Vector Boson Fusion Production @ATLAS

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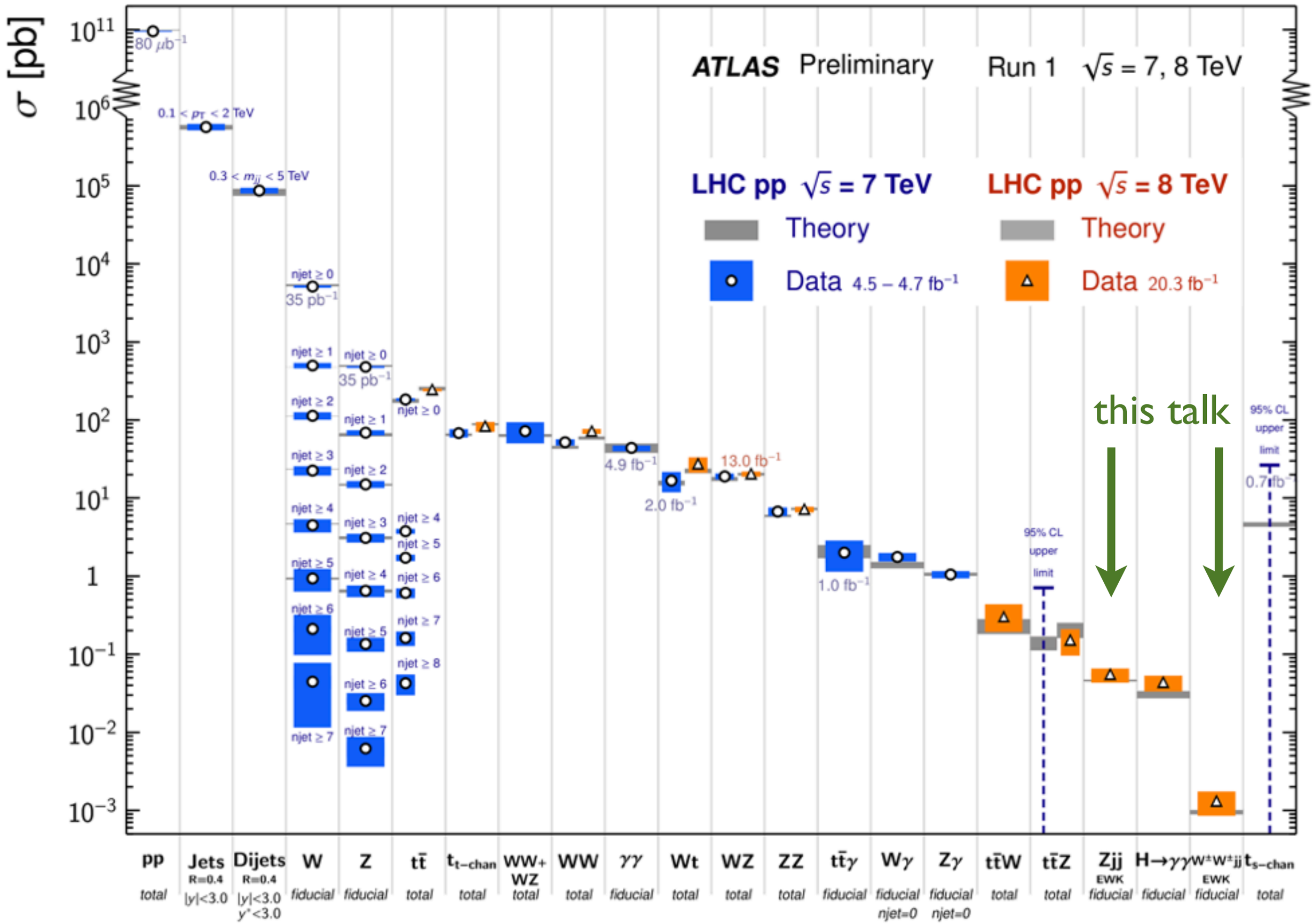
Standard Model Production Cross Section Measurements

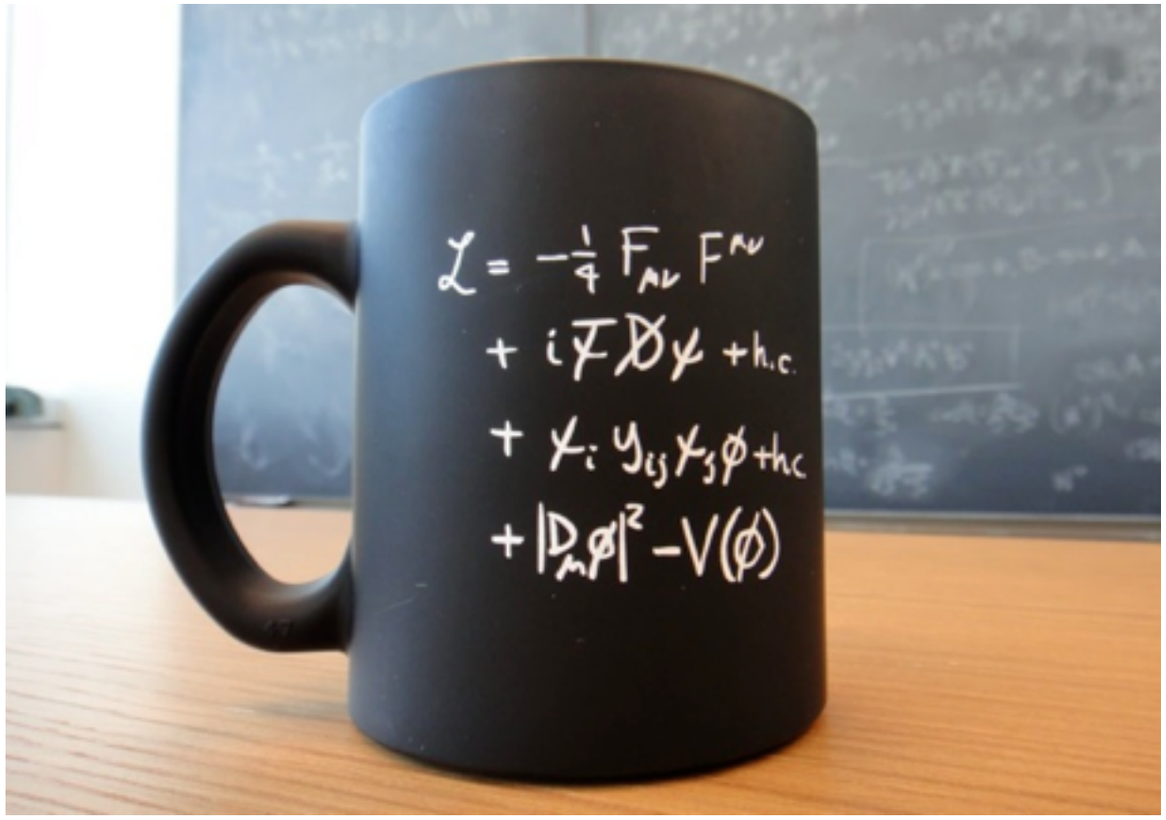
Status: July 2014



Outline

- Theoretical introduction and historical context
- VBF signature
- EW Z+2jet production JHEP04(2014)031
  - Test case for heavy boson production via VBF
  - EW Zjj extraction techniques
  - Anomalous triple gauge boson couplings (aTGC)
- VBF Higgs ATLAS-CONF-2014-009 ATLAS-CONF-2013-108 *Phys. Lett. B 726 (2013), pp. 120-144*
- EW $W^{\pm}W^{\pm}$ production arXiv:1405.6241
  - Complementary test of EW symmetry breaking
  - Anomalous quartic gauge boson couplings (aQGC)
- Outlook

Standard Model Lagrangian



$SU(3)_c \times SU(2)_L \times U(1)_Y$

3 charge types	2 charge types	1 charge type
red, green, blue	isospin $I_3^W = \pm 1/2$	hypercharge
8 gauge bosons	3 gauge bosons	1 gauge boson
8 gluons	$W+, W-, W_3$	B

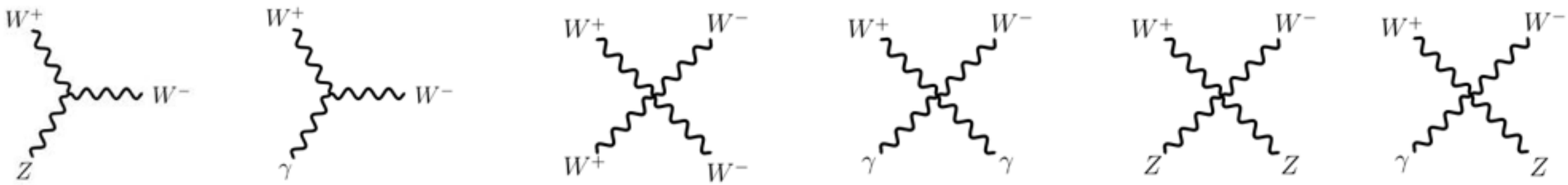
$\underbrace{W_3 \quad B}_{Z,\gamma}$

- All 3 SM forces and how they allow matter to interact is contained in the SM Lagrangian
  - strong force and unified EW force
- The Lagrangian density must be invariant under the symmetries observed in the universe
  - conservation laws
- Local gauge invariance is the fundamental principle on which the Standard Model is built

Testing EW Theory - Fusion of EW Bosons

EW theory is non-Abelian $\Longrightarrow$ gauge bosons possess weak charge $\Longrightarrow$ they interact with each other

The following triple and quartic self-interactions between EW Bosons appear:



Triple gauge couplings

Quartic gauge couplings

$\mathcal{L}_{WWV}$ contains the gauge three-point self interactions.

$$\mathcal{L}_{WWV} = -ig[(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})(A^\nu \sin\theta_W - Z^\nu \cos\theta_W) + W^-_\nu W^+_\mu (A^{\mu\nu}\sin\theta_W - Z^{\mu\nu}\cos\theta_W)]$$

$\mathcal{L}_{WWVV}$ contains the gauge four-point self interactions

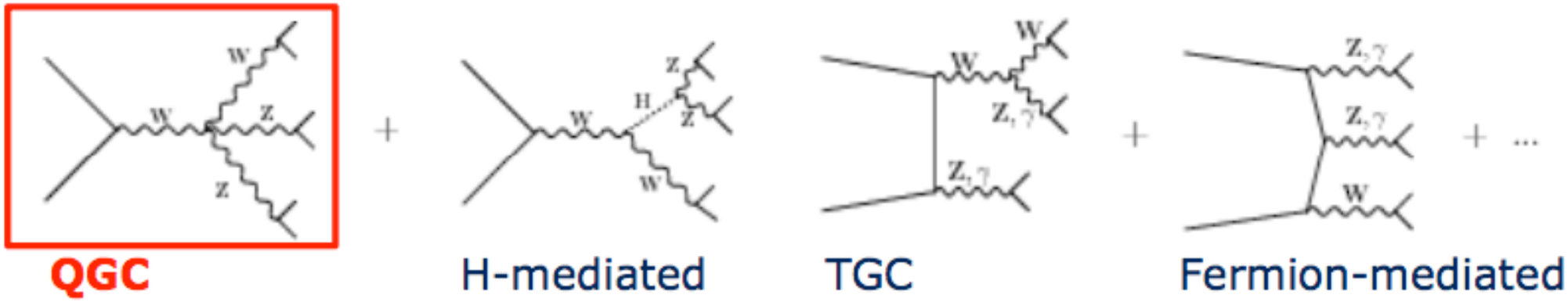
$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W^+_\mu W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2 - [W^+_\mu W^-_\nu + W^+_\nu W^-_\mu + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\Big\}$$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$$

Anomalous Couplings

- Triple and quartic gauge vertices never occur alone in a given process

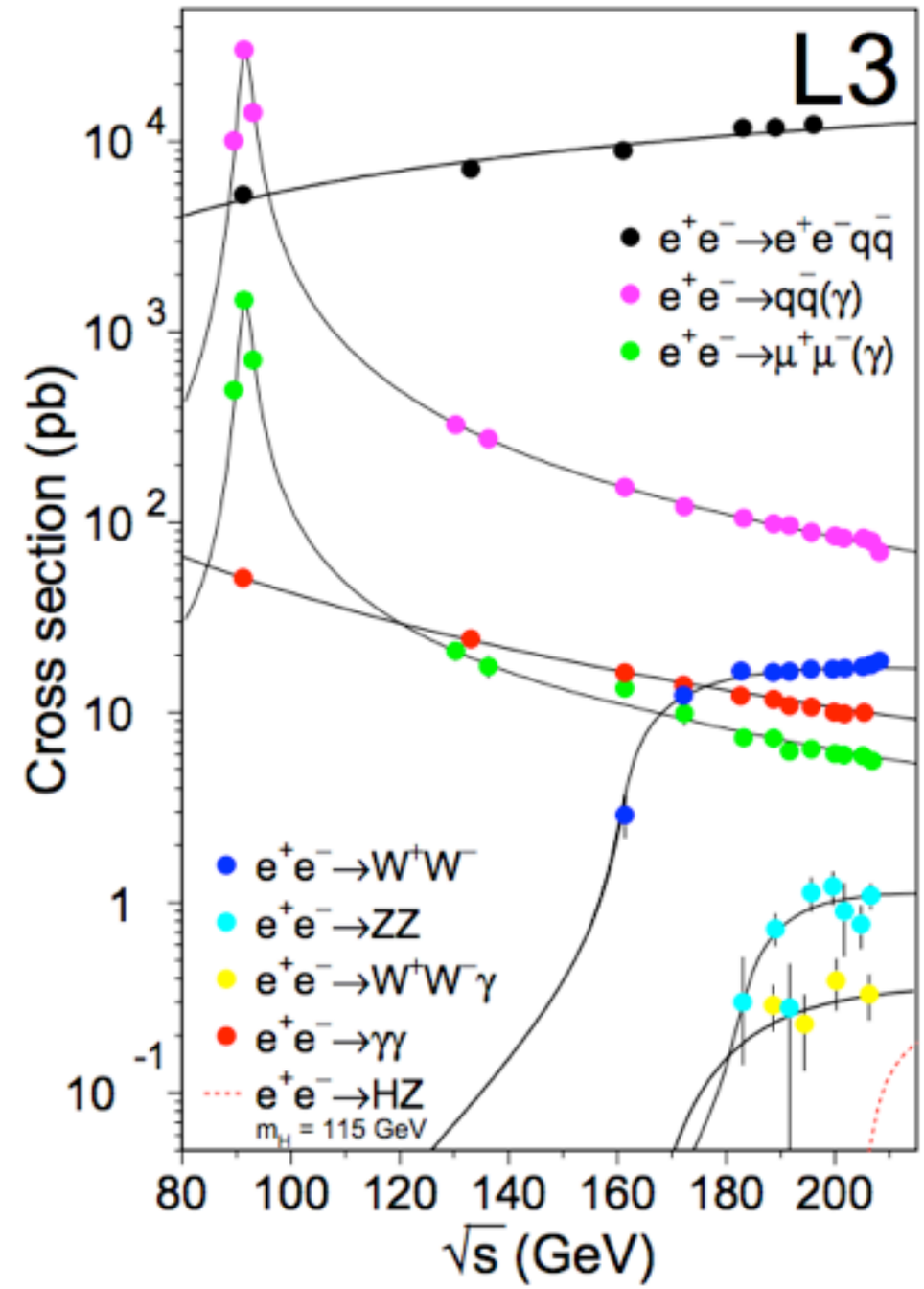
e.g. triple gauge boson production



- Anomalous triple and quartic couplings modify the expected cross sections
- We would like to constrain extensions to the SM using experimental measurements in a model independent way
  - Assume SM is an effective theory of a more complex one: $\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}}$ + modifications
    - e.g. strong dynamics, resonances
    - usually implies modified couplings
  - Can introduce unphysical predictions at high energies
  - Requires unitarization, which kills model independence, but provides realistic constraints on couplings
- To place constraints on your favorite model, you must first deconvolute the effects of the unitarization scheme.

Experimental Tests of EW Theory

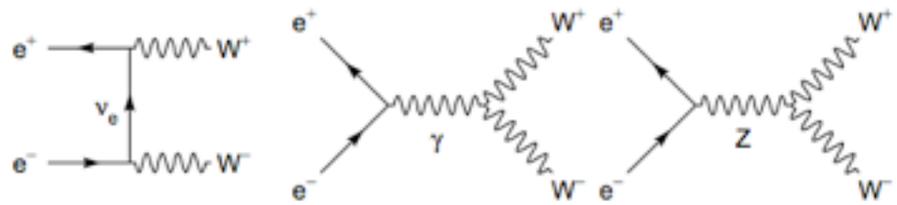
- EW Interactions were measured extensively by LEP experiments
- Apart from few features that were experimentally inaccessible (including observing Higgs Boson), SM theory has been confirmed at very high precision

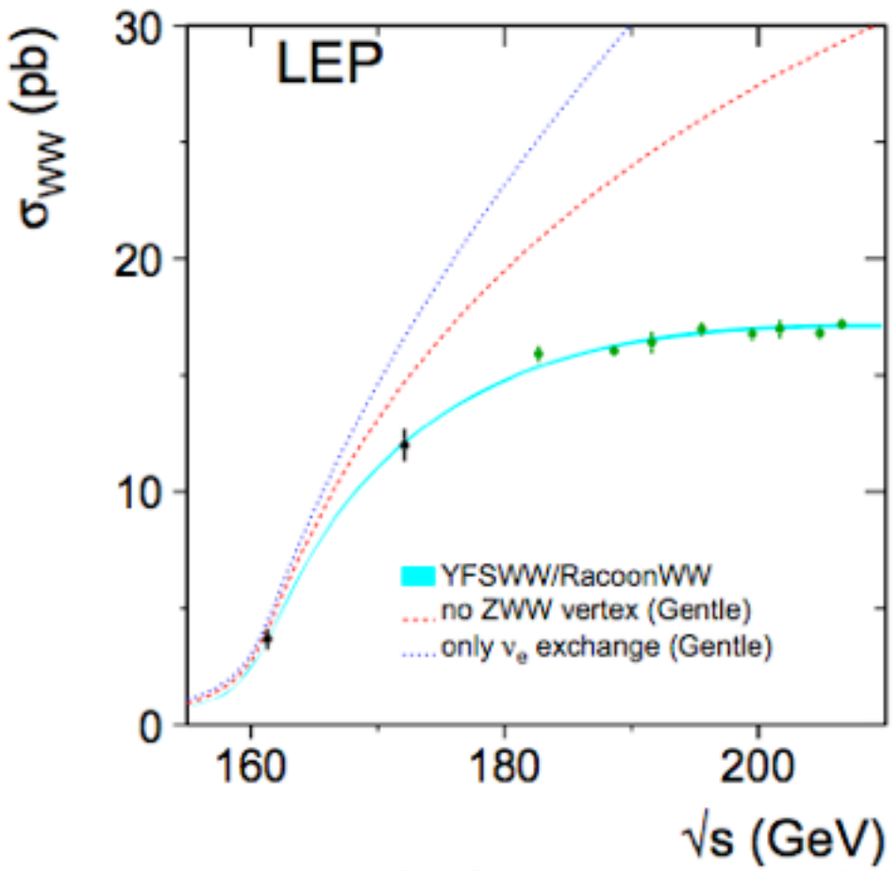


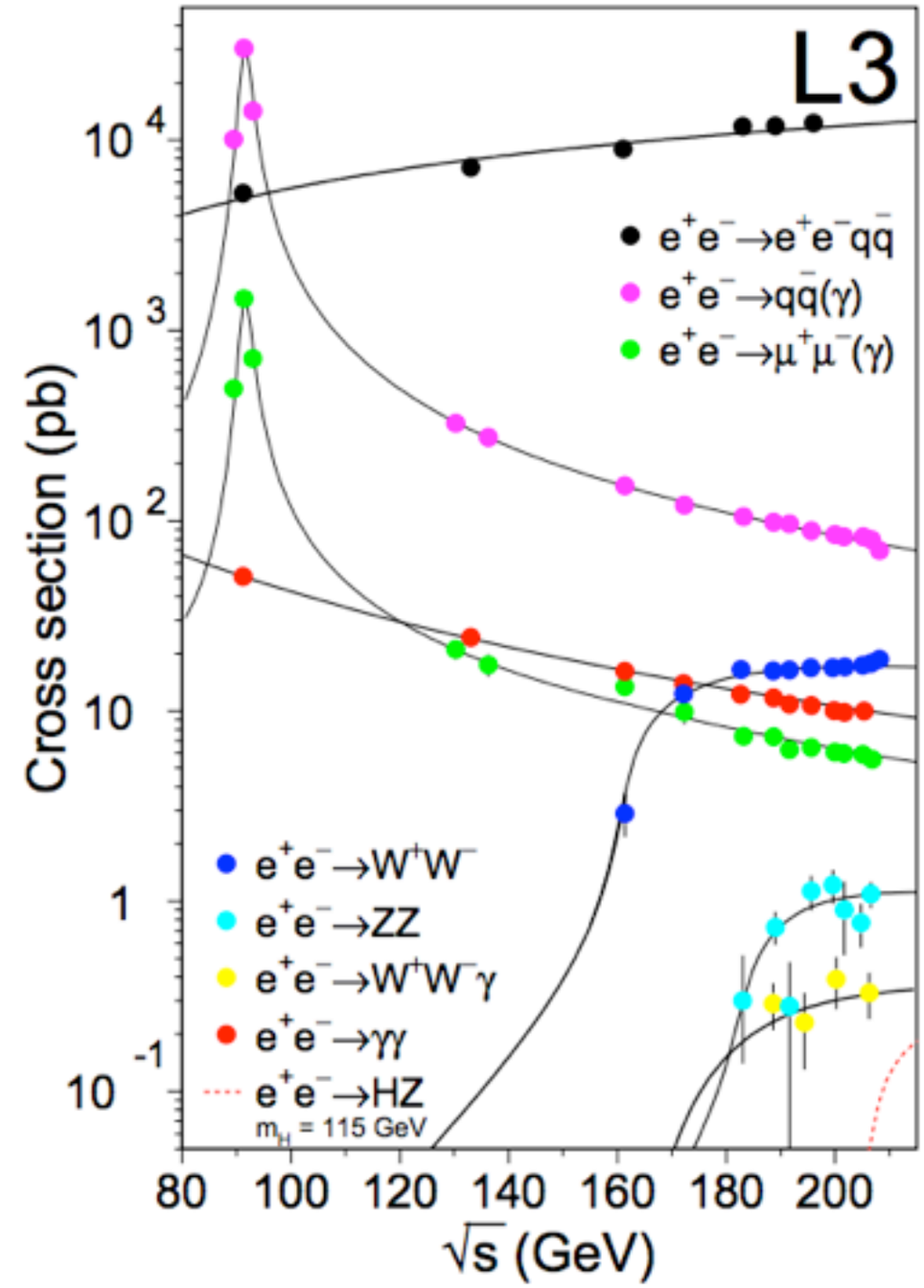
LEP EW Working Group
Physics Reports, 532 (2013)
arXiv:1302.3415

Experimental Tests of EW Theory

- Triple gauge boson couplings (TGCs) validated through $e^+e^- \rightarrow W^+W^-$ cross section measurements







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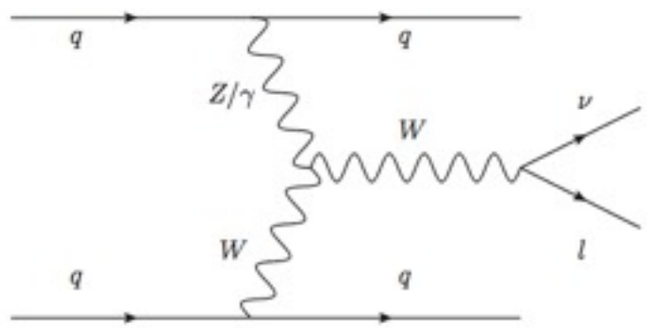
- validation of non-abelian nature of weak force
- LEP only performed limits on anomalous quartic gauge couplings (QGCs), which have meanwhile been superseded by the LHC

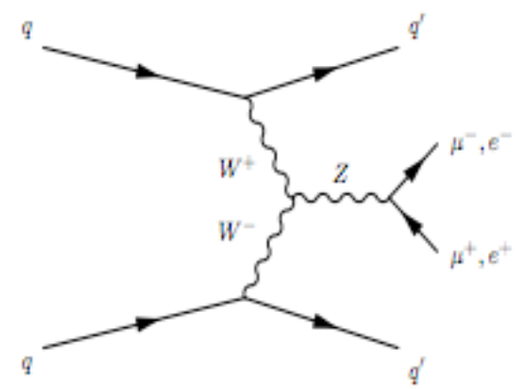
EW gauge couplings at LHC

Vector Boson Fusion with single boson final states

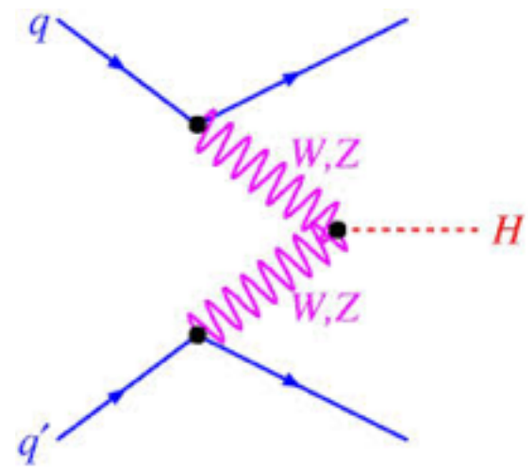
W-channel



Z-channel

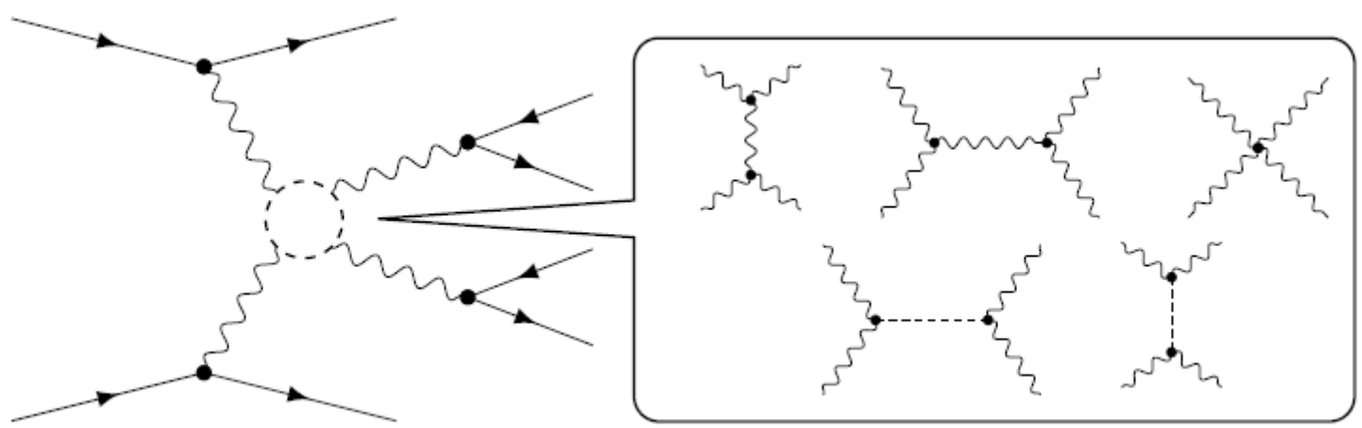


H-channel



- Protons in LHC serve as source for beams of vector bosons
- Final state bosons accompanied by two final state quarks which hadronize into jets
- W, Z Bosons most easily triggered/measured through their leptonic decay products
- Colorless exchange ⇒ region between two quarks free of hadronic activity

Vector Boson Fusion with 2 boson final states (also called Vector Boson Scattering)

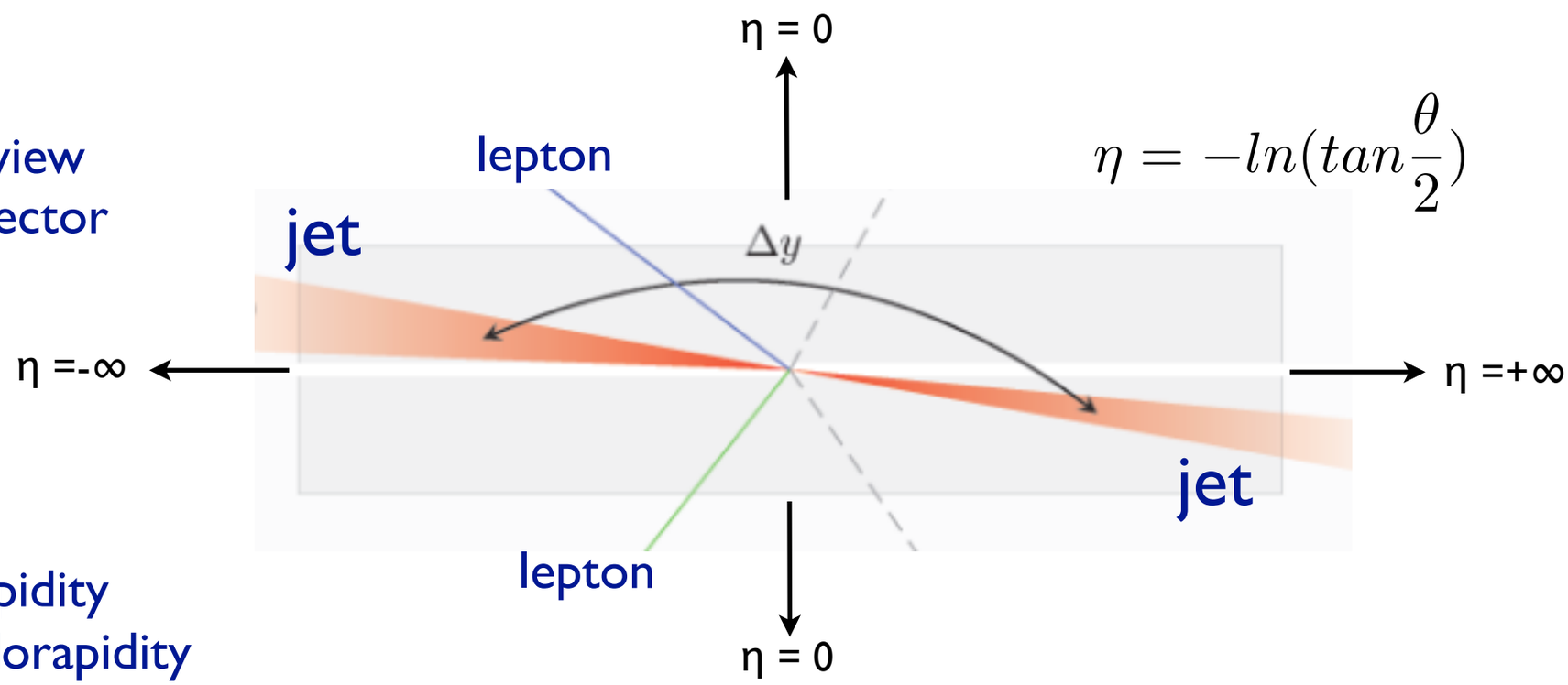


Probes TGC and QGC couplings

These processes are beginning to become accessible at LHC energies and luminosities

VBF - Distinguishing Topology

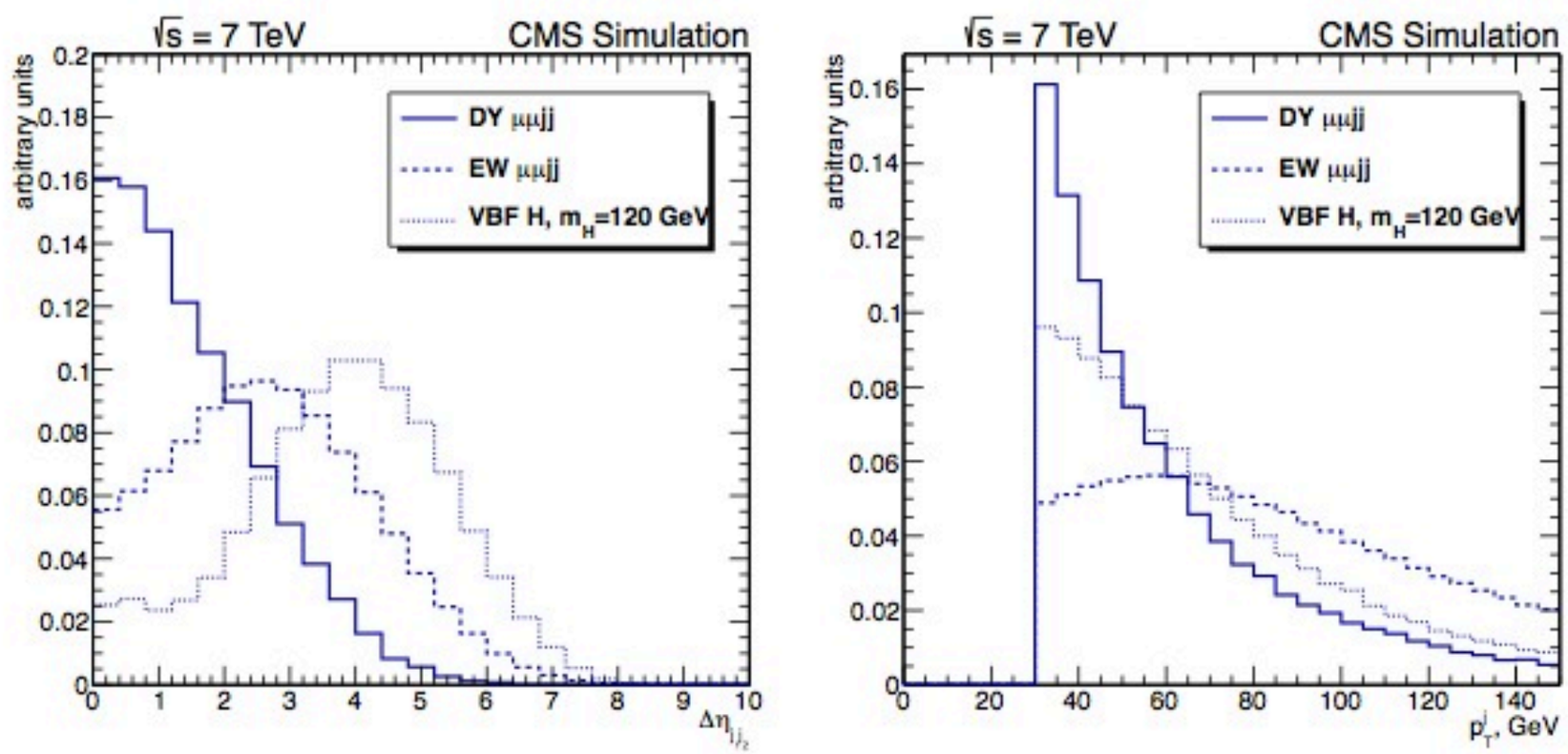
side view
of detector



$$\eta = -ln(tan\frac{\theta}{2})$$

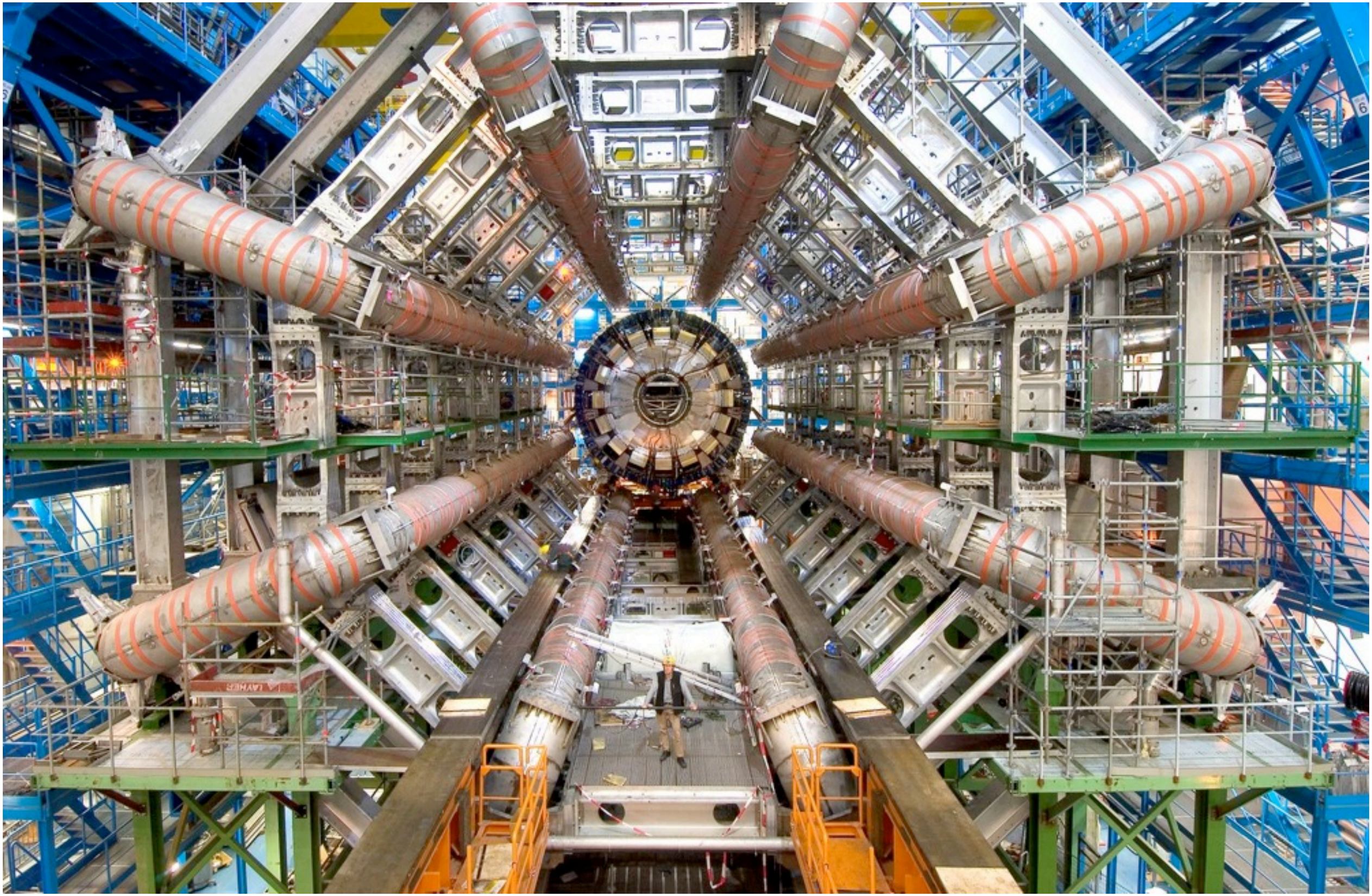
y = rapidity
η = pseudorapidity
y ~ η

VBF events are distinguished by jets widely separated in (pseudo)rapidity and a harder jet p_T spectrum



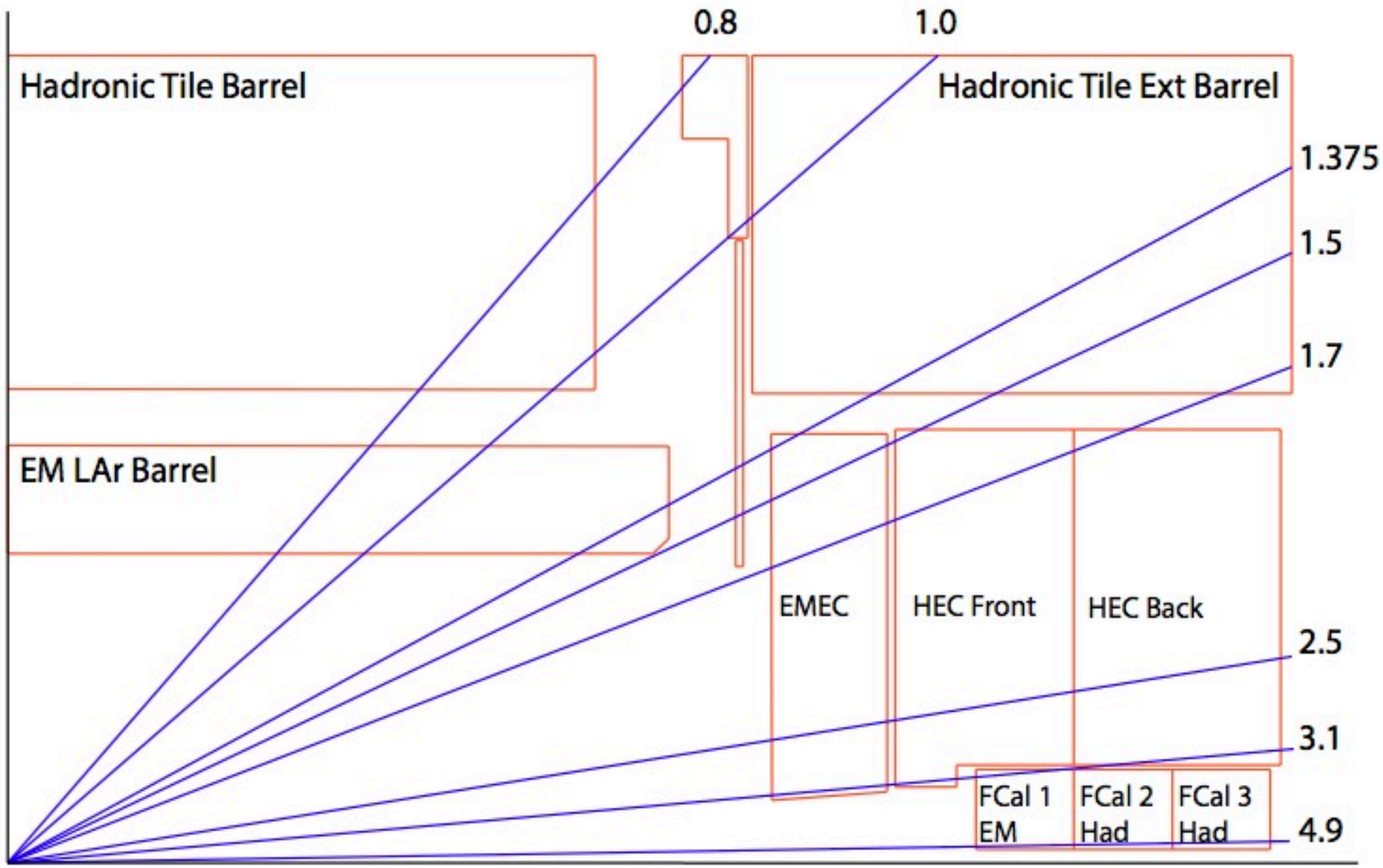
J. High Energy Phys. 10 (2013) 062

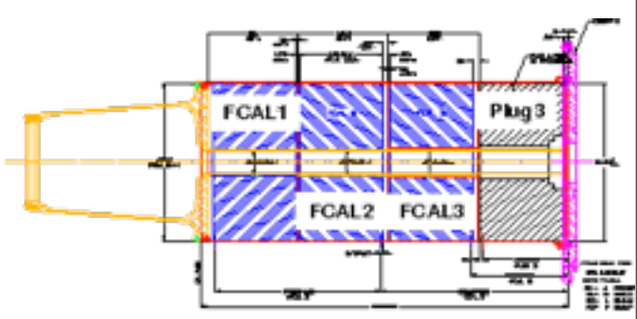
A Toroidal LHC ApparatuS



ATLAS Detector

Calorimetry in forward region crucial for VBF jet reconstruction
Liquid argon calorimeter coverage: $|\eta| < 3.2$
Forward calorimeter coverage $3.0 < |\eta| < 4.9$
Tracking coverage: $|\eta| < 2.6$





Modules

0.9 m Diameter

.45 m long

	FCAL1	FCAL2	FCAL3
η_{min}	3.0	3.1	3.2
η_{max}	4.9	4.9	4.9
Absorber material	Cu	W	W
Mass (t)	2.3	4.1	4.0
dE/dx sampling %	1.49	1.36	1.68
Depth (λ)	2.6	3.5	3.4
Gap width (mm)	0.25	0.375	0.50
Drift time (ns)	50	75	100

Channel count for both ends: 2822

Measurement of Electroweak Z + 2 jets (Zjj) Production

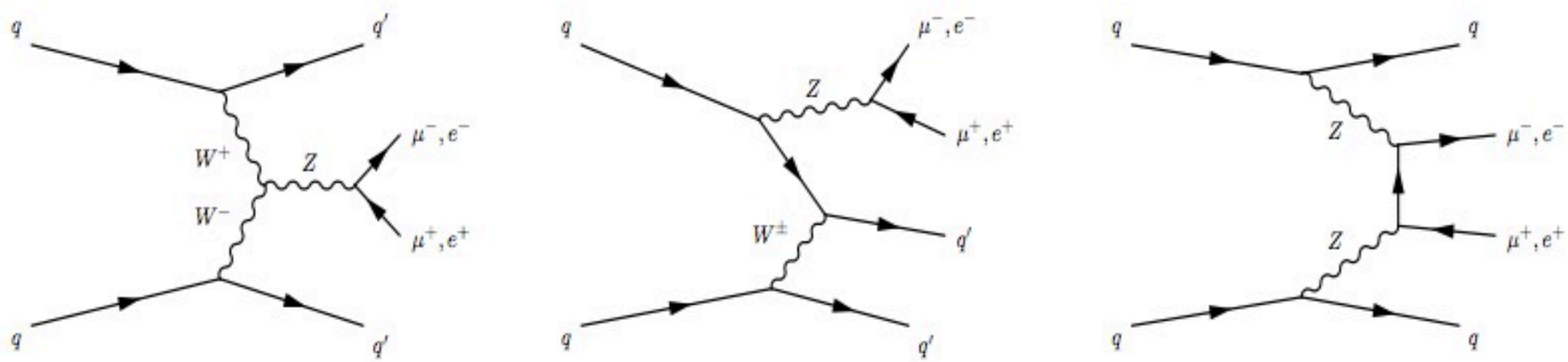
Motivations:

- testbed for VBF Higgs
- measurement of TGC for space-like momentum transfer

(complementary to diboson production)

VBF Z production is Z+2jets at tree level

Representative LO EW Zjj contributions



(a) vector boson fusion (b) Z-boson bremsstrahlung (c) non-resonant $\ell^+\ell^- jj$

VBF component (left) cannot be calculated independently without breaking gauge invariance

Measurement of Electroweak Z + 2 jets (Zjj) Production

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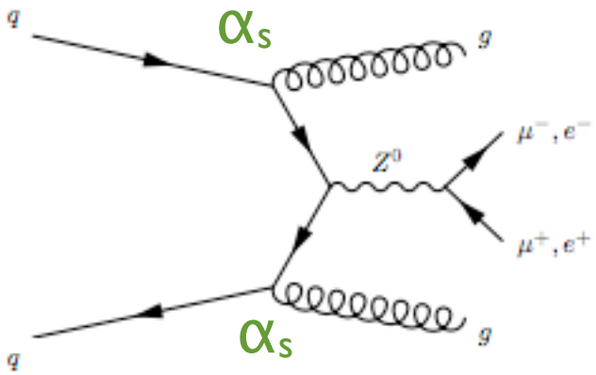
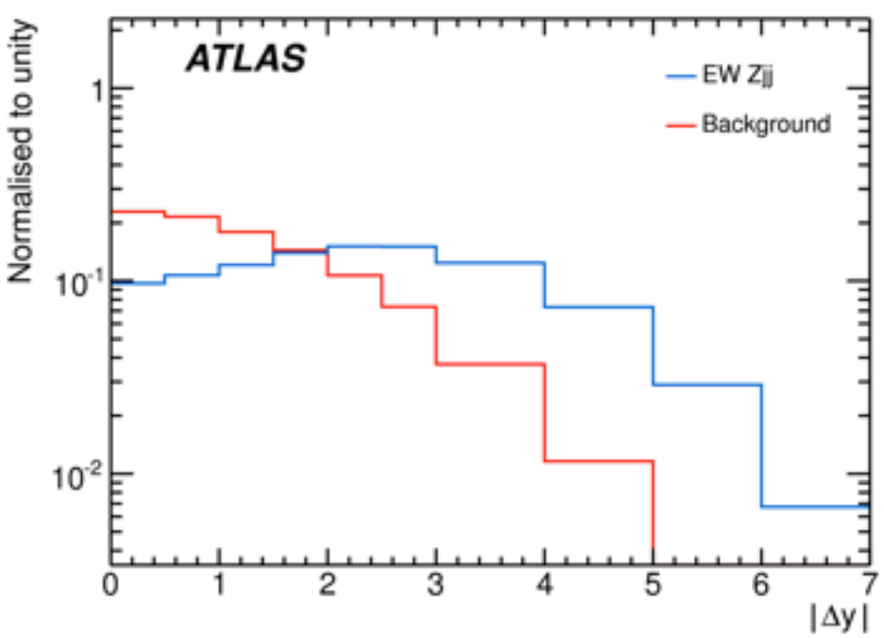
VBF Z process has irreducible EW and strong backgrounds

strong Zjj production:

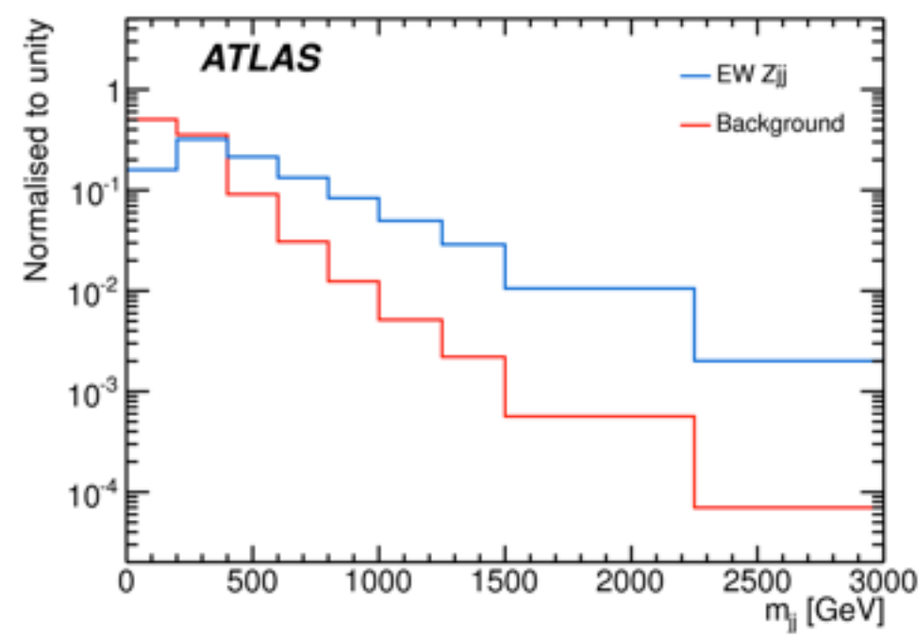


Strategy: Select a phase space where EW Zjj production is kinematically distinguishable from backgrounds and VBF is the dominant contribution to EW signal.

Rapidity separation of jets



Invariant mass of dijet system M_{jj}



Electroweak Zjj - Object selection

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Z Boson Candidates

- $Z \rightarrow \mu\mu$: muon p_T>25 GeV,
  $|\eta| < 2.4$,
  isolation requirements
- $Z \rightarrow ee$: electron p_T>25 GeV,
  $|\eta| < 2.47$ except $1.37 < |\eta| < 1.52$,
  isolation requirements
- Impact parameter requirements ensure leptons originate from primary vertex

Jets

- anti-k_T jets with radius R = 0.4
- p_T > 25 GeV
- $|y| < 4.4$
- Jet Vertex Fraction (JVF) > 0.5 for jets with p_T < 50 GeV and $|\eta| < 2.4$

JVF = fraction of tracks in jet associated with primary vertex

Event Requirements

- reconstructed vertex with at least 3 inner detector tracks
- data quality requirements

Electroweak Zjj challenges

JHEP04(2014)031

- Challenging measurement due to:
  - unfavorable signal to background ratio S/B, with backgrounds overwhelmingly produced by strong Zjj
  - experimental uncertainties on jets
  - theoretical uncertainties on signal and background processes
- 5 fiducial regions studied, each with different sensitivity to EW Zjj

1. Baseline: inclusive region for studying inclusive Zjj production
2. High-mass: dijet invariant mass Mjj > 1 TeV - probes kinematic features of EW Zjj
3. Search: optimal significance for EW Zjj extraction
4. Control: suppress EW Zjj contribution
5. High-pT: harder jet pT cuts - probes kinematic features of EW Zjj

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^\ell\rvert < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^j\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j_1} > 55$ GeV				$p_T^{j_1} > 85$ GeV
	$p_T^{j_2} > 45$ GeV				$p_T^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\text{jet}}^{\text{gap}} = 0$	$N_{\text{jet}}^{\text{gap}} \geq 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance},3} < 0.15$	—

Electroweak Zjj - event composition

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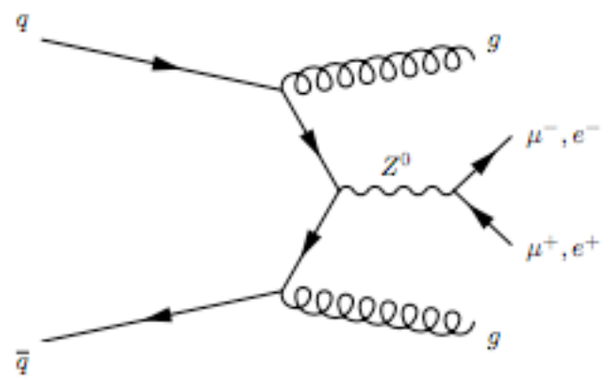
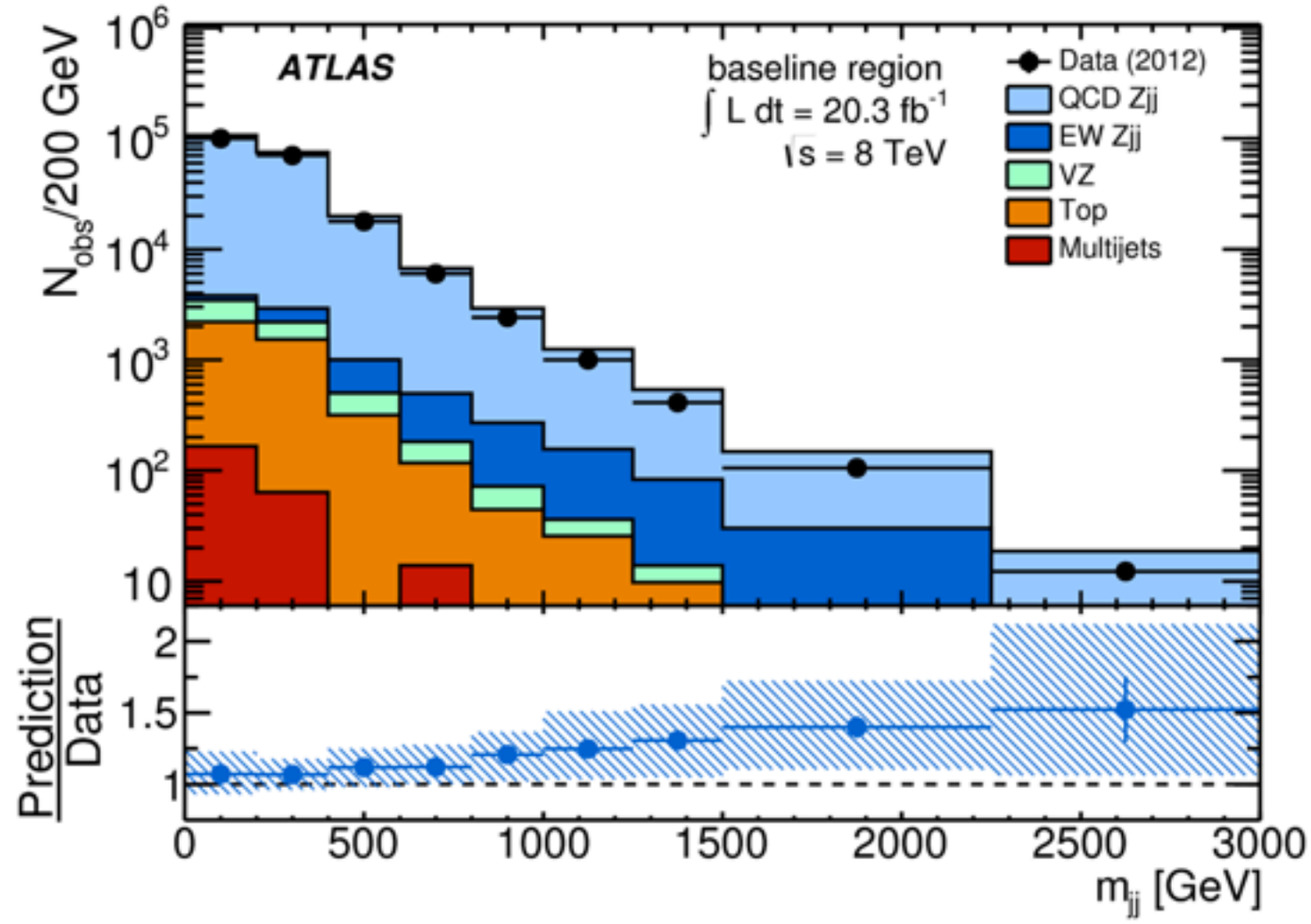
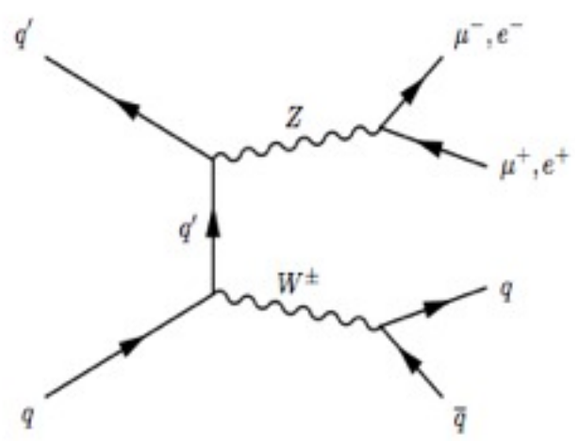
Backgrounds

Strong Zjj (dominant)





Diboson production
(suppressed with kinematic constraints)



MC simulated

data driven →

Process	Composition (%) *baseline*	*high-p_T*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

Zjj Fiducial Cross Sections

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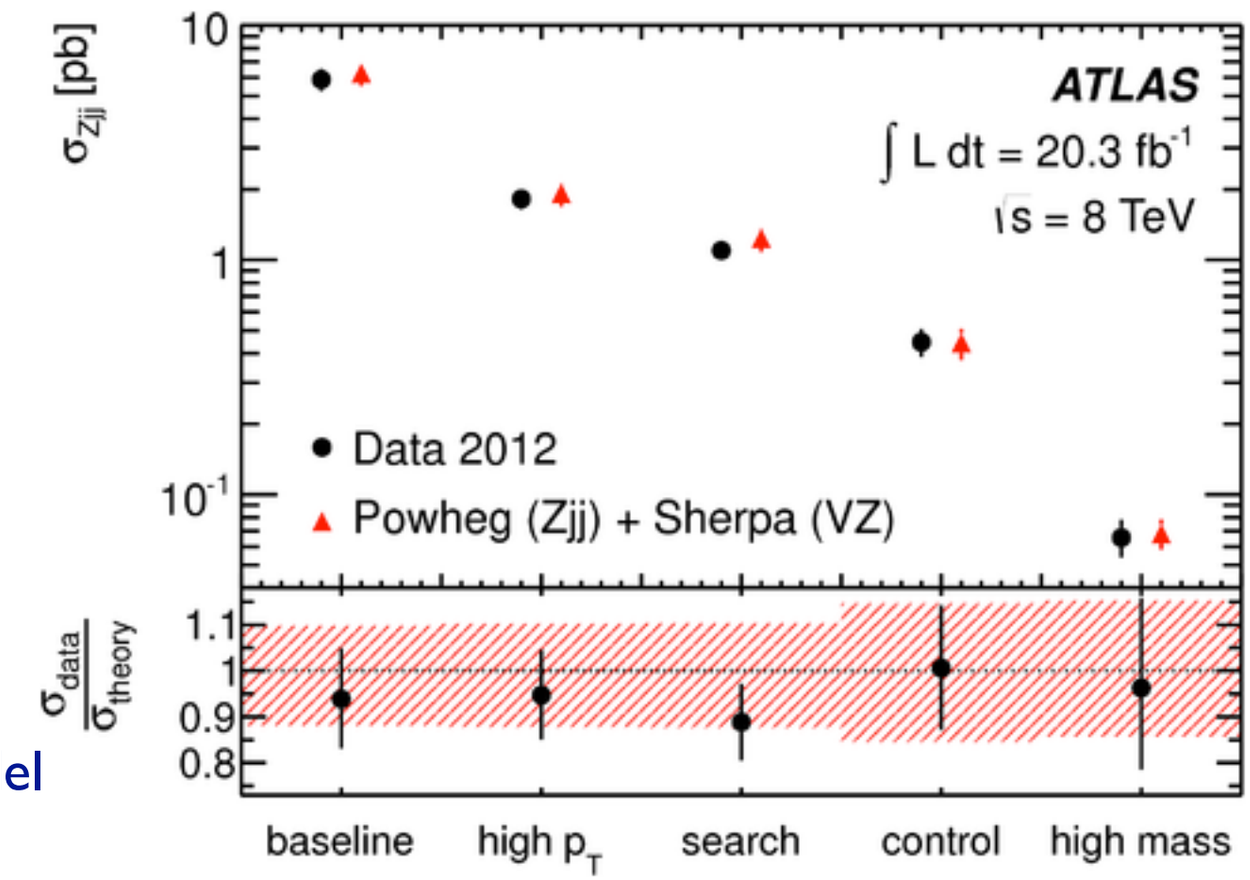
- Inclusive (Strong + EW) Zjj measured in 5 fiducial regions
- Theoretical predictions calculated with Powheg Box and Sherpa 1.4.3

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\int L\,\mathrm{d}t \cdot \mathcal{C}}$$

POWHEG Box
- NLO matrix elements interfaced with Pythia 6 for parton showering, hadronization and multiple parton interactions.
- CT10 PDFs
- Perugia 2011 tune for underlying event

Sherpa
- LO matched matrix element + parton shower generator with native hadronization and MPI model
- CT10 PDFs
- Native tune for underlying event



Data and predictions are in good agreement

Differential cross sections

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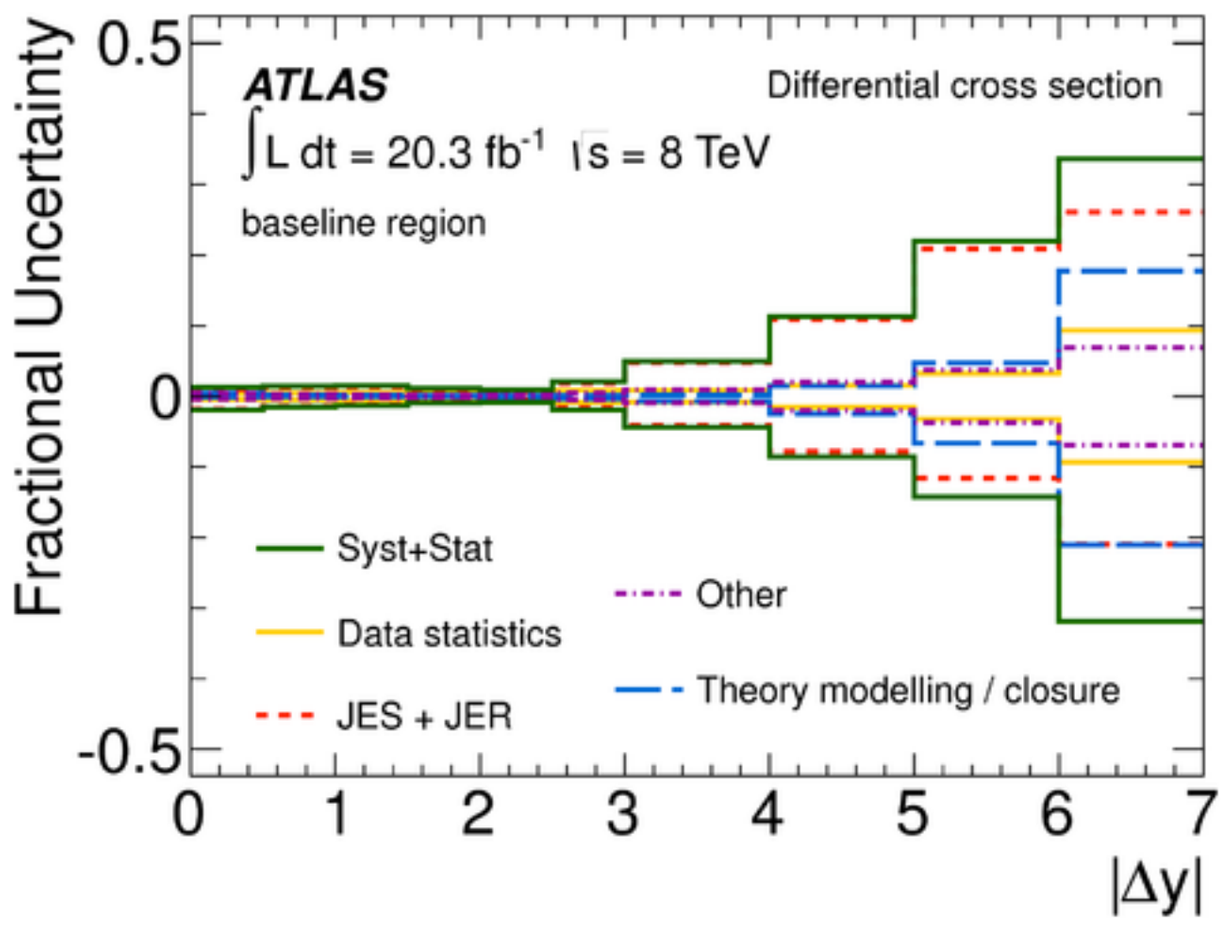
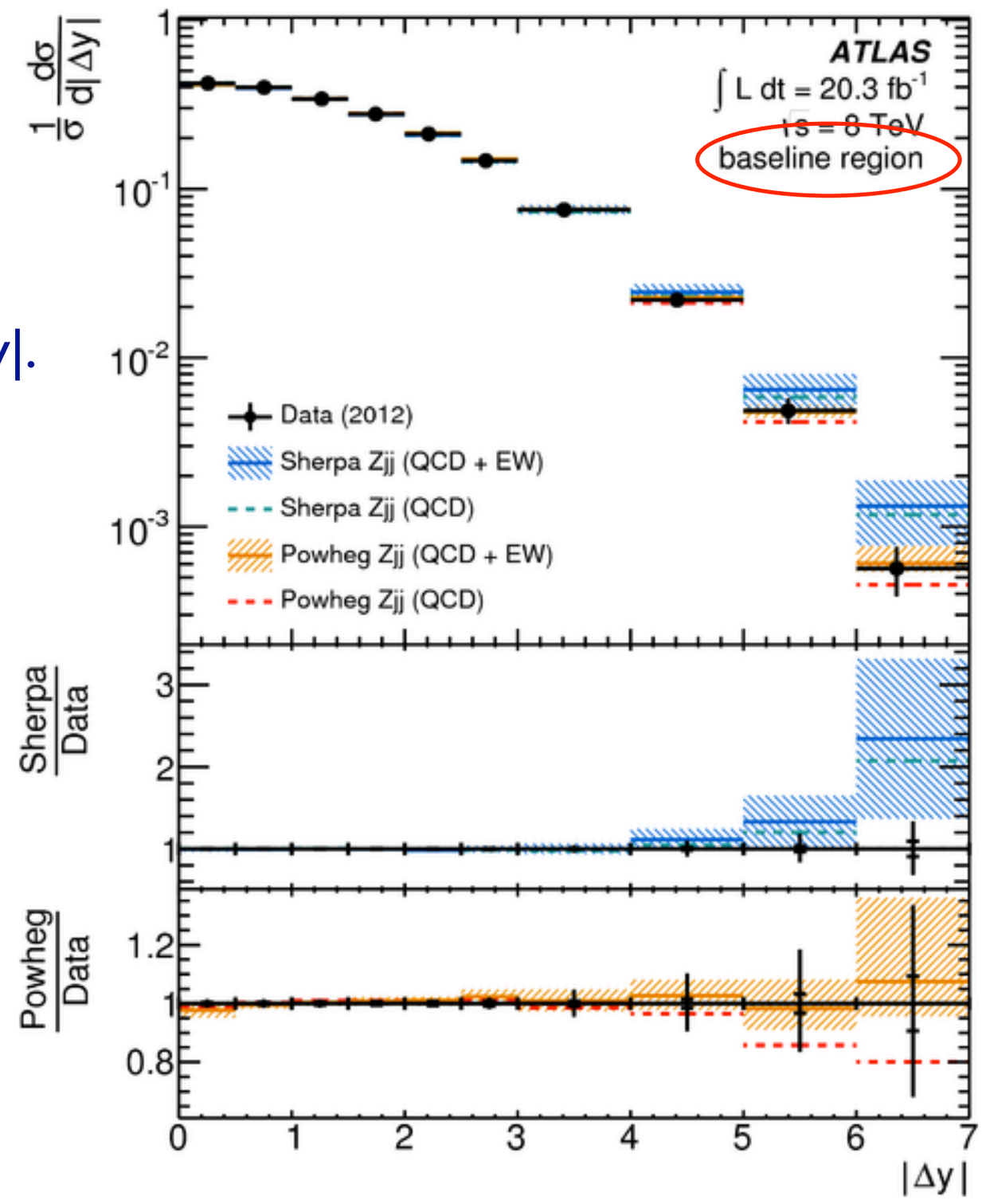
Differential cross sections are obtained using Bayesian unfolding.

- Powheg can describe Zjj data over entire spectrum in baseline region.
- Sherpa predicts a higher rate in the most forward region.
- Uncertainties increase rapidly at large |Δy|.





Differential cross sections

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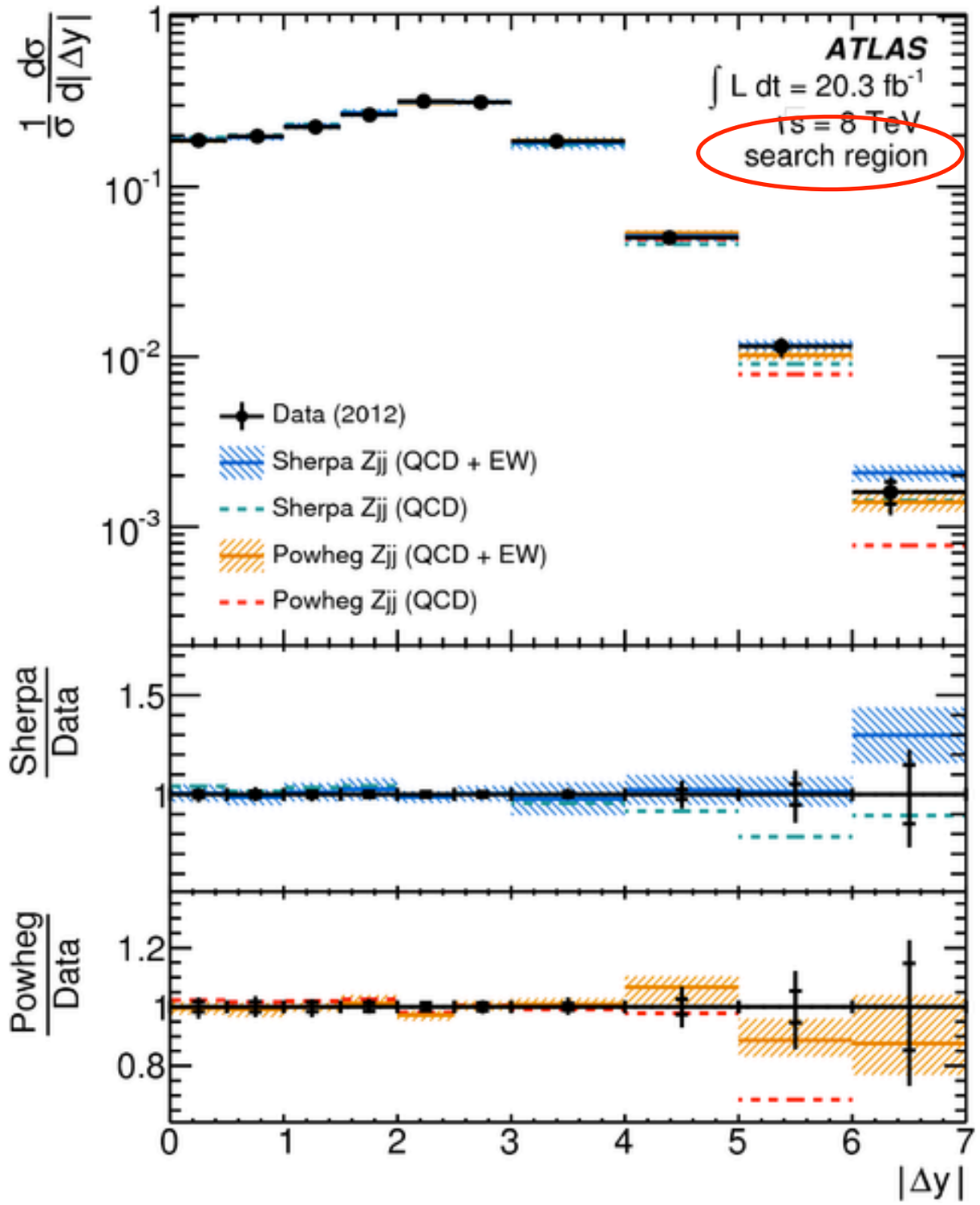
Differential cross sections are obtained using Bayesian unfolding.

Sherpa and Powheg are LO in the search region due to the jet veto.

Both Sherpa and Powheg can distinguish EW contribution at high |Δy|



EW Zjj Extraction and Control Region

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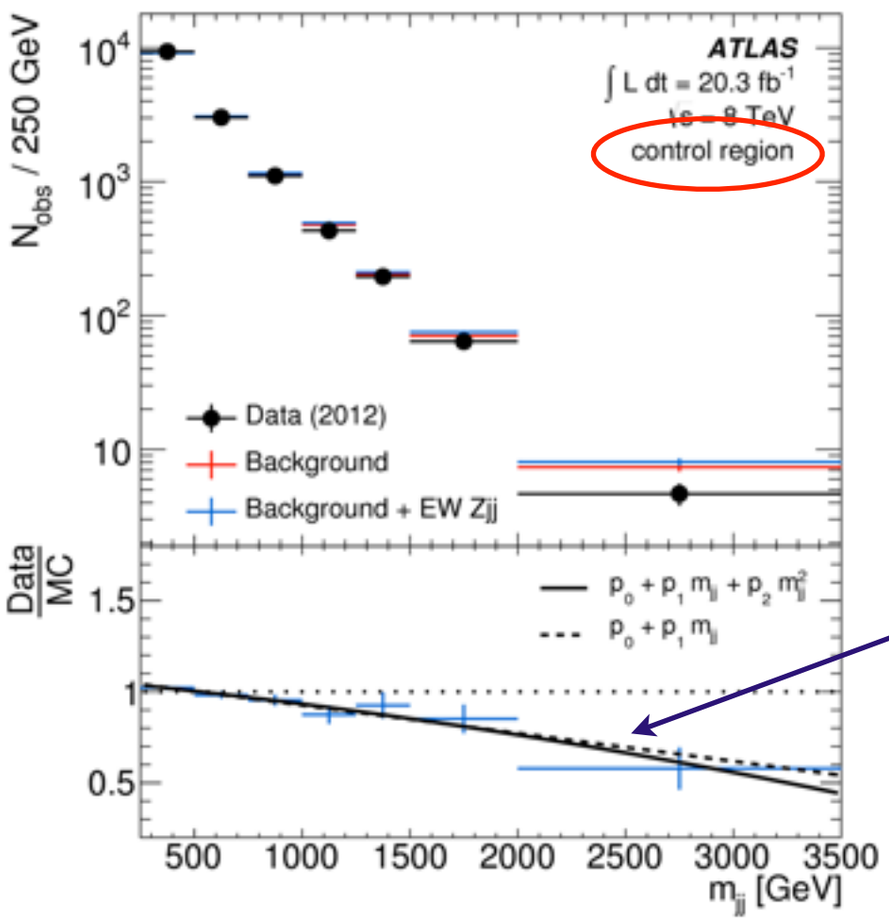
To improve background modeling and reduce systematic uncertainties, the control region is used to constrain the shape of the dijet mass distribution.

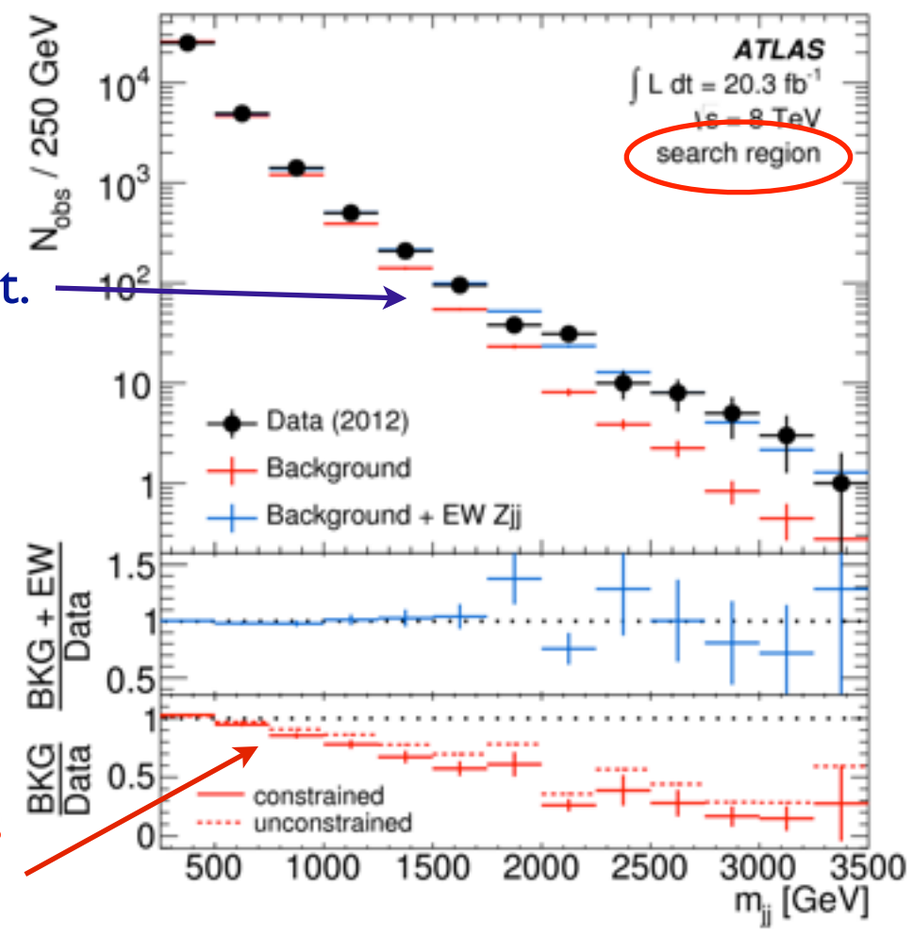
- A fit of the DATA/MC simulation ratio in the control region (98.6% background) is made and applied to the background template in the search region (96% background).
- Background and signal templates are fit to the data in the search region using log-likelihood maximization, extracting the number of signal (N_{EW}) and background events.



Background only and background + signal distributions using normalization found from fit.

Reweighting function applied to background template in search region

Unconstrained results without reweighting



EW Zjj Extraction and Control Region

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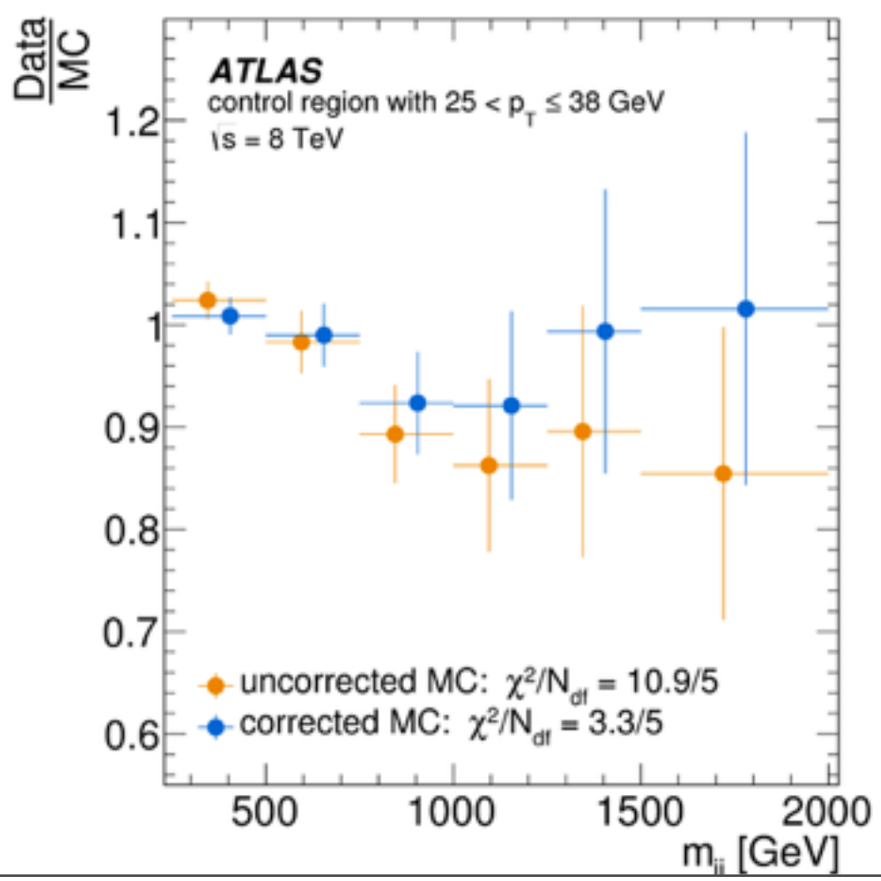
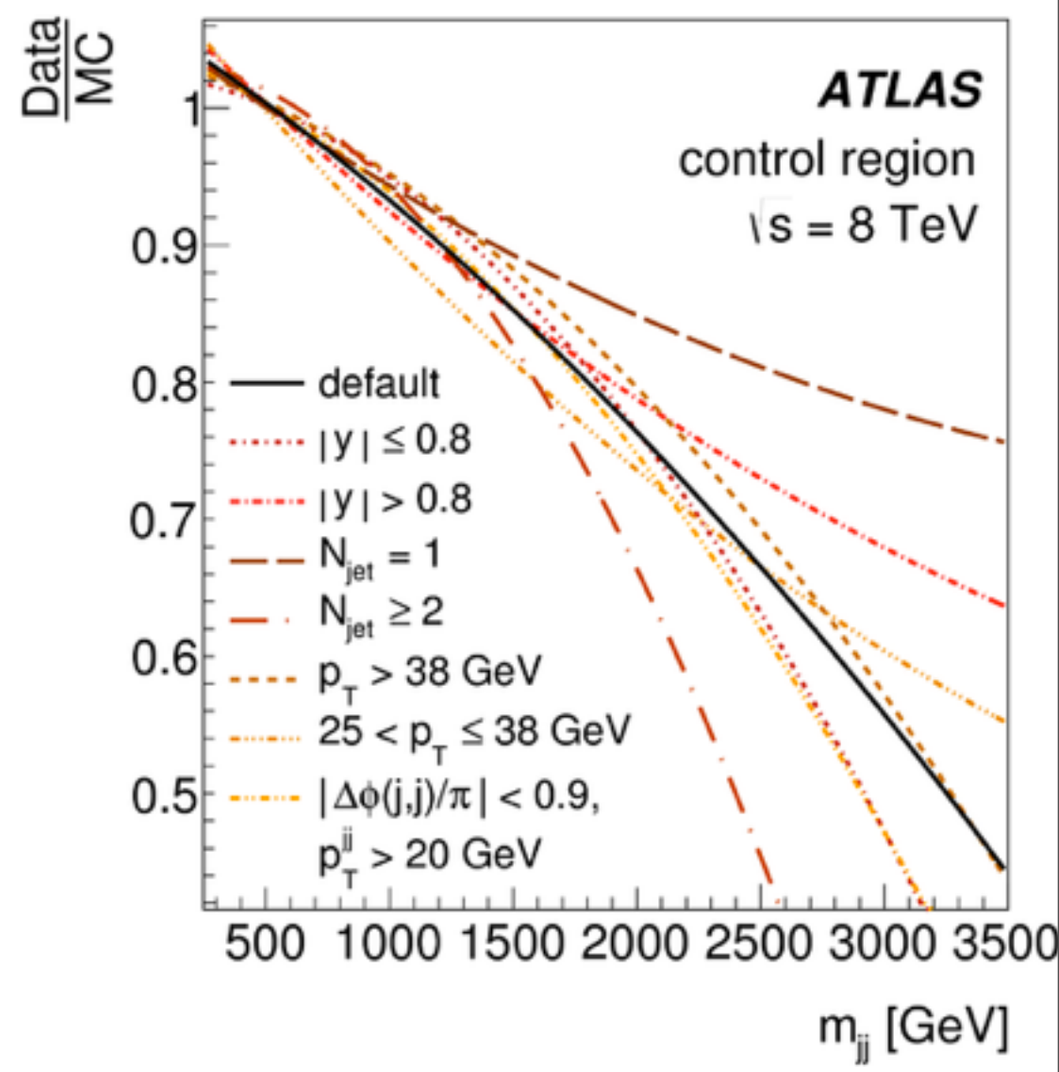
Control region constraint is validated with cross-checks:

Cross-check	Impact on # EW Zjj events
Changing generator: Sherpa -> POWHEG	0.80%
Alternate control regions	<5%
Alternate reweighting functional form	<2%

Number of EW Zjj events found from fit to data changes by maximum 5% under differing constraint conditions



Reweighting function for different choices of control region



The use of any control region improves the description of the data when constraining the background with another control region

EW Zjj Results

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- Signal extraction performed using template fit to the dijet mass spectrum, varying the signal EW Zjj and background normalization independently.
- Number of EW Zjj events N_{EW} extracted from fit and converted to cross section

$$\sigma_{\mathrm{EW}} = \frac{N_{\mathrm{EW}}}{\int L\,\mathrm{d}t \cdot C_{\mathrm{EW}}}$$

- Result significance is evaluated using pseudoexperiments: background is excluded at >5σ confidence.
- Measurement is systematics dominated; largest contributions from
  - Control region statistics
  - Jet Energy Scale (experimental)
  - Signal modeling, background modeling and signal/background interference (theoretical)

First 5σ validation of the EW Zjj process!

$$\sigma_{\mathrm{EW}}^{ee} = 67.2 \pm 6.9\,(\mathrm{stat})\,^{+12.7}_{-13.4}\,(\mathrm{syst}) \pm 1.9\,(\mathrm{lumi})\,\mathrm{fb}$$
$$\sigma_{\mathrm{EW}}^{\mu\mu} = 45.6 \pm 6.1\,(\mathrm{stat})\,^{+9.1}_{-9.6}\,(\mathrm{syst}) \pm 1.3\,(\mathrm{lumi})\,\mathrm{fb}.$$

weighted average:

$$\sigma_{\mathrm{EW}} = 54.7 \pm 4.6\,(\mathrm{stat})\,^{+9.8}_{-10.4}\,(\mathrm{syst}) \pm 1.5\,(\mathrm{lumi})\,\mathrm{fb}.$$

Powheg prediction:

$$46.1 \pm 0.2\,(\mathrm{stat})\,^{+0.3}_{-0.2}\,(\mathrm{scale}) \pm 0.8\,(\mathrm{PDF}) \pm 0.5\,(\mathrm{model})\,\mathrm{fb}$$

Source	ΔN_{EW} Electrons	ΔN_{EW} Muons
Lepton systematics	—	—
Control region statistics	±8.9 %	±11.2 %
JES	±5.6 %	
JER	±0.4 %	
Pileup jet modelling	±0.3 %	
JVF	±1.1 %	
Signal modelling	±8.9 %	
Background modelling	±7.5 %	
Signal/background interference	±6.2 %	
PDF	$^{+1.5}_{-3.9}$ %	

EW Zjj - Limits on Anamolous Couplings

JHEP04(2014)031

In VBF, the two radiated gauge bosons entering the WWZ vertex have space-like four-momentum transfer. This provides complementary information on TGCs to the WWZ vertex with time-like four-momenta seen in diboson production.

Modified Effective Lagrangian

$$\frac{\mathcal{L}}{g_{WWZ}} = i\left[g_{1,Z}\left(W^{\dagger}_{\mu\nu}W^{\mu}Z^{\nu} - W_{\mu\nu}W^{\dagger\mu}Z^{\nu}\right) + \kappa_Z W^{\dagger}_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho}\right]$$

SM values: $g_{1,Z} = 1$, $k_Z = 1$, $\lambda_Z = 0$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$$

This Lagrangian violates unitarity at large energies;
unitarity is restored by modifying couplings by dipole form factor:

$$a(\hat{s}) = \frac{a_0}{(1+\hat{s}/\Lambda^2)^2}$$

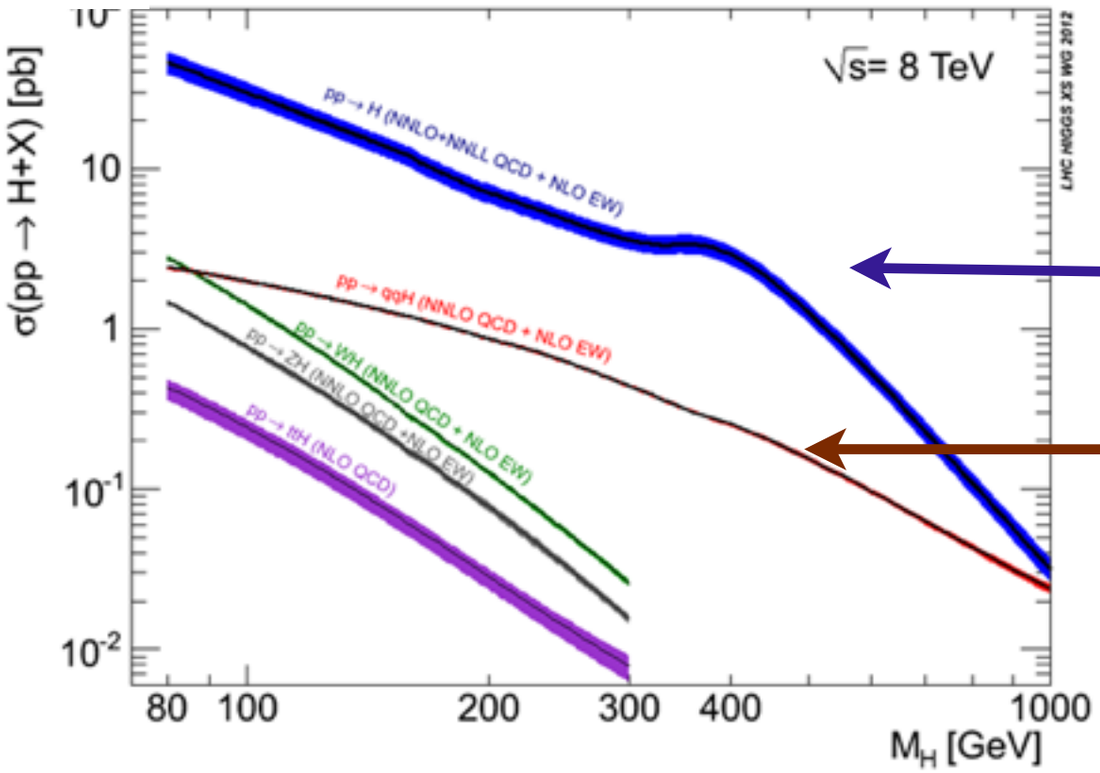
Λ = unitarization scale

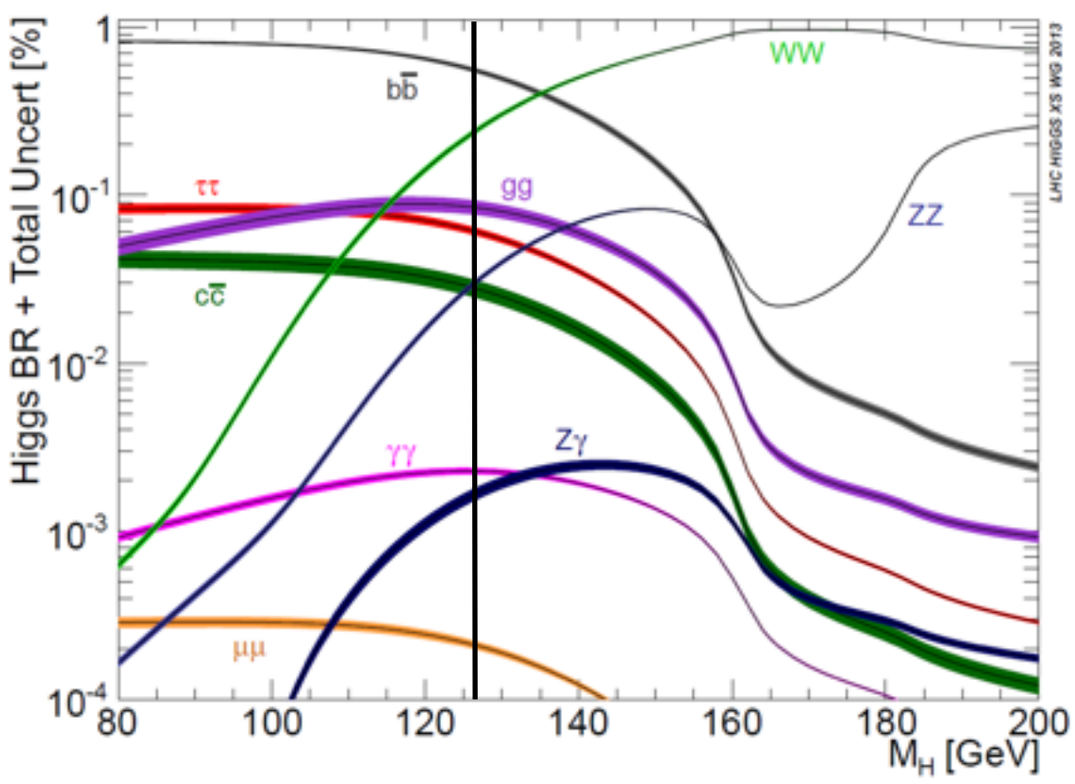
Λ = 6 TeV is the largest common value allowed by unitarity considerations for all anomalous couplings probed in the measurement.

aTGC 95% CL limits using search region with Mjj > 1 TeV

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

Higgs Production at LHC

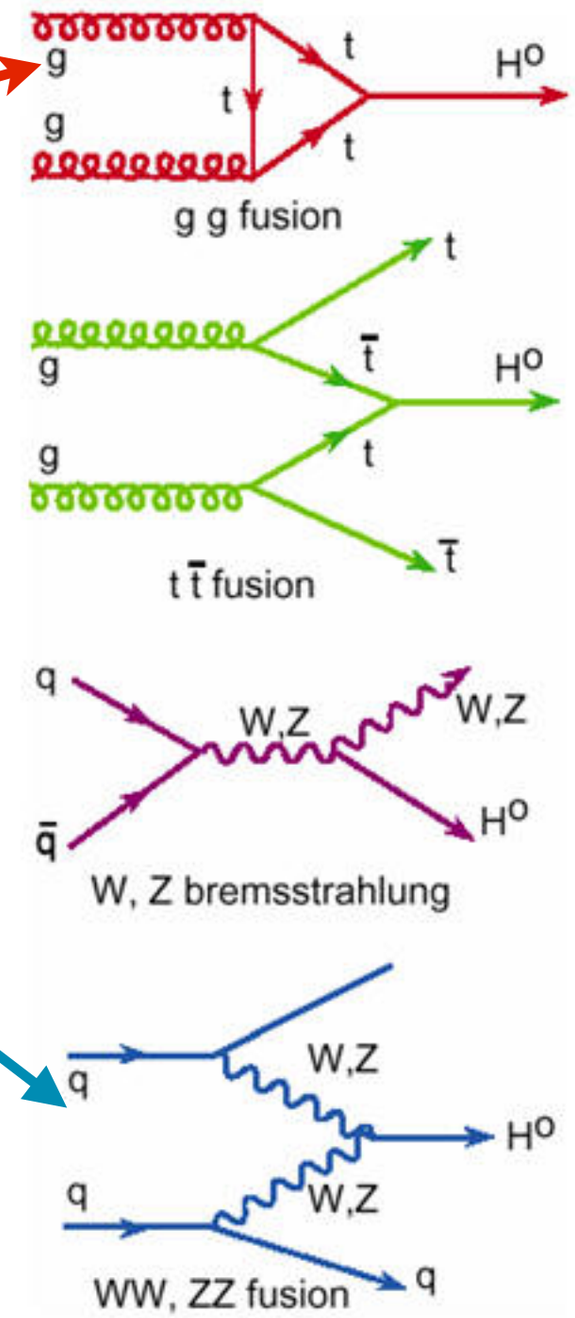




Production dominated by gluon fusion (ggF)

Second most copious production mode- Vector Boson Fusion (WW, ZZ fusion)

Decay to pairs of fermions or bosons, with different BRs depending on the mass



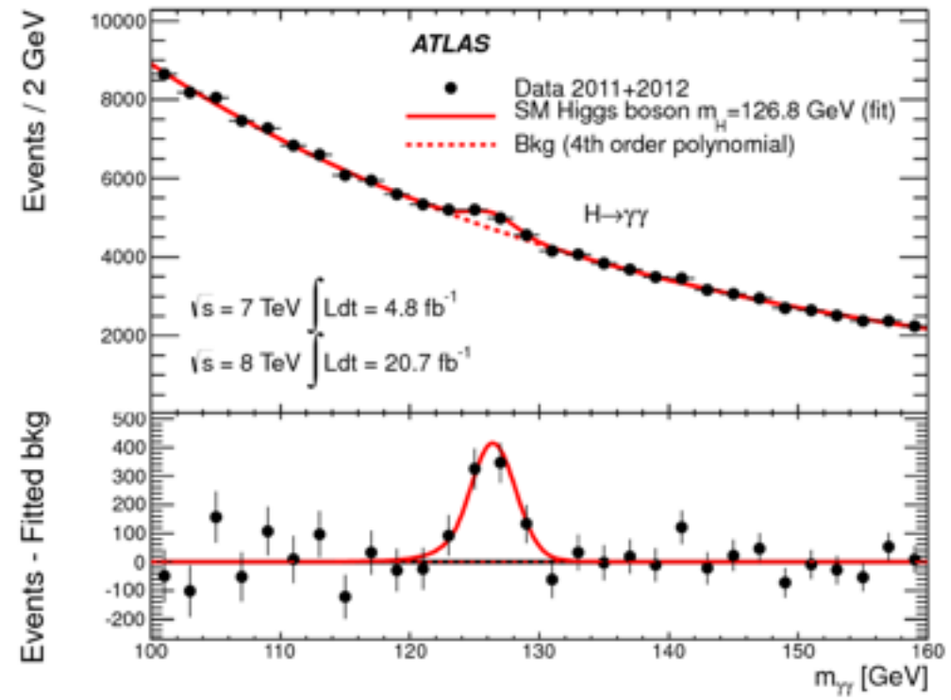
Higgs Measurement

Phys. Lett. B 726 (2013), pp. 88-119

The Higgs Boson discovery was announced July 4, 2012 by the ATLAS and CMS experiments, and was made by combining data from all production and decay channels.

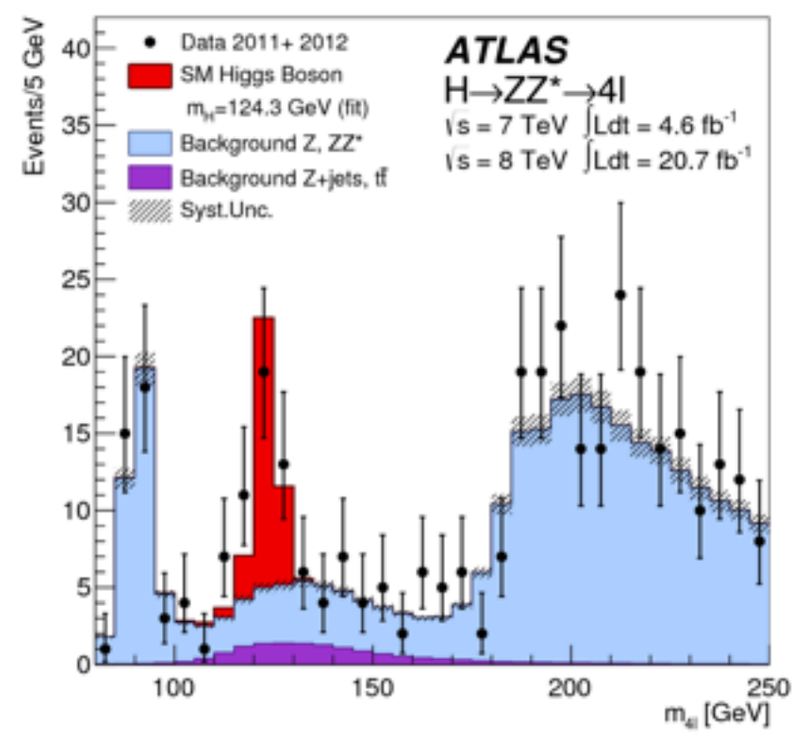
With the full Run1 dataset, the Higgs resonance is visible in some individual production/decay channels

→ testing compatibility of the resonance properties in different channels is important to gain confidence that this is, indeed, the SM Higgs



Higgs properties of interest: mass, coupling, spin, CP

Example: m_H (H→γγ) = 126.8 ± 0.2 (stat) ± 0.7 (sys) GeV



m_H (H→ZZ) = 124.3 ± 0.6(stat) $^{+0.5}_{-0.3}$ (sys) GeV

slight difference in preferred mass

Higgs Measurement

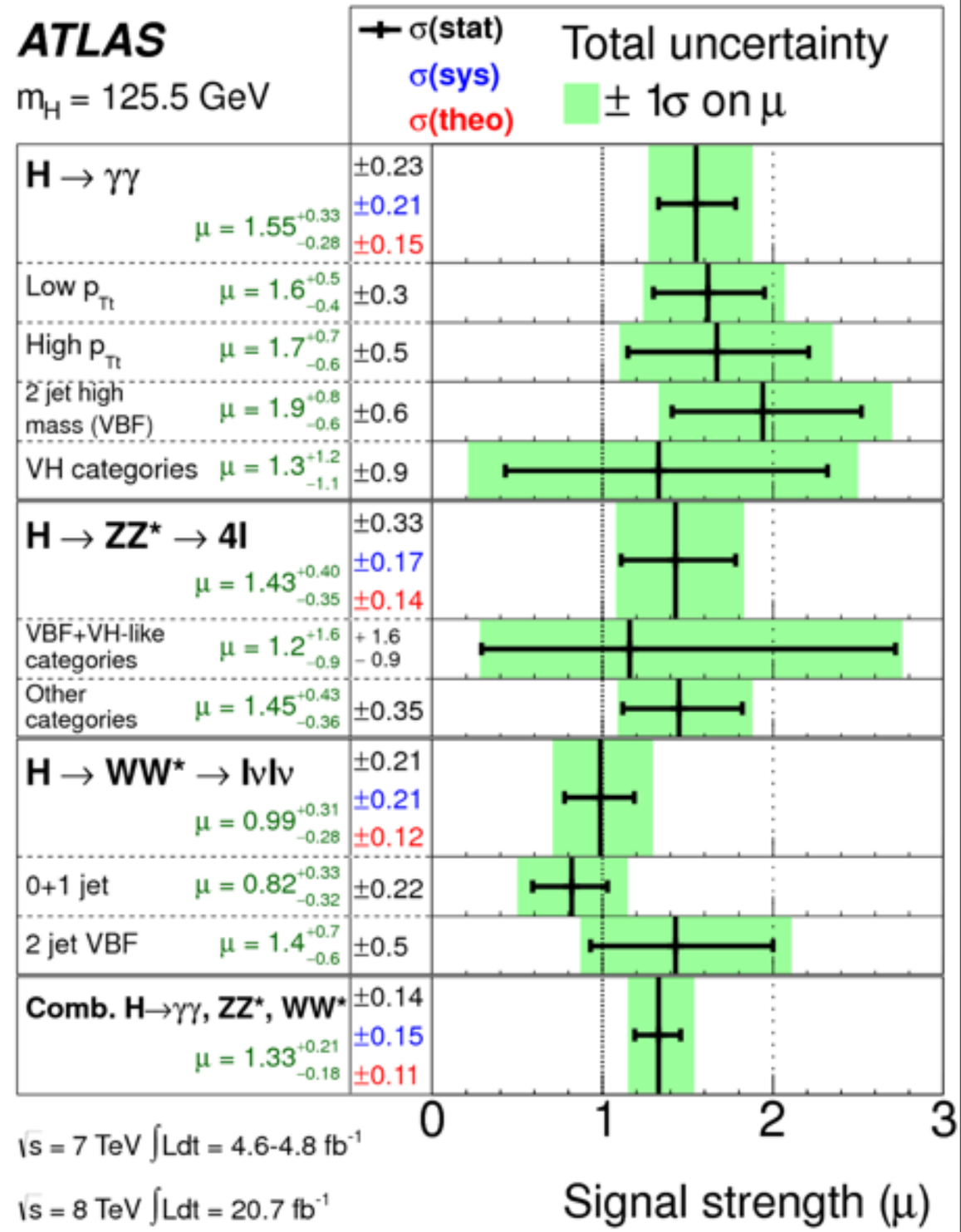
Phys. Lett. B 726 (2013), pp. 120-144

Measurements of compatibility between observed Higgs rates and SM expectation for couplings to gauge bosons and m_H = 125.5

Signal strength $\mu = \frac{\sigma_{data}}{\sigma_{SM}}$

- several channels show a slight excess above SM expectation (μ=1), but none are significant enough to interpret as non-SM
- dedicated VBF analysis channels, but with lower sensitivity to Higgs

Insufficient sensitivity for >3σ single channel VBF Higgs measurement with Run I data.



updated numbers in ATLAS-CONF-2014-009

VBF search in H → ττ

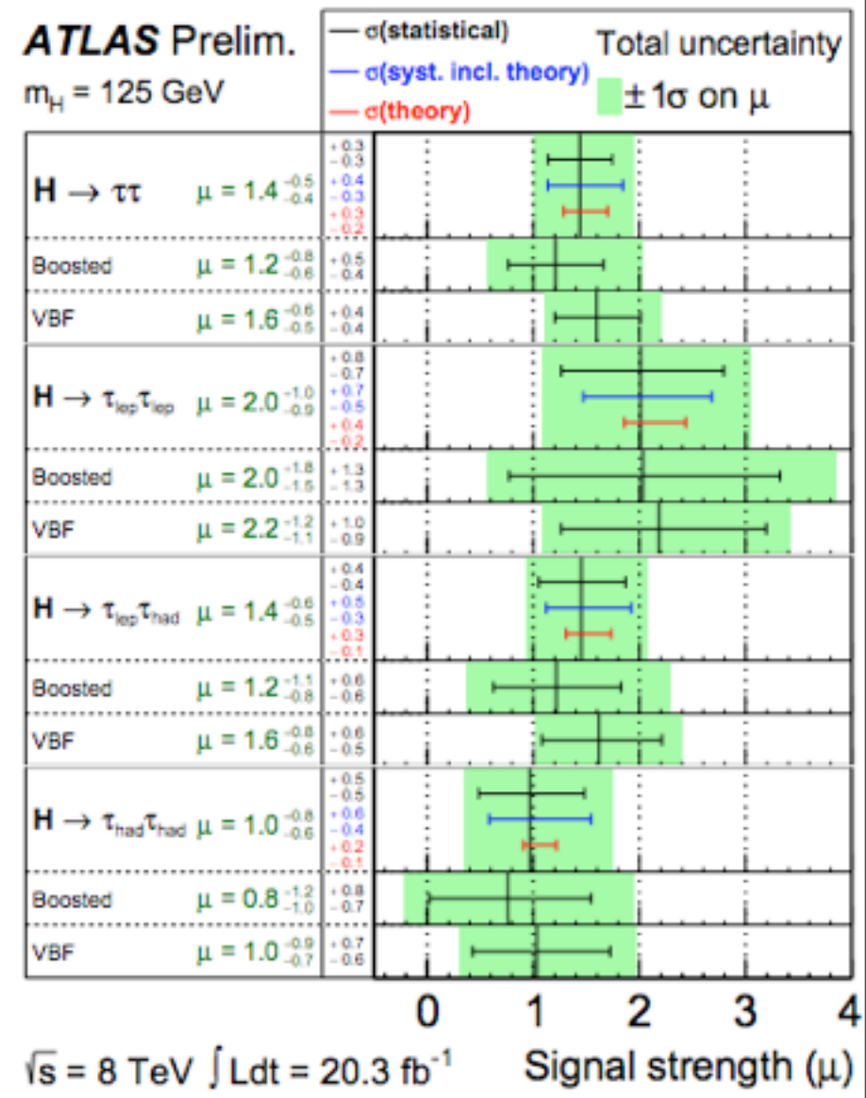
ATLAS-CONF-2013-108

First evidence for Higgs → ττ recently presented by ATLAS.
VBF Higgs production mechanism is enhanced in one selection.

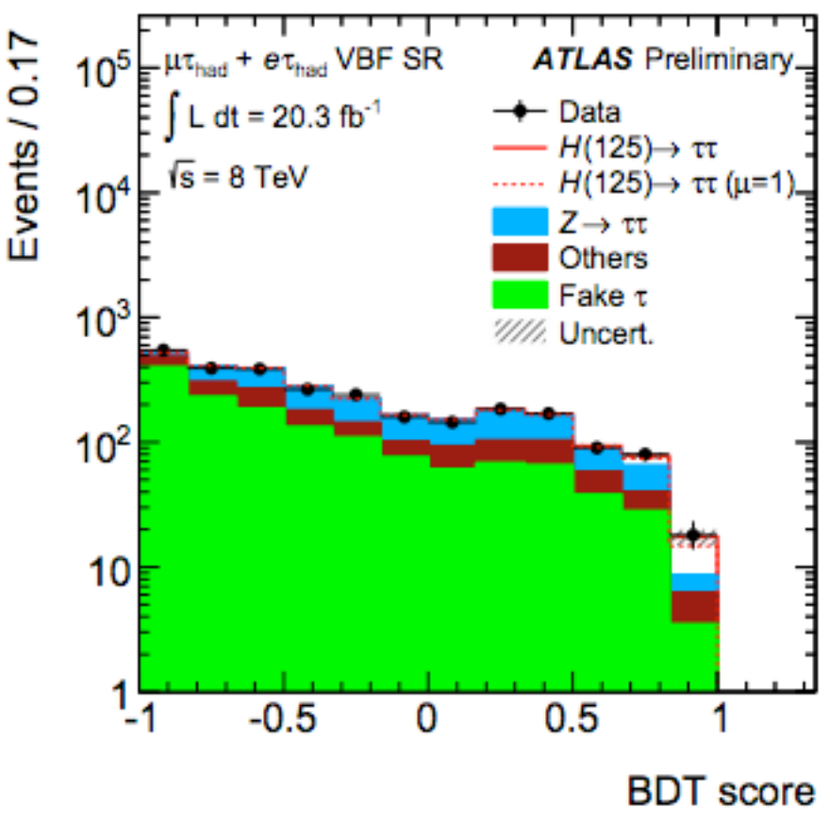
Category	Selection	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
VBF	$p_T(j_1)$ (GeV)	40	50	50
	$p_T(j_2)$ (GeV)	30	30	30/35
	$\Delta\eta(j_1, j_2)$	2.2	3.0	2.0
	b–jet veto for jet p_T (GeV)	25	30	-
	p_T^H (GeV)	-	-	40

$\tau_{lep}\tau_{had}$ is most sensitive decay mode

All channels combined: 4.1σ significance



Boosted Decision Tree Score:



Event yields in 3 highest BDT bins:

Process/Category	VBF		
BDT score bin edges	0.5-0.667	0.667-0.833	0.833-1.0
ggF	2.2 ± 0.9	3.5 ± 1.5	1.2 ± 0.6
VBF	4.1 ± 1.2	9.2 ± 2.7	7.5 ± 2.2
WH	< 0.05	< 0.05	< 0.05
ZH	< 0.05	< 0.05	< 0.05
$Z \to \tau^+\tau^-$	28.6 ± 1.4	25.0 ± 1.6	2.41 ± 0.35
Fake	37.7 ± 1.8	27.9 ± 2.1	3.5 ± 0.5
Top	6.5 ± 0.7	4.1 ± 0.8	1.5 ± 0.4
Diboson	2.9 ± 0.4	3.0 ± 0.5	0.23 ± 0.04
$Z \to \ell\ell(j \to \tau_{had})$	8.7 ± 1.7	3.3 ± 0.5	0.40 ± 0.10
$Z \to \ell\ell(\ell \to \tau_{had})$	2.8 ± 1.2	1.9 ± 1.2	0.7 ± 0.6
Total Background	87.2 ± 2.7	65 ± 5	8.7 ± 2.5
Total Signal	6.3 ± 1.8	12.7 ± 3.5	8.7 ± 2.4
S/B	0.07	0.20	1.0
Data	90	80	18

Result compatible with SM expectation

More data needed to study VBF Higgs in detail

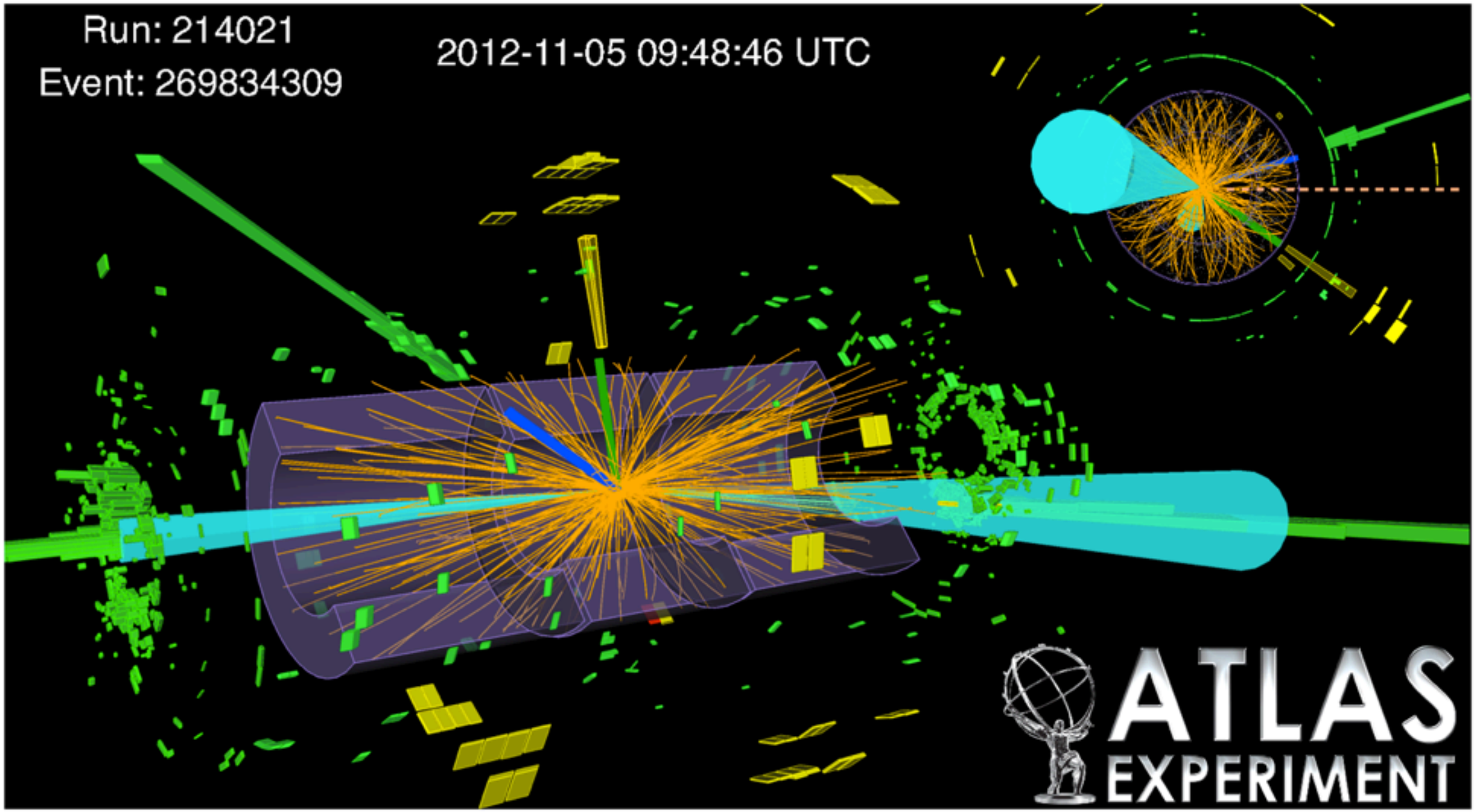


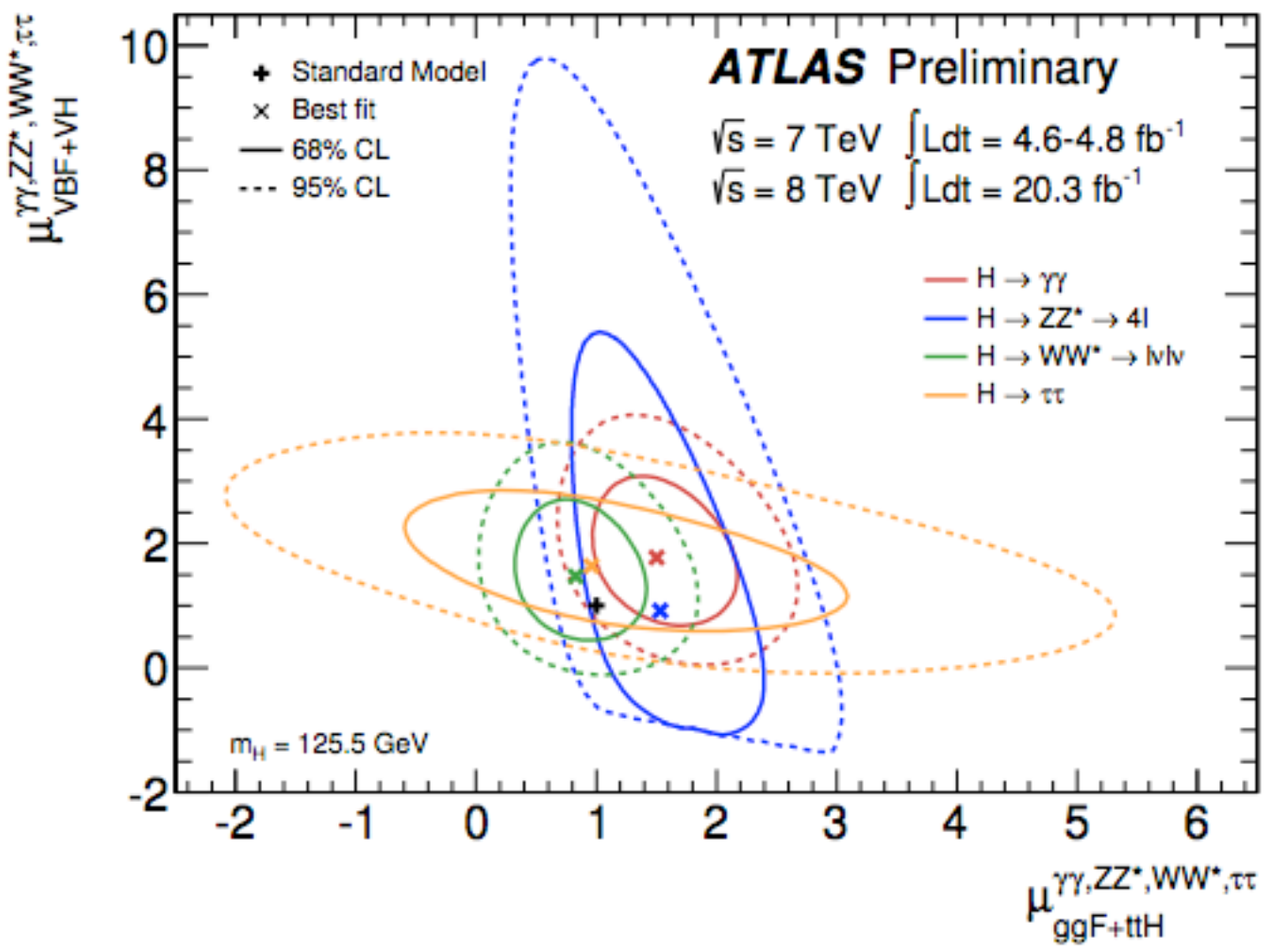
Figure 28: Display of an event selected by the $H \rightarrow \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel in the VBF category, where one τ decays to an electron. The hadronically decaying τ lepton (1 prong decay) is indicated by a green track and the yellow cluster. The electron is indicated by the blue track match to the green cluster. The approximately horizontal dashed line in the $R-\phi$ view represents the direction of the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector, and there are two VBF jets marked with turquoise cones. The electron p_{T} is 56 GeV, the τ_{had} p_{T} is 27 GeV, $E_{\mathrm{T}}^{\mathrm{miss}} = 113$ GeV, $m_{j_1,j_2} = 1.53$ TeV, $m_{\tau\tau}^{\mathrm{MMC}} = 129$ GeV, and the BDT score is 0.99. The S/B ratio in the BDT score bin of this event is 1.0.

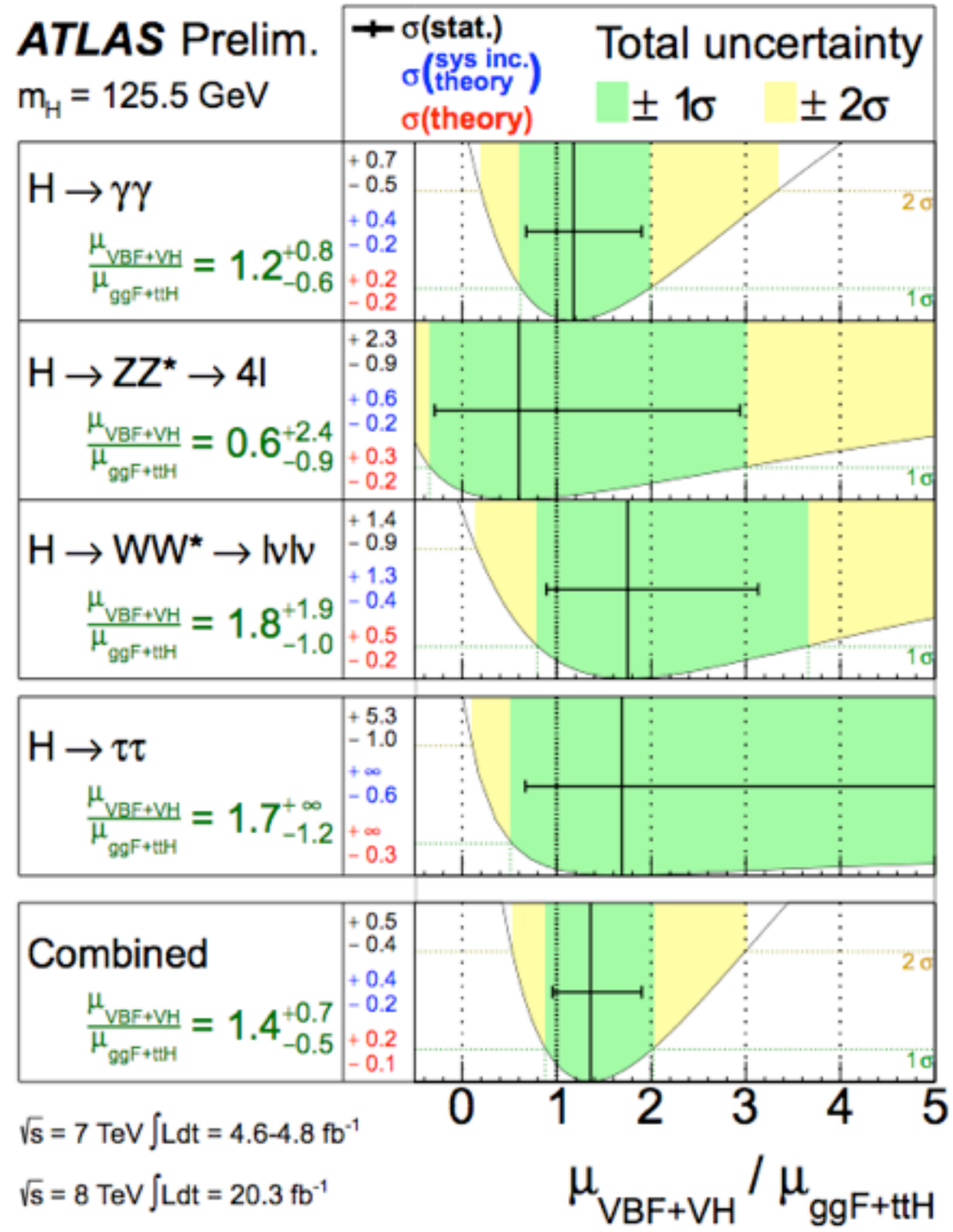
ATLAS-CONF-2013-108

VBF Higgs

ATLAS-CONF-2014-009

VBF rates systematically higher than ggF



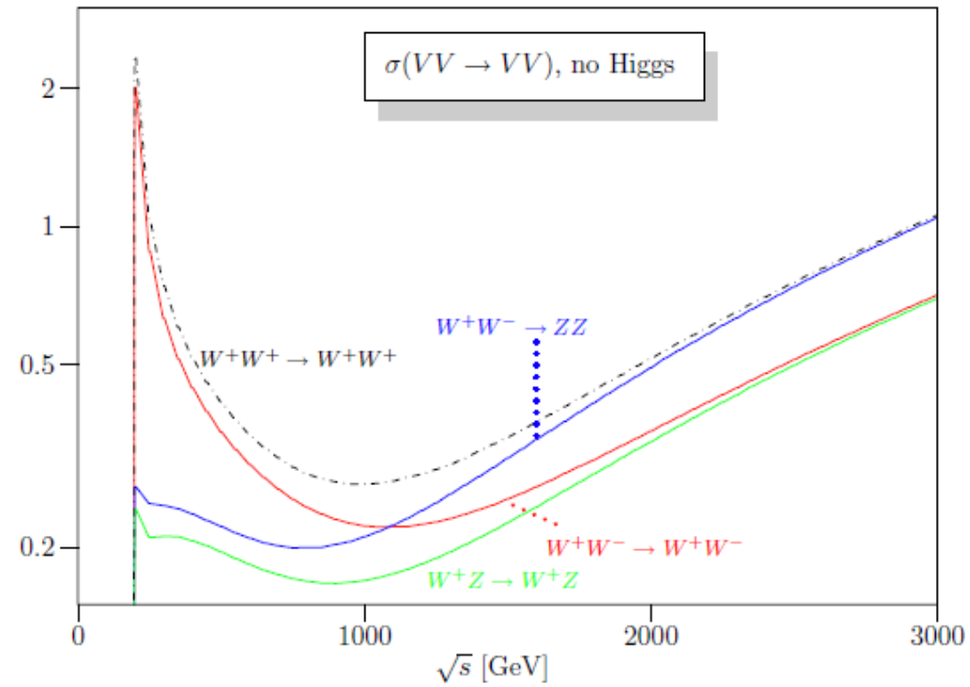


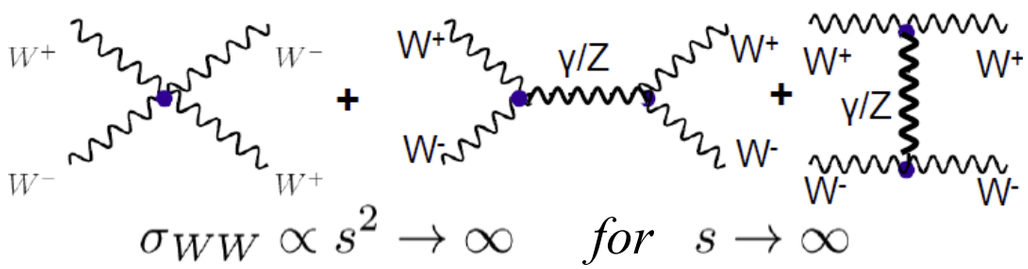
All cross sections and couplings compatible with SM

VV Scattering - Role of the Higgs

Without the Higgs, the VV scattering cross section rises unbounded with increasing center-of-mass energy

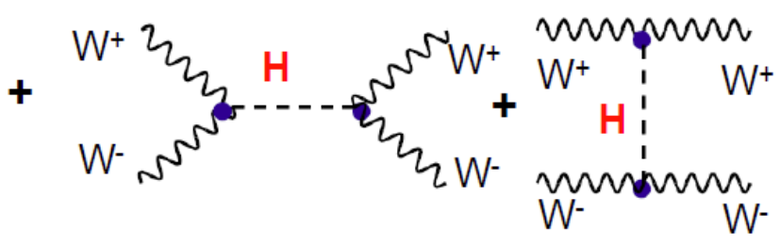
⇒ unphysical! violates unitarity - integrated probability density cannot be larger than 1



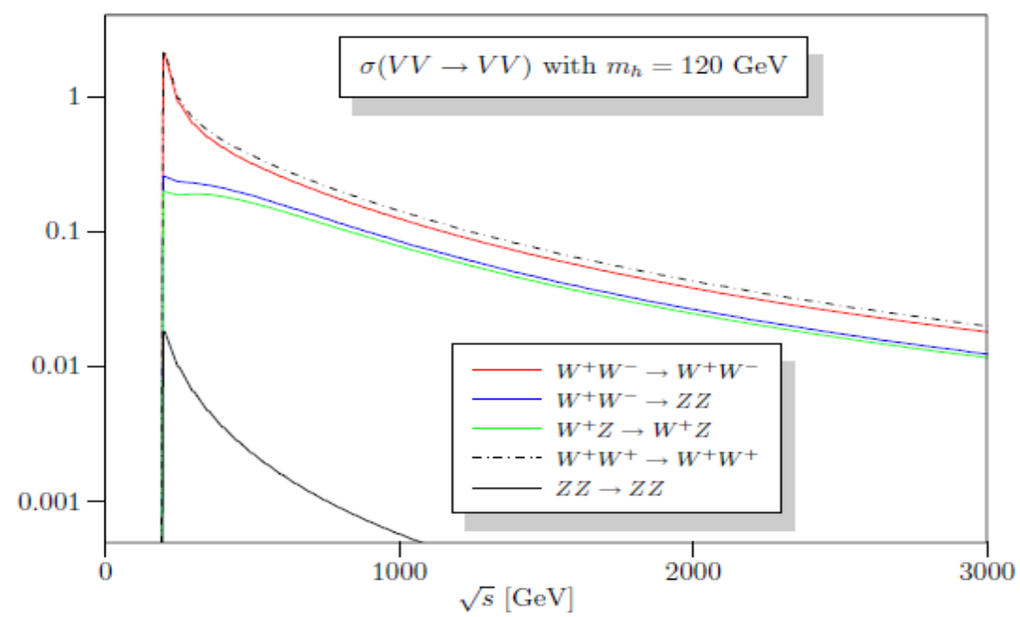


$$\sigma_{WW} \propto s^2 \to \infty \quad for \quad s \to \infty$$

By including additional diagrams:



where H is the SM Higgs, an exact cancellation unitarizes the high energy behavior of σ(WW→WW)

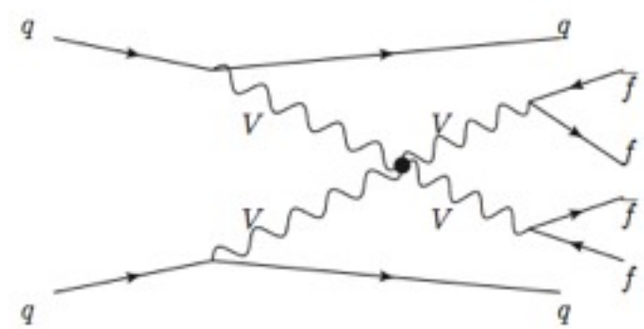


Alboteanu, Kilian and Reuter,
JHEP 0811:010,2008,
arXiv: 0806:4145

Vector Boson Scattering

Complementary approach for studying Electroweak Symmetry Breaking

- Verify if the newly discovered Higgs Boson fully restores the unitarity in $V_L V_L$ scattering
- Search for alternative mechanisms for the unitarity restoration: new resonances or strong VV interactions or ...



Several channels:

Final state	Process	VVjj-EW	VVjj-QCD
$\ell^\pm \nu \ell'^\pm \nu' jj$ (same sign, arbitrary flavor)	$W^\pm W^\pm$	19.5 fb	18.8 fb
$\ell^\pm \nu \ell'^\mp \nu' jj$ (opposite sign)	$W^\pm W^\mp$	91.3 fb	3030 fb
$\ell^+ \ell^- \nu' \nu' jj$	ZZ	2.4 fb	162 fb
$\ell^\pm \ell^\mp \ell'^\pm \nu' jj$	$W^\pm Z$	30.2 fb	687 fb
$\ell^\pm \ell^\mp \ell'^\pm \ell'^\mp jj$	ZZ	1.5 fb	106 fb

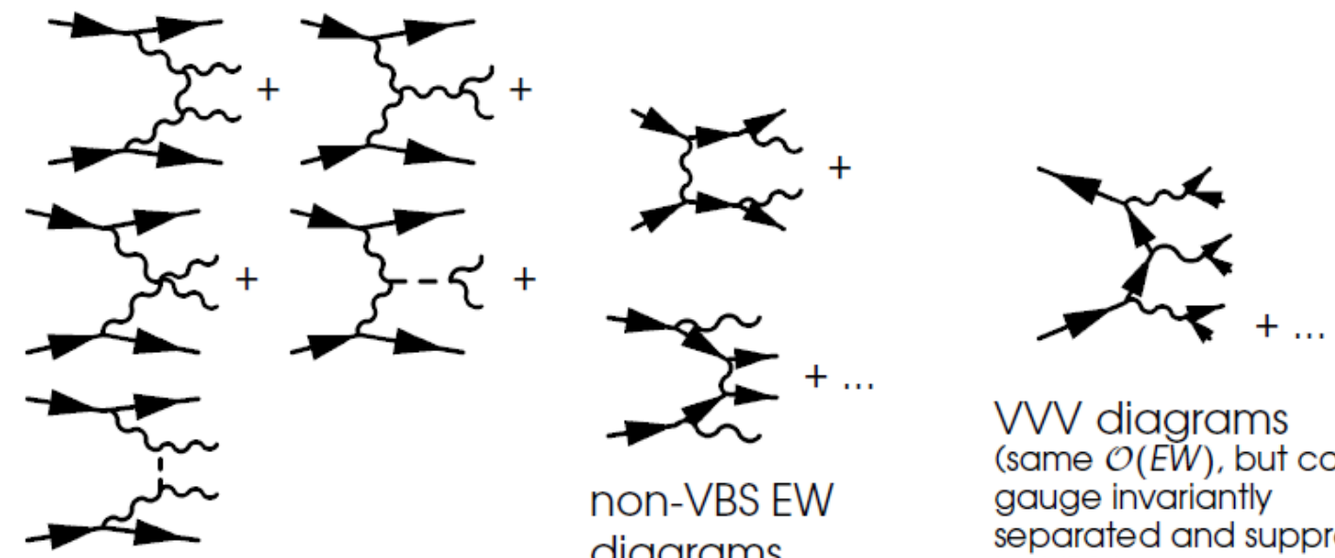
Calculated using Sherpa with 2 leptons > 5 GeV, M_{ll} > 4 GeV and ≥2 jets with p_T > 10 GeV

same sign WW - very good s/b
opposite sign WW - larger σ, but smaller s/b
WZ - larger σ, but smaller s/b
ZZ - process available only after more years of LHC running

Extremely small signal cross section

VBS Signal and Backgrounds

Signal Processes (EW)



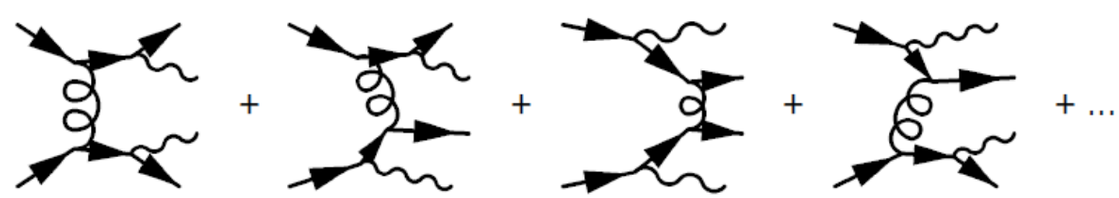
VV scattering diagrams
(including triple and quartic gauge vertices, Higgs channels

non-VBS EW diagrams
(not gauge invariantly separable)

VVV diagrams
(same $\mathcal{O}(EW)$, but can be gauge invariantly separated and suppressed by VBS topology cuts)

Background Processes (QCD)

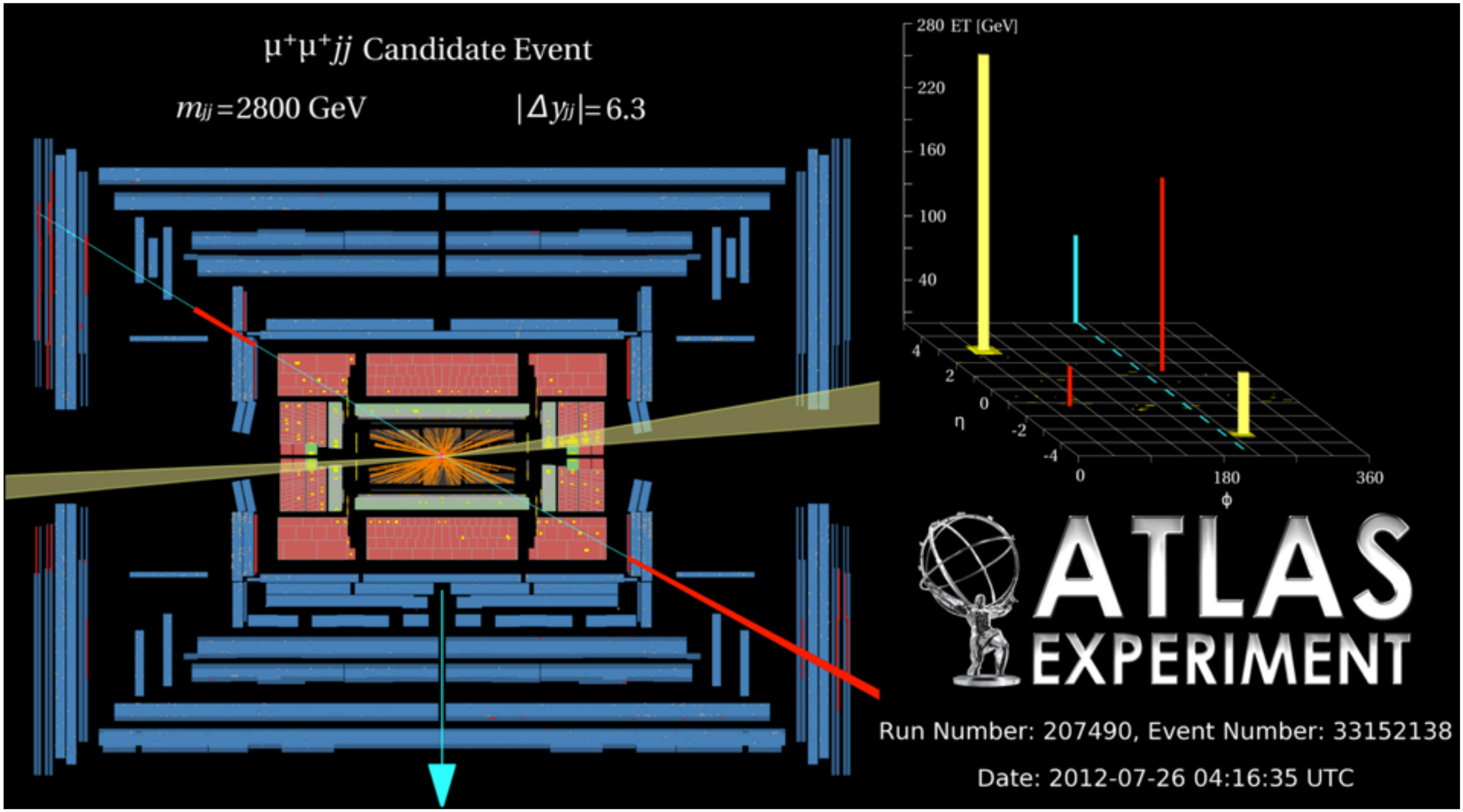
VVjj-QCD diagrams: $\mathcal{O}(EW) = 4 \bigoplus \mathcal{O}(QCD) = 2$



Plus, sources of instrumental backgrounds, e.g. lepton charge misidentification, fake lepton backgrounds, double parton scattering

Each source of background simulated using either MC or data-driven technique.

$W^{\pm}W^{\pm}$ VBS event



$W^{\pm}W^{\pm}$ VBS Result

arXiv:1405.6241
Submitted to PRL

2 phase space regions:

Inclusive region (EW/QCD ~ 3.5)
EW+QCD $W^{\pm}W^{\pm}$ jj:

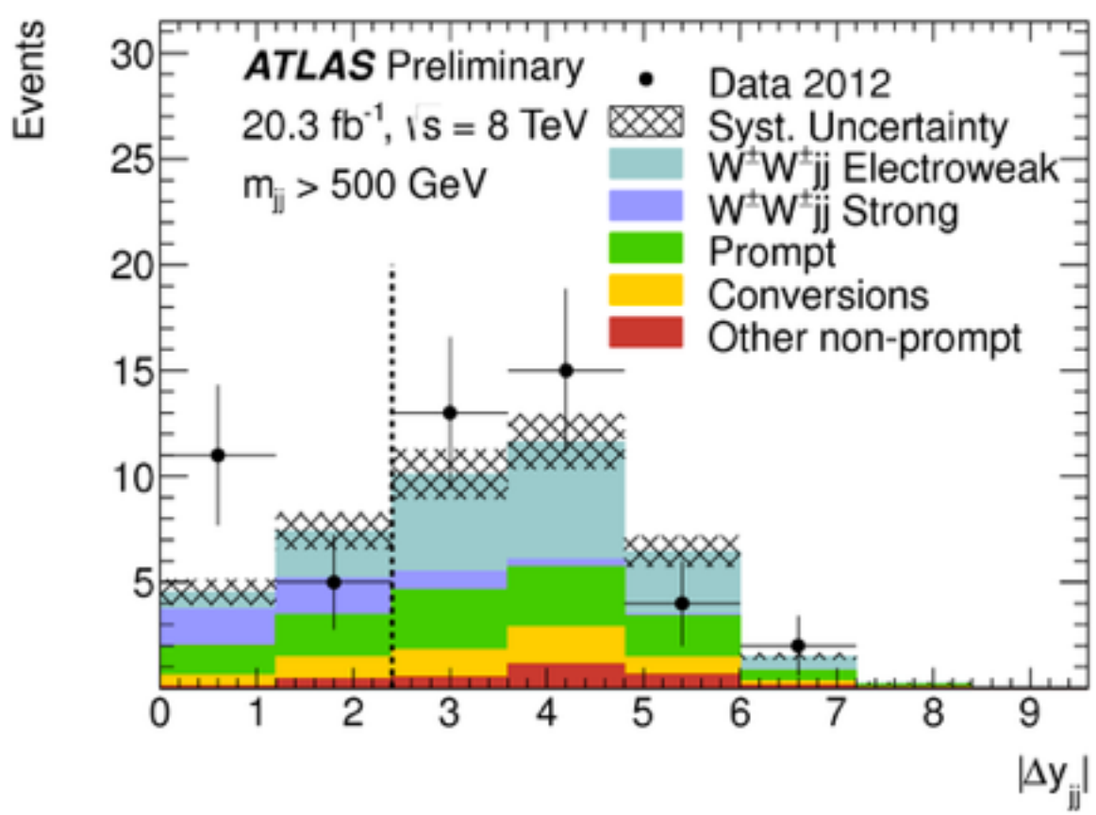
- **Exactly 2(e/μ):** p_T > 25 GeV
- **Neutrinos:** p_T^{miss} > 40 GeV
- **≥2 non-b Jets:** p_T > 30 GeV, m_{jj} > 500 GeV
- Other cuts: $m_{\ell\ell}$>20GeV, $\Delta R_{iso}(\ell)$>0.3, Z→ee veto

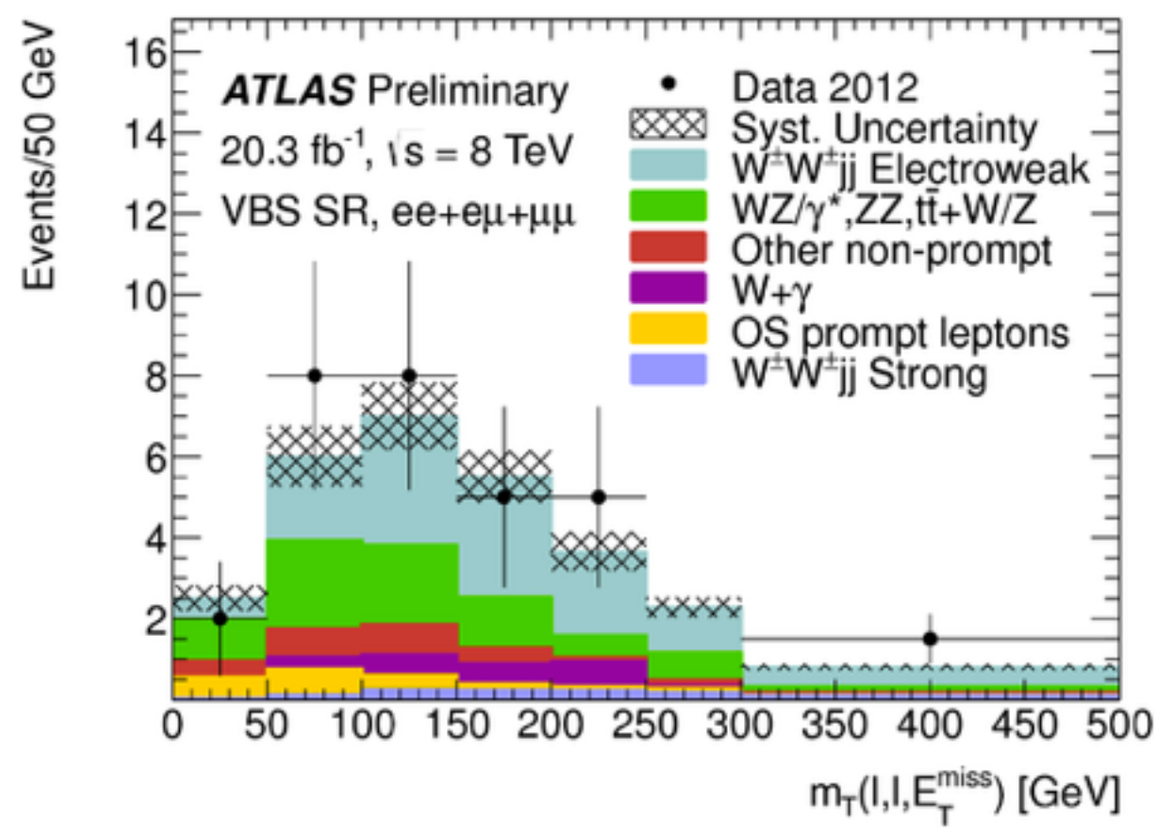
Signal region (EW/QCD ~ 10)
EW $W^{\pm}W^{\pm}$ jj:
(includes interference with QCD)

Inclusive selection plus:

- **Rapidity gap:** Δy_{jj} > 2.4

Results extracted using counting experiment





$W^{\pm}W^{\pm}$ VBS Result

arXiv:1405.6241
Submitted to PRL

2 phase space regions:

Inclusive region (EW/QCD ~ 3.5)
EW+QCD $W^{\pm}W^{\pm}$ jj:

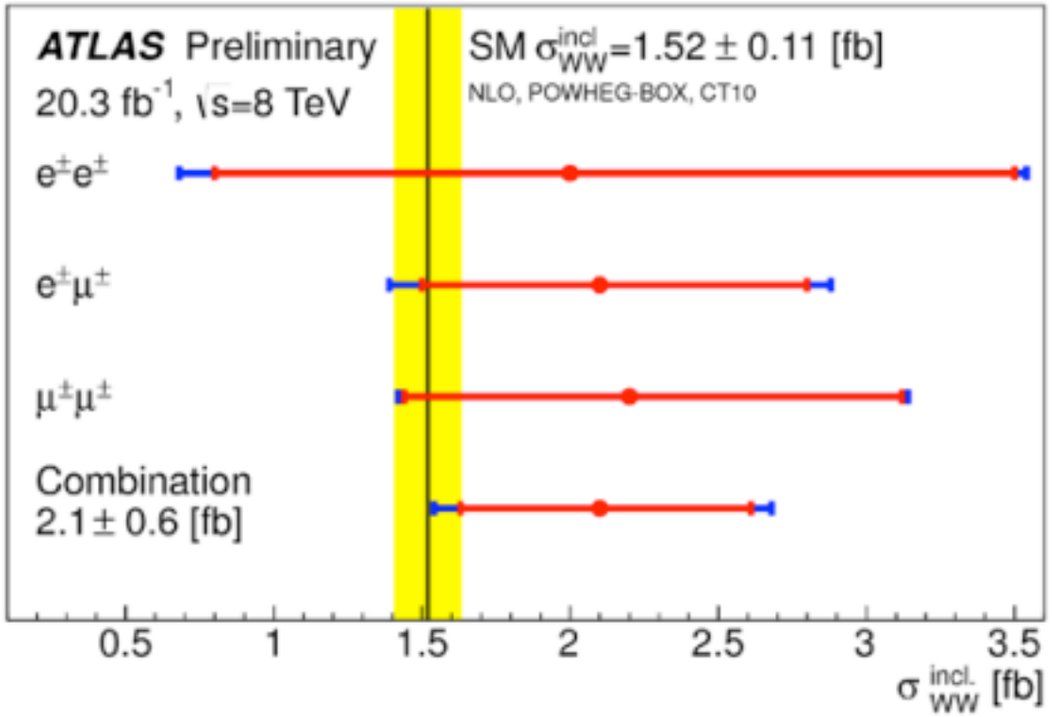
σ_{fid} = 2.1 ± 0.5 (stat) ± 0.3 (sys) fb

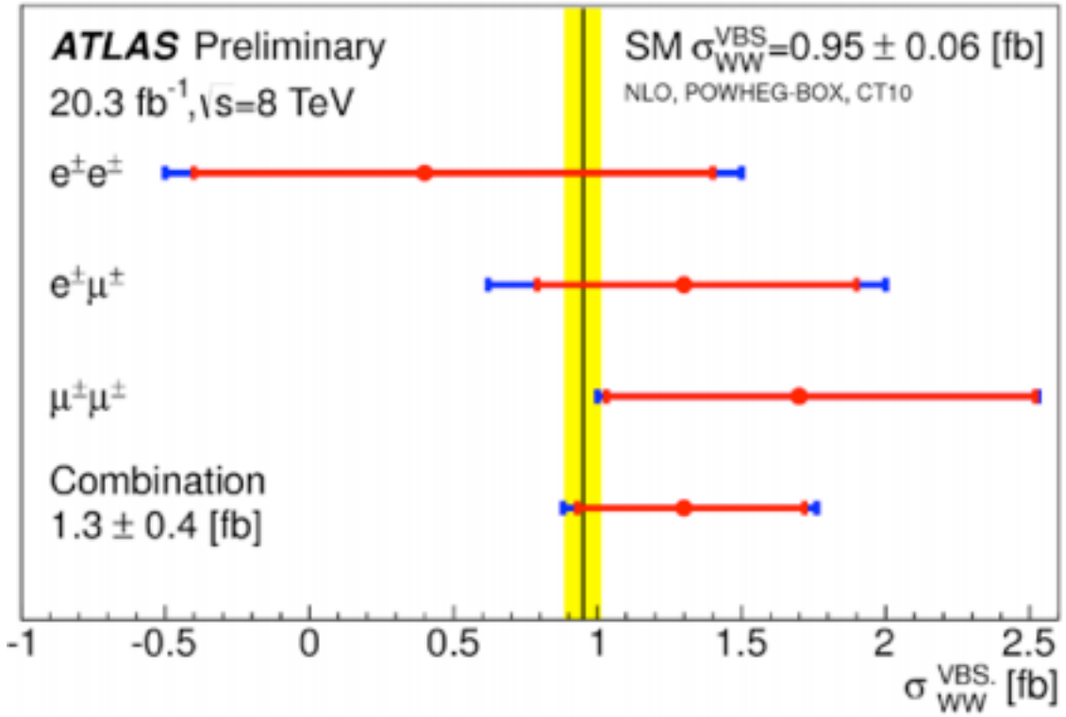
Expected significance: 3.4σ
Observed significance: 4.5σ

Signal region (EW/QCD ~ 10)
EW $W^{\pm}W^{\pm}$ jj:
(includes interference with QCD)

σ_{fid} = 1.3 ± 0.4 (stat) ± 0.2 (sys) fb

Expected significance: 2.8σ
Observed significance: 3.6σ





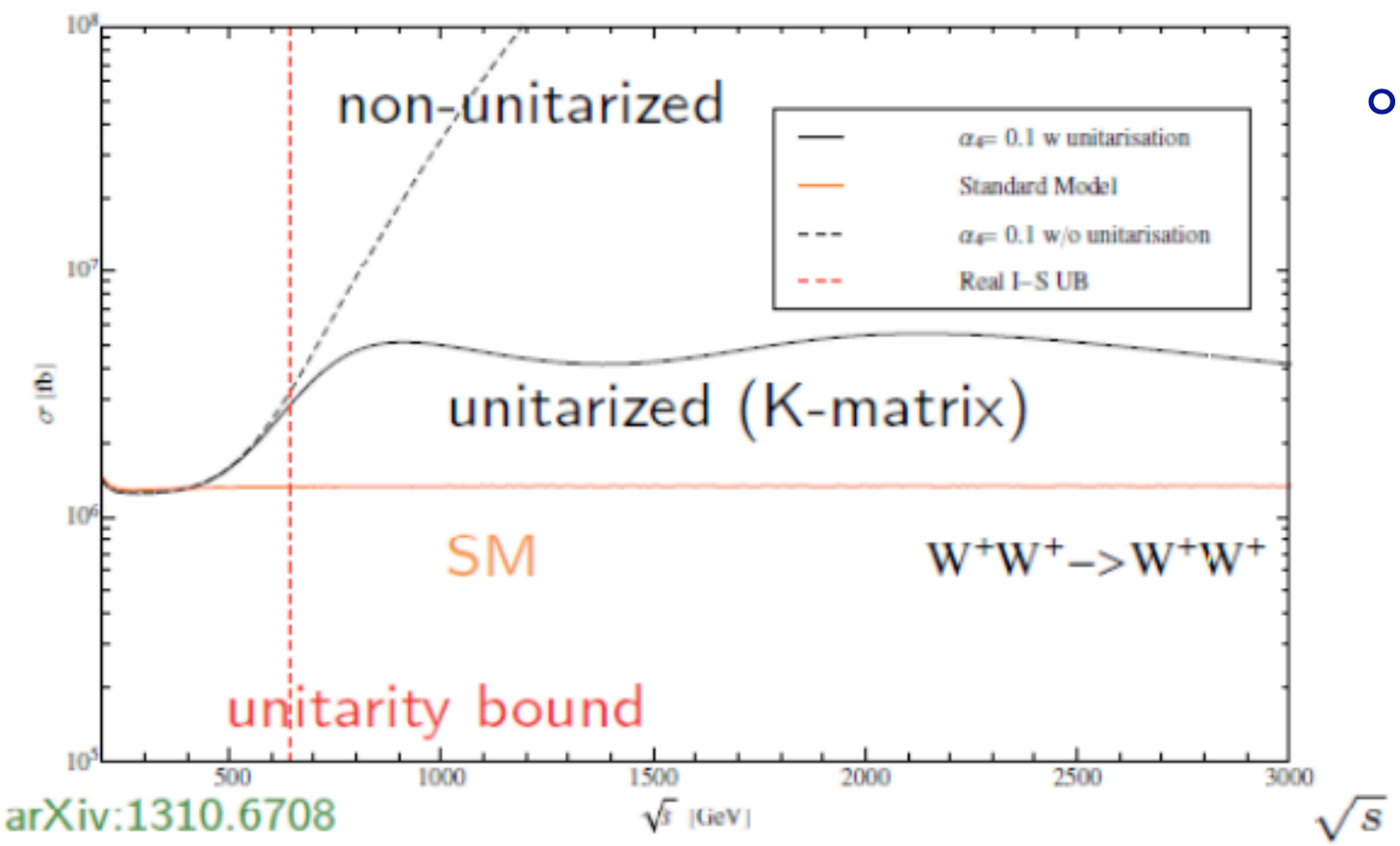
First evidence for EW WW Vector Boson Scattering!

Anomalous Quartic Gauge Couplings

Generic extension of SM Lagrangian from effective theory:

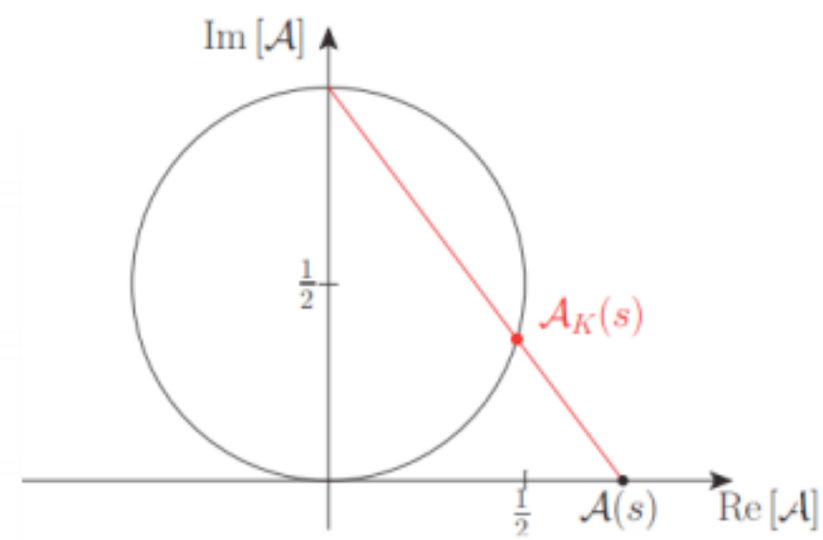
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- The terms that affect quartic couplings are α_4 and α_5
- Unitarization scheme implemented by WHIZARD collaboration: K-matrix



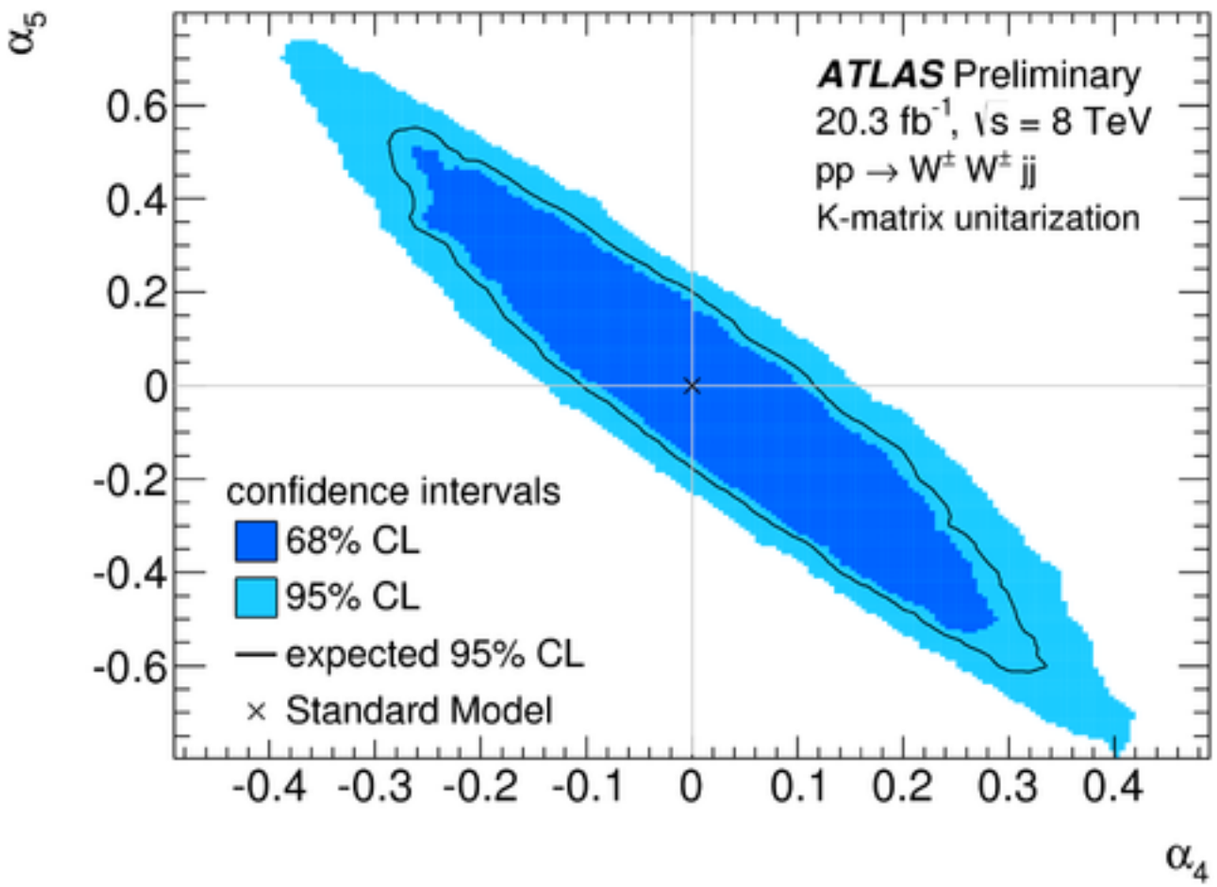
arXiv:1310.6708

Projection of scattering amplitude on Argand Circle saturates amplitude and satisfies optical theorem



$W^{\pm}W^{\pm}$ Limits on aQGC

arXiv:1405.6241
Submitted to PRL



1D aQGC limits:

$\alpha_4 \propto$ [-0.139, 0.157] obs. [-0.104, 0.116] exp.

$\alpha_5 \propto$ [-0.229, 0.244] obs. [-0.180, 0.199] exp.

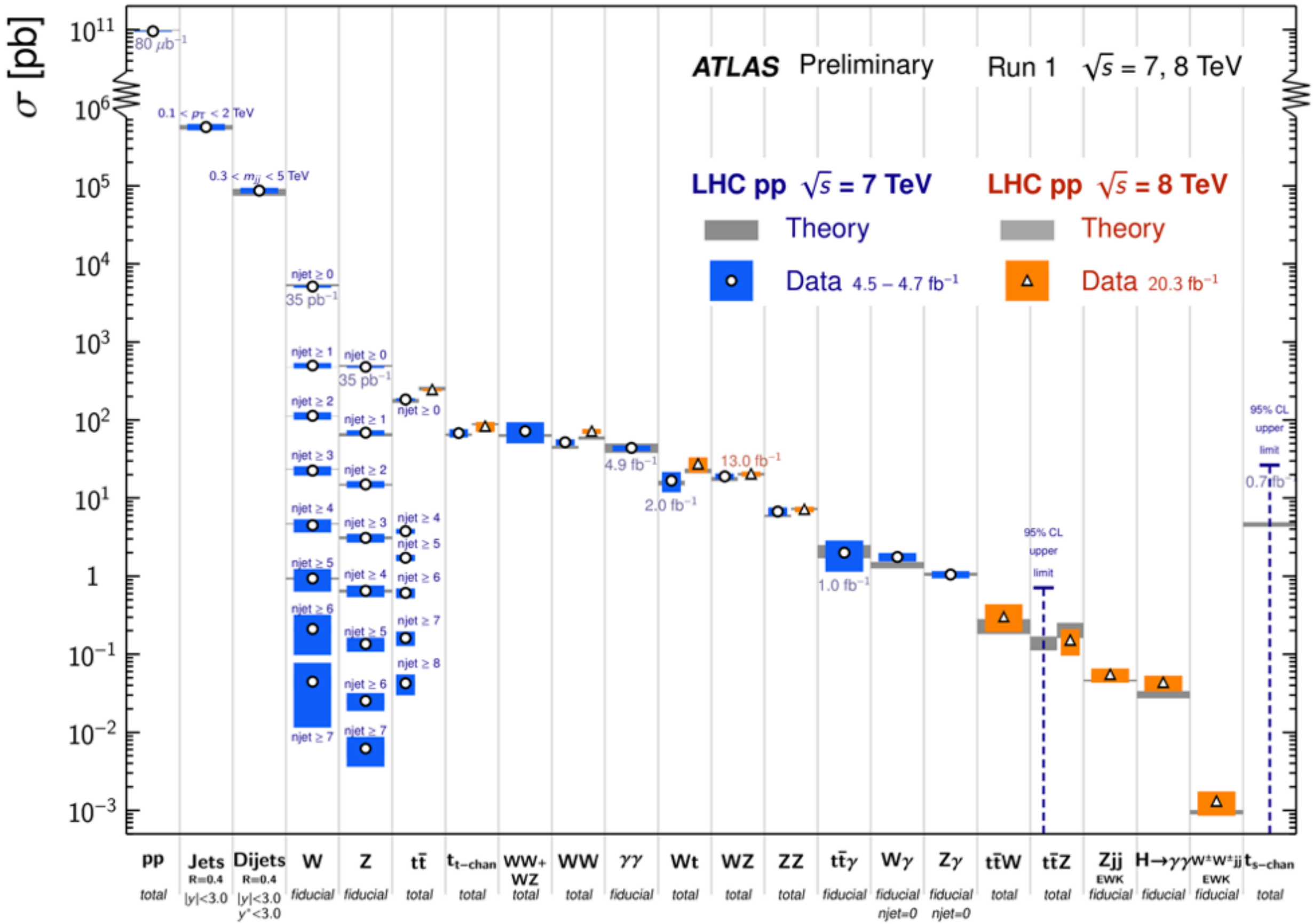
compare with indirect constraints from precision EW data:

$-0.35 < \alpha_4 < 0.06$ and $-0.87 < \alpha_5 < 0.15$

Eboli et al, PRD 74, 073005 (2006)

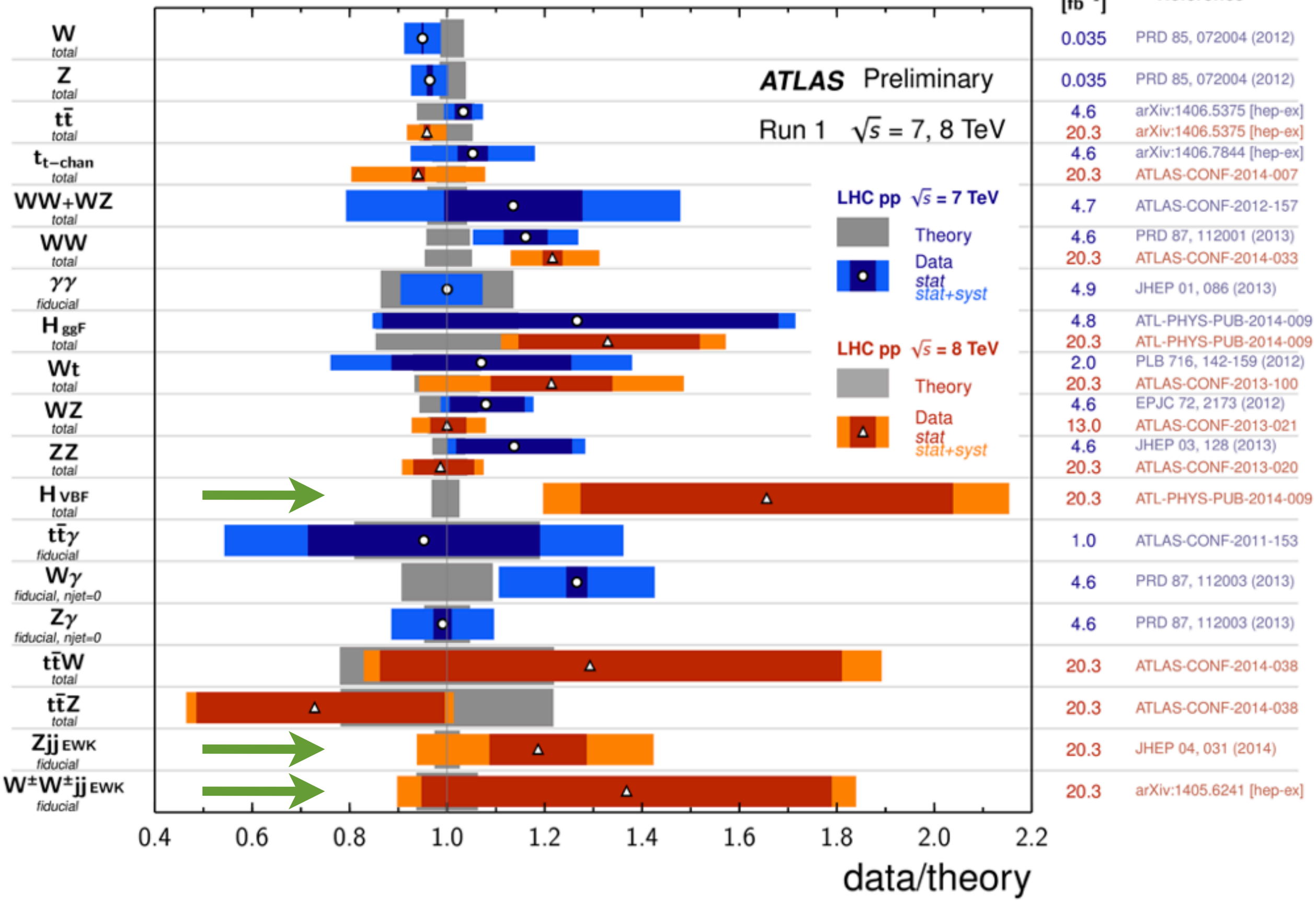
Standard Model Production Cross Section Measurements

Status: July 2014



Standard Model Production Cross Section Measurements

Status: July 2014



	$\int \mathcal{L}\,dt$ [fb^{-1}]	Reference
W total	0.035	PRD 85, 072004 (2012)
Z total	0.035	PRD 85, 072004 (2012)
$t\bar{t}$ total	4.6	arXiv:1406.5375 [hep-ex]
	20.3	arXiv:1406.5375 [hep-ex]
t_{t-chan} total	4.6	arXiv:1406.7844 [hep-ex]
	20.3	ATLAS-CONF-2014-007
WW+WZ total	4.7	ATLAS-CONF-2012-157
WW total	4.6	PRD 87, 112001 (2013)
	20.3	ATLAS-CONF-2014-033
$\gamma\gamma$ fiducial	4.9	JHEP 01, 086 (2013)
H_{ggF} total	4.8	ATL-PHYS-PUB-2014-009
	20.3	ATL-PHYS-PUB-2014-009
Wt total	2.0	PLB 716, 142-159 (2012)
	20.3	ATLAS-CONF-2013-100
WZ total	4.6	EPJC 72, 2173 (2012)
	13.0	ATLAS-CONF-2013-021
ZZ total	4.6	JHEP 03, 128 (2013)
	20.3	ATLAS-CONF-2013-020
H_{VBF} total	20.3	ATL-PHYS-PUB-2014-009
$t\bar{t}\gamma$ fiducial	1.0	ATLAS-CONF-2011-153
$W\gamma$ fiducial, njet=0	4.6	PRD 87, 112003 (2013)
$Z\gamma$ fiducial, njet=0	4.6	PRD 87, 112003 (2013)
$t\bar{t}W$ total	20.3	ATLAS-CONF-2014-038
$t\bar{t}Z$ total	20.3	ATLAS-CONF-2014-038
Zjj_{EWK} fiducial	20.3	JHEP 04, 031 (2014)
$W^{\pm}W^{\pm}jj_{EWK}$ fiducial	20.3	arXiv:1405.6241 [hep-ex]

Looking Forward

- Upgrades of the LHC will provide more luminosity with greater kinematic reach due to increased center of mass energy.
  - Run 2 (2015-2018): 75-100 fb^{-1} of data @ $\sqrt{s}$ = 13-14 TeV
  - Run 3 (2020-2023): ~350 fb^{-1} of data @ $\sqrt{s}$ = 14 TeV
  - Run 4 High Lumi LHC (2023-?): ~3500 fb^{-1} of data @ $\sqrt{s}$ = 14 TeV
- Slight excesses of VBF Z, Higgs and $W^{\pm}W^{\pm}$ above SM expectation will be explored with greater precision.
- More sensitive probe of anomalous couplings.
- Is longitudinal VV scattering fully unitarized by SM Higgs?

Physics In Collision 2014

XXXIV International Symposium on Physics in Collision
Indiana University; Bloomington, Indiana
September 16-20, 2014

Invited speakers give plenary reviews on topics in elementary particle and astroparticle physics. Timetable encourages informal discussions on experimental results and their implications. Abstracts for poster sessions are welcome from all participants.

Topics Include:

Electroweak Phenomena
Neutrino Physics
Higgs Measurements
Quantum Chromodynamics
Heavy Flavor Physics
Heavy Ion Physics
Astroparticle Physics
Searches for Phenomena
Beyond the Standard Model

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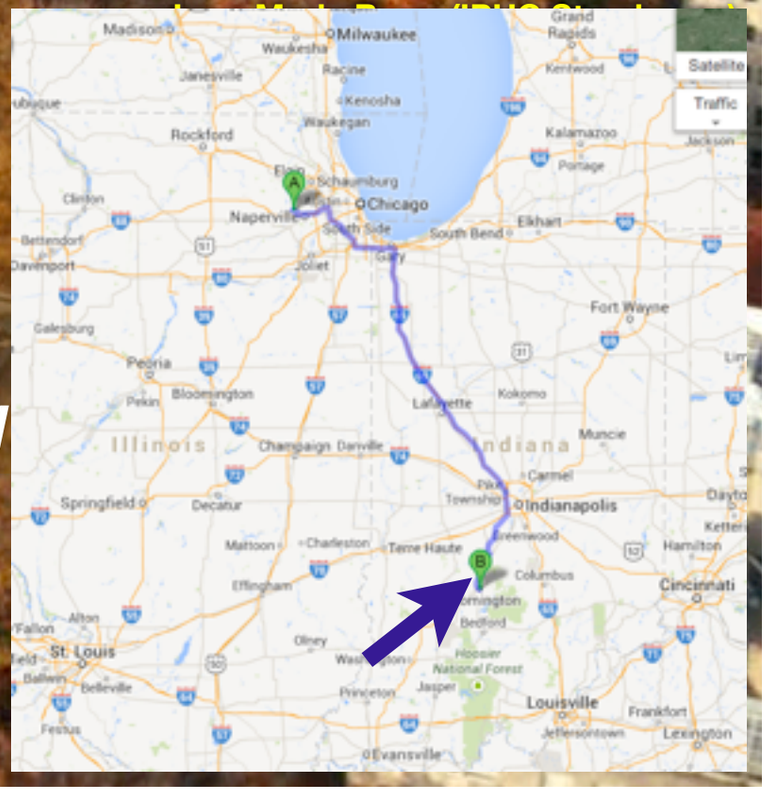

Conference site:
Indiana Memorial Union

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http://pic2014.indiana.edu

Extra Slides

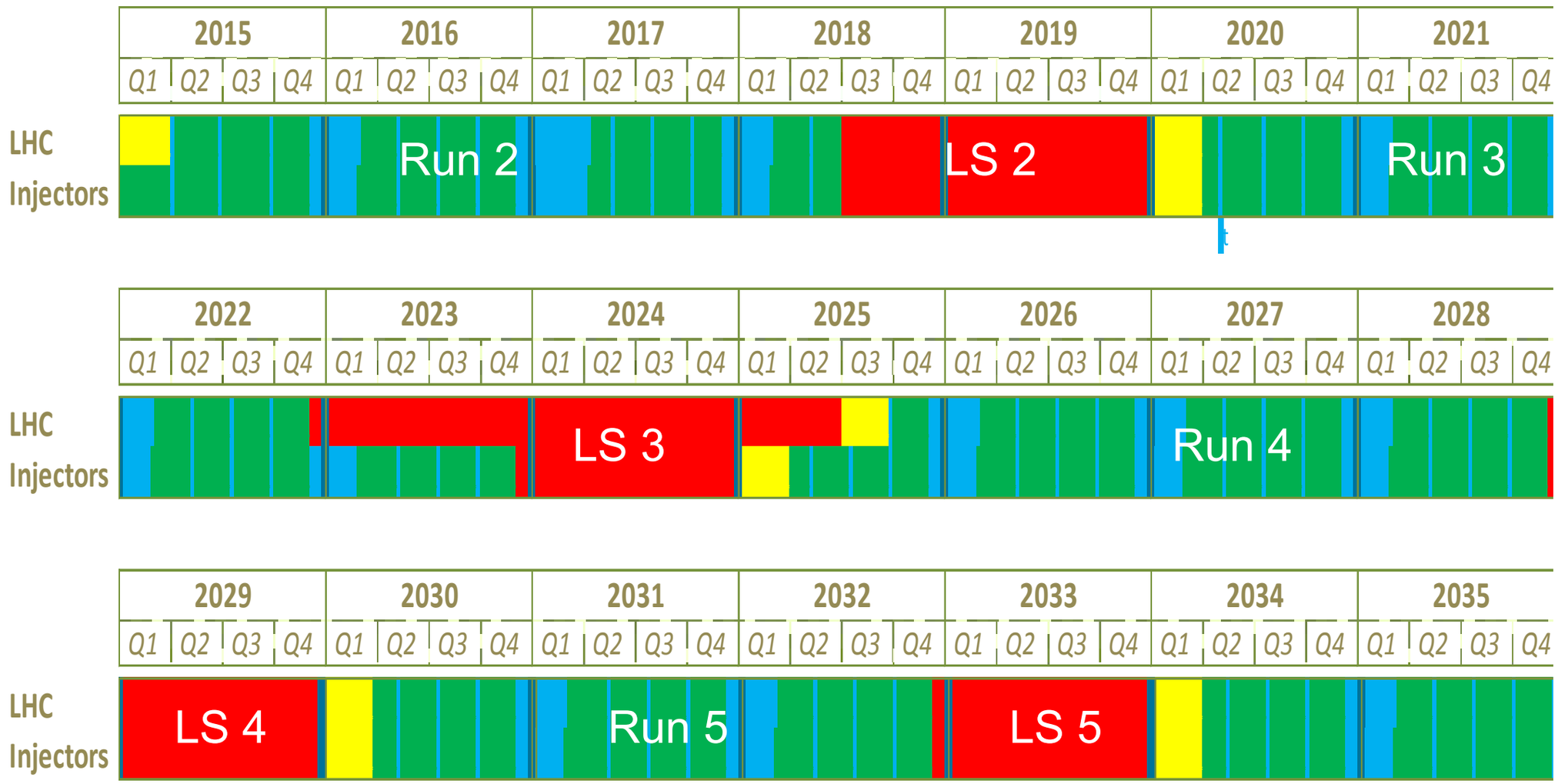
LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

injectors: in 2024 => 13 months + 3 BC



LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

Electroweak Zjj Extraction

Signal region definition

- A Z-boson candidate, defined as exactly two oppositely charged, same-flavour leptons with a dilepton invariant mass of $81 \leq m_{\ell\ell} < 101$ GeV.
- The transverse momentum of the dilepton pair must satisfy $p_{\mathrm{T}}^{\ell\ell} > 20$ GeV.
- At least two jets that satisfy $p_{\mathrm{T}}^{j_1} > 55$ GeV, $p_{\mathrm{T}}^{j_2} > 45$ GeV, where j_1 and j_2 label the highest and second highest transverse momentum jets in the event.
- The invariant mass of the two leading jets is required to satisfy $m_{jj} > 250$ GeV.
- No additional jets with $p_{\mathrm{T}} > 25$ GeV in the rapidity interval between the two leading jets.
- The normalised transverse-momentum balance between the two leptons and the two highest transverse momentum jets, $p_{\mathrm{T}}^{\mathrm{balance}}$, is required to be less than 0.15. The $p_{\mathrm{T}}^{\mathrm{balance}}$ is defined as

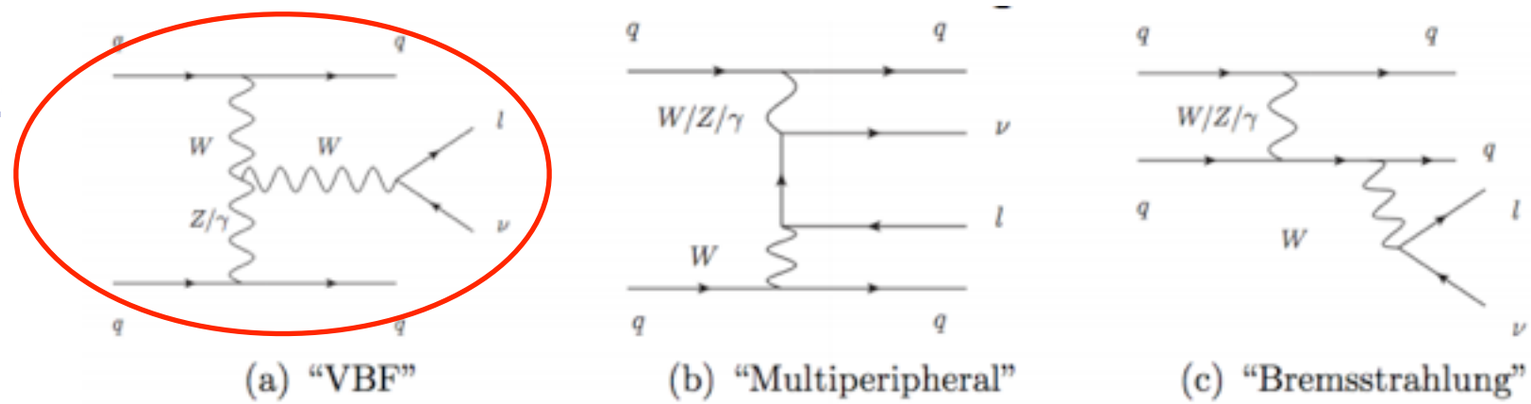
$$p_{\mathrm{T}}^{\mathrm{balance}} = \frac{\left|\vec{p}_{\mathrm{T}}^{\ell_1} + \vec{p}_{\mathrm{T}}^{\ell_2} + \vec{p}_{\mathrm{T}}^{j_1} + \vec{p}_{\mathrm{T}}^{j_2}\right|}{\left|\vec{p}_{\mathrm{T}}^{\ell_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\ell_2}\right| + \left|\vec{p}_{\mathrm{T}}^{j_1}\right| + \left|\vec{p}_{\mathrm{T}}^{j_2}\right|}, \tag{6.2}$$

where $\vec{p}_{\mathrm{T}}^{i}$ is the transverse momentum vector of object i, and ℓ_1 and ℓ_2 label the two leptons that define the Z-boson candidate.

VBF - W Production

VBF is part of gauge invariant set which defines "signal" process

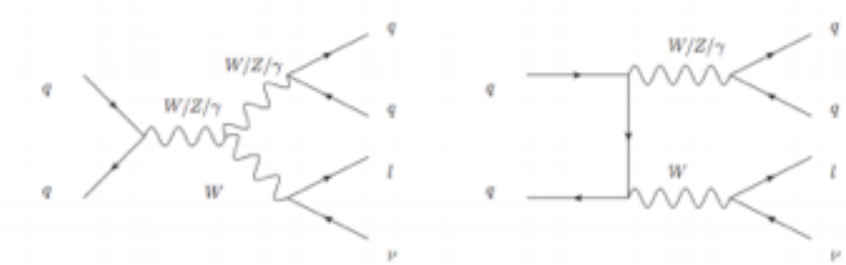
- VBF diagram not separable
- Other processes suppressed through kinematic cuts



(a) "VBF" (b) "Multiperipheral" (c) "Bremsstrahlung"

Backgrounds dominated by strong Wjj production:

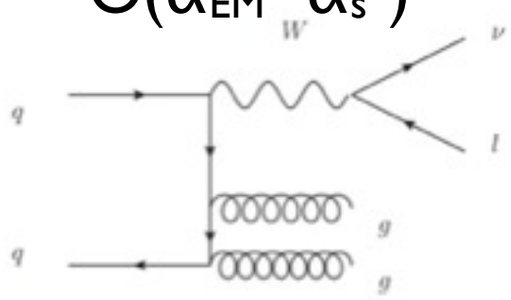
$O(\alpha_{EM}^4)$



(a) Diboson (annihilation or s-channel) (b) Diboson (converstion or t-channel)

Gauge invariant set of diagrams

$O(\alpha_{EM}^2\ \alpha_s^2)$



Additionally,

- W Backgrounds:
  - Single Top - Leads to W + Jets final state
  - $t\bar{t}$ - Two Ws + Jets final state - one W decays hadronically, other leptonically
  - Diboson - WZ/WW leptonically decaying W and Jets, ZZ one lepton missing cuts
  - Z + Jets - One lepton falls outside cuts and identified as MET
  - Multijets - hadronic multijets with mis-identified lepton (data-driven)

Has never been observed at hadron collider.
No public result (ATLAS or CMS) yet.

VBF - W Backgrounds

Systematic uncertainties on the background simulation can bury the signal

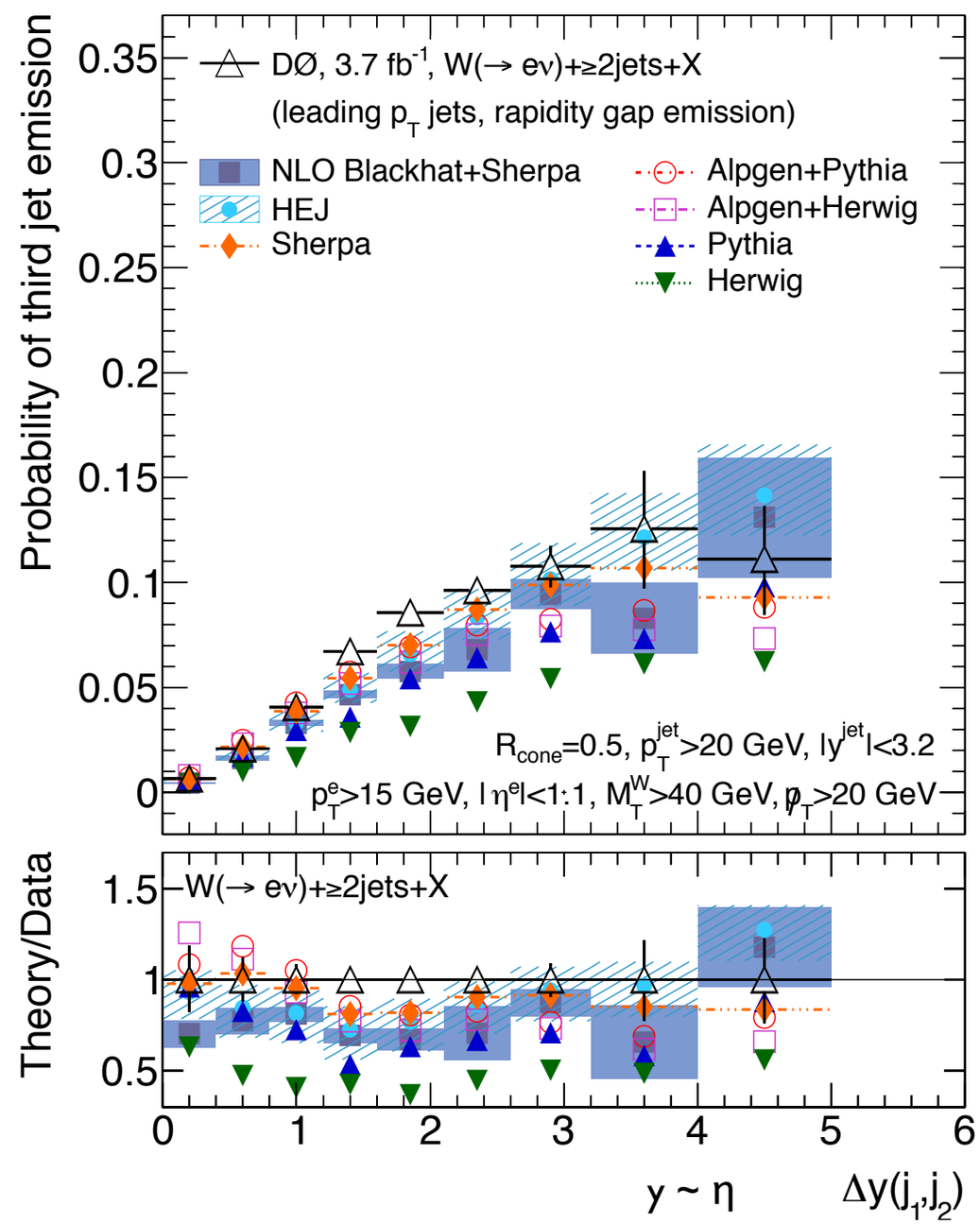
→ e.g. theoretical imprecision on the production rates or jet energy measurement uncertainties

Backgrounds can be measured in other phase space regions or even other experiments (to validate the MC simulation)

Theory Predictions

- NLO Blackhat + Sherpa - fixed order parton-level calc,, corrected to particle level with Sherpa
- HEJ - all-order resummation in large-η limit
- Sherpa, Alpgen+Pythia/Herwig: LO matrix element + parton shower MCs, with different schemes for matching matrix elements and PS.
- Pythia, Herwig: parton shower MCs

Probability to find 3rd jet in rapidity gap spanned by two highest p_T jets in W+≥2 jet events at DZero ($p\bar{p}$ experiment)



CMS VBF - Z results

Method I result: $\sigma(\mathrm{EWK}\ \ell\ell + \mathrm{jj})_{\mathrm{I}} = 191 \pm 29_{\mathrm{stat}} \pm 39_{\mathrm{syst}}$ fb,

combine using BLUE

Method II result: $\sigma(\mathrm{EWK}\ \ell\ell + \mathrm{jj})_{\mathrm{II}} = 303 \pm 29_{\mathrm{stat}} \pm 57_{\mathrm{syst}}$ fb.

$\sigma(\mathrm{EWK}\ \ell\ell\mathrm{jj}) = 226 \pm 26_{\mathrm{stat}} \pm 35_{\mathrm{syst}}$ fb,

Compare with SM NLO prediction of 239 fb.

Signal Strength μ and associated uncertainties

	Analysis			
	Method I	Method II		
	$\mu\mu$	ee	$\mu\mu$	Combination
$\mu = \sigma/\sigma_{\mathrm{th}}$	0.80 ± 0.20	0.82 ± 0.37	1.30 ± 0.30	1.27 ± 0.27
Statistical uncertainty	0.12	0.23	0.16	0.12
Systematic uncertainty	0.16	0.28	0.25	0.24
Luminosity	0.03	0.03	0.03	0.03
Trigger/lepton selection	0.01	0.03	0.03	0.02
JES+residual response	0.05	0.05	0.04	0.04
JER	0.02	0.02	0.02	0.02
Pileup	0.06	0.03	0.03	0.02
QCD Zjj	0.13	0.26	0.23	0.22
Top, dibosons	0.01	0.04	0.03	0.02
Signal	0.05	0.08	0.07	0.06

Measurement uncertainty dominated by strong QCD Zjj production

CMS PAS FSQ-12-035

Sensitivity to VBS and aQGC in RunII

model	baseline	500 GeV scalar	800 GeV vector	1150 GeVvector
(a_4, a_5)	$(0, 0)$	$(0.01, 0.009)$	$(0.009, -0.007)$	$(0.004, -0.004)$
S/B	$(3.3 \pm 0.3)\%$	$(0.7 \pm 0.1)\%$	$(4.9 \pm 0.3)\%$	$(5.8 \pm 0.3)\%$
$S/\sqrt{B}$ $(L = 300\text{fb}^{-1})$	2.3 ± 0.3	0.6 ± 0.1	3.3 ± 0.4	3.9 ± 0.4
$S/\sqrt{B}$ $(L = 3000\,\text{fb}^{-1})$	7.2 ± 0.1	1.6 ± 0.1	10.4 ± 0.7	12.4 ± 0.7

Table 1: Summary of sensitivity to various resonance hypotheses in the lepton plus jets WW channel.

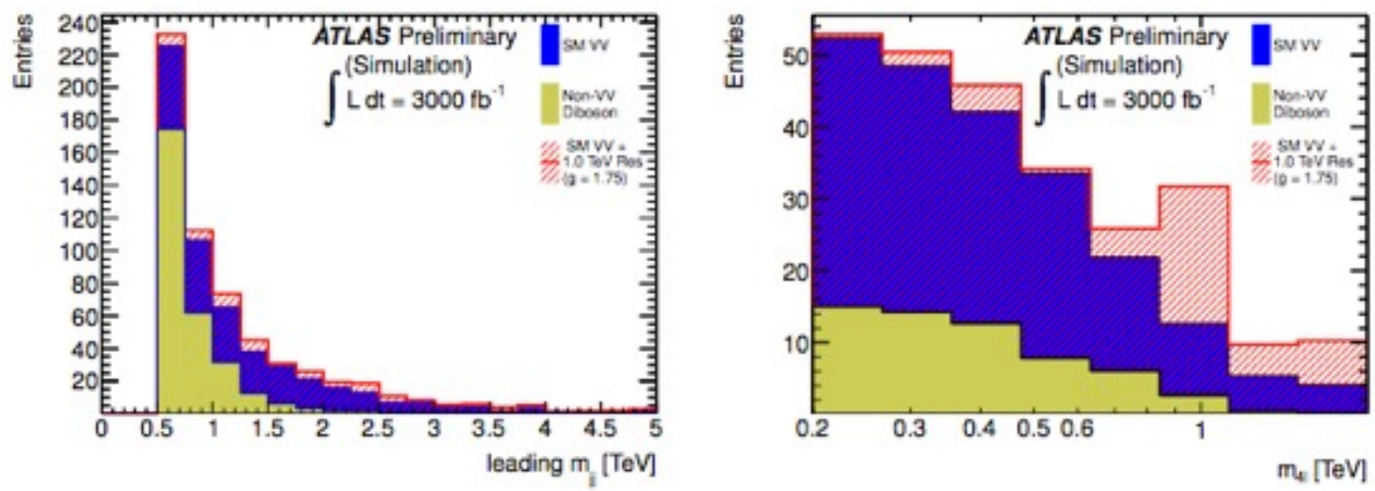


Figure 3: The leading jet-jet invariant mass (m_{jj}) distribution for simulated events in the $pp \to ZZ + 2j \to \ell\ell\ell\ell + 2j$ channel (left), and the reconstructed 4-lepton mass ($m_{4\ell}$) spectrum for this channel after requiring $m_{jj} > 1$ TeV (right). The spectra are normalized to 3000 fb^{-1}.

Process	σ BR (fb)
non-VBS $ZZjj$	6.66
SM VBS ZZ	0.80
SM VBS + 500 GeV Resonance, $g = 1.0$	1.03
SM VBS + 1 TeV Resonance, $g = 1.75$	0.91
SM VBS + 1 TeV Resonance, $g = 2.5$	0.98

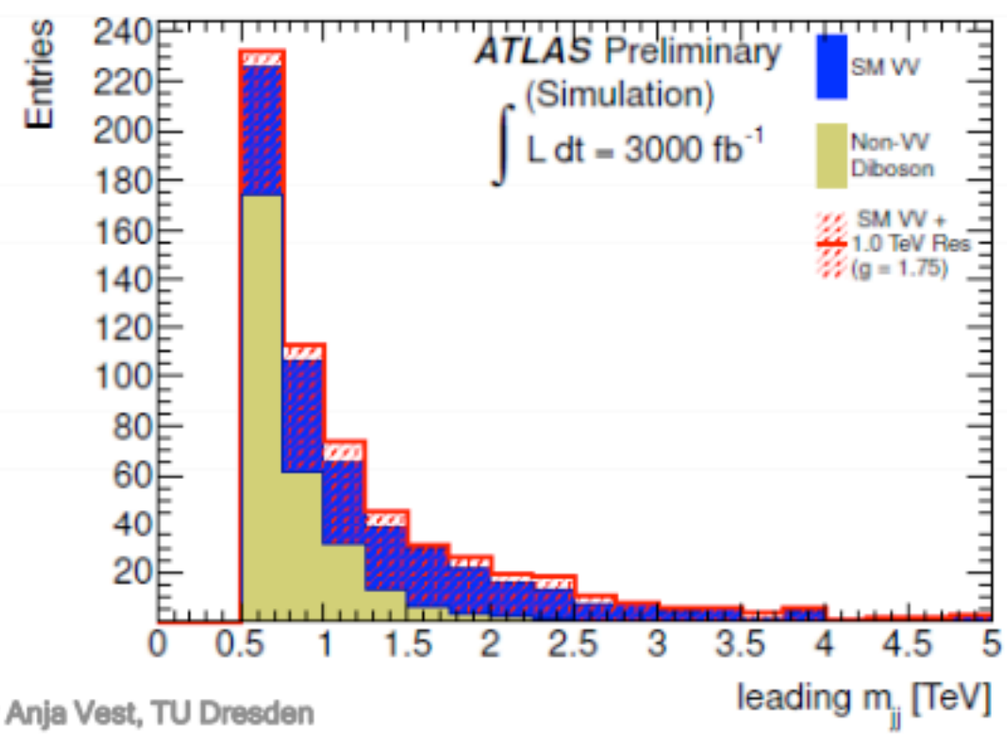
Table 4: Summary of $ZZ \to 4\ell$ production cross sections. The non-VBS $ZZjj$ background was generated with a jet $p_T > 20$ GeV requirement.

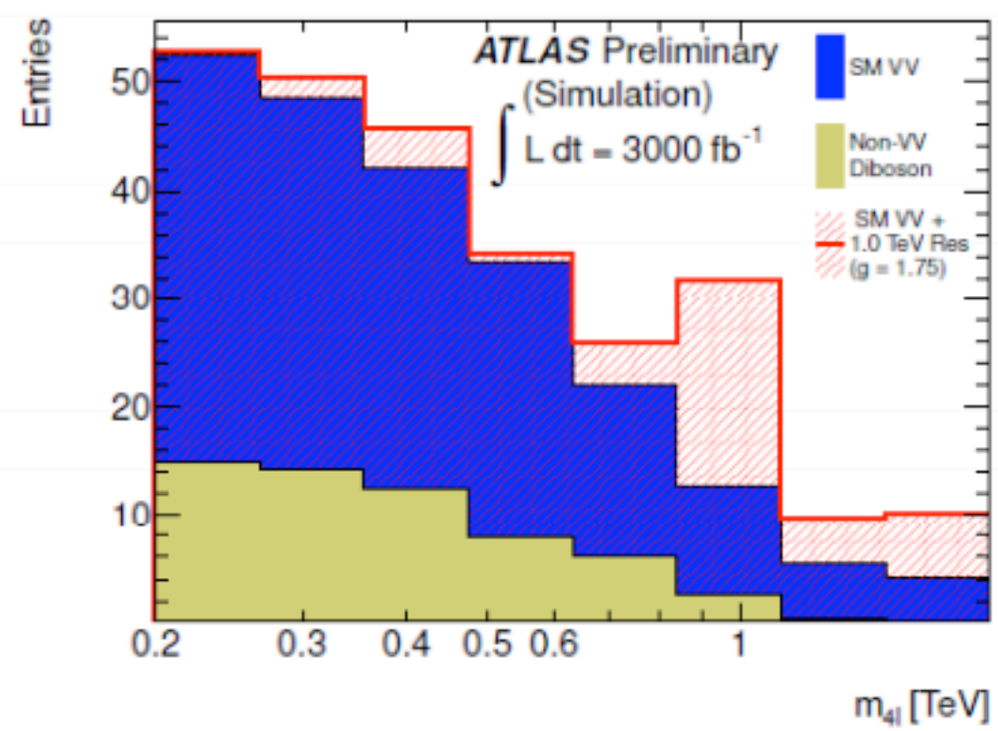
Outlook: LHC@14 TeV : resonances

European strategy CERN-ESG-005, ATLAS-PHYS-PUB-2012-005

- LHC @ 14 TeV → VBS centre-of-mass energy of $\sim 1-2$ TeV
- signal: anomalous VBS ZZ tensor singlet resonance f^0
  - → signal chosen is a hard benchmark, sensitivity higher for other resonances

$m_{\text{resonance}}$	coupling	width	300 fb^{-1}	3000 fb^{-1}
500 GeV	$g = 1$	$\Gamma = 2$ GeV	2.4σ	7.5σ
1 TeV	$g = 1.75$	$\Gamma = 50$ GeV	1.7σ	5.5σ
1 TeV	$g = 2.5$	$\Gamma = 100$ GeV	3.0σ	9.4σ

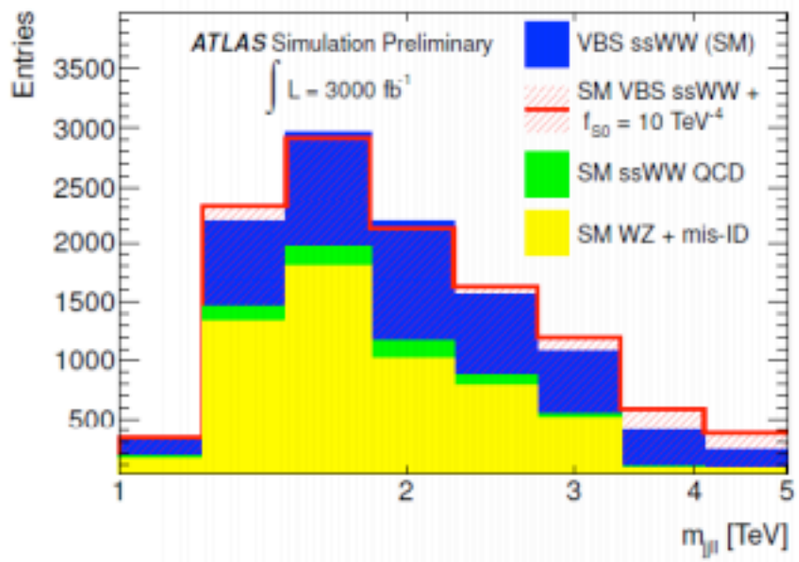


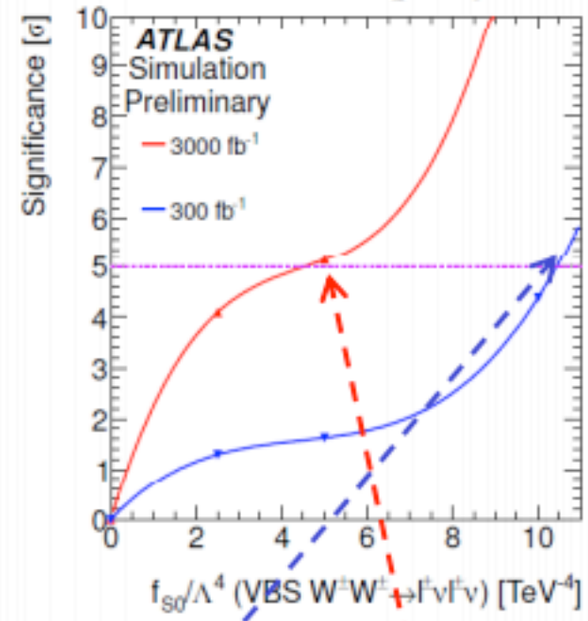


Slide by Anja Vest, TU Dresden

Outlook: LHC@14 TeV: aQGCs

- Snowmass Studies 2013: ATLAS-PHYS-PUB-2013-006
  - Example: Fully simulated $W^{\pm}W^{\pm}jj$ events under high pileup conditions





- Sensitivity for studies in untarity conserving region $\sqrt{\hat{s}} < \Lambda_{UV}$

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^{\pm}W^{\pm}$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Table 5: 5σ-significance discovery values and 95% CL limits for coefficients of higher-dimension operators. Λ_{UV} is the unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1} of integrated luminosity.