Measurement of Higgs boson properties in ATLAS

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Motivation

we discovered a new particle at low mass

→ what can we say more on this new boson?

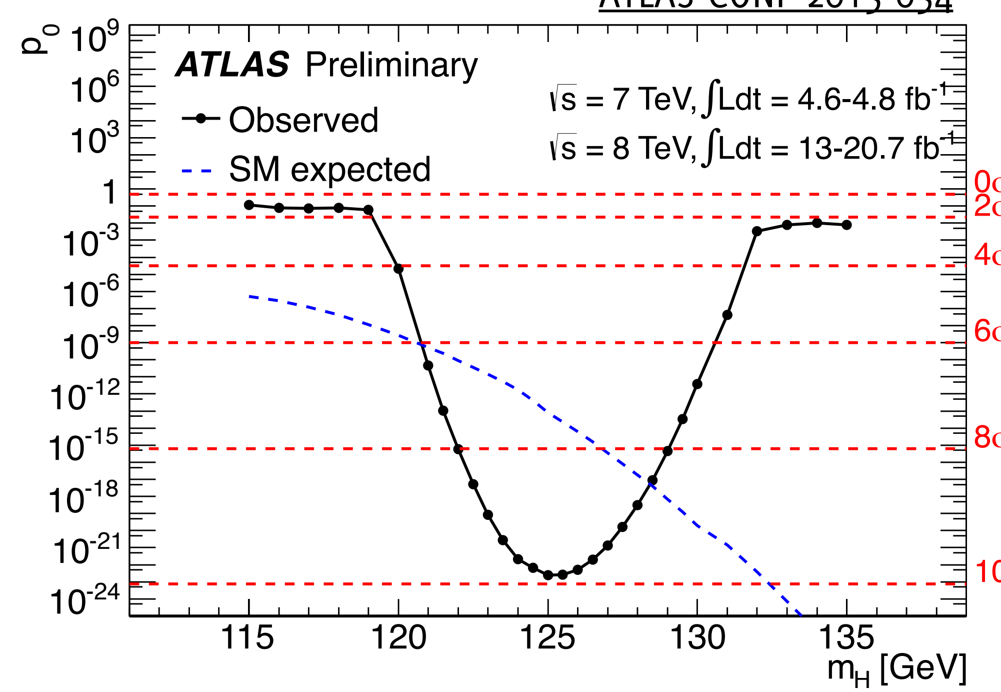
many handles to investigate its nature

- mass measurement (mass is the only free parameter in the SM)
- observed yield (signal strength measurements)
- probe Higgs couplings
- spin-parity (determine J^{PC} state)

following results are based on full 2011+2012 dataset (20.7 fb^{-1} at 8 TeV, 4.8 fb^{-1} at 7 TeV) for $H\rightarrow\gamma\gamma$, $H\rightarrow WW$, $H\rightarrow ZZ\rightarrow 4\ell$

(still 10 fb^{-1} at 8 TeV to be analyzed for other channels)

ATLAS-CONF-2013-034

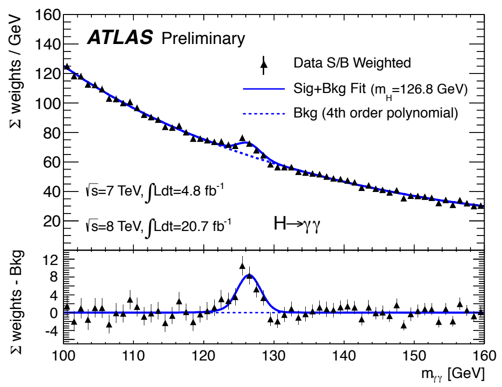


Mass measurement

if it's the SM Higgs boson, its mass m_H is the (only) free parameter of the theory

* measurement dominated by high-resolution channels
* using full 2011+2012 *pp* dataset (20.7 fb^{-1} at 8 TeV, 4.6÷4.8 fb^{-1} at 7 TeV)

[$H \to \gamma\gamma$]

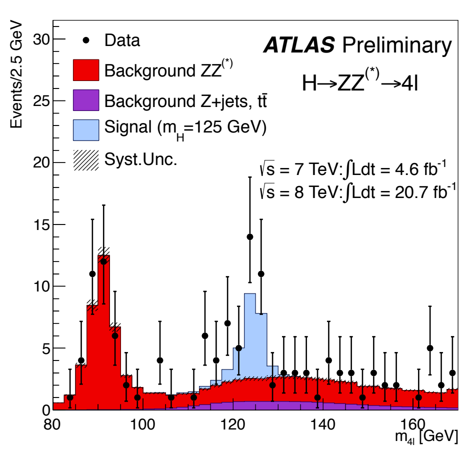


signature: peak in $m_{\gamma\gamma}$ distribution

combination of 14 categories (S/B ~ 0.01÷0.6, ~355 signal events at 8 TeV)

main systematics from photon energy scale uncertainty

[$H \to ZZ^* \to 4\ell$]



signature: peak in $m_{4\ell}$ distribution

4 final states; lower signal yield but high purity (S/B~1.4, ~27 signal events)

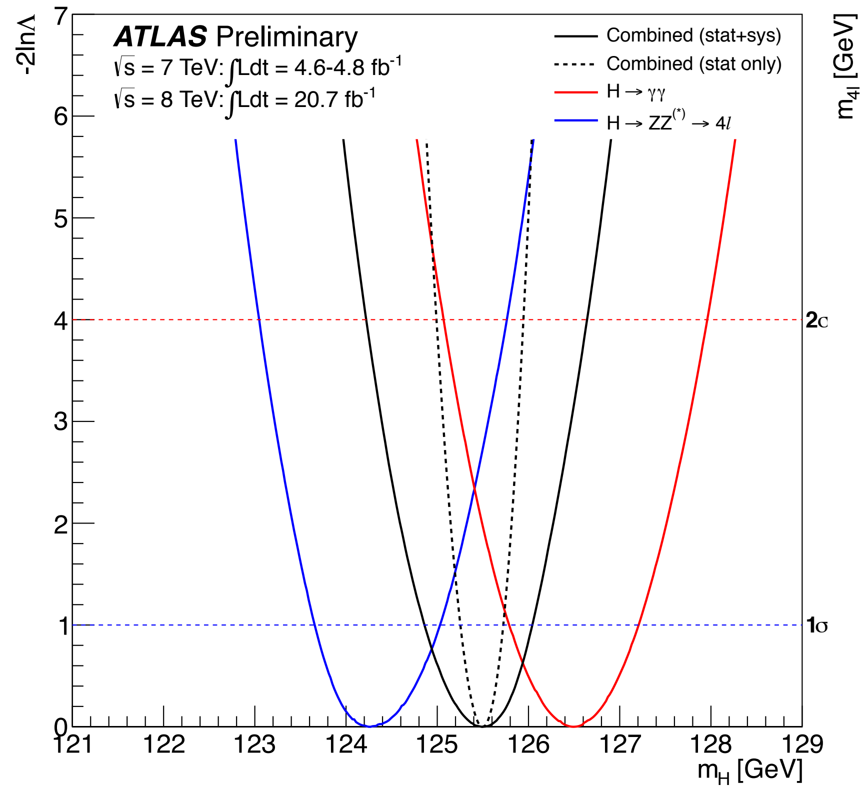
measure dominated by muon channels ($\sigma(m_{4\mu})$ ~ 1.6 GeV, $\sigma(m_{4e})$ ~ 2.4 GeV)

mass is extracted from profile likelihood fit to data

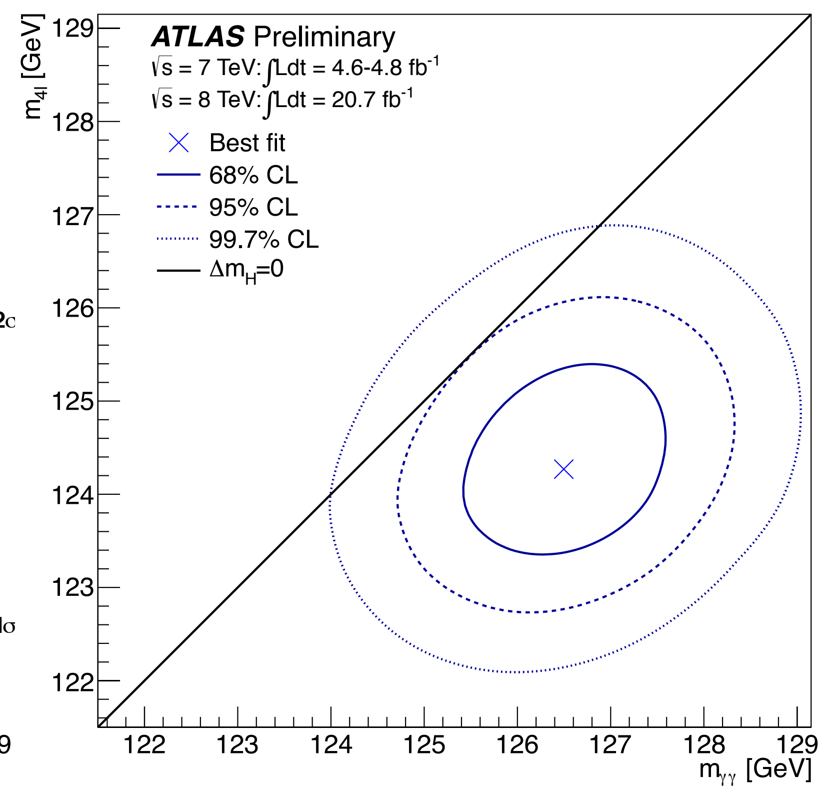
combine together individual channels, test their compatibility

Results

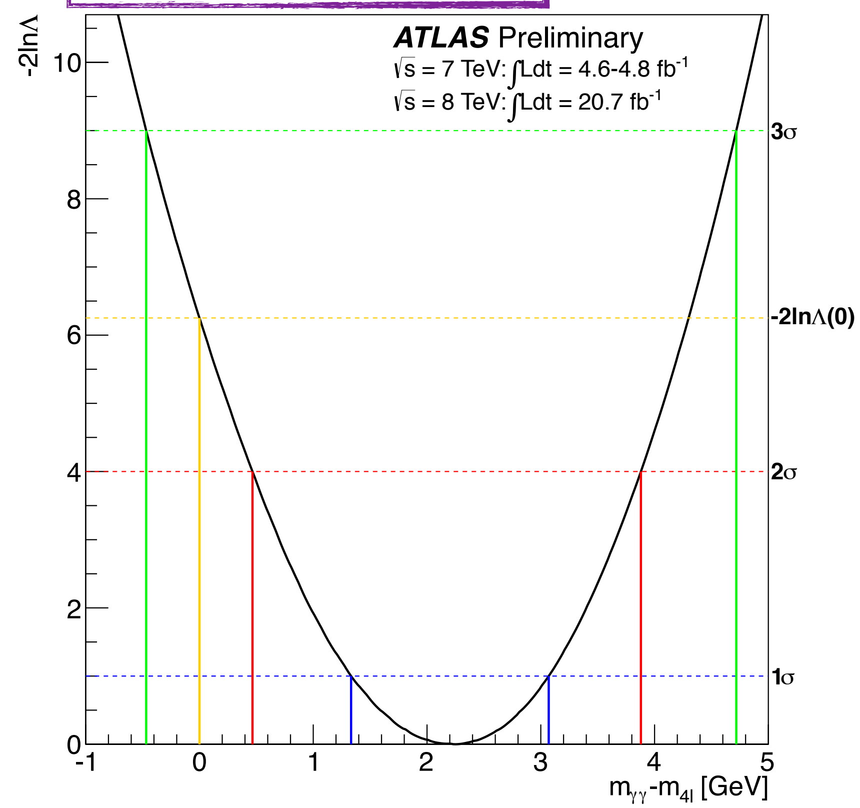
profile likelihood scan vs m_H



2D scan vs $m_H(4\ell)$, $m_H(\gamma\gamma)$



$-2\ln\Lambda(\Delta m_H)$ (m_H is profiled)



γγ: 126.8±0.2(stat)±0.7(sys) GeV

4ℓ: $124.3^{+0.6}_{-0.5}$(stat)$^{+0.5}_{-0.3}$(sys) GeV

combined: 125.5±0.2(stat)$^{+0.5}_{-0.6}$(sys) GeV

$$\Lambda(m_H) = \frac{L(m_H\,,\, \hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\, \hat{\hat{\mu}}_{4\ell}(m_H)\,,\, \hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta})}$$

- main correlation from e/γ energy scale systematics
- individual measurements compatible at 1.5% (2.4σ) level

Signal strength

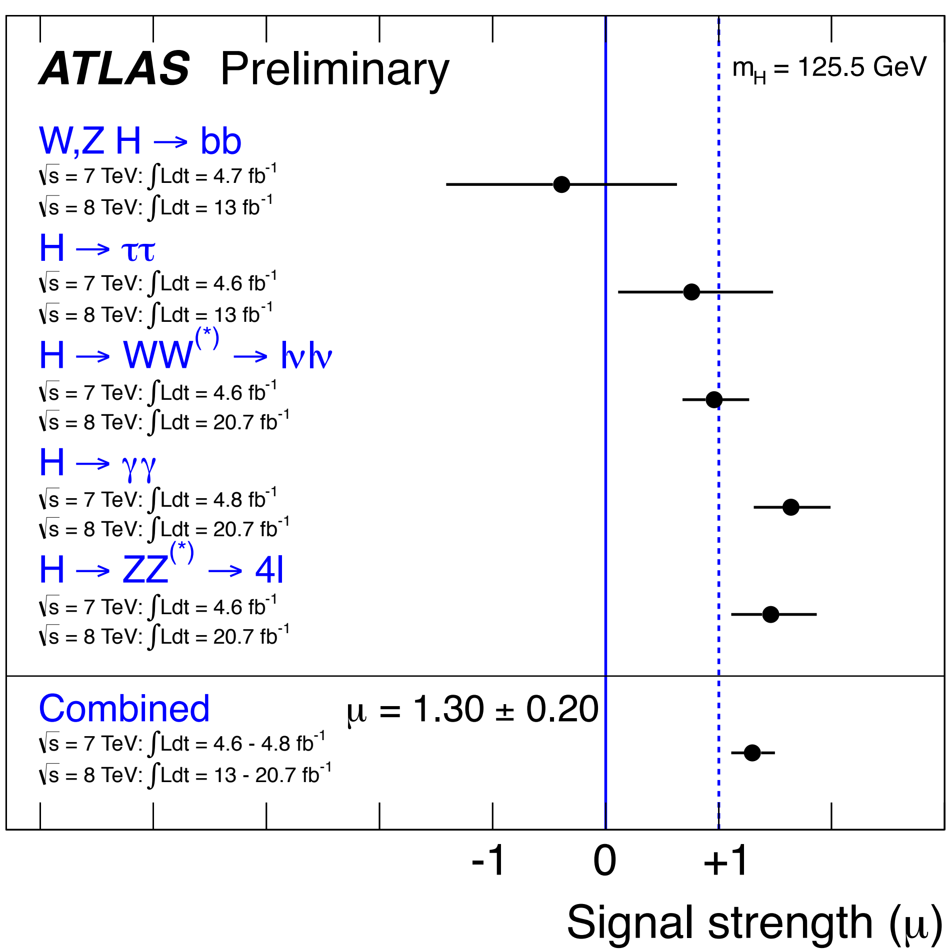
once m_H is measured, SM cross sections are uniquely determined

* we can test the agreement with SM measuring deviations from predicted yields
* assume $m_H = 125.5$ GeV and define a signal strength μ such as

$$N_{tot} = \mu \cdot N_{sig} + N_{bkg} \qquad (N_{tot} > 0)$$

* combine measurements from all decay channels

  result is stable within ~4% for ±1 GeV variations of assumed m_H



μ = 1.30±0.13(stat)±0.14(sys)
9% agreement with SM (μ=1)

Production processes

μ

different decay channels have contributions from common production modes

→ e.g.: VBF production accounts for 7% of the total $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ cross-sections

we can separate them passing from a single μ to $\mu_{ggF+ttH}$ and μ_{VBF+VH}

* use analysis sub-categories with ggF/VBF/VH-enriched samples (e.g. $N_{jet}(VBF) \geq 2$)
* in the SM, $\mu_{ggF+ttH}$ scales with top Yukawa coupling
* in the SM, μ_{VBF+VH} scales with WH/ZH couplings

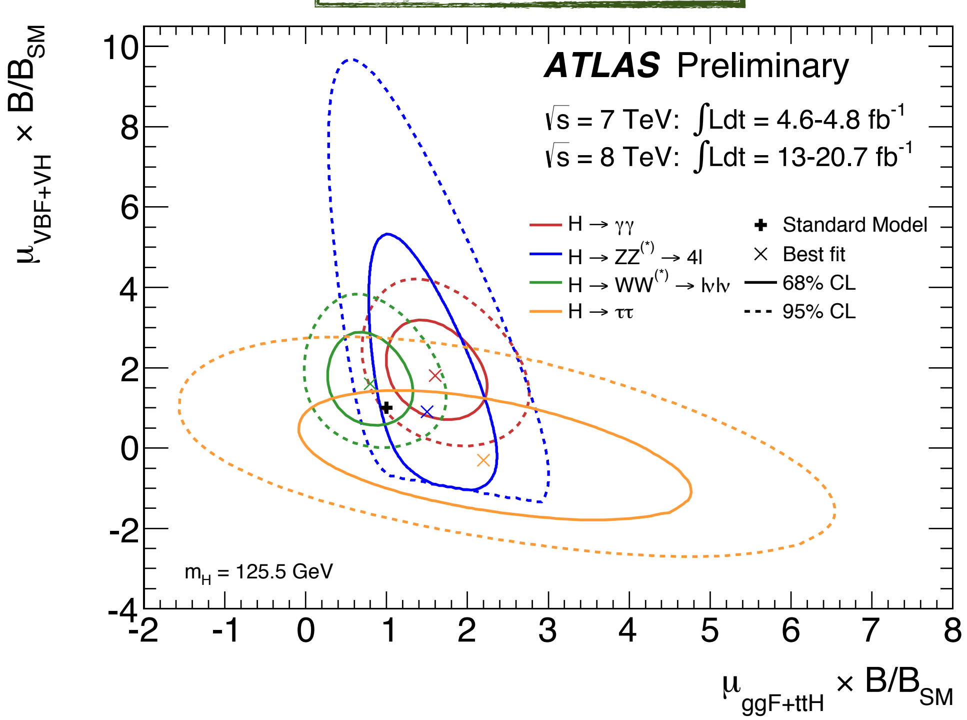
alternative "model-independent" approach: study ratio of branching ratio factors

$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3}$
$\rho_{\gamma\gamma/WW} = 1.7^{+0.7}_{-0.5}$
$\rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$

comparison between channels needs ratios

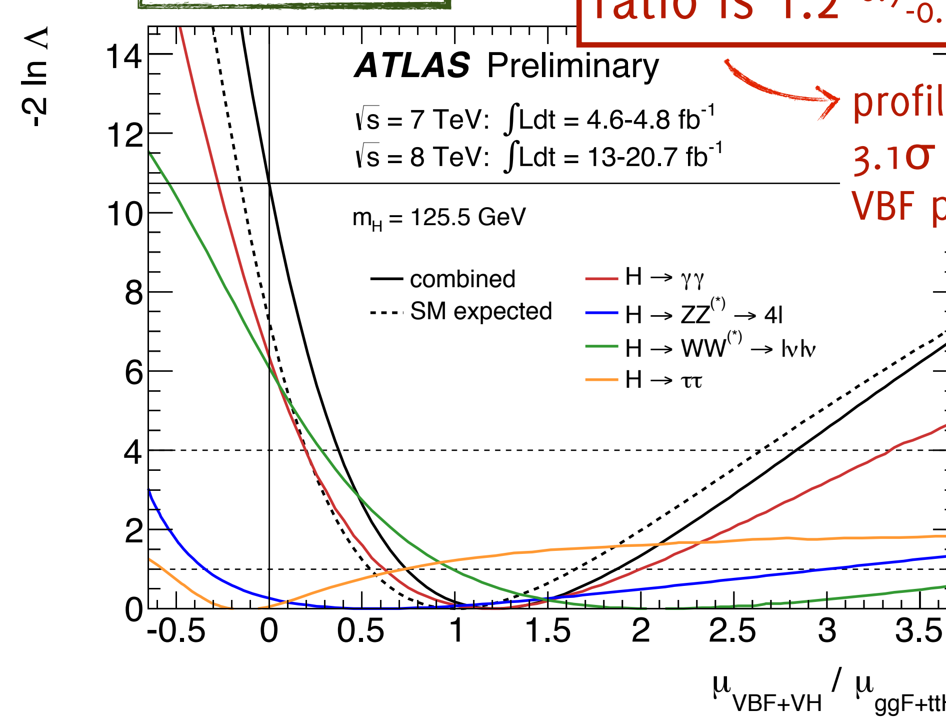
in this way branching ratio factor B/B_{SM} cancels out

2D likelihood contour



$\mu_{VBF+VH}/\mu_{ggF+ttH}$

ratio is $1.2^{+0.7}_{-0.5}$ (SM: 1)



→ profiling μ_{VH}: 3.1σ evidence of VBF production

κ_j

Coupling measurement

probe Higgs boson couplings under a LO tree level motivated framework

- assume that all observed signals originate from a single resonance at 125.5 GeV
- zero-width approximation: $(\sigma\times BR)(ii\rightarrow H\rightarrow ff) = \sigma_{ii}\cdot\Gamma_{ff}/\Gamma_H$
- same lagrangian structure as in the SM (only modifications in coupling strengths)

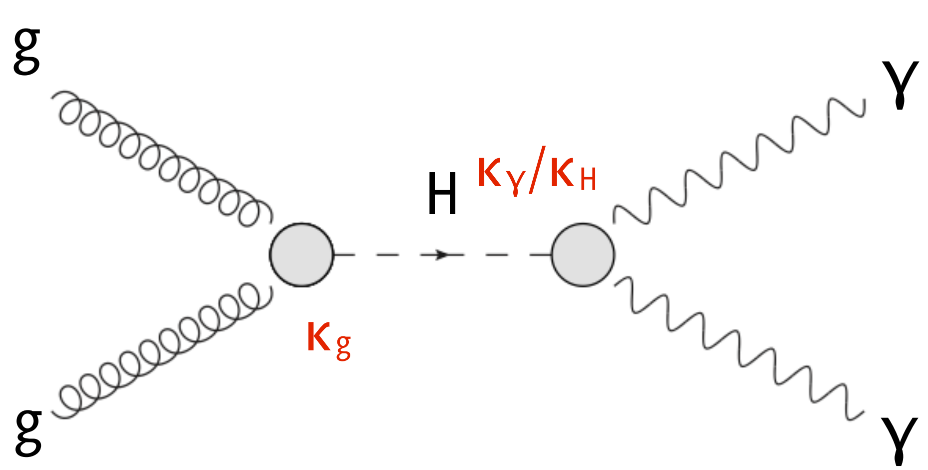
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsLightMass

fit for coupling scale factors κ_g^2

example:

$$(\sigma\times BR)(gg\rightarrow H\rightarrow\gamma\gamma) = \sigma_{SM}(gg\rightarrow H)\cdot BR_{SM}(H\rightarrow\gamma\gamma)\cdot\boldsymbol{\kappa_g^2\cdot\kappa_\gamma^2/\kappa_H^2}$$

→ κ_g^2 and κ_γ^2 can be expressed in terms of coupling scale factors associated to all other particles contributing to SM loops



Fermion vs vector couplings / 1

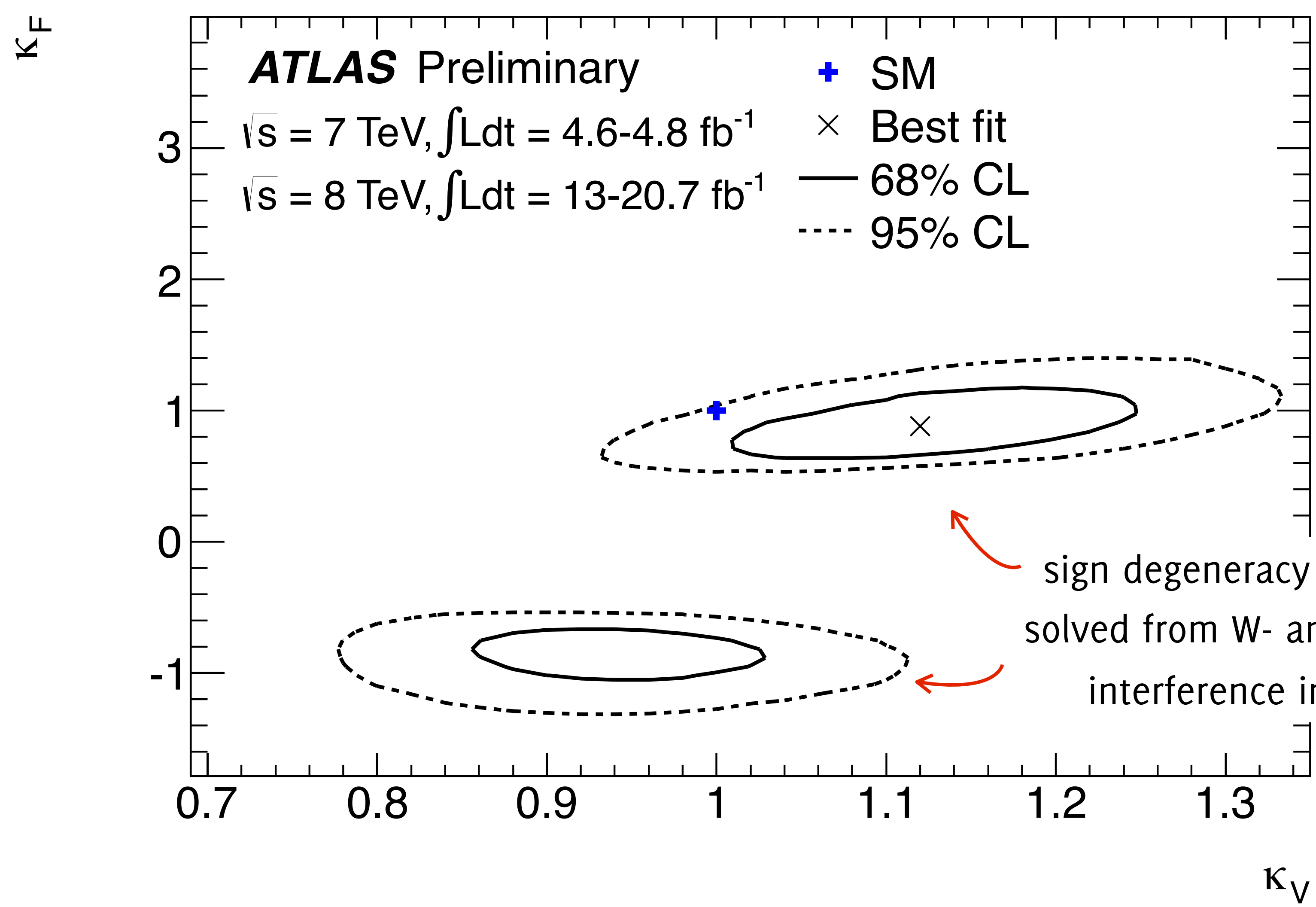
in the SM, ggH and H→γγ are loop-induced

1. assume only SM particles contribute to these loops

→ fit for $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$

$\kappa_V = \kappa_W = \kappa_Z$

2D likelihood contour



sign degeneracy partially solved from W- and t-loop interference in H→γγ

$\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$

$\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21]$

(68% CL intervals)

8% compatibility with SM (1,1)

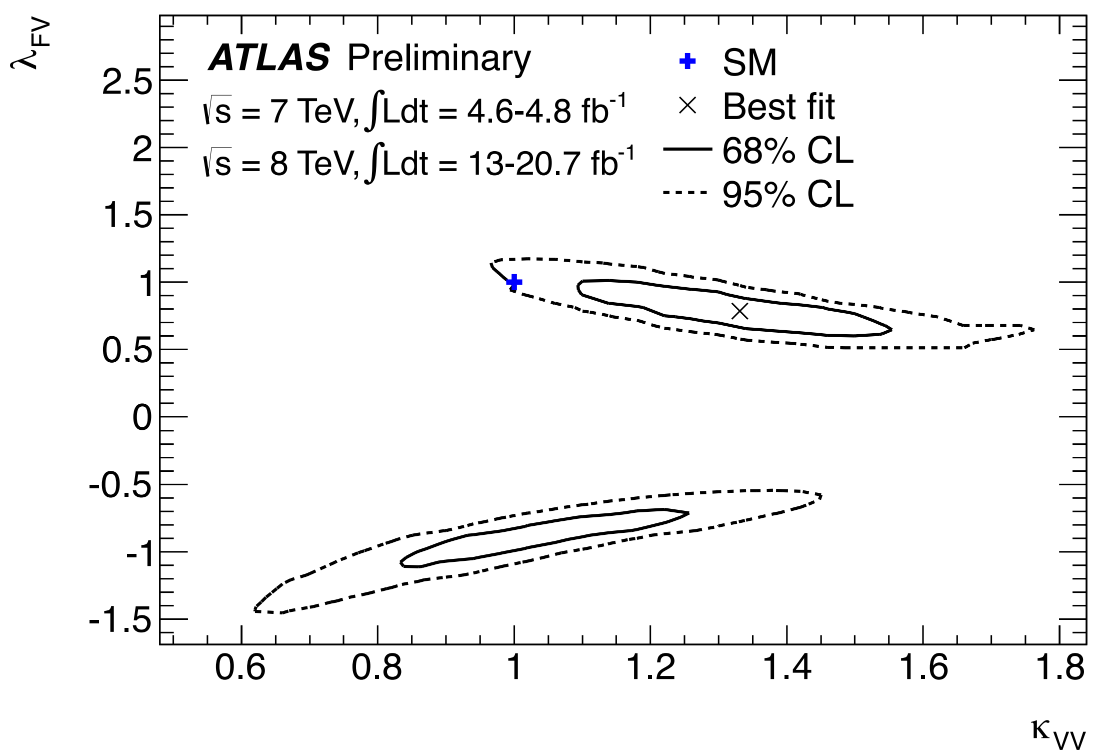
Fermion vs vector couplings / 2

2. no assumption on the total decay width

→ fit for $\lambda_{FV} = \kappa_F/\kappa_V$

$\kappa_{VV} = \kappa_V \cdot \kappa_V/\kappa_H$

2D likelihood contour



$\lambda_{FV} \in [-0.94, -0.80] \cup [0.67, 0.93]$

$\kappa_{VV} \in [0.96, 1.12] \cup [1.18, 1.49]$

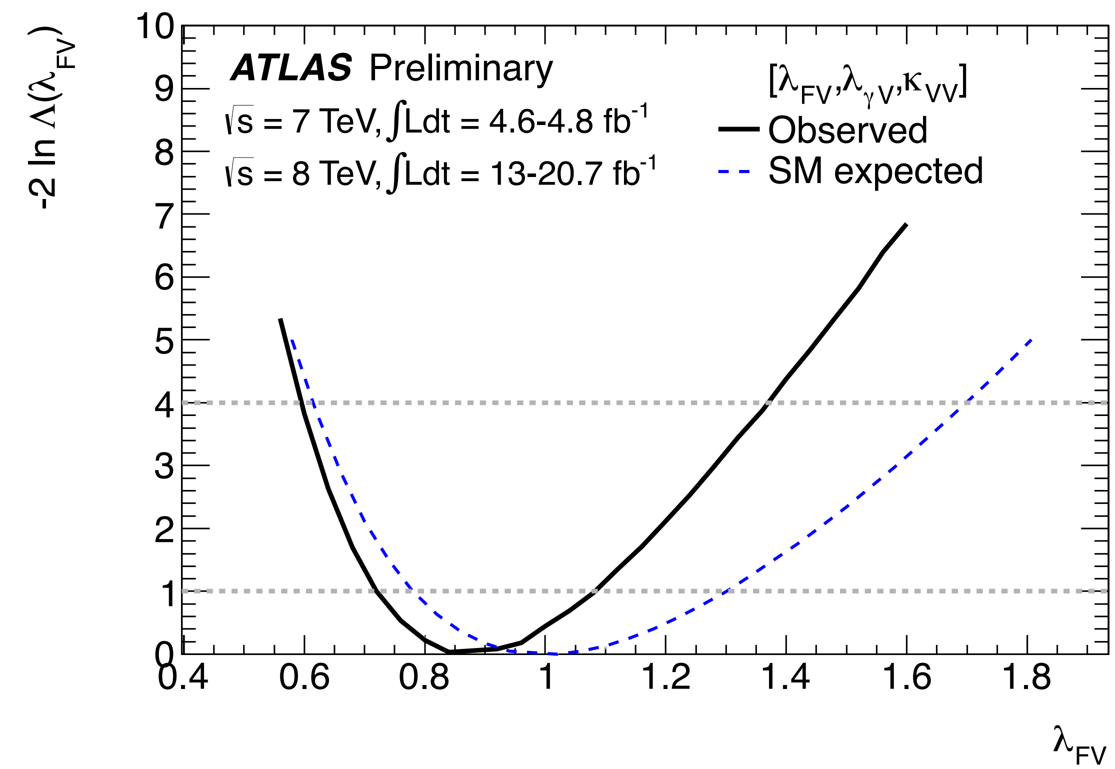
3. no assumption on the total decay width and on the H→γγ loop content

→ fit for $\lambda_{FV} = \kappa_F/\kappa_V$

$\kappa_{VV} = \kappa_V \cdot \kappa_V/\kappa_H$

$\lambda_{\gamma V} = \kappa_\gamma/\kappa_V$

1D projection (profiling other parameters)



$\lambda_{FV} = 0.85^{+0.23}_{-0.13}$

$\kappa_{VV} = 1.15 \pm 0.21$

$\lambda_{\gamma V} = 1.22^{+0.18}_{-0.14}$

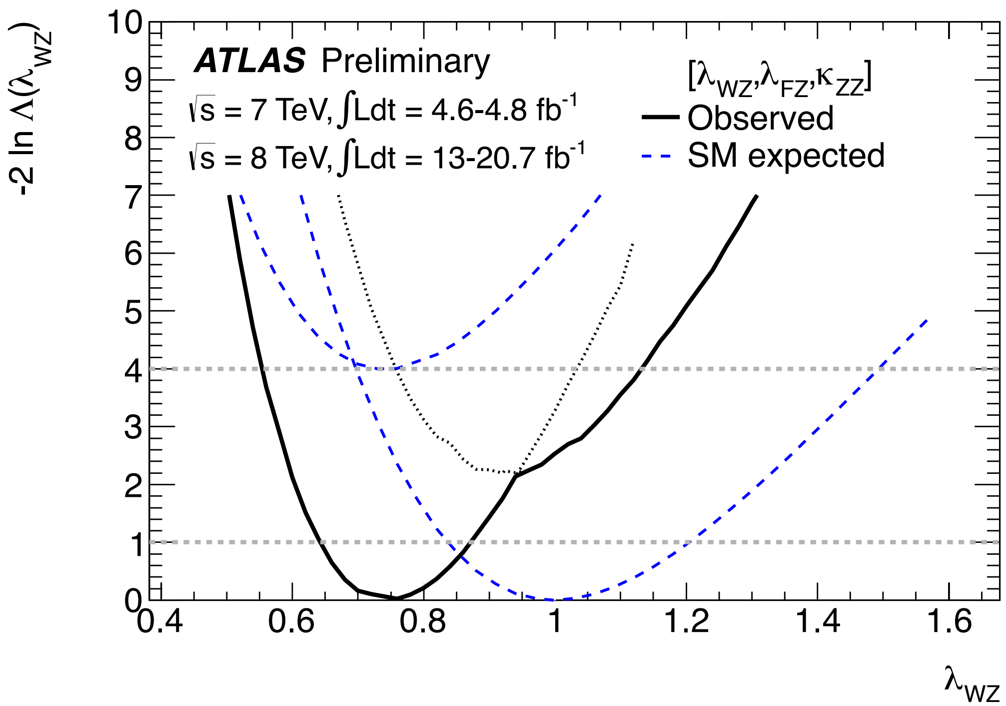
7/9% compatibility with SM (1,1[,1])

W/Z couplings

SM requires identical coupling scale factors for W and Z

- direct test of custodial symmetry
- strong constraint from LEP measurements

1. assume only SM particles contribute to ggH/H$\gamma\gamma$ loops

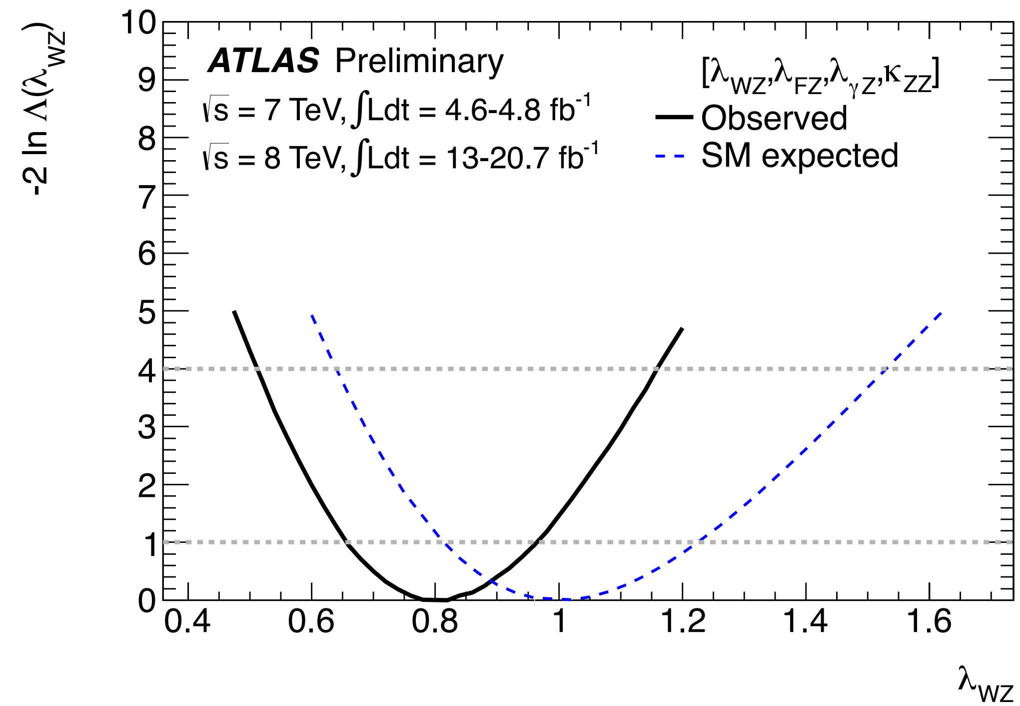


$\lambda_{WZ} = \kappa_W/\kappa_Z \in [0.64, 0.87]$

$\lambda_{FZ} = \kappa_F/\kappa_Z \in [-0.89, -0.55]$

$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z/\kappa_H \in [1.20, 2.08]$

2. decouple possible new physics contribution in $\gamma\gamma$



$\lambda_{WZ} = \kappa_W/\kappa_Z = 0.80 \pm 0.15$

$\lambda_{FZ} = \kappa_F/\kappa_Z = 0.74^{+0.21}_{-0.17}$

$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z/\kappa_H = 1.5^{+0.5}_{-0.4}$

$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z = 1.10 \pm 0.18$

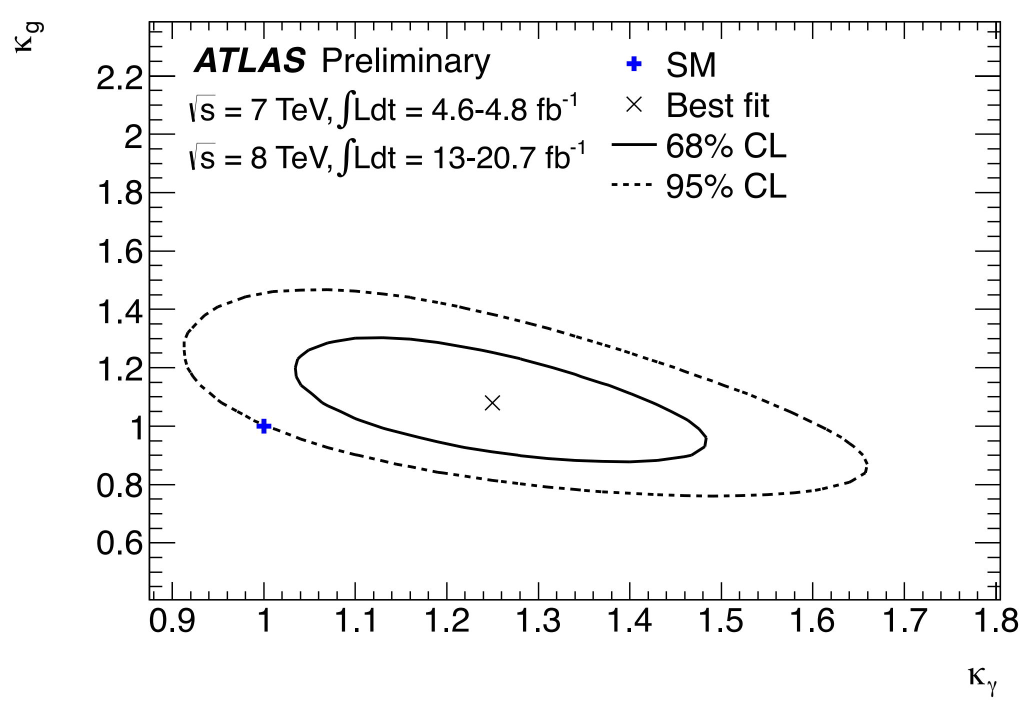
5/9% compatibility with SM (1,1,1[,1])

Probing BSM contributions

new particles can contribute either in loops or in new final states

- assume SM tree-level coupling scale factors ($\kappa_i = 1$)
- fit for effective coupling scale factors κ_g and κ_γ

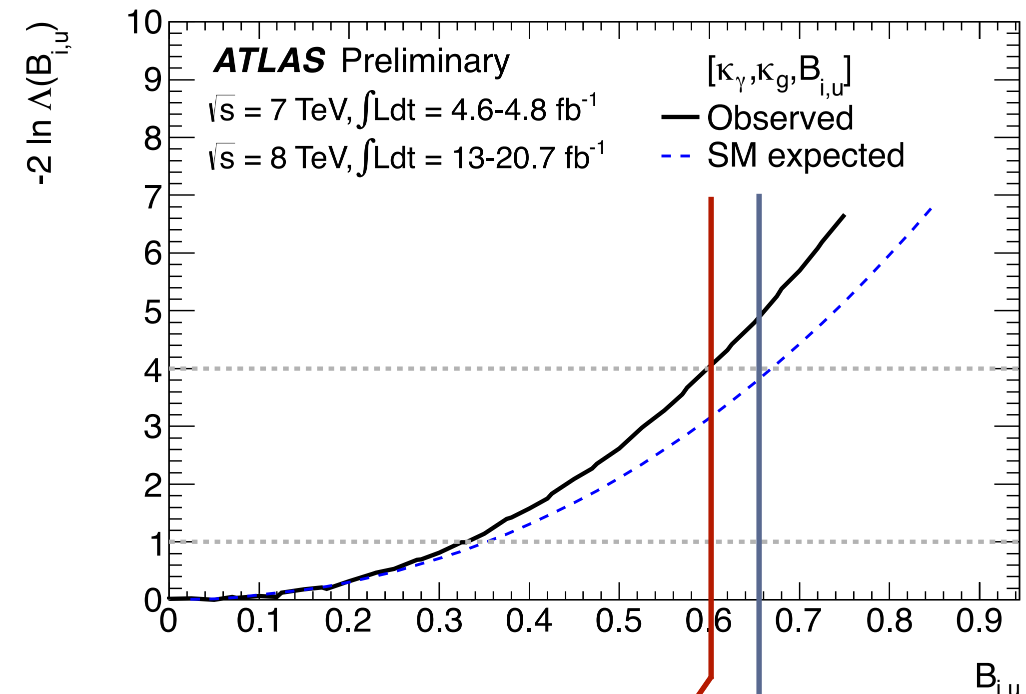
1. assume no new contribution to total Higgs width



$\kappa_g = 1.08 \pm 0.14$

$\kappa_\gamma = 1.23^{+0.16}_{-0.13}$

2. allow for invisible/undetectable final states



$BR_{inv.,undet.} < 0.33$ (< 0.6 @ 95%CL)

direct search ZH(→inv): BR<0.65 @ 95%CL

$\kappa_g = 1.08^{+0.32}_{-0.14}$

$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$

5/10% compatibility with SM (1,1[,1])

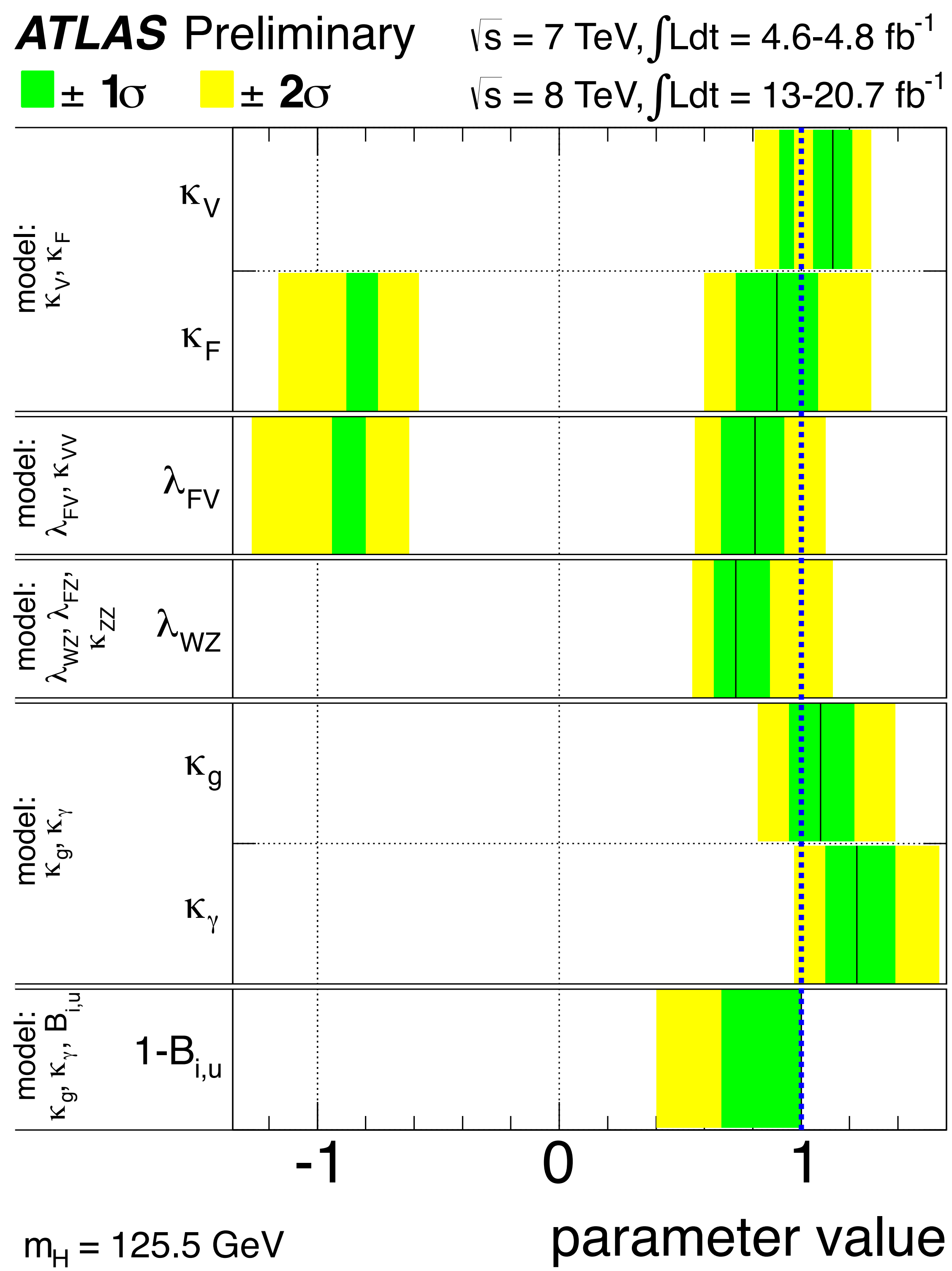
Summary

many tested benchmark models

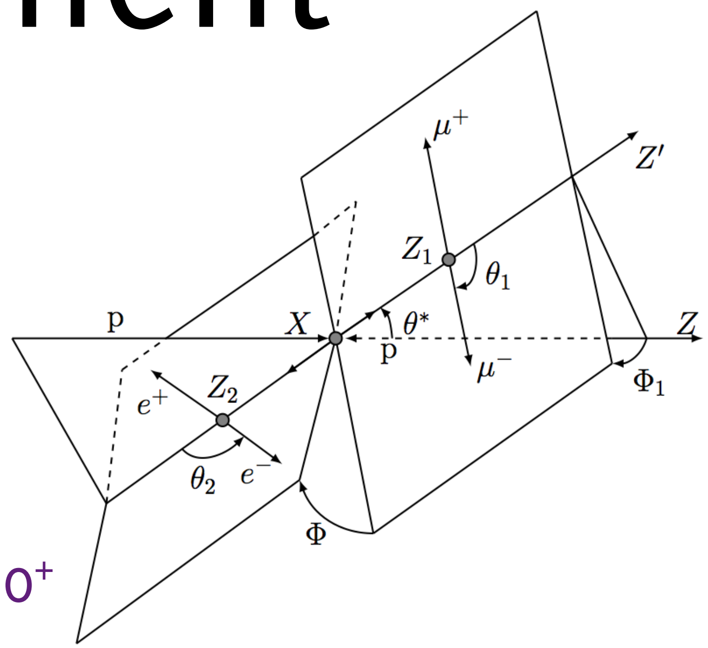
- common assumption: single resonance with SM-like tensor structure, zero width
- remark: various scenarios are correlated (based on same experimental data!)

no significant deviation from Standard Model prediction

compatibility with SM at 5÷10% level



Spin-parity measurement



J^{PC} state influences final state kinematic distributions

e.g.: in $H \to ZZ \to 4\ell$, dilepton invariant masses
and 5 production/decay angles

the idea: pair-wise test of different specific scenarios against SM 0^+

- * $\gamma\gamma$, WW, ZZ: test 2^+ minimal coupling model with different gg/qq production fractions
- * ZZ: test also 0^-, 1^+, 1^-, 2^-

approach: build discriminant using input sensitive to different spin-parity hypotheses

- $H \to \gamma\gamma$: use $|\cos(\theta^*)|$ distribution ($m_{\gamma\gamma}$ for S/B separation)
- $H \to WW$: train two BDT classifiers (0^+ vs bkg, 2^+ vs bkg) using $m_{\ell\ell}$, $p_{T\ell\ell}$, $\Delta\varphi_{\ell\ell}$, m_T
- $H \to ZZ \to 4\ell$: multivariate discriminant built using full 7D final state information (two approaches: matrix element technique and BDT)

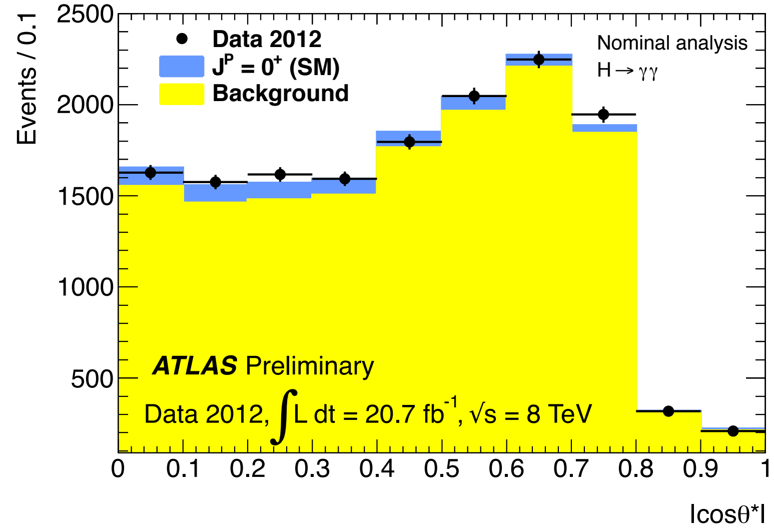
→ discriminant distributions used to build test statistics $Q = \log(L(0^+)/L(J^P))$

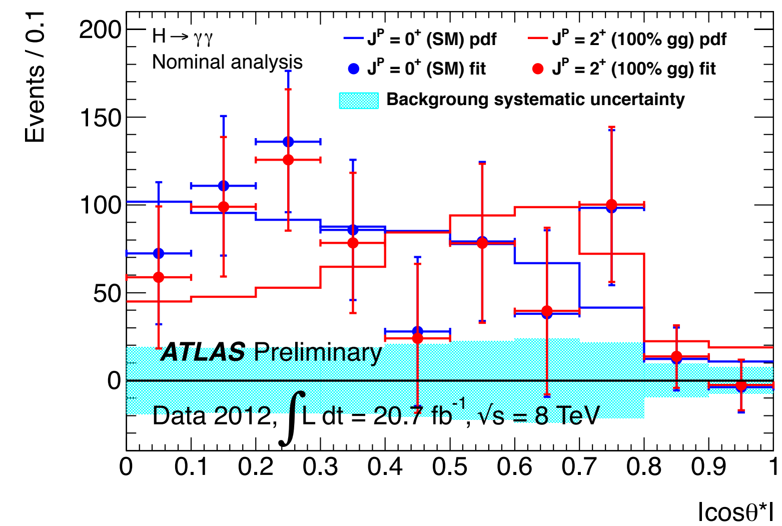
CLs method: $CL_s(J^P) = p_0(J^P) / (1 - p_0(0^+))$

Discriminating hypotheses

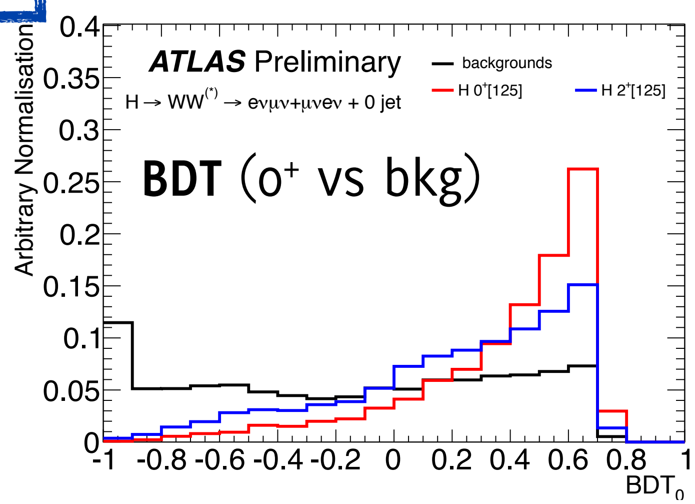
H→γγ

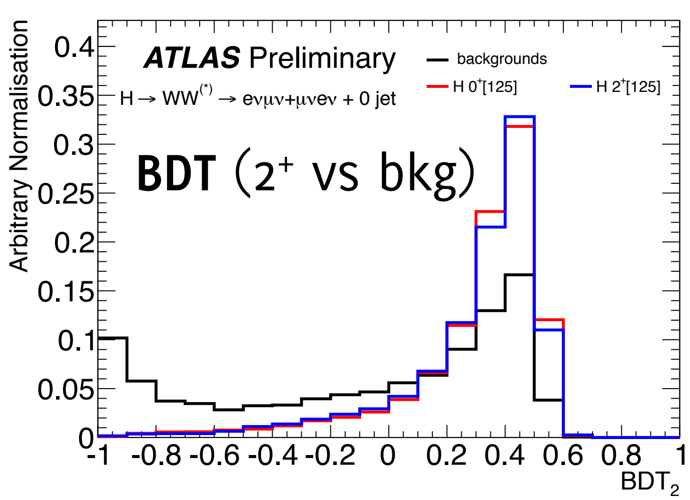
|cos(θ*)| distribution → background subtracted





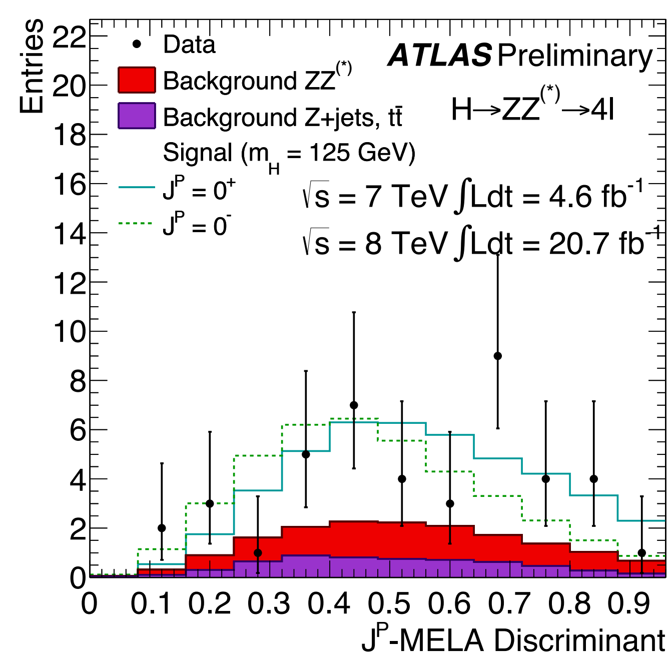
H→WW

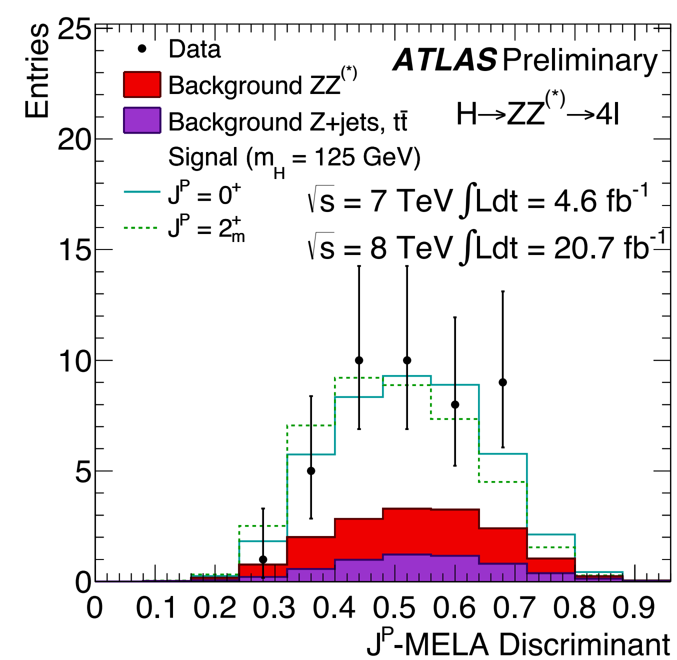




H→ZZ→4ℓ

$$J^P\text{-MELA}(0^+ \text{ vs } J^P) = \frac{L(\text{data} \mid 0^+)}{[\, L(\text{data} \mid 0^+) + L(\text{data} \mid J^P)\,]}$$

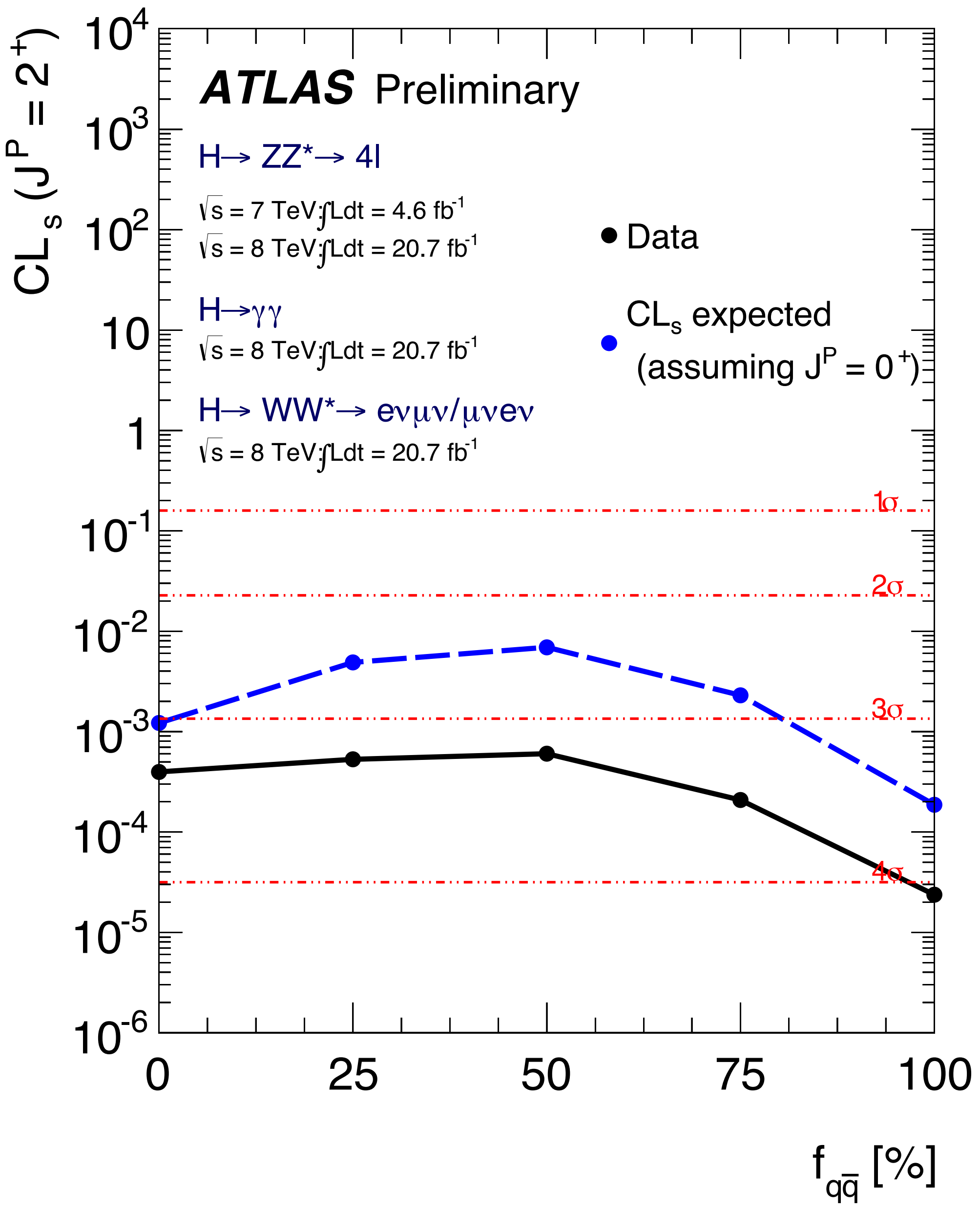




Results

combination: exclude 2^+ model against 0^+ at more than 99% CL

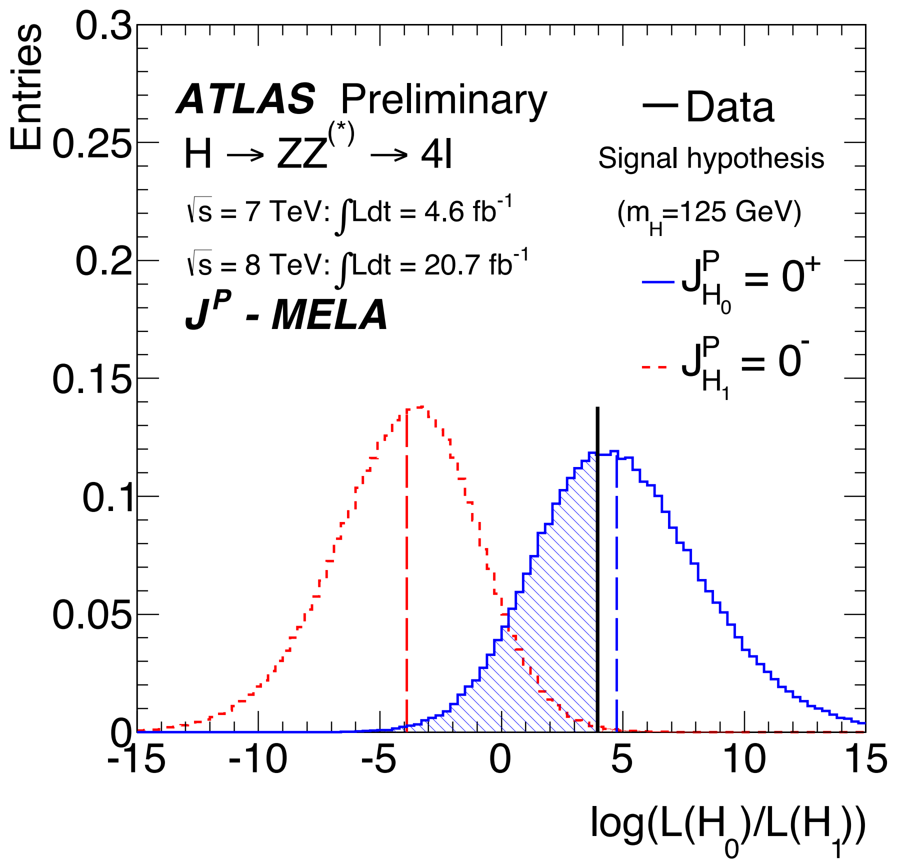
all combinations of qq/gg production excluded as well



H→ZZ→4ℓ channel alone:

exclude 0^-, 1^+, 1^- at more than 96.9% CL

test of 2^- against 0^+ still inconclusive



Conclusions

- $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV
- $\mu = 1.30 \pm 0.13(\text{stat}) \pm 0.14(\text{sys})$
- $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.2^{+0.7}_{-0.5}$
  - 3.1σ evidence for VBF production
- couplings consistent with SM expectation
- spin-parity studies
  - new boson is compatible with SM $J^{PC}=0^+$
  - excluded 0^-, 1^+, 1^-, 2^+ specific scenarios against SM at more than 96.9% CL
- perspectives
  - update fermion channels to full data sample
  - optimization of coupling measurement in individual channels
  - probe CP admixtures

Bibliography

- Individual channels
  - ATLAS-CONF-2013-013 ($H \to ZZ \to 4\ell$)
  - ATLAS-CONF-2013-012 ($H \to \gamma\gamma$)
  - ATLAS-CONF-2013-030, ATLAS-CONF-2013-031 ($H \to WW$)
- Mass measurement
  - ATLAS-CONF-2013-014
- Couplings
  - ATLAS-CONF-2013-034
- Spin
  - ATLAS-CONF-2013-040
- Perspectives
  - ATL-PHYS-PUB-2012-004

Backup slides

After the LHC shutdown

CP violation in the Higgs sector

$$A(X \to VV) \sim \left(a_1 M_X^2 g_{\mu\nu} + a_2 (q_1+q_2)_\mu (q_1+q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

SM: $a_1=1$, $a_2=a_3=0$

test $a_1=1$, $a_2=0$, $a_3 \neq 0$

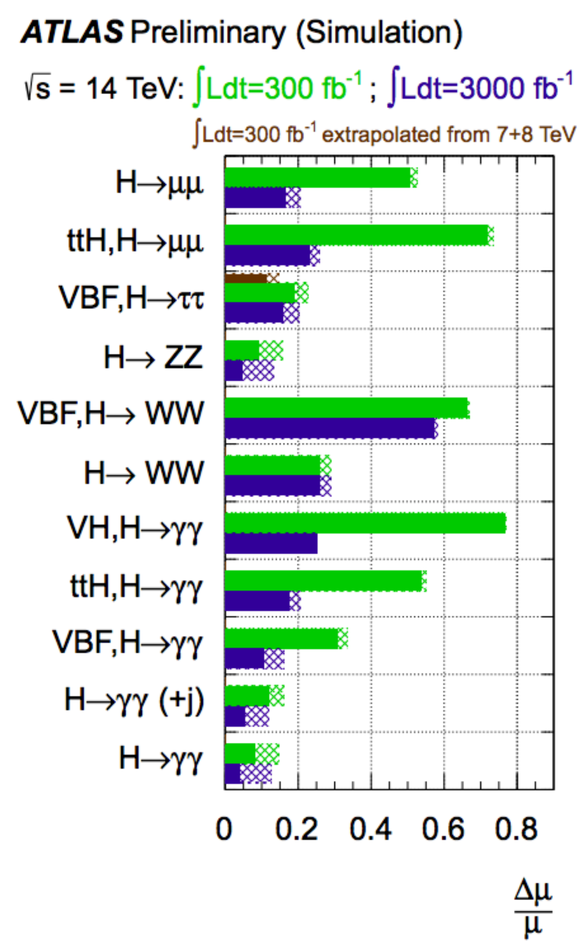
separation (in σ @14 TeV)

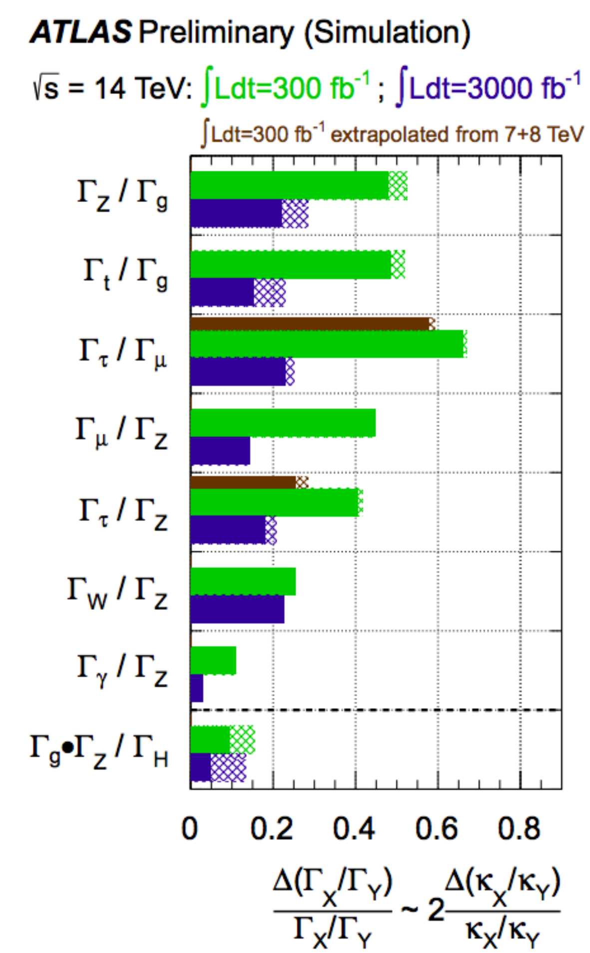
Integrated Luminosity	Signal (S) and Background (B)	$6+6i$	$6i$	$4+4i$
100 fb^{-1}	S = 158; B = 110	3.0	2.4	2.2
200 fb^{-1}	S = 316; B = 220	4.2	3.3	3.1
300 fb^{-1}	S = 474; B = 330	5.2	4.1	3.8

coupling measurements

precision in κ_V, κ_F fit

	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)



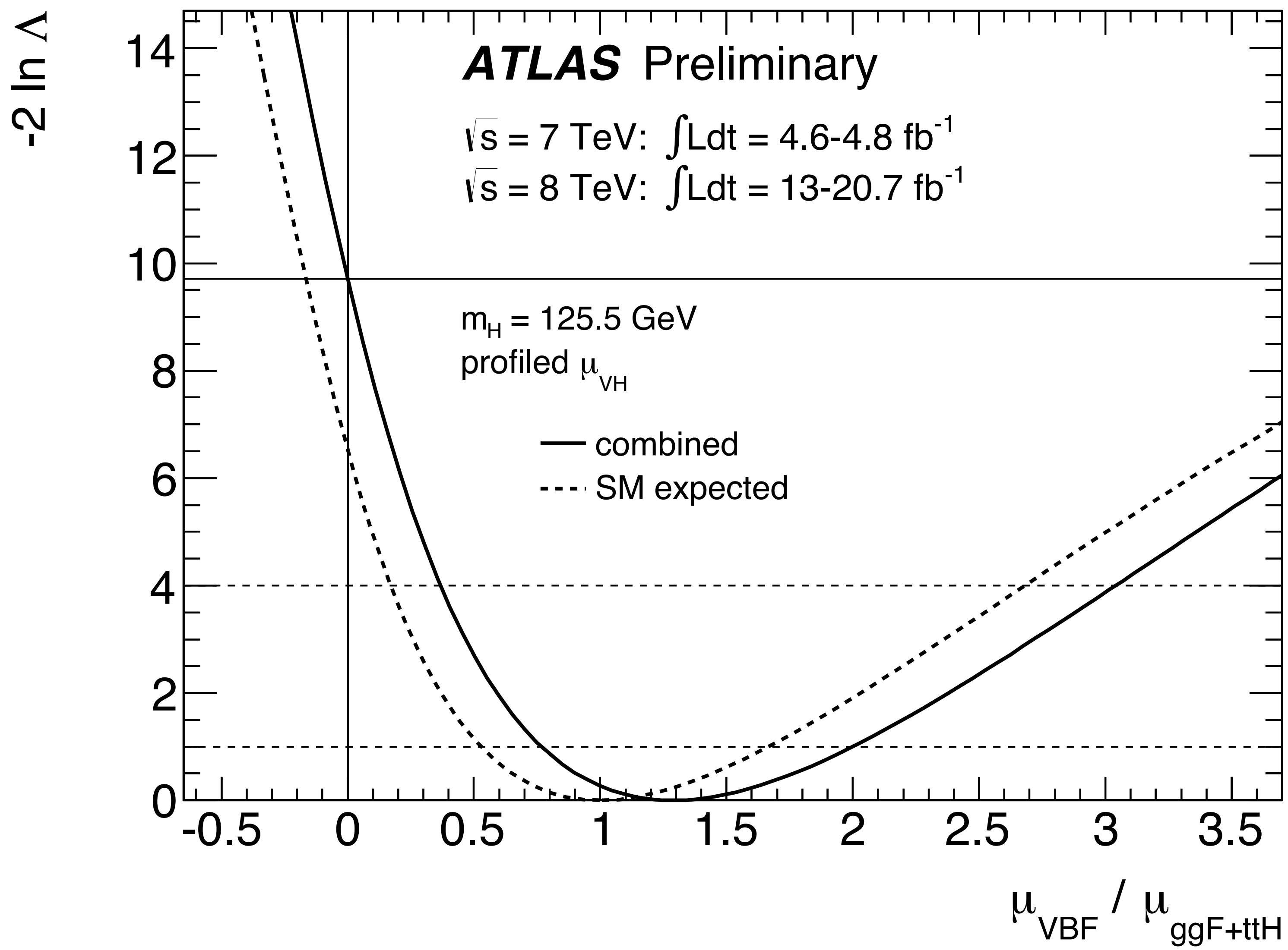


Combined channels

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.6
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\}$	4.8
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, p_{\mathrm{T},\tau\tau} > 100\ \text{GeV}, VH\}$	4.6
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet}, p_{\mathrm{T},\tau\tau} > 100\ \text{GeV, 2-jet}\}$	4.6
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet, 2-jet}\}$	4.6
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \text{GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\ \text{GeV}\}$	4.7
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\ \text{GeV}\}$	4.7
		2012 $\sqrt{s}$ =8 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	20.7
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\} \oplus \{\ell\text{-tag}, E_{\mathrm{T}}^{\mathrm{miss}}\text{-tag, 2-jet VH}\}$	20.7
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet}\}$	13
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, p_{\mathrm{T},\tau\tau} > 100\ \text{GeV}, VH\}$	13
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet}, p_{\mathrm{T},\tau\tau} > 100\ \text{GeV, 2-jet}\}$	13
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet, 2-jet}\}$	13
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \text{GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	13
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\ \text{GeV}\}$	13
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\ \text{GeV}\}$	13

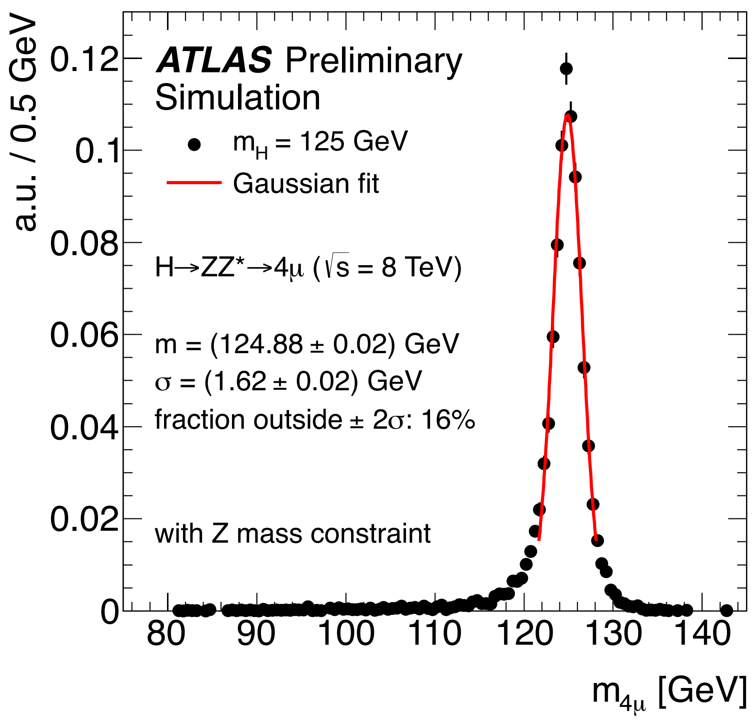
Evidence of VBF production

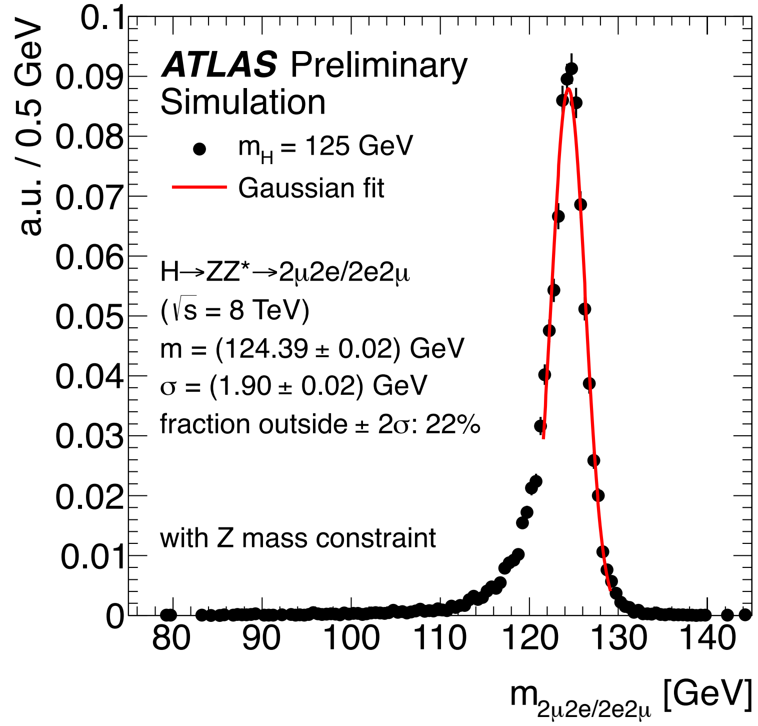
$\mu_{VBF}/\mu_{ggF+ttH}$ (μ_{VH} is profiled)

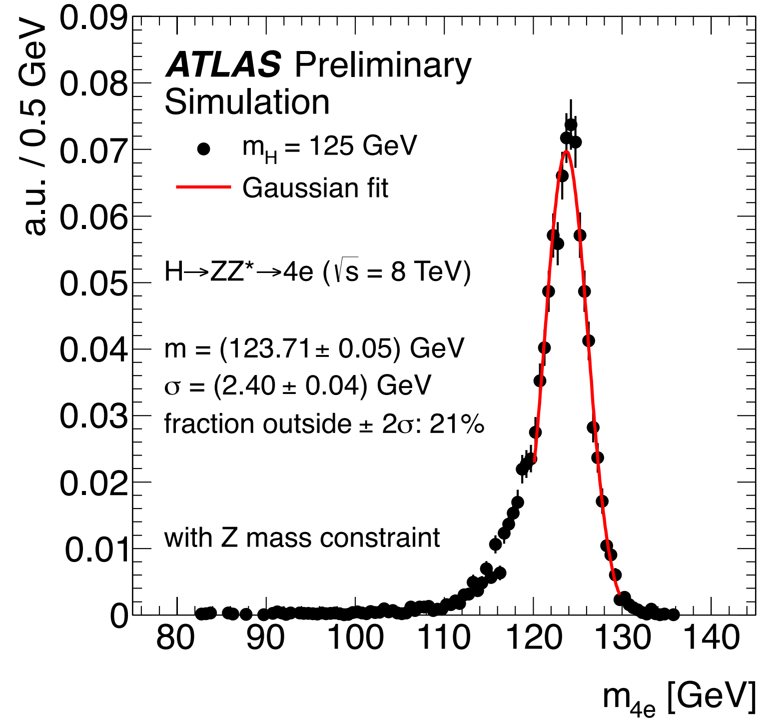


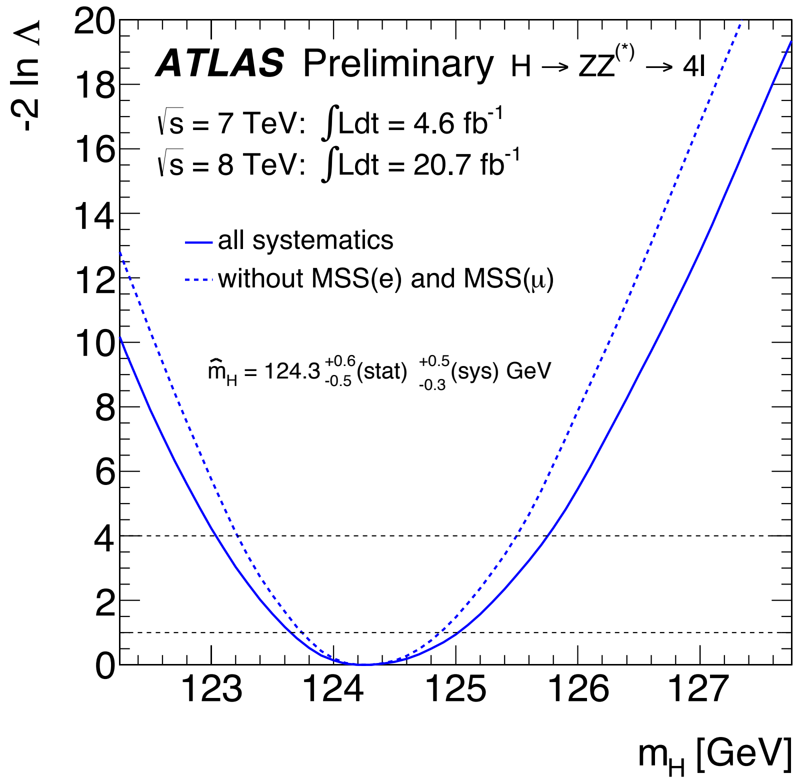
3.1σ evidence of VBF production

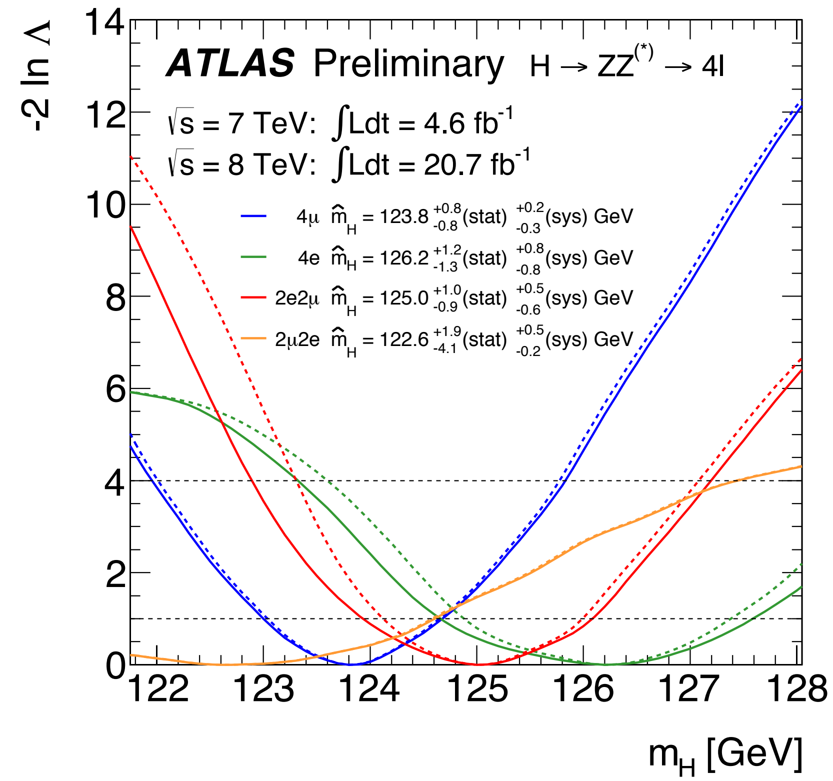
Mass resolution in H→ZZ→4ℓ



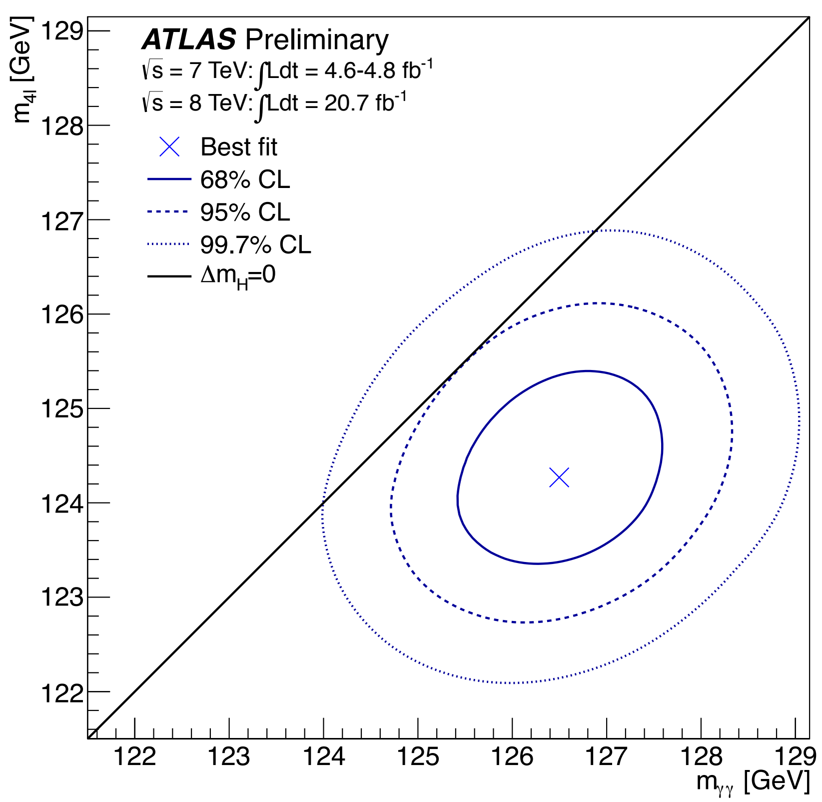


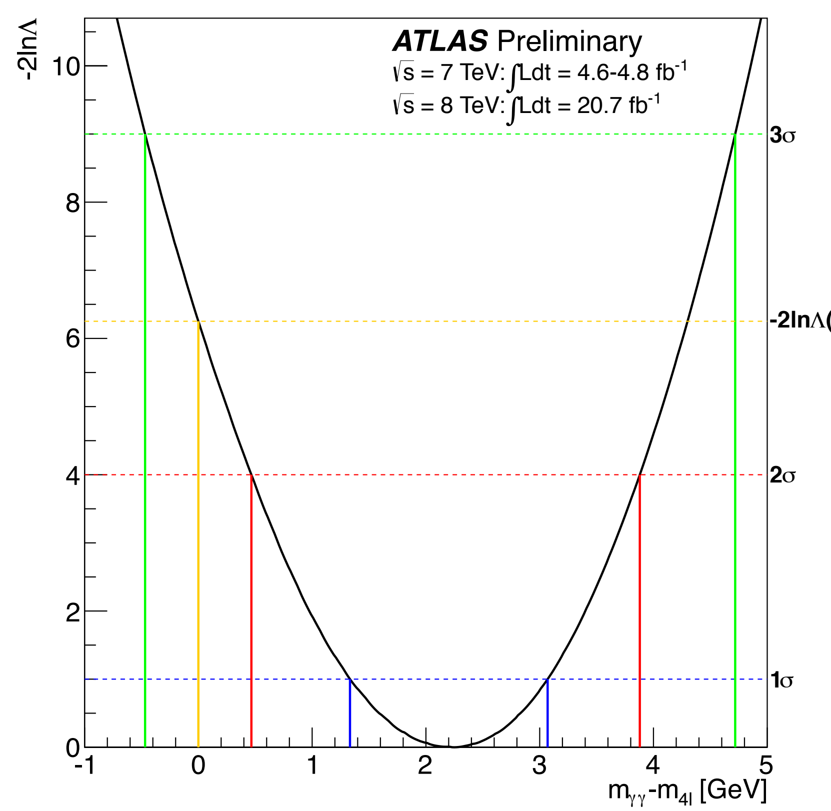


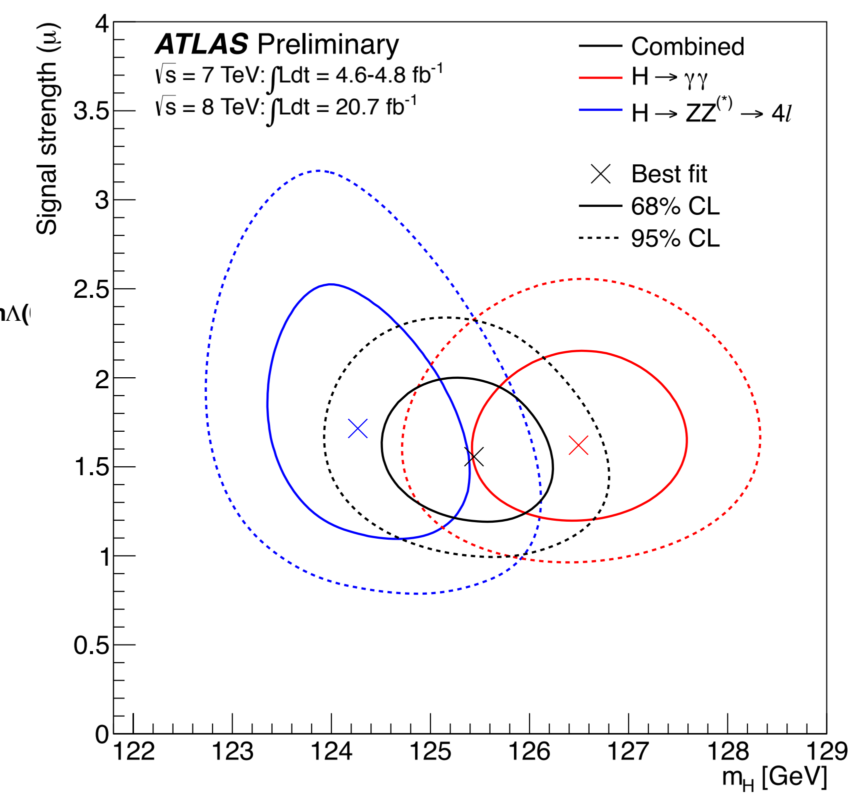




Are γγ and ZZ masses compatible?

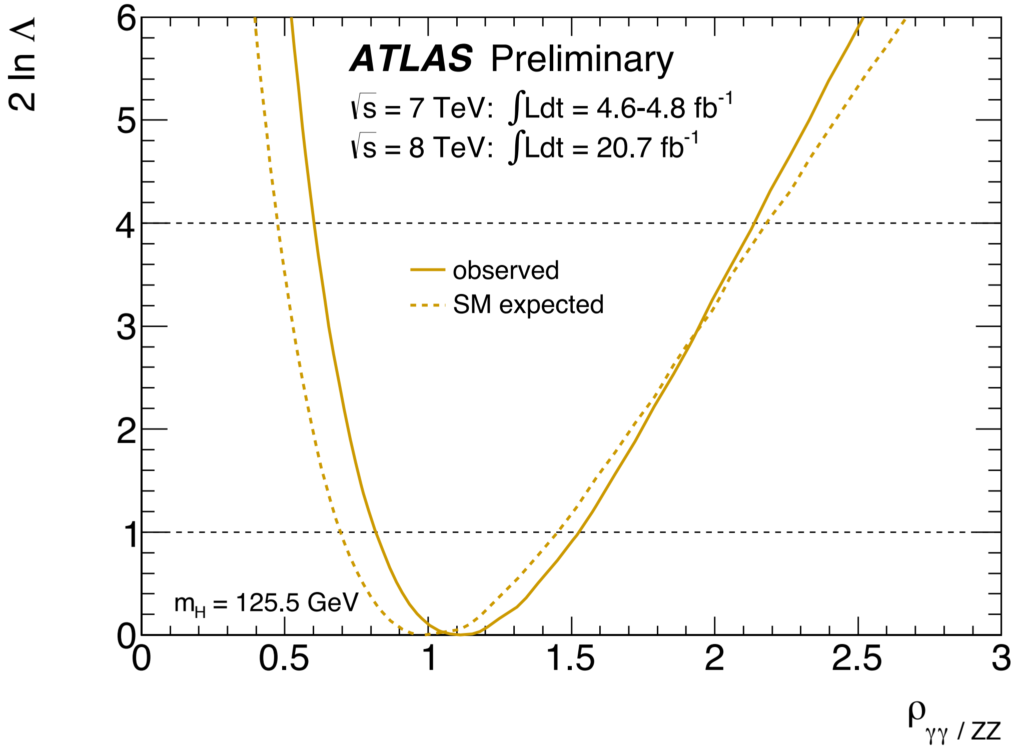


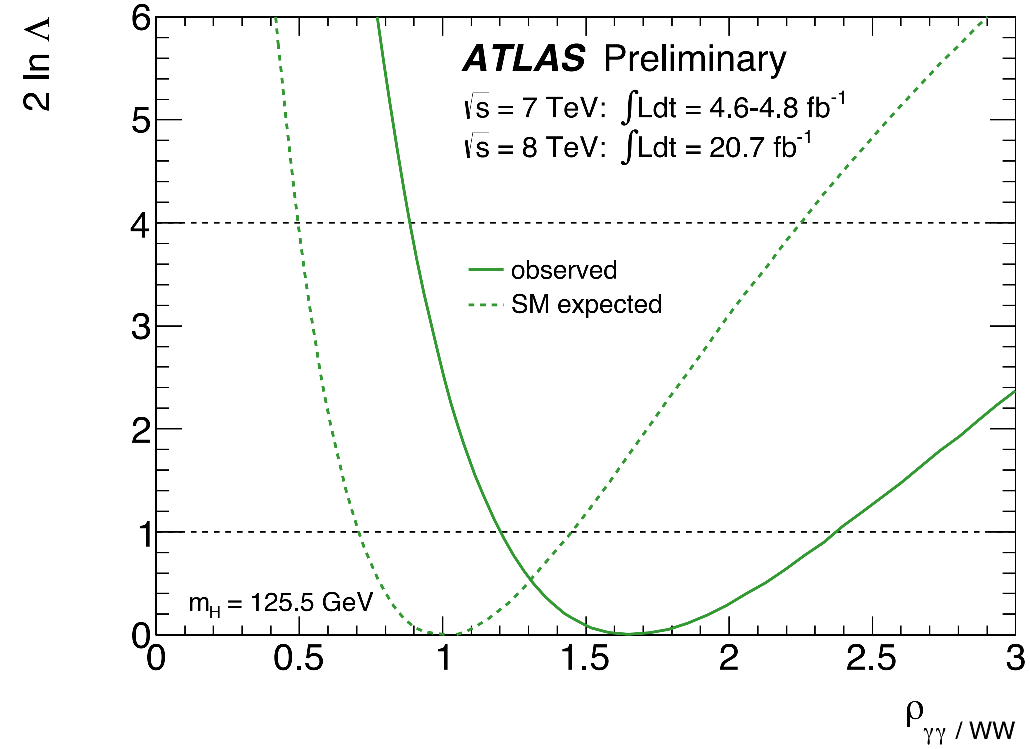




- main correlation from e/γ energy scale systematics
- individual measurements compatible at 1.5% (2.4σ) level

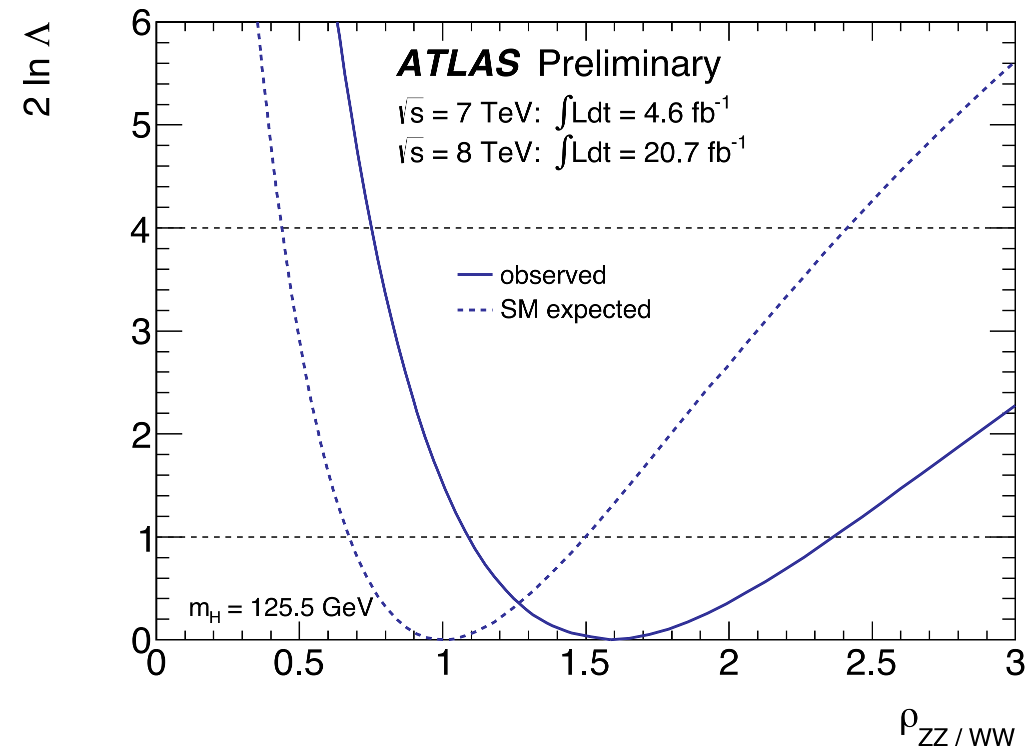
Ratio of branching ratios / SM





$$\rho_{\gamma\gamma/ZZ} = \frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^{(*)})} \times \frac{\mathrm{BR_{SM}}(H\to ZZ^{(*)})}{\mathrm{BR_{SM}}(H\to\gamma\gamma)}$$

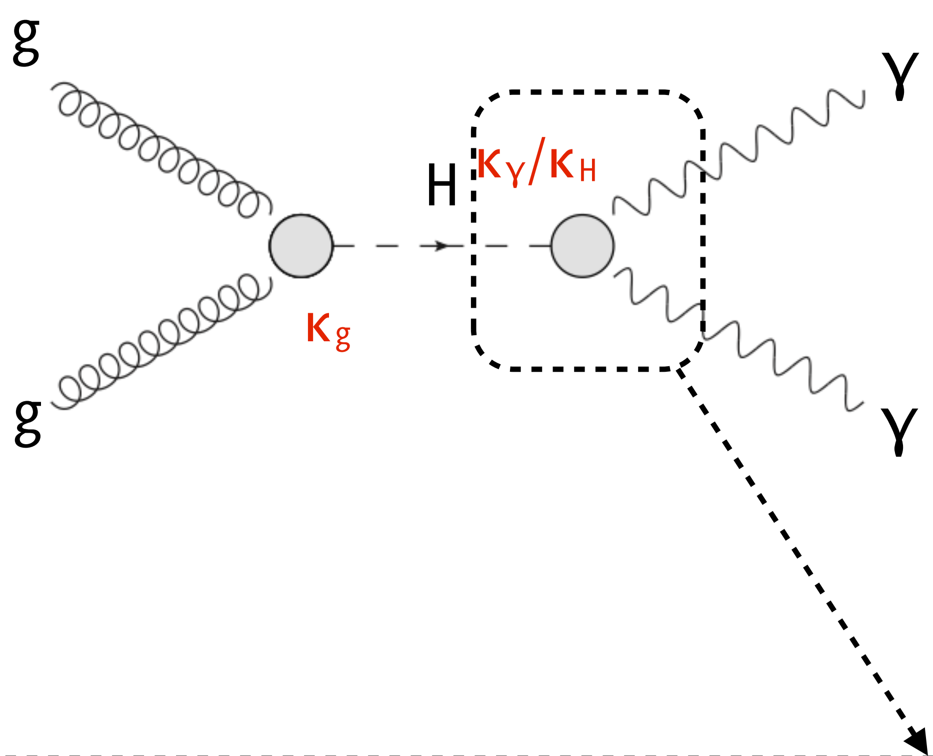
$$\begin{aligned}
\sigma(gg\to H)*\mathrm{BR}(H\to\gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}}\cdot\rho_{\gamma\gamma/ZZ}\\
\sigma(qq'\to qq'H)*\mathrm{BR}(H\to\gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}}\cdot\mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}\cdot\rho_{\gamma\gamma/ZZ}\\
\sigma(gg\to H)*\mathrm{BR}(H\to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}}\\
\sigma(qq'\to qq'H)*\mathrm{BR}(H\to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}}\cdot\mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}
\end{aligned}$$



$$\begin{aligned}
\rho_{\gamma\gamma/ZZ} &= 1.1^{+0.4}_{-0.3}\\
\rho_{\gamma\gamma/WW} &= 1.7^{+0.7}_{-0.5}\\
\rho_{ZZ/WW} &= 1.6^{+0.8}_{-0.5}
\end{aligned}$$

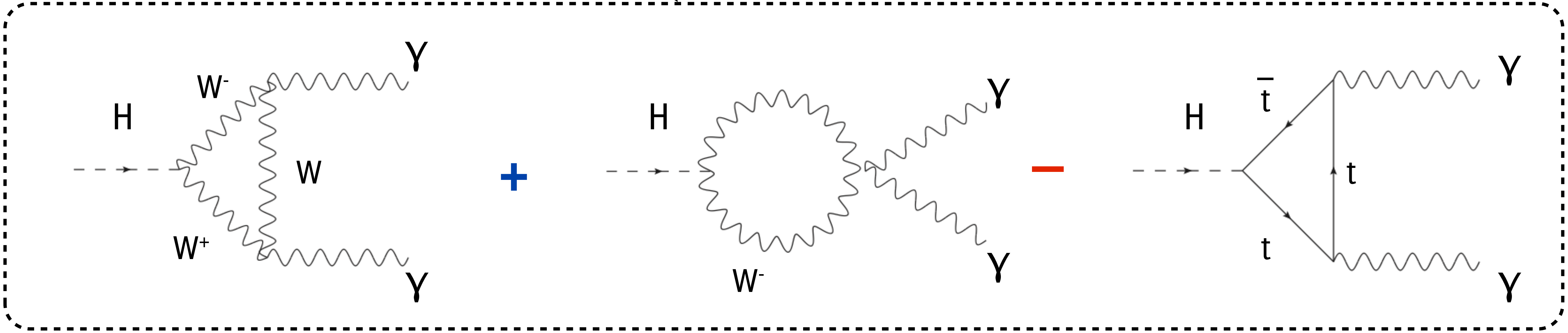
Solving sign degeneracy

$(\sigma \times BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2$



interference effect

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



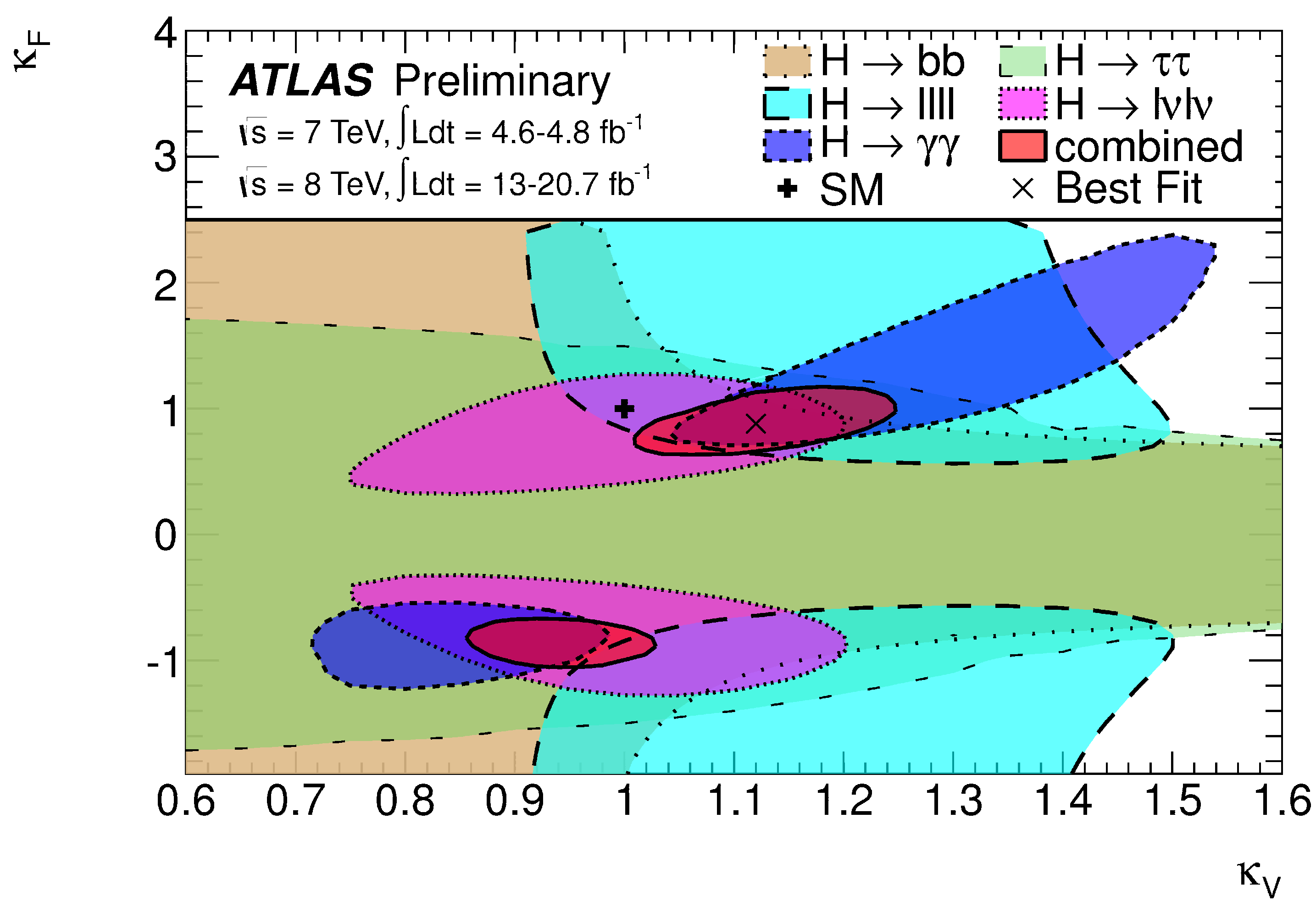
Fermion vs vector couplings / 1

in the SM, ggH and $H \to \gamma\gamma$ are loop-induced

1. assume only SM particles contribute to these loops

fit for $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$

$\kappa_V = \kappa_W = \kappa_Z$



$\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$

$\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21]$

Fermion vs vector couplings / 2

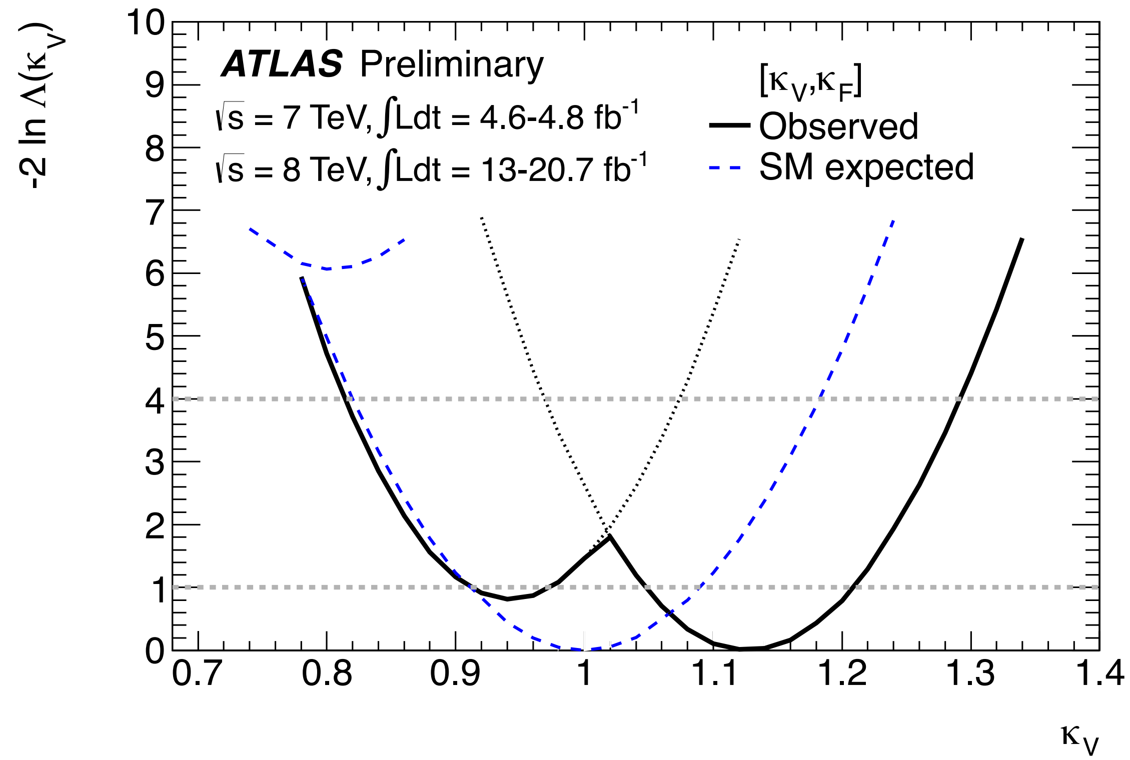
in the SM, ggH and H→γγ are loop-induced

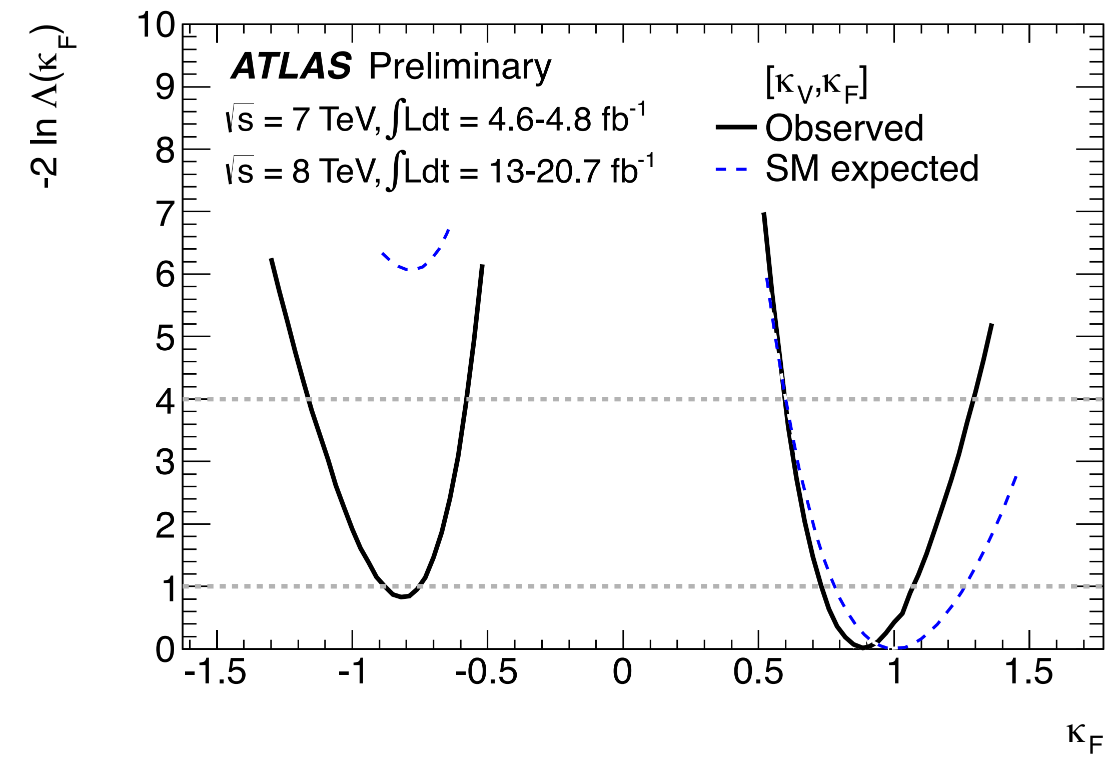
1. assume only SM particles contribute to these loops

fit for $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$

$\kappa_V = \kappa_W = \kappa_Z$

1D projections (profiling the other parameter)





$\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$

$\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21]$ (68% CL intervals)

8% compatibility with SM (1,1)

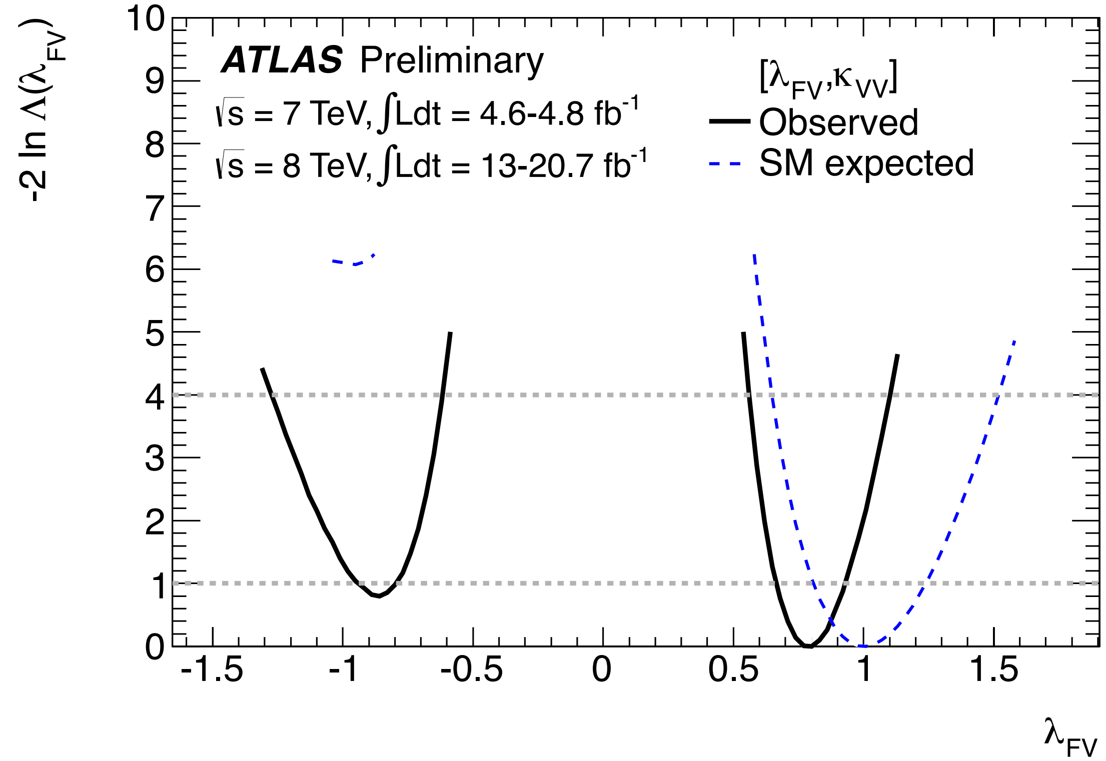
Fermion vs vector couplings / 3

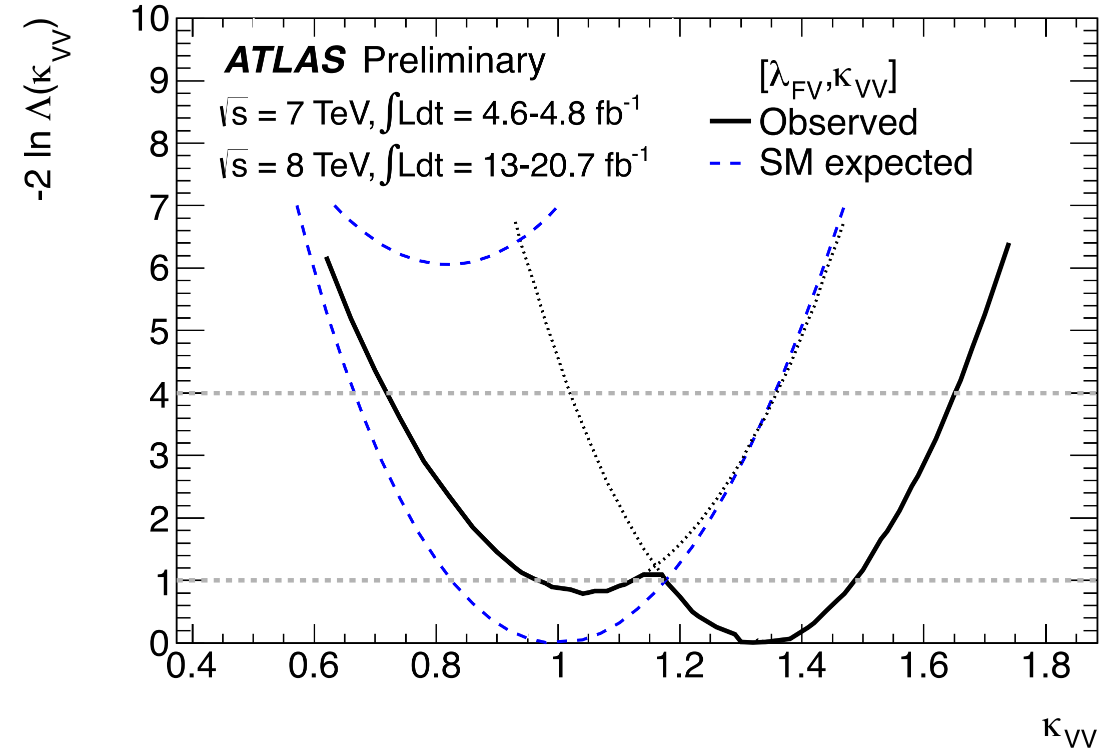
2. no assumption on the total decay width

fit for $\lambda_{FV} = \kappa_F / \kappa_V$

$\kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$

1D projections (profiling the other parameter)





$\lambda_{FV} \in [-0.94, -0.80] \cup [0.67, 0.93]$

$\kappa_{VV} \in [0.96, 1.12] \cup [1.18, 1.49]$

7% compatibility with SM (1,1)

Fermion vs vector couplings / 4

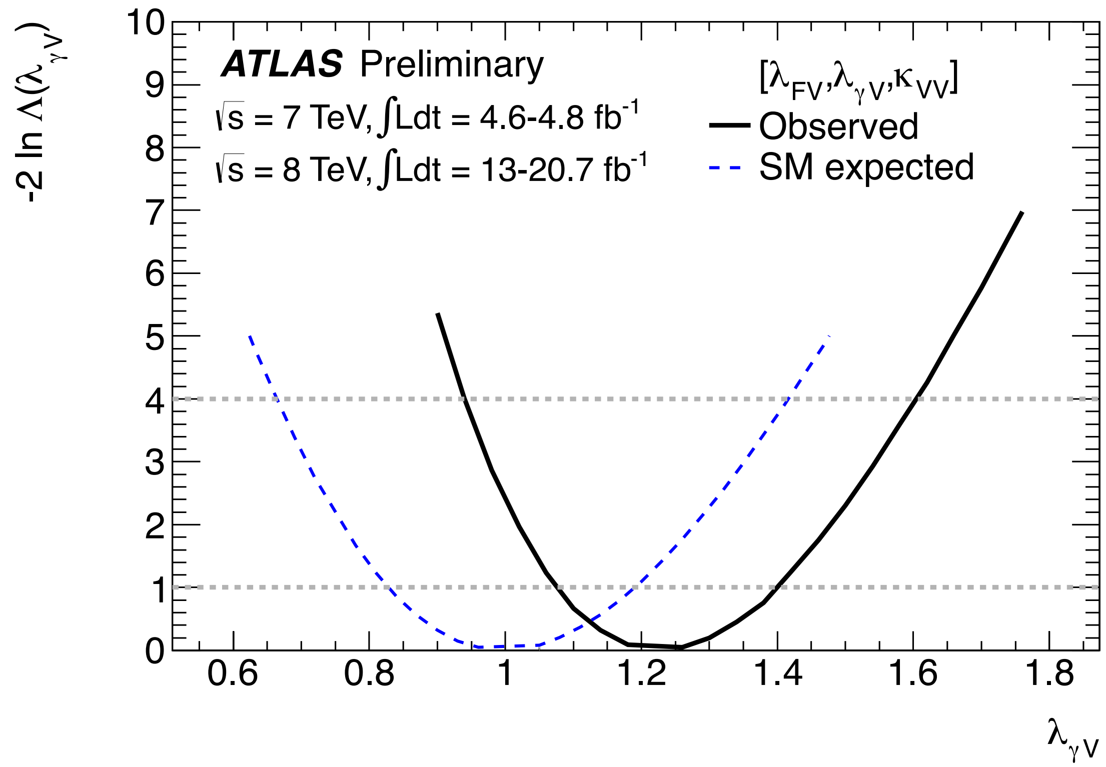
3. no assumption on the total decay width and on the $H\rightarrow\gamma\gamma$ loop content

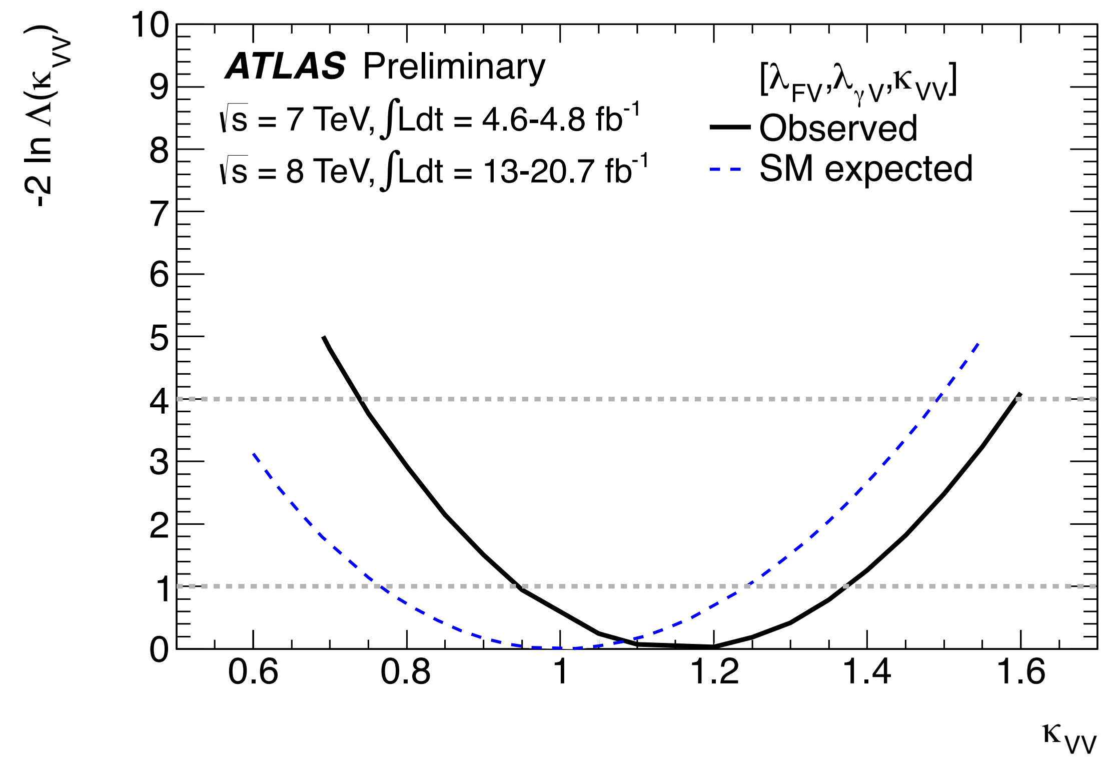
fit for $\lambda_{FV} = \kappa_F/\kappa_V$

$\kappa_{VV} = \kappa_V \cdot \kappa_V/\kappa_H$

$\lambda_{\gamma V} = \kappa_\gamma/\kappa_V$

1D projections (profiling the other parameters)





$\lambda_{FV} = 0.85^{+0.23}_{-0.13}$

$\kappa_{VV} = 1.15 \pm 0.21$

$\lambda_{\gamma V} = 1.22^{+0.18}_{-0.14}$

9% compatibility with SM (1,1,1)

Benchmark models

1. fermion vs vector couplings; only SM particles

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

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

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

$$\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$$
$$\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21] \quad .$$

Benchmark models

2. fermion vs vector couplings; no assumption on total decay width

$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, 1) \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, 1) \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \kappa_{VV}^2 \\
\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) &\sim \kappa_{VV}^2 \cdot \lambda_{FV}^2
\end{aligned}$$

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

$$\begin{aligned}
\lambda_{FV} &= \kappa_F / \kappa_V \\
\kappa_{VV} &= \kappa_V \cdot \kappa_V / \kappa_H
\end{aligned}$$

$$\begin{aligned}
\lambda_{FV} &\in [-0.94, -0.80] \cup [0.67, 0.93] \\
\kappa_{VV} &\in [0.96, 1.12] \cup [1.18, 1.49]
\end{aligned}$$

κ_j

Benchmark models

3. fermion vs vector couplings; no assumption on total decay width and on H→γγ loop content

$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \cdot \lambda_{\gamma V}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \kappa_{VV}^2 \cdot \lambda_{\gamma V}^2 \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \kappa_{VV}^2 \\
\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) &\sim \kappa_{VV}^2 \cdot \lambda_{FV}^2
\end{aligned}$$

$$\begin{aligned}
\lambda_{FV} &= \kappa_F / \kappa_V \\
\lambda_{\gamma V} &= \kappa_\gamma / \kappa_V \\
\kappa_{VV} &= \kappa_V \cdot \kappa_V / \kappa_H
\end{aligned}$$

$$\begin{aligned}
\lambda_{FV} &= 0.85^{+0.23}_{-0.13} \\
\lambda_{\gamma V} &= 1.22^{+0.18}_{-0.14} \\
\kappa_{VV} &= 1.15 \pm 0.21
\end{aligned}$$

Benchmark models

1. W/Z couplings; only SM particles contribute to loops

$$
\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, 1) \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, 1) \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{\mathrm{WZ}}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{\mathrm{WZ}}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{FZ}^2
\end{aligned}
$$

$$
\begin{aligned}
\kappa_{ZZ} &= \kappa_Z \cdot \kappa_Z / \kappa_H \\
\lambda_{WZ} &= \kappa_W / \kappa_Z \\
\lambda_{FZ} &= \kappa_F / \kappa_Z
\end{aligned}
$$

$$
\begin{aligned}
\lambda_{WZ} &\in [0.64, 0.87] \\
\lambda_{FZ} &\in [-0.89, -0.55] \\
\kappa_{ZZ} &\in [1.20, 2.08]
\end{aligned}
$$

Benchmark models

2. W/Z couplings; decouple possible new physics contribution in $\gamma\gamma$

$$
\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{\gamma Z}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{\gamma Z}^2 \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{WZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{WZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{FZ}^2
\end{aligned}
$$

$$
\begin{aligned}
\kappa_{ZZ} &= \kappa_Z \cdot \kappa_Z / \kappa_H \\
\lambda_{WZ} &= \kappa_W / \kappa_Z \\
\lambda_{\gamma Z} &= \kappa_\gamma / \kappa_Z \\
\lambda_{FZ} &= \kappa_F / \kappa_Z
\end{aligned}
$$

$$
\begin{aligned}
\lambda_{WZ} &= 0.80 \pm 0.15 \\
\lambda_{\gamma Z} &= 1.10 \pm 0.18 \\
\lambda_{FZ} &= 0.74^{+0.21}_{-0.17} \\
\kappa_{ZZ} &= 1.5^{+0.5}_{-0.4}
\end{aligned}
$$

Benchmark models

1. BSM contributions; assume no new contribution to total Higgs width

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_g^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$$

$$\kappa_g = 1.08 \pm 0.14$$

$$\kappa_\gamma = 1.23^{+0.16}_{-0.13}$$

Benchmark models

2. BSM contributions; allow for invisible/undetectable final states

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}})$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}})$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_g^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}})$$

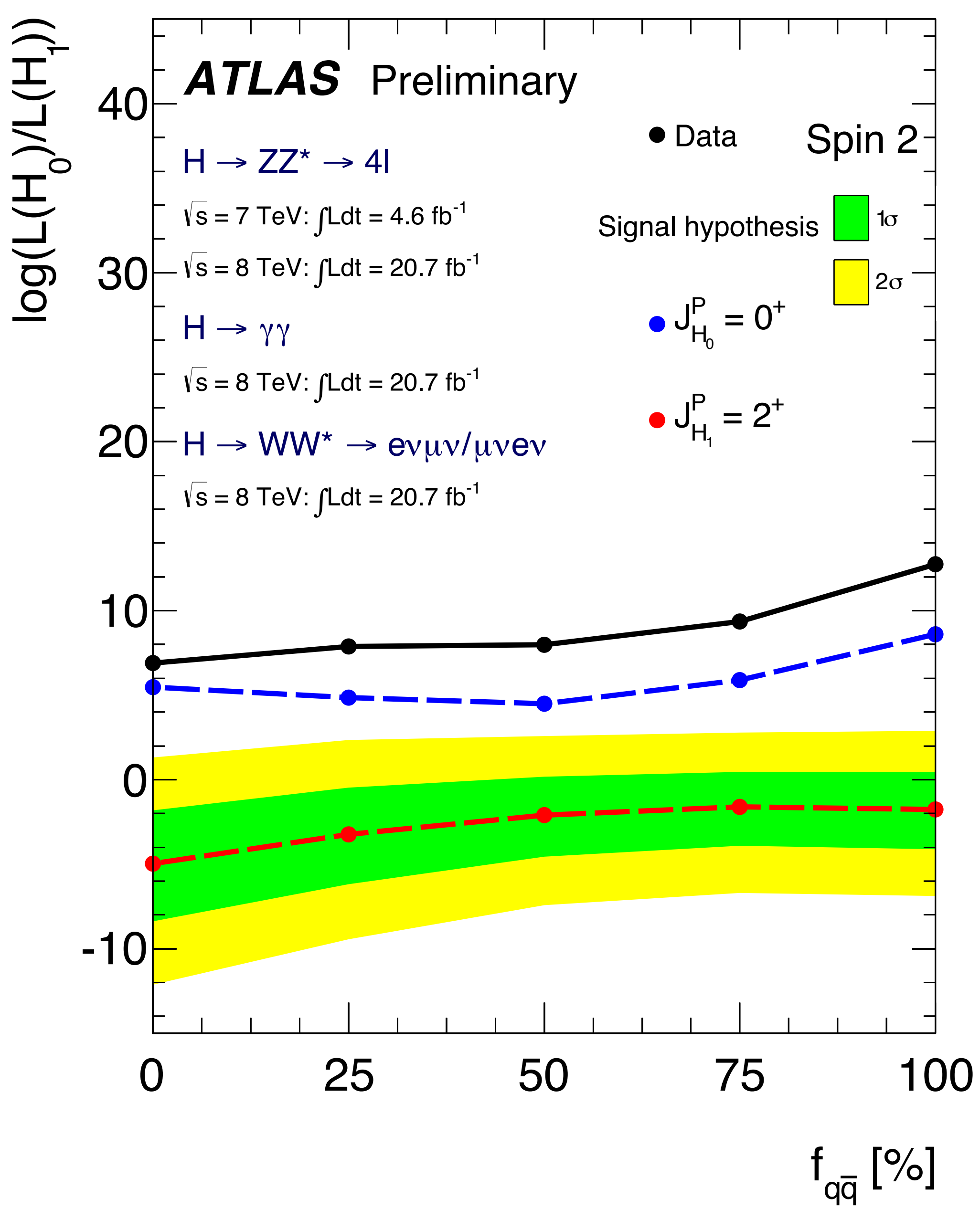
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}})$$

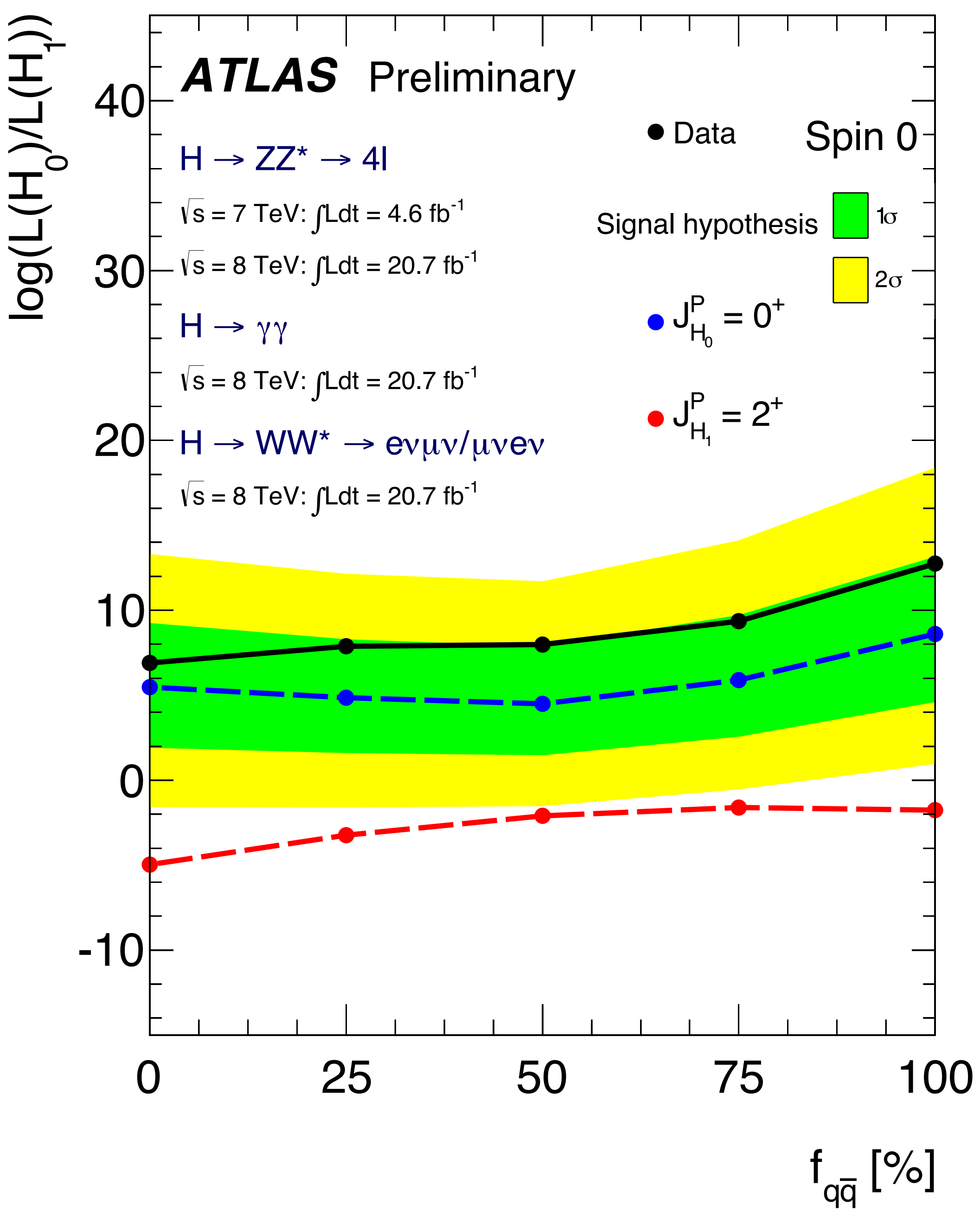
$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}})$$

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - \mathrm{BR}_{\mathrm{inv.,undet.}})} \Gamma_H^{SM}$$

$$\kappa_g = 1.08^{+0.32}_{-0.14}$$
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$
$$\mathrm{BR}_{\mathrm{inv.,undet.}} < 0.33$$

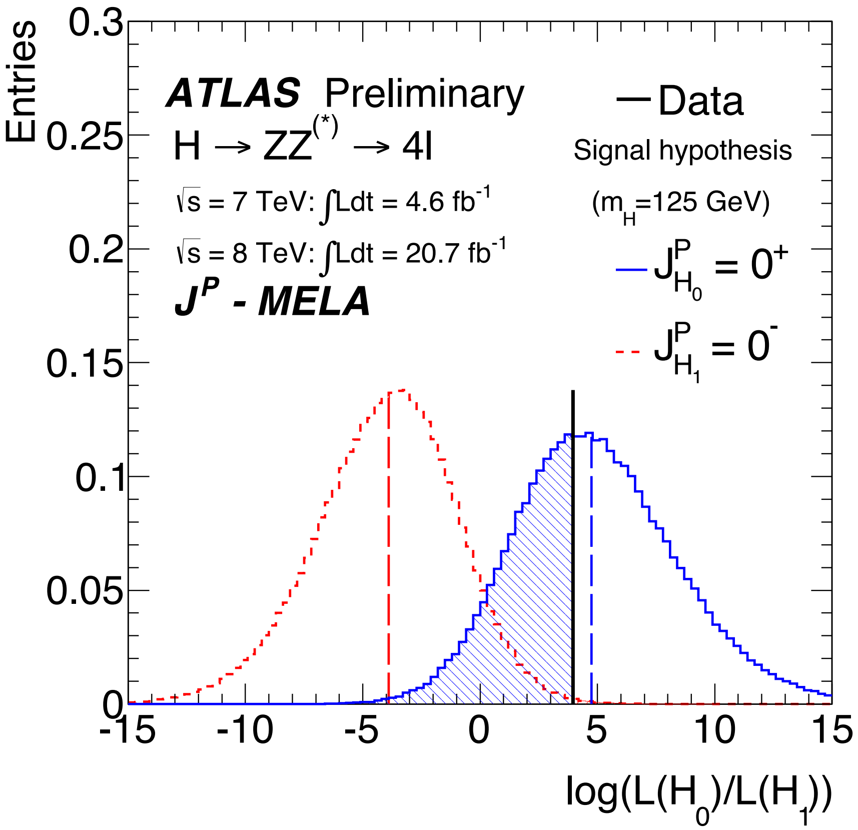
J^P: test statistics vs f_{qq}



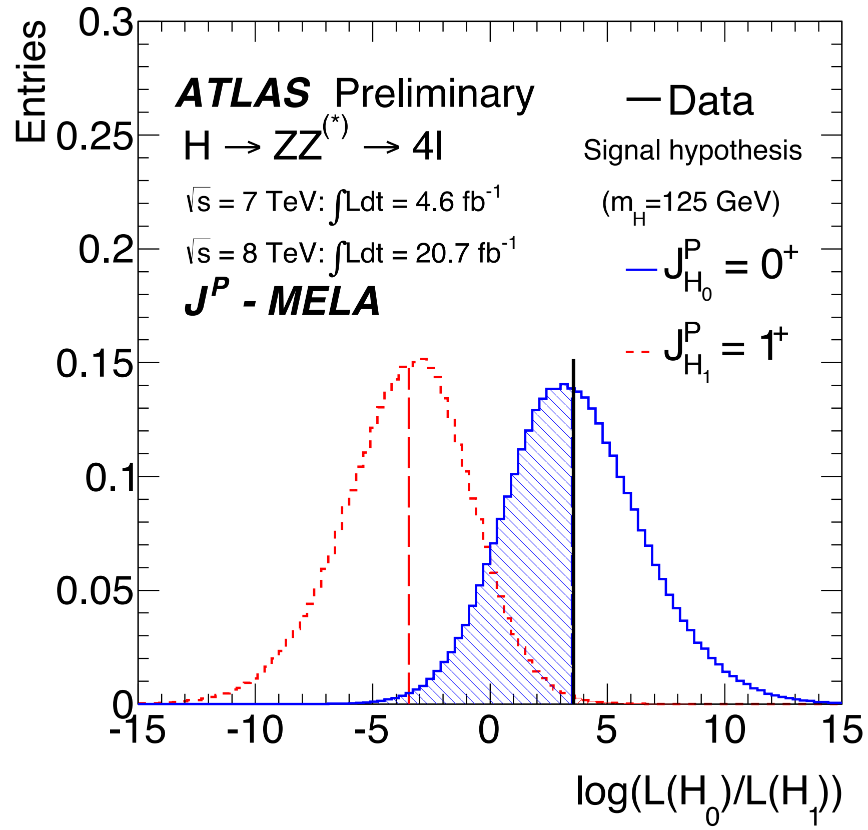


$H \to ZZ \to 4\ell$ spin

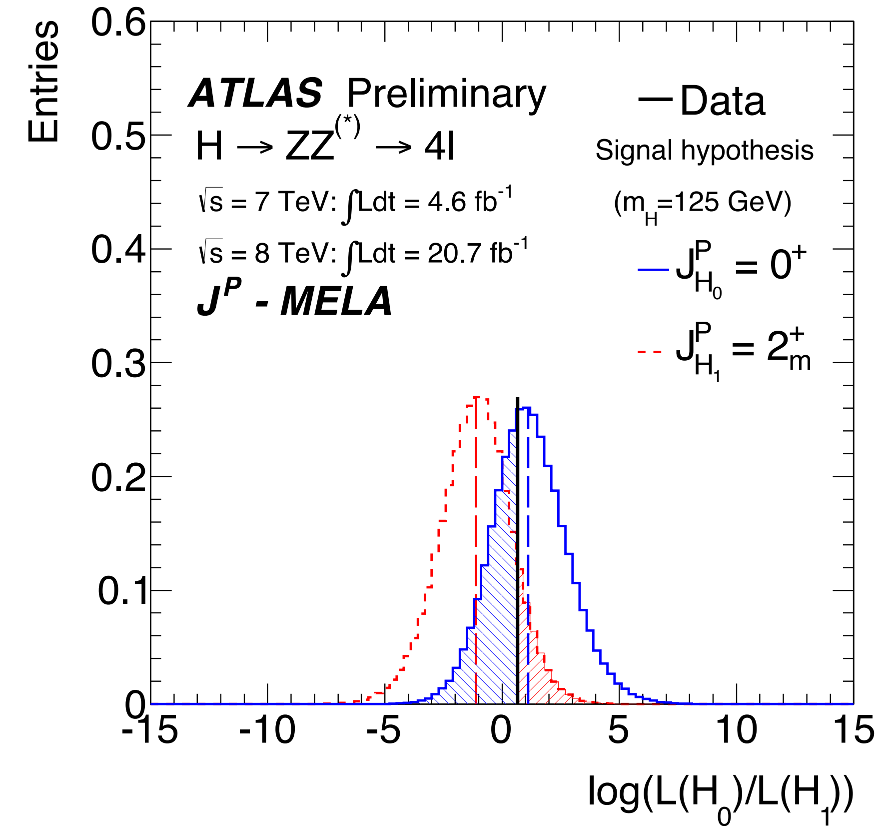
0^+ vs 0^-



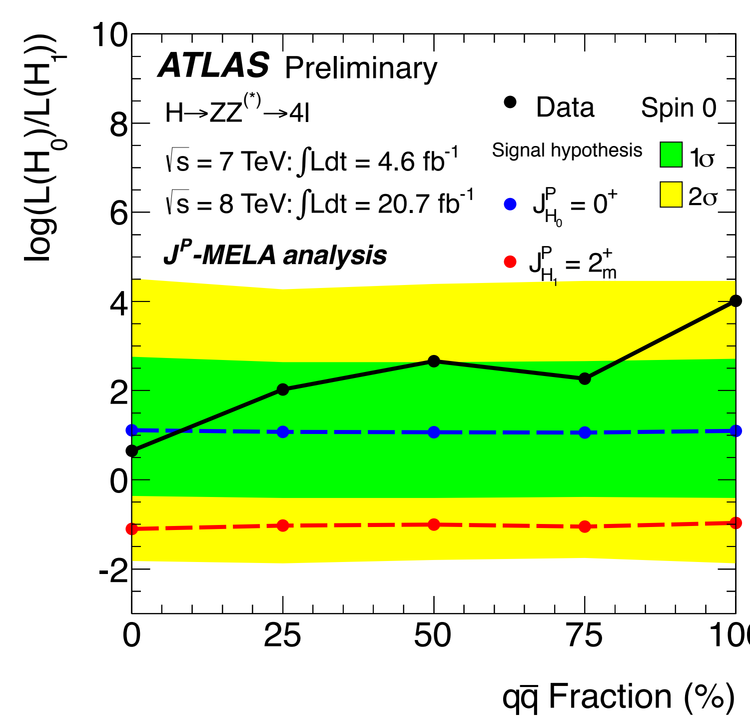
0^+ vs 1^+



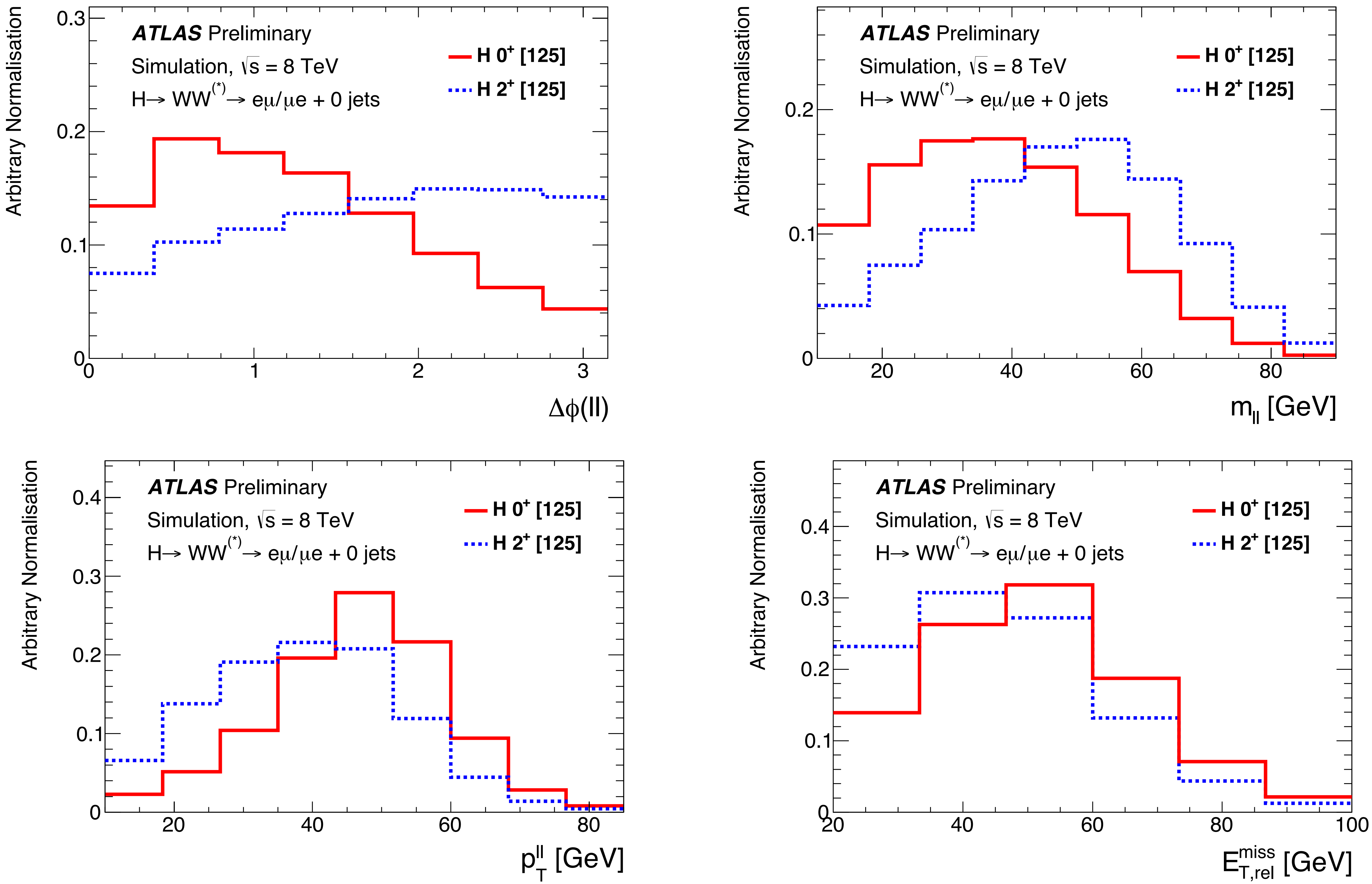
0^+ vs 2^+



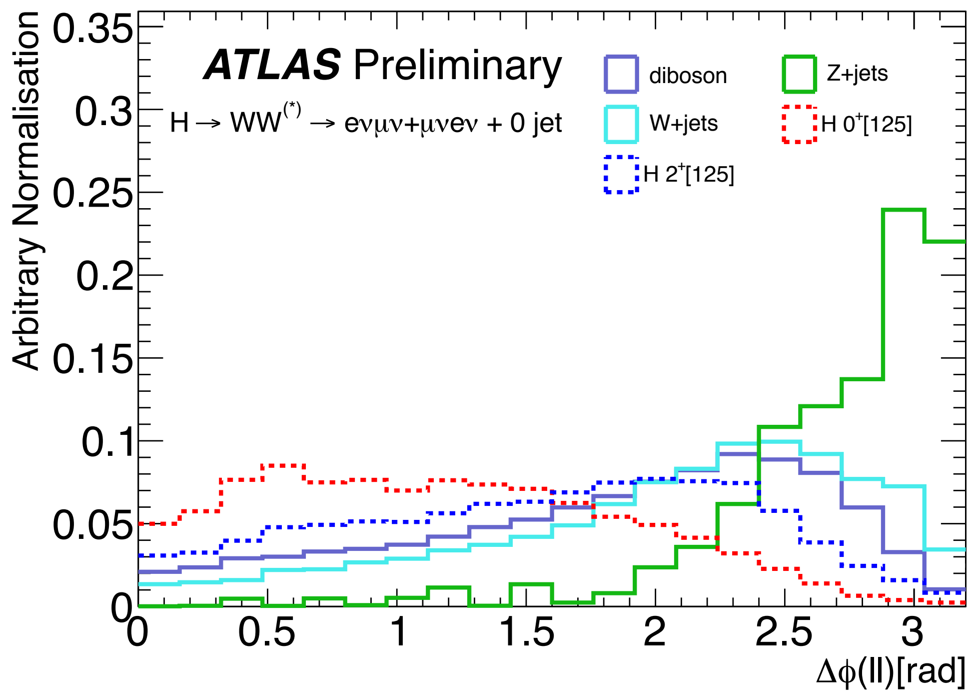
0^+ vs 2^+ (qq/gg)

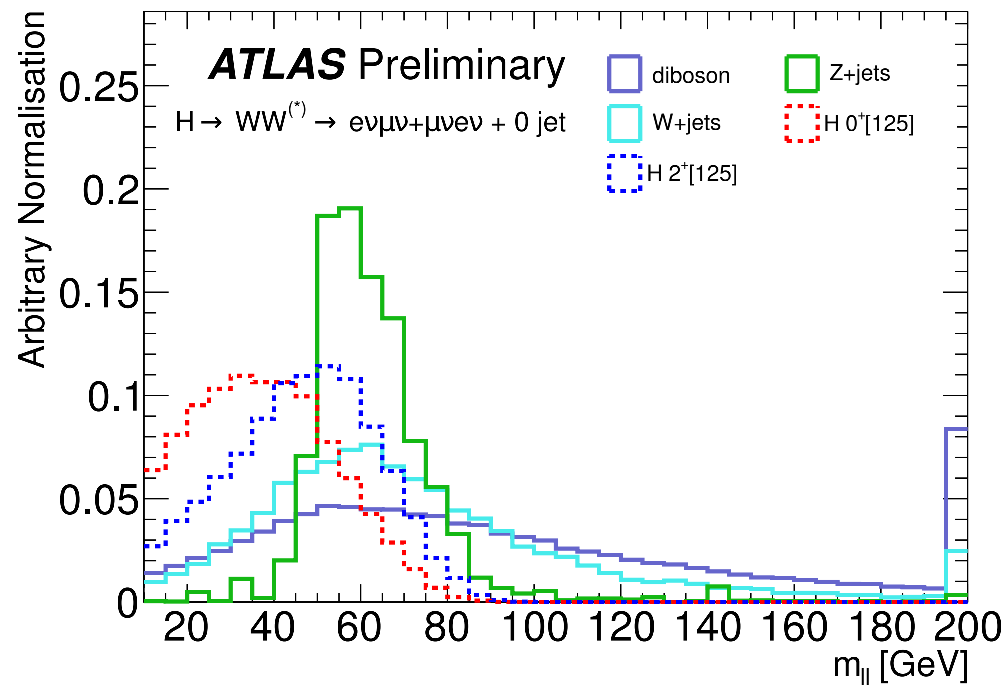


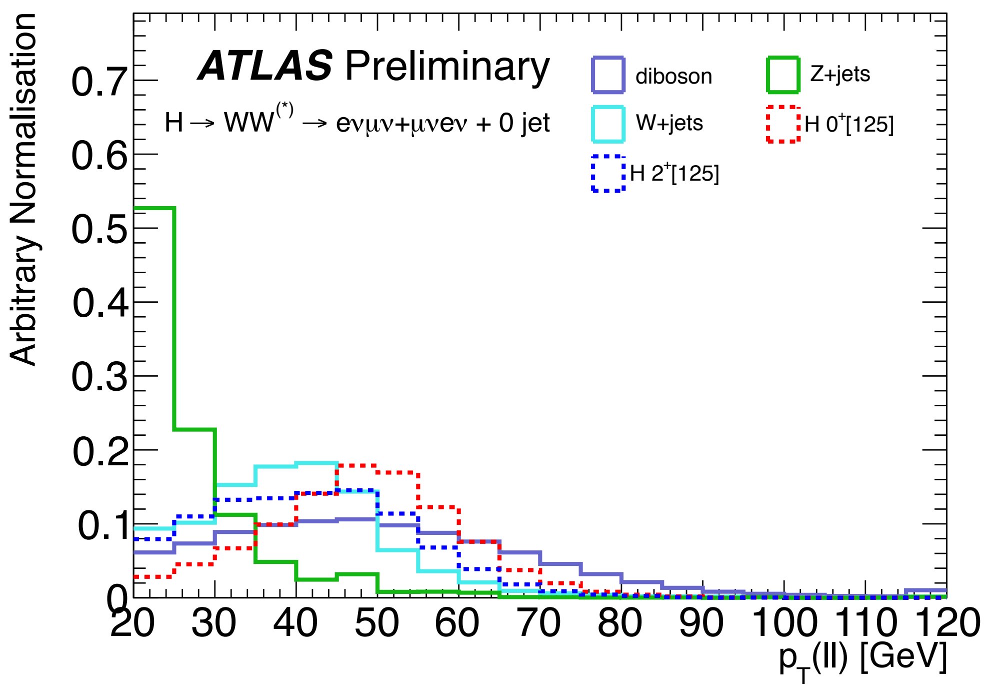
J^P discrimination in WW

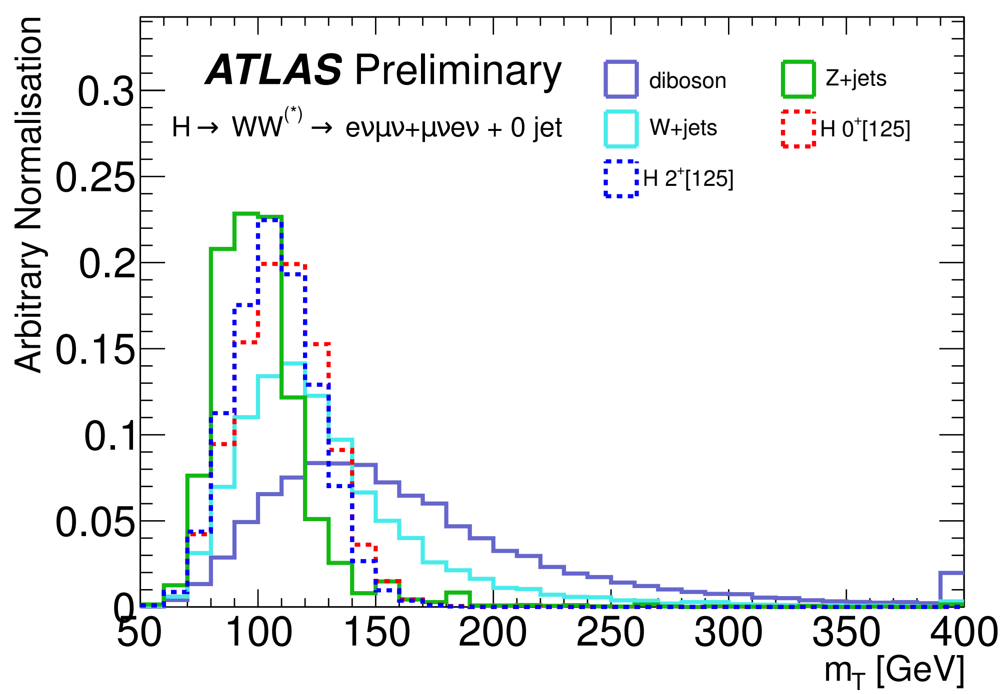


J^P discrimination in WW







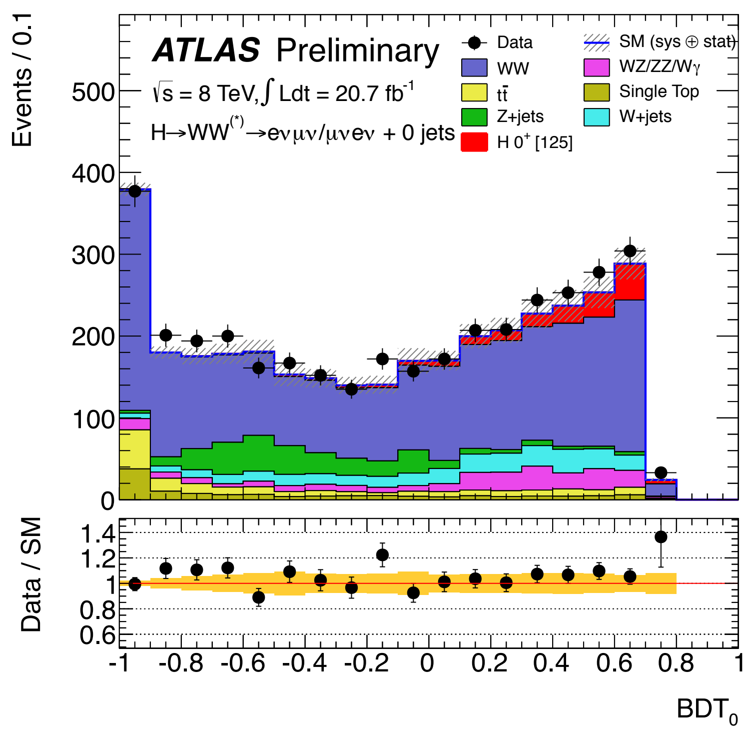


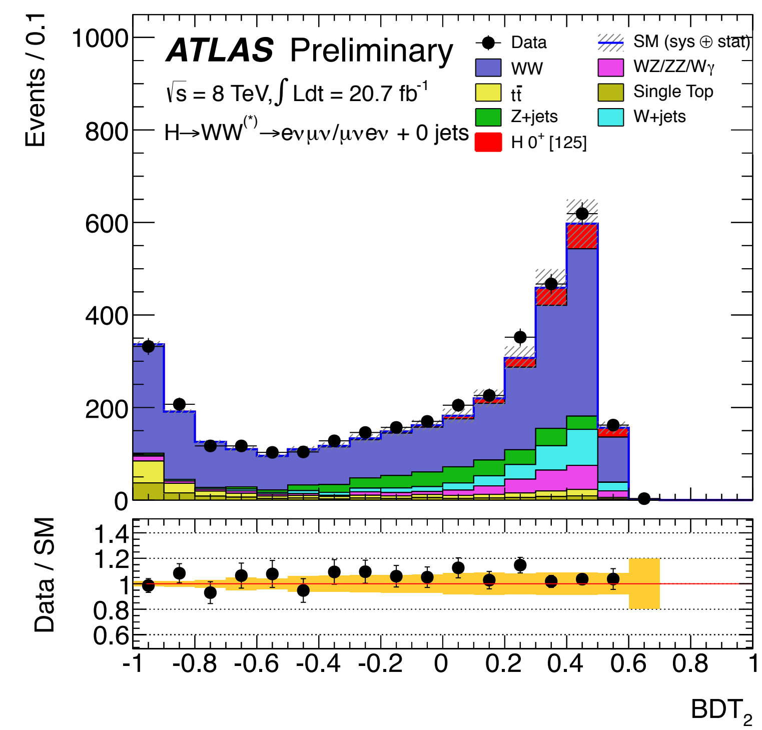
J^P discrimination in WW

BDT (0^+ vs bkg)

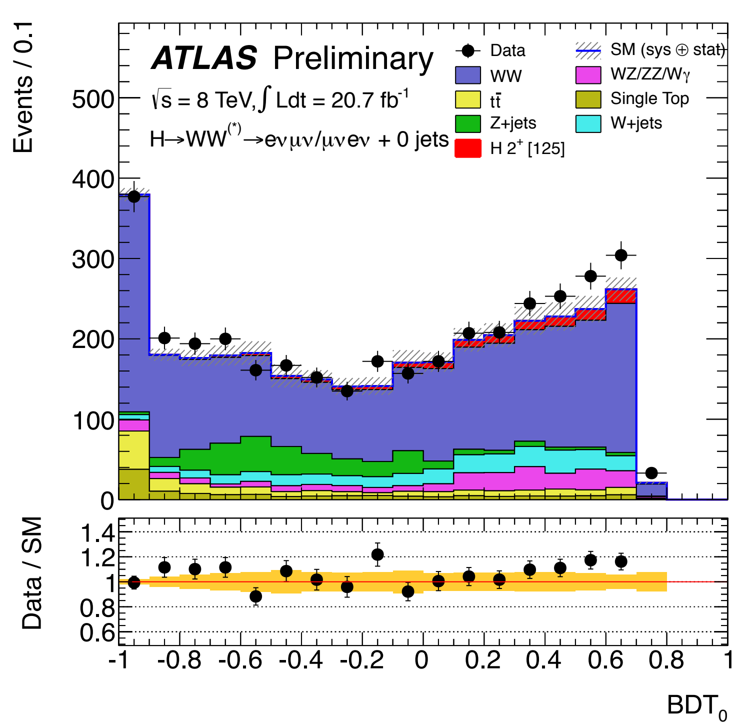
BDT (2^+ vs bkg)

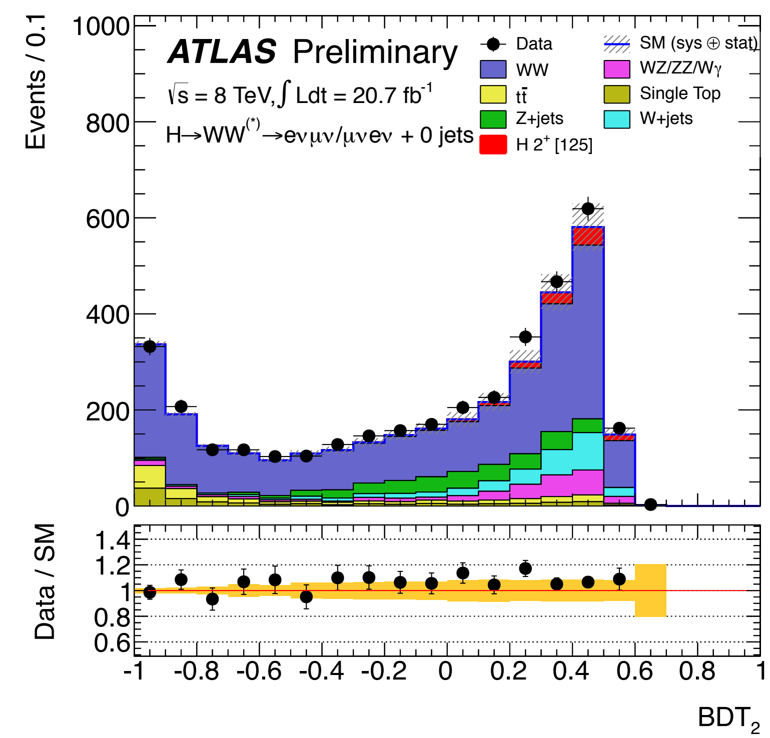
red: 0^+



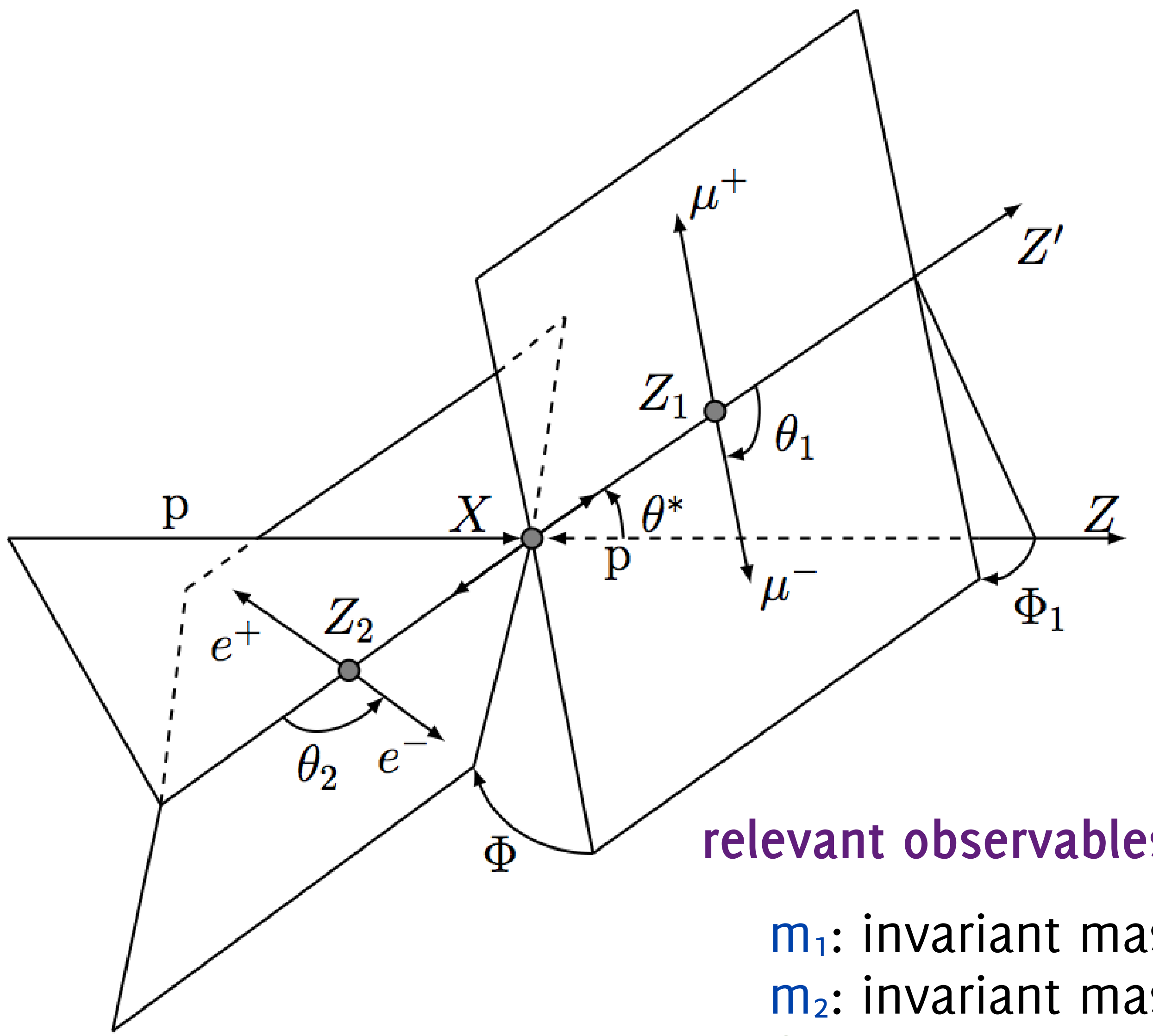


red: 2^+





Angular variables

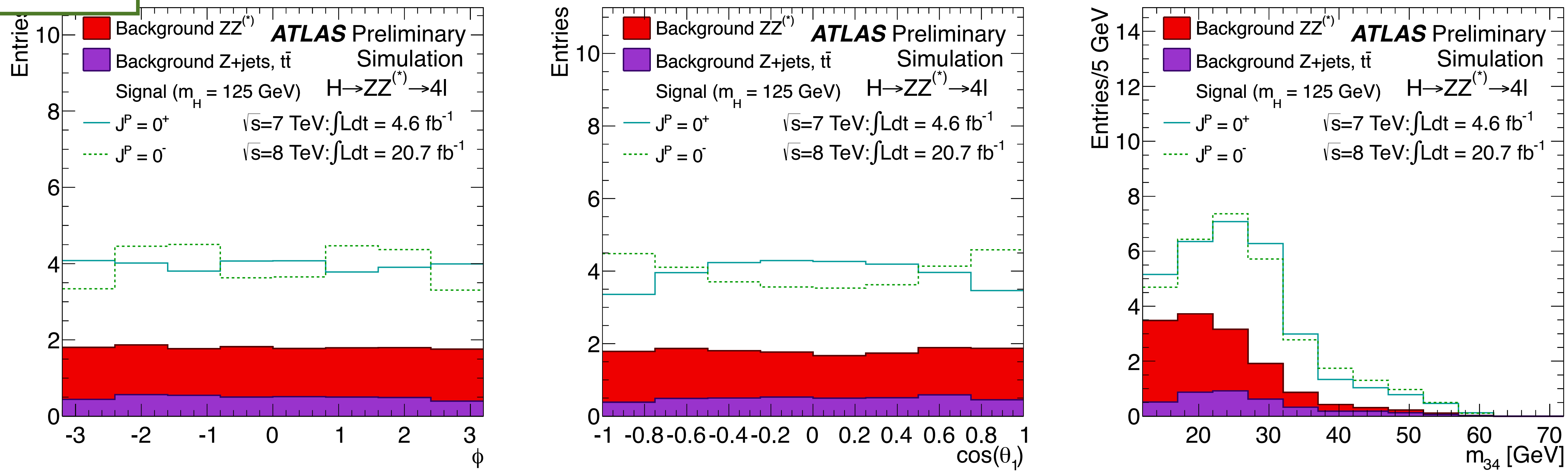


relevant observables in $H \to ZZ \to 4\ell$ J^{PC} analysis (similar for $H \to WW, \gamma\gamma$)

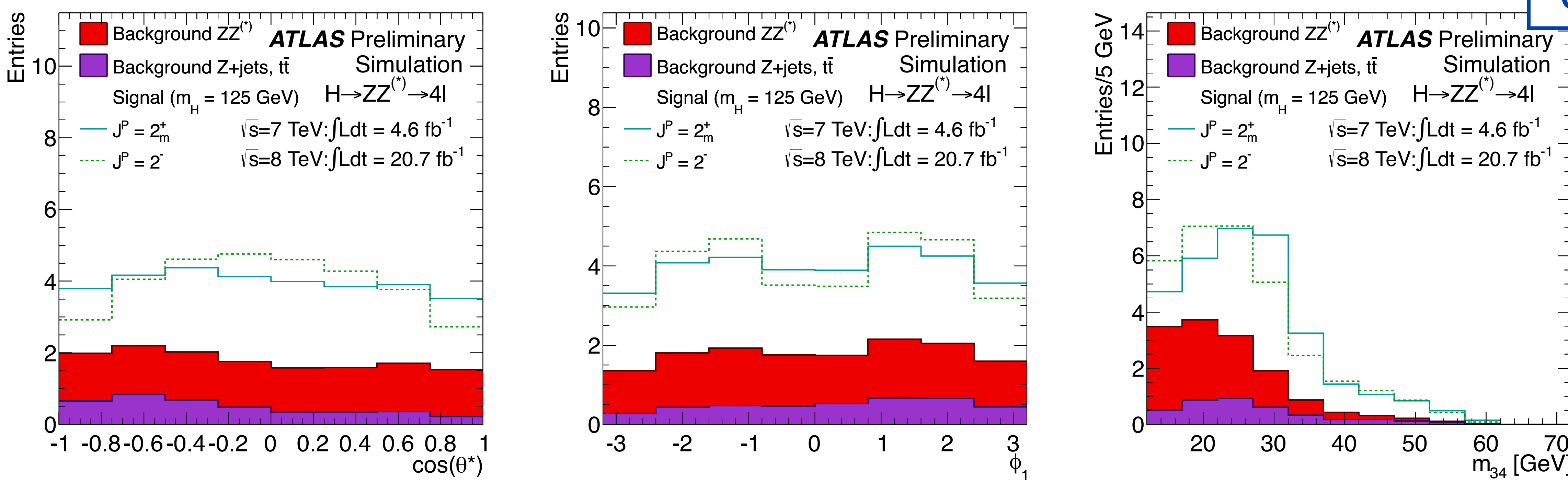
- m_1: invariant mass of the on-shell Z (Z_1)
- m_2: invariant mass of the off-shell Z (Z_2)
- θ^*: angle, in X reference frame, between Z_1 and beam axis
- φ, φ_1: azimuthal angles, in X reference frame, between X, Z_1 and Z_2 decay planes
- θ_i: angle, in Z_i reference frame, between lepton and Z_i flight line

Mass/angular distributions

0^+ vs 0^-



0^+ vs 2^-



JPC

Individual spin results

H→WW

$f_{q\bar{q}}$	$N_{fit}(0^+)$	$N_{fit}(2^+_m)$	exp. $p_0(0^+)$	exp. $p_0(2^+_m)$	obs. $p_0(0^+)$	obs. $p_0(2^+_m)$	1-CL_S (2^+_m)
100%	270^{+100}_{-80}	110^{+110}_{-90}	0.013	0.005	0.543	0.005	0.99
75%	250^{+100}_{-80}	170^{+110}_{-100}	0.034	0.007	0.591	0.005	0.99
50%	250^{+100}_{-80}	230^{+140}_{-100}	0.035	0.012	0.619	0.007	0.98
25%	260^{+110}_{-80}	260^{+130}_{-110}	0.048	0.019	0.613	0.010	0.97
0%	260^{+100}_{-80}	320^{+130}_{-110}	0.091	0.057	0.725	0.014	0.95

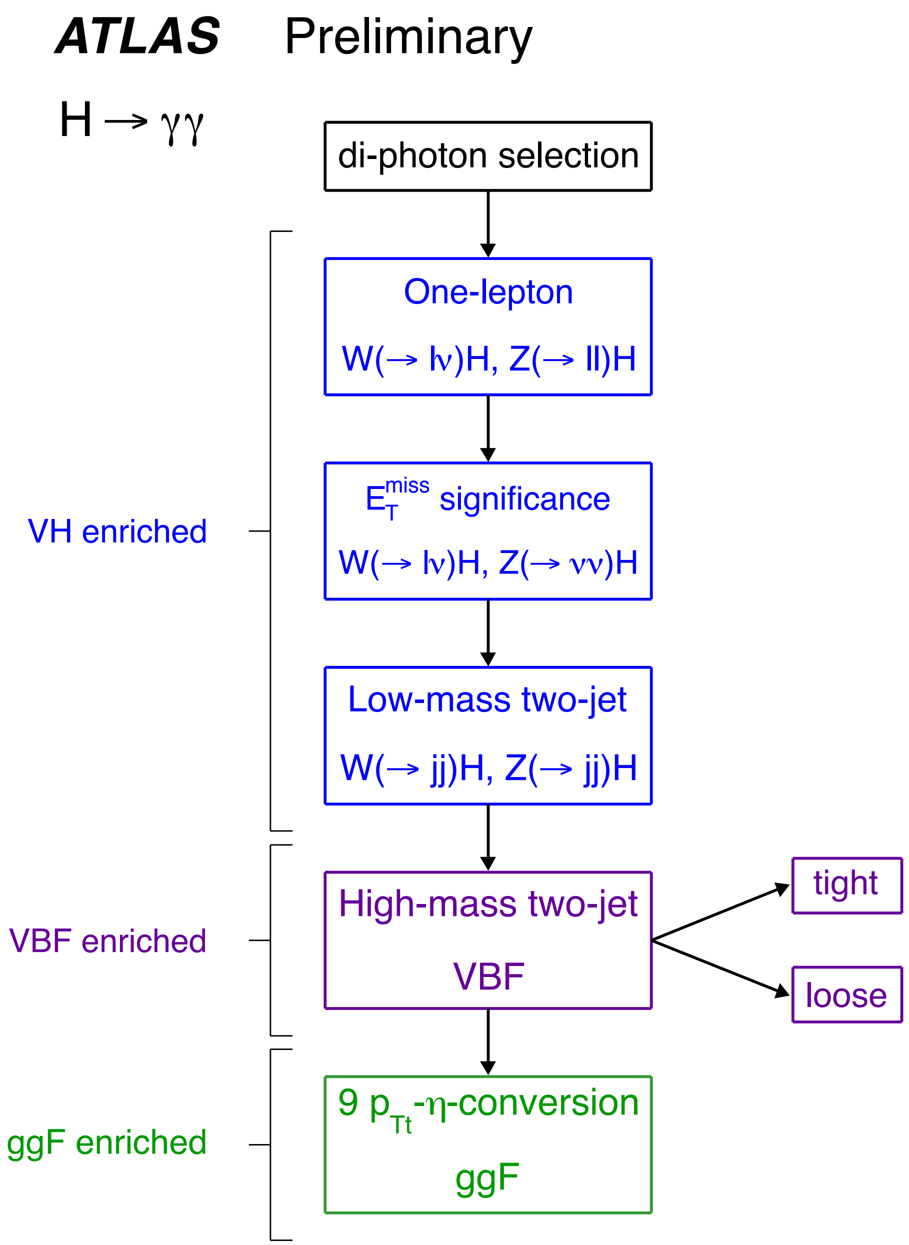
H→γγ

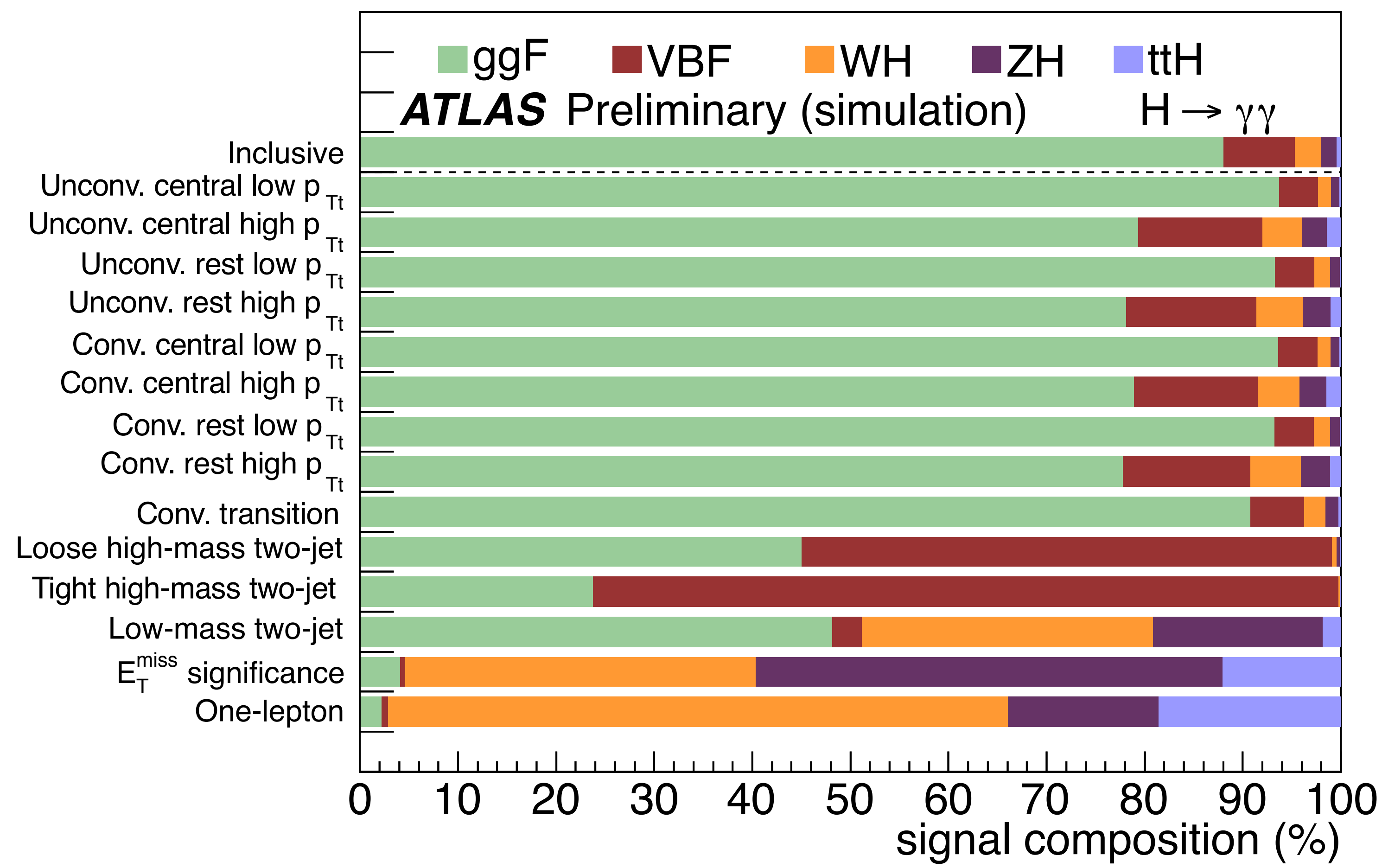
$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%) expected	p-values (%) observed	$1-CL_S(2^+)$ (%)
0	0^+	1.2	58.8	99.3
	2^+	0.5	0.3	
25	0^+	6.3	60.2	92.2
	2^+	5.3	3.1	
50	0^+	24.3	75.2	68
	2^+	23.4	7.9	
75	0^+	29.4	88.6	70
	2^+	28.0	3.4	
100	0^+	14.8	79.8	88
	2^+	13.5	2.5	

H→ZZ→4ℓ

		BDT analysis				J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S	tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0016	0.001	0.55	0.002	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0038	0.051	0.15	0.060	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.092	0.079	0.53	0.168	0.064	0.11	0.38	0.182
2^-	p_0	0.0053	0.25	0.034	0.258	0.0032	0.11	0.08	0.116

γγ categorization





σ_{fid}

Fiducial cross-section

measure production and decay cross section in $H \to \gamma\gamma$

* inclusive analysis (no categories: more model-independent approach)
* fiducial region: photon $|\eta| < 2.37$, $E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV

$$\sigma_{\text{fid}} \times \text{BR} = \frac{N^{\text{signal}}}{C_H \times L_{\text{int}}}$$

from S+B fit to $m_{\gamma\gamma}$ distribution

748±39(stat)±11.2%(syst)

correction factor for detector effect
(efficiencies for photons within acceptance)

0.643 (±2.7%)

integrated luminosity (20.7 fb^{-1} at 8 TeV)

main systematics:
mass resolution, background modelling, photon identification

56.2±10.5(stat)±6.5(syst)±2.0(lumi) fb
good agreement with SM expectation from MC