… but is it the Standard Model Scalar? Searching for Brout-Englert-Higgs boson to fermions at ATLAS

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RSE YOUNG ACADEMY OF SCOTLAND

LHC Run 1

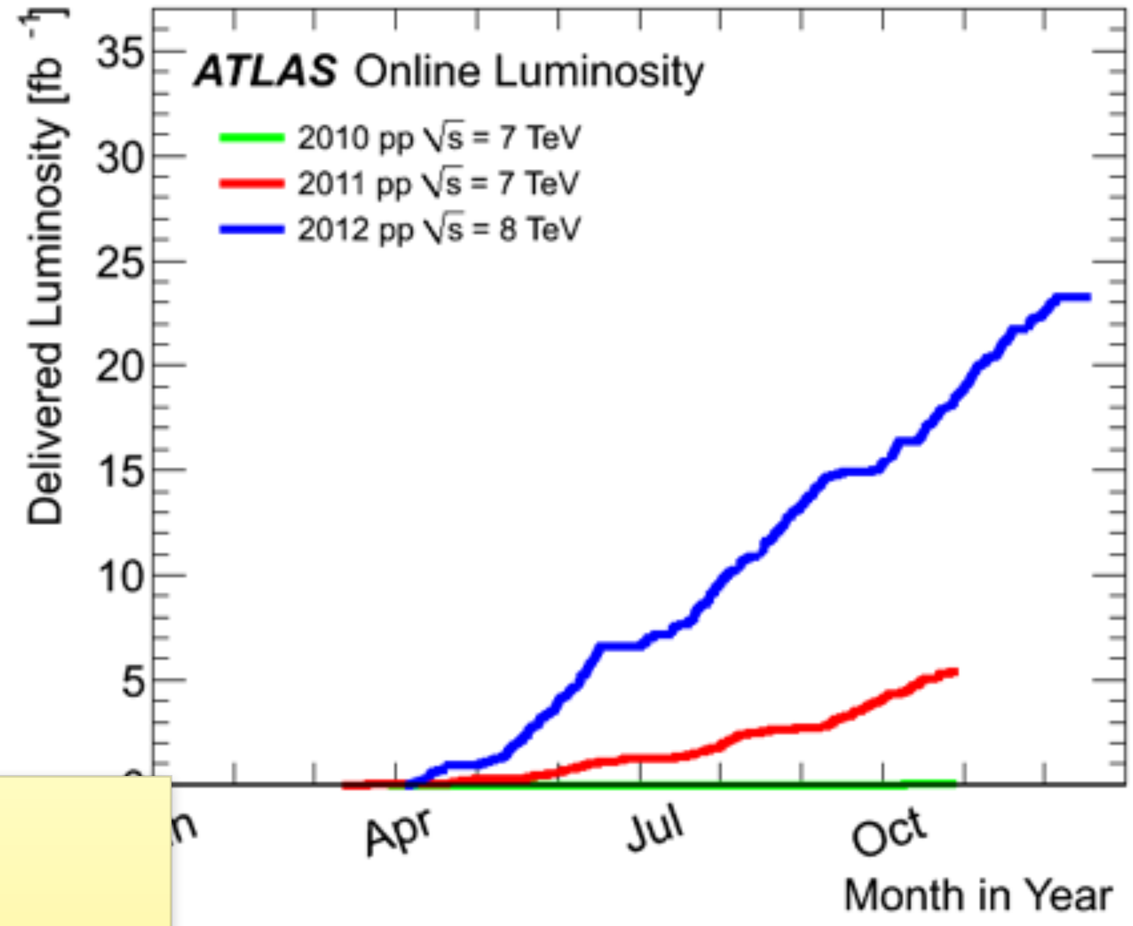
IN

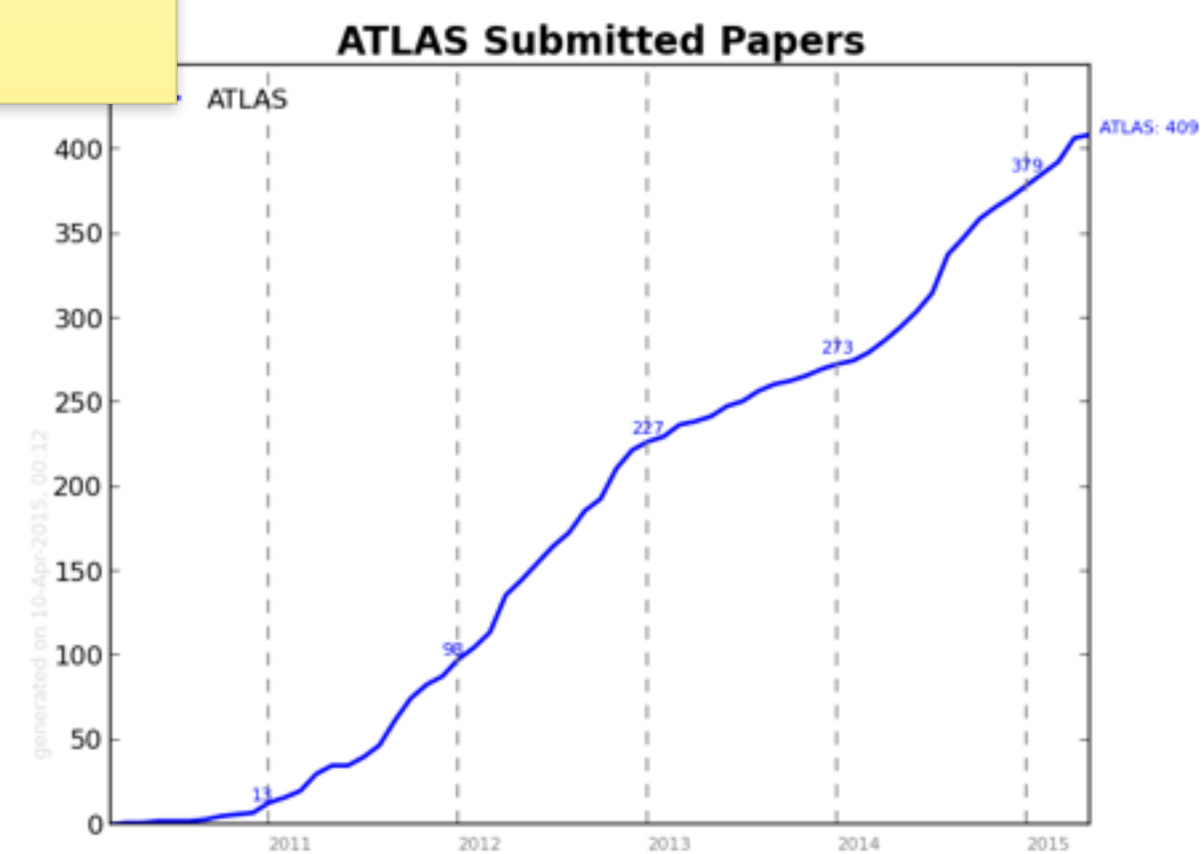
proton-proton collisions at AT

- 2010 $\sqrt{s}$=7 TeV, 44 pb^{-1}
- 2011 $\sqrt{s}$=7 TeV, 6 fb^{-1}
- 2012 $\sqrt{s}$=8 TeV, 23 fb^{-1}

Total ~30 fb^{-1}

need new atlas papers plot





OUT

Physics results!

- 422 submitted papers on collision data from ATLAS
- (Another ~400 from CMS)

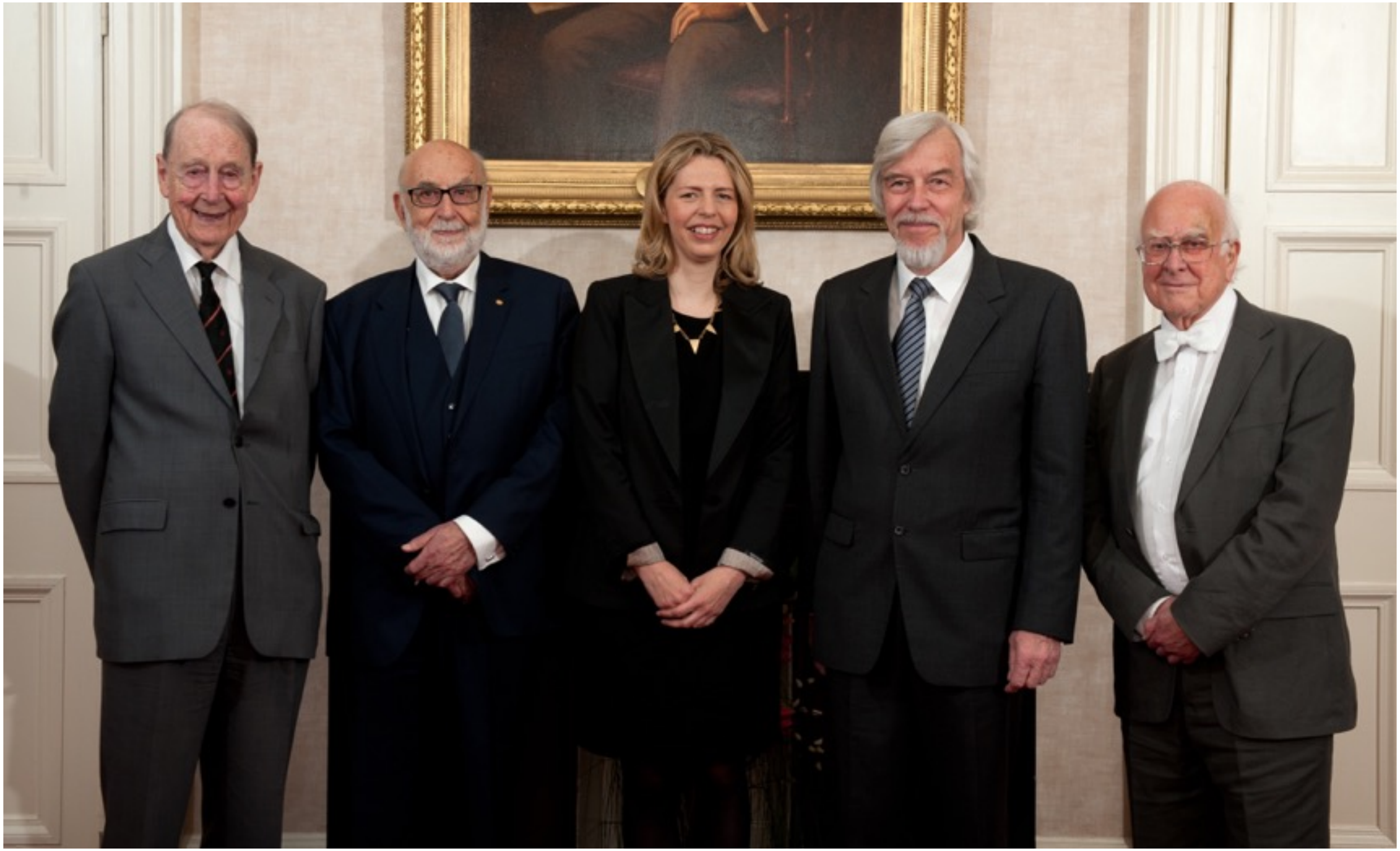
MIDDLE

Over 6,000 ATLAS and CMS physicists operating the detectors; collecting and analysing the data.

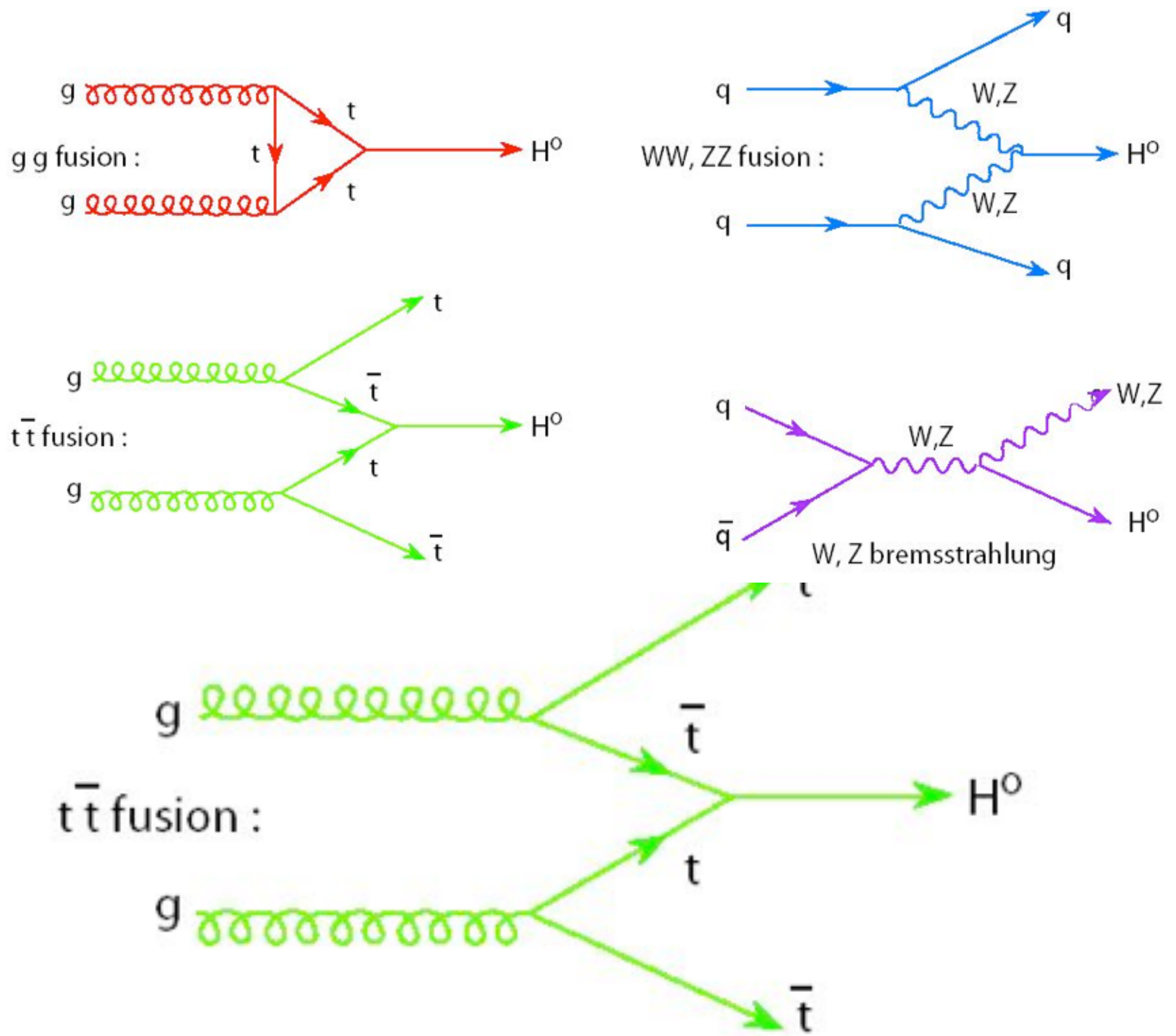
CERN beam division team operating the whole LHC chain.

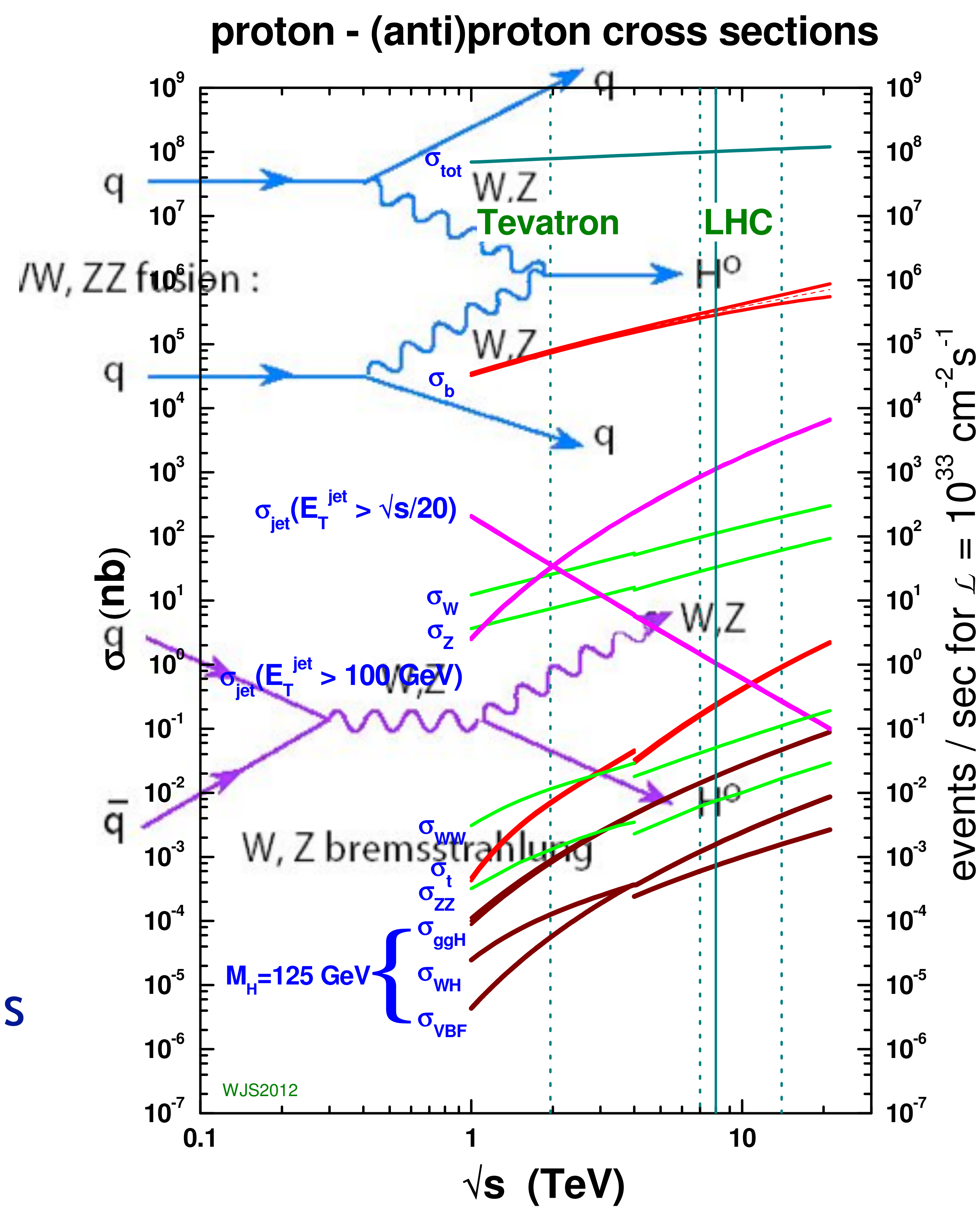
The Nobel Prize in Physics 2013
François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



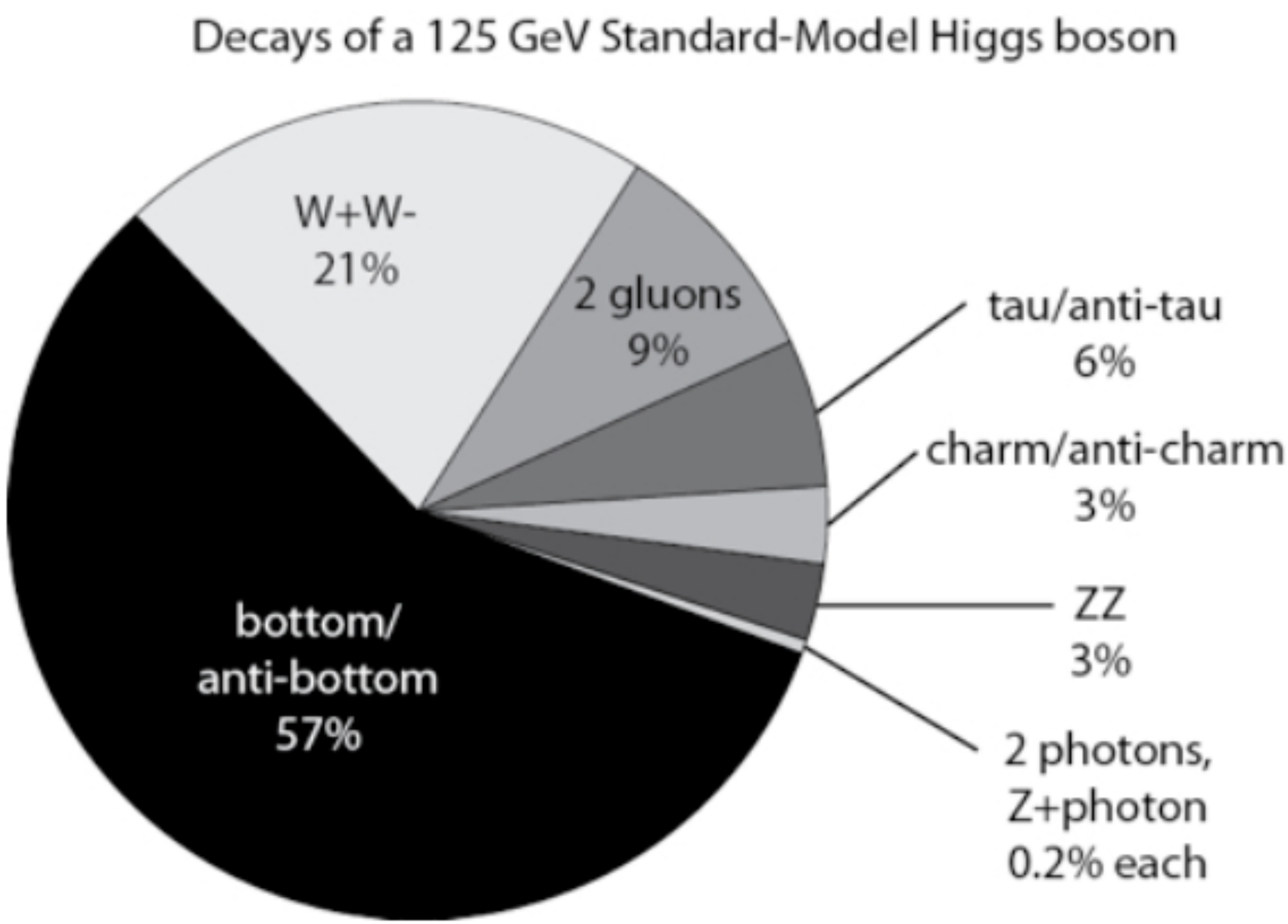
BEH Boson Production at the LHC





- One in 10^{12} proton-proton interactions creates a BEH boson.

BEH Boson Decay



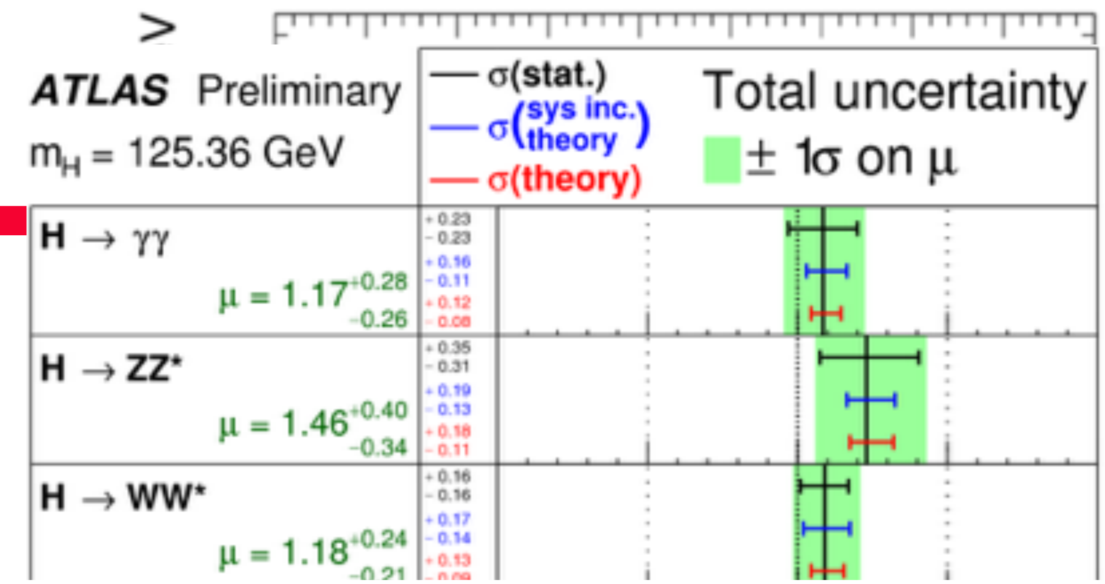
BEH Boson Results

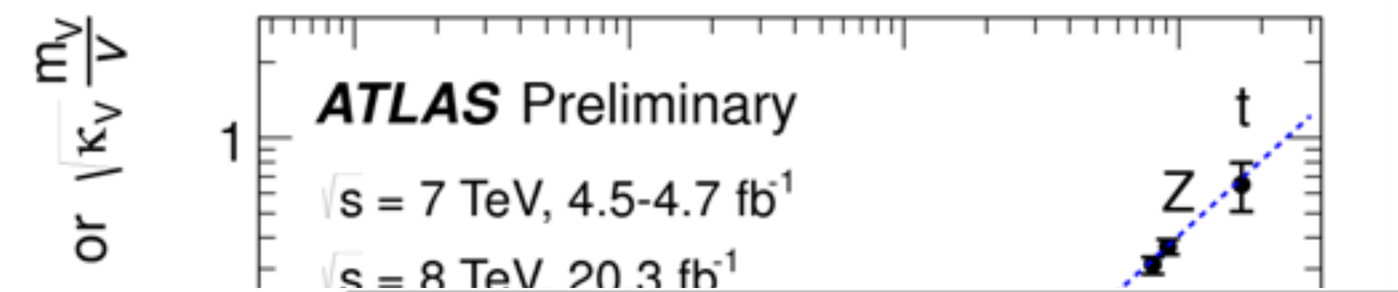
All observations from the LHC consistent with a Standard Model BEH boson with $m_H \sim \mathbf{125\ GeV}$.

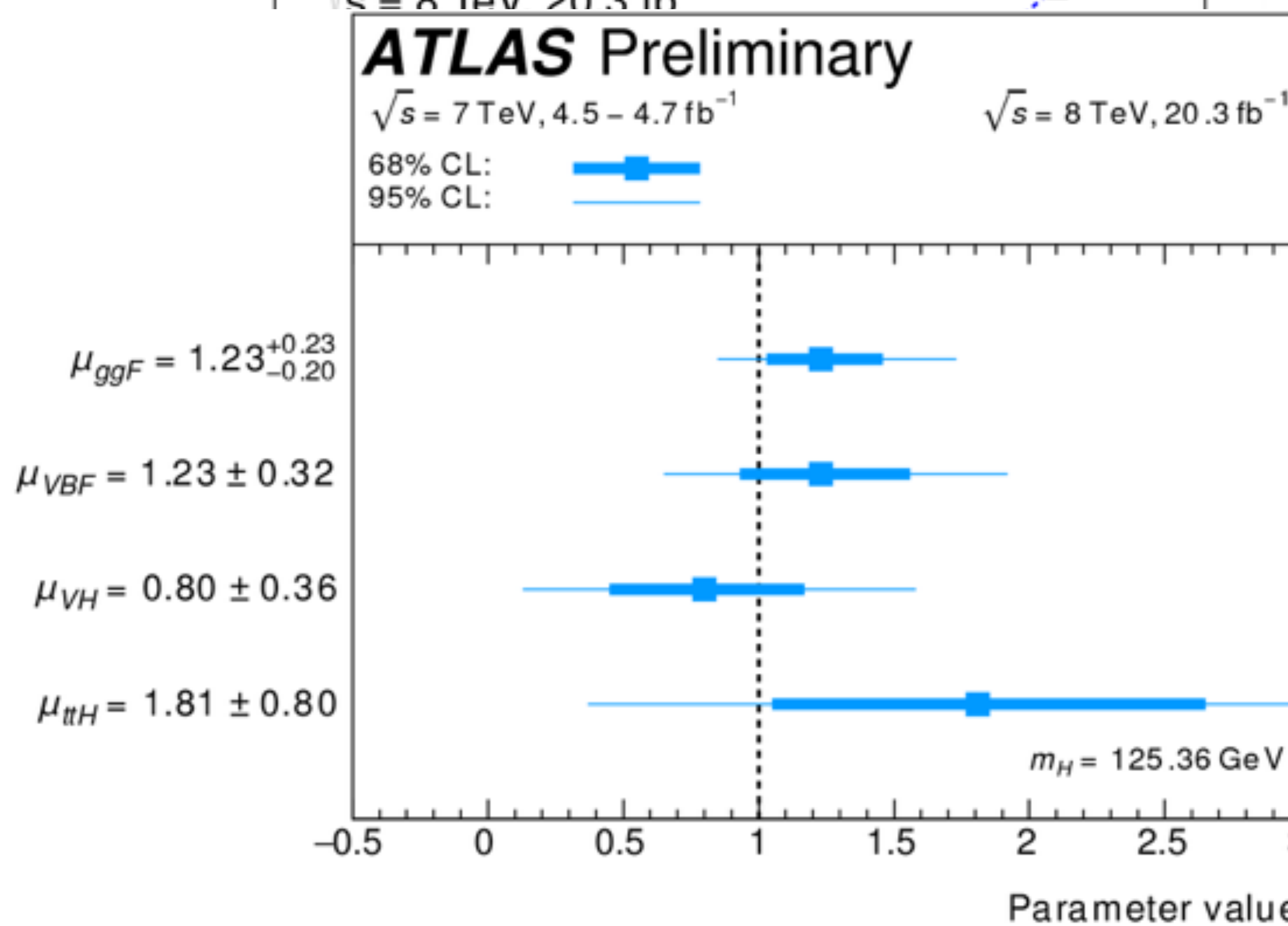
➡ m_H measured in ZZ and $\gamma\gamma$ final states consistent with $\mathbf{125\ GeV}$.

➡It decays like a SM BEH boson

➡It's produced like a SM BEH boson





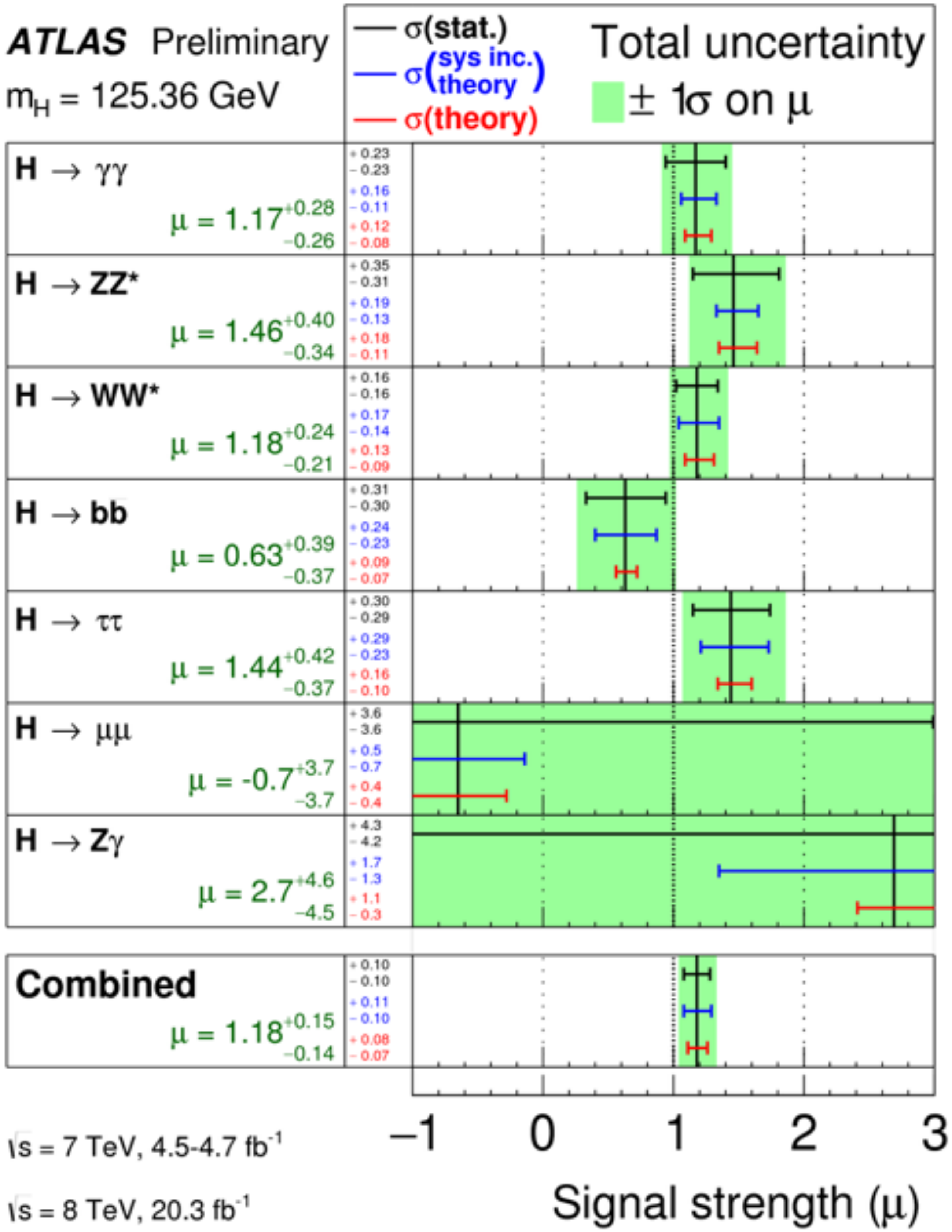


Phys. Rev. D. 90, 052004 (2014)

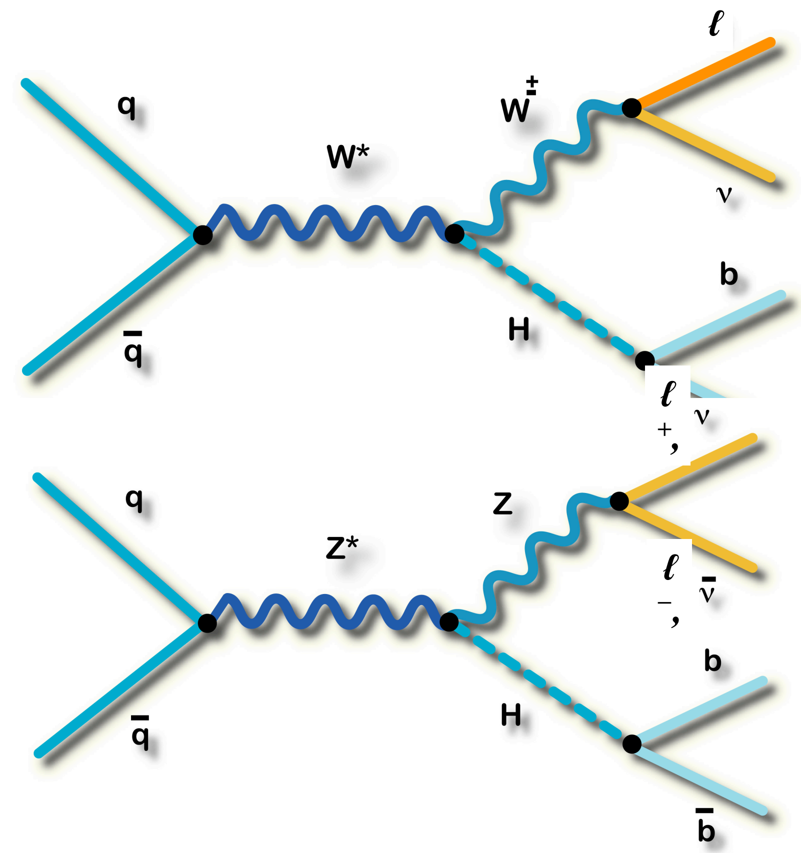
ATLAS-CONF-2015-007

arXiv:1503.07589

BEH → Leptons



ATLAS Preliminary
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.17 +0.28 −0.26
H → ZZ*
μ = 1.46 +0.40 −0.34
H → WW*
μ = 1.18 +0.24 −0.21
H → bb
μ = 0.63 +0.39 −0.37
H → ττ
μ = 1.44 +0.42 −0.37
H → μμ
μ = -0.7 +3.7 −3.7
H → Zγ
μ = 2.7 +4.6 −4.5
Combined
μ = 1.18 +0.15 −0.14
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
−1
0
1
2
3
Signal strength (μ)



$H \rightarrow b\bar{b}$ searches using WH and ZH

ATLAS-CONF-2012-161

$VH \rightarrow Vb\bar{b}$ Analysis Strategy

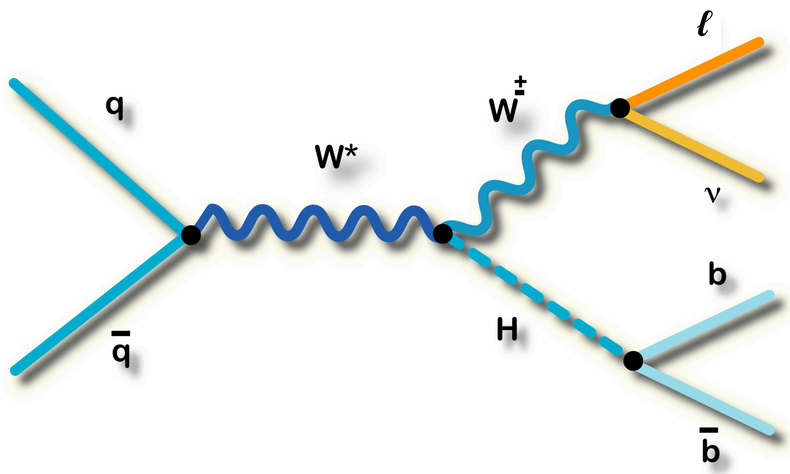
$H \rightarrow b\bar{b}$ produced in association with leptonically decaying W or Z

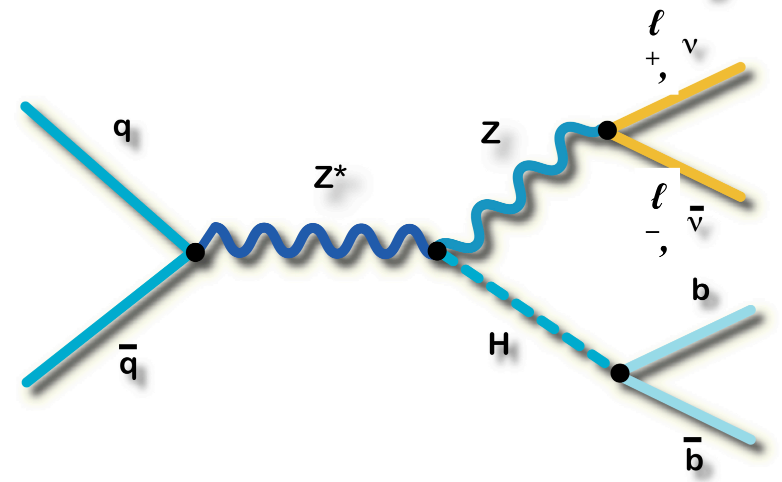
Three channels: based on exactly 0, 1 or 2 charged leptons, $\ell = \{e, \mu\}$

➡ Two or three jets with two b-tags

➡ To improve sensitivity analysis performed in bins of vector boson p_T ($p_T^{\ell\ell/\ell\nu}$ or E_T^{miss}): **16 bins in total**

➡ $m_{b\bar{b}}$ used as discriminating variable





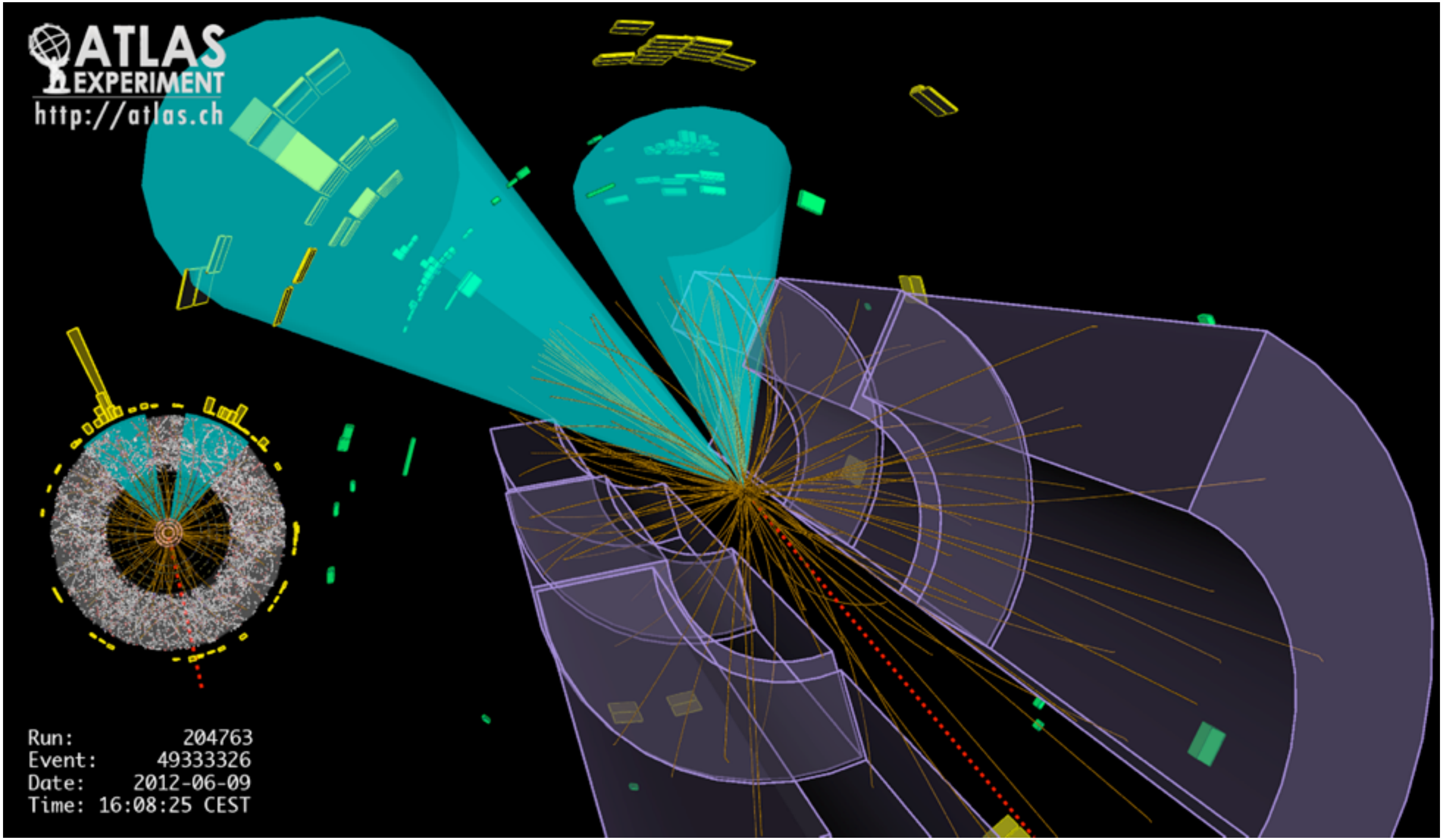
zero lepton ($ZH \rightarrow \nu\bar{\nu}b\bar{b}$)
- No electrons or muons
- $E_T^{miss} > 120$ GeV

one lepton ($WH \rightarrow \ell\nu b\bar{b}$)
- Exactly one high-p_T lepton
- $E_T^{miss} > 25$ GeV
- $40 < m_T^{\ell\nu}$ / GeV < 120

two leptons ($ZH \rightarrow \ell^+\ell^- b\bar{b}$)
- Exactly two high-p_T leptons
- opposite charge
- $E_T^{miss} < 60$ GeV
- $83 < m_{\ell\ell}$ / GeV < 99

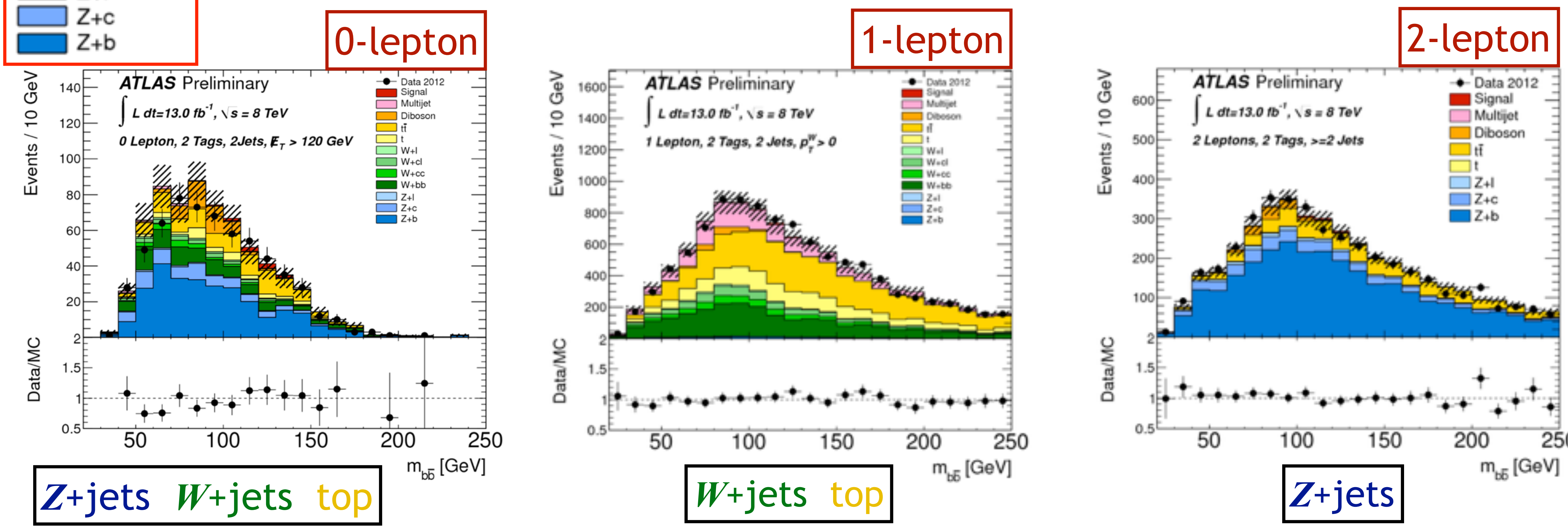
$ZH \to \nu\bar{\nu}\, b\bar{b}$ candidate event

- $m_{b\bar{b}} = 123$ GeV $E_T^{miss} = 271$ GeV



$VH \to Vb\bar{b}$ Backgrounds and Systematics

- Background shapes from simulation, normalised using data
- Multijet bkg determined by data-driven techniques
- $WZ(Z \to b\bar{b})$ & $ZZ(Z \to b\bar{b})$ background normalisation and shape from simulation



Main uncertainties:

➡ b-/c-tagging ; jet energy scale & resolution ; MC statistics

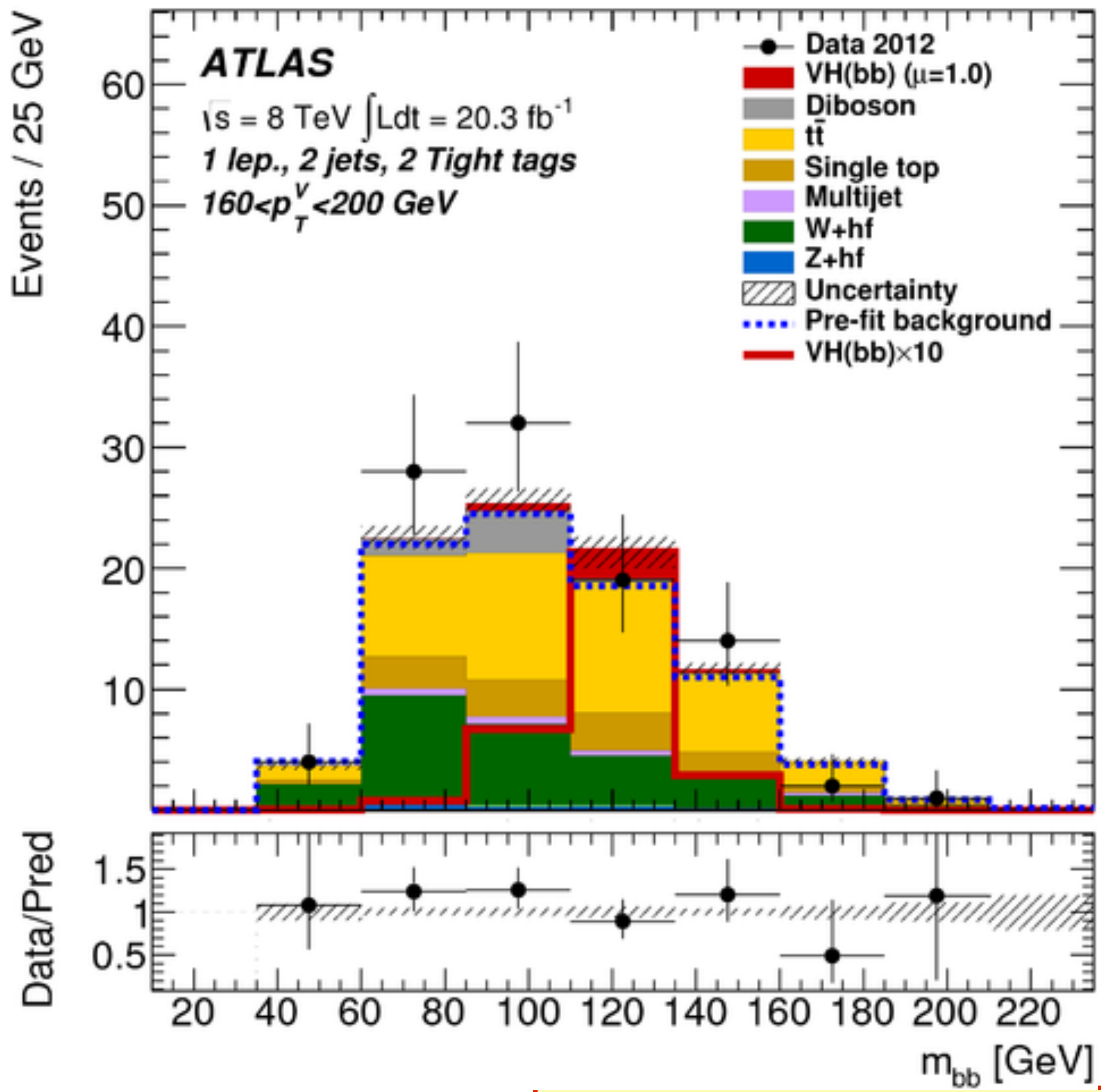
➡ Systematics are constrained by fitting m_{bb} distributions to the data

m_{bb} distributions at $\sqrt{s} = 8$ TeV

- Highest $p_T^{(W,Z)}$ bins are the most sensitive to Higgs signal

$160 < p_T^{(W,Z)}/\mathrm{GeV} < 200$

1-lepton



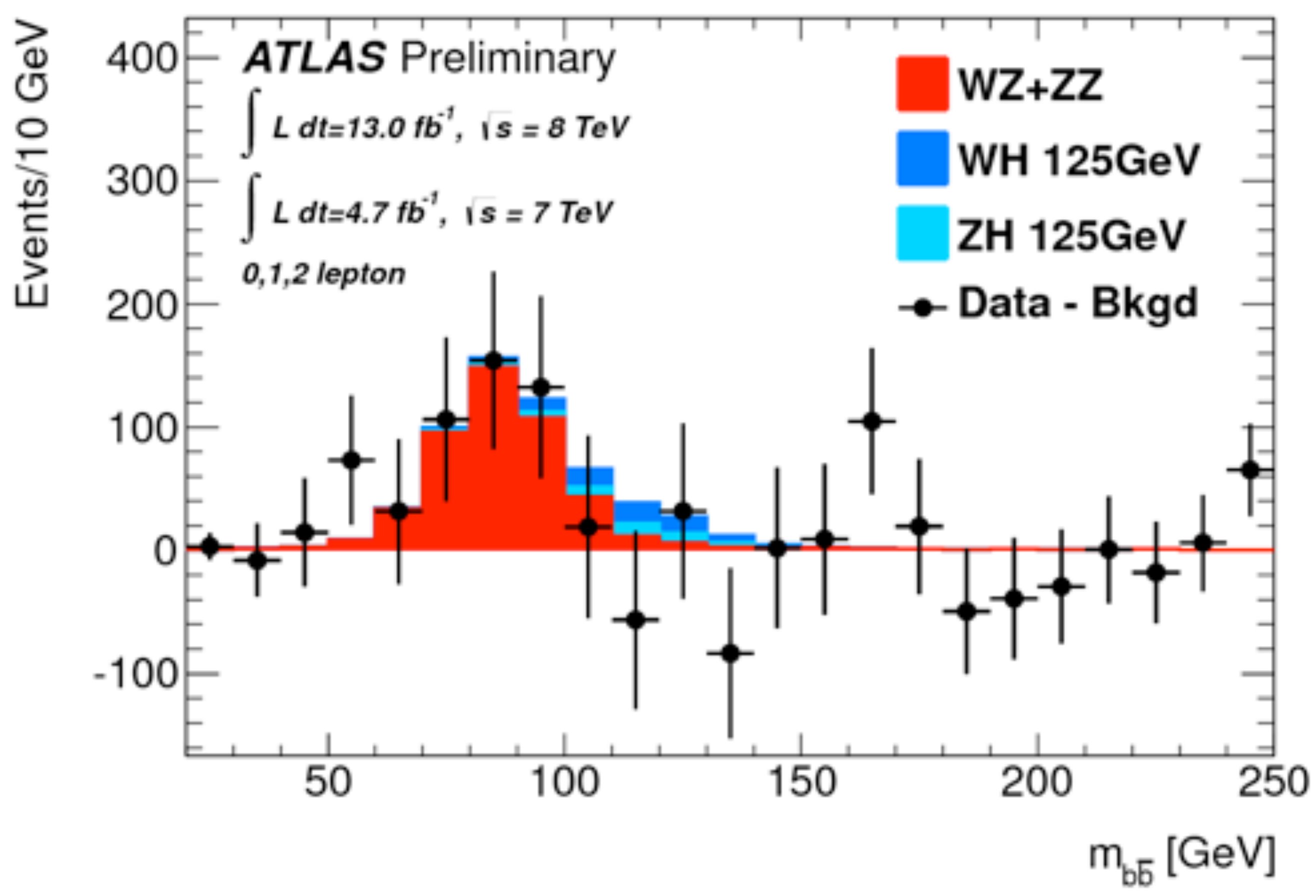
No observation of deviation from SM backgrounds

95% CL limit on σ/σ_{SM} for m_H=125 GeV:

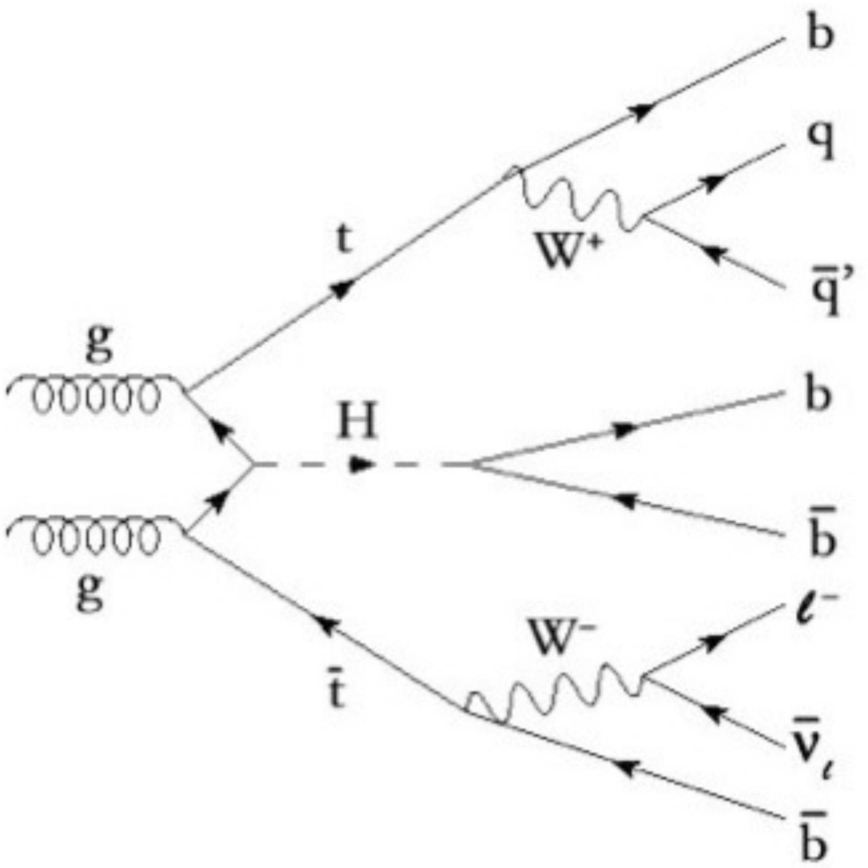
1.4 (measured); **2.6** (expected)

$VH \to Vb\bar{b}$ cross check: observation of $VZ \to Vb\bar{b}$

- WZ, ZZ production with $Z \to b\bar{b}$ similar signature, but $5\times$ cross-section
- Perform a separate fit to find $Z \to b\bar{b}$ and validate the analysis
  - ➡ Backgrounds - except VZ & VH are subtracted
  - ➡ Uses full $p_T^{W,Z}$ range, performed individually for 0, 1, 2-lepton channels and for $\sqrt{s}=7, 8$ TeV



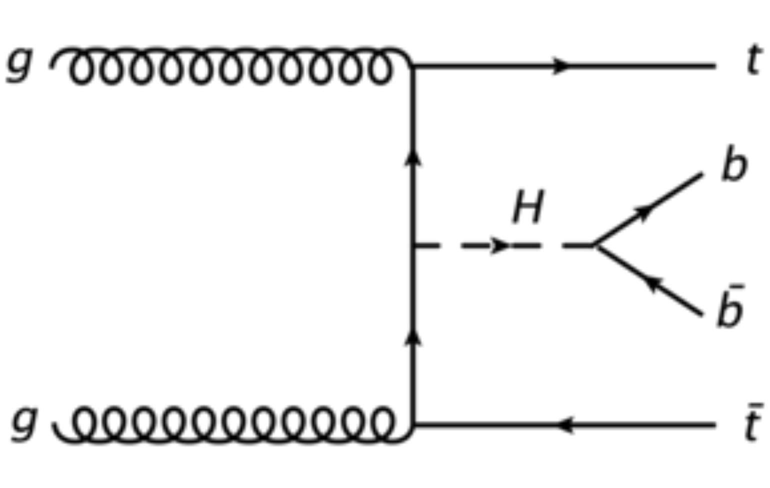
Result: $\sigma/\sigma_{SM} = \mu_D = 1.09 \pm 0.20$ (stat) ± 0.22 (syst). Significance of 4.0σ

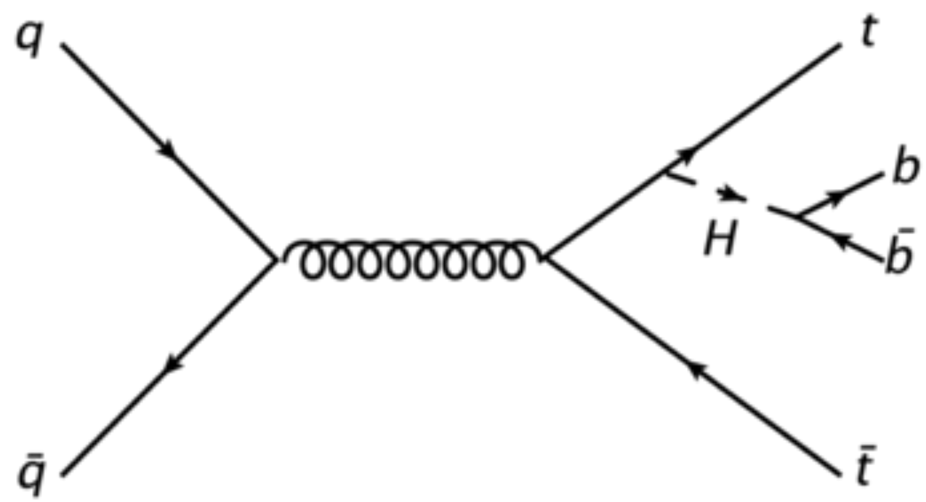


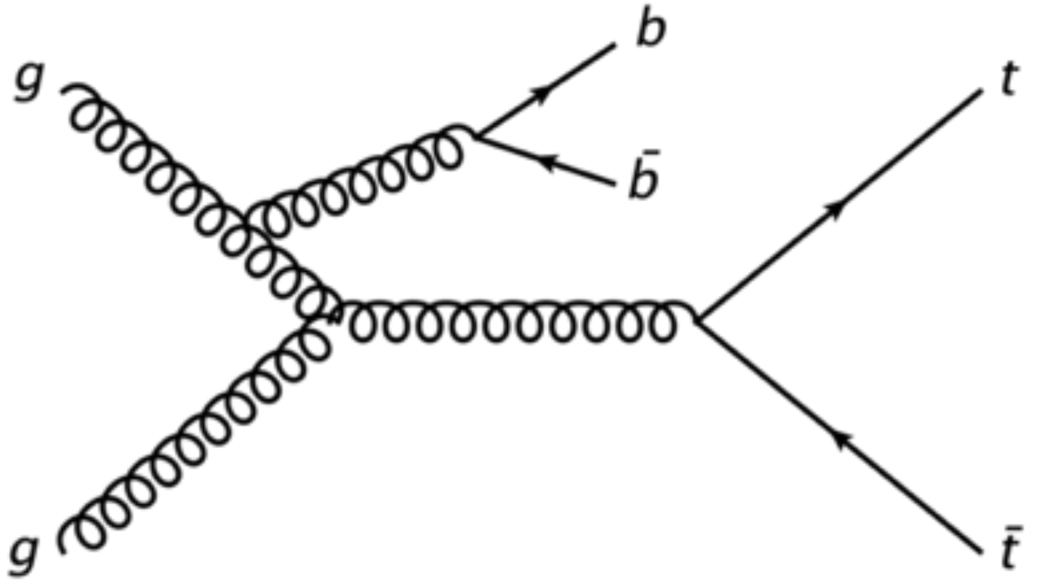
$t\bar{t}H, H \to b\bar{b}$ searches

arxiv:1503.05066

$t\bar{t}H, H \to b\bar{b}$





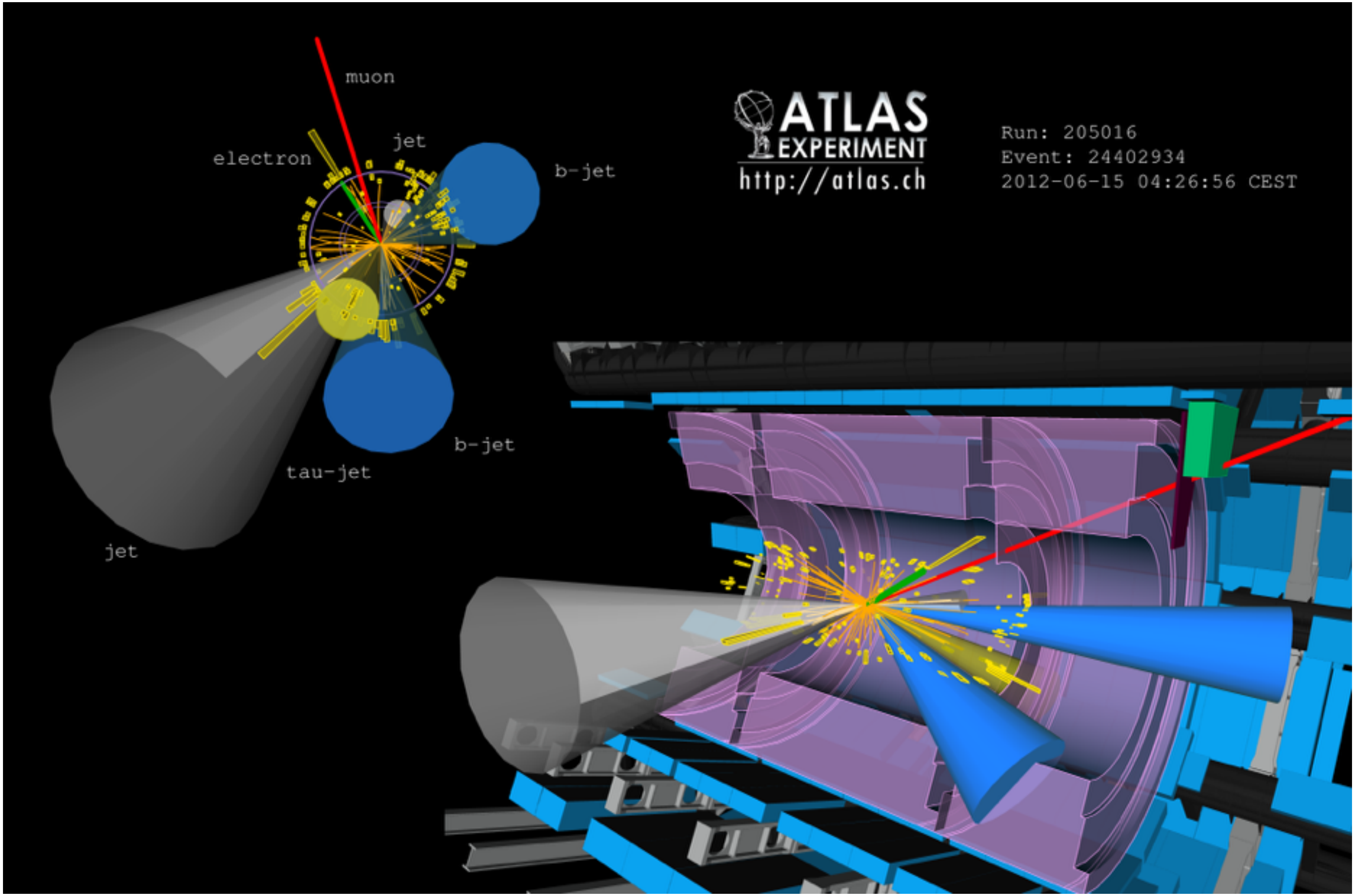


- ***t→Wb***; ***W*** decays to ***2 "light jets"*** or ***ℓν***
- Select events with 1 or 2 e or μ
- Bins of number of b-tags and number of jets are used to characterise events.

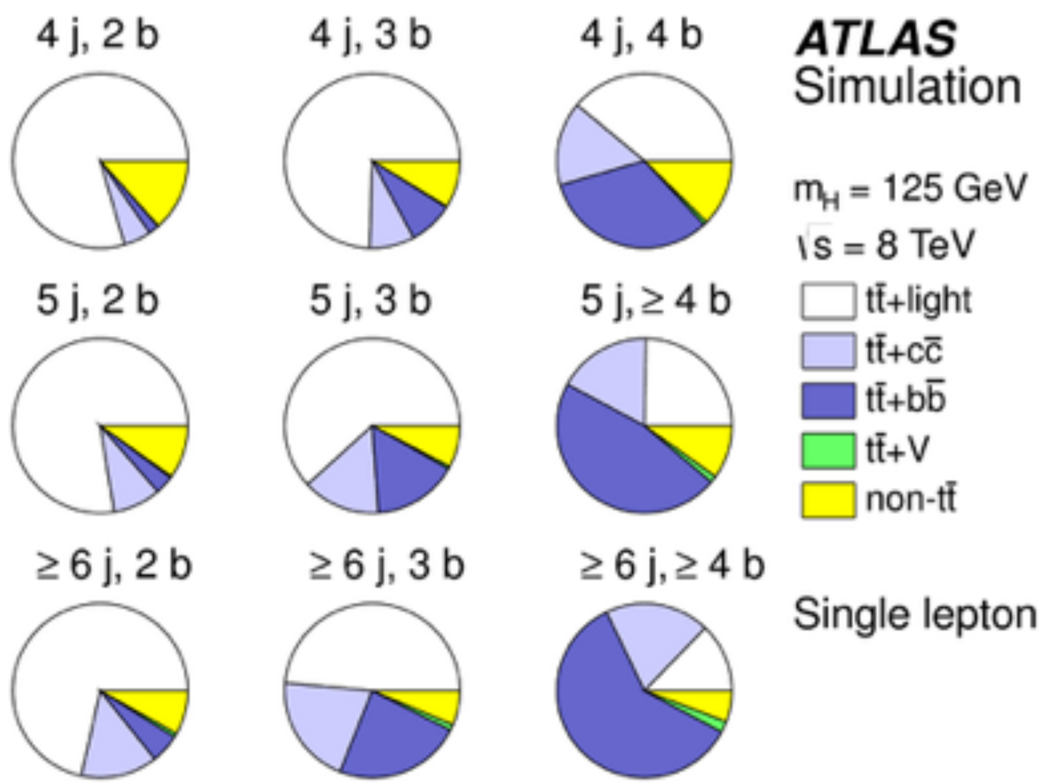
- Discriminating variables are:
  - H_T^{had}, scalar sum of jet p_{T}
  - neural net, NN

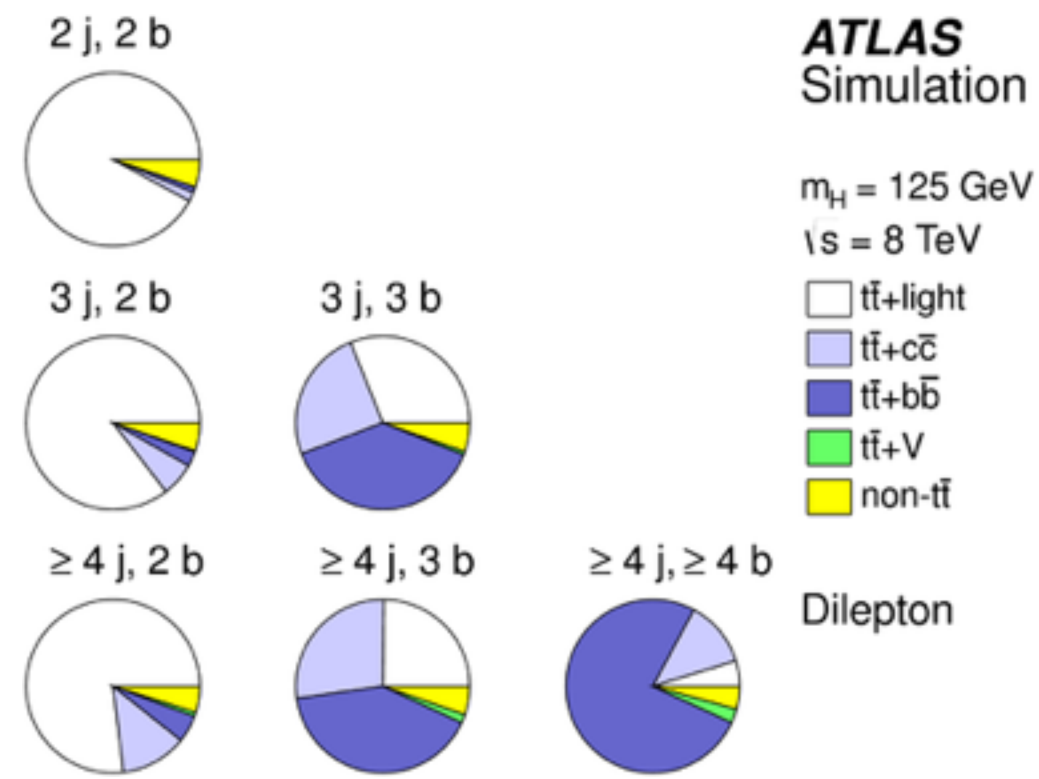
ttH, $H \rightarrow b\bar{b}$ candidate event

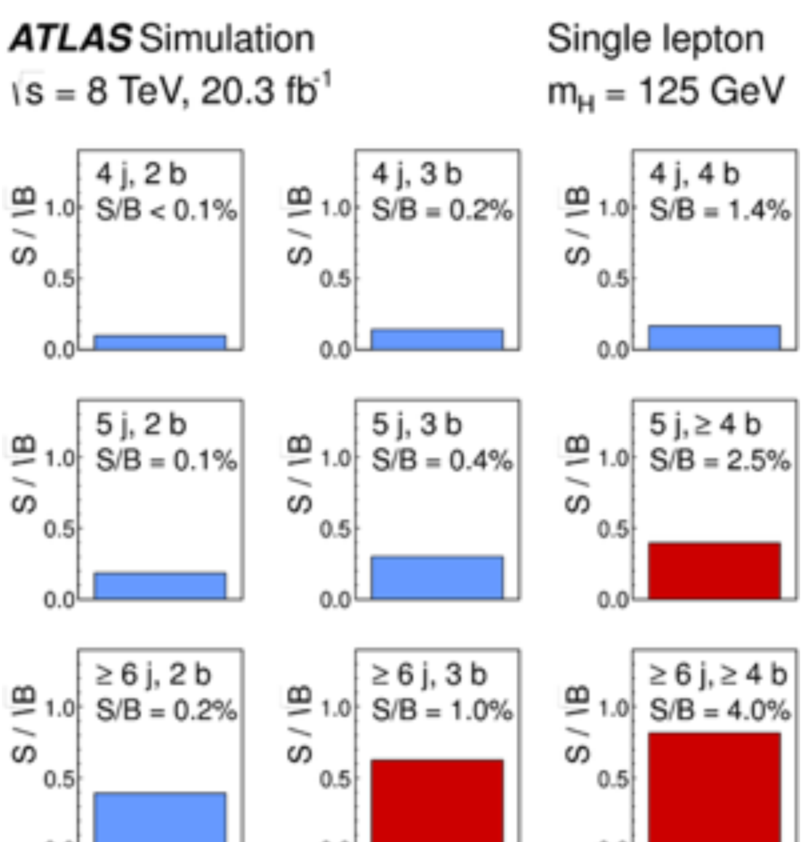
arxiv:1503.05066

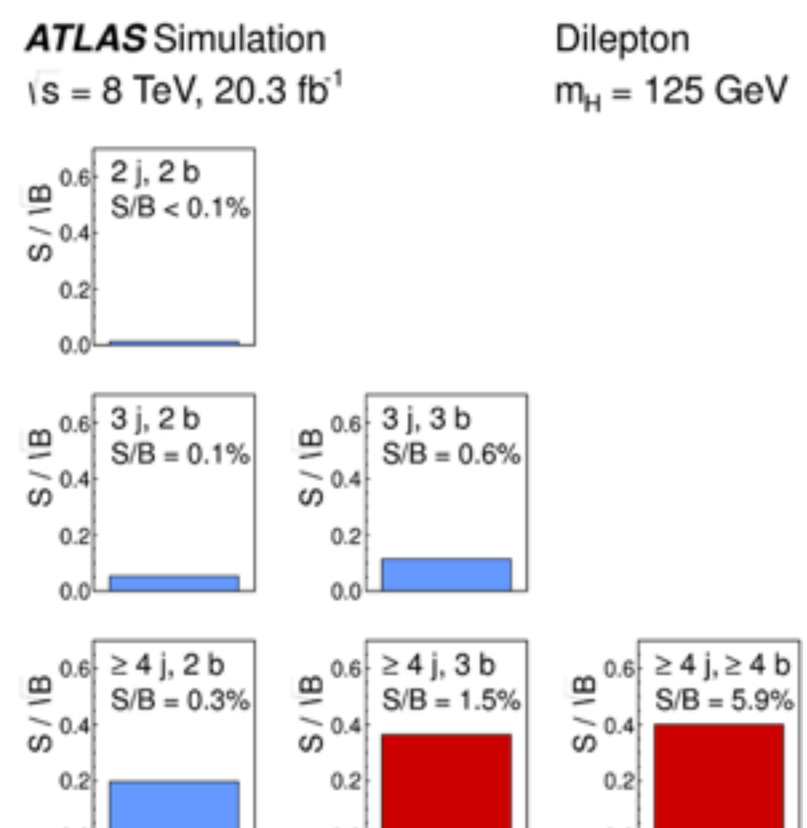


$t\bar{t}H, H \rightarrow b\bar{b}$ background challenge



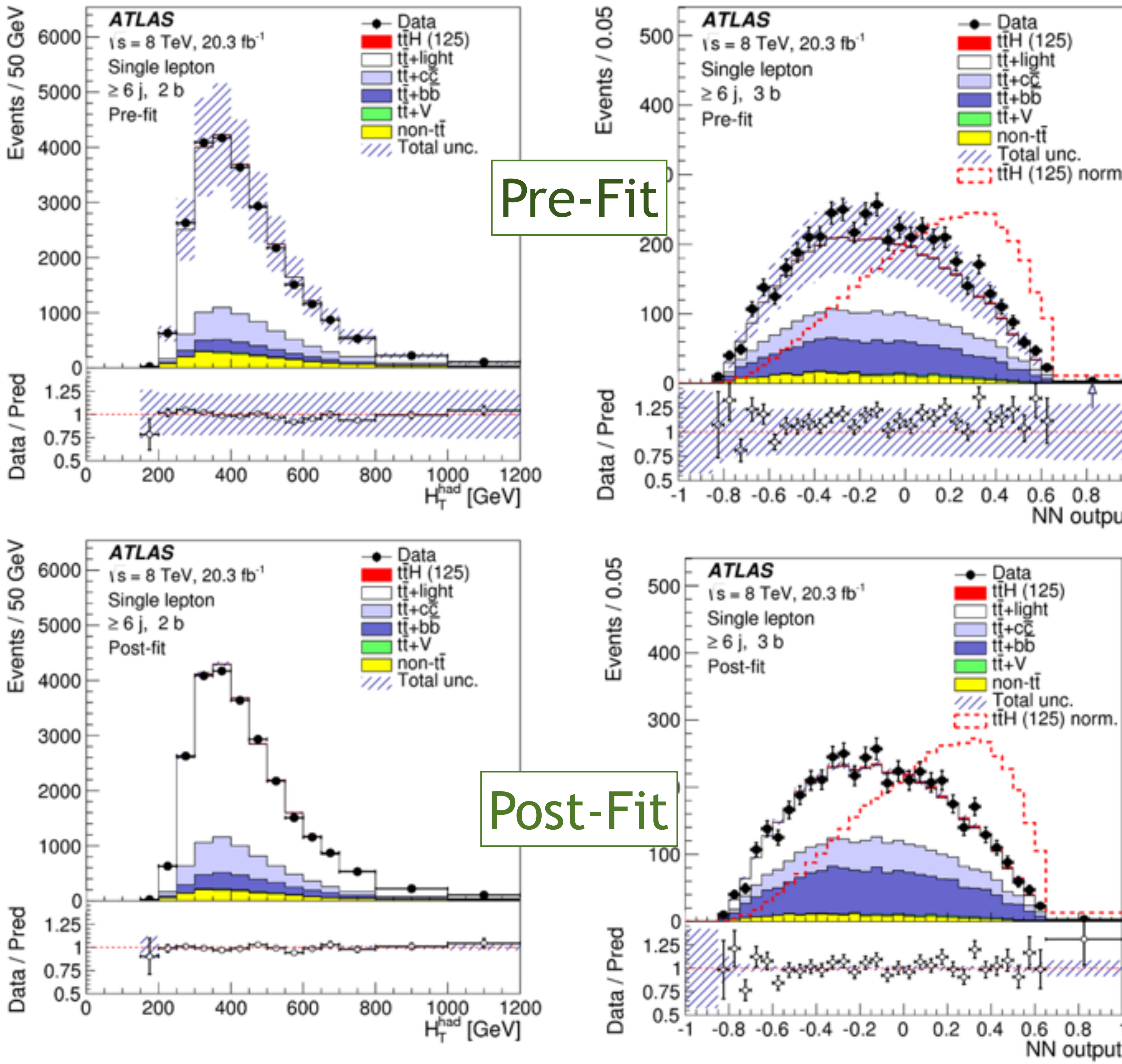






$t\bar{t}H, H \to b\bar{b}$ Fitting

- Systematics are constrained by fitting the distributions to the data
- Normalisations and shapes are allowed to vary in NN and H_T^{had}.



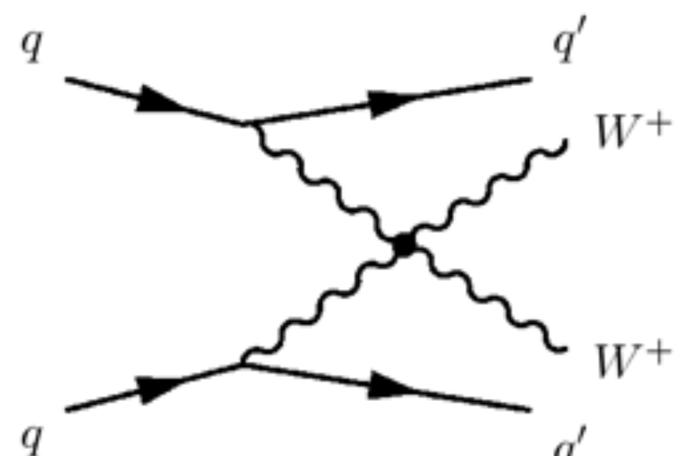
95% CL limit on σ/σ_{SM} for m_H=125 GeV:

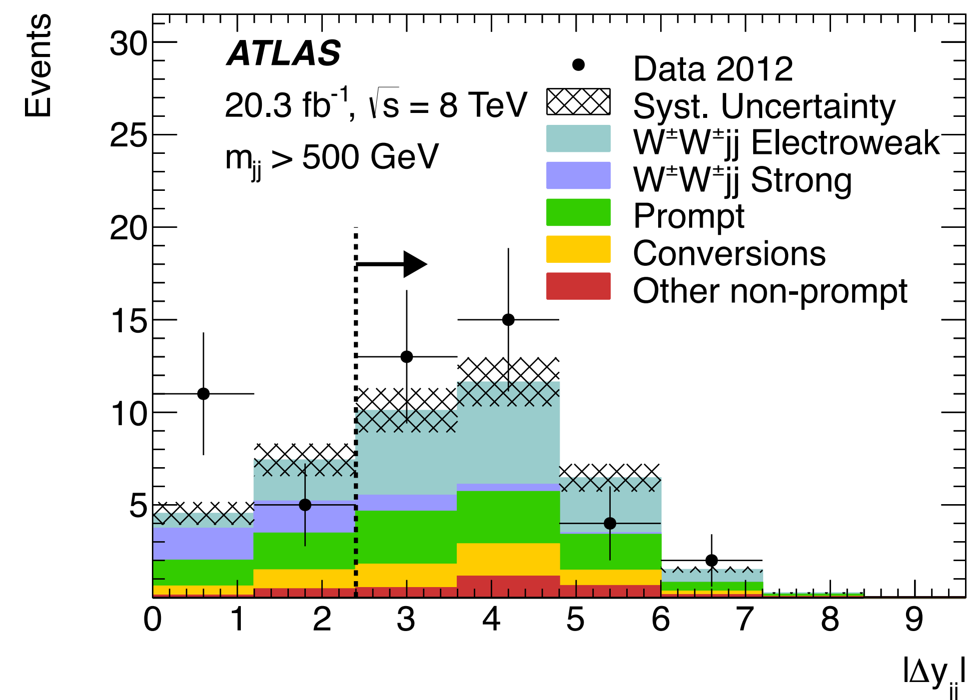
3.4 (measured);
2.2 (expected)

First Evidence for Weak Boson Scattering

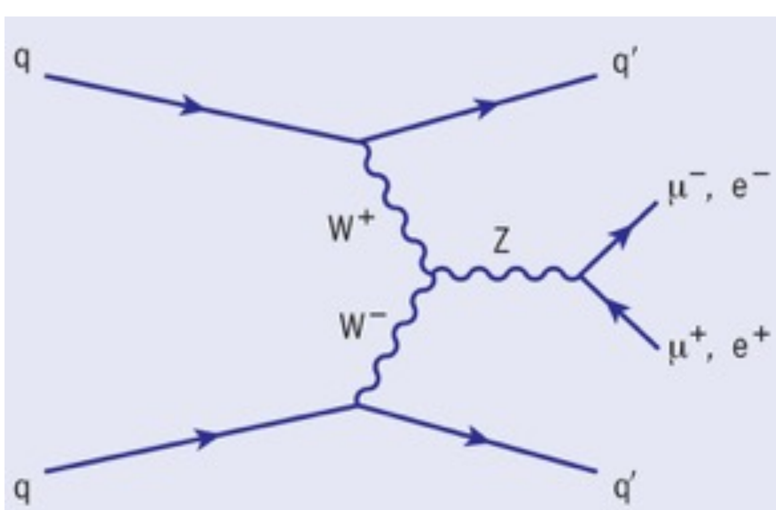
arXi:1401.7610 arXiv:1405.6241

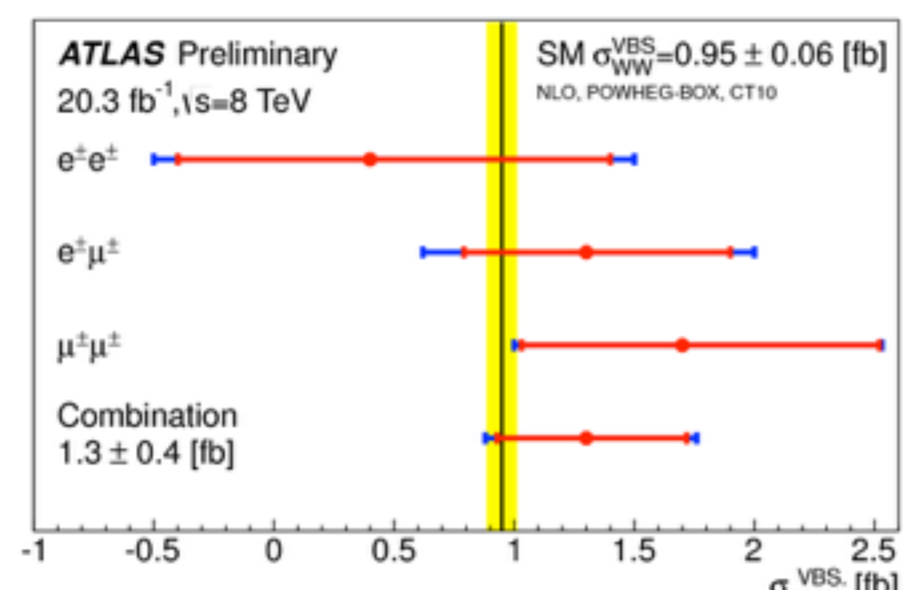
- Same sign *ee, eμ, μμ* signature
  - ATLAS observes **4.5σ** evidence for $W^{\pm}W^{\pm}jj$ production





- Also observed *Zjj* production consistent with $W^{+}W^{-}jj \rightarrow Zjj$





First Evidence for Weak Boson Scattering

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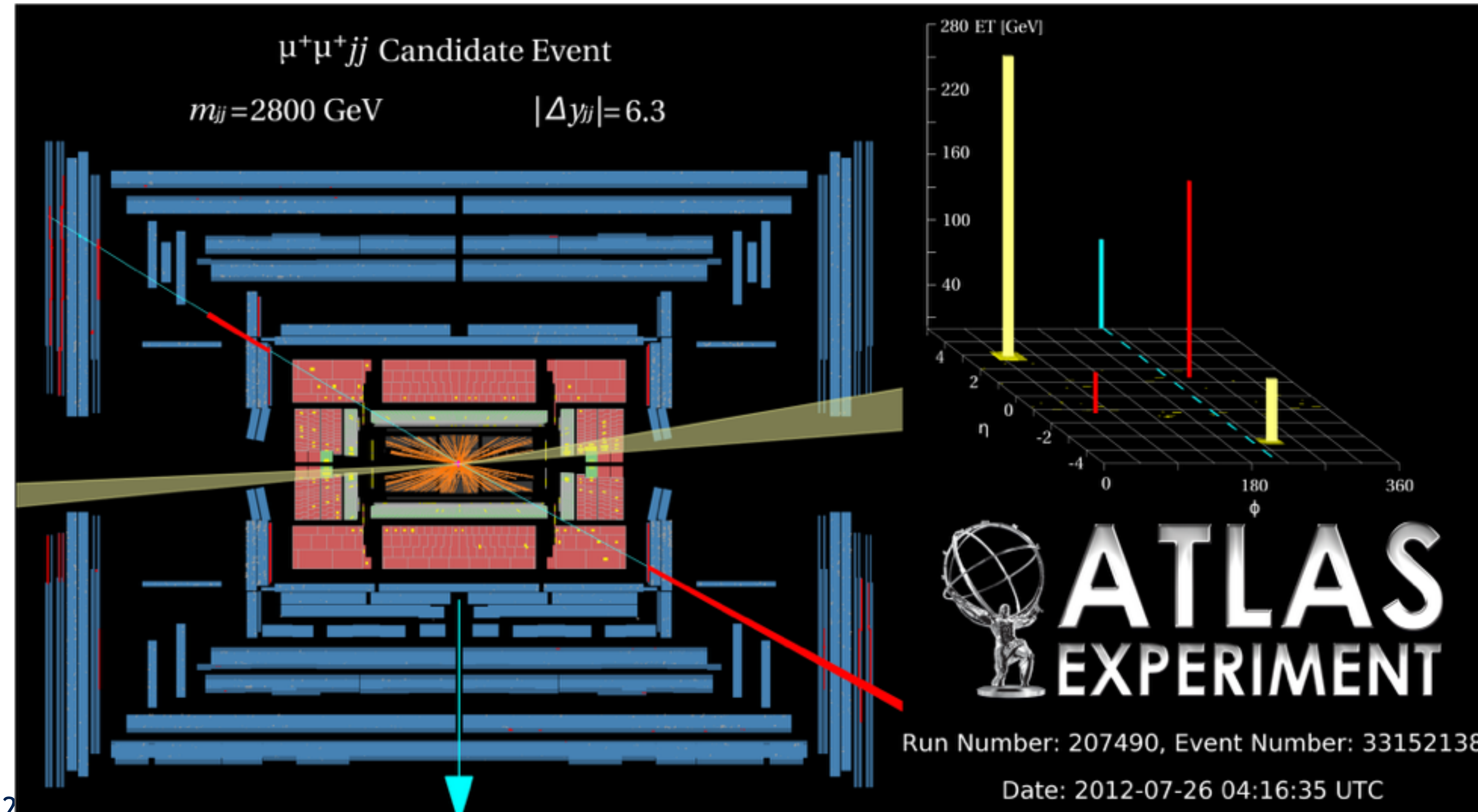
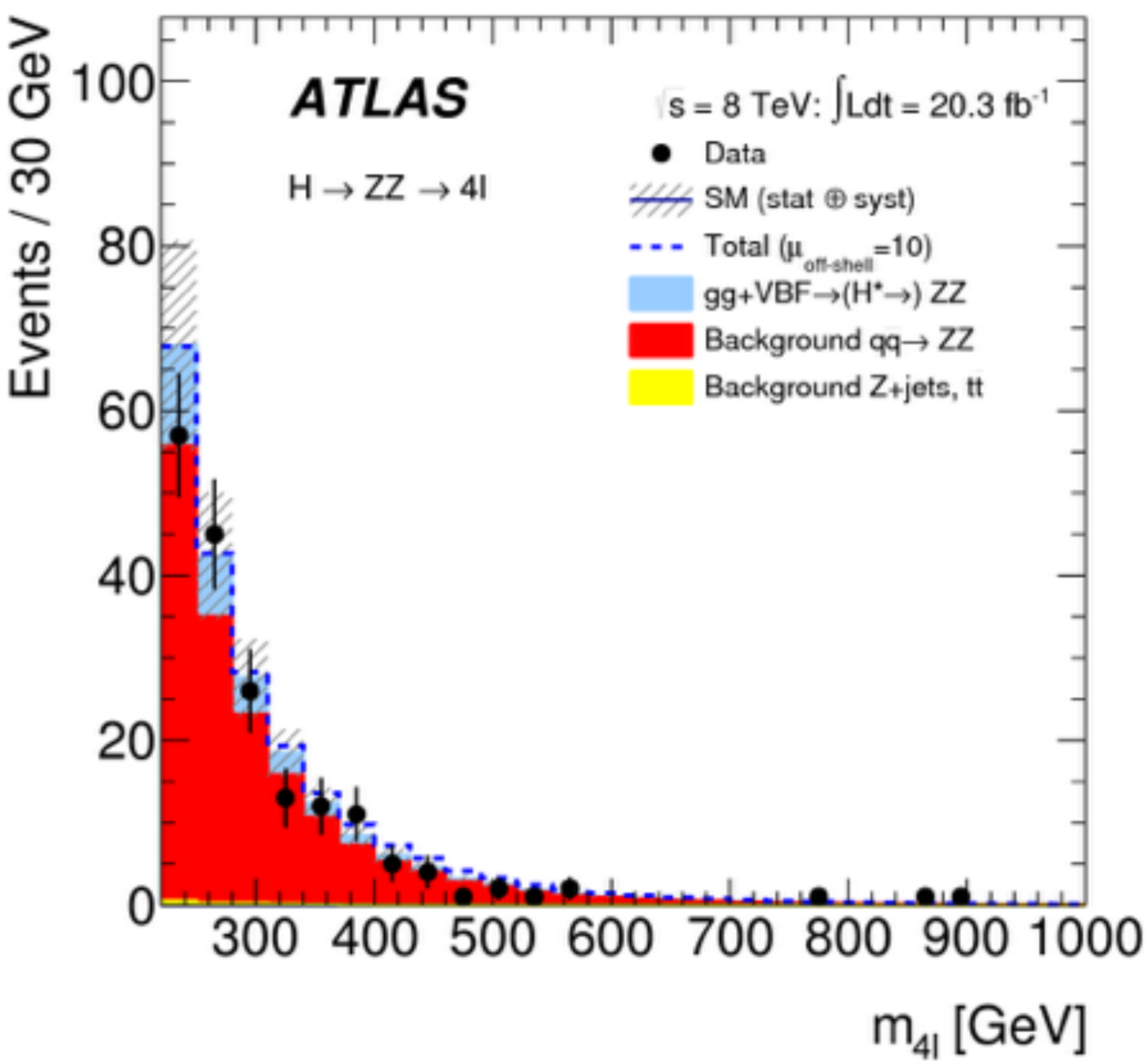


Indirect limit on BEH boson width

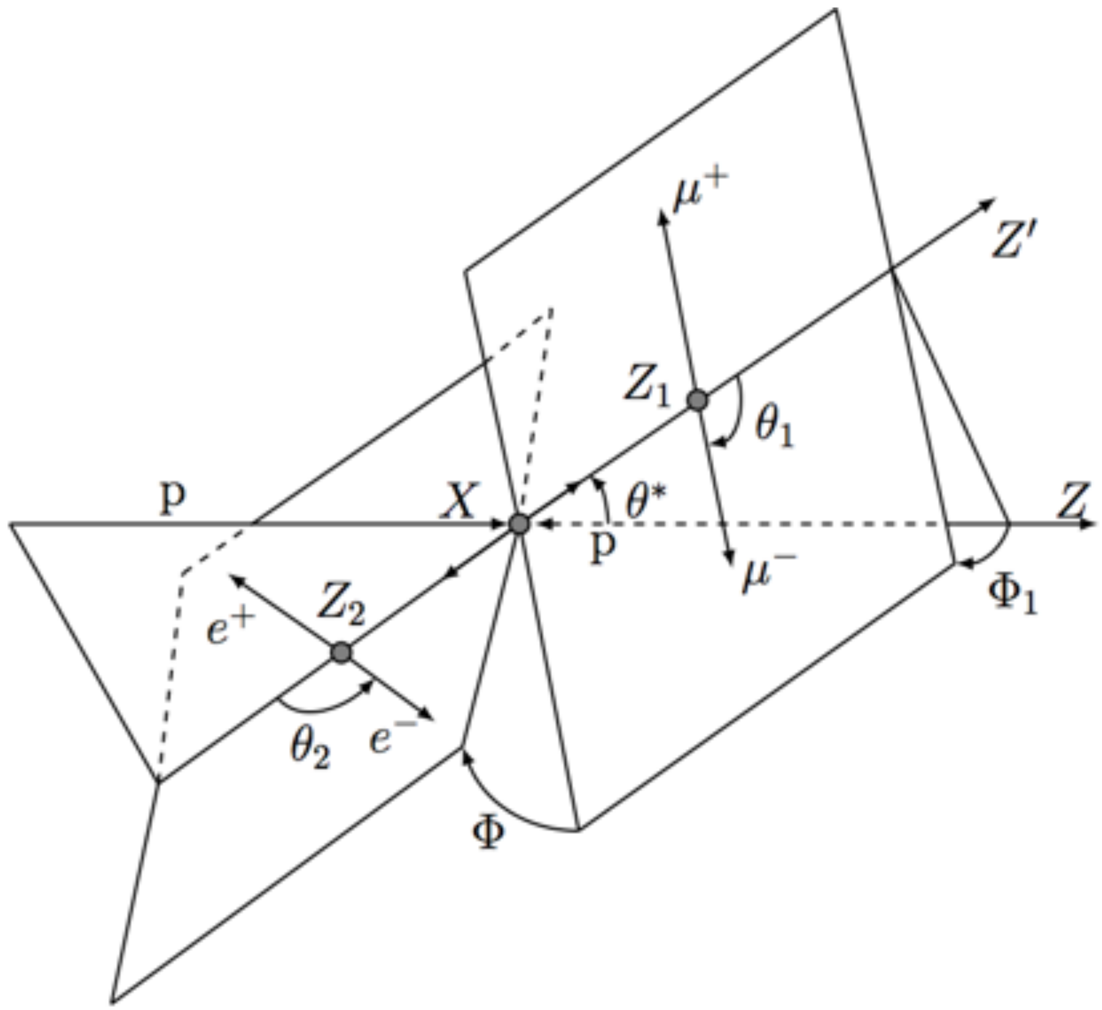
- In the SM, $\Gamma(H_{125}) = 4$ **MeV**
- The BEH boson prefers to decay into WW and ZZ.
- However as BEH boson mass is **125 GeV**, at least one of the W or Z must be off-shell.
- The number of events at high m_{ZZ}, m_{WW} depends on the actual width $\Gamma(H)$.
- Look for events at high m_{ZZ}, m_{WW}.

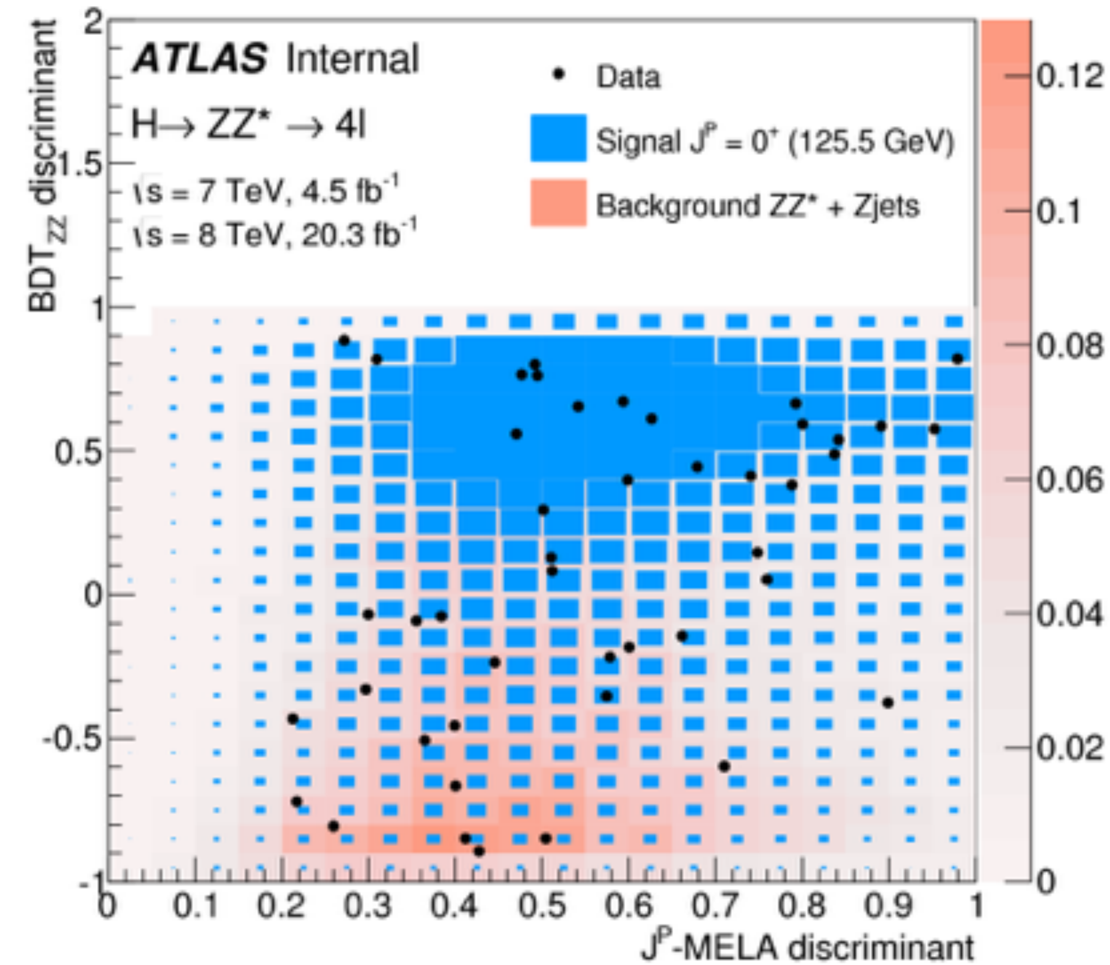


- **$\Gamma(H)$ observed $< 6.5 \times \Gamma(H)$ SM at 95% CL**

BEH Boson Spin

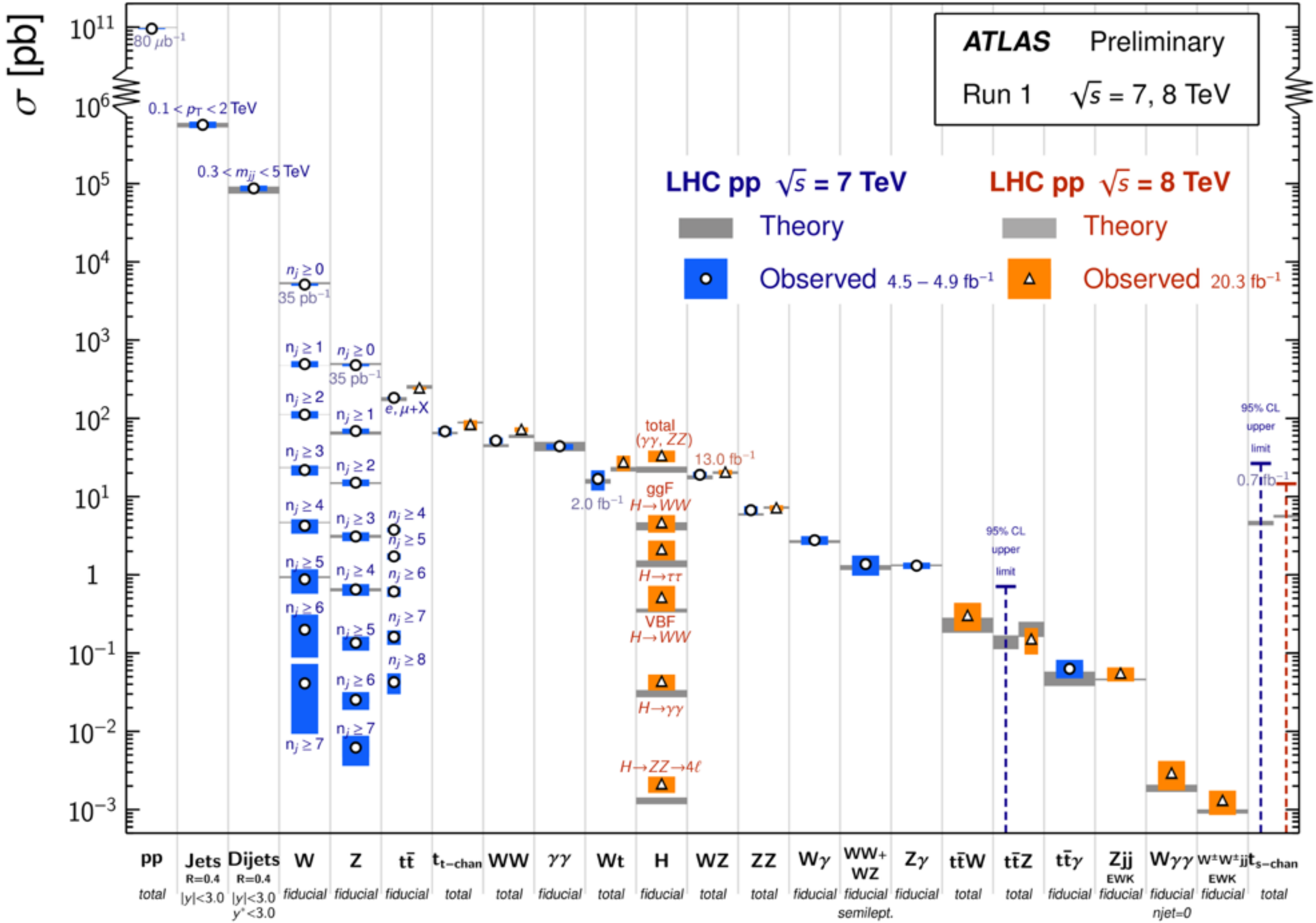
ATLAS-CONF-2015-008





- "The results presented here exclude all of the alternative models in favour of the SM BEH boson hypothesis at more than 99% confidence level."

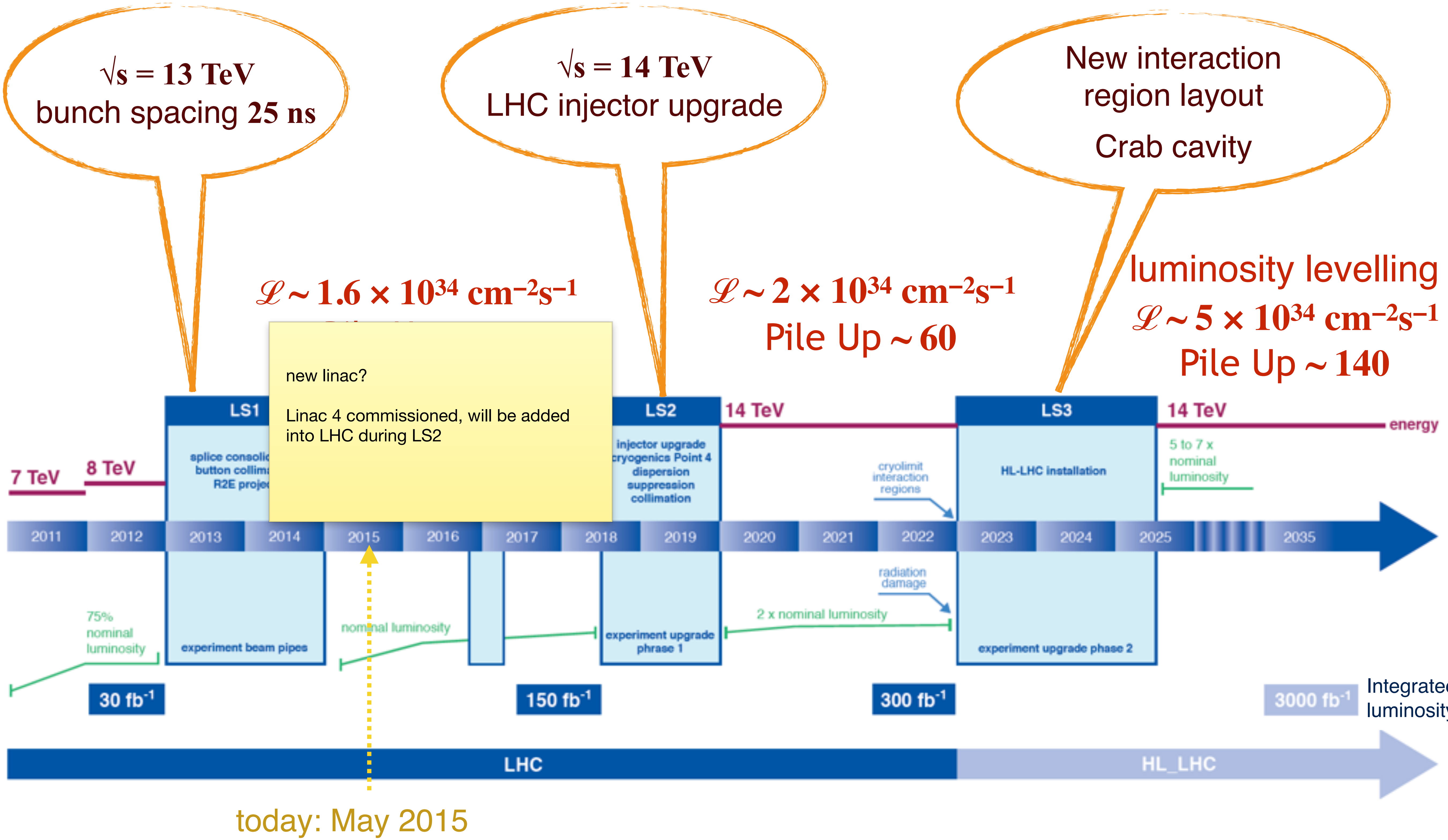
Standard Model Production Cross Section Measurements



Beyond Run 1

LHC → Run2 → HL-LHC

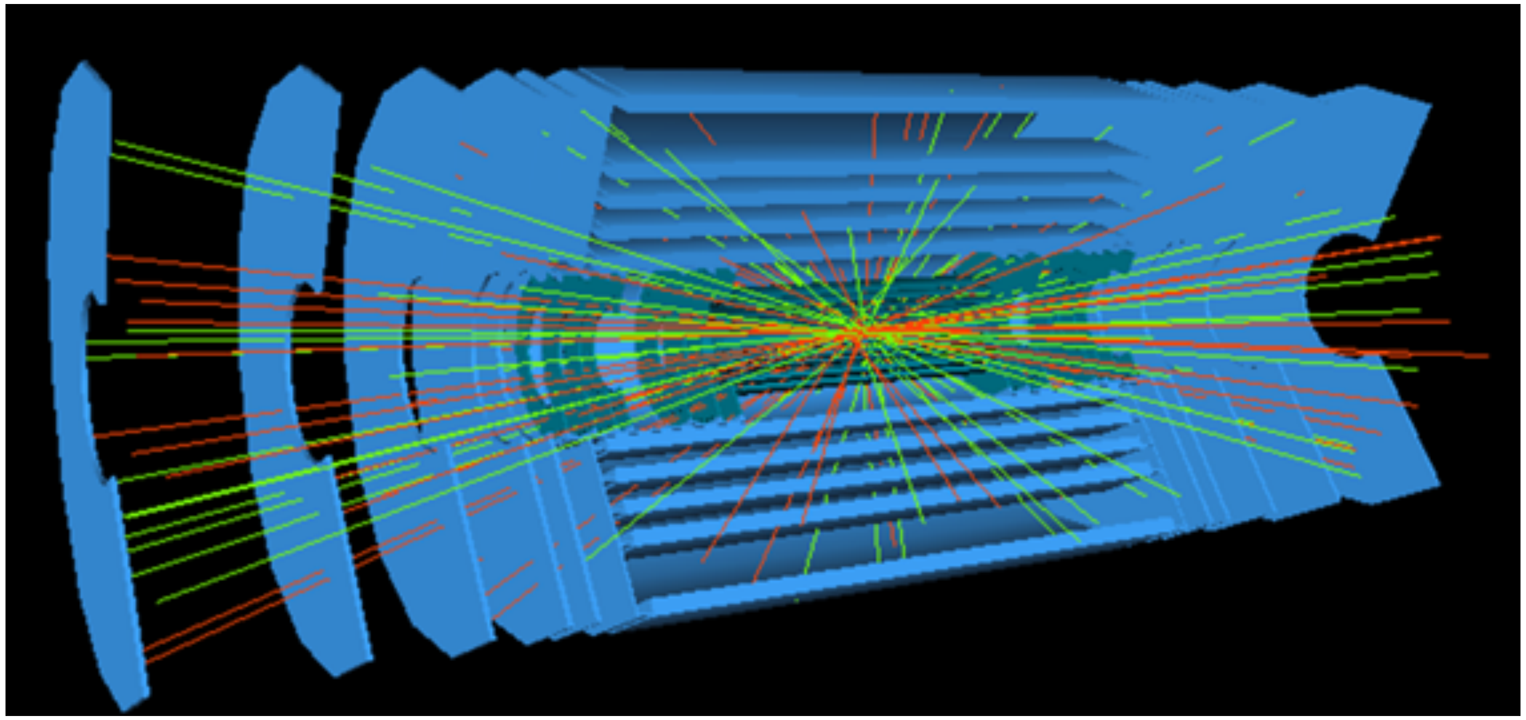
http://hilumilhc.web.cern.ch/about/hl-lhc-project



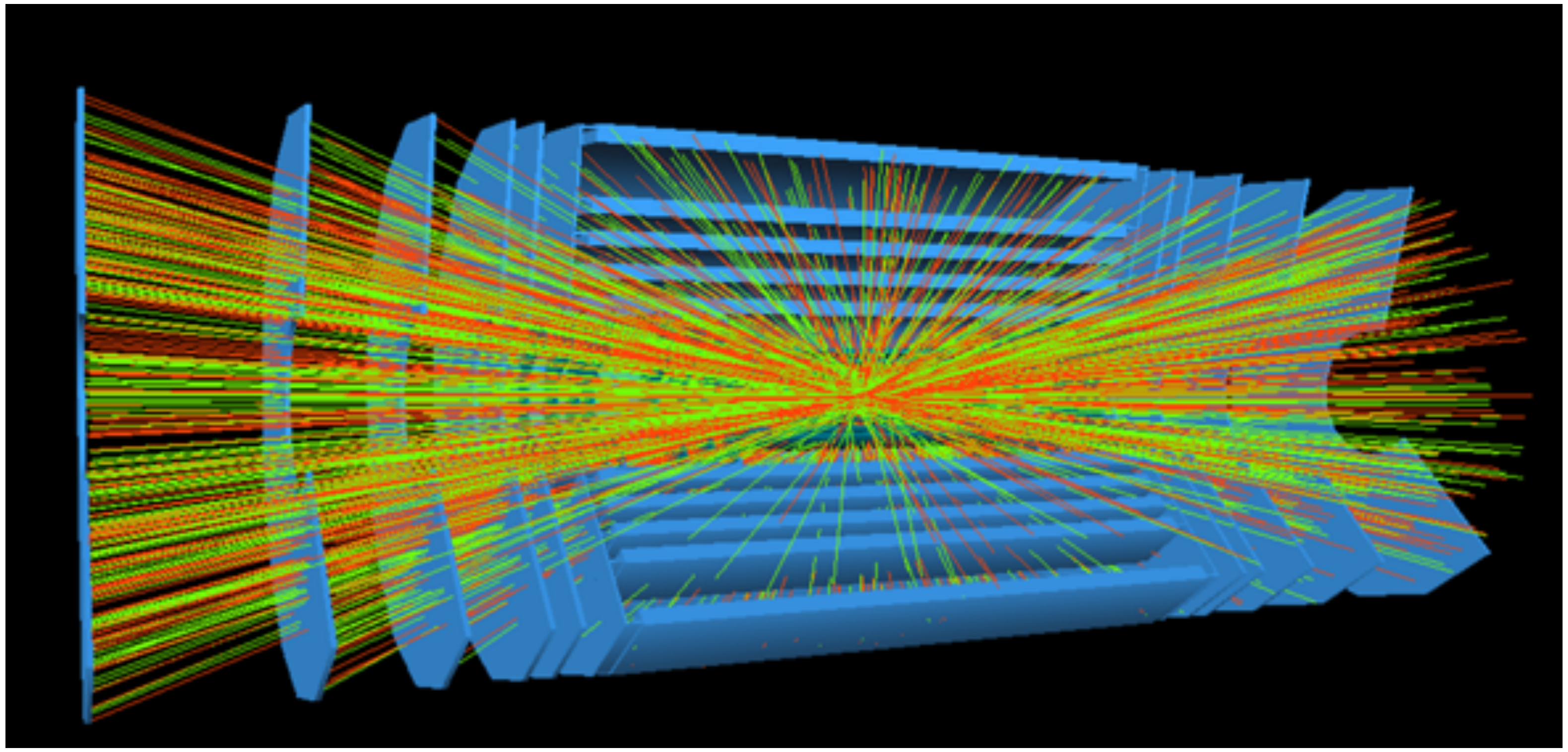
The Challenge of Pileup

- Pileup = number of proton-proton collision per bunch crossing

Simulated pileup in ATLAS tracker



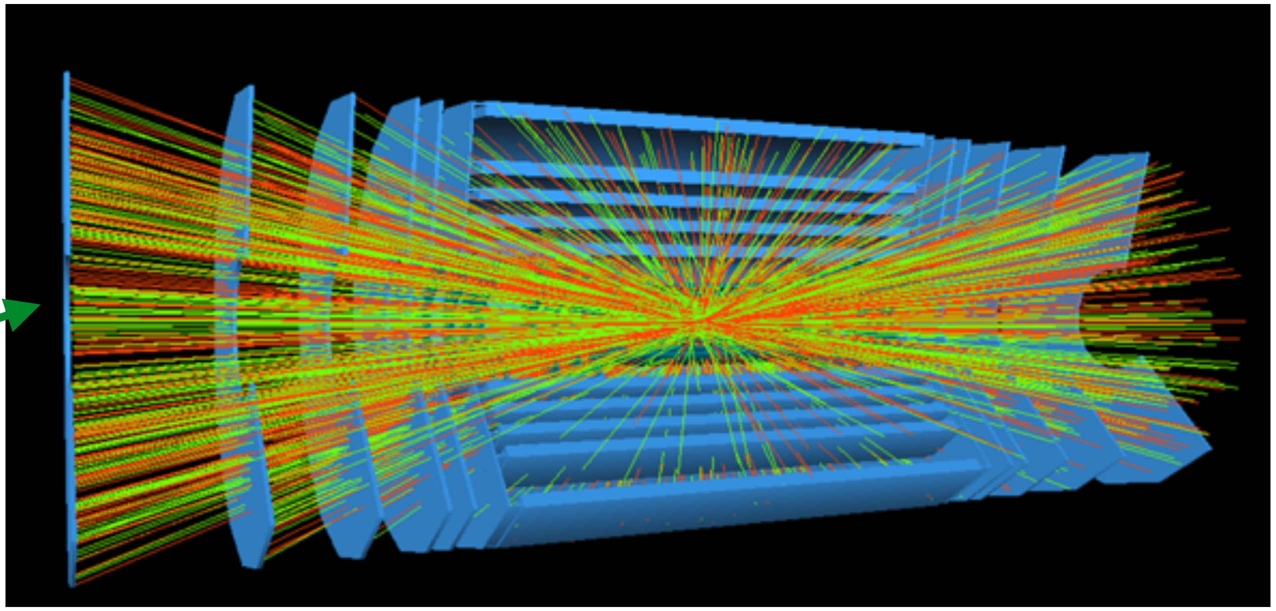
Run 1
Pile up of 23



HL-HLC
Pile up of 230

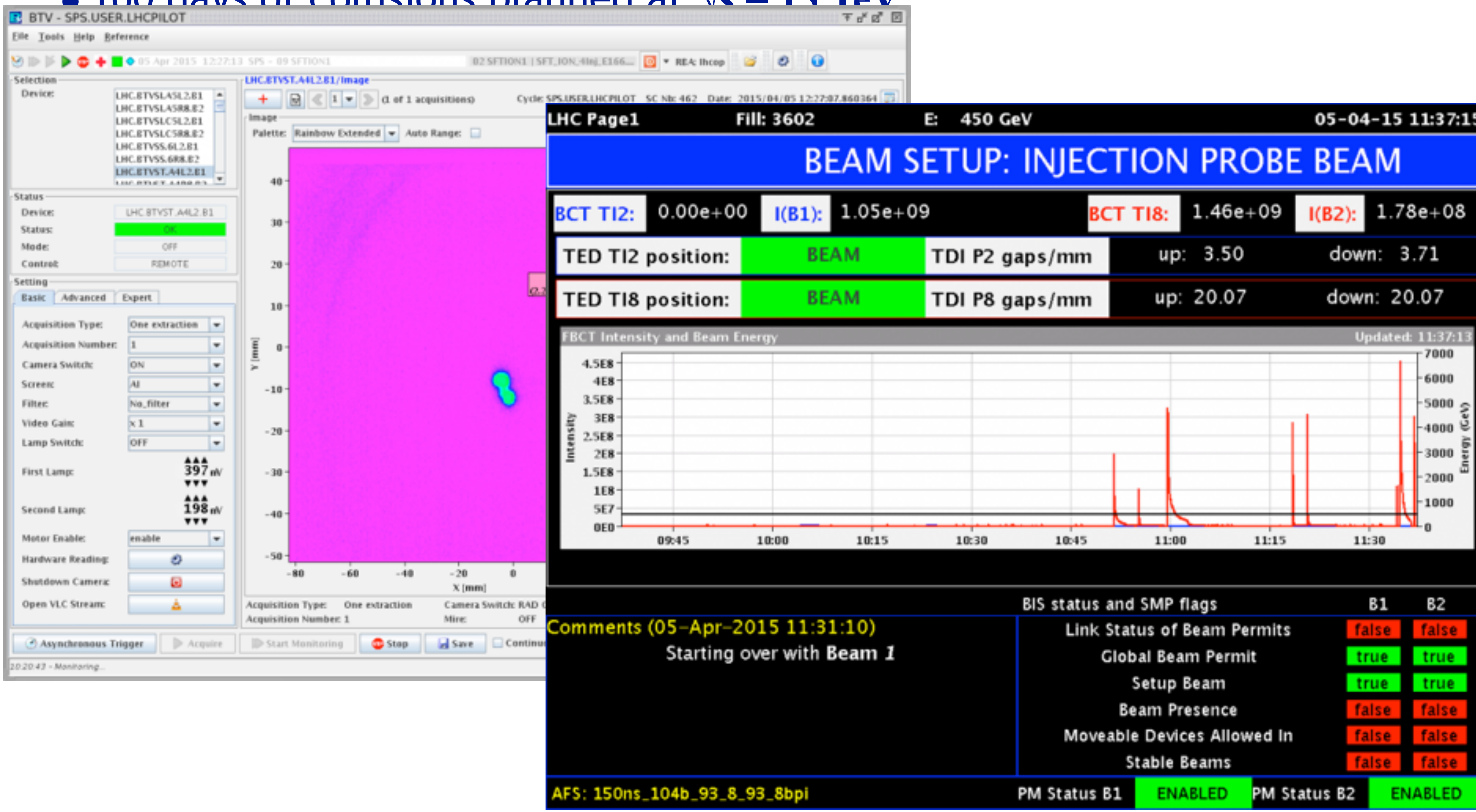
ATLAS Upgrades

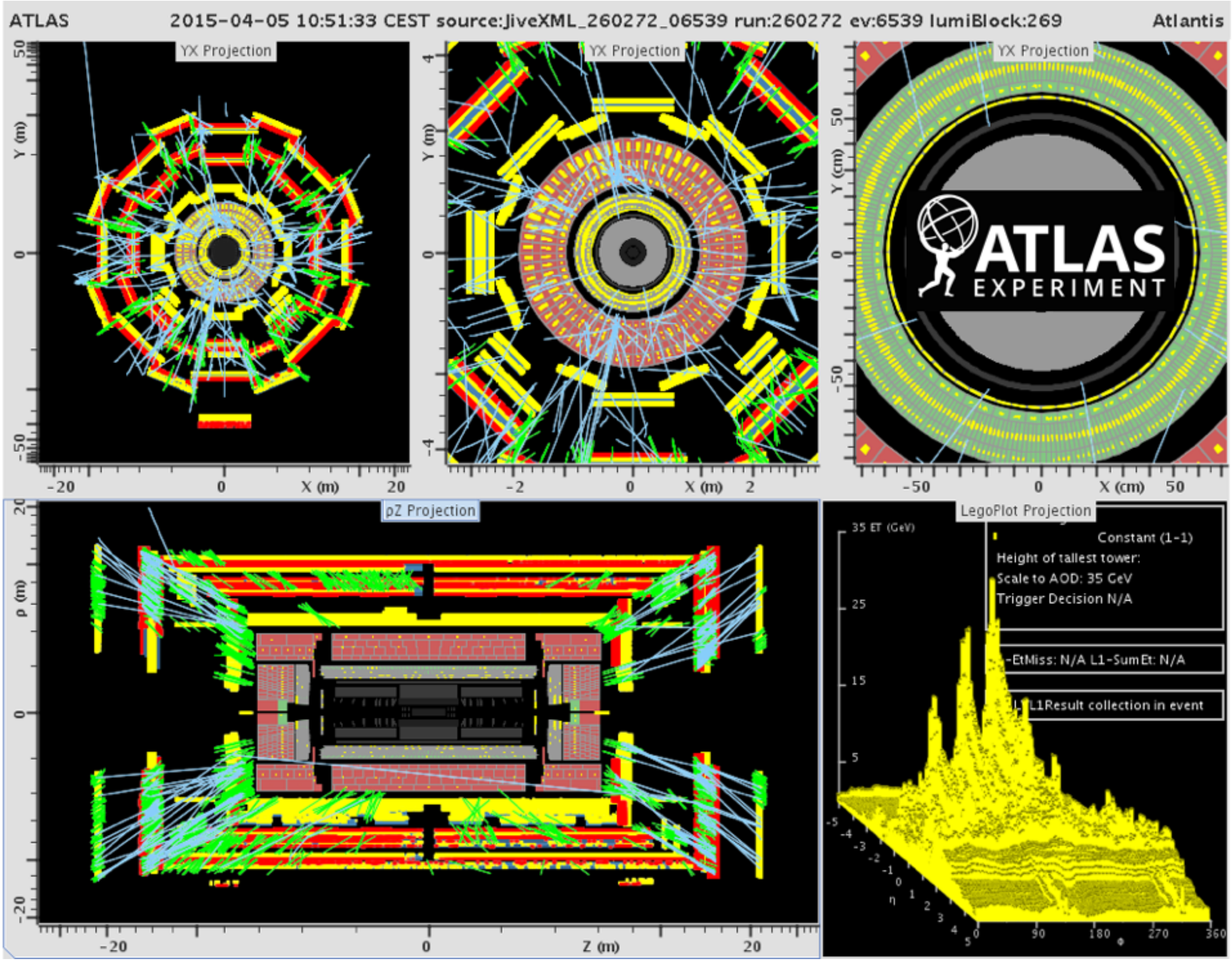
- Long Shutdown 1
  - New beam pipe at r=25mm
  - New insertable *b*-layer at $31 < r/mm < 40$
  - Refurbished pixel readout
  - More complete muon coverage: extended endcap installation complete
- Fast Tracking for L2-trigger will come online during run 2
- Long Shutdown 2
  - New muon small wheel forward spectrometer
  - Topological L1-trigger processors
  - New forward detectors
- For HL-LHC
  - Completely new trigger architecture with new hardware at L0/L1
  - Completely new tracking detector
  - Calorimeter electronics upgrades



Run 2 Start Up

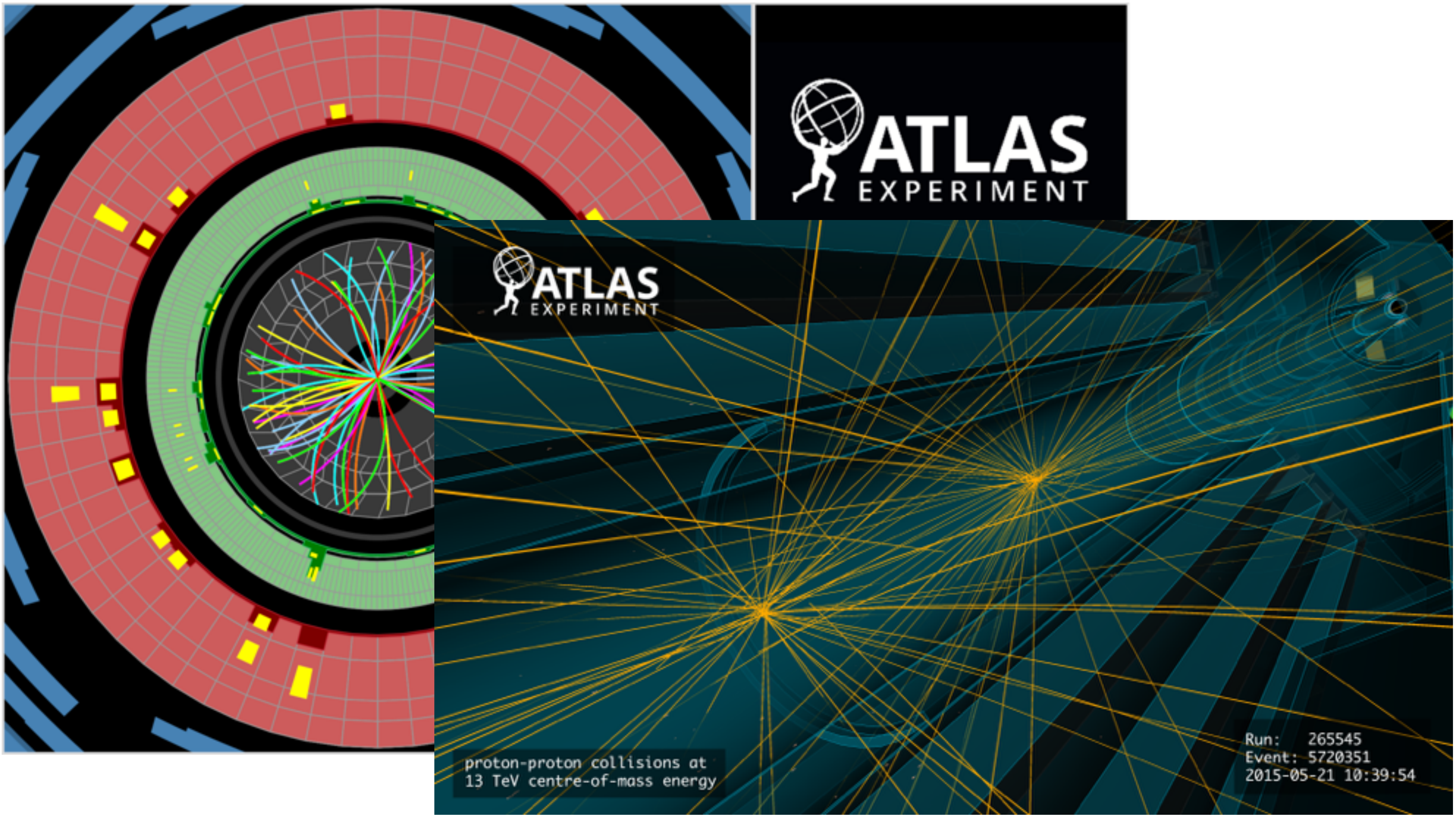
- First run 2 beam was on Easter Sunday, 5th April 2015!
    - 100 days of collisions planned at $\sqrt{s} = 13$ TeV




ATLAS
2015-04-05 10:51:33 CEST source:JiveXML_260272_06539 run:260272 ev:6539 lumiBlock:269
Atlantis
YX Projection
YX Projection
YX Projection
Y (m)
X (m)
Y (cm)
X (cm)
ATLAS
EXPERIMENT
ρZ Projection
ρ (m)
Z (m)
LegoPlot Projection
35 ET (GeV)
Constant (1-1)
Height of tallest tower:
Scale to AOD: 35 GeV
Trigger Decision N/A
-EtMiss: N/A L1-SumEt: N/A
L1Result collection in event
η
φ

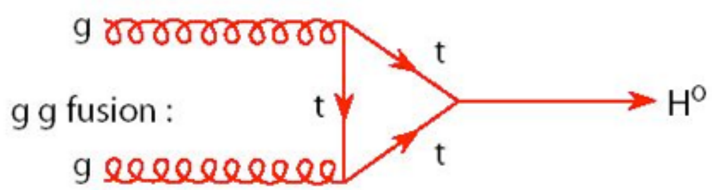
First Run 2 collisions in Atlas

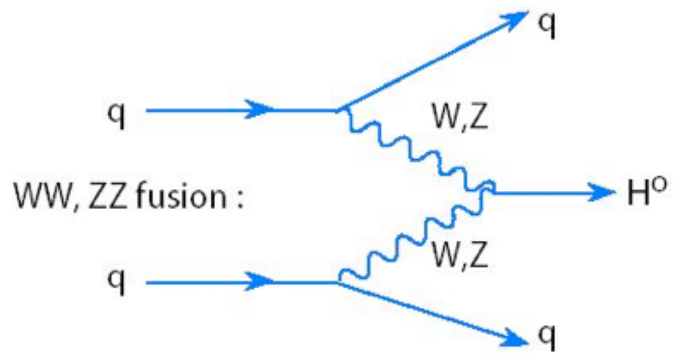
- First 13 TeV “test” collisions on 20th May 2015.

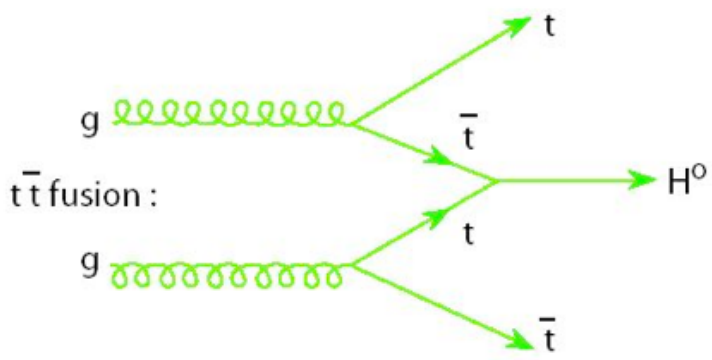


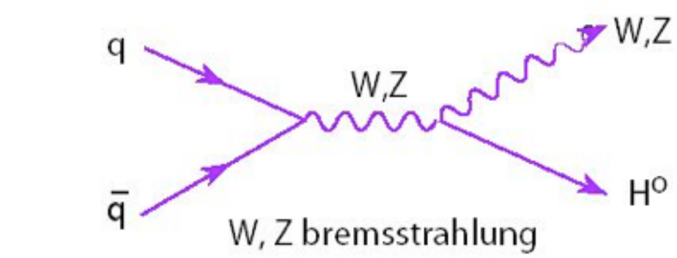
- First “physics” collisions planned for next week.

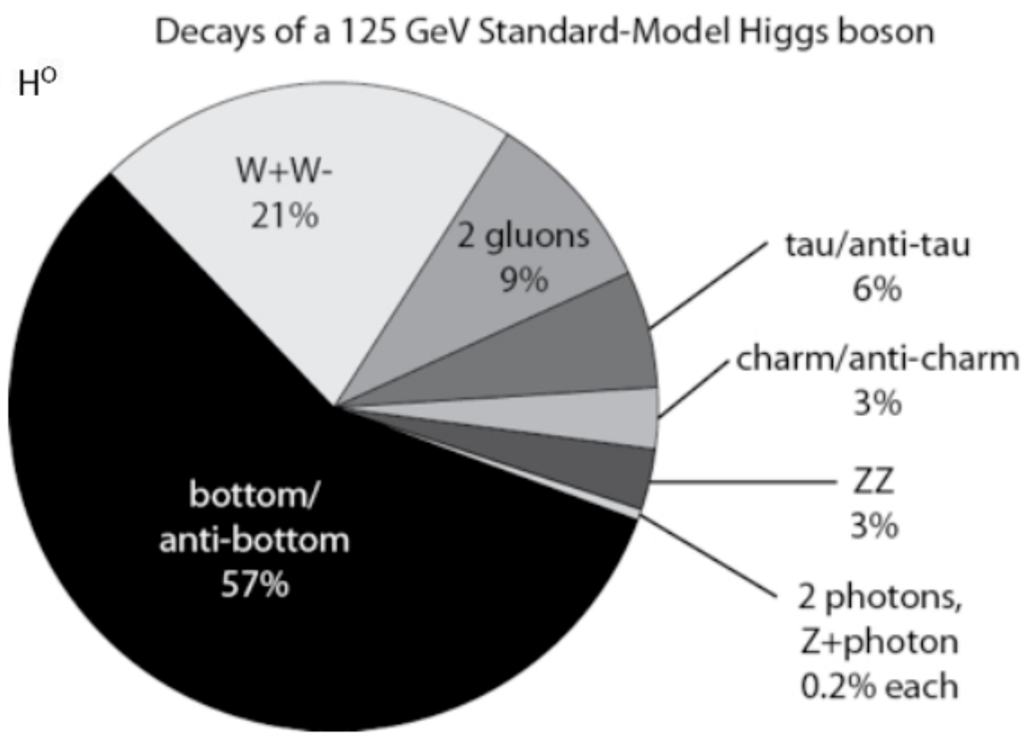
ATLAS Run 2: BEH Boson Prospects







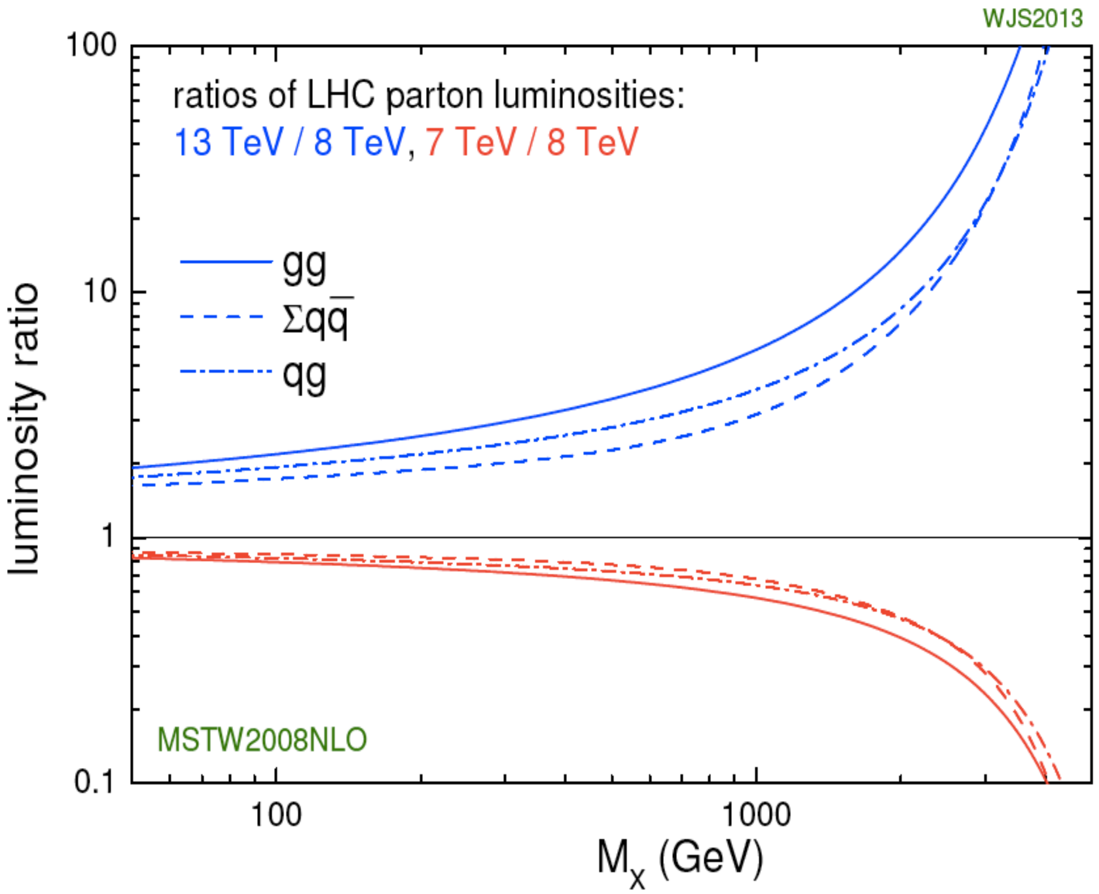


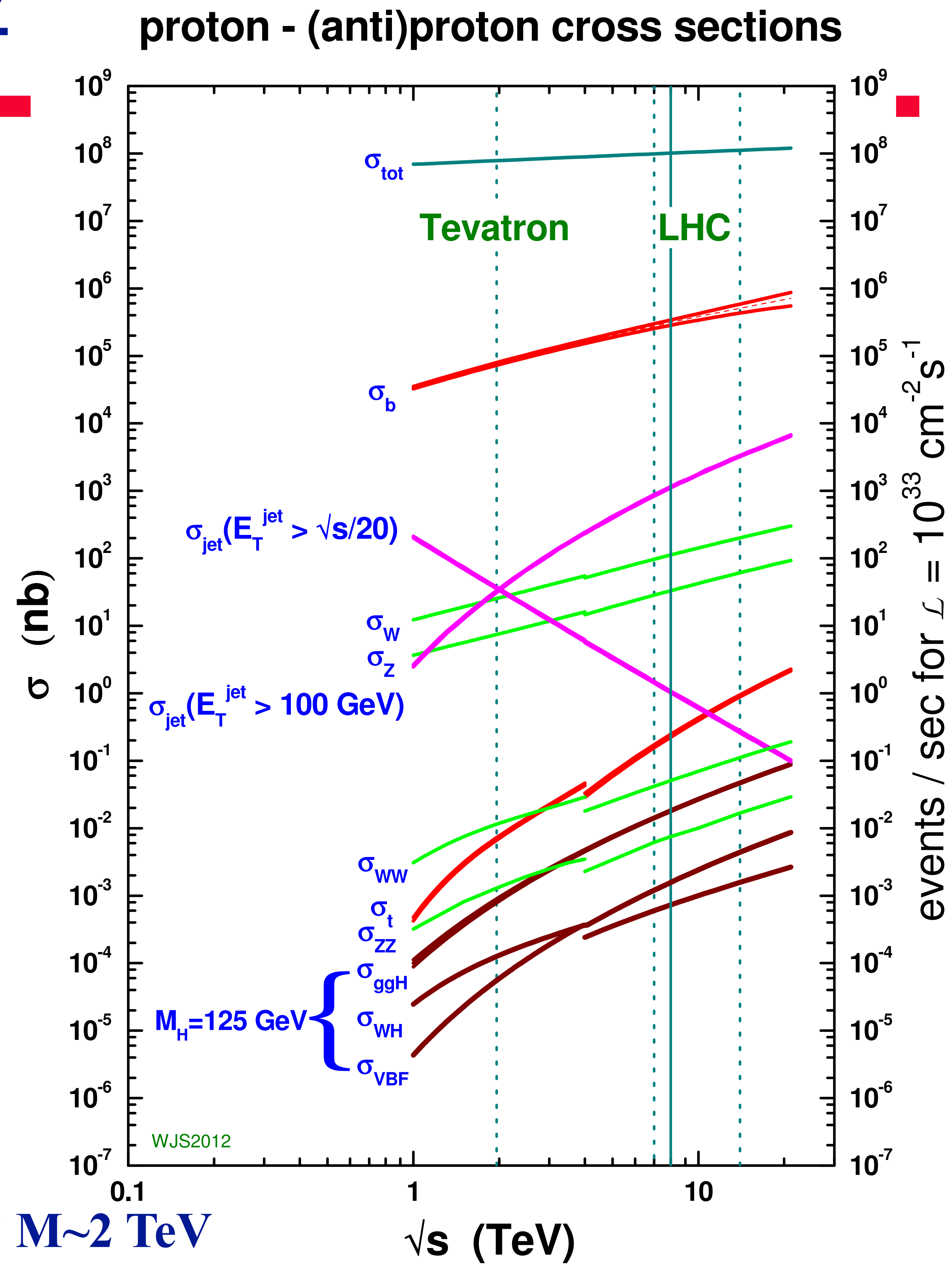


Physics Prospects for Run 2

Huge increase in cross section for many interesting processes

- but life is harder for states lighter than 2 top quarks ($t\bar{t}$)





- Increase in cross section by factor ~10 for **M~2 TeV**

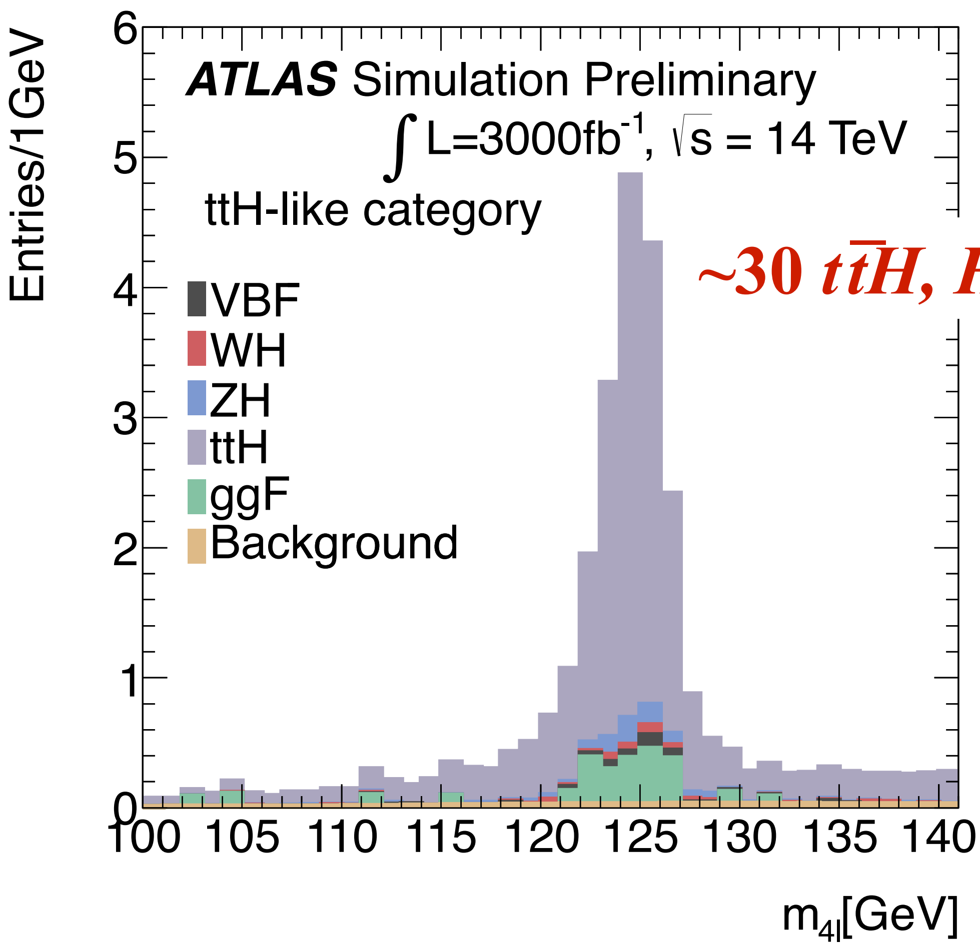
➡ Discovery of TeV-scale particles possible with a few fb^{-1} !!

Projection for Run 2 and HL-LHC

- Projections from refining current analyses or designing new ones
- Different systematic uncertainty scenarios often considered, in particular the different theoretical uncertainties on the signal cross section.
- Results are presented for $\mathbf{300\ fb^{-1}}$ (2022) and/or $\mathbf{3000\ fb^{-1}}$ (2035?)
- Many results are presented in the context of specific models.

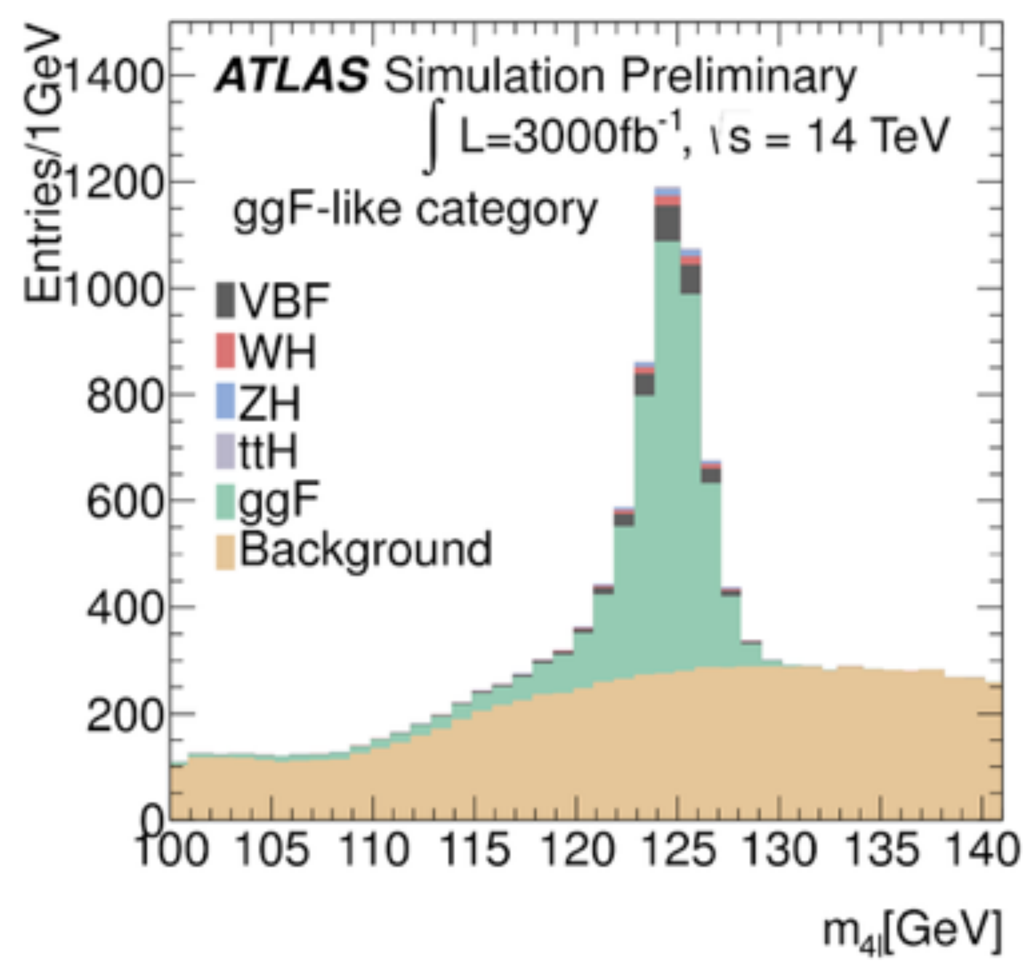
Still the Golden Channel: $H \to ZZ^* \to 4\ell$

- $H \to ZZ^* \to 4\ell$: very clean signature and small backgrounds.
- Large statistics will allow a probe of all main production modes.
- BEH boson production cross-section uncertainty constrained to $\mathcal{O}$(10%)
- Allows measurement of **CP** properties of the BEH boson.



~30 $t\bar{t}H$, $H \to 4\ell$ events

$\mathcal{O}$(3000) $gg \to H \to 4\mu$ events

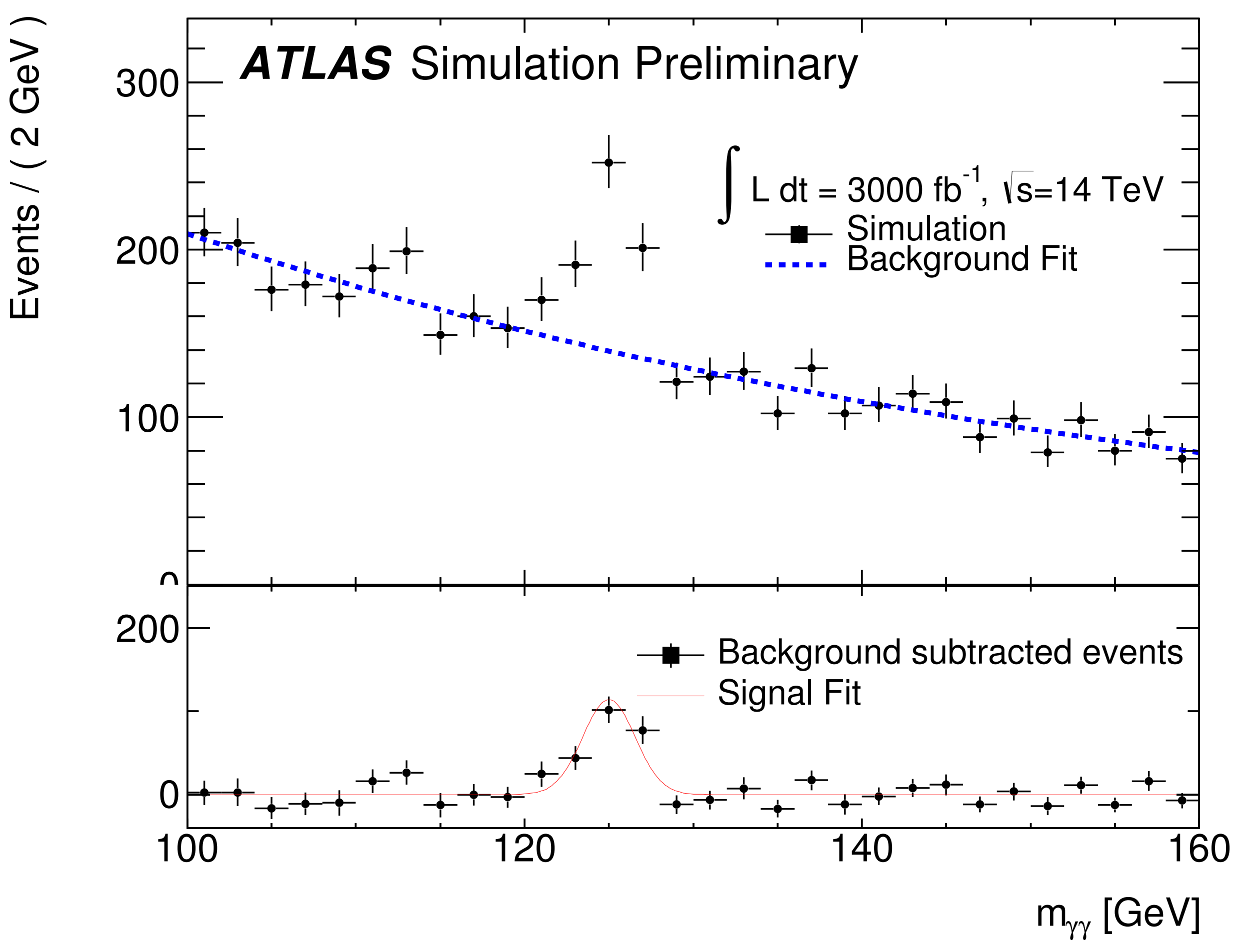


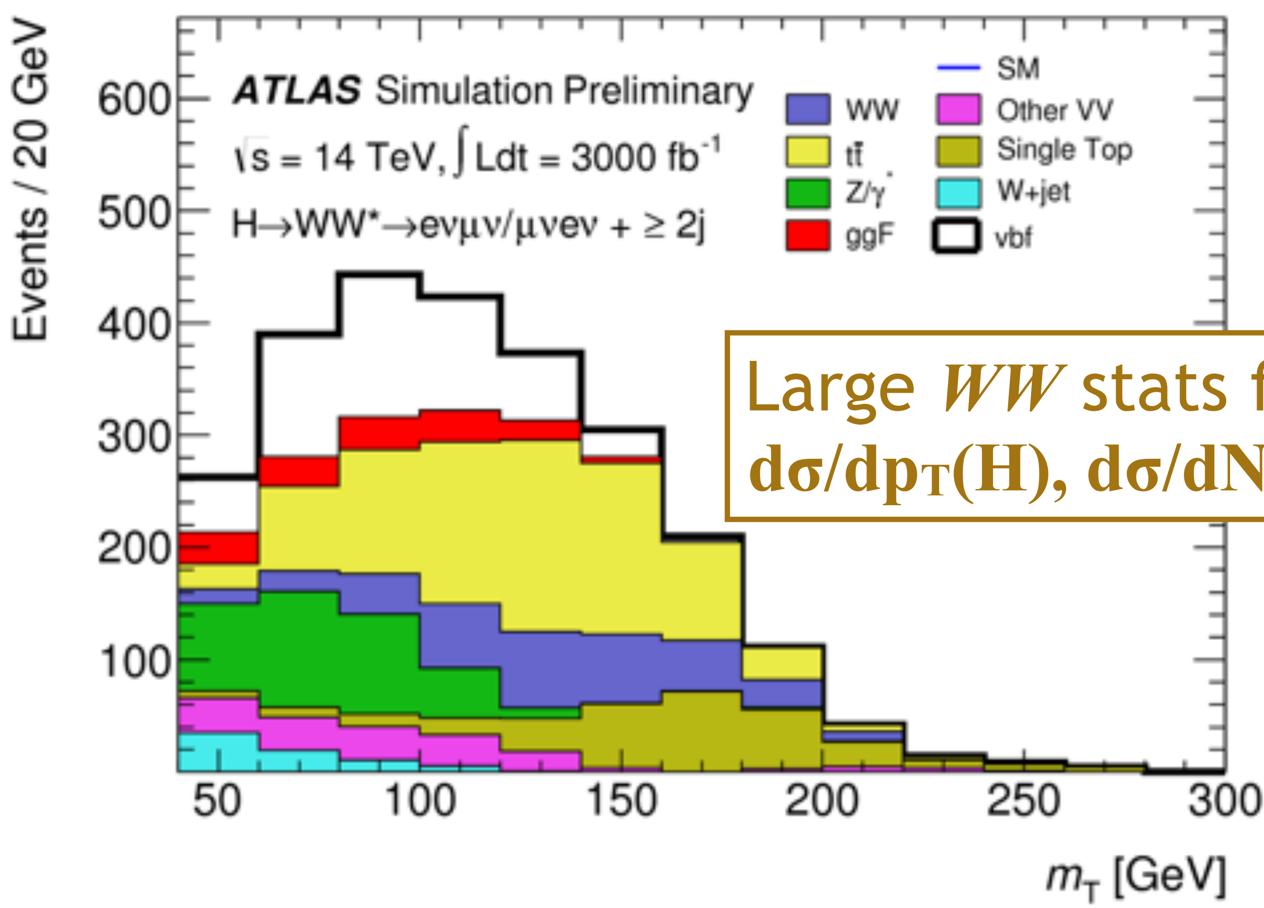
ATL-PHYS-PUB-2013-014

$H \to \gamma\gamma$ and $H \to WW$

- Clean signal of $H \to \gamma\gamma$ can be used to look for different BEH boson production mechanisms.
- Large statistics of $H \to WW$ can be used for differential cross section measurements

$t\bar{t}H$, $H \to \gamma\gamma$; 1 lepton





Large WW stats for $d\sigma/dp_T(H)$, $d\sigma/dN_{jets}$

$H \to b\bar{b}$ at Run 2

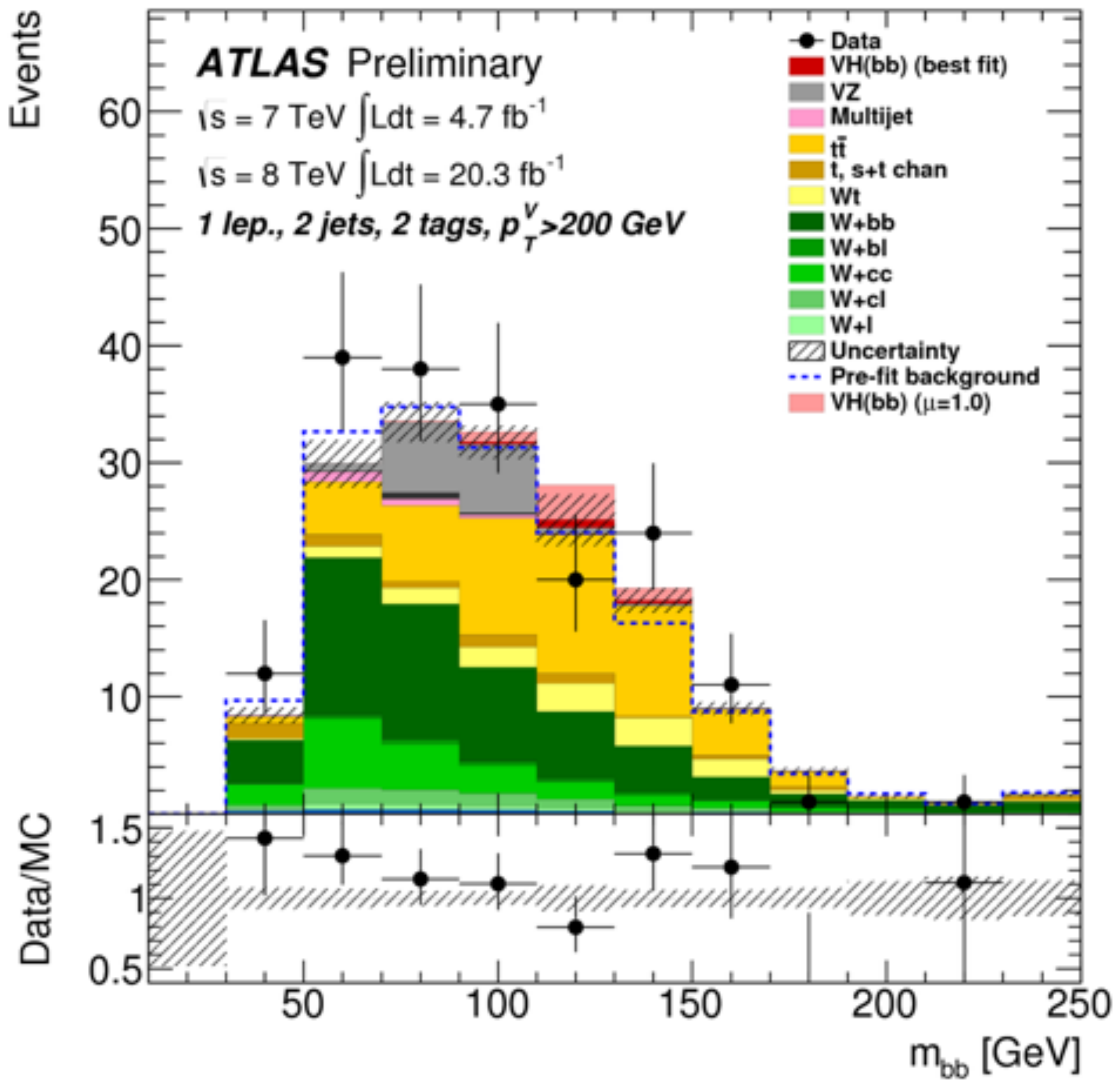
ATL-PHYS-PUB-2014-011

- Looking for pairs of b-quarks in the detector very challenging as b-quarks are ubiquitous.

$WH, H \to b\bar{b}$

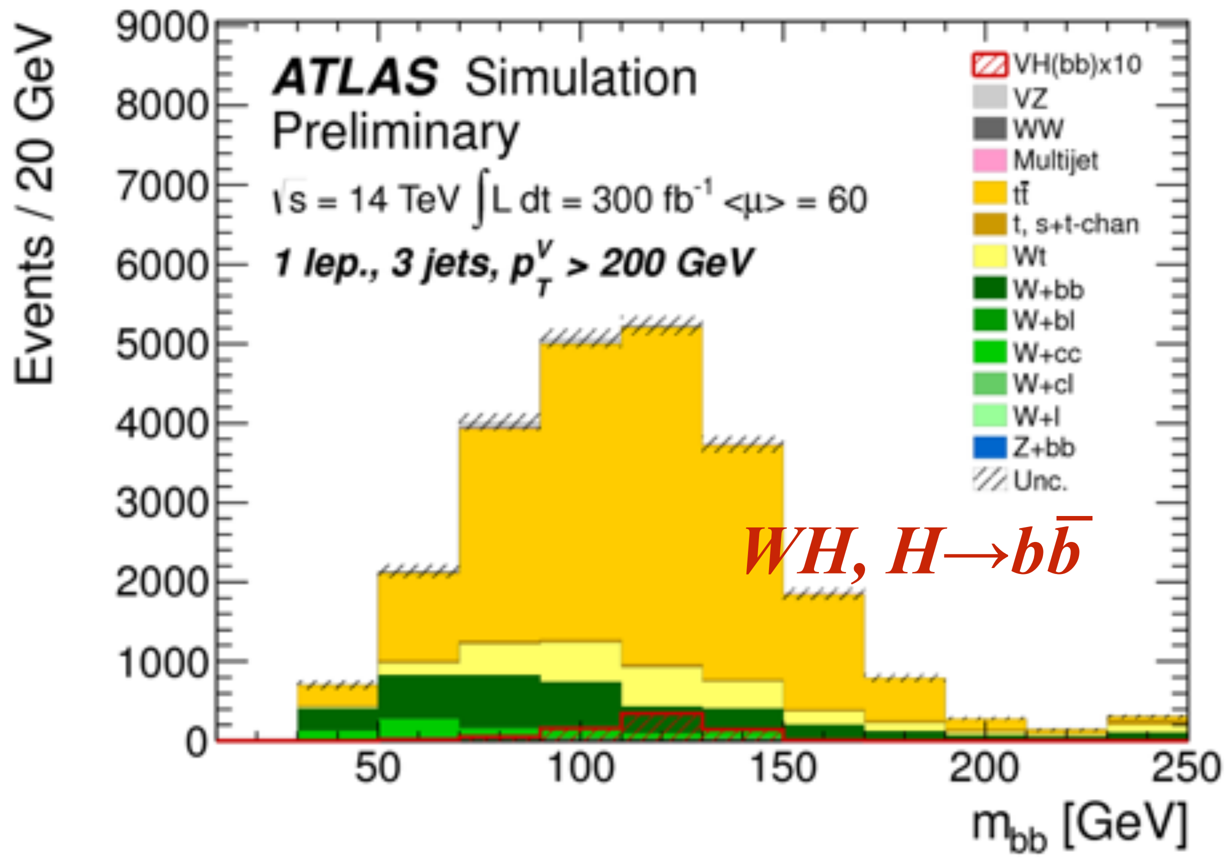
Run 2 projections, compared to run 1 data

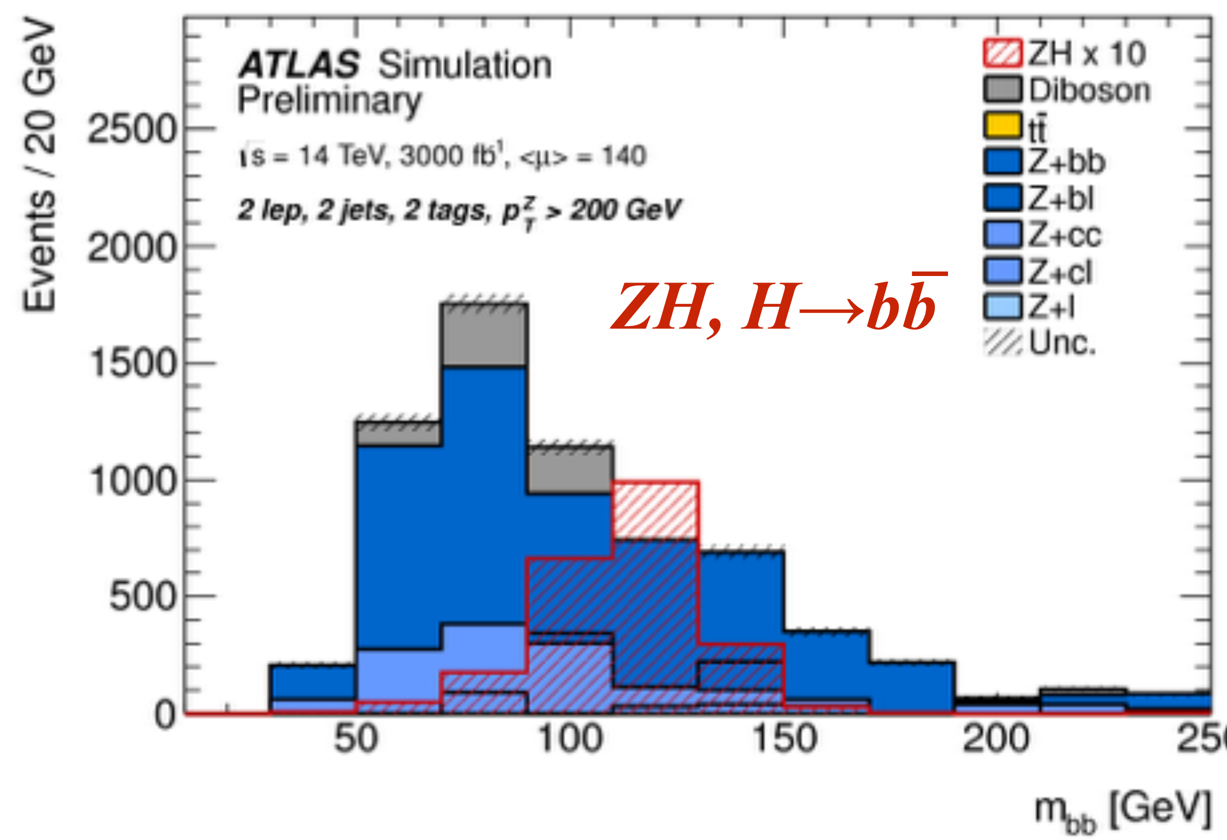
- Instead search for BEH bosons produced along with a W or Z boson or top quarks:
  - $WH \to e\nu\, b\bar{b}$, $\mu\nu\, b\bar{b}$
  - $ZH \to e^+e^-\, b\bar{b}$, $\mu^+\mu^-\, b\bar{b}$, $\nu\bar{\nu}\, b\bar{b}$
  - $ttH \to t\,\bar{t}\, b\,\bar{b} \to e\,\nu\, q\bar{q}\, b\bar{b}$



$H \rightarrow b\bar{b}$ at Run 2

ATL-PHYS-PUB-2014-011





$VH, H \rightarrow b\bar{b}$ expected significance in 300 fb^{-1}

		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	5.5	4.6	7.1
	$\hat{\mu}_{\text{Stats}}$ error	+0.18 − 0.18	+0.23 − 0.22	+0.14 − 0.14
Theory-only	$\hat{\mu}_{\text{Theory}}$ error	+0.08 − 0.05	+0.08 − 0.06	+0.09 − 0.06
Scenario I	Significance	1.8	3.5	3.9
	$\hat{\mu}_{\text{w/Theory}}$ error	+0.57 − 0.57	+0.30 − 0.29	+0.27 − 0.26
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.56 − 0.57	+0.29 − 0.29	+0.26 − 0.26
Scenario II	Significance	2.1	-	4.1
	$\hat{\mu}_{\text{w/Theory}}$ error	+0.48 − 0.47	-	+0.26 − 0.25
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.46 − 0.46	-	+0.25 − 0.24

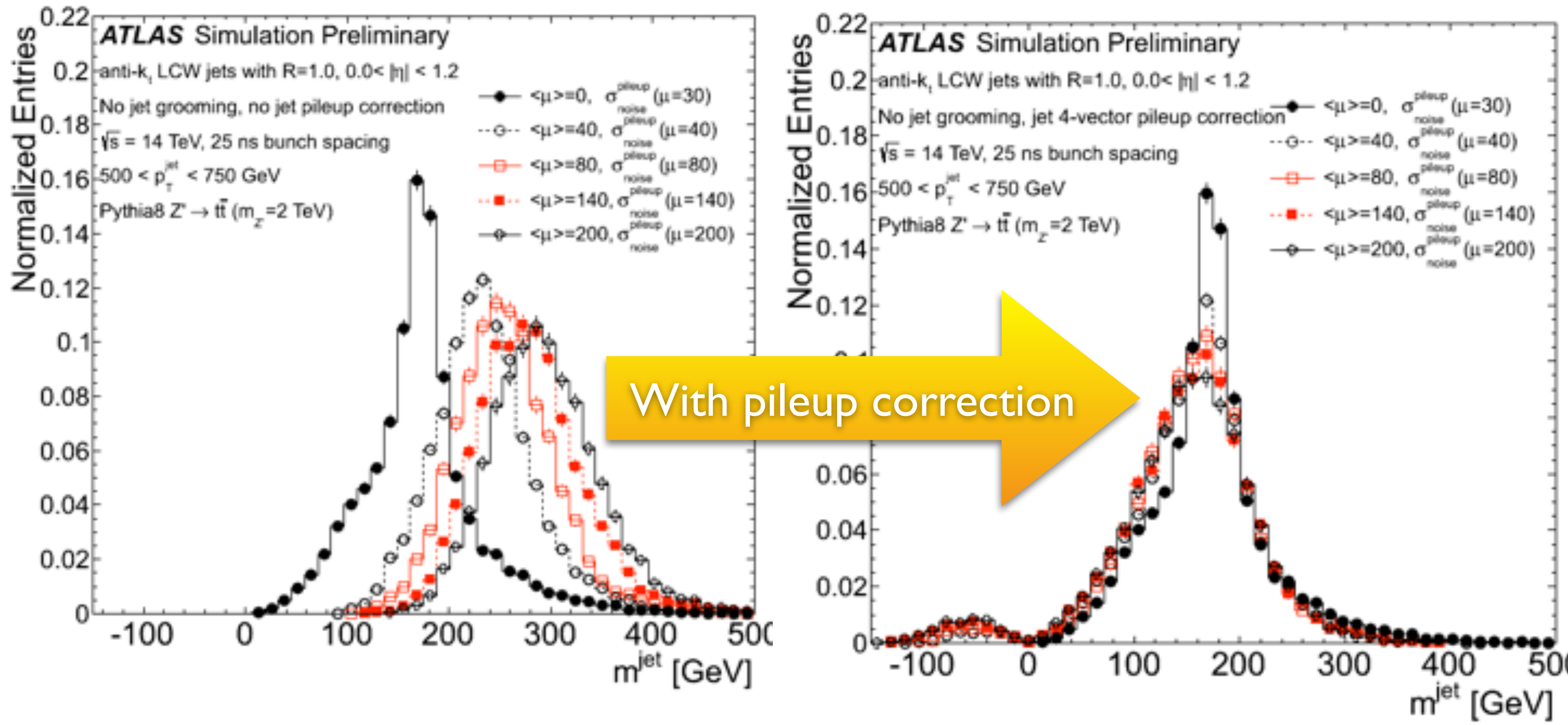
$VH, H \rightarrow b\bar{b}$ expected significance in 3000 fb^{-1}

		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{\text{Stats}}$ error	+0.07 − 0.06	+0.09 − 0.09	+0.05 − 0.05
Theory-only	$\hat{\mu}_{\text{Theory}}$ error	+0.09 − 0.07	+0.07 − 0.08	+0.07 − 007
Scenario I	Significance	2.7	8.4	8.8
	$\hat{\mu}_{\text{w/Theory}}$ error	+0.37 − 0.36	+0.15 − 0.15	+0.14 − 0.14
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.36 − 0.36	+0.14 − 0.12	+0.12 − 0.12
Scenario II	Significance	4.7	-	9.6
	$\hat{\mu}_{\text{w/Theory}}$ error	+0.23 − 0.22	-	+0.13 − 0.13
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.21 − 0.21	-	+0.11 − 0.11

Jet Reconstruction at Run 2

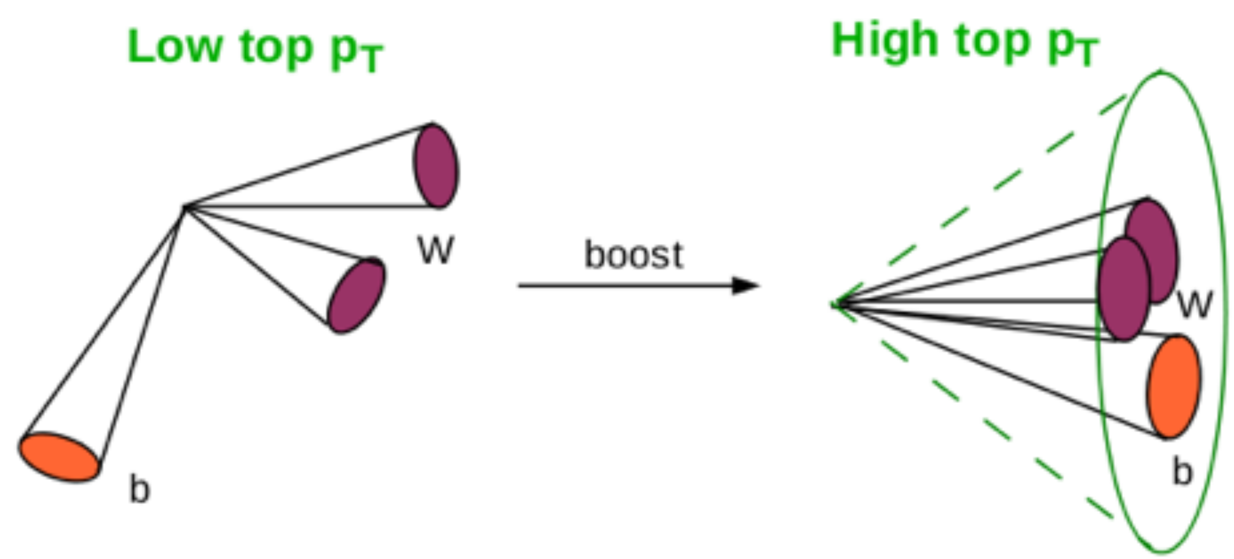
High Pileup

High pileup requires improved algorithms e.g. primary vertex reconstruction, b-tagging, pileup jet rejection.



Jet Substructure

- High mass final states and high collision energy lead to highly boosted and close objects e.g. $W\rightarrow jj$, $Z\rightarrow jj$, $t\rightarrow Wb\rightarrow jjb$
- Jet substructure techniques will be key to reconstruct some of these signals; may be crucial for new high-mass objects.

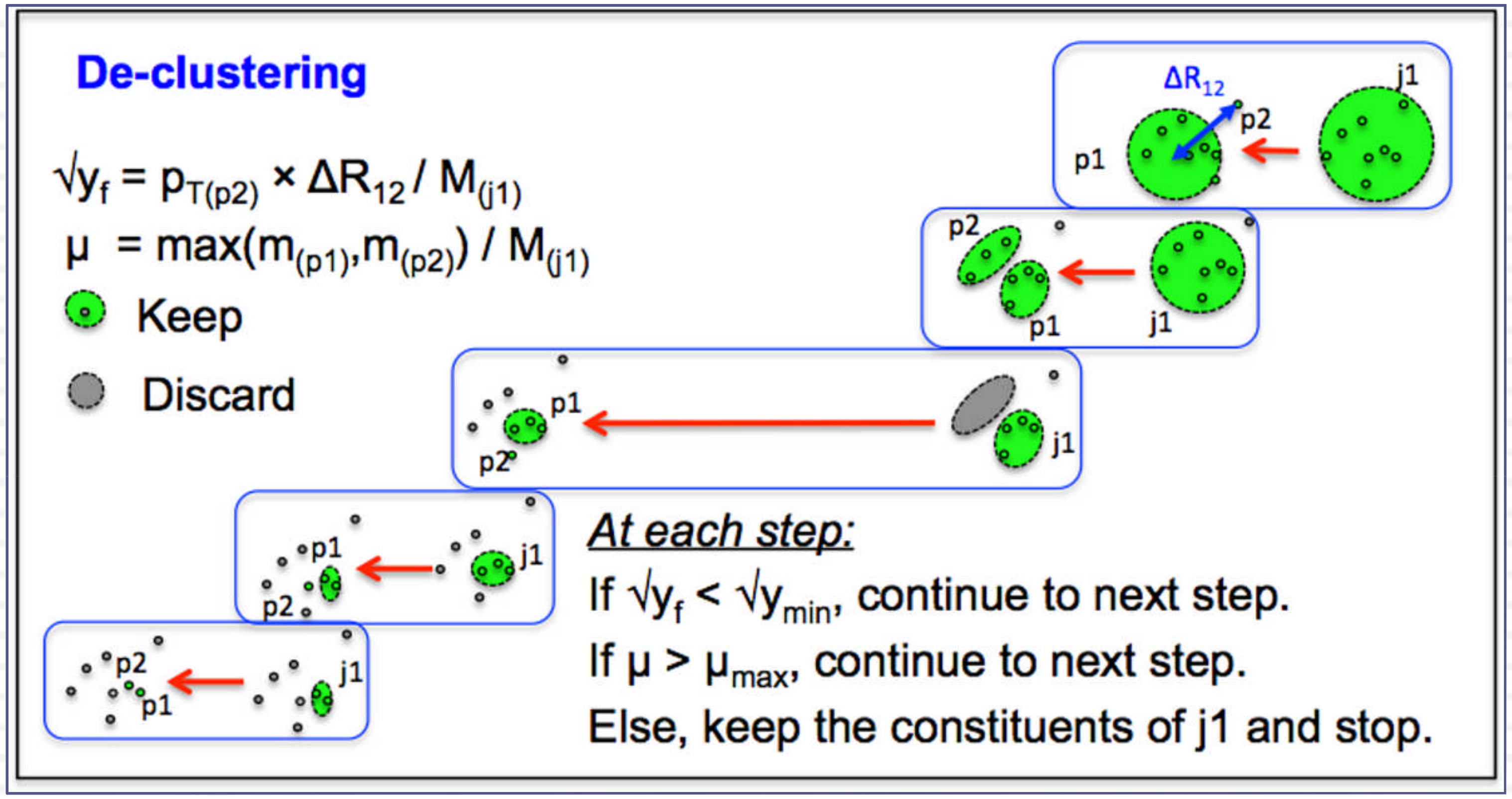


Jet Substructure - Grooming

- Three grooming techniques are currently used for Run II boosted W boson tagging:

Pruning - jets are re-clustered, cutting on the angular distance between two sub-jets and the fraction of the p_T carried by the lighter sub-jet. These should do well since the boson p_T spectrum is expected to be symmetrical between sub-jets.

https://cds.cern.ch/record/1577417



Trimming - Jets are un-clustered into sub-jets, where each one has a certain fraction of the total jet momentum. This uncovers hard substructure independently of pileup.

BDRS (or mass drop filtering) – jets are unclustered using the reverse of the initial clustering steps into 3 sub-jets. The mass drop (mass of the hardest sub-jet as a fraction of the jet's mass) and momentum balance between the sub-jets and jet is calculated. If there is a large mass drop or the momentum balances, the sub-jet is presumed to be a hard structure and is returned as a jet.

arXiv:0912.1342, arXiv:1306.4945

arXiv:0802.2470

Jet Substructure - New Variables

- Variables describing the substructure within a jets helps identify if boosted jets are from a single particle

- *N* subjettiness (τ_N): The degree to which the substructure resembles ≤*N* sub-jets. This is the p_T weighted ΔR between each constituent and its nearest sub-jet axis. The ratio $\tau_{21}, \tau_2/\tau_1$, gives good two body sub-jet identification.

- Energy correlation variables (EEC): Angular separation weights are used for each sub-jet multiplied by the sum of the sub-jet momenta. Variations of ratios of these functions offer good two body identification.

$$\tau_0(\beta) = \sum_{i \in J} p_{\mathrm{T}_i} \Delta R^{\beta},$$

$$\tau_1(\beta) = \frac{1}{\tau_0(\beta)} \sum_{i \in J} p_{\mathrm{T}_i} \Delta R^{\beta}_{a_1,i},$$

$$\tau_2(\beta) = \frac{1}{\tau_0(\beta)} \sum_{i \in J} p_{\mathrm{T}_i} \min(\Delta R^{\beta}_{a_1,i}, \Delta R^{\beta}_{a_2,i}),$$

β=1; *k* over all constituents; ΔR is rapidity between subjet axis *a* and *k*; R_0 characteristic radius

http://arxiv.org/pdf/1410.4227v1.pdf

$$E_{CF}0(\beta) = 1,$$

$$E_{CF}1(\beta) = \sum_{i \in J} p_{\mathrm{T}_i},$$

$$E_{CF}2(\beta) = \sum_{i<j \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} \left(\Delta R_{ij}\right)^{\beta},$$

$$E_{CF}3(\beta) = \sum_{i<j<k \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta},$$

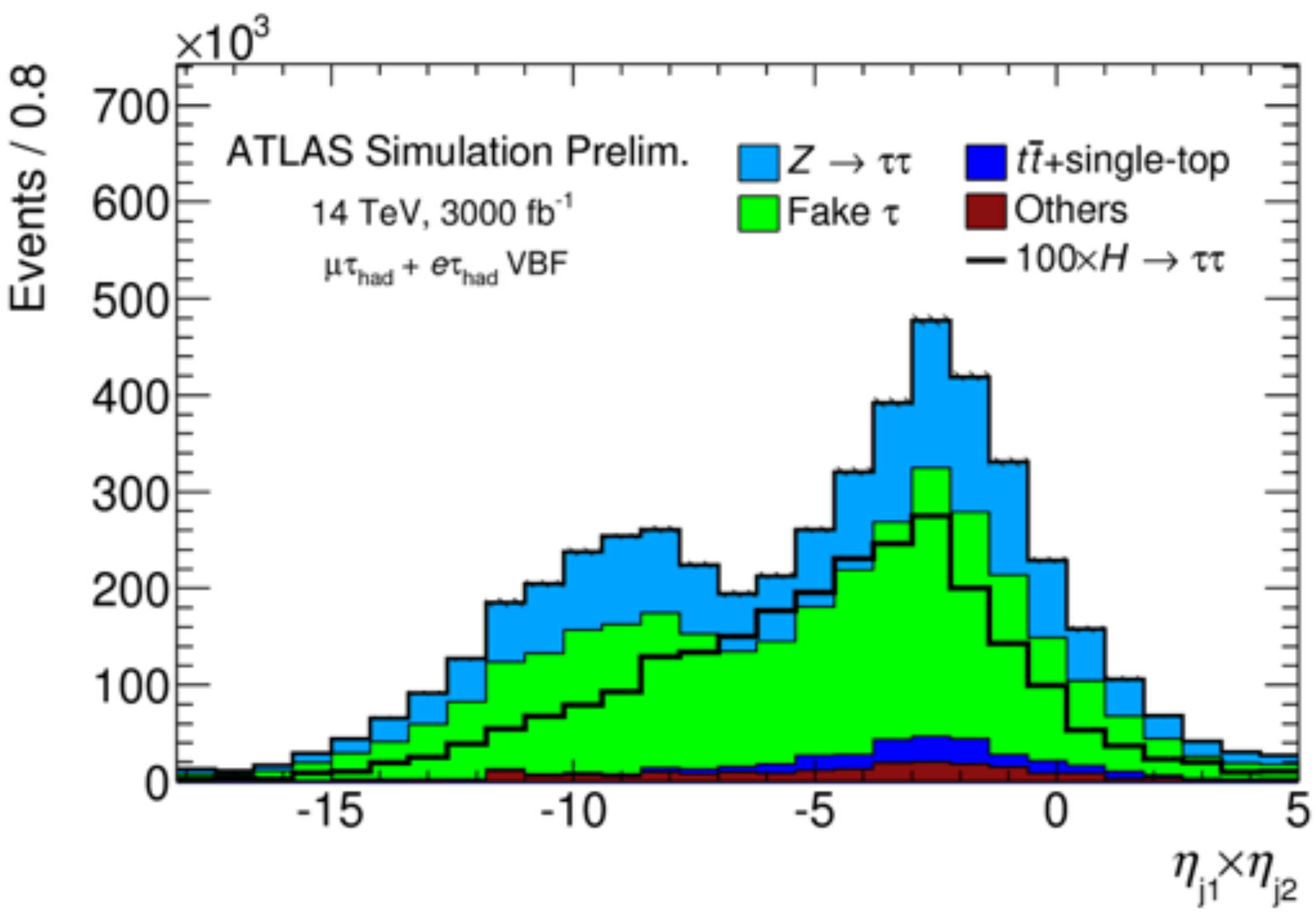
β=0.5 or 1; *l*, *k* over all jet constituents; ΔR is rapidity between clusters.

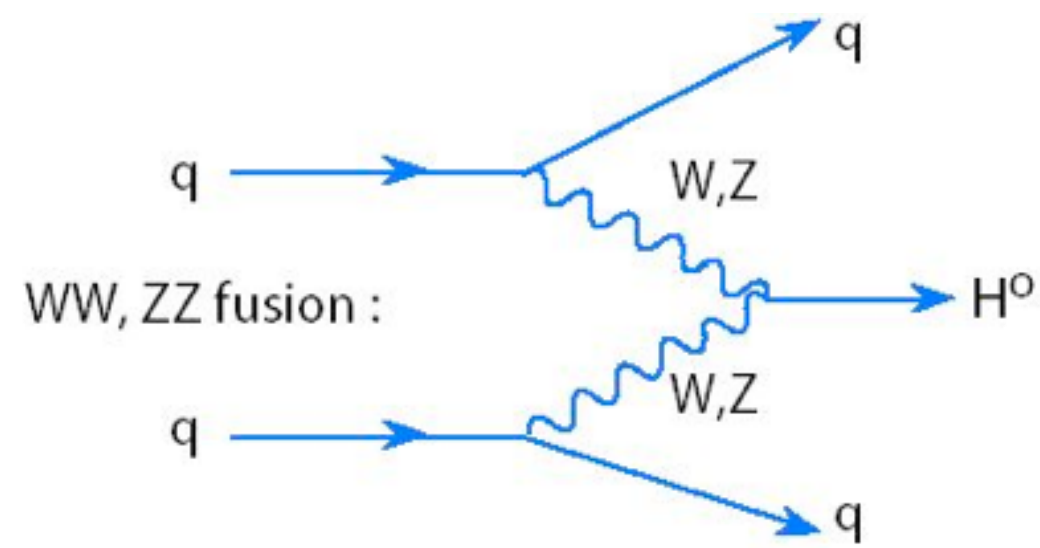
http://arxiv.org/abs/1411.0665

$H\to\tau^+\tau^-$ at Run 2

ATL-PHYS-PUB-2014-018

- *WW, ZZ* fusion production of the BEH boson best for $H\to\tau^+\tau^-$





- Number of signal and background events in 3000 fb^{-1}

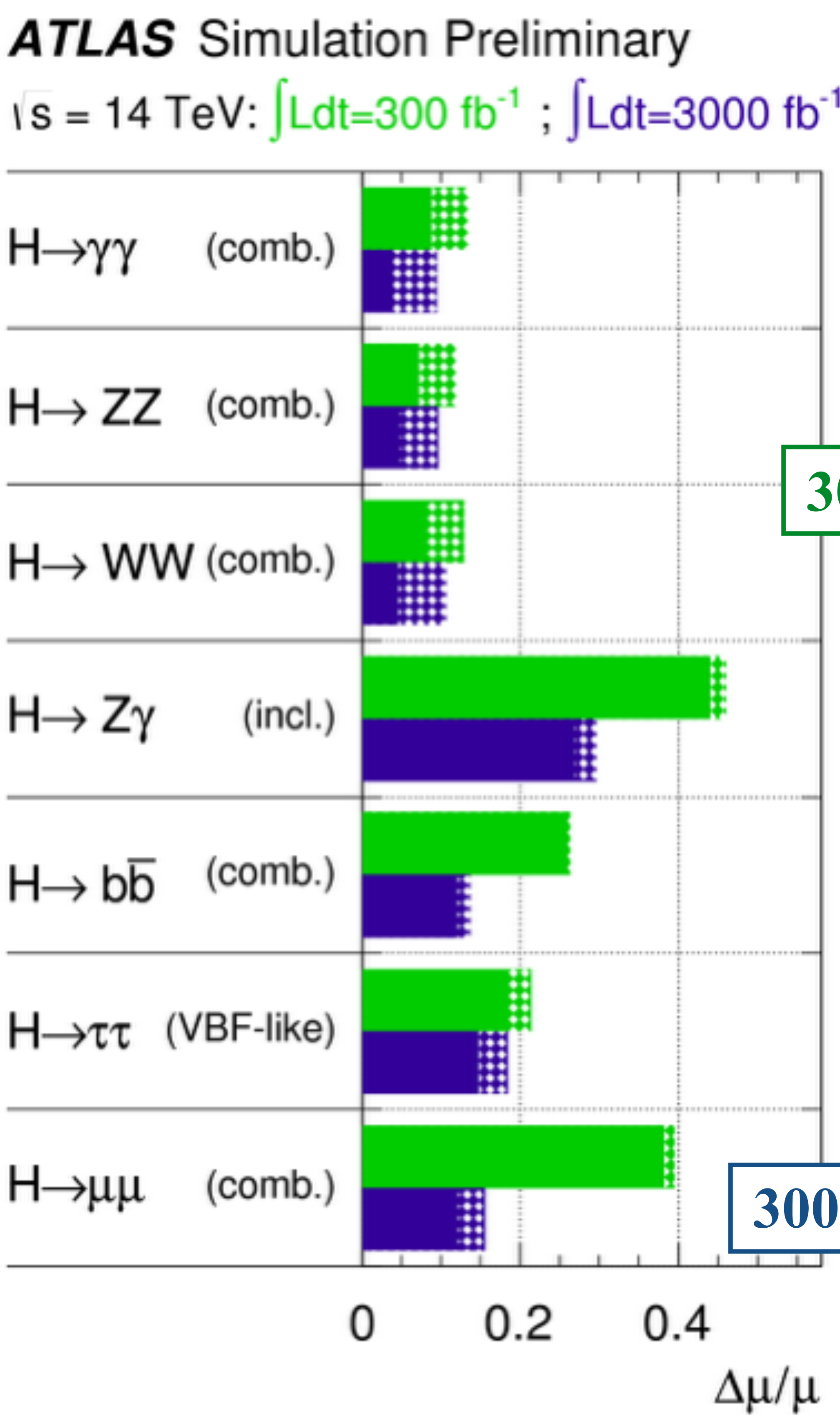
process	VBF category	third highest bin	second highest bin	highest bin
VBF $H\to\tau\tau$	8970	114	147	206
ggF $H\to\tau\tau$	16410	44	46	39
$Z\to\tau\tau$	1682400	875	720	514
fakes	2959800	205	190	155
$t\bar{t}$	191400	100	20	< 20
other	198600	< 20	< 20	< 20
signal	25380	158	193	245
background	5032200	1180	930	669

- Uncertainty on SM BEH production of $\mu=1$ with 3000 fb^{-1}

		current $\sigma_S^{theo.}$	no $\sigma_S^{theo.}$
$\sigma_B^{syst.}$	$\sigma_S^{syst.}$	$\Delta\mu$	$\Delta\mu$
10%	5%	0.25	0.24
5%	5%	0.16	0.13

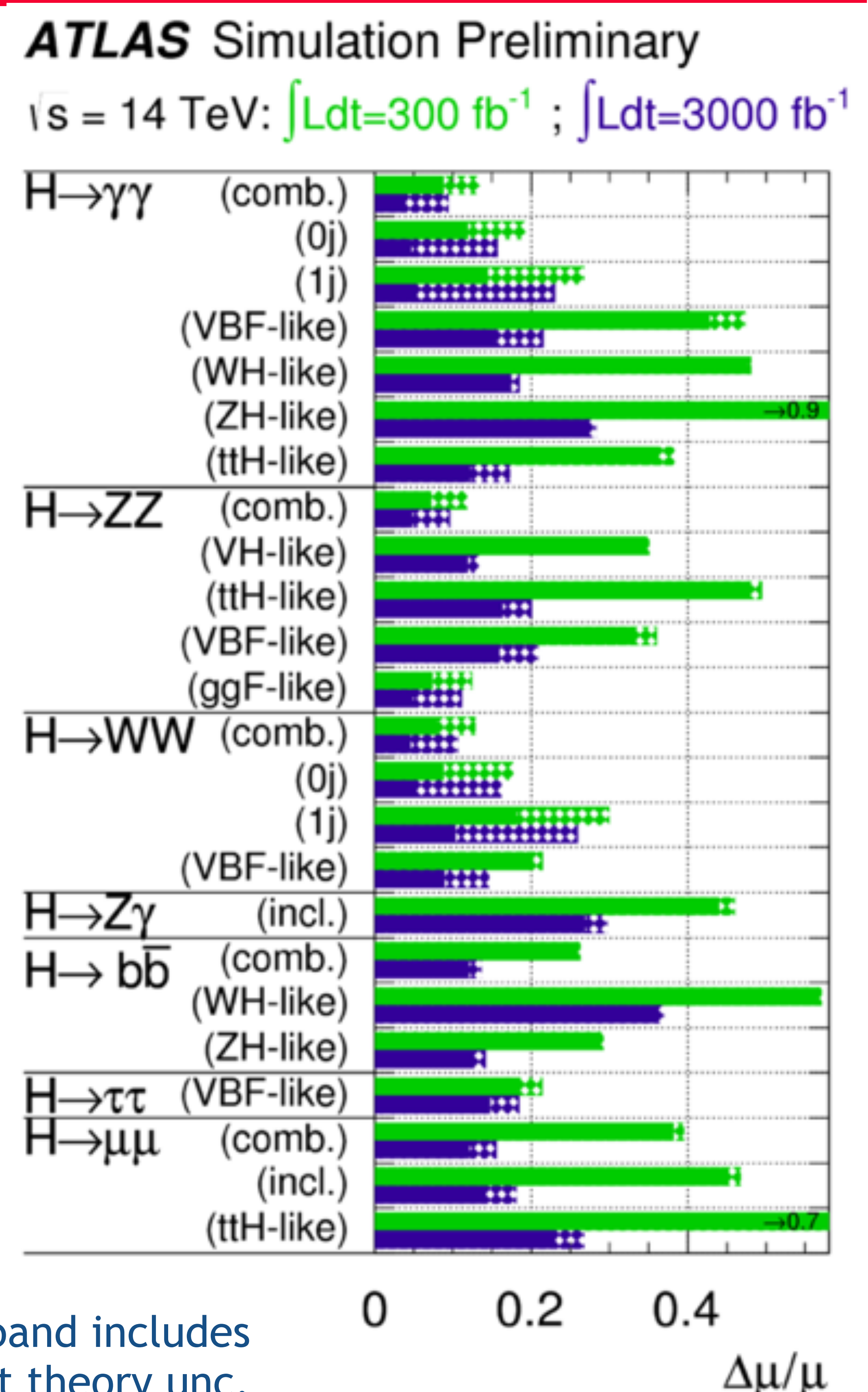
BEH Boson Decay Sensitivity

ATL-PHYS-PUB-2014-016



300 fb^{-1}

3000 fb^{-1}



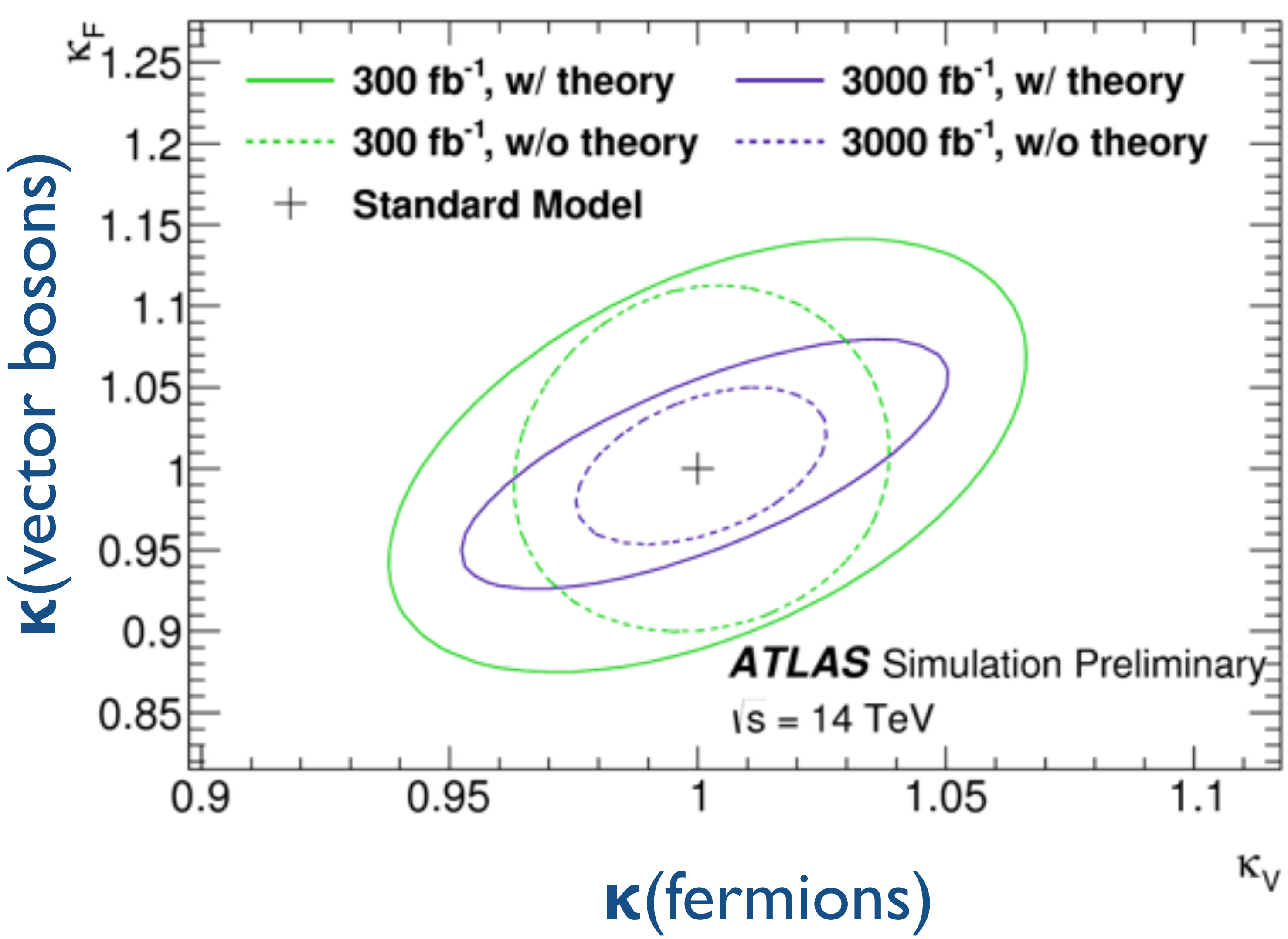
Dashed band includes
current theory unc.

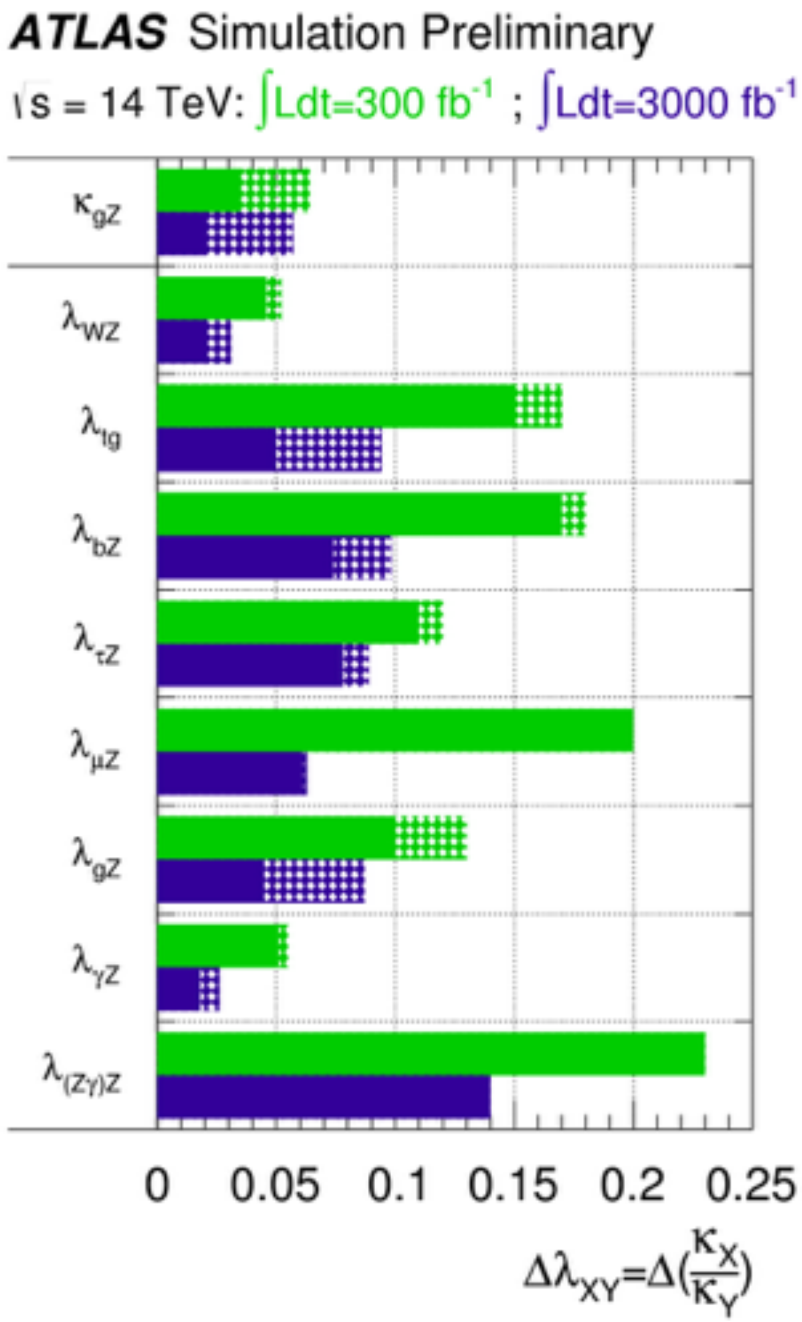
BEH Boson Couplings Fit

ATL-PHYS-PUB-2014-016

- Assuming Γ_H is sum of SM widths, calculate uncertainties on BEH boson couplings.
- Deviations from the SM are quantified using κ multiplier, in SM $\kappa_i = 1$, *e.g.*:

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





BEH Boson Coupling Fit

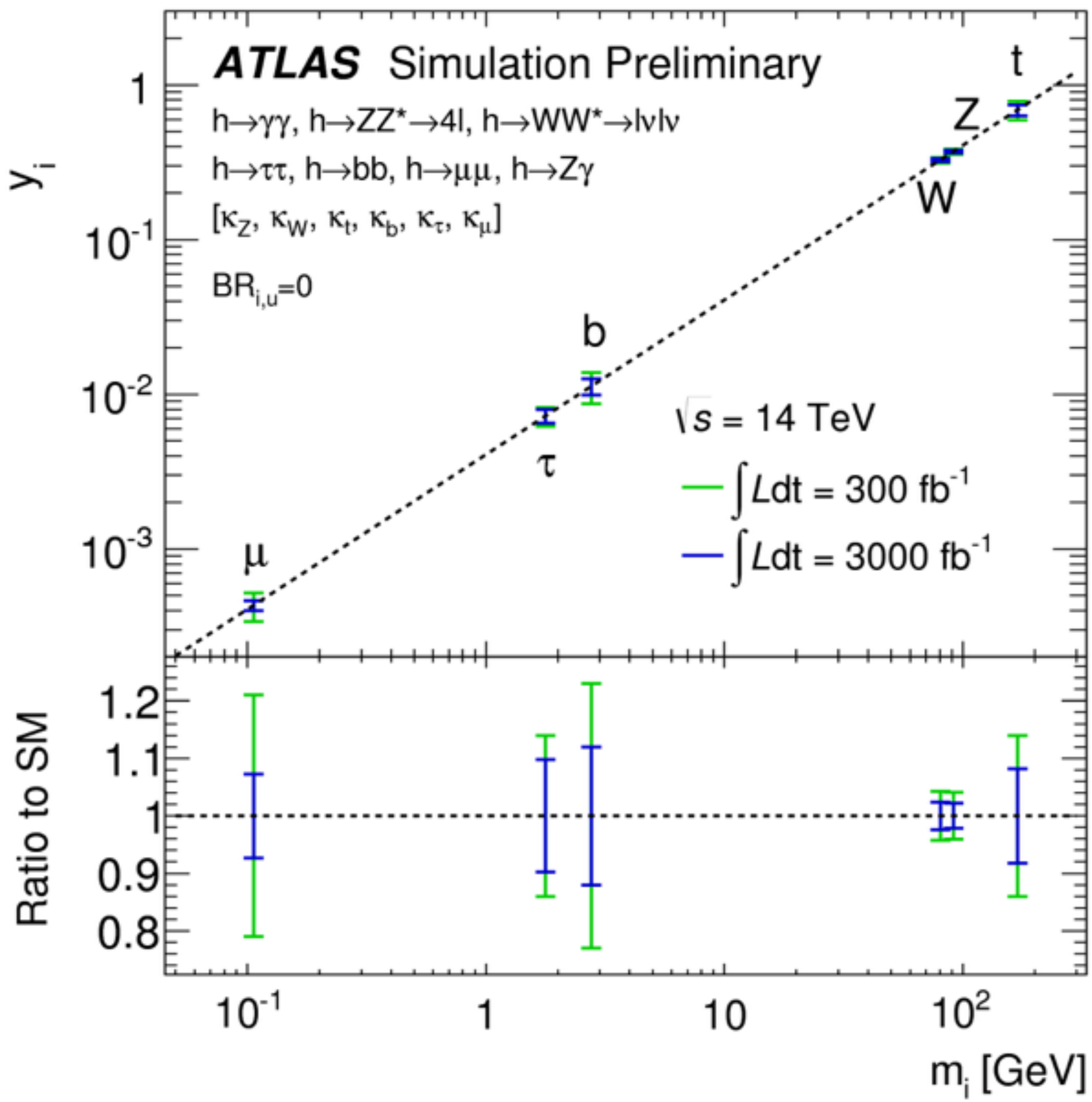
Parameterise in y, linear relationship in Standard Model

For vector bosons:

$$y_{V_i} = \sqrt{\frac{\kappa_{V_i} g_{V_i}}{2v}} = \sqrt{\kappa_{V_i}} \frac{m_{V_i}}{v}$$

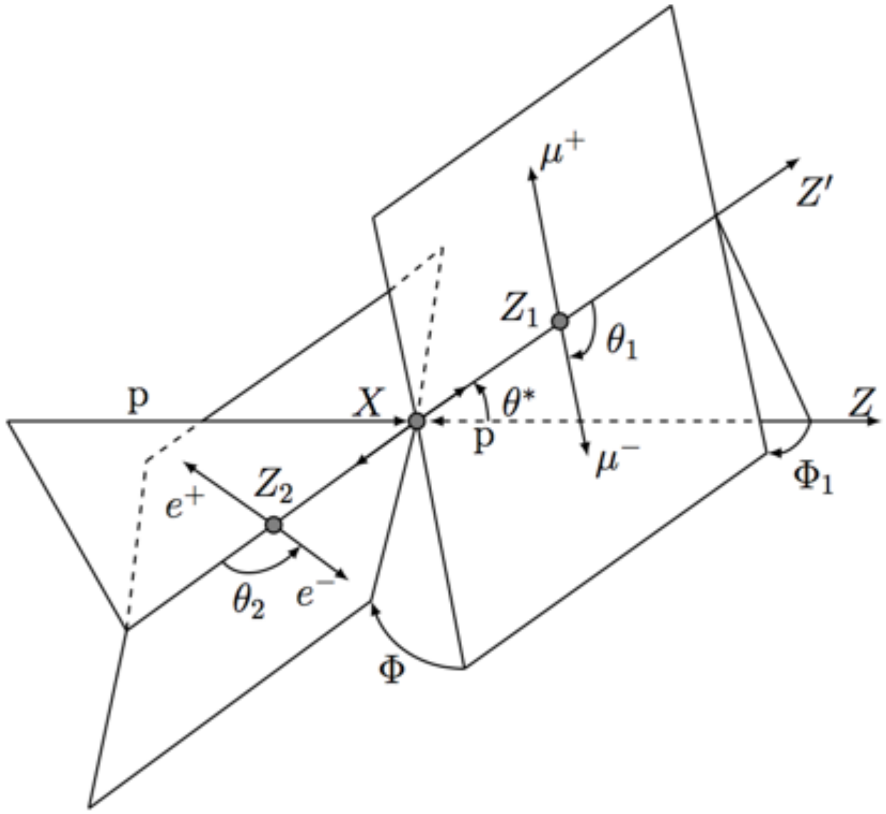
For fermions:

$$y_{F_i} = \frac{\kappa_{F_i} g_{F_i}}{\sqrt{2}} = \kappa_{F_i} \frac{m_{F_i}}{v}$$



BEH CP Studies

- $H \to ZZ \to 4\ell$ used to reconstruct the full angular decay structure.



- Very sensitive to non-SM (**CP** = **0**$^+$) contributions.

$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^\star \epsilon_2^\star + a_2 f_{\mu\nu}^{\star(1)} f^{\star(2),\mu\nu} + a_3 f_{\mu\nu}^{\star(1)} \tilde{f}^{\star(2),\mu\nu}\right)$$

SM tree processes — loop **CP**-even contributions — **CP**-odd contributions (BSM)

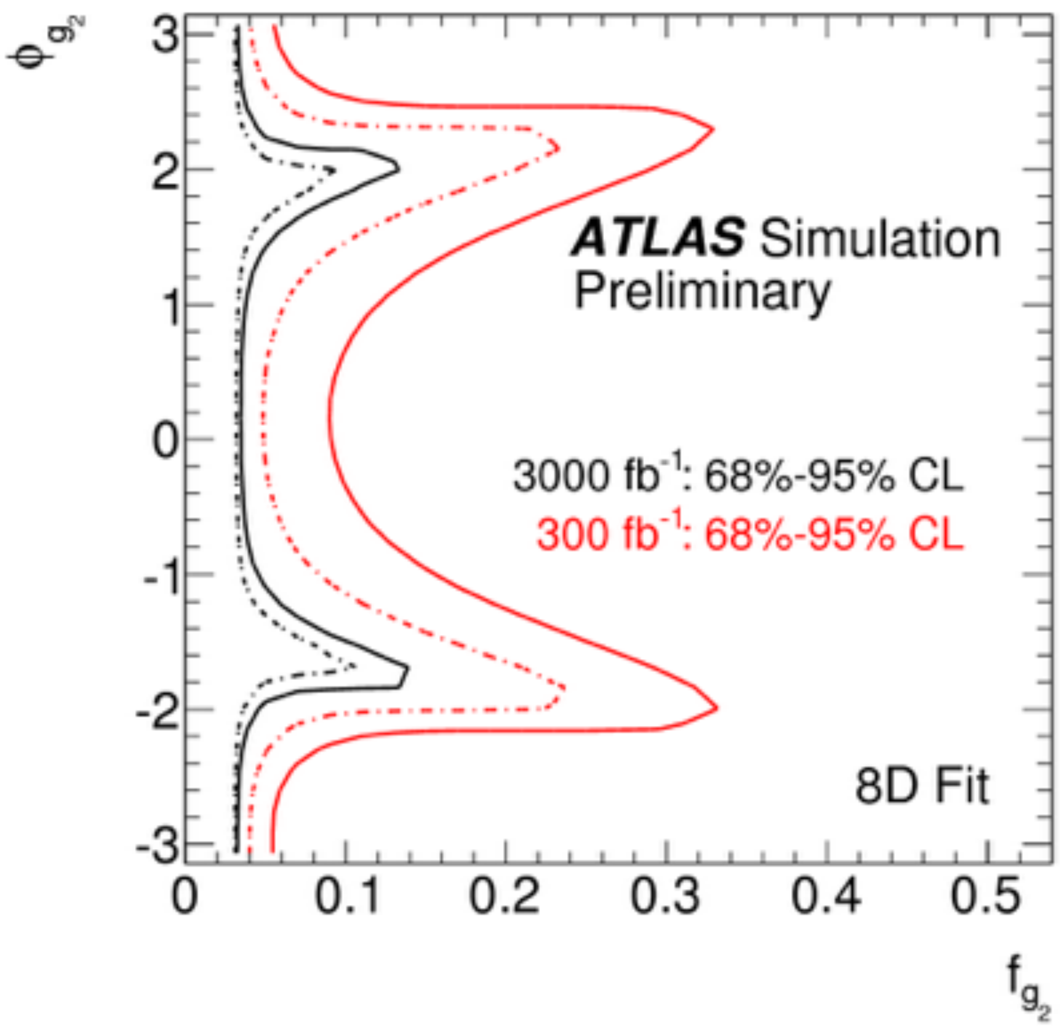
- Fit fraction of event (f_{ai}) and phases (ϕ_i) to observed decay:

$$\phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right) \qquad f_{a_i} = \frac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1 + |a_i|^2\sigma_i}$$

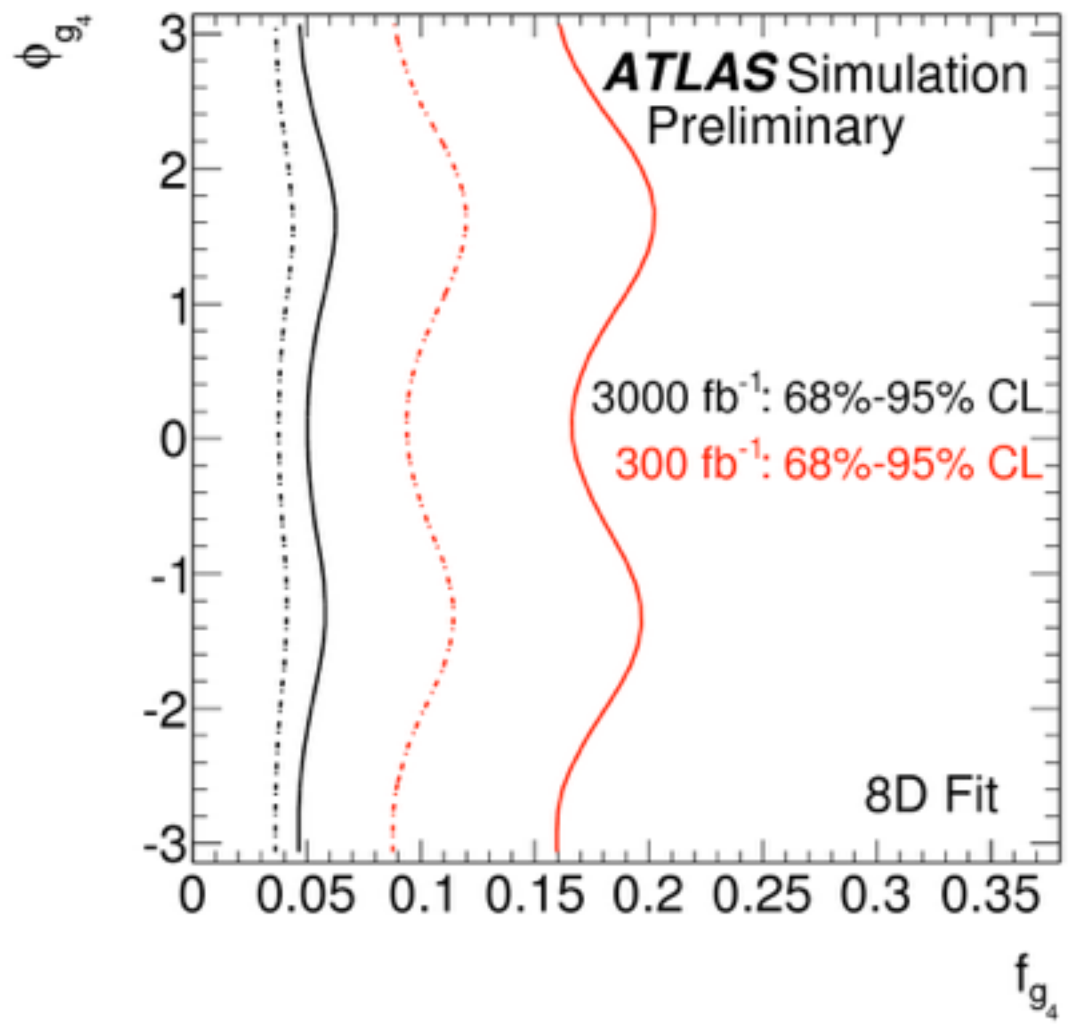
$$a_1 = g_1 \frac{m_V^2}{m_H^2} + \frac{s}{m_H^2}\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right); \quad a_2 = -\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right); \quad a_3 = -2g_4,$$

BEH CP Studies

ATL-PHYS-PUB-2013-013



Loop-induced CP-even contribution



CP-odd contribution

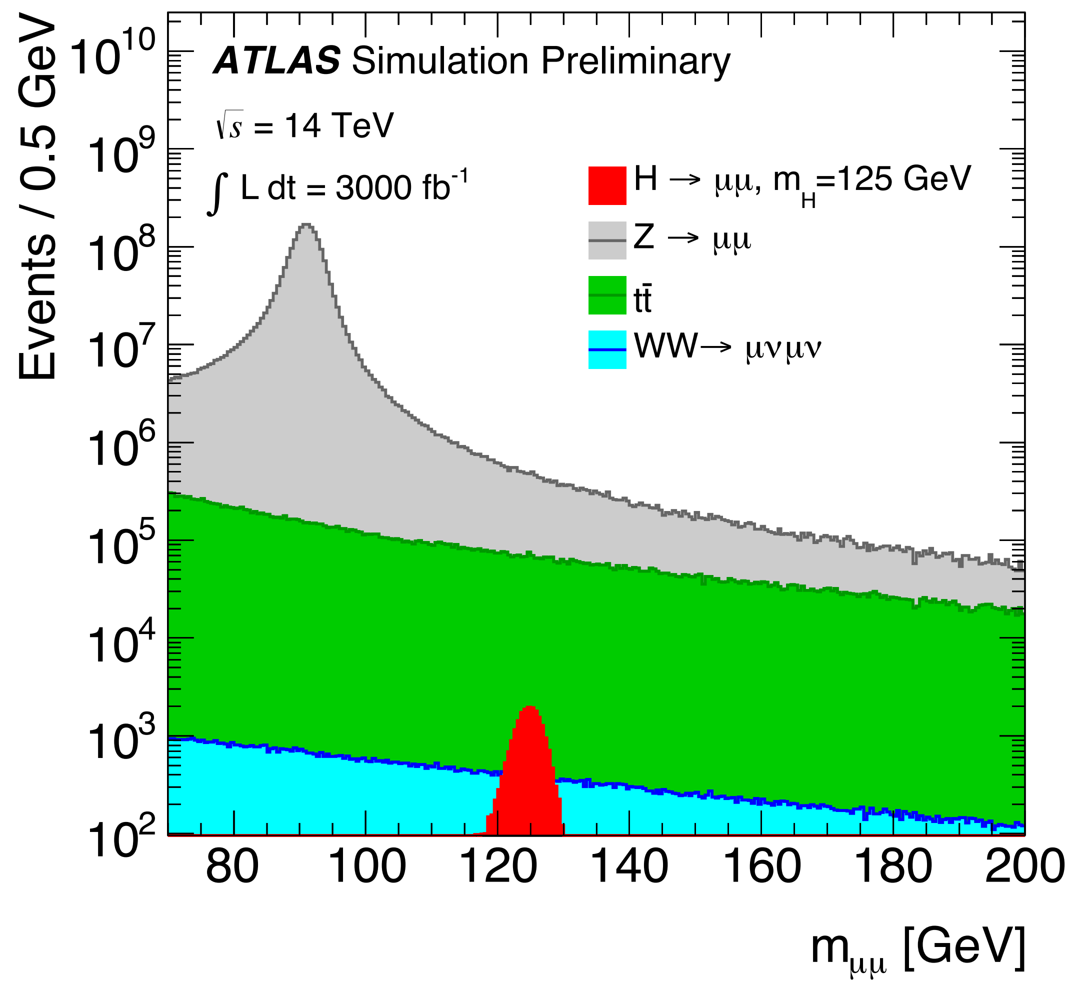
- Extra contributions constrained to $|f| \sim 10$ % with **3000 fb^{-1}.**

$$a_1 = g_1 \frac{m_V^2}{m_H^2} + \frac{s}{m_H^2}\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right); \quad a_2 = -\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right); \quad a_3 = -2g_4,$$

BEH Boson Rare Decays

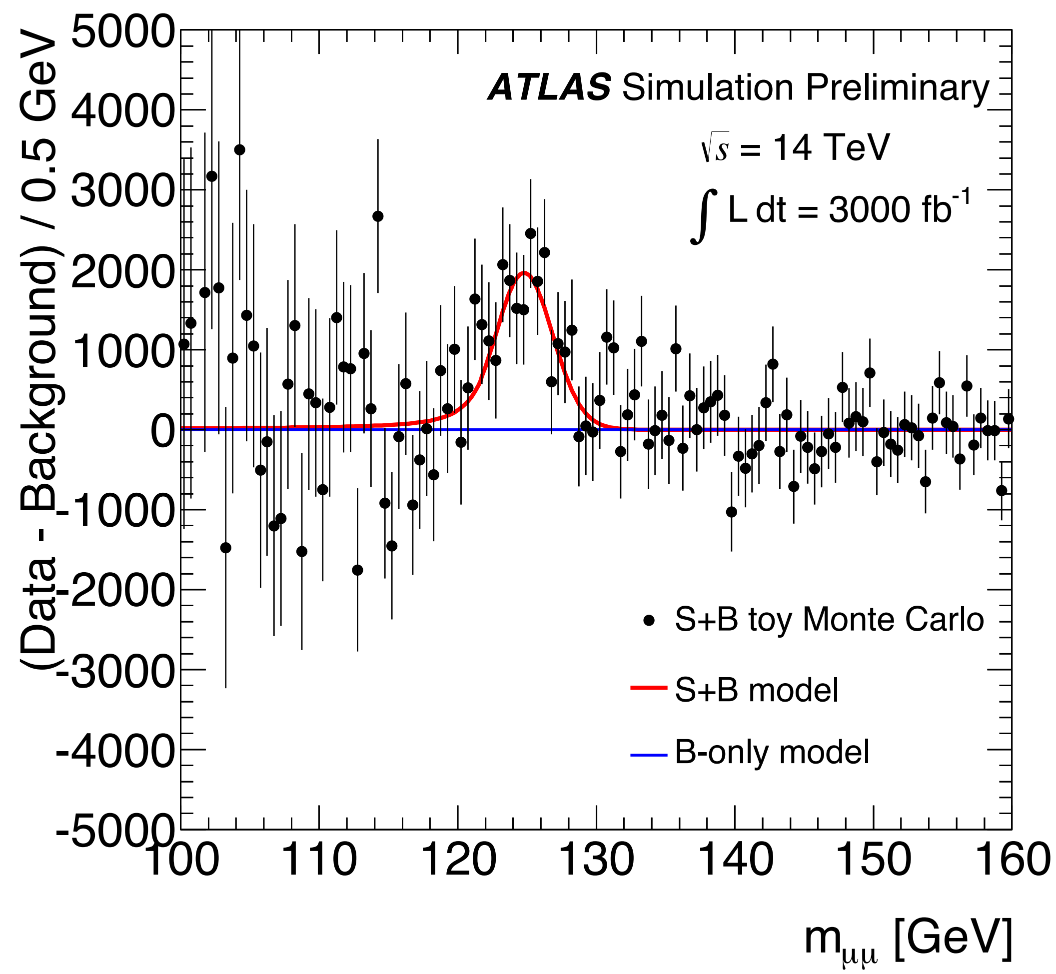
$H\rightarrow\mu\mu$

- SM prediction is $\mathbf{BR}(H\rightarrow\mu\mu) = 2.19 \times 10^{-4}$
- Observation of $H\rightarrow\mu\mu$ gives access to BEH coupling to 2nd generation of fermions.
- Run 1 limit is 7 × SM
- With $3000\ \mathrm{fb}^{-1}$:
  - Observation at ~7σ
  - uncertainty of 20-25 % on signal strength (~8% on κ_μ)



***ATLAS* Simulation Preliminary**

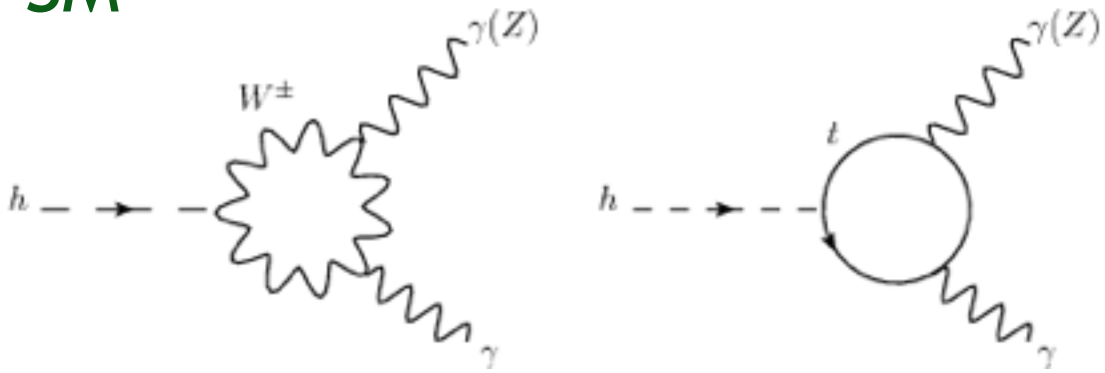
$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
$\Delta^{\mathrm{sys}}_{Bkg}$ (model)	68	110
$\Delta^{\mathrm{sys}}_{Bkg}$ (fit)	190	620
$\Delta^{\mathrm{stat}}_{\mathrm{S+B}}$	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%



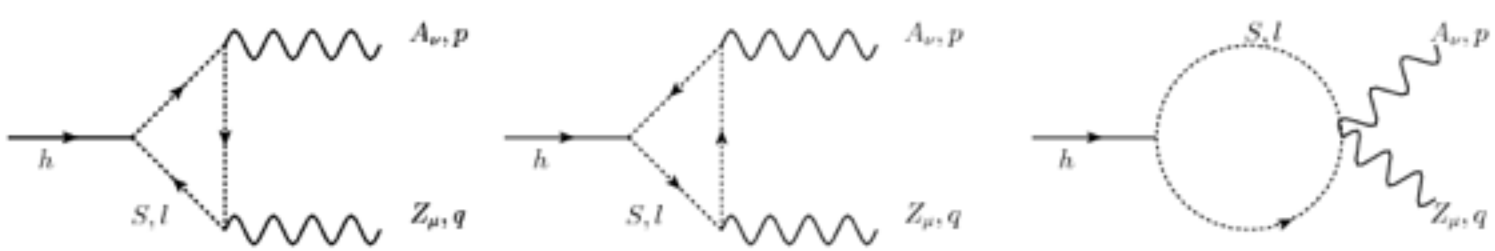
$H\rightarrow Z\gamma$

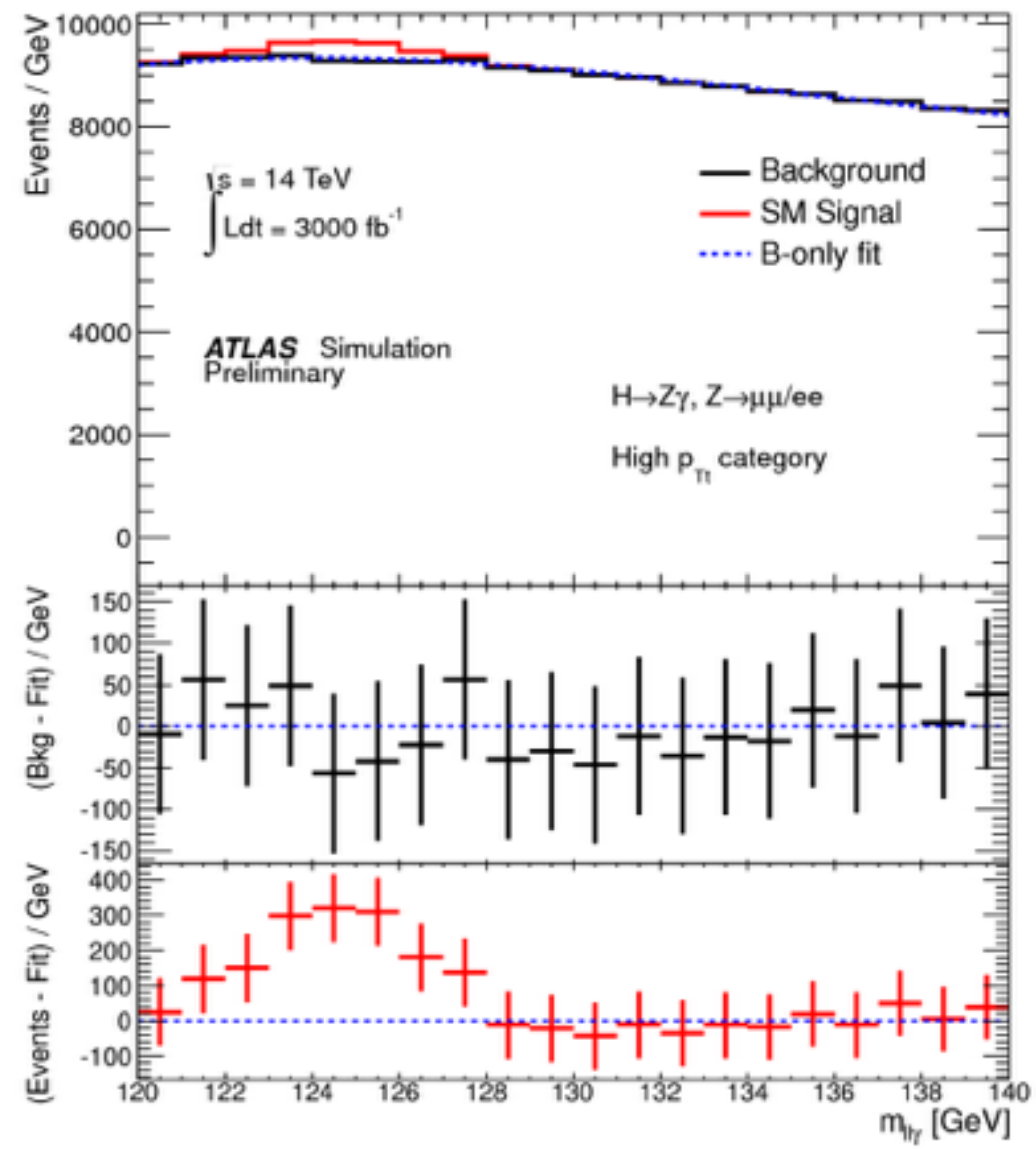
- SM prediction is $\mathbf{BR}(H\rightarrow Z\gamma) = \mathbf{1.54 \times 10^{-3}}$
- $H\rightarrow Z\gamma$ sensitive to potential new particles in loop

SM



e.g. new scalar contribution



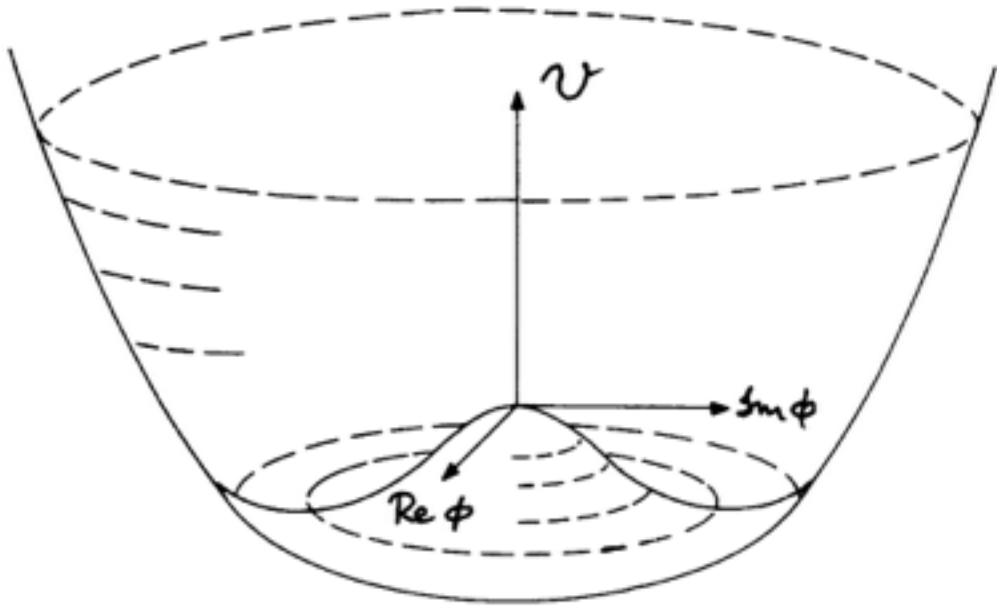


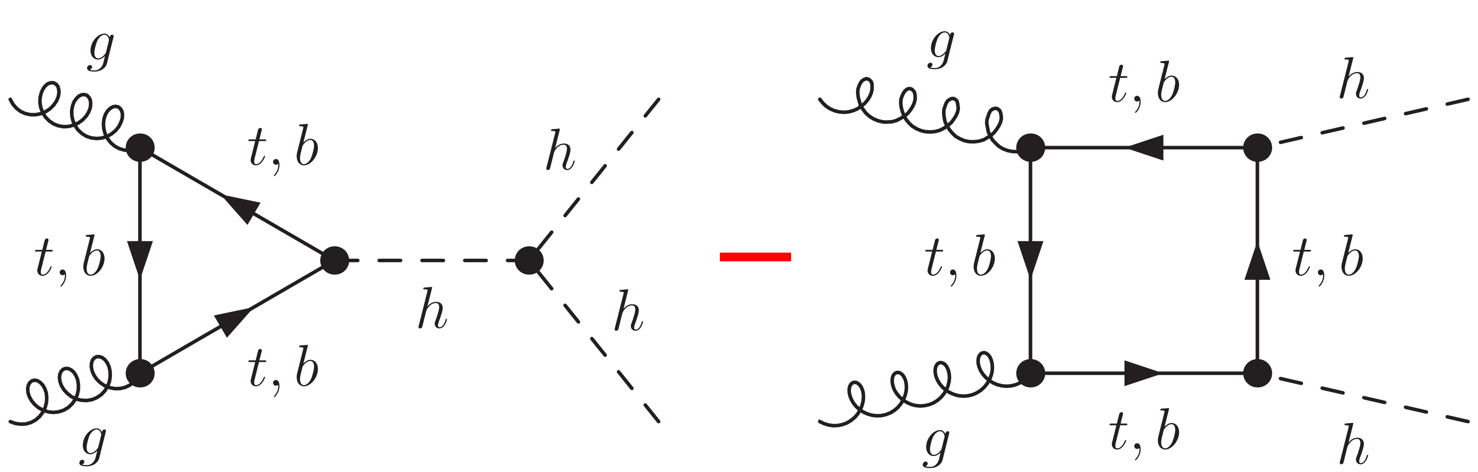
- Run 1 limits are 10 × SM
- At $\mathbf{3000\ fb^{-1}}$ a precision of 20-30% on the signal strength (~10% on $\kappa_{Z\gamma}$)

Di-BEH Boson Production

- We want to probe the shape of the BEH potential

- Observation of di-BEH production is a first step… but very challenging

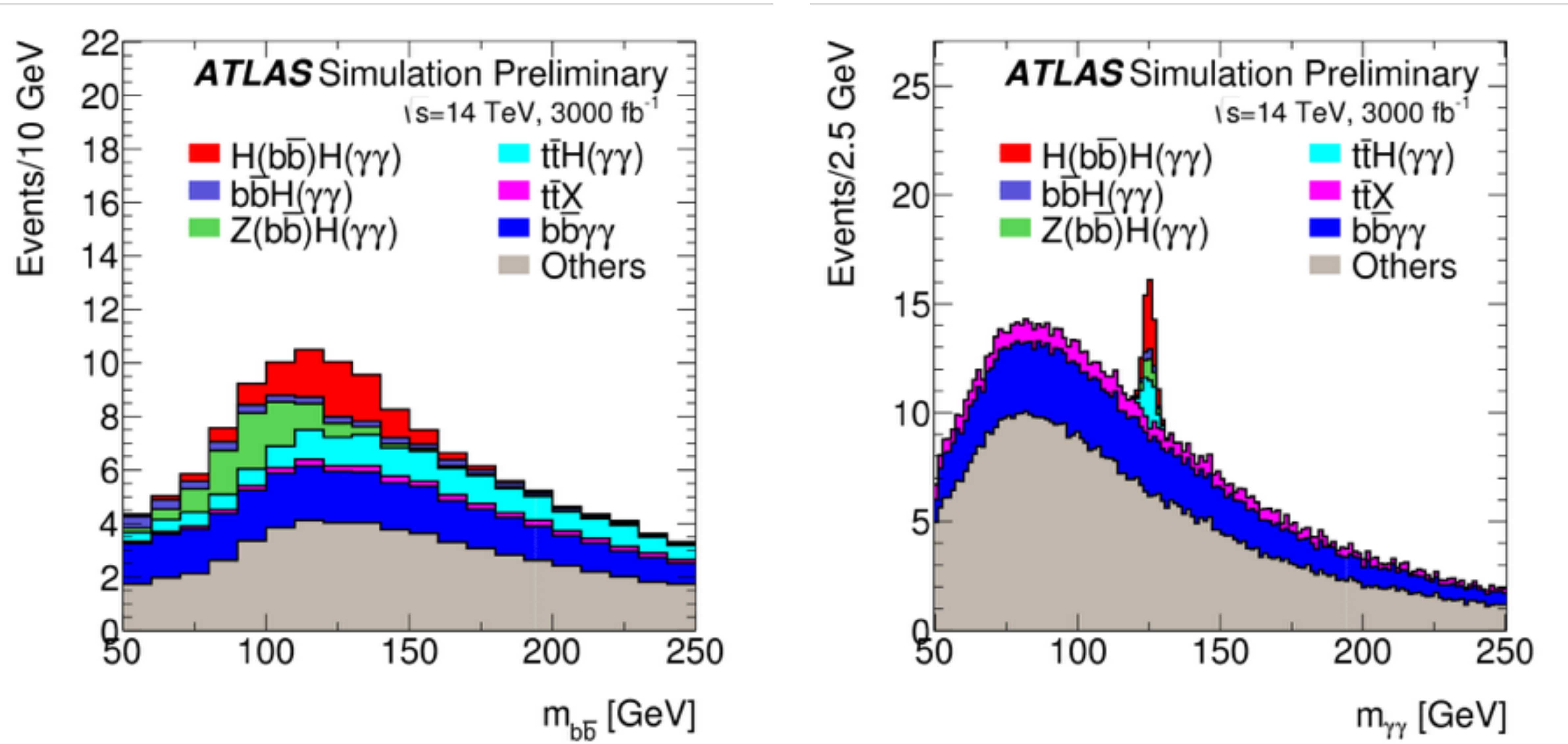




- Production dominated by box diagram, negative interference with self-coupling diagrams

Di-BEH Boson Production

$HH \rightarrow \gamma\gamma b\bar{b}$

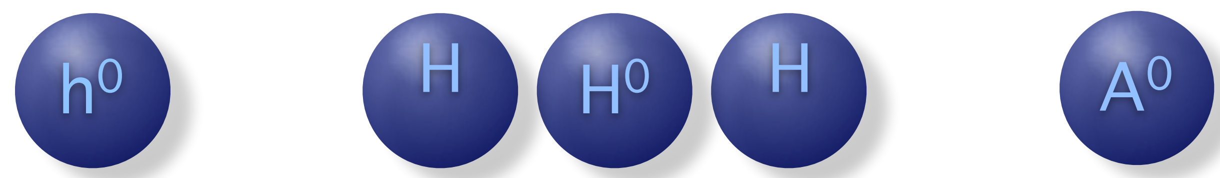


- With 3000 fb^{-1}: 8 events, significance of ~**1.3 σ**

BEH beyond the Standard Model

Additional Heavy BEH bosons

- Additional BEH doublets predicted in many models, including Supersymmetry.
- e.g. A two-BEH doublet (2HDM) model includes four new BEH bosons:



125 GeV CP odd

- **tanβ** is the ratio between the vev of the BEH doublets

$A \to Zh \to \ell\ell bb$ reconstruction (2HDM)

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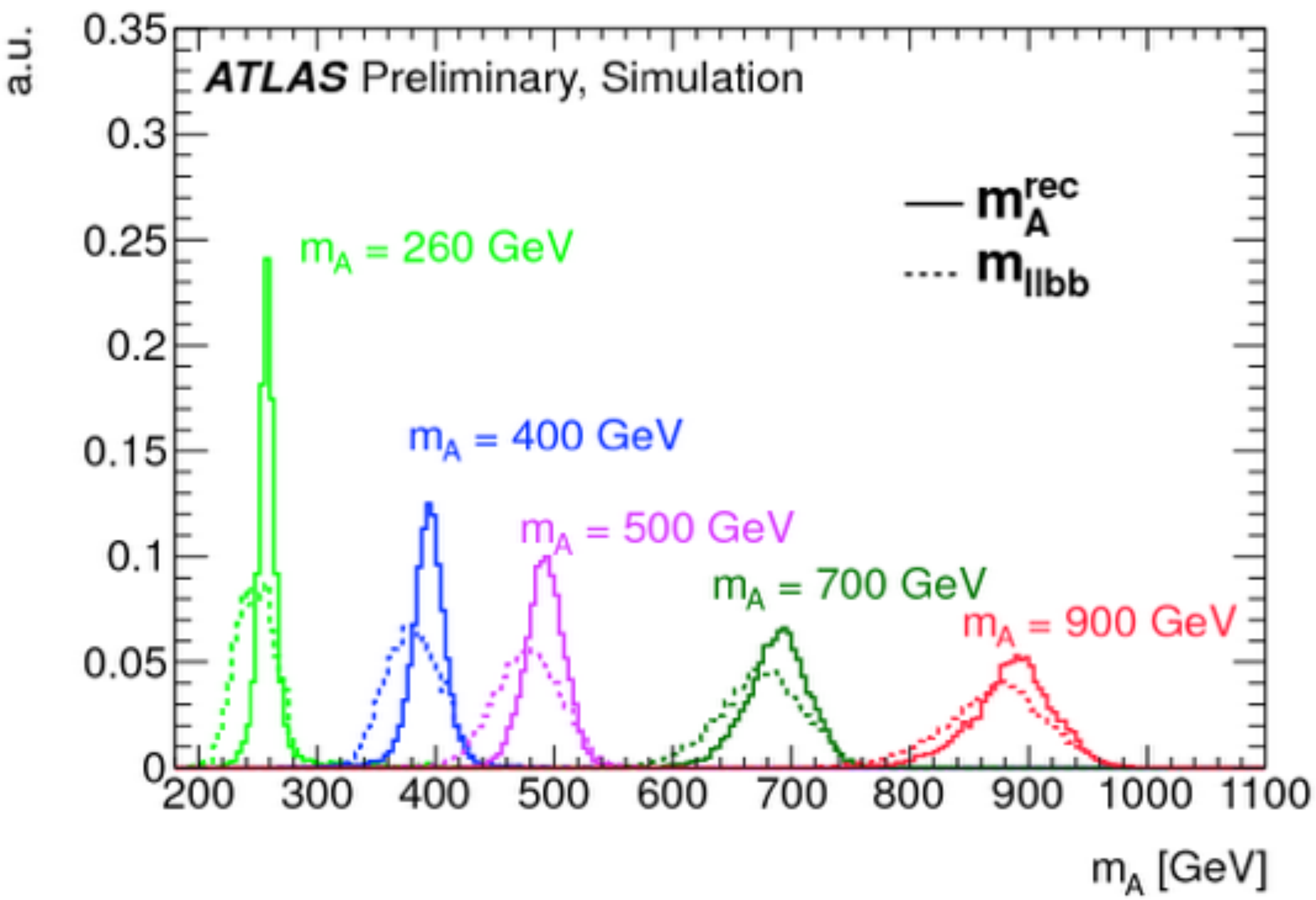

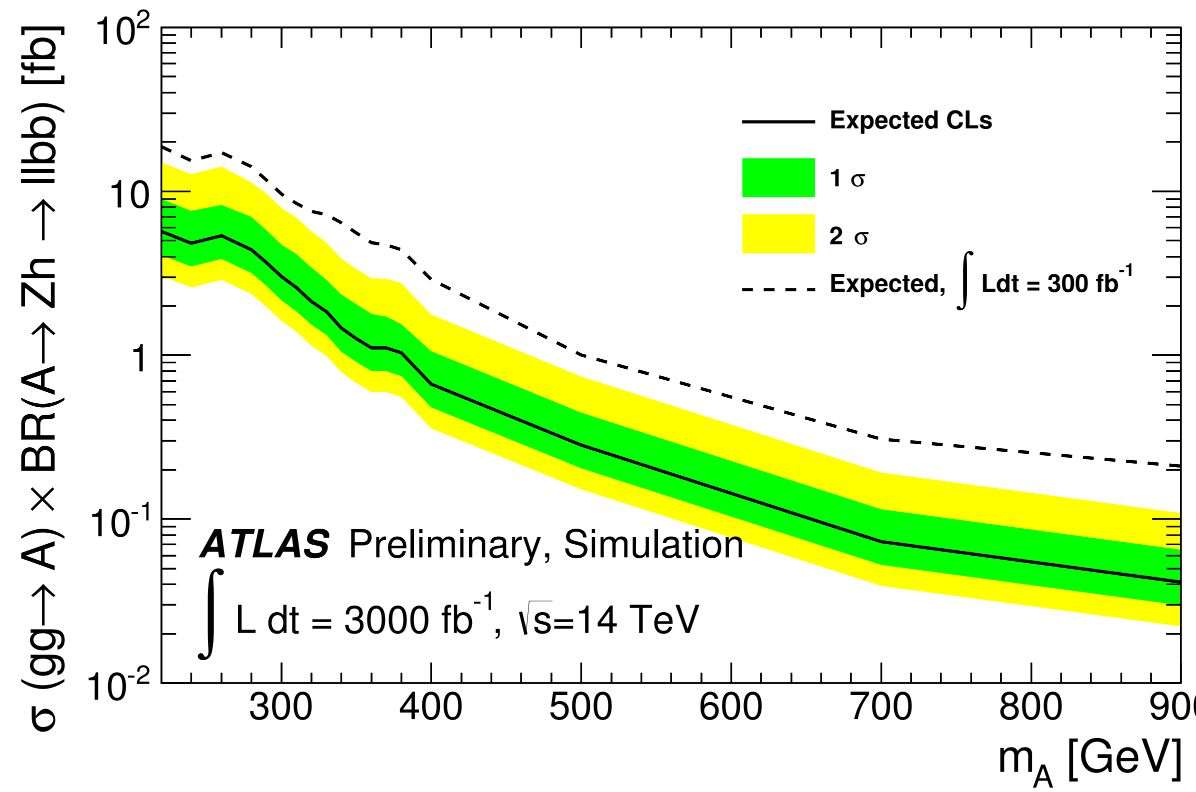

Additional Heavy BEH bosons

Prospects for $H' \to ZZ \to 4\ell$ production

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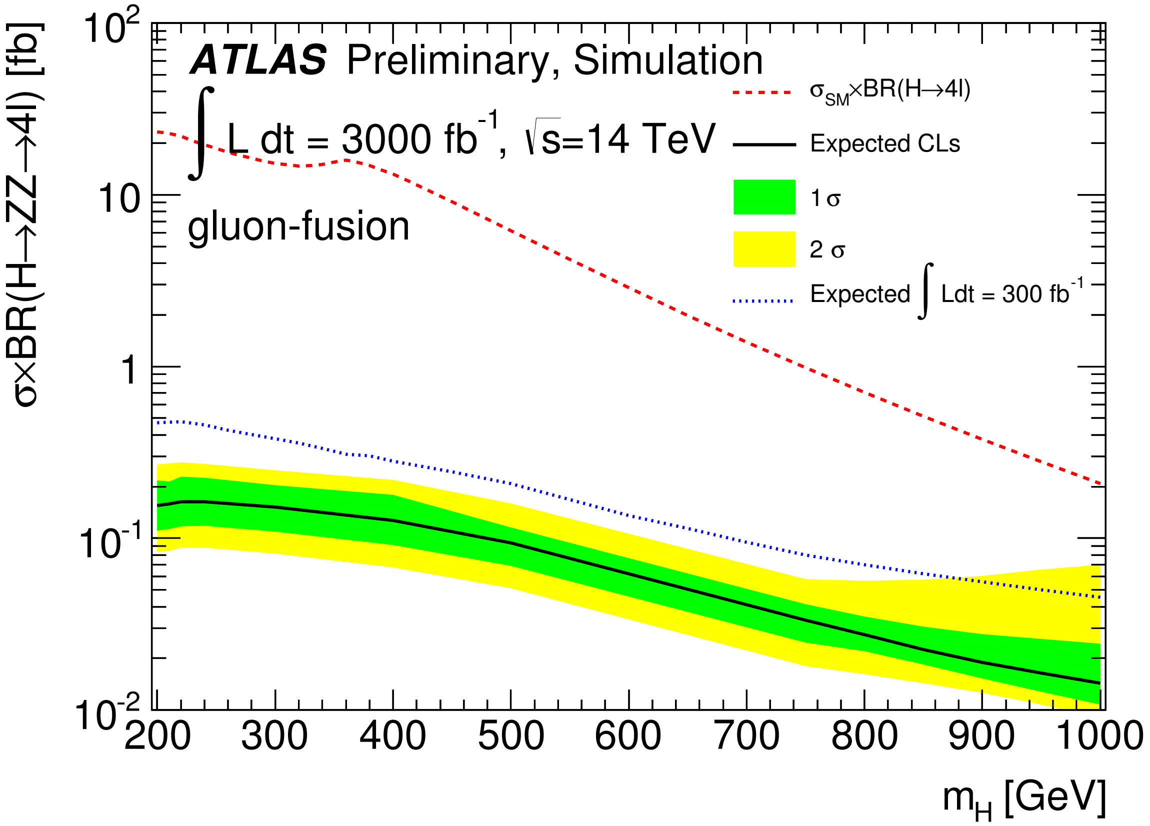
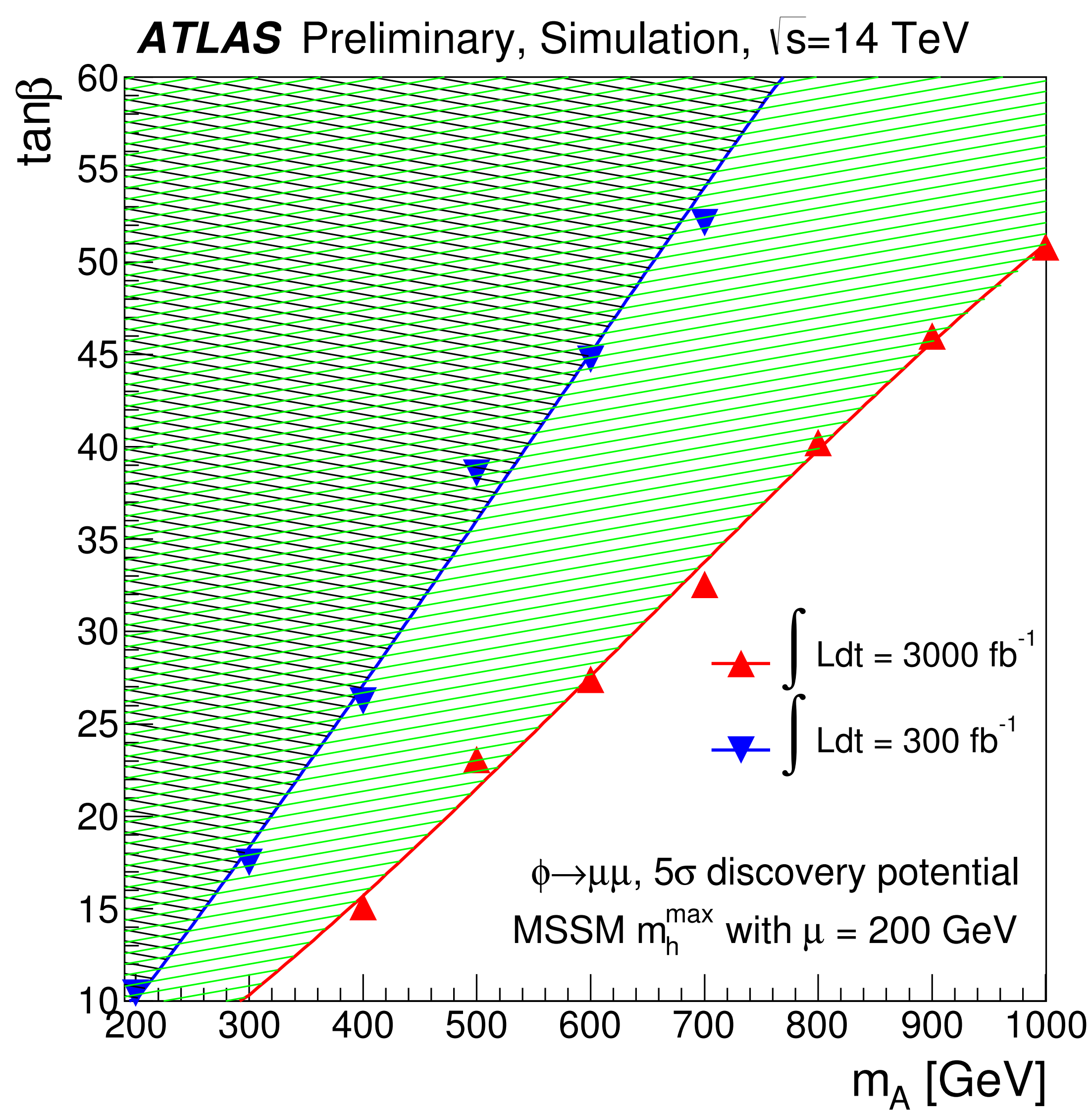
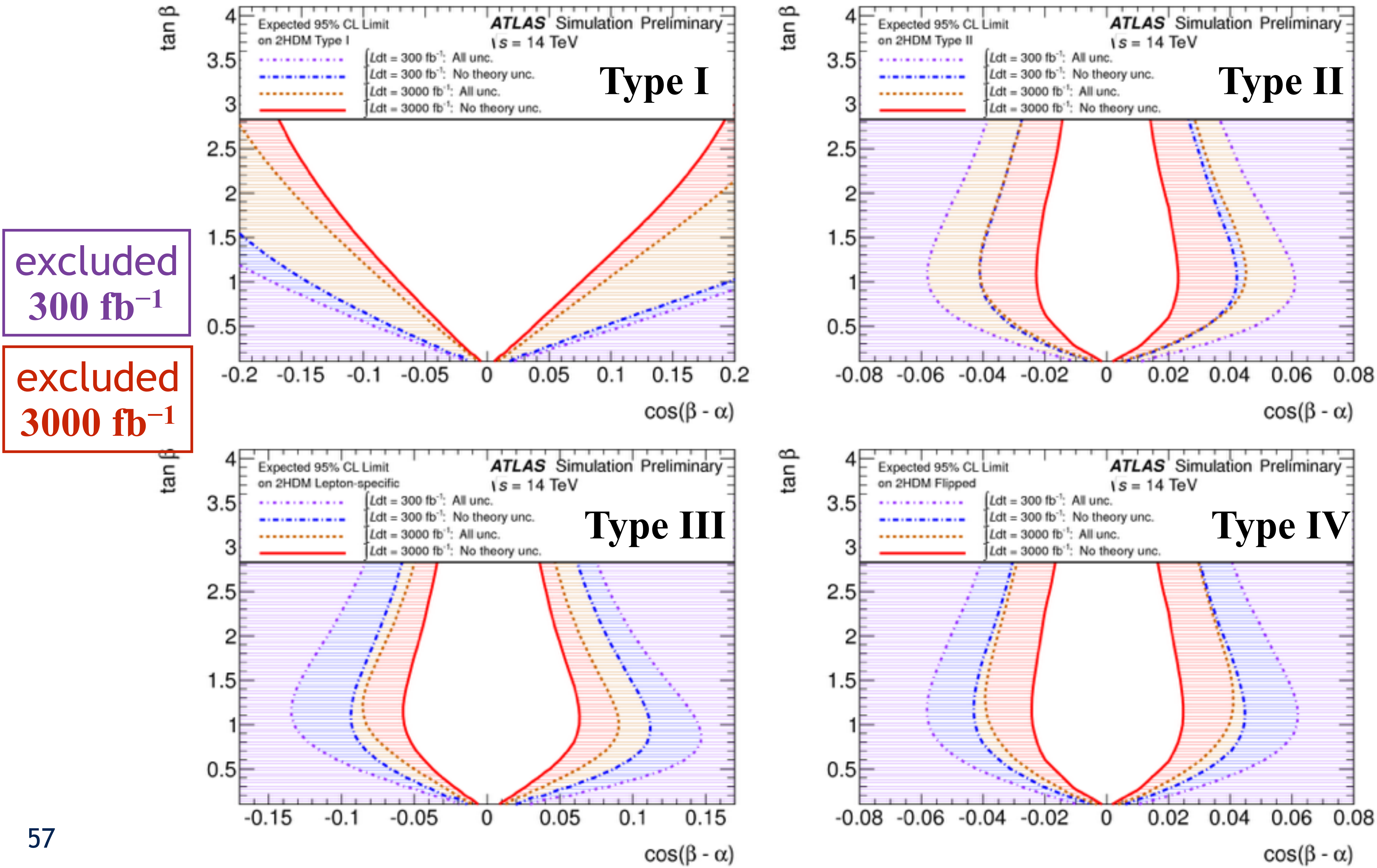


Prospects for $\phi \to \mu\mu$ production



Indirect limits on BSM BEH bosons in 2HDMs

ATLAS-PHYS-PUB-2013-015



Edinburgh Higgsteria

Some letters…

10 DOWNING STREET
LONDON SW1A 2AA

THE PRIME MINISTER

13 July 2012

Dear Professor Higgs,

I would like to take the opportunity of CERN's historic announcement last week to congratulate and thank you for all you have done for British physics.

Your research papers of 1964, despite their initial rejection as being 'of no obvious relevance to physics' have underpinned the theories of particle physicists for decades now and their recent validation was a great triumph for you and the other theorists, illustrating the real knowledge gains that can arise from the seemingly obscure puzzles and mental exercises that theoretical physics explores.

The work of the engineers, experimentalists, theorists and computer scientists, many of them British, that has made the Large Hadron Collider a successful research facility has captured the imagination of the public at all levels and ages. The lead taken by yourself and other UK researchers has inspired much of the nation and will stimulate more young people to pursue scientific enquiry and training, providing the skilled work force upon which a modern economy like ours depends for growth. I know just by looking at the number of hits my comments about the announcement have had on the No.10 website how much this has captured the public imagination and interest.

Your research will form part of the UK's rich heritage in scientific advances and on behalf of the nation, I wanted to express my sincere thanks.

Yours sincerely,

Professor Peter W Higgs

Ministear airson Ionnsachadh, Saidheans agus Cànain na h-Alba
Meinister for Lear, Science an Scotland's Leids
Minister for Learning, Science and Scotland's Languages
Alasdair Allan BPA/MSP

F/T: 0845 774 1741
E: scottish.ministers@scotland.gsi.gov.uk

The Scottish Government
Riaghaltas na h-Alba

Professor Peter Higgs, FInstP, FRSE, FRS

DELIVERING
A GAMES LEGACY FOR SCOTLAND

4 July 2012

Dear Professor Higgs

I was delighted to see the exciting announcement from CERN on the observation of a new particle consistent with Higgs boson. I can only imagine what you must be feeling.

I know these results are preliminary and are part of a huge and inspiring international collaborative effort, but I would like to offer my congratulations to both you personally, for inspiring the search, and the teams in Glasgow and Edinburgh involved in ATLAS, for helping to make this discovery happen.

I look forward to hearing more as the analysis continues.

ALASDAIR ALLAN

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LEADER OF THE OPPOSITION

HOUSE OF COMMONS
LONDON SW1A 0AA

Mr Peter Higgs
c/o The University of Edinburgh
Old College
South Bridge
Edinburgh
EH8 9YL

28 August 2012

Dear Peter,

I wanted to offer my congratulations for the tremendous contribution you have made to the development of particle physics and to our understanding of the world in which we live.

It does not fall to many people in history to predict the theoretical existence of a sub-atomic particle which is then confirmed, mere decades later. The Higgs Boson will take its rightful place in the history of science.

Your work in the 1960s helped to inspire the very concept of the Large Hadron Collider which in turn has been an inspiring example of international scientific collaboration in which UK science has played a very prominent part.

The recent announcement by CERN (following the results of the ATLAS and CMS experiments) represents both the culmination of one scientific endeavour and the start of a new era in our continuous quest to understand our Universe.

Science is international but this country can be truly proud of the role you personally have played. Thank you and congratulations again.

Best wishes,

Ed Miliband

Rt Hon Ed Miliband MP

Received 5/9/12 PH

Some emails...


Higgs
How to find a fitting name, was rather a challenge. Until my husband suggested your's : this boat was our divine particle, the missing part in our life.


<< The theories and science are for me a source of inspiration and to thank Peter Higgs with this portrait.>>

More emails…

Dear Sirs,

We are a craft beer micro company (Ca l'Arenys-GUINEU BEER), and we would like to make a Brewing Special Edition (10hl) as an Homage to Mr. Higgs

First of all we would like to know if there is any concern about it.

The idea is absolutely NON lucrative

-We would like to know, if possible, if Mr. Higgs likes beer and what styles does he prefer in order to adapt our receipt.

Best Regards

Xavier Serra

info@calarenys.com

Ca l'Arenys brewing Manager

Valls de Torruella (Barcelona)

Spain

Belgians also know how to party!

Outlook:
BEH boson measurements at run 2 & beyond

- We've come a long way baby, but there's still far to go...
- With $\mathbf{300\ and\ 3000\ fb^{-1}}$ the LHC will offer a comprehensive BEH physics programme:

Precision BEH physics: measure production rates to a few %

Observation of $H \to bb$

Observation of $H \to Z\gamma$ and $H \to \mu^+\mu^-$

Discovery of additional BEH bosons up to $O\ (\mathbf{1\ TeV})$

Theory uncertainty dominant for many analyses

- Some analyses do remain challenging, event at HL-LHC:

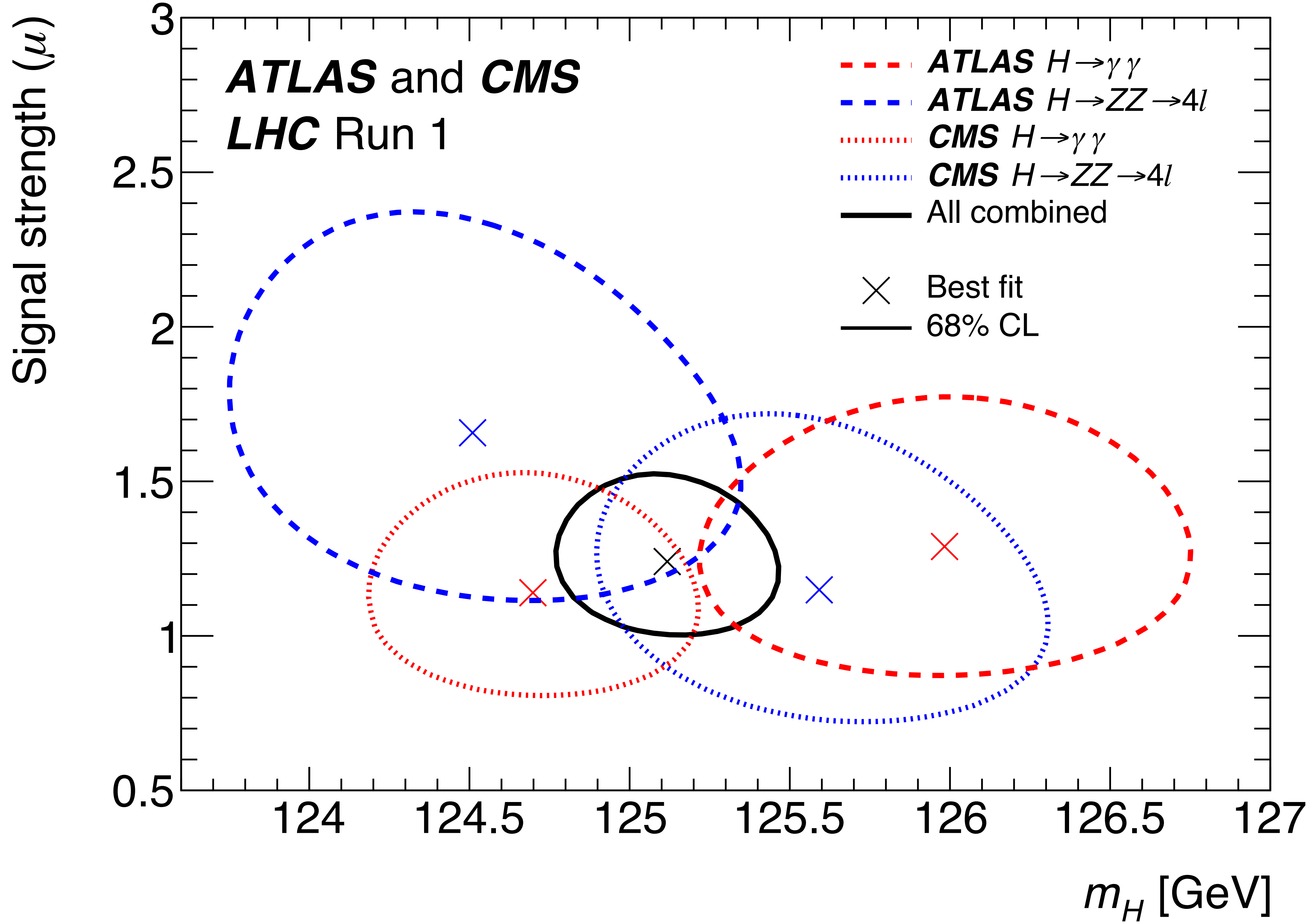
di-BEH boson

$H \to c\bar{c}$

triple-BEH boson

Backup

Run 1 BEH Mass Combination



BEH boson width uncertainties

Systematic uncertainty	95% CL lim. (CL_s) on $\mu_{\text{off-shell}}$
Interference $gg \to (H^* \to)VV$	7.2
QCD scale $\text{K}^{H^*}(m_{VV})$ (correlated component)	7.1
PDF $q\bar{q} \to VV$ and $gg \to (H^* \to)VV$	6.7
QCD scale $q\bar{q} \to VV$	6.7
Luminosity	6.6
Drell–Yan background	6.6
QCD scale $\text{K}^{H^*}_{gg}(m_{VV})$ (uncorrelated component)	6.5
Remaining systematic uncertainties	6.5
All systematic uncertainties	8.1
No systematic uncertainties	6.5