Evidence for VBF in Higgs Production at the LHC

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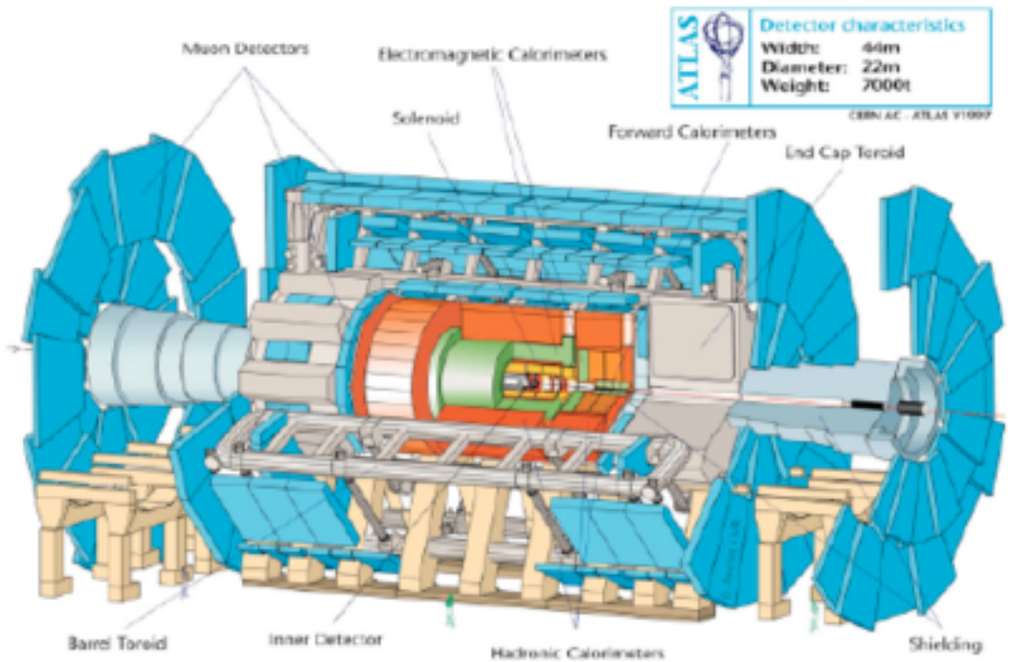
with results of the ATLAS and CMS Collaboration
June 5th 2014

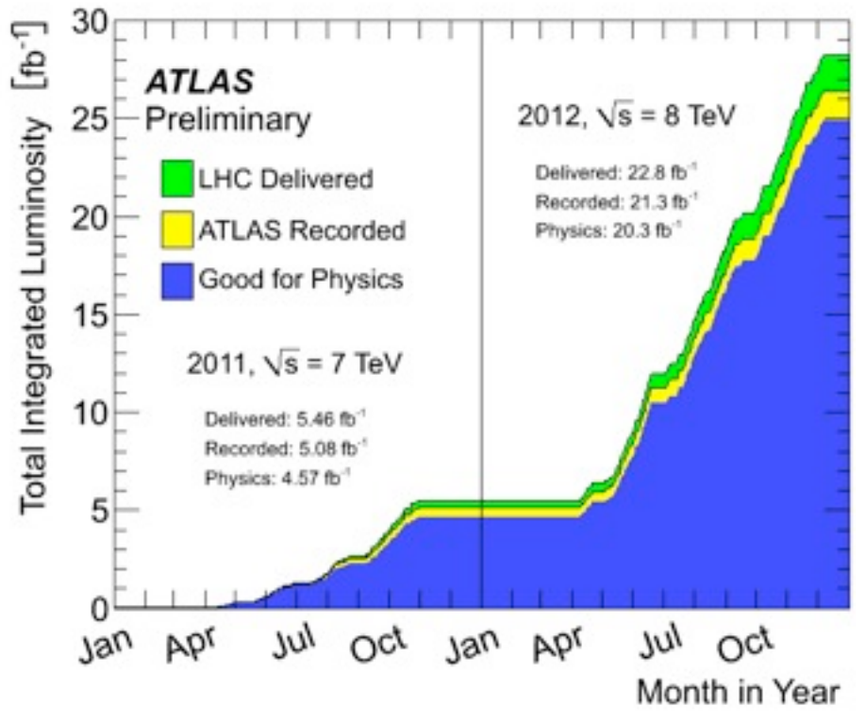
THE UNIVERSITY OF WARWICK

Overview

- quick aside on LHC detectors
- individual higgs production and decay channels
- introduction to coupling fits
- results for VBF couplings
- summary

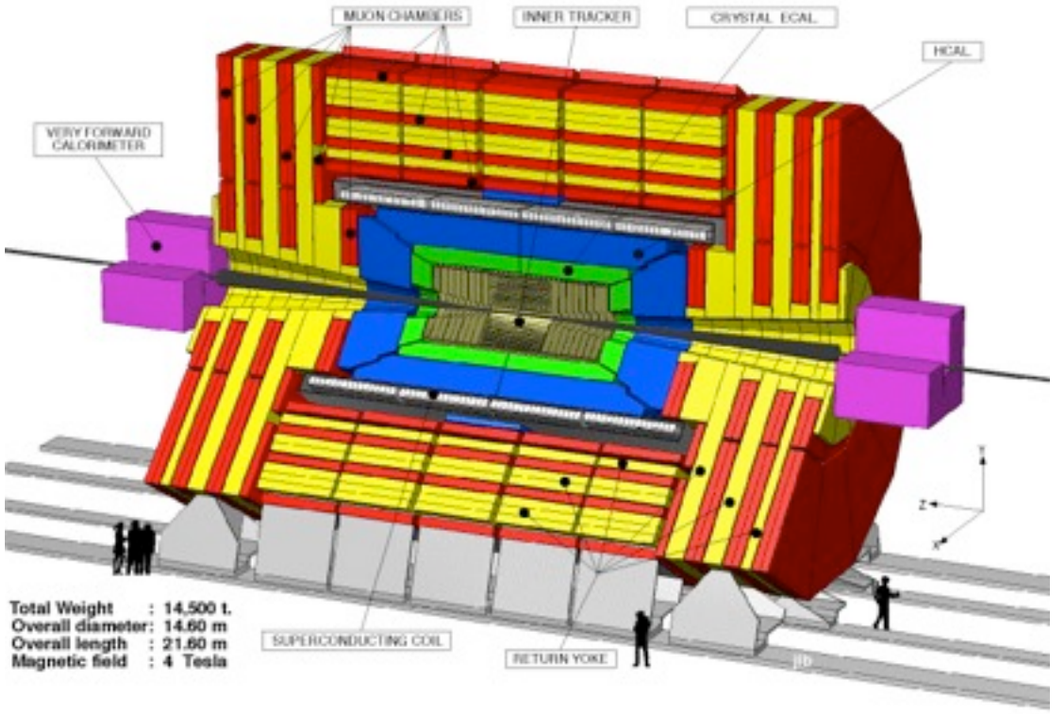
ATLAS

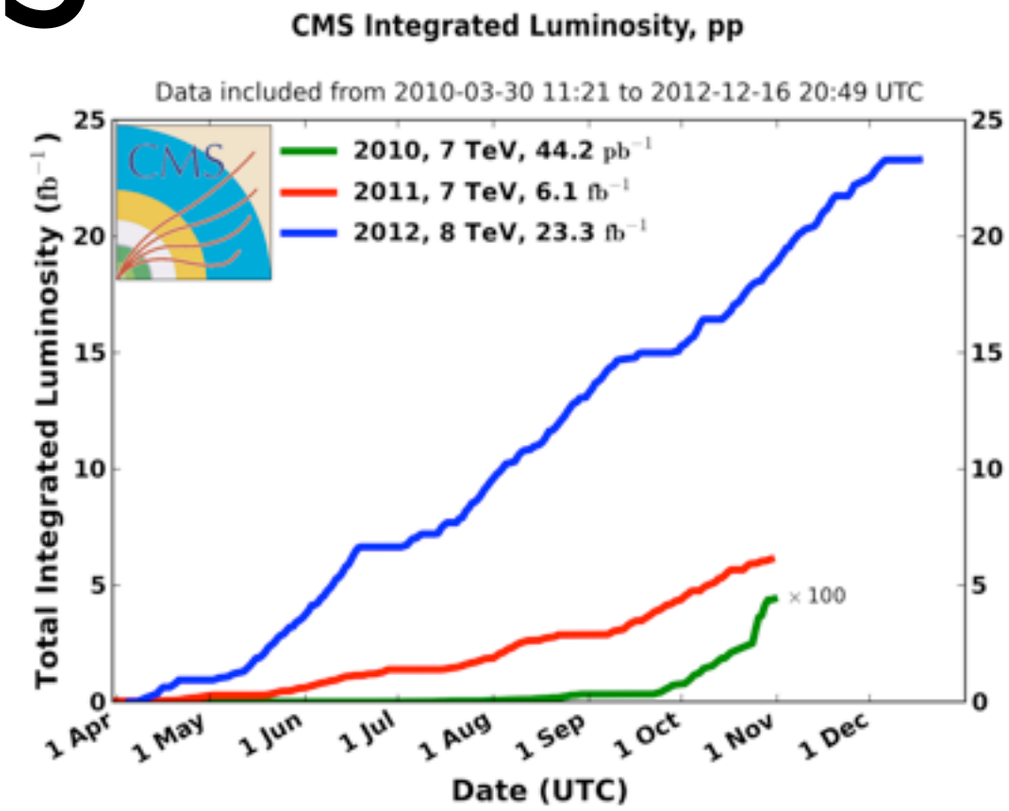




- **Inner Detector (ID):** silicon pixels and strips, transition radiation tracker
- **Calorimetry:** near 4 π electromagnetic (ECAL) and hadronic (HCAL)
- **Muon System (MS):** precision and trigger tracking chambers
- **Magnet System:** 2 Tesla central solenoid to bend ID tracks and air-core toroid for MS

CMS

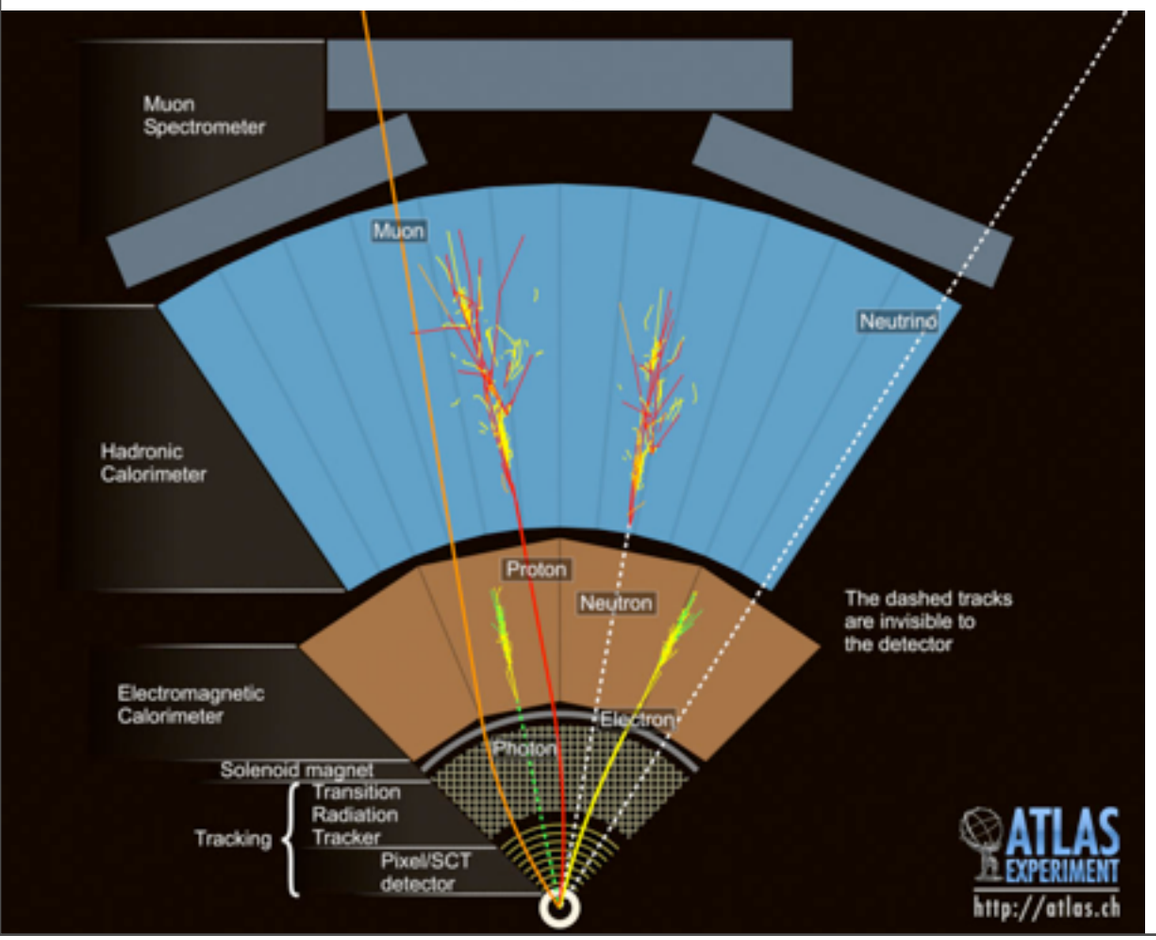


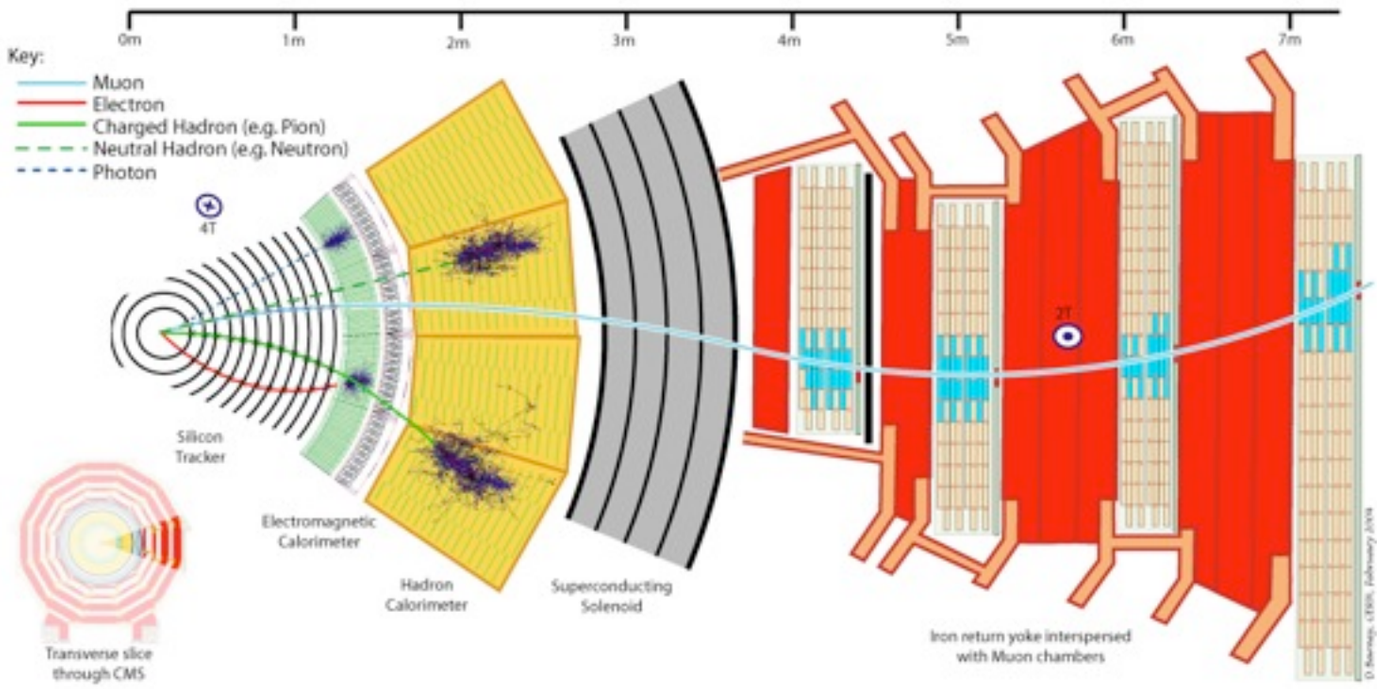


- **Inner Detector (ID):** silicon pixels and strips, transition radiation tracker
- **Calorimetry:** near 4 π electromagnetic (ECAL) and hadronic (HCAL)
- **Muon System (MS):** precision and trigger tracking chambers
- **Magnet System:** 4 Tesla central solenoid (encompassing calorimeters) to bend ID tracks and magnetic field from return yoke for MS

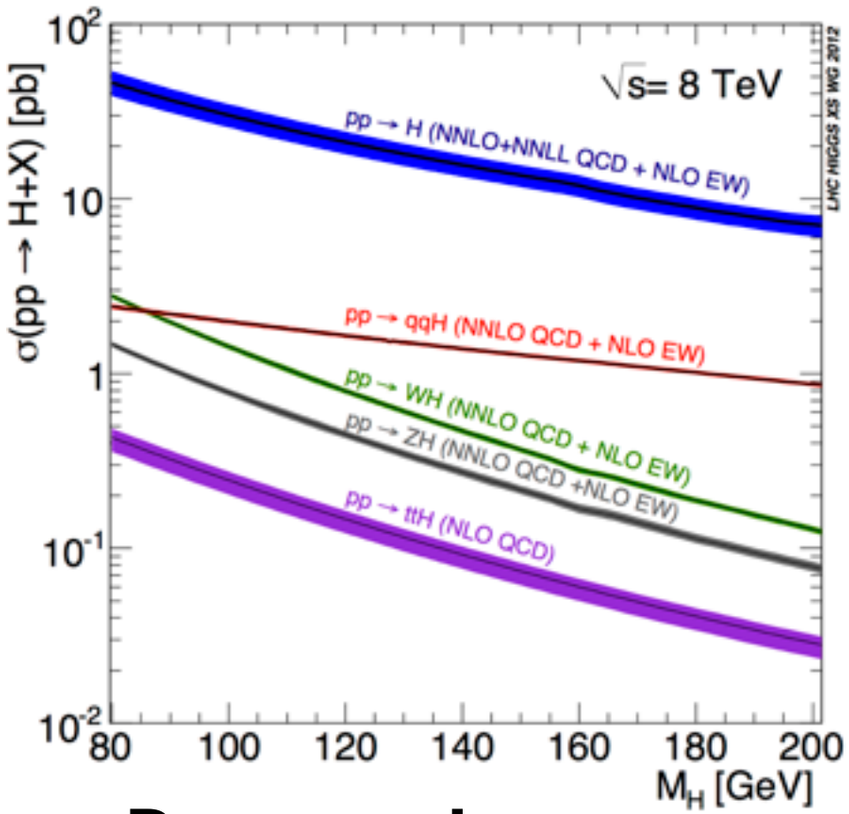
How we "see" particles

- **Electrons:** track (p_T) in ID, energy in ECAL
- **Muons:** p_T in ID and muon system, almost no signal in calorimeter
- **Hadrons:** tracks in ID (charged only), energy in ECAL and HCAL
- **Missing Transverse Momentum:** E_T^{Miss} = - Σ E_T (all objects) - isolated muons



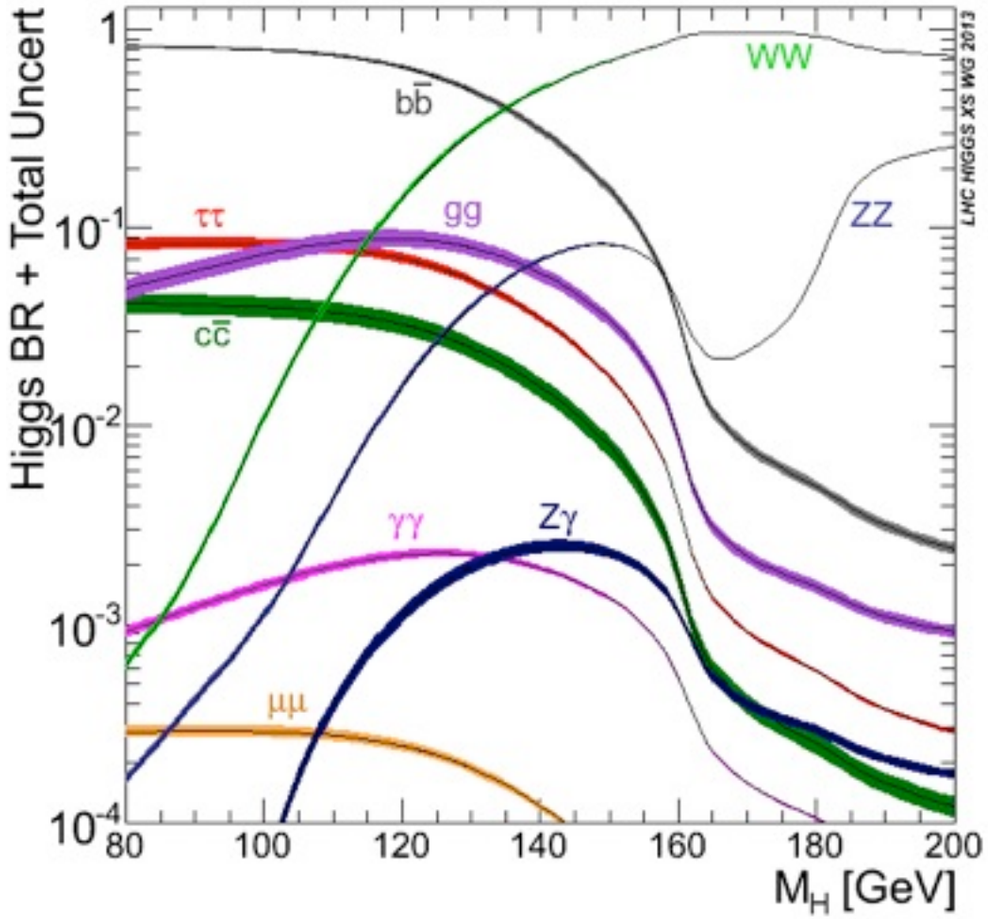


How we "see" Higgs Bosons



- **Production modes:**
  - main mode is ggF
  - rare modes have characteristic signatures

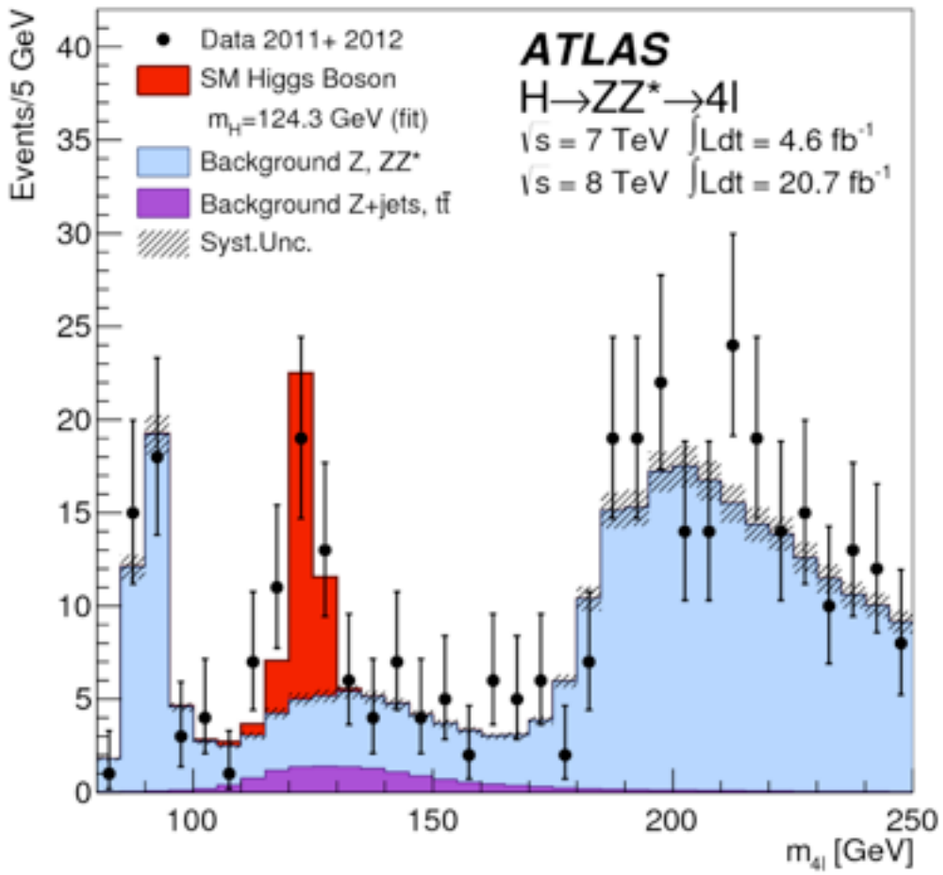
- **Decay modes:**
  - ZZ, γγ: low branching fractions (BR), clean signal
  - WW: good sensitivity, difficult backgrounds
  - ττ, bb: medium-high BR, fermion couplings, very difficult backgrounds

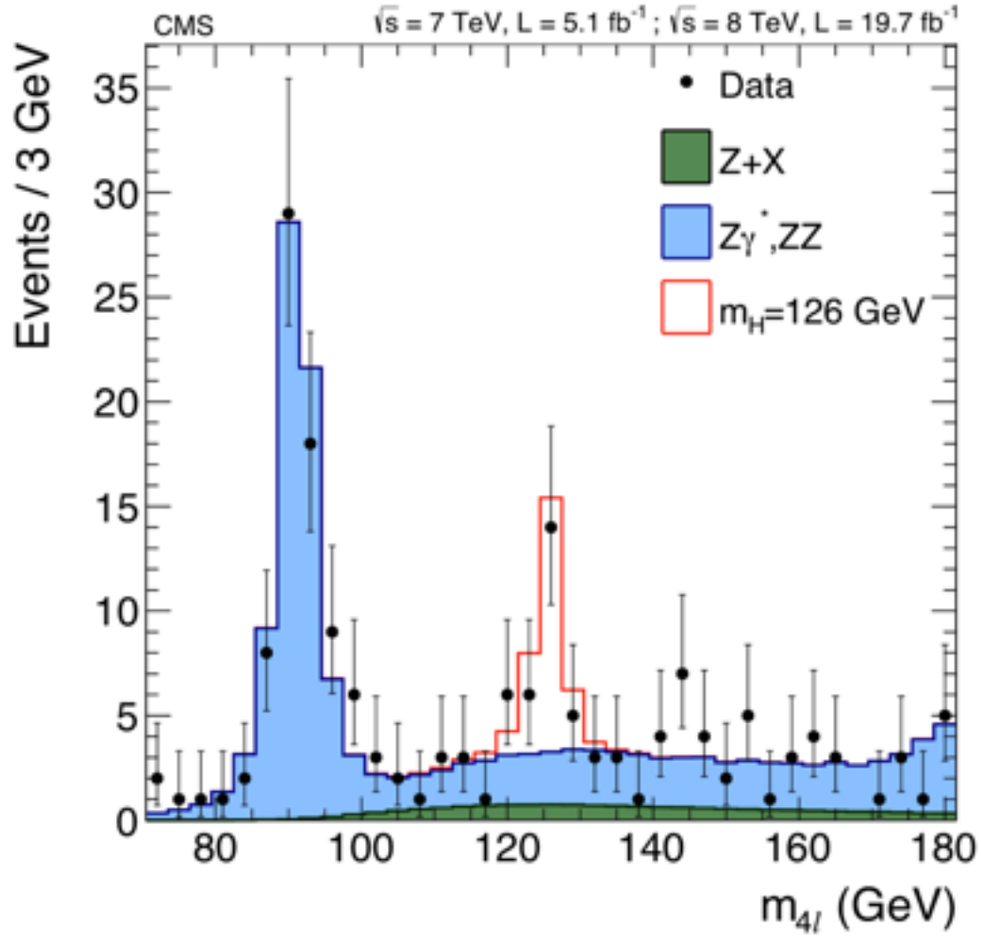


Channels included in coupling fits

PLB 726, pp 88-119 / PhysRevD.89.092007

H → ZZ*

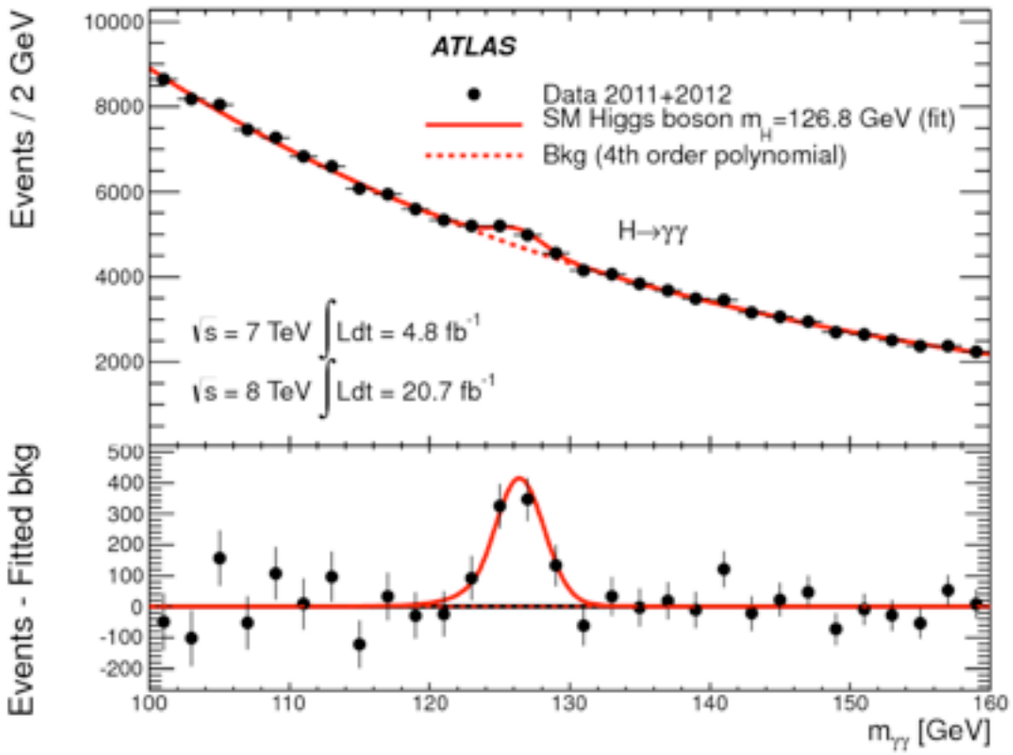


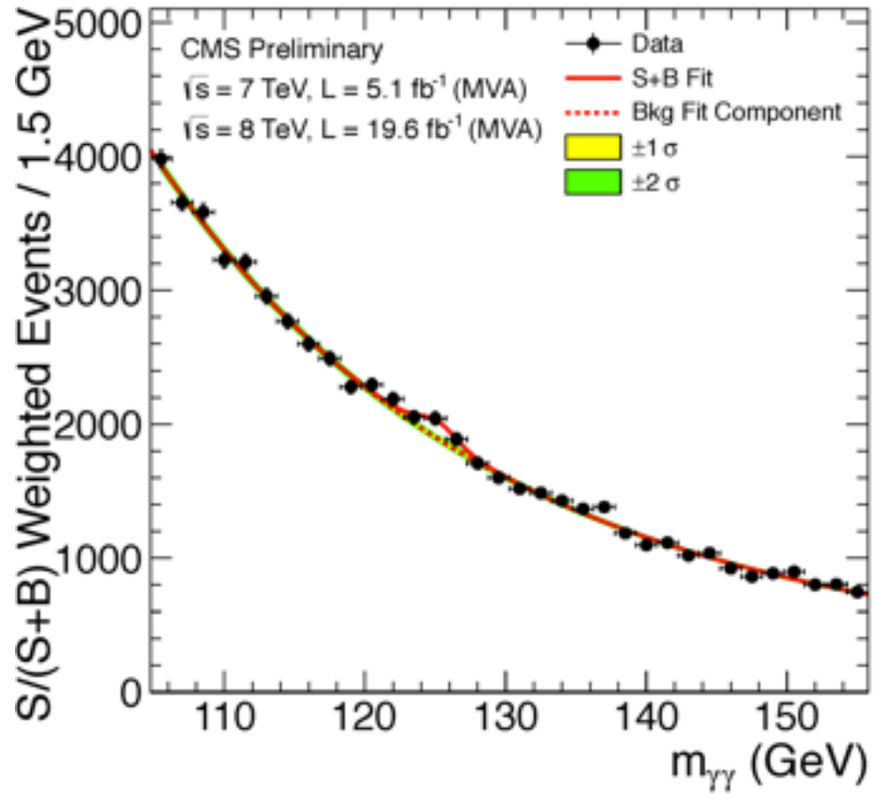


- **Selection:** 2 pairs of isolated, opposite sign leptons, lead pair consistent with Z mass
- **Backgrounds:** ZZ* continuum, Z+jets and ttbar
- **CMS Results:** obs. (exp.) 6.8 (6.7) σ at 125.7 GeV, corresponding to $\mu = 0.9^{+0.3}_{-0.2}$
- **ATLAS Results:** obs. (exp.) 6.6 (4.4) σ at 124.3 GeV, corresponding to $\mu = 1.7^{+0.5}_{-0.4}$

PLB 726, pp 88-119 / CMS-PAS-HIG-13-001

$H \rightarrow \gamma\gamma$

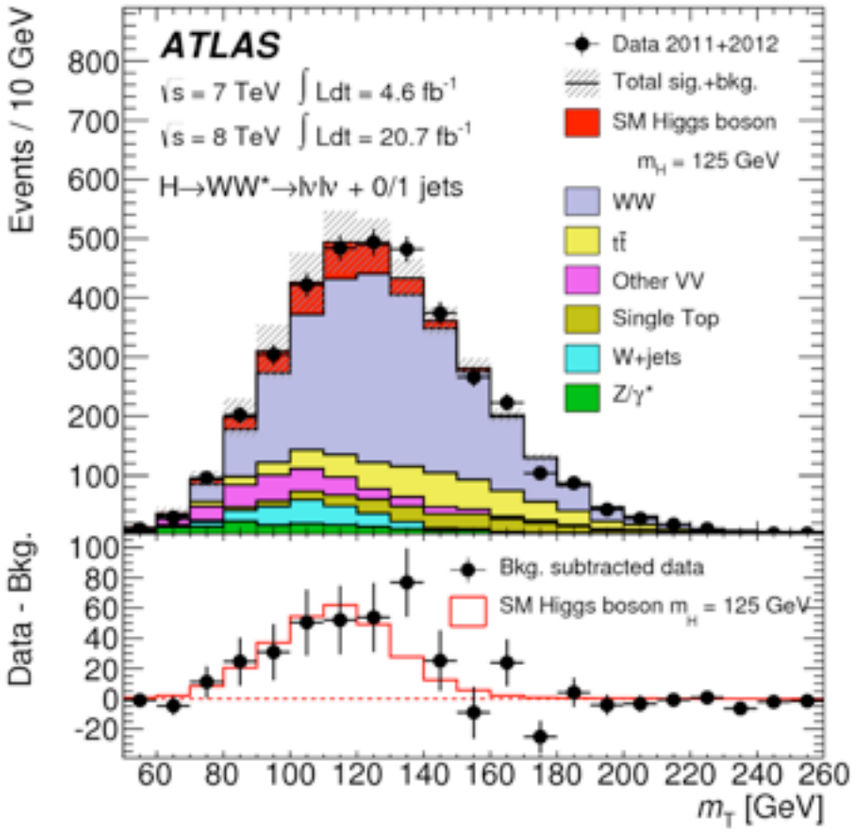


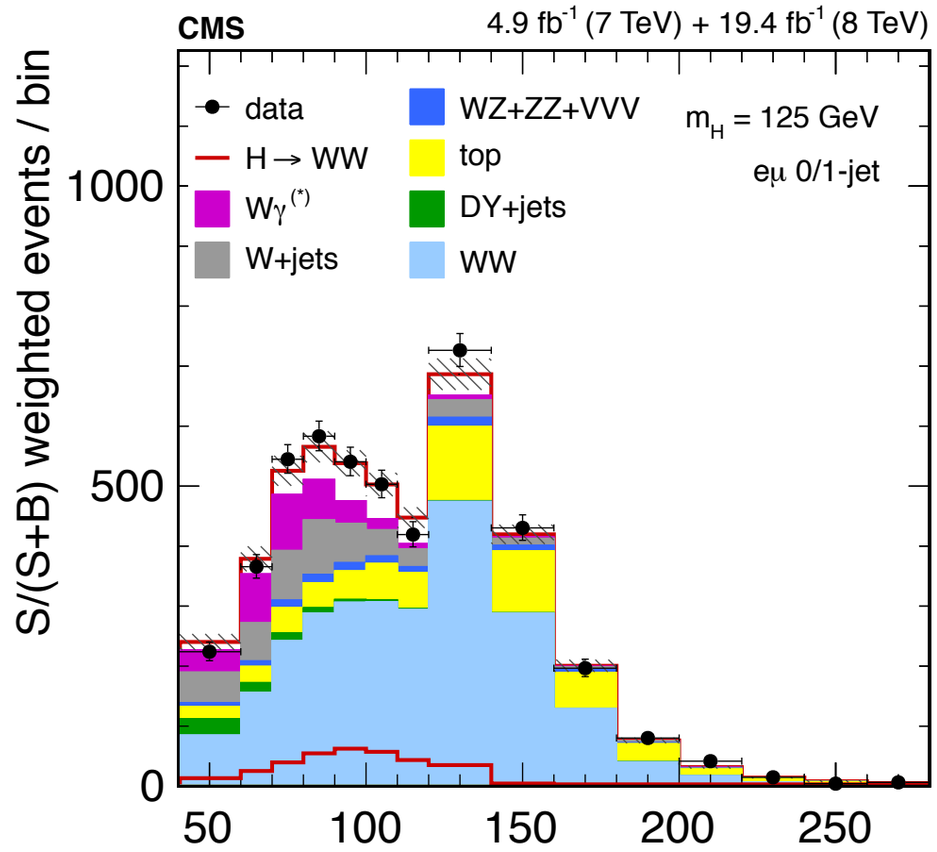


- **Selection:** 2 high E_T, isolated photons
- **Backgrounds:** γ-γ, γ-jet, jet-jet and Drell-Yan fit in mass sidebands
- **CMS Results:** obs. (exp.) 3.2 (4.2) σ at 125.0 GeV, corresponding to $\mu = 0.78^{+0.27}_{-0.27}$
- **ATLAS Results:** obs. (exp.) 7.4 (4.1) σ at 126.8 GeV, corresponding to $\mu = 1.65^{+0.35}_{-0.30}$

PLB 726, pp 88-119 / CMS-PAS-HIG-13-023

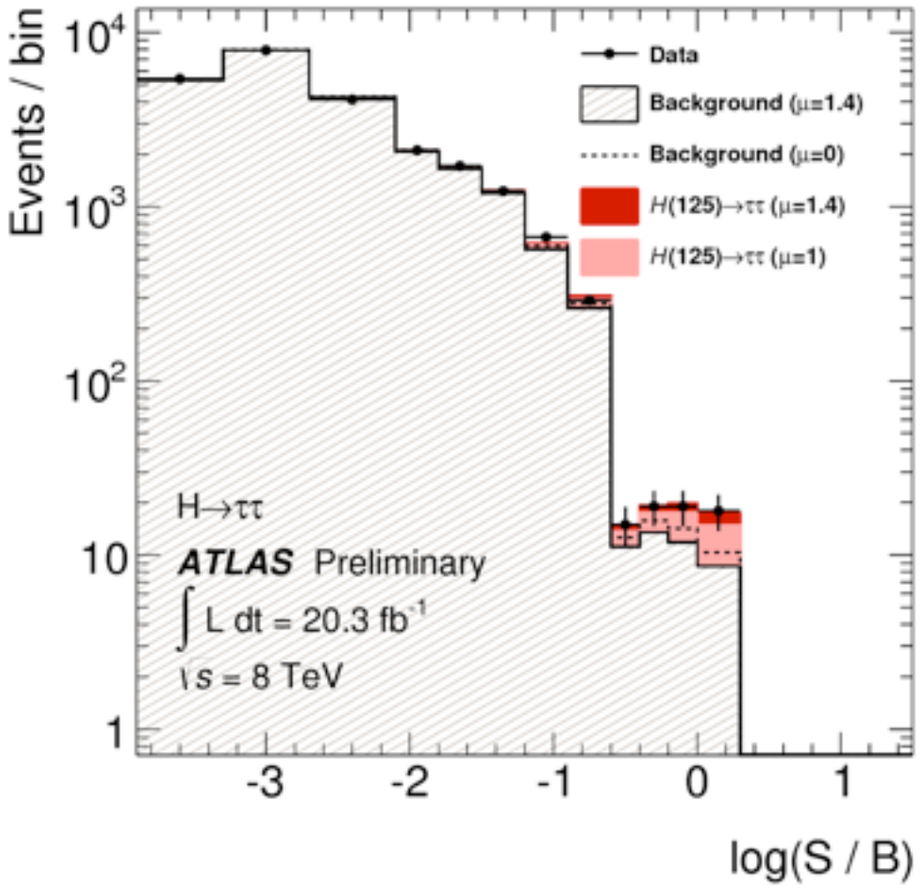
H → WW(lνlν)

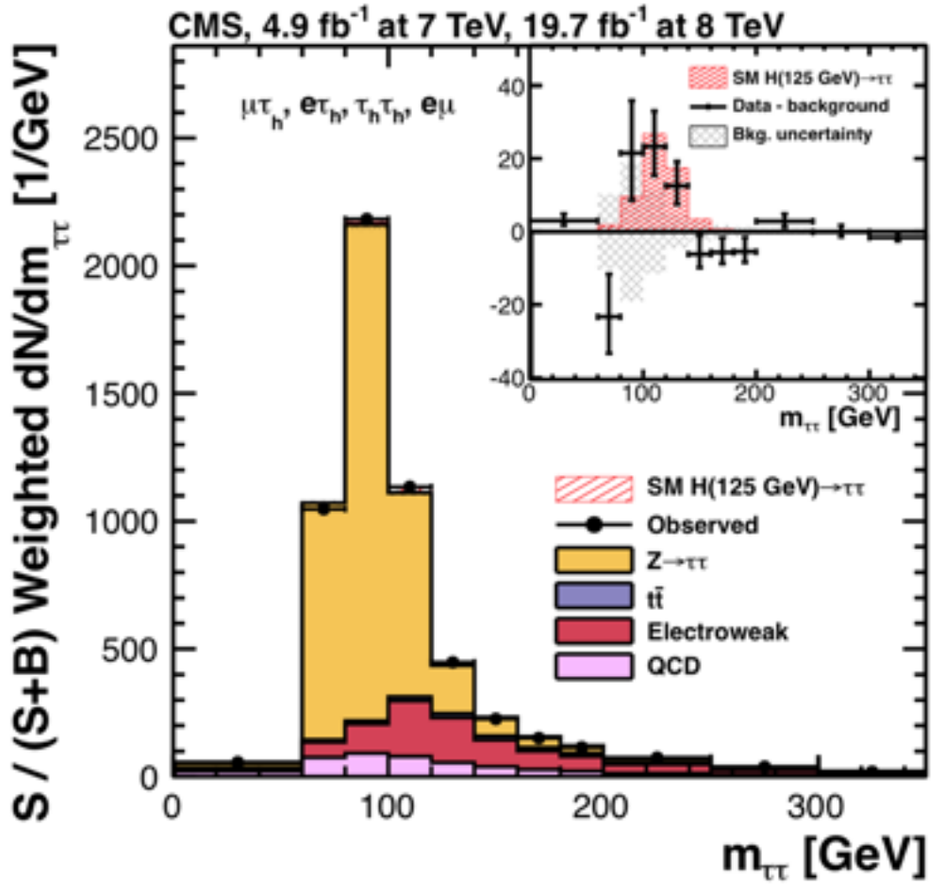




- **Selection:** 2 isolated, opposite sign leptons, large E_T^{Miss}
- **Backgrounds:** WW continuum, other VV, top, V+jets
- **CMS Results:** obs. (exp.) 4.3 (5.8) σ at 125.6 GeV, corresponding to $\mu = 0.72^{+0.20}_{-0.18}$
- **ATLAS Results:** obs. (exp.) 3.8 (3.7) σ at 125 GeV, corresponding to $\mu = 1.01^{+0.31}_{-0.31}$

$H \rightarrow \tau\tau$





- **Selection:** 2 opposite sign τ lepton decays (all modes)
- **Backgrounds:** Z→ττ, ttbar, VV Depending on tau decay: Drell-Yan, W+jets, QCD multijet
- **CMS Results:** obs. (exp.) 3.4 (3.6) σ at 125 GeV, corresponding to $\mu = 0.8^{+0.3}_{-0.3}$
- **Main Results:** obs. (exp.) 4.1 (3.2) σ at 125 GeV, corresponding to $\mu = 1.4^{+0.5}_{-0.4}$

Coupling Measurements

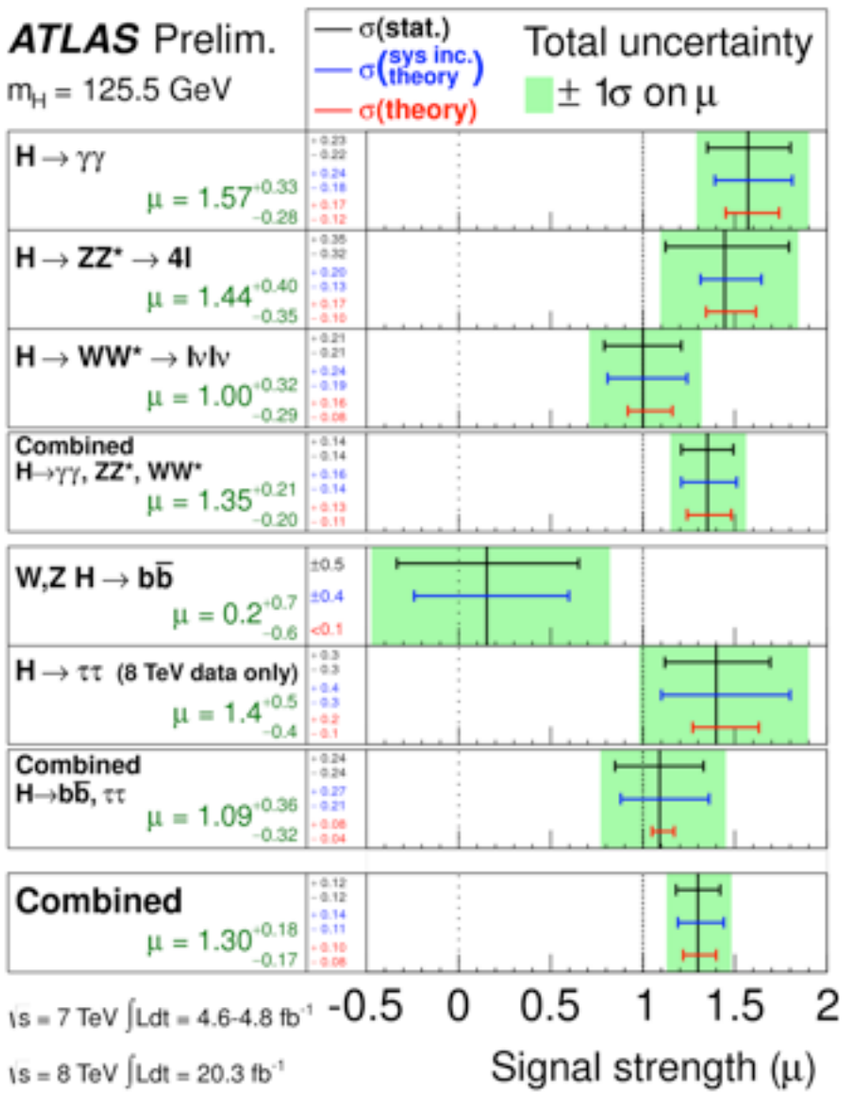
Couplings: fit model

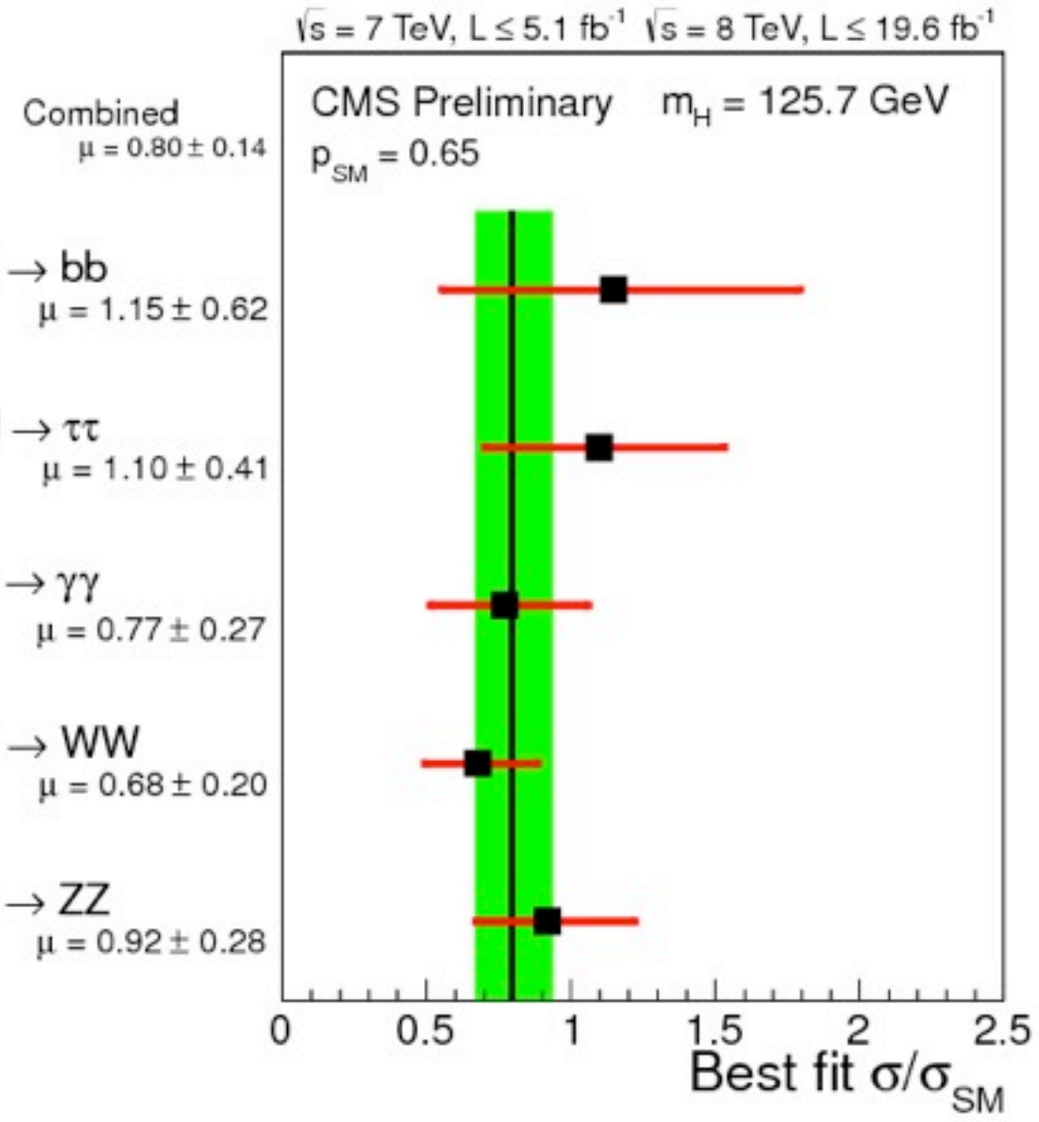
$$n^k_{\text{signal}} = \left(\sum_i \mu_i \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^k$$

- we derive couplings from event yields n in the different analysis channels k
- parameters of interest are the "signal strengths" μ_i for production and μ_f for decay modes
- these are defined such that $\mu_{i,f} = 1$ represents signal strength consistent with the SM
- other parameters are:
  - $\sigma_{i,SM}, B_{f,SM}$: standard model production cross section and branching ratios
  - A^k_{if} : detector acceptance for production mode i, decay mode f and analysis channel k
  - ε^k_{if} : selection efficiency for production mode i, decay mode f and analysis channel k
  - L^k : integrated luminosity analysed in channel k

Fitted Couplings

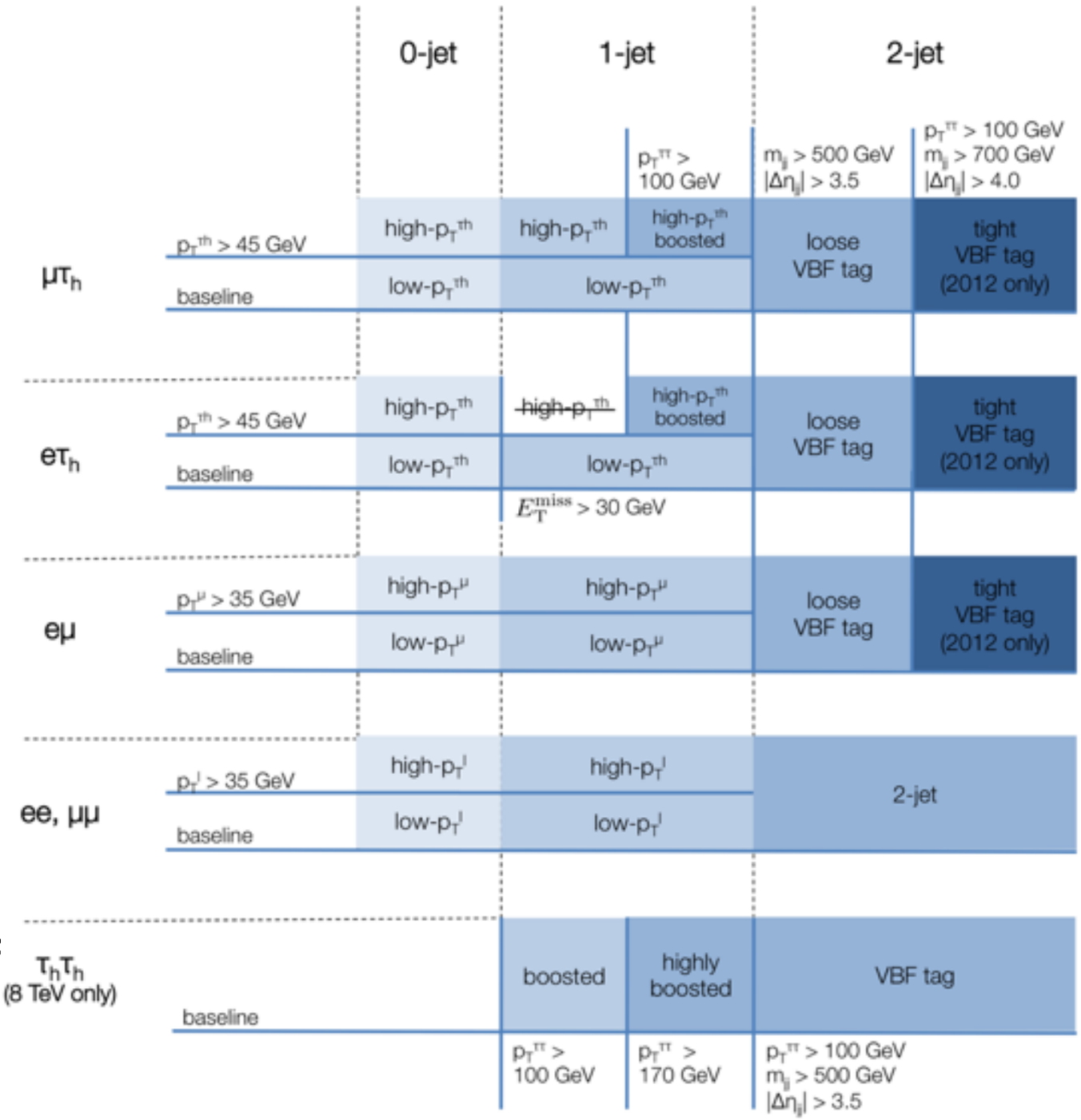
- measure signal strength in units of SM cross section X branching ratio
- not possible to measure either by itself
- in all decay channels signal strength agrees with SM expectation within 1-2 σ



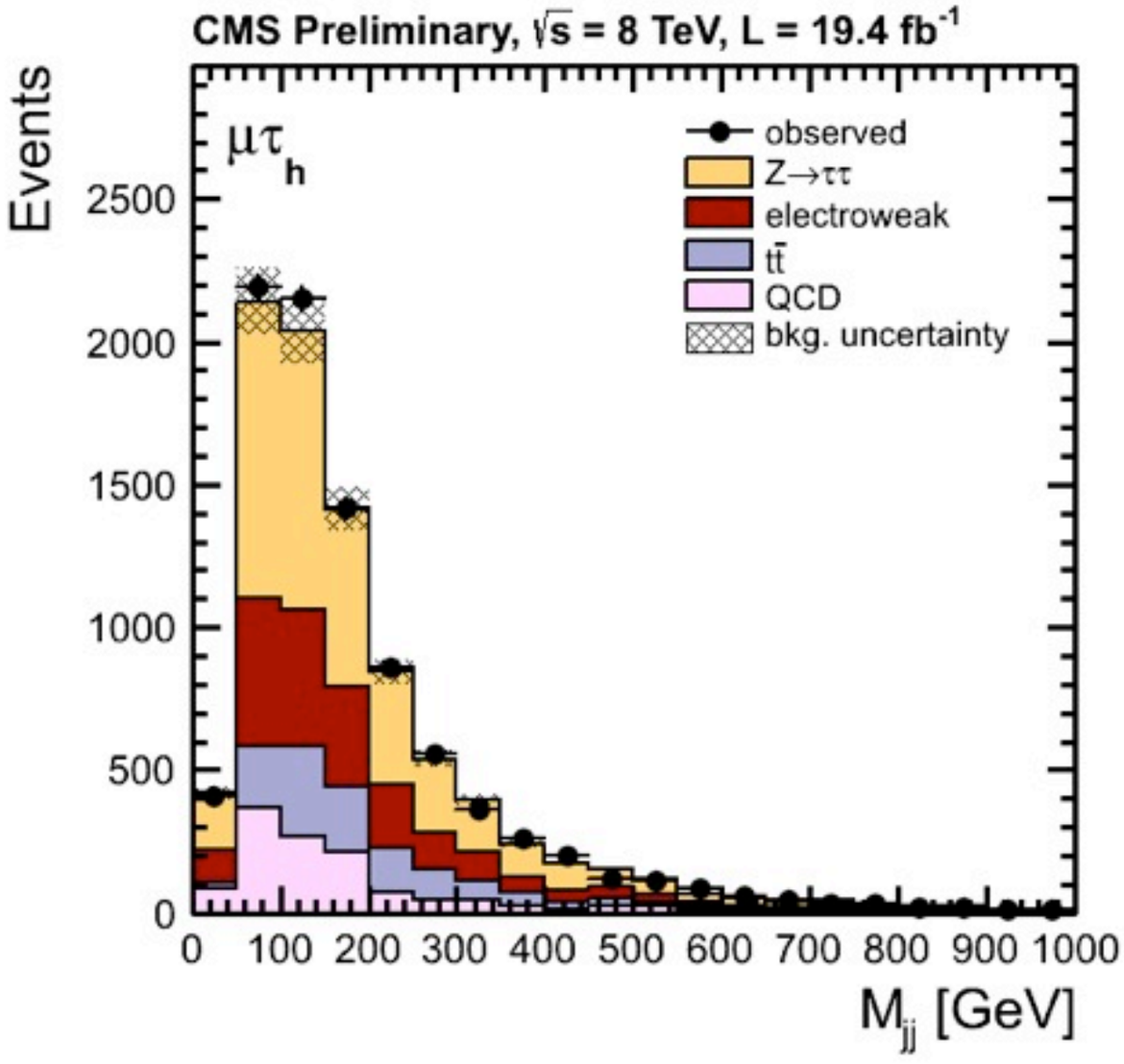


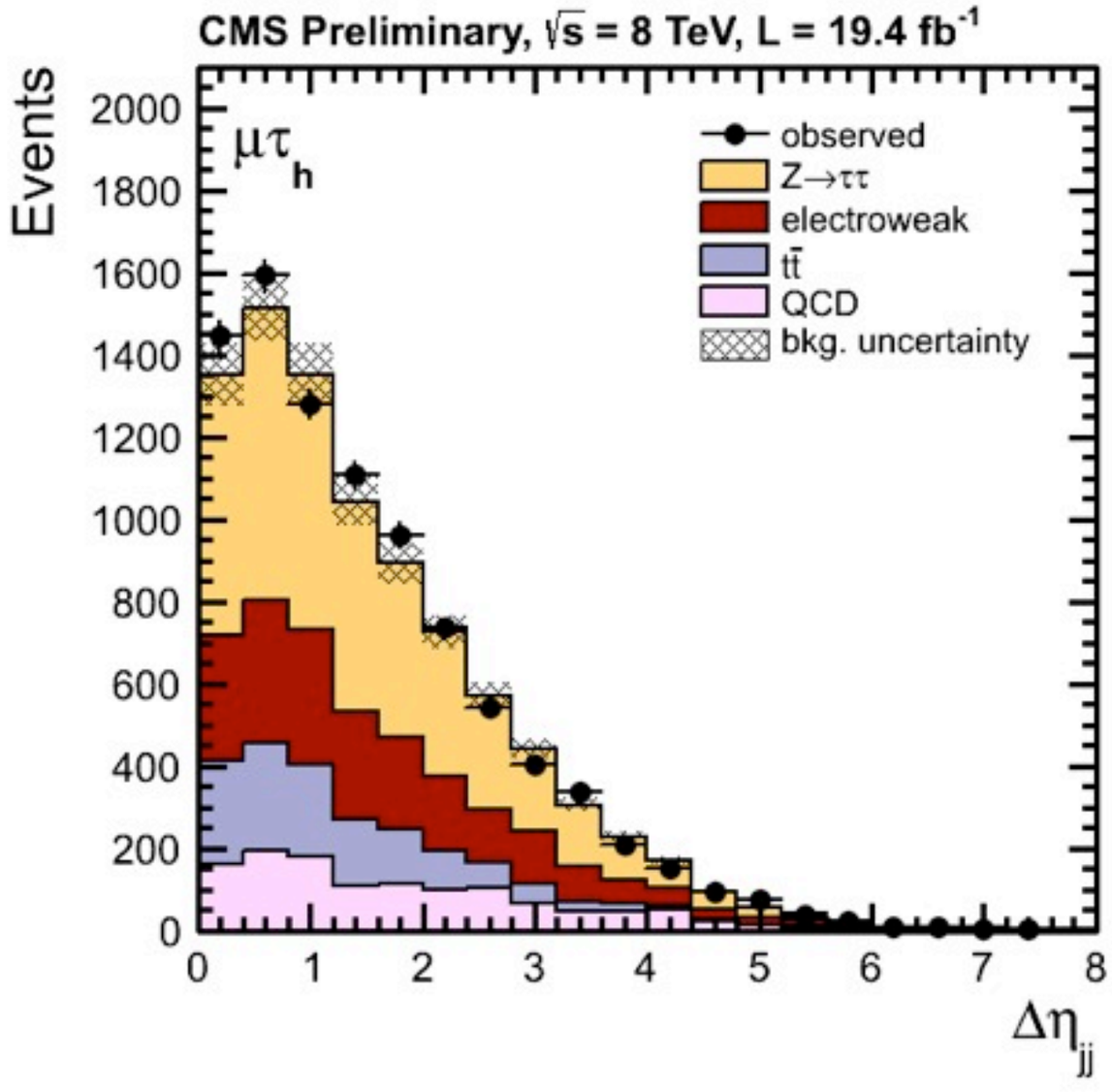
“Tagging” Production Modes

- separating production modes by jet multiplicity
- 2-jet categories enriched with VBF
- Increase purity with selections on $\Delta\eta_{jj}$, m_{jj} and similar variables
- Third-Jet veto sometimes used, but introduces large theory uncertainties
- high Higgs-candidate p_T improves sensitivity
- Higgs from gluon fusion (ggF) has large theory uncertainties on p_T spectrum
- QCD-scale uncertainties on ggF one of the dominant uncertainties in all channels



Validating VBF Tagging





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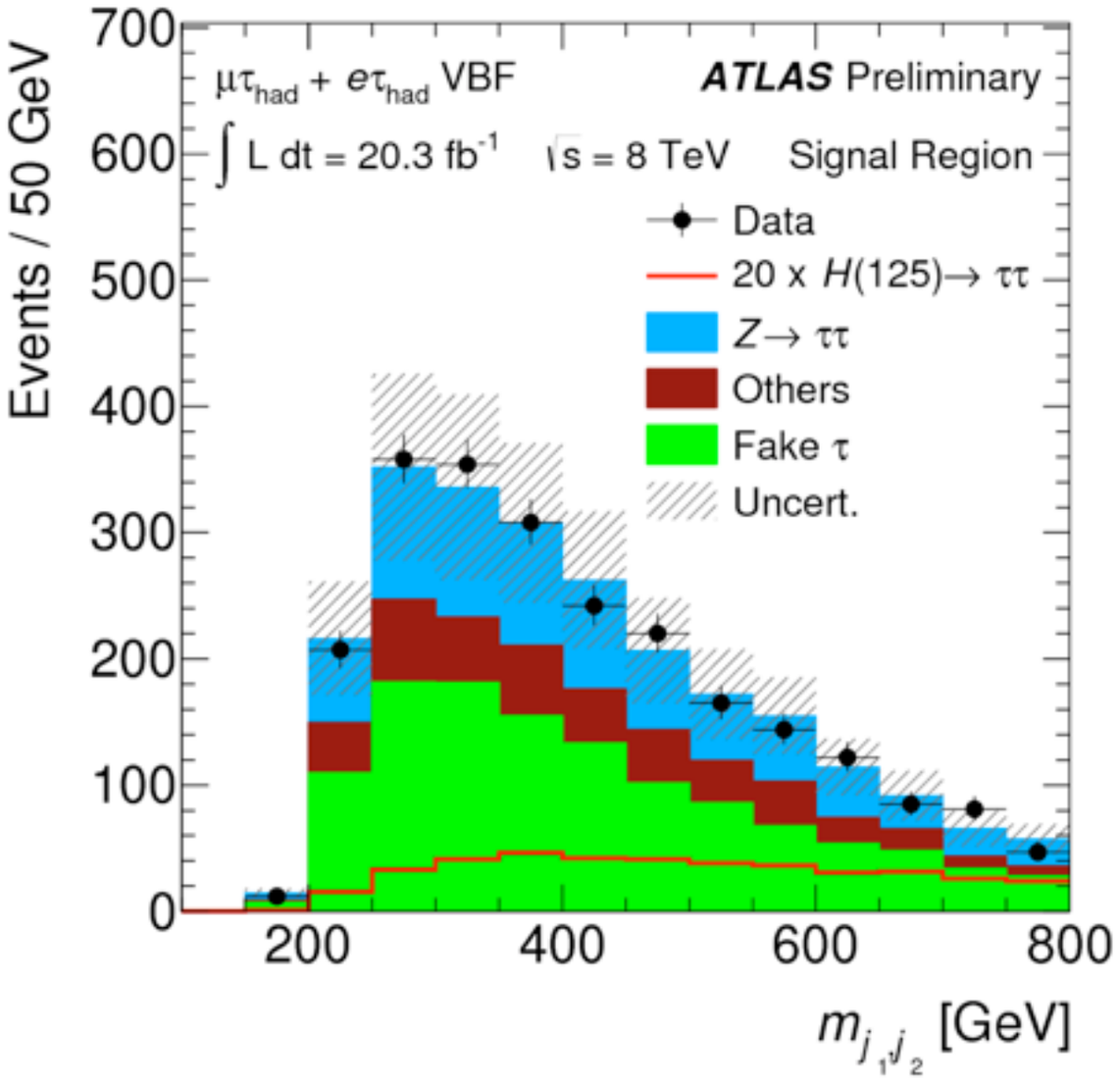
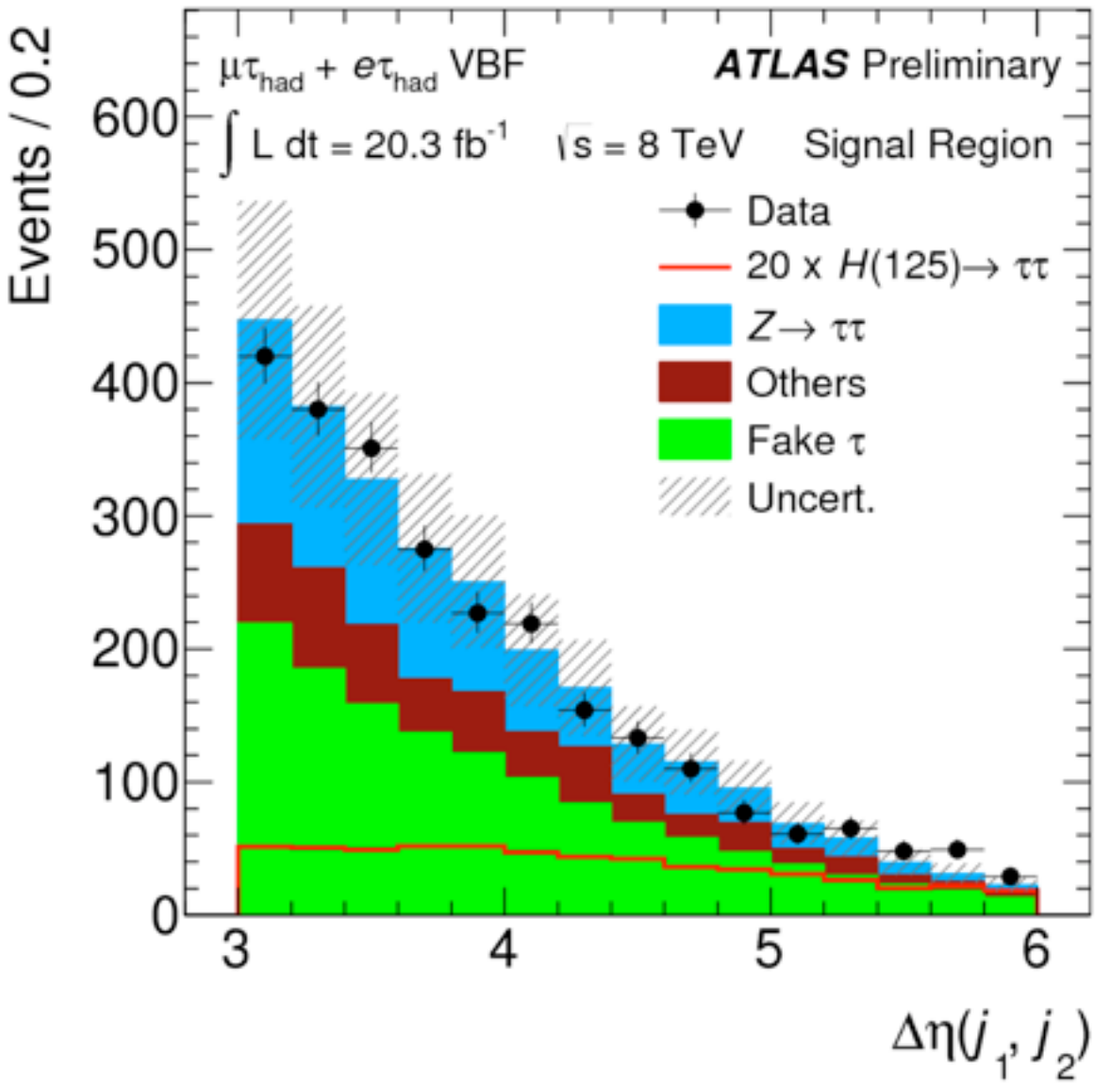
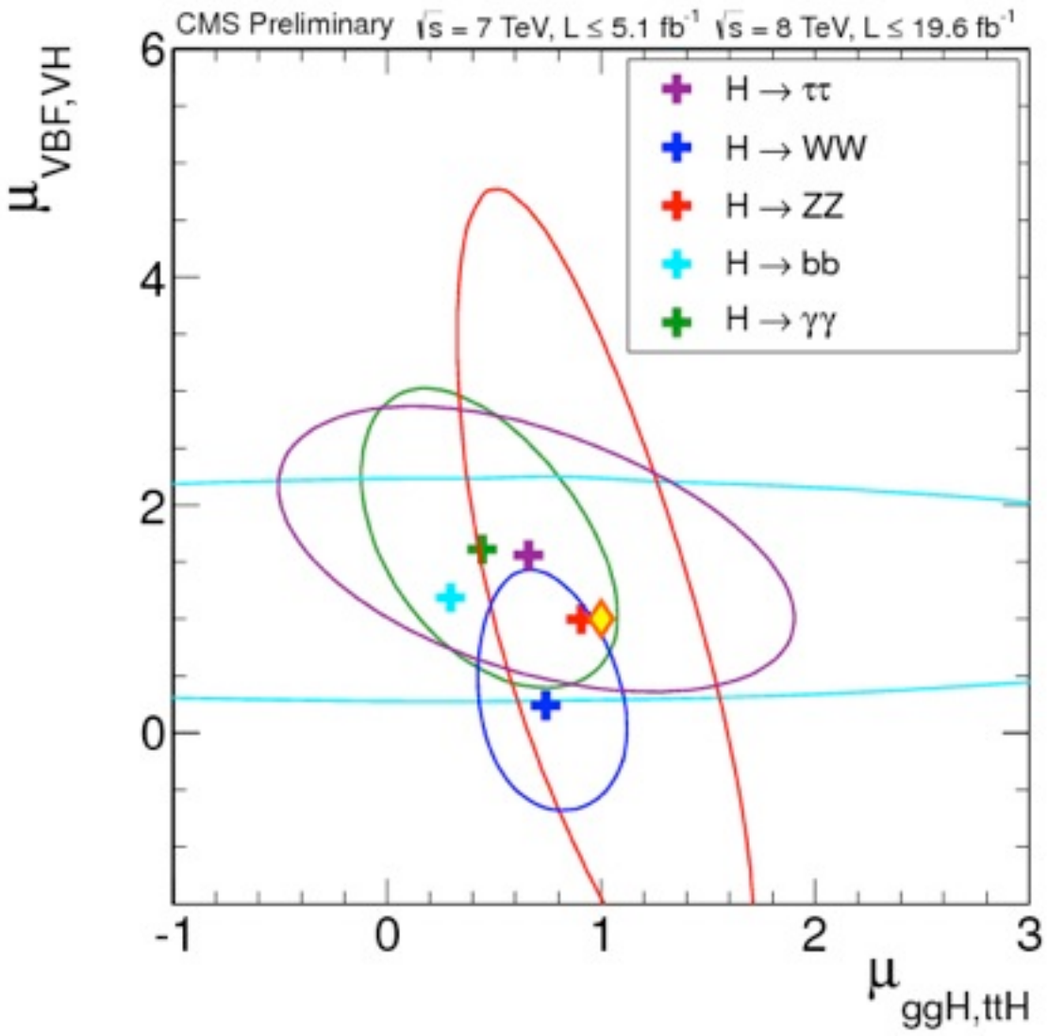
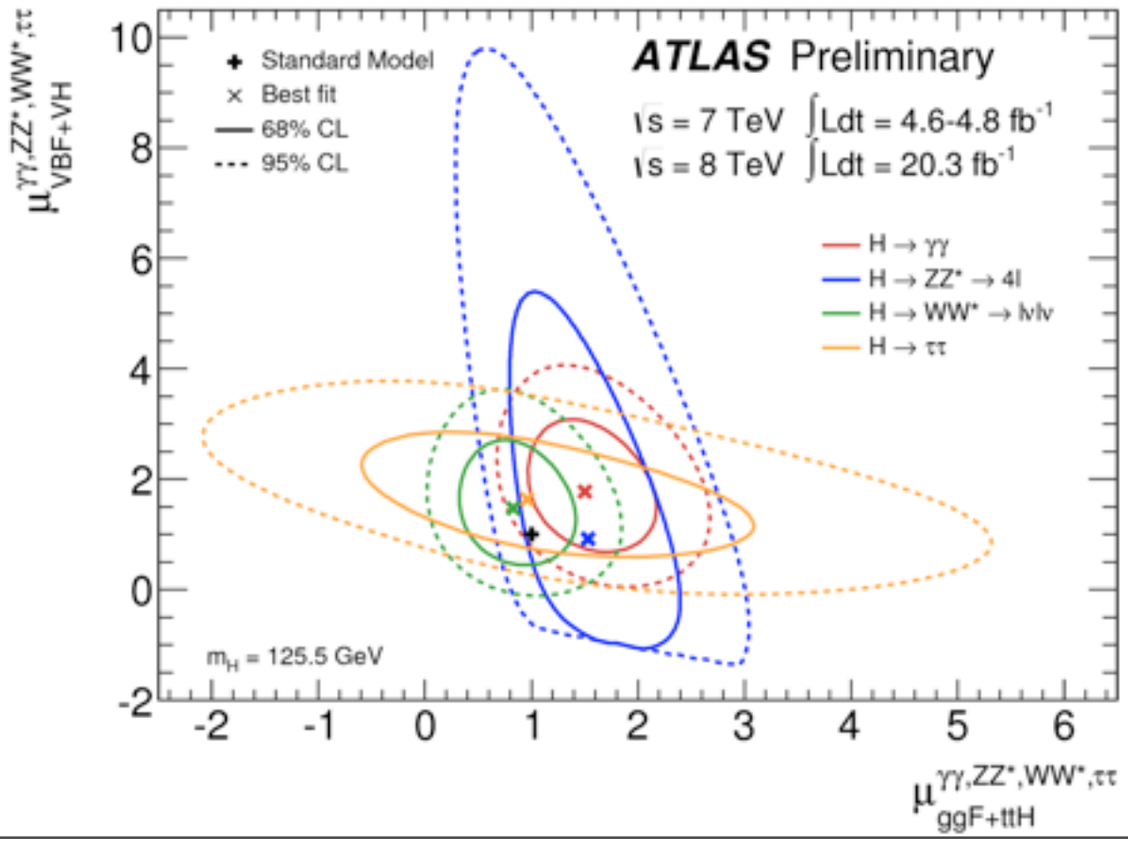




Production Couplings

- separately fit couplings in production
- fix decay BR to SM values
- simplify production couplings
  - VBF = VH : "VBF+VH"
  - ttH = ggF : "ggF+ttH"





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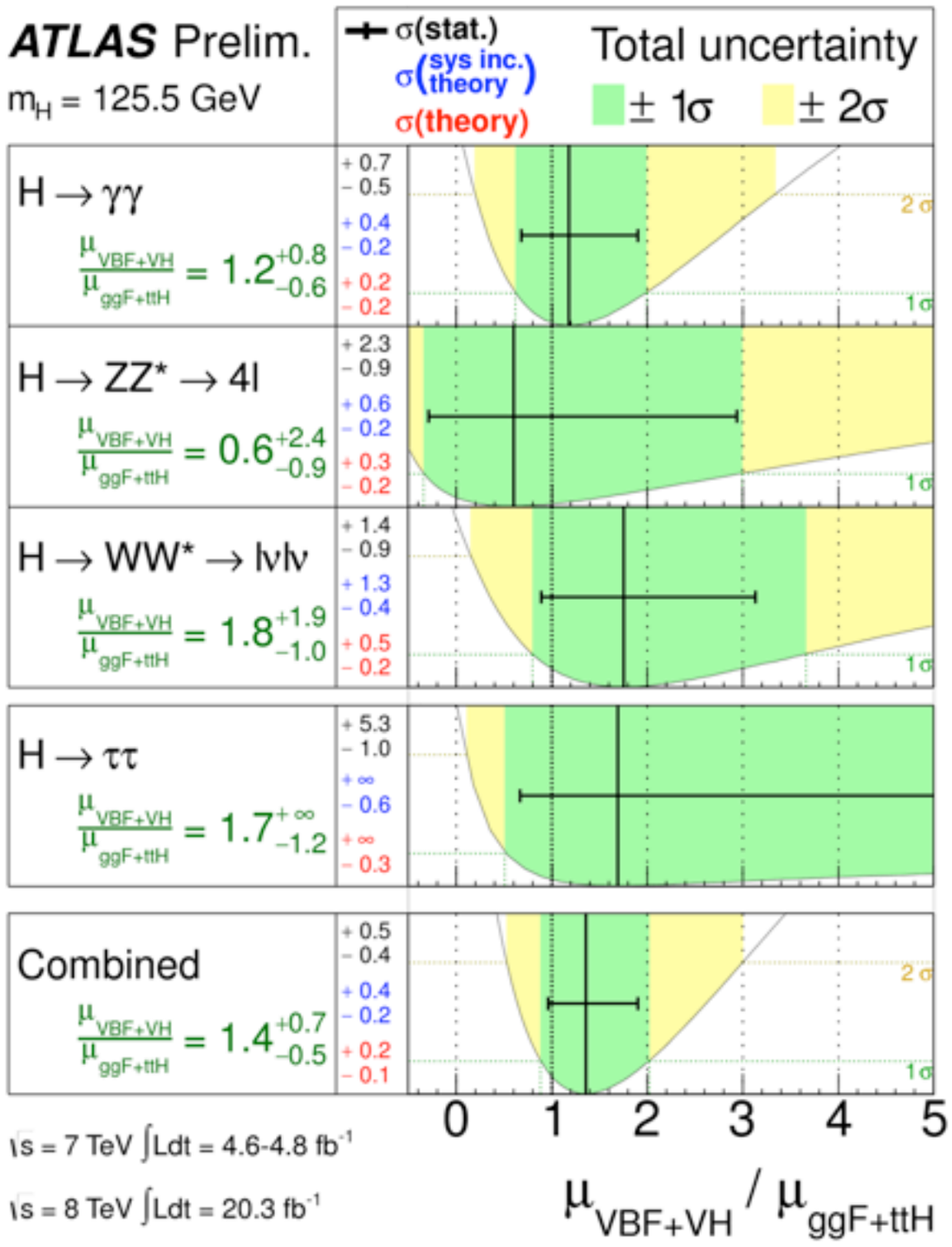
Production Ratios

- ratio of VBF+VH over ggH+ttH production is not dependant on BR's of decay modes
- shows the relative sensitivity of channels to the two production modes:
  - sensitivity in tautau mostly from VBF
- can also measure ratio with VBF alone
- this provides 4.1σ evidence of VBF production
  - similar evidence seen in CMS coupling fits ($\mu_{VBF} = 1.0^{+0.4}_{-0.3}$)



Summary

- presented current state-of-the-art of Higgs measurements at the LHC
- evidence for Higgs boson production from diboson and two fermionic channels
- evidence for fermionic decays of Higgs boson at 3-4σ level per experiment
  - for simple combination of ATLAS and CMS significance goes beyond 5σ
- no clear tensions in coupling parameters wrt SM
- 4.1σ evidence for VBF production from ATLAS coupling combination
  - similar evidence seen in CMS coupling fits ($\mu_{VBF} = 1.0^{+0.4}_{-0.3}$)

Backup

Basic τ Properties

τ^- Branching ratios (m_τ=1.78 GeV):

$e^-/\mu^- \upsilon_{e/\mu} \upsilon_\tau$ (35%)

$\pi^- \upsilon_\tau$ (11%)
$\rho^- \upsilon_\tau$ (25%)
$\pi^- \pi^0 \pi^0 \upsilon_\tau$ (9%)
$\pi^- \pi^0 \pi^0 \pi^0 \upsilon_\tau$ (1%)
K^- + neutrals (1.5%)

} 1-prong

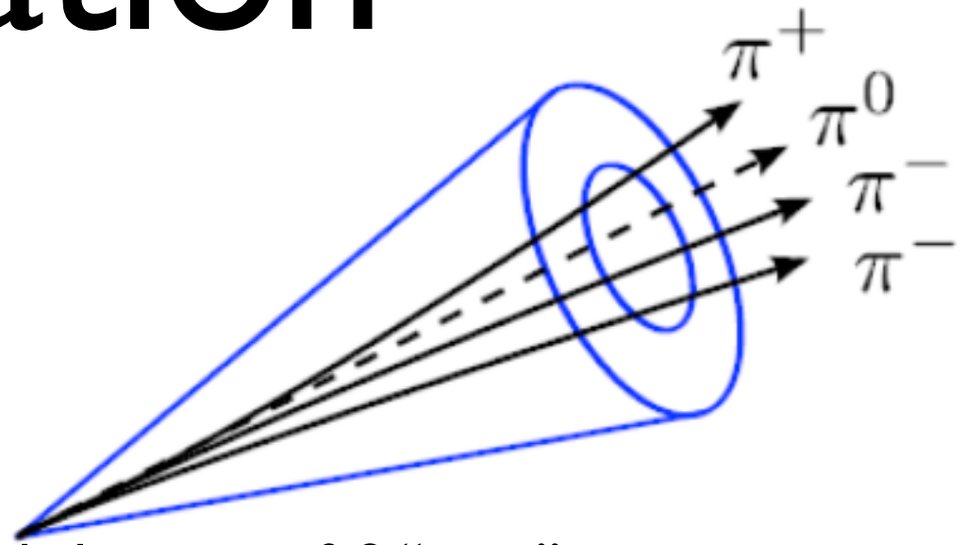
$\pi^- \pi^+ \pi^- \upsilon_\tau$ (9%)
$\pi^- \pi^+ \pi^- \pi^0 \upsilon_\tau$ (4.5%)
$K^- \pi^+ \pi^- \upsilon_\tau$ (0.4%)

} 3-prong

other modes (~3%)

- properties of hadronically decaying τ's:
- very well collimated object of charged and neutral pions
- charged component of τ reproduces the direction of visible τ well (particularly leading pion)
- most τ's have one or three charged decay products (pions)
- modest but significant proper lifetime (87 microns)

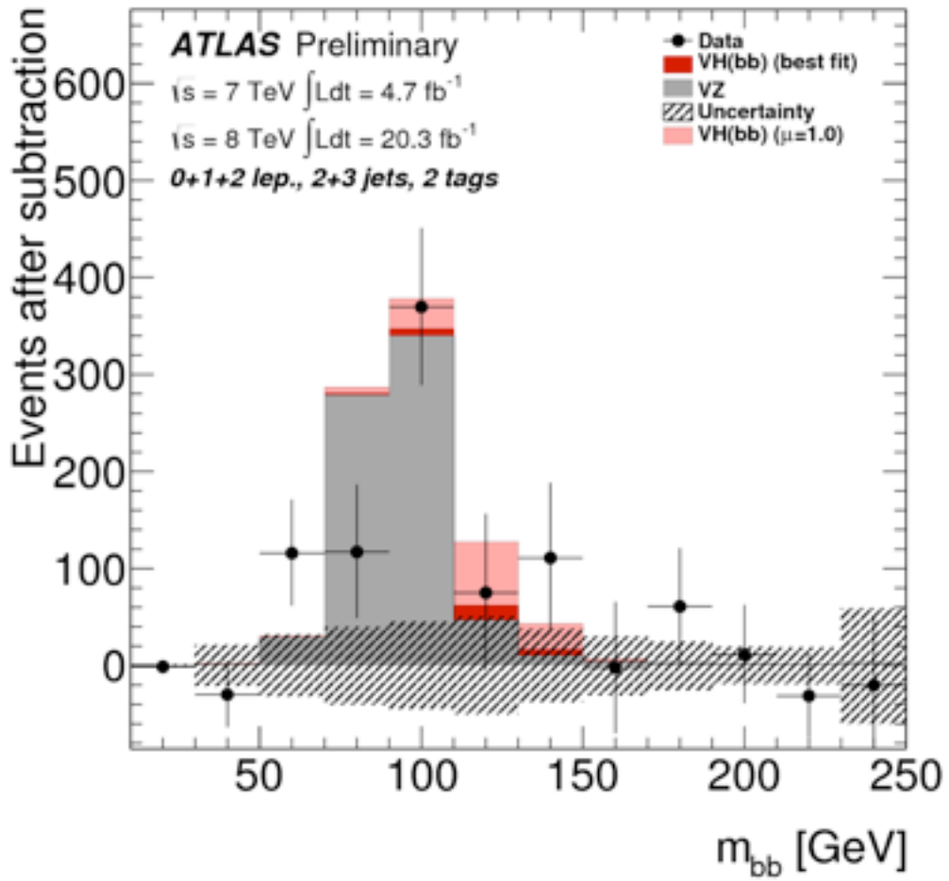
τ Identification

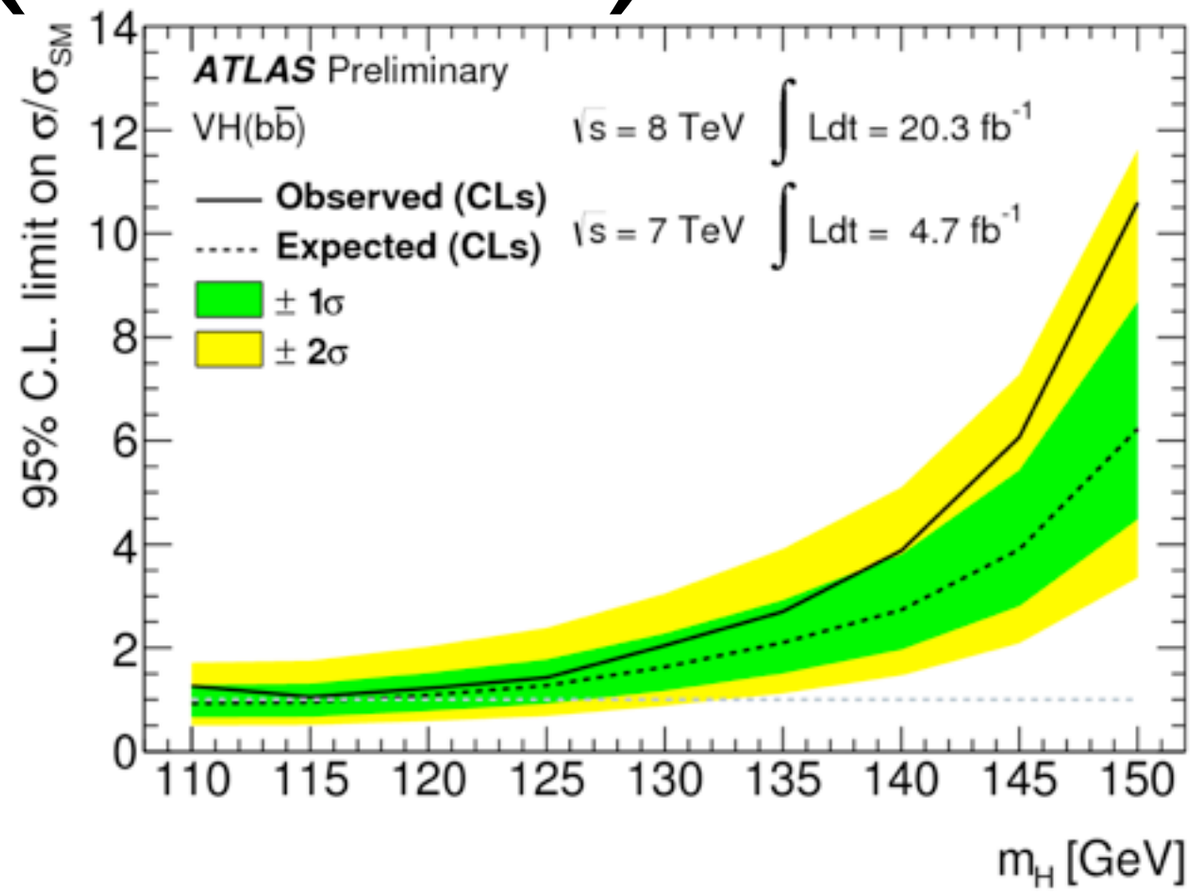


- reconstructed from antiKt 0.4 topojet seeds
- direction and p_T measured from LC calibrated clusters in 0.2 "core" cone

- τ-specific calibration from MC to bring true τ decays to proper τ energy scale (TES)
- need to separate hadronically decaying τ's both from QCD jets as well as from electrons (muons too)
- two multivariate classifiers using tracking and shower shape info (BDT)
- τ CP group provides TES uncertainties and scale factors for both BDT's

VH → (ll,lν,νν)bb





- **Selection:** 2 b-tagged jets and either large E_T^{Miss} or 1-2 leptons
- **Categorization:** split by W/Z decay, jet multiplicity and di-jet system p_T
- **Backgrounds:** ttbar, V+heavy flavour, VV, QCD multijet
- **Main Results:** obs. (exp.) 95% CL 1.4 (1.3) x SM at 125 GeV, $\mu = 0.2^{+0.7}_{-0.6}$

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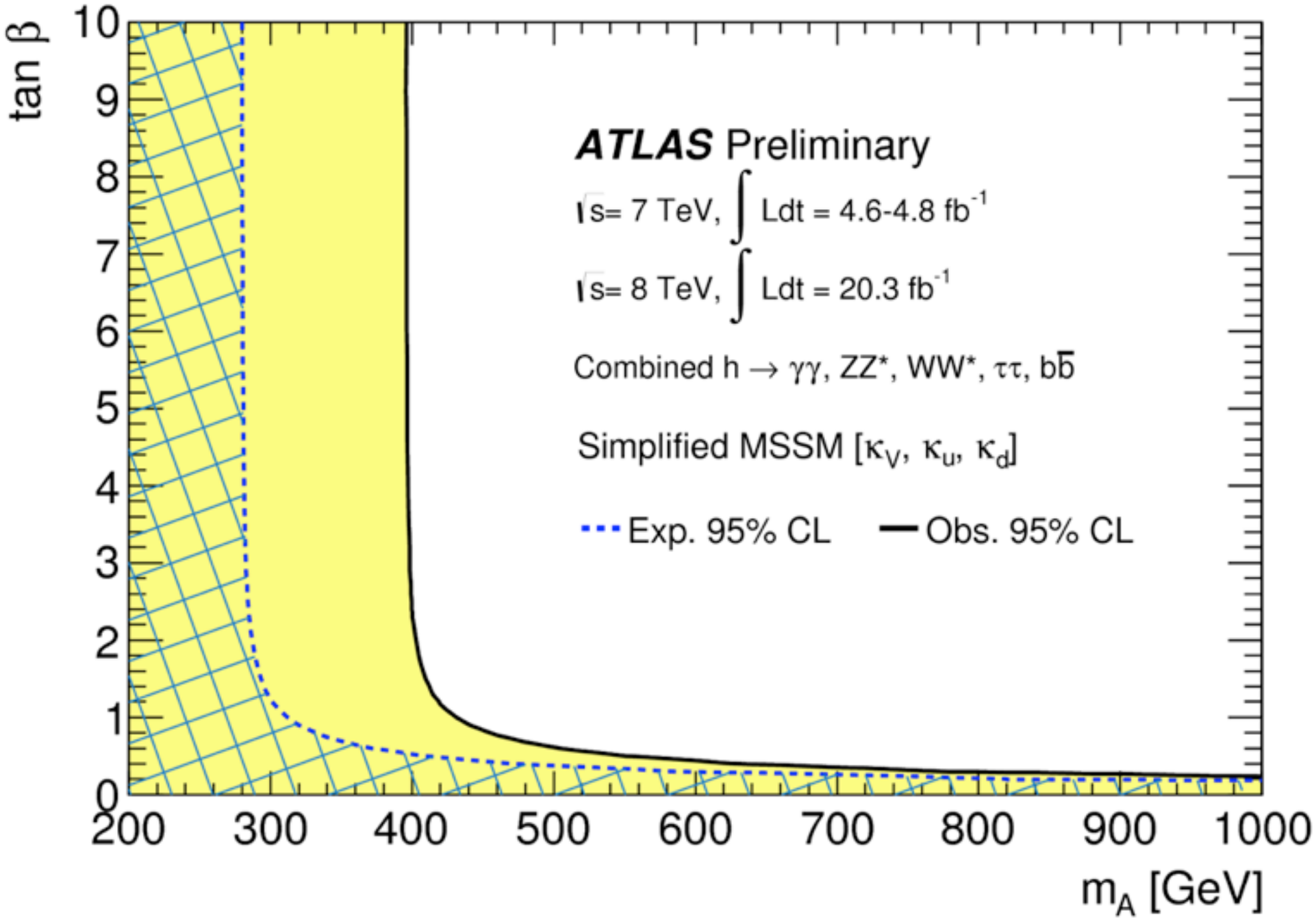
Couplings: Inputs

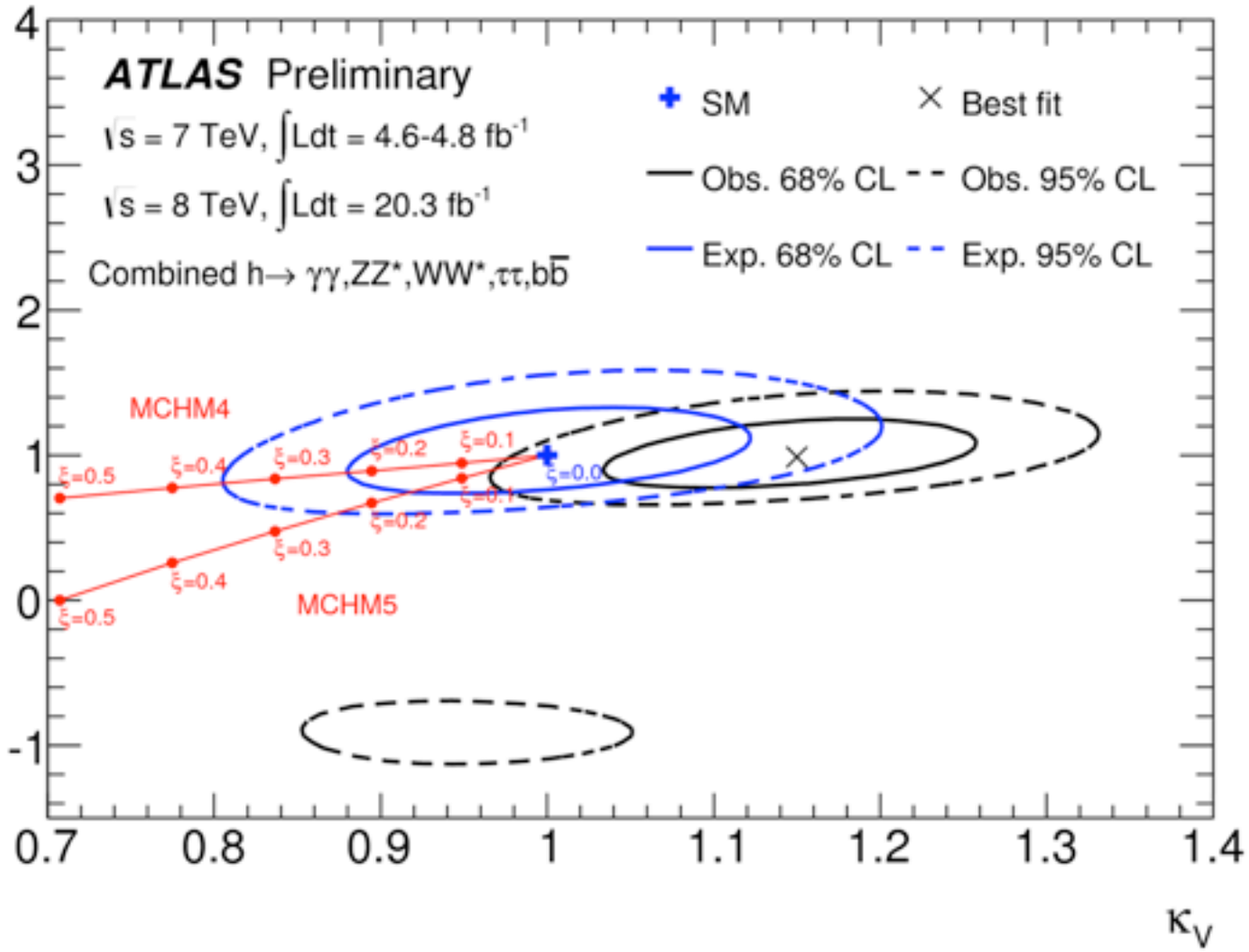
Higgs boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\}$	4.8	[3]
$H \to ZZ^*$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, \text{2-jet VBF}, \ell\text{-tag}\}$	4.6	[3]
$H \to WW^*$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	4.6	[3]
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \mathrm{GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6	[5]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{<50, 50-100, 100-150, 150-200, \geq 200\ \mathrm{GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{<50, 50-100, 100-150, 150-200, \geq 200\ \mathrm{GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to \gamma\gamma$	–	14 categories: $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus$ $\{\text{loose, tight 2-jet VBF}\} \oplus \{\ell\text{-tag}, E_{\mathrm{T}}^{\mathrm{miss}}\text{-tag, 2-jet VH}\}$	20.3	[3]
$H \to ZZ^*$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, \text{2-jet VBF}, \ell\text{-tag}\}$	20.3	[3]
$H \to WW^*$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	20.3	[3]
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \mathrm{GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3	[5]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{<90, 90\text{-}120, 120\text{-}160, 160\text{-}200, \geq 200\ \mathrm{GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{<90, 90\text{-}120, 120\text{-}160, 160\text{-}200, \geq 200\ \mathrm{GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3	
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{ee, e\mu, \mu\mu\} \otimes \{\text{boosted, 2-jet VBF}\}$	20.3	[6]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{boosted, 2-jet VBF}\}$	20.3	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{boosted, 2-jet VBF}\}$	20.3	

2HDM M_Hmax Scenario



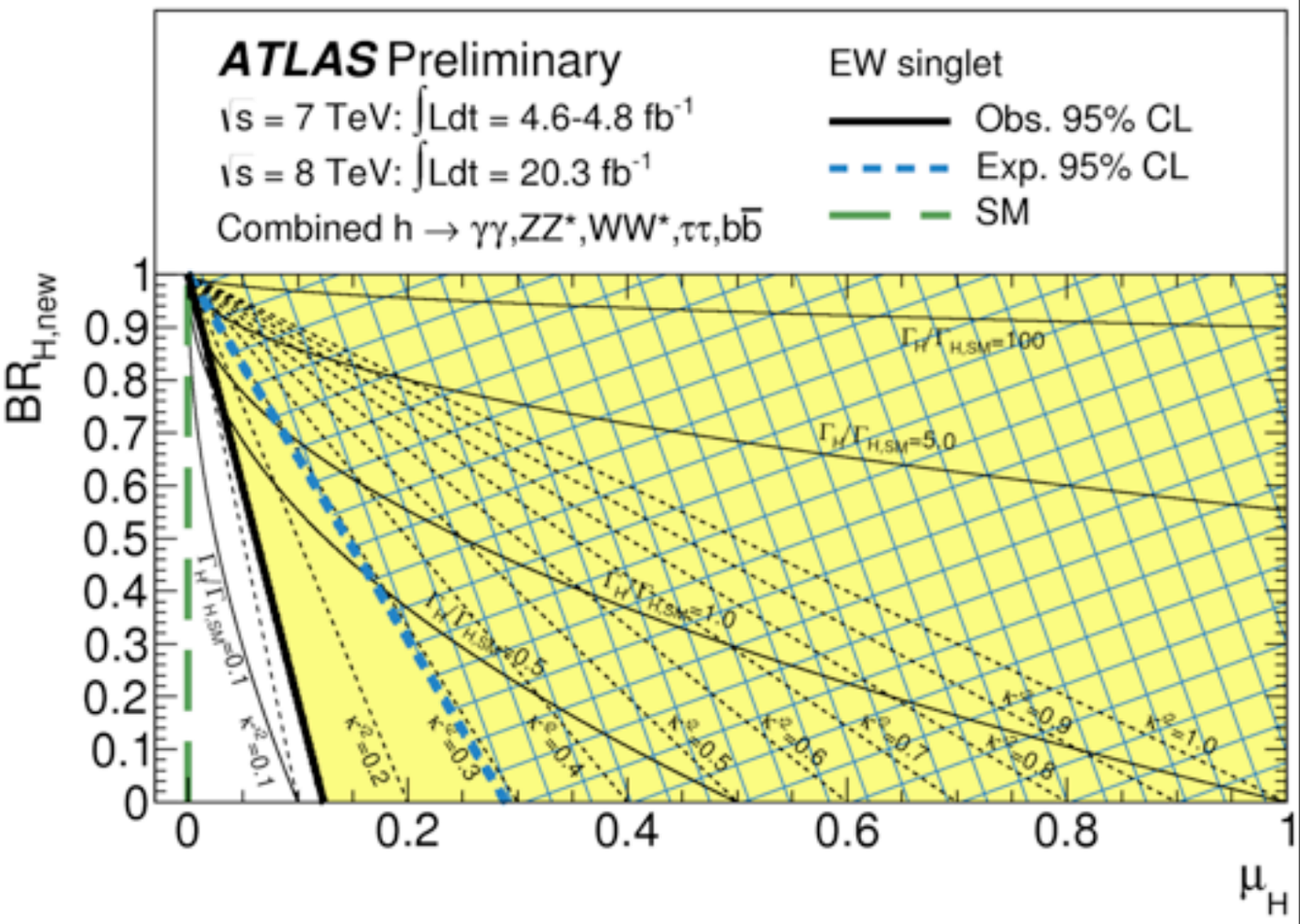
Constraints on New Physics

- Minimal Composite Higgs Models
- assume same production and decay modes as SM
- couplings get reduced compared with SM by k-factor
- Two models considered:
  - MCHM4: $k = k_V = k_f = \mathrm{sqrt}(1-\xi)$
  - MCHM5:
    - $k_V = \mathrm{sqrt}(1-\xi)$
    - $k_f = (1-2\xi)/\mathrm{sqrt}(1-\xi)$

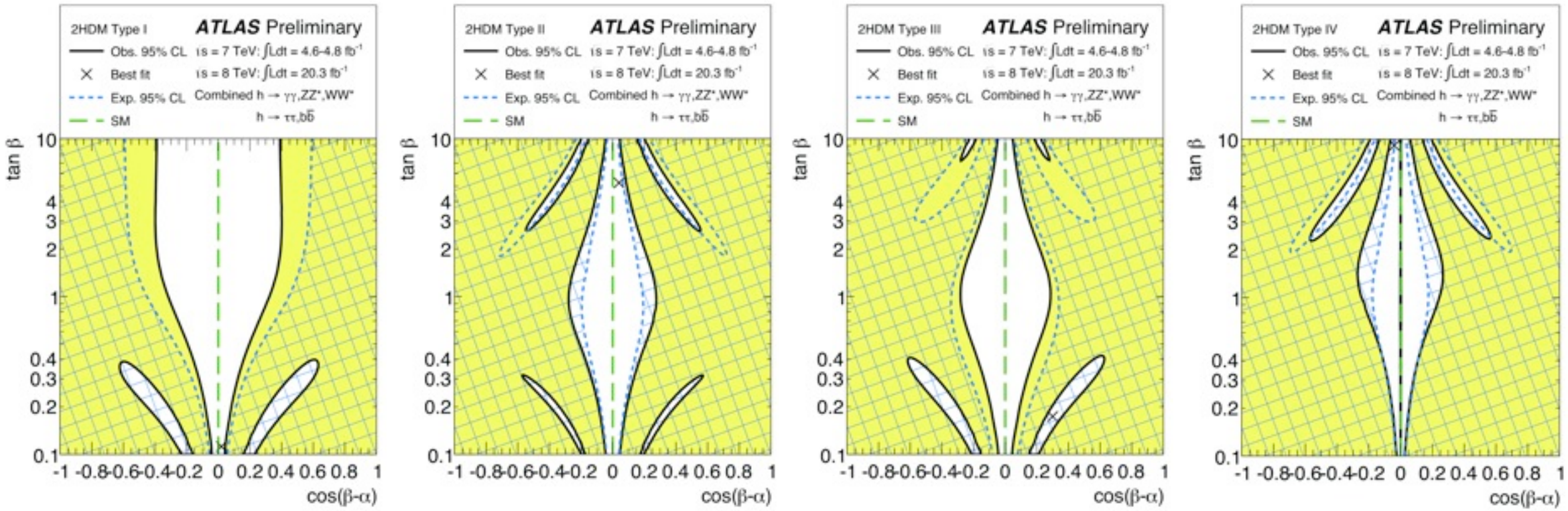


Constraints on New Physics

- Extra Higgs Singlet
- two higgs bosons are non-degenerate and we found the lighter one
- couplings to fermions and bosons similar to SM but with different k-factors k and k'
- Unitarity requires: $k^2 + k'^2 = 1$
- production rate and width of lighter higgs scale with k^2
- fitted value for k'^2 actually negative
- constraining to >0 yields to <0.12 95%CL



Constraints on New Physics



- 2 Higgs Doublet Models (2HDM)
- 5 Higgs bosons: 2 charged, 1 CP-odd and 2 CP-even (1 for up/down-type fermions)
- can be parametrised by 4 masses and two angles:
  - tan(β): ratio of vev's of two higgs doublets
  - α: mixing angle of two neutral higgs bosons
- 4 model types with modified coupling ratios between boson, up- and down-type fermions

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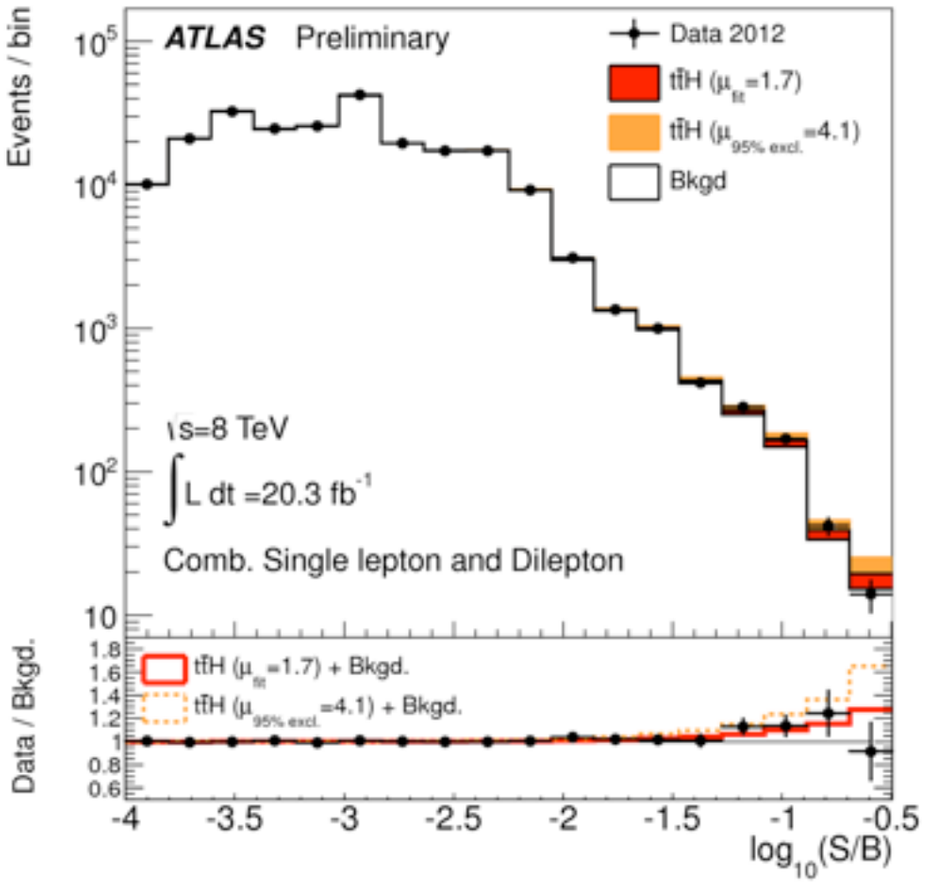
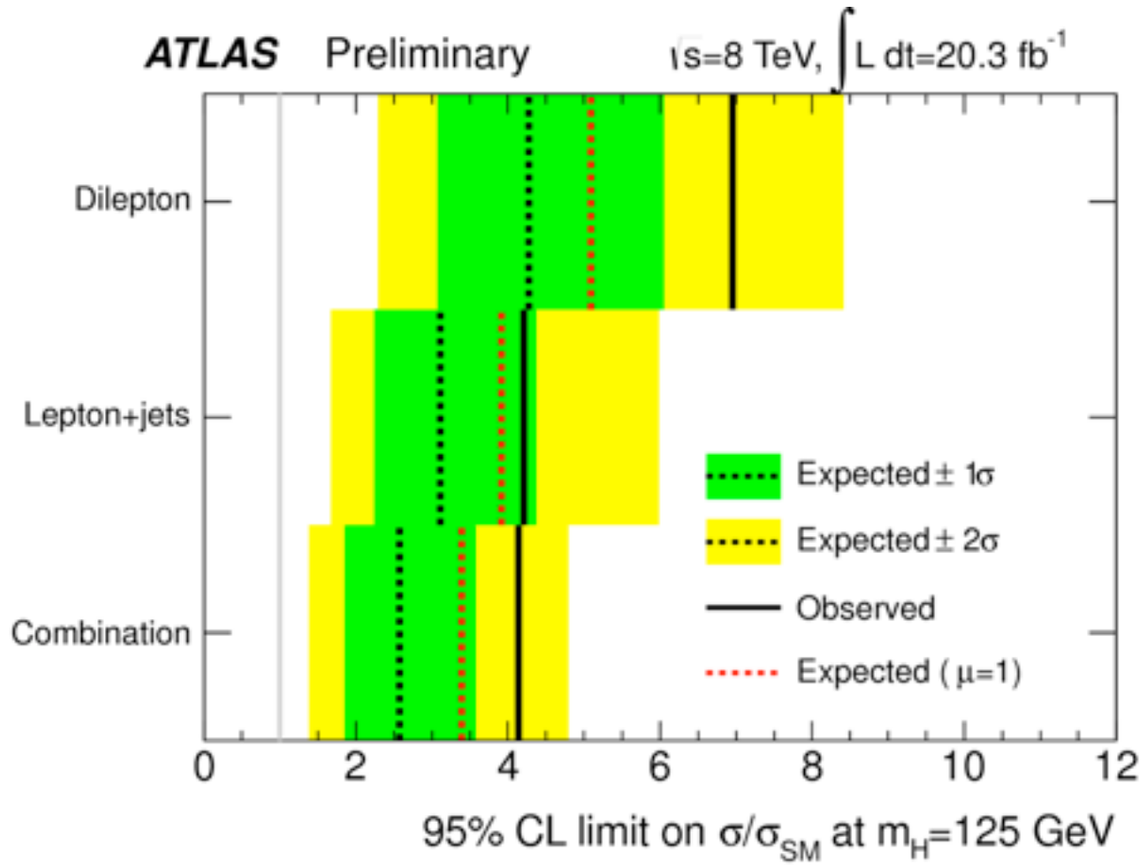
Types of 2HDM

- Type I: One Higgs doublet couples to vector bosons, while the other couples to fermions. The first doublet is “fermiophobic” in the limit of no mixing.
- Type II: This is an “MSSM-like” model, in which one Higgs doublet couples to up-type quarks and the other to down-type quarks and leptons.
- Type III: This is a “lepton-specific” model, where the Higgs bosons have the same couplings to quarks as in the Type I model and to leptons as in Type II.
- Type IV: This is a “flipped” model, where the Higgs bosons have the same couplings to quarks as in the Type II model and to leptons as in Type I.

Channels still waiting for SM Higgs sensitivity

ttH → bb

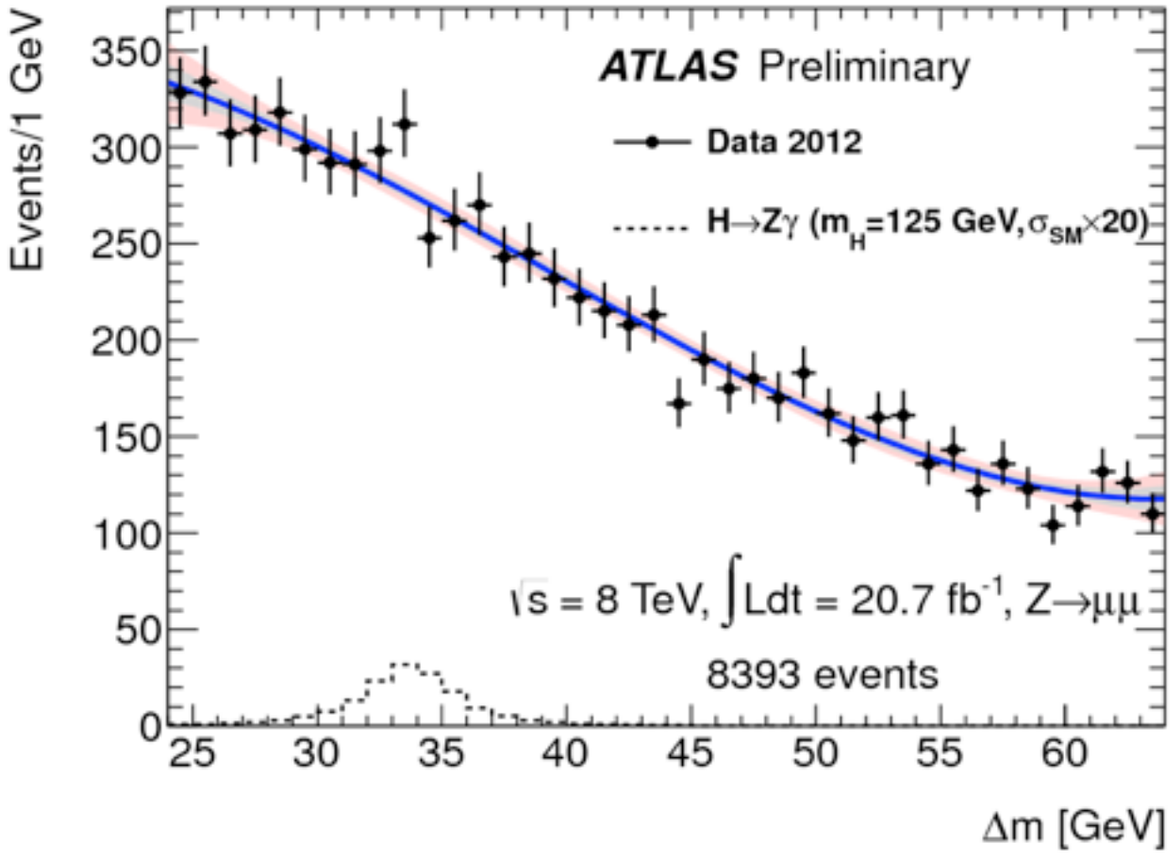


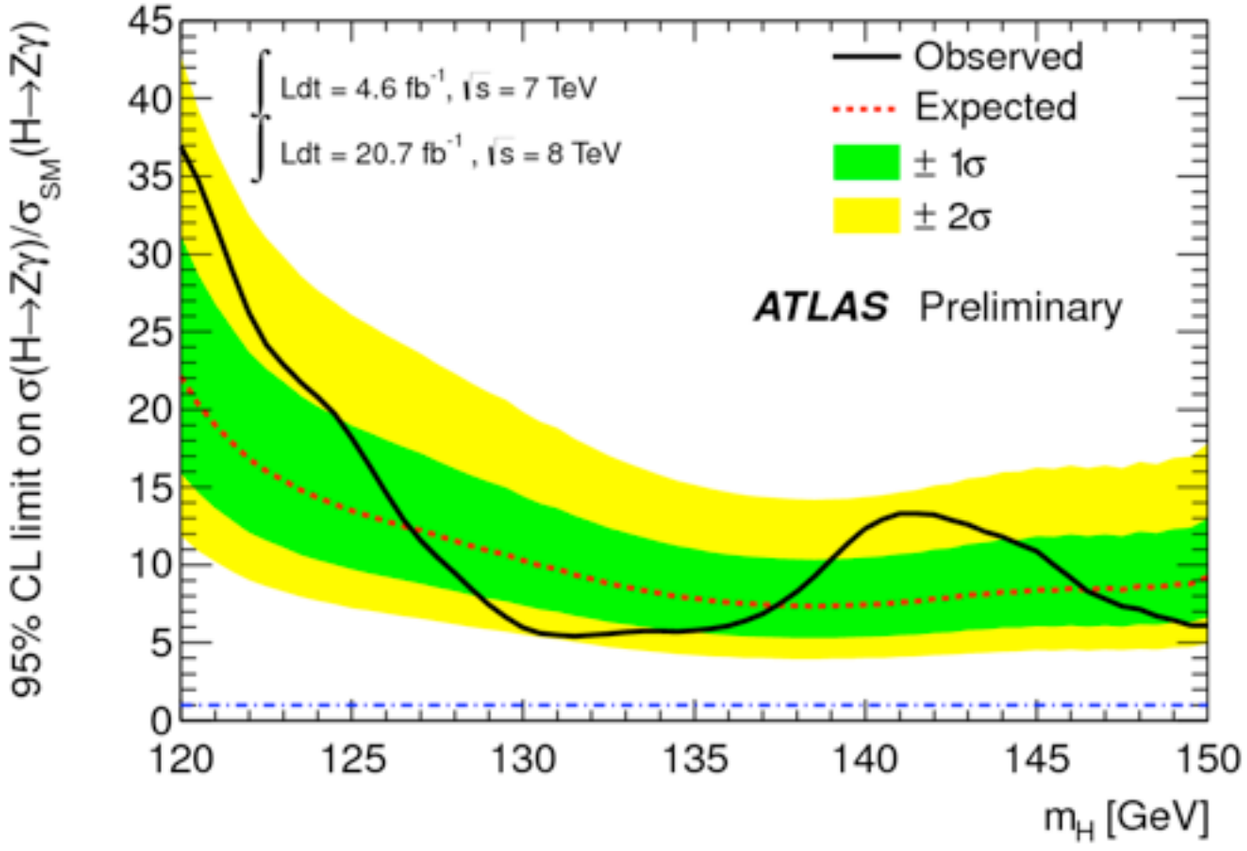


- **Unique feature:** direct sensitivity to Htt Yukawa
- **Selection:** 1 or 2 leptons, in combination with different number of b-jets
- **Categorization:** split by number of b-jets and leptons
- **Backgrounds:** ttbar continuum (in association with heavy flavour)
- **Main Results:** 95% CL obs. (exp.) 4.1 (2.6) times Standard Model, $\mu = 1.4^{+1.7}_{-1.7}$

PLB 732C, pp 8-27

$H \rightarrow Z\gamma$

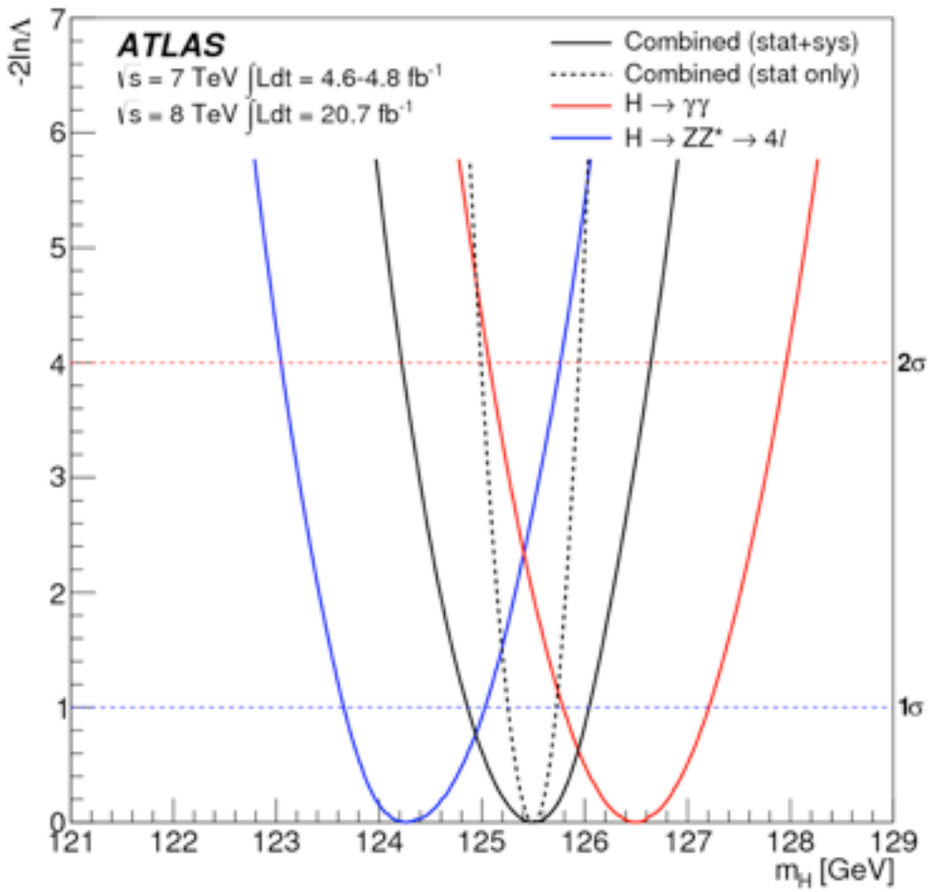


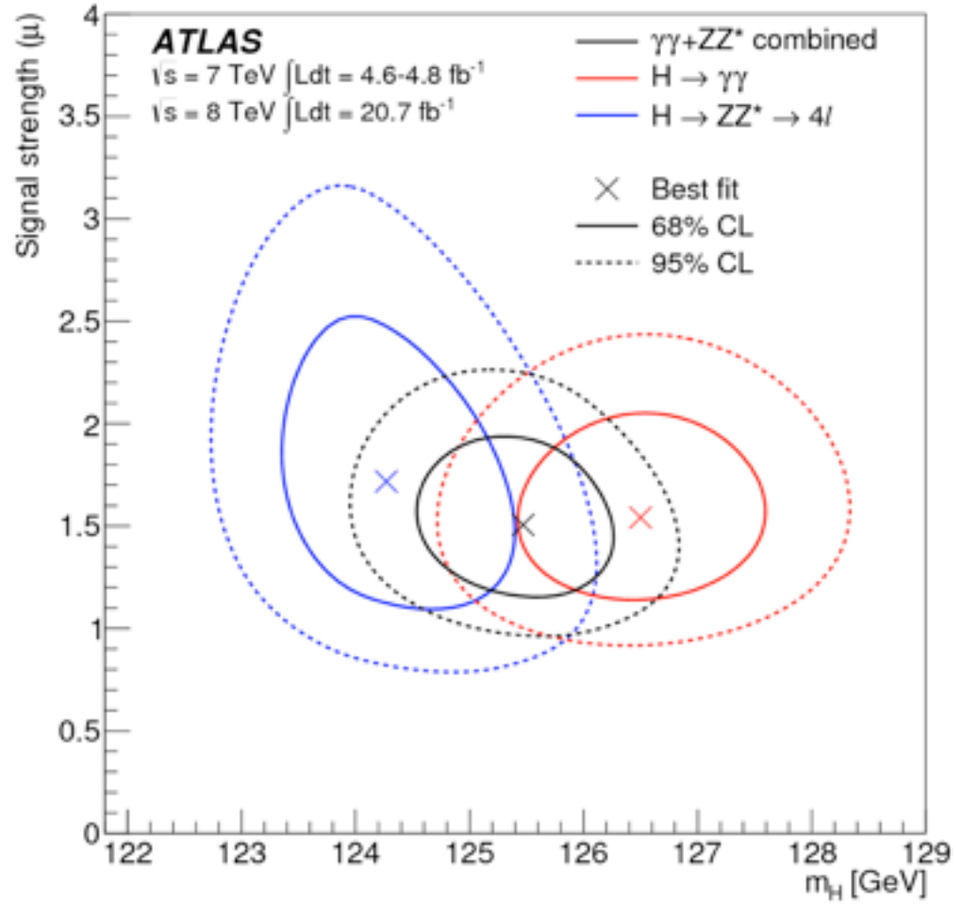


- **Unique feature:** sensitive to many BSM Higgs hypotheses and NP in loops
- **Selection:** 2 opposite sign, same flavour leptons and one isolated photon
- **Categorization:** by $\Delta\eta$ between Z and γ and H cand. p_T transverse to thrust axis
- **Backgrounds:** $Z\gamma$ continuum, Z+jets and small contributions from ttbar and WZ
- **Main Results:** no sig. excess seen, so 95% CL obs. (exp.) 11 (9) times Standard Model

Property Measurements

Properties: Mass





- **Channels:** γγ and ZZ*
- **Result:** 126.8 ± 0.2 (stat) ± 0.7 (sys) GeV vs. 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (sys) GeV
- **Combination:** 125.5 $^{+0.2}_{-0.2}$ (stat) $^{+0.5}_{-0.6}$ (sys) GeV
- **Mass difference:** 2.3 $^{+0.6}_{-0.7}$ (stat) $^{+0.6}_{-0.6}$ (sys) GeV - compatible with 0 at 2.4 σ

PLB 726, pp 120-144

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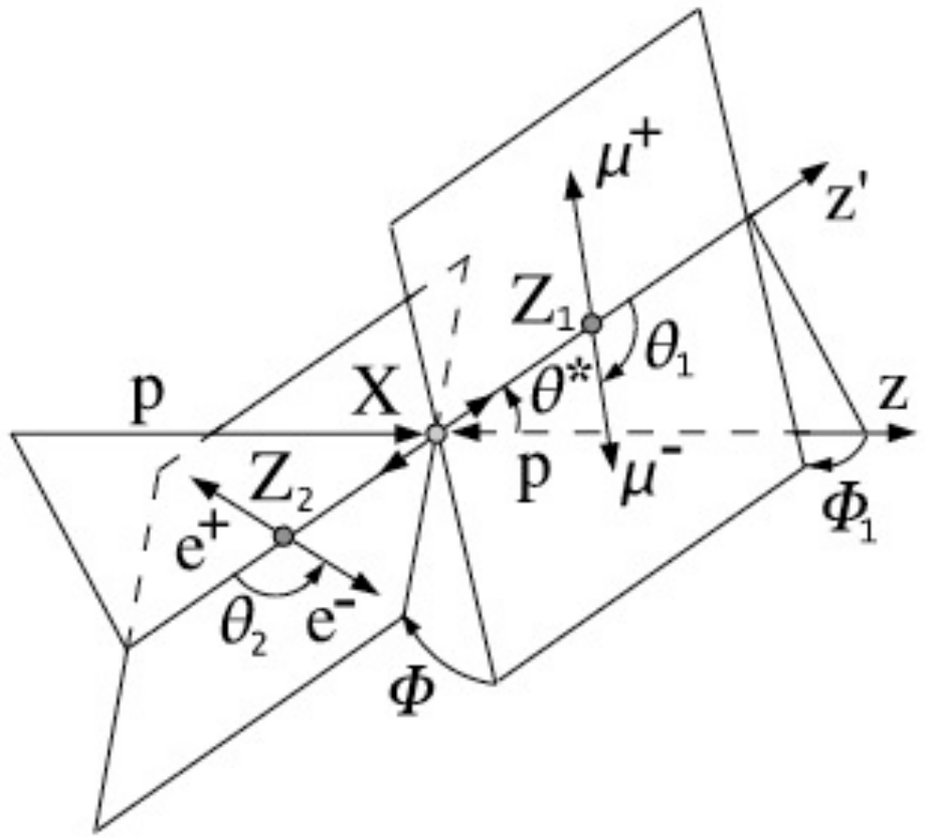
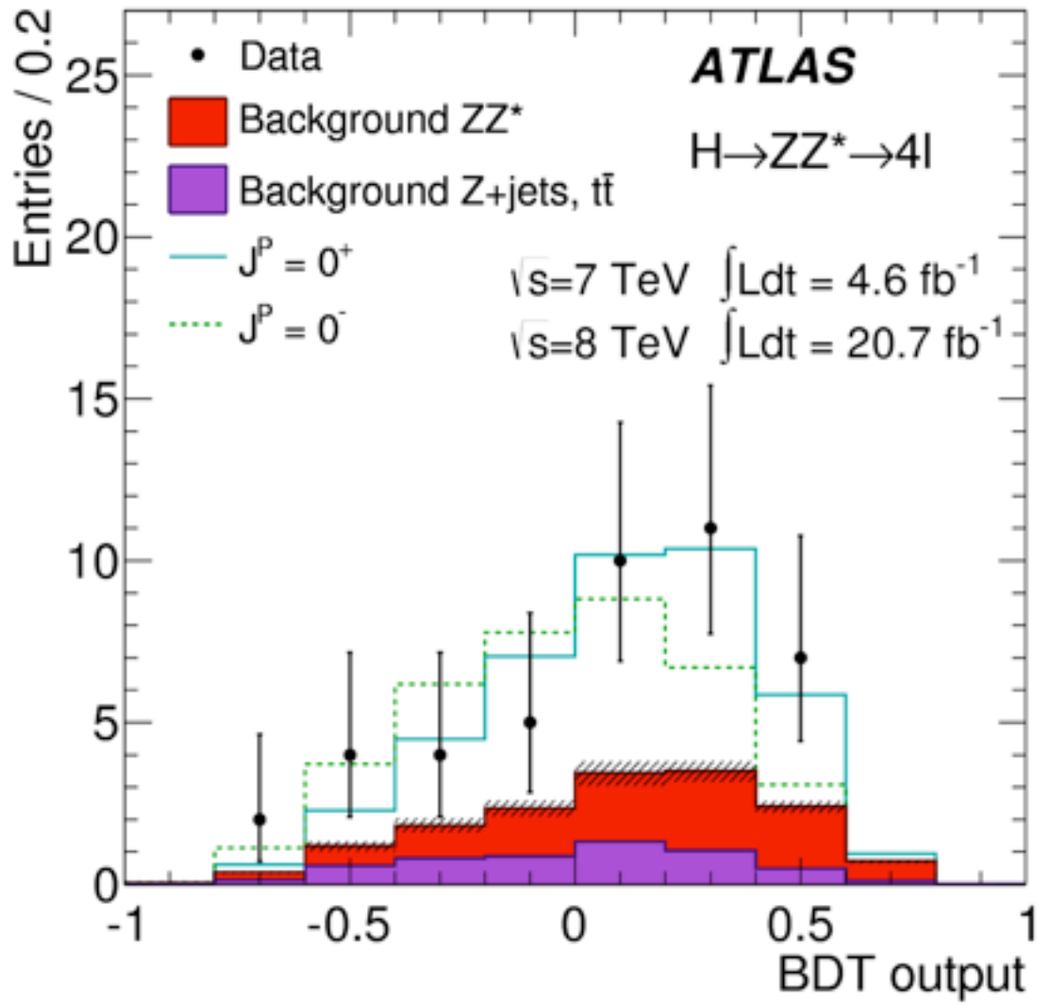
ZZ*: Spin/CP





- **Sensitivity:** all J^P hypotheses
- **Variables:** full 4 lepton decay kinematics available, combined into BDT
- **Unique feature:** Only channel sensitive to 0^-

PLB 726, pp 120-144

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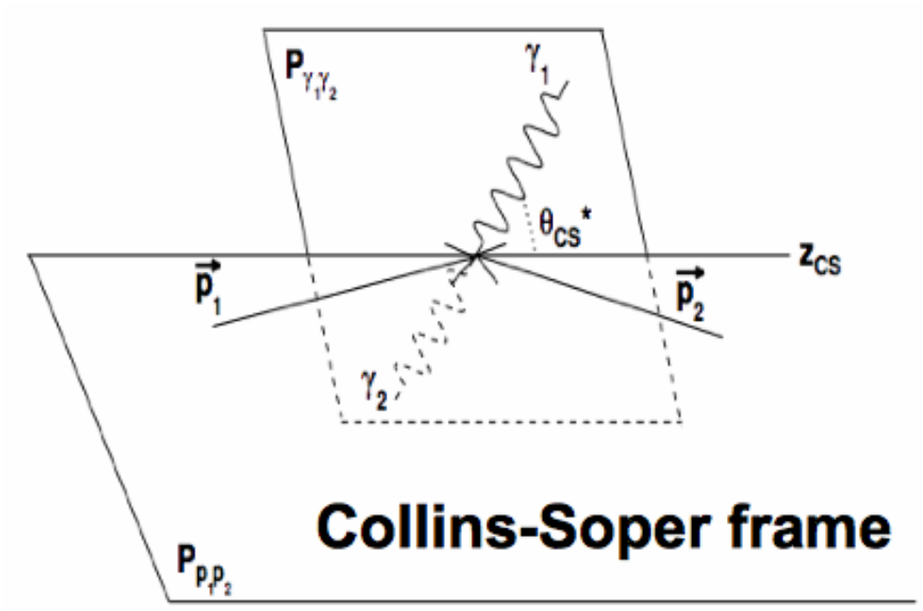
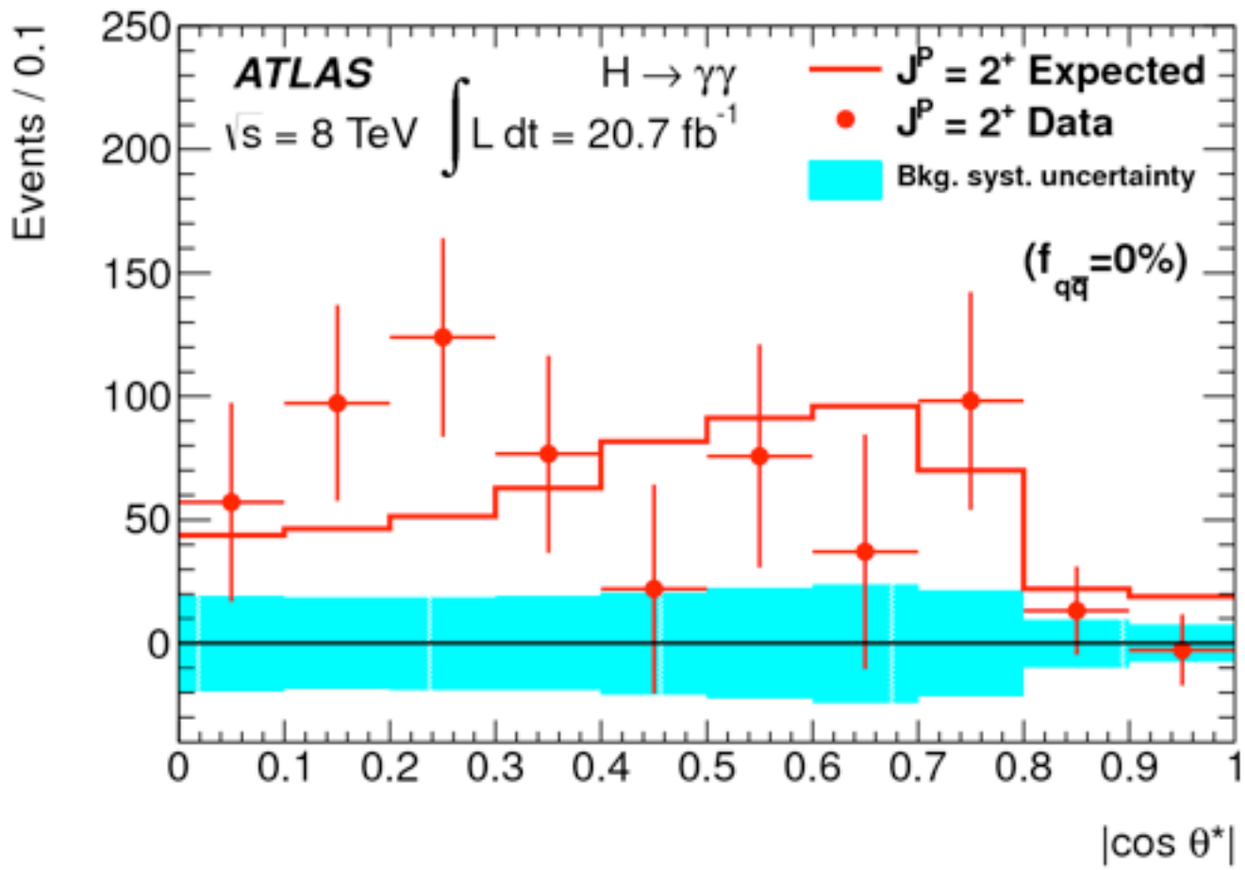
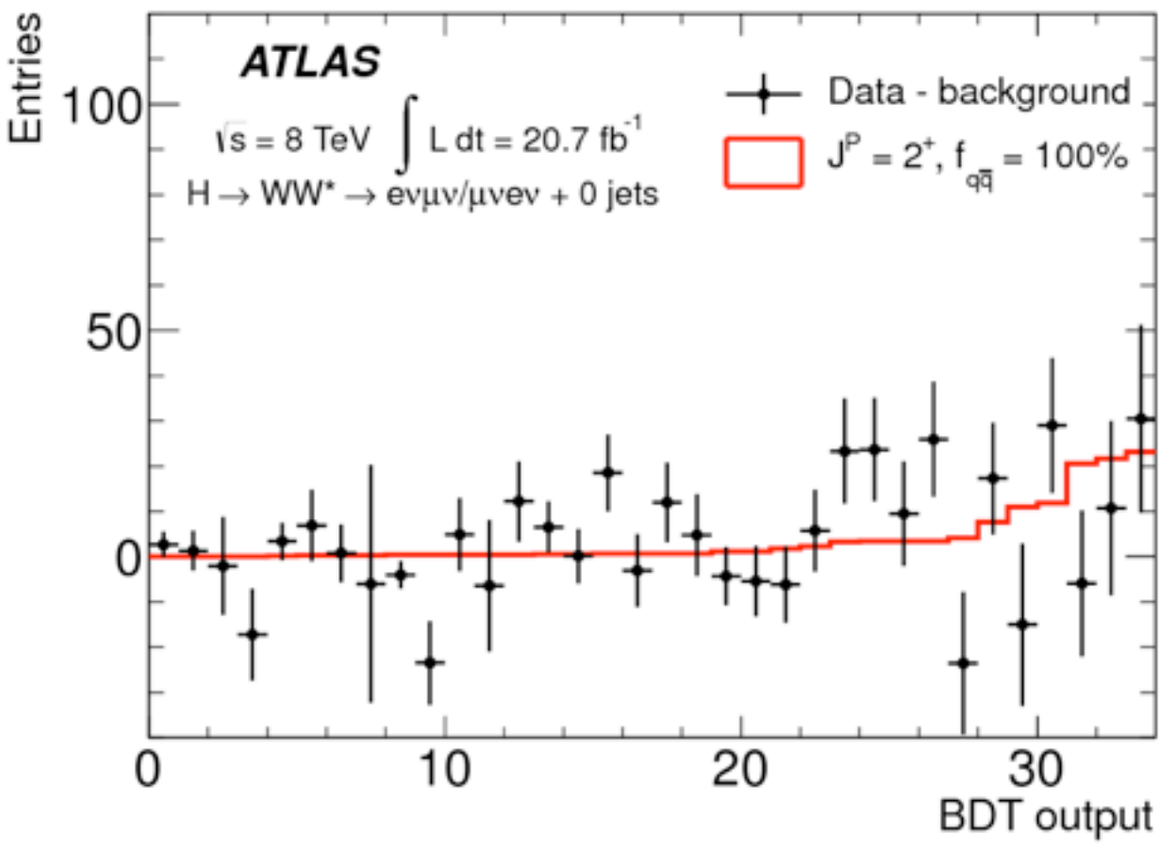
γγ: Spin/CP

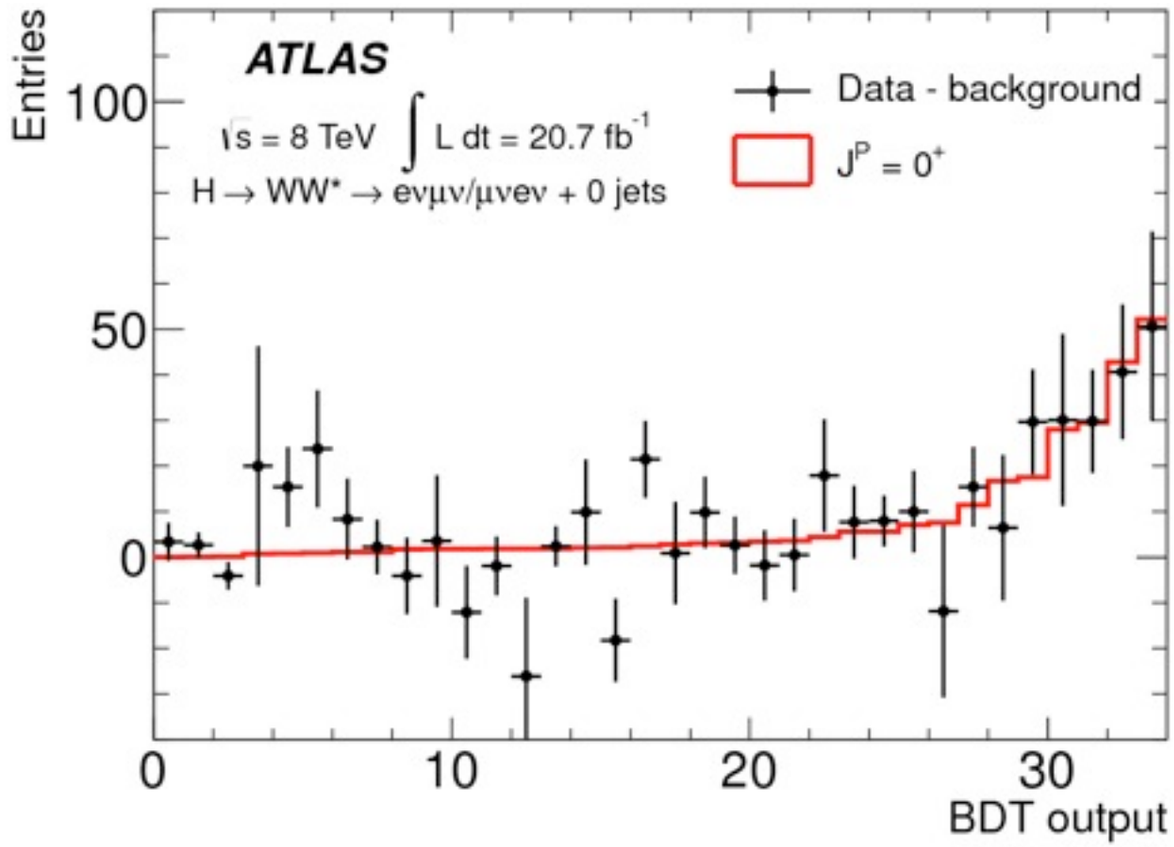




- **Sensitivity:** only sensitive to 0^+ and 2^+
- **Variables:** cos(θ*) in Collins-Soper frame
- **Unique feature:** observation of this decay strongly disfavors spin 1 (Landau-Yang theor.)

WW: Spin/CP





- **Sensitivity:** all Jp hypotheses, except 0^-
- **Variables:** $\Delta\varphi(ll)$, $p_T(ll)$, $m(ll)$ and m_T, combined into BDT
- **Unique feature:** higher event yields than ZZ*, but difficult due to E_T^{Miss}

PLB 726, pp 120-144

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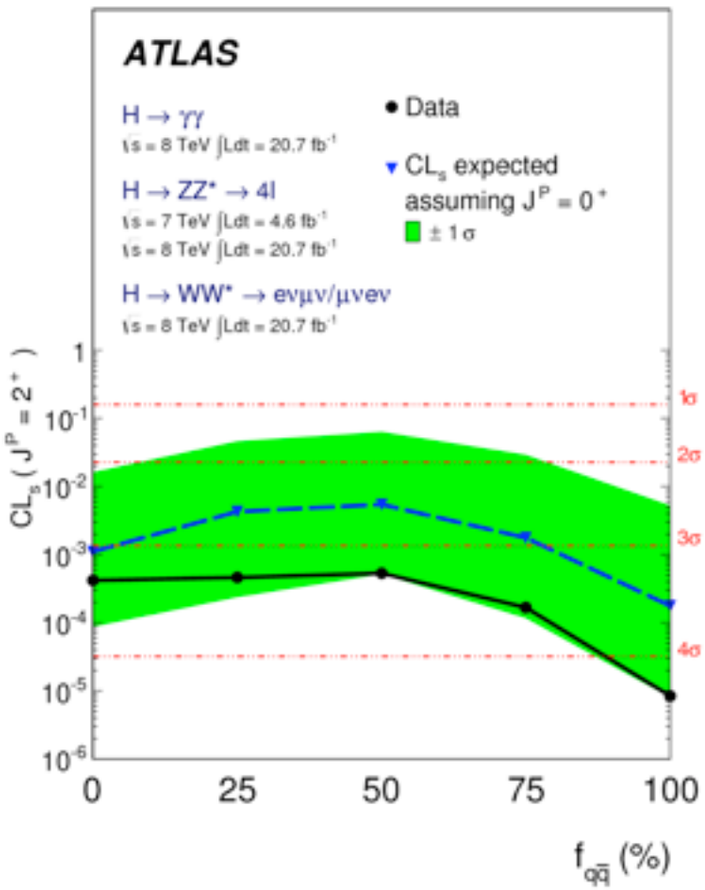
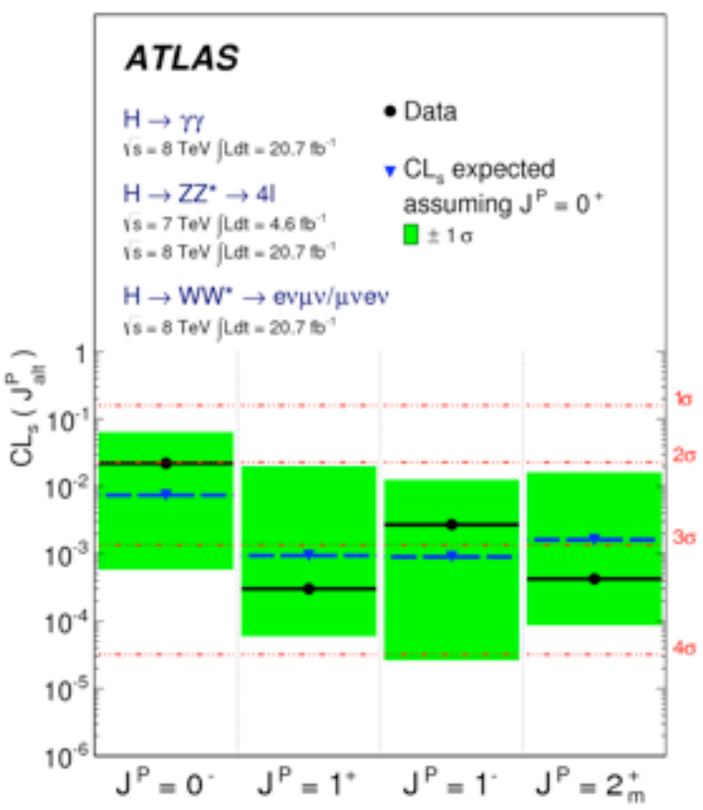
Properties: Spin CP





JP	Channels	CL[%]
0^-	ZZ	97.8
1^+	ZZ,WW	99.97
1^-	ZZ,WW	99.7
2^+	γγ,ZZ,WW	99.99

- **Channels:** γγ, ZZ* and WW
- **Signal models:** 0^- quark-induced, $1^{+/-}$ gluon-induced, 2^+ different mixtures
- **Results:** All hypotheses except 0^+ excluded at >97.7% confidence level

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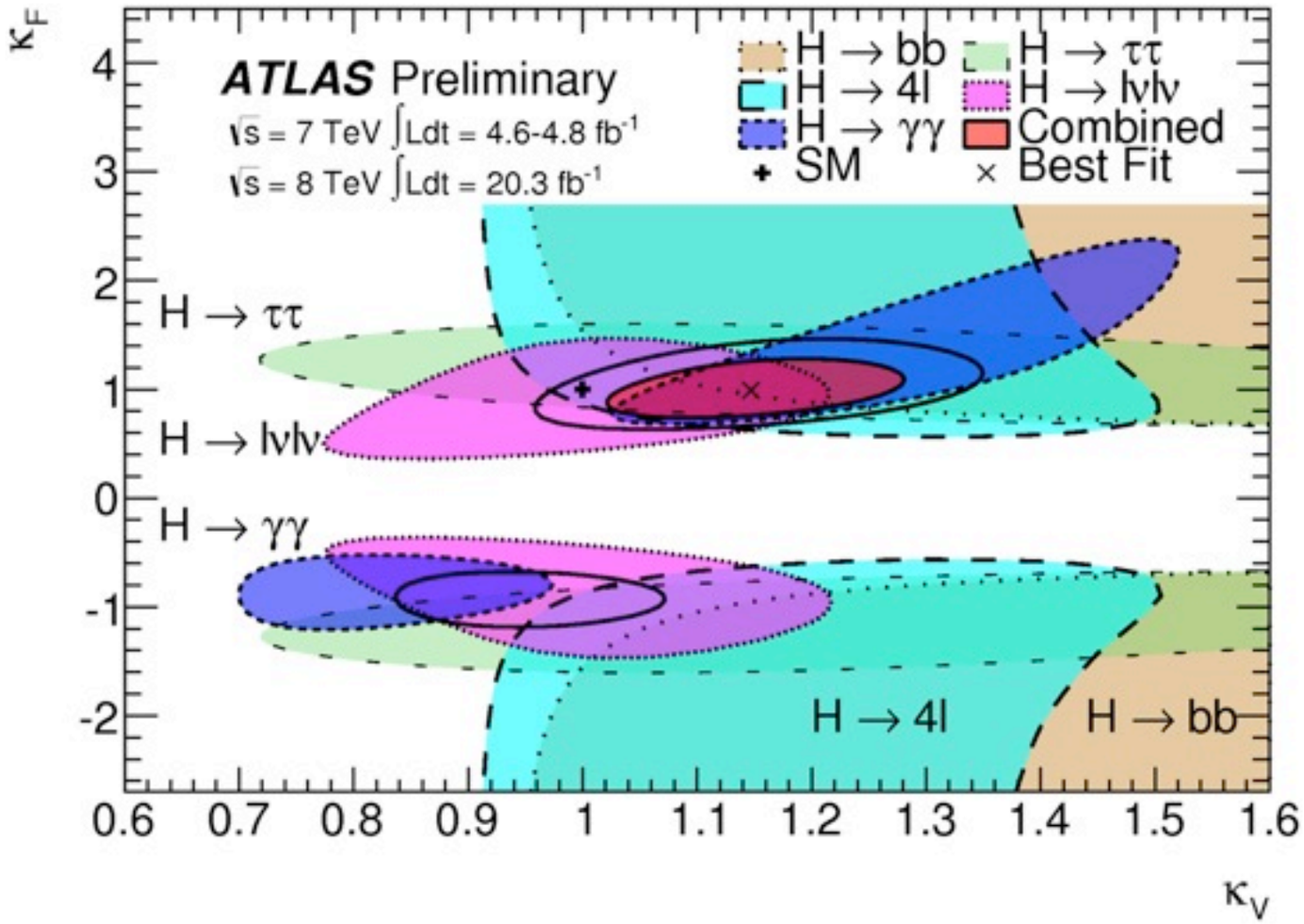
Couplings: K_V vs. K_f

- to test deviations of specific Higgs couplings introduce scale factors k_i
- set all vector boson couplings equal and scale with k_V
- set all fermion couplings equal and scale with k_f
- SM ratio should be 1
- new physics could change ratio and relative sign
- measurement compatible with SM and positive sign preferred



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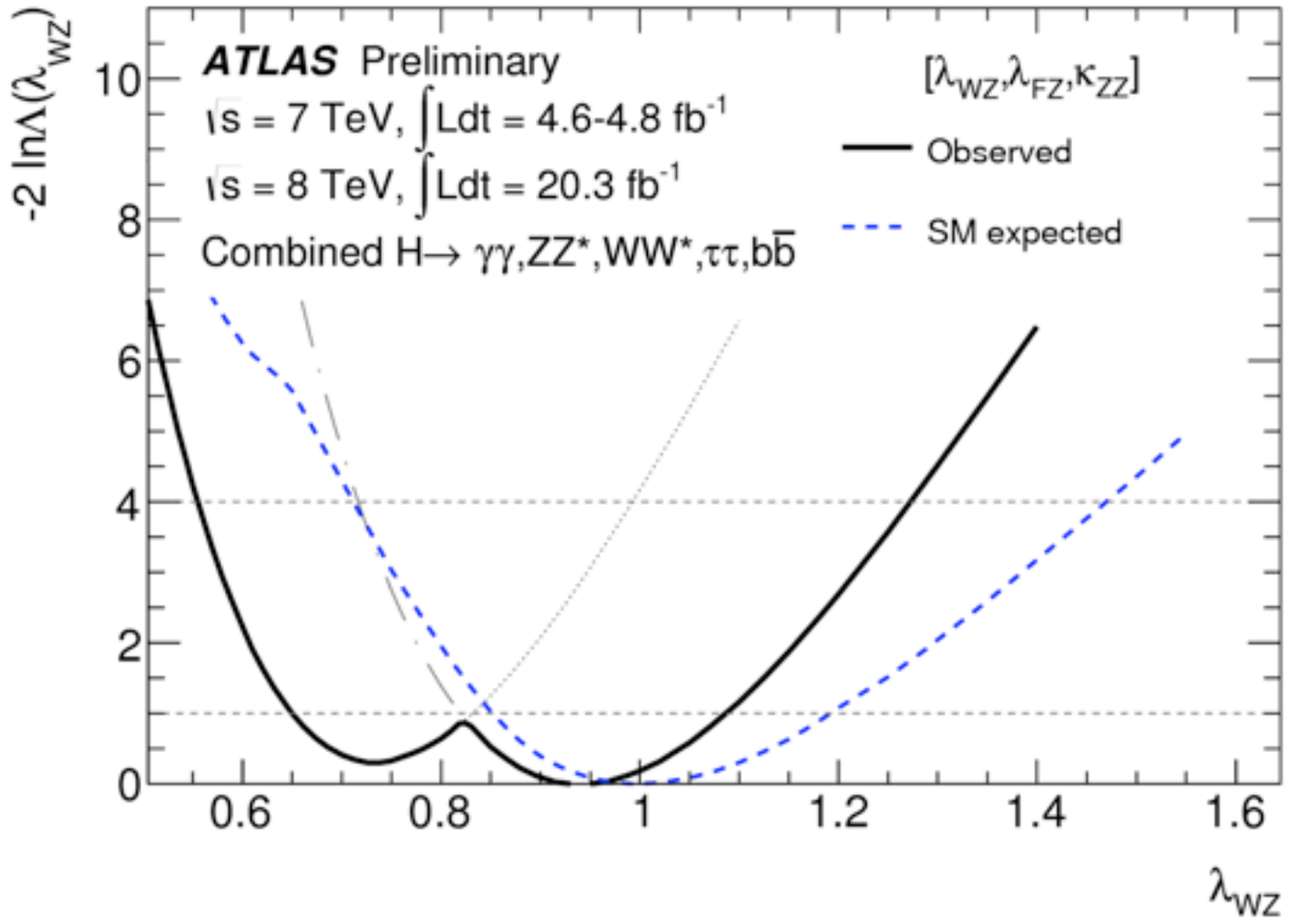
Custodial Symmetry

- SM SU(2) requires identical higgs couplings between W and Z
- profile ratio of W over Z coupling
- keep fermion couplings identical
- results depend on allowed NP in loops:
  - no NP: [0.64,0.87]
  - allow NP: 0.8 ± 0.15



Couplings: 5D fit

- can also allow for individual k-factors for all five measurable couplings
- k_Z and k_W assumed positive
- fit sensitive to relative sign to k_t
- bb decay mode accounts for ~60% of Higgs width
- low rate in this channel pulls all couplings down
- overall compatibility with SM is 14%
- coupling measurements can also be interpreted in context of new physics
- see Hal Evans talk in this session