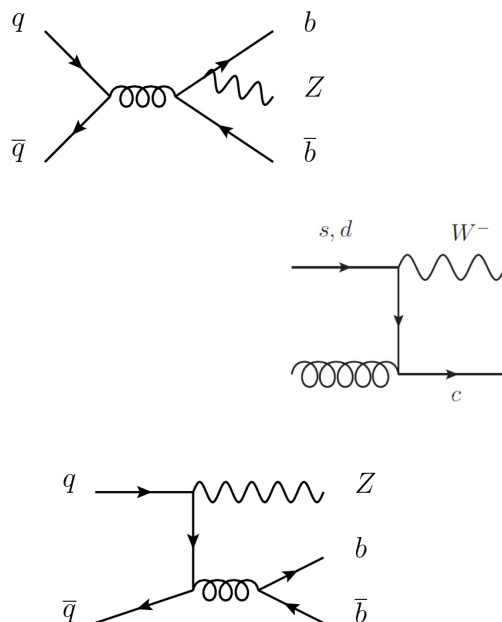# Measurements of the production of vector bosons in association with heavy flavour quarks at the LHC

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on behalf of the ATLAS collaboration

Motivation and results

W+charm (see also EW1)

- Sensitive to strange PDF
  → e.g. W mass measurement

W+J/Ψ (see also HF2)
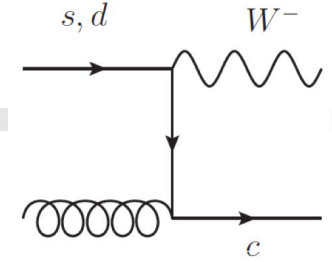
- Quarkonium production
- Double parton interaction

W+b(b)/Z+b(b)

- pQCD, flavour/mass schemes,
- Benchmark/background for Higgs and BSM

ATLAS publications @ 7TeV

- W+c/D   5fb^{-1} JHEP05(2014)068
- W+J/Ψ   5fb^{-1} JHEP 04 (2014) 172
- W+b   5fb^{-1} JHEP 06 (2013) 084
- Z+b(b)   5fb^{-1} Paper in preparation

W and charm

W+c dominated by LO production
→ handle on strange PDF at x ~0.01

Strange PDF

- SU3(flavour): symmetric light quark sea
  Strange mass → strange suppression?
- dependence on x?
- Mixed experimental results:
  suppressed ↔ symmetric , $s ↔ \bar{s}$?

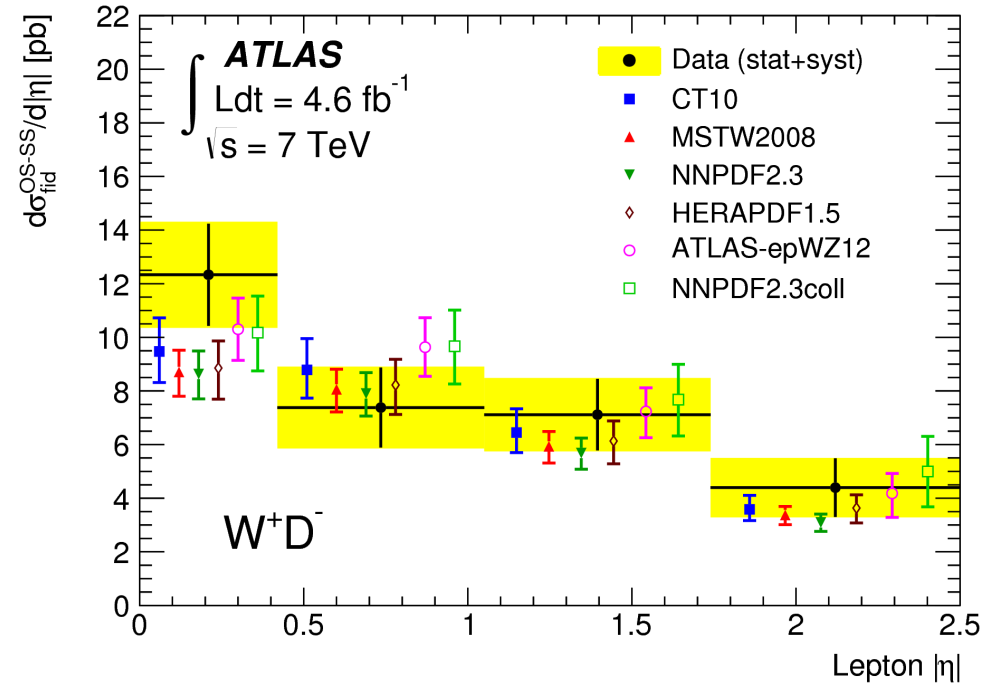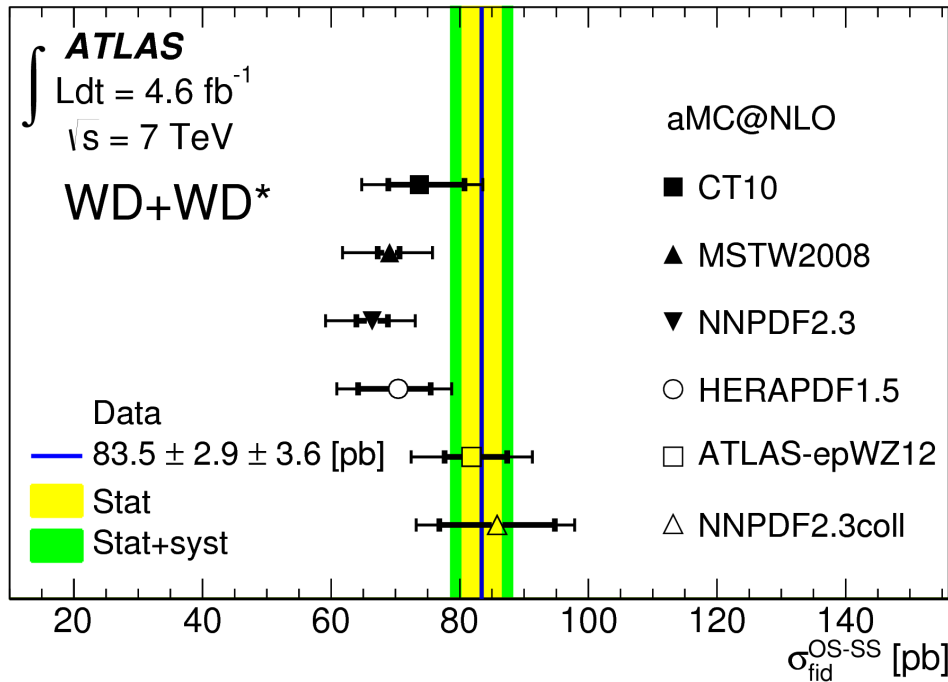## Measurement strategy

- $W → e\nu/\mu\nu$ selection
- charm tagging: 2 measurements:
  1) jet with $c → \mu$ (soft-muon tagger)
  2) reconstructed $D^{\pm}, D^{*\pm}, D^0 → K + n\pi$
- OS-SS subtraction → signal extraction
- Correction to particle level

→ 6 measurements: $W^{\pm}$+c-jet, $W^{\pm}$+D, $W^{\pm}$+D*
  Kinematic reach: pT(D) > 8GeV, pT(c-jet) > 25GeV
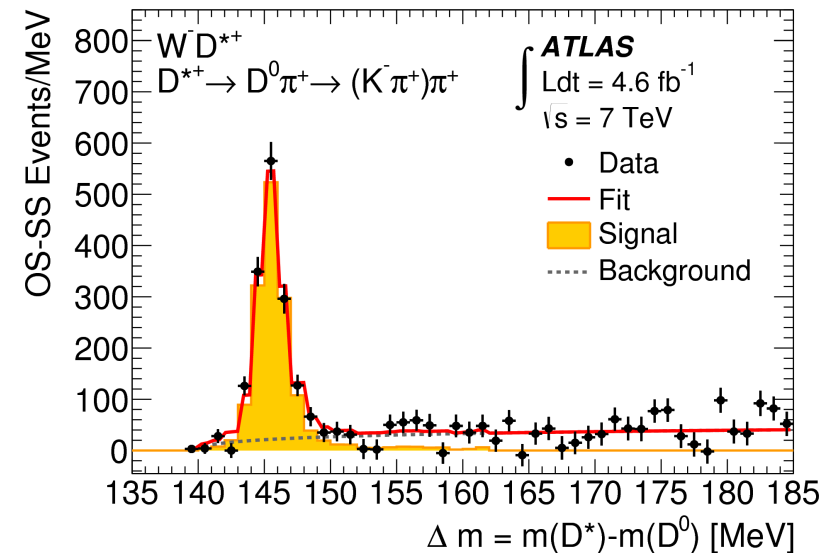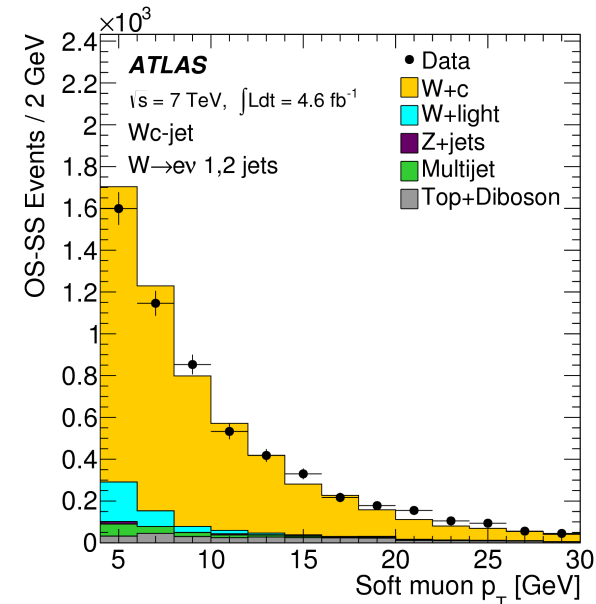
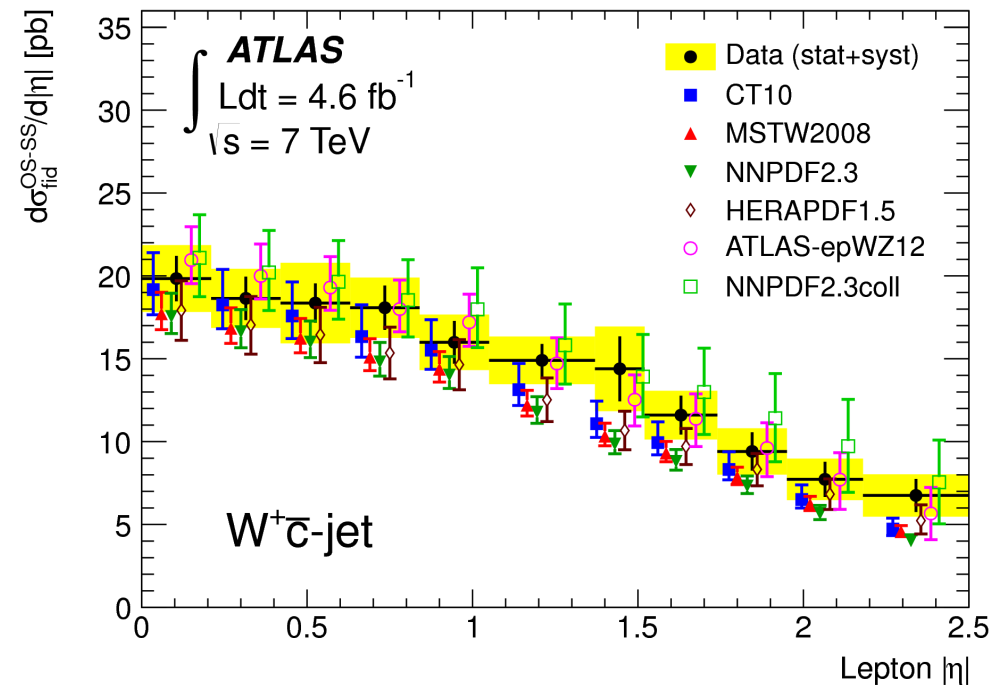-- *Syst. unc.: W+D: 4-5% (Tracking, BR), W+c-jet: 5-7% (Bkg, JES, D fragm.)*
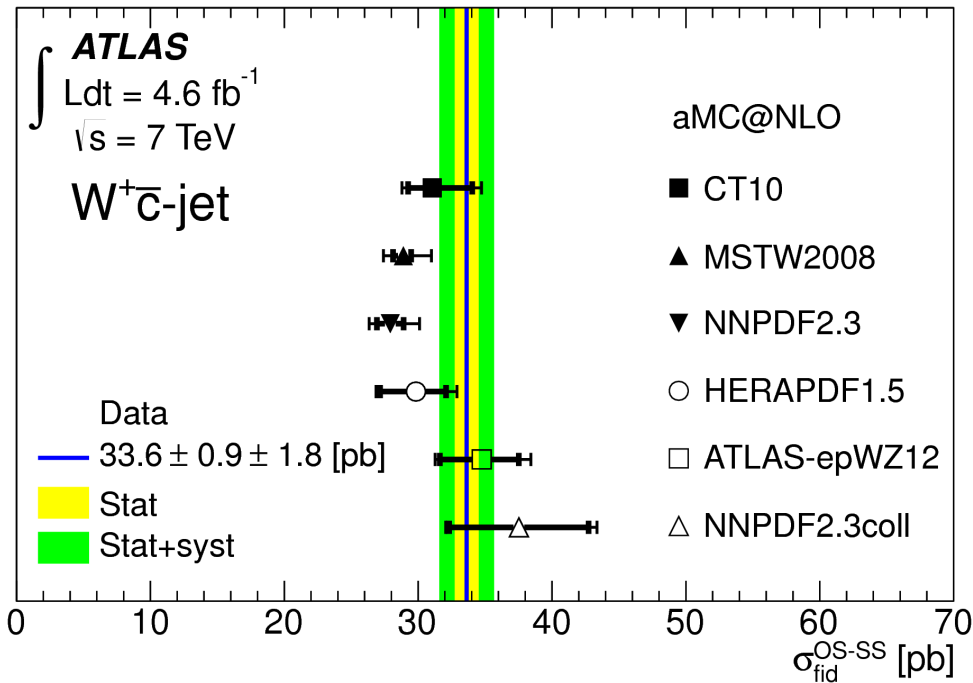
W+charm: strange suppression

- Cross sections compared to predictions of aMCatNLO with different PDF sets
- Data favours PDFs with symmetric light-quark sea

*ATLAS-epWZ and NNPDF2.3coll: symmetric light quark sea*

W+charm: strange suppression

- Cross sections compared to predictions of aMCatNLO with different PDF sets
- Data favours PDFs with symmetric light-quark sea
- Potential for improvement: theory accuracy → scale uncertainty
- Consistent picture between $W^{\pm}$+c-jet, $W^{\pm}$+D, $W^{\pm}$+D*

ATLAS-epWZ and NNPDF2.3coll: symmetric light quark sea
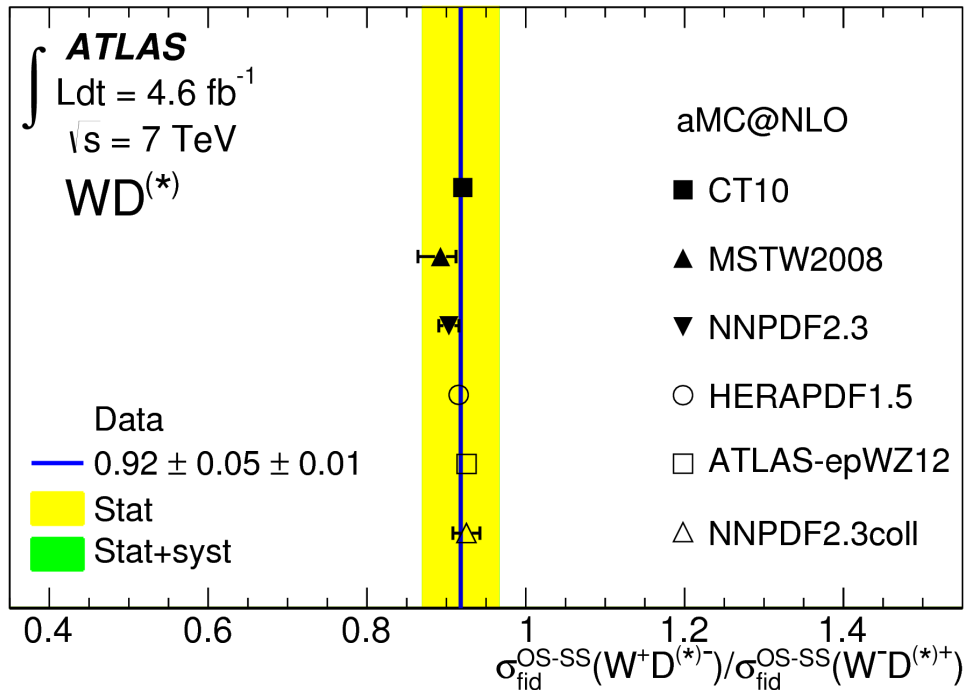
W+charm: strange suppression
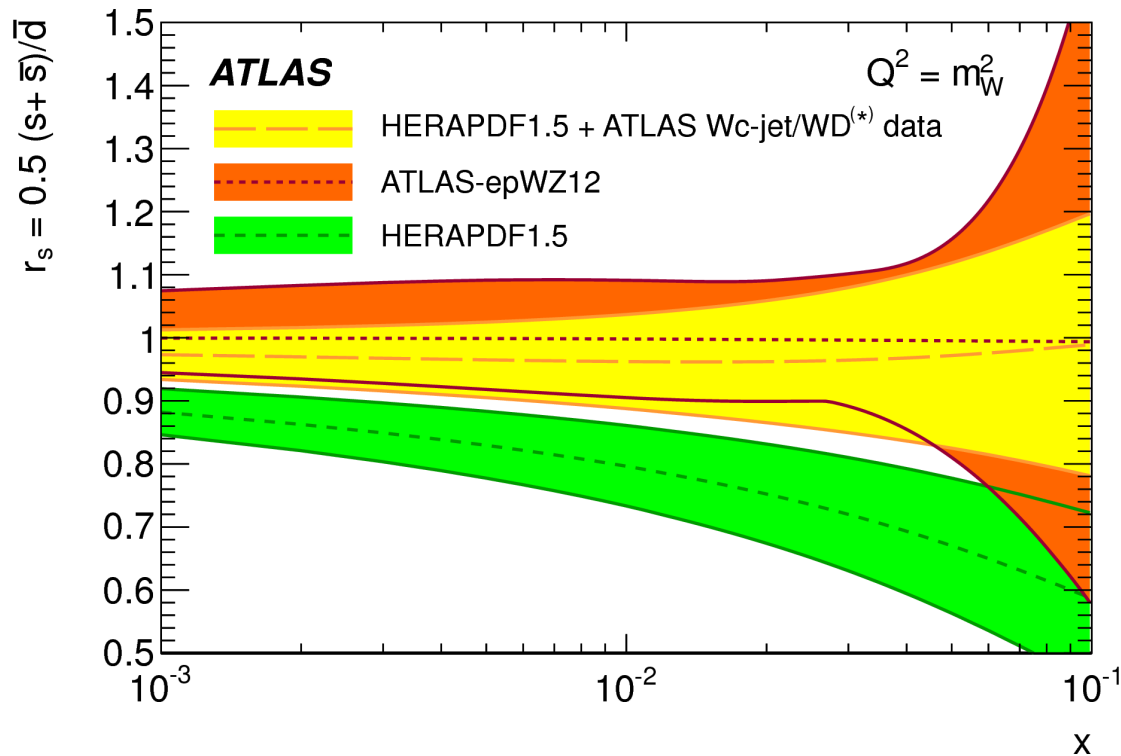
- HERAPDF1.5: from HERA DIS data, insensitive to s fraction: from ν-N scattering
- Free fit of s- fraction → compatible with W/Z rapidity → symmetric light quark sea

$$r_s \equiv 0.5(s + \bar{s})/\bar{d} = f_s/(1 - f_s) = 0.96\,^{+0.16\,+0.21}_{-0.18\,-0.24} \qquad Q^2 = 1.9\ \mathrm{GeV}^2$$
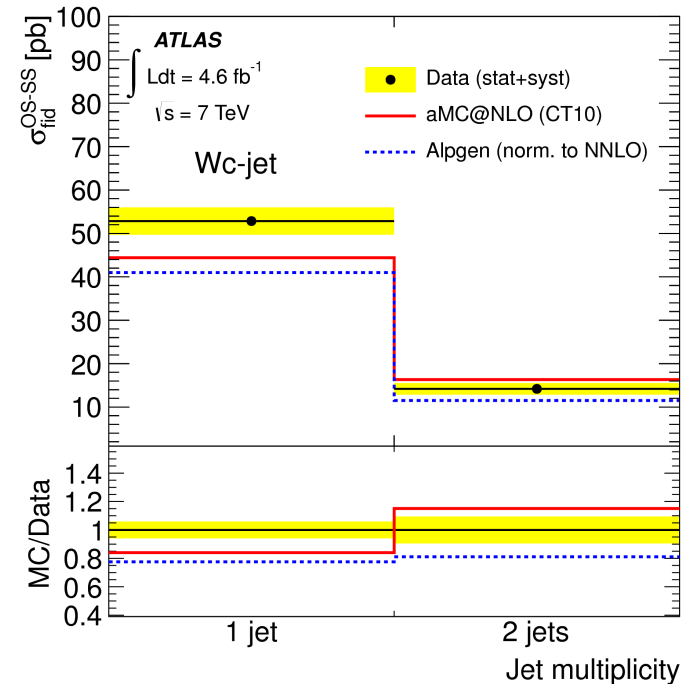
W+c: charge asymmetry, pT, Njets

- Charge asymmetry consistent with both s=s̄ and with neutrino data

$$A_{s\bar{s}} = \frac{\langle s(x,Q^2)\rangle - \langle \bar{s}(x,Q^2)\rangle}{\langle s(x,Q^2)\rangle} = (2\pm3)\%$$

MSTW2008 and NNPDF2.3 with ss̄ asymmetry

- W+c cross section as a function of pT(D) and c-jet multiplicity

  → aMCatNLO overestimates 2j/1j ratio

V+b jets

Motivation:
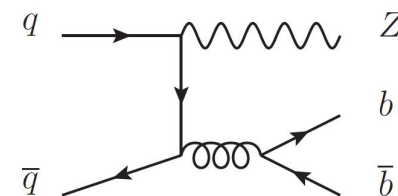
- pQCD with HF: many unknowns
  - competing flavour schemes
  - massive/massless quarks
  - LO/NLO +PS

- irreducible bkg to VH, H → bb
  Single-top and searches

Measurements:

- W+b: exactly 1 b-tagged jet:
  → W+b , W+b+jet
  → Inclusive and $p_T(b)$

- Z+b: 1 b-tagged jet
         (+ additional b-jets)
  → $p_T(b)$. angles (Z,b), $p_T(Z)$

- Z+bb: 2 b-tagged jets
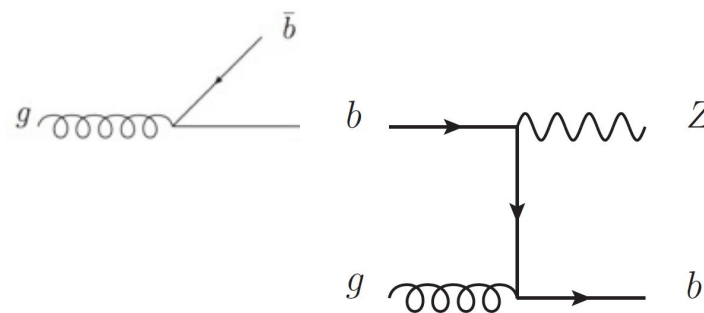 → m(bb), ΔR(bb), $p_T(Z)$,

- **Gluon splitting (PS)**

  4FNS ME (LO, NLO), PS

- **b-quark in initial state**

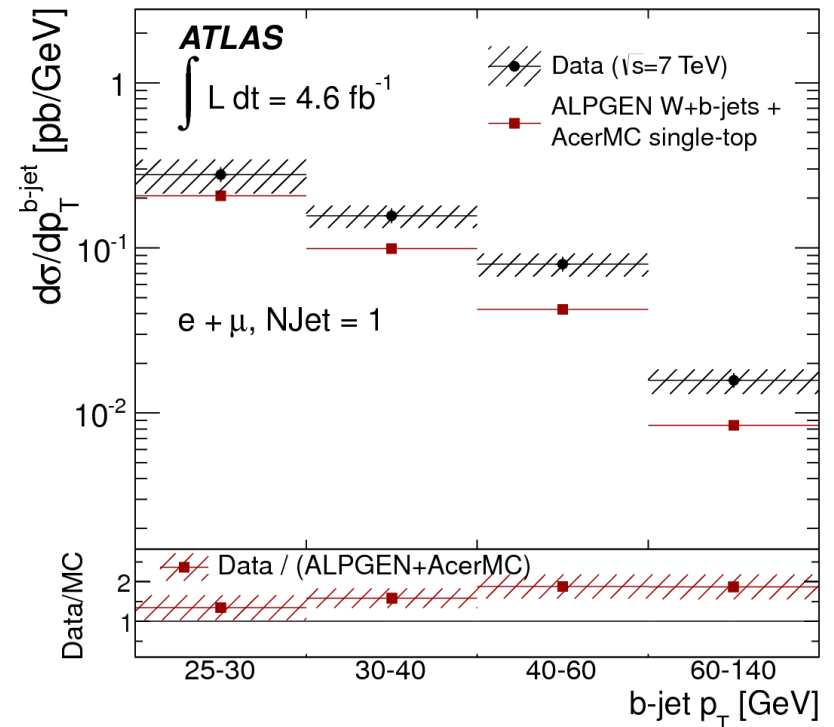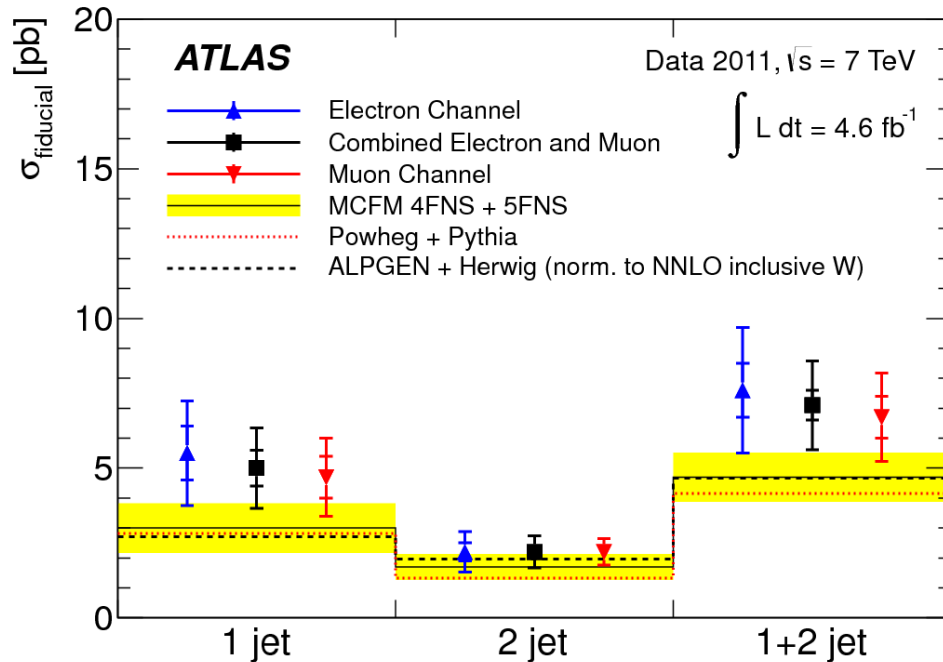 4FNS NLO/multi-leg   5FNS (LO, NLO)

- **DPI**
  Alpgen, Sherpa, Madgraph

Reminder: W+b results

Strategy:
- Successive Background fits, signal fit in continuous b-tagger
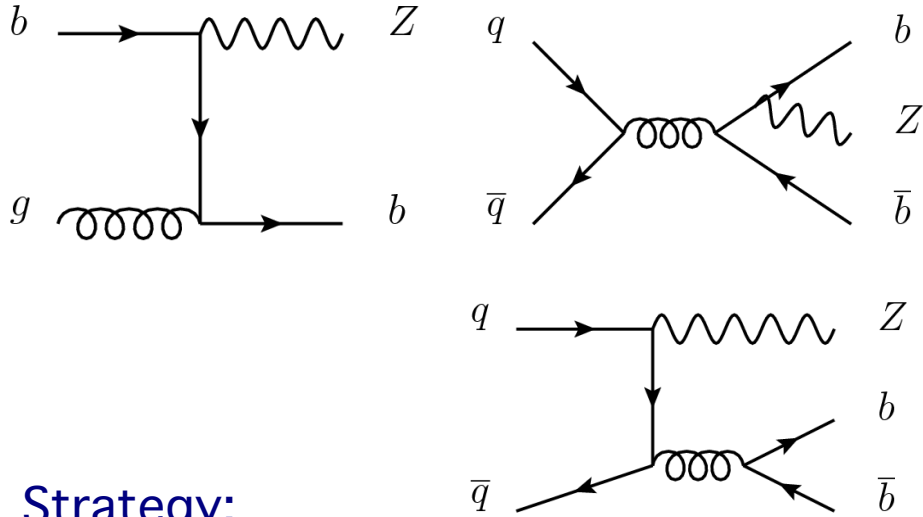- Unfolding to particle level

- 1jet: consistent within 1.5 σ
- 2jets: good agreement (MCFM, Alpgen)

- 1 jet: MC underestimates data for large $p_T(b)$

Exp. Unc.
- Statistical: 7-10%
- Systematics: 20-25% (JES, JER, MC modelling) → fit, unfolding
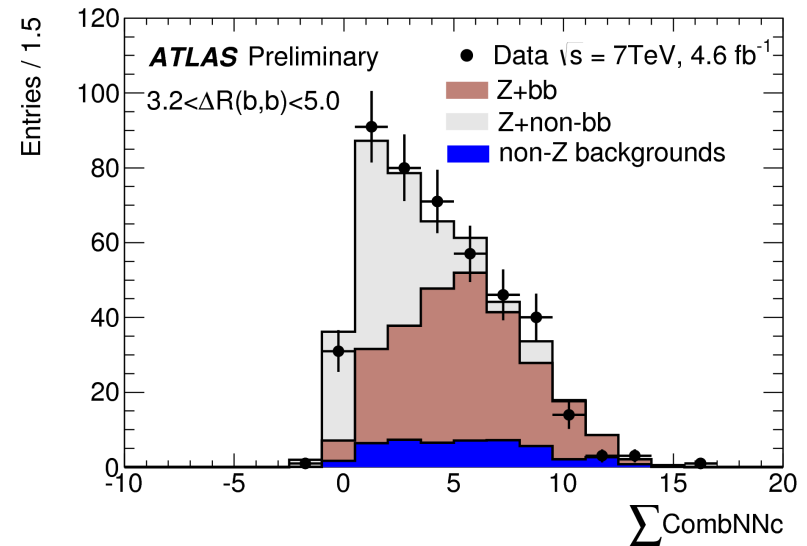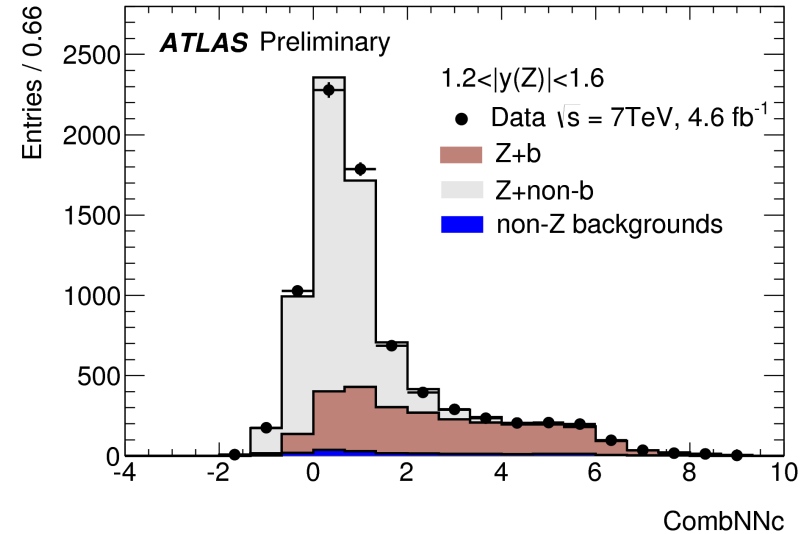
Z+b(b)

Strategy:

- Template fit in continuous b-tagger
  (one fit per differential bin)
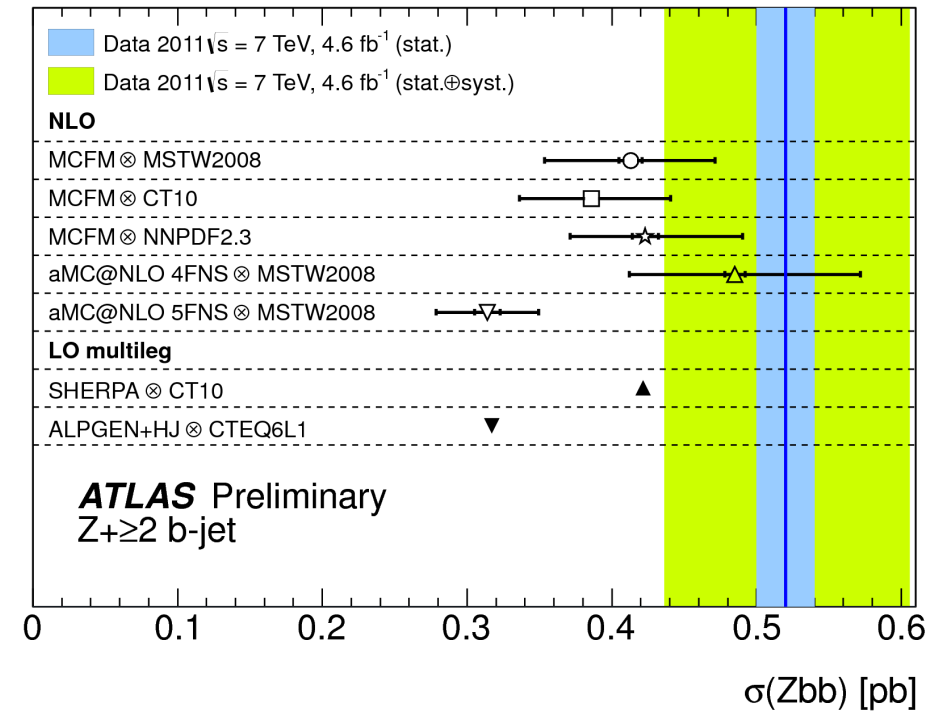- Unfolding to particle level

Fiducial phase space

- m(ll) = mZ±15GeV
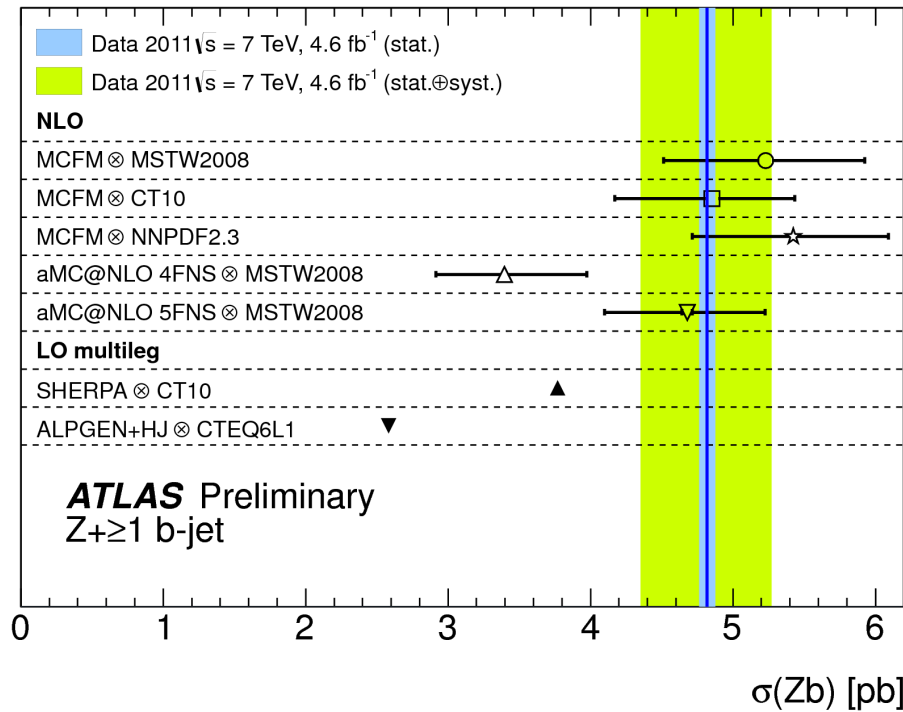- b-jet: pT > 20GeV, |y| < 2.4, ΔR(l,j) > 0.5

Exp. Uncertainties:

- Z+b: 8% (b-tagging, template shape, JES)
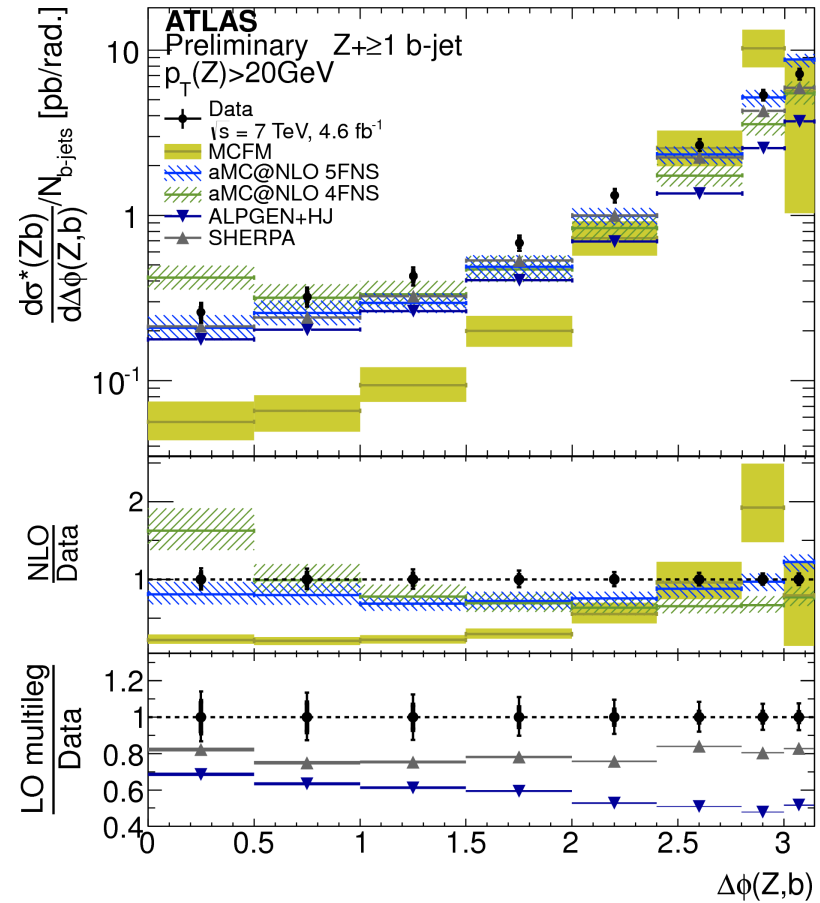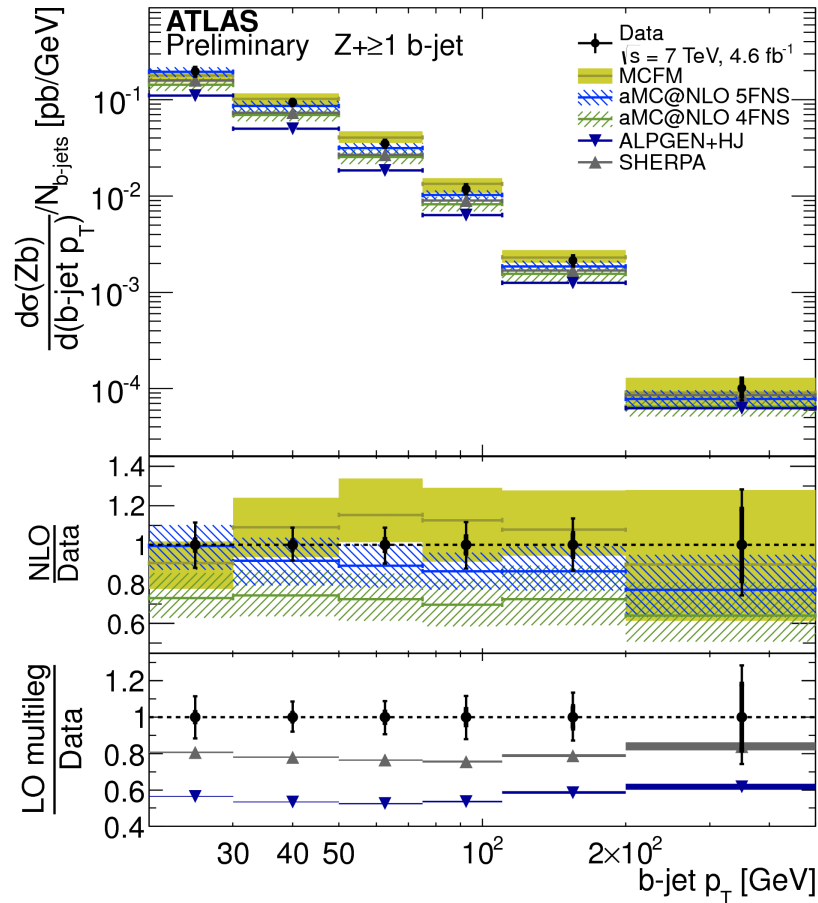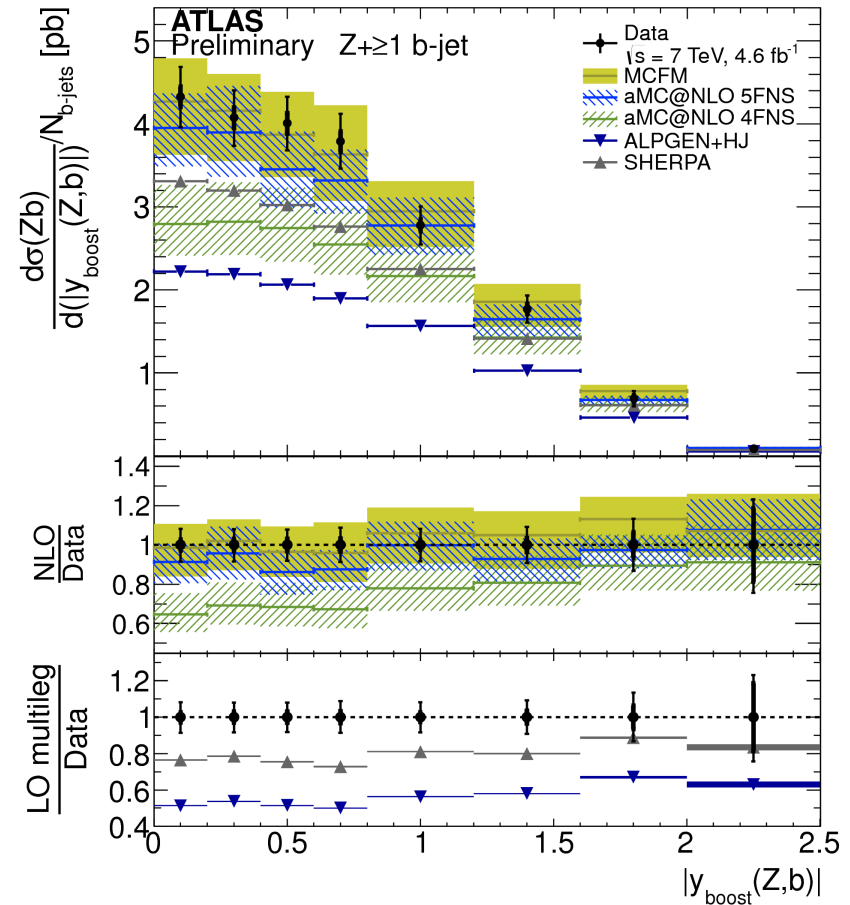- Z+bb: 14% (b-tagging, template shape, JES)
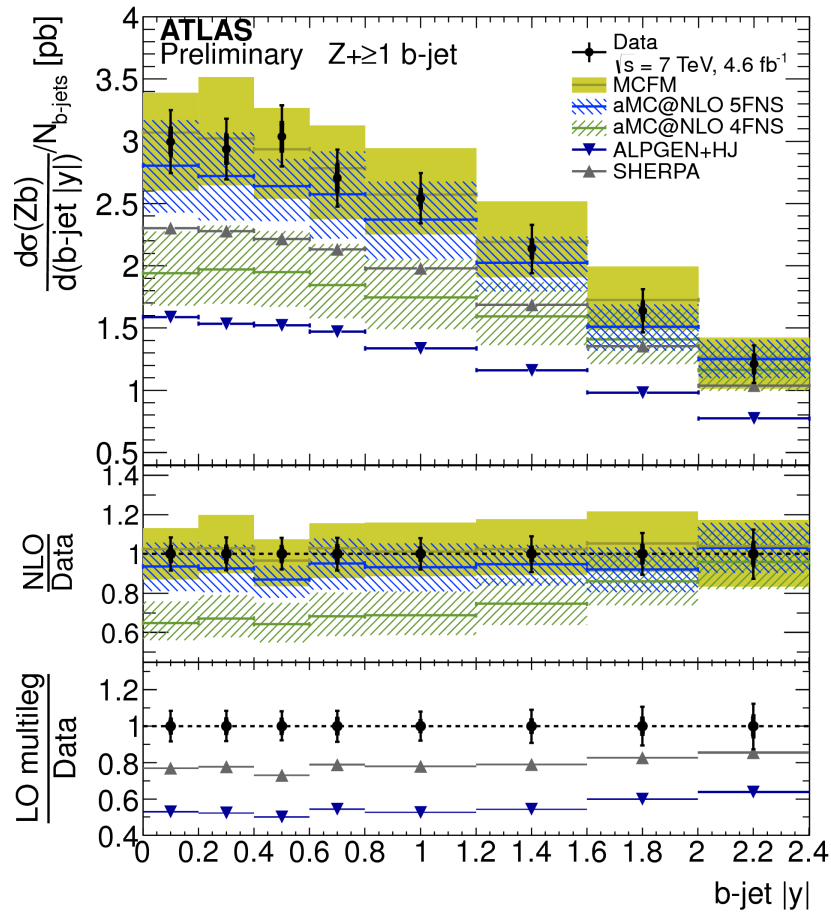
Z+b(b) Results

- MCFM (5FNS, NLO) compatible with data
- aMCatNLO: Z+b preferes 5FNS, Z+bb preferes 4FNS
- LO+PS generators underestimate b cross section. Sherpa (5FNS) closer to data

Z+b differential Results

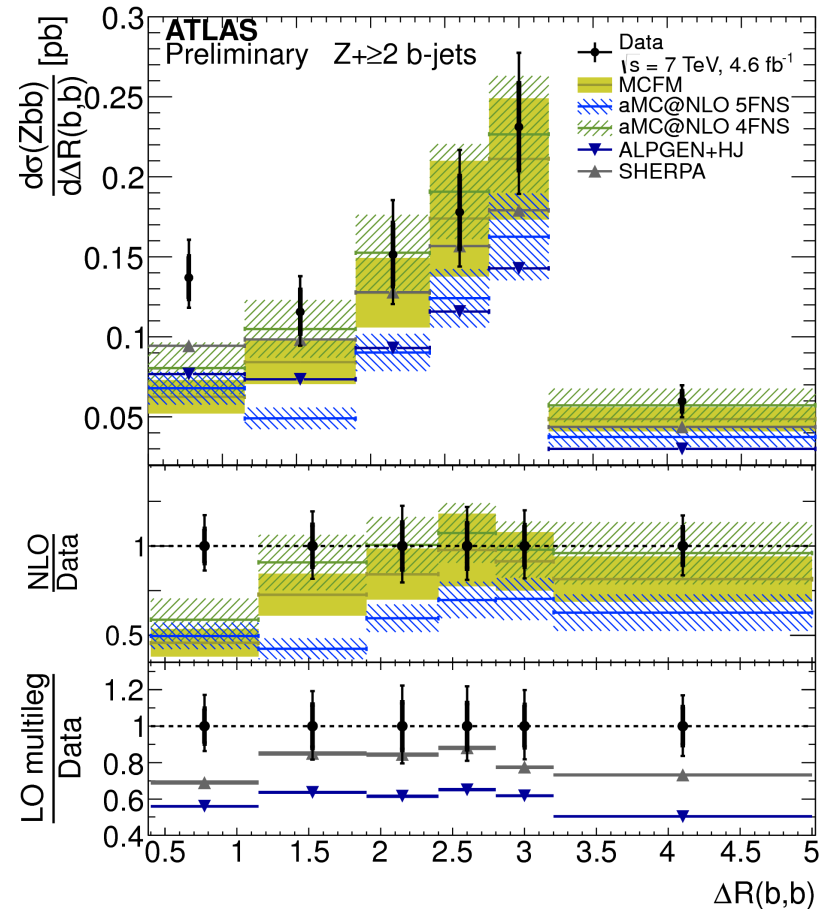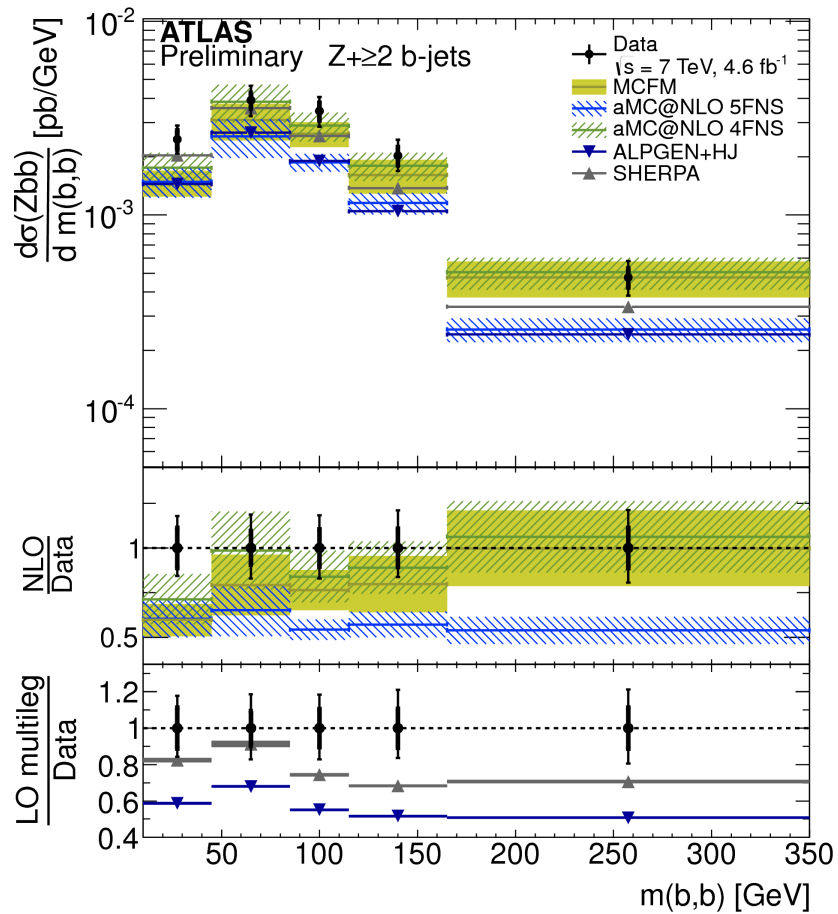- pT(b) shape described by all generators
- Angular relations not decribed by MCFM, better with LO+PS

Z+b differential Results

- aMCatNLO 4FNS underestimates cross section mostly in central region

Z+bb differential Results

- Theory predictions too low for low ΔR(bb) → low-angle gluon splitting?
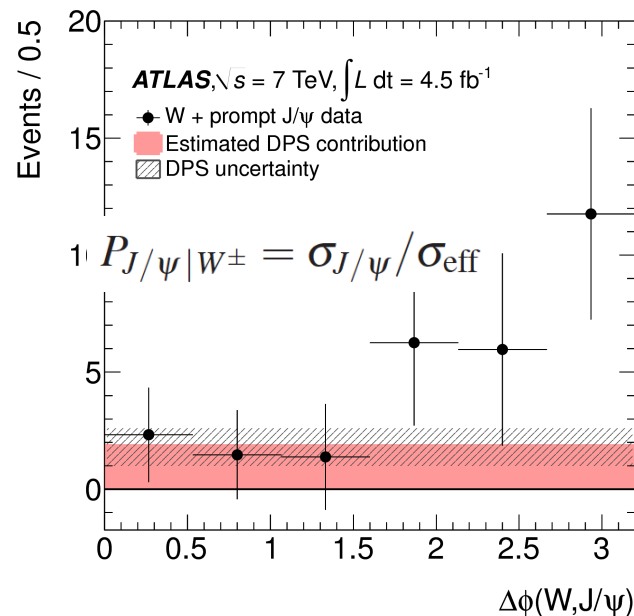
W+J/Ψ production

Motivation:

- Tests of QCD at perturbative/ non-perturbative boundary
- Relative fractions of color singlet and color octet?
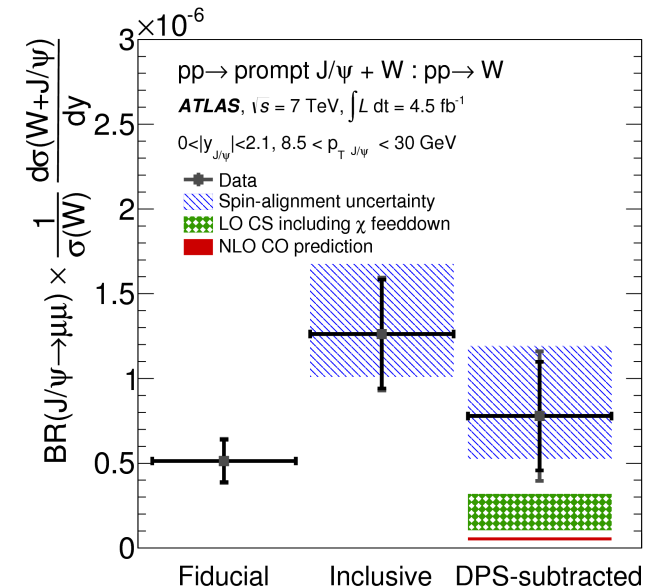- Sensitive to DPS
- Benchmark: H → cc, BSM

Extracted $27.4^{+7.5}_{-6.5}$ prompt W+J/Ψ → 5.1 σ

→ first observation

Extraction:

- Selection of W → $\mu\nu$ + J/Ψ → $\mu\mu$ candidates

- Unbinned max.-LLH fit to life time and m($\mu\mu$)
- Fit of mT(W) → multi-jets
- Ratio $R_{J/\psi}$ to inclusive W

$$P_{J/\psi|W^{\pm}} = \sigma_{J/\psi}/\sigma_{eff}$$

ATLAS, $\sqrt{s}$ = 7 TeV, $\int L$ dt = 4.5 fb^{-1}

- W + prompt J/ψ data
- Estimated DPS contribution
- DPS uncertainty

Events / 0.5

$\Delta\phi$(W,J/ψ)

3×10^{-6}

pp→ prompt J/ψ + W : pp→ W

ATLAS, $\sqrt{s}$ = 7 TeV, $\int L$ dt = 4.5 fb^{-1}

0<|y$_{J/\psi}$|<2.1, 8.5 < p$_{T\ J/\psi}$ < 30 GeV

- Data
- Spin-alignment uncertainty
- LO CS including χ feeddown
- NLO CO prediction

BR(J/ψ→μμ) × $\frac{1}{\sigma(W)}$ $\frac{d\sigma(W+J/\psi)}{dy}$

Fiducial   Inclusive   DPS-subtracted

- DPS fraction compatibe with ATLAS σ_{eff} results

- SPS fraction consistent with color singlet prod.

Summary

W+c-jet/D production

- Consistent results between W+c-jet and W+D
- Data preferes symmetric light quark sea
- s-$\bar{s}$ asymmetry compatible with 0 and with ν data
- aMCatNLO over estimates W+2j/W+1j ratio

Z+b/Z+bb cross sections

- MCFM (5FS) Compatible with Zb and Zbb data, fails to model angular Z-b relation
- aMCatNLO: Zb preferes 5FS, Zbb preferes 4FS
- LO+PS underestimates b fraction, shapes ok
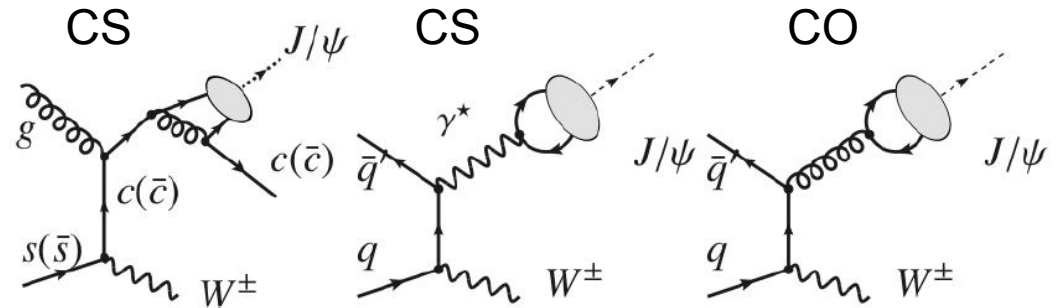- All generators under estimate low $\Delta R(bb)$

First observation of prompt W+J/Ψ production:

- Data suggest dominating CS contribution, consistent with DPS prediction

W+J/Ψ

Motivation:

- Tests of QCD at the perturbative/ non-perturbative boundary
- Relative fractions of color singlet and color octet ?
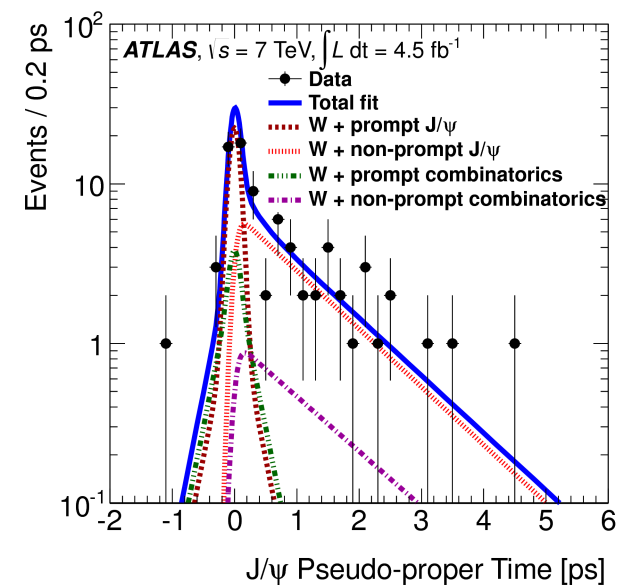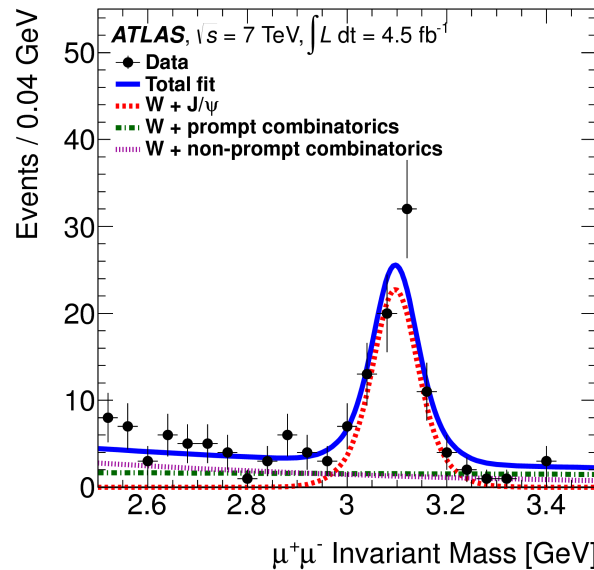- Sensitive to DPS
- Benchmark for $H \to cc$, BSM

Extraction:

- Selection of $W \to \mu\nu$ + $J/\Psi \to \mu\mu$ candidates
- Unbinned maximum-LLH fit to life time and $m(\mu\mu)$
- Fit of $m_T(W) \to$ multi-jets
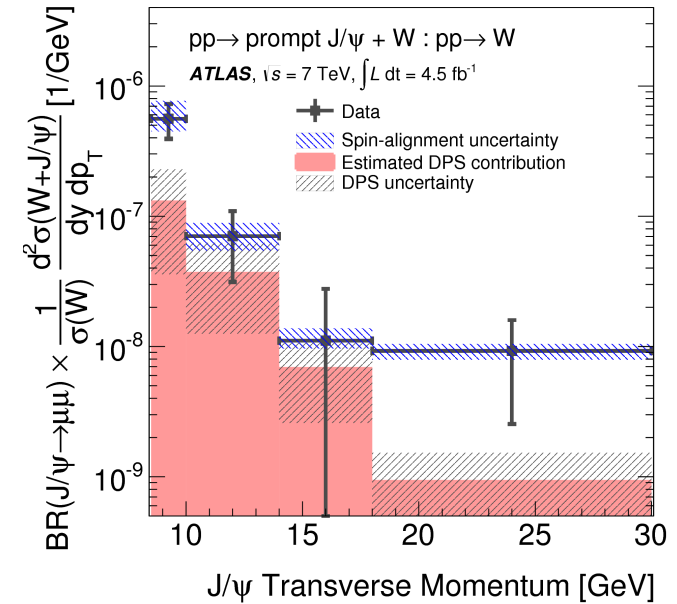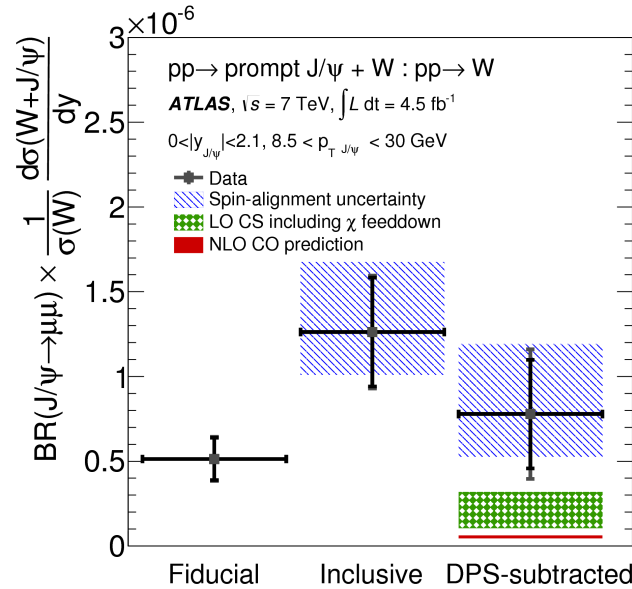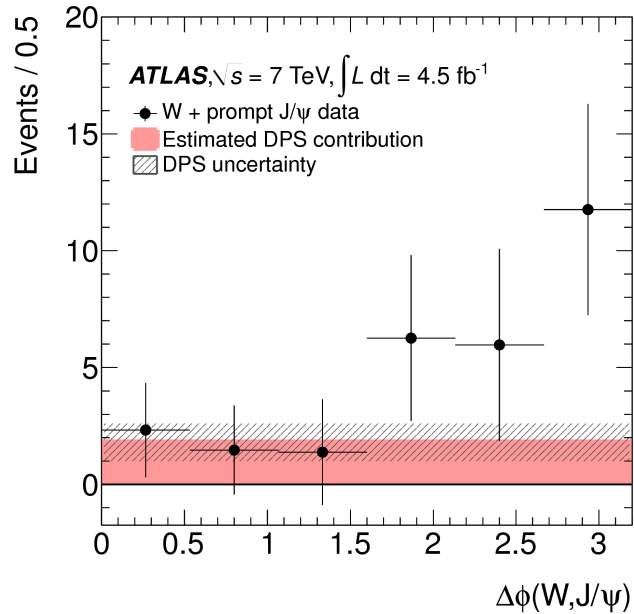- Ratio $R_{J/\Psi}$ to inclusive W

Pseudo-proper time:

$$\tau \equiv \frac{\vec{L} \cdot \vec{p}_T^{J/\psi}}{p_T^{J/\psi}} \cdot \frac{m_{\mu^+\mu^-}}{p_T^{J/\psi}}$$

Extracted $27.4^{+7.5}_{-6.5}$ prompt W+J/Ψ → 5.1 σ
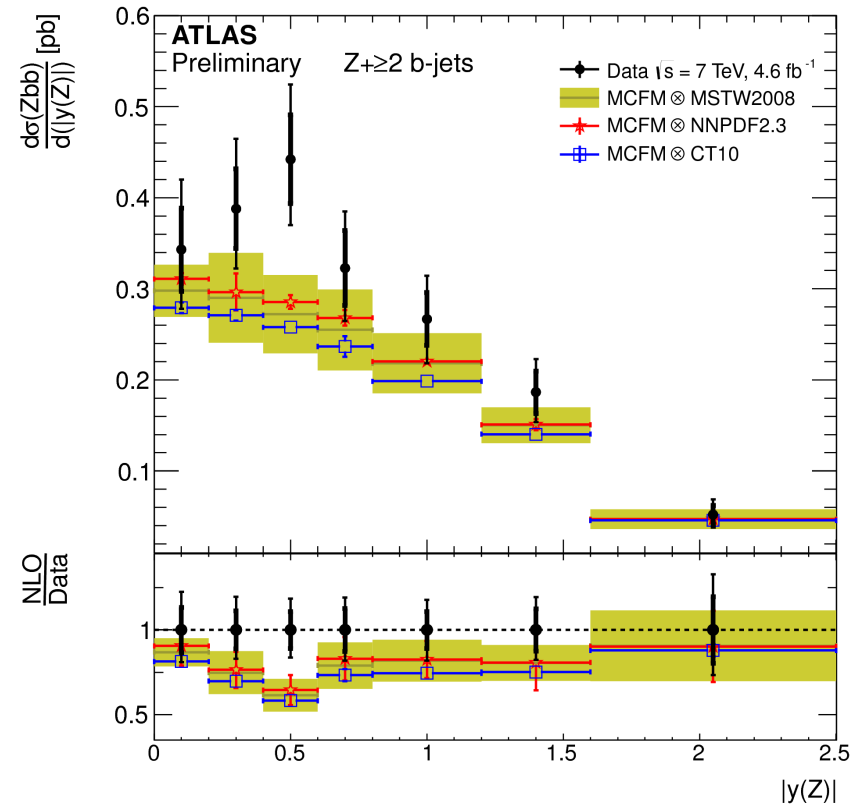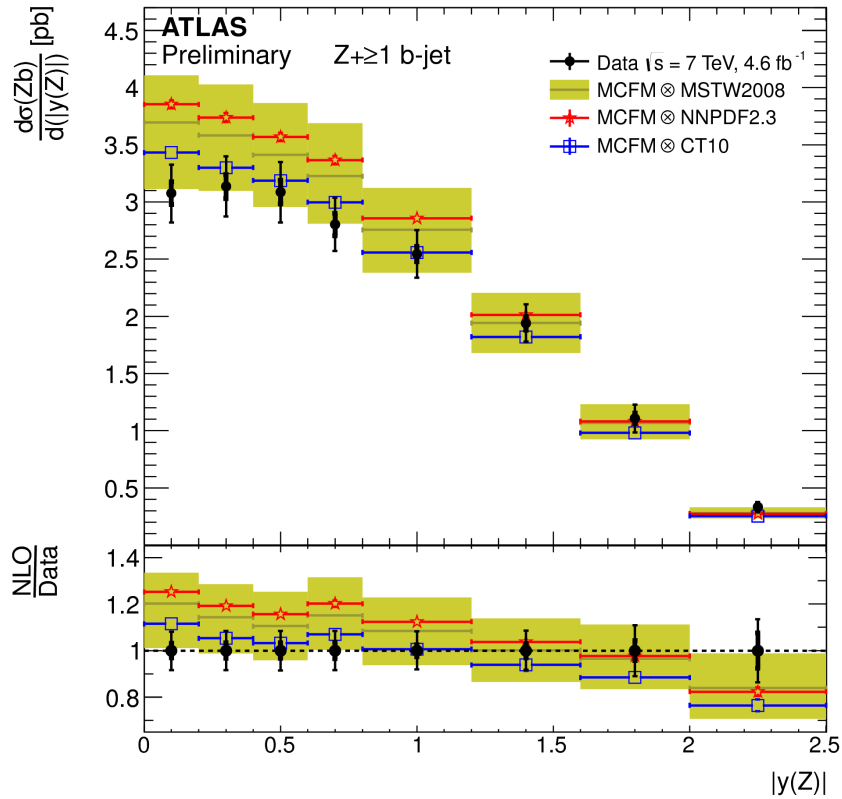
→ first observation

W+J/Ψ: results after DPS subtraction

- DPS fraction compatibe with ATLAS σ_{eff} measurement
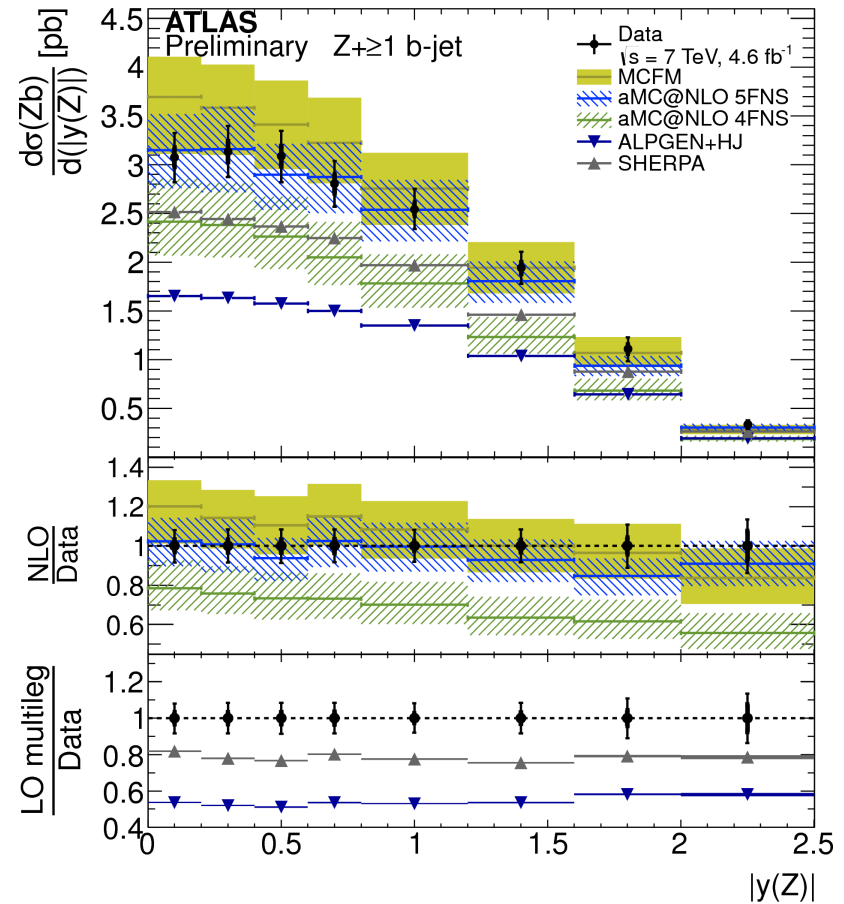
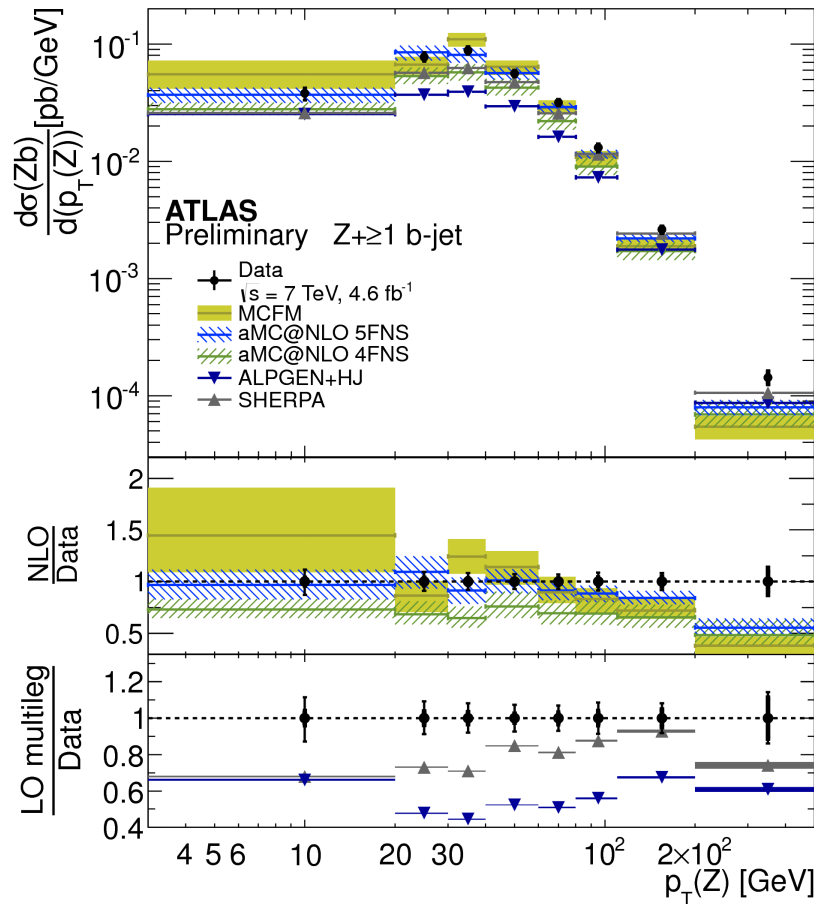$$P_{J/\psi|W^\pm} = \sigma_{J/\psi}/\sigma_{eff}$$

- SPS fraction dominated by color singlet contribution

- SPS fraction dominating at low pT(J/Ψ)

Z+b: PDF

Z+b: pT(Z) and y(Z)

V+b jets