$H \rightarrow WW^* \rightarrow l\nu l\nu$ in ATLAS

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CoEPP Annual Workshop
July 10th 2013

Let’s celebrate...

Last Thursday was the first birthday of the discovery of the Higgs boson!

Outline

Introduction and analysis strategy

Event selection and backgrounds

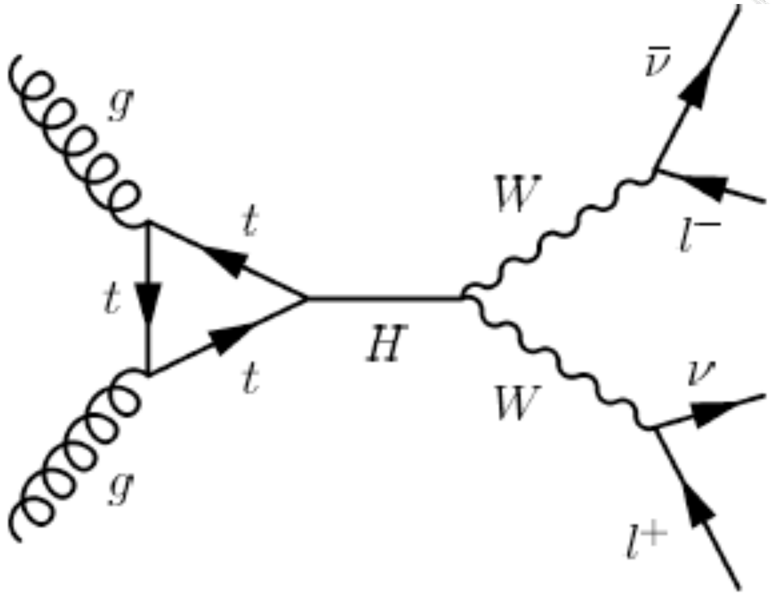
Signal strength results

Spin and Parity results

$H \to WW^* \to l\nu l\nu$

Large BF over wide range of m_H

Challenge is poor mass resolution



Event signature

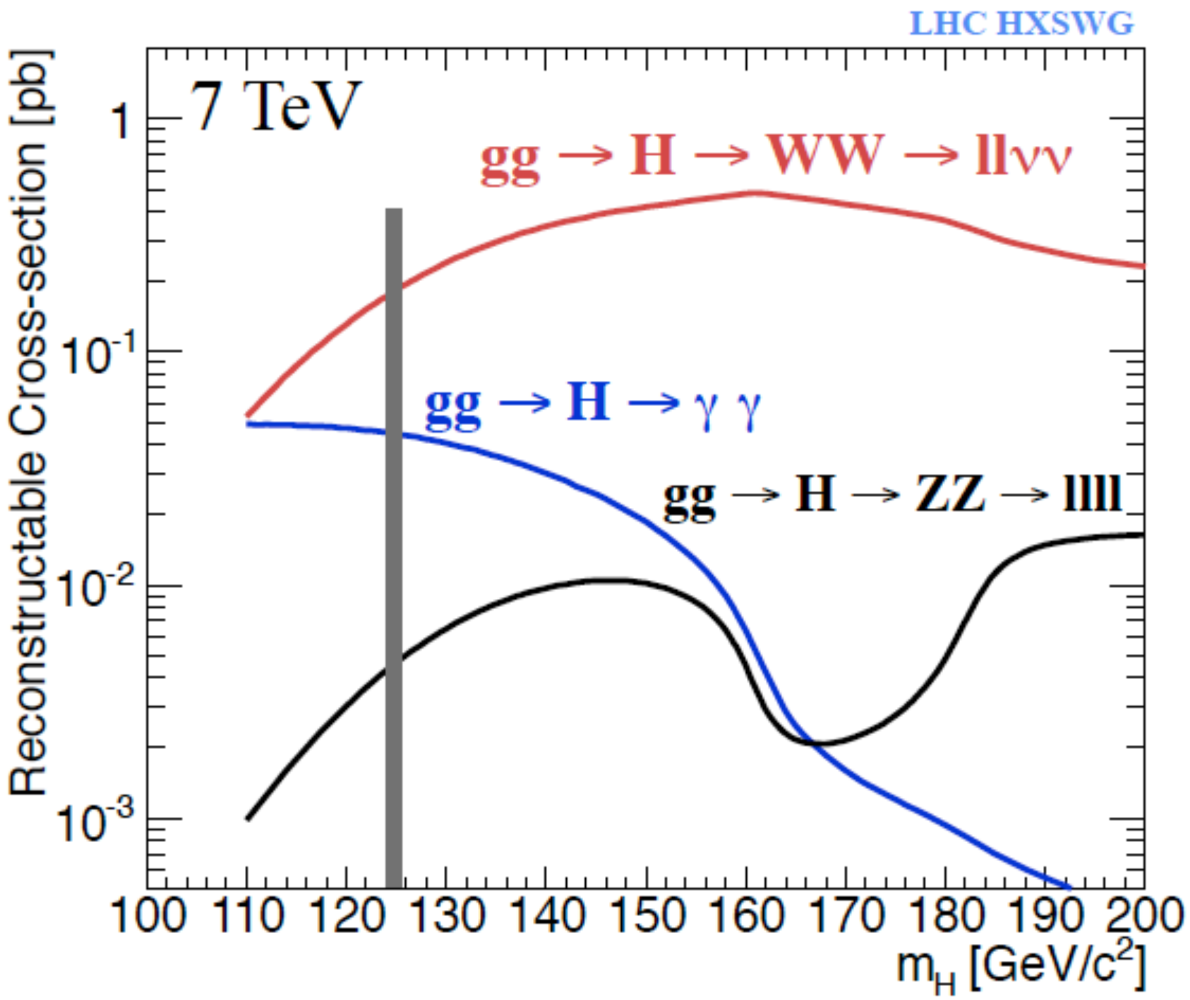
- Di-lepton (e, μ) and missing E_T
- Lepton $p_T > 25/15$ GeV

Analysis done in 4 channels

- Different flavor: eμ and μe
- Same flavor: ee and μμ

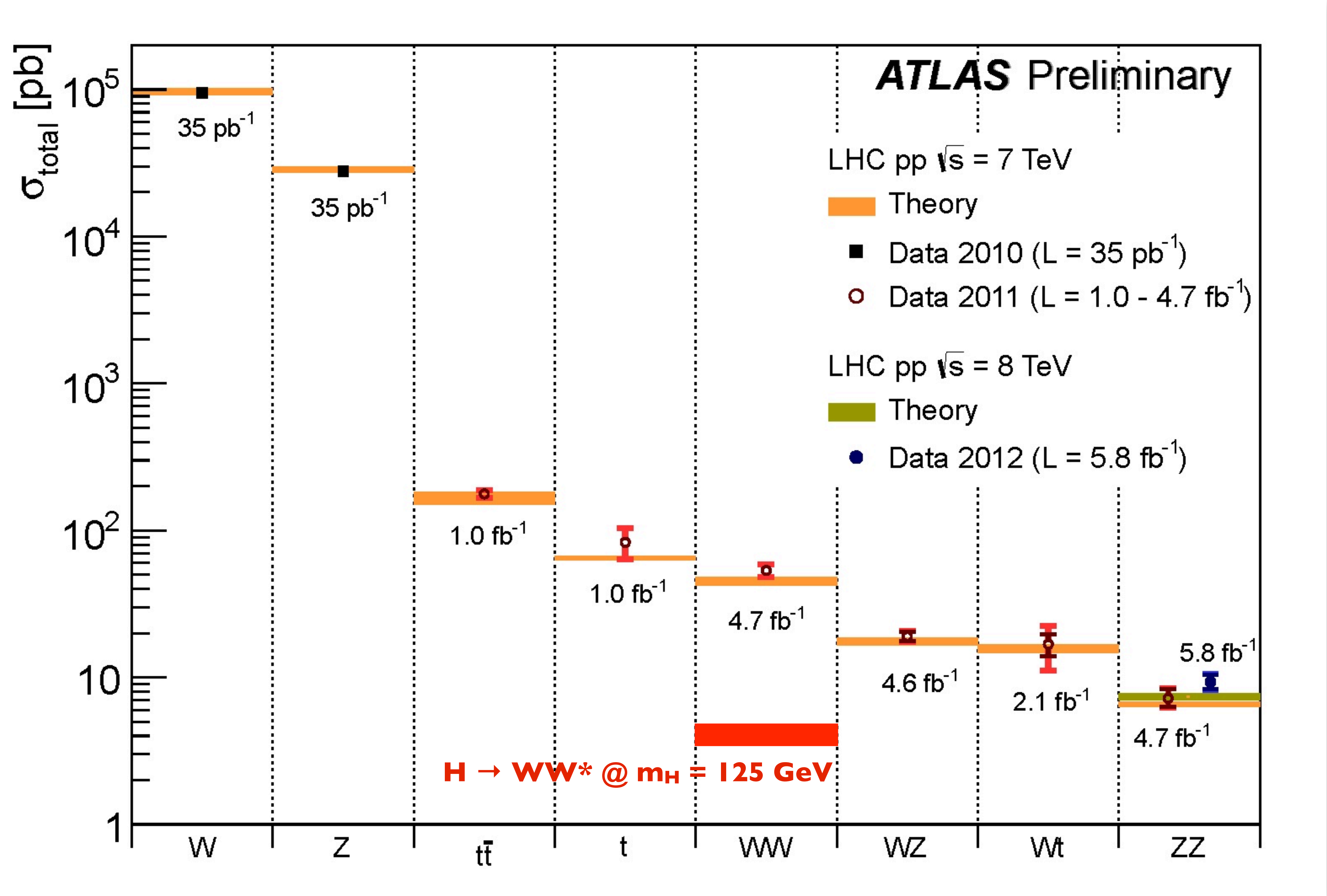
Split according to jet multiplicity

- 0 jets, 1 jet, 2 or more jets



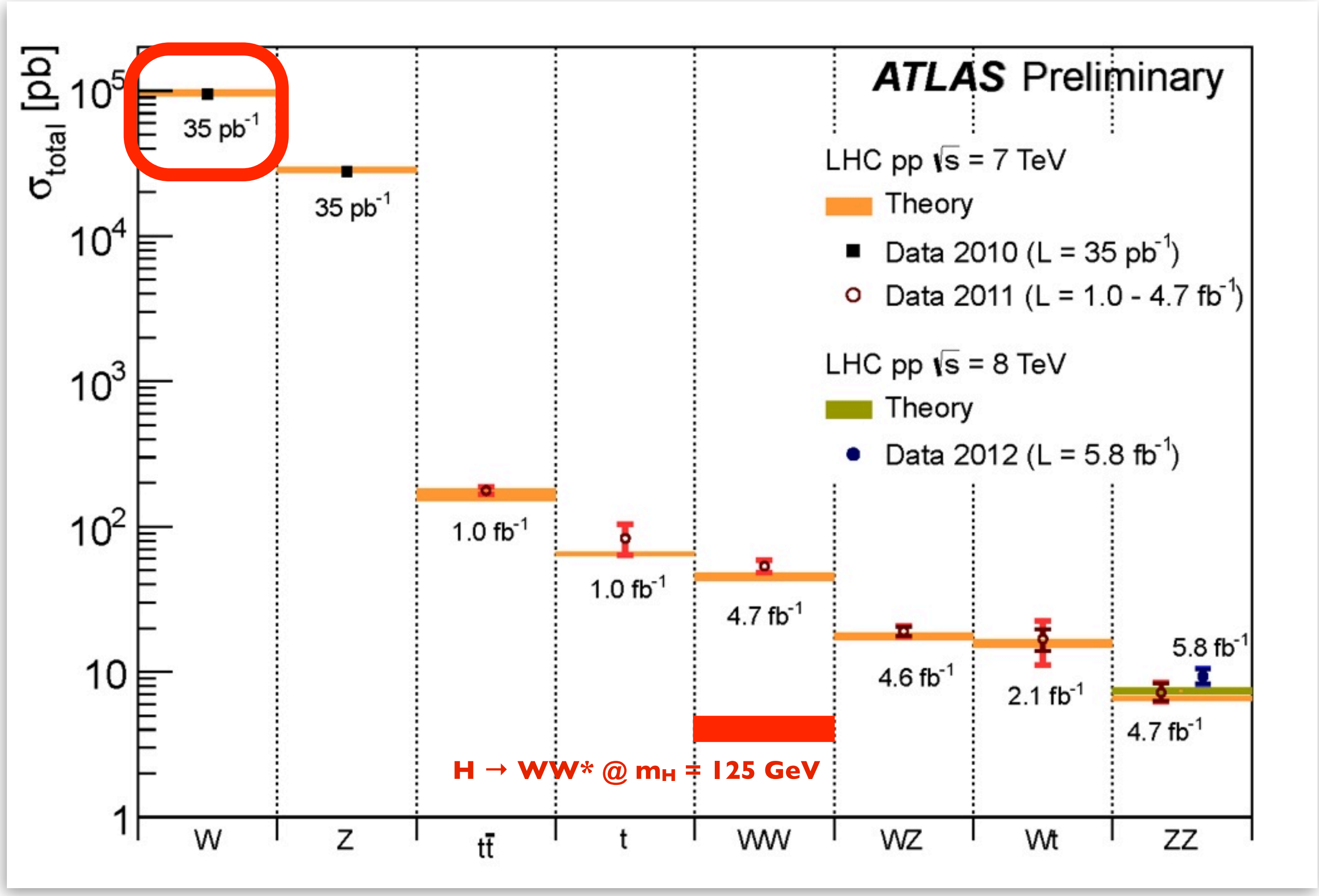
Background overview

Suppressing and understanding backgrounds is key issue!



plus Wγ and Wγ*

Backgrounds: W+jets



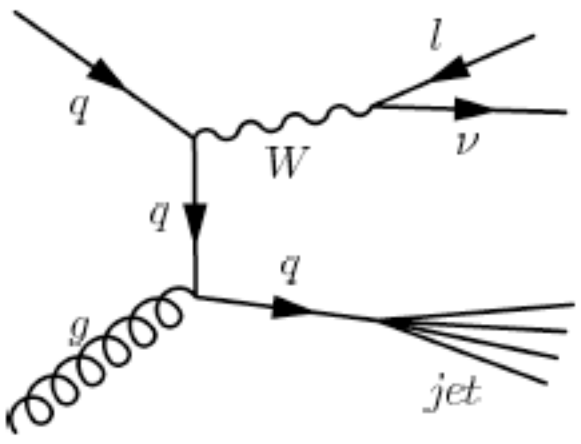
W+jets with the jet mis-identified as a lepton

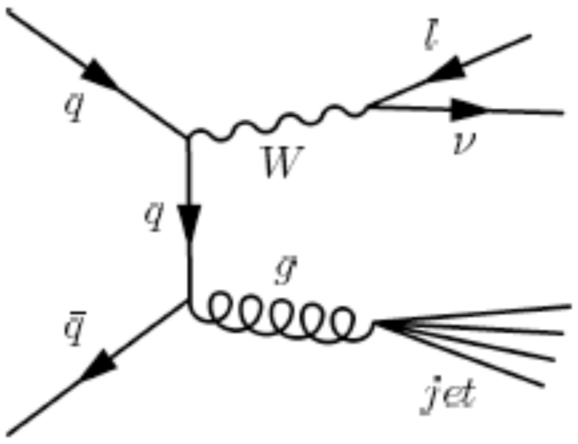
Lepton identification and isolation suppress W+jets by factor 10^{-5}

Also, kinematic cuts:

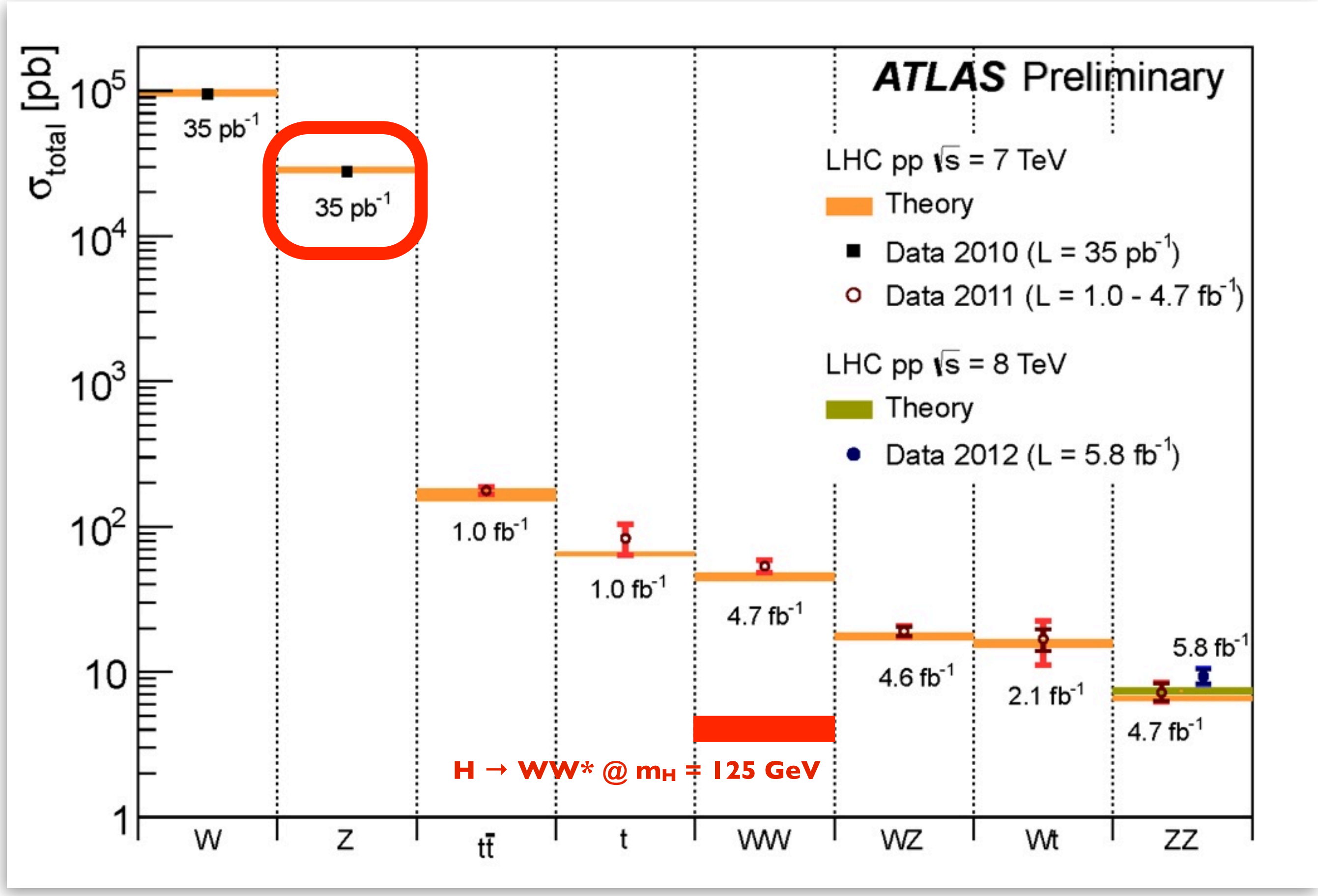
- $p_T(l_1) > 25$ GeV
- $p_T(l_2) > 15$ GeV

Use data-driven method





Backgrounds: Z+jets

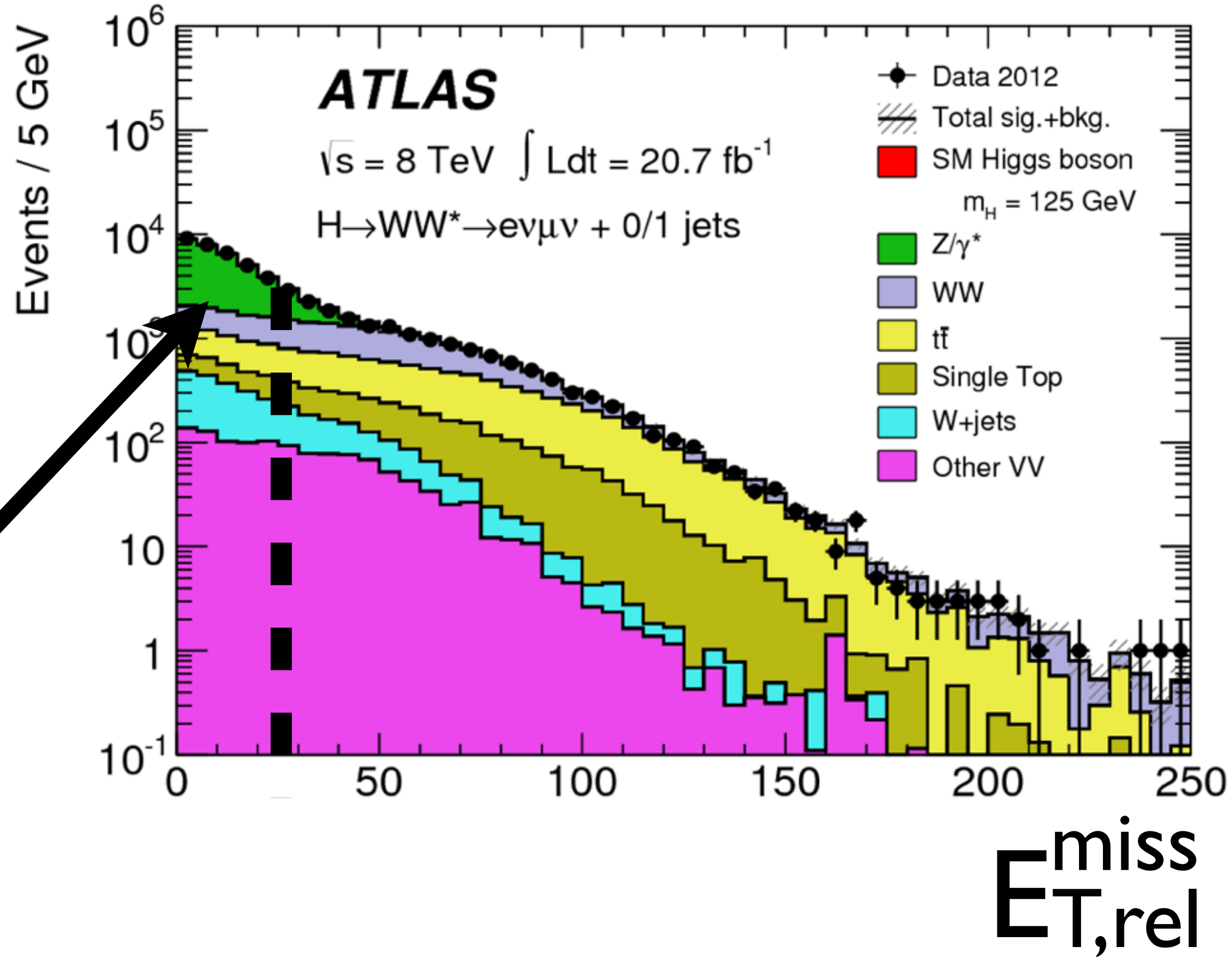


Z+jets suppressed by

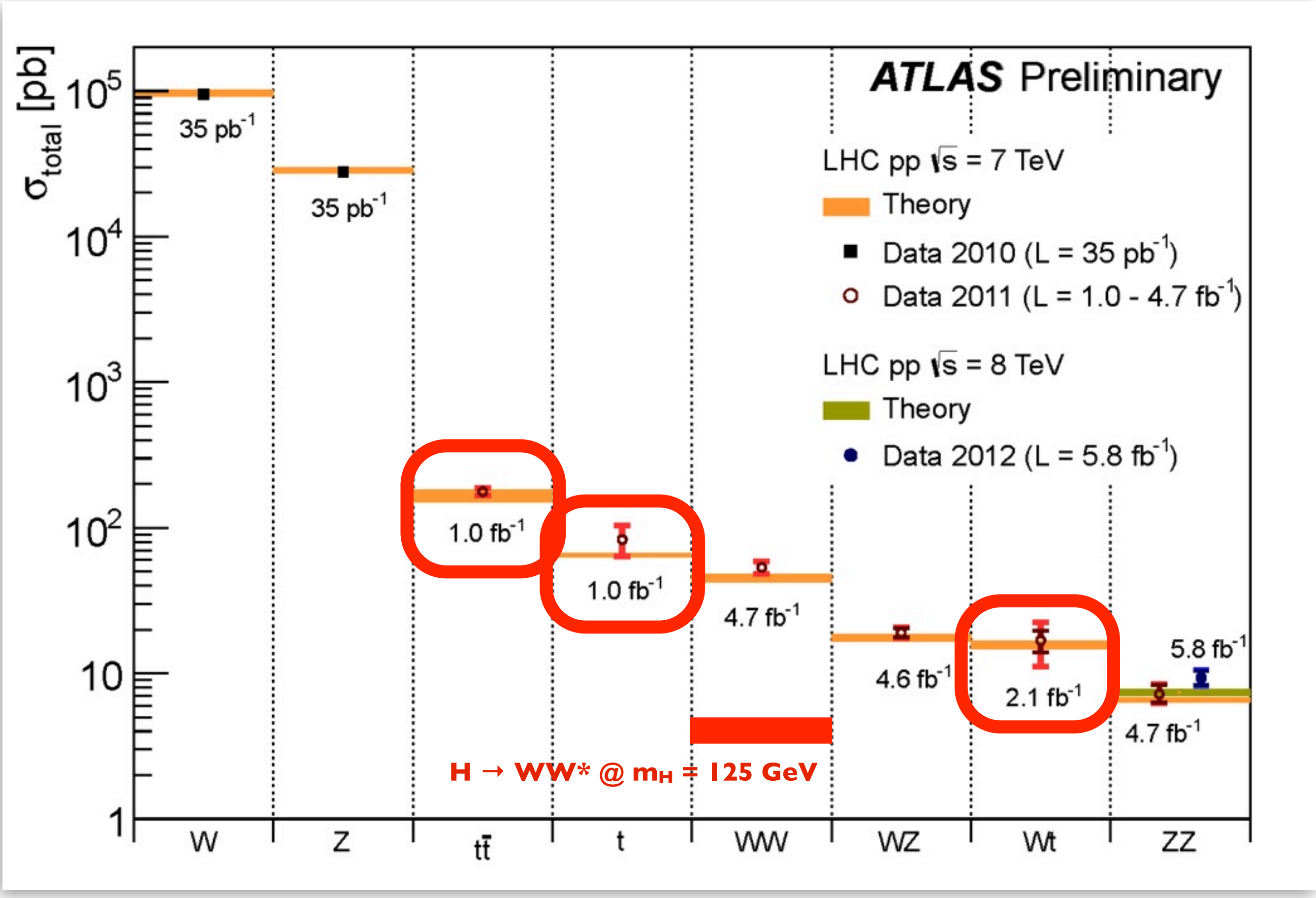
- reject events consistent with Z mass
- require missing E_T

Data control region

Z+jets



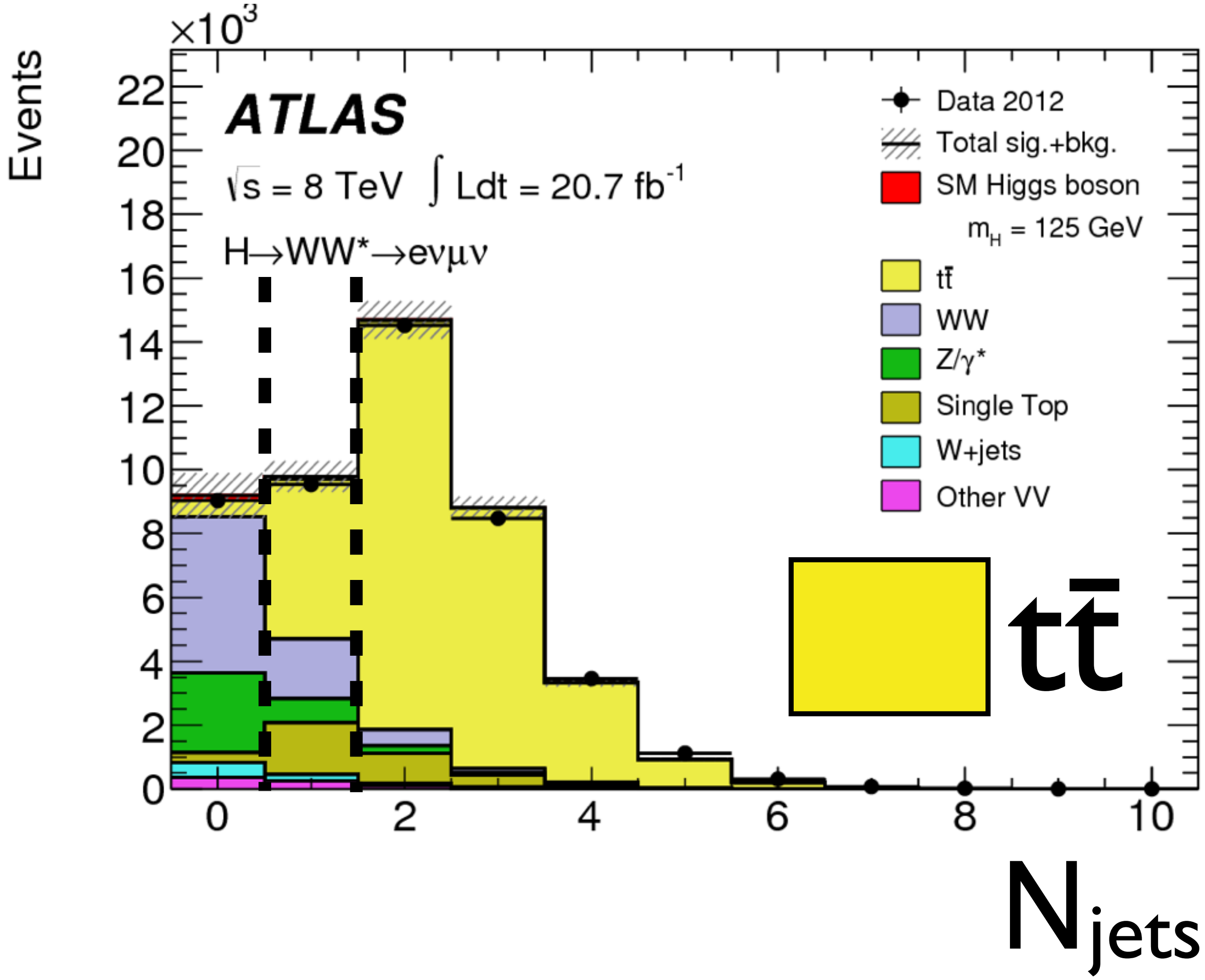
Backgrounds: top



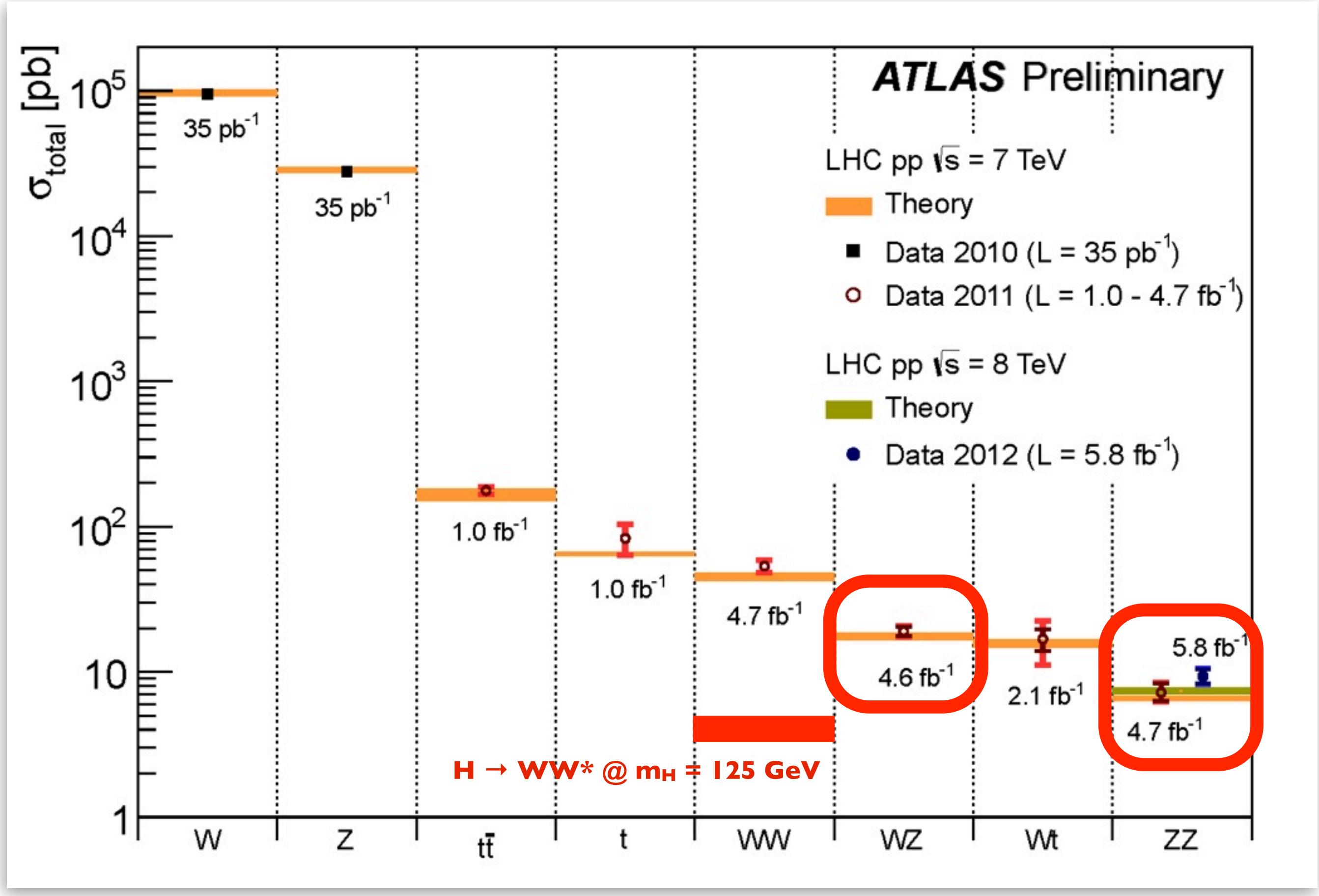
b-jet veto for all events

top background strongly depends on N_{jets} bin

Data control region



Backgrounds: other di-boson



plus $W\gamma$ and $W\gamma^*$

$WZ \to l\nu ll$, $ZZ \to llll$, and $W\gamma^* \to l\nu ll$:

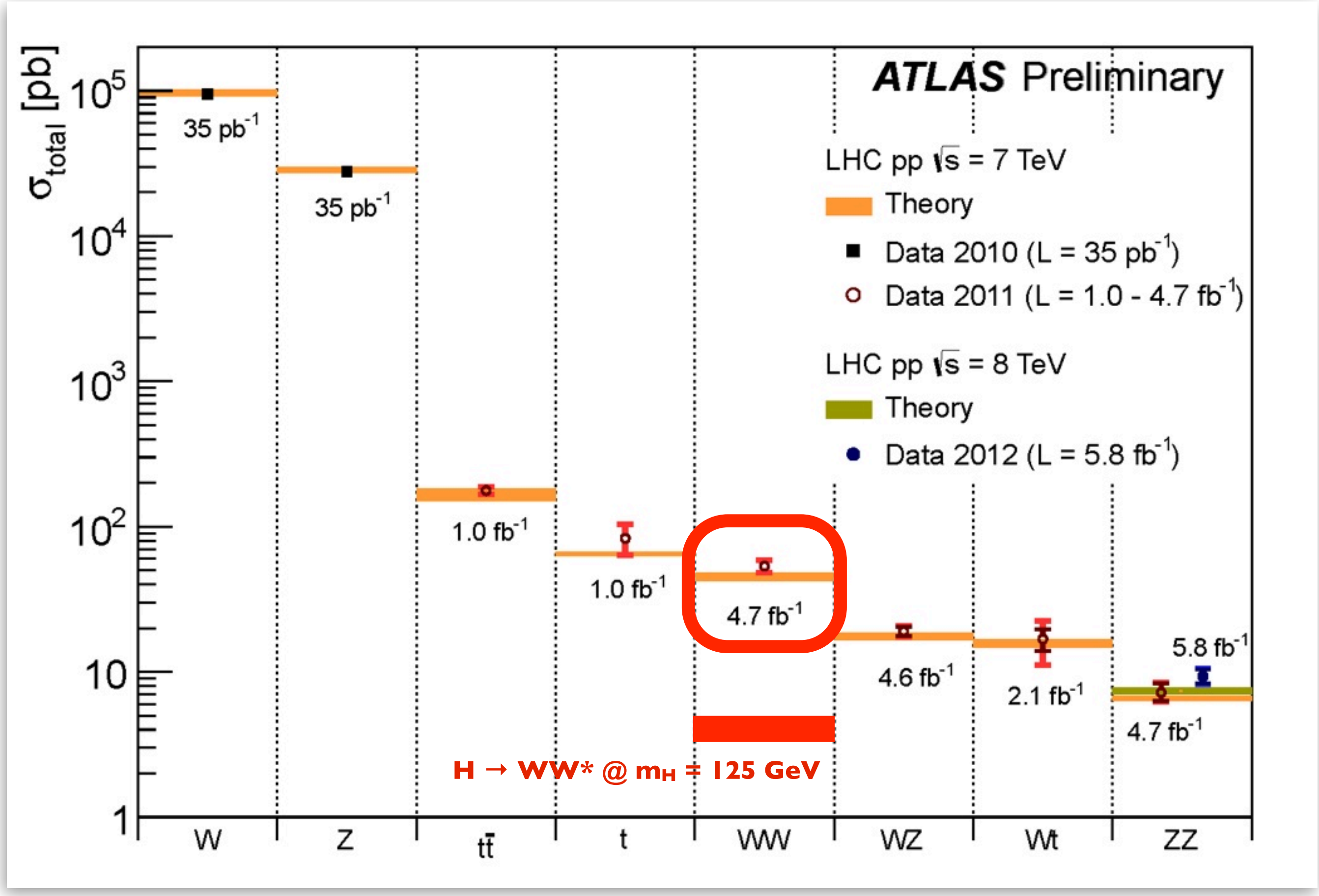
- Remove events with >2 leptons

$W\gamma \to l\nu\,\gamma$ with γ conversion:

- Use electron identification to veto photon conversions
  - e.g., measurement in the innermost layer of the tracker

$W\gamma$ and $W\gamma^*$ are cross-checked with same-sign di-lepton data and low missing $E_{T,rel}$ data

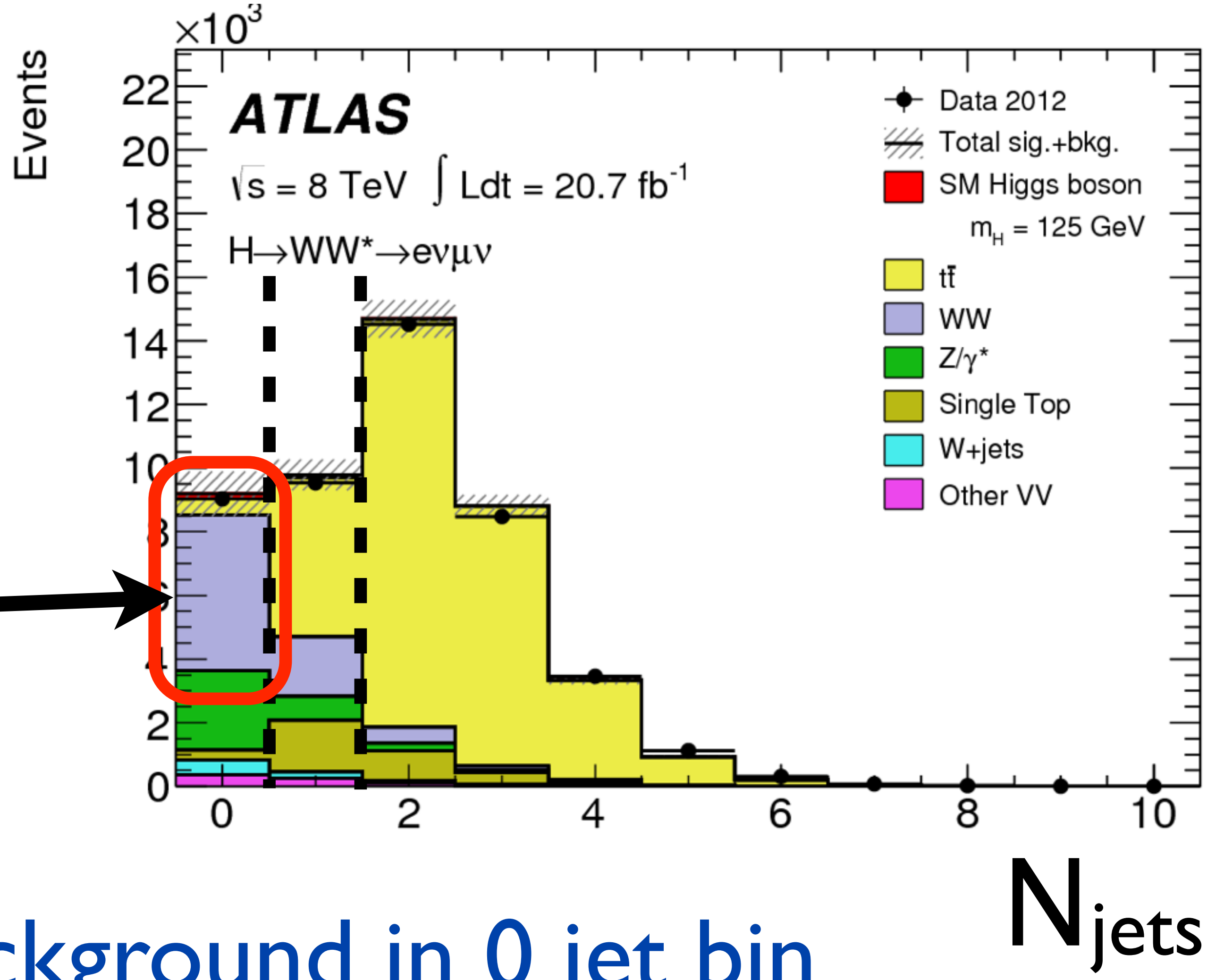
Backgrounds: WW



Irreducible

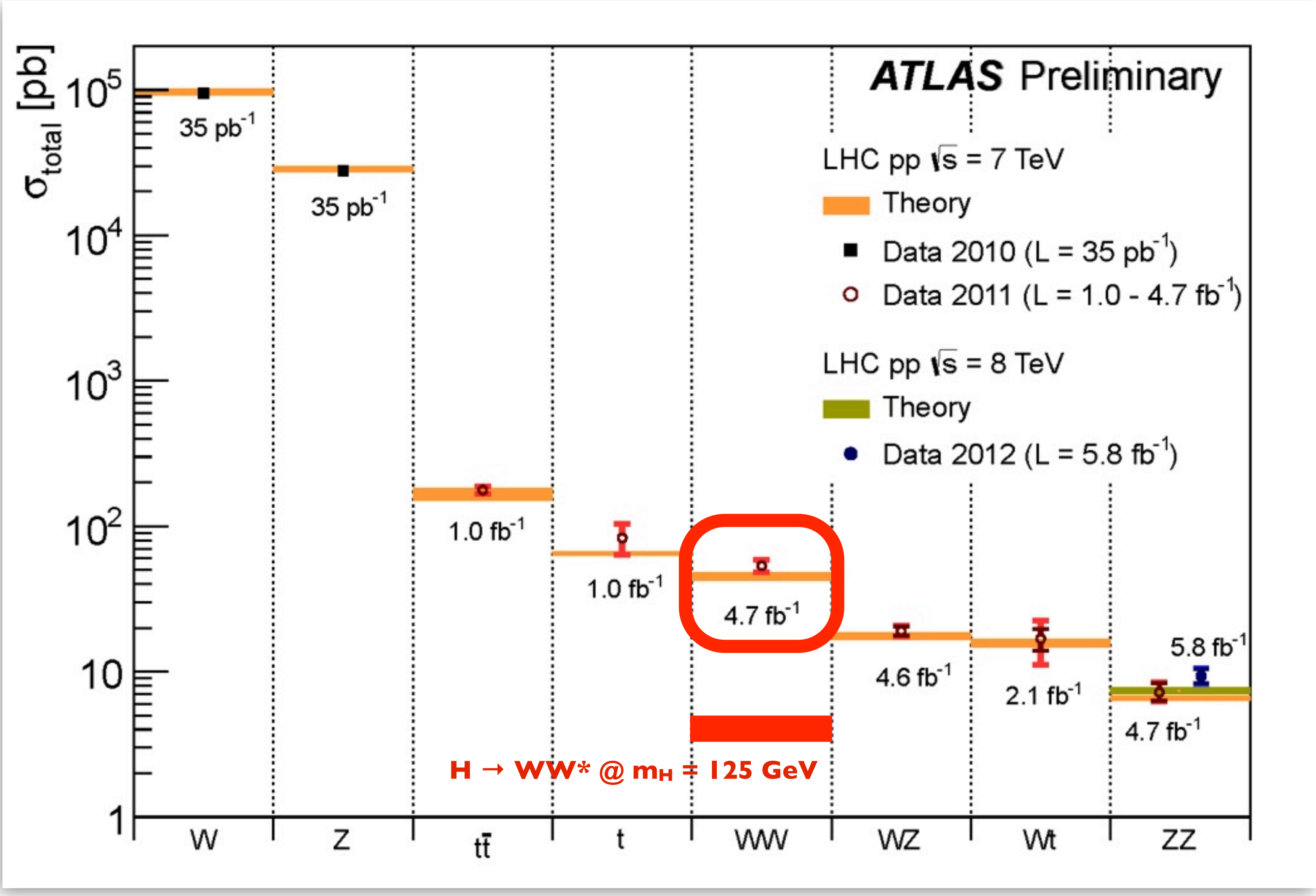
- exactly 2 good leptons
- missing E_T
- but...

WW

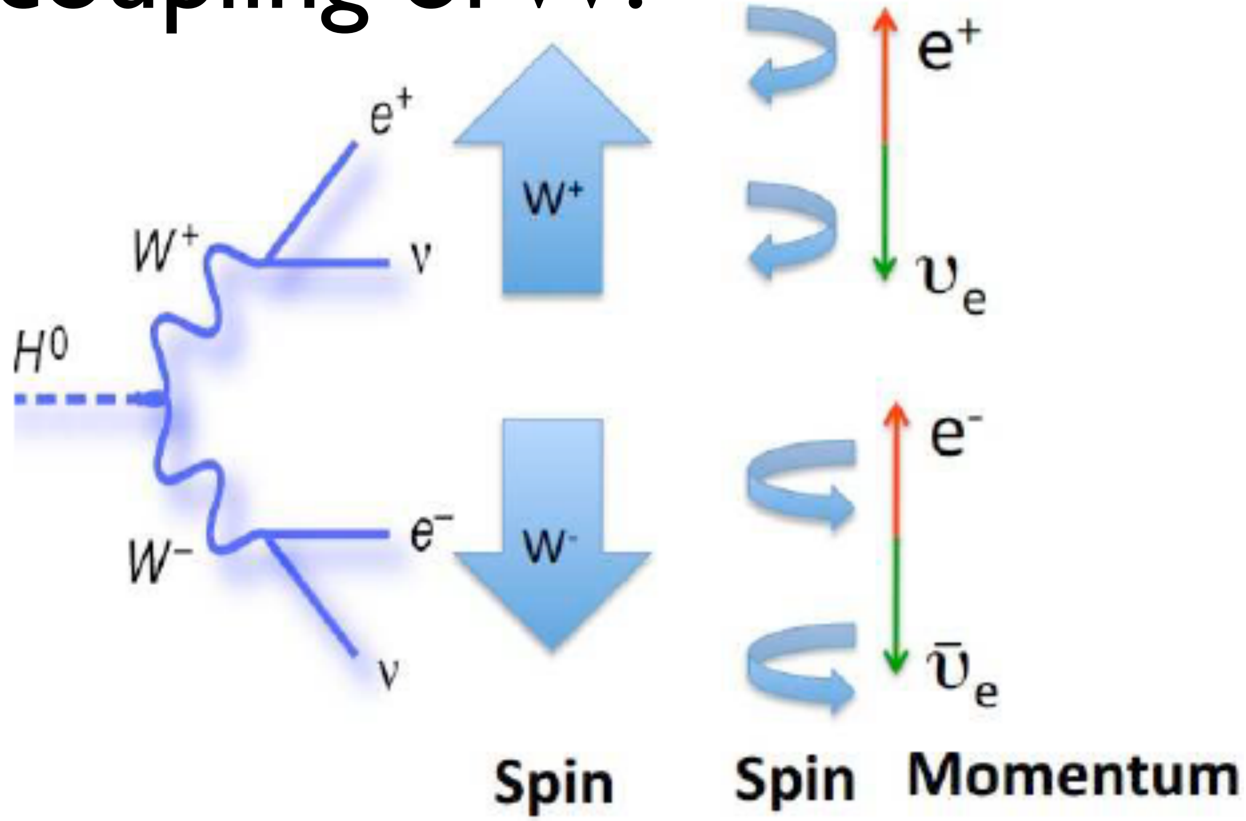


Largest background in 0 jet bin

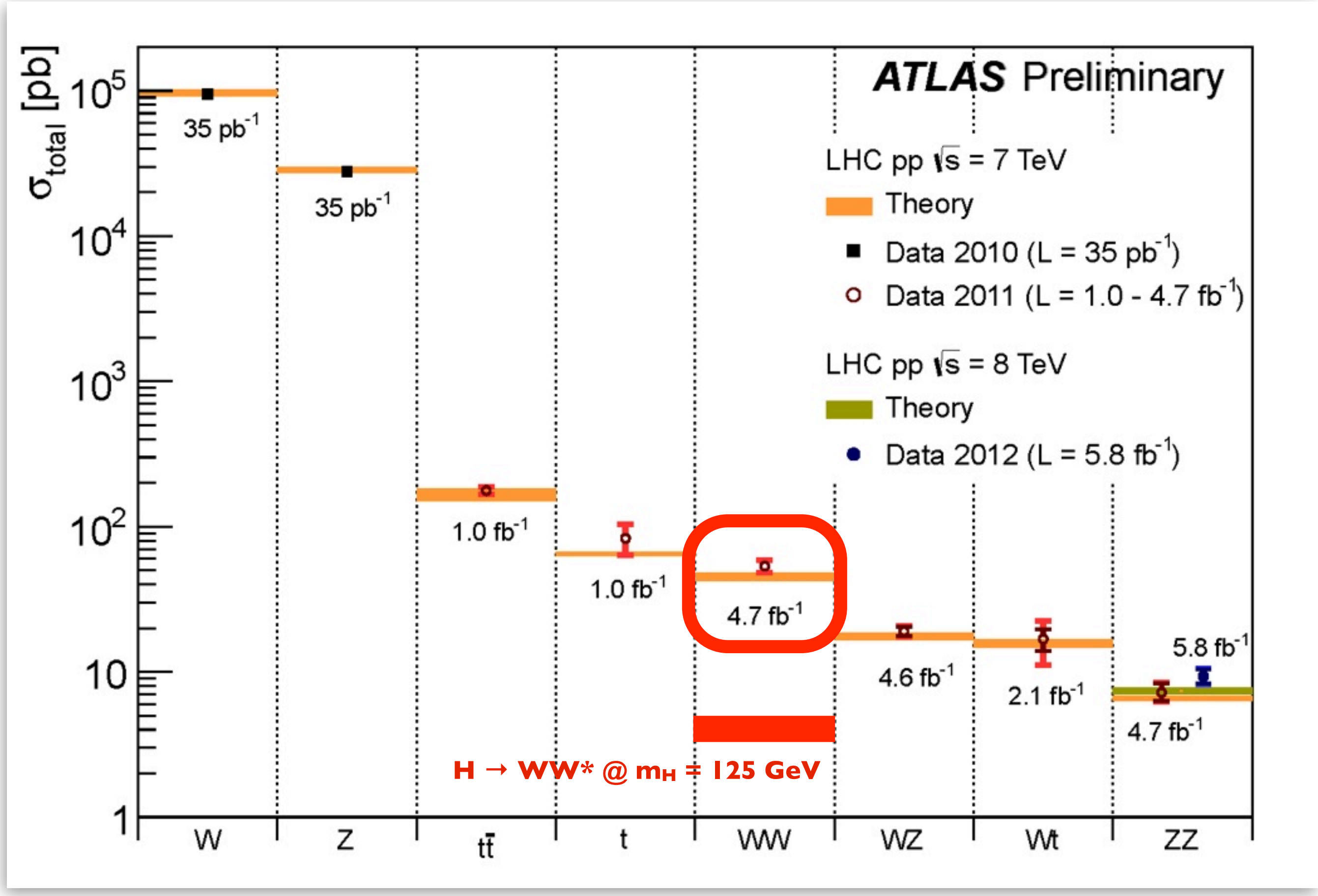
Backgrounds: WW



Spin structure and V-A coupling of W:



Backgrounds: WW



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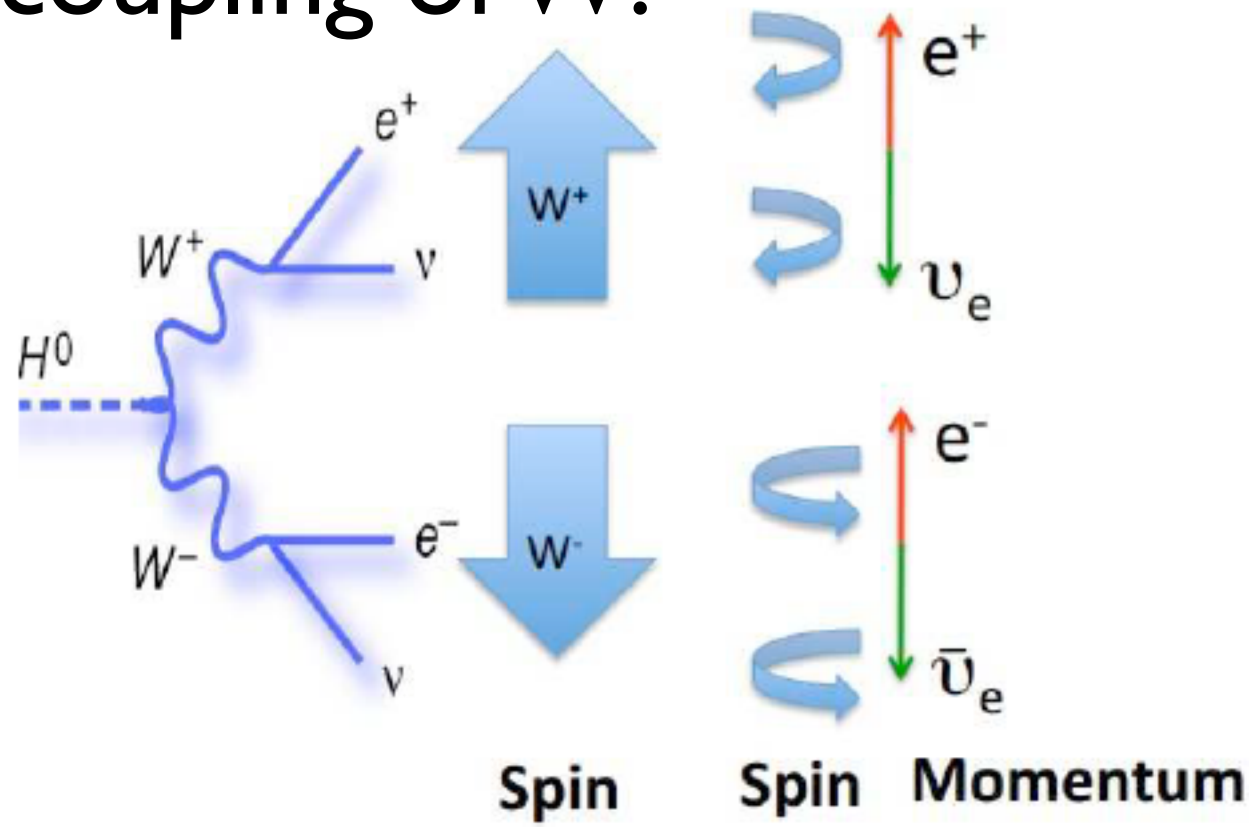
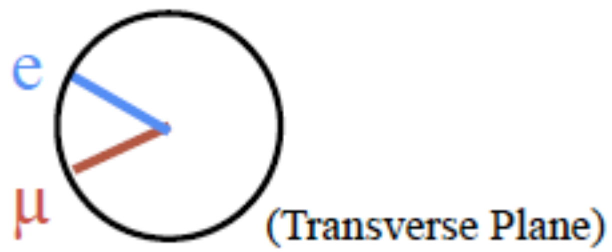
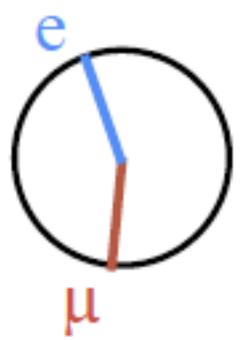


H → WW

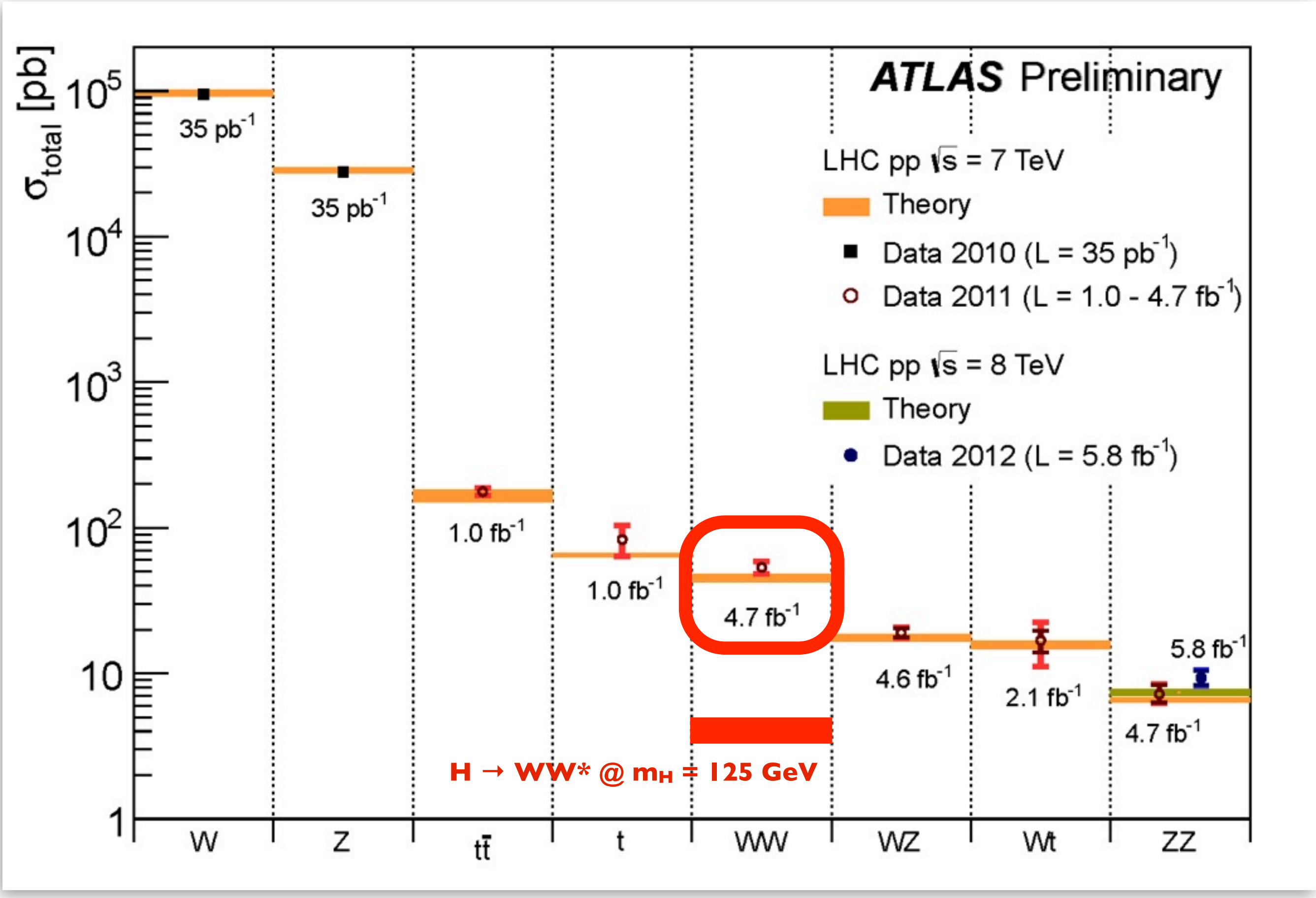


VS

Background WW

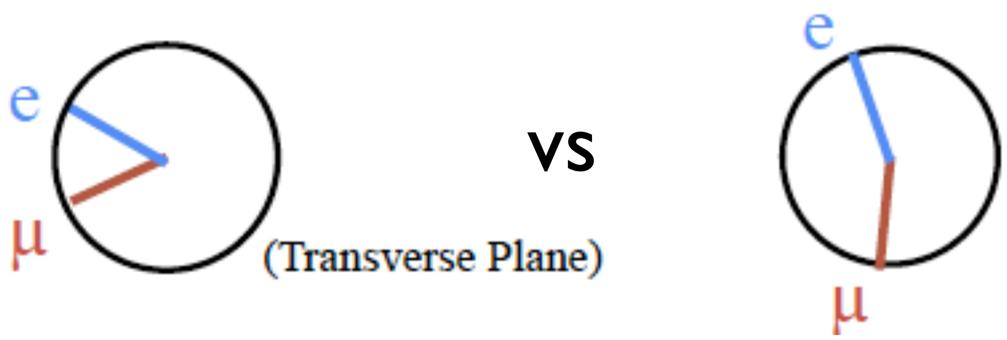


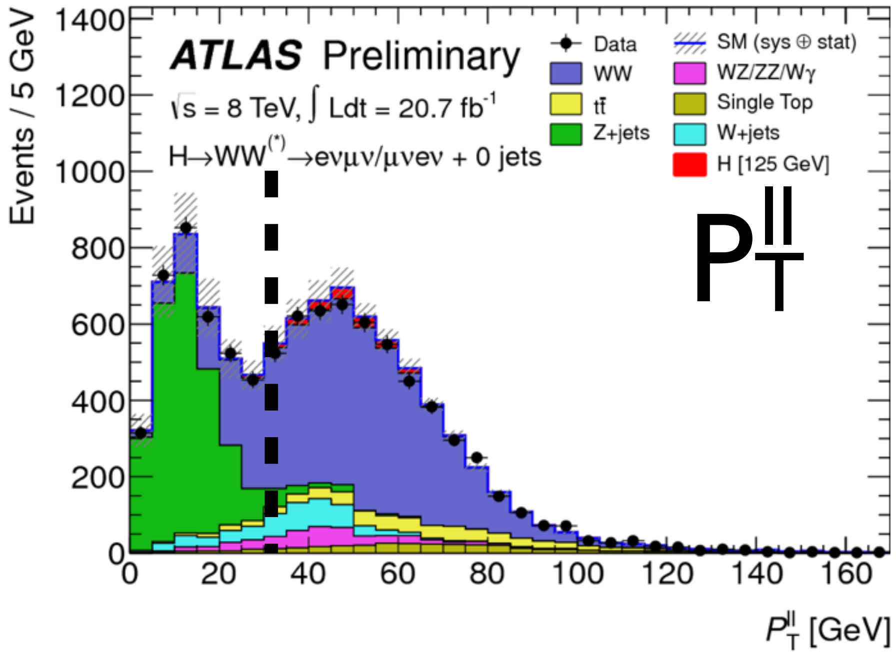
Backgrounds: WW

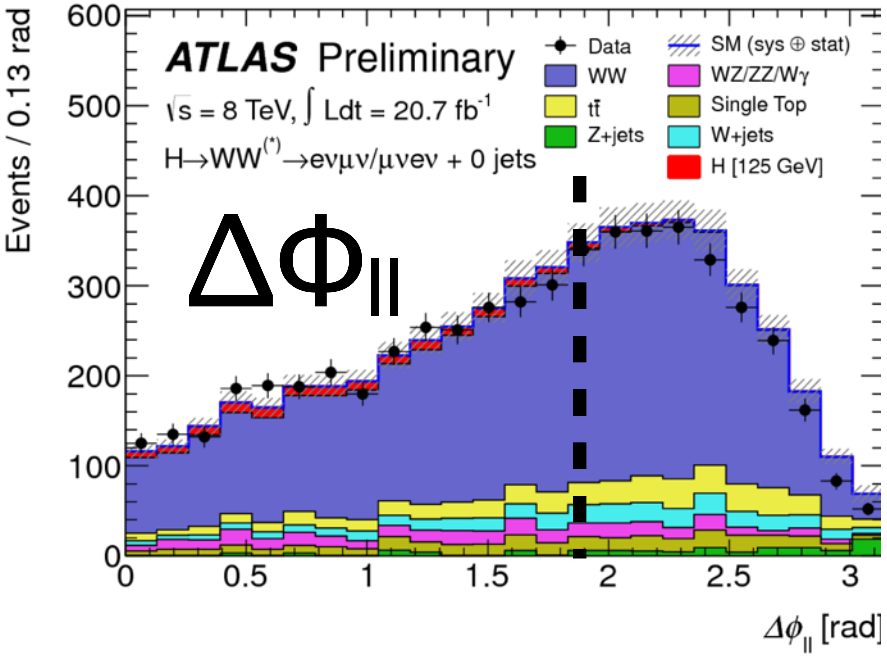


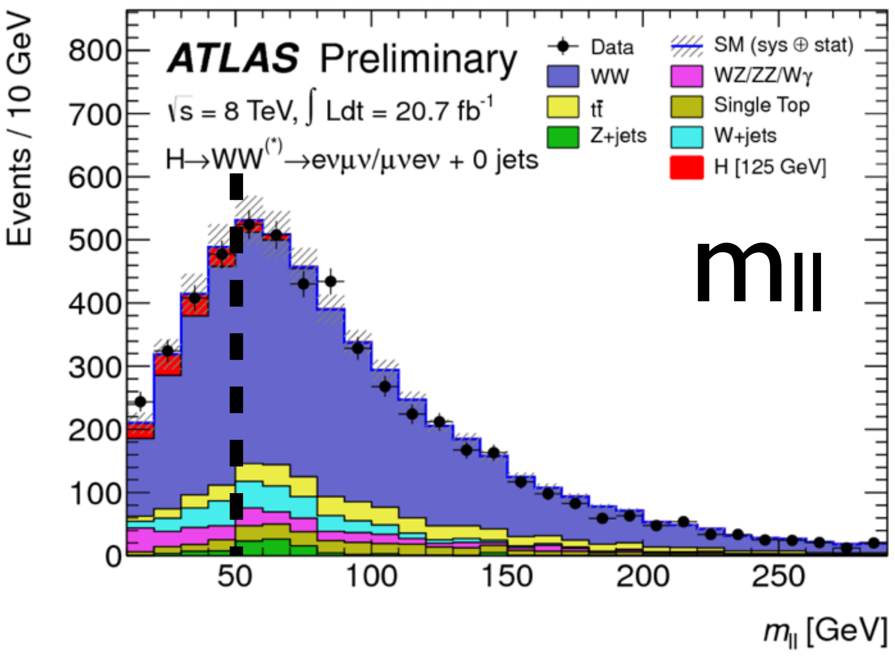
Spin structure and V-A coupling of W:

H → WW   Background WW

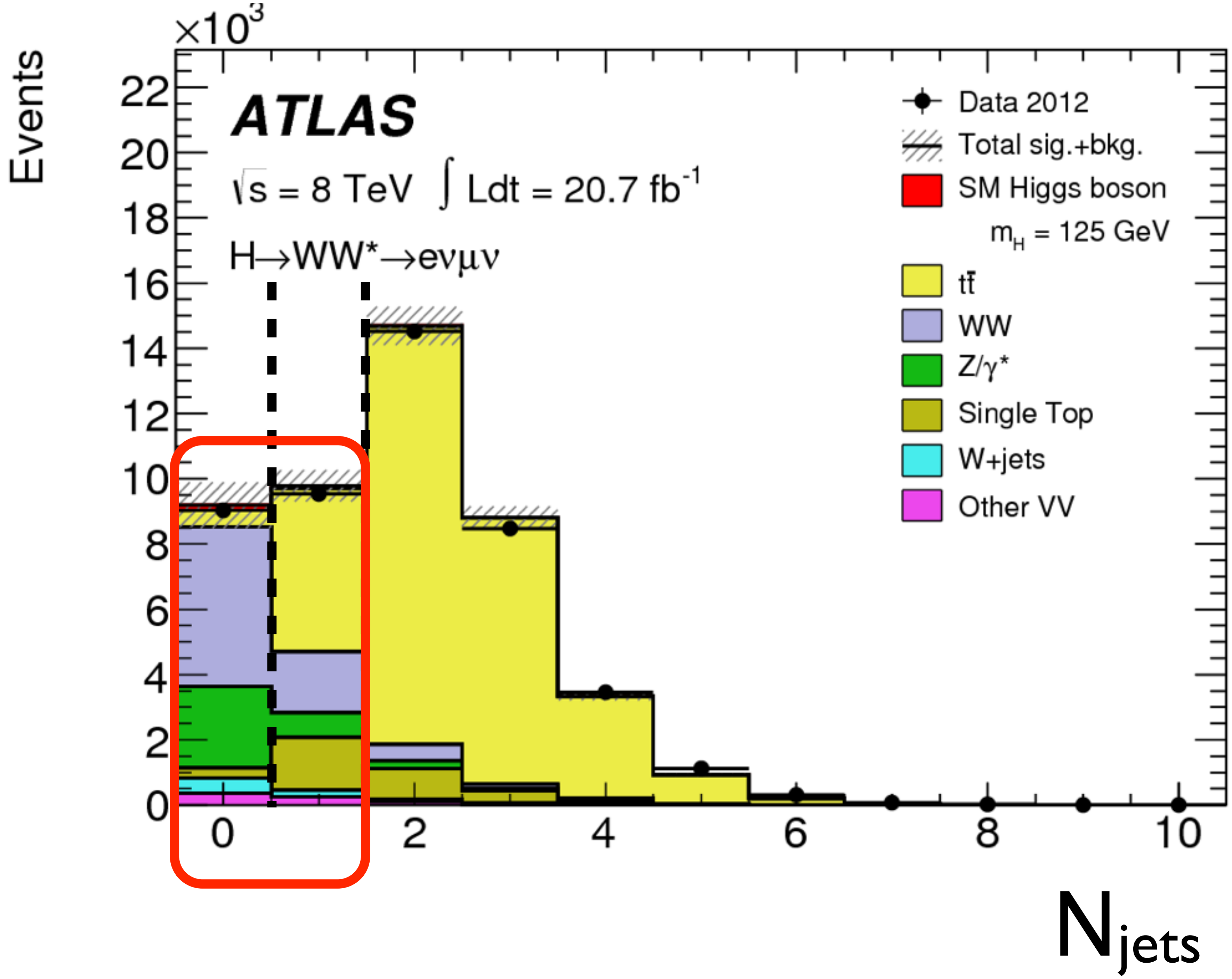






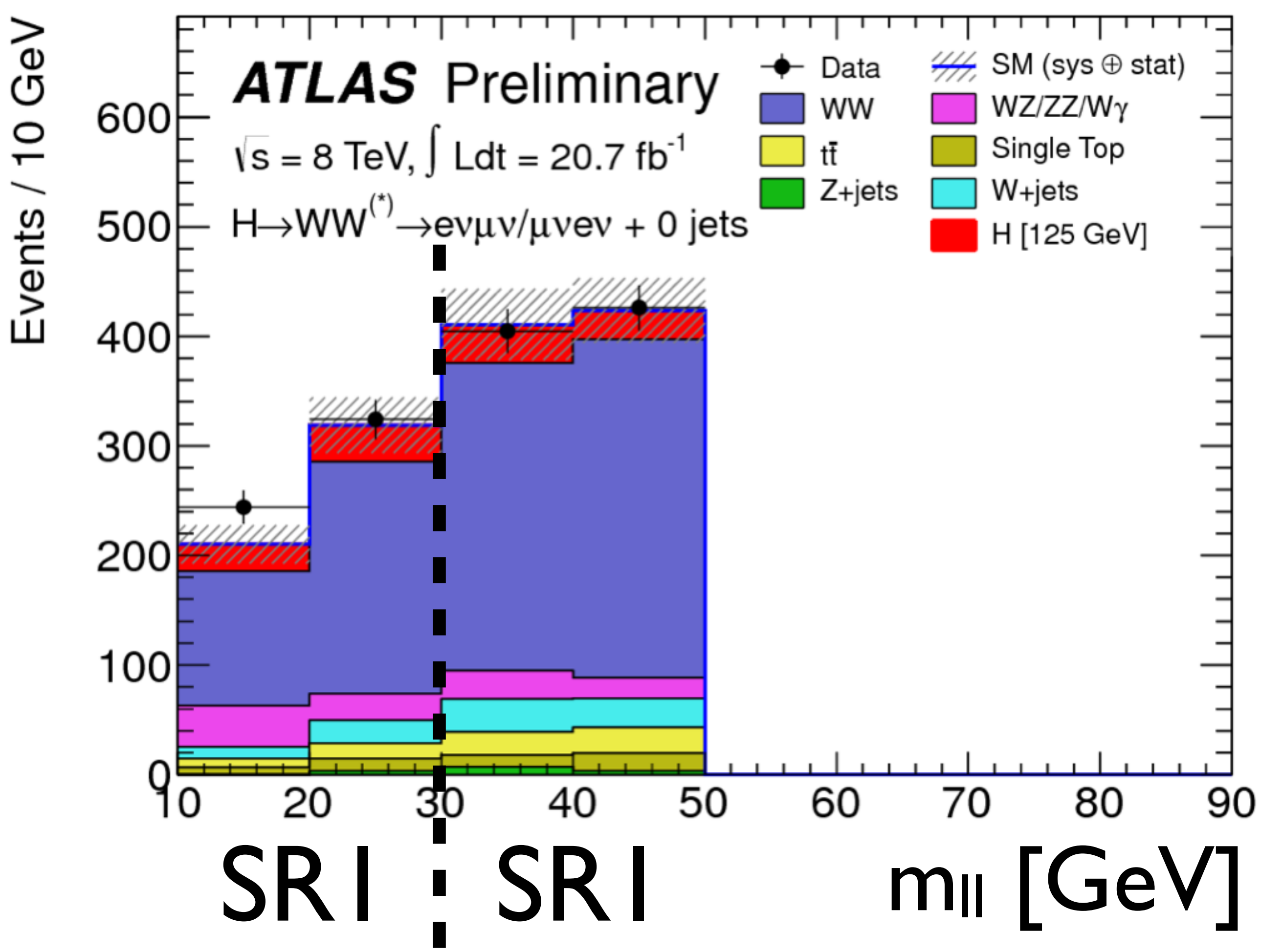


0 and 1 jet analysis



Signal extraction

Split 0 jet eμ signal region:

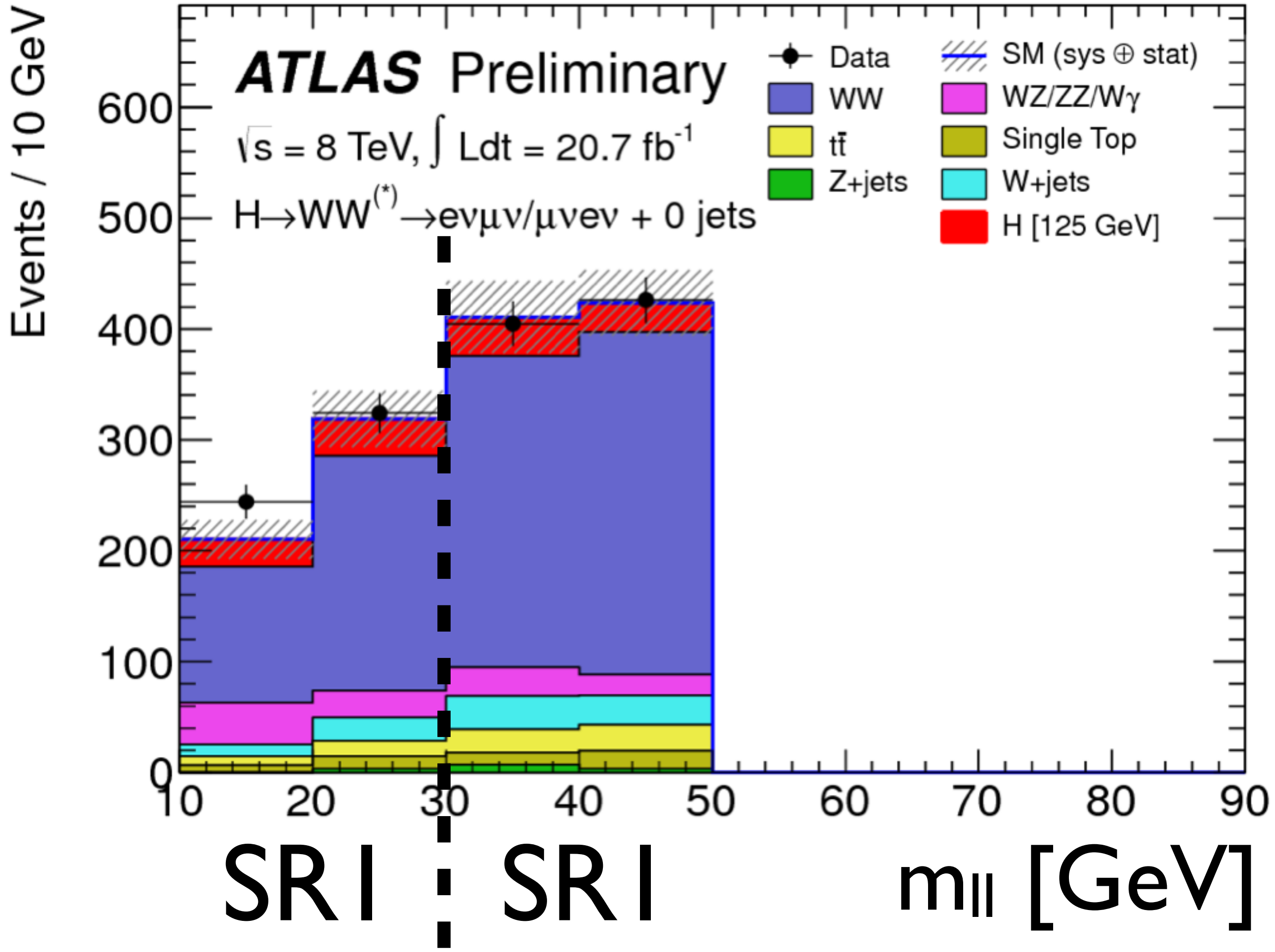


Split improves sensitivity:

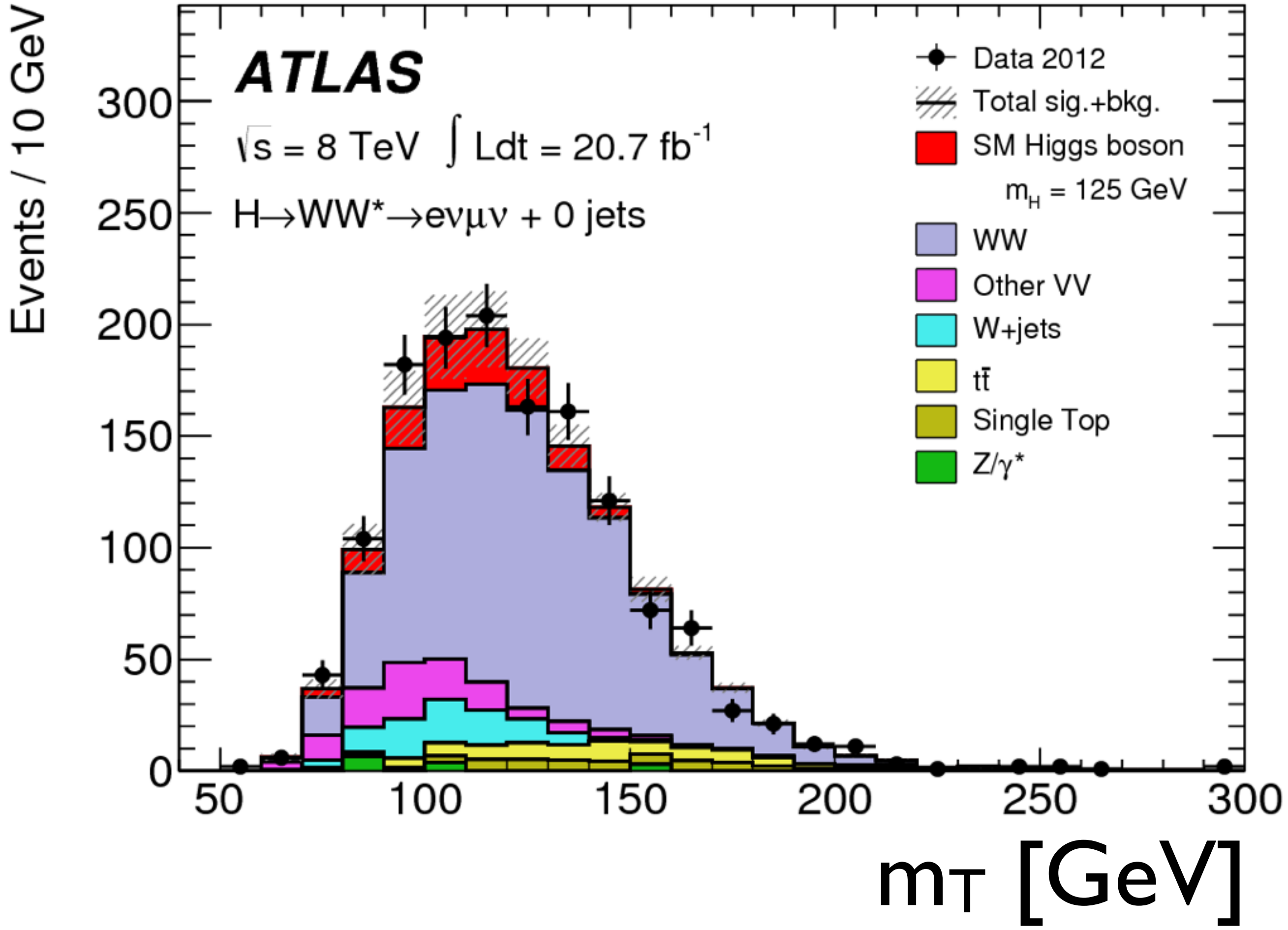
- Different Signal/Bkg
- Different background composition

Signal extraction

Split 0 jet eμ signal region:



Fit to transverse mass:



Split improves sensitivity:

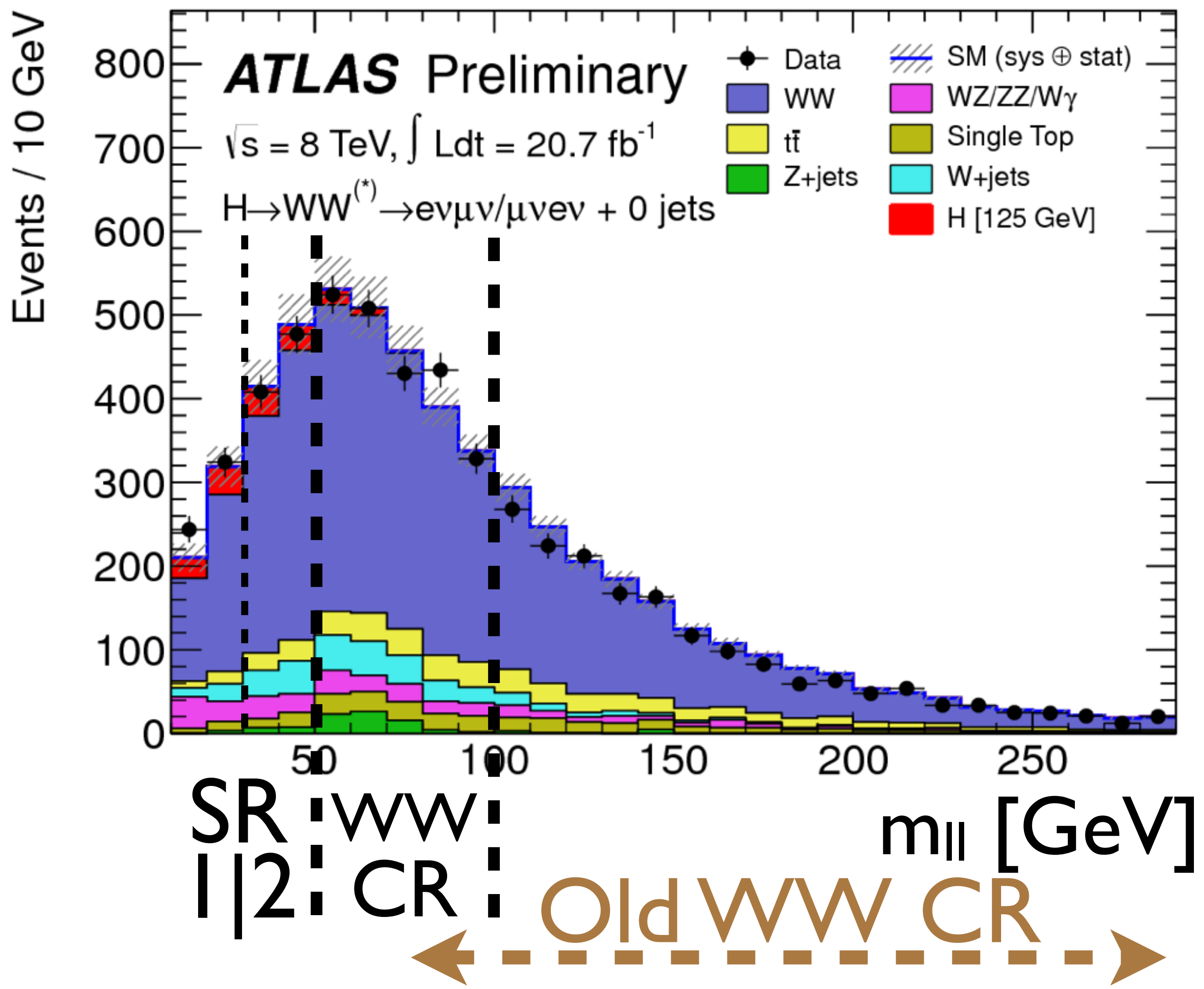
- Different Signal/Bkg
- Different background composition

Use (transverse) mass info:

$$\boxed{m_T^2 = \left(\sqrt{m_{ll}^2 + |\vec{p}_{Tll}|^2} + E_T^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{Tll} + \vec{E}_T^{\mathrm{miss}}\right)^2}$$

WW data control region

Extrapolate in fit from control region to signal regions:

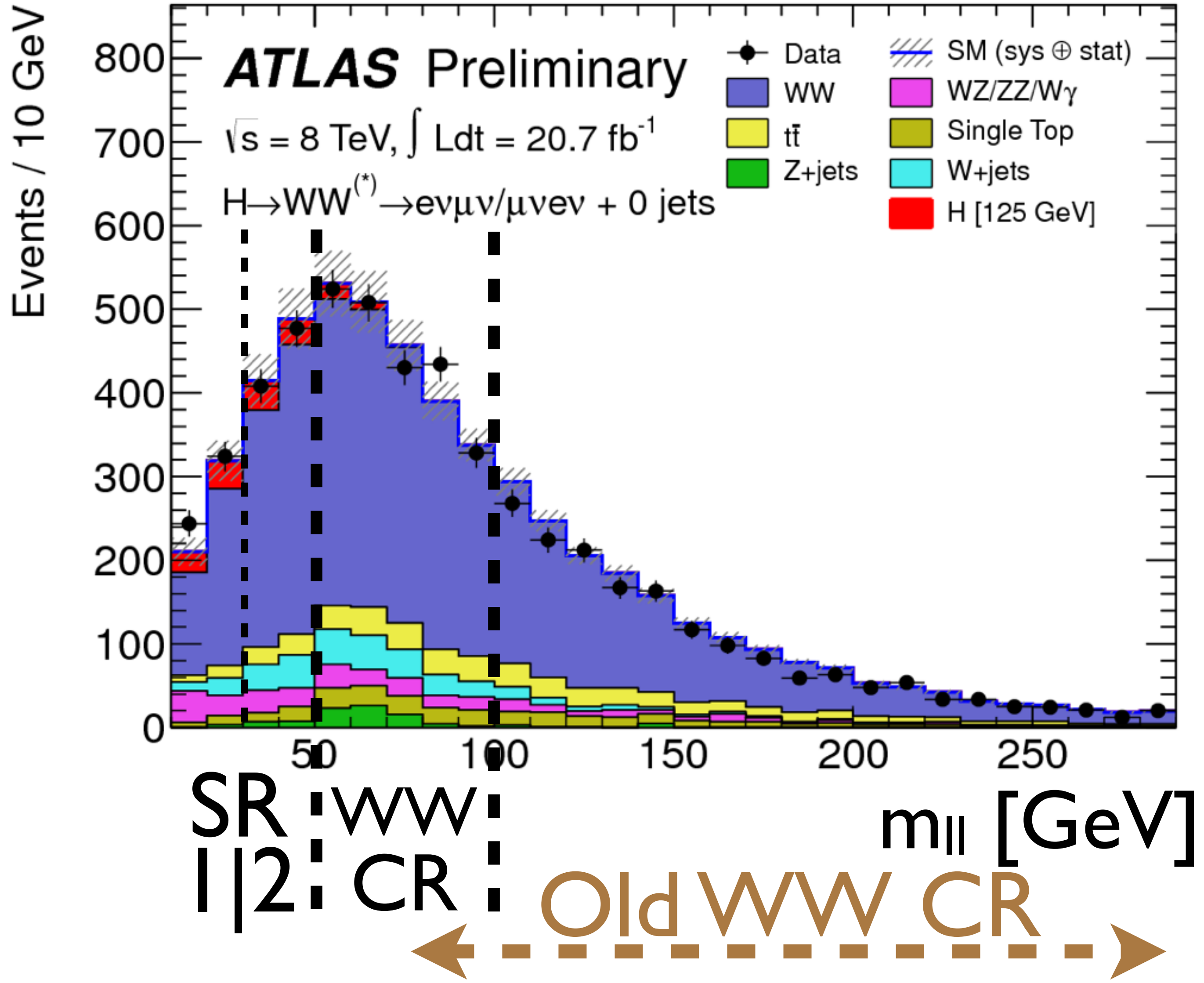


Smaller extrapolation uncertainties from CR to SR

Use migh-m$_{ll}$ region to validate

WW data control region

Extrapolate in fit from the control region to signal regions:



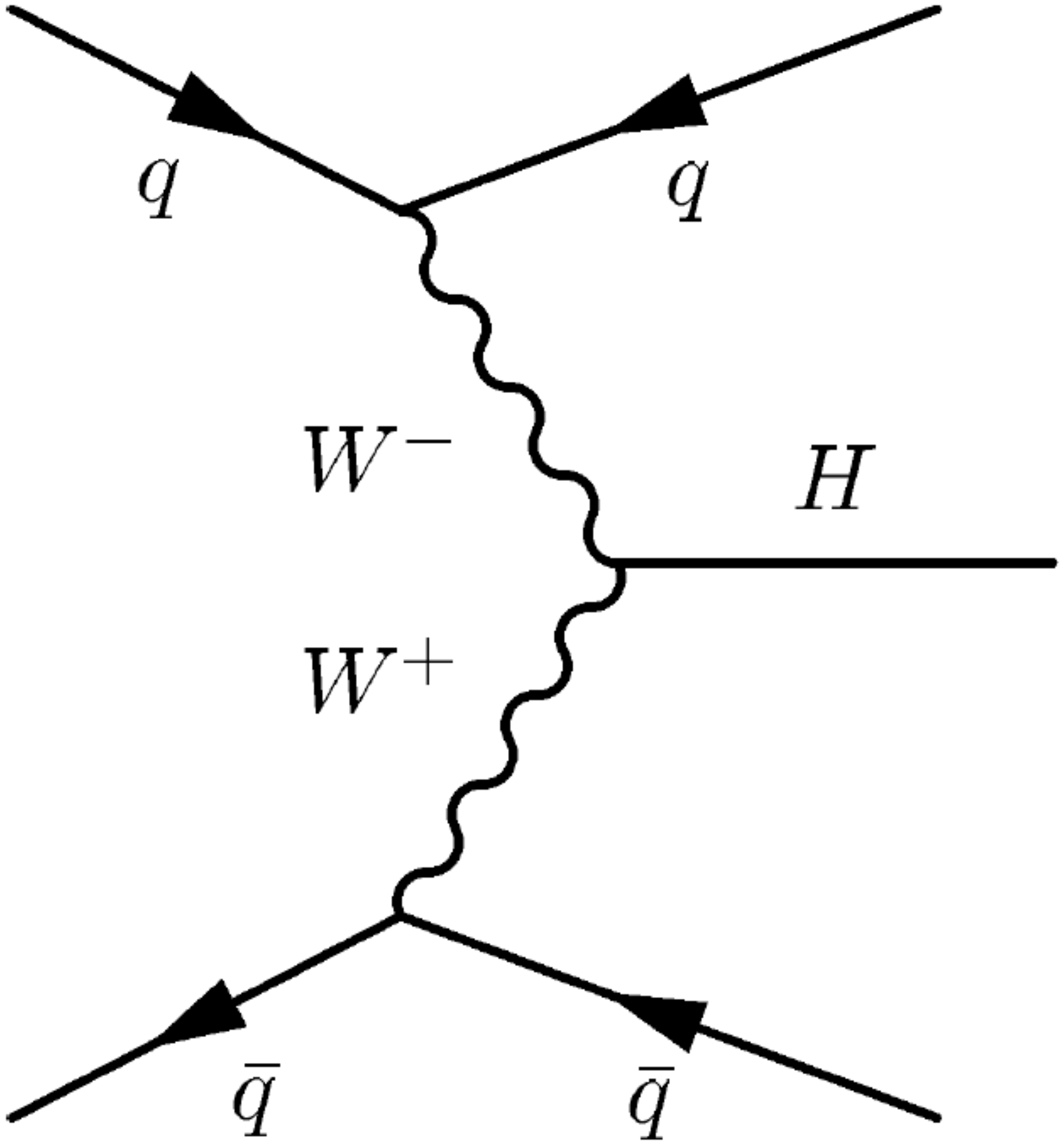
WW extrapolation systematics

Source	Old	New
Scale	2.5%	0.9%
PDF	3.7%	1.1%
Parton shower	4.5%	0.8%
MC model	3.5%	1.4%
Total	7.2%	2.1%

Smaller extrapolation uncertainties from CR to SR

Use migh-m$_{ll}$ region to validate

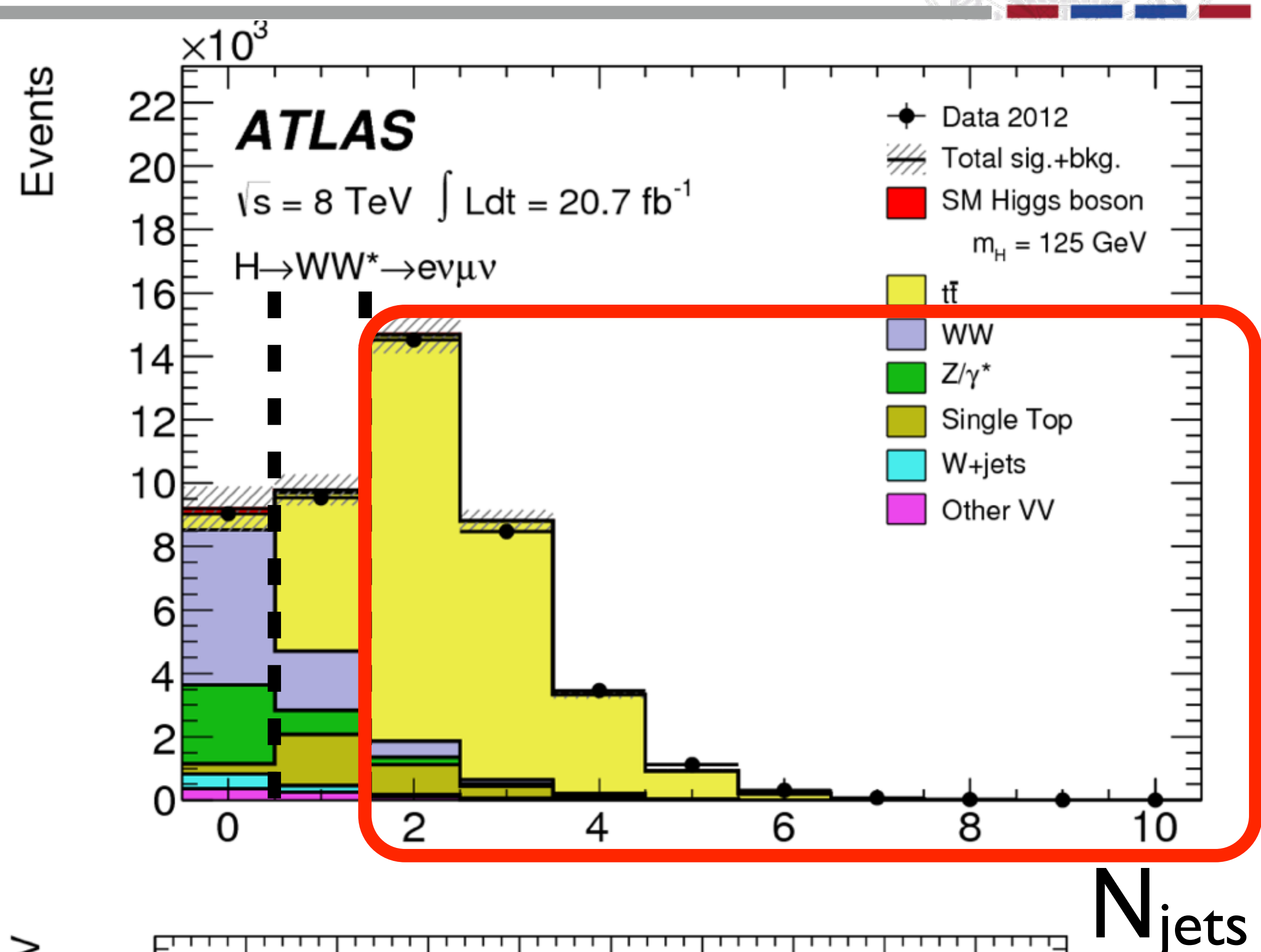
VBF analysis

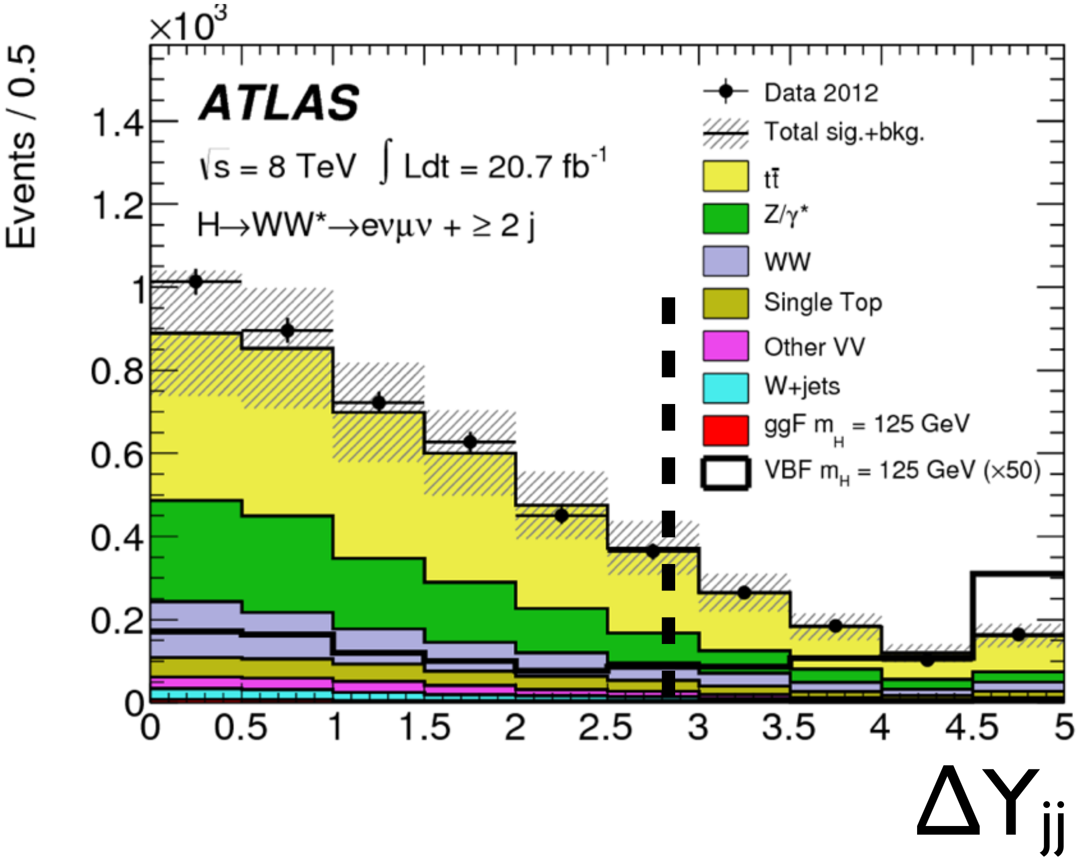


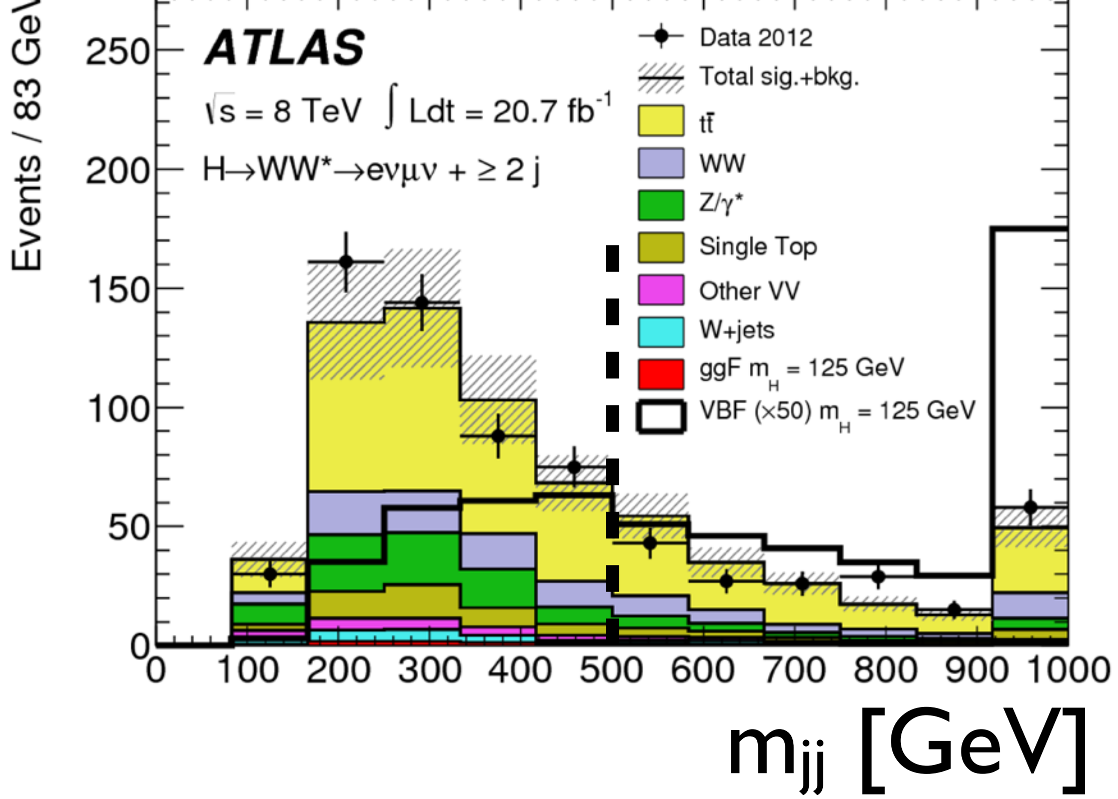
VBF event selection

WW + 2 frwd jets w/ large rapidity gap

- Top is dominant background
  - Constrained w/ data control
- Tighten event selection:
  - b-tag veto
  - $\Delta Y_{jj} > 2.8$ and $m_{jj} > 500$ GeV
  - No additional central jets
  - Both leptons central



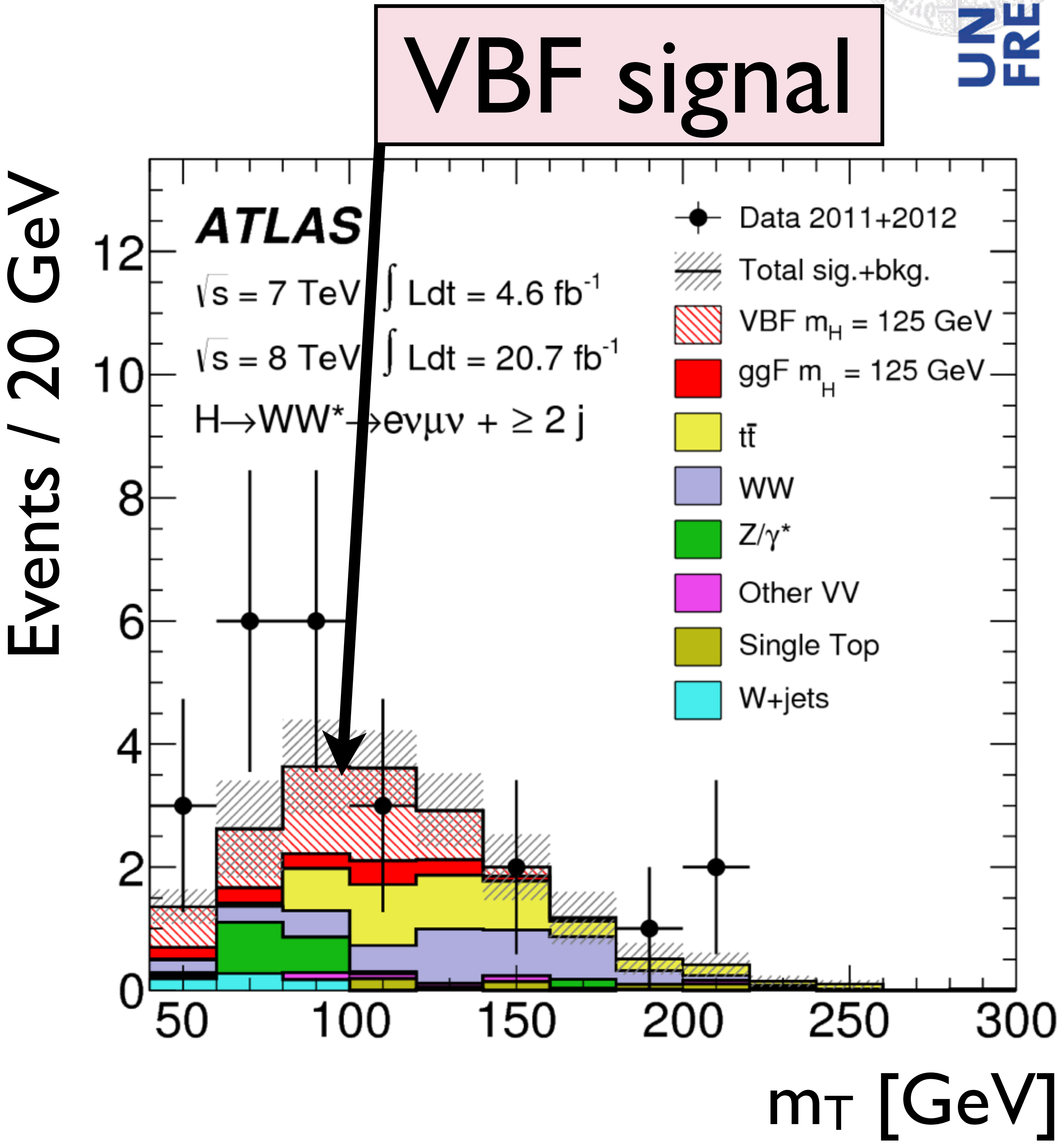




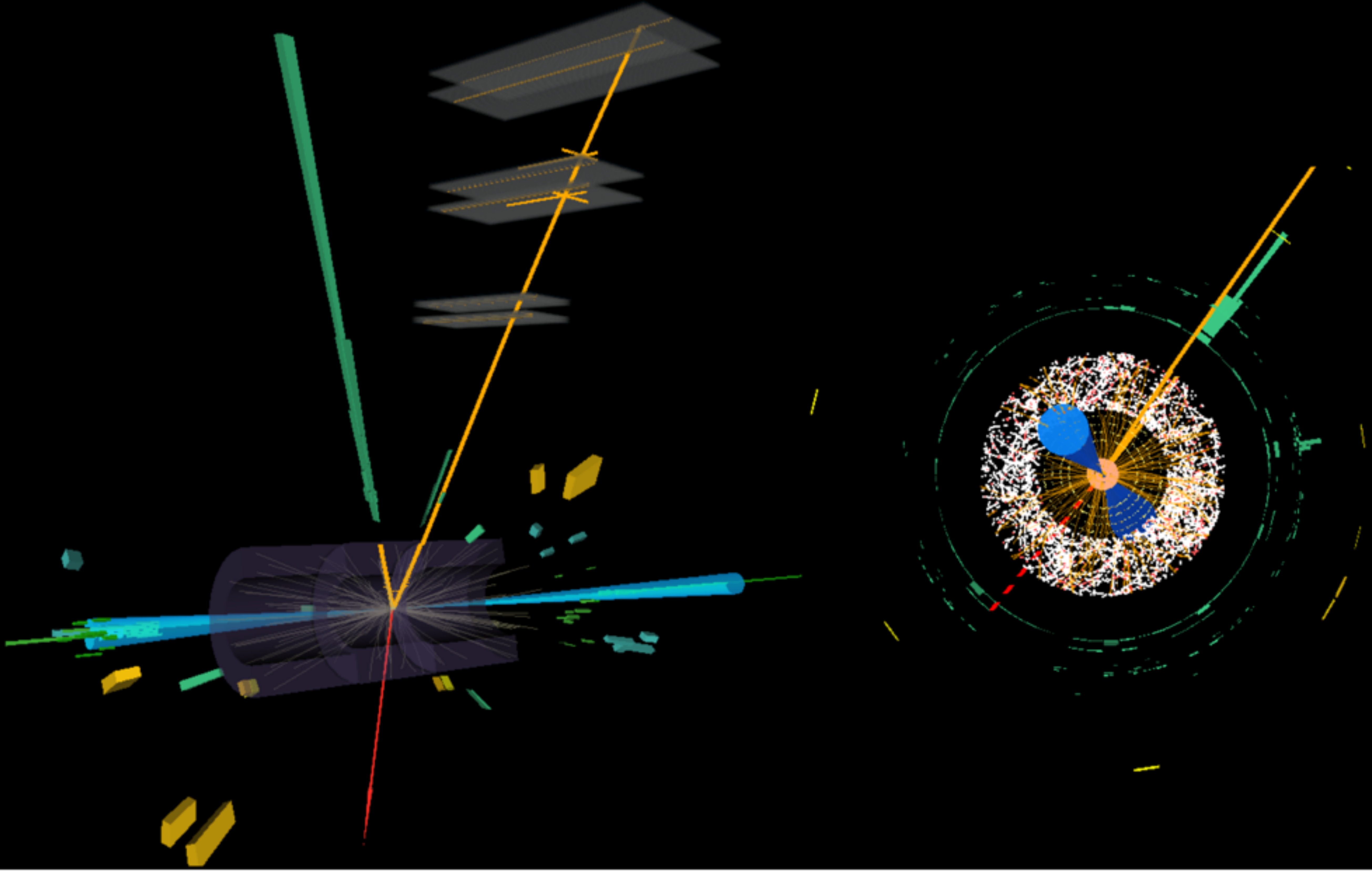
VBF signal extraction

Fit m_T distribution:

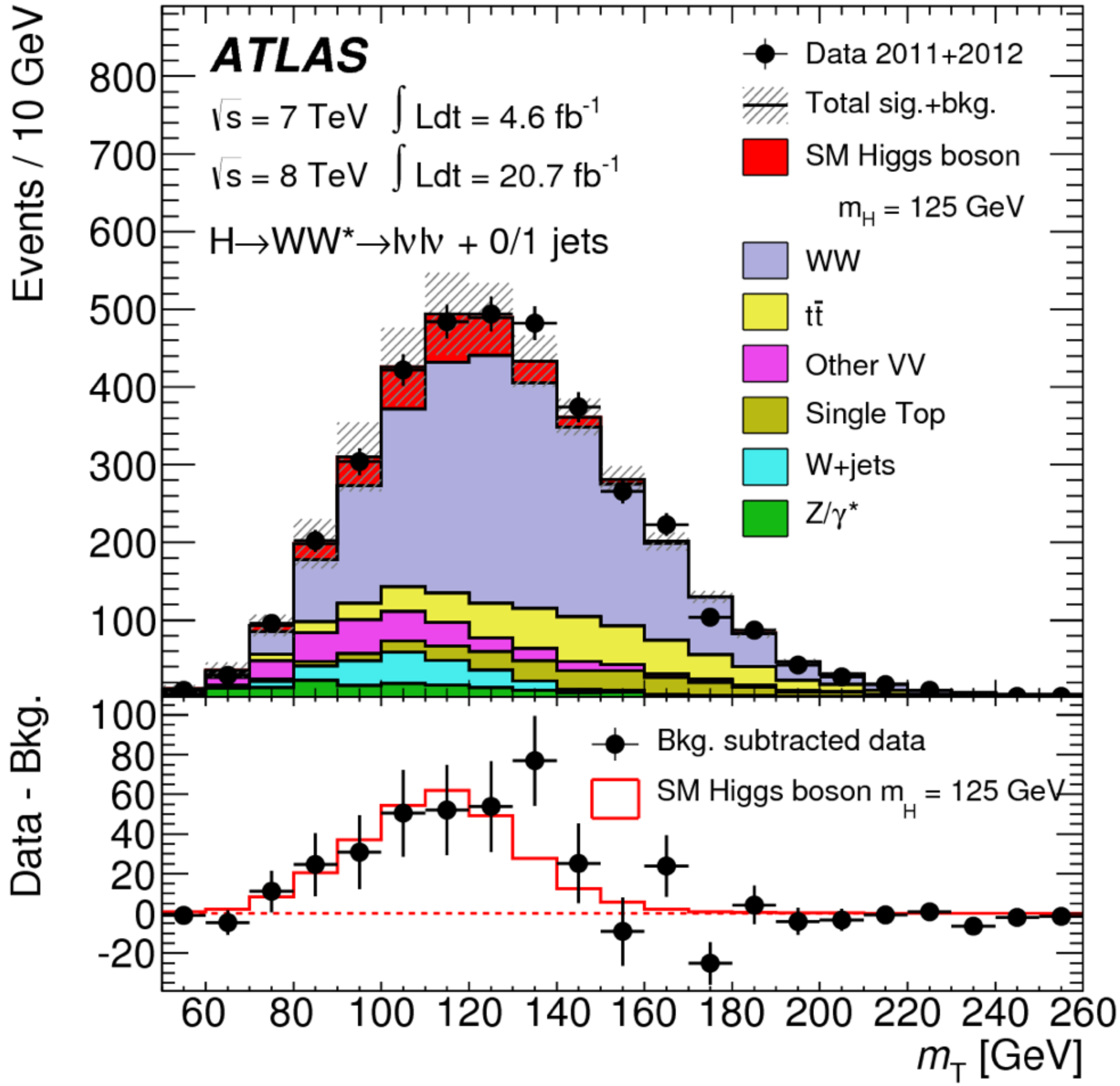
- w/ top data control region
  - 1 b-tag
- w/ Drell-Yan data control region
  - large $\Delta\Phi_{ll}$
- WW from theory



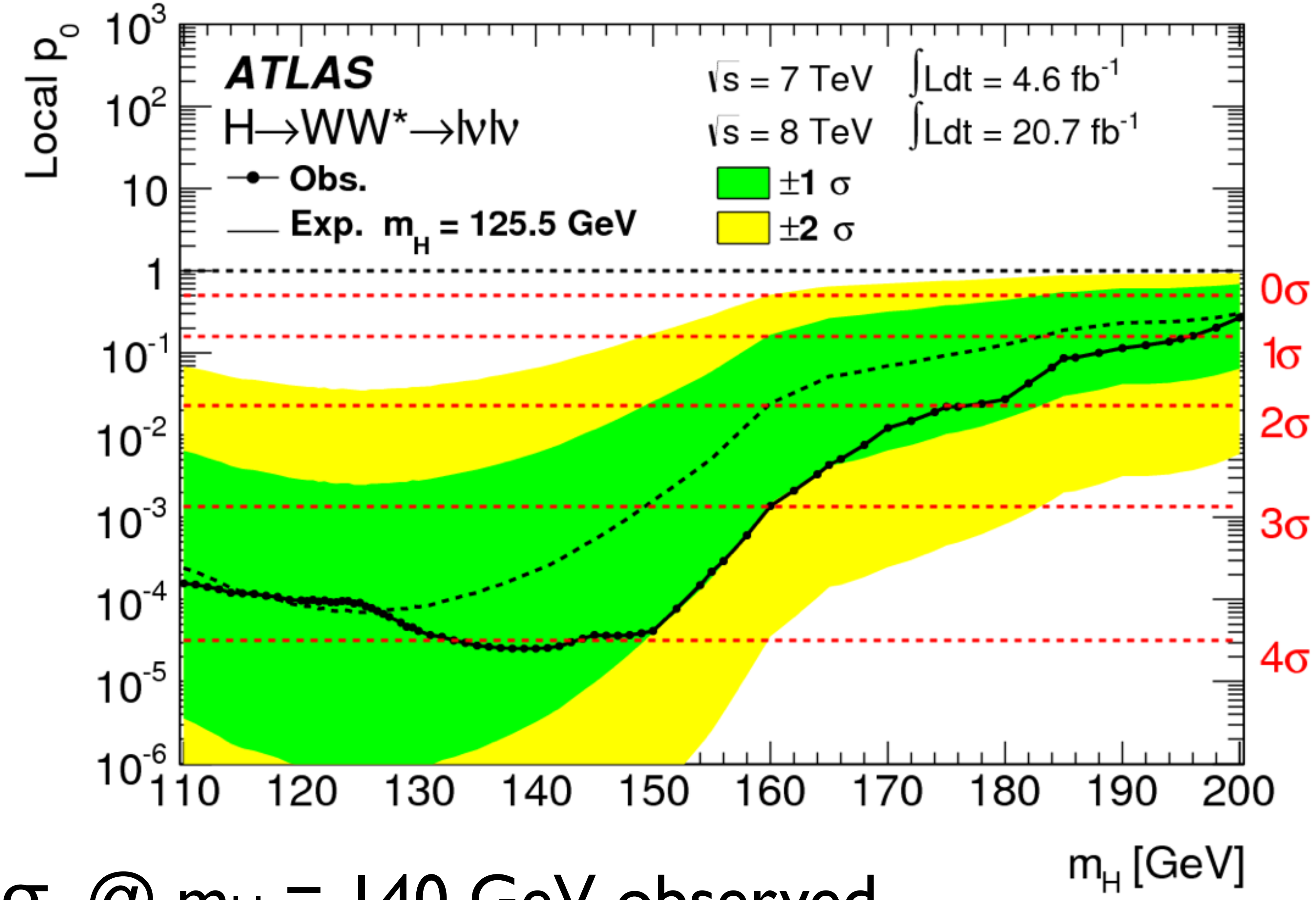
VBF signal


ATLAS EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET

Results


ATLAS
√s = 7 TeV ∫Ldt = 4.6 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
H→WW*→lνlν + 0/1 jets
Data 2011+2012
Total sig.+bkg.
SM Higgs boson
mH = 125 GeV
WW
tt̄
Other VV
Single Top
W+jets
Z/γ*
Events / 10 GeV
800
700
600
500
400
300
200
100
Data - Bkg.
100
80
60
40
20
0
-20
Bkg. subtracted data
SM Higgs boson mH = 125 GeV
60
80
100
120
140
160
180
200
220
240
260
mT [GeV]

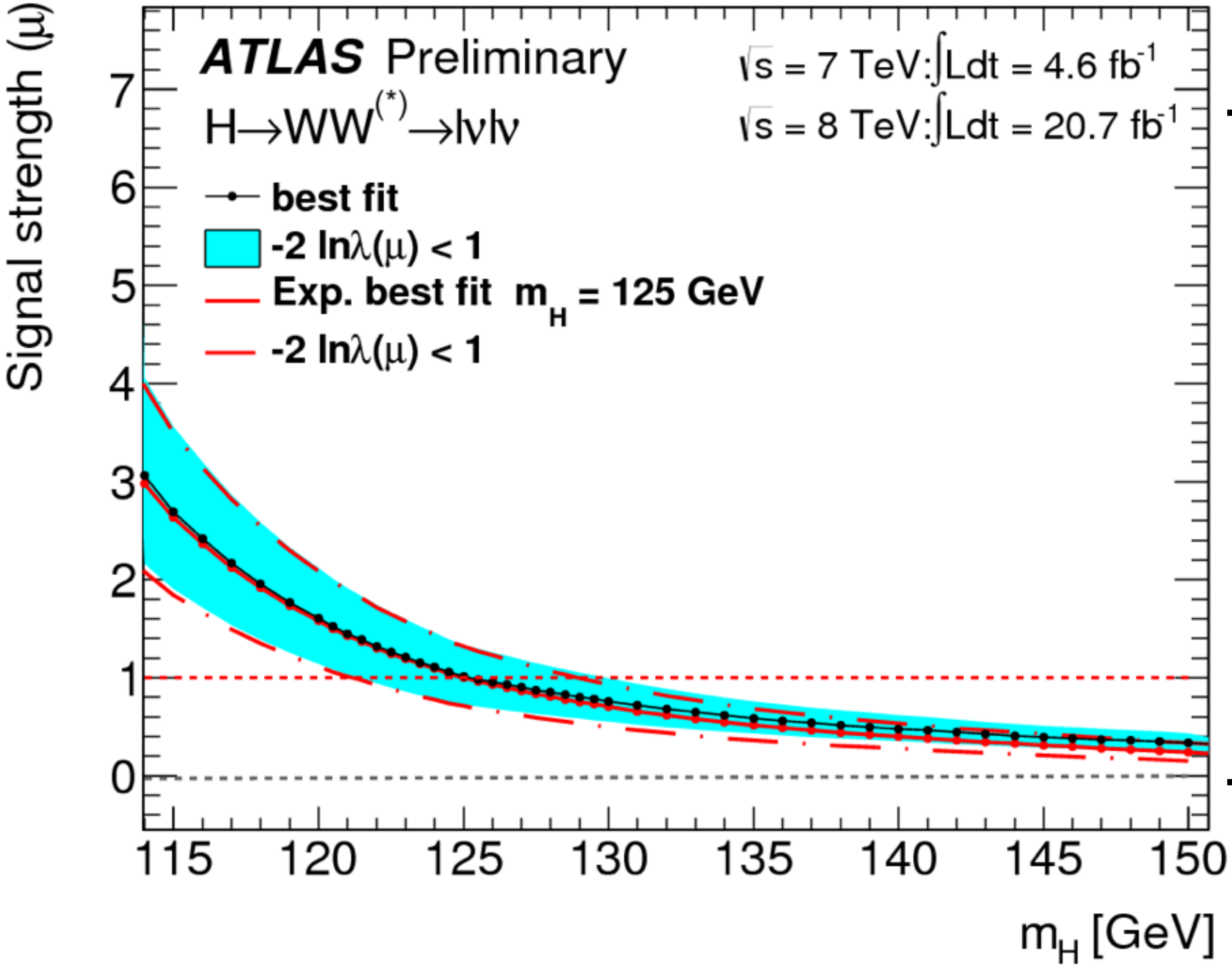
Combined results



4.1σ @ m_H = 140 GeV observed

3.8σ @ m_H = 125 GeV observed (expected: 3.7σ)

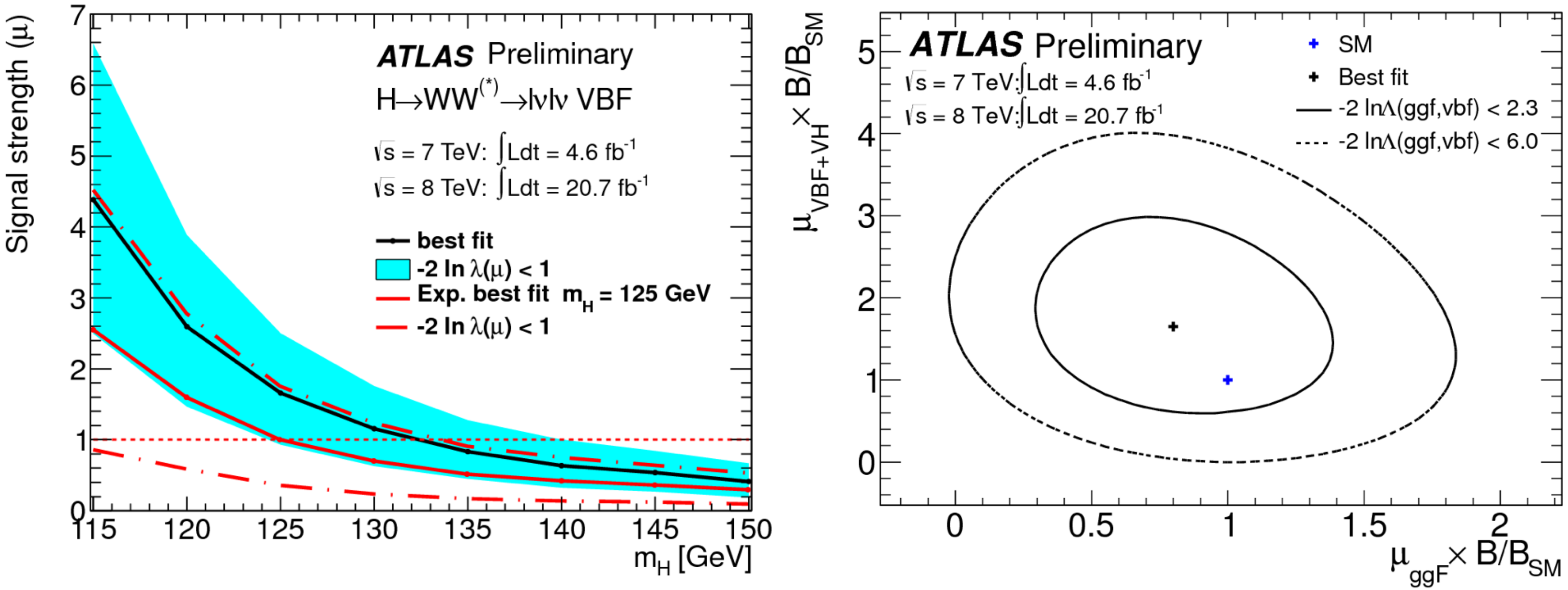
Signal strength



Uncertainty on μ	**up (%)**	**down (%)**
Data statistics	+21	-21
Signal yield (theo)	+12	-9
WW norm (theo)	+12	-12
Object/DY bkg (exp)	+9	-8
Signal acc. (theo)	+9	-7
MC statistics	+7	-7
W+jets fake factor	+5	-5
Other bkg (theo)	+5	-4
Luminosity	+4	-4
Total	**+32**	**-29**

$\boldsymbol{\mu_{obs}} = \mathbf{1.01} \pm \mathbf{0.21}$(stat.) $\pm$ $\mathbf{0.19}$(theo. syst.) $\pm$ $\mathbf{0.12}$(exp. syst.) $\pm$ $\mathbf{0.04}$(lumi.)

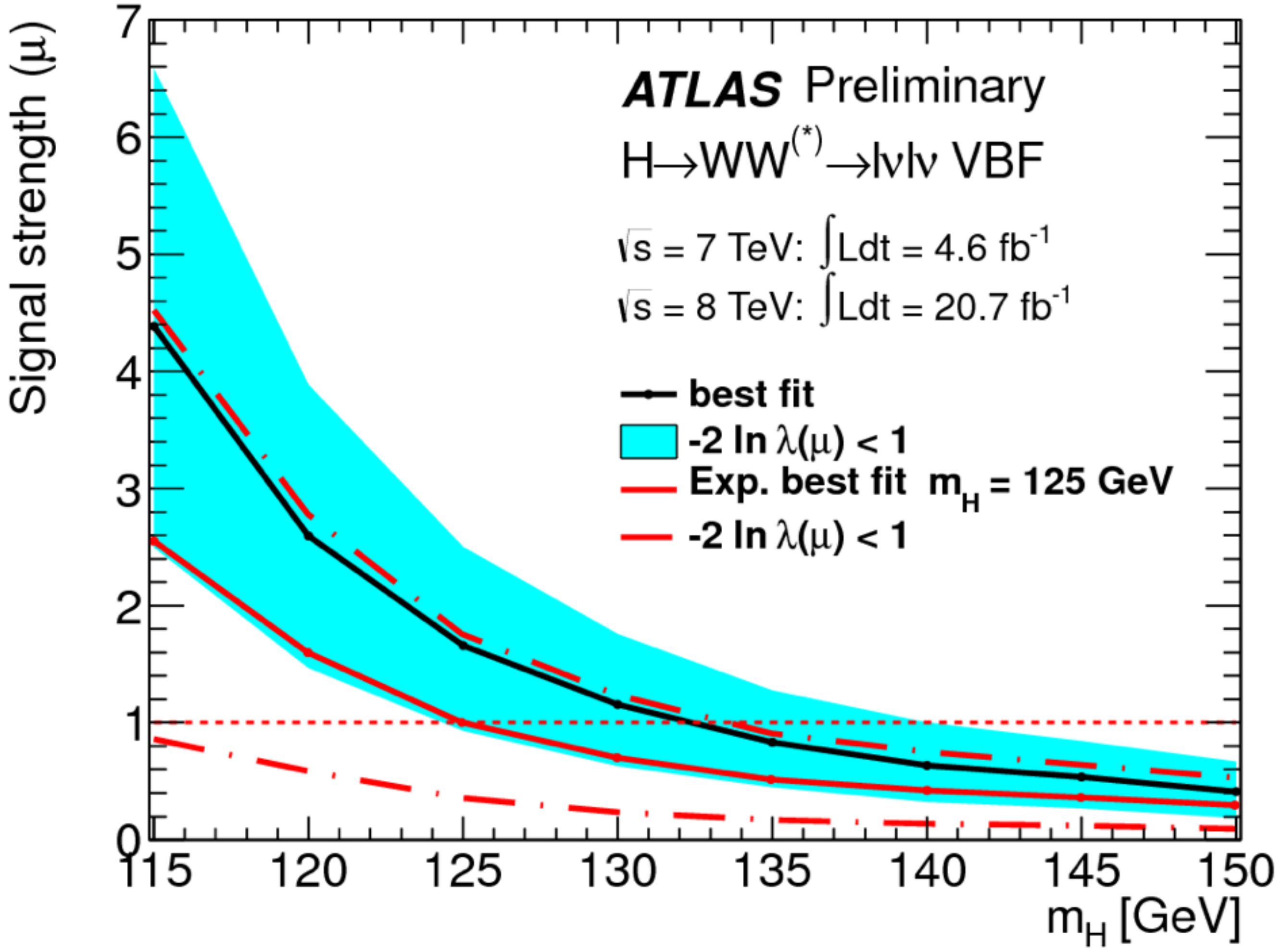
Results for VBF

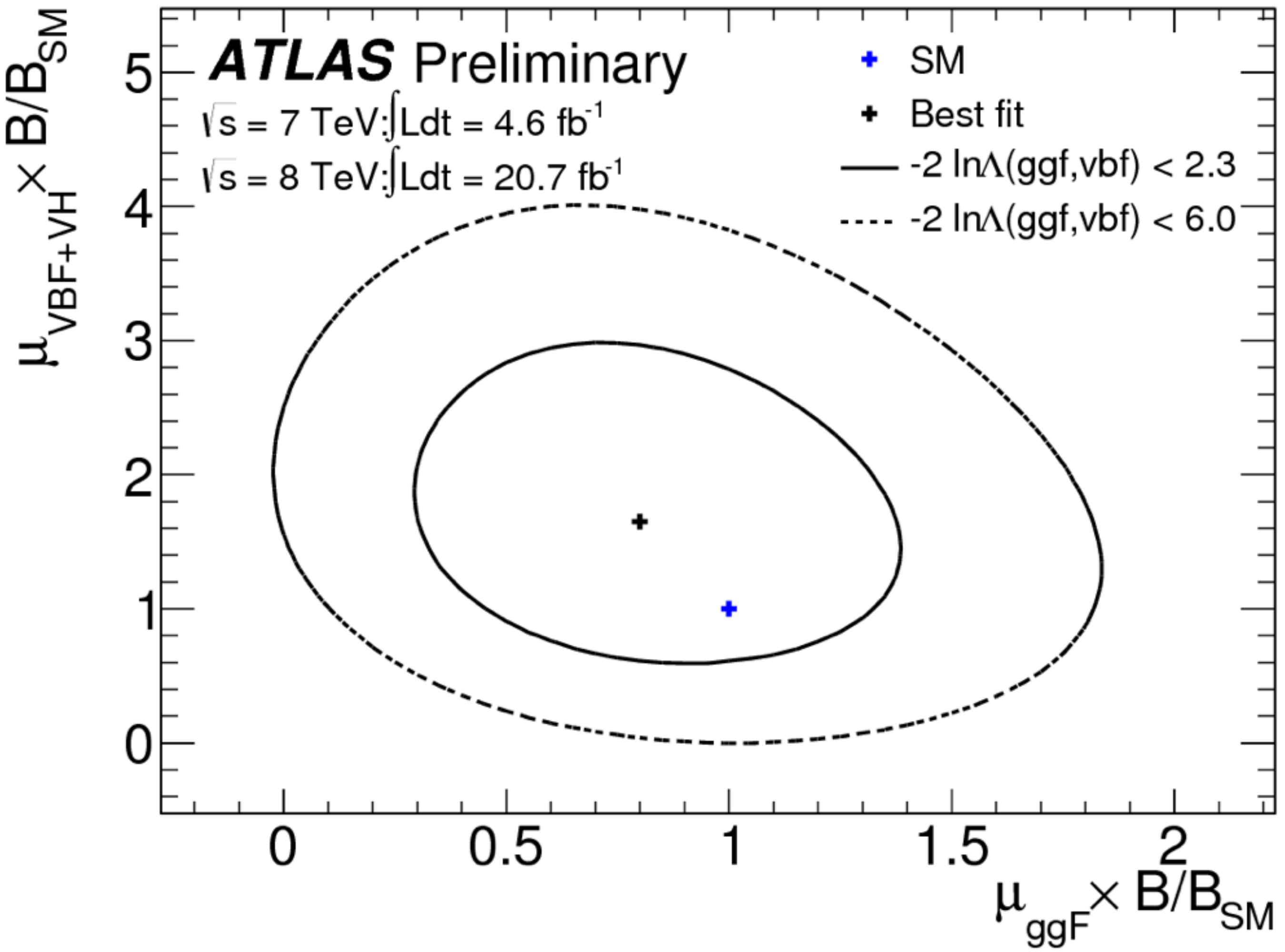


μ_{obs} = **1.66 ± 0.67**(stat.) ± **0.42**(syst.) @ m_H = 125 GeV

Observed significance: 2.5σ (expected 1.6σ)

Results for VBF



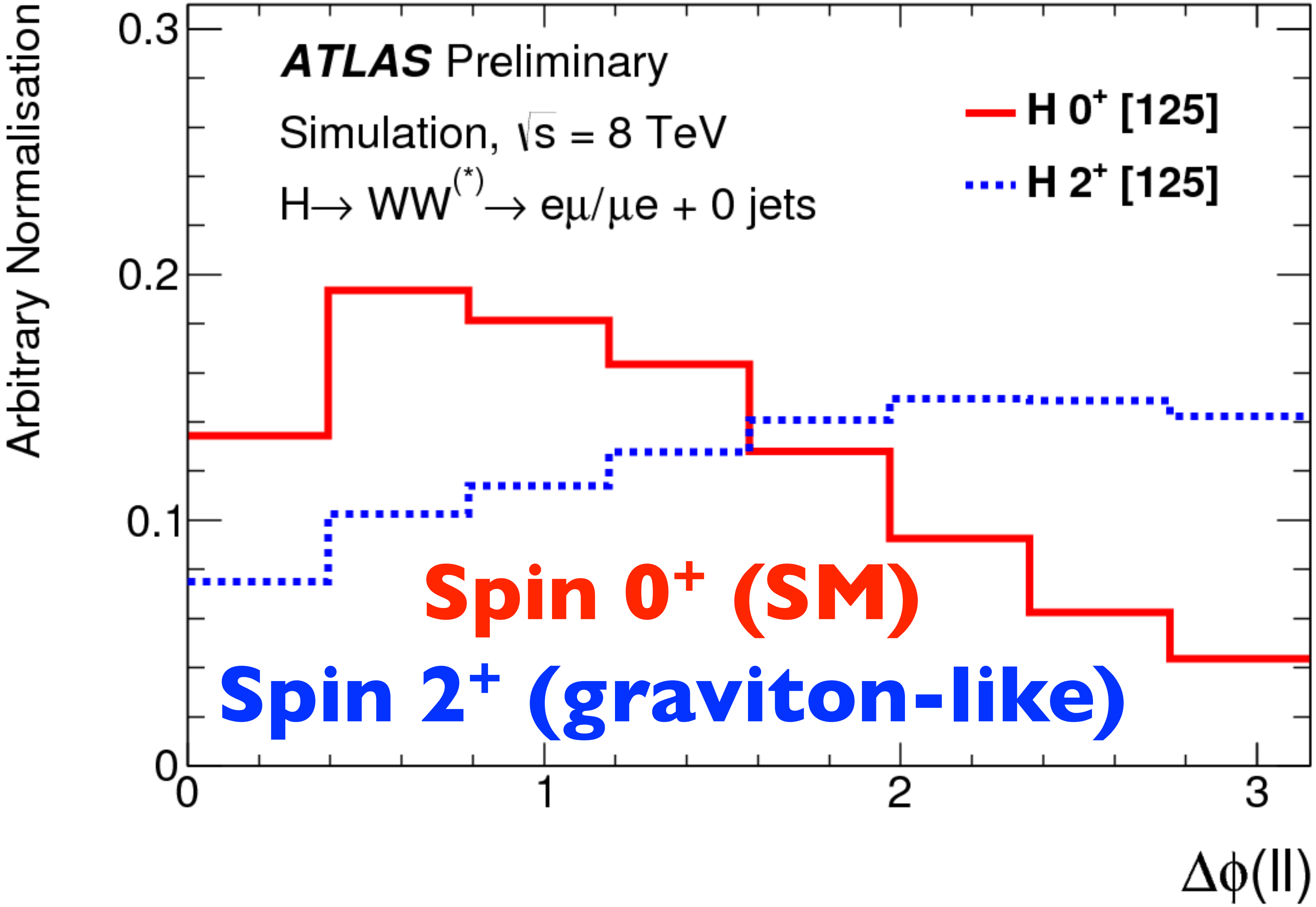


μ_{obs} = **1.66** ± **0.67**(stat.) ± **0.42**(syst.) @ m_H = 125 GeV

Observed significance: 2.5σ (expected 1.6σ)

Combined with other channels: **3.3σ first evidence!**

Spin and Parity



Spin 0^+ (SM)

Spin 2^+ (graviton-like)

Spin and Parity analysis

Standard Model Higgs boson: $J^P = 0^+$

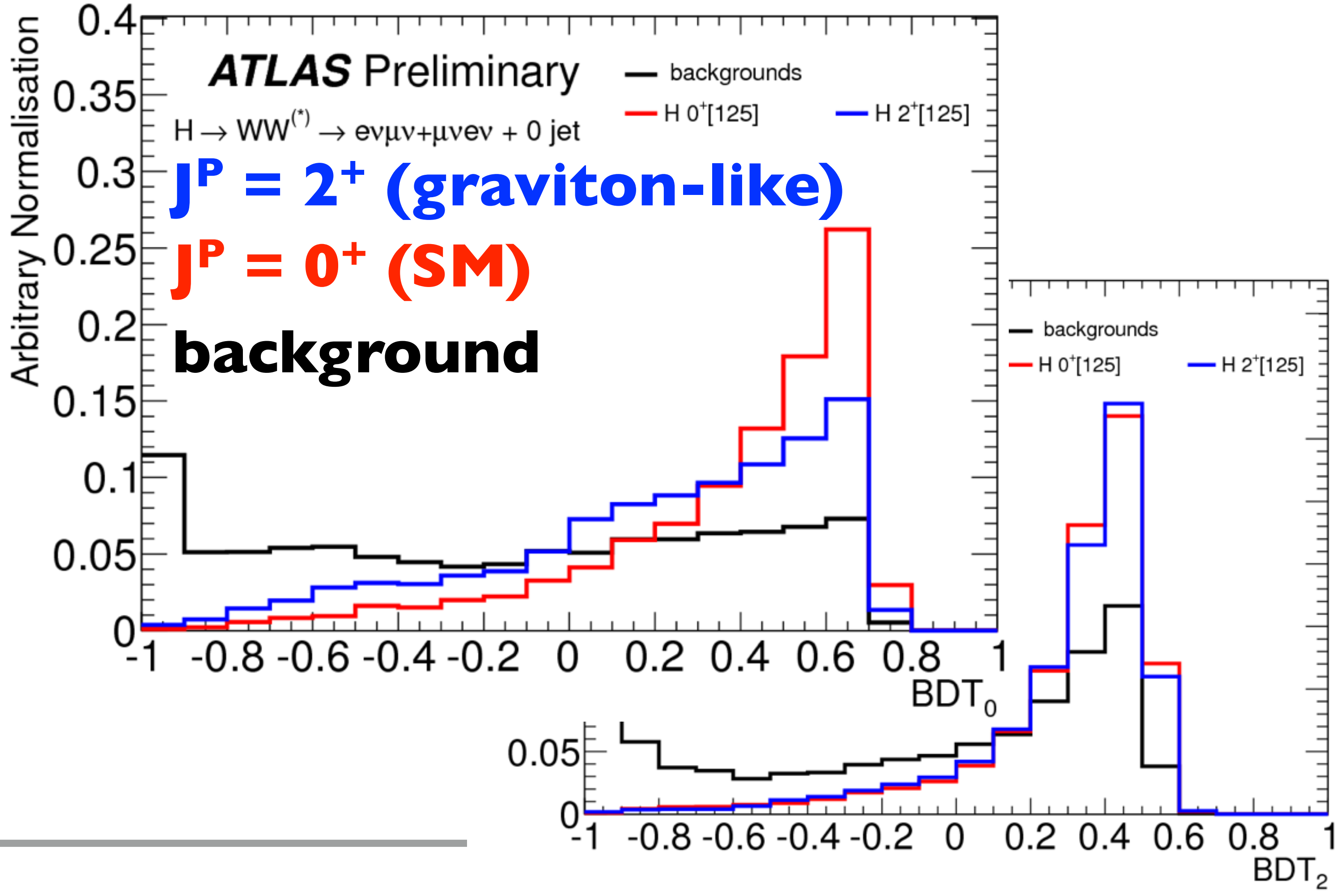
- Focus on 8 TeV eμ/μe 0-jet
- Looser event selection compared to rate analysis

	Spin	Rate
$E_{T,rel}^{miss}$	> 20 GeV	> 25 GeV
P_{Tll}	> 20 GeV	> 30 GeV
m_{ll}	< 80 GeV	< 50 GeV
$\Delta\Phi_{ll}$	< 2.8	< 1.8

Strategy: check consistency with 0^+, falsify other hypos (1^+, 1^-, 2^+)

Build comb. discriminants (BDT) with sensitive variables (m_T, $\Delta\Phi_{ll}$, m_{ll}, P_{Tll})

- One for SM 0^+ hypo, one for alternative hypo
- Calculate likelihood ratio between alternative hypo and SM 0^+ hypothesis



$J^P = 2^+$ (graviton-like)

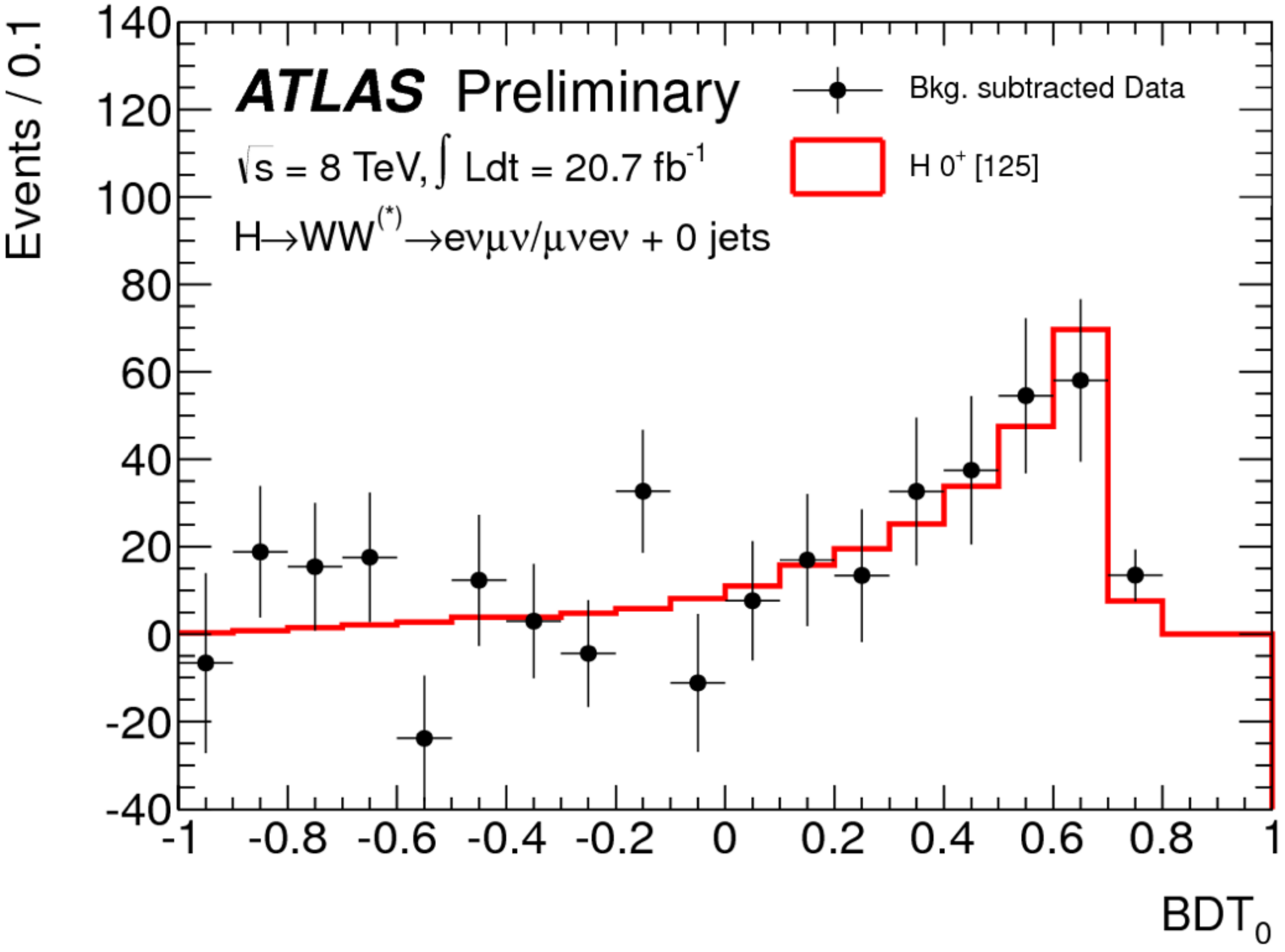
$J^P = 0^+$ (SM)

background

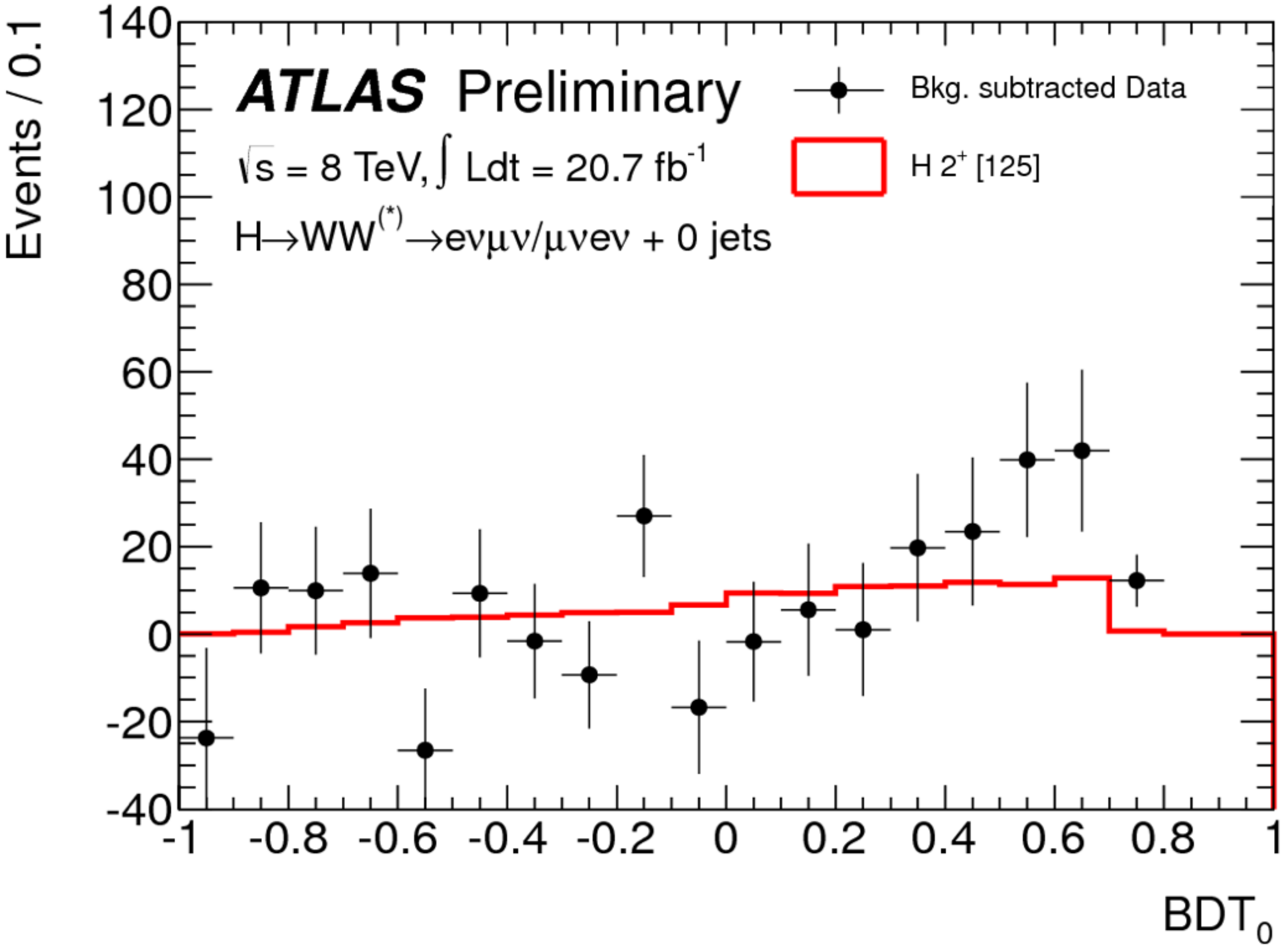
Spin and parity results

Same data!

(background subtracted)
(both show $J^P = 0^+$ BDT)



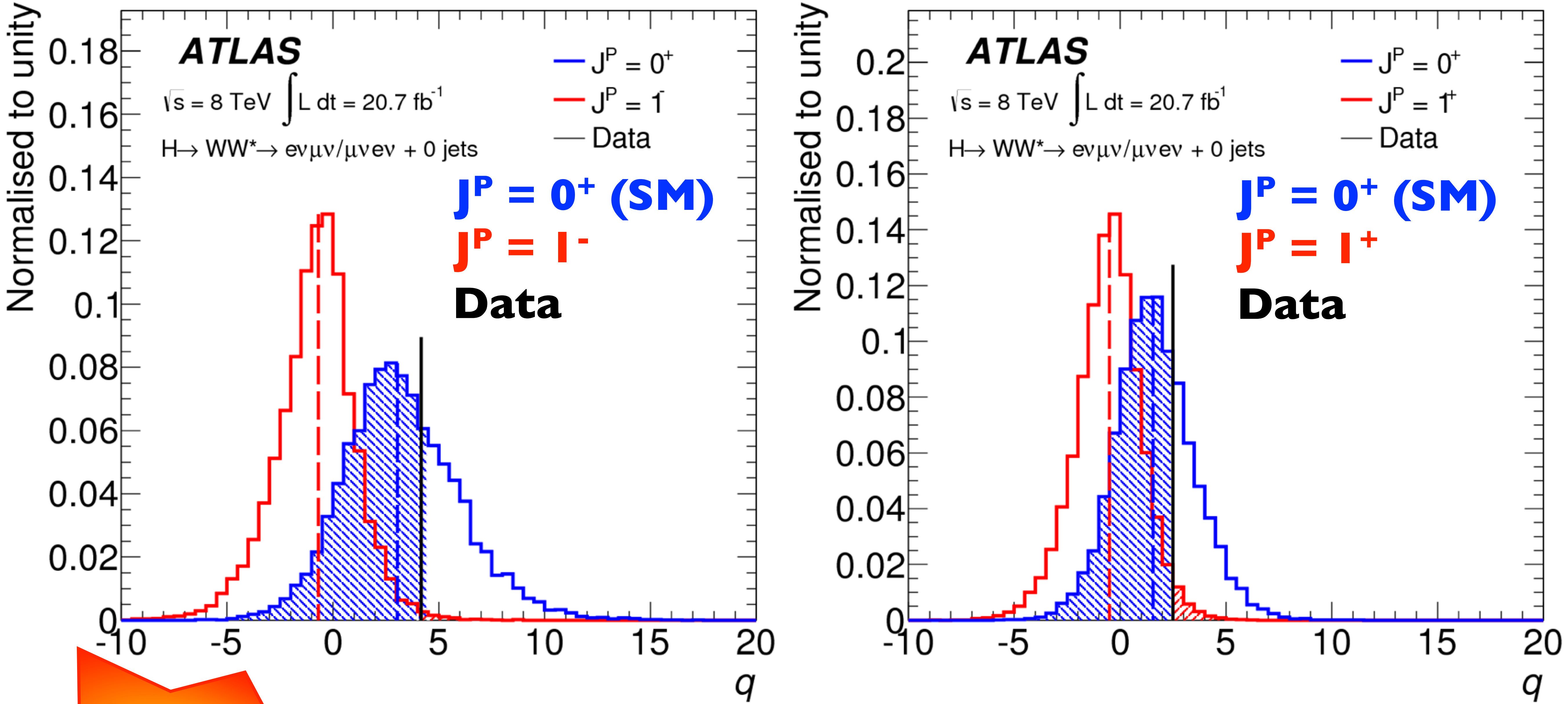
$J^P = 0^+$ (SM)



$J^P = 2^+$

Spin and Parity results

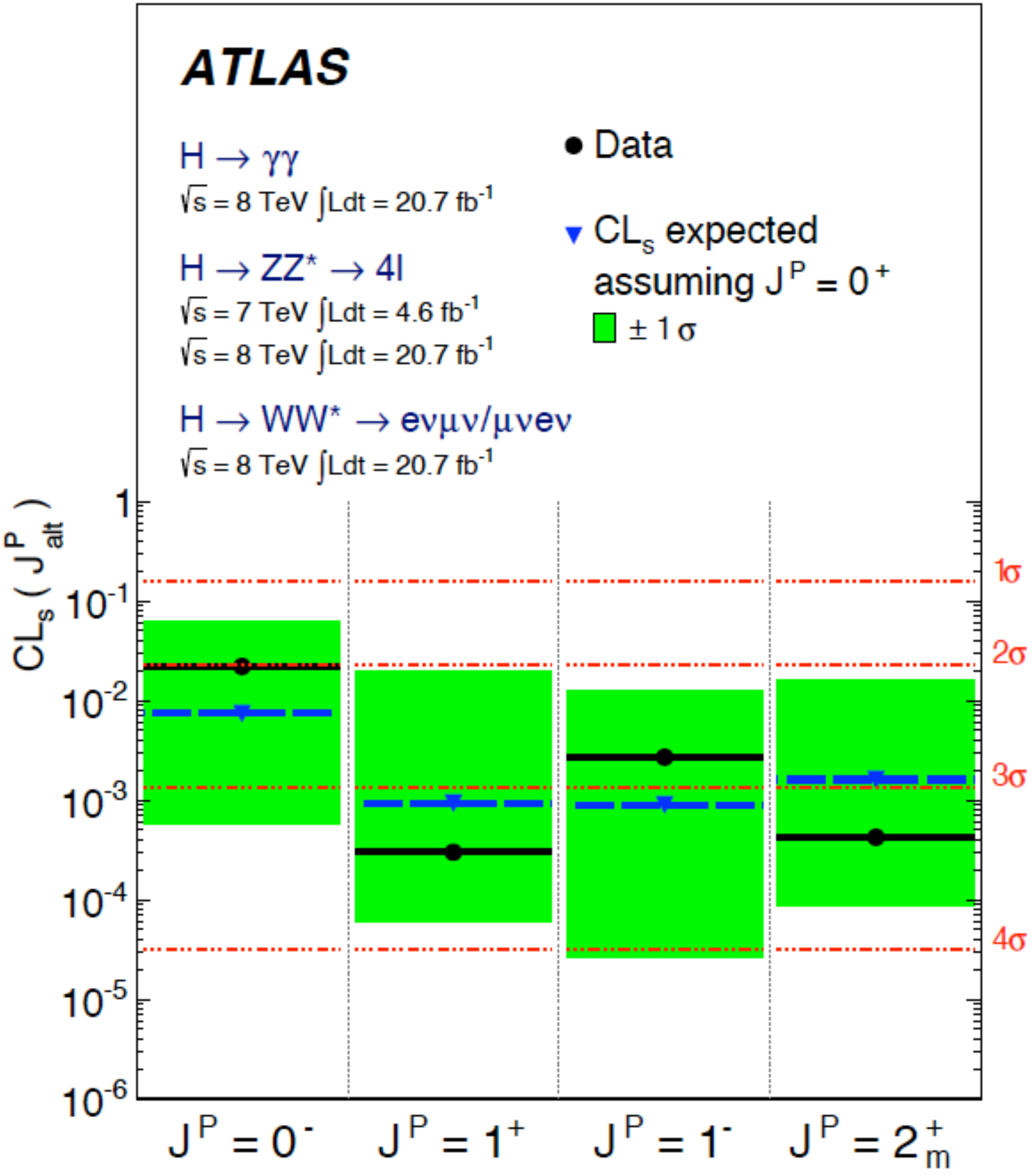
arxiv:1307.1432



NEW

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})} \qquad \mathrm{CL_s}(J^P_{\mathrm{alt}}) = \frac{p_0(J^P_{\mathrm{alt}})}{1 - p_0(0^+)}$$

Spin and Parity combined results



- SM $J^P = 0^+$ favored
- 1^+, 1^-, 2^+ are disfavored at the 3σ level
- 0^- excluded at 97.8% CL

arxiv:1307.1432

Summary

Signal strength in full agreement with SM

μ_{obs} = 1.01 ± 0.31

VBF: μ_{obs} = 1.66 ± 0.79 (2.5σ)

VBF combination: 3.3σ

New results on Spin and Parity

Added $J^P = 1^+$ and 1^-

Data clearly favors $J^P = 0^+$

New ATLAS papers just came out

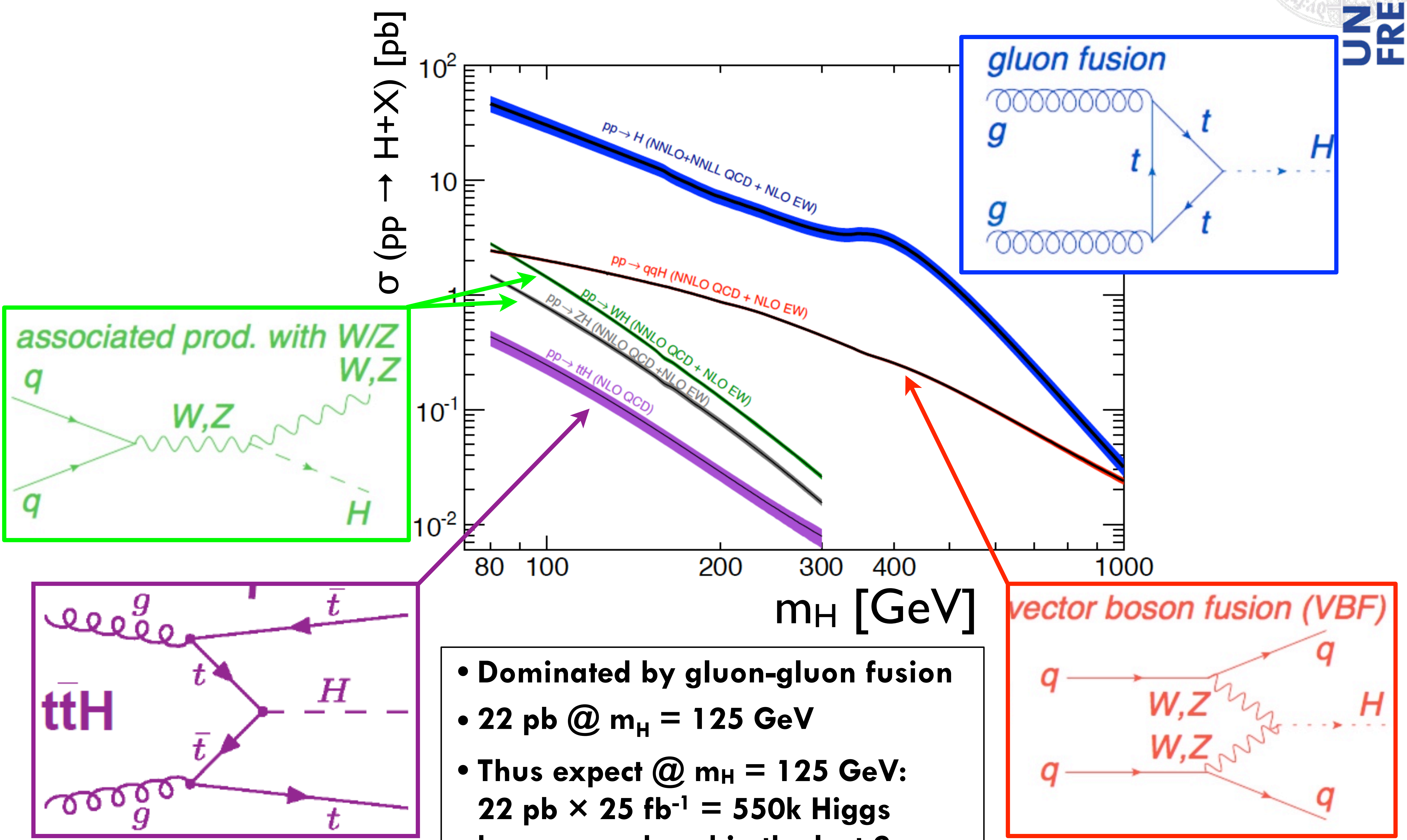
On July 4th, exactly one year after 1st discovery announcement of Higgs boson

Coupling: arxiv.org:1307.1427

Spin and Parity: arxiv:1307.1432

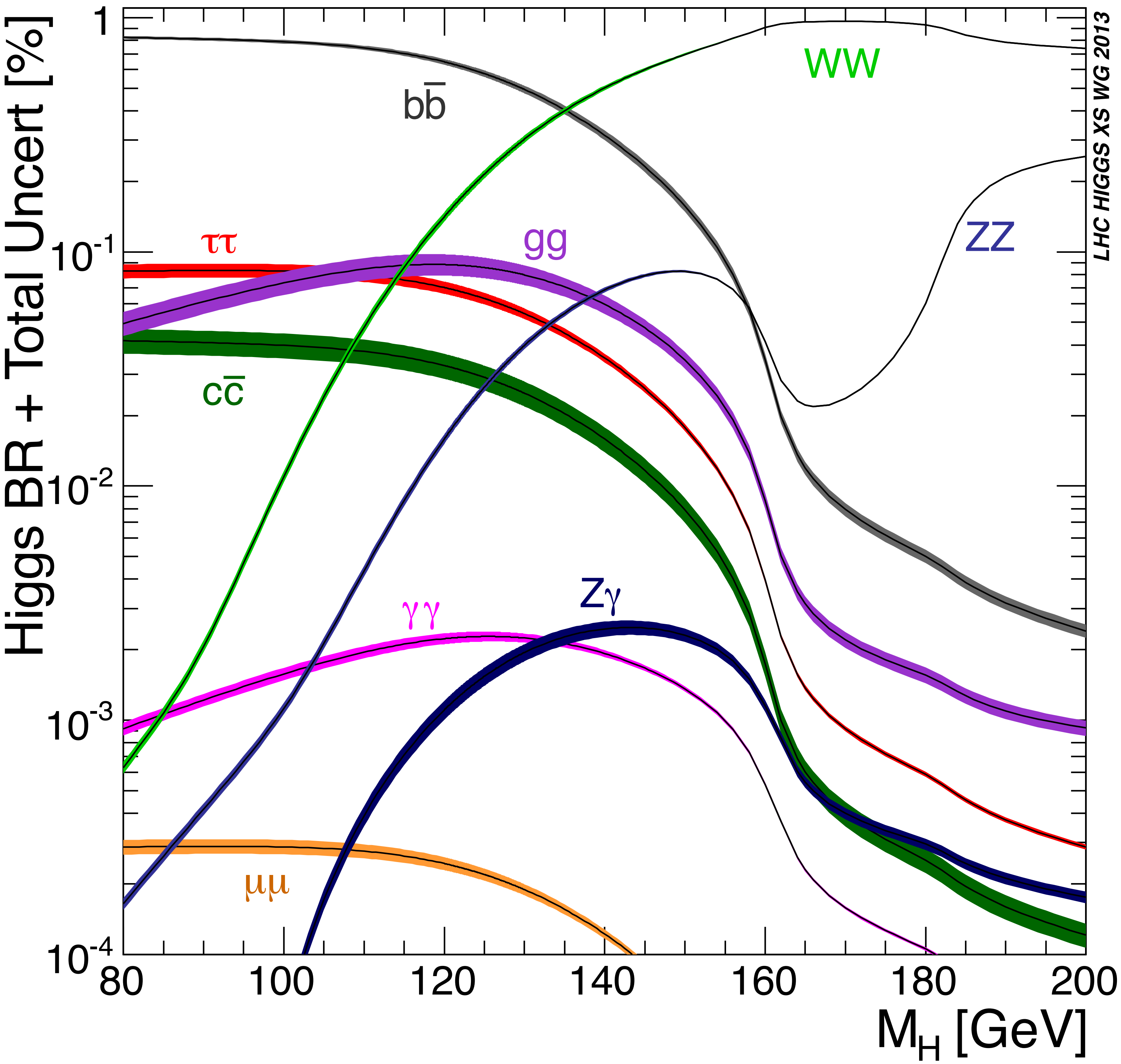
backup

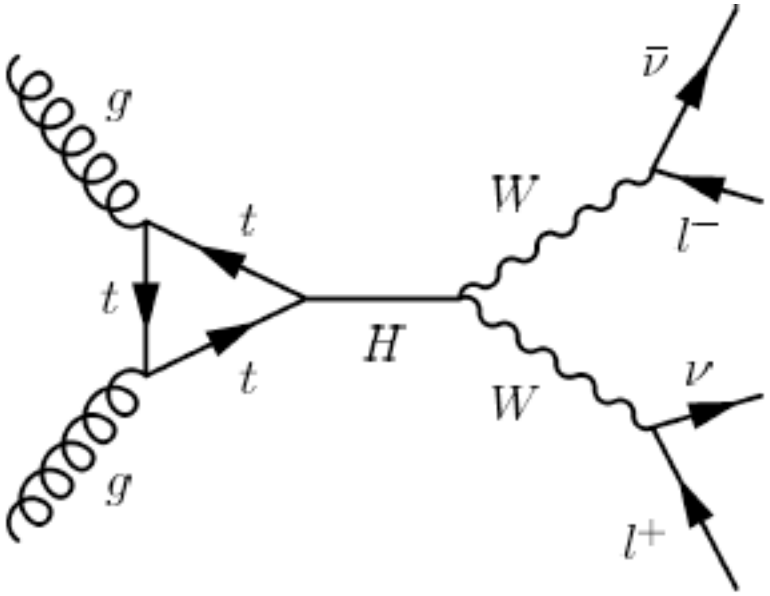
Higgs boson production



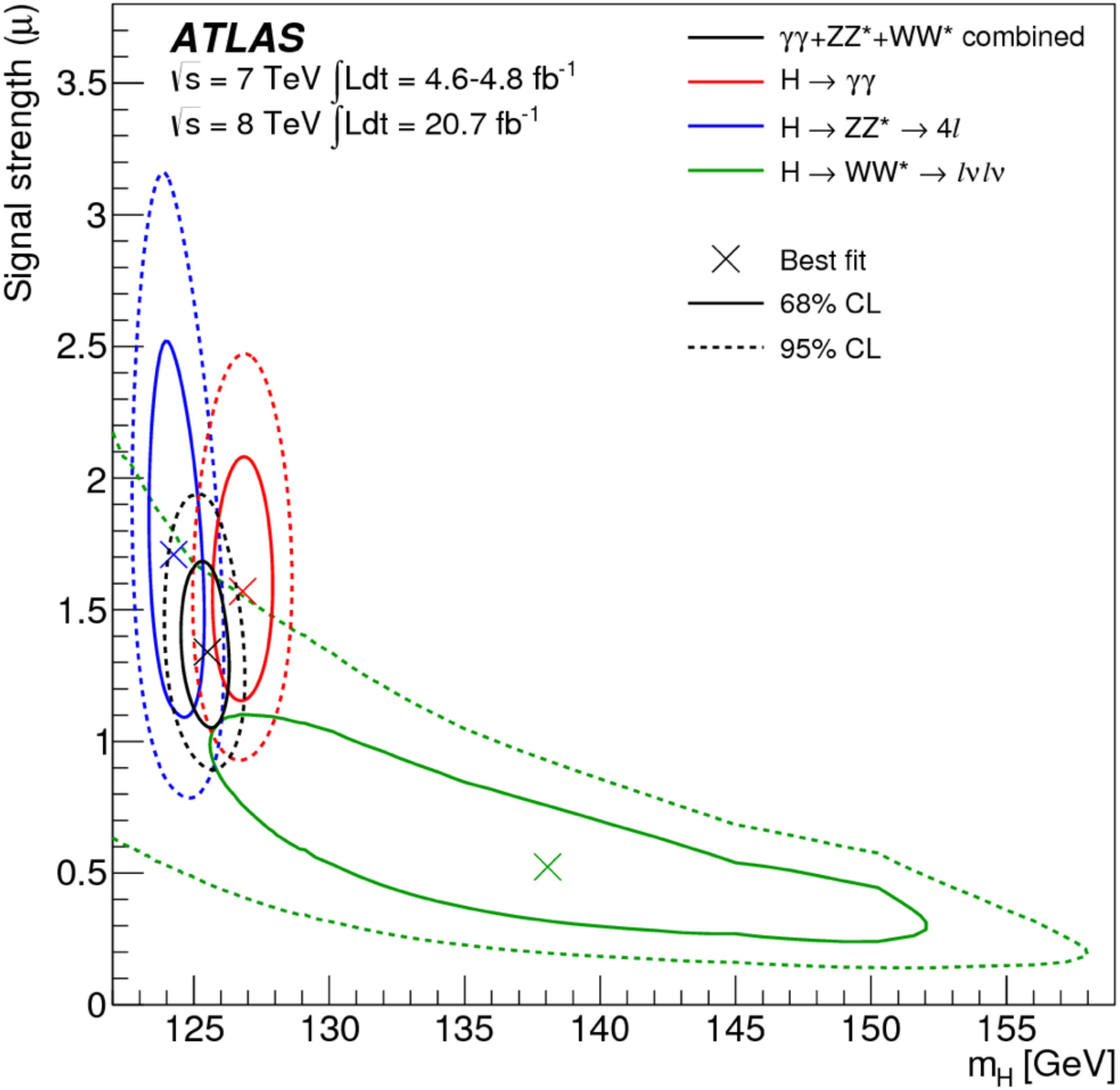
- **Dominated by gluon-gluon fusion**
- **22 pb @ m_H = 125 GeV**
- **Thus expect @ m_H = 125 GeV: 22 pb × 25 fb^{-1} = 550k Higgs bosons produced in the last 2 years**

Higgs boson decay

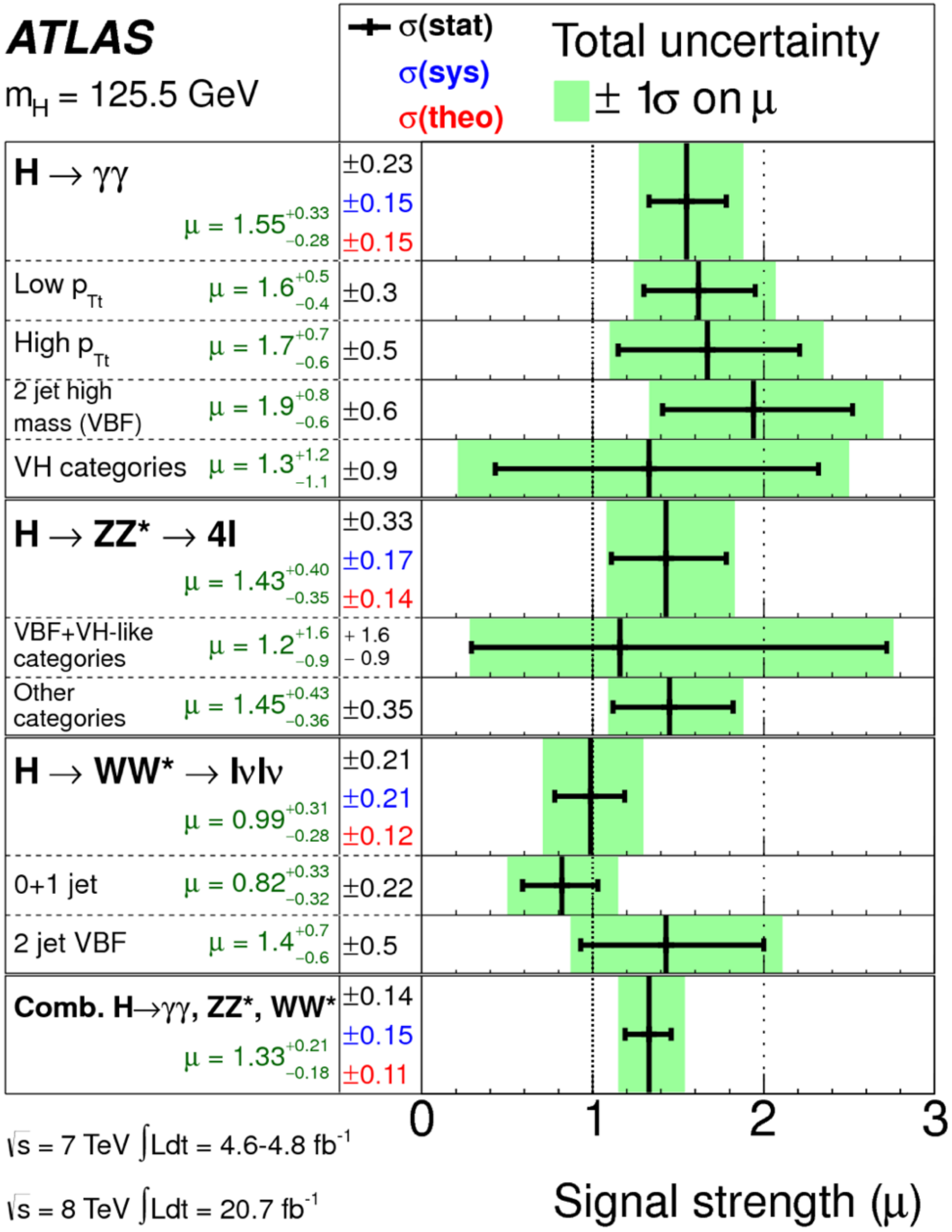




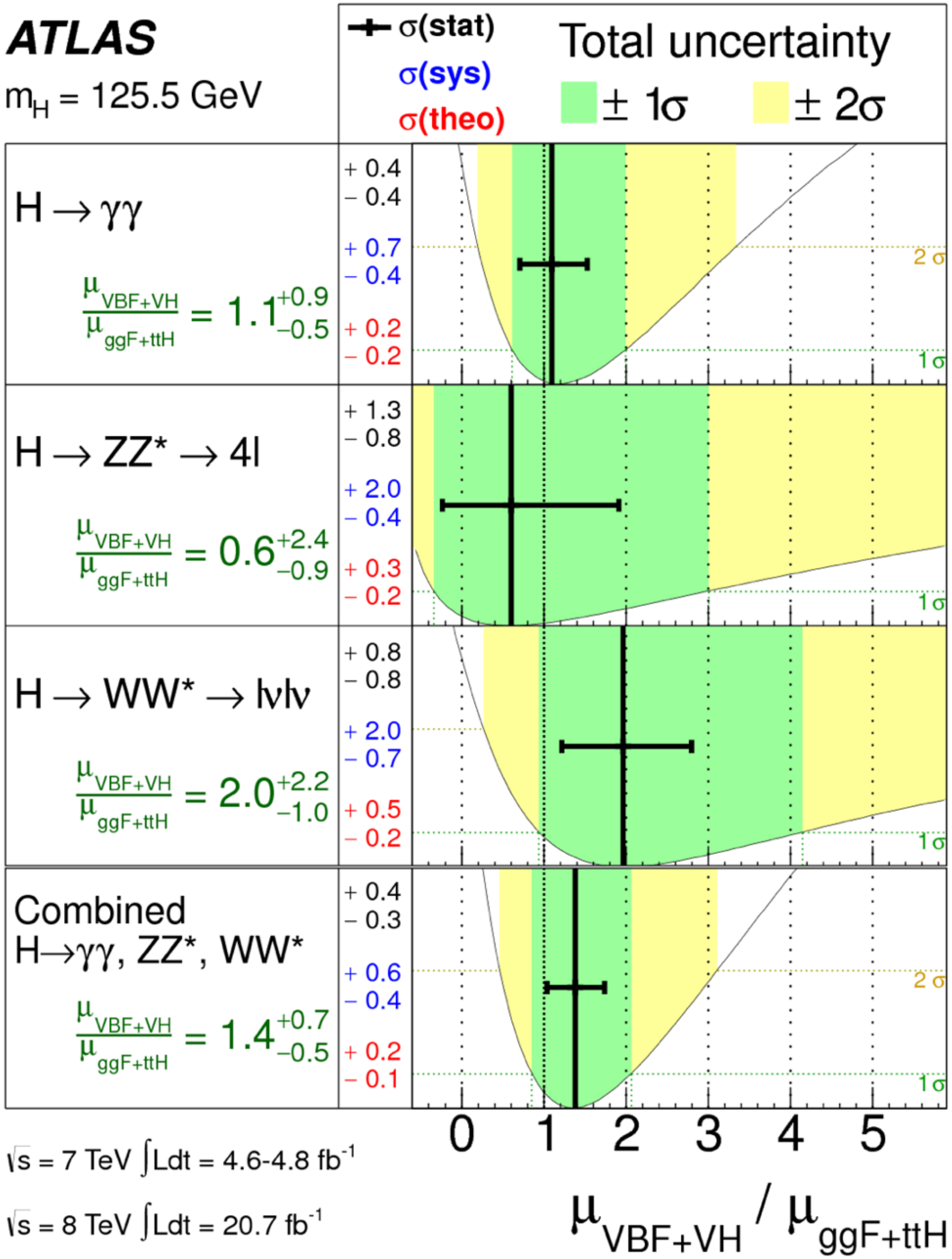
Higgs mass

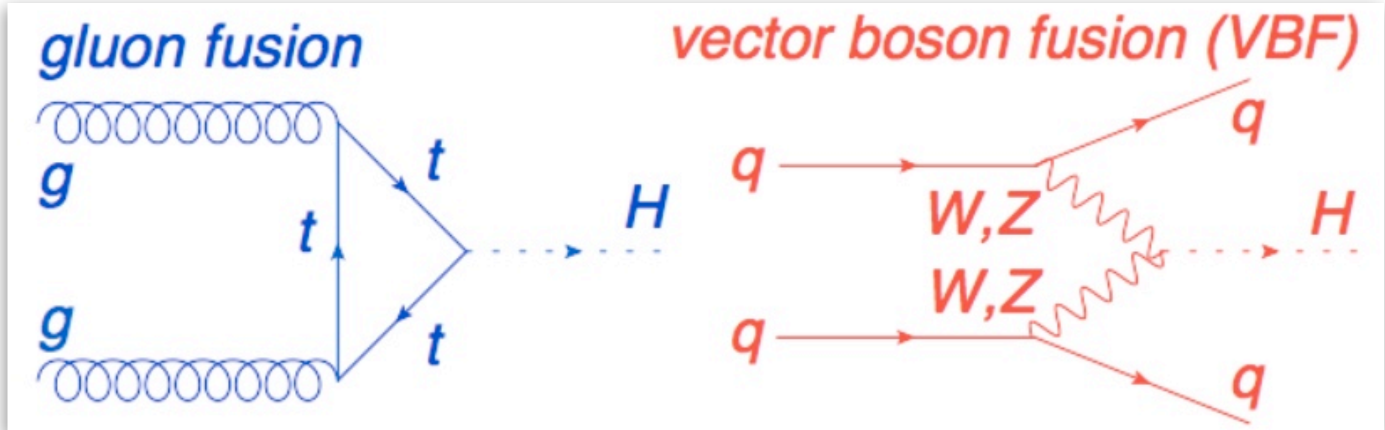

ATLAS
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
$\gamma\gamma$+ZZ*+WW* combined
H → $\gamma\gamma$
H → ZZ* → 4l
H → WW* → $l\nu l\nu$
Best fit
68% CL
95% CL
Signal strength (μ)
0
0.5
1
1.5
2
2.5
3
3.5
125
130
135
140
145
150
155
m_H [GeV]

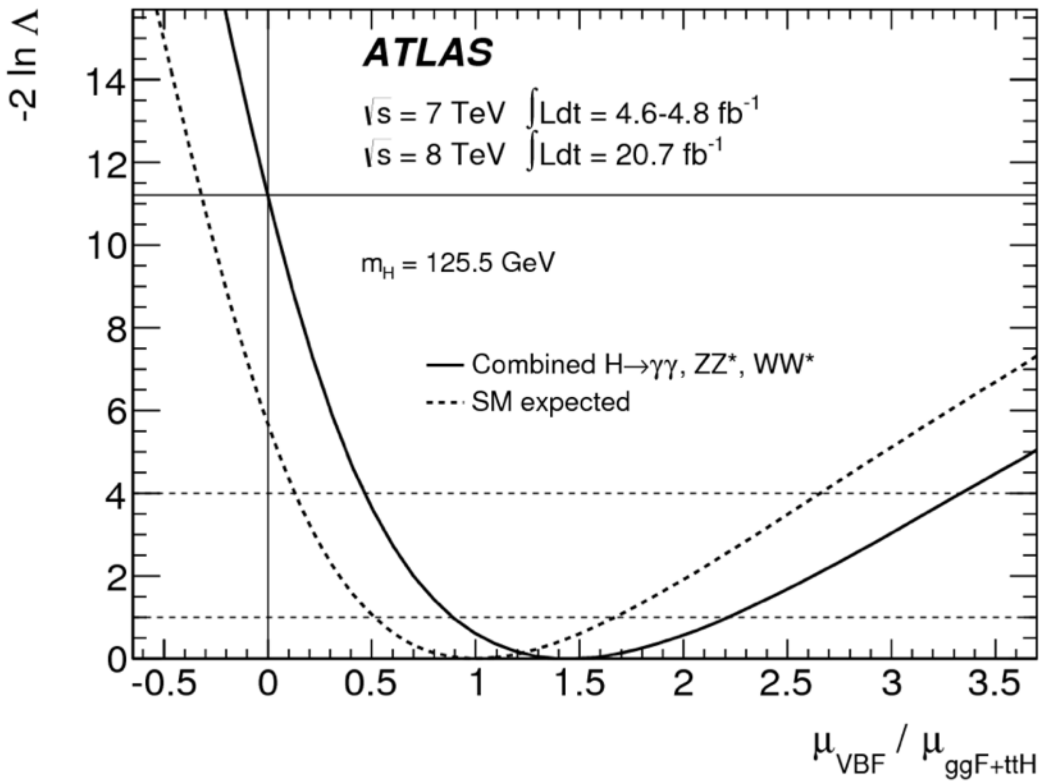
Signal strengths



Other production modes

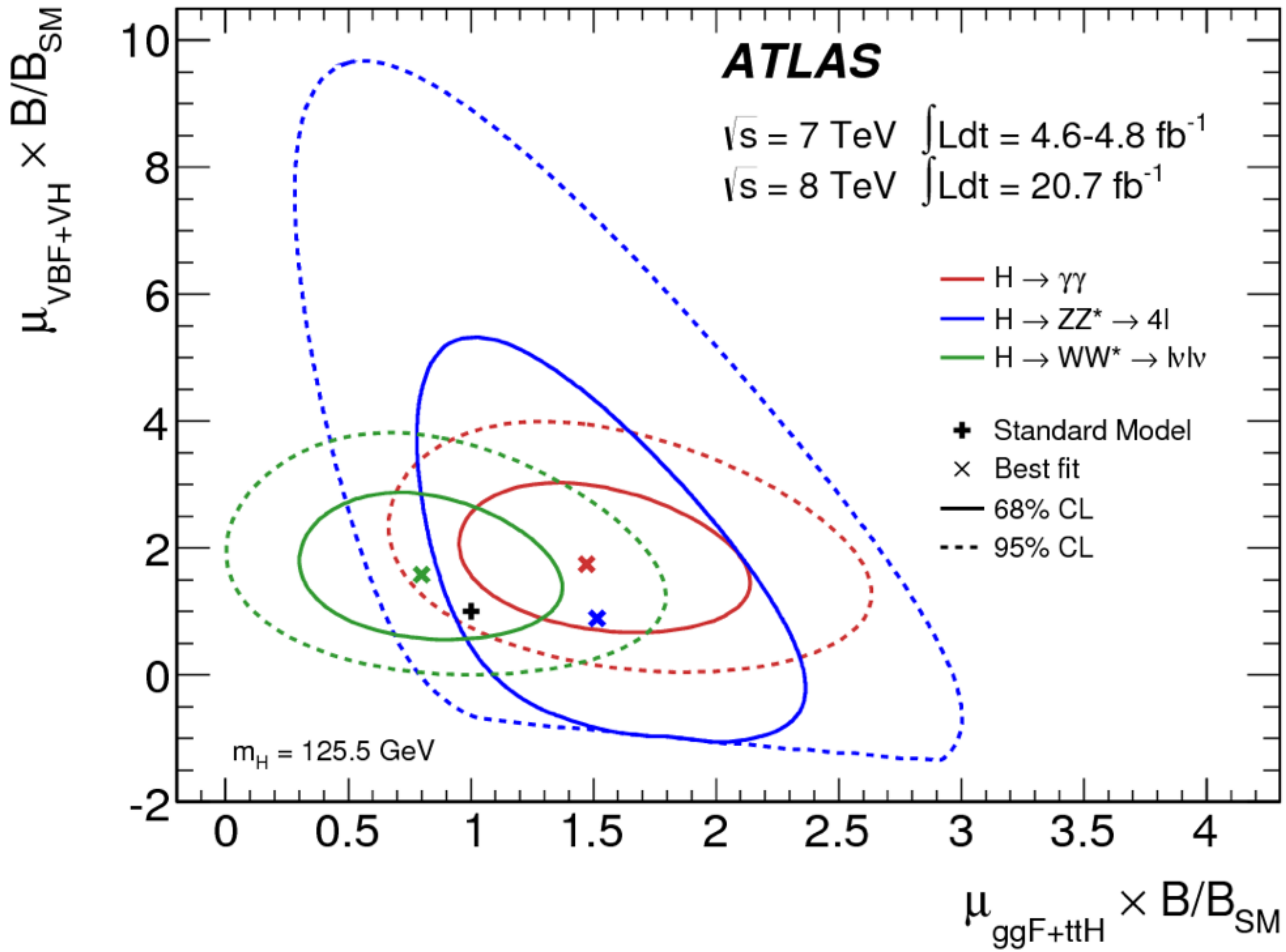




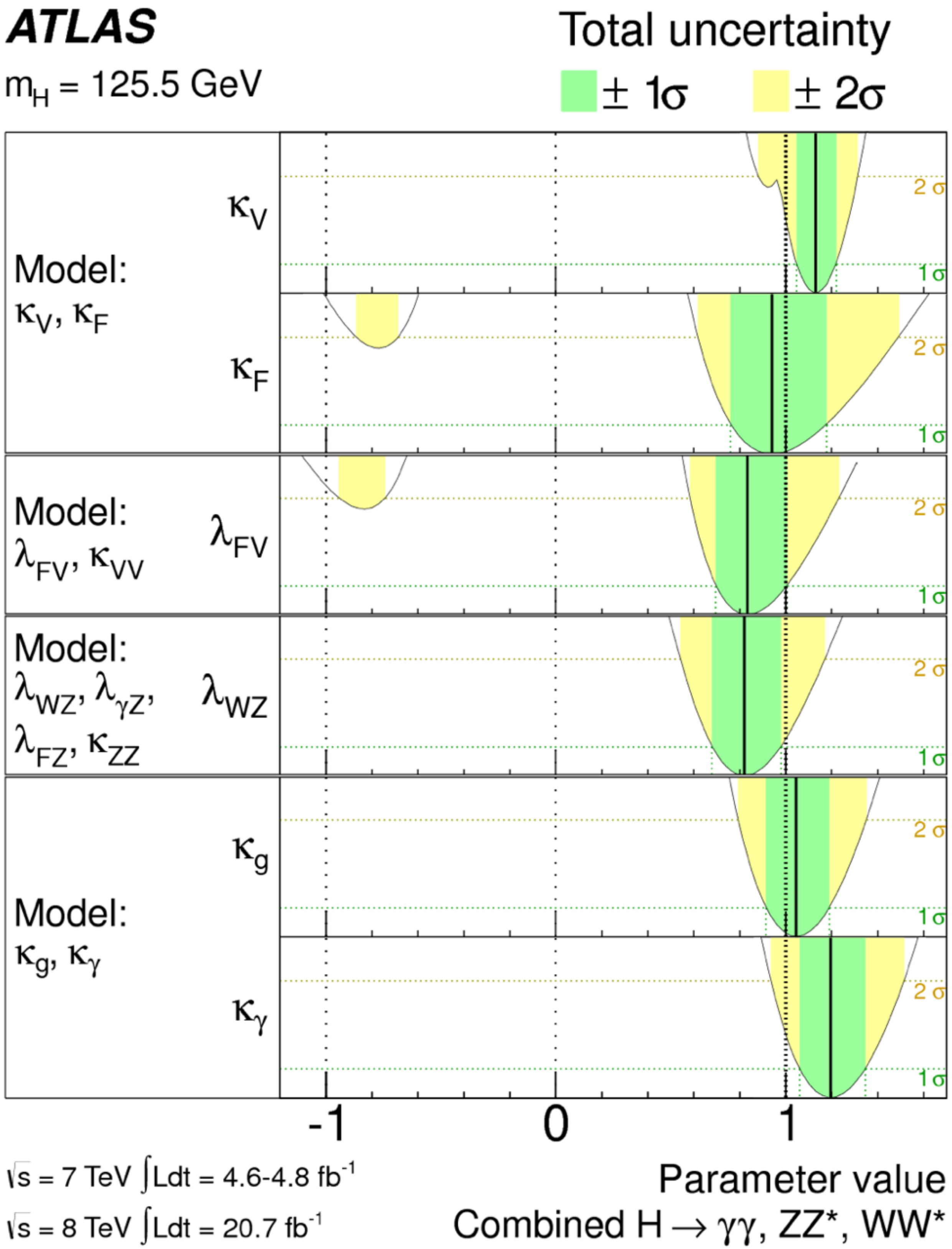


3.3σ evidence for VBF production plus 2σ from CMS

Other production modes



Coupling scale factors



If assumption of no contributions from new particles to the Higgs boson width is relaxed, only the ratio of κ_F/κ_V can be measured

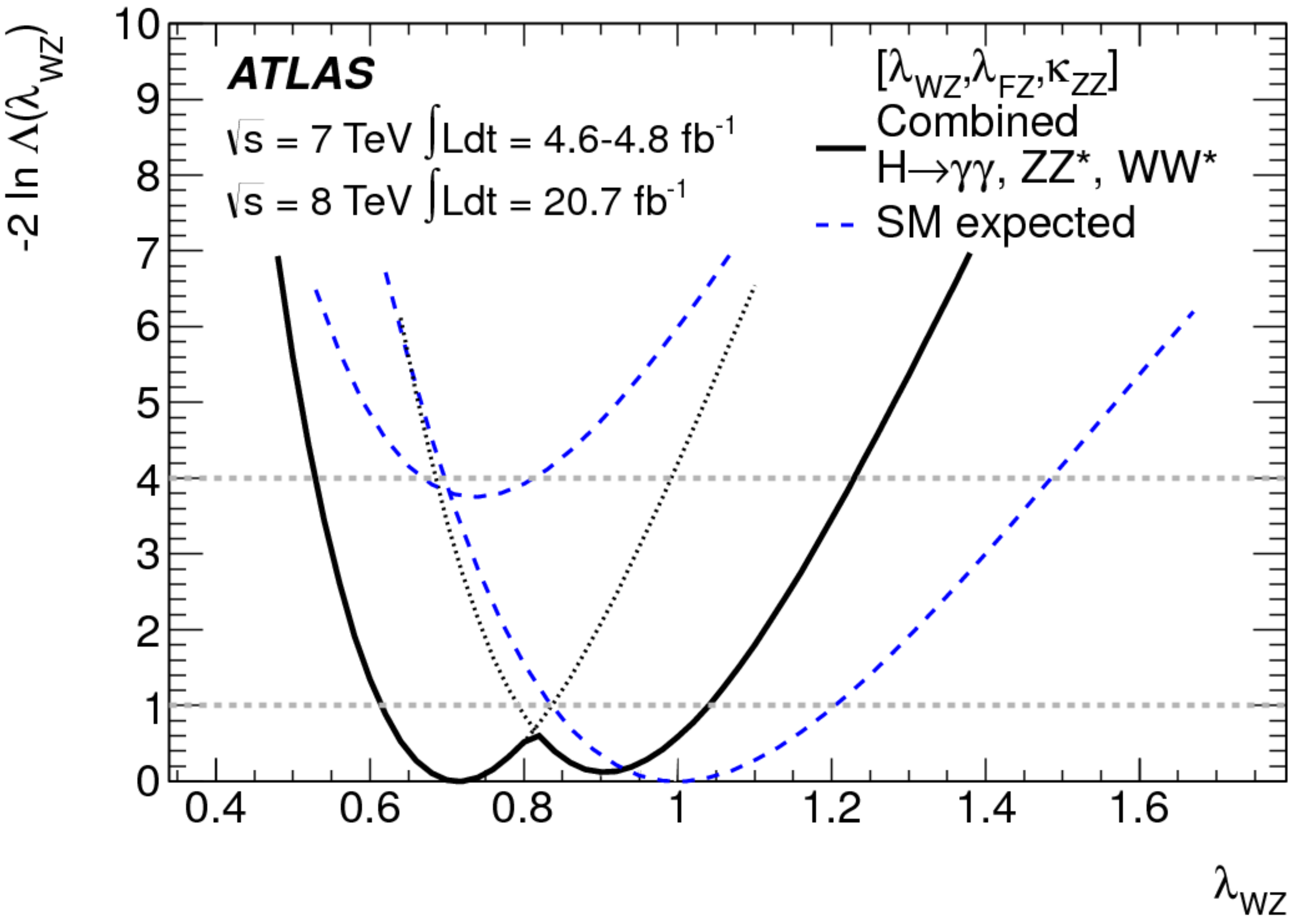
Extended fit, decouple H → γγ event rate from the measurement of λ_{WZ}

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

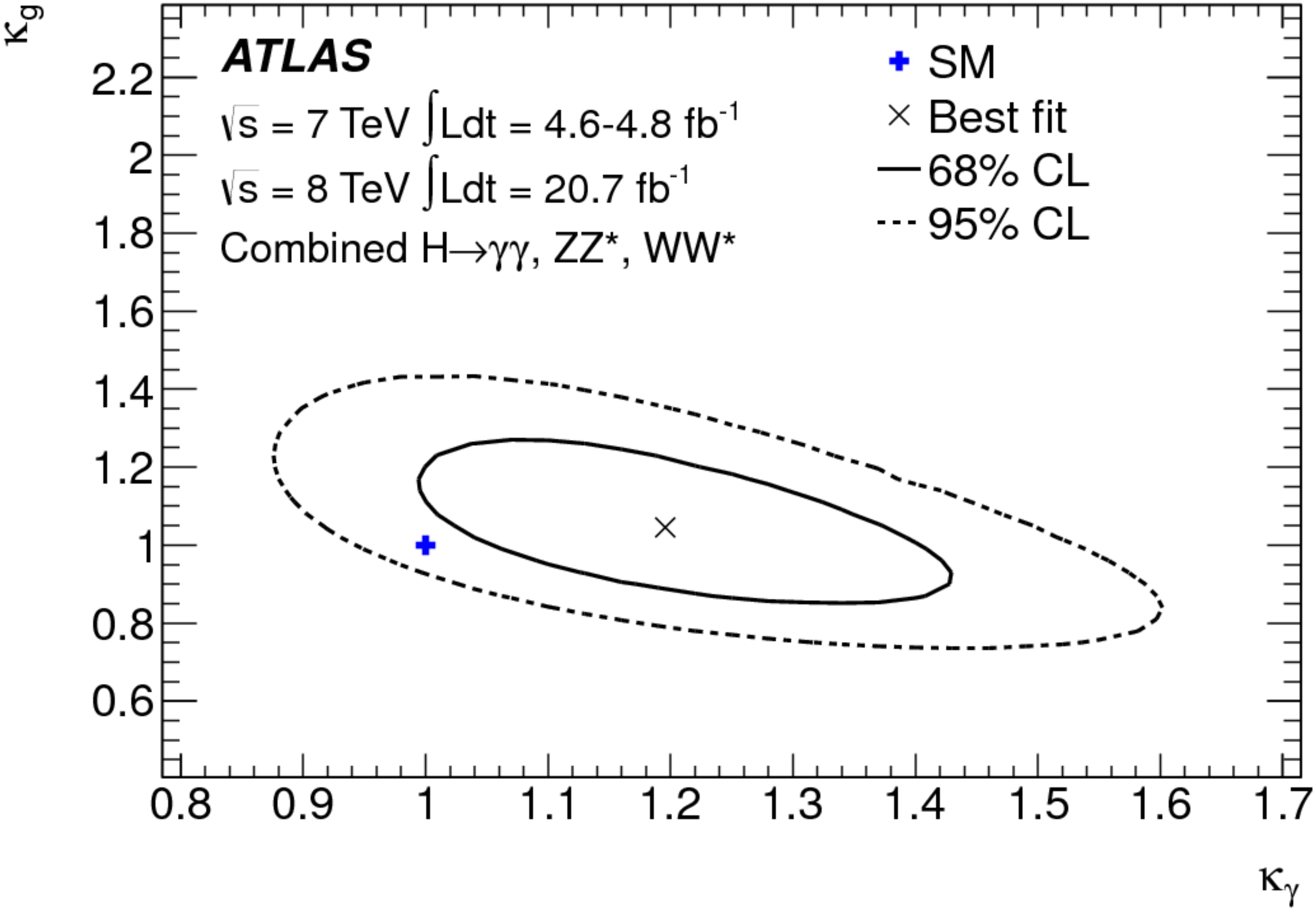
$$\kappa_{VV} = \kappa_V\kappa_V/\kappa_H$$

- κ_V constrained at 10% level
- Couplings to fermions indirectly observed (5σ)
- κ_W/κ_Z found to be consistent with 1
- No evidence for significant anomalous contributions to the gg → H and H → γγ loops
  (for fixed nominal couplings of SM particles and no BSM contributions to Higgs width)

Custodial symmetry



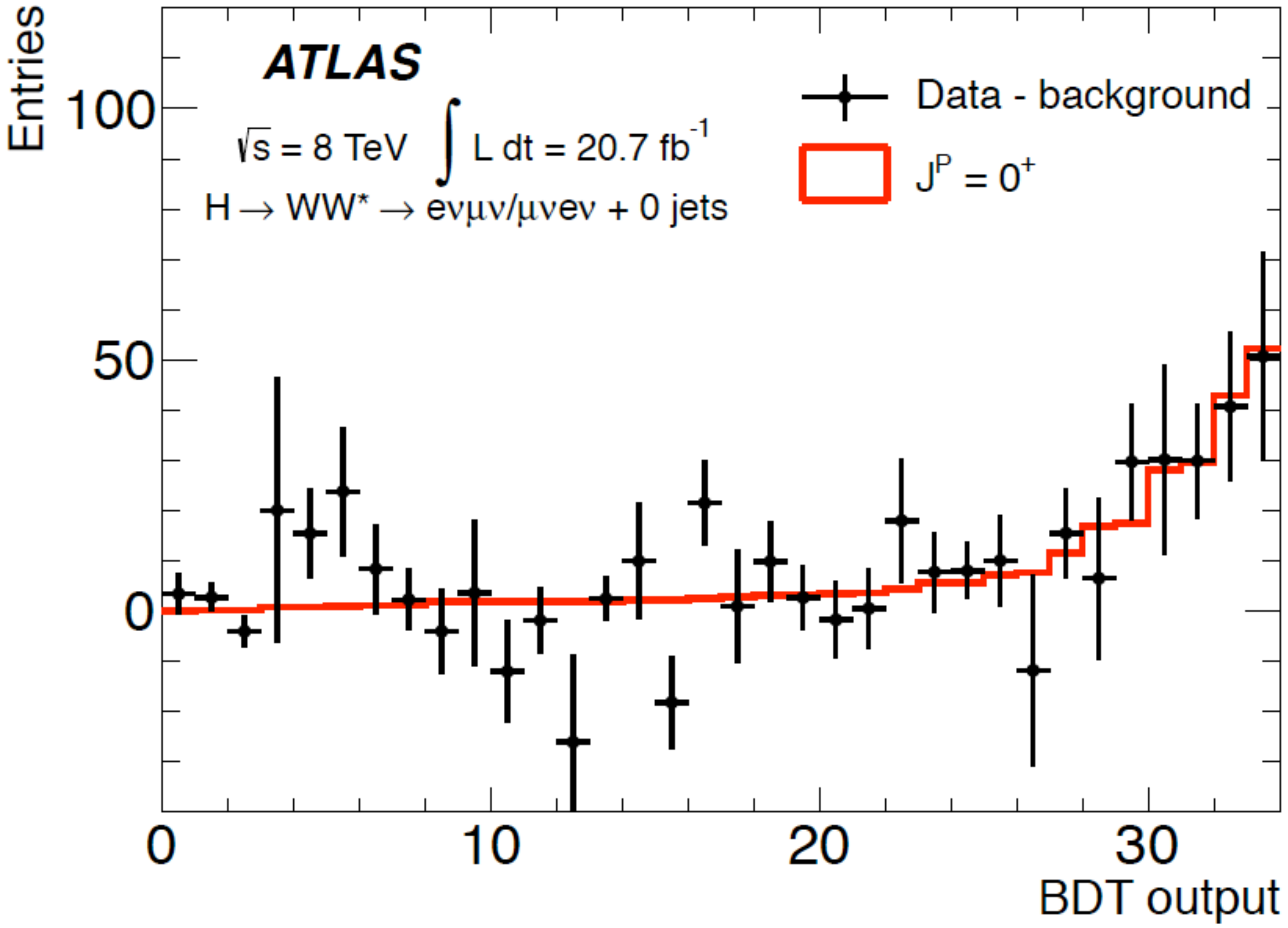
Gluon and Photon couplings



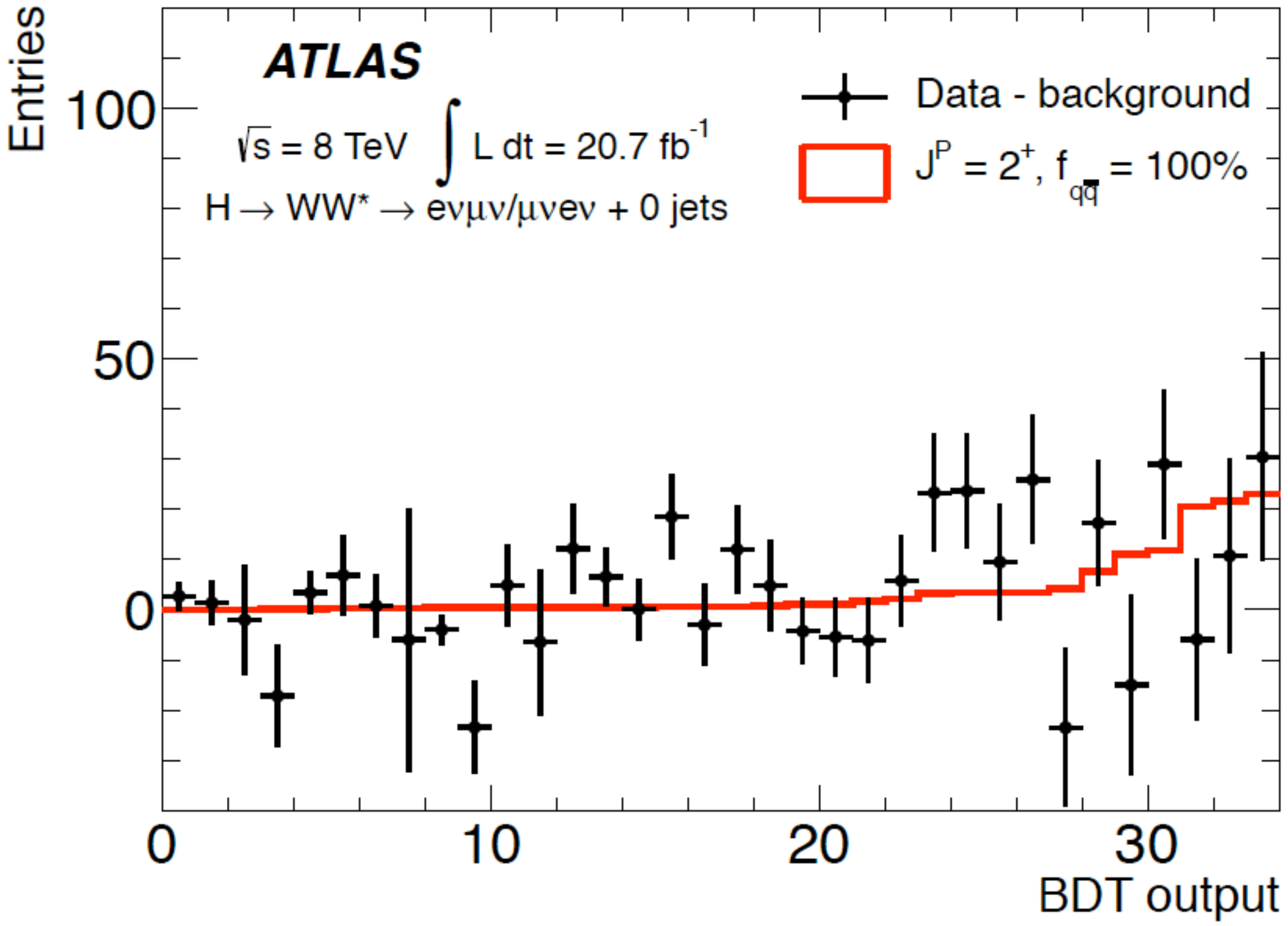
Spin and parity results

Same data!

(different BDT discriminant)



$J^P = 0^+$ (SM)



$J^P = 2^+$

New Spin Parity results

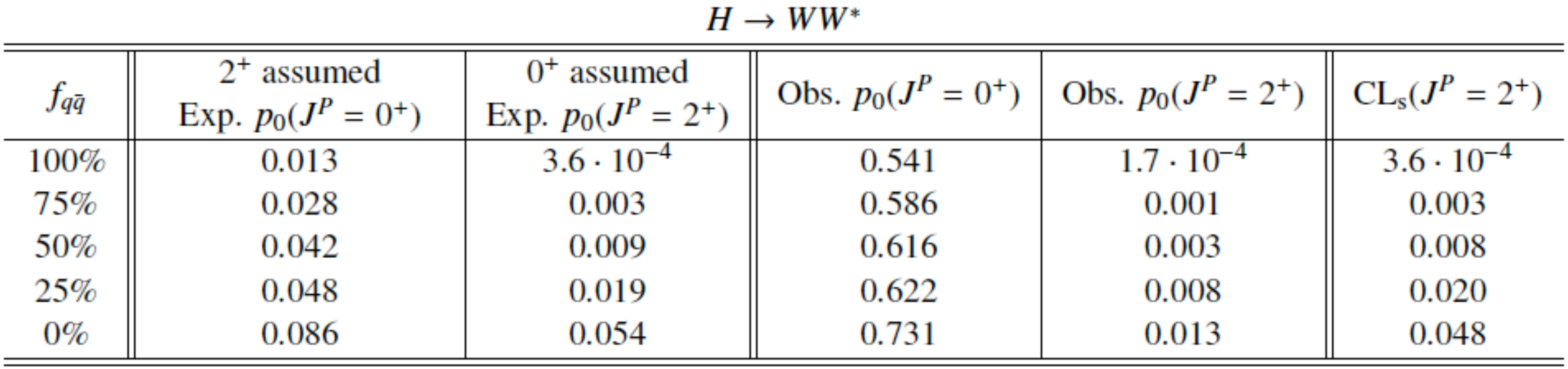
Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$\mathrm{CL_s}(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	0.62	$1.2 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$

Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$\mathrm{CL_s}(J^P = 1^-)$
$H \to ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.33	$1.8 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$

NEW

arxiv:1307.1432

WW Spin Parity results



$H \to WW^*$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$\mathrm{CL_s}(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048