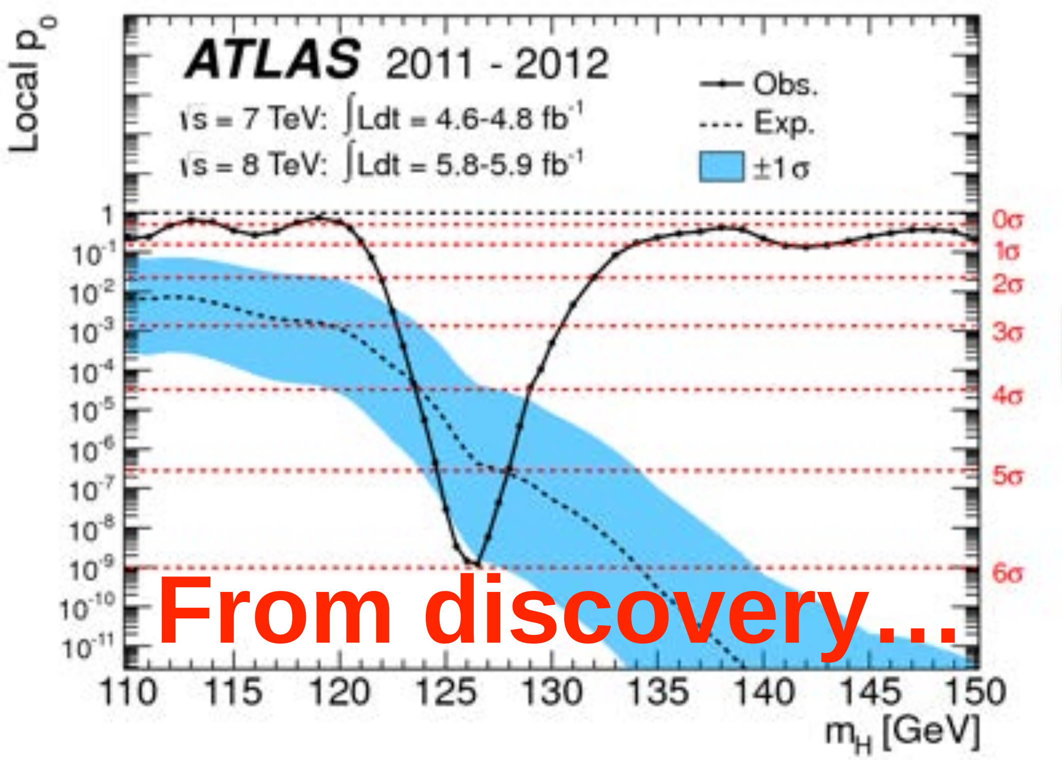
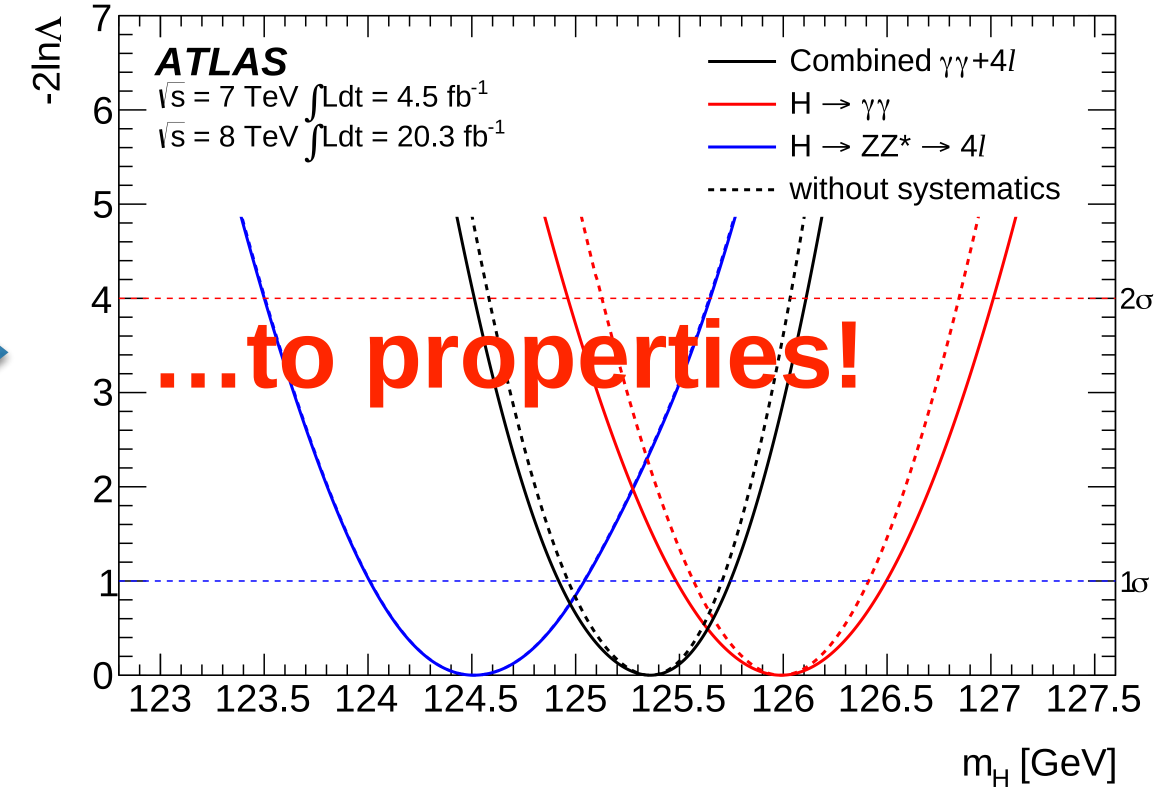
Run-I Higgs results and prospects for Run-II (HL-LHC)

Giacinto Piacquadio (SLAC)
on behalf of the **ATLAS** Collaboration

Rencontres de Moriond
17 March 2015

The Higgs sector today

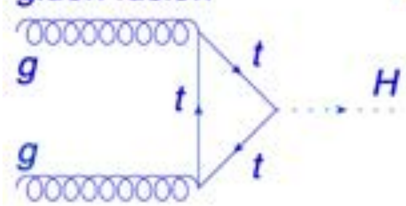
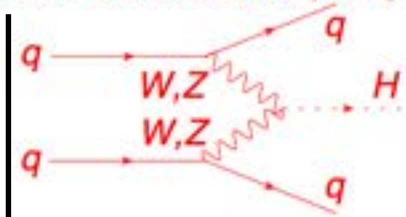
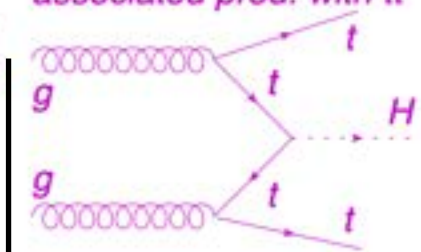
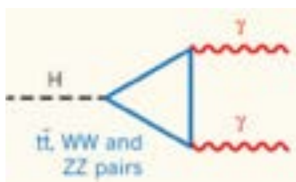
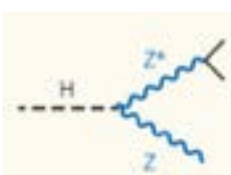
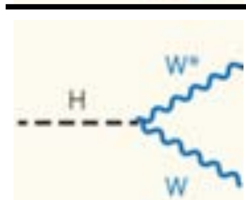
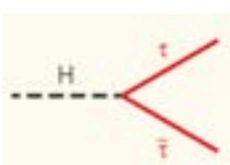
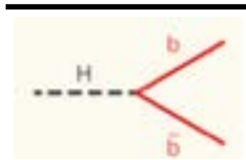




- Higgs boson discovery already “old news”
- Main focus measuring Higgs boson properties:
  - (**On/off-shell/invisible**) **couplings**
  - **Mass**, **Spin/CP** state
- Or look for **rare decays** or coupling to **exotic particles** (discussed **by Paolo Meridiani later today**)

- Finalized most of **Run-I** Higgs analyses!
  - Reduced experimental/theory **systematic uncertainties**
  - Increased sensitivity, especially to **sub-leading production modes**
  - Interpret possible deviations from SM within more general theory frameworks (e.g. **Effective field theory**)

What do we look for…

	gluon fusion 	vector boson fusion (VBF) 	associated prod. with W/Z 	associated prod. with tt 
	✓	✓	✓	✓
	✓	✓	✓	✓ NEW!
	✓	✓	✓ NEW!	✓ NEW!
	✓	✓	*planned*	✓ NEW!
		*in preparation*	✓	✓ NEW!

✓ Coupling analysis

Discussed by **Stephanie Majewski** in "top quark" session **on Wednesday**

+ mass measurement

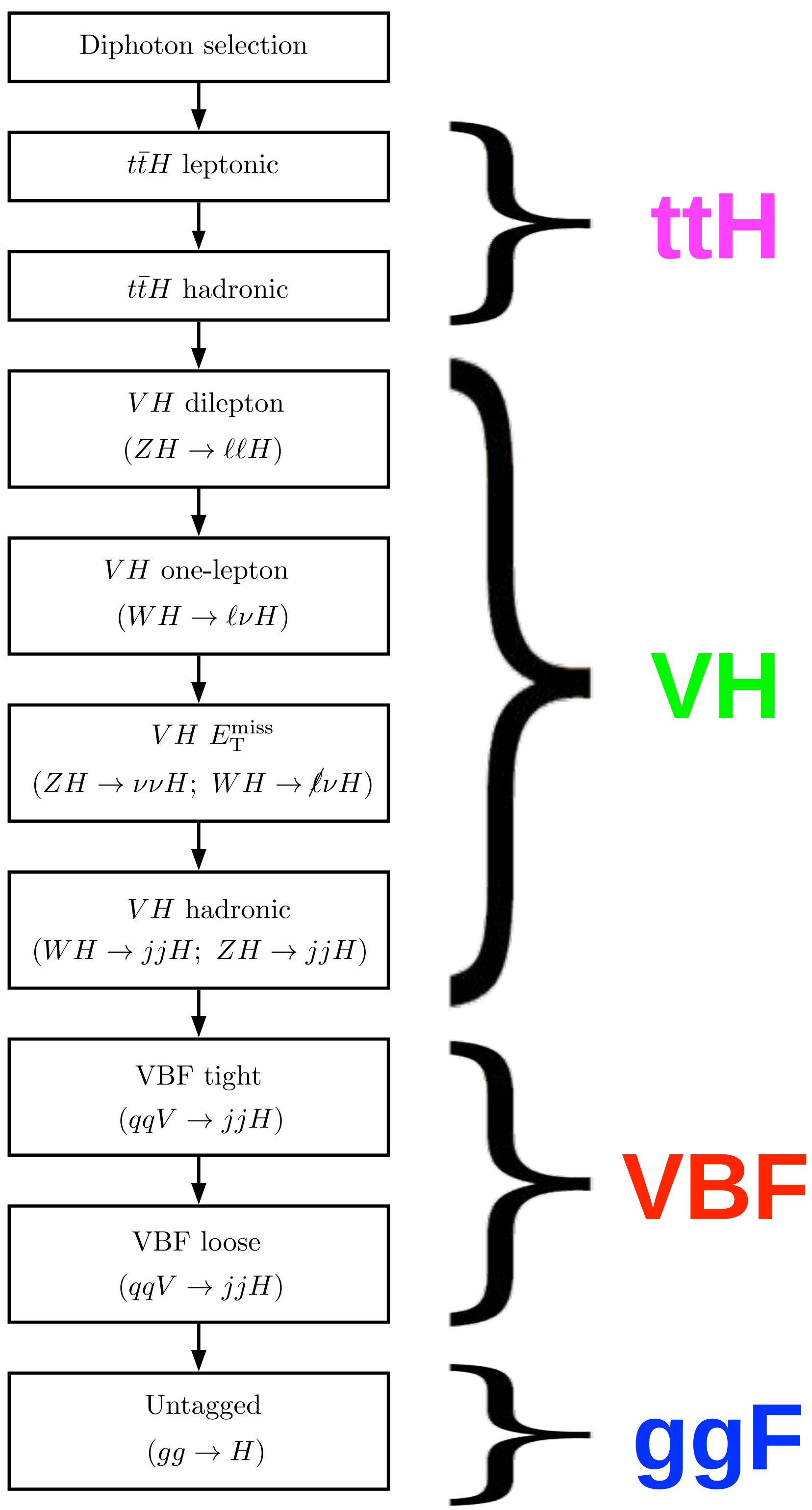
+ measurement of spin/CP NEW!

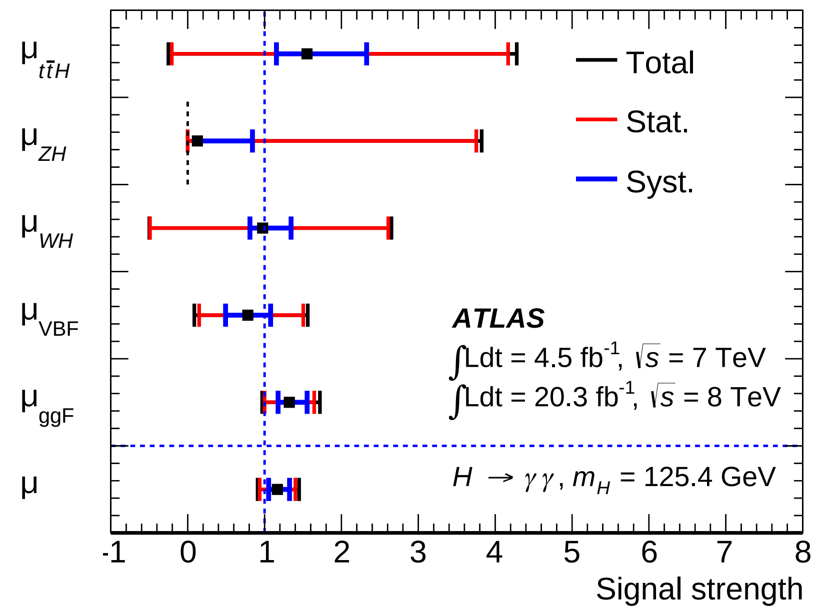
+ off-shell coupling analysis NEW!

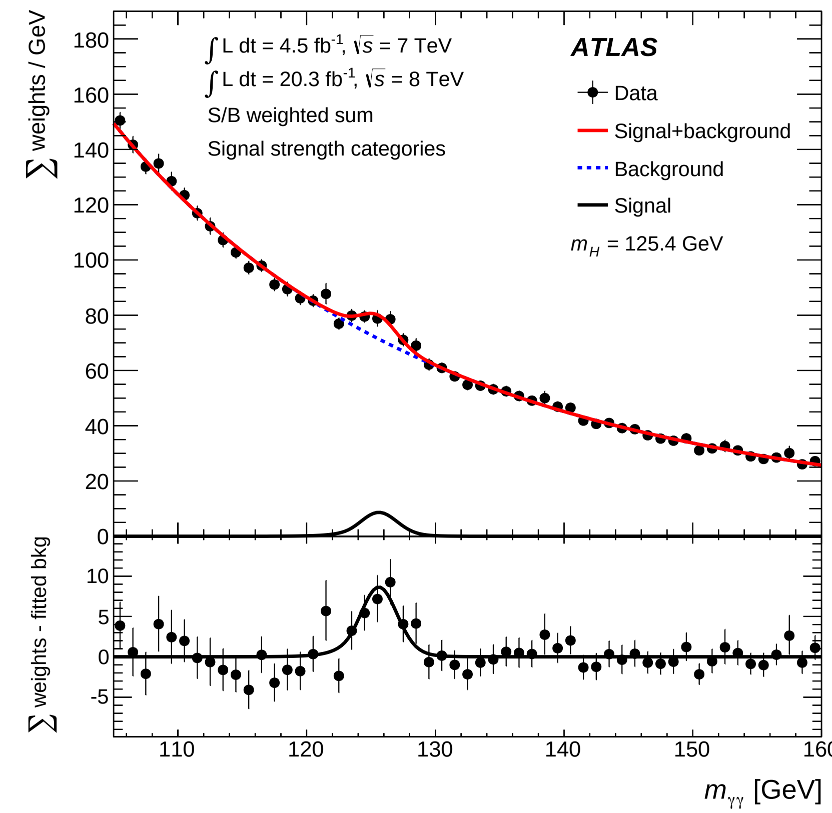
+ search for invisible decays NEW!

H to γγ

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







$$\mu = 1.17 \pm 0.27$$

Uncertainty group	$\sigma_\mu^{syst.}$
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

Theory uncertainties:
- QCD scale (ggF: ±7%)
- PDF (ggF: ±7%)
- BR(H to γγ) (±5%)
- Leading uncertainty despite NNLO+NNLL QCD computation

Energy resolution:
- Determined in Z to ee + MC extrapolation

H to 4ℓ

pT>20/15/10/6-7 GeV
50<m_{12}<106 GeV
12-50<m_{34}<115 GeV

$4l$ selection

↓

High mass two jets
VBF

VBF enriched
$\mathcal{P}(m_{4\ell}, \mathrm{BDT_{VBF}})$

↓

Low mass two jets
W(→ jj)H, Z(→ jj)H

↓

Additional lepton
W(→ $l\nu$)H, Z(→ ll)H

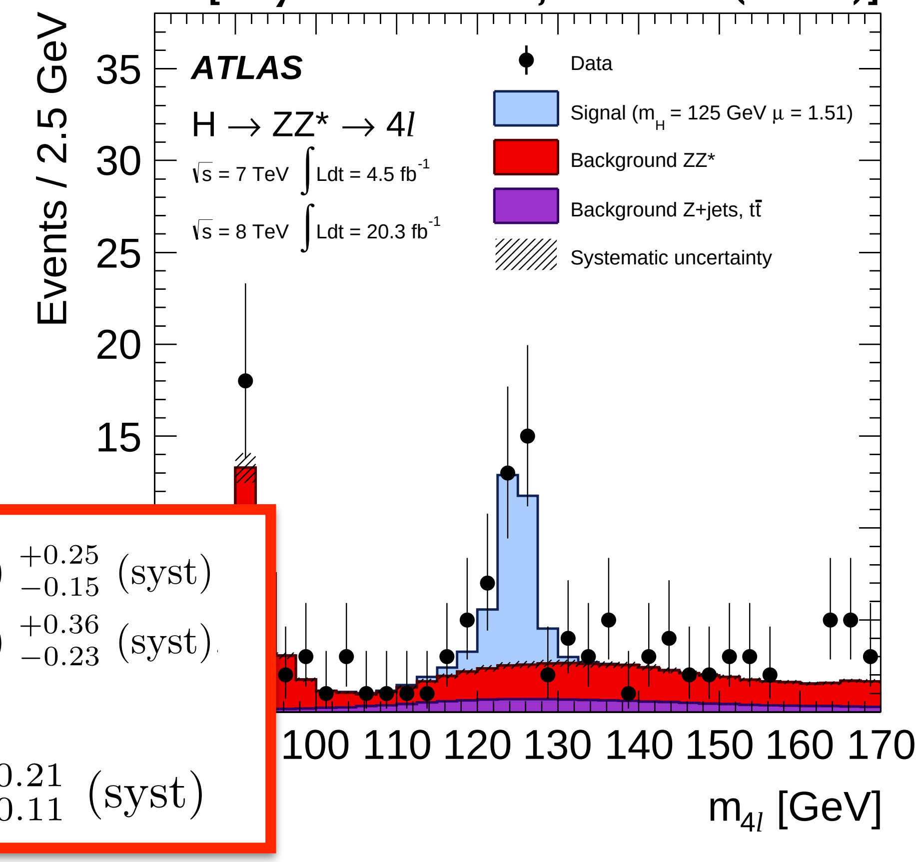
VH enriched
$\mathcal{P}(m_{4\ell})$

↓

ggF
ME against ZZ

ggF enriched
$\mathcal{P}(m_{4\ell}, O_{\mathrm{BDT}_{ZZ^*}} \mid m_H)$

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



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

Combined:

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

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%

- Theory uncertainty again dominant systematics
- Even higher for VBF (~20%), similar for VH (~10%)
- Jet energy scale systematics important for VBF and VH categories (~10%)

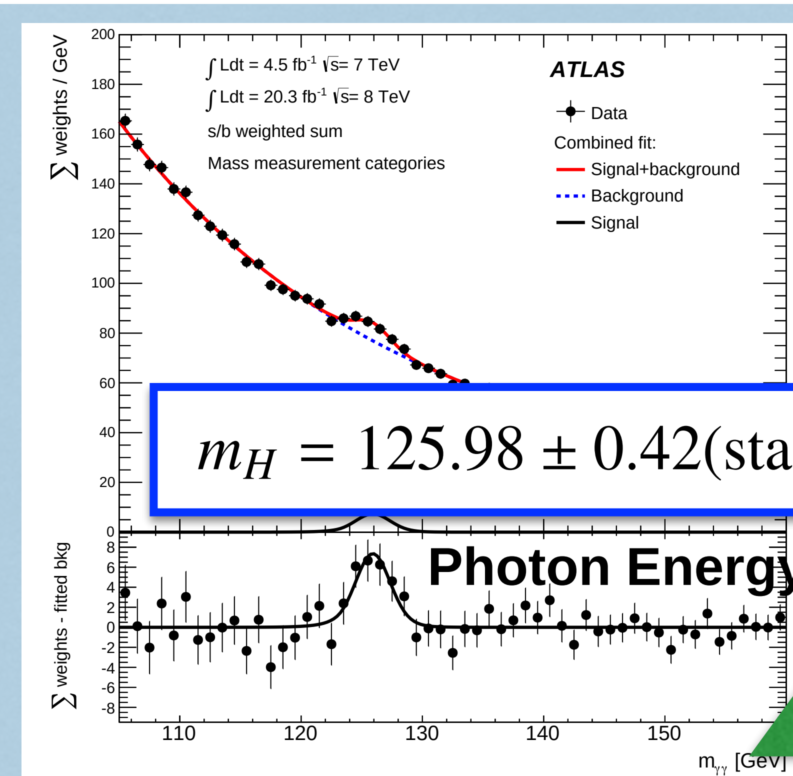
[Phys. Rev. D 90, 052004 (2014)]

Mass measurement

Optimized categorization

H → γγ

Category	$\sigma_{\rm eff}$ [GeV]	$s/\sqrt{b}$
Inclusive	1.67	3.50
Unconv. central low $p_{\rm Tt}$	1.35	1.88
Unconv. central high $p_{\rm Tt}$	1.21	1.26
Unconv. rest low $p_{\rm Tt}$	1.53	1.69
Unconv. rest high $p_{\rm Tt}$	1.36	0.96
Unconv. transition	1.86	0.78
Conv. central low $p_{\rm Tt}$	1.52	1.38
Conv. central high $p_{\rm Tt}$	1.35	0.88
Conv. rest low $p_{\rm Tt}$	1.88	1.56
Conv. rest high $p_{\rm Tt}$	1.64	0.89
Conv. transition	2.41	0.85



$$m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\ \text{GeV}$$

Photon Energy Scale σ: 0.2 ÷ 0.9%

~2σ comp.

combined mass:

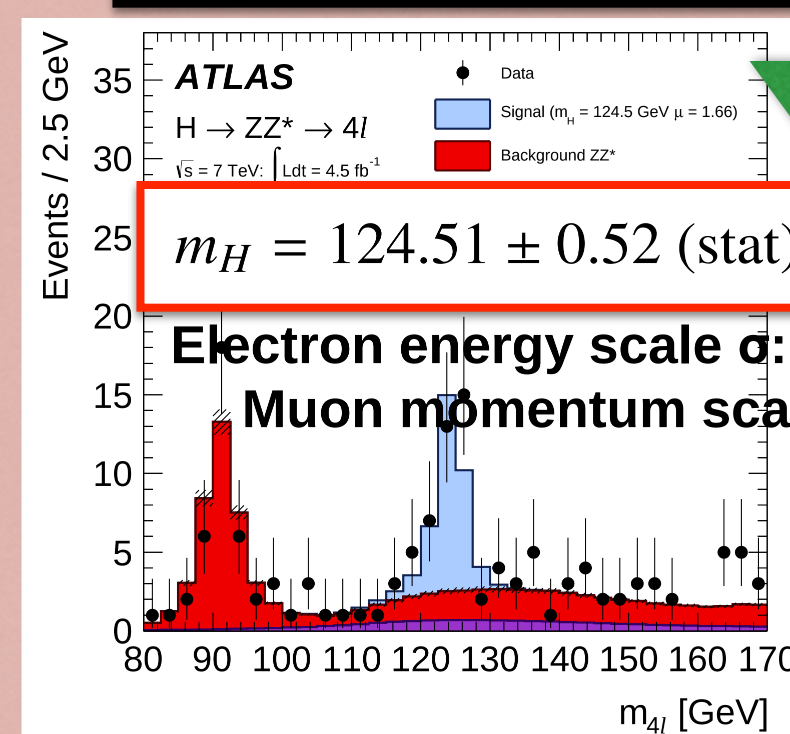
$$m_H = 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}$$

H → 4ℓ

- Similarly to coupling analysis, fit 2-dim PDF:

$$\boxed{\mathcal{P}_{\rm bkg}(m_{4\ell}, O_{BDT_{ZZ^*}})}$$

- Z mass constraint improves resolution by 15%



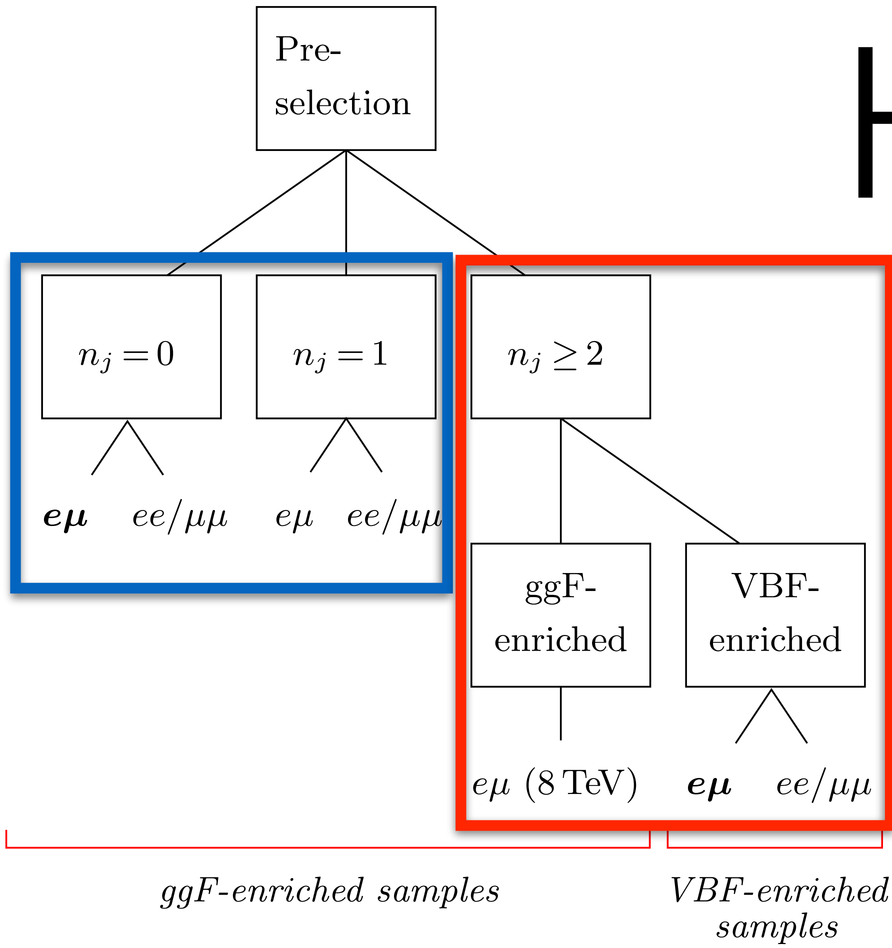
$$m_H = 124.51 \pm 0.52\ (\text{stat}) \pm 0.06\ (\text{syst})\ \ \text{GeV}$$

Electron energy scale σ: 0.03 ÷ 0.2% (40 GeV)

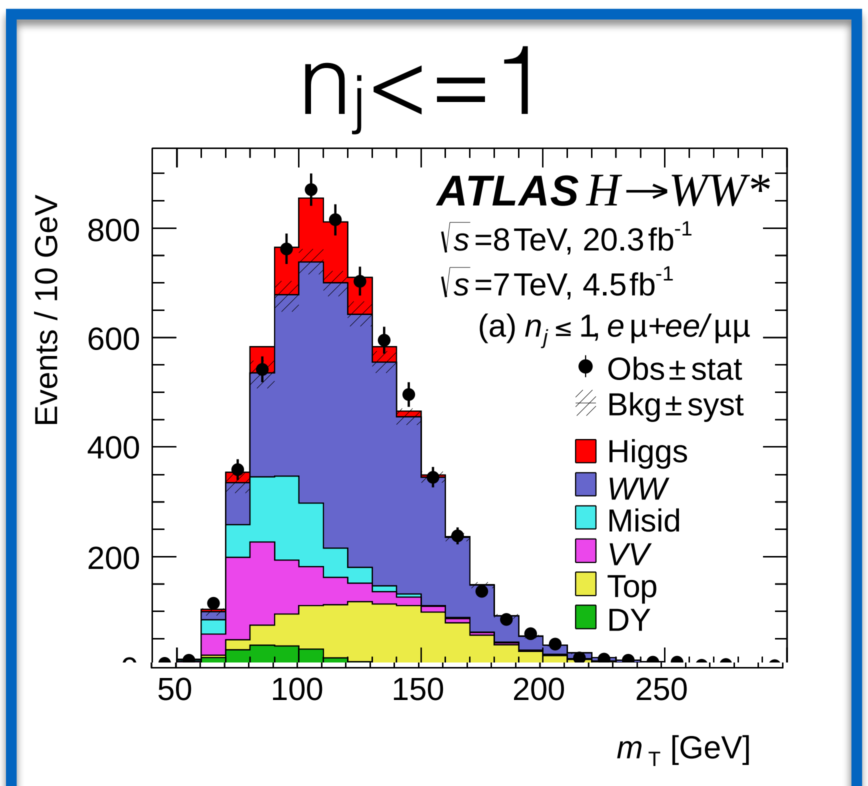
Muon momentum scale σ: 0.04% ÷ 0.2%

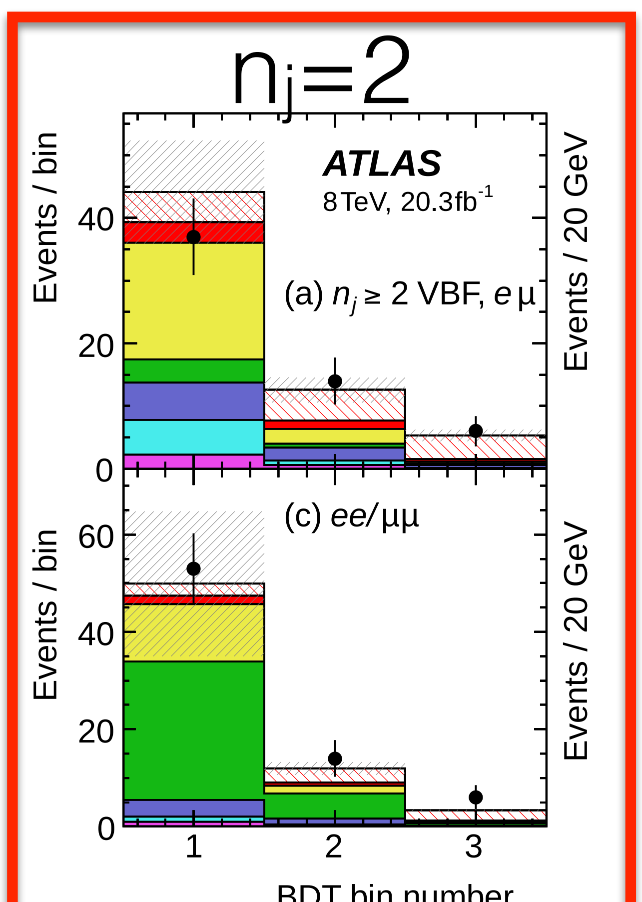
[arXiv:1412.2641]

H to WW (ggF/VBF)

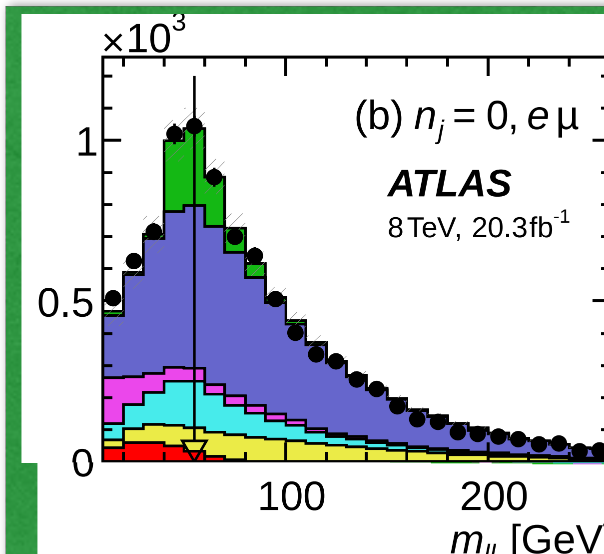


- Categories in **n. jets**, **Diff.Flav/SameFlav leptons**, **VFB/ggF** enriched, **pT of the sub-leading lepton** and **m(ll)**.
- Fit to **mT** **(BDT)** discriminant for **ggF** **(VBF)** mode
- One normalization factor per **control region (CR)**
  - Avoids risk of “overprofiling”.





e.g. WW CR



Revert m(ll) cut

In nj=0, choose [55,110] GeV

Minimize theory extrapolation!

Results

$$\mu_{\mathrm{ggF}} = 1.02 \pm 0.19 \; {}^{+0.22}_{-0.18} = 1.02 \; {}^{+0.29}_{-0.26}$$
$$\mu_{\mathrm{VBF}} = 1.27 \; {}^{+0.44}_{-0.40} \; {}^{+0.30}_{-0.21} = 1.27 \; {}^{+0.53}_{-0.45}$$
(stat.) (syst.)

Combined:

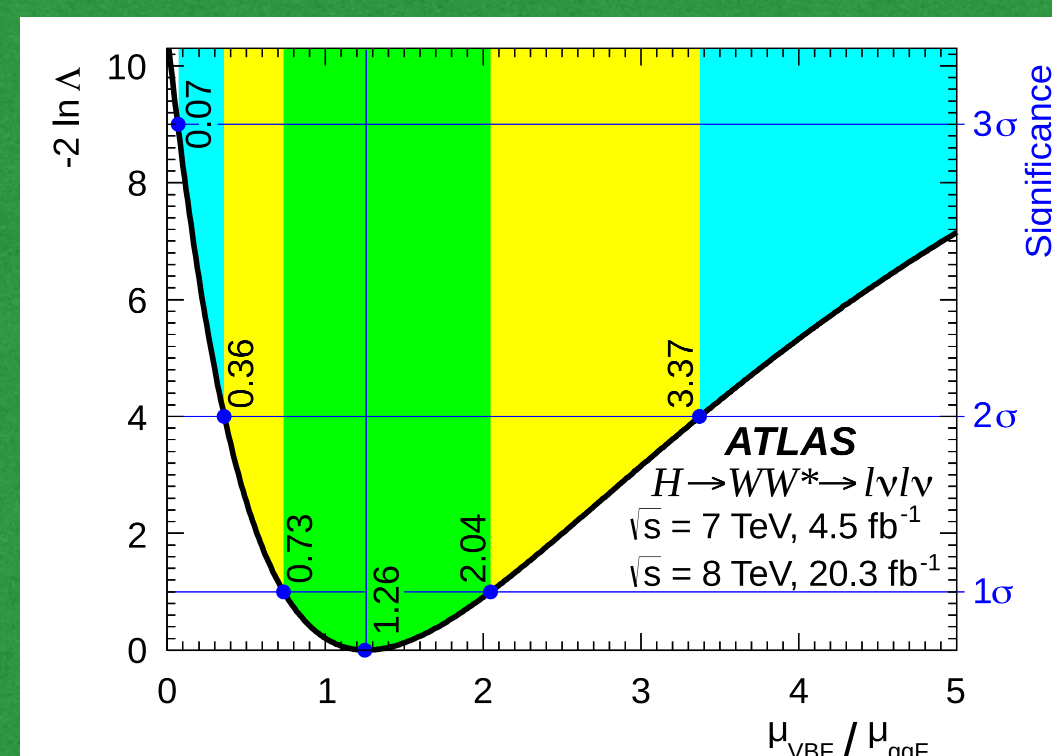
$$\mu = 1.09 \; {}^{+0.23}_{-0.21}$$

Source	Error + (Observed $\mu = 1.09$)	Error −	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^* \mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Background WW	0.06	0.06	
Experimental systematics	0.07	0.06	
Integrated luminosity	0.03	0.03	
Total	0.23	0.21	

- **Signal cross-section** dominant systematics, but **signal acceptance** (esp. VBF) and **WW background** extrapolation also important

- Leading experimental uncertainties **lepton efficiency** and **misid**. rate (and jet energy scale for VBF)

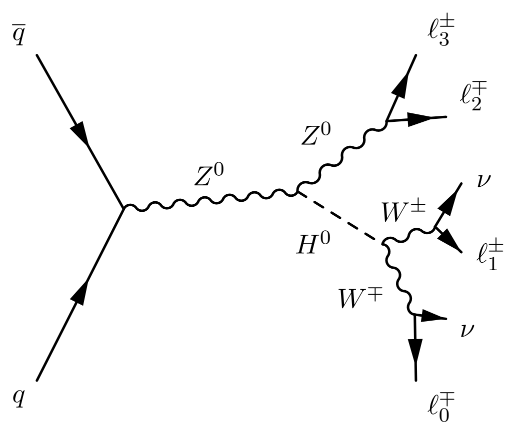
3σ evidence for VBF production (2.1 expected)



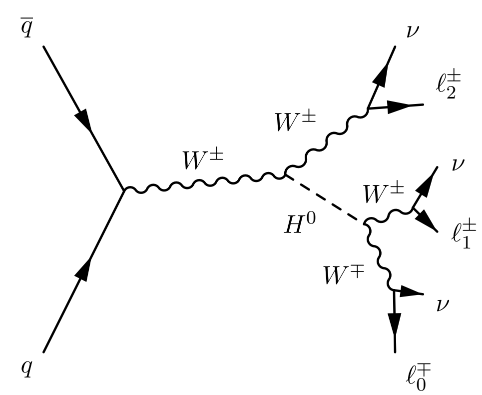
[ATLAS-CONF-2015-005]

VH to WW (multi-lepton)

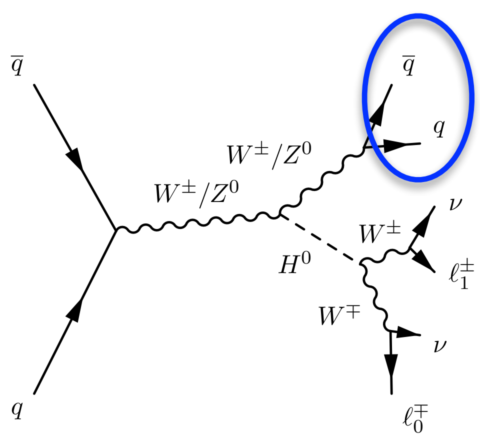
4 leptons



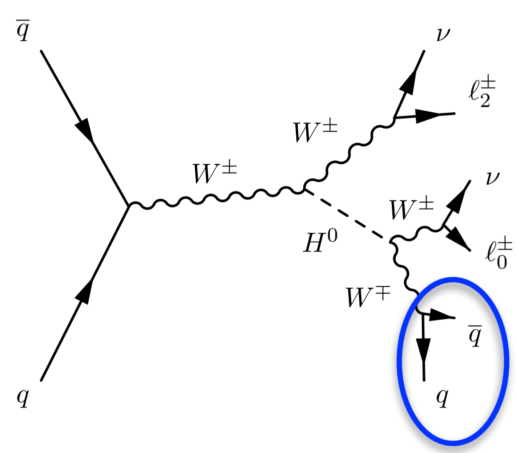
3 leptons



2 OS leptons



2 SS leptons



SS = same sign, OS = opposite sign

- Categories depending on number of leptons and jets
  - Sub-categories depending on number of same flavor opposite sign leptons
- **VV**, **VVV** (V=W,Z,γ) are the main backgrounds, in add. **top** and **Z/W +jets** in the 2 lepton channels
- **Results:**

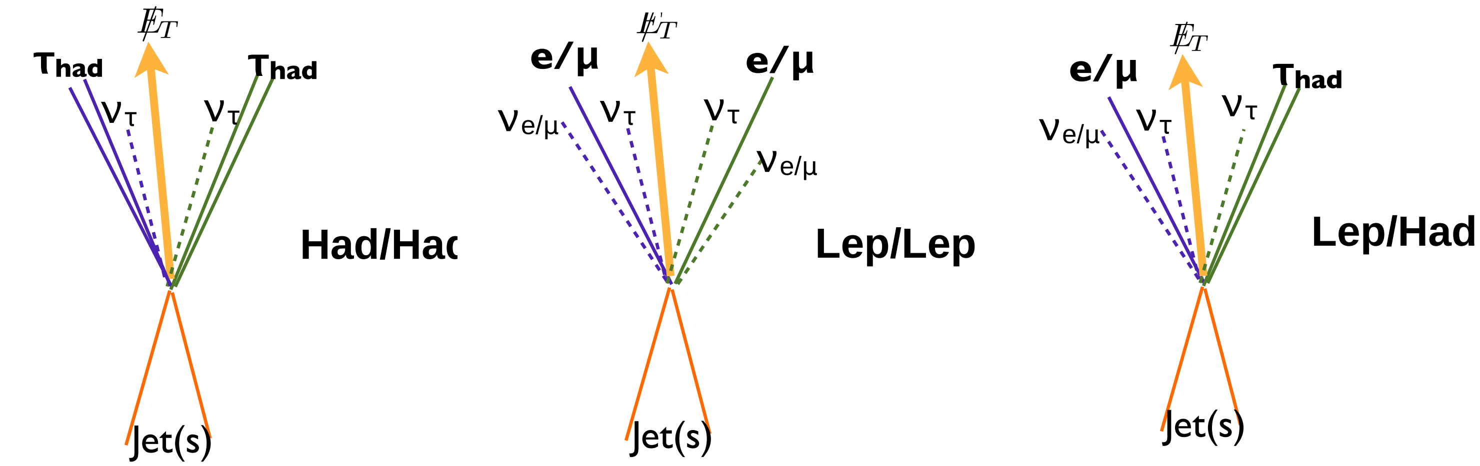
$$\mu^{\mathrm{WW}}_{\mathrm{WH}} = 2.1^{+1.5}_{-1.3}\,(\mathrm{stat.})^{+1.0}_{-0.9}\,(\mathrm{sys.}),\ \ \mu^{\mathrm{WW}}_{\mathrm{ZH}} = 4.9^{+3.7}_{-2.9}\,(\mathrm{stat.})^{+1.7}_{-1.0}\,(\mathrm{sys.})$$

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

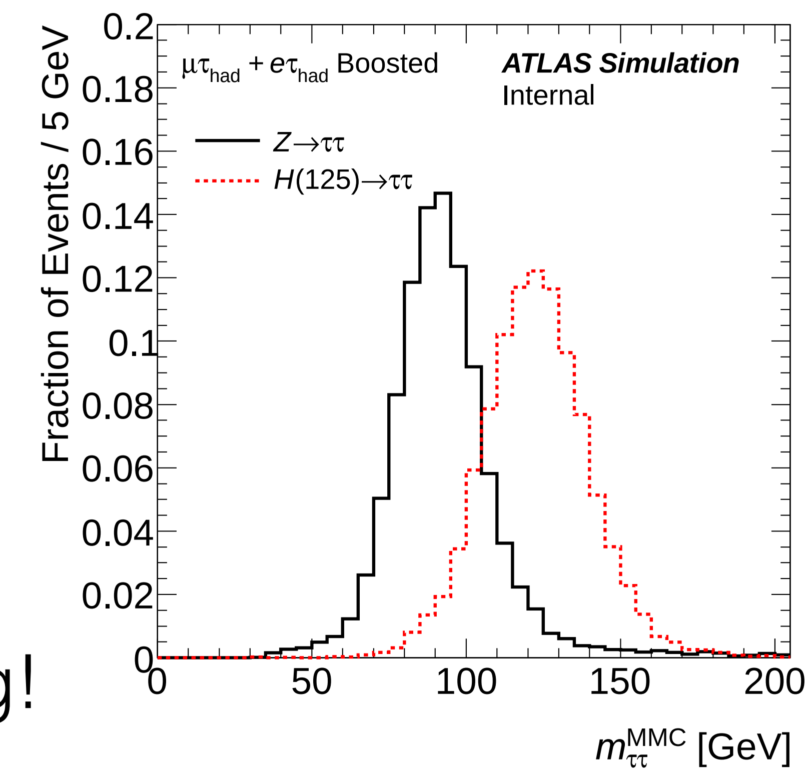
- Combined with the ggF and VBF channels, helps constraining the fermionic coupling.

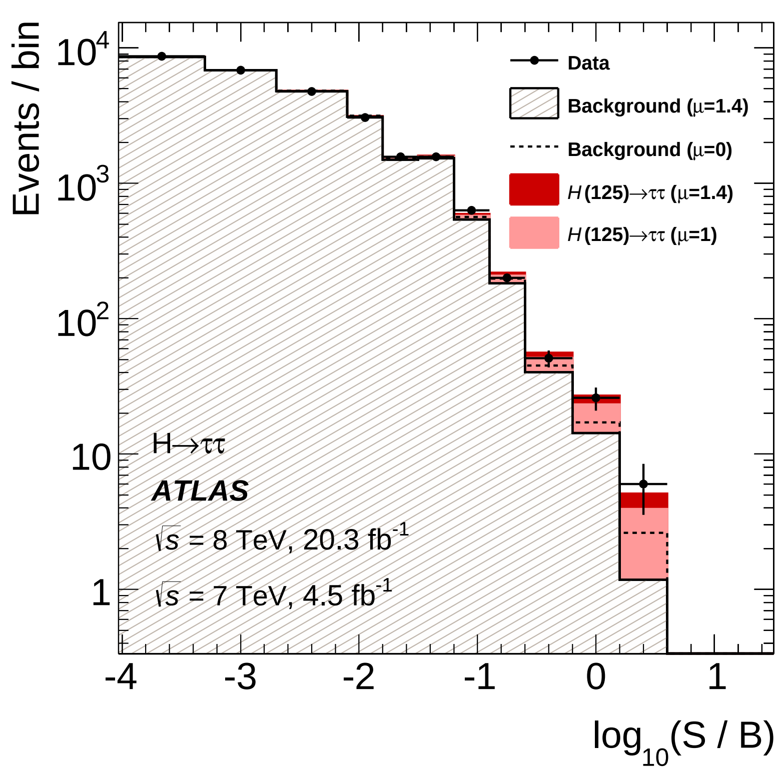
[arXiv:1501.04943]

H to ττ



- Direct probe of **fermionic couplings** (as H to bb)
- **Three** channels, **two** main categories:
  - **VBF, Boosted** (~ggF with pT(H)>100 GeV)
- **BDT** with main discriminant: **m(ττ) mass**





- **4.5σ** evidence for tau Yukawa coupling! (3.4σ expected)

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR ($H \to \tau\tau$)	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$

- Jet energy scale: especially forward/ central eta inter-calibration

- Background normalization (esp. Z to ττ and top)

$$\mu^{\tau\tau}_{ggF} = 2.0 \ \pm 0.8(\text{stat.}) \ ^{+1.2}_{-0.8}(\text{syst.}) \ \pm 0.3(\text{theory syst.})$$

$$\mu^{\tau\tau}_{\text{VBF}+VH} = 1.24 \ ^{+0.49}_{-0.45}(\text{stat.}) \ ^{+0.31}_{-0.29}(\text{syst.}) \ \pm 0.08(\text{theory syst.})$$

Combined:

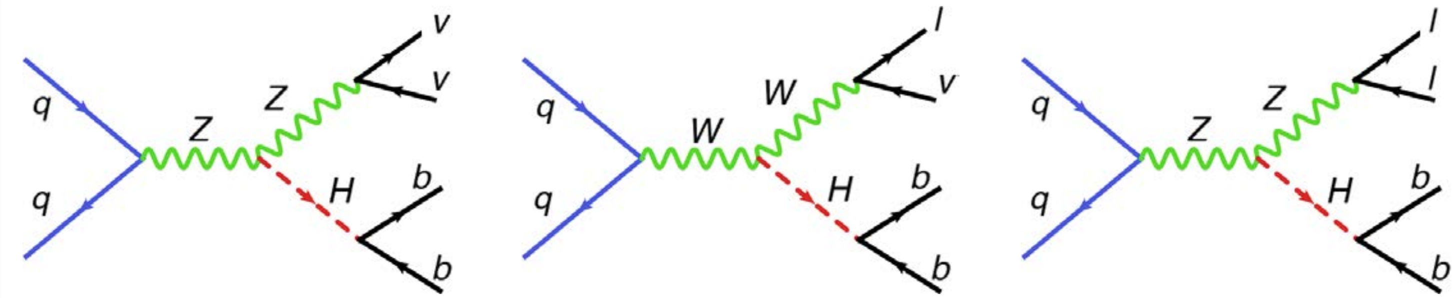
Alex Tuna's talk in YSF

[JHEP 01(2015) 069]

VH to Vbb

- BR(H to bb) ~60%: *leading contribution* to Higgs width

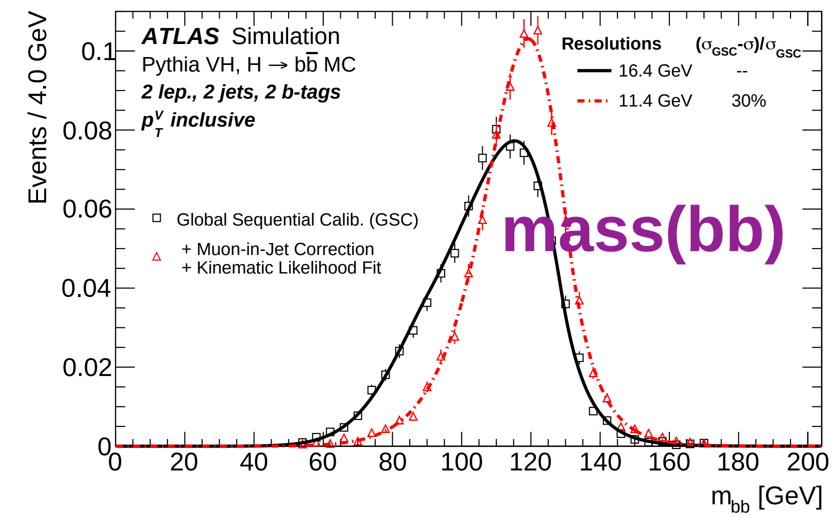
Three channels

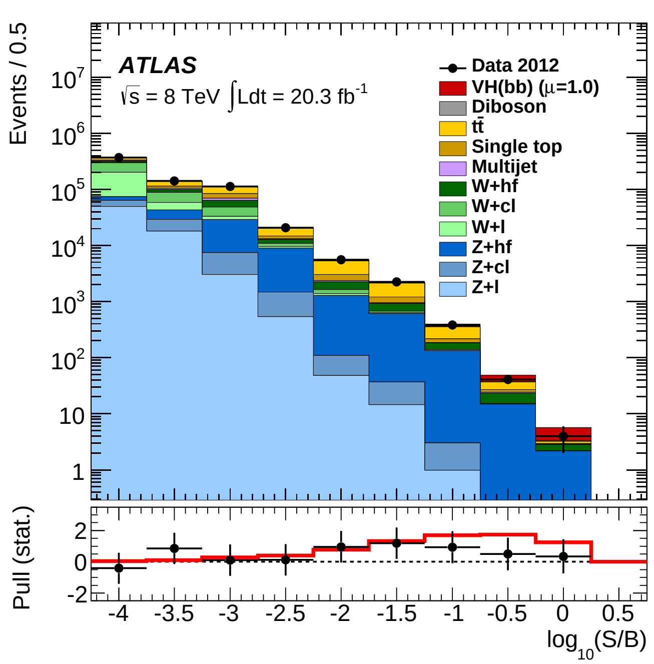


0-lepton **1-lepton** **2-lepton**

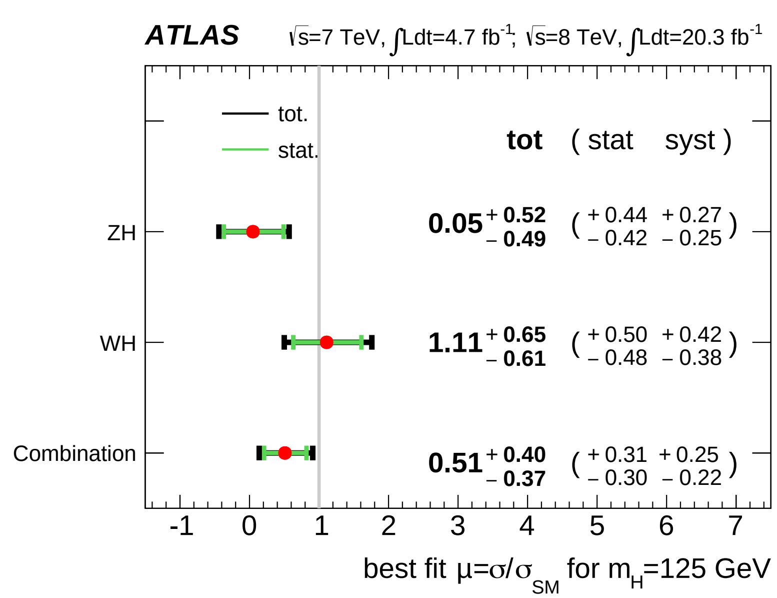
- **Categorization**
  - **Two** pT(W/Z) regions (<120, >120 GeV)
  - **Four** b-tag regions (1-tag + **3 x** 2-tag)
  - **Two** jet bins (2 and 3 jets)
- Use b-tagging discriminant (**MV1c**)

- Fit variables:
  - **1-tag**: MV1c
  - **2-tag**: BDT (esp. **mass(bb), pT(V), MV1c)**





- **1.4σ** excess (**2.5σ** exp.), excluded **1.2xSM**



Experimental uncertainties		
Jets		0.08
E_T^{miss}		0.03
Leptons		0.01
b-tagging$^{(*)}$	b-jets	0.07
	c-jets	0.04
	light jets	0.04
Luminosity		0.03
Theoretical and modelling uncertainties		
Signal		0.07
Floating normalisations	W+jets	0.06
	Z-jets	0.03
	$t\bar{t}$	0.04
Background modelling	W+jets	0.11
	Z-jets	0.08
	$t\bar{t}$	0.05
Single-top		0.04
Diboson		0.02
Multijet		0.06

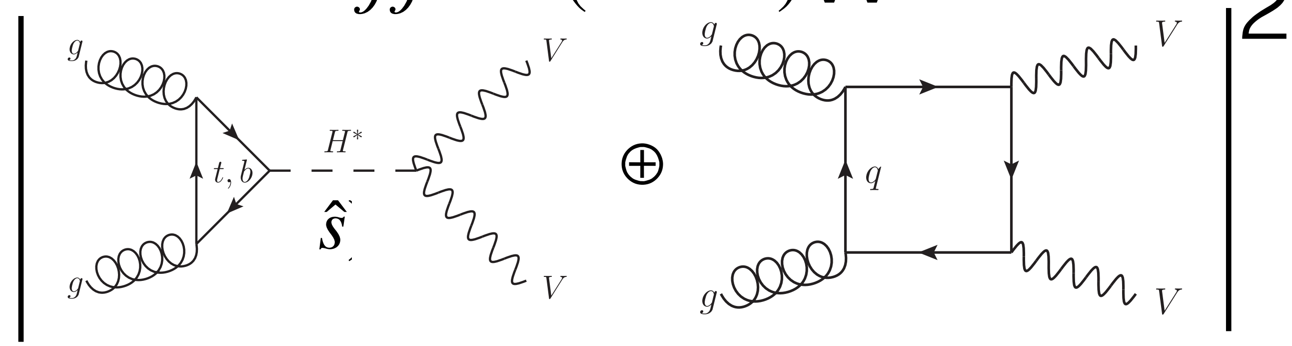
- Jet energy scale and b-tagging

- Theory modeling of backgrounds dominant (esp. W+bb, W+bl)

[arXiv:1503.01060]

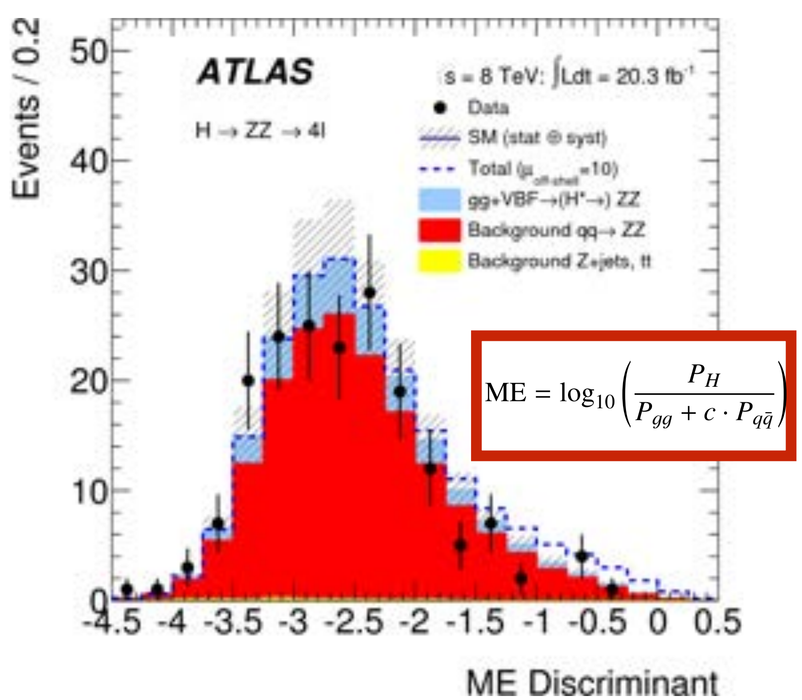
Off-shell coupling analysis

$$\left| gg \to (H^* \to) VV \right|^2$$



- Measure the Higgs boson signal strength for m(ZZ/WW) >> 2 $m_{Z/W}$
    - Can look for coupling deviation from SM at high energies $\hat{s}$!
- **Three channels** considered:

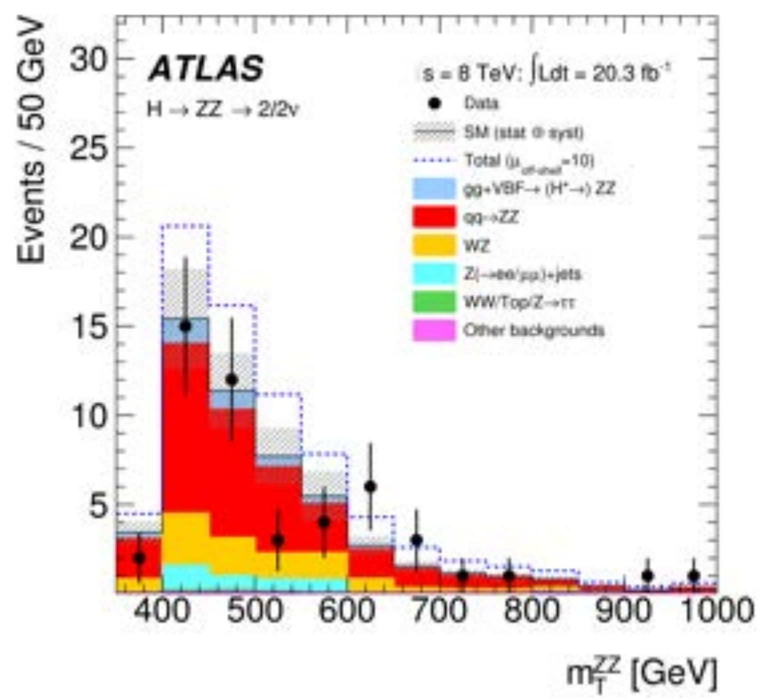
$ZZ \to 4\ell$



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

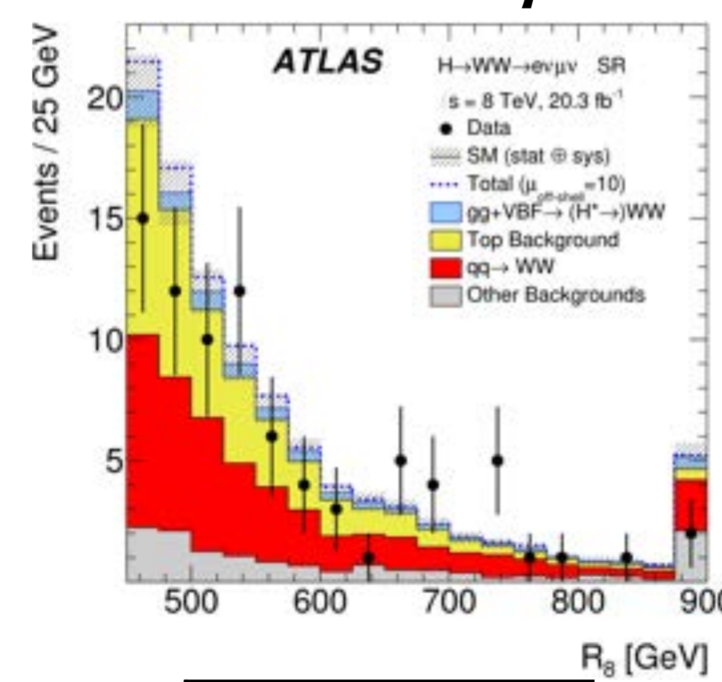
220 GeV $< m_{4\ell} <$ 1000 GeV

$ZZ \to 2\ell\, 2\nu$



380 GeV $< m_{\mathrm{T}}^{ZZ} <$ 1000 GeV

$WW \to e\nu\, \mu\nu$



$$R_8 = \sqrt{m_{\ell\ell}^2 + \left(0.8 m_{\mathrm{T}}^{WW}\right)^2} > 450 \text{ GeV}$$

- pT(VV) distribution for signal only known to ~LO
    - Reduce pT(VV) dependence: ME method (no BDT), no jet binning, R_8 variable

Results

[arXiv:1503.01060]

NEW!

Off-shell signal strengh ($\mu_{\text{off-shell}}$)

1. Assume SM ratio of gg to H* w.r.t. VBF signal strength ($\mu^{gg\to H^*}_{\text{off-shell}}/\mu^{VBF}_{\text{off-shell}}=1$), measure common $\mu_{\text{off-shell}}$

2. Assume SM off-shell VBF cross section, measure $\mu^{gg\to H^*\to VV}_{\text{off-shell}}$

95% CL upper limits

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

- Measure as a function of unknown K-factor ratio $R^B_{H^*} = \frac{K(gg\to VV)}{K(gg\to H^*\to VV)}$
- Systematics worsens limits by 30%
  - Interference term, scale variations on signal K factor, PDF/scale variations of qq to VV

Combine with on-shell analysis

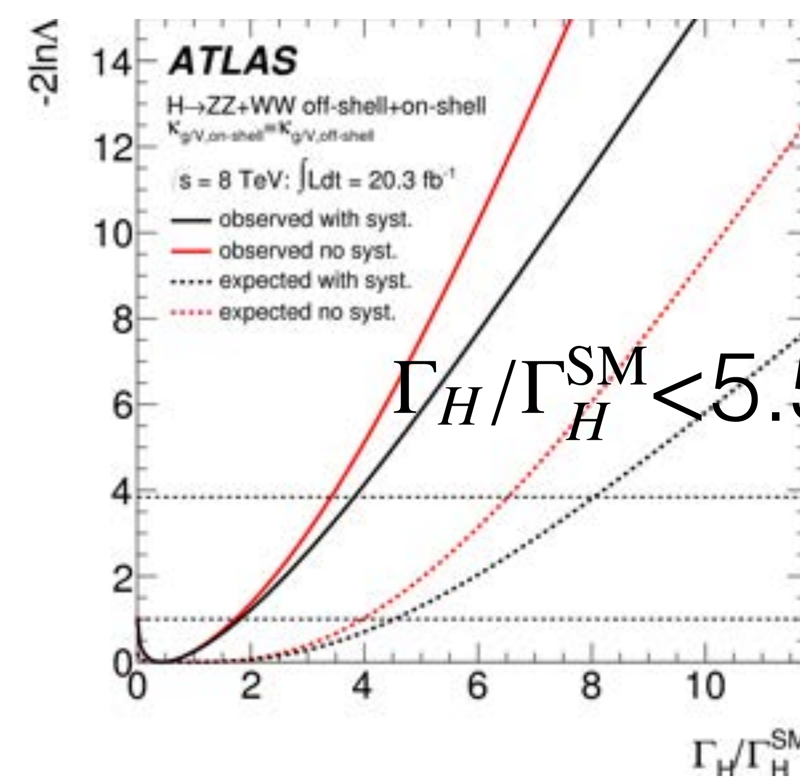
$$\mu_{\text{off-shell}}(\hat{s}) \equiv \kappa^2_{g,\text{off-shell}}(\hat{s})\cdot\kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}}\cdot\kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma^{SM}_H}$$

3. ~Assume $\kappa_{g,\text{on-shell}}\cdot\kappa_{V,\text{on-shell}} \le \kappa_{g,\text{off-shell}}\cdot\kappa_{V,\text{off-shell}}$ and determine upper limit on Γ_H/Γ^{SM}_H

4. Assume $\kappa_V = \kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$. Determine $R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$.

3.



$R^B_{H^*}=1$

$\Gamma_H/\Gamma^{SM}_H<$5.5 (8.0 exp)

4. $R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}<$6.0 (9.0 exp)

Higgs to invisible

(e.g. the Higgs boson might decay into dark matter particles)

VBF

NEW!

- 2 jets from VBF signature + high missing E_T (>150 GeV)

Process	Yield ± Stat ± Syst
ggH Signal	20 ± 5.5 ± 9.7
VBF Signal	286 ± 5 ± 49
$Z \to \nu\nu$+jets	339 ± 22 ± $\boxed{13}$
$W \to \ell\nu$+jets	237 ± 17 ± $\boxed{18}$
Multijet	1.9 ± 2.4
Other Backgrounds	0.4 ± 0.2 ± 0.3
Total Background	578 ± 38 ± 30
Data	539

- Dedicated $Z\to ll$ and $W\to l\nu$ control regions (CRs), emulating missing E_T

- Simultaneous fit to yields in signal and Z+jets and W+jets control regions.

$\mathrm{BR}(H \to \text{invisible}) < 29\%$ @ 95 CL (35% exp)

VH

- Two signatures:
  - ZH to $\ell\ell$ + invisible

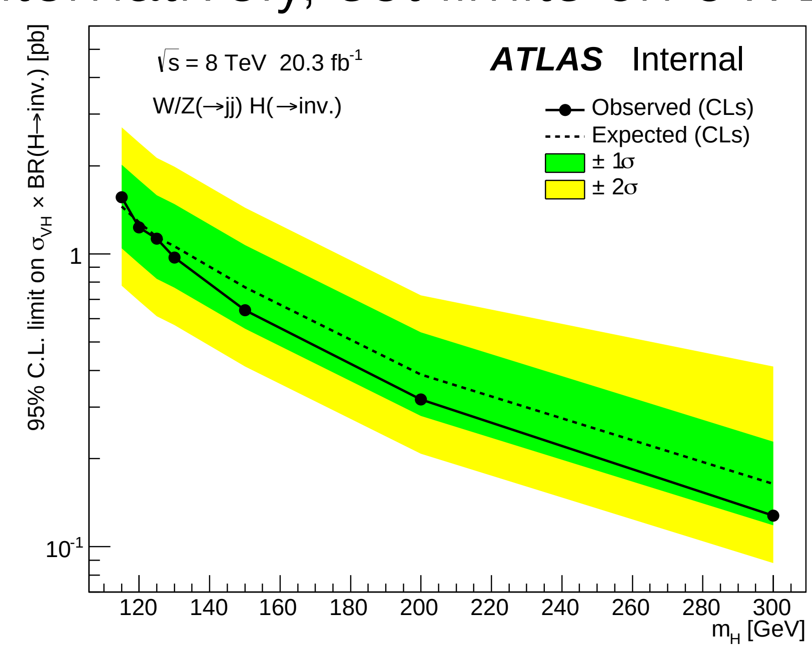
$\mathrm{BR}(H \to \text{invisible}) < 75\%$ @ 95 CL (62% exp)

NEW!

  - W/ZH to jj + invisible
    - Includes ggF contamination

$\mathrm{BR}(H \to \text{invisible}) < 78\%$ @ 95 CL (86% exp)

- Alternatively, set limits on σ x BR:



[ATLAS-CONF-2015-004]

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

[ATLAS-CONF-2015-008]

Spin/CP: testing spin-2 EFT

NEW!

Graviton-like

energy momentum tensor

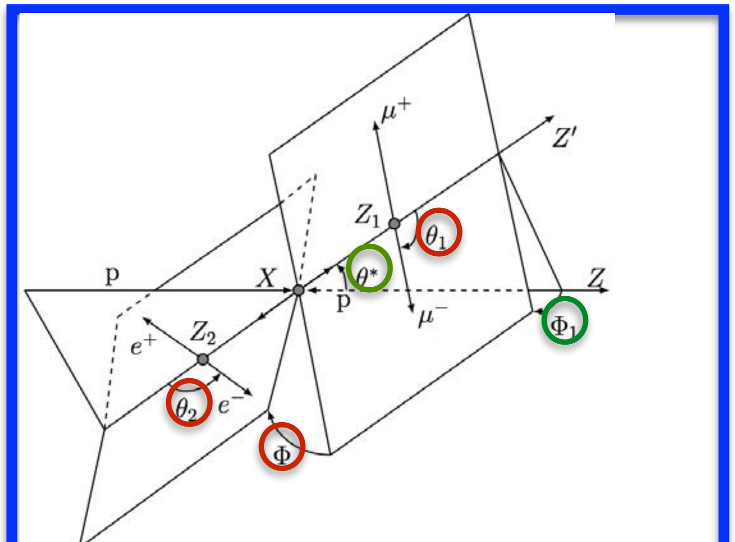
$$\mathcal{L}_2^p = \sum_{p=V,f} -\frac{1}{\Lambda}\kappa_p T^p_{\mu\nu} X_2^{\mu\nu}$$

particle field

variable couplings (κ_g, κ_q)

cutoff at pT(H)=125/300 GeV

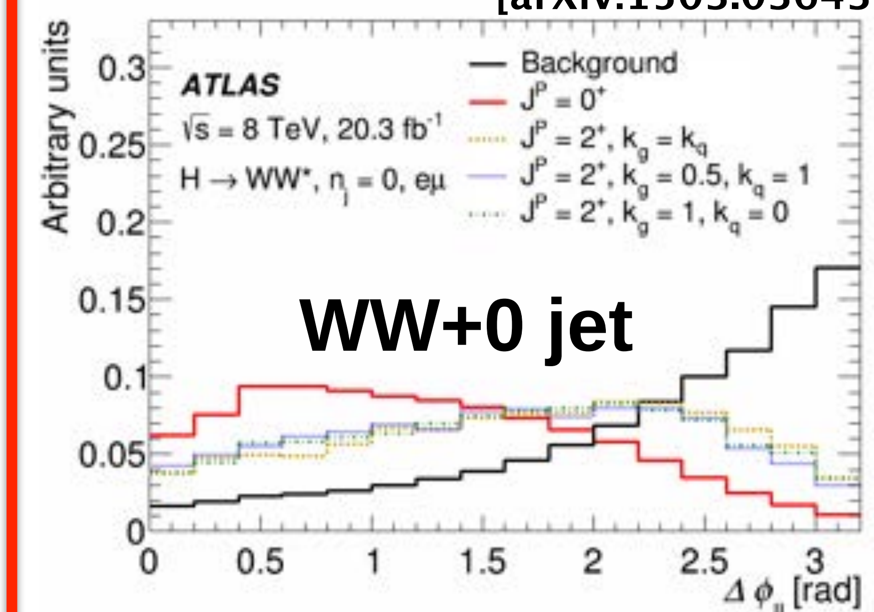
H to ZZ* to 4ℓ

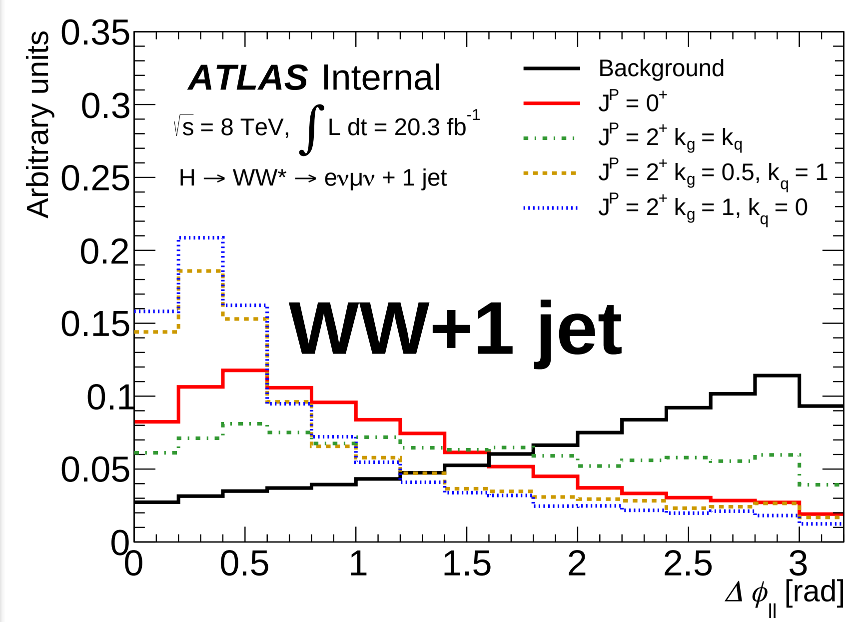


PDF(MELA,BDT_{ZZ}**)**

H to WW to ℓνℓν

[arXiv:1503.03643]





WW+1 jet sensitive to pT(H)

Spin2 vs bkg

PDF($\boxed{BDT_0}$,$\boxed{BDT_2}$)

SM vs bkg

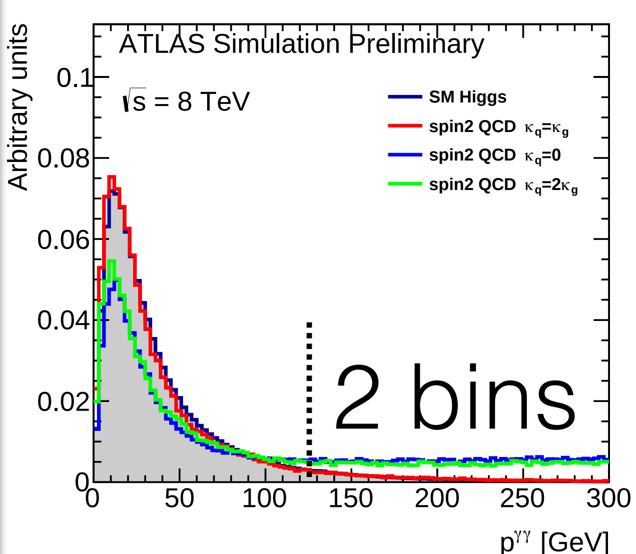
- Strongest exclusions of alternative spin-2 hypotheses (**CLs~0.01-1%**) from H to 4ℓ

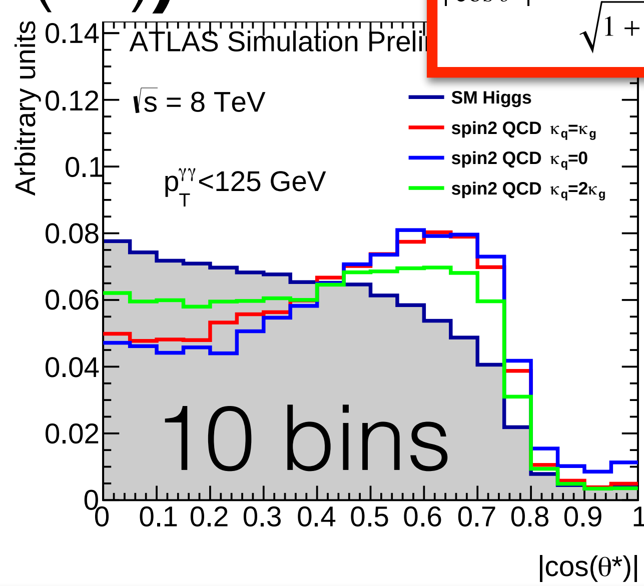
H to γγ

Combination → see Michael's talk

- **PDF(**mγγ,pTγγ,cos(θ*)**)**

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\frac{2p_T^{\gamma1}p_T^{\gamma2}}{m_{\gamma\gamma}^2}$$





[ATLAS-CONF-2015-008] NEW!

Spin/CP: parity / CP mixing

Spin-0 with CP mixing

coupling to SM-Higgs

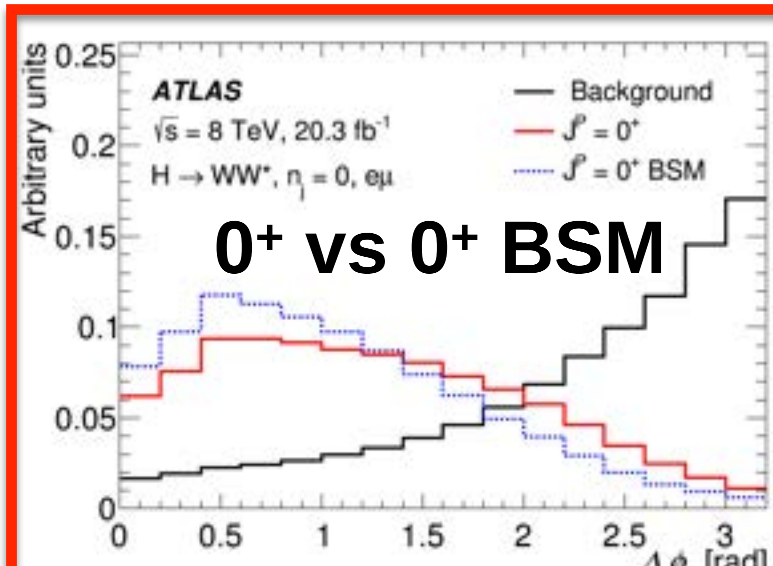
$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM}\left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_{+\mu} W^{-\mu}\right] - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right] - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha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

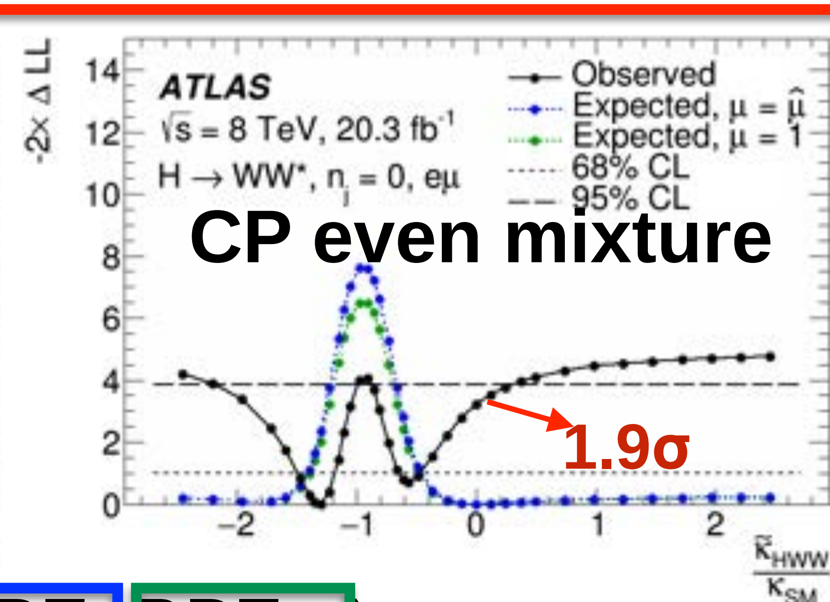
coupling to CP-even BSM-Higgs

coupling to CP-odd BSM-Higgs

H to WW to $\ell\nu\ell\nu$

Combination → see Michael's talk





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PDF($\boxed{BDT_0}$,$\boxed{BDT_{CP}}$)

SM vs bkg

SM vs CP alternative

[arXiv:1503.03643]

H to ZZ* to 4ℓ

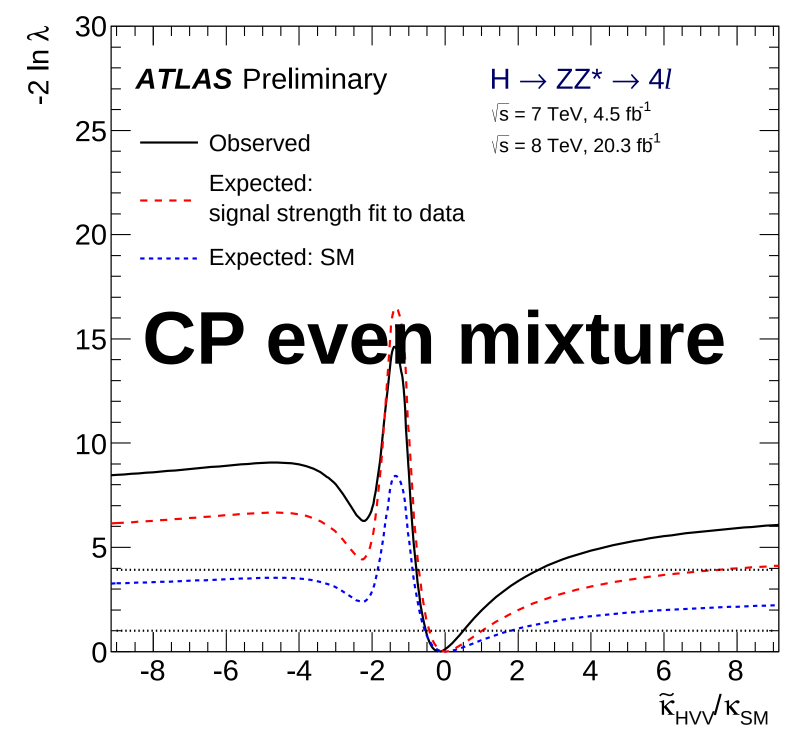
- Define new observables:

$$O_1(\kappa_{HVV}) \sim \frac{2R(ME(\kappa_{HVV})^*, ME(SM))}{|ME(\kappa_{HVV})|^2}$$

$$O_2(\kappa_{HVV}) \sim \frac{|ME(SM))|^2}{|ME(\kappa_{HVV})|^2}$$

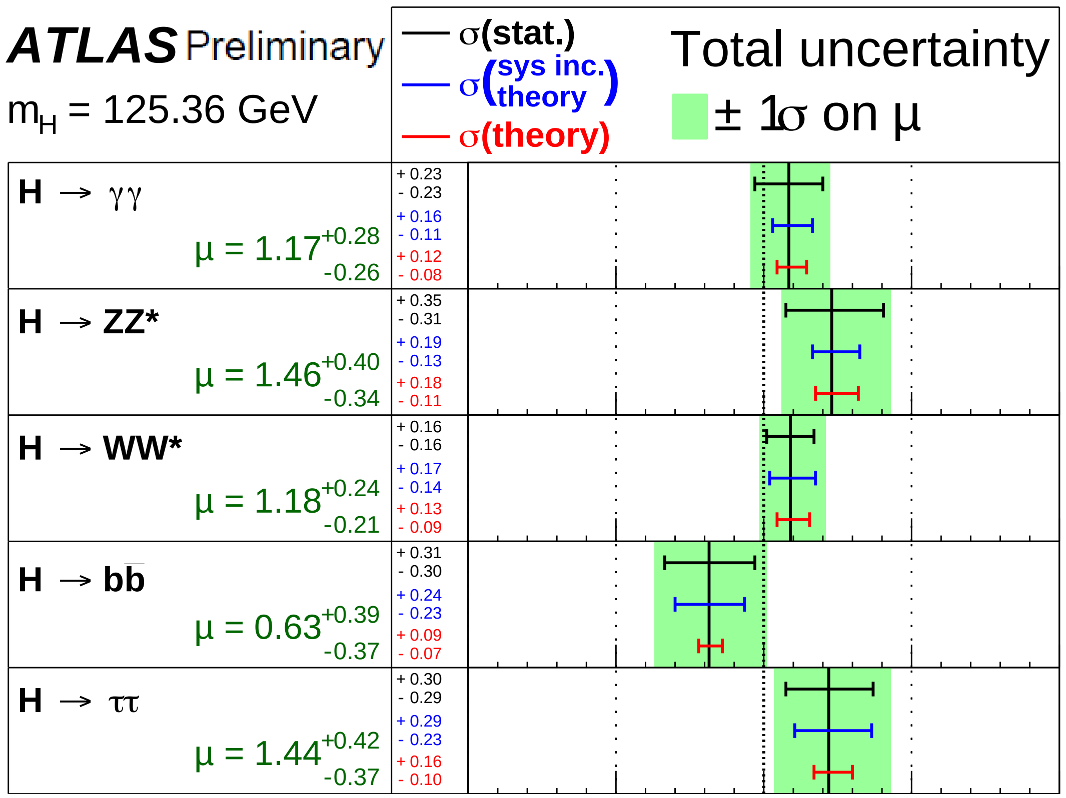
and similarly for κ_{AVV} tan(α)

- Perform CP mixing scan fitting O_1,O_2 and BDT_{ZZ}



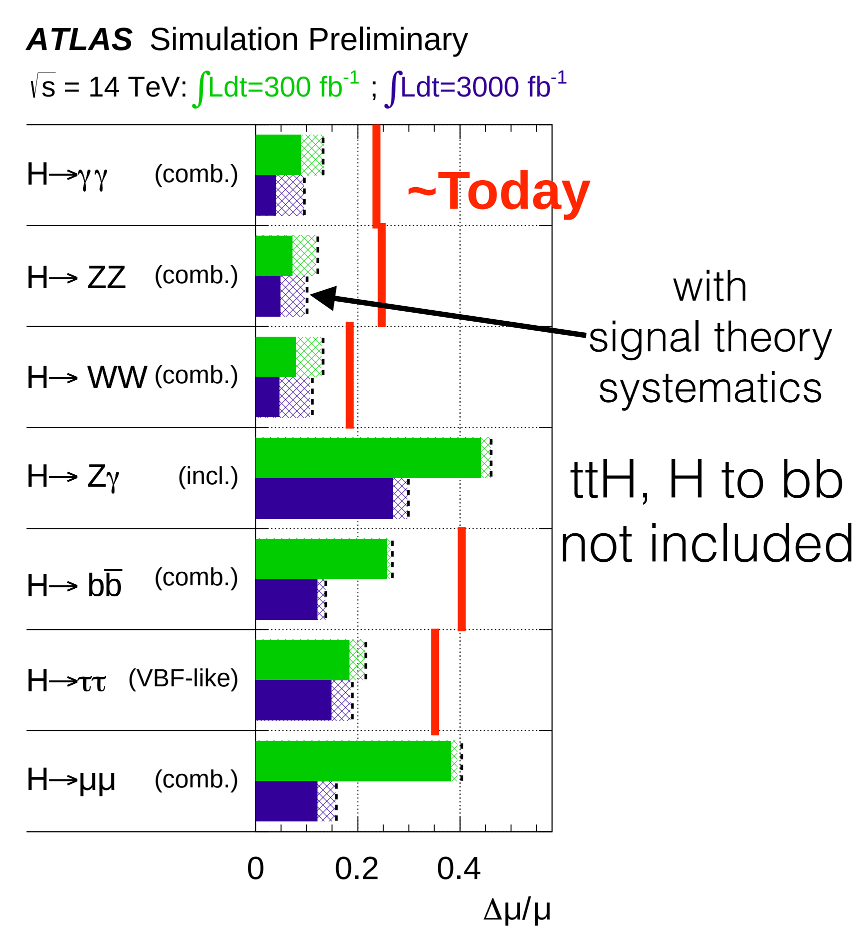
Conclusions

[ATLAS-CONF-2015-007]



- Final Run-I Higgs analyses!
  - Improved sensitivity, especially to different production modes
  - No significant deviations from SM so far.
- Signal strength in all **production** and **decay** modes input to coupling fits (→ **Michael's talk later today!**)

[ATL-PHYS-PUB-2014-016]



- **Important lessons for Run-II and beyond**
  - Despite huge progress, in many cases systematics (esp. theory) dominant
    - Theory uncertainty on cross section + acceptance of Higgs signal
    - Background modeling (e.g. **V+bb**, **tt+bb** for **H to bb**)
  - Need improved experimental and theory techniques to fully profit from improved statistical sensitivity.