Measurements of vector boson production in association with jets at ATLAS

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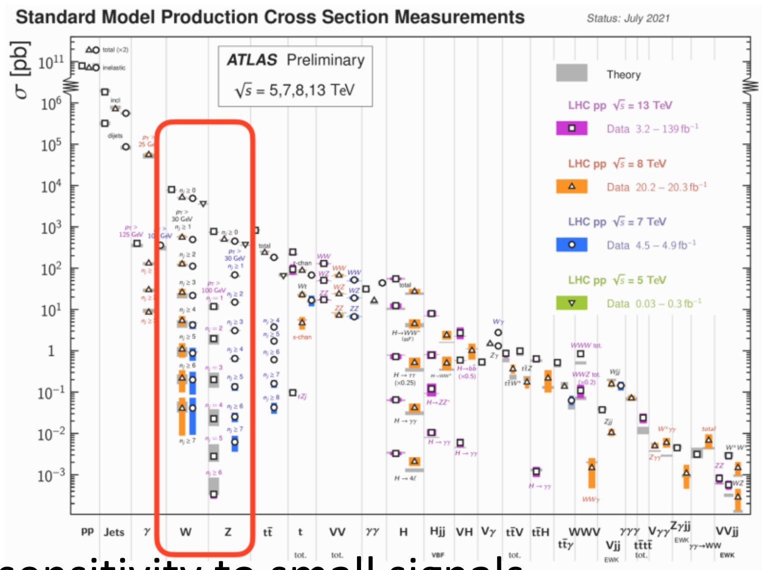
Vast V+jets – SM Standard Candles



- High production rate & Span six orders of cross sections
  - possibility to systematic measurements of all accessible SM observables
- Semi-leptonic final states
  - clean signature against QCD backgrounds
  - high trigger efficiency & precise reconstruction
- Sensitive to perturbative QCD, generator modelling, PDF
  - excellent EW/QCD probe tool
  - improve MC background description for BSM/Higgs analysis ⇨ enhance sensitivity to small signals
  - better understand proton structure ⇨ constrain PDFs' uncertainty
- Significant processes in precise era
  - deepen knowledge of EW/QCD physics in SM ⇨ confirm the vague measurement results
  - provide valuable input for MC tunning ⇨ which is the most state of art prediction?
    - how b-quark participate in hard scattering? how many high orders should be counted in ME at least?
    - how to improve hard glue splitting in parton shower? how much effect from the merging techniques?

Things in Common

- Measurements of the associated production of vector bosons
  - W/Z/γ decaying to one or two leptons
  - resolved or boosted (b- or c-tagged) jets
  - measure inclusive and differential cross sections as a function of meaningful kinematic observables
  - compare with several theoretical predictions
  - dominant systematics –energy/resolution of jet reconstruction, jet tagging, unfolding, background norm.
- This talk will focus on the most competitive results, avoiding lengthy technical details

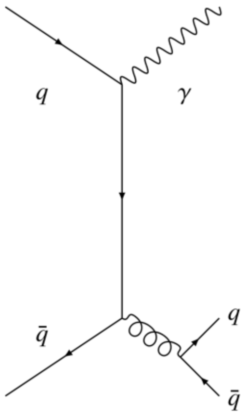
Observables:

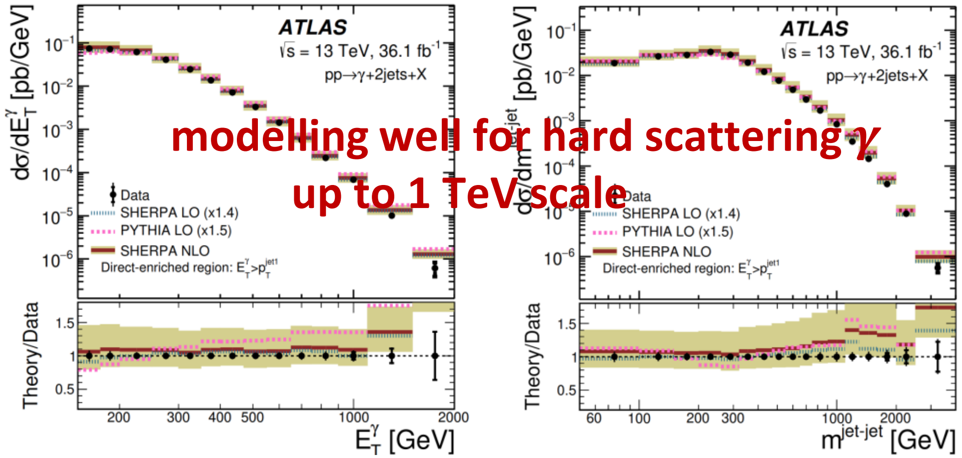
- $\Delta\emptyset_{Vj}$ Sensitive to additional radiation
- ΔY_{Vj} Sensitive to PDFs and to higher order diagram contributions
- ΔR_{bb} Sensitive to various production Mechanisms, low region dominated by gluon splitting
- m_{bb} Important for VH (H→bb) and searches for BSM
- $p_T^{V/j}$ Test EW and QCD correction
- ratio Characterized by cancellation of large correlated uncertainties, such as QCD scale

γ+2jets

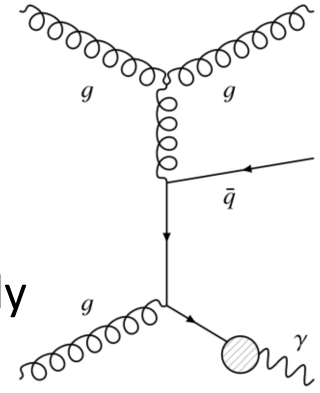
JHEP 03 (2020) 179

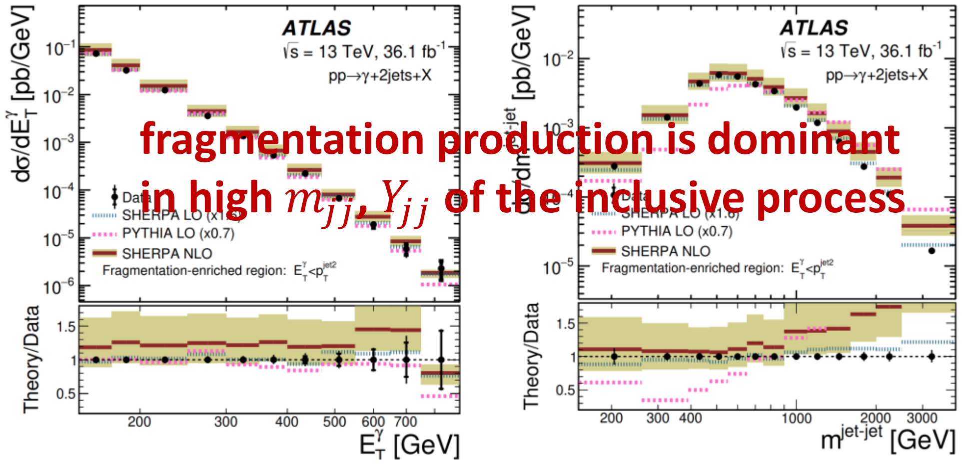
- Explore the dynamics where EW contributions could be relevant
  - pure electroweak processes or electroweak virtual corrections are expected to play an important role for p_T^γ at the TeV scale, large m_{jj} and Y_{jj}
- Selection
  - $p_T^\gamma > 150$ GeV & $p_T^{jet} > 100$ GeV
  - signal purity up to 95%
- Splitting in 3 regions
  - inclusive
  - direct enriched - $p_T^\gamma > p_T^{jet1}$
  - fragmentation enriched - $p_T^\gamma < p_T^{jet2}$
- Sherpa NLO
  - mismodelling in high m_{jj}, Y_{jj} inclusively
  - describe ϕ_{jj} and p_T^γ well





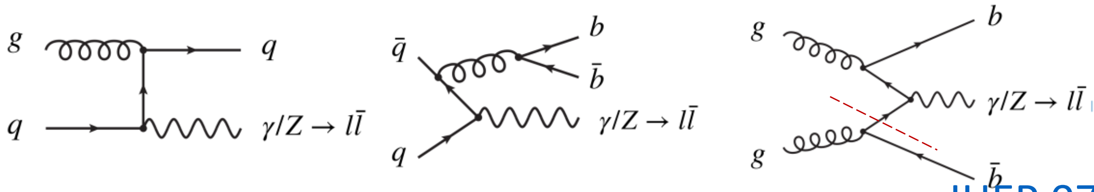
modelling well for hard scattering γ up to 1 TeV scale





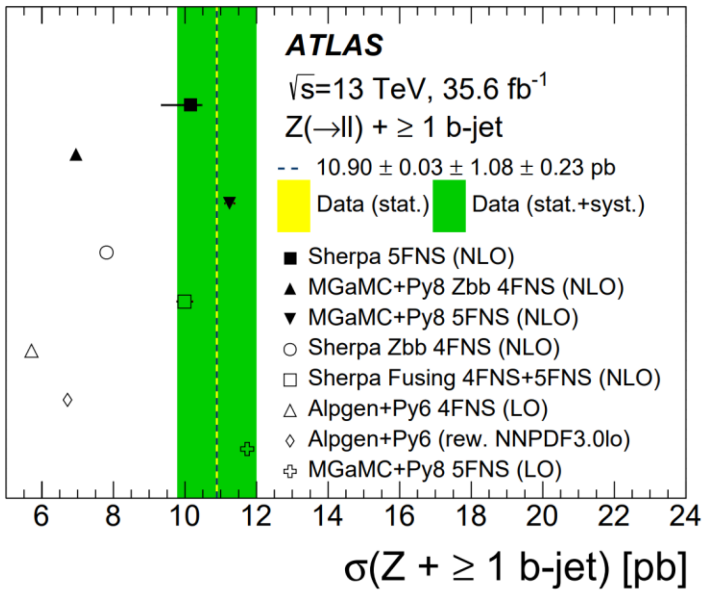
fragmentation production is dominant in high m_{jj}, Y_{jj} of the inclusive process

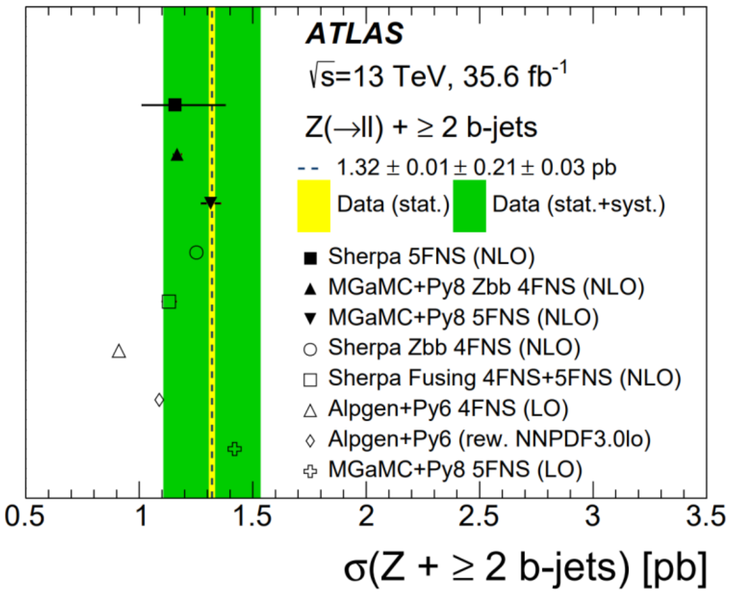
Z+b(b) – Flavor Scheme

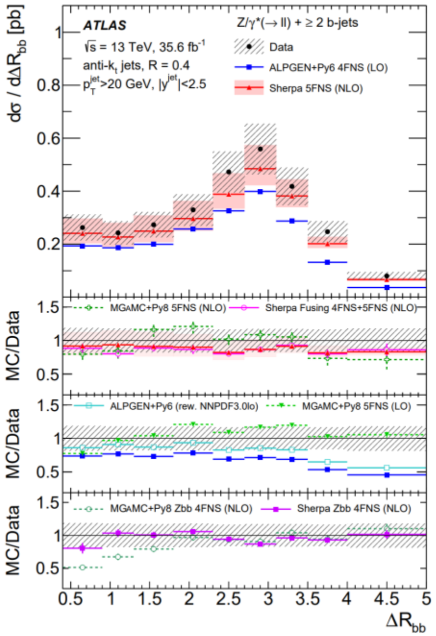


JHEP 07 (2020) 44

- The initial state: how b-quark participate to hard scattering?
  - 4 Flavor Number Scheme: bb only from gluon-splitting in ME
  - 5 Flavor Number Scheme: b-content in the proton PDF (massless approximation)
  - Fusing scheme (4+5FNS): in principle more accurate scheme in all kinematic regions
- 5FNS calculation at NLO better describe Inclusive and differential cross-sections
  - all 4FNS predictions largely underestimate the Z+≥1b-jets cross section, although describe Z+≥2b-jets well
  - MadGraph 4FNS gives large mismodelling in the g-splitting region (low ΔR(bb))
  - Sherpa Fusing (4+5FNS) agrees with 5FNS (NLO), the merging technique doesn't improve simulation



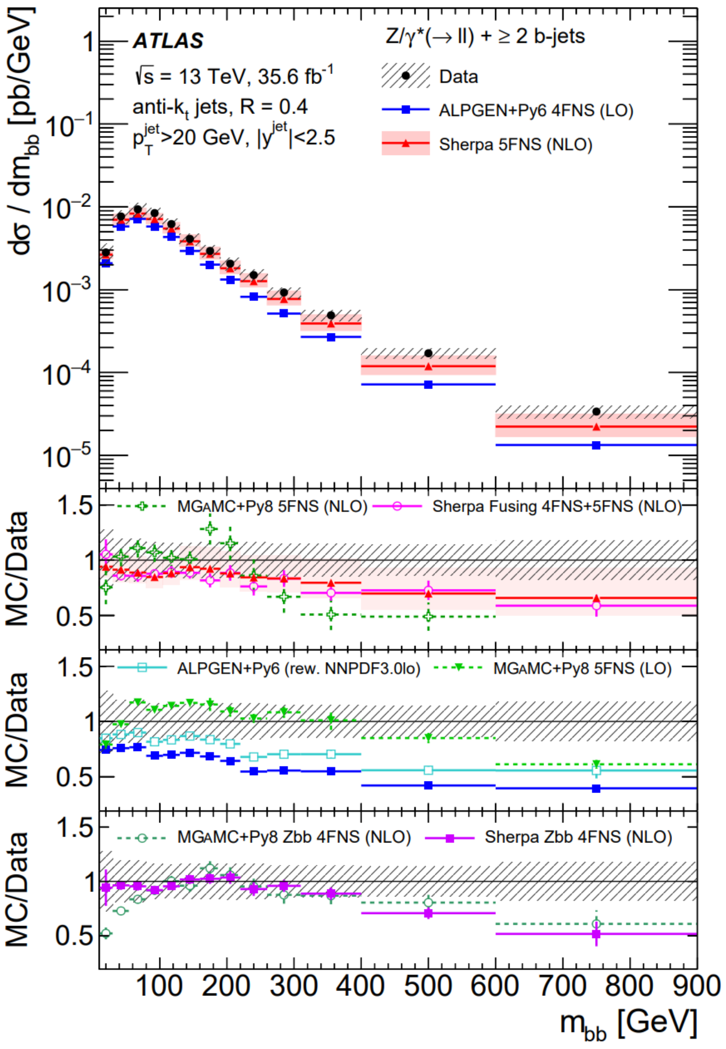




Z+b(b) – Differential Cross Section

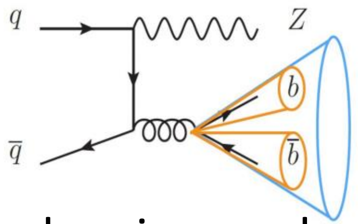
JHEP 07 (2020) 44

- m_{bb} and p_T^V – important for ZH (H→bb) and searches for BSM



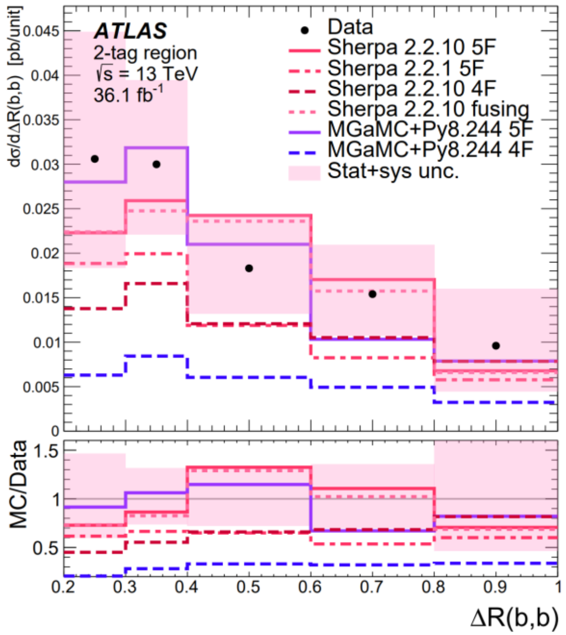
- **Selection**
  - $76 \leq m_{ll} \leq 106$ GeV & $p_T^l > 27$ GeV
  - bjet with $p_T > 20$ GeV, $|y| < 2.5$, 70% tagging efficiency
  - ΔR(bjet, l) > 0.4
- **Results**
  - m_{bb} < 300 GeV
    - all Sherpa predictions provide quite good modelling of shape
    - other predictions show various discrepancies (gluon splitting)
  - m_{bb} > 300 GeV
    - **all predictions underestimate the data – call for MC tunning**
    - $\Longrightarrow$ sizeable mismodelling problematic for other analyses
  - p_T^V
    - all predictions (4NFS, 5NFS) give good description

Z+boosted bb New!

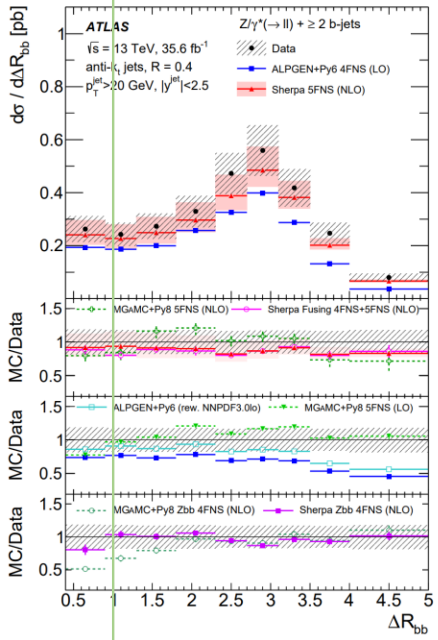


[arXiv:2204.12355](https://arxiv.org/abs/2204.12355)
submitted to PRD

- First measurement of Z+jet in the boosted regime and with b-content substructure
  - Z production in association with (doubly b-tagged) large-radius jets
  - large irreducible backgrounds for searching heavy resonances with hadronic decays
  - ability to probe lower ΔR region (dominated by hard gluon splitting), mismodelled in Run 1 measurement,
  - complementary to resolved Zbb analysis
  - measurements already competitive with MC predictions despite limited statistics (2b-tag selection)
- Selection
  - p_T^l > 27 GeV & m_{ll} > 50 GeV
  - large-R jet with R = 1, $p_T > 200$ GeV
  - substructure jet with R = 0.2, 70% b-tag efficiency
- Differential cross section
  - kinematics of large-R jet: m_J and p_T^J
  - Z-Jet properties and correlations: p_T^{Z+J} and $\Delta\emptyset_{ZJ}$
  - g->bb splitting properties: ΔR_{bb}(2-tag selection)

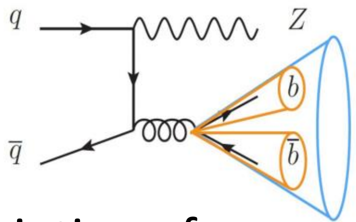


Boosted analysis



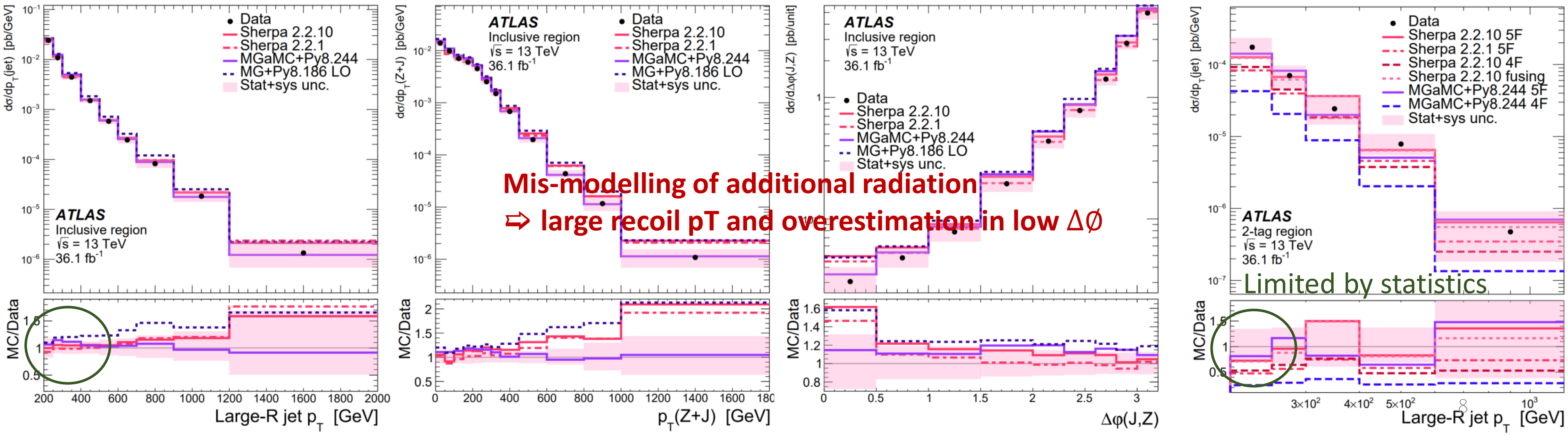
Resolved analysis

Z+boosted bb New!



[arXiv:2204.12355 submitted to PRD]

- NLO + 5FNS scheme gives the best description of cross sections for Z+boosted jets
  - NLO MadGraph well describes jet kinematics and Z+J correlations
  - **serious mis-modelling of NLO Sherpa's and LO MadGraph in the extreme phase space regions**
- Statistically limited measurements prevents from strong conclusions for Z+b-tagged boosted jets
  - inclusive cross section: 5FNS preforms best, fusing scheme closes to 5FNS, discrepancy observed for 4FNS
  - differential cross section : rather flat data/MC ratios (within uncertainties) for all predictions
    - indicate no specific mismodelling issues contrary to Z+boosted jets



Mis-modelling of additional radiation

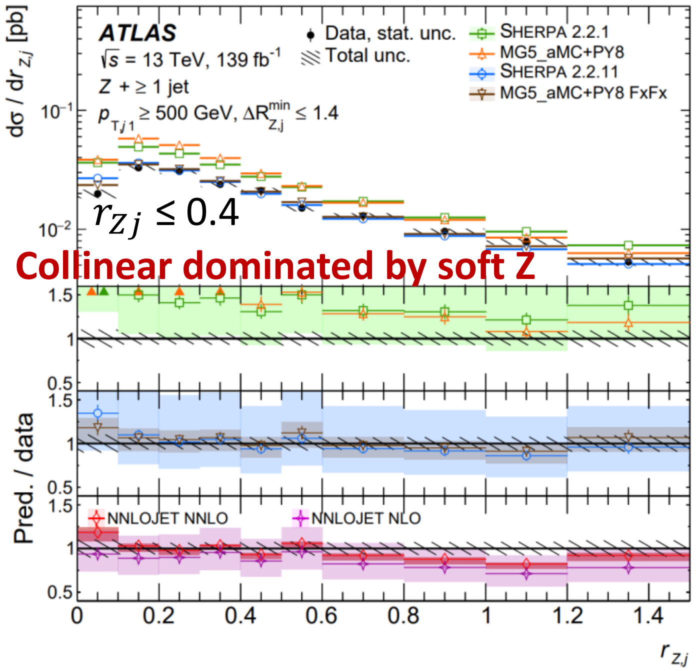
⇨ large recoil pT and overestimation in low Δ∅

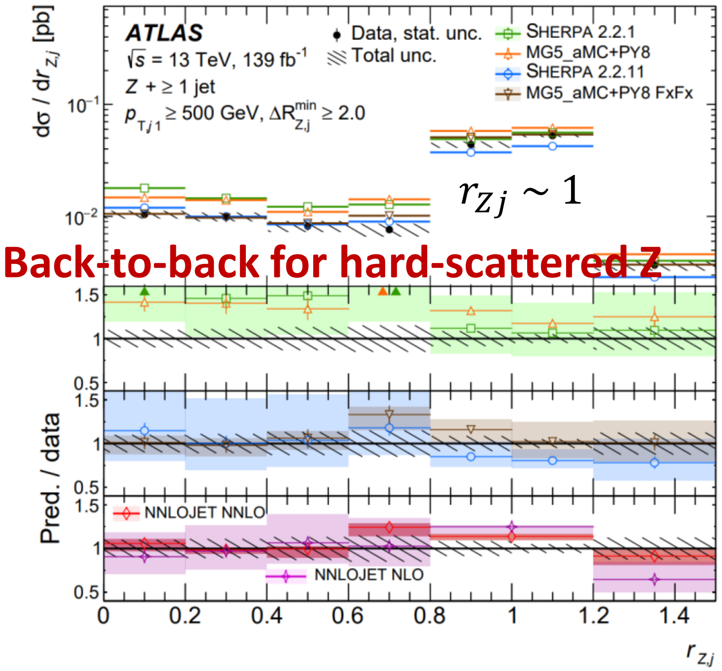
Limited by statistics

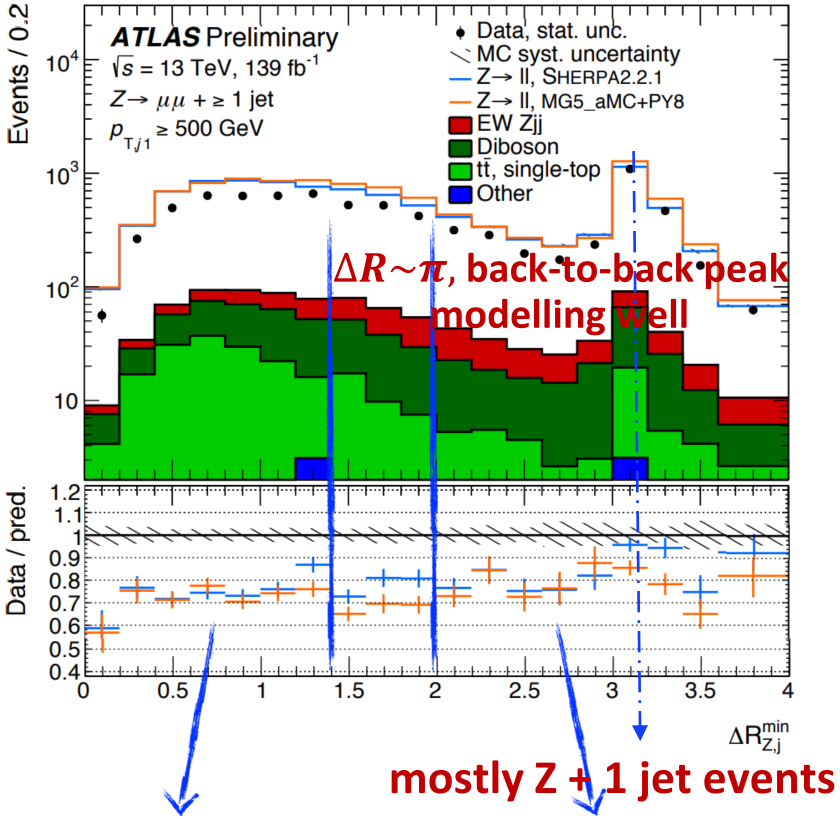
Z + high pT jets New!

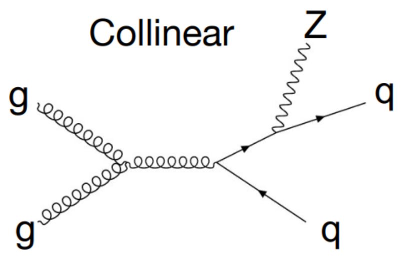
- First time to disentangle collinear and back-to-back Z emission
- Splitting in 5 regions:
  - inclusive – $p_T^j > 100$ GeV
  - high pT – $p_T^j > 500$ GeV
  - collinear – high pT + min(ΔR) < 1.4
  - back-to-back – high pT + min(ΔR) < 2
  - high S_T – scalar sum of p_T^j > 600 GeV

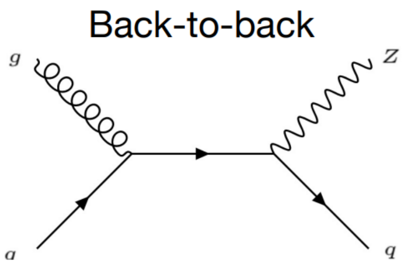
$$r_{Zj} = p_T^Z / p_T^j$$







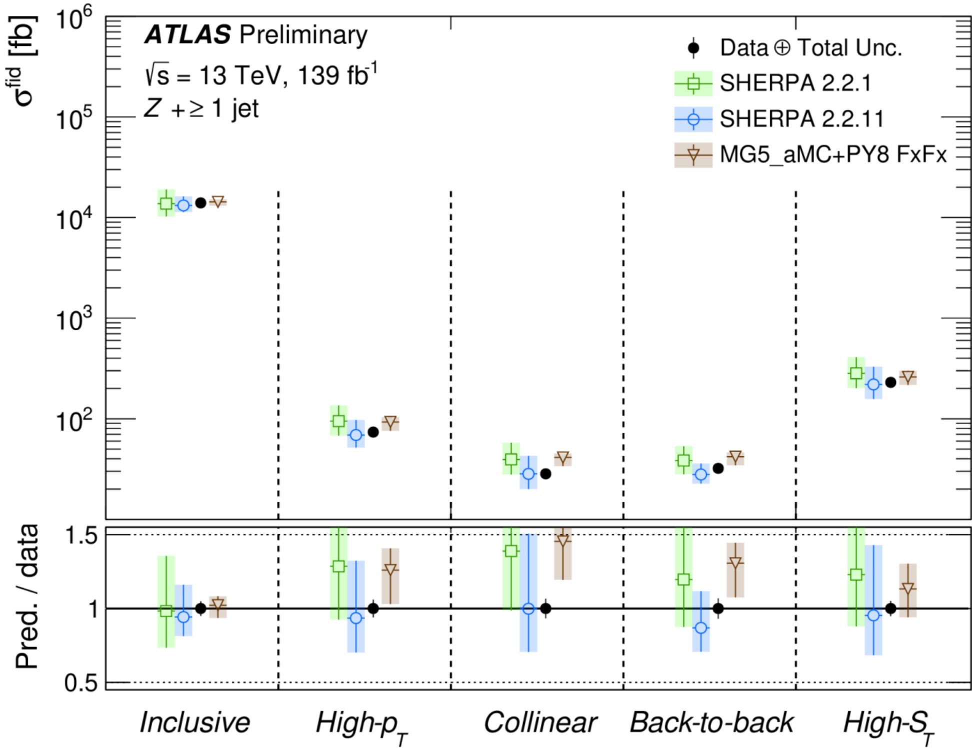


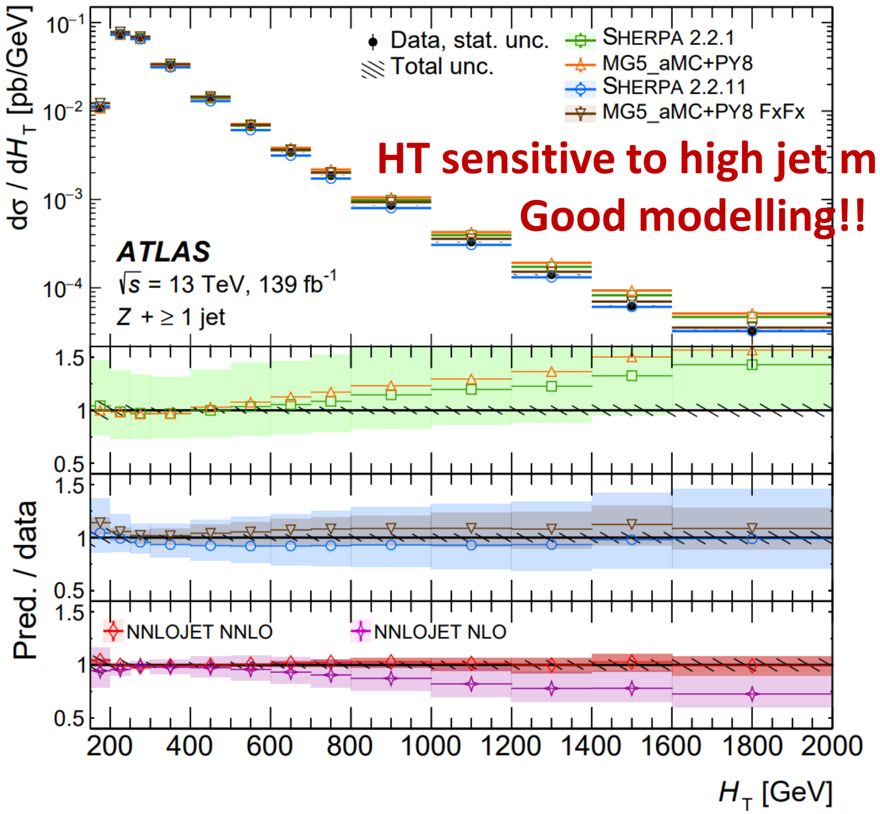


Z + high pT jets New!

arXiv:2205.02597
submitted to JHEP

- Large QCD scale uncertainties on the predictions in high pT cases
- MG5_aMC+PY8 FxFx and SHERPA v.2.2.11 are in better agreement with data
  - Sherpa 2.2.11 include virtual EW corrections which reduces the predicted cross-section providing a better agreement;
- Back-to-back region better modelled than collinear region – Include mostly Z + 1 jet events

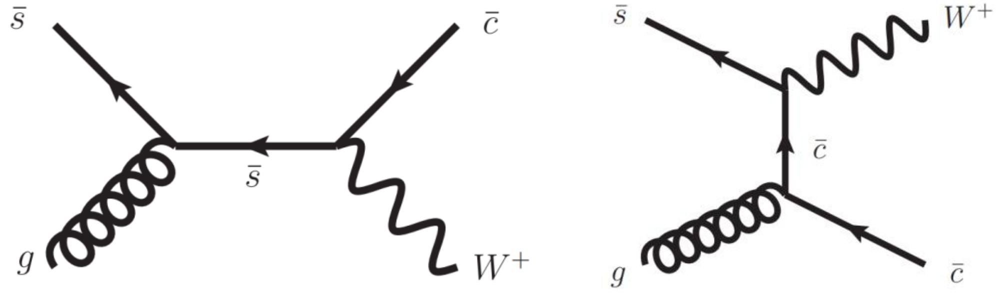




HT sensitive to high jet multiplicities
Good modelling!!

W+D Come soon!

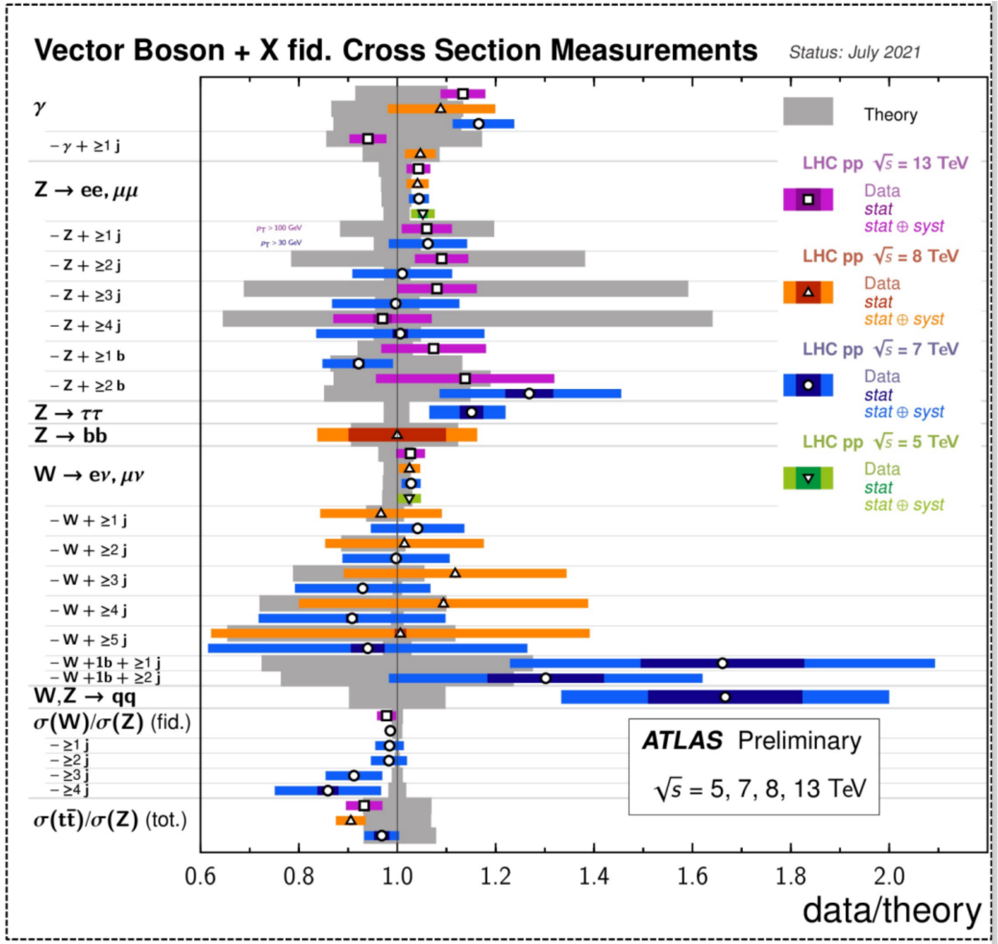
- Goal for probing strange quark PDF
- Measure W+D production targeting 2 channels
  - $D^+ \to K\pi\pi$
  - $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$



- Observable
  - p_T^D - Useful for MC validation and modeling
  - $|\eta(l)|$ - Sensitive to PDF choice
  - $R_c^{\pm} = \sigma(W^+D^{(*)-})/\sigma(W^-D^{(*)+})$ - Sensitive to $s - \bar{s}$ asymmetry
- Measurements consistent with NLO predictions with modern NNLO PDFs
- $R_c^{\pm}$ consistent with predictions for PDFs that impose symmetric $s - \bar{s}$
  - $R_c^{\pm}(D^{(*)}) =$

Mini Summary

- Lots of recent beautiful results appeared in Run2
  - with strong power discriminating predictions
  - NLO + 5FNS provides a quite good modelling
    - Sherpa 2.2.11 is promising, followed by MadGraph FxFx
    - Sherpa 2.2.11 gives mismodelling for Z+boosted jets
- What Run3 could bring to us? (Good prospects)
  - precision measurements
    - double differential
    - ratio characterized by cancellation of large scale uncert.
    - improved predictions – NNLO QCD, N3LO PDF, PS model
  - access to rare process/extreme region
    - b-/c- tagged boosted jets channel
    - high pT
  - performed some measurements not proceeded in Run2
  - better harmonized with search analysis



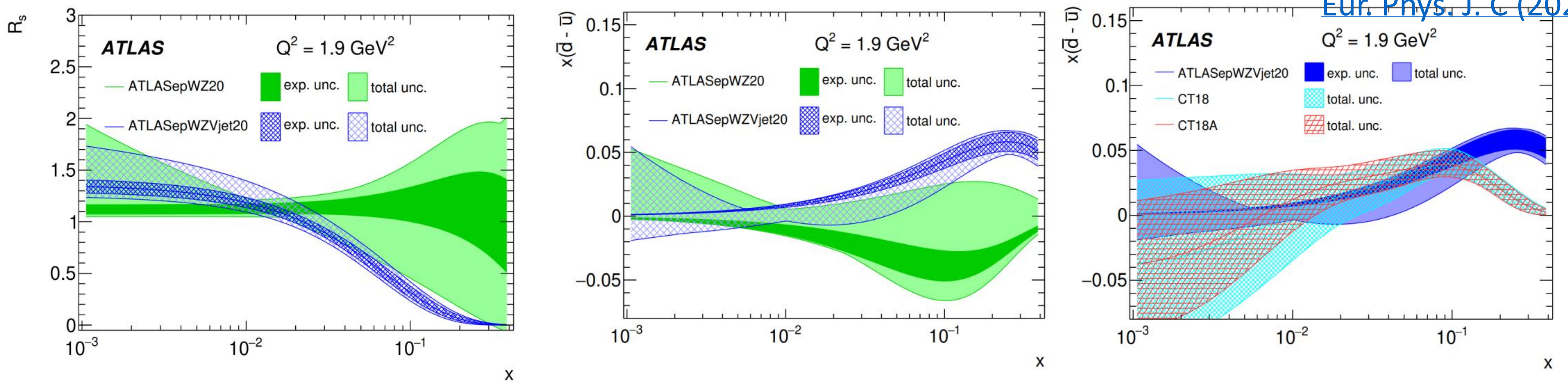
PDF Constraints with V+jets Data

epWZVjets20 PDF fit
JHEP 07 (2021) 223

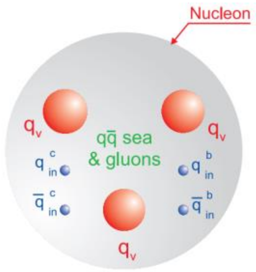
- Only use ATLAS data (W,Z, W + jets, Z + jets) with a minimum of other input (HERA)
  - allows to considering correlated systematic uncertainties correctly (global PDF fits group didn't)
  - observed ATLAS global PDFs agree with global fits (CT18, MSHT20 and NNPDF3.1) well
    - proved ATLAS data seem to be able to replicate many of features that the fixed target DIS and DY data plus the Tevatron data bring to the global PDFs
- V+jets data sensitive to PDFs up to x ~ 0.3 for R_s

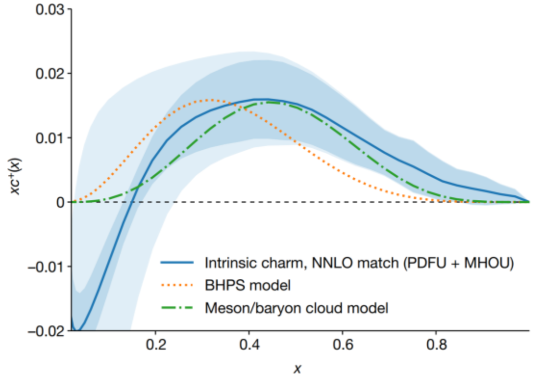
$$\boldsymbol{R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}}$$

  - fantastic improvement of its determination at high-x
- Nice agreement for all PDFs, but positive $x(\bar{d} - \bar{u})$ found in higher x with V+jets data
  - the effect of not considering uncertainty correlated by global PDFs, suggested by latest ATLASpdf21 Eur. Phys. J. C (2022) 82:438

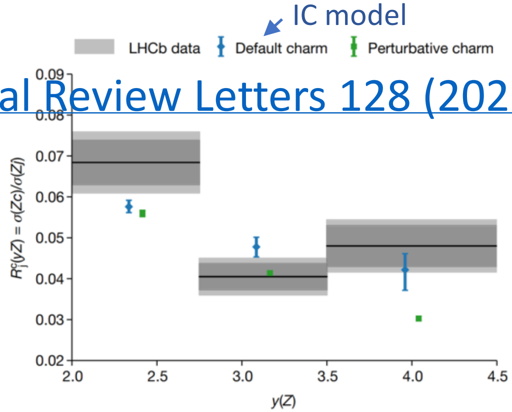


Intrinsic Charm? – debate for decades





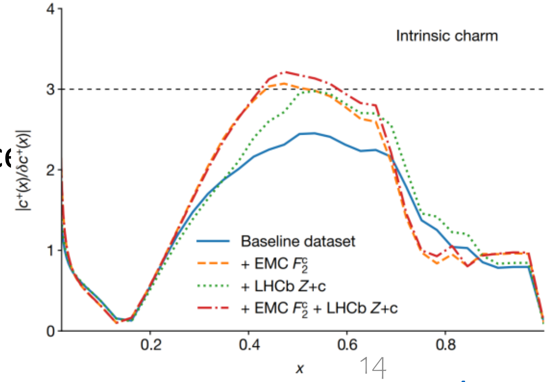
- Enhancement of charm production in high x
  - experiment indications in x > 0.1
    - high production rate of c hardrons in large x range, lower than the prediction of pQCD by 1 order
    - excess in $\bar{p}p \to \gamma c$ at Tevatron, excess in $\bar{p}p \to \gamma b$ at D0
    - Intrinsic strange assumption agree well with the description of t HERMES data
  - assume there is $|uudc\bar{c}>$ component in the wave function of proton, with nonperturbative origin, rather from QCD radiation, which could explain these experimental phenomenon



Physical Review Letters 128 (2022)

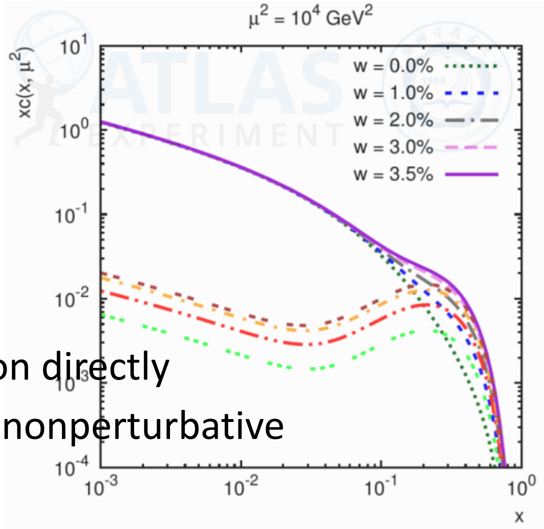
- Difference for intrinsic quark & pentaquark state
  - intrinsic quark is the valence-like sea quark, existing over a longer time scale in proton
  - pentaquark state has 5 valence quarks
- Besides deep inelastic scattering and fixed-target experiments,
  - CMS(Run1), ATLAS(Run1) also searched for the IC

    Eur. Phys. J. C 79, 92 (2019)
  - ATLAS γ+jets measurements for upper limit of the IC probability in the proton at 1.93% with 68% C.L
- Recent News (2022)
  - LHCb gave an excess in high η region with Z+c process, which agrees well with IC model
  - recent global PDF analyses, which includes LHCb measurements or early EMC data, gives an evidence
  - and presents valence-like peak structure of PDF for IC, which agrees with IC calculations well



Nature 608, 483–487 (2022)

Prospect for Intrinsic Charm



sensitive when x > 0.1

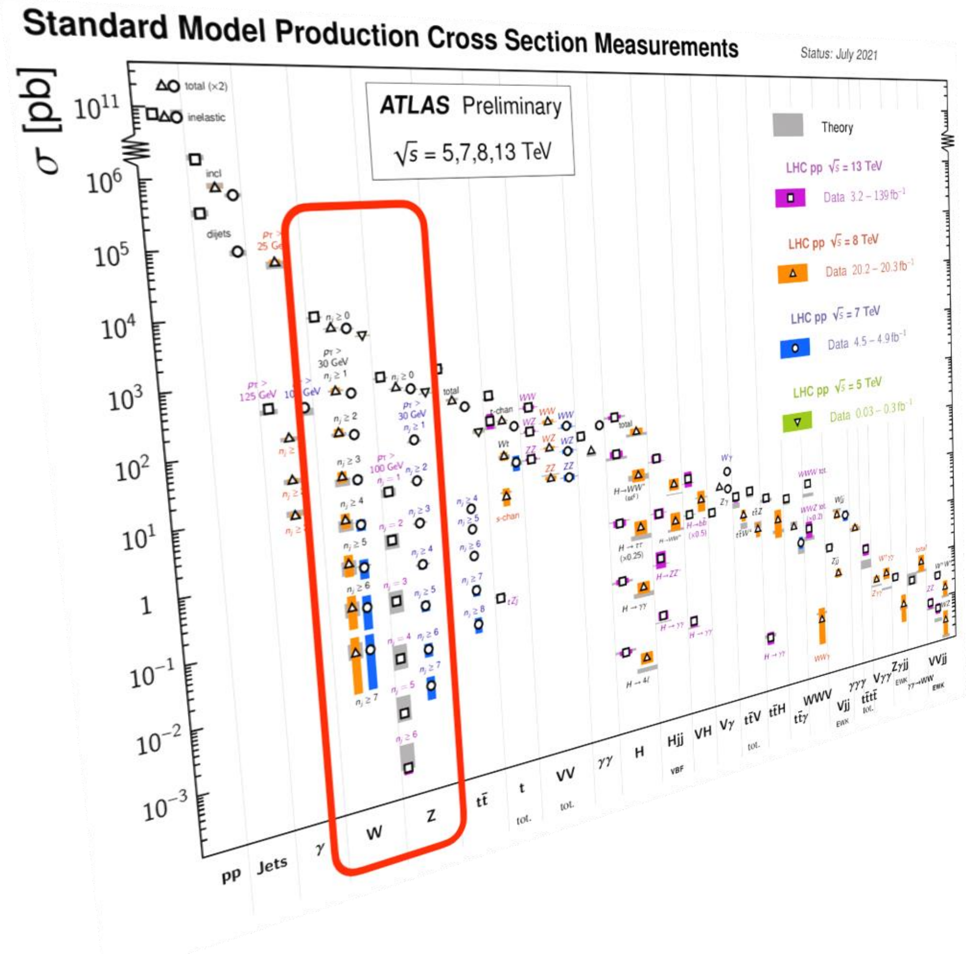
$$x_c \geq x_F^V = \frac{2p_T^V}{\sqrt{s}} \sin h(\eta_V)$$

- **Why LHC?**
  - tensions in data sets from **deep inelastic scattering** and **fixed-target experiments**
    - sensitive to valence-like c-quark content, measuring the cross sections of D meson in high X region directly
    - while interpreting the low-Q data is challenging since it requires careful theoretical treatment of nonperturbative hadronic and nuclear effects.
- **Why Vc?**
  - Vjet production is inherently at large Q, above the electroweak scale, hadronic effects are small
  - gc(b)→ Vc(b) scattering, where in the forward region one of the initial partons must have large x
- That's expected IC produces enhancement for high p_T forward c-jets or Z or high $x_F^{V/jet}$
- PDF reweighting is used to model the IC effect with Sherpa Z+jets (NNPDF30NNLO)
  - $w(x_1, x_2, Q) = \frac{f_i^{new}(x_1, Q^2) f_j^{new}(x_2, Q^2)}{f_i^{old}(x_1, Q^2) f_j^{old}(x_2, Q^2)}$ From NNPDF30NNLO to CT14nnloIC with different amount of IC: BHPS1, BHPS2
  - works well only for generators used fixed PDF for PS (e.g. Madgraph or Alpgen interfaced with Pythia)
  - No closure is guaranteed otherwise, since PDF enters non-linearly in Sudakov form factor (Sherpa), use MadGraph as validation

Concluding…

W, Z physics in ATLAS is a very active field !

⇨ It will be one of the main drivers of the LHC measurements in case of no-discovery of New-Physics



Thank you for your attention

Backup

Reference

- Papers listed in main text
- ATLAS SM Talks
  - Heberth Torres (TU Dresden), EPS-HEP Conference 2021, Isolated photons with jets
  - Alexander Law (University of California), QCD@LHC 2015, V+HF Review in Run1
  - Alexandre Laurier (Carleton University), Particles and Nuclei International Conference 2021, V+jets at LHC
  - Benedetto Giacobbe, ICHEP 2022, Z+boosted jets
  - Laura Fabbri (INFN and University of Bologna), INFN and University of Bologna, Z+jets at ATLAS
  - Rémie Hanna (CEA/IRFU), QCD@LHC 2015, PDF sensitivity from ATLAS measurements
  - Federico Sforza (Geneva University), Physics & Performance Week 2017, Insights in WZ physics