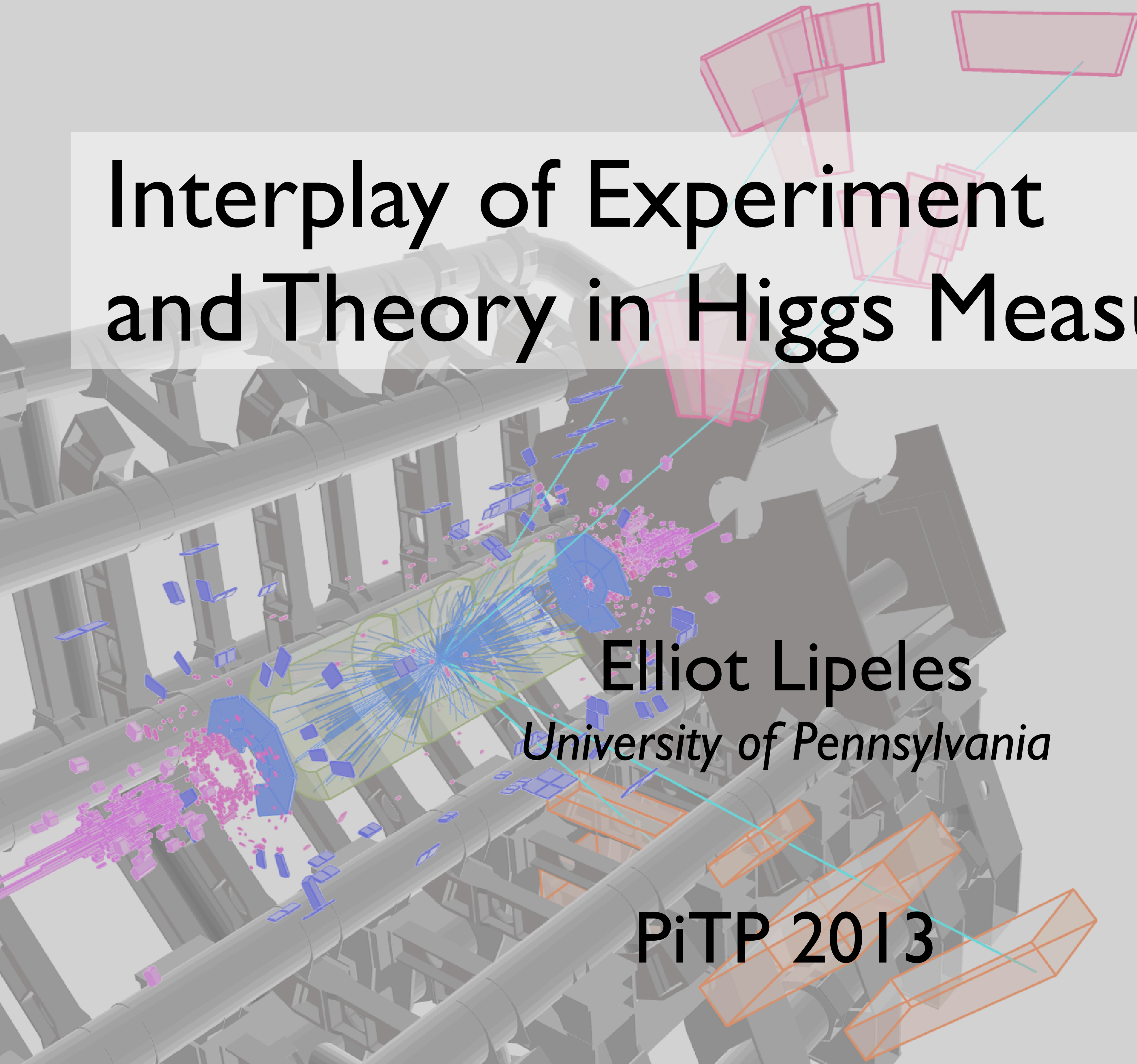
Interplay of Experiment and Theory in Higgs Measurement



Elliot Lipeles

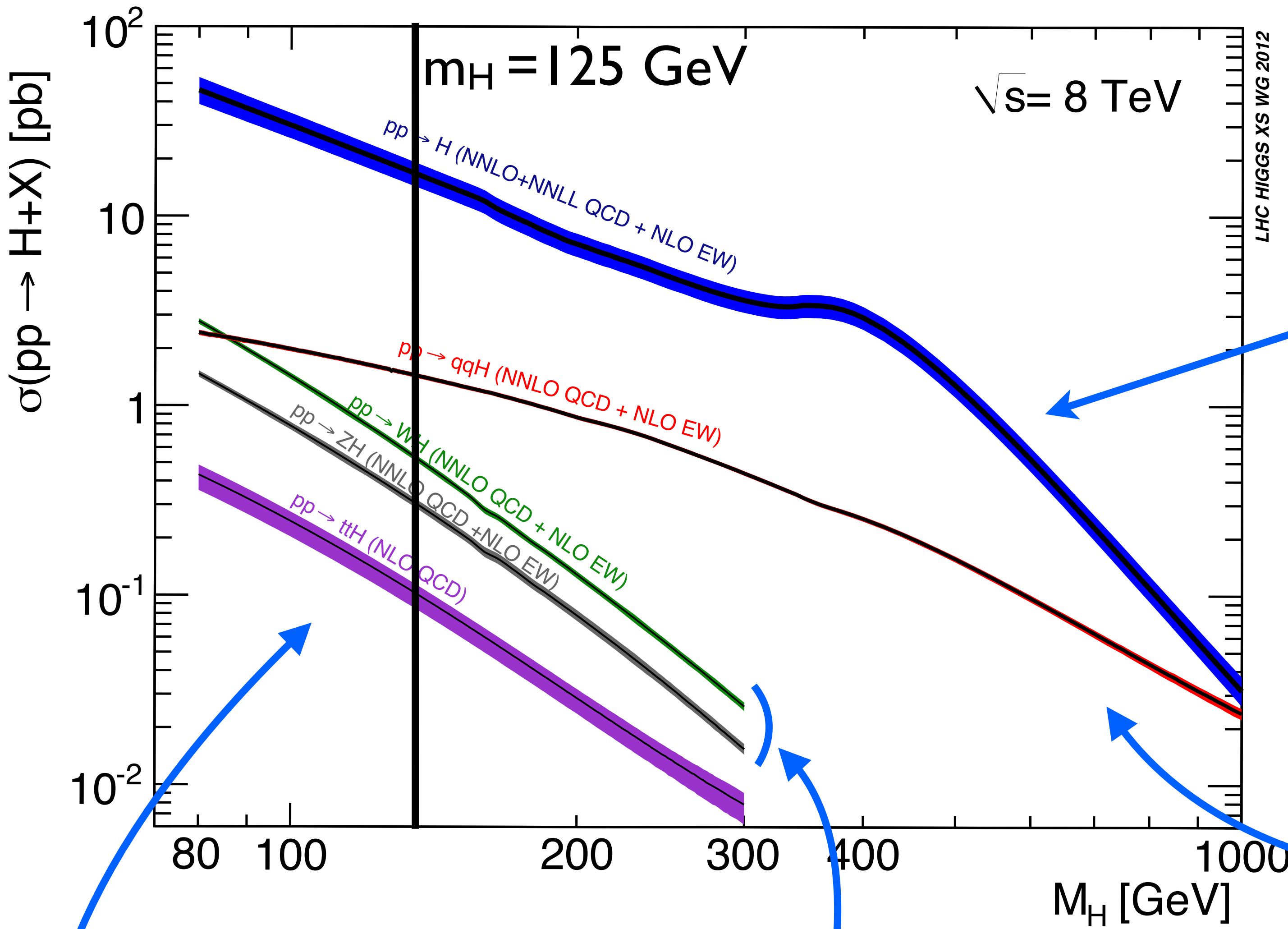
University of Pennsylvania

PiTP 2013

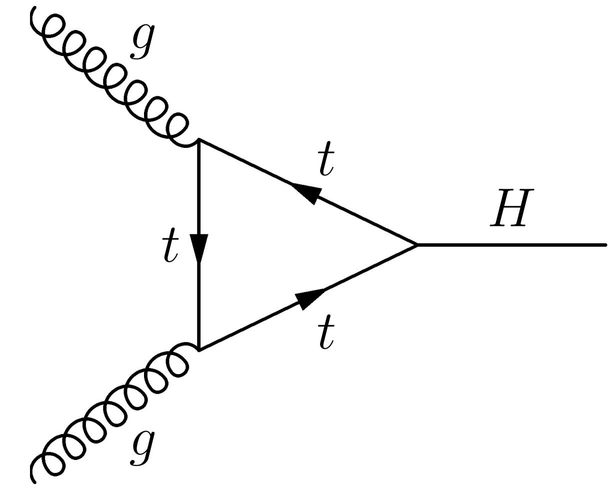
Introduction

- Brief Review of Higgs Channels
- Theory and H to WW
  - Review of H to WW Analysis
  - ggH Background Modeling
  - ggH Signal Modeling
  - VBF Background Modeling
- Interpreting Higgs Results
  - Coupling Fits
  - Aside on Higgs to Invisible
  - Advertisement: Differential Distributions

Higgs Production Summary

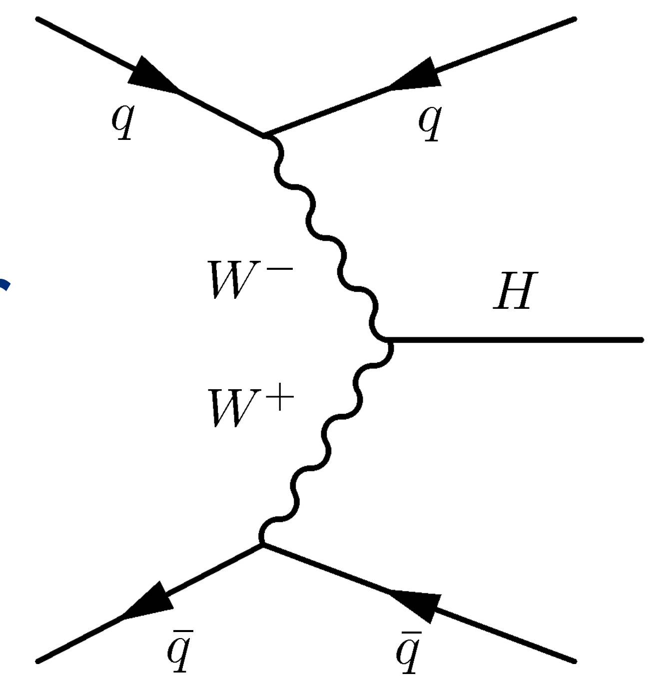


ggF



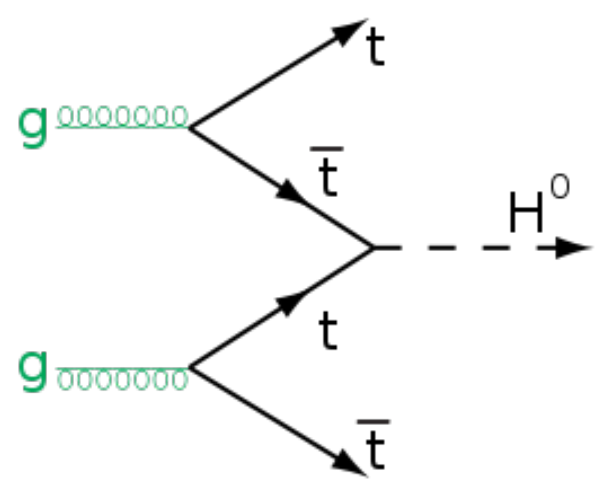
Large QCD Uncertainties
Sensitive to new physics in the loop

VBF (vector boson fusion)



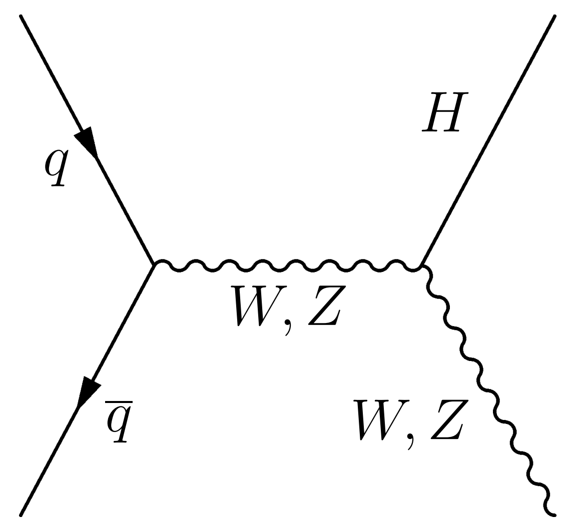
Small QCD Uncertainties
Distinctive forward jet tags

ttH



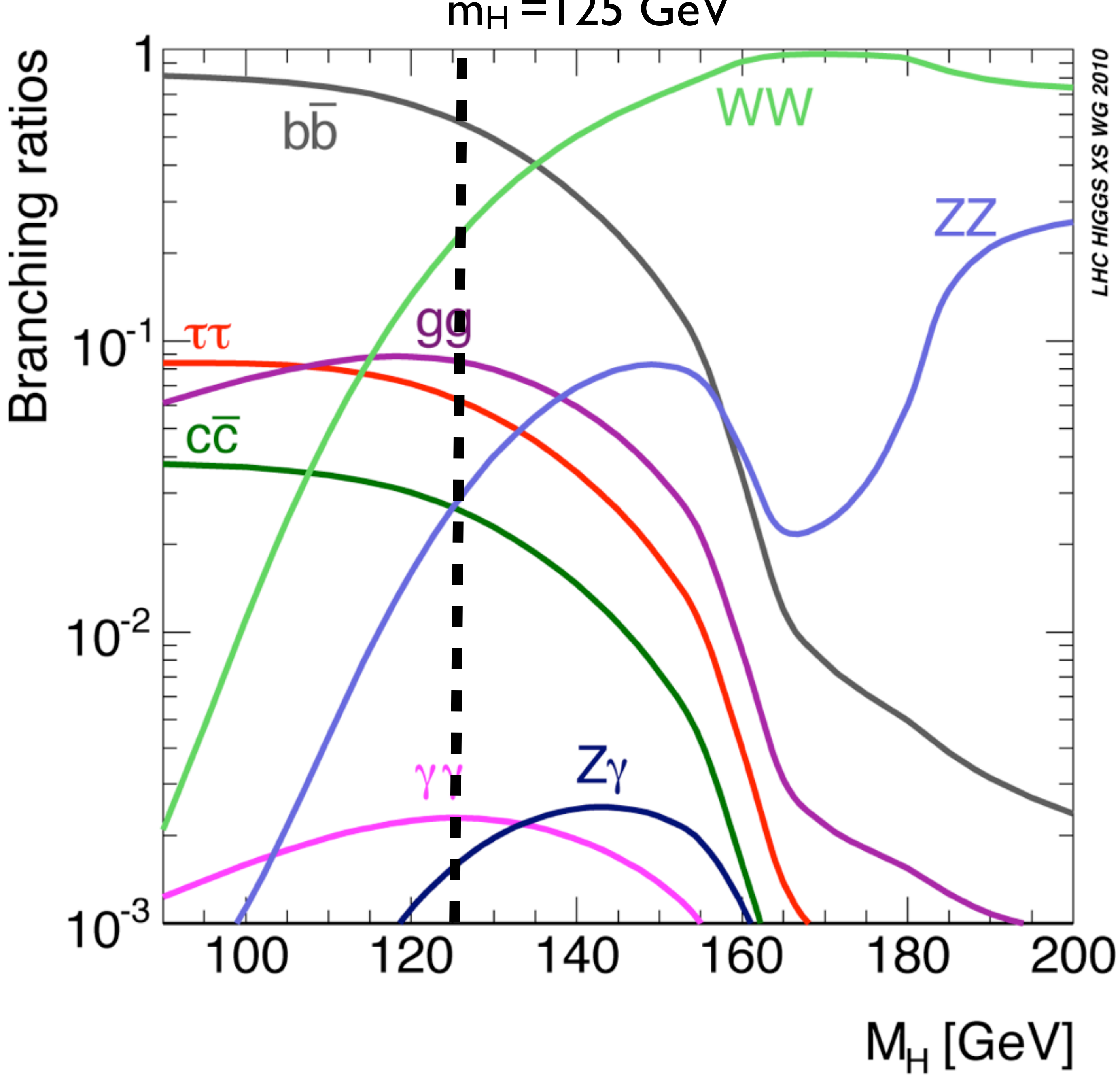
Access to top coupling

VH



Usually tagged w/ W/Z decay to leptons (inc. neutrinos)

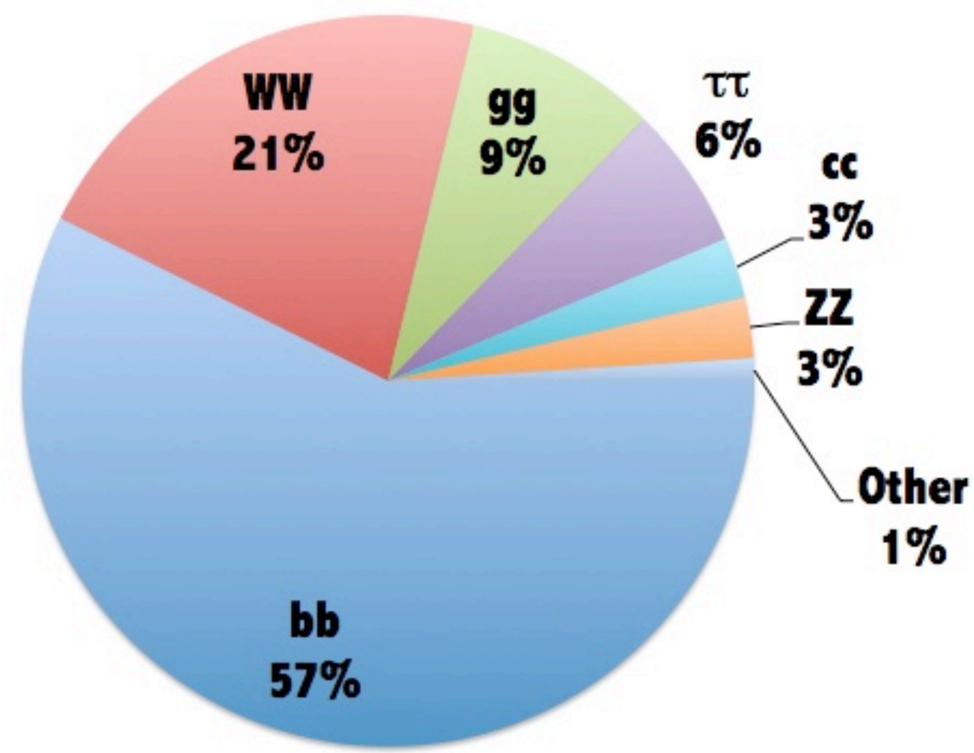
Higgs Decay Summary



Observed:
WW, ZZ, and $\gamma\gamma$

Searches:
bb, $\tau\tau$, $Z\gamma$, and $\mu\mu$

Higgs decays at m_H=125GeV



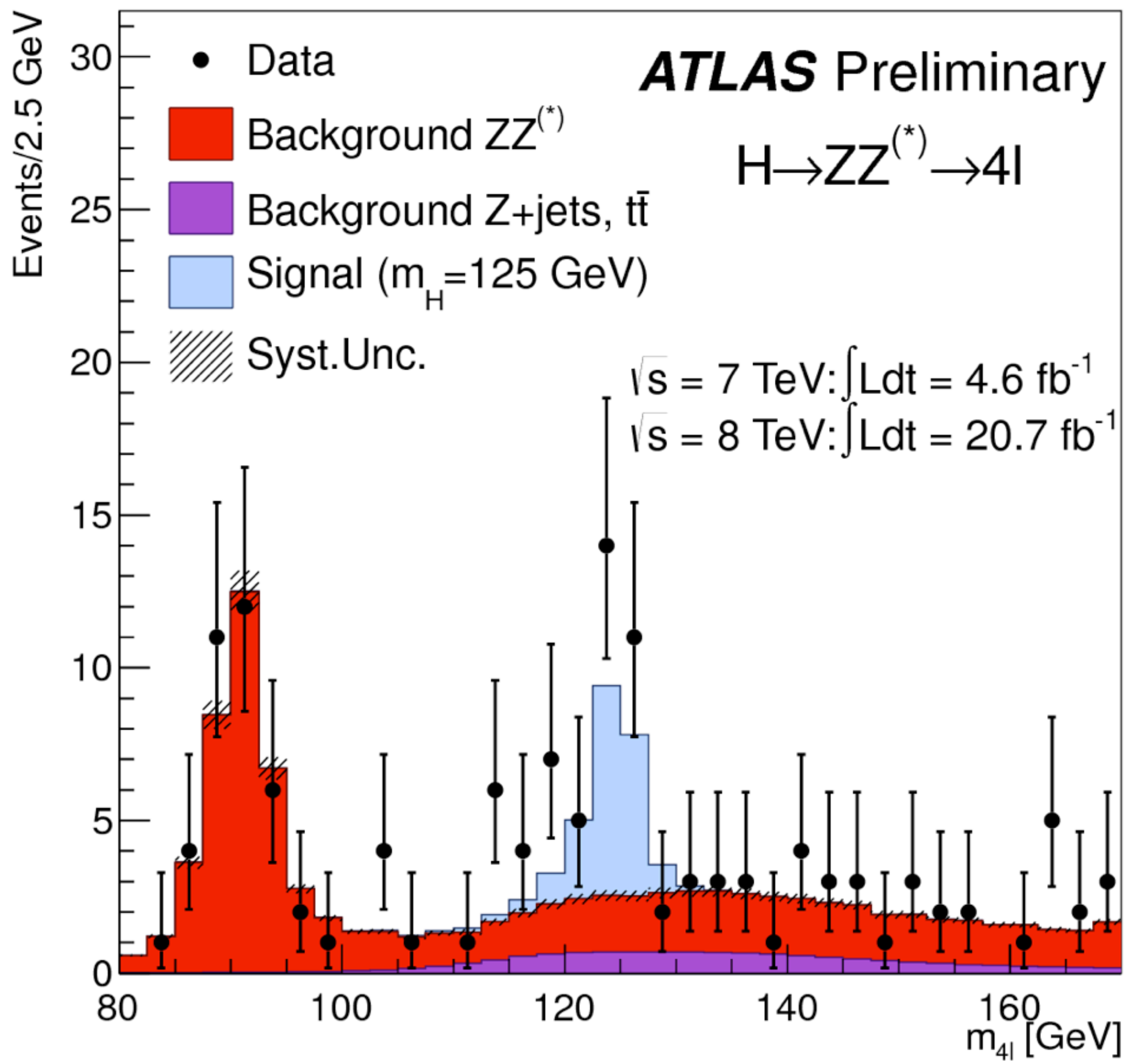
Each decay probes a different Higgs (Yukawa) coupling

$H \to WW$ vs $H \to \gamma\gamma$ and $H \to ZZ$

The Higgs has been observed in 3 channels: $WW, \gamma\gamma, ZZ$
(with two others on the edge of significance: $\tau\tau, bb$)

$H \to ZZ \to \ell\ell\ell\ell$ is low background

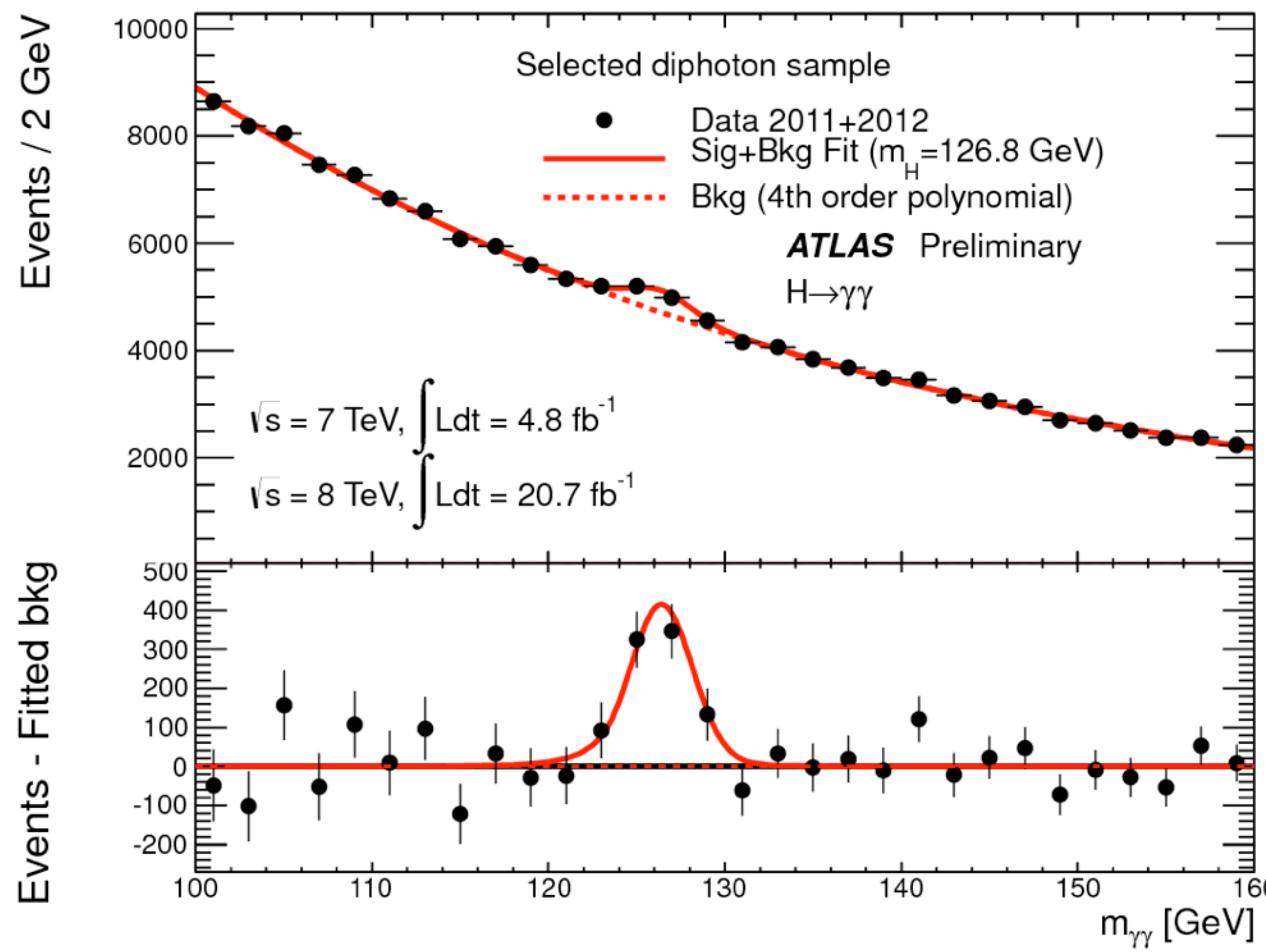
Signal/Background ~1.5



$H \to WW$ vs $H \to \gamma\gamma$ and $H \to ZZ$

The Higgs has been observed in 3 channels: $WW, \gamma\gamma, ZZ$
(with two others on the edge of significance: $\tau\tau, bb$)

$H \to \gamma\gamma$ is high background, but resonance allows background to be determined from sideband



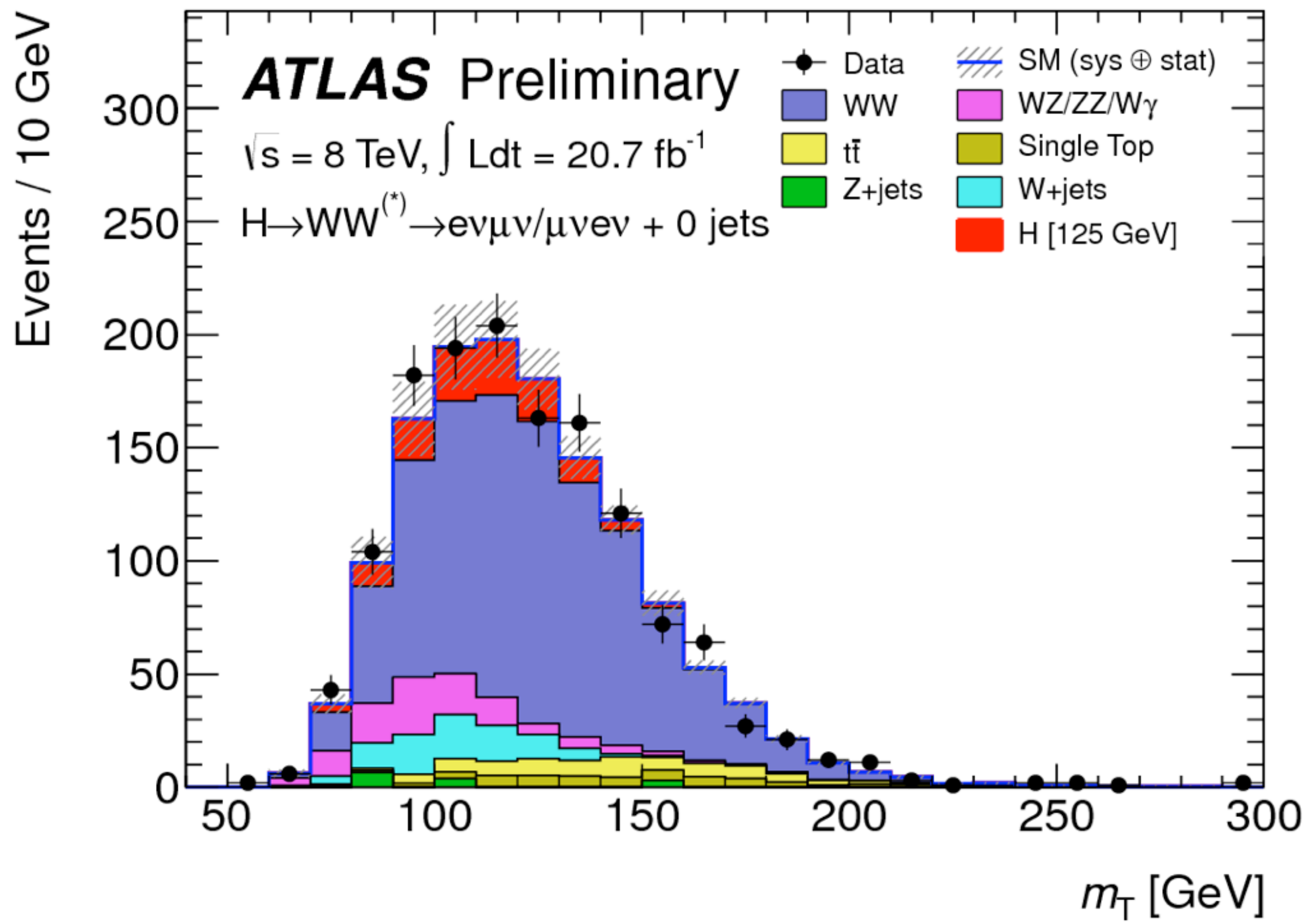
Signal/Background ~ 1/30

$H \to WW$ vs $H \to \gamma\gamma$ and $H \to ZZ$

$H \to WW \to \ell\nu\ell\nu$ is intermediate background, but there is no mass peak

We must model all backgrounds in detail

Selection is complex and its effect on signal has to be modeled



Use approximate mass variable m_T

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\text{miss}})^2}$$

Signal/Background ~ 1/8

H to WW relies heavily on theory

$H \to WW$ sources of uncertainty

Penn University of Pennsylvania

From the ATLAS H to WW conference note ATLAS-CONF-2013-030

$$\mu \equiv \sigma_{observed}/\sigma_{SM}$$

Table 13: Leading uncertainties on the signal strength μ for the combined 7 and 8 TeV analysis.

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

Main systematics are theory uncertainties

Uncertainty is 50% statistical and 50% systematics

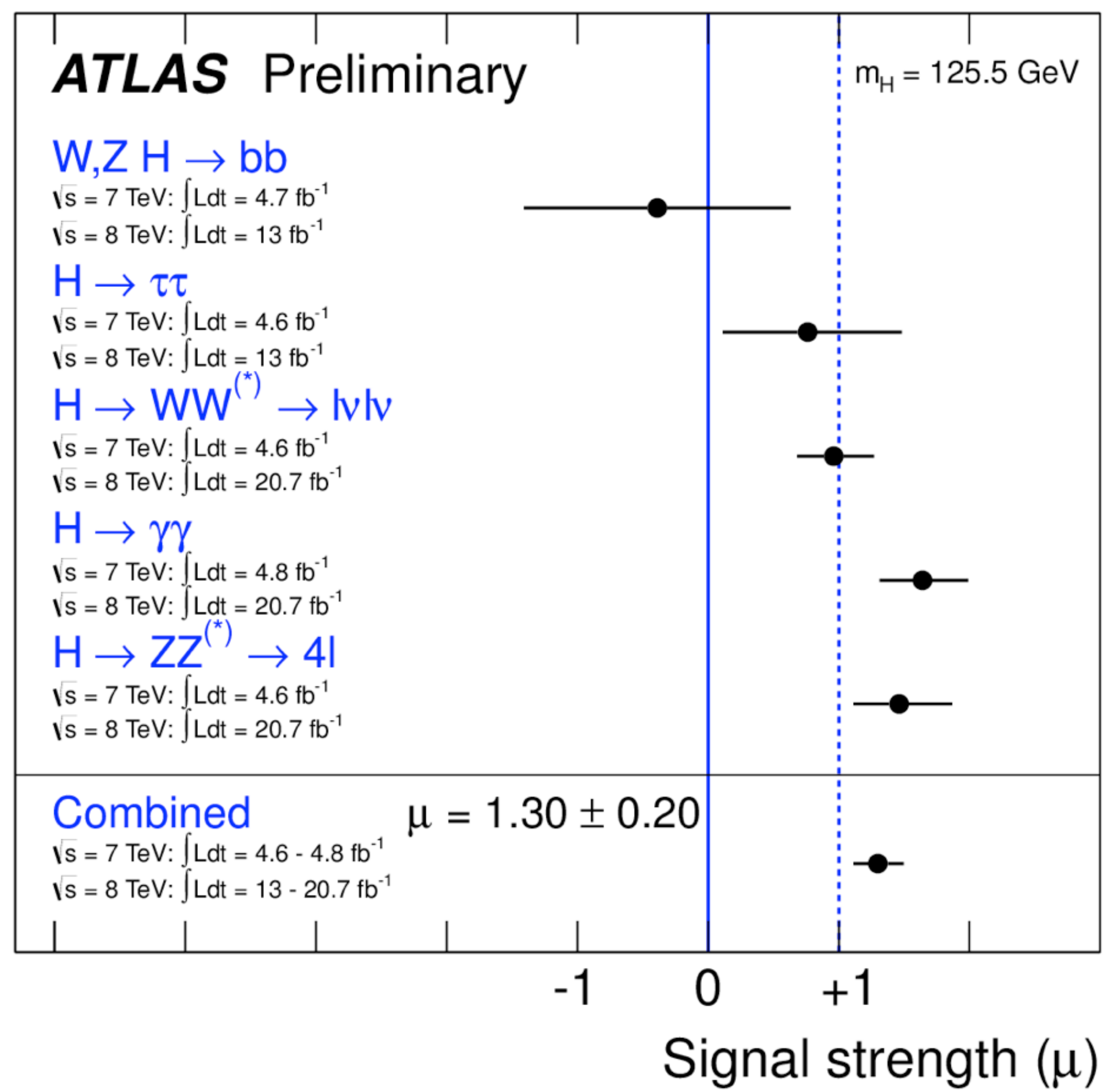
Why bother with $H \to WW$?

Electroweak fits make it hard to mess with the ratio of HWW/HZZ couplings, can't we just measure $H \to ZZ$?

WW uncertainty is smaller than ZZ

$$\mu_{WW} = 1.01 \pm 0.31$$
$$\mu_{ZZ} = 1.7^{+0.5}_{-0.4}$$

Difference will big bigger at13 TeV, ***IF*** the theory uncertainties can be controlled



Scaling to 13 TeV

LHC Plans to Run at 13-14 TeV for the next ~15 years

- 2015-2016 13 TeV, 100 fb^{-1}
- 2018-2020 13(?) TeV, 300 fb^{-1}
- 2022-202(?) 13(?) TeV, 3000 fb^{-1}

Have

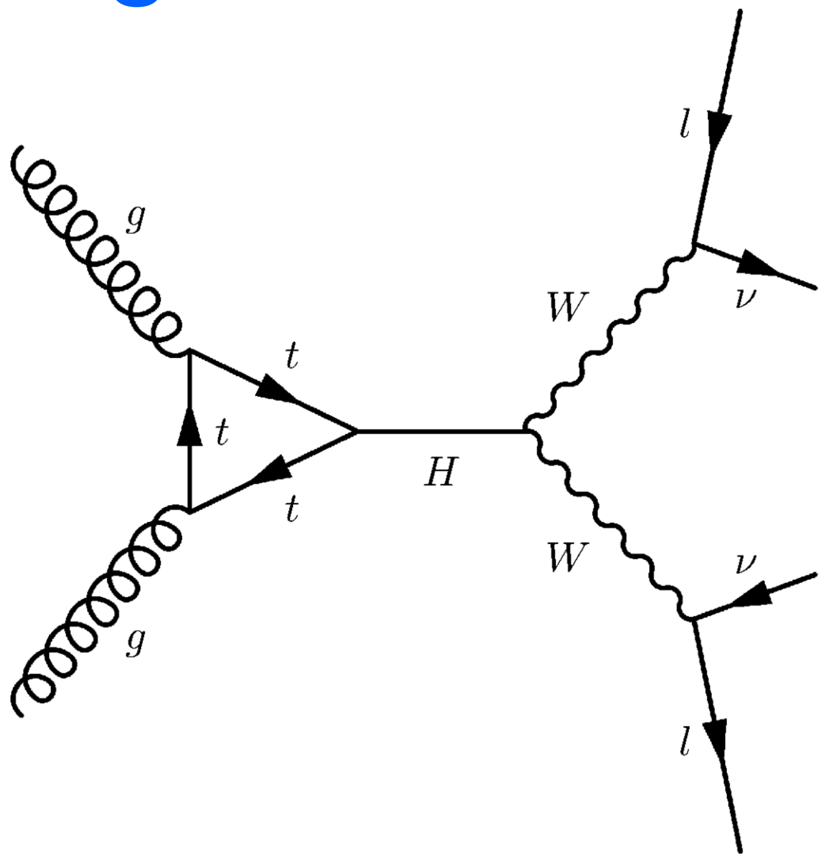
- 2011 7 TeV 5 fb^{-1}
- 2012 8 TeV, 20 fb^{-1}

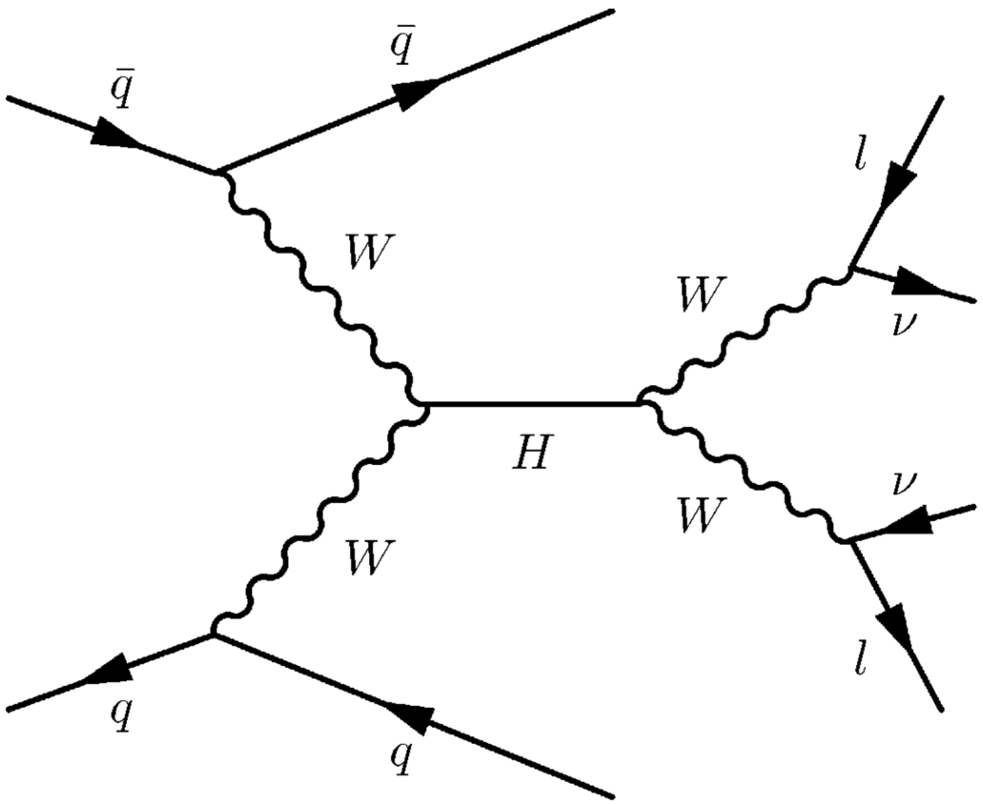
Signal	14 TeV/8 TeV
ggF	2.6
VBF	2.6
ttH	4.7
WH	2.1
ZH	2.1
qq to WW background	2.1
gamma gamma bkg	2.1

In 2016, 4*2.6~10 more signal, 4*2.1~8 more background

Review of H to WW Analysis

Signature: two e or μ leptons and two neutrinos





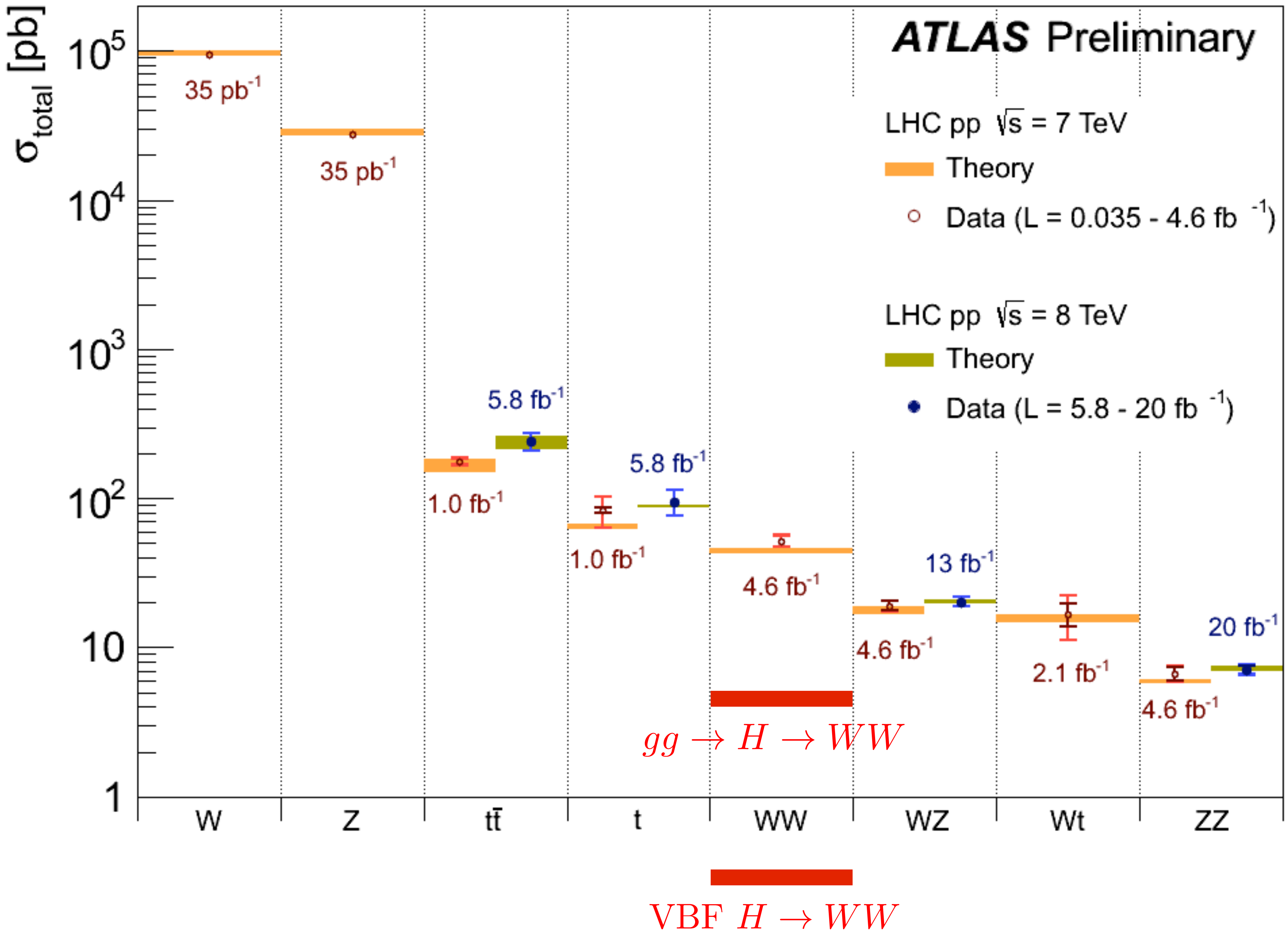
Gluon Fuison (ggH)
typically gives 0 or 1 jets

Vector Boson Fusion
gives 2 or more jets

Many of the lessons in H to WW will apply to other searches where the signal is under significant SM background and does not peak

Review of H to WW Analysis

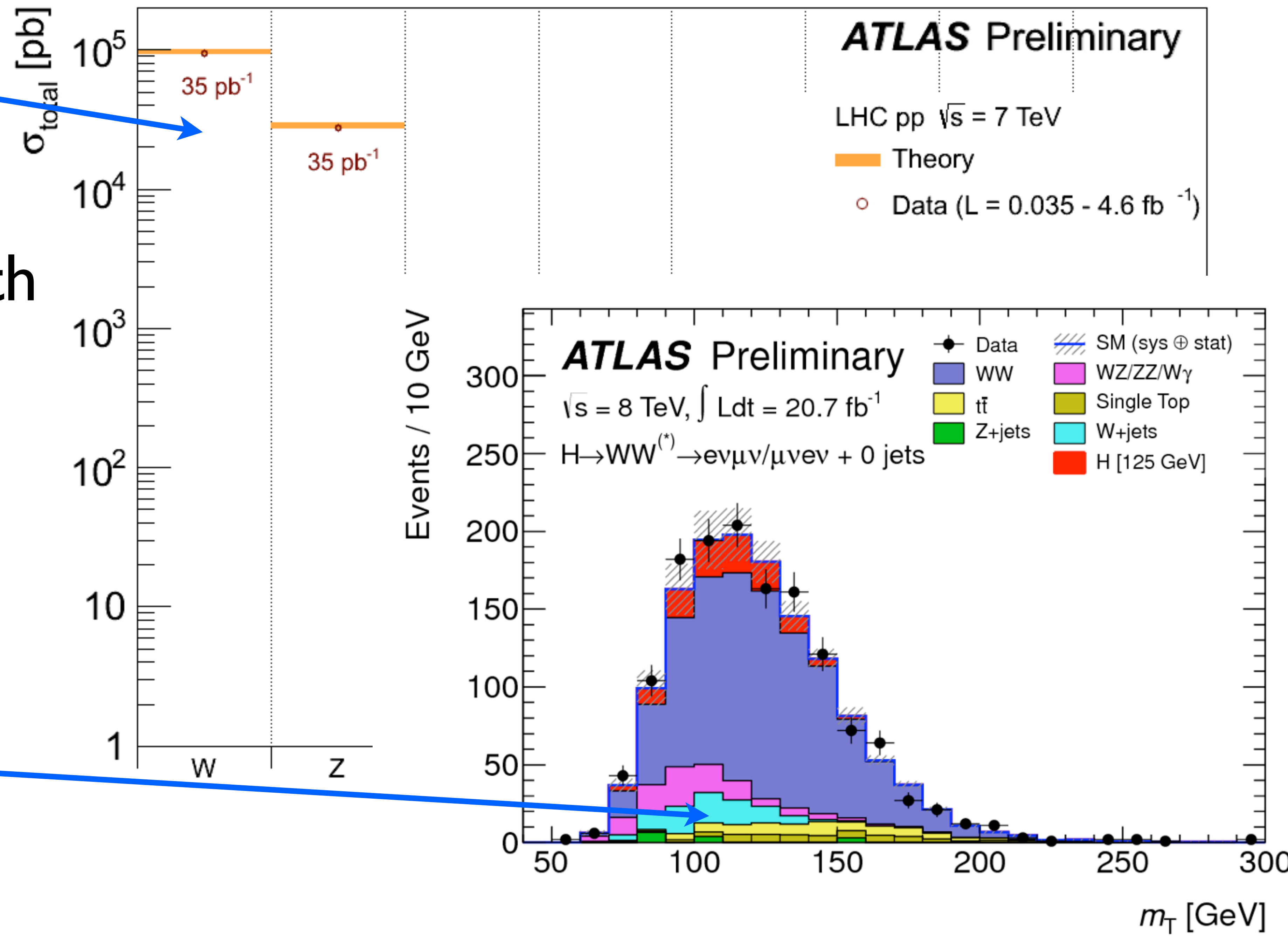
Just about everything in the hadron collider zoo is a background



Review of H to WW Analysis

W+jets background

- $q\bar{q} \rightarrow W \rightarrow l\nu$ with an associated jet...
- the jet is misidentified as a lepton
- small background, but uncertainty is large
- one of the largest experimental uncertainties

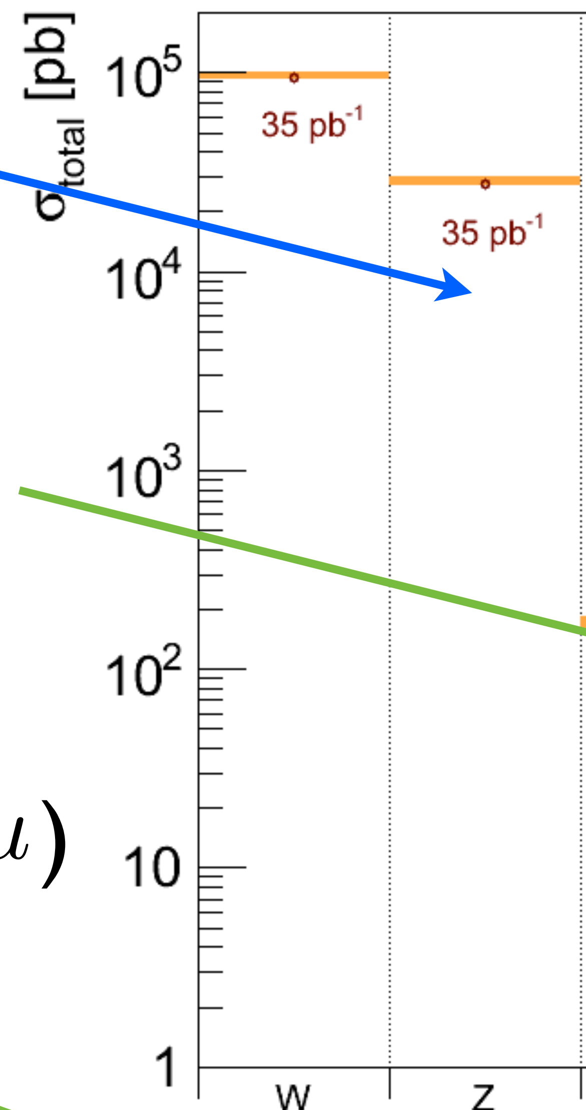


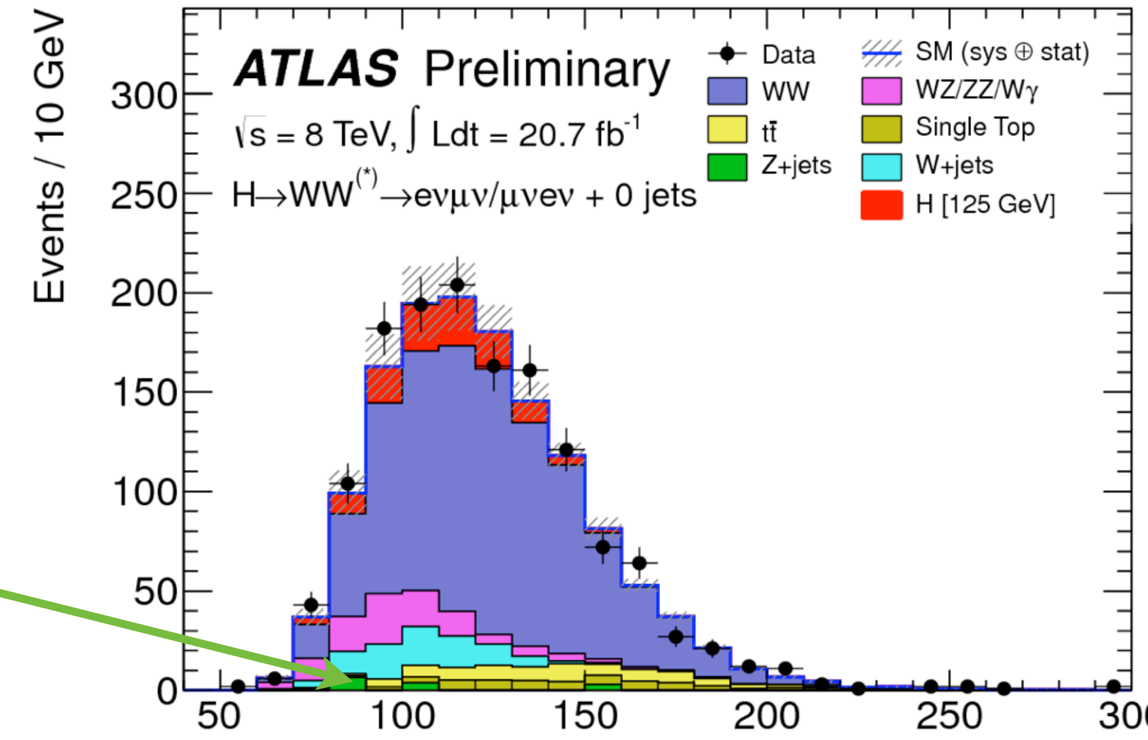
Hard to predict theoretically, because of dependence on fragmentation and detector response

Review of H to WW Analysis

Z+jets background

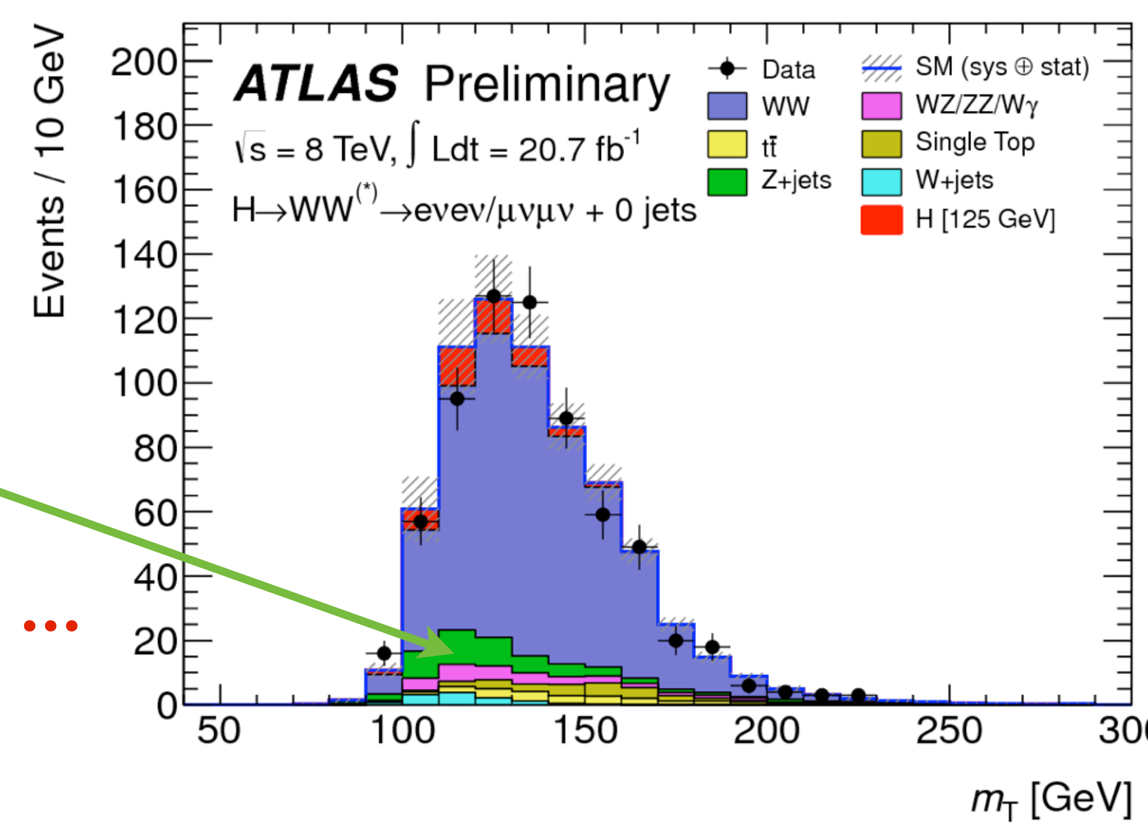
- Different-flavor $(e\mu)$ background mainly from $Z \rightarrow \tau\tau$
- Tiny Background





- Same-flavor $(ee\,\&\,\mu\mu)$ background from $q\bar{q} \rightarrow Z/\gamma^* \rightarrow ll$ with false missing momentum signature
- again, a small background, but uncertainty is large

Hard to predict ... see next slide



Challenges in predicting missing energy distributions

We make multiple cuts to suppress $Z/\gamma^* \to \ell\ell$ and $Z \to \tau\tau$

Missing Transverse "Energy"

$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = \sum_{\mathrm{calorimeter}} \vec{p}_{\mathrm{T}}$$

Missing Transverse Energy Relative

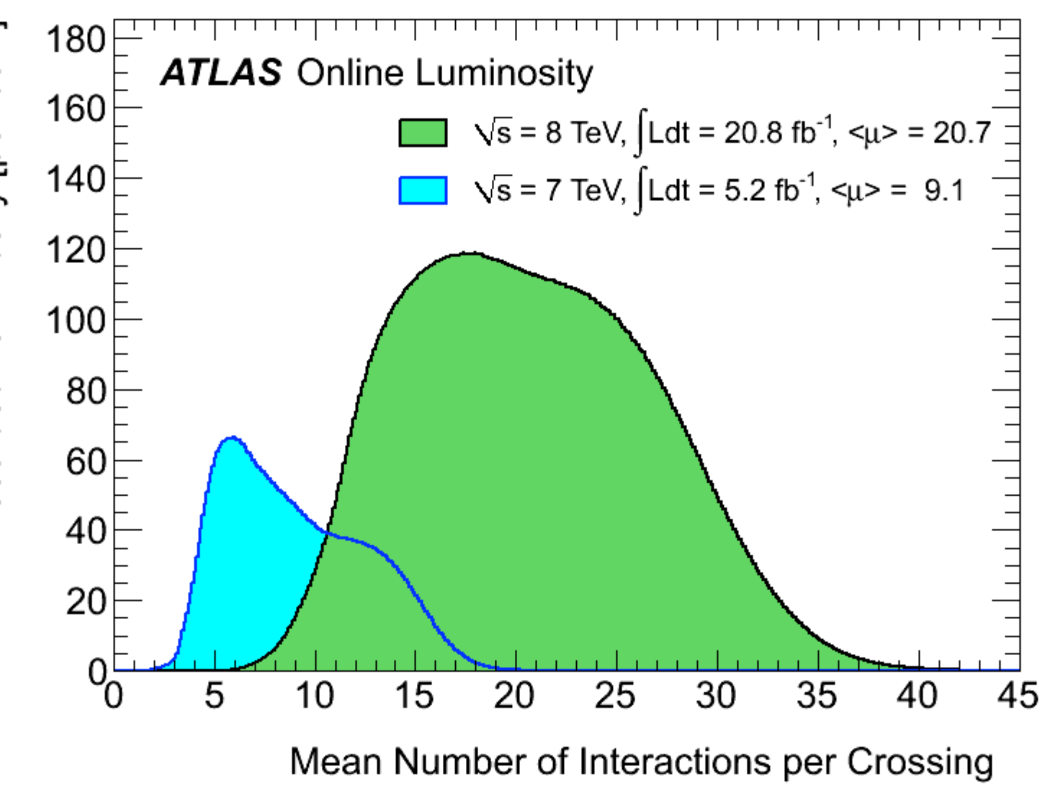
$$E_{\mathrm{T}}^{\mathrm{miss,rel}} \equiv \begin{cases} |E_{\mathrm{T}}^{\mathrm{miss}}| & \text{if } \Delta\phi \geq \pi/2 \\ |E_{\mathrm{T}}^{\mathrm{miss}}| \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

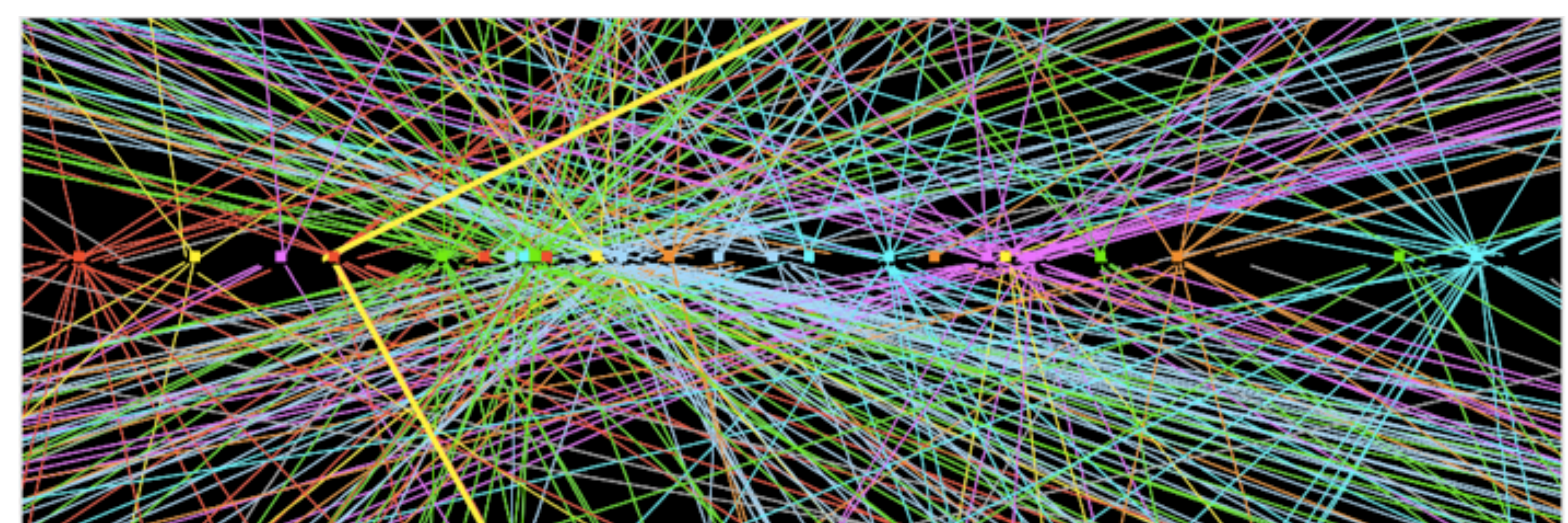
where $\Delta\phi$ is the angle between $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and the nearest lepton or jet

$E_{\mathrm{T}}^{\mathrm{miss,rel}}$ is less sensitive to mismeasurements of leptons and jets

Challenges in predicting missing energy distributions: Pile-up

- You should think great $H \to WW \to \ell\nu\ell\nu$ has $E_{\mathrm{T}}^{\mathrm{miss}}$ and $Z/\gamma^* \to \ell\ell$ doesn't, so we are done
- But it's difficult to measure hadronic energies precisely
- There is still too much left after a reasonable cut for the same-flavor so we have to use the soft recoil system and calibrate it with data
- Made much worse by pile-up:

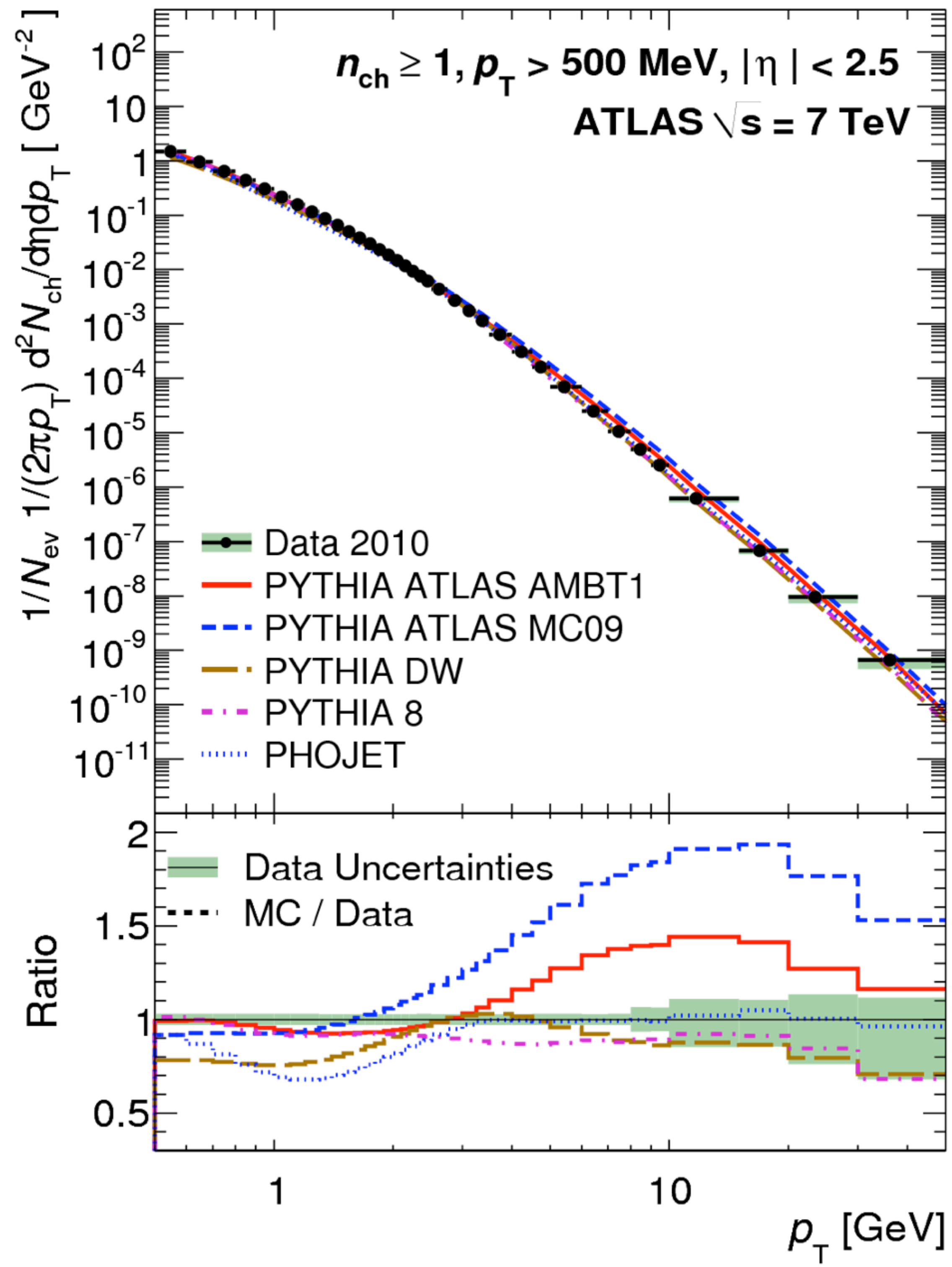




Challenges in predicting missing energy distributions: Pile-up

Pile-up is hard to model: Soft QCD

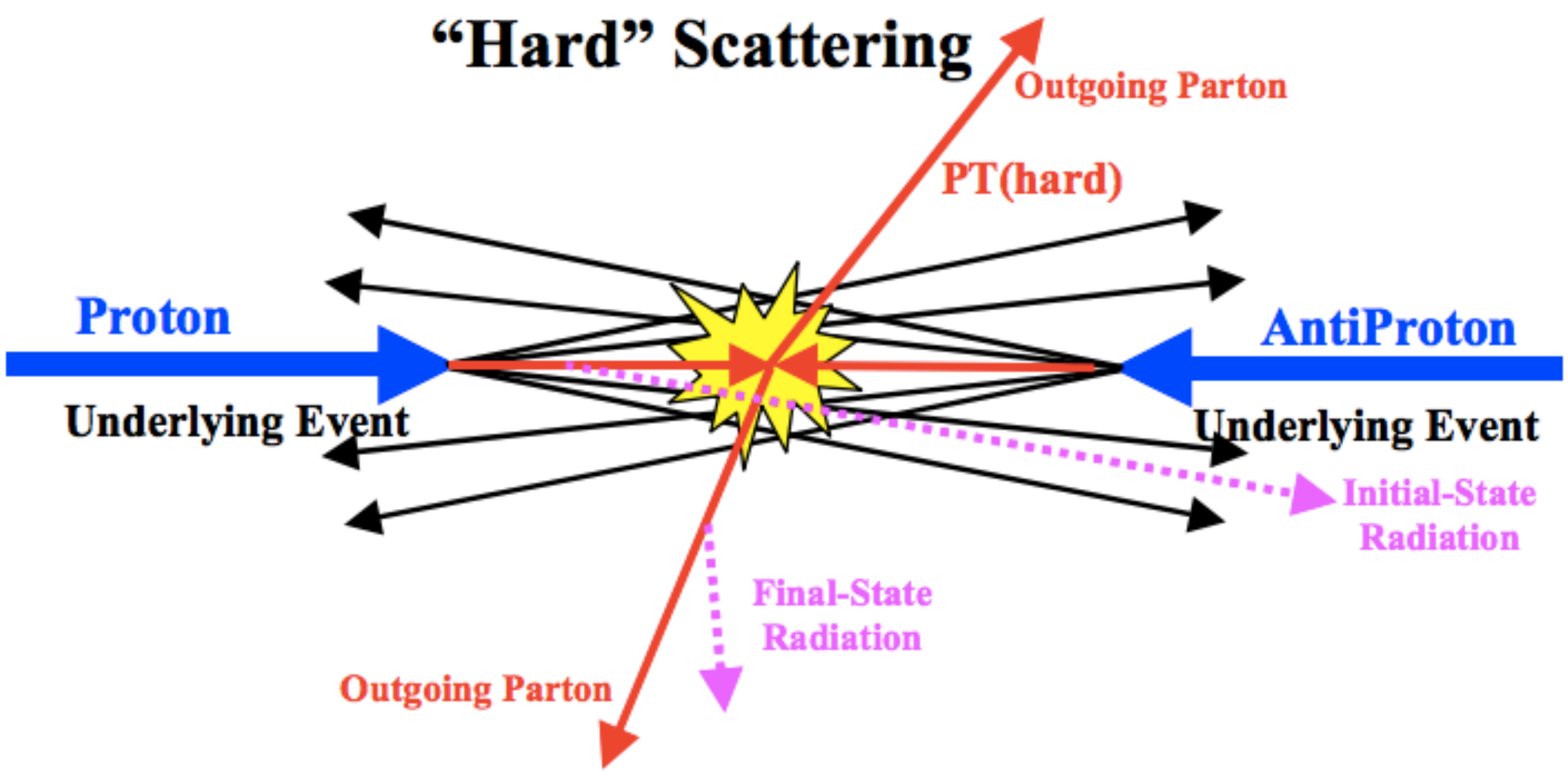
- These properties are very hard to model
- Models are tuned directly to data, but we still find modeling issues which grow with pile-up



Challenges in predicting missing energy distributions: Underlying Event

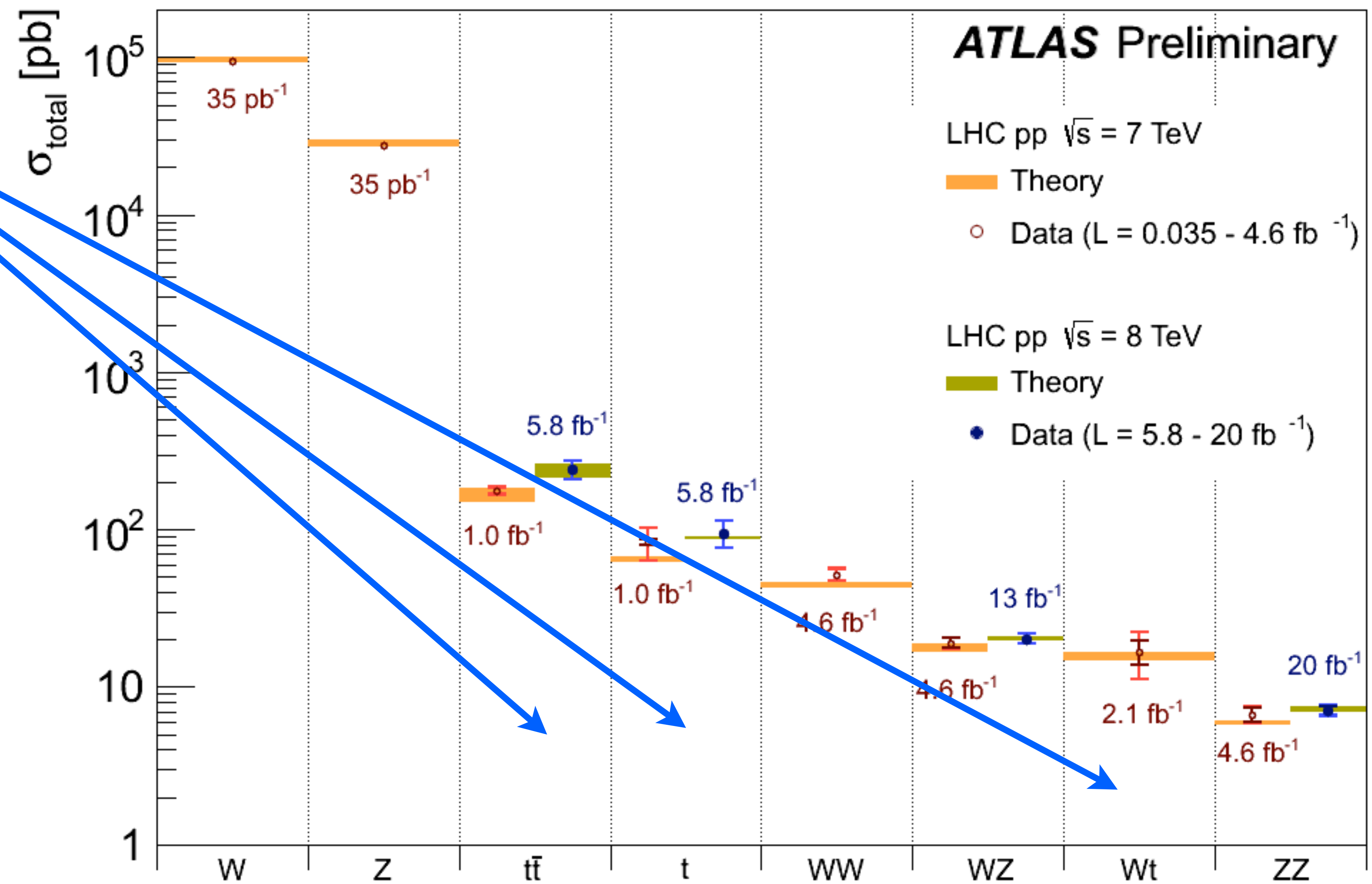
Underlying event is due to a variety of soft QCD effects

- To use simulation, total amount of energy needs to be simulated in data
- Simulation is tuned to data, but the modeling is limited



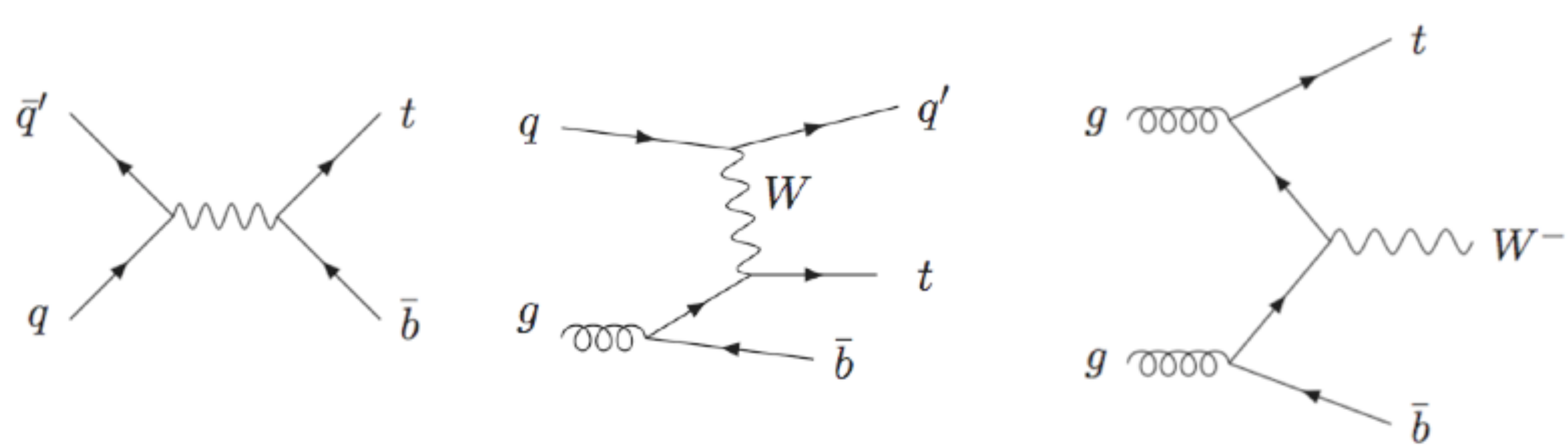
Review of H to WW Analysis

Top and Single top



Looks just like WW but with more jets

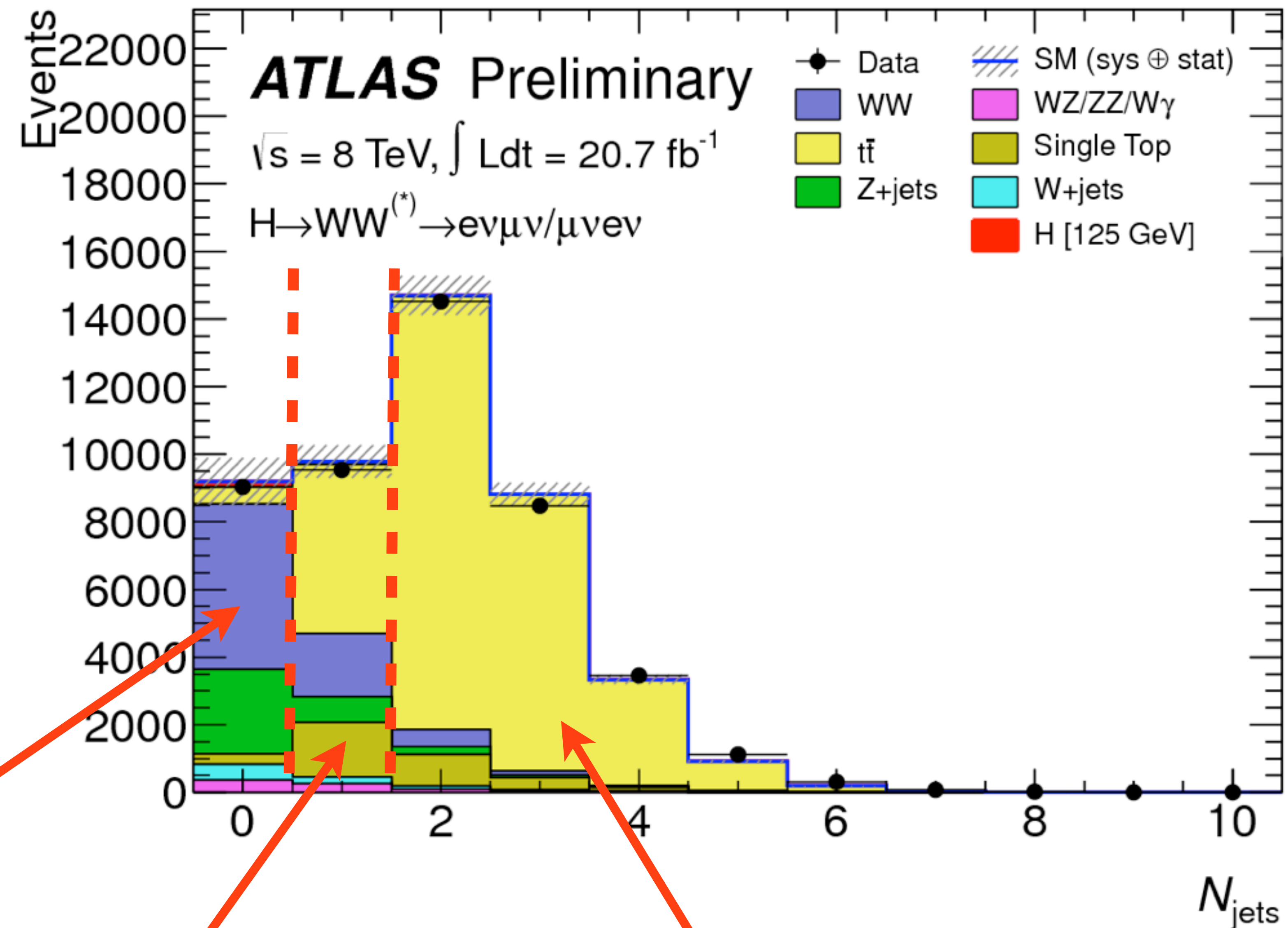
Single Top Diagrams



Review of H to WW Analysis

Jet Counting Strategy:

- Divide analysis into 0-jet, 1-jet, and 2+-jets
- "controls" top background, but leads to many of the uncertainties



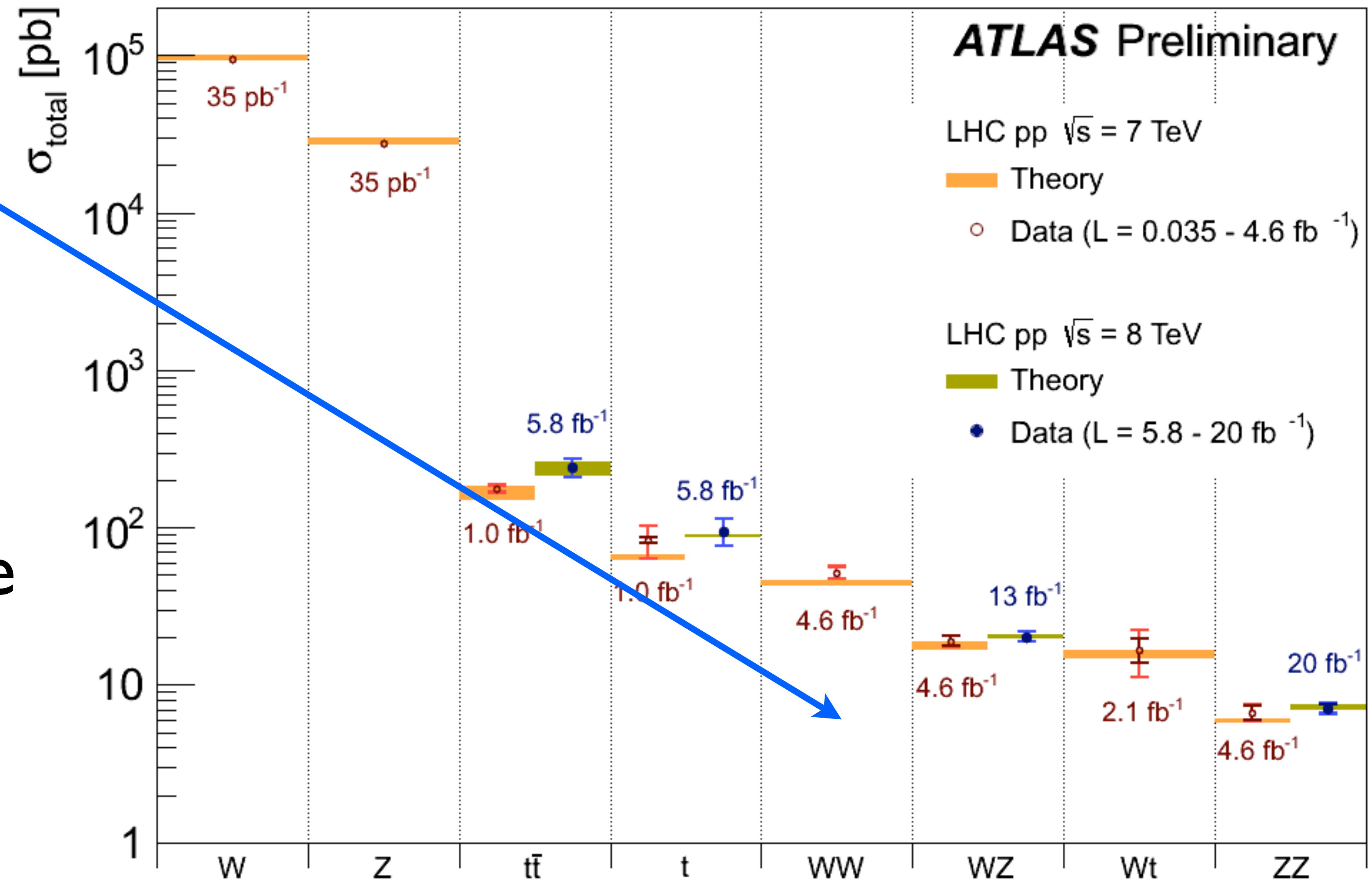
Most of the sensitivity is from 0-jets

Use b-jet "tagging" to suppress top bkg in 1-jet

Specialize the 2+-jets to looking for the VBF signature

Review of H to WW Analysis

WW background



- WW is considered "irreducible"
- It can be partially suppressed using the effect of spin correlations on the angles because the leptons
- It can also be suppressed using kinematics

Gets contributions from both $q\bar{q} \rightarrow WW$ and $gg \rightarrow WW$

$gg \rightarrow WW$ will become more important at 13 TeV

Review of H to WW Analysis

WW suppression using spin correlations

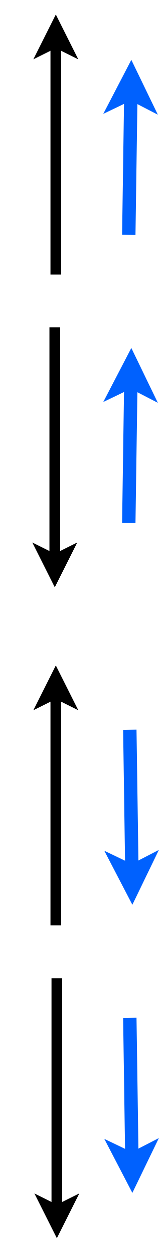
Roughly at rest — W products back-to-back

$H \rightarrow$

Spin=0

W^+ ↑ $\rightarrow$

W^- ↓ $\rightarrow$



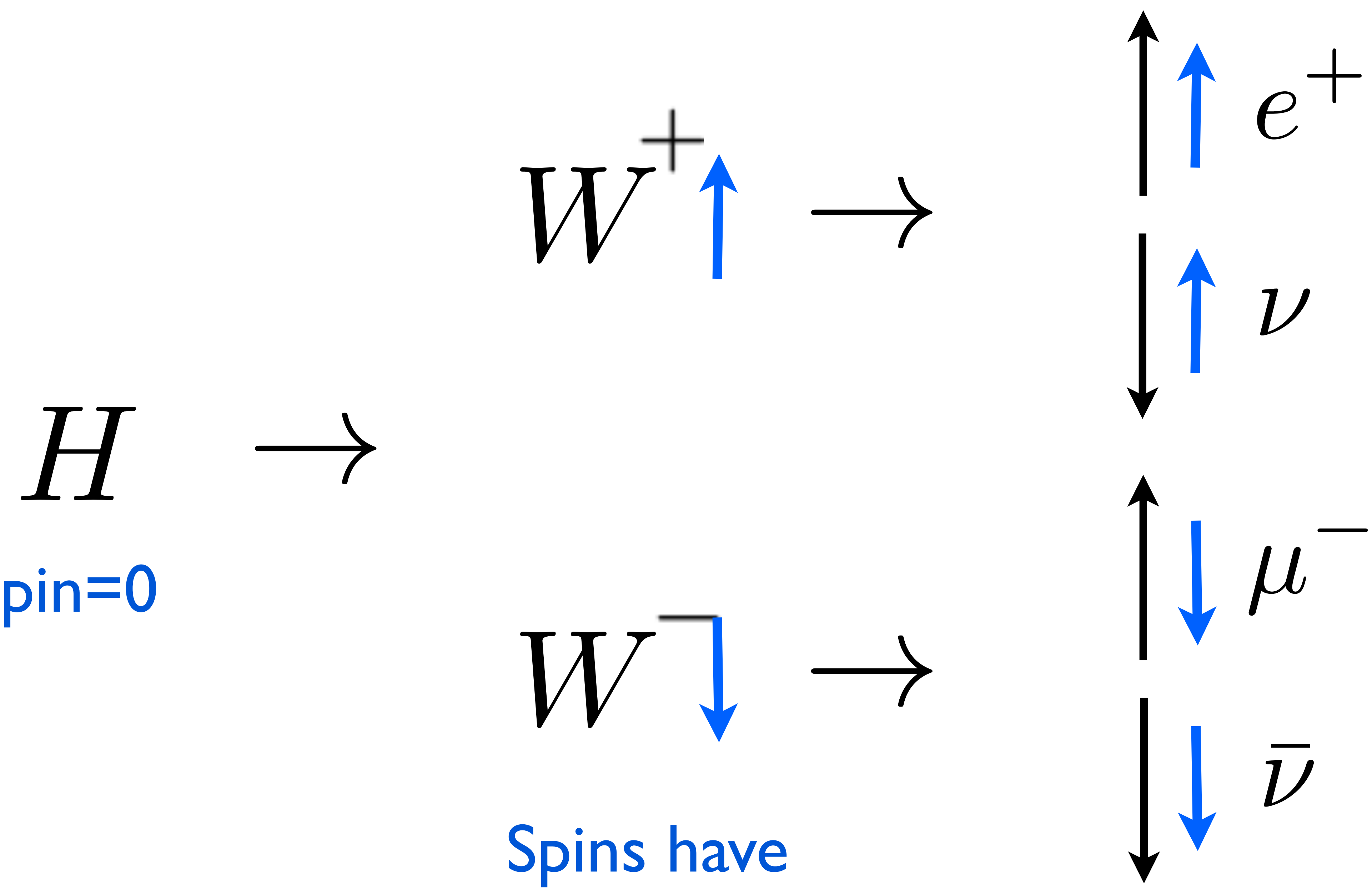
Spins have to add to zero

For each W spins add to one

Review of H to WW Analysis

WW suppression using spin correlations

Roughly at rest W products back-to-back



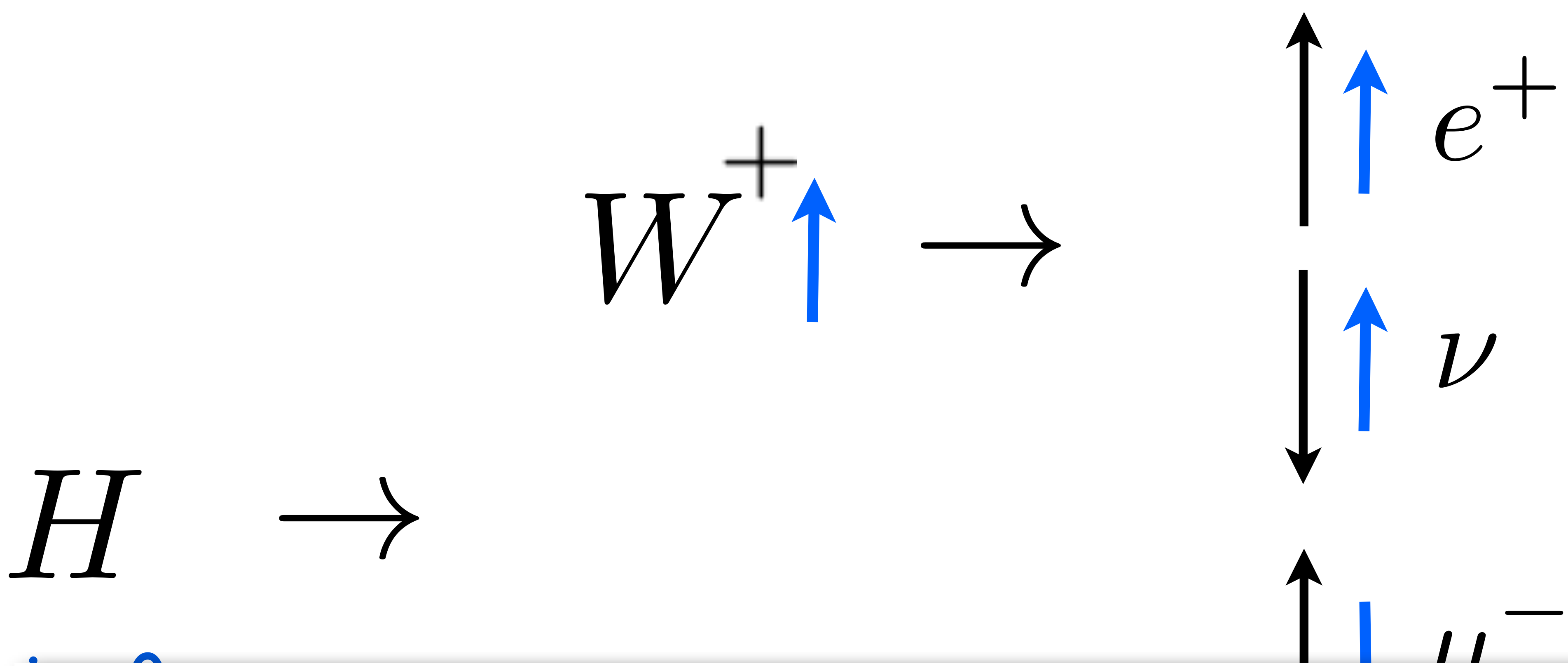
Spins have to add to zero

For each W spins add to one

Review of H to WW Analysis

WW suppression using spin correlations

Roughly at rest W products back-to-back



Consequences

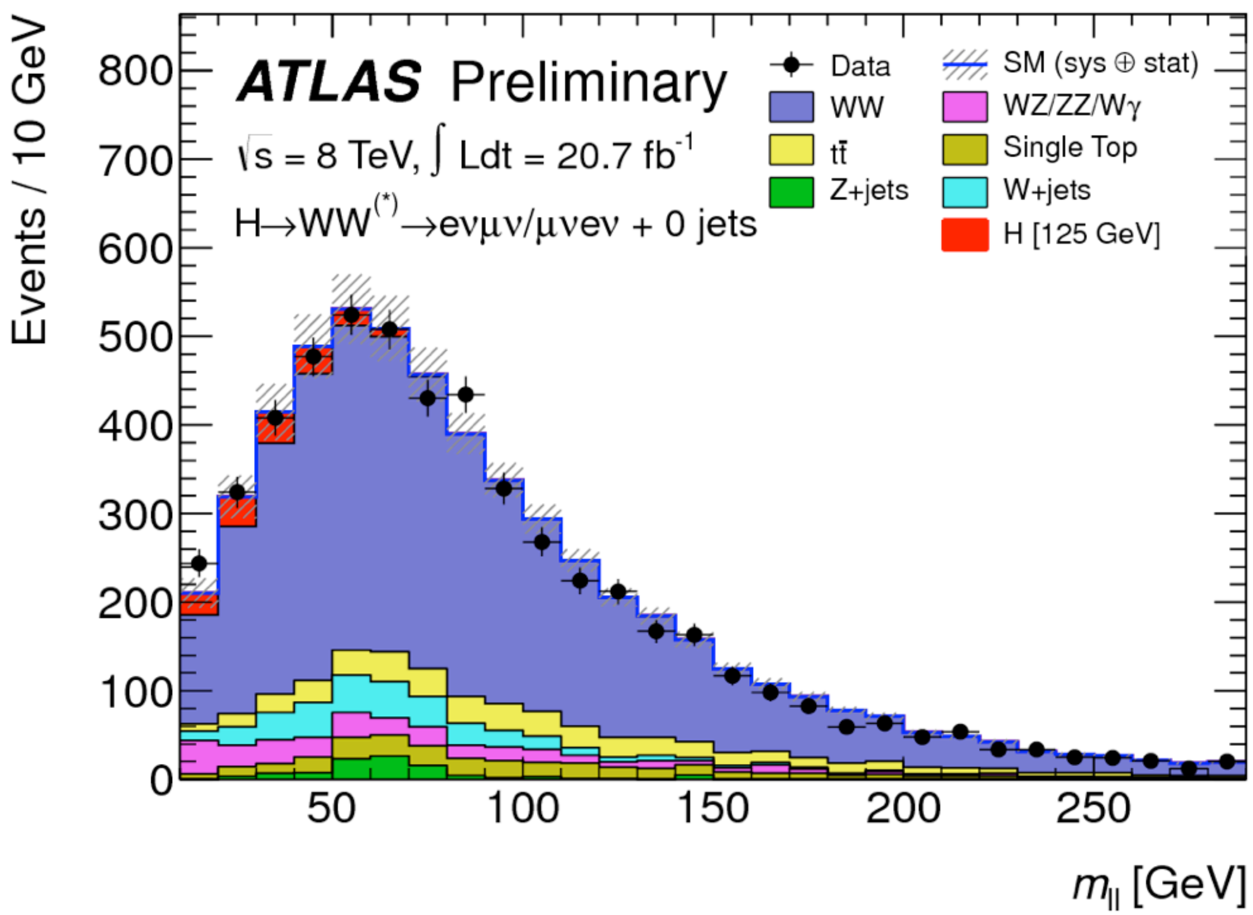
Small angle $\Delta\phi_{ll}$ between charged-lepton directions

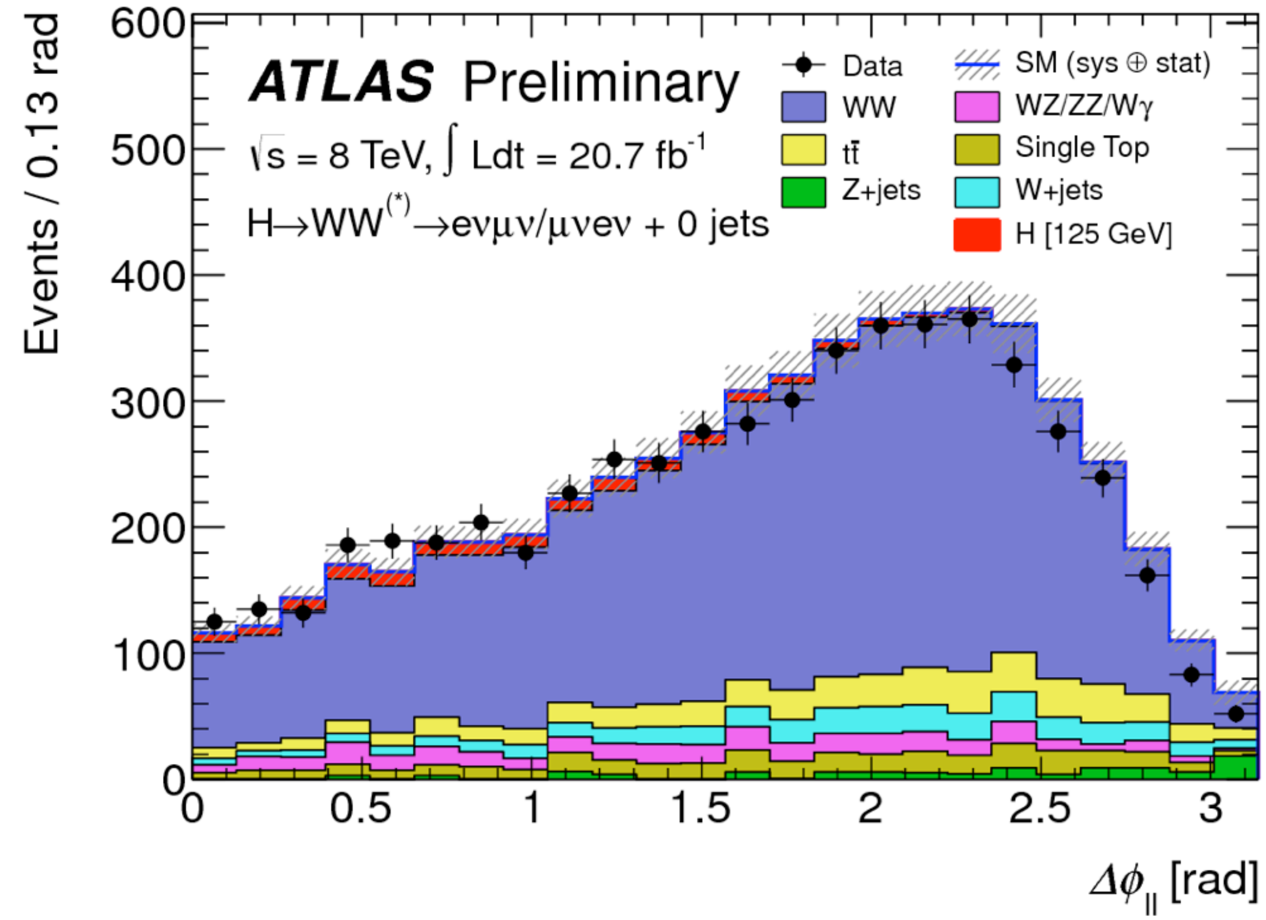
Small invariant mass m_{ll} of the two charged-leptons

Review of H to WW Analysis

WW suppression using spin correlations

Consequences of spin correlations





Small invariant mass m_{ll} of the two charged-leptons

Small angle $\Delta\phi_{ll}$ between charged-lepton directions

Review of H to WW Analysis

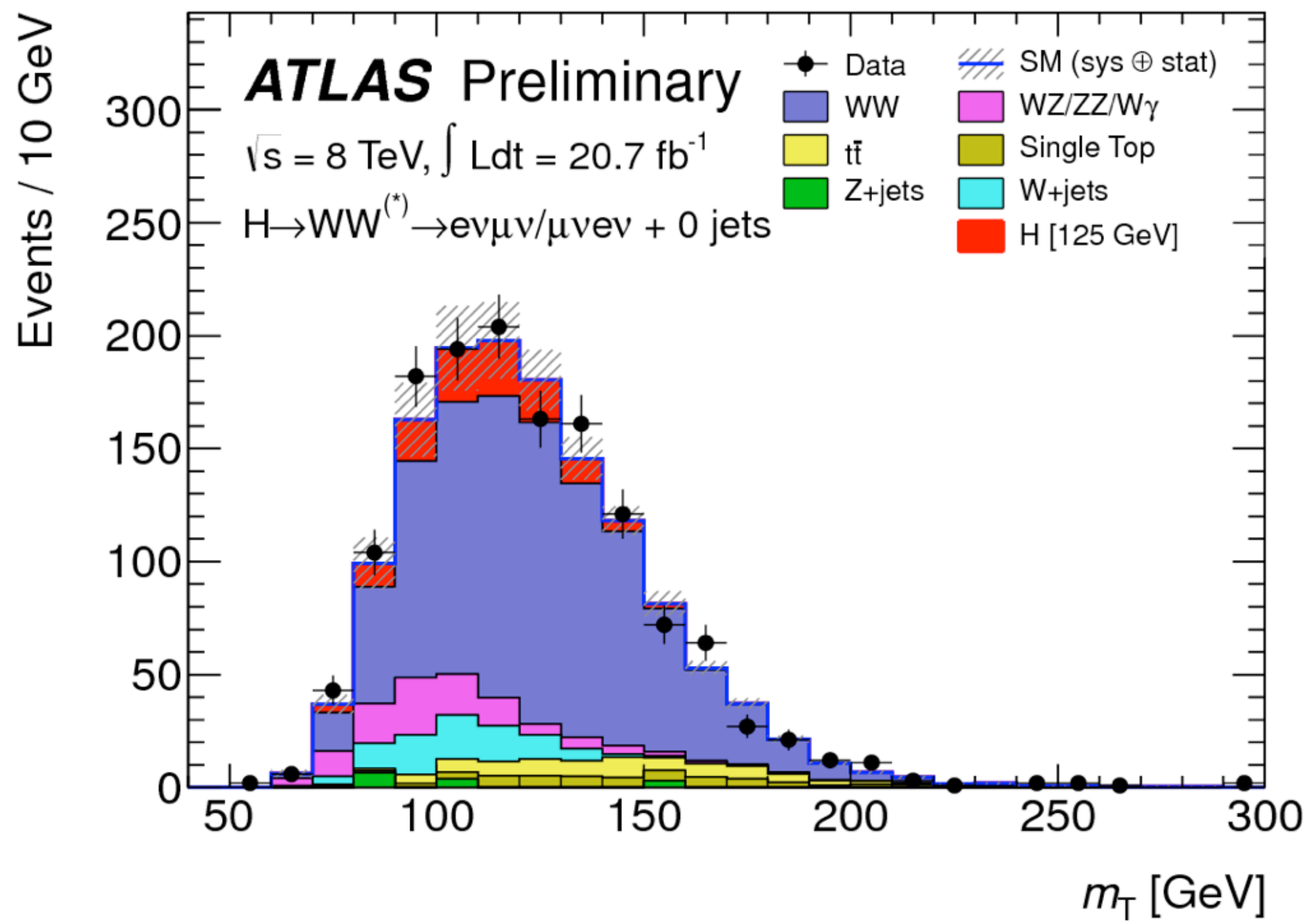
WW suppression approximate mass calculation

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

This obeys the right basic kinematics

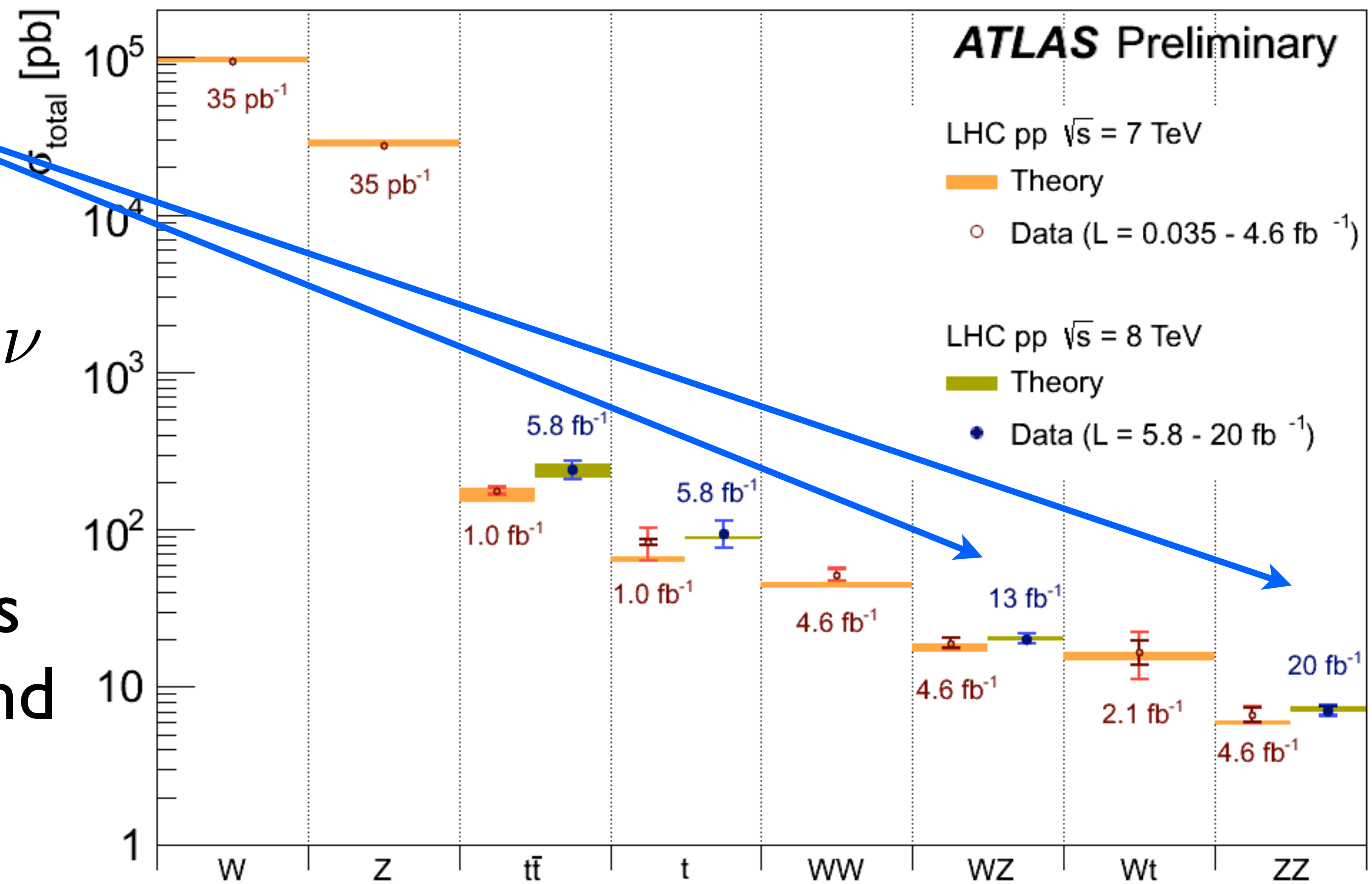
$$m_{\mathrm{T}} < m_H$$

But width of distribution for both signal and background is broad



Review of H to WW Analysis

Diboson Backgrounds



- $q\bar{q} \rightarrow WZ/\gamma^* \rightarrow lll\nu$ with a lost lepton
- $q\bar{q} \rightarrow Z\gamma^* \rightarrow ll\nu\nu$ is also a small background

- These are generally modeled with simulation
- There is special case $W\gamma^*$ where the γ^* is nearly massless that is difficult to predict

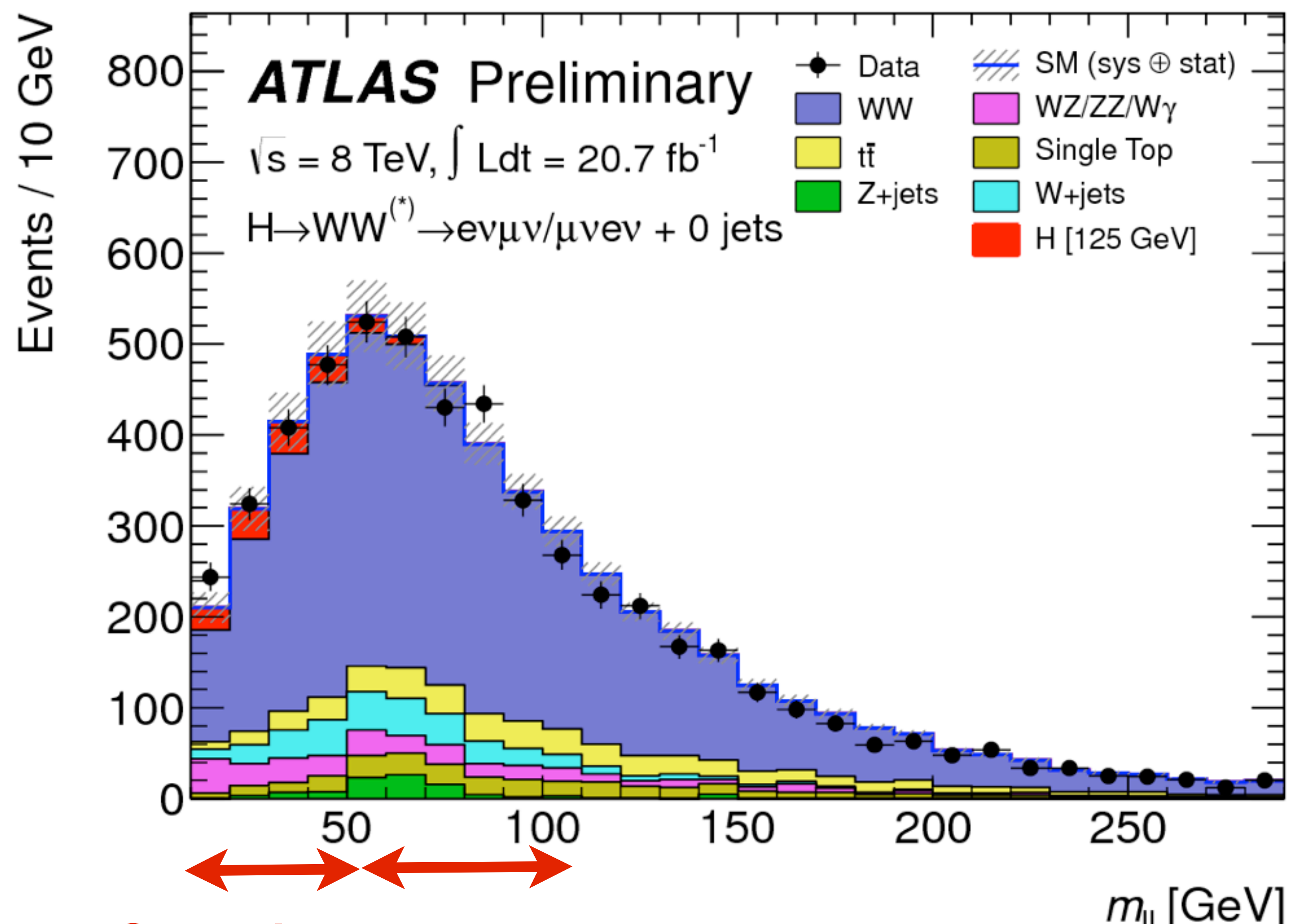
Modeling of the WW background

Focusing on 0-jet

- Jet requirements adds a dependence on the modeling of QCD jet emission

- Signal to background ratio means need to model WW at the 20% * 1/8 = 2.5% level to not be dominated by this uncertainty

- We are claiming 1.6% modeling! → Use control regions



Signal Region

Control Region

Uncertainty on ratio of signal/ control is ~ 1.6%

Modeling of the WW background

Uncertainty on ratio of signal/control is ~ 1.6%

WW cross-section uncertainty ~ 6% using NLO

Example for 10 < m_{ll} < 30 GeV

Source	Uncertainty
Vary factorization and renormalization scales	0.9%
PDFs	1.5%
Underlying Event and Parton Shower Models	0.2%
"Modeling" •Choice of Generator •Different Generators make difference approximations: zero width, massless b-quarks....	1.2%

Modeling of the WW background

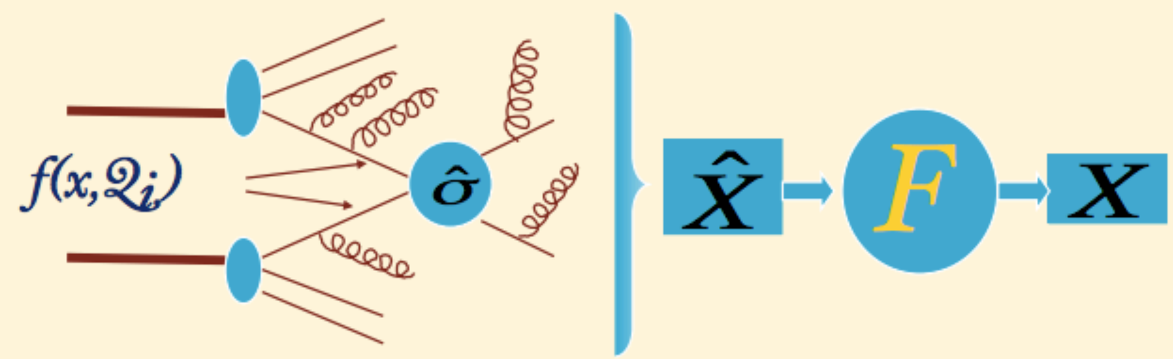
Why vary the factorization and renormalization scales?

- An all orders calculation wouldn't depend on these scales, so any dependence is a rough estimate of the uncalculated terms

From Michelangelo Mangano's slides →

Factorization Theorem

$$\frac{d\sigma}{dX} = \sum_{j,k} \int_{\hat{X}} f_j(x_1,Q_i)\, f_k(x_2,Q_i)\, \frac{d\hat{\sigma}_{jk}(Q_i,Q_f)}{d\hat{X}}\, F(\hat{X} \to X; Q_i, Q_f)$$



$f_j(x,Q)$ Parton distribution functions (PDF)

- sum over all initial state histories leading, at the scale Q, to:

$$\vec{p}_j = x\,\vec{P}_{proton}$$

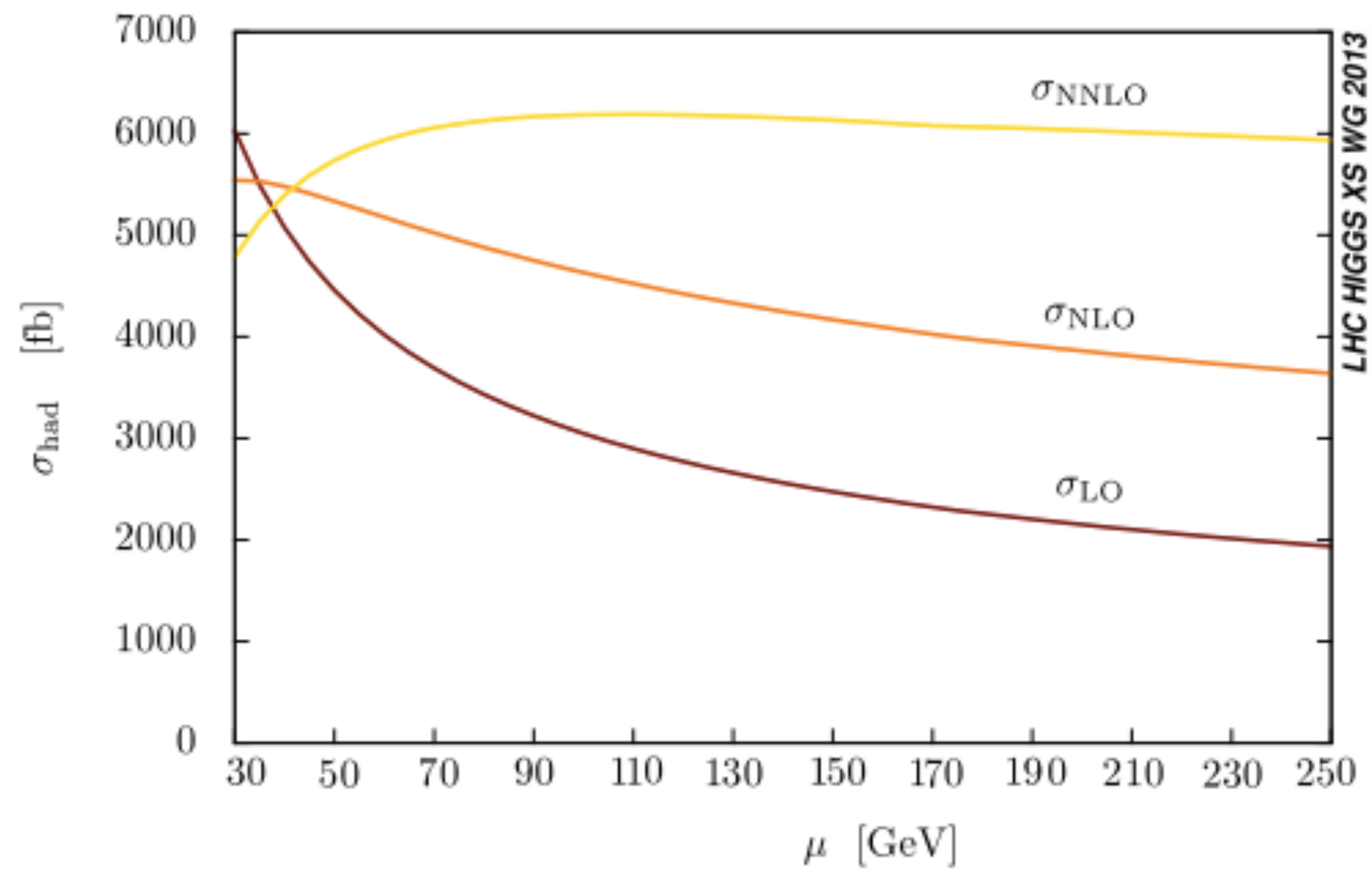
$F(\hat{X} \to X; Q_i, Q_f)$

- transition from partonic final state to the hadronic observable (hadronization, fragm. function, jet definition, etc)
- Sum over all histories with X in them

11

Example: ggH signal

- This is actually the single largest systematic uncertainty on $\mu \equiv \sigma_{observed} / \sigma_{SM}$
- I.e the denominator from theory is bigger than all the experimental errors, but not yet the statistical uncertainty
- We determine the uncertainty from renormalization and scale variation



Modeling the ggH Signal Acceptance

Next two slides from Stewart-Tackmann,(arXiv:1107.2117 [hep-ph])

- $gg \to H$ is full of gluons ➔ lots of strong interactions
- Jet cuts make it significantly harder to calculate acceptance.
- Adding a jet cut adds a new scale into the problem

Inclusive cross-section

$$\sigma_{\mathrm{total}} \simeq \sigma_B \left[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right]$$

Cross-section requiring a jet $p_T > 30$ GeV

$$\sigma_0(p_T^{\mathrm{cut}}) = \sigma_B \Big(1 - \frac{3\alpha_s}{\pi} 2 \ln^2 \frac{p_T^{\mathrm{cut}}}{m_H} + \cdots\Big)$$

1-jet cross-section looks schematically like this

$$\sigma_{\geq 1}(p^{\mathrm{cut}}) \simeq \sigma_B \big[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\big]$$

where $L^2 = \ln^2(p^{\mathrm{cut}}/Q)$

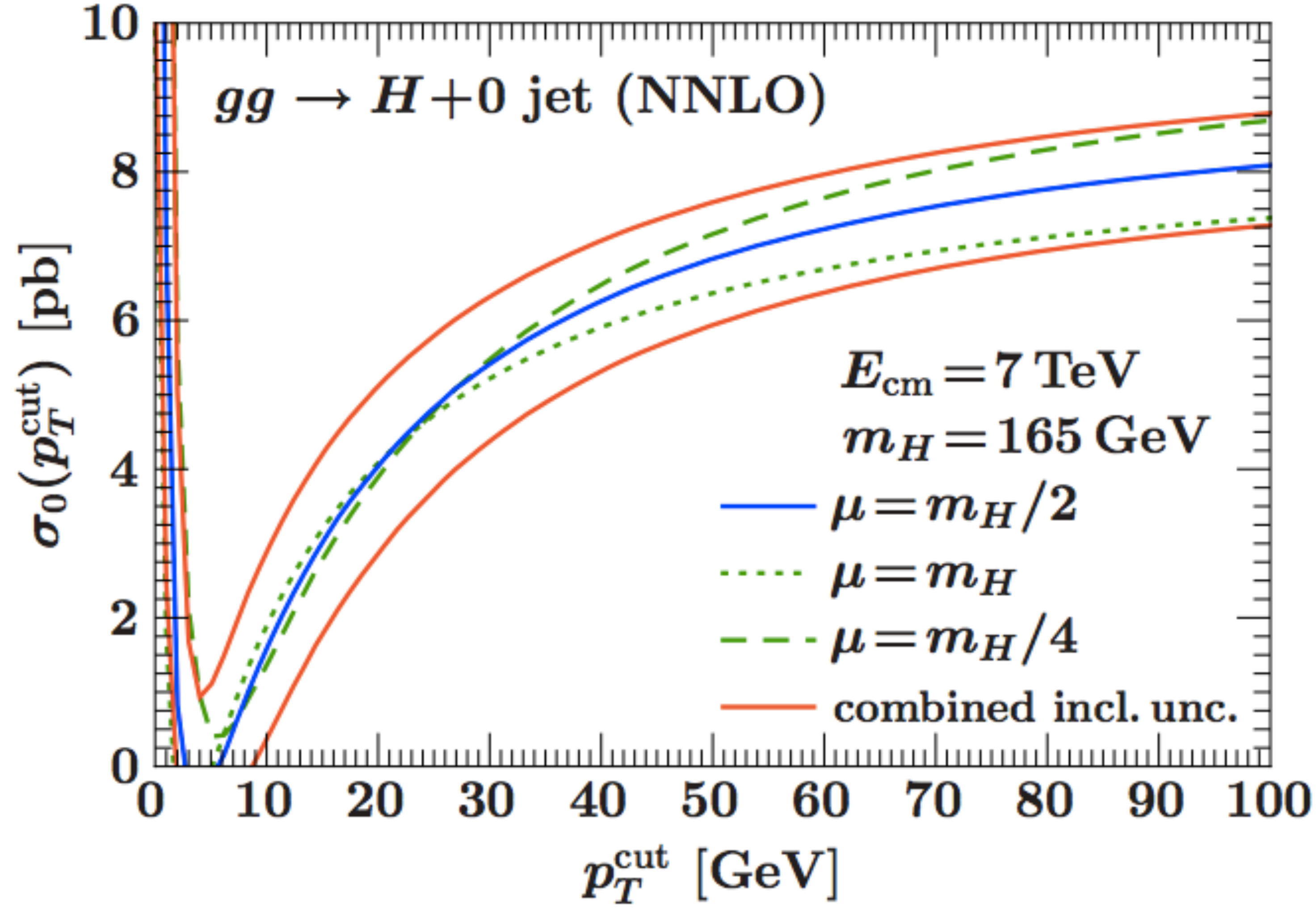
Modeling the ggH Signal Acceptance

Then 0-jet looks like this:

$$\sigma_0(p^{\rm cut}) \simeq \sigma_B \Big\{ \big[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\big] - \big[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\big] \Big\}$$

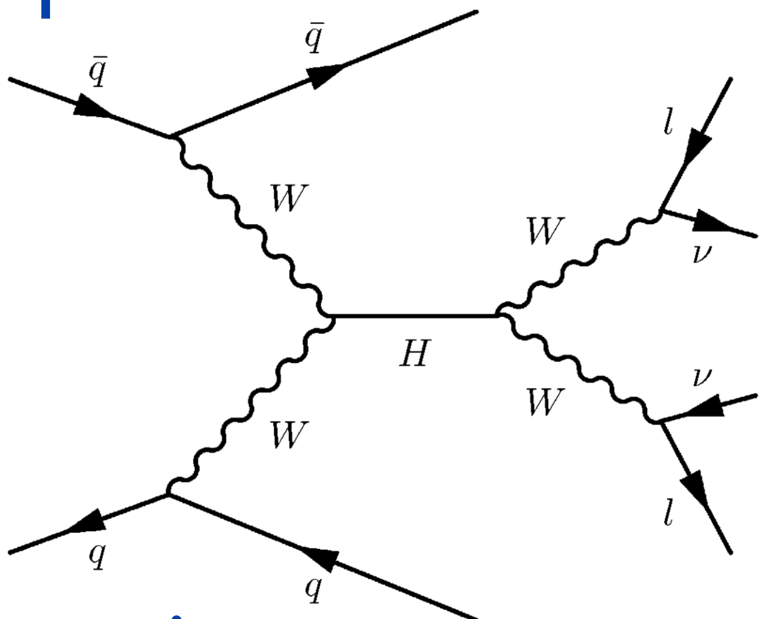
Cancelation between terms with L and without at roughly the experimental cut

Suggested procedure to fix this gives large uncertainty introduced due to jet cuts

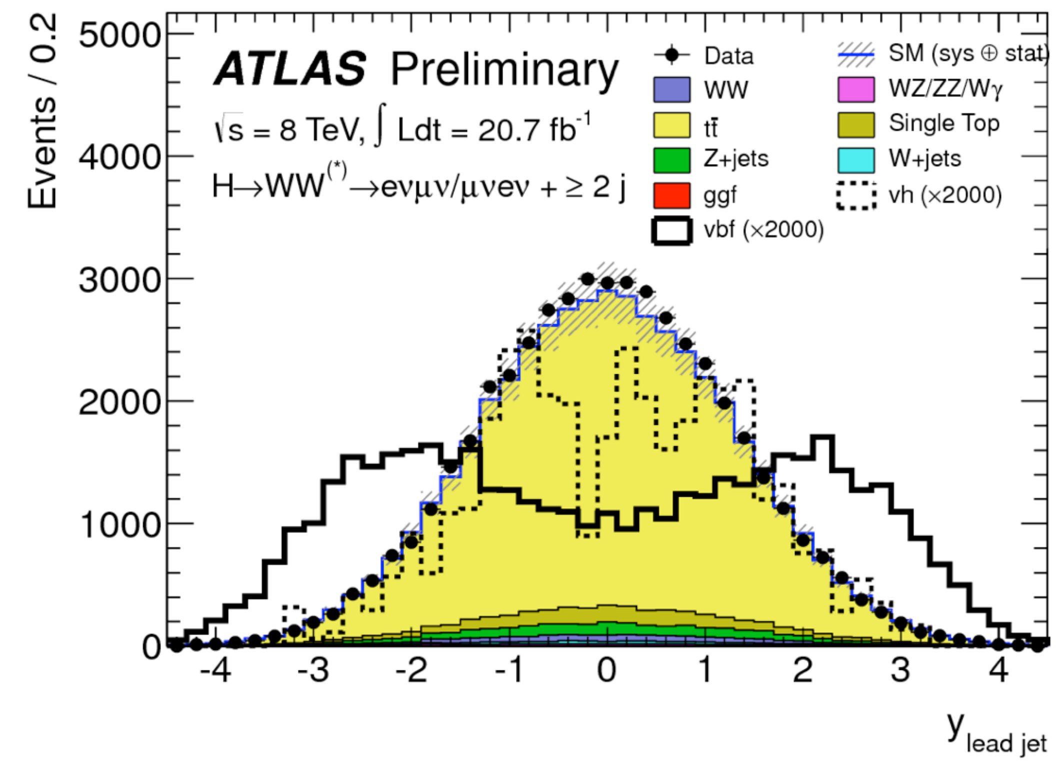


VBF analysis in a slide

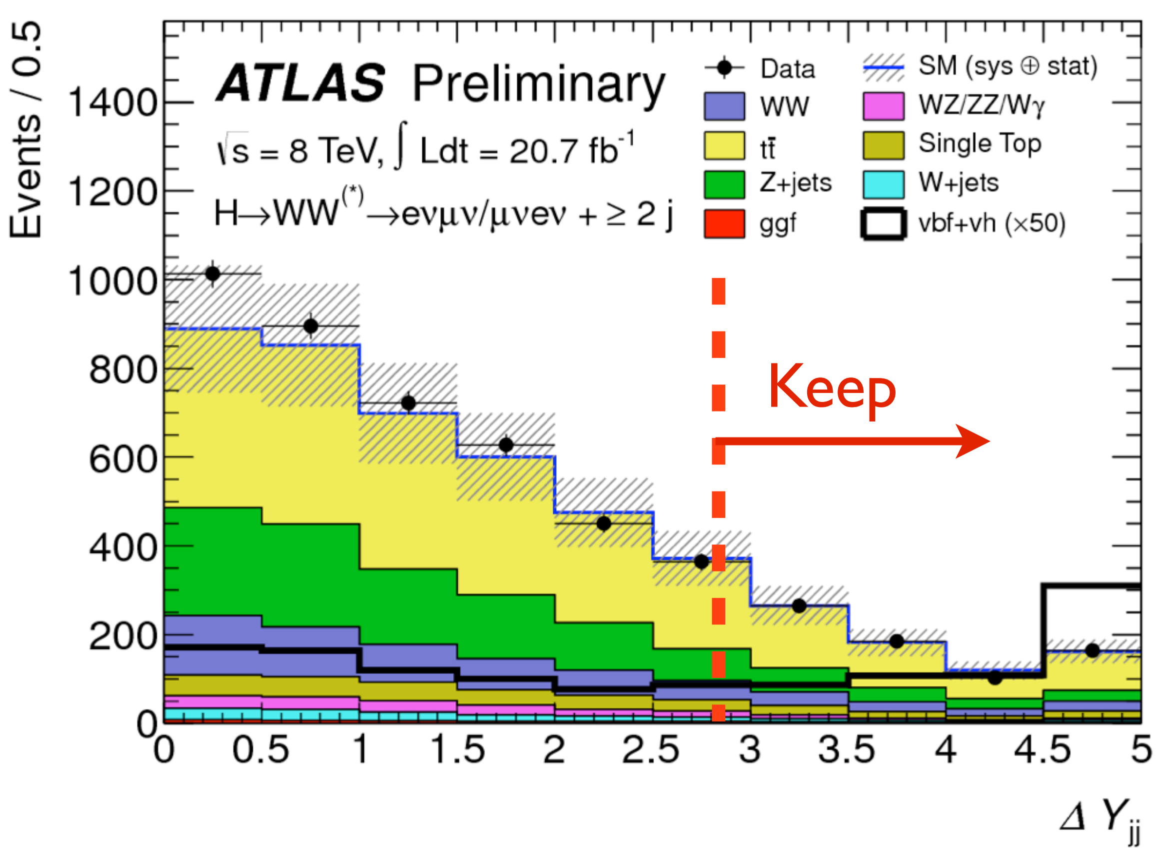
The process

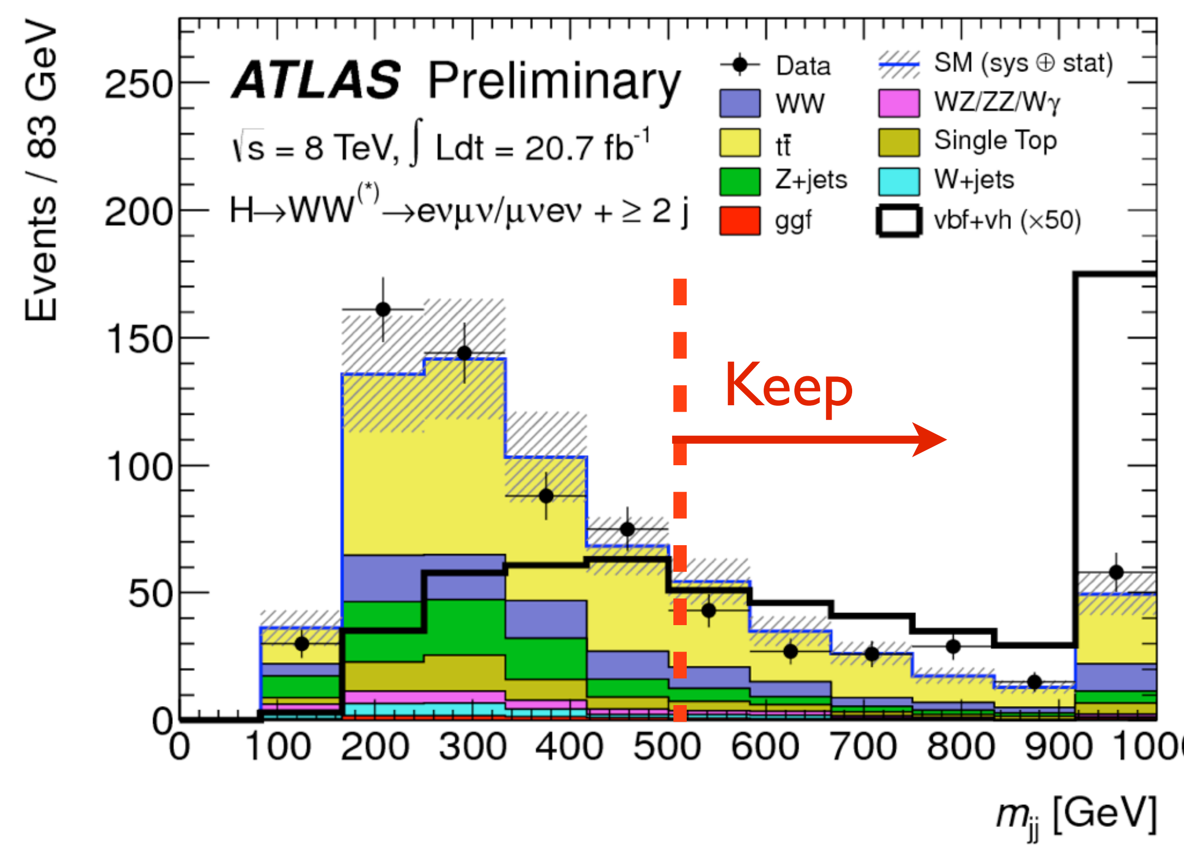


Veto jets between the tagging jets in Y



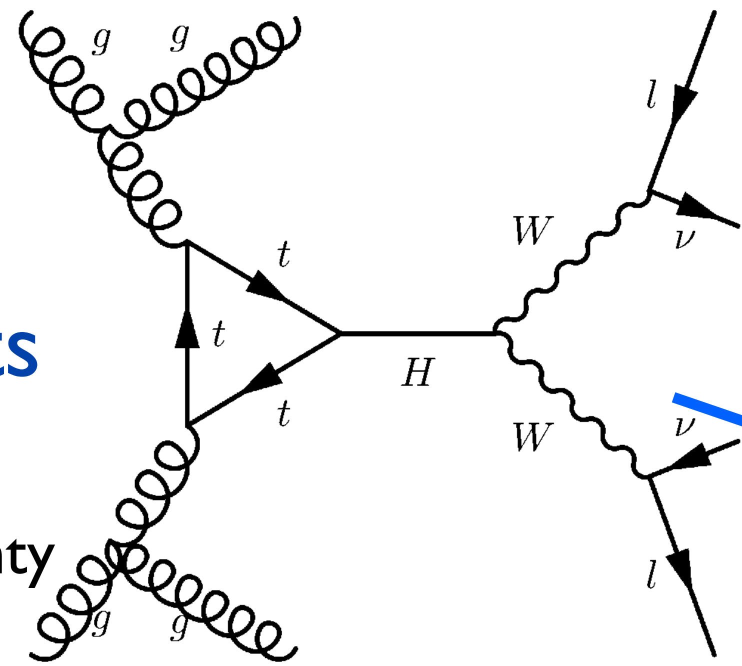
Properties



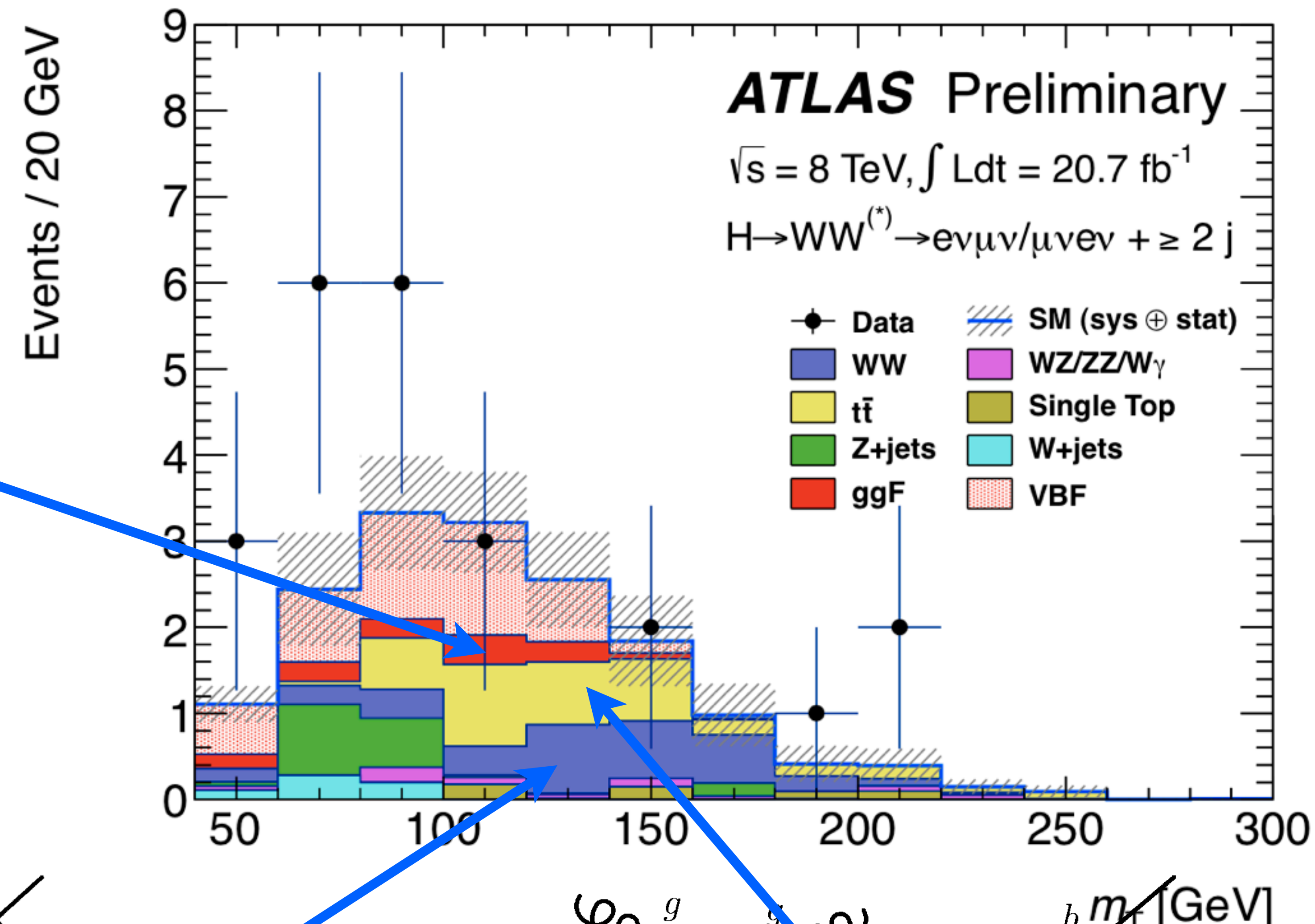


Modeling the VBF Backgrounds

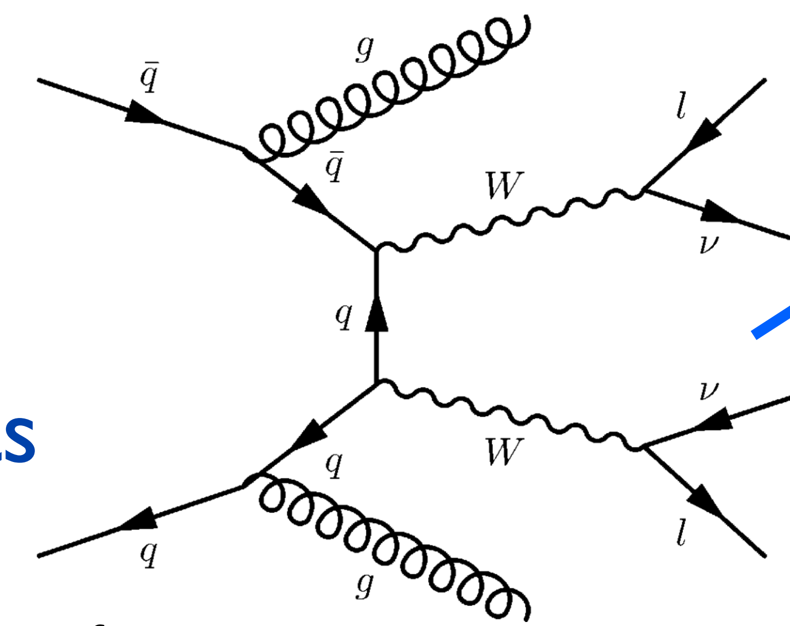
ggF+2 jets



43% uncertainty from QCD scale and PDFs

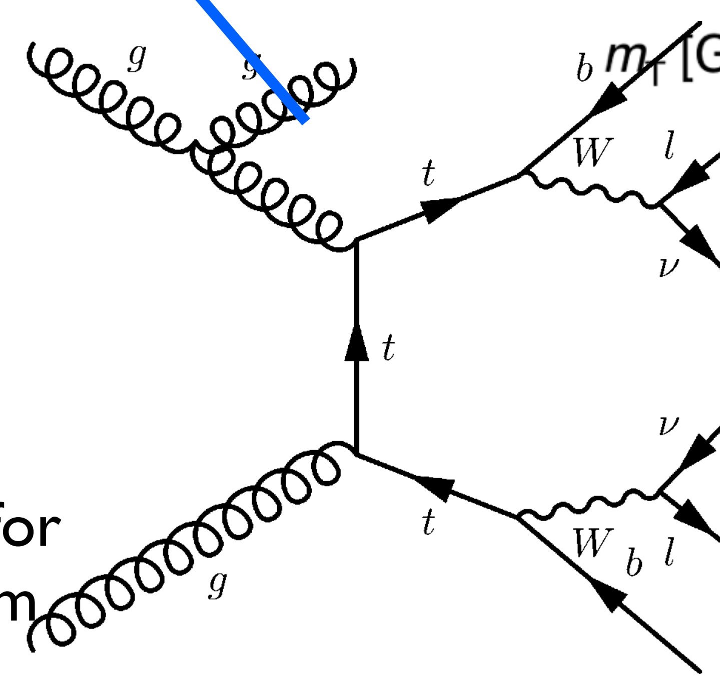


WW+2jets



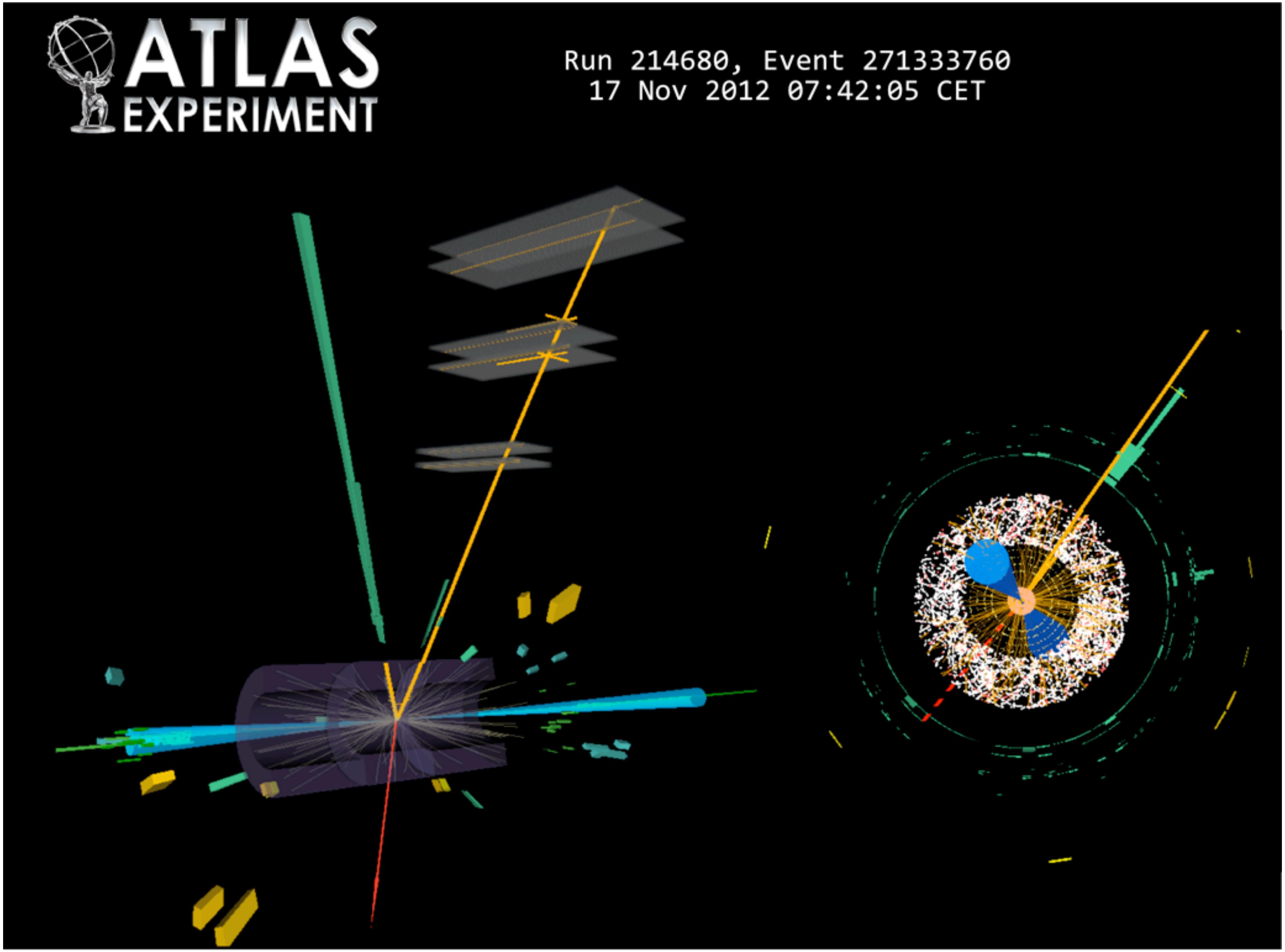
42% uncertainty from QCD scale and PDFs

ttbar +2jets



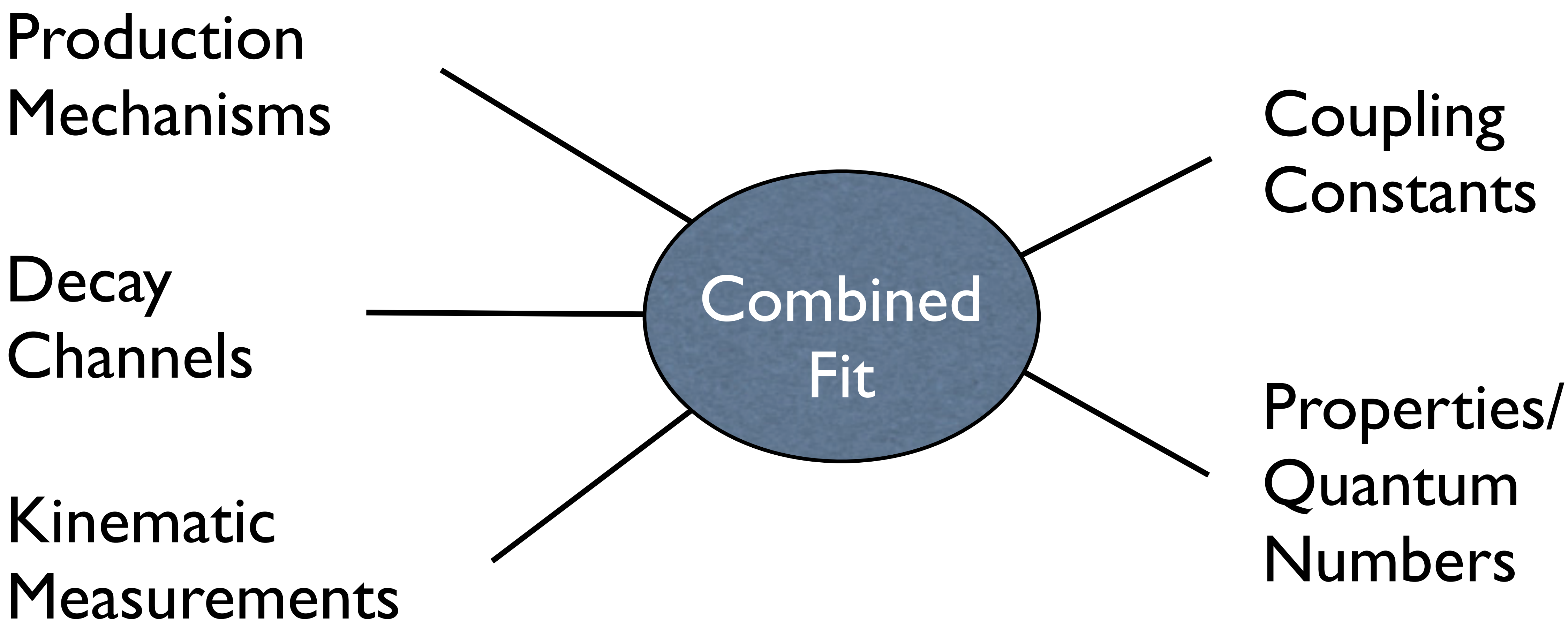
15% uncertainty for extrapolation from control region

$H \rightarrow WW$ VBF event

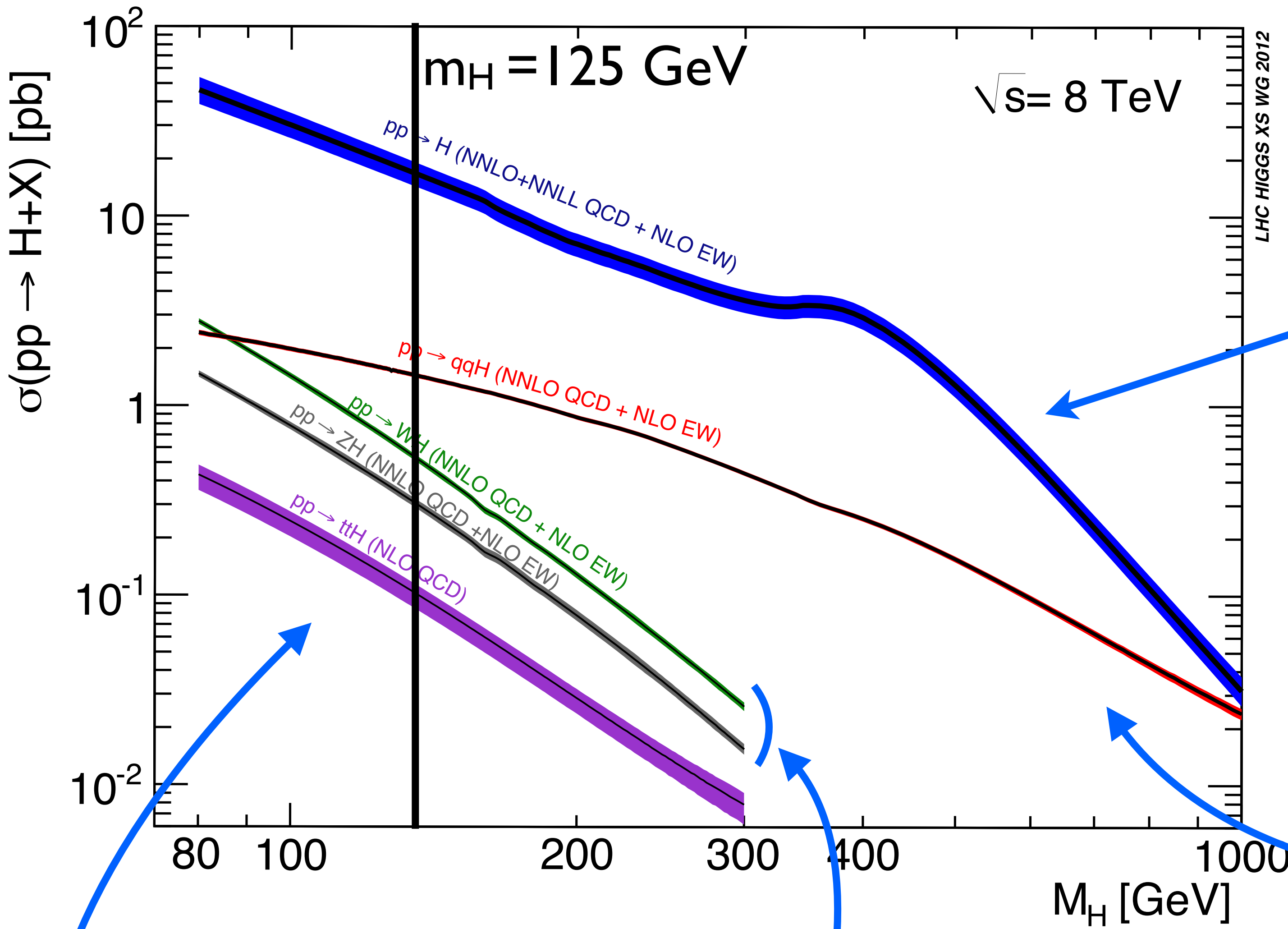


A “Higgs” Boson has been Observed

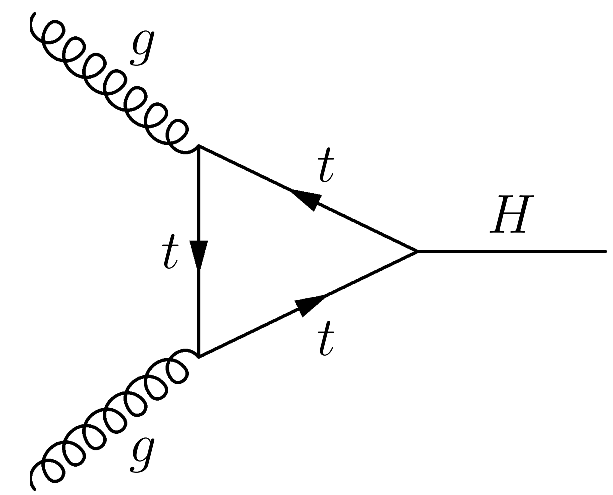
Higgs: Understanding what have we found



Higgs Production Summary

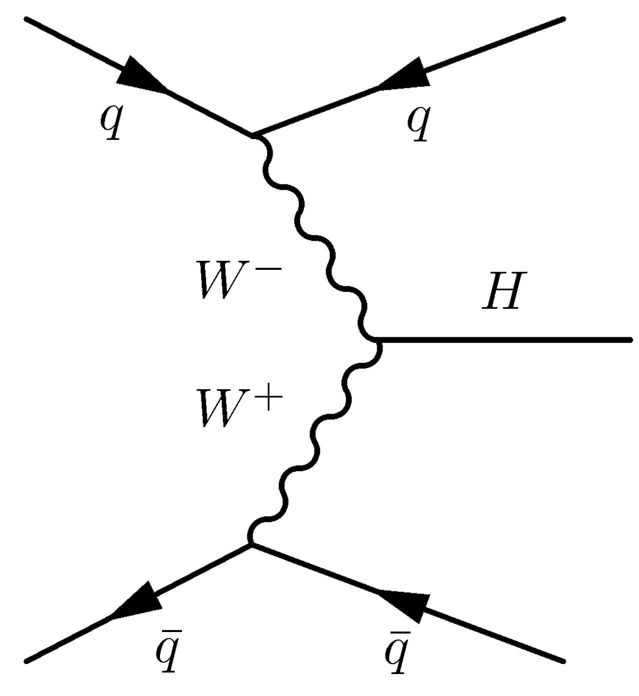


ggF



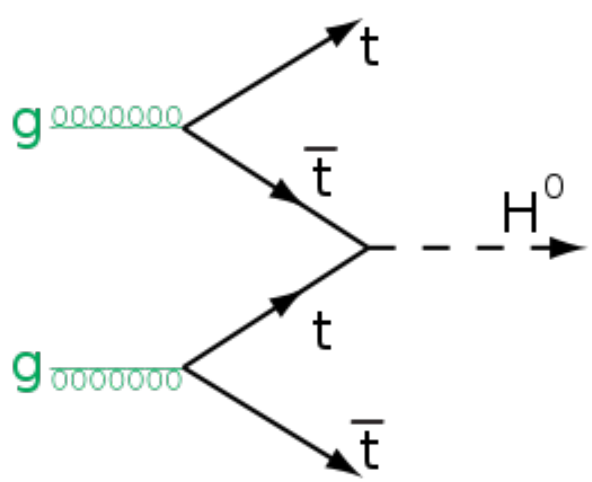
Large QCD Uncertainties
Sensitive to new physics in the loop

VBF (vector boson fusion)



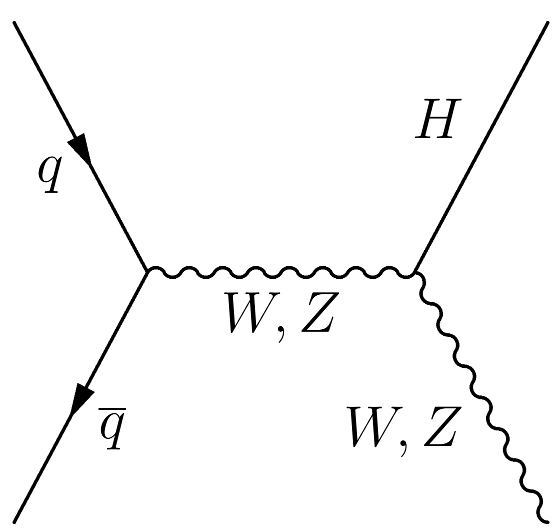
Small QCD Uncertainties
Distinctive forward jet tags

ttH



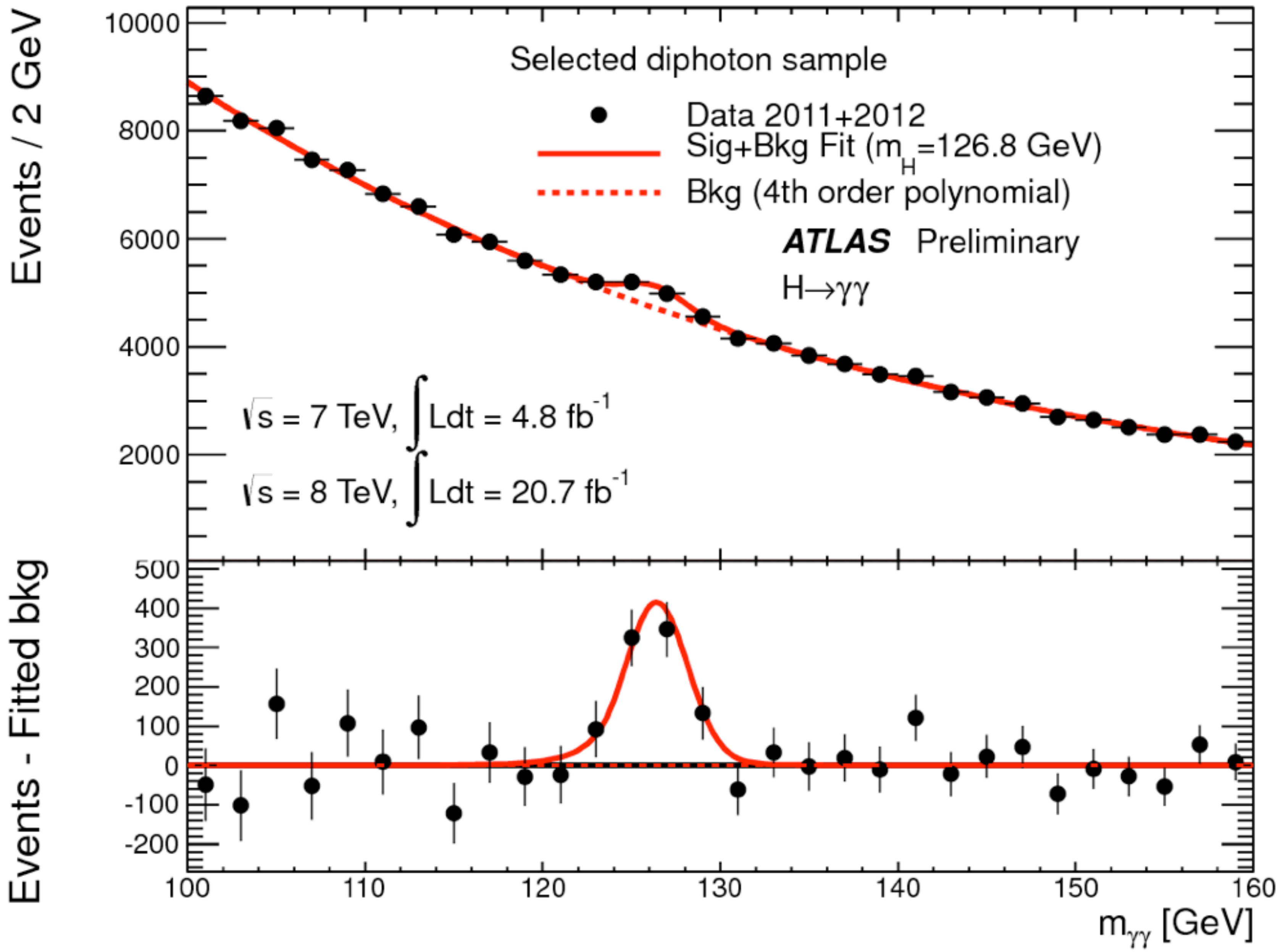
Access to top coupling

VH



Usually tagged w/ W/Z decay to leptons (inc. neutrinos)

$H \to \gamma\gamma$ Signal

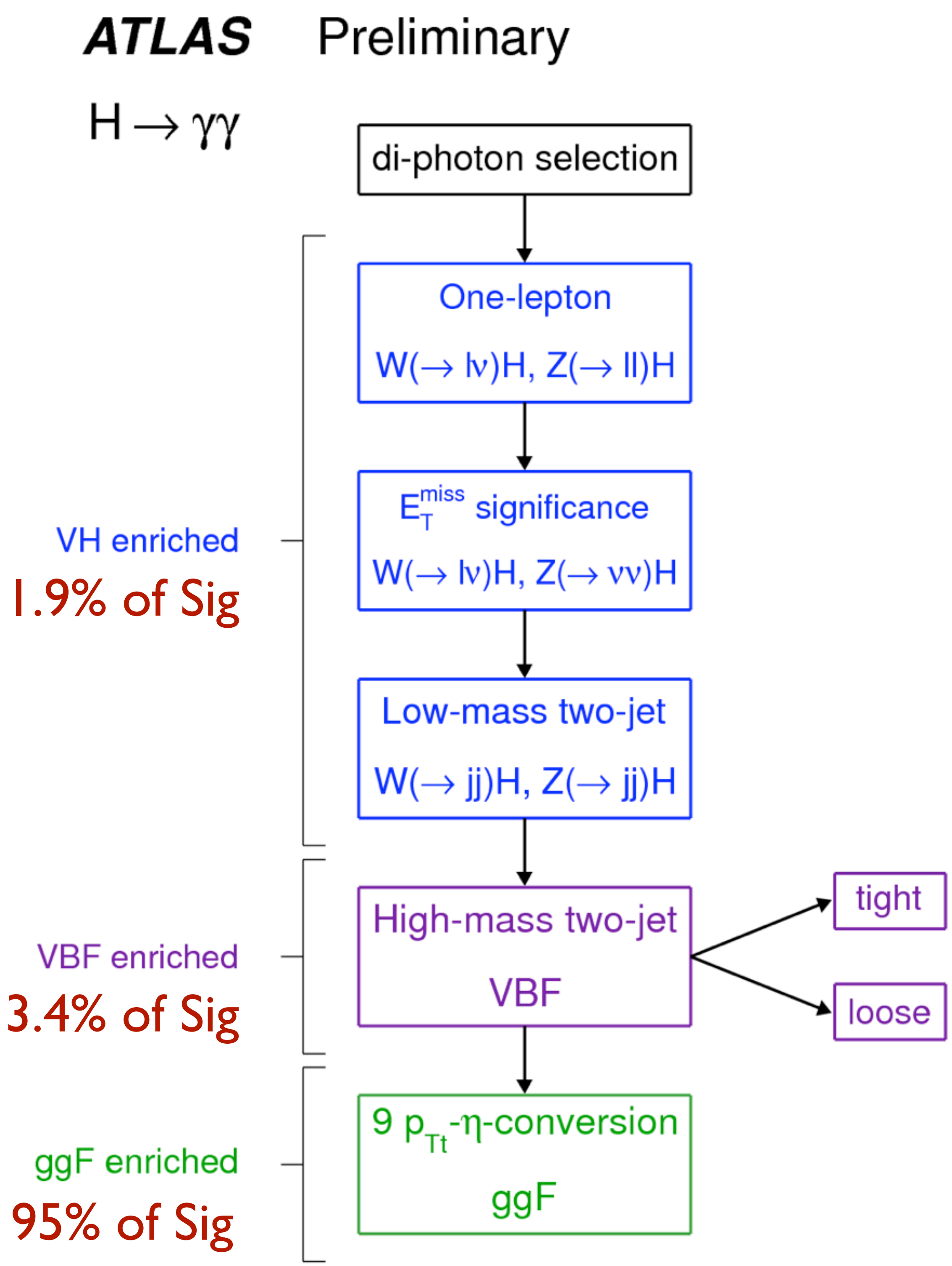


Inclusive: All production modes with $\gamma\gamma$ final state

Signal strength relative to SM: $1.65 \pm 0.24(\mathrm{stat})^{+0.25}_{-0.18}(\mathrm{syst})$

ATLAS-CONF-2013-012

$H \to \gamma\gamma$ by Production Channel



Diphoton sample divided into exclusive subsets for different production mechanisms

- 80-90% leptonic WH and ZH remainder ttH
- 50% hadronic WH and ZH remainder ggF
- 54(76)%VBF for loose(tight) remainder ggF
- 75-95% ggF depending on category

Most categories not very pure in one production mode

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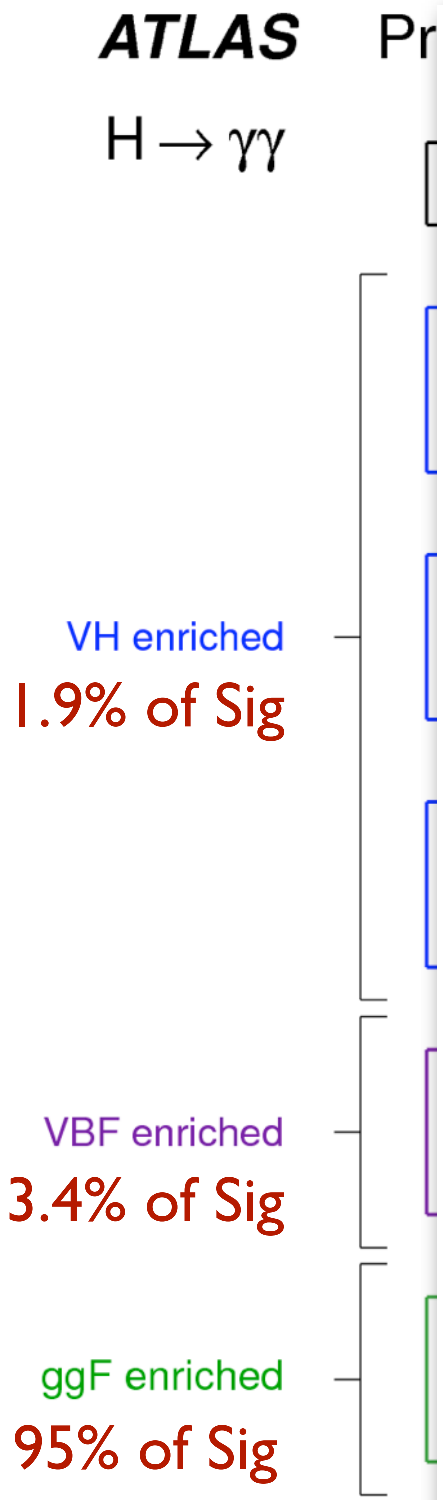
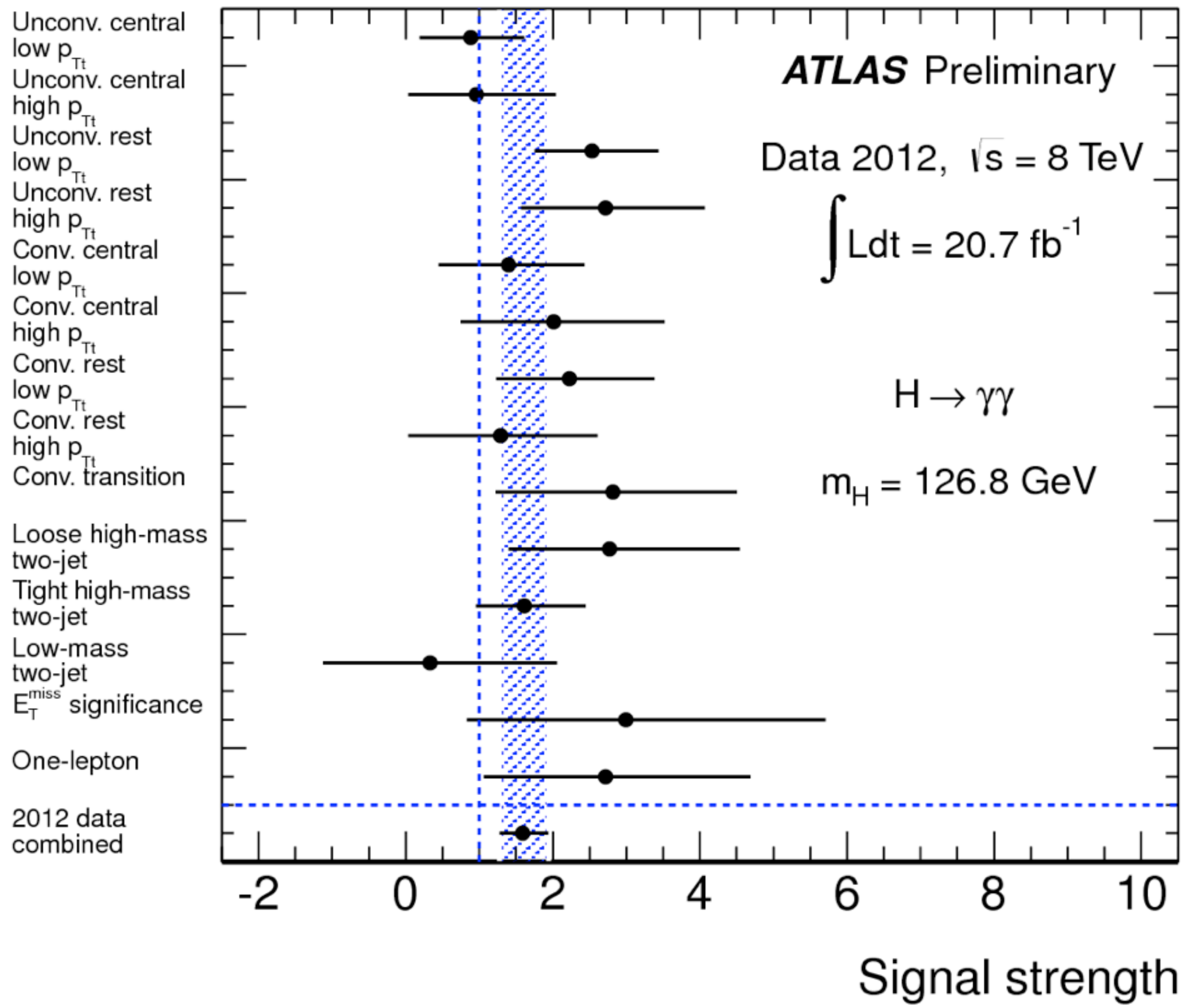
$H \rightarrow \gamma\gamma$ by Production Channel



Result is yield in each category



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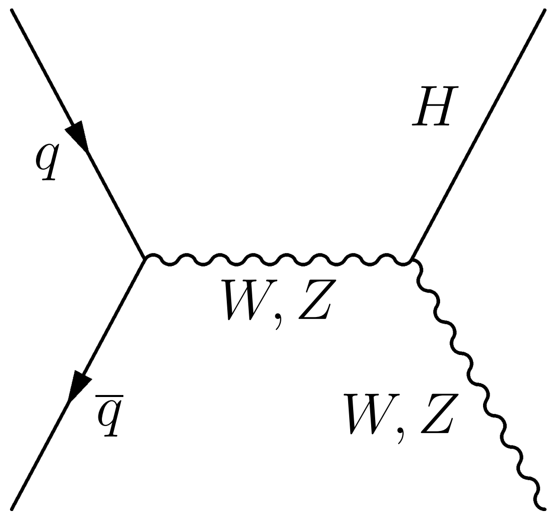
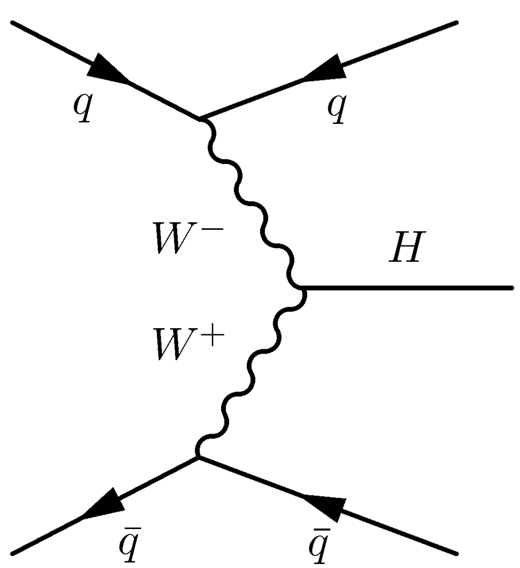
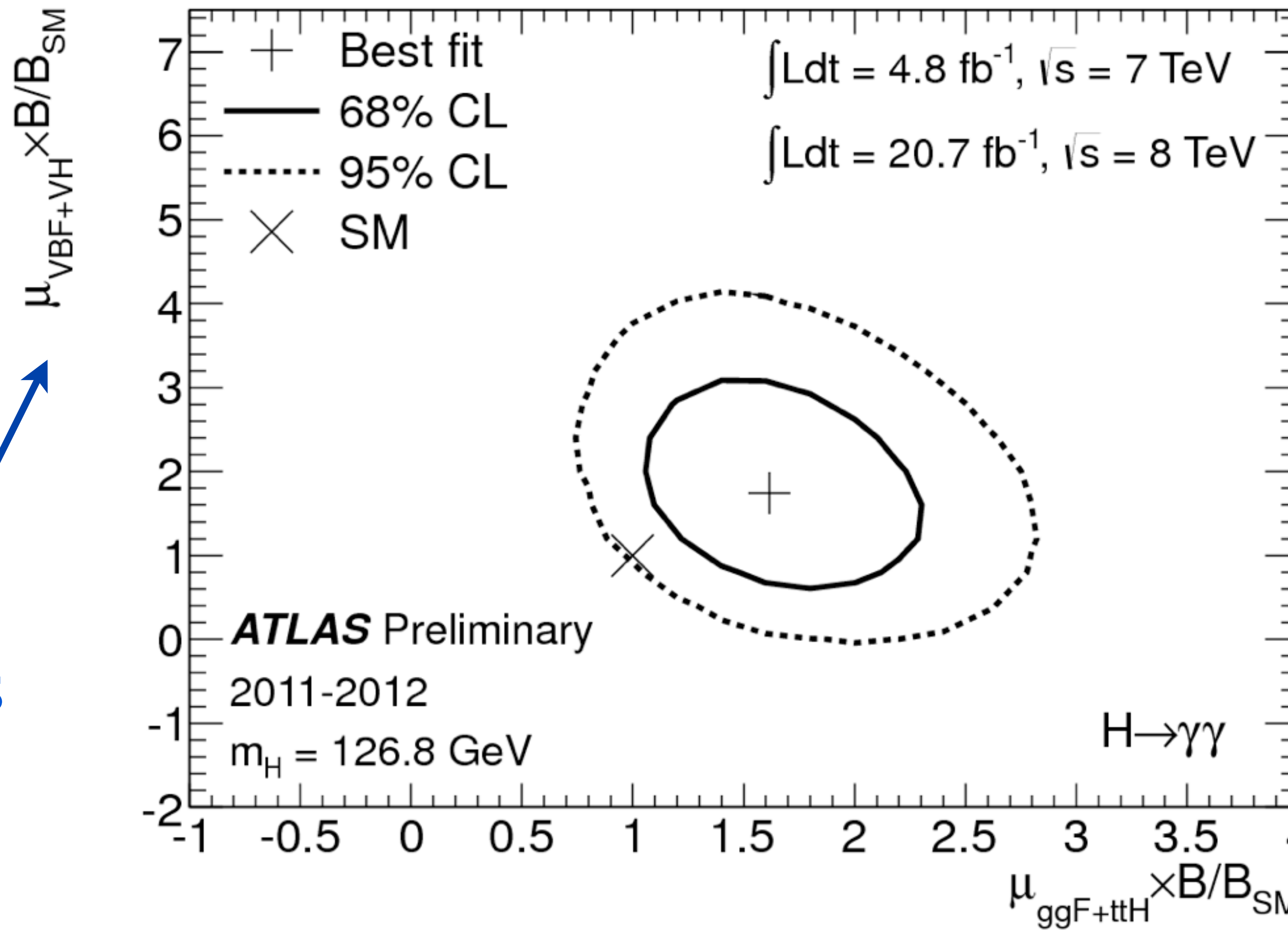
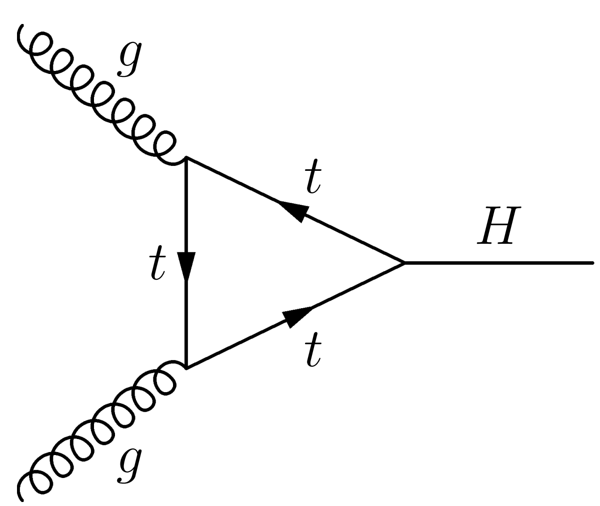
$H \to \gamma\gamma$ by Production Channel

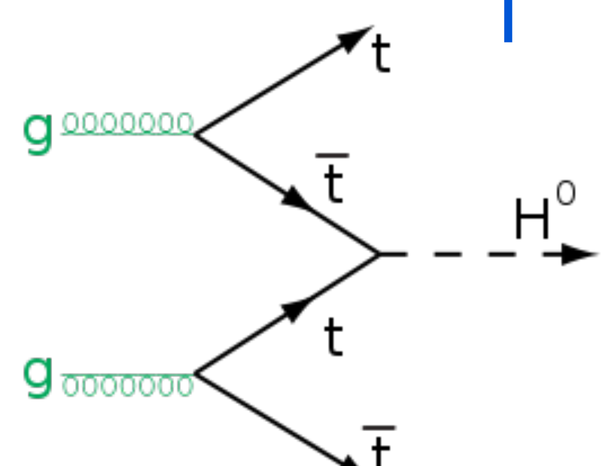




Involved the WWH and ZZH couplings in SM







Involved the ttH coupling in SM

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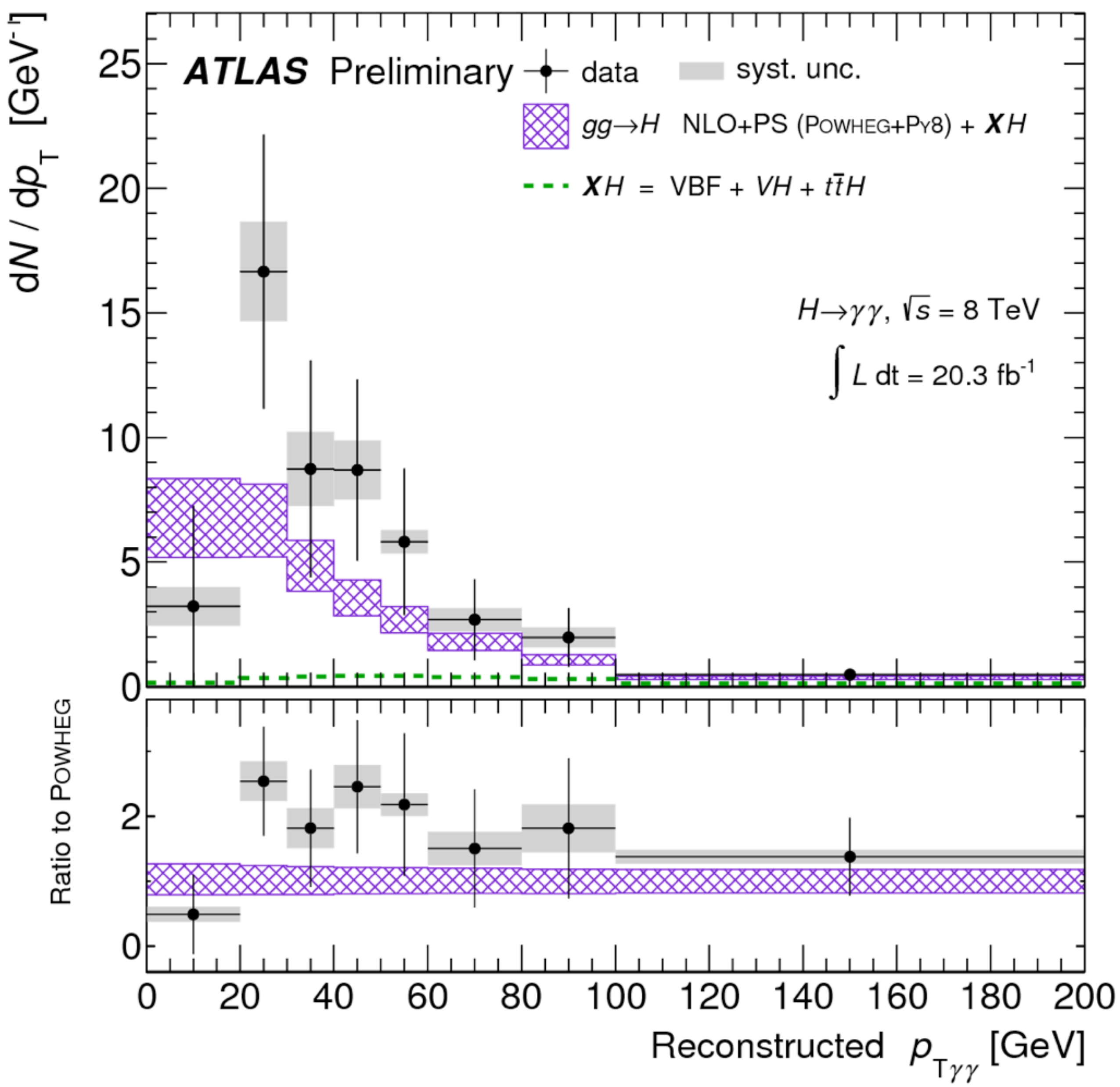
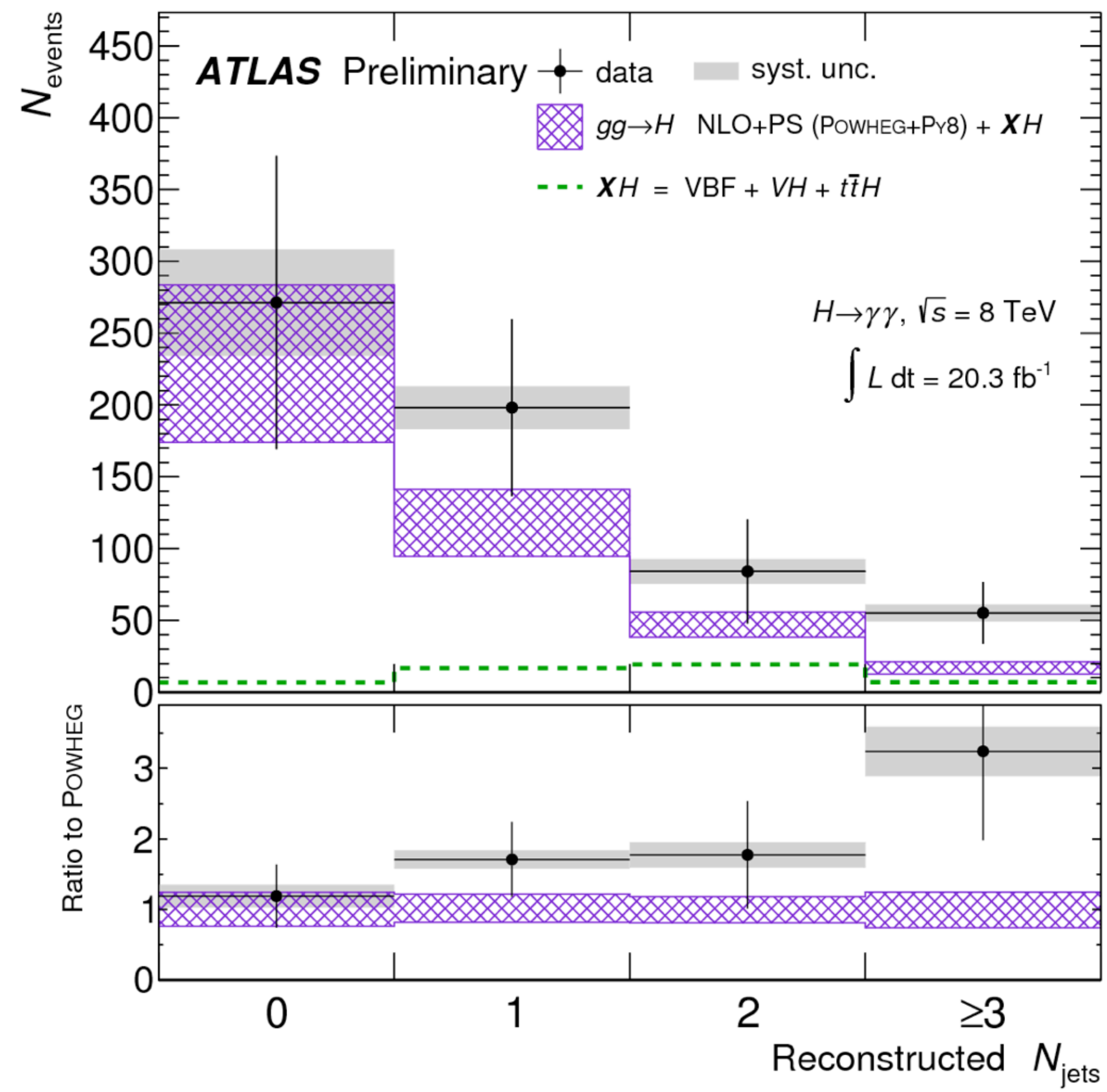
$H \to \gamma\gamma$ differential cross-sections

ATLAS now has preliminary differential distributions





P_T Higgs: p-value=0.39

N_{jets} : p-value=?

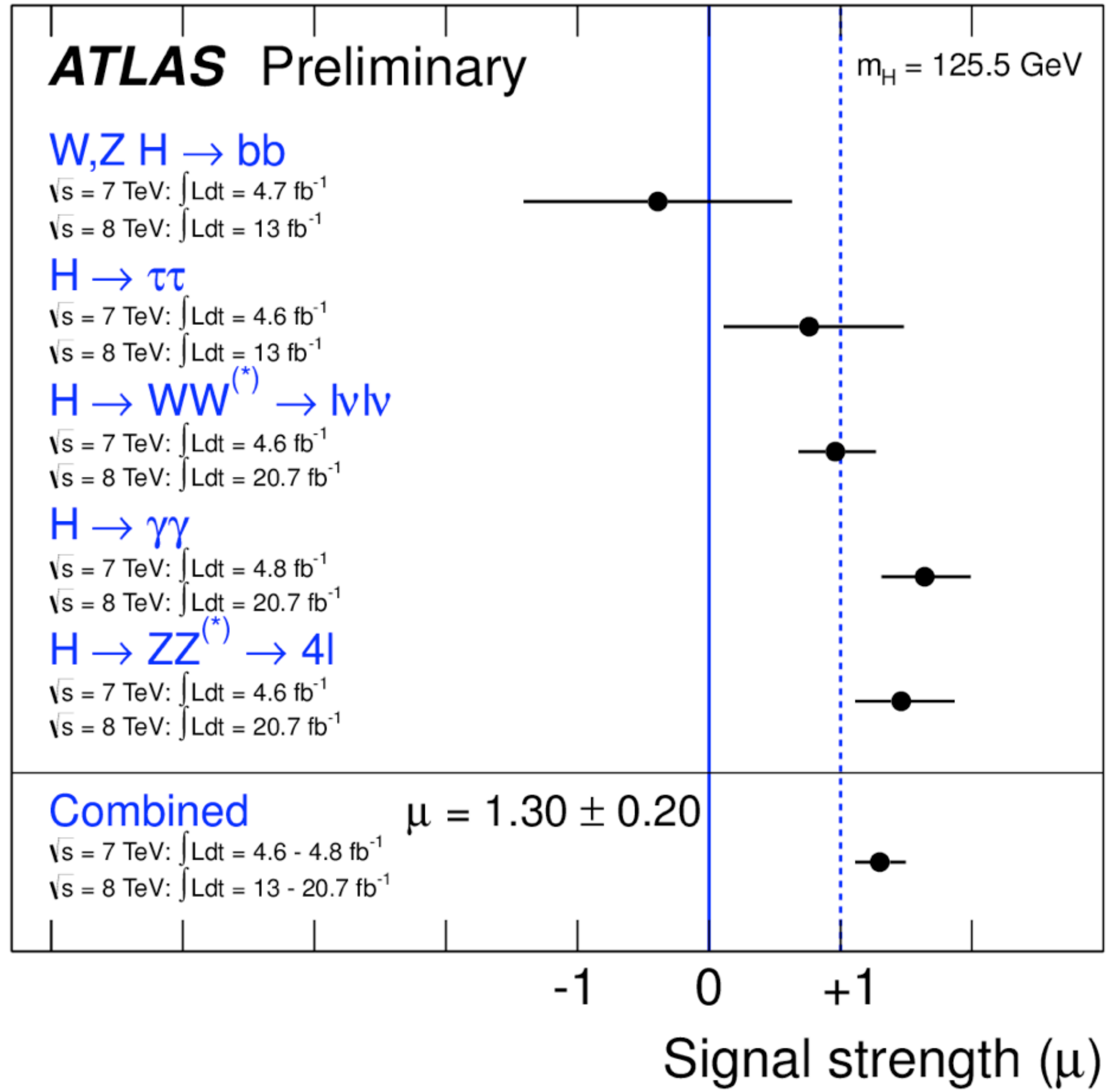
Grand Combination

We combine all the inputs just discussed into global likelihood fit

Includes correlations of systematics!

Summary of Production Modes

	ggF	VBF	VH	ttH
$\gamma\gamma$	✓	✓	✓	✓
WW	✓	✓		
ZZ	✓	✓	✓	
$\tau\tau$	✓	✓	✓	
$b\bar{b}$			✓	✓



Inclusion of uncertainties

Each analysis has a table like this....only more complicated

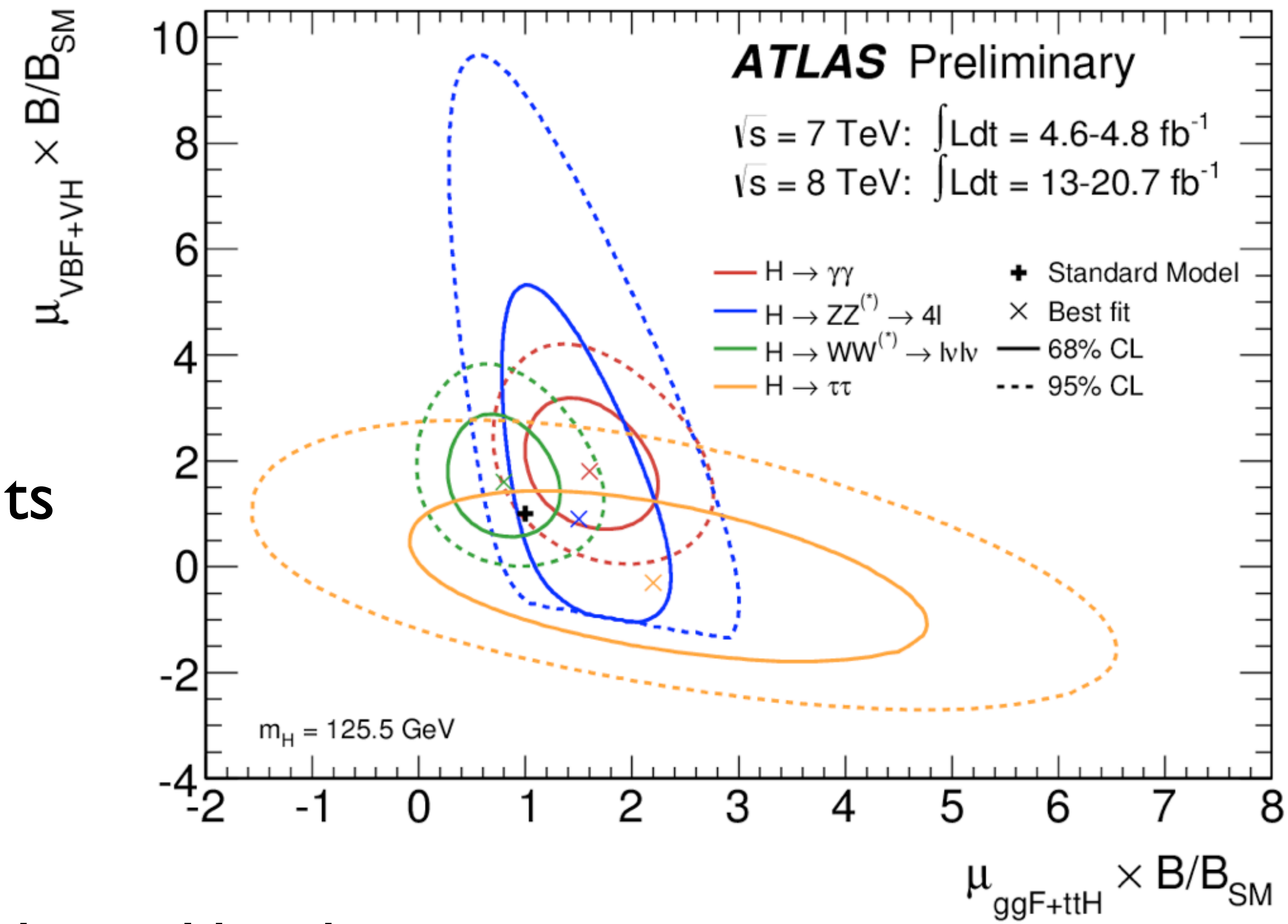
- In order to correctly fit all the data you need to include these correlations

Table 13: Leading uncertainties on the signal strength μ for the combined 7 and 8 TeV analysis.

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

Evidence of VBF production

3.1σ evidence of VBF production



Important because if you've only seen ggF then all measurements are proportional to

$$\frac{\sigma_{gg}}{\Gamma_{total}}$$

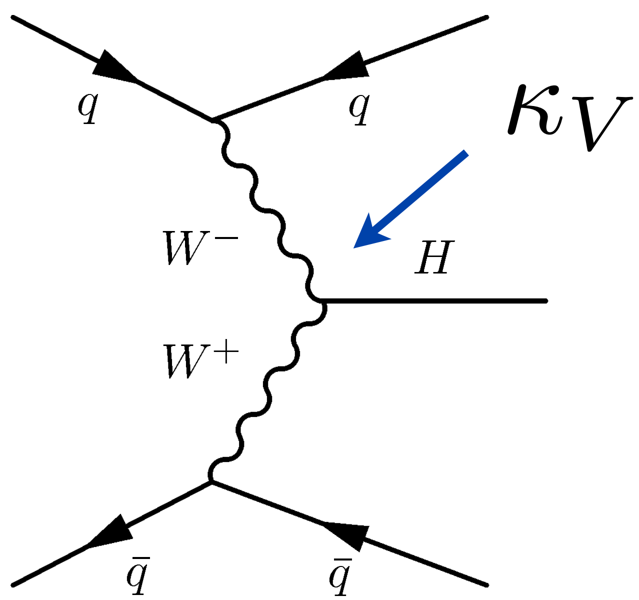
Recall we measure things like this

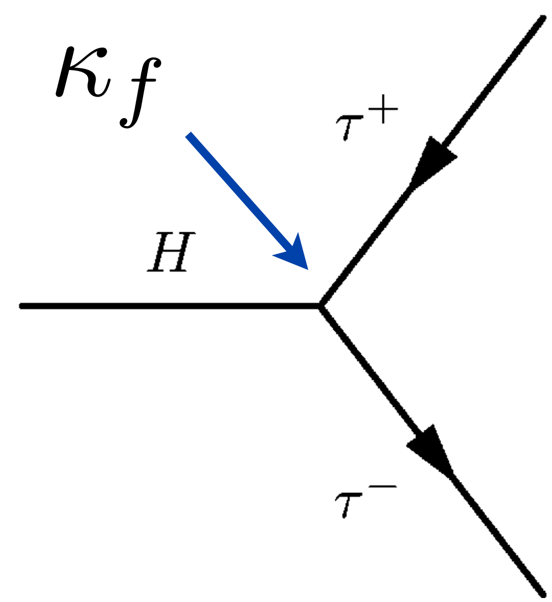
$$\sigma_{gg} \times \mathcal{B}_{\gamma\gamma} = \sigma_{gg} \times \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\text{total}}}$$

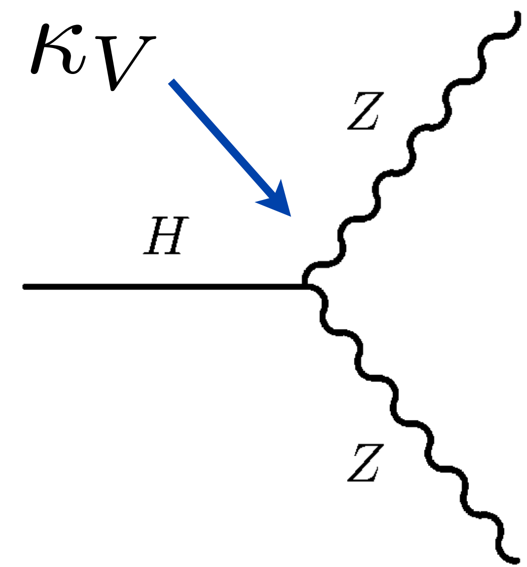
Coupling Interpretation

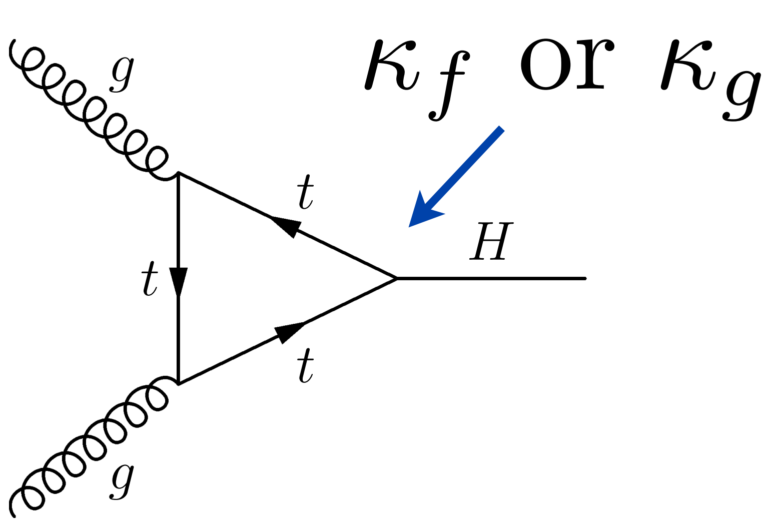
Several different models depending on assumptions:

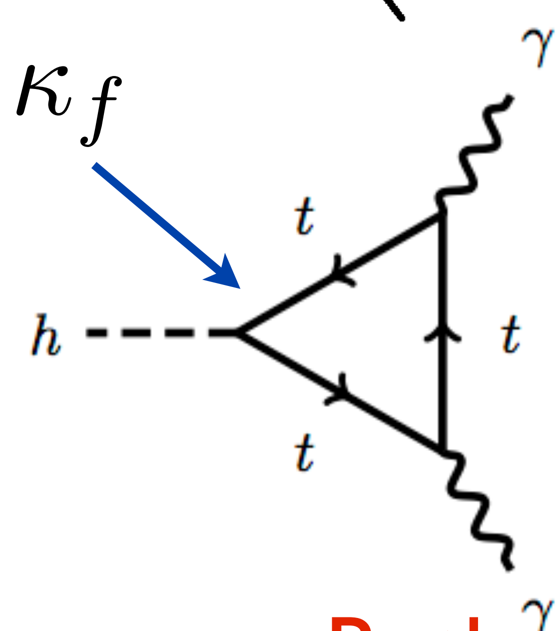
- New particles in loops?
- BSM contributions to total width (invisible decays, other decays to BSM)?

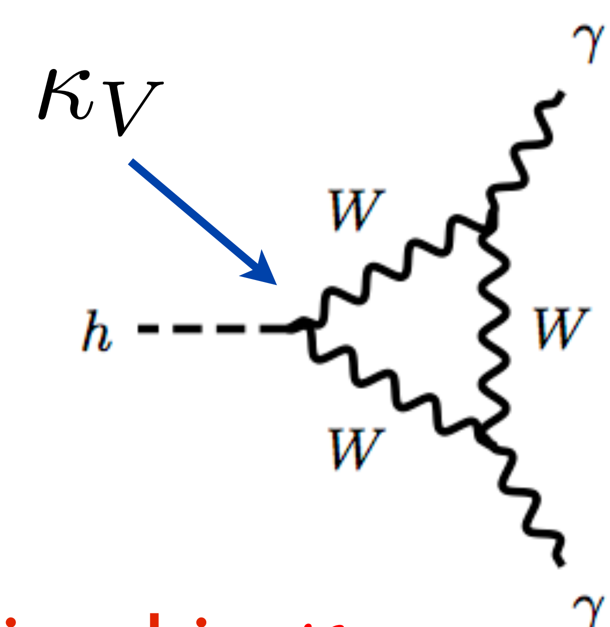












Both combined in κ_γ

Relationship between measurements and coupling

An individual measurement looks like this

$$\sigma_{gg} \times \mathcal{B}_{\gamma\gamma} = \sigma_{gg} \times \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\rm total}}$$

We include this in our fitting

$$\frac{\sigma_{gg} \times \mathcal{B}_{\gamma\gamma}}{\sigma_{gg,\rm SM} \times \mathcal{B}_{\gamma\gamma,\rm SM}} = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

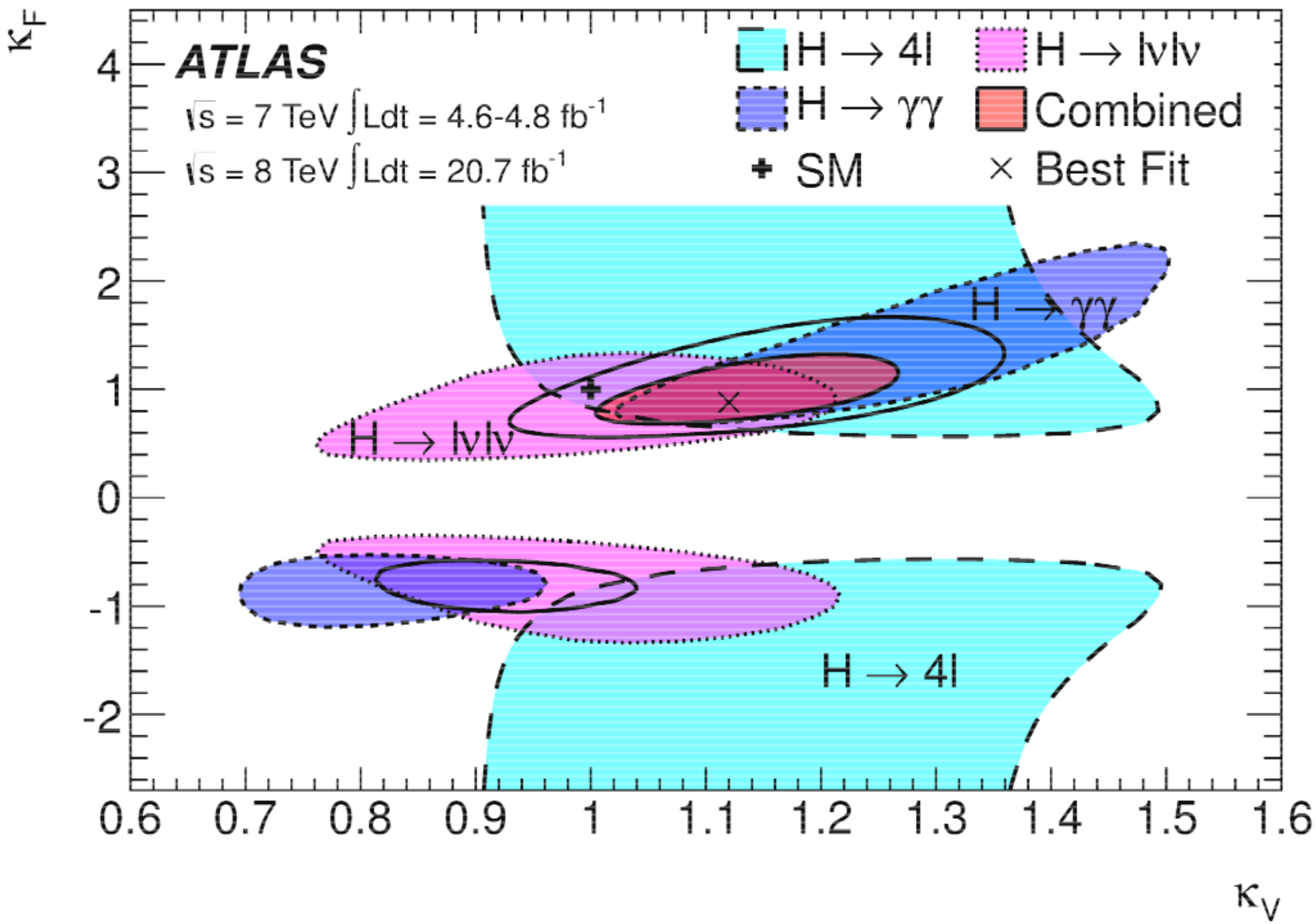
where we define

$$\Gamma_{\rm total} \propto \kappa_H^2$$

Example Fit: change couplings to SM

Many combinations of assumptions you can make

Assume only SM particles, but give fermions one scale factor and bosons another



Example Fit 2: add BSM in loops

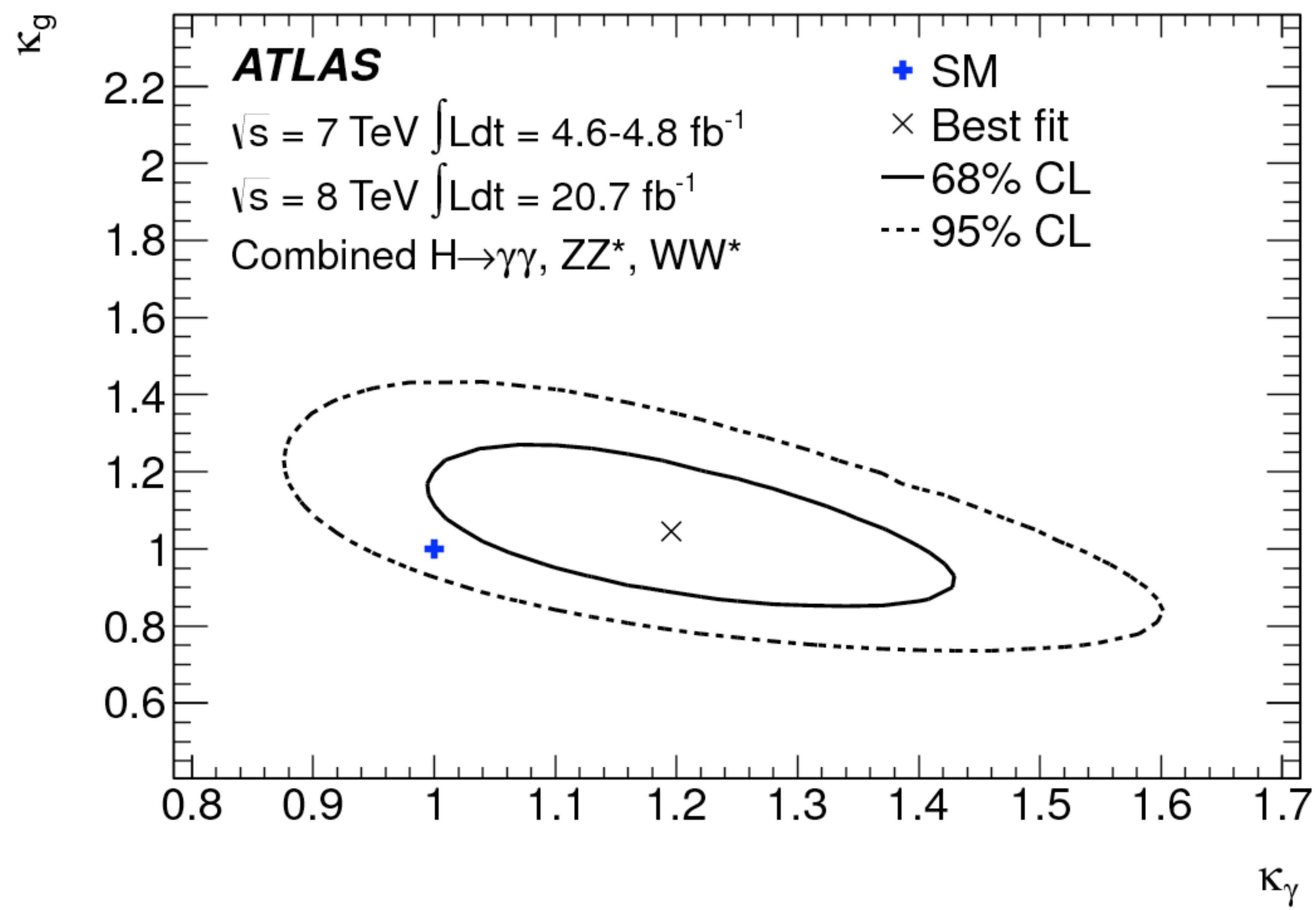
Keep SM couplings fixed, but add BSM in loops

Only decays to SM particles

$$\kappa_g = 1.08 \pm 0.14$$
$$\kappa_\gamma = 1.23^{+0.16}_{-0.13}$$

Include invisible or other BSM

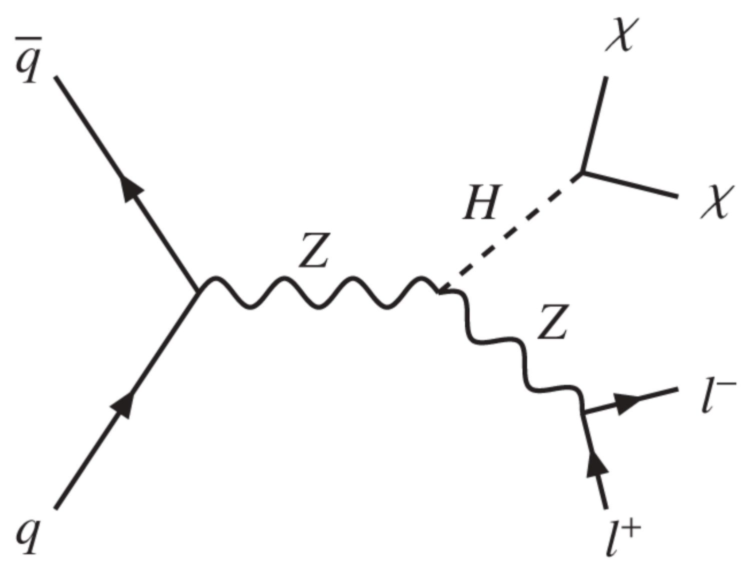
$$\kappa_g = 1.08^{+0.32}_{-0.14}$$
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$



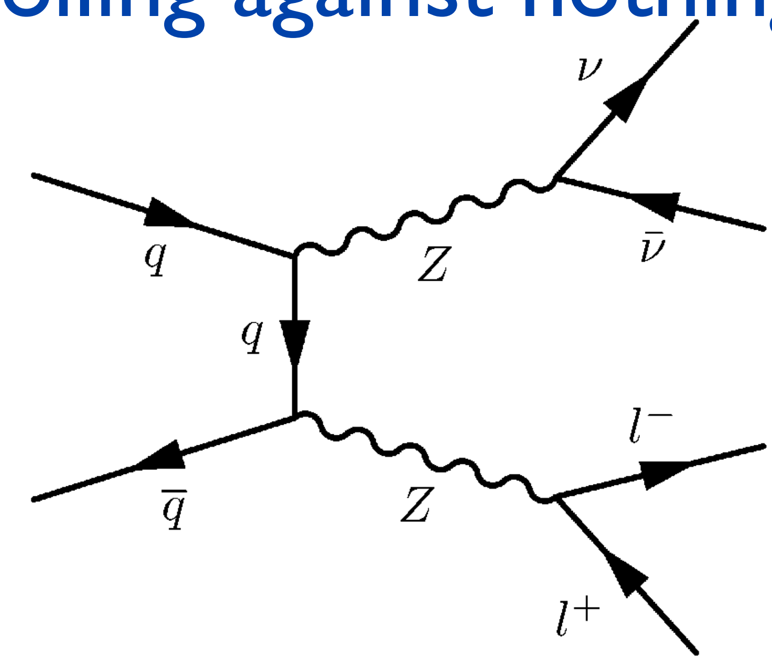
$BR_{\text{invisible or non-SM}} < 0.6$ at 95% CL

Higgs to Invisible

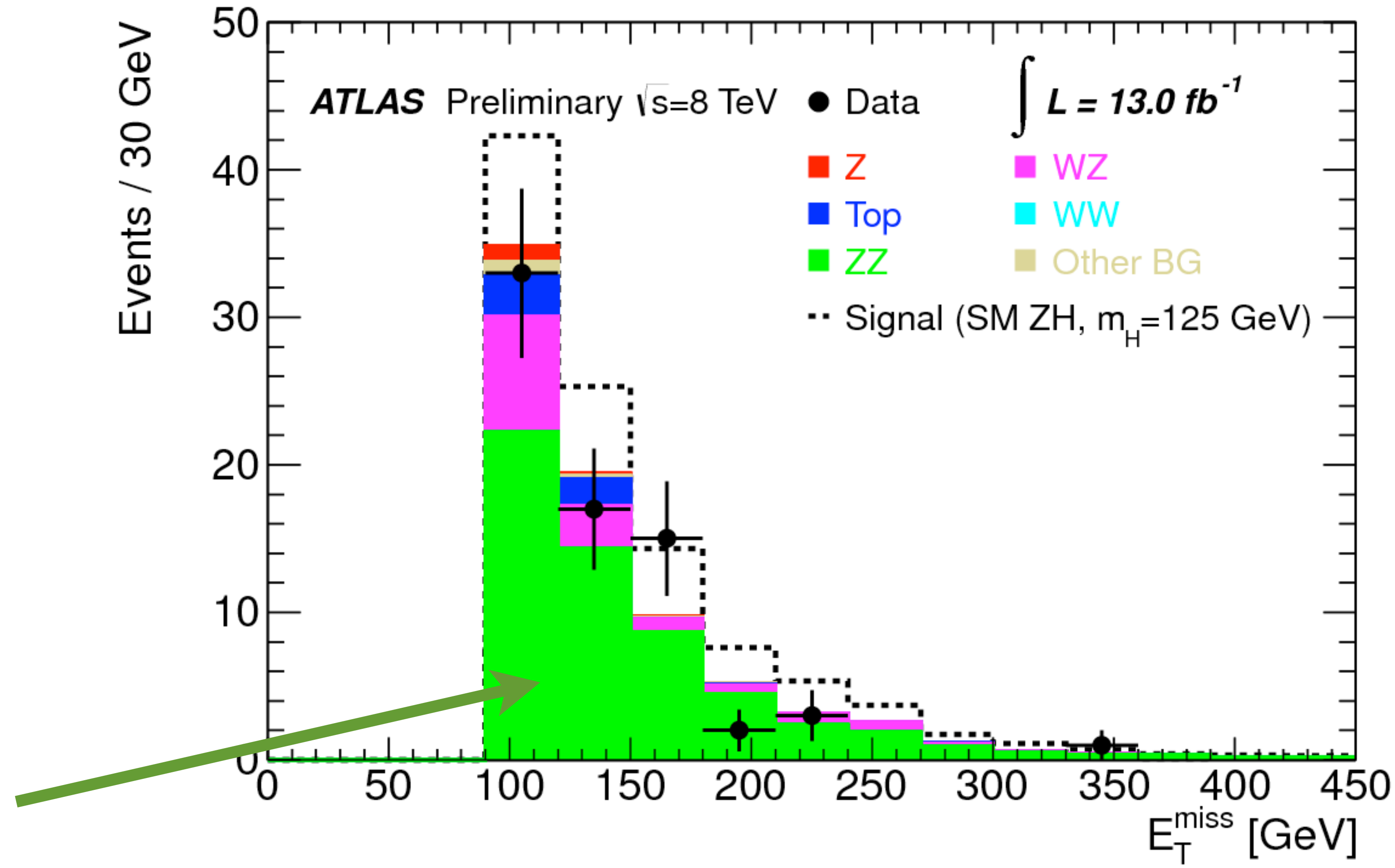
We have also searched directly for Higgs to invisible...



Z recoiling against nothing



SM source of Z recoiling against nothing

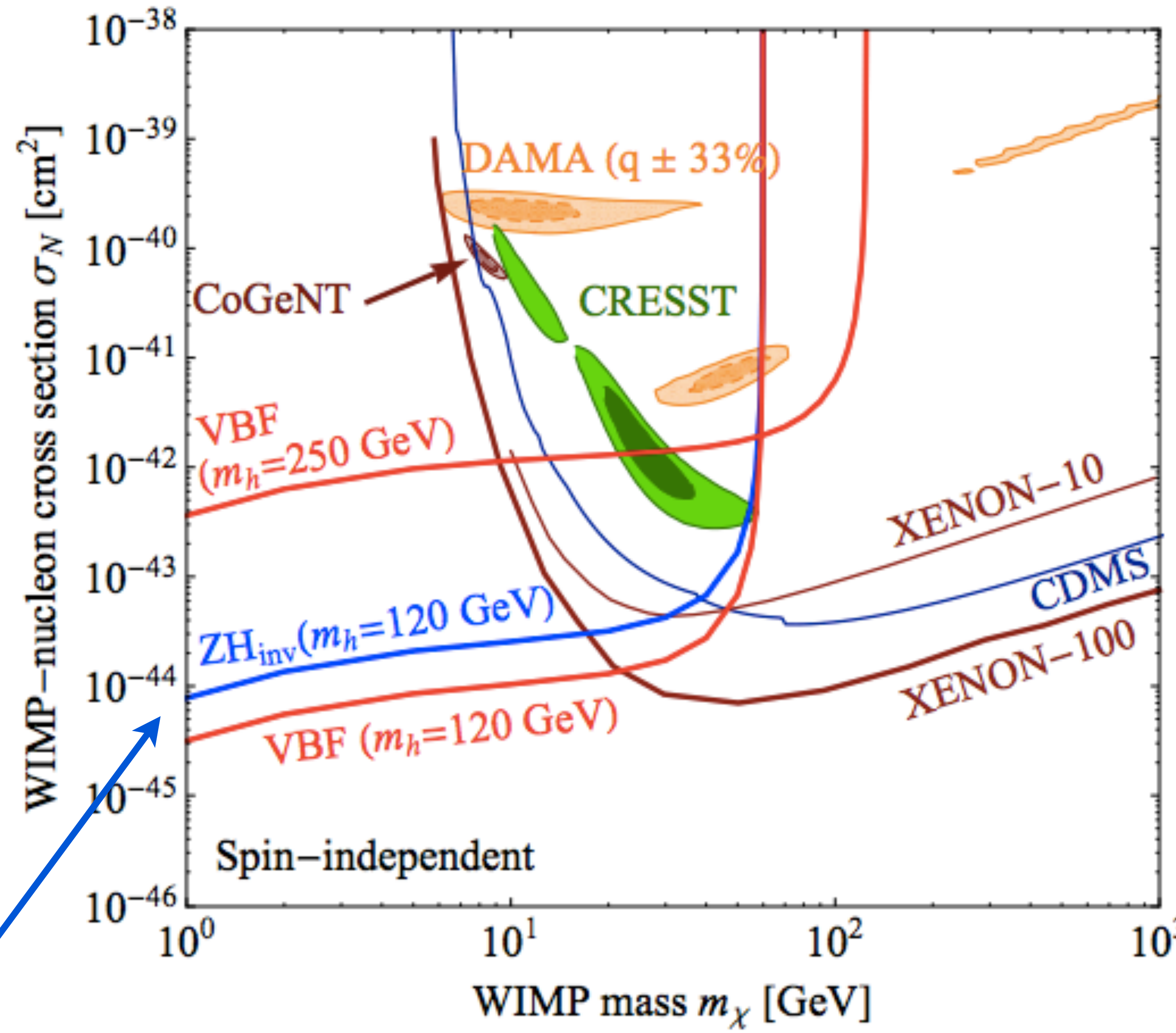


$BR_{invisible}$ < 0.65 (observed) at 95% CL, (0.84 expected)

Higgs to Invisible Interpretation

from arXiv:1109.4398v1 [hep-ph]

Implications for dark matter searches if DM to nucleon couplings is entirely Higgs



Based on expected sensitivity (BR_{inv}<0.75) very close to observed

Summary

There is an important interplay between theory and experiment

- Theory is an input into Experiment
- Experiment is an input into Theory
- Some important measurements are close to being theory limited

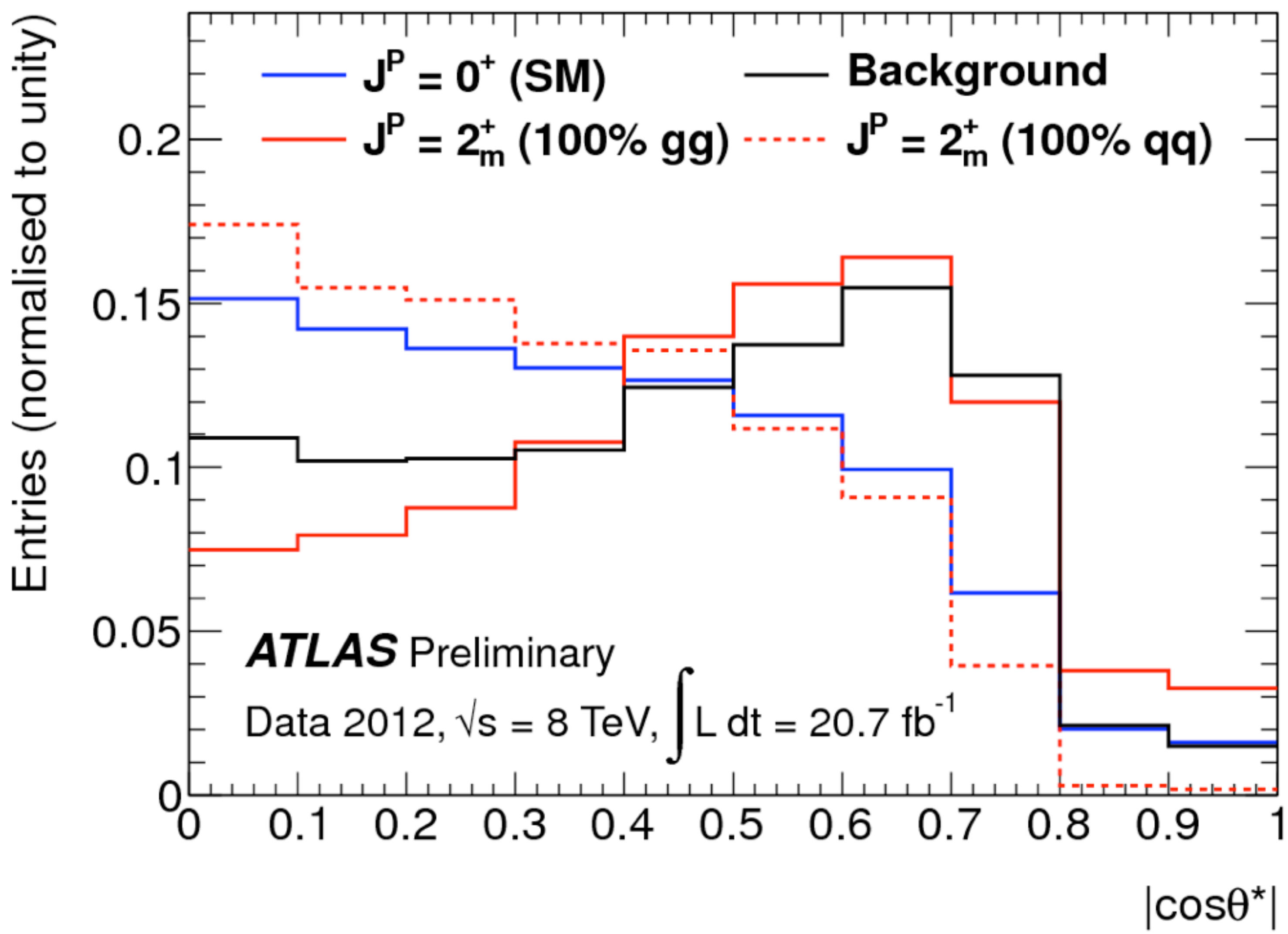
Couplings:

- order 20-30% constraints on vectors, fermions just crossing the sensitivity thresholds
- Interesting sensitivity to dark matter and other BSM

Spin:

- various combinations of 0^-, 1^+, 1^-, and 2^+ excluded

$H \to \gamma\gamma$ Spin



A spin-1 resonance cannot decay to two photons

so spin-1 is excluded

Photon spins are not observed

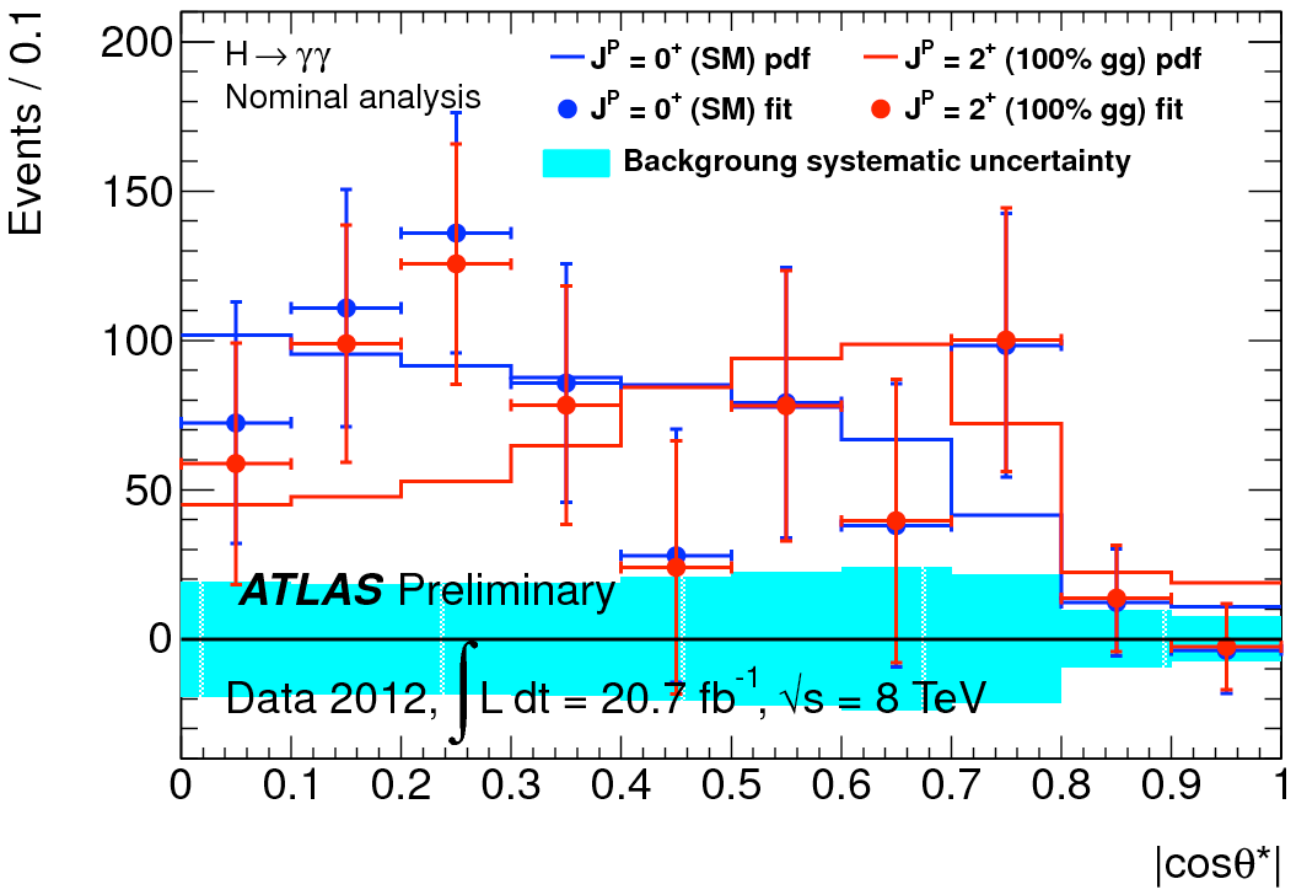
Spin-2 with initial state of gg or $q\bar{q}$ will have different decay kinematics

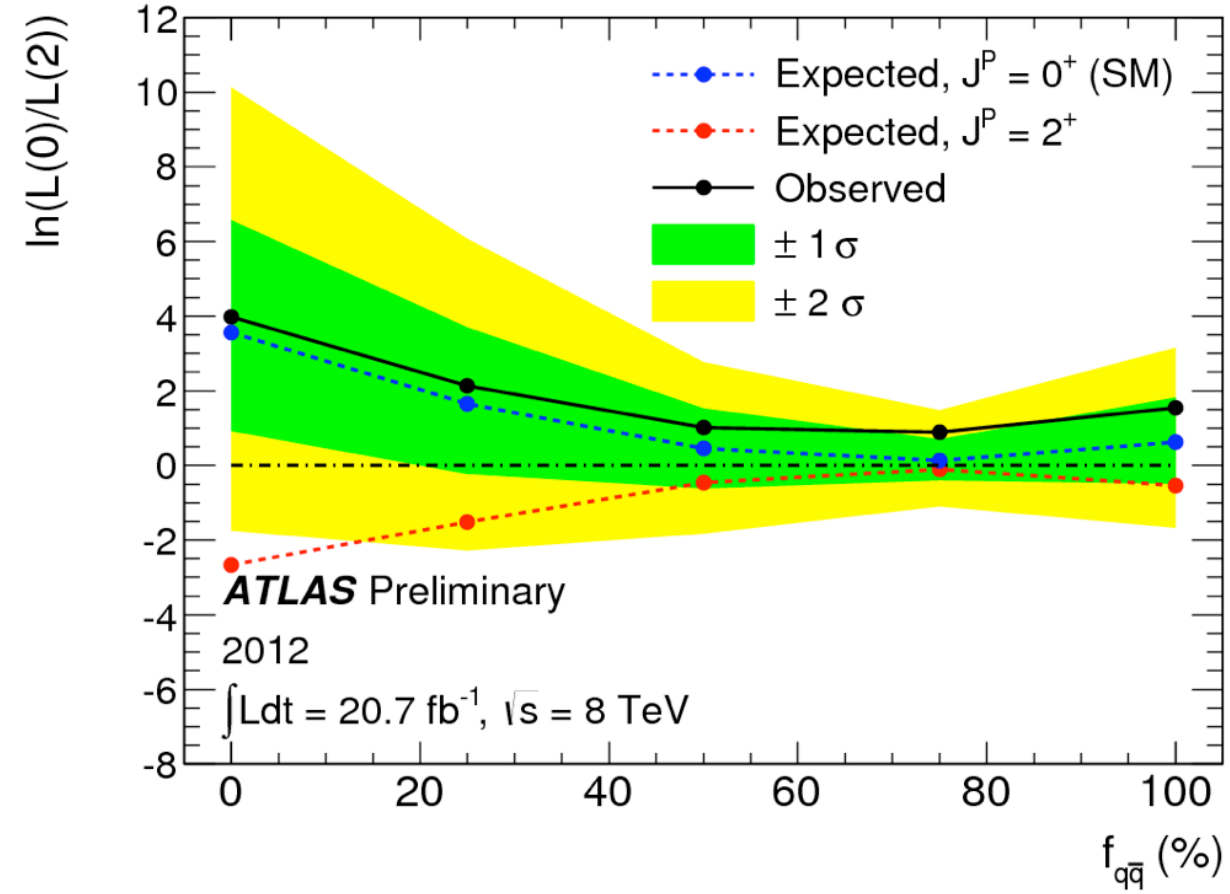
$\cos\theta^*$ is the angle of photons relative to beam direction with a correction for the boost of the $\gamma\gamma$ system

Selection modified to reduce $m_{\gamma\gamma} - \cos\theta^*$ correlation

ATLAS-CONF-2013-029

$H \to \gamma\gamma$ Spin





The data are fit for signal and background yields for spin-0 and spin-2

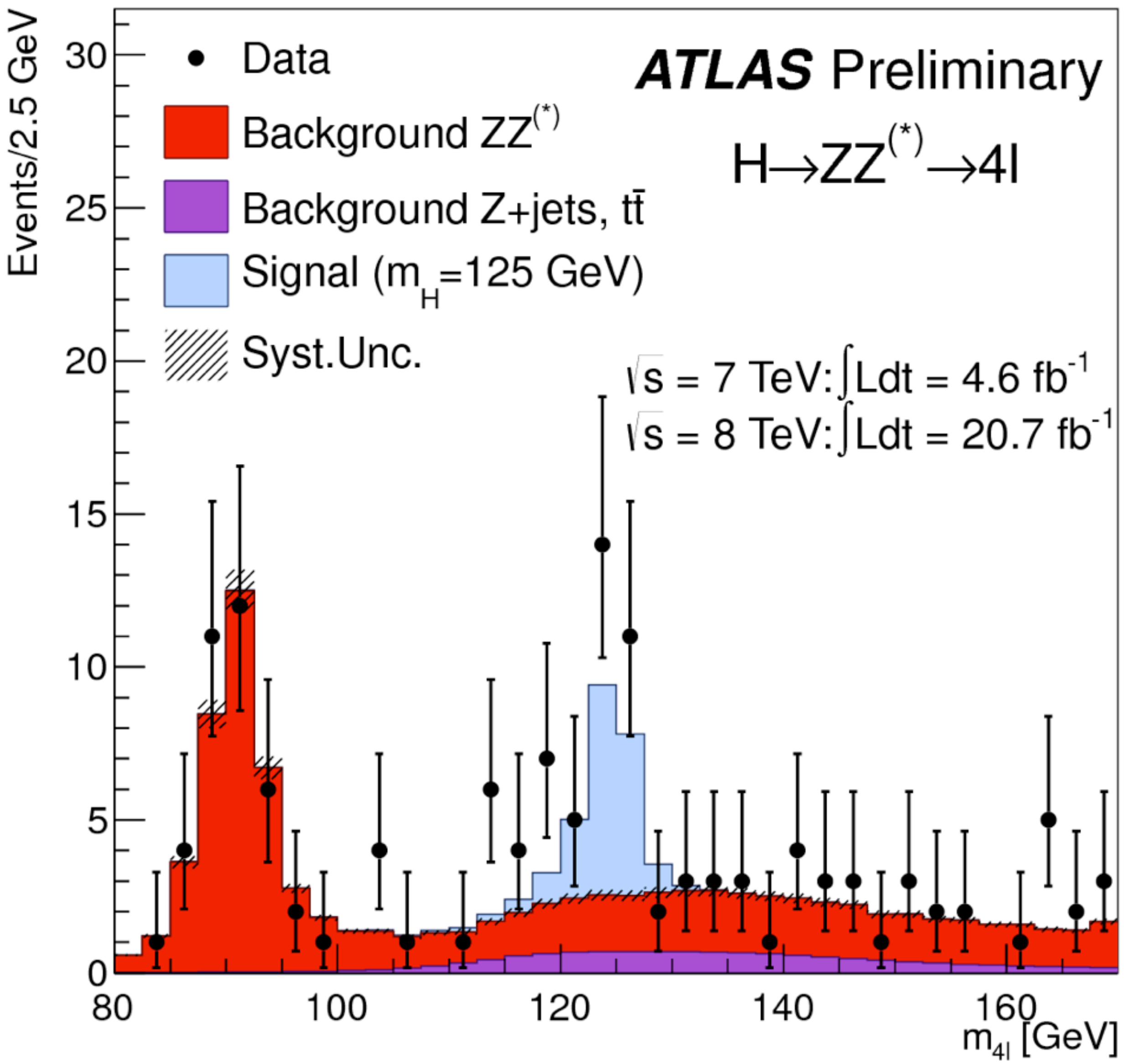
The ratio of the best fit likelihoods is used as a test statistic to set limits

Only 8 TeV data are used at this point

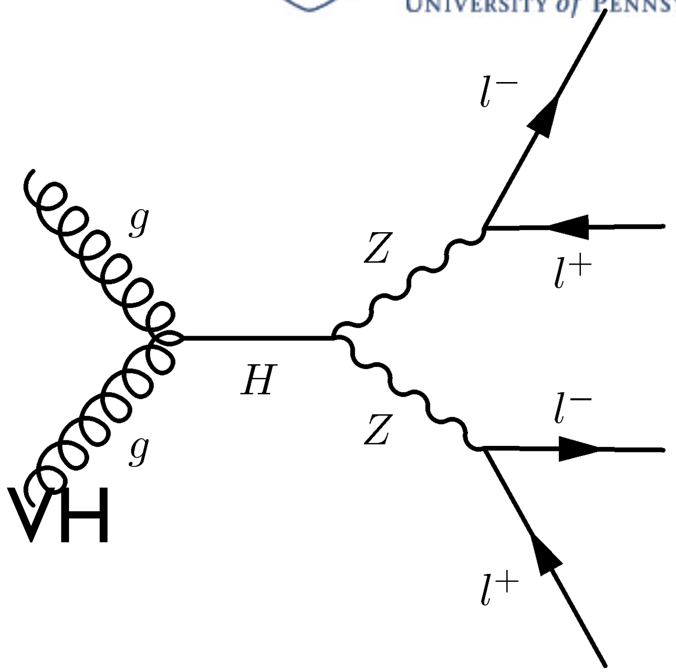
Spin-2 produced by gluon fusion is excluded at 99% CL

ATLAS-CONF-2013-029

$H \to ZZ$ Production

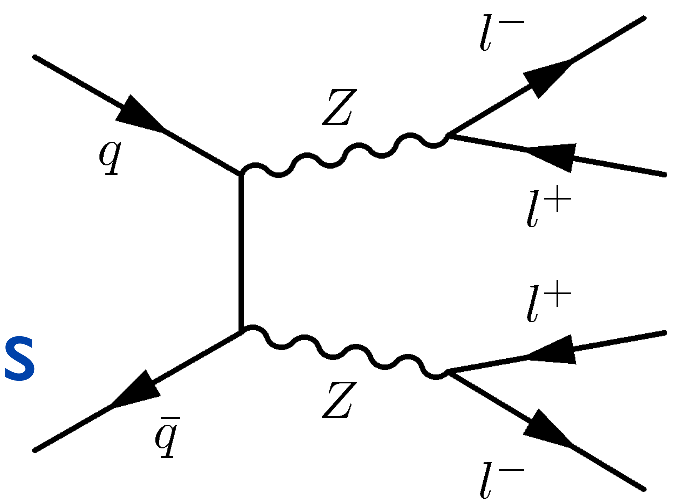


Signal + VBF, VH, ttH

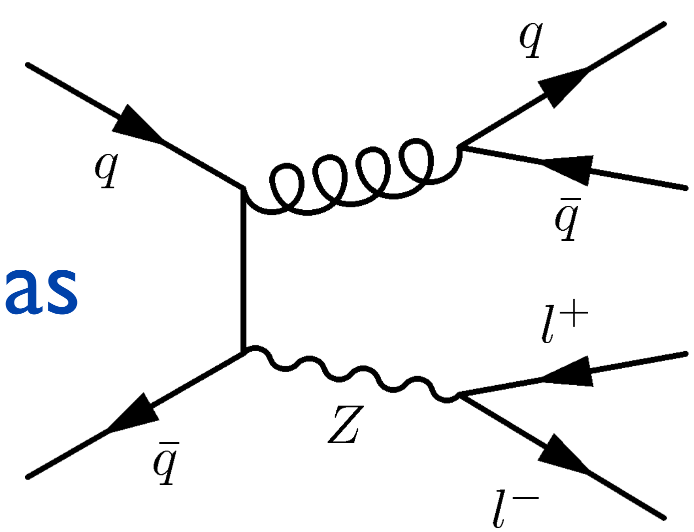


Separate VBF and VH categories added

Irreducible background: 4 real leptons



Z+2 jets misidentified as leptons

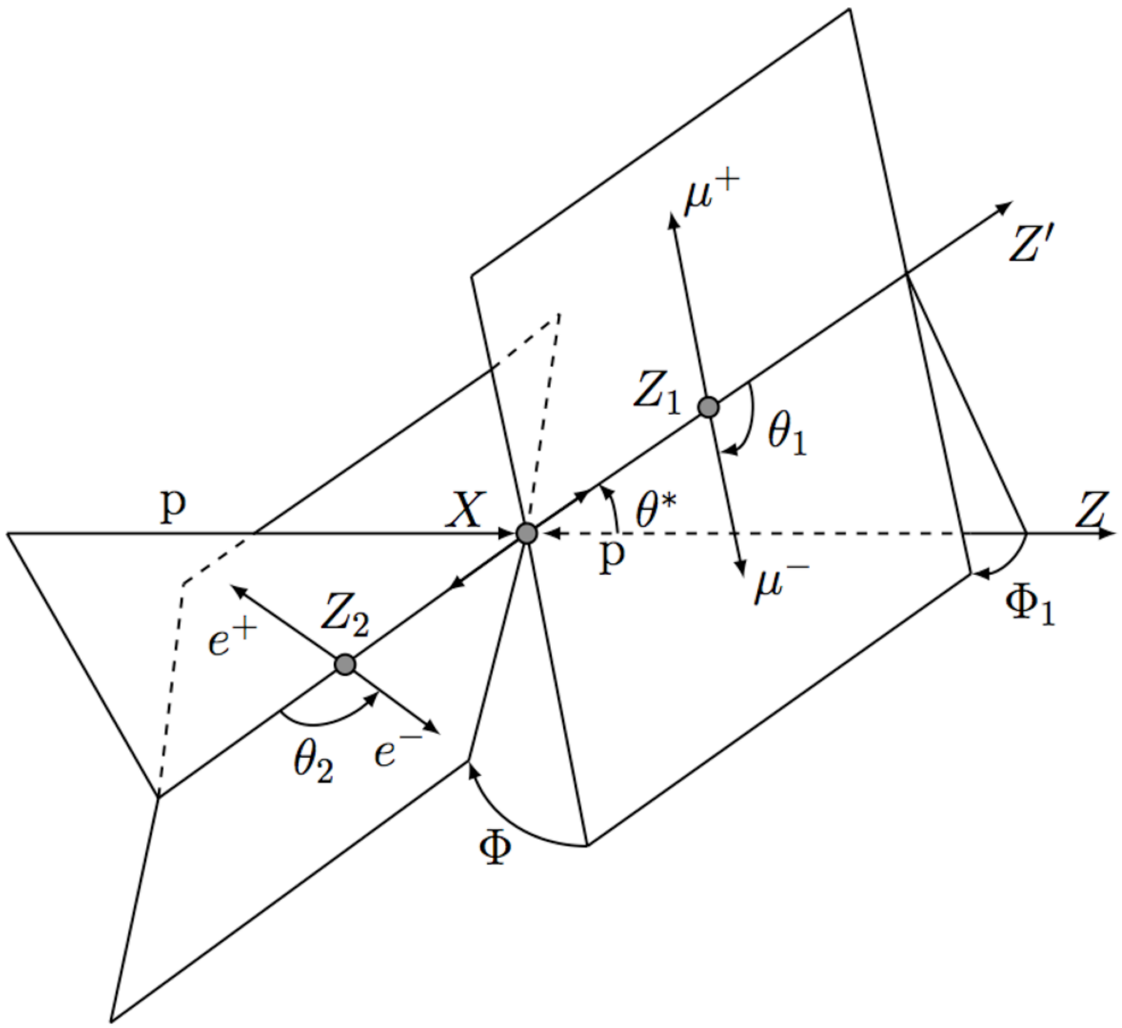


Main Issue is getting the highest efficiency without letting this get out of control

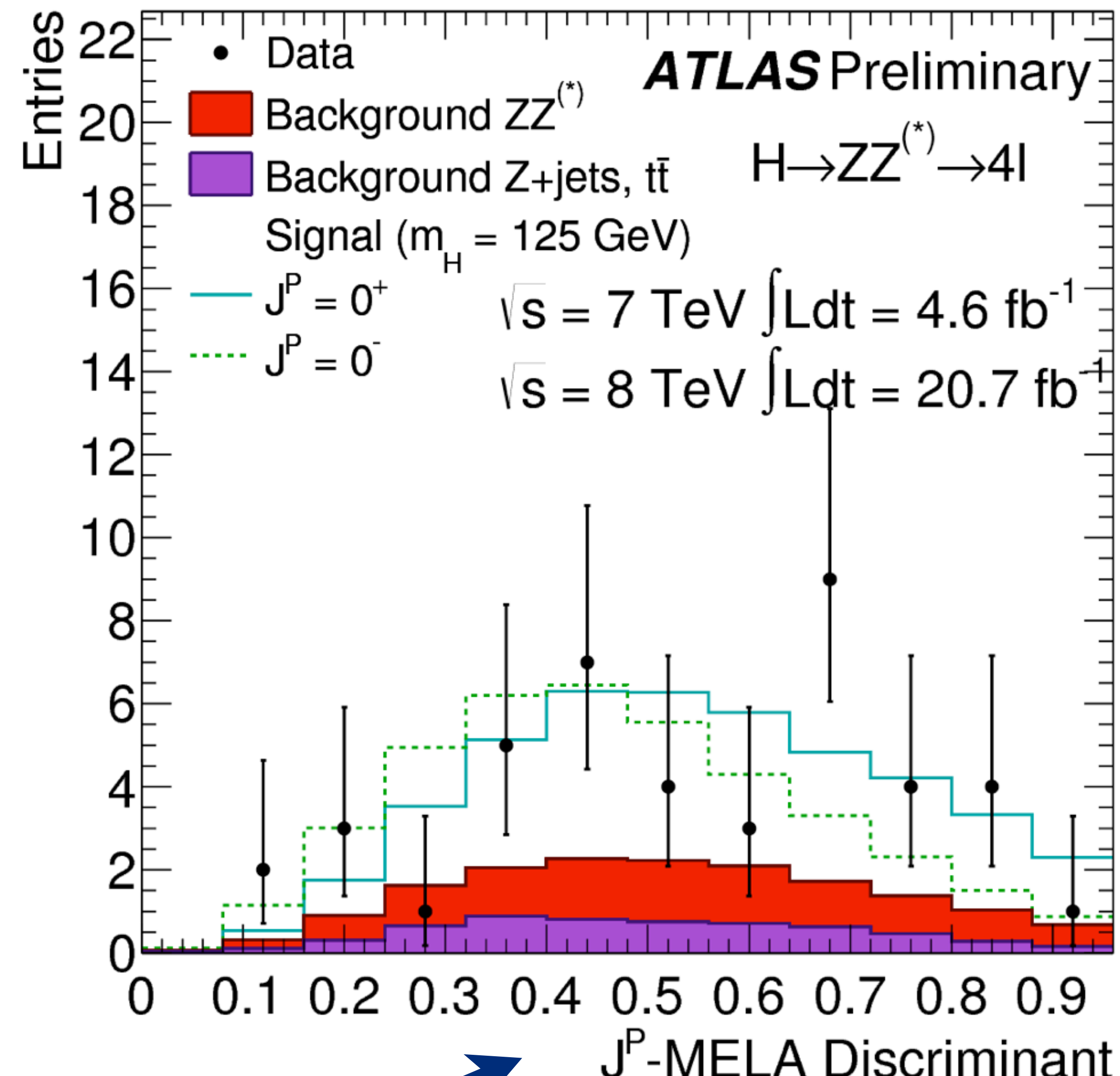
Acceptance:

39% 4μ, 26% $2e2\mu/2\mu2e$, 19% $4e$

$H \to ZZ$ Spin



Considered J^P: 0^+, 0^-, 1^+, 1^-, 2^+, 2^-



<u>Full kinematics measured</u> = 5 angles

Decay products sensitive to Z spins

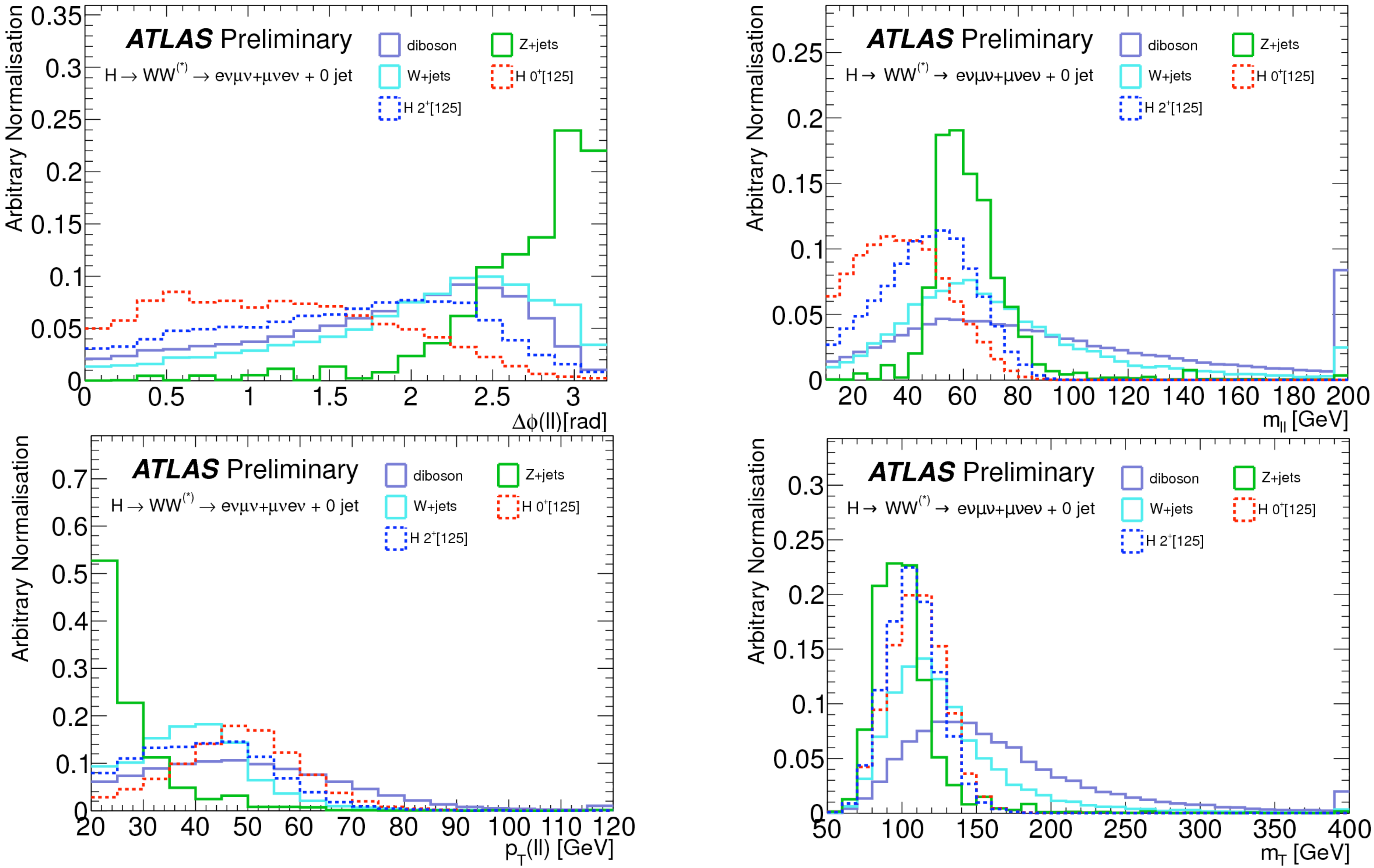
Two analysis methods:

- BDT with MC for input
- MELA = an analytic probability based on field theory matrix element

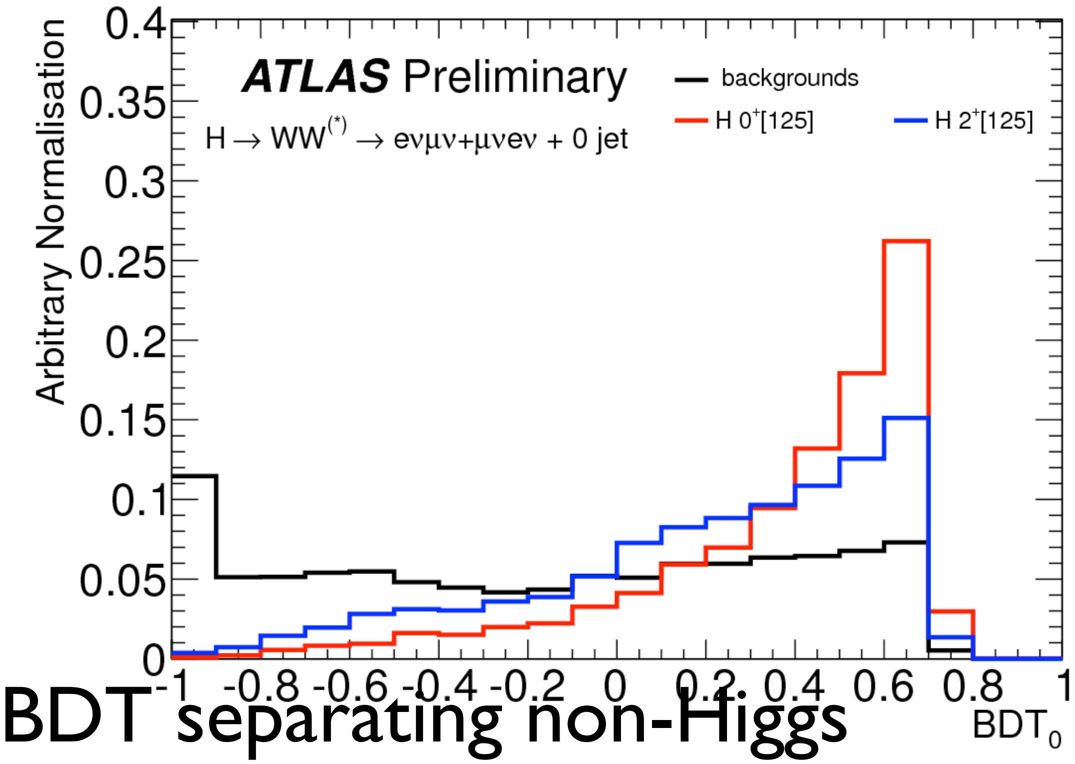
0^-, 1^+ excluded at 97.8% CL

$H \to WW$ Spin

Discriminating variables: spin-2 looks more like background

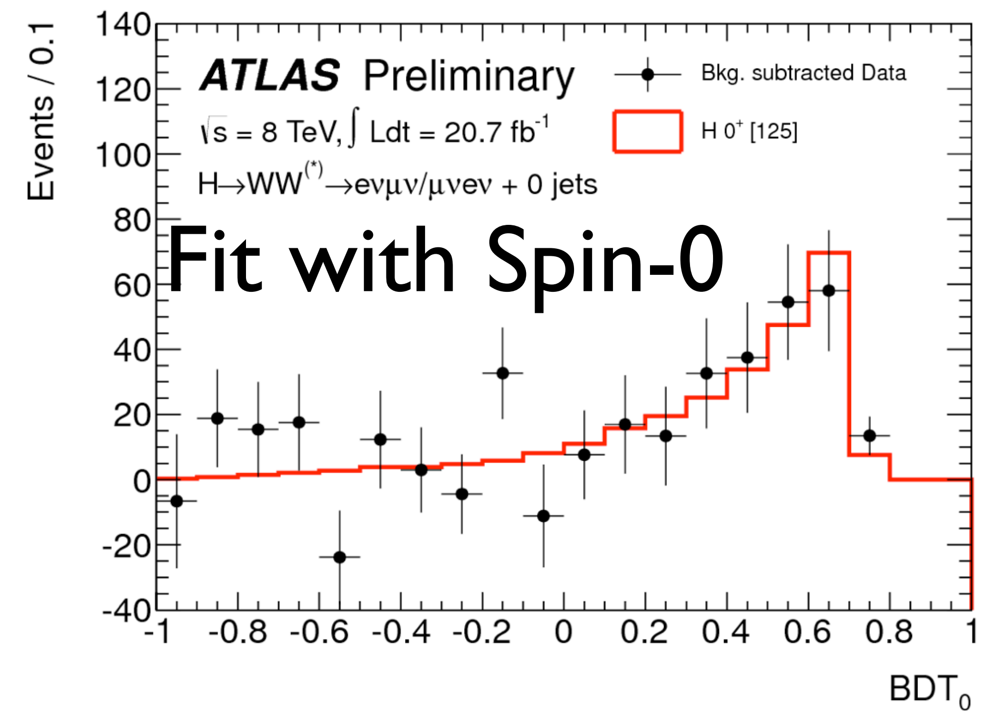


$H \to WW$ Spin

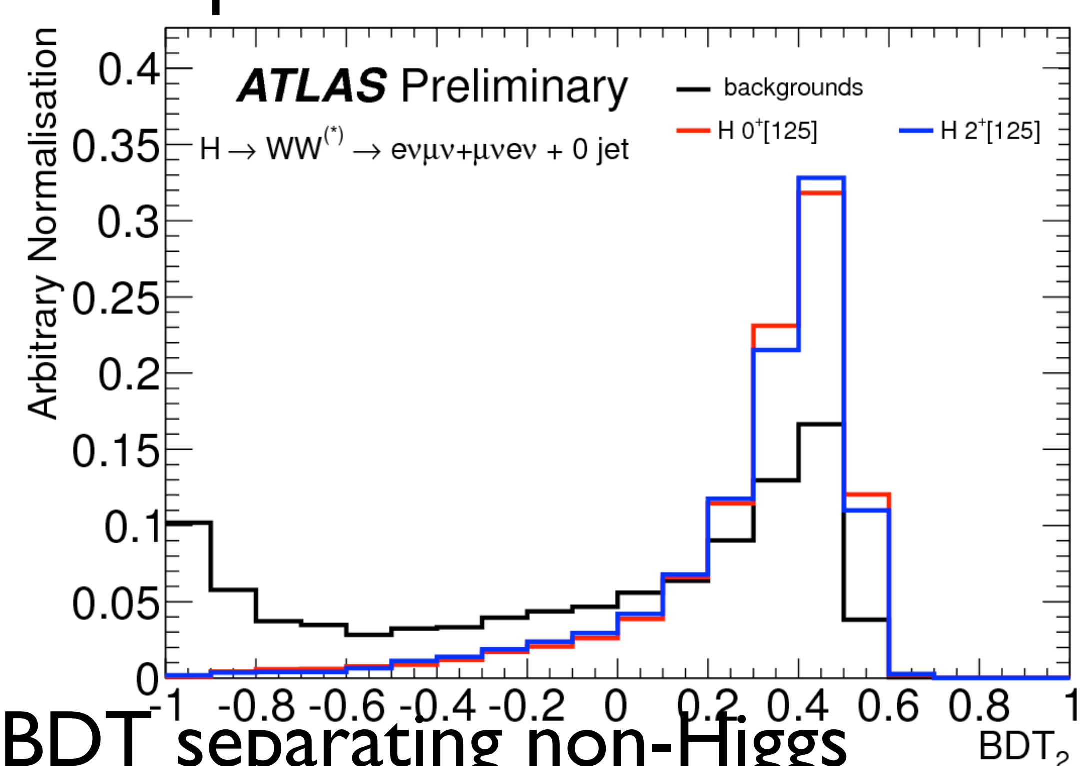


BDT separating non-Higgs from spin-0

2d binned fit BDT0 vs BDT2

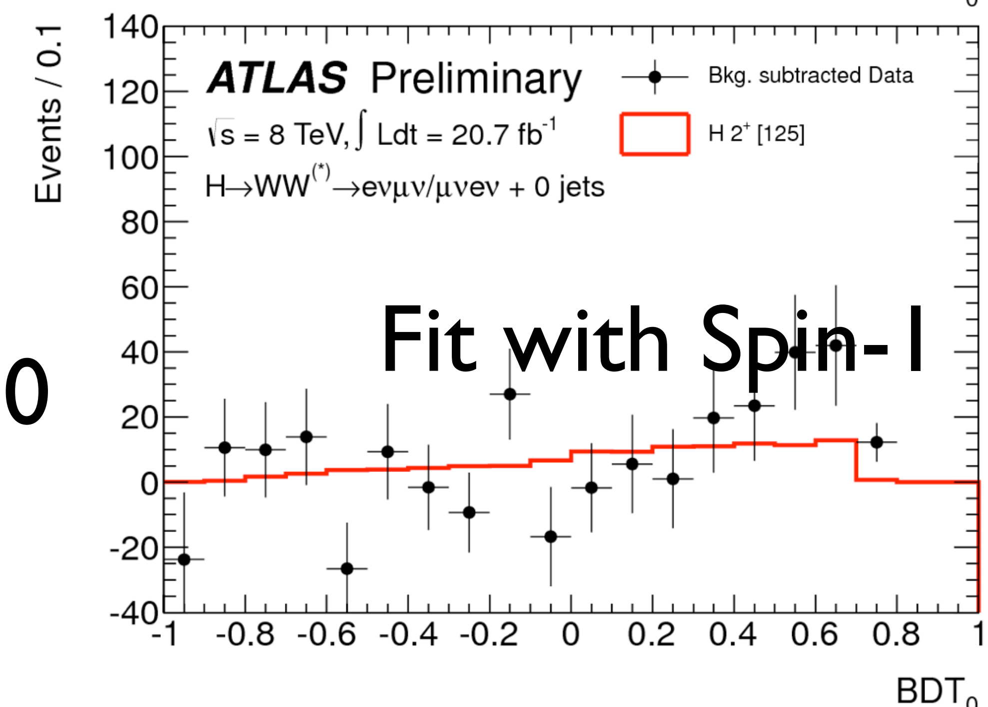


Fit with Spin-0



BDT separating non-Higgs from spin-1

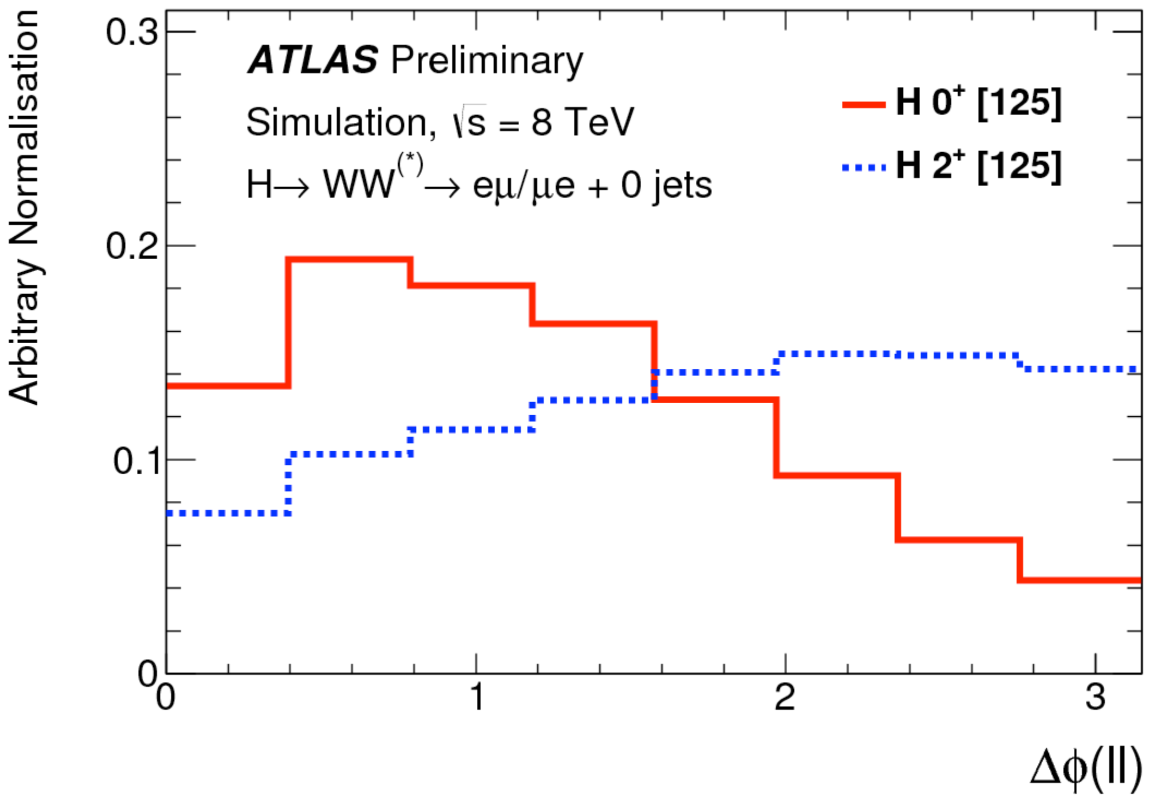
Test statistic likelihood ratio of spin-0 over spin-2

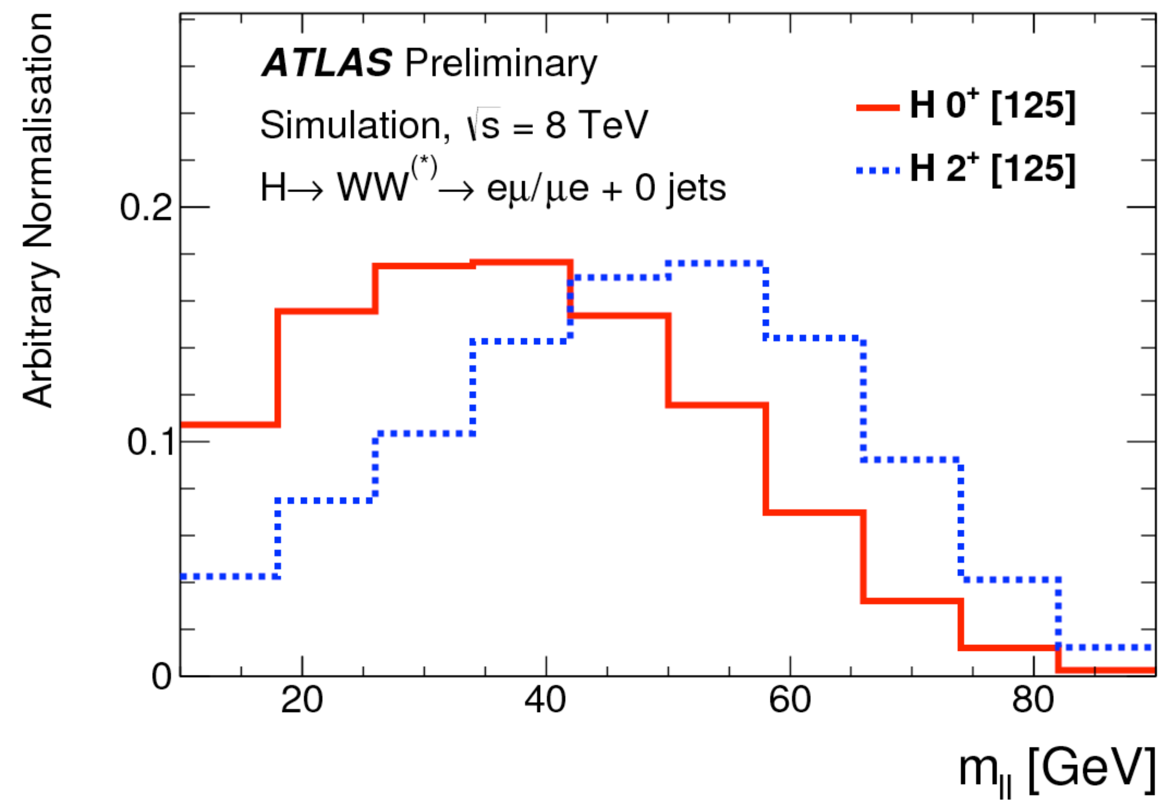


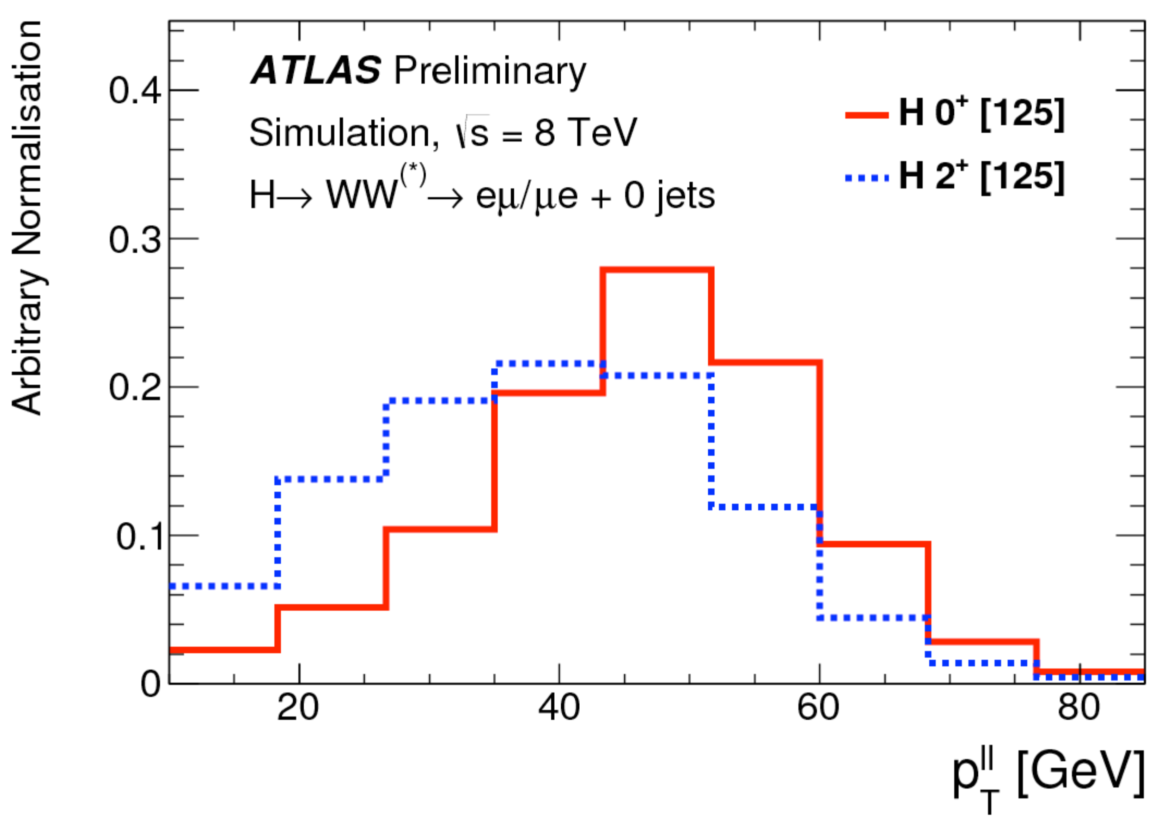
Fit with Spin-1

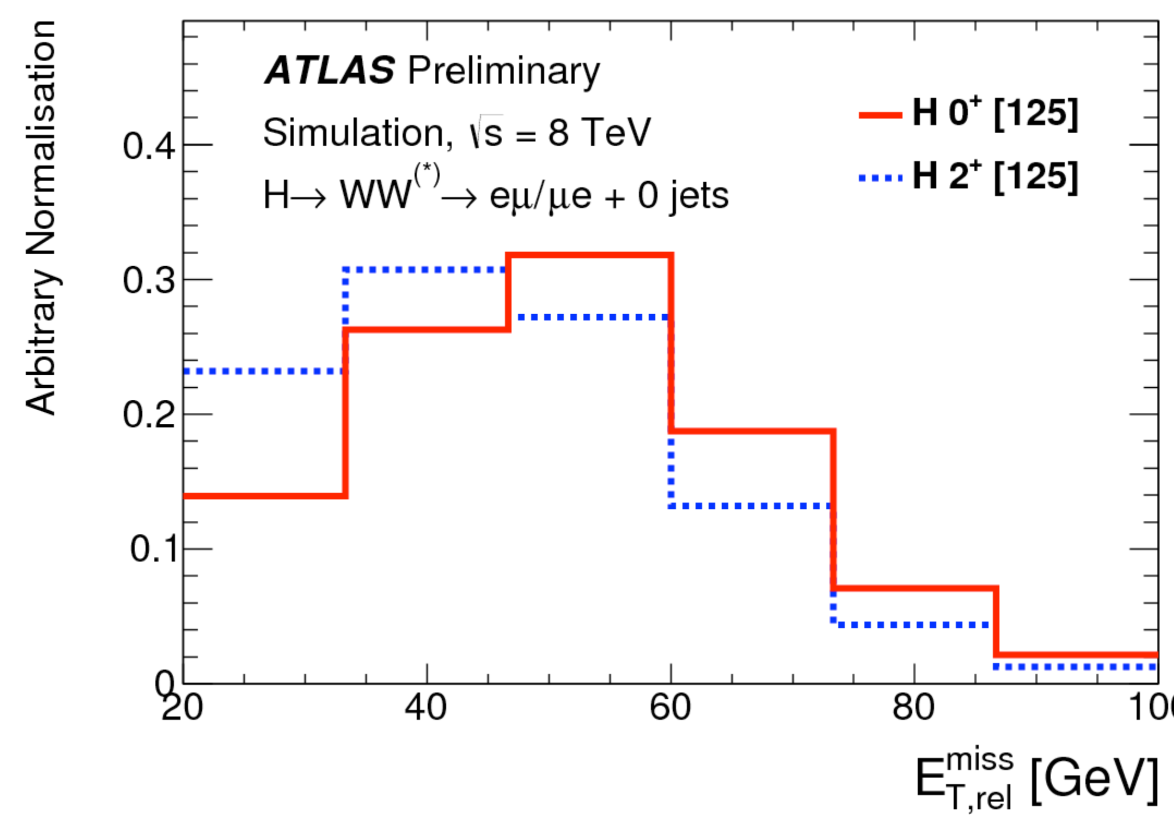
Exclusion of 2+ varies from 99% for 100% $q\bar{q}$ to 95% for 100% gg production

$H \to WW$ Spin Variables



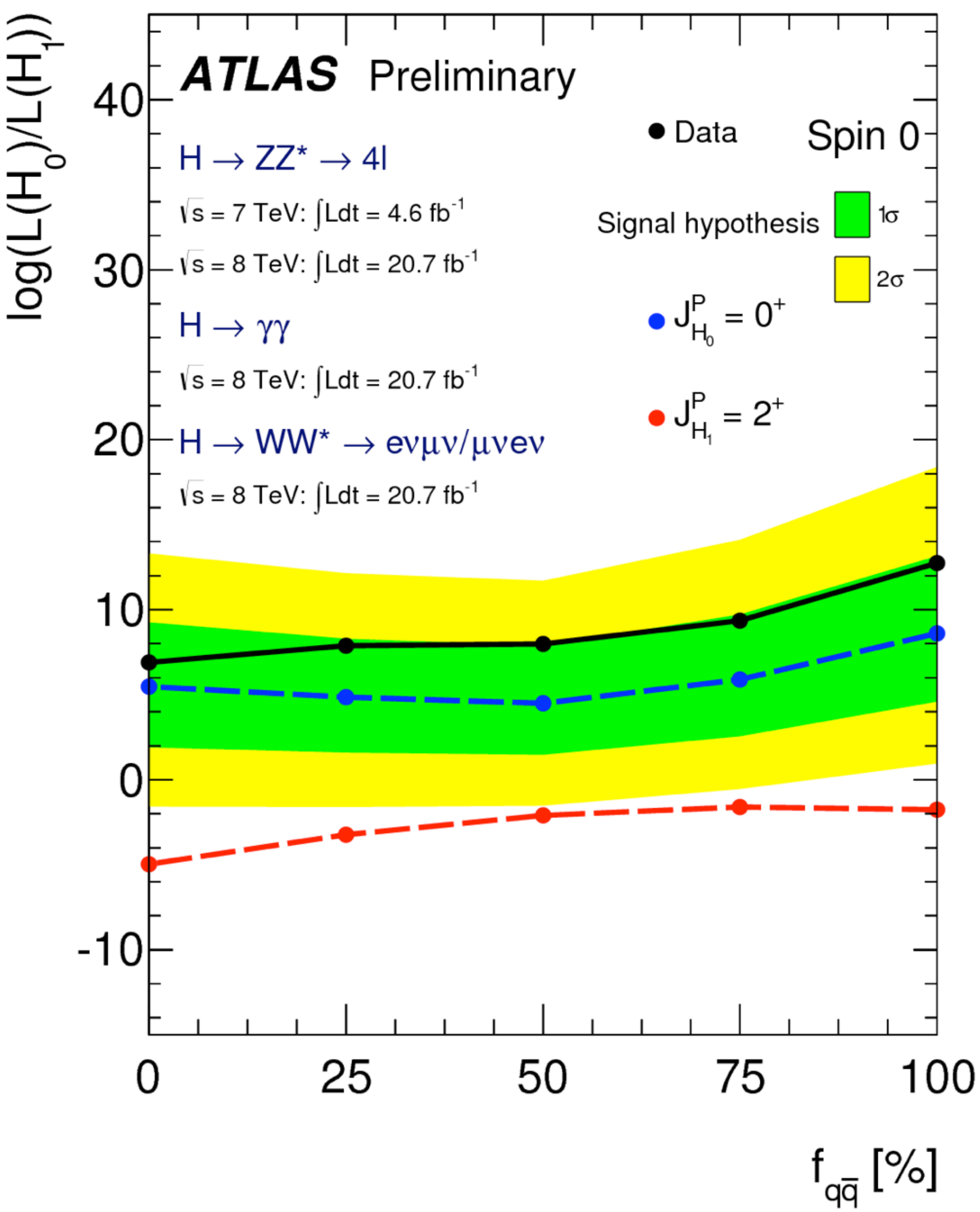


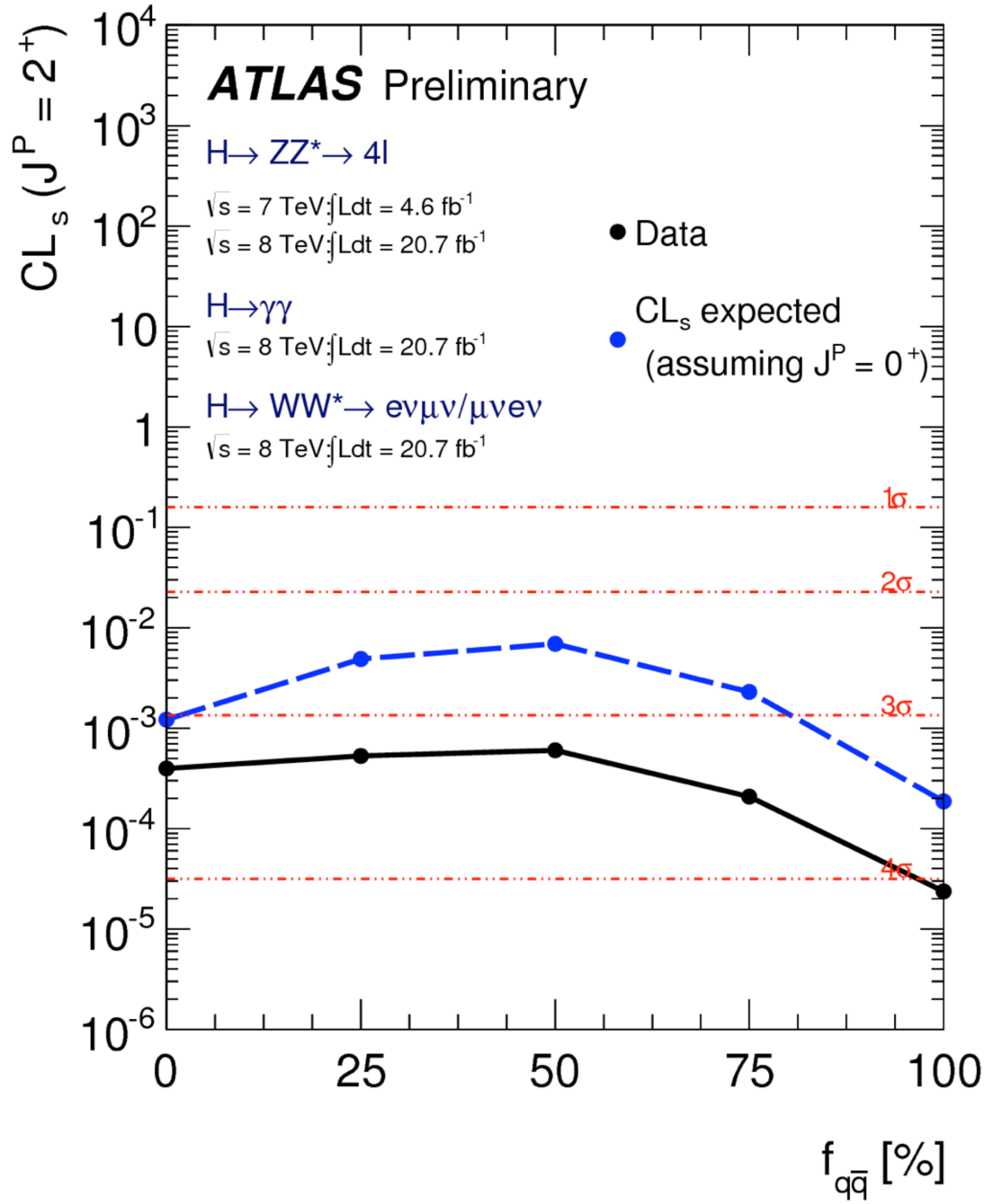




Spin Combination

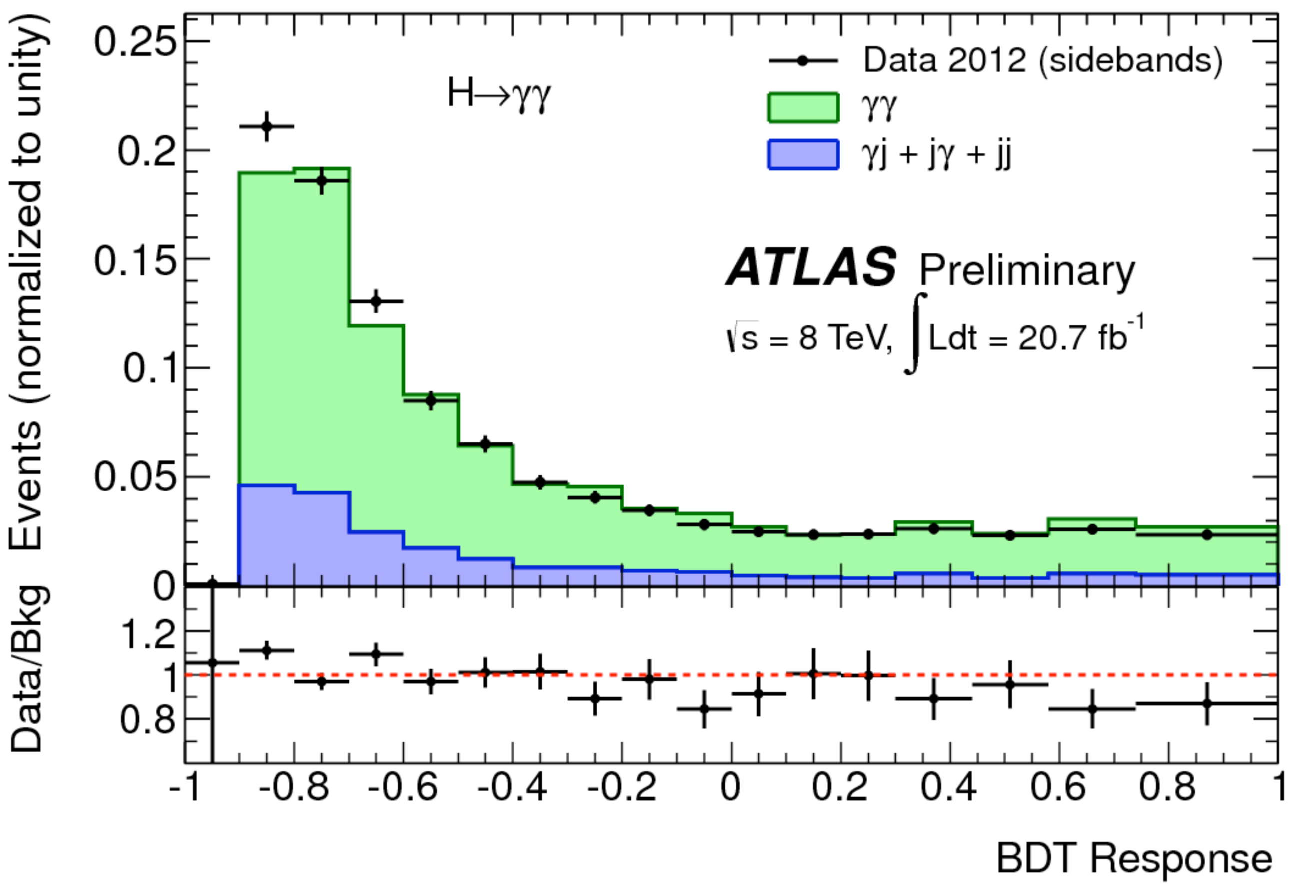
Spin results from WW, ZZ, and $\gamma\gamma$ combined

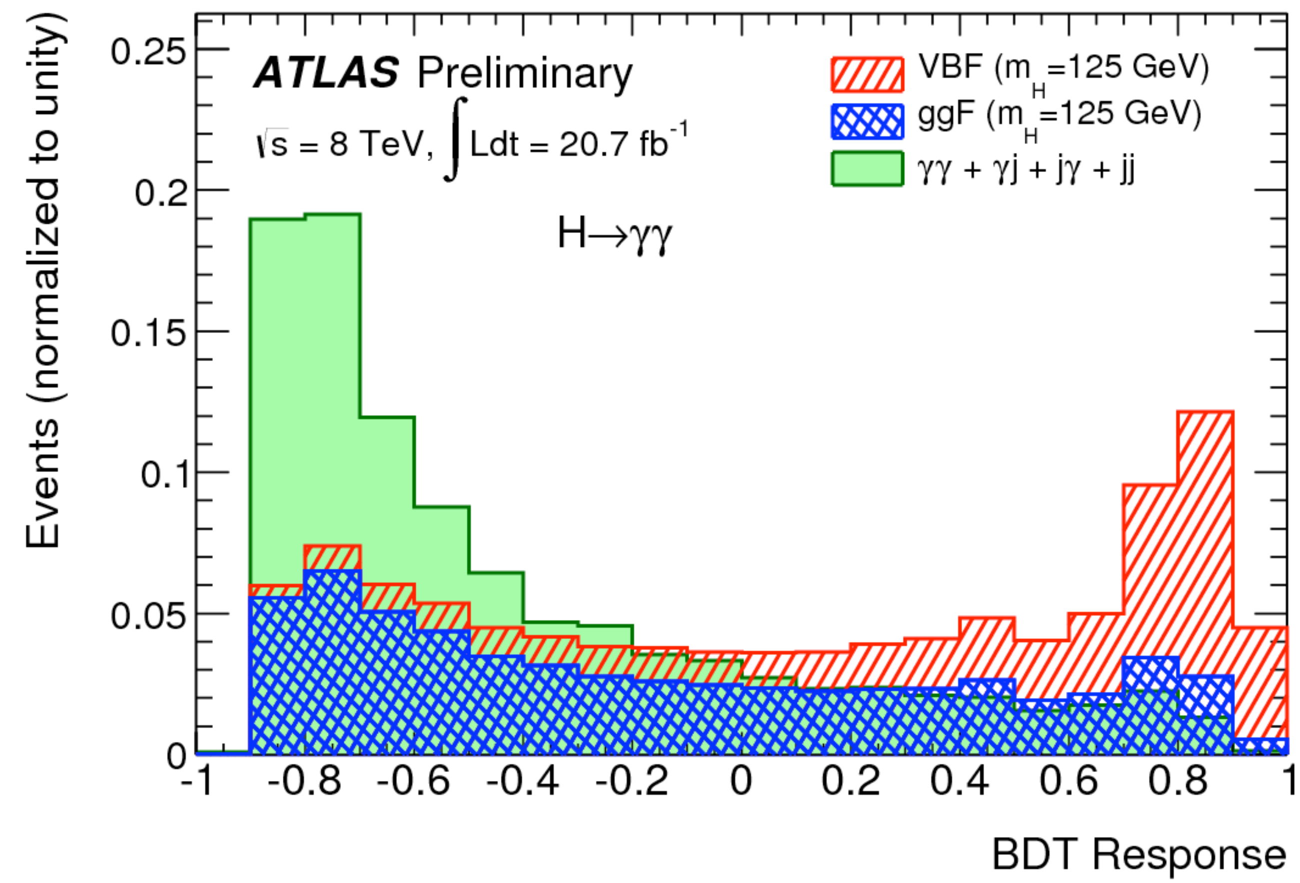




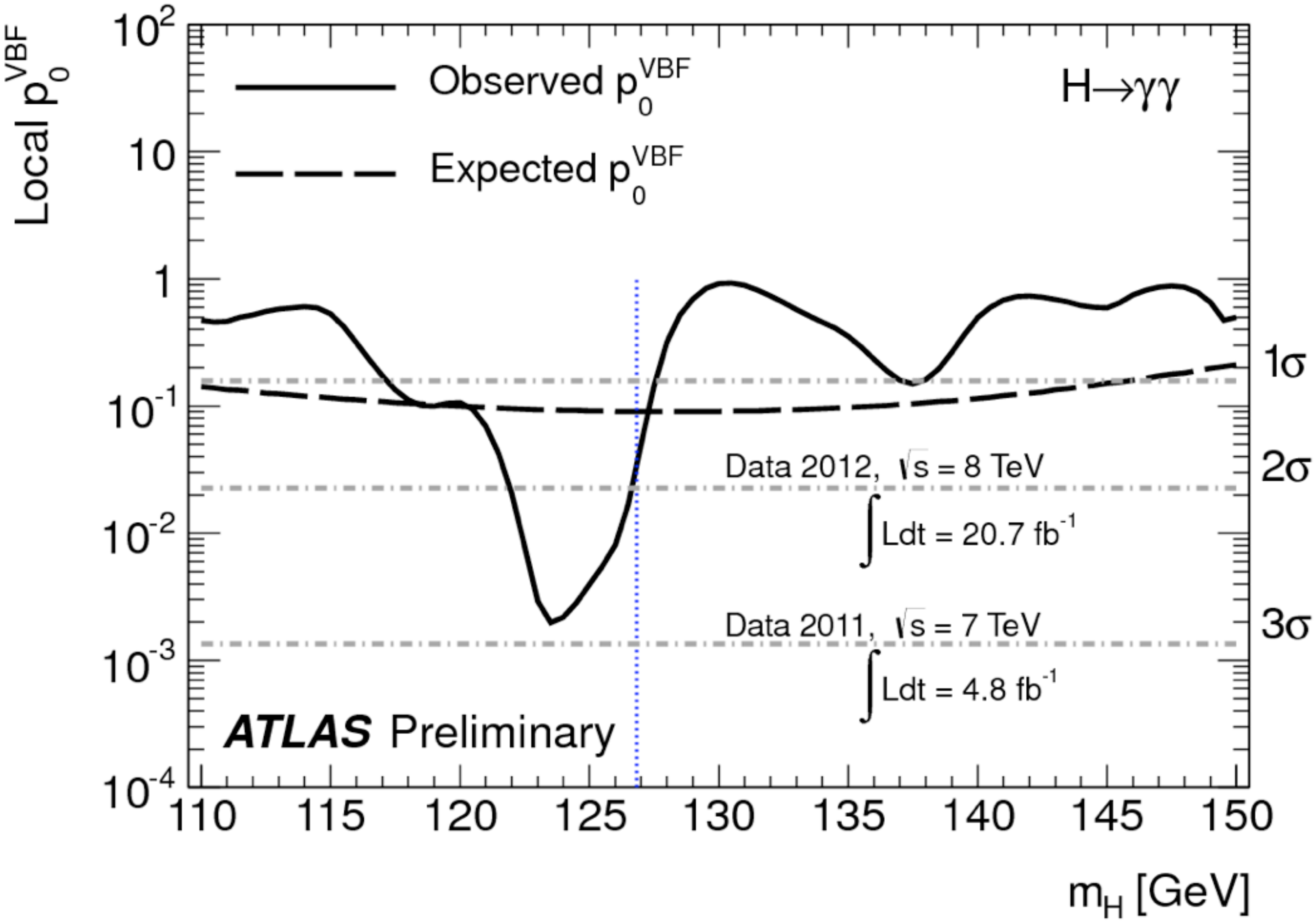
$J^P=2^+$ excluded at 99.9% CL independent of $f_{q\bar{q}}$

$H \to \gamma\gamma$ VBF BDT



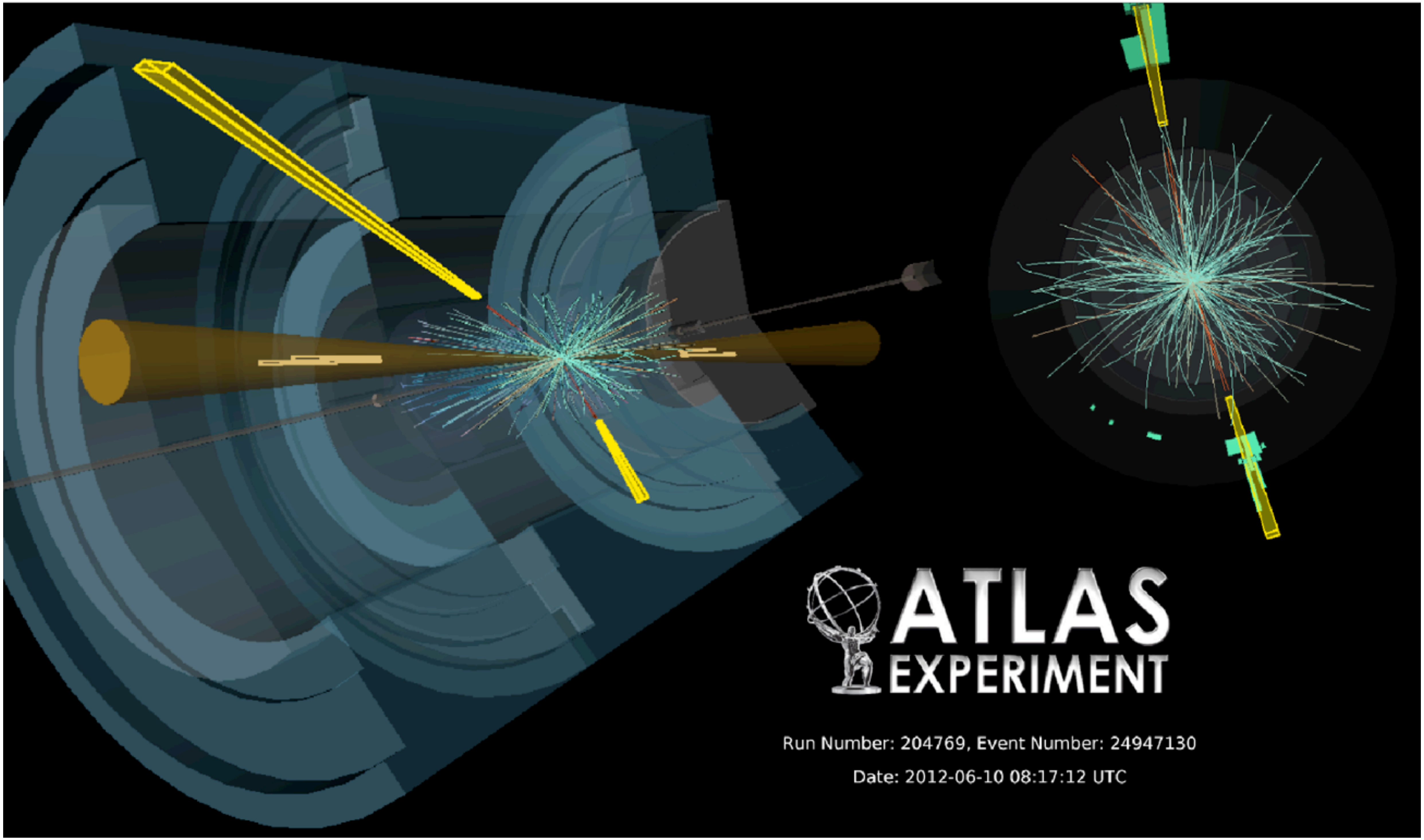


$H \rightarrow \gamma\gamma$ VBF Significance



Add S/B numbers

$H \rightarrow \gamma\gamma$ VBF Candidate



VBF Channel has a high purity, S/B ~=