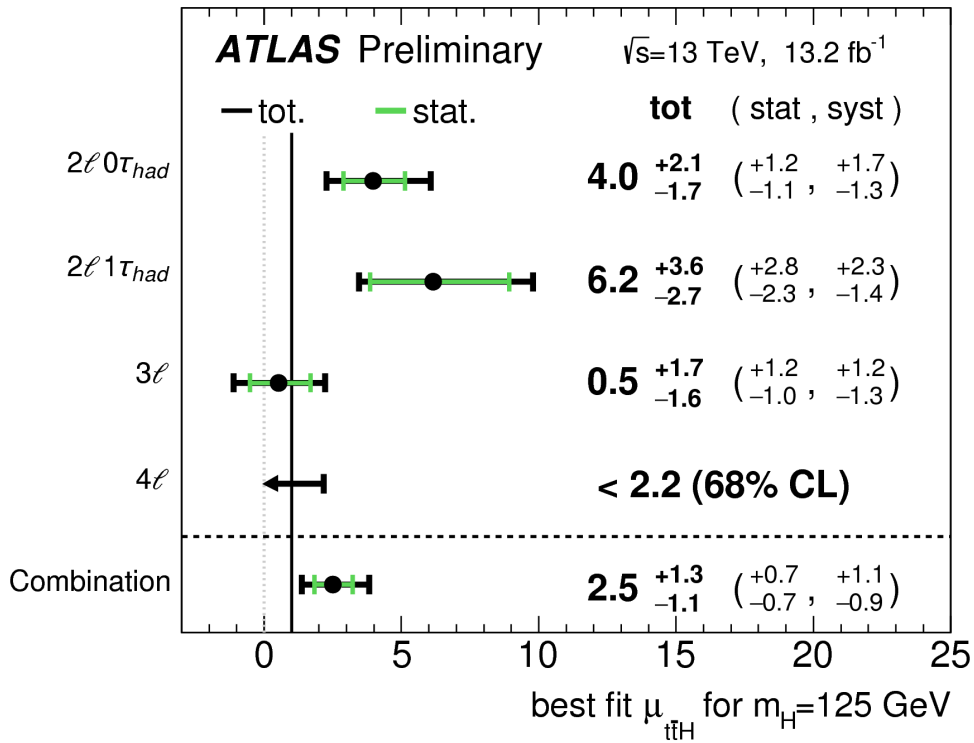
Higgs boson mass: systematic uncertainty



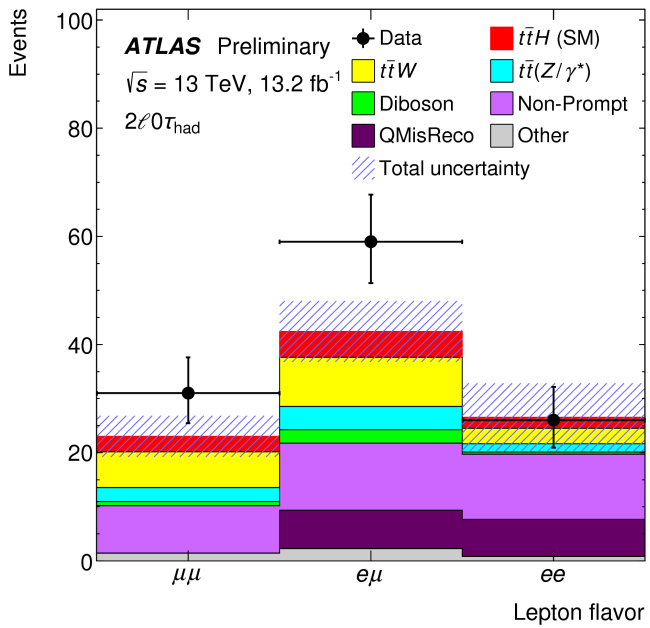
ATLAS: $\Delta_{\text{syst}}(m_H^{4\mu}) \sim 10$ MeV

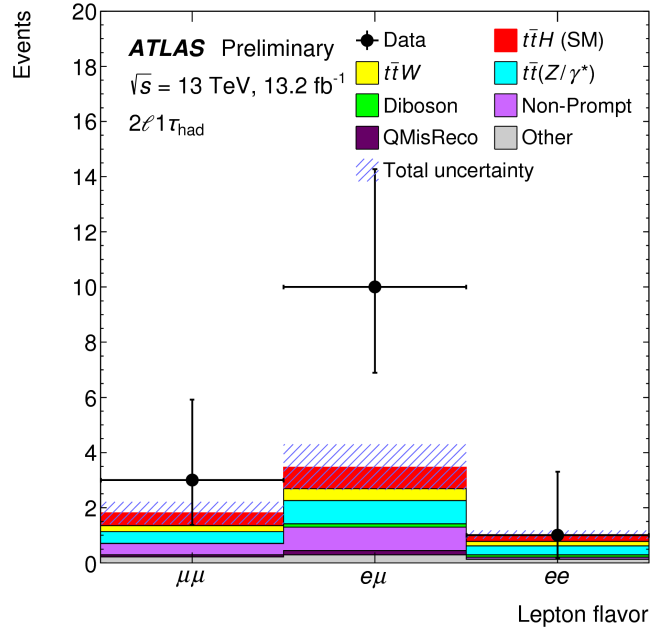
LEP: $m_Z = 91.1876 \pm 0.0021$ GeV

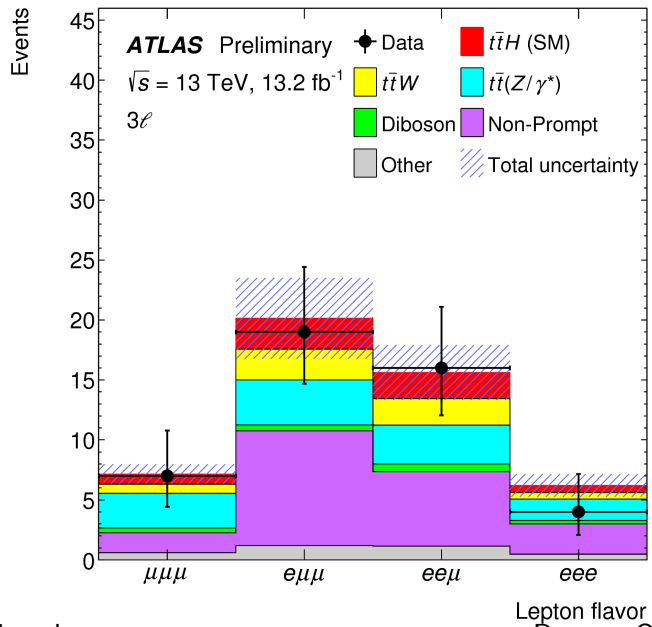
Search for $t\bar{t}H$ in multi-lepton final states at 13 TeV



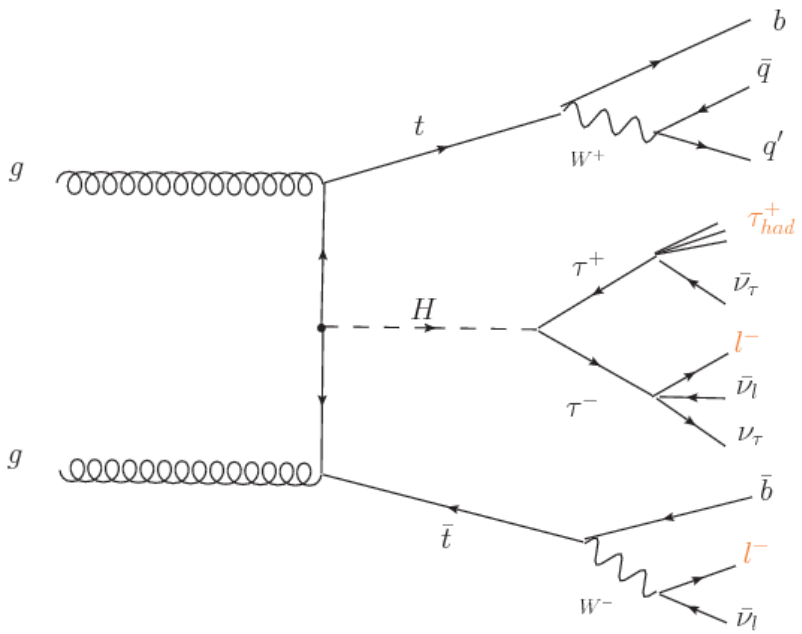
Search for $t\bar{t}H$ in multi-lepton final states at 13 TeV

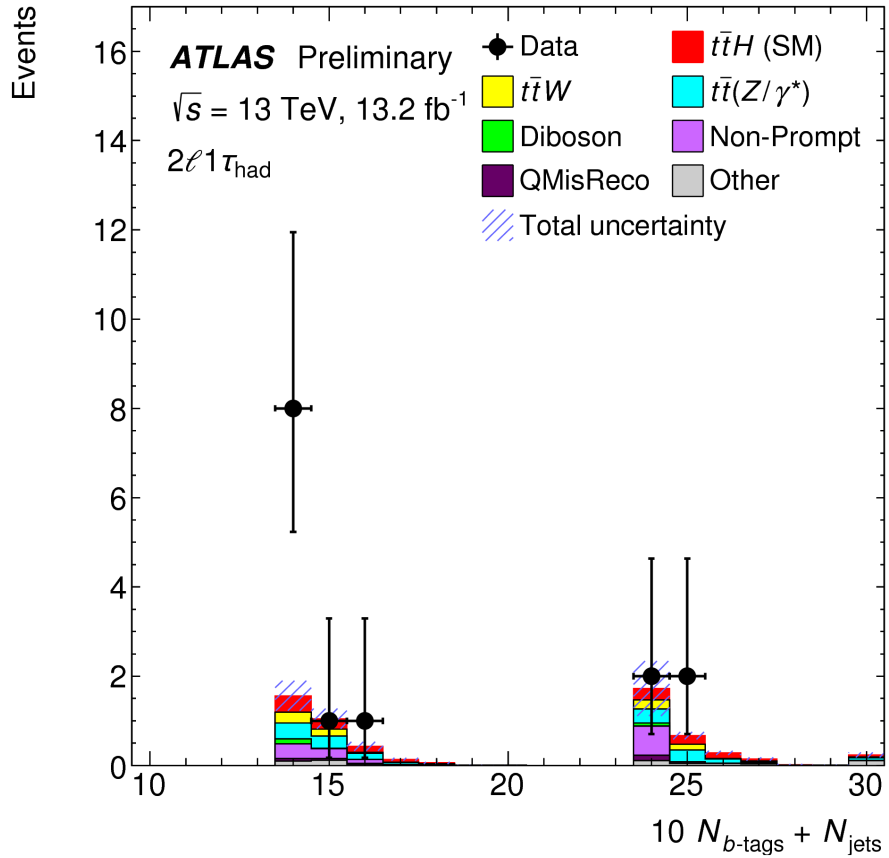






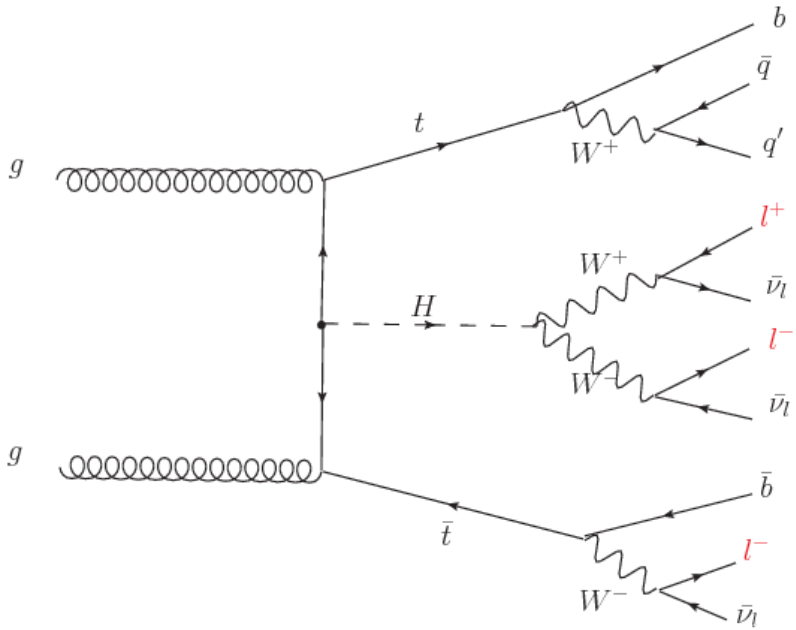
Search for $t\bar{t}H$ in multi-lepton final states at 13 TeV

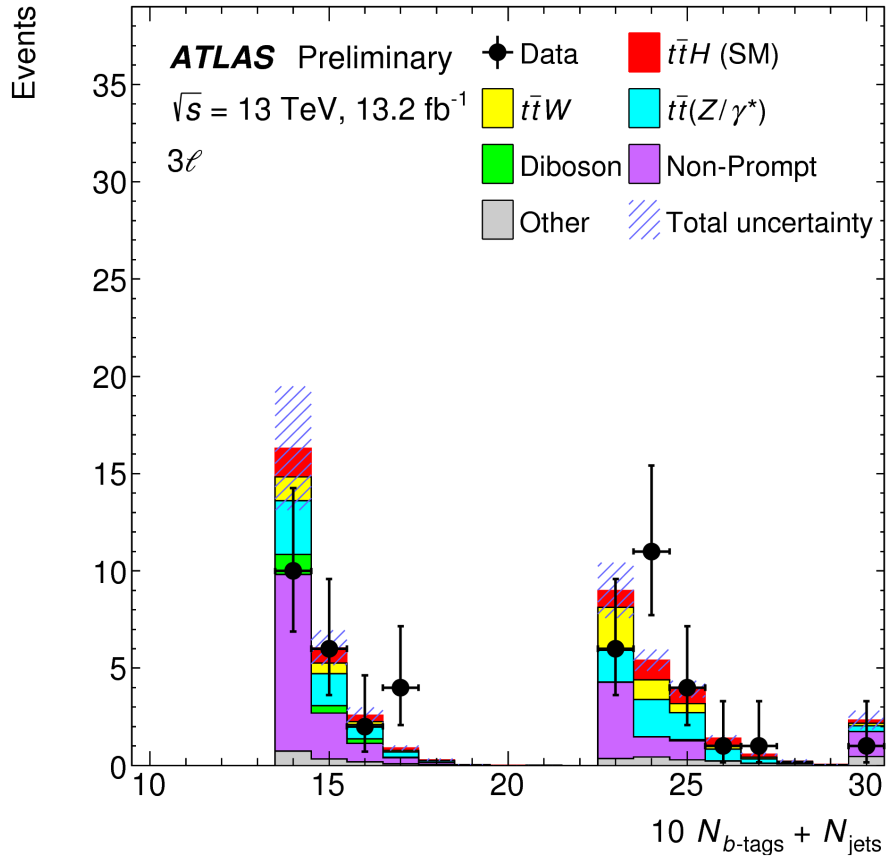




- 2 same sign electron or muon with $1\tau_{had}$, ≥ 1 b-tagged jets and ≥ 4 jets

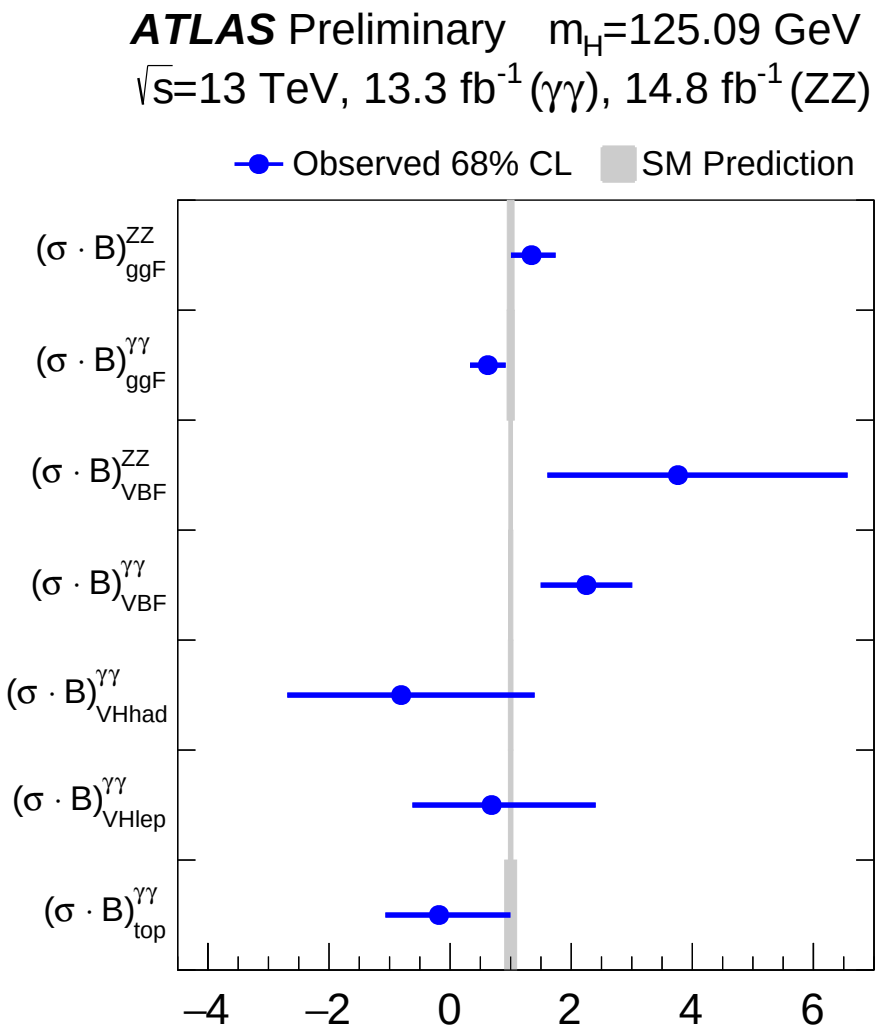
Search for $t\bar{t}H$ in multi-lepton final states at 13 TeV



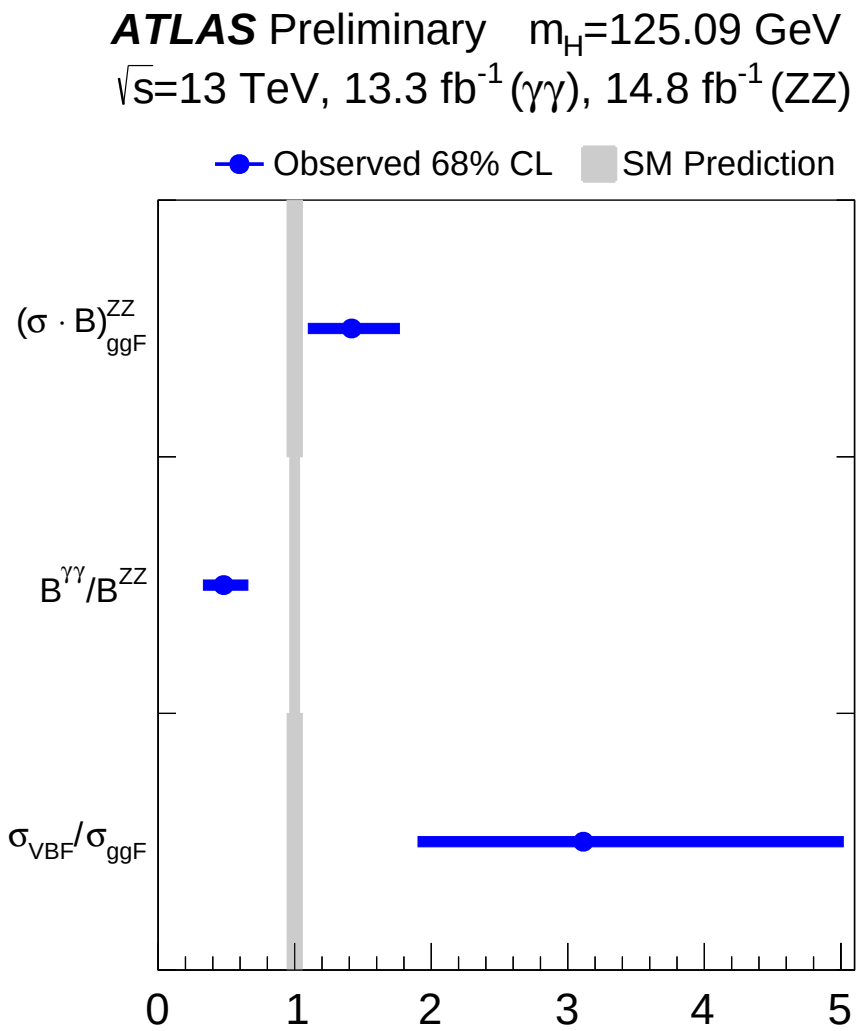


- 3 electron or muon with $\geq$ 1 b-tagged jets and $\geq$ 3 jets

Higgs boson at 13 TeV



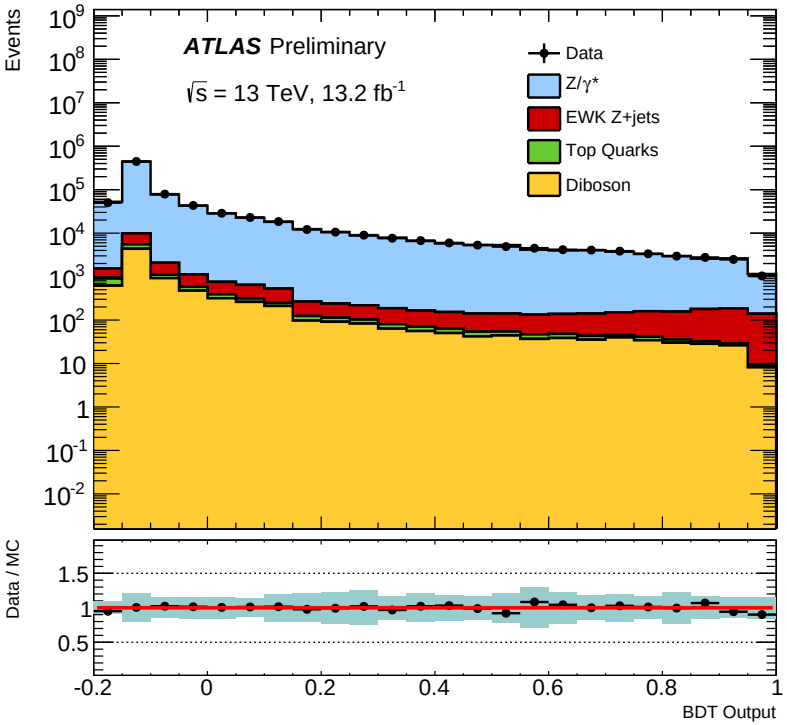
SM compatibility = 11%

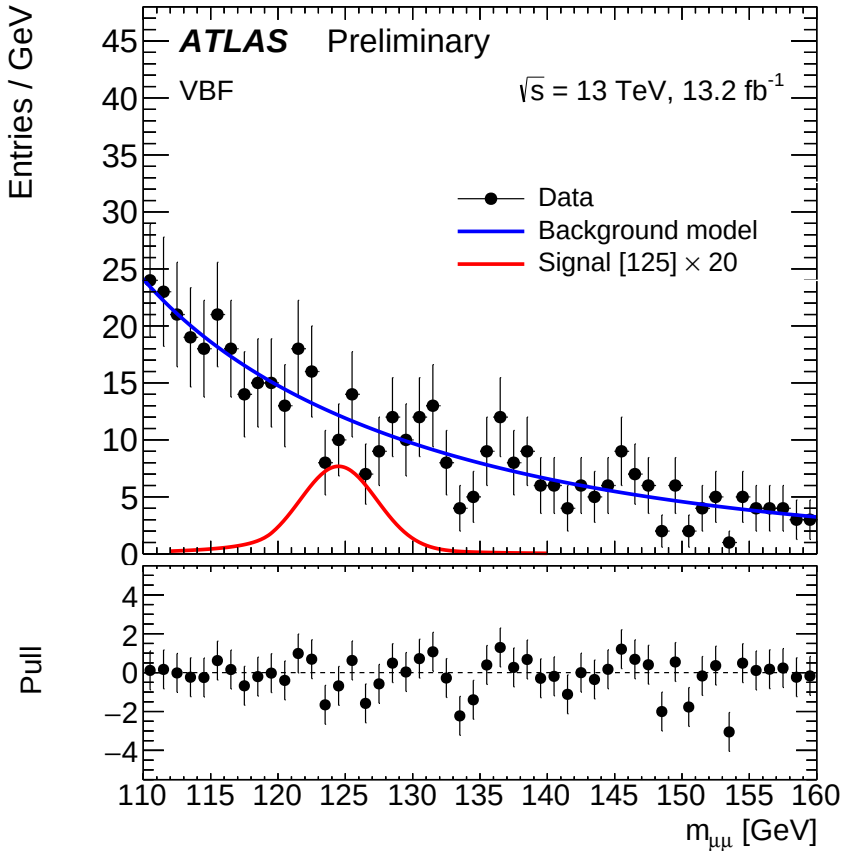


SM compatibility = 5%

Search for $H \to \mu\mu$: ATLAS VBF category

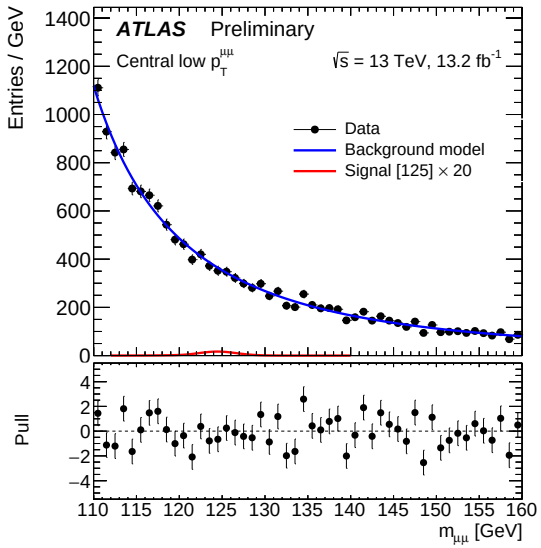
BDT output for 76 GeV $< m_{\mu\mu} <$ 106 GeV

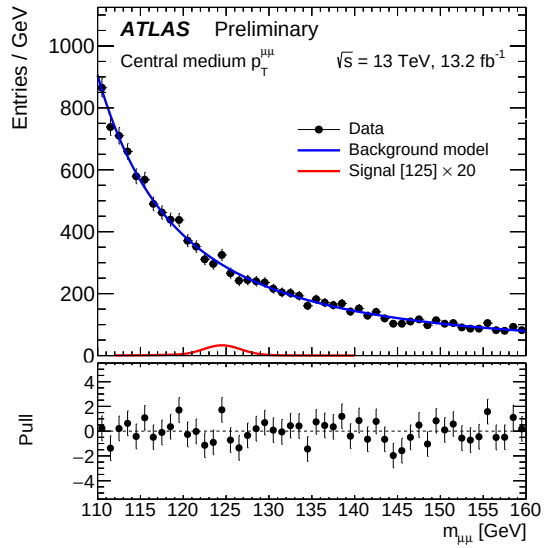


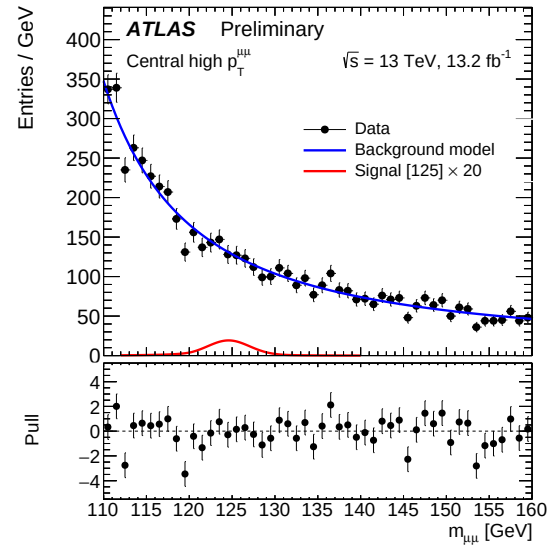


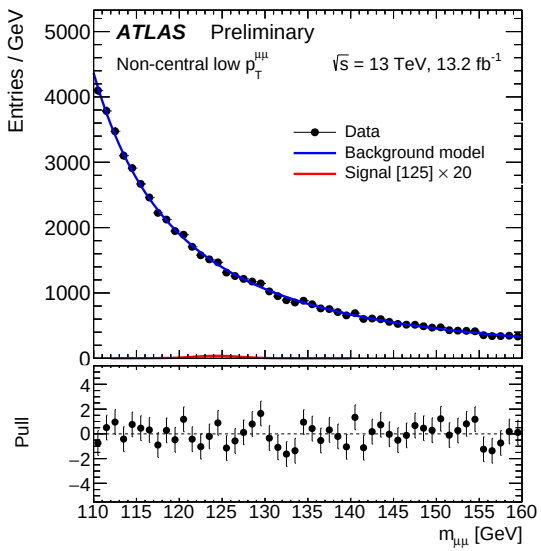
- 14 input variables: muons, MET, HT and di-jet
- $BDT > 0.7$ results in 51.3 (2.4)% efficiency for VBF signal (for total background)
- 38% ggF contamination

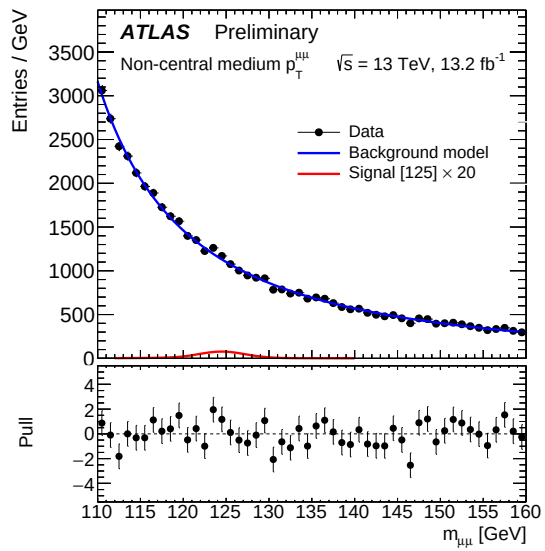
Search for $H \to \mu\mu$: $m_{\mu\mu}$ spectra

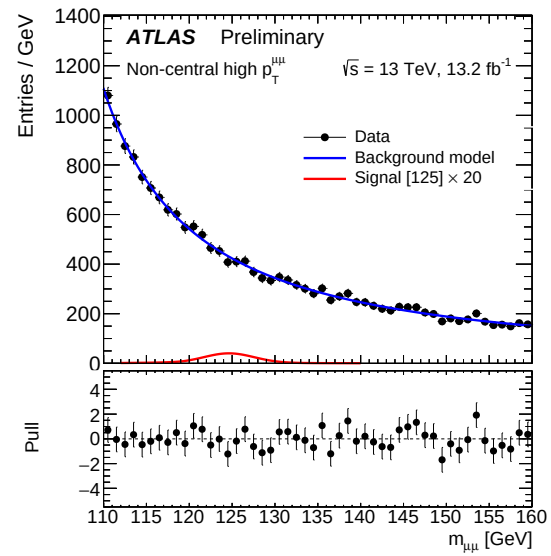












Search for $H \to \mu\mu$: ATLAS systematic uncertainty

Event yields for 120 GeV $< m_{\mu\mu} <$ 130 GeV

	Signal[125]	Z+jets	Top	Di-boson	Total background	S/$\sqrt{B}$	Data
Central, low $p_{\mathrm{T}}^{\mu\mu}$	4.0	3404	6	10	3419	0.07	3552
Non-central, low $p_{\mathrm{T}}^{\mu\mu}$	10.8	13184	23	45	13252	0.09	14262
Central, medium $p_{\mathrm{T}}^{\mu\mu}$	9.0	2872	49	31	2952	0.17	2883
Non-central, medium $p_{\mathrm{T}}^{\mu\mu}$	23.9	10255	177	157	10590	0.23	11269
Central, high $p_{\mathrm{T}}^{\mu\mu}$	6.6	1128	106	27	1261	0.19	1272
Non-central, high $p_{\mathrm{T}}^{\mu\mu}$	15.4	3939	334	106	4379	0.23	4264
VBF	2.5	78	7	1	85	0.28	117

Experimental and theory uncertainty

	ggF signal	VBF signal
Experimental		
Luminosity	2.9%	
Muon efficiency	1%	
Muon momentum resolution	<1%	
Muon trigger	<1%	
Muon isolation	2%	
Jet energy scale	-	5%
Theoretical		
Higgs branching ratio	1.23%	
QCD scales	4%	0.8%
PDFs and α_s	1.9%	2.1%
ggF contribution to VBF	22% (VBF region only)	-
Multi-parton interactions	9%	4%
Higgs p_{T} distribution	22% for $p_{\mathrm{T}} < 10$ GeV 13% for $p_{\mathrm{T}} > 10$ GeV	-

Background modelling uncertainty

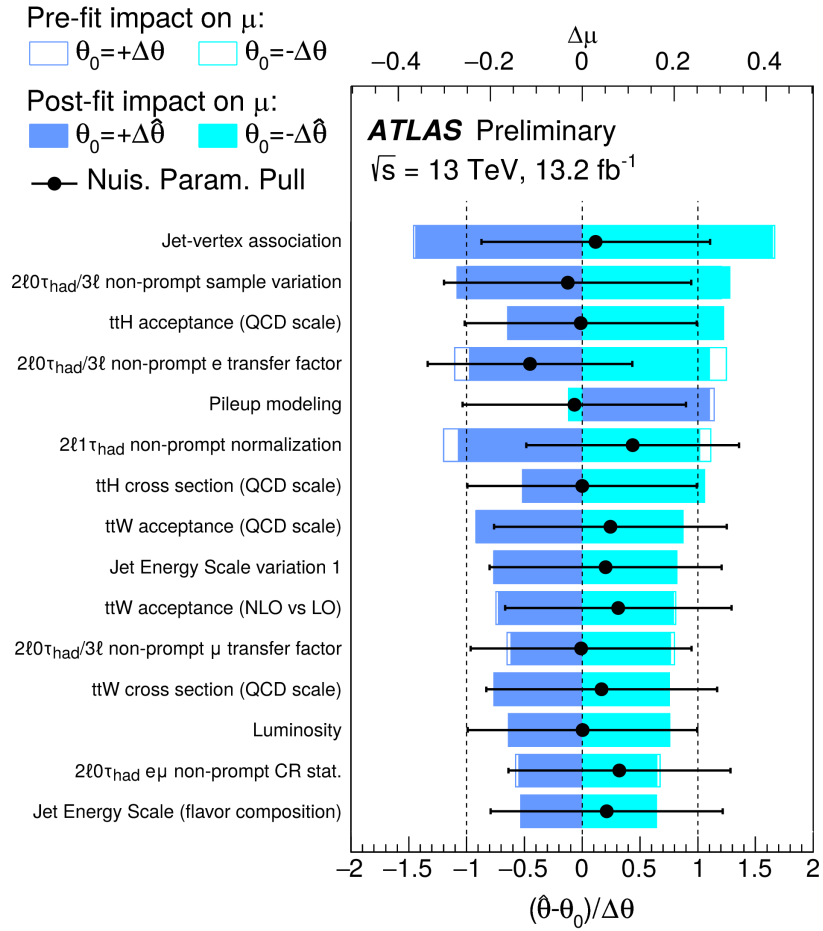
Categories	Spu. sig.	Spu./Signal[125]
Central low $p_{\mathrm{T}}^{\mu\mu}$	21	5.3
Non-central low $p_{\mathrm{T}}^{\mu\mu}$	74	6.9
Central medium $p_{\mathrm{T}}^{\mu\mu}$	20	2.2
Non-central medium $p_{\mathrm{T}}^{\mu\mu}$	43	1.8
Central high $p_{\mathrm{T}}^{\mu\mu}$	18	2.8
Non-central high $p_{\mathrm{T}}^{\mu\mu}$	35	2.3

Search for $H \to e\tau$: results

- Similar search for $H \to e\tau$ decays by both experiments
- CMS also searched for $H \to e\mu$ decays

			Obs. (%)	Exp.(%)
ATLAS	8 TeV	$\mathcal{B}(H \to e\tau)$	< 1.04	< 1.21
CMS	8 TeV	$\mathcal{B}(H \to e\tau)$	< 0.69	< 0.75
CMS	8 TeV	$\mathcal{B}(H \to e\mu)$	< 0.035	< 0.048

Search for $t\bar{t}H$



	$2\ell 0\tau_{\text{had}}$ ee	$2\ell 0\tau_{\text{had}}$ $e\mu$	$2\ell 0\tau_{\text{had}}$ $\mu\mu$	$2\ell 1\tau_{\text{had}}$	3ℓ	4ℓ
$t\bar{t}W$	3.2 ± 0.9	10.4 ± 2.9	7.4 ± 1.8	1.0 ± 0.5	6.5 ± 1.5	—
$t\bar{t}(Z/\gamma^*)$	1.53 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.7 ± 0.4	11.3 ± 1.9	1.08 ± 0.20
Diboson	0.40 ± 0.26	2.6 ± 1.5	0.8 ± 0.5	0.21 ± 0.15	1.9 ± 1.0	0.04 ± 0.04
Non-prompt leptons	9 ± 4	11 ± 4	8.9 ± 3.3	1.9 ± 1.6	15 ± 4	0.17 ± 0.10
Charge misreconstruction	7.2 ± 1.4	7.6 ± 1.8	—	0.25 ± 0.03	—	—
Other	0.83 ± 0.16	2.3 ± 0.6	1.5 ± 0.4	0.66 ± 0.16	3.4 ± 0.8	0.12 ± 0.05
Total background	22.2 ± 3.4	39 ± 5	21 ± 4	5.7 ± 1.7	39 ± 5	1.42 ± 0.24
$t\bar{t}H$ $(2.5 \times \text{SM})$	5.3 ± 1.8	13 ± 4	7.6 ± 2.5	4.0 ± 1.2	16 ± 5	1.5 ± 0.5
Data	26	59	31	14	46	0