Higgs Measurements

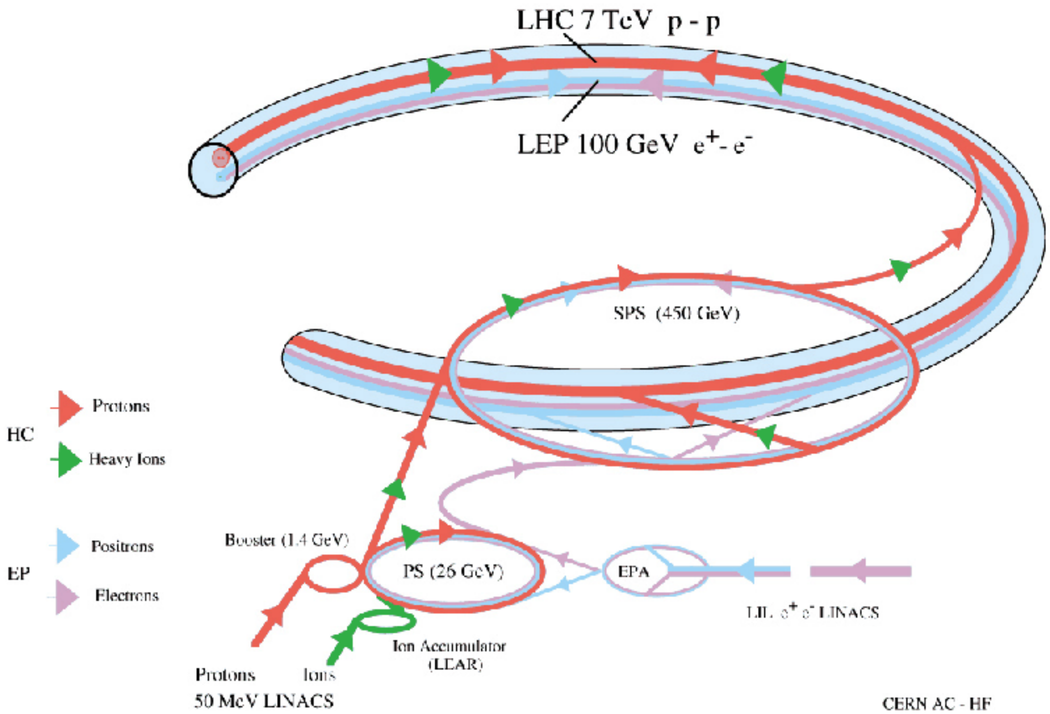
Part 1: Higgs results from Run 1

Xin Chen

Tsinghua University

International Summer School on TeV Experimental Physics (iSTEP 2015)
Shandong Univerisity, August 11-19, 2015

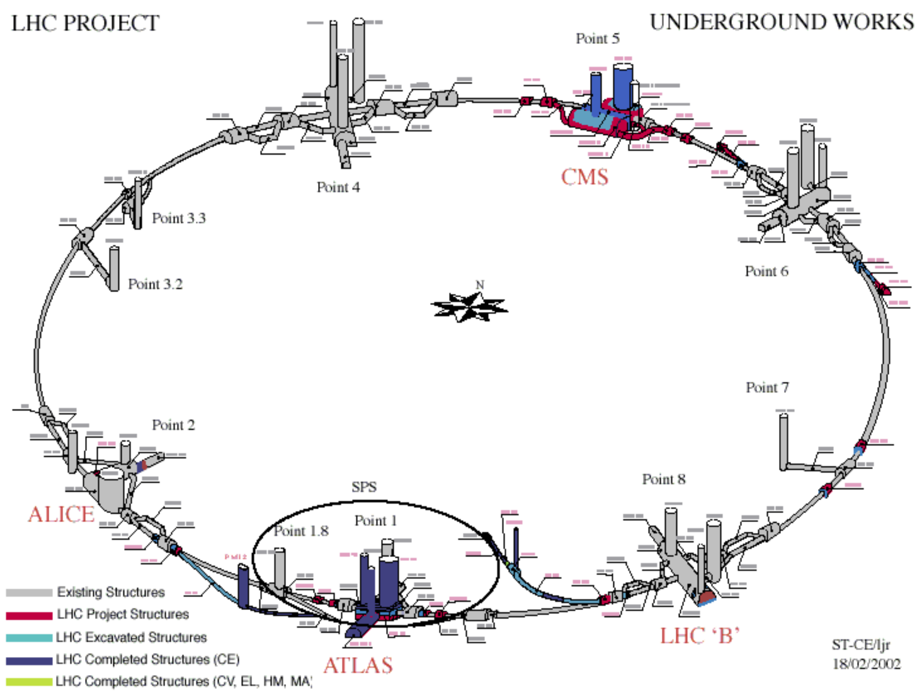
The Large Hadron Collider (LHC)



ATLAS and CMS: general purpose detectors

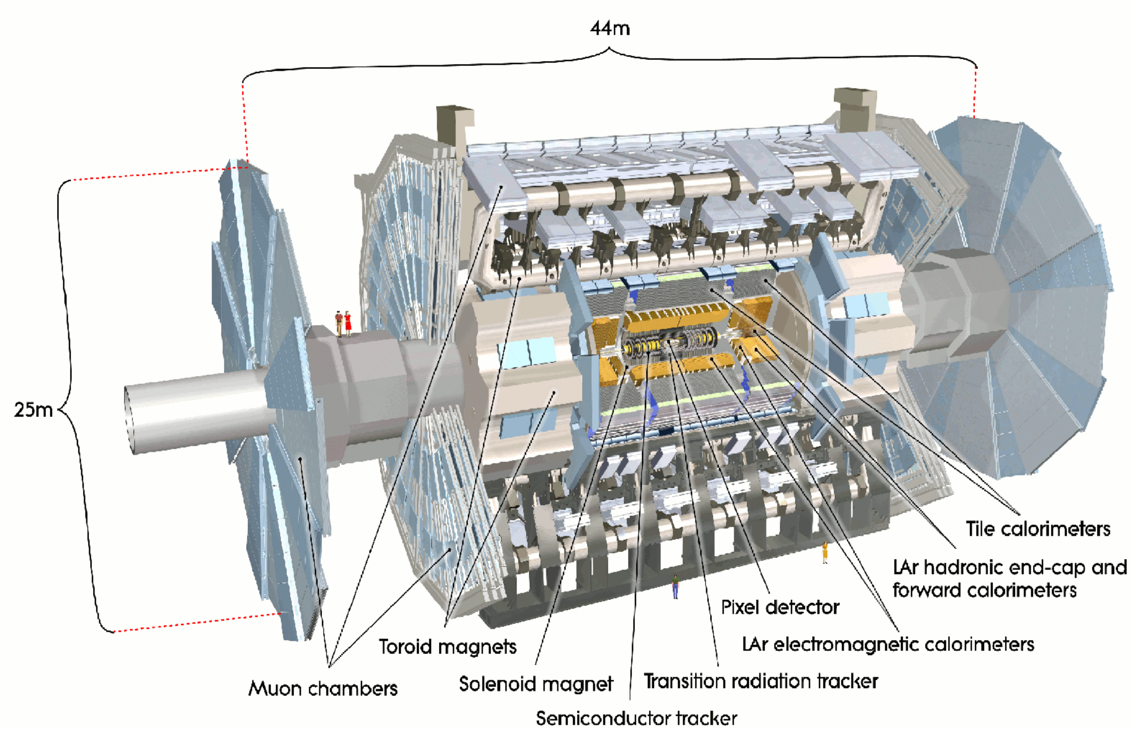
ALICE: heavy ions

LHC-B: b-physics



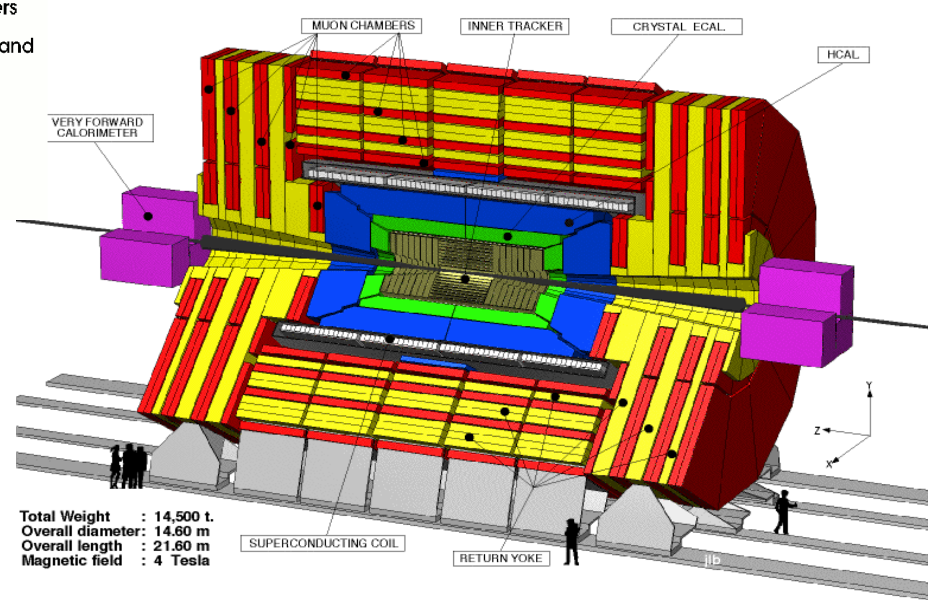
- 27 km circumference, 100 m underground
- Two proton beam in parallel pipes, rotating in opposite directions
- Dipole field increases from 0.54 T to 8.3 T in about 20 minitues. Protons are stored for 10 – 24 hours
- 25 ns bunch separation, 23 pp collisions per bunch crosing @ $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

ATLAS and CMS detector

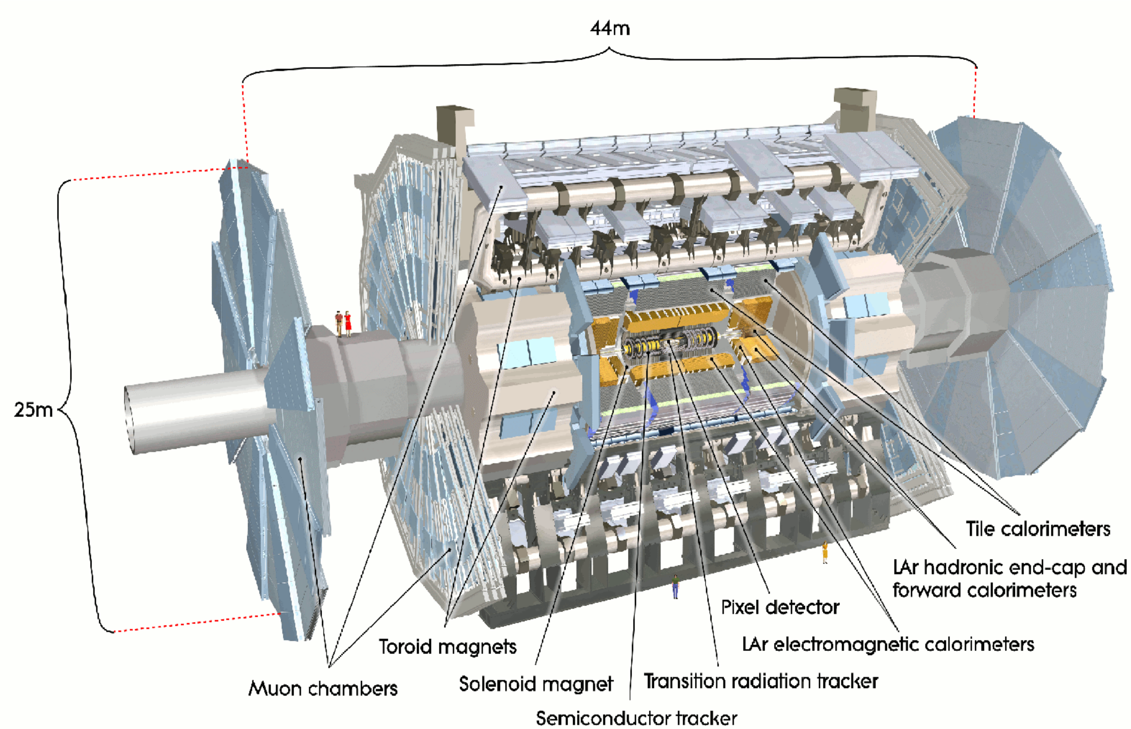


ATLAS
37+ Countries
170+ Institutions
3000+ Physicists

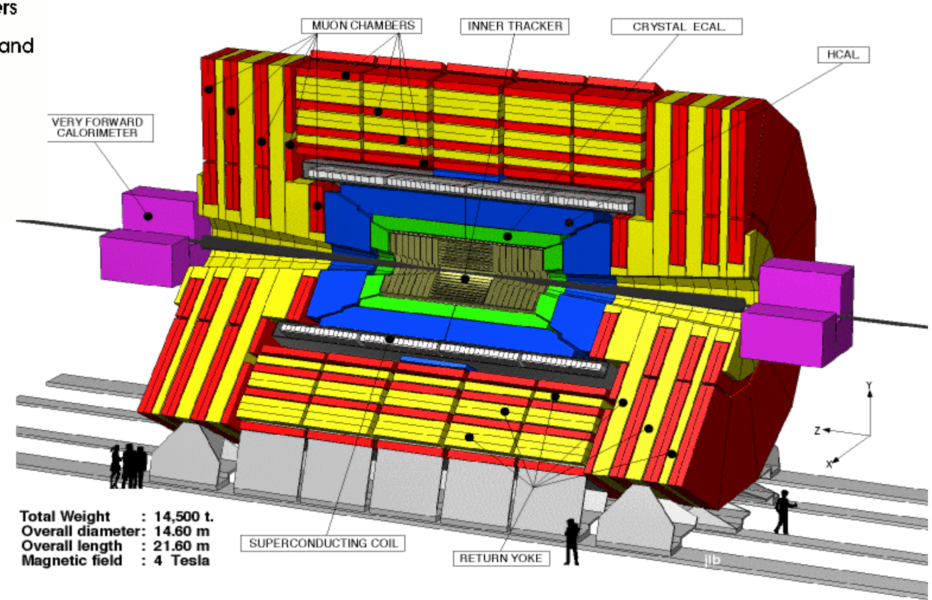
CMS
37+ Countries
160+ Institutions
3000+ Physicists



ATLAS and CMS detector



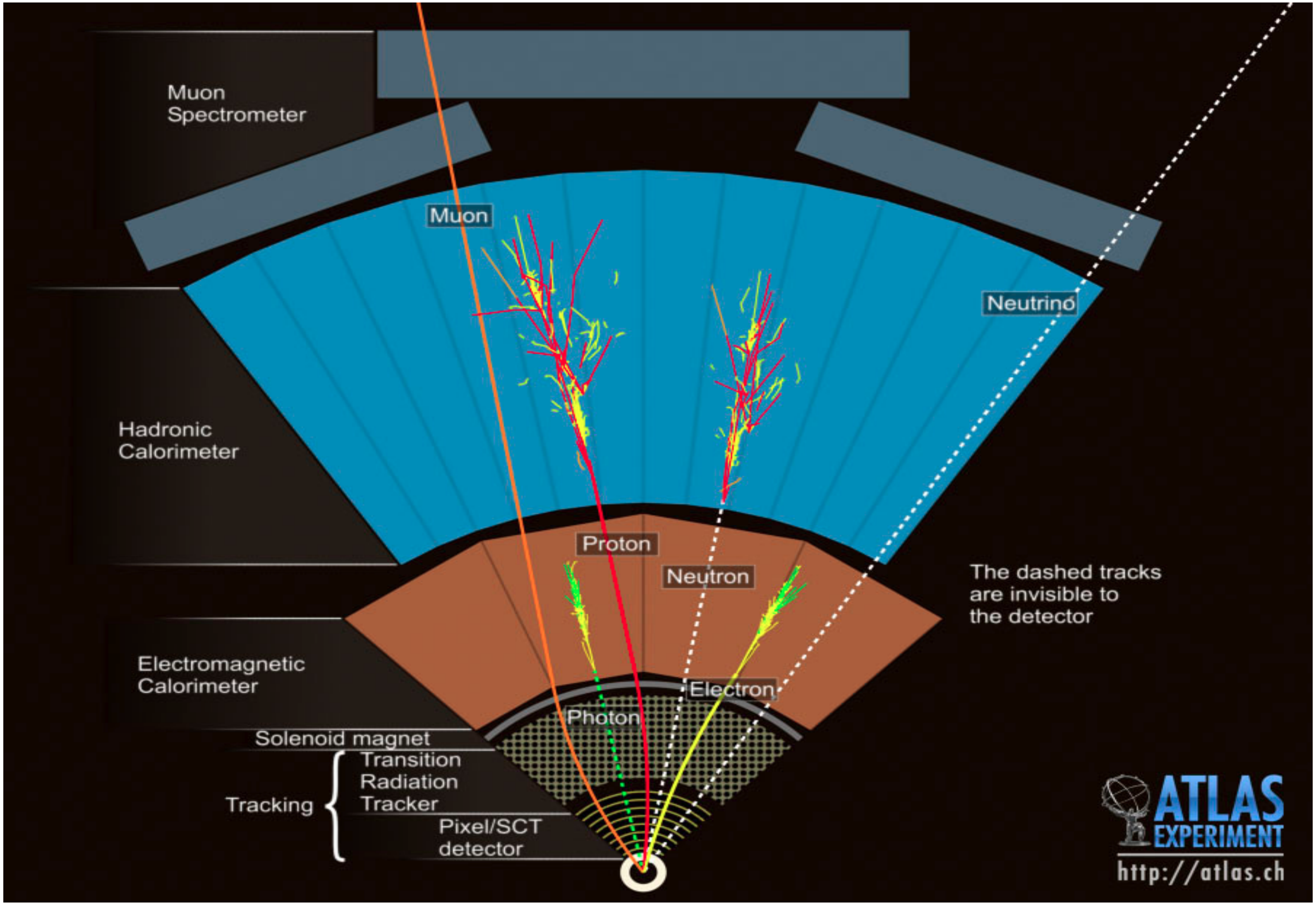
CMS
37+ Countries
160+ Institutions
3000+ Physicists



ATLAS
37+ Countries
170+ Institutions
3000+ Physicists

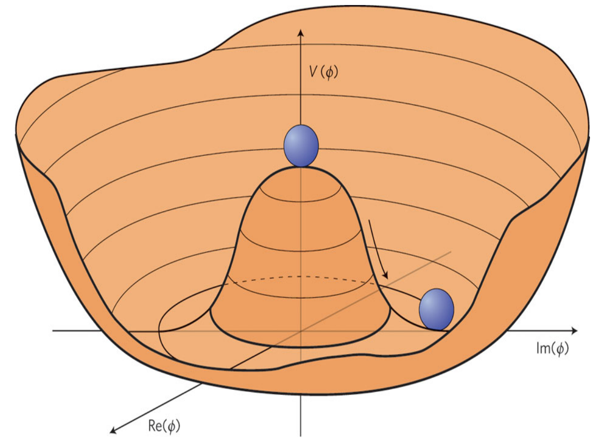
Due to personal work experience, my talk will focus on ATLAS results. Expect similar results from CMS

Tracking and calorimetry



Missing transverse energy (**MET**): we are not able to (and it does not help to) measure z-component of the missing energy

Higgs mechanism in a nutshell



The local gauge invariant Higgs (ϕ) Lagrangian is

$$L_\phi = \left| \left(i\partial_\mu - g\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu - g'\frac{Y}{2}B_\mu \right)\phi \right|^2 - V(\phi),$$

with the Higgs potential defined as

$$V(\phi) = -\mu^2\phi^+\phi + \lambda\left(\phi^+\phi\right)^2,$$

which has a minimum at $\phi = \upsilon/\sqrt{2} = \sqrt{\mu^2/2\lambda}$. Make the substitution:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad \rightarrow \quad \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \upsilon + h \end{pmatrix},$$

ϕ_1, ϕ_2 and ϕ_3 become the Goldstone bosons in the Lorentz gauge – absorbed into the longitudinal polarizations of the three weak bosons in the Unitarity gauge. Electroweak gauge symmetry is broken, and Higgs field aquires a mass:

$$m_H = \sqrt{2\lambda}\upsilon, \quad \upsilon = \left(\sqrt{2}G_F\right)^{-1/2} = 246 \;\; \text{GeV}$$

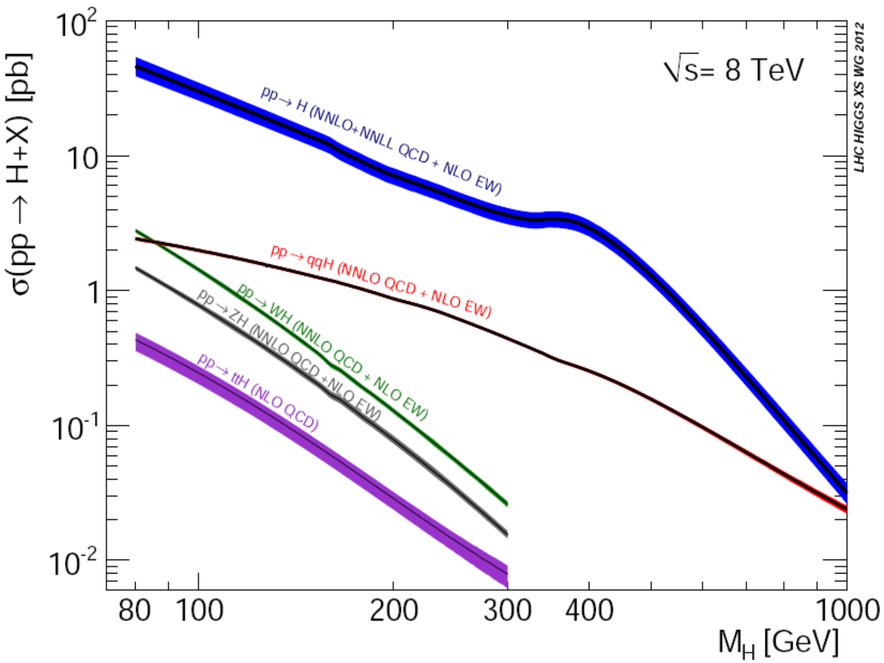
Thus, Higgs mass is not predicted in the Standard Model

Higgs production modes

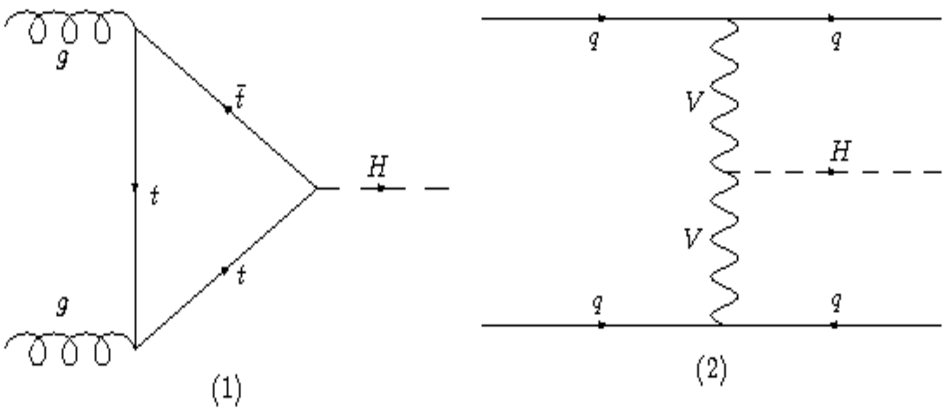
Higgs couplings to fermions and bosons:

$$g_{hf\bar{f}} = \frac{gm_f}{2m_W}, \quad g_{hWW} = gm_W, \quad g_{hZZ} = \frac{gm_Z}{\cos\theta_W}$$

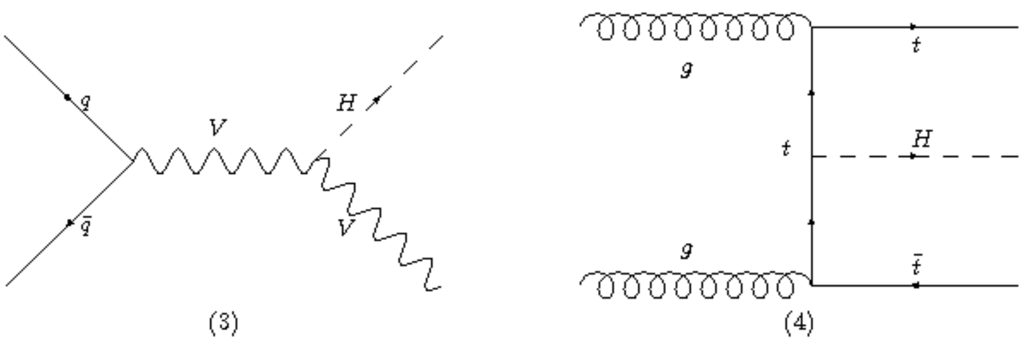
Yukawa Gauge Gauge



Higgs production channels at LHC:



Gluon-gluon fusion Vector-boson fusion

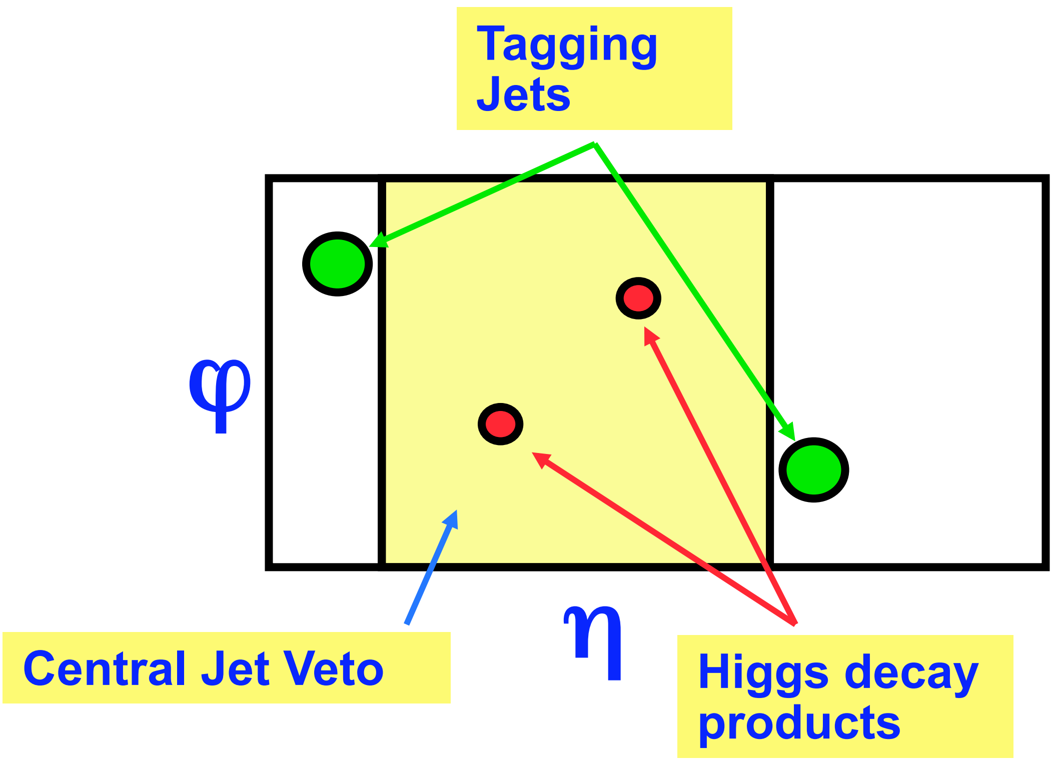


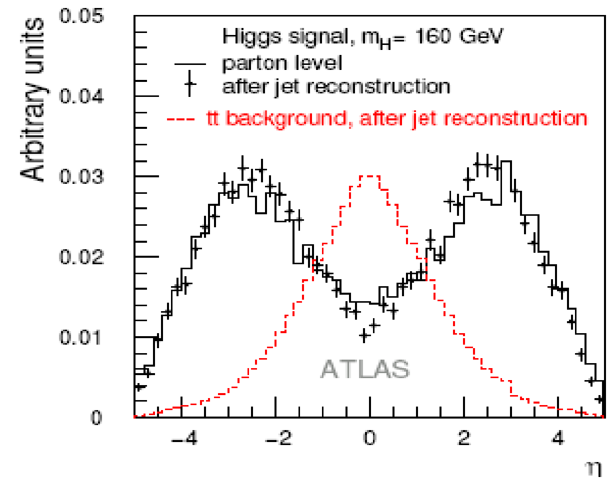
VH Associated ttH

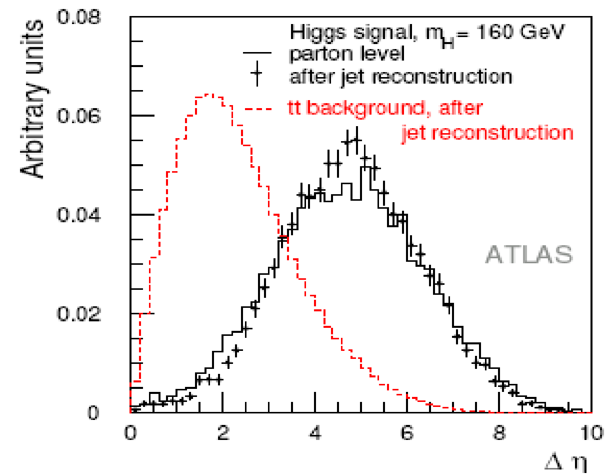
Low mass SM Higgs + 2jets – VBF

Wisconsin Pheno (D. Zeppenfeld, D. Rainwater, et al.) proposed searching for a low mass Higgs in association with 2 jets plus central jet veto

- **Central jet veto is initially suggested by V. Barger, K. Cheung and T. Han in PRD 42 3052 (1990)**

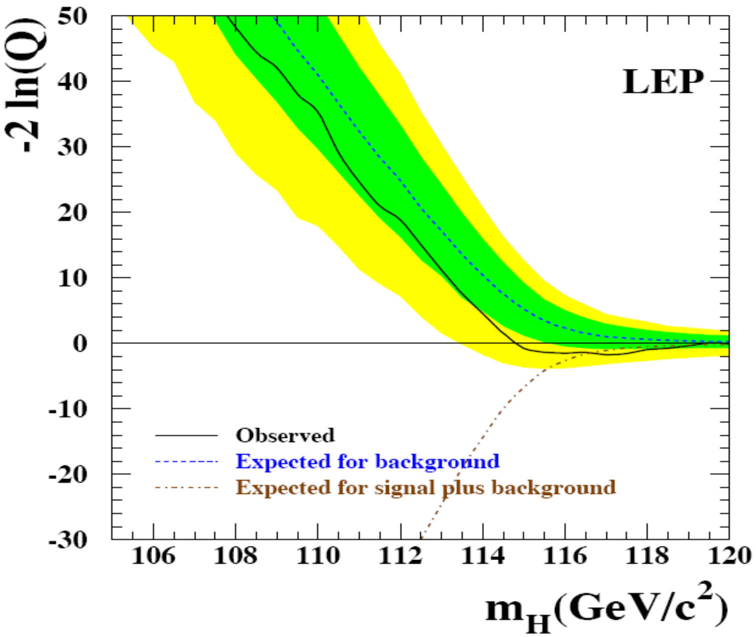




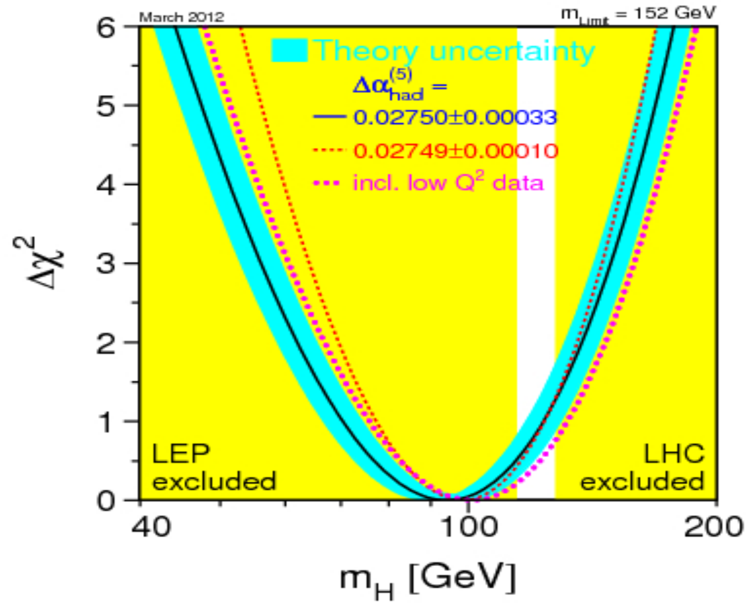


Very powerful to suppress the color-exchanging QCD backgrounds. Best suited for $\mathbf{H\rightarrow\tau\tau}$ and $\mathbf{H\rightarrow\gamma\gamma}$

Bounds on the Higgs mass as of June 2012

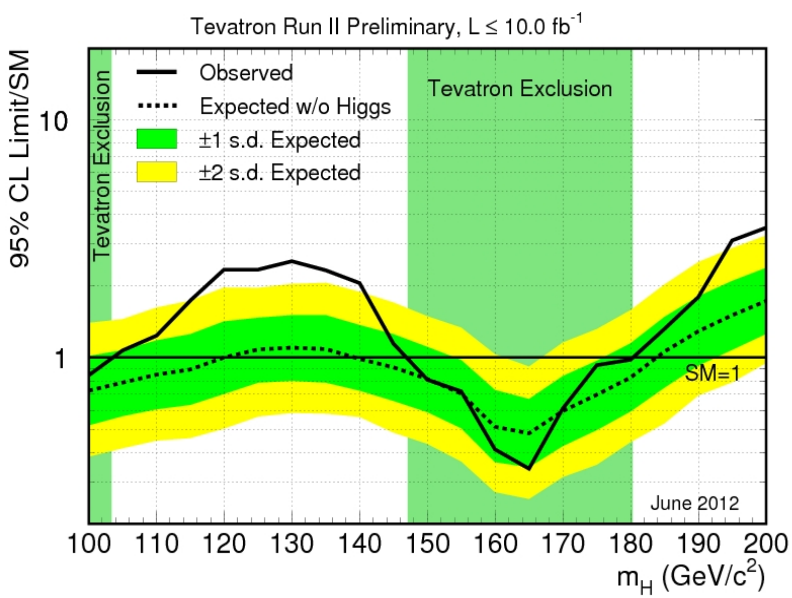


Electroweak precision measurements

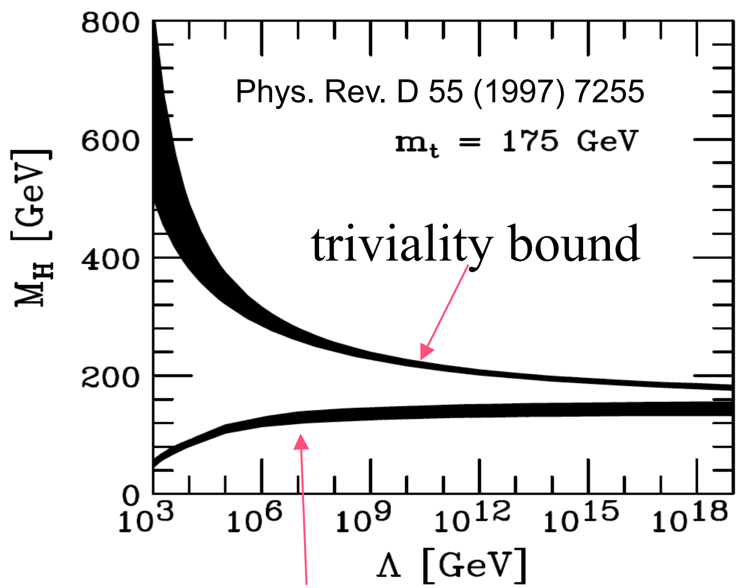


$m_H = 94^{+29}_{-24}\,\mathrm{GeV}$

$m_H < 152\,\mathrm{GeV}$, at 95% CL



Tevatron direct search limit as of June 2012



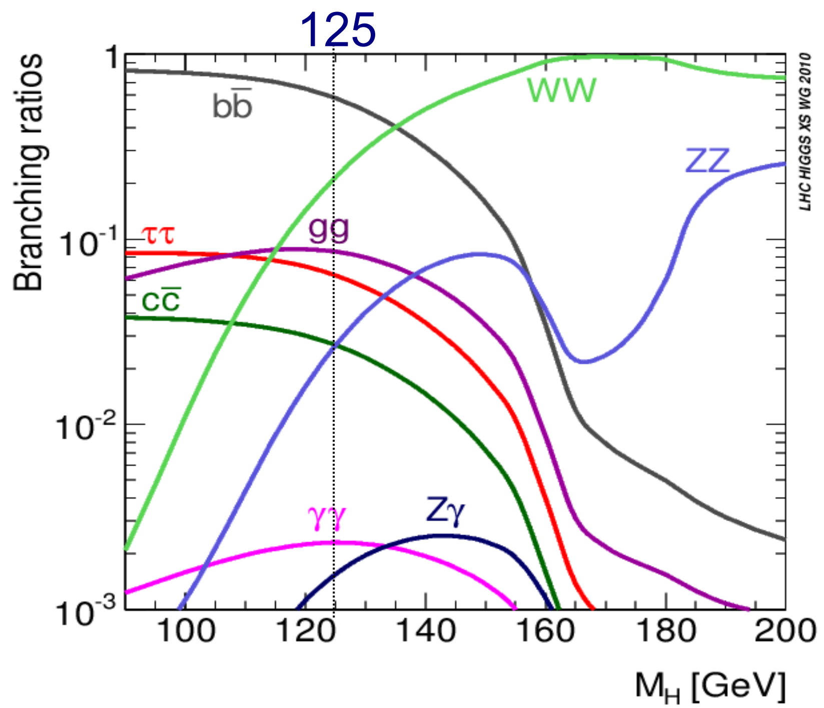
From theory

vacuum stability bound

Higgs decay channels

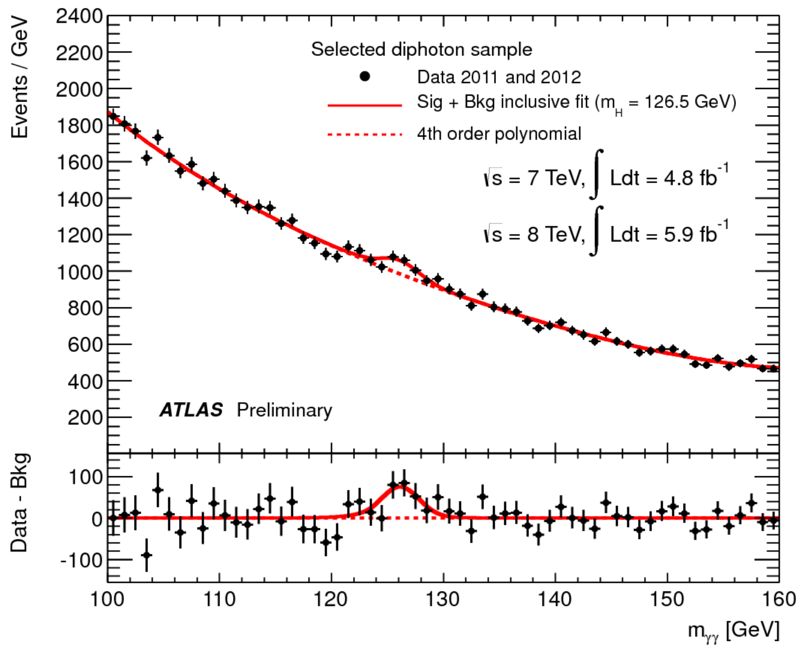
Braching ratios for a Higgs mass of 125 GeV:

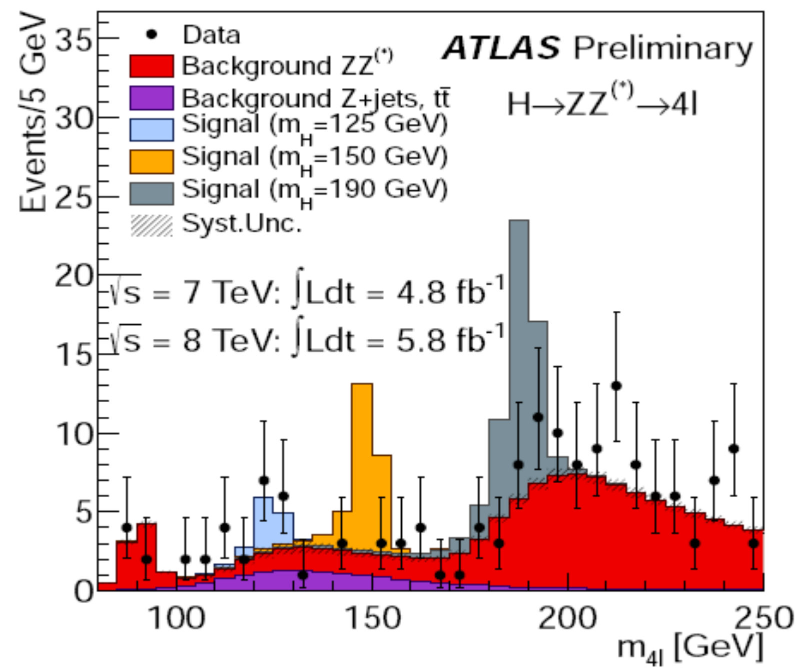
channel	BR
bbar	57.7%
WW	21.5%
ττ	6.3%
ZZ	2.6%
γγ	0.23%

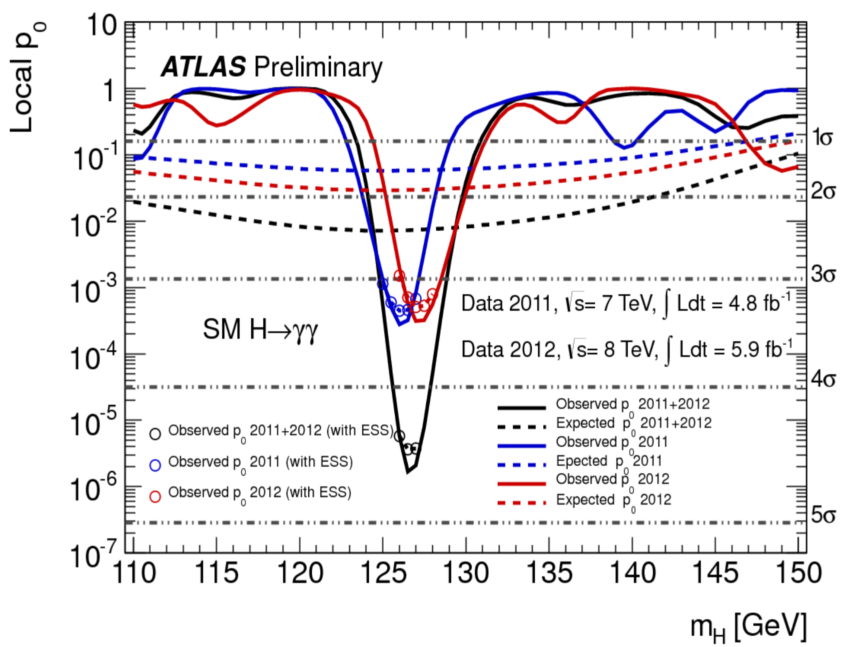


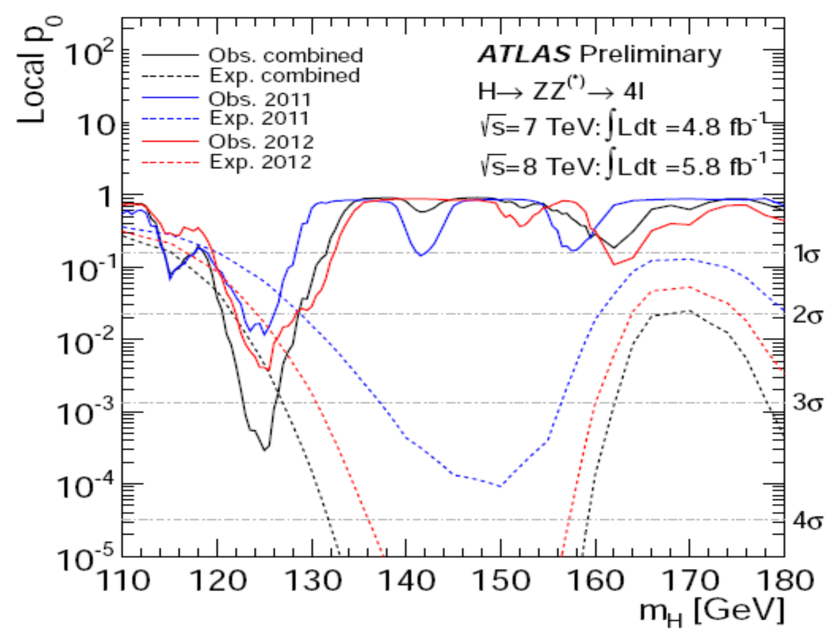
- bbar: highest BR, but suffers from bad mass resolution and large QCD background
- WW: only the dilepton decay modes are useful at low mass, and can not reconstruct the mass
- ττ: bad mass resolution (MET used), high signal efficiency (all final states are used: ll, lh, hh)
- ZZ and γγ: low BR, but good mass resuliton. Very low background for ZZ and powerful S/B shape separation for γγ

H→γγ and H→4l in the first day





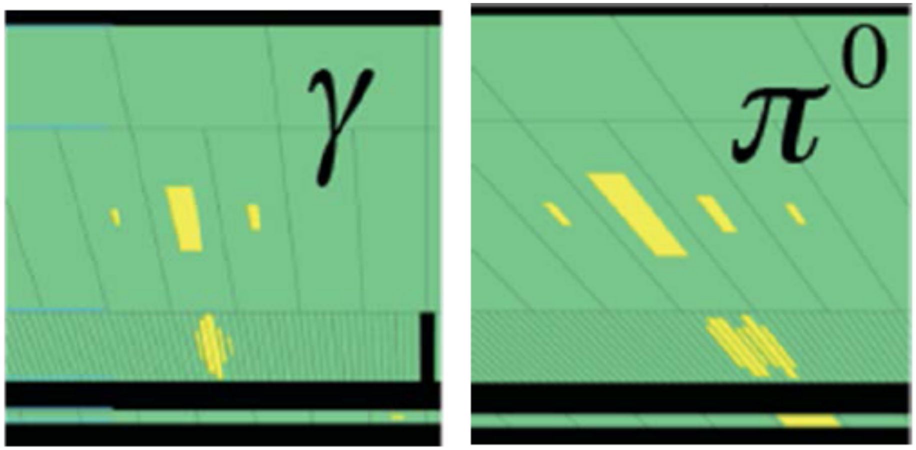




Photon ID and calibration

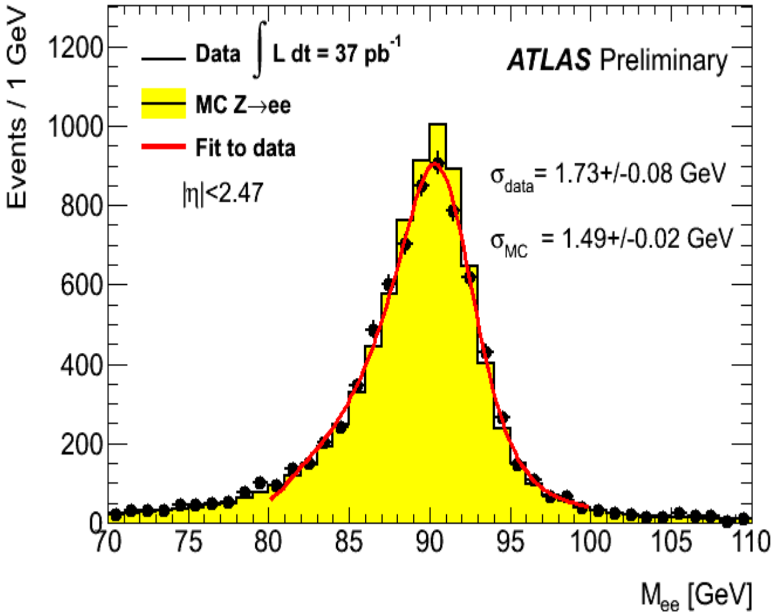
Photon ID:

- Calorimeter shower shape variables – separate γ from π^0
- About 40% photon are converted photons when passing material – e+e- pairs
- Combine variables with likelihood/ MVA or use pure cuts for photon ID

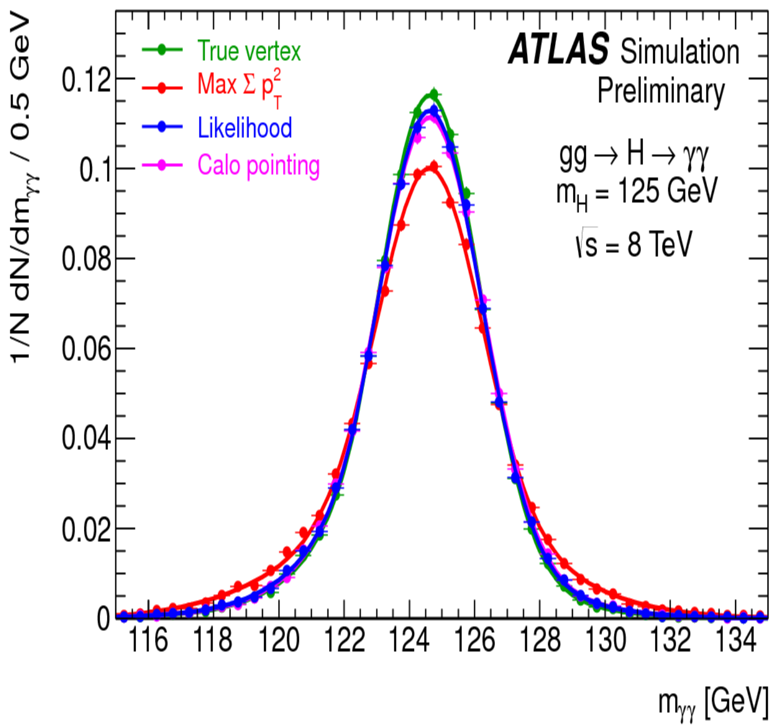


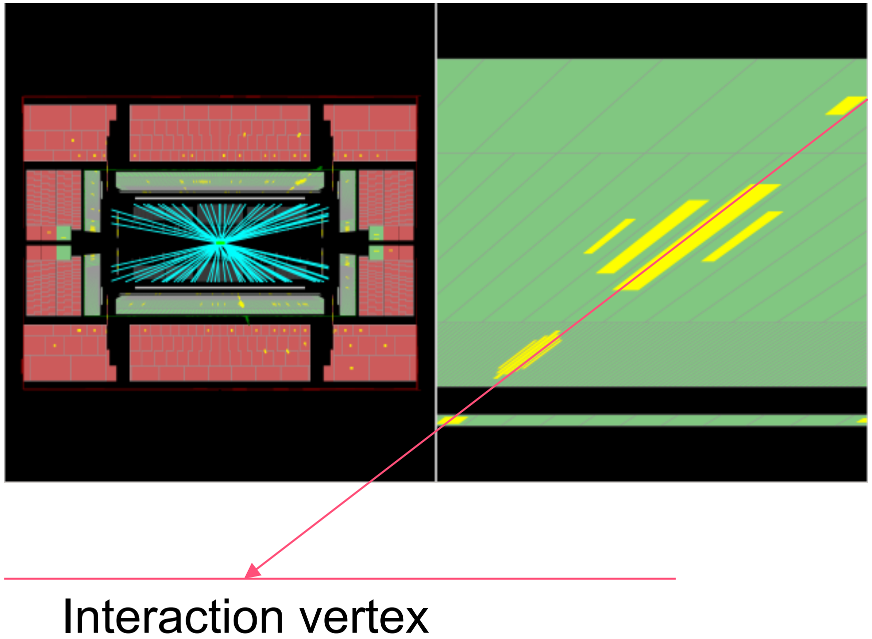
Photon calibration:

- Calibrate the EM energy using $Z \rightarrow ee$ and $J/\Psi \rightarrow ee$ events
- Extrapolate from e to γ using MC simulation
- Check calibration in the $Z \rightarrow ee\gamma$, $Z \rightarrow \mu\mu\gamma$ FSR events – limited statistics and low photon pt



Mass resolution and vertex



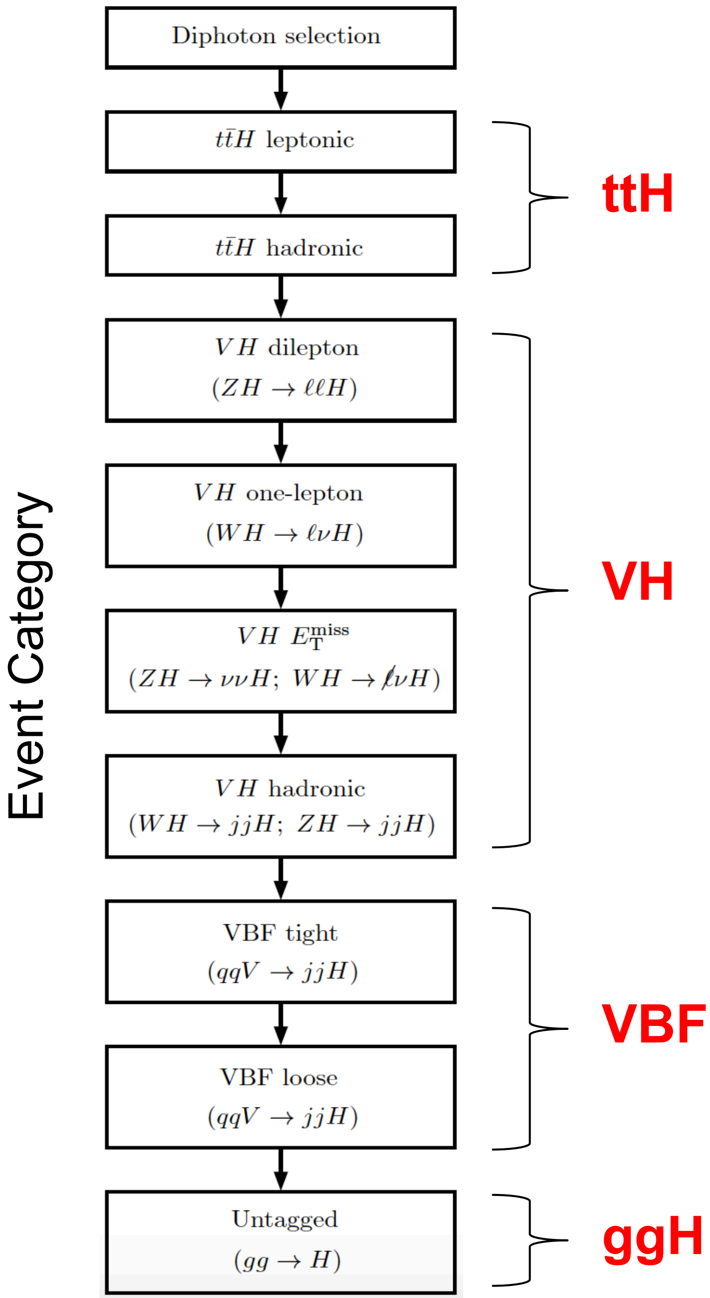


$$m^2 = 2 E_{\gamma_1} E_{\gamma_2} \left(1 - \cos \Delta\phi_{\gamma\gamma}\right)$$

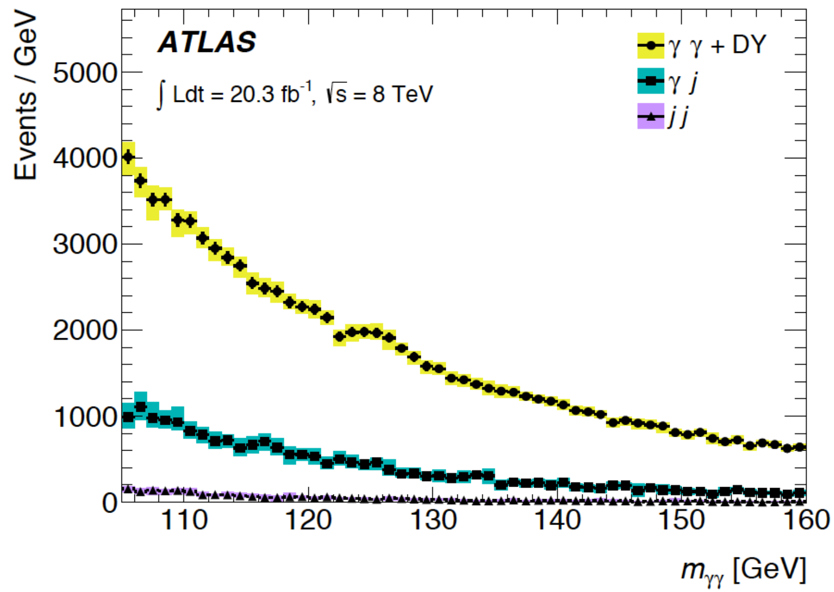
- No tracks for the unconverted photons in the tracking system – need calorimeter granularity to find the vertex (calo-pointing)
- Calo-pointing combined with tracking (likelihood) provides the best mass resolution for H→γγ: ~1.6 GeV
- Converted photons: conversion vertex extrapolation

H→γγ updated

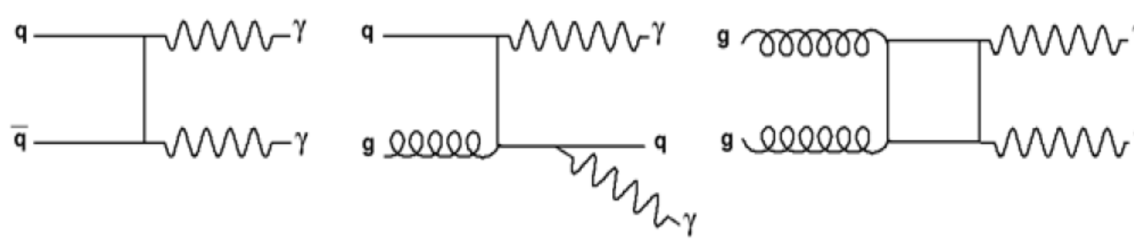
[Phys. Rev. D 90 (2014) 112015]



Background composition



★ Irreducible γγ background (σ≈40 pb, theoretical error ~20%)

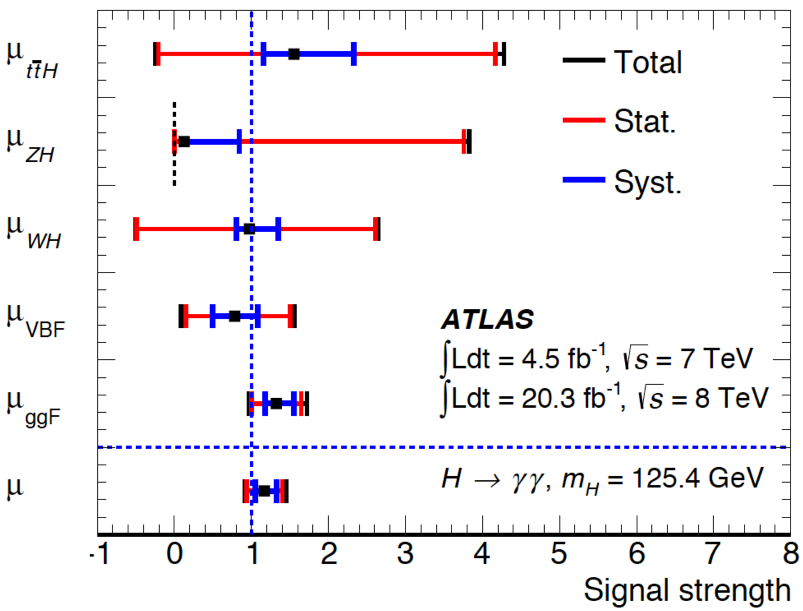


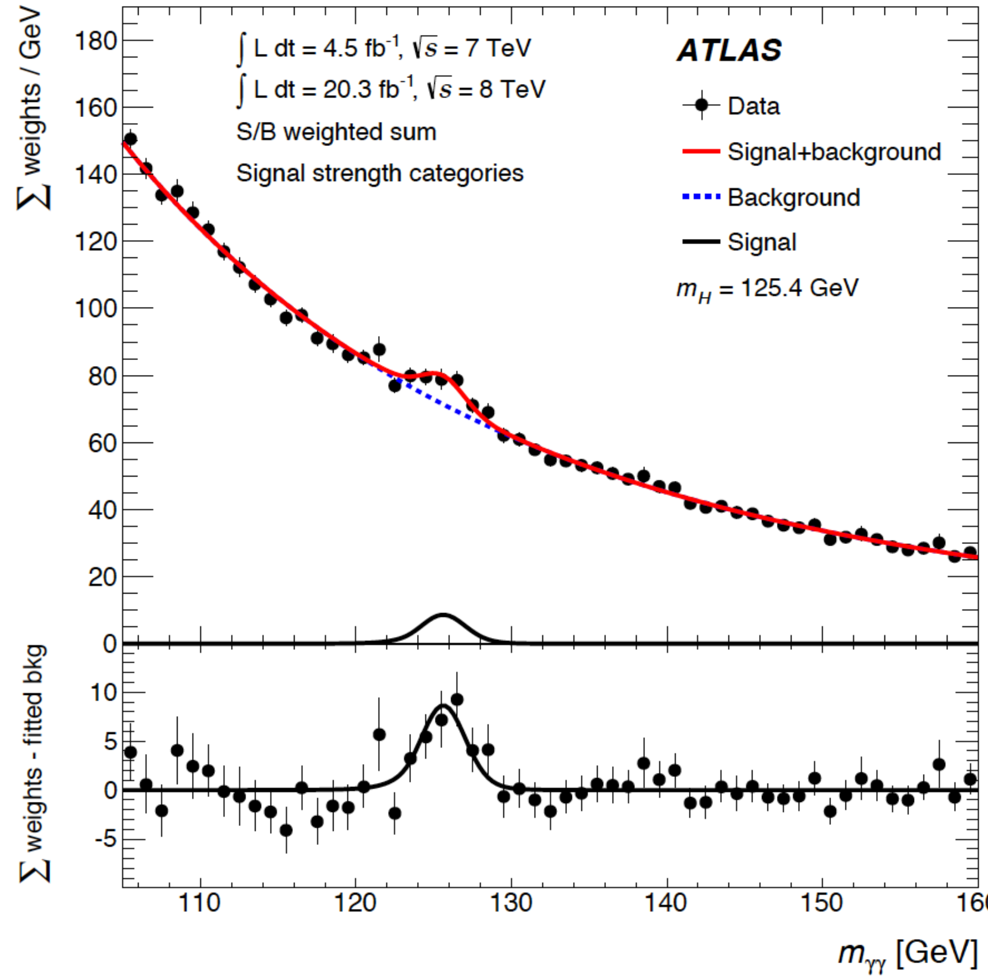
★ Reducible background: γ+jet (σ≈μb), and jet+jet (σ≈mb): mainly π^0 faking photon – hard to model

With simulation, have to rely on data

H→γγ updated

Uncertainty group	$\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02





Now fitted signal strength is more consistent with SM:

$$\mu = 1.17 \pm 0.27$$

H→ZZ→4l updated

- H→ZZ→4l is the gold-plated channel – good mass resolution, powerful rejection of SM background due to 4-lepton requirement

- Suffers from low rate and total lepton acceptance loss

  BR(ZZ→4l)=0.45%, σxBR(H→ZZ→4l)=2.6 fb

  Single lepton acceptance (tracking volume, trigger and reconstruction) is high (~80%), but the total acceptance is low (0.84^4~0.4)

- Require 2 pairs of same-flavor opposite-sign leptons

  4 leptons with pT > 20, 15, 10, 7 (6 for muon) GeV (lep1, 2, 3, 4)

  50 GeV < m12 < 106 GeV, and 12-50 < m34 < 115 GeV

  mll > 5 GeV for all same-flavor opposite-sign pair – J/ψ rejection

  Lepton isolation (calo-energy and tracks around real leptons should be small) and track d0 cut (should come from hard IP)

- Main background is ZZ* and Zbb. Invert isolation or d0 to estimate Zbb

[Phys. Rev. D 91 (2015) 012006]

H→ZZ→4l updated

4l selection

↓

High mass two jets VBF — VBF enriched

↓

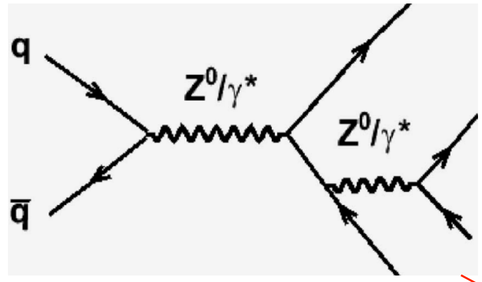
Low mass two jets $W(\to jj)H$, $Z(\to jj)H$

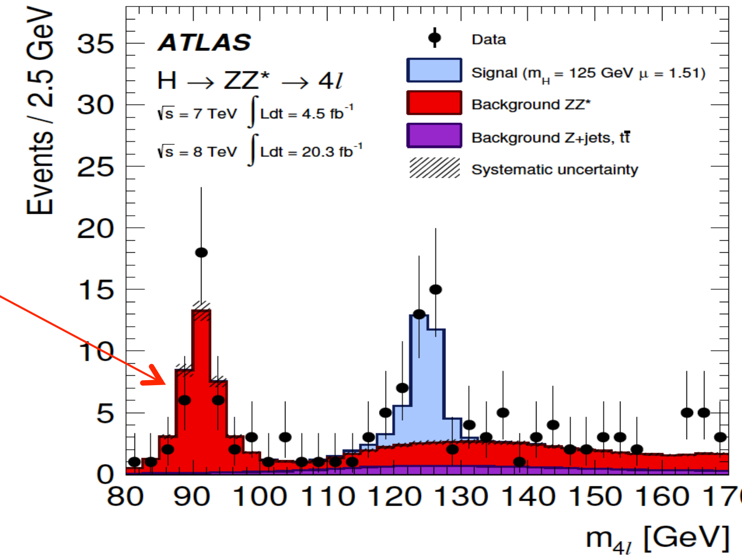
↓

Additional lepton $W(\to l\nu)H$, $Z(\to ll)H$ — VH enriched

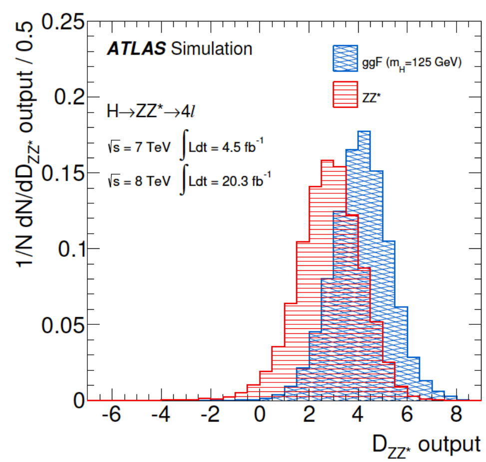
↓

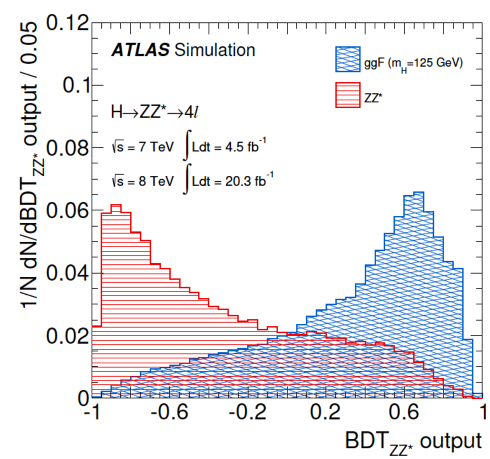
ggF — ggF enriched





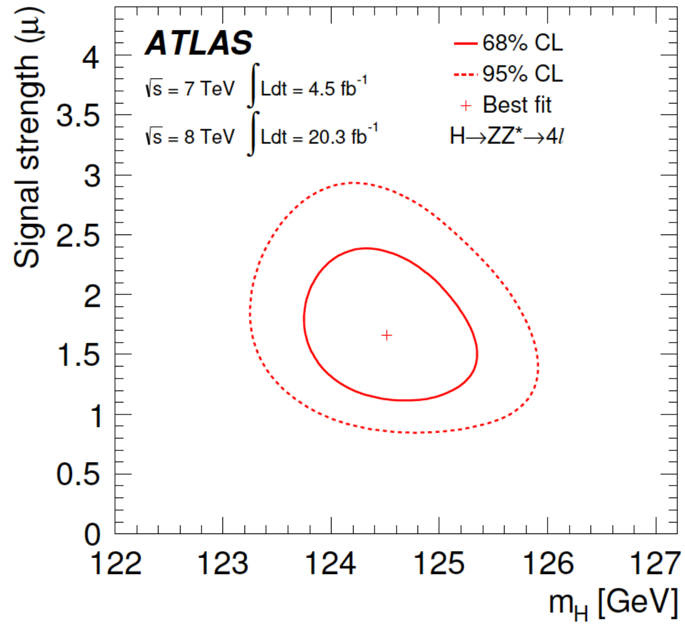
Very rich final state phase space – exploit Matrix Element (ME) discriminant and Boosted Decision Trees (BDT) methods:

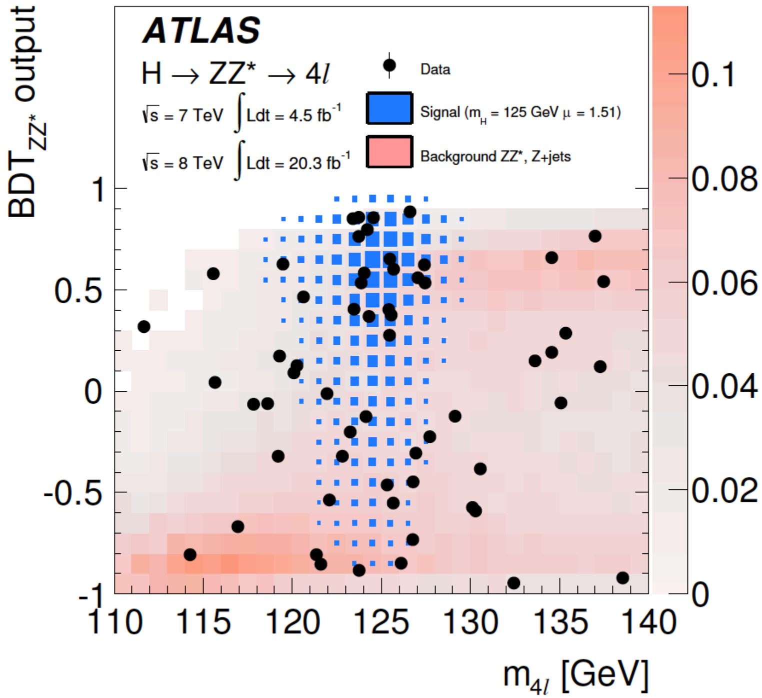




H→ZZ→4l updated

Source of uncertainty	combined
Electron reconstruction and identification efficiencies	1.6%
Electron isolation and impact parameter selection	0.5%
Electron trigger efficiency	<0.2%
$\ell\ell + ee$ backgrounds	1.3%
Muon reconstruction and identification efficiencies	1.5%
Muon trigger efficiency	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.2%
QCD scale uncertainty	6.5%
PDF, α_s uncertainty	6.0%
$H \to ZZ^*$ branching ratio uncertainty	4.0%





Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	S/B	Expected	Observed
16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

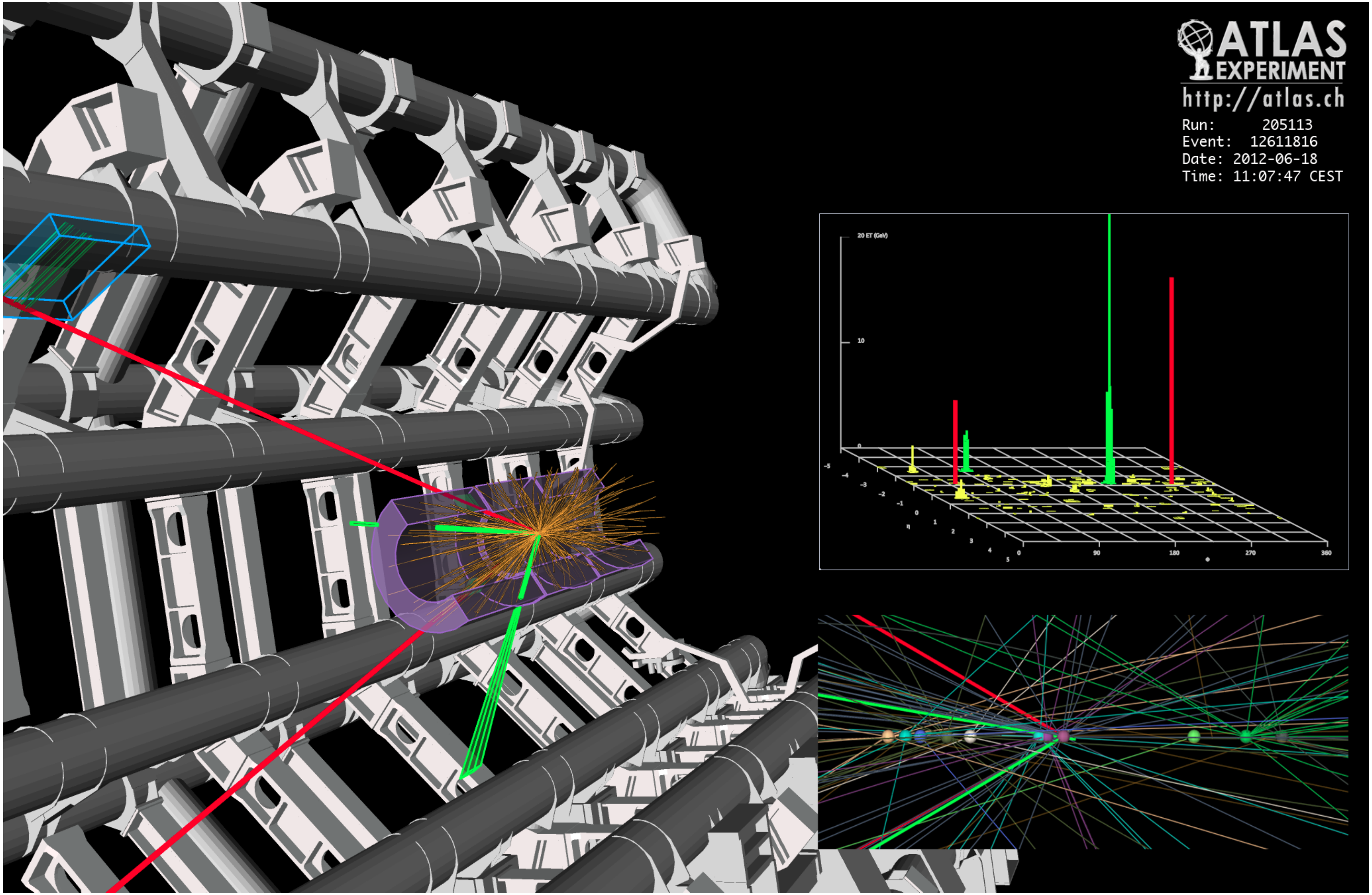
$$\mu_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \times B/B_{\mathrm{SM}} = 1.66\ ^{+0.45}_{-0.41}\ (\mathrm{stat})\ ^{+0.25}_{-0.15}\ (\mathrm{syst})$$

$$\mu_{\mathrm{VBF+VH}} \times B/B_{\mathrm{SM}} = 0.26\ ^{+1.60}_{-0.91}\ (\mathrm{stat})\ ^{+0.36}_{-0.23}\ (\mathrm{syst})$$

Combined:

$$\mu \times B/B_{\mathrm{SM}} \text{ is } 1.44\ ^{+0.34}_{-0.31}\ (\mathrm{stat})\ ^{+0.21}_{-0.11}\ (\mathrm{syst})$$

H→ZZ→2e2μ candidate event

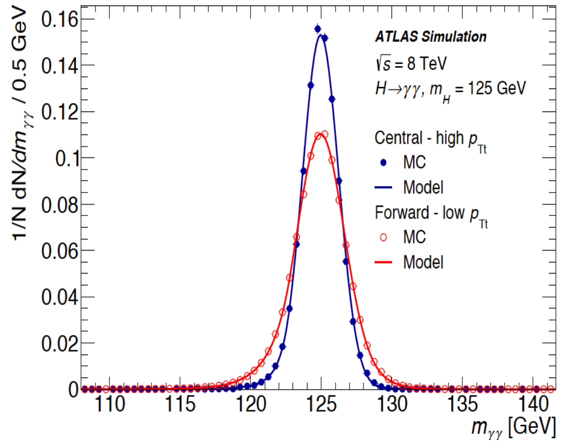


[Phys. Rev. D 90 (2014) 052004]

Higgs Mass measurement

categories	width
Inclusive	1.67
Unconv. central low p_{Tt}	1.35
Unconv. central high p_{Tt}	1.21
Unconv. rest low p_{Tt}	1.53
Unconv. rest high p_{Tt}	1.36
Unconv. transition	1.86
Conv. central low p_{Tt}	1.52
Conv. central high p_{Tt}	1.35
Conv. rest low p_{Tt}	1.88
Conv. rest high p_{Tt}	1.64
Conv. transition	2.41

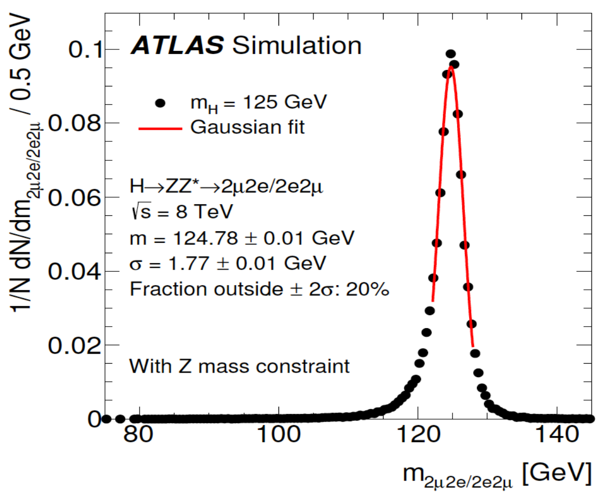
Classify events for best mass resolution



H→γγ : $125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst})$

Similar to coupling measurement, fit 2-dim PDF of mass of BDT output

Z mass constraint improves Higgs mass resolution by ~15%



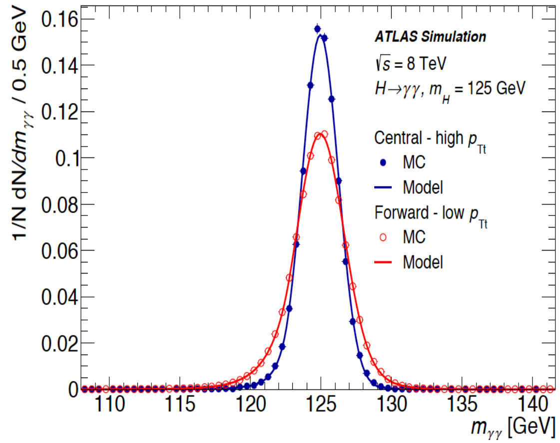
H→4l : $124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst})$

Higgs Mass measurement

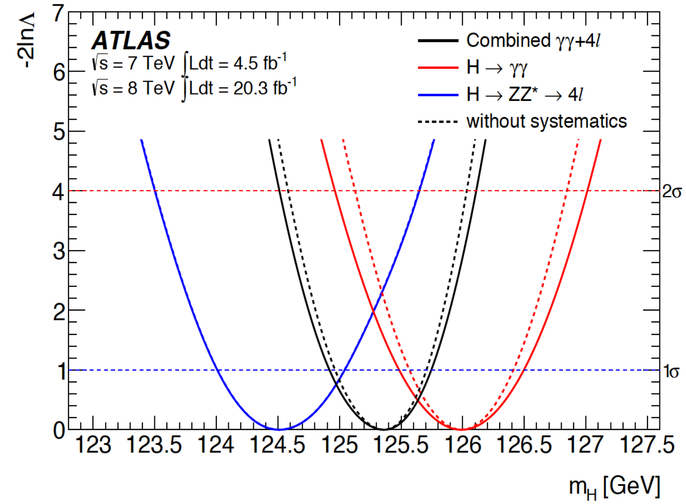
[Phys. Rev. D 90 (2014) 052004]

categories	width
Inclusive	1.67
Unconv. central low p_{Tt}	1.35
Unconv. central high p_{Tt}	1.21
Unconv. rest low p_{Tt}	1.53
Unconv. rest high p_{Tt}	1.36
Unconv. transition	1.86
Conv. central low p_{Tt}	1.52
Conv. central high p_{Tt}	1.35
Conv. rest low p_{Tt}	1.88
Conv. rest high p_{Tt}	1.64
Conv. transition	2.41

Classify events for best mass resolution

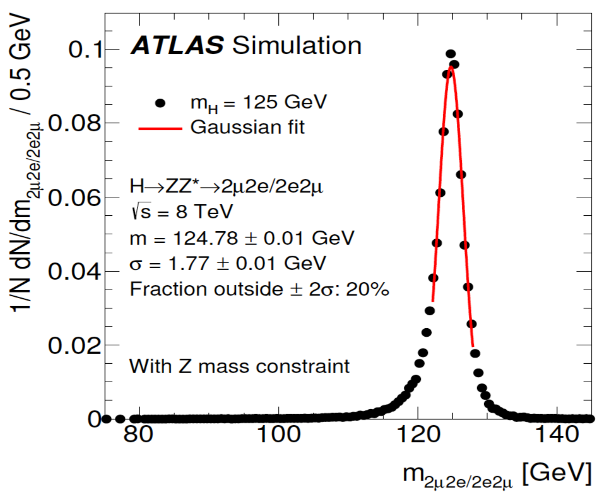


H→γγ : $125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst})$



Similar to coupling measurement, fit 2-dim PDF of mass of BDT output

Z mass constraint improves Higgs mass resolution by ~15%



H→4l : $124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst})$

Combined mass measurement:

$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})$

The compatibility of the two measurements are at 2σ level (4.8%)

H→WW→2l2ν

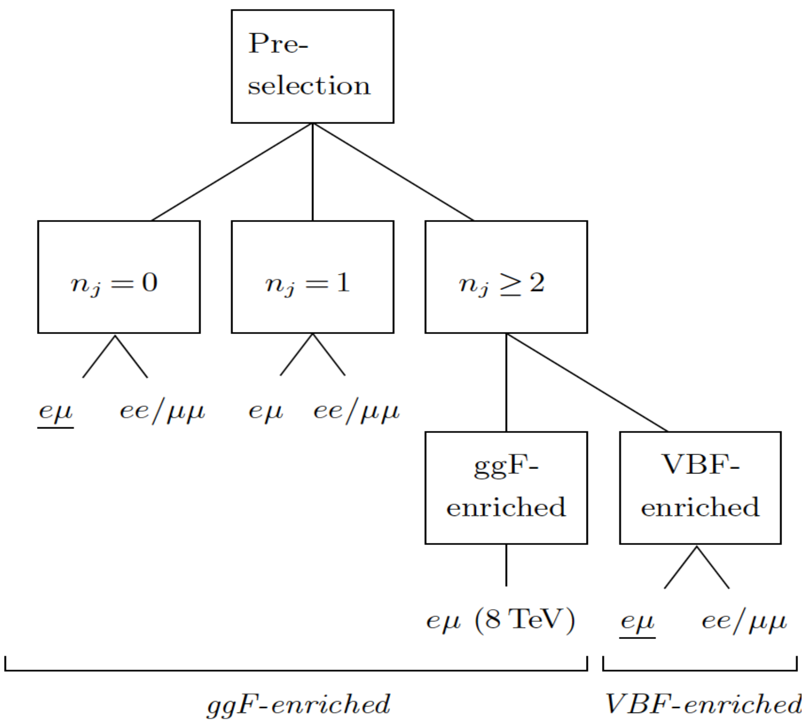
[Phys. Rev. D 92 (2015) 012006]

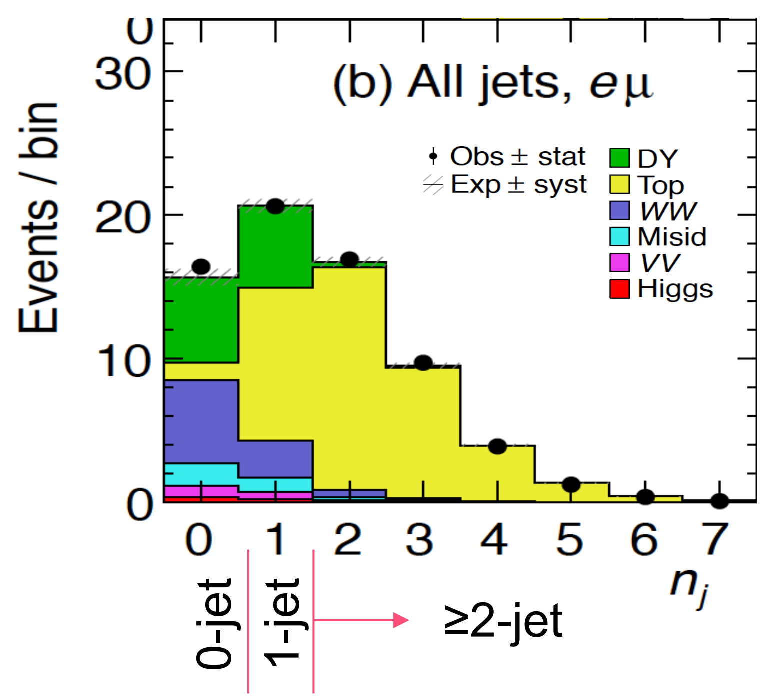
Can not reconstruct the Higgs mass – background rates estimation is crucial in this channel

Devide analysis into 6 categories: (eμ, μe) x (0-jet, 1-jet, ≥2-jet)

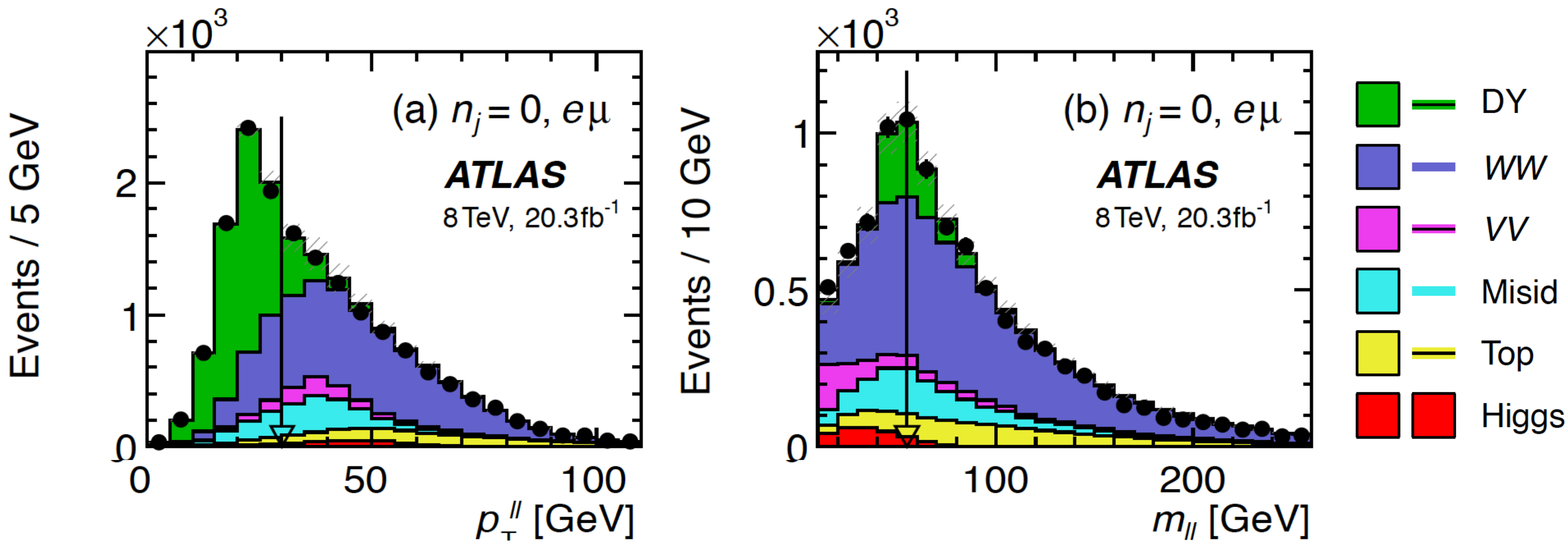
Preselection

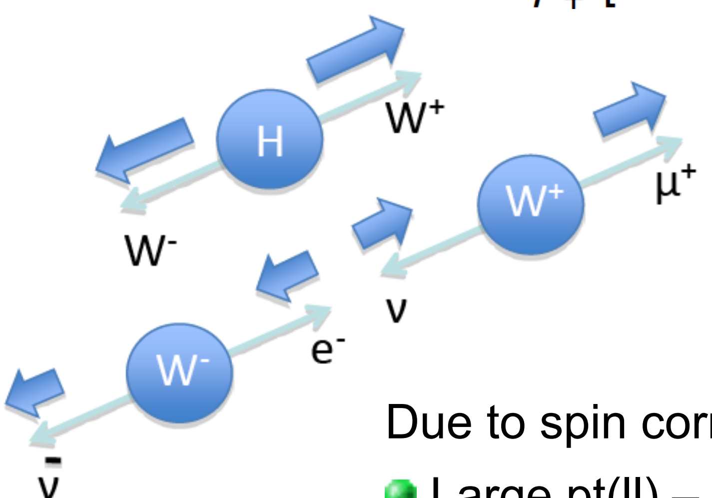
- Leptons pt > 22/10 GeV, mll>10/12 GeV, opposite charges
- $E_{\mathrm{T,rel}}^{\mathrm{miss}}$ > 40 GeV. $E_{\mathrm{T,rel}}^{\mathrm{miss}}$ is the MET component perpendicular to the closest lepton or jet. $E_{\mathrm{T,rel}}^{\mathrm{miss}} = E_{\mathrm{T}}^{\mathrm{miss}}$ if ΔΦ > π/2
- anti-kt jet pt>25 GeV (>30 GeV if |η|>2.5)

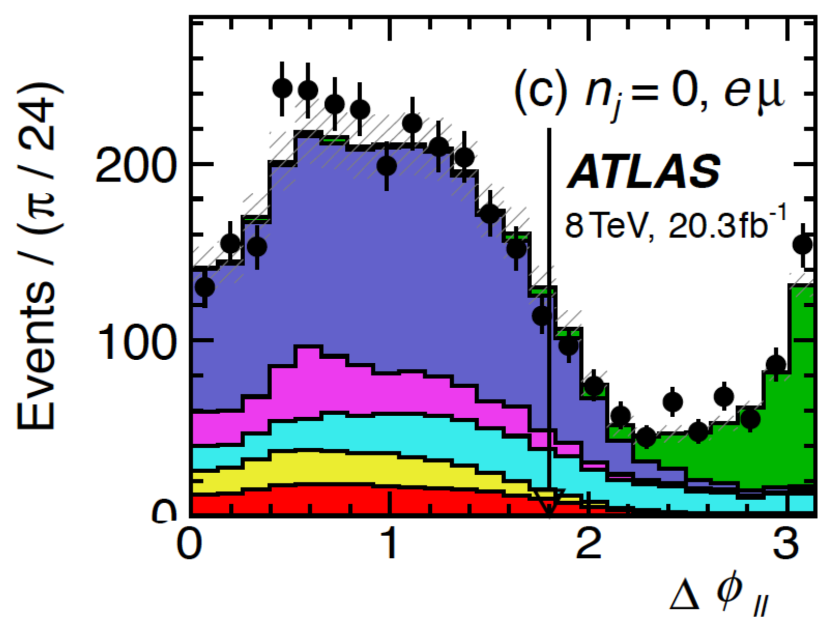




H→WW→2l2ν







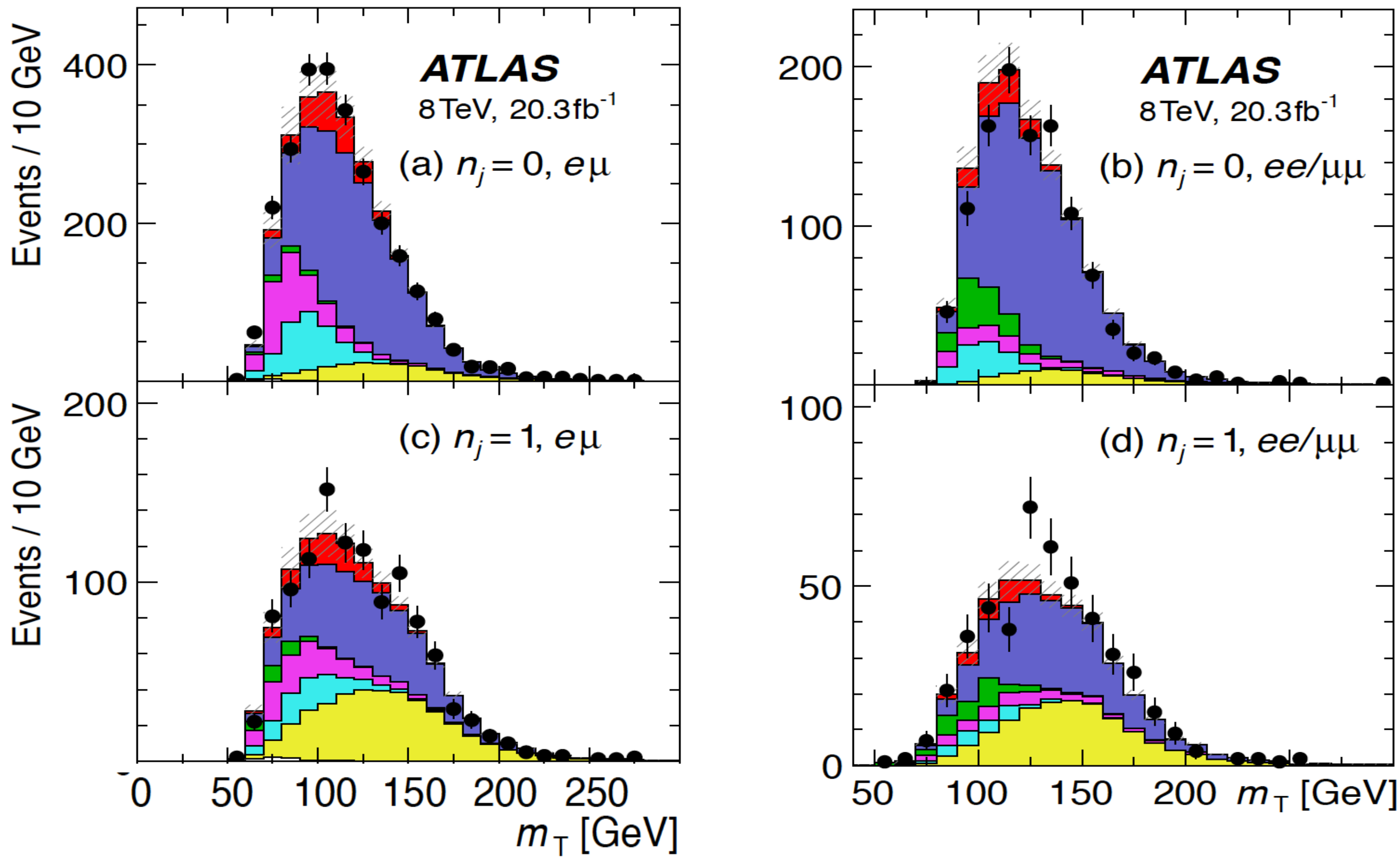
Due to spin correlation:

- Large pt(ll) – kill Z+jets
- Small mll
- Small ΔΦ(ll)

H→WW→2l2ν

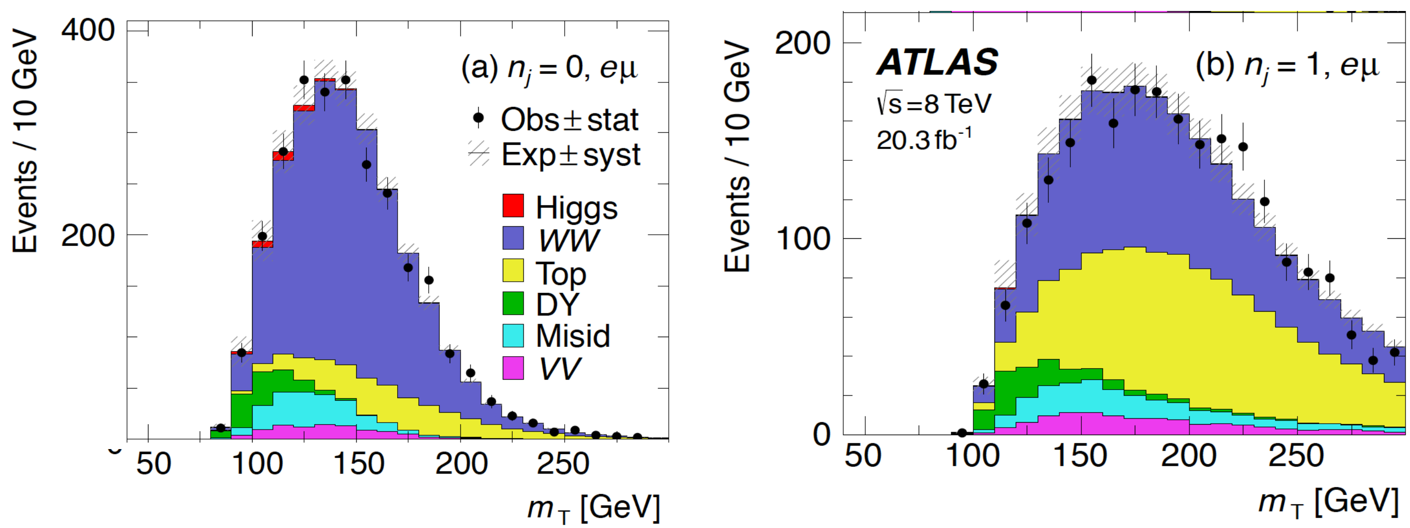
Unable to reconstruct Higgs mass – reconstruct transverse mass instead:

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + p_{\mathrm{T}}^{\nu\nu}\right)^2 - \left|\,\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\nu\nu}\,\right|^2}$$



H→WW→2l2ν

Obtain the WW control sample by the ptLL or mT cut:



Obtain the top survival probability in 0-jet bin with MC correction factors obtained from b-tagged control sample:

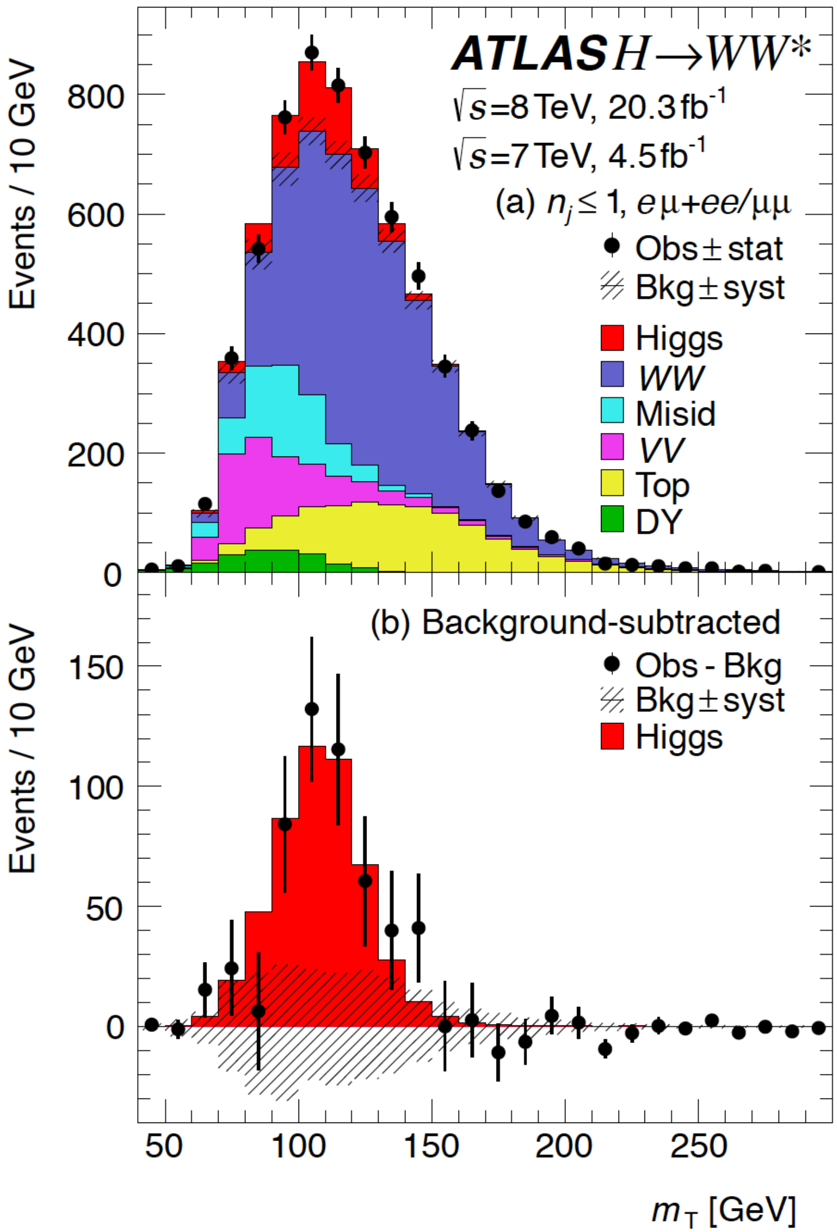
$$N_{\mathrm{top}}^{\mathrm{exp}}(\ell\ell + E_T^{\mathrm{miss}}, 0j) \simeq N_{\mathrm{top}}^{\mathrm{exp}}(\ell\ell + E_T^{\mathrm{miss}}) \times \overbrace{\boxed{P_2^{\mathrm{MC}} \times \left(\frac{P_1^{\mathrm{Btag,exp}}}{P_1^{\mathrm{Btag,MC}}}\right)^2}}^{P_2^{\mathrm{exp}}}$$

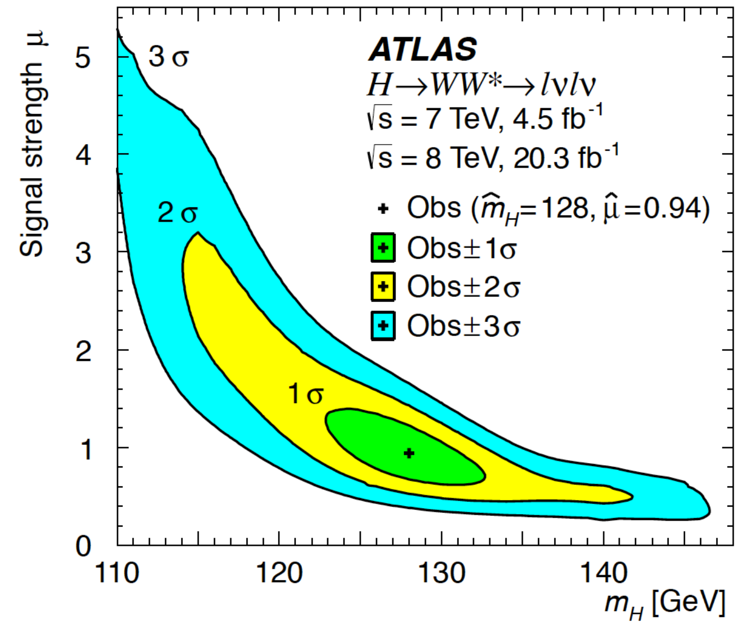
P_2: full-jet veto survival probability

P_1: jet veto survival probability derived from b-tagged sample

Top background events in 0-jet bin (Signal region) ≈ ($N_{Data} - N_{Non\text{-}top}$) in initial ll+$E_T^{miss}$ sample × (Expected) full-jet veto survival probability

H→WW→2l2ν





Final fit to mT (BDT) distribution for ggF (VBF) category, with one norm factor per control region

$$\mu_{\rm ggF} = 1.02 \ \pm 0.19 \ {}^{+0.22}_{-0.18} = 1.02 \ {}^{+0.29}_{-0.26}$$

$$\mu_{\rm VBF} = 1.27 \ {}^{+0.44}_{-0.40} \ {}^{+0.30}_{-0.21} = 1.27 \ {}^{+0.53}_{-0.45}$$

(stat.) (syst.)

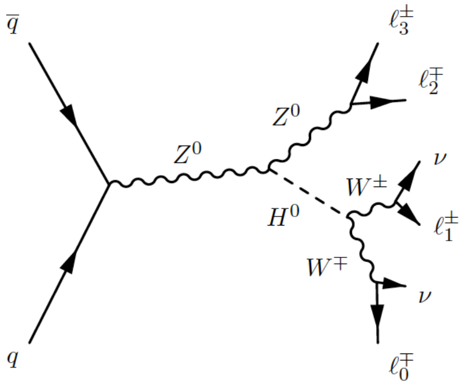
Combined:

$$\mu = 1.09 \ {}^{+0.23}_{-0.21}$$

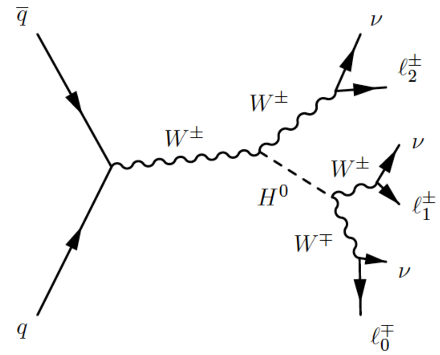
[ATLAS-CONF-2015-005]

VH→WW multilepton channel

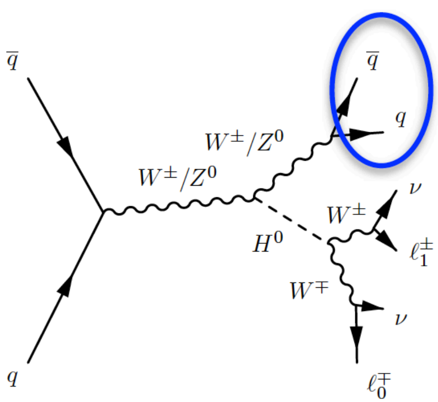
4 leptons



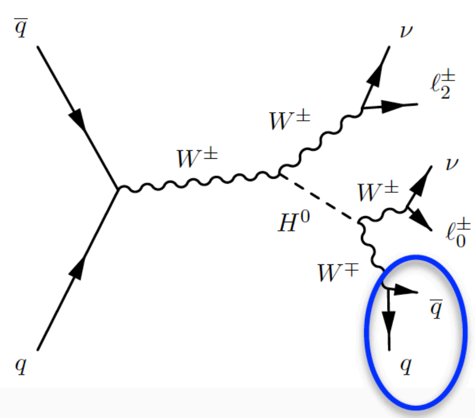
3 leptons



2 OS leptons



2 SS leptons



Analysis is divided into a number of categories:

- Different numbers of leptons and jets
- Whether the leptons are of Same-Sign (SS) or Opposite-Sign (OS)

VV and VVV (V=W/Z/γ) are the main background. Top and single W/Z also present in 2-lepton modes

Final fit result:

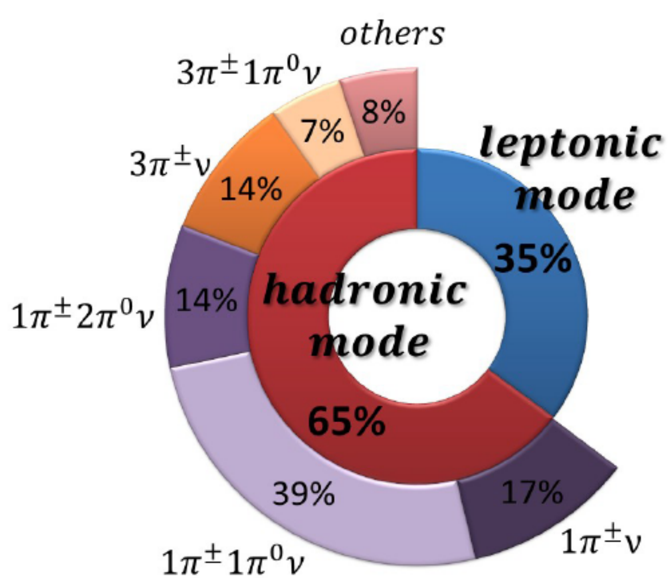
$$\mu_{\mathrm{VH}}^{\mathrm{WW}} = 2.9^{+1.2}_{-1.1}\,(\mathrm{stat.})^{+0.8}_{-0.6}\,(\mathrm{sys.})$$

Combined with the ggH and VBF modes to contribute to the coupling measurement

$H\to\tau\tau$ Update

[JHEP 04 (2015) 117]

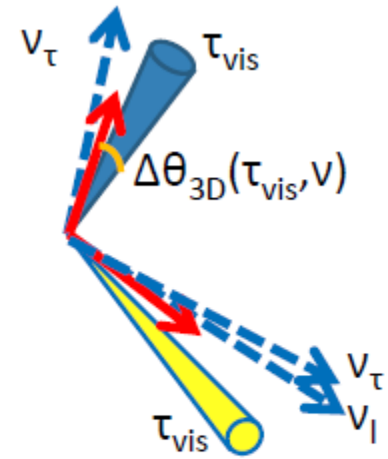
Higgs Yukawa coupling is a crucial part in the SM. Direct search for Htt decay will confirm it is a SM Higgs

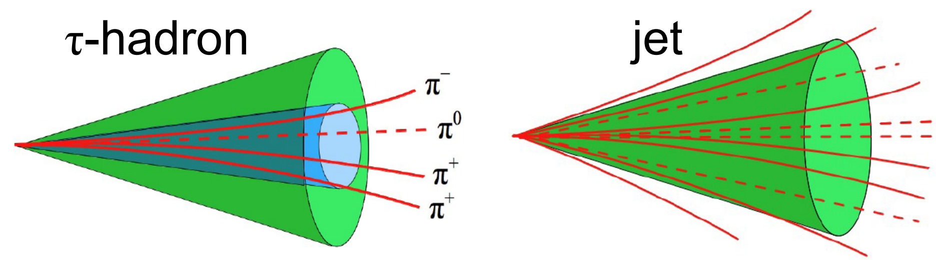


$\underbrace{ee,\ e\mu,\ \mu\mu}_{\tau_{lep}\tau_{lep}},\ \underbrace{e\tau_h,\ \mu\tau_h}_{\tau_{lep}\tau_{had}},\ \underbrace{\tau_h\tau_h}_{\tau_{had}\tau_{had}}$

Leptonic and hadronic decays of taus

- **MMC** ditau mass reconstruction: scan in the allowed phase space region (MET, angles...) for the most likely solutions that are consistent with the kinematics of tau decays



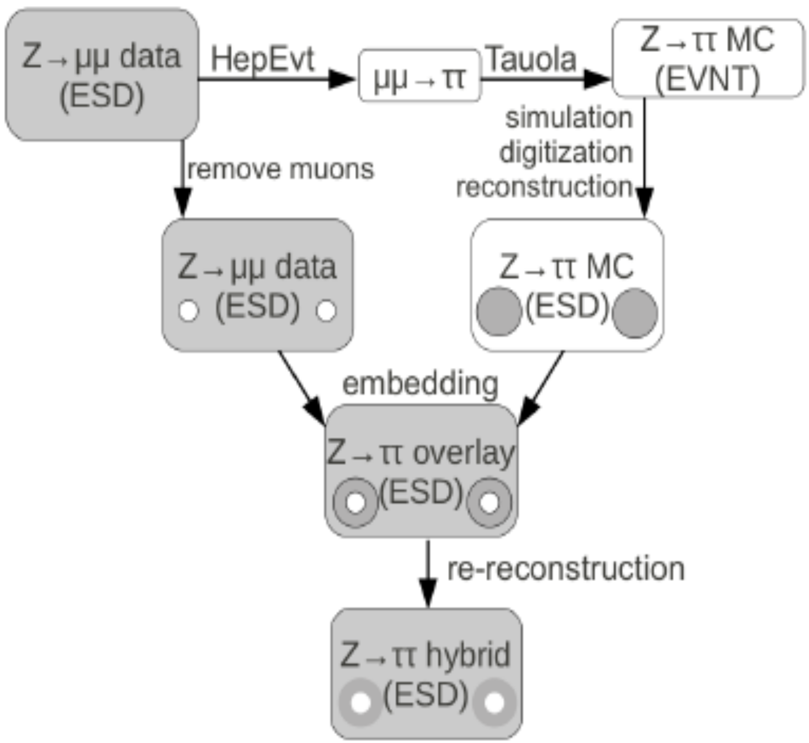


- Boosted Decision Trees (BDT) is used for the final fit for signal strength

- MC-data consistency is checked for each BDT input variable, before the BDT fit is carried out

Z→ττ background

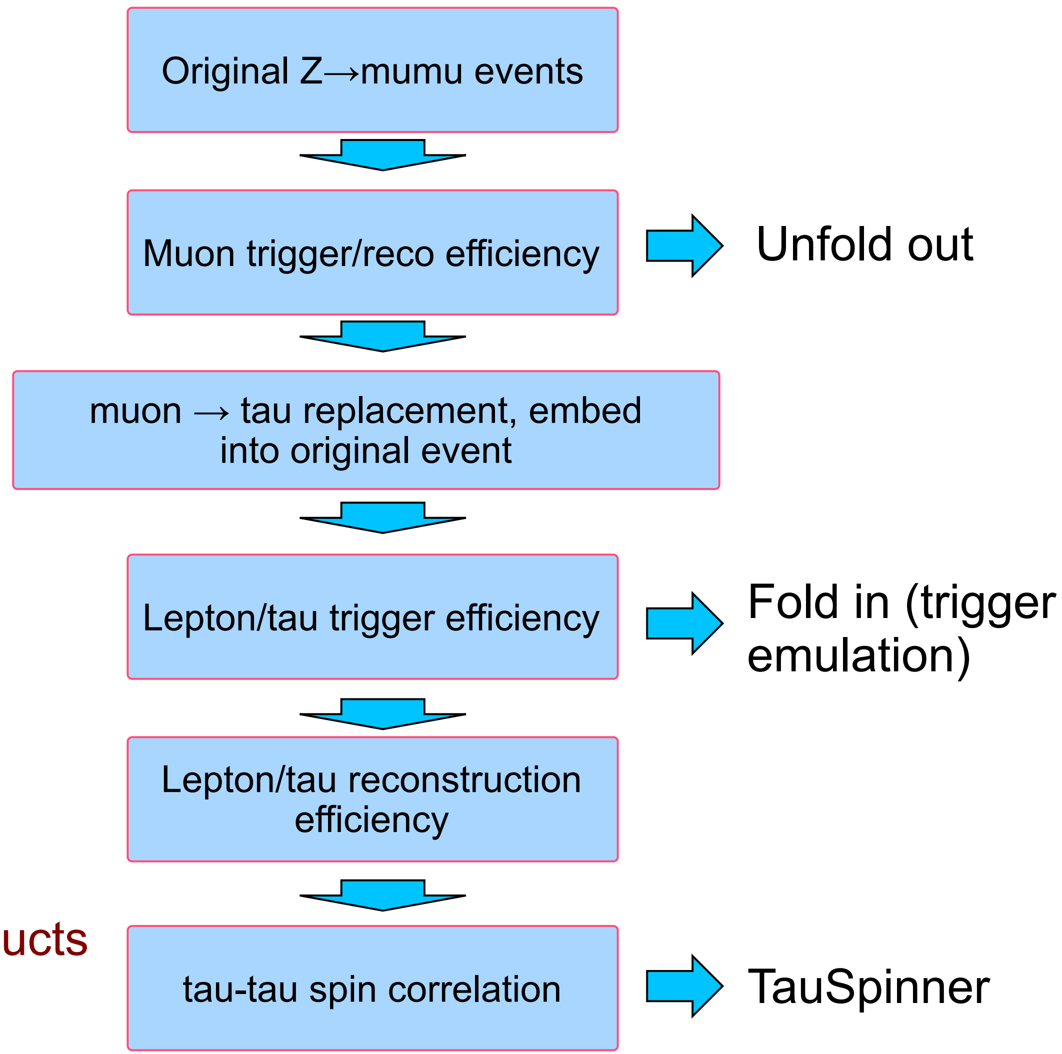
- Z→ττ (dominant background) is estimated from data using embedding:



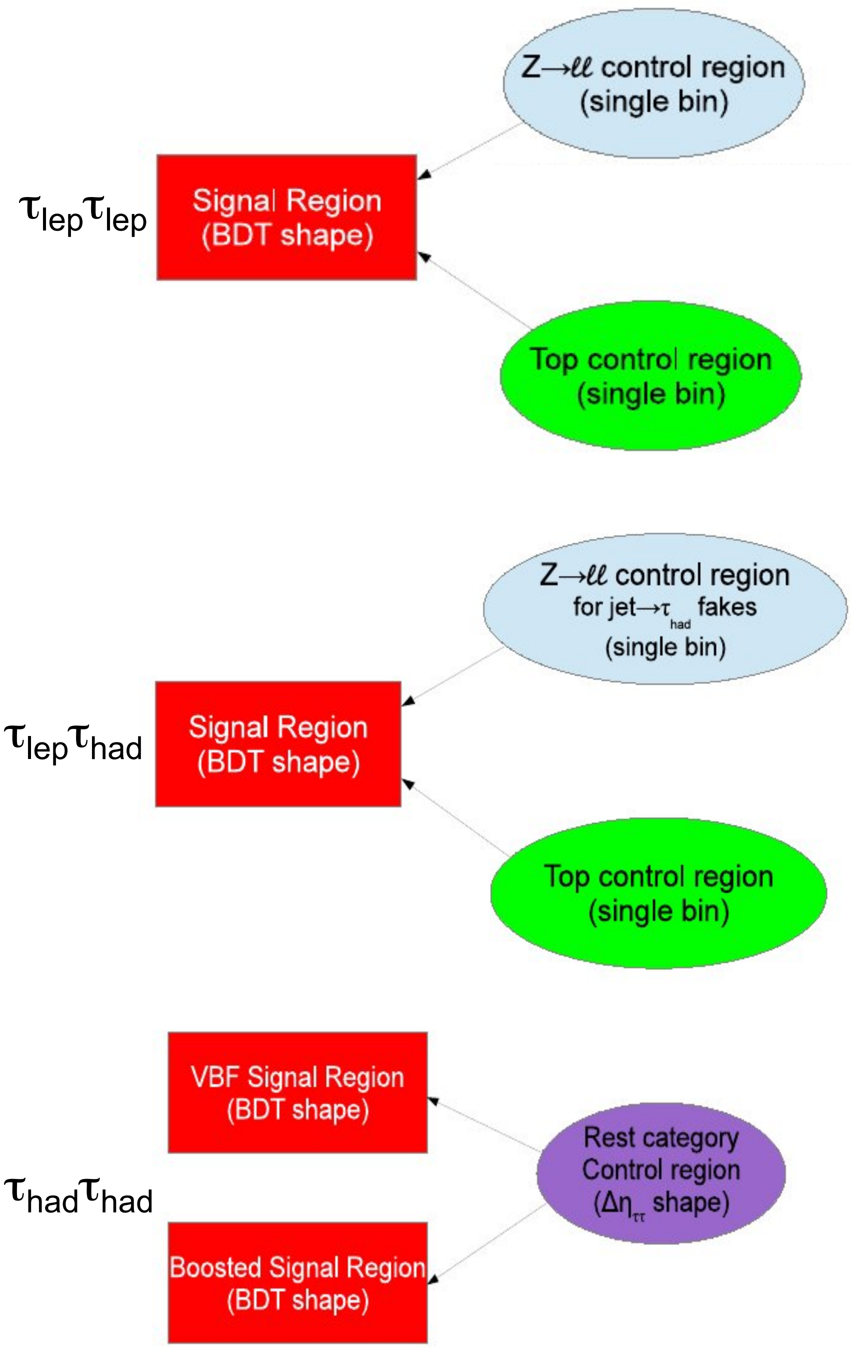
1) Replace muons from Z→μμ data by taus and decay the taus

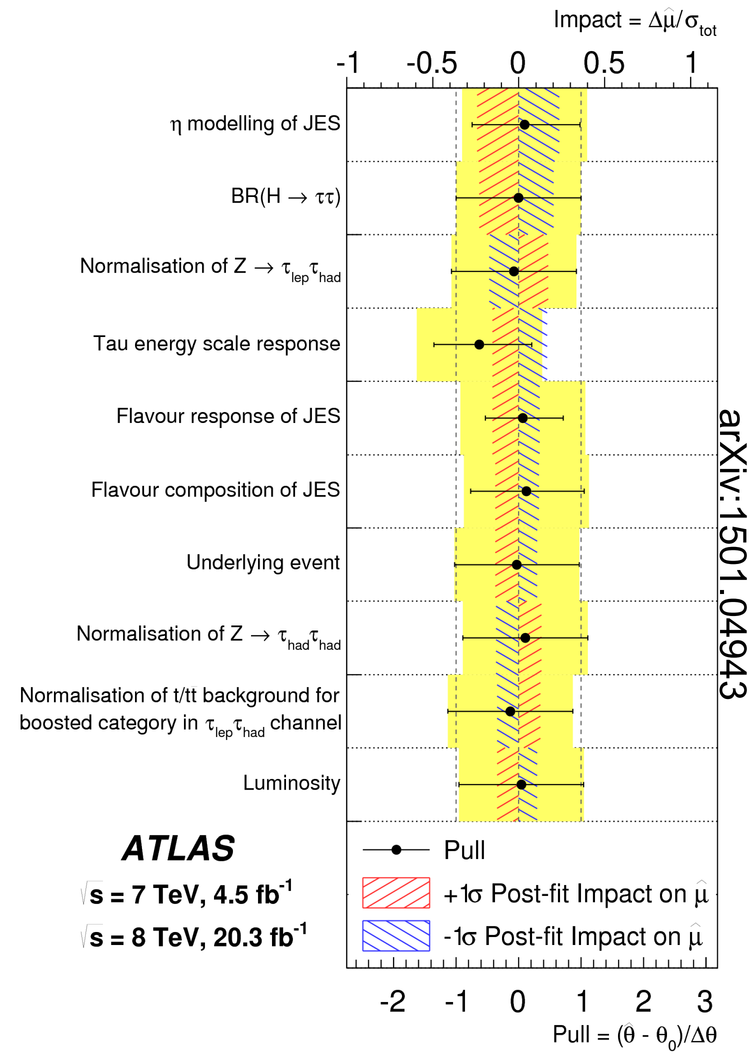
2) Embed the simulated tau decay products into the original event

Correction for trigger and acceptance:



$H \rightarrow \tau\tau$ Simultaneous Fit

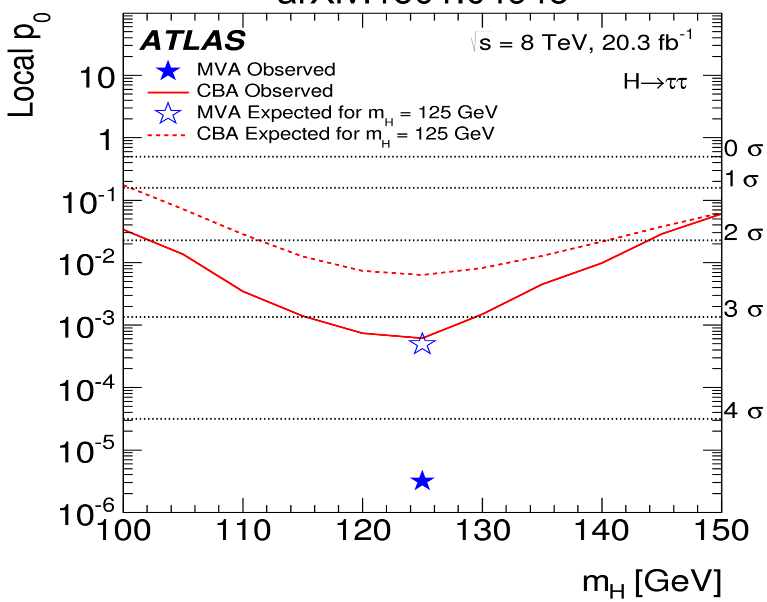




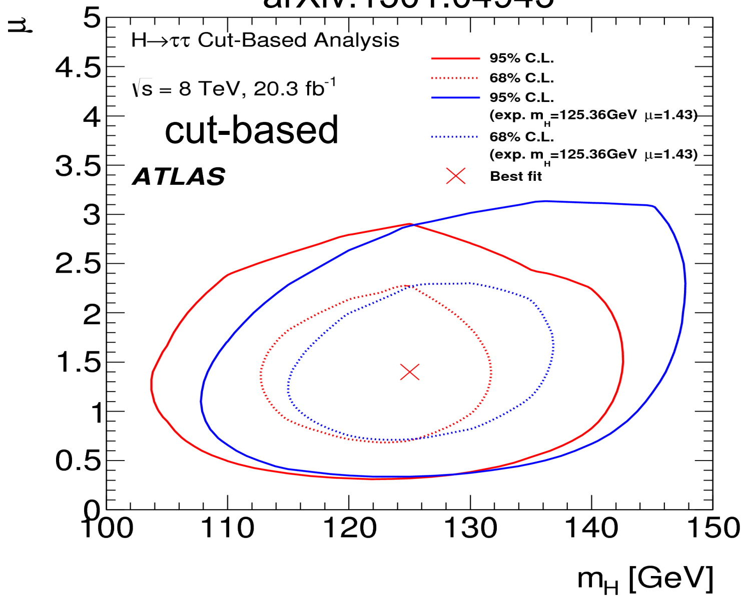
- The signal and control regions in each channel and the systematic errors are fed into a combined **likelihood ratio** for simultaneous fit

H→ττ Result

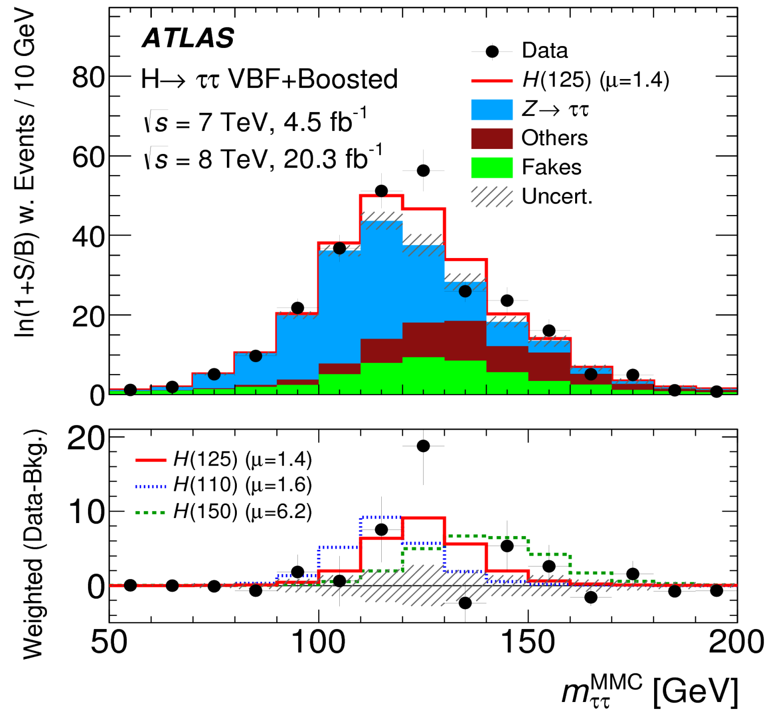
arXiv:1501.04943



arXiv:1501.04943



MMC weighted by ln(1+S/B) in each BDT bin:



arXiv:1501.04943

The combined fitted signal strength:

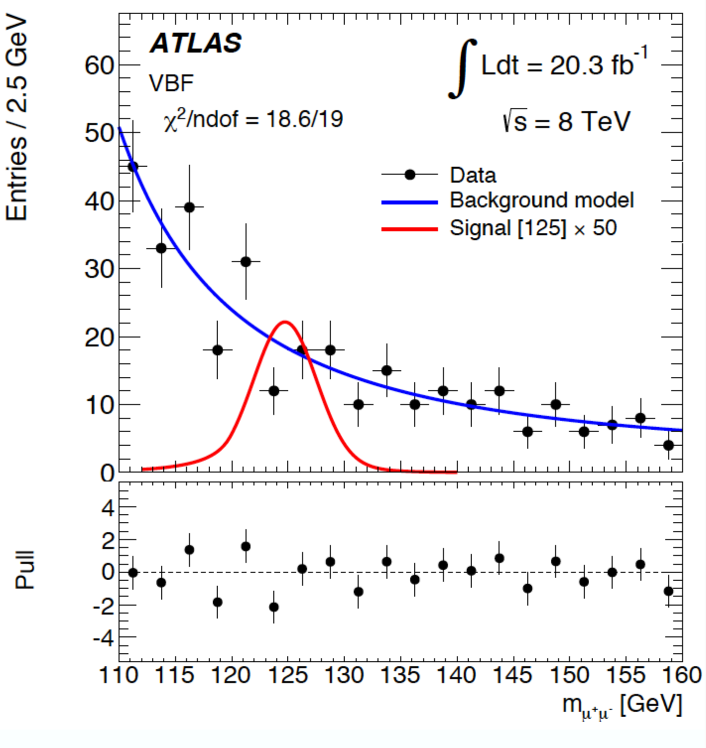
$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{sys.}) \pm 0.09(\text{theo.})$$

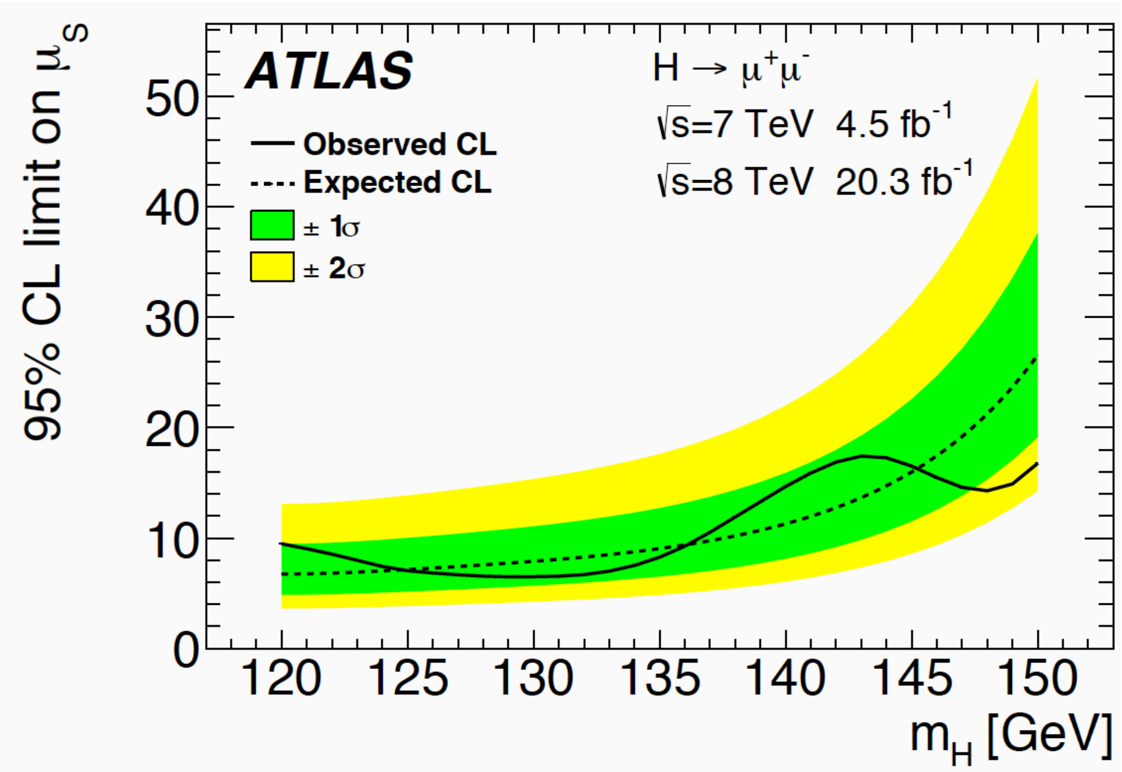
This corresponds to 4.5σ for 125 GeV (3.4σ expected)

H→μμ

[Phys. Lett. B 738 (2014) 68]

- “Simple” analysis but made difficult by low branching fraction and overwhelming $Z/\gamma^* \rightarrow \mu^+\mu^-$ background
  - Analysis categories: VBF / 3 separate pT(H) bins
  - Result: observed μ < 7.0 (95% CL) (expected: μ < 7.2)



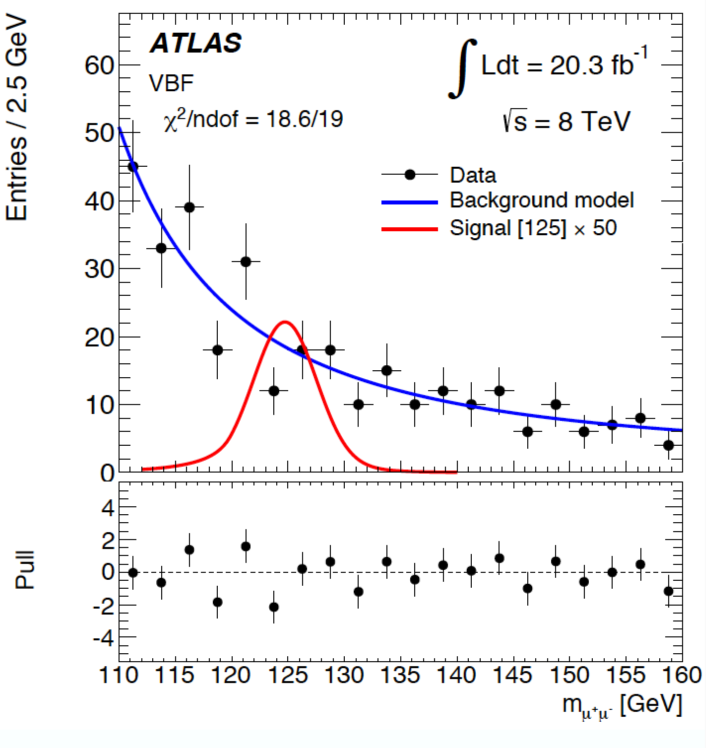


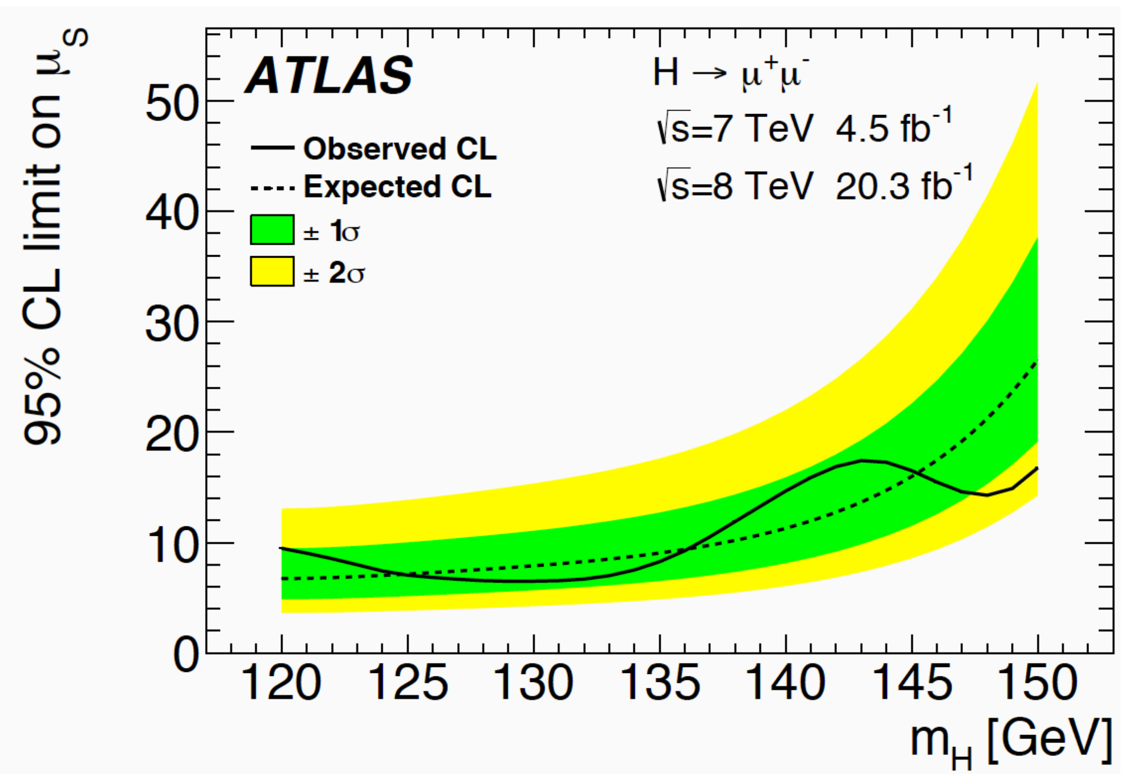
H→μμ

[Phys. Lett. B 738 (2014) 68]

➢ "Simple" analysis but made difficult by low branching fraction and overwhelming $Z/\gamma^* \to \mu^+\mu^-$ background

- Analysis categories: VBF / 3 separate pT(H) bins
- Result: observed μ < 7.0 (95% CL) (expected: μ < 7.2)



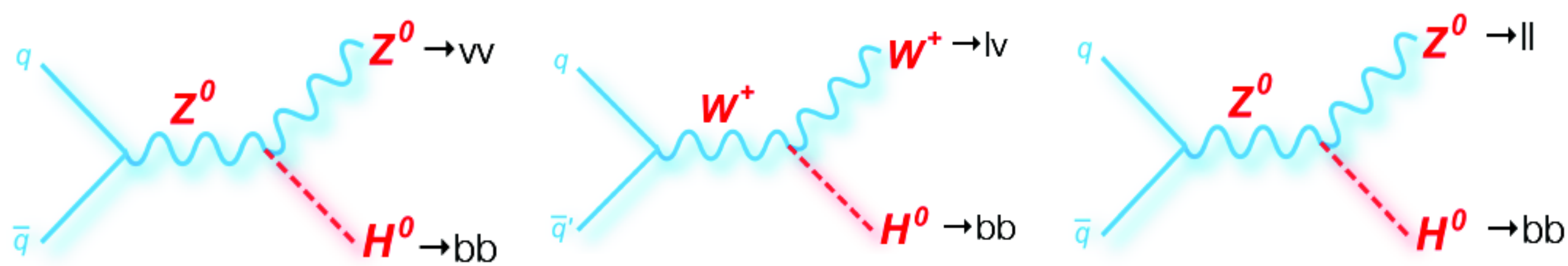


We'd better see this signal before building future $\mu^+\mu^-$ colliders

H→bbar

[JHEP 01 (2015) 069]

$ZH \to \nu\bar{\nu}b\bar{b}$	$WH \to \ell\nu b\bar{b}$	$ZH \to \ell^+\ell^- b\bar{b}$
0 lepton	1 lepton	2 leptons
2 b-jets	2 b-jets	2 b-jets
2 or 3 jets	2 jets	no N_{jet} requirement
MET > 30	MET > 25-50	MET < 60
	mT < 120	83 < mLL < 99
2 bins in pT(Z)	2 bins in pT(W)	1 bin in pT(Z)

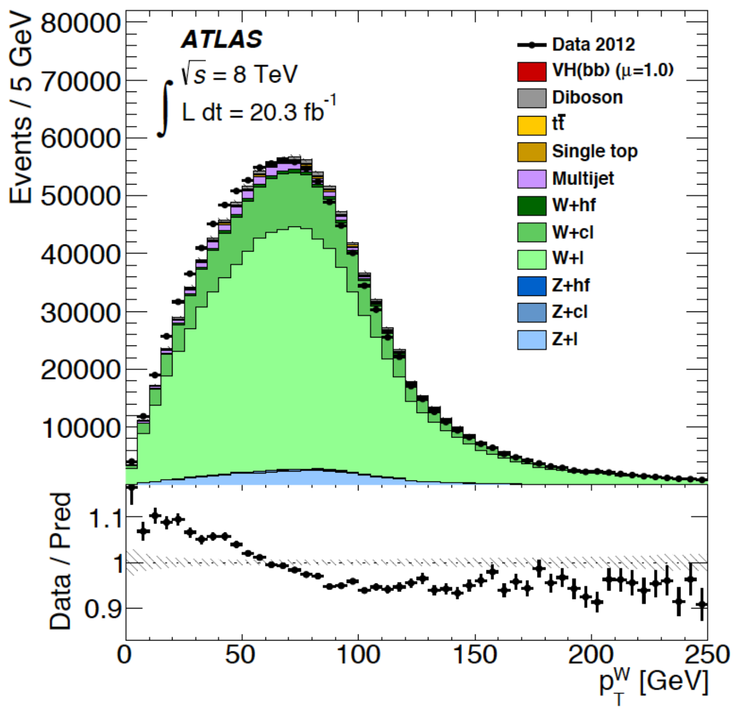


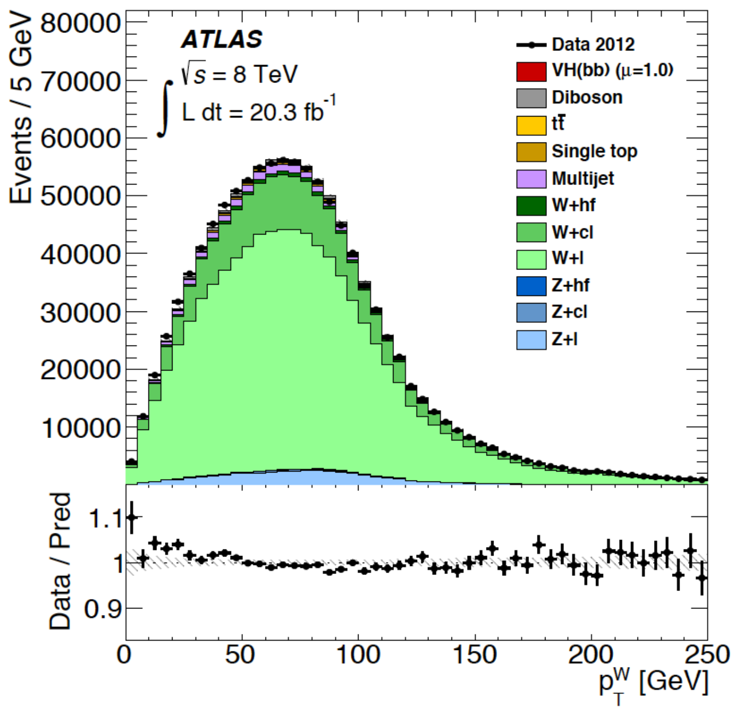
H→bbar

[JHEP 01 (2015) 069]

➢ Extensive background modelling required (multijet background is small due to large MET or lepton requirement)

❖ SHERPA modelling of pT(W) distribution improved by reweighting Δφ(j1, j2)

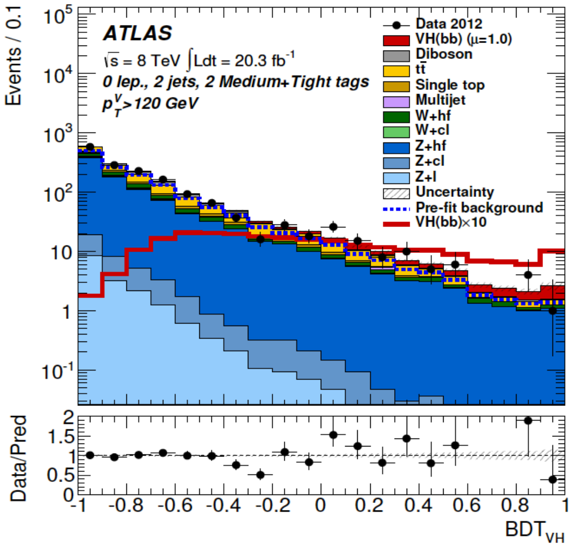


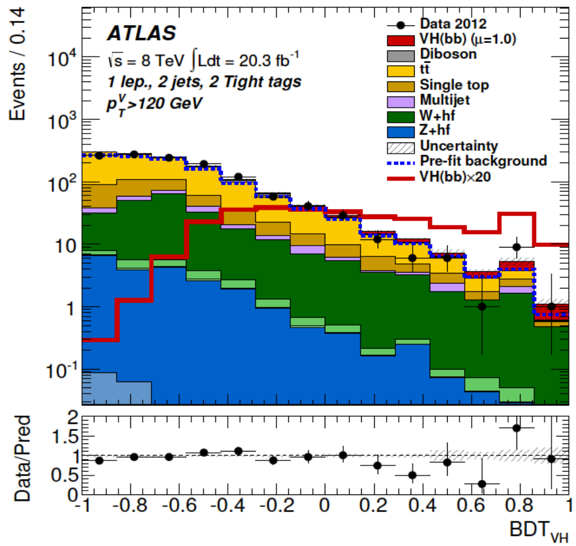


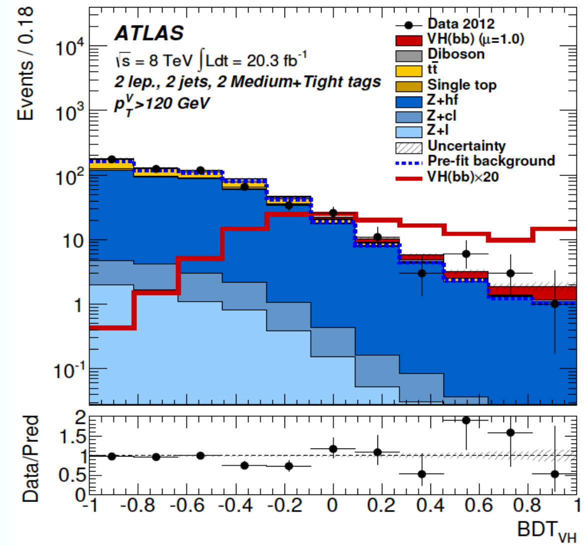
❖ Similar reweighting is carried out for other SHERPA samples, such as the Z+jets background

H→bbar

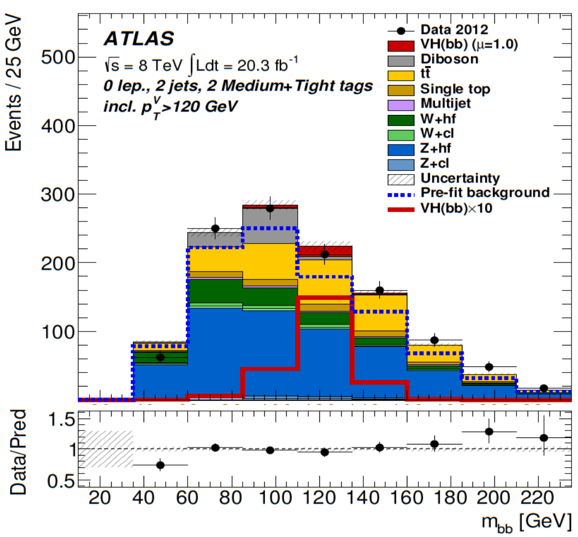
- BDT output distributions in most discriminating 0-, 1-, 2-lepton regions:

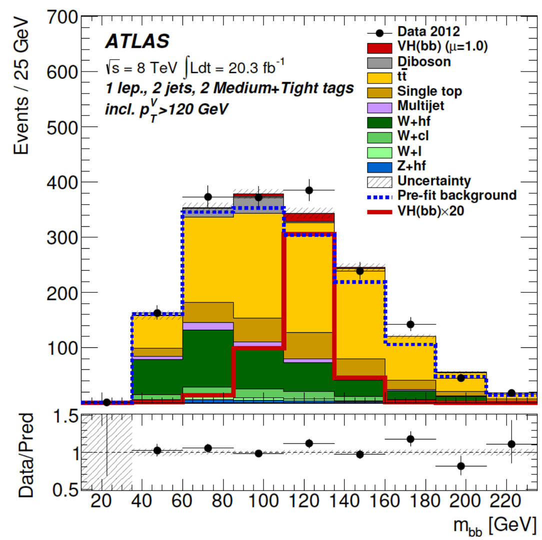


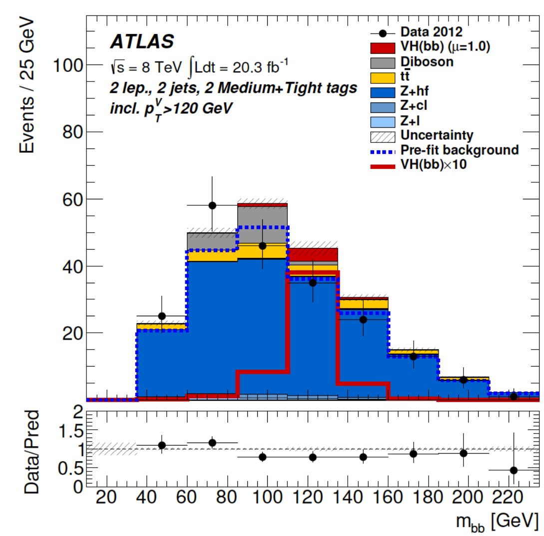




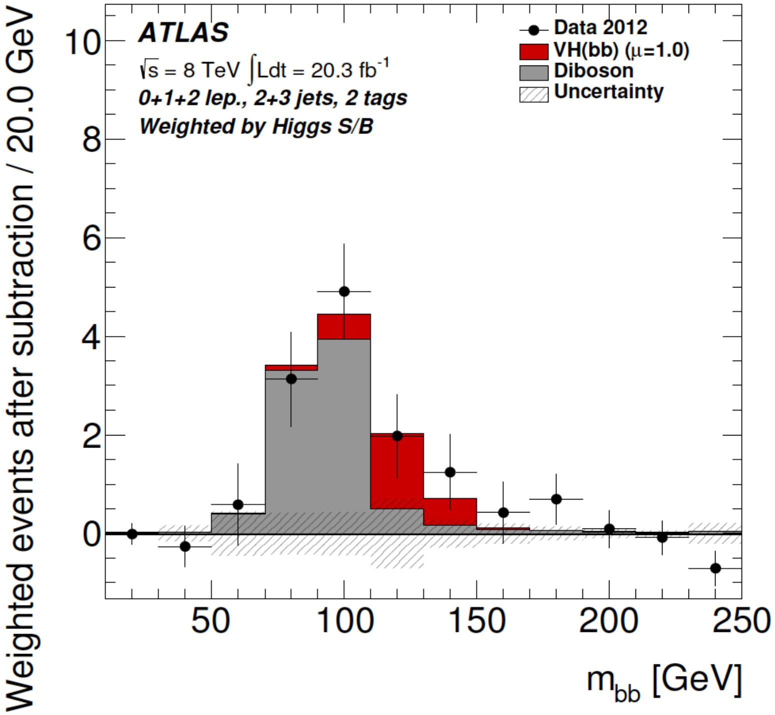
- Dijet mass in most discriminating 0-, 1-, 2-lepton regions:







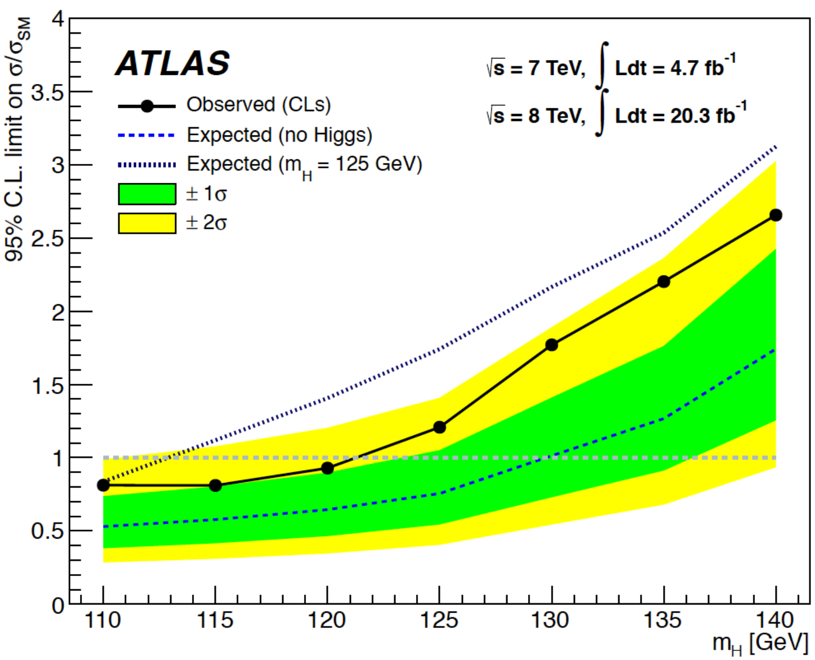
H→bbar



A SM Higgs in bbar decay is excluded for 1.2xSM rate.

The fitted signal strength

$$\mu = 0.51^{+0.31}_{-0.30}(\text{stat.})^{+0.25}_{-0.22}(\text{sys.})$$ $\boxed{1.4\sigma}$

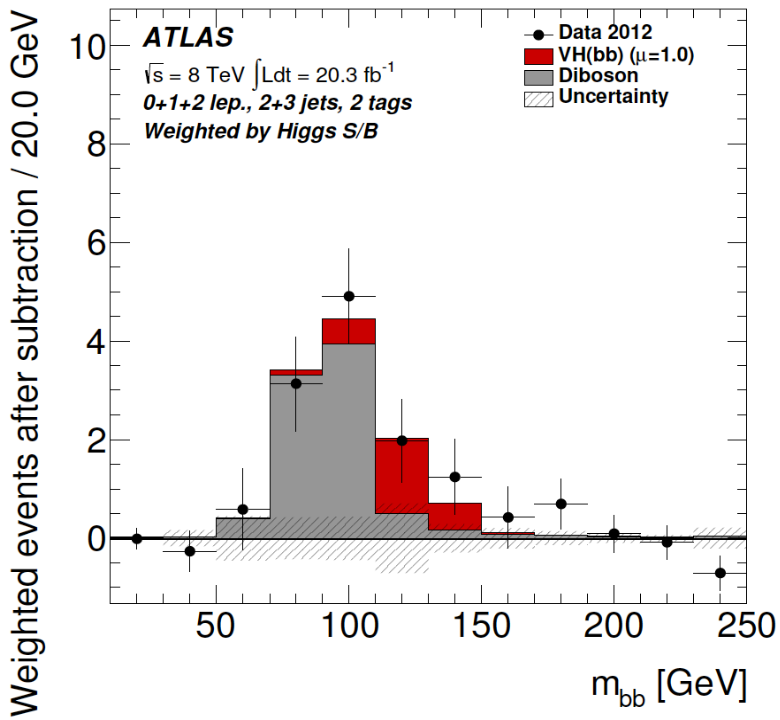


To validate the bbar analysis Method, the process decays of V+Z→bb is extracted to give

$$\mu = 0.74 \pm 0.09(\text{stat.}) \pm 0.14(\text{sys.})$$

– confidence in signal modeling

H→bbar



A SM Higgs in bbar decay is excluded for 1.2xSM rate.

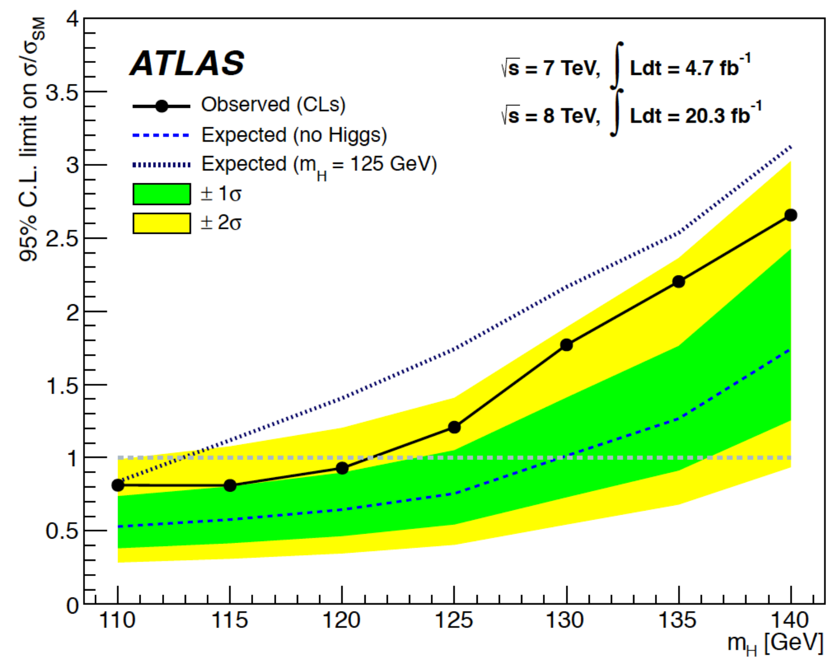
The fitted signal strength

$$\mu = 0.51^{+0.31}_{-0.30}(\text{stat.})^{+0.25}_{-0.22}(\text{sys.})$$ 1.4σ

To validate the bbar analysis Method, the process decays of V+Z→bb is extracted to give

$$\mu = 0.74 \pm 0.09(\text{stat.}) \pm 0.14(\text{sys.})$$

– confidence in signal modeling



Does Higgs couple less to down-type fermions ?

Higgs coupling combination

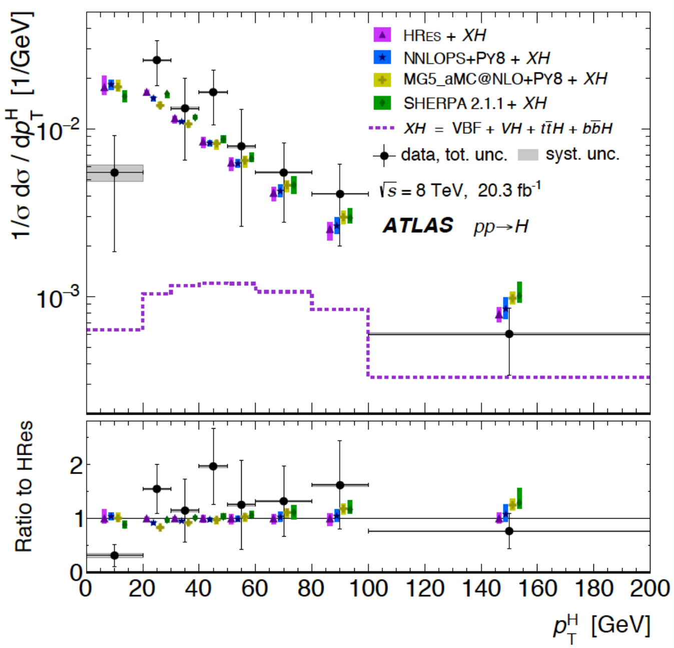
- Some terms we used without explanation:

Signal strength: $$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{obs}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

Coupling strength: $$\sigma \cdot \mathrm{BR}(i \to H \to f) = \frac{\sigma_i^{\mathrm{SM}} \cdot \Gamma_f^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}} \cdot \frac{\kappa_i^2 \kappa_f^2}{\kappa_{\mathrm{H}}^2}$$

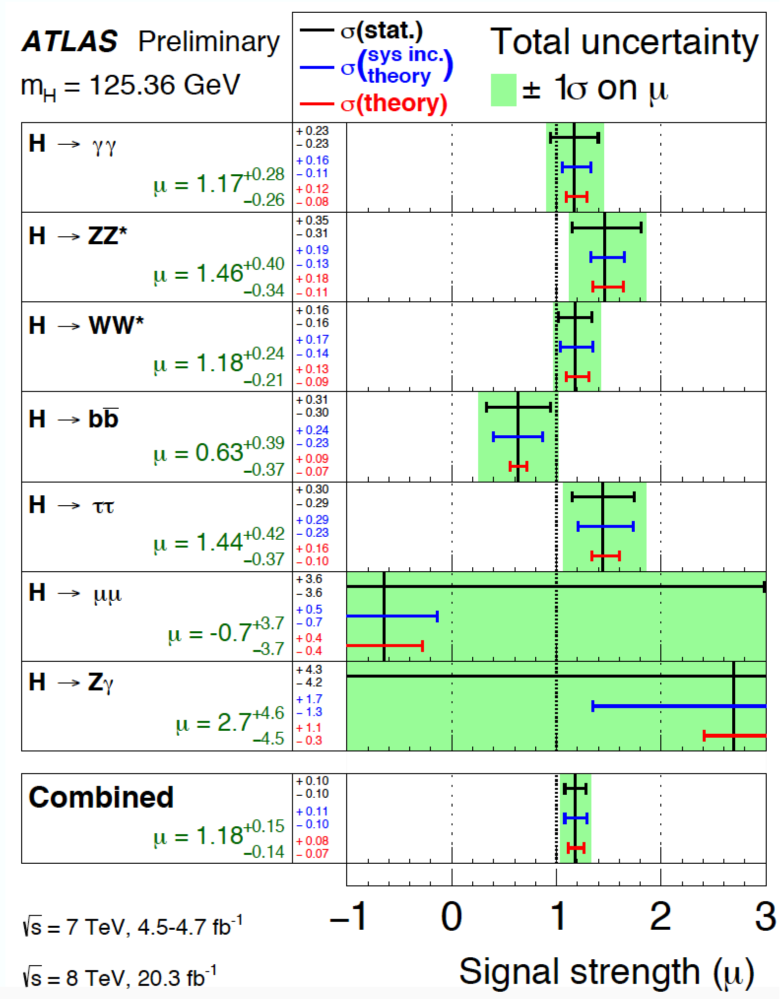
- Coupling framework assumes only modifications to the coupling strengths, not tensor structures

  - Assume it is a SM CP-even scalar
  - Assume production and decay kinematics do not change appreciably the SM expectations, e.g., the Higgs differential cross sections



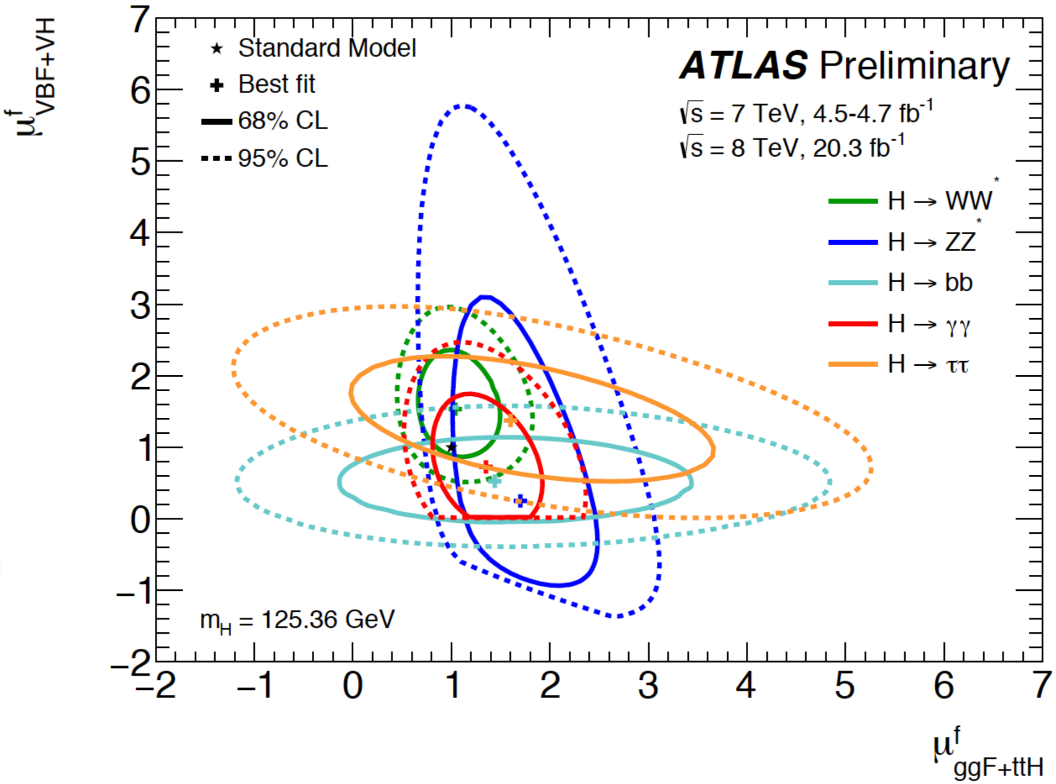
[ATLAS-CONF-2015-007]

Higgs coupling combination



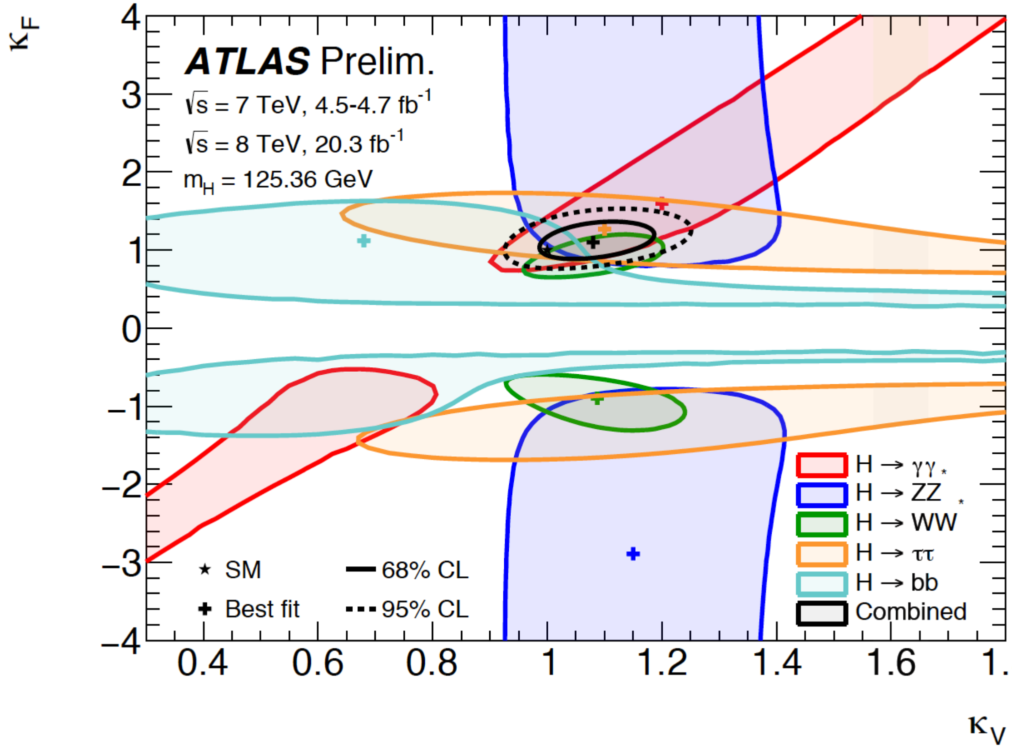
We assume the following:

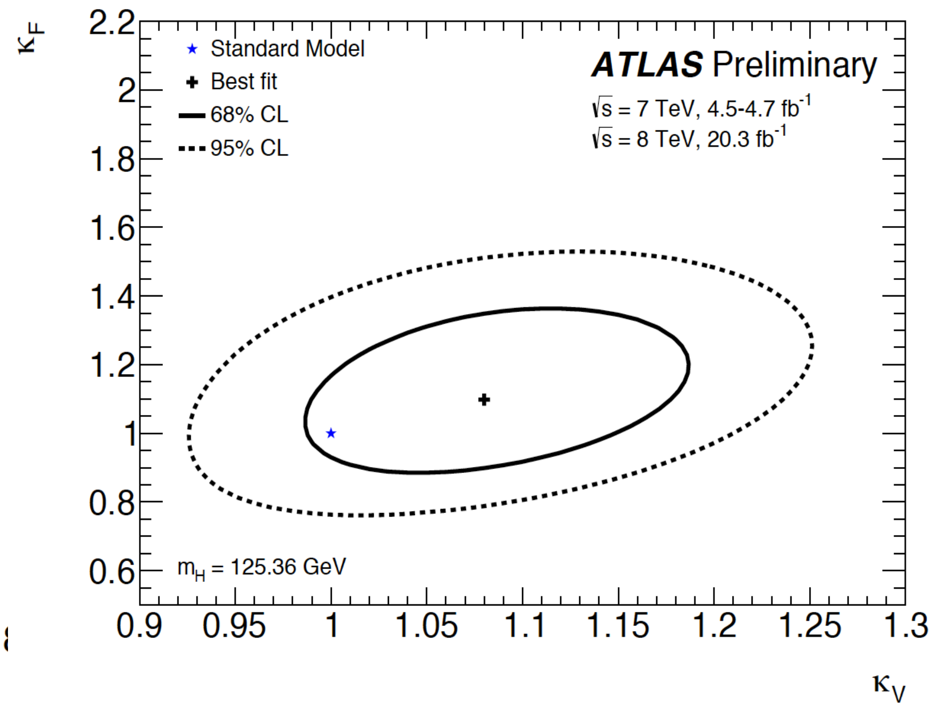
$$\mu_{\mathrm{ggH,ttH}} = \mu_{\mathrm{ggH}} = \mu_{\mathrm{ttH}}$$
$$\mu_{\mathrm{VBF,VH}} = \mu_{\mathrm{VBF}} = \mu_{\mathrm{VH}}$$



Combined μ: $1.18^{+0.15}_{-0.14}$

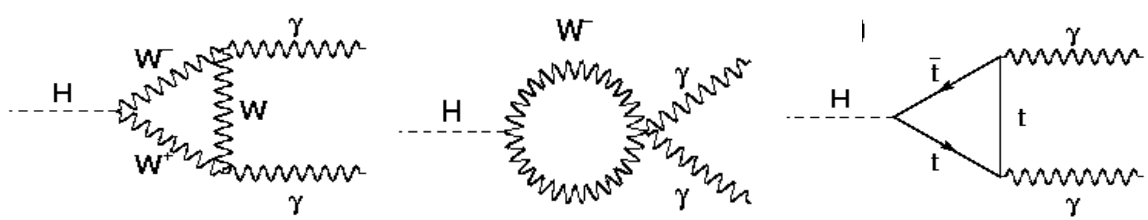
Higgs coupling combination





Double minima because of the H→γγ loop:

$$\sim \kappa_\gamma^{\ 2} = |1.28\ \kappa_W - 0.28\ \kappa_t|^2$$

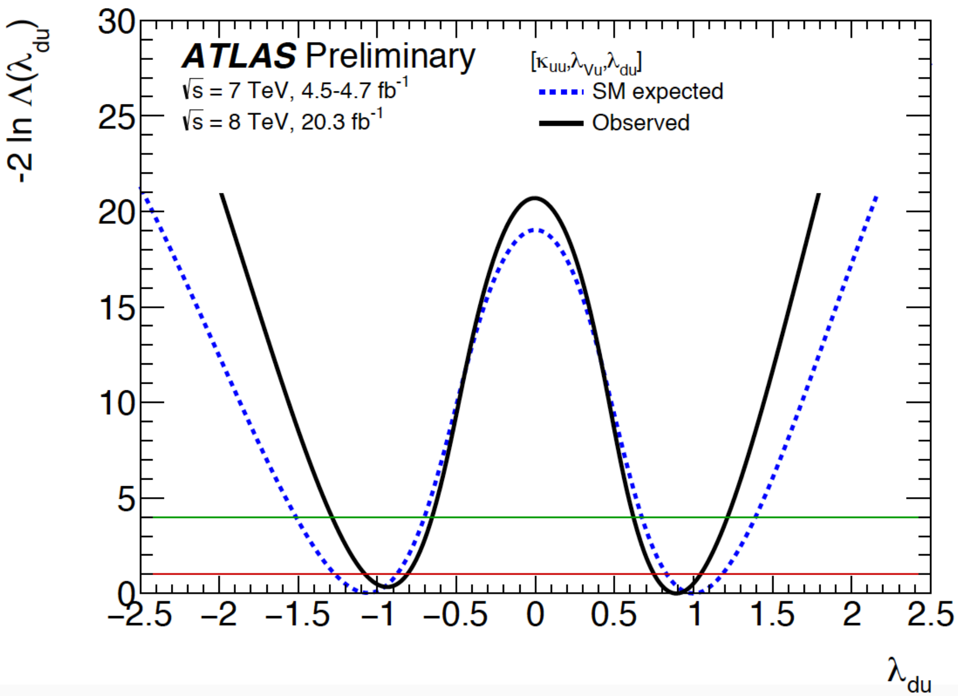


- Probe coupling of Higgs boson to fermions and bosons
- $\kappa_F \bullet \kappa_V < 0$ is disfavored at the ~4σ level by profiling
- Assume only SM particles in the loop

Higgs coupling combination

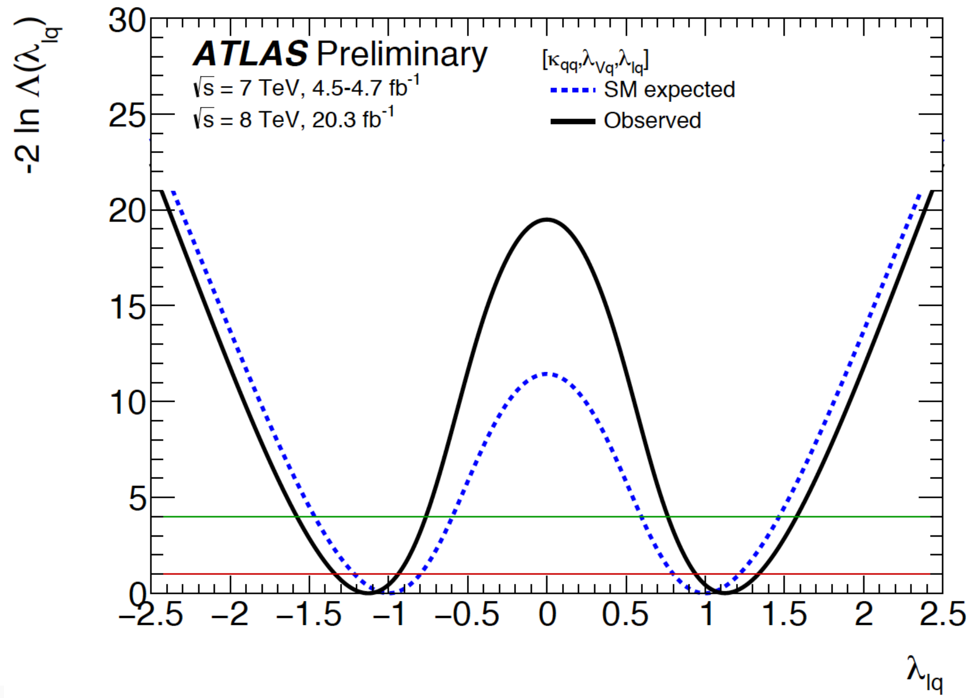
- Use data from H→ττ and H →bbar to determine the Yukawa ratios

Is the Yukawa coupling democratic in up- and down-type?



$$\lambda_{du} = \kappa_d / \kappa_u$$

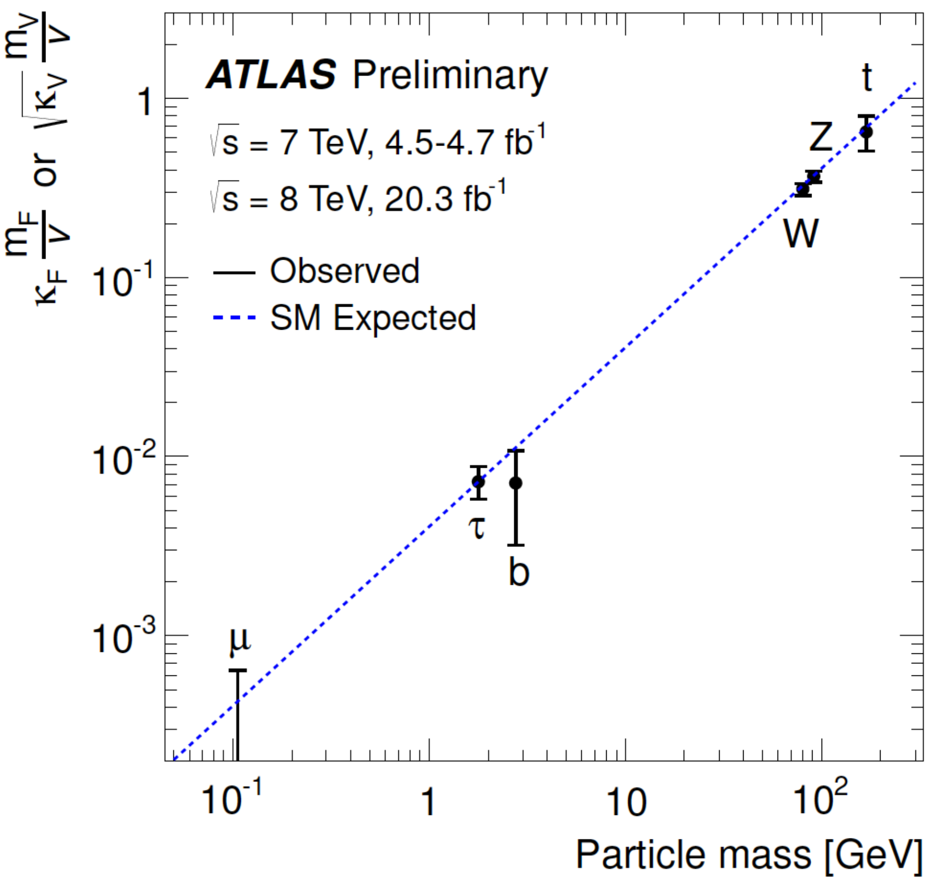
Is the Yukawa coupling democratic in leptons and quarks?

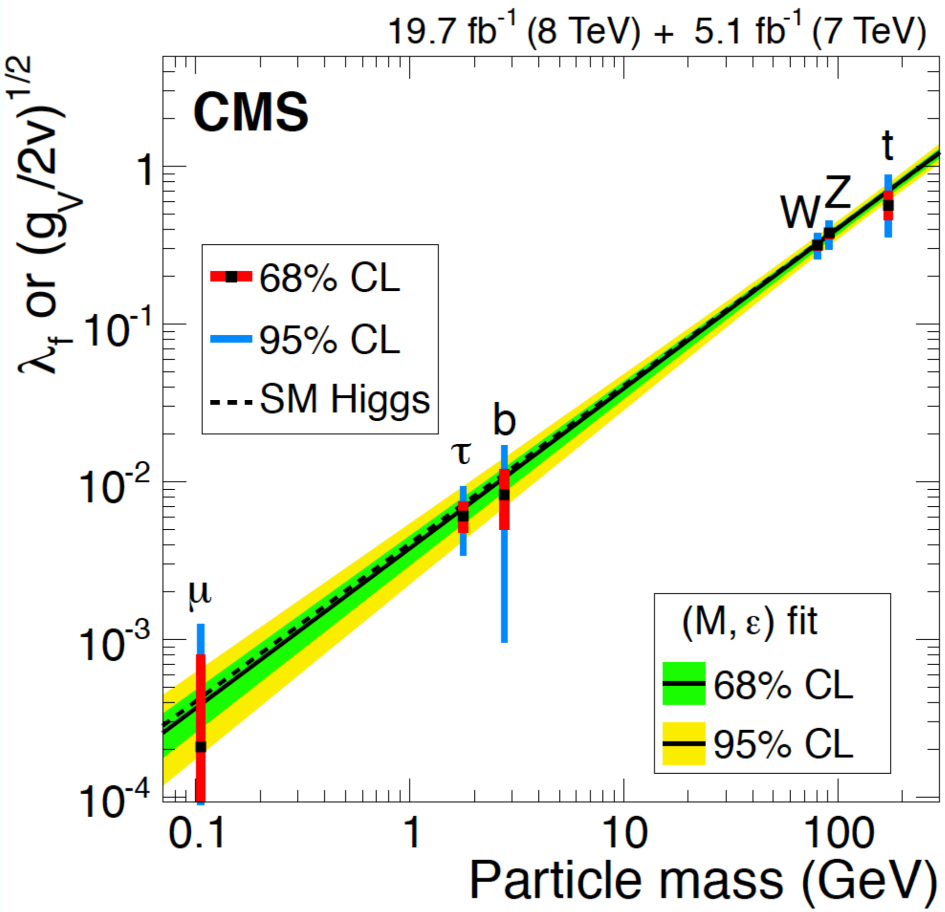


$$\lambda_{lq} = \kappa_l / \kappa_q$$

[arXiv:1507.04548]

Higgs coupling combination (ATLAS + CMS)



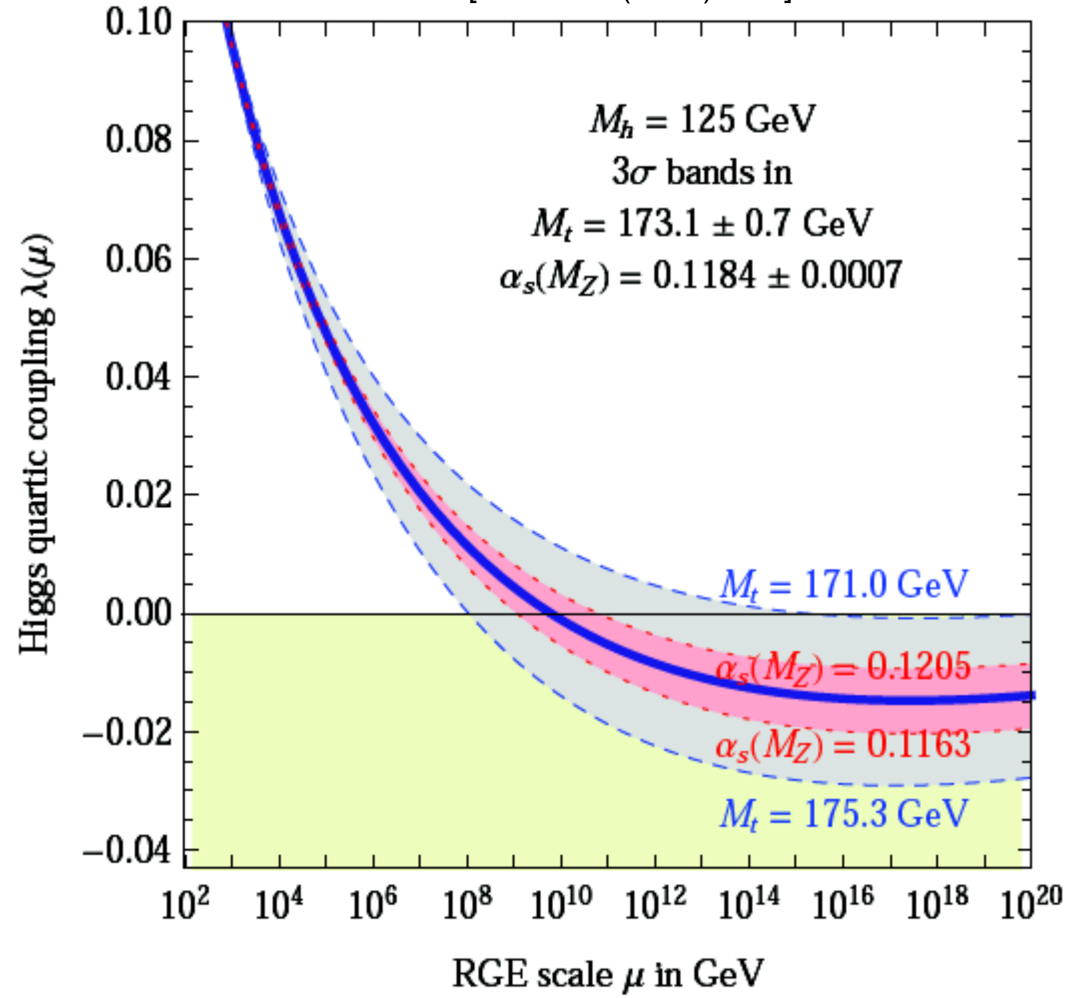


$$g_V \sim \frac{\kappa_V \cdot m_V^2}{\upsilon}, \lambda_f \sim \frac{\kappa_f m_f}{\upsilon}$$

Implication of a light Higgs

The running of Higgs quartic coupling λ

[JHEP 08 (2012) 098]



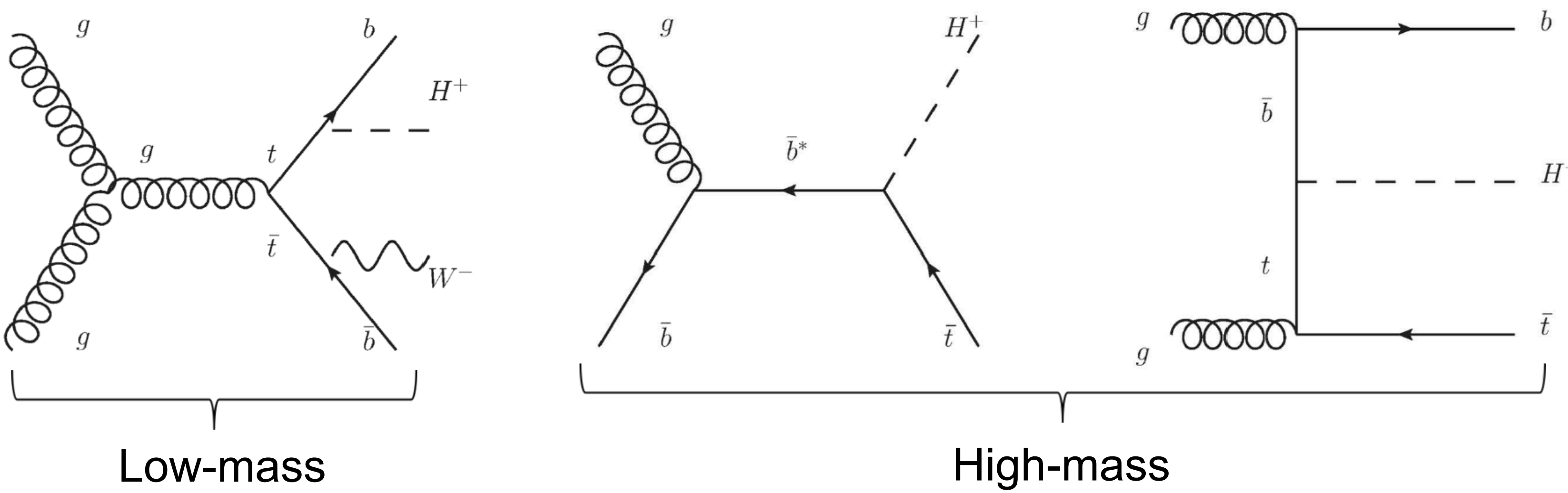
Higgs potential positive – vacuum stability

Expect new physics at high energy scales – is it SUSY ?

Charged Higgs

[JHEP03 (2015) 088]

- Analysis is divided into low mass (< top mass) or high mass (> top mass) regions:

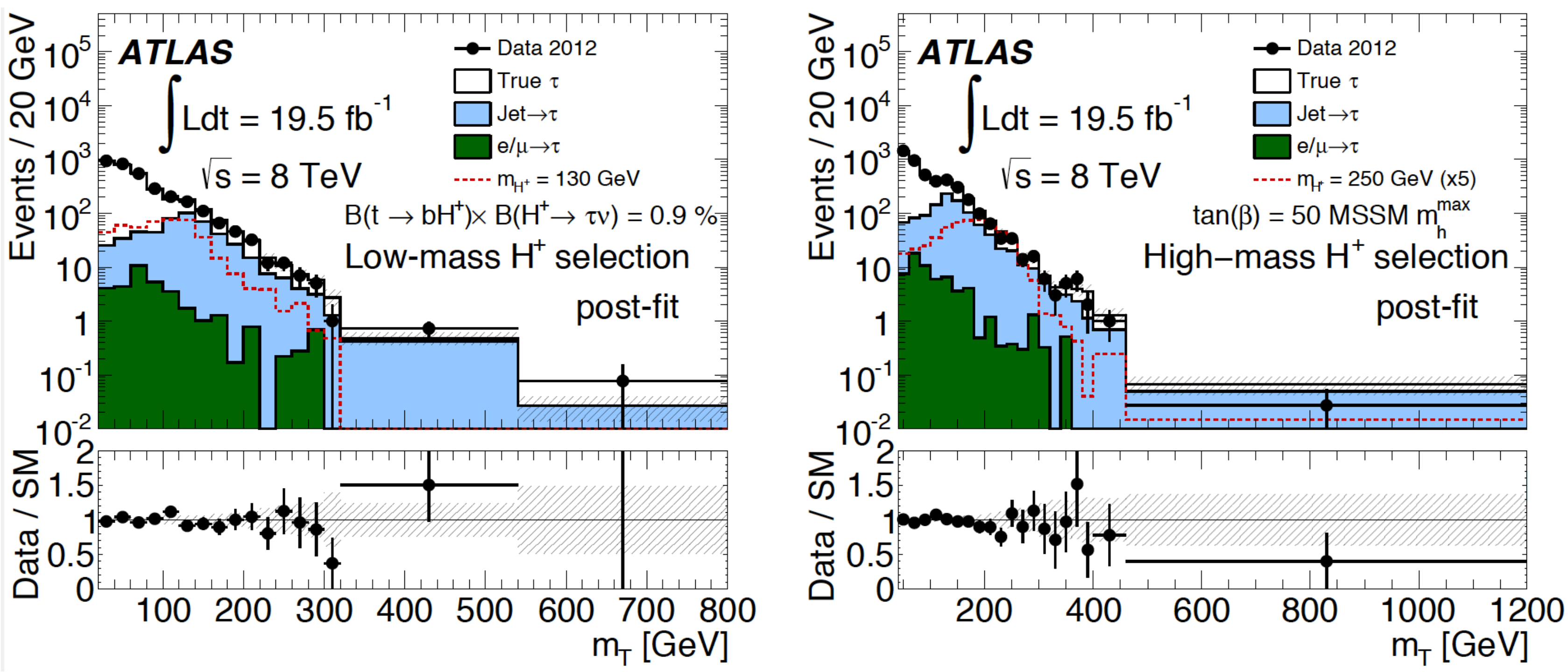


- Search for all-hadronic mode (to construct mT), and require tau+MET trigger

    - ✧ At least four (three) selected jets for the low-mass (high-mass)
    - ✧ At least one of these selected jets being b-tagged
    - ✧ At least one hadronic tau with pt>40 GeV
    - ✧ MET > 65 (80) GeV in the low (high) mass region

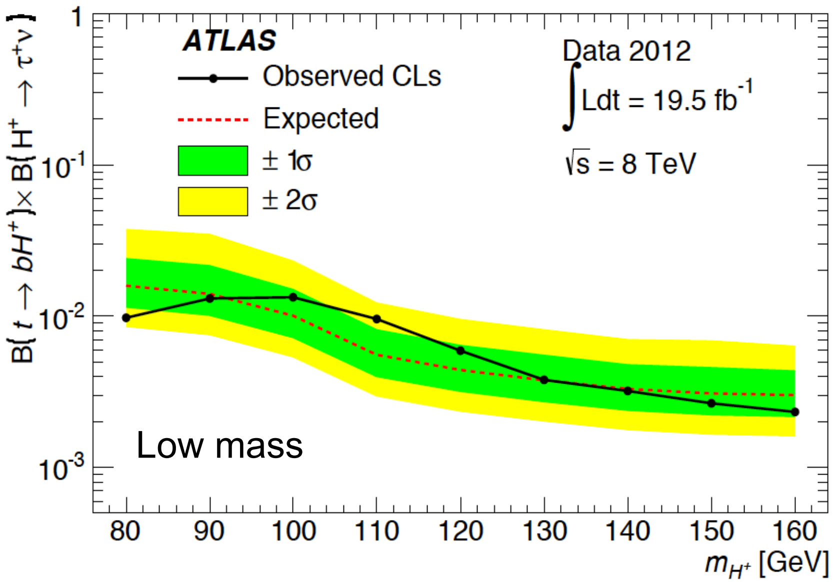
Charged Higgs

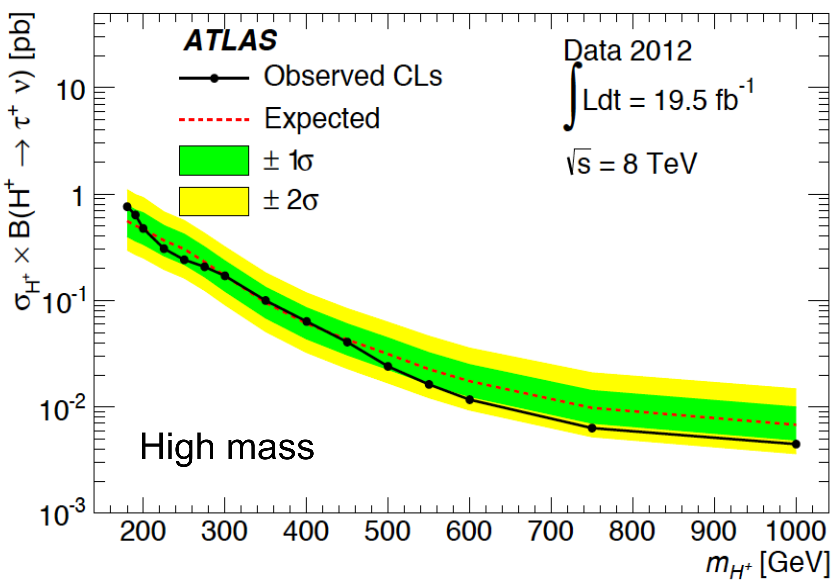
- Main backgrounds are real taus (from ttbar, W/Z) and fake taus (from QCD)
  - ✧ Real tau background is estimated from muon+jets data, with muon replaced by tau simulation and embed into the original event
  - ✧ The fake tau is estimated by loosening tau ID
- Transverse mass distributions after selection:



Charged Higgs – result interpretation

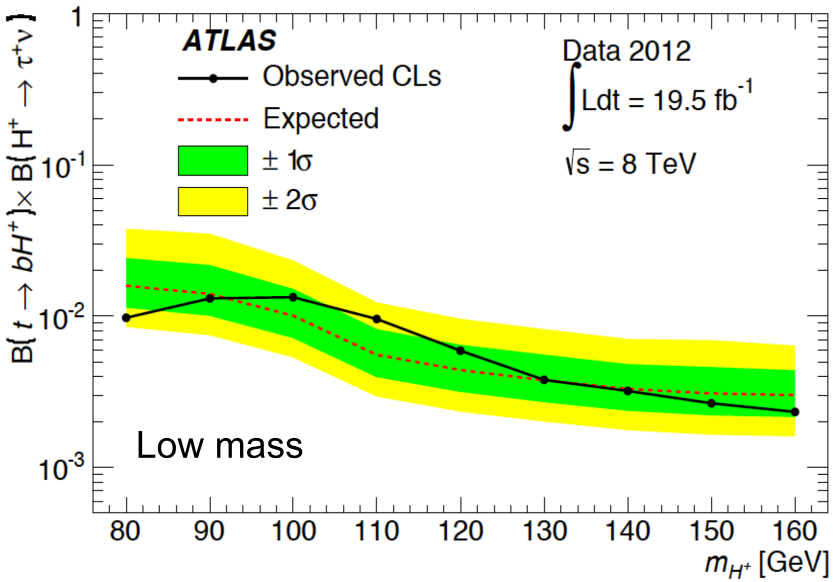
- Model independent search limits:

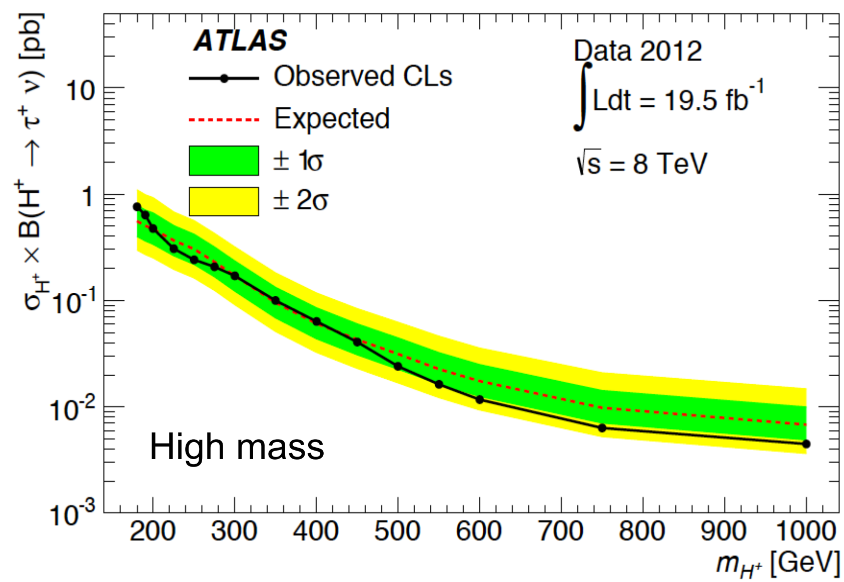




Charged Higgs – result interpretation

- Model independent search limits:





- MSSM tree-level relations:

$$
\begin{aligned}
m_{\pm}^2 &= m_A^2 + m_W^2, \\
m_{h,H}^2 &= \tfrac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right) \\
\tan 2\alpha &= \tan 2\beta \frac{m_A^2+m_Z^2}{m_A^2-m_Z^2} \quad \left(\text{with } -\tfrac{\pi}{2} < \alpha < 0\right),
\end{aligned}
$$

$$m_h \leq (m_Z, m_A) \leq m_H, \ \text{and} \ m_W \leq m_{\pm}$$

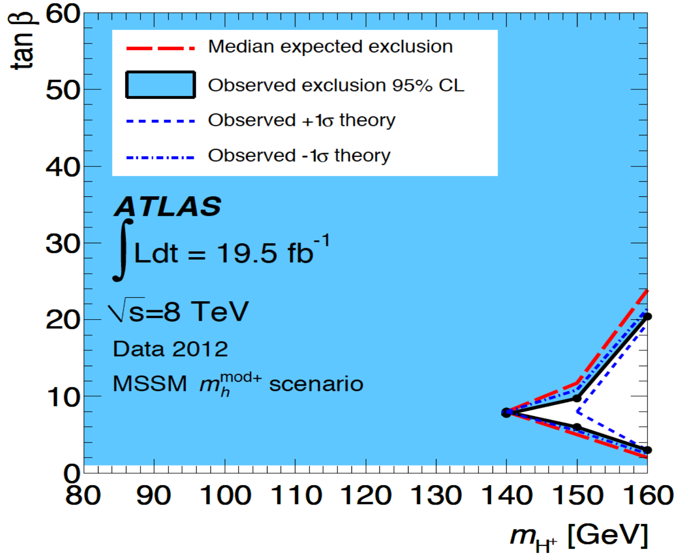
$$g_{H^- t\bar{b}} = -\frac{g}{2\sqrt{2}m_W}\left[m_t \cot\beta\,(1+\gamma_5) + m_b \tan\beta\,(1-\gamma_5)\right]$$

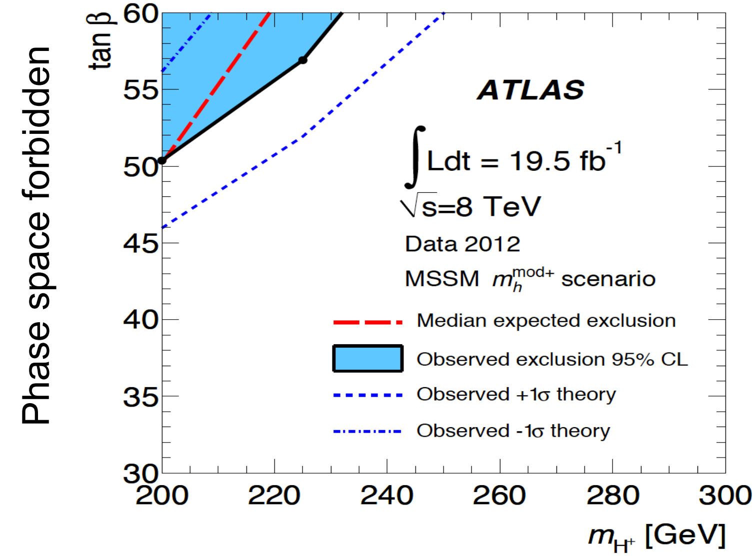
However, loop level top ans stop corrections significantly shift the light CP even Higgs mass to between 100 and 400

Two bench mark models, $m_h^{mod\pm}$, has parameter tuning such that the light Higgs mass is consistent with 125 GeV

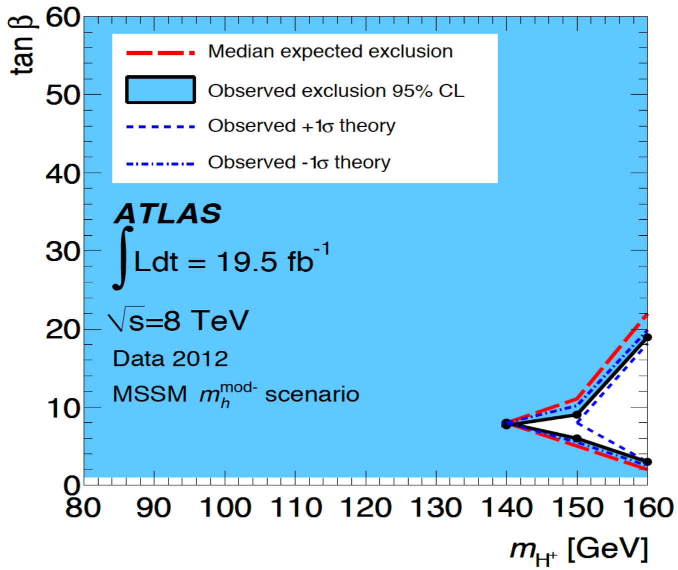
Charged Higgs – result interpretation

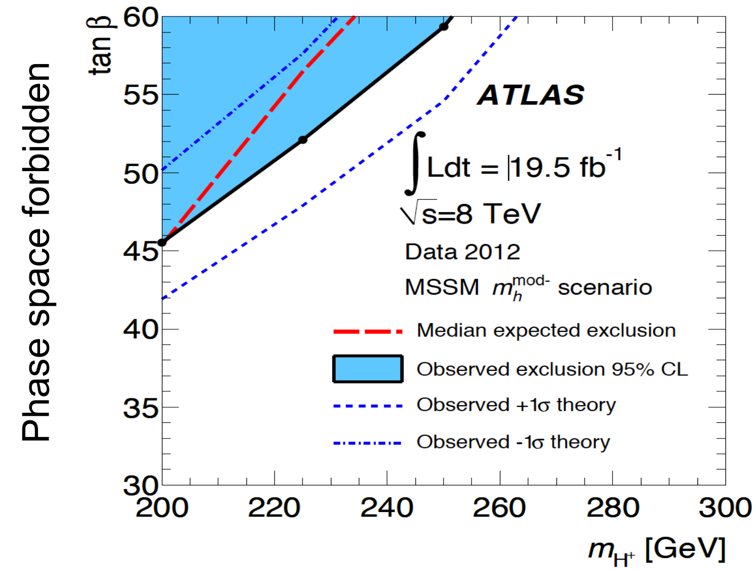
m_h^{mod+}





m_h^{mod-}



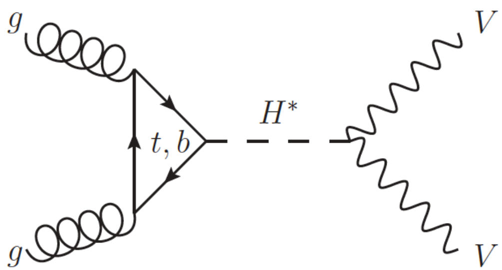


Low mass

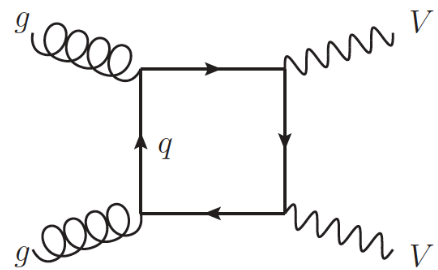
High mass

[Eur. Phys. J. C (2015) 75:335]

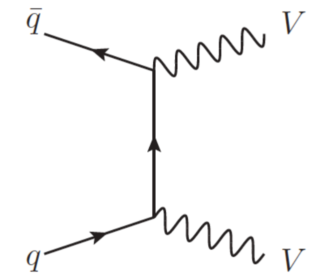
Probing the off-shell Higgs



Off-shell signal
gg→H*→VV



ggVV background
(interfere with signal)



qqVV background

- Signal strength and coupling scale factors:

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

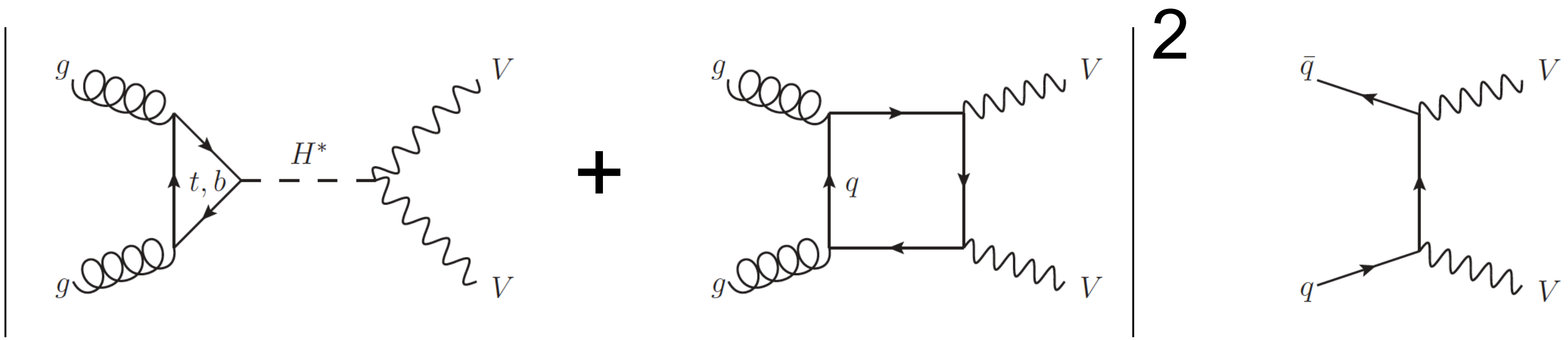
A way to measure Γ_H

In general, we can assume $\kappa_{\text{on-shell}} = \kappa_{\text{off-shell}}$, but due to possible new physics entering the ggH loop, we can also have

$$\kappa^2_{g,\text{on-shell}} < \kappa^2_{g,\text{off-shell}}$$

[Eur. Phys. J. C (2015) 75:335]

Probing the off-shell Higgs



Off-shell signal
gg→H*→VV

ggVV background
(interfere with signal)

qqVV background

- Signal strength and coupling scale factors:

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

A way to measure Γ_H

In general, we can assume $\kappa_{\text{on-shell}} = \kappa_{\text{off-shell}}$, but due to possible new physics entering the ggH loop, we can also have

$$\kappa^2_{g,\text{on-shell}} < \kappa^2_{g,\text{off-shell}}$$

Probing the off-shell Higgs

- The analysis considers gg→H*→VV and ggVV together as signal (due to their interference). However, higher-order correction (K-factors) is known for the former, not for the latter
- Parametrize the results in terms of their K-factor ratios:

$$\begin{aligned}\sigma_{gg\to(H^*\to)VV}(\mu_{\text{off-shell}}, m_{VV}) &= \mathrm{K}^{H^*}(m_{VV})\cdot\mu_{\text{off-shell}}\cdot\sigma^{\mathrm{SM}}_{gg\to H^*\to VV}(m_{VV}) \\ &+ \sqrt{\mathrm{K}^{H^*}_{gg}(m_{VV})\cdot\mathrm{K}^{\mathrm{B}}(m_{VV})\cdot\mu_{\text{off-shell}}}\cdot\sigma^{\mathrm{SM}}_{gg\to VV,\,\text{Interference}}(m_{VV}) \\ &+ \mathrm{K}^{\mathrm{B}}(m_{VV})\cdot\sigma_{gg\to VV,\,\text{cont}}(m_{VV})\,.\end{aligned}$$

$$\mathrm{R}^{B}_{H^*} = \frac{\mathrm{K}(gg\to VV)}{\mathrm{K}(gg\to H^*\to VV)} = \frac{\mathrm{K}^{\mathrm{B}}(m_{VV})}{\mathrm{K}^{H^*}_{gg}(m_{VV})}$$

- For ZZ→4l final state, calculate the Matrix Element (ME) for each event based on $\{m_{4l}, m_{12}, m_{34}, \cos\theta_1, \cos\theta_2, \phi, \cos\theta^*, \phi_1\}$ using MCFM (can fully construct the initial and final state 4-momenta). The discriminant:

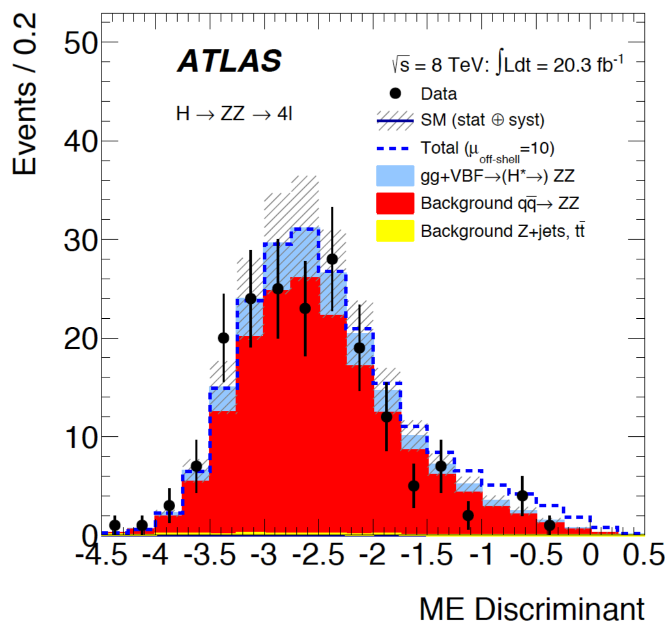
$$\mathrm{ME} = \log_{10}\left(\frac{P_H}{P_{gg} + c\cdot P_{q\bar{q}}}\right)$$

P is the Matrix Element squared for each process, c=0.1 to balance gg and qq

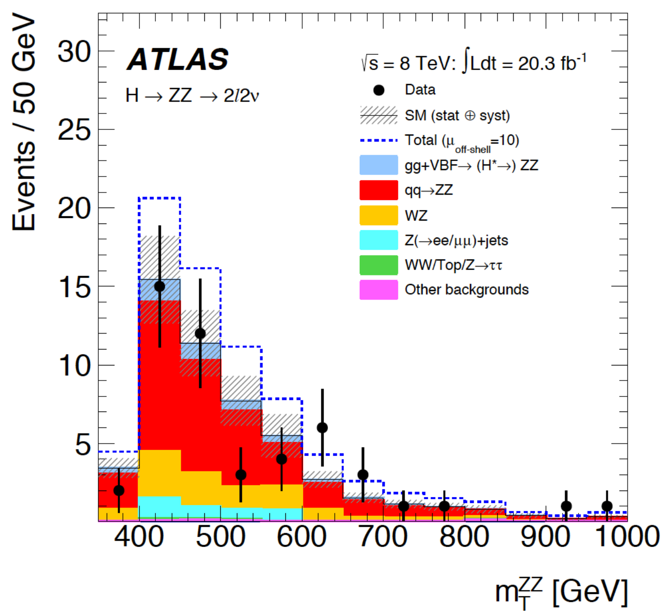
Probing the off-shell Higgs

- For ZZ→2l2ν, and WW→eνμν, use m_T as the discriminant, but to reduce the higher order effect on ggWW, a new definition is used: $R_8 = \sqrt{m_{ll}^2 + (a \cdot m_T^{WW})^2}$

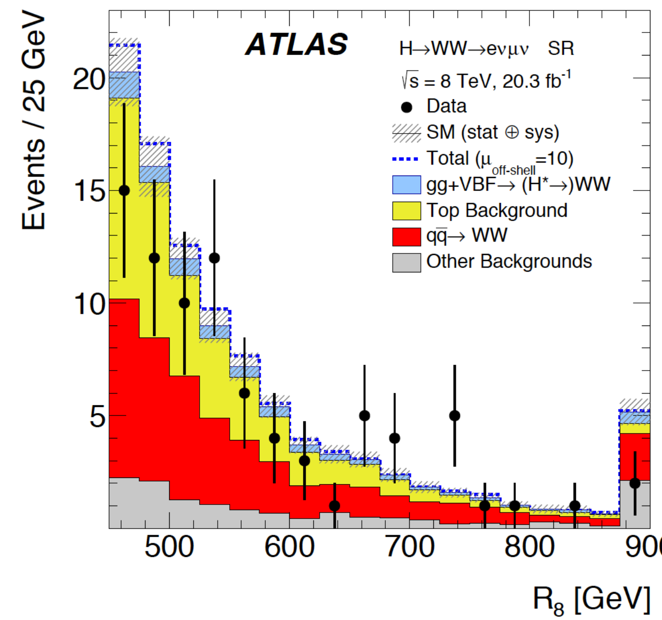
ZZ→4l



ZZ→2l2ν



WW→eνμν

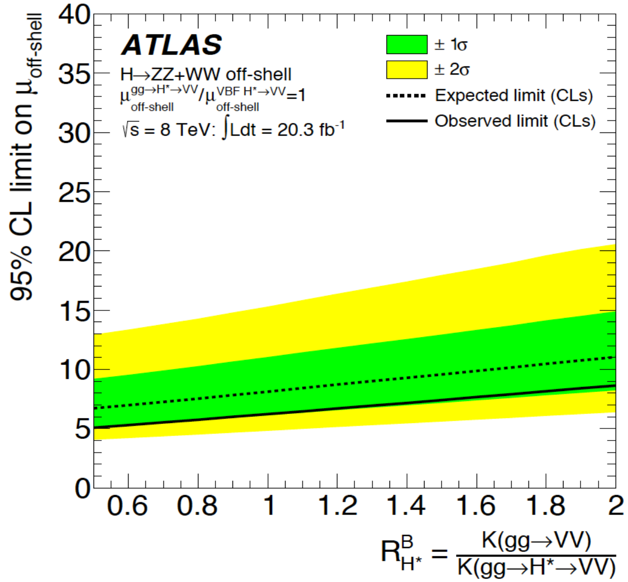


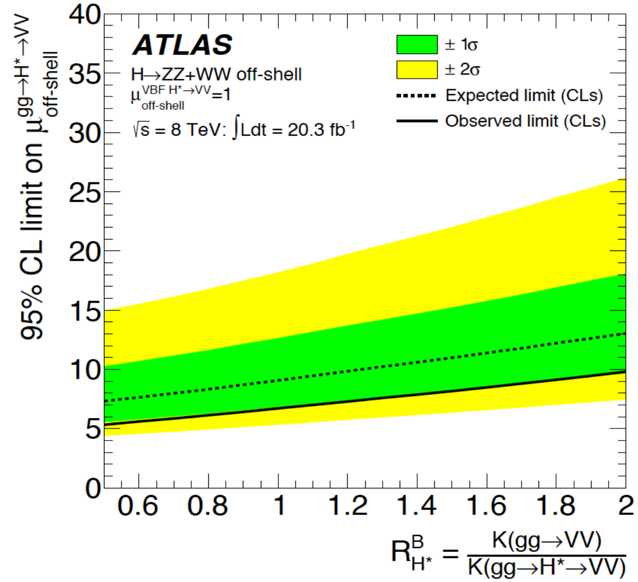
- Combined 95% CL upper limit on $\mu_{\text{off-shell}}$:

$R^B_{H^*}$	Observed 0.5	Observed **1.0**	Observed 2.0	Median expected 0.5	Median expected **1.0**	Median expected 2.0	Assumption
$\mu_{\text{off-shell}}$	5.1	**6.2**	8.6	6.7	**8.1**	11.0	$\mu^{gg\to H^*}_{\text{off-shell}}/\mu^{VBF}_{\text{off-shell}}=1$
$\mu^{gg\to H^*\to VV}_{\text{off-shell}}$	5.3	**6.7**	9.8	7.3	**9.1**	13.0	$\mu^{\text{VBF}\ H^*\to VV}_{\text{off-shell}}=1$

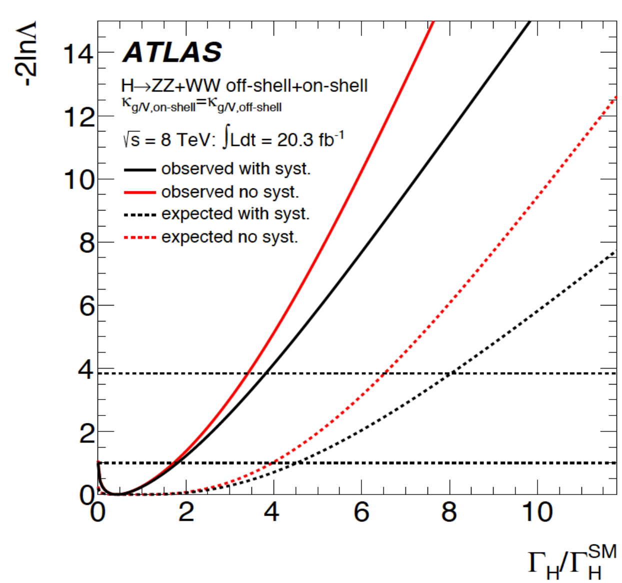
Probing the off-shell Higgs

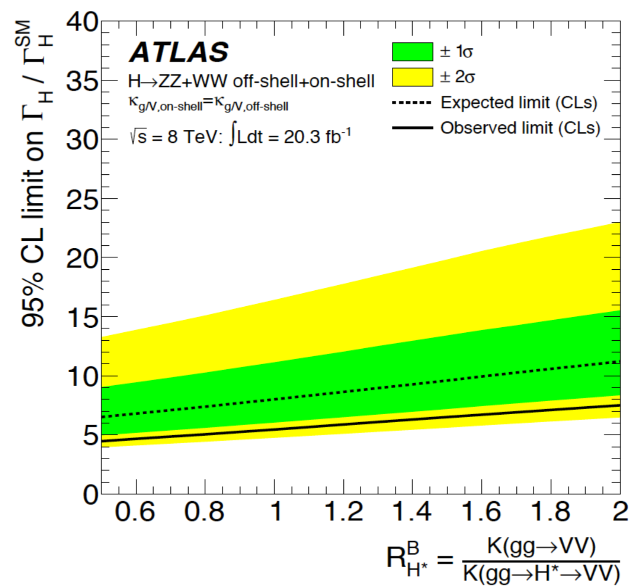
- The off-shell signal strength limit:





- Can be combined with the on-shell measurements to estimate Higgs width:





Higgs $\rightarrow$ invisible

[ATLAS-CONF-2015-004]

VBF Higgs$\rightarrow$ invisible:

- Require MET trigger
- Basically rate counting
- Have dedicated Zll and Wlν control regions

Process	Yield ± Stat ± Syst
ggH Signal	20 ± 6 ± 10
VBF Signal	286 ± 5 ± 49
$Z \rightarrow \nu\nu$+jets	339 ± 22 ± 13
$W \rightarrow \ell\nu$+jets	237 ± 17 ± 18
Multijet	2 ± 2
Other Backgrounds	0.7 ± 0.2 ± 0.3
Total Background	578 ± 38 ± 30
Data	539

95% CL Upper limit result:

$$\mathrm{BR}(\mathrm{H} \rightarrow \mathrm{invisible}) < 0.29$$

(<0.35 is expected)

Higgs → invisible

[ATLAS-CONF-2015-004]

VBF Higgs→ invisible:

- Require MET trigger
- Basically rate counting
- Have dedicated Zll and Wlν control regions

Process	Yield ± Stat ± Syst
ggH Signal	20 ± 6 ± 10
VBF Signal	286 ± 5 ± 49
$Z \rightarrow \nu\nu$+jets	339 ± 22 ± 13
$W \rightarrow \ell\nu$+jets	237 ± 17 ± 18
Multijet	2 ± 2
Other Backgrounds	0.7 ± 0.2 ± 0.3
Total Background	578 ± 38 ± 30
Data	539

95% CL Upper limit result:

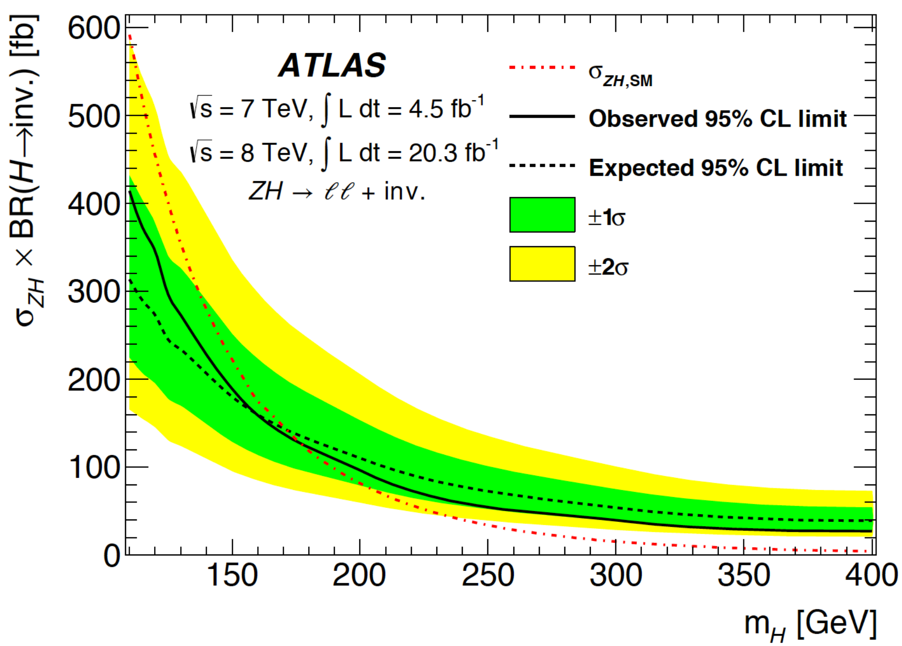
$\mathrm{BR}(\mathrm{H} \rightarrow \mathrm{invisible}) < 0.29$
(<0.35 is expected)

[Phys. Rev. Lett. 112 (2014) 201802]

VH with H→ invisible:

- ZH→ll+invisible

$\mathrm{BR}(\mathrm{H} \rightarrow \mathrm{invisible}) < 0.75$ (0.62 exp.)



- VH→jj+invisible

$\mathrm{BR}(\mathrm{H} \rightarrow \mathrm{invisible}) < 0.78$ (0.86 exp.)

[ATLAS-CONF-2015-008]

Higgs Spin/CP

- Use Effective Field Theory (EFT) to parametrize the HVV vertex (assume Higgs is a spin-0 scalar):

$$
\begin{aligned}
\mathcal{L}_0^V = & \left\{ c_\alpha \kappa_{\rm SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right. \\
& - \tfrac{1}{4} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
& \left. - \tfrac{1}{2} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \right\} X_0
\end{aligned}
$$

where $\tilde{V}^{\mu\nu} = \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$ is the dual tensor, and α is the mixing angle:

$$c_\alpha = \cos\alpha, \; s_\alpha = \sin\alpha$$

- The definition of the pure Higgs CP states:

J^P	Model	Choice of tensor couplings			
		$\kappa_{\rm SM}$	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

Higgs Spin/CP

- If the Higgs is a spin-2 tensor, the relevant Lagrangian is

$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu}\mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu}\mathcal{T}^f_{\mu\nu}\right]$$

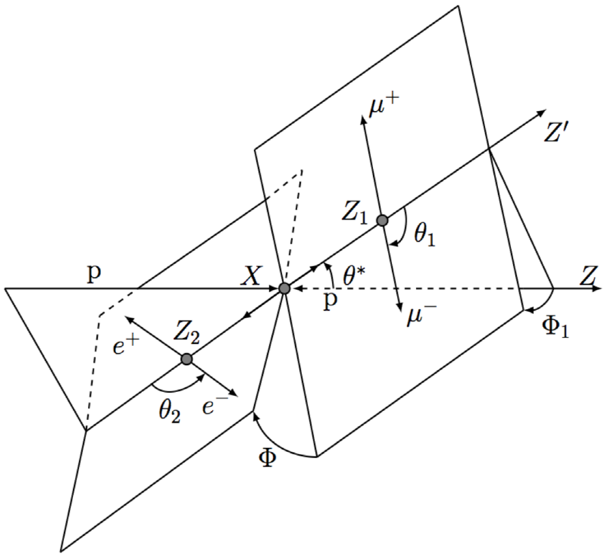
For the EFT to be valid upto Λ=1 TeV, an cut ($p_T^X < 300$ GeV) on the Higgs pt is applied

- To test the fixed spin/CP states against alternatives, the following are used

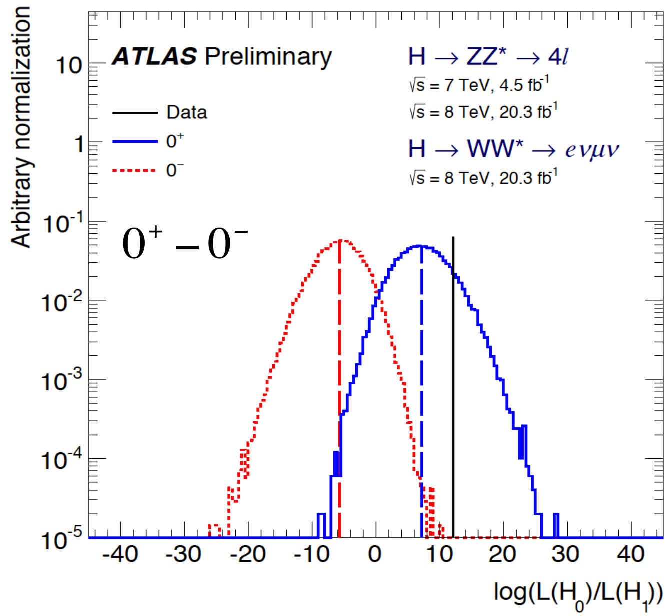
WW→$e\nu\mu\nu$ 0-jet category: $m_{ll}, \Delta\phi_{ll}, p_T^{ll}, E_{ll\nu\nu}, \Delta p_T$

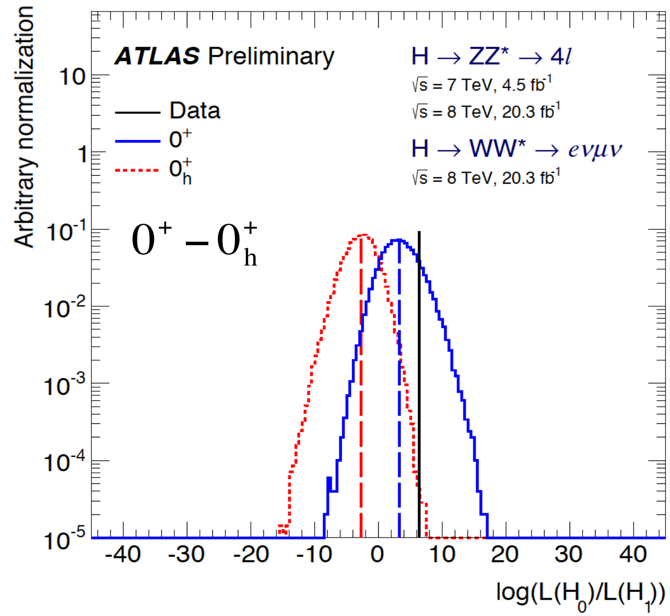
$\gamma\gamma$: Collins-Soper frame angle $|\cos\theta^*|$ and diphoton $p_T^{\gamma\gamma}$

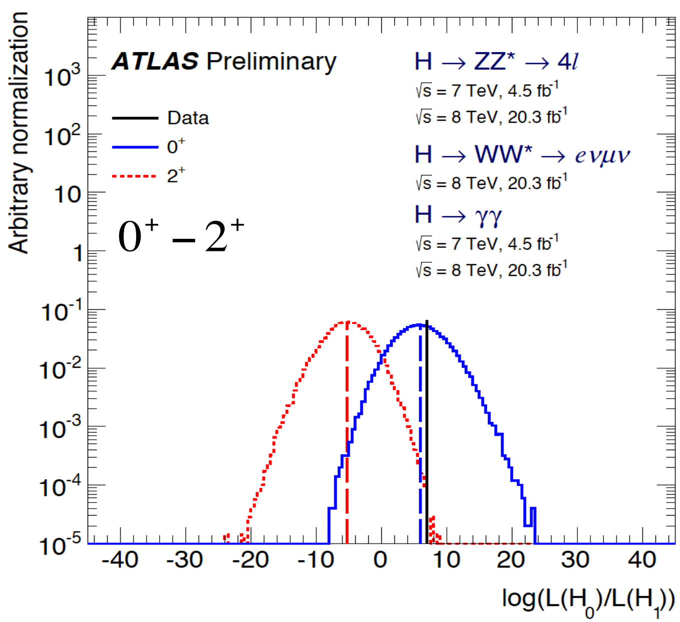
ZZ→4l: angles $\theta^*, \Phi_1, \Phi, \theta_1, \theta_2$ and BDT$_{ZZ}$ (to reject ZZ background)

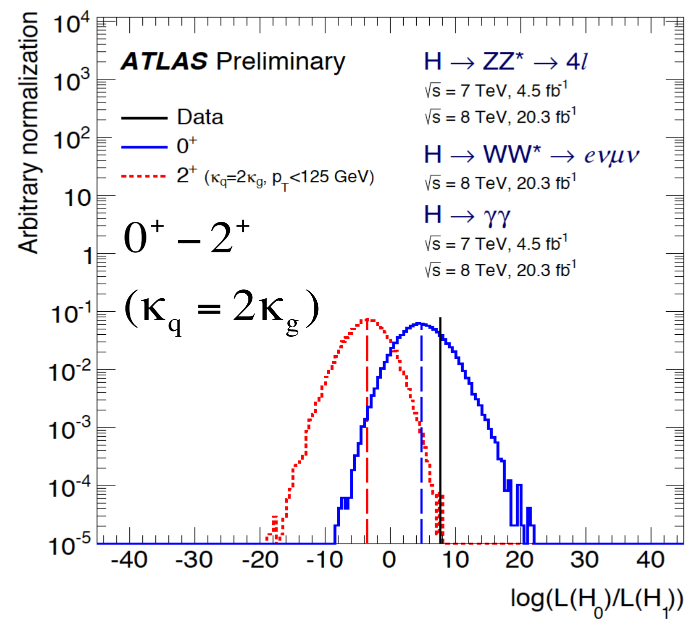


Fixed spin/CP test results





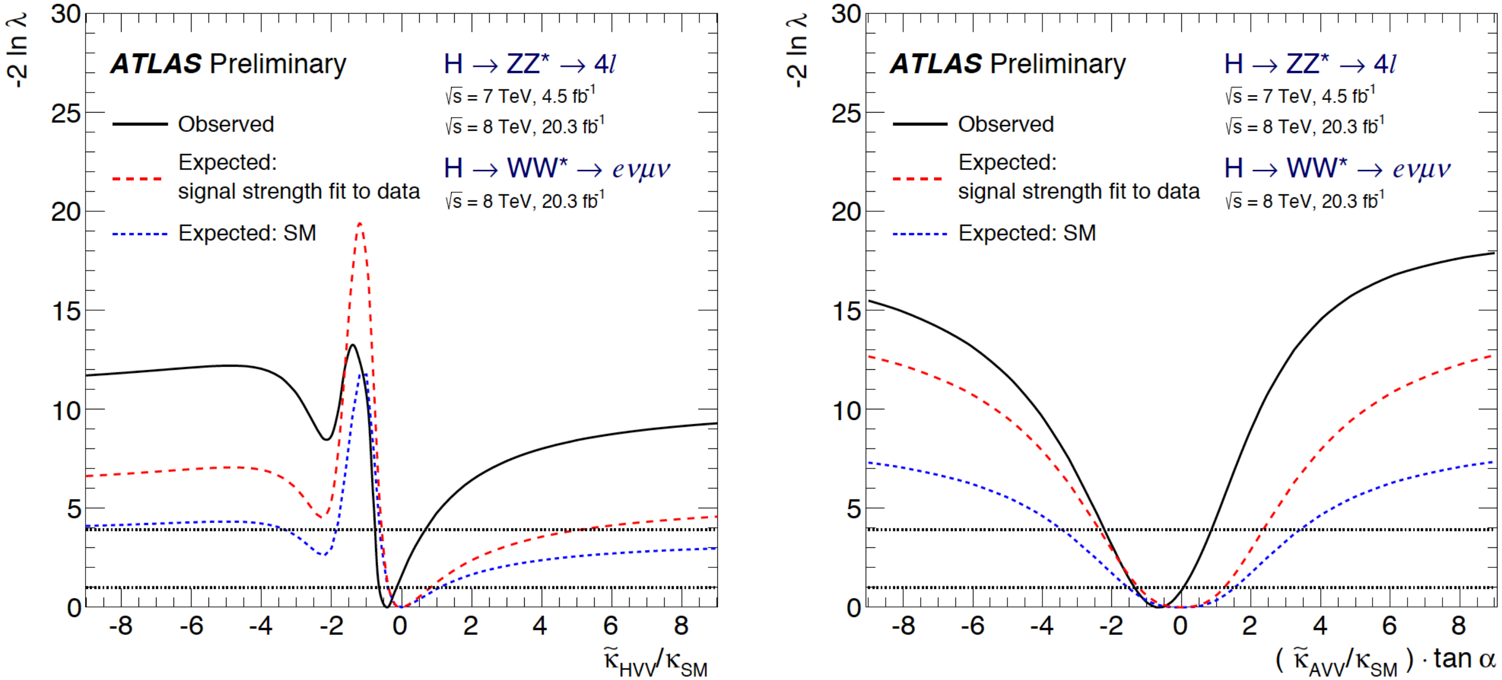




Mixed spin/CP states test

- Also consider the mixture of SM and BSM CP even/odd

  For ZZ→4l, use ME-based variables instead of angles



Coupling ratio	Best fit value		95% CL Exclusion Regions	
Combined	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	0.0	−0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	0.0	−0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \quad \text{and} \quad \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$

Summary

After Higgs boson discovery, main focus has shifted to its property measurements:

- Its precise mass determination ($\gamma\gamma$ and $ZZ \rightarrow 4l$)
- Its couplings to different SM particles
- Its spin/CP, and its tensor couplings
- Its total width, other decays (such as invisible)

Summary

After Higgs boson discovery, main focus has shifted to its property measurements:

- Its precise mass determination ($\gamma\gamma$ and ZZ$\rightarrow 4l$)
- Its couplings to different SM particles
- Its spin/CP, and its tensor couplings
- Its total width, other decays (such as invisible)

Most Run 1 Higgs results are finalized with improved methods, sensitivity and errors. Our understanding of the new particle has been push to an unprecedented level

Summary

After Higgs boson discovery, main focus has shifted to its property measurements:

- Its precise mass determination ($\gamma\gamma$ and ZZ$\rightarrow 4l$)
- Its couplings to different SM particles
- Its spin/CP, and its tensor couplings
- Its total width, other decays (such as invisible)

Most Run 1 Higgs results are finalized with improved methods, sensitivity and errors. Our understanding of the new particle has been push to an unprecedented level

Combination of coupling measurements are always made to test any deviations from SM predictions. So far, no significant deviations are observed

Summary

After Higgs boson discovery, main focus has shifted to its property measurements:

- Its precise mass determination ($\gamma\gamma$ and ZZ$\rightarrow$4l)
- Its couplings to different SM particles
- Its spin/CP, and its tensor couplings
- Its total width, other decays (such as invisible)

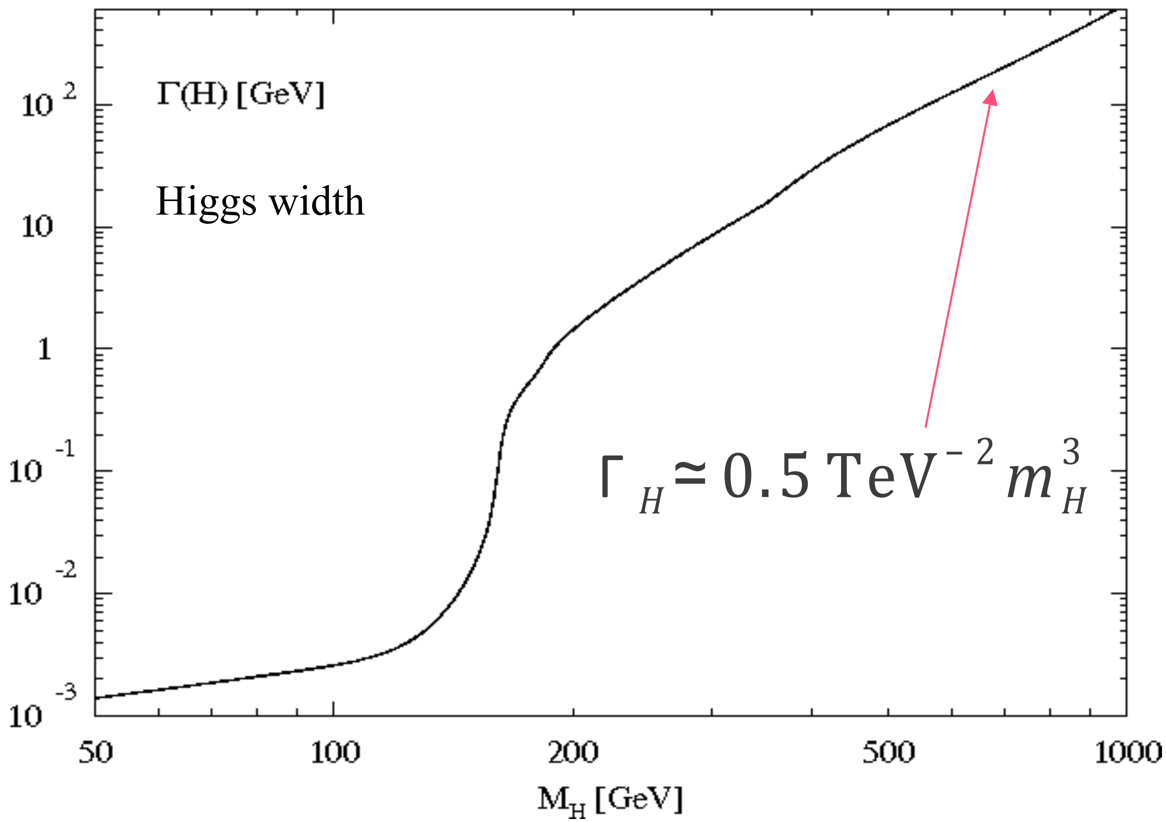
Most Run 1 Higgs results are finalized with improved methods, sensitivity and errors. Our understanding of the new particle has been push to an unprecedented level

Combination of coupling measurements are always made to test any deviations from SM predictions. So far, no significant deviations are observed

While some measurements with Run 1 are still on-going (not all analyses are covered in this talk), most analyses is geared toward precision measurements with Run 2

Backup Slides

Higgs decay width



The Higgs decay width increases dramatically when above 200 GeV, and its interference with SM processes becomes sizable – tough for heavy SM-like Higgs search