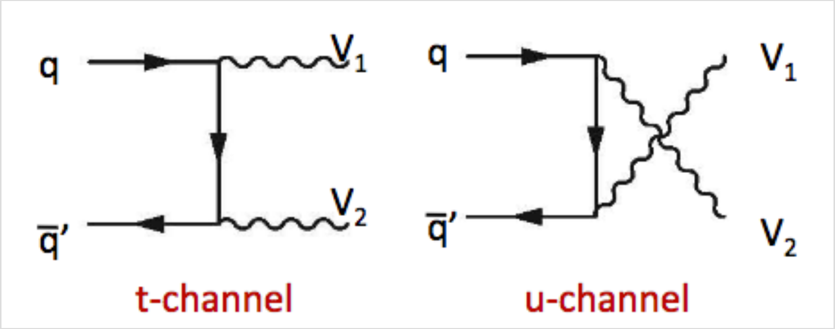
ATLAS measurements of diboson production at 13 TeV

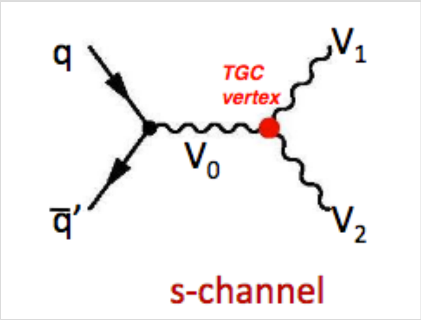
C.Roda – Universita` di Pisa and INFN Pisa

Motivation and outline

- Important test of the structure of the non-abelian electroweak gauge sector of the SM

LO diagrams

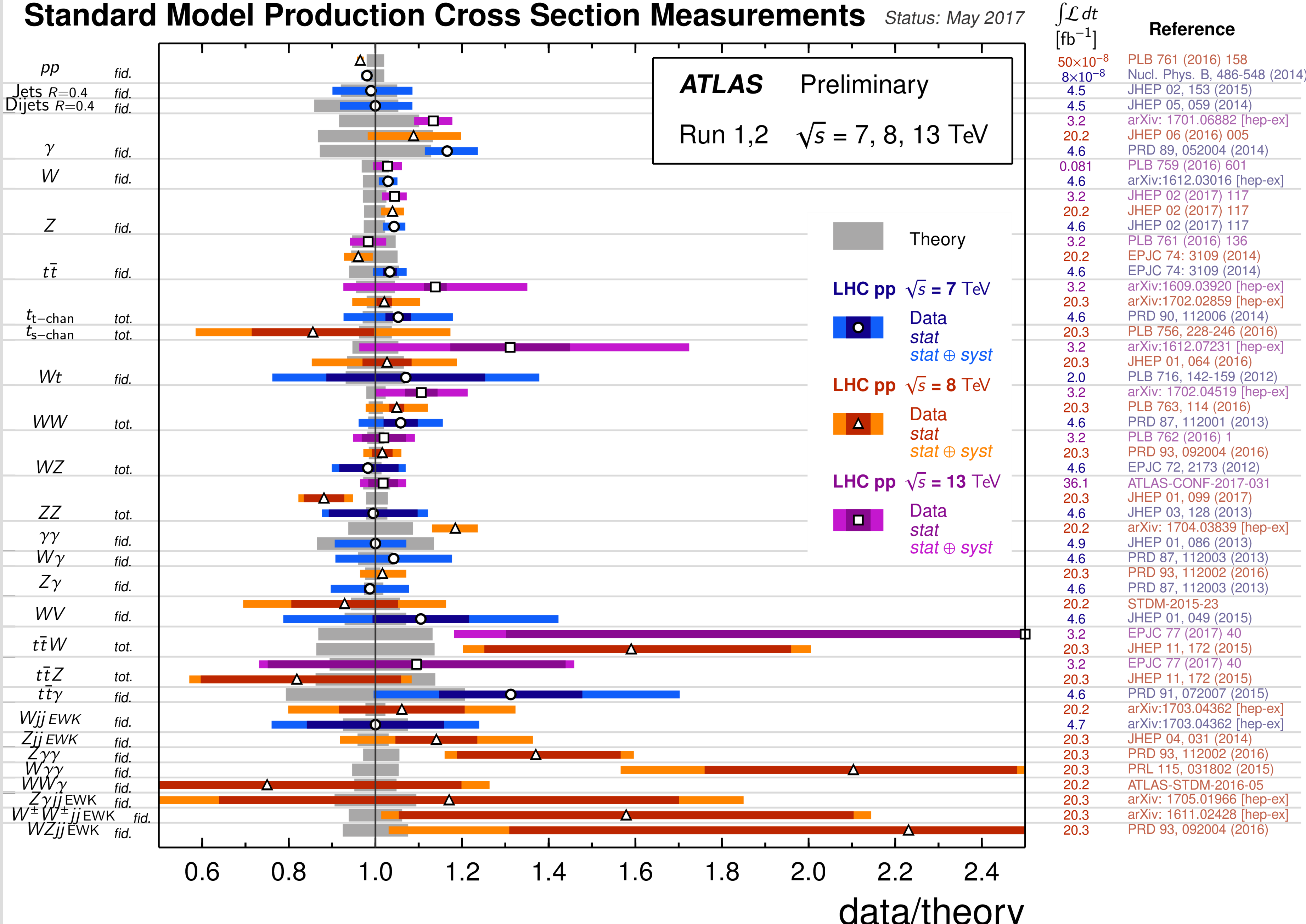




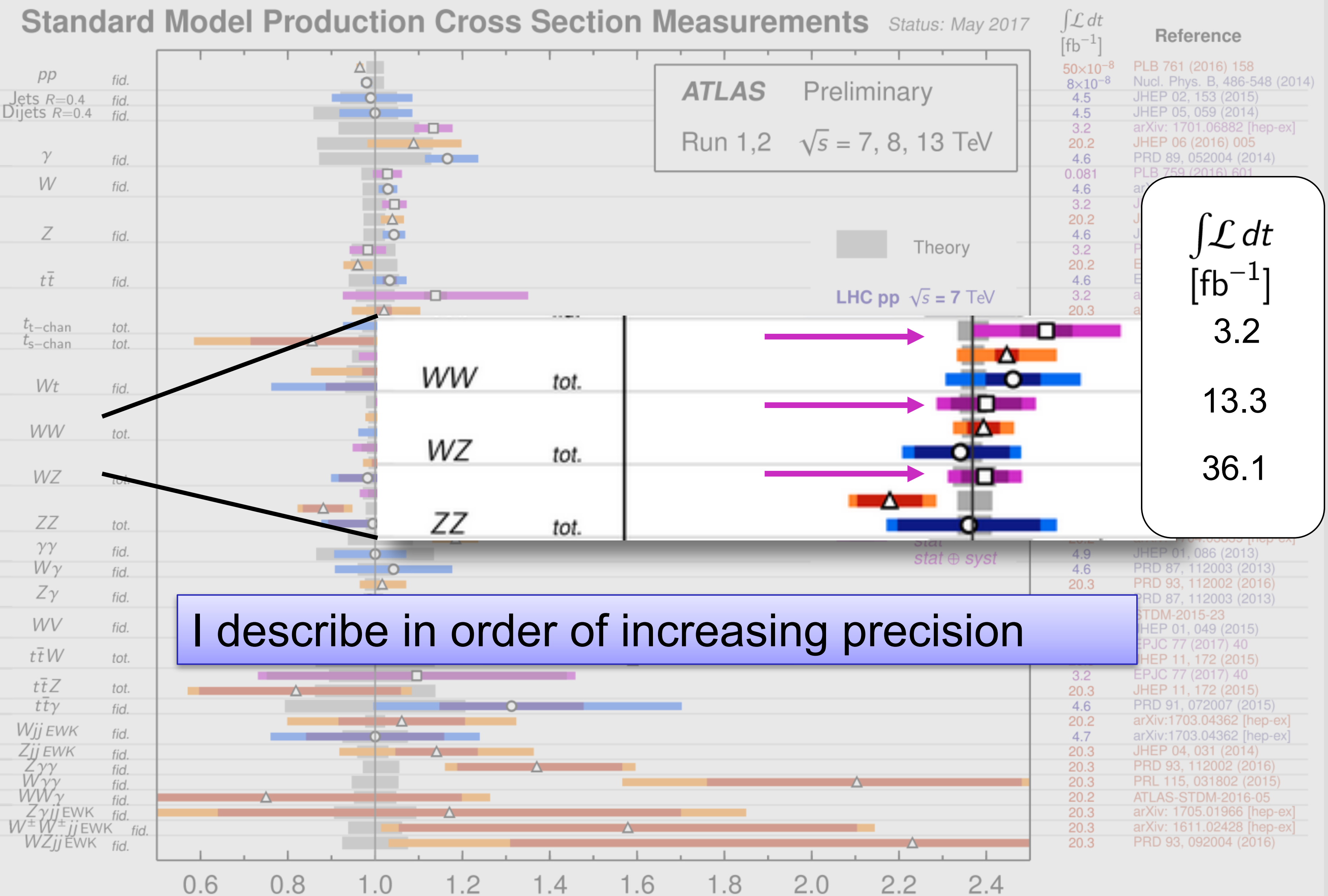
- Sensitive to new physics through the measurement of a possible anomalous Triple Gauge Coupling (aTGC)
- Diboson productions are important background processes for new physics searches and Higgs precise measurements
- I will only discuss recent cross-sections measurements @ $\sqrt{s}$ = 13 TeV : WW, WZ, ZZ in fully leptonic final states (overall picture in I.G.Caballero talk)

Standard Model Production Cross Section Measurements

Status: May 2017



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/



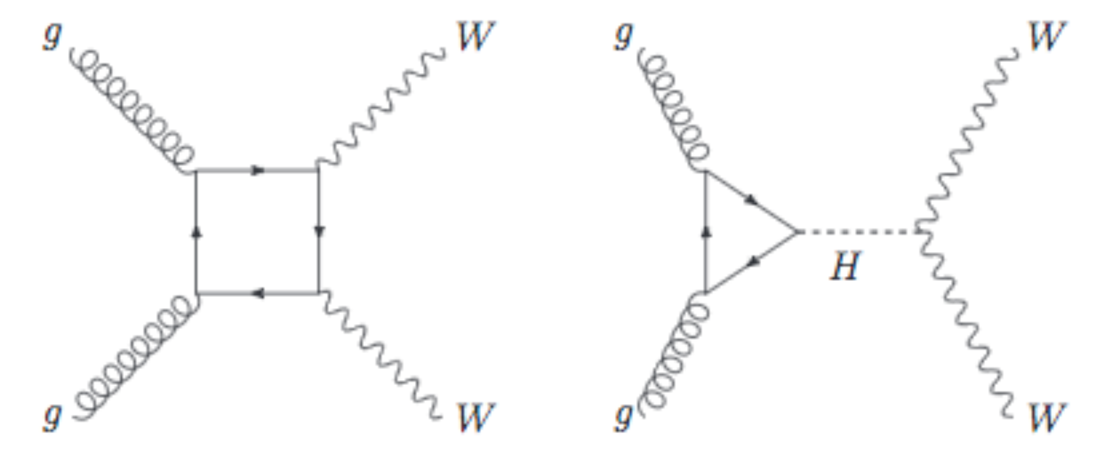
I describe in order of increasing precision

arXiv: 1702.04519 Feb.2017

WW→enu μnu

BR e + mu is about 2% → small BR but good natural suppression against DY

- Predictions nNNLO+H include: qq scattering + gg non-resonant (~5%) and resonant processes (~8%)
- Processes known at different orders in α_s → qq(α_s^2), gg-non-res(α_s^3), gg-res(α_s^5)



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Event selection in a nutshell

- Two oppositely charged isolated leptons with different flavours with pT>25 GeV
- Background reduction:
  - Other diboson processes → No additional e or muons with pT > 10 GeV
  - DY → opposite flavour + use ETMiss
  - Top processes → No jet with pT >25 GeV / no b-jet with pT>20 GeV

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Background evaluations in a nutshell

- Main background processes: DY and top → estimated with control regions
- W+jet is estimated using a data-driven estimate of the lepton mis-id
- minor background processes are estimated using MC
- S/B after selection ~ 3

WW Cross-section extraction

N_{obs} and N_{bkg} : number of signal and background events in fiducial space are obtained from a likelihood fit to the signal and control regions

$$\sigma^{\text{fid}}_{WW\to e\mu} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

C: correction factor reconstructed events in fiducial volume → truth events in fiducial volume

WW Cross-section extraction

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$$\sigma^{tot}_{WW\to e\mu} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L} \times A \times BR^2}$$

A: Acceptance fiducial → total vol
BR: branching ratio

C: correction factor reconstructed events in fiducial volume → truth events in fiducial volume

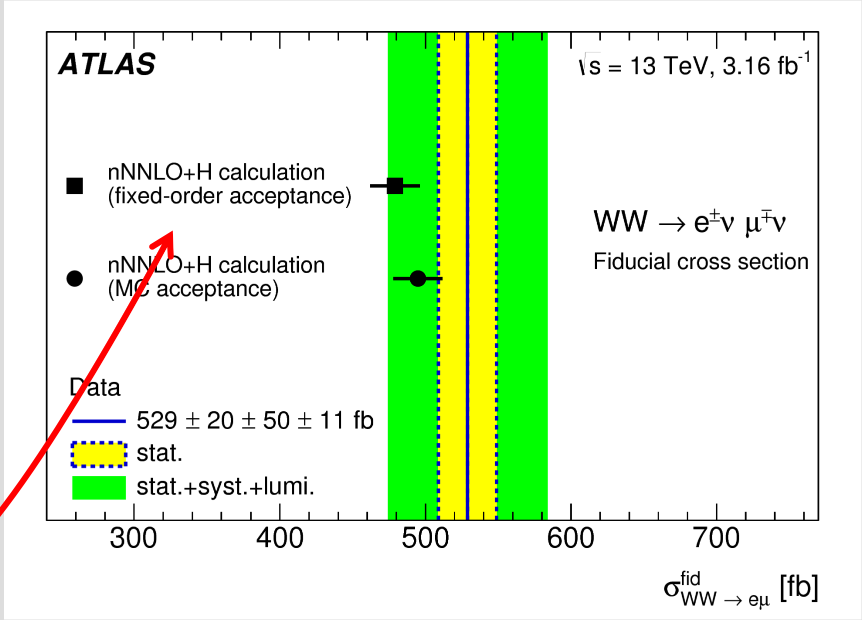
WW Cross-section

$$\sigma^{\text{fid}}_{WW\to e\mu} = 529 \pm 20\ (\text{stat.}) \pm 50\ (\text{syst.}) \pm 11\ (\text{lumi.})\ \text{fb}.$$

$$\sigma^{tot} = 142 \pm 5(stat) \pm 13\ (syst) \pm 3\ (lumi)\ pb$$

10% tot unc

- Measurement dominated by systematic uncertainties
- Largest experimental systematic uncertainties: Jet veto, Jet energy and resolution uncertainties followed by W+jet and multi-jet modelling.
- Good agreement with nNNLO+H SM prediction



See also F.Cossutti's and F.Caola's talks

PLB, Vol762 (2016) 1-22 and ATLAS-CONF-2016-043

WZ→enuμμ, enuee, μnuee, μnuμμ

4 production channels with BR ~0.4% per channel

Event selection in a nutshell

- Two oppositely charged same flavour isolated leptons + one more lepton
- Background reduction
  - other diboson → No additional electron or muons with pT > 7 GeV
  - Z+jet reduction → tight criteria on candidate lepton from W and M_T>30GeV
- no request on jet veto

Background evaluations in a nutshell

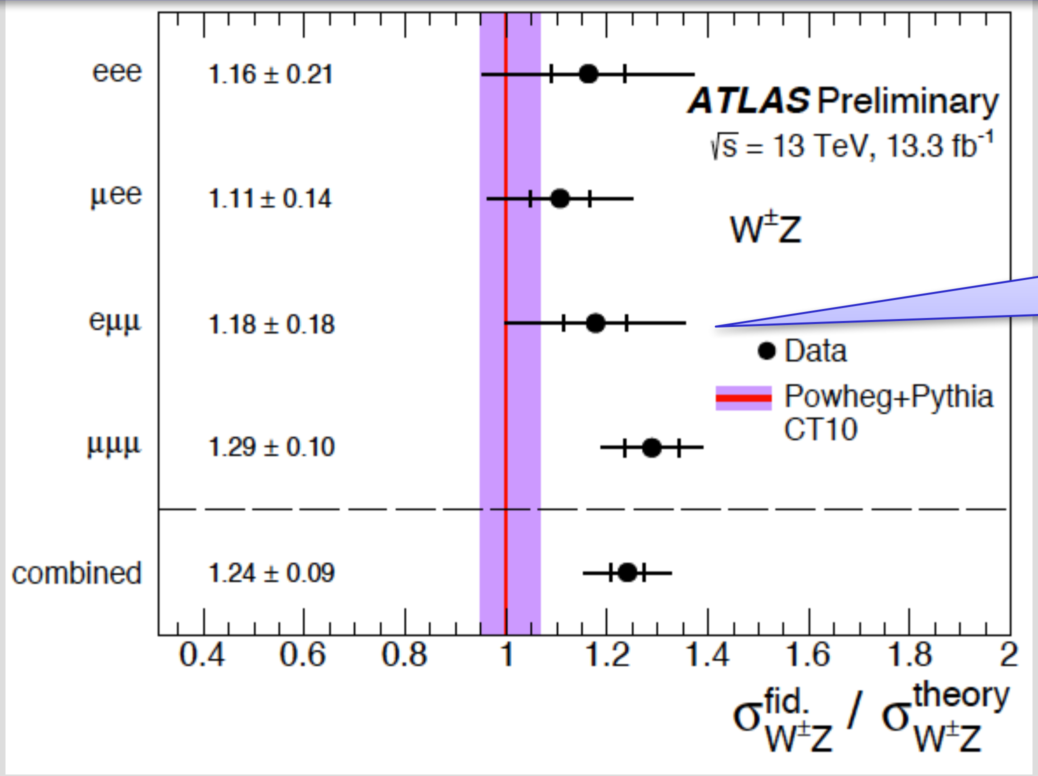
- Reducible background (≥ non-prompt/fake lepton) → data driven estimate
- Irreducible background → MC based estimate
- After selection main backgrounds → S/B ~ 3.6
- Background composition: ~52% Z+jet/Z+γ, ~30% ZZ, ~10% ttbar+V

WZ – cross-section

Fiducial $\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 66.2 \pm 1.8\,(\text{stat.}) \pm 3.6\,(\text{sys.}) \pm 2.1\,(\text{lumi.})$ fb.

7% tot unc

Measurement dominated by systematic uncertainty, main source: lepton mis-identification in background, lepton reconstruction and id



Inner bar = statistical
Outer bar = total

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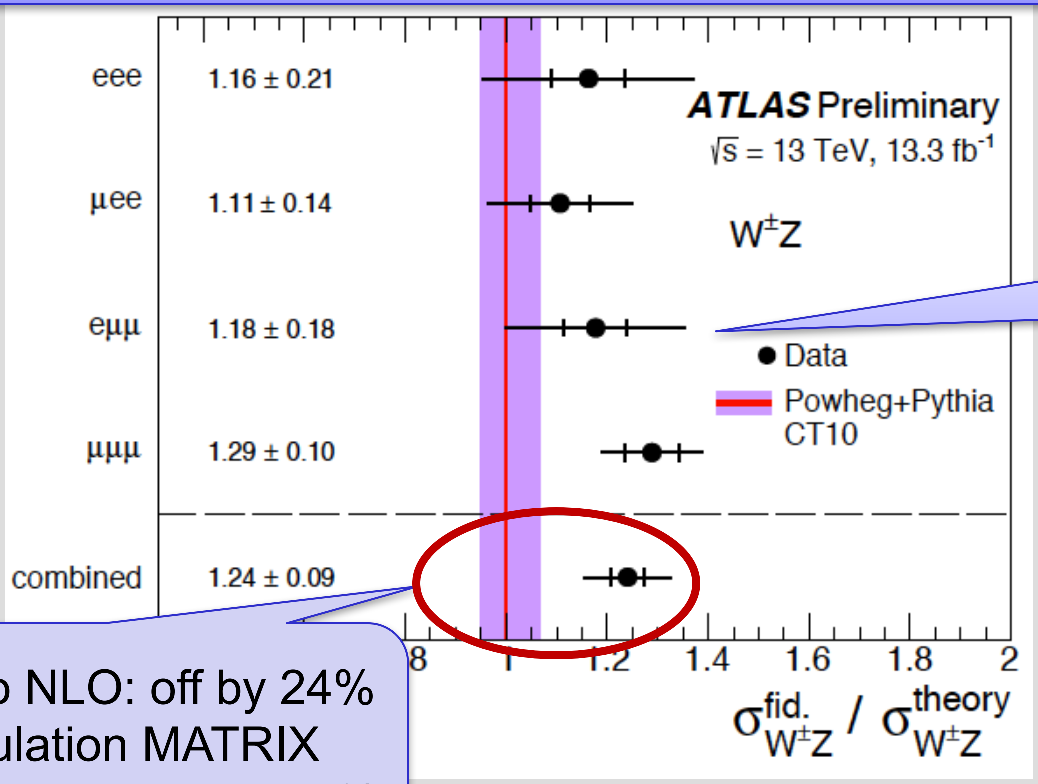
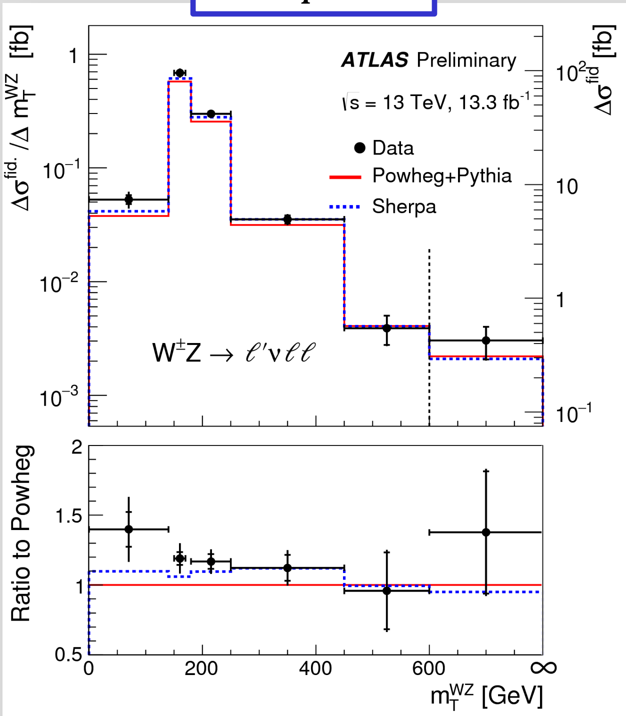


Inner bar = statistical
Outer bar = total

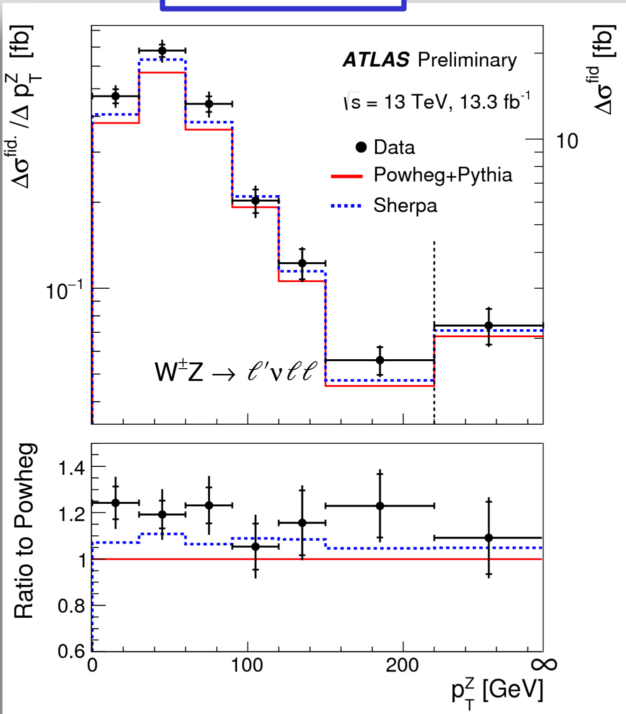
Comparison to NLO: off by 24%
NNLO calculation MATRIX
reduces the discrepancy to <5%

WZ – differential cross-sections

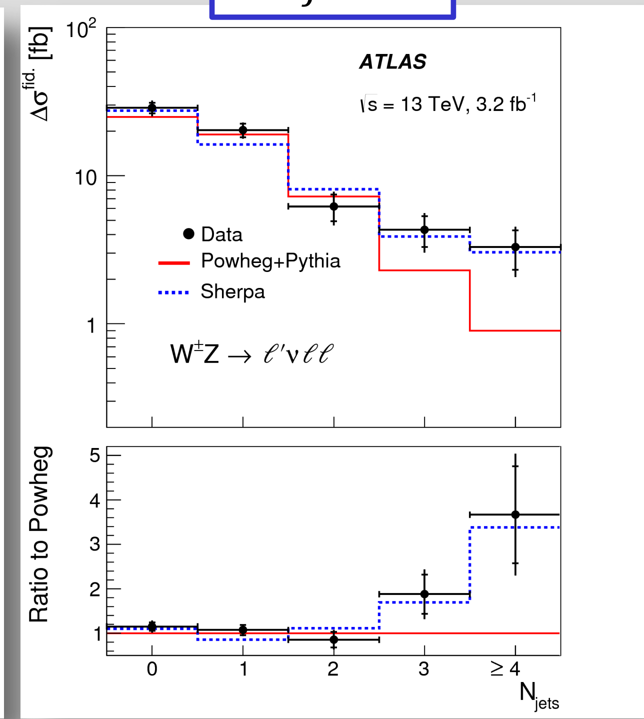
m_T^{WZ}



p_T^{WZ}



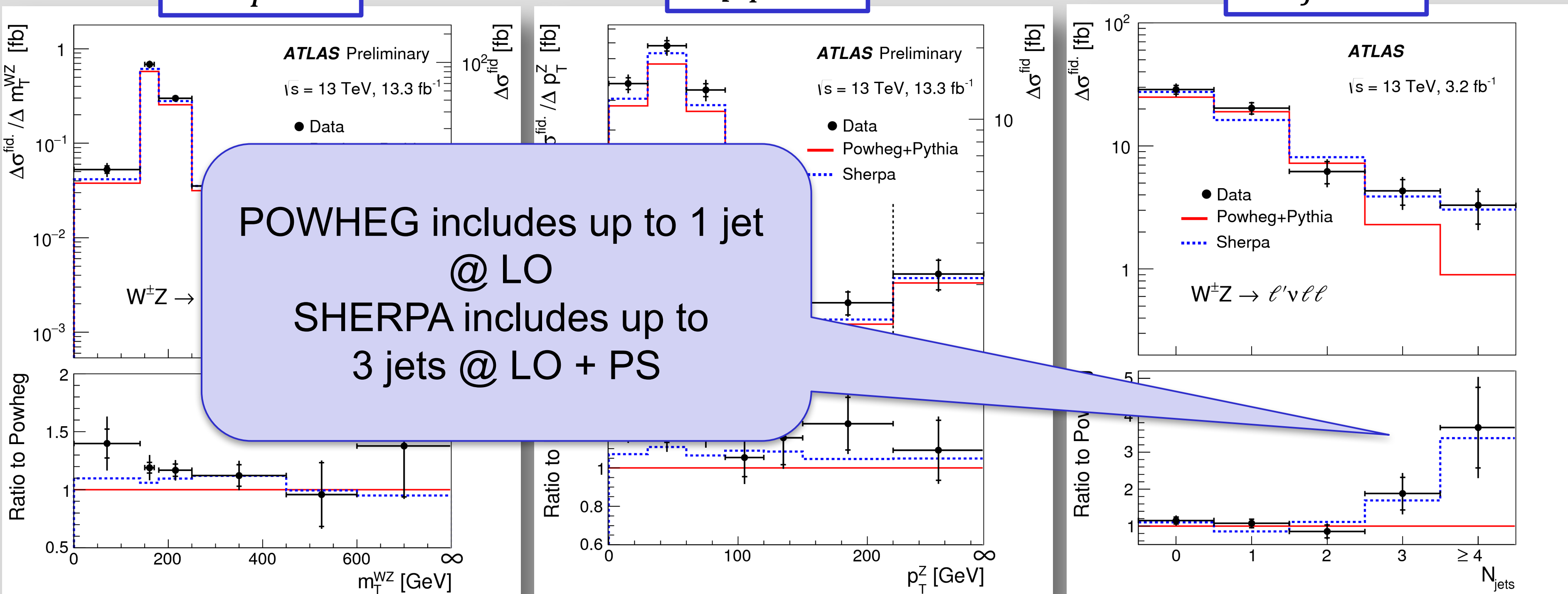
N_{jets}



Sherpa and POWHEG give a good description of both m_T and p_T

WZ – differential cross-sections

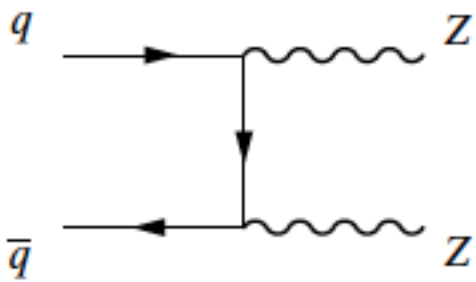
m_T^{WZ} | p_T^{WZ} | N_{jets}



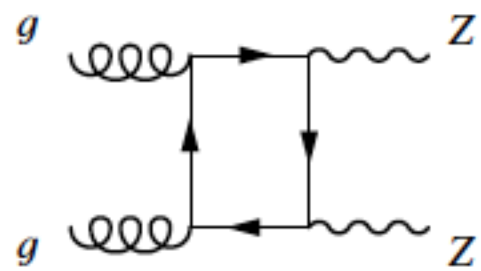
POWHEG includes up to 1 jet @ LO
SHERPA includes up to 3 jets @ LO + PS

Sherpa and POWHEG give a good description of both m_T and p_T

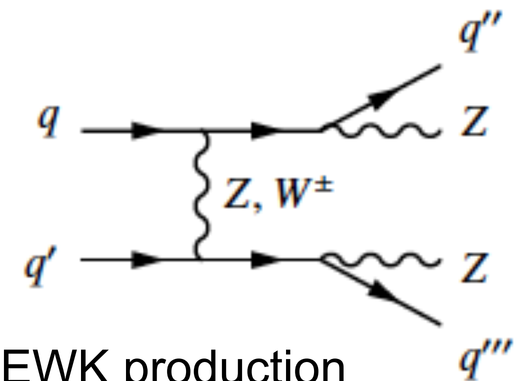
ZZ – integral and differential cross-sections



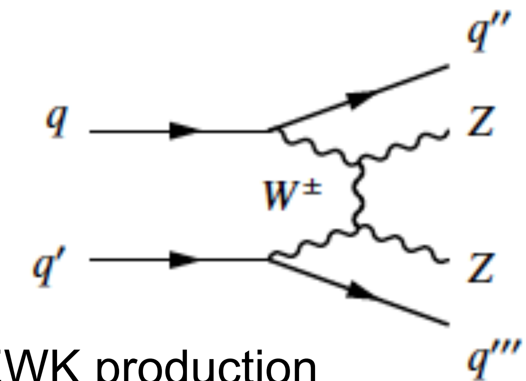
qqbar scattering



gg fusion



EWK production



EWK production
with VB scattering

ZZ→eeμμ, eeee, μμμμ

3 production channels with BR ~0.1% per channel

Event selection in a nutshell

- 4 leptons: pT1, pT2, pT3 > 20, 15, 10 GeV
- resolve ambiguities choosing smallest |mll-MZ| + |ml'l'-MZ|
- ZZ events with both Z on shell: 66 < mll < 116 GeV
- Signal after selection 87% qqbar, 11% gg, 2% EWK

Background evaluations in a nutshell

- Background after selections cuts ~2%
  - processes with at least 4 leptons (~40% of tot bkg) → MC samples
  - processes with lepton misidentification → estimate from data driven
- Contribution of H to ZZ <1%

Integrated fiducial cross-section

Channel	Measurement [fb]	Prediction [fb]
Combined	$46.4^{+2.4}_{-2.2}$ [± 1.5 (stat.) ±1.0 (syst.) $^{+1.5}_{-1.4}$ (lumi.)]	$44.6^{+3.0}_{-2.4}$

7% tot unc

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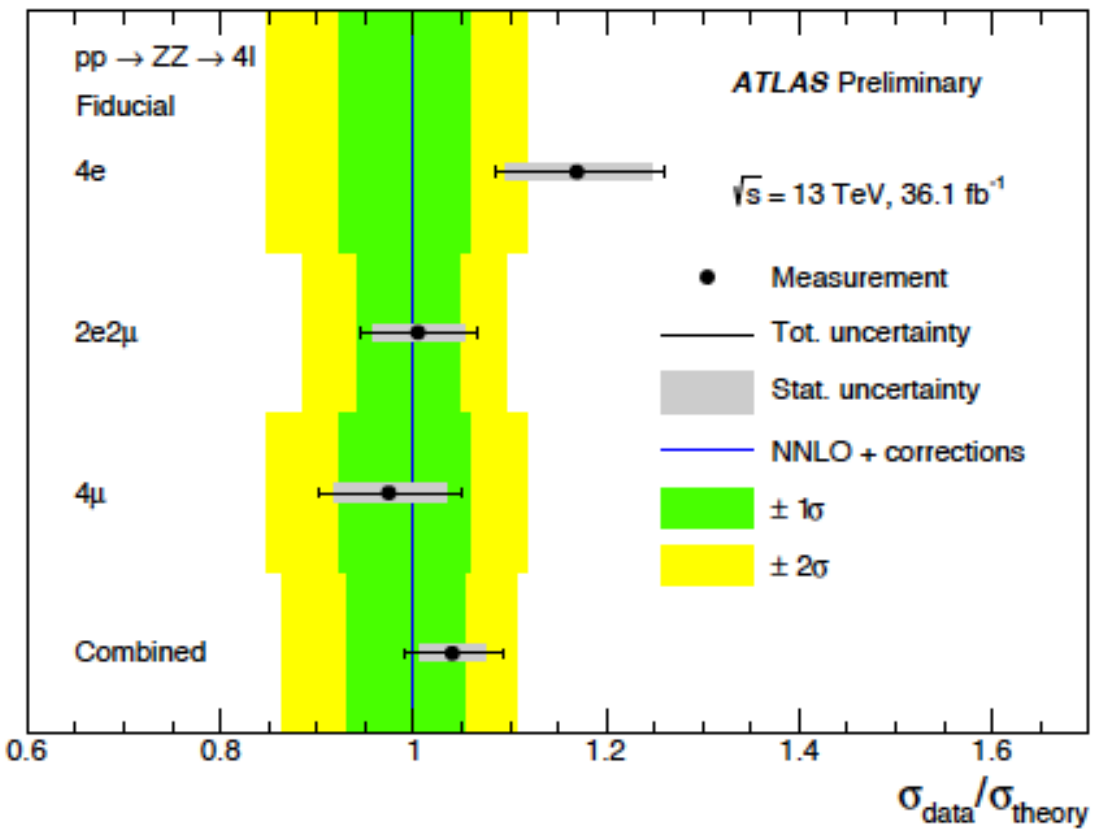


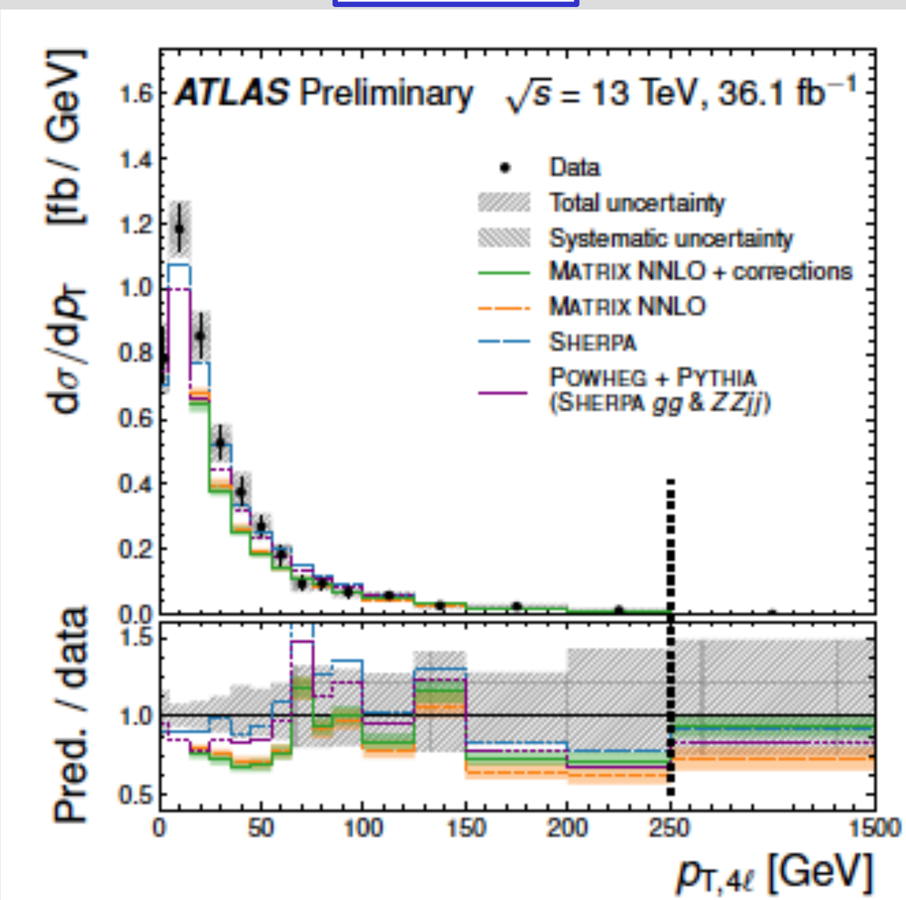
Measurement dominated by statistical uncertainty

Largest systematic uncertainty on measurement from lepton identification efficiency (Nsig and C)

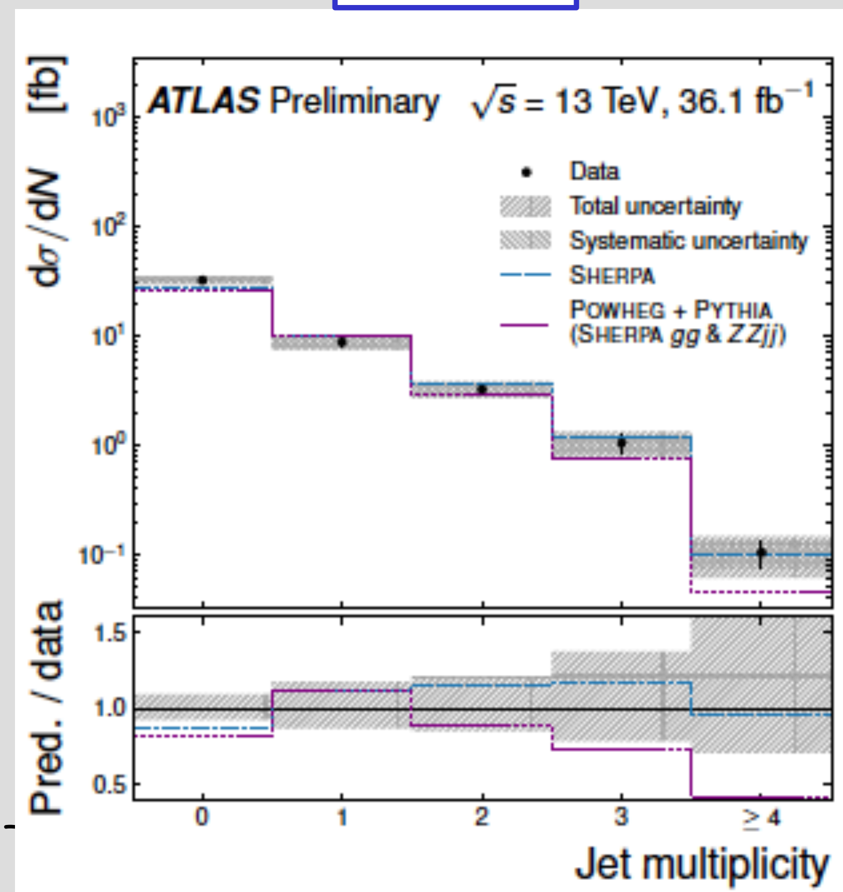
ZZ- differential cross-sections

Differential cross-section produced for 20 variables: lepton, jet activity, global event … just few examples

p_T^{4l}



N_{jets}



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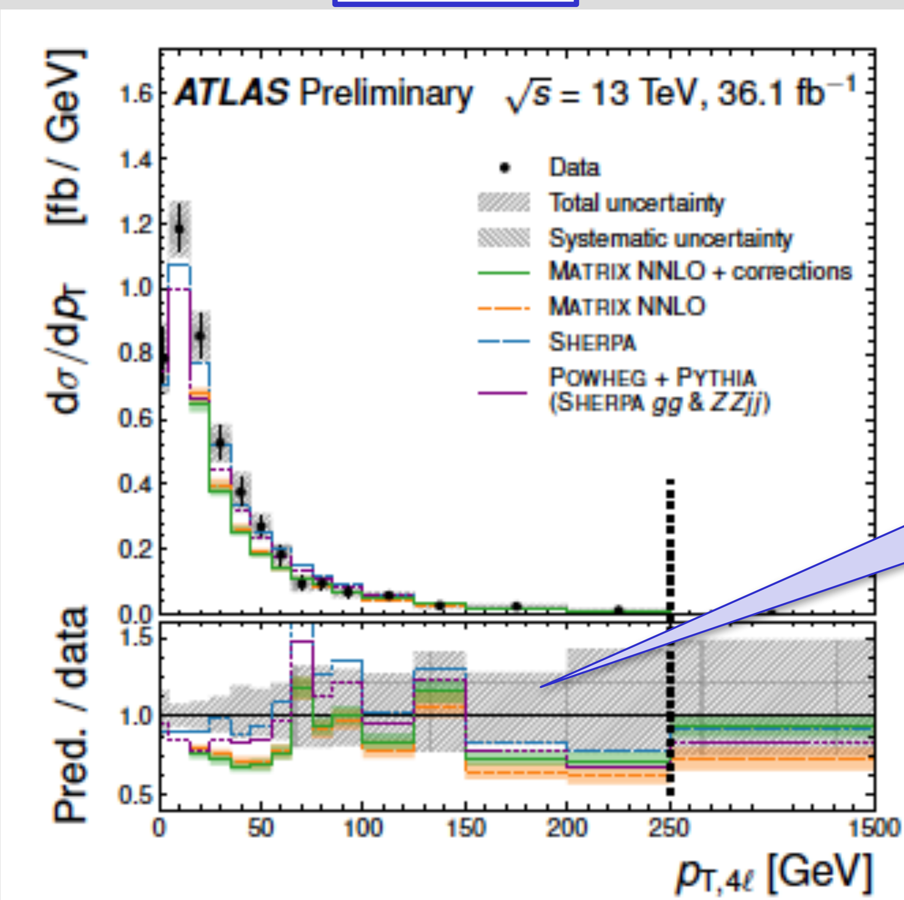

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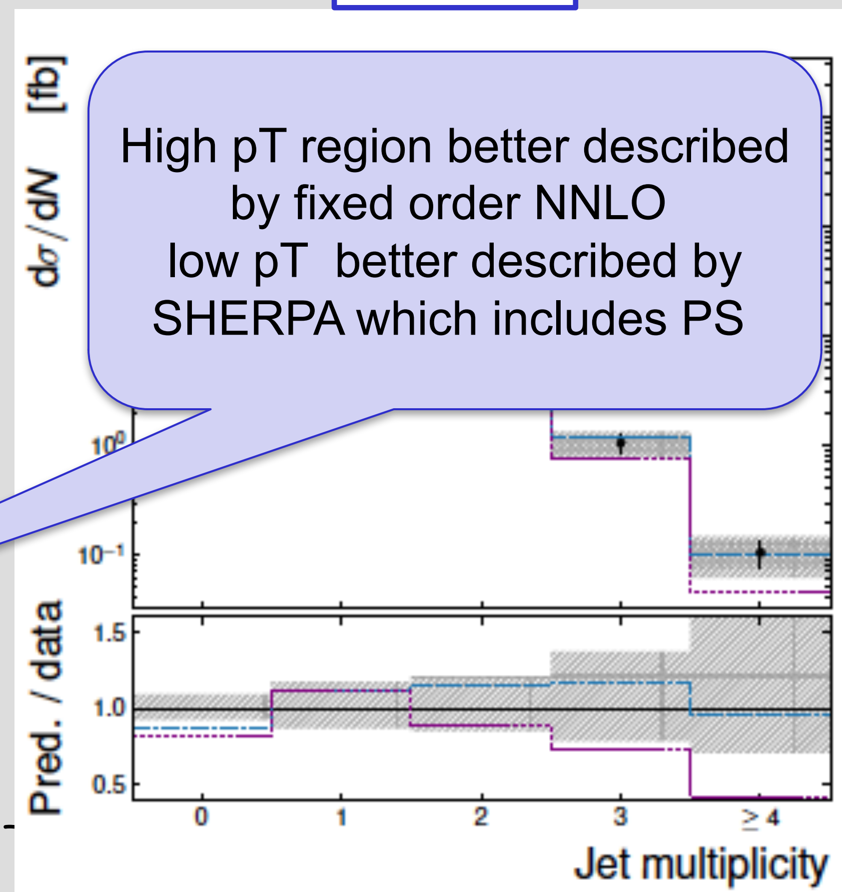

High pT region better described by fixed order NNLO
low pT better described by SHERPA which includes PS

ZZ- differential cross-sections

Differential cross-section produced for 20 variables: lepton, jet activity, globa event … just few examples

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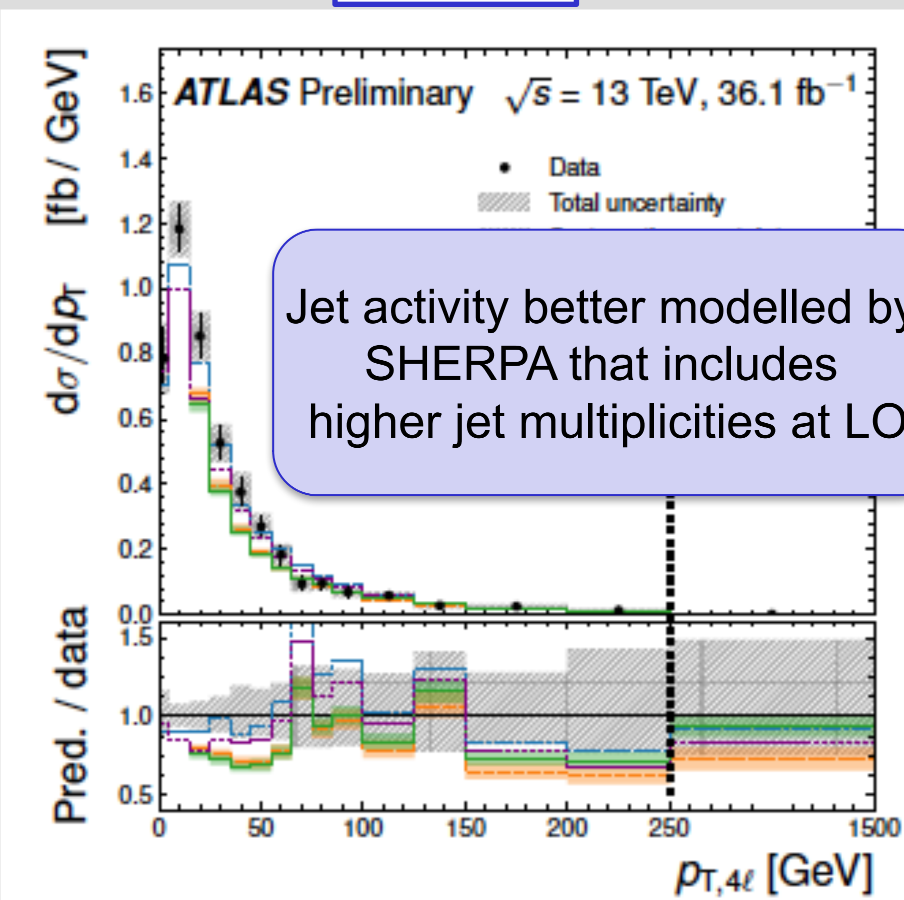

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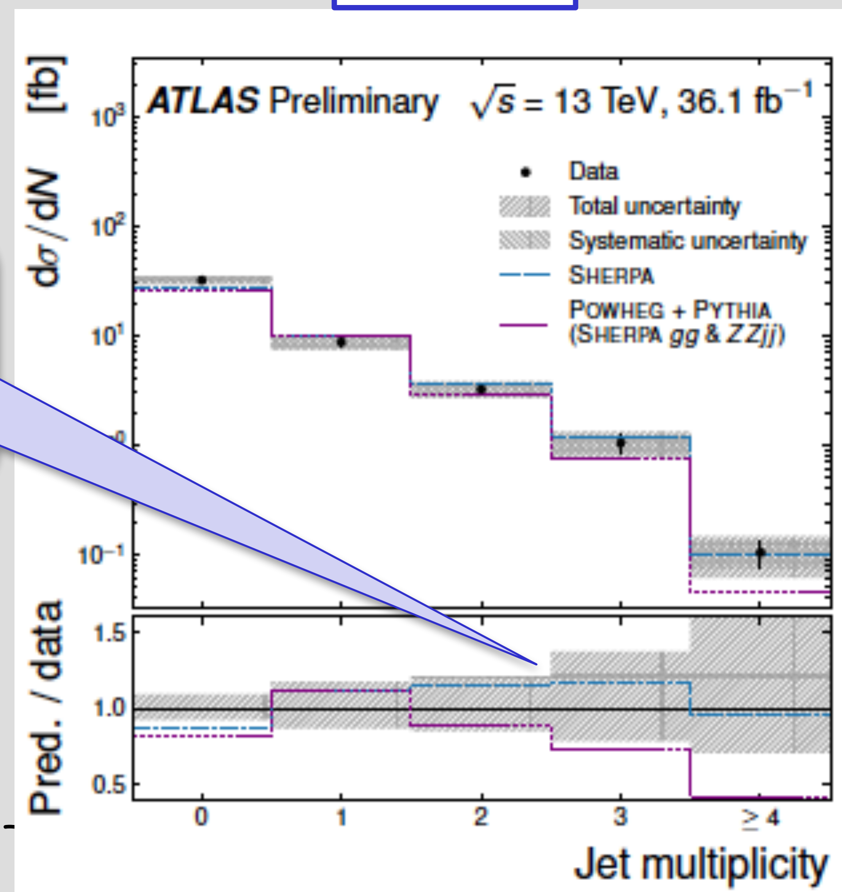
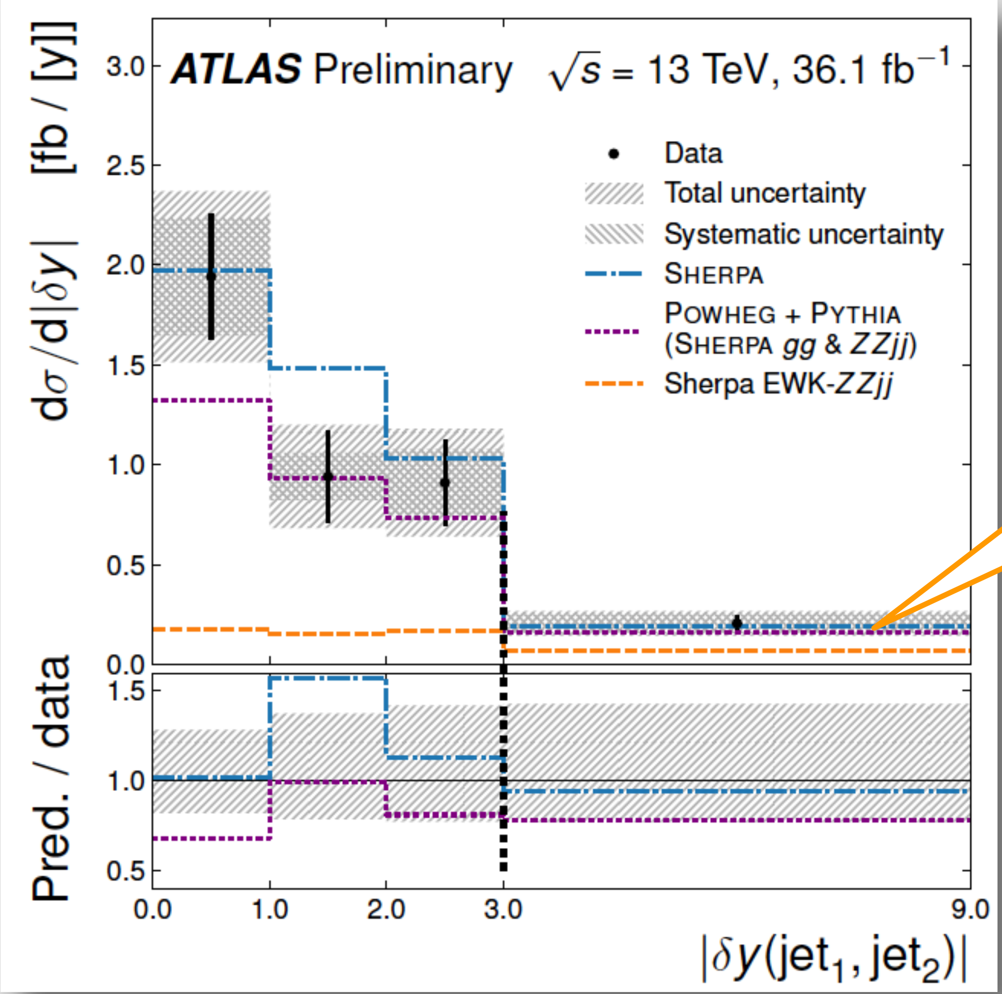


Jet activity better modelled by SHERPA that includes higher jet multiplicities at LO

Jet distributions sensitive to EWK-ZZjj production



Sherpa EWK-*ZZjj*

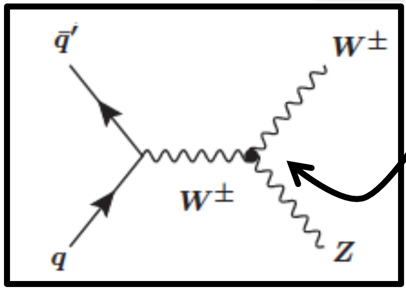
High rapidity bin has large Percent contribution from EWK-ZZjj process

Measurement of the EWK-Zjj cross-section
S.Liu talk in this session

Anomalous Triple Gauge Coupling

• The triple gauge coupling is strictly related to the non-abelian nature of the EWK gauge theory.
• Limits are given with respect to the expected SM coupling: charged (WWZ,WWγ) neutral (ZZγ,ZZZ)

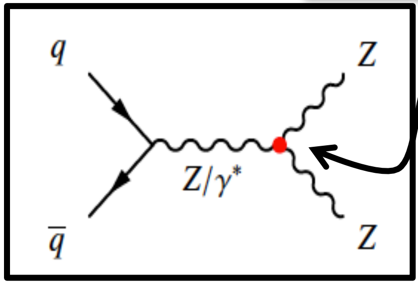
Charged



Effective Lagrangian

$\Delta g_1^Z \ \kappa_1^Z \ \lambda_Z$

Neutral



Effective Vertex

$f_4^{Z/\gamma} \ f_5^{Z/\gamma}$

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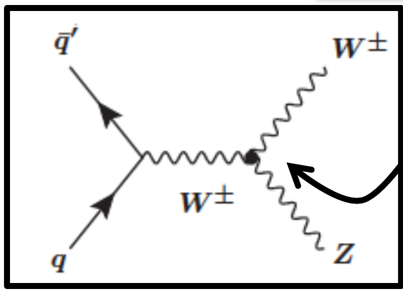

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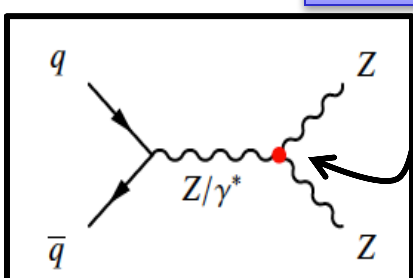
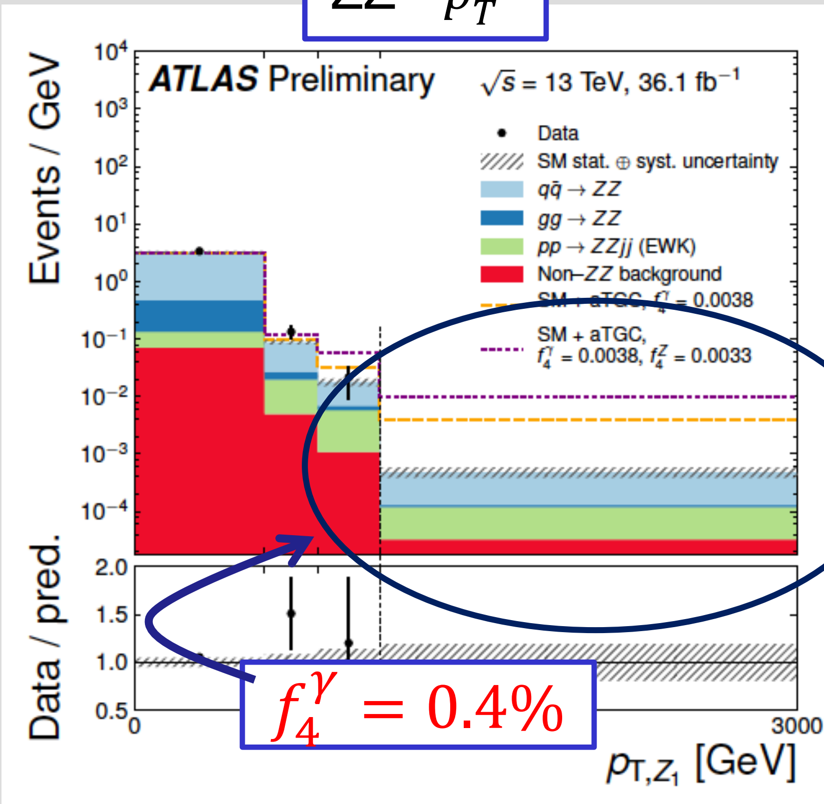


Effective Vertex

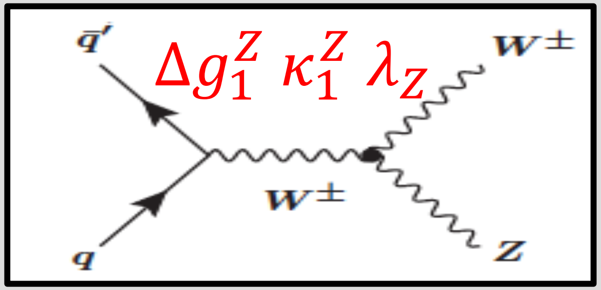
$f_4^{Z/\gamma} \; f_5^{Z/\gamma}$

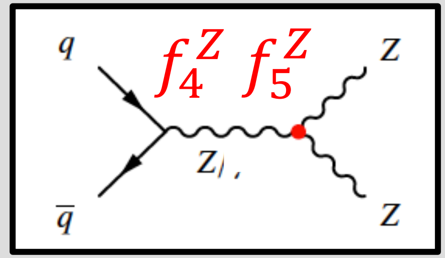
ZZ - $p_T^{Z_1}$

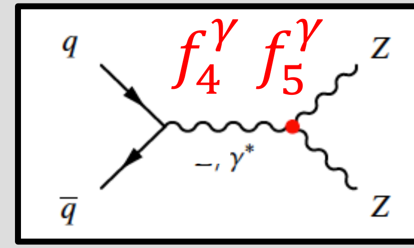


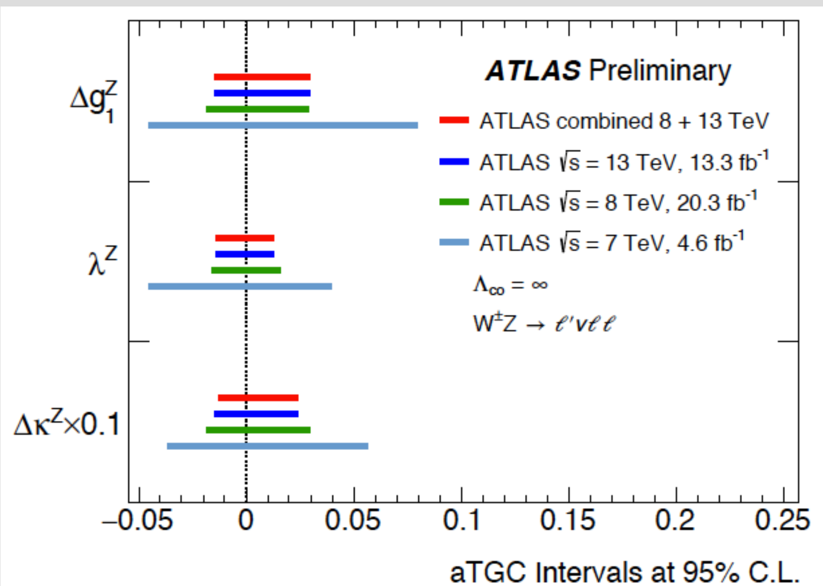
$f_4^\gamma = 0.4\%$

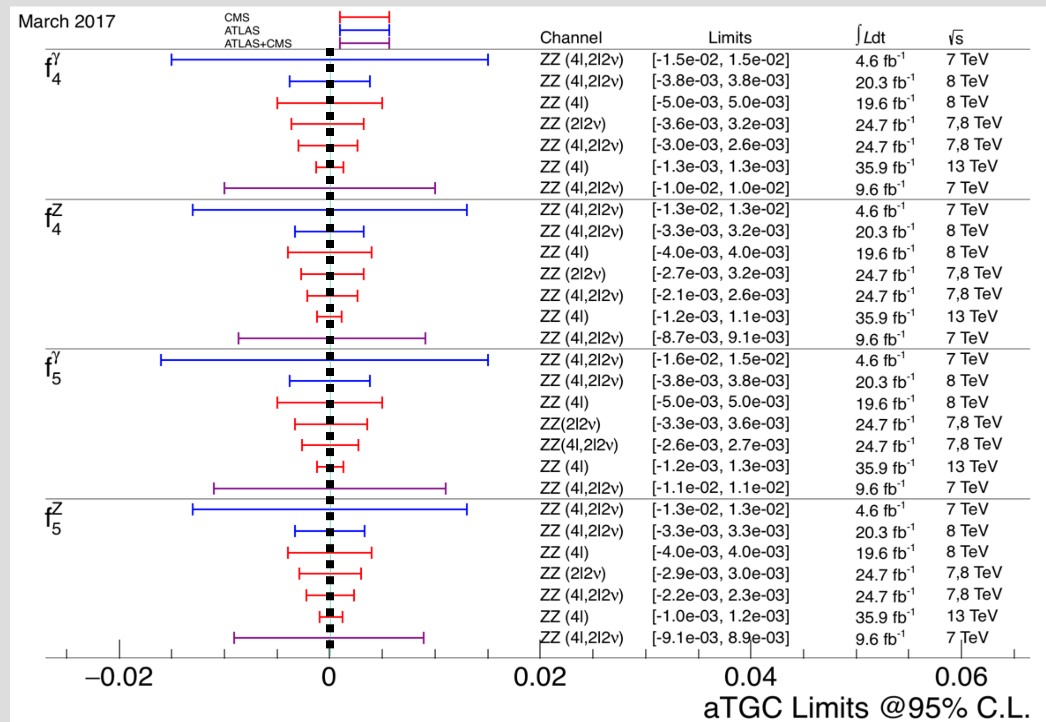
Anomalous Triple Gauge Coupling



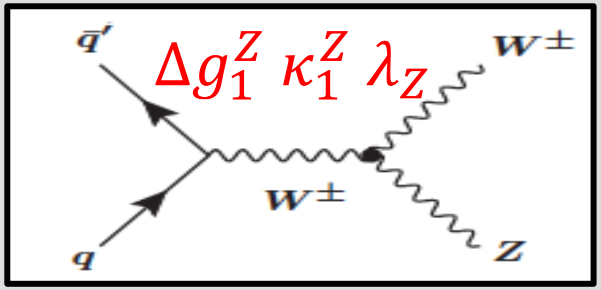


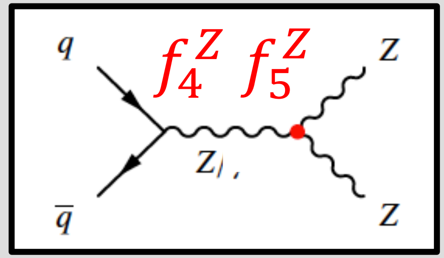


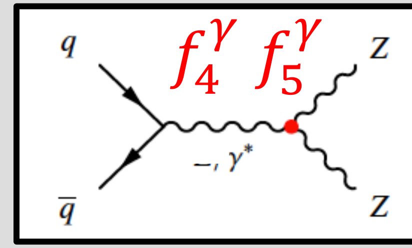


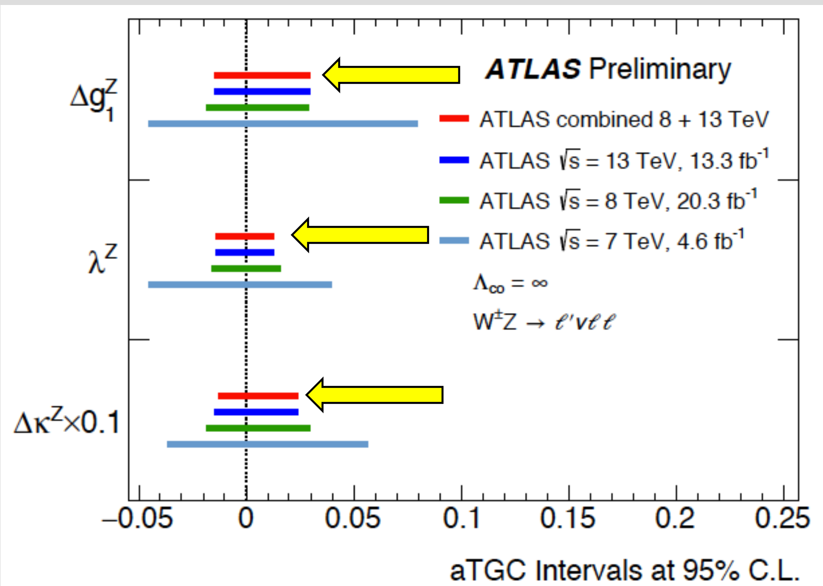


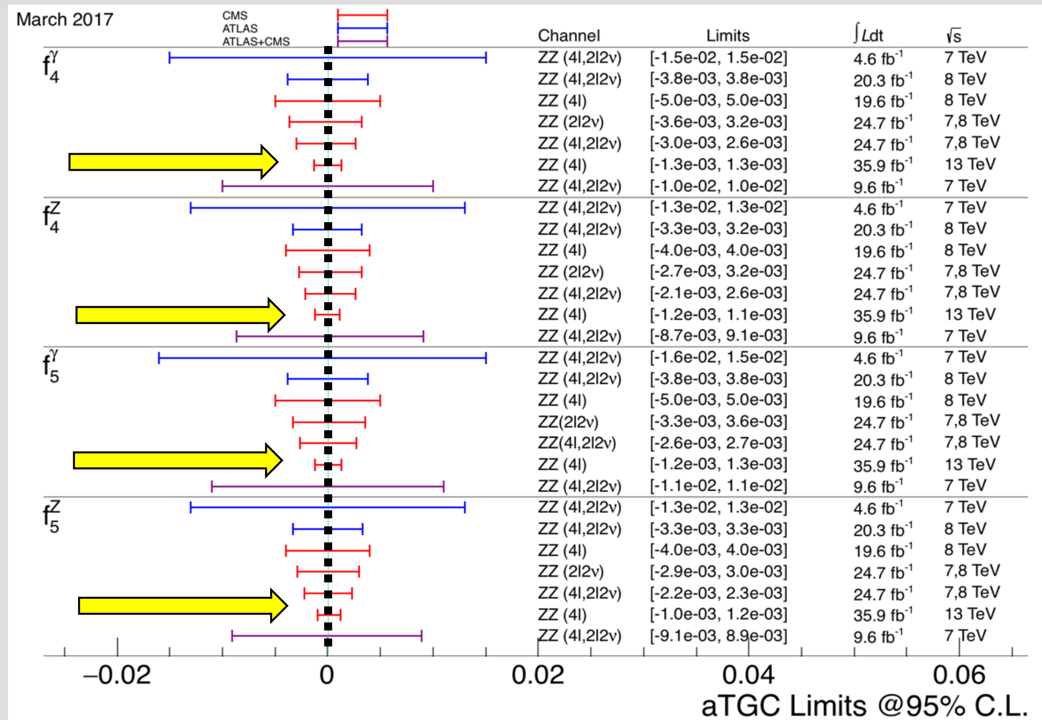
Anomalous Triple Gauge Coupling







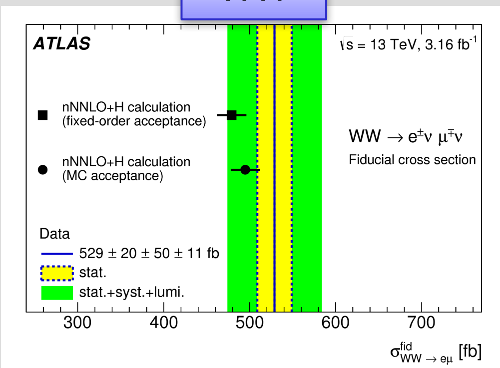




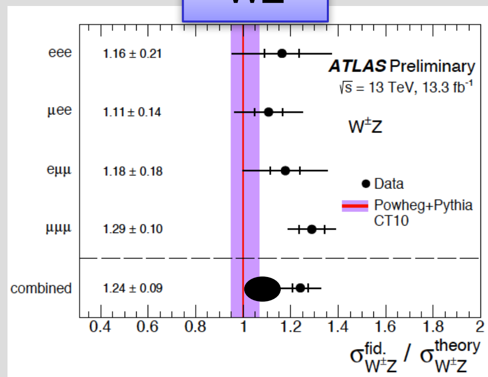
Limits in the region of few percent for charged couplings, fractions of percent for neutral coupling

Conclusions

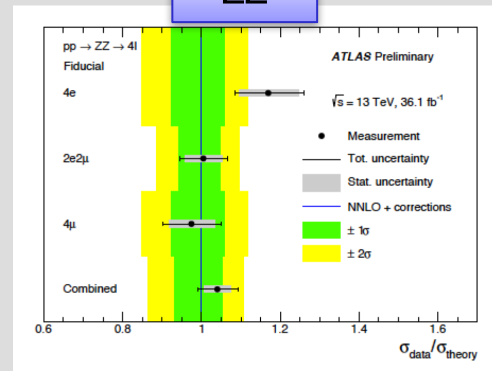
WW



WZ



ZZ

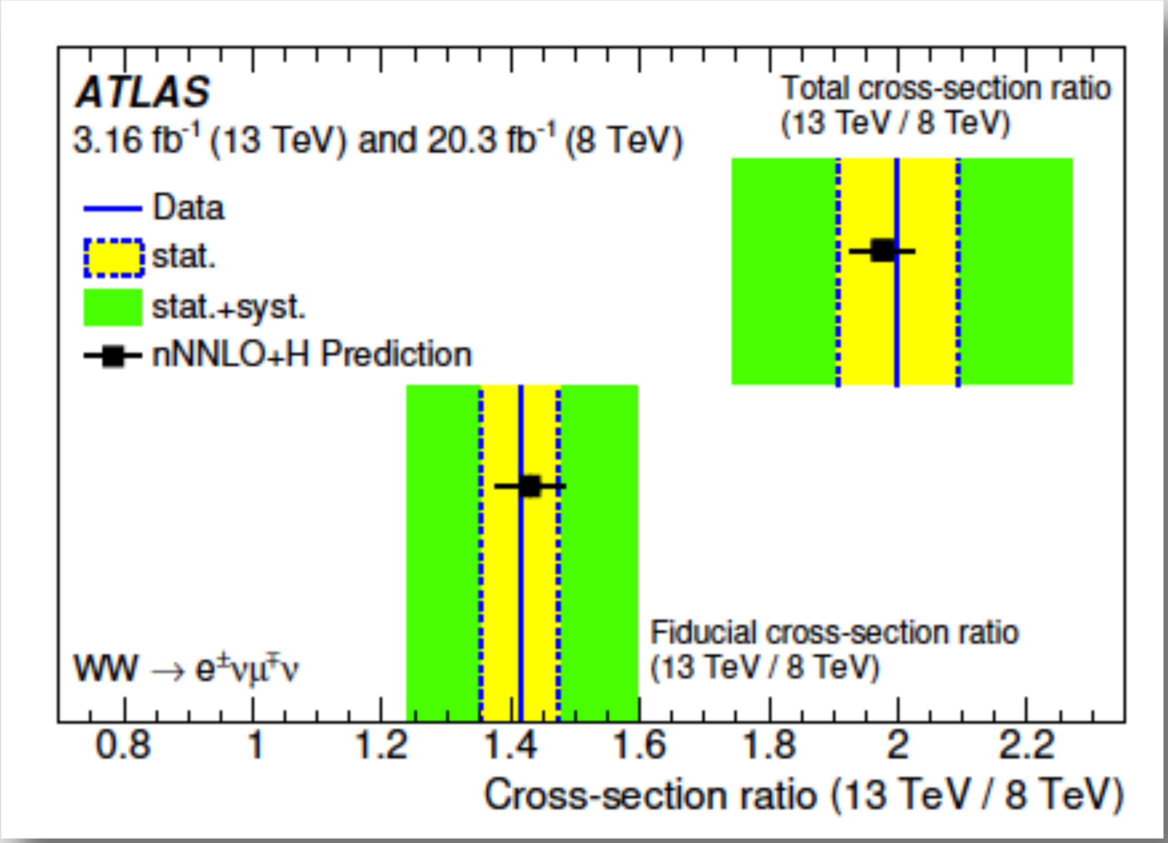


- ✓ Integral cross-sections measurements all in agreement with NLO or >NLO predictions at the <10% precision
- ✓ Unfolded integral c.s. in many variables have been obtained for WZ, ZZ processes → good descriptions of many variables
- ✓ Search for anomalous Triple Gauge Couplings gives no significant deviation from SM expectations but limits have reached O(1)-O(10) percent level

Higher statistics will allow measurements in more exclusive final states and higher precisions in differential distributions

backup

WW – total Cross-section ratios



WW - Backup

$pp \to WW$ sub-process	Order of α_s	σ^{tot}_{WW} [pb]	A [%]	$\sigma^{fid}_{WW\to e\mu}$ [fb]
$q\bar{q}$ [9, 13]	$O(\alpha_s^2)$	111.1 ± 2.8	16.20 ± 0.13	$422\ ^{+12}_{-11}$
gg (non-resonant) [33]	$O(\alpha_s^3)$	$6.82\ ^{+0.42}_{-0.55}$	$28.1\ ^{+2.7}_{-2.3}$	44.9 ± 7.2
$gg \to H \to WW$ [67][30]	$O(\alpha_s^5)$ tot. / $O(\alpha_s^3)$ fid.	$10.45\ ^{+0.61}_{-0.79}$	4.5 ± 0.6	11.0 ± 2.1
$q\bar{q}$ + gg (non-resonant) + $gg \to H \to WW$	nNNLO+H	$128.4\ ^{+3.5}_{-3.8}$	$15.87\ ^{+0.17}_{-0.14}$	478 ± 17

Table 5: Theoretical predictions for the WW cross-section sub-processes and their associated uncertainties in the full phase space (σ^{tot}_{WW}) calculated up to the given order in α_s together with the respective acceptance corrections (A) for the fiducial phase space and the fiducial cross sections ($\sigma^{fid}_{WW\to e\mu}$). The resonant $gg \to H \to WW$ is calculated up to $O(\alpha_s^5)$ for σ^{tot}_{WW} and to $O(\alpha_s^3)$ for $\sigma^{fid}_{WW\to e\mu}$ and A. A correction is applied to $\sigma^{fid}_{WW\to e\mu}$ and A to account for non-perturbative effects. The quoted uncertainties include scale variations and PDF uncertainties, with the latter being evaluated at NLO. The scale uncertainties are treated as correlated, whereas PDF uncertainties are treated as uncorrelated between the $q\bar{q}$ and the gg-induced processes. A branching ratio of leptonic W-boson decays of $\mathcal{B} = 0.1083$ [59] is used.

WW backup

Sources of uncertainty	Relative uncertainty for $\sigma^{\mathrm{fid}}_{WW\to e\mu}$
Jet selection and energy scale & resolution	7.3%
b-tagging	1.3%
$E_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{\mathrm{miss}}$	1.7%
Electron	1.0%
Muon	0.4%
Pile-up	0.9%
Luminosity	2.1%
Top-quark background theory	2.4%
Drell–Yan background theory	1.5%
W+jet and multi-jet background	3.8%
Other diboson backgrounds	1.1%
Parton shower	3.1%
PDF	0.2%
QCD scale	0.2%
MC statistics	1.2%
Data statistics	3.7%
Total uncertainty	11%

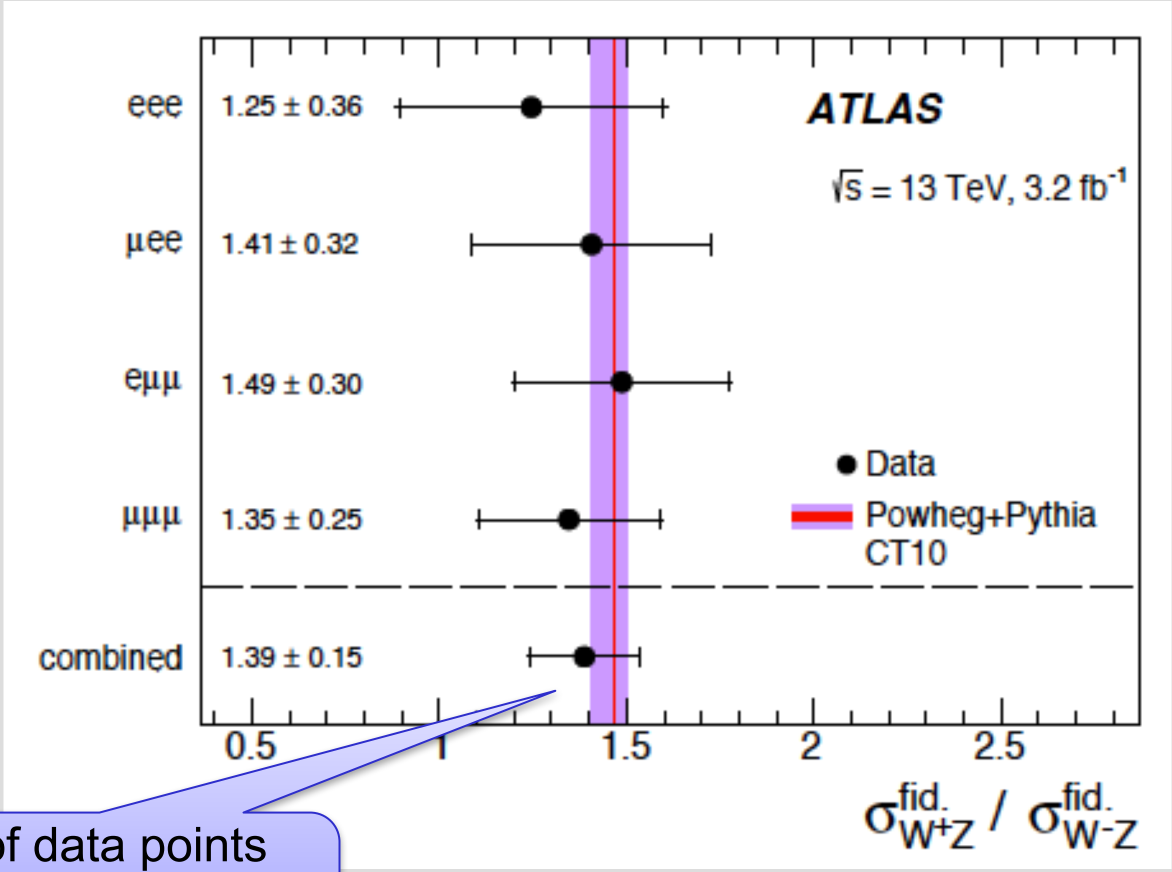
Table 4: Breakdown of the relative uncertainties in the fiducial cross-section measurement as a result of the simultaneous fit to signal and control regions. "Electron" and "Muon" uncertainties include contributions from trigger, energy/momentum reconstruction, identification and isolation.

WZ – background composition

Channel	*eee*	*μee*	*eμμ*	*μμμ*	All
Data	98	122	166	183	569
Total expected	102 ± 10	118 ± 9	126 ± 11	160 ± 12	506 ± 38
WZ	74 ± 6	96 ± 8	97 ± 8	129 ± 10	396 ± 32
$Z + j, Z\gamma$	16 ± 7	7 ± 5	14 ± 7	9 ± 5	45 ± 17
ZZ	6.7 ± 0.7	8.7 ± 1.0	8.5 ± 0.9	11.7 ± 1.2	36 ± 4
$t\bar{t} + V$	2.7 ± 0.4	3.2 ± 0.4	2.9 ± 0.4	3.4 ± 0.5	12.1 ± 1.6
$t\bar{t}, Wt, WW + j$	1.2 ± 0.8	2.0 ± 0.9	2.4 ± 0.9	3.6 ± 1.5	9.2 ± 3.1
tZ	1.28 ± 0.20	1.65 ± 0.26	1.63 ± 0.26	2.12 ± 0.34	6.7 ± 1.1
VVV	0.24 ± 0.04	0.29 ± 0.05	0.27 ± 0.04	0.34 ± 0.05	1.14 ± 0.18

Table 1: Observed and expected numbers of events after the $W^{\pm}Z$ inclusive selection described in Section 5 in each of the considered channels and for the sum of all channels. The expected number of $W^{\pm}Z$ events from Powheg+Pythia and the estimated number of background events from other processes are detailed. The total uncertainties quoted include the statistical uncertainties, the theoretical uncertainties in the cross sections, the experimental uncertainties and the uncertainty in the integrated luminosity.

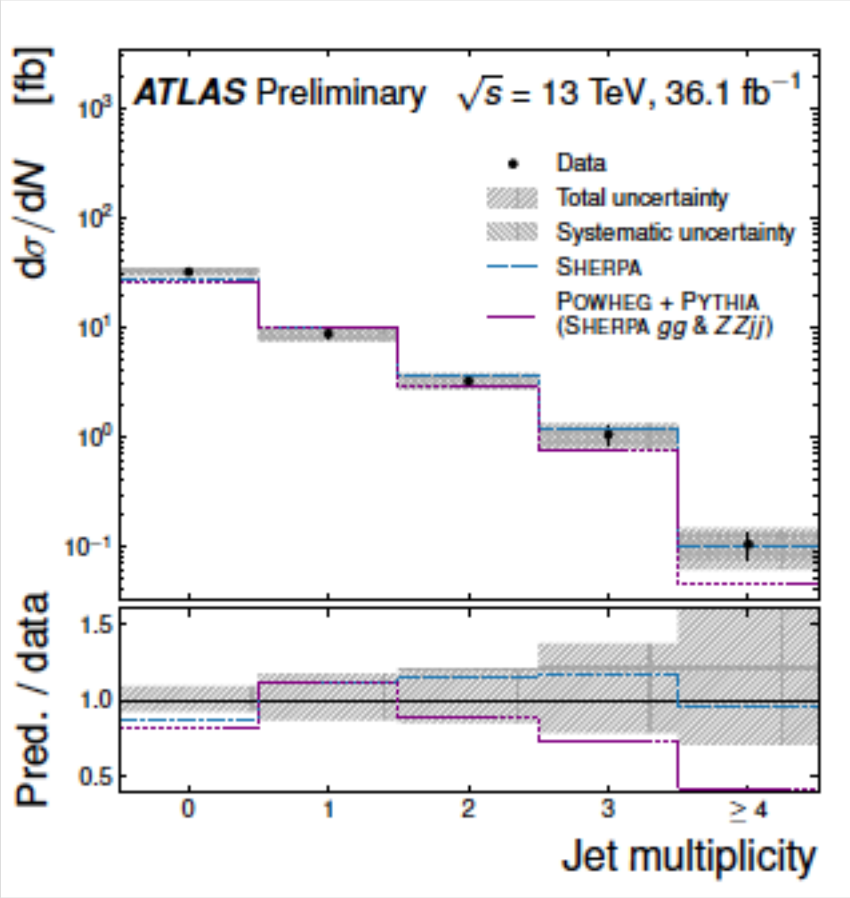
WZ – cross-section charge ratios

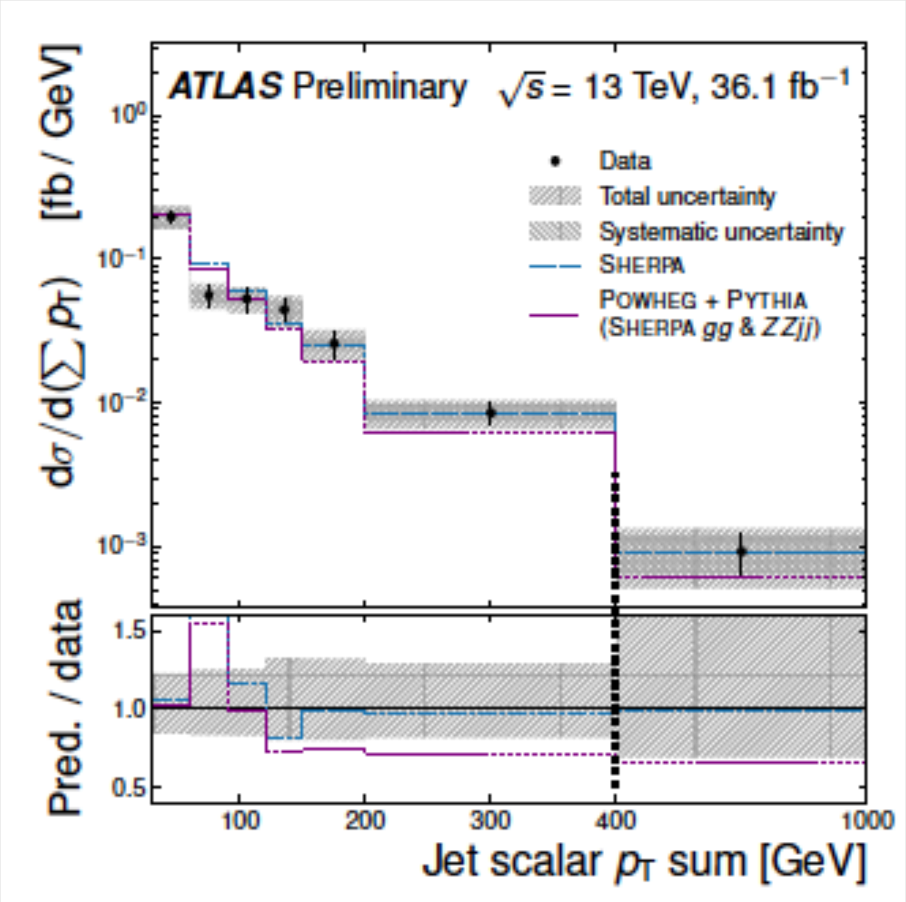


Errors of data points dominated by statistical uncertainty

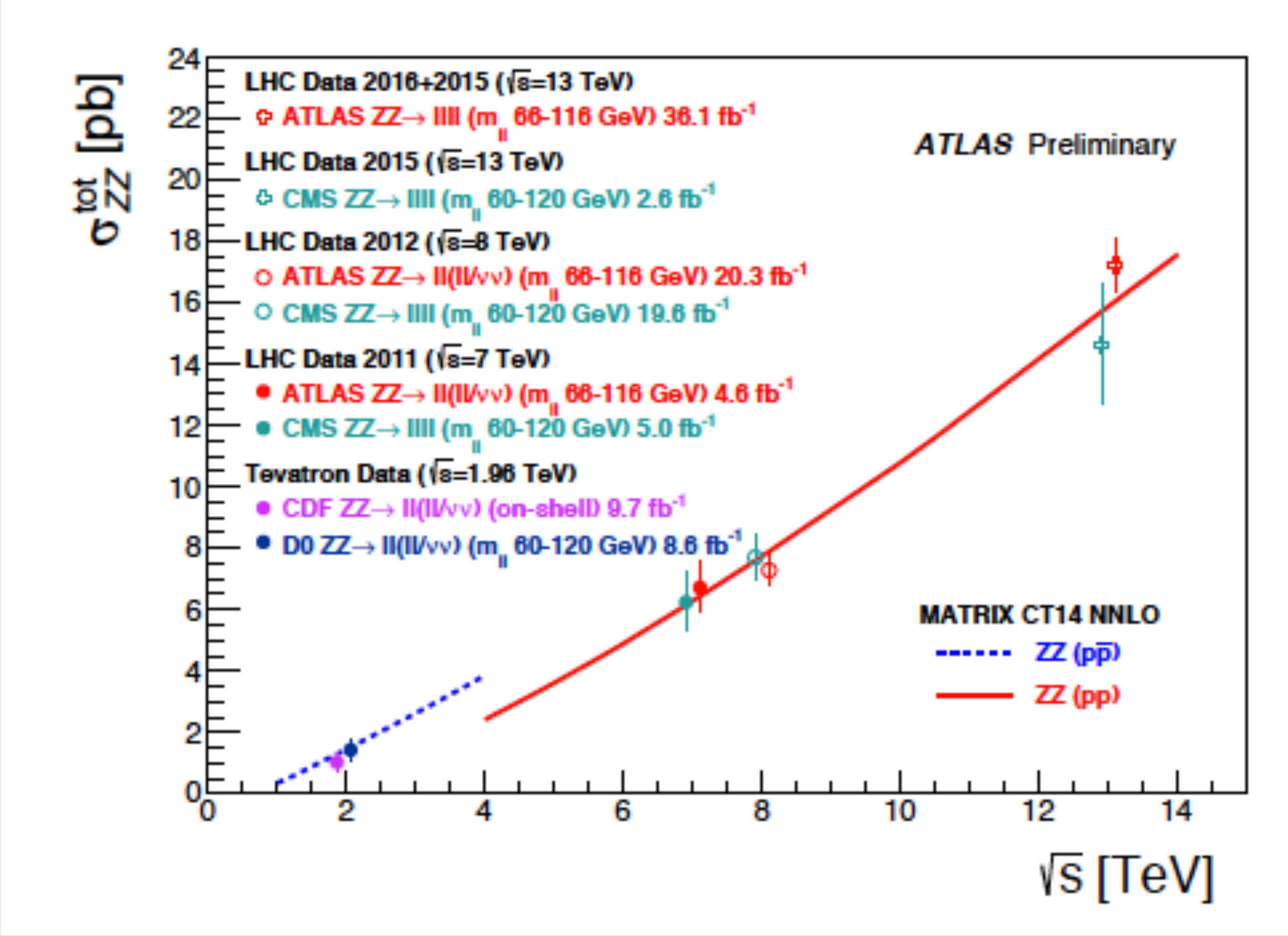
ZZ - Unfolded differential distributions

Jet activity





ZZ - Extrapolated total cross-section



ZZ – backup - Background estimate

Contribution	$4e$	$2e2\mu$	4μ	Combined
Data	249	465	303	1017
Total prediction (SHERPA)	207 ± 10	470 ± 23	298 ± 17	975 ± 46
Signal ($q\bar{q}$-initiated)	177.6 ± 8.3	400 ± 19	253.7 ± 13.4	832 ± 36
Signal (gg-initiated)	21.3 ± 3.5	50 ± 8	30 ± 5	101 ± 16
Signal (EWK-jj)	4.4 ± 0.6	10.3 ± 1.3	6.5 ± 1.0	$21.3^{+1.7}_{-2.6}$
$ZZ \to \tau^+\tau^-[\ell^+\ell^-, \tau^+\tau^-]$	0.6 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	1.7 ± 0.2
Triboson	0.7 ± 0.2	1.5 ± 0.5	1.0 ± 0.3	3.1 ± 0.9
$t\bar{t}Z$	0.8 ± 0.2	1.9 ± 0.6	1.4 ± 0.4	4.1 ± 1.2
Misid. lepton background	2.0 ± 1.1	4.9 ± 2.8	5.2 ± 5.0	12.1 ± 8.3
Total prediction (POWHEG + PYTHIA with higher-order corrections, SHERPA)	193 ± 9	456 ± 23	286 ± 16	934 ± 47

ZZ backup

Source	Effect on total predicted yield [%]
MC signal sample statistics	1.2
Electron efficiency	0.9
Electron energy scale & resolution	< 0.1
Muon efficiency	1.7
Muon momentum scale & resolution	$^{+0.1}_{-0.0}$
Pileup modeling	0.7
Luminosity	3.2
QCD scales	$^{+2.3}_{-2.2}$
PDFs	$^{+2.0}_{-1.7}$
Background prediction	0.9
Total	$^{+5.0}_{-4.9}$

Table 3: Relative uncertainties in percent of the predicted integrated signal yields after event selection, derived using the nominal Sherpa setup. All uncertainties are rounded to one decimal place.

ZZ - Uncertainty on Czz

Source	$4e$	$2e2\mu$	4μ
MC signal sample statistics	1.1	0.6	0.6
Electron efficiency	2.0	1.0	< 0.1
Electron energy scale & resolution	$^{+0.1}_{-0.3}$	$^{+0.0}_{-0.1}$	$^{+0.1}_{-0.0}$
Muon efficiency	< 0.1	1.6	3.2
Muon momentum scale & resolution	< 0.1	$^{+0.0}_{-0.1}$	$^{+0.3}_{-0.1}$
Pileup modeling	0.2	0.8	1.0
QCD scales & PDFs	0.1	0.1	0.1
Generator	0.9	0.7	< 0.1
Total	2.4	2.2	3.4

Table 4: Relative uncertainties of the correction factor C_{ZZ} by channel, given in percent. All uncertainties are rounded to one decimal place.

Triple Gauge Coupling - backup

$$\mathcal{L}_{WWV} = ig_{WWV}\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right]$$

$V = Z, \gamma$

$g_{WW\gamma} = -e$

$g_{WWZ} = -e\cot\theta_W$

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

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

→ Parameterize deviation form SM using 4 parameters: f_4^Z, f_4^γ (CP-violating), f_5^Z, f_5^γ (CP-conserving).