Studying hadronization at LHCb

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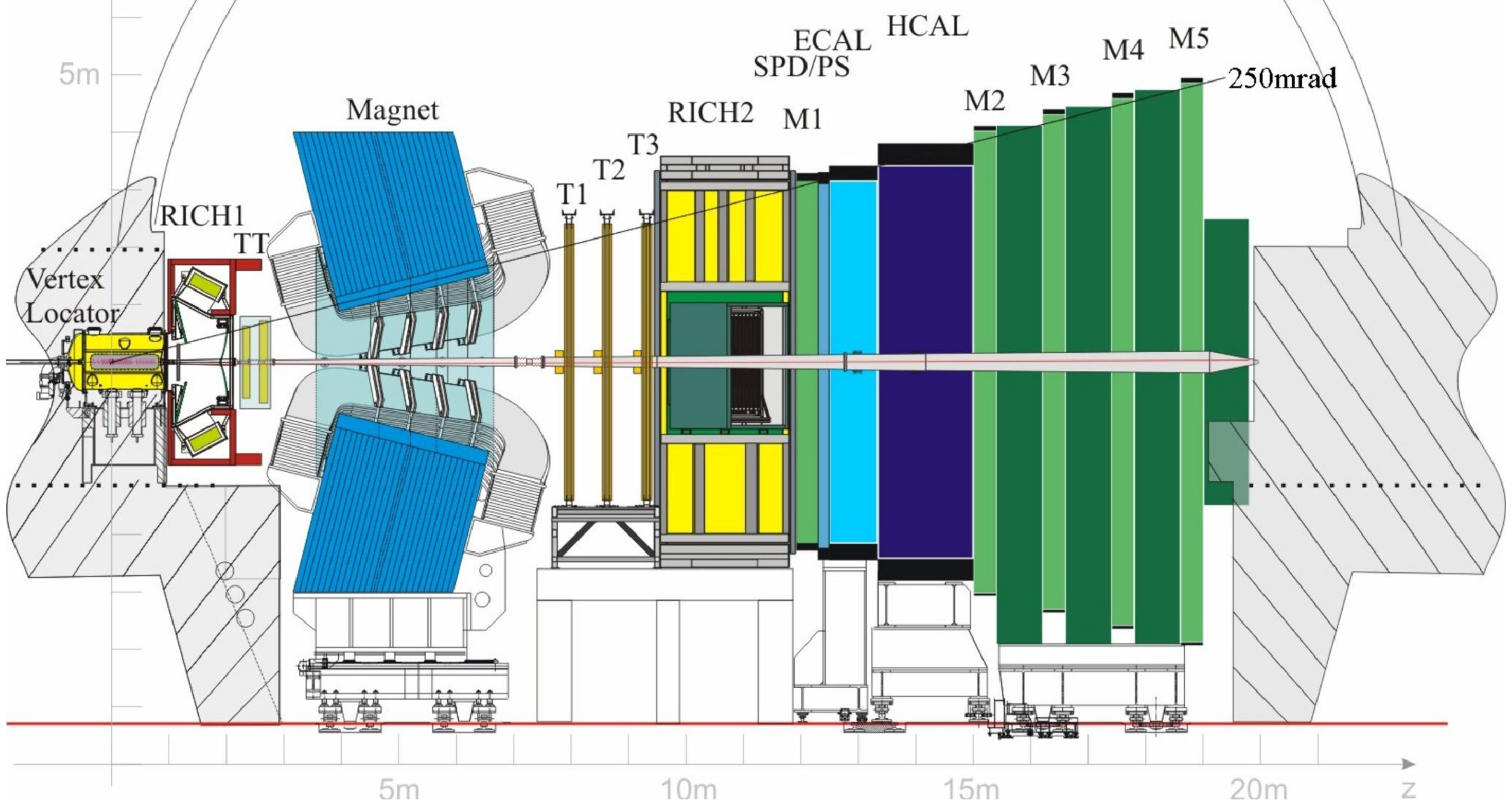
On behalf of the LHCb Collaboration

The LHCb detector



Good tracking and hadronic PID.

π/K separation $\gtrsim$**90%** up to $p = 60$ GeV$/c$

Vertexing and muon ID for heavy flavor tagging.

impact parameter resolution $\sim$ **15** $\boldsymbol{\mu}$**m** at high p_T

EM and hadronic calorimetry, for jet reconstruction.

} heavy flavor jet tagging

65% *b*-tag efficiency
25% *c*-tag efficiency
0.3% light jet mistag rate

... and every subdetector covers $\mathbf{2 < \boldsymbol{\eta} < 5}$.

Image and stats from: arXiv:1412.6352 / Int. J. Mod. Phys. A **30** 1530022 (2015).

Which sorts of hadronization physics do we do with this detector?

Transverse momentum-dependent jet structure → 1904.08878

... with identified hadrons → forthcoming

... with heavy flavor jets → forthcoming

J/ψ polarization puzzle → 1307.6379, 1701.05116

... and Υ's in jets → forthcoming

Forward Λ polarization puzzle → forthcoming

Λ_b^0-$\bar{\Lambda}_b^0$ production asymmetry → 2107.09593

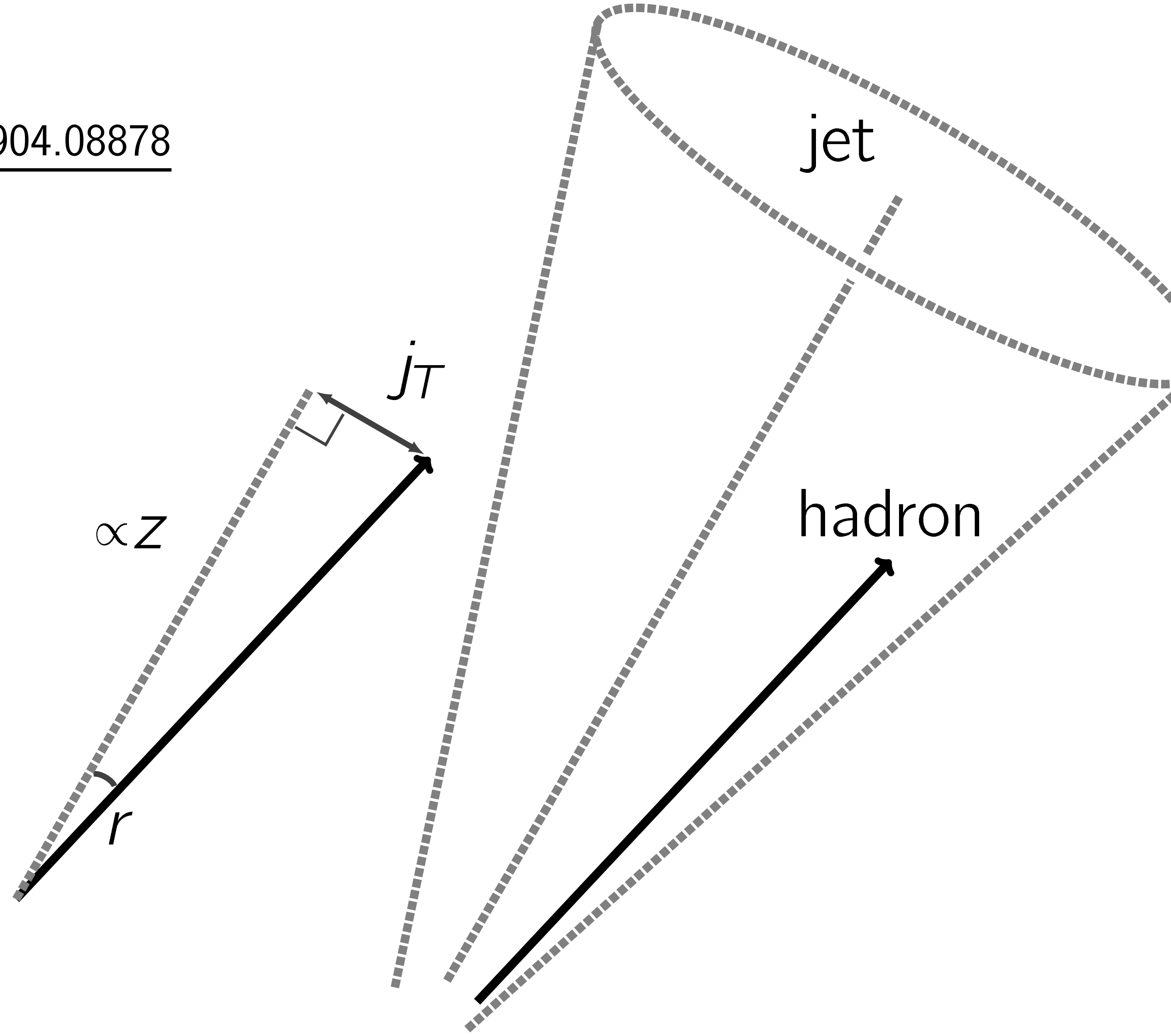
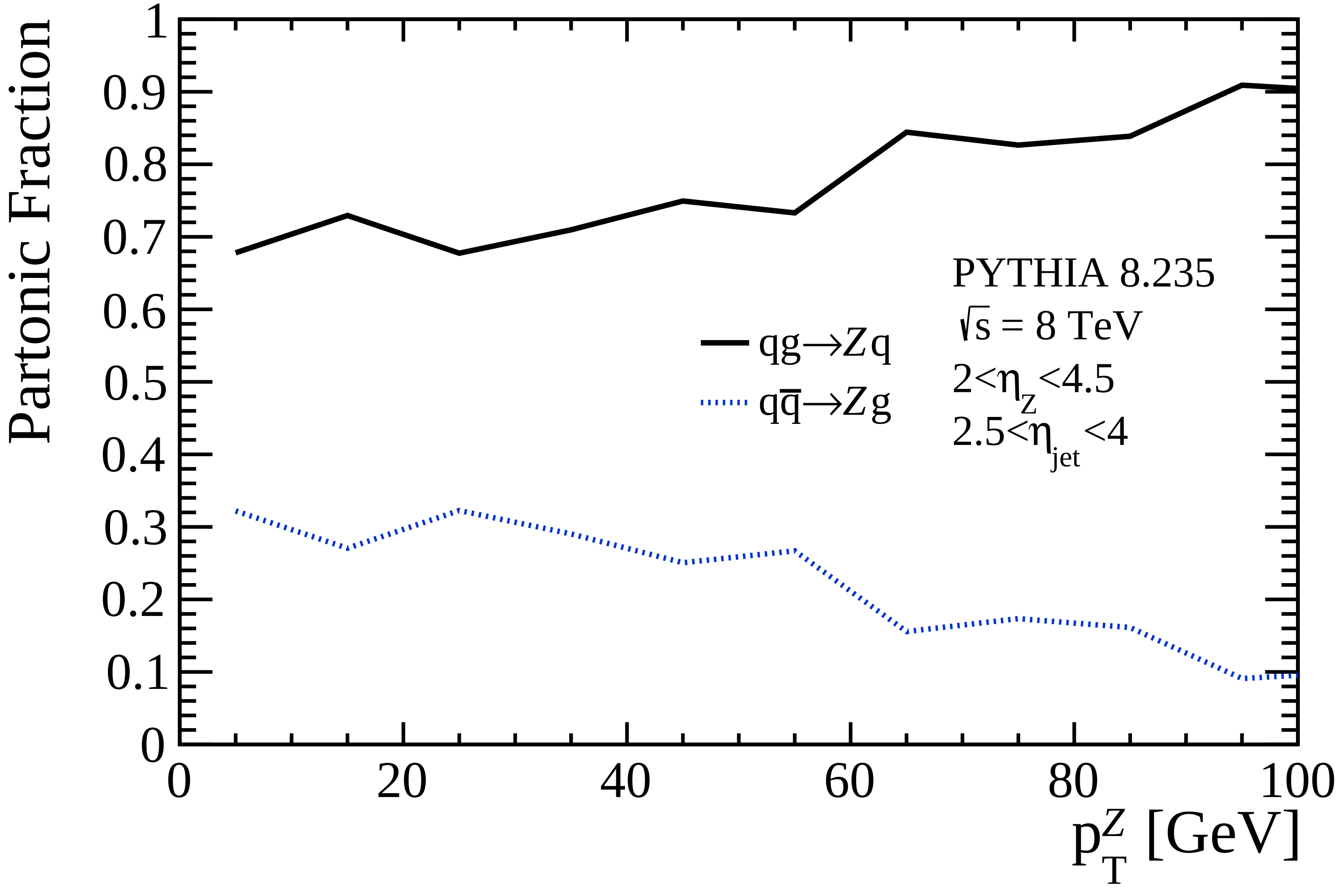


Figure: TMD jet structure variables. It's like an FF in 3D.

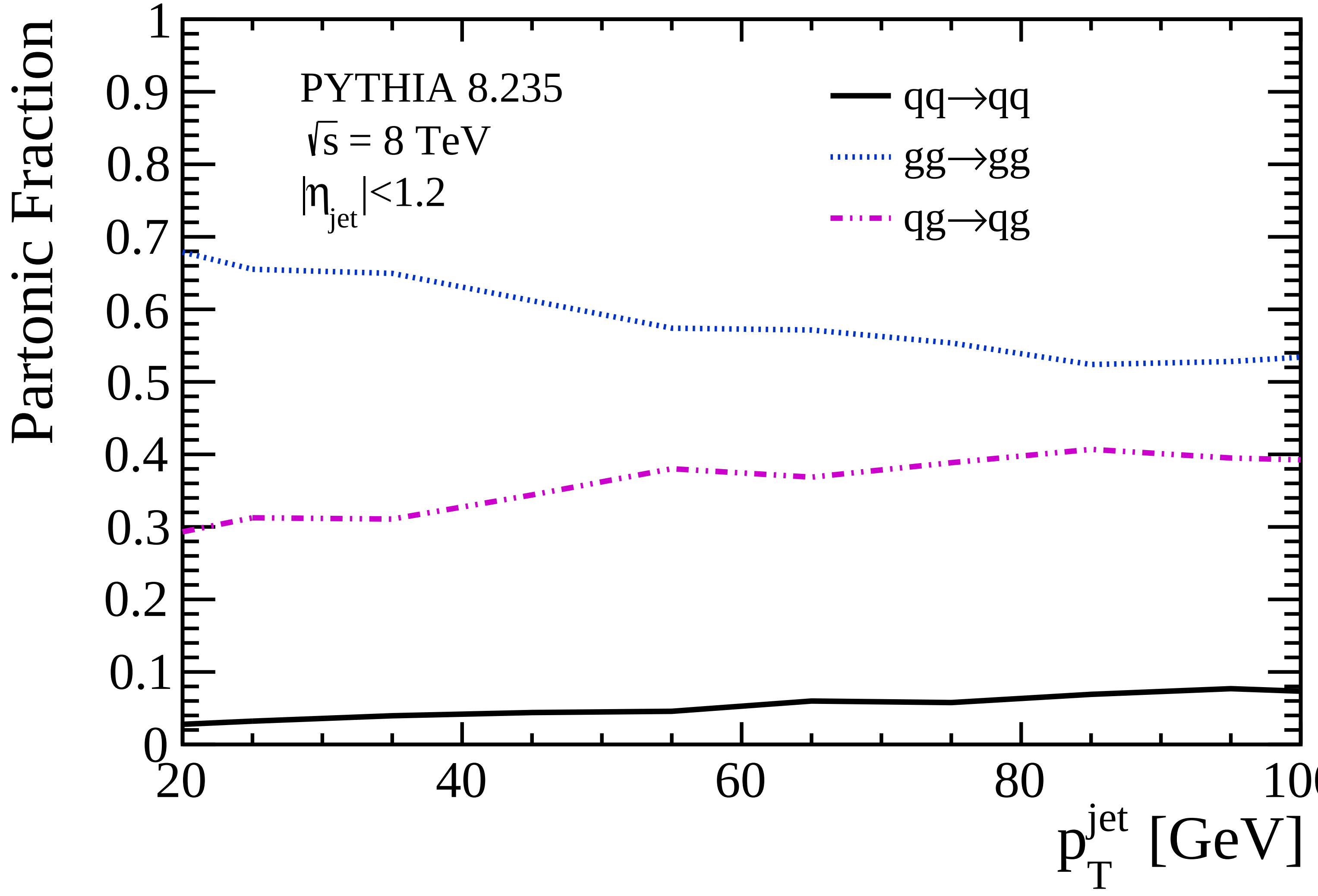
$$z = \frac{\boldsymbol{p}^h \cdot \boldsymbol{p}^j}{\boldsymbol{p}^j \cdot \boldsymbol{p}^j} \ , \ \boldsymbol{j}_T = \boldsymbol{p}^h \times \frac{\boldsymbol{p}^j}{|\boldsymbol{p}^j|} \ , \ r^2 = (\phi^h - \phi^j)^2 + (\eta^h - \eta^j)^2 \ .$$

TMD jet structure at LHCb

LHCb Z-tagged jets



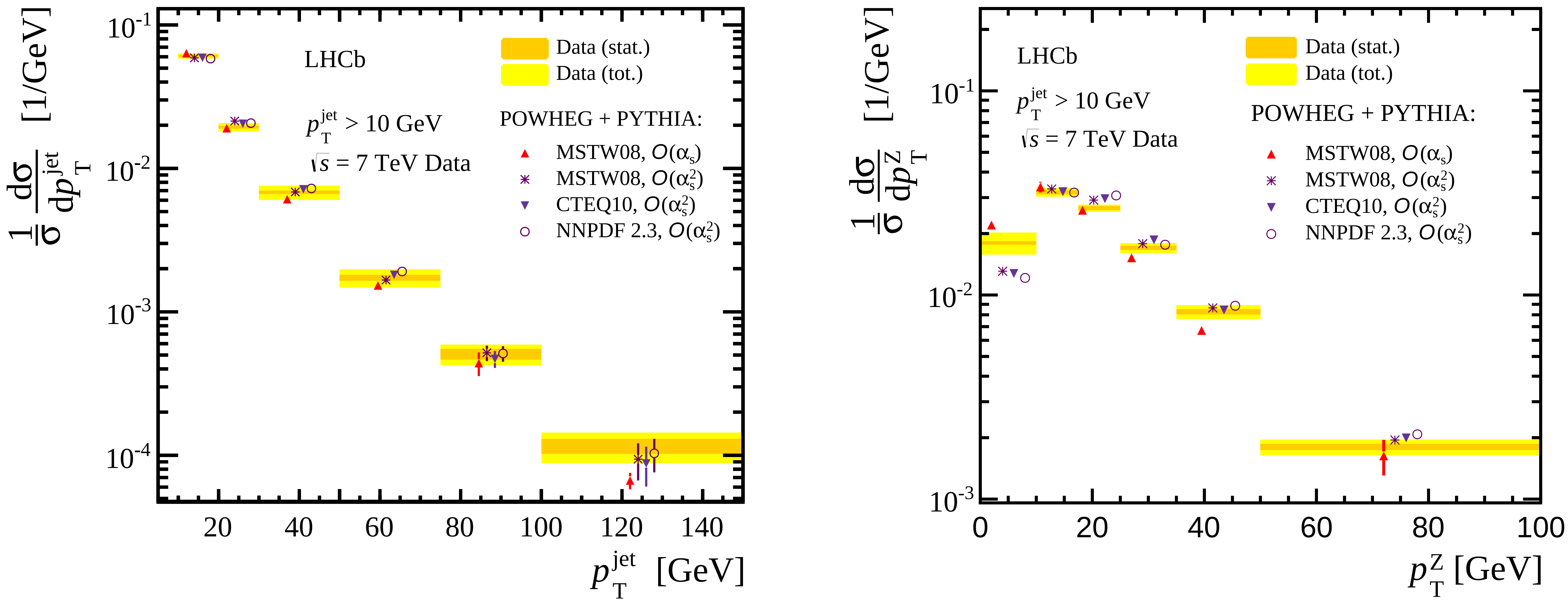
ATLAS inclusive jets



Compare LHCb and ATLAS : compare mostly **quark jets** and mostly **gluon jets**.

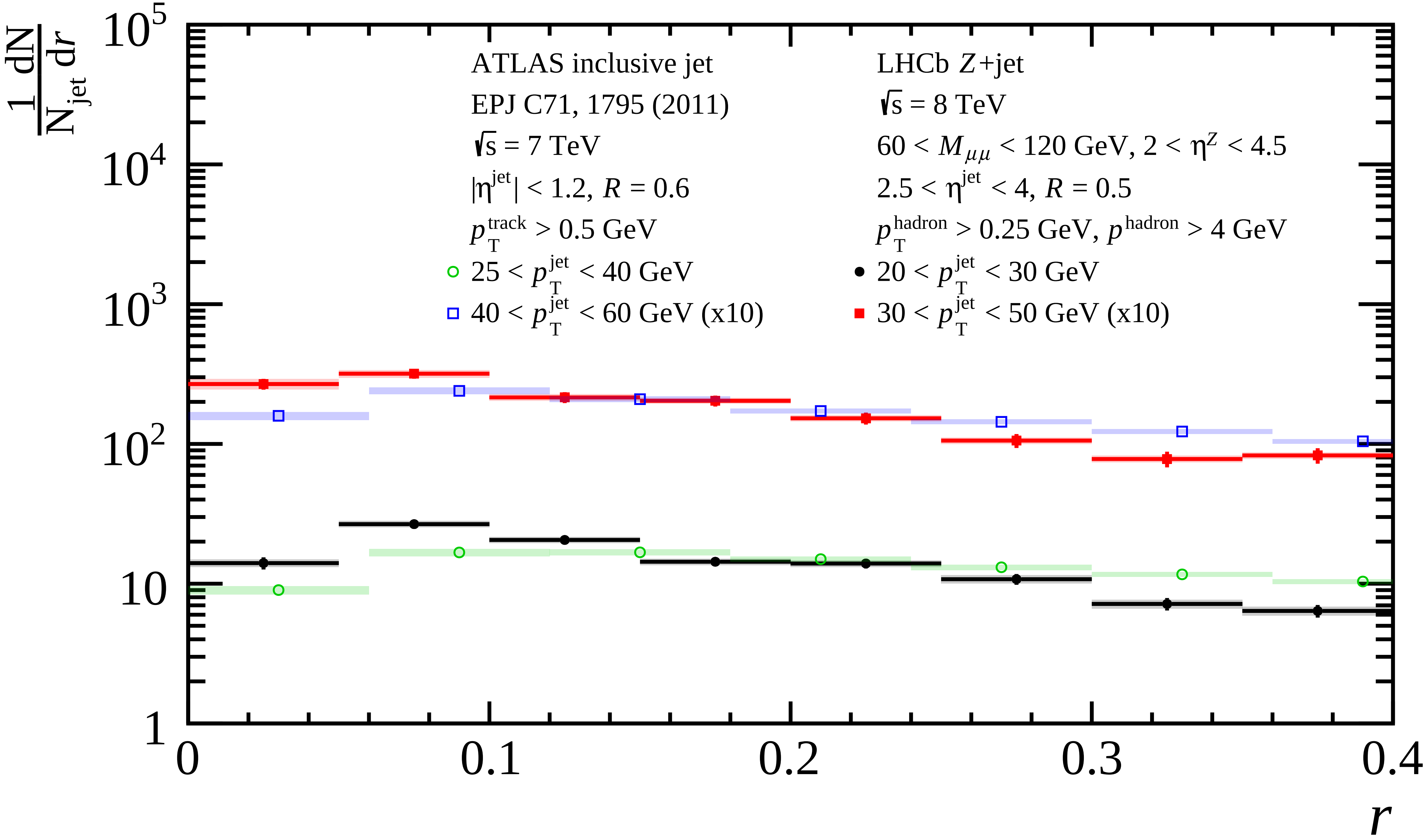
Figures from: arXiv:1904.08878 / PRL **123** 232001 (2019).

TMD jet structure at LHCb



Forward detector: jets at LHCb also tend to access lower p_T than jets at ATLAS or CMS.

TMD jet structure at LHCb



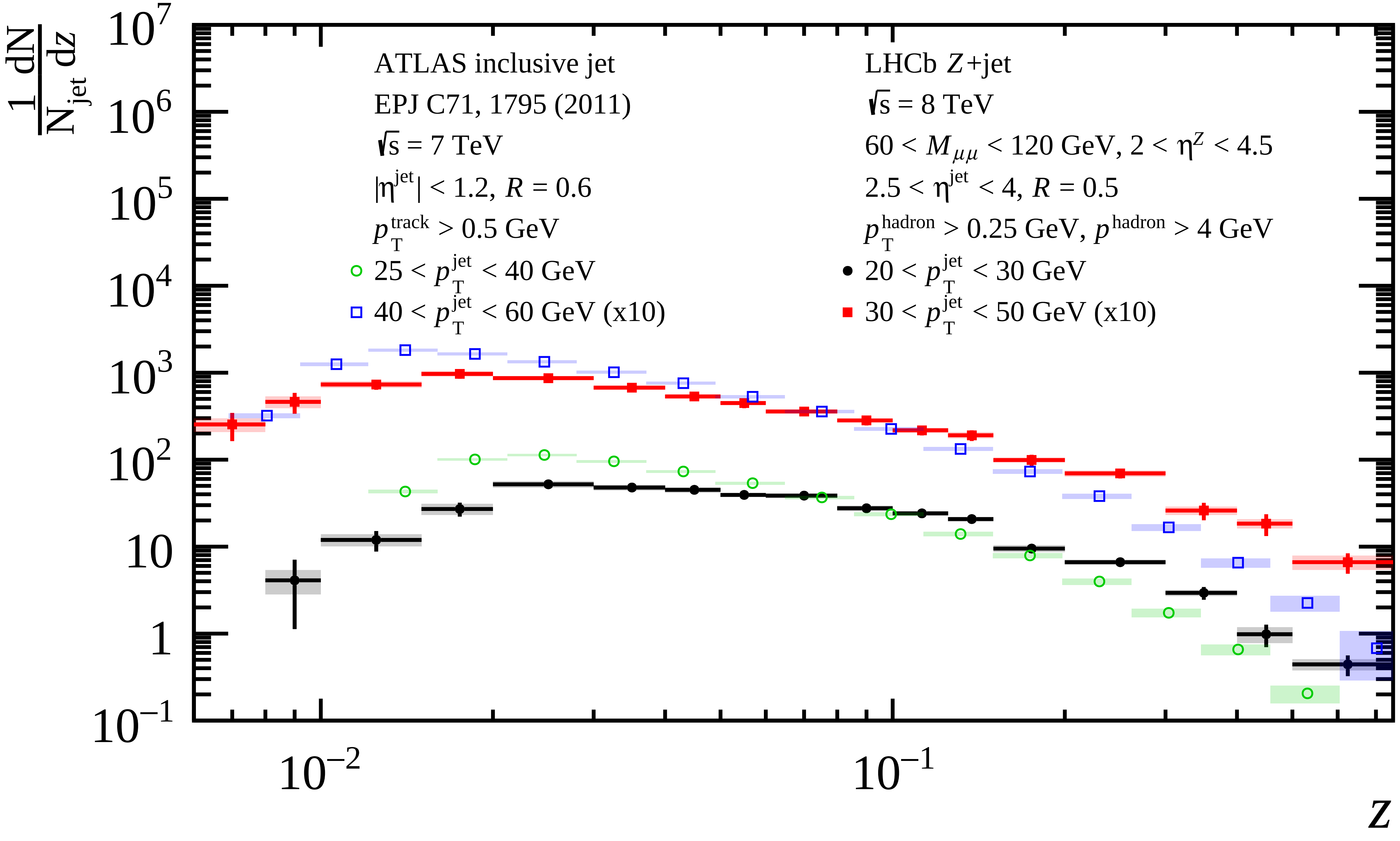
red/black: *q*-jets

blue/green: *g*-jets

Quark jets have a denser core: quantitative measurements match qualitative expectations.

Figure from: arXiv:1904.08878 / PRL **123** 232001 (2019).

TMD jet structure at LHCb

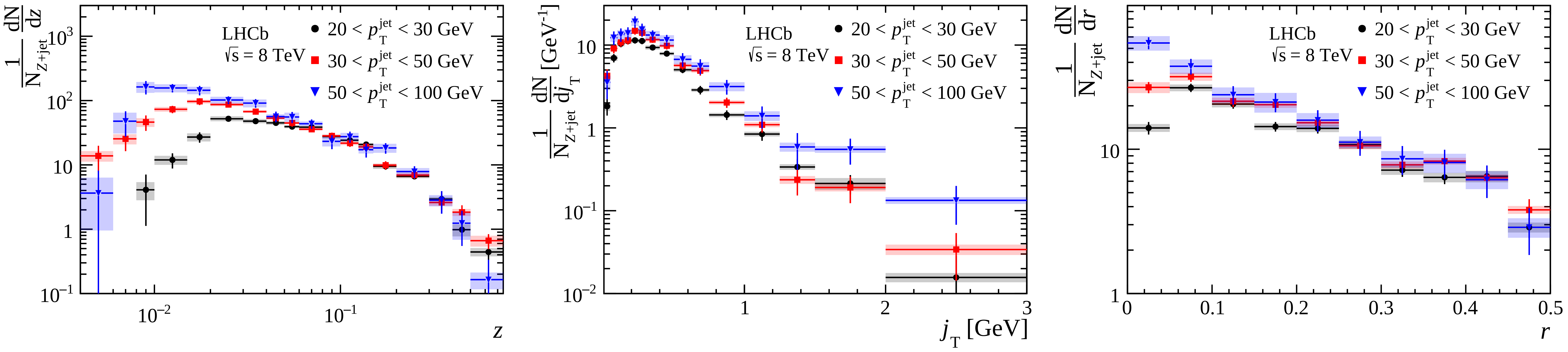


red/black: *q*-jets

blue/green: *g*-jets

Quark jets tend to make harder fragments. Quantitatively confirms expectations.

TMD jet structure at LHCb



All in all: a suite of new TMD measurements from a unique kinematic region.

Figures from: arXiv:1904.08878 / PRL **123** 232001 (2019).

Which sorts of hadronization physics do we do with this detector?

Transverse momentum-dependent jet structure → 1904.08878

The **first step** in LHCb's jet substructure program.

... with identified hadrons → forthcoming
... with heavy flavor jets → forthcoming

} Similar, but also leverage the LHCb detector's strengths.

J/ψ polarization puzzle → 1307.6379, 1701.05116

... and Υ's in jets → forthcoming

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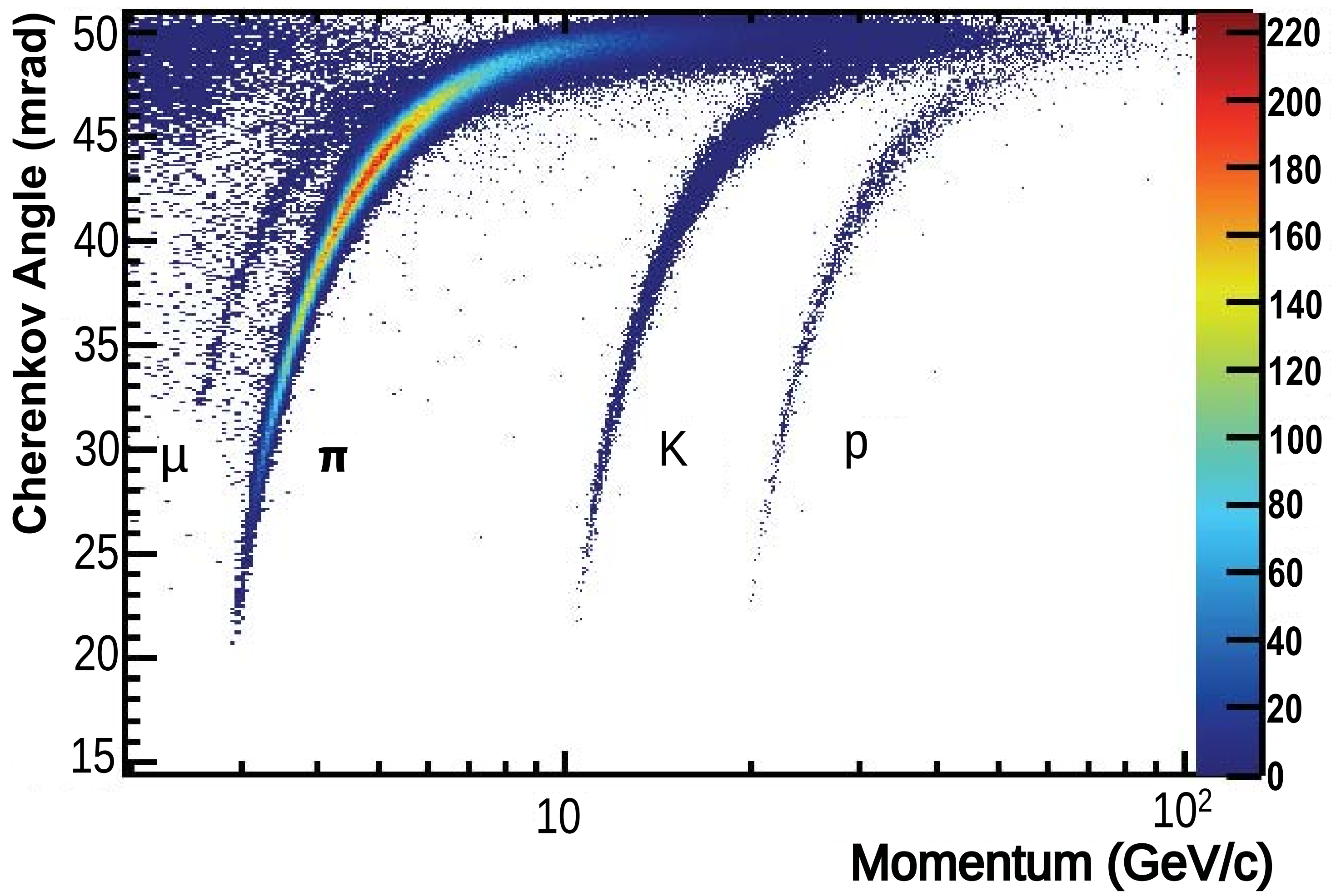
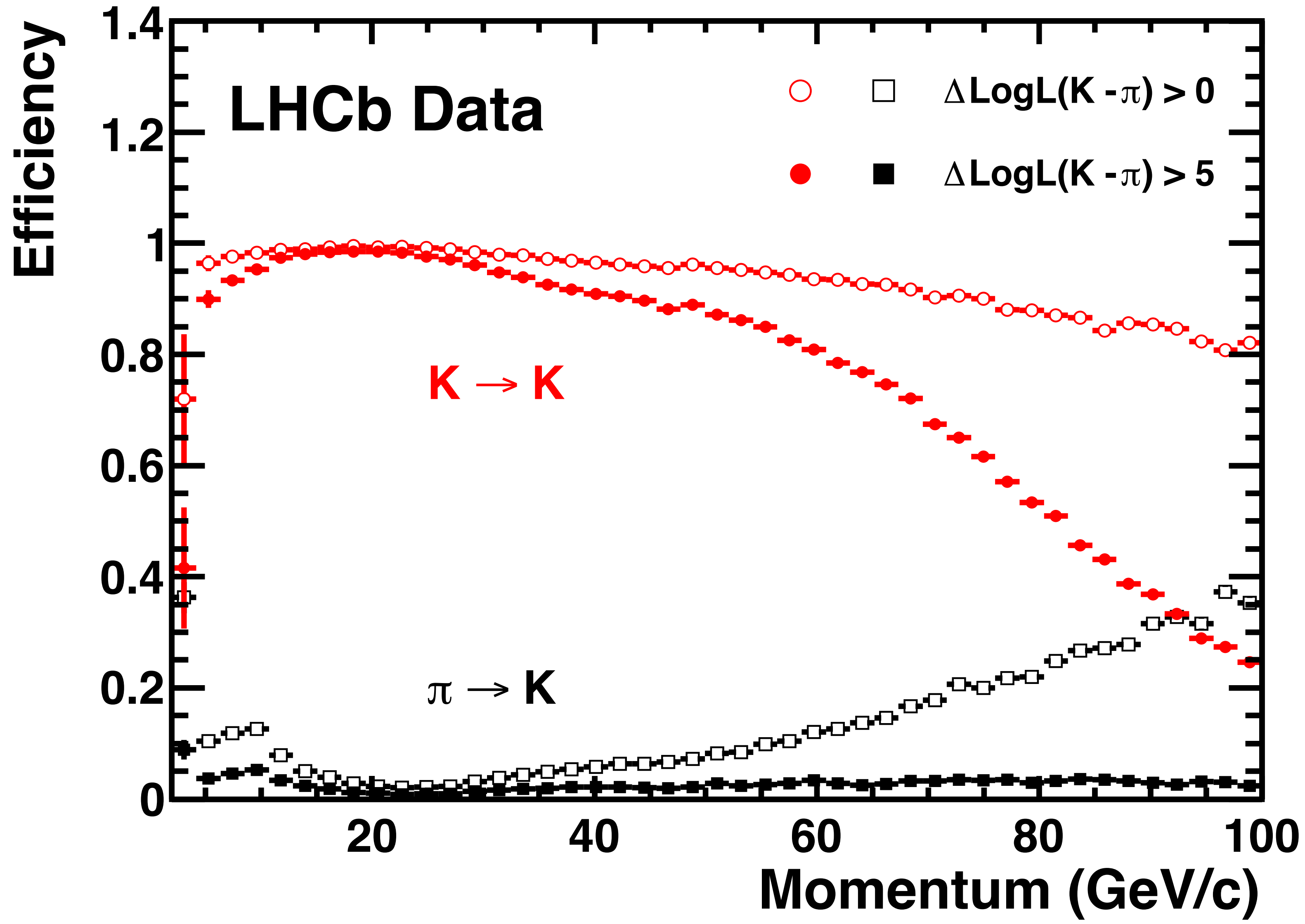
Identified hadrons in jets: particle ID at LHCb



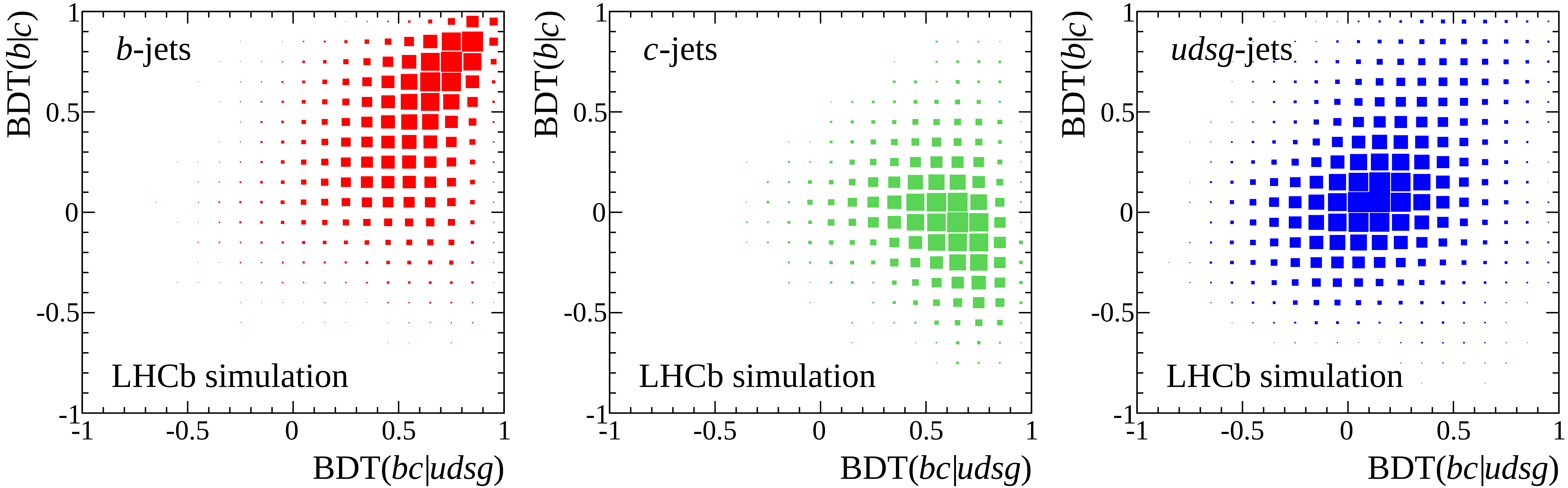


The hadronic PID comes from two Cherenkov detectors, with three diffractive media.

Use to make TMD fragmentation distributions for each hadron species.

Figures from: arXiv:1412.6352 / Int. J. Mod. Phys. A **30** 1530022 (2015).

Heavy flavor jet structure: tagging performance at LHCb



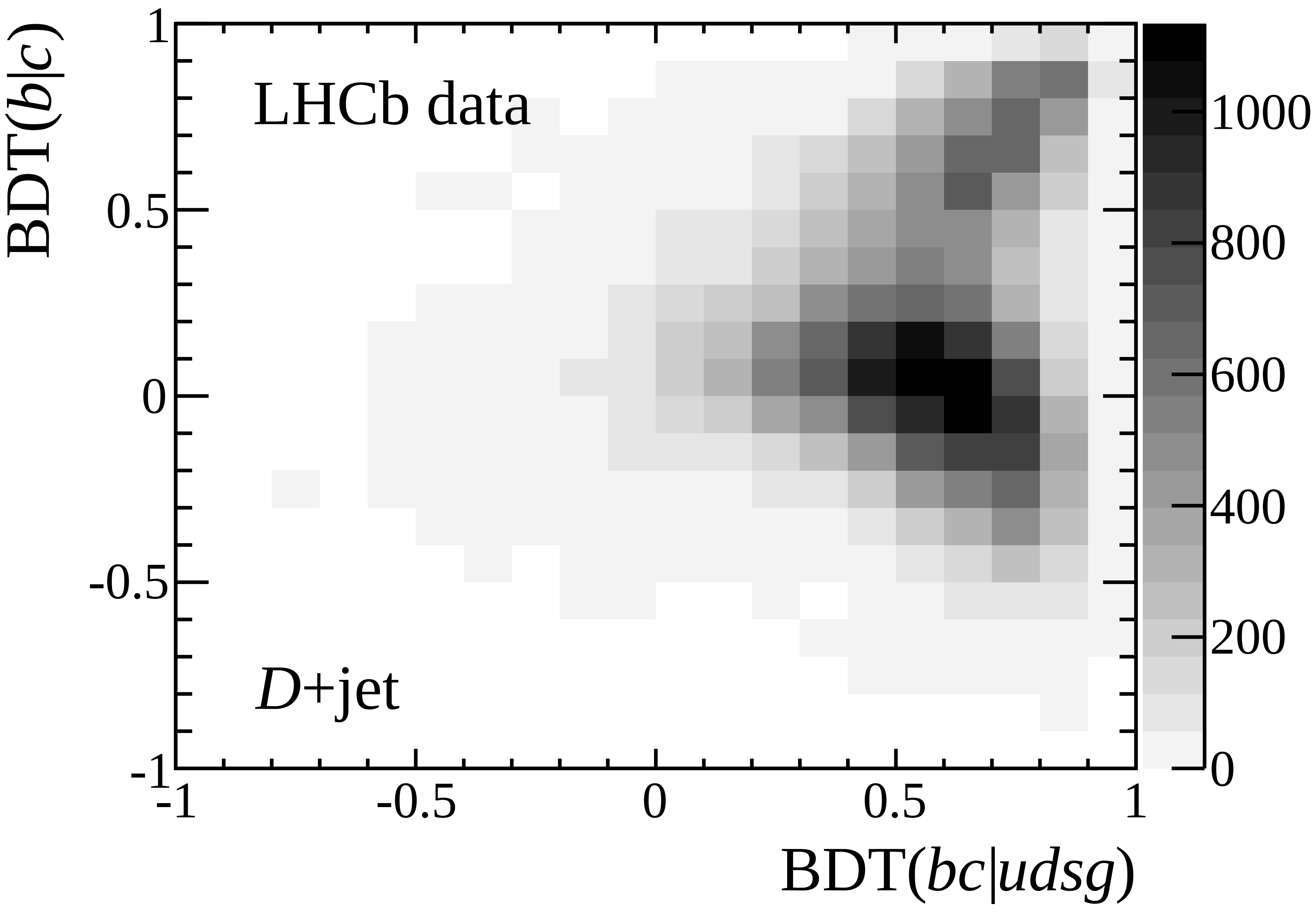
Tagger takes jets with a **well-separated decay vertex**: uses mass, flight distance, net charge, daughter count, and similar to tag **"heavy or light" and "*b* or *c*."**

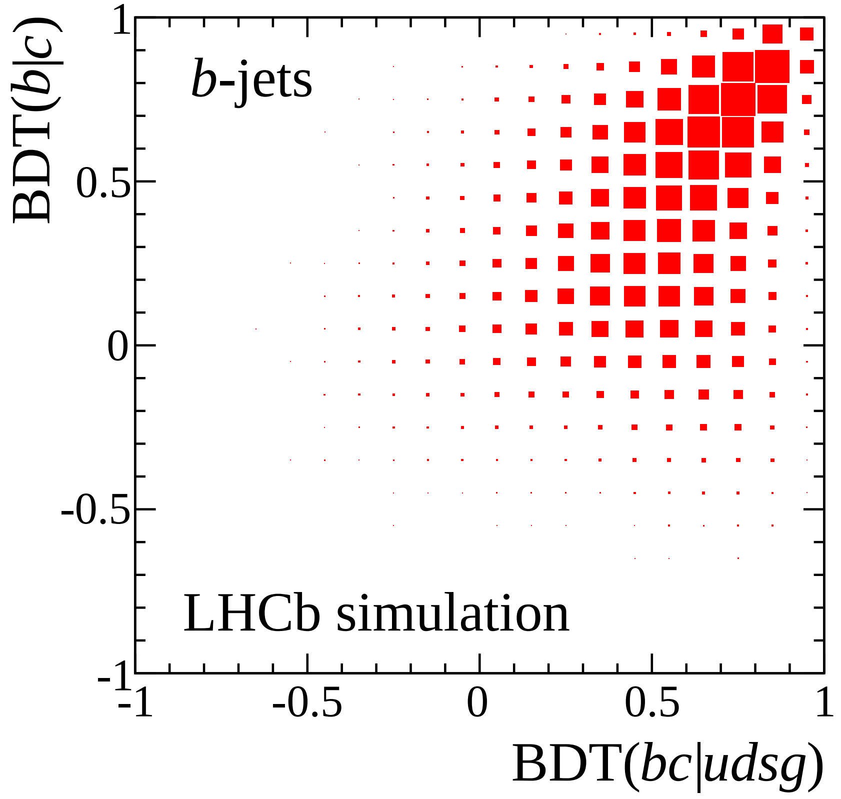
Output distributions are different enough to statistically extract yield fractions with fits.

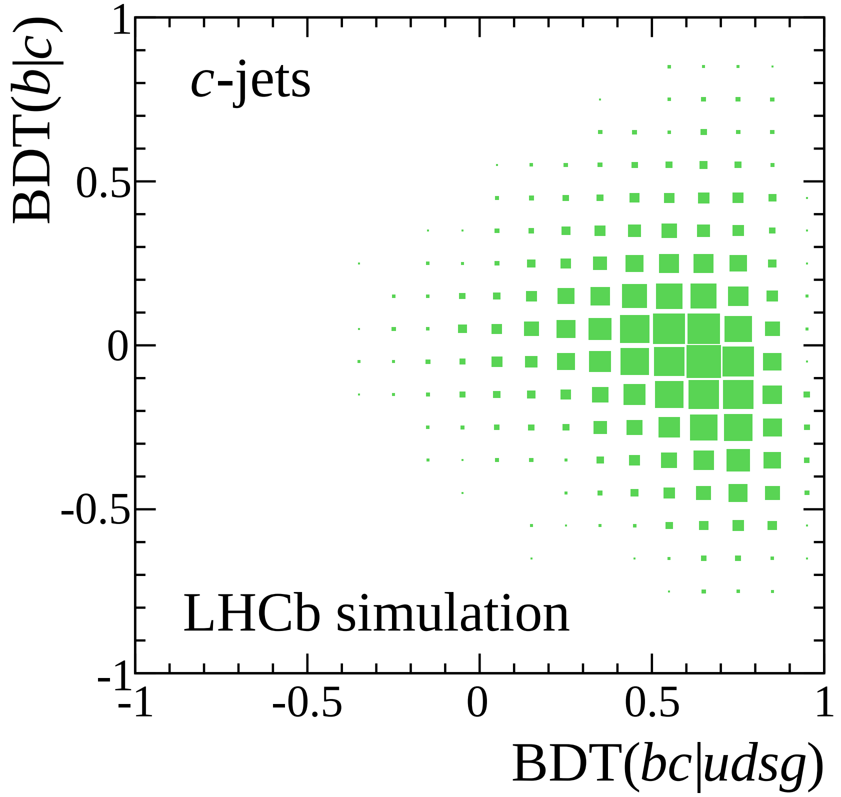
Use to make TMD distributions for fragmentation of flavor-tagged jets.

Figures from: arXiv:1504.07670 / JINST **10** P06013 (2015).

Heavy flavor jet structure: tagging performance at LHCb







You can see "prompt D" and "D from B" by eye!

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J/ψ polarization puzzle $\rightarrow$ 1307.6379, 1701.05116

NRQCD global fits predict large J/ψ polarization, but almost no polarization is seen... role of ${}^1S_0^{[8]}$ spin.
NRQCD global fits also predict mostly isolated J/ψs... role of ${}^1S_0^{[8]}$ color.

... and Υ's in jets $\rightarrow$ forthcoming

Forward Λ polarization puzzle $\rightarrow$ forthcoming

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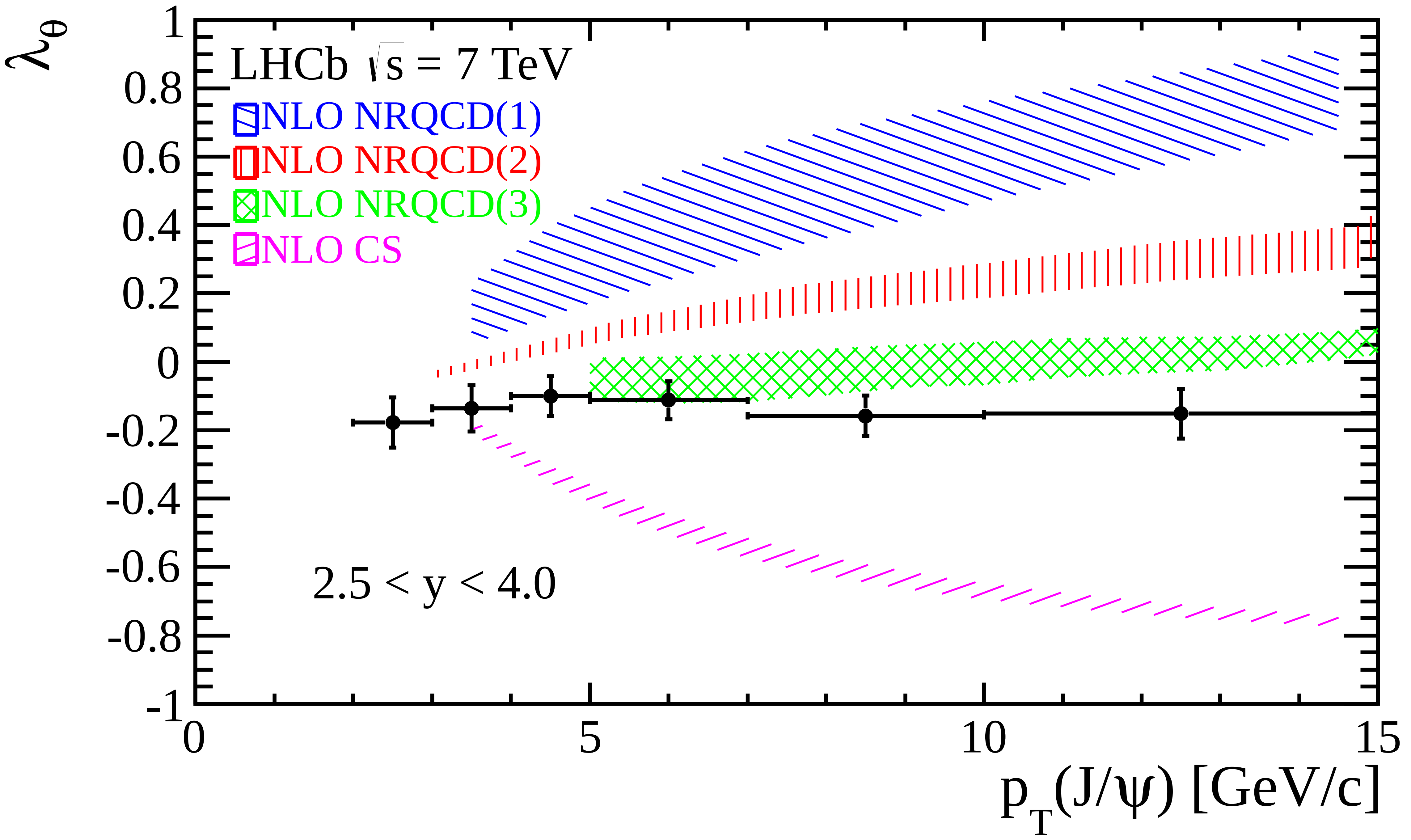
"NRQCD" refers to the Non-relativistic QCD effective field theory.

The J/ψ polarization puzzle



Green band from Chao et al. arXiv:1201.2675 / PRL **108** 242004 (2012)

Pink and blue bands from: arXiv:1201.1872 / PRL **108** 172002 (2012)

Red band from: arXiv:1205.6682 / PRL **110** 042002 (2013)

NRQCD global fits predict large J/ψ polarization at high p_T. It's not so.

Figure from: arXiv:1307.6379 / Eur. Phys. J. C **73** 2631 (2013).

The J/ψ polarization puzzle

Figure from: arXiv:1701.05116 / PRL **118** 192001 (2017).

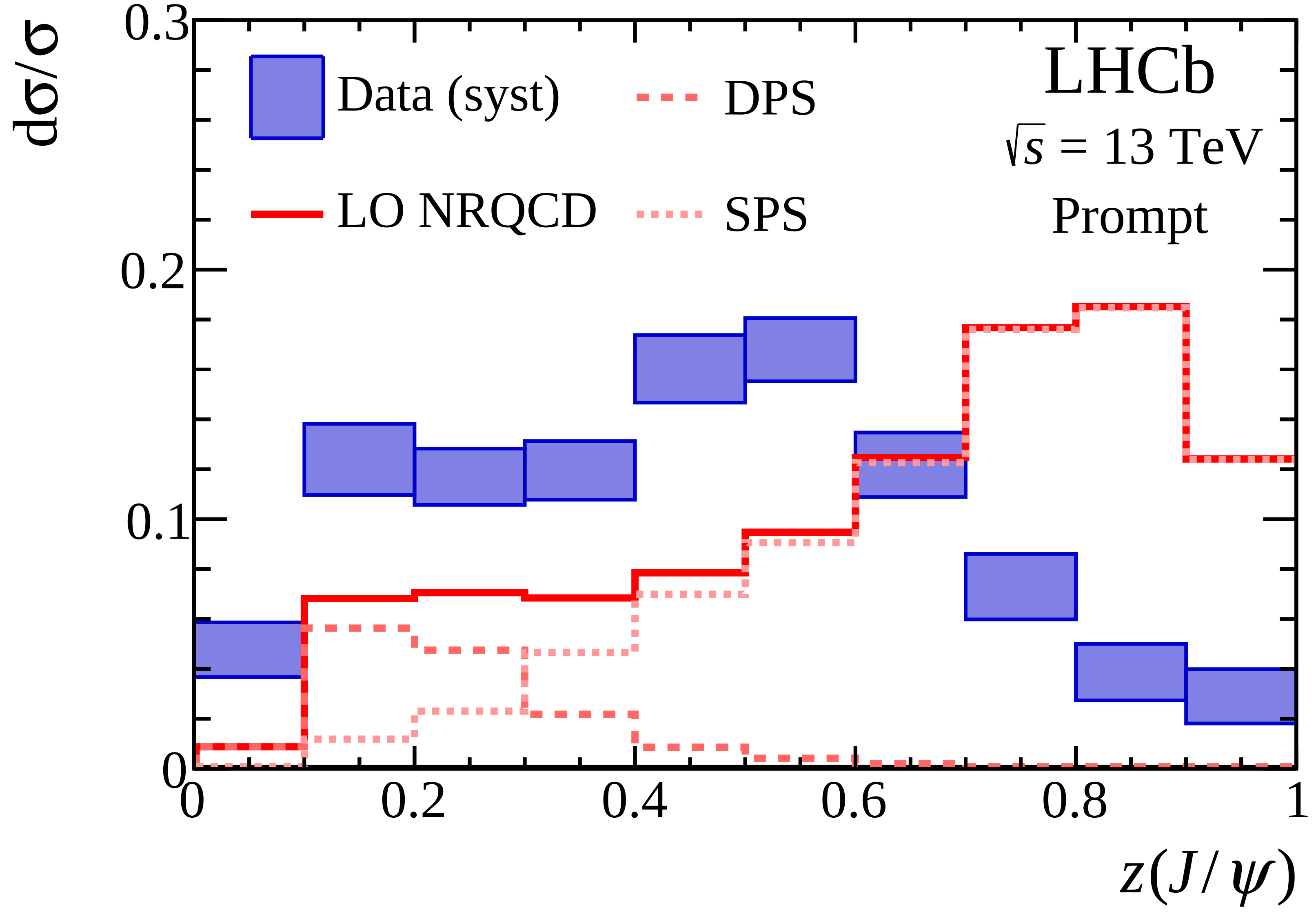
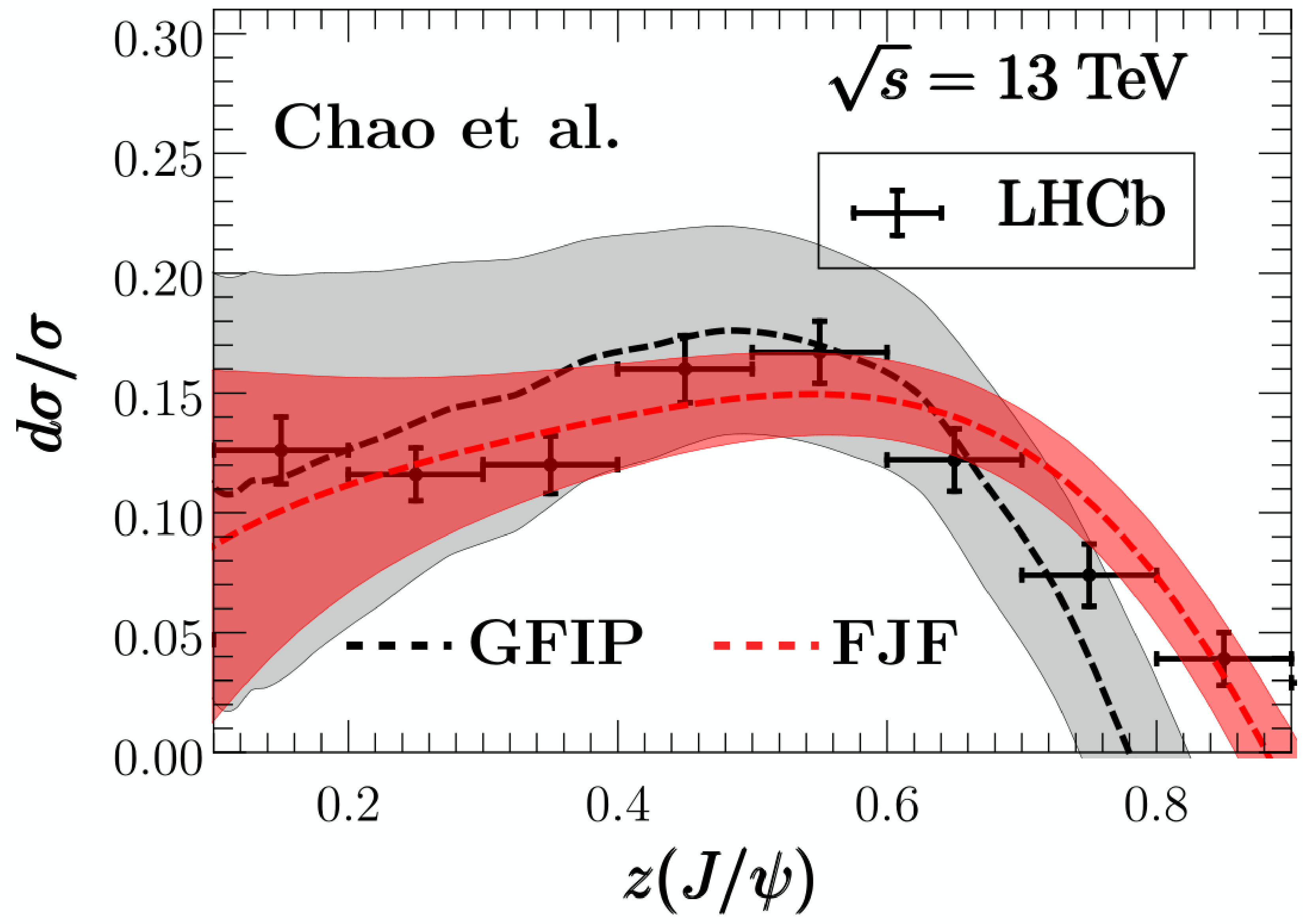


Figure from: arXiv:1702.05525 / PRL **119** 032002 (2017).



LDMEs fit by Chao et al: arXiv:1201.2675 / PRL **108** 242004 (2012).
They used only J/ψ at high p_T.

Pythia's leading-order NRQCD also predicts isolated J/ψs. It's not so.

An NLL / modified shower NRQCD calculation does pretty well: **J/ψ from g, not $c\bar{c}$.**

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Like J/ψ, but heavier mass for more robust theory comparison.

Forward Λ polarization puzzle $\rightarrow$ forthcoming

In this case: different hyperons show diverse and often large polarizations that have never been explained.

Λ_b^0-$\bar{\Lambda}_b^0$ production asymmetry $\rightarrow$ 2107.09593

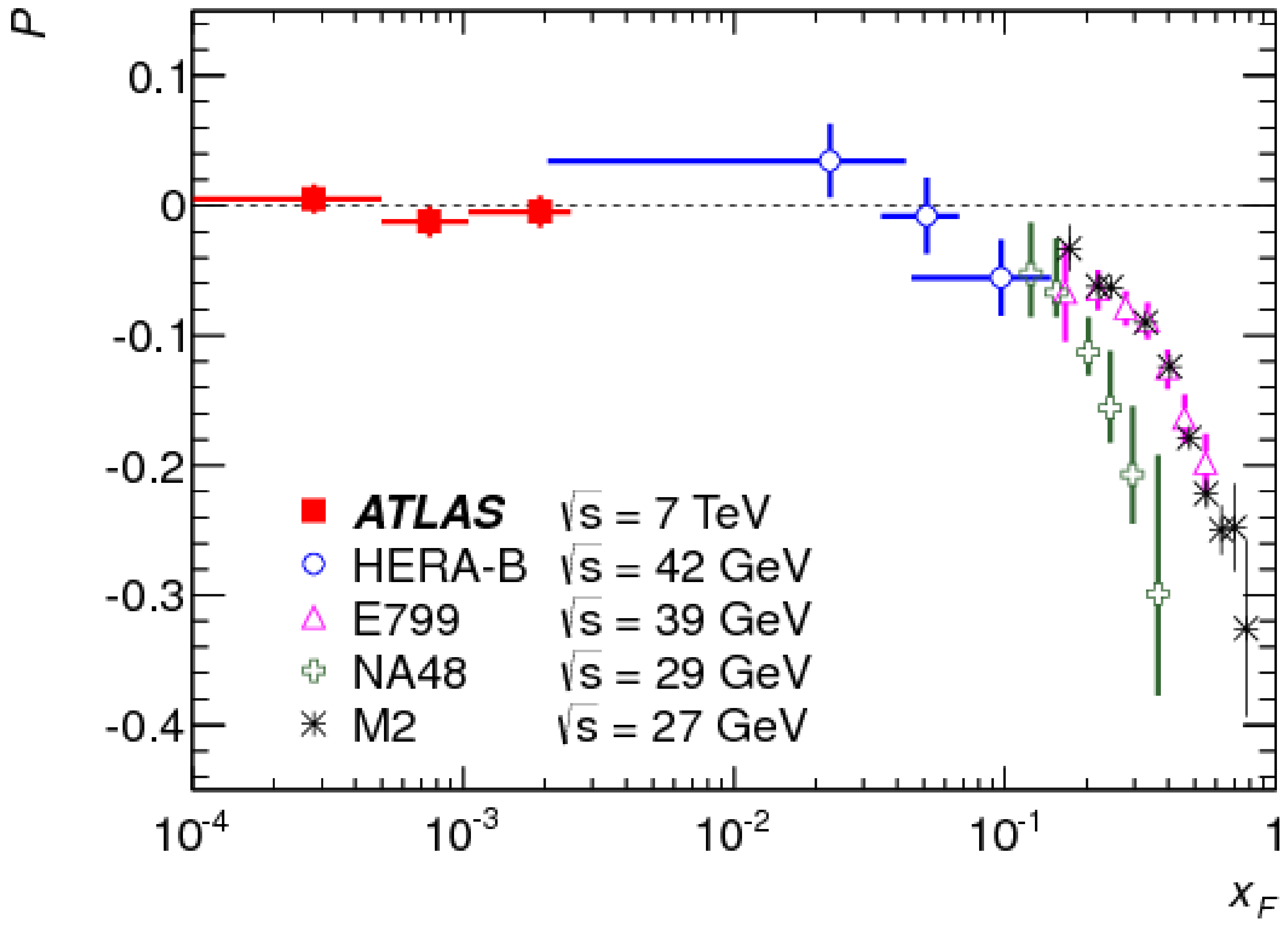

Figure: Λ polarized only in forward region: $x_F \sim 1$ is like $y \gg 1$.

Figure from: arXiv:1412.1692 / PRD **91** 032004 (2015).

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Test models for effect of beam remnant on heavy hadron formation.

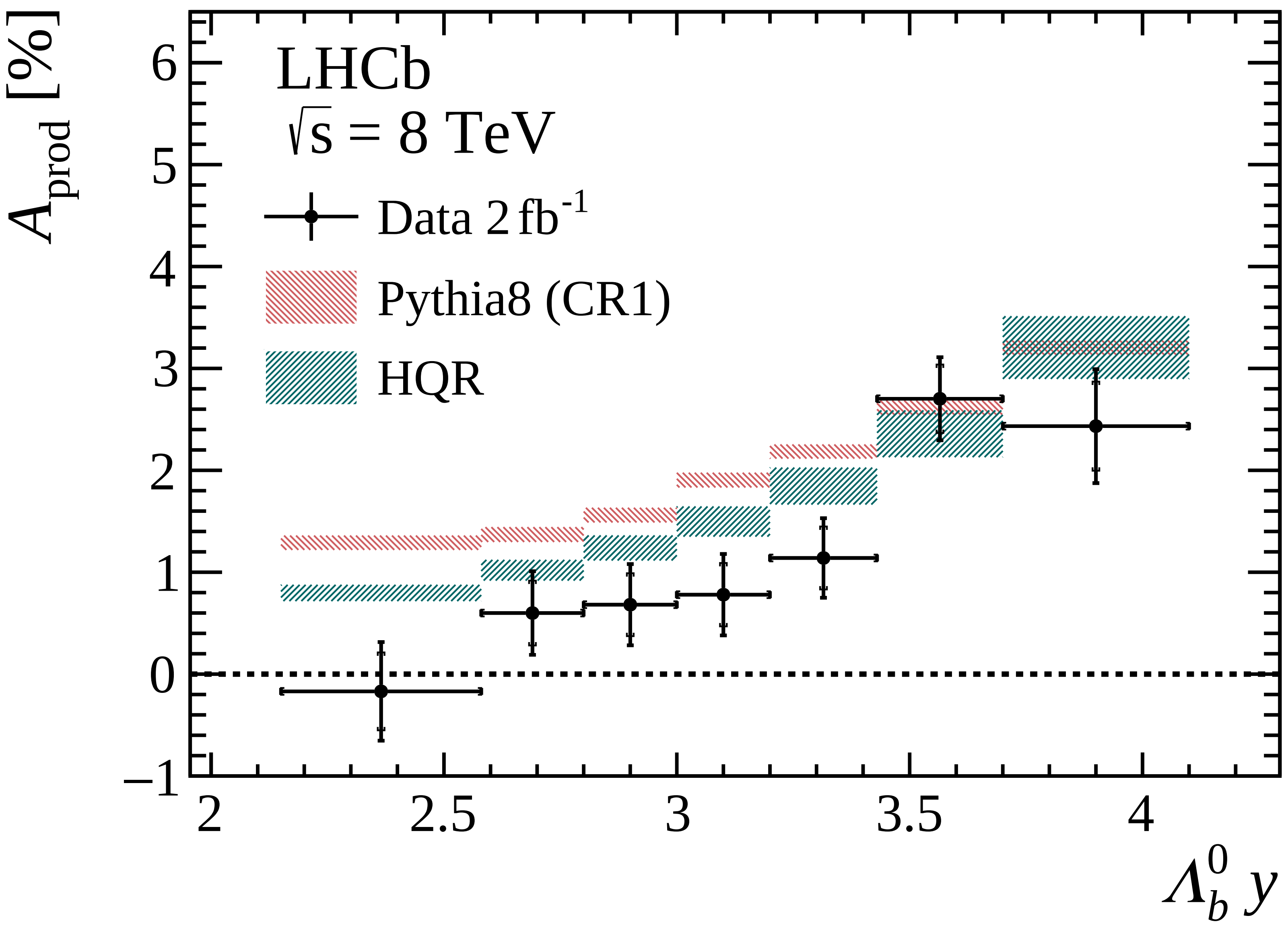

Figure: CR1: color reconnection that minimizes string tensile potential.
HQR: mostly-perturbative $\mathcal{O}(\Lambda_{\mathrm{QCD}} m_Q / p_T^2)$ correction to fragmentation.

Summary

LHCb is a forward spectrometer with excellent tracking and PID, plus electromagnetic and hadronic calorimetry.

We already have several measurements that probe prompt hadron production mechanisms. That includes measurements of TMD fragmentation and quarkonium fragmentation.

The LHCb hadronization program is going to produce many more measurements in the future.