Measurements of single and multi-boson production with the ATLAS detector

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Topics

Measurements of:

1. single real W/Z
2. Drell-Yan
3. Diboson
4. VBF/VBS
5. Triboson

Physics Motivations:

a) probe predictions, improve parameter bounds & modelling for SM
b) constrain PDF
c) understand bkg for many (Higgs, BSM, …) analyses
d) search/constrain new physics (anomalous couplings)

crucial interplay: precise measurements ↔ good modelling

Reference Guides

1) *Measurement of W and Z Boson Production Cross Sections in pp Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector* [ATLAS-CONF-2015-039]

2) *Measurement of the Production Cross Sections of a Z Boson in Association with Jets in collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector* [ATLAS-CONF-2015-041]

3) *Measurement of the transverse momentum and Φ_η^* distributions of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector* [ArXiv:1512.02192, submitted on 7 Dec 2015]

4) *Measurement of the ZZ Production Cross Section in pp Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector* [ArXiv:1512.05314, submitted on 16 Dec 2015]

5) *Measurements of four-lepton production in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector* [Phys. Lett. B 753, 10 February 2016, p. 552–572]

6) *Measurement of the W^+W^- production cross section in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector* [ATLAS-CONF-2014-033]

7) *Measurement of the WW+WZ cross section and limits on anomalous triple gauge couplings using final states with one lepton, missing transverse momentum, and two jets with the ATLAS detector at $\sqrt{s}$ = 7 TeV* [JHEP 01(2015)049]

8) *Measurement of the electroweak production of dijets in association with a Z-boson and distributions sensitive to vector boson fusion in proton-proton collisions at $\sqrt{s}$ = 8 TeV using the ATLAS detector* [JHEP 04(2014)031]

9) *Evidence for Electroweak Production of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s}$ = 8 TeV with the ATLAS Detector* [Phys. Rev. Lett. 113, 141803 (2014)]

10) *Evidence of $W\gamma\gamma$ production in pp collisions at $\sqrt{s}$ = 8 TeV and limits on anomalous quartic gauge couplings with the ATLAS detector* [Phys. Rev. Lett. 115, 031802 (2015)]

Some Ingredients

Cross Section Estimation

- Use decays to leptons to get a better background suppression
- Selecting high p_T leptons/jets
- Require high missing E_T if ν involved
- Apply selection based on process topology

- Irreducible backgrounds (estimated using simulation)
- Backgrounds including non prompt leptons using data-driven methods ($t\bar{t}$, V+ jets)

$$\sigma_{tot}^{fid} = \frac{N_{data} - N_{backg.}}{A * BR * C * \int L dt}$$

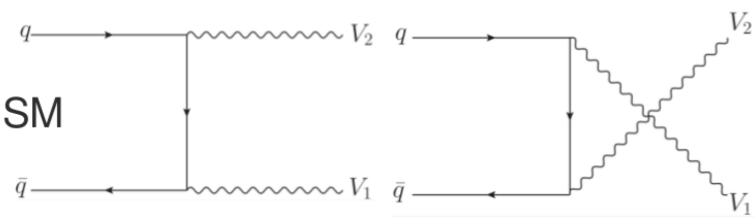
- Extrapolation to full phase space via an acceptance factor (A) (and the branching ratio)
- Correction for detector inefficiencies

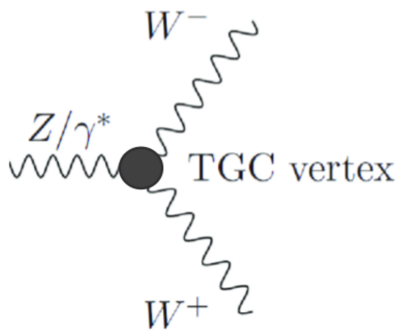
- Estimate systematic uncertainties from:
  - Experimental: energy-resolution/scale, reconstruction, ID, luminosity, …
  - Theoretical: PDFs, parton shower, renorm./fact. scale, …

Anomalous Couplings

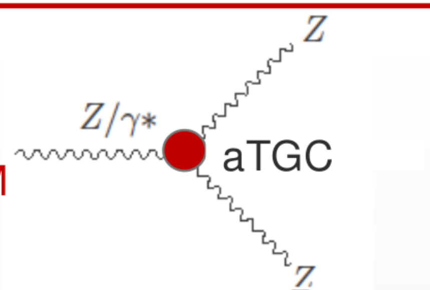
- Non abelian structure of $SU(2)_L \times U(1)_Y$ allows boson self-coupling

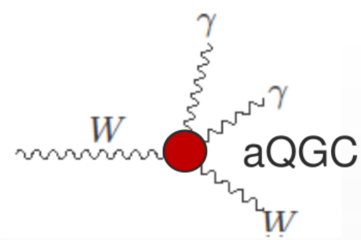
SM





BSM





coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta k_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

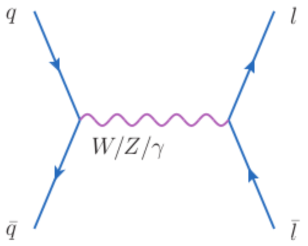
Ref.: http://arxiv.org/abs/1305.3773

- Possible to introduce additional parameter in effective field theories that parametrize SM forbidden couplings

anomalous Triple Gauge Couplings (aTGC.s): dibosons, VBF
anomalous Quartic Gauge Couplings (aQGC.s): tribosons, VBS

Modelling

[The MC Generator Zoo] Large efforts on theory side to provide the most appropriate modelling ... almost each analysis uses a different set of generators.

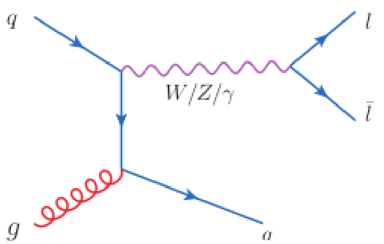


Low P_T (multiple soft-gluon radiation):

resummation up to NNLL (RESBOS, w/ 2 different non-perturbative parameterization to perform the resummation)

parton shower (PS) techniques (PYTHIA, HERWIG)

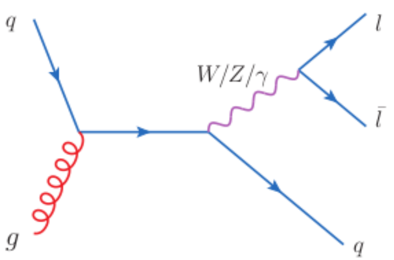
ME+PS with ME $O(\alpha_S)$ (MC@NLO, POWHEG)



High P_T (hard-gluon emission):

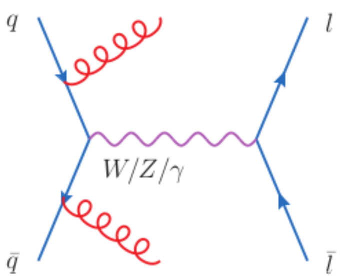
fixed-order calculations up to $O(\alpha^2_S)$ (FEWZ, DYNNLO)

multi-leg tree-level ME+PS (SHERPA, ALPGEN)

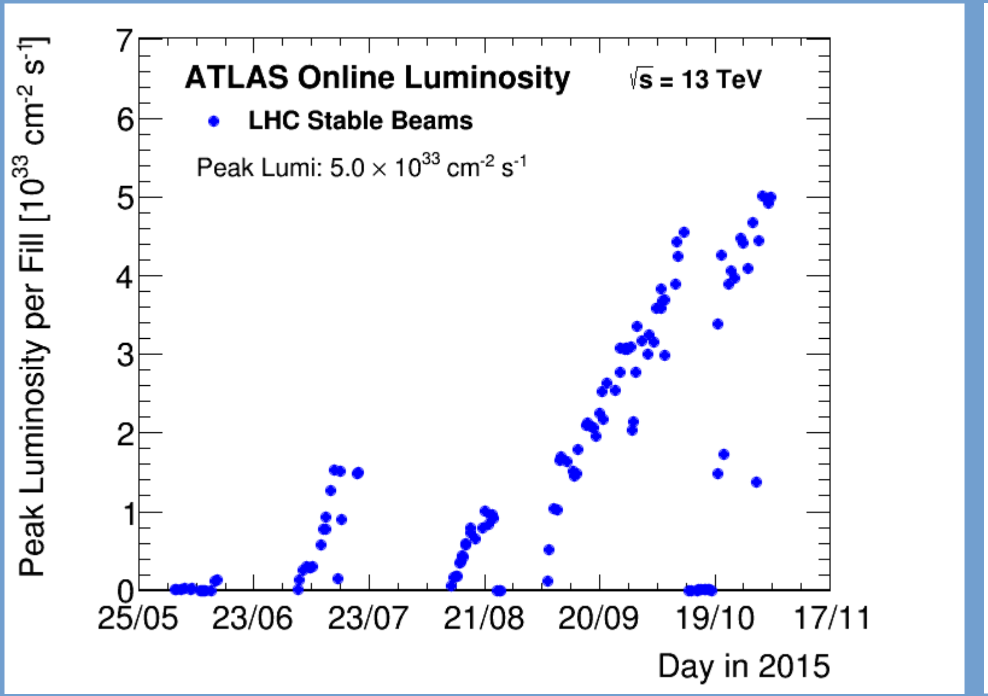


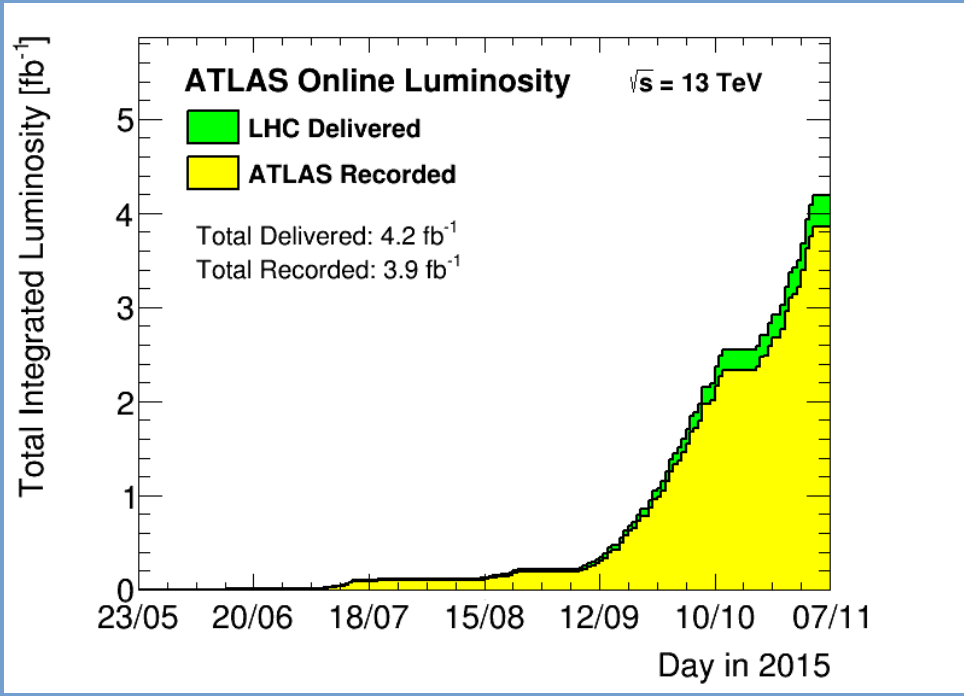
Not-exhaustive List!!

PDF.s : CT10, CTEQ6L1, NNPDF3.0, ...



2015 LHC Performance



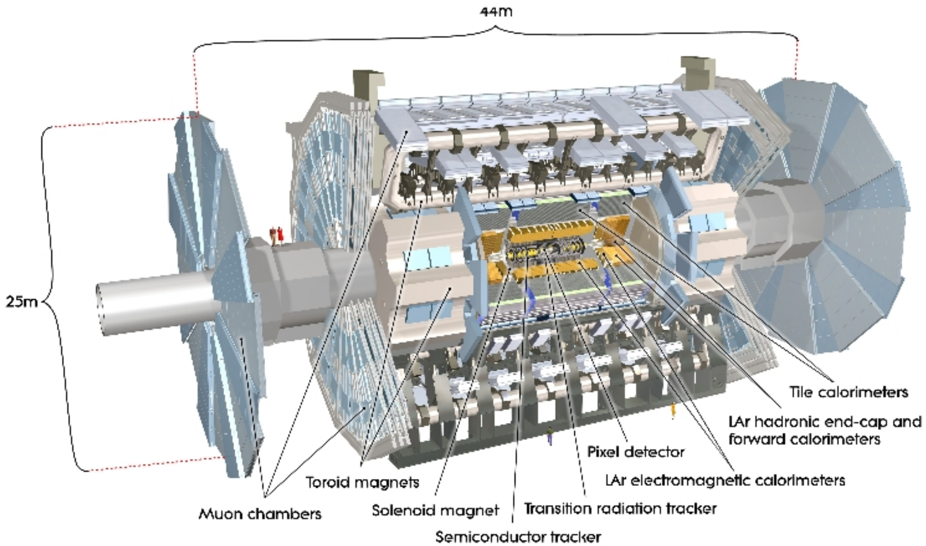


Peak luminosity (before final calibration):

Run1: 7.6×10^{33} cm^{-2} s^{-1}

Run2: 5.2×10^{33} cm^{-2} s^{-1}

2015 ATLAS Performance



Data:

7 TeV	**L = 4.5 fb^{-1}**
8 TeV	**L = 20.3 fb^{-1}**
13 TeV	**L = 3.2 fb^{-1}**

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	99.0%
SCT Silicon Strips	6.3 M	98.9%
TRT Transition Radiation Tracker	350 k	97.3%
LAr EM Calorimeter	170 k	100%
Tile calorimeter	4900	99.2%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	98.7%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	357 k	99.8%
CSC Cathode Strip Chambers	31 k	98.4%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	99.8%

Single Boson Production @ 13 TeV

@13TeV - W/Z production

$W \to e\nu, \mu\nu$ ($m_T > 50$ GeV)

$Z \to e^+e^-, \mu^+\mu^-$ ($66 < m_{ll} < 116$ GeV)

$P_T(l,\nu) > 25$ GeV

Signal modelling: Powheg + Pythia 8 (normalised to NNLO predictions)

→ Cross-section ratios provide (partial) uncertainty cancellation

→ Ratio $R_{W/Z}$ may constraint strange-quark distribution

→ Ratio $R_{W+/W-}$ sensitive to u-d valence quark distribution

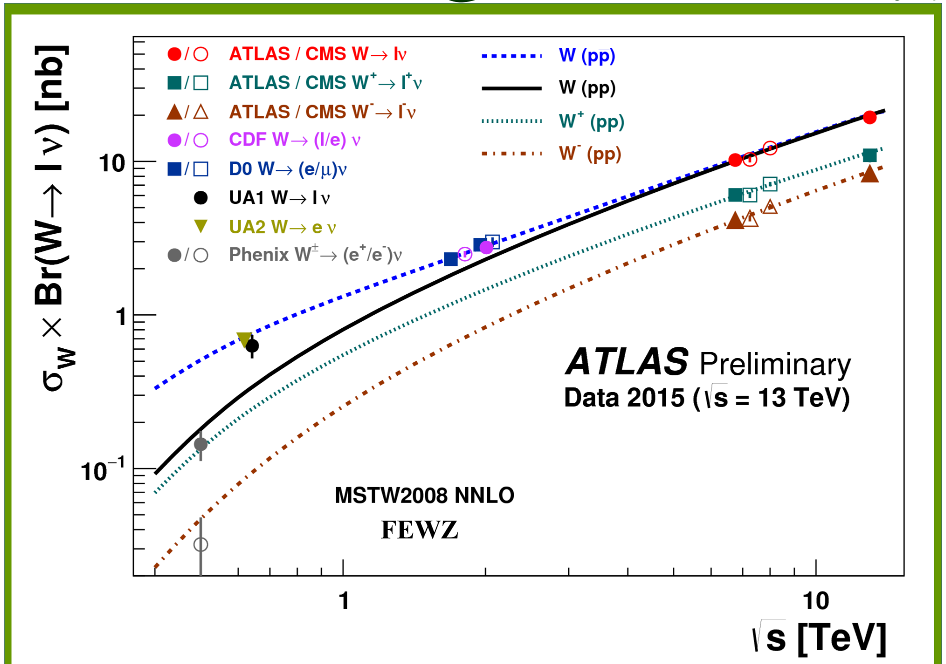
$\sigma_{tot}(W^+)$ = [10960 ± 20(stat) ± 440(stat) ± 990(lumi)] pb

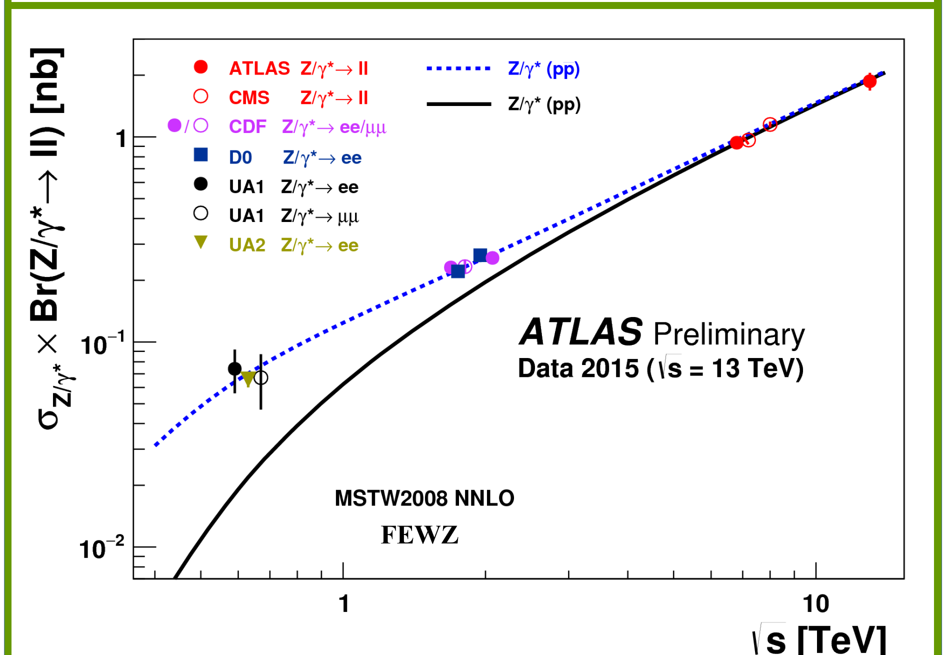
$\sigma_{tot}(W^-)$ = [8380 ± 20(stat) ± 350(stat) ± 750(lumi)] pb

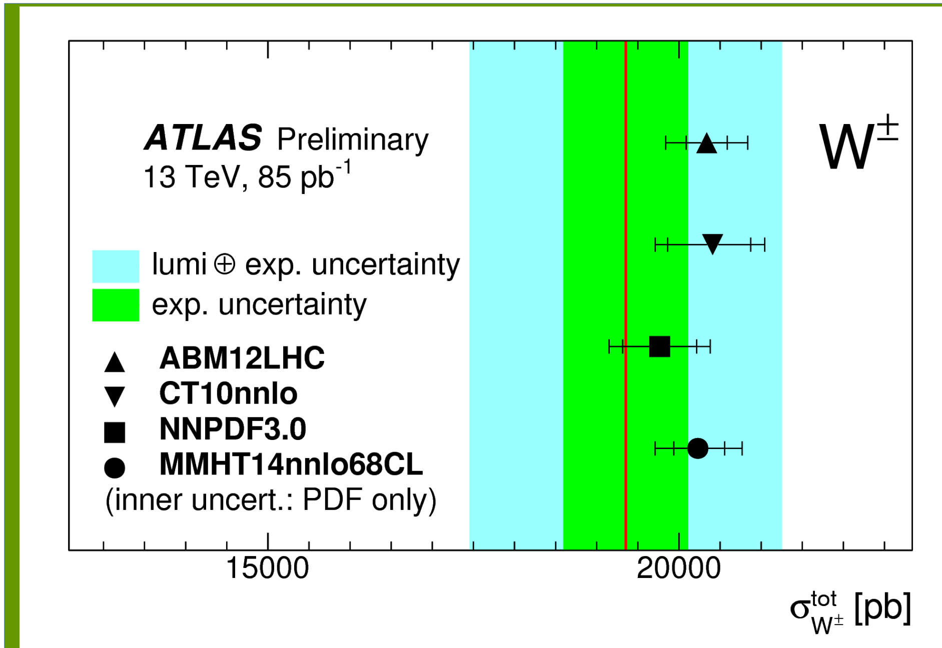
$\sigma_{tot}(Z)$ = [1869 ± 7(stat) ± 42(stat) ± 168(lumi)] pb

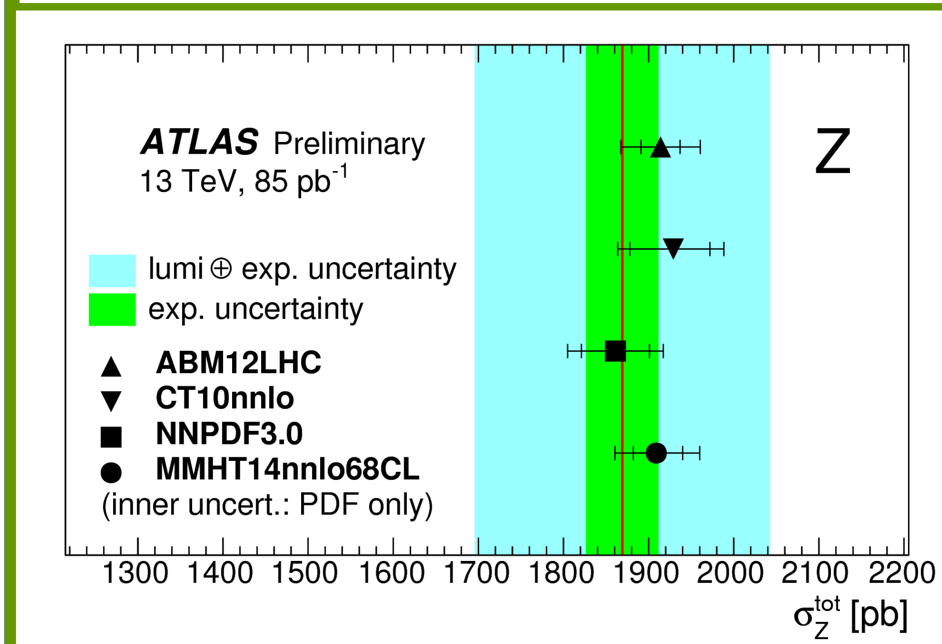
ATLAS-CONF-2015-039

@13TeV - W/Z cross sections



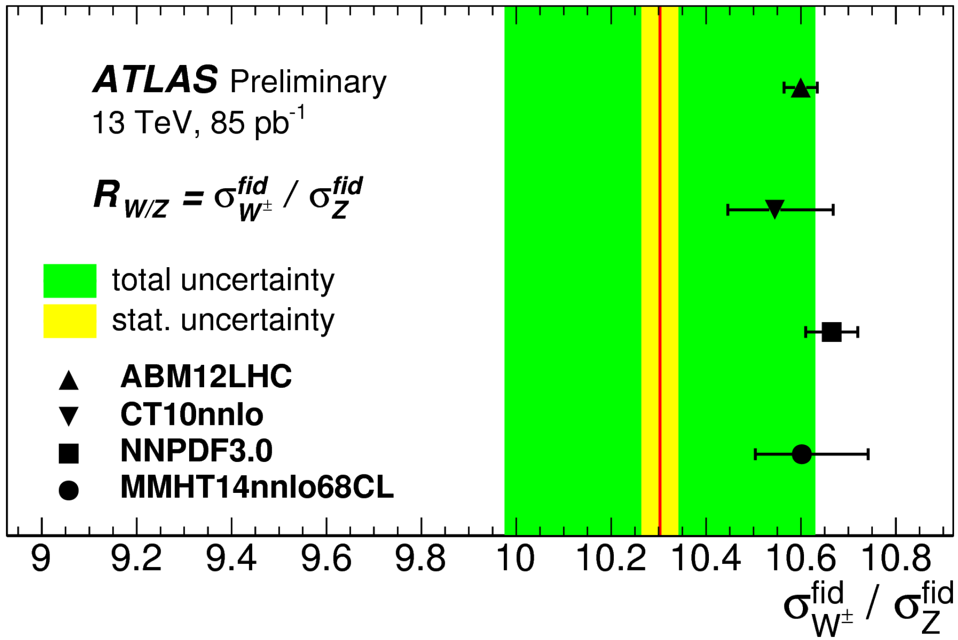


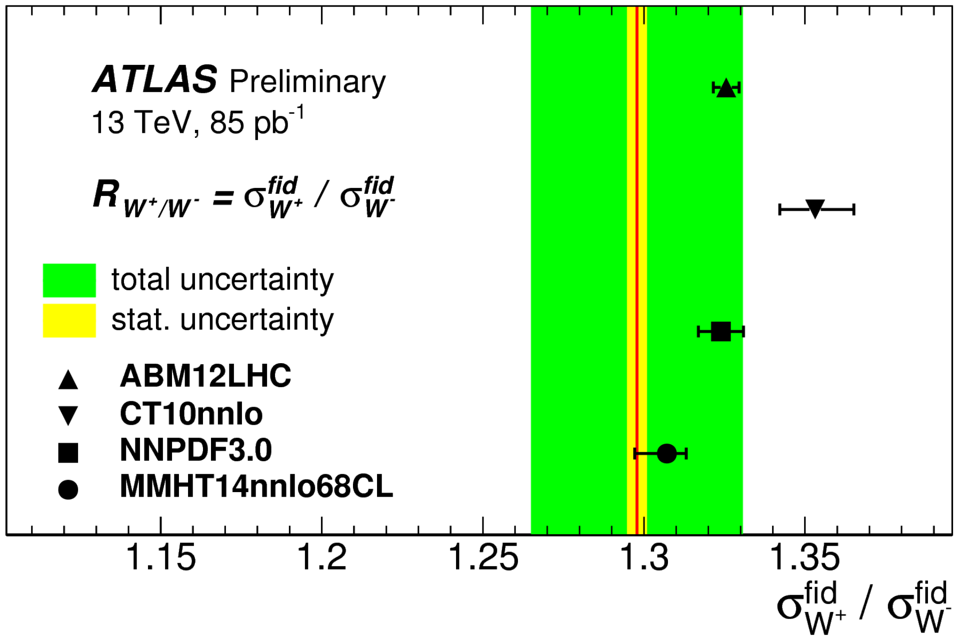




ATLAS-CONF-2015-039

@13TeV - W/Z cross section ratios





→ General agreement with different PDF-set predictions

→ $R_{W+/W-}$ as PDF probe (mostly sensitive u-d valence quark PDF.s)

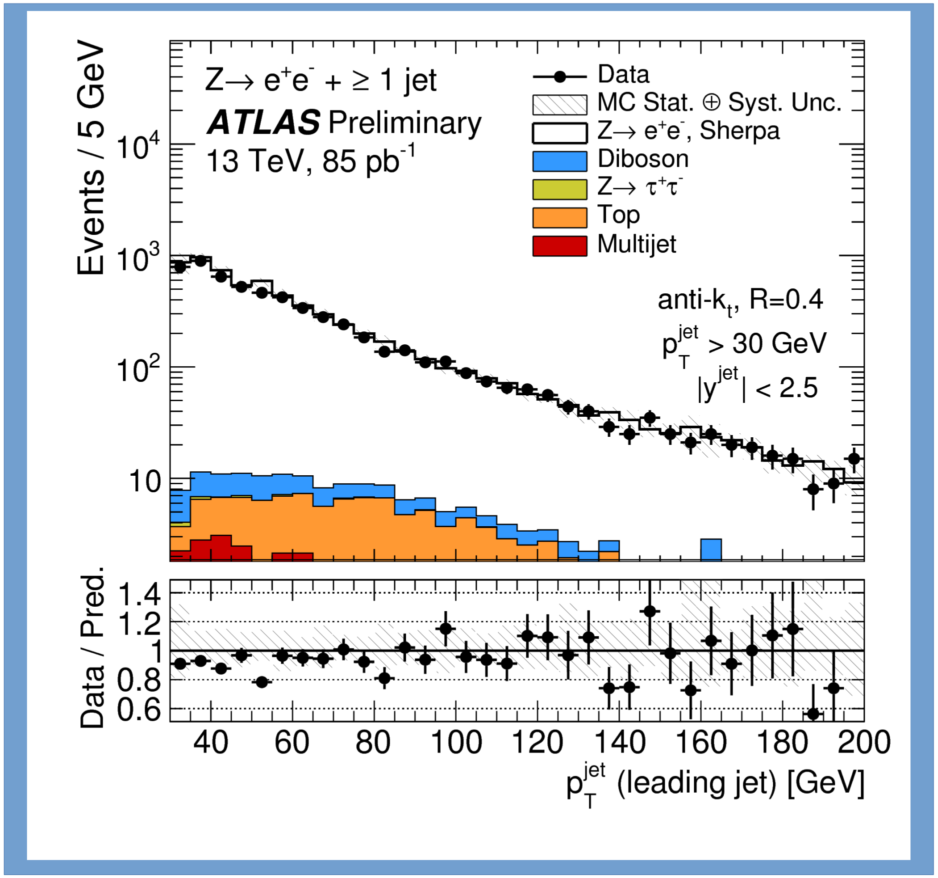
precision now at ~3% level → discrimination power threshold ~2%

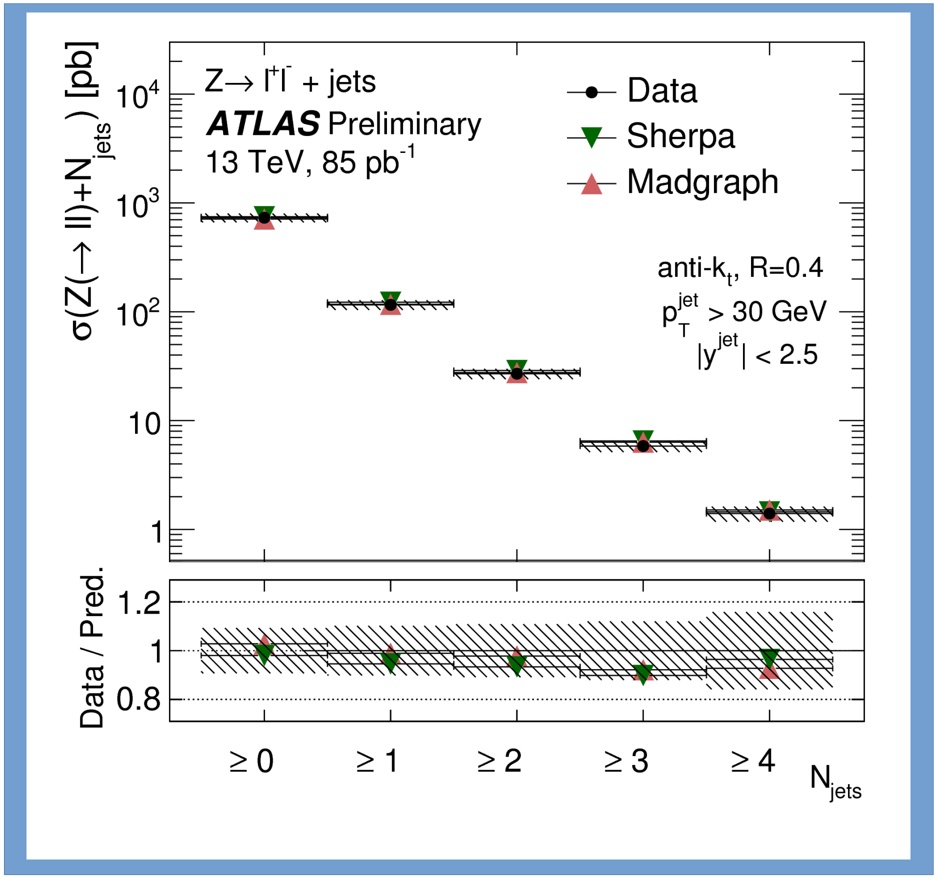
ATLAS-CONF-2015-039

@13TeV - Z+jets

$Z \rightarrow e^+e^-, \mu^+\mu^-$

Jets defined by anti-k_T, R=0.4: P_T > 30 GeV, |y| < 2.5





Important test of perturbative QCD
Ok for both Sherpa and MadGraph predictions

ATLAS-CONF-2015-041

Drell-Yan Production @ 8 TeV

P_T .vs. Φ_η* for DY Pairs

$P_{T,Z}$

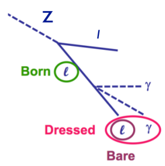
- Low $P_{T,Z}$ range is governed by
  - initial state parton radiation
  - intrinsic transverse momentum of the initial state parton inside the proton

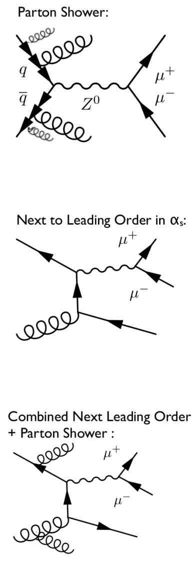
  is modelled by
  - resummation of soft-gluon emission
  - parton shower model

- High $P_{T,Z}$ range is governed by
  - quark-gluon scattering

  is modelled by
  - perturbative QCD

- Monte Carlo predicts three levels: Born, Dress, Bare



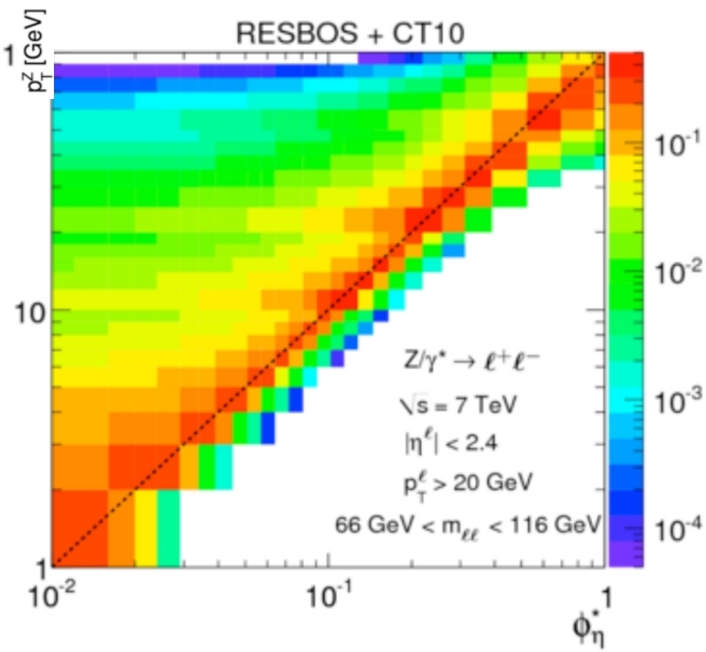


$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta_\eta^*)$$

$$\cos\theta_\eta^* = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

At born level: $\sqrt{2} M_Z \phi_\eta^* \approx P_{T,Z}$

Correlation matrix ($P_{T,Z}$, Φ)



$P_{T,Z}$ reconstruction is affected by energy and momentum measurement uncertainty

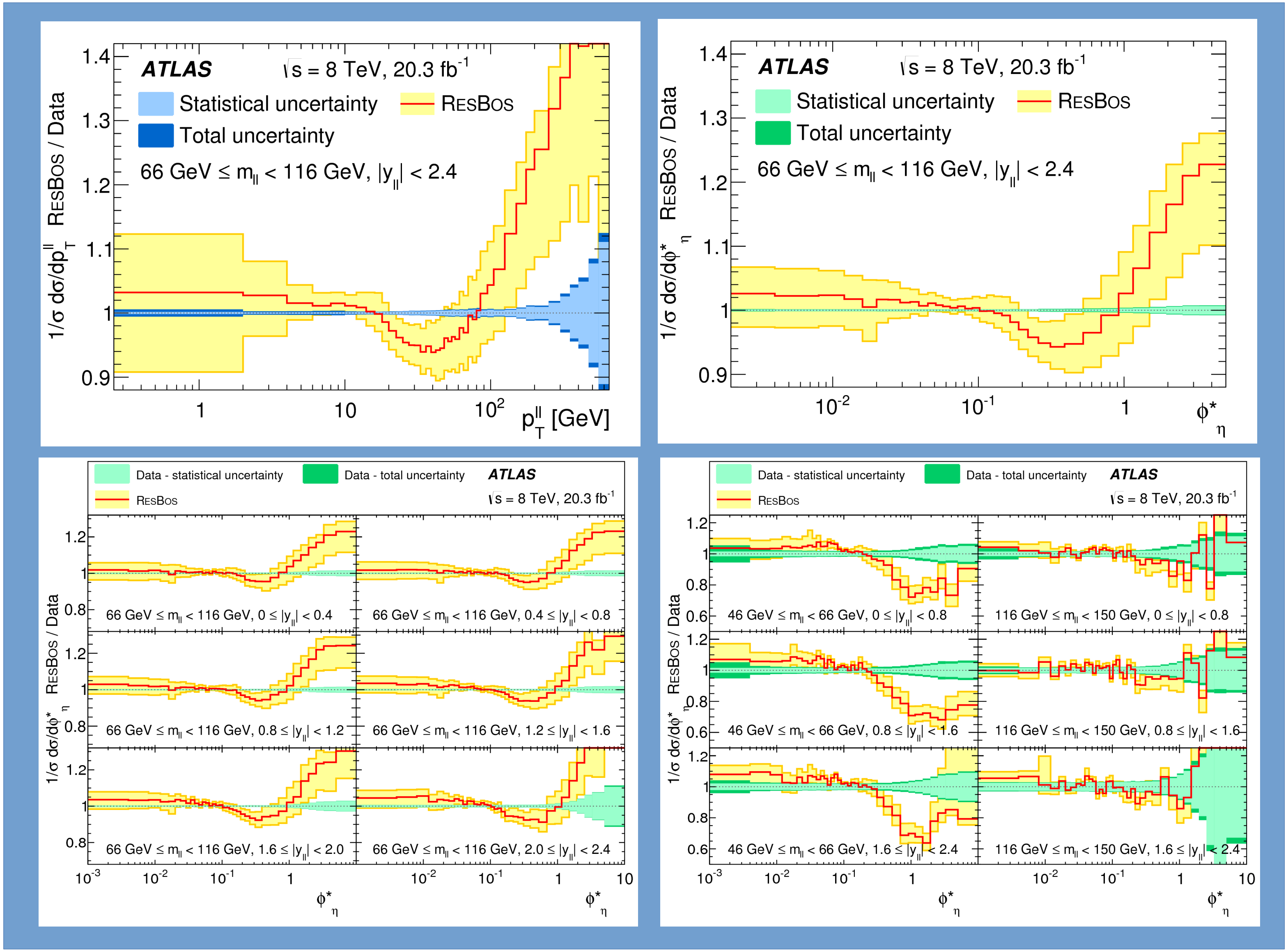
to minimize systematics → Φ* as alternative probe of $P_{T,Z}$

Φ* provides a measure of the angular correlation between the leptons

@8TeV - P_T & Φ_η^* Distributions for DY Pairs

ResBos

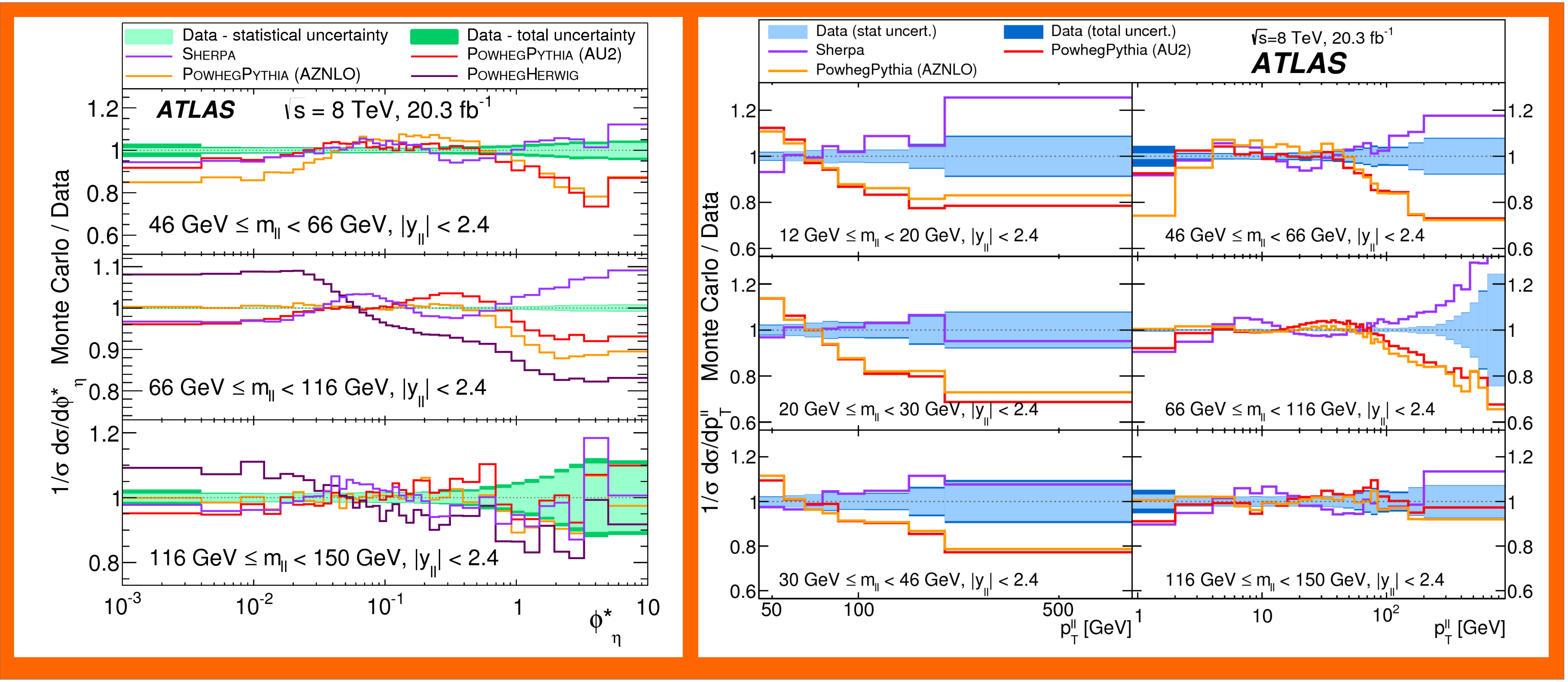
ArXiv:1512.02192



predictions ok for ~low values of Φ_η^*

@8TeV - P_T & Φ_η* Distributions for DY Pairs

Parton Shower MC



for $5<P_T(ll)<100$, $m(ll)>46$ GeV agreement <~10%

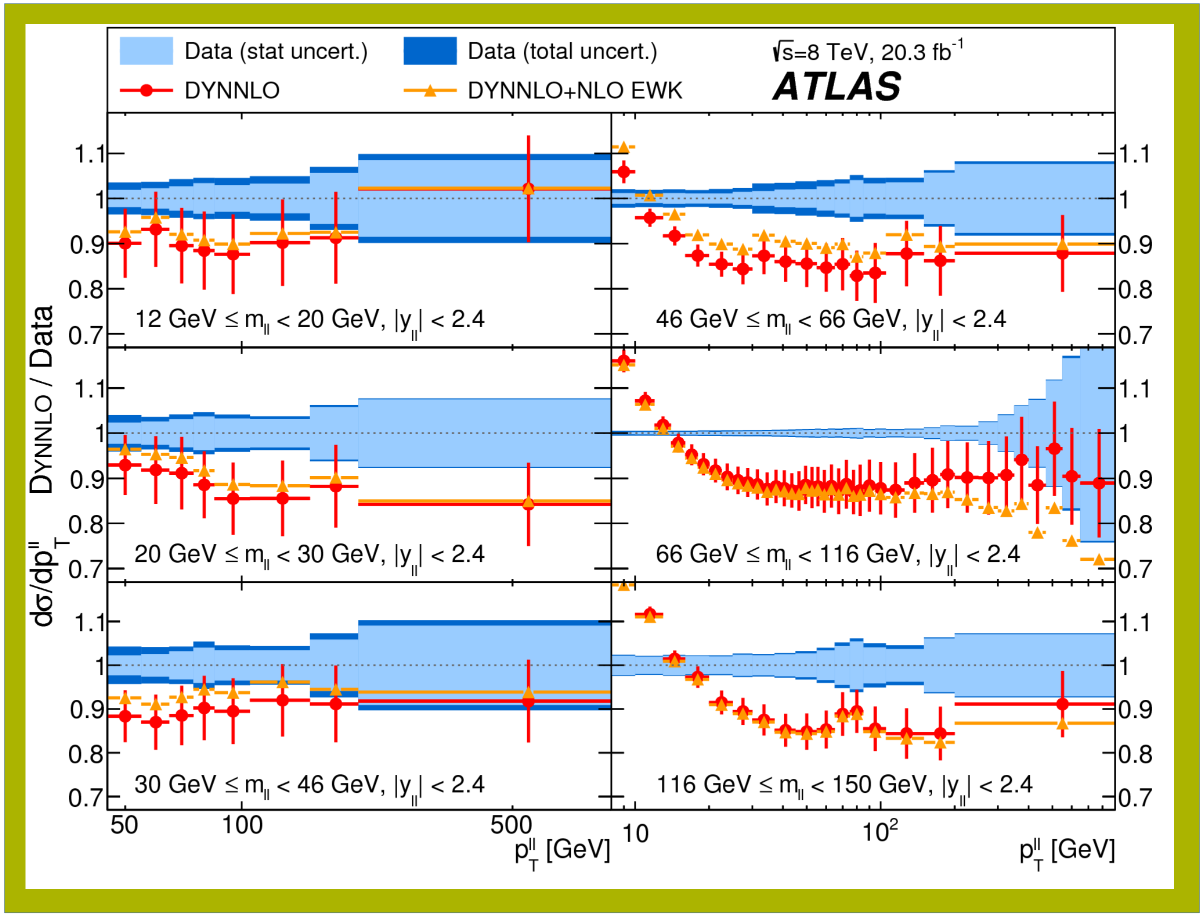
ArXiv:1512.02192

@8TeV – P_T & Φ_η* Distributions for DY Pairs

Fixed-order MC

absolute predictions ~15%

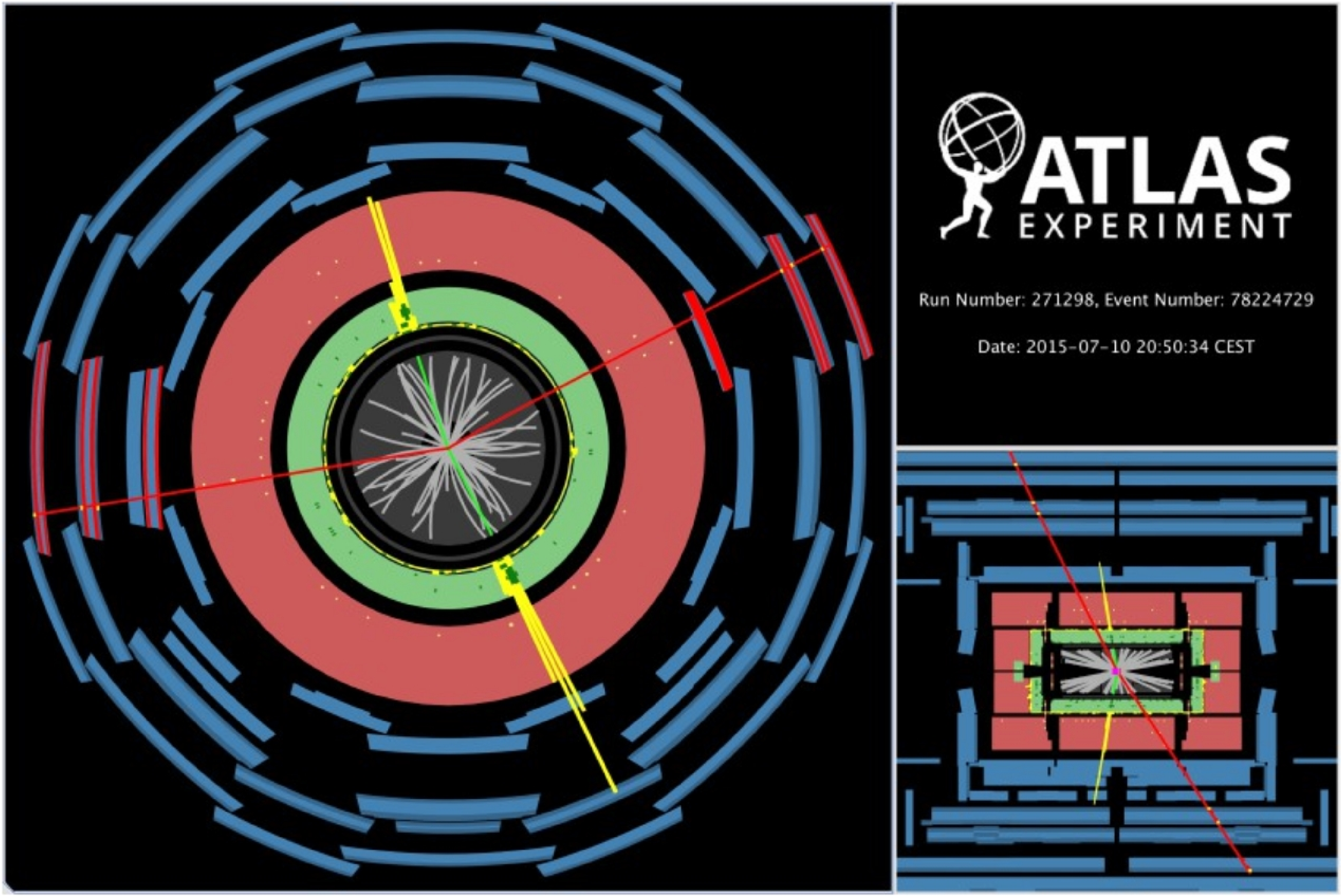
ArXiv:1512.02192



note: not yet sensitive to NLO EW corrections

Diboson Production @ 13 & 8 TeV

@13TeV - ZZ



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions

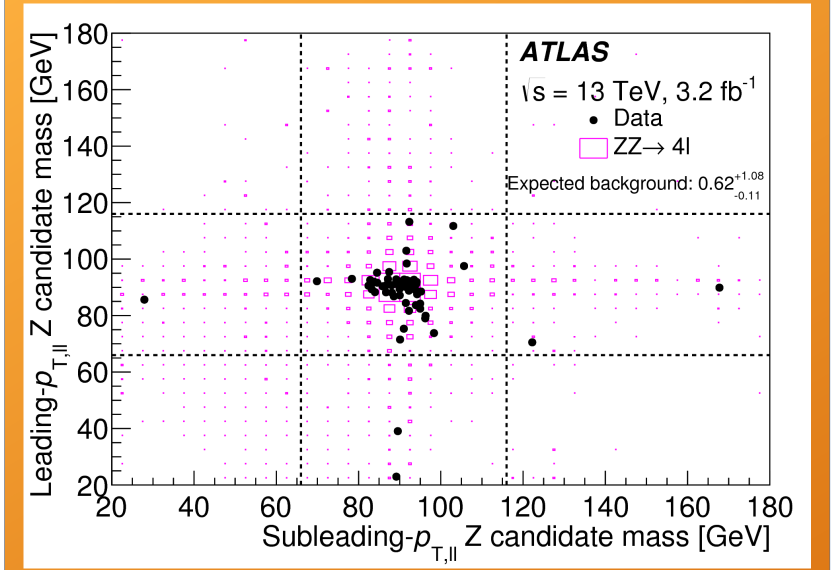
@13TeV - ZZ Cross Section

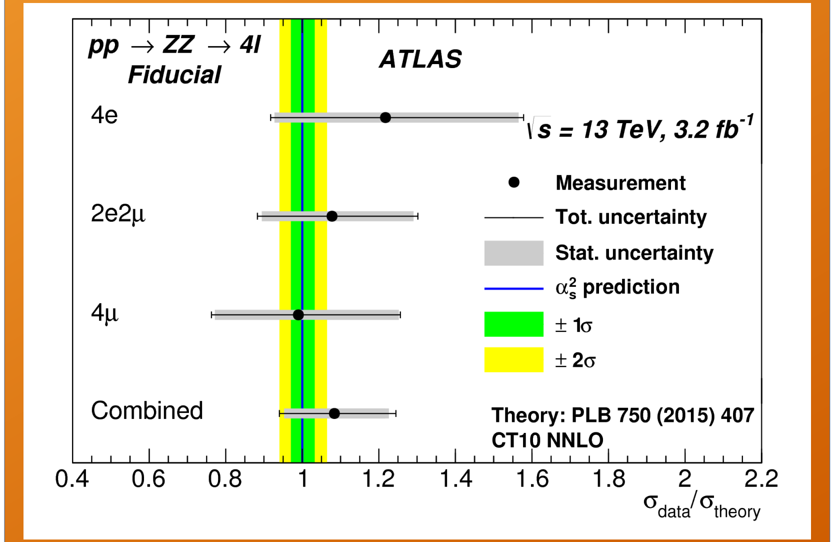
4l channel: 2 OS-SF [e,μ] pairs

P_T > 20GeV, 66 < m_{ll} < 116 GeV

63 events in 3 channels, total exp. bkg.: $0.62^{+1.08}_{-0.11}$

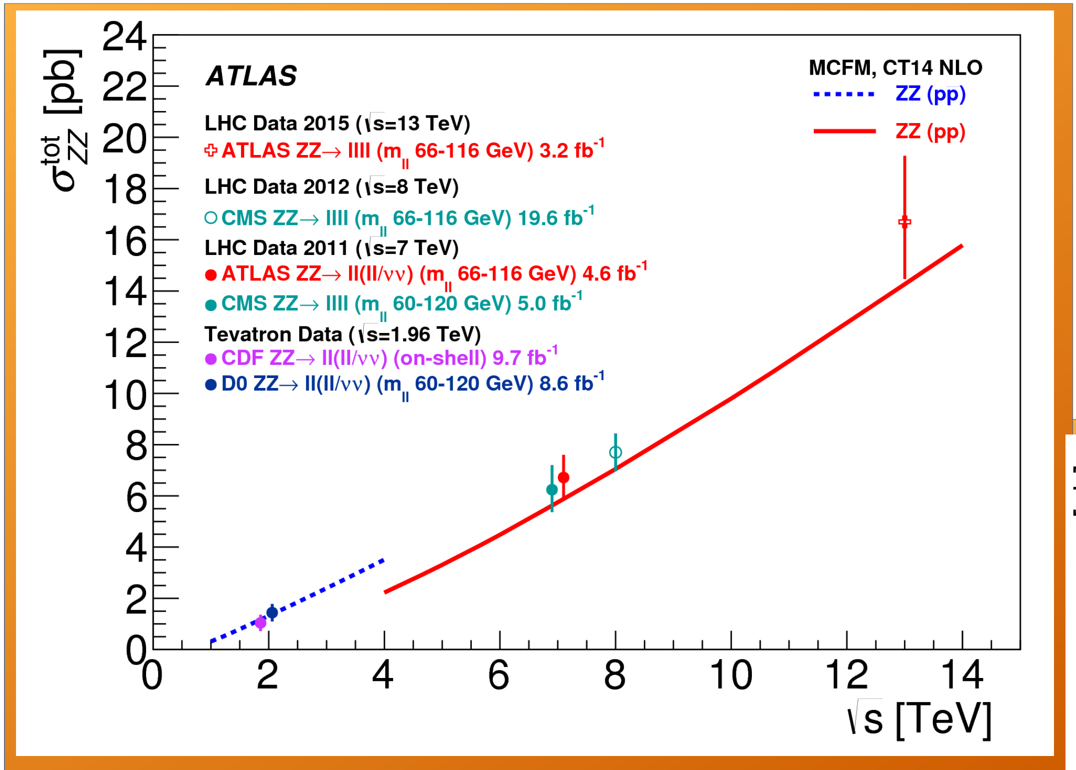
	Measurement	$O(\alpha_S^2)$ prediction
$\sigma^{fid}_{ZZ\to e^+e^-e^+e^-}$	8.4 $^{+2.4}_{-2.0}$(stat.) $^{+0.4}_{-0.2}$(syst.) $^{+0.5}_{-0.3}$(lumi.) fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{fid}_{ZZ\to e^+e^-\mu^+\mu^-}$	14.7 $^{+2.9}_{-2.5}$(stat.) $^{+0.6}_{-0.4}$(syst.) $^{+0.9}_{-0.6}$(lumi.) fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{fid}_{ZZ\to\mu^+\mu^-\mu^+\mu^-}$	6.8 $^{+1.8}_{-1.5}$(stat.) $^{+0.3}_{-0.3}$(syst.) $^{+0.4}_{-0.3}$(lumi.) fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{fid}_{ZZ\to\ell^+\ell^-\ell'^+\ell'^-}$	29.7 $^{+3.9}_{-3.6}$(stat.) $^{+1.0}_{-0.8}$(syst.) $^{+1.7}_{-1.3}$(lumi.) fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	16.7 $^{+2.2}_{-2.0}$(stat.) $^{+0.9}_{-0.7}$(syst.) $^{+1.0}_{-0.7}$(lumi.) pb	$15.6^{+0.4}_{-0.4}$ pb



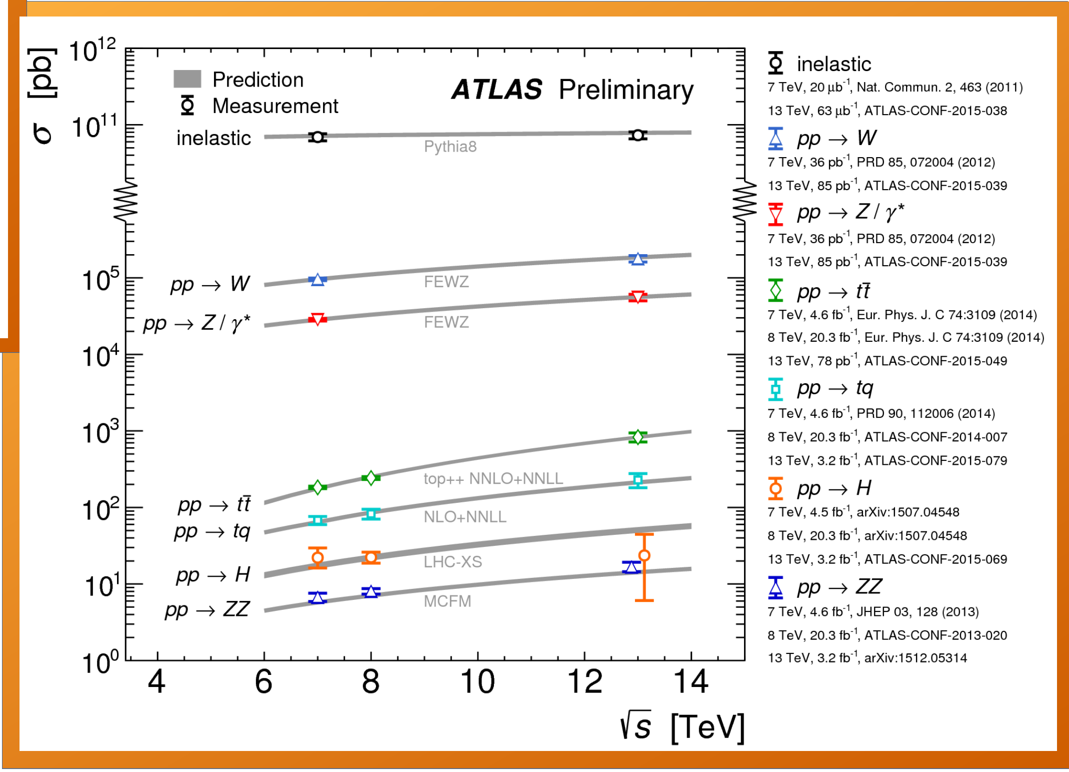


ArXiv:1512.05314

Cross-Section √s Dependence



Summary



ZZ: predictions still miss a full $O(\alpha_s^2)$ simulation

ArXiv:1512.05314

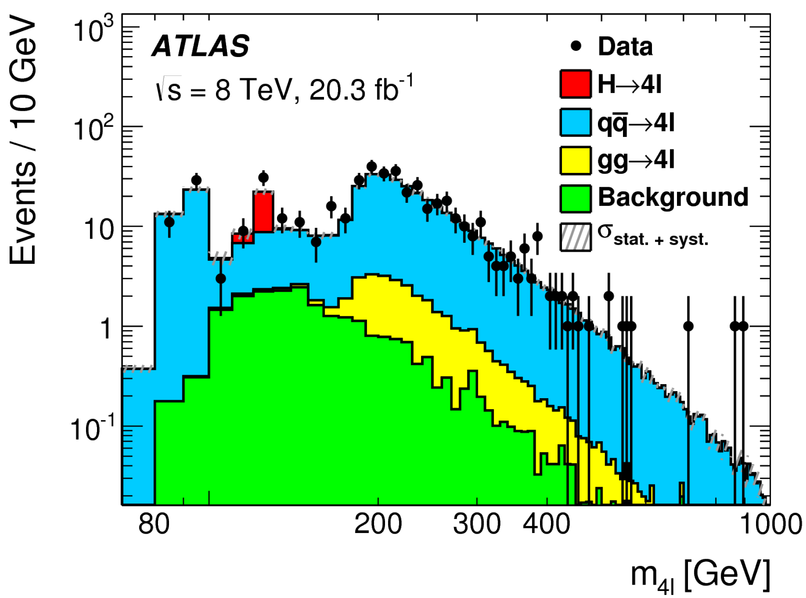
@8TeV – 4l Cross Section

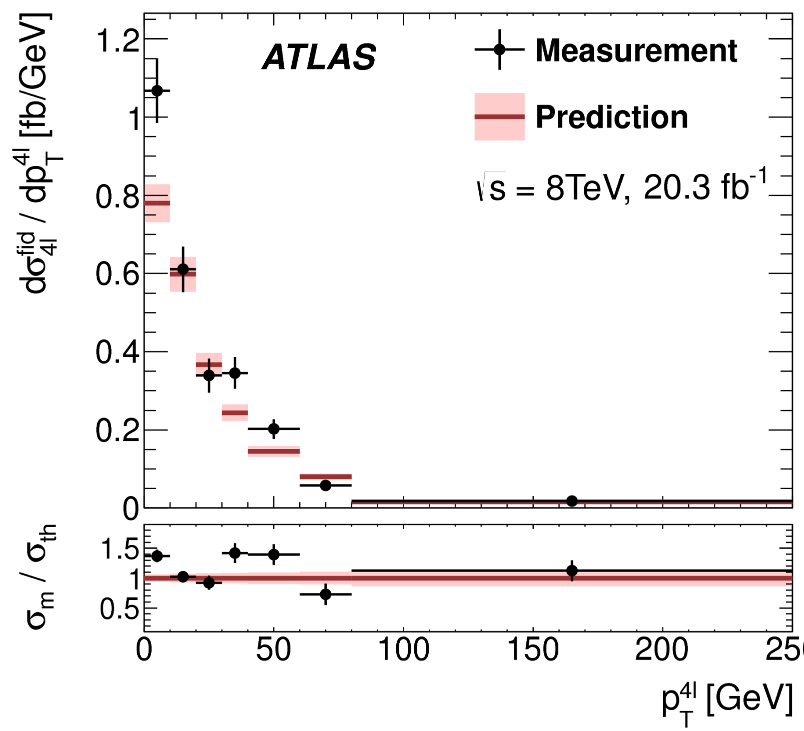
- probe SM predictions over a large mass range: 80-1000 GeV
- very small bkg (~5%)

2 OS, SF pairs of high-PT isolated leptons

$50<m_{12}<120$ GeV, $12<m_{34}<120$ GeV

476 ev. [bkg 26.2 ± 3.6]





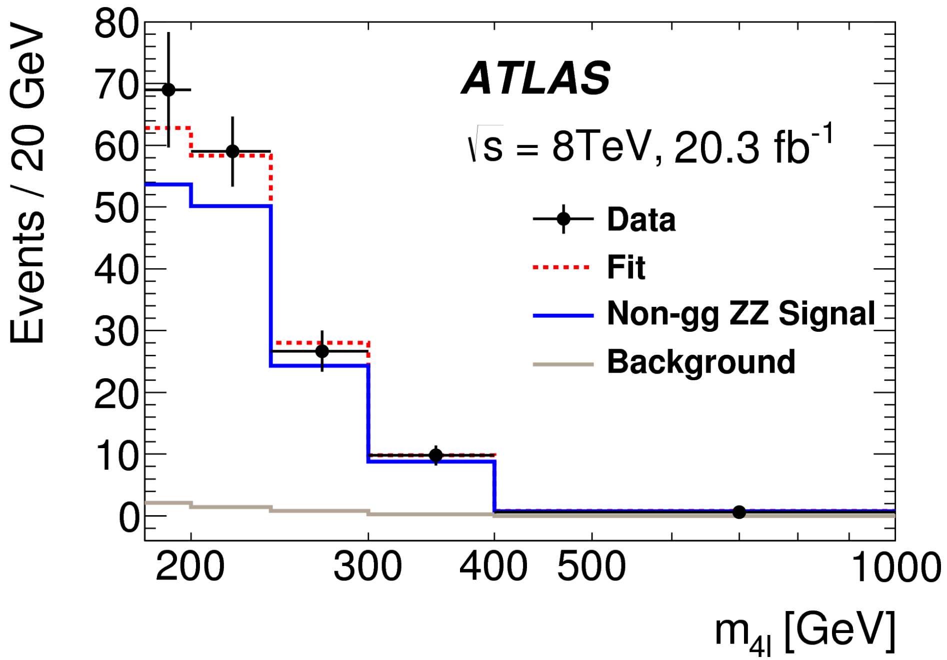
Phys. Lett. B 753 (2016) 552-572

overall good agreement w/ predictions NNLO QCD, NLO EW for qq/H→4l but only LO QCD gg→4l

@8TeV – 4l Cross Section

→ try to estimate NLO $gg \to 4l$ contribution from data

estimation of signal strength $\mu_{gg} = \sigma(\text{data})/\sigma(gg \to 4l;\ \text{LO})$ for $m_{4l} > 180$ GeV

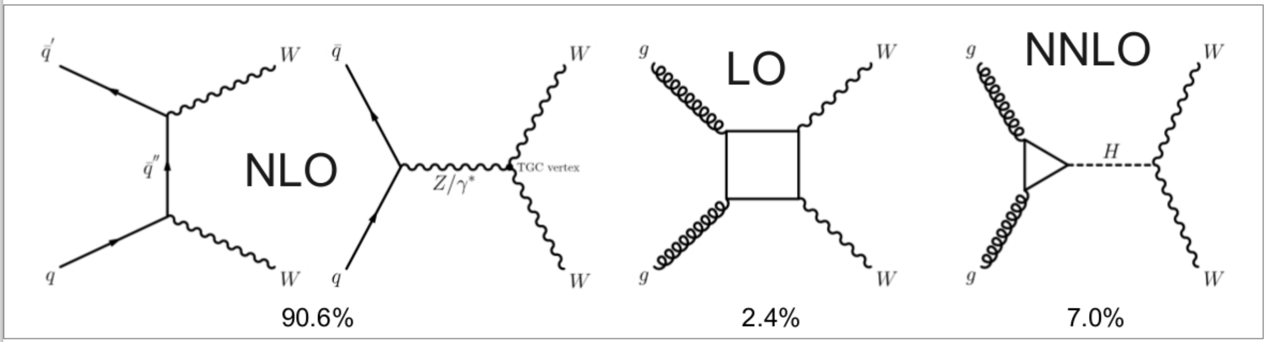


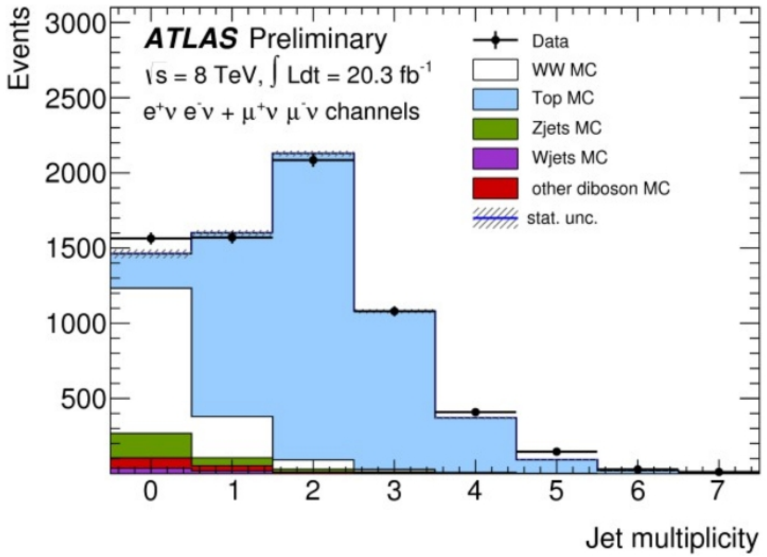
$$\mu_{gg} = 2.4 \pm 1.0(stat.) \pm 0.5(syst.) \pm 0.8(theory)$$

Phys. Lett. B 753 (2016) 552-572

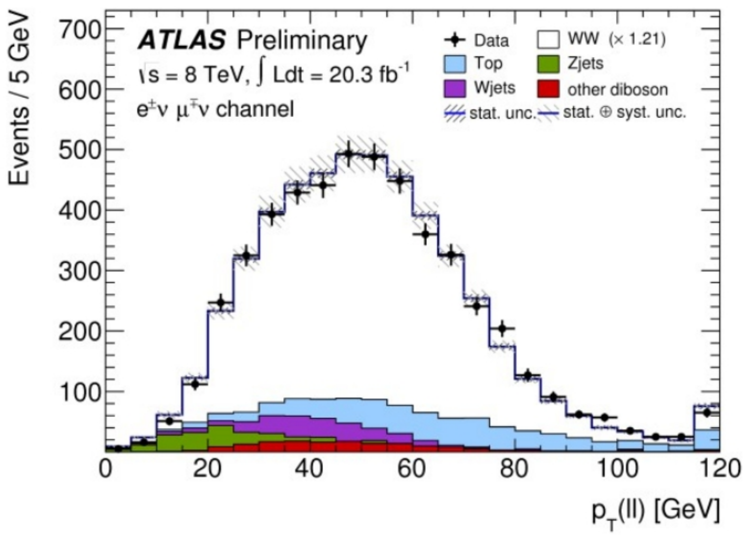
@8TeV - WW→lνlν Cross Section

ATLAS-CONF-2014-033





- total and fiducial cross section measurements
- test of SM non-abelian structure
- sensitive to anomalous triple gauge couplings (aTGC)
- irreducible bkg to Higgs searches



Backgrounds:

- top, drell-yan. W+jets (data driven)
  other dibosons (MC based)
- hard criteria on E_T^{miss} and jet-veto against tt

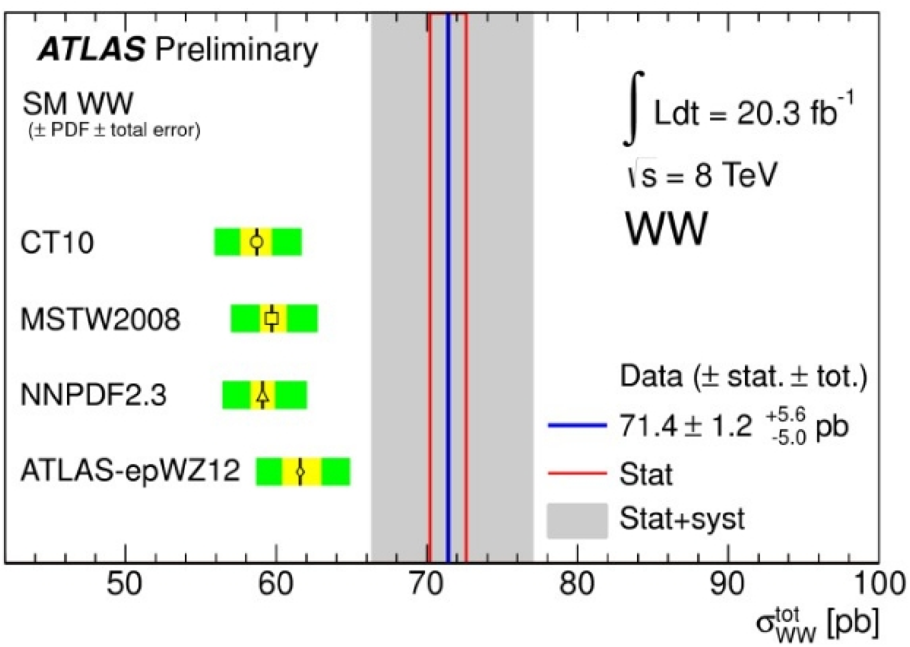
ATLAS-CONF-2014-033

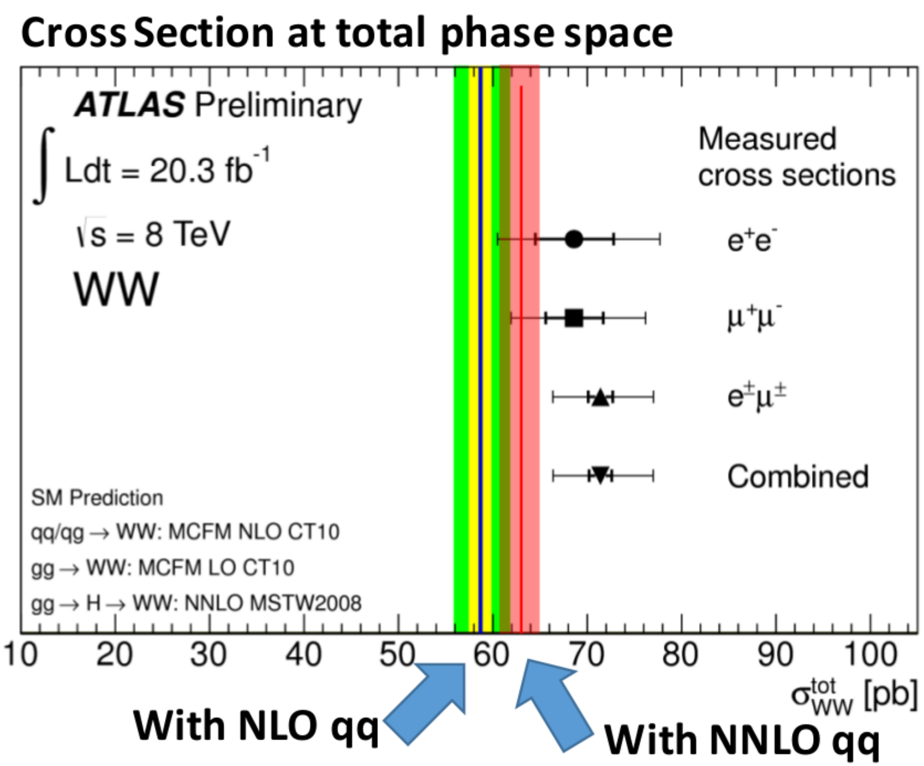
@8TeV - WW Cross Section

- individual channels compatible
- ~2σ discrepancy wrt partial-NNLO predictions

$$\sigma_{WW}^{tot} = 71.4^{+1.2}_{-1.2}(\text{stat})\ ^{+5.0}_{-4.4}(\text{syst})\ ^{+2.2}_{-2.1}\ (\text{lumi})\ \text{pb} \qquad \sigma_{WW}^{predicted} = 58.7^{+3.0}_{-2.7}\ \text{pb}$$

- compatible at ~1σ w/ full-NNLO predictions





ATLAS-CONF-2014-033

@7TeV - WZ/WW→lνjj

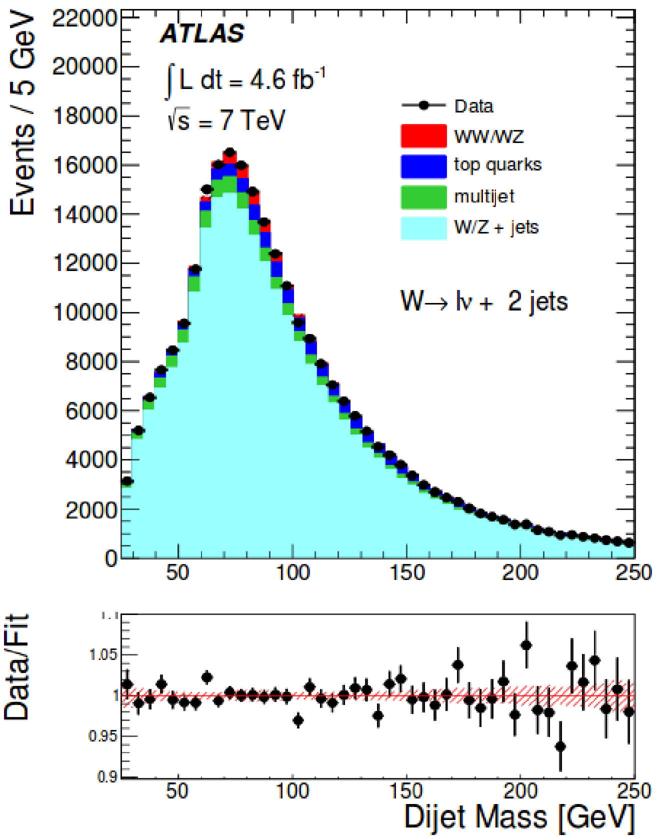
a) one high P_T, isolated lepton

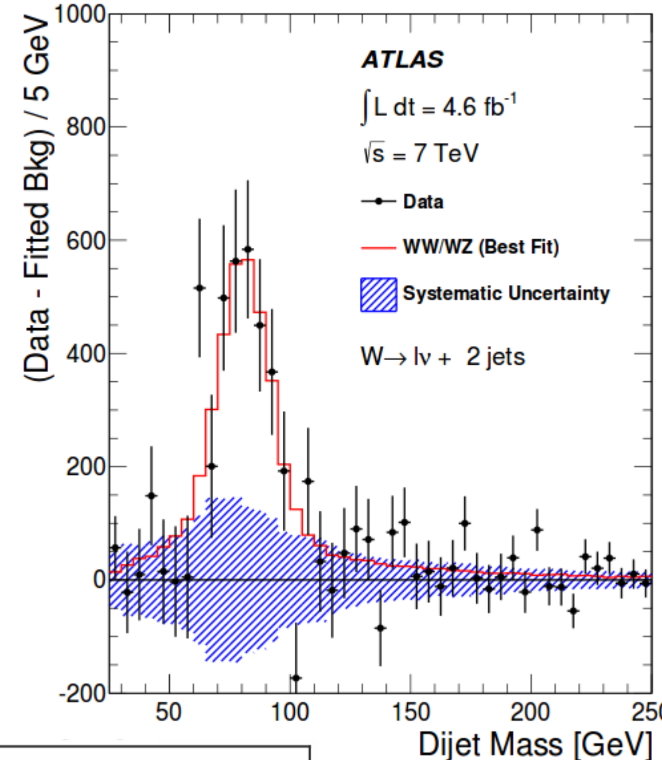
b) E_T^{miss} >30 GeV, M_T>40 GeV

Backgrounds:

- W/Z+jets: ~89% (data driven)
- multi-jets: ~5% (data driven)
- top: ~4% (MC)

Total bkg modeled w/ combined LH fit





Measured (tot. comb.) [pb]	**68 ±7(stat.)±19(sys.)**
Theory pred. [pb]	**61.1±2.2**

JHEP 01(2015)049

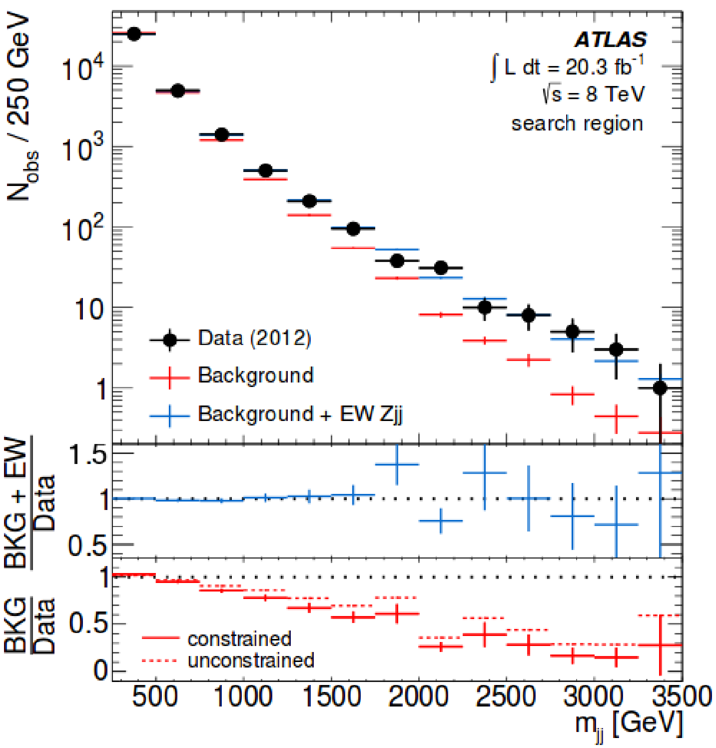
agreement w/ SM → limits on aTGC couplings

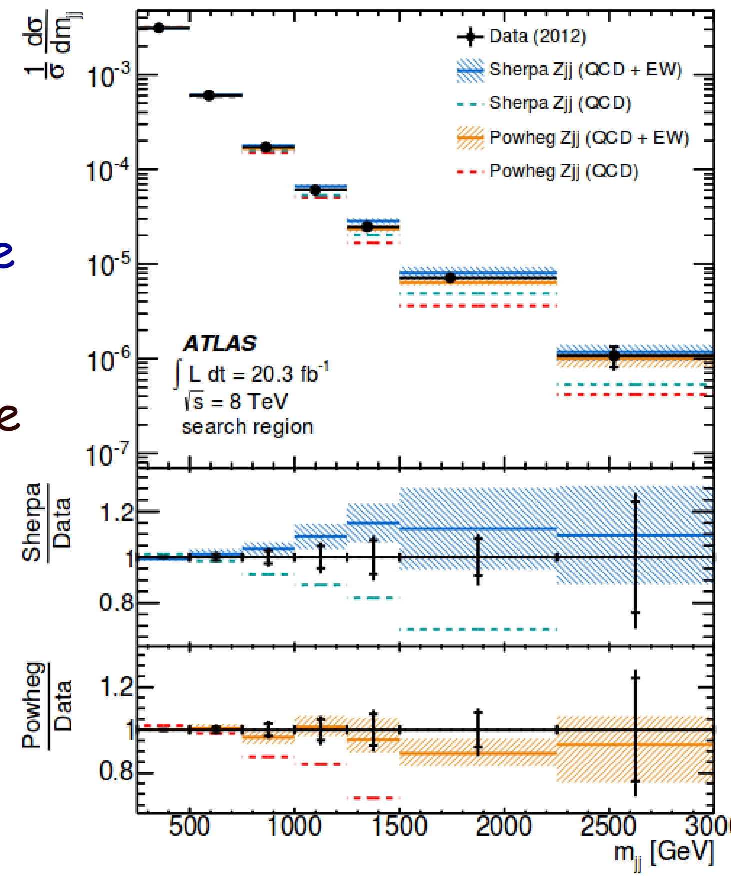
Vector Boson Fusion/Scattering @ 8 TeV

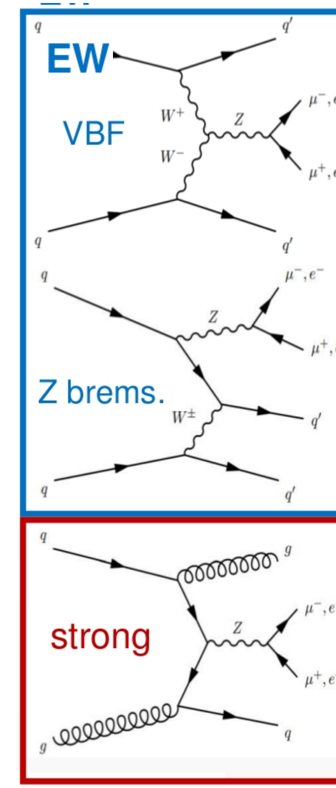
@8TeV - Zjj VBF

a) differential cross section
→ constrain theor. models
b) EW cross section → limits on aTGC

2 high-P_T, isolated leptons in Z mass range
2 jets w/ P_T > 25 GeV
+ tighter cuts for EW Zjj estimate







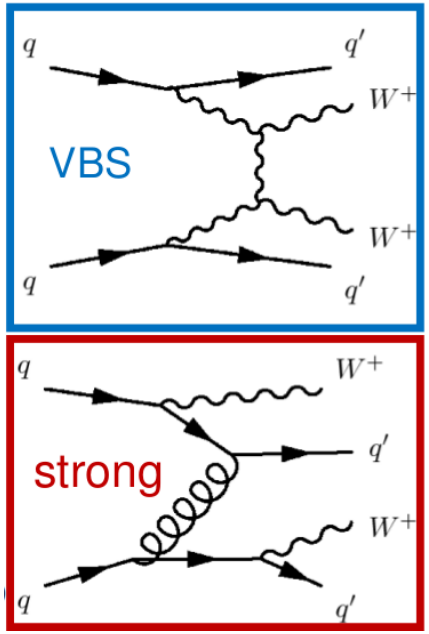
Both MC generators don't fully describe the data → constraints for modelling

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

$$\sigma_{EW,Powheg} = 46.1 \pm 0.2\,(\text{stat}) \pm 0.8\,(\text{PDF}) \pm 0.5\,(\text{model})\,\text{fb}$$

JHEP 04(2014)031

@8TeV – ssWWjj VBS



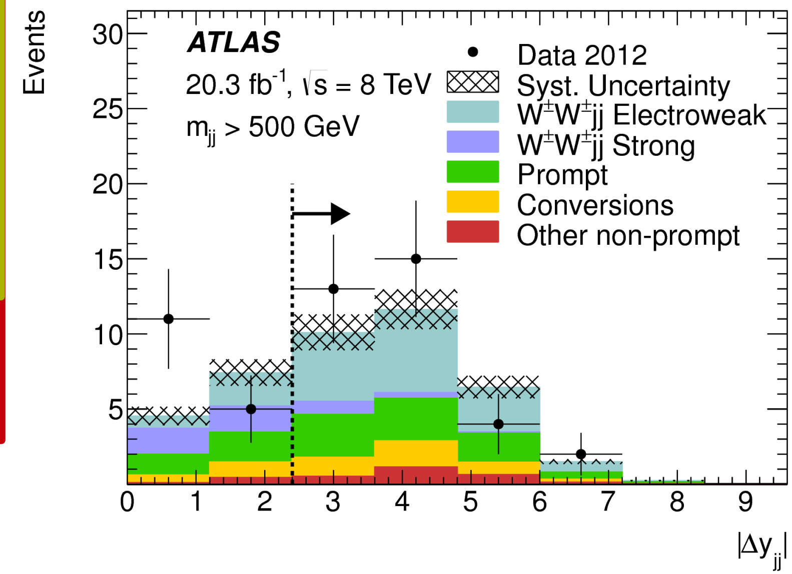
Probe EW symmetry breaking

2 isolated SS leptons, P_T>25 GeV

≥2 jets P_T> 30 GeV, |η|<4.5

E_t^{miss}> 40 GeV *Inclusive*

$|\Delta y_{jj}|$>2.4 *VBS*

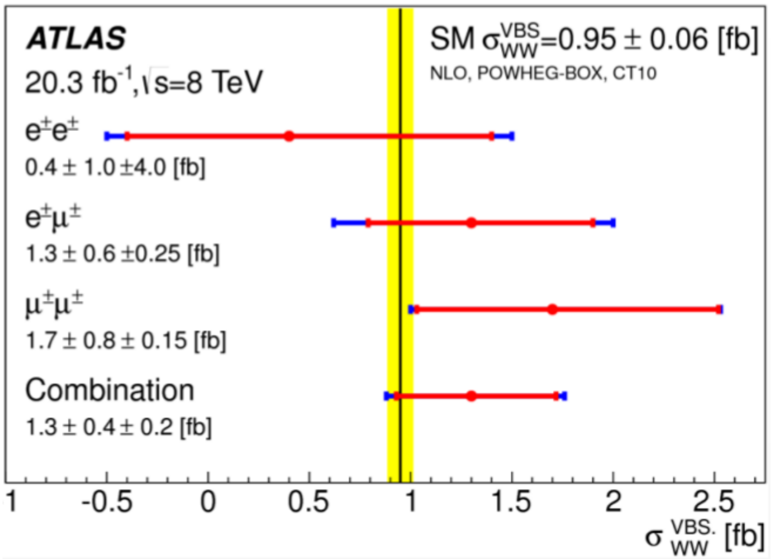


Main bkg from tt (charge flip), WZ

Main sys. uncertainty from bkg determination

Combined signal over bkg only hypothesis

- inclusive (EW+ strong): 4.5σ (exp. 3.4σ)
- VBS (EW only): 3.6σ (exp. 2.8σ)



Phys.Rev.Lett. 113, 141803 (2014)

Triboson Production
@ 8 TeV

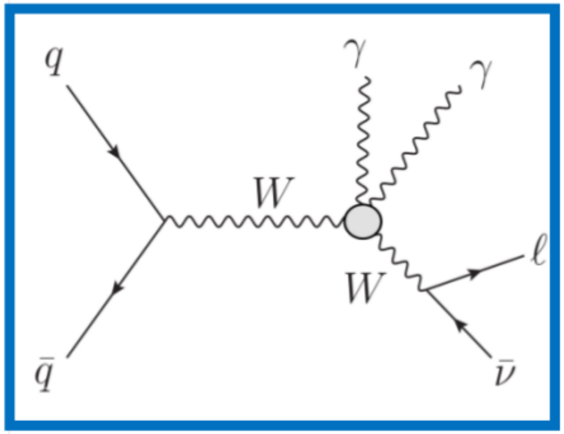
@8TeV – Wγγ

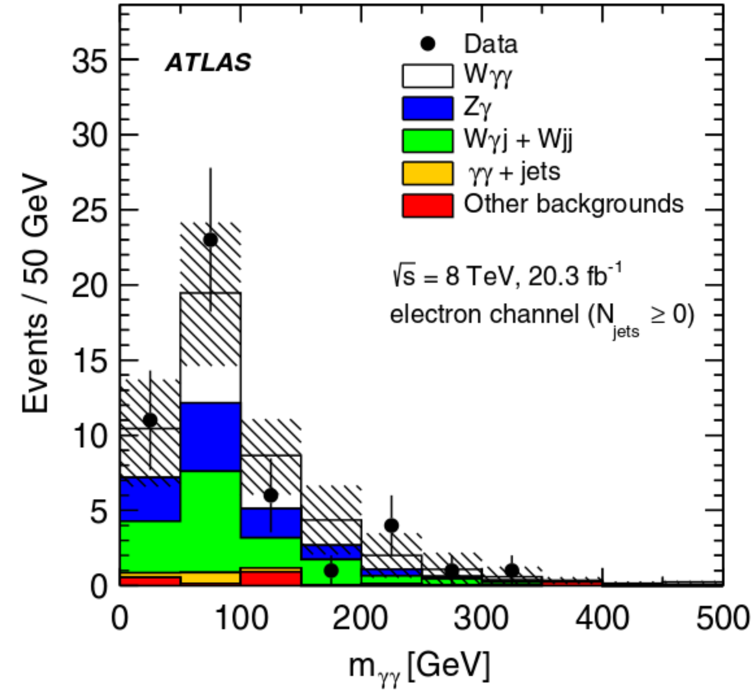
- 1 isolated lepton $p_T > 20$ GeV; $|\eta| < 2.47$ (2.4) (muons)
- $p_T^\gamma > 20$ GeV; $|\eta_\gamma| < 2.37$
- $E_T^{miss} > 25$ GeV; $m_T > 40$ GeV

Inclusive

- $N_{jets} = 0$

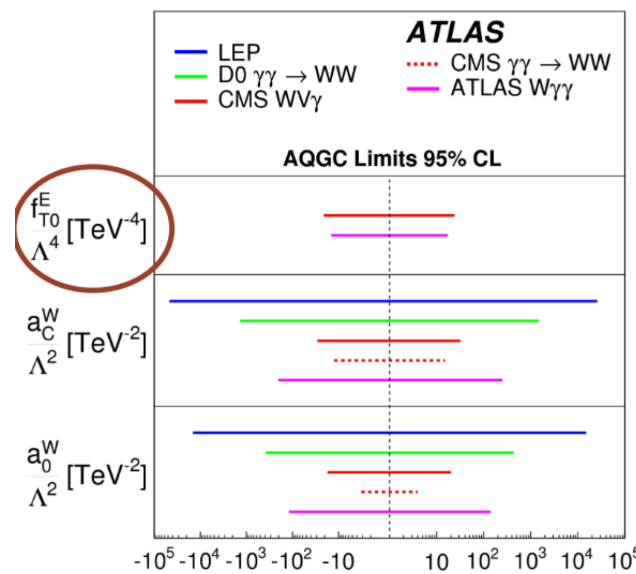
Exclusive





Backgrounds:

- multijet (data driven)
- prompt leptons (MC)



	σ^{fid} [fb]	σ^{MCFM} [fb]
Incl.	$6.1^{+1.1}_{-1.0}$(stat) $\pm$ 1.2(syst) $\pm$ 0.2(lumi)	2.90 $\pm$ 0.16
Excl.	$2.9^{+0.8}_{-0.7}$(stat)$^{+1.0}_{-0.9}$(syst) $\pm$ 0.1(lumi)	1.88 $\pm$ 0.20

- Combined significance over background only: 3.6 σ
- Consistent within SM → Limits set on aQCG

Phys.Rev.Lett. 115, 031802 (2015)

Limits on aTGCs (Summary)

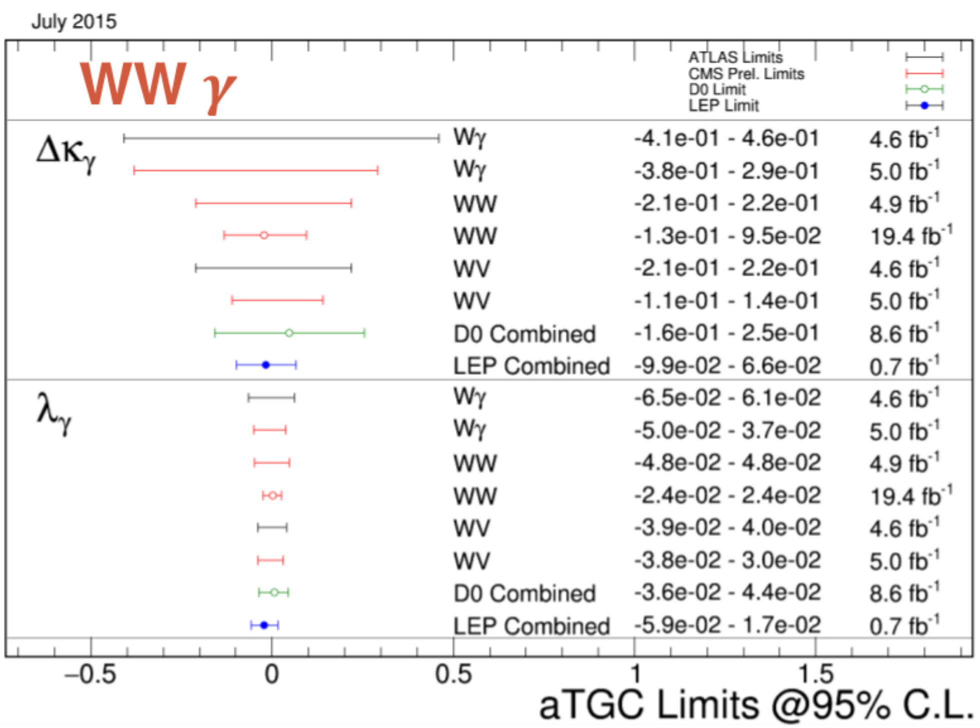
Cross sections would be higher for aTGC

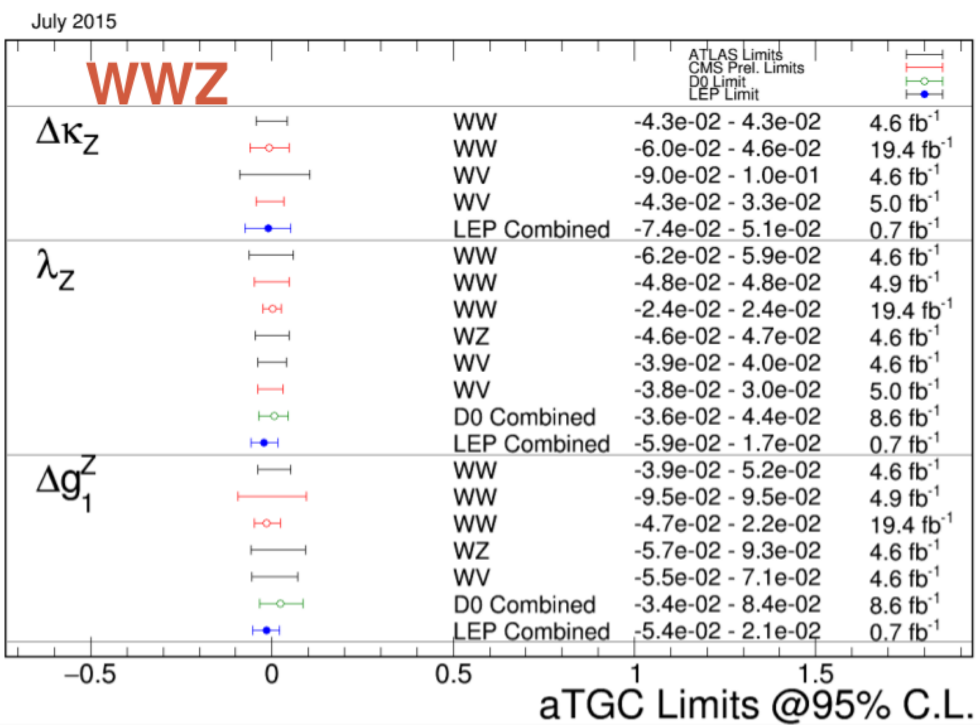
aTGC mostly affect high P_T regions

Parametrization of aTGC in a perturbative, model independent way

Parameters ($\Delta\kappa_\gamma$, λ_γ, ...) all 0 in SM

→ no deviation from SM predictions found





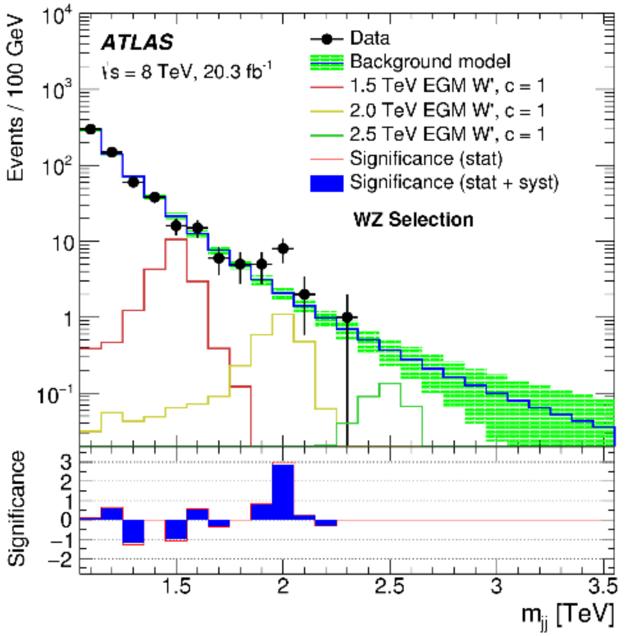
A Search
@ 13, 8 TeV

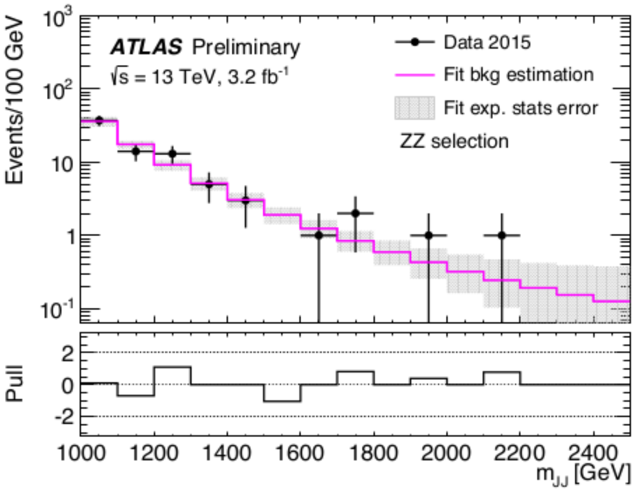
Fully Hadronic JJ Diboson Searches

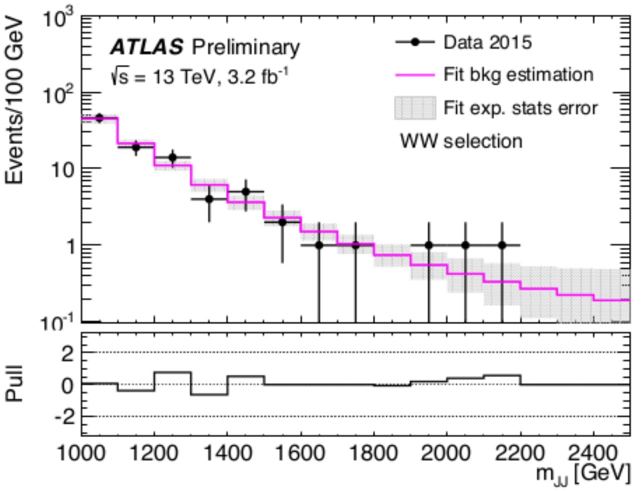
ATLAS-CONF-2015-073

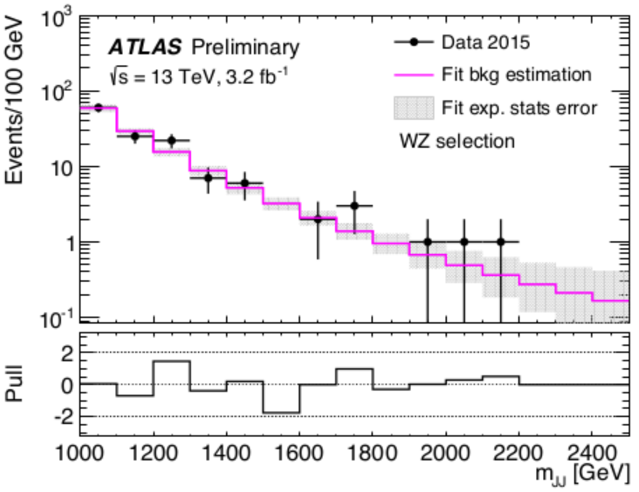
Run-1

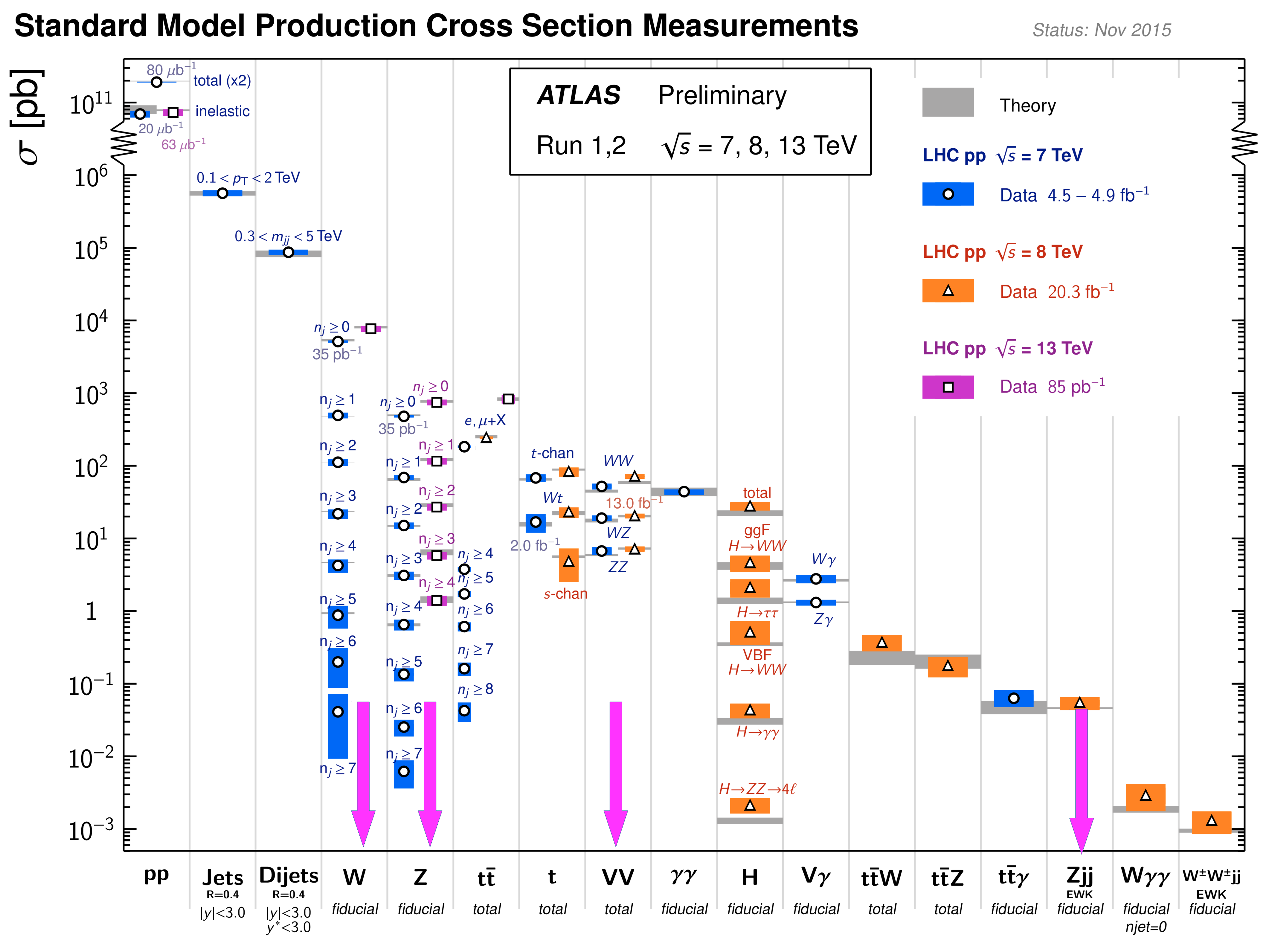
- **Modest excess at Run-1: 3.4σ** local / **2.5σ global**
- **Analysis very similar to Run 1**, with functional fit of the background
- **No significant excess is observed**
  however sensitivity not high enough for conclusive probe of the Run 1 excess










Standard Model Production Cross Section Measurements
Status: Nov 2015
σ [pb]
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 85 pb⁻¹
total (x2)
inelastic
80 μb⁻¹
20 μb⁻¹
63 μb⁻¹
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
35 pb⁻¹
e, μ+X
t-chan
Wt
s-chan
2.0 fb⁻¹
WW
WZ
ZZ
13.0 fb⁻¹
total
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
pp
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ total
t total
VV total
γγ fiducial
H fiducial
Vγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial

Conclusions

Large (non-exhaustive) set of ATLAS results from the analysis of single and multi boson final states have been presented. In particular:

a) W, Z, Z+jets, ZZ cross sections at 13 TeV
b) D-Y, ZZ, WW, ZW, cross sections at 13 / 8 TeV, limits on aTGC.s
c) electroweak production of Zjj, sensitive to vector boson fusion
d) first evidence of vector boson scattering
e) first measurement of triboson ($W\gamma\gamma$) production, limits on aQGC

→ Many results, no evidence for new physics, but significant input for improving SM theoretical modelling

→ New, better results likely soon but … systematics often already dominating [i.e. will improve but not as √(statistics)]

Thank for Your Attention [and Patience]

Backup

@8TeV - WZ→lllν Cross Section

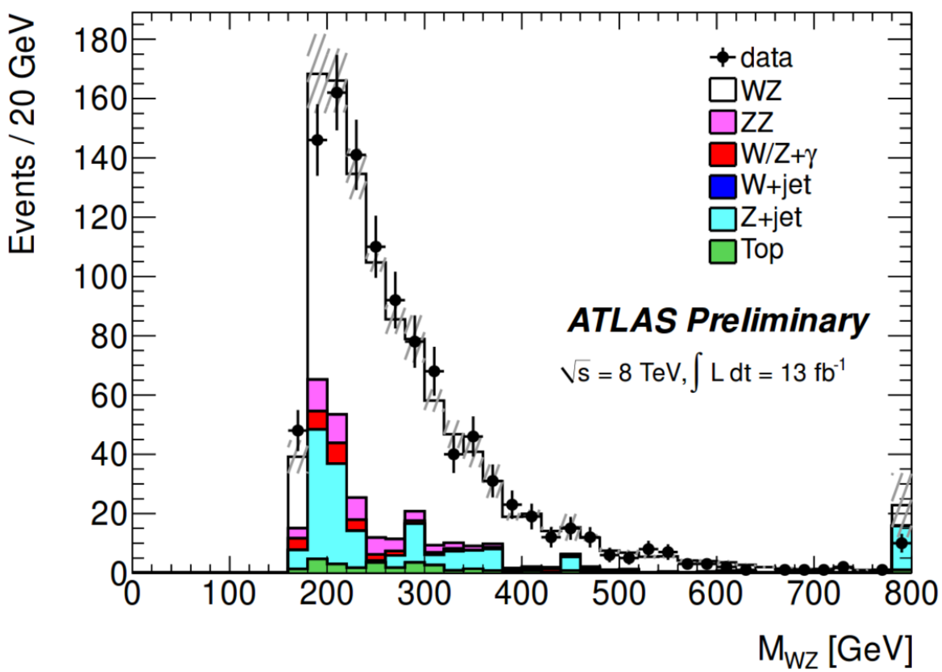
a) 3 high-P_T, isolated leptons

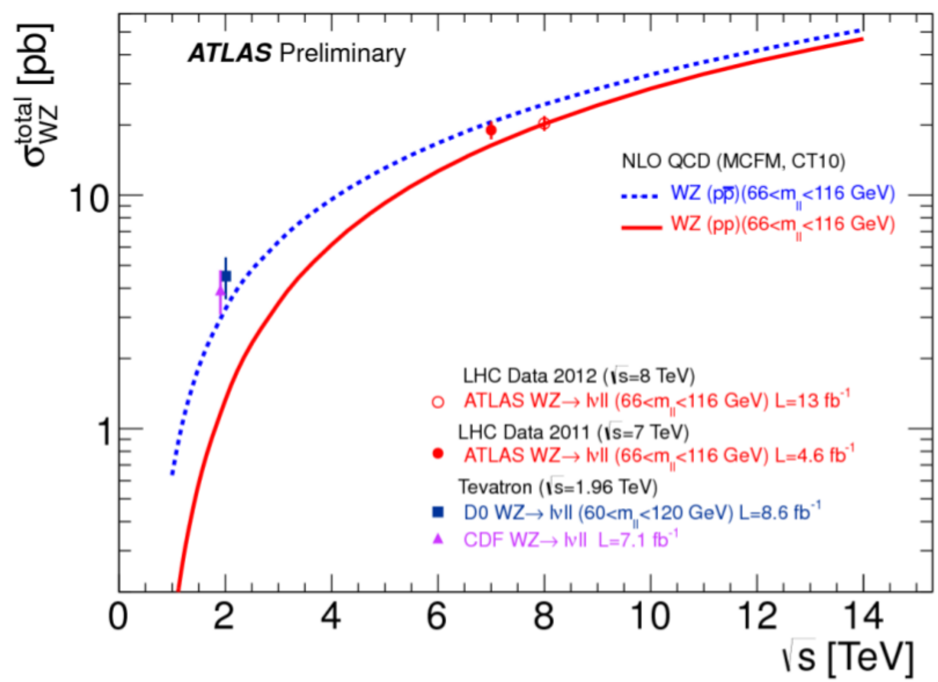
b) E_T^{miss} > 25 GeV

c) 66 < M_{ll} < 116 GeV

Backgrounds:

- Z+jets: ~15% (data driven)
- ZZ: ~5% (MC)
- W/Z+γ: ~3 (MC)





$$\sigma_{WZ}^{tot} = 20.3^{+0.8}_{-0.7}(\text{stat.})\ ^{+1.2}_{-1.1}(\text{syst.})\ ^{+0.7}_{-0.6}(\text{lumi.})\ \text{pb}$$

$$\sigma^{exp}(NLO) = 20.3 \pm 0.8\ \text{pb}$$

- very precise measurement
- limits on WWZ aTGC not yet updated,
  → 7 TeV results: Eur. Phys. J. C (2012) 72:2173

ATLAS-CONF-2013-021

@7TeV – Wγ/Zγ Cross Sections

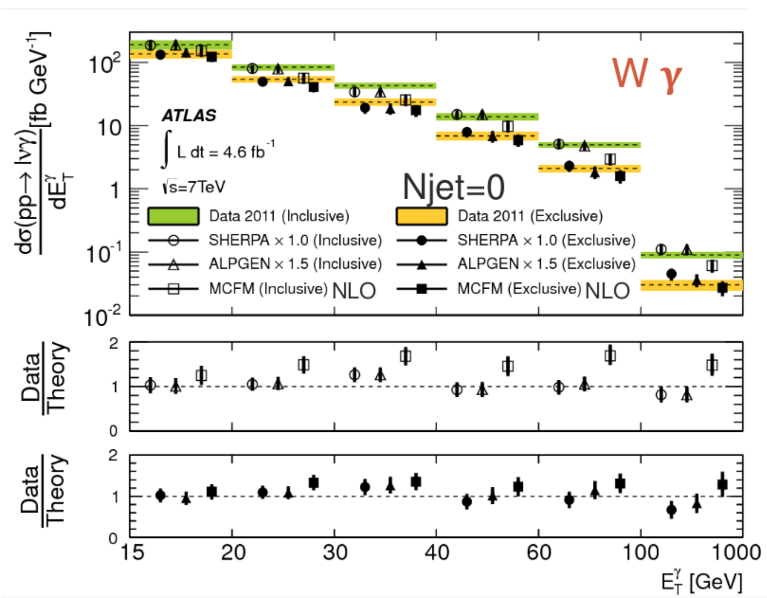
Wγ/Zγ → lνγ, llγ, ννγ

a) high P_T, isolated γ/leptons

b) ν → high E_T^{miss}

c) γ/l well separated

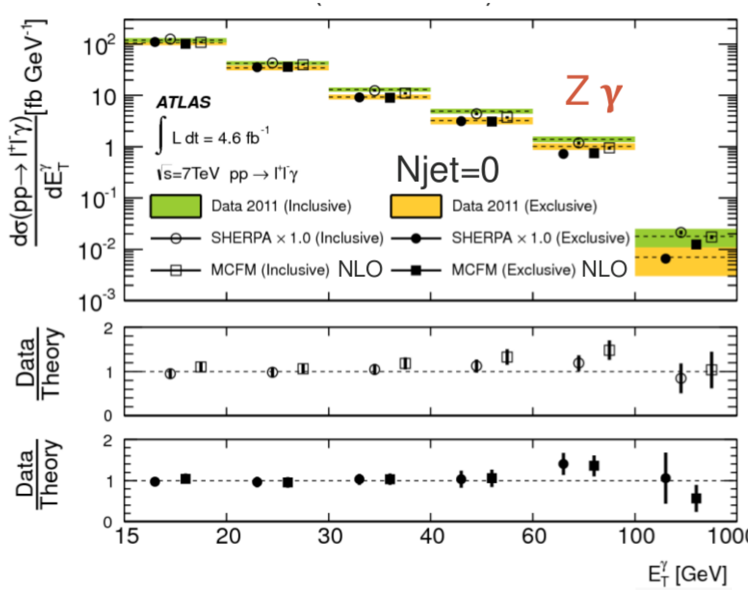
Exclusive (Njet=0) region more sensitive to aTGC



Phys.Rev.D 87,112003 (2013)

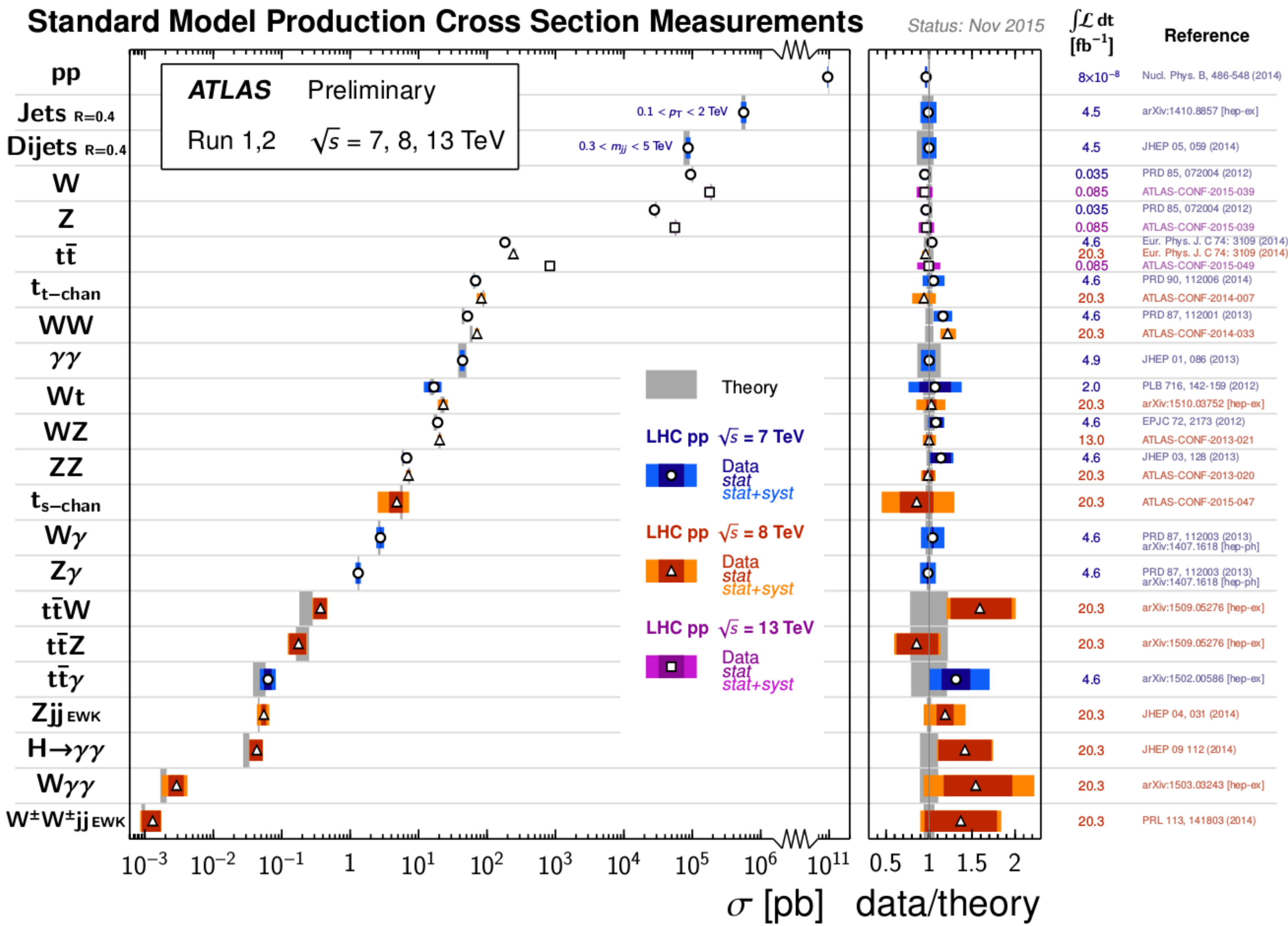
Backgrounds:

- W+jets: 15-25% (data driven)
- Z+jets: ~10% (data driven)
- γ+jets: 5-10% (data driven)
- tt: <5% (MC)

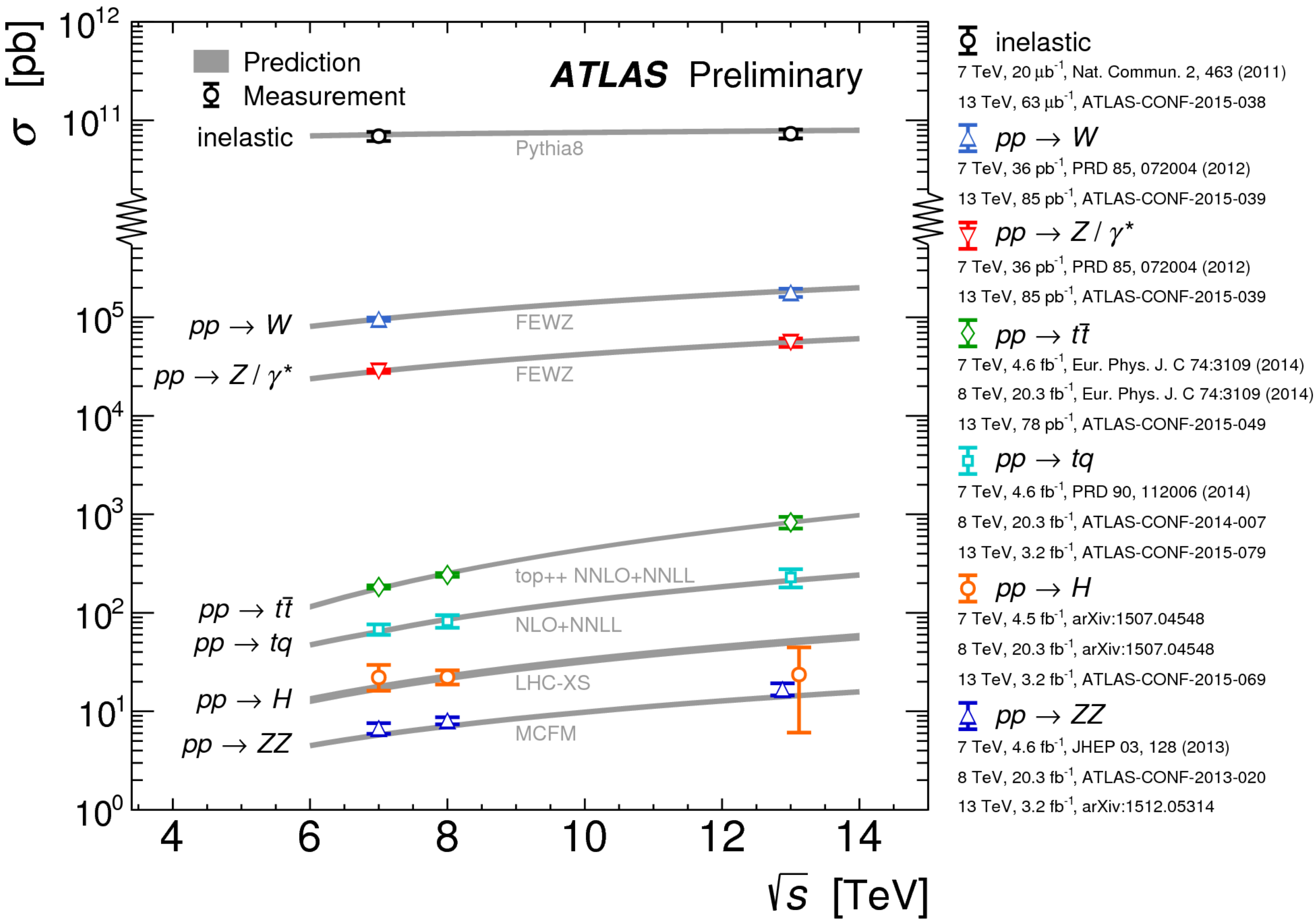


- differences at high $E_t^γ$
- improve w/ NNLO corrections
  → new theoretical predictions

SM Cross Sections



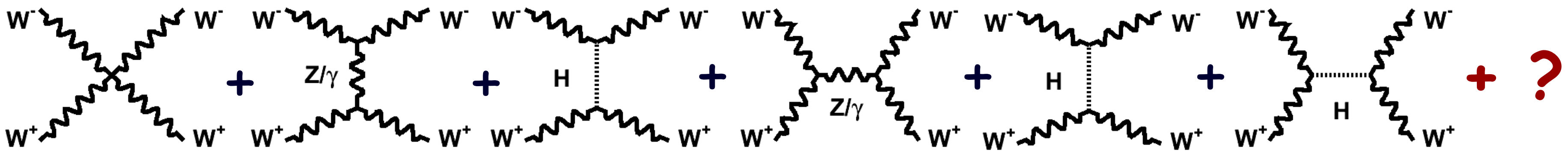
Summary of Run-2 Total Cross Section Measurements



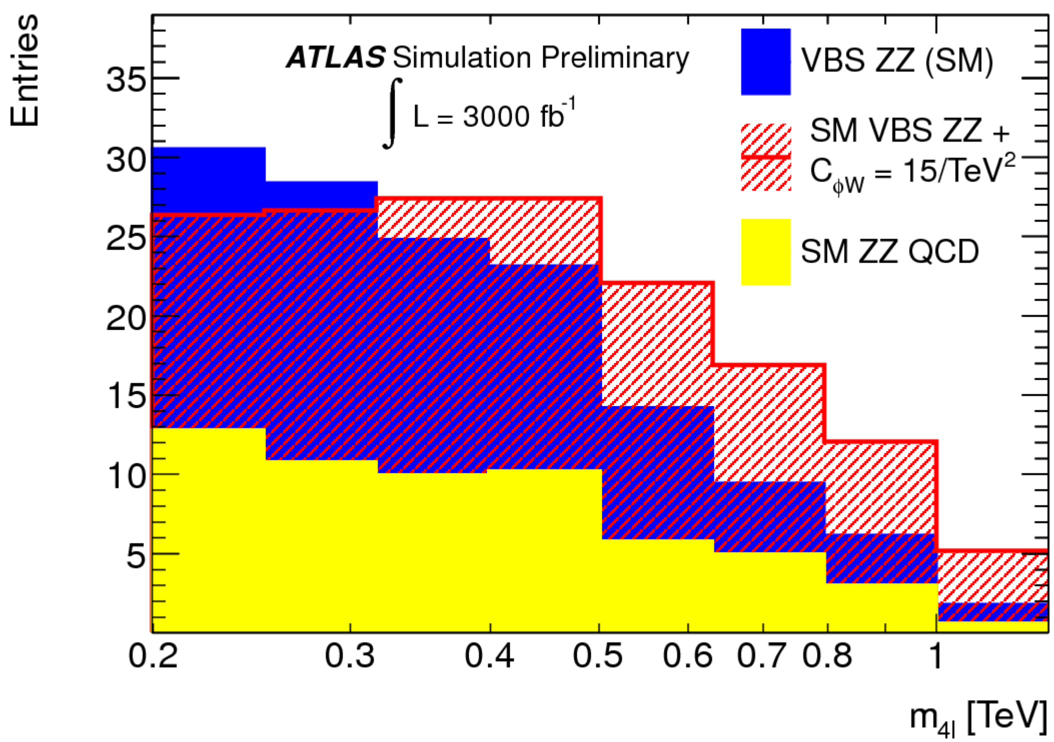
Vector Boson Scattering

Confirm that Higgs Boson provides cancellation of divergences at HE

Generic EFT framework: add all possible gauge-invariant boson couplings



ATL-PHYS-PUB-2013-006



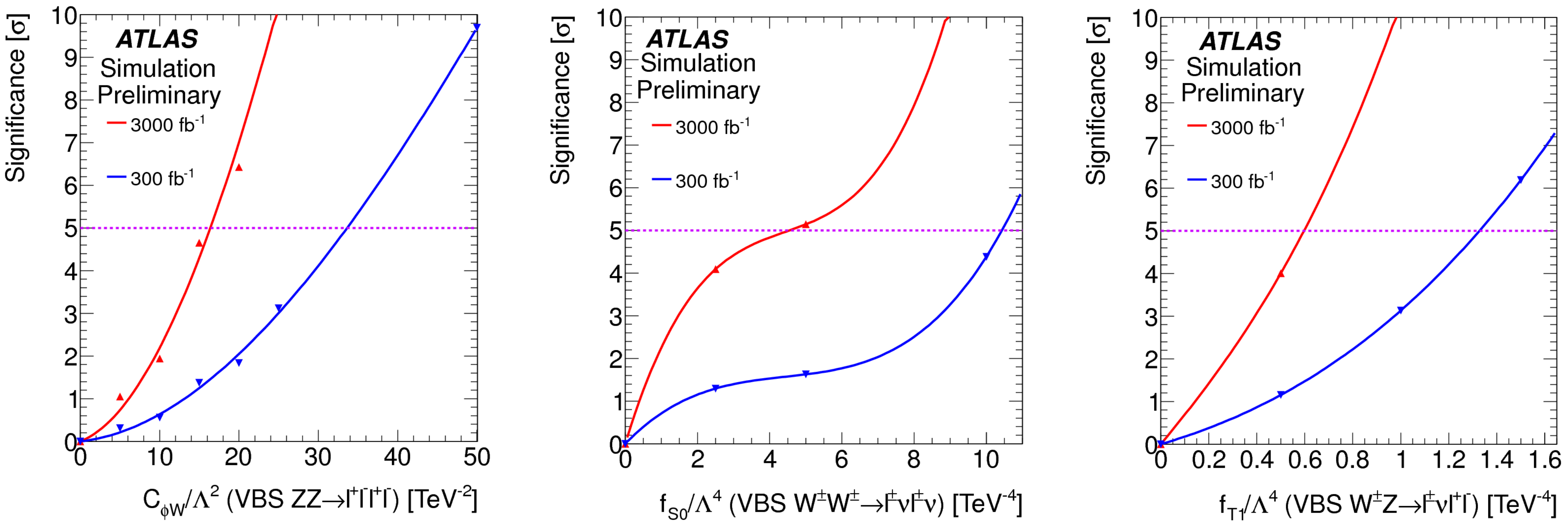
Vector Boson Scattering (2)

Parameterize BSM using higher dimensional operator

ZZ dim-6 operator → $\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2}\mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$

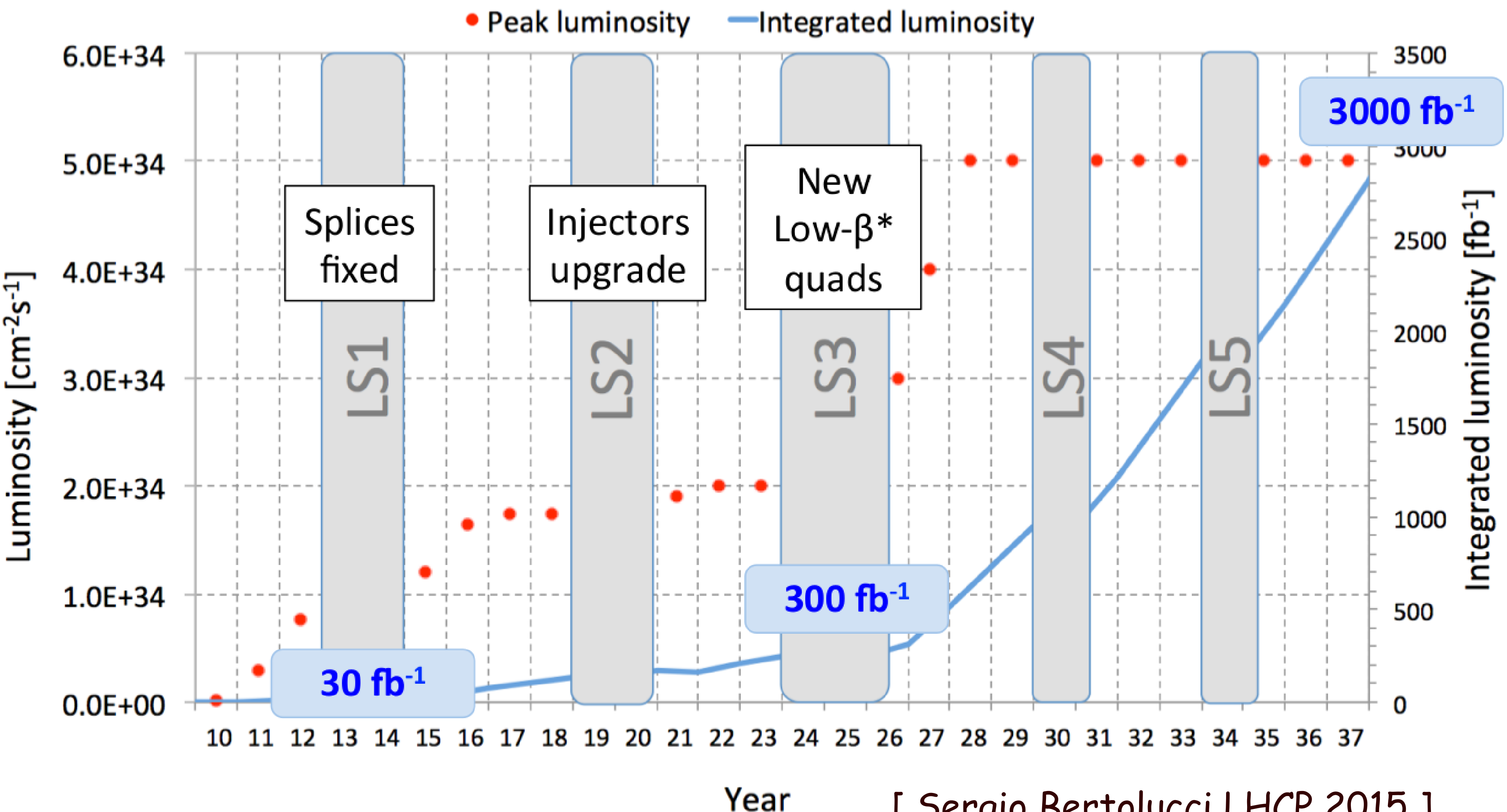
ssWW dim-8 operator → $\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4}[(D_\mu\phi)^\dagger D_\nu\phi)] \times [(D^\mu\phi)^\dagger D^\nu\phi)]$

WZ dim-8 operator → $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$



ATL-PHYS-PUB-2013-006

the road to HL-LHC



[Sergio Bertolucci LHCP 2015]

goal: fully exploit the LHC potential