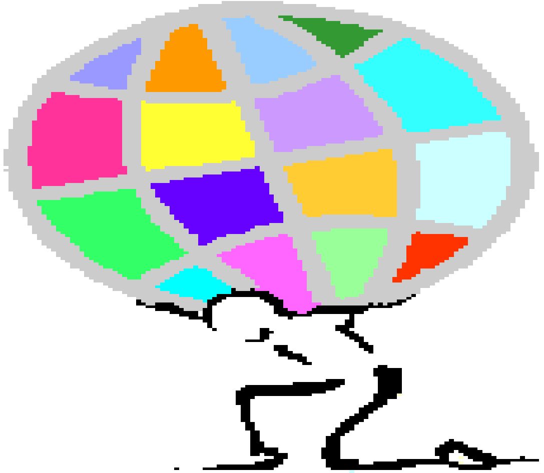
# *New results on W boson production with the ATLAS detector*

E. Meoni

UNIVERSITA DELLA CALABRIA

On behalf of the

**ATLAS Collaboration**



Rencontres du Vietnam August 5 – 11, 2018 • ICISE • Quy Nhon, Vietnam

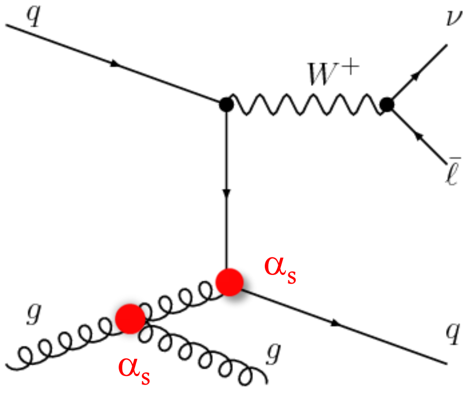
WINDOWS ON THE UNIVERSE

# Motivations

Latest ATLAS results concern W production in association with jets

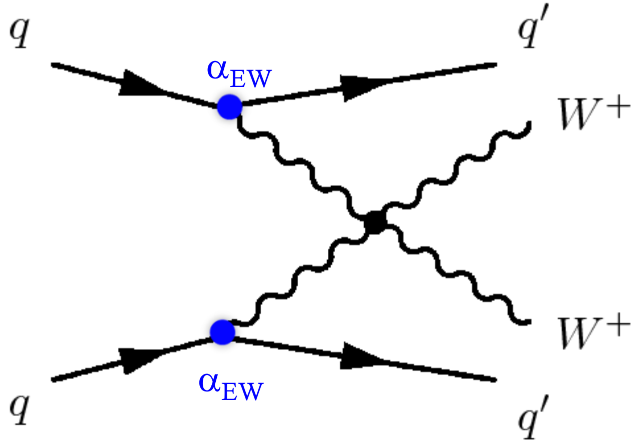
W+jets production dominated by **strong interactions:**

- Precision test of pQCD
  → test state-of-the-art (N)NLO pQCD calculations
- Background to Higgs and New Physics
  → important validation of the Matrix Element (ME) + Parton Shower (PS) MCs
- Impact on PDFs understanding




Production via purely **electroweak processes** rarer:

- Probe triple and quadratic gauge boson self-interactions
  → explore new physics in a model independent way (anomalous couplings)
- Probe the nature of the EW symmetry breaking, testing the unitarization in VV scattering by HVV contribution (VBS)
- Understand irreducible background to Higgs and beyond-SM searches
  → Constrain MC modelling of QCD-initiated processes in VBF-like regions



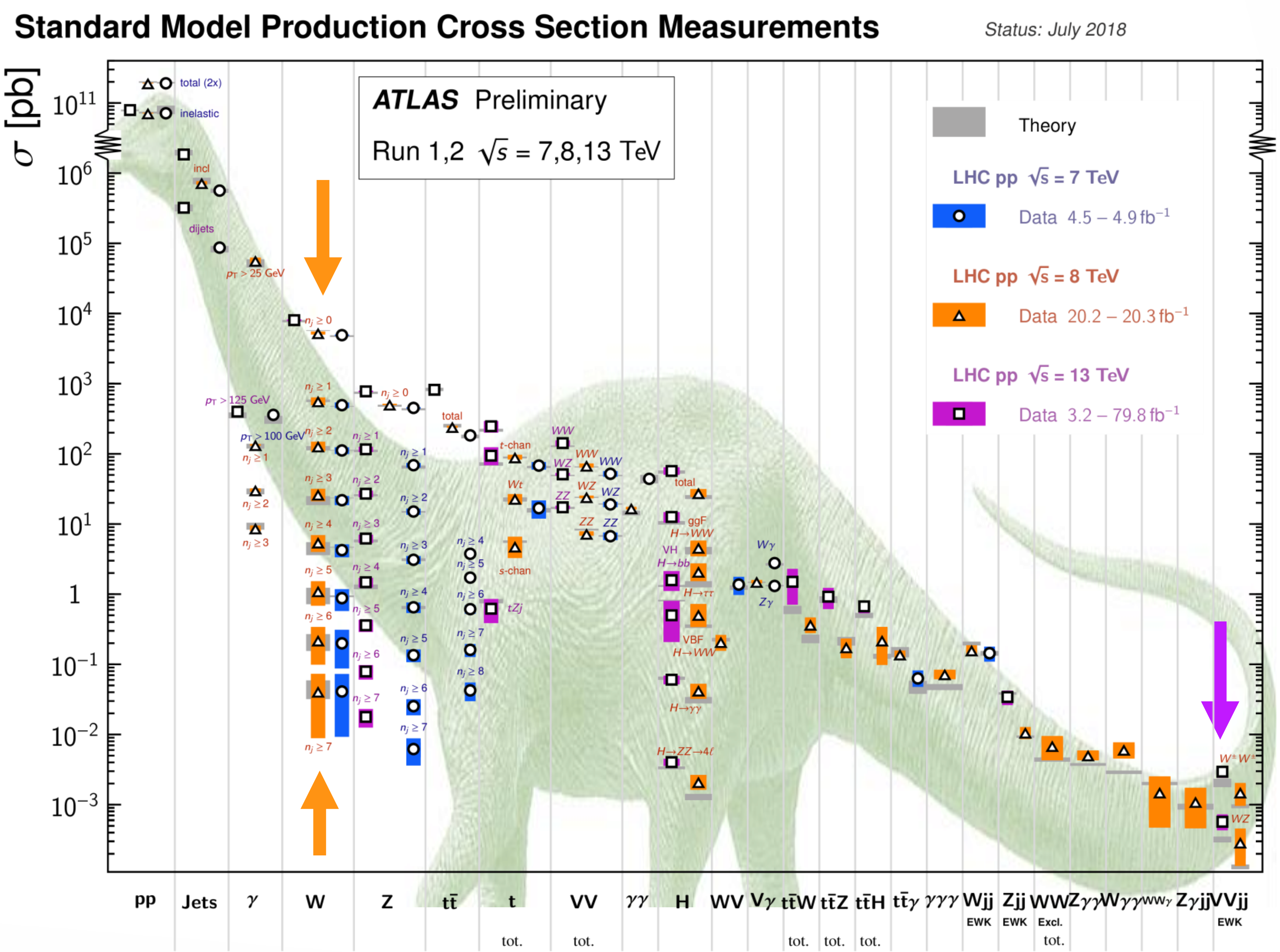

**Vector Boson Scattering (VBS)**

# Outline

Measurements presented today:

**QCD production:**
W+jets@8TeV
JHEP 05 (2018) 077

**EW production:**
EW WW same sign +jets@13TeV
(ATLAS-CONF-2018-030)



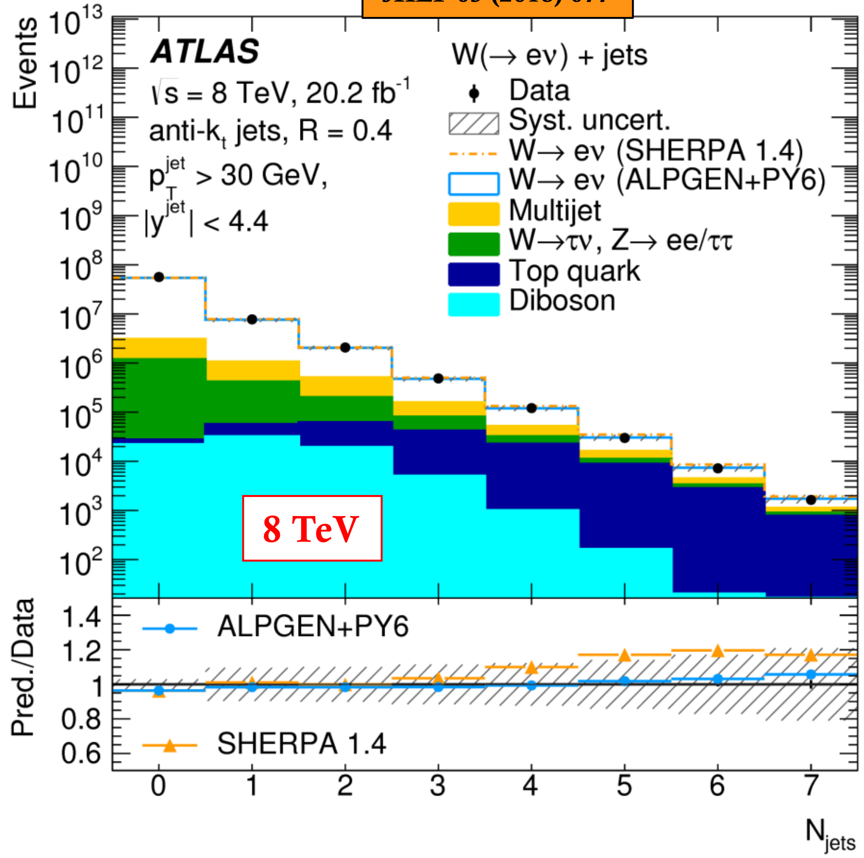
# W+jets: detector level

Look at leptonic decays **W→eν**

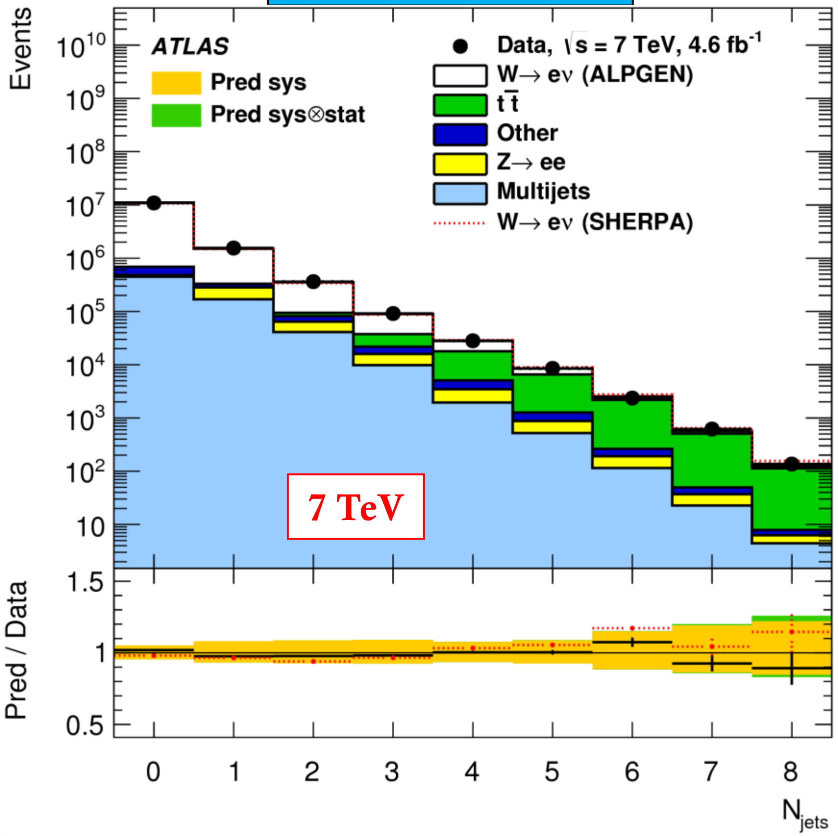
Kinematical region with high efficiencies, good detector performances and low backgrounds

**Leptons**: 1 lepton with $p_T$>25 GeV, |η|<2.47
**W:** Missing $E_T$ >25 GeV; $m_T^W$>40 GeV
**Jets:** antikt4, $p_T$>30 GeV, |y|<4.4 ΔR (l,j)>0.4
**b-jets veto:** reject events with >=1 b-jet with $p_T$>20 GeV |η|<2.5

JHEP 05 (2018) 077




Eur. Phys. J. C (2015) 75:82




b-jet veto reduces ttbar background for events with three or more associated jets by more than a factor two compared to the previous ATLAS measurement@7TeV (60% → 27%)

# W+jets : particle level

**JHEP 05 (2018) 077**

## The Detector Level

**Signal= Data –BKGs**

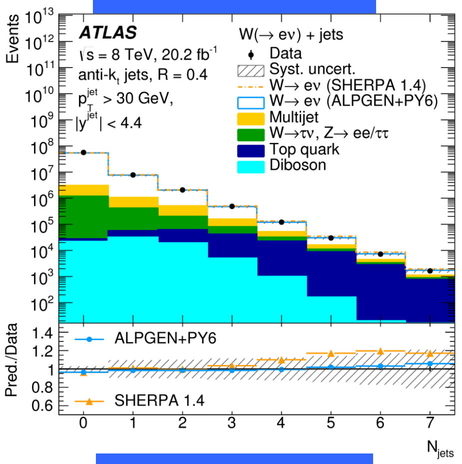
**UNFOLDING with MC**
- Correct for detector effects (trigger and reconstruction efficiency, resolution, scales)
- Fiducial phase space close to the detector-level's one

## The Particle Level

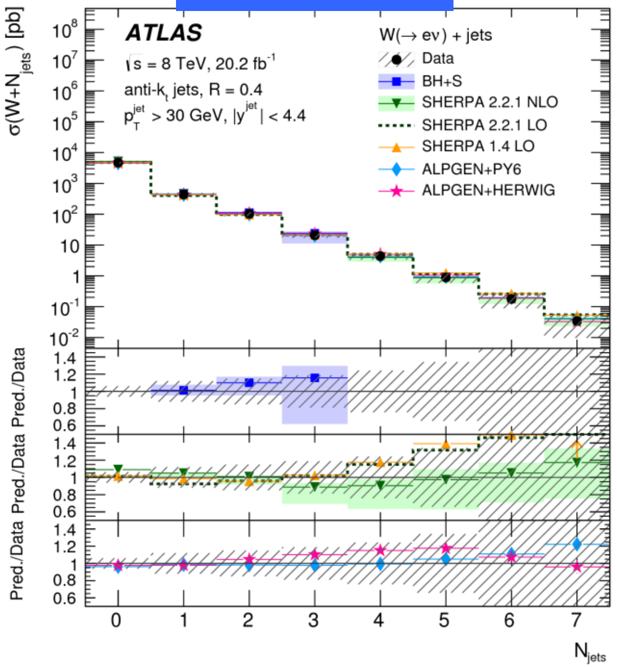
**Comparisons : Data unfolded – MCs**
**Data unfolded – Fixed order calculations** corrected for non perturbative effect (Underlying event, fragmentation)

| MCs/Calculations | Features | Tools |
|---|---|---|
| MC | mP LO ME +PS MC | Alpgen (up to 5 partons) |
| | | Sherpa 1.4 (up to 4 partons) |
| | NLO ME+PS MC | Sherpa 2.2.1 (NLO up to 2 partons) |
| Fixed order calculation | NLO | BlackHat+Sherpa (NLO up 3 partons in this paper) |
| | | MCFM (NLO up 1 parton in this paper) |
| | NNLO | $N_{jetti}$ (NNLO up to 1 partons) |

Detector Level




Particle Level



# W+jets : $N_{jets}$

JHEP 05 (2018) 077

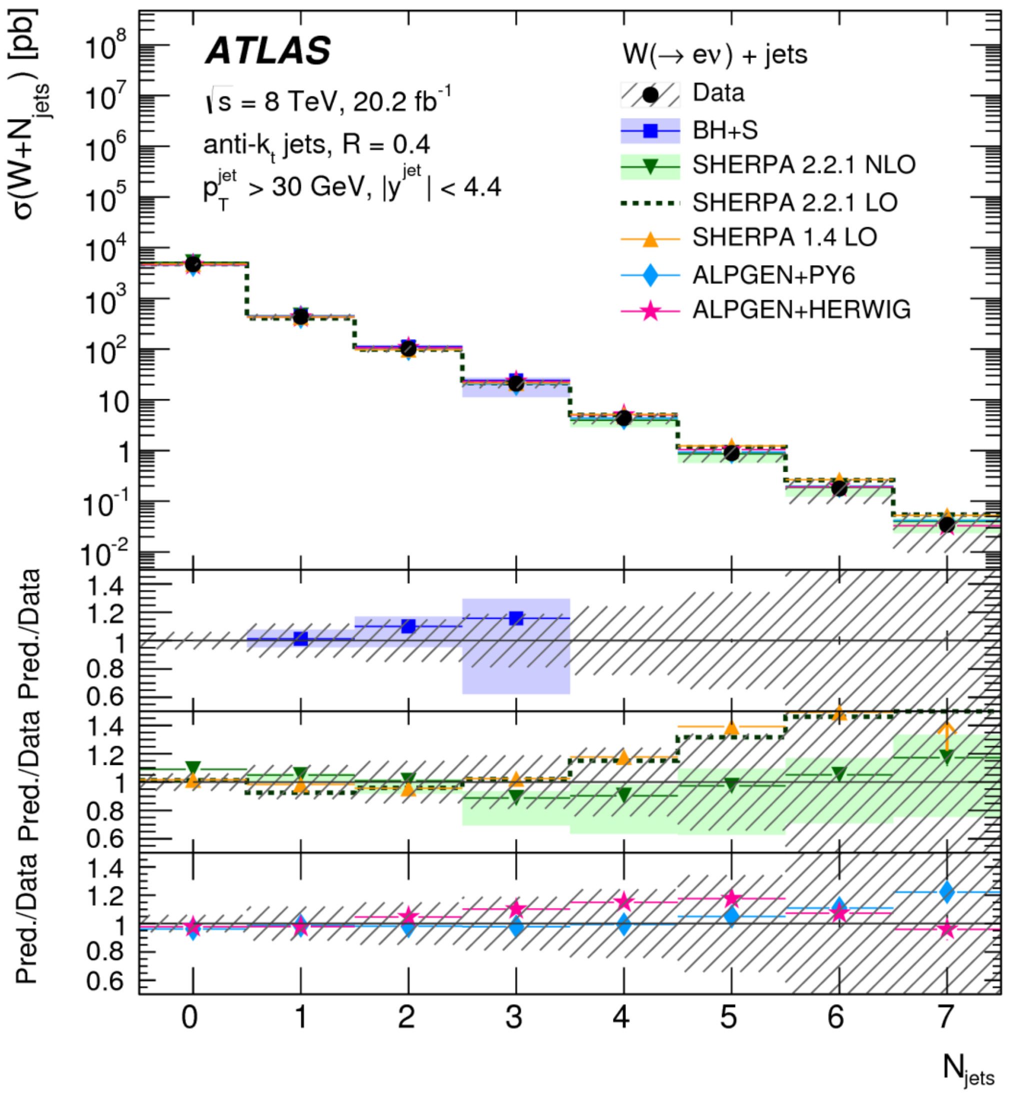
Figure of merit of goodness of QCD predictions

Jet counting important discriminator with respect to the background in Higgs and searches

Predictions agree with the data within the experimental uncertainties.

At high multiplicities, the **LO Sherpa** predictions start to diverge from the data, while the **NLO Sherpa** predictions provide a much better description of the data.

**LO Alpgen** predictions (with 2 different PS models) are consistent with the data within the experimental uncertainties.



# W+jets: $H_T$

$$H_T = \sum_{leptons,jets} |p_T|$$

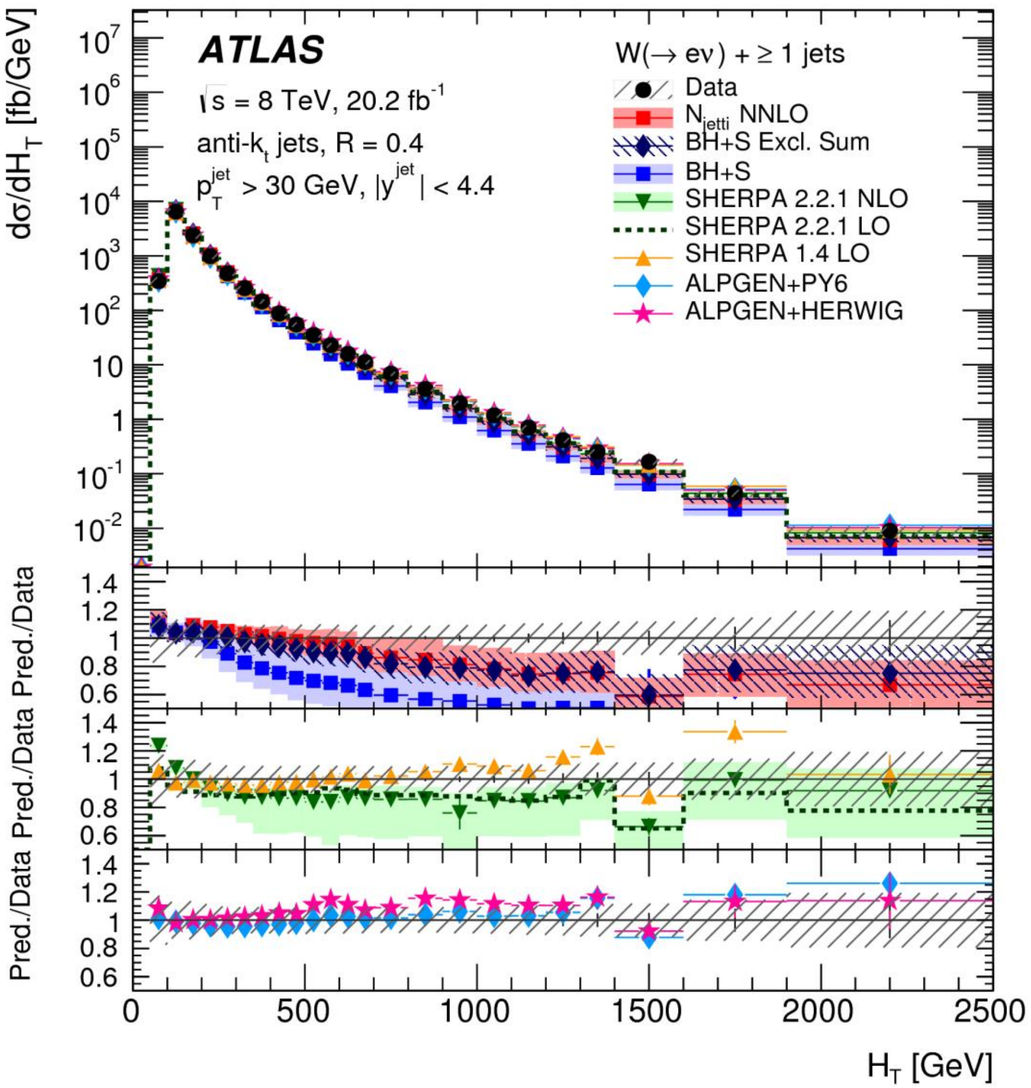
Important for searches: signal topologies with large jet activity (discriminant with respect to SM background)

LO Alpgen and LO & NLO Sherpa describe the data best.

NLO BlackHat+Sherpa underestimates the data at large values of $H_T$, due to missing higher order contributions.

**BlackHat+Sherpa exclusive sums** and **NNLO $N_{jetti}$** calculation, which include an additional jet emission at NLO, provide better agreement with the data.

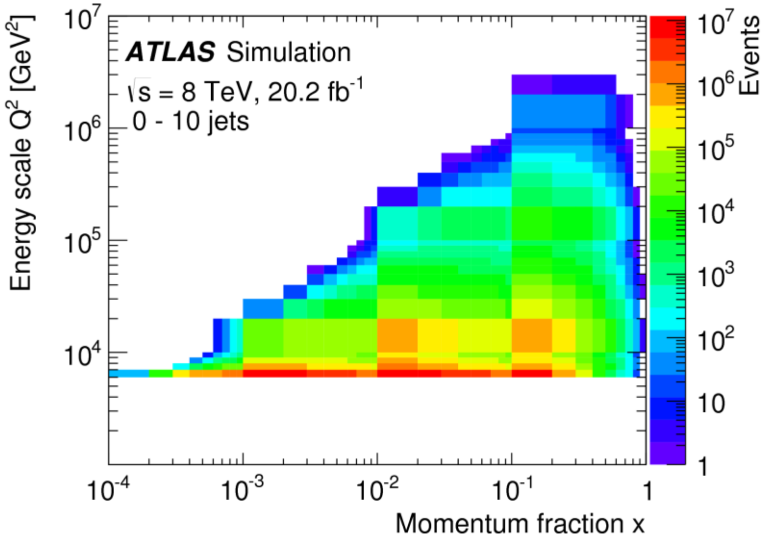
JHEP 05 (2018) 077

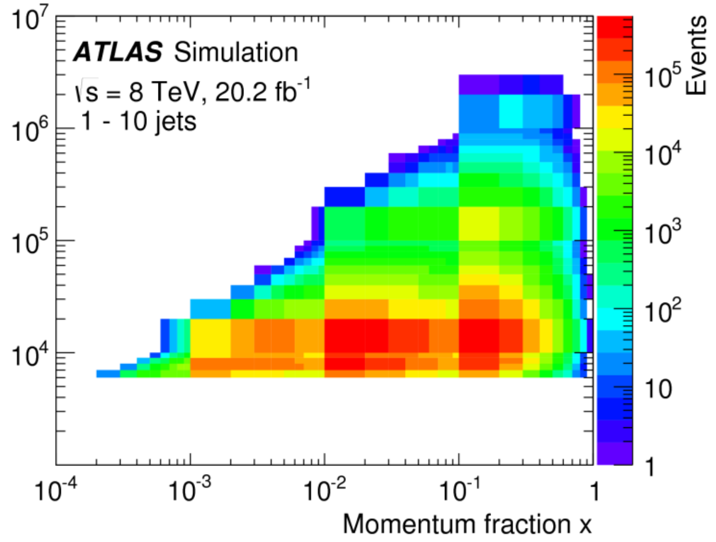


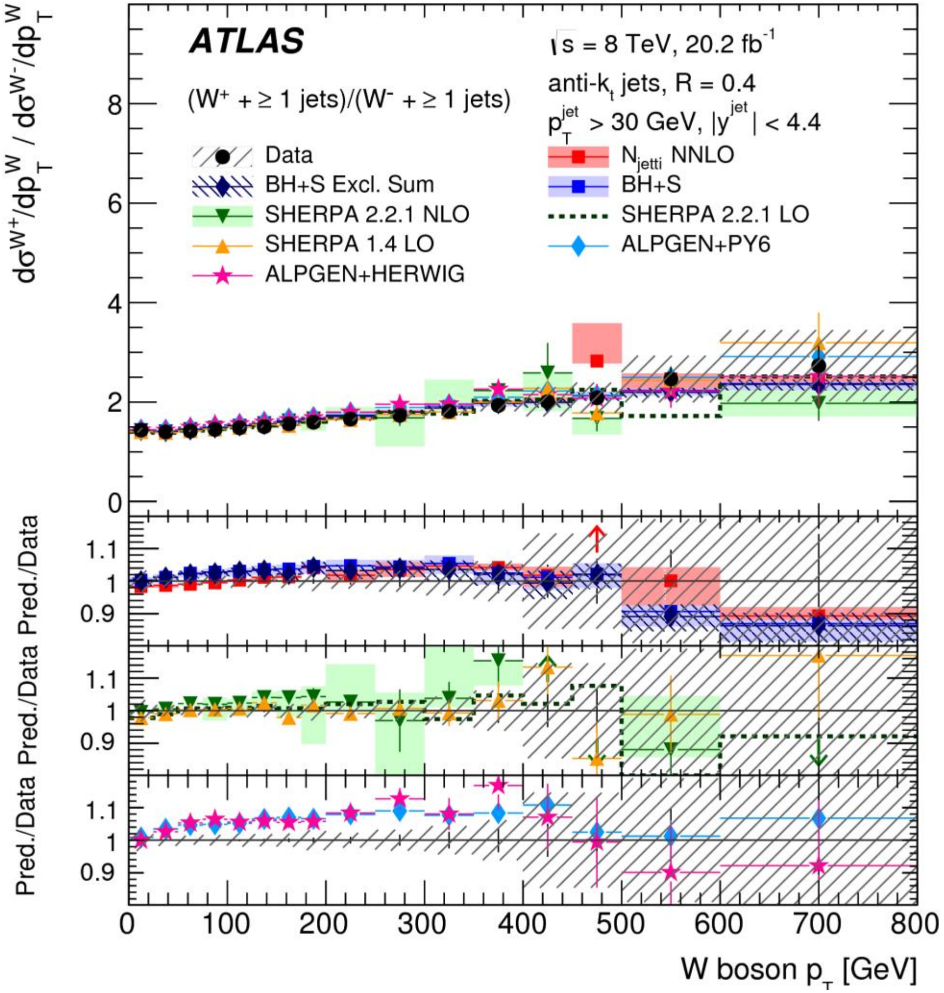
# Ratio $W^+$+jets/$W^-$+jets

JHEP 05 (2018) 077

Ratio of $W^+$ to $W^-$ production:
- more precise test of the theoretical predictions: cancellation of many experimental and theoretical uncertainties
- sensitive to the PDFs for up and down quarks: presence of at least one jet shifts to higher x-$Q^2$ range than inclusive W analyses → Complementary to W asymmetry



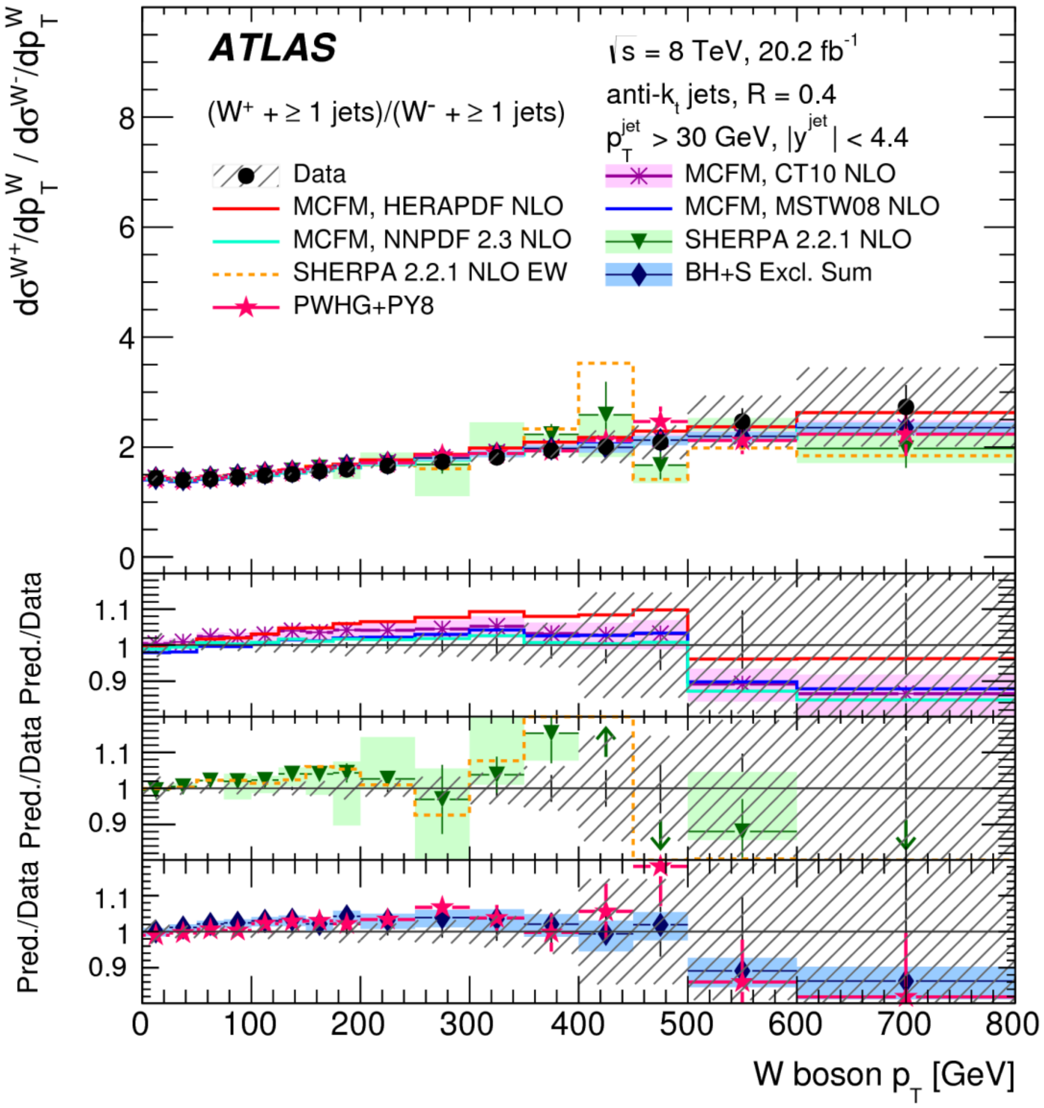



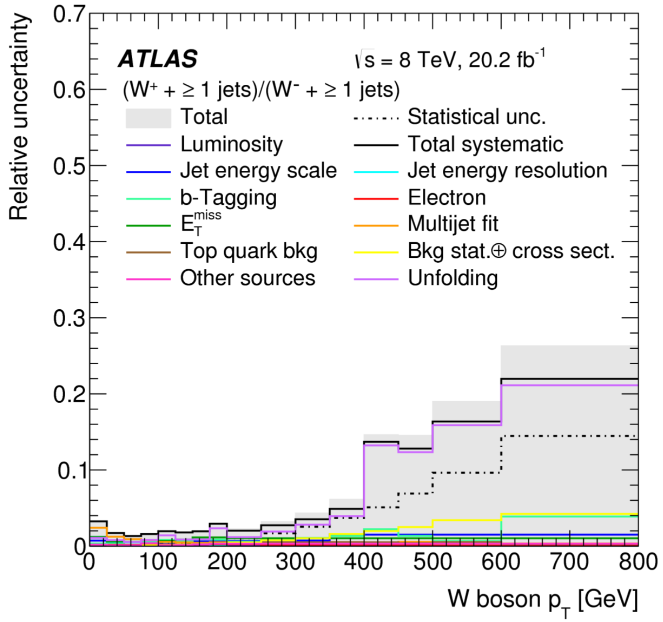

Neither of the predictions describe the data well. Most predictions (except $N_{jetti}$ **NNLO** and **LO Sherpa**) overestimate the data between one to almost four times the experimental uncertainties. This effect is largest for **Alpgen**

# Ratio $W^+$+jets/$W^-$+jets

JHEP 05 (2018) 077




**MCFM predictions with four different PDF sets** differ of ~2-5% between 200-400 GeV, where data uncertainty is very small




Differences MCFM-Data up to 2-3 times the experimental uncertainty → Measurement useful in global PDF fits

# W+jets :$\Delta R_{jj}$

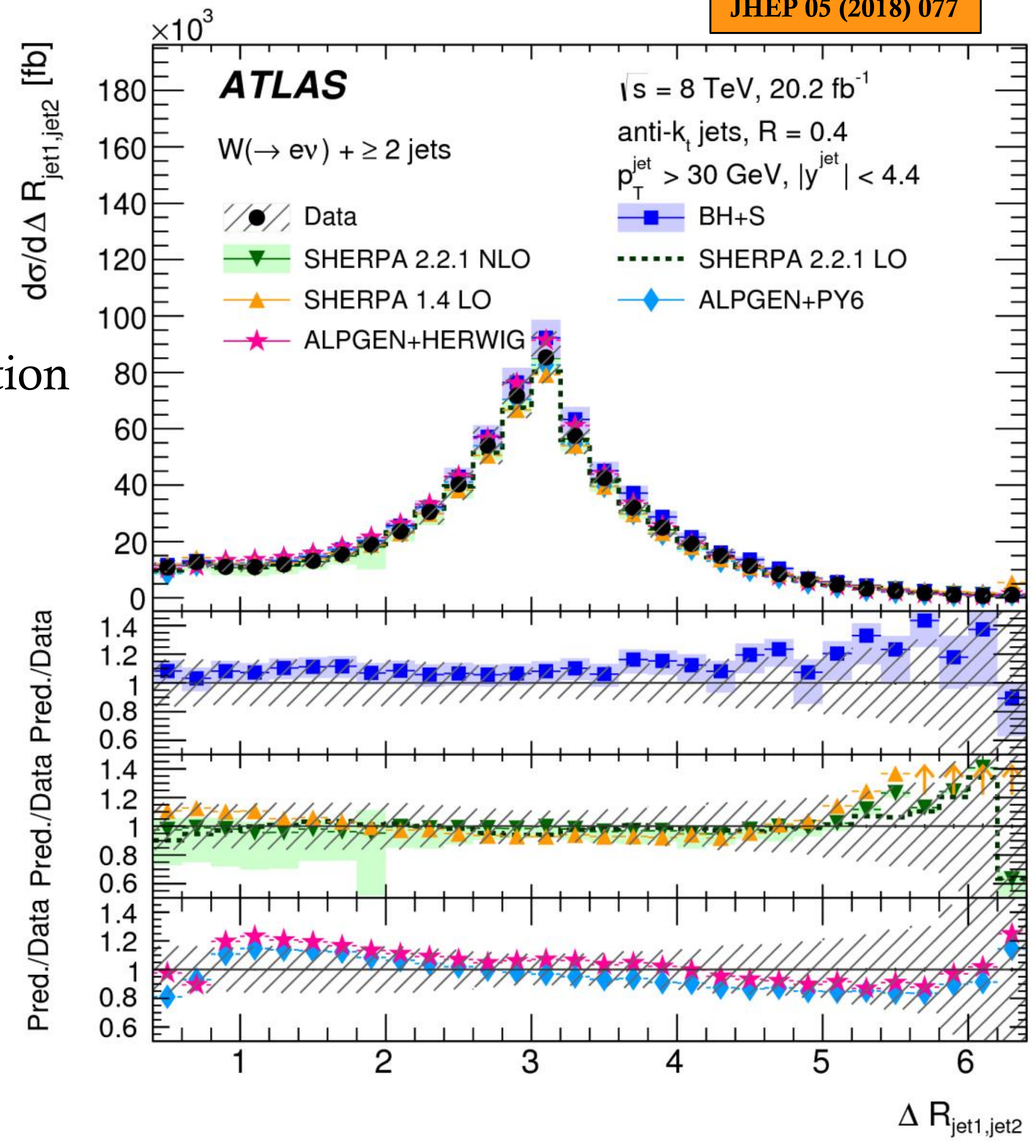
JHEP 05 (2018) 077

Dijets angular observables test hard radiation at large angles from ME and soft collinear radiation from PS and ME/PS matching schemes.

NLO BlackHat+Sherpa describes the data well with a cross section slightly higher than in the data

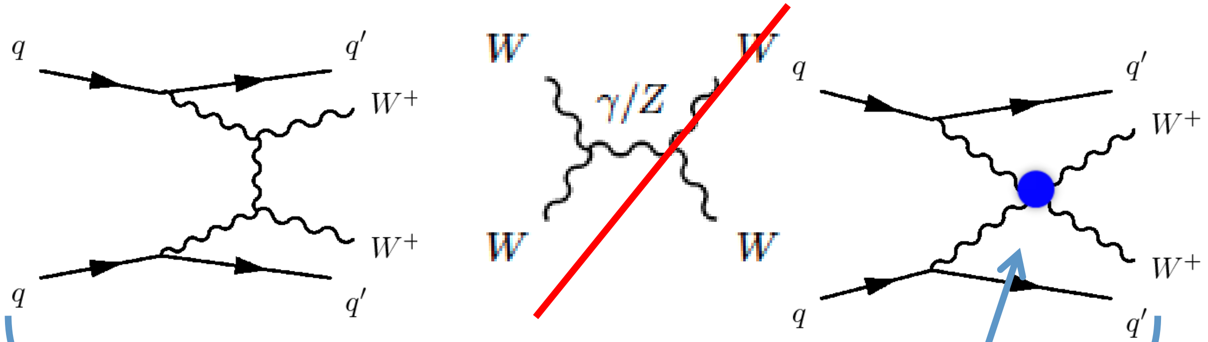
LO Sherpa predicts too many events at large angular separations, NLO Sherpa describe the data better

LO Alpgen show a systematic trend to data

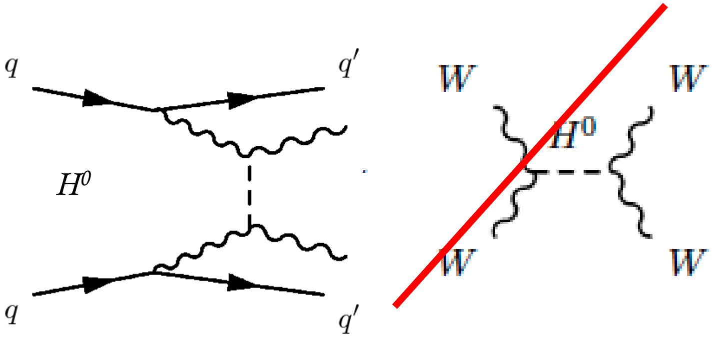


# $W^{\pm}W^{\pm}jj$

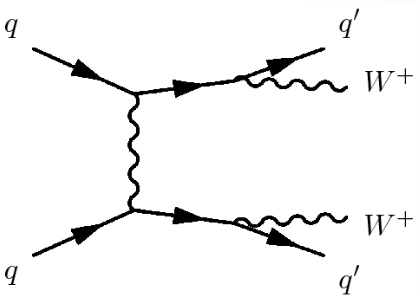
**Electroweak processes:**



**Self-interactions**



**Higgs contributions**

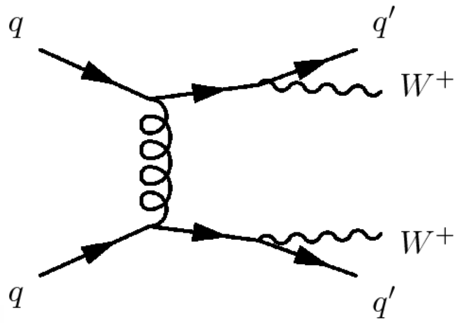


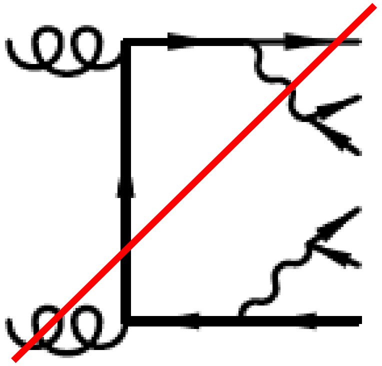
**Non resonant**

Sensitive to quadratic gauge couplings (QGCs)

$W_LW_L \rightarrow W_LW_L$ violates unitarity without a SM Higgs

**QCD processes:**





In $W^{\pm}W^{\pm}jj$ (same sign) production some diagrams do not contribute

→Smaller cross-section than $W^{+}W^{-}jj$ (opposite sign), but also large suppression of QCD processes

→ **Golden channel to study VBS**

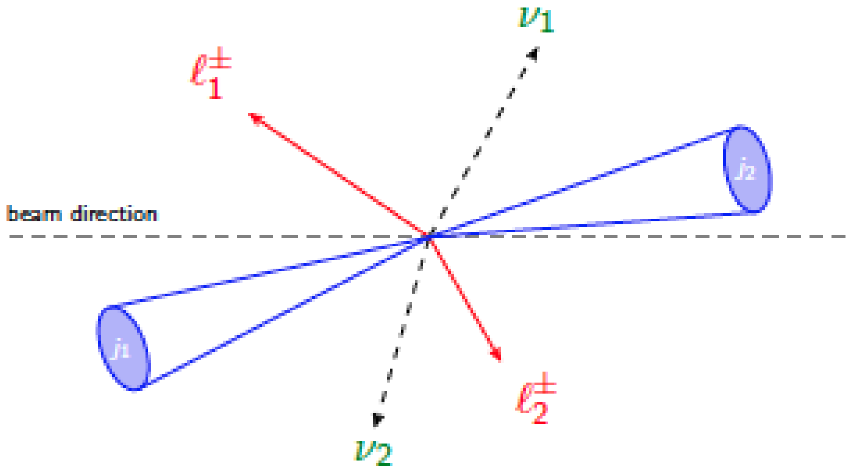
# $W^{\pm}W^{\pm}jj$: Event Selection

ATLAS-CONF-2018-030

**Detector level selection :**

-2 isolated same-sign leptons ($e^{\pm}e^{\pm}$,$\mu^{\pm}\mu^{\pm}$,$e^{\pm}\mu^{\pm}$) central and with $p_T >$ 27 GeV and $m_{ll}$>20 GeV
- Missing $E_T >$ 30 GeV
- >=2 jets with $p_T^{j1} >$ 65 GeV , $p_T^{j2}$ >35 GeV
- $|\Delta y_{jj}|>2$
- $m_{jj}$> 500 GeV

To enhance VBS against QCD (similar to VBF analyses)




→ **Fiducial phase-space to extract cross-section measurement** very close to detector level selection

**Further background reduction (applied only at detector level):**

-additional leptons veto events → reduce background with prompt leptons

-Z veto in ee final state → reduce Z+jets background from charge mis-ID

-veto events containing b-jets → reduce ttbar

→ **EW signal extracted with fit on $m_{jj}$ distribution**

# $W^{\pm}W^{\pm}jj$: Signal & Background

ATLAS-CONF-2018-030

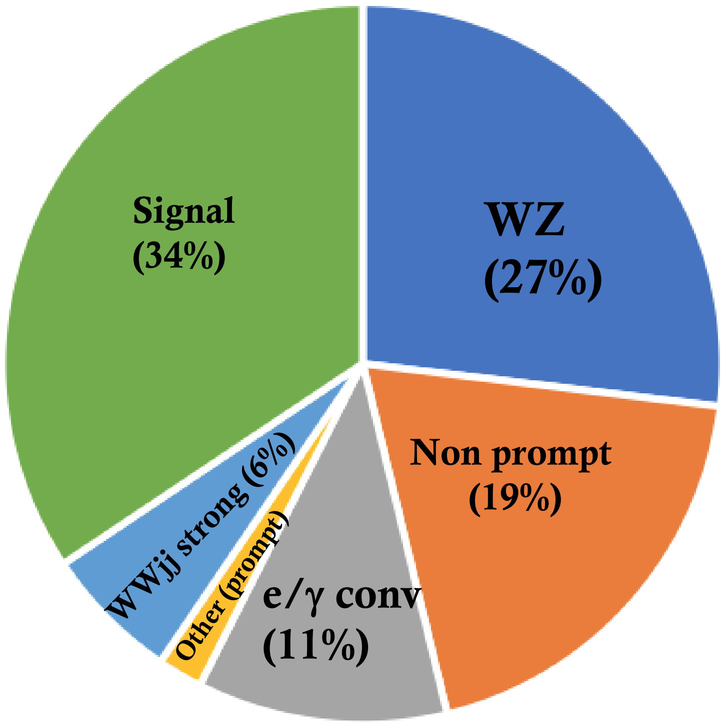
**Non-prompt lepton backgrounds** (W+jets, ttbar (semi-leptonic), dijet) with data-driven technique in control region with a 50-90% uncertainty, dominant one pre-fit

**Electron charge mis-identification & prompt photon conversions:**
- Electron charge mis-ID (Z+jets, $W^+W^-$, ttbar (di-leptonic)) with data-driven technique
- Prompt photon conversion: $W\gamma$ from MC normalization from control region

**Prompt backgrounds:**
**WZ** from MC with normalization from a trilepton control region
**strong $W^{\pm}W^{\pm}jj$** **subtracted as background**.

**Signal** modeled with Sherpa v 2.2.2
- Alternative NLO in QCD sample with PowhegBox +Pythia8

**A total of 122 candidate events is observed for a background expectation of 78 ± 15 events before the fit**




**Expected Signal and background composition before fit**

# $W^{\pm}W^{\pm}jj$: the observation

ATLAS-CONF-2018-030

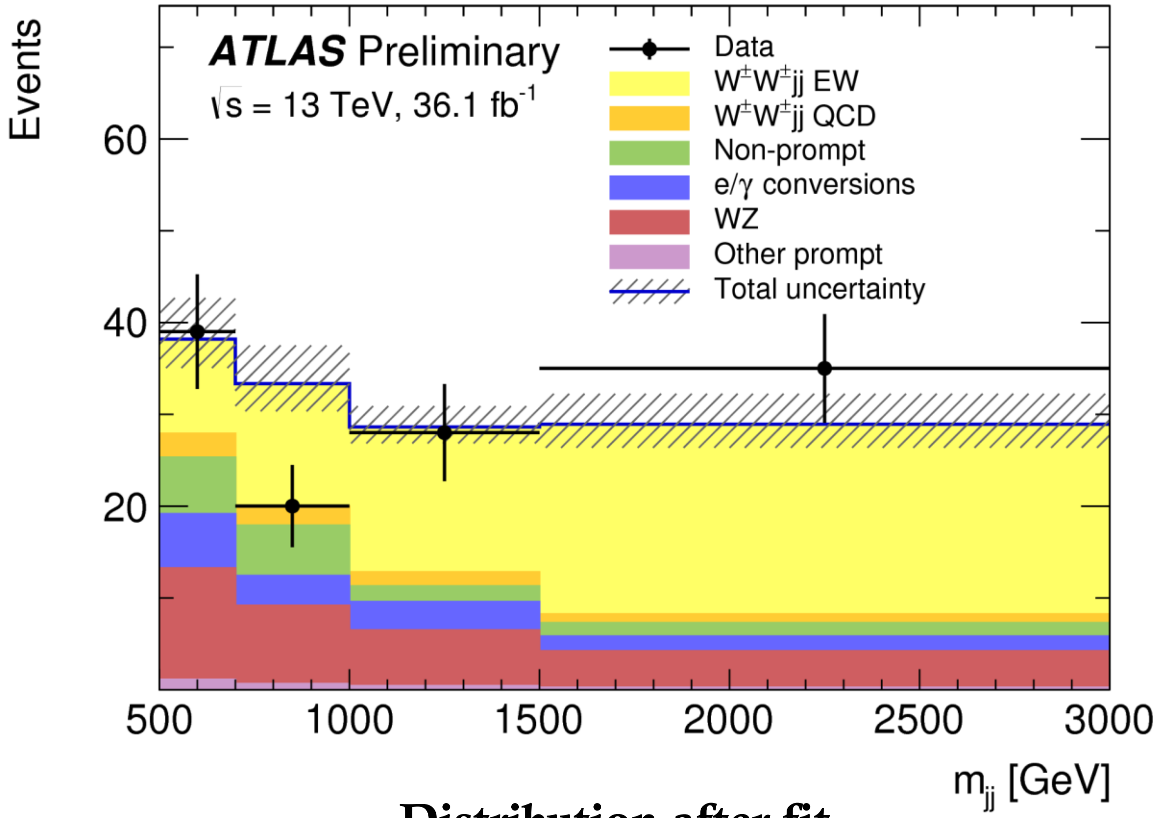
Analysis performed in **six channels:**
$e^+e^+$, $\mu^+\mu^+$, $e^+\mu^+$ and $e^-e^-$, $\mu^-\mu^-$, $e^-\mu^-$

Signal extracted in a **binned fit** to $\mathbf{m_{jj}}$ distributions (4 bins) in signal region ($m_{jj}$ > 500GeV) and control regions (200 < $m_{jj}$ < 500GeV) dominated by WZ and non-prompt lepton background

**The background-only hypothesis is rejected with an observed (expected-Sherpa) significance of 6.9σ (4.6σ)**

Measured signal strength parameter:

$$\mu = 1.45^{+0.25}_{-0.24}(\text{stat.})^{+0.13}_{-0.14}(\text{sys.})$$




**Distribution after fit**

# $W^{\pm}W^{\pm}jj$: cross section

ATLAS-CONF-2018-030

The measured signal strength translates to a fiducial cross-section measurement of

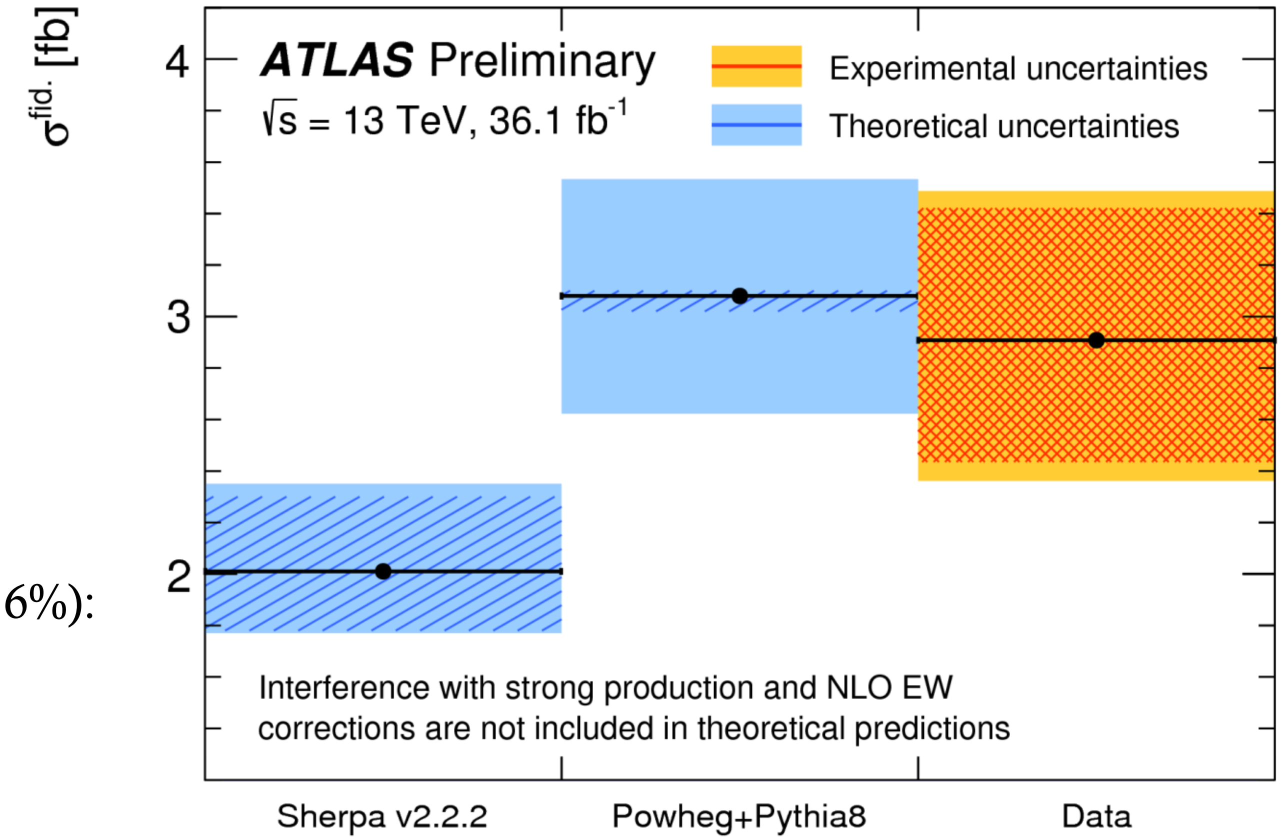
$$\sigma_{\text{fid}} = 2.91^{+0.51}_{-0.47}(\text{stat.}) \pm 0.27(\text{syst.})\ \text{fb}$$

it includes $W^{\pm}W^{\pm}jj$ electroweak plus interference with $W^{\pm}W^{\pm}jj$ strong

Predictions not include interference with the strong production (+6%) and NLO EW corrections (-16%):

$$\sigma^{\text{Sherpa}}_{\text{fid}} = 2.01^{+0.33}_{-0.23}\ \text{fb}$$

$$\sigma^{\text{Powheg}}_{\text{fid}} = 3.08^{+0.45}_{-0.46}\ \text{fb}$$




Data about 1σ higher than the theoretical prediction from Sherpa and in agreement with Powheg

# Conclusions

Most recent results of ATLAS on W production centred on production in association with jets:

- Last W+jets measurement @ 8 TeV focused on production in association with one or two jets includes also $W^+$+jets/$W^-$+jets ratio:
  in addition of allowing an improvement in our understanding on pQCD and on MC modelling, it provides inputs for global PDF fits

- Observed EW same-sign WW production @ 13 TeV with a significance of 6.9 σ following the evidence found by ATLAS in Run-1 and confirming CMS result @ 13 TeV

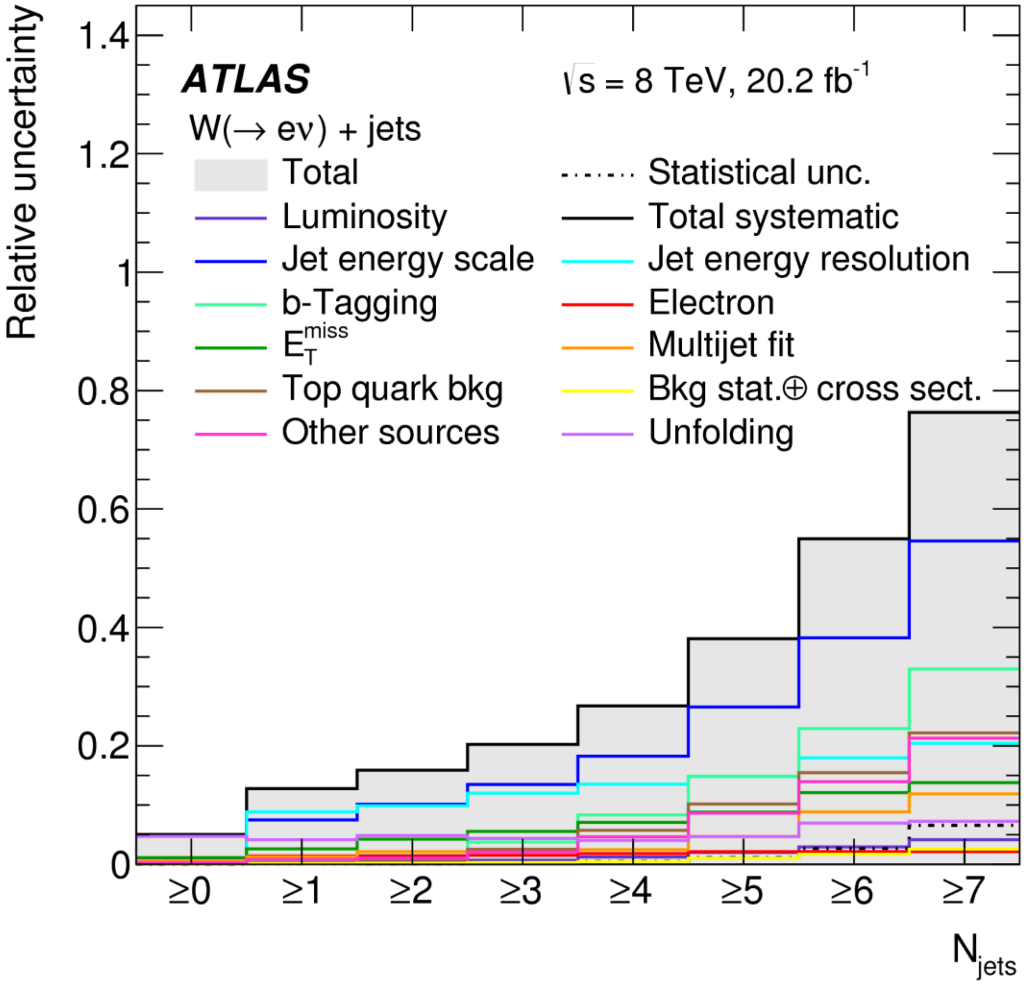
A lot of other exciting results recently published in VBS contest and boson (γ)+jets
→ **see overview talk** of Ludovica Aperio Bella at plenary
A lot of new exciting results are coming @13TeV mainly in the contest of W/Z+heavy flavour
→ **Stay tuned!**

# BACKUP

# W+jets

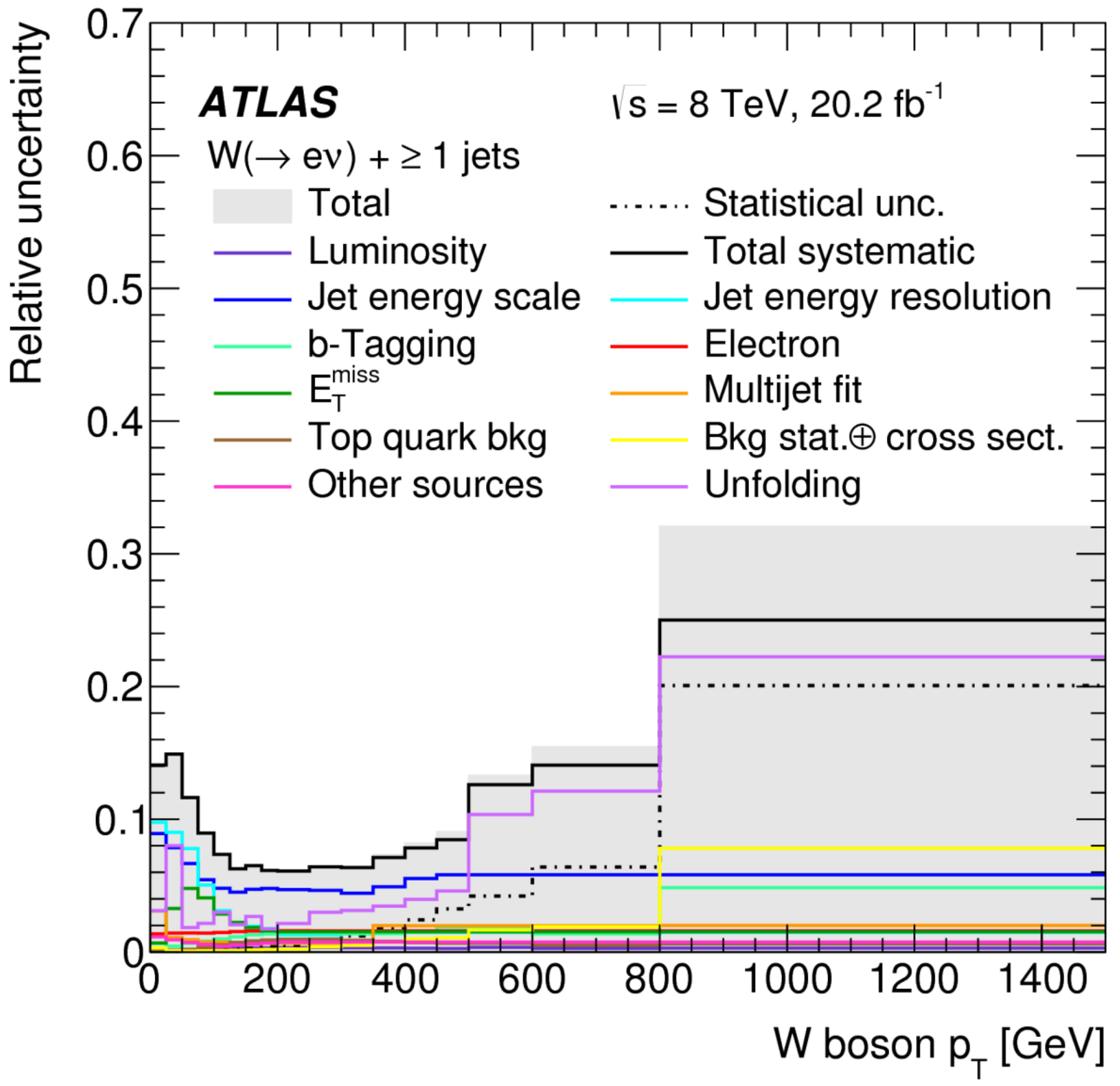
| $N_{jets}$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| $W \to e\nu$ | 94 % | 86 % | 75 % | 67 % | 57 % | 47 % | 40 % | 35 % |
| Multijet | 3 % | 8 % | 15 % | 16 % | 16 % | 16 % | 14 % | 14 % |
| $t\bar{t}$ | <1 % | <1 % | 1 % | 6 % | 16 % | 27 % | 36 % | 43 % |
| Single $t$ | <1 % | <1 % | 1 % | 1 % | 2 % | 2 % | 2 % | 1 % |
| $W \to \tau\nu$ | 2 % | 2 % | 2 % | 2 % | 2 % | 1 % | 1 % | 1 % |
| Diboson | <1 % | <1 % | 1 % | 1 % | 1 % | 1 % | <1 % | <1 % |
| $Z \to ee$ | <1 % | 3 % | 5 % | 6 % | 6 % | 6 % | 5 % | 5 % |
| $Z \to \tau\tau$ | <1 % | <1 % | <1 % | <1 % | <1 % | <1 % | <1 % | <1 % |
| Total predicted | 54 310 000 ±22 000 | 7 611 700 ±4000 | 2 038 000 ±1700 | 478 640 ±720 | 120 190 ±320 | 30 450 ±150 | 7430 ±63 | 1735 ±20 |
| Data observed | 56 342 232 | 7 735 501 | 2 070 776 | 486 158 | 120 943 | 29 901 | 7204 | 1641 |

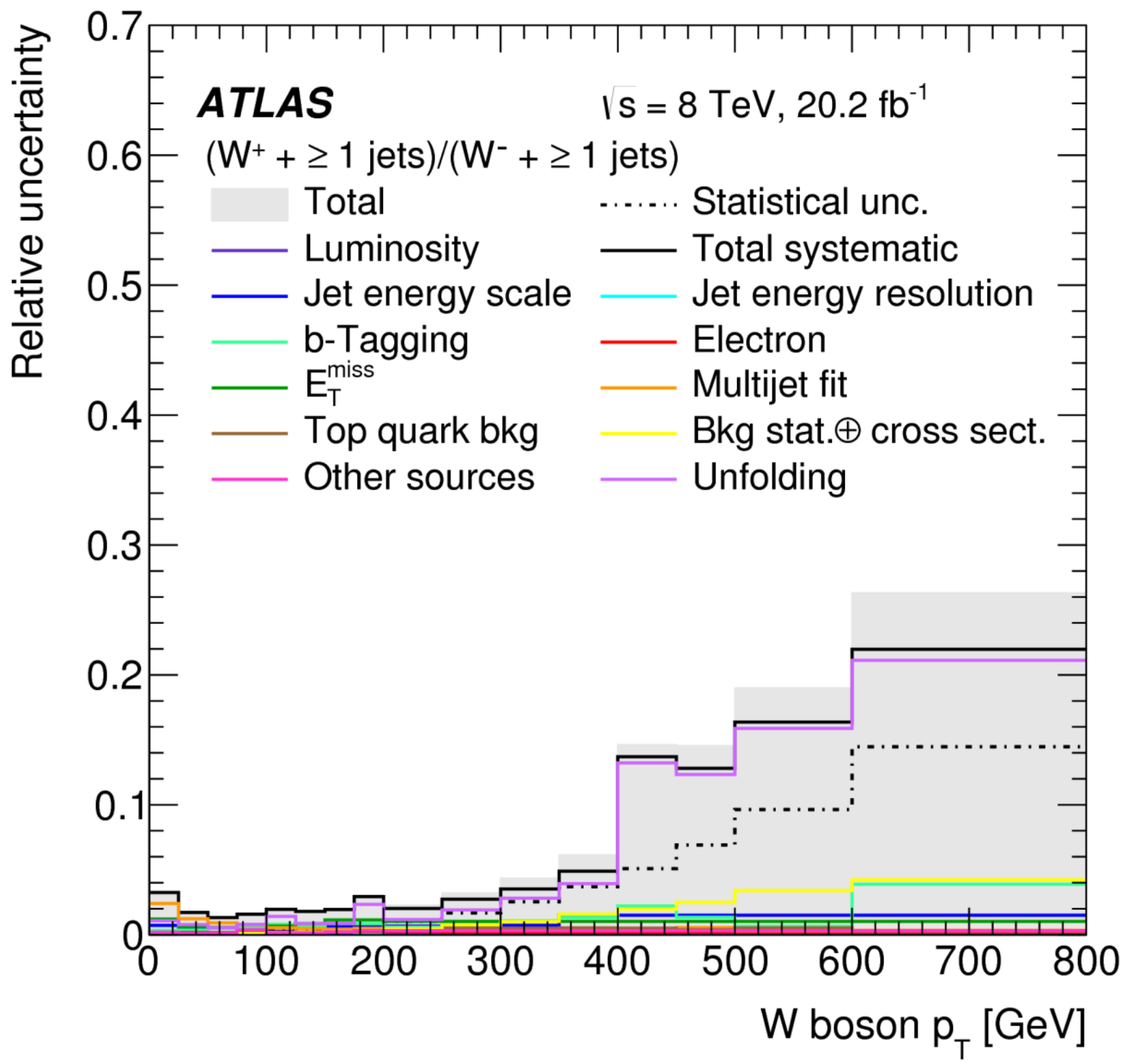
# W+jets




| | Inclusive | ≥ 1 jet | ≥ 2 jets | ≥ 3 jets | ≥ 4 jets | ≥ 5 jets | ≥ 6 jets | ≥ 7 jets |
|---|---|---|---|---|---|---|---|---|
| Jet energy scale | 0.1 | 7.5 | 10 | 14 | 18 | 27 | 38 | 55 |
| Jet energy resolution | 0.5 | 8.8 | 9.9 | 12 | 14 | 15 | 18 | 20 |
| *b*-tagging | 0.1 | 0.5 | 1.5 | 3.8 | 8.3 | 15 | 23 | 33 |
| Electron | 1.1 | 1.4 | 1.4 | 1.5 | 1.8 | 2.1 | 2.1 | 2.1 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | 1.1 | 2.6 | 4.2 | 5.5 | 7.1 | 8.8 | 12 | 14 |
| Multijet background | 0.5 | 1.3 | 2.1 | 2.6 | 2.5 | 4.7 | 8.8 | 12 |
| Top quark background | <0.1 | 0.2 | 0.8 | 2.5 | 5.7 | 10 | 16 | 22 |
| Other backgrounds | <0.1 | 0.1 | 0.2 | 0.3 | 0.5 | 1.0 | 1.7 | 2.6 |
| Unfolding | 4.7 | 4.1 | 4.9 | 4.4 | 4.0 | 4.7 | 6.9 | 7.2 |
| Other | 0.3 | 0.8 | 1.0 | 2.1 | 4.6 | 8.7 | 14 | 21 |
| Luminosity | 0.1 | 0.2 | 0.4 | 0.7 | 1.2 | 2.0 | 2.9 | 4.2 |
| Total systematic uncert. | 5.0 | 13 | 16 | 20 | 27 | 38 | 55 | 76 |

# W+jets


ATLAS
√s = 8 TeV, 20.2 fb-1
W(→ eν) + ≥ 1 jets
Total
Statistical unc.
Luminosity
Total systematic
Jet energy scale
Jet energy resolution
b-Tagging
Electron
E_T^miss
Multijet fit
Top quark bkg
Bkg stat.⊕ cross sect.
Other sources
Unfolding
Relative uncertainty
W boson p_T [GeV]


ATLAS
√s = 8 TeV, 20.2 fb-1
(W+ + ≥ 1 jets)/(W- + ≥ 1 jets)
Total
Statistical unc.
Luminosity
Total systematic
Jet energy scale
Jet energy resolution
b-Tagging
Electron
E_T^miss
Multijet fit
Top quark bkg
Bkg stat.⊕ cross sect.
Other sources
Unfolding
Relative uncertainty
W boson p_T [GeV]

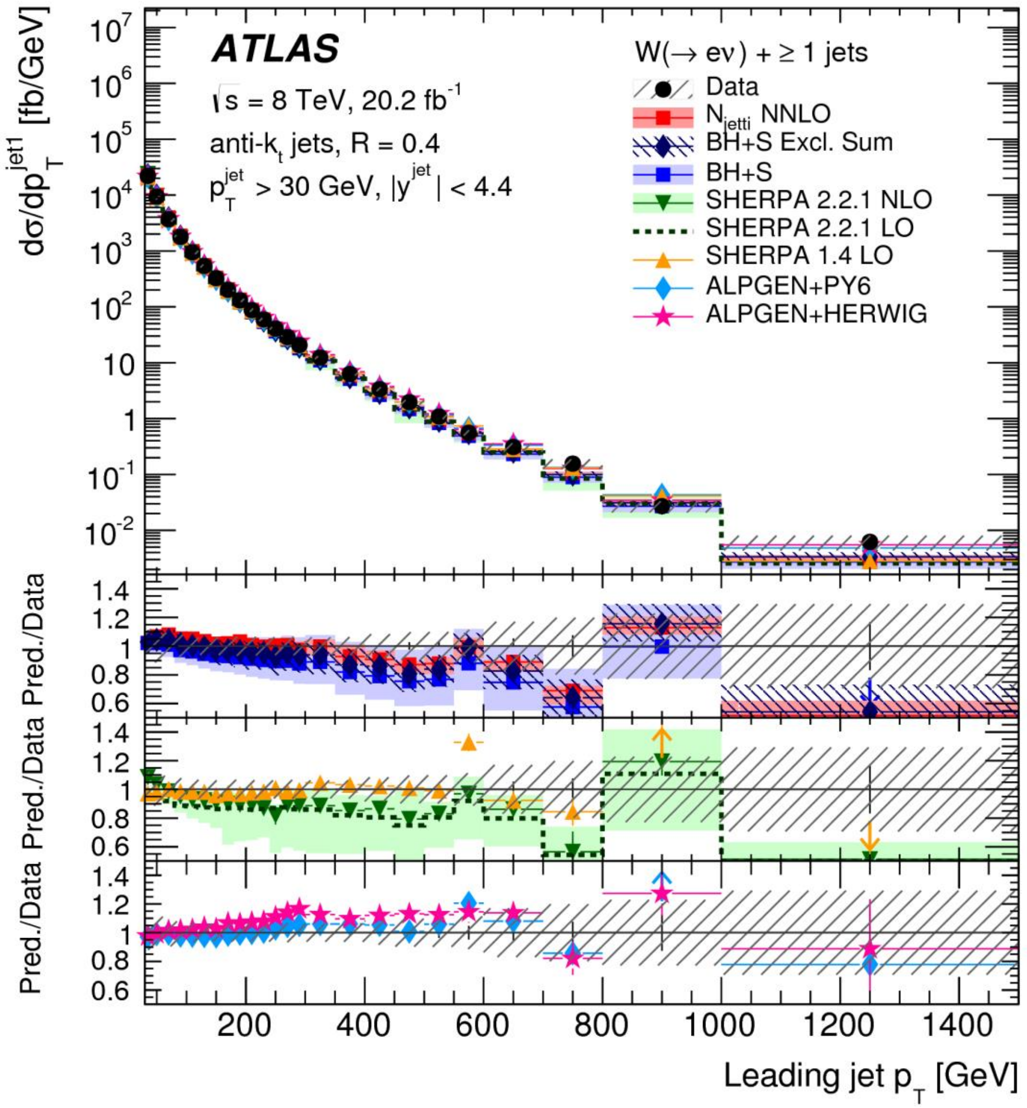
# W+jets

| Program | Order in $\alpha_S$ | $N_{partons}^{max}$ at highest order | PDF set | NPC | PS |
|---|---|---|---|---|---|
| $N_{jetti}$ | NNLO | 1 | CT14 | ✓ | |
| BlackHat+Sherpa | NLO | 1, 2 or 3 | CT10 | ✓ | |
| MCFM 6.8 | NLO | 1 | CT10 + 3 more | ✓ | |
| Powheg+Pythia 8 | NLO | 1 | CT14 | | ✓ |
| Sherpa 2.2.1 | NLO | 2 | CT10 | | ✓ |
| Sherpa 2.2.1 | LO | 2 (3) | NNPDF 3.0 | | ✓ |
| Alpgen+Pythia 6 | LO | 5 | CTEQ6L1 (LO) | | ✓ |
| Alpgen+Herwig | LO | 5 | CTEQ6L1 (LO) | | ✓ |
| Sherpa 1.4.1 | LO | 4 | CT10 | | ✓ |

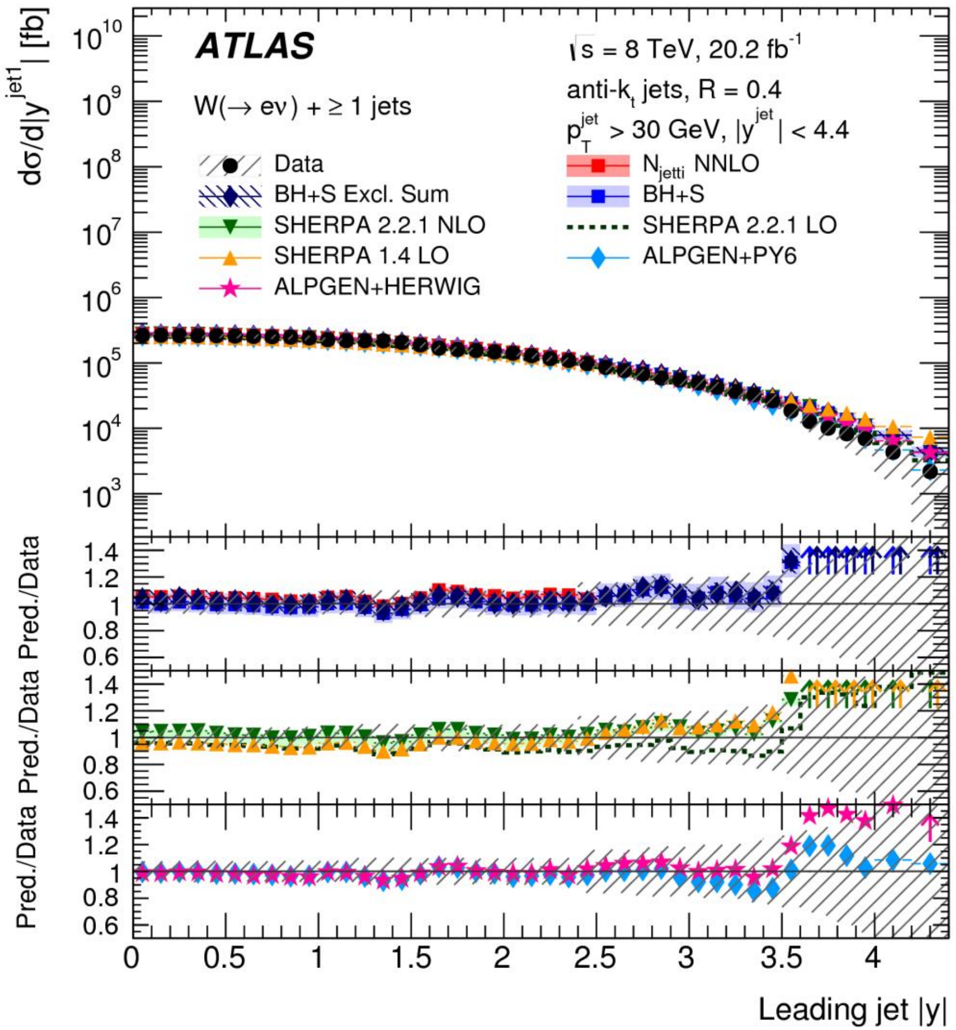
# W+jets

$N_{jetti}$, **Alpgen** and **LO Sherpa 1.4.1** show fair agreement with the data.

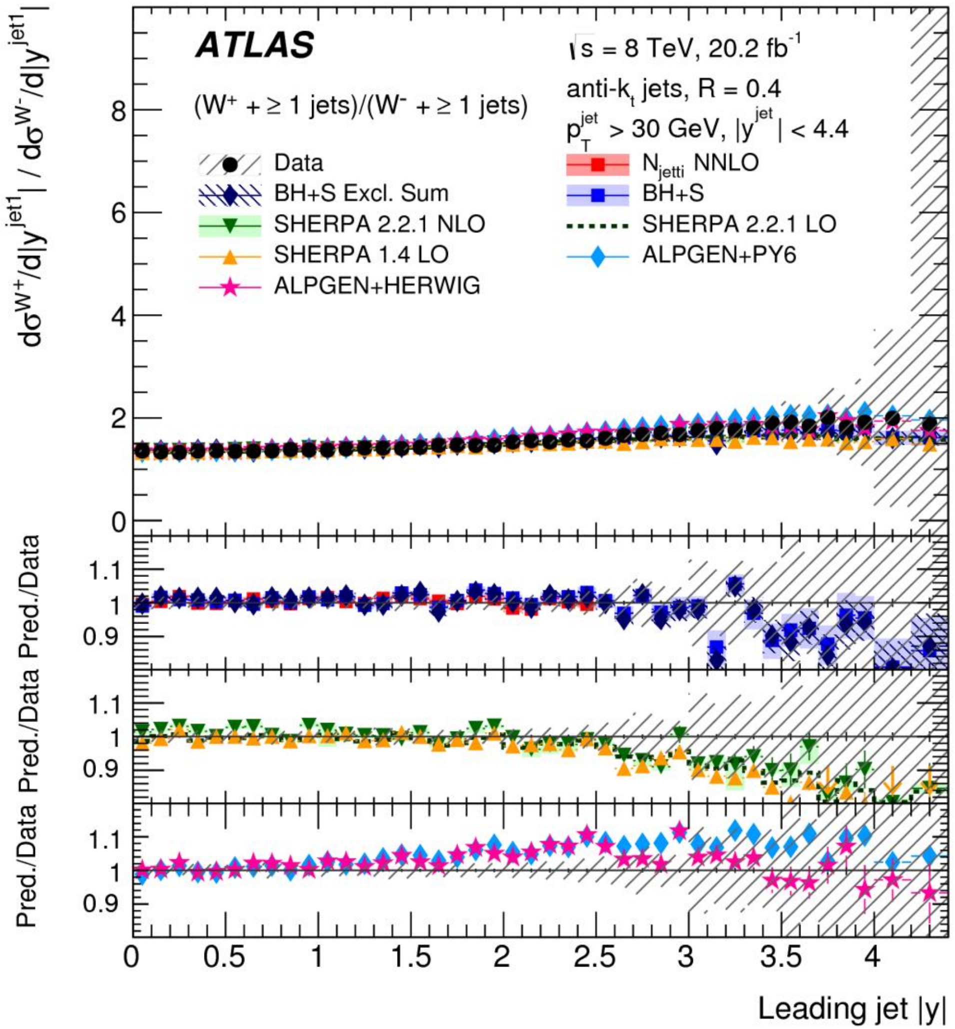
**Sherpa 2.2.1** and **BlackHat+Sherpa** tend to predict a softer $p_T$ distribution.



# W+jets




In forward region, data turn down more sharply than predictions, that show larger cross section. Prediction still consistent with data due to the large uncertainties of data




Mismodelling in the forward region largely cancels out in the ratio, resulting in good agreement with data

# $W^{\pm}W^{\pm}jj$: pre-fit

| | $e^+e^+$ | $e^-e^-$ | $e^+\mu^+$ | $e^-\mu^-$ | $\mu^+\mu^+$ | $\mu^-\mu^-$ | combined |
|---|---|---|---|---|---|---|---|
| $WZ$ | 1.7 ± 0.6 | 1.2 ± 0.4 | 13 ± 4 | 8.1 ± 2.5 | 5.0 ± 1.6 | 3.3 ± 1.1 | 32 ± 9 |
| Non-prompt | 4.1 ± 2.4 | 2.3 ± 1.8 | 9 ± 6 | 6 ± 4 | 0.57 ± 0.16 | 0.67 ± 0.26 | 23 ± 12 |
| $e/\gamma$ conversions | 1.74 ± 0.31 | 1.8 ± 0.4 | 6.1 ± 2.4 | 3.7 ± 1.0 | - | - | 13.4 ± 3.5 |
| Other prompt | 0.17 ± 0.06 | 0.14 ± 0.05 | 0.90 ± 0.24 | 0.60 ± 0.25 | 0.36 ± 0.12 | 0.19 ± 0.07 | 2.4 ± 0.5 |
| $W^{\pm}W^{\pm}jj$ strong | 0.38 ± 0.13 | 0.16 ± 0.06 | 3.0 ± 1.0 | 1.2 ± 0.4 | 1.8 ± 0.6 | 0.76 ± 0.26 | 7.3 ± 2.5 |
| Expected background | 8.1 ± 2.4 | 5.6 ± 1.9 | 32 ± 7 | 20 ± 5 | 7.7 ± 1.7 | 4.9 ± 1.1 | 78 ± 15 |
| $W^{\pm}W^{\pm}jj$ electroweak | 3.80 ± 0.30 | 1.49 ± 0.13 | 16.5 ± 1.2 | 6.5 ± 0.5 | 9.1 ± 0.7 | 3.50 ± 0.29 | 40.9 ± 2.9 |
| Data | 10 | 4 | 44 | 28 | 25 | 11 | 122 |