QCD measurements at the LHC

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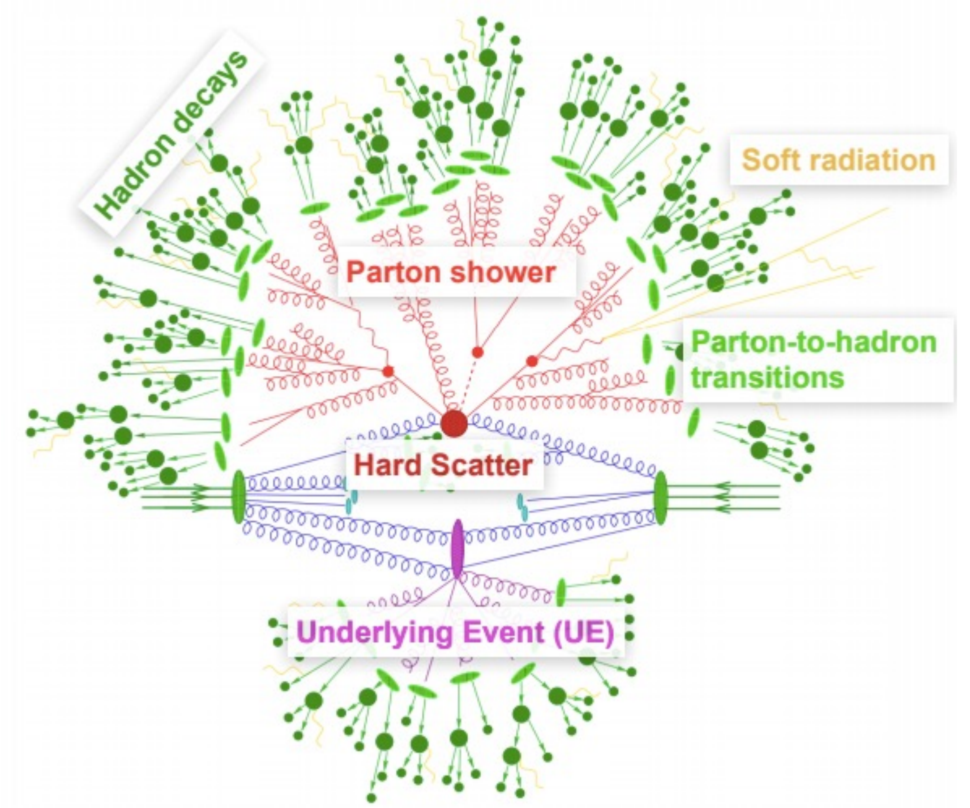
Introduction

- Strong interactions are challenging at the LHC!
- Mainly observed as jets
- Important source of background for many searches
- Not well modelled in Monte Carlo (MC) simulation yet
- Can be probed by a multitude of measurements
- We will review several analyses both from ATLAS and CMS
- The impact of these new measurements on parton distribution functions (PDFs) will be shown as well



Event shape variables

- Sensitive to the details of the hadronisation process and useful to determine α_S and MC tune parameters and search for new physics phenomena
- Transverse thrust: $T_{\perp} \equiv \max_{\hat{n}_{\mathrm{T}}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_{\mathrm{T}}|}{\sum_i p_{\mathrm{T},i}}$ JHEP 12 (2018) 117

  where $\hat{n}_T$ is the unit vector that defines the transverse thrust axis

- Used to define

$$\tau_{\perp} \equiv 1 - T_{\perp}$$

= 0 for a perfectly balanced two-jet event

= 1- 2/π for an isotropic multijet event

Sensitive to hard scattering

- Jet broadening:

$$B_X \equiv \frac{1}{2\,P_T} \sum_{i \in X} p_{\mathrm{T},i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

Sensitive to hadronization and NP effects

- Total jet mass: $\rho_X \equiv \frac{M_X^2}{P^2}$, with X = U (upper) or L (lower) region

Event shape variables

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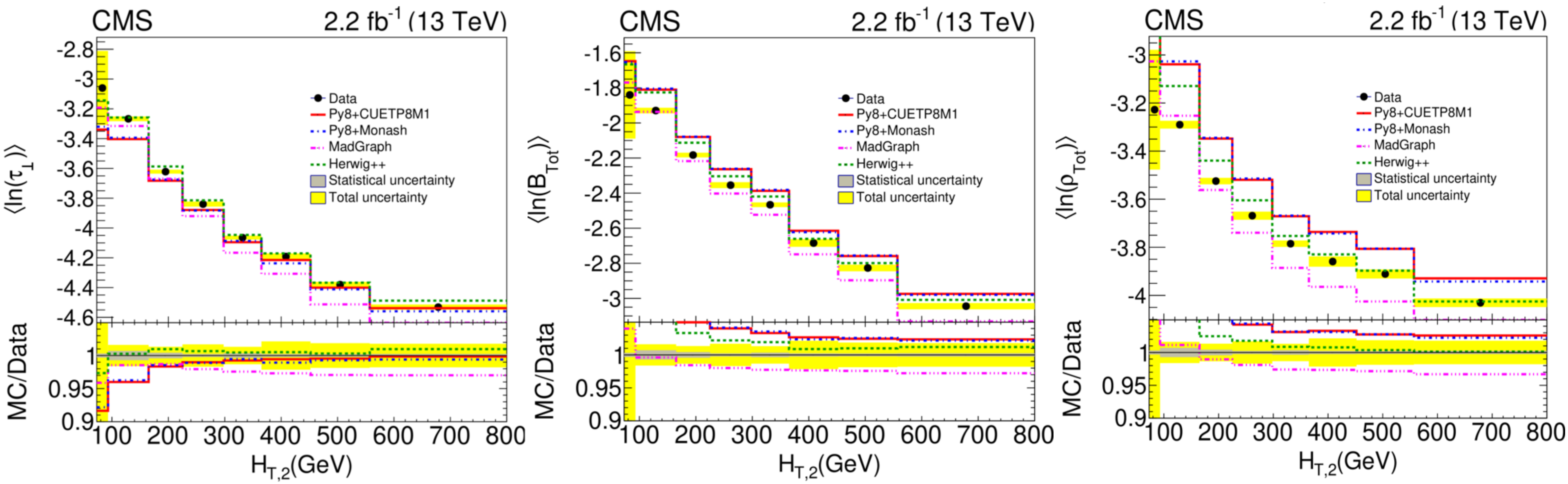


where $H_{T,2} = (p_{T,jet1} + p_{T,jet2})/2$ and Tot = U + L

- Monash and CUETP8M1 Pythia8 tunes model energy flow in plane transverse to the beam well (whereas the energy flow out of the transverse plane is not well described)
- Herwig++ performs well, better than Pythia8 for B_{Tot} and ρ_{Tot}
- Madgraph much better than Pythia8 (transverse and longitudinal flows of energy better modelled by ME approach)

Event shape variables

JHEP 01 (2021) 188

- Six event-shape variables measured as a function of jet multiplicity in three interval of $H_{T,2}$
- **Thrust major/minor**

$$T_{\perp} = \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_{\mathrm{T}}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}; \qquad T_{\mathrm{m}} = \frac{\sum_i |\vec{p}_{\mathrm{T},i} \times \hat{n}_{\mathrm{T}}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}$$

- **Sphericity** and **aplanarity** from linear combinations of the eigenvalues of

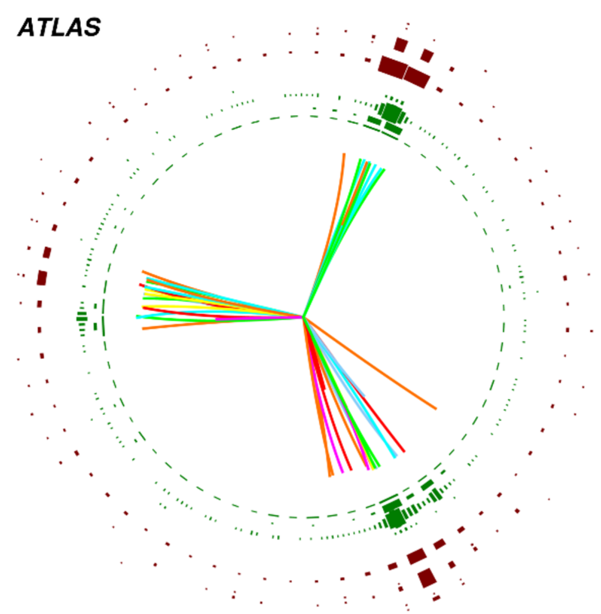
$$\mathcal{M}_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{\mathrm{x},i}^2 & p_{\mathrm{x},i}p_{\mathrm{y},i} & p_{\mathrm{x},i}p_{\mathrm{z},i} \\ p_{\mathrm{y},i}p_{\mathrm{x},i} & p_{\mathrm{y},i}^2 & p_{\mathrm{y},i}p_{\mathrm{z},i} \\ p_{\mathrm{z},i}p_{\mathrm{x},i} & p_{\mathrm{z},i}p_{\mathrm{y},i} & p_{\mathrm{z},i}^2 \end{pmatrix}$$

$$S = \frac{3}{2}(\lambda_2 + \lambda_3); \quad A = \frac{3}{2}\lambda_3$$

- **C** and **D** from cubic and quartic combinations

$$C = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3),$$
$$D = 27(\lambda_1\lambda_2\lambda_3)$$

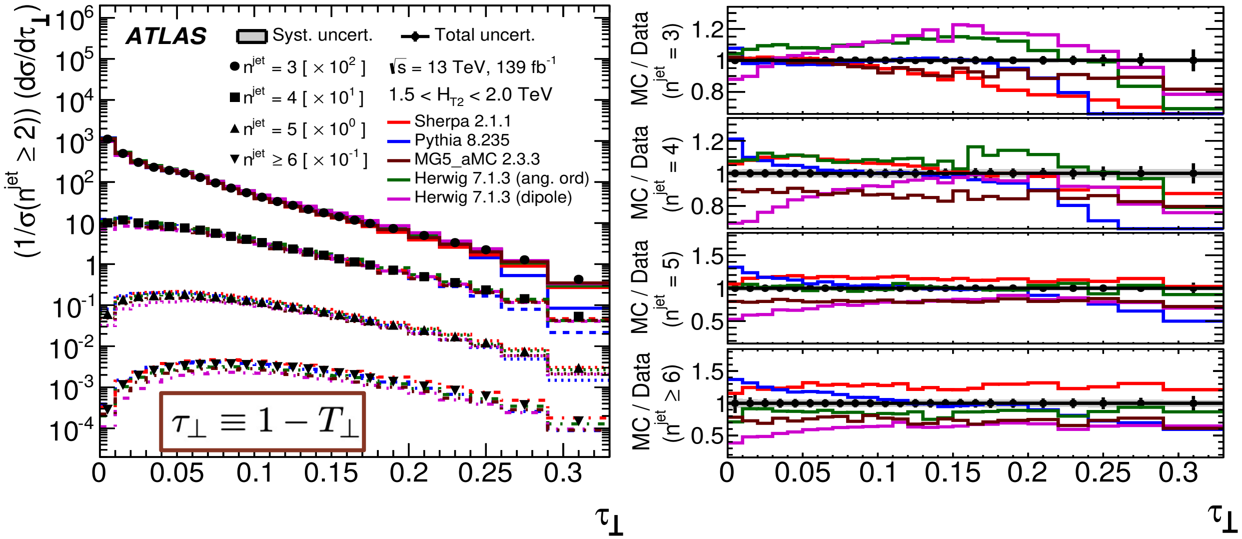
- 3-jets (5-jets) event with high (low) values of $T_{\perp}$and S

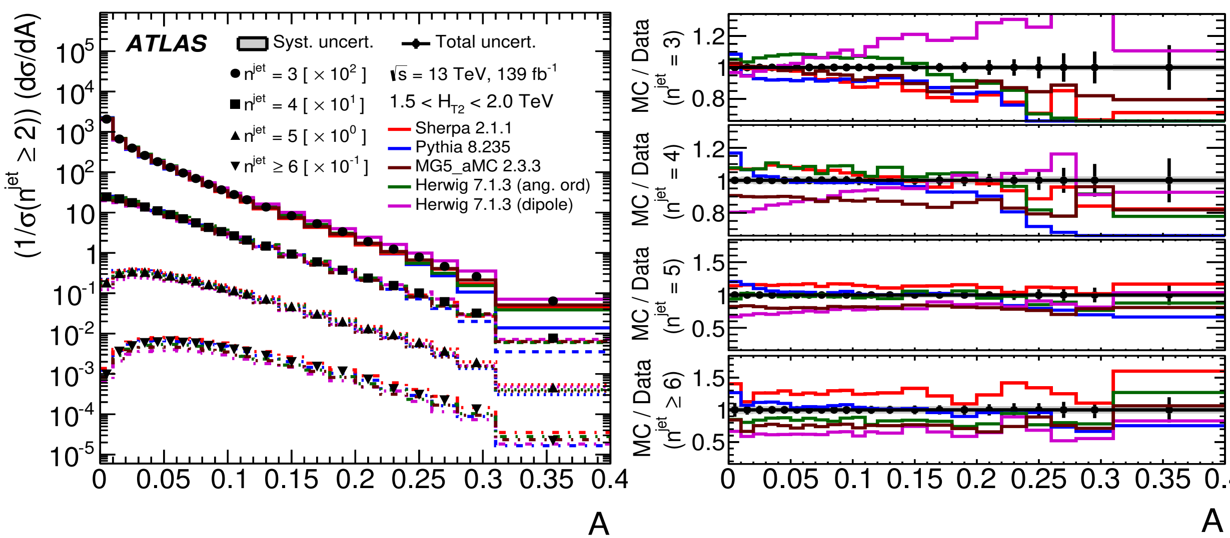


Event shape variables

JHEP 01 (2021) 188

- MC normalised to data in each $H_{T,2}$ bin (Pythia8 xsec +30%, MG5 -35%)
- Sherpa overestimates high multiplicities
- Herwig dipole model underestimates high multiplicities (better when considering Herwig with angular ordered PS)
- Pythia8 (A14 tune) describes data well only for intermediate thrusts
- MG5_aMC gives the best overall description → importance of including in ME beyond LO terms



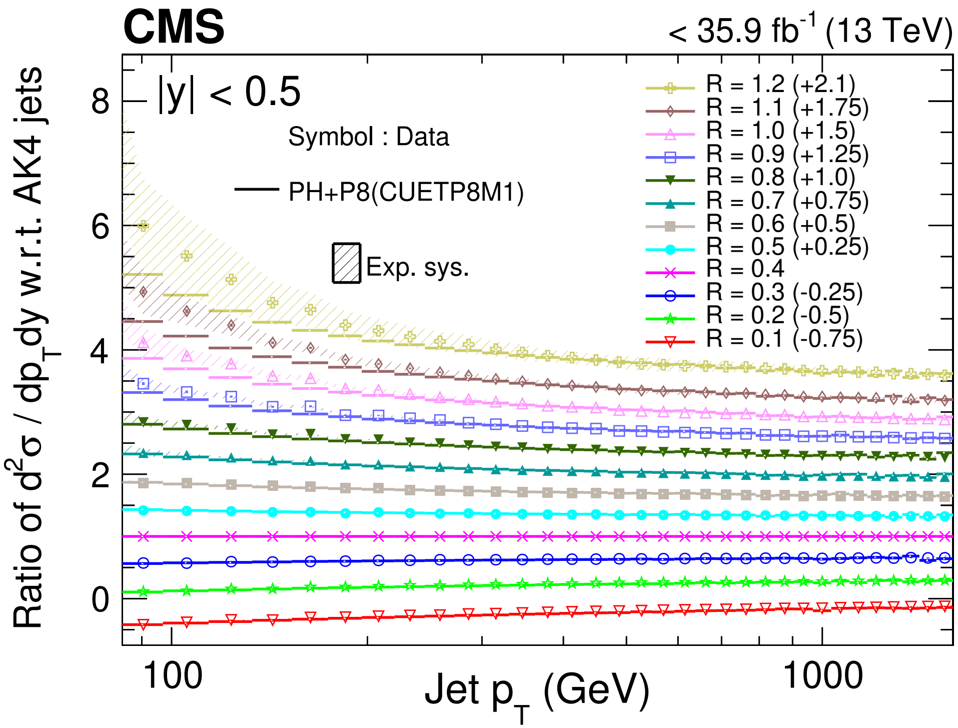


None of the MC provide a good description of the data in all the regions

Inclusive jet cross section

JHEP 12 (2020) 082

- Double differential (p_T , y) jet cross sections measured and compared to fixed-order calculations and MC predictions
- Sensitive to PDFs over a wide range of x and Q^2, in particular high-x gluon and valence quark
- Dependence on the jet anti k_T algorithm distance parameter R (jet size) is studied via ratios
- 84 < jet p_T < 1588 GeV
- Jet $|y|$ < 2.0
- Data well modelled at moderate values of jet size
- Deviation visible at low p_T for very large values of jet size



Inclusive jet cross section

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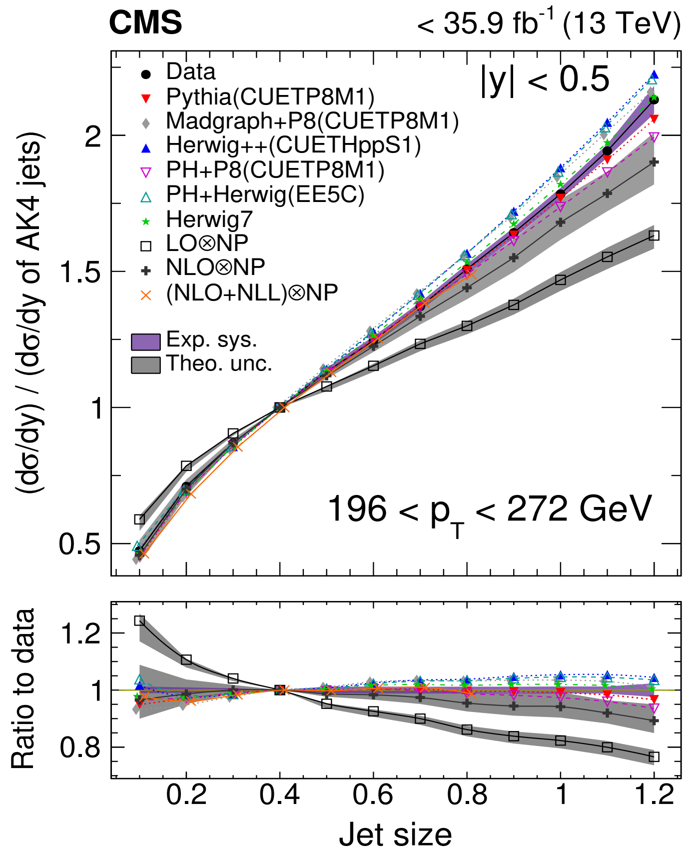
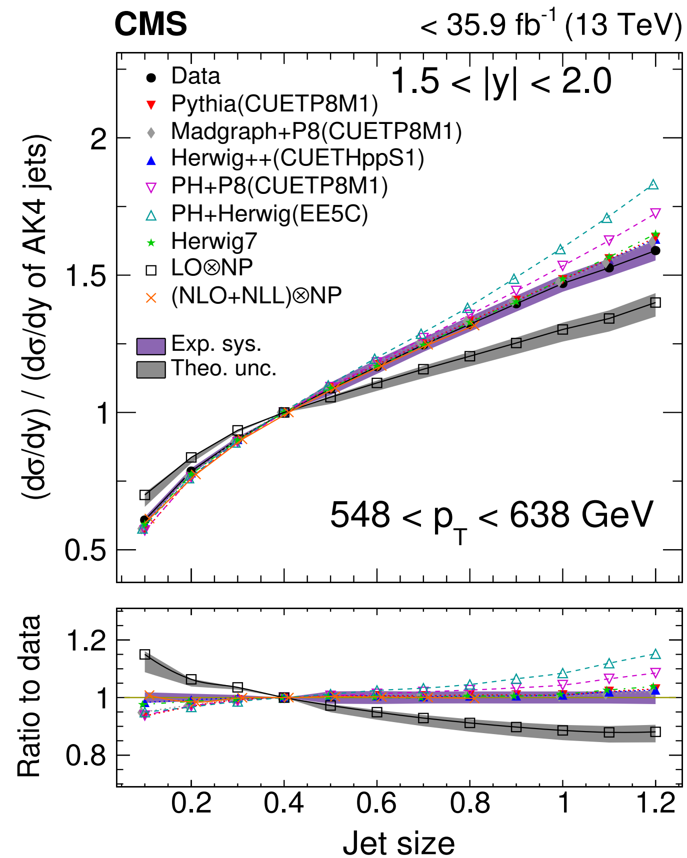


- R is sensitive to various components of the evolution of partons into jets
  - radiation & parton shower (PS)
  - hadronization, underlying event (UE)



- PS calculations agree well with data
- NLO corrections are needed
- Accurate modelling of NP effects is essential

Multi-jet correlation

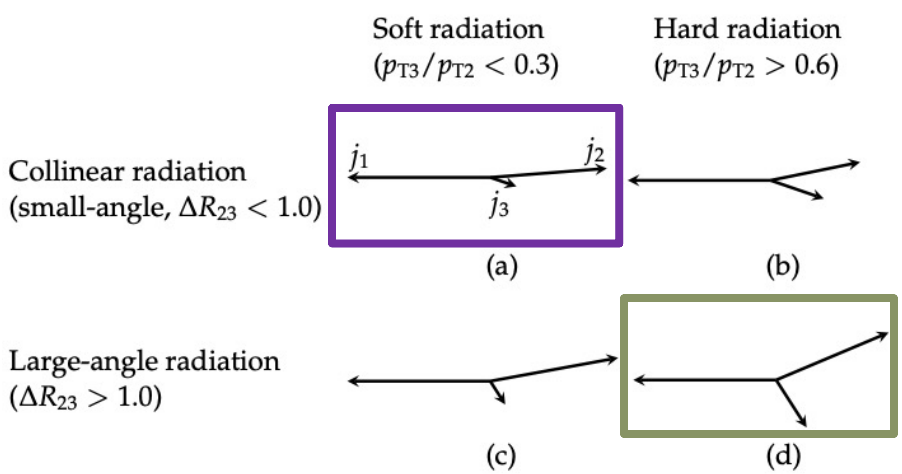
2102.08816

- Two categories of events selected:
  - 3-jet events (8 & 13 TeV) & Z+2-jet events (8 TeV)
- Two observables of sub-leading jets:
  - Transverse momentum ratio: p_{T3}/p_{T2}
  - Angular separation: $\Delta R_{23} = \sqrt{(y_3 - y_2)^2 + (\varphi_3 - \varphi_2)^2}$

j_1, j_2 and j_3 ordered in p_T

- Split events into categories of interest:

Should be well-described by PS



Should be well-described by Matrix Element (ME)

Multi-jet correlation

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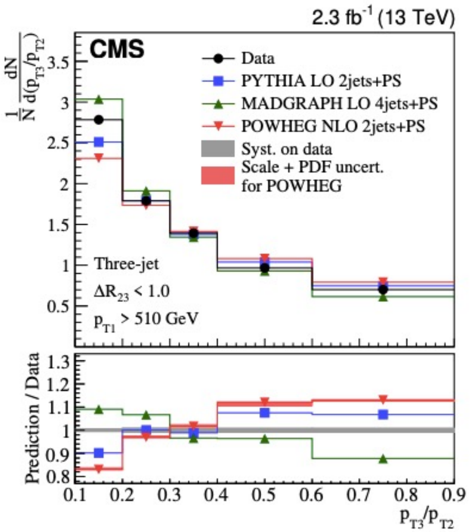
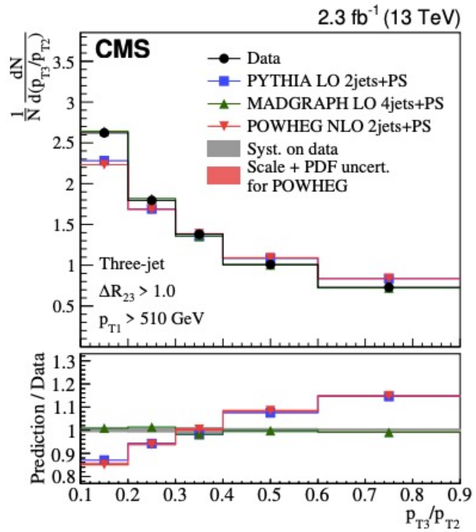
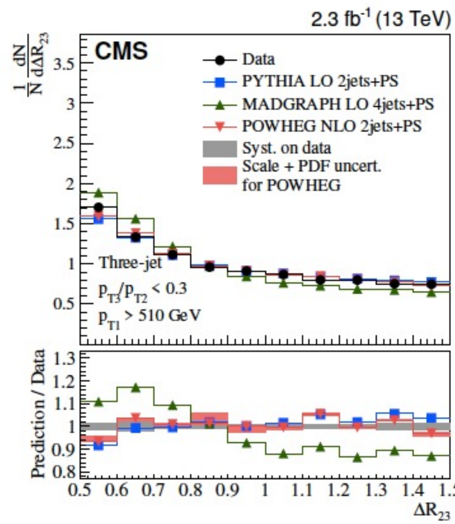


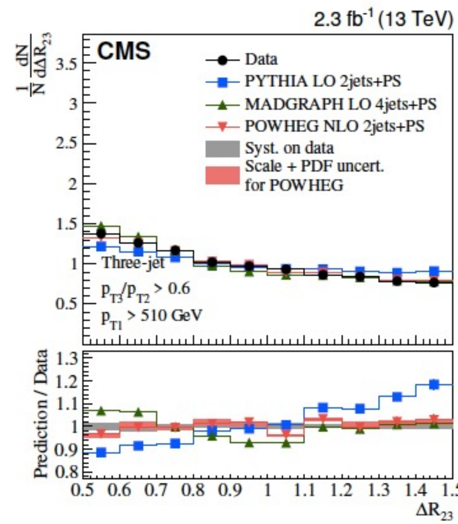
Collinear radiation



Large-angle radiation



Soft radiation



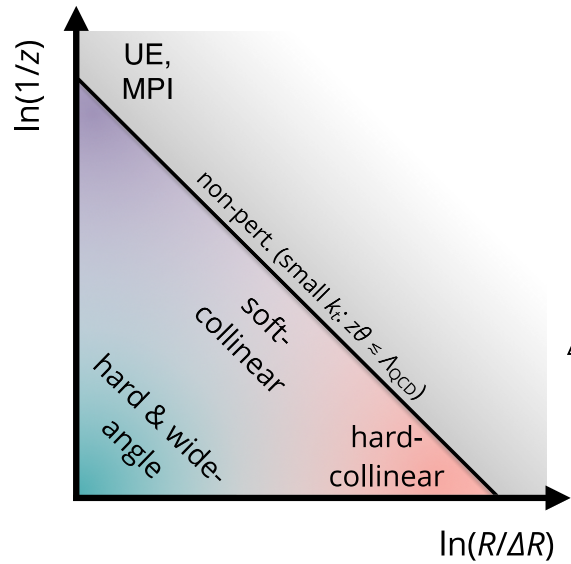
Hard radiation

- Large-angle and hard radiation well described by ME (LO 4j+PS and NLO 2j+PS – only for hard radiation region)
- Soft radiation well described by PS approach (LO 2j+PS)
- Collinear region not well described by either

Lund Jet Plane measurement

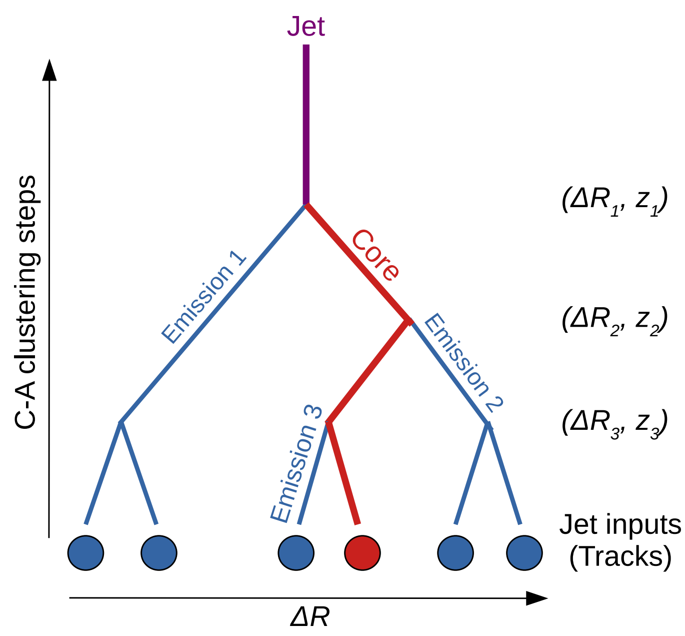
Phys. Rev. Lett. 124 (2020) 2 22002

- The LJP is an abstract description of jet development, with each entry corresponding to the transverse momentum and angle of any given emission with respect to the emitter
- Regions of plane point to various physical processes
- Dijet (anti-k_t algorithm, R = 0.4) events with $p_{T,1}$ / $p_{T,2}$ < 1.5
- Reconstructed by reversing the C/A clustering algorithm
- Only charged tracks in jets with p_T^{jets}> 675 GeV



$$z = \frac{p_T^{\text{emission}}}{p_T^{\text{emission}} + p_T^{\text{core}}}$$

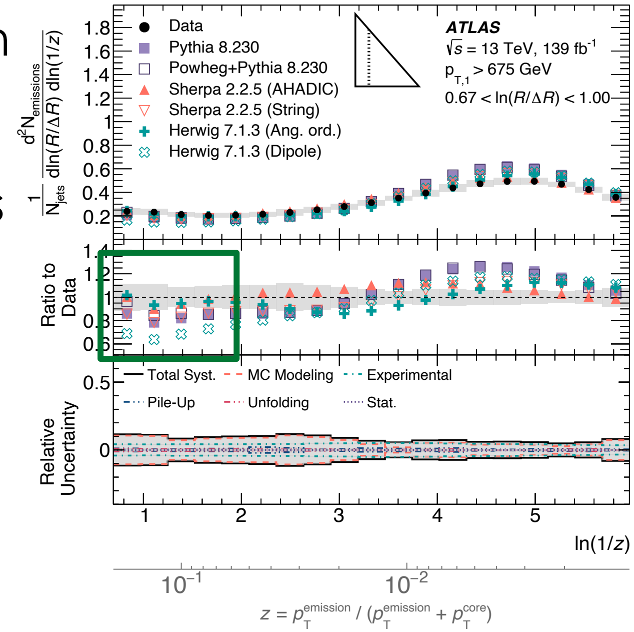
$$\Delta R^2 = (y_{\text{emission}} - y_{\text{core}})^2 + (\phi_{\text{emission}} - \phi_{\text{core}})^2$$

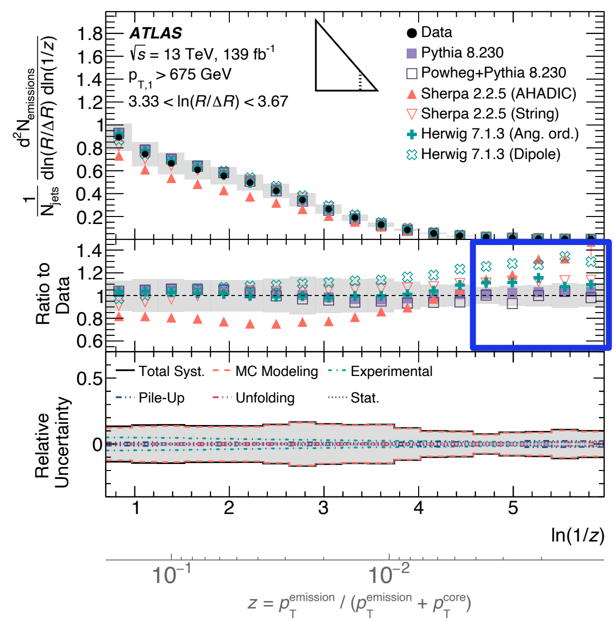


Lund Jet Plane measurement

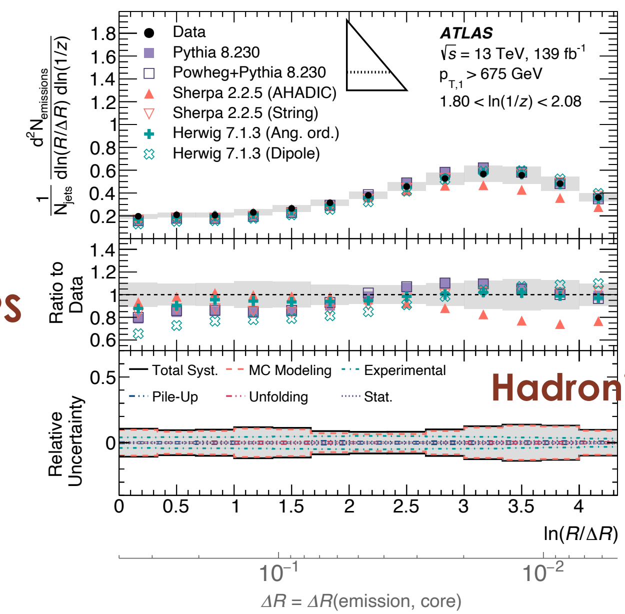
Phys. Rev. Lett. 124 (2020) 2 22002

- Probing PS (wide angle, left) to hadronization (collinear, right)
- **Hard wide angle**: differences in PS algorithms in Herwig7, as well as Pythia8 and Sherpa
- **Soft collinear**: different hadronization models in Sherpa
- Most MC good in describing jet core, but fail at small z e.g. large angle emission





PS



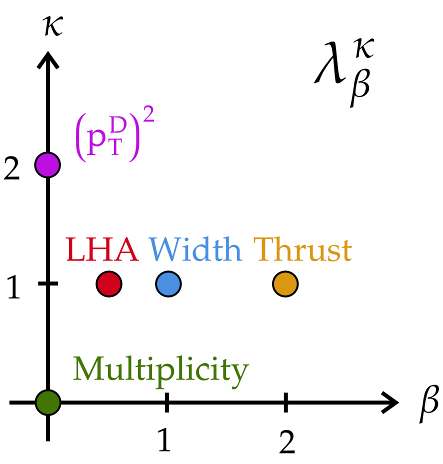
Hadronization

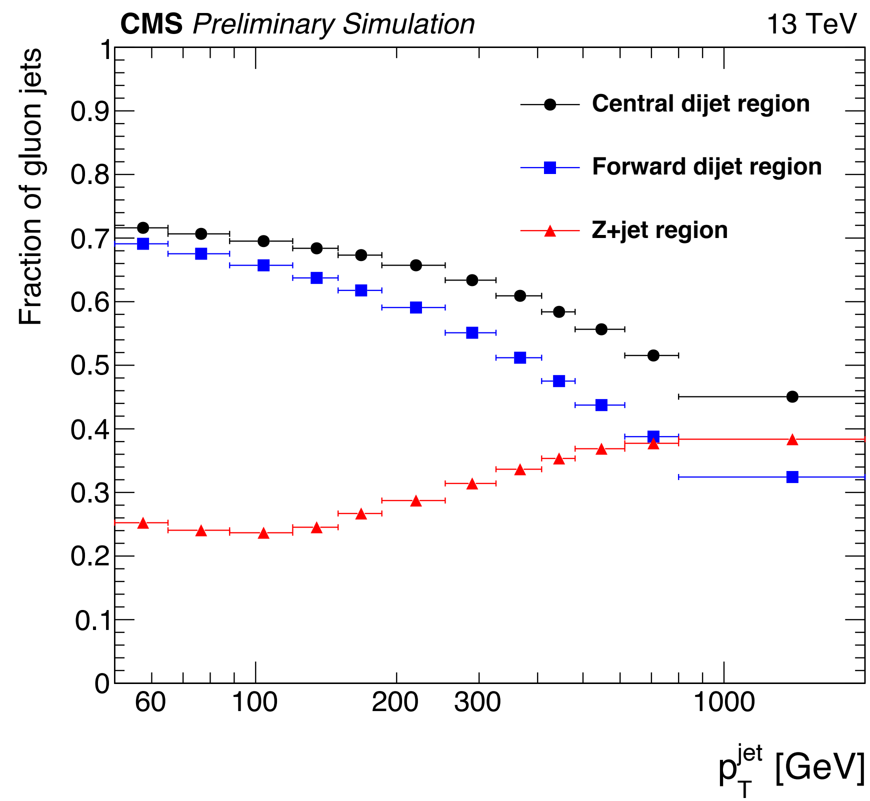
Jet substructure

CMS-SMP-20-010

- Important to study the jet origin (quark or gluon) and constituents
- Two different subsets: **Z+jets** and di-jets (**1 central** + **1 forward**)
- Five jet substructure observables studied: $\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$

$$z = \frac{p_T^{\text{emission}}}{p_T^{\text{emission}} + p_T^{\text{core}}} \qquad \Delta R_i = \sqrt{(\Delta y_i)^2 + (\Delta \phi_i)^2}$$

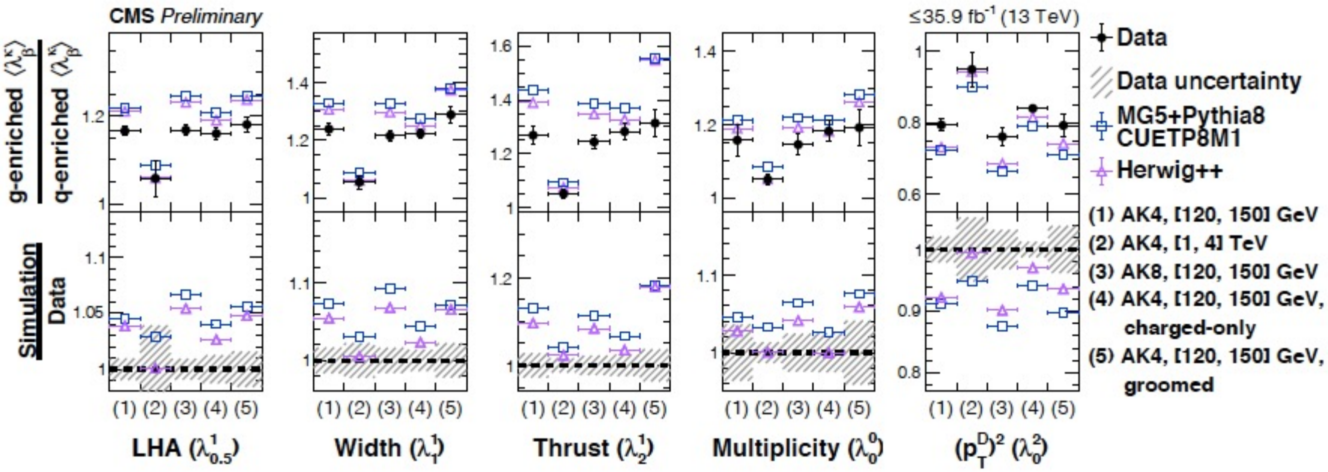


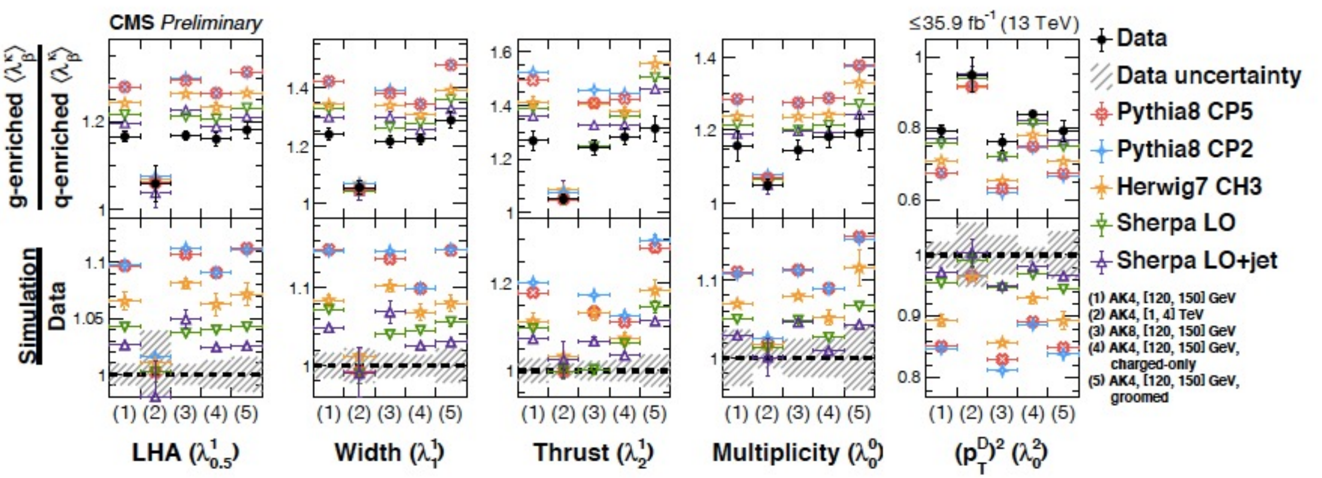


- Different fractions of gluon jets observed, especially at low p_T values

Jet substructure

CMS-SMP-20-010

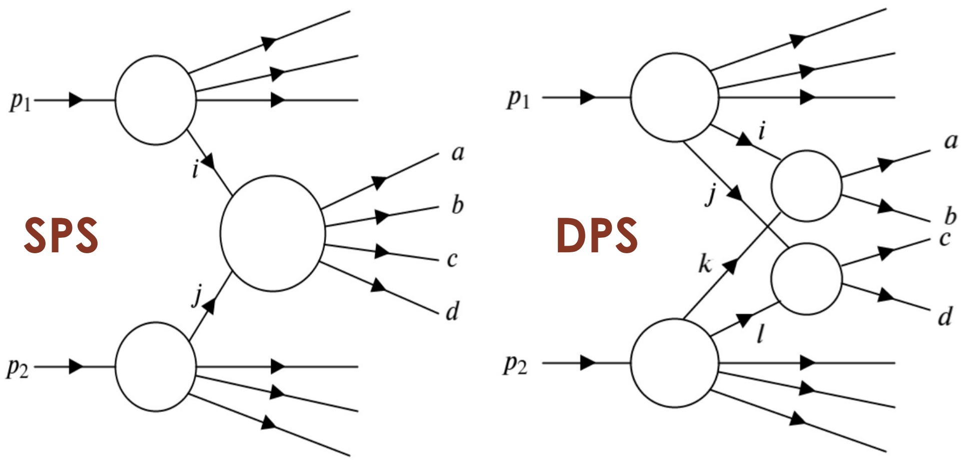


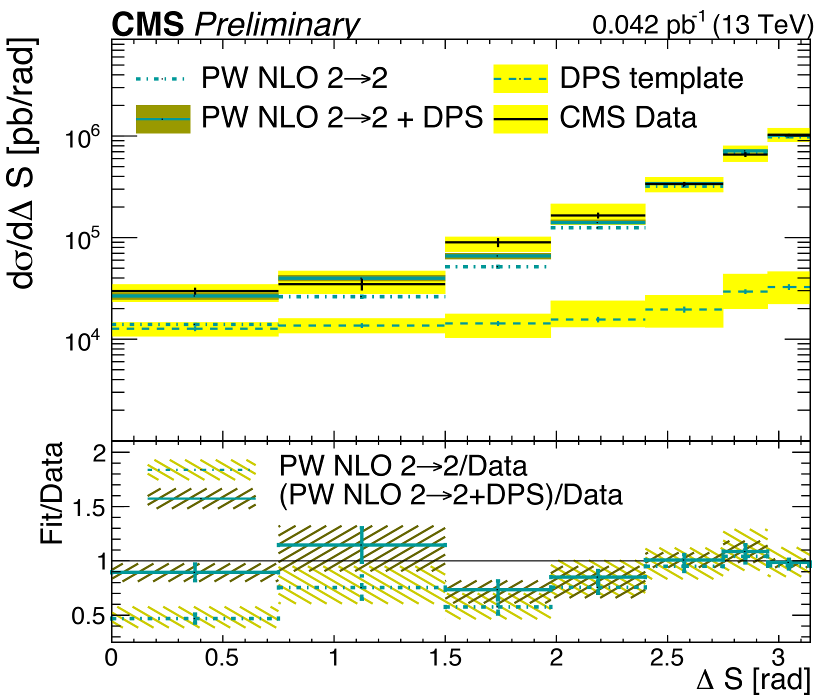


- Ratio of the mean of substructure observables in regions with gluon-enriched and quark-enriched jets
- All generators overestimate the difference between quark and gluon jets at low p_T
- At high p_T, all generators give a reasonable description of the ratio

Double parton scattering in 4 jets

CMS-SMP-20-007





- SPS processes exhibit strong kinematic correlations between all jets
- In DPS processes jets are often produced in two independent pairs in a back-to-back configuration
- DPS needed in the models to describe data

$$\Delta S = \arccos\left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}|\,|\vec{p}_{T,3} + \vec{p}_{T,4}|}\right)$$

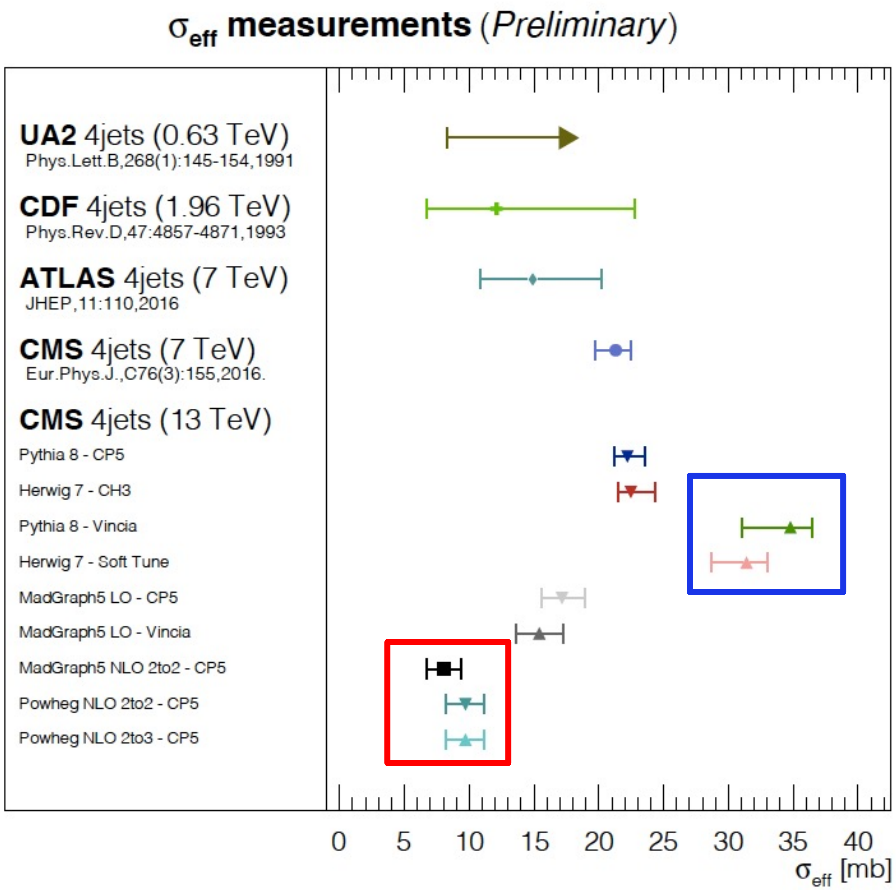
Double parton scattering in 4 jets

CMS-SMP-20-007

- The DPS contribution extracted with a template fit of distributions for SPS obtained from MC event generators and a double-parton scattering distribution constructed from inclusive single-jet events in data

$$\sigma^{\mathrm{DPS}}_{\mathrm{A,B}} = \frac{\epsilon_{4\mathrm{j}}}{\sigma_{\mathrm{eff}}}\left(\frac{1}{2}\sigma_{\mathrm{A}}^2 + \sigma_{\mathrm{A}}\cdot(\sigma_{\mathrm{B}} - \sigma_{\mathrm{A}})\right) = \frac{\epsilon_{4\mathrm{j}}\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}\left(1 - \frac{1}{2}\frac{\sigma_{\mathrm{A}}}{\sigma_{\mathrm{B}}}\right)$$

- Model with **NLO 2 → 2 or 2 → 3** matrix elements yield the smallest values of σ_{eff}
- **Including 4 partons** in the matrix element calculation of the SPS model yields higher values of σ_{eff}
- **Clear need for further development of models**



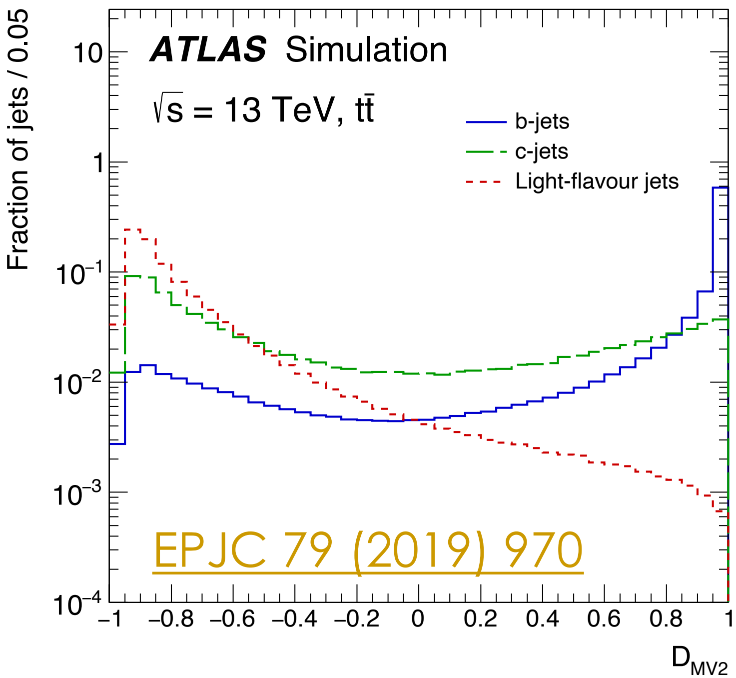
σ_{eff} shows a strong dependence on the model

Z+b-jets at 13 TeV

JHEP 07 (2020) 044

- **$Z \to ll$ + jets selection**:
  - Single lepton trigger of p_T > 25 GeV, 2 OS leptons (ee/$\mu\mu$), with p_T > 27 GeV, $|\eta|$< 2.5, 76 < m_{ll} <1 06 GeV
  - ≥ 1 or ≥ 2 jets reconstructed with Anti-kt algorithm (ΔR = 0.4) with p_T > 20 GeV and $|\eta|$< 2.5

- **b-jet candidate selection** relies on long lifetime, secondary vertices, decay pattern, etc.



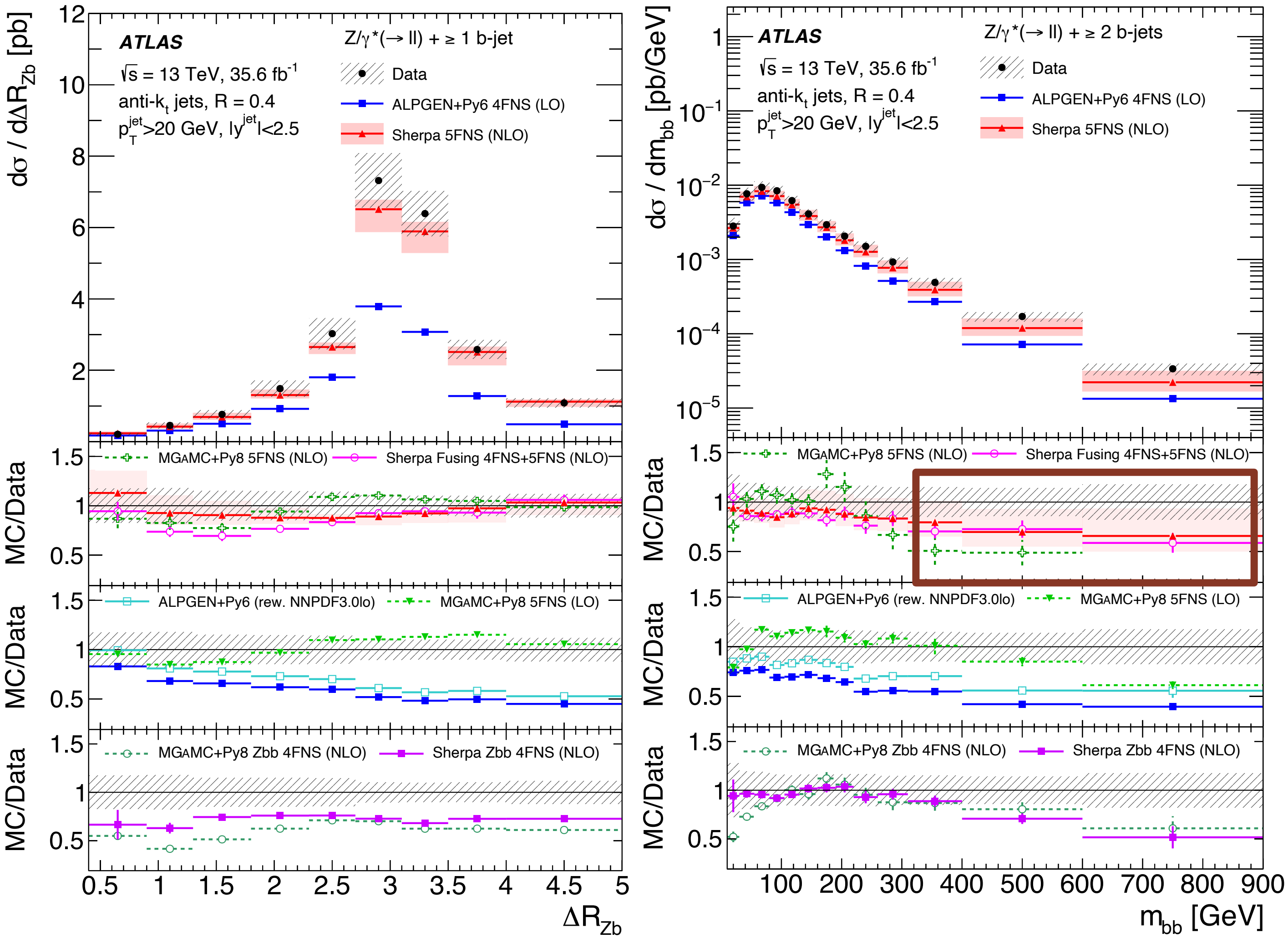
EPJC 79 (2019) 970

- Tracking & jet information condensed using multivariate algorithms for separation of b-jets vs different flavour jets (c- or light-flavour)

- Require 1 or 2 jets passing a "cut" on MV b-tagging algorithm corresponding of 70% efficiency for b-jets (vs mistag of ~10% c-jets and ~0.4% for light-jets)

Z+b-jets at 13 TeV

JHEP 07 (2020) 044



- Z+≥1 b-jet & Z+≥2 b-jets phase space (mostly) well described by 5FS, while 4FS shows deficits in Z+≥1 b-jet
- Some tensions with data at high m_{bb} (and high jet- p_T) but large errors in both theory and measurement

- **Challenge for searches and test of other process in such phase space**

epWZVjets20 PDF fit

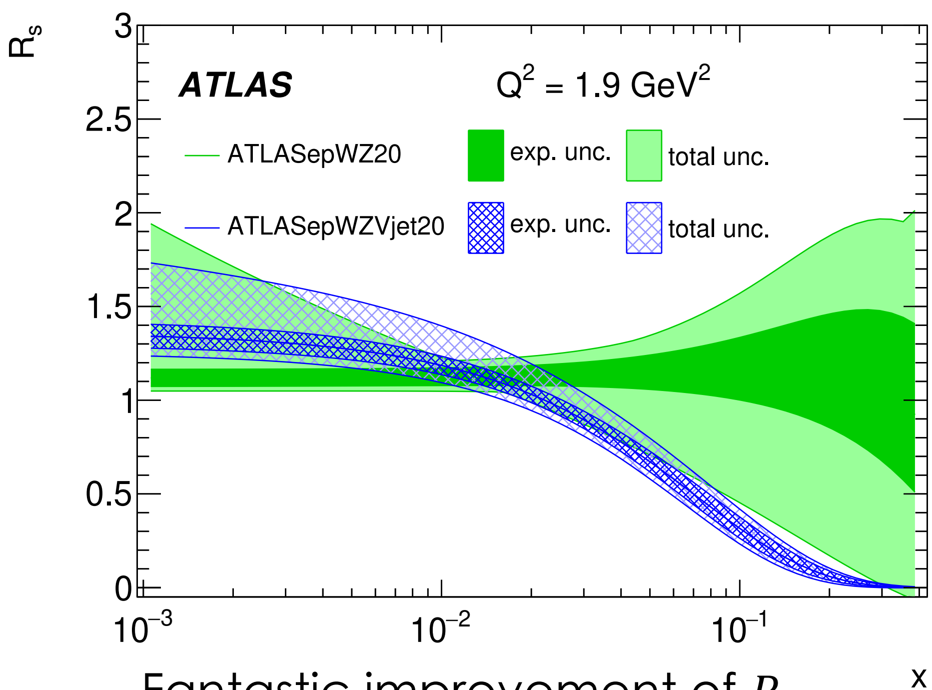
JHEP 07 (2021) 223

- QCD fit to DIS data from HERA and the ATLAS Electroweak boson data: **W,Z** at 7 TeV (Eur. Phys. J. C 77 (2017) 367), **W + jets** (JHEP 05 (2018) 077) and **Z + jets** at 8 TeV (EPJC 79 (2019) 847)

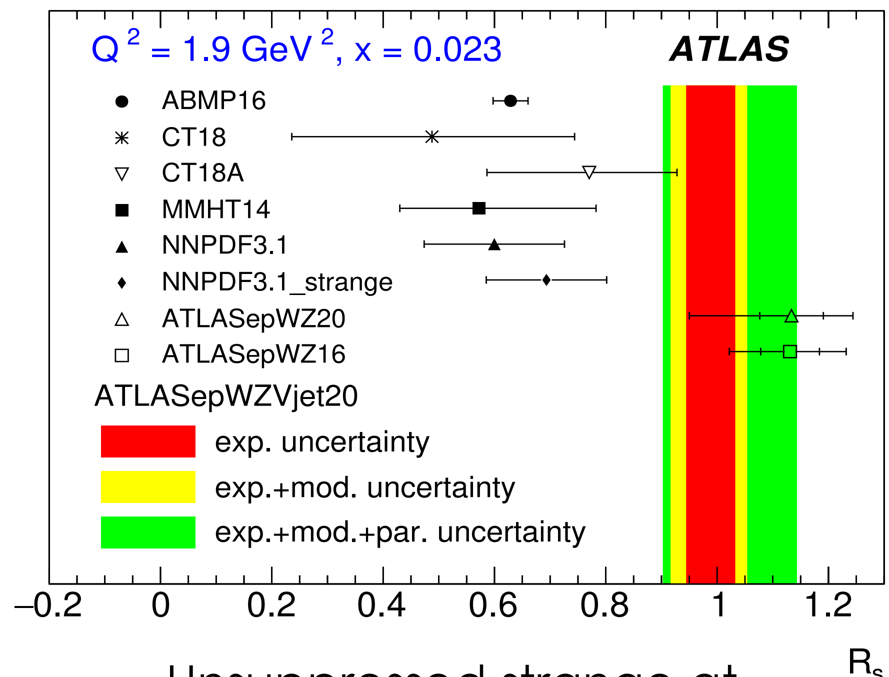
- V+jets data sensitivity to PDFs up to x ~ 0.3

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

- As soon as global fitters include ATLAS W,Z at 7 TeV data, they get in better agreement with ATLAS predictions



Fantastic improvement of R_s determination at high-x



Unsuppressed strange at low-x maintained

epWZVjets20 PDF fit

JHEP 07 (2021) 223

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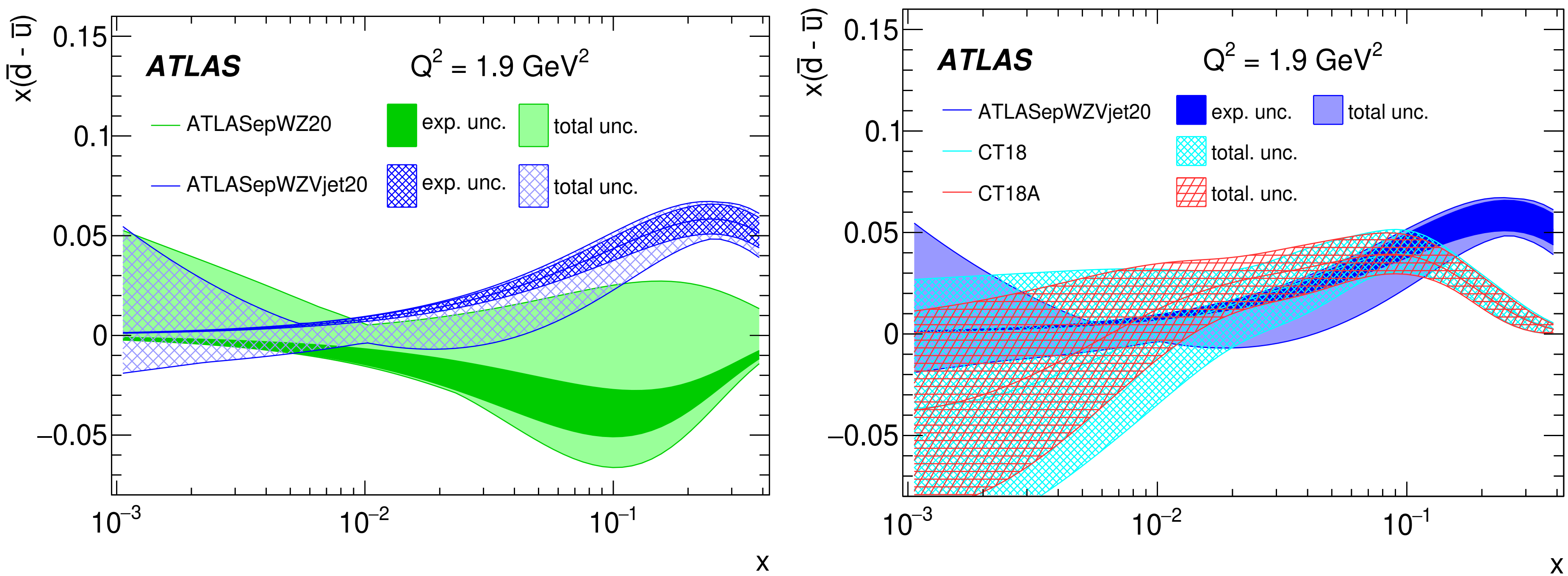
- Nice agreement up to $x \simeq 0.1$ (negative $x(\bar{d} - \bar{u})$ without V+jets 8 TeV data)



Other distributions in better agreement with global fitters!

Conclusion and outlook

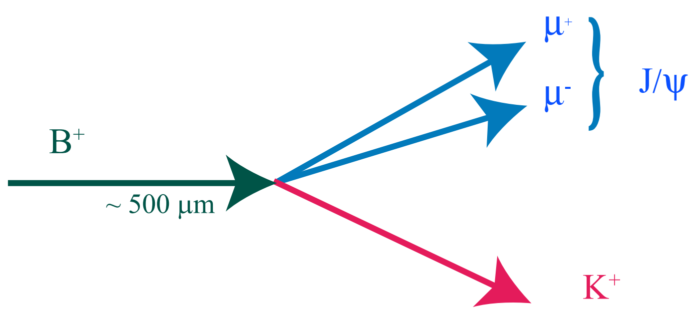
- QCD is an essential ingredient of SM, its apparent formal simplicity covers a very complex phenomenology
- Important to improve precision on other measurements, but a very interesting and intellectually challenging problem/process by itself
- Enormous theory effort to improve precision, now being matched by important measurements in specific regions of phase space
- Despite many improvements, still many divergences exist, and more corners of phase space need to be measured
- Many more clever measurements needed, I just presented some of them
- **Stay tuned! More results coming soon!**

Backup Slides

b-quark fragmentation properties

2108.11650

- Identify B hadron from $B^{\pm} \rightarrow J/\psi K^{\pm} \rightarrow \mu^{+}\mu^{-}K^{\pm}$



- Associate B meson to jet and compute

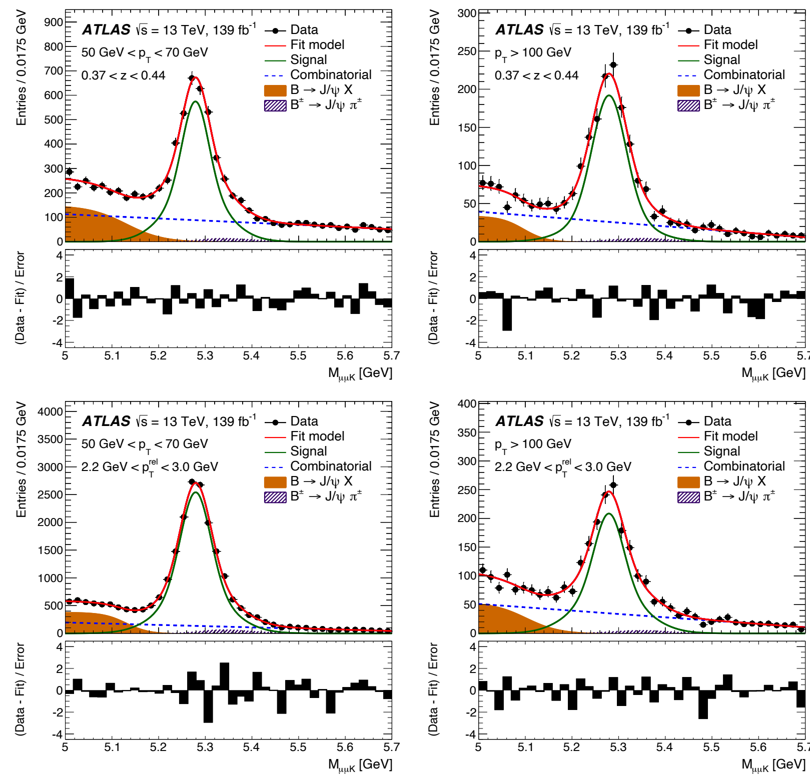
$$z = \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_j|^2}; \quad p_{\mathrm{T}}^{\mathrm{rel}} = \frac{|\vec{p}_B \times \vec{p}_j|}{|\vec{p}_j|}$$

- Unfold at particle level in different bins of z, p_T^{rel} and p_T^{j}

- $\boldsymbol{J/\psi}$: 2 OS μ with $p_T > 6$ GeV, $|\eta| < 2.5$ and $2.6 < m_{\mu\mu} < 3.6$ (displaced vertex)

- $\boldsymbol{K^{\pm}}$: third track from the same vertex, $p_T > 4$ GeV, $|\eta| < 2.5$

- Main systematics:
  - Jet Energy Scale and resolution
  - B meson reconstruction
  - Use of a specific MC model in the unfolding procedure

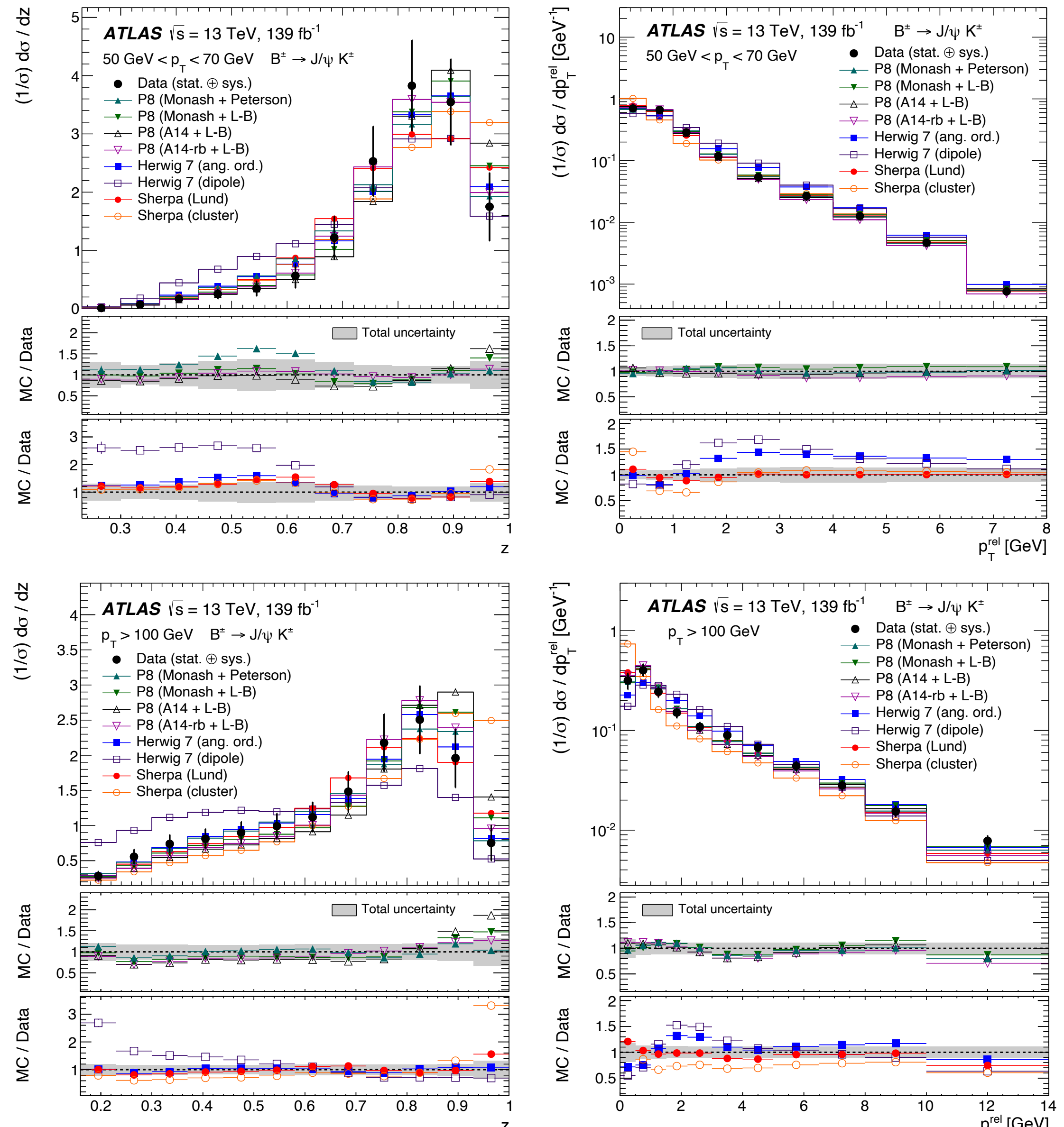


b-quark fragmentation properties

2108.11650

- Disagreement with Herwig7 dipole PS due to larger gluon splitting $g \rightarrow b\bar{b}$
- Sherpa cluster model disagrees at high z and low p_T^{rel}
- Herwig7 angle-ordered PS and Sherpa Lund model give similar results for z (not true for p_T^{rel})
- Pythia8 Monash overestimates data at middle z and low p_T^{rel}
- Data well described by Pythia8 A14+r_b = 1.05 (value fitted from LEP data)

r_b = Pythia8 tune parameter controlling b-fragmentation



Pairs of isolated photons at 13 TeV

2107.09330

- $p_{T,\gamma}$ > 40 (30) GeV and $|\eta_\gamma|$ < 2.37 (excluding 1.37 < $|\eta_\gamma|$ < 2.37)
- **Dominant systematics:** jets misidentification as photons, photon isolation and identification
- NNLOJET and Sherpa provide the best description of data in the regions expected to be modelled well by perturbative QCD
- Good data description by Sherpa where the effects of multiple collinear or soft QCD emissions are relevant

Fiducial cross section [pb]	$\sigma_{\gamma\gamma}$	$\pm$ unc.
SHERPA MEPS@NLO	33.2	$^{+7.7}_{-5.6}$
NNLOJET NNLO	29.7	$^{+2.4}_{-2.0}$
NLO	19.6	$^{+1.6}_{-1.3}$
LO	5.3	$^{+0.5}_{-0.5}$
DIPHOX NLO	20.8	$^{+3.2}_{-2.9}$
Data	31.4	2.4