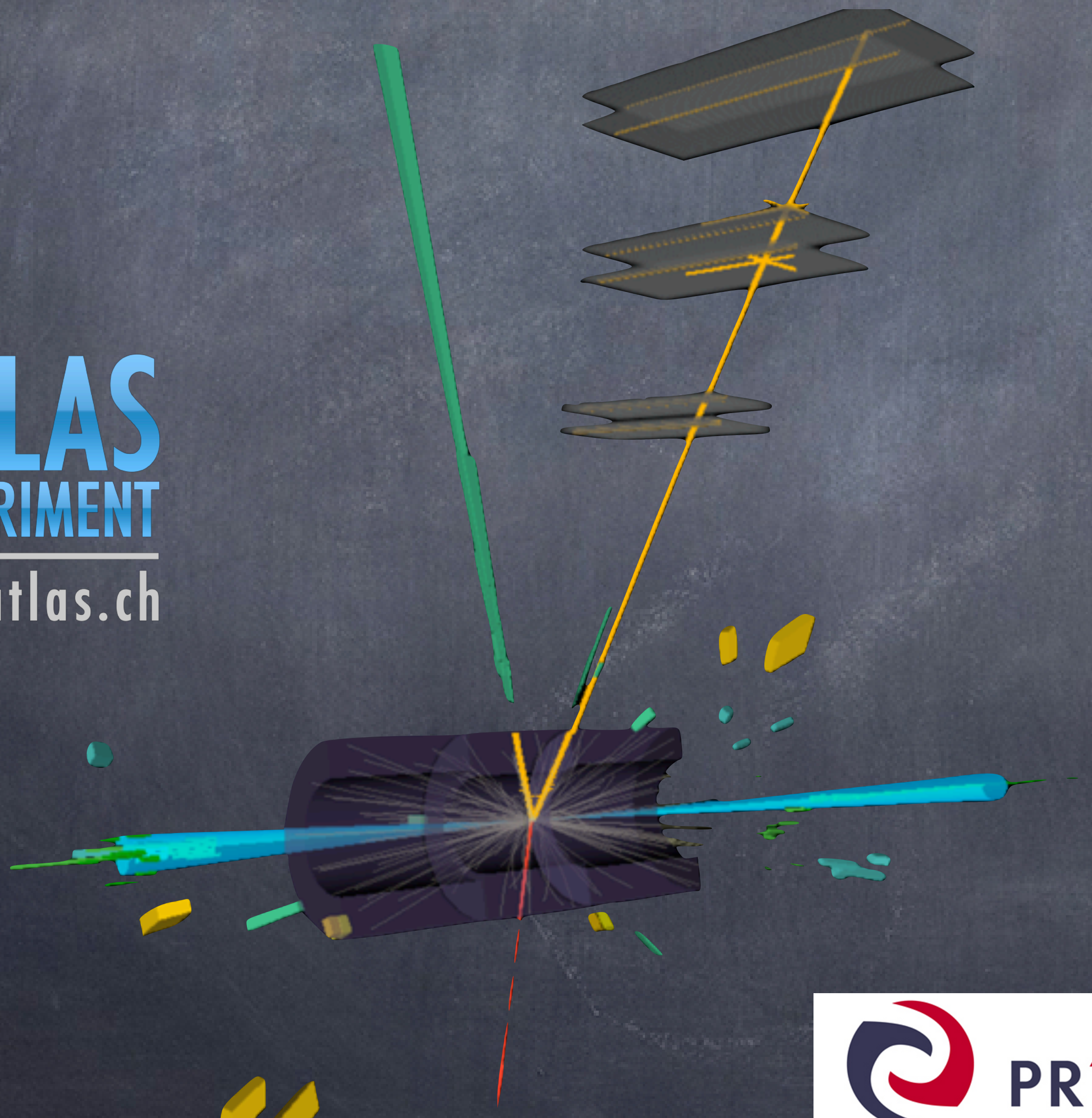
Latest Higgs results from ATLAS

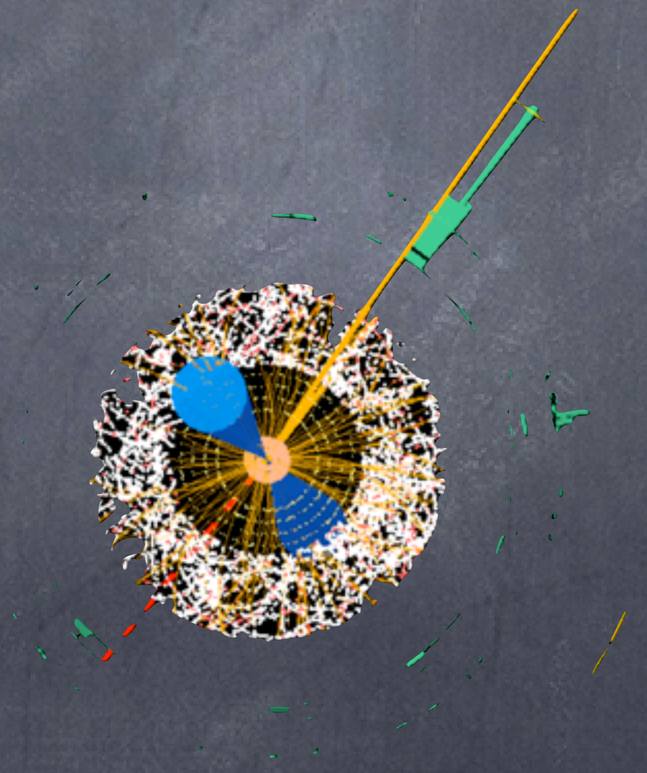
MITP Workshop "The first three years of the LHC"

Christian Schmitt
University of Mainz

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

ATLAS EXPERIMENT
http://atlas.ch





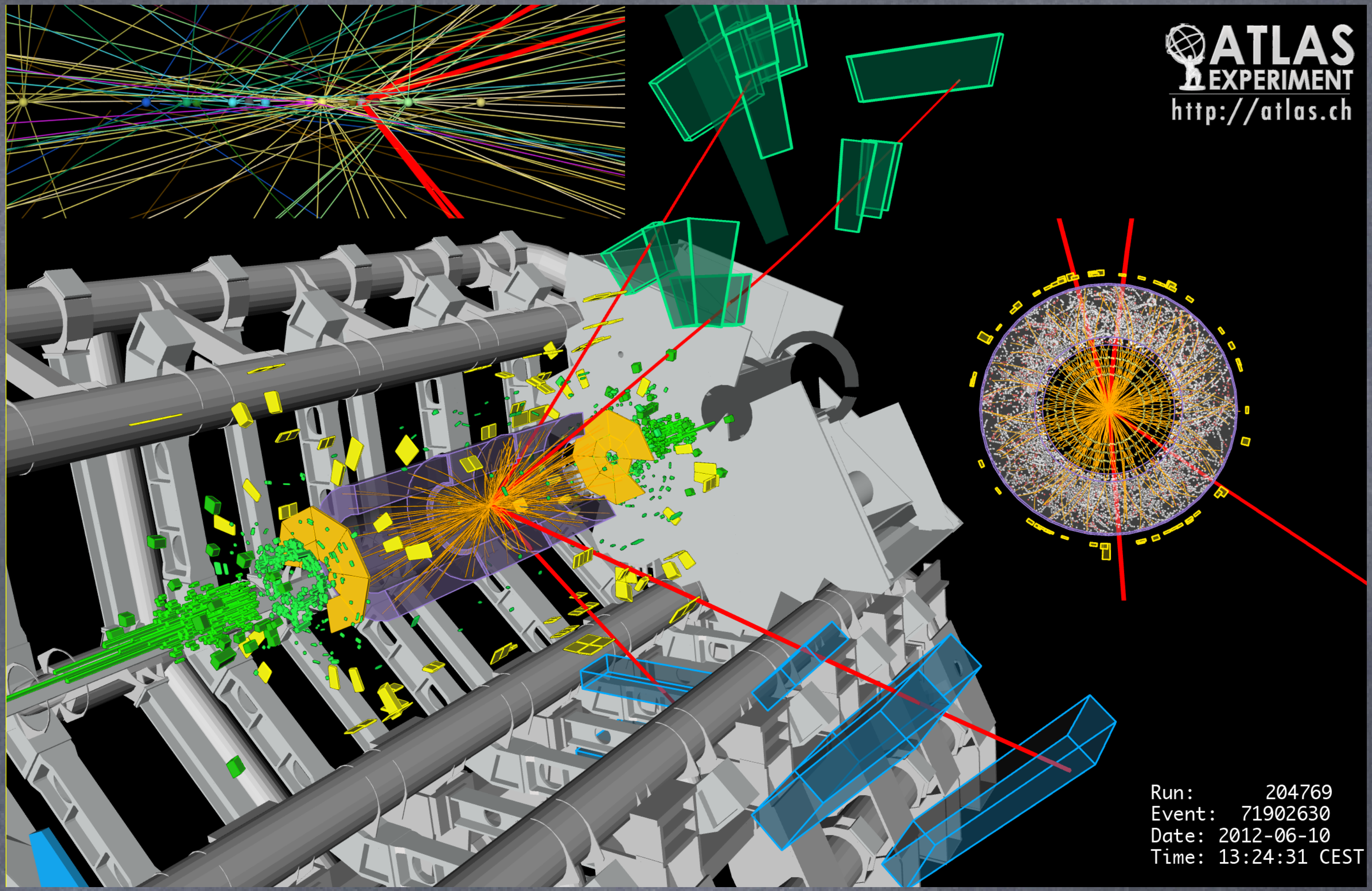
PRiSMA
Cluster of Excellence

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

FSP 101
ATLAS

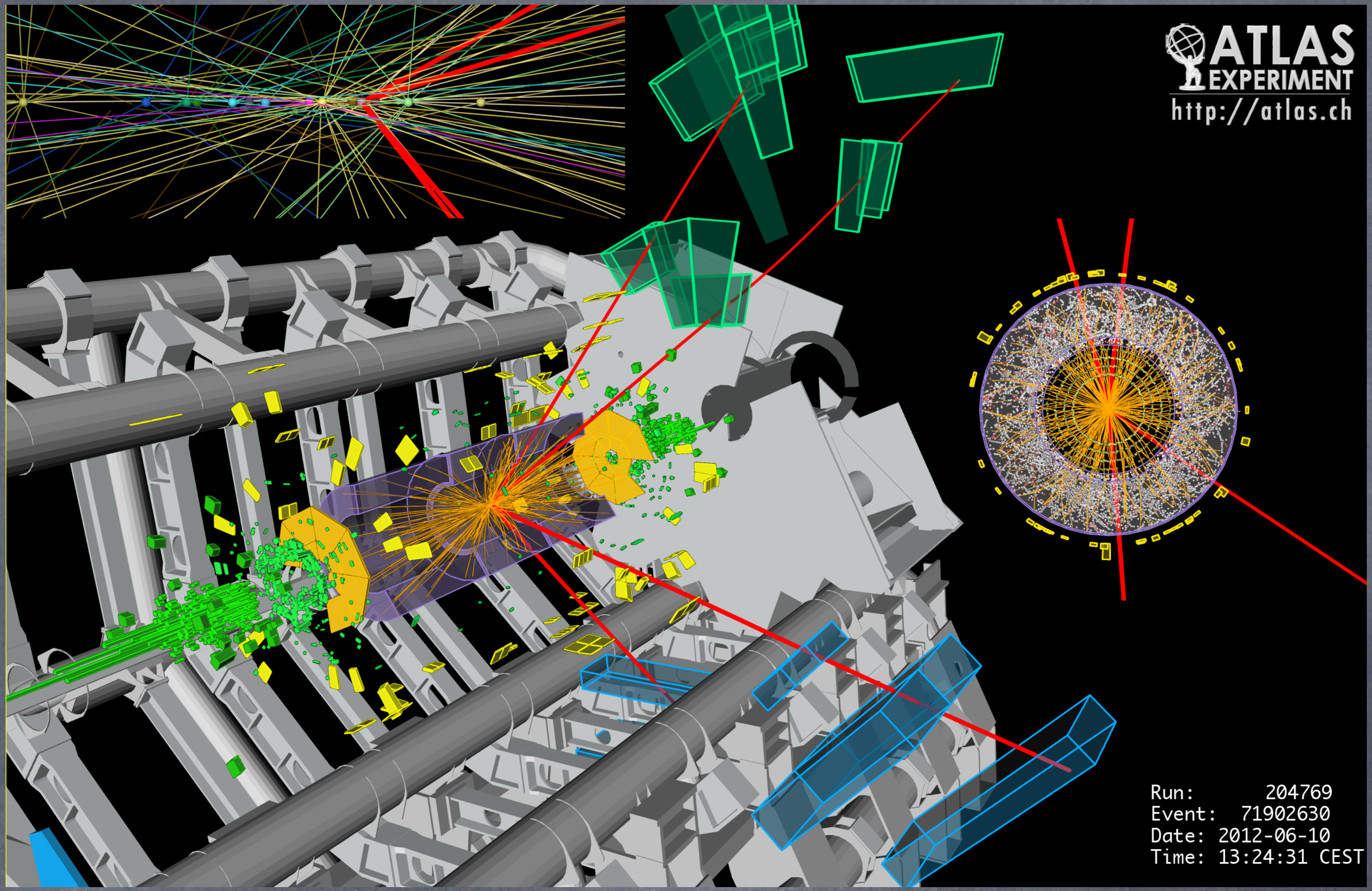
Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook



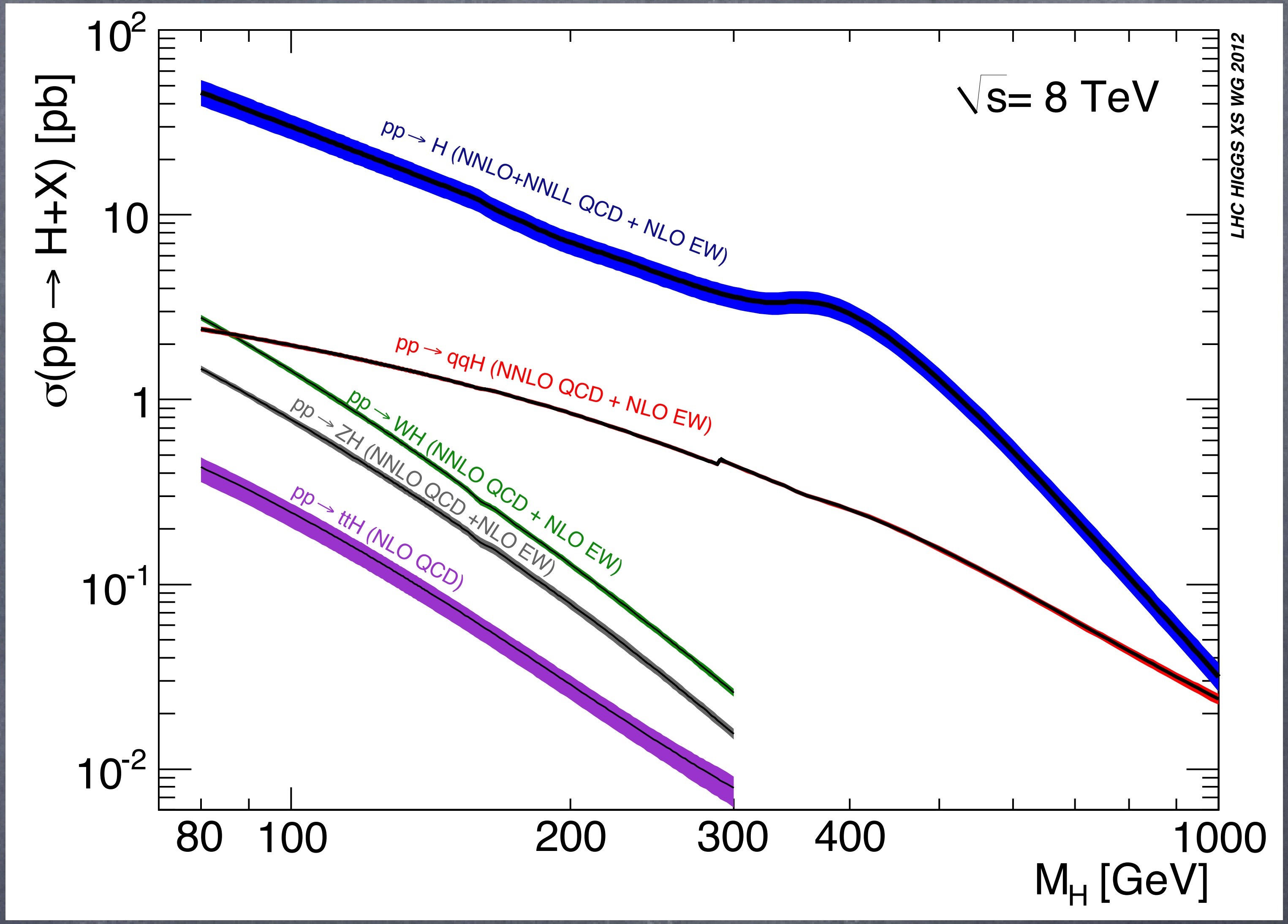
Overview

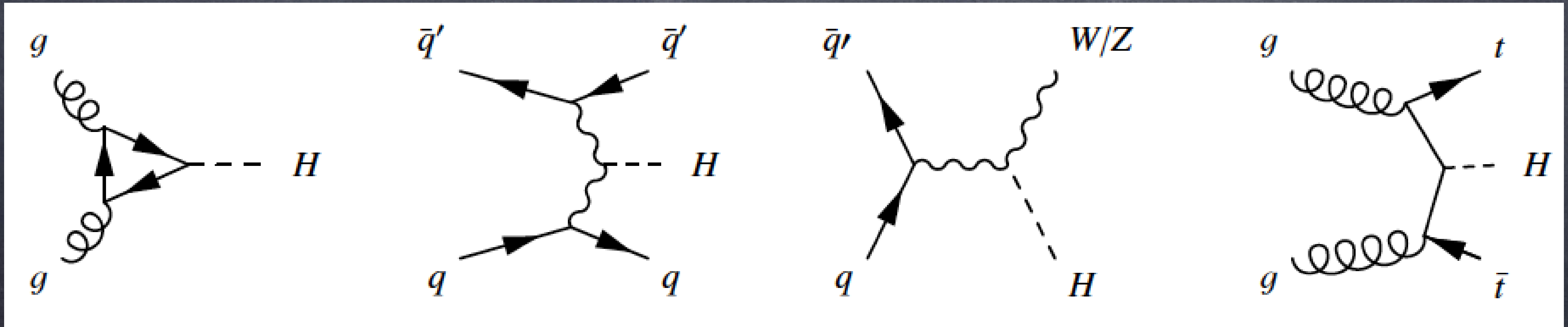
- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook



Higgs production

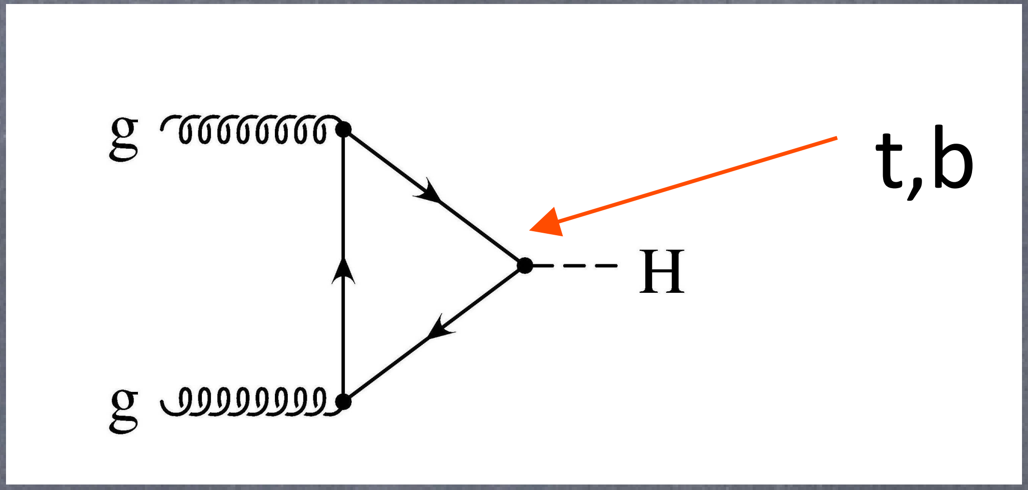
- Dominant process: Gluon fusion
- Also relevant
  - Vector Boson Fusion (VBF)
  - Associated production (VH)
  - $t\bar{t}H$





(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

Gluon fusion

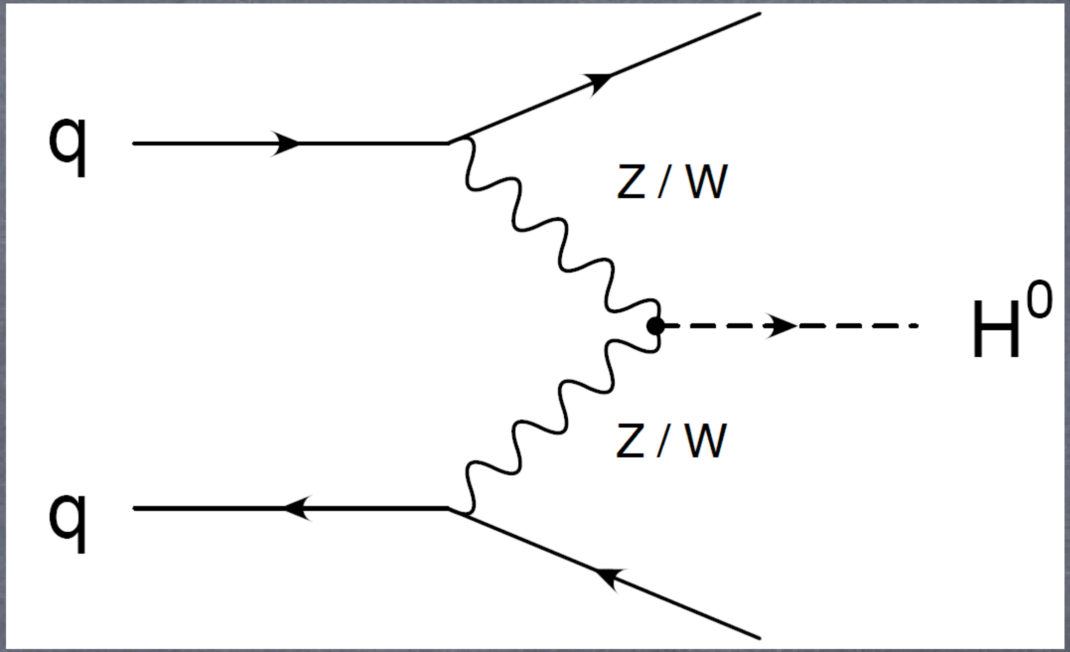


- Largest production rate for all Higgs masses at the LHC
- Gluon-gluon initial state
- sensitive to top quark Yukawa coupling
  - largest contribution in loop from top quark
  - b quark contribution small (about 5% in SM)
- Effectively counts number of heavy fermions ($F_{1/2}$ -> -4/3)

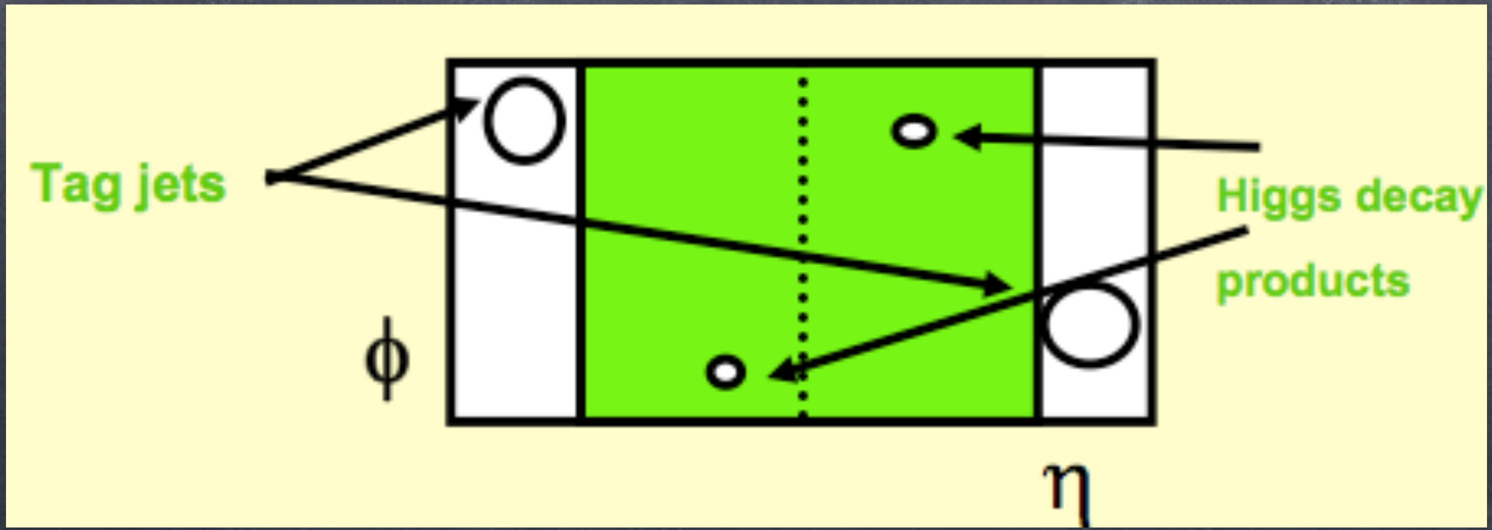
$$\sigma_{gg\to h}(\hat{s}) \sim \left| \sum_q F_{1/2}(q) \right|^2$$

Vector Boson Fusion

- Vector Boson Fusion
  - Sensitive to VVH couplings
  - Interaction vanishes if vev=0
  - Needed to cancel divergence in WW scattering

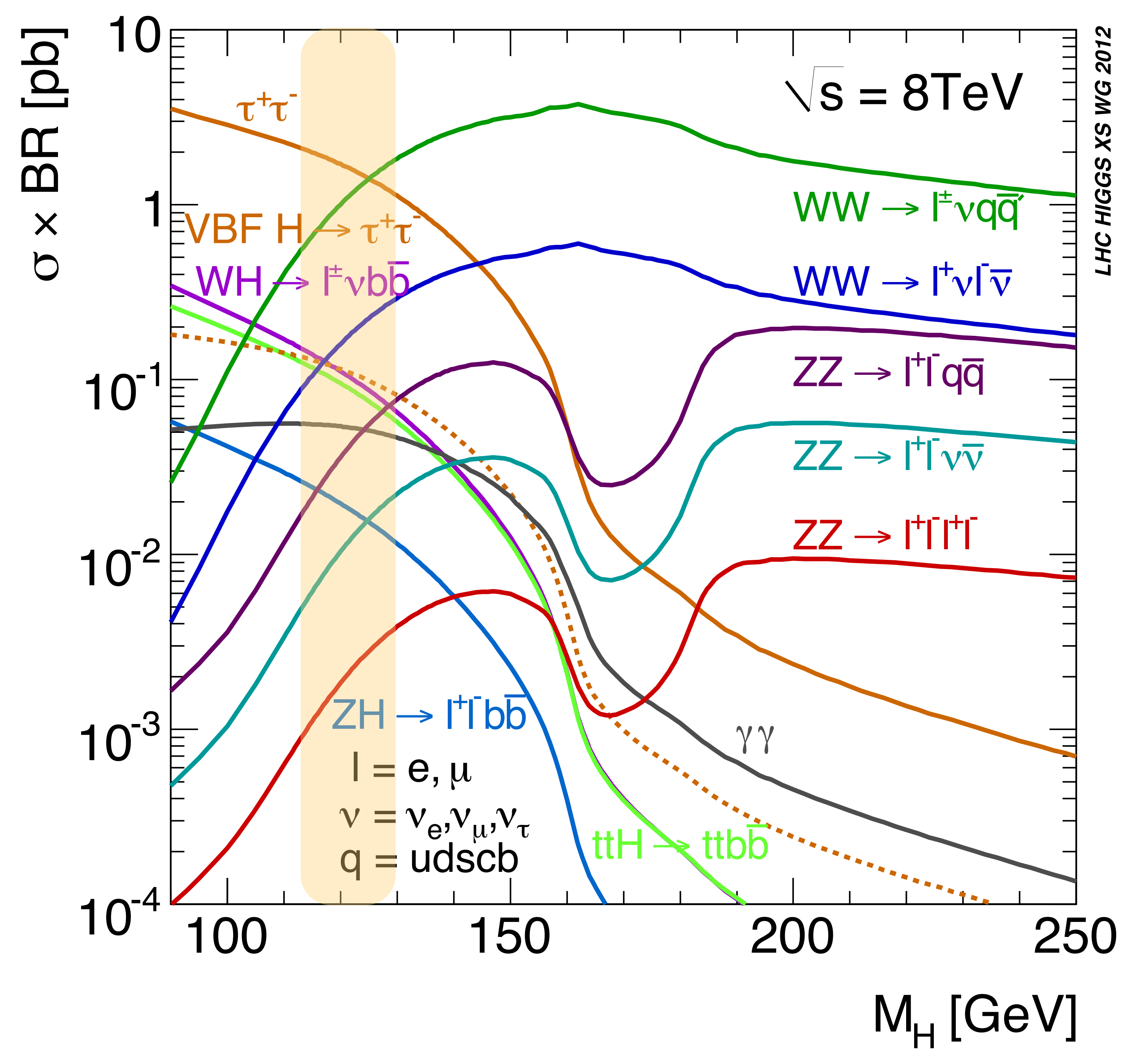


- Distinct event signature
  - 2 "tagging" jets with high invariant dijet mass and large rapidity difference
  - No color flow between tagged jets - suppressed hadronic activity in central region

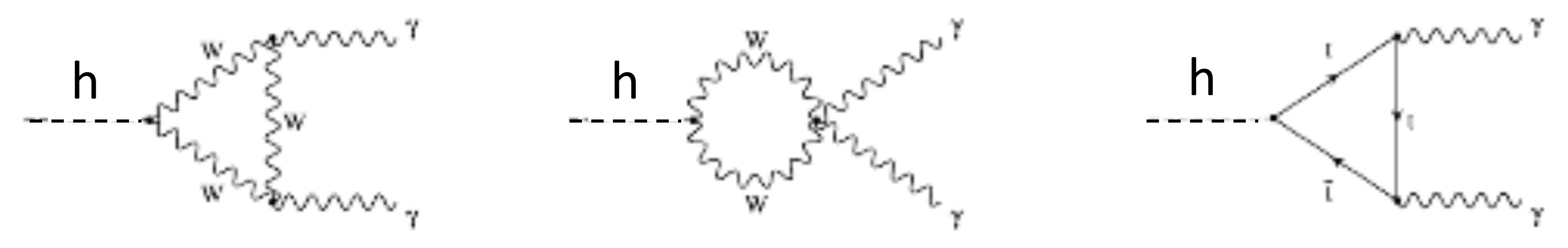


Higgs decay

- Most sensitive channels in low mass region:
  - H->WW
  - H->γγ
  - H->ZZ
- H->b$\bar{b}$ only in VH production due to background and trigger
- H->ττ



Higgs decays to photons



- Dominant contribution is W loop!
- Contribution from top is small and has opposite sign

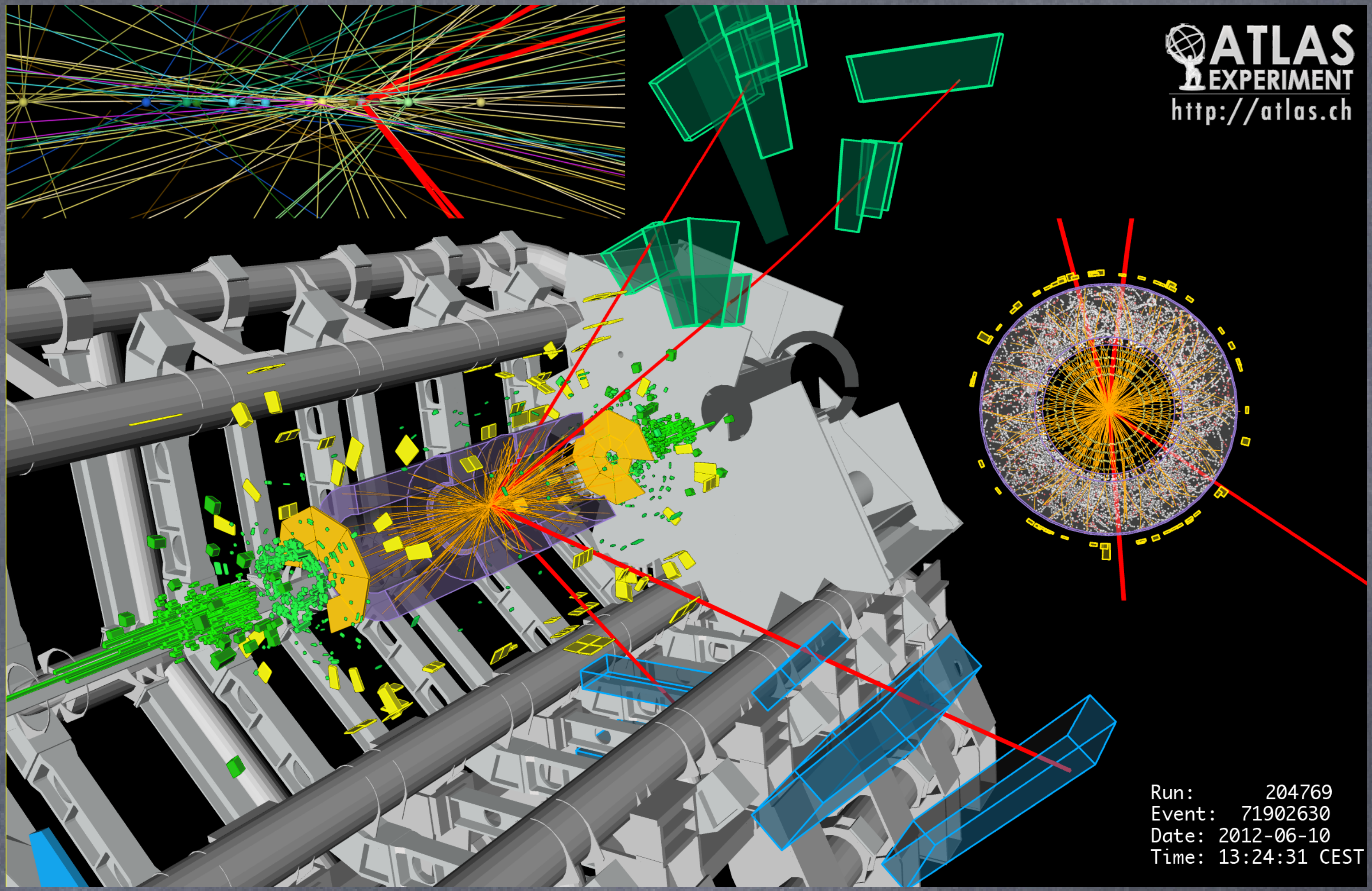
$$\Gamma(h\rightarrow\gamma\gamma)\approx\frac{\alpha^3}{256\pi^2 s_W^2}\frac{M_h^3}{M_W^2}\left|\overset{\text{W}}{7}-\overset{\text{top}}{\frac{16}{9}}+\ldots\right|^2$$

- Rate of H->γγ can be changed by rescaling the couplings to fermions (c_F) and to vector bosons (c_V)

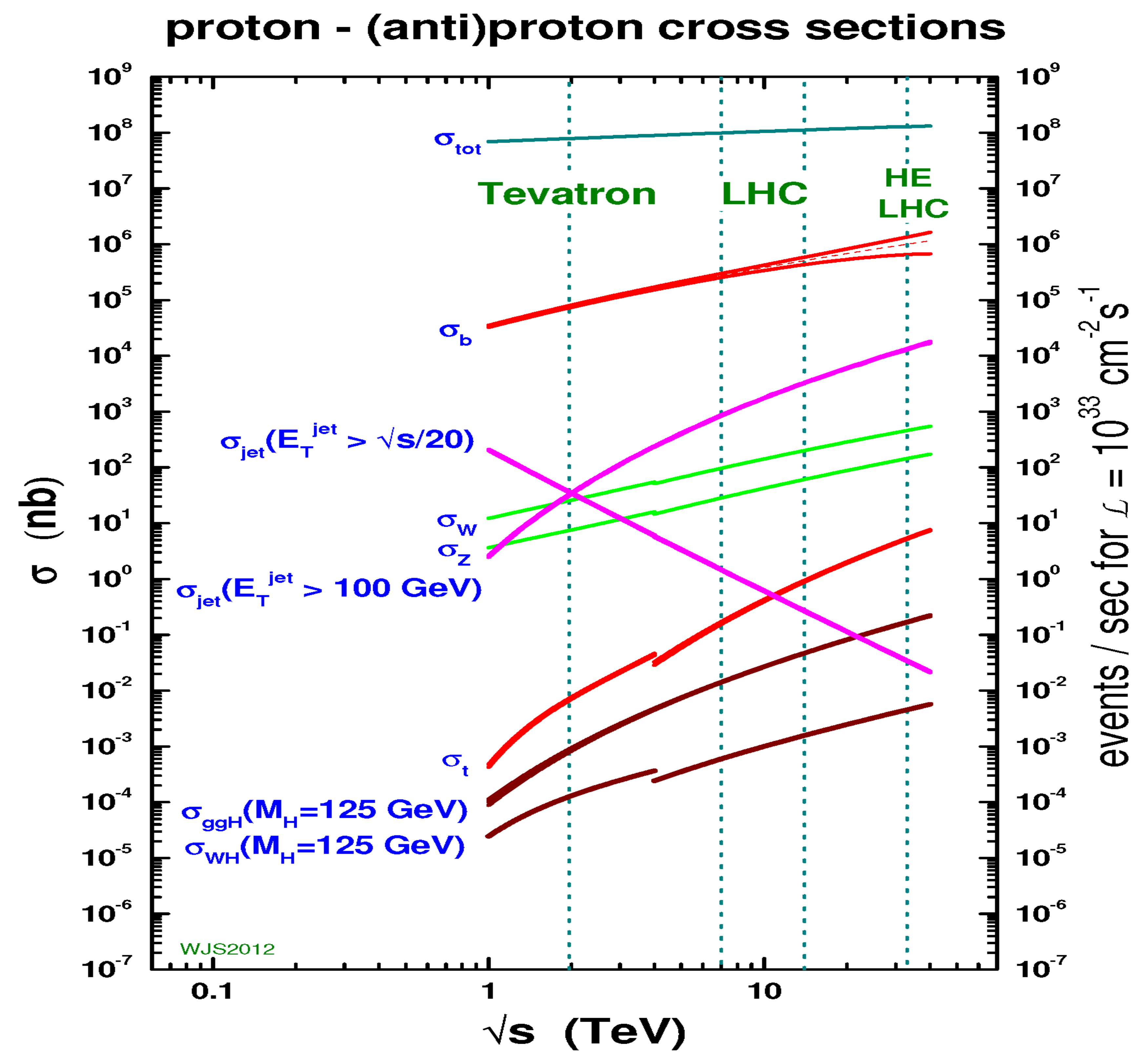
$$\frac{\Gamma(h\rightarrow\gamma\gamma)}{\Gamma(h\rightarrow\gamma\gamma)_{SM}}\sim\left(1-.2\frac{c_F}{c_V}\right)^2$$

Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook

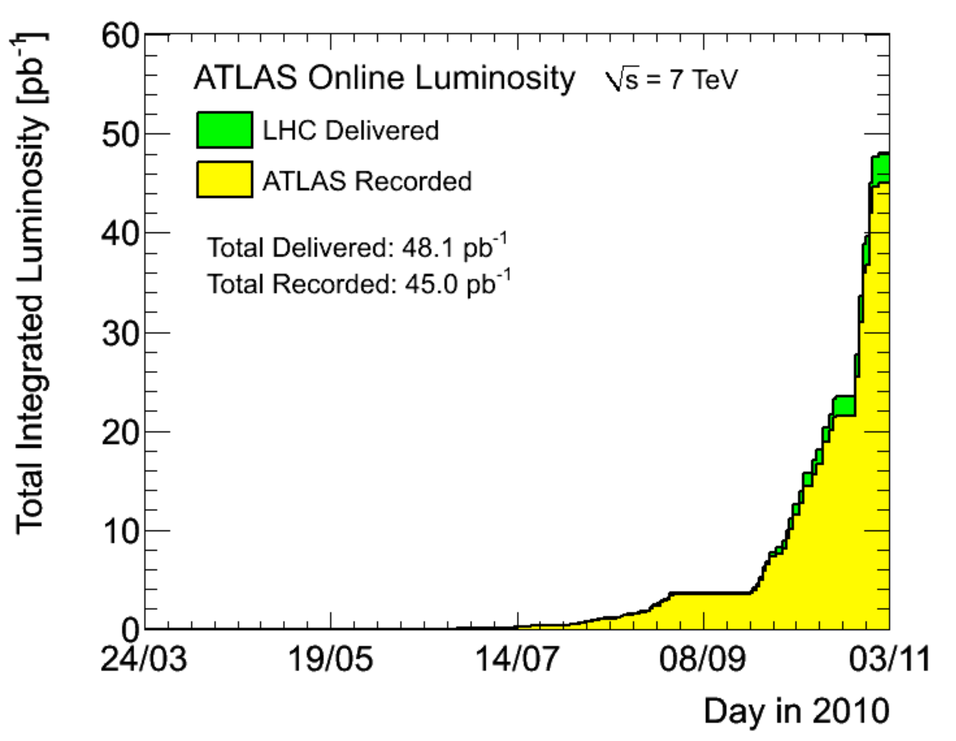


The challenge

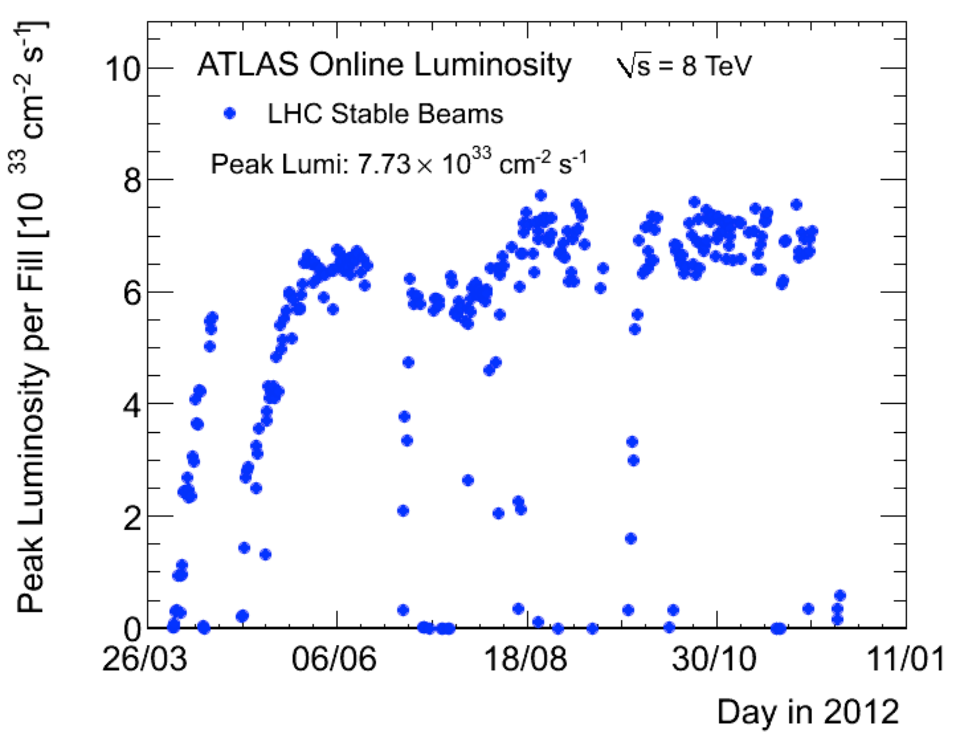


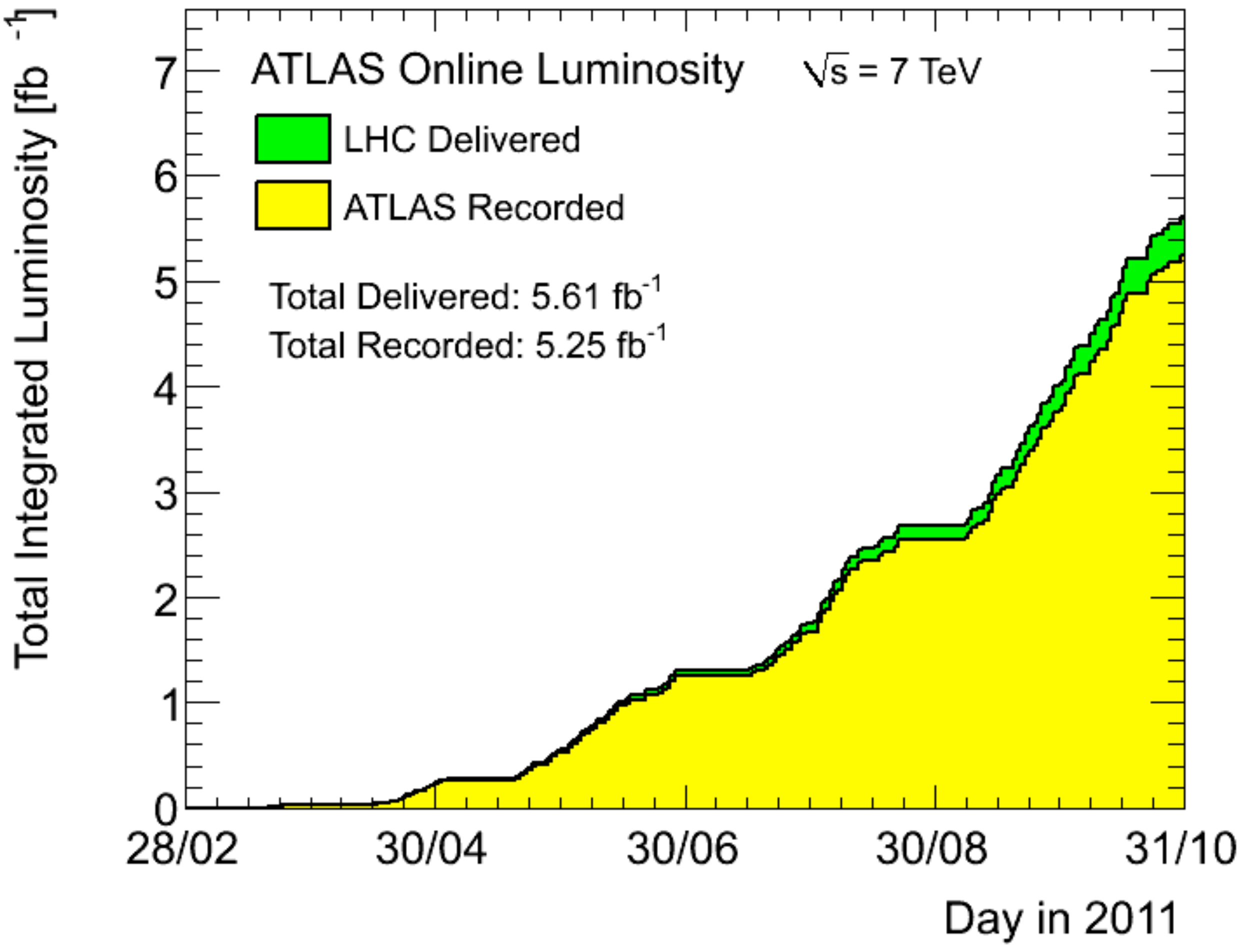
- Tiny cross section for Higgs production
  - need large integrated luminosity
- Large background rates
  - needle in the haystack

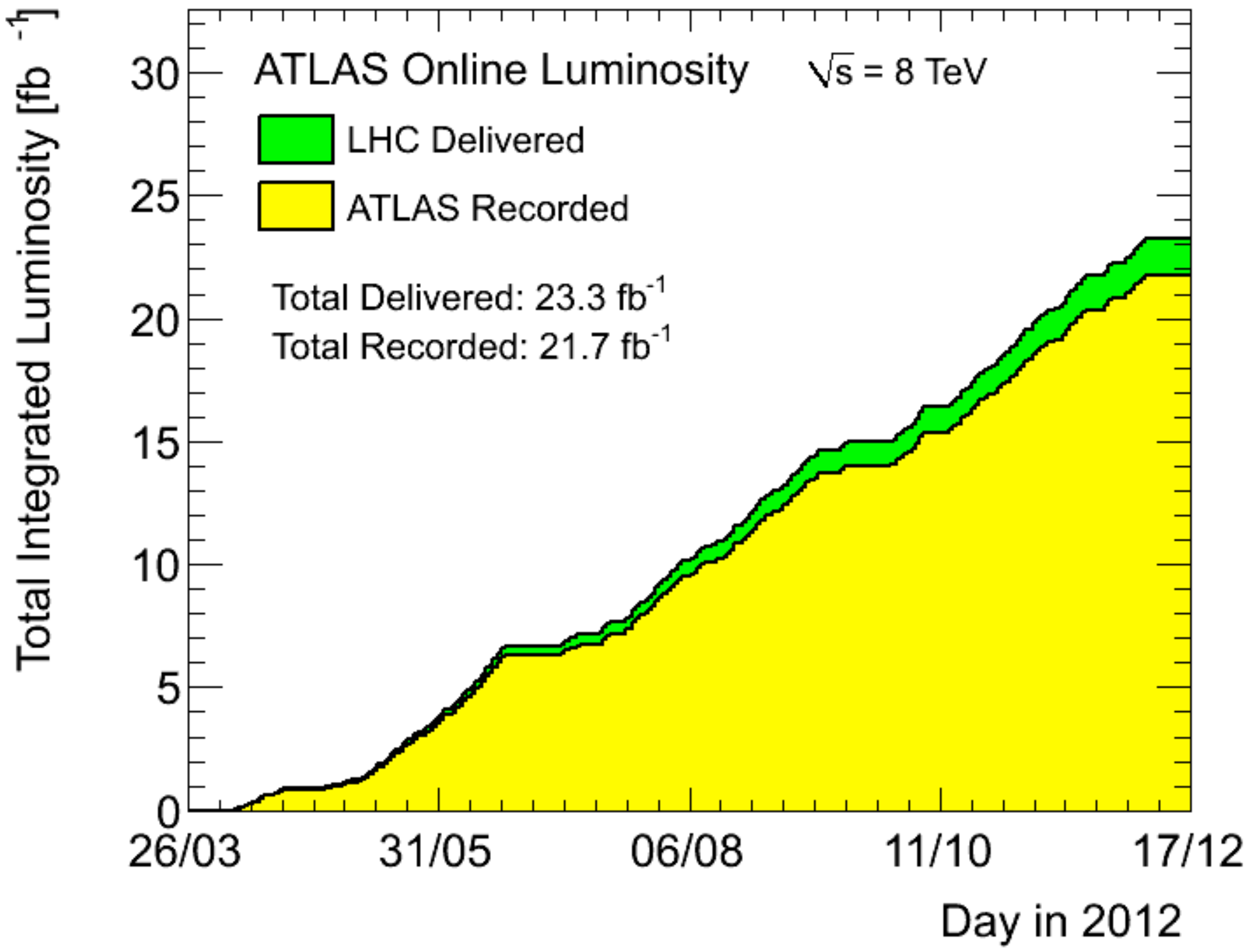
The first three years of the LHC



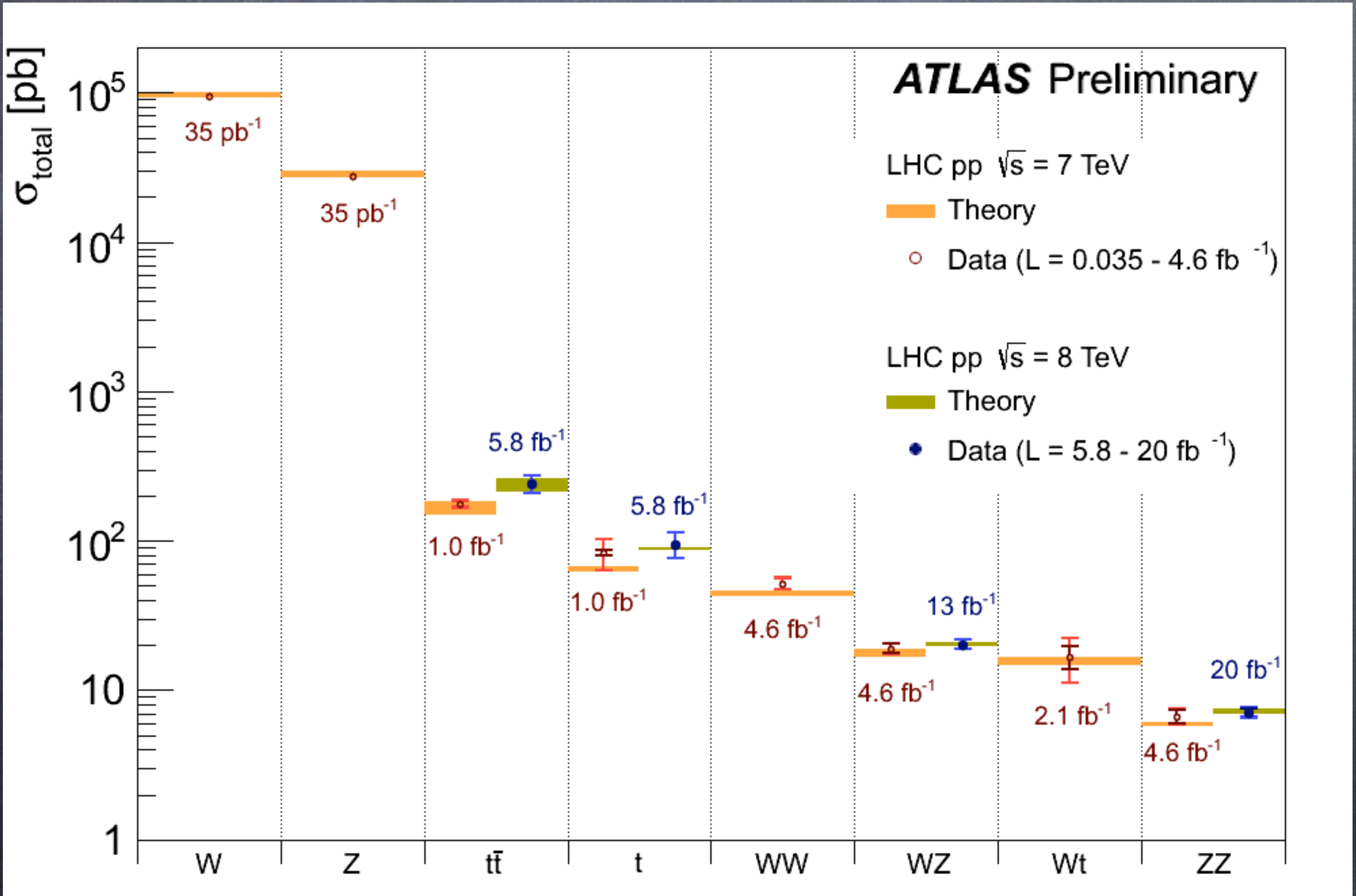
Amazing performance of the LHC!



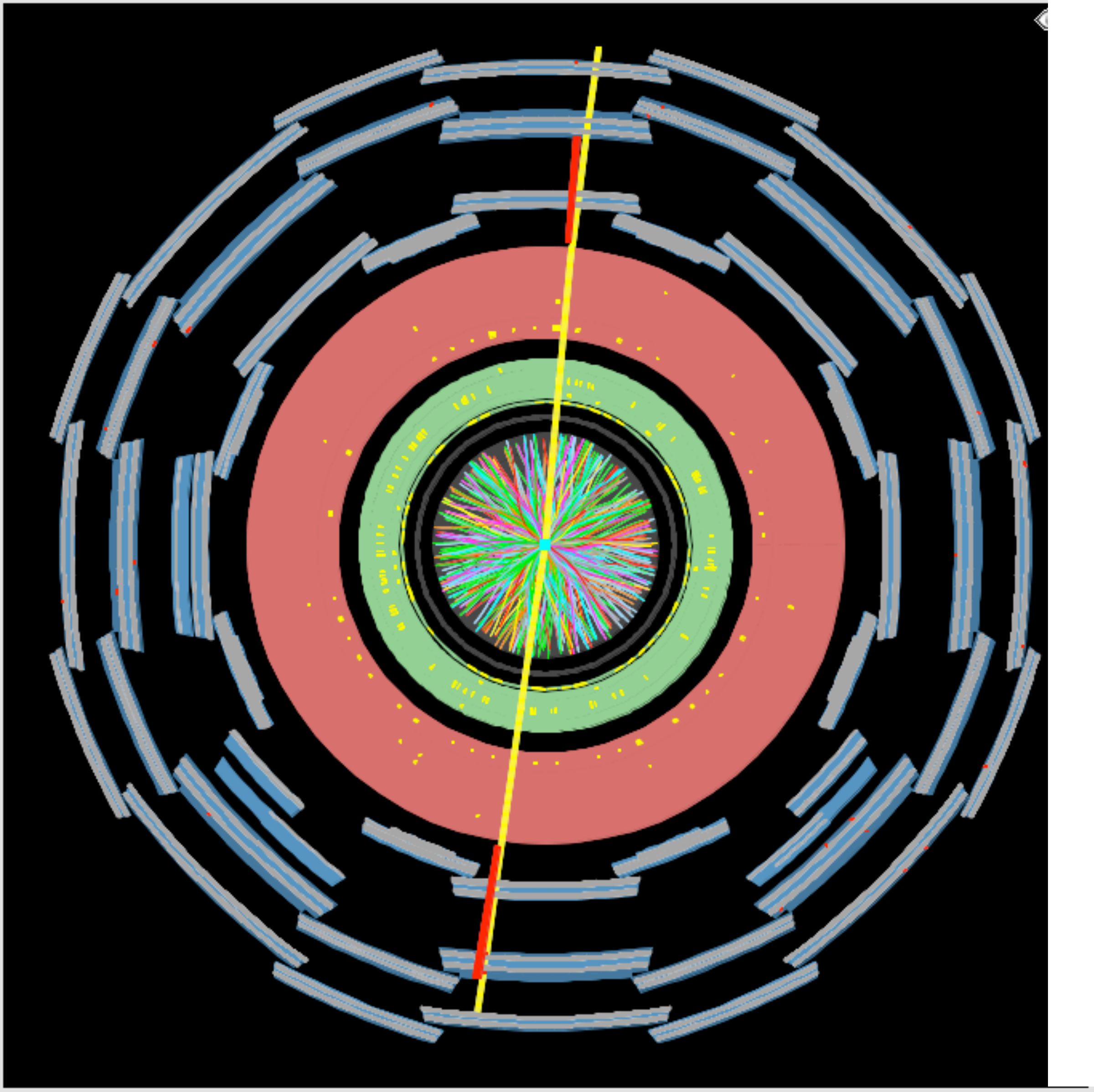


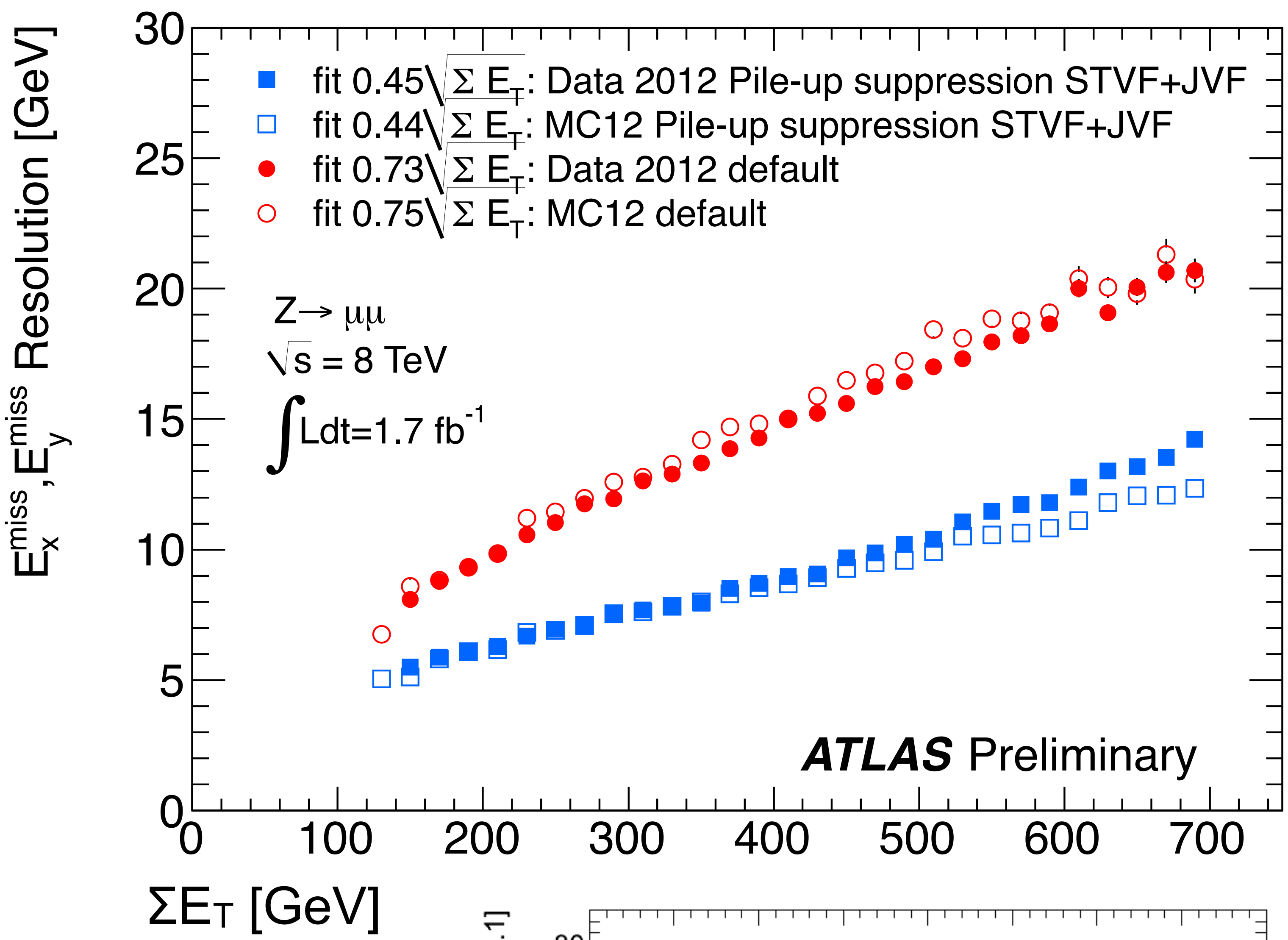


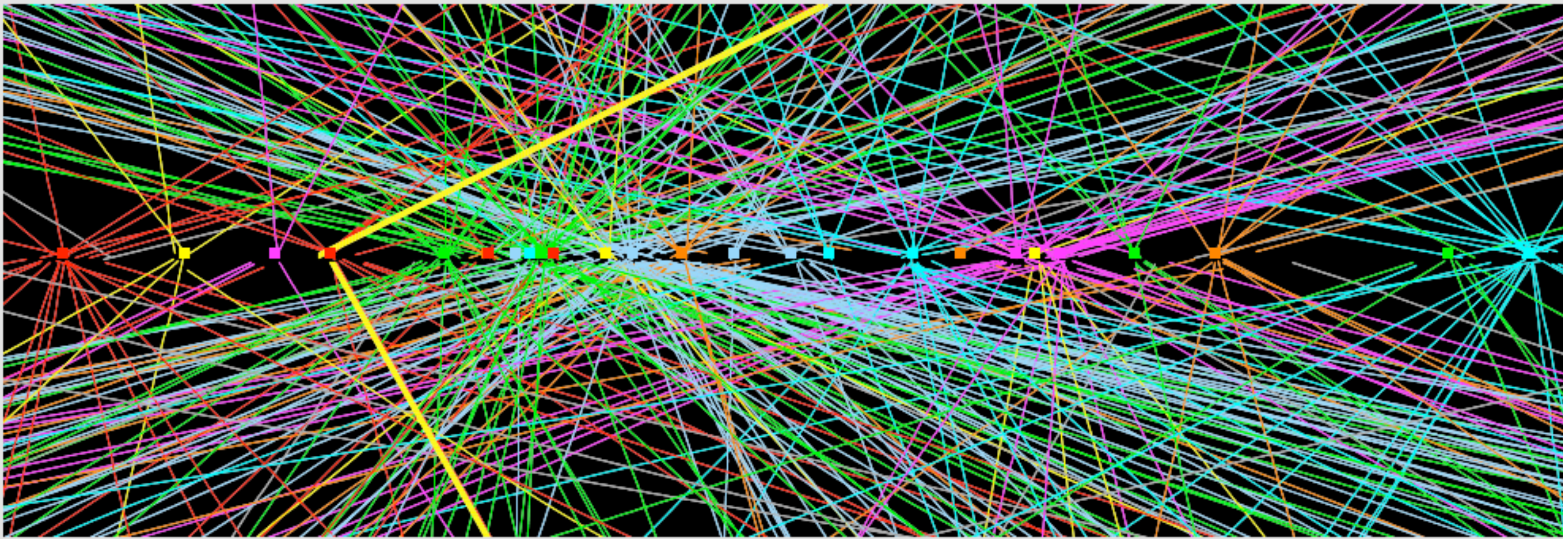
Need to understand the SM background!

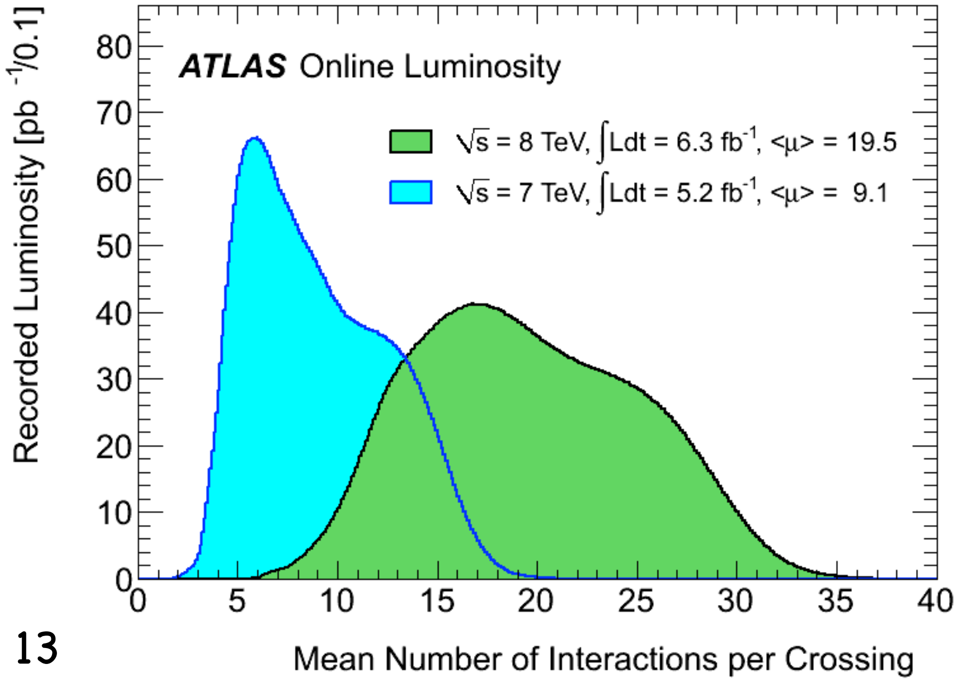


A not so clean environment ...



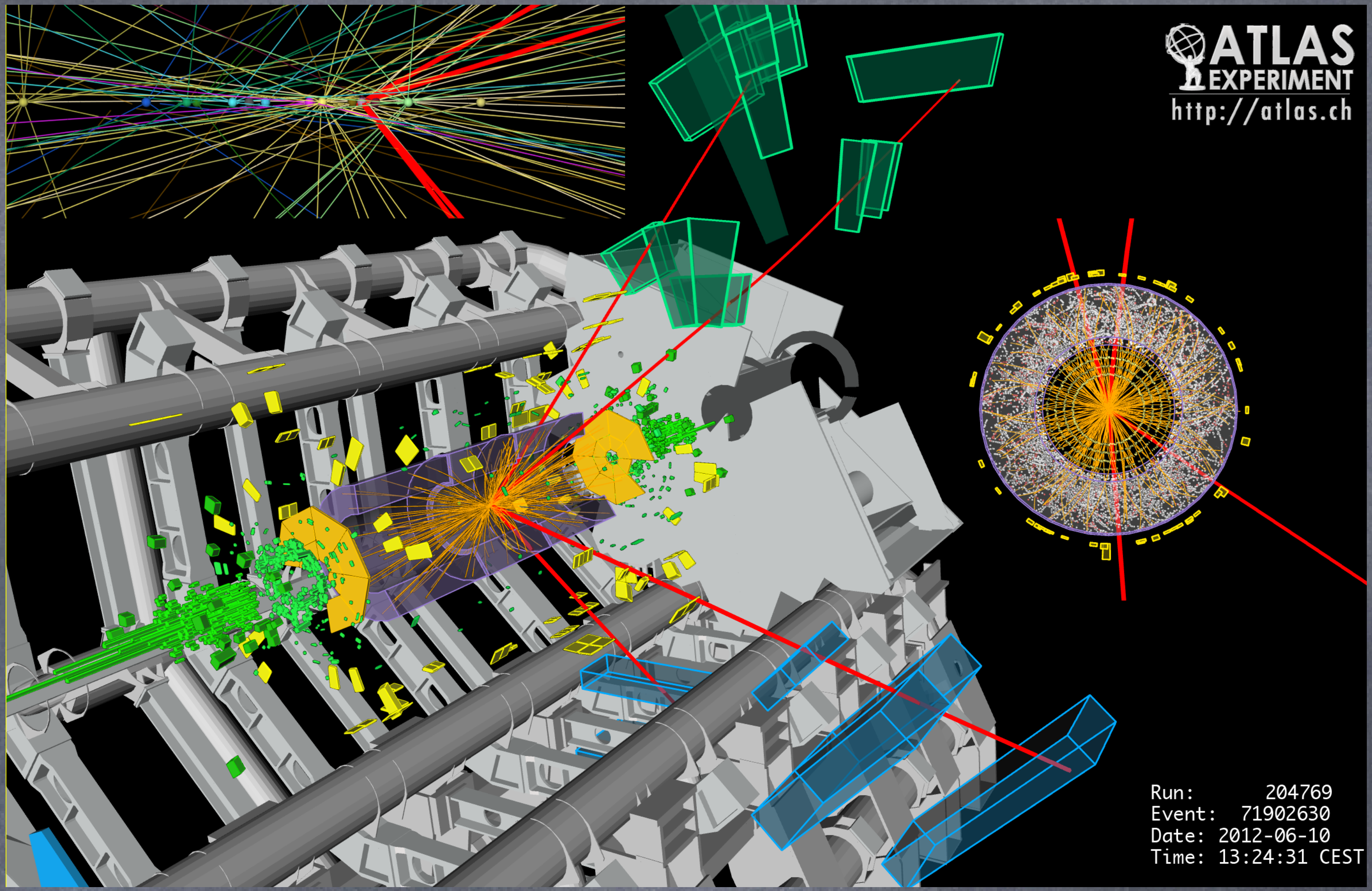




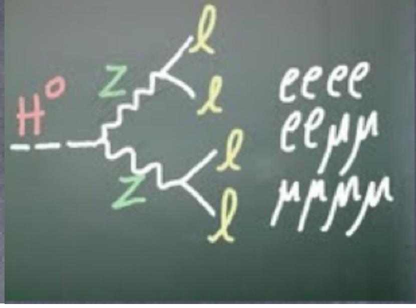


Overview

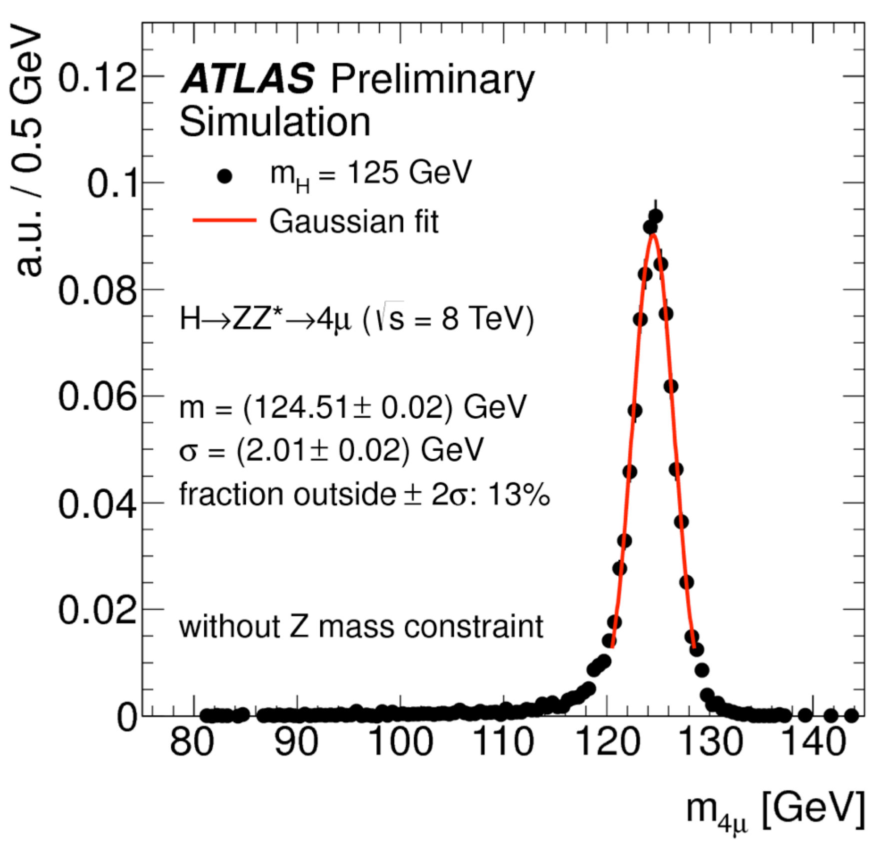
- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook

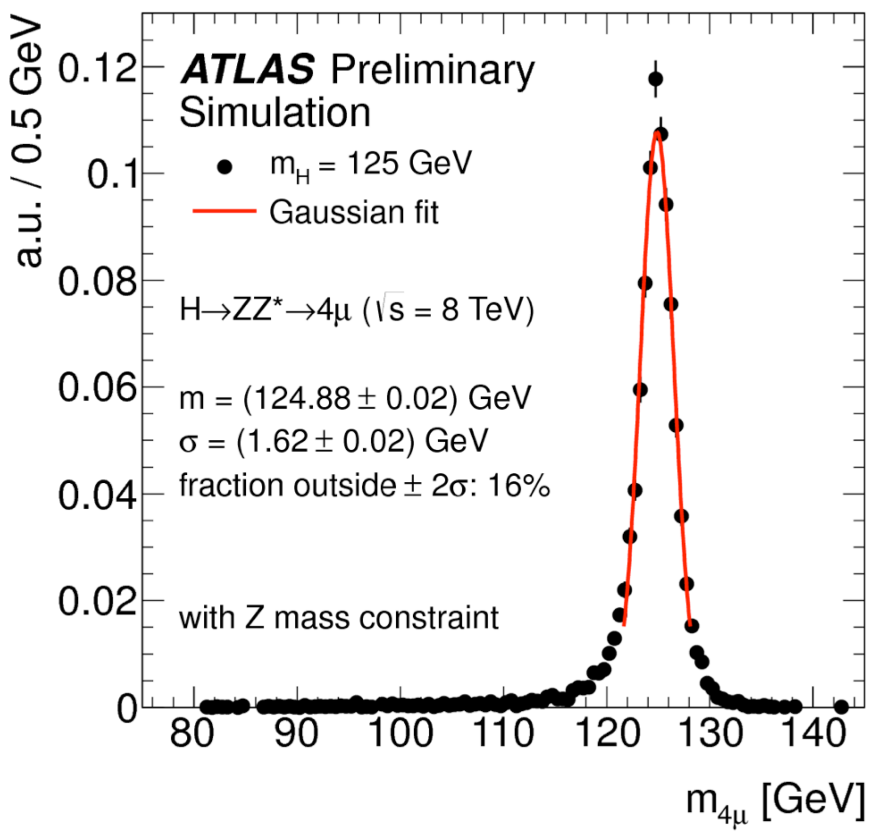


H -> ZZ -> 4 Leptons



- Challenges
  - very small rate
  - lepton identification and reconstruction efficiency
  - about 15 selected events in $21fb^{-1}$
- Advantage
  - Mass can be fully reconstructed -> narrow peak
  - Pure, i.e. S/B~1
- Main backgrounds:
  - ZZ$^{(*)}$ production (irreducible)

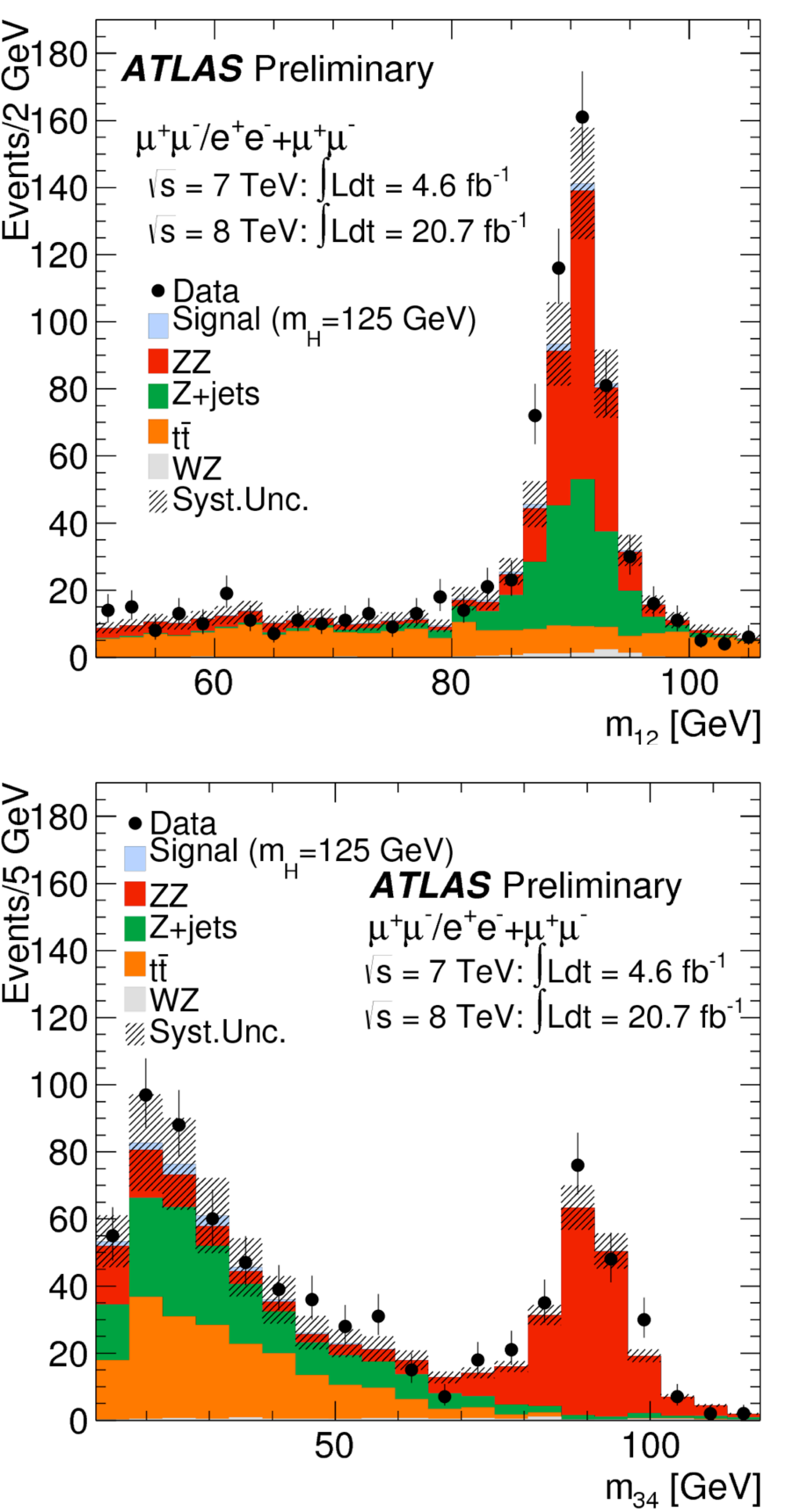




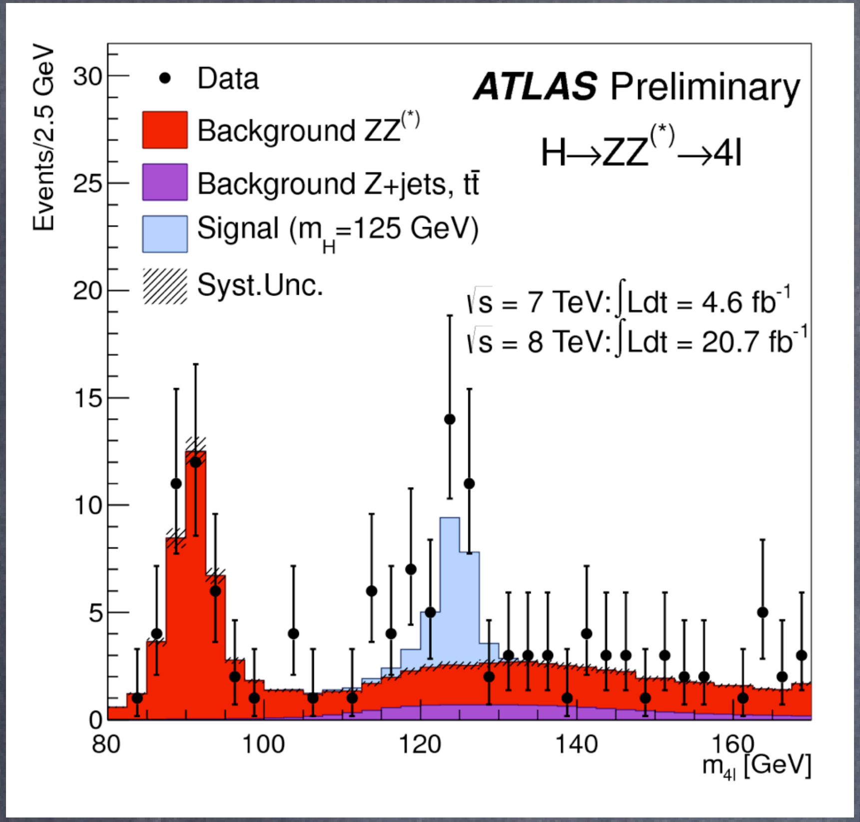
ATLAS-CONF-2013-013

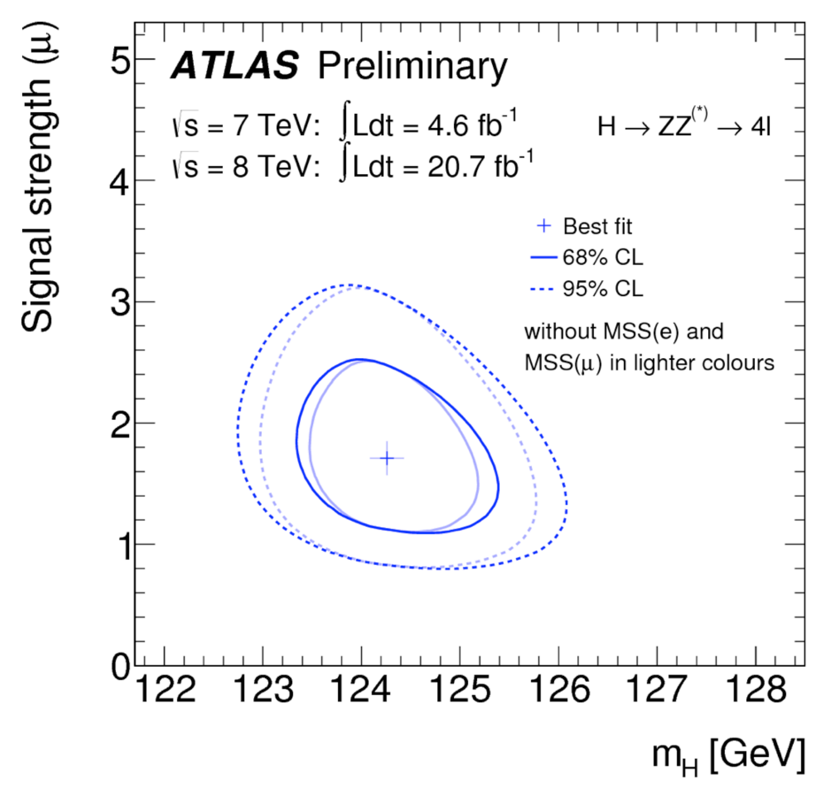
H -> ZZ -> 4l: backgrounds

- Given the low rate, a precise background estimate is crucial
  - Use control regions to measure the background processes with cuts very close to actual analysis selection
- Example on the right:
  - Z+jets and ttbar estimate by relaxing lepton criteria on the 3rd and 4th lepton
  - Clear separation of the backgrounds allows for the extraction of both backgrounds



H -> ZZ -> 4l: results





- Mass:

$$m_H = 124.3^{+0.8}_{-0.6}\ \text{GeV}$$

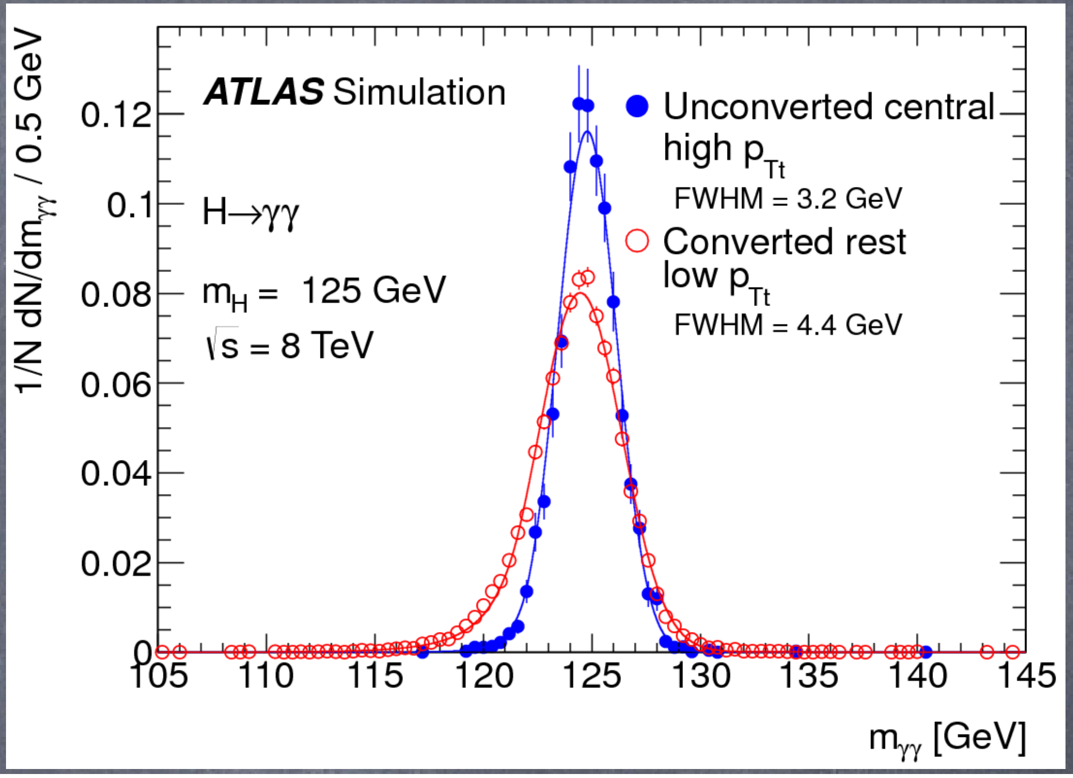
- Signal strength:

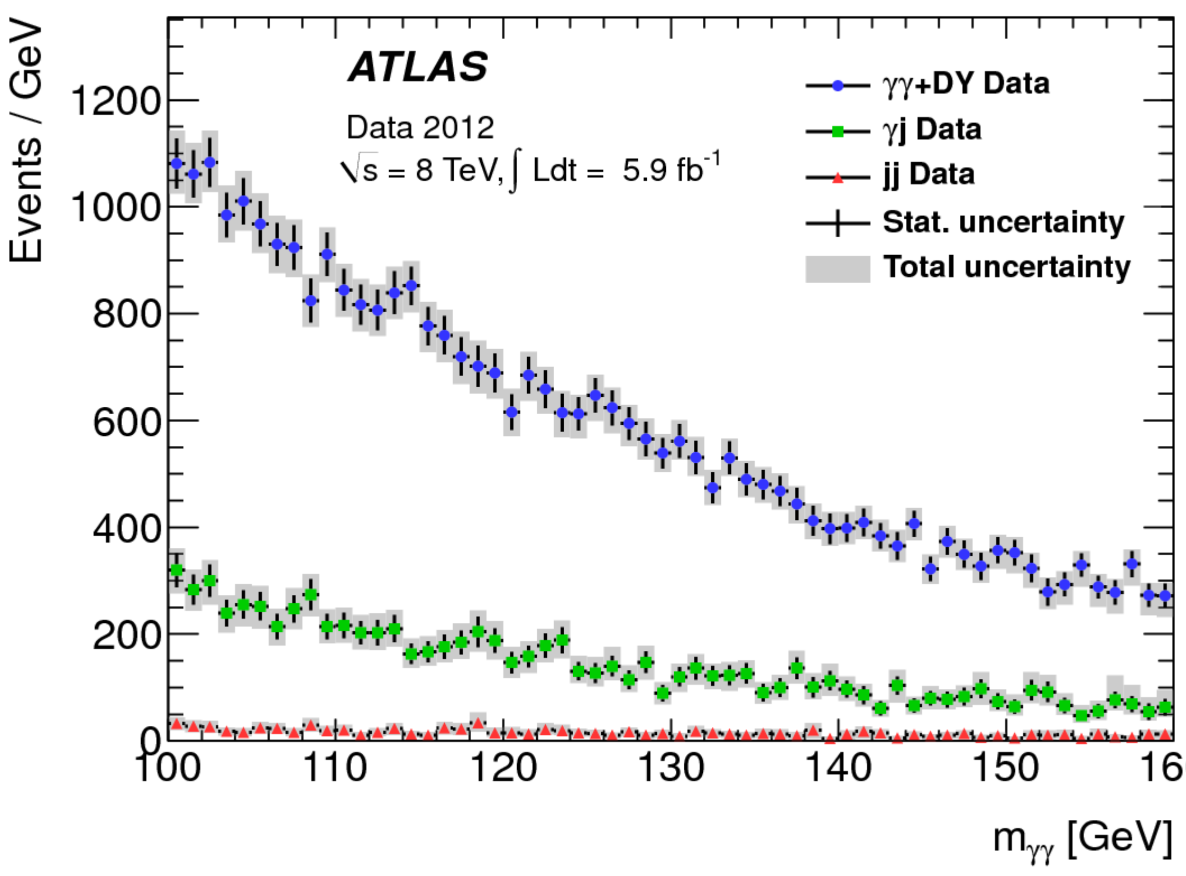
$$\mu = \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}} = 1.7^{+0.5}_{-0.4}$$

	total signal full mass range	signal 125^{+5}_{-5} GeV	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	S/B	expected	observed
			$\sqrt{s}$ = 8 TeV and $\sqrt{s}$ = 7 TeV				
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

H->γγ

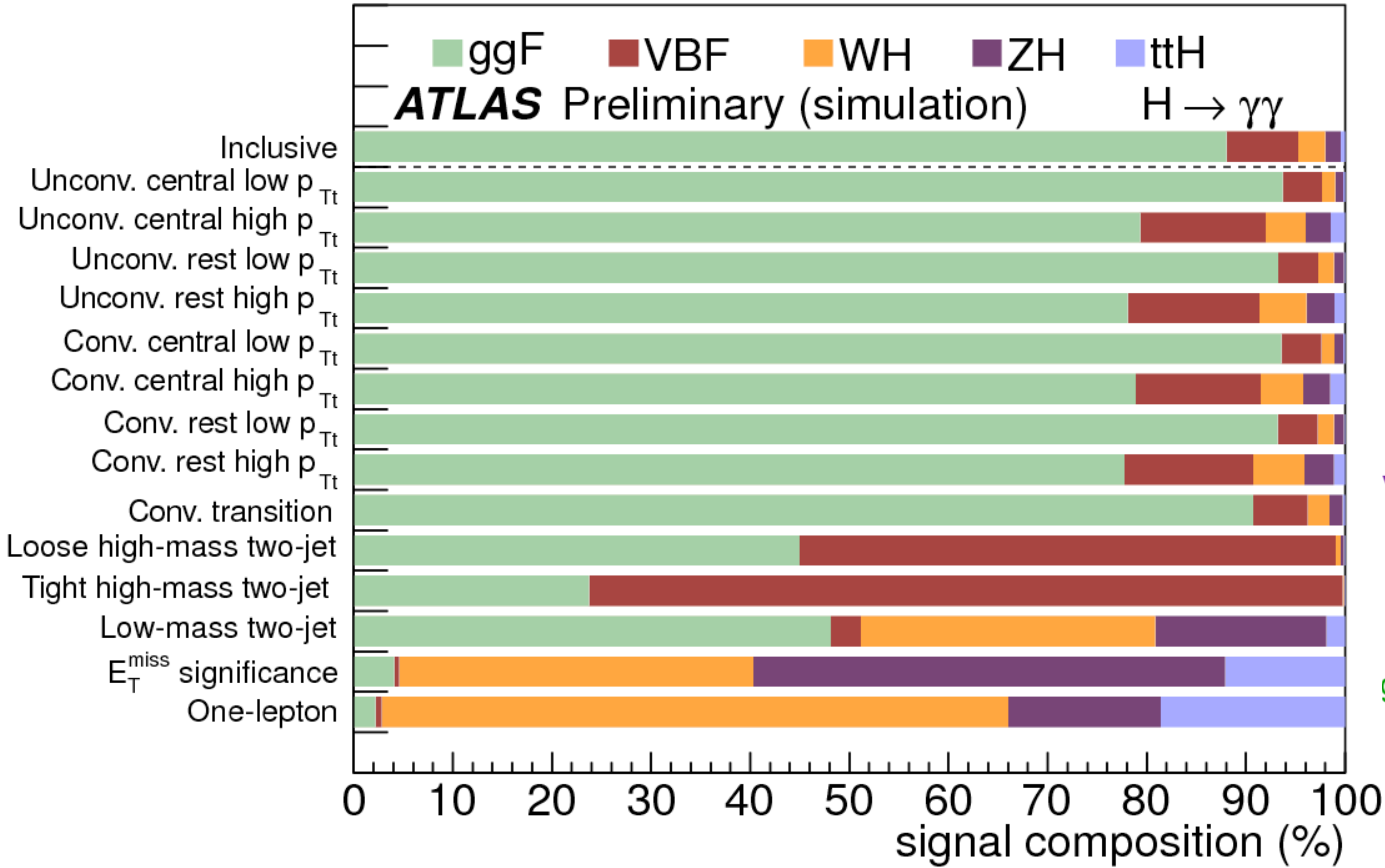
- Signature:
  2 isolated energetic photons
- Small branching ratio but good signal yield
  - Expect O(500) signal events after selection in current data
- Good mass resolution -> clear peak over smooth background
- Main backgrounds:
  - γγ(30 pb, irreducible)
  - γj (200 pb, reducible)
  - jj (500 mub, reducible)
  - Need powerful γ-jet rejection O(10^4)

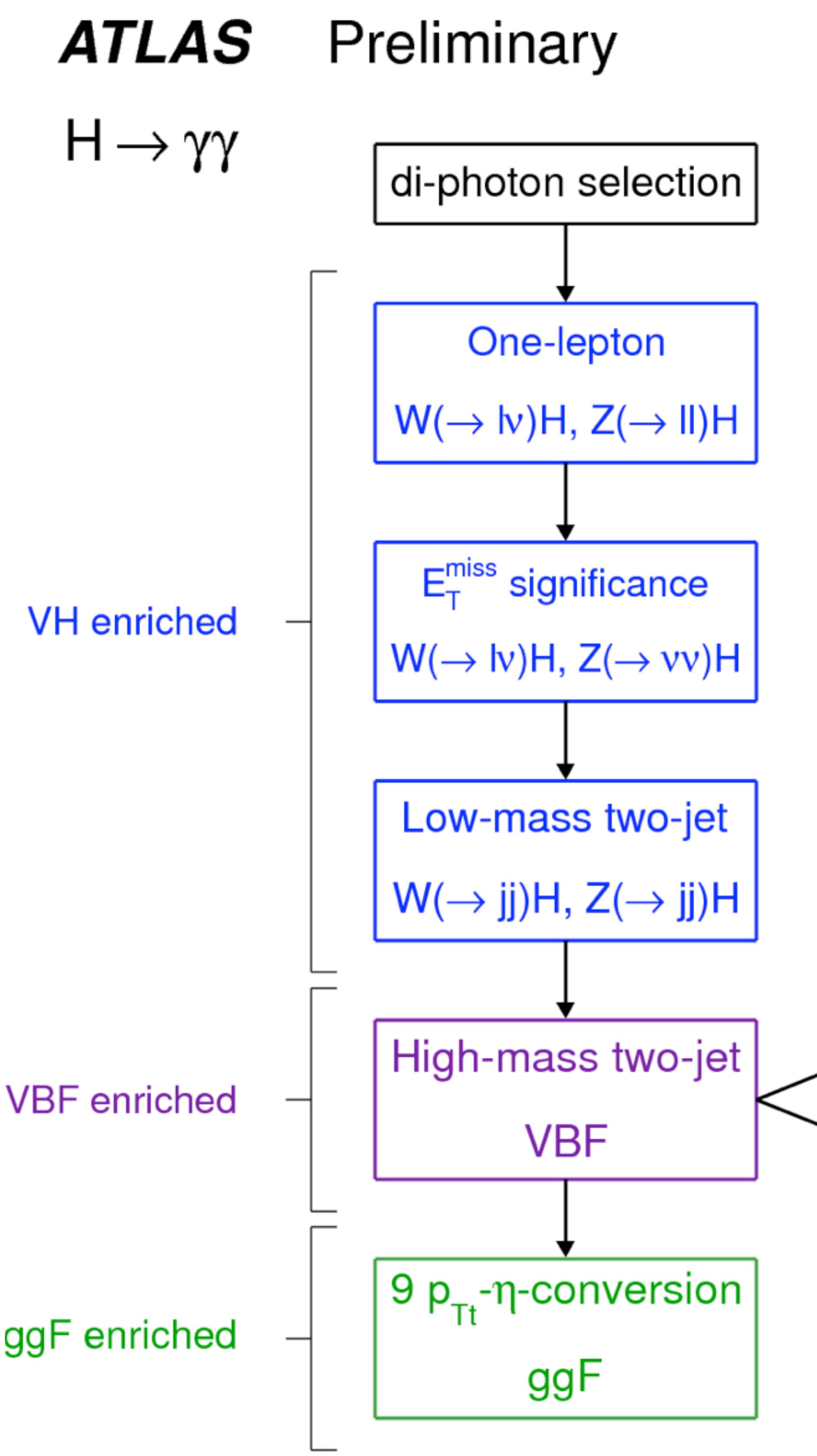




ATLAS-CONF-2013-012

H->γγ categories





ATLAS Preliminary

$H \rightarrow \gamma\gamma$

di-photon selection

VH enriched

One-lepton

$W(\rightarrow l\nu)H$, $Z(\rightarrow ll)H$

E_T^{miss} significance

$W(\rightarrow l\nu)H$, $Z(\rightarrow \nu\nu)H$

Low-mass two-jet

$W(\rightarrow jj)H$, $Z(\rightarrow jj)H$

VBF enriched

High-mass two-jet

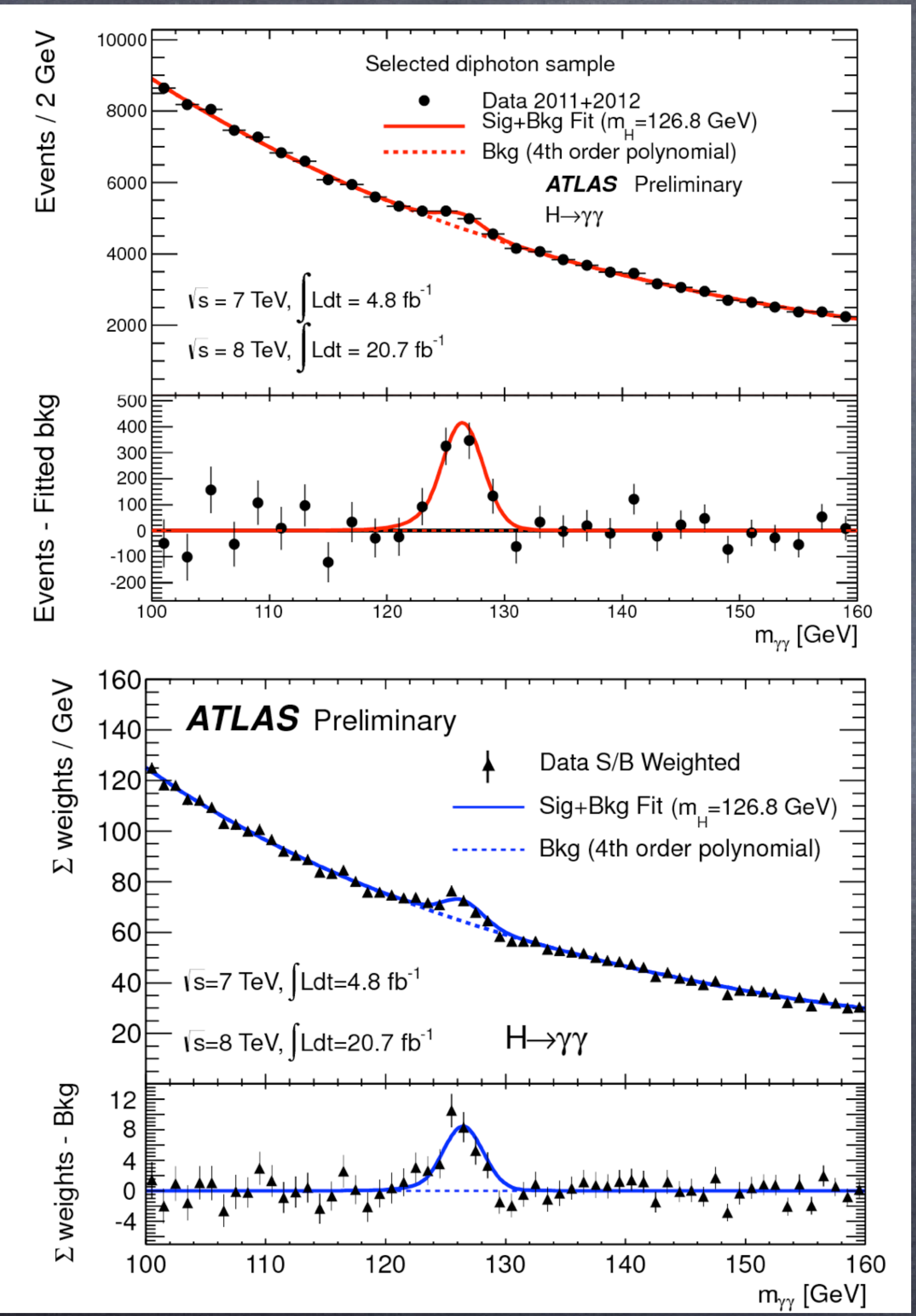
VBF

ggF enriched

9 p_{Tt}-η-conversion

ggF

H->γγ: mass spectra and classes (ATLAS)

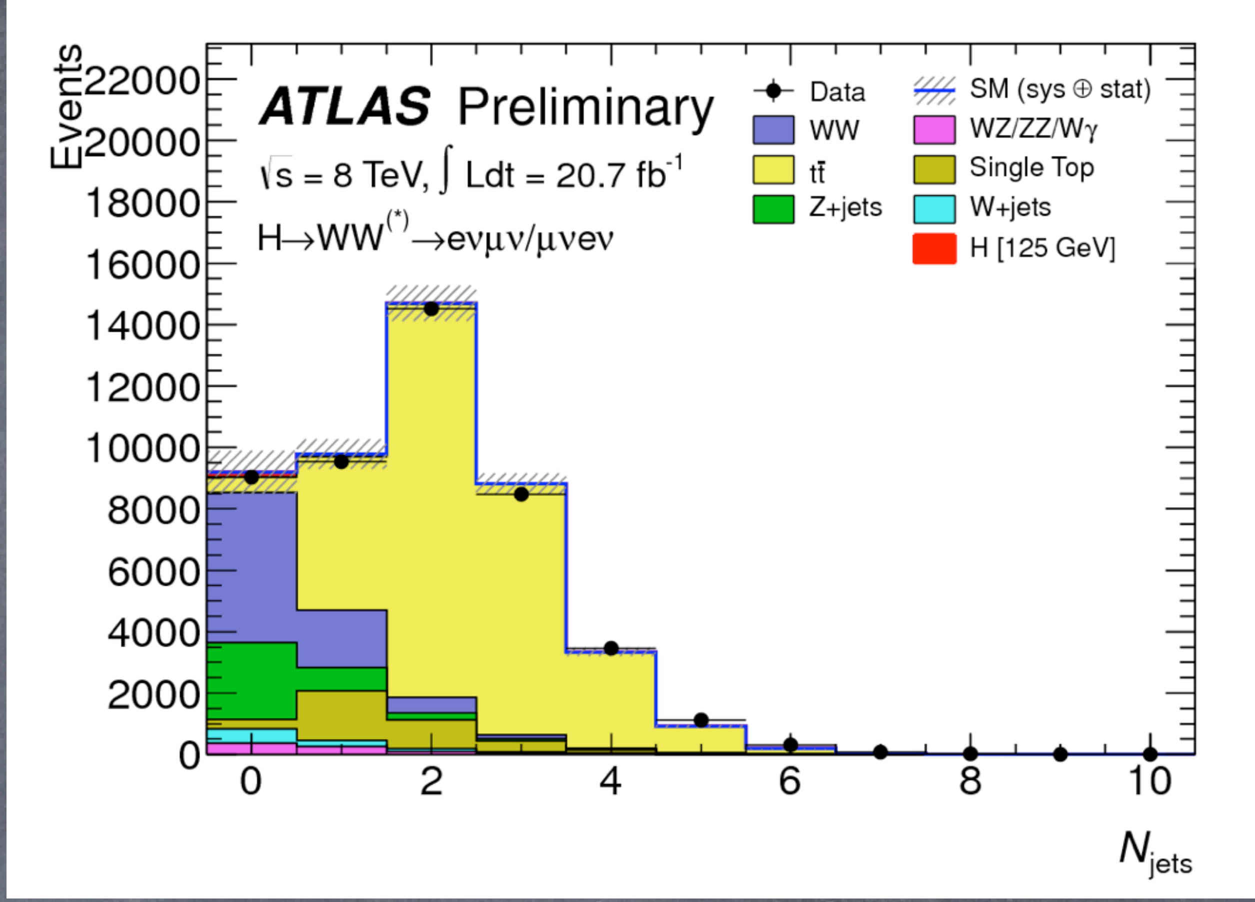


- Enhance sensitivity by splitting into event categories
  - 2 VBF + 3 VH + 9 ggF categories converted, central/forward,...

Category	S/B	σ_M/GeV
best	0.57	1.64
worst	0.01	2.52
inclusive	0.03	1.77

- category weight = ln (1+ s/b)
  s/b evaluated in mass window
  containing 90% signal
- analytic model for s and b
- significant excess at M= 126.8 GeV
  signal strength 1.65±0.3 x SM

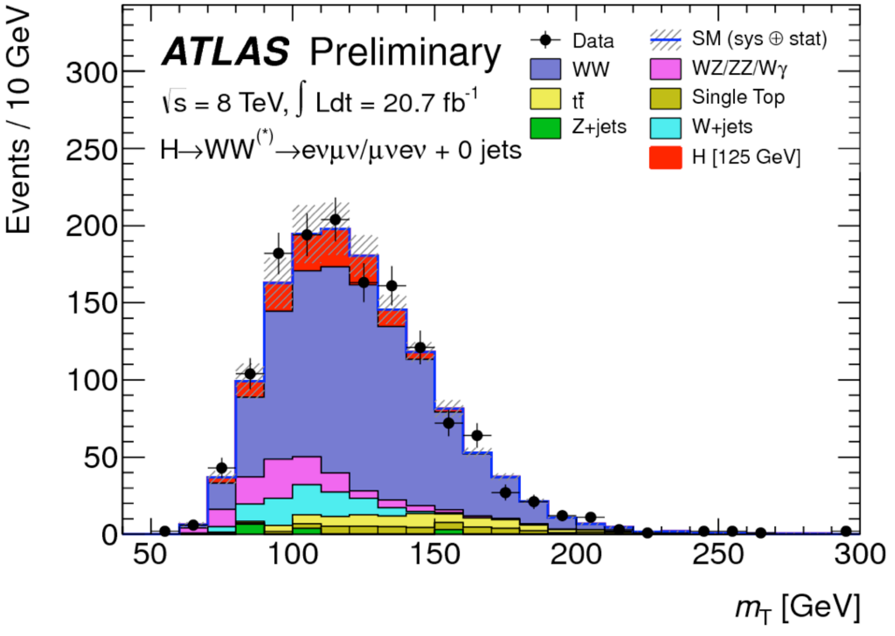
H->WW->lvlv

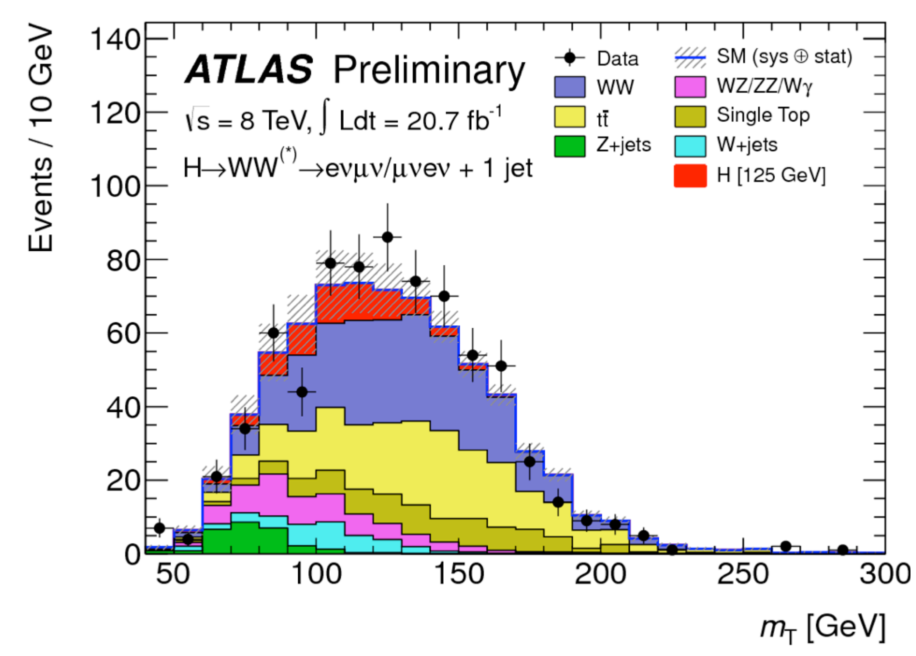


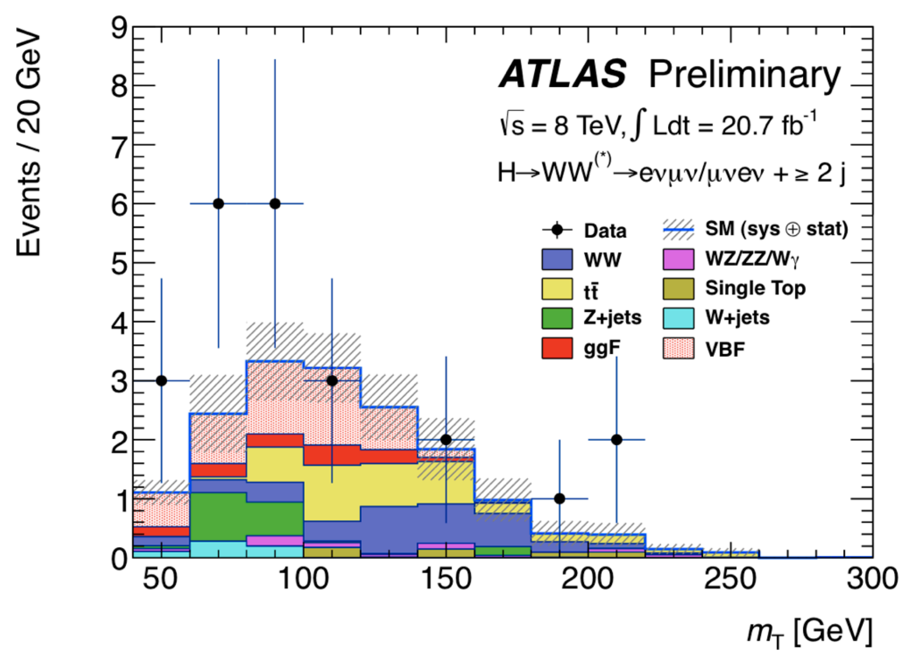
- Most sensitive channel in a wide mass range
- Signature:
  - 2 oppositely charged leptons
  - large missing E_T
- Challenge: poor mass resolution due to 2 neutrinos
  - Use Transverse mass $m_T = \sqrt{(E_T^{ll} + E_T^{\text{miss}})^2 - |\vec{p}_T^{ll} + \vec{p}_T^{\text{miss}}|^2}$
  - Fit shape of mT to extract signal contribution
  - Classify events by number of jets
    - 0 jets dominated by WW background, sensitive to ggF
    - 1+2 jets dominated by top background
    - 2 jets selection to isolate VBF production

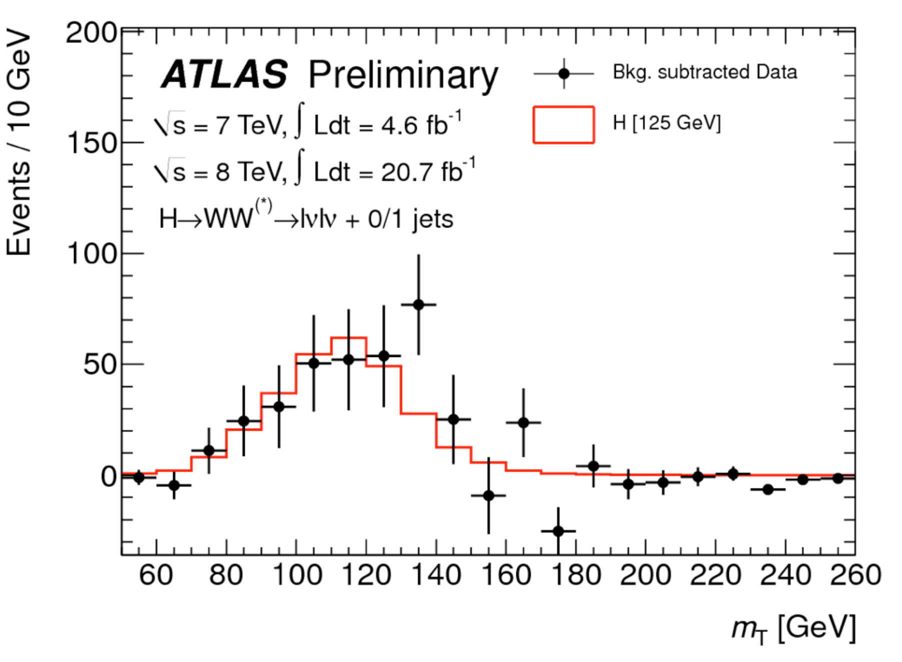
ATLAS-CONF-2013-030

H->WW->lvlv: Results







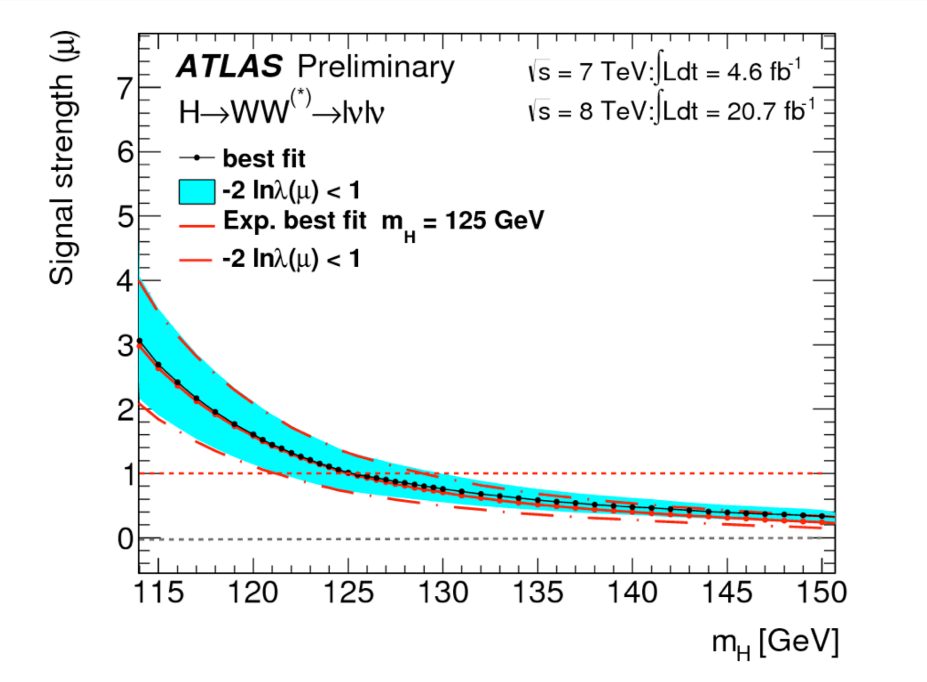


- Signal strength:

$$\mu_{\text{obs}} = 1.01 \pm 0.31$$

$$\mu_{\text{obs,ggF}} = 0.82 \pm 0.36$$

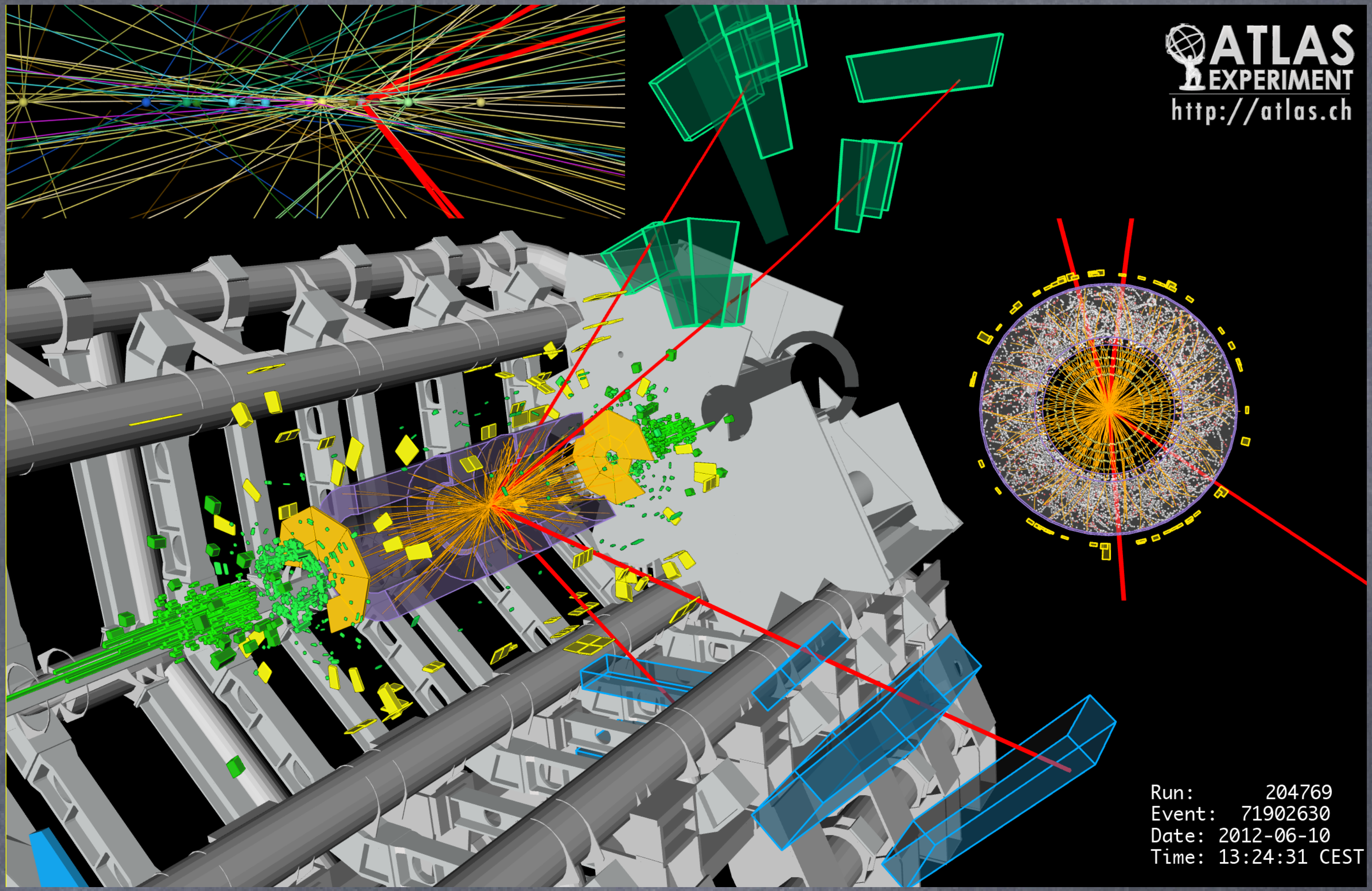
$$\mu_{\text{obs,VBF}} = 1.66 \pm 0.79$$



N_{jet}	N_{obs}	N_{bkg}	N_{sig}
$= 0$	831	739 ± 39	97 ± 20
$= 1$	309	261 ± 28	40 ± 13
≥ 2	55	36 ± 4	10.6 ± 1.4

Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
    - Couplings
    - Spin and CP
- Other searches
- Summary & Outlook

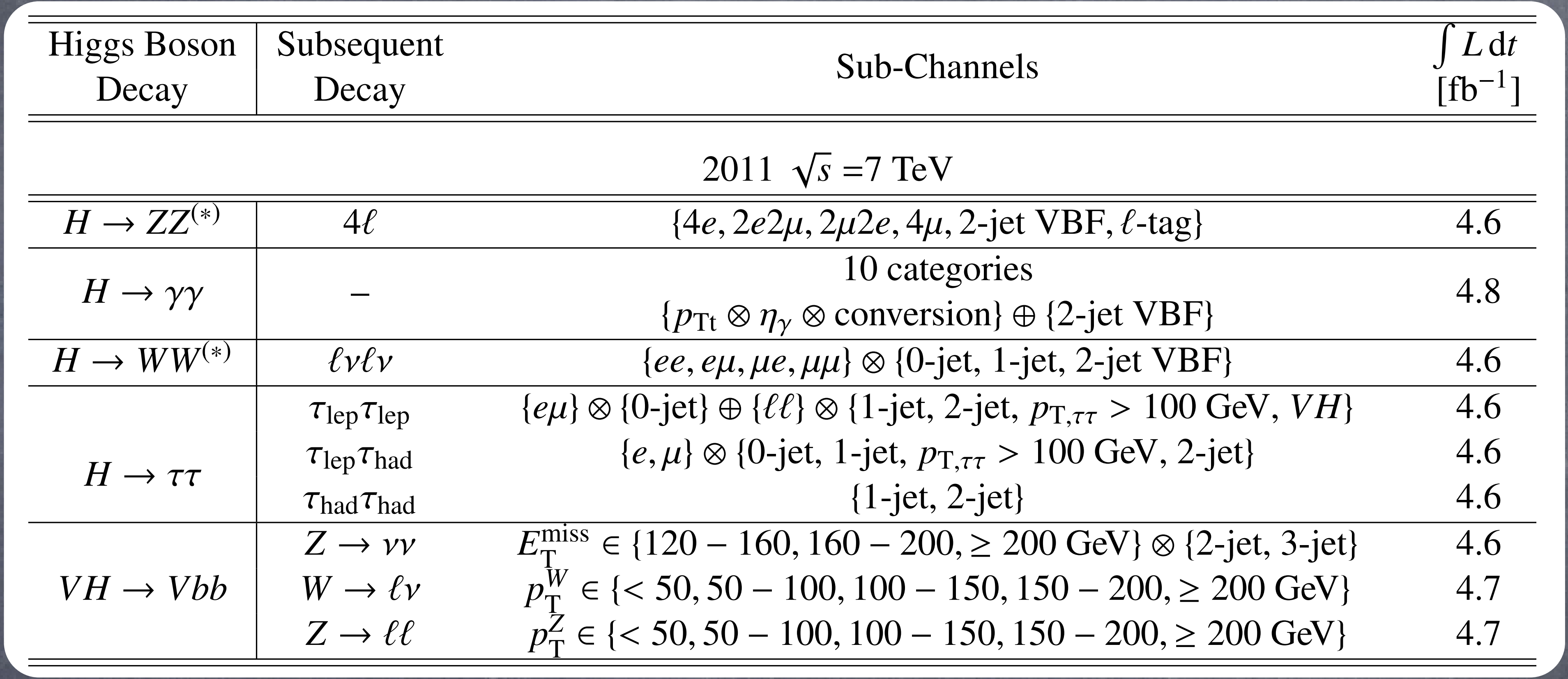


Inputs to the combination

- Combination of many different channels. Further subdivision enhances sensitivity (e.g. H->γγ)

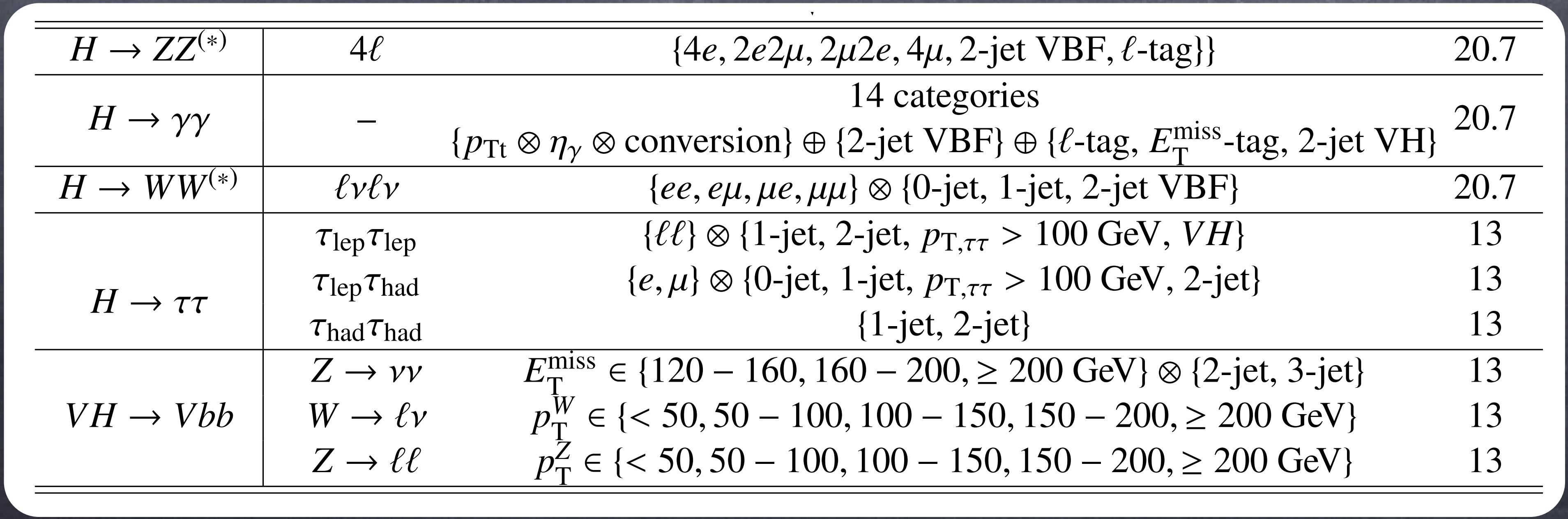
ATLAS-CONF-2013-014
ATLAS-CONF-2013-034

2011



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

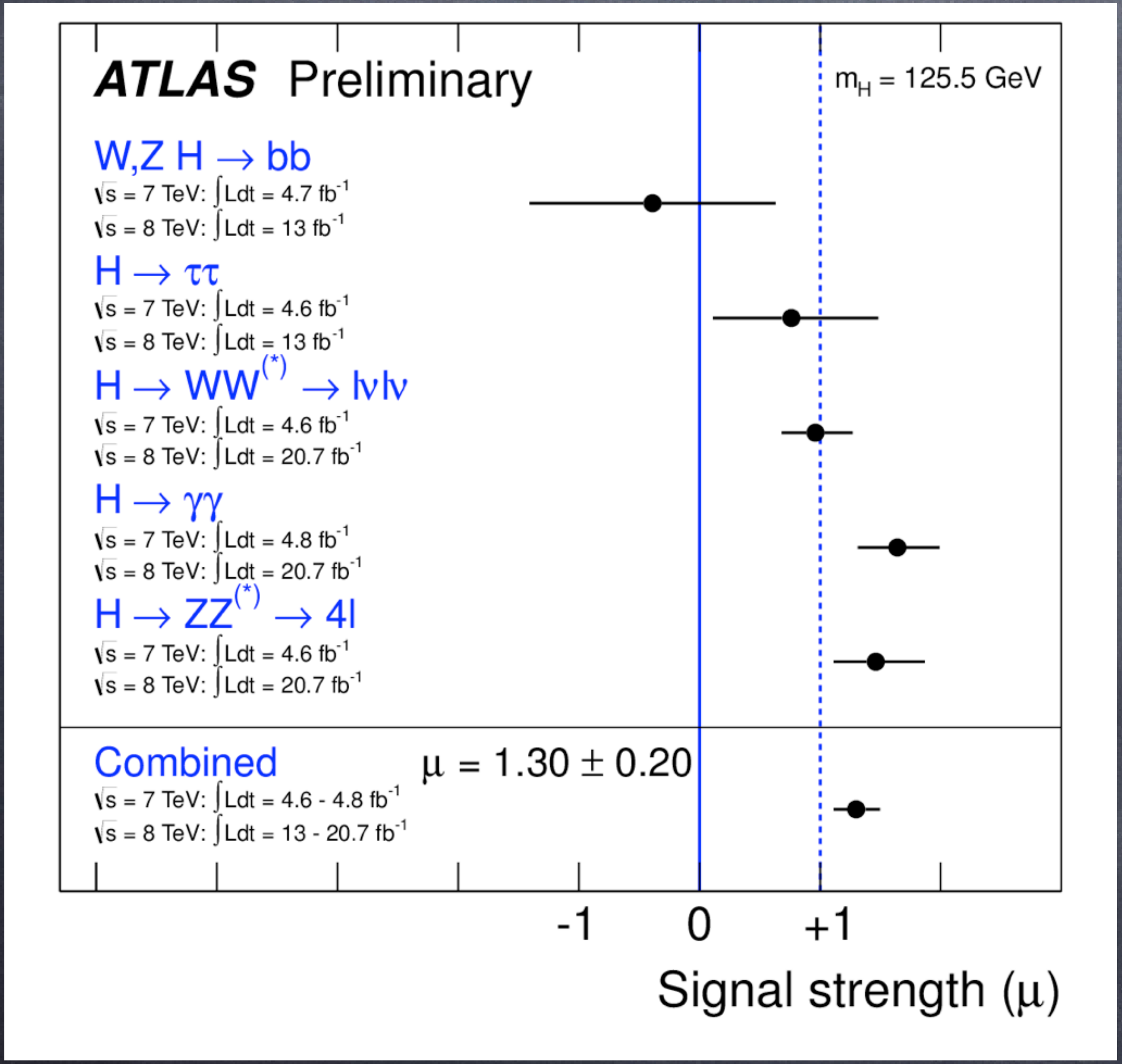
2012

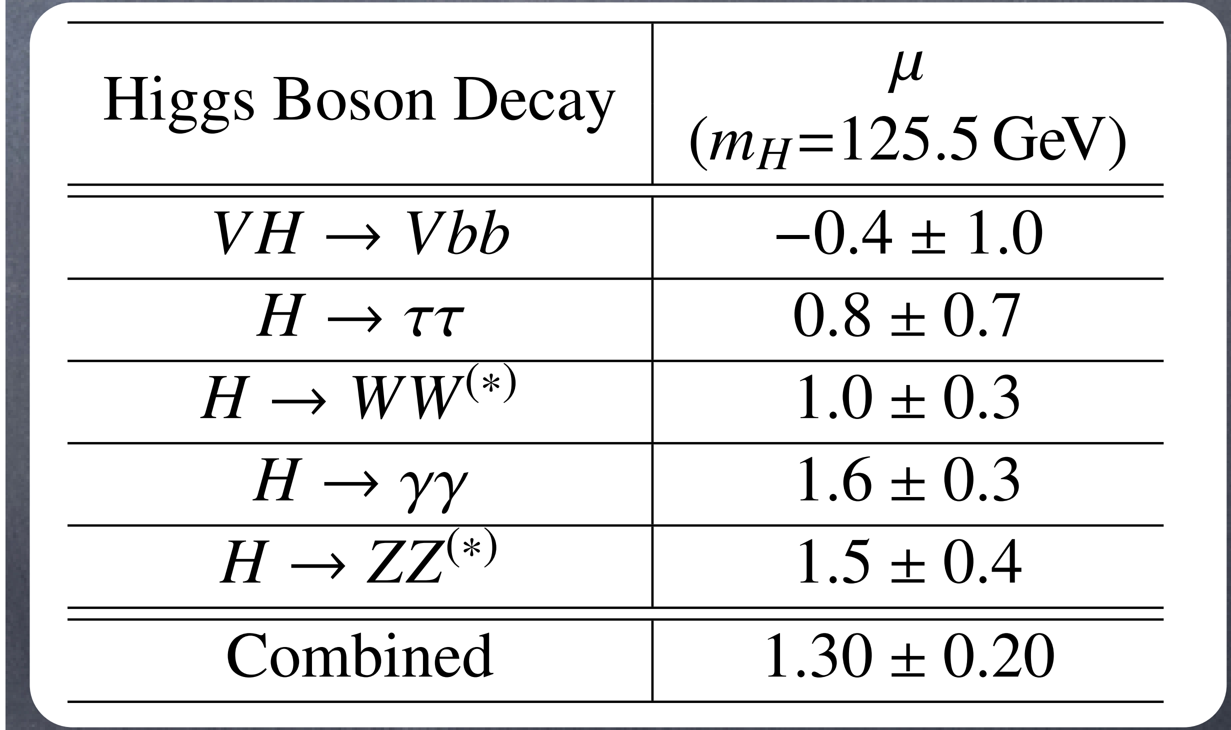


$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu$, 2-jet VBF, ℓ-tag$\}\}$	20.7
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH$\}$	20.7
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	20.7
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	13
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	13
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	13
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	13
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13

Signal strength $\mu = \sigma_{\mathrm{obs}}/\sigma_{\mathrm{SM}}$

- Significant excess in all three dominant channels (γγ, ZZ, WW) compared to background only
    - H->b$\bar{b}$ and H->ττ not yet updated to full dataset

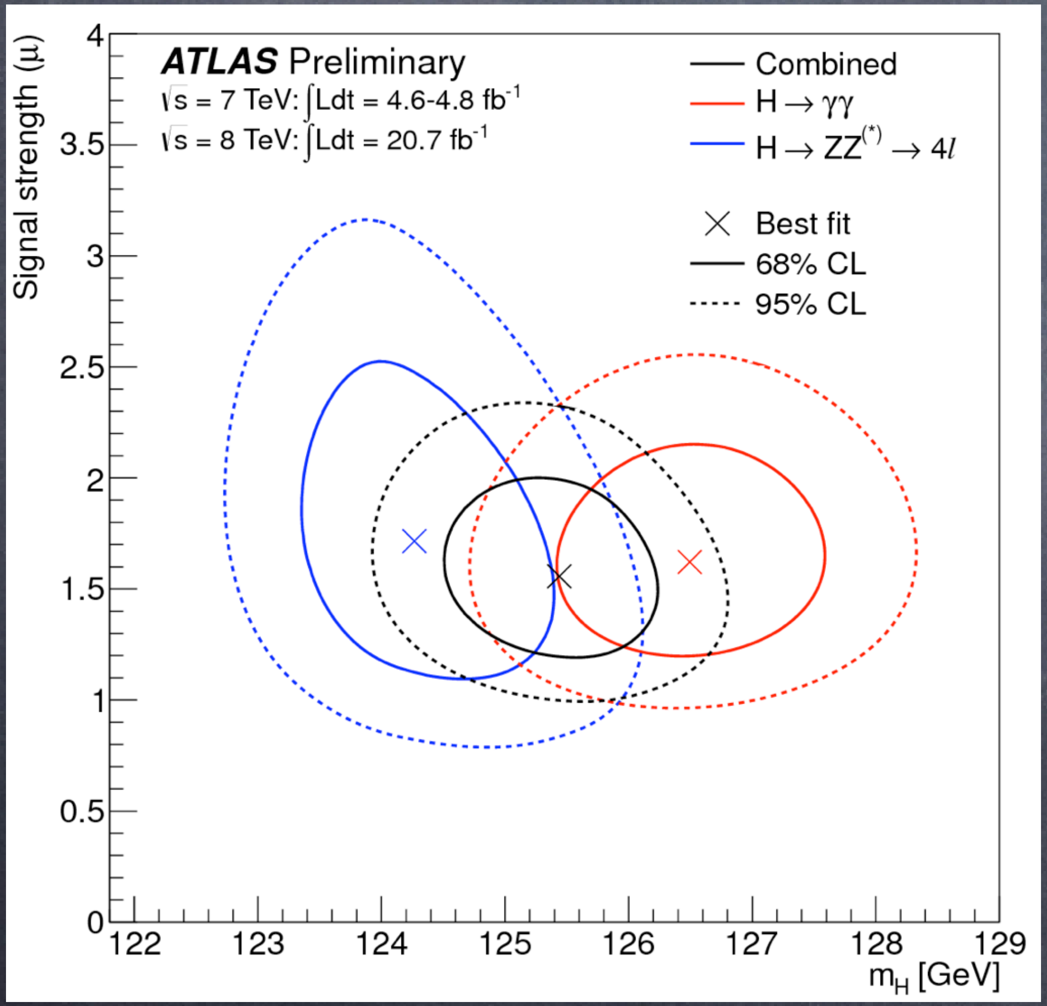


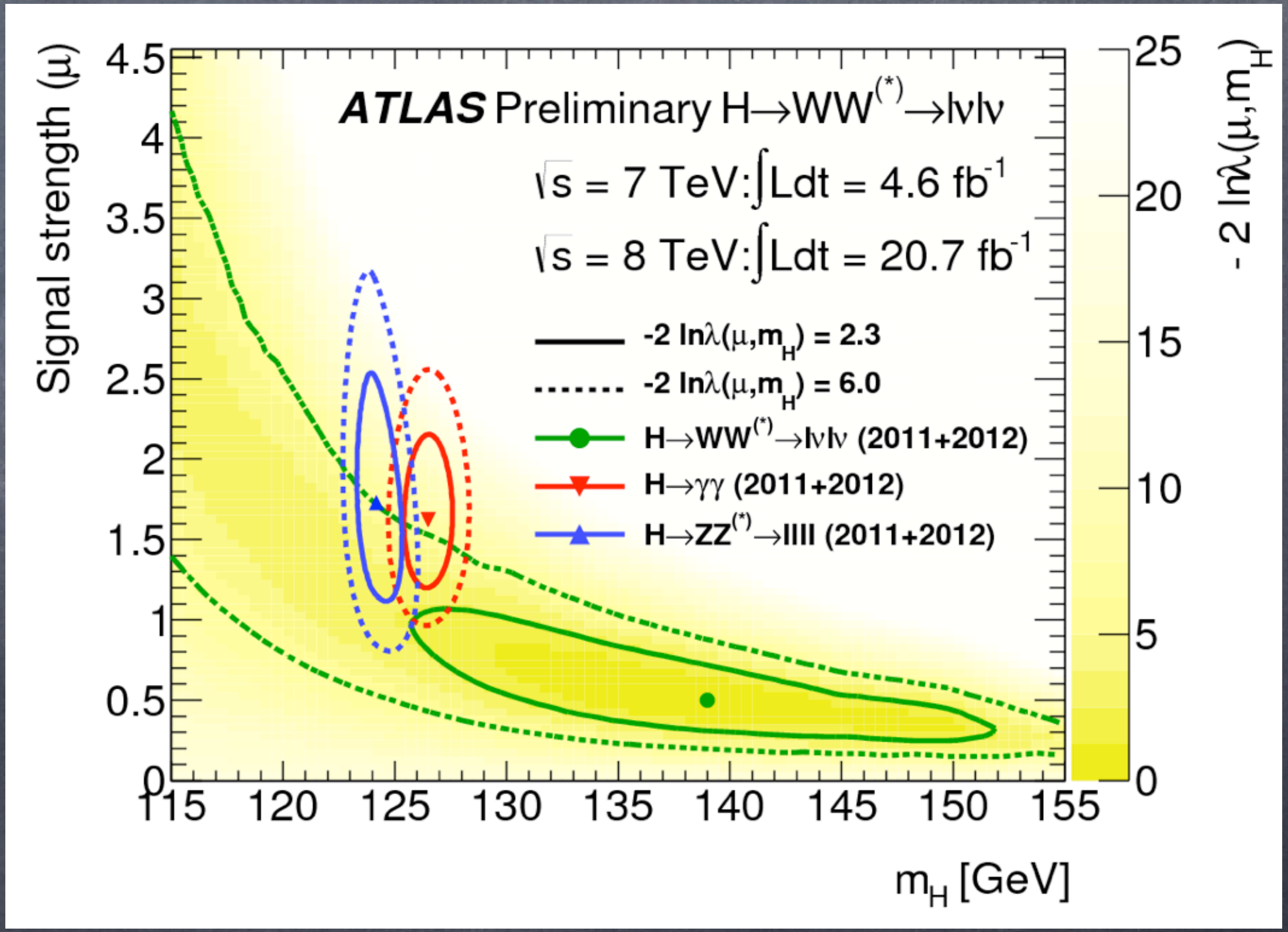


Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \rightarrow Vbb$	–0.4 ± 1.0
$H \rightarrow \tau\tau$	0.8 ± 0.7
$H \rightarrow WW^{(*)}$	1.0 ± 0.3
$H \rightarrow \gamma\gamma$	1.6 ± 0.3
$H \rightarrow ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

Compatibility of m_H and μ

- Mass information from high resolution channels H->γγ and H->ZZ->4l
  - H->WW->lνlν has only poor resolution due to the neutrinos in the final state

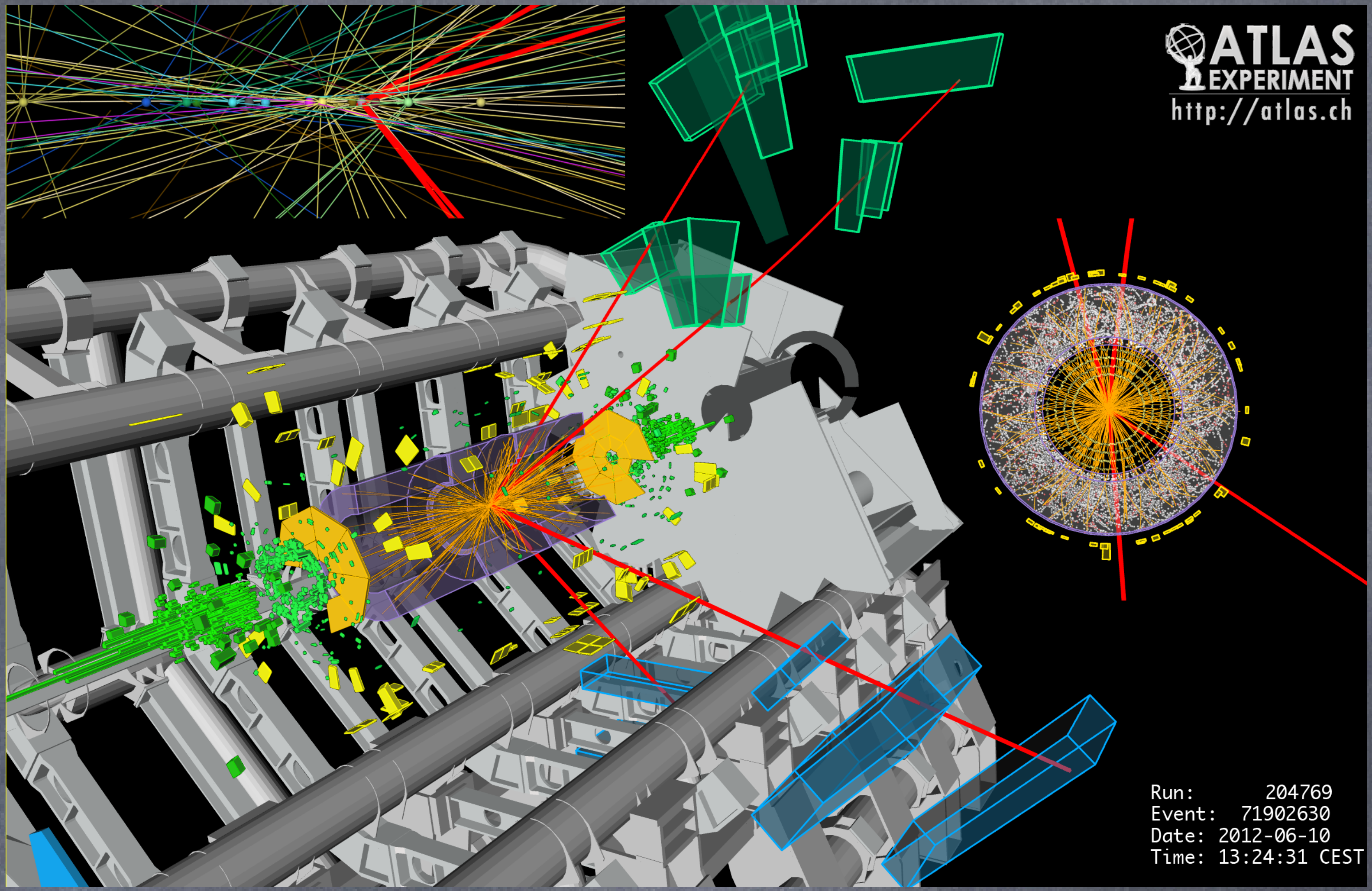




$$m_{\rm H} = 125.5 \pm 0.2({\rm stat})^{+0.5}_{-0.6}({\rm sys})\ {\rm GeV}$$

Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook

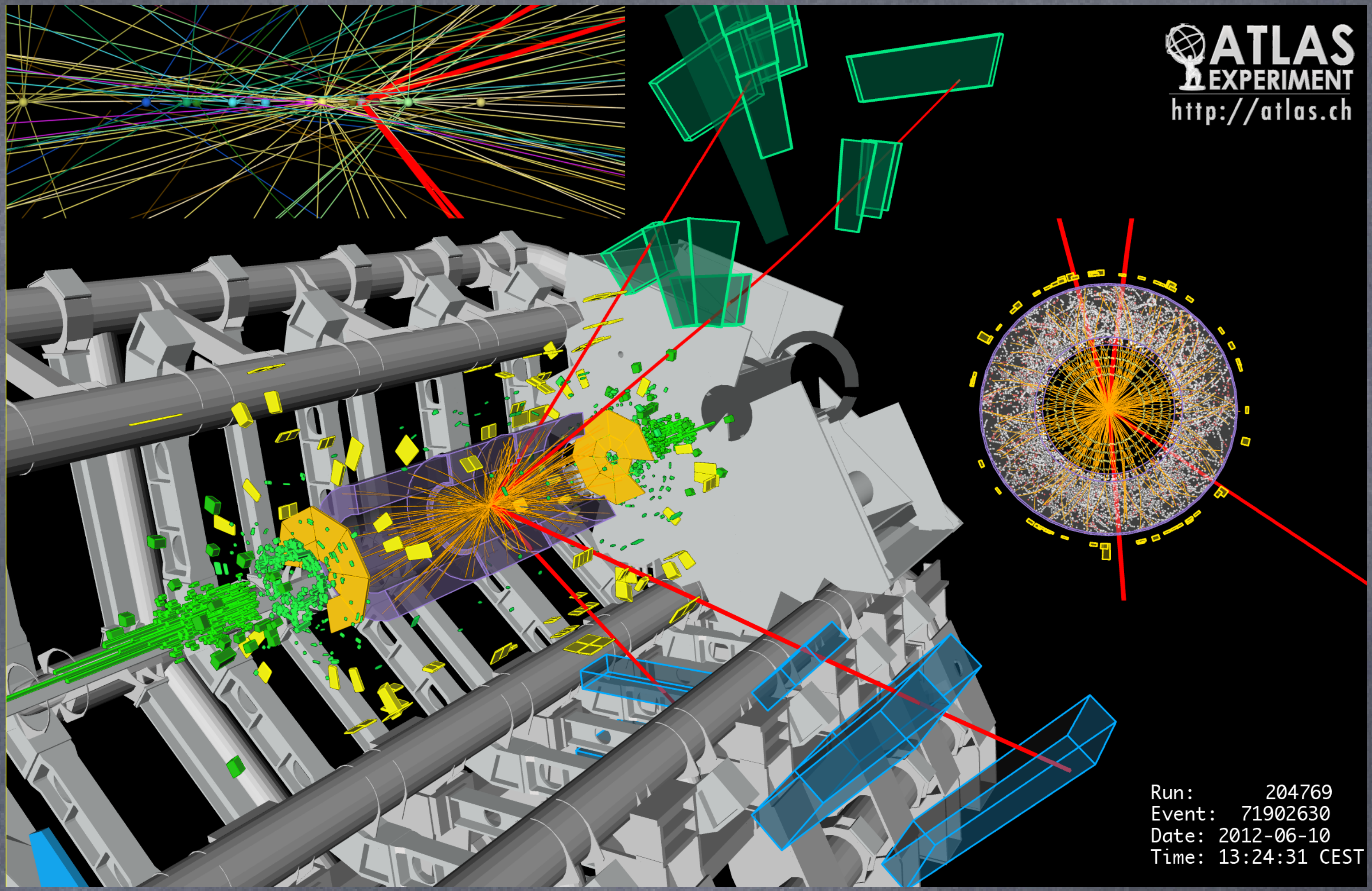


Is it the SM Higgs?

- New particle decays into two particles with identical spin and charge sum 0
  - Discovery of a neutral boson
- Overall signal strength consistent with SM prediction (also for individual channels with still large uncertainties)
- Couplings of the Higgs in the SM are fixed for a given m_H
  - Need to probe coupling structure of new particle!
- Spin and CP?
  - Spin 1 hypothesis very unlikely due to the decay into two photons (disfavoured for spin 1 by Landau-Yang theorem)
  - Selection in H->WW makes use of predictions for spin 0

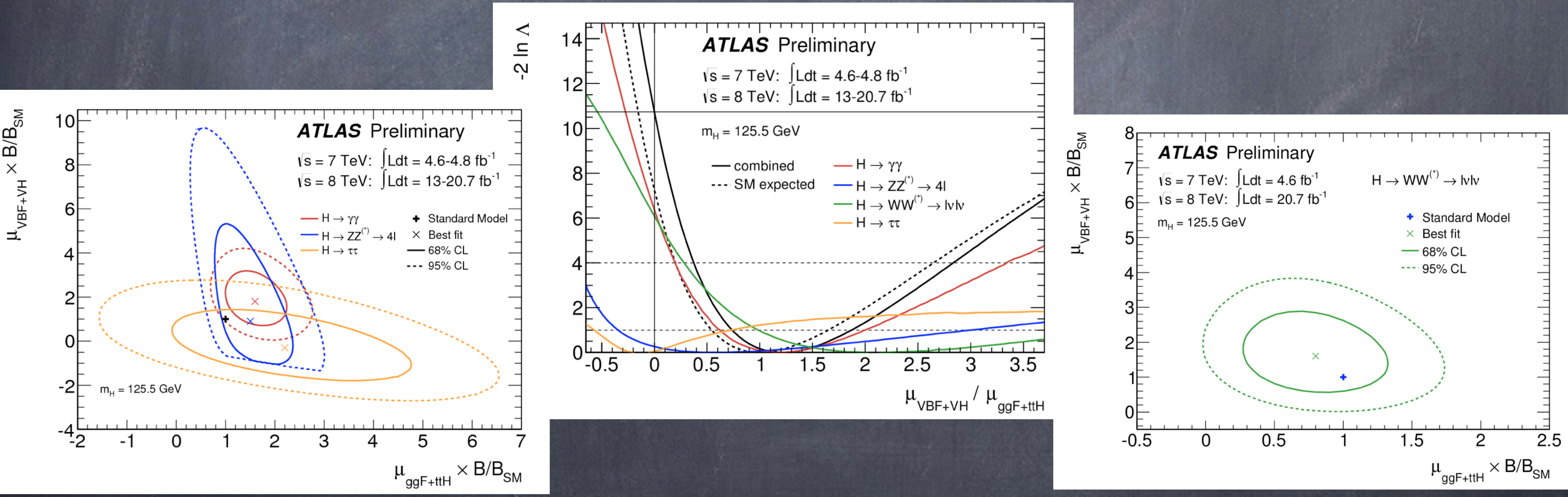
Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook



Production mechanism

- Group the production modes into 2 groups
  - ggF and $t\bar{t}H$ scale with the $t\bar{t}H$ coupling in the SM
  - VBF and VH scale with the WWH/ZZH coupling in the SM
- m_H fixed to 125.5 GeV



$$\mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} = 1.2^{+0.7}_{-0.5}$$

Closer look at couplings

- Assumptions:
  - Signals originate from a single resonance with mass of 125.5 GeV with a negligible width.
    Narrow width approximation can be used:

$$(\sigma \cdot \mathrm{BR})(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

  - Only modifications of coupling strengths, i.e. absolute values of couplings, are taken into account: the observed state is assumed to be scalar, CP even
- Introduce scale factors k_i such that the cross sections and partial decay width associated with particle i scale with k_i^2

$$(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma) = \kappa_g^2 \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \frac{\kappa_\gamma^2}{\kappa_\mathrm{H}^2} \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)$$

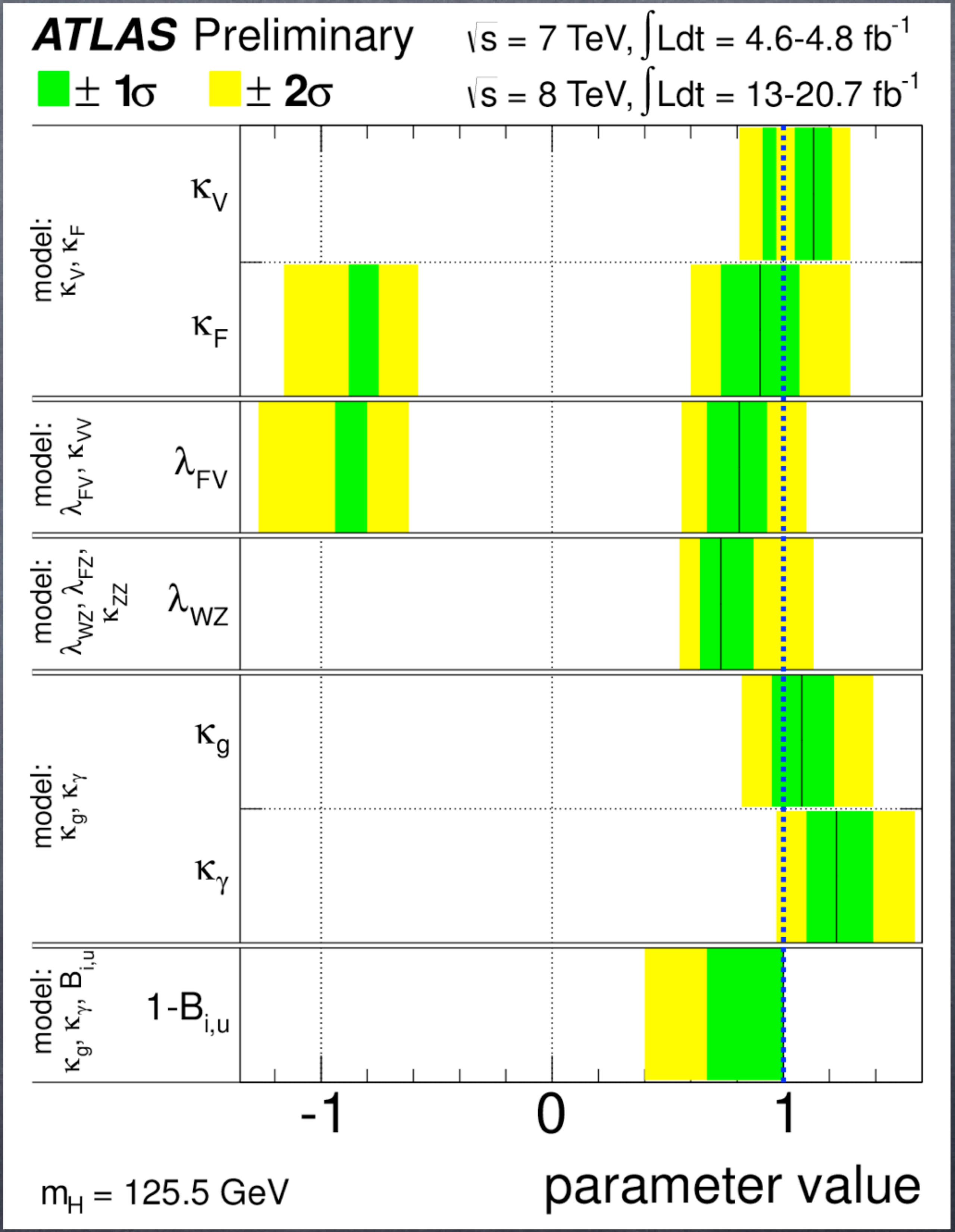
Summary of coupling tests

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

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

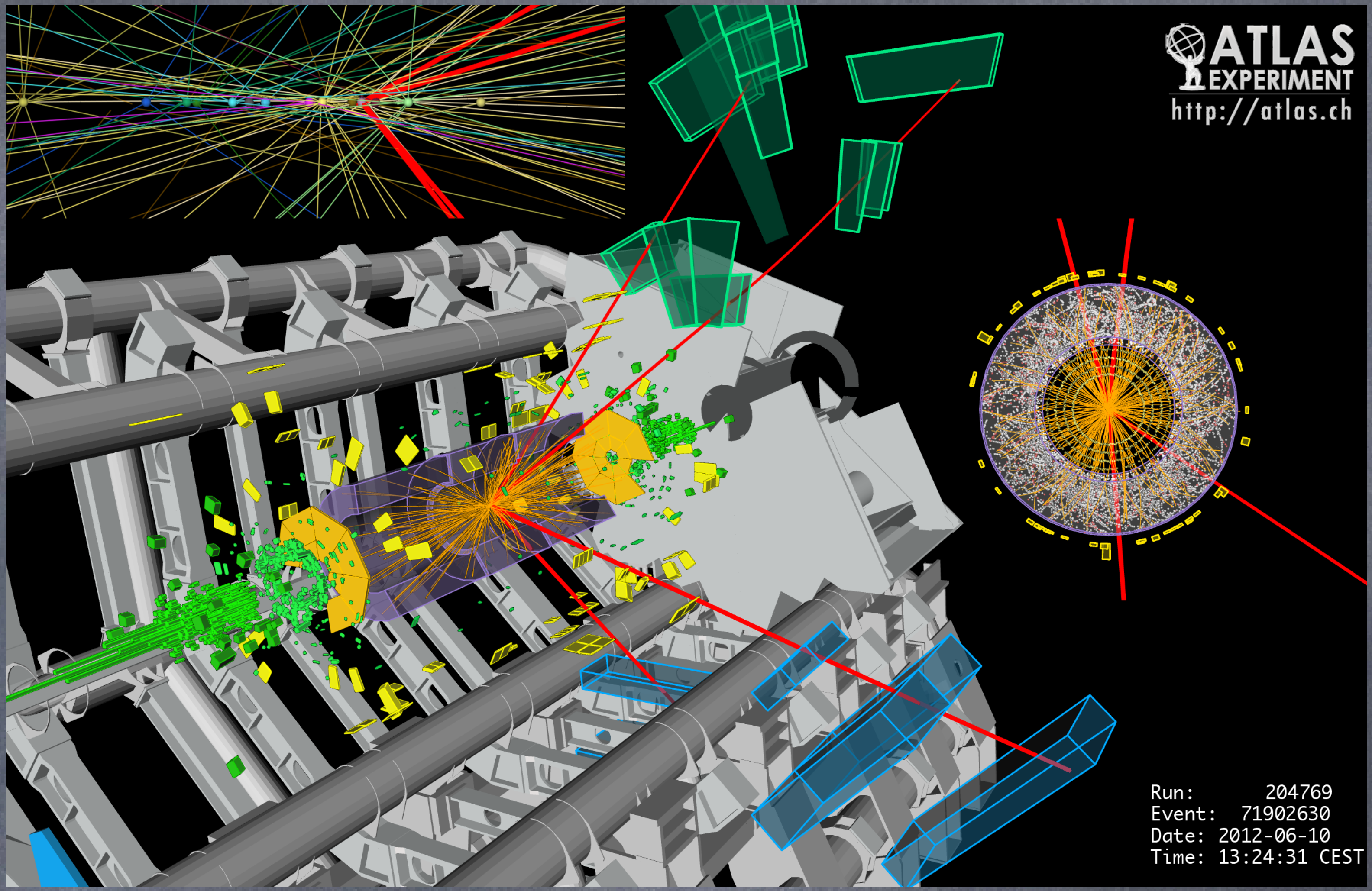
$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z / \kappa_\mathrm{H}$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{FZ} = \kappa_F / \kappa_Z$$

$$\Gamma_\mathrm{H} = \frac{\kappa_\mathrm{H}(\kappa_i)}{1-\mathrm{BR}_\mathrm{inv.,undet.}} \Gamma_\mathrm{H}^\mathrm{SM}$$



Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook



Maybe it is a spin-2 particle?

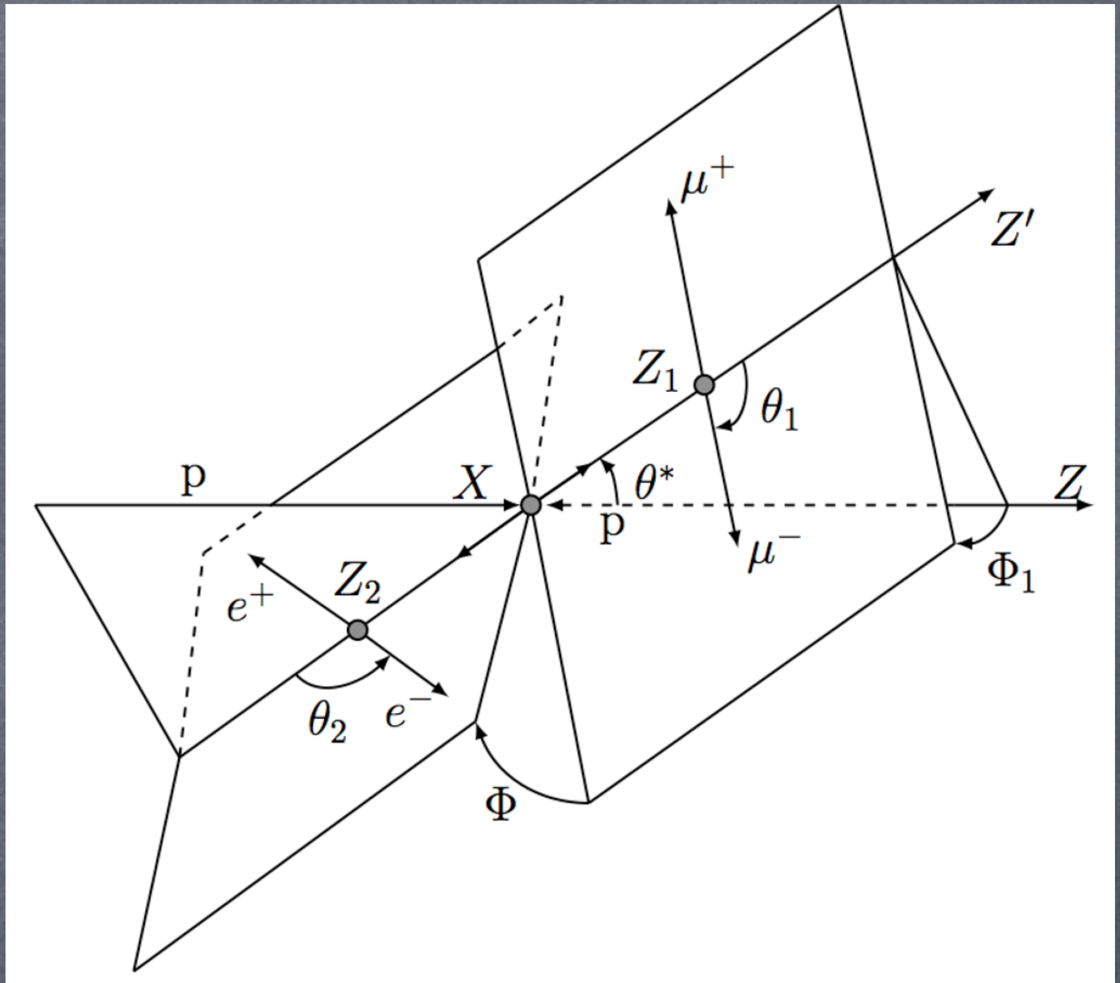
$$\begin{aligned}A(H\to VV) = \Lambda^{-1}\Big[&2g_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2 t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\ &+g_3\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\ &+m_V^2\left(2g_5 t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2g_6\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}) + g_7\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2} t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right) \\ &+g_8\frac{\tilde{q}_\mu\tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta} + g_9 t_{\mu\alpha}\tilde{q}^\alpha\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho} q^\sigma \\ &+\frac{g_{10} t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma} q^\rho\tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\Big]\end{aligned}$$

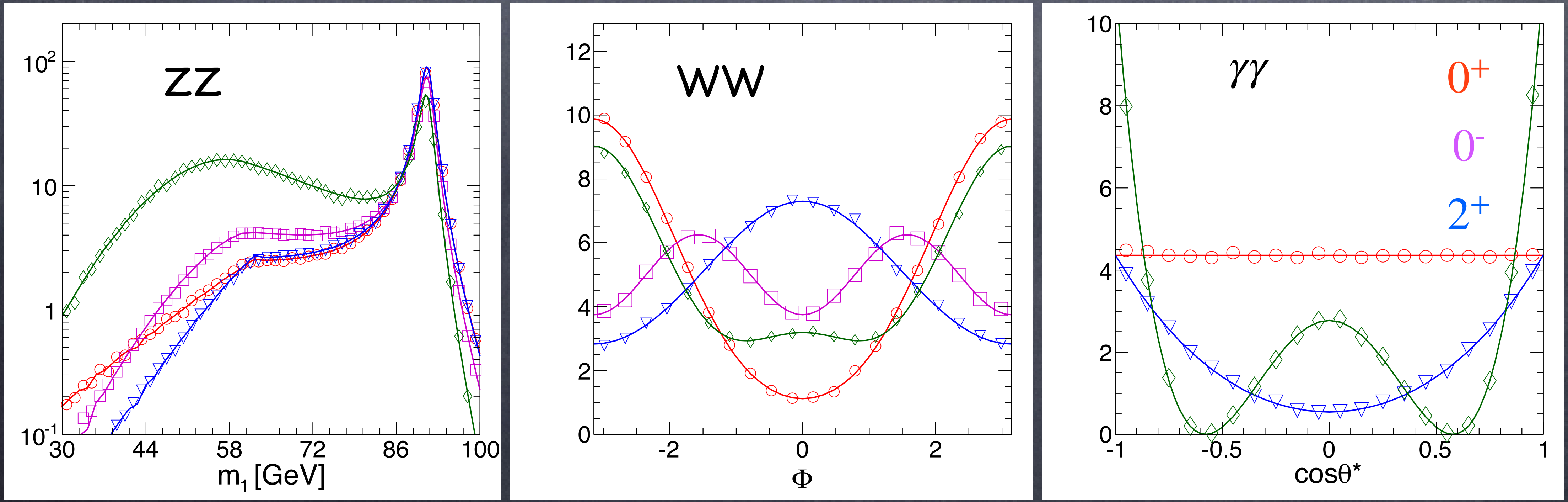
arXiv:1001.3396

- General amplitude for decay into two identical vector bosons contains 10 effective coupling constants g_i
  - Assume $g_1=g_5=1$ (graviton like tensor with minimal couplings)
- Production mode can be via ggF as well as via qqbar
  - Scan as function of the qqbar fraction

Information on spin from decay angle distribution

- Kinematics fully described by five angles and two invariant masses (assuming fixed m_H)
  - Only ZZ events can provide full information (but low statistics)
  - Other channels in principle less sensitive (but higher statistics)



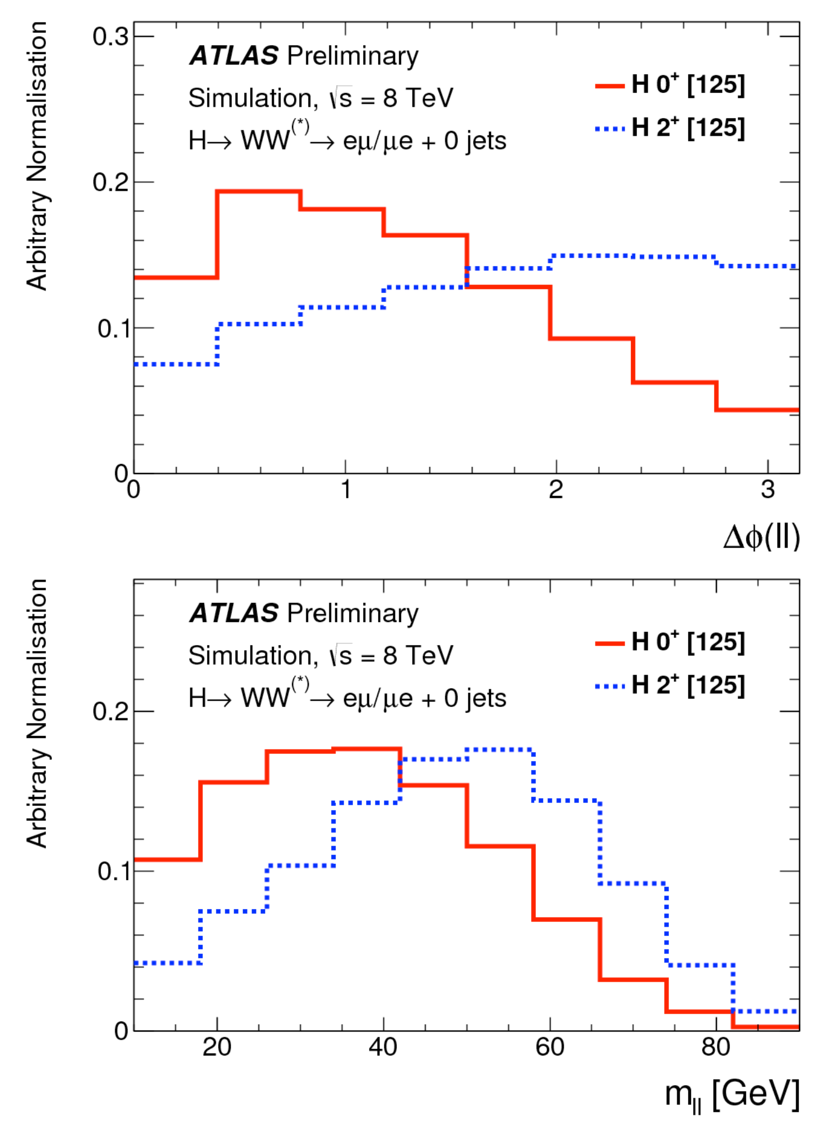


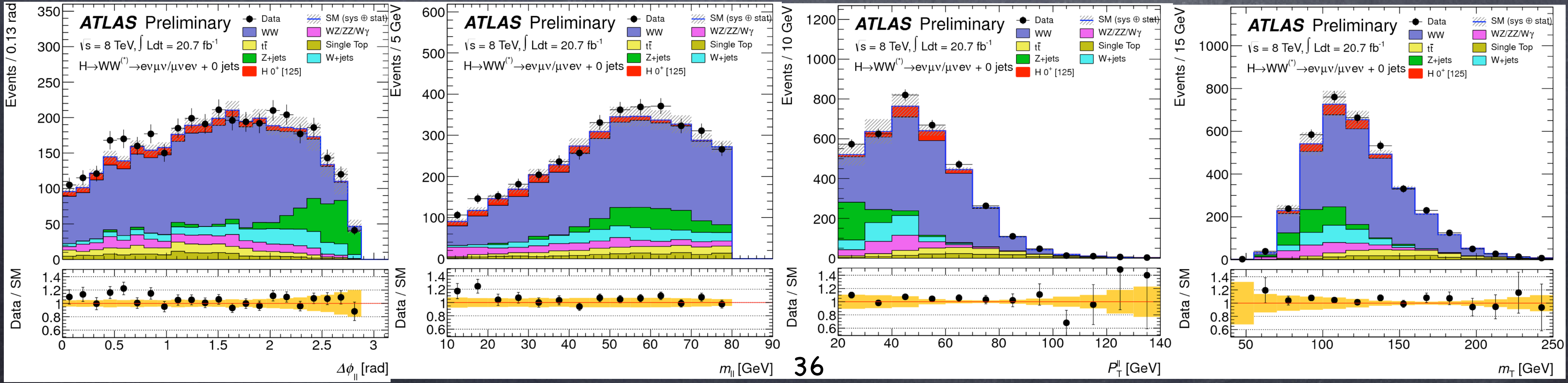
arXiv:1208.4018

Spin in H->WW: method

ATLAS-CONF-2013-031

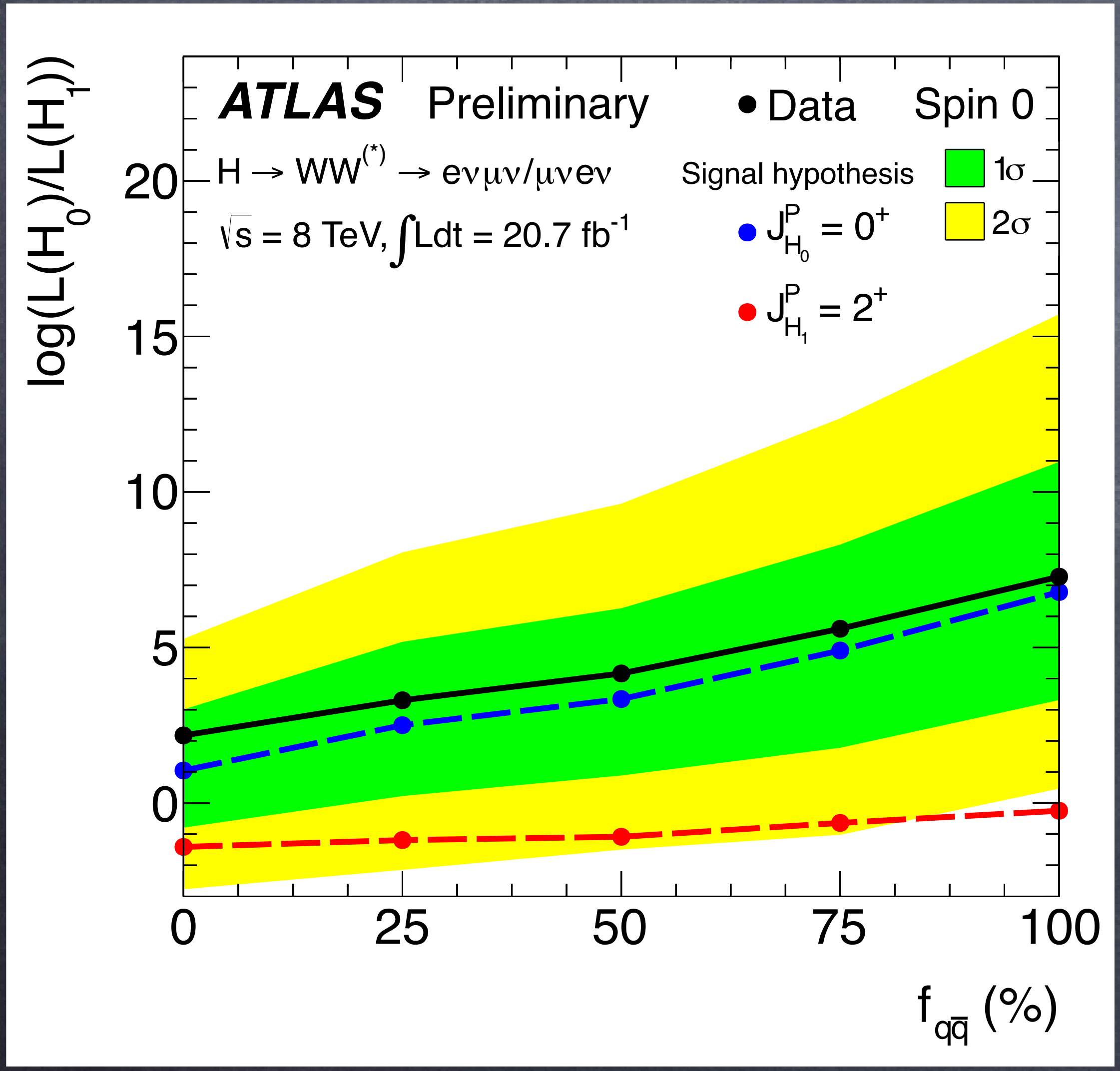
- Nominal H->WW analysis makes use of spin-0 nature of SM Higgs boson via cut on angle between leptons
  - Need to relax this cut (and others) in order to maximize sensitivity to spin-2
- Use 2 BDTs with 4 variables to deal with increased background and spin separation
  - Train spin-0/spin-2 vs. background
  - Input variables: $\Delta\phi_{ll}$, m_{ll}, p_{T}^{ll}, m_{T}

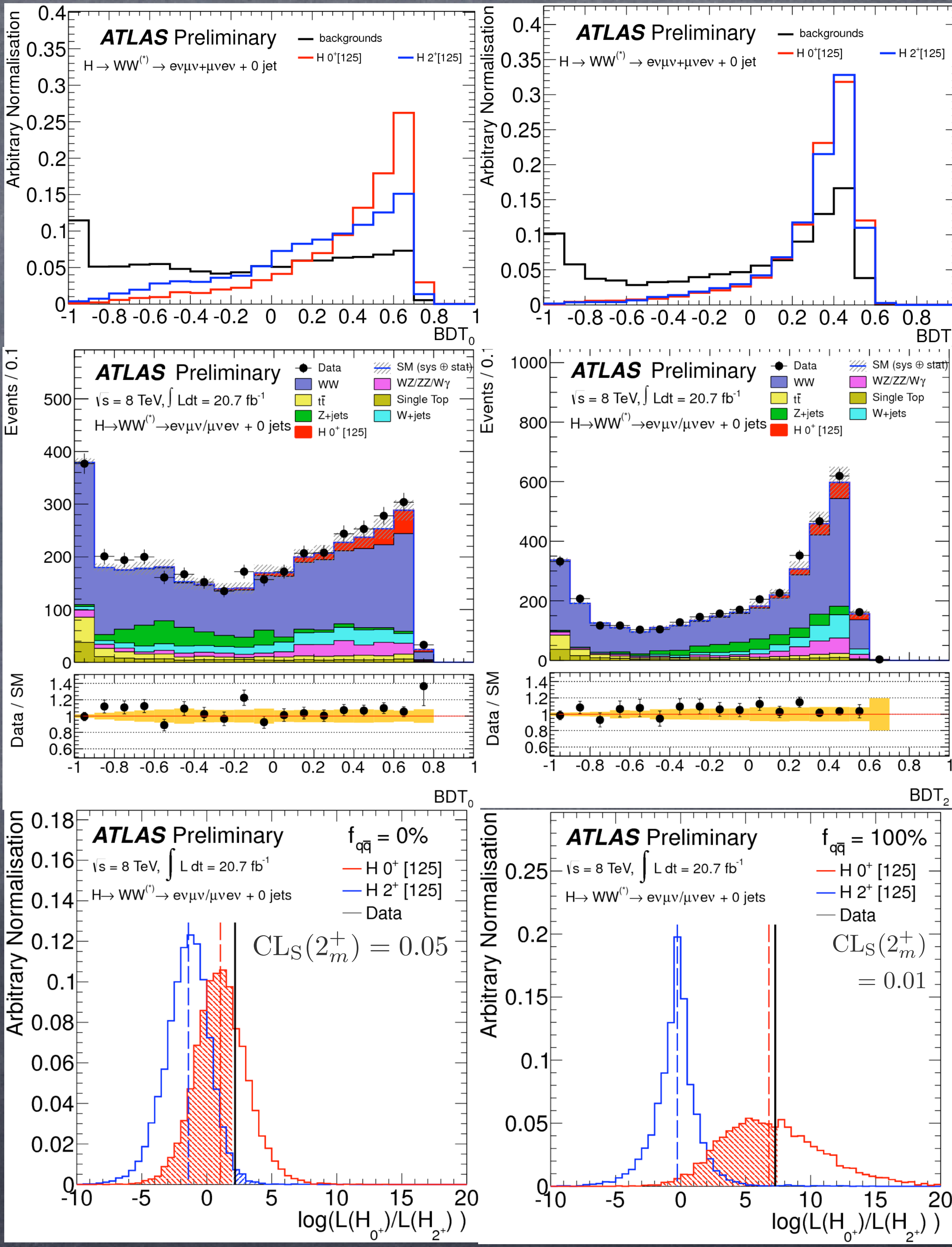




Spin in H->WW: result

- Benchmark spin-2 model excluded at 95% confidence level in favour of SM Higgs boson
  - even stronger (up to 99%) with increased qqbar fraction

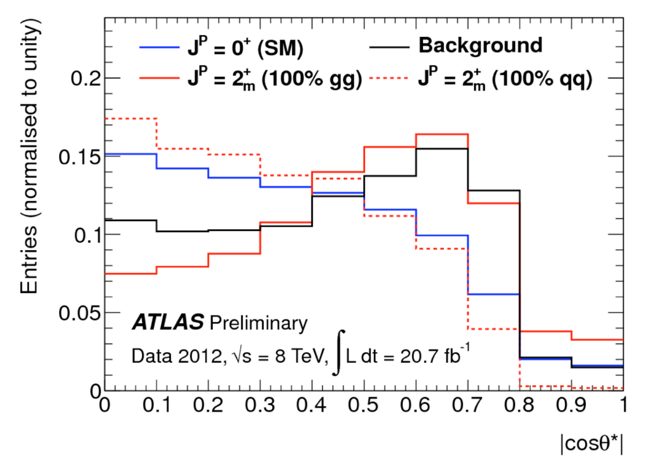


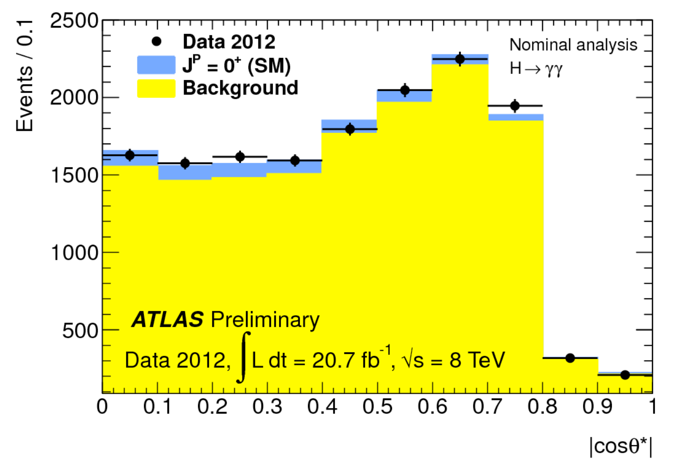


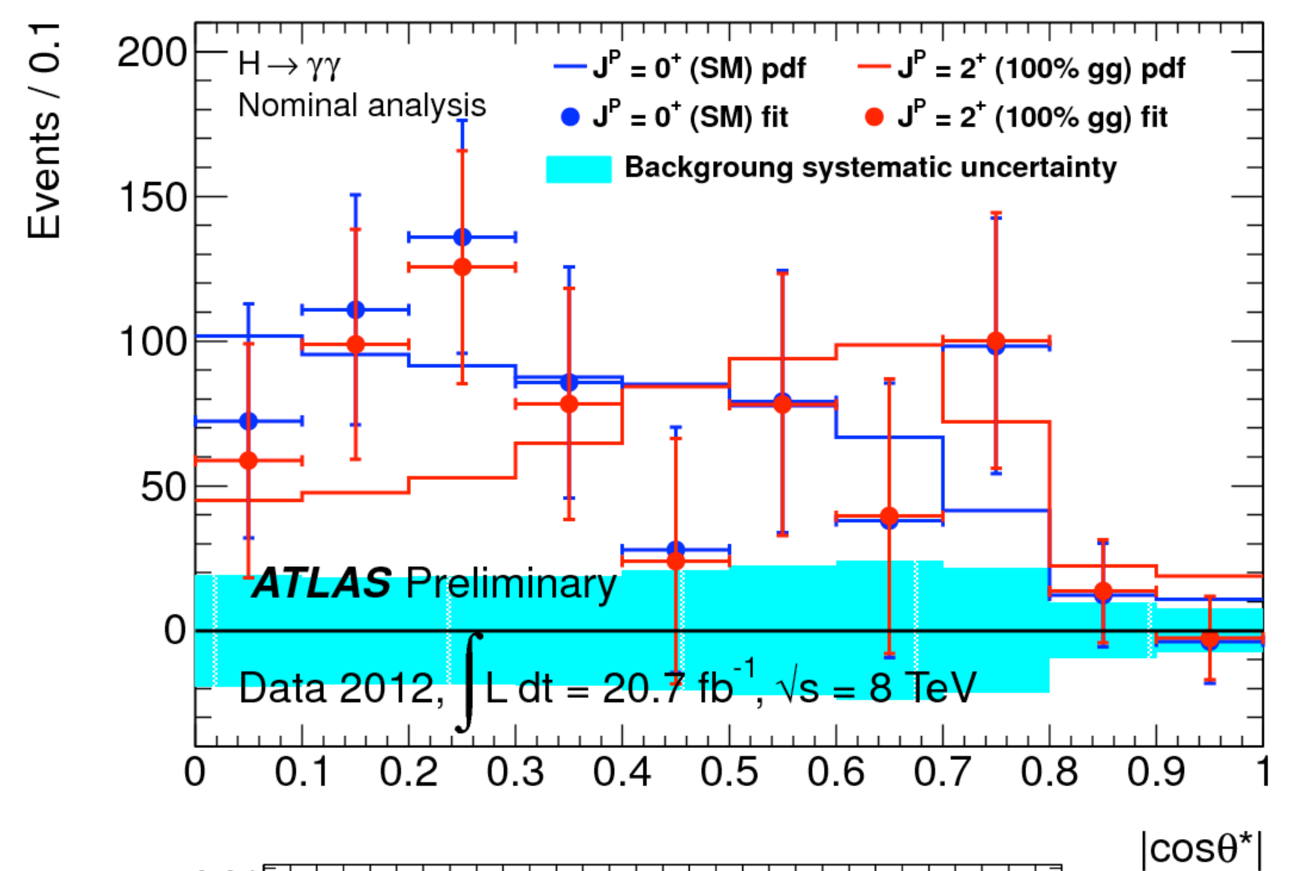
Spin in H->γγ

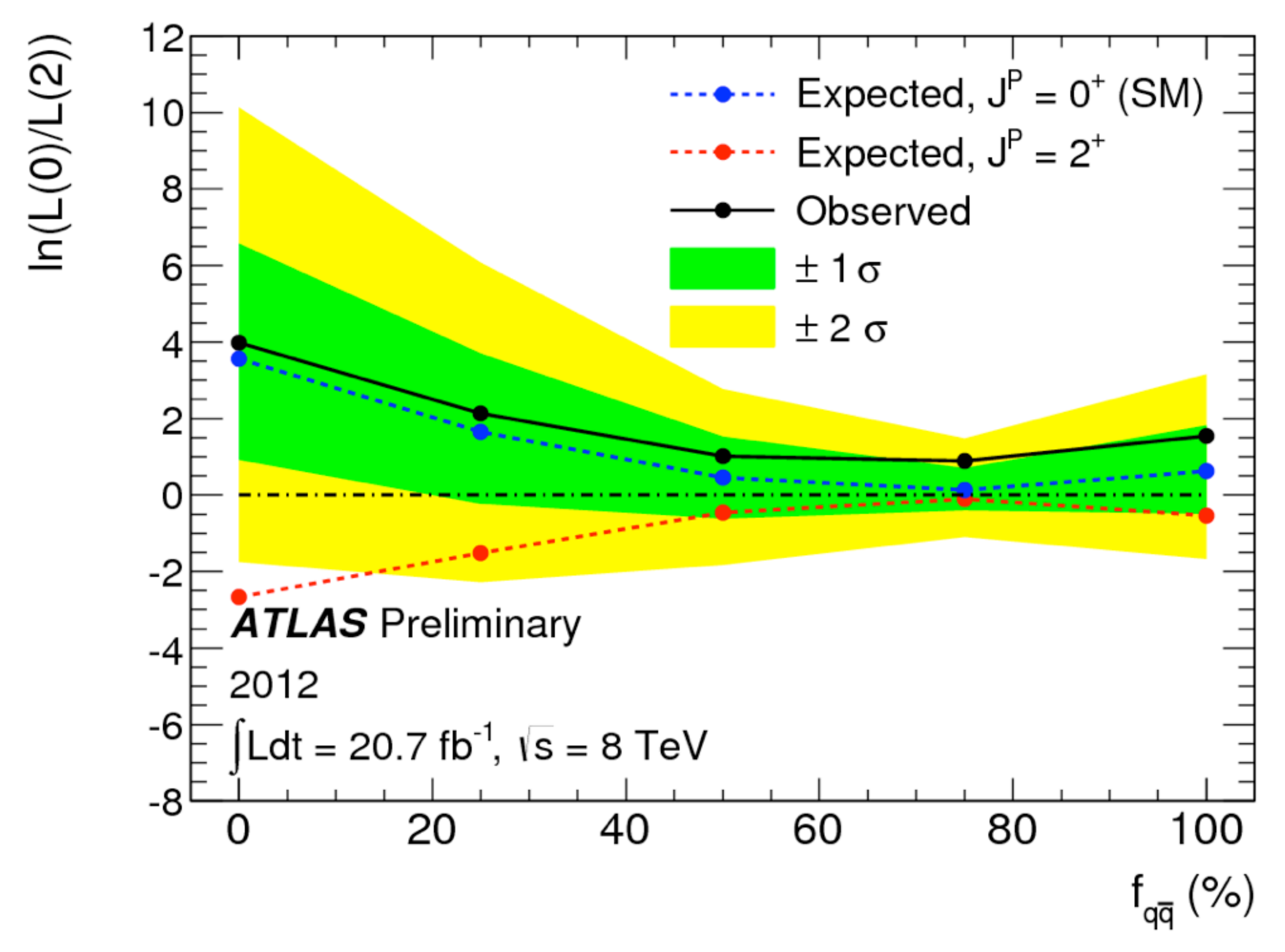
- Method: fit background subtracted cos(theta*) distribution
- Result: benchmark spin-2 model excluded with up to 99% CL (0% qqbar) in favour of SM Higgs

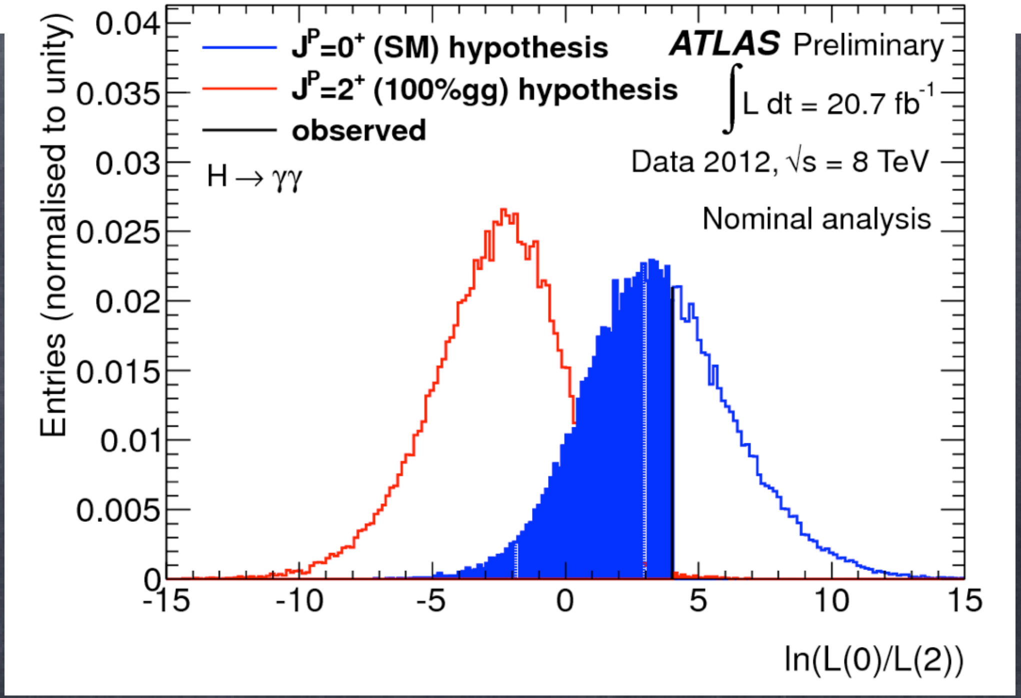
ATLAS-CONF-2013-029







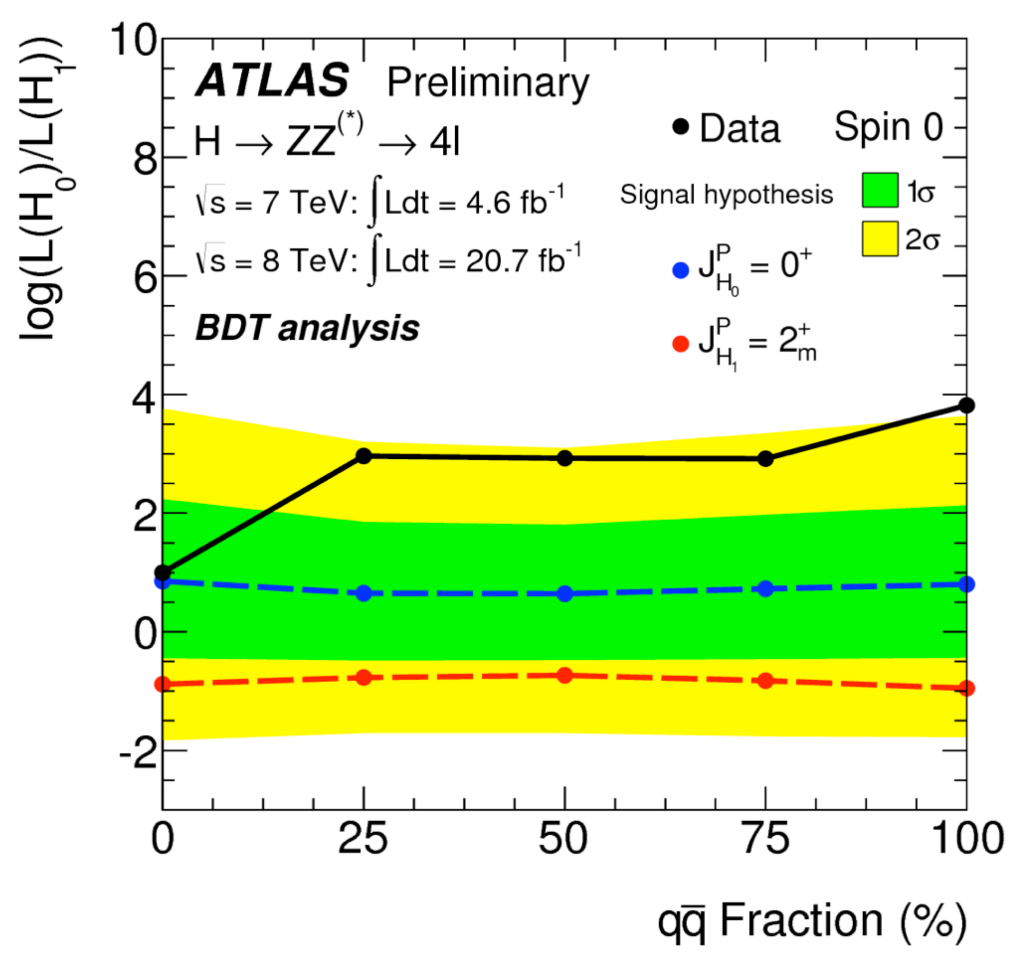


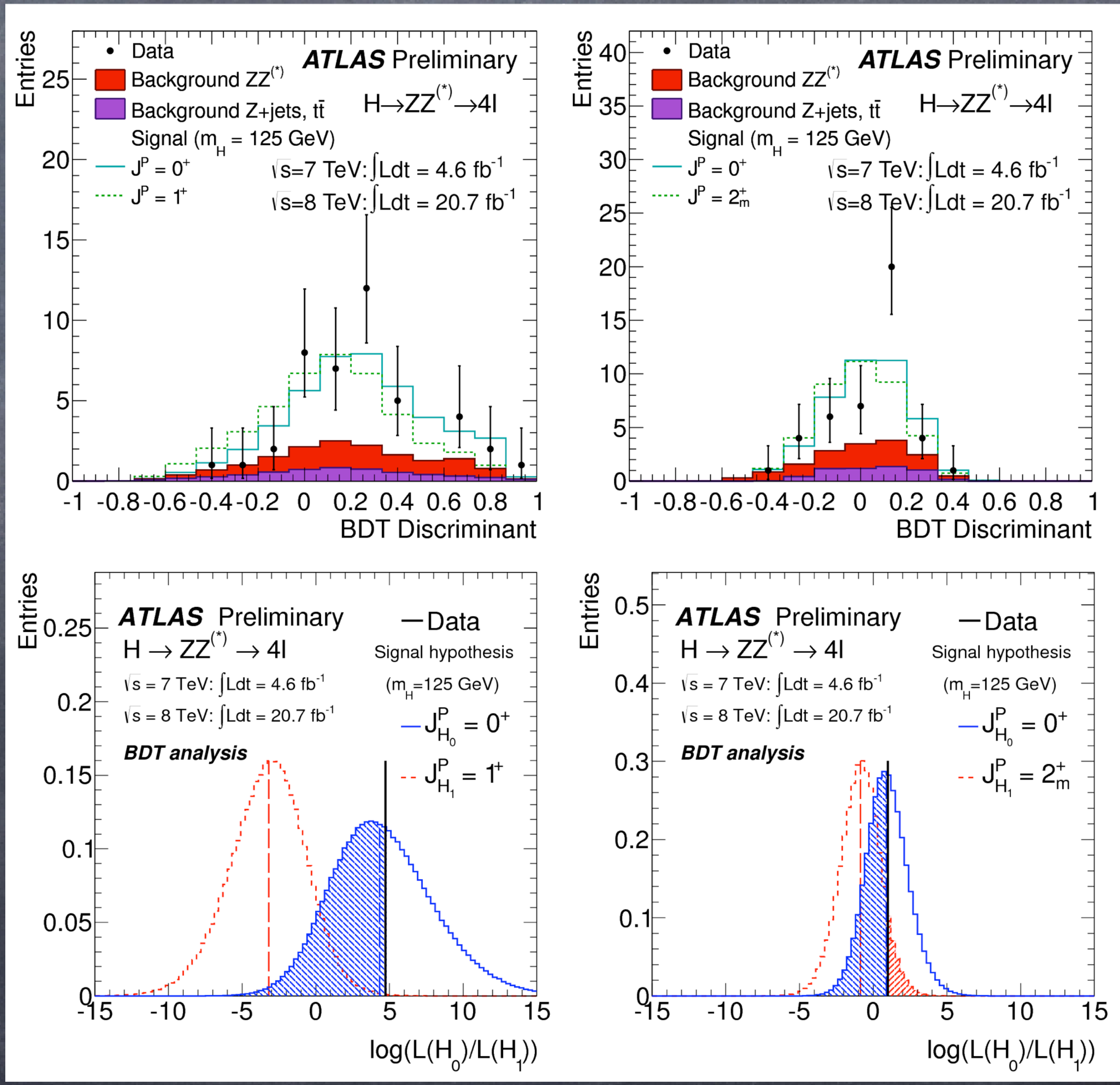


Spin in H->ZZ

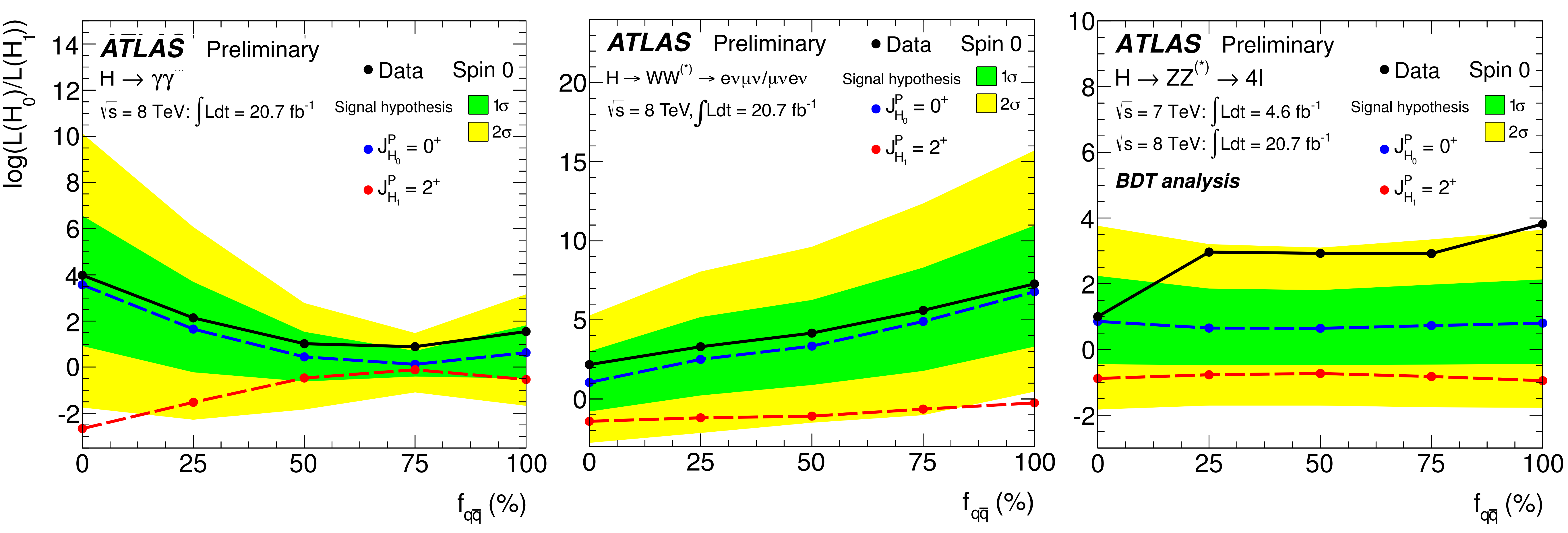
- BDT with decay angles and invariant masses trained to separate between spin hypotheses
- In addition to spin-2 also spin-1 has been investigated
- Results:
  - spin-1 excluded at 99.8% CL
  - spin-2 excluded with >=83% CL

ATLAS-CONF-2013-013





Summary on Spin

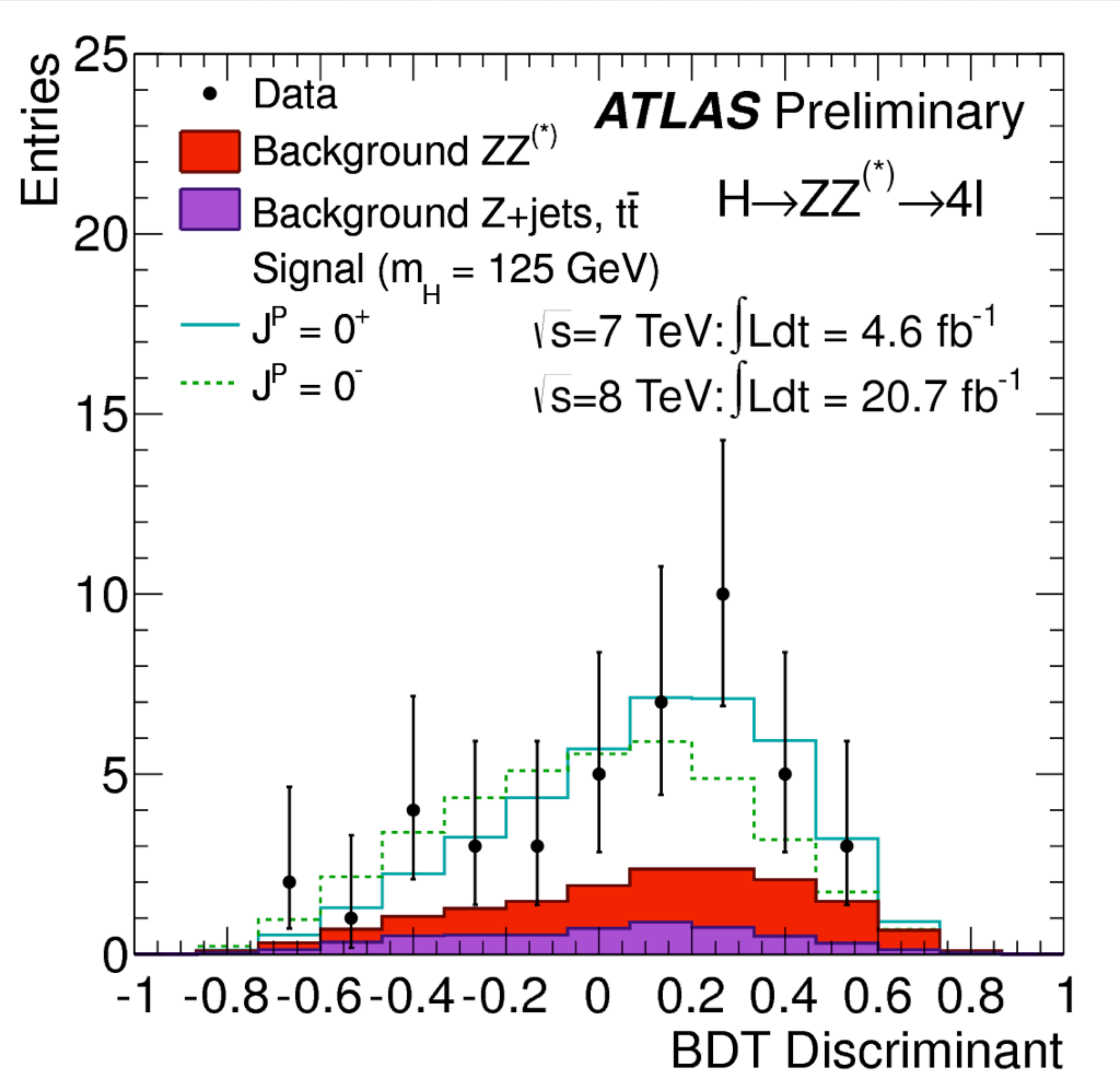


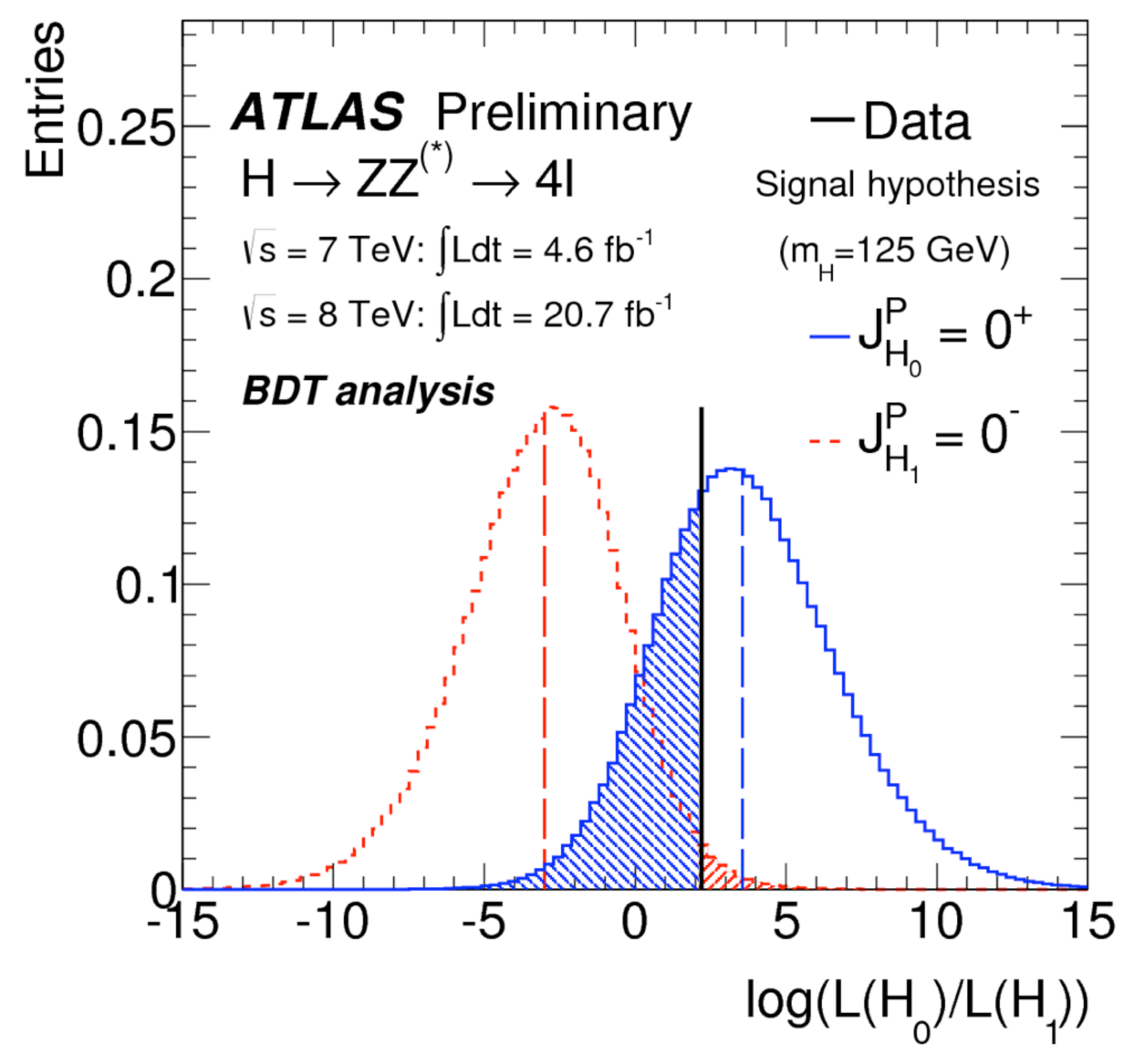
- All three channels clearly prefer the SM Higgs over the benchmark spin-2 model
- WW and γγ have complementary sensitivity as a function on the production mode
  - beneficial for combination!!

CP in H->ZZ

- Similar BDT with decay angles and invariant masses trained to separate between CP hypotheses (0^+ and 0^-)
- Result:
  - CP odd (spin-0) excluded at 97.8% CL

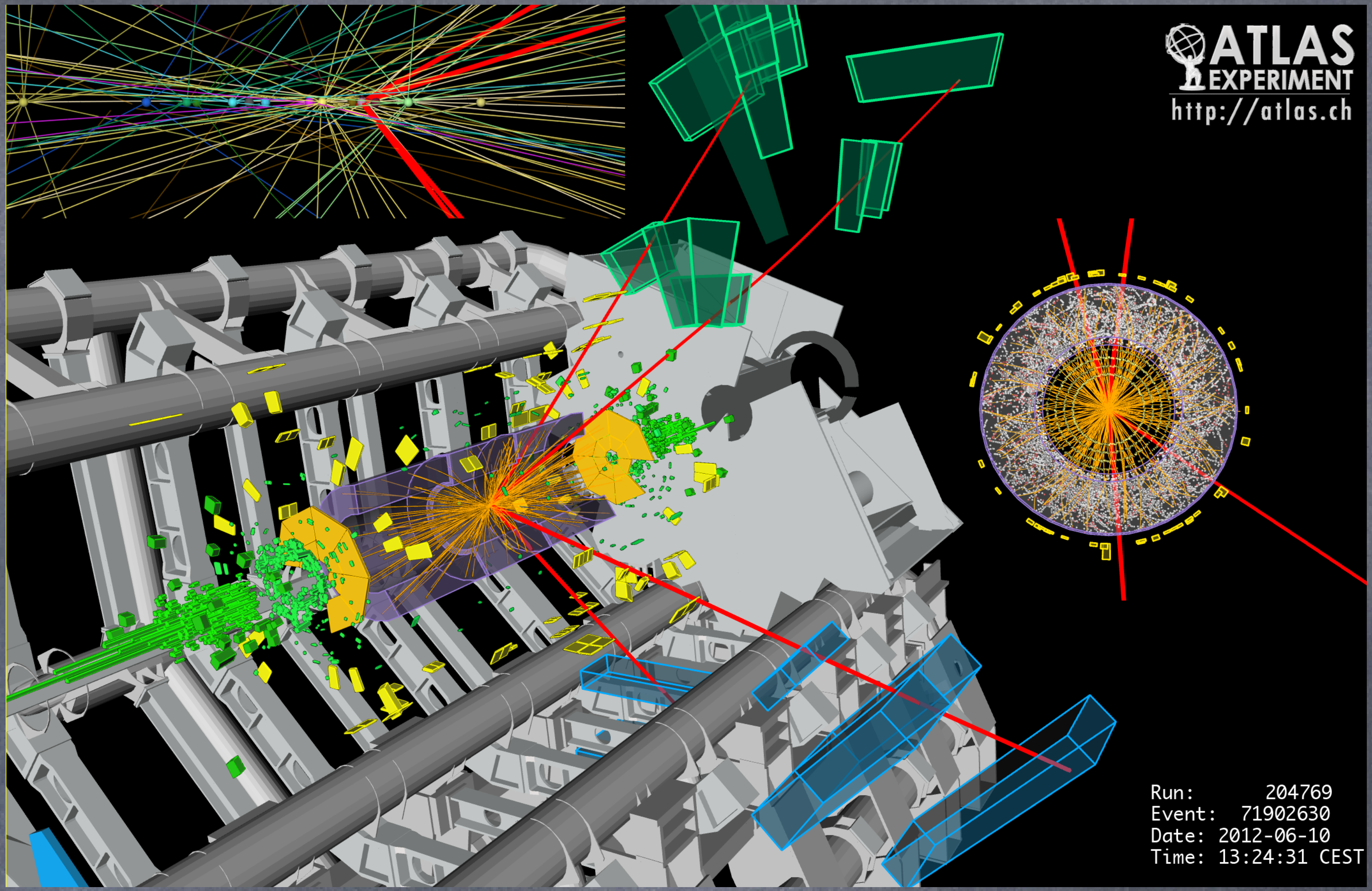
ATLAS-CONF-2013-013



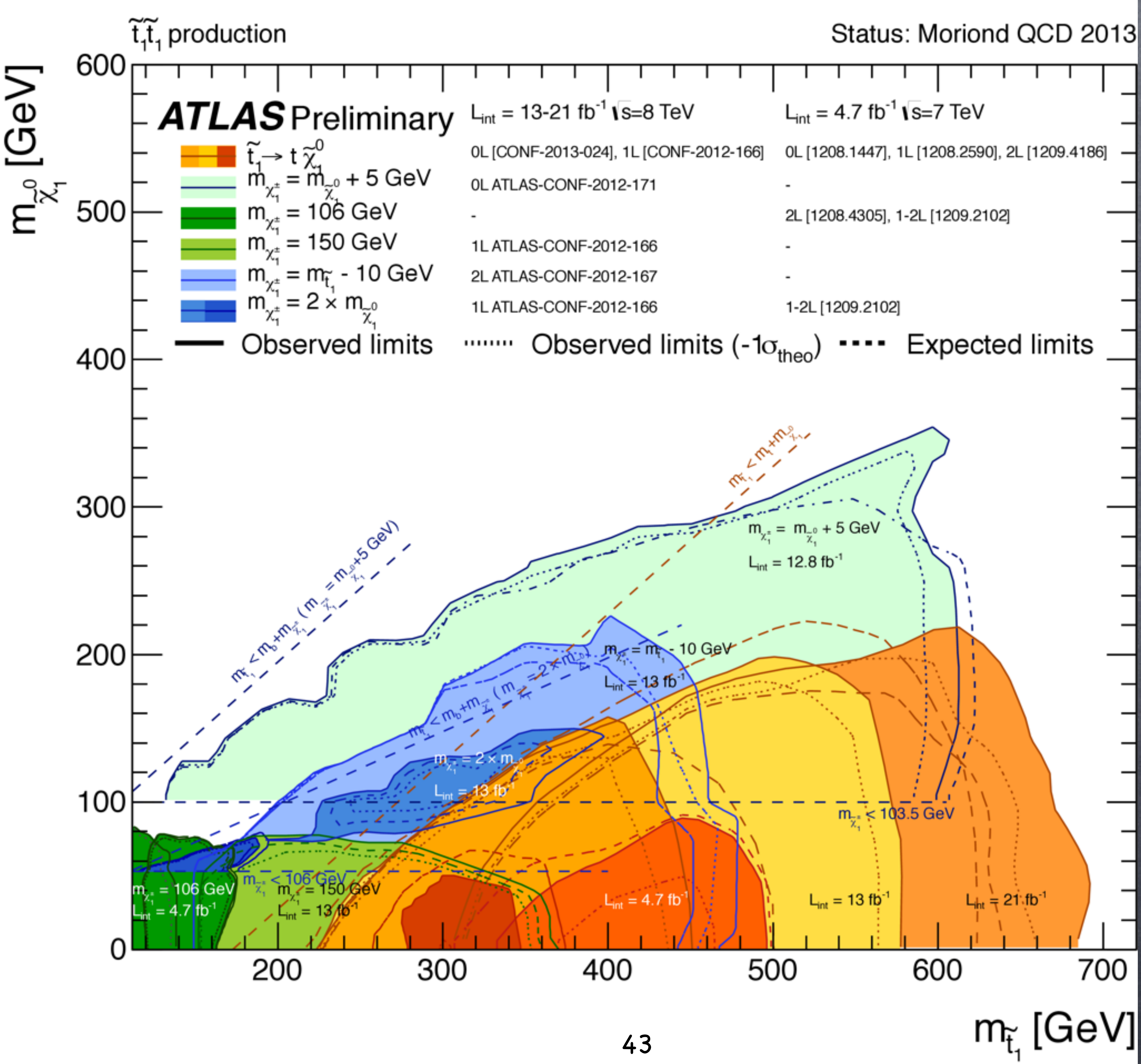


Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook



SUSY: search for stop particle



SUSY search summary

*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Nothing found so far ...

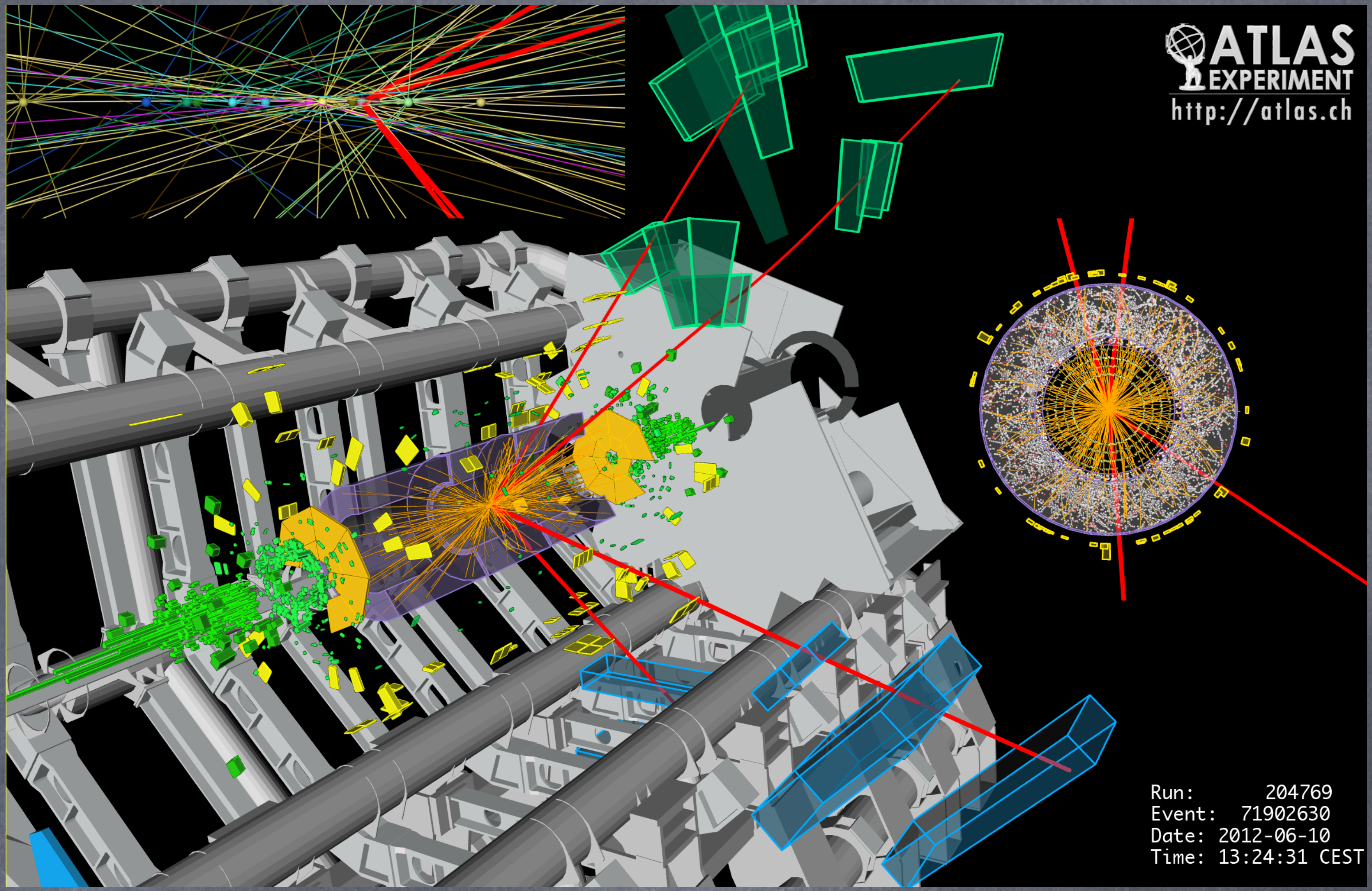
Searches for other particles

*Only a selection of the available mass limits on new states or phenomena shown

Nothing found so far...

Overview

- Higgs production and decay
- Challenges
- Higgs search in individual channels
- Combination of signal strength and mass
- Is it the SM Higgs?
  - Couplings
  - Spin and CP
- Other searches
- Summary & Outlook



Summary & Conclusions

- Neutral boson discovered last year
  - Overall production cross section compatible with prediction for SM Higgs

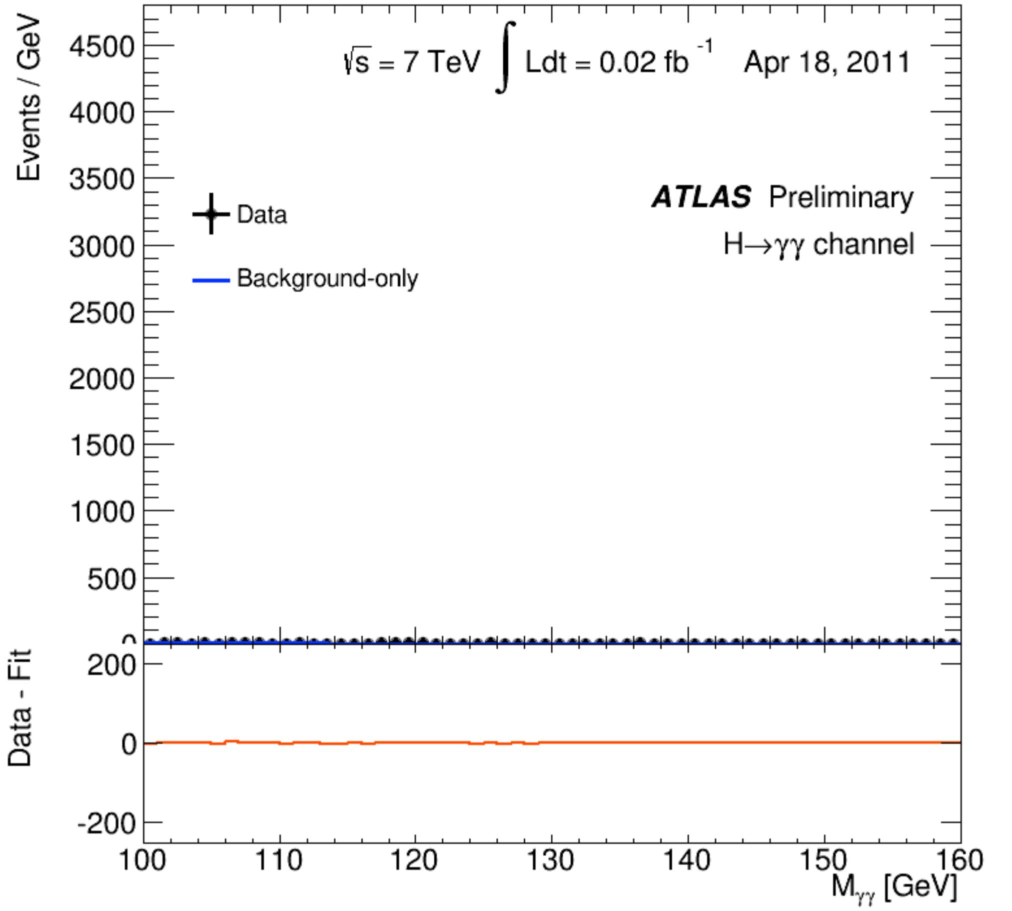
$$\mu = 1.30 \pm 0.13(\mathrm{stat}) \pm 0.14(\mathrm{sys})$$

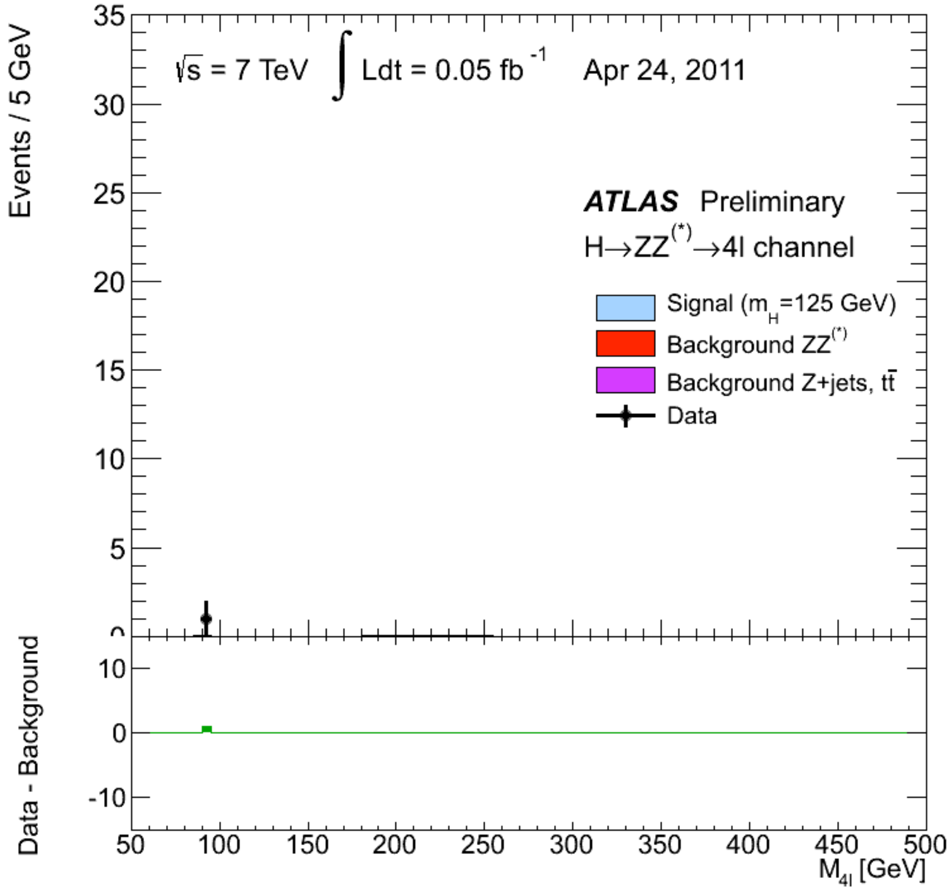
  - Mass of the new particle:

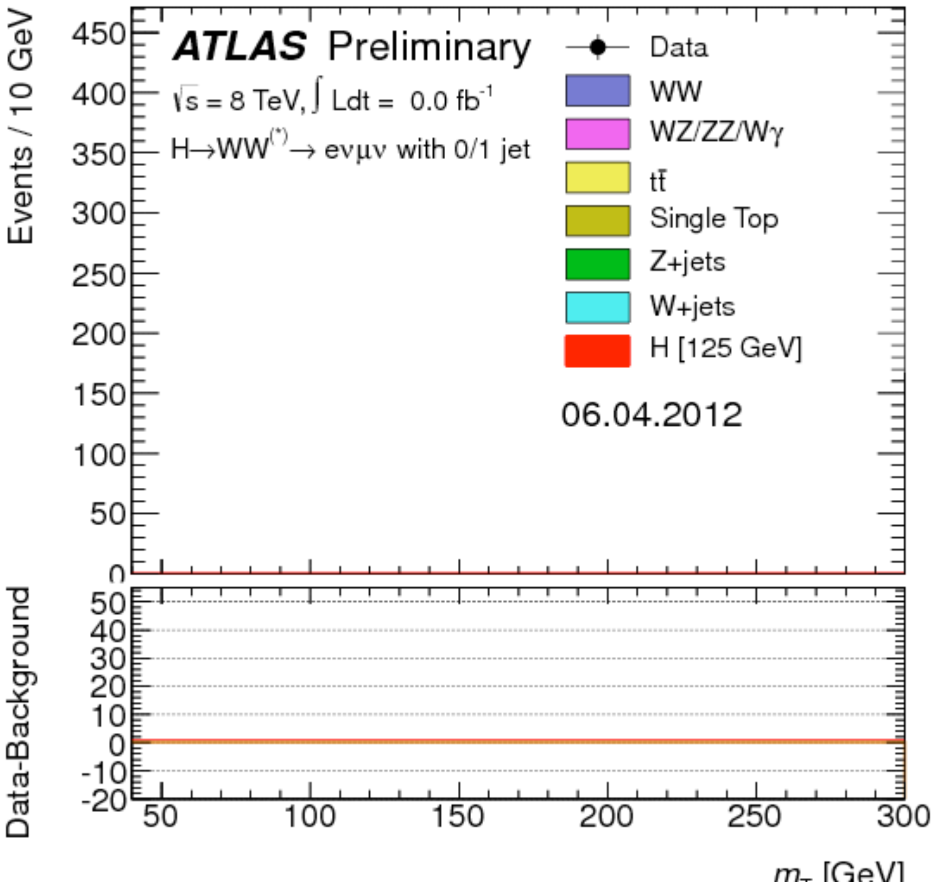
$$m_{\mathrm{H}} = 125.5 \pm 0.2(\mathrm{stat})^{+0.5}_{-0.6}(\mathrm{sys})\,\mathrm{GeV}$$

  - First coupling measurements in agreement with SM Higgs prediction
  - Dedicated spin and CP studies exclude alternative models (0^-, 1^+, 1^-, 2^+) in favour of SM Higgs
- Everything points to the new particle being a Higgs boson!

Time evolution

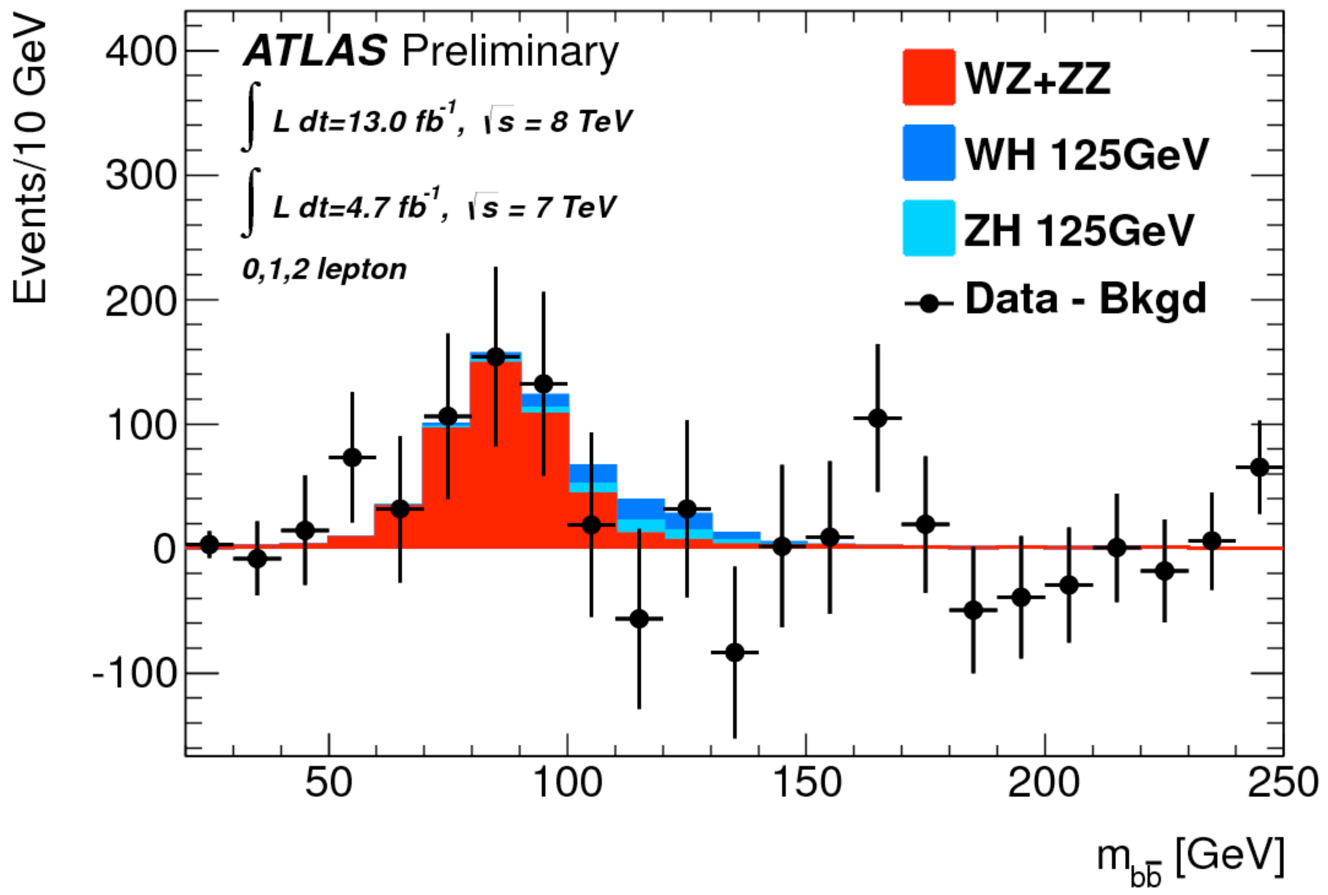




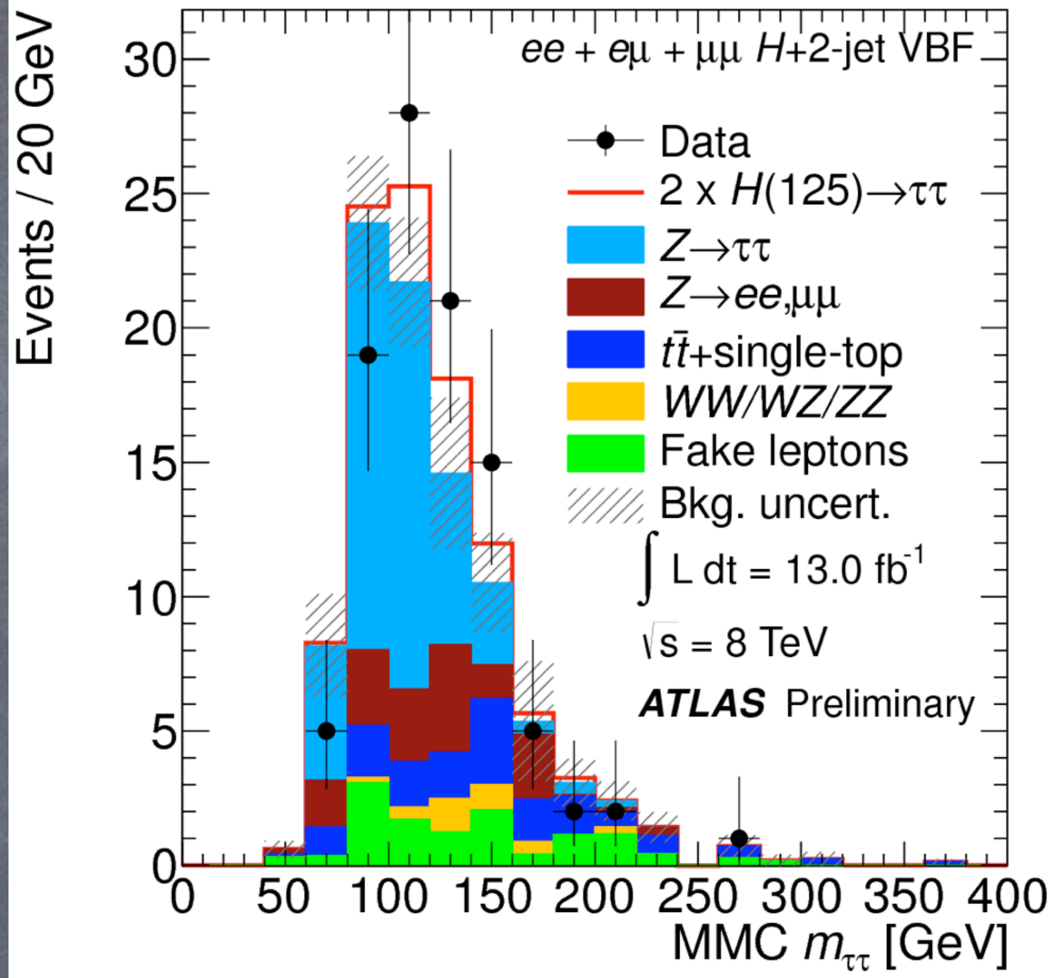


Backup

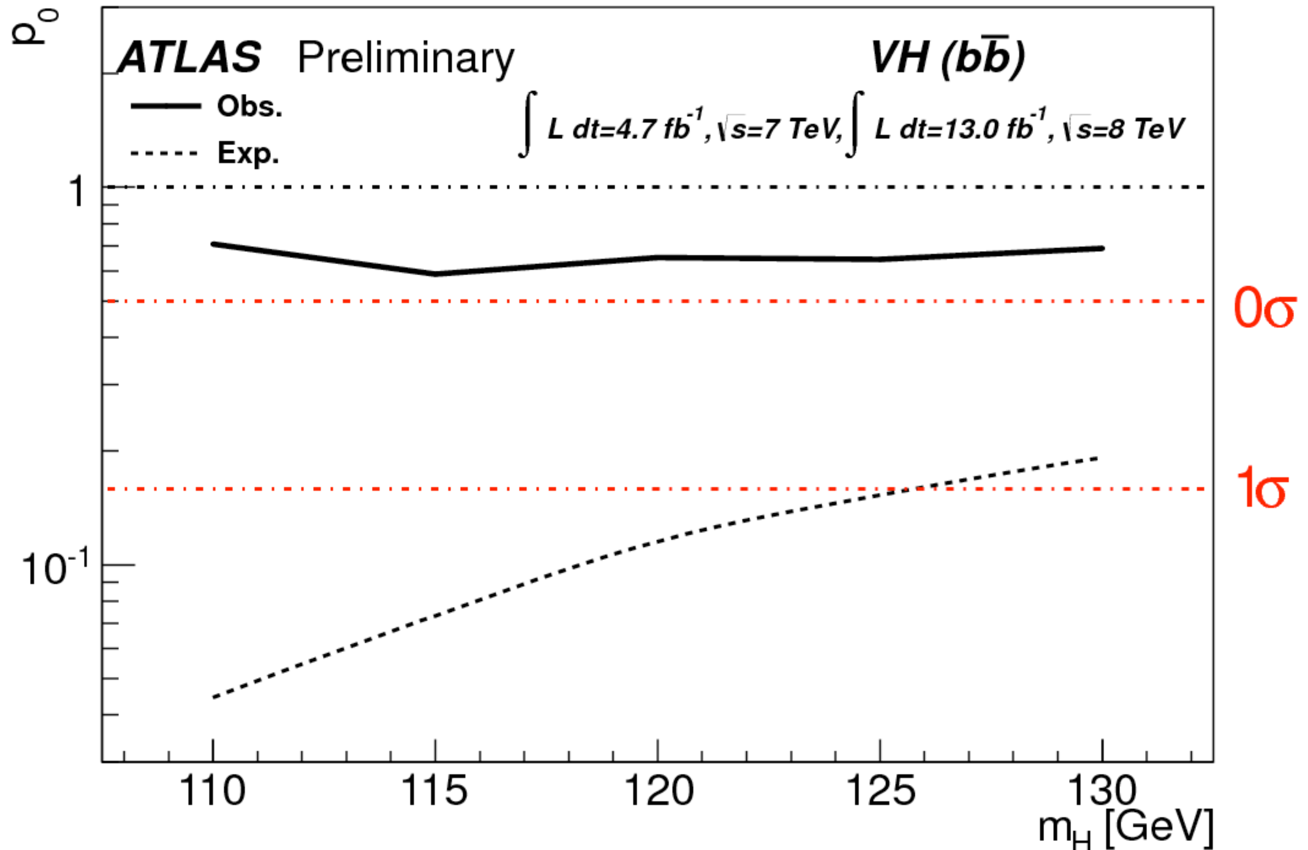
H->$b\bar{b}$ & H->ττ



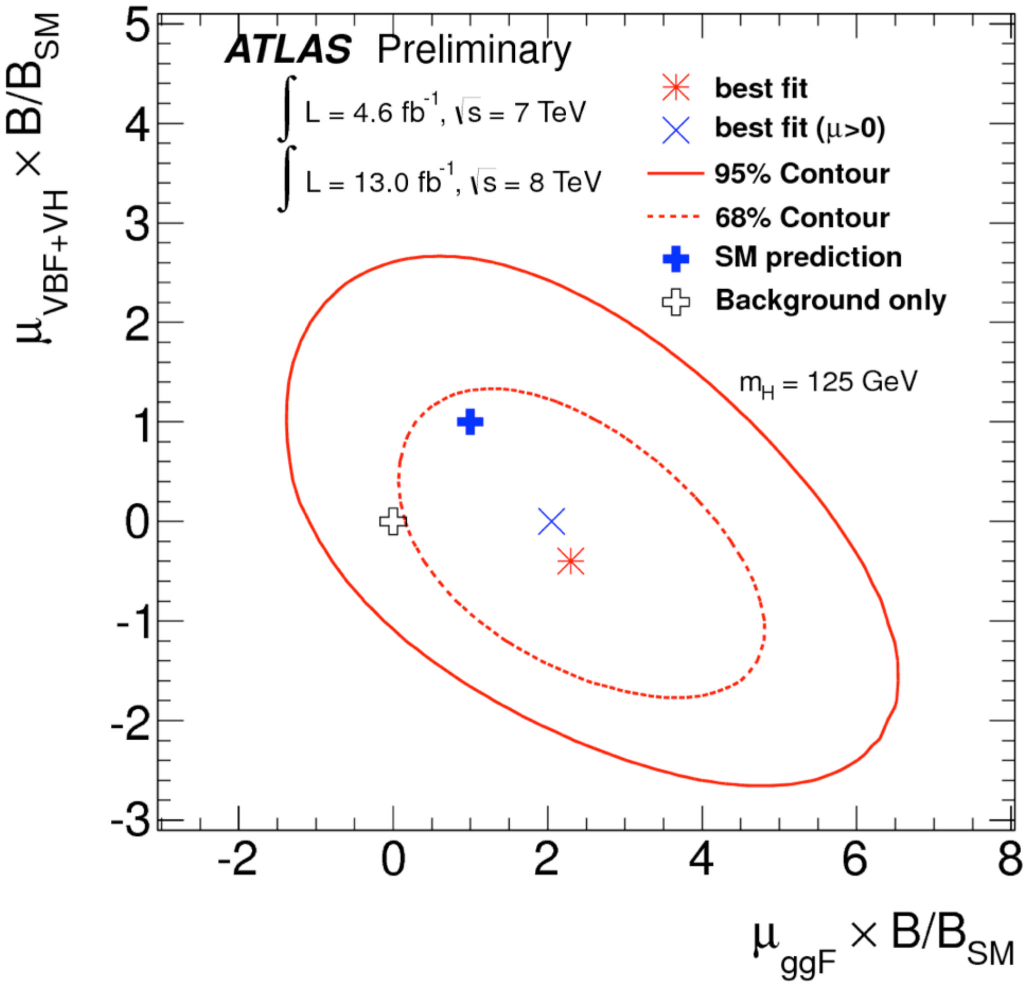
ATLAS Preliminary
∫ L dt=13.0 fb⁻¹, √s = 8 TeV
∫ L dt=4.7 fb⁻¹, √s = 7 TeV
0,1,2 lepton
WZ+ZZ
WH 125GeV
ZH 125GeV
Data - Bkgd
Events/10 GeV
400
300
200
100
0
-100
50
100
150
200
250
m_bb̄ [GeV]



ee + eμ + μμ H+2-jet VBF
Data
2 x H(125)→ττ
Z→ττ
Z→ee,μμ
tt̄+single-top
WW/WZ/ZZ
Fake leptons
Bkg. uncert.
∫ L dt = 13.0 fb⁻¹
√s = 8 TeV
ATLAS Preliminary
Events / 20 GeV
30
25
20
15
10
5
0
0
50
100
150
200
250
300
350
400
MMC m_ττ [GeV]



ATLAS Preliminary
VH (bb̄)
Obs.
Exp.
∫ L dt=4.7 fb⁻¹, √s=7 TeV, ∫ L dt=13.0 fb⁻¹, √s=8 TeV
p₀
1
10⁻¹
0σ
1σ
110
115
120
125
130
m_H [GeV]

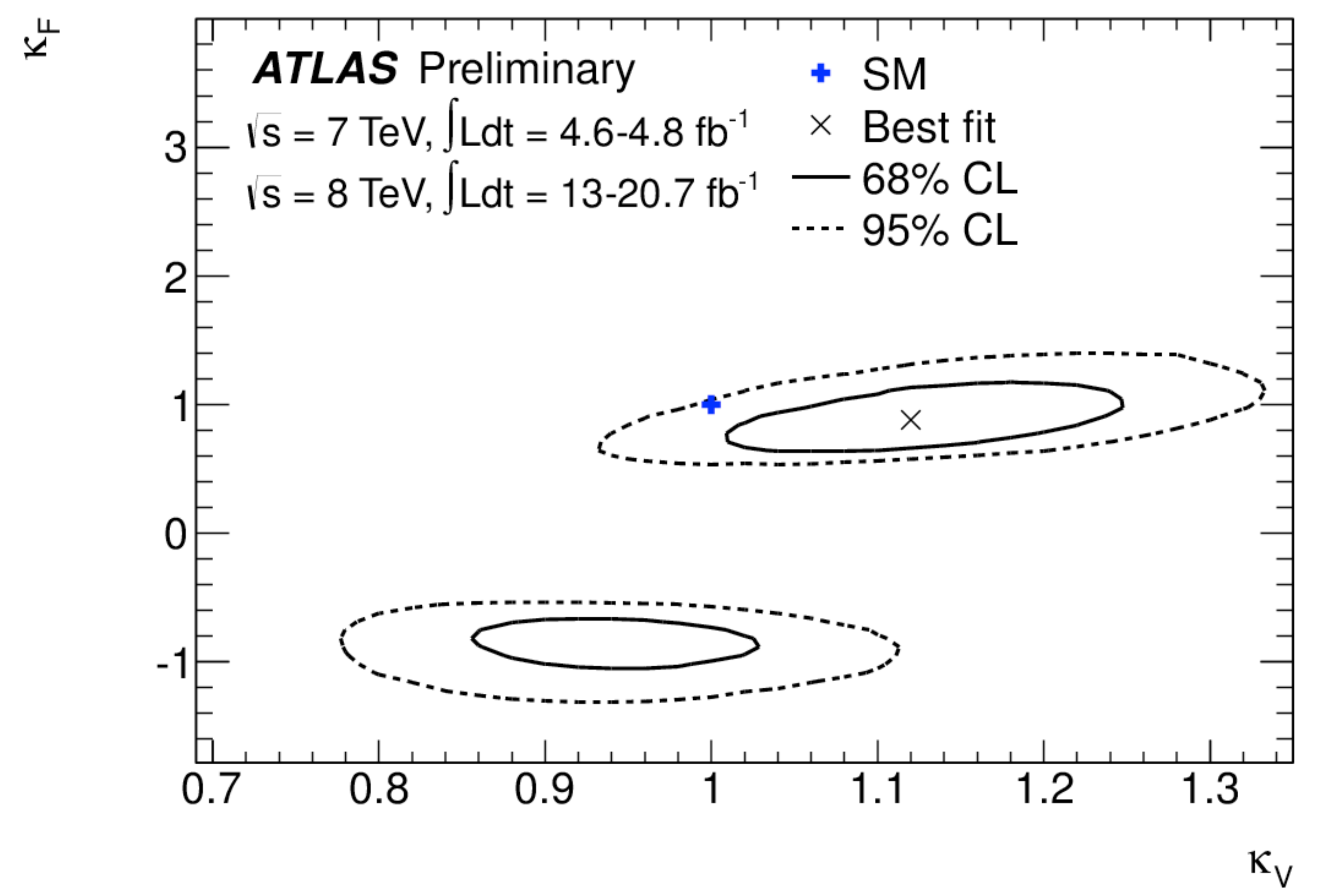


ATLAS Preliminary
∫ L = 4.6 fb⁻¹, √s = 7 TeV
∫ L = 13.0 fb⁻¹, √s = 8 TeV
best fit
best fit (μ>0)
95% Contour
68% Contour
SM prediction
Background only
m_H = 125 GeV
μ_VBF+VH × B/B_SM
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
μ_ggF × B/B_SM

Couplings to Gauge Bosons and Fermions

- 2 Fit parameters:
- Assumption:
  - only SM particles contribute to the total width

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

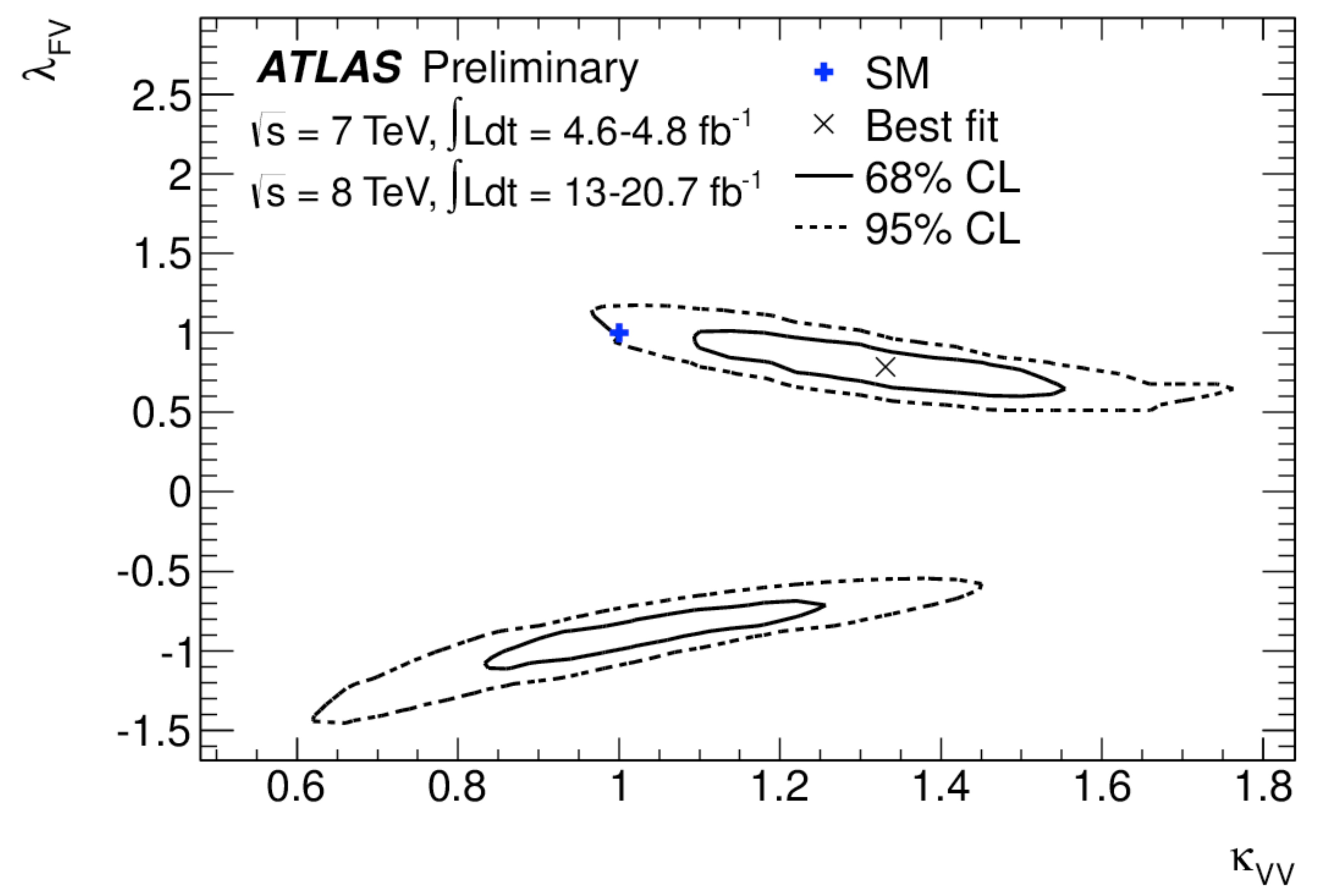


Couplings to Gauge Bosons and Fermions

- 2 Fit parameters:

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

- No assumption on total width

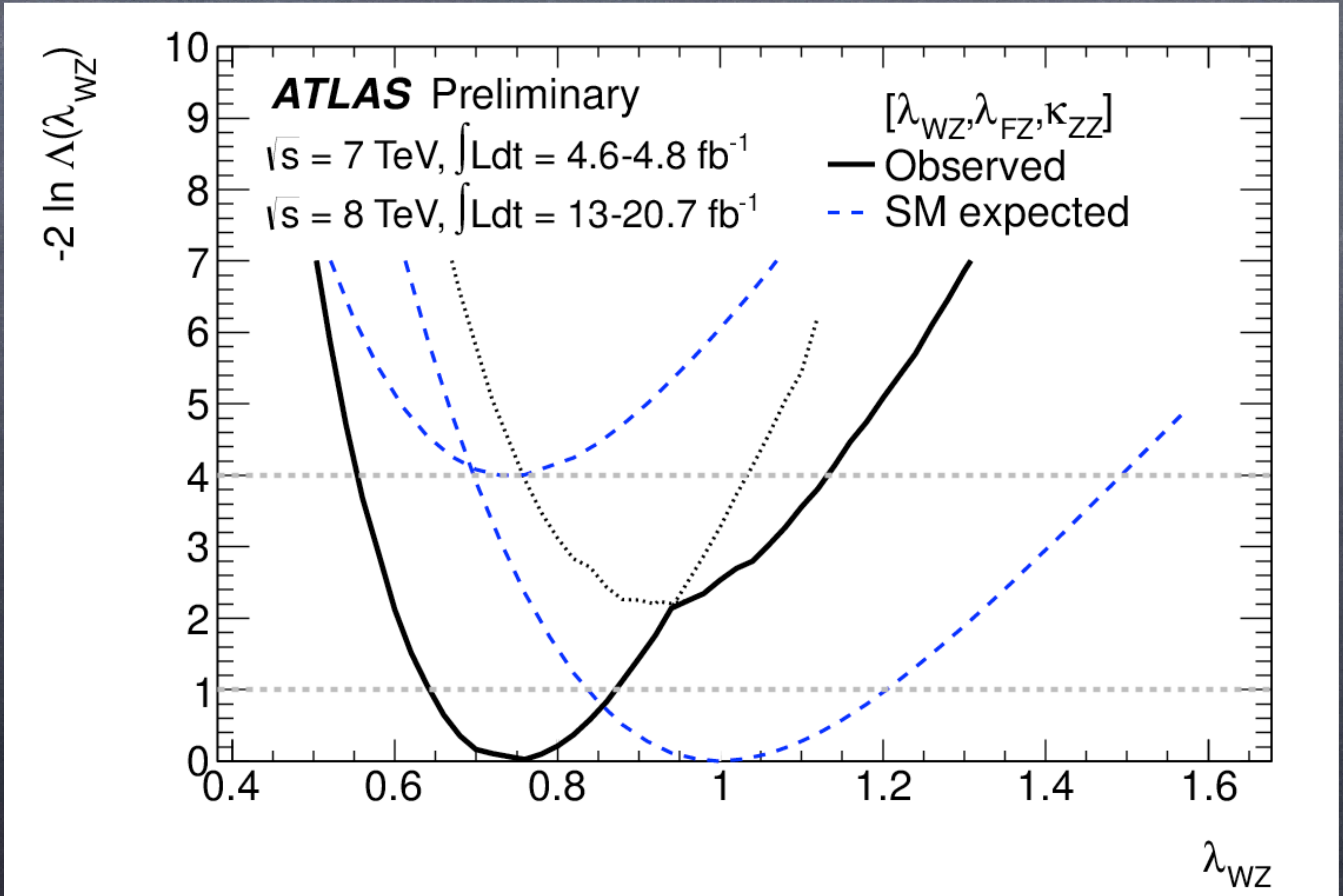


Symmetry of the W and Z coupling

- 3 Fit parameters:

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

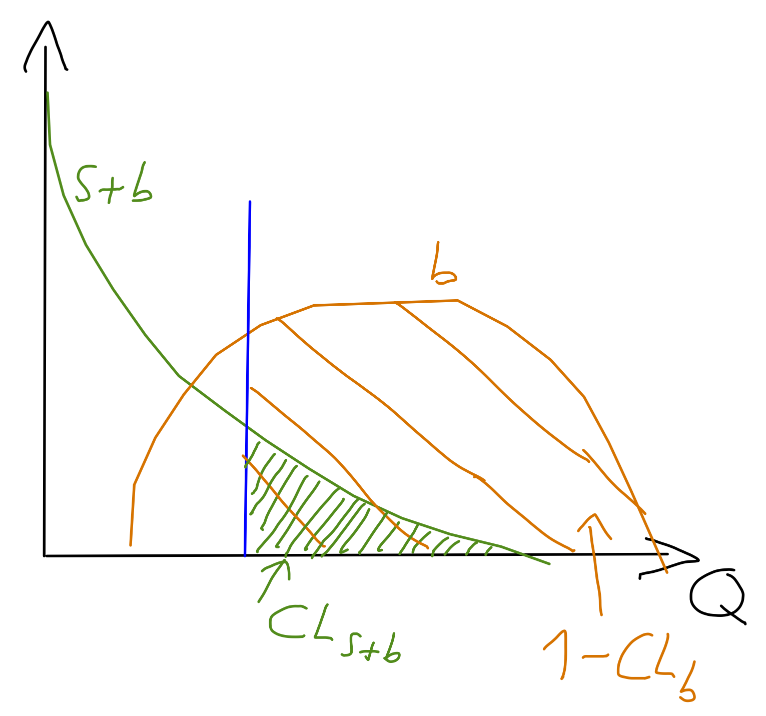
- Again no assumption on total width



CLs method

- Test statistics Q as ratio of likelihoods:

$$Q = \frac{\mathcal{L}_{\mathrm{Poiss}}(data|signal + background)}{\mathcal{L}_{\mathrm{Poiss}}(data|background)}$$



- Confidence level for signal+background hypothesis

$$CL_{s+b} = P(Q \geq Q_{\mathrm{obs}}|signal + background)$$

- Consistency with background hypothesis

$$1 - CL_b = P(Q \geq Q_{\mathrm{obs}}|background)$$

- To avoid excluding low sensitivity regions define CLs

$$CL_s = CL_{s+b}/(1 - CL_b)$$

- Signal hypothesis is excluded at 95% C.L. if CLs < 0.05

Inclusion of systematic uncertainties

- Systematic uncertainties included in the likelihood using nuisance parameter (Θ) pdf's

$$\mathcal{L}(data|\mu,\theta) = \text{Poisson}(data|\mu \cdot s(\theta) + b(\theta)) \cdot \rho(\tilde{\theta}|\theta)$$

- Test statistics now defined after maximizing likelihood with respect to nuisance parameters

$$Q_\mu = -2\ln\frac{\mathcal{L}(data|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data|\hat{\mu},\hat{\theta})} \qquad 0 \leq \hat{\mu} \leq \mu$$

- Ad hoc improvement of systematic uncertainties
  - Data can tell us the preferred value

References

H->ZZ: ATLAS-CONF-2013-013

H->WW: ATLAS-CONF-2013-030

H->WW (spin): ATLAS-CONF-2013-031

H-> $\gamma\gamma$ (spin): ATLAS-CONF-2013-029

H-> $\gamma\gamma$: ATLAS-CONF-2013-012

H combination (mass): ATLAS-CONF-2013-014

H combination (couplings): ATLAS-CONF-2013-034