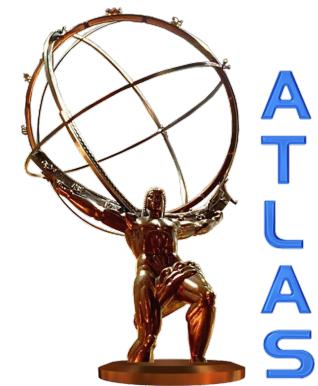
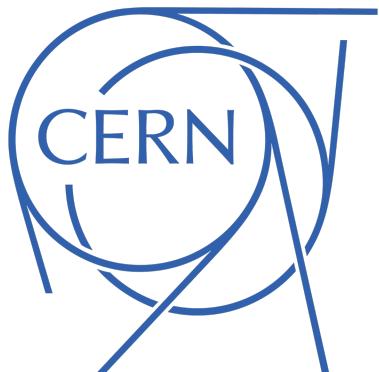


W and Z boson production in association with heavy flavour jets at ATLAS

Francesco Giuli (on behalf of the ATLAS Collaboration)

30th International Workshop on Deep Inelastic Scattering and Related Topics (MSU, USA)

28/03/2023

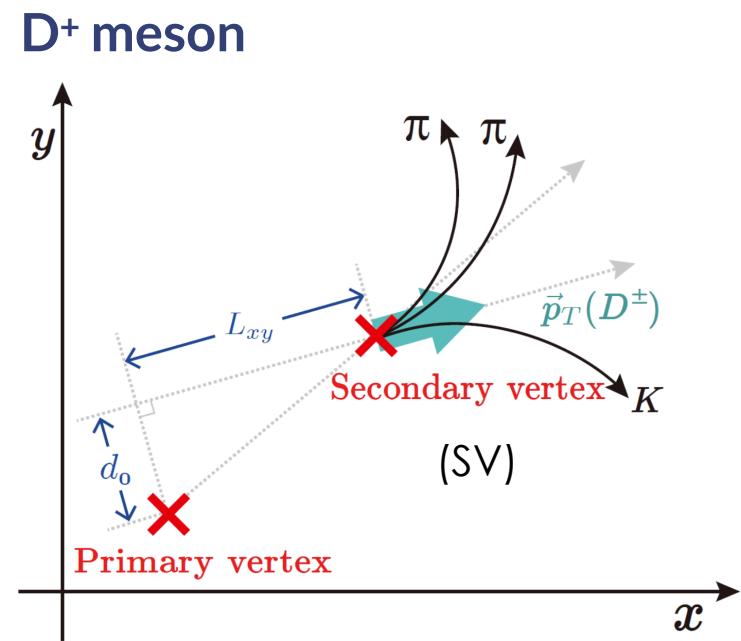
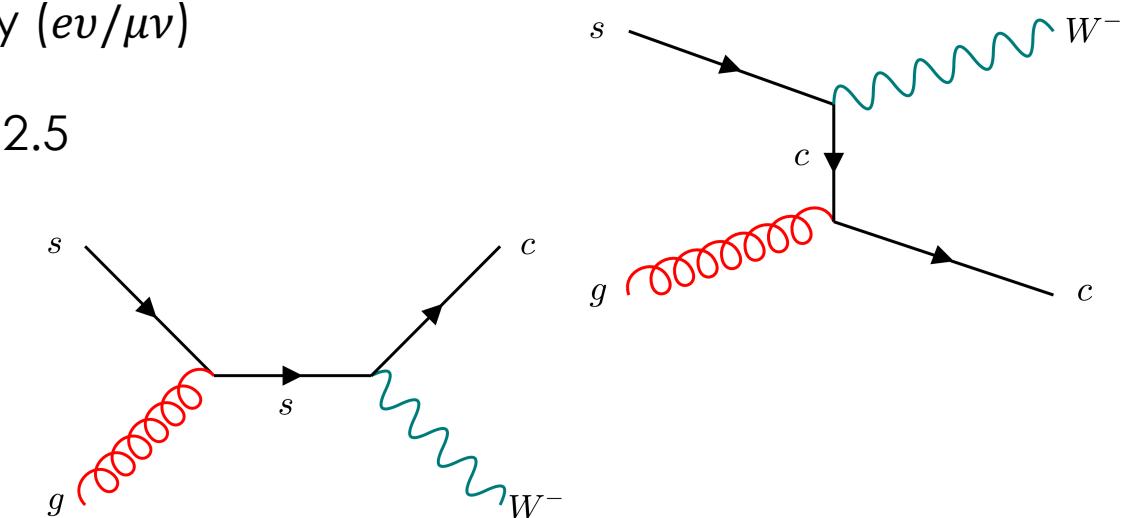


Introduction

- Measurements of W and Z vector-boson production cross section in association with heavy-flavour jets are central in the LHC physics program
- They allow to:
 - Test precisely perturbative Quantum ChromoDynamics (pQCD)
 - Measure fundamental parameters of the Standard Model (SM)
 - Improve our understanding of Parton Distribution Functions (PDFs)
 - Understand import background to searches beyond the SM (BSM) and Higgs measurements
 - Provide important inputs to simulations
- Two recent results from the ATLAS experiment are presented:
 - Measurement of W + charmed hadron - [2302.00336](#) (submitted to PRD)
 - Sensitive to the s-quark PDF
 - Confirm unsuppressed s-quark content at low-x from ATLAS W,Z 7 TeV data - [Eur. Phys. J. C 77 \(2017\)](#)
 - Z production in association with (b-tagged) large-radius jets - [2204.12355](#) (submitted to PRD)

Measurement of W + charmed hadron

- W boson decaying leptonically ($e\nu/\mu\nu$)
- Lepton $p_T > 30 \text{ GeV}$ and $|\eta_l| < 2.5$
- $p_T(D) > 8 \text{ GeV}$ and $|\eta(D)| < 2.2$
- $E_T^{\text{miss}} > 30 \text{ GeV}$
- $m_T(W) > 60 \text{ GeV}$
- Strategy: identify c-jet via charmed hadron reconstruction
 - $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$
 - $D^{*\pm} \rightarrow D^0 \pi^\pm \rightarrow (K^\mp \pi^\pm) \pi^\pm$
- D^* mesons decay prompt
- Combine with prompt tracks (π^\pm)
- Check candidates against selection criteria



Measurement of W + charmed hadron

➤ Main backgrounds:

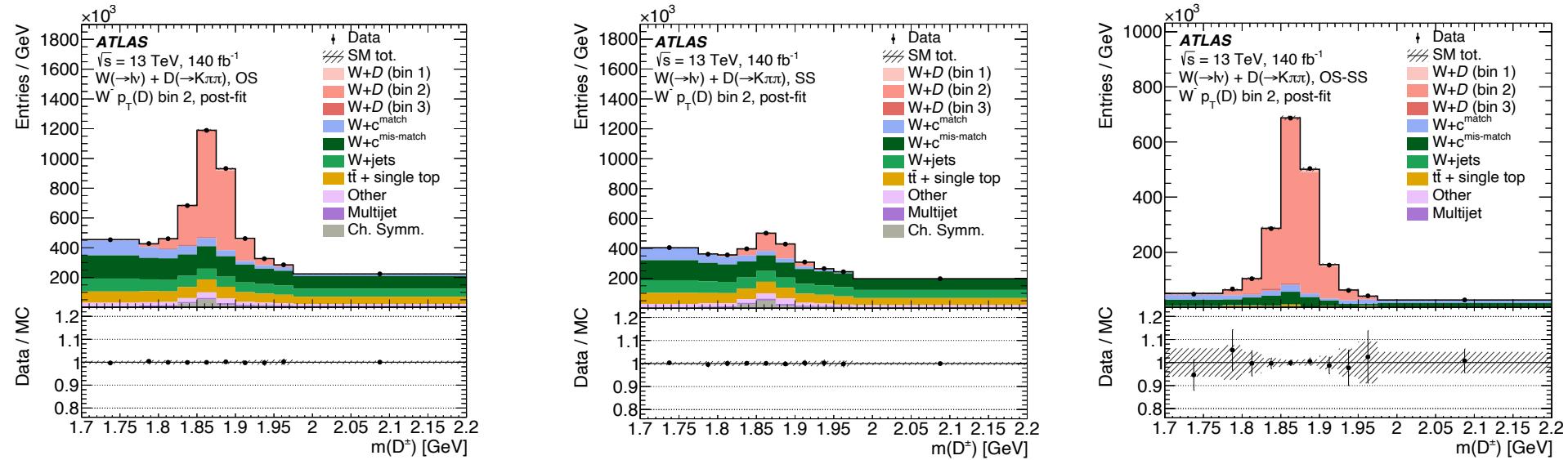
- W + c^{match}: tracks in SV belong to different c-hadron or decay mode
- W + c^{mis-match}: not all tracks belong to $D^{\pm(*)}$ candidate
- W + jets: no track belong to $D^{\pm(*)}$ candidate
- Top constrained in data region with ≥ 1 b-jet
- Multijet from fake-enriched region in data

Backgrounds

Z + jets	SHERPA 2.2.11	0–2j@NLO+3–5j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA	
$t\bar{t}$	POWHEG Box v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EvtGEN	
Single- t , Wt	POWHEG Box v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EvtGEN	
Single- t , t -channel	POWHEG Box v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EvtGEN	
Single- t , s -channel	POWHEG Box v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EvtGEN	
$t\bar{t}V$	AMC@NLO	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EvtGEN	
Diboson fully leptonic	SHERPA 2.2.2	0–1j@NLO+2–3j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA	
Diboson hadronic	SHERPA 2.2.1	0–1j@NLO+2–3j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA	

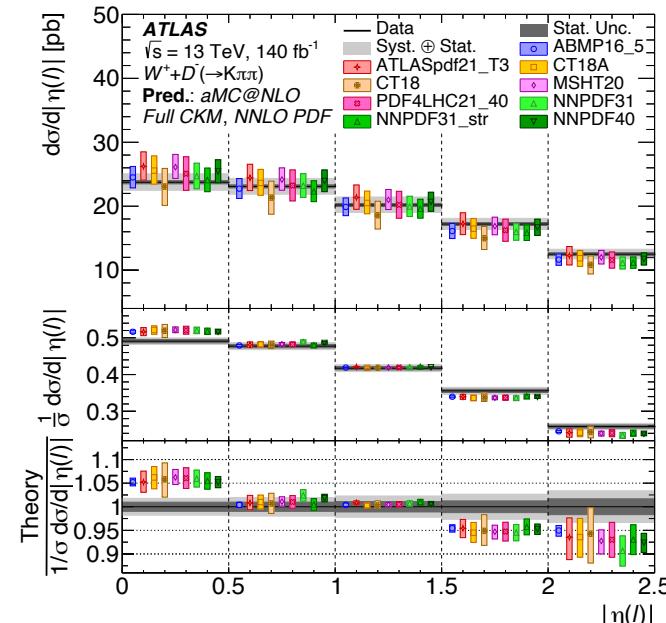
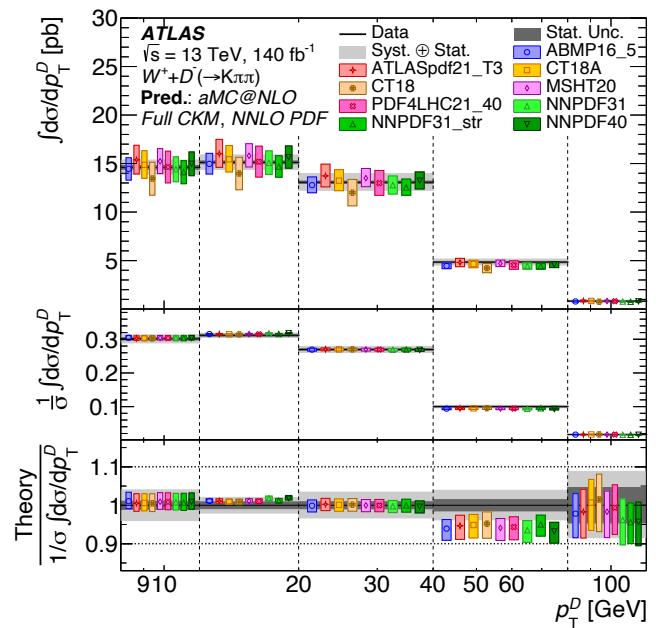
Measurement of W + charmed hadron

- Signal events have opposite-sign (OS) W boson and D meson
- Backgrounds mostly charge-symmetric, suppressed by subtracting same-sign (SS) events
- **Binned profile likelihood fit** of OS and SS $m(D^{(*)})$ template
- $m(D^{(*)})$ fit at particle level in bins of $p_T(D^{(*)})$ and $|\eta_l|$
- Simultaneous fit to SS and OS templates, extract signal cross sections in a background-subtracted OS-SS region



Measurement of W + charmed hadron

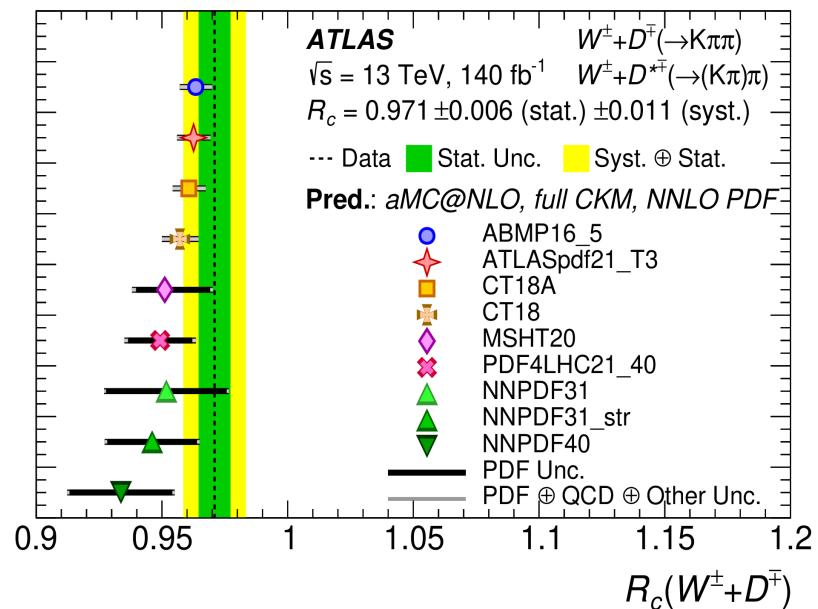
- Background normalisation and systematic constraints via likelihood fit of 5 $p_T(D^{(*)})$ or $|\eta_l|$ bins
- **Systematics** in the "+" and "-" channels mostly cancel out in R_C^\pm
- MC and data **statistics dominate** (from 0.7% to 1.3%)
- Smaller systematics in $|\eta_l|$ than $p_T(D^{(*)})$
 - SV reconstruction independent of $|\eta_l|$
- Similar trend observed for various PDF sets and different predictions (different MC generators, but same 'merged' accuracy)



Measurement of $W + \text{charmed hadron}$

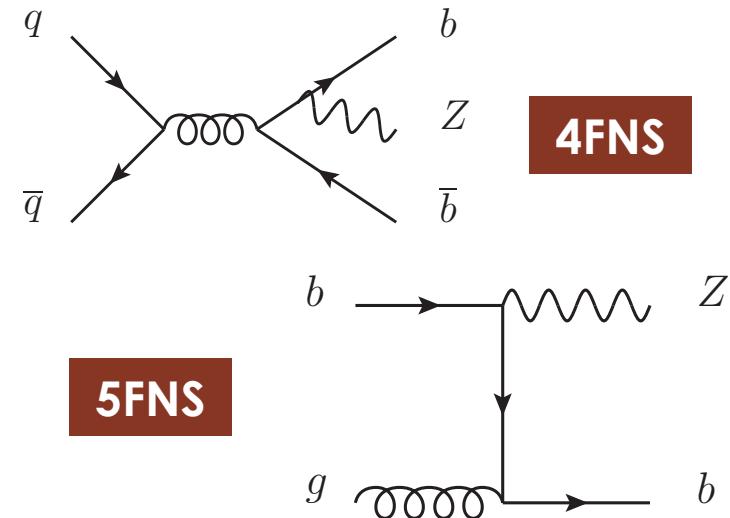
- R_C^\pm with smaller uncertainties using CT18, ABMP16 and ATLASpdf21
- This suggests **$(s - \bar{s})$ asymmetry** is **small** in the region probed by this analysis
- PDFs which assume $(s - \bar{s})$ asymmetry in worse agreement with our data
- Ratio of σ in 2 decay channels in agreement within uncertainties

Channel	$\sigma_{\text{fid}}^{\text{OS-SS}}(W+D^{(*)}) \times B(W \rightarrow \ell\nu)$ [pb]
W^-+D^+	50.2 ± 0.2 (stat.) $^{+2.4}_{-2.3}$ (syst.)
W^++D^-	48.5 ± 0.2 (stat.) $^{+2.3}_{-2.2}$ (syst.)
W^-+D^{*+}	51.1 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
W^++D^{*-}	50.0 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
$R_c^\pm = \sigma_{\text{fid}}^{\text{OS-SS}}(W^++D^{(*)}) / \sigma_{\text{fid}}^{\text{OS-SS}}(W^-+D^{(*)})$	
$R_c^\pm(D^+)$	0.965 ± 0.007 (stat.) ± 0.012 (syst.)
$R_c^\pm(D^{*+})$	0.980 ± 0.010 (stat.) ± 0.013 (syst.)
$R_c^\pm(D^{(*)})$	0.971 ± 0.006 (stat.) ± 0.011 (syst.)



Measurement of Z + boosted b-jets

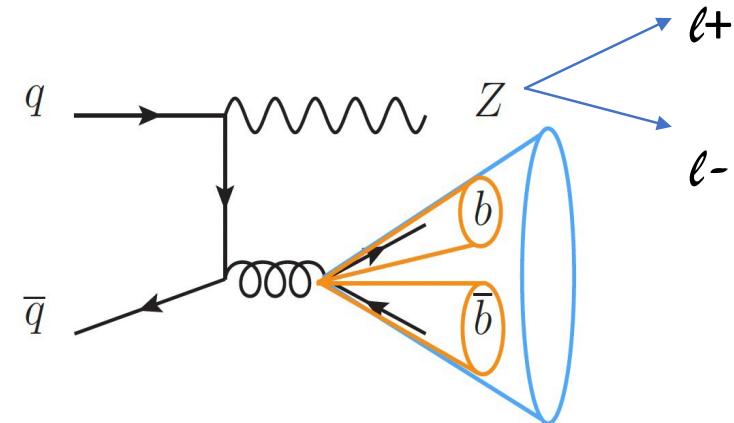
- Relatively larger production of boosted population at 13 TeV wrt 7 TeV
- Boosted jet production with Z boson to reduce QCD background
- Boosted jet topology **sensitive to New Physics**: heavy resonances decaying into boosted jets
- Understand **background for $H \rightarrow b\bar{b}$** in boosted regime
- Test of our understanding of **hard collinear gluon splitting**
 - Description of gluon splitting into Heavy Quarks (HQ) from Parton Shower (PS) models
 - Slicing of HQ production between ME and PS
- How b-quark participate to hard scattering?
 - **4FNS**: $b\bar{b}$ only from gluon splitting in ME
 - **5FNS**: massless b-quark in the proton PDF
 - **Fused scheme** (4FNS+5FNS): in principle, more accurate scheme in all kinematic regions



Measurement of Z + boosted b-jets

➤ Lepton and Z-boson selection:

- $e^\pm (\mu^\pm)$ pairs in the calorimeter (muon system) acceptance
- PID, Isolation, $p_T > 27 \text{ GeV}$, $m_{ll} > 50 \text{ GeV}$



➤ Jet selections:

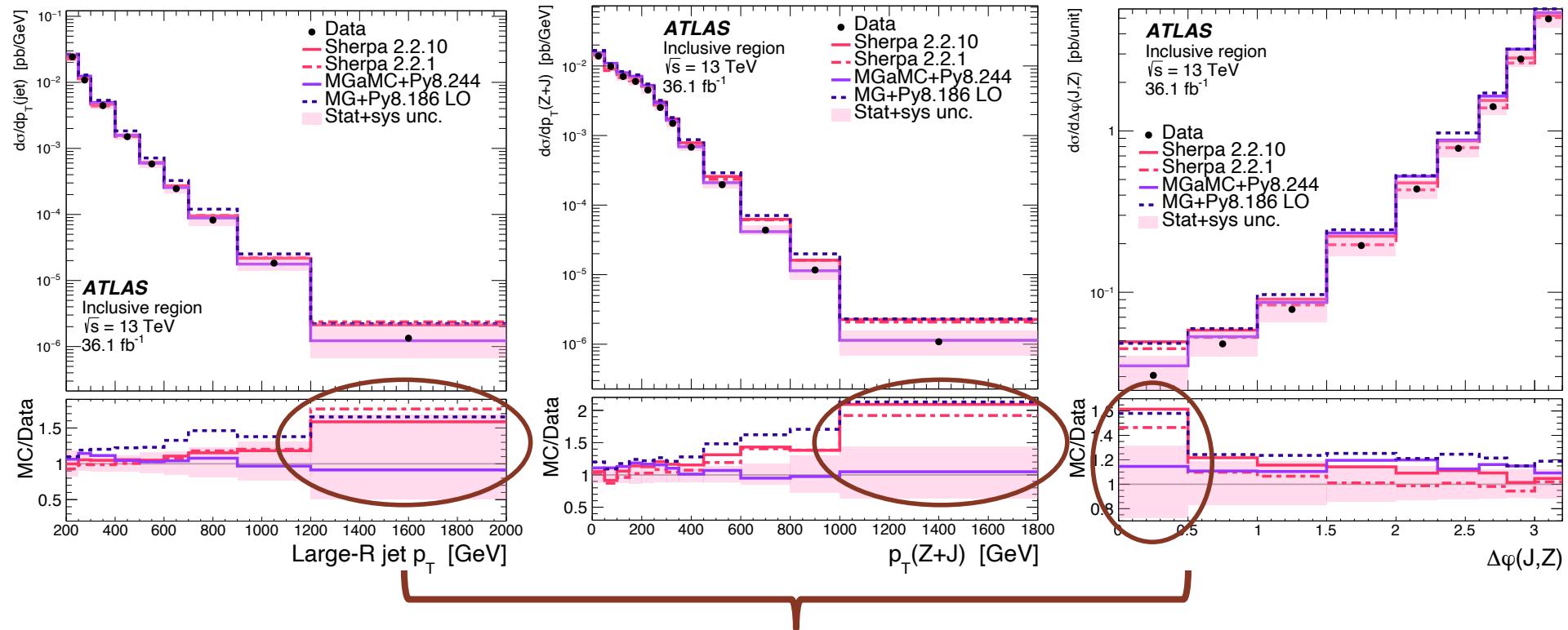
- Inclusive Large-R jet (hadronically decaying high-energy gluon)
 - Anti- k_t with $R = 1$, trimming to suppress PU and UE, $p_T > 200 \text{ GeV}$, $|\eta| < 2$
- Large-R jets with 2 b-tagged sub-jets
 - Anti- k_t with $R = 0.2$, matching with tracks pointing to IP, $p_T > 10 \text{ GeV}$, $|\eta| < 2.5$
 - b-tagging with MV2c10 at 70% b-tag efficiency (large rejection of c- and light-jets)

➤ Differential cross sections:

- m_j and \mathbf{p}_T^j (both inclusive and 2-tag) – overall kinematics of the large-R jets
- \mathbf{p}_T^{Z+j} and $\Delta\phi(Z, j)$ (inclusive) – Z-jet properties and correlations
- $\Delta R(b\bar{b})$ (2-tag) - $g \rightarrow b\bar{b}$ splitting properties

➤ Total cross sections from integration of differential ones – test of overall scale

Measurement of Z + boosted b-jets

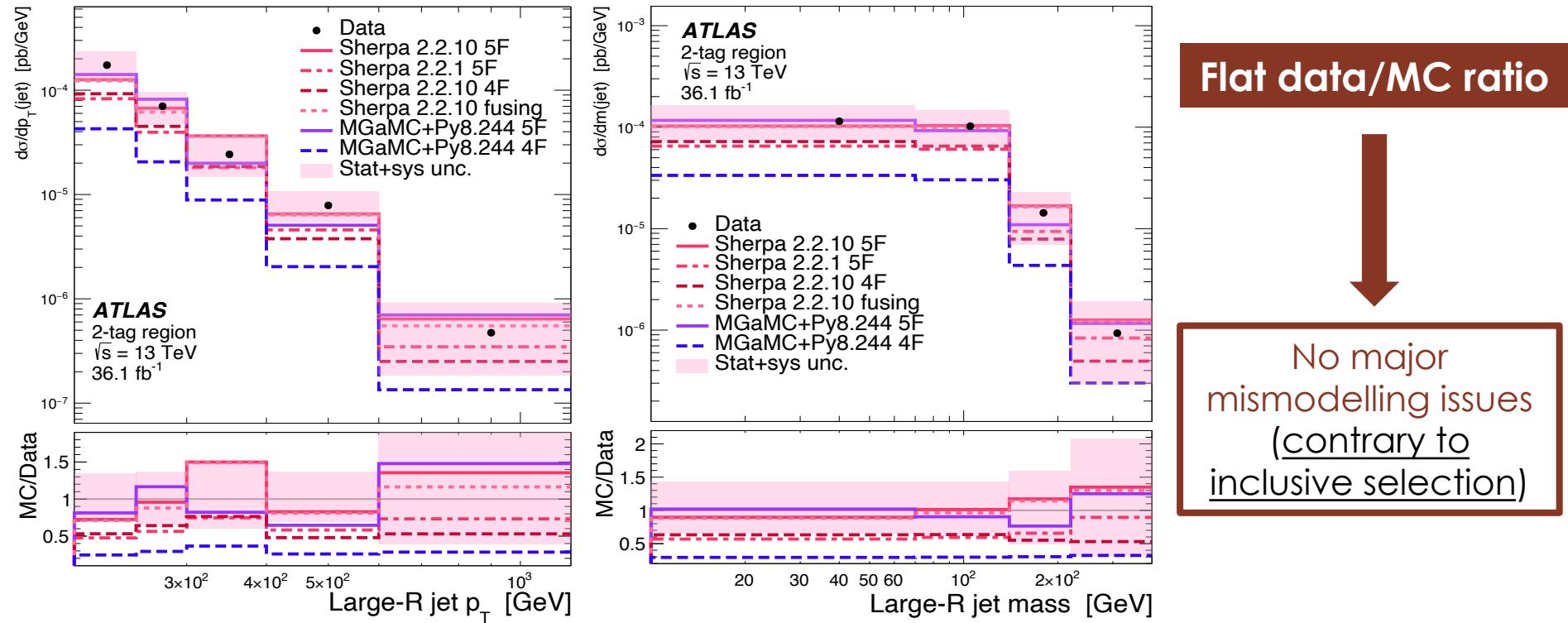


Large additional event activity Z-jet collinear

- **Serious mis-modelling** of NLO Sherpa and LO MadGraph
 - Poor description of extra radiation (larger transverse recoil of jet and Z+jet) → **call for MC tuning**
- NLO MadGraph **well describes** jet kinematics and Z+jet correlations

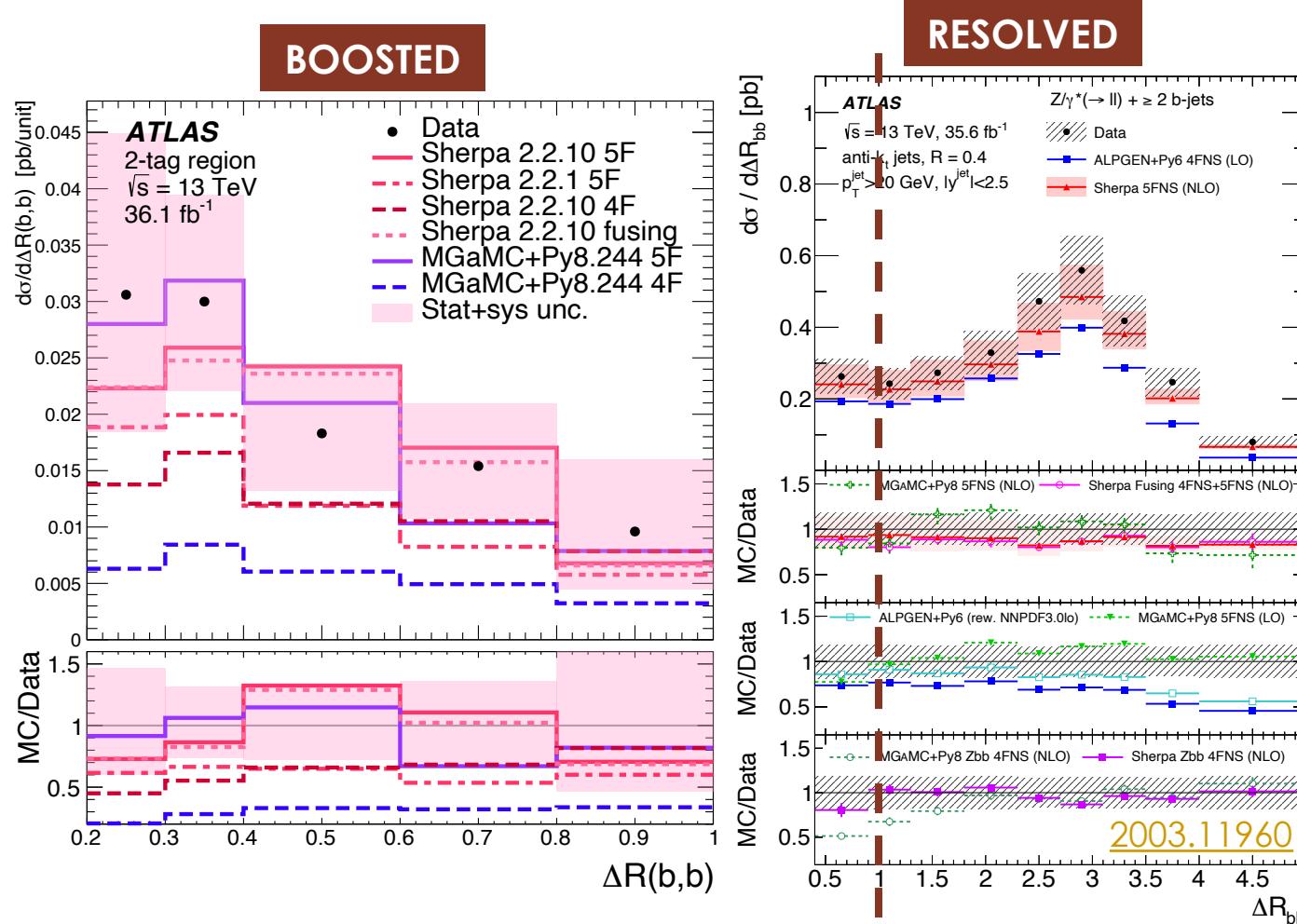
Measurement of Z + boosted b-jets

- Statistically limited measurement prevents from strong conclusions
- Interesting to explore full Run 2 data set to possibly provide stronger discriminations among models
- **5FNS** provide **better normalisation** (see total cross section)
- **Fusing scheme close to 5FNS** also in differential distributions



Measurement of Z + boosted b-jets

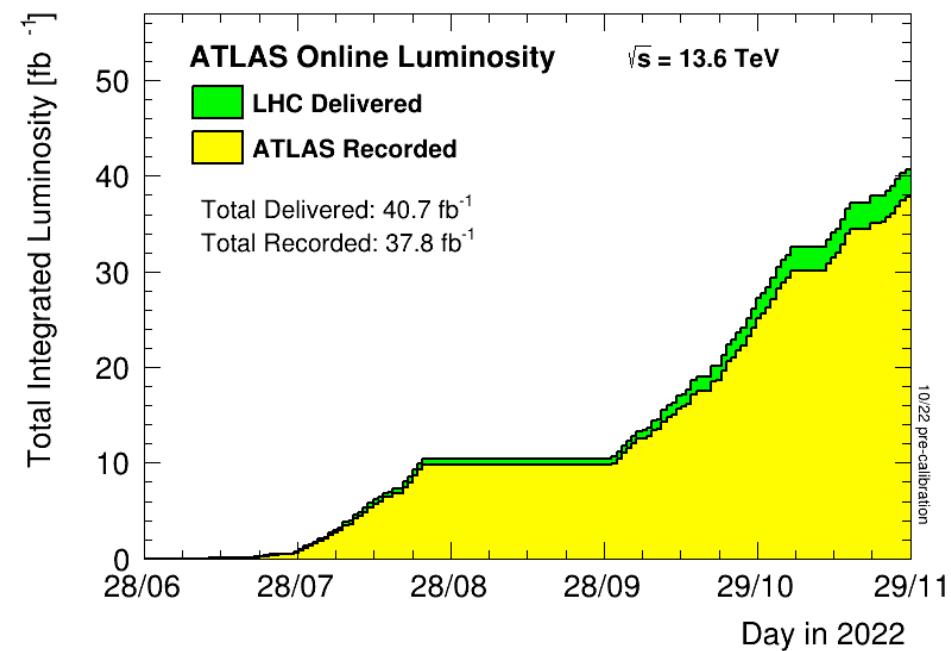
- 2 b-tag boosted jets explore low $\Delta R(b\bar{b})$ – extreme phase space in resolved analysis
- Overall normalisation discrepancy observed for 4FNS (in particular MGaMC)



- All MC show flat ratios to data within errors
- MGaMC (4FNS) gives largest disagreement in resolved analysis

Conclusions

- Precision measurements with Run 2 data sets provide a rich environment to probe QCD
 - Measurements to provide valuable feedback for generators and PDF development
- W,Z production in association with HF jets is a relevant part of the ATLAS physics program
- Run 3 has started
 - ~300 fb^{-1} expected by end of 2025
 - 80 fb^{-1} per year
- Even more impressive results with larger dataset and always-improving theoretical predictions
- Stay tuned! ☺



THANKS FOR YOUR ATTENTION!
ANY QUESTIONS?

