WG5 Spin and 3D structure

Studying Transverse-momentum-dependent Fragmentation Functions at LHCb

Sookhyun Lee (U Michigan/U Tennessee)

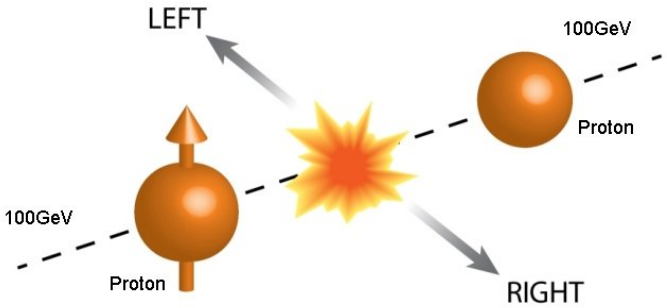
on behalf of the **LHCb** collaboration

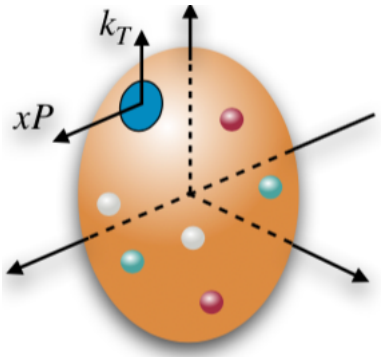
XXX International Workshop on Deep-inelastic Scattering and Related Subjects

March 30, 2023

Motivation

- Collinear fragmentation functions for identified hadrons well understood
- Spin-spin and spin-momentum correlations are key to explaining various transverse spin asymmetries
- Multi-differential analysis reveals complex structure underlying hadron formation
- Jet TMD fragmentation measurements are interesting in their own right as they enable us to study the nature of emergent QCD

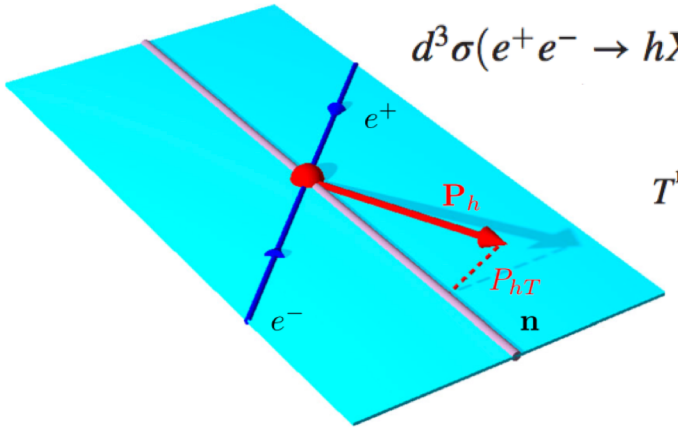




How do we access TMD FF at experiments?

- Previously, *single inclusive annihilation* in e^+e^- and *transverse momentum dependent cross section and multiplicity* in ***Semi-Inclusive DIS***, and $\gamma - h$ *correlations* in pp
  - Ambiguity by transverse momenta of two hadrons involved and less direct measurements

PRD **99** (2019) 112006 **[BELLE collaboration]**



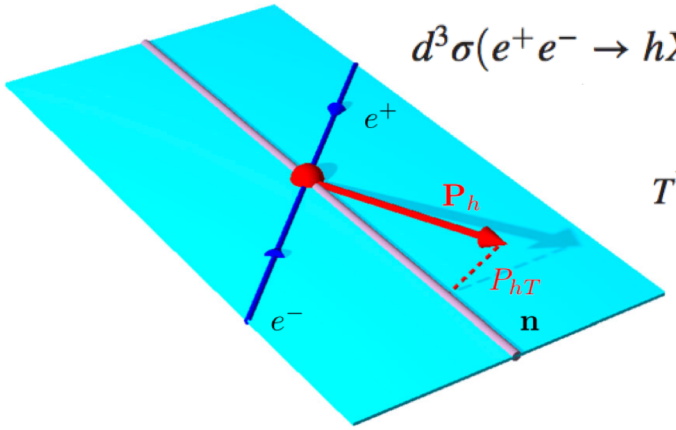
$$d^3\sigma(e^+e^- \to hX)/dzdP_{hT}dT$$

$$T \overset{\text{max}}{=} \frac{\sum_h |\mathbf{P}_h^{\text{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\text{CMS}}|}$$

How do we access TMD FF at experiments?

- Previously, *single inclusive annihilation* in e^+e^- and *transverse momentum dependent cross section and multiplicity* in ***Semi-Inclusive DIS***, and $\gamma - h$ *correlations* in pp
  - Ambiguity by transverse momenta of two hadrons involved and less direct measurements

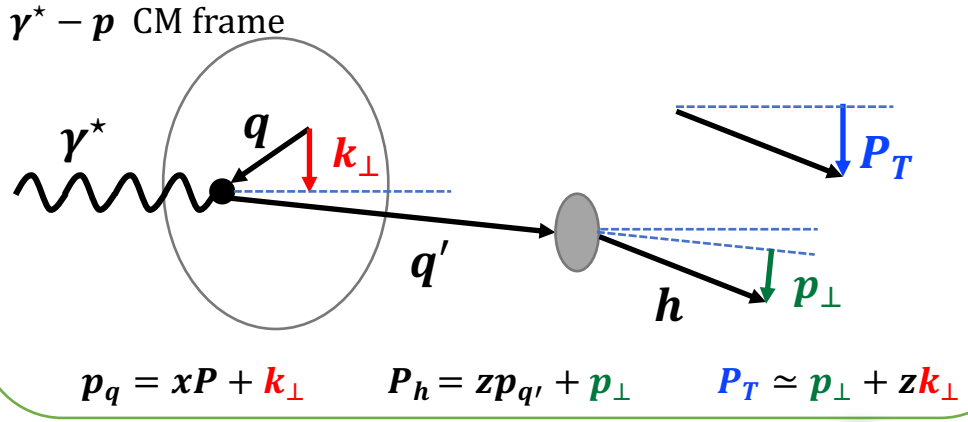
PRD **99** (2019) 112006 **[BELLE collaboration]**



$$d^3\sigma(e^+e^- \to hX)/dzdP_{hT}dT$$

$$T \overset{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}$$

SIDIS *in parton model with* ***intrinsic motion***

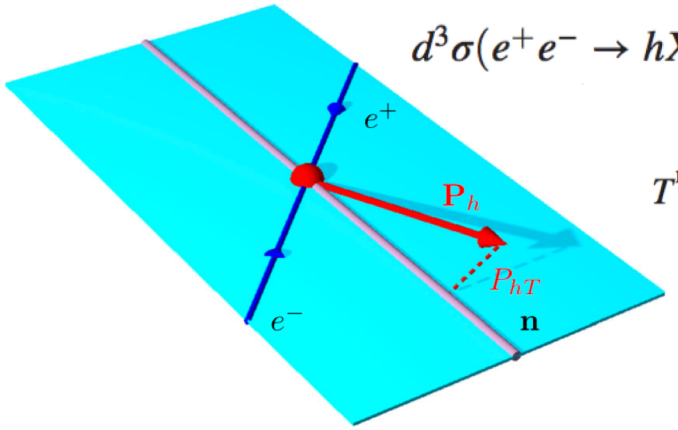


How do we access TMD FF at experiments?

- Previously, *single inclusive annihilation* in e^+e^- and *transverse momentum dependent cross section and multiplicity* in ***SIDIS***, and $\gamma - h$ *correlations* in pp
  - Ambiguity by transverse momenta of two hadrons involved and less direct measurements

- ***Jets and jet substructure*** measurements opened up new ways to access this information at ***RHIC*** and ***LHC***
  - Transversity & Collins FF at STAR
  - ***TMD Jet FF at LHCb***

PRD **99** (2019) 112006 **[BELLE collaboration]**

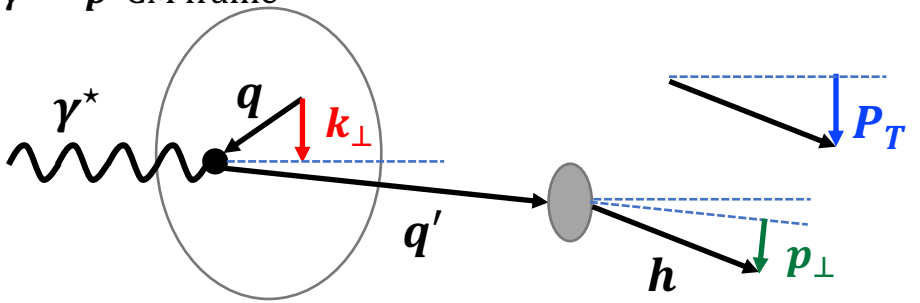


$$d^3\sigma(e^+e^- \to hX)/dzdP_{hT}dT$$

$$T \overset{\text{max}}{=} \frac{\sum_h |\mathbf{P}_h^{\text{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\text{CMS}}|}$$

SIDIS *in parton model with* ***intrinsic motion***

$\gamma^\star - p$ CM frame

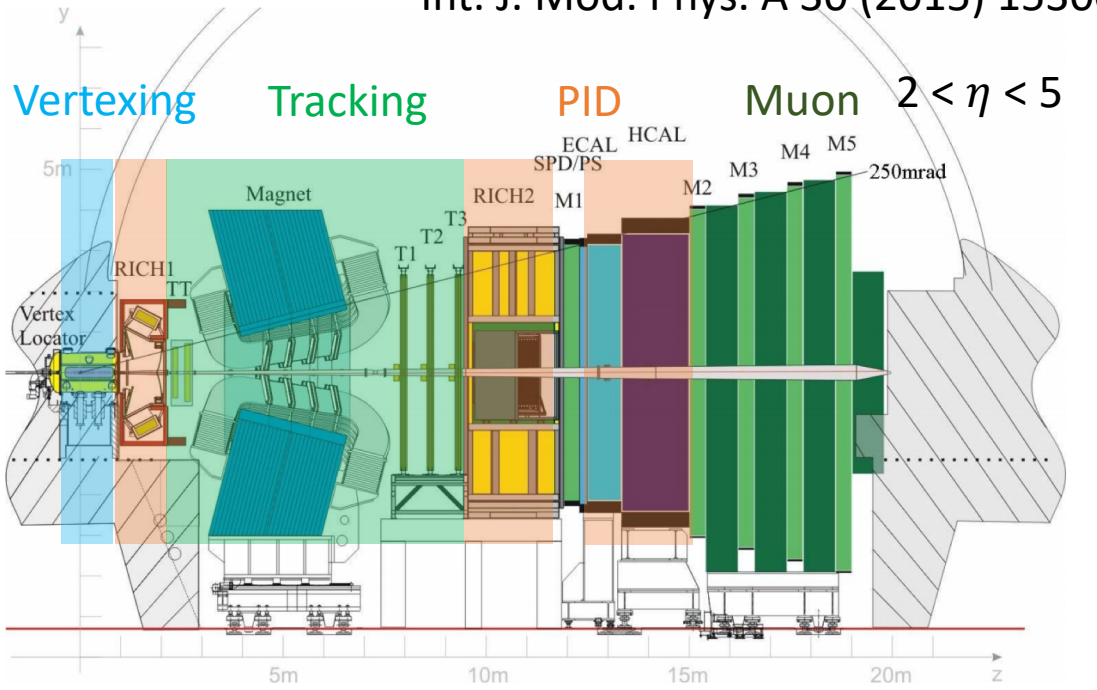


$p_q = xP + k_\perp$ $\quad P_h = zp_{q'} + p_\perp$ $\quad P_T \simeq p_\perp + zk_\perp$

The LHCb experiment

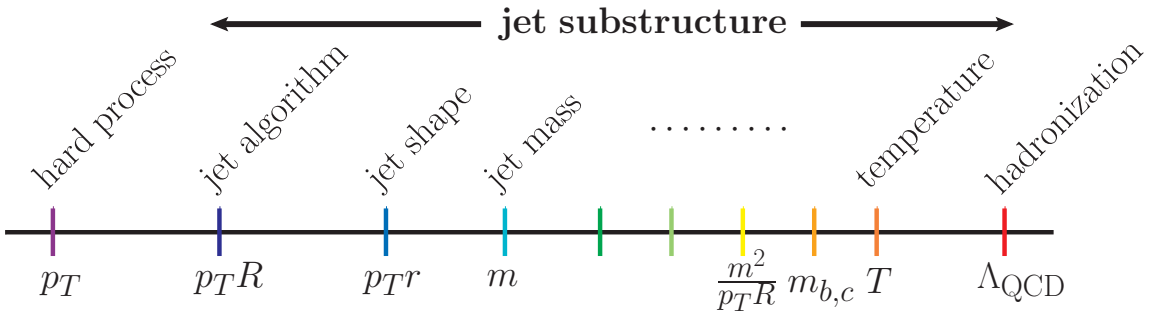
- General purpose detector in the forward region ($2 < \eta < 5$)
- Charged particle identification
- Impact parameter resolution $15+29/p_{\mathrm{T}}$ [GeV]
- Muon reconstruction for resonance states
- Full jet reconstruction with tracking, ECAL and HCAL + Tagging of jets from light-quark, c- and b-quark

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

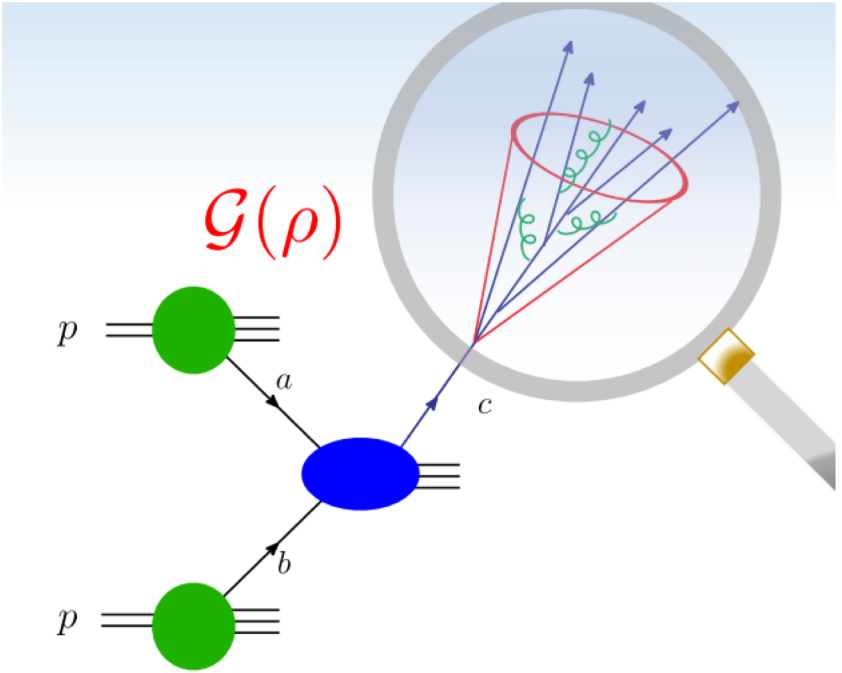


Jets and their substructure

- Jet substructure ρ
- Jet mass
- Jet angularity
- fragmenting jet function (FJF)
- TMD FJF
- …



Courtesy by Y-T Chien



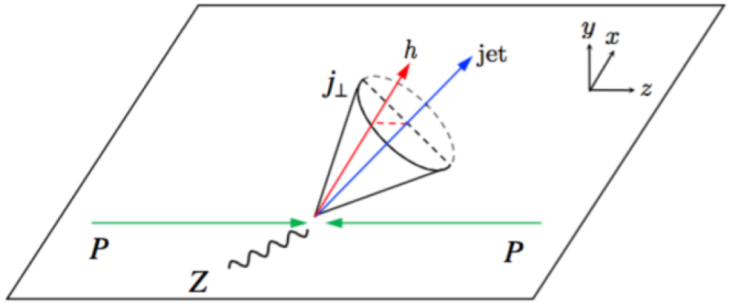
$$\frac{d\sigma^{pp\to jet\,(\rho)X}}{dp_T d\eta\, d\rho} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c(\rho)$$

PRD **81** (2010) 074009, Procura, Stewart
PRD **92** (2015) 054015, Kaufmann, Mukherjee
JHEP **11** (2016) 155, Kang, Ringer, Vitev
JHEP **1804** (2018) 110, Kang, Lee, Ringer

Light quarks fragmenting into a jet

JHEP **05** (2011) 035
JHEP **11** (2017) 068
PLB **798** (2019) 134978

$gq \to Zq \to Z + \text{jet}$



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

$$\mathcal{G}^h_c(z_h, j_\text{T}, \dots) \propto \widehat{D}_{h/c}(z_h, j_\perp, \dots)$$

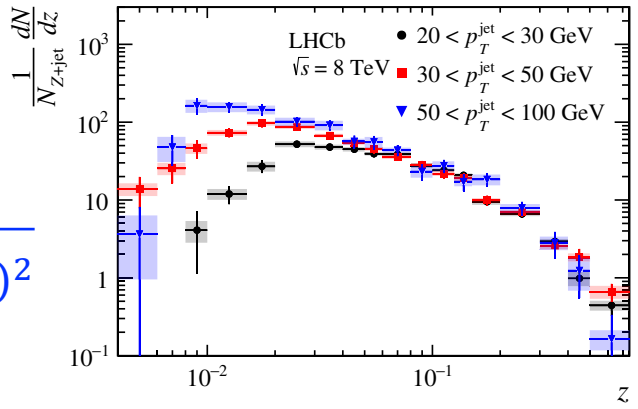
TMD FF

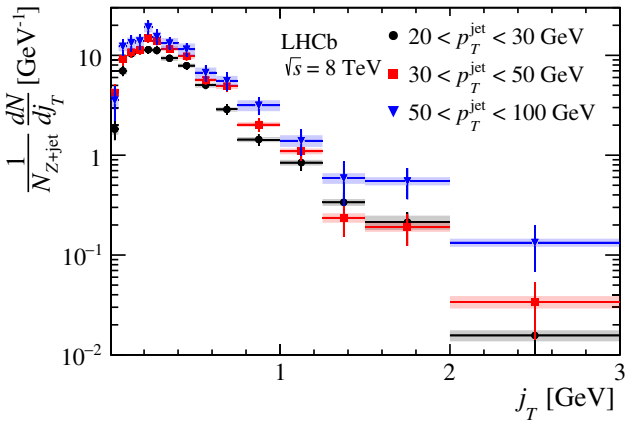
$$z = \frac{p_{jet} \cdot p_h}{|\, p_{jet}\,|^2}$$

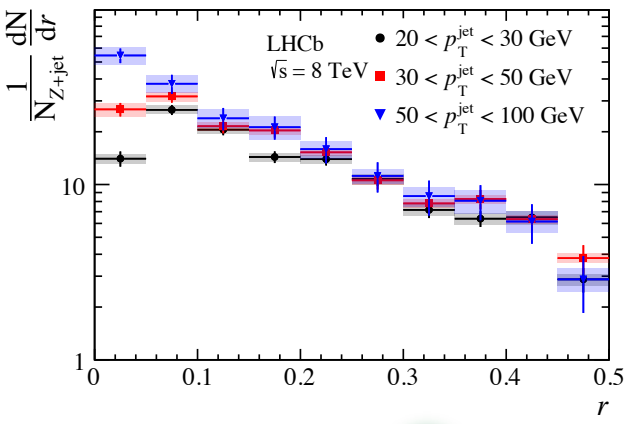
$$j_T = \frac{|\, p_{jet} \times p_h\,|}{|\, p_{jet}\,|}$$

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

PRL **123** (2019) 232001 1D measurements of nonidentified $h^\pm$ in Z+jets



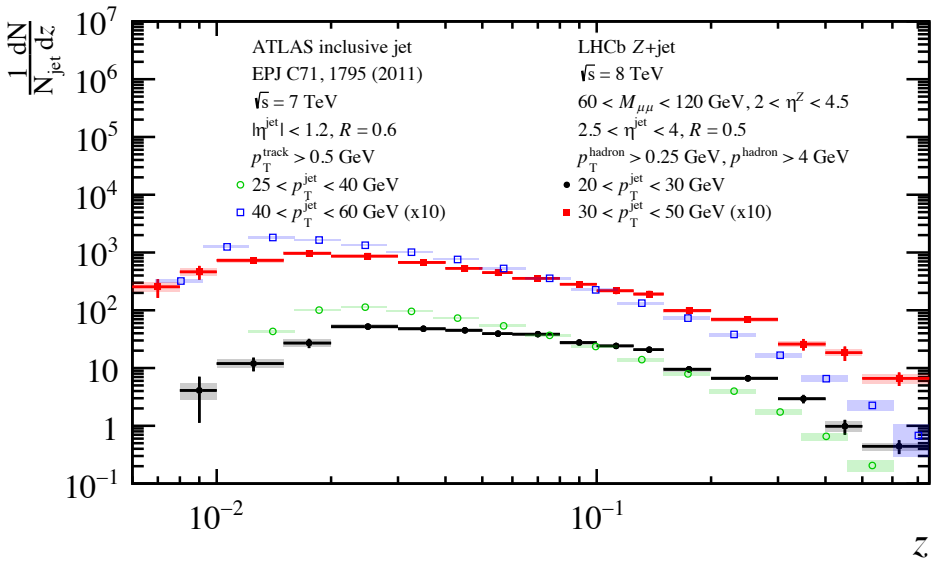




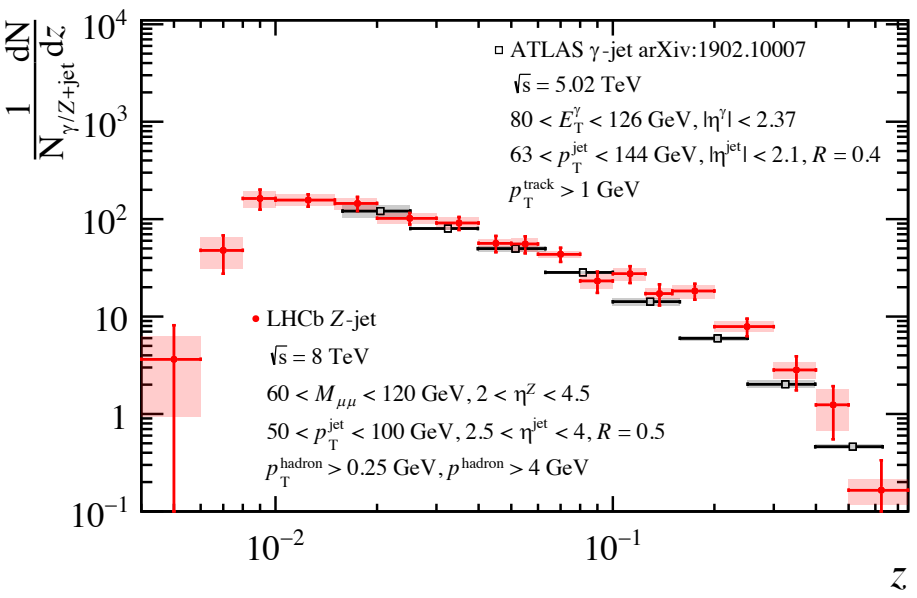
Gluon- vs. quark-initiated jets

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

PRL **123**, 232001 (2019) - Supplemental material



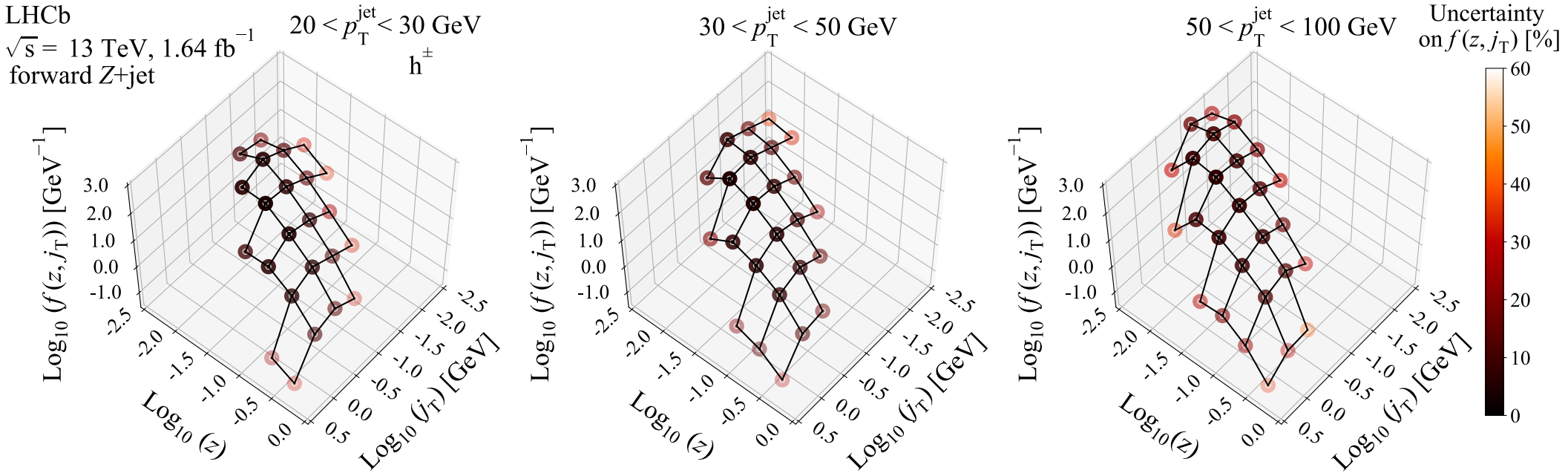
PRL **123**, 232001 (2019) - Supplemental material



TMD JFF for charged hadrons $h^{\pm}$

First multi-differential jet substructure measurements

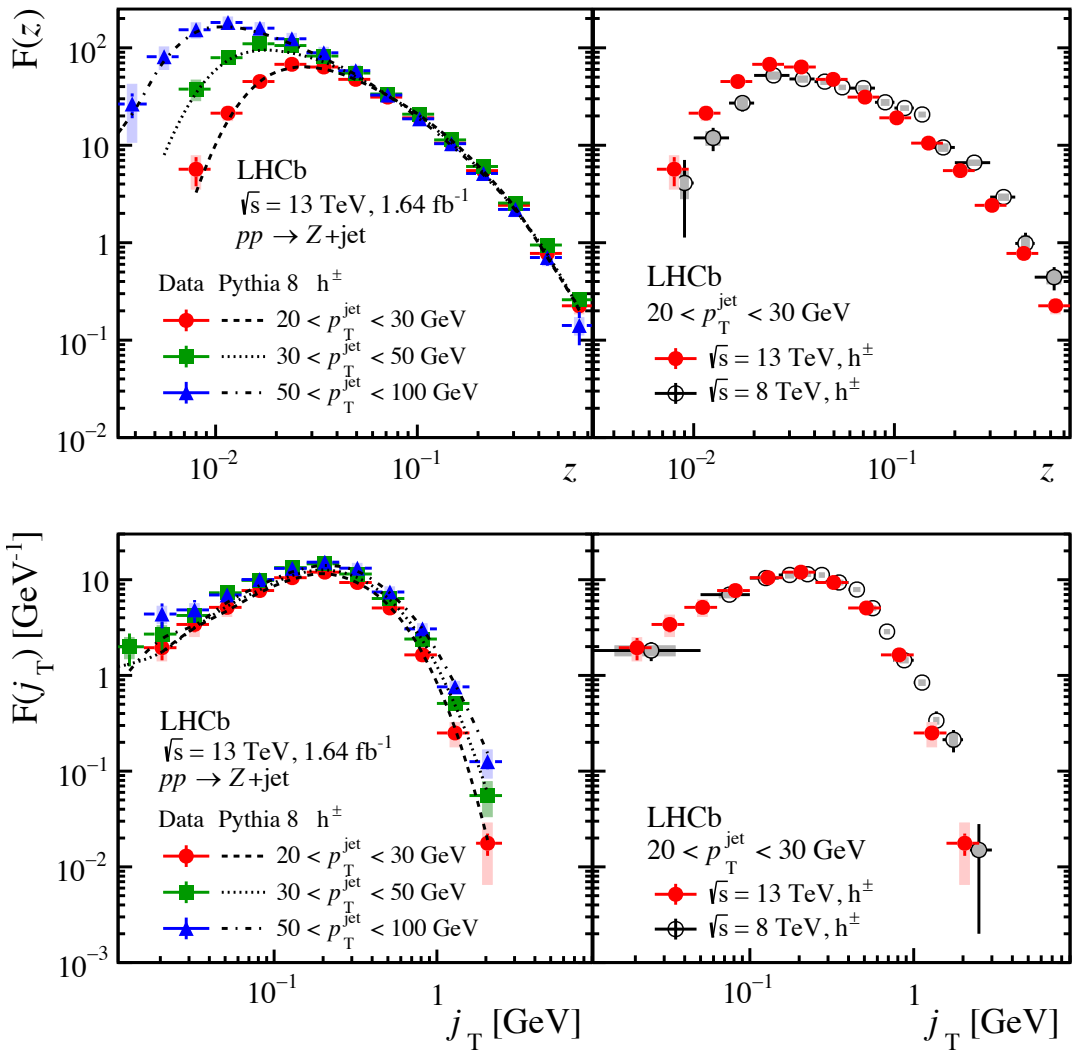
arxiv:2208.11691 (accepted by PRD Lett.)



- 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

Light-quark JFF at LHCb

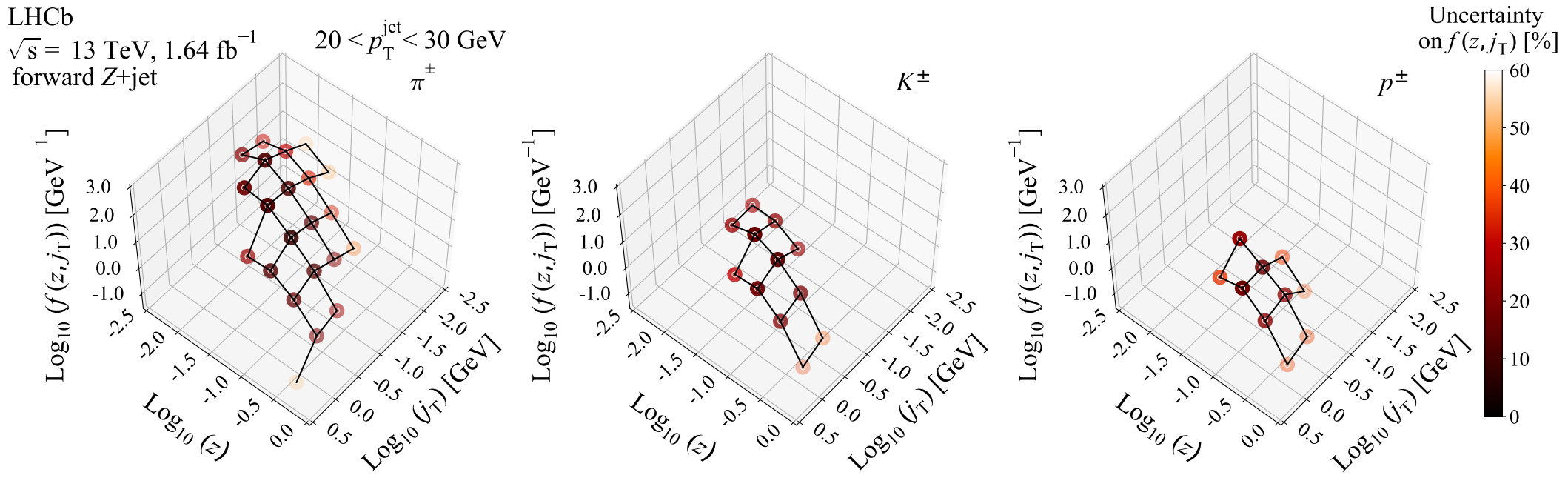
arxiv:2208.11691 (accepted by PRD Lett.)



- 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

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

arxiv:2208.11691 (accepted by PRD Lett.)

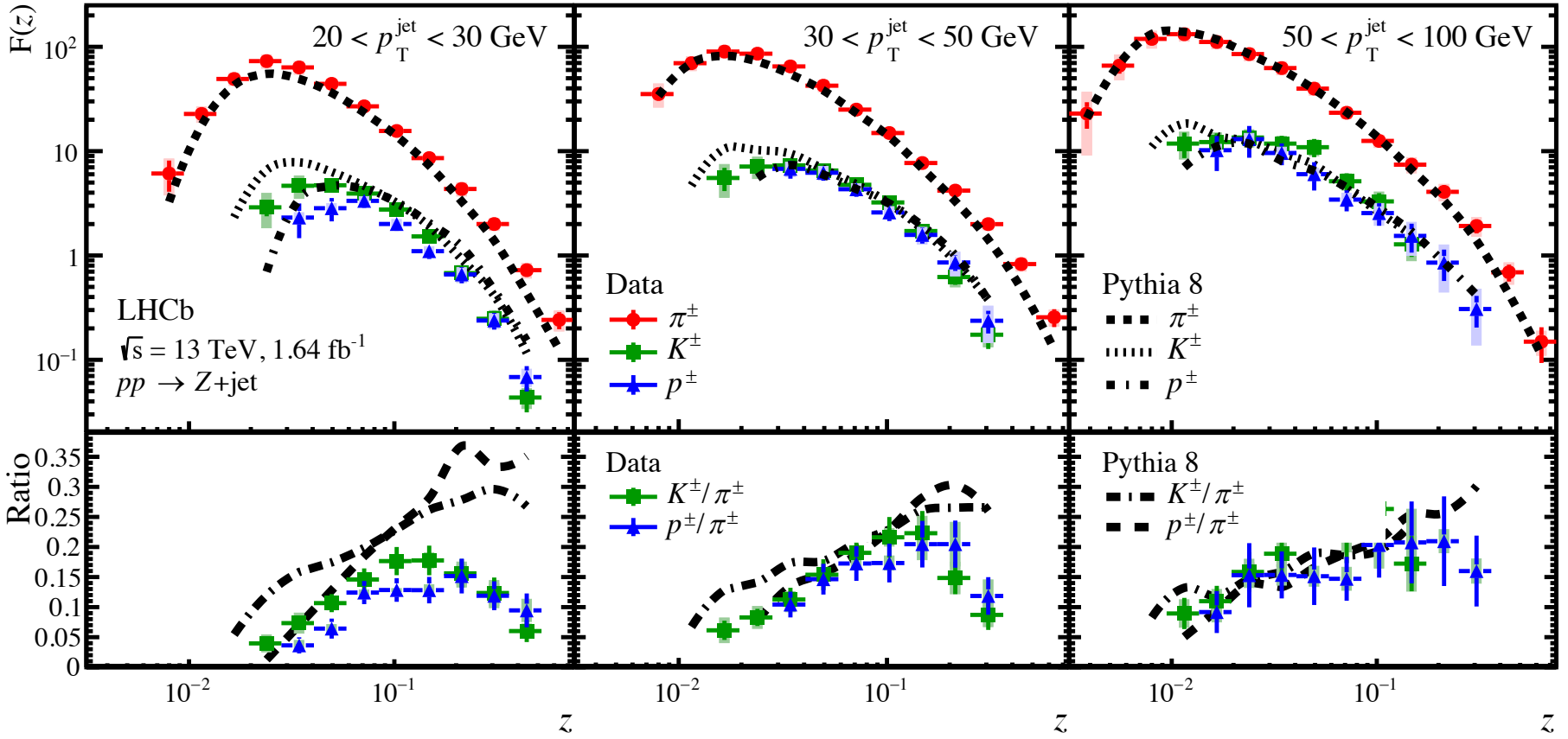


- Multidifferential distributions for pions, kaons and protons at 20 < jet p_{T} < 30 GeV/c
- Heavier hadrons produced from harder partons, i.e. larger j_{T} as well as larger z

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

arxiv:2208.11691 (accepted by PRD Lett.)

- 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

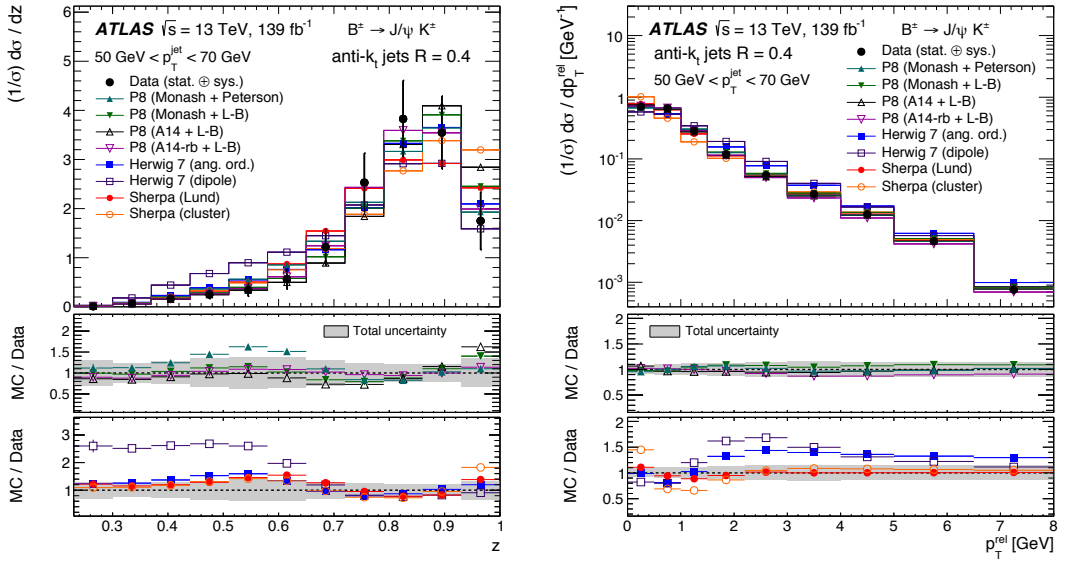


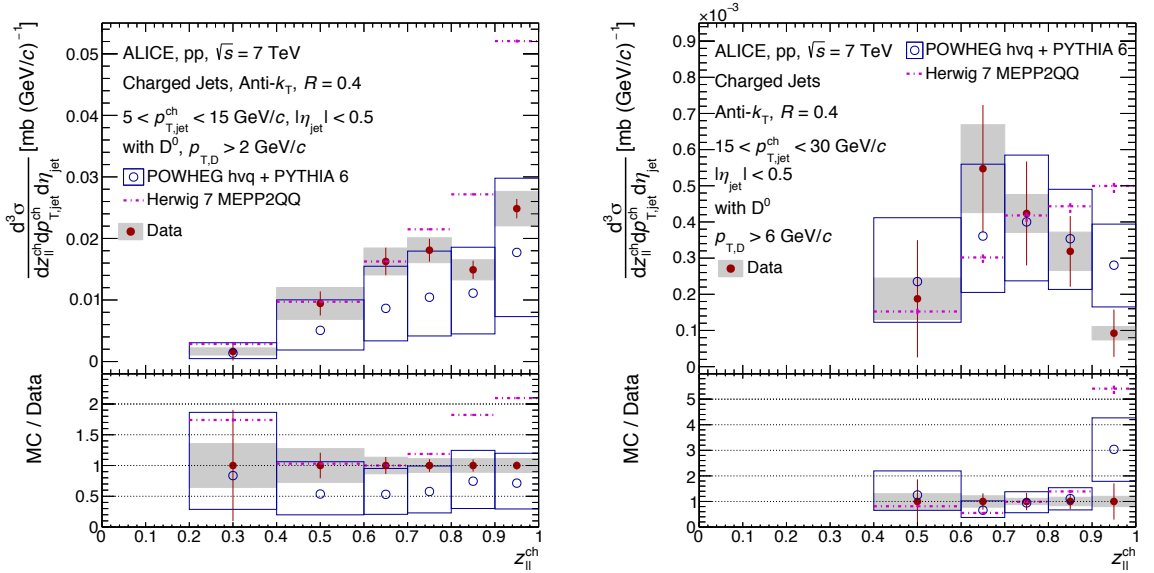
- In lowest jet p_T interval:
  - Proton production relative to kaons clearly suppressed at lower z
  - Pythia 8 overestimates $K^{\pm}, p^{\pm}$ production relative to $\pi^{\pm}$

Heavy quark TMD JFF

- Heavy quark (b and c) mass naturally enhances quark fragmentation into hadrons
- Collinear fragmentation studies exist from e^+e^- and $p\bar{p}$
- Heavy-quark jet fragmentation functions from pp most recently by ATLAS, CMS and ALICE
  - B^{+-}, $\mathrm{D}^{\star+-}$, D^0 and Λ_c
- Multi-differential analysis will allow for direct access to heavy-quark TMD

JHEP **12** (2021) 131 [ATLAS collaboration]





JHEP **08** (2019) 133 [ALICE collaboration]

b- and c-jet tagging @ LHCb

- Two classes of BDT

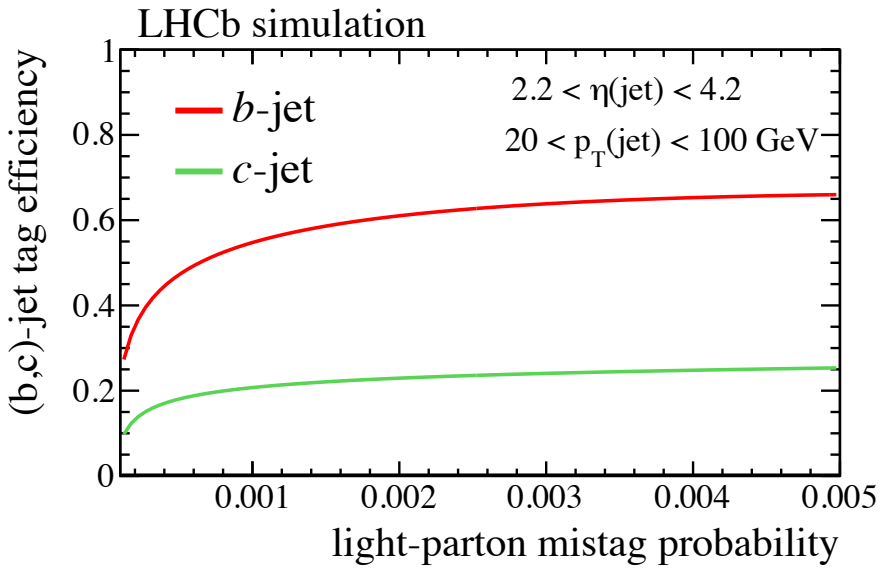
  BDT(bc|udsg) : b/c jets vs. light-quark jets

  BDT(b|c) : b-jets vs. c-jets

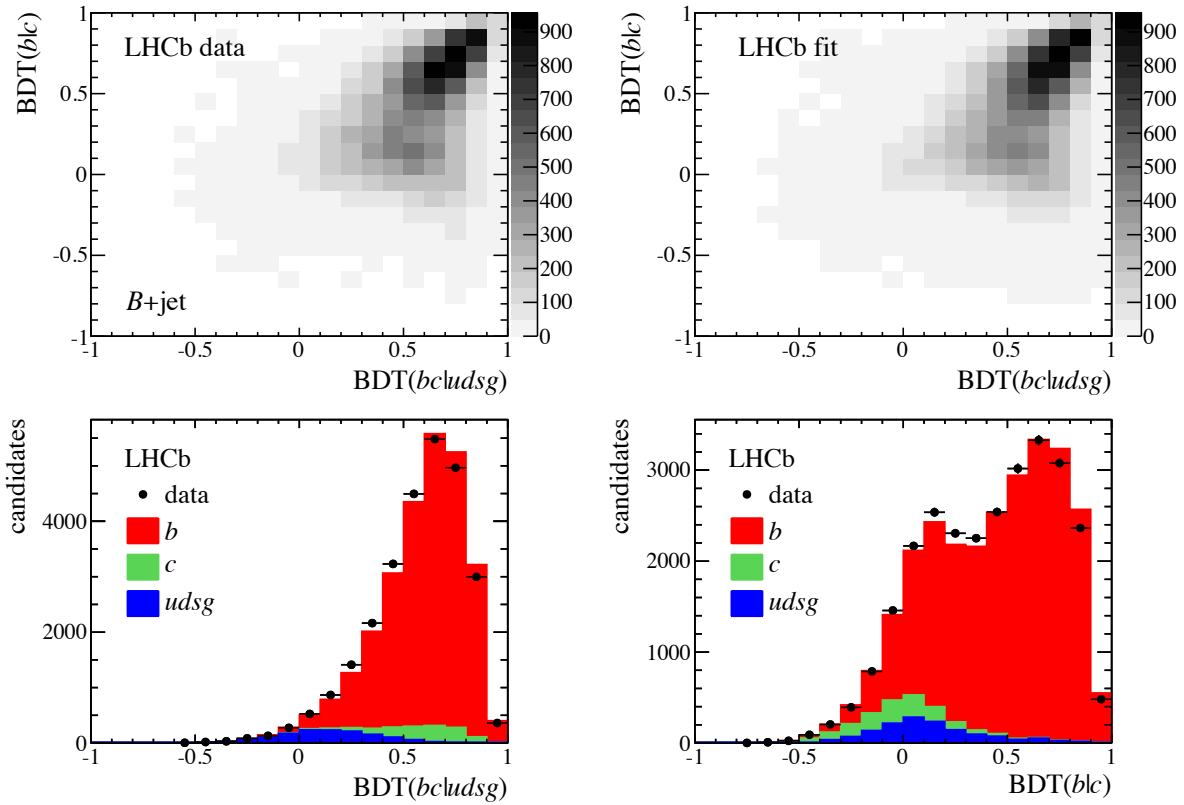
- Describe corrected mass and SV track multiplicity distributions at 1-2% level

$$M_{\mathrm{cor}} = \sqrt{M^2 + p^2 \sin^2\theta} + p\sin\theta$$

- Efficienty-mistagging performance



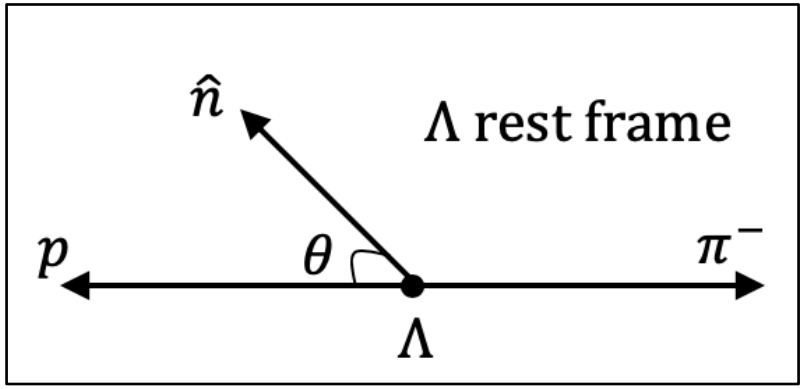
JINST **10** (2015) P06013 [LHCb collaboration]



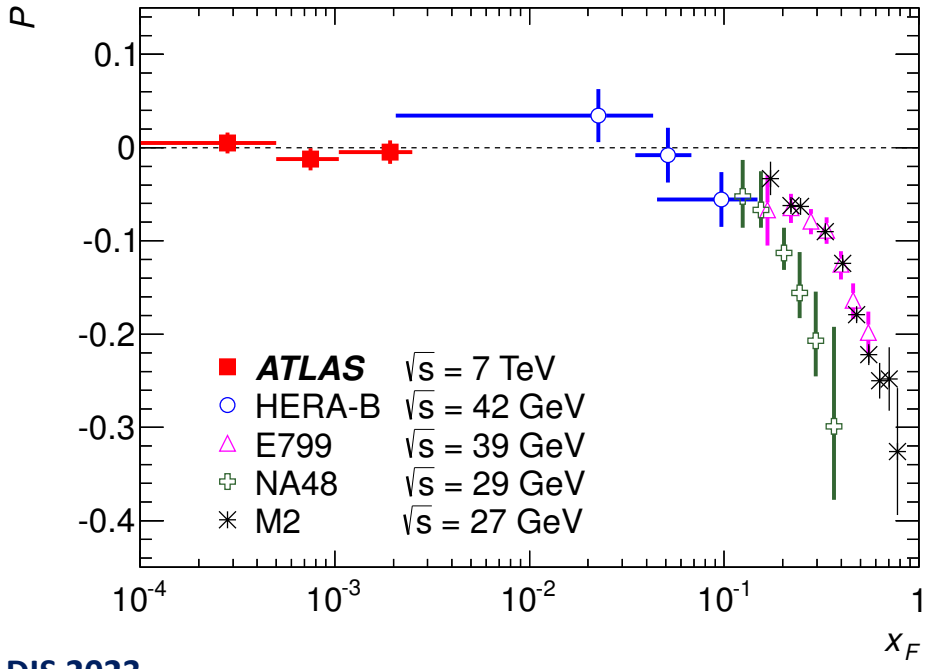
Spontaneous Λ hyperon polarization

- Transverse Λ ($\bar{\Lambda}$) polarization measured via self analyzing parity-violating decays to $p\pi^-$ ($\bar{p}\pi^+$)
- LO leading twist predicts transverse Λ polarization P_Λ suppressed by $\alpha_s m_q/Q^2$ PRL **41** (1978) 1689

$$\vec{n}_{lab} = \vec{p}_{beam} \times \vec{p}_\Lambda$$



$$\frac{d\Gamma}{d\cos\theta} = \frac{\Gamma}{2}(1 + \alpha_{PV} P_\Lambda \cos\theta)$$



PRD **91** (2015) 032004 [ATLAS collaboration]

- The *probability densities* for finding hadrons from *unpolarized* partons is encoded in

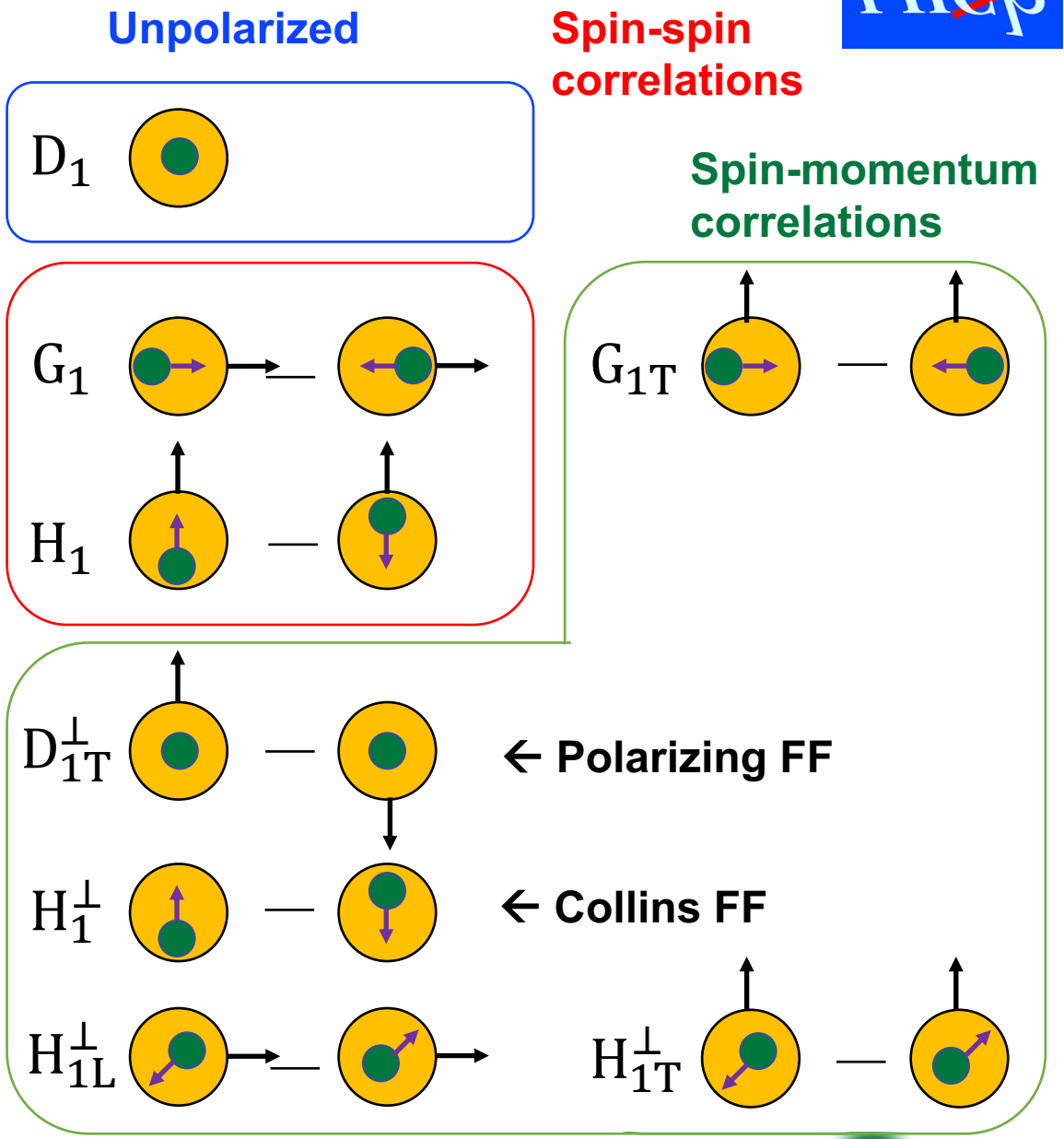
  Collinear fragmentation functions $D_i^h(z)$

  or ***TMD fragmentation functions*** $D_i^h(z, k_T)$

- The *probability densities* for finding *polarized* hadrons from *unpolarized* partons is encoded in

  TMD polarizing FF $D_{1T}^{\perp}(z, k_T)$

: Λ polarization and TMD FF



See talk by C Nunez March 29 in WG5

Summary and outlook

- ❑ **Multi-differential TMD JFF** measured for charged pions, kaons and protons for the first time
- Results shed lights on role of hadron mass and valence quark contents of proton in hadronization processes within jets
- Heavier hadrons are produced from harder partons.
- Hadrons carrying larger jet momentum fraction in longitudinal direction tend to carry larger transverse momentum w.r.t. jet axis as well.
- Confirm some of features shown in measurements at lower $\sqrt{s}$ = 8 TeV.

- ❑ Hadronization in **heavy flavor jet** measurements most suitable at LHCb due to abundant statistics and heavy-quark tagging capabilities.
- Measurements of charged hadrons in b-tagged and c-tagged jets underway
- Measurements of fully reconstructed D and B mesons in jets getting started

- ❑ Parity-violating **Lambda polarization** is sensitive to polarizing FF
- Measurements using pp, pPb and fixed target p-gas data underway

Thank you!