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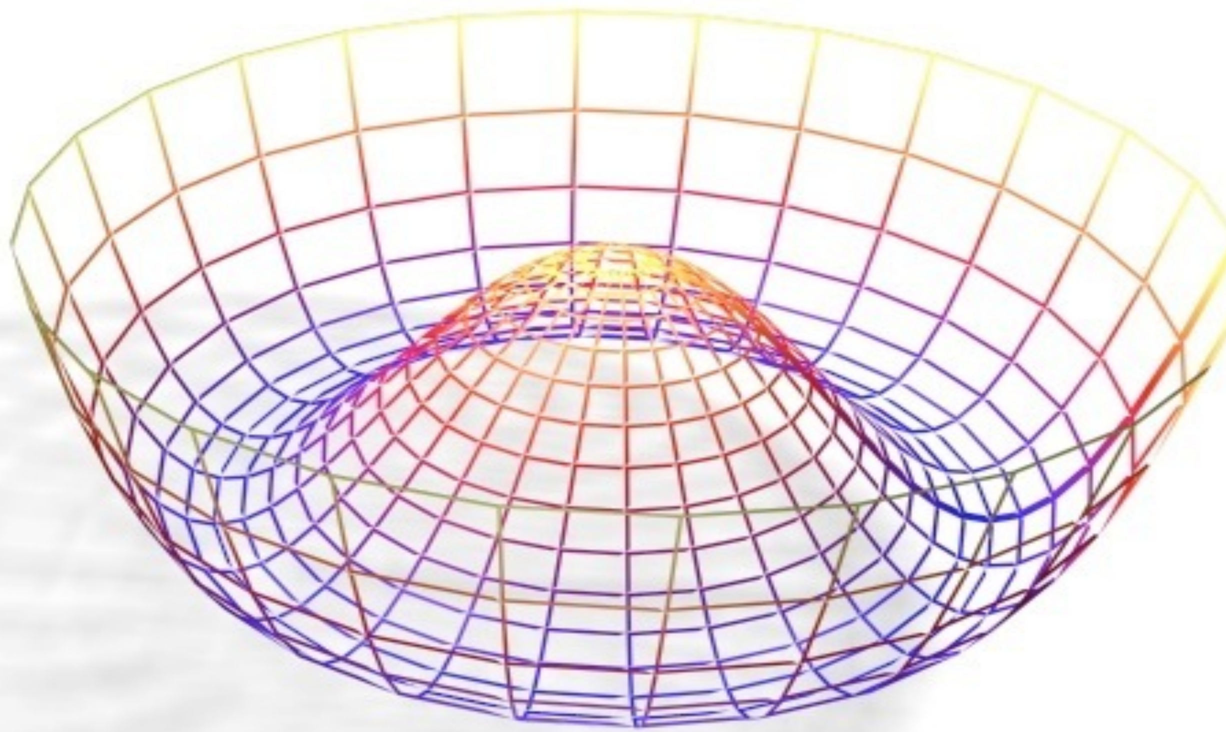
Standard Model Higgs Combination and Higgs Properties Measurements in ATLAS



Kyle Cranmer,
New York University

SM Higgs @ the LHC

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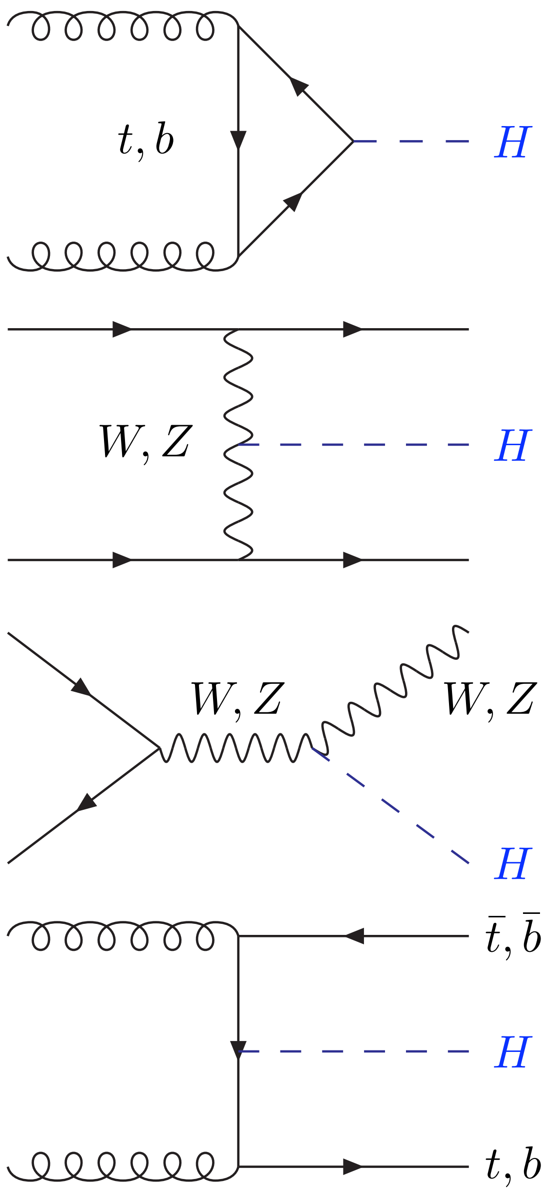
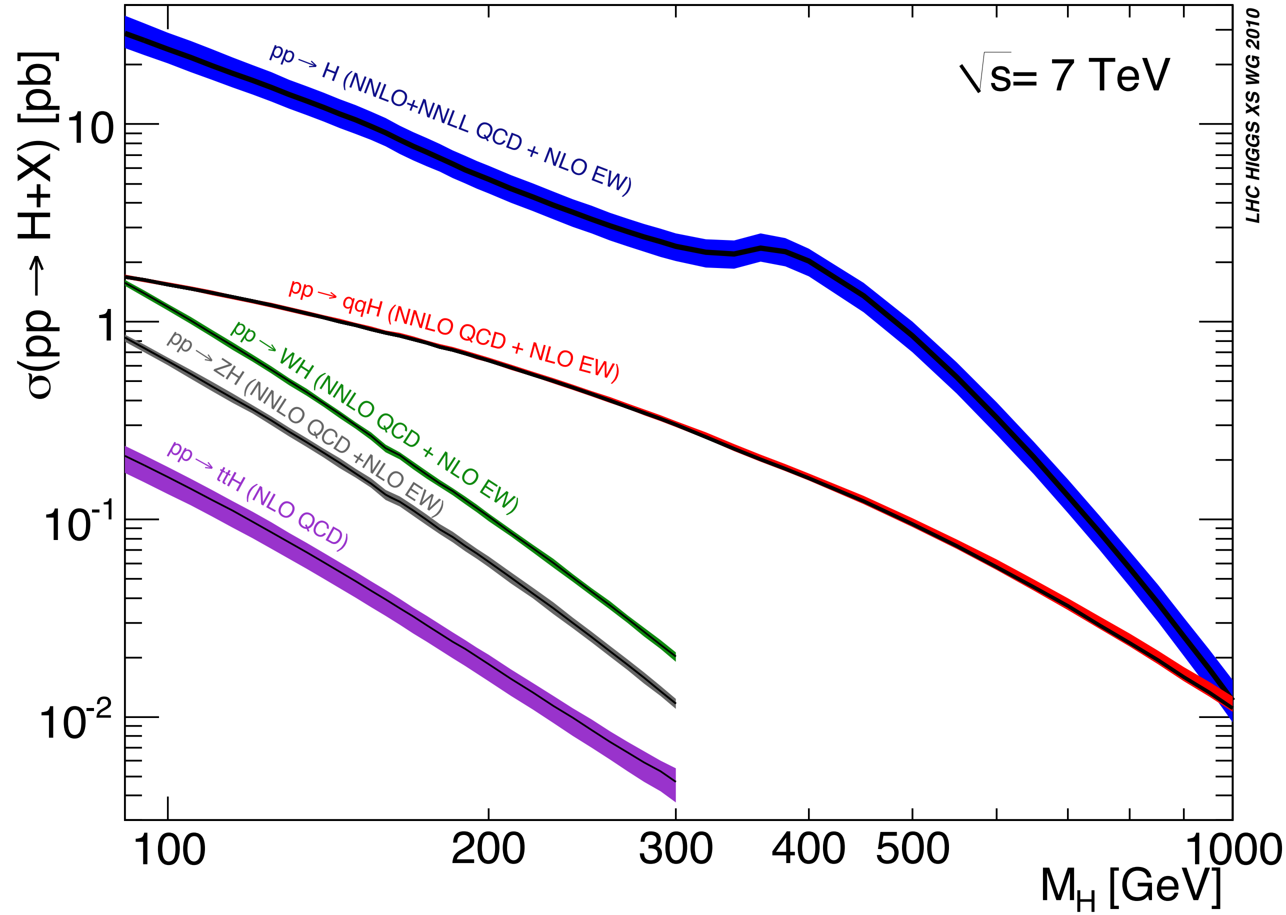
in ⟶ out





Gluon fusion: produced with little pT

Vector boson fusion: hard jets, high pT

Associated: extra handle from leptons

SM Higgs @ the LHC

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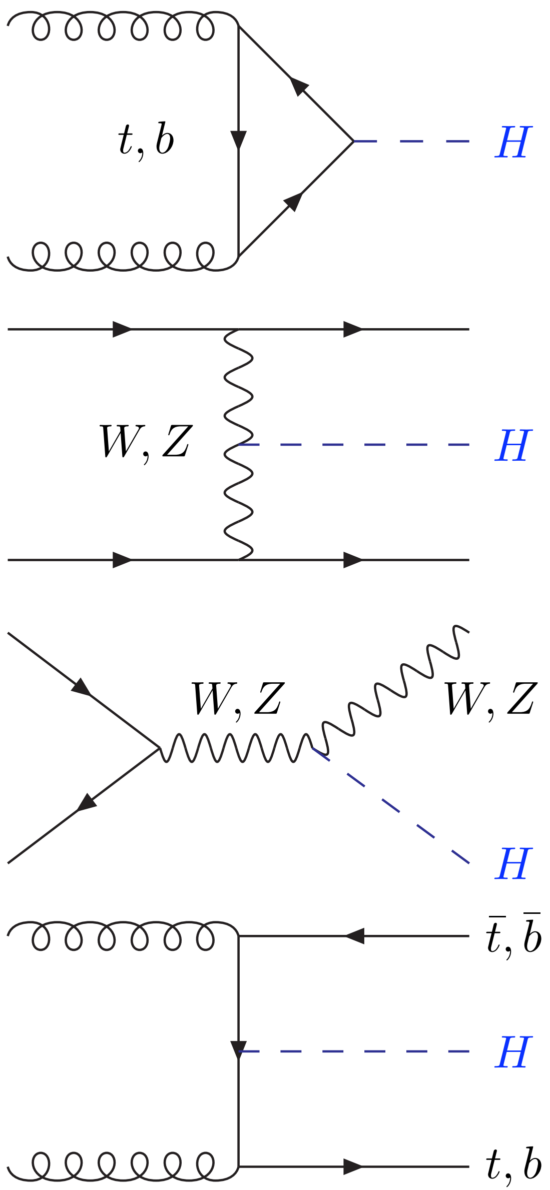

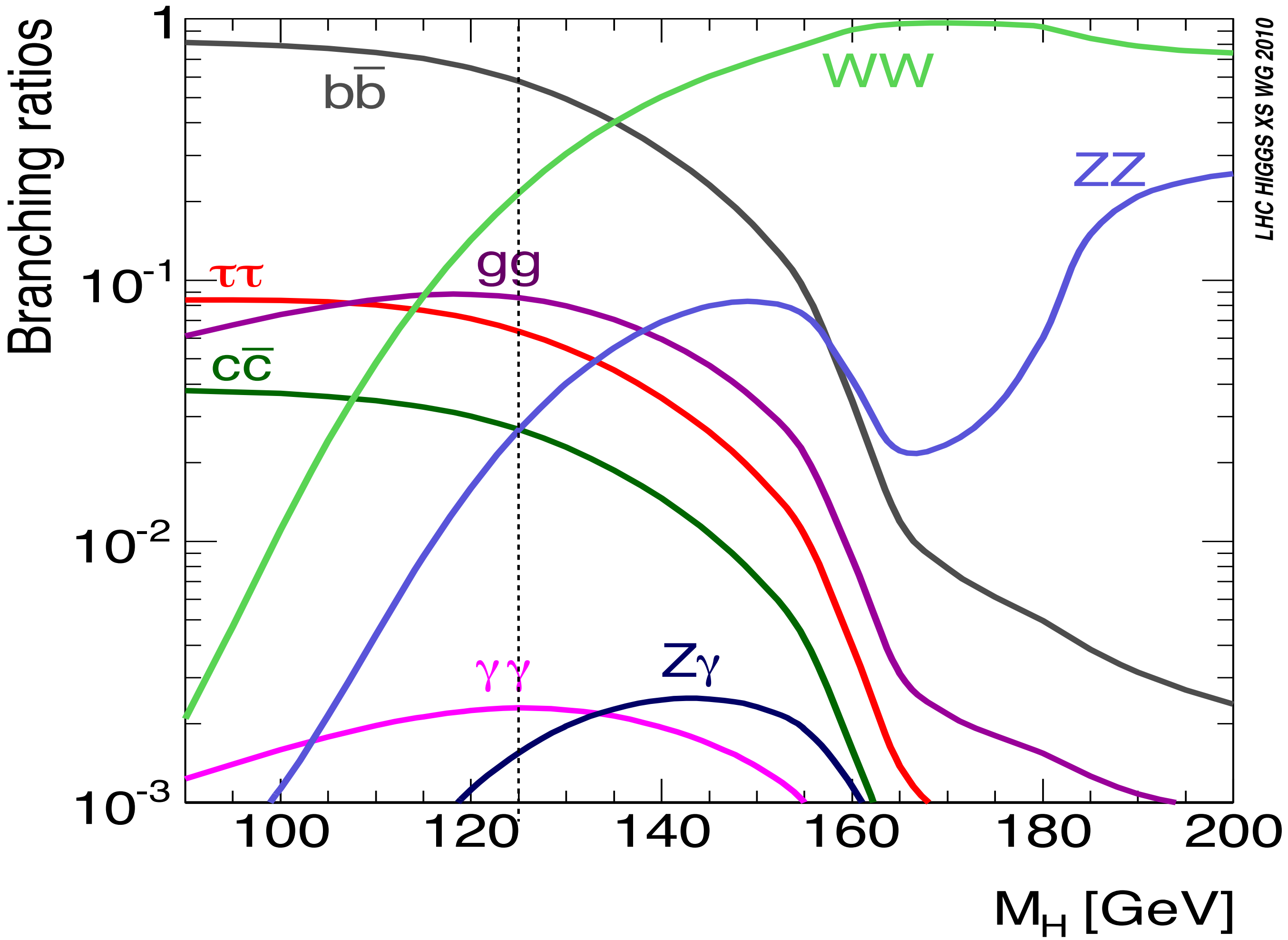

Many decays accessible at 126 GeV

bb dominates, but is difficult

γγ small branching ratio, but clean

SM Higgs @ the LHC

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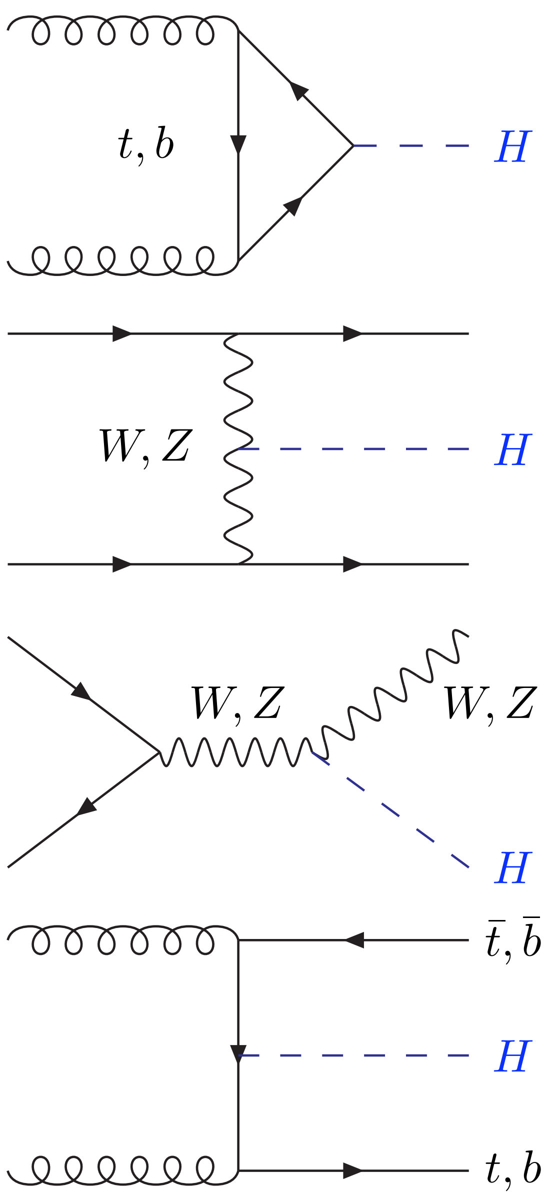

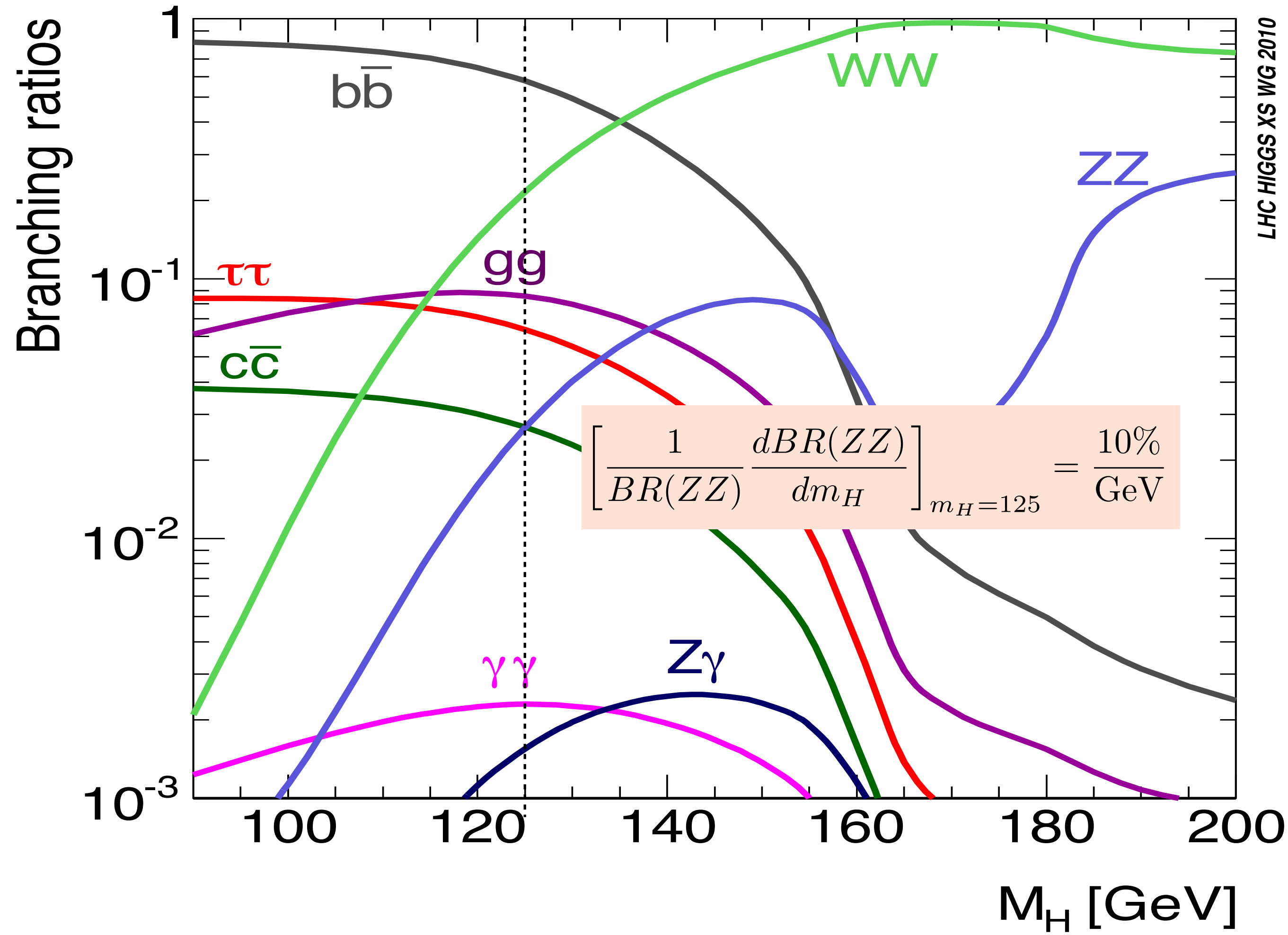

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Discovery!

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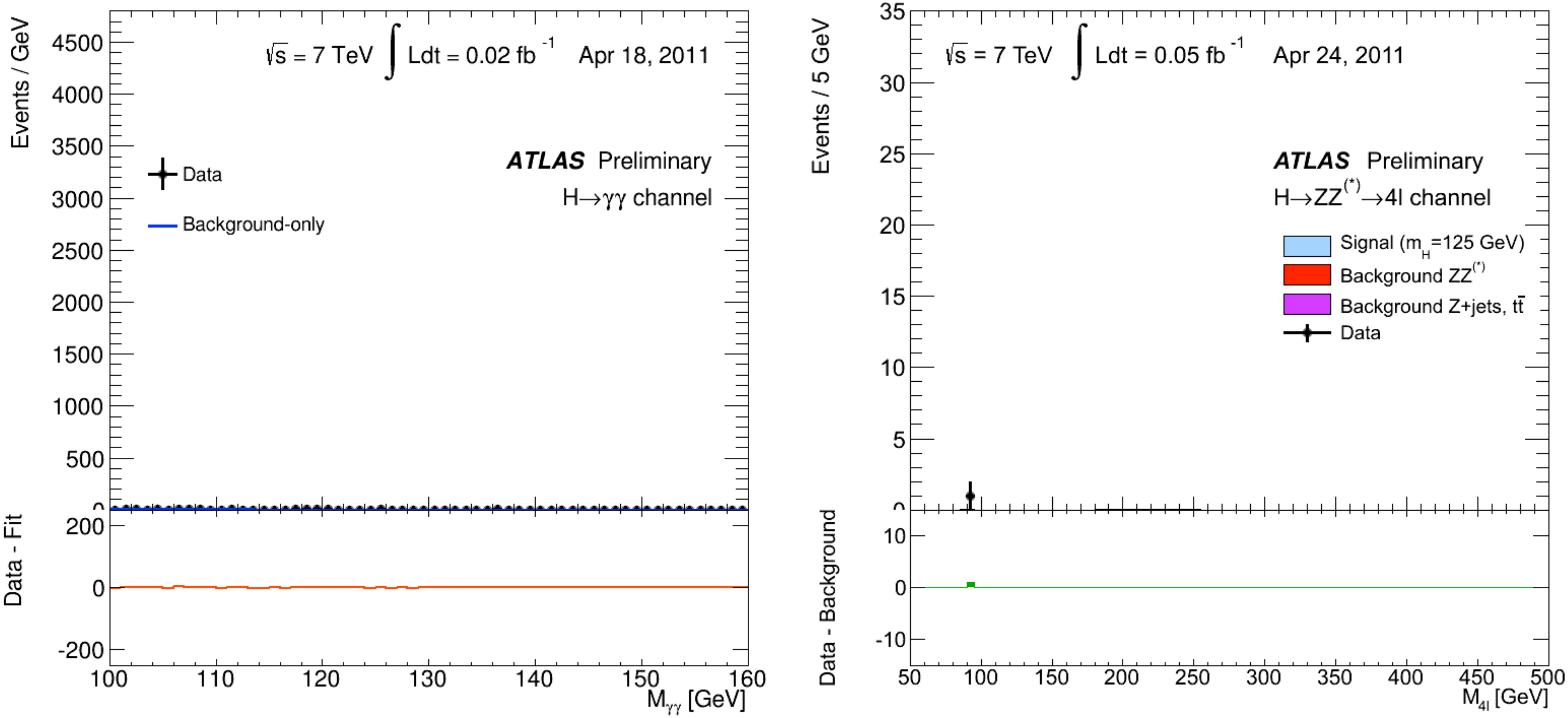

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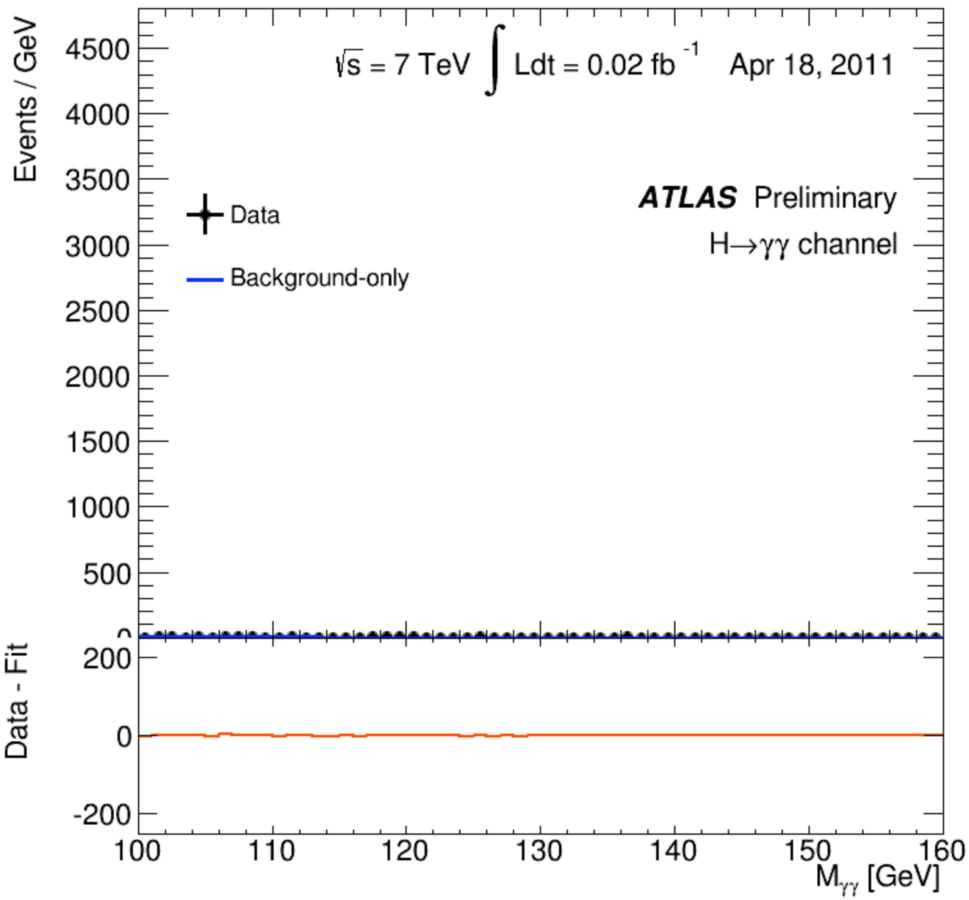
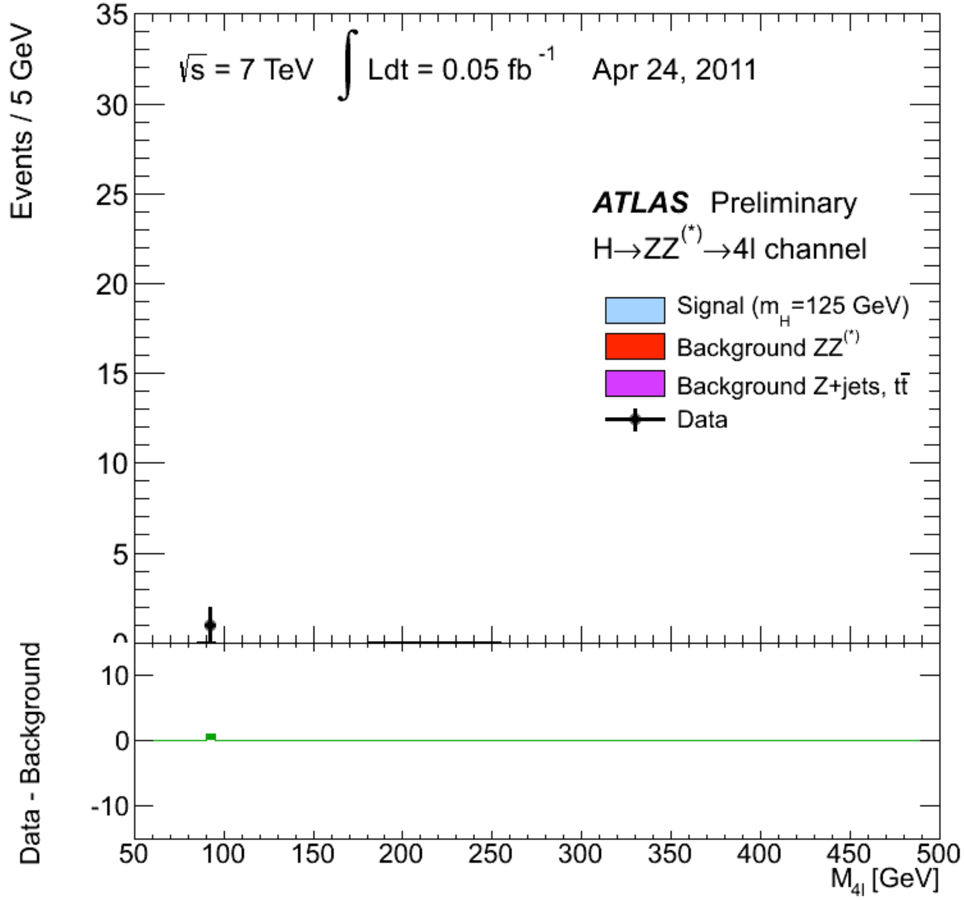
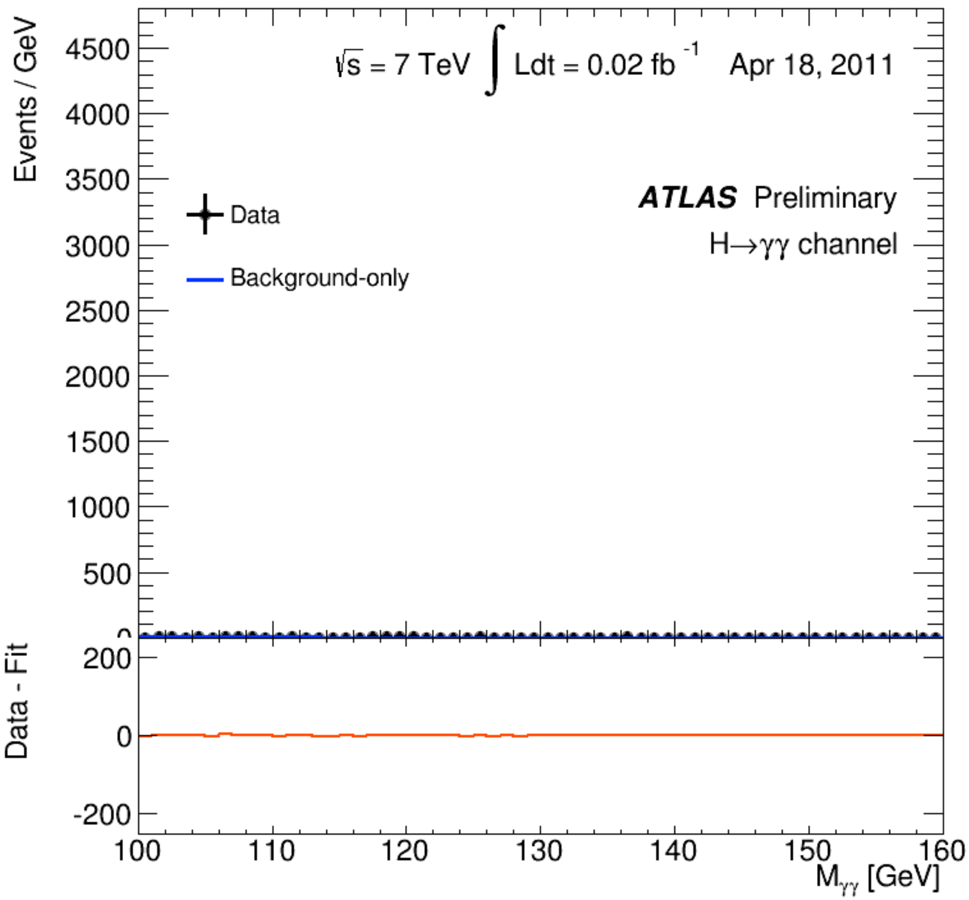

√s = 7 TeV ∫ Ldt = 0.02 fb-1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]


√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
35
30
25
20
15
10
5
0
Data - Background
10
0
-10
50
100
150
200
250
300
350
400
450
500
M4l [GeV]

Discovery!



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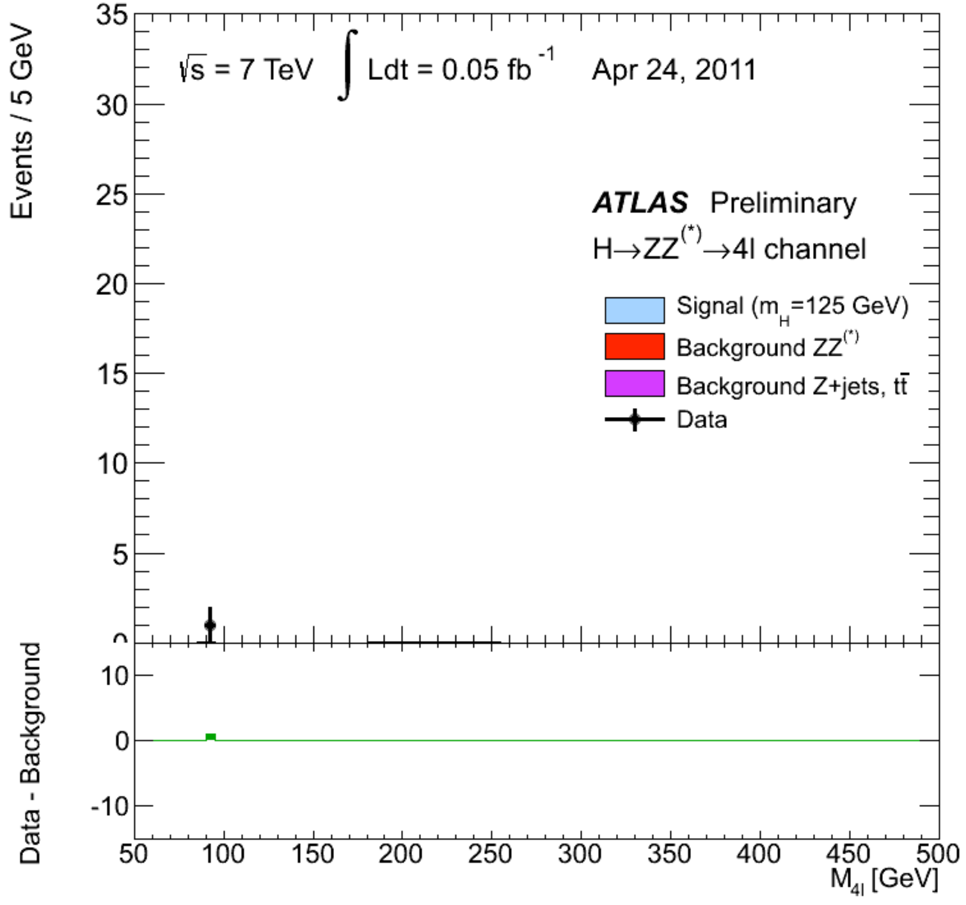

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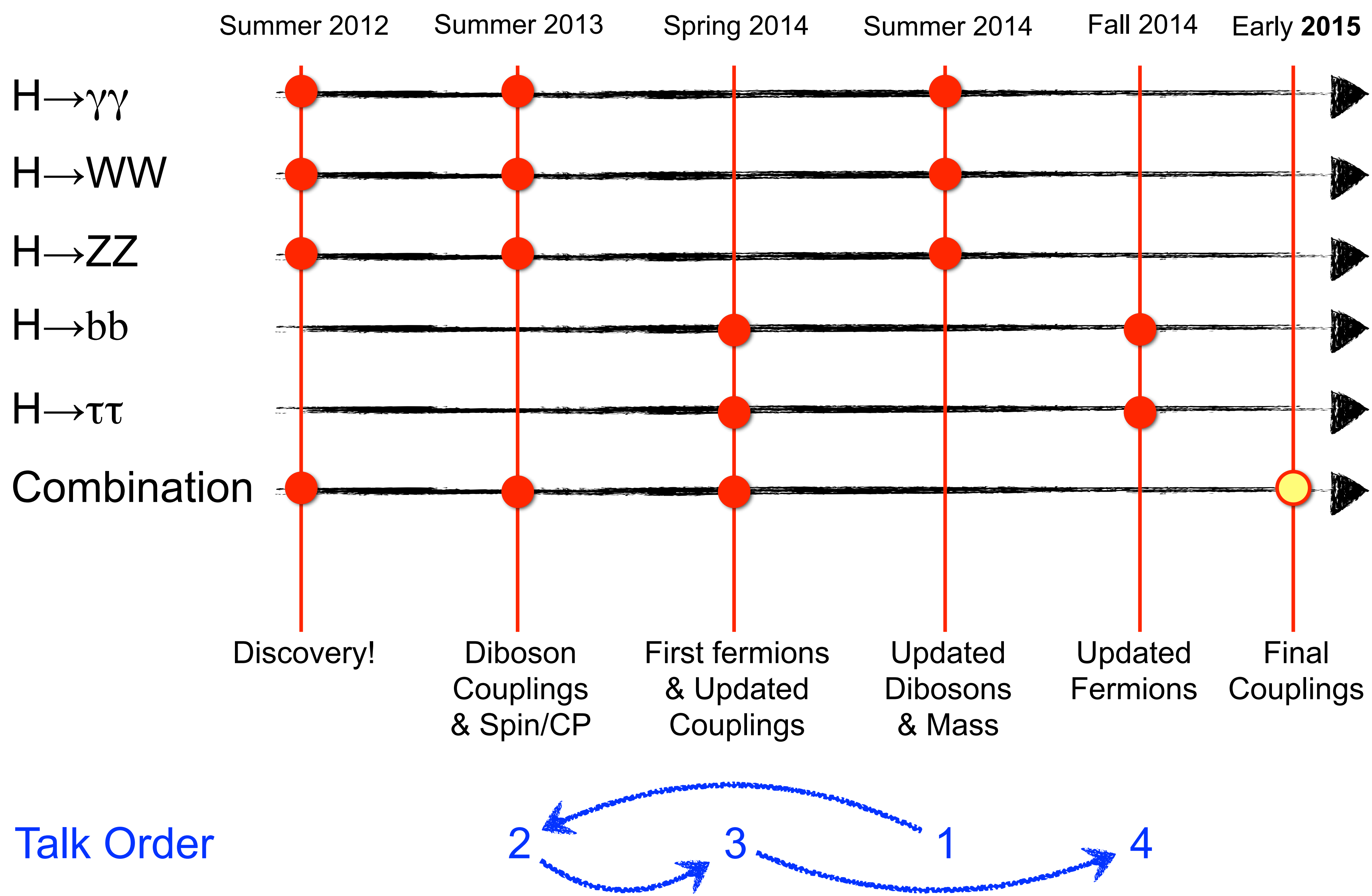
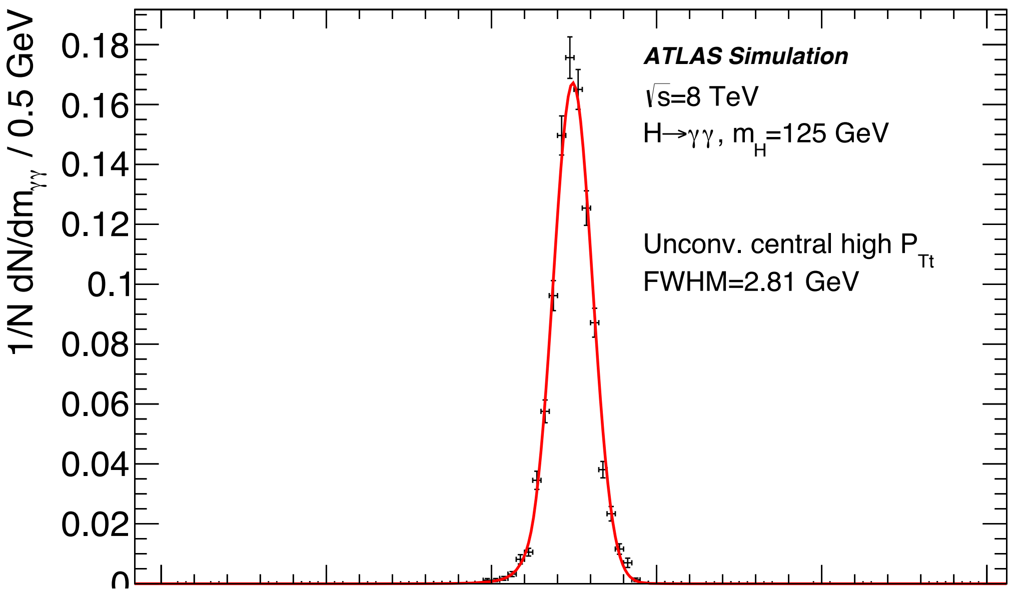
M4l [GeV]

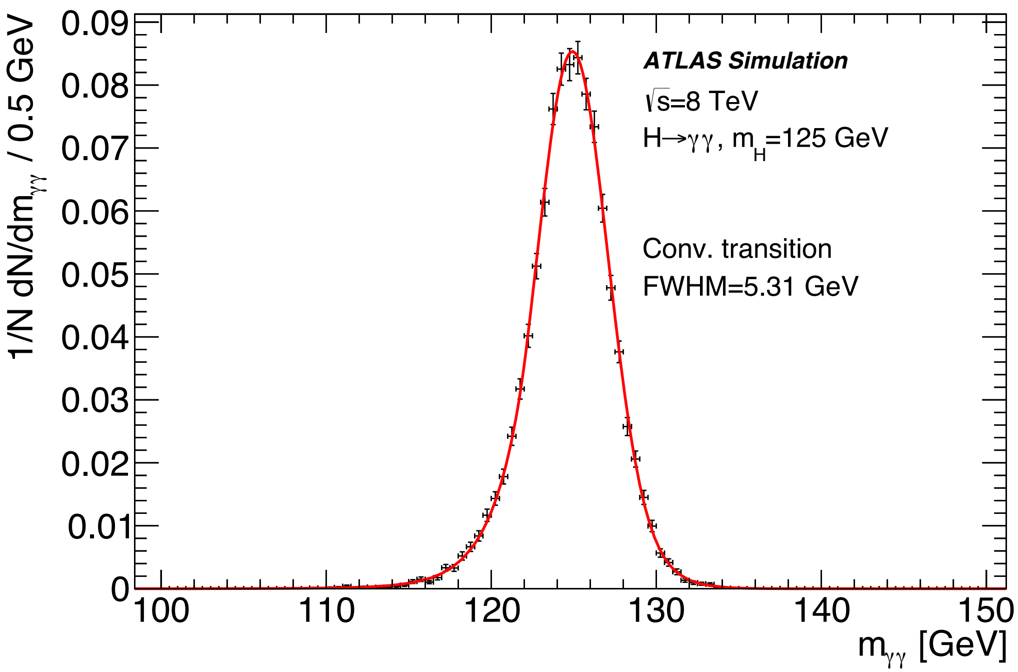
Timeline


Summer 2012
Summer 2013
Spring 2014
Summer 2014
Fall 2014
Early **2015**
H→γγ
H→WW
H→ZZ
H→bb
H→ττ
Combination
Discovery!
Diboson Couplings & Spin/CP
First fermions & Updated Couplings
Updated Dibosons & Mass
Updated Fermions
Final Couplings
Talk Order
2
3
1
4

Mass & Width

Mass Measurement in $H\to\gamma\gamma$



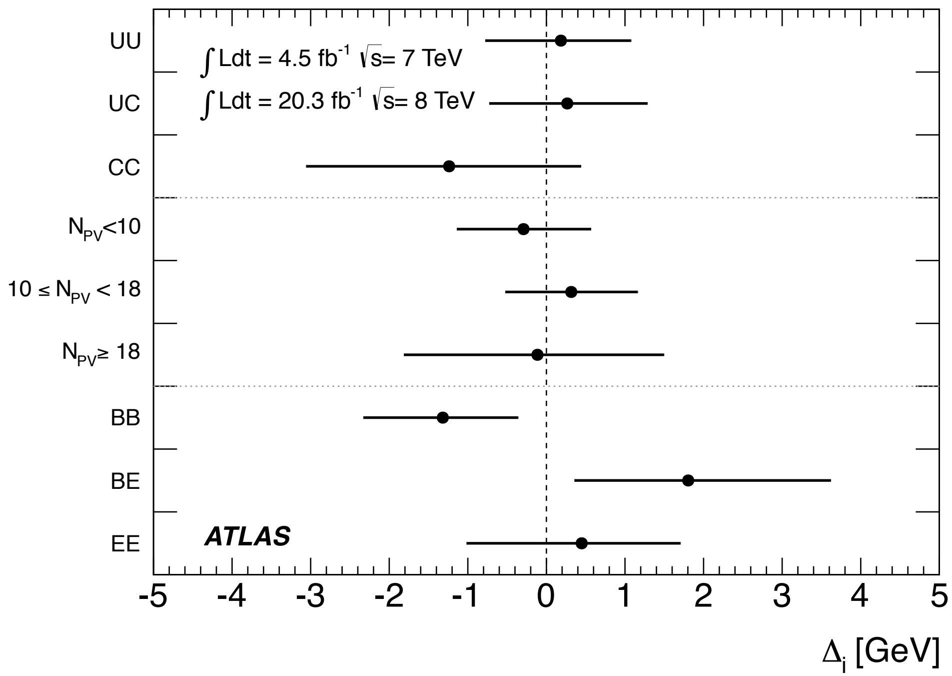


Events separated into 10 categories based on p_T, η, and conversion status. Resolution varies ~2x

Multivariate regression for energy calibration gives ~10% improvement

Consistent across subsamples

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



Mass Measurement in $H \rightarrow ZZ \rightarrow 4\ell$

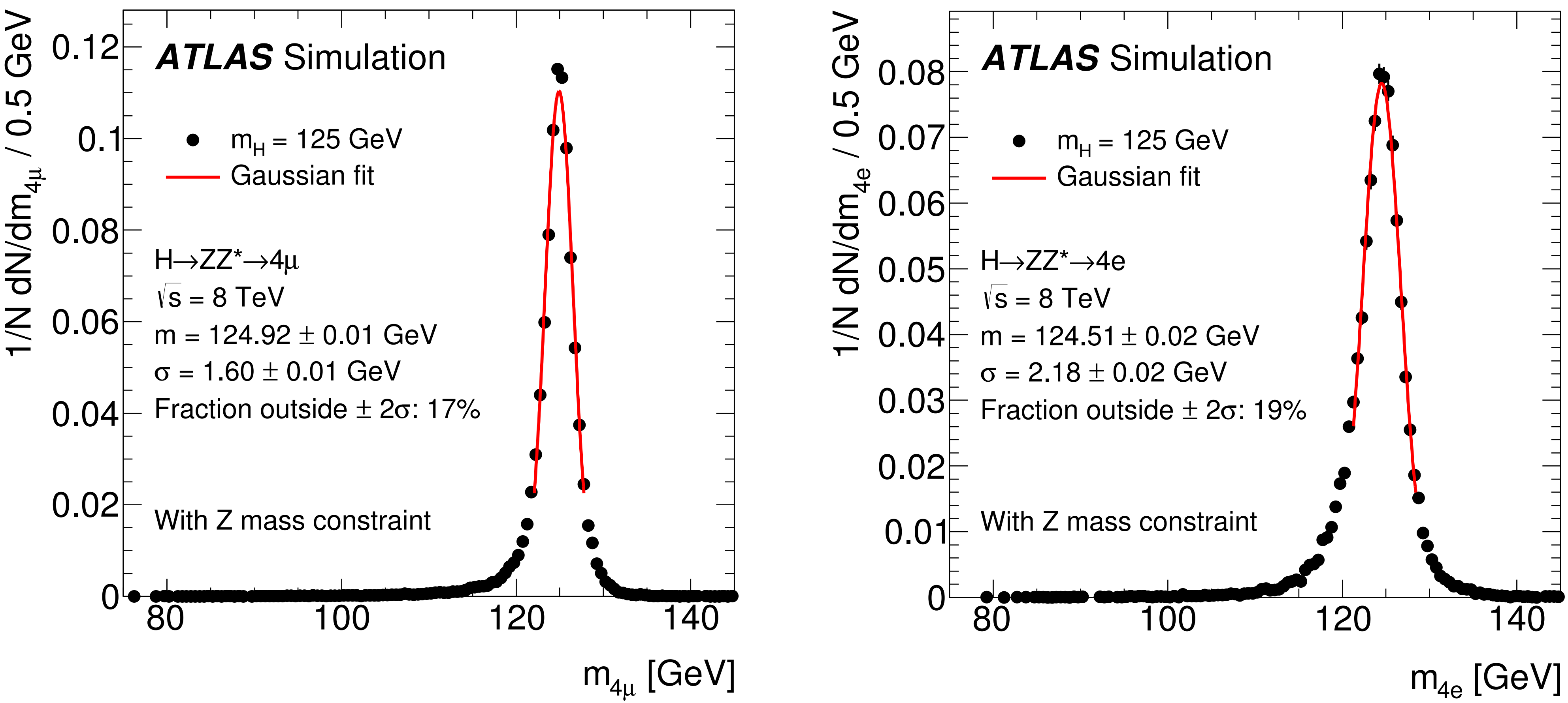
arXiv:1406.3827

Excellent mass resolution in the 4ℓ channel

Multivariate regression used for electron energy calibration

Gaussian Sum Filter for brehmstrahlung energy losses

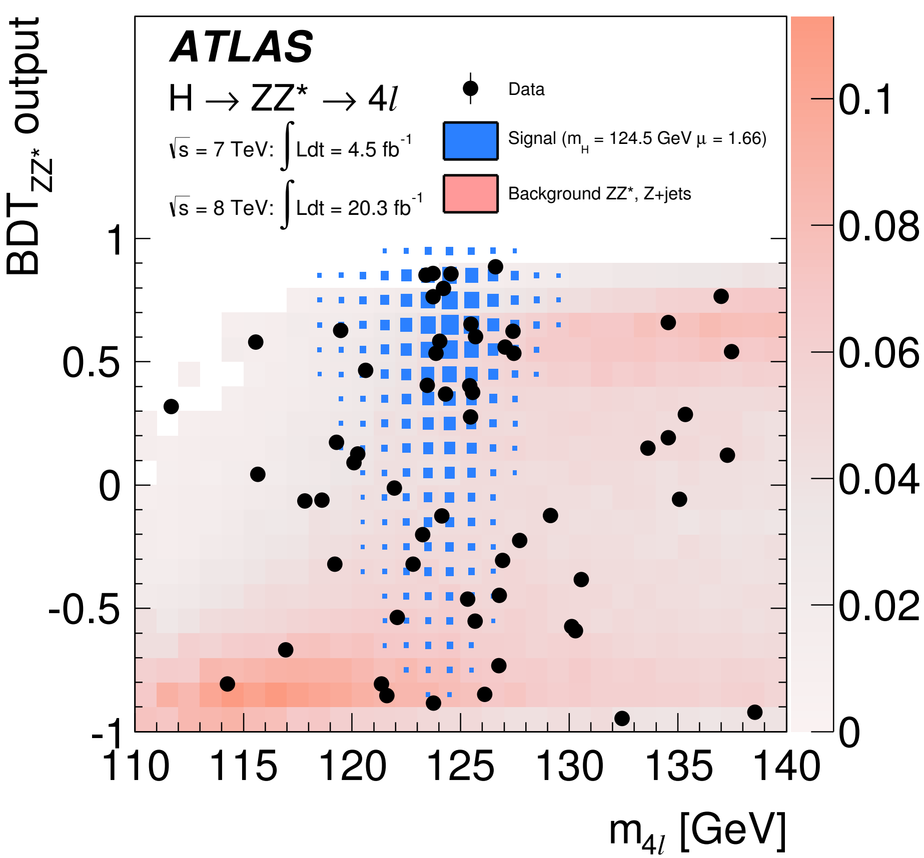
A kinematic fit is used for the lepton pair closest to the Z mass

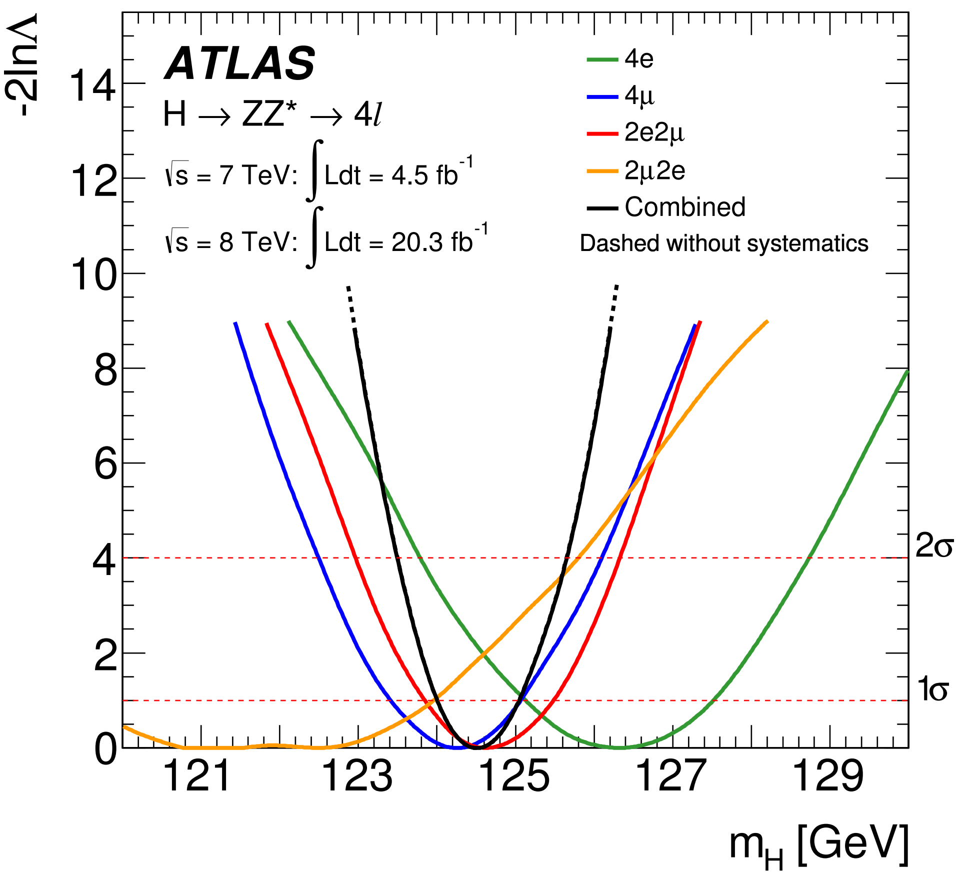


Baseline is a 2d mass fit (m4l x 4 BDT bins)

The BDT is used for ZZ separation, and includes a matrix-element (MELA) discriminant as input

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





Mass difference

arXiv:1406.3827

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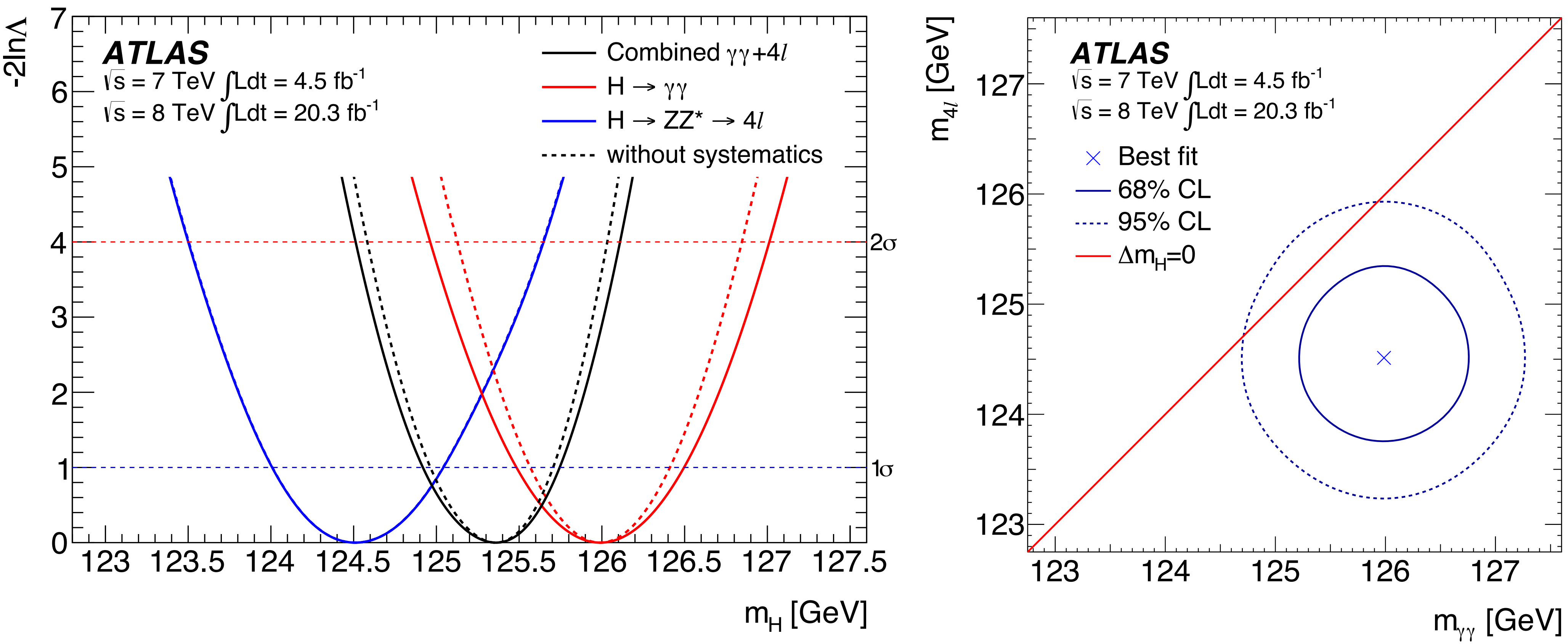
The combined mass measurement is

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

The discrepancy between the two measurements has reduced to ~2σ

$$\Delta m_H = 1.47 \pm 0.67\,(\text{stat}) \pm 0.28\,(\text{syst})\ \text{GeV}$$



Higgs Width at the LHC

The width of the Standard Model Higgs is 4.15 MeV << O(GeV) resolution

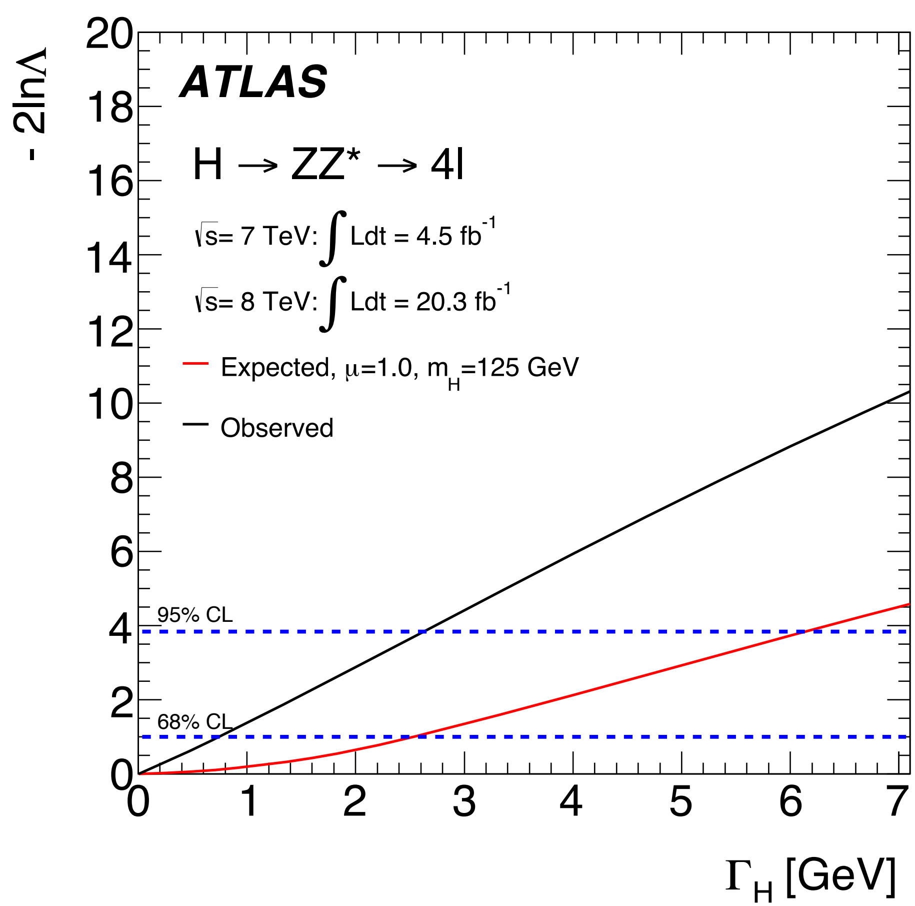
➡ ambiguity as Rate ∝ Br = Γ/Γ_{SM}

off-shell effects sensitive to width

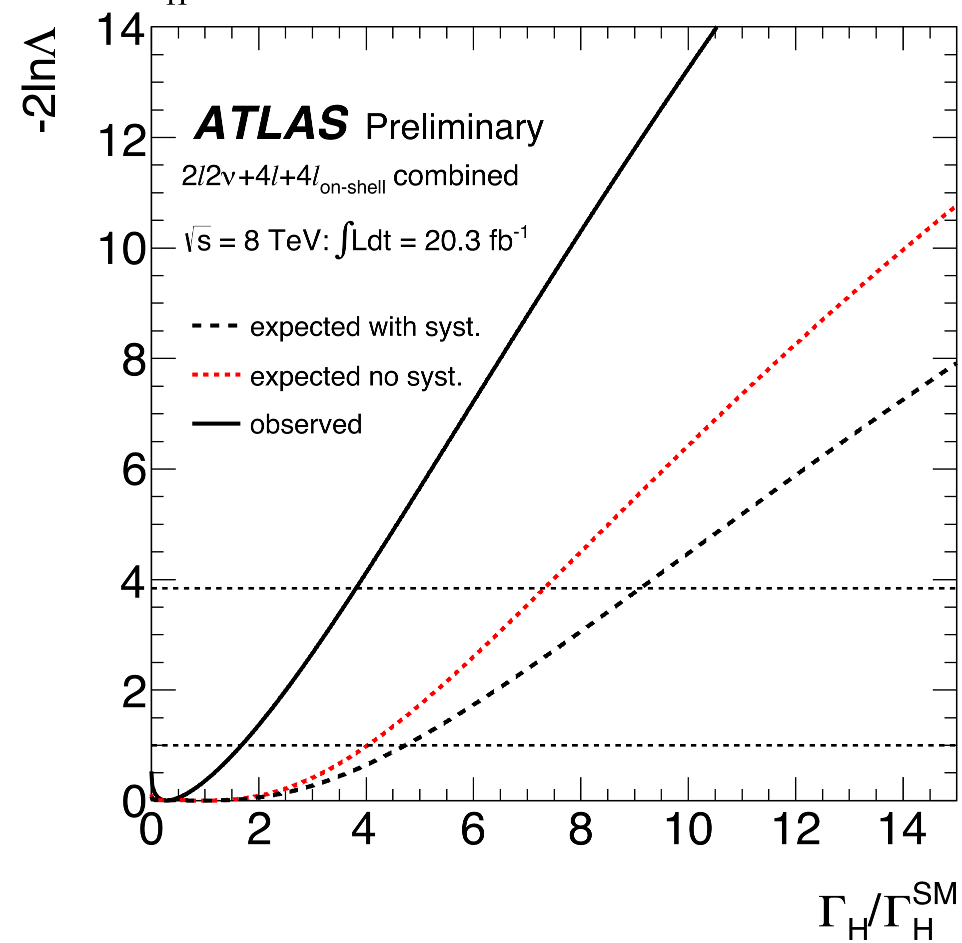
F. Caola and K. Melnikov, [arXiv:1307.4935]
See also: N. Kauer, G. Passarino, Campbell et al

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}.$$

$\Gamma_H < 2.6$ GeV at a 95%



$\Gamma_H \lesssim 24$ MeV (requires assumptions)



Higgs Width at the LHC

ATLAS-CONF-2014-042

Center for Cosmology and Particle Physics

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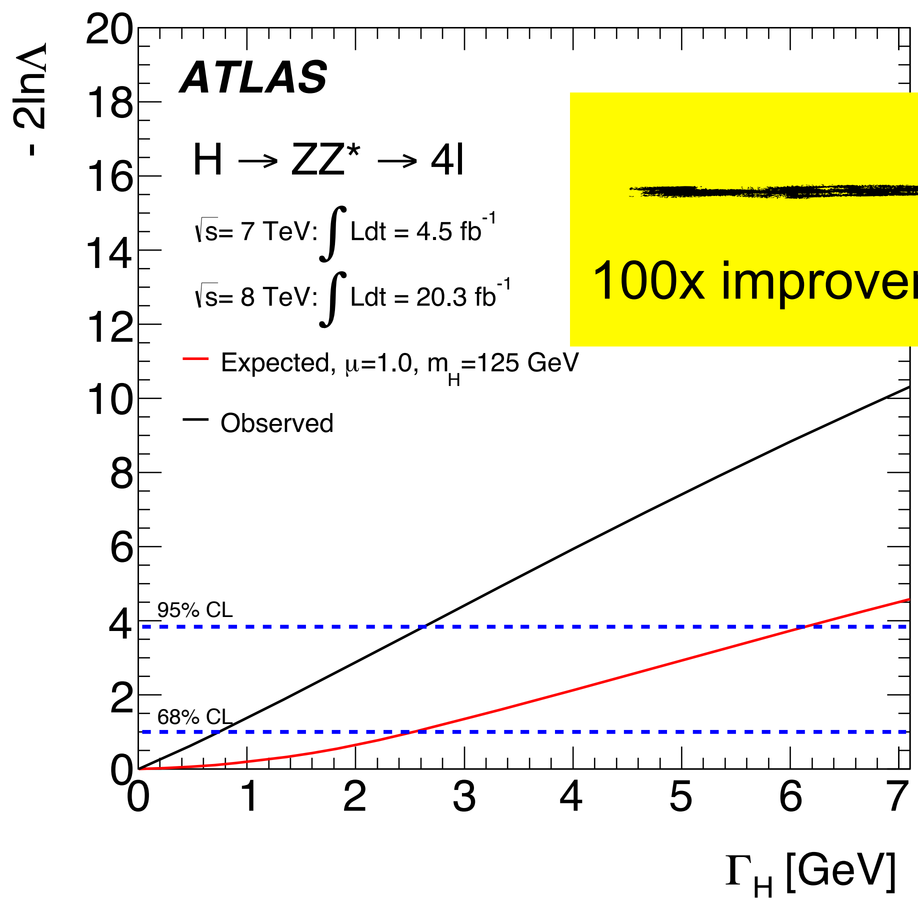
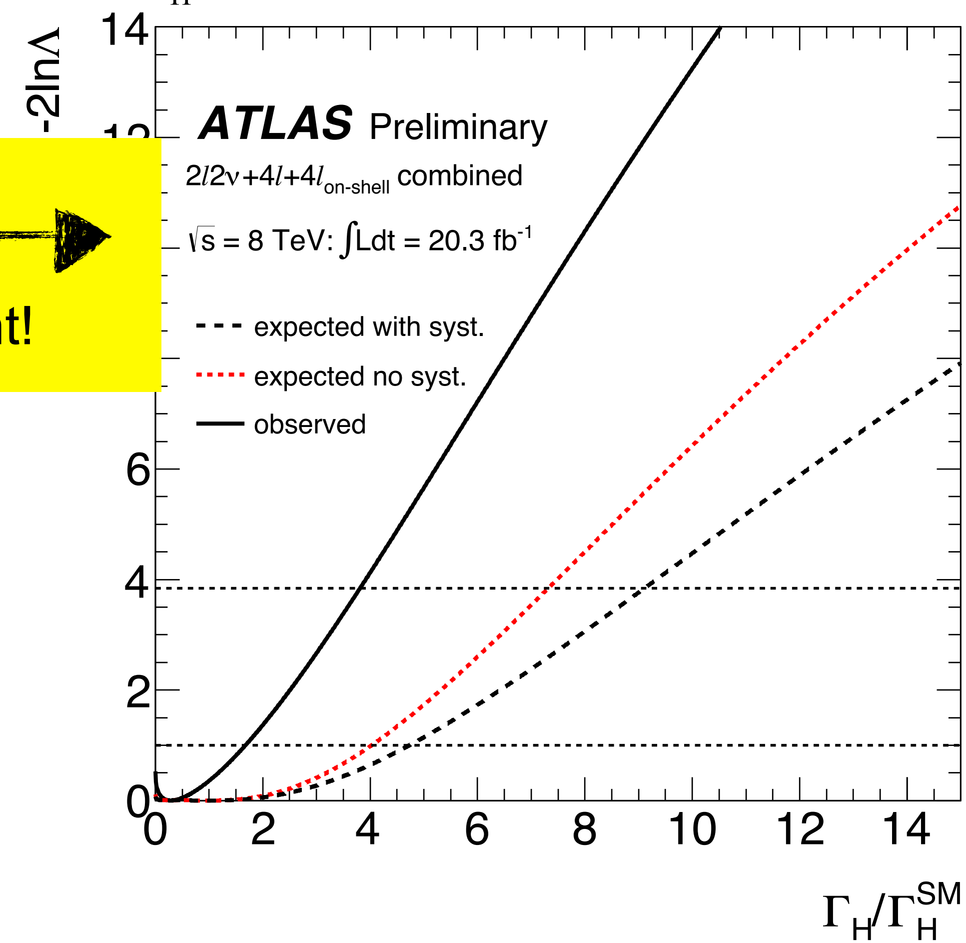


100x improvement!

$\Gamma_H \lesssim 24$ MeV (requires assumptions)



Spin & CP Properties

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Higgs' J^{PC}

Have we observed a scalar?

Spin $\leftrightarrows$ angular distribution of final decay products

- ☑ spin-1: forbidden by Landau-Yang's theorem (ie Bose symmetry)
- ☑ $gg \to X \to \gamma\gamma$ and $q\bar{q} \to X \to \gamma\gamma$ e.g., Gao et al '10
  - ❖ spin-0: flat in cos θ*
  - ❖ spin-2: quartic in cos θ*: $\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$
- ☑ $gg \to X \to ZZ^\star \to 4l$ Choi et al '02 De Rujula et al. '10
- ☑ $gg \to X \to WW^\star \to 2l2\nu$ Ellis, Hwang '12

Parity $\leftrightarrows$ angular distribution of final decay products

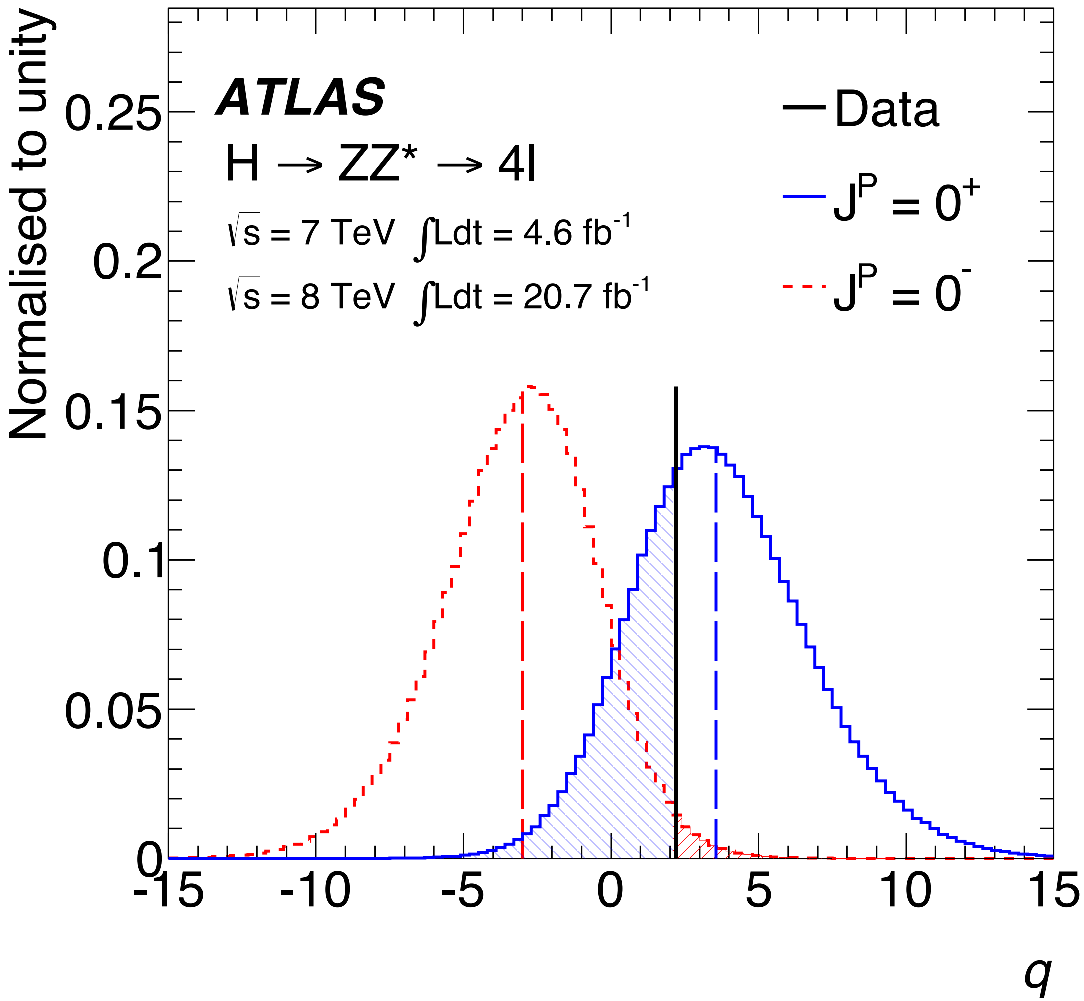
- ☑ CP-odd: couplings to W and W are loop-induced only! Hard to explain data.
- ☑ angular distribution of leptons in $gg \to X \to ZZ^\star \to 4l$
- ☑ angular distribution of jets produced in VBF Plehn et al '01
- ☑ spin correlations in $X \to \tau\tau$ Berge et al '08

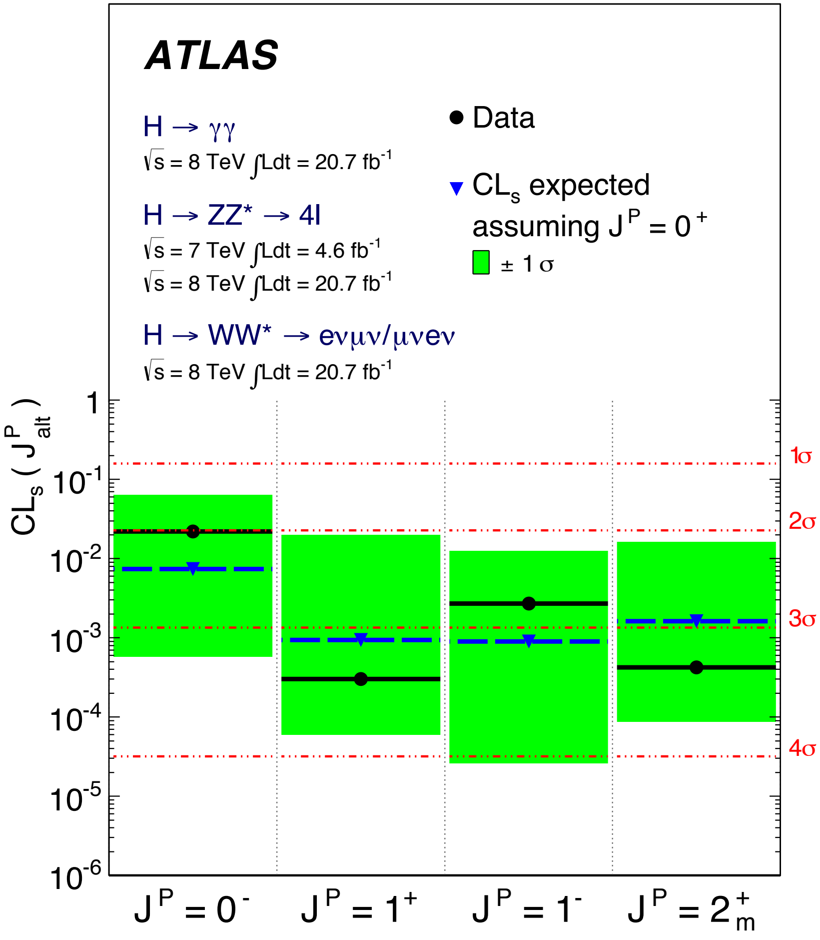
Can be solved at LHC_8 (may be), LHC_{14} (for sure)

too academic questions? Sensitivity to degree admixture of admixture even/odd?

Exactly 1 year after the discovery

Standard Model quantum numbers are favored, focus now on CP-violating admixtures





Cross-sections and Branching Ratios

(assuming 0^+ SM tensor structure)

Details

Channels are sub-divided to enhance sensitivity either for experimental reasons or take advantage of production features

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	4.6	[8]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\}$	4.8	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	4.6	[9]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	4.6	[10]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	4.6	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	4.6	[11]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}\}$	20.7	[8]
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH$\}$	20.7	[7]
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The signal strength

Many Higgs results presented in terms of a signal strength μ

$$\mu \neq \frac{\sigma}{\sigma_{SM}}$$

sloppy shorthand causes confusion

$$\mu \neq \frac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}}$$

Global signal strength is an awkward quantity, not very interesting

$$\mu \approx \frac{\sum_i \sigma_i \cdot BR \cdot \epsilon_i \cdot A_i}{\sum_i \sigma_{i,SM} \cdot BR_{SM} \cdot \epsilon_i \cdot A_i}$$

More interesting is signal strength for each production mode

$$\mu_i = \frac{\sigma_i}{\sigma_{i,SM}}$$

Disentangling multiple production modes

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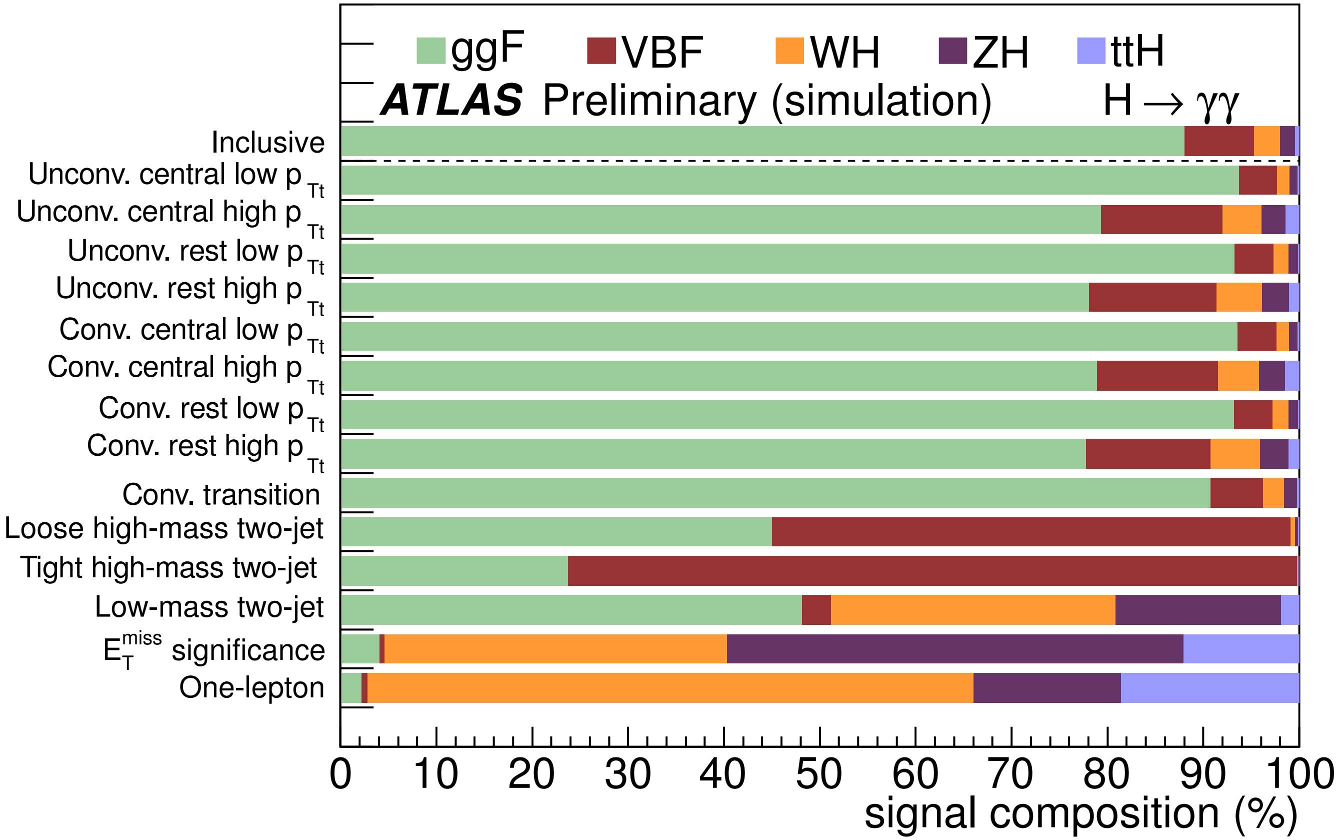
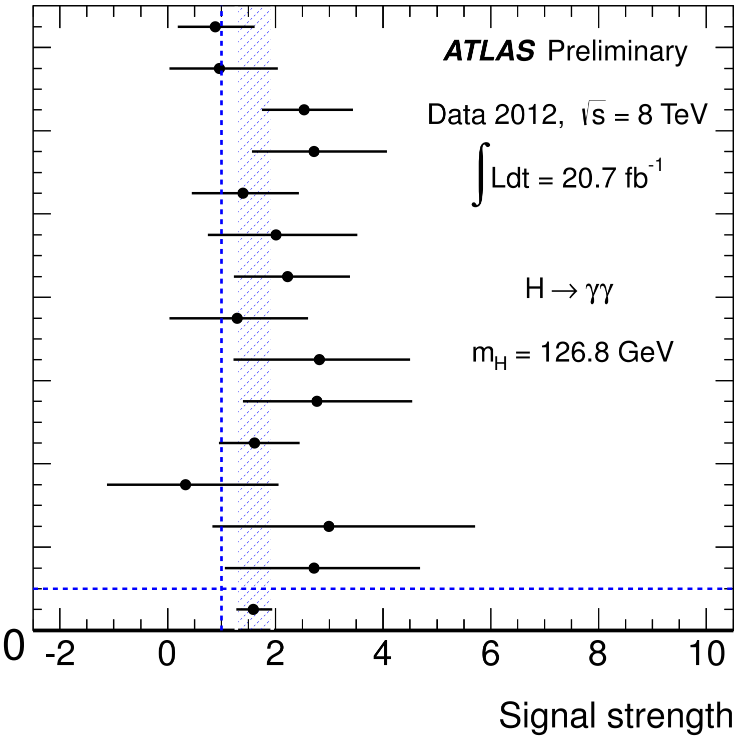
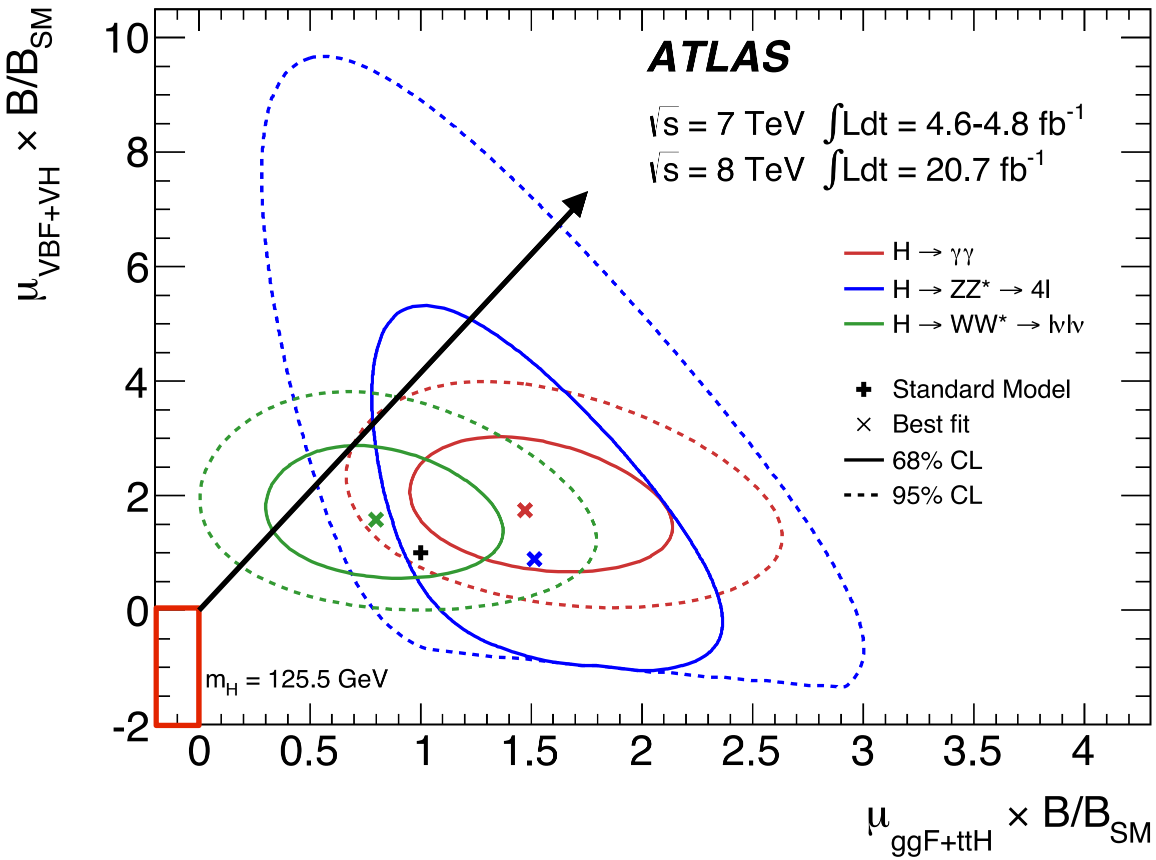




$$n^k_{\text{Signal}} = \left(\sum \mu_i \sigma_{i,SM} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \mathcal{B}_{f,SM} \times \mathcal{L}^k$$

- $\sigma_i = \mu_i \sigma_{i,SM}$ is the i^{th} hypothesized production cross section
- $\mathcal{B}_f = \mu_f \mathcal{B}_{f,SM}$ is the f^{th} hypothesized branching fraction
- Detector acceptance A^k_{if}, reconstruction efficiency ε^k_{if}, and integrated luminosity $\mathcal{L}^k$ are fixed by above assumptions

Model-independent presentation



Also 1 year after discovery

Phys. Lett. B 726 (2013)

Diboson decays only

Can't compare contours directly, b/c there is a different BR for axis

All coupling measurements pass through this σ_i x BR_j space

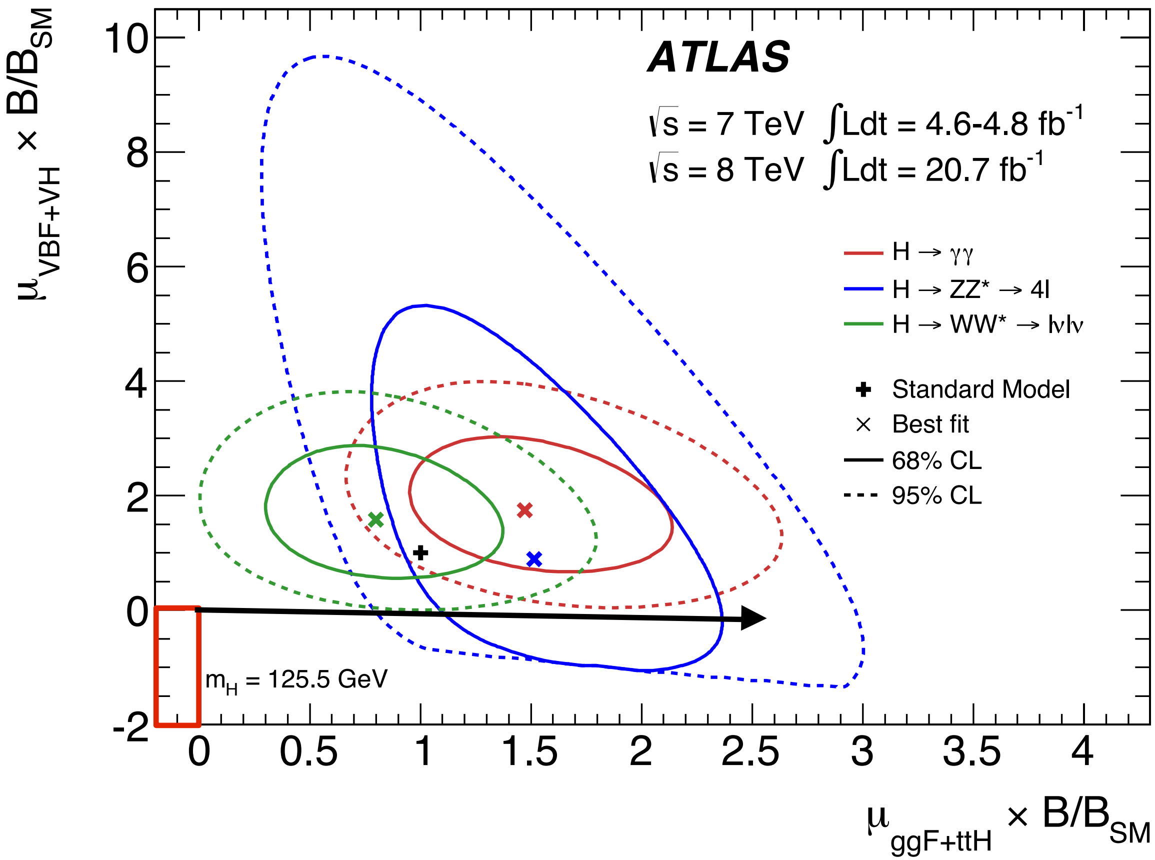
See also [arXiv:1401.0080] for new approach to decouple theory uncertainty from experimental results

Data from Figure 7 from: Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

ATLAS Collaboration (Aad, Georges (Freiburg U.) [...]) *Show all 2923 authors*

Cite as: ATLAS Collaboration (2013) HepData, http://doi.org/10.7484/INSPIREHEP.DATA.A78C.HK44

Model-independent presentation



Also 1 year after discovery

Phys. Lett. B 726 (2013)

Diboson decays only

Can't compare contours directly, b/c there is a different BR for axis

All coupling measurements pass through this σ_i x BR_j space

Information | Citations (4) | Files

See also [arXiv:1401.0080] for new approach to decouple theory uncertainty from experimental results

Data from Figure 7 from: Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

ATLAS Collaboration (Aad, Georges (Freiburg U.) [...]) *Show all 2923 authors*

Cite as: ATLAS Collaboration (2013) HepData, http://doi.org/10.7484/INSPIREHEP.DATA.A78C.HK44

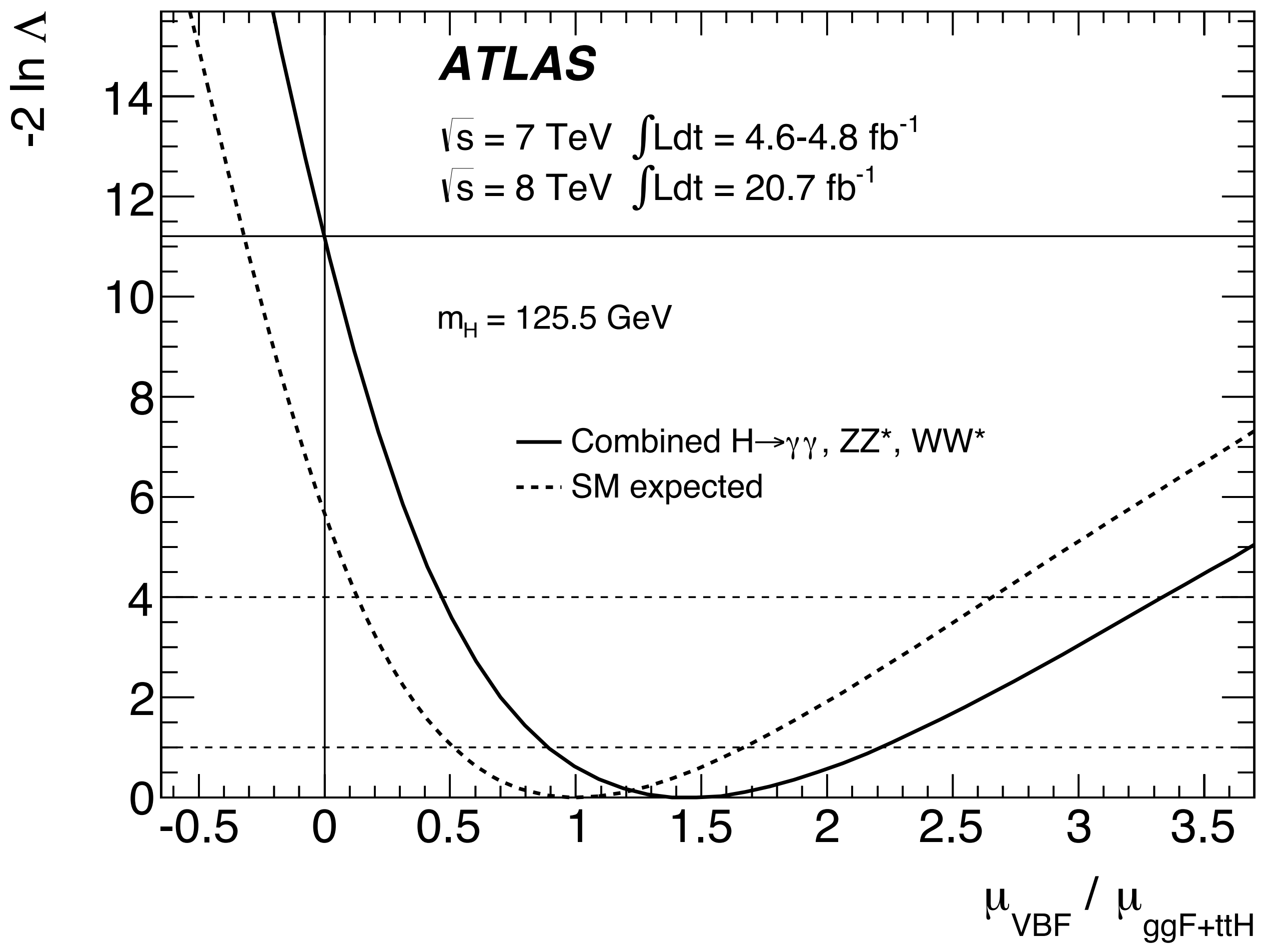
Model-independent presentation

Center for Cosmology and Particle Physics

Can't compare contours directly, b/c there is a different BR for axis

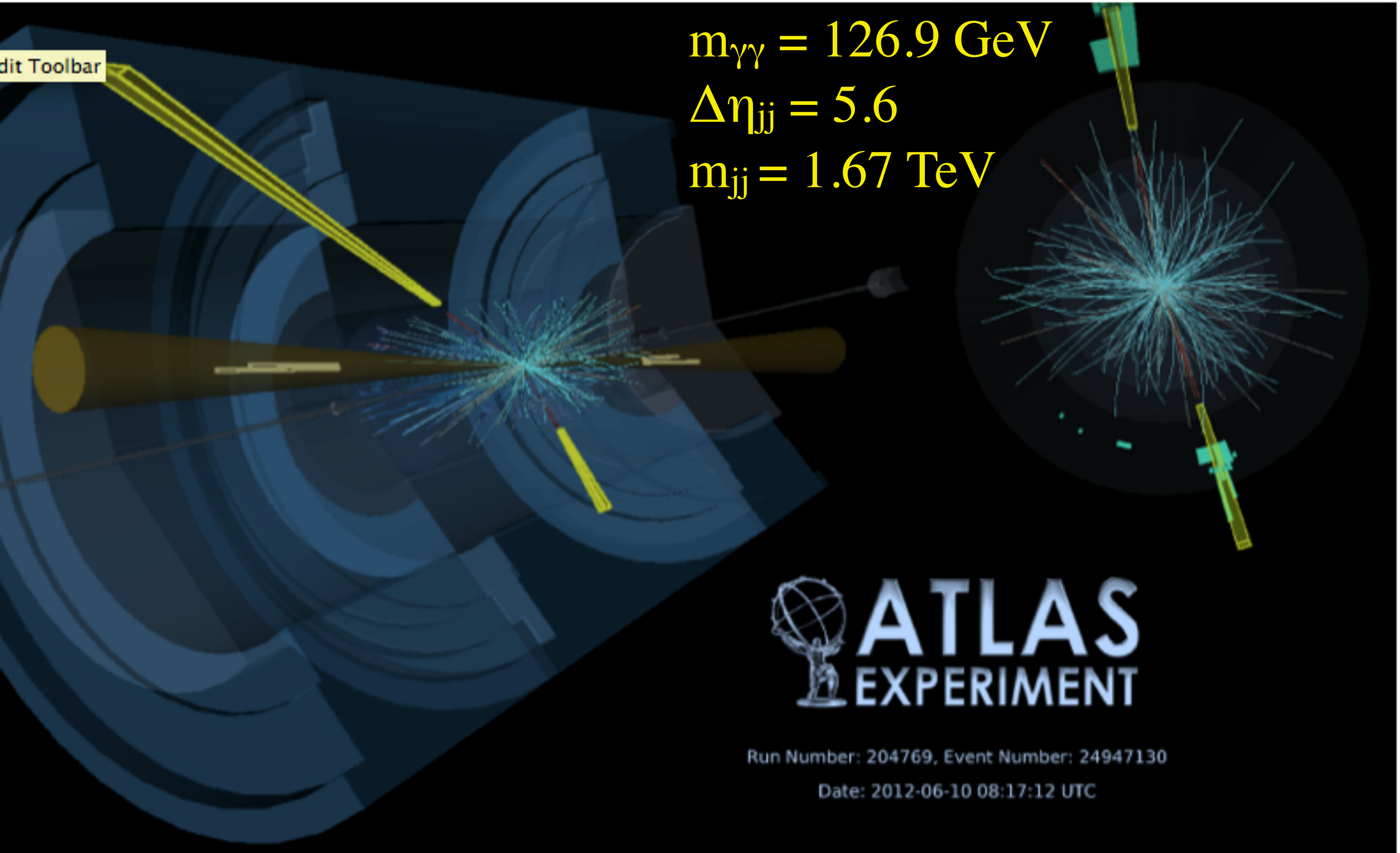
But, BR cancels when considering slope in this plane

- mild sensitivity to theory uncertainties (jet veto, ggH+2jet contamination,...)



>3σ evidence for VBF Higgs production!

VBF 2-photon candidate



VBF H→ 4l candidate

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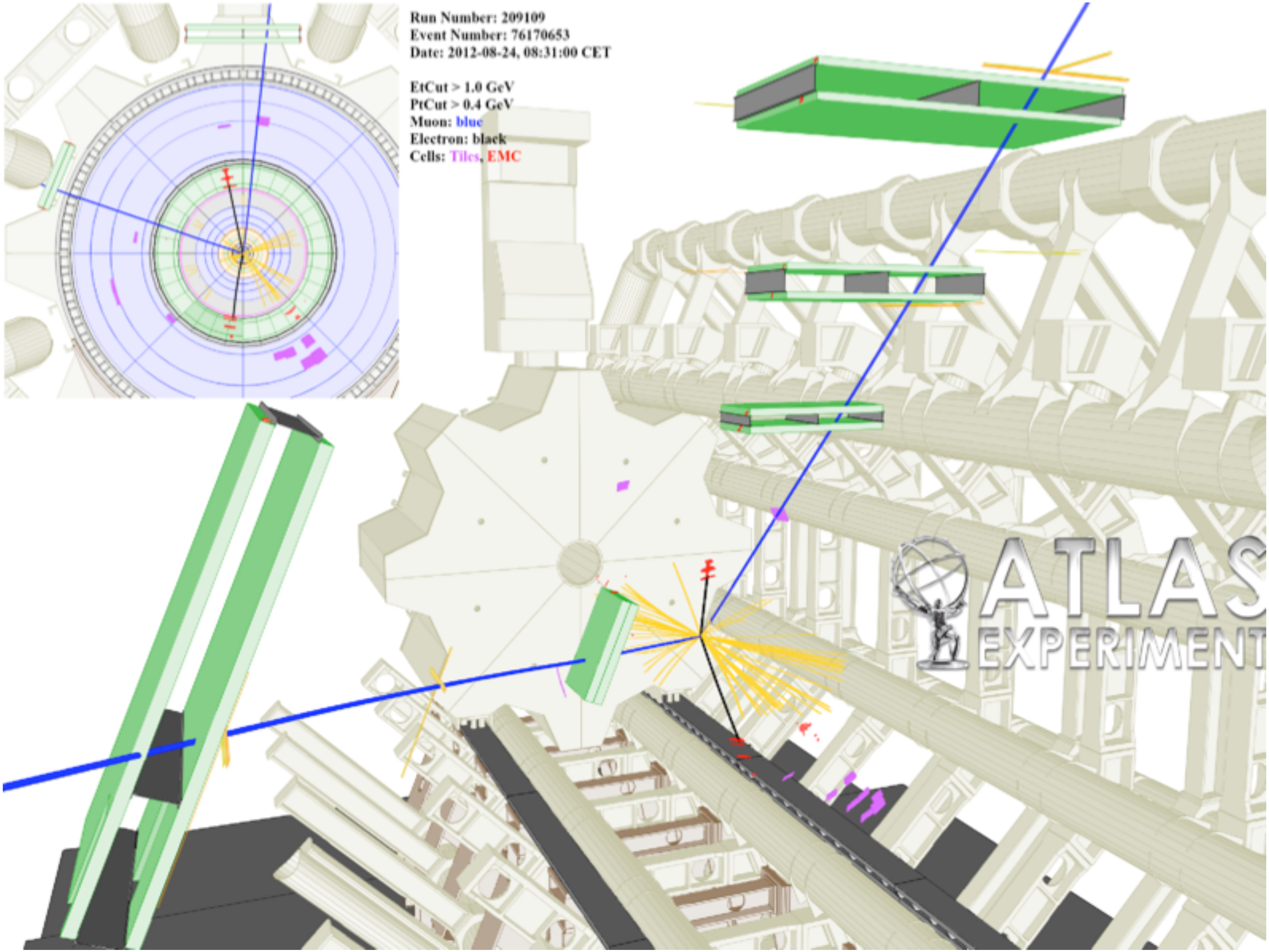

Ratio of Branching Ratios

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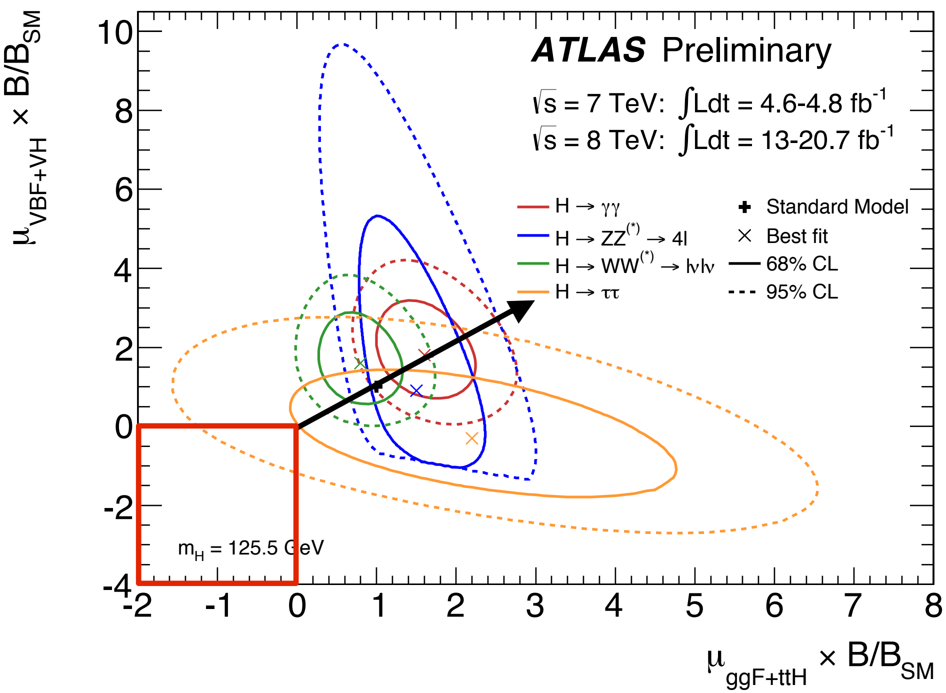
A model independent approach less sensitive to theory uncertainties

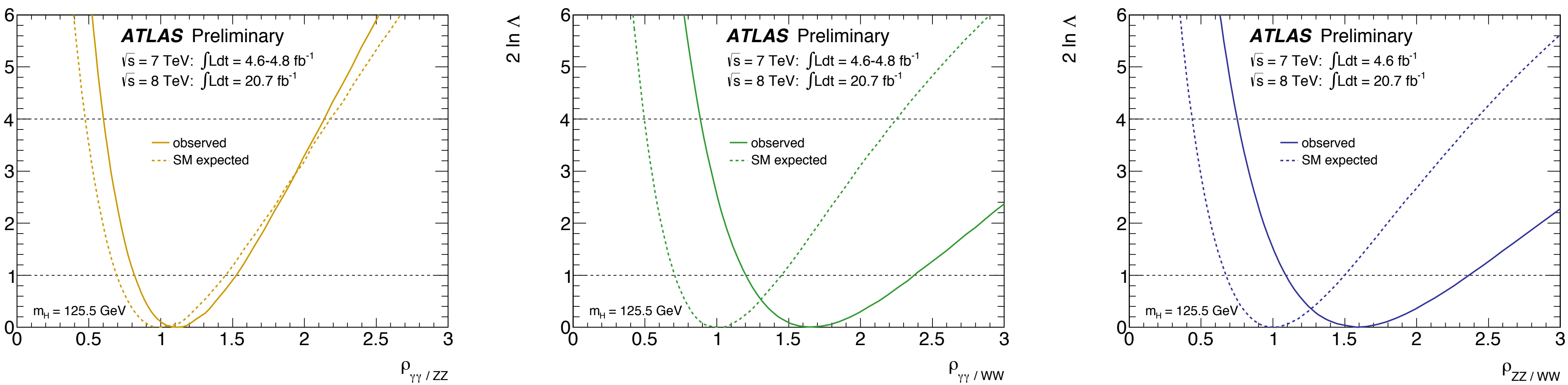


$$\rho_{\gamma\gamma/ZZ} = \frac{\mathrm{BR}(H\rightarrow\gamma\gamma)}{\mathrm{BR}(H\rightarrow ZZ^{(*)})} \times \frac{\mathrm{BR_{SM}}(H\rightarrow ZZ^{(*)})}{\mathrm{BR_{SM}}(H\rightarrow\gamma\gamma)}$$

$$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3}$$

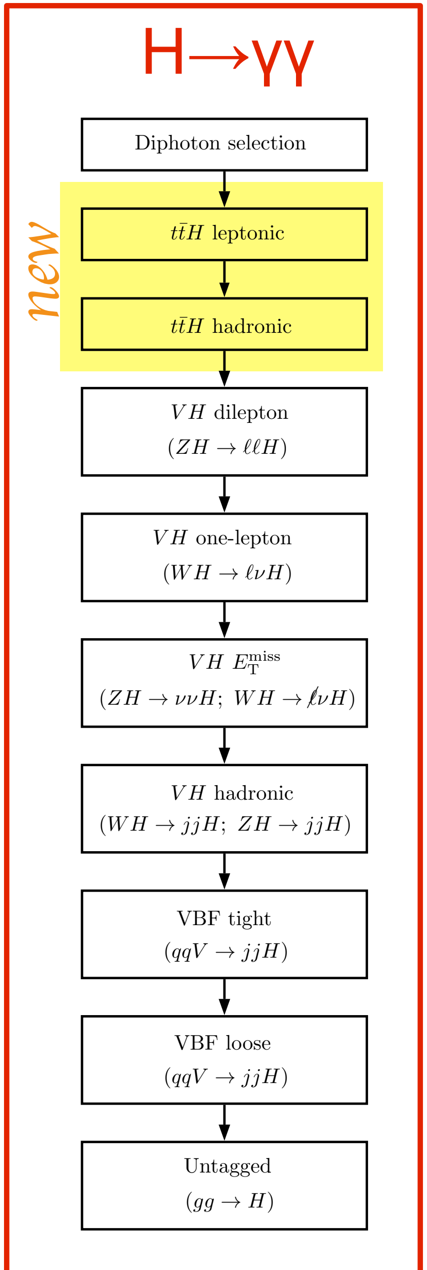
$$\rho_{\gamma\gamma/WW} = 1.7^{+0.7}_{-0.5}$$

$$\rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$$

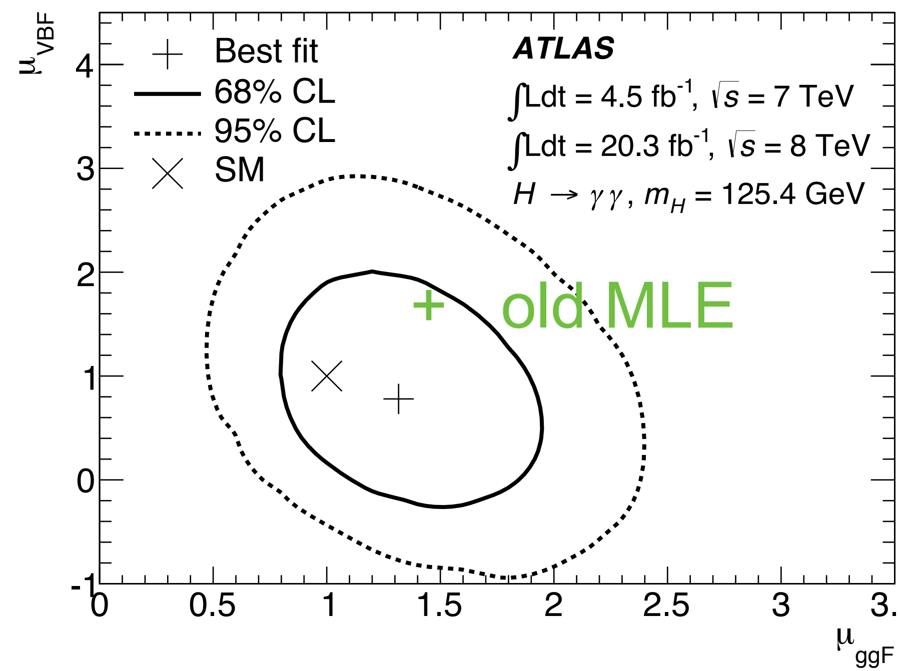


Updated $H\to\gamma\gamma$

arXiv:1408.7084

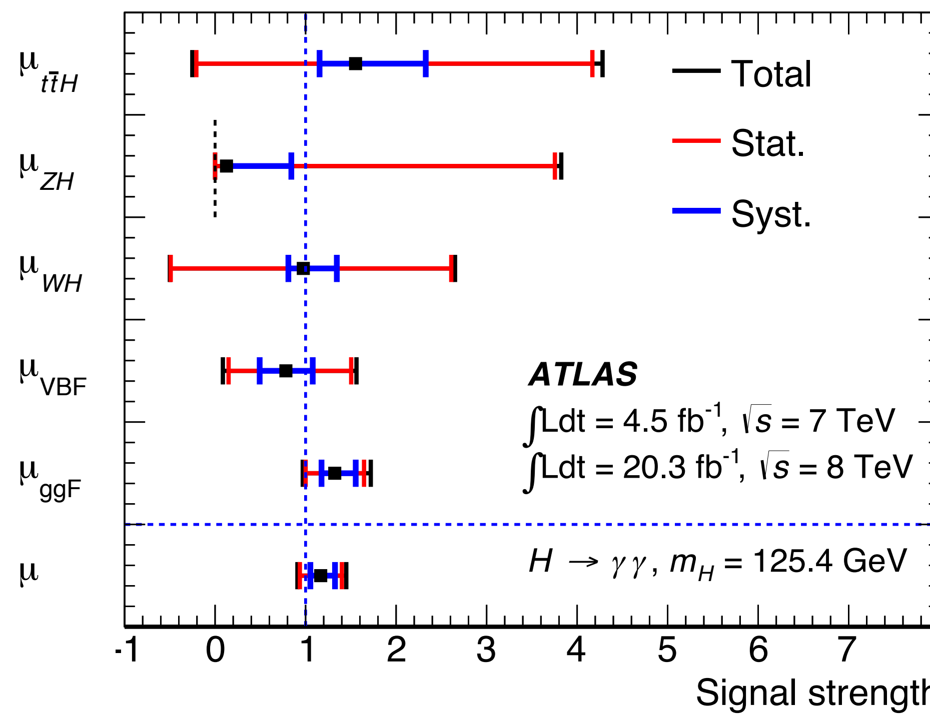


New categories, improved calibration
Overall signal strength came down from 1.5 ± 0.3 to μ = 1.17 ± 0.27



Here we see the results on the signal strength for each production mode.

Based on the 5-D version of top plot.



Updated $H \to ZZ \to 4\ell$

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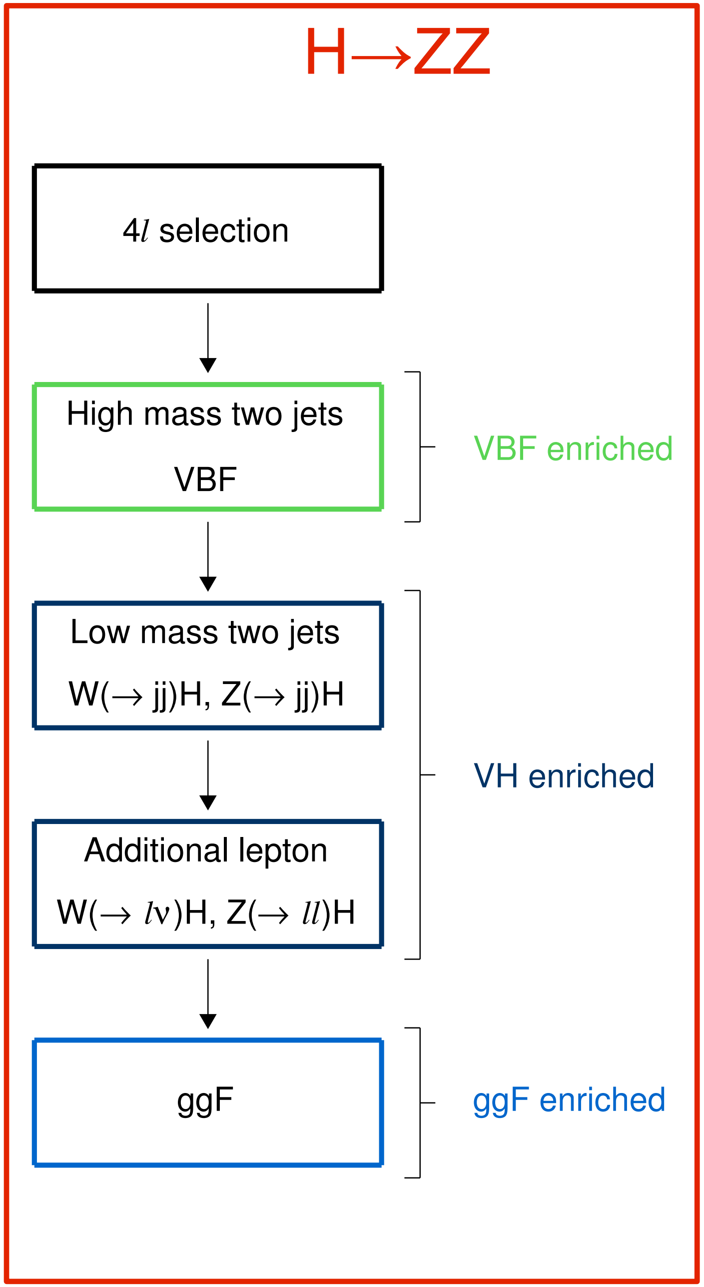
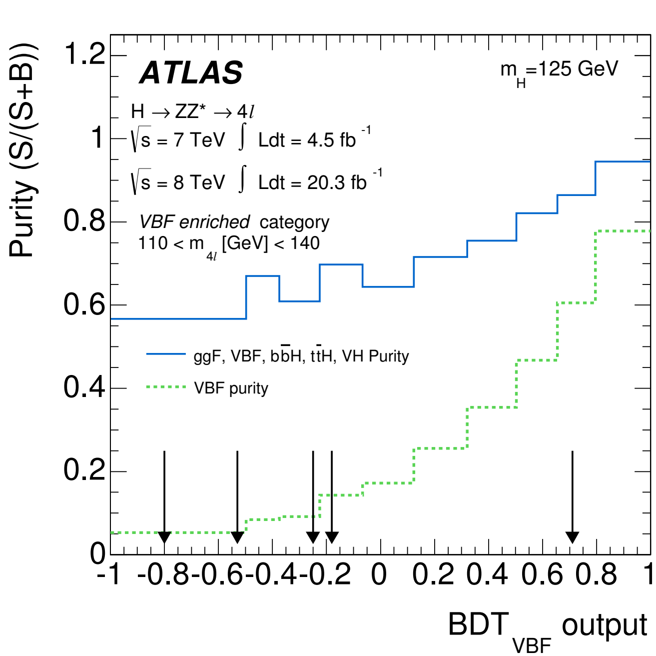
arXiv:1408.5191

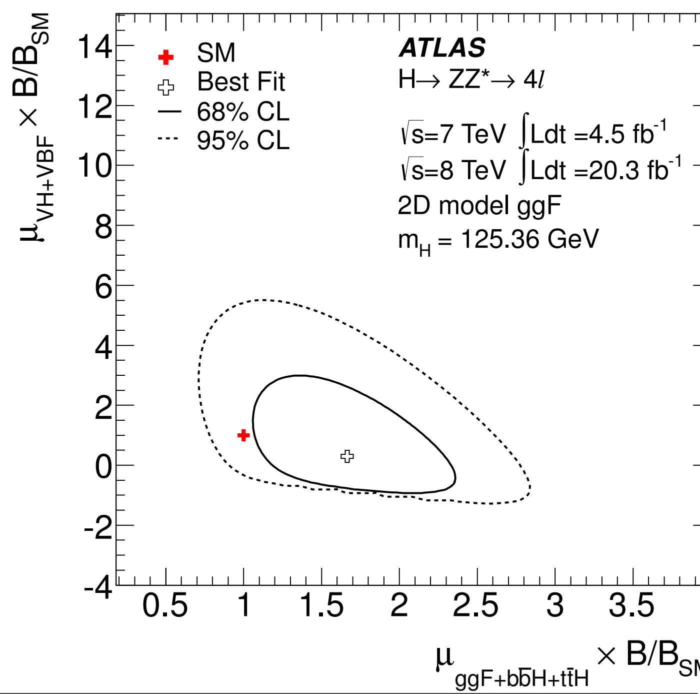


New BDT-based VBF enriched categories

Added VH hadronic, and VH leptonic categories

	ggF	VBF	VH	BKG	Obs
ggF-tag	13	0.6	0.3	10	34
VBF-tag	1.6	1.4	0.1	0.6	4
VH-tag	0.4	0.03	0.2	0.4	0

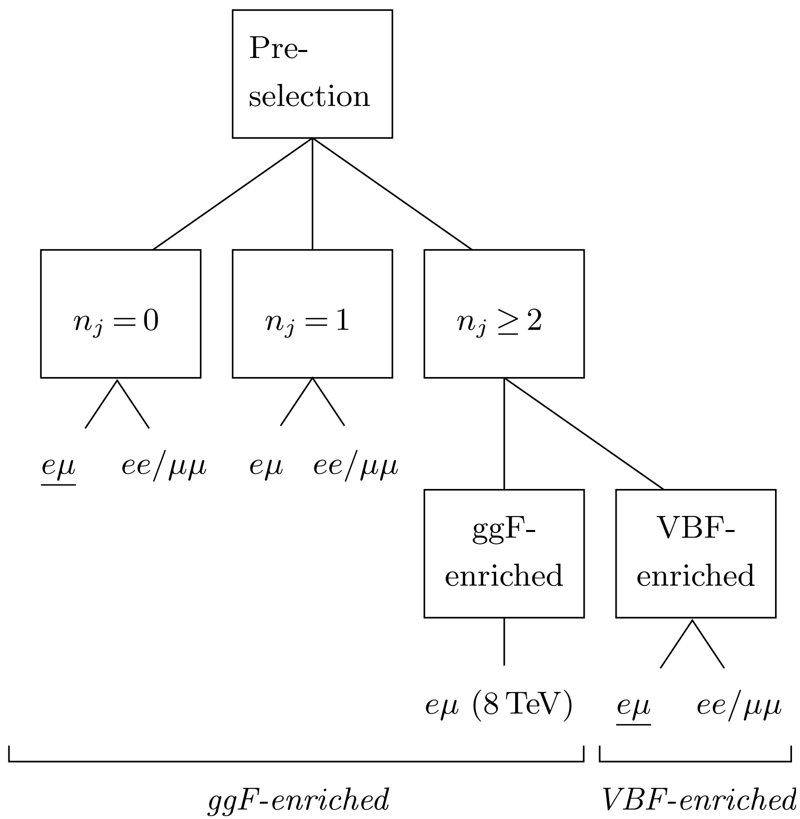




Updated $H \to WW \to \ell\nu\ell\nu$

ATLAS-CONF-2014-060

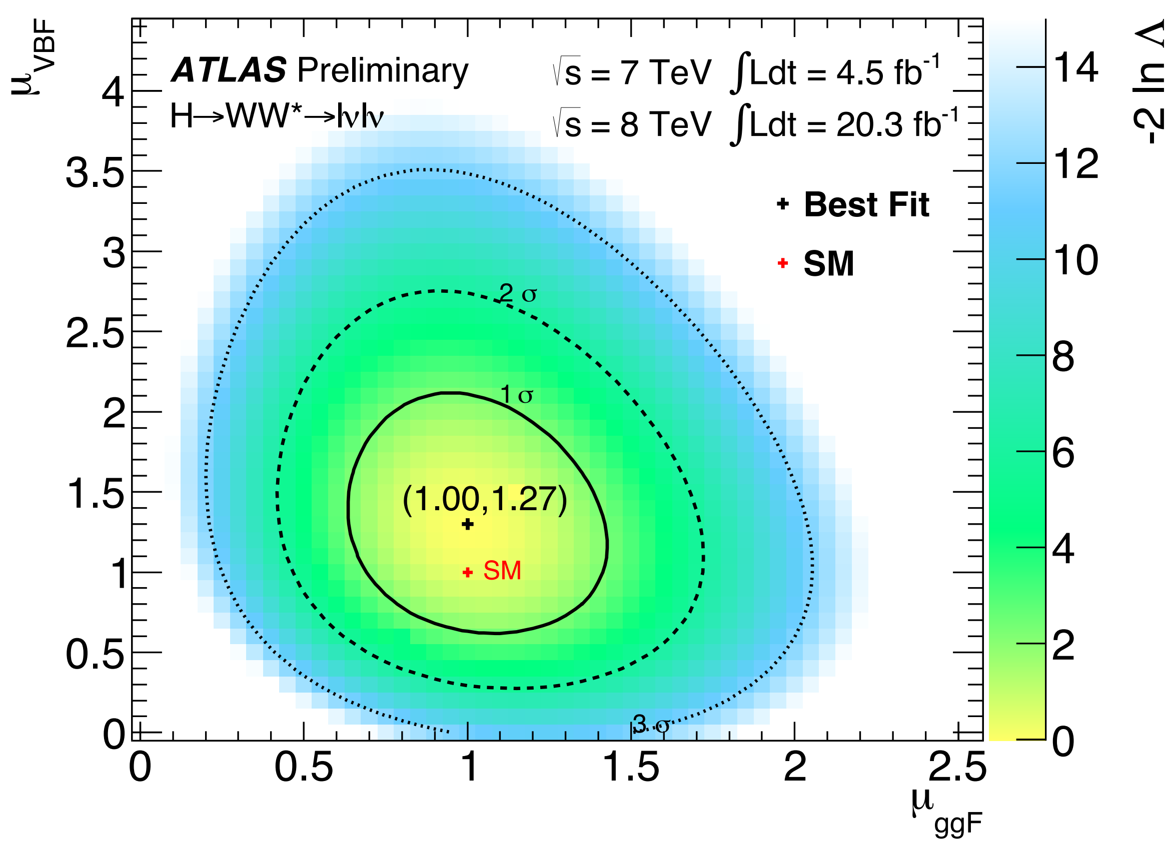
H→WW



Improvements in signal acceptance, background determination and rejection, and the signal yield extraction.

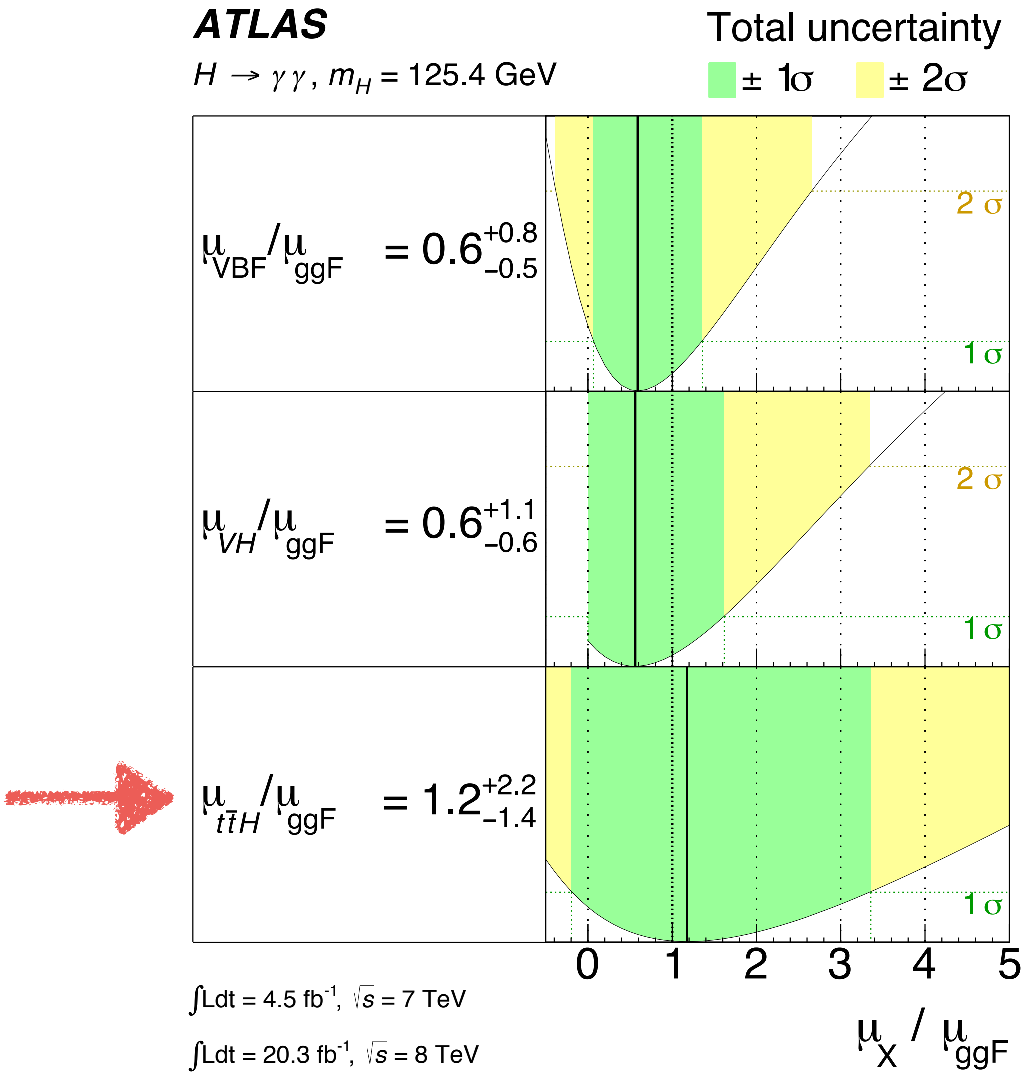
Increase the expected significance from 3.7 to 5.8σ and they reduce expected uncertainty on μ by 30%.

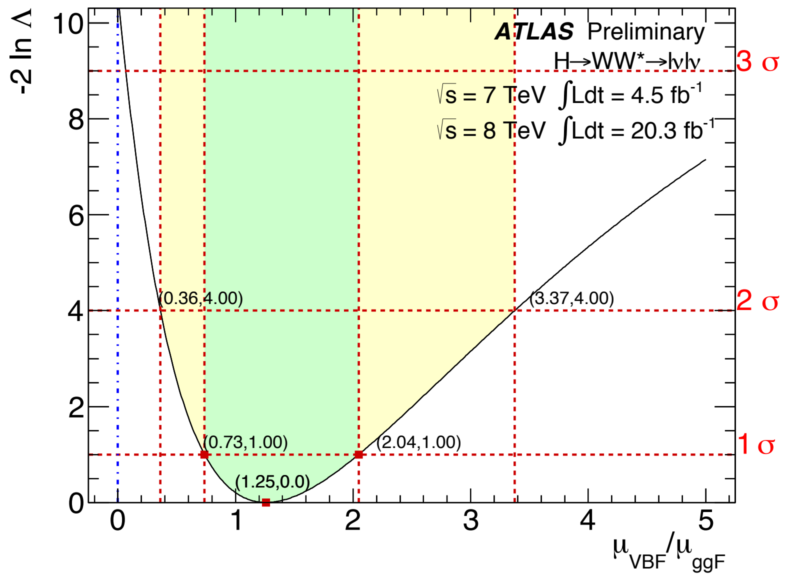
Enormous effort, beautiful plot

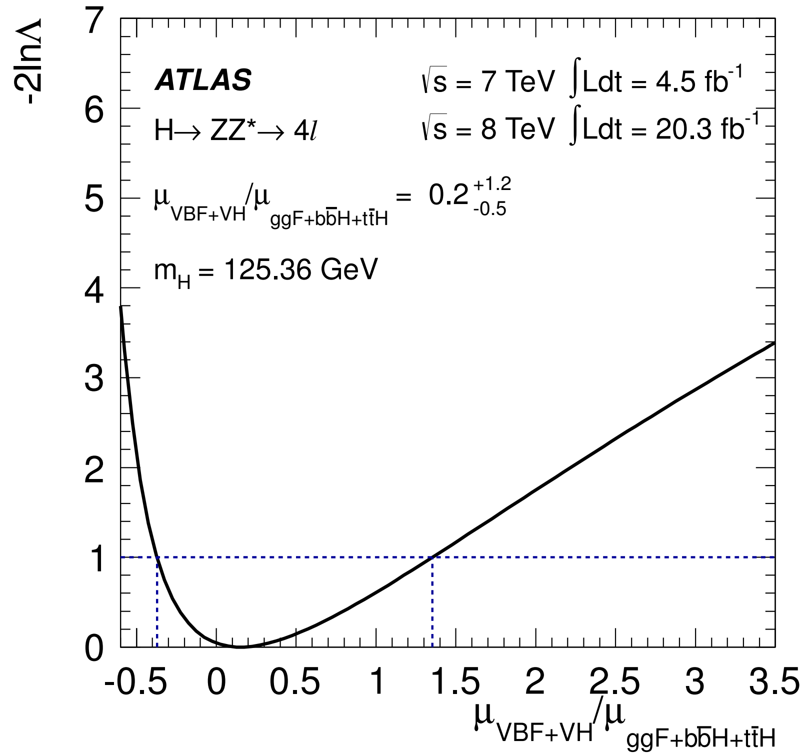


Summer 2014: Production Updates

Updated results in diboson decays using similar approach to test for VBF, VH, and ttH production modes







Couplings

Narrow width approximation

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The basic starting point for the various parametrizations :

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma}$$

No useful direct constraint on total width at LHC (but getting close)

- ideally, allow for invisible or undetected partial widths
- leads to an ambiguity unless something breaks degeneracy

Various strategies / assumptions break this degeneracy

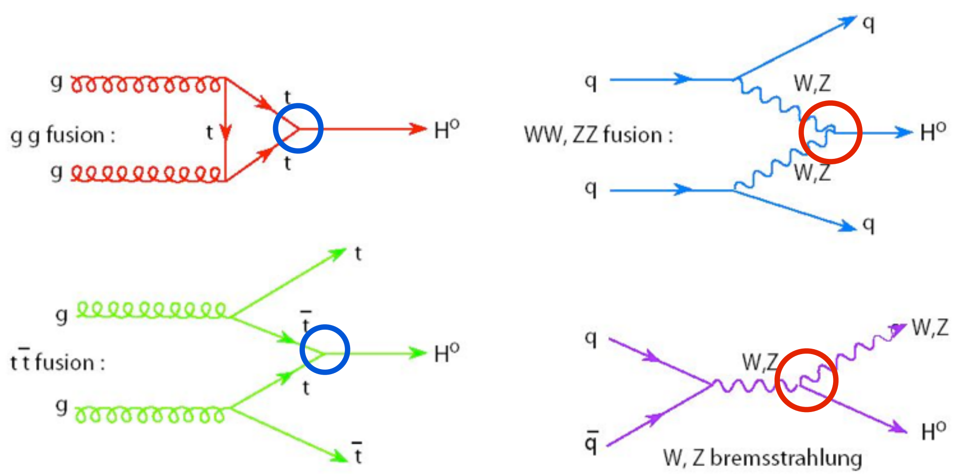
- Assume no invisible decays
- Fix some coupling to SM rate
- Only measure ratios of couplings
- Limit $\Gamma_V \leq \Gamma_V^{\mathrm{SM}}$ eg. Dührssen et. al, Peskin, ...
  - valid for CP-conserving H, no H^{++}, ... Gunion, Haber, Wudka (1991)
  - together with $\Gamma_V^2/\Gamma = \mathrm{meas} \quad \Rightarrow \quad \Gamma_{\mathrm{vis}} \leq \Gamma \leq \Gamma_{V,SM}^2/\mathrm{meas}$

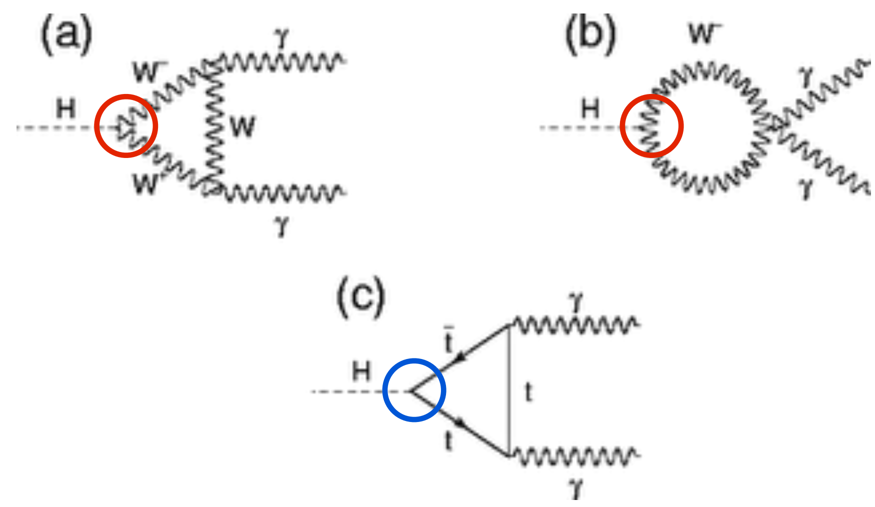
Parametrizing the couplings

Approach: scale couplings w.r.t. SM values by factor κ or ratio λ

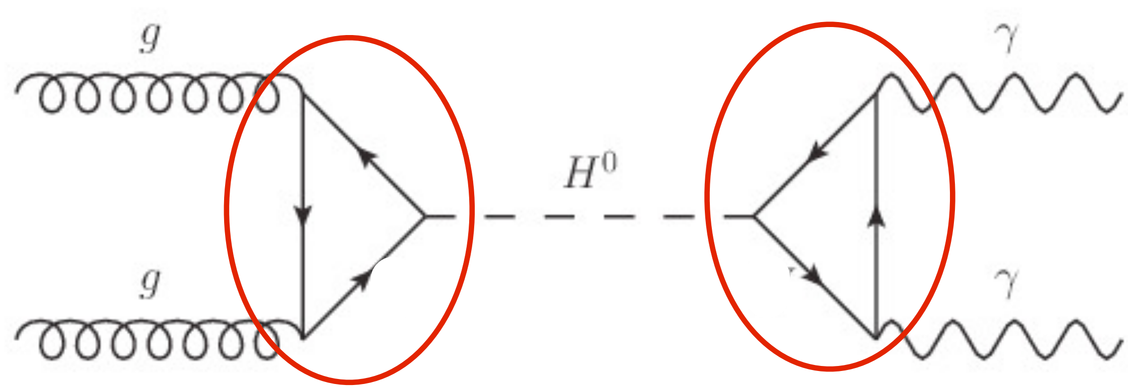
- Expansion around SM point with state-of-the-art predictions

Option 1) relate ggH and $\gamma\gamma$H assuming no new particles in loop





Option 2) introduce κ_g and κ_γ as effective coupling to ggH and $\gamma\gamma$H



Benchmark models

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Fully model independent fit is not very informative with current data

- Benchmarks proposed by joint theory/experiment LHC XS group arXiv:1209.0040

Probe Fermionic vs. Bosonic couplings:

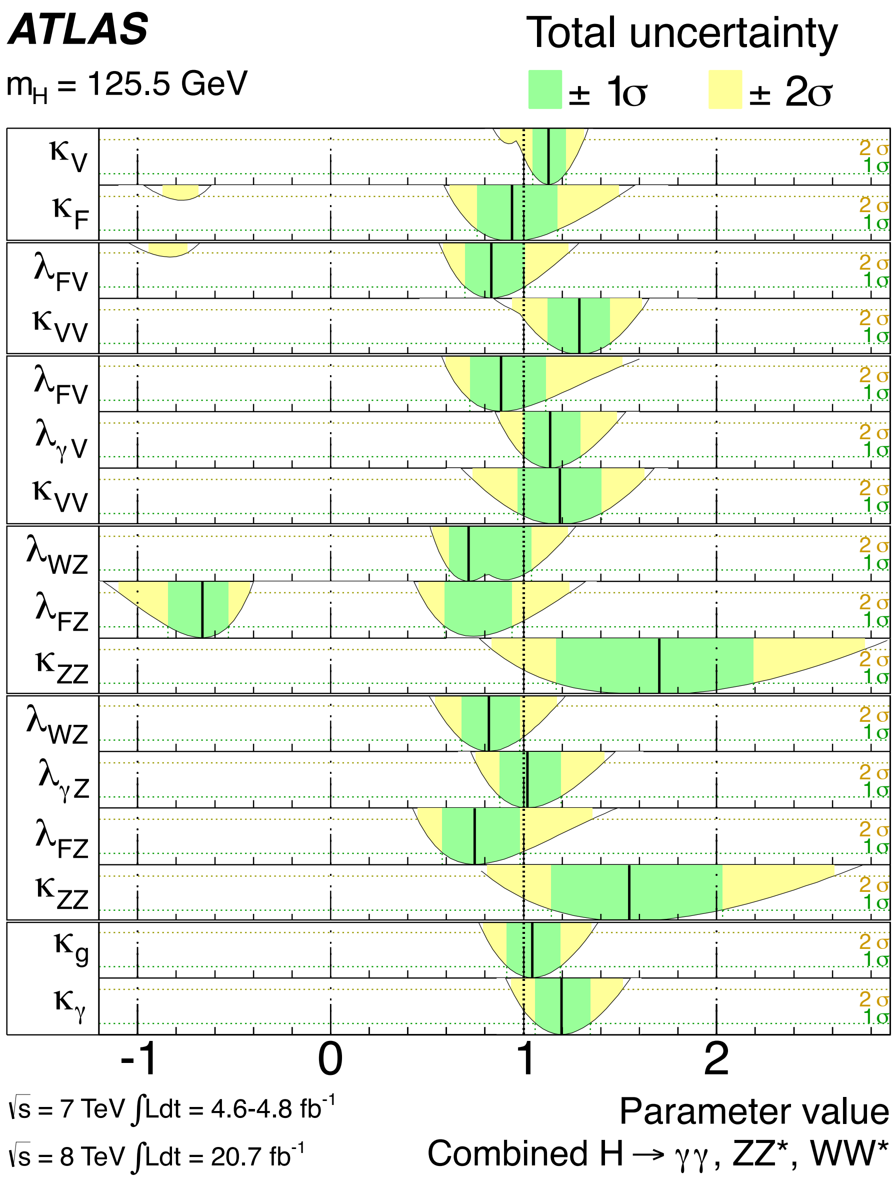
Probe W vs. Z couplings (custodial symmetry)

Probe up. vs. down fermion couplings

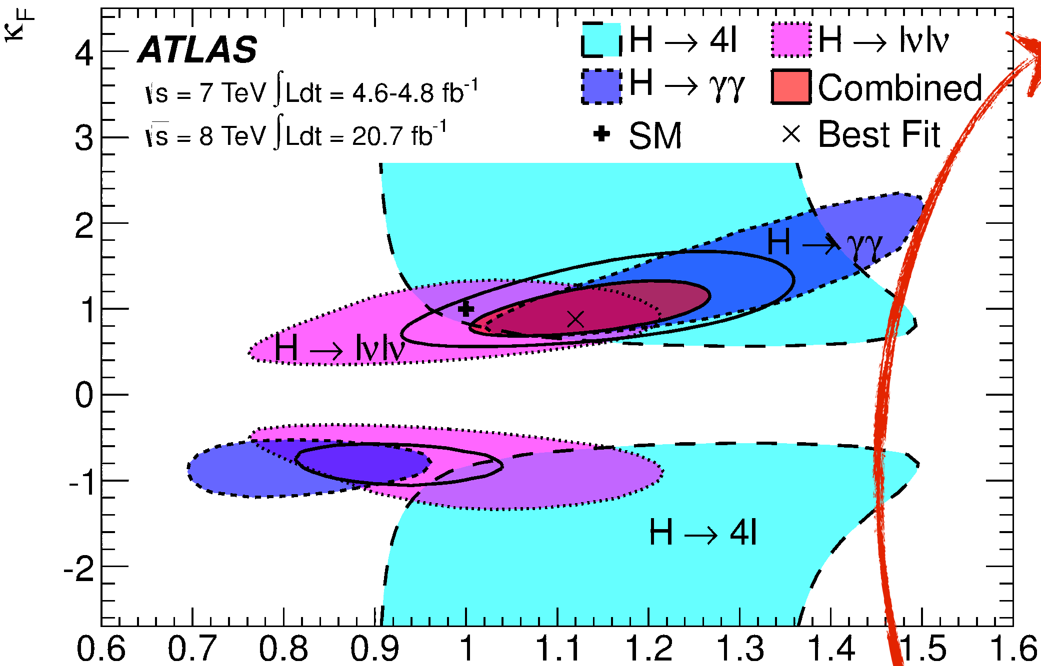
Probe quark vs. lepton couplings

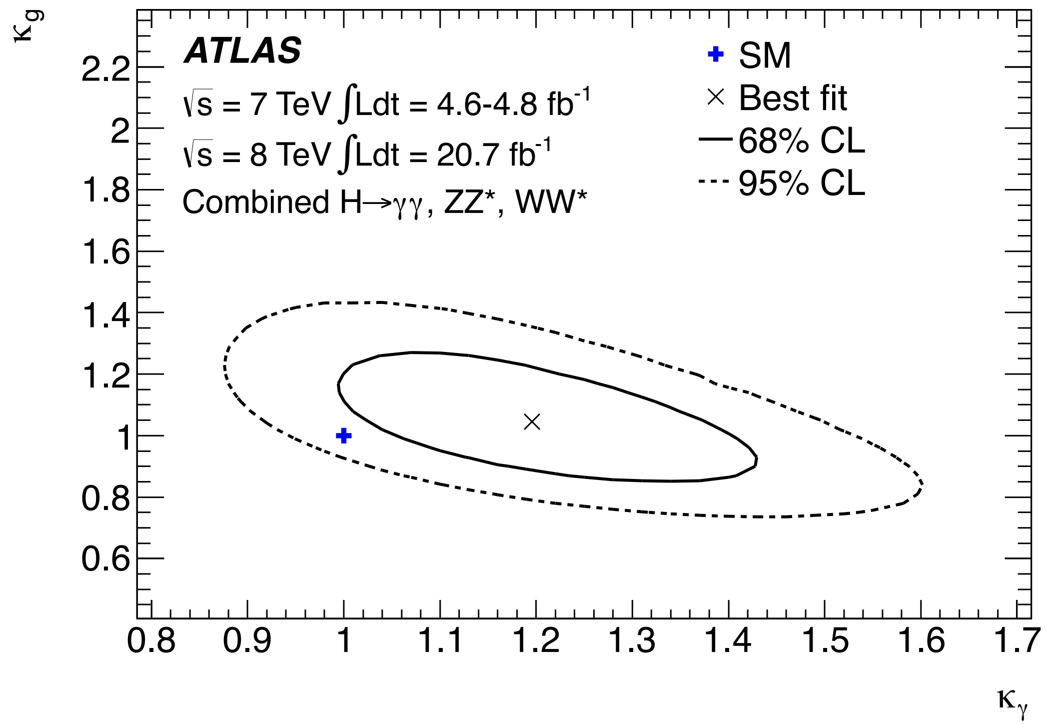
Probe new particles in ggH and γγH loops

Probe invisible decays



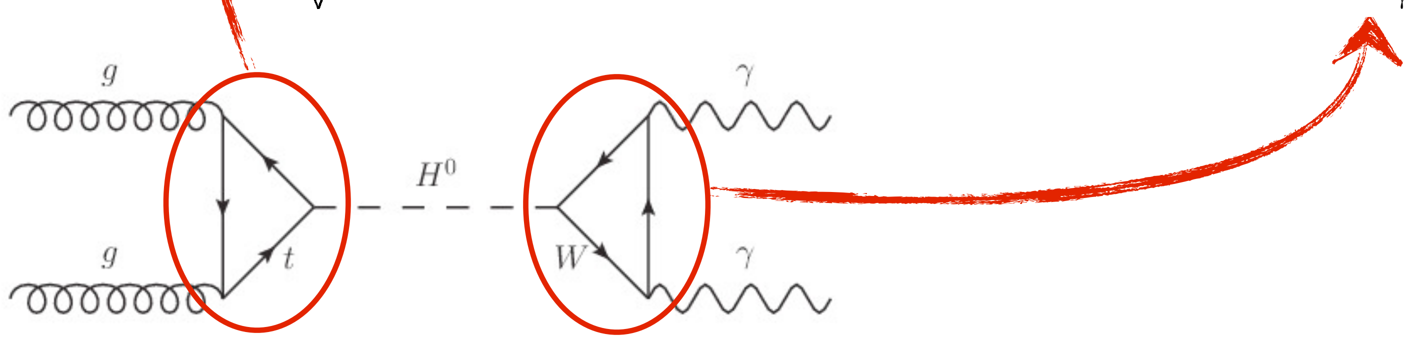
Here, evidence for fermion couplings is indirect



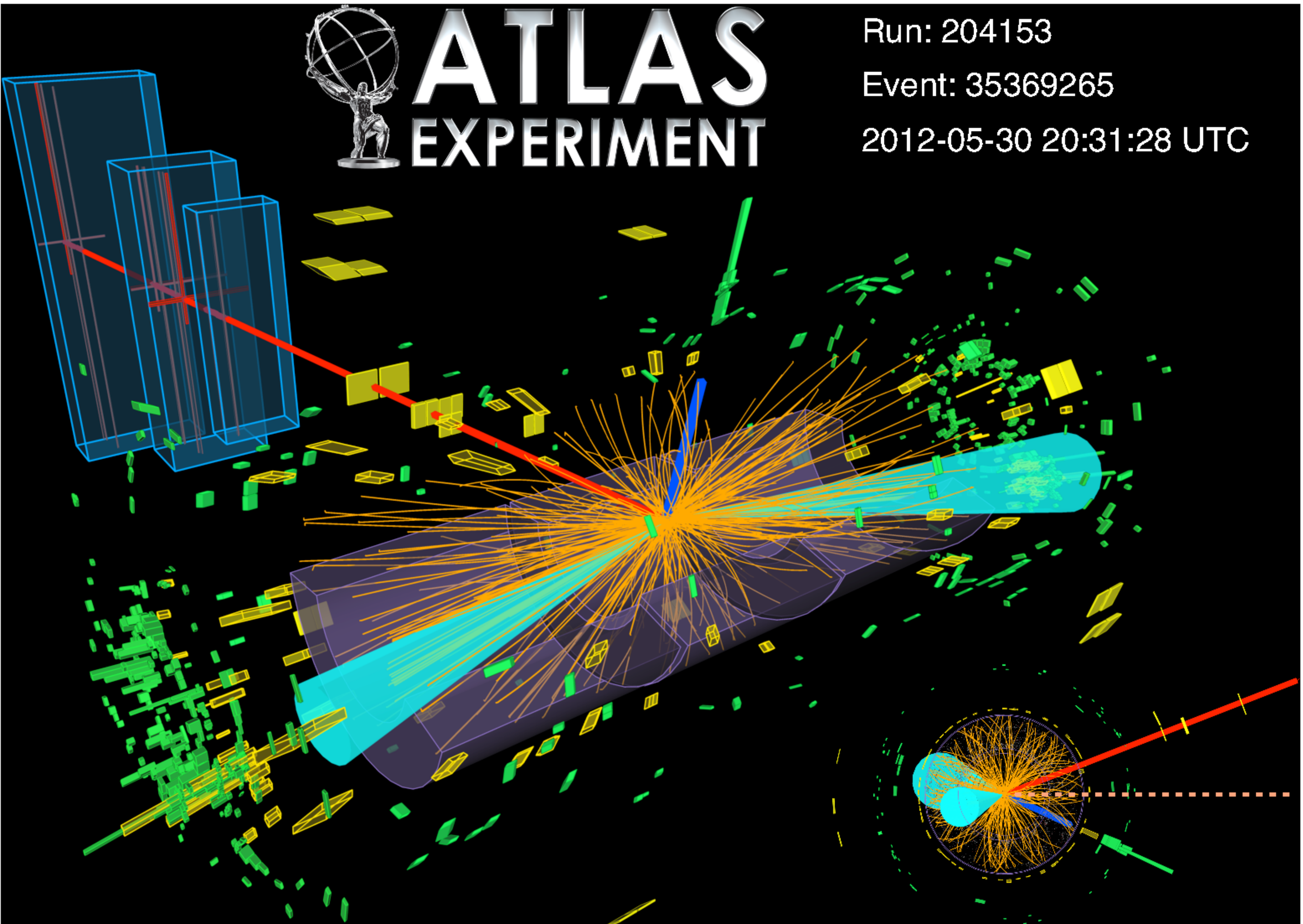


$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$$

$$\kappa_V = \kappa_W = \kappa_Z$$



ETmiss=102 GeV, m_{jj}=1.04 TeV and $m_{\tau\tau}$=127 GeV



Example Coupling results

ATLAS-CONF-2014-009

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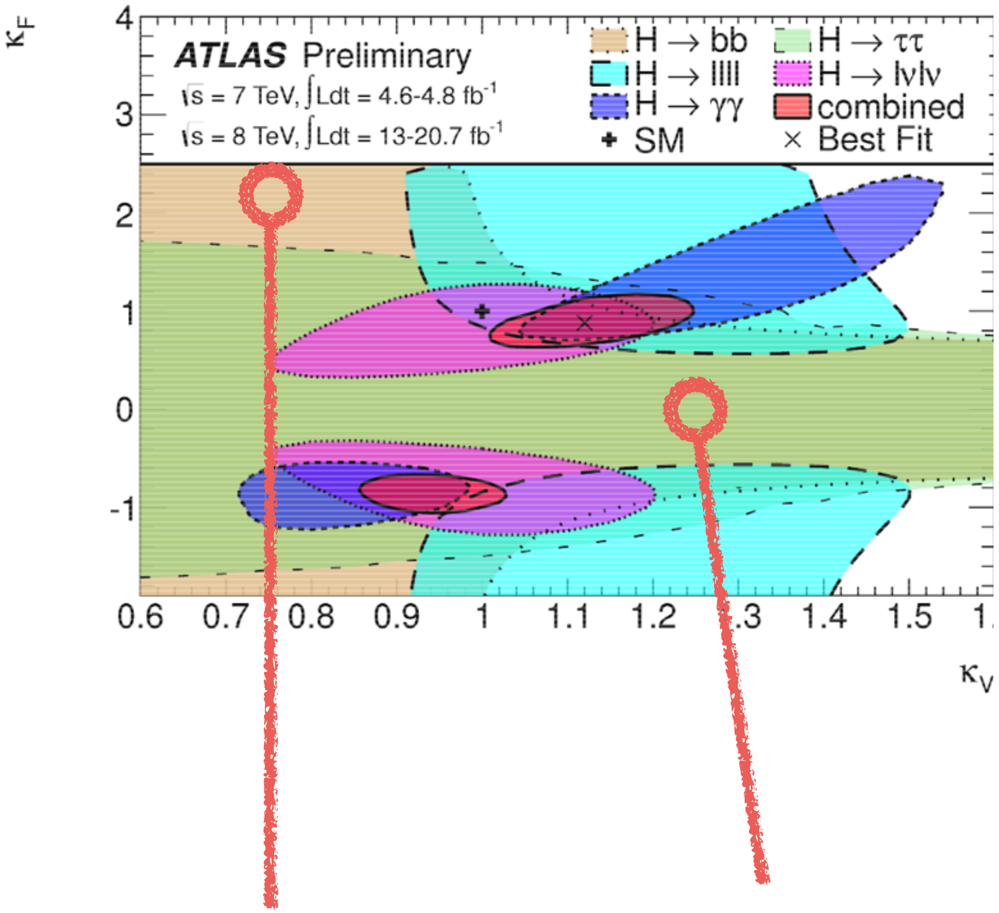
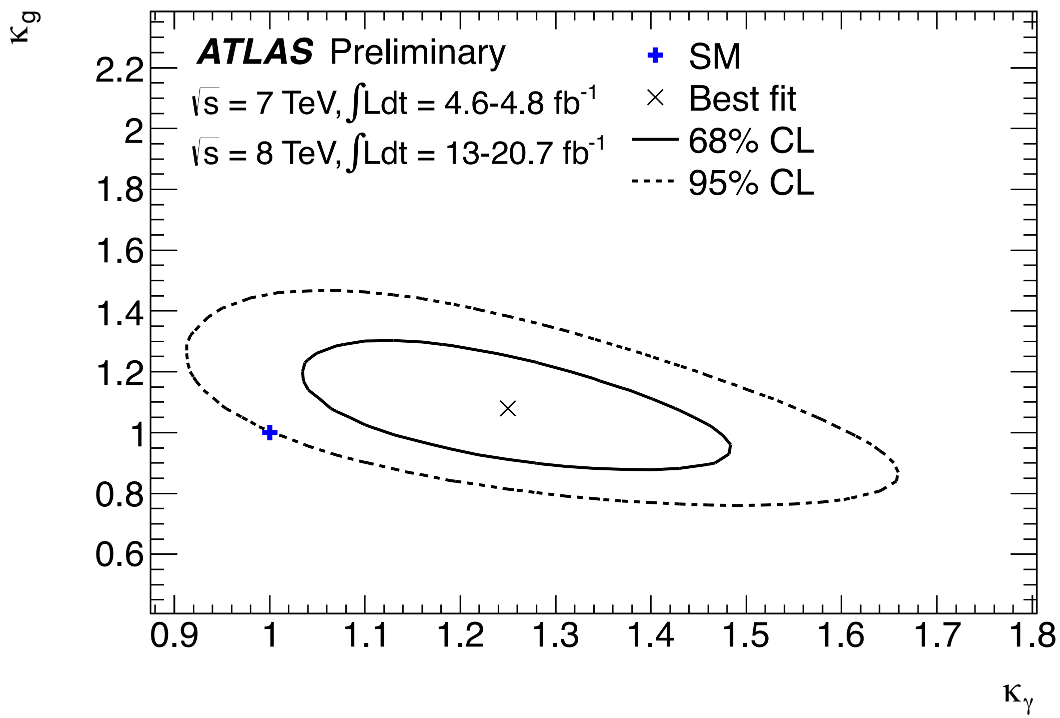
Spring 2014: Updated results with preliminary fermionic channels

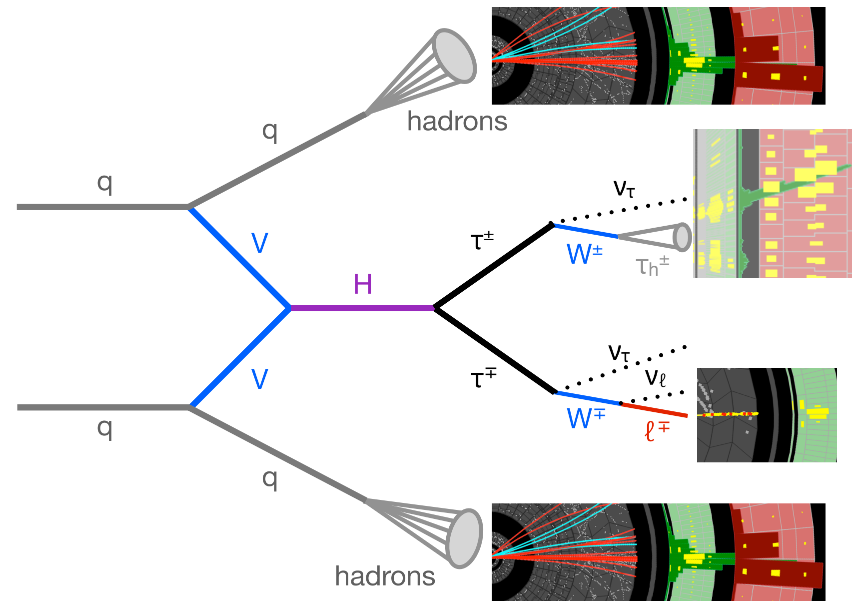


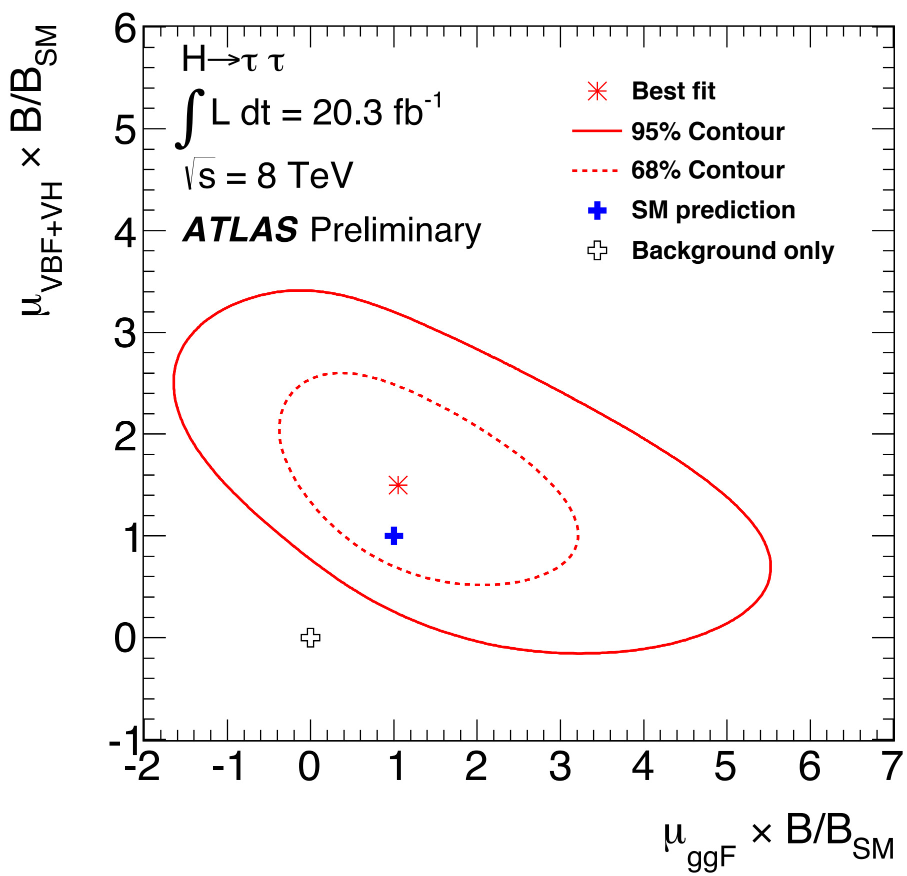


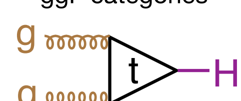
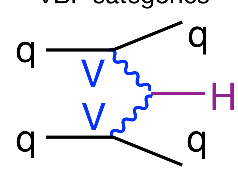
Constraints from direct fermionic coupling

$H\to\tau\tau$ analyses are challenging and complicated

- New Oct 2014 result: 4.5σ excess with 20.3 fb^{-1} using MVA
- Uses 7 & 8 TeV data $\mu = 1.42\,^{+0.44}_{-0.38}$





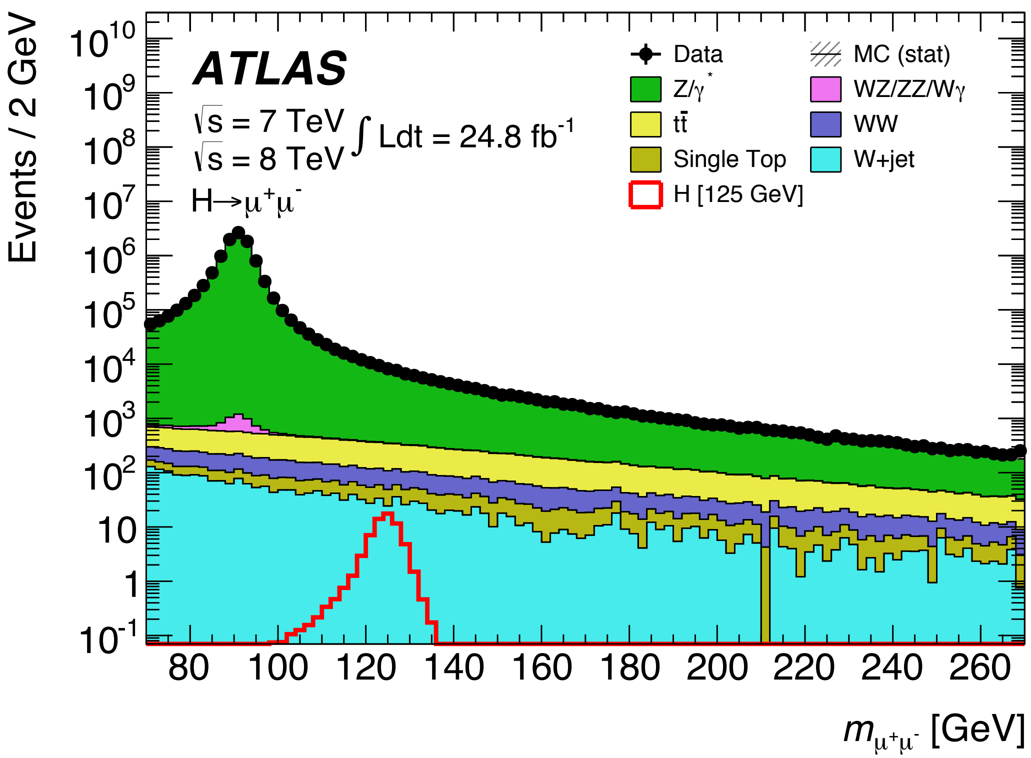
	$H\to\tau_\ell\tau_h$	$H\to\tau_h\tau_h$	$H\to\tau_\ell\tau_\ell$
Nickname	"lep-had"	"had-had"	"lep-lep"
Trigger	single ℓ $\ell+\tau_h$	di-τ_h	single ℓ di-ℓ
ggF categories 	0 jet 1 jet boosted H	boosted H	0 jet 1 jet boosted H
VBF categories 	2-jet VBF	2-jet VBF	2-jet VBF

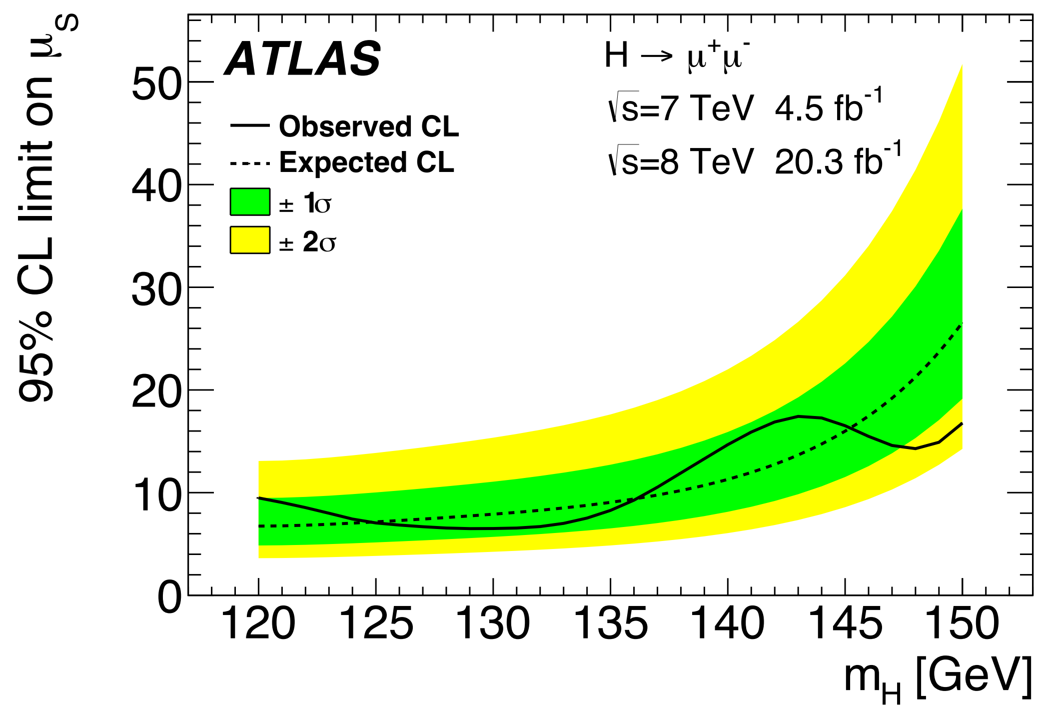
Higgs branching ratios to fermions proportional to mass^2

Unlike the universal coupling of Z→ ee, μμ, ττ

SM branching ratio for the H→μμ decay is 21.9×10^{-5}

Limit is <7x SM rate, universal coupling with τ is *very* excluded!





New Results on H→bb

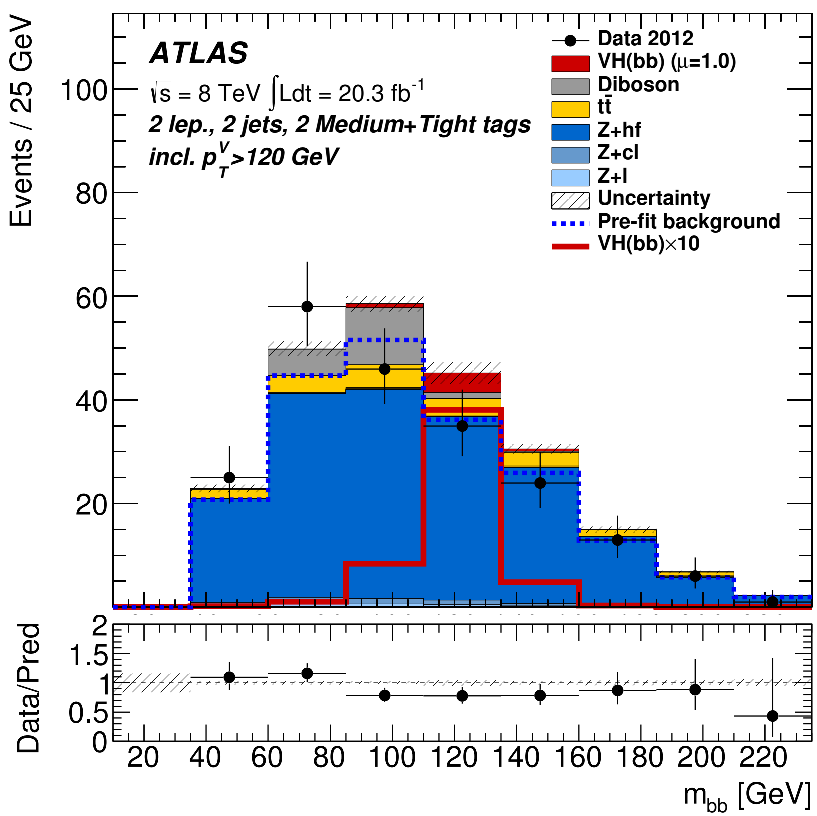
arXiv:1409.6212

Challenging analysis, improved b-tagging, dedicated calibration

Event categorization based on:

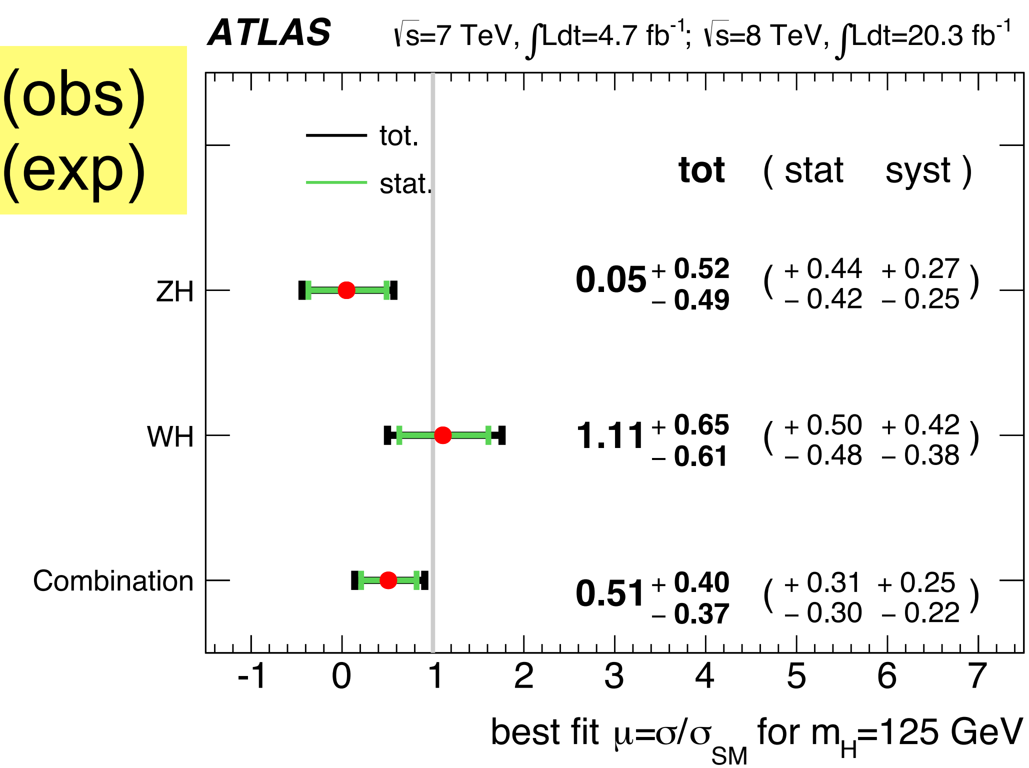
(0,1,2-leptons) ⊗ (2,3-jets) ⊗ (p_T^V bin) ⊗ (TT, MM, LL b-tag)

Nearly ~20,000 templates needed to cover systematic variations for this highly categorized analysis! Many cross-checks, including SM dibosons.



Results based on m_{bb} & BDT for 7 & 8 TeV

1.4σ (obs)
2.6σ (exp)



Conclusions

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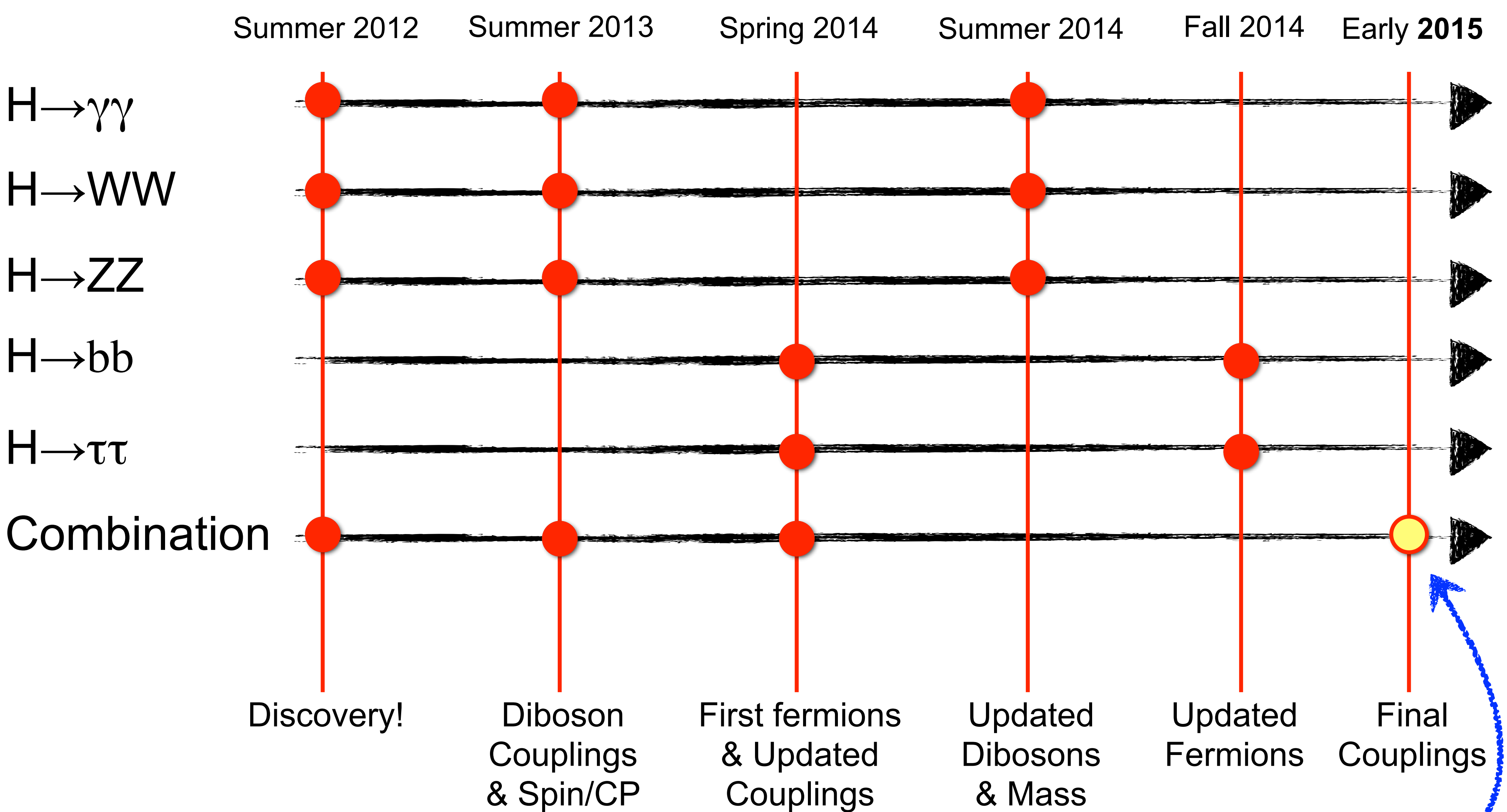


Keep an eye out for final combined coupling measurements!

Backup

Summary of what we have established

Mass, spin, CP, and flavor

- mH ~125.5 ± 0.5 GeV
- looks like 0^+ as in SM, though only marginally favored over some alternatives
- fraction of CP odd coupling in ZZ is < ~50%
- no FCNC seen, BR($t \rightarrow Hc$) $\lesssim$ 1%

Production:

- discovery established ggF production & now VBF production also firmly established
- evidence for VH ~2σ
- ttH: not yet, look out for Run-II

Decays:

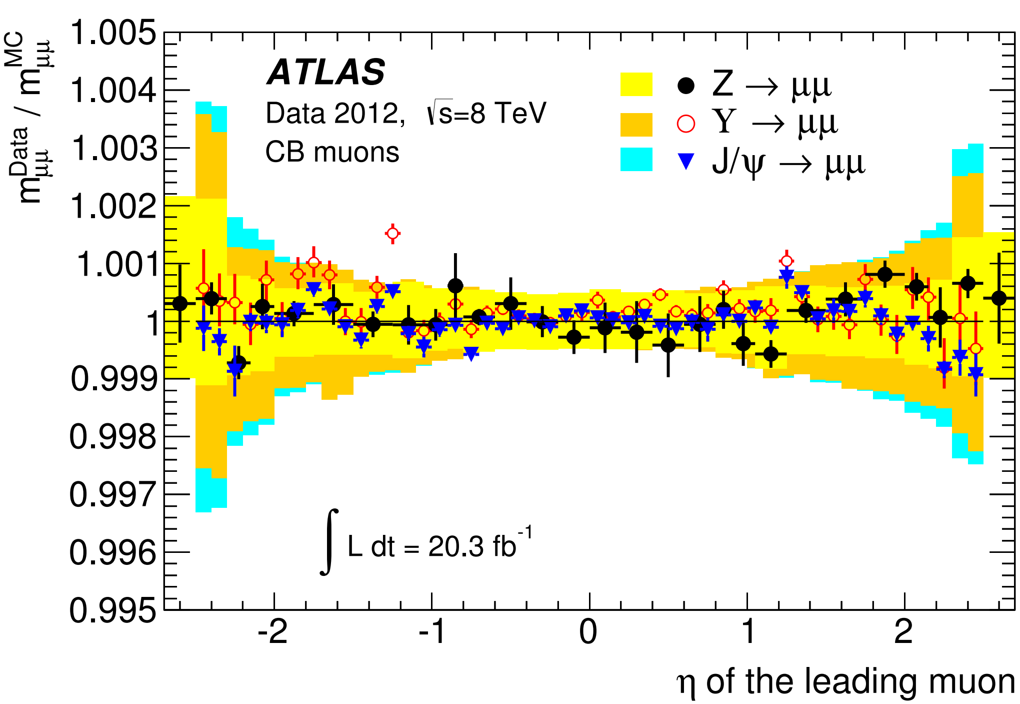
- $\gamma\gamma$, WW, ZZ >> 5σ
- $\tau\tau$ at ~4σ (lack of μμ as expected ⇒ not a flavor-universal coupling)
- bb ~2σ
- BR($H \rightarrow$invisible/undetected) < ~60%
- total width < ~4.2x SM

Overall coupling pattern:

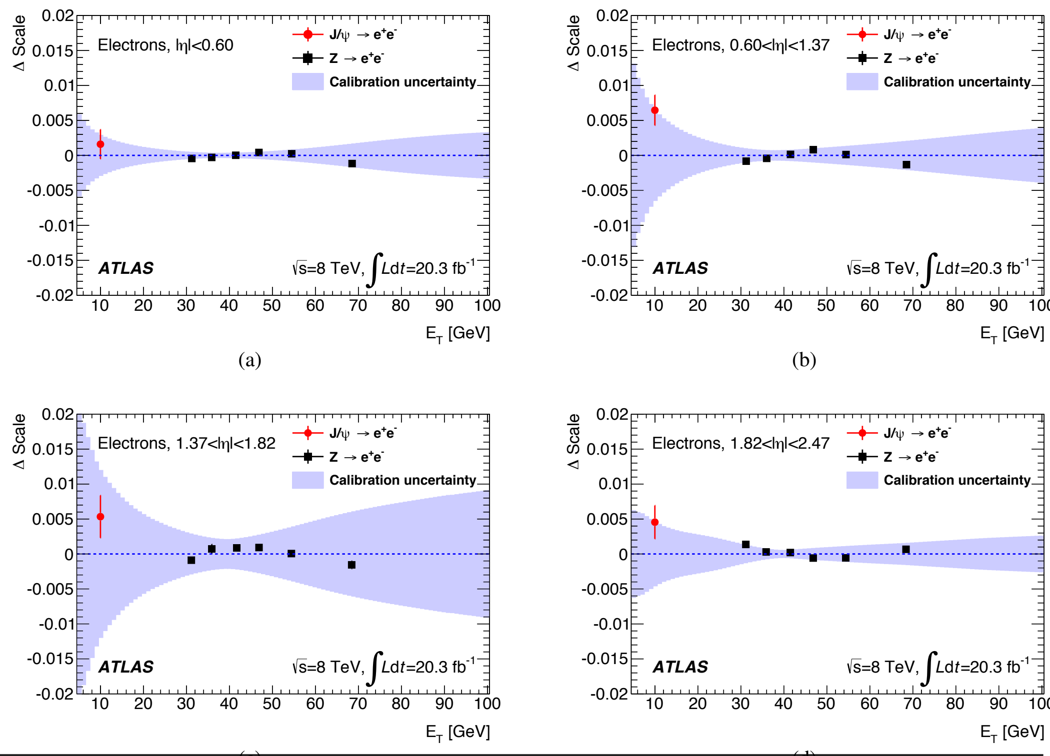
- consistent with the SM, though ~2σ tension seen

Calibration Checks

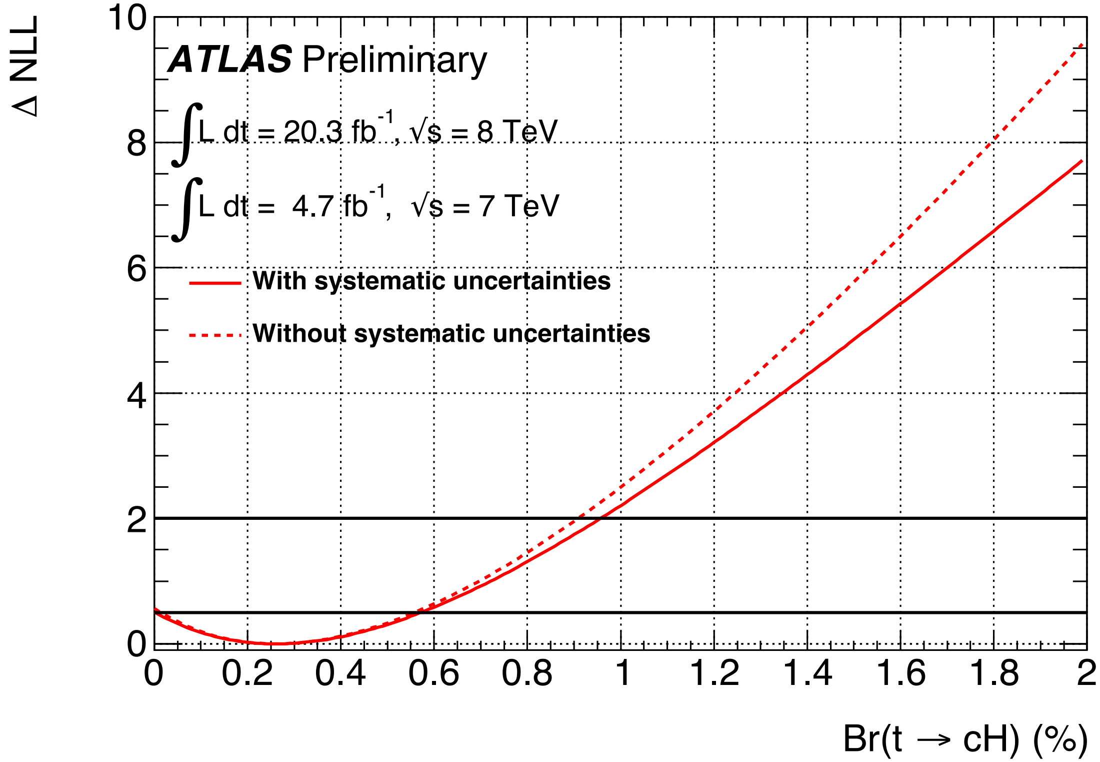
Center for Cosmology and Particle Physics



(a)



- ATLAS Public Higgs Results
  - Mass Paper — Phys. Rev. D. 90, 052004 (2014)
  - $H \to \gamma\gamma$ — arxiv:1408.7084
  - $H \to ZZ^* \to 4l$ — arxiv:1408.5191
  - $H \to WW^* \to l\nu l\nu$ — ATLAS-CONF-2014-060
  - $H \to \tau\tau$ — ATLAS-CONF-2014-061
  - $H \to bb$ — arxiv:1409.6212
- All results using full Run 1 dataset
  - ~5 fb^{-1} @ $\sqrt{s}$ = 7 TeV + ~20 fb^{-1} @ $\sqrt{s}$ = 8 TeV



ATLAS Preliminary
∫L dt = 20.3 fb-1, √s = 8 TeV
∫L dt = 4.7 fb-1, √s = 7 TeV
With systematic uncertainties
Without systematic uncertainties
Δ NLL
Br(t → cH) (%)
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2