14 th Conference on the intersections of particle and nuclear physics (CIPANP 2022)

Proton structure and hadronization at LHCb

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on behalf of the **LHCb** collaboration

Conference on the Intersections of Particle and Nuclear Physics 2022

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Nonperturbative dynamics inside proton and hadronization at LHCb

- Precision measurements, proton structure, and hadronization are main parts of QCD/EW program at LHCb.
- W mass, Z production, quark PDFs (light- and heavy-quarks, transverse momentum dependent (TMD) distributions) …
- Jet substructure, jet fragmentation functions (JFFs) for light- and heavy-quarks, and resonances.

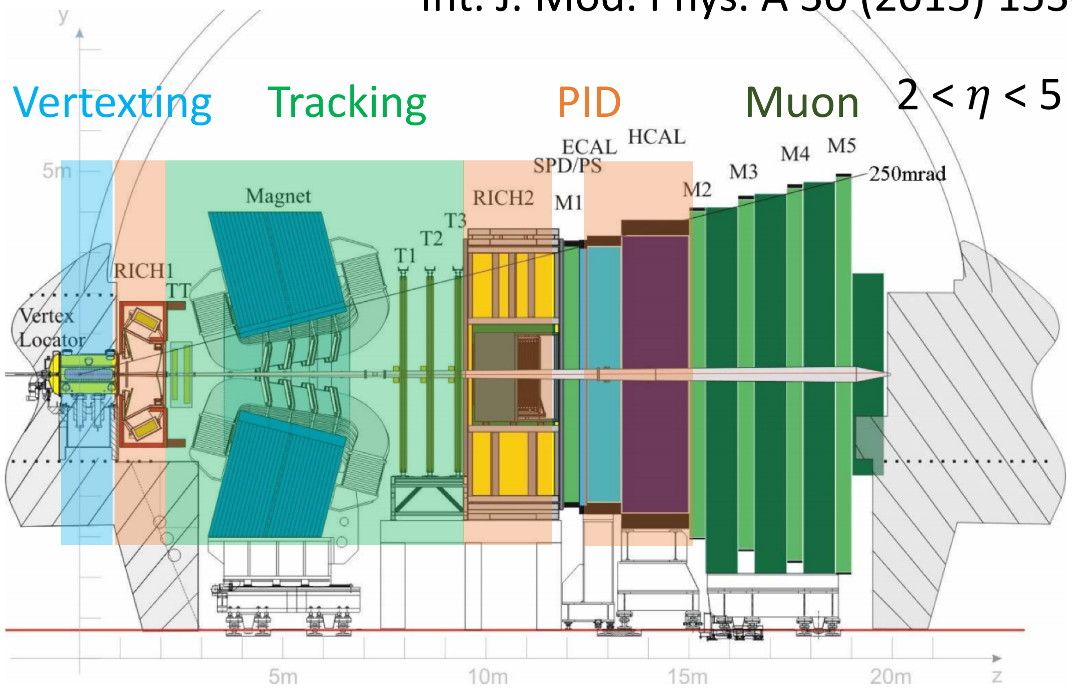
→ This talk presents new results in the following topics:

- ❑ Intrinsic charm in $Z + c$
- ❑ Angular coefficients in DY
- ❑ Multi-differential TMD JFFs for different charged hadrons in $Z +$ jet

The LHCb experiment

- General purpose detector in the forward region ($2 < \eta < 5$)
- Charged particle identification
- Impact parameter resolution $15+29/p_{\mathrm{T}}$ [GeV]
- Decay time resolution 45 fs
- Muon reconstruction for resonance states
- Full jet reconstruction with tracking, ECAL and HCAL + Tagging of jets from light-quark, c- and b-quark

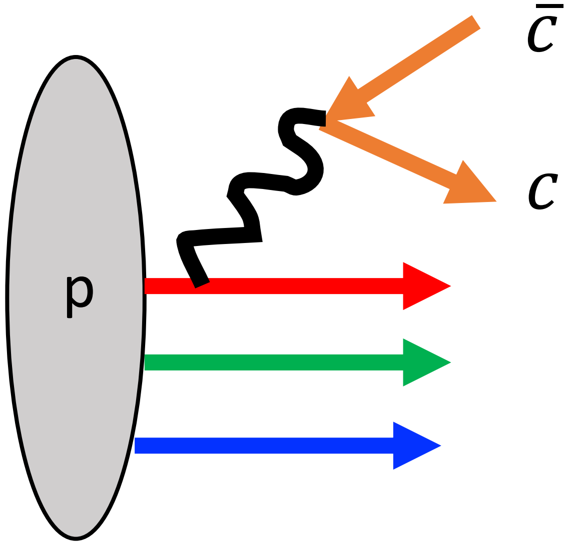
JINST 3 (2008 S08005)
Int. J. Mod. Phys. A 30 (2015) 1530022

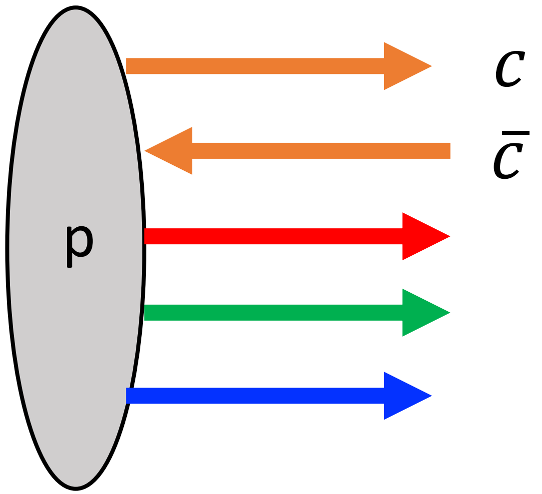


Physics at LHCb :

- Matter-antimatter symmetry
- CP Violation and rare decays of beauty and charm hadrons
- QCD, Electroweak and exotica ...

Is there charm in the proton?





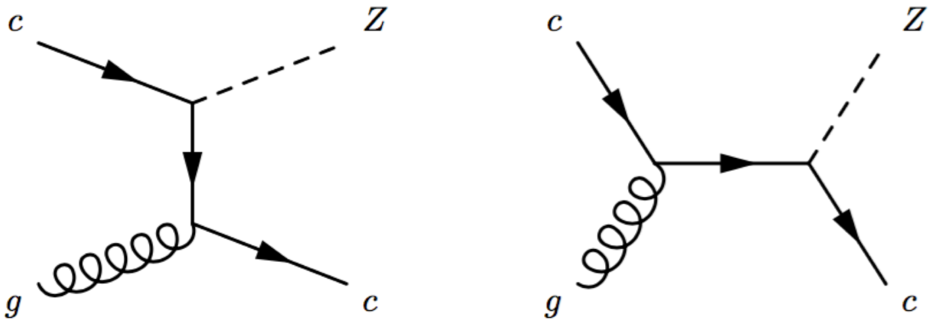
Phys. Lett. B **93** (1980) 451
Phys. Rev. D **23** (1981) 2745

Extrinsic
: Perturbative charm content via gluon radiation $g \rightarrow c\bar{c}$.
: Charm pairs created from DGLAP evolution.
: Charm PDF will resemble gluon PDF, and decrease sharply at large x.

Intrinsic
: $|uudc\bar{c} >$ component allowed in the proton wave function .
: Both valance-like and sea-like charm possible.

Intrinsic charm at LHCb

Phys. Rev. D **93** (2016) 074008

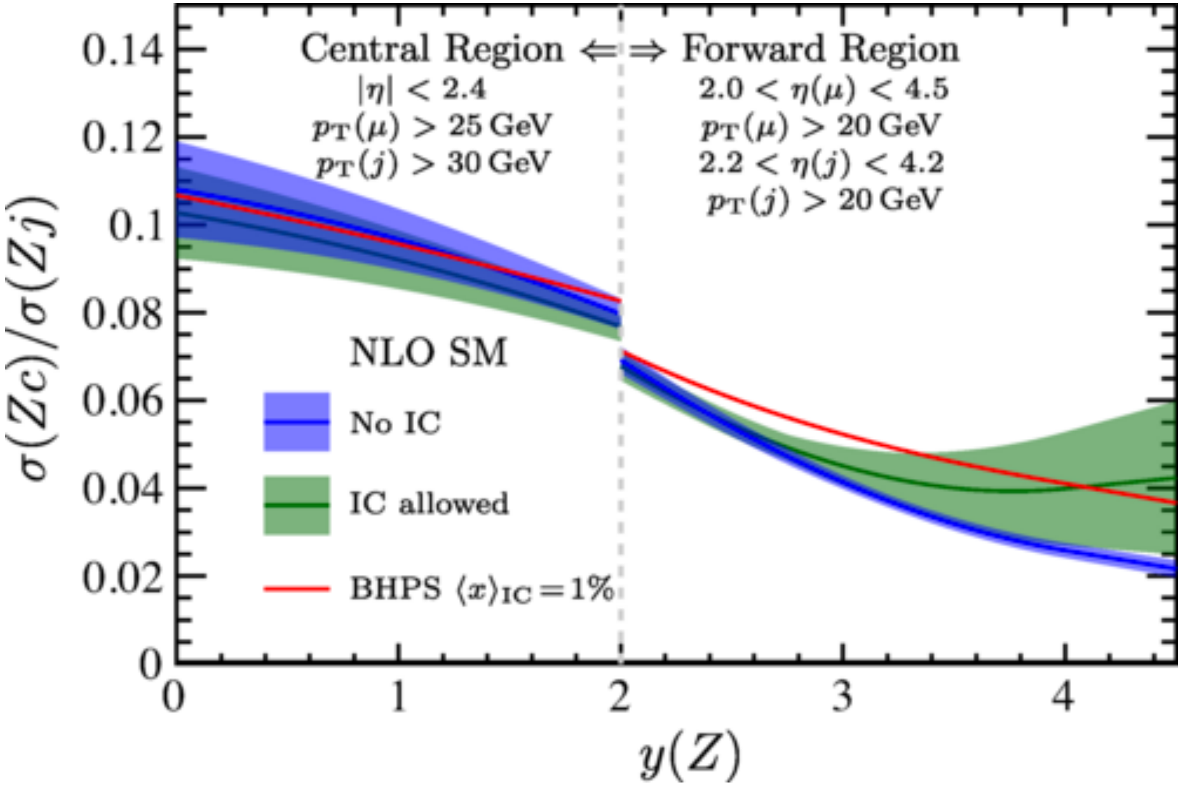


Leading order Zc production via
gc $\rightarrow Zc$ scattering at LHCb

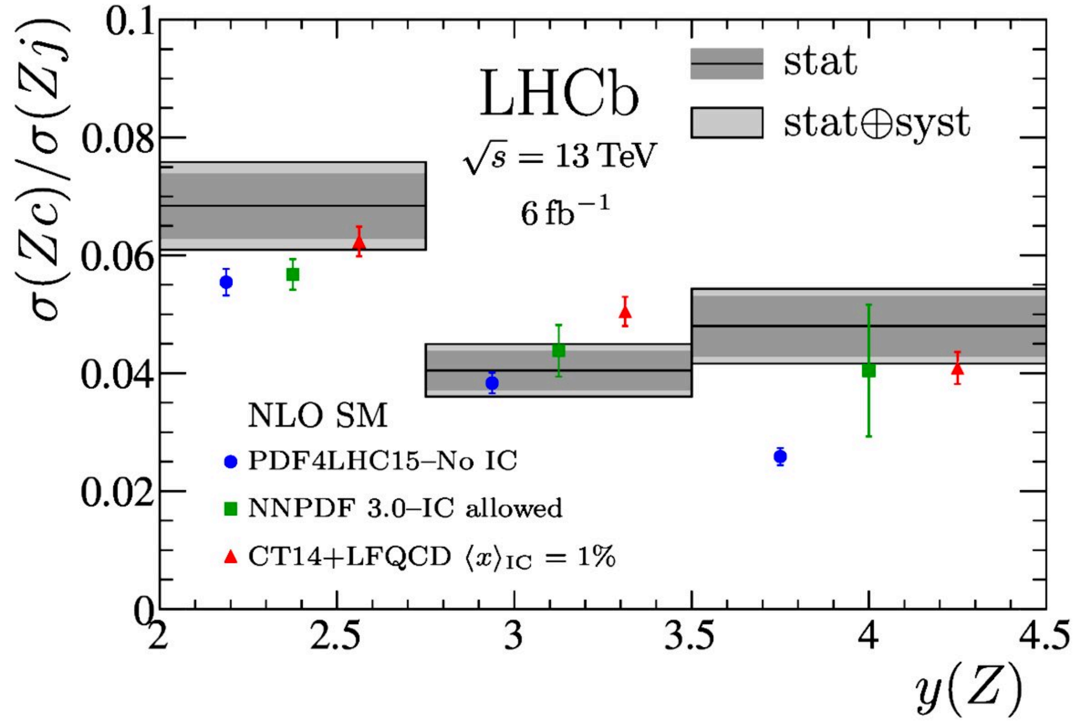
$$\mathcal{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$$

- $Z + c$ production at forward rapidity requires one initial parton to have large momentum fraction x.
- $Z + c$ requires large momentum transfer Q above EW scale, hence small nuclear and hadronic effects.
- $Z + c$ to $Z + j$ ratio to reduce sensitivities to experimental and theoretical uncertainties.

Phys. Rev. Lett. **128** (2022) 082001

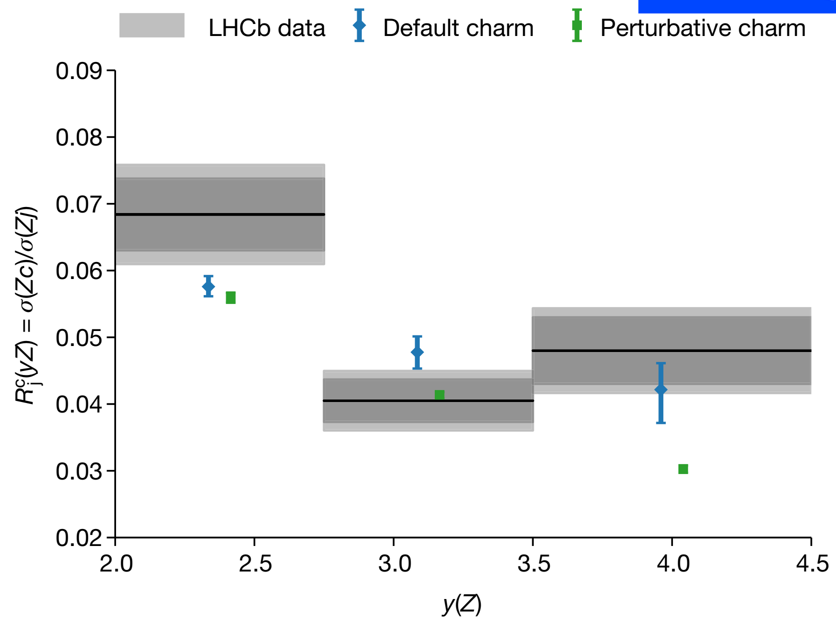


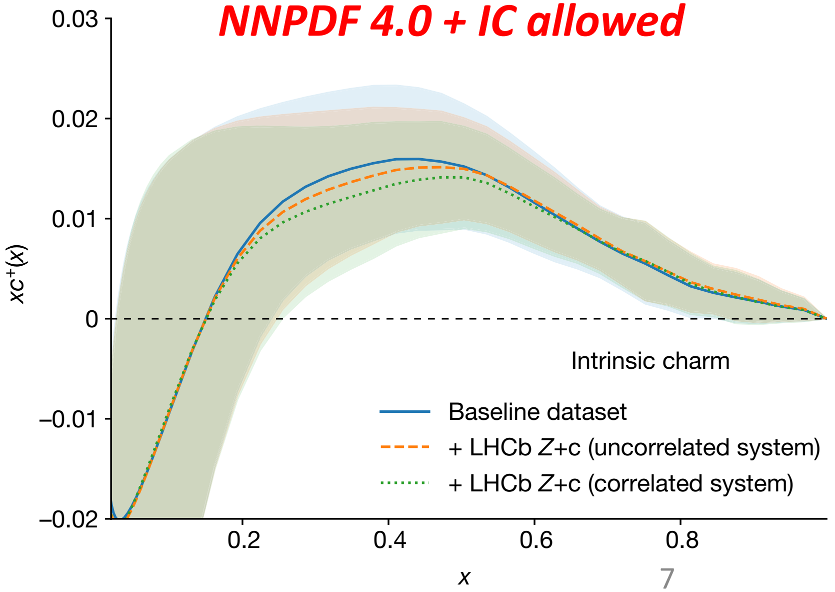
- Light Front QCD: Non-perturbative IC manifests as valence-like charm content in the parton distribution functions (PDFs) of the proton at large x.
- Perturbative charm content via gluon radiation $g \to c\bar{c}$ is expected to be suppressed at large x, at forward rapidity.
- A percent-level valence-like IC contribution would produce a clear enhancement in R_j^c for large (more forward) values of Z rapidity, $y(Z)$.



Phys. Rev. Lett. **128** (2022) 082001

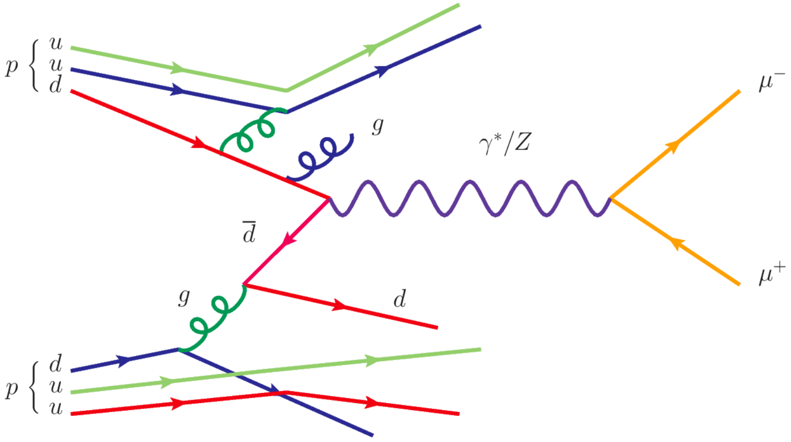
Nature **608** (2022) 483





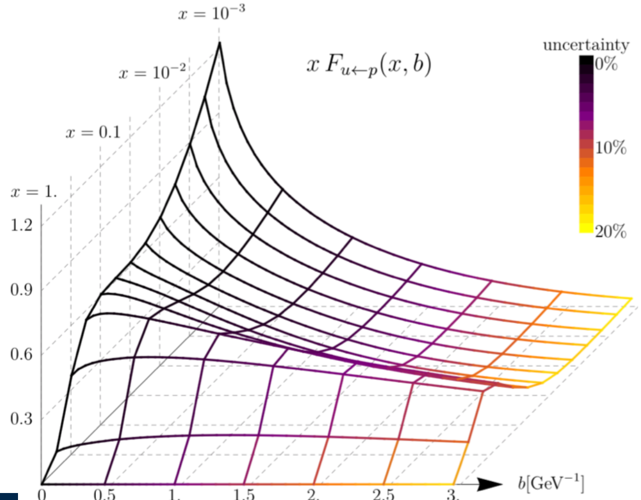
- Three scenarios, assuming no IC, IC allowed and valence-like IC (BHPS).
- A sizable enhancement at forward Z rapidities, consistent with the effect expected if the proton wave function contains the $|uudc\bar{c}>$ component.
- LHCb results rules out no IC prediction from global analysis performed by NNPDF group at 3σ deviation level, supporting existence of IC.
- Consistency between prediction and the measurements indicates success of DGLAP evolution from low Q in DIS to EW scale at LHC.

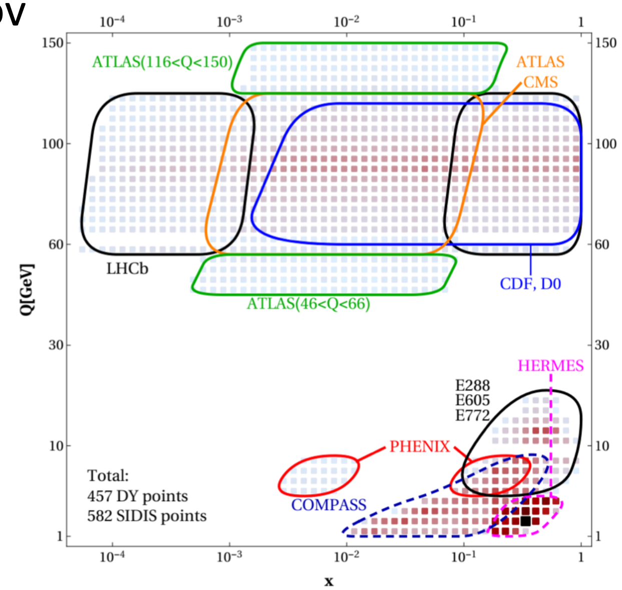
DY neutral current process



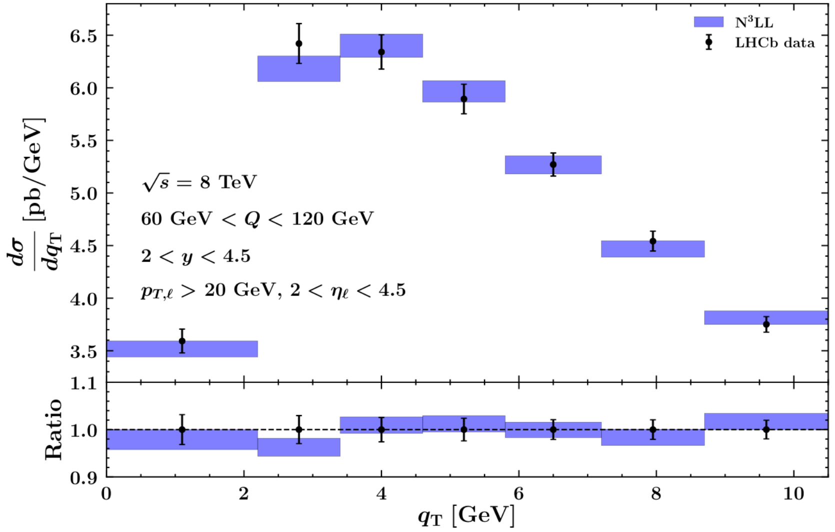
- Rich physics encoded in angular distribution of muons from $\gamma^*/Z \to \mu^+\mu^-$ decay in the forward region.
- Z-boson cross-section measurements at low Z p_T (< 0.2 m_Z) already used for global analyses of unpolarized TMD PDFs.

JHEP **06** (2020) 137 Scimemi, Vladimirov

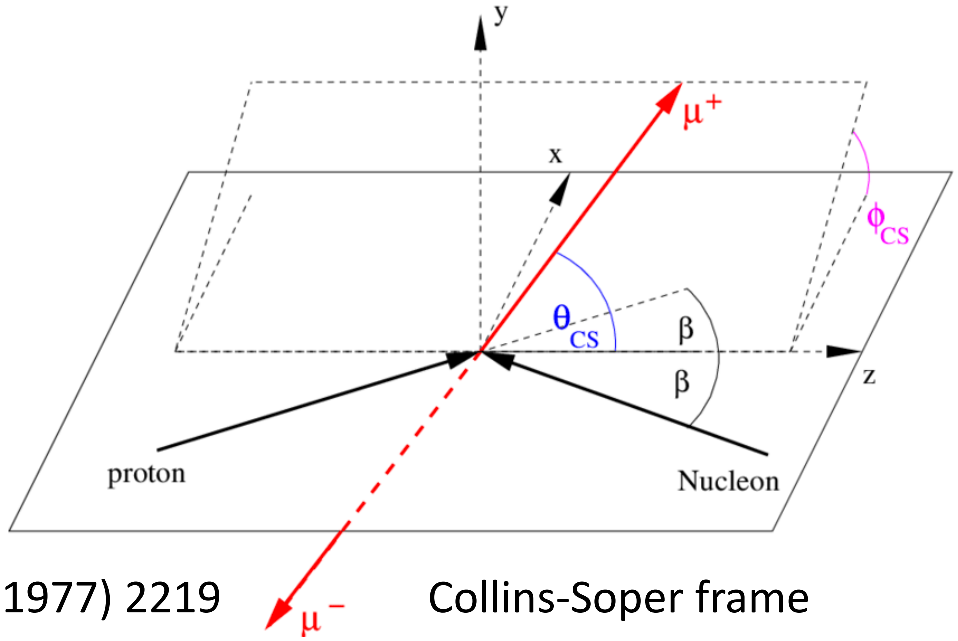




JHEP **07** (2020) 117 Bacchetta et al.



Angular coefficients



Phys. Rev. D **16** (1977) 2219

Collins-Soper frame

- Production mechanisms for spin 1 particles decaying into dileptons can be expressed using 8 angular coefficients A_i (i =0,… 7).
- *Lam-Tung* relation $A_0 = A_2$ at LO; can be violated by NP effects, e.g. Boer-Mulders TMD PDF, or even perturbatively at higher order in FO as well as resummation pQCD calculation.
- A_3, A_4 : V-A structure.

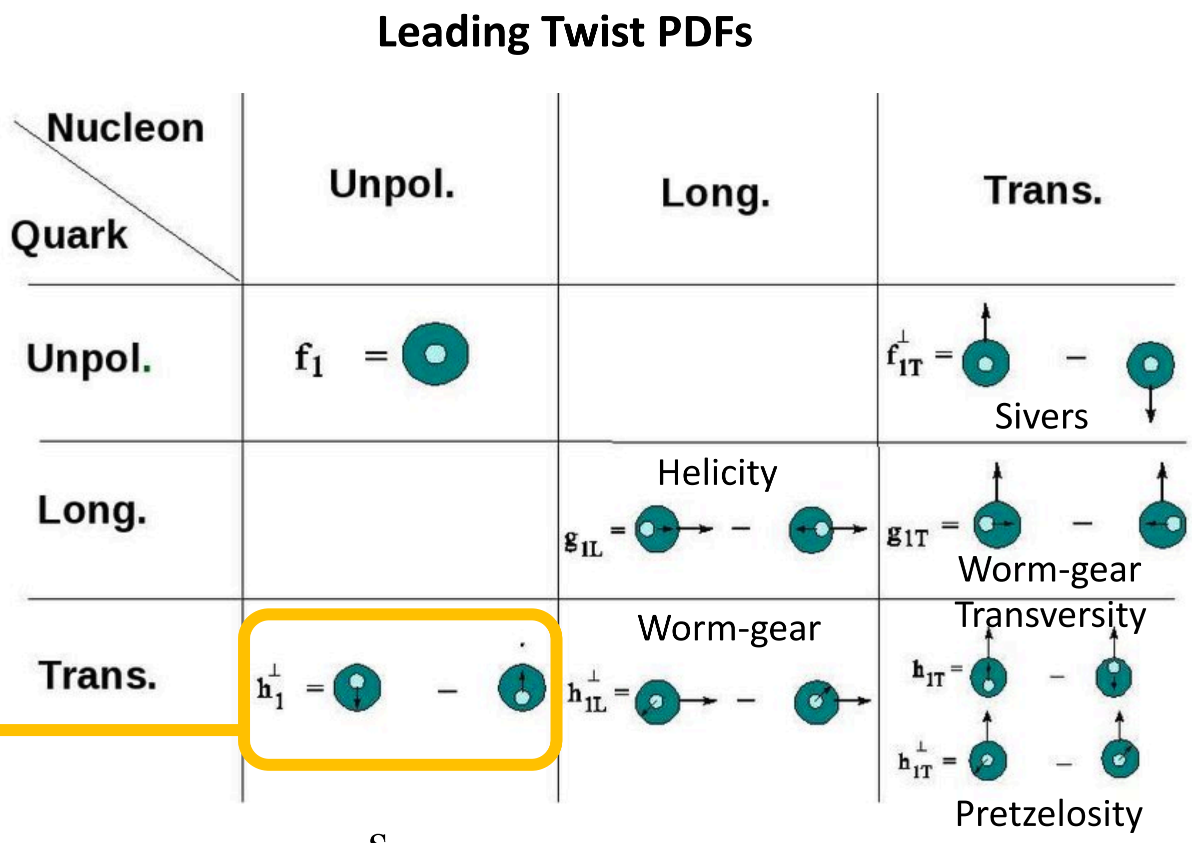
Lepton angular distribution

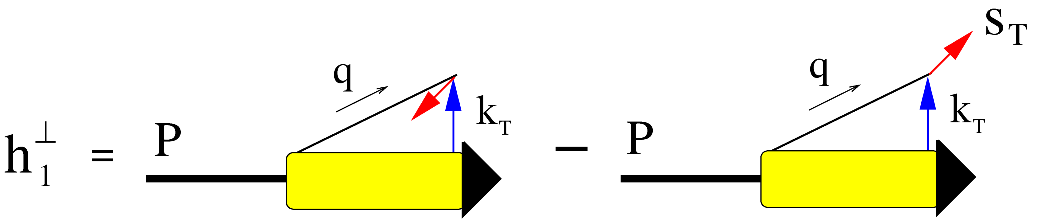
$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi$$
$$+A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi,$$

TMD PDFs and DY

Boer-Mulders Fn

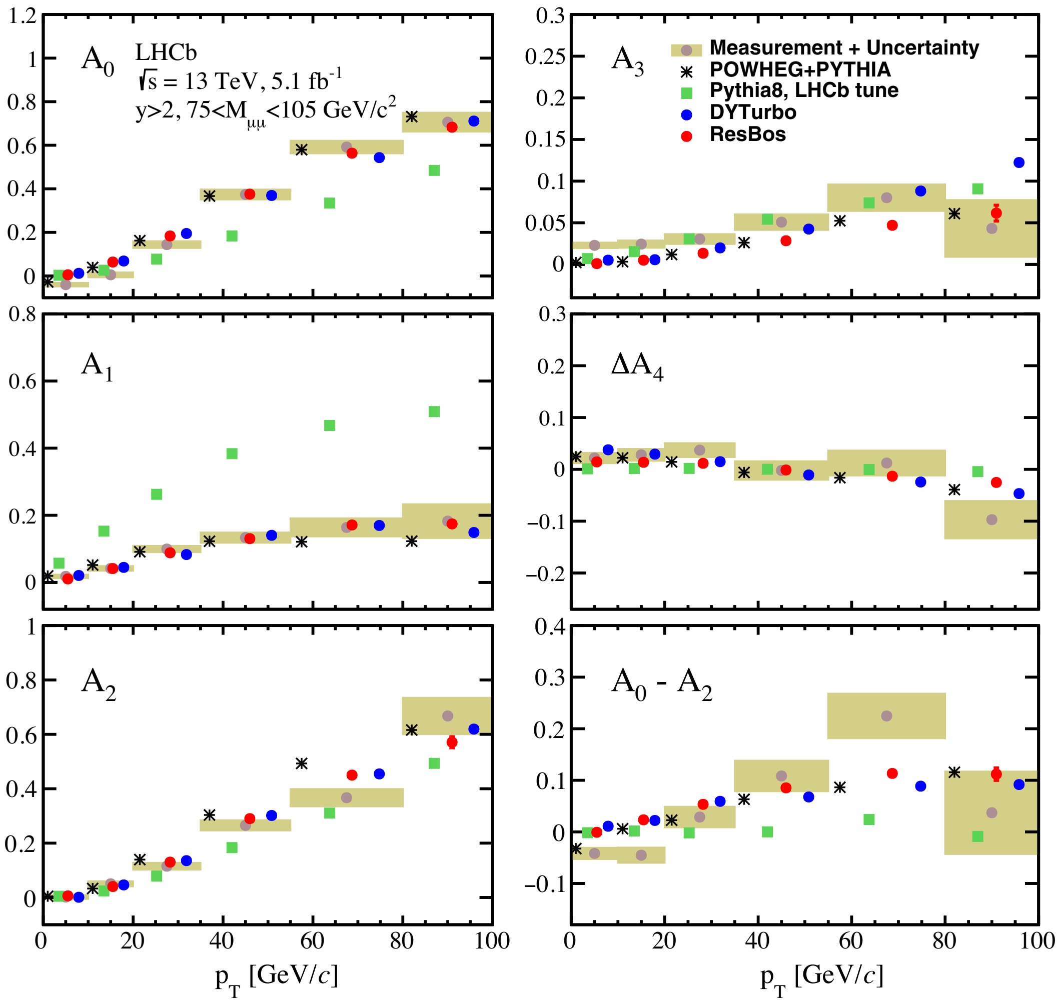
: quark spin-momentum correlation
: can be measured via DY angular distribution at low p_T ($\cos 2\varphi$ modulation) at LHCb.





DY angular coefficients

Phys. Rev. Lett. **129** (2022) 091801

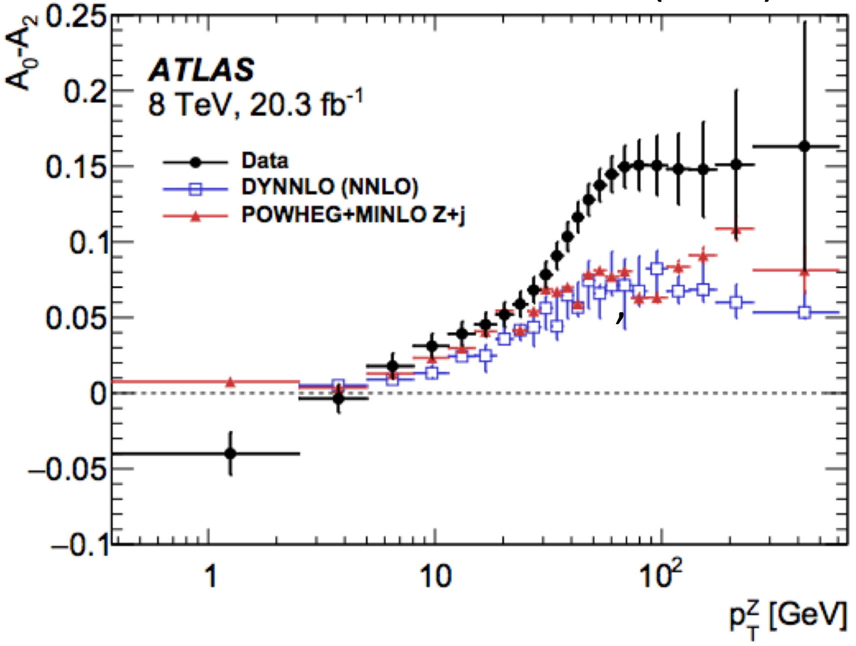


- New LHCb results!
- Overall agreement in trends between data and predictions with an exception of Pythia.
- Significant violation of Lam-Tung relation observed.

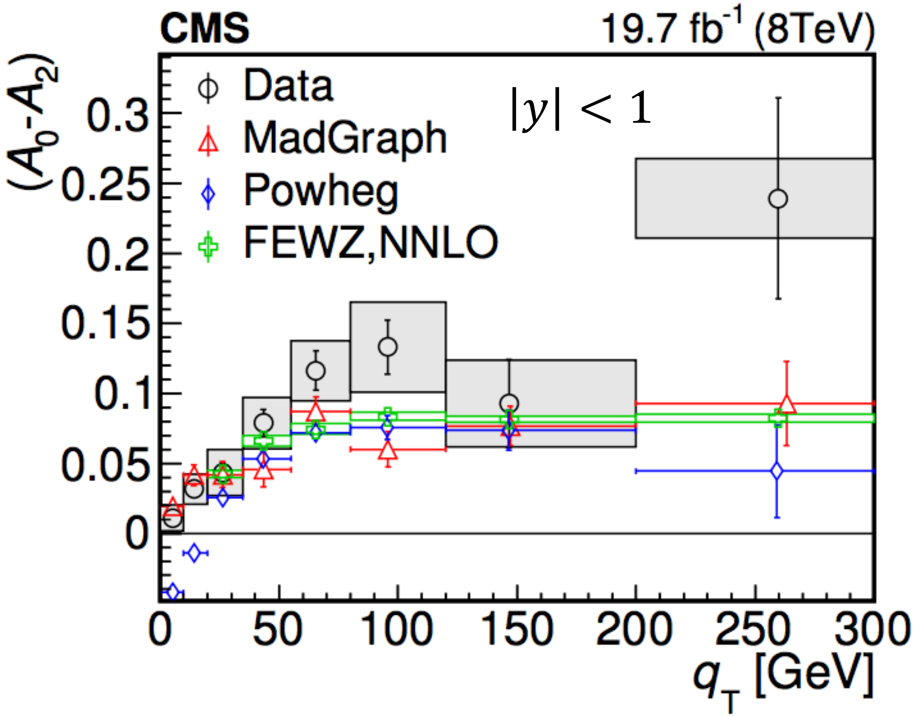
- Significant violation of Lam-Tung relation observed.
- Consistent with measurements by CMS and ATLAS.

$|y| < 3.5$

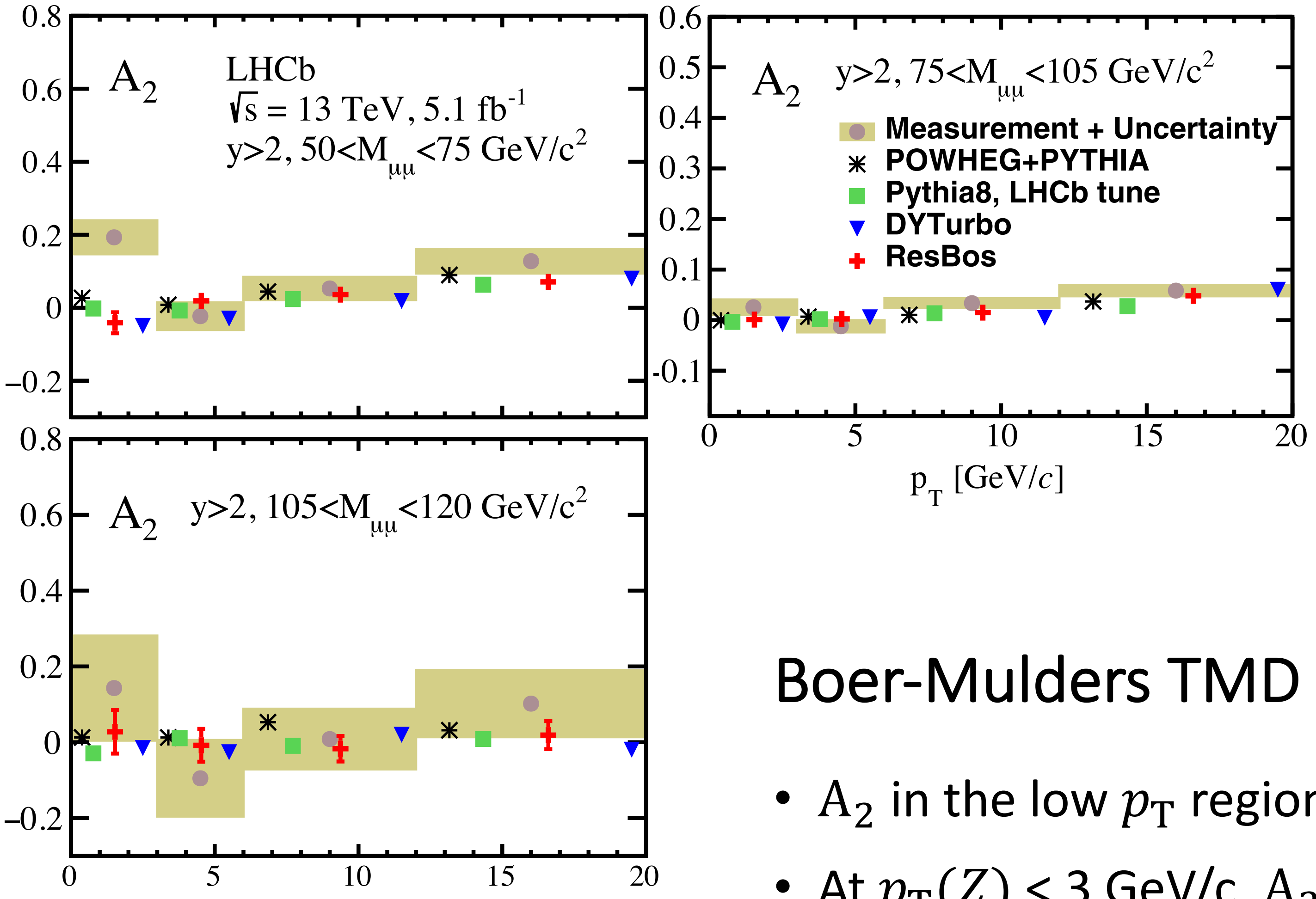
JHEP **08** (2016) 159



Phys. Lett. B **750** (2015) 154



Phys. Rev. Lett. **129** (2022) 091801



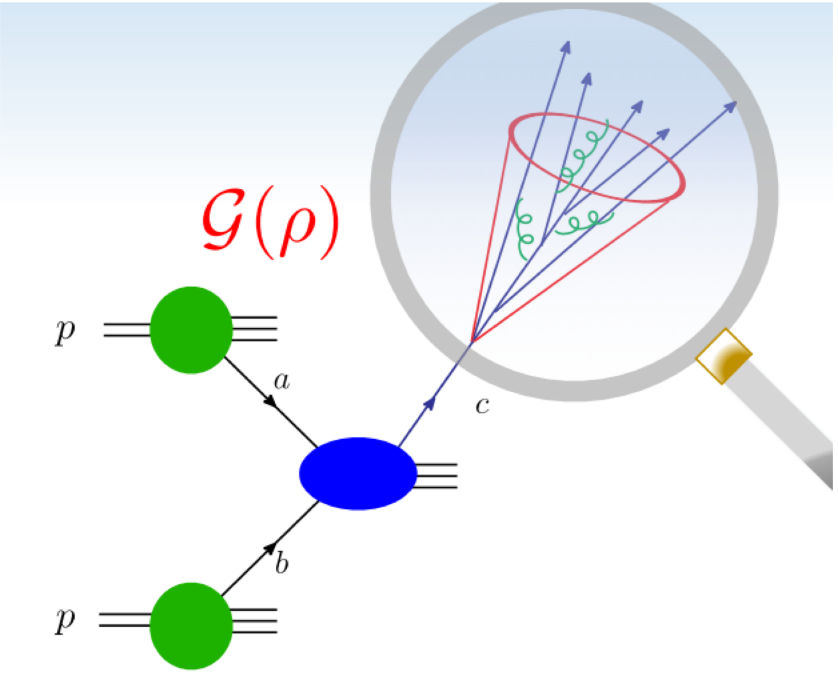
Boer-Mulders TMD PDF

- A_2 in the low p_T region sensitive to the Boer-Mulders TMDPDF
- At $p_T(Z)$ < 3 GeV/c, A_2 measured to be ~ 5 times all predictions.
- No phenomenological calculations available.

Jet substructure

Jet substructure ρ

- fragmenting jet function (FJF)
- TMD FJF
- Jet angularity
- …

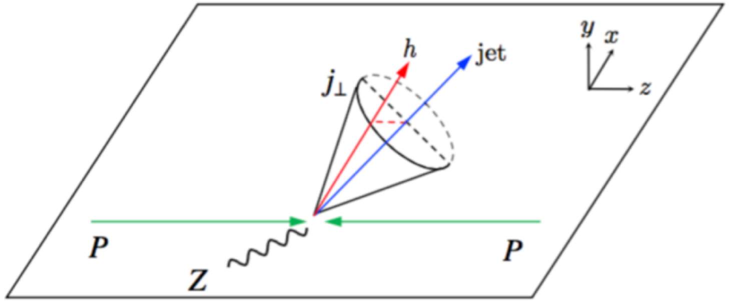


$$\frac{d\sigma^{pp\to jet\ (\rho)X}}{dp_T d\eta\ d\rho} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^{c} \otimes \mathcal{G}_c(\rho)$$

Phys. Rev D **81** (2010) 074009
Phys. Rev. D **92** (2015) 054015
JHEP **11** (2016) 155
JHEP **1804** (2018) 110

Accessing TMD FF using hadrons in jets

JHEP **05** (2011) 035
JHEP **11** (2017) 068
Phys. Lett. B **798** (2019) 134978



$$\frac{d\sigma^{pp\to \text{jet}(h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes H_{ab}^c \otimes \mathcal{G}_c^h(z_h, \boldsymbol{j}_\perp)$$

$\sim \widehat{D}_{h/c}(z_h, j_\perp, \mu_J)$
: TMD FF

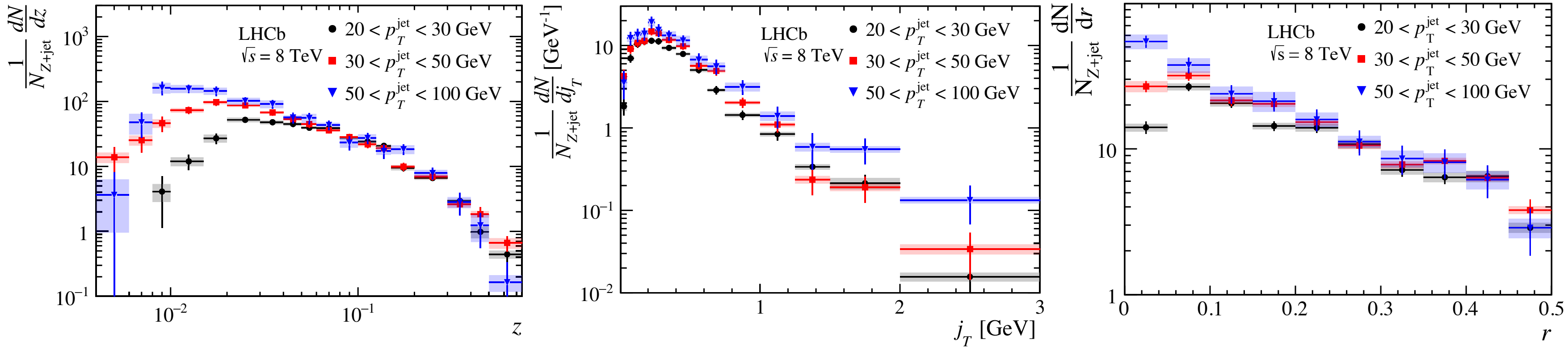
$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

$$j_T = \frac{|p_{jet} \times p_h|}{|p_{jet}|}$$

$$r = \sqrt{(\phi_{jet} - \phi_h)^2 + (y_{jet} - y_h)^2}$$

Phys. Rev. Lett. **123** (2019) 232001

1D measurements of nonidentified $h^\pm$ in Z+jets



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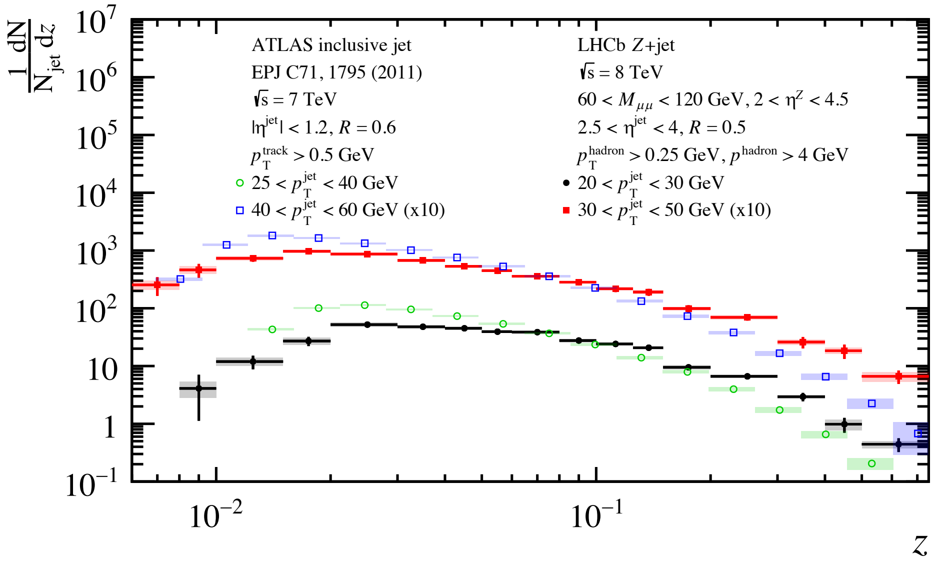
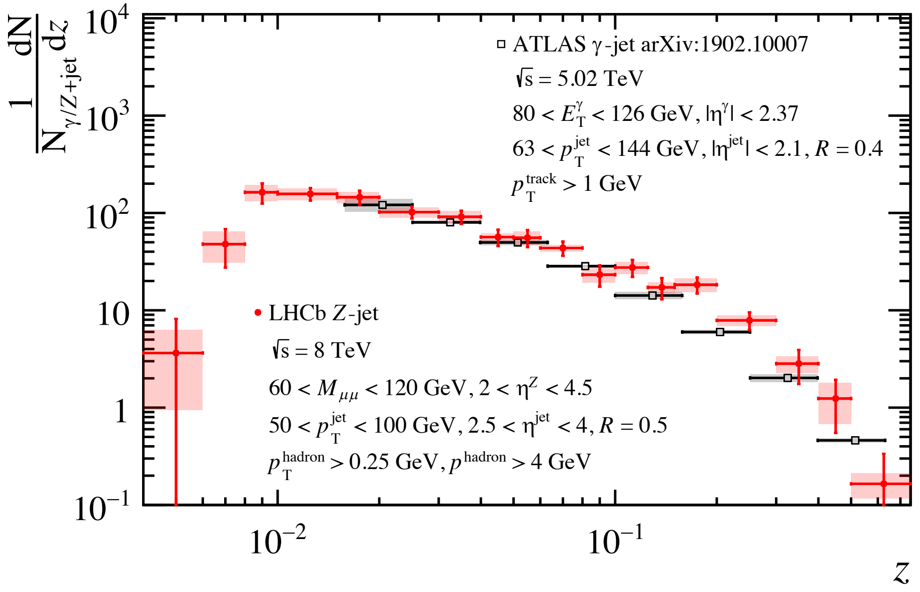
Gluon- vs. quark-initiated jets

- LHCb Z+jets (quark jet) vs. ATLAS inclusive jets (gluon jet)
- Quark-initiated jets are more collimated and takes a larger partonic momentum fraction than gluon jets.

PRL 123, 232001 (2019) - Supplemental material

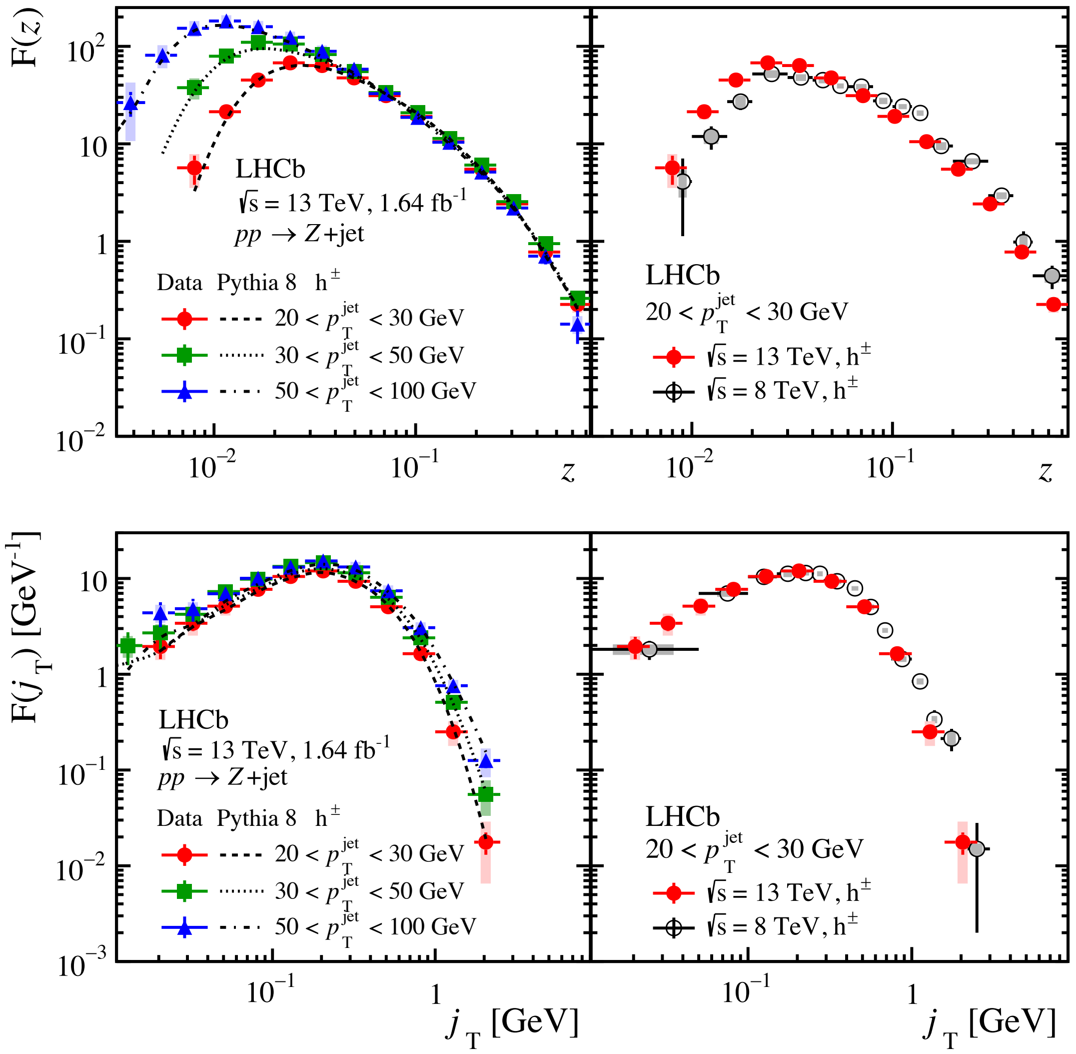


PRL 123, 232001 (2019) - Supplemental material



JFF at LHCb

arxiv:2208.11691

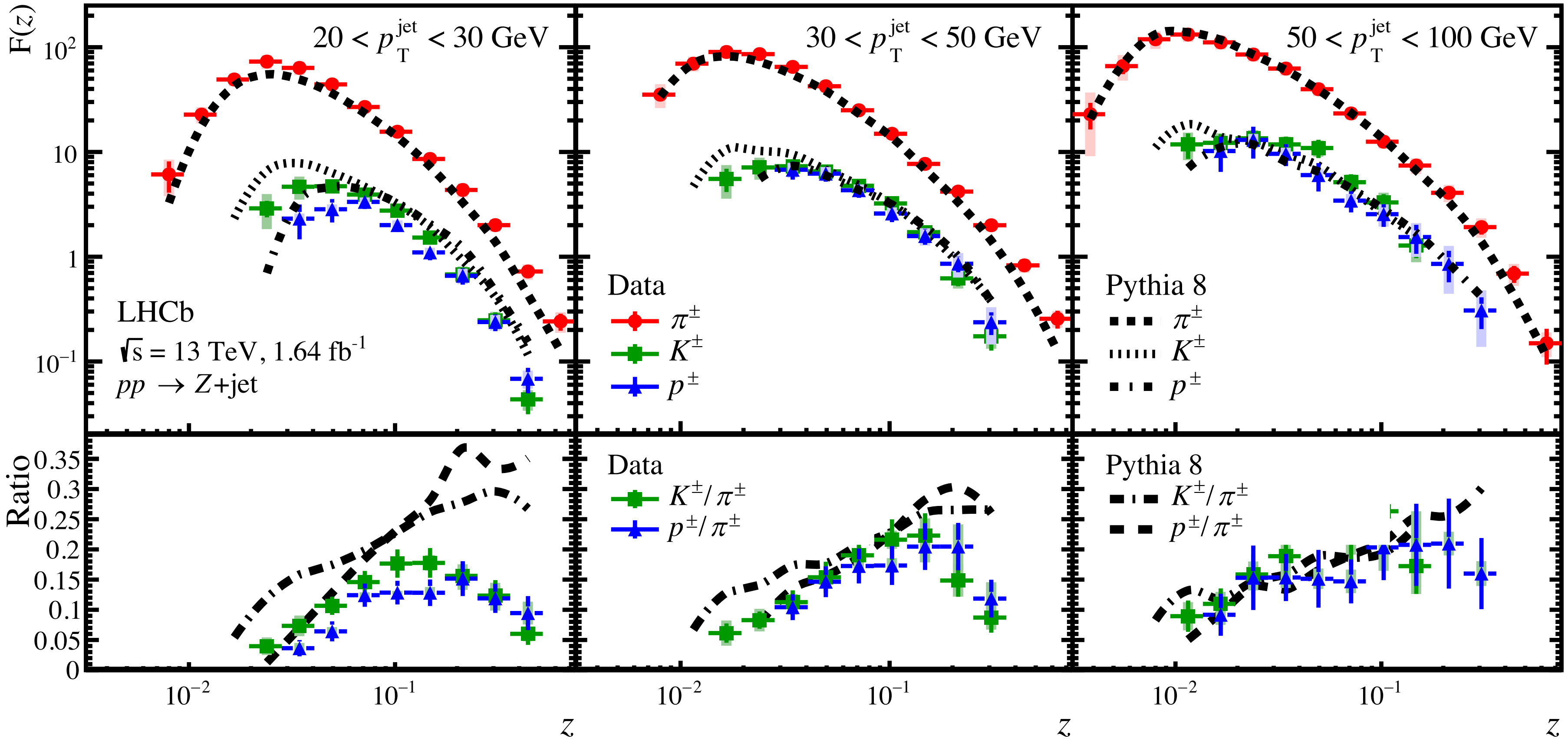


- New results at LHCb!
- Charged hadrons in Z–tagged jets.
- At small z < 0.02, effects of color coherence as well as kinematic cuts manifest as a humped-back structure.
- Harder jets, higher p_{T} or higher $\sqrt{s}$, produce an excess of soft particles per jet; access smaller z .
- Scaling behavior at large z > 0.04.
- Similar pattern in j_{T} between $\sqrt{s}$ = 8 TeV vs 13 TeV.

JFF for $\pi^{\pm}, K^{\pm}$ and $p^{\pm}$

arxiv:2208.11691

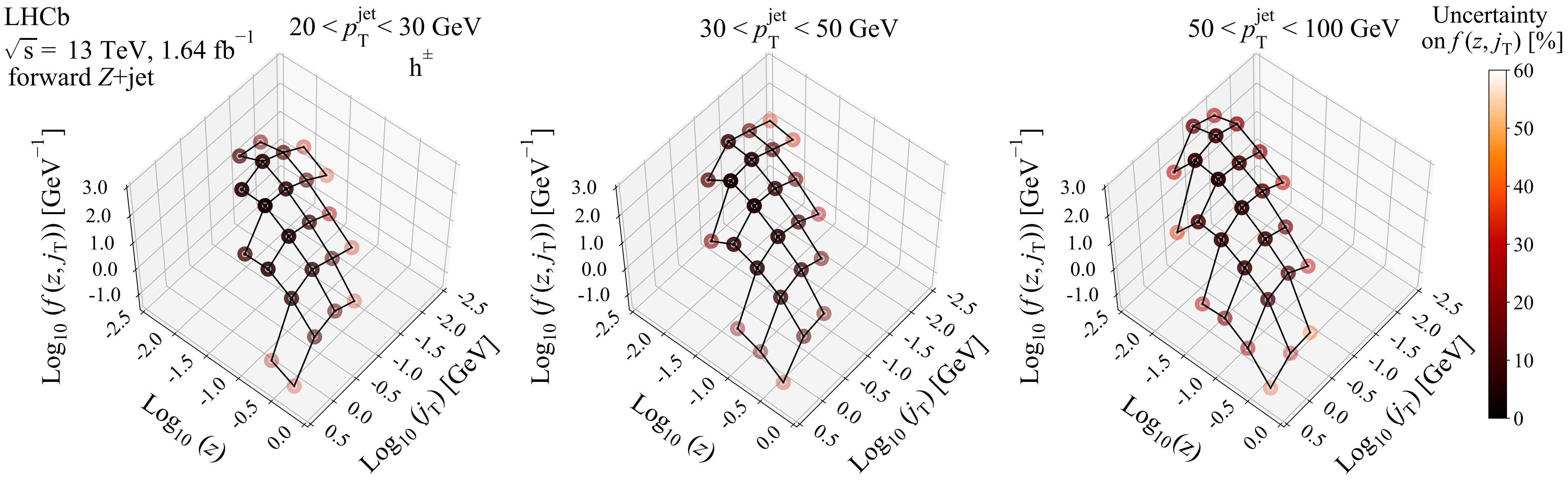
- Charged hadron formation within jets predominantly by $\pi^{\pm}$ due to its low mass and flavor content of initial-state proton.
- Hadrons with higher mass require a larger z threshold for their formation. Delayed scaling behavior shown in heavier charged particles.



- In lowest jet p_T interval:
  - Proton production relative to kaons clearly suppressed at lower z.
  - Pythia 8 overestimates $K^{\pm}, p^{\pm}$ production relative to $\pi^{\pm}$.

Multi-differential TMD JFF for charged hadrons $\boldsymbol{h}^{\pm}$

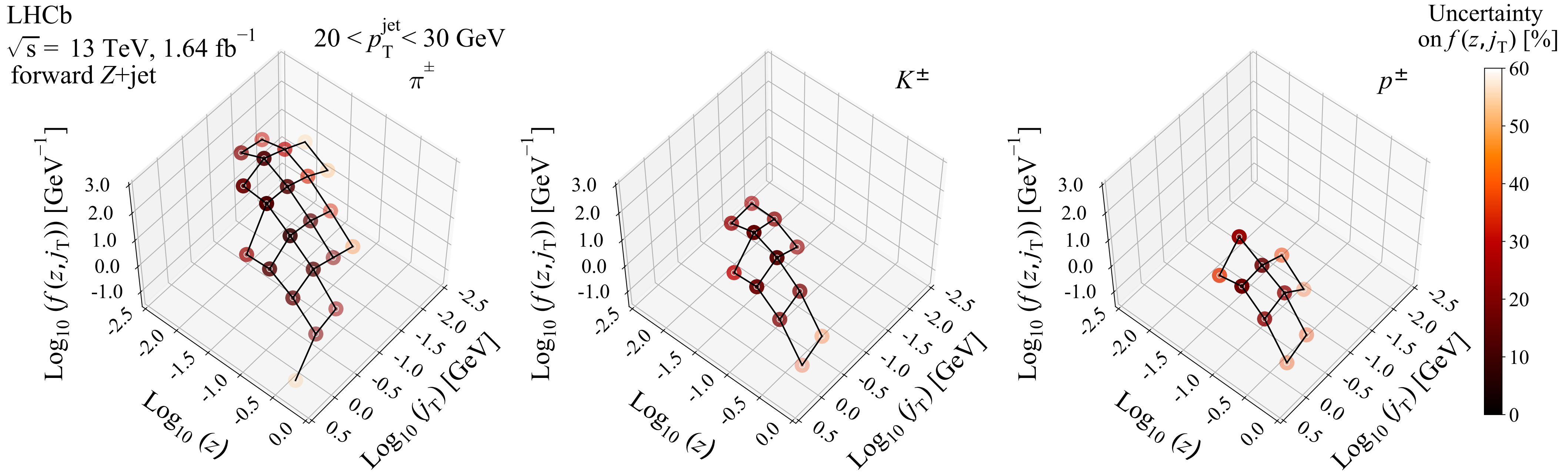
arxiv:2208.11691



- Hadrons carrying large momentum fraction along jet axis tend to have large transverse momentum w.r.t. jet axis.
- Centroid of harder jets shifted towards smaller z (soft particle production) and larger j_{T} (wider jet).
- Larger j_{T} for given z in jets with higher p_{T}; consistent with Markov chain fragmentation models, e.g. string or cluster models.

Multi-differential TMD JFF for $\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$

arxiv:2208.11691



- Multidifferential distributions for pions, kaons and protons at 20 < jet p_T < 30 GeV/c
- Heavier hadrons produced from harder partons, i.e. larger j_T as well as larger z .

Summary and outlook

- LHCb QCD/EW program performed precision and jet substructure measurements to advance our understanding of nonperturbative dynamics inside proton and hadronization.
- **Charm jet to Z jet ratio** measurements revealed presence of valence-like intrinsic charm component at large momentum fraction x.
  - New LHCb measurements rule out no-IC predictions based on global analysis by NNPDF at 3 σ deviation level.
  - Consistency between measurements and predictions indicates successful DGLAP scale evolution from DIS to EW scale at LHC.
- **DY angular coefficient** measurements saw violation of Lam-Tung relation and hints of NP Boer-Mulders effect for the first time.
  - Results consistent with CMS and ALTAS results that also saw significant violation of Lam-Tung relation.
  - Phenomenological calculations needed to use new results to extract BM fn.
- **Multi-differential TMD JFF** measured for charged pions, kaons and protons for the first time.
  - Results shed lights on particle dependent hadronization processes within jets.
  - Hadrons carrying larger jet momentum fraction in longitudinal direction tend to carry larger transverse momentum w.r.t. jet axis as well.
  - Heavier hadrons are produced from harder partons.
  - Confirm some of features shown in measurements at lower $\sqrt{s}$ = 8 TeV.
- Hadronization in heavy flavor jets, excited resonance states under way. Results expected to come out soon.

Thank you!