Newly discovered Higgs-like boson with the ATLAS detector : production modes and couplings

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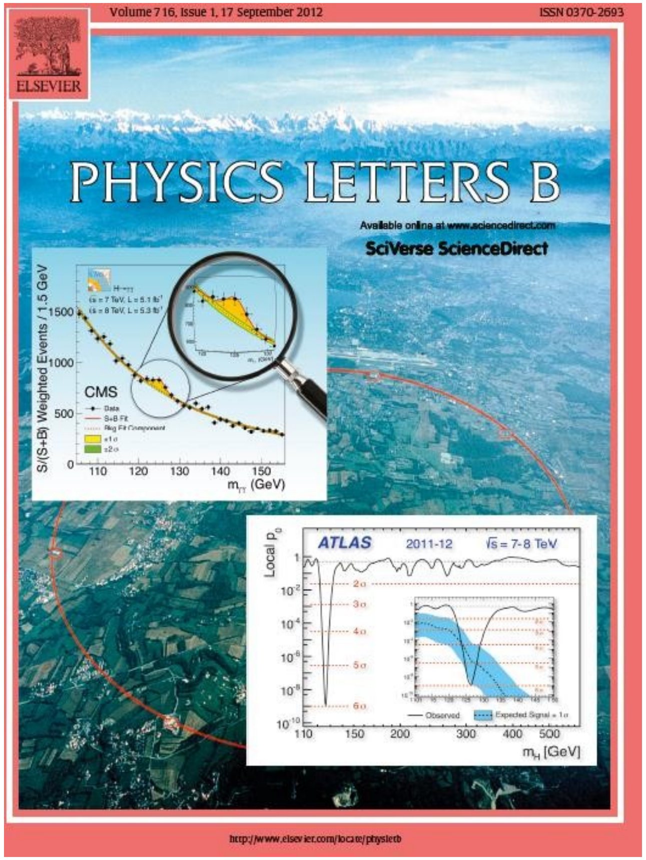
Introduction

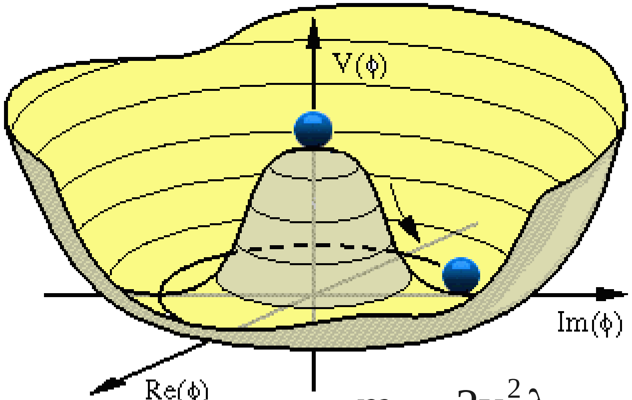
- Discovery of a new boson last summer!



- To understand if SM Higgs boson, need to study
  - spin
  - mass
  - couplings

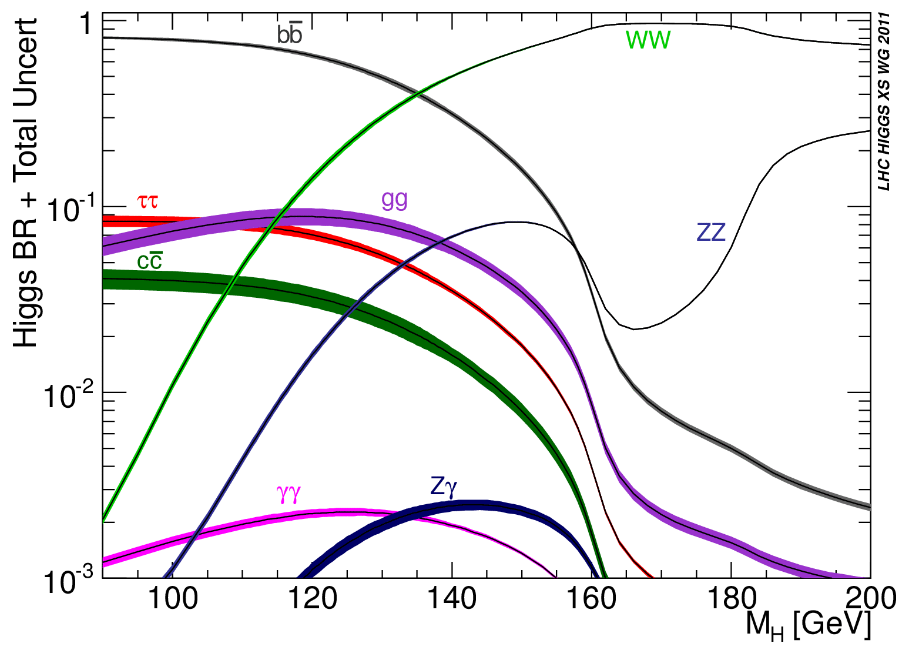
Higgs couplings

- Higgs couplings to particles $\propto$ their mass
  - bosons: $g_{HVV} \propto \frac{m_V^2}{v} \propto m_W \propto \frac{m_Z}{2\cos(\theta_W)}$
  - fermions: $g_{Hff} \propto \frac{m_f}{v} \propto \frac{m_f}{2m_W}$
  - v : vacuum expectation value, $v = \frac{1}{(\sqrt{2}\,G_F)^{1/2}} = \frac{2m_W}{g}$



$m_H = 2v^2\lambda$

- Once mass known, all couplings known

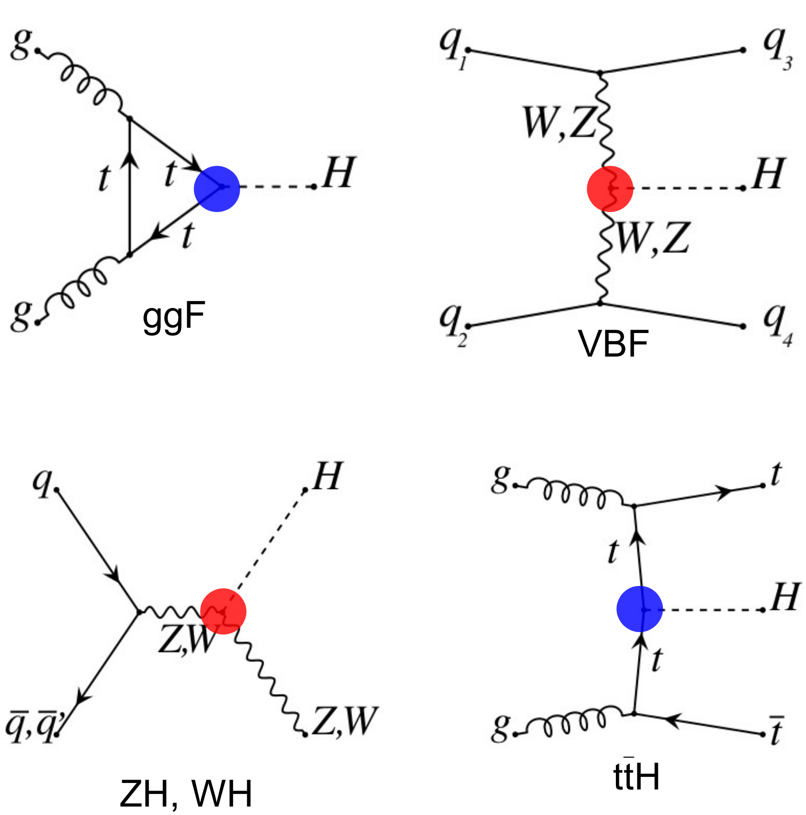


$$\Gamma(H \to f\bar{f}) \propto m_H . m_f^2$$

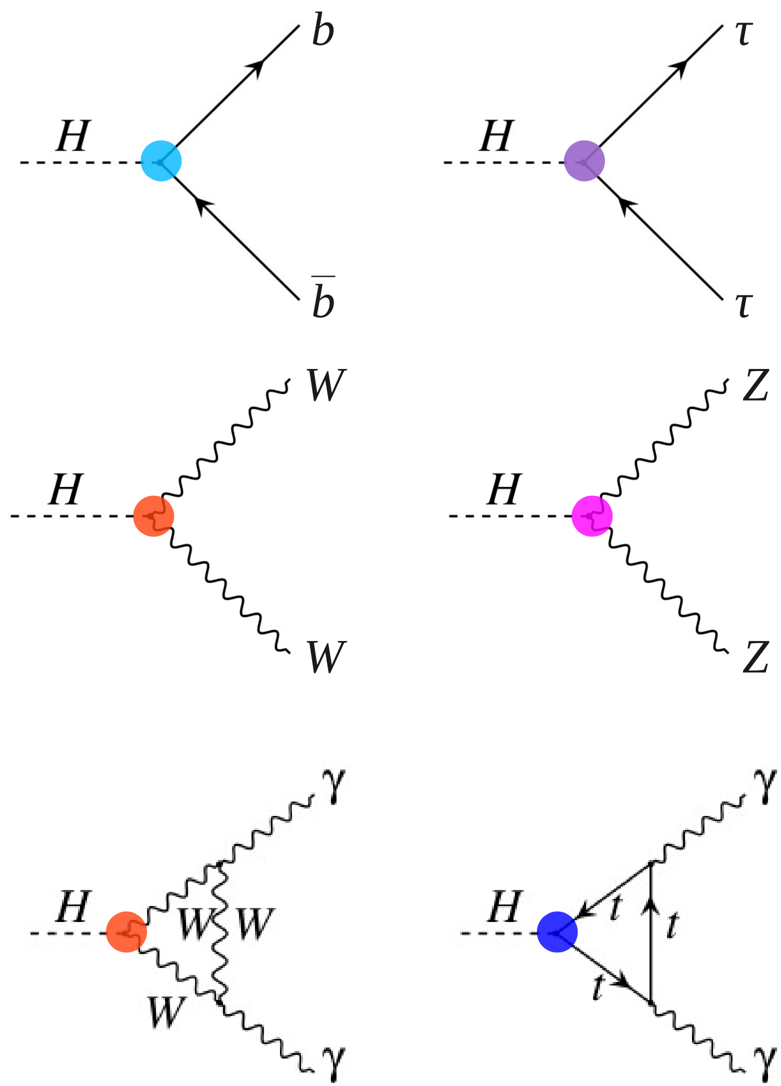
$$\Gamma(H \to VV^*) \propto m_H . f\left(\frac{m_f}{m_H}\right)$$

Higgs boson production and decays modes

- Production modes:



- Decay modes:

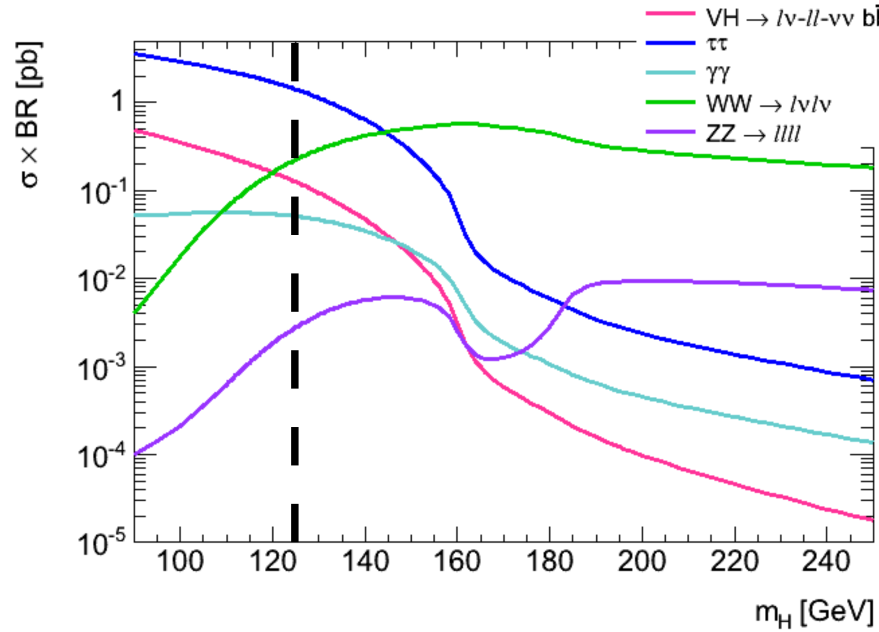


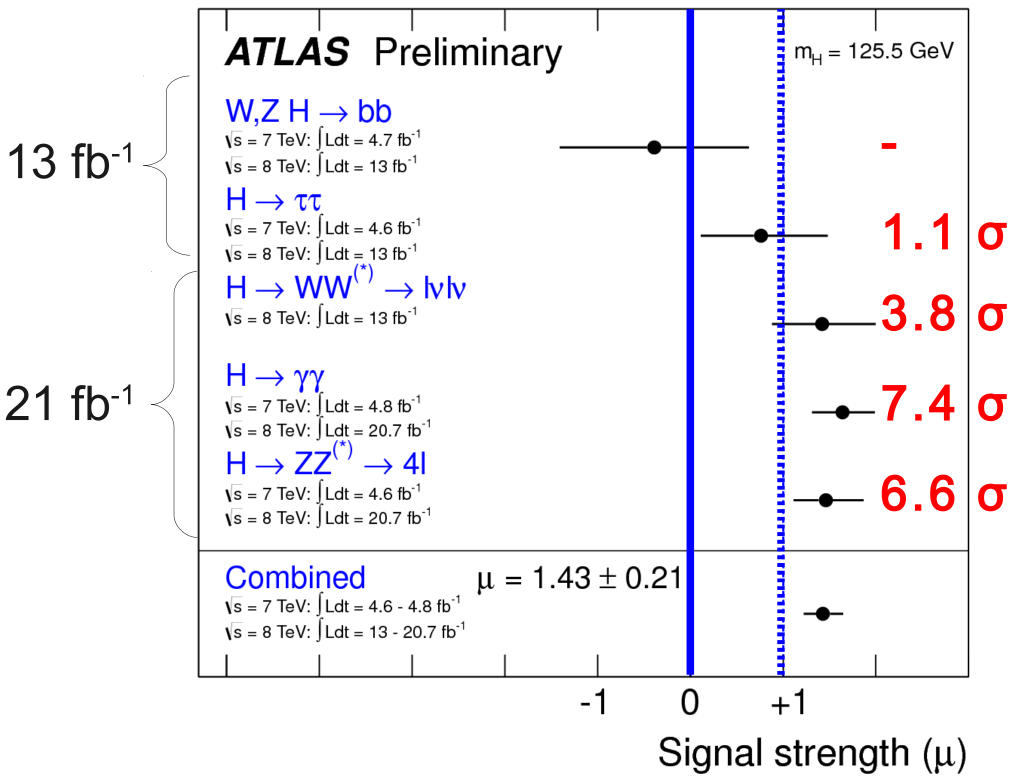
: fermions (t, b, τ)
: vector bosons

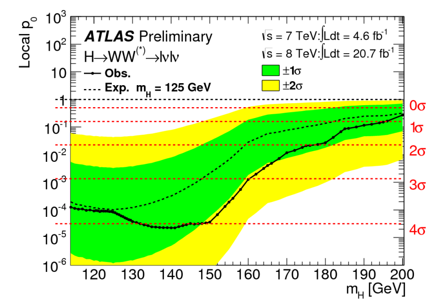
- Measuring cross-sections and partial widths ⇒ go back to couplings

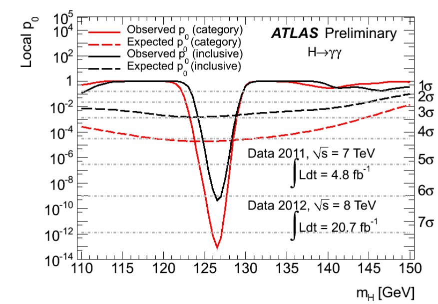
Sensitivity /channel

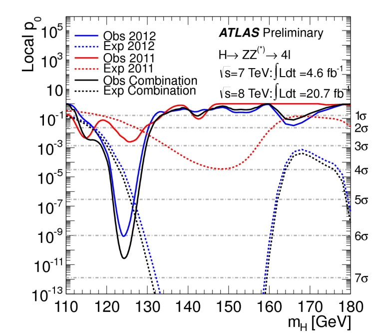
- Main decay channels (sensitivity ordered):
  - $ZZ \rightarrow 4l$, $\gamma\gamma$, WW, $\tau\tau$, $b\bar{b}$
- One important parameter:
  - signal strength μ
  - $\mu = \frac{N_{\text{observed}}}{N_{\text{SM Higgs}}}$
    - = 0: background only
    - = 1: SM Higgs boson





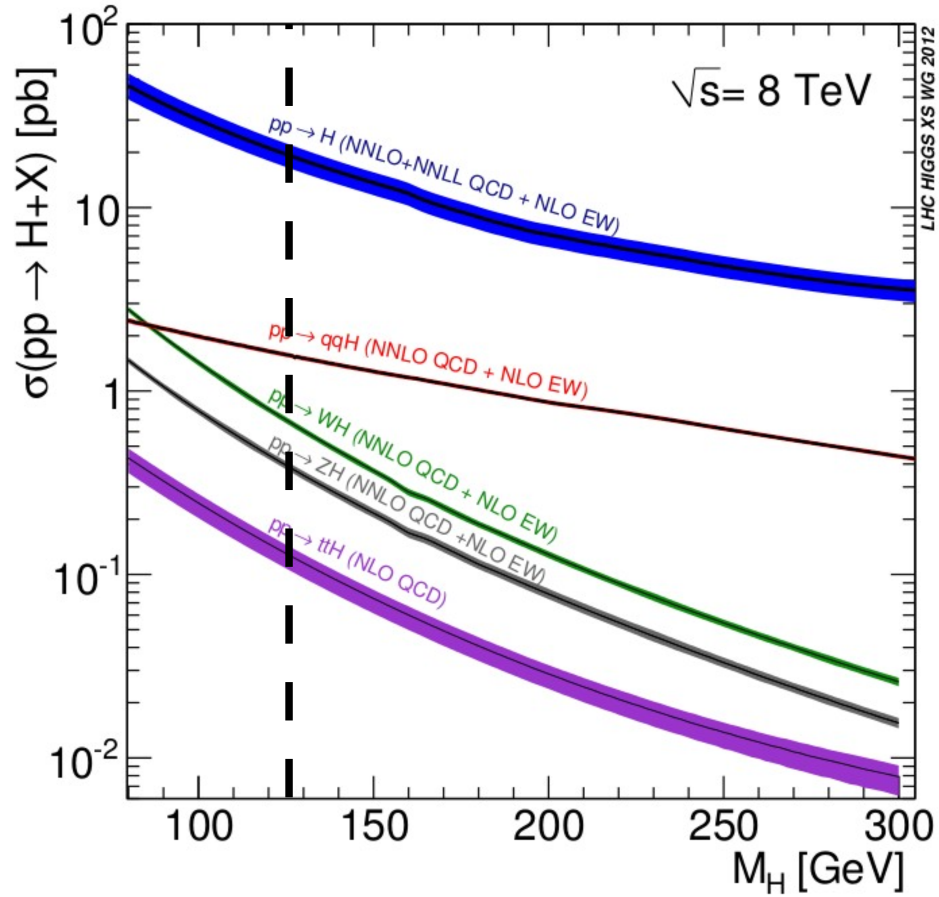


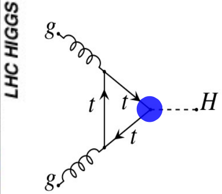


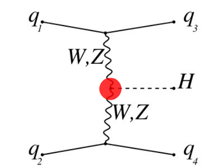


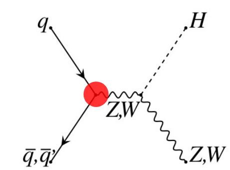
Production modes

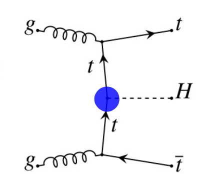
- At m_H ~ 125 GeV
  - ggF ~90%
  - VBF ~7%
  - VH ~ 5%
  - ttH ~ 0.5%









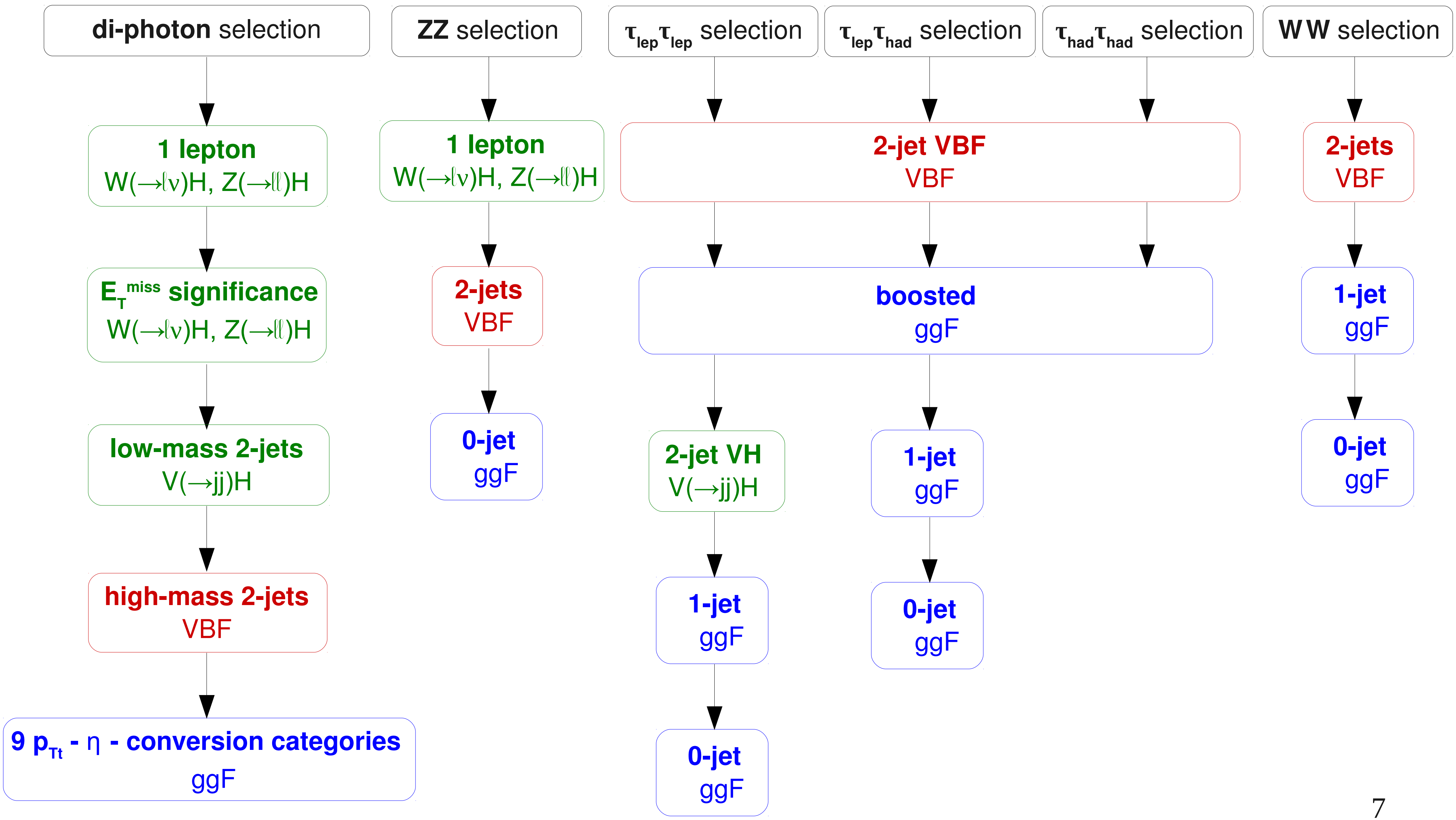


- Studied in ATLAS:

channel	mH (GeV)	ggF	VBF	VH	ttH
H→ZZ→4l	110-600	✓	✓	✓	
H→γγ	110-150	✓	✓	✓	
H→WW→lνlν	110-600	✓	✓	✓	
H→ττ	110-145	✓	✓	✓	
$H\to b\bar{b}$	110-130			✓	✓

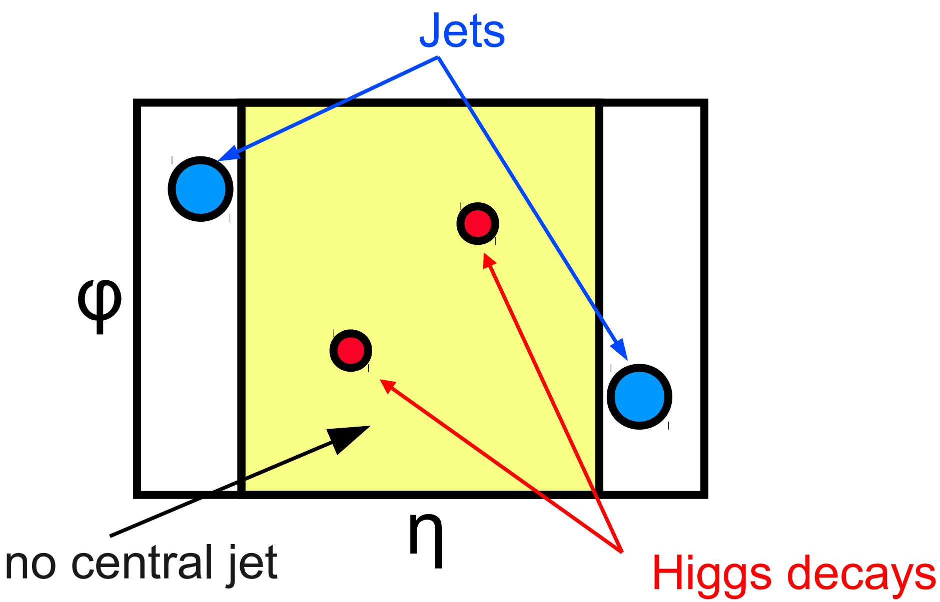
Analyses flow-charts

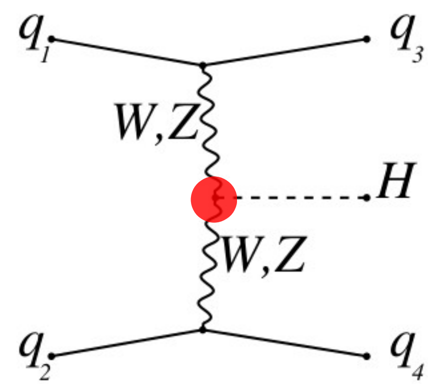
- Datasets divided in exclusive categories

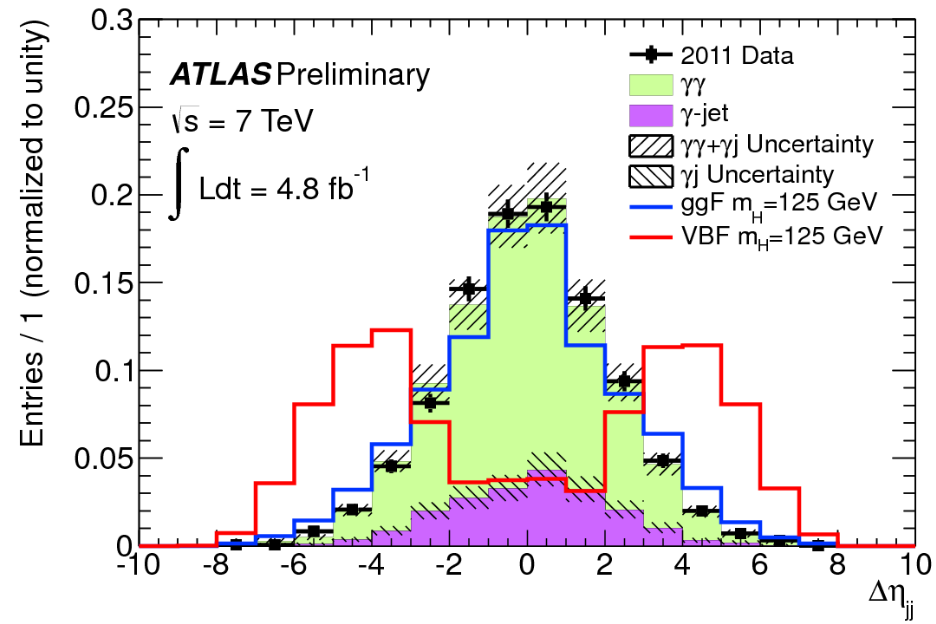


Look for VBF mode

- Cross-section at 125 GeV: 1.578 pb
- Higgs boson produced with 2 forward jets:



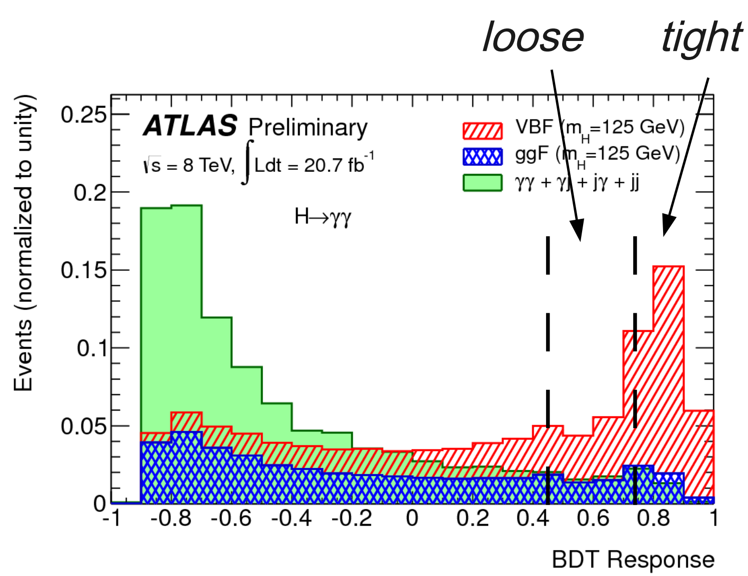


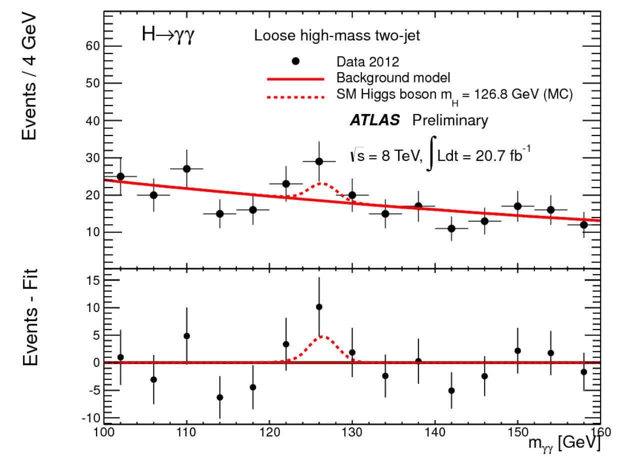


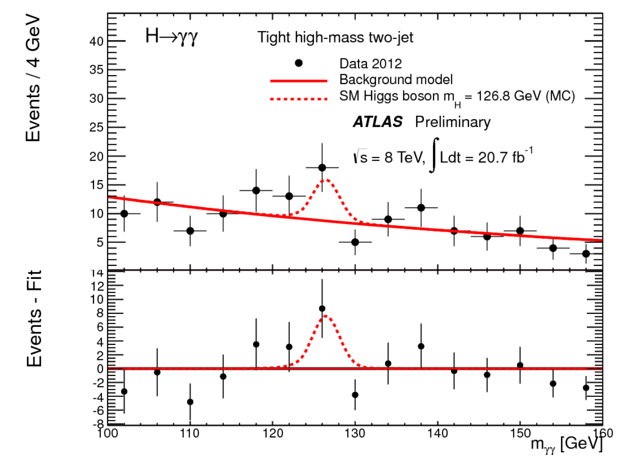
- Usual cuts:
  - $\Delta\eta_{jj}$
  - m_{jj}
  - veto 3[rd] central jet
- One of main uncertainties: knowledge of ggF + 2 jets
  - 25% to 30%

VBF for $H \to \gamma\gamma$

- 4.8 fb^{-1} $\sqrt{s}$=7 TeV, 21 fb^{-1} $\sqrt{s}$=8 TeV
- Ask for two well identified, isolated photons
  - $E_T^{leading} > 40$ GeV, $E_T^{subleading} > 30$ GeV
- 2 VBF categories:
  - MVA analysis
  - $|\Delta\eta_{jj}|$, m_{jj}, $\Delta\varphi(\gamma\gamma;jj)$, pTt, $\Delta R_{min}(\gamma,j)$, $\eta^{\gamma\gamma} - (\eta^{j1}+\eta^{j2})/2$





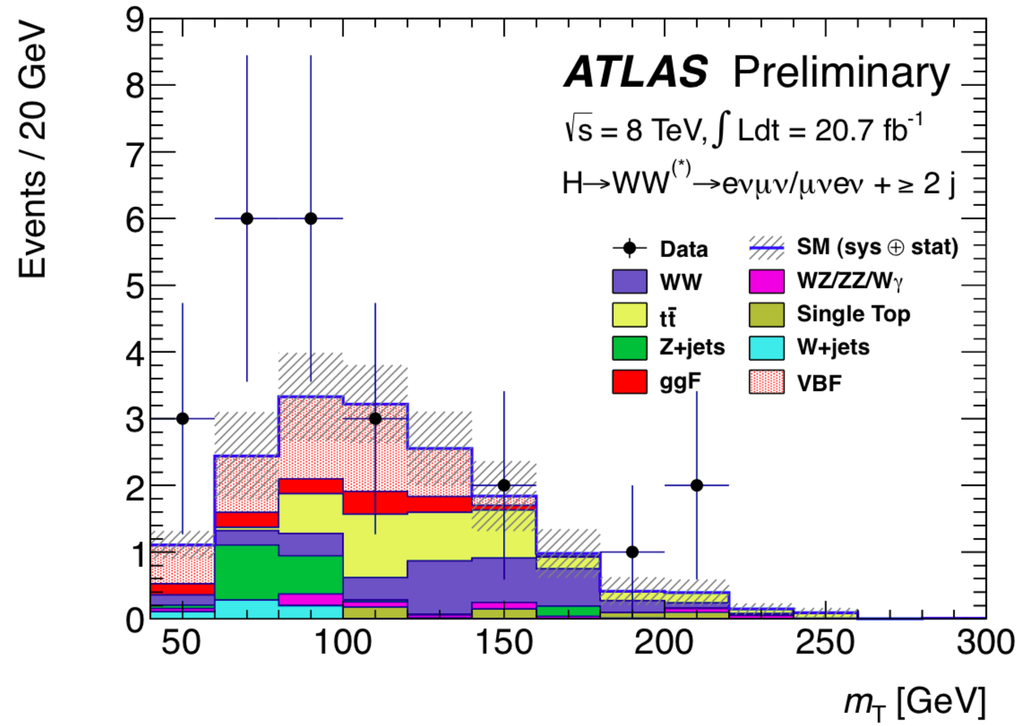


- Expected number of events for m_H = 126.5 GeV, 8 TeV and 21 fb^{-1}:

	N_S	VBF purity	data	N_S/N_B
tight 2-jet VBF	8.1	76%	136	0.57
loose 2-jet VBF	5.3	54%	276	0.17
inclusive	395	7.3%	118893	0.03

VBF for H→WW*

- 4.8 fb^{-1} $\sqrt{s}$=7 TeV, 21 fb^{-1} $\sqrt{s}$=8 TeV
- Decay mode: WW → lνlν
- No complete reconstruction of the event: m_T
- Divided in 0-jet, 1-jet, 2-jet
- 2-jet:
  - $|\Delta y_{jj}| > 2.8$
  - m_{jj} > 500 GeV
  - veto events with 3rd central jet

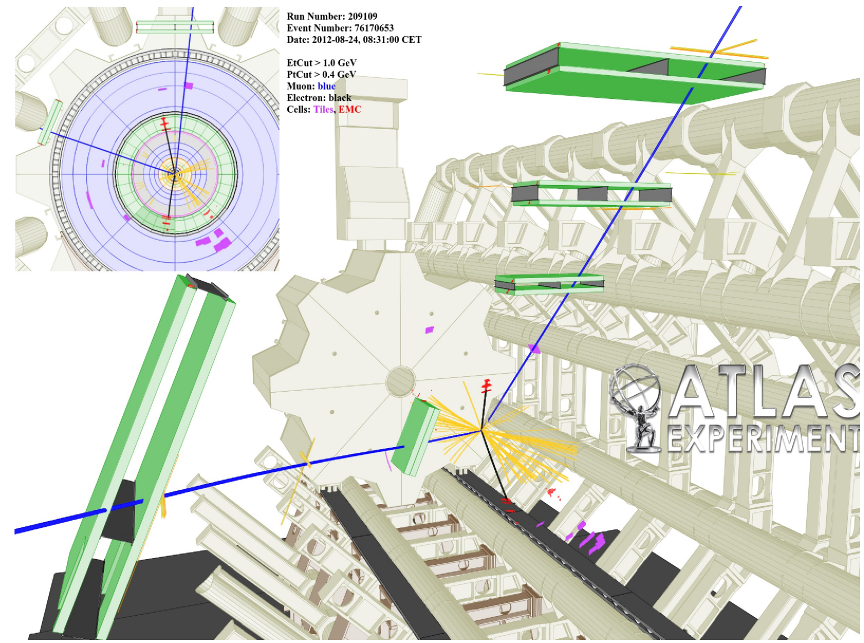


- Expected number of events for 8 TeV and 21 fb^{-1}:

	N_S	VBF purity	data	N_S/N_B
0-jet	97	2%	831	0.13
1-jet	40	12%	309	0.13
2-jet	10.6	81%	55	0.29

VBF for $H \to ZZ^*$

- 4.8 fb^{-1} $\sqrt{s}$=7 TeV, 21 fb^{-1} $\sqrt{s}$=8 TeV
- Ask for 4 well identified, isolated leptons
  - p_T > 20-15-10-7/6 GeV
  - 50 < m_{12} < 106 GeV, 12 < m_{34} < 115 GeV



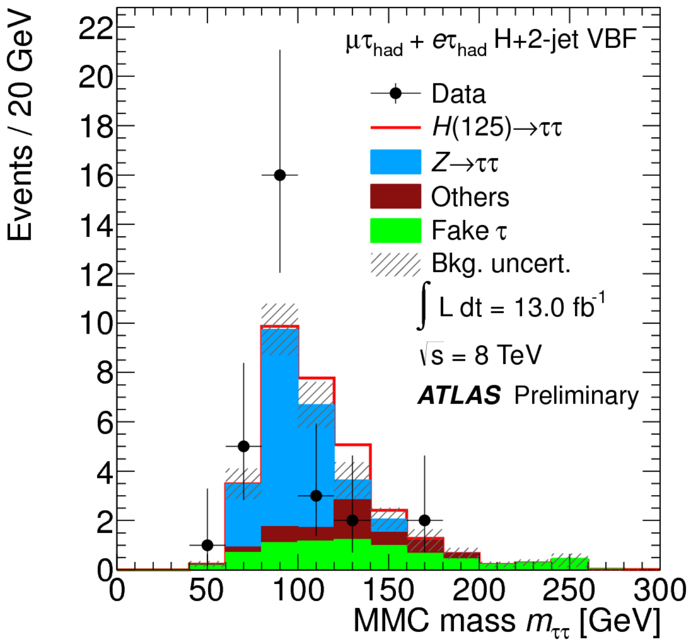
- VBF categories:
  - $|\Delta\eta_{jj}| > 3$
  - m_{jj} > 350 GeV
- Expected number of events for m_H = 125 ± 5 GeV:

	N_S	VBF purity	data	N_S/N_B
VBF category	0.7	60%	1	5
inclusive	13.7	~7%	27	1.6

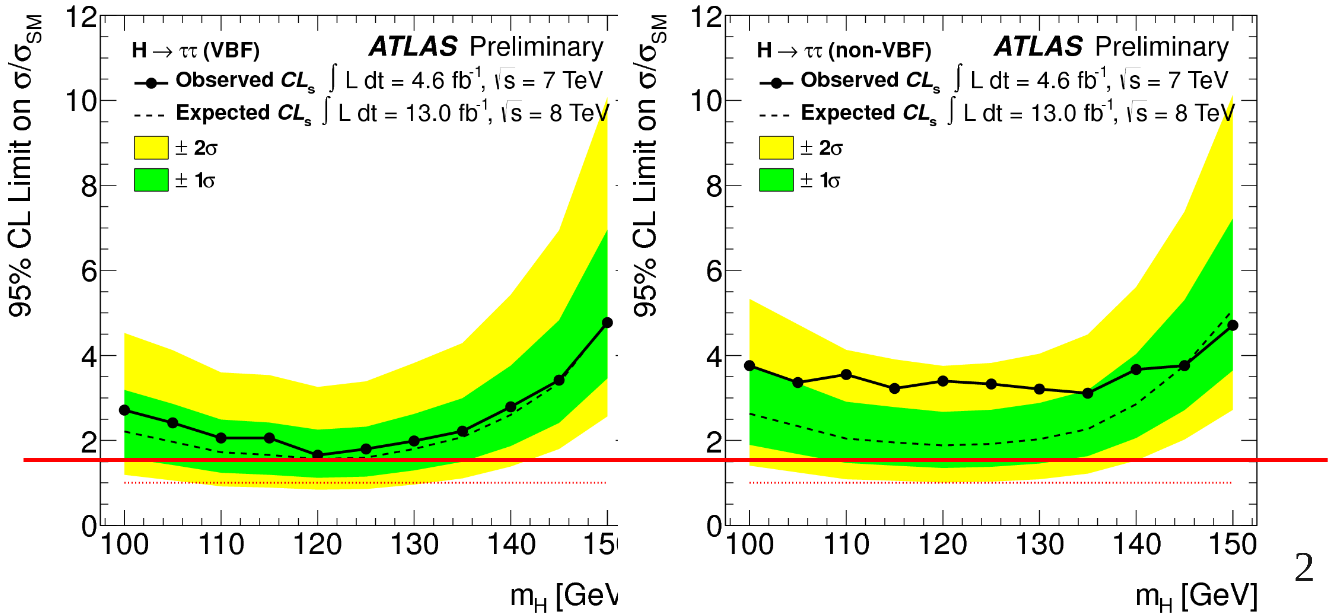
VBF for $H\rightarrow\tau\tau$

- 4.8 fb^{-1} $\sqrt{s}$=7 TeV, 13 fb^{-1} $\sqrt{s}$=8 TeV
- Three decay modes: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- Cuts on : $|\Delta\eta_{jj}|$, m_{jj} > 400 GeV, τ decays between jets, 3rd jet veto, etc
- Expected number of events for 8 TeV and 13 fb^{-1}:

	N_S	VBF purity	data
$H\rightarrow\tau_{lep}\tau_{lep}$	4.9	73.3%	98
$H\rightarrow\tau_{lep}\tau_{had}$	3.0	83.3%	29
$H\rightarrow\tau_{had}\tau_{had}$	4.1	75.1%	110

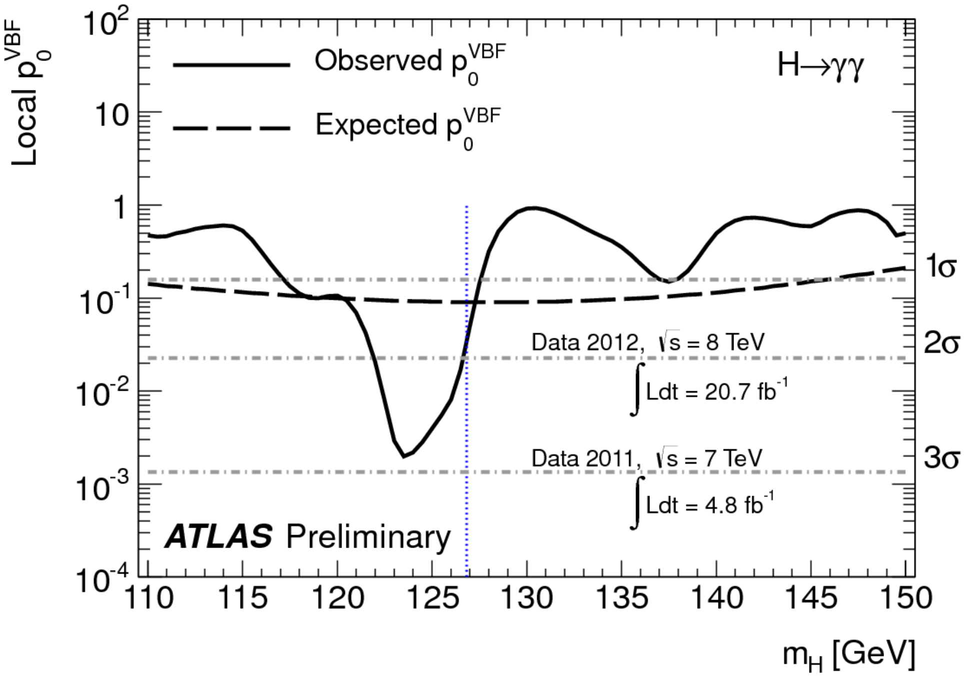


- Expected sensitivity:

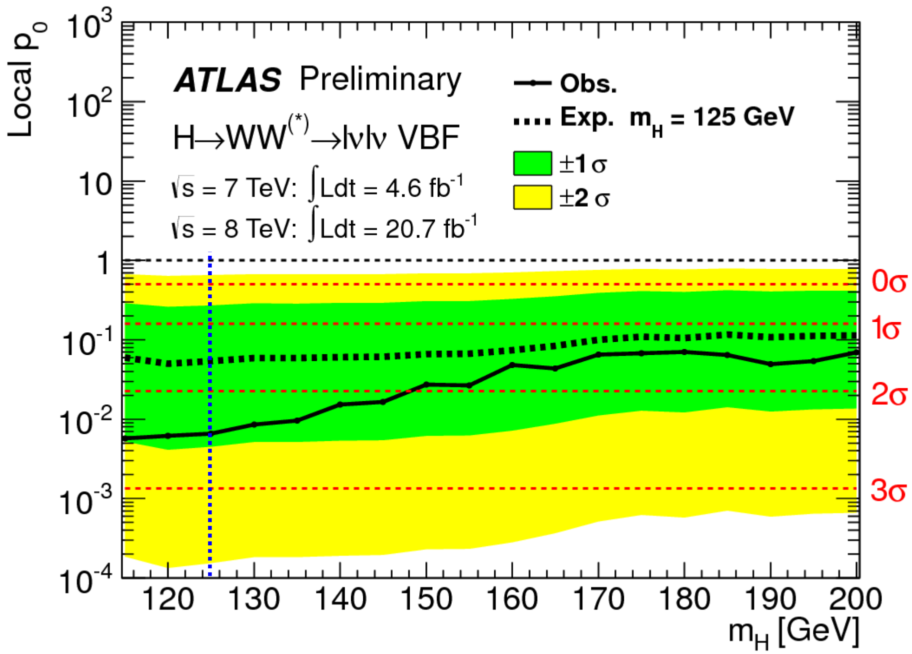


Hint of VBF signal

- H → γγ:



- H → WW*:

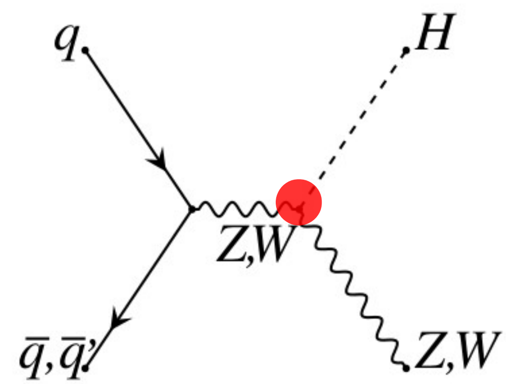


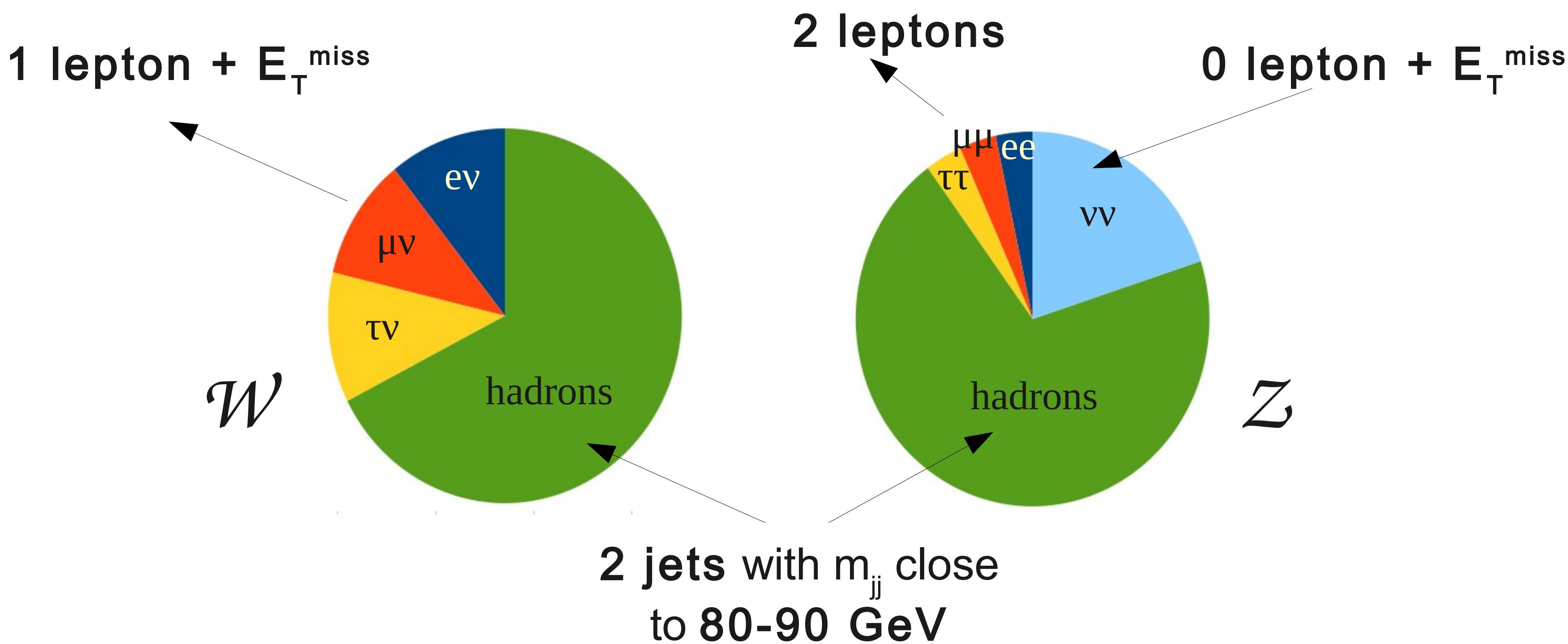
- Significance at 126.8 GeV:
  - 2.0 σ observed
  - 1.3 σ expected

- Significance at 125 GeV:
  - 2.5 σ observed
  - 1.6 σ expected

Look for VH mode

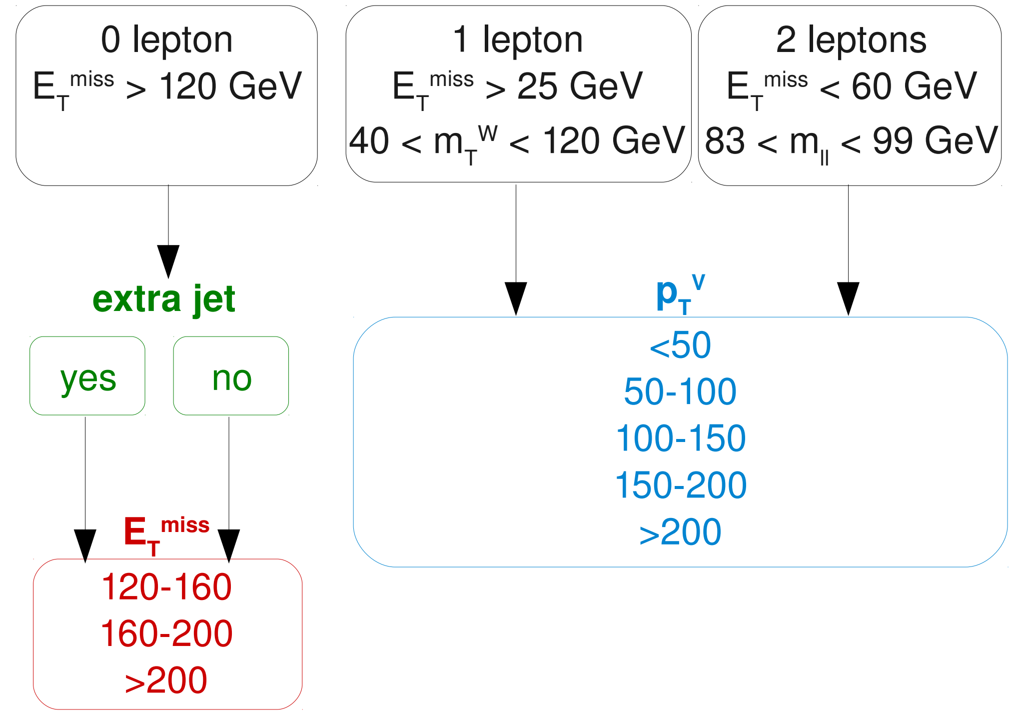
- ♦ Cross-section at 125 GeV: 0.6966 + 0.3943 pb
- ♦ Divide into categories depending on the W/Z decay

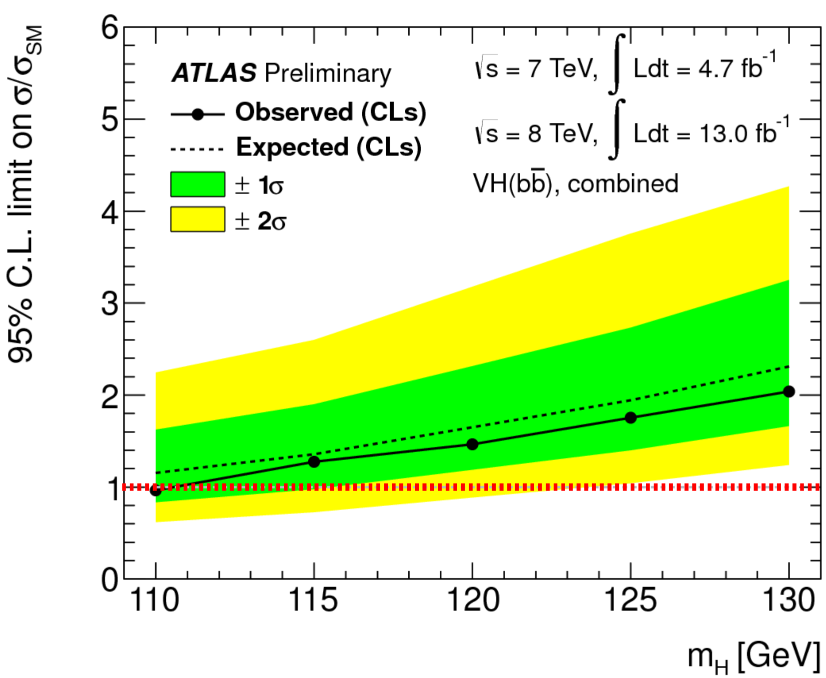




VH: leptons ($b\bar{b}$)

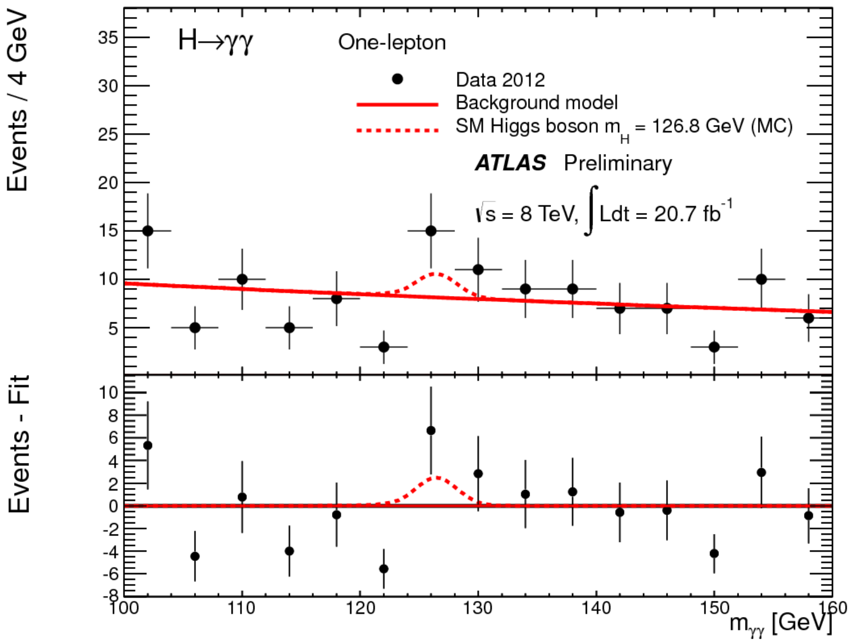
- BR($H \to b\bar{b}$) = 57.7% at m_H = 125 GeV
  - but only WH, ZH
- 2 b-jets
  - 70% eff
  - p_T > 45/20 GeV
- $Z(\to \nu\nu)H$, $W(\to l\nu)H$, $Z(\to ll)H$





VH: 1 lepton

- for H → γγ and H → 4l channel
- Ask for ≥1 lepton
  - sensitive to both W(→lν)H and Z(→ll)H
  - $E_T^{ele} > 15$ GeV, $p_T^{\mu} > 10$ GeV (γγ)
  - $p_T^{lep} > 8$ GeV (ZZ*)
  - well identified, isolated

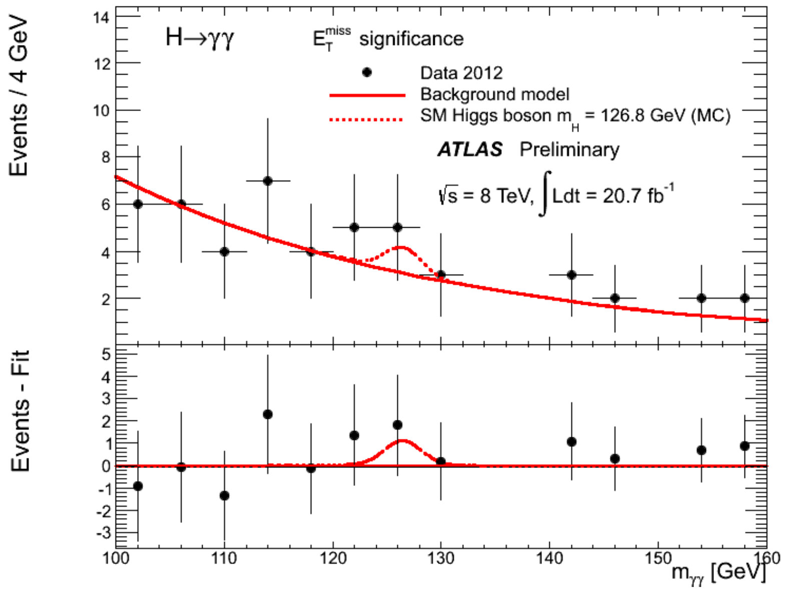


- Expected number of events for 8 TeV and 21 fb^{-1}:

	Nsignal	VH purity	N data
H→γγ	2.9	79%	123
H→ZZ	0.2	70%	0

VH: E_T^{miss}

- for $H \to \gamma\gamma$ channel
- Ask for E_T^{miss} significance $\frac{E_T^{miss}}{0.67\sqrt{\Sigma E_T}} > 5$
  - 0 lepton
  - sensitive to both $W(\to l\nu)H$ and $Z(\to \nu\nu)H$

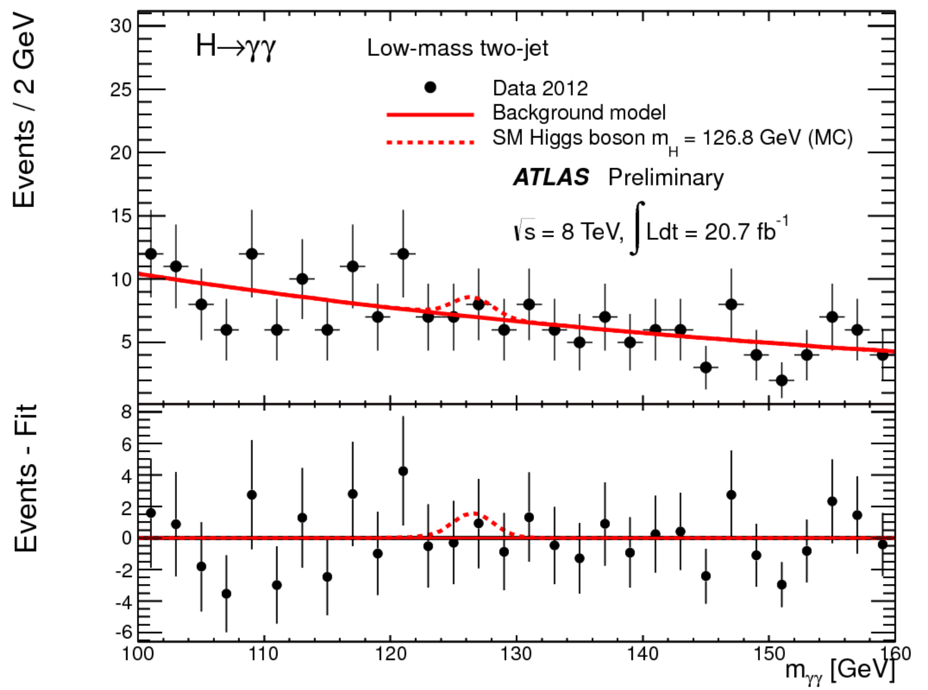


- Expected number of events for 8 TeV and 21 fb^{-1}:

	N_S	VH purity	data	N_S/N_B
E_T^{miss} significance	1.3	83%	49	0.24
inclusive	395	7.3%	118893	0.03

VH: 2 central jets

- for H→γγ and H→ττ channels
- sensitive to both W(→jj)H and Z(→jj)H



- Ask for two jets:
  - $|\Delta\eta_{jj}| < 3.5/2.0$ for γγ/ττ
  - $60 < m_{jj} < 100$ GeV for γγ
    $30 < m_{jj} < 100$ GeV for ττ
  - b-tag jet veto for ττ

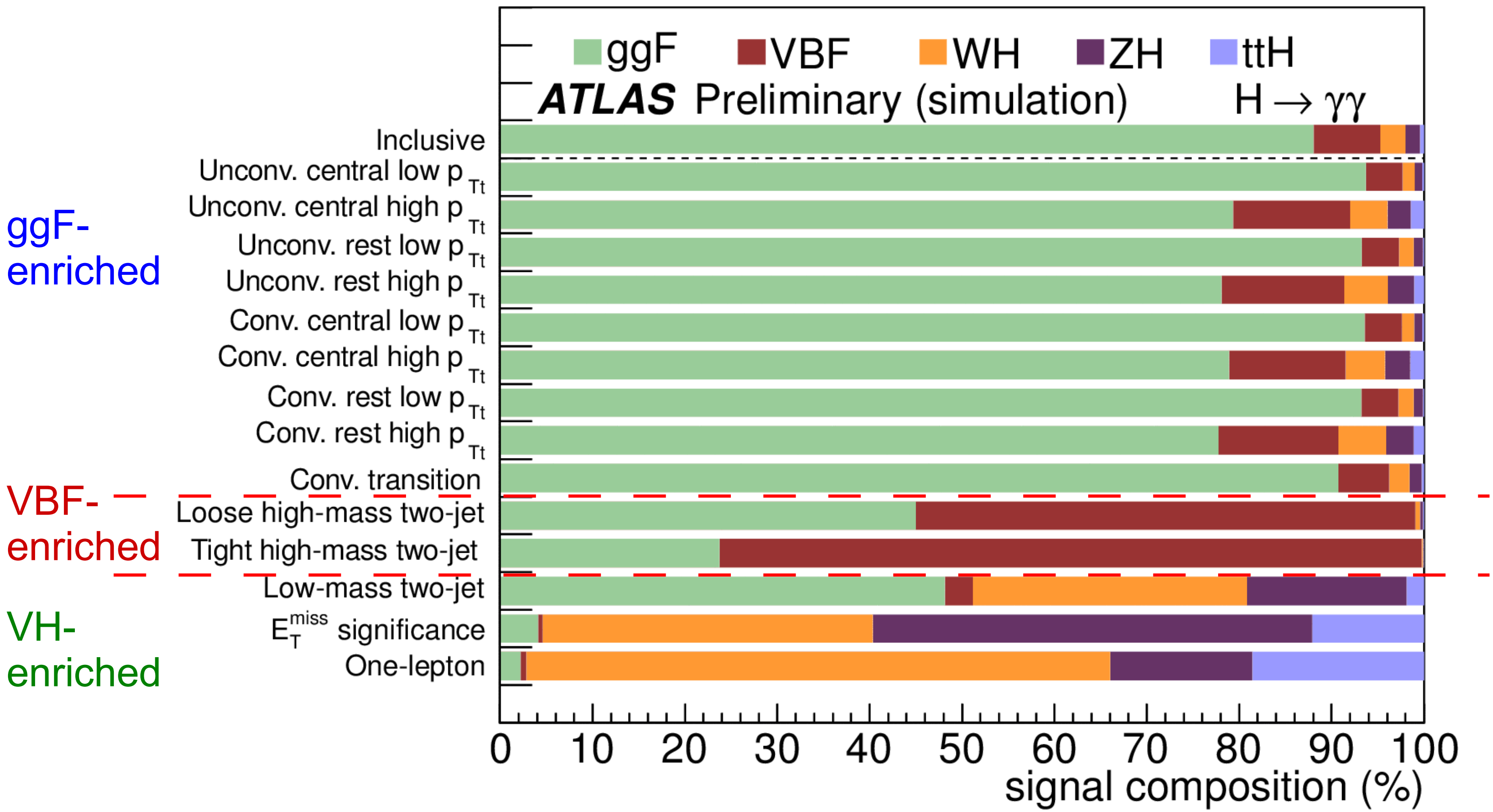
- Number of expected events for 8 TeV and 21 fb^{-1}:

	Nsignal	VH purity	N data
H→γγ	3.3	47%	210
H→ττ	0.65	31%	176

  - difficult to get rid of ggF

H→γγ: signal strength / category (1)

- Signal composition /category:



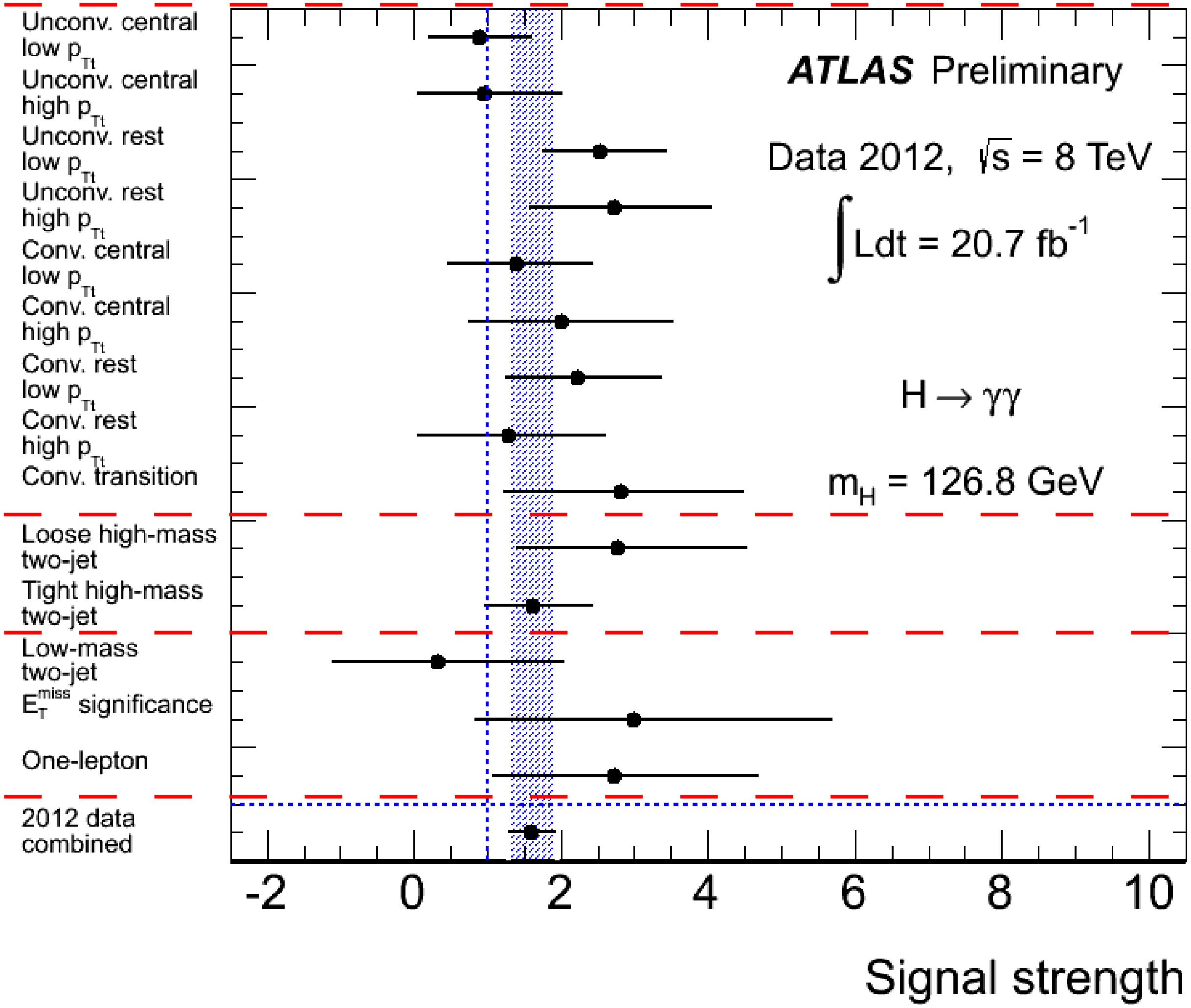
- None of those categories is 100% pure in targeted process

H→γγ: signal strength / category (2)

ggF-enriched

VBF-enriched

VH-enriched

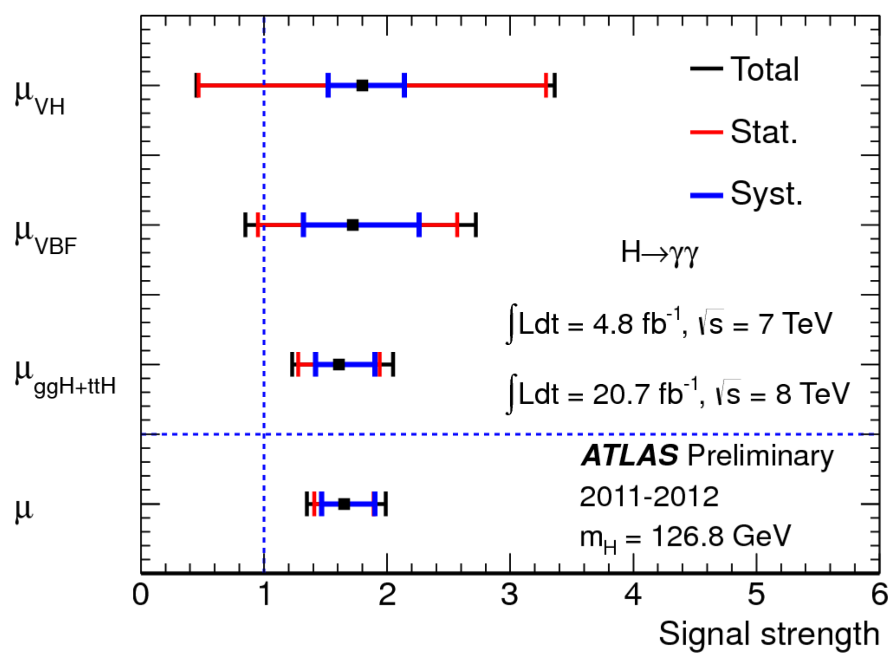


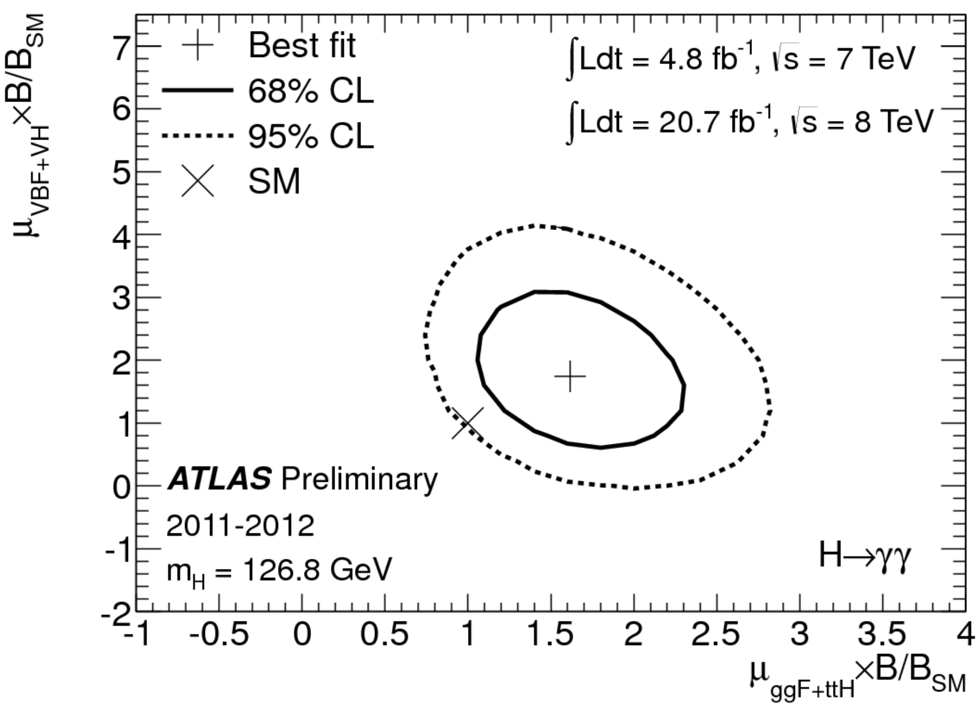
$$\mu_i = \frac{N_i^{observed}}{N_i^{SM\,Higgs}}$$

Signal strength / production mode (1)

- Signal strength parameter for each production mode: $\mu_i = \frac{N_i^{\text{observed}}}{N_i^{\text{SM Higgs}}}$
  - i = ggF, VBF, VH, ttH

- For $H \rightarrow \gamma\gamma$ channel:
  - $\mu_{ggF+ttH} = 1.6^{+0.3}_{-0.3}(\text{stat})^{+0.3}_{-0.2}(\text{syst})$
  - $\mu_{VBF} = 1.7^{+0.8}_{-0.8}(\text{stat})^{+0.5}_{-0.4}(\text{syst})$
  - $\mu_{VH} = 1.8^{+1.5}_{-1.3}(\text{stat})^{+0.3}_{-0.3}(\text{syst})$

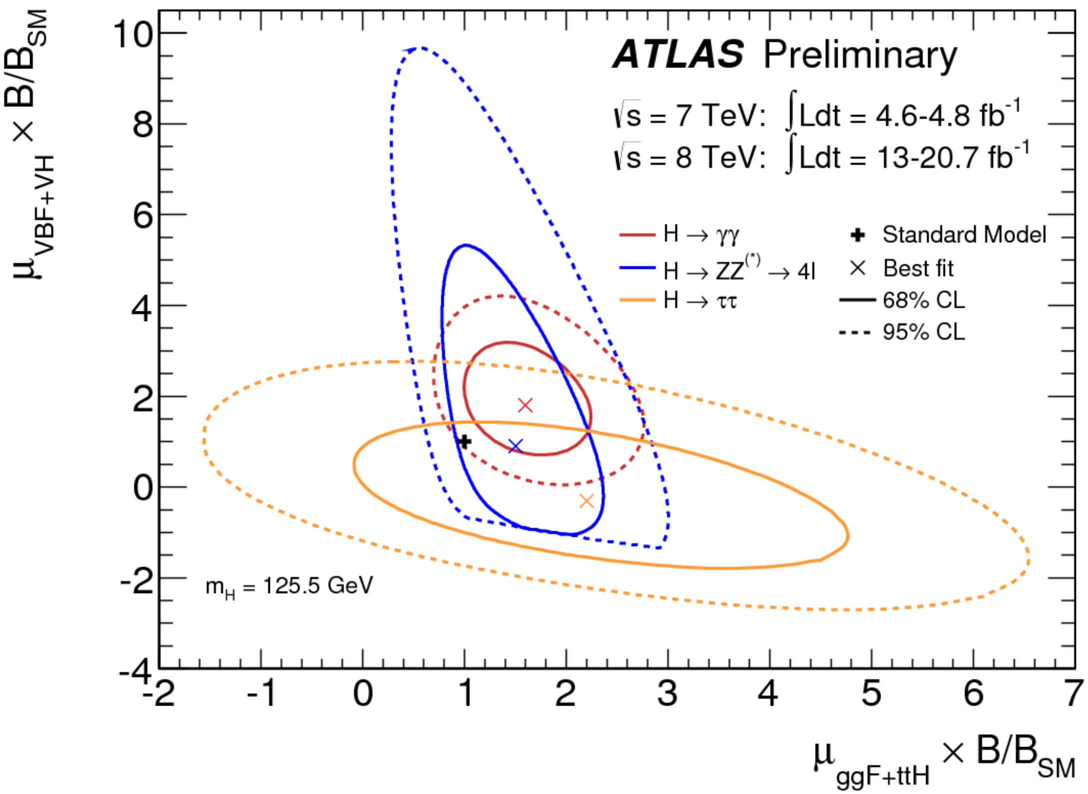


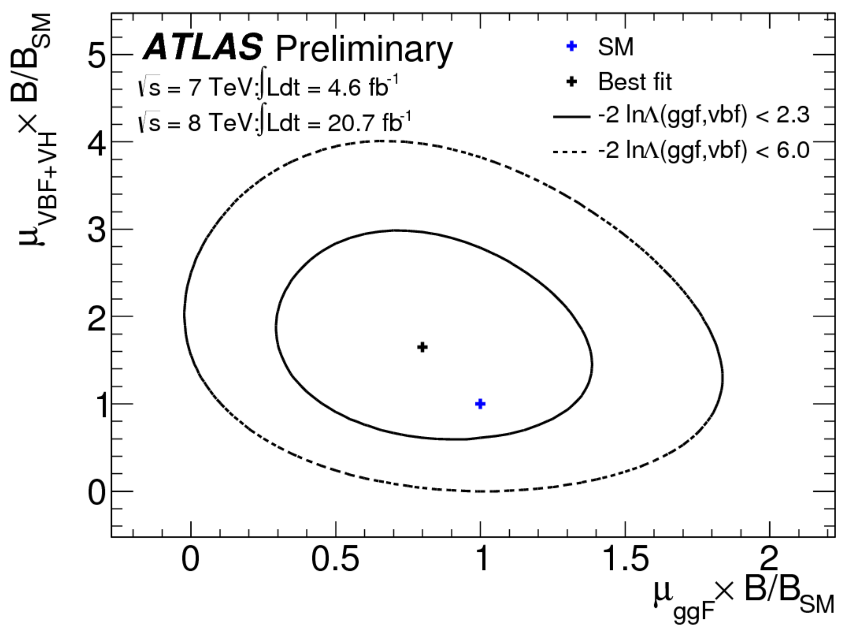


Signal strength / production mode (2)

- Signal strength parameter for each production mode: $\mu_i = \frac{N_i^{observed}}{N_i^{SM\,Higgs}}$
  - i = ggF, VBF, VH, ttH

- For $H \rightarrow ZZ$, $H \rightarrow \tau\tau$ and $H \rightarrow WW$ channels

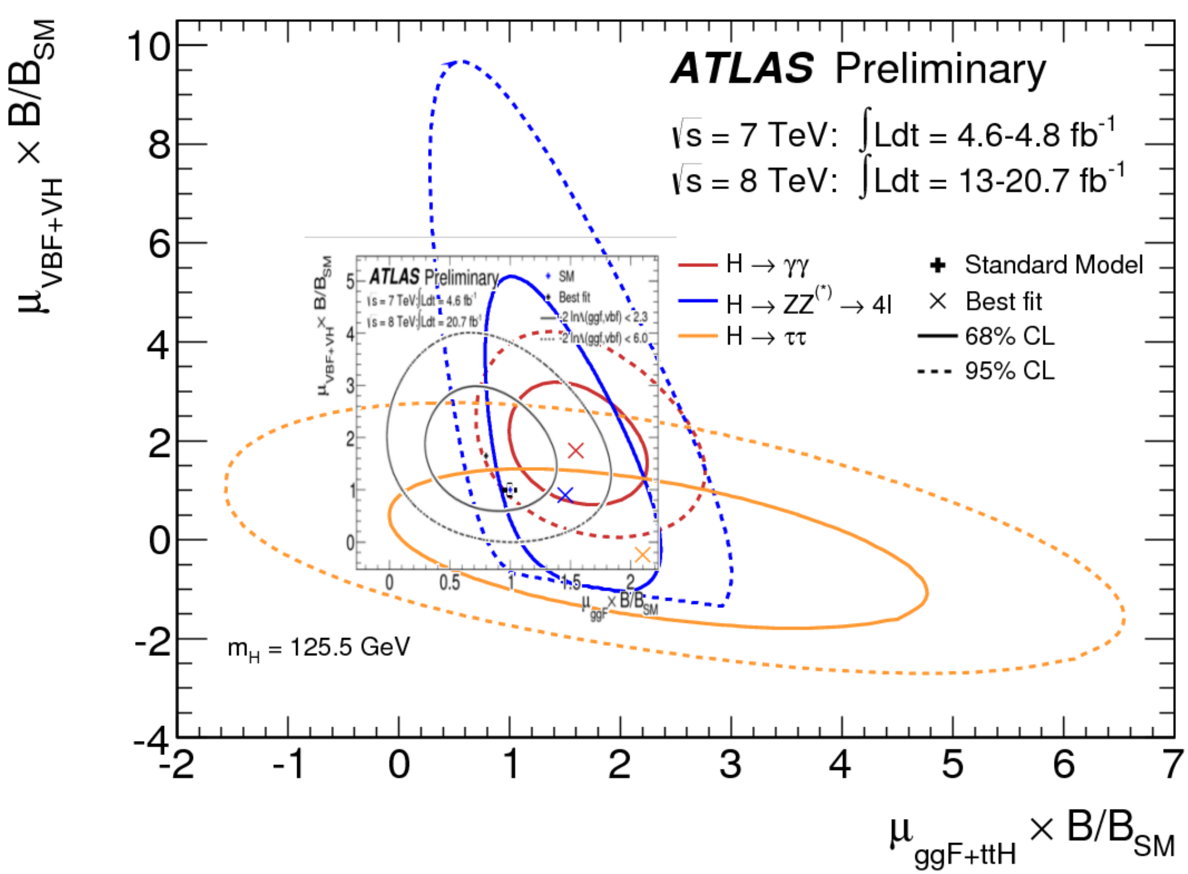




Signal strength / production mode (2)

- Signal strength parameter for each production mode: $\mu_i = \dfrac{N_i^{\text{observed}}}{N_i^{\text{SM Higgs}}}$
  - i = ggF, VBF, VH, ttH

- For $H \rightarrow ZZ$, $H \rightarrow \tau\tau$ and $H \rightarrow WW$ channels
  - unofficial combination

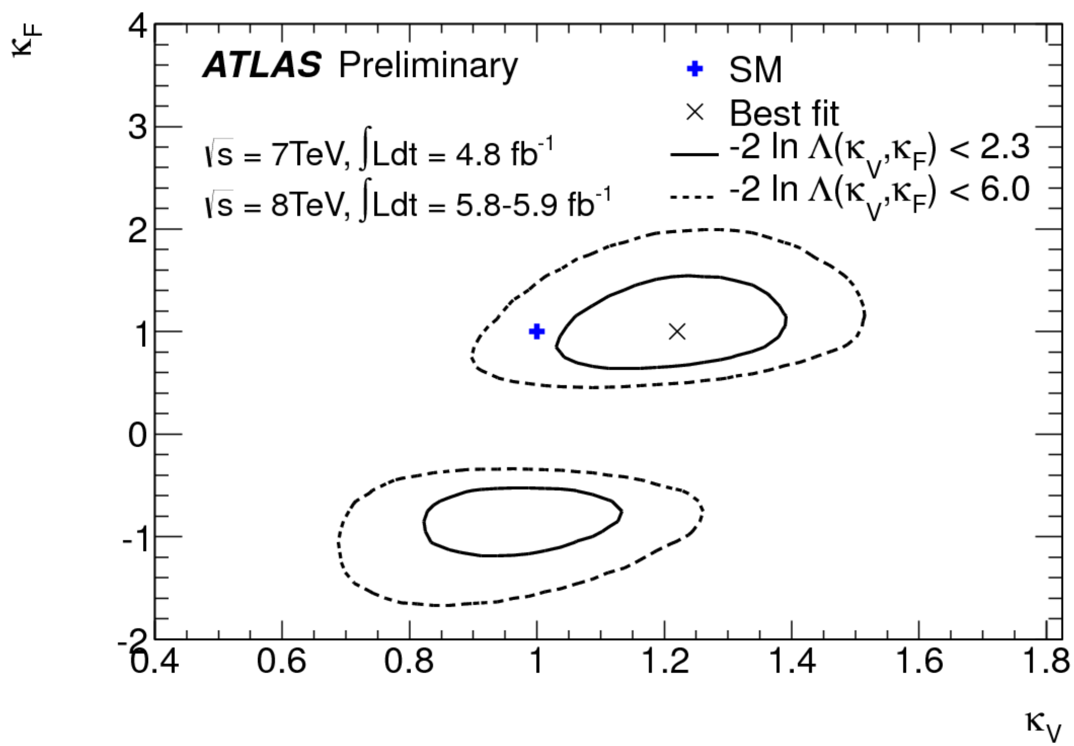


Coupling fits

- 4.8 fb^{-1} $\sqrt{s}$=7 TeV, 5.8 fb^{-1} $\sqrt{s}$=8 TeV
- Global fits with 5 channels
- Hypotheses:
  - single resonance
  - spin 0
  - Higgs boson width negligible
- Cross-section expressed as: $\sigma \cdot BR(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$
- To compare σ_{ii} and Γ_{ii} to SM predictions, introduce scale factors κ_i
  - example 1 : $\kappa_W^2 = \frac{\sigma_{WH}}{\sigma_{WH}^{SM}}$ and $\kappa_W^2 = \frac{\Gamma_{WW^*}}{\Gamma_{WW^*}^{SM}}$
  - example 2: $\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, \kappa_{BSM\,particule}?, m_H)$

Couplings to fermions and vector bosons

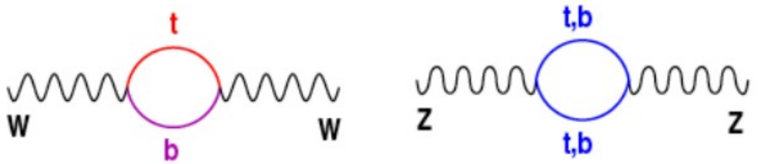
- Assume same scale factors for bosons and fermions
  - $\kappa_V = \kappa_W = \kappa_Z$
  - $\kappa_F = \kappa_\tau = \kappa_b = \kappa_t$
- Assume no BSM contribution to total width or to γγ loop:



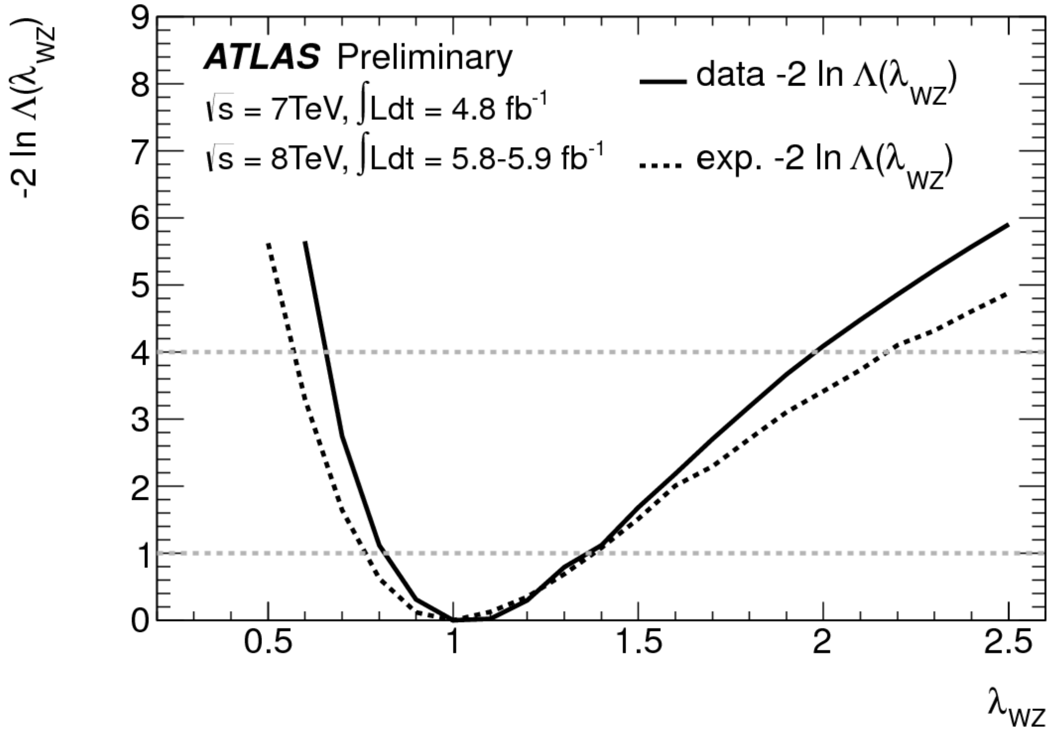
- Compatibility of SM with best fit point: 21%

Custodial symmetry

- $\rho = \left(\frac{m_W}{m_Z \cdot \cos(\theta_W)}\right)^2 = 1 + \text{radiative corrections}$



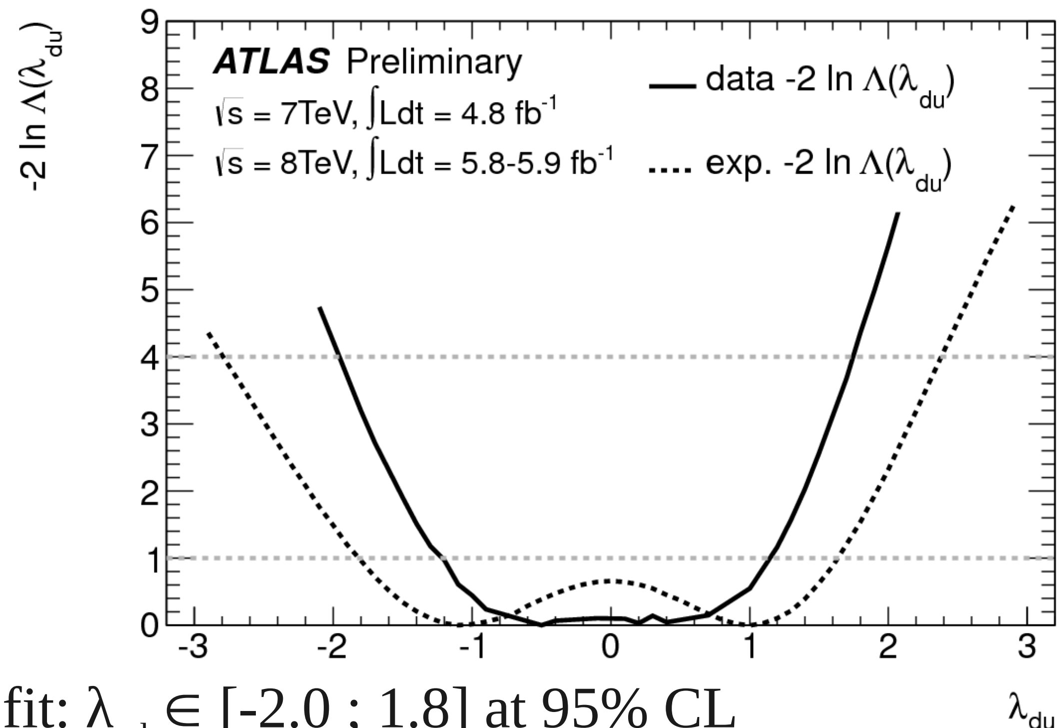
- Define $\lambda_{WZ} = \kappa_W/\kappa_Z$
  - keep $\kappa_F = \kappa_\tau = \kappa_b = \kappa_t$



- Best fit: $\lambda_{WZ} = 1.07^{+0.35}_{-0.27}$

Up/down symmetry

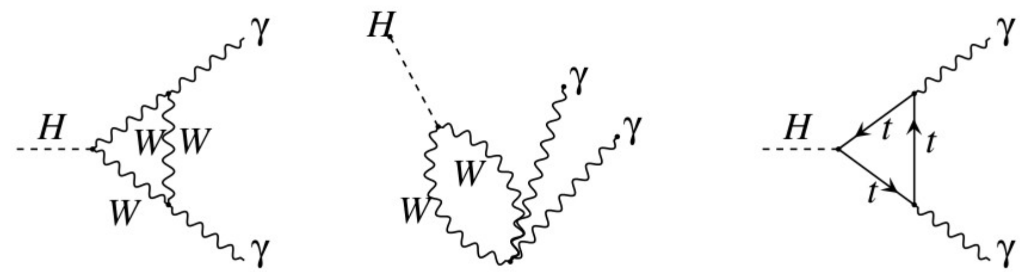
- Some super-symmetry scenarios: different couplings to up and down type quarks
- Define $\lambda_{ud} = \kappa_u/\kappa_d$
  - keep $\kappa_V = \kappa_W = \kappa_Z$



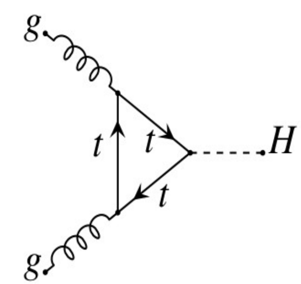
- Best fit: $\lambda_{ud} \in [-2.0 ; 1.8]$ at 95% CL
  - dominated by $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$

New contributions to gg/γγ loops

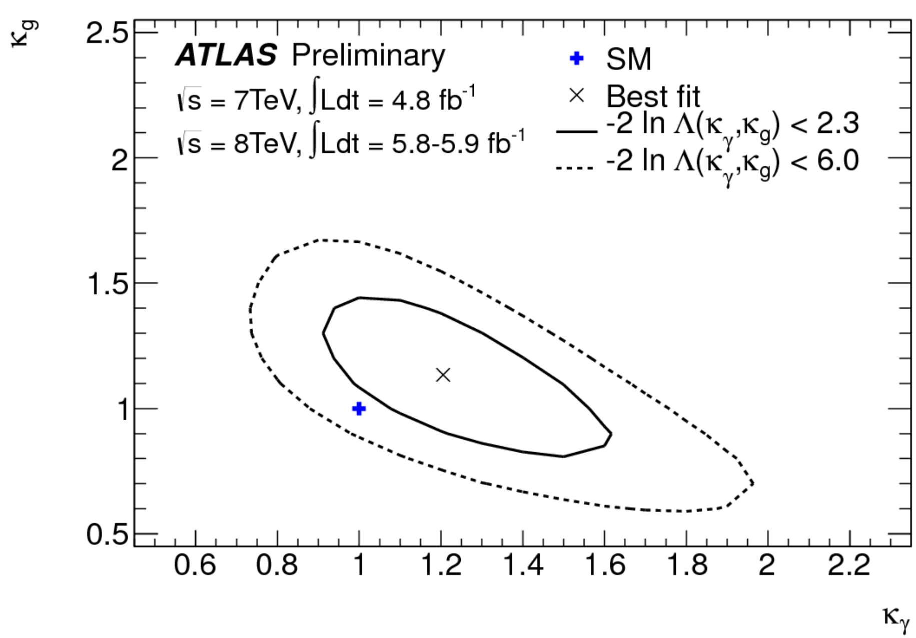
- Main contributions to $H \rightarrow \gamma\gamma$ decay:



- Best fit signal strength: $\mu = 1.65^{+0.34}_{-0.30}$
  - one hypothesis: non-SM particles in γγ loop



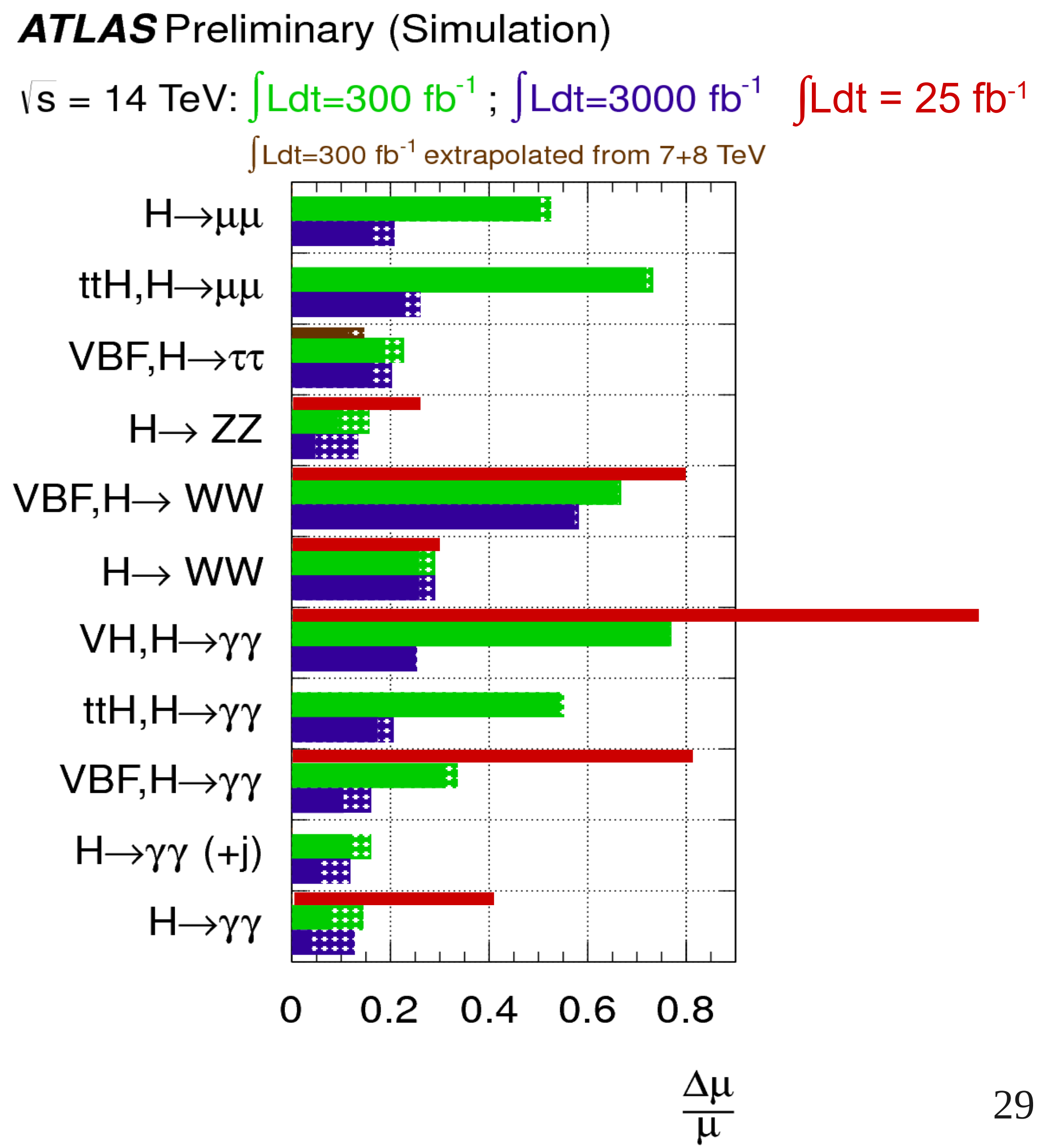
- Assume no Higgs boson decays into BSM particles
- All $\kappa_i = 1$, except κ_g and κ_γ



- Best fit:
  - $\kappa_g = 1.1^{+0.2}_{-0.3}$
  - $\kappa_\gamma = 1.2^{+0.3}_{-0.2}$
- Compatibility of SM with best fit point: 18%

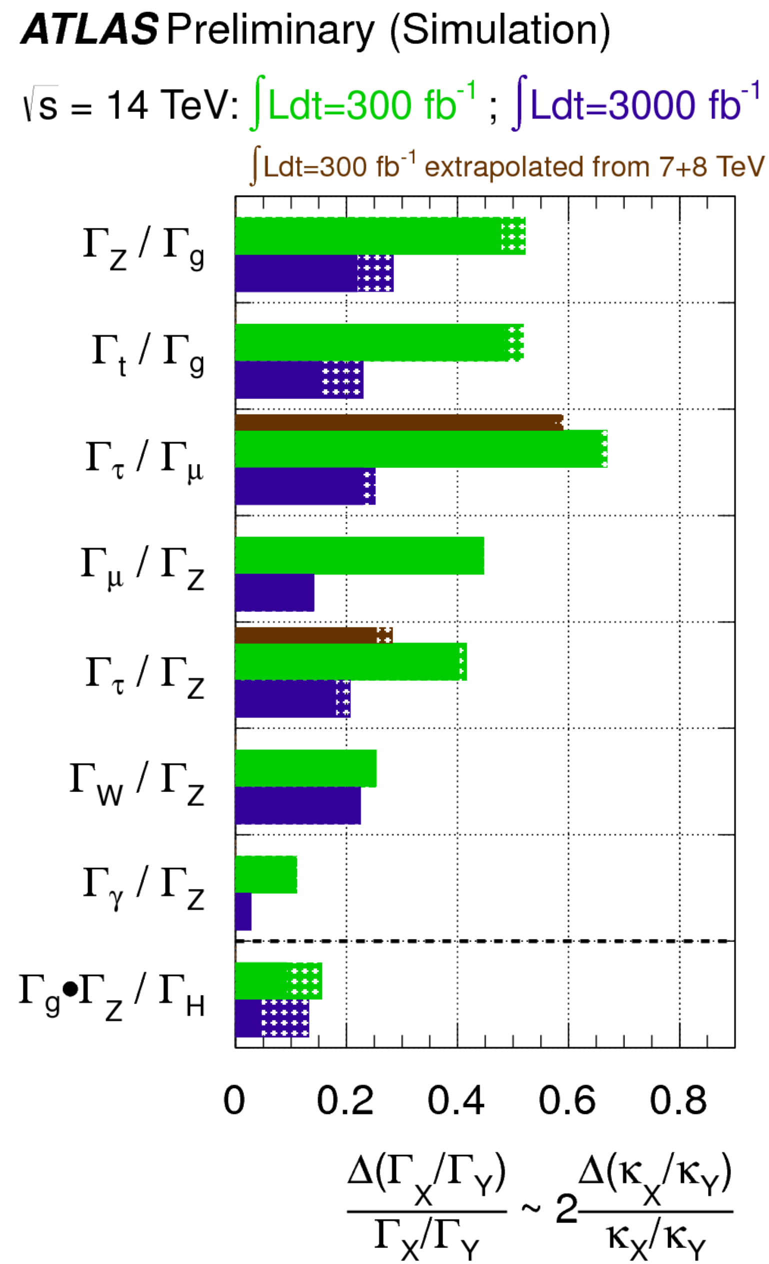
Long term prospects (1)

- With 2011+2012 dataset, possible to have first test of couplings
  - look for deviations due to Beyond SM physics
- Future of LHC
  - ~2018-2022: 300 fb^{-1}
  - > ~2022: HL-LHC: 3000 fb^{-1}
- Signal strengths:



Long term prospects (2)

- Couplings parameters
  - no measurement of total width
  - only ratios: $\frac{\Gamma_i}{\Gamma_j}$
- With 300 fb^{-1}
  - 20-60% precision
- With 3000 fb^{-1}
  - almost all couplings better than 20%
  - at minimum: ~5% uncertainties



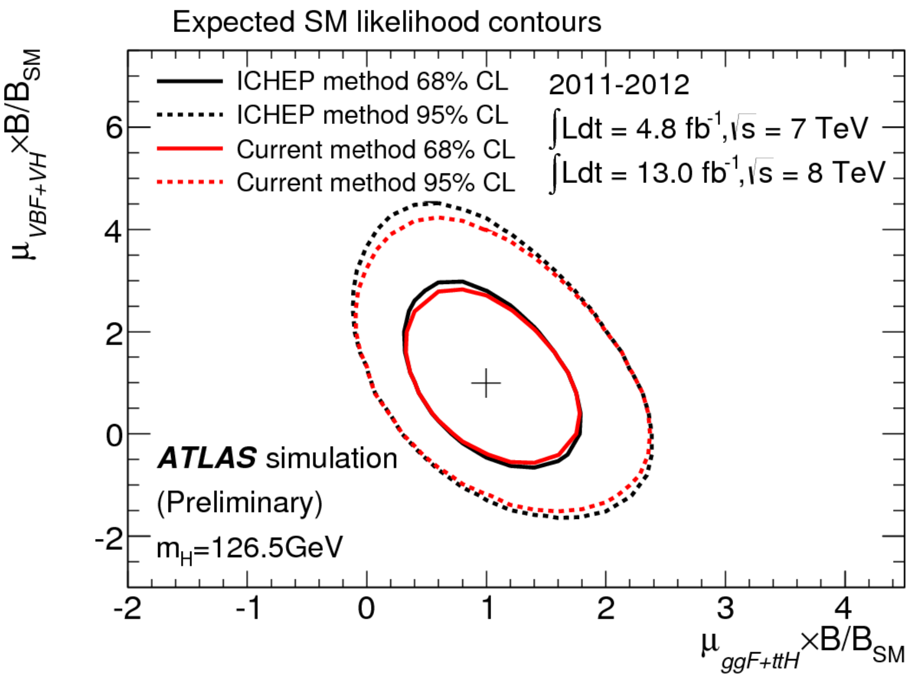
Conclusions

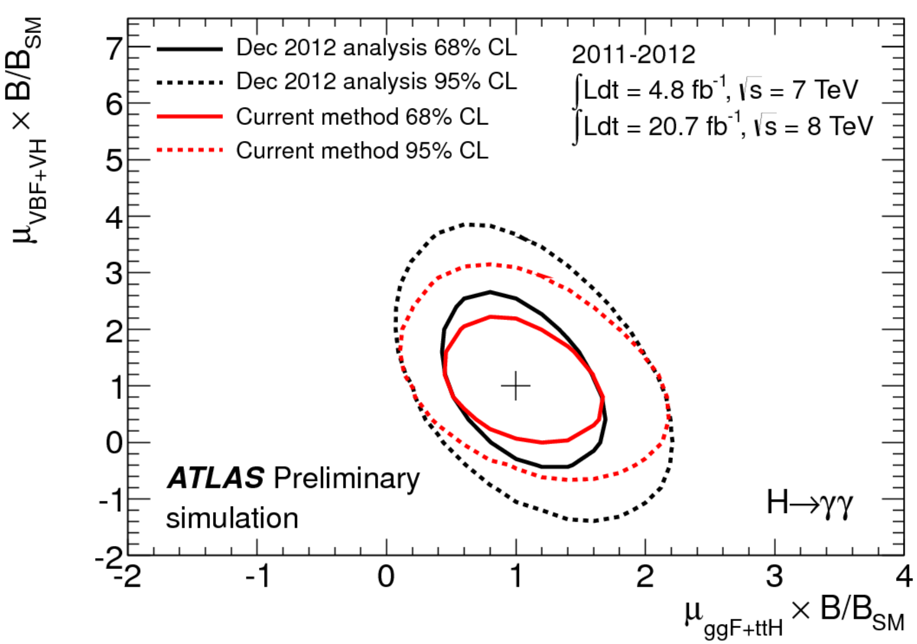
- Discovery of a Higgs-like particle: have to work on whether we need the "like"
- Many properties to measure: mass, spin, couplings
- Several decays modes available to probe the production modes and go back to couplings
- Data divided in categories enriched in production modes
  - VBF: γγ, ττ, WW
  - VH: γγ, ZZ, ττ, bb
- Global fits to extract coupling scale factors
  - test of SM hypothesis and look for Beyond SM
  - update with full luminosity (for γγ, ZZ, WW) today
- High luminosity LHC will be needed for precise measurements

Back-up slides

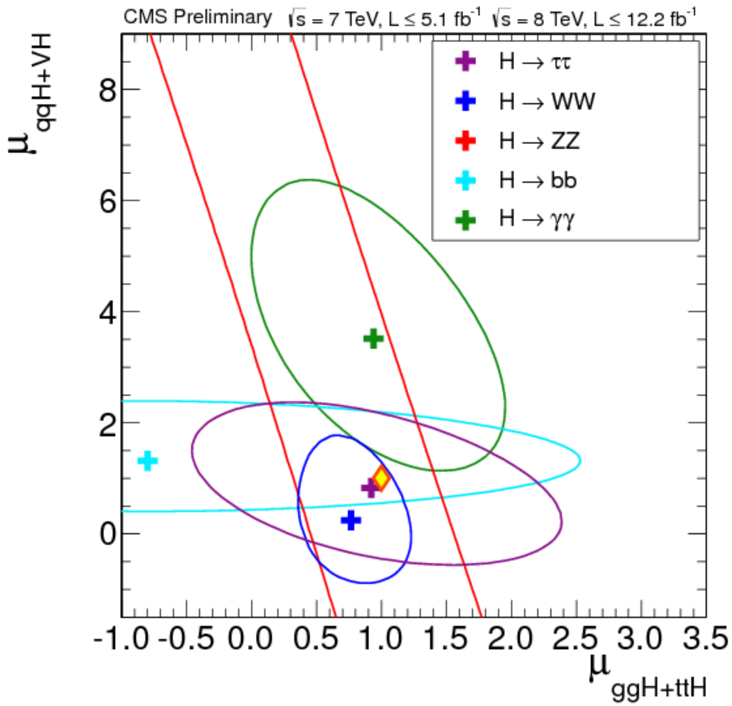
Improvement with categories

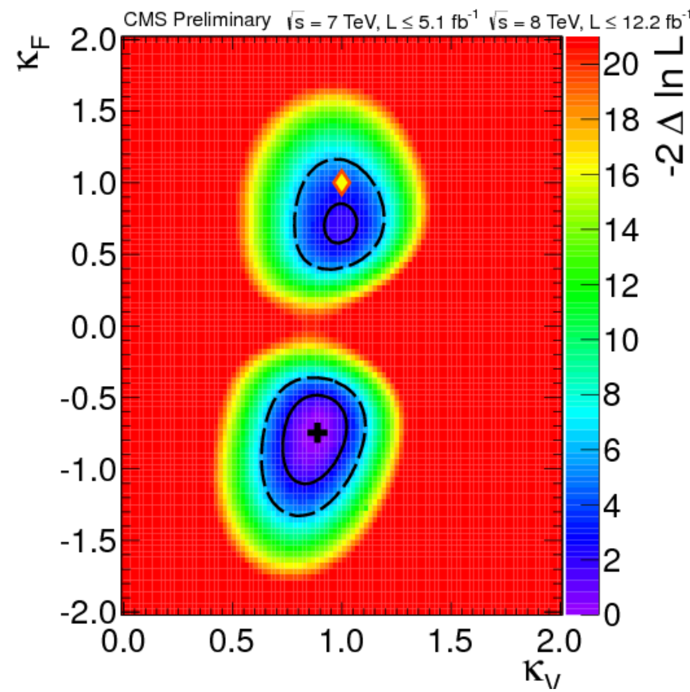
- 10 → 12 categories
  - 2 VH-enriched categories
- 12 → 14 categories
  - improve VBF-enriched cat (splitted in two)
  - 1 VH-enriched category

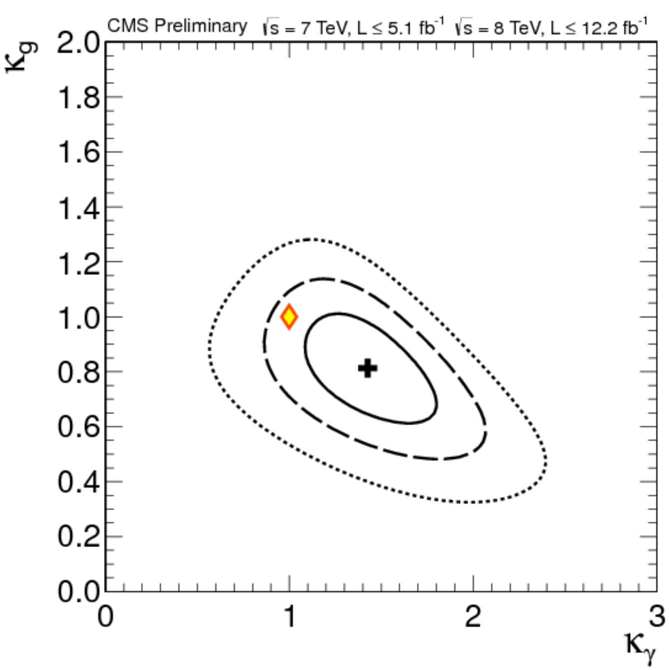


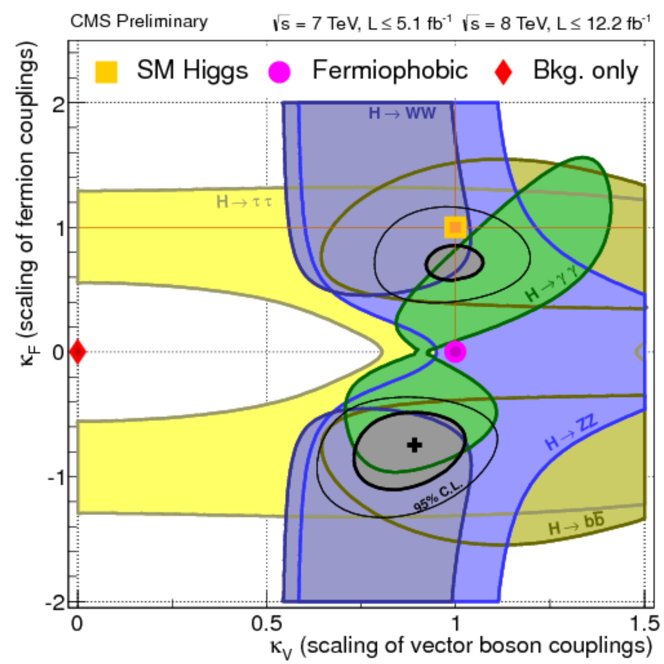


($\mu_{ggF+ttH}$, μ_{VBF+VH}) plots for CMS

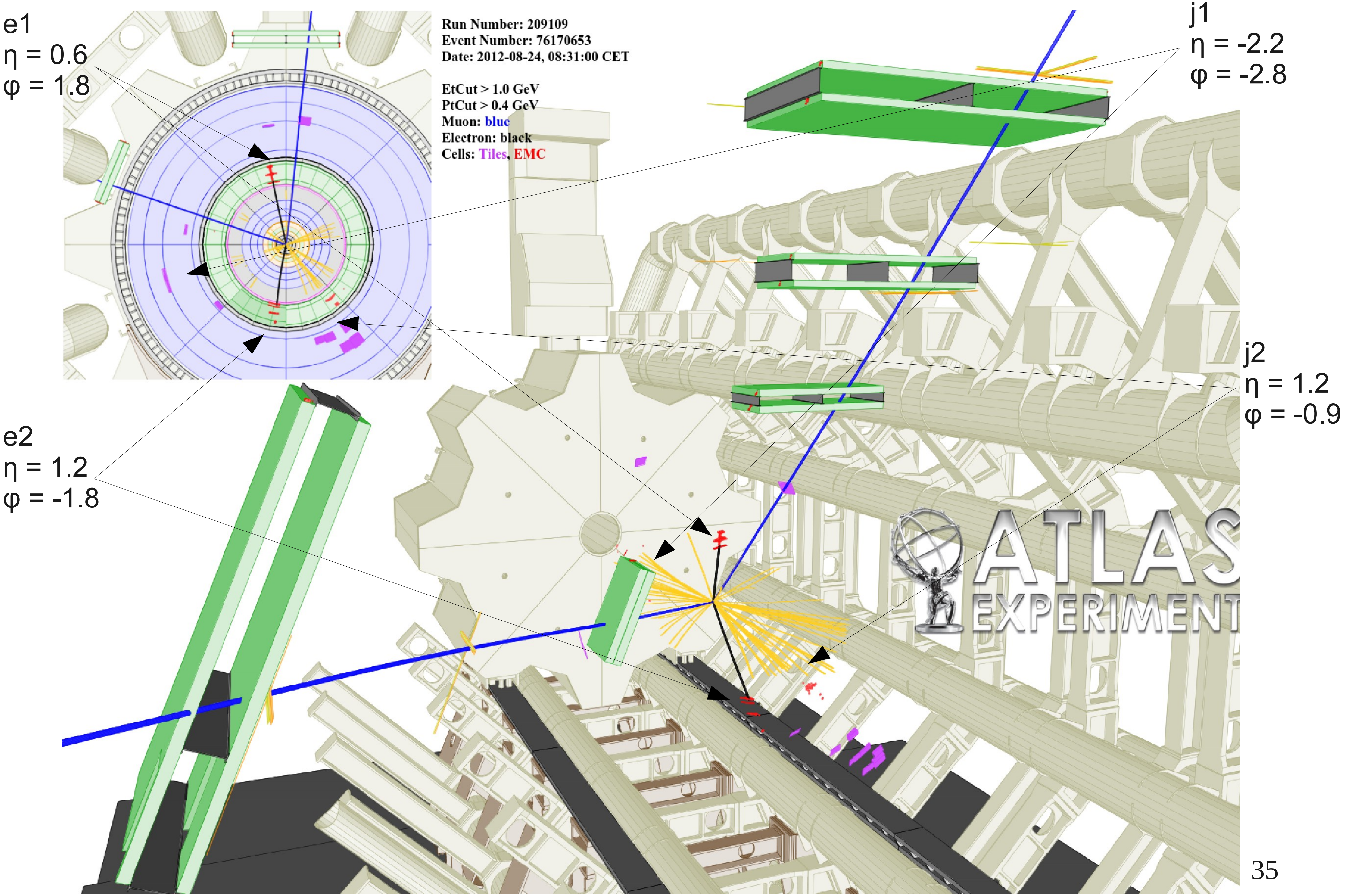








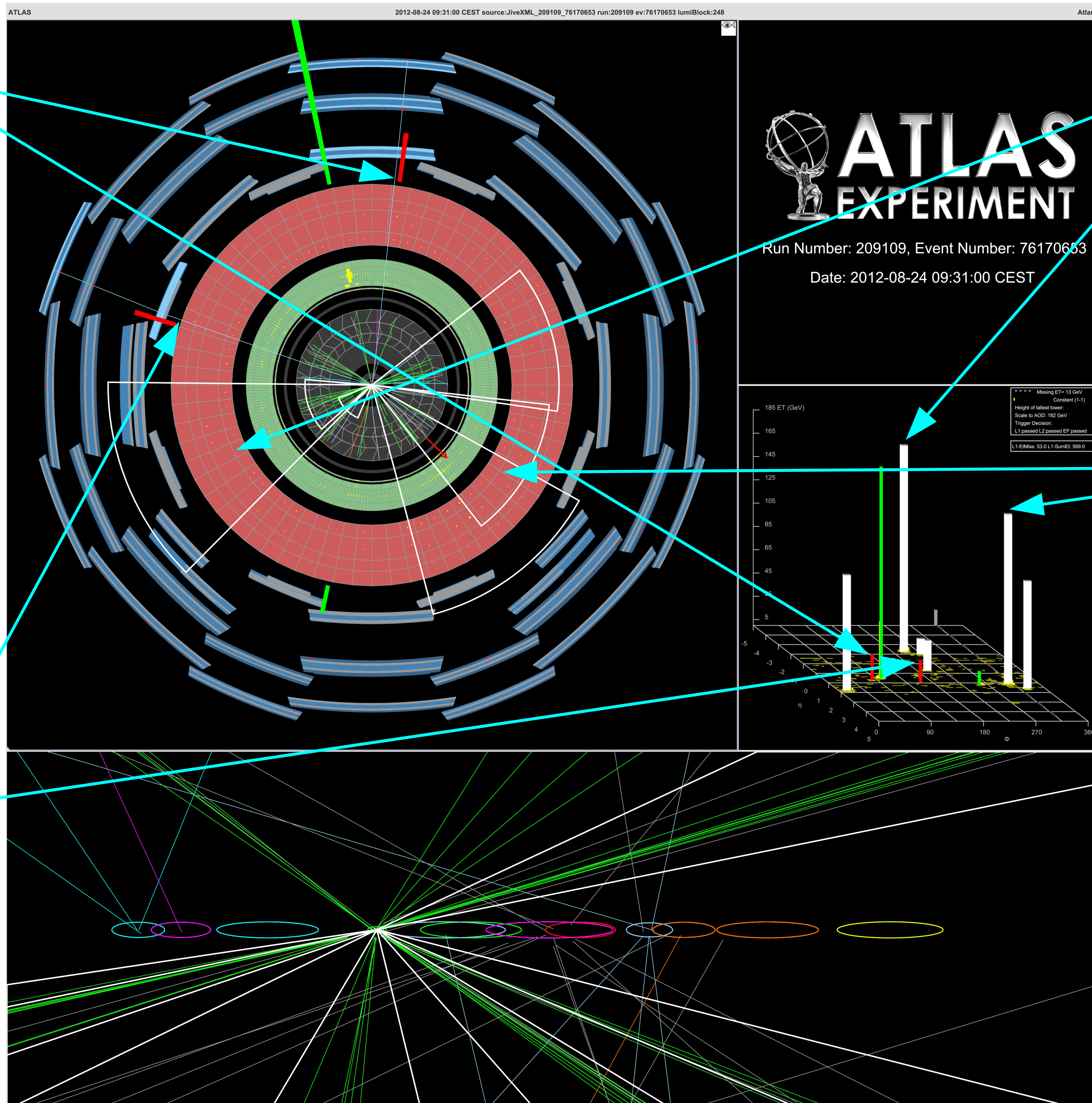
2e2μ2j event display (1)



2e2μ2j event display (2)

e1
η = 0.6
φ = 1.8

j1
η = -2.2
φ = -2.8



j2
η = 1.2
φ = -0.9

e2
η = 1.2
φ = -1.8

Input to coupling fits

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
2011 $\sqrt{s}$ =7 TeV				
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	4.8	[10]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	4.8	[11]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet}\} \otimes \{\text{low, high pile-up}\}$	4.7	[12]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, VH\}$	4.7	[13]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet}\} \otimes \{E_{\mathrm{T}}^{\mathrm{miss}} < 20\text{ GeV}, E_{\mathrm{T}}^{\mathrm{miss}} \geq 20\text{ GeV}\}$ $\oplus \{e, \mu\} \otimes \{\text{1-jet}\} \oplus \{\ell\} \otimes \{\text{2-jet}\}$	4.7	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet}\}$	4.7	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\text{ GeV}\}$	4.6	[14]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-200, \geq 200\text{ GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-200, \geq 200\text{ GeV}\}$	4.7	
2012 $\sqrt{s}$ =8 TeV				
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	5.8	[10]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	5.9	[11]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet, 2-jet}\}$	5.8	[15]

Leading order coupling scale factors (1)

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \quad (5)$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H) \quad (6)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2 \quad (7)$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2 \quad (8)$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2 \quad (9)$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2 \quad (10)$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2 \quad (11)$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2 \quad (12)$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2 \quad (13)$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases} \quad (14)$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases} \quad (15)$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2 \quad (16)$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} = \begin{cases} \kappa_{(H\to gg)}^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \quad (17)$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2 \quad (18)$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2 \quad (19)$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2 \quad (20)$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases} \quad (21)$$

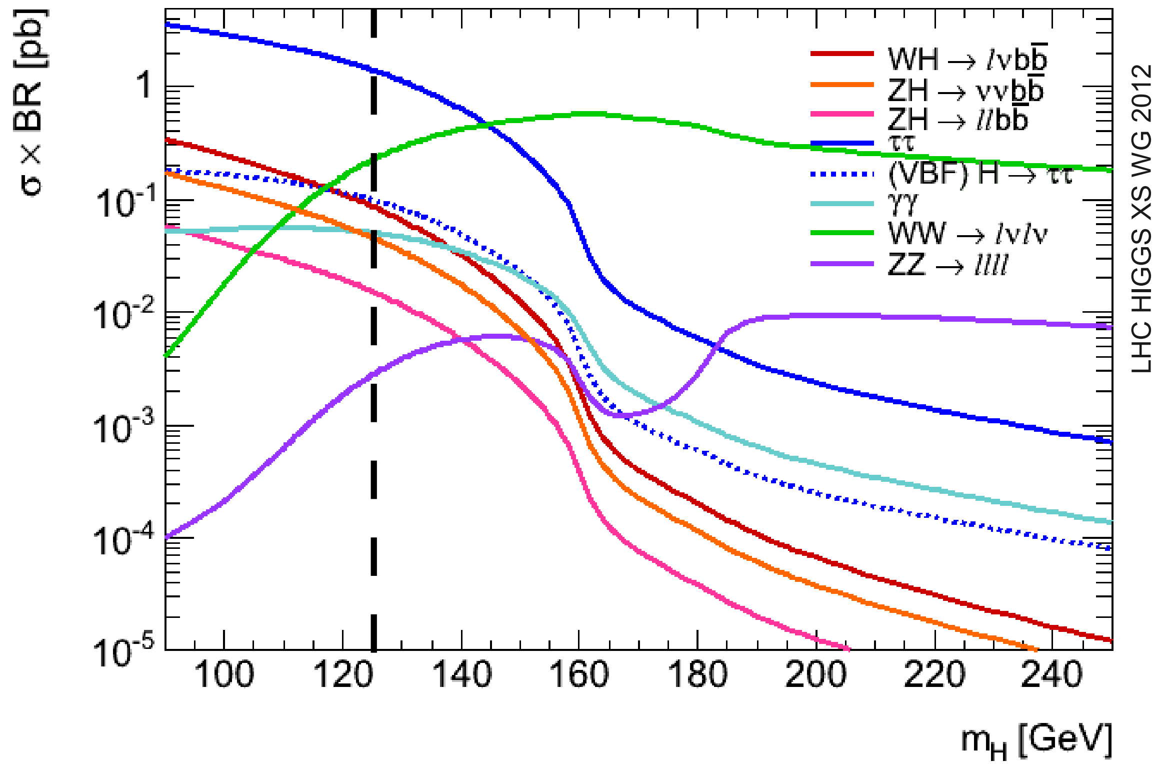
Leading order coupling scale factors (2)

- VBF cross section: $\kappa^2_{VBF}(\kappa_W, \kappa_Z, m_T) = \dfrac{\kappa^2_W . \sigma_{WF}(m_H) + \kappa^2_Z . \sigma_{ZF}(m_H)}{\sigma_{WF}(m_H) + \sigma_{ZF}(m_H)}$

- gg production/decay:
  - $\kappa^2_g(\kappa_b, \kappa_t, m_T) = \dfrac{\kappa^2_t . \sigma^{tt}_{ggF}(m_H) + \kappa^2_b . \sigma^{bb}_{ggF}(m_H) + \kappa_t \kappa_b . \sigma^{tb}_{ggF}(m_H)}{\sigma^{tt}_{ggF}(m_H) + \sigma^{bb}_{ggF}(m_H) + \sigma^{tb}_{ggF}(m_H)}$
  - $\dfrac{\Gamma_{gg}}{\Gamma^{SM}_{gg}(m_H)} = \dfrac{\kappa^2_t . \Gamma^{tt}_{ggF}(m_H) + \kappa^2_b . \Gamma^{bb}_{ggF}(m_H) + \kappa_t \kappa_b . \Gamma^{tb}_{ggF}(m_H)}{\Gamma^{tt}_{ggF}(m_H) + \Gamma^{bb}_{ggF}(m_H) + \Gamma^{tb}_{ggF}(m_H)}$

- $H \rightarrow \gamma\gamma$ decay:
  - $\kappa^2_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_T) = \dfrac{\sum_{ij} \kappa_i \kappa_j . \Gamma^{ij}_{\gamma\gamma}(m_H)}{\sum_{ij} \Gamma^{ij}_{\gamma\gamma}(m_H)}$
  - ij = bb, tt, ττ, WW, bt, bτ, bW, tτ, tW, τW

Channels studied

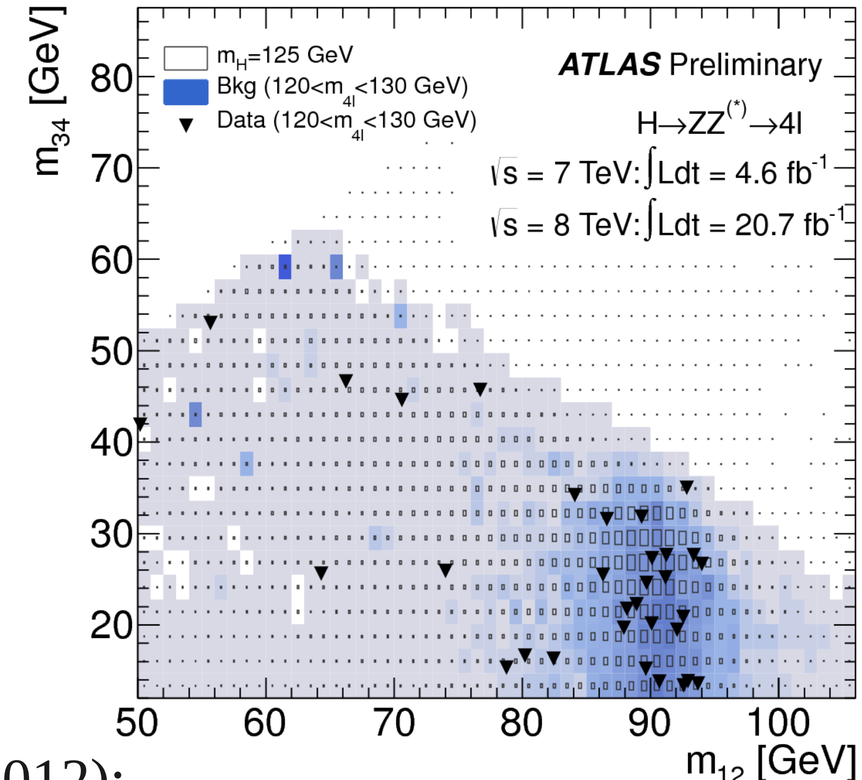


- $\sqrt{s} = 8$ TeV

	expected reco Nsignal	S/B	main backgrounds	
ZZ→4l	~15	100%	ZZ, Z+jets, top	21 fb^{-1}
γγ	~400	1-20%	γγ, γj, jj	21 fb^{-1}
WW→lνlν	~100	10%	WW, W+jets, top, ...	21 fb^{-1}
ττ	~150	0.3-30%	Z, Z+jets, top	13 fb^{-1}
VH→b$\bar{b}$	~70	0.3-2%	Wbb, Zbb, top	13 fb^{-1}

H→ZZ* (1)

- Two same flavour, opposite sign lepton pairs
  - well identified and isolated
  - p_T^l > 20-15-10-7/6 GeV



- $50 < m_{12} < 106$ GeV
- $12 < m_{34} < 115$ GeV for $m_{4l} < 145$ GeV

- Number of expected signal events (2011+2012):

category	ggF	VBF	VH
ggF-like	15.7	0.93	0.76
VBF-like	0.31	0.49	0.01
VH-like	0.07	-	0.17

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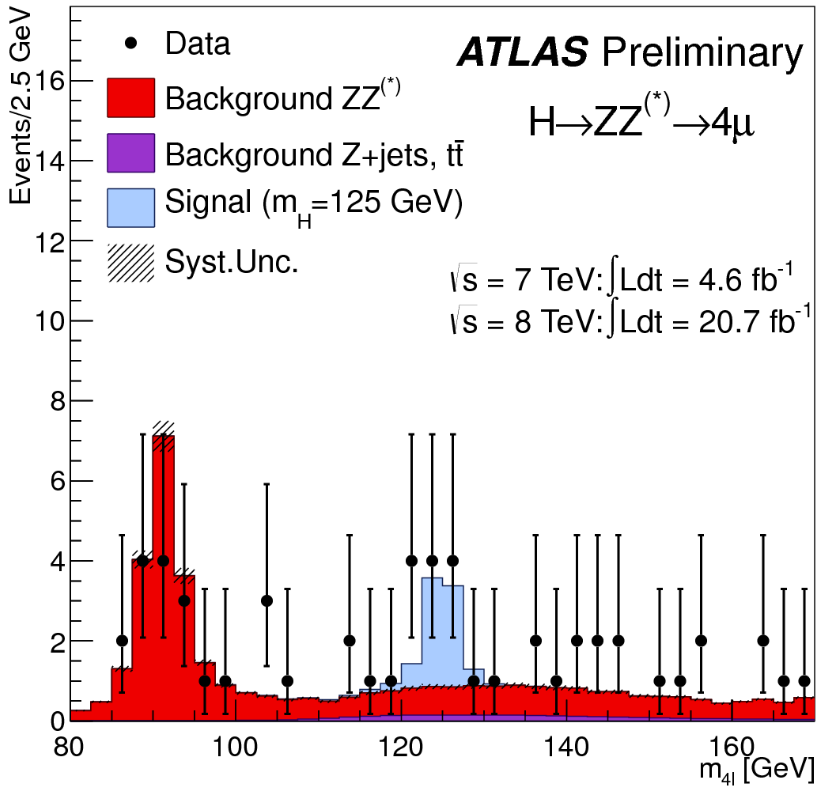
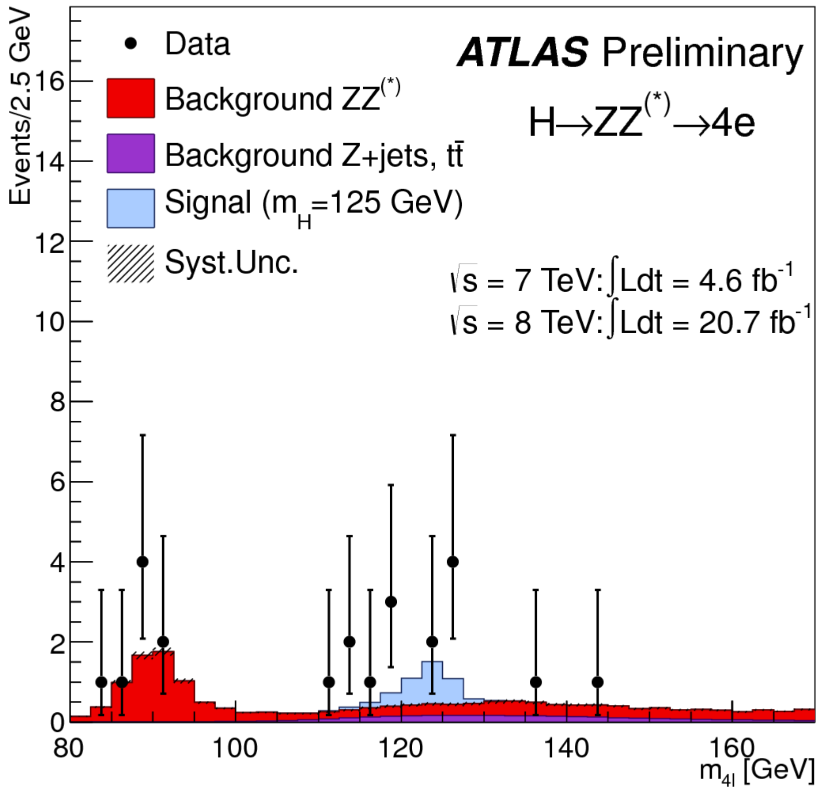
H→ZZ* (2)



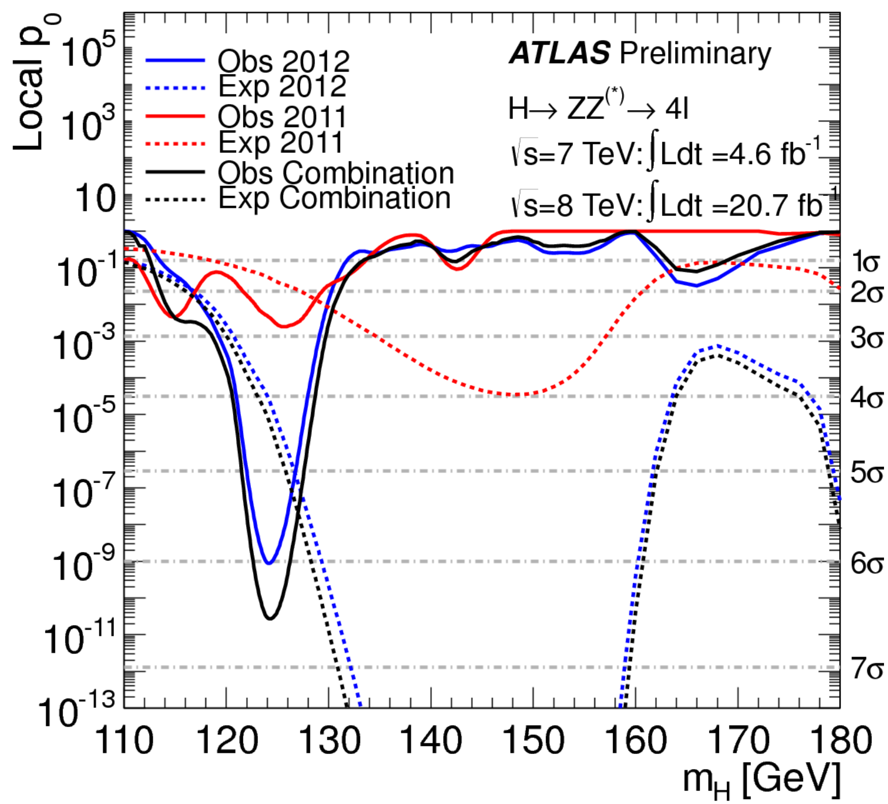


- In 120-130 GeV window (7+8 TeV):

	4μ	2e2μ	2μ2e	4e	total
signal	6.3	3.0	4.0	2.6	15.9
ZZ	2.8	1.4	2.1	1.2	7.4
Z, Zb$\bar{b}$, t$\bar{t}$	0.55	1.6	0.6	1.1	3.7
observed	13	5	8	6	32

H→ZZ* (3)

- Excess:
  - expected: 3.1σ
  - observed: 4.1σ



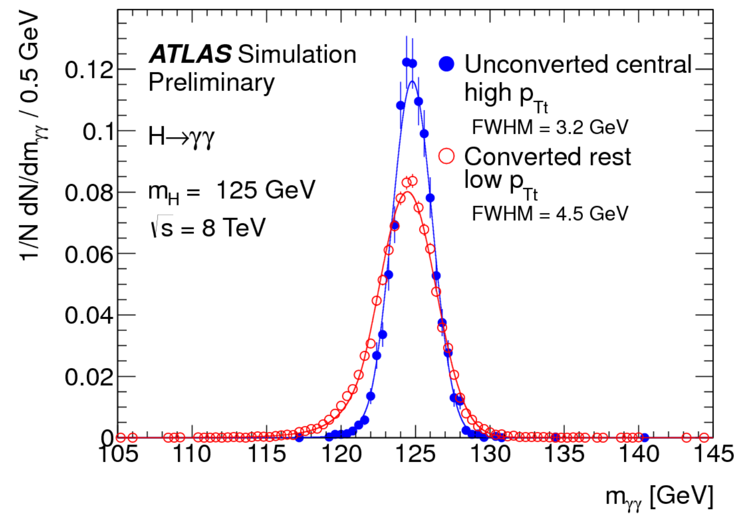
- Best fit for mass:

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

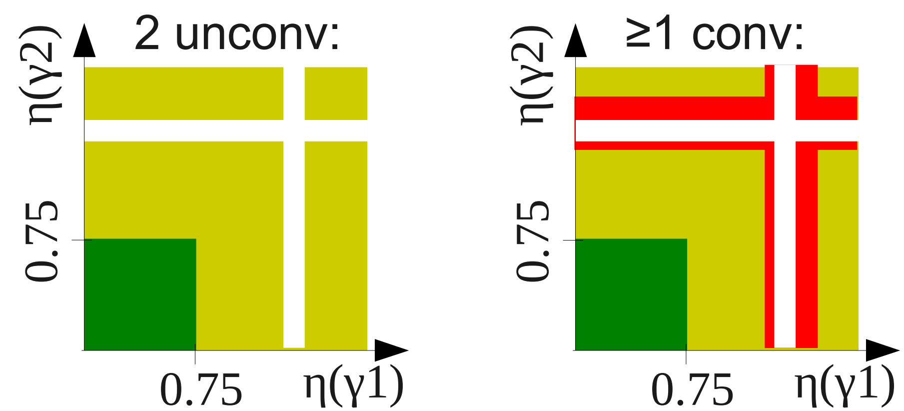
- Signal strength at 124.3 GeV: $\boxed{\mu = 1.7^{+0.5}_{-0.4}}$

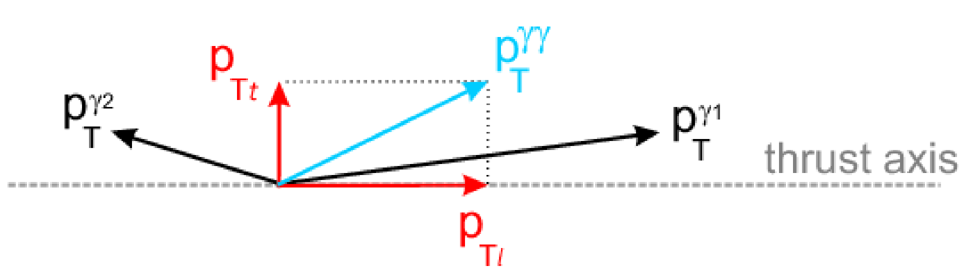
H→γγ (1)

- Two well identified and isolated photons
  - $E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV
  - γγ purity: 75%



- Events divided in 12 exclusive categories
  - with ≠ resolution: 1.4 → 2.5 GeV
  - with ≠ S/B: 0.014 → 0.204
  - with ≠ production modes fractions
    - 9 ggF enriched
    - 1 VBF enriched
    - 2 VH enriched





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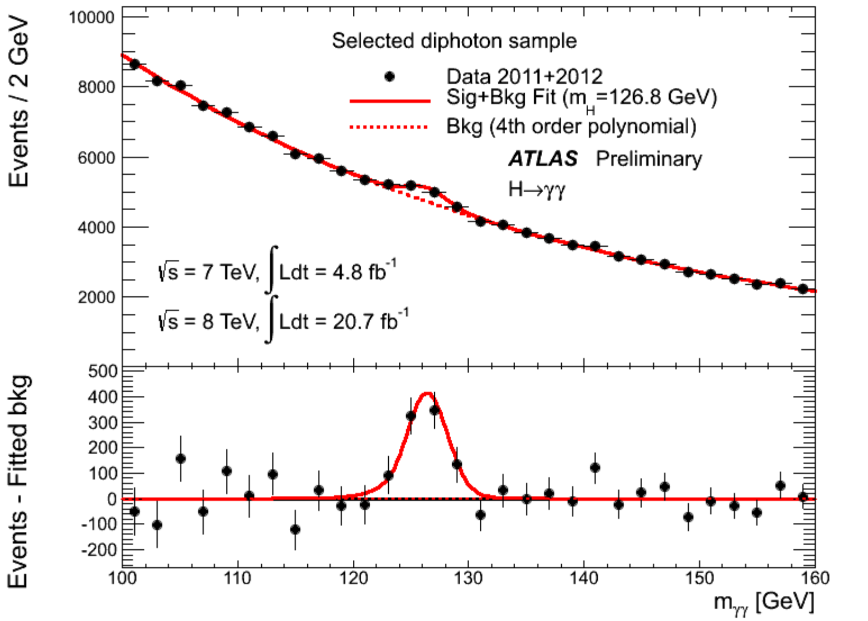
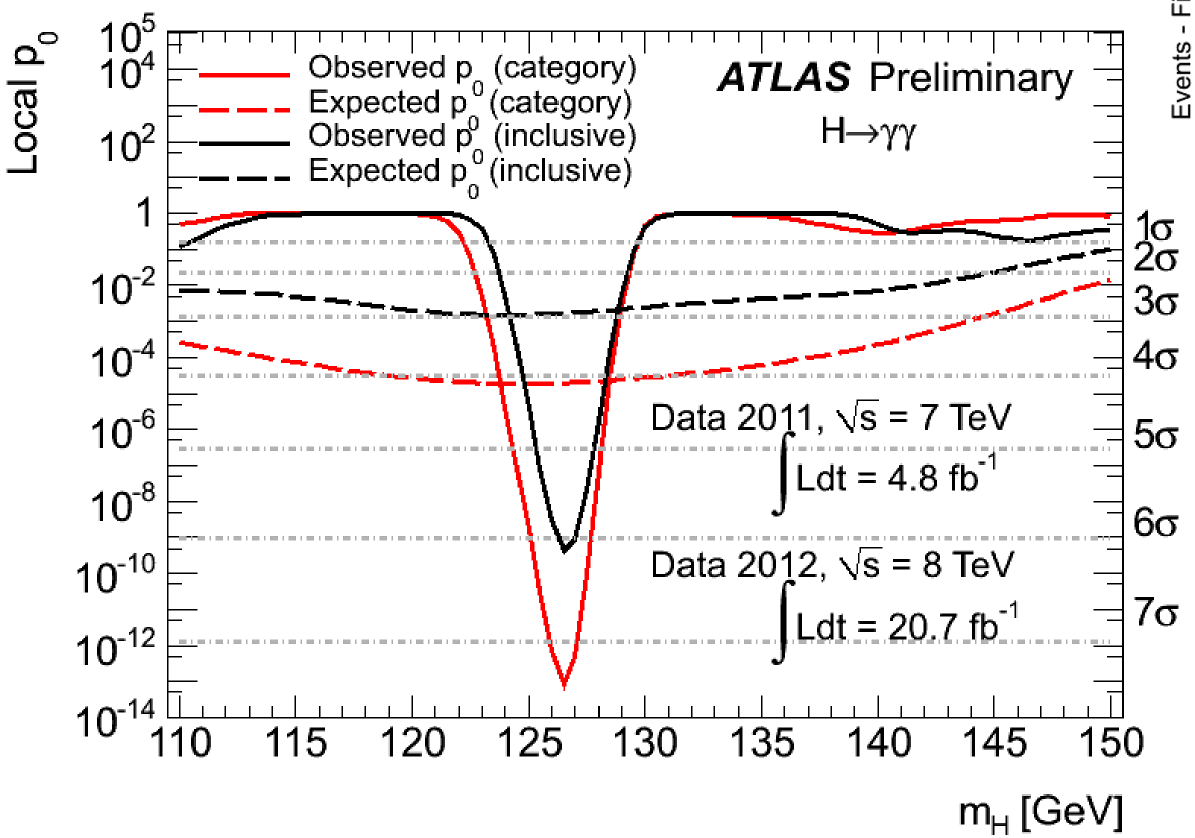
H→γγ (2)

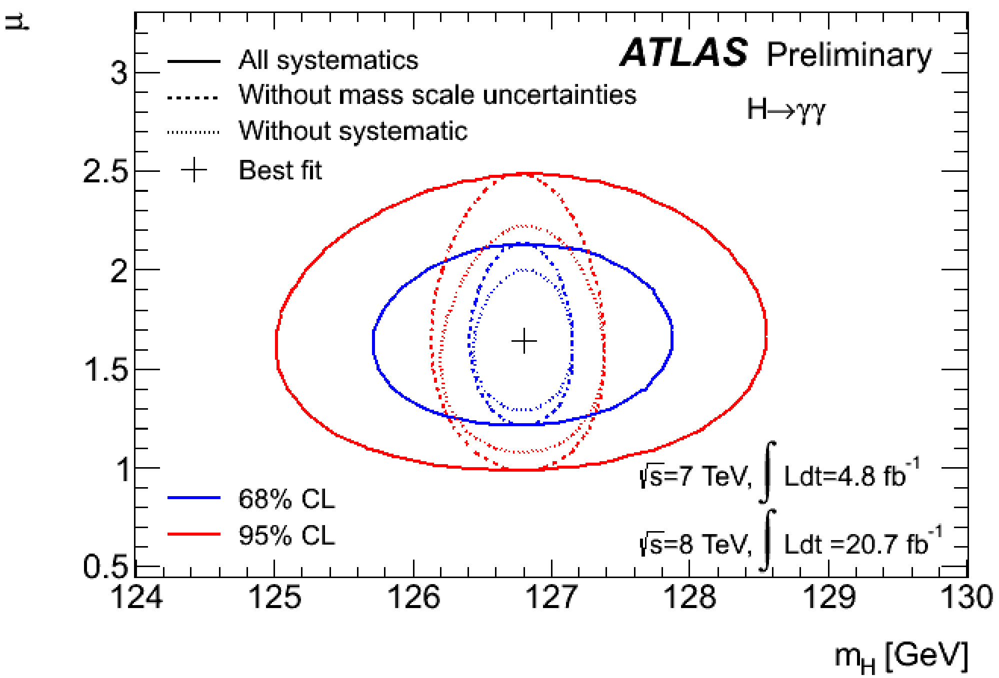
- Observation confirmed for γγ channel
  - observed: 7.4 σ at 126.5 GeV
  - expected: 4.1 σ





H→γγ (3)

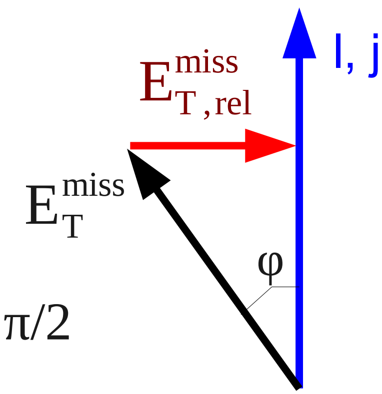
- Best fit for mass:
  - 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

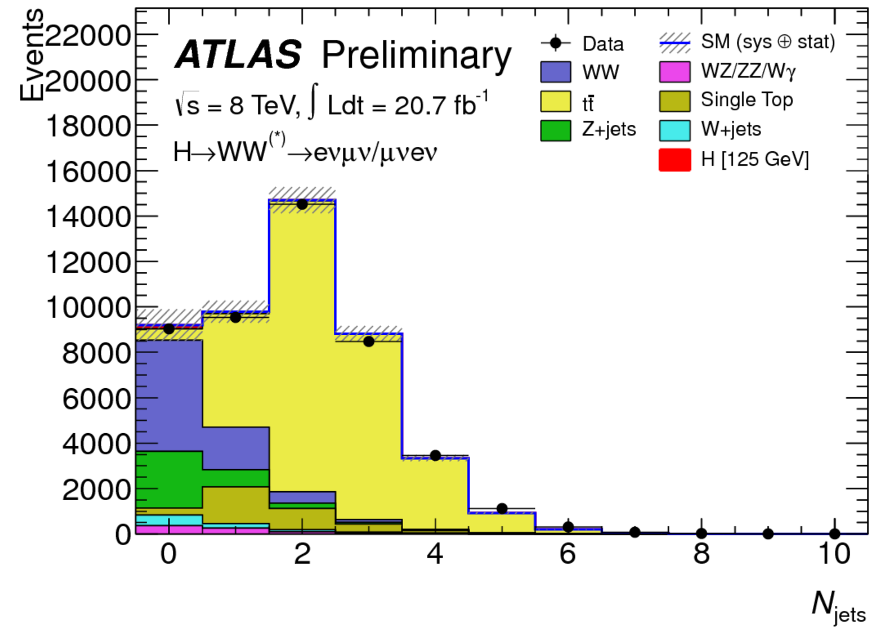


- Best fit signal strength at 126 .8 GeV
  - $\boxed{\mu = 1.65 \pm 0.24\,(\text{stat})^{+0.25}_{-0.18}(\text{syst})}$
  - 2.3 σ from SM hypothesis

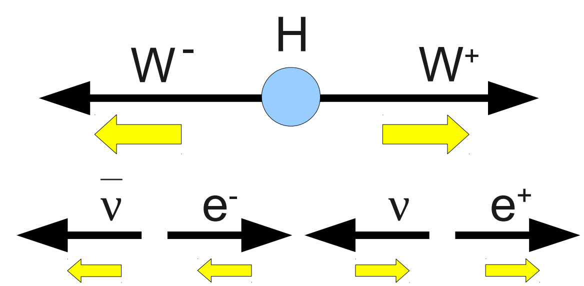
H→WW* (1)

- $H \to WW^* \to$ eνμν only
- isolated leptons with $p_T > 25/15$ GeV
- $E_{T\ \ rel}^{miss} > 25$ GeV
  - E_T^{miss} if $\Delta\varphi > \pi/2$
  - $E_T^{miss}.\sin(\Delta\varphi)$ if $\Delta\varphi < \pi/2$





- Spin correlations
  - $m_{ll} < 50$ GeV and $\Delta\varphi_{ll} < 1.8$



- Divide events in H+0 jet, H+1 jet and H+2 jets

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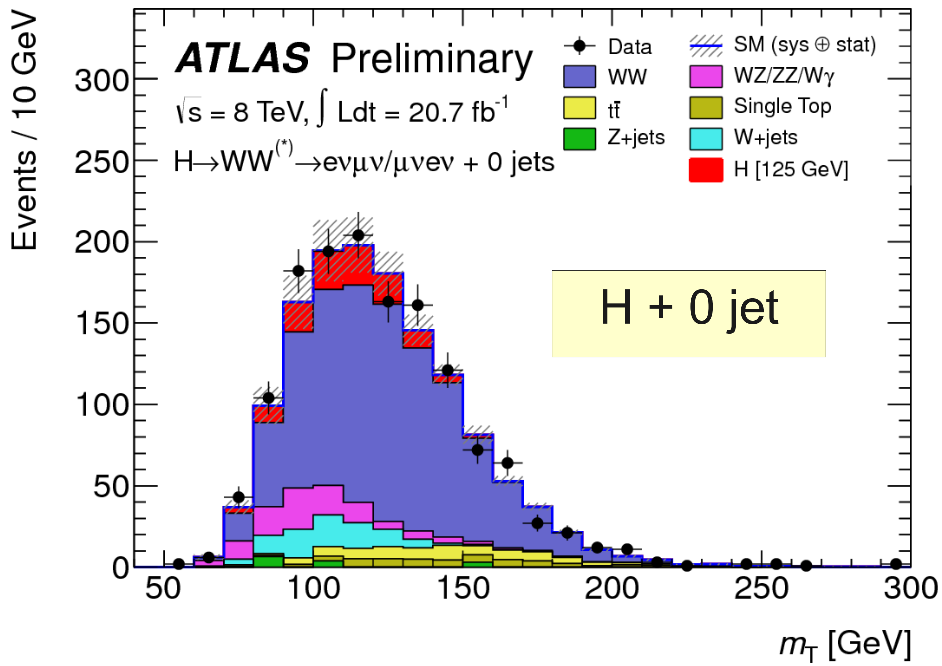
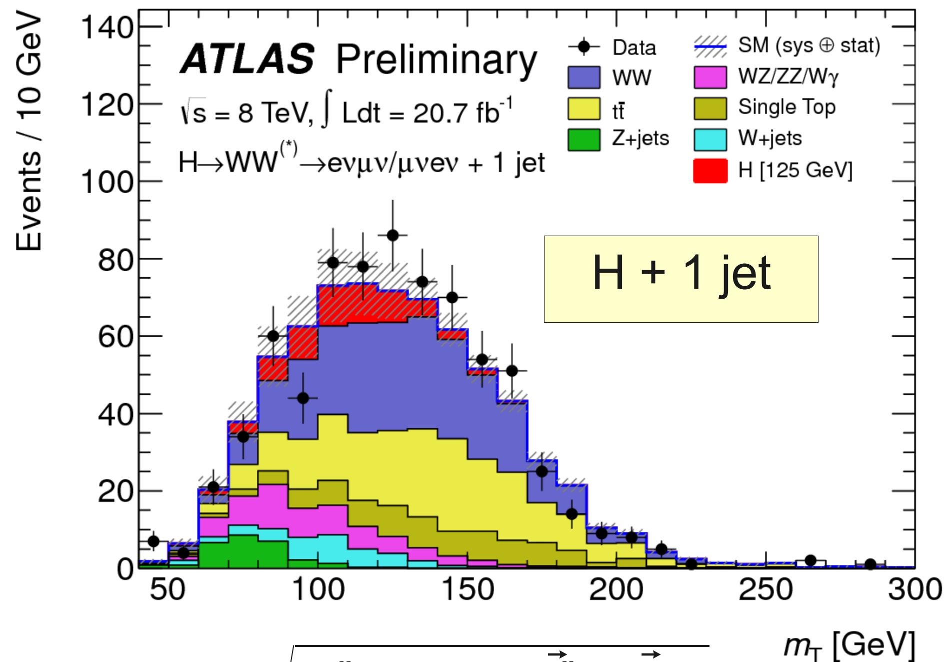
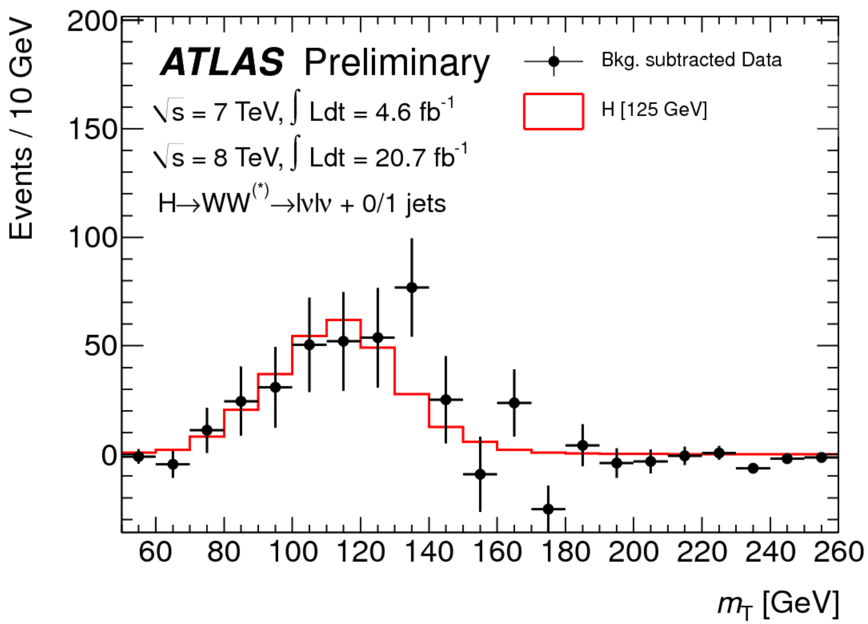
H→WW* (2)







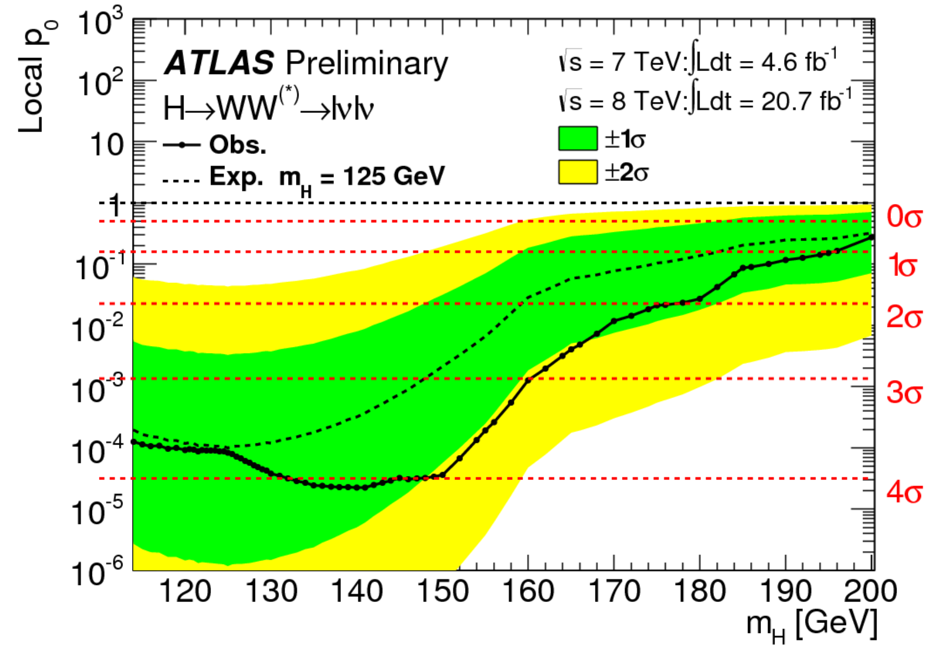
$$m_T = \sqrt{\left(E_T^{ll} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\,ll} + \vec{E}_T^{miss}\right|^2}$$

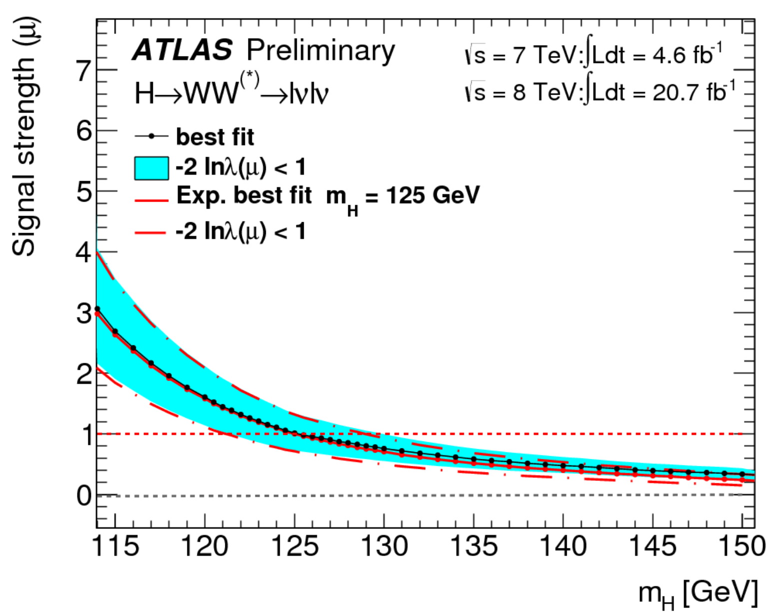
$$E_T^{ll} = \sqrt{\left|\vec{p}_T^{\,ll}\right|^2 + m_{ll}^2}$$

	H + 0 jet	H + 1jet	H + 2jets
signal	97	40	10.6
background	739	261	36
observed	831	309	55

H→WW* (3)

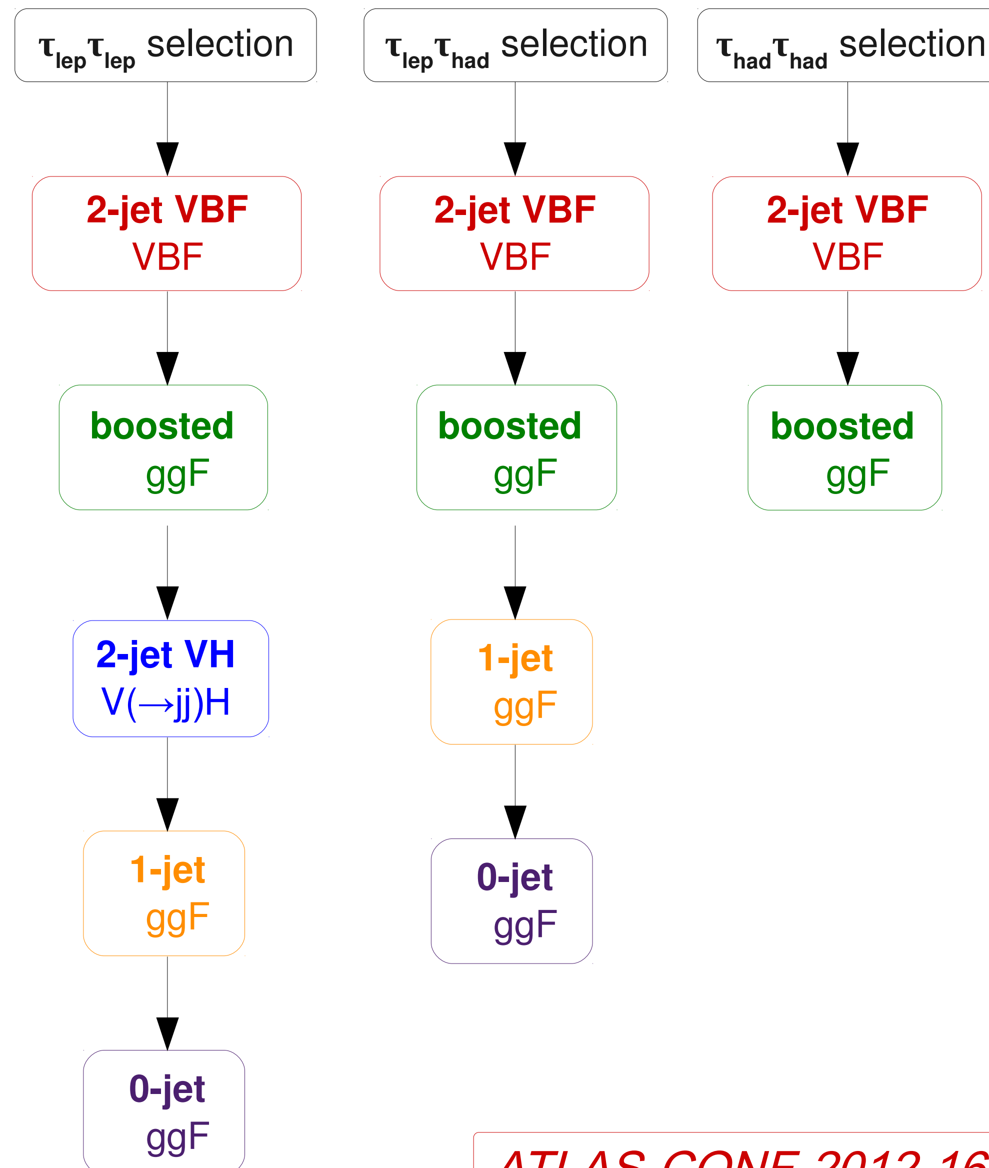
- Excess of events for $m_H < 150$ GeV
- For $m_H = 125$ GeV
  - observed: 3.8 σ
  - expected: 3.7 σ
- Signal strength at 125 GeV:
  - $\boxed{\mu = 1.01 \pm 0.31}$





$H \to \tau\tau$ (1)

- Quite large σxBR,
  - but large bkg from $Z \to \tau\tau$
- Separate $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- VBF category
  - 2 forward jets
- Boosted category
  - $m_{\tau\tau}$ better resolution



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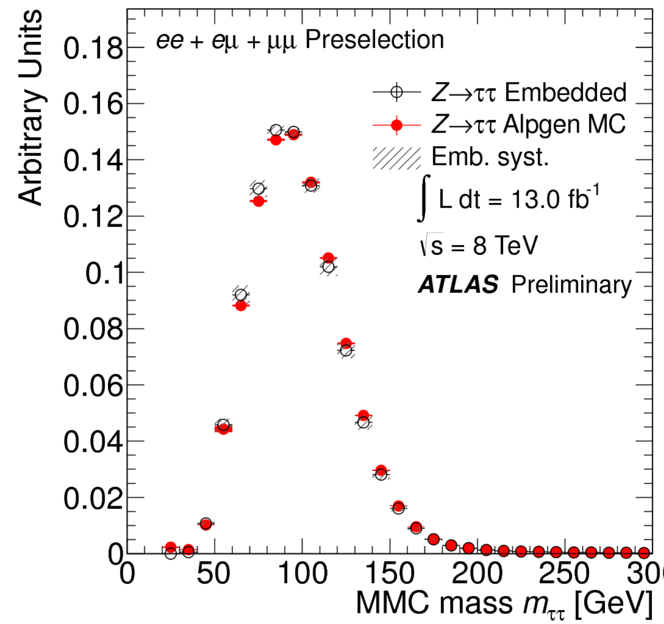
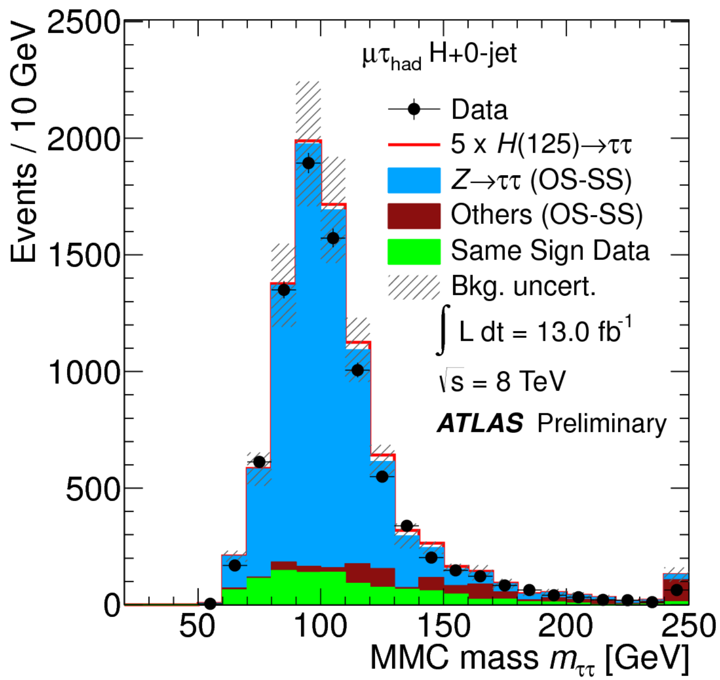
H→ττ (2)

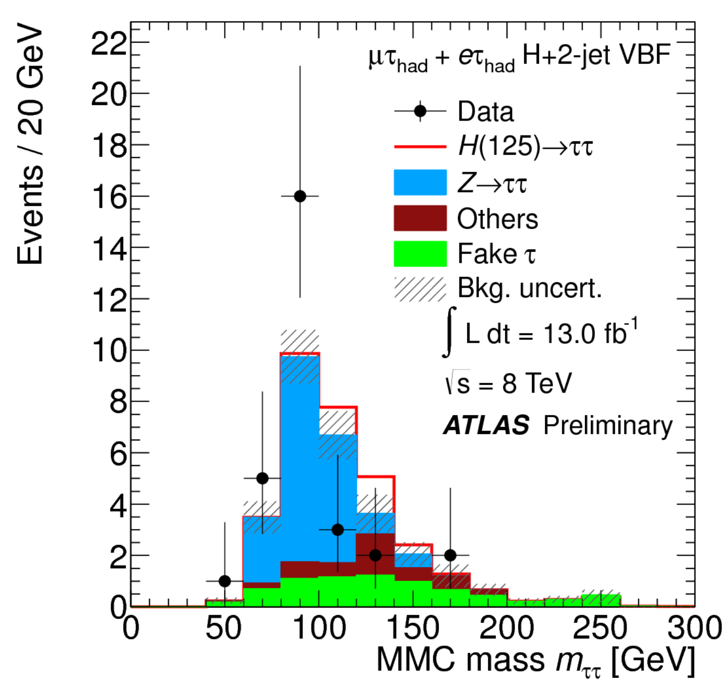
- Main background: Z → ττ, "embedded"
  - data Z → μμ
  - μ replaced by simulated τ

- Lowest and highest S/B:

τlepτhad	H + 0 jet	VBF
signal	76.3	4.04
background	18100	38.5
observed	17334	39

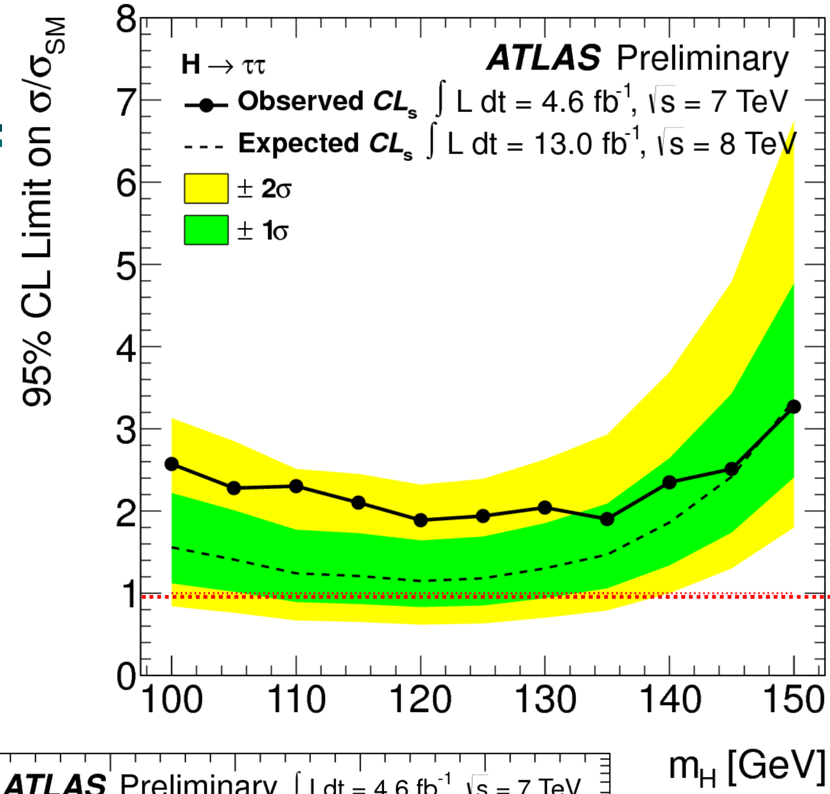


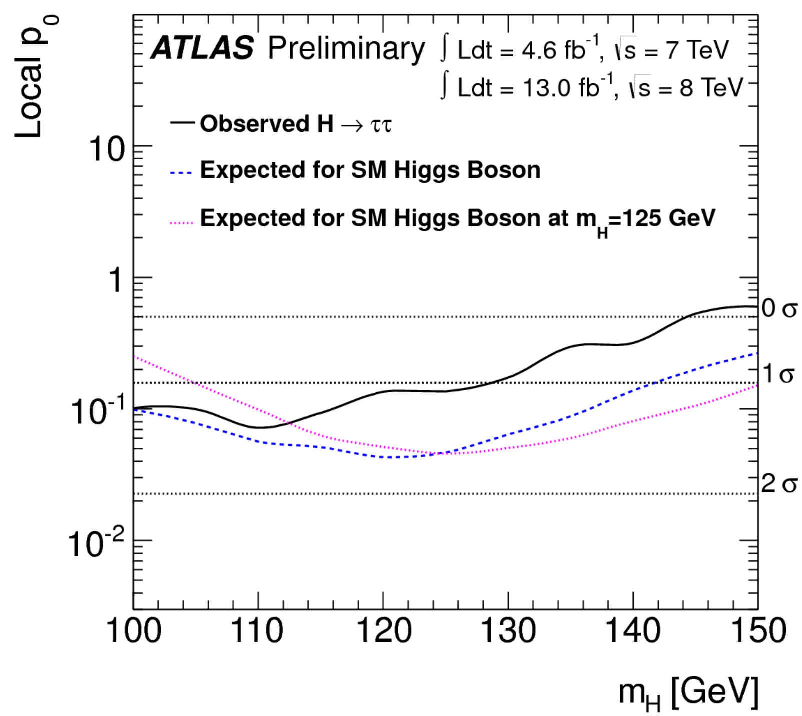




H→ττ (3)

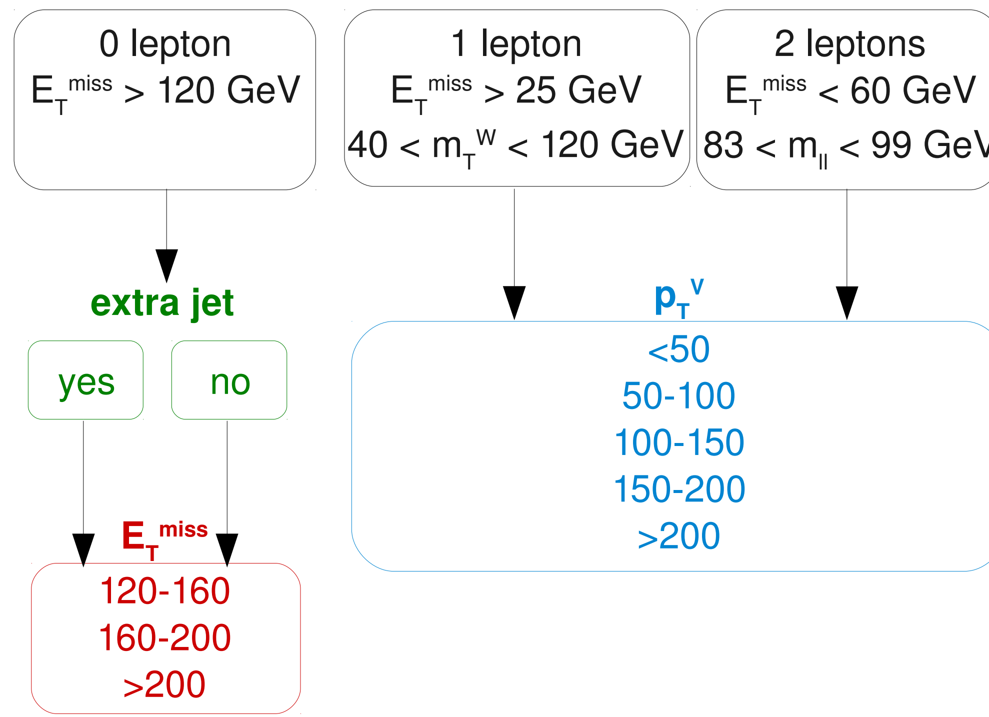
- 95% CL exclusion at m_H = 125 GeV:
  - observed: 1.9*SM
  - expected: 1.2*SM
- p_0 at m_H = 125 GeV:
  - observed: 1.1σ
  - expected: 1.7σ
- Signal strength at m_H = 125 GeV:
  - $\boxed{\mu = 0.7 \pm 0.7}$





$H \rightarrow b\bar{b}$ (1)

- BR($H \rightarrow b\bar{b}$) = 57.7% at m_H = 125 GeV
  - but only WH, ZH
- 2 b-jets
  - 70% eff
  - p_T > 45/20 GeV
- $Z(\rightarrow \nu\nu)H$, $W(\rightarrow l\nu)H$, $Z(\rightarrow ll)H$
- 16 categories



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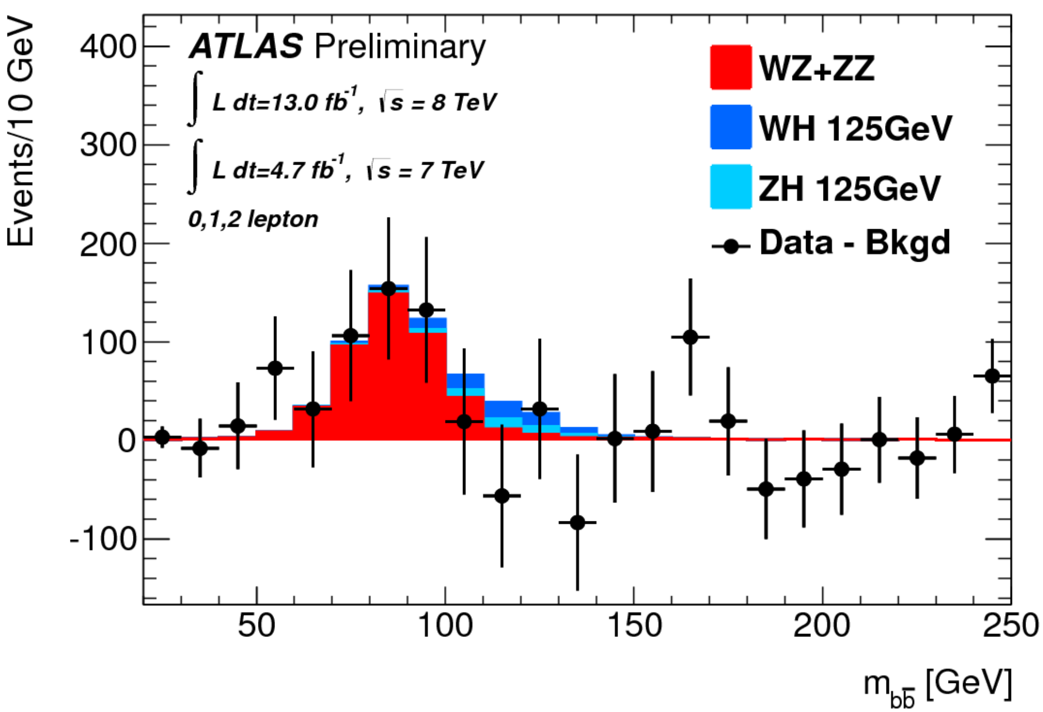
H→b$\bar{b}$ (2)

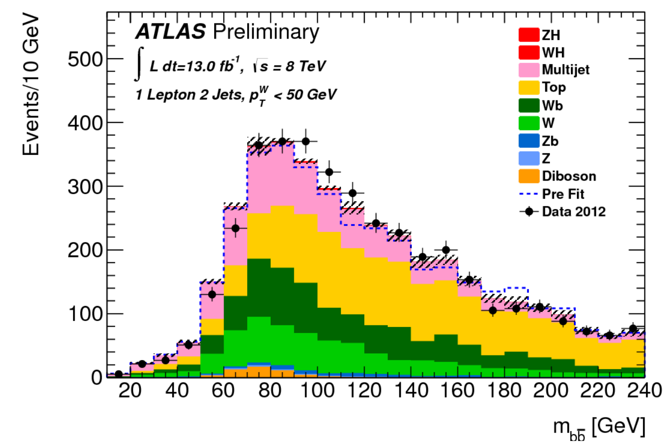
- Main backgrounds
  - t$\bar{t}$
  - W+jets, Z+jets

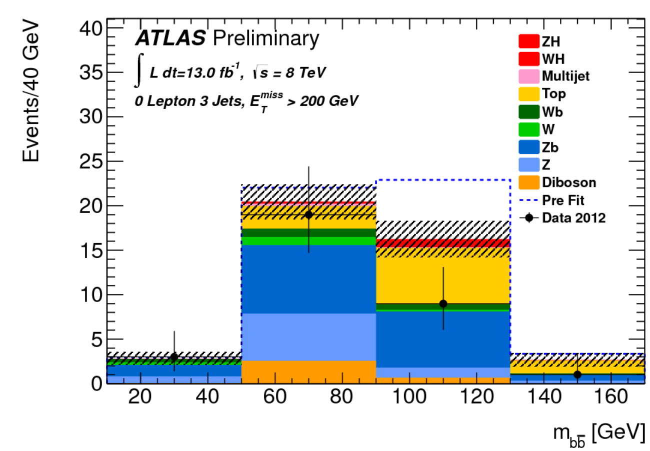
- Lowest and highest S/B:

	1 lepton p_T^W<50 GeV	0 lepton, 3 jets E_T^{miss} > 200 GeV
signal	10.9	1.3
background	3810	42
observed	3821	32

- All but di-boson bkg substraction:

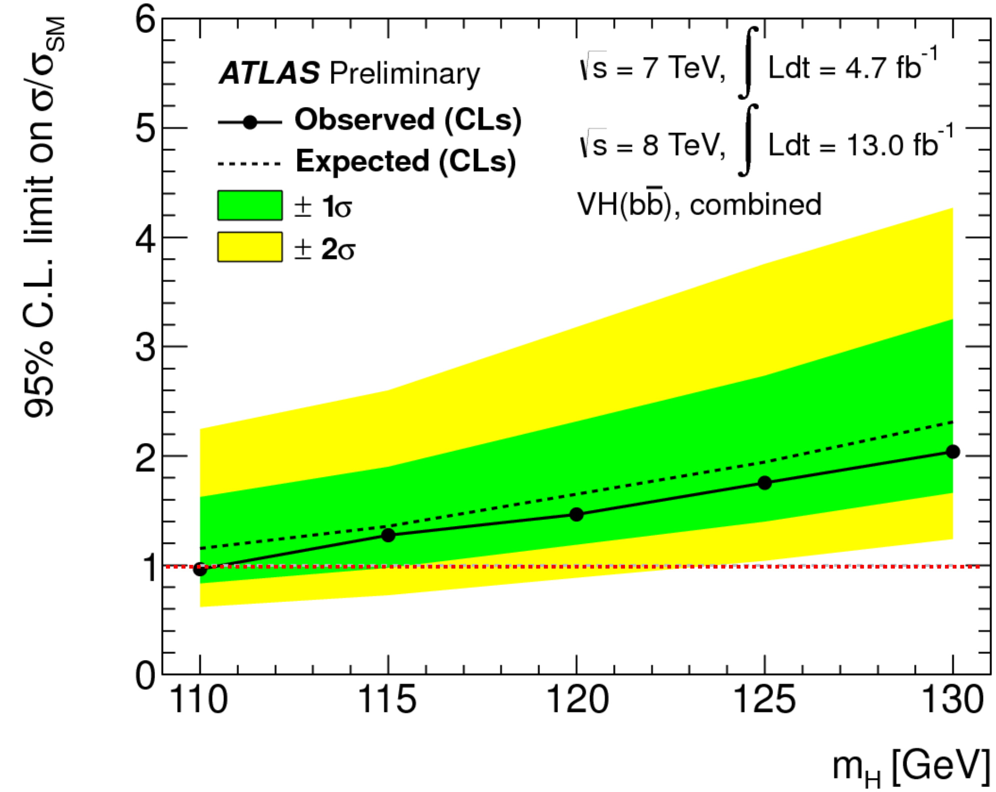




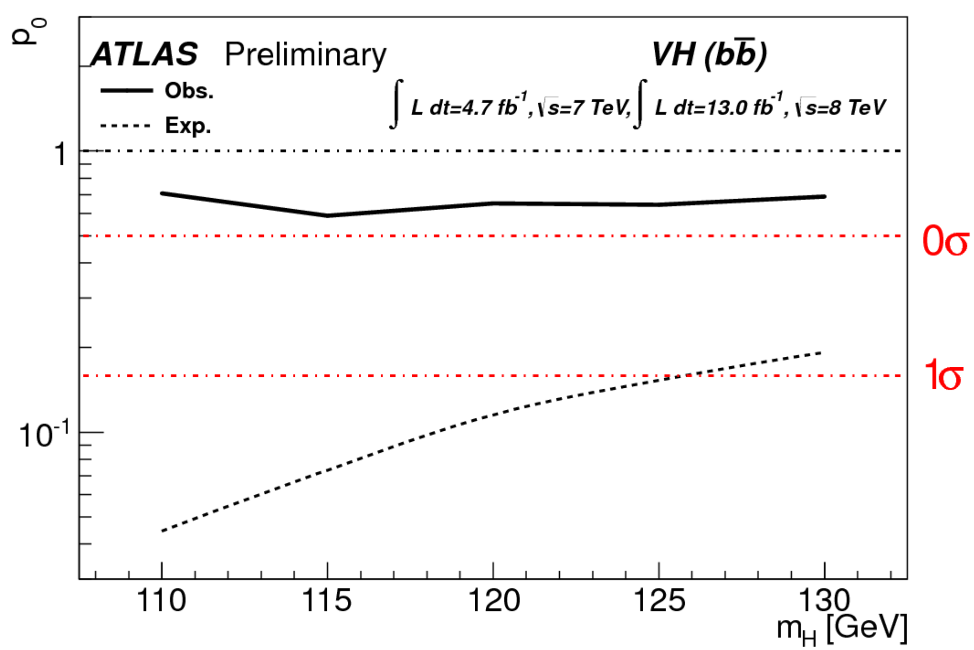


H→$b\bar{b}$ (3)

- 95% CL exclusion at m_H = 125 GeV:
  - observed: 1.8*SM
  - expected: 1.9*SM

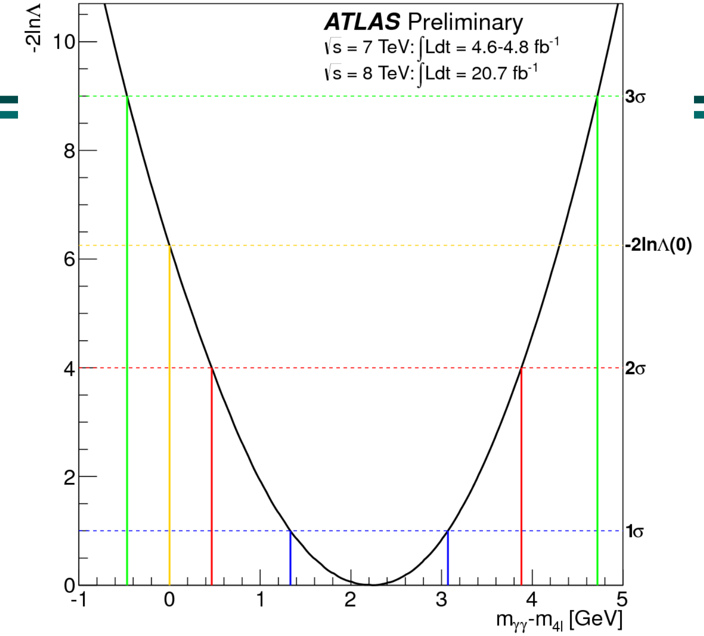


- Signal strength at m_H = 125 GeV:
  - $\boxed{\mu = -0.4 \pm 0.7\ (\mathrm{stat}) \pm 0.8\ (\mathrm{syst})}$

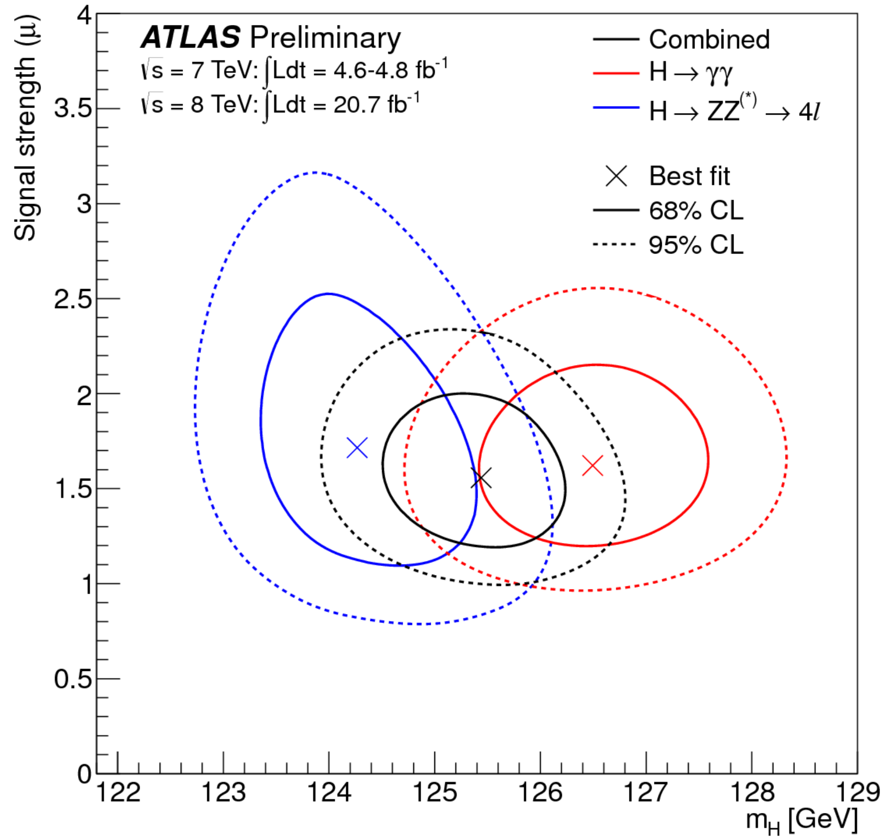


Combination: mass

- Mass from individual channels:
  - $H \to ZZ^*$: $124.3^{+0.6}_{-0.5}\,(\mathrm{stat})^{+0.5}_{-0.3}\,(\mathrm{syst})\,\mathrm{GeV}$
  - $H \to \gamma\gamma$: 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV



- Difference between both:
  $2.3^{+0.6}_{-0.7}\,(\mathrm{stat})^{+0.6}_{-0.6}\,(\mathrm{syst})\,\mathrm{GeV}$
  - 1.8 to 2.4 standard deviations



- Combined mass:
  $124.3 \pm 0.2\,(\mathrm{stat})\ ^{+0.6}_{-0.5}\,(\mathrm{syst})\,\mathrm{GeV}$

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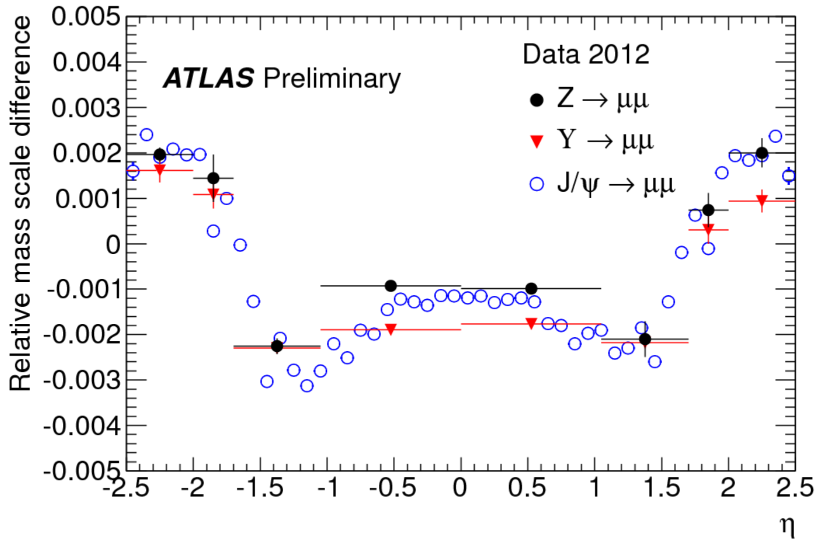
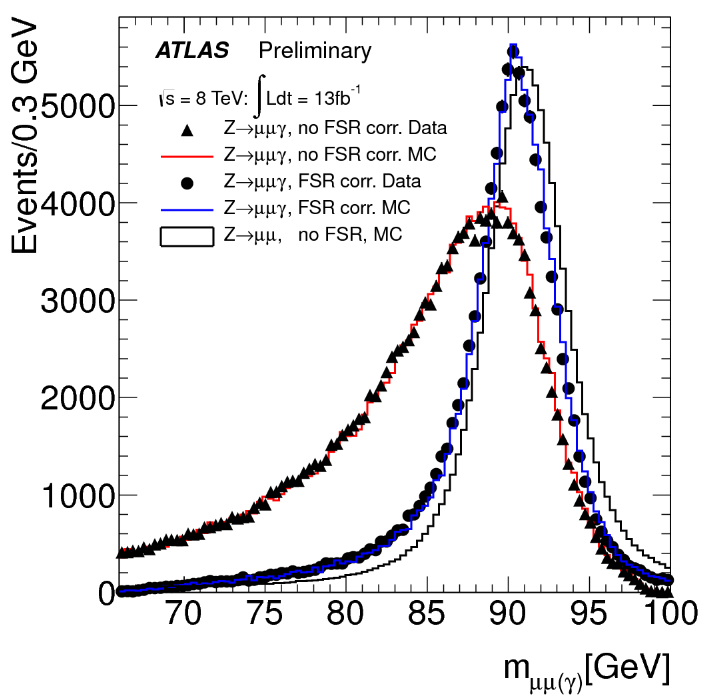
Mass: H→ZZ*→4l

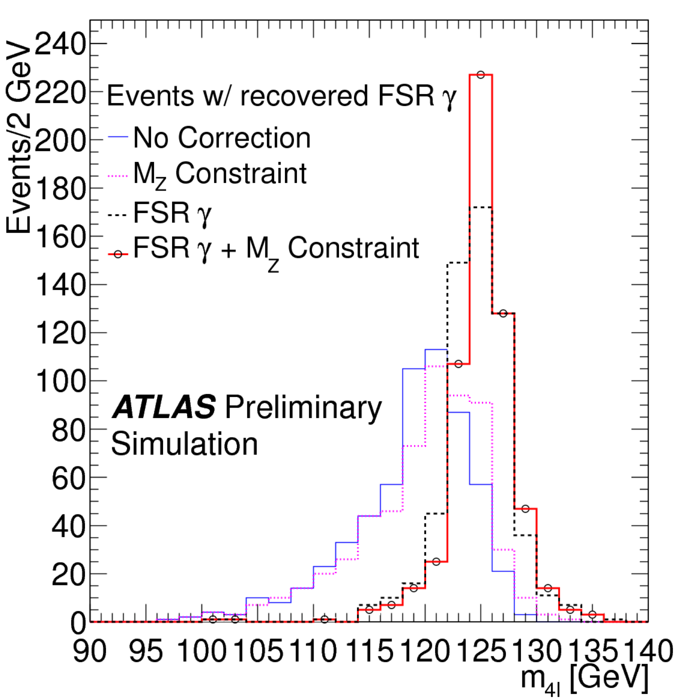
- Dominated by 4μ channel
- Mass scale systematics
  - absolute energy scale (from Z): 0.4%
  - low E_T electrons: 0.2%
  - muon momentum scale: 0.2%
- Checks:
  - mass measurement with ID tracks alone
  - bkg unconstrained
  - Z mass constraint on m_{12}
- More checks:
  - check of kinematic distributions
  - scale measurement with ID or MS tracks only
  - FSR: data/MC agreement to 0.1%
  - event-by-event errors



H→ZZ*: FSR correction

- New: FSR correction for muons for Z1 pair ($66 < m_{12} < 89$ GeV)
  - ~4% of the events
- Add to invariant mass any reconstructed photon with $E_T > 1$ GeV ($\Delta R <$ 0.08-0.15 depending on E_T) if corrected $m_{12} < 106$ GeV
- Recovers 70% of FSR photons
  - 85% of corrected events have FSR photon
- Tested on $Z \rightarrow \mu\mu\gamma$ events





Mass: H→γγ

- Uncertainties:
  - absolute energy scale ($Z \rightarrow ee$): 0.3%
  - material before calo: 0.3%
  - relative calibration of calo layers: 0.2 and 0.1%
  - difference in lateral shower-shape photons-electrons: 0.1%
  - read-out electronic gain: 0.15%

- More uncertainties:
  - converted photons: data/MC diff: 0.13%
  - background modelling: 0.1%
  - ~~stability with mass resolution: 0.15%~~