Z boson production associated with Charm and Beauty Jets in ATLAS

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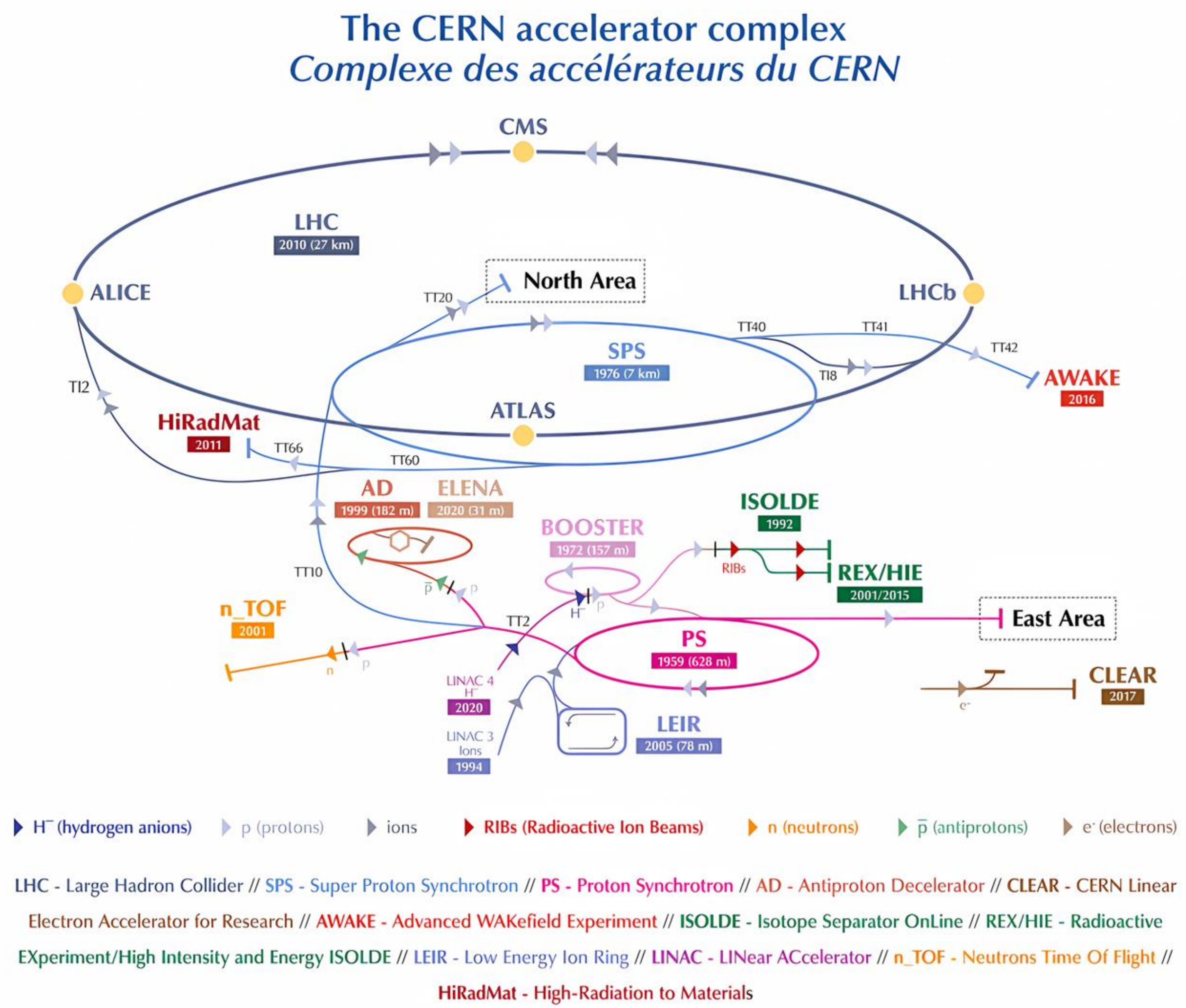
16th June 2024, ISSP Summer School, Erice

The Large Hadron Collider

Snowmass White Paper Contribution:
Physics with the Phase-2 ATLAS and CMS Detectors



CERN-GRAPHICS-2019-002

- Frontier particle physics @ TeV scale
  - Higgs physics: Yukawa coupling, self interactions
    - ⇨ mass origin of matter particles
    - ⇨ evolution of vacuum and universe
  - SM precision: bosons, top, fundamental parameters
    - ⇨ confront with PDF, electroweak and QCD theory
  - New physics: dark matter, exotics, symmetry breaking
    - ⇨ search for BSM interaction and particles directly
- Why New Physics?
  - Neutrino mass, baryon asymmetry, dark matter inflation ☜ experimental challenges
  - Fermion/Higgs hierarchy, gauge unification, vacuum stability ☜ theoretical motivation

ATLAS Experiment Detectors

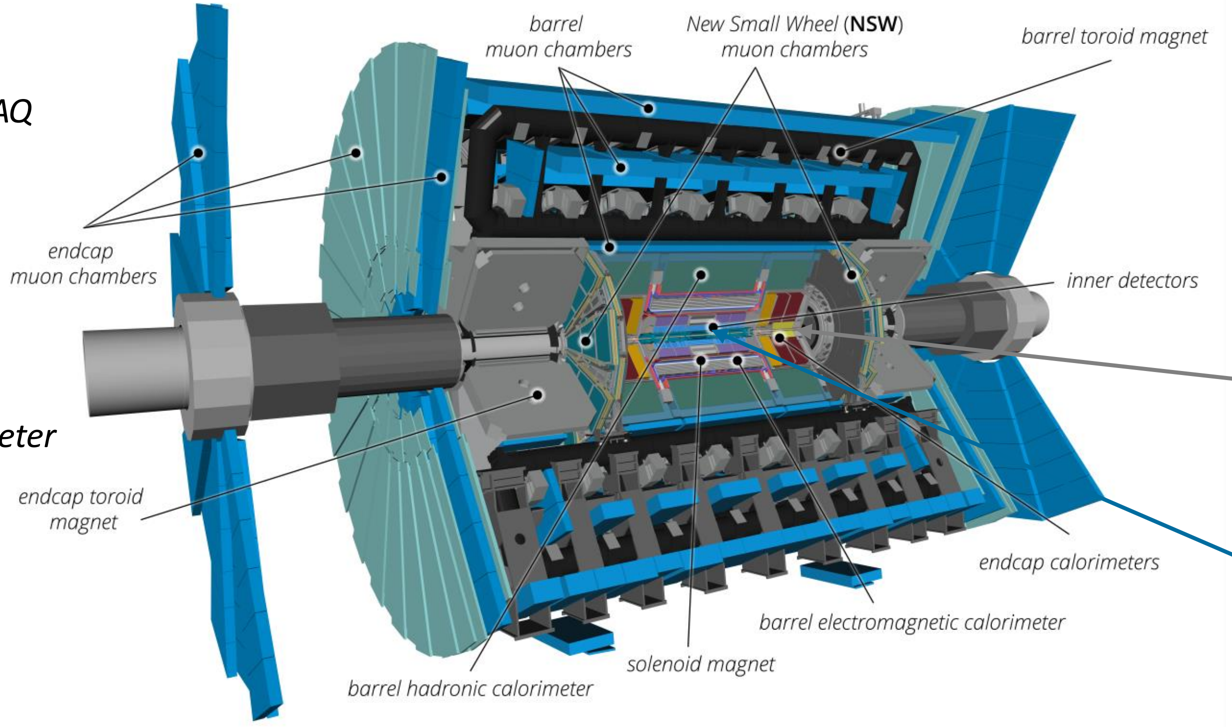
Diagram of particle paths in the detector

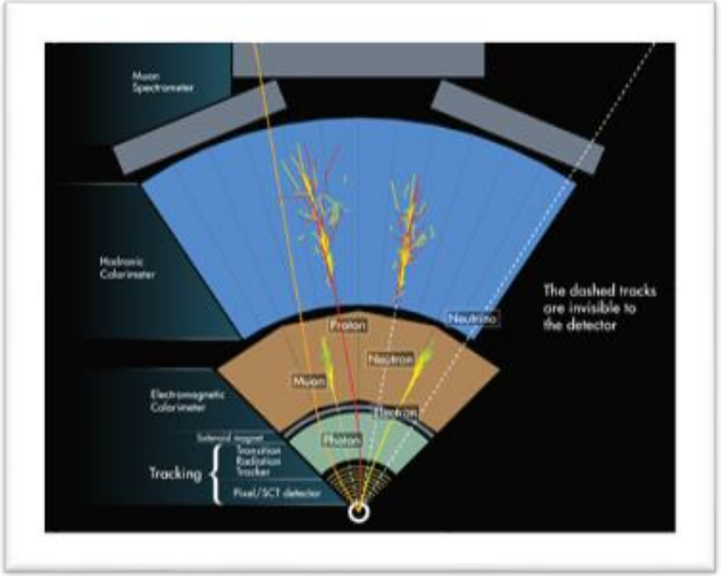
- Multipurpose detector targeting Higgs, SM, and New physics
  - Onion layer structure: inner detector -> calorimeters -> muon spectrometer

Improved muon coverage and trigger

Upgraded Trigger and DAQ
- *L0 rate: 1 MHz*
- *Event Filter: 10 kHz*

Upgraded electronics
- *Liquid Argon Calorimeter*
- *Tile Calorimeter*
- *Muon system*





NEW endcap high-granularity timing detector

NEW all-silicon Inner Tracker coverage up tp $|\eta| = 4.0$

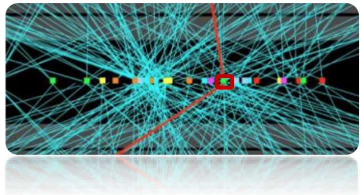
[ATLAS Configuration for Run 3] and HL-LHC

Hard QCD and EWK at ATLAS

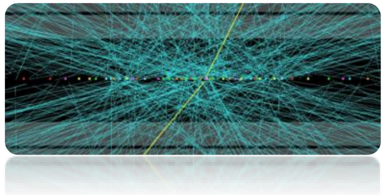
[Muon: Eur. Phys. J. C 81 (2021) 578]
[E/γ: JINST 14 (2019) P12006]
[FT: Eur.Phys.J.C 83 (2023)]

- Hard interactions are challenging at LHC
  - Excellent analysis results depend on the precise *modelling*, *experiment performance*, *analysis strategies*

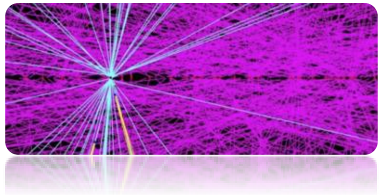
$< \mu > = 30$

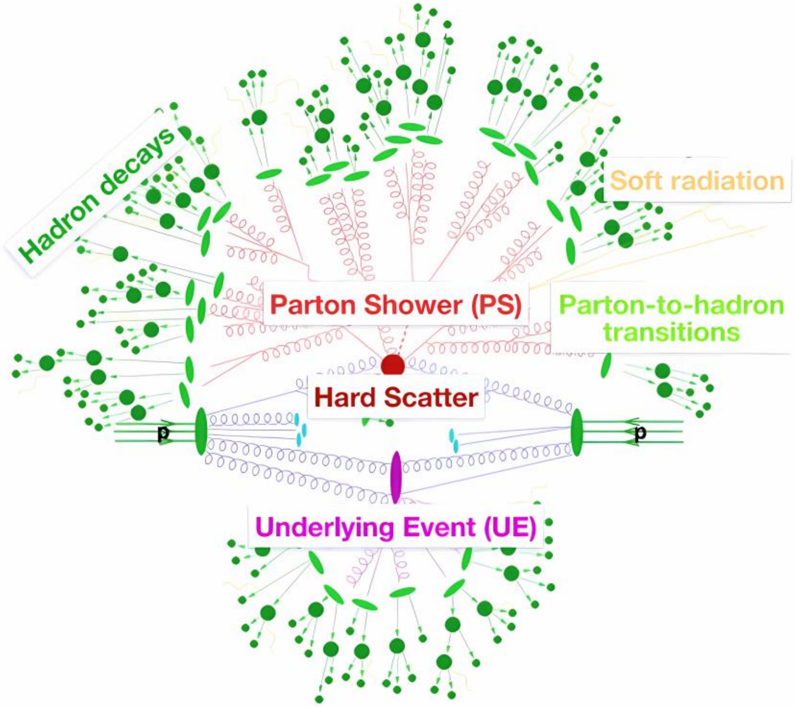


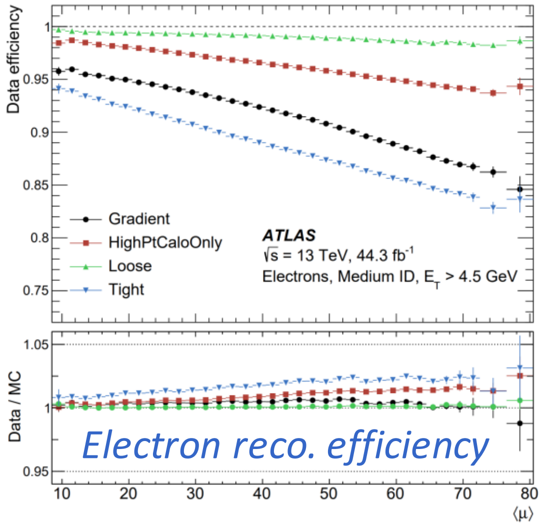
$< \mu > = 60$



$< \mu > = 140 - 200$

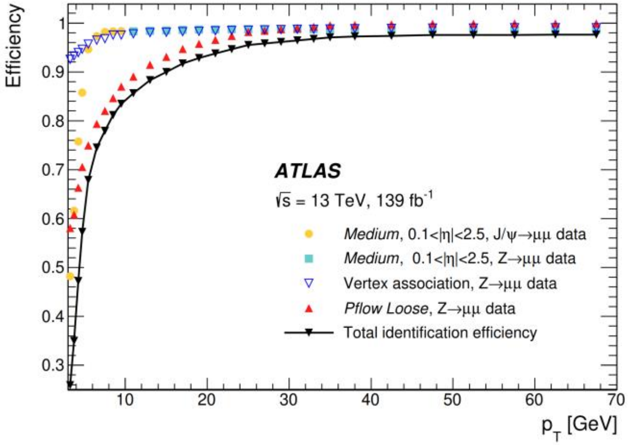


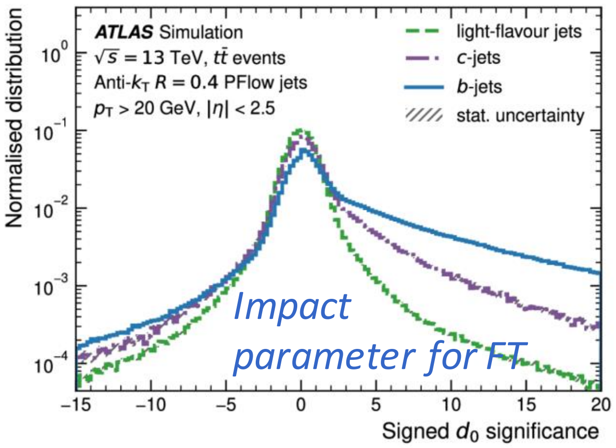




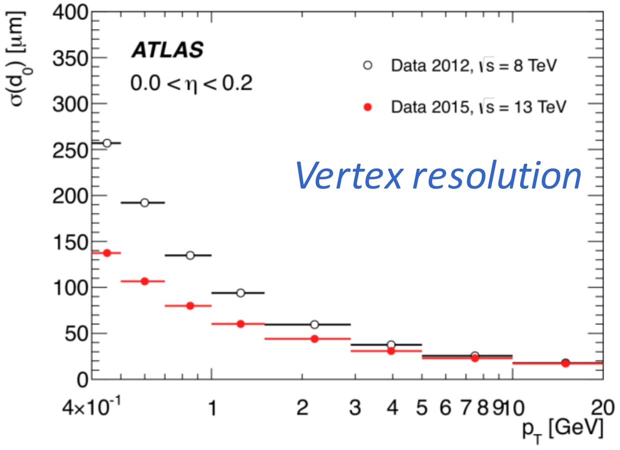
Electron reco. efficiency

Muon reconstruction efficiency





Impact parameter for FT

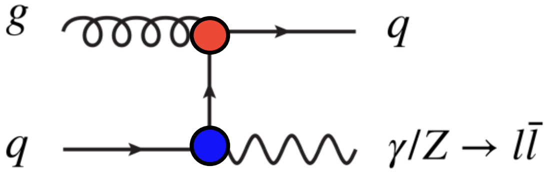


Vertex resolution

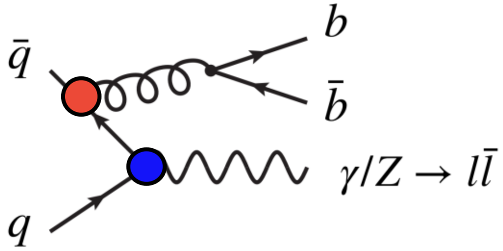
V + HF jets at hadron collider

- V(=W/Z) + jets production has the largest cross-section after multi-jet and inclusive V-boson productions
  - At LHC, 1/3 of W/Z production is in association with a jet (p_T > 30 GeV)
  - Heavy-Flavour (HF) jets = jets originating from the hadronization of c- and b-quark

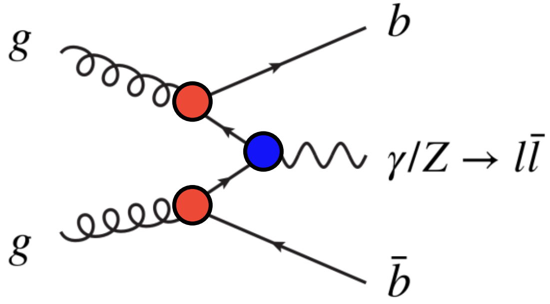
qg initial state

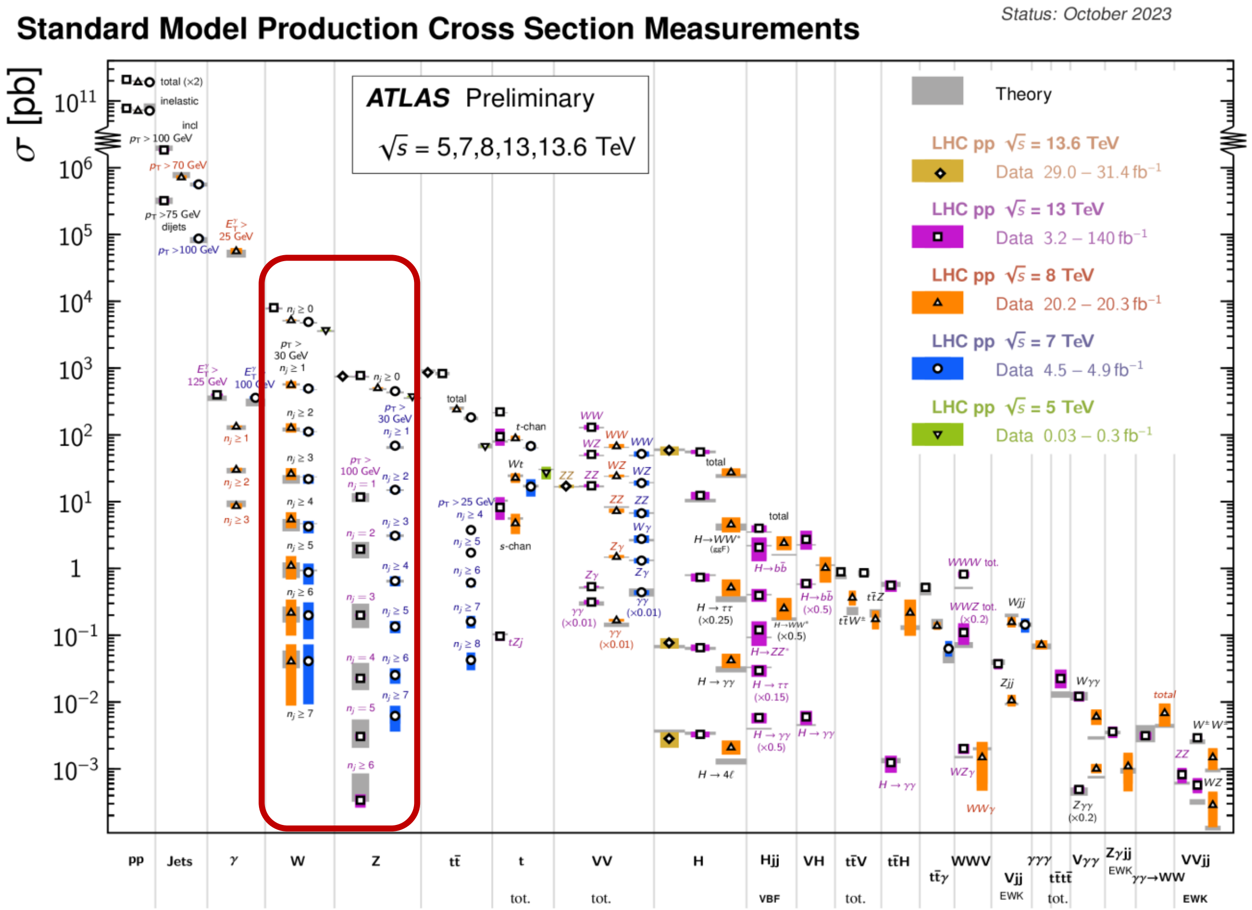


q q̄ initial state



gg initial state





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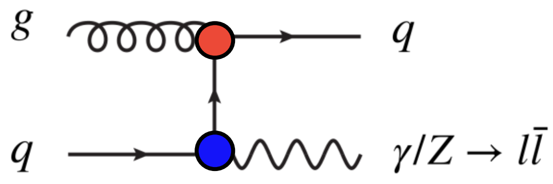
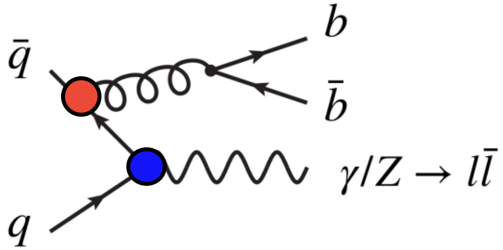
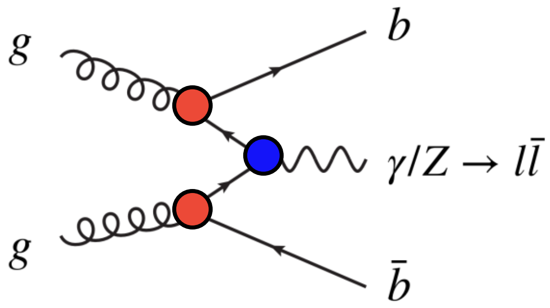
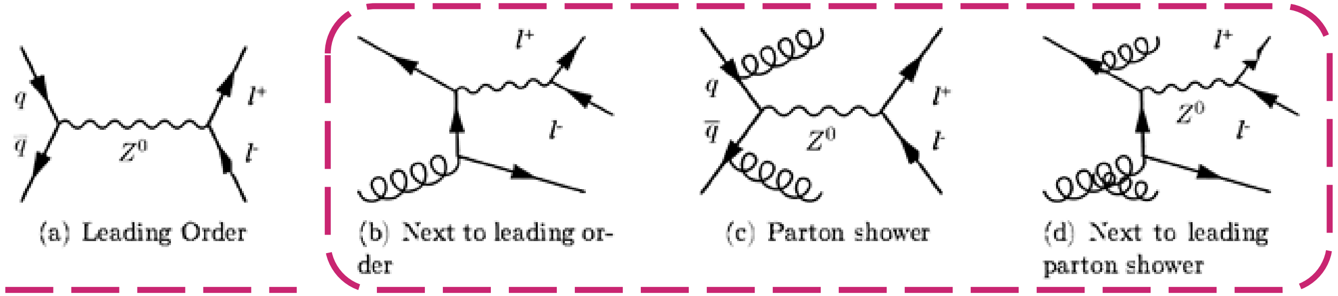


$q\bar{q}$ initial state



gg initial state





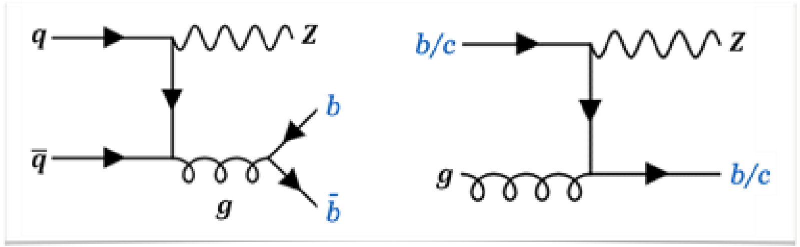
V+jets are the high order of Drell-Yan process
-- standard candle at LHC

- Perform **perturbative-QCD (pQCD)** studies at a wide kinematic range and jet multiplicities
- Increase our understanding of **Parton Distribution Functions (PDFs)**
- Improve background modelling in **Monte Carlo (MC)** simulation in New Physics (NP) searches

Goals and Motivations

Inclusive and differential Z+≥1b, ≥2b, ≥1c x-sections and fwd/central ratio for Z+≥1c events with 139 fb^{-1}

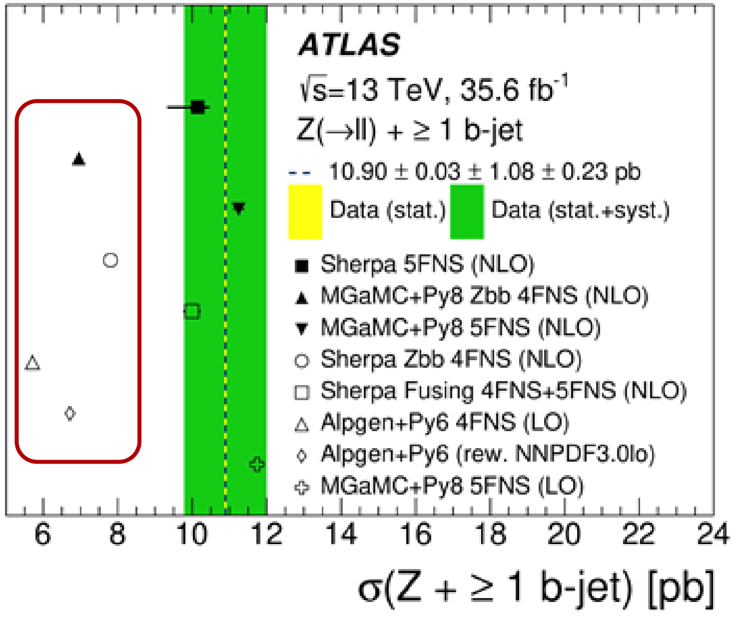
- Z+≥1b: Z p_T, lead b-jet p_T and ΔR(Z, lead b-jet)
- Z+≥2b: m_{bb}, $\Delta\Phi_{bb}$
- Z+≥1c: Z p_T, lead c-jet p_T, lead c-jet x_F and fwd/central vs Z p_T } **First time in ATLAS!**



- Precise test of the latest-of-art pQCD predictions (NNLO available)
- **Sensitive to b-, c-quark and gluon PDFs**
  - **Z+c** sensitive to intrinsic charm component
- Valuable inputs for tuning of MC simulations
  - V+HF background in Higgs and BSM searches
- **Previous ATLAS analysis with 36 fb^{-1}**
  - Precision limited by flavour-tagging and Z+c/light-jet background,
  - Large statistical and ttbar modelling uncertainty in Z+2b

⇨ **improved > 2x in this round with optimized strategies**

JHEP 07 (2020) 044

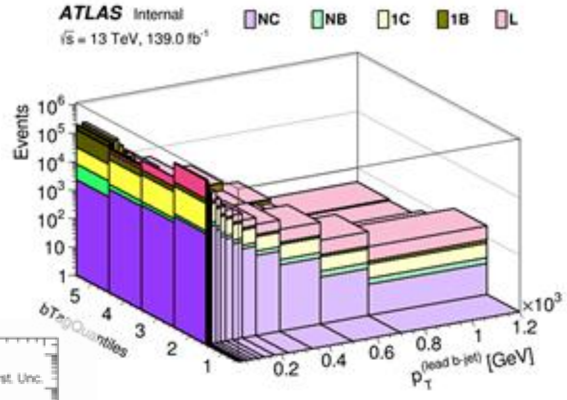


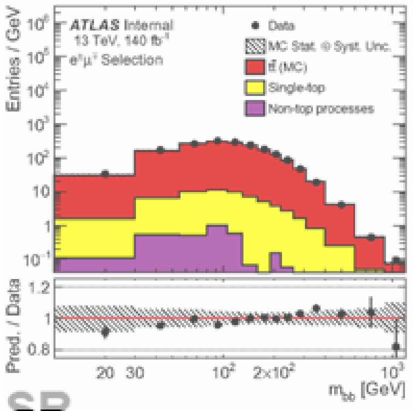
- Earlier $\sqrt{s}$ =13 TeV measurements:
  - ATLAS: *Z + 1,2 b* with 36 fb^{-1} JHEP 07 (2020) 044
  - ATLAS: *Z + b* at hight p_T with 36 fb^{-1} JHEP06(2023)080

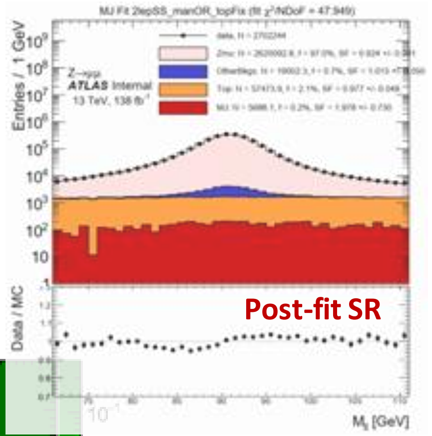
Analysis strategy

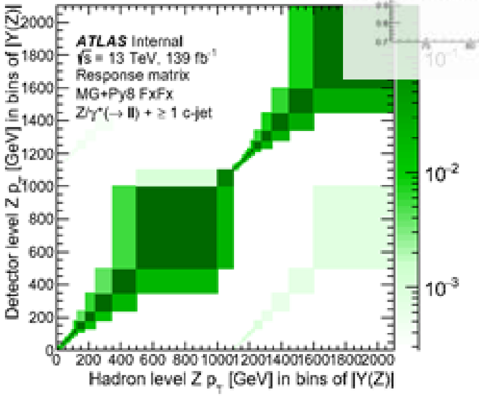
SR: 2 leptons (e^+e^- or $\mu^+\mu^-$) with ≥ 1, 2 flavour-tagged jets

- Loose 85% WP DL1r flavour-tagger to allow a fraction of c-jets









- **Z+jets determined by bin-wise flavour fits**
  - Clear trends of scale factors correct both of shape and norm.
- **$t\bar{t}$ estimated with transfer factors from $e^{\pm}\mu^{\mp}$ CR**
  - Data-driven uncert ~ 25% (7%) of modelling uncert in Z+1b (Z+2b)
- **QCD multi-jets validated by simultaneous fit of anti-iso CR and SR**
  - Permille level in SRs hence neglected in the analysis
- **Central and forward Z pT unfolded at meanwhile to keep correlations**
  - Small forward ↔ central migrations

Theoretical predictions

arXiv:2109.02653
Phys. Lett. B 843 (2023)
Eur. Phys. J. C 83, 336
PhysRevLett.130.161901

- Measured cross-sections compared with several predictions, test sensitivity to

Different FS in matrix-element calculation

IC-component in proton PDFs
MGAMC+PY8 FXFX with several PDF sets with different IC-models (PDF reweighting)

Higher order terms in QCD
Fixed-order predictions with jet flavour dressing (infrared and collinear safe)

‘ Generator/settings	Flav. scheme	PDF	LHAPDF ID
		Main MC samples	
MGAMC+PY8 FxFx	5FS	NNPDF3.1 (NNLO) LuxQED	325100
SHERPA 2.2.11	5FS	NNPDF3.0 (NNLO)	303200
		Predictions to test various flavour schemes	
MGAMC+PY8	5FS	NNPDF2.3 (NLO)	229800
MGAMC+PY8 Zbb	4FS	NNPDF3.1 (NLO) PCH	321500
MGAMC+PY8 Zcc	3FS	NNPDF3.1 (NLO) PCH	321300
		Intrinsic charm (IC) predictions	
MGAMC+PY8 FxFx	5FS	NNPDF4.0 (NNLO) PCH (no IC)	332100
		NNPDF4.0 (NNLO)	331100
		NNPDF4.0 (NNLO) EMC+LHCbZc	– [25]
		CT18 (NNLO) (no IC)	14000
		CT18FC – CT18 BHPS3	14087
		CT18FC – CT18 MCM-E	14093
		CT14 (NNLO) (no IC)	13000
		CT14 (NNLO)IC – BHPS1	13082
		CT14 (NNLO)IC – BHPS2	13083
		Fixed-order predictions [3]	
NLO	5FS	PDF4LHC21	93000
NNLO	5FS	PDF4LHC21	93000

Flavour Scheme

JHEP07(2012)022

- V+HF is characterized by ***hard scale Q*** and mass of a ***heavy quark m***
  - pQCD calculations contain both powers of m^2/Q^2 and $\ln(Q^2/m_b^2)$ for g/q collinear splitting

- Variety assumptions on dealing with heavy quark masses in ME calculations

  - **3FNS:** massive c-quarks → c-quark appear only via gluon splitting
  - **4FS**: massive b-quarks → *b-quark* appear only via *gluon splitting*
    - power and logarithm corrections appear at fixed order explicitly
    - suitable for $\boldsymbol{Q^2 \sim m_b^2}$
  - **5FNS**: massless b-quarks → *b-quark* allowed via intrinsic *PDF*
    - $({m_b}^2/Q^2)^n$ pushed to higher orders
    - $\ln(Q^2/m_b^2)$ resummed to all orders into b-quark PDF
    - adequate at $\boldsymbol{Q^2 \gg m_b^2}$
  - *Collinear logarithms resummation* affects several key processes in L*HC*→ *Impact* increases in high *Bjorken x* and *Q*
    - amounts to adding different O(α_S^{n+1}) higher-order terms at a fixed order n in perturbation theory

Inclusive cross-section results

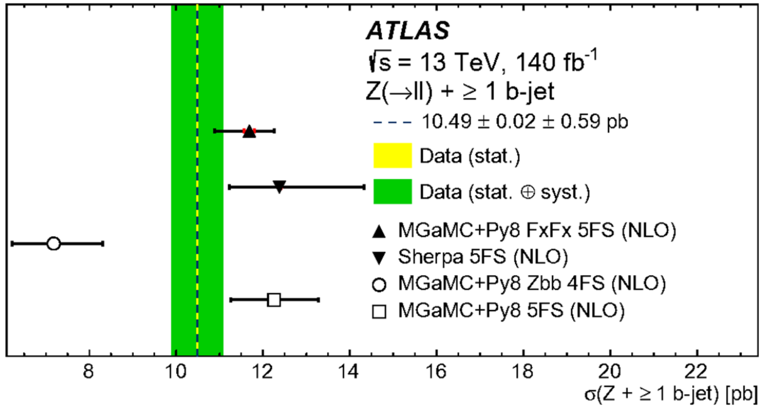
σ(Z+≥1 b-jet) = 10.49 ± 0.02 (stat.) ± 0.59 (syst.) pb

σ(Z+≥2 b-jets) = 1.39 ± 0.01 (stat.) ± 0.13 (syst.) pb

σ(Z+≥1 c-jet) = 20.89 ± 0.07 (stat.) ± 2.77 (syst.) pb

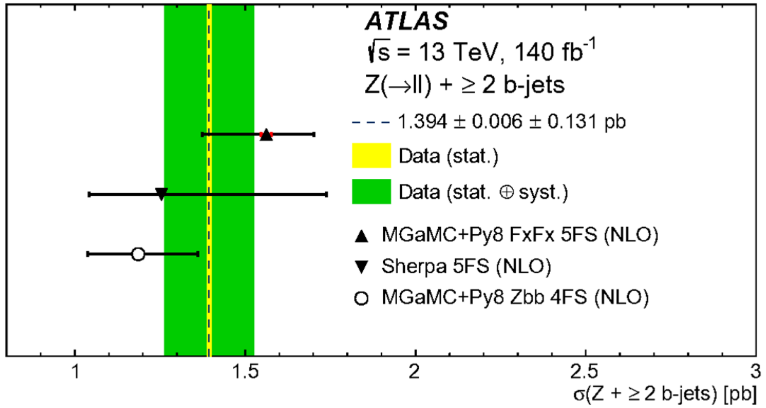
$Z+\geq 1\ b$-jet

- Good description from 5FS
- 4FS with large underestimation



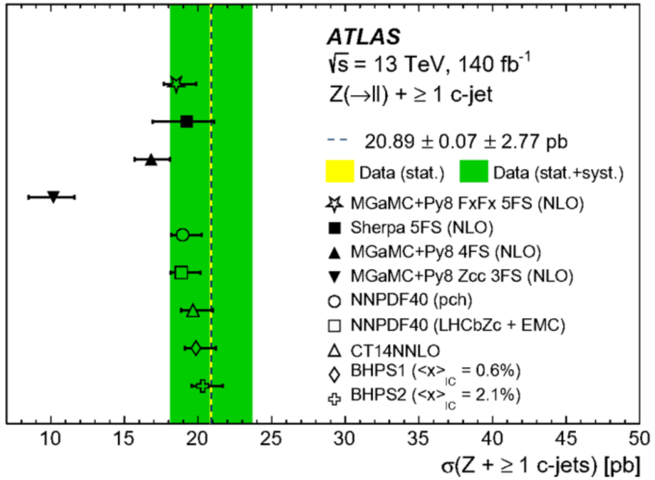
$Z+\geq 2\ b$-jet

- 4FS and 5FS agrees with data
- much sizable MHOU for Sherpa



$Z+\geq 1\ c$-jet

- 5FS in agreement with data
- 3FS with large underestimation

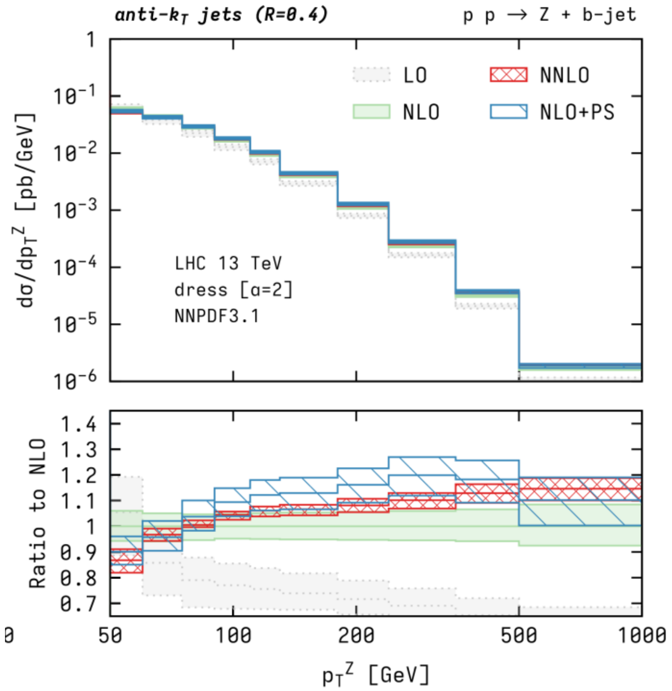


Results consistent with previous ATLAS measurement with 36 fb^{-1}

High-order QCD calculation

[Eur. Phys. J. C 83, 336](#)
[SM@LHC 2024](#)

- The complexity of V+HF processes requires calculations with high order precision in QCD
  - State of the art **MC generators** with matrix-element (ME) calculations at **NLO in QCD**, interfaced with **parton-shower (PS)** for the description of the soft QCD emissions
  - **Fixed-order** theoretical predictions available up to **NNLO** in QCD
    - Effect of missing higher order terms not negligible
    - IRC-safe jet flavour algorithms ⇨ soft flavored pairs clustered without ambiguity



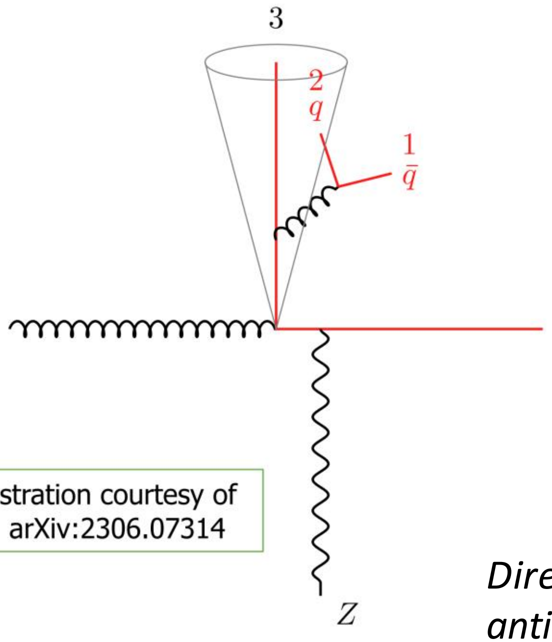


Illustration courtesy of ref. arXiv:2306.07314

- ***partonic* ~ *hadronic jet-flavour*** duality ambiguous starting from ***NNLO***

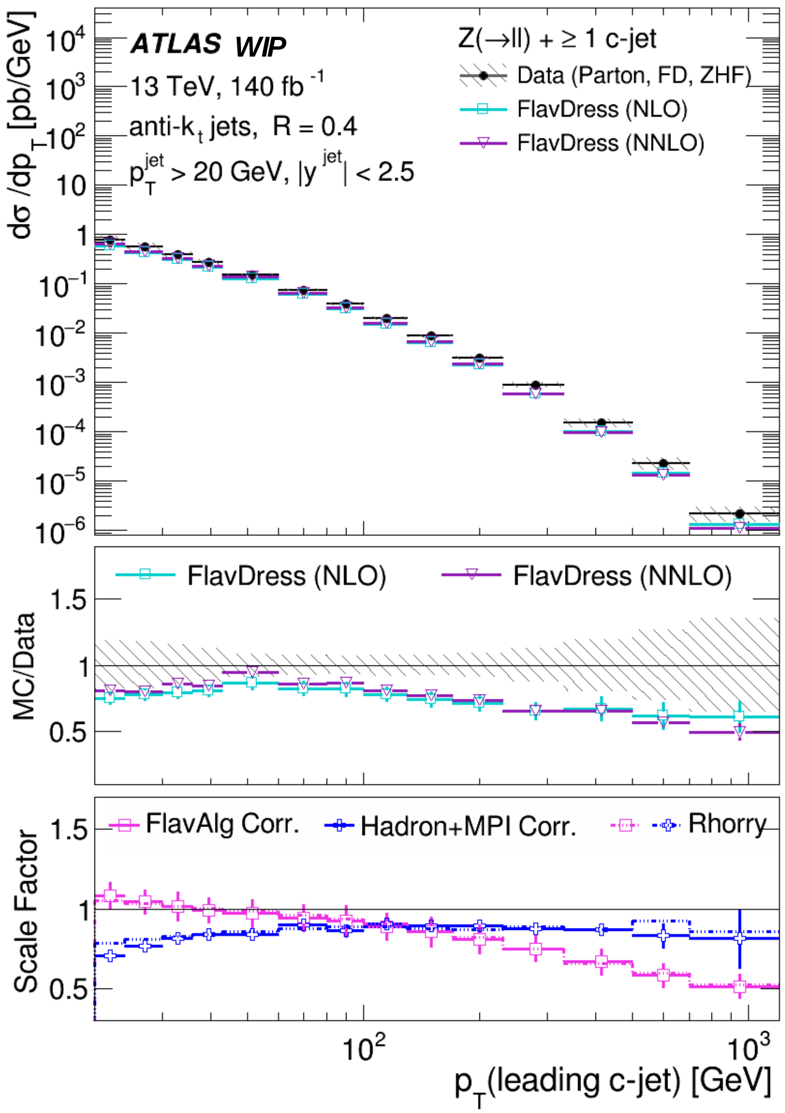
Consider a soft $g \to b\bar{b}$ emission

- If one of them is clustered in an unrelated hard jet, while another one forms its own jet

⇨ kinematic is unchanged but the flavor is (so called as IR unsafe)

Direct comparison of NNLO with data unfeasible:
anti-kt jet algorithm used at LHC is flavor-blind to cluster hadrons

Differential Z+>= 1c-jet cross-section results



Two scale factors used to correct data for a fair comparison with parton-level fixed-order predictions obtained with flavor-dressing algorithm (IRC-safe)

- **Jet flavour** algorithm correction ~ **50% (40%) in high pT region for Z+c (Z+b)**:
  - ratio of *FD-alg.* to *Exp-alg.* predictions

    (obtained with NLO+PS, hadron-level)
- **Hadronization and MPI** effects ~ **20% in low pT region**:
  - ratio of *parton-level* to *hadron-level* predictions

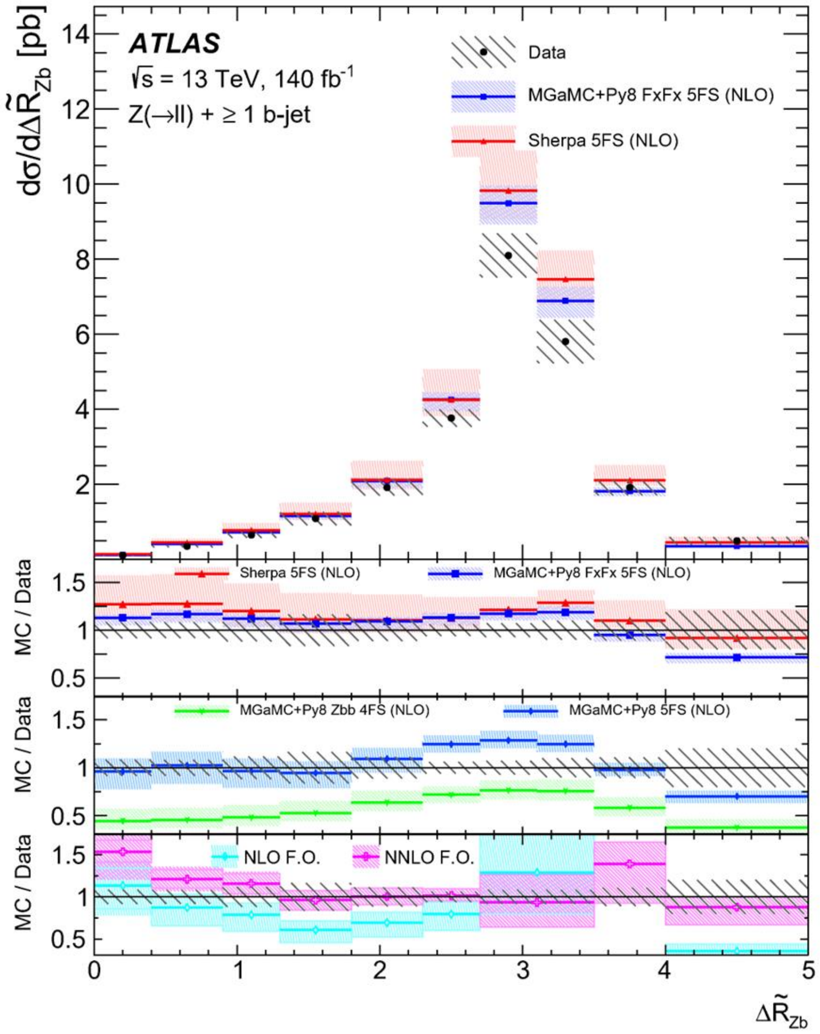
    (obtained with NLO+PS, FD algorithm)

SFs derived with ***MG+ Py8 FxFx (for FlavAlg Corr)***, ***Pythia (for Hadron+MPI Corr.)*** consistent with the one derived with ***MG+Py8 (for both)*** from Rhorry Gauld for Z+c process

Cons.:

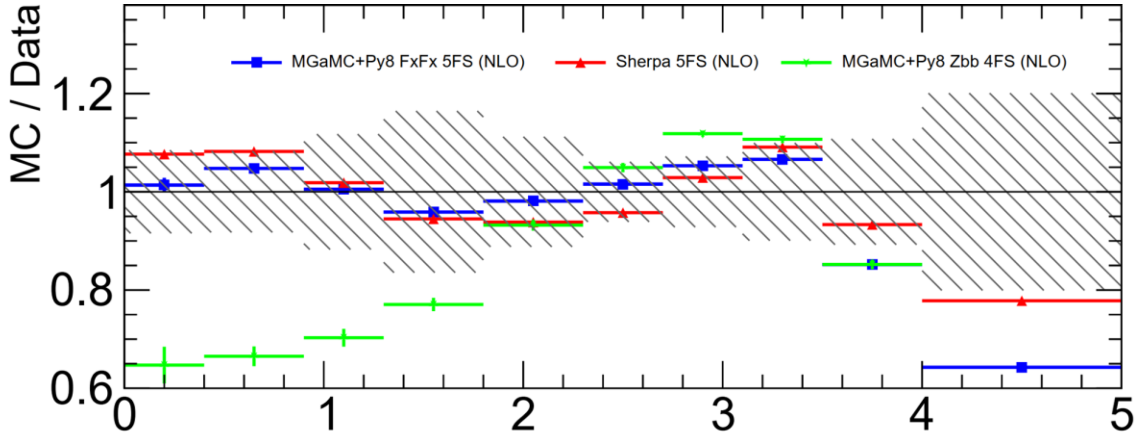
- **Additional uncertainties** for the SFs should be been taken counted for the universal purpose
- **Not sure** if the SFs derived at **NLO+PS suitable for NNLO predictions**

Differential Z+>= 1b-jet cross-section results



5FS: good description by both NLO ME+PS state-of-the-art MCs (MGAMC+PY8 FXFX and SHERPA 2.2.11)

4FS: mismodelling of collinear and large ΔR(Z, b−jet)



Shape Only

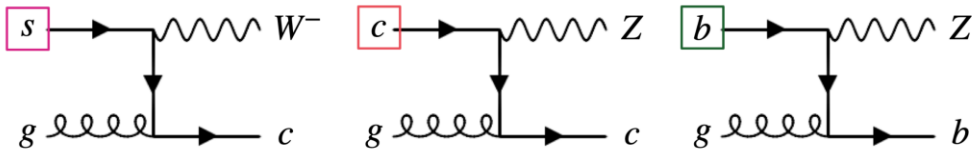
Fixed-order: NLO discrepancies improved with NNLO. Calculations suffer from divergences at ΔR(Z,b −jet) ~ π uncertainties increase

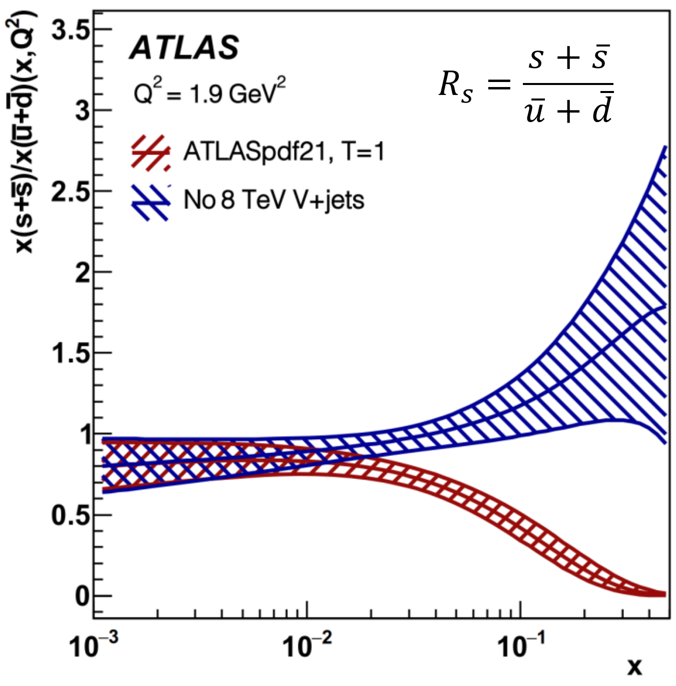
Proton PDFs

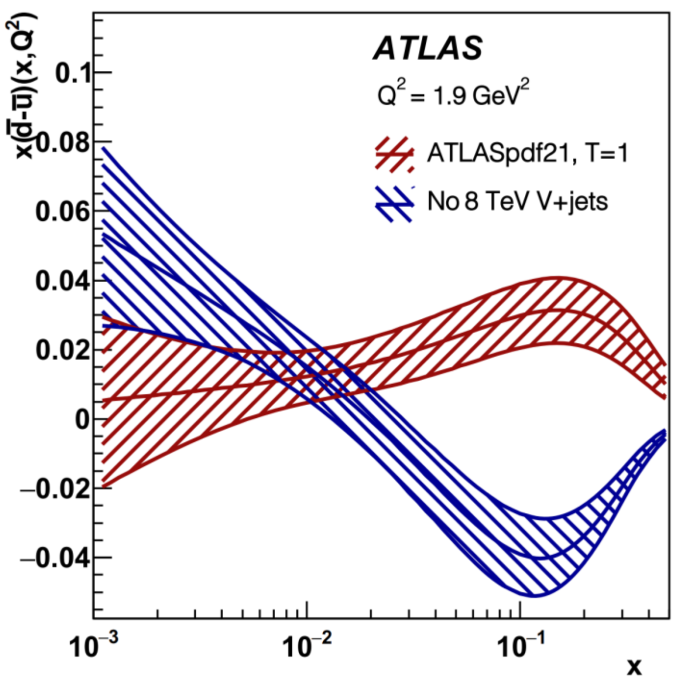
Eur. Phys. J. C (2022) 82

- **V + HF** expected to effect at medium and high Bjorken x and momentum transfer Q^2

- Unique access to ***s-, c-, b****-quark* and ***gluon*** PDFs in proton
- Allow to determinate the ***PDF shape*** and ***constrain uncertainties*** further







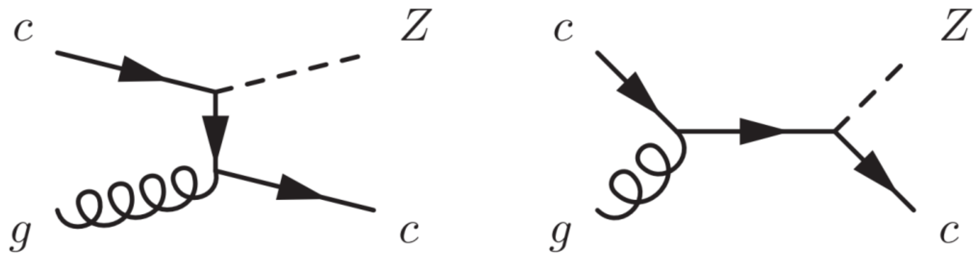
- Vjets play a key role in the R_s and $x(\bar{d}-\bar{u})$ PDF determinations in the high x regions - **ATLASpdf21**

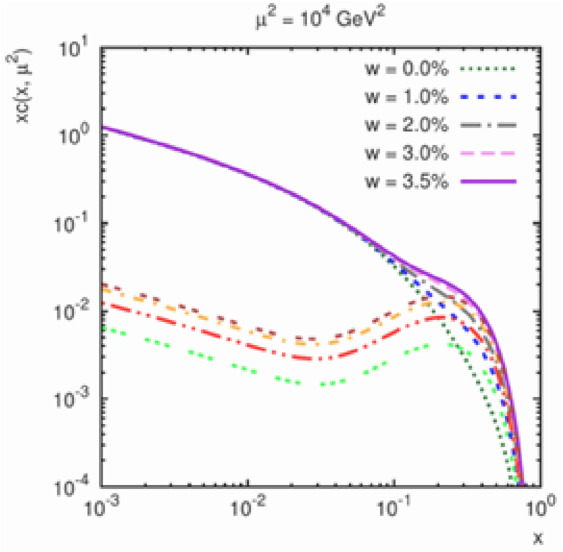
Intrinsic Charm

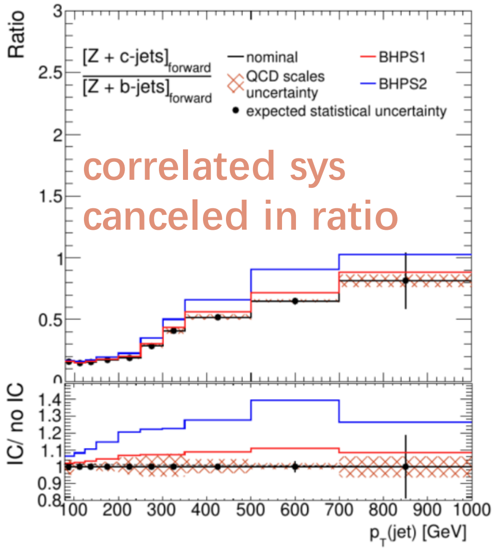
Physical Review Letters 128 (2022)
Nature 608, 483–487 (2022)

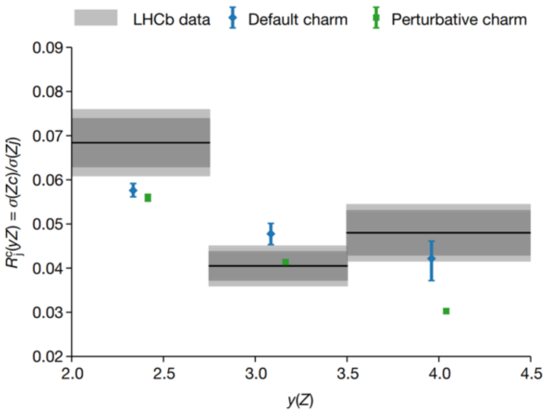
- ***Intrinsic-Charm (IC)*** component in the proton ~ debated for 40 years (upper limits on $<x_c>$ differ from 0.5% to 2%)
  - c-quarks pairs are considered as part of the proton wave function at rest - valence-like structure

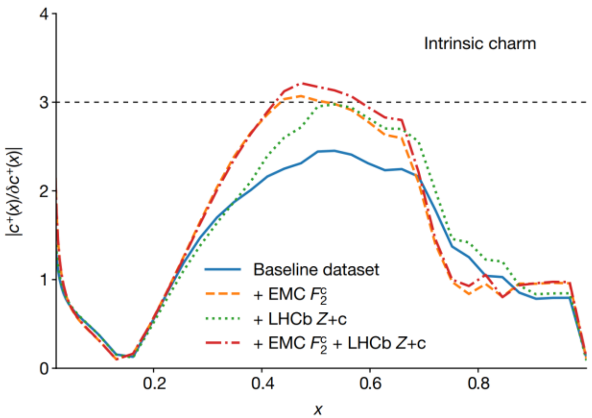
$\Psi_p = |uudc\bar{c}>$, IC not via $g \to c\bar{c}$









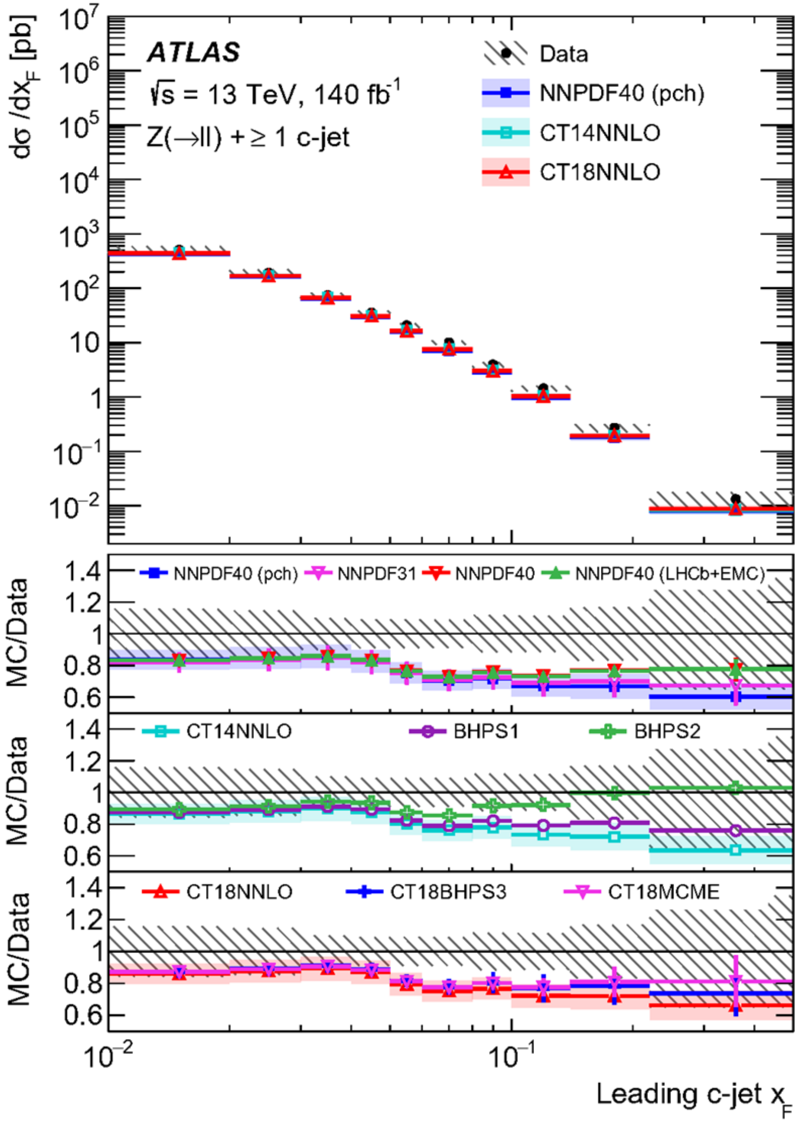


- IC enhanced in $x_c > 0.1$ accessible via **V+HF in LHC**
- **LHCb** reports an excess in high η region with Z + c
- **NNPDF** gives an evidence on the existence of IC
  - $<x_c>$ = (0.62 ± 0.28) % with peaking at ~ 0.4

Differential Z+>= 1c-jet cross-section results

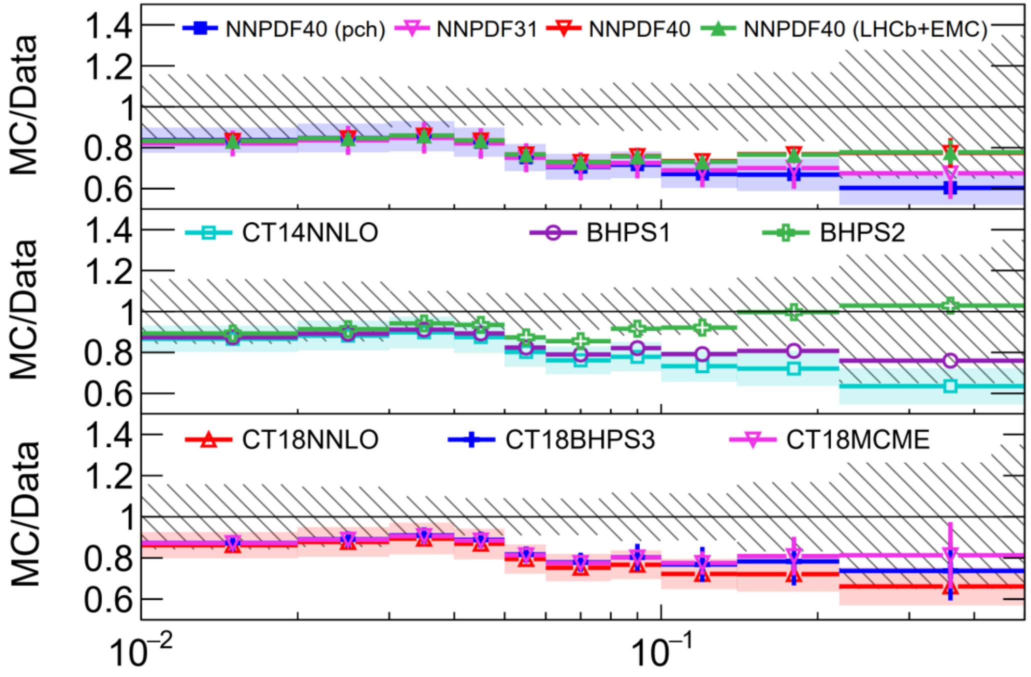
PhysRevD.92.034014

Feynman-variable $x_F = 2p_Z/\sqrt{s}$



MGAMC+PY8 with **several PDF sets** testing **different IC-models**

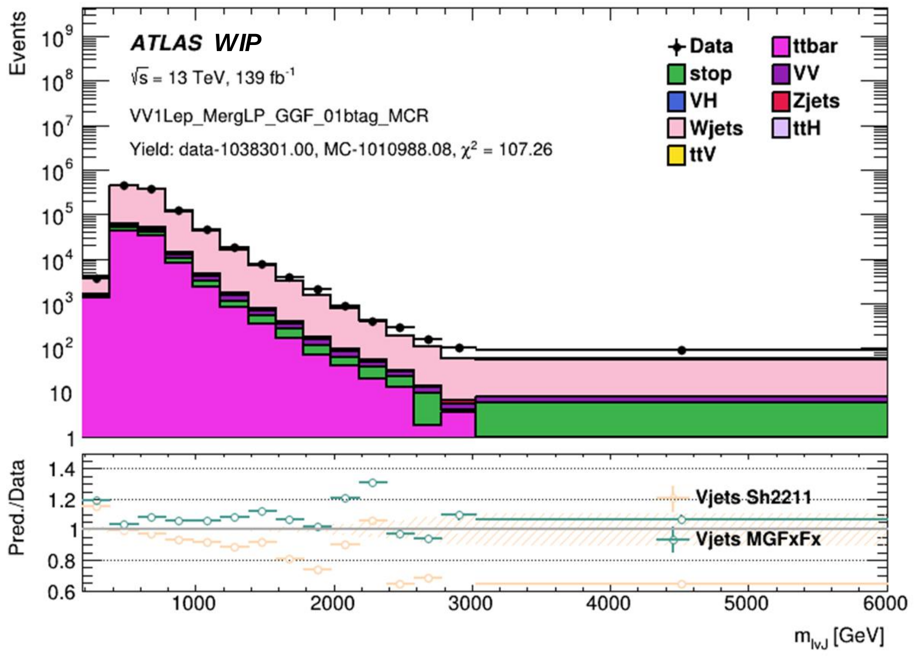
- ✦ BHPS2 (with $<x_c>\sim 2\%$) improves the description of data
  - In more realistic scenarios (NNPDF and CT18) the improvement is still marginal related to the uncertainties

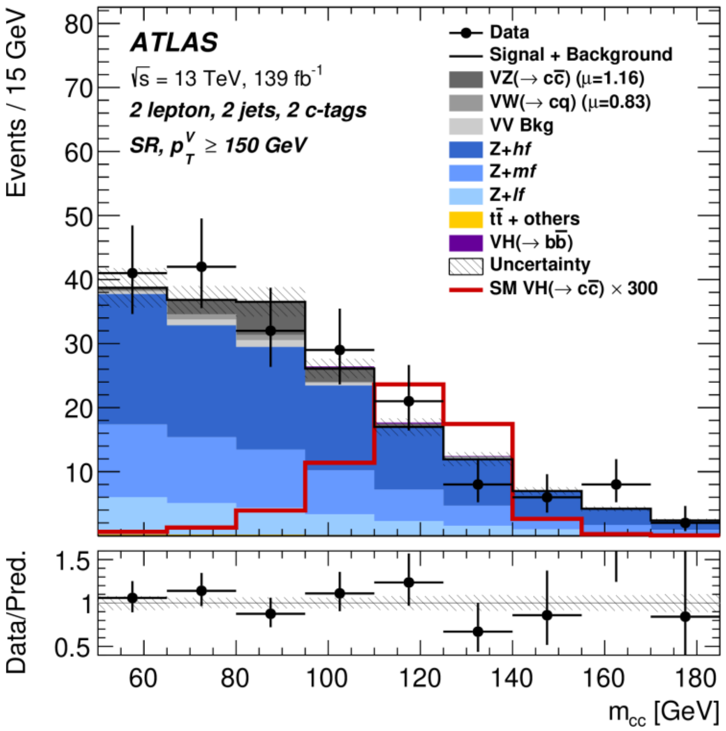


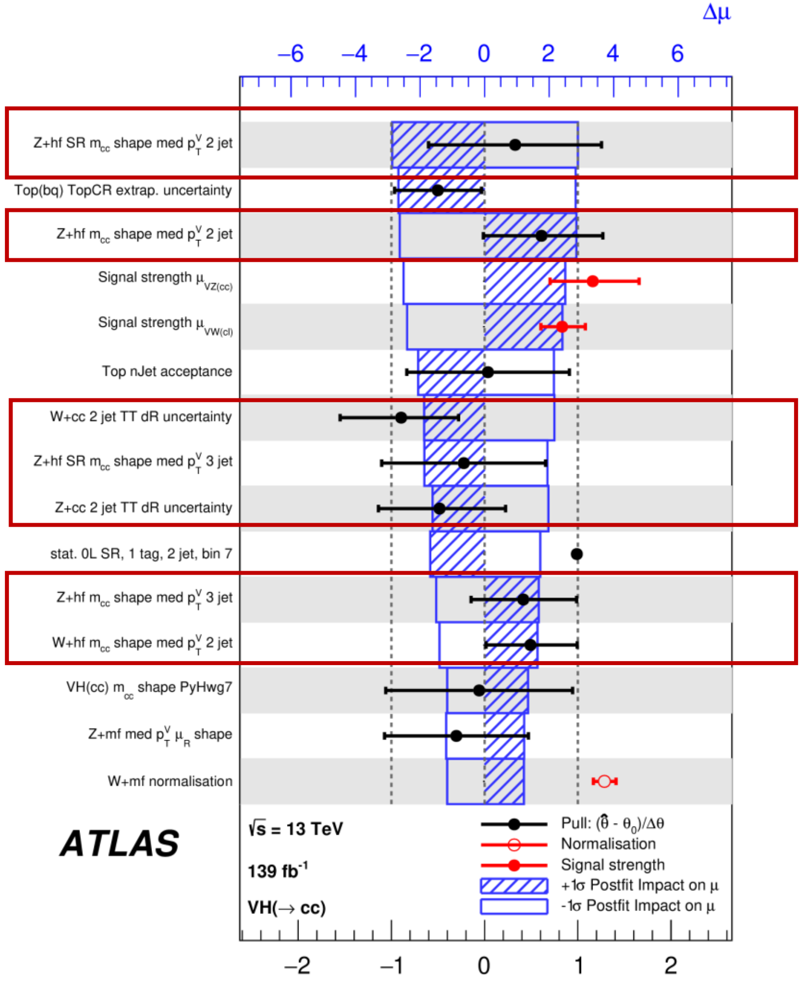
V + HF jets as background for Higgs and NPs

Eur. Phys. J. C 82 (2022)717

- V+HF jets dominant background & modelling as the limiting factor for a good sensitivity
  - VH ($\rightarrow b\bar{b}, c\bar{c}$) measurement
  - HVT/2HDM/Radion/Graviton search via VV/VH ($\rightarrow ll + q\bar{q}$)





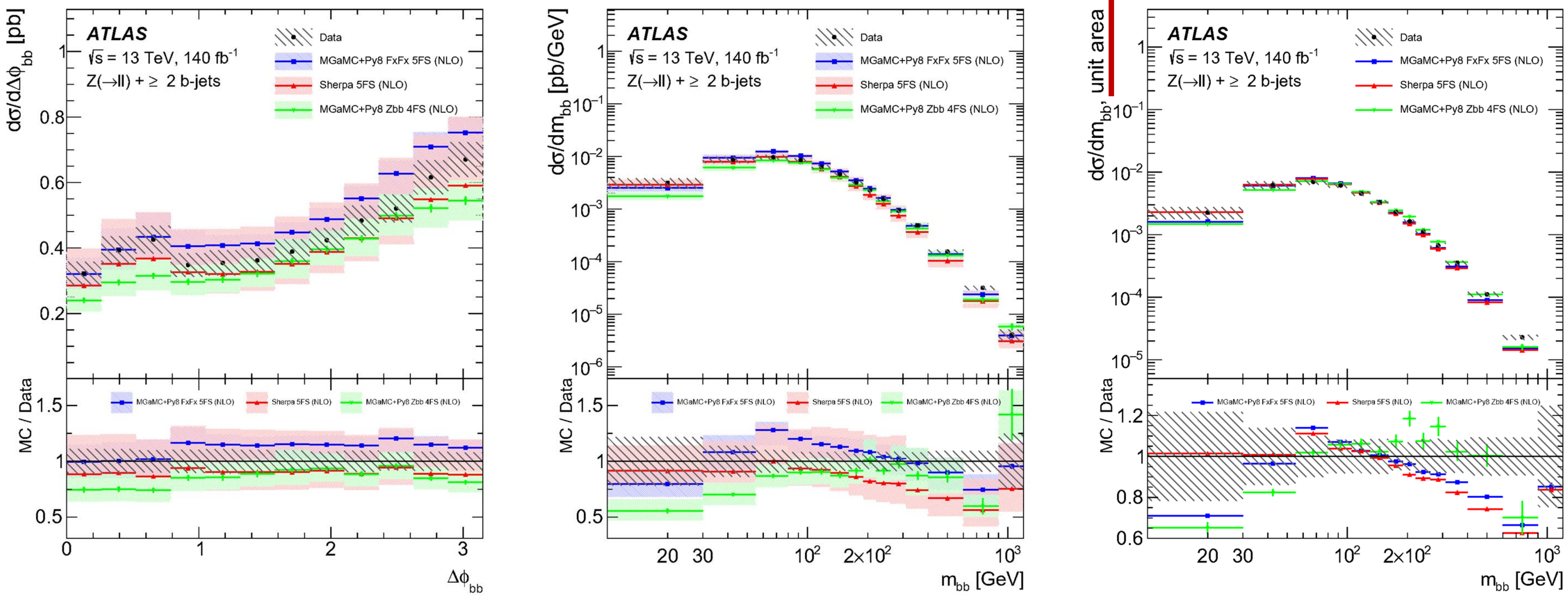


Differential Z+>= 2b-jet cross-section results

- $\Delta\phi_{bb}$: good modelling by all predictions
- m_{bb}: similar description by all predictions, with steep decrease for m_{bb} > 80 GeV

  none of the predictions in agreement with data in the full spectrum

Shape Only

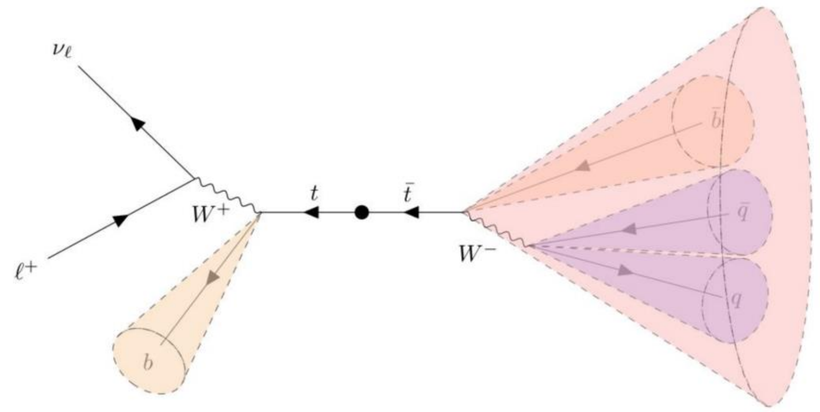


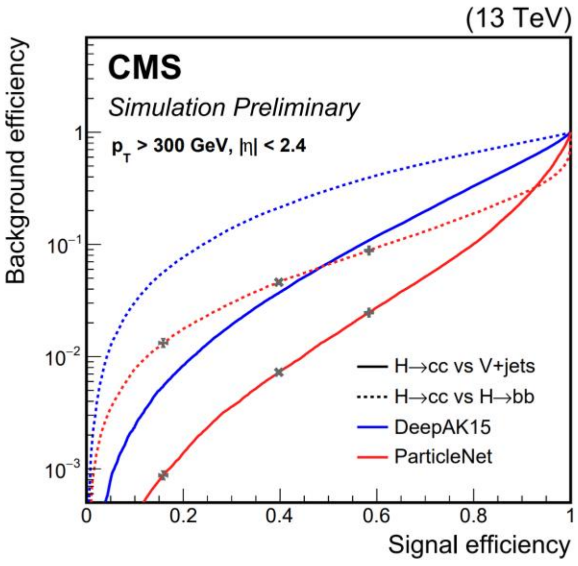
Looking inside Jets: jet substructure phenomenology

[Lecture Notes in Physics volume 958 (2019)]

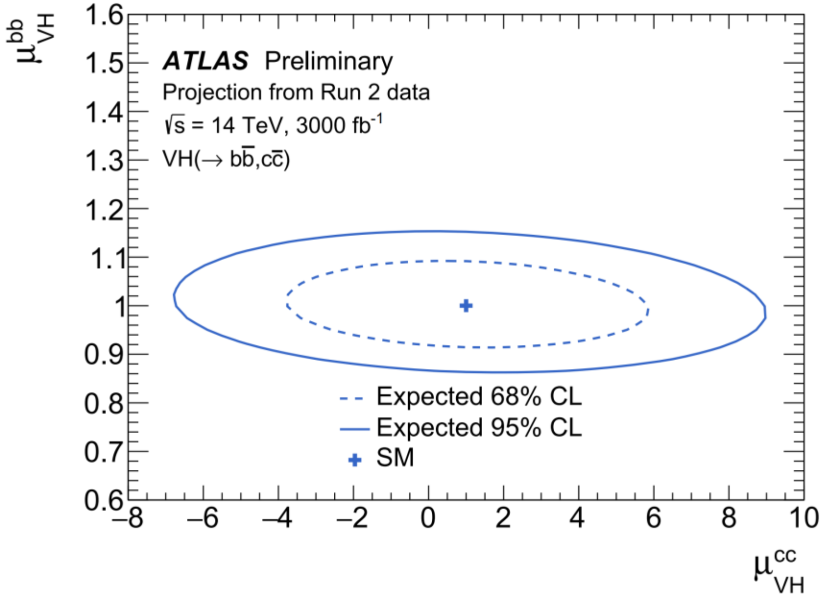
[ATL-PHYS-PUB-2021-039]

- **Jet substructure variables** are making great progress in the boosted object tagging





- ***ParticleNet*** exploits information related to jet substructures, flavour, and pileup with an advanced graph neutral network

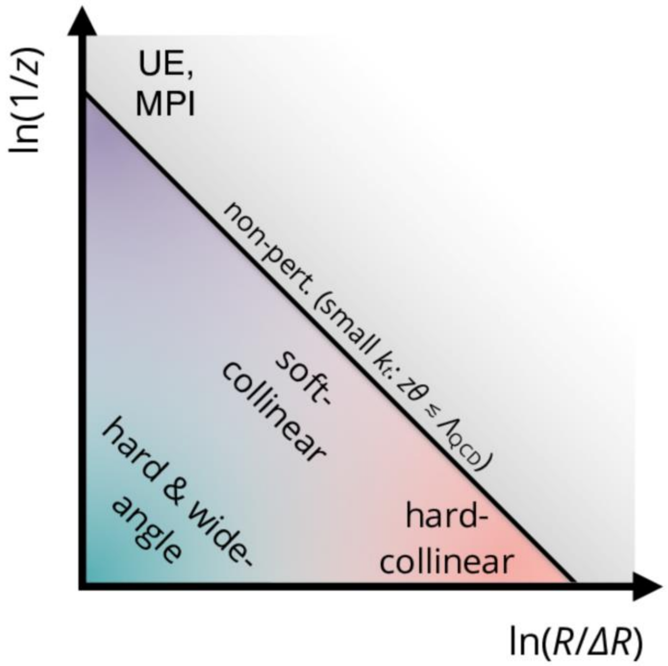


- **Jet tagging** for top, W, Z, quark, gluon adopt with JSS variables
  - Observation of the **Higgs coupling to charm** at the **HL-LHC** will be difficult, new analysis techniques of multivariate techniques and jet substructure observables provide a feasible direction

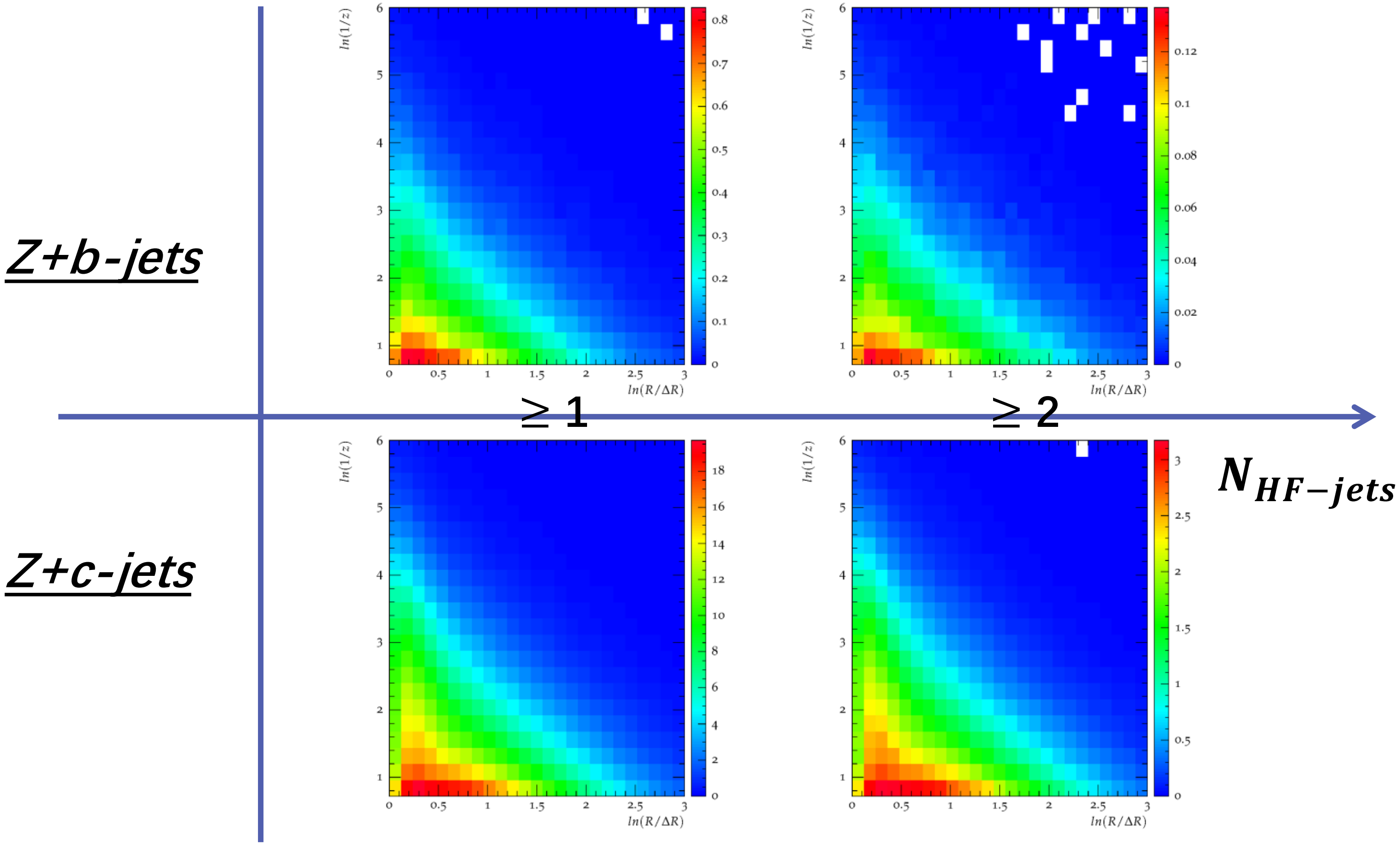
Lund Jet Plane and Jet Substructure Variables

Physical Review Letters 124 (2020)

- **Lund Jet Plane** provides an overview of the **pT-fraction** and **angular distributions** of **radiations inside a jet**
  - *each region* of the diagram is dominated *by different origins of radiation* such as hard-scatter processes, underlying event or pileup

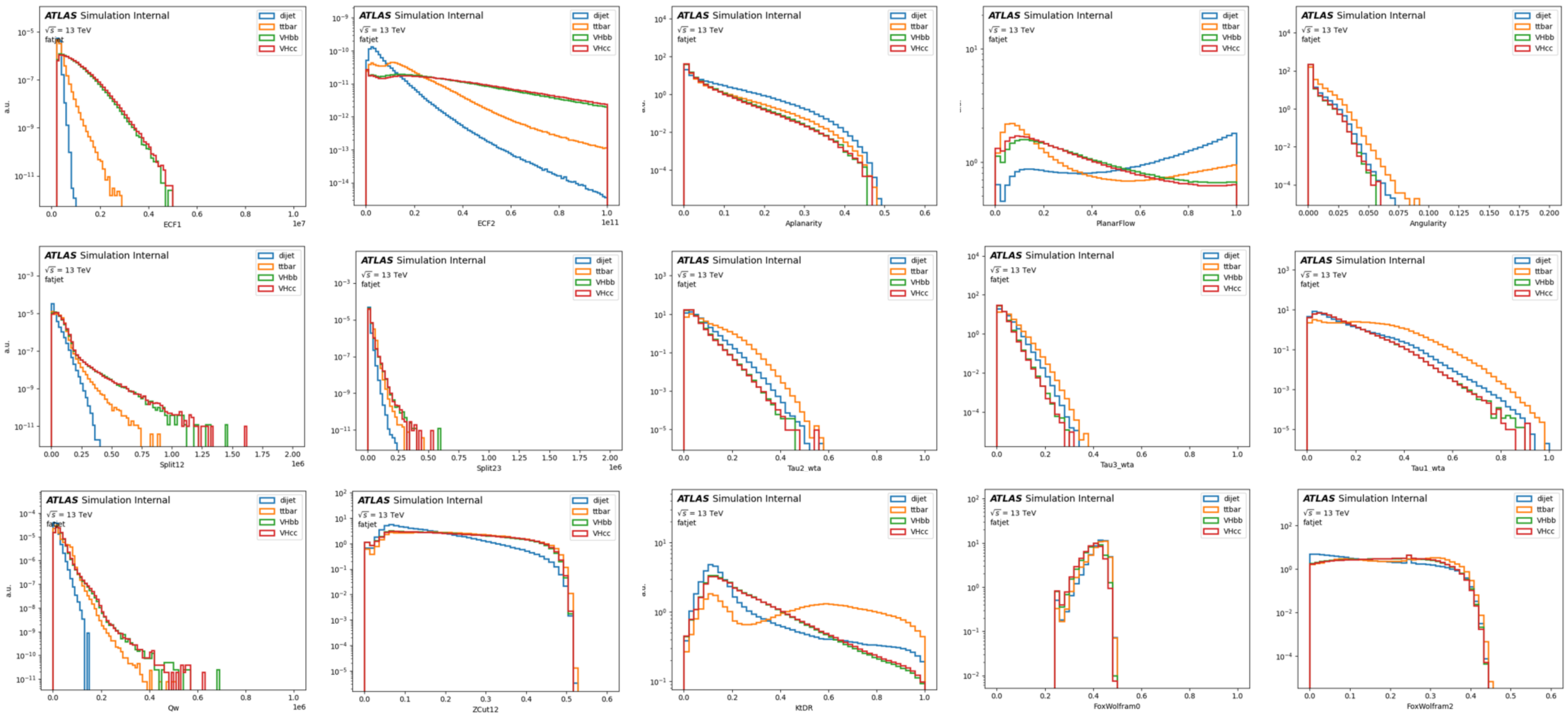


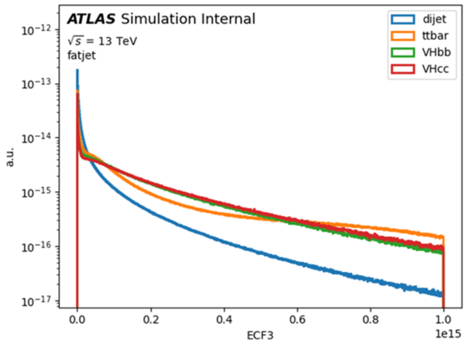
$$\Delta R = \sqrt{\Delta y_{ij}^2 + \Delta\Phi_{ij}^2}\,,\ z = p_T^j/(p_T^i + p_T^j)$$



Looking inside Jets: jet substructure phenomenology

- Possibility to test **SM validity in phase-spaces** that are **not accessible** in **simple differential cross-section** measurements.
  - calculated with features of jet constituents (pt, energy, correlation,…)
  - sensitive to **jet origins** and might **dark jet**





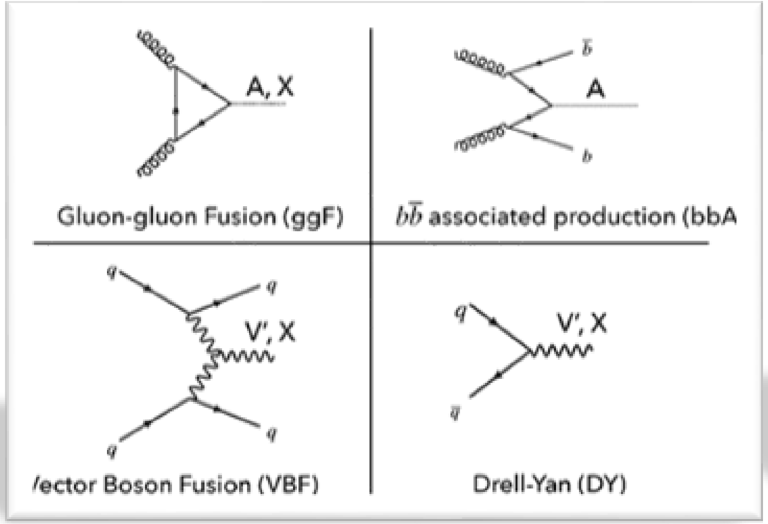
$$\mathrm{ECF}(1,\beta) = \sum_{i \in J} p_{Ti},$$

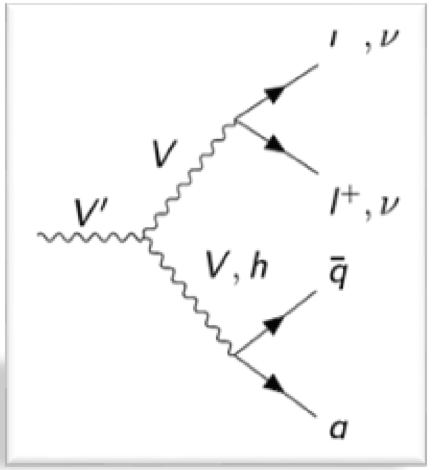
$$\mathrm{ECF}(2,\beta) = \sum_{i<j \in J} p_{Ti} p_{Tj} (R_{ij})^{\beta},$$

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k \in J} p_{Ti} p_{Tj} p_{Tk} (R_{ij} R_{ik} R_{jk})^{\beta}.$$

VV + VH Semi-leptonic Search for BSM

- **New heavy resonance search**
  - Heavy Vector Triplet (HVT)
  - Randall-Sundrum Radion
  - Graviton
  - 2HDM pseudo-scalar boson A



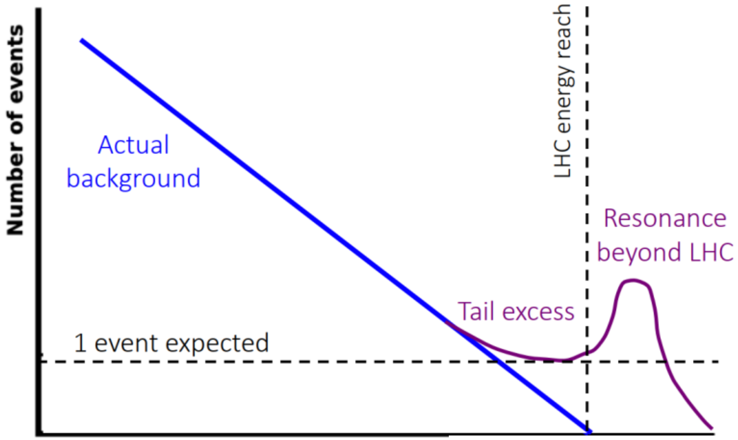


- **VV Semi-leptonic measurement**
  - Sensitive to D-6 EFT operators ⇨ cW, cHW

SM lagrangian extended with higher dimensional operators

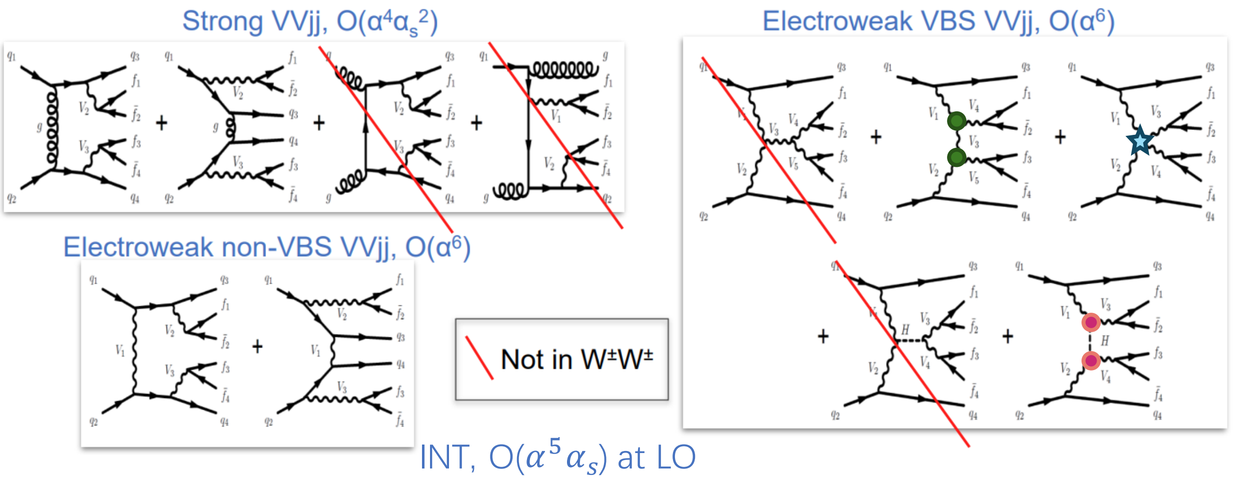
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} O_i^{(8)} + \cdots$$

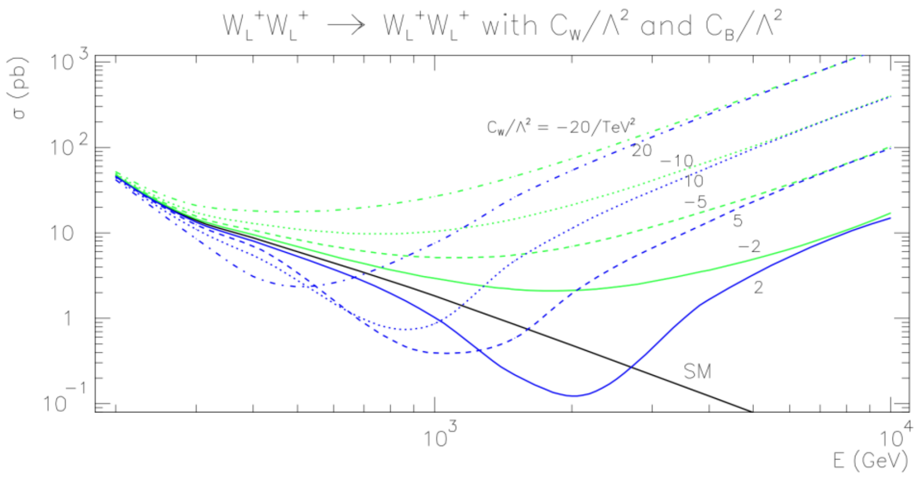
$$\sigma = |\mathcal{A}_{\rm SMEFT}|^2 = |\mathcal{A}_{\rm SM}|^2 + \frac{c_i^{(6)}}{\Lambda^2} 2{\rm Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\rm SM}^*\right) + \Sigma_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \cdots$$



Same-signed WW Polarization Measurement

- **Vector boson scattering** is one of the paramount interesting process in standard model
  - Sensitive to (abnormal) gauge structure via s- and t-channel exchanges of a gauge and Higgs
  - Probe to EWSB – divergency cancellation in the $\boldsymbol{V_L V_L \rightarrow V_L V_L}$ from Higgs contributions

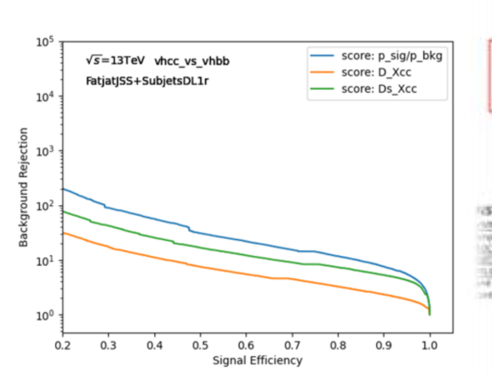


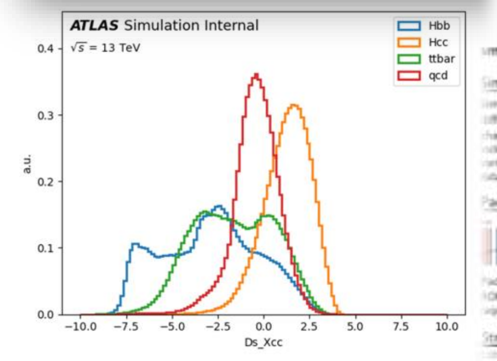


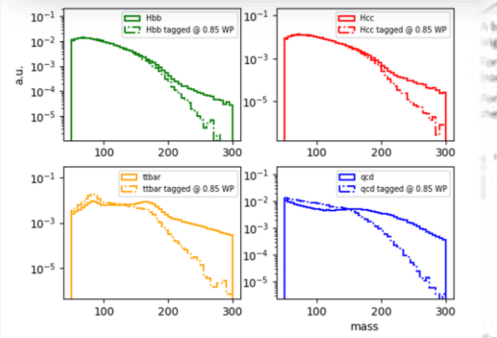
  - Aiming to achieve evidence of $V_L V_L \rightarrow V_L V_L$ in Run3 and HL-LHC
  - Study the BSM/EFT sensitivity with decoupled polarization components

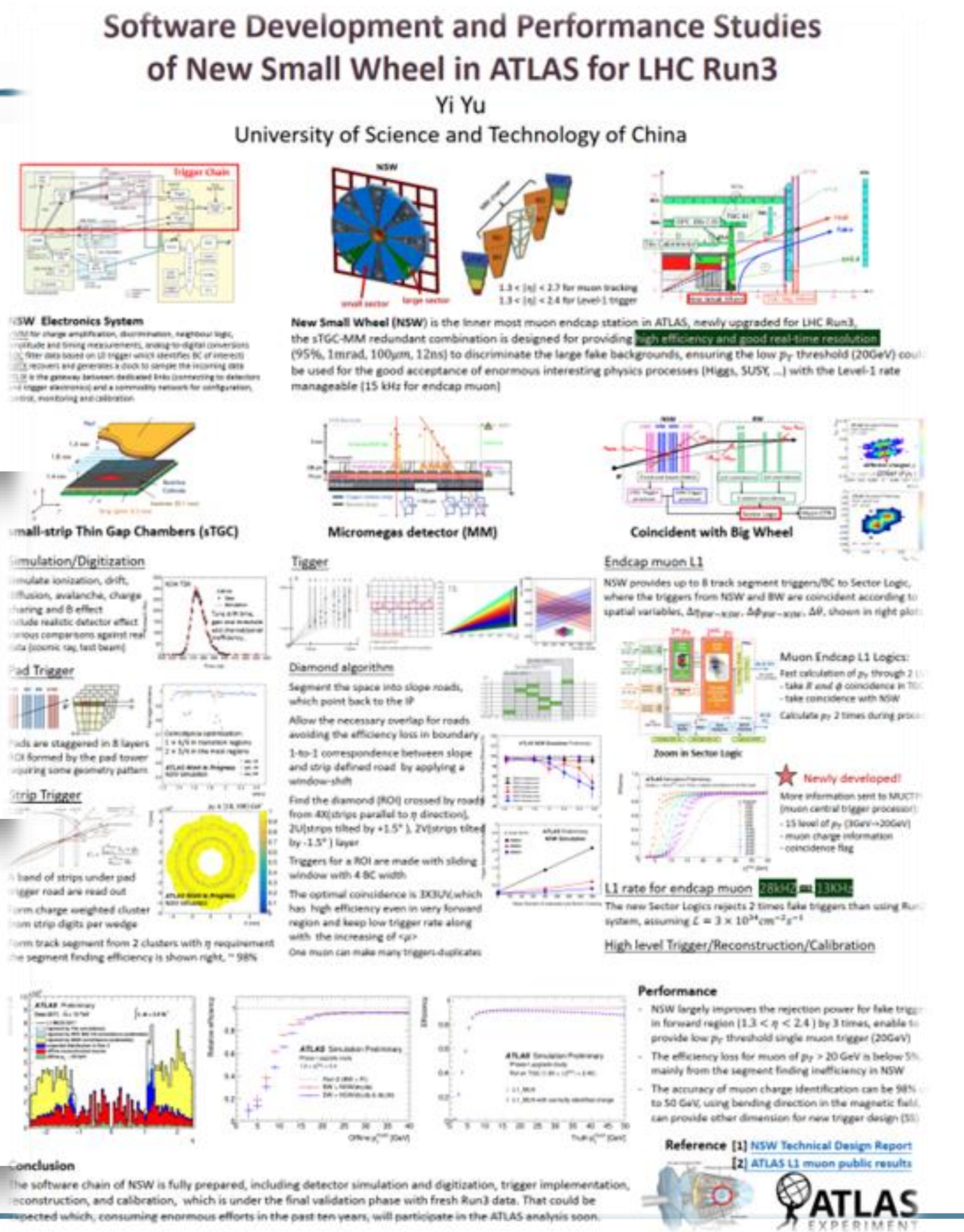
ATLAS Supporting Work

- Software development and performance studies for L1-muon trigger in **New Small Wheel**
  - Pad trigger, strip trigger logics, efficiency, resolution and geometry coincidence with Big wheel
- Development and performance studies of **multi-classifier boosted** objects **tagger** with JSS variables
- **Monte Carlo generation** support for Flavour Tagging and HDBS physics groups
  - GN2 tagger training calibrations
  - BSM searches with VV/VH/HH









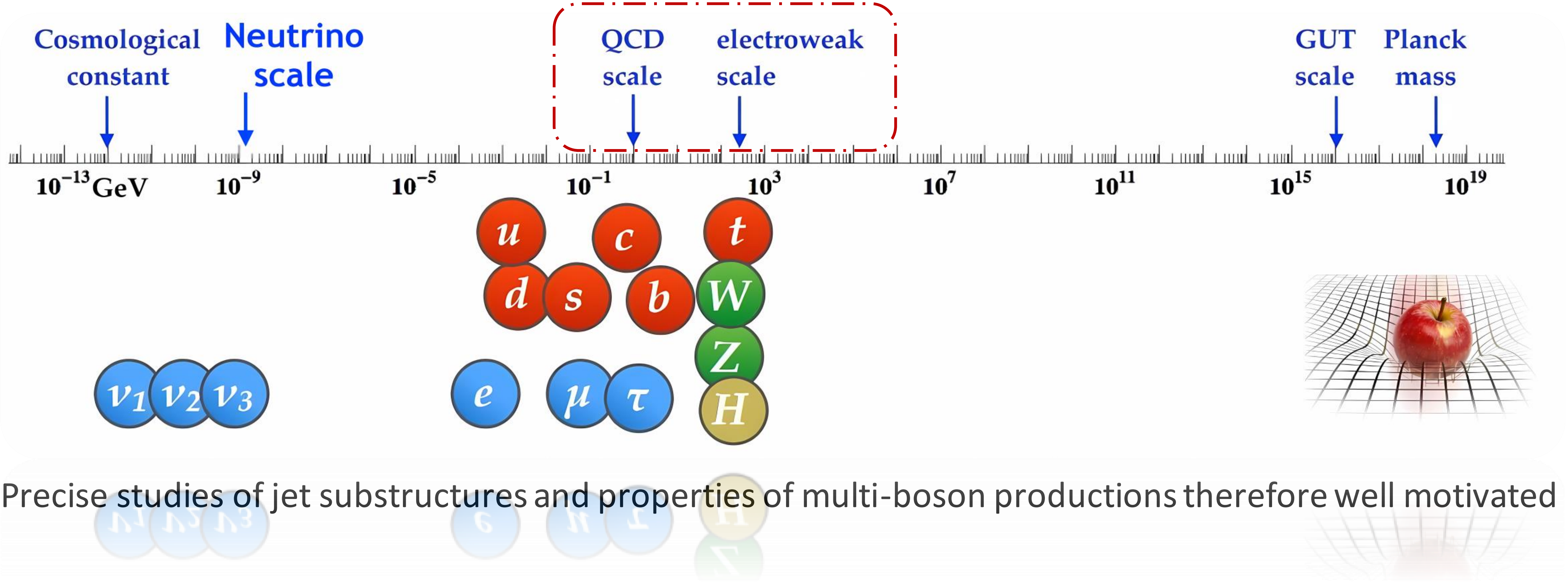
Conclusion

- EWK gauge bosons production associated with jets represents an essential ingredient of Standard Model
  - V + b/c jets measurement
    - provide useful inputs for global fit PDF, sensitive to s-, c-, b-quark, and gluon PDFs
    - serve as benchmarks for Monte Carlo simulations and theoretical predictions available at NNLO
    - allow to explore the sensitivity to new phenomenon, i.e. intrinsic charm
  - Di-boson measurement
    - provide unique probe to the gauge structure and the spontaneous symmetry breaking mechanism
    - paramount portal in the EKW sector for BSM and EFT interpretations
  - Most of dark matter searches can be benefit from improved modellings of these substantial EWK processes
- Precise studies of jet substructures and properties of multi-boson productions therefore well motivated

Thank You!

Conclusion

- EWK gauge bosons production associated with jets represents an essential ingredient of Standard Model



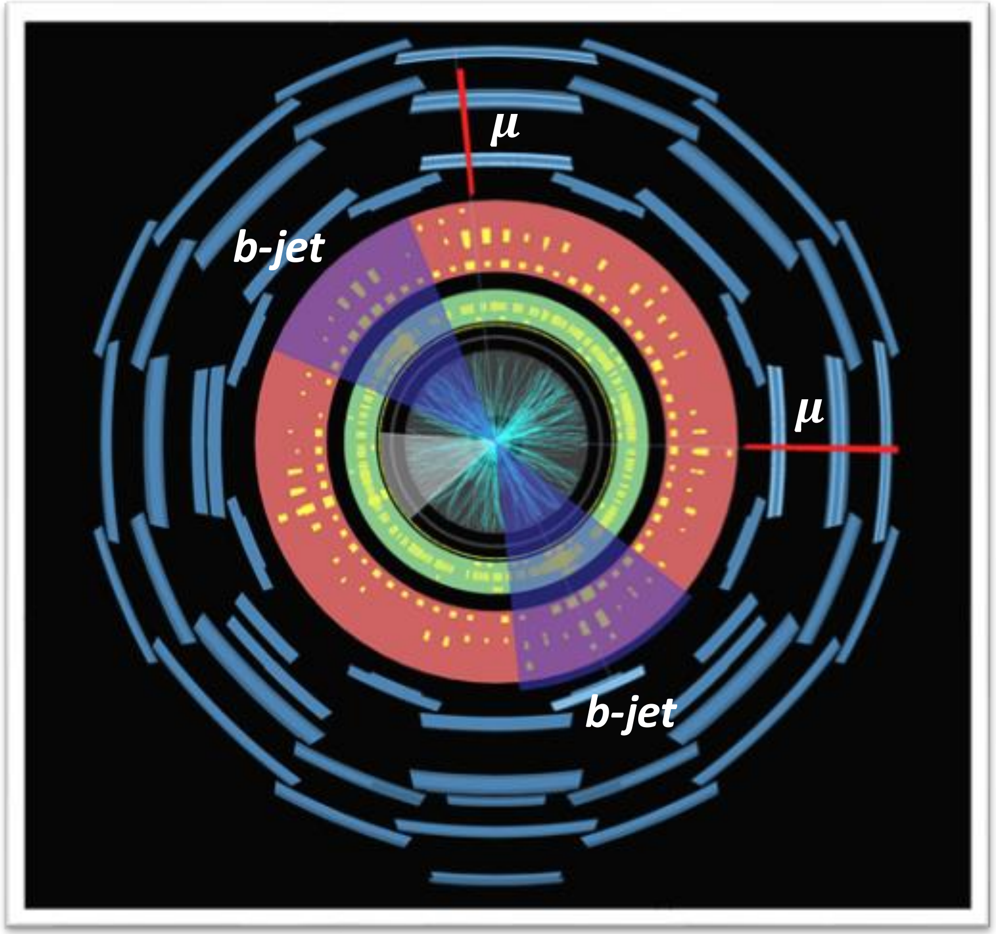
- Precise studies of jet substructures and properties of multi-boson productions therefore well motivated

Thank You!

* Back up

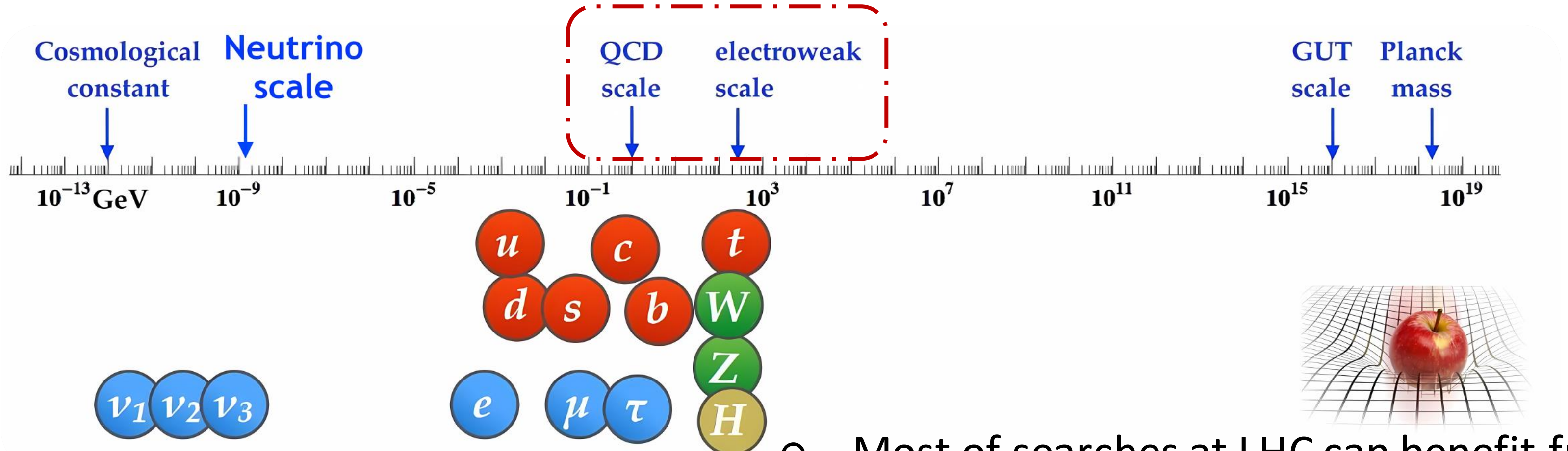
Event display of

Z+>=2b-jets candidate from data recorded by ATLAS



Conclusion

- EWK gauge bosons production associated with jets represents an essential ingredient of Standard Model
  - V + b/c jets measurement as benchmarks for theoretical predictions
    - allow to explore the sensitivity to new phenomenon i.e. intrinsic charm
    - provide useful inputs for global fit PDF, sensitive to s-, c-, b-quark, and gluon PDFs
    - ⇨ alignment of IRC jet-flavour algorithm in experimental and theoretical communities highly demanded to benefit from the precise NNLO calculations
  - Precise studies of jet substructures also well motivated from both of SM and BSM views



- Most of searches at LHC can benefit from improved modellings of this substantial EWK+QCD process

✓ Multi-tags in the collinear cases might be inaccurate in the MC mimicing the high $<\mu>$ experimental conditions → possibly large unfolding uncertainty

✓ How to implement IRC-safe flavour algorithms into the ATLAT Jet reconstruction algorithm/analysis level properly should be clear

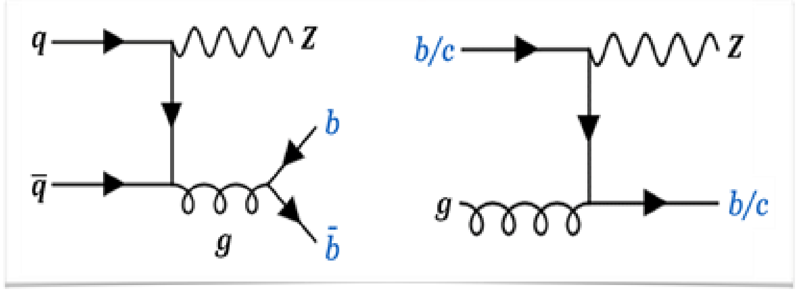
Worthy to make the attempts in Run3 ZHF measurements

Thank You!

Z + HF jets Measurement

Inclusive and differential Z+≥1b, ≥2b, ≥1c x-sections and fwd/central ratio for Z+≥1c events with 139 fb^{-1}

- Z+≥1b: Z p_T, lead b-jet p_T and ΔR(Z, lead b-jet)
- Z+≥2b: m_{bb}, $\Delta\Phi_{bb}$
- Z+≥1c: Z p_T, lead c-jet p_T, lead c-jet x_F and fwd/central vs Z p_T



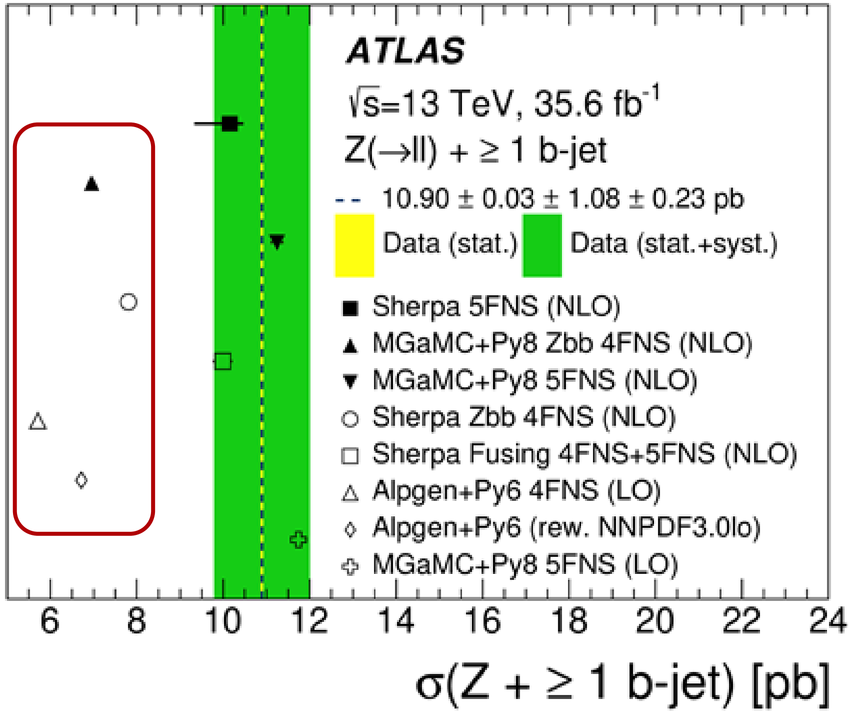
✤ **Z+≥1 b-jet and Z+≥2 b-jets**: update 36 fb^{-1} results with larger statistics, new FT algorithm and optimized strategy for main backgrounds

✤ **Z+≥1 c-jet**: first time in ATLAS!

⇨ Test effect of missing higher-order terms in QCD

⇨ Investigate different Flavour-Schemes in predictions

⇨ Explore possible sensitivity to Intrinsic-Charm



Analysis strategy

Event selection:
select **Z(→$\mu\mu$,ee)+ flavour-tagged jets candidates**

Background estimation:
- data-driven $t\bar{t}$ in dedicated CR
- *Z*+jets from fit to data ("***flavour-fit***")
- other minor backgrounds from MC samples

From detector to particle level:
correction for resolution and efficiency effects with Bayesian unfolding

Cross-section measurements

Comparison with theoretical predictions

✦ Z+HF events categorized at both reconstructed and particle level

- Single jet flavor classified as B, C, L

  using cone-based (ΔR<0.3) matching between truth hadrons and jets

  correct place to replace with IRC safe jet-flavour algorithm

- Event flavor classified as 1B, NB, 1C, NC, L

  according to the leading jet flavour and number of HF-jets

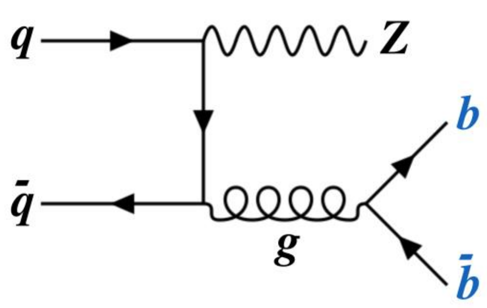
For the ***background estimation*** and ***detector effect corrections*** to the dedicated HF processes, such as Z+>=1b [1B+NB]

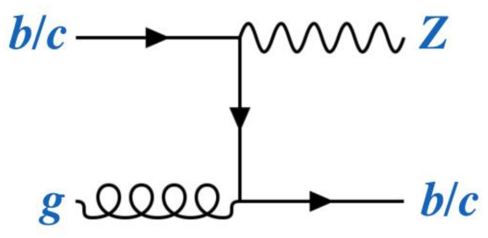
Dataset and event selection

Dataset

- Full Run-2 data, $L = 140\ fb^{-1}$
- Monte Carlo samples
  - NLO ME+PS state-of-the-art generators with high parton-multiplicity in ME (MGAMC@NLO + PY8 with FXFX merging and SHERPA 2.2.11)

Event selection





2 good leptons: e+e μ+μ- — with p_T > 27 GeV, $|\eta|$ < 2.5; 76 GeV < m_{ll} < 106 GeV

≥ 1 good jet — with p_T > 20 GeV, $|y|$ < 2.5; **b-tagging DL1r @ 85%**

- **Define 2 Signal Regions (SR) based on the number of flavour-tagged jets:**

***1-tag*: Z+≥1 b-jet** and **Z+≥1 c-jet** measurements

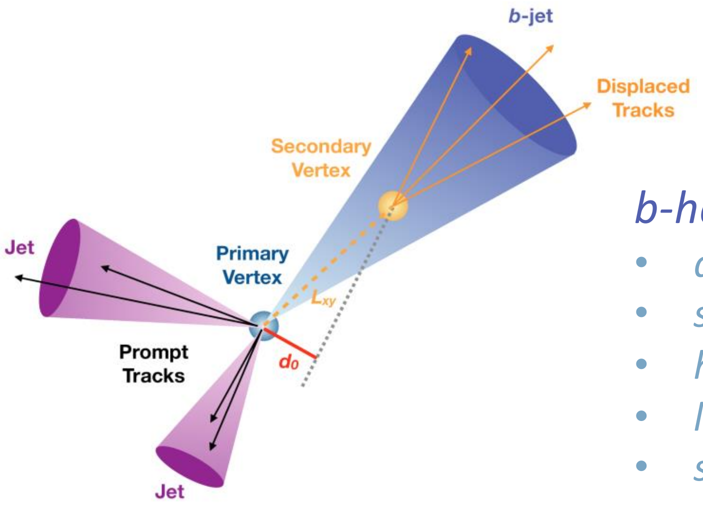
***2-tag*: Z+≥2 b-jets** measurement

Flavour Tagging

DL1r

- High level neural network algorithm operating on outputs from intermediate track and vertex algorithms
- DL1r discriminant calculated from the b-, c- and light-jet probabilities

$$D_{\mathrm{DL1r}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c \cdot p_{light})}\right)$$

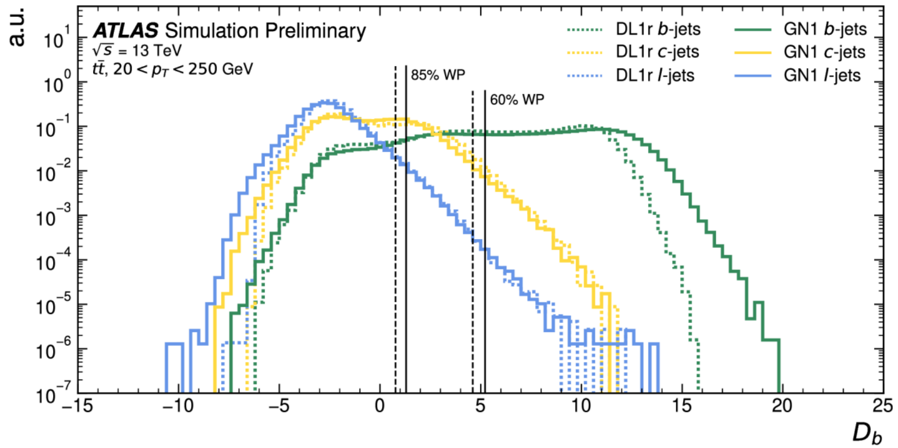


b-hadron decay signature

- *displaced tracks*
- *secondary vertex*
- *high-track multiplicity*
- *longitudinal impact parameter*
- *semi-leptonic decays*

b-tagging based on D_{DL1r}

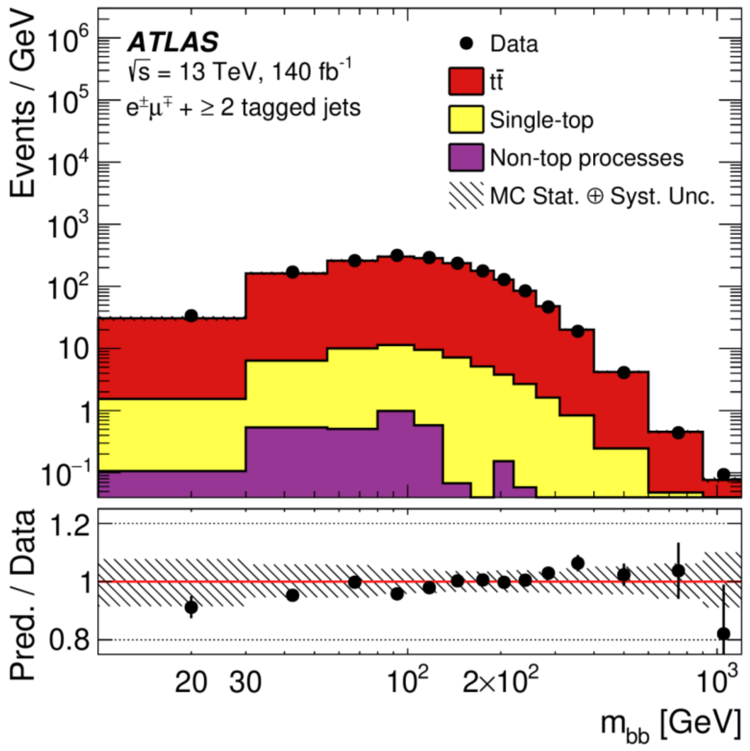
- Selections provided with 60%, 70%, 77% and 85% b-tagging efficiency
- Flavour-sensitive distribution available with 5 exclusive bins obtained with different b-tagging selections



✵ DL1r @ 85% WP retains *85%* b-jets and *38%* c-jets

Data-driven $t\bar{t}$ background

- Dileptonic events represent the second largest background
  - Using **data-driven technique** to avoid large modelling uncertainties (up to ~70% at high Z pT)
- **Method of the Transfer Factors**
  - opposite flavour eμ CR enhanced with $t\bar{t}$ events (>90%)
  - **$t\bar{t}$ template in CR** obtained by subtracting other MC from data
  - **Transfer Factors (TFs)** as ratio of $t\bar{t}$ MC distributions in SR and CR



$$t\bar{t}^{SR} = t\bar{t}^{CR}_{Data} \cdot TR^{CR\rightarrow SR}$$

$$TF^{CR\rightarrow SR} = \frac{t\bar{t}^{SR\,(ee/\mu\mu)}_{MC}}{t\bar{t}^{CR\,(e\mu)}_{MC}}$$

- Systematics:

  Strong reduction of detector-level systematics propagated through TFs

  CR→SR extrapolation uncertainty derived via MC v.s. DD $t\bar{t}$ in VR

Z+jets background and flavour fit

- Z+jet process with jet-flavour different from the one measured is the largest source of background

	1-tag SR		2-tag SR
Analysis	*Z*+≥1 *b*-jet	*Z*+≥1 *c*-jet	*Z*+≥2 *b*-jets
***Z*+jets bkg**	*Z*+*c*, *Z*+l	*Z*+*b*, *Z*+l	*Z*+1*b*, *Z*+*c*, *Z*+l

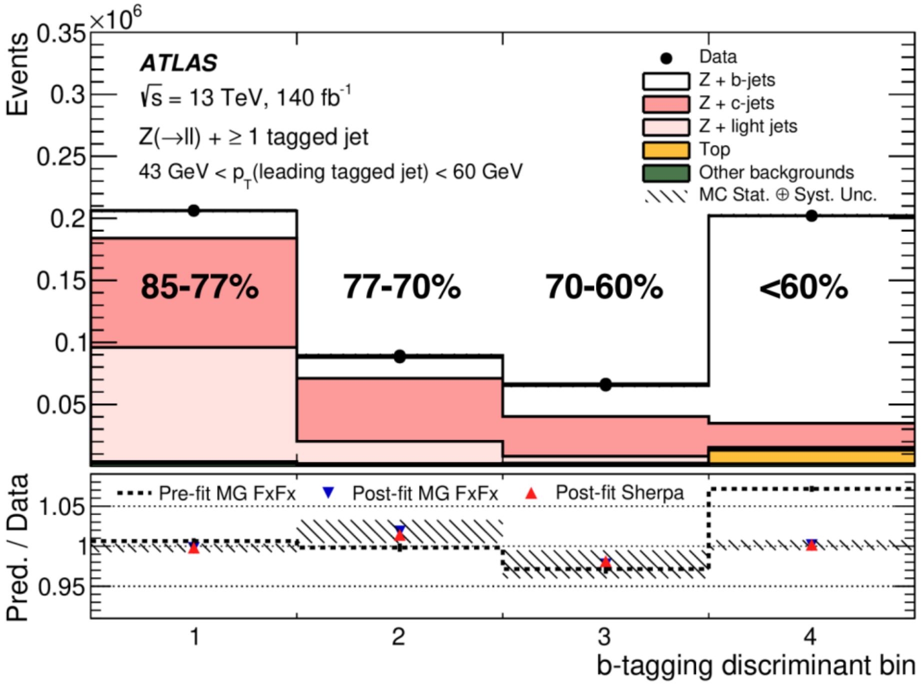
➞ **Correct Z+jets flavour components** and constrain systematics **with flavour-fit**

Maximum-likelihood fit to data based on flavour sensitive distribution

Example for 1-tag SR:

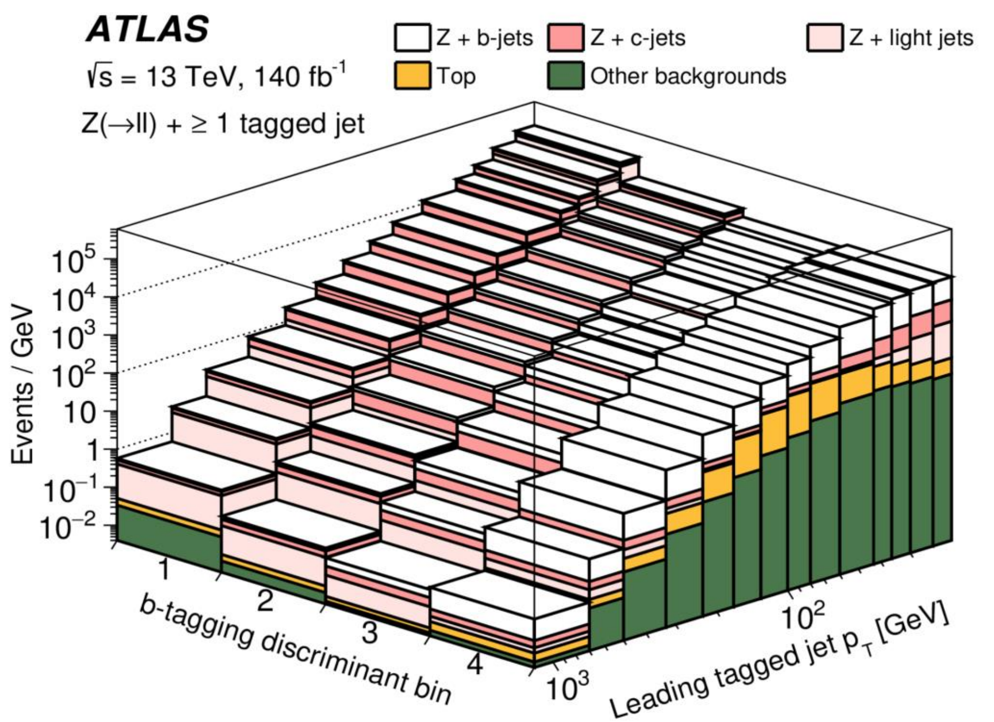
Fit of **flavour-tagging score (DL1r) in calibrated bins**

3 free parameters corresponding to **Z+≥1 b-jet, Z+≥1 c-jet** and **Z+≥light** jets normalization

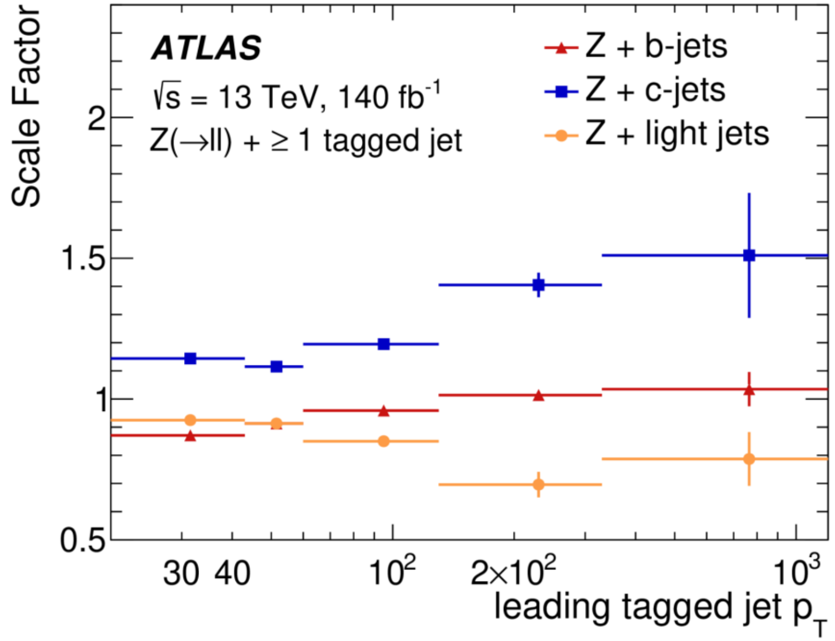


Z+jets background and flavour fit

- **Fit performed in individual** (optimized) **bins of each measured observable**



- **Bin-by-bin scale factors** allow to **correct** both **normalization** and **shape** of Z+flavoured-jets contributions



- **Systematics**

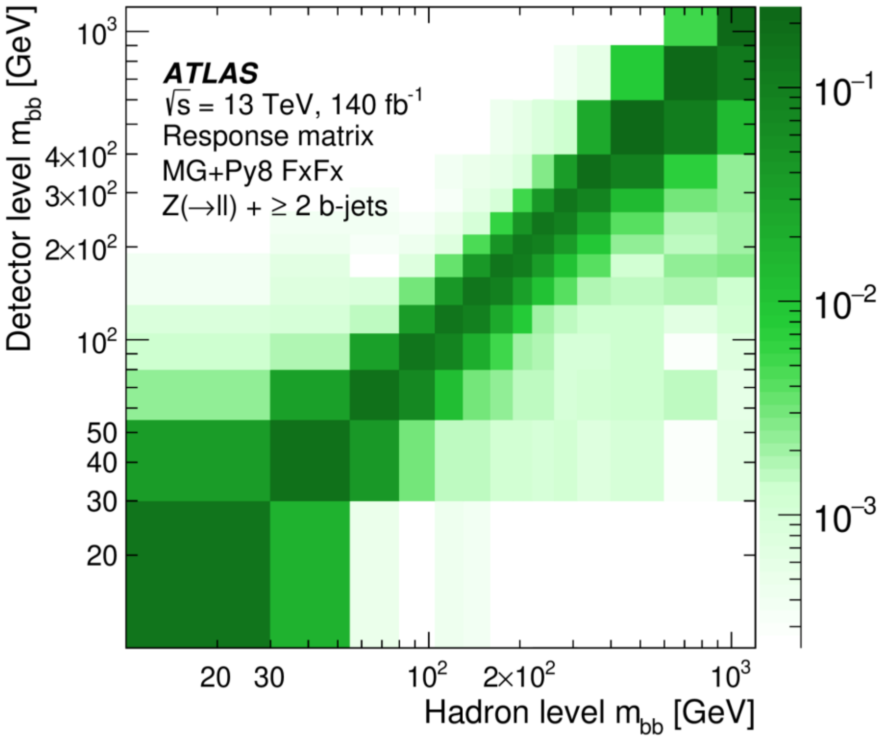
  detector-level systematics affect Z+jets templates - repeat flavour fit

  uncertainty on Z+jets background yields from comparison of two MCs

From detector to particle level

✦ **Differential cross sections** corrected to particle level with **iterative Bayesian unfolding**:

selection efficiency, resolution effects and differences between detector level and fiducial phase spaces



Object Selection	Acceptance cuts
Lepton	$p_T > 27$ GeV, $\|\eta\| < 2.5$ 2 same flavour and opposite charge, 76 GeV $< m_{\ell\ell} <$ 106 GeV
b-jet	$p_T > 20$ GeV, $\|y\| < 2.5$, $\Delta R(b\text{-jet}, \ell) > 0.4$
c-jet	$p_T > 20$ GeV, $\|y\| < 2.5$, $\Delta R(c\text{-jet}, \ell) > 0.4$
Event Selection	**Acceptance cuts**
$Z + \geq 1$ b-jet	$Z + \geq 1$ b-jet and a b-jet is the leading heavy-flavour jet
$Z + \geq 2$ b-jets	$Z + \geq 2$ b-jets and a b-jet is the leading heavy-flavour jets
$Z + \geq 1$ c-jet	$Z + \geq 1$ c-jet and a c-jet is the leading heavy-flavour jet
Rapidity regions	**Acceptance cuts**
Central rapidity	Z boson rapidity $\|y(Z)\| < 1.2$
Forward rapidity	Z boson rapidity $\|y(Z)\| \geq 1.2$

Z+≥1 b-jet, Z+≥1 c-jet and Z+≥2 b-jets cross sections measured at **particle level** in **fiducial phase space**

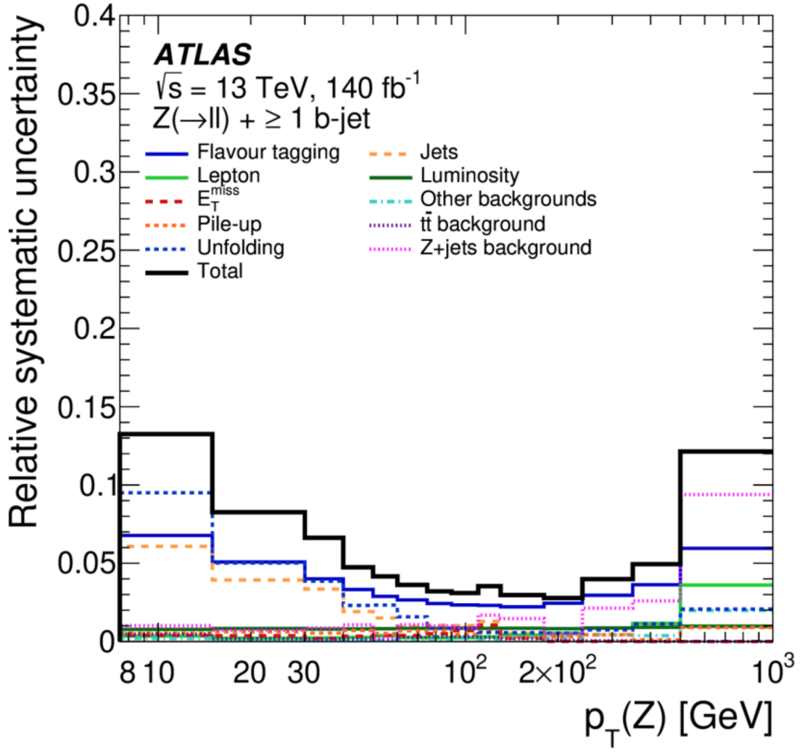
Uncertainties on the cross section measurements

- **x2 improved precision on Z + b-jets** measurements with respect to previous ATLAS results
- Dominant uncertainty contributions from

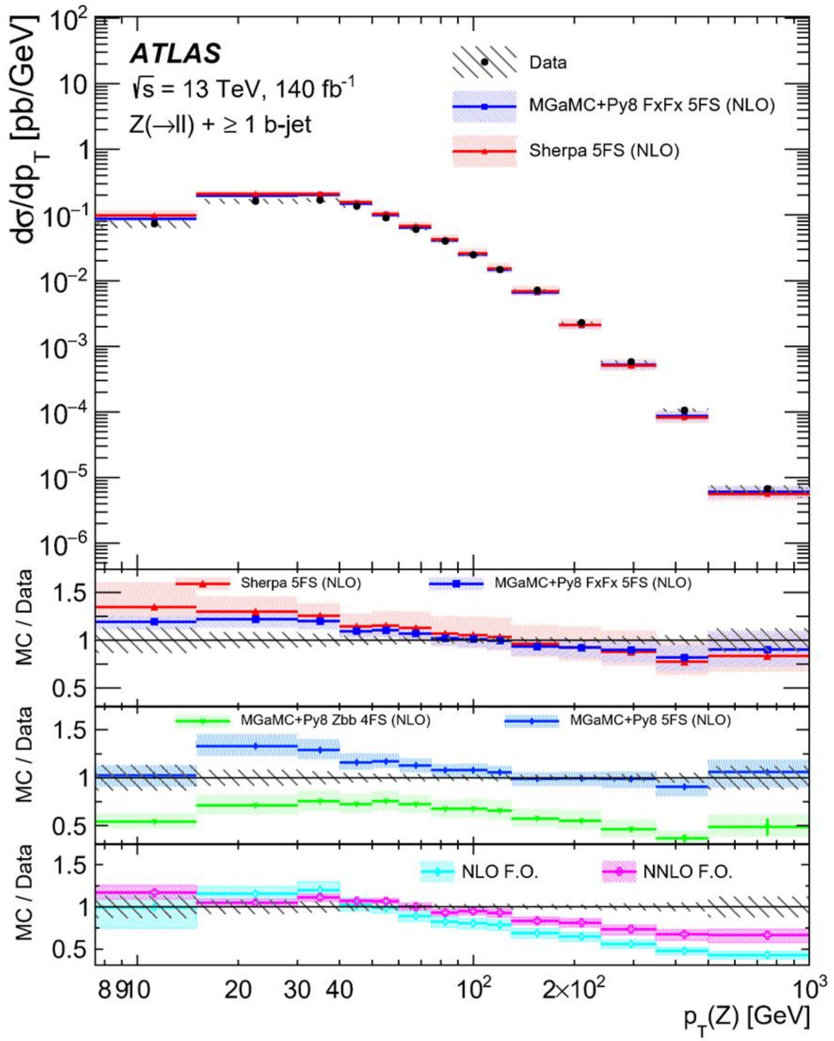
  flavour-tagging, jet energy scale and resolution and unfolding
- Statistical uncertainty on data <1%

  Differential distributions: total unc. **<5% in Z+≥1 b-jet, ~10-15% in Z+≥2 b-jets and Z+≥1 c-jet** for modest p_T

Source of uncertainty	$Z(\to \ell\ell) + \geq 1$ *b*-jet [%]	$Z(\to \ell\ell) + \geq 2$ *b*-jets [%]	$Z(\to \ell\ell) + \geq 1$ *c*-jet
Flavour tagging	3.6	5.7	10.3
Jet	2.4	4.3	6.5
Lepton	0.3	0.3	0.4
E_T^{miss}	0.4	0.5	0.3
Z+jets background	0.6	1.5	1.6
Top background	0.1	0.3	<0.1
Other backgrounds	<0.1	0.2	0.1
Pile-up	0.6	0.6	0.2
Unfolding	3.3	5.8	5.0
Luminosity	0.8	0.9	0.7
Total [%]	5.6	9.4	13.2

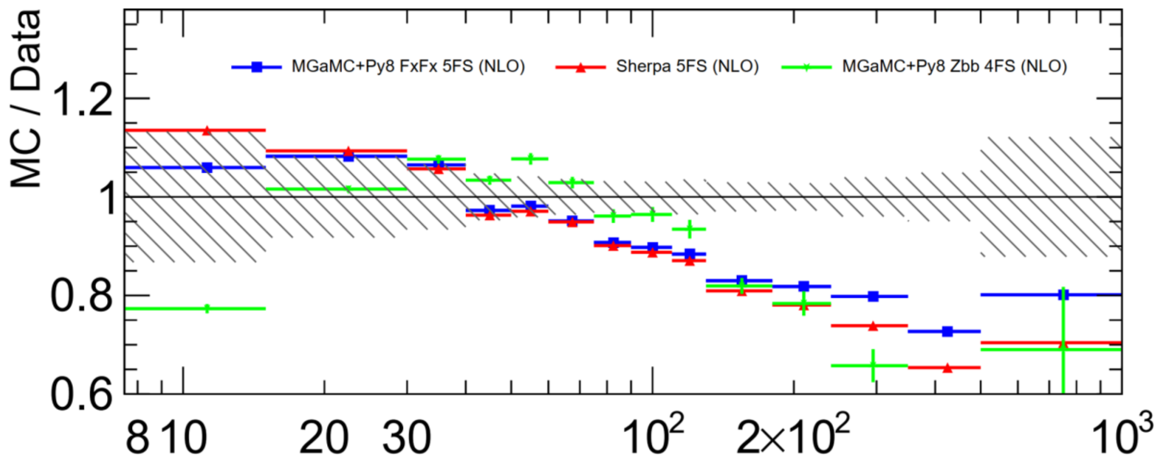


Differential Z+>= 1b-jet cross-section results



5FS: good description by both NLO ME+PS state-of-the-art MCs (MGAMC+PY8 FXFX and SHERPA 2.2.11)

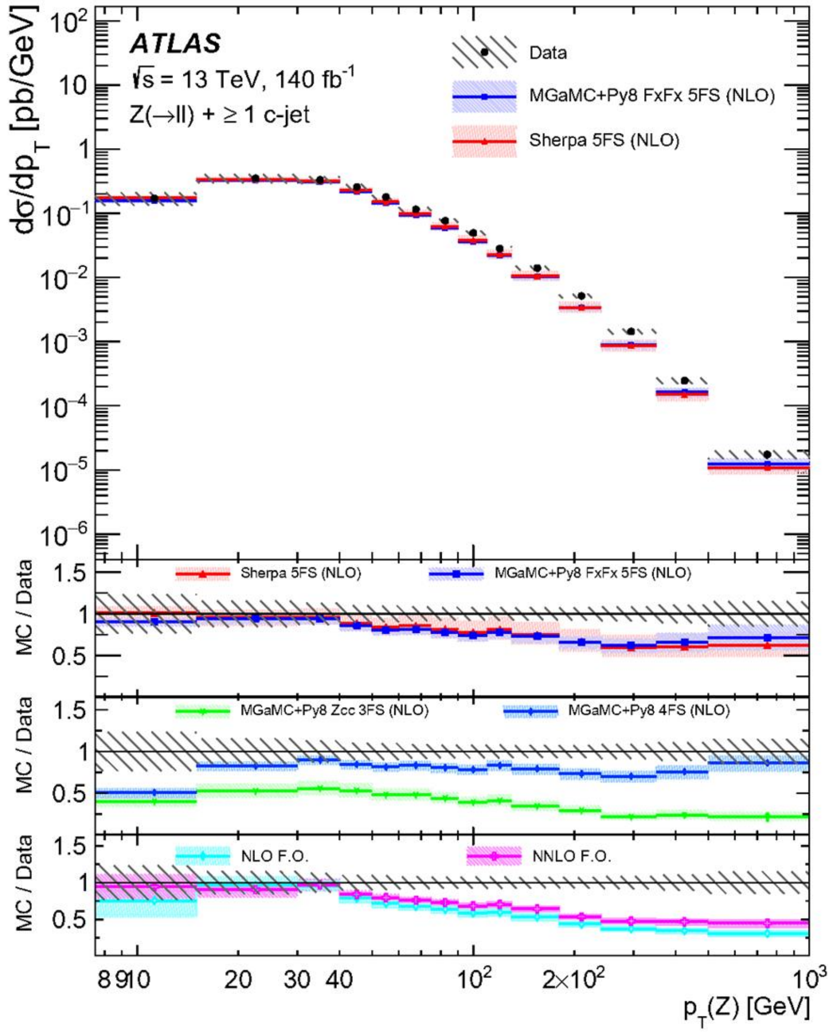
4FS: similar modelling of 5FS, but large underestimation of data
- no log term resummation in PDF evolution!



Shape Only

Fixed-order: Large divergences founded in the high p_T region for all predictions. Uncertainty related to the correction scale factor for different jet algorithms.

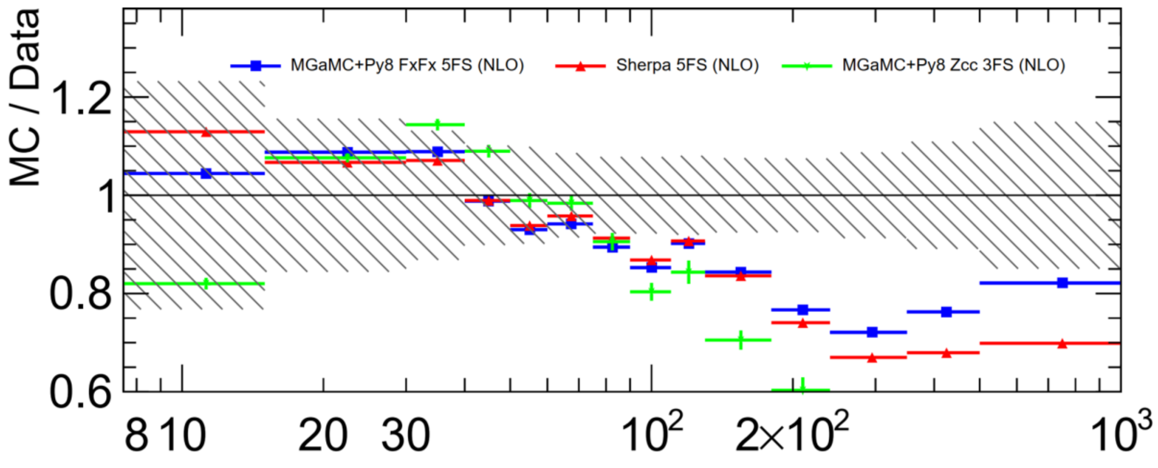
Differential Z+>= 1c-jet cross-section results



5FS: soft pT spectra well described by NLO ME+PS state-of-the-art MCs (MGAMC+PY8 FXFX and SHERPA 2.2.11)

3FS: large underestimation of normalization by a factor ~3

- **no log-term resummation in PDF evolution!**

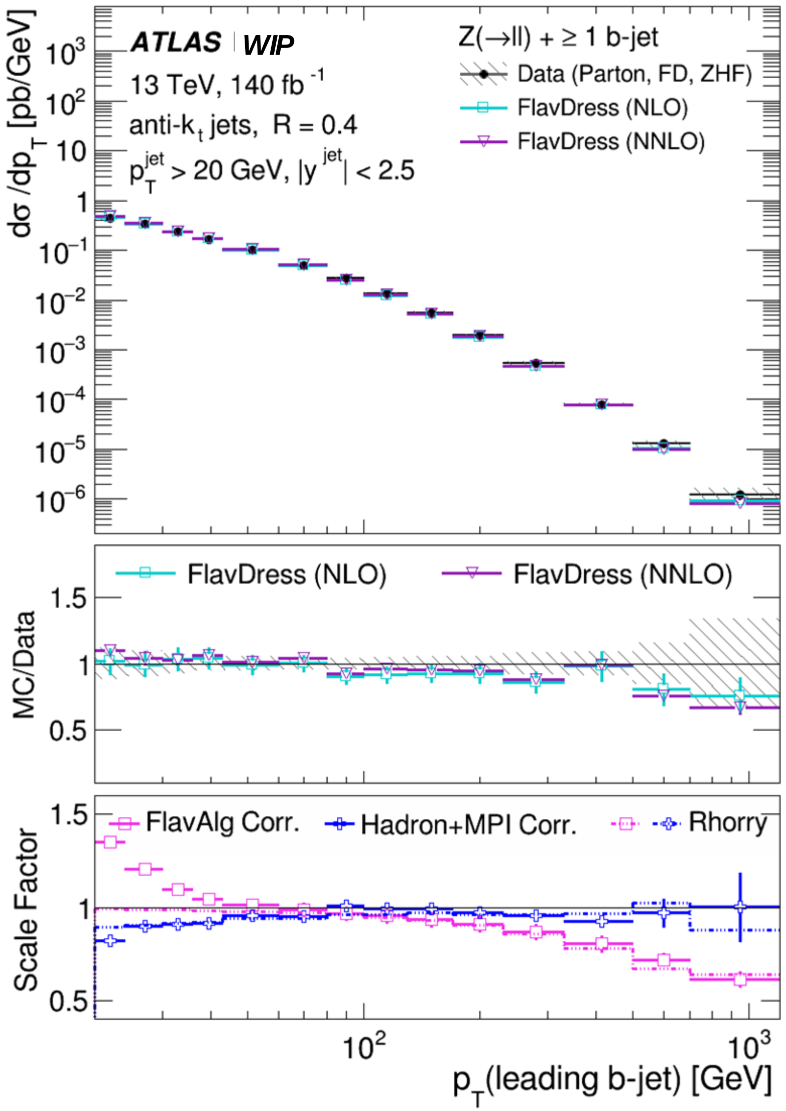


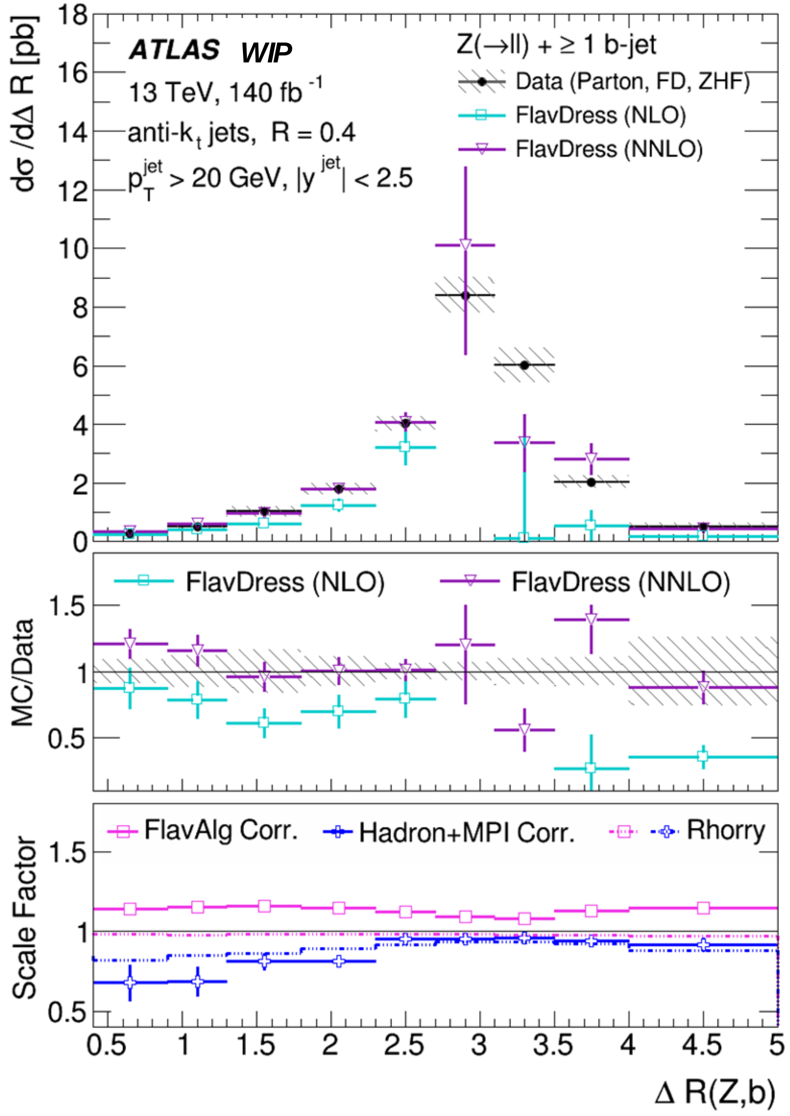
Shape Only

Fixed-order: at high p_T NNLO calculations in worst agreement than NLO ME+PS. NLO predicts softer p_T spectra, which is slightly improved with NNLO, **why?**

Differential Z+>= 1b-jet cross-section results

Thanks to discussions from Federico and Giovanni!





SFs derived with ***MG+ Py8 FxFx (for FlavAlg Corr)***, ***Pythia (for Hadron+MPI Corr.)***

inconsistent with the one derived with ***MG+Py8 (for both)*** from Rhorry Gauld for **Z+b** process

As it contains one additional correction:

Jet clustering **all particles after b-hadron decay (ATLAS)**

-->

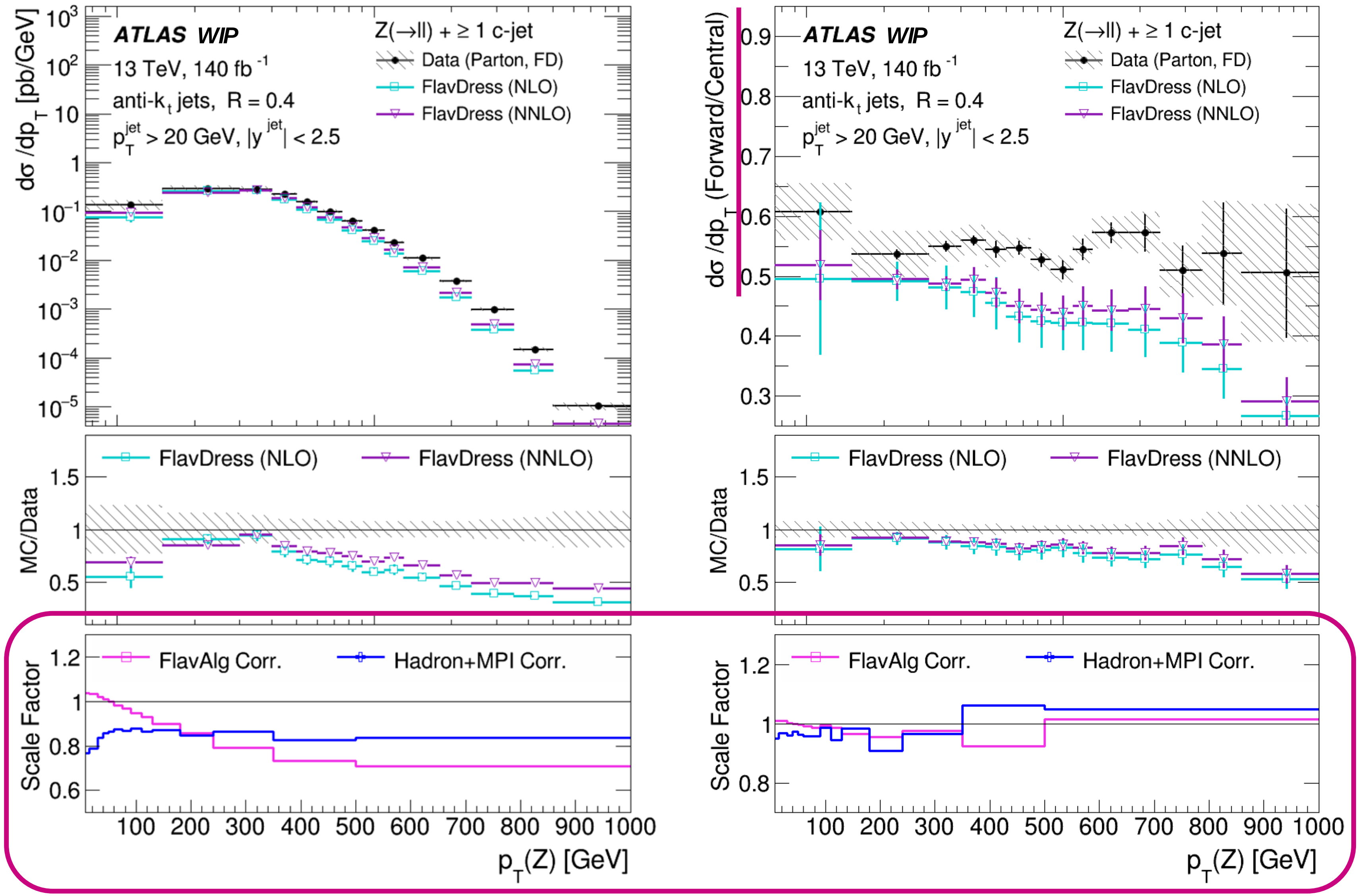
Jet clustering other particles **and stable b-hadrons (R.G.)**

- ✓ Sizable effects for only Z+b results from b hadrons have more cascade decays than c hadrons

Differential Z+>= 1c-jet cross-section results

PhysRevLett.130.161901

Central: $|Y_Z| < 1.2$; Forward: $|Y_Z| > 1.2$



Interesting point:

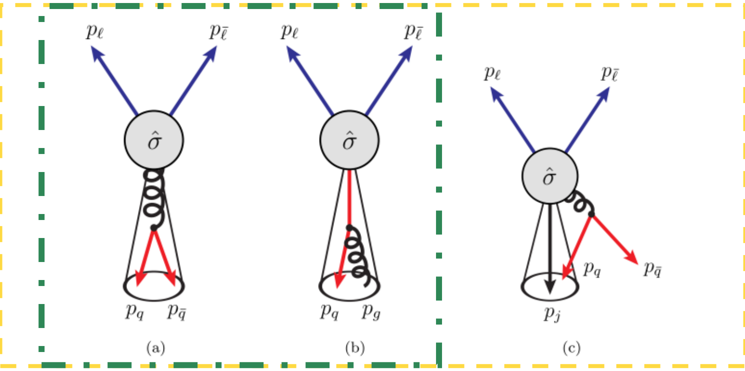
the IRC-unsafe components relevant to the high p_T rather η

HF-quark mass dependent..

High-Q dependent..

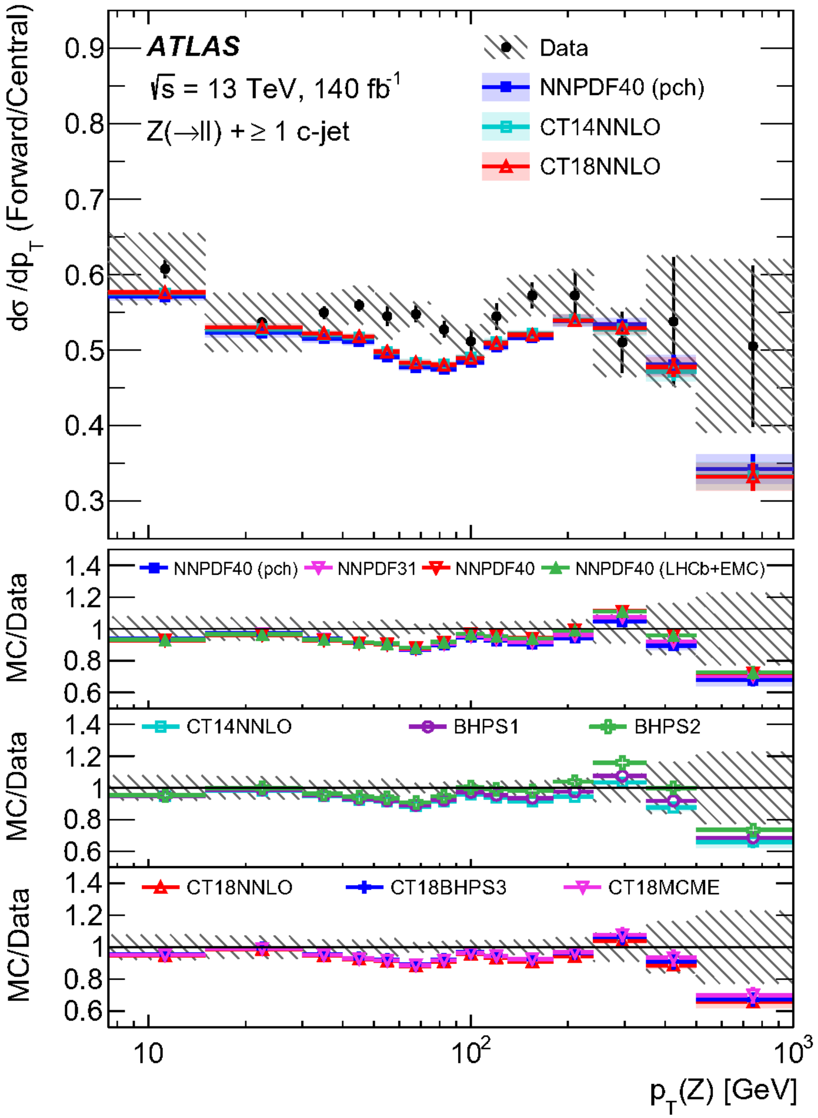
We can image the dynamical origin of IRC-unsafe components are mostly those collinear splittings with the type $\ln(Q^2/m_q^2)$

IRC-unsafe components



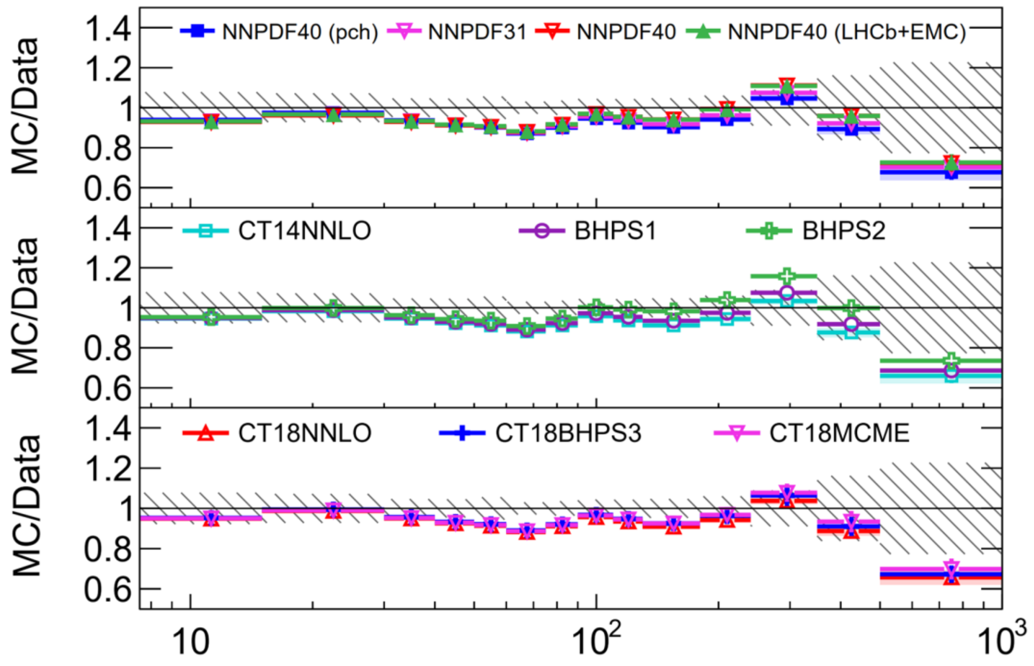
Differential Z+>= 1c-jet cross-section results

Forward/Central ratio of Z pT

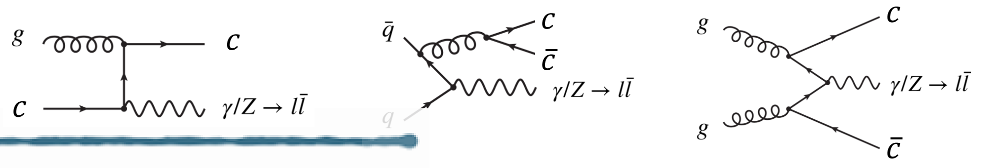


MGAMC+PY8 with **several PDF sets** testing **different IC-models**

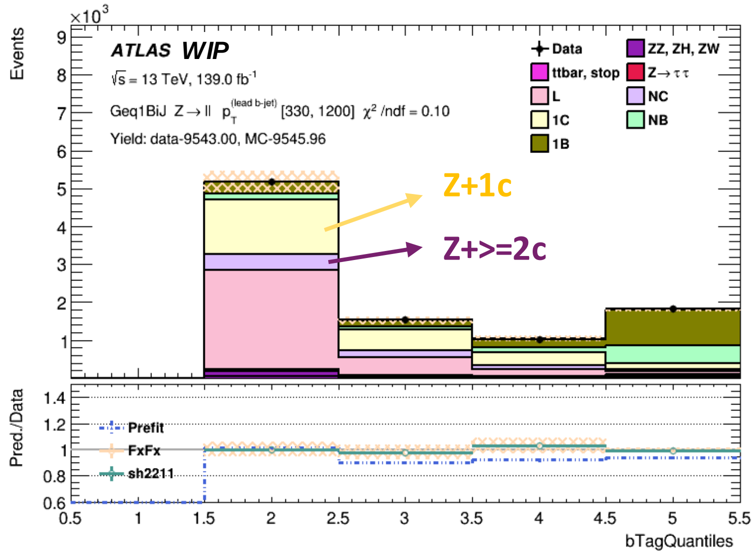
- Large reduction of systematics in the ratio (~8%)
- **Similar trend by all IC models** from NNPDF, CT14 and CT18
  - PDF sets with only perturbative charm (no IC): NNPDF40 (pch), CT14NNLO and CT18NNLO

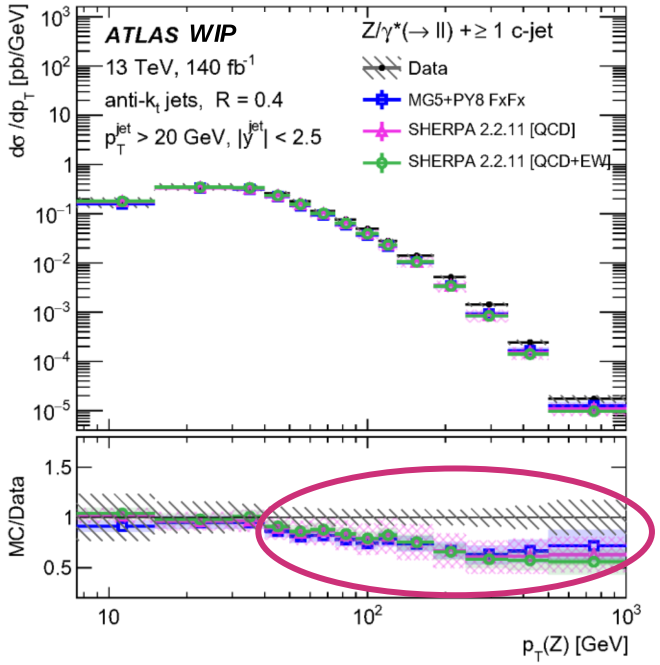


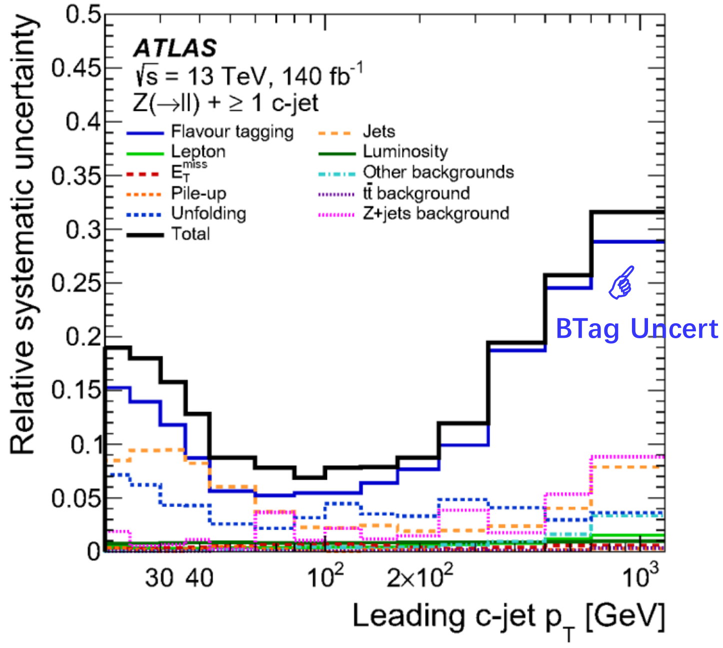
Z + Charm Jets Measurement



- **Z+c(c) process is the missing corner** of measurements **in ATLAS**
  - No dedicated charm tagging used in the first time Z+c measurement in ATLAS
  - Z+>=2c rarely contained in the Z+>=1c measurement
  - Latest-of-the-art predictions provide sizable mis-modelling for Z+>=1c spectrum







- **Z+c(c) measurement with GNN c-tagging** at $\sqrt{s}$ =13 TeV and 13.6 TeV starts with goals of
  - test *3FS, 4(5)FS* in $Z + \geq 2c$
  - compare with ***NNLO*** predictions
  - explore ***intrinsic charm*** further
  - constrain *c-quark* and *gluon* ***PDFs***
  - ***MC tunning***

Z + Charm Jets Measurement

- Measure **fiducial kinematic** observables – QCD Predictions, MC Modelling, charm and gluon PDFs
  - Jet multiplicity and jet properties: N_{jets}, p_T^c, Y_c
  - Dijet distributions: m_{cc}, p_{cc}^T, $\Delta\phi_{cc}$, ΔY_{cc}, ΔR_{cc}
  - Boson and Boson-jet distributions: p_T^Z, Y_z, ΔY_{Zc}

- Measure **optimal observables** – Sensitive to intrinsic charm, glue splitting, jet origins
  - Ratio of central/forward, p_T^{cc}/m_{cc}
  - LJP of leading c-jet and resolved 2 c-jets, observable related to q/g difference

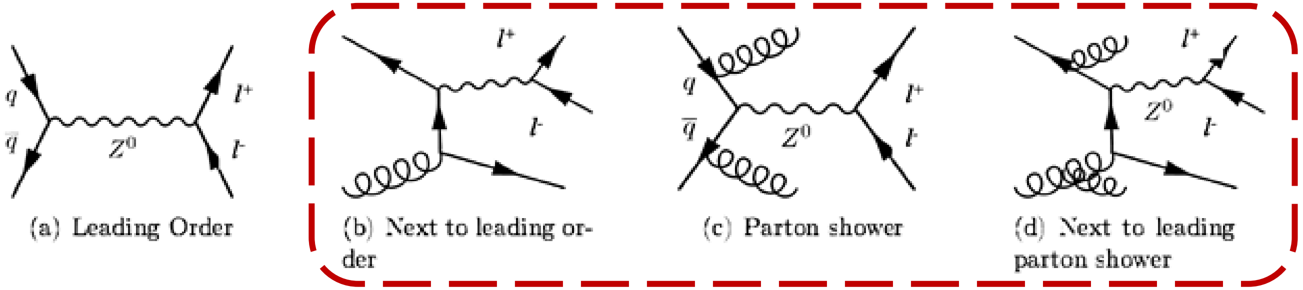
- Measure **Jet substructure observables** – Parton shower, W/Z/H/Top/quark-gluon/polarization tagger designment
  - Select from jet mass, charge, shapes, splitting functions, Lund jet plane
  - Studies show which's topology-sensitive ☞ JSS distributions, flavour-sensitive ☞ LJP of b/c/l jets

- **Collaboration effort**
  - Charm tagger (GN2v01) calibration
  - Background estimation for NP search with mono-charm

More words:
QCD studies in the **boosted regime** is **important**, as **tagging performance decreases in high pT** besides the necessary of testing theoretical predictions

V + jets at hadron collider

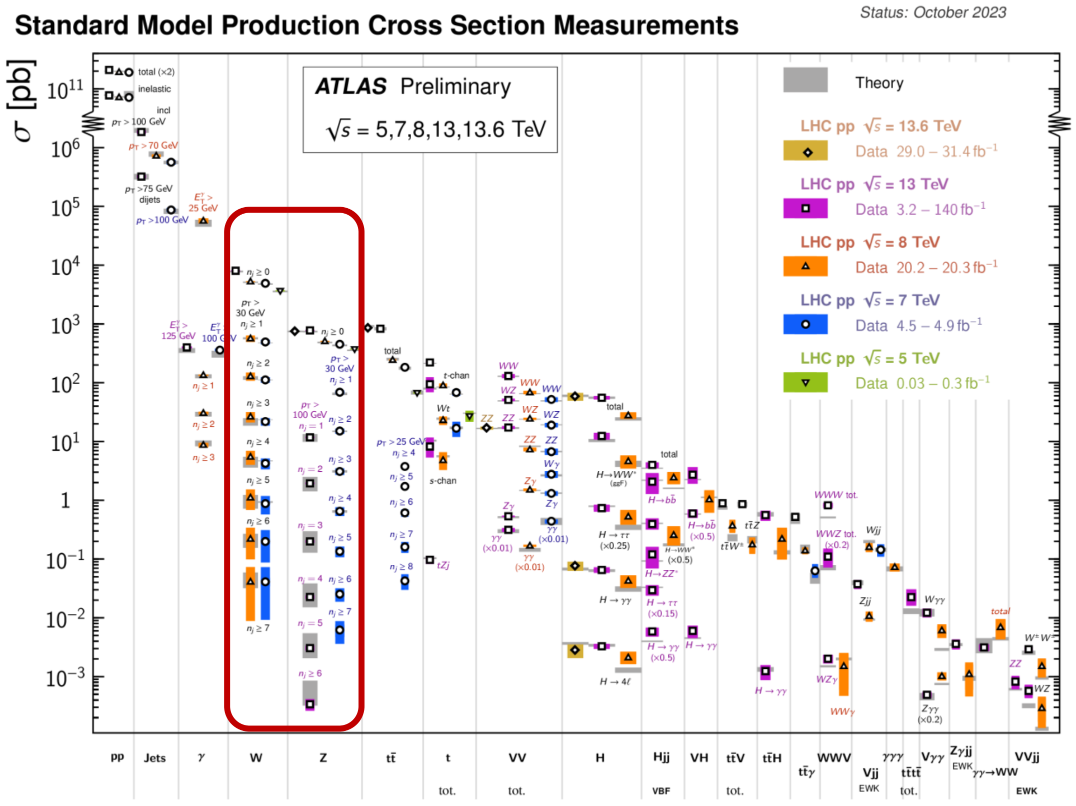
- V(=W/Z) + jets production has the largest cross-section after multi-jet and inclusive V-boson productions
  - At LHC, 1/3 of W/Z production is in association with a jet (p_T > 30 GeV)



(a) Leading Order
(b) Next to leading order
(c) Parton shower
(d) Next to leading parton shower

V+jets are the high order of Drell-Yan process

-- standard candle at LHC for Modellings and Calibrations



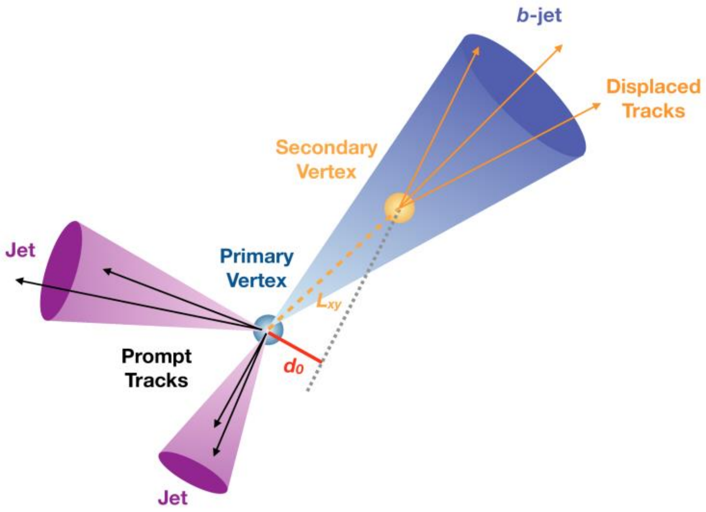
Pile-up Effects on Flavour Tagging Performance

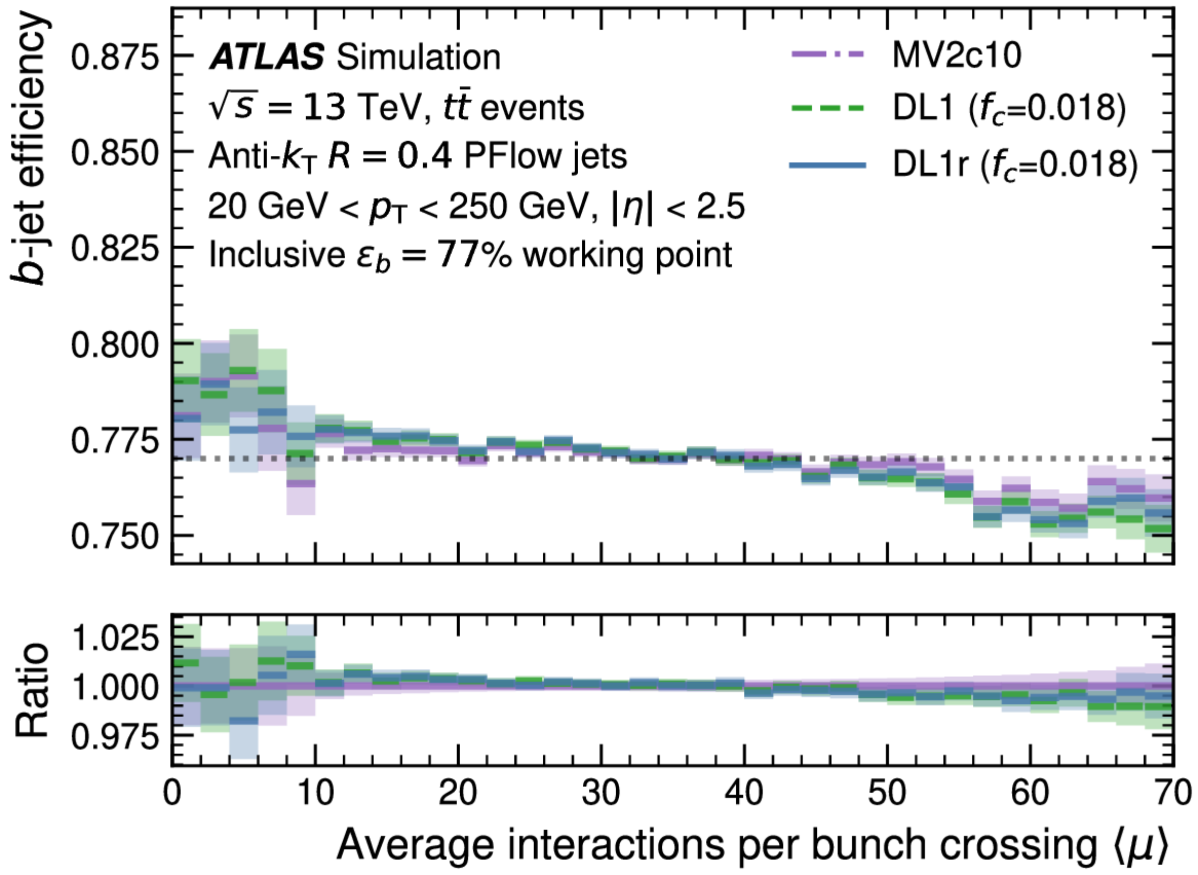
Eur.Phys.J.C 83 (2023)

✤ DL1r

- High level algorithm operating on outputs from intermediate track and vertex algorithms
- DL1r discriminant calculated from the b-, c- and light-jet probabilities

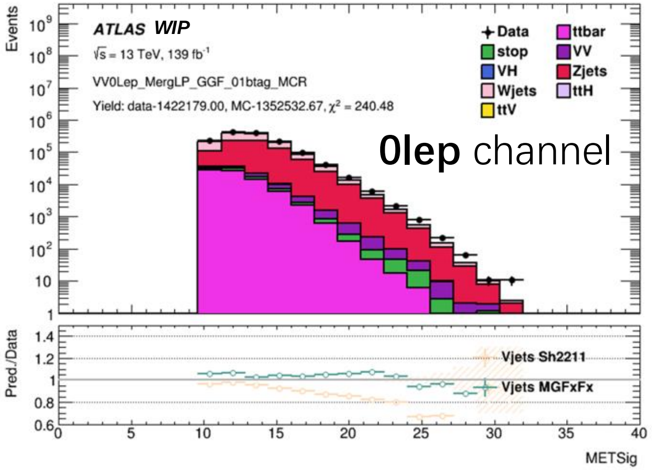
$$D_{\mathrm{DL1r}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c \cdot p_{light})}\right)$$

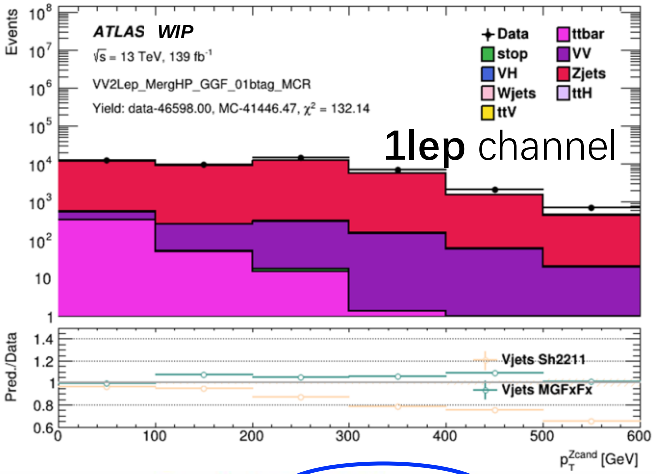


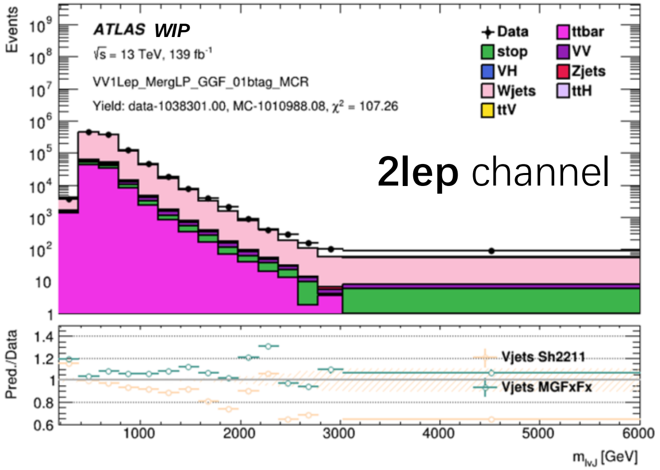


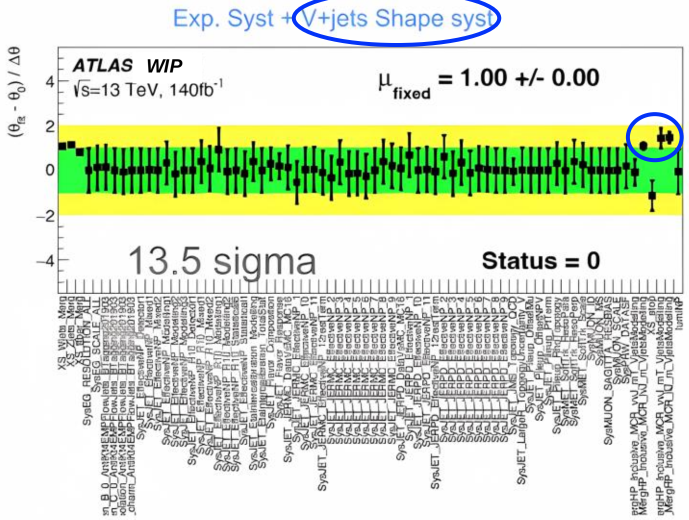
V + HF jets as background for Higgs and NPs

- V+HF jets dominant background & modelling as the limiting factor for a good sensitivity
  - Example 1: VV+VH semi-leptonic measurement and search

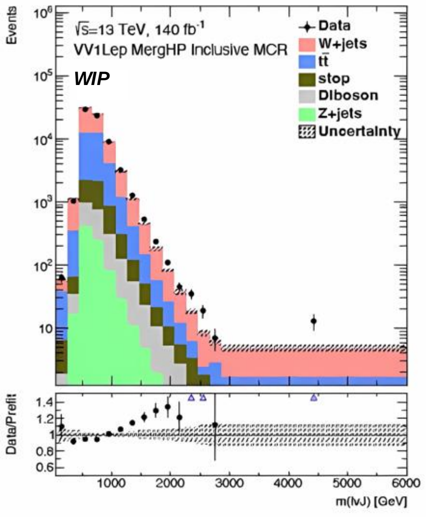




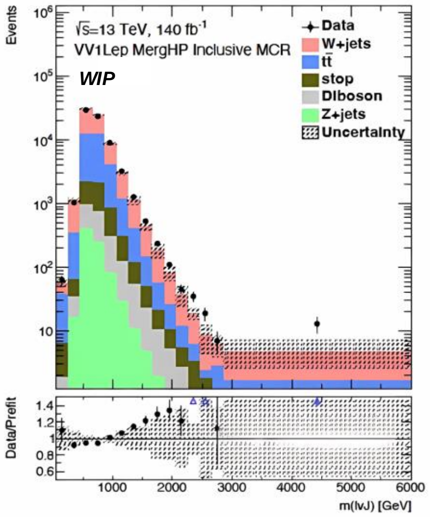




Post-fit with exp sys only



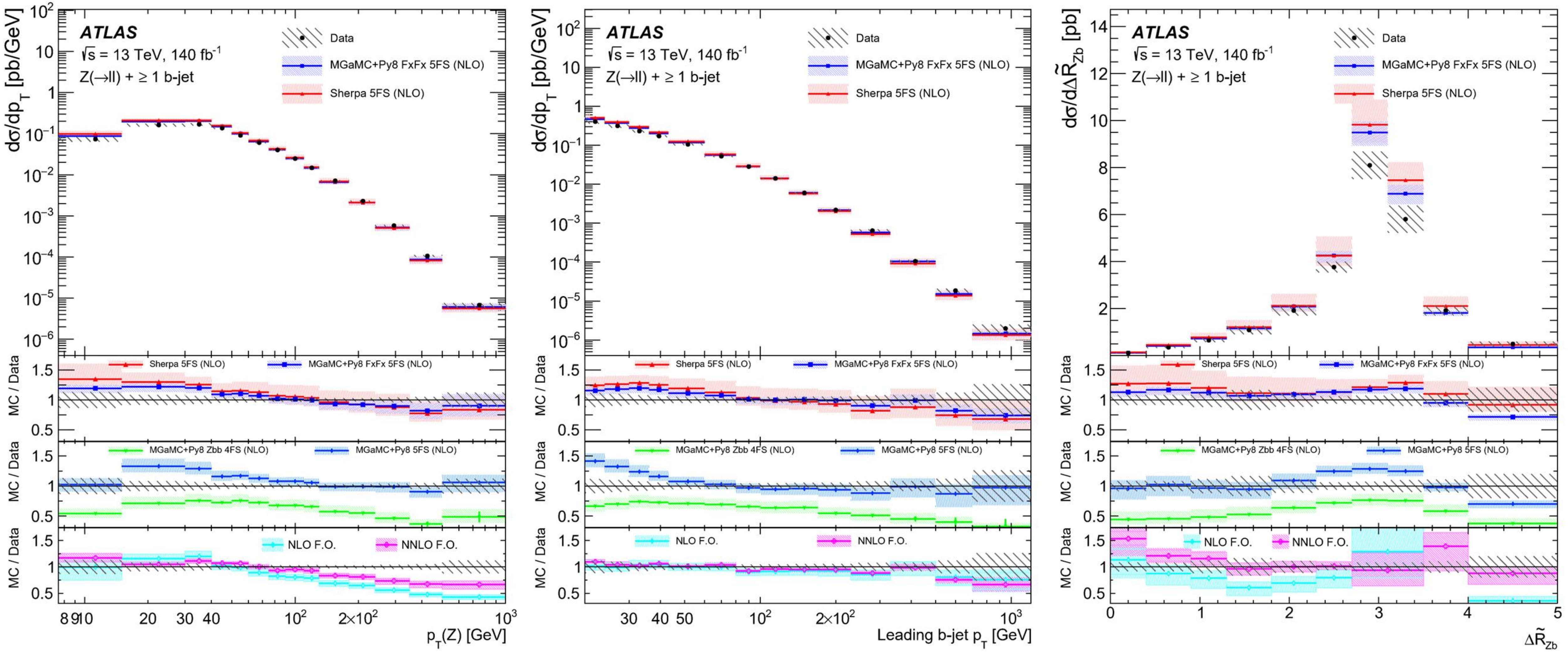
Post-fit with exp +Vjets shape syst from generator choice



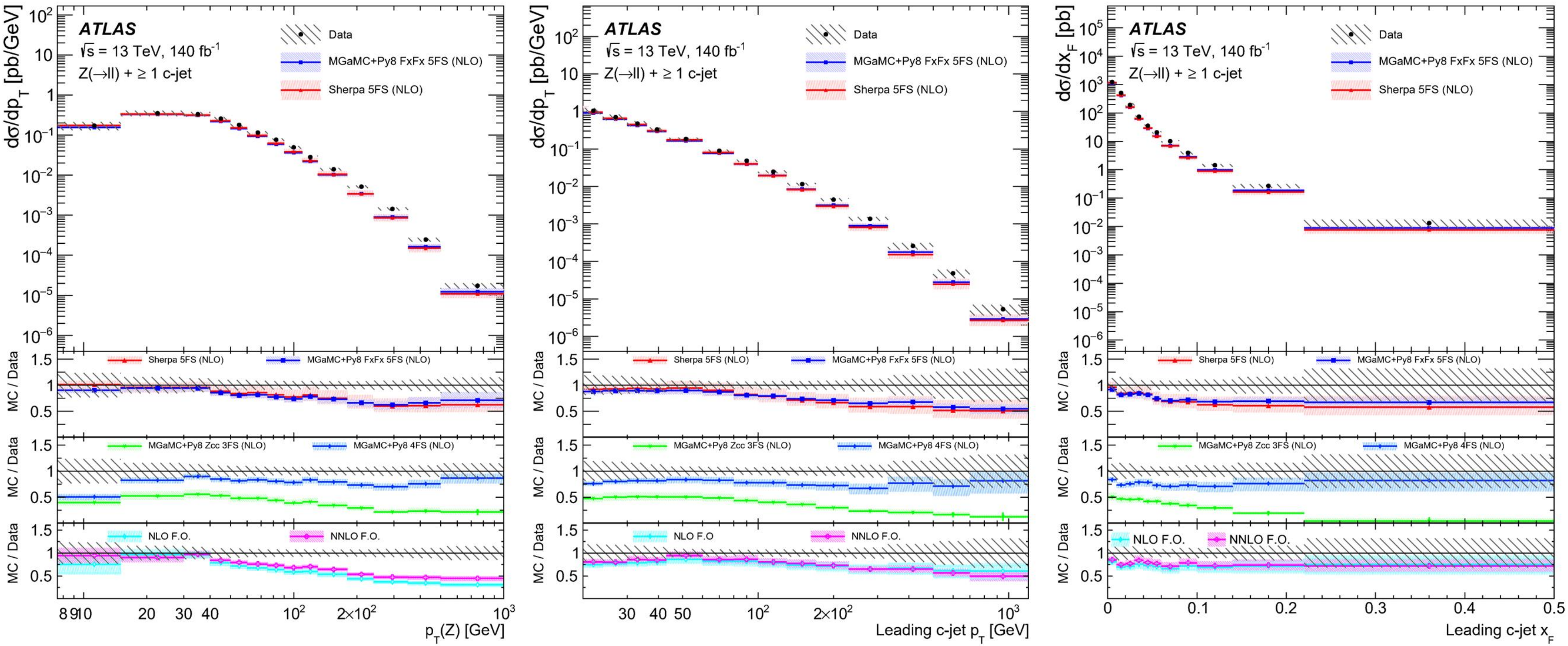
Fit performed with Vjets divided to **HL, LL, HH** categories with floating normalization SFs

- V+jets mis-modelling drastically decrease the sensitivity
- Importance to well describe *separated V+HF (L)* processes by predictions

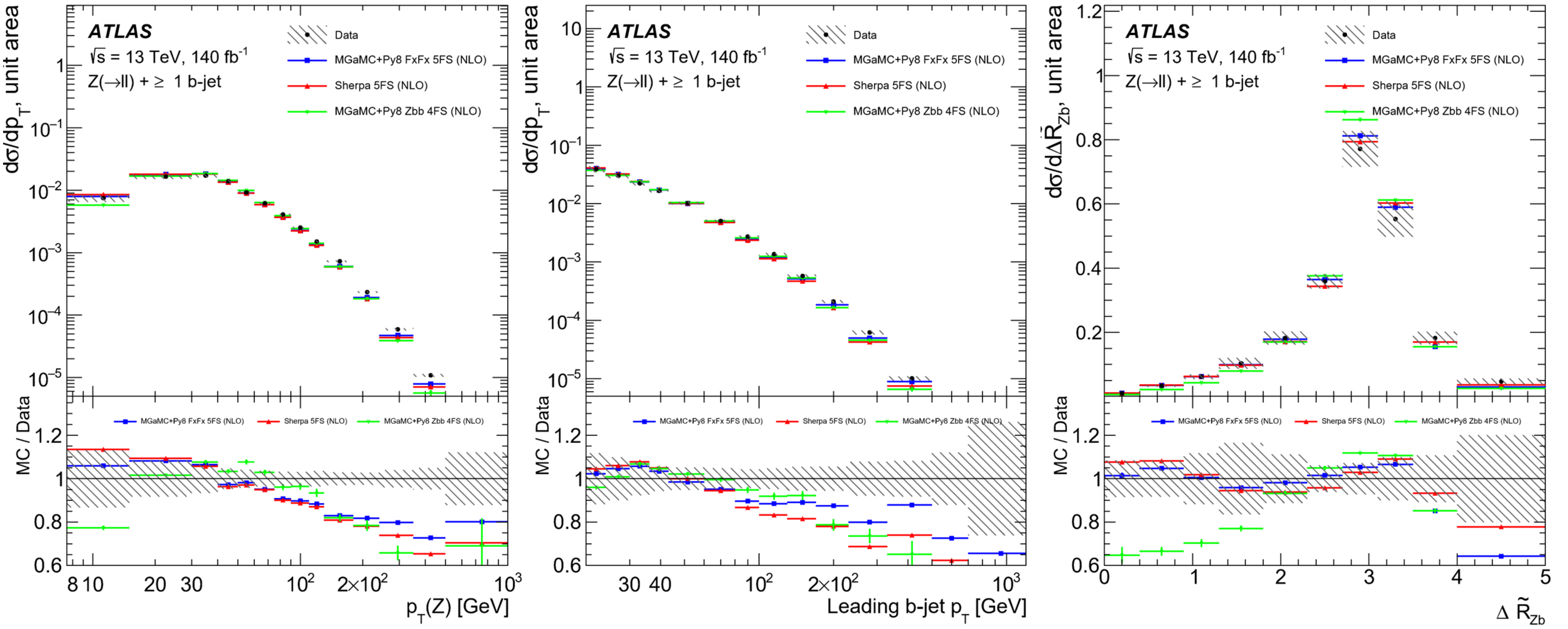
Differential Z+>= 1b-jet cross-section results



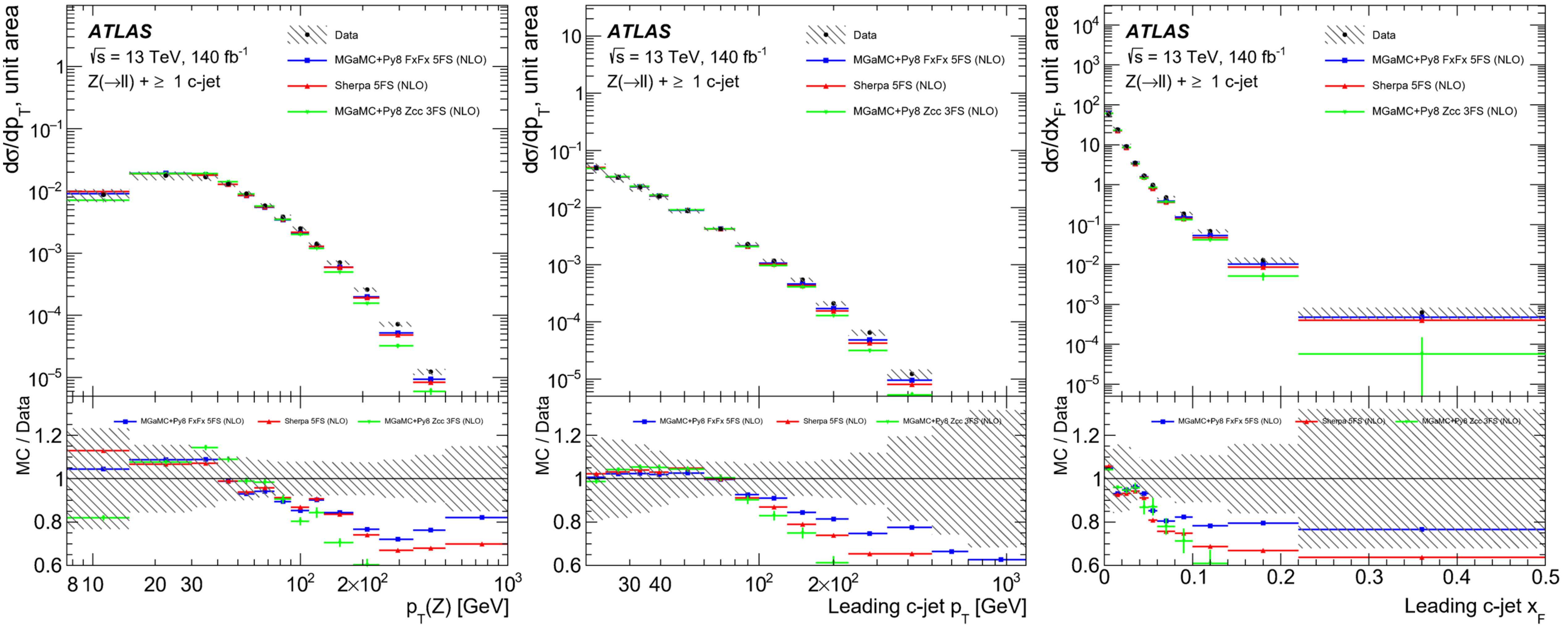
Differential Z+>= 1c-jet cross-section results



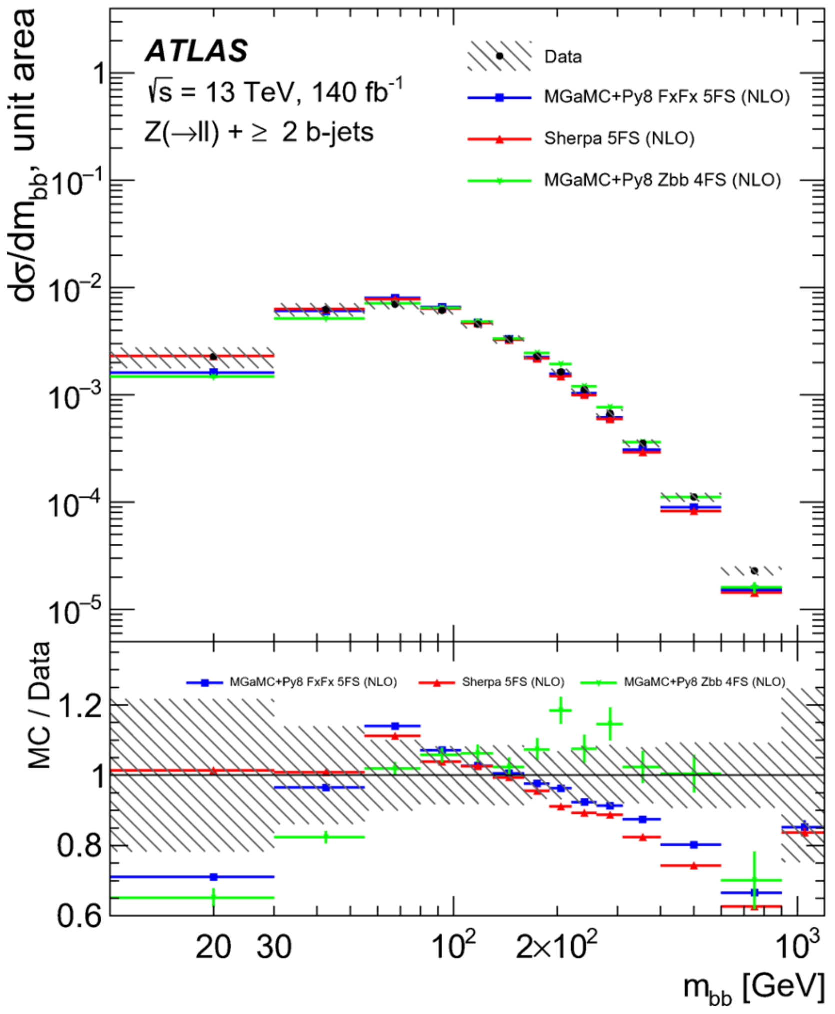
Differential Z+>= 1b-jet cross-section results (Norm.)

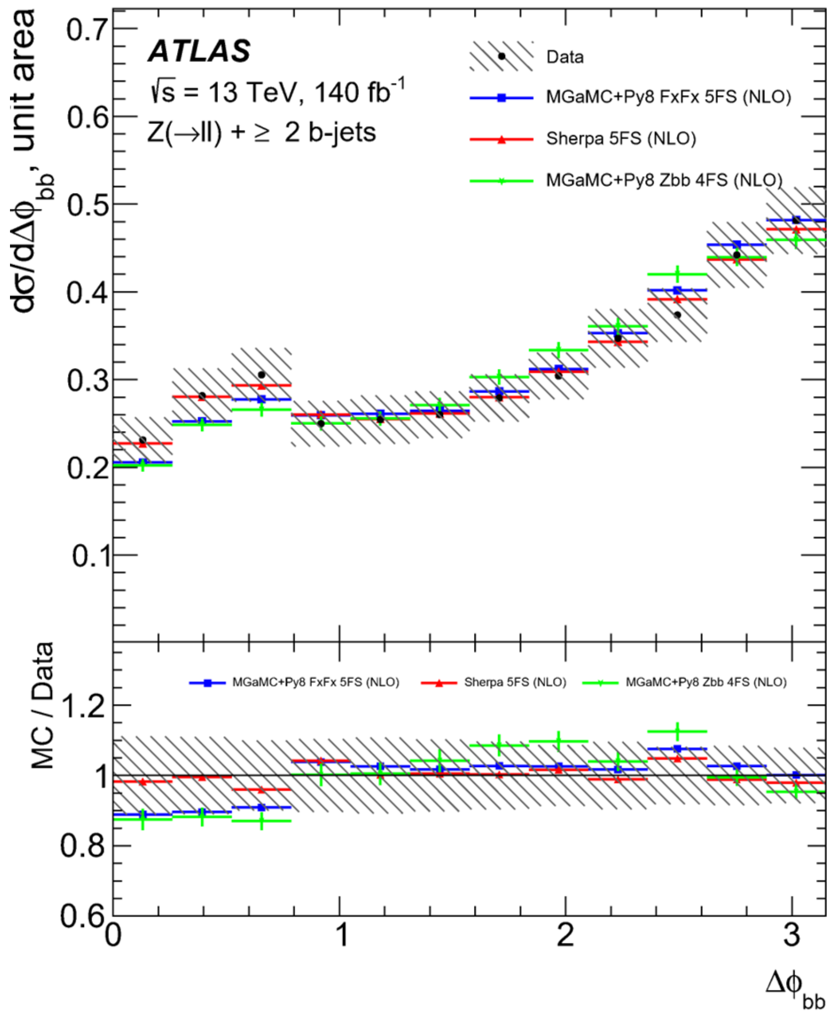


Differential Z+>= 1c-jet cross-section results (Norm.)

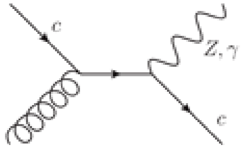


Differential Z+>= 2b-jet cross-section results (Norm.)





Intrinsic Charm

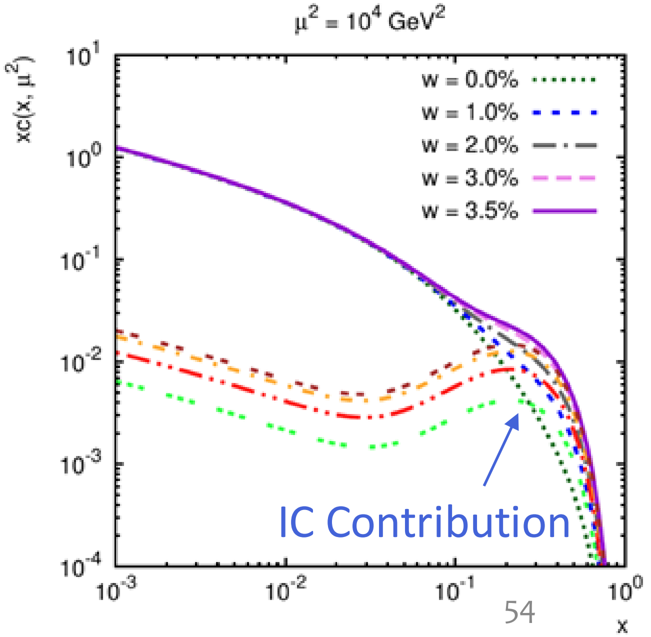


[1] PLB 93 (1980) 451
[2] PRD 92 (2015) 034014

- Idea of intrinsic charm (IC)[1] contribution to proton PDF debated for ~40 years
  - Initially introduced to describe enhanced charmed hadron production at ISR
  - Still no reliable experimental confirmation/exclusion
- Valence-like c quarks have large x ≥ 0.1, unlike perturbative charm with smaller x
  - Understanding of heavy quark PDF is very important for Higgs and BSM background modelling
  - Studying charm associated production with Z or γ more sensitive than inclusive charm production[2]
    - IC sensitive in $x_c > 0.1$, where $x_c \geq x_F^V = \frac{2p_T^V}{\sqrt{s}} \sinh(\eta_V)$
    - Selection criteria - hard c-jet and Z in forward region
- CT14 and NNPDF
  - Provide PDF sets with inclusion of IC in the fits according to BHPS model
  - PDF reweighting is used to model the IC effect with Z+jets NLO sample

	$w(\lvert uudc\bar{c}\rangle)$	$\langle x \rangle_{\text{IC}}$
BHPS1	1.1%	0.6%
BHPS2	3.5%	2.1%

$$w(x_1, x_2, Q) = \frac{f_i^{\text{new}}(x_1, Q^2) f_j^{\text{new}}(x_2, Q^2)}{f_i^{\text{old}}(x_1, Q^2) f_j^{\text{old}}(x_2, Q^2)}$$

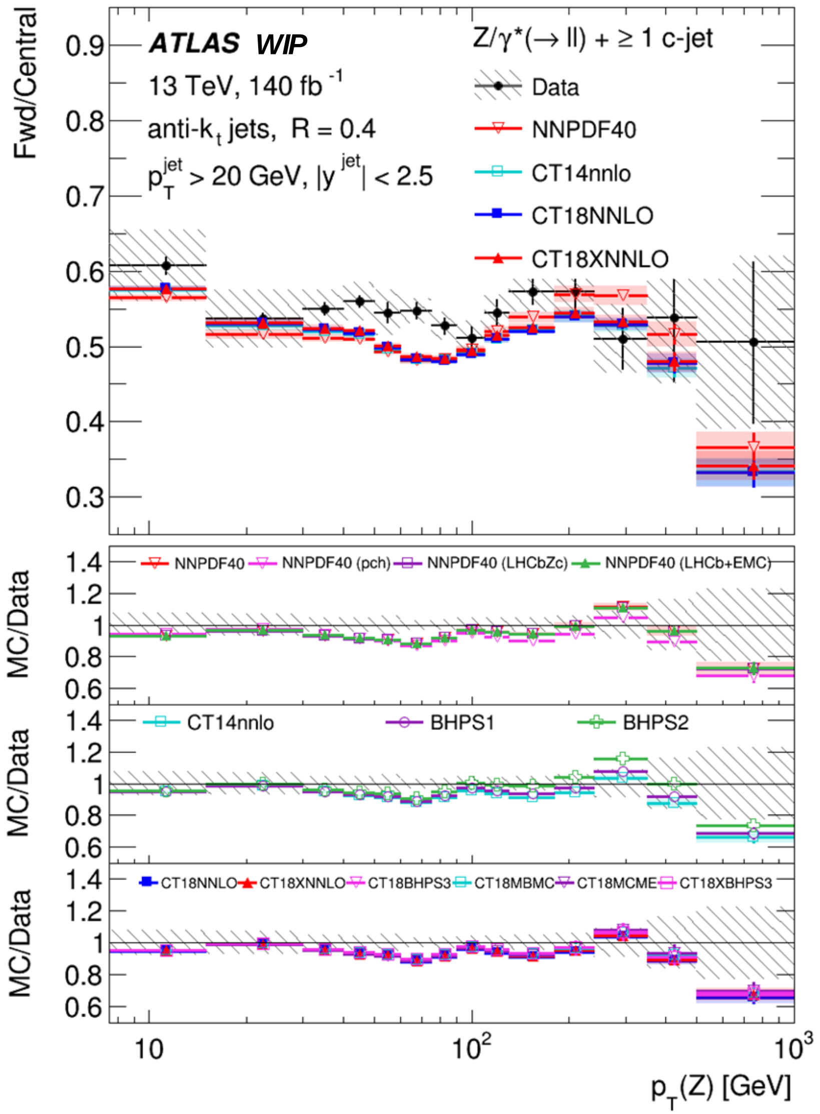


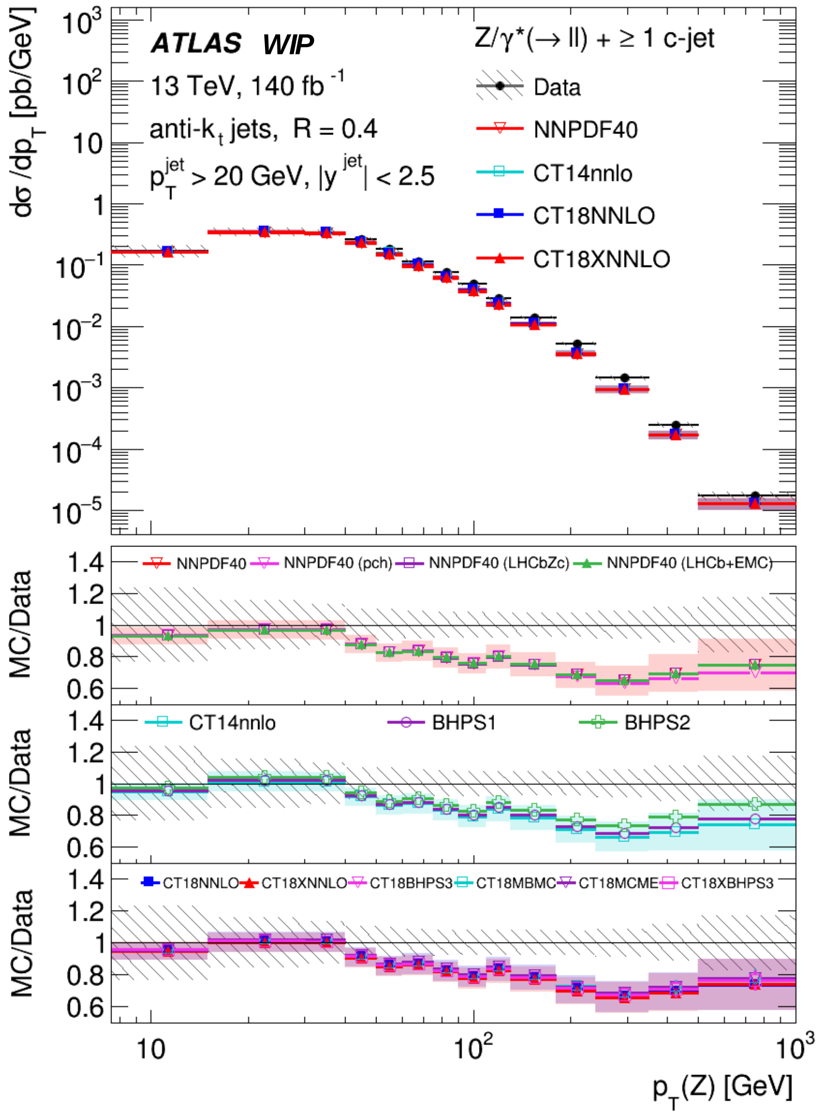
CT18FC PDF set

- An updated CTEQ paper on IC PDFs: PLB 843 (2023) 137975
  - All PDF sets available at web page, also included in LHAPDF
- Baseline no-IC PDF to be used: **CT18NNLO** (14000)
  - Uncertainties: 58 eigenvector variations
- Four variants including IC:
  1. CT18 BHPS3 (14087) – similar to earlier BHPS variants, different amount of IC (?)
  2. CT18 MBM-C (14090) – *meson-baryon model (confining)*, asymmetric $c\bar{c}$ contributions
  3. CT18 MBM-E (14093) – *meson-baryon model (effective-mass)*, similar to 2, but more constrained
  4. CT18X BHPS3 (14096) – same as 1, but using **CT18XNNLO** fit as a baseline (with DIS data fitted using x-dependent μ_F to model small-x saturation)
- For each of them – two variations with $\Delta\chi^2 = 10, 30$
  - $\Delta\chi^2 = 30$ – standard CT 68% CL tolerance
  - $\Delta\chi^2 = 10$ – more restrictive, compatible with MSHT20 tolerance
- Options suggested by Tim Hobbs:
  - Minimal: use *CT18 BHPS3* and *CT18 MBM-C* in comparison to nominal *CT18NNLO*, evaluate uncertainties with $\Delta\chi^2 = 30$ variations
  - Ideal: test all options (note that for *CT18X BHPS3* need a different nominal *CT18XNNLO*)

Differential Z+>= 1c-jet cross-section results (ICs)

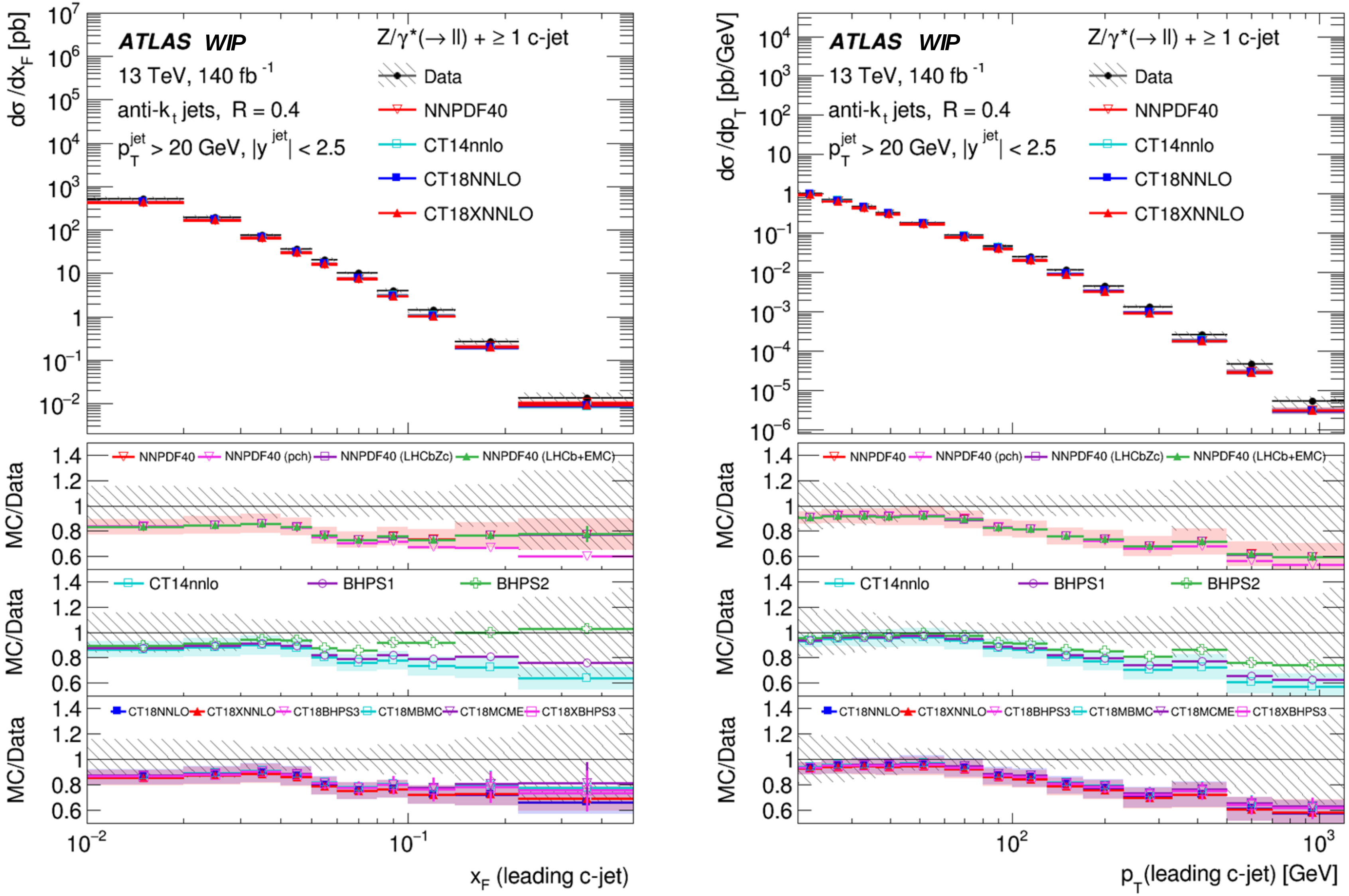
Forward/Central ratio of Z pT



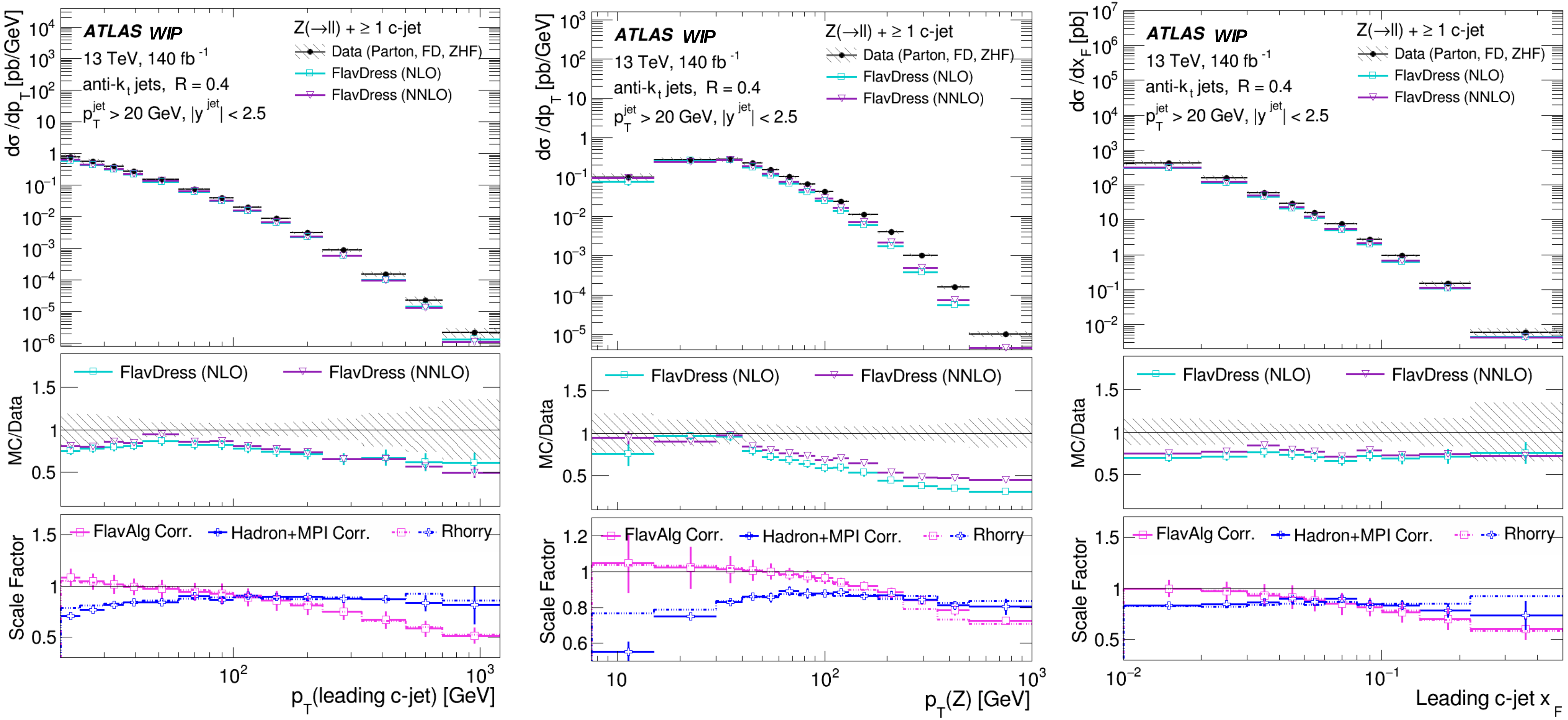


Differential Z+>= 1c-jet cross-section results (ICs)

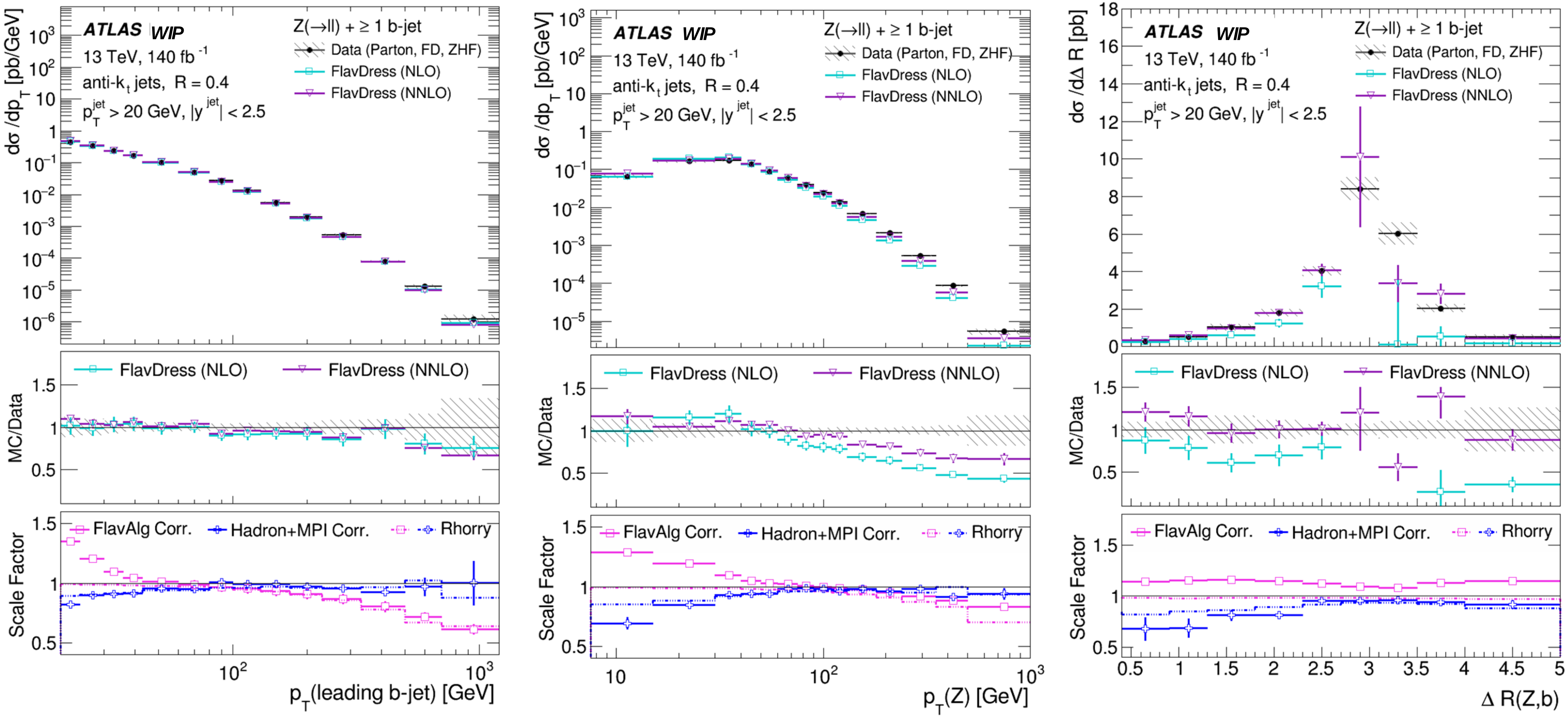
Feynman-variable $x_F = 2p_Z/\sqrt{s}$



Differential Z+>= 1c-jet cross-section results



Differential Z+>= 1b-jet cross-section results



NLO+PS (5FNS) + NLO EW Correction

- **Data:** full Run 2, 140 fb^{-1}
- **MC samples**
  - **MGaMC@NLO with FxFx merging** - up to 3 partons in NLO ME!
  - Sherpa 2.2.11 - up to 2 partons in NLO ME
  - Besides the QCD-only nominal, Sherpa provides on-the-fly weights including approximate NLO electroweak corrections using up to three different approaches

⇨ additive, multiplicative, exponentiated

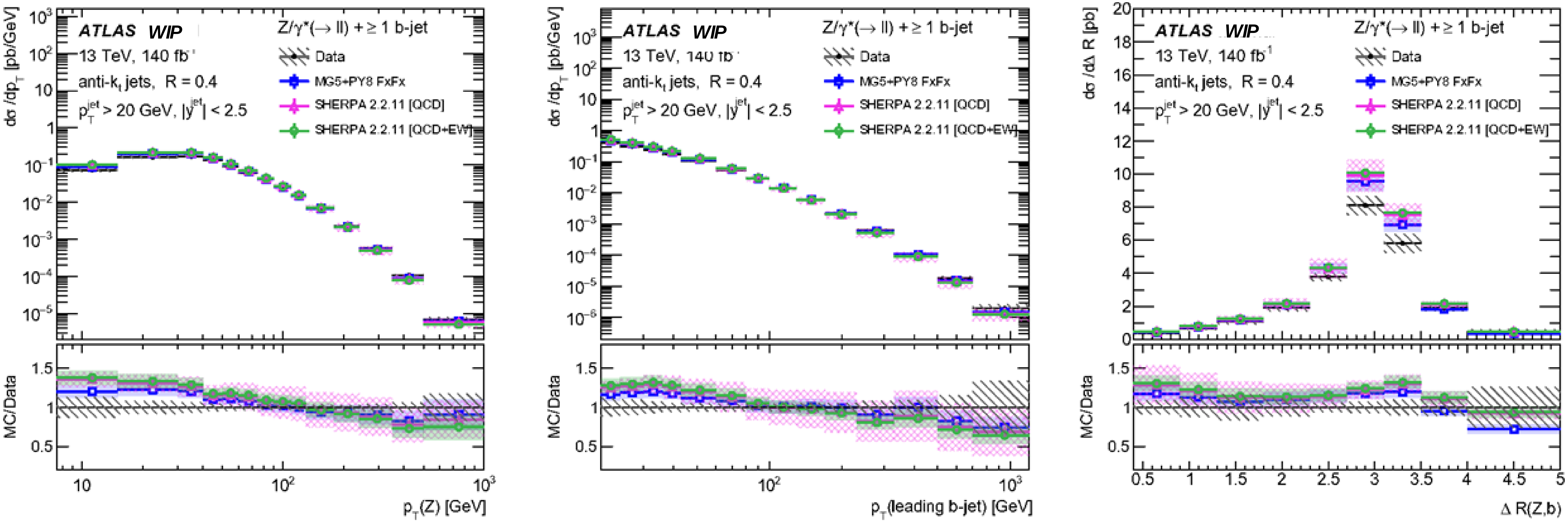
Approach that yields **the smallest overall correction with respect to the QCD-only curve** as the nominal prediction

Assign the difference to the curve with the **largest correction from other approaches as a (symmetrised) uncertainty**

*backup

NLO+PS (5FNS) + NLO EW Correction: Z+≥1b

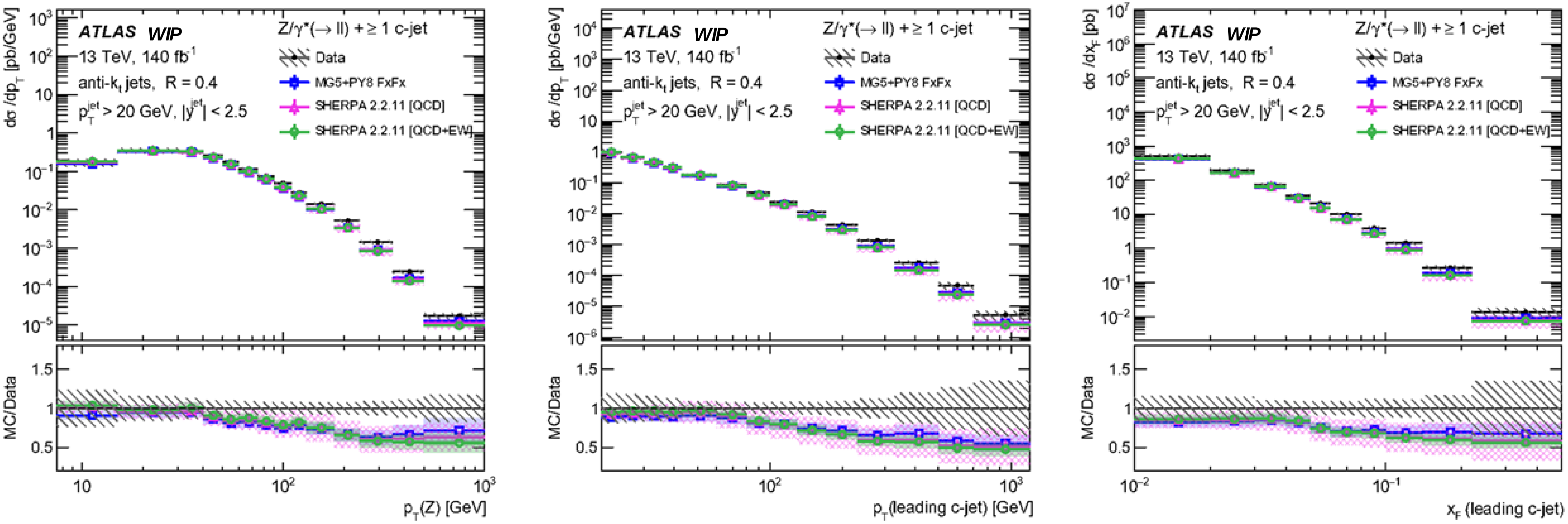
- **Good agreement** for both of MG FxFx and Sherpa 2.2.11, with the former giving better modelling



- **NLO EW correction** is negligible, with difference from QCD-only only visible in the high p_T^Z region (~ 10%)
  - With the uncertainty taken from different EW virtual correction approaches at 10% ~ 20% at the most

NLO+PS (5FNS) + NLO EW Correction: Z+≥1c

- **Mis-modelling visible in the high p_T^Z tails**, with softer spectrum for lead c-jet pT and xF than data

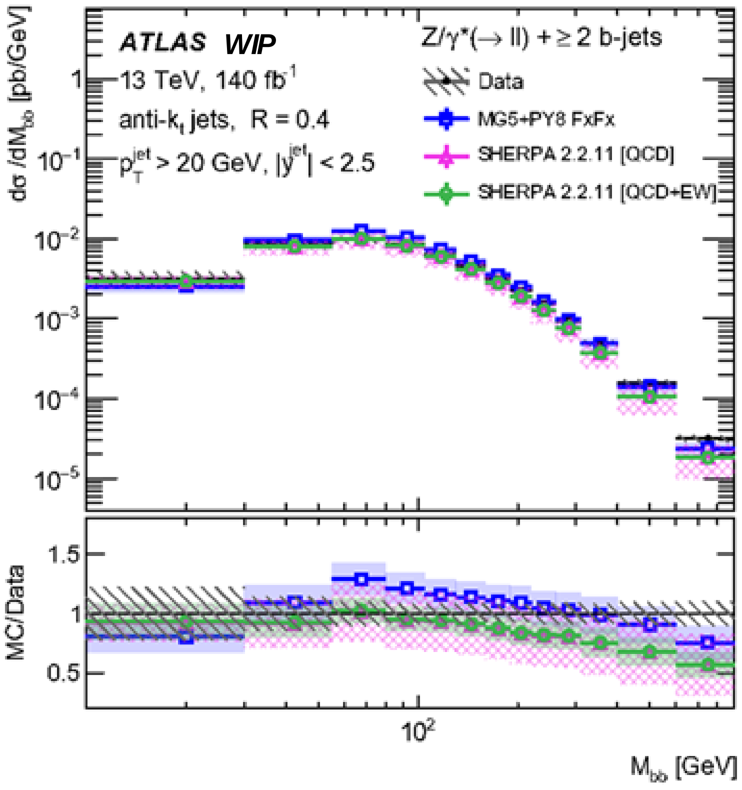


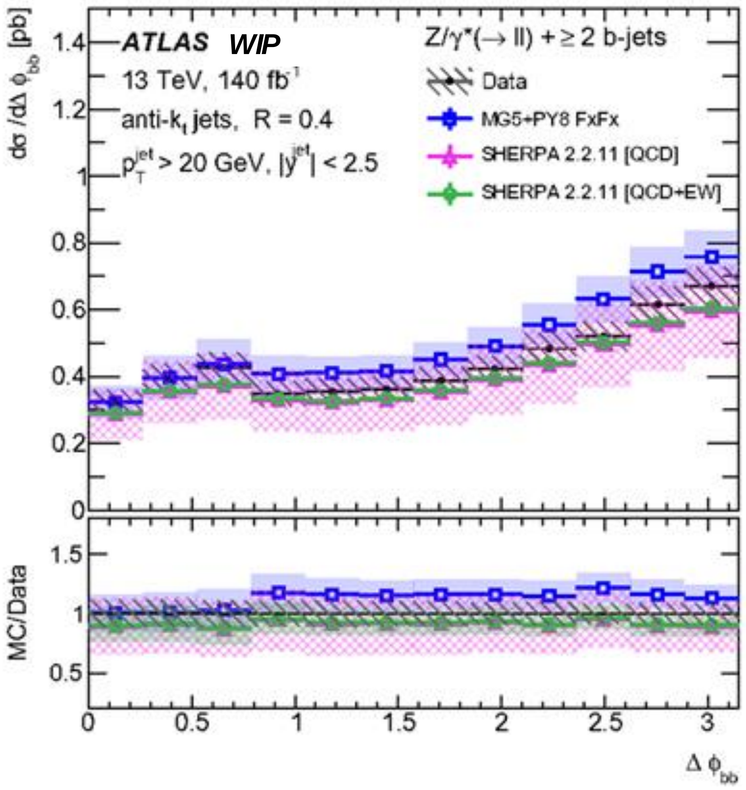
- **NLO EW correction** is negligible, with difference from QCD-only only visible in the high p_T^Z region (~ 10%)
  - With the uncertainty taken from different EW virtual correction approaches at 10% ~ 20% at the most

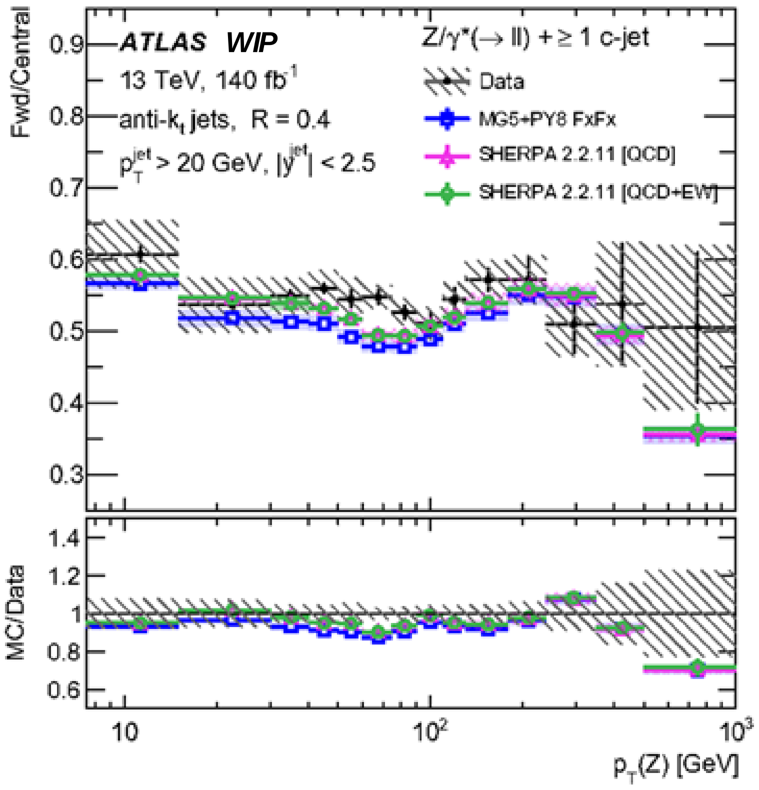
NLO+PS (5FNS) + NLO EW Correction: Z+≥2b

- **Perfect modelling for the shape of $\Delta\phi_{bb}$ and overall agreement for m_{bb}**
  - Sherpa gives much larger theoretical uncertainty as the case in Z+1b

Ratio observable for Z+c







- **QCD scale uncertainty (for missing higher order effects) reduced largely for p_T^Z (fw | cen)**