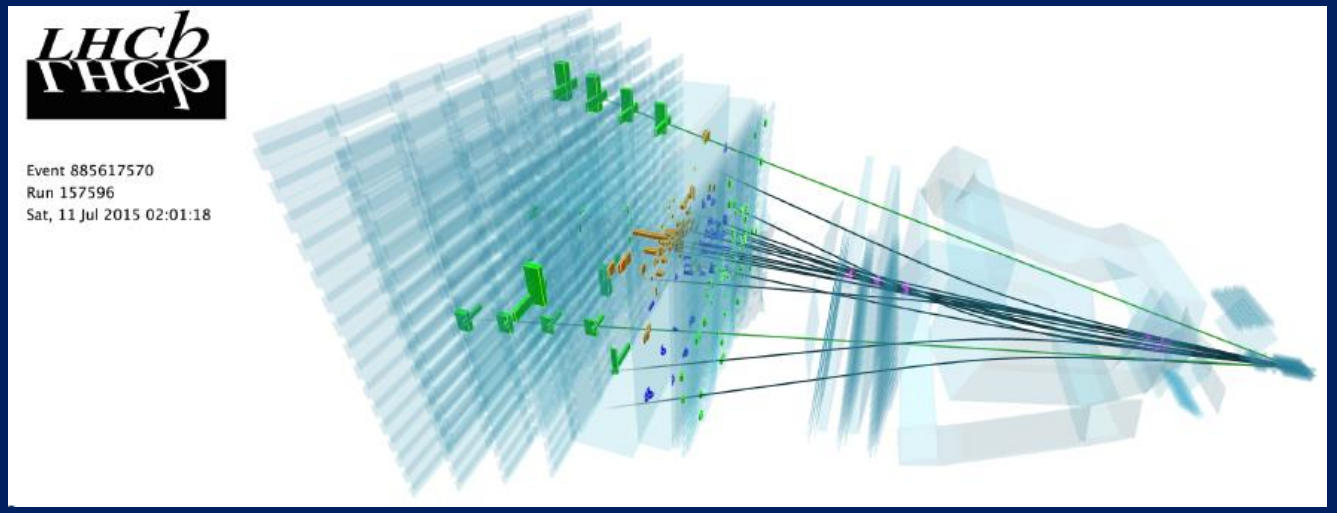
Studying Jet Fragmentation and Hadronization at LHCb



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On behalf of the LHCb Collaboration

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Kolymbari, Greece
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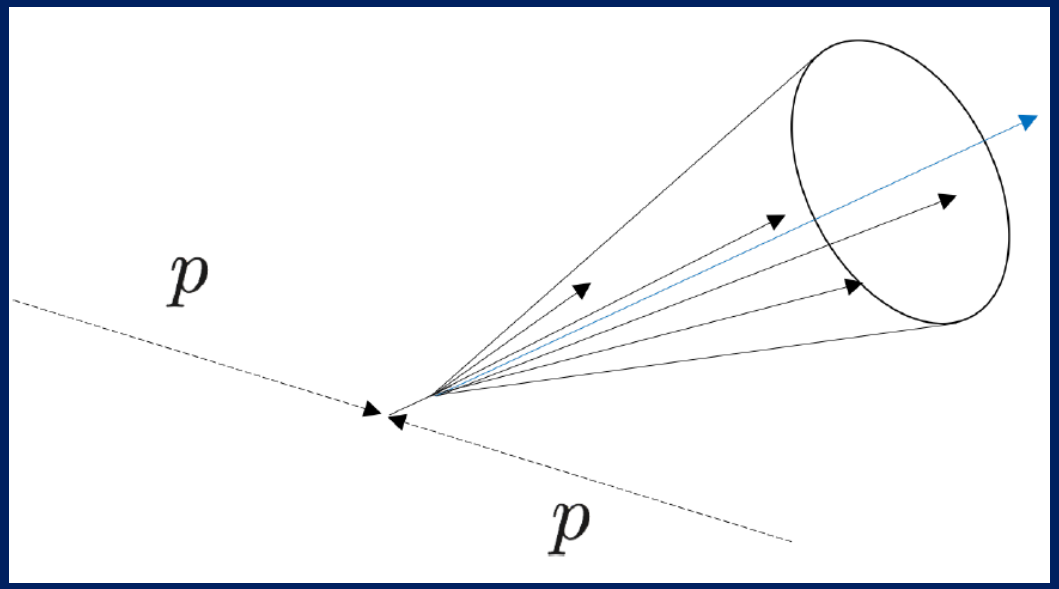
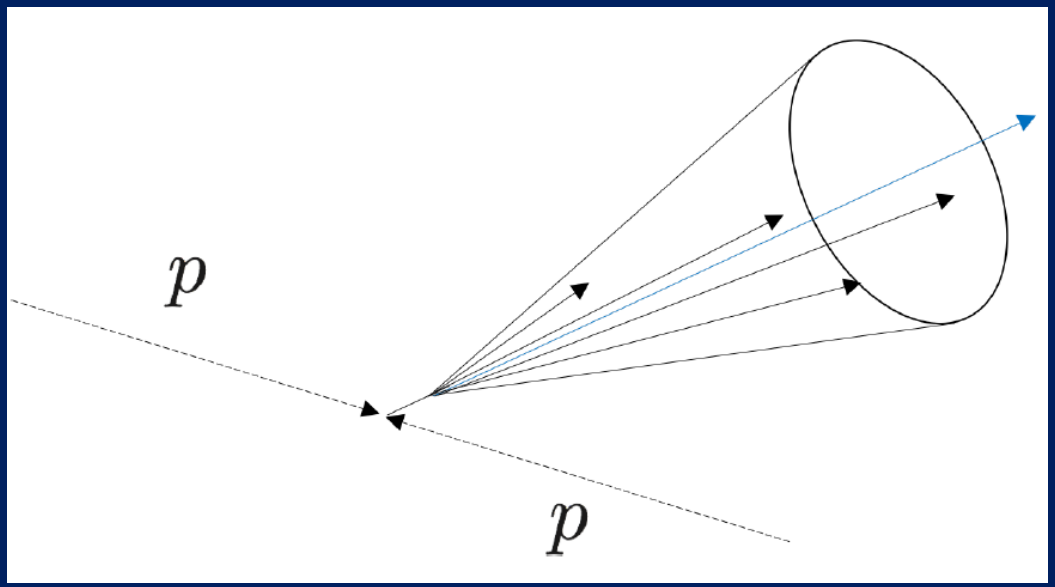
Jet hadronization



- Jets are a proxy for partons, thus providing sensitivity to the underlying partonic dynamics
- Robust comparison between experiment and theory enabled by e.g. anti-k_T jet algorithm has made jets powerful tools at the LHC

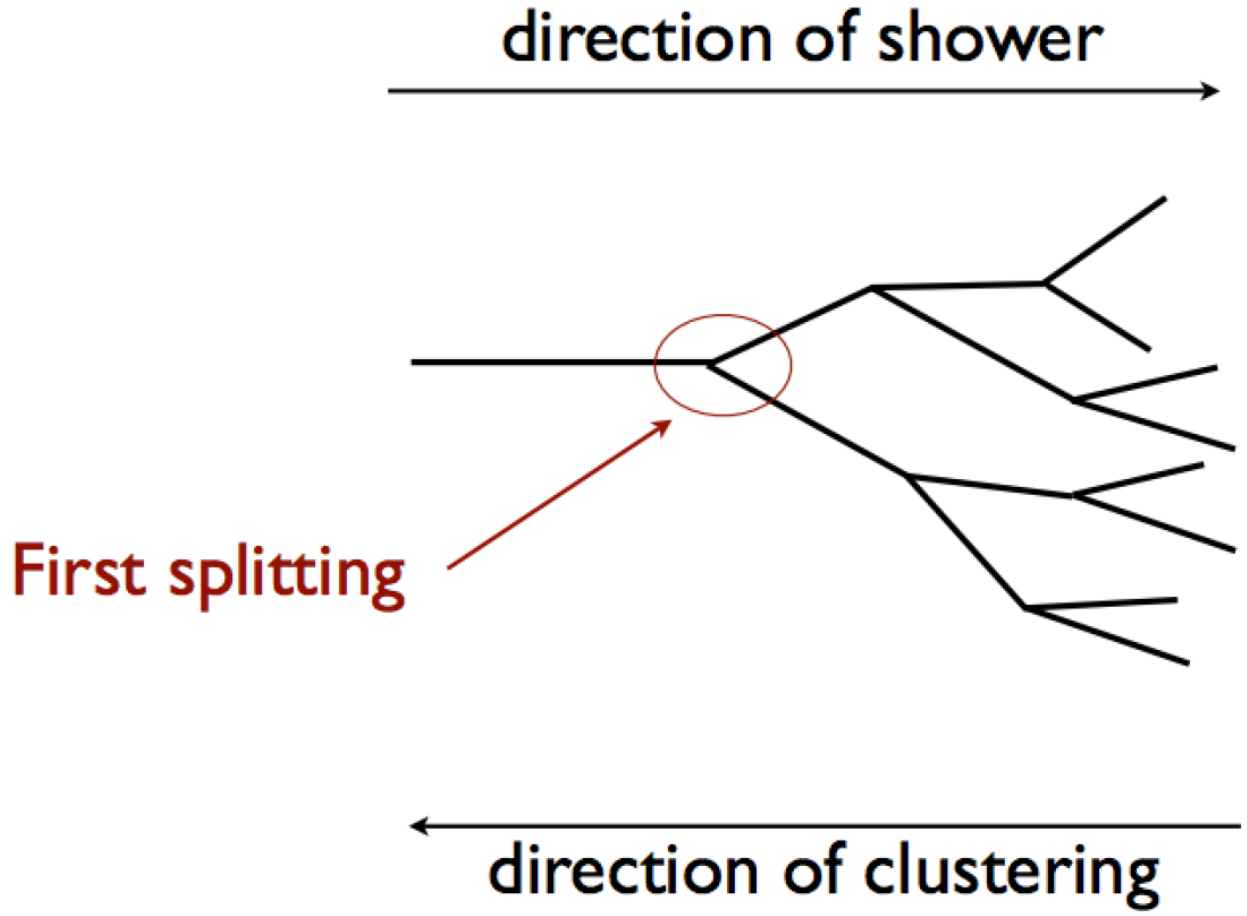
Jet hadronization



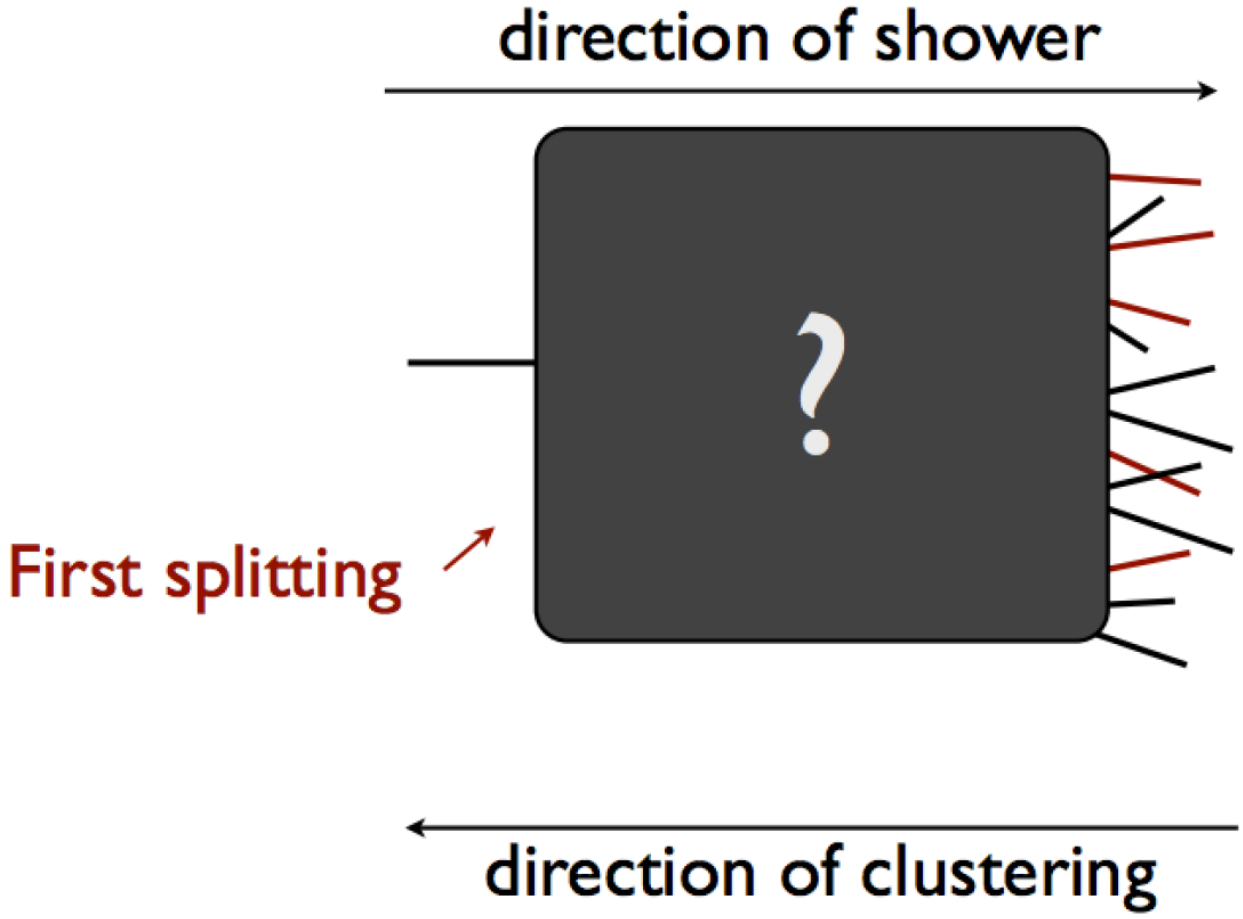
- Jets are a proxy for partons, thus providing sensitivity to the underlying partonic dynamics
- Robust comparison between experiment and theory enabled by e.g. anti-k_T jet algorithm has made jets powerful tools at the LHC

- But jets are formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jet formation
- We can study a perturbative object to learn also about nonperturbative physics

Parton shower: in theory....



Parton shower: in practice



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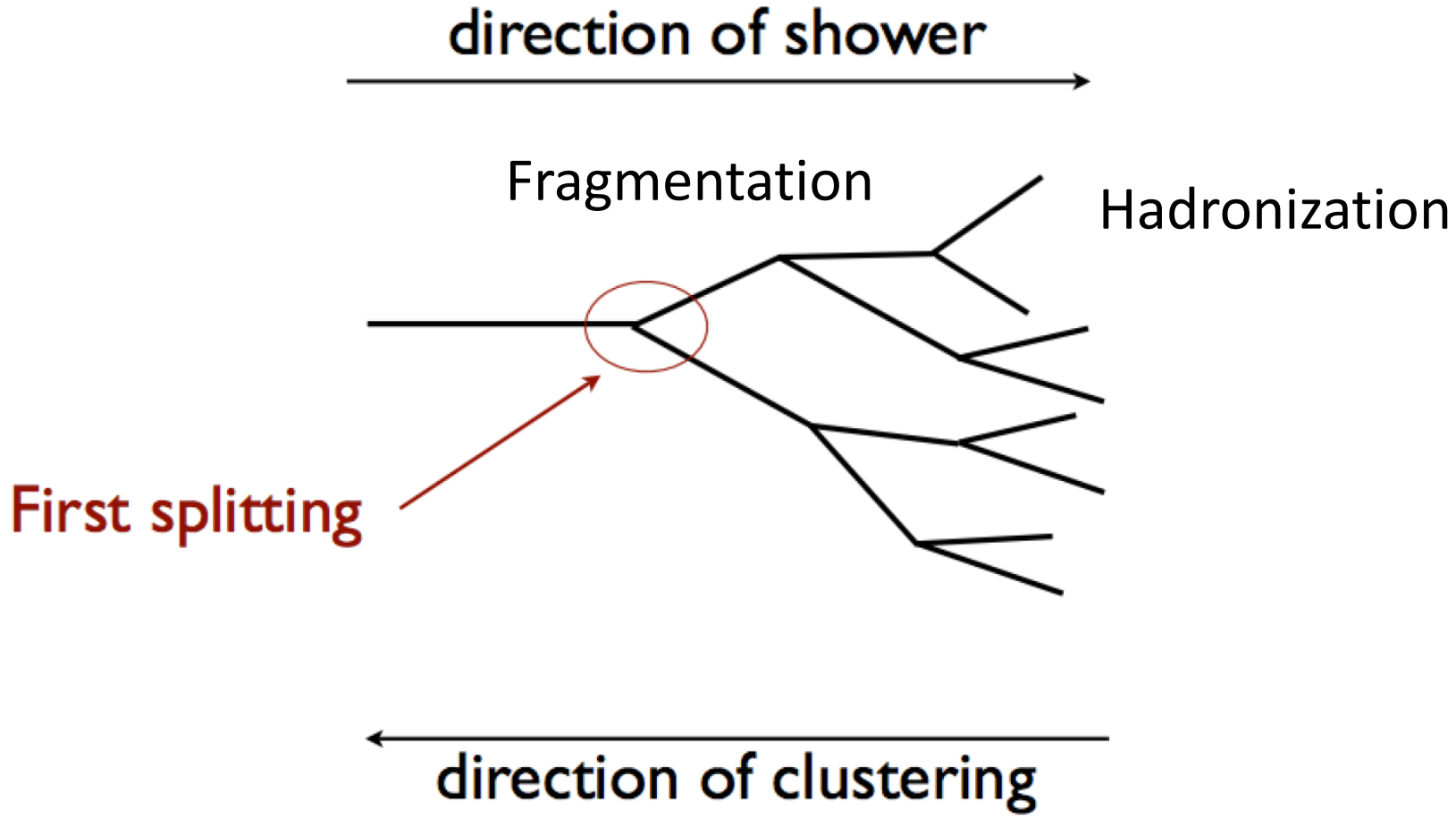
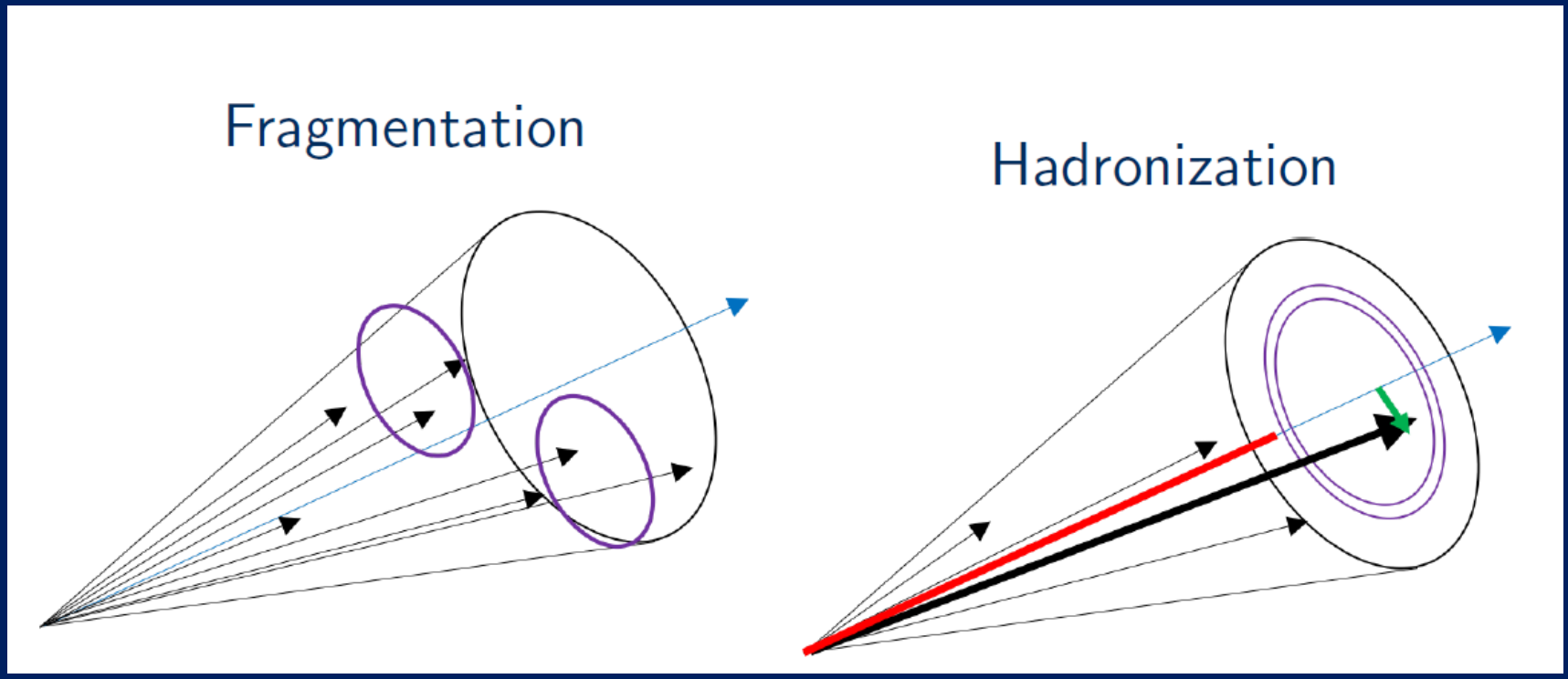
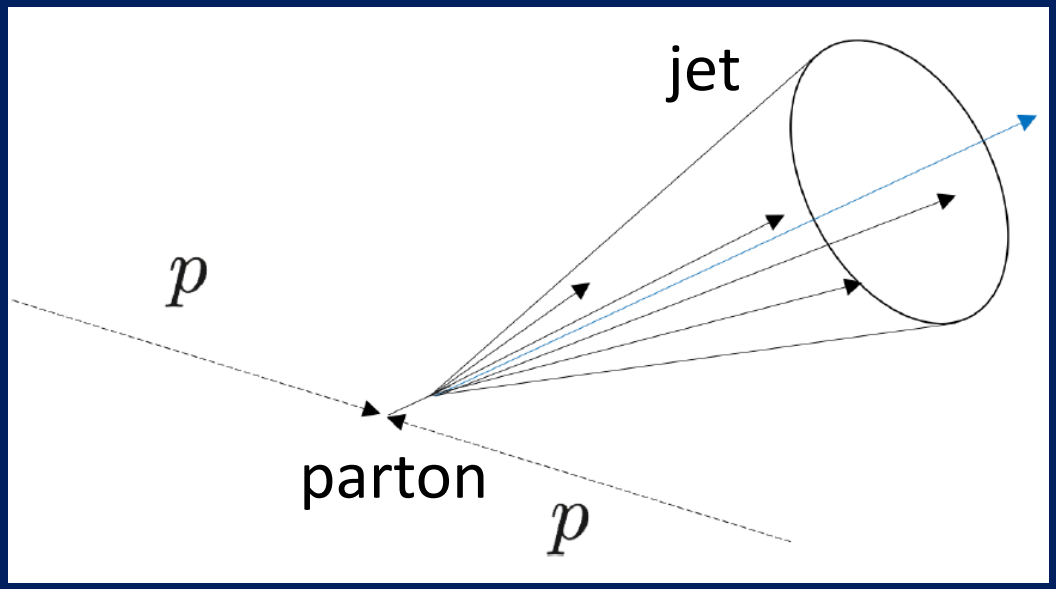


Fragmentation vs. Hadronization



- Use jet grooming algorithms to identify “prongs” of jet, as proxy for partonic splittings
- Study correlations of individual hadrons with jet axis and each other

Understanding hadronization: A wish list



1. A way to connect the initial-state parton to the final-state hadrons

   - Jets, as a proxy for a parton, are a tool to connect the perturbative to nonperturbative

2. A way to connect the flavor of the initial-state parton to the final-state hadrons

   - Would allow for complete characterization of parton → hadron

Courtesy Joe Osborn

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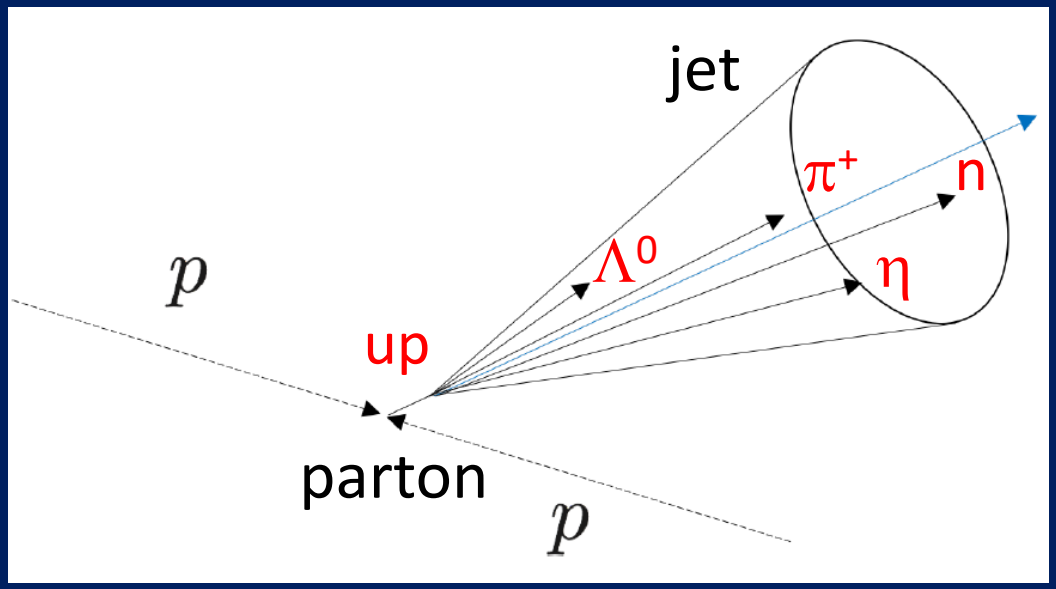

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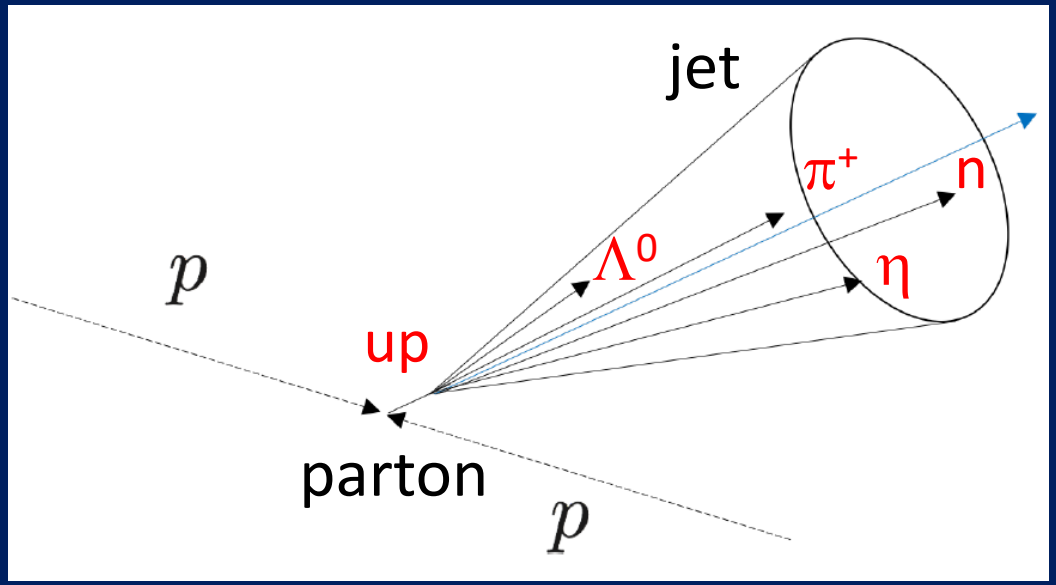

- Baryon vs. meson
- Correlations (e.g. strangeness, heavy flavor)
- Resonance production (ϕ, J/ψ, Y)
- Increase projectile/target size (hadronization in medium)
- …

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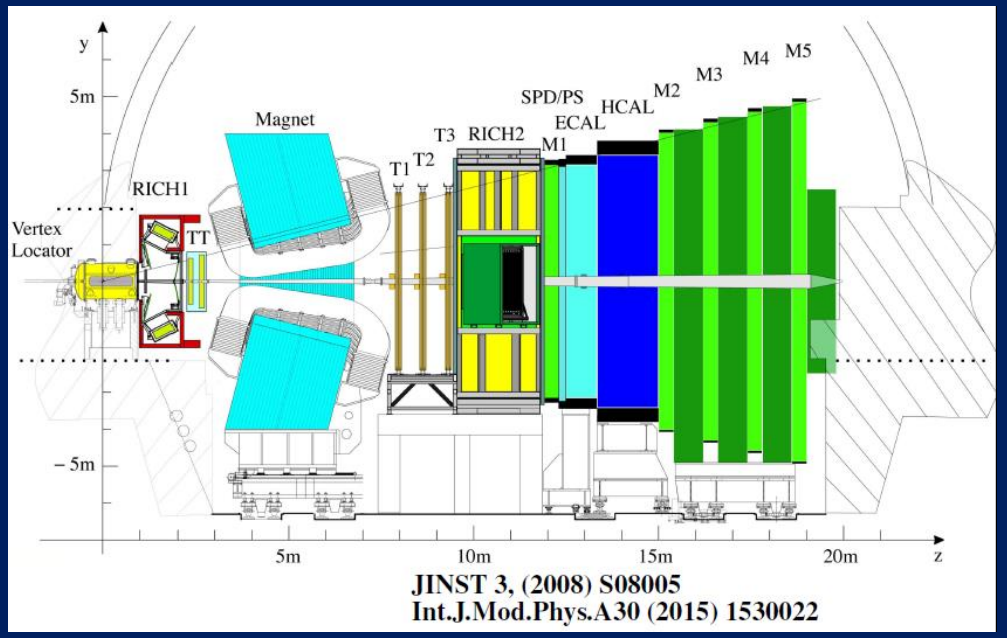
The LHCb experiment

LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

- Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Tracking: Momentum resolution <1% for p < 200 GeV/c
- Particle ID: Excellent capabilities to select exclusive decays



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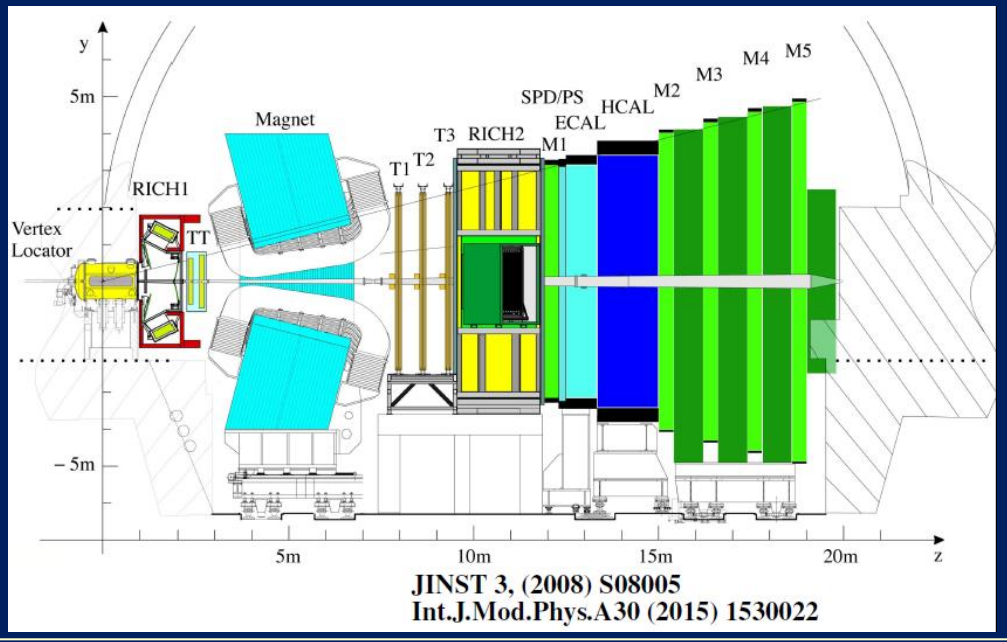


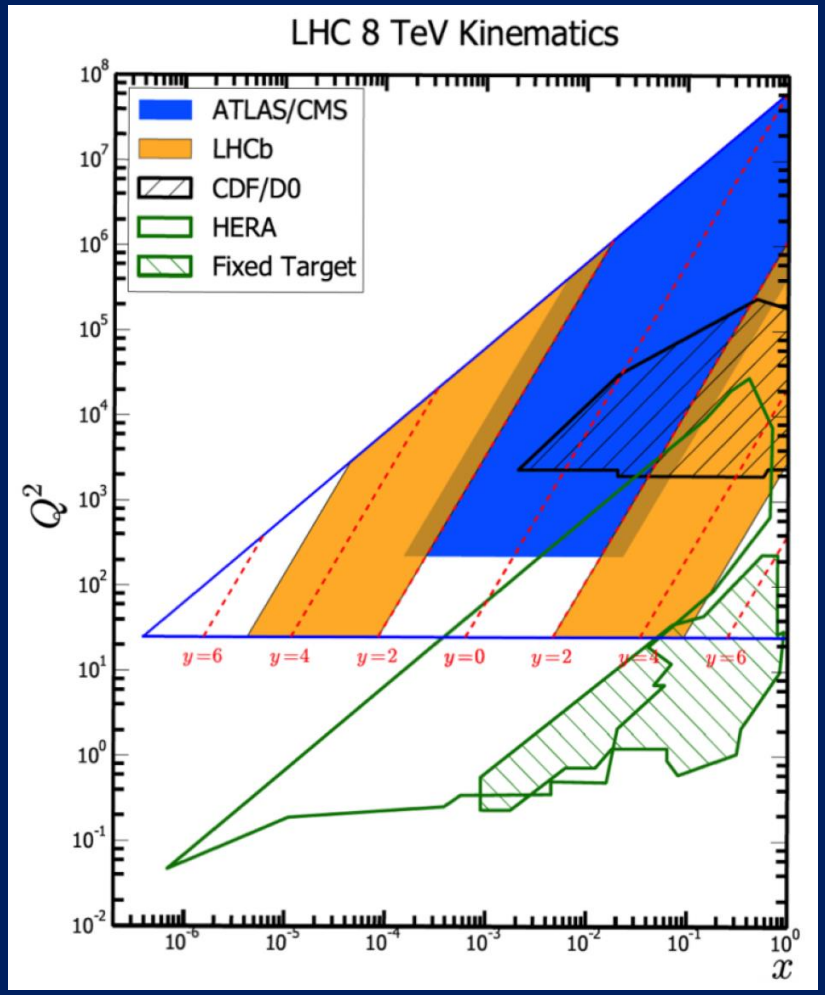
Some features specifically attractive for hadronization:

- Full jet reconstruction with tracking, ECAL, HCAL
  - Heavy flavor tagging of jets
- Charged hadron PID from 2 < p < 100 GeV

Can study identified particle distributions within jets!

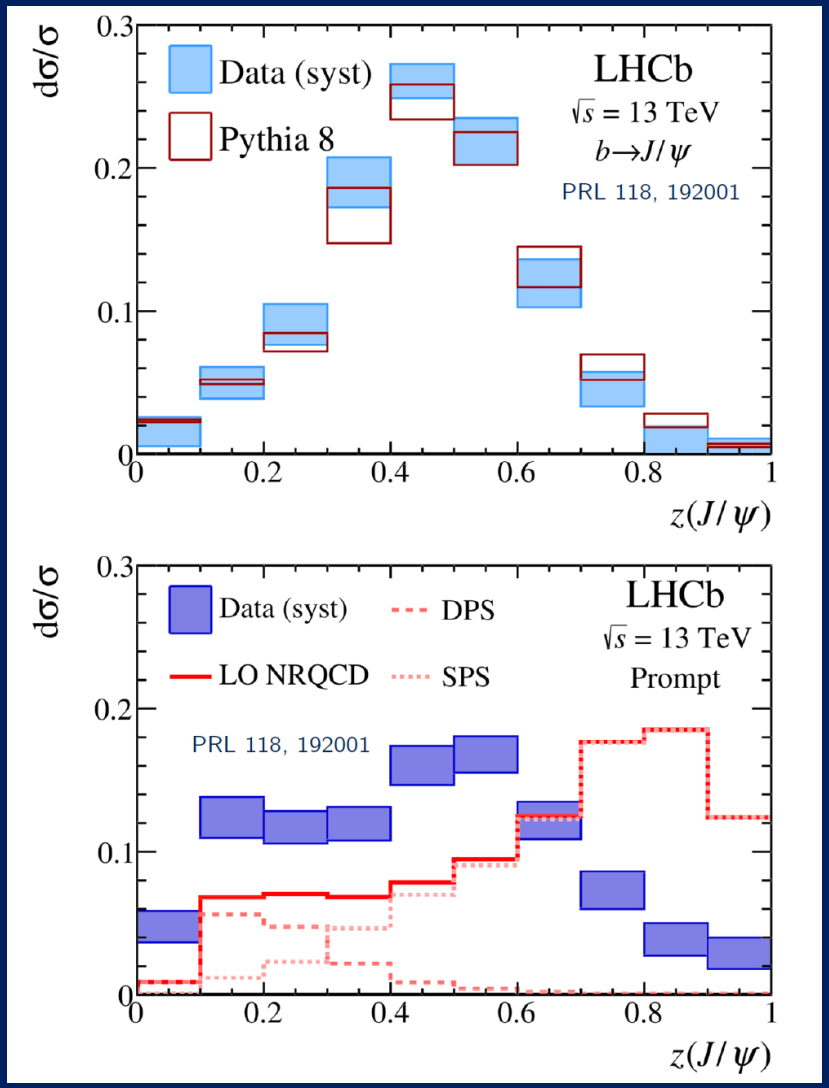
x-Q^2 coverage affects parton mix

- LHCb also has unique x-Q^2 coverage
  - Enhanced light quark jet fraction in forward region

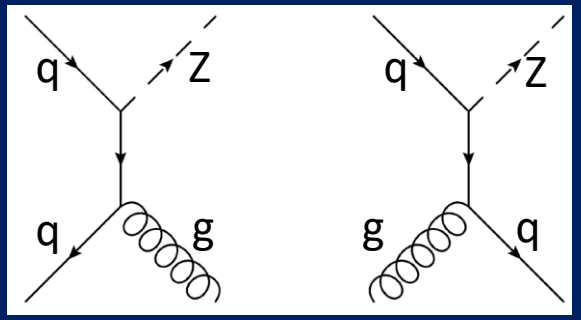


J/Ψ production in jets at LHCb

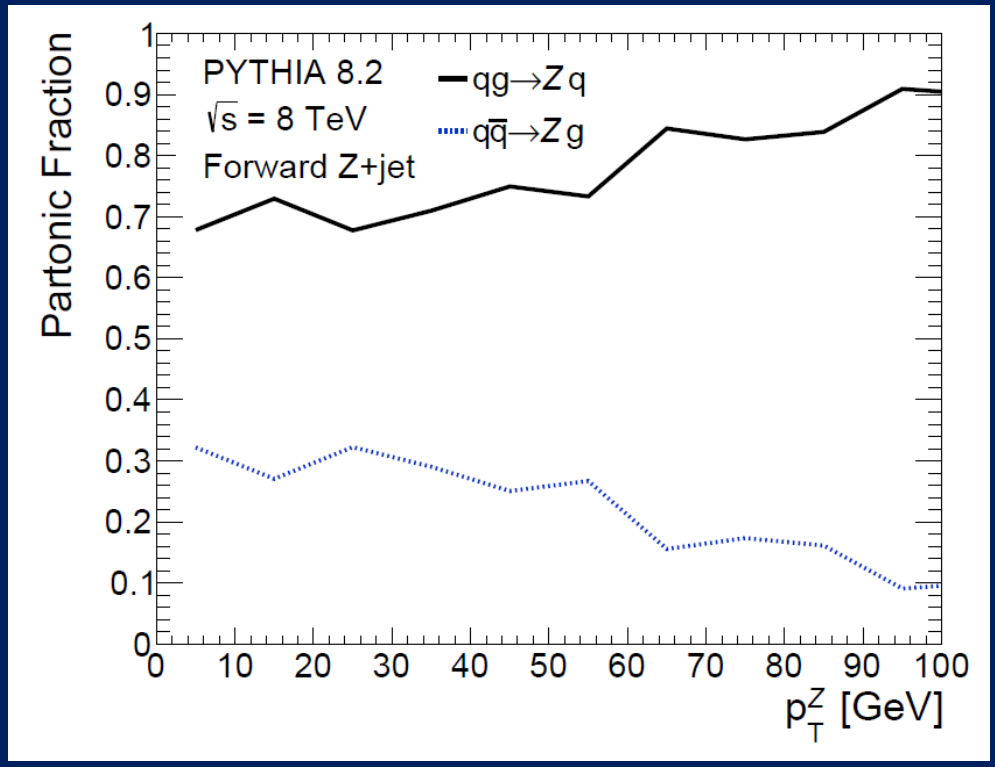
- First LHCb jet substructure measurement was J/ψ-in-jet production
  - J/ψ from b decay well described by PYTHIA
  - Prompt J/ψ-in-jet not! Can shed light on prompt J/ψ production mechanism(s). How is a prompt J/ψ produced within a jet??



Forward Z+jet

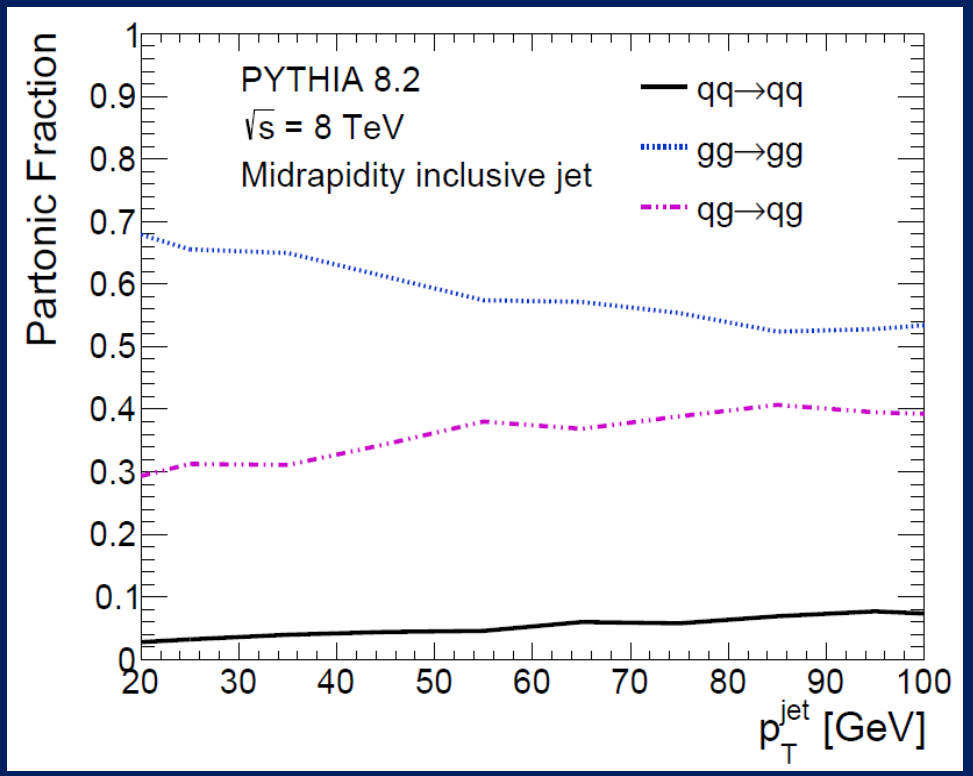


- Z+jet is predominantly sensitive to quark jets
- Forward kinematics increases fraction of light quark jets



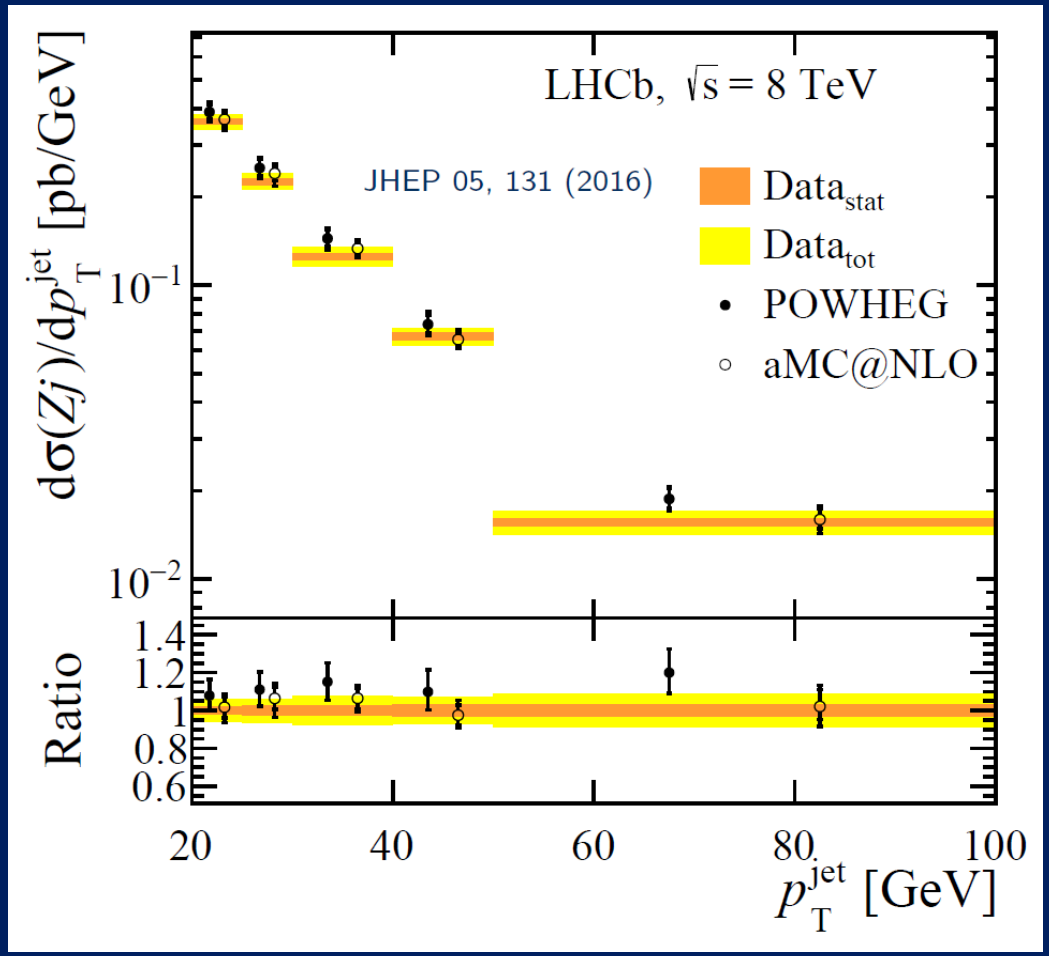
Forward Z+jet

- In contrast to midrapidity inclusive jets, dominated by gluons
- Opportunity to study light quark vs. gluon jets
  - Hadronization dynamcs
  - Jet properties



Forward Z+jet

- LHCb previously measured the forward Z+jet cross section
  - JHEP 05, 131 (2016)
- Now have measured charged hadron distributions within the jet, in the same data set
  - arXiv:1904.08878
- First LHC measurement of charged hadrons within Z-tagged jets
- First LHC measurement of charged hadrons-in-jets at forward rapidity

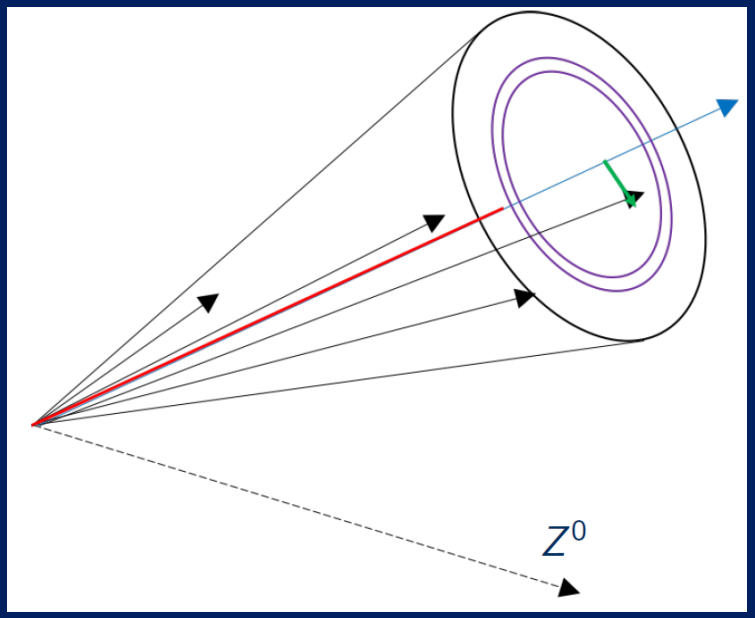


Charged hadrons in jets: Observables

- Longitudinal momentum fraction z
- Transverse momentum with respect to jet axis j_T
- Radial profile r

Lays the foundation for a broader hadronization program at LHCb utilizing

- Particle ID
- Heavy flavor jet tagging
- Resonance production within jets
- Correlations with flavor ID



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

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

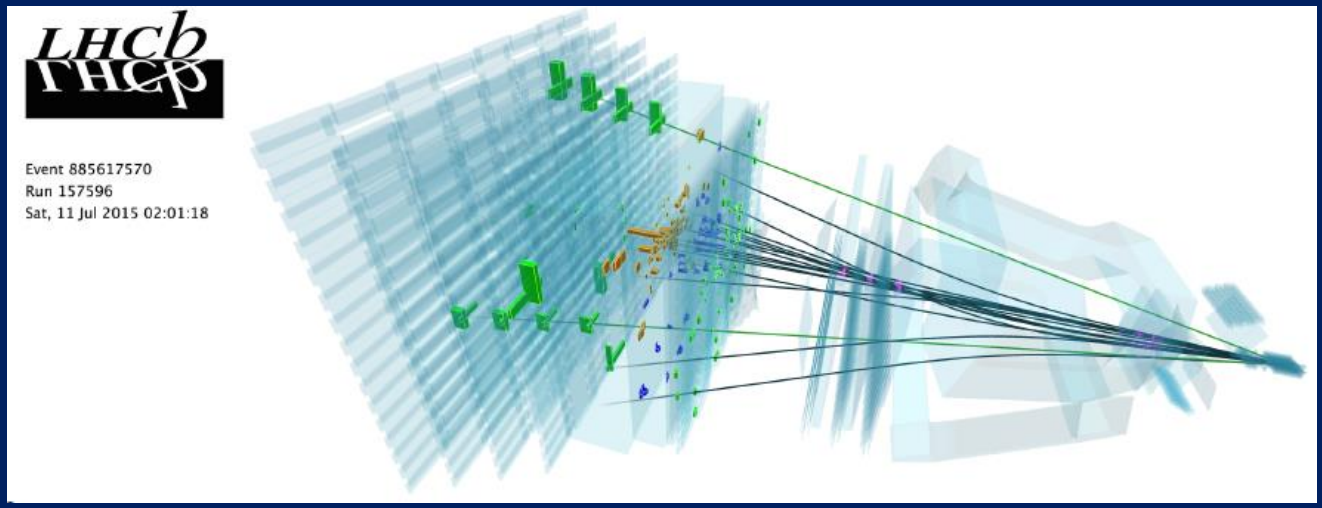
$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}$$

Analysis details

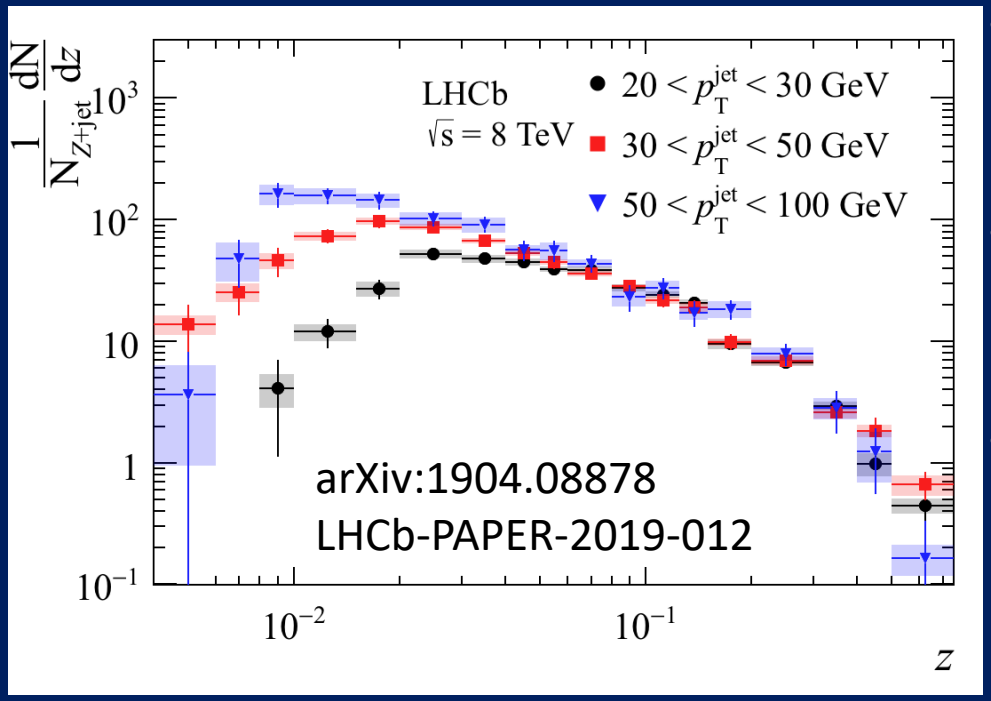
arXiv:1904.08878
LHCb-PAPER-2019-012

- Follow similar analysis strategy to ATLAS and previous LHCb papers
  - ATLAS: EPJC 71, 1795 (2011), NPA 978, 65 (2018)
  - LHCb: PRL 118, 192001 (2017)

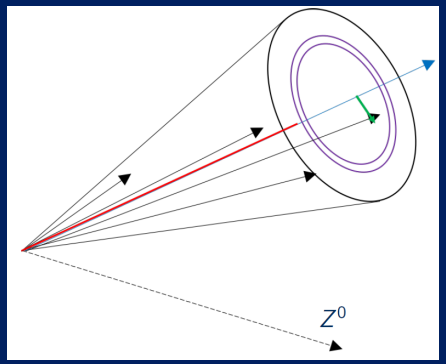
- $Z \to \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-k_T jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2 < \eta < 4.5$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects 2→2 event topology
- Charged hadrons selected with $p_T > 0.25$ GeV, $p > 4$ GeV, $\Delta R < 0.5$
- Results efficiency corrected and 2D Bayesian unfolded



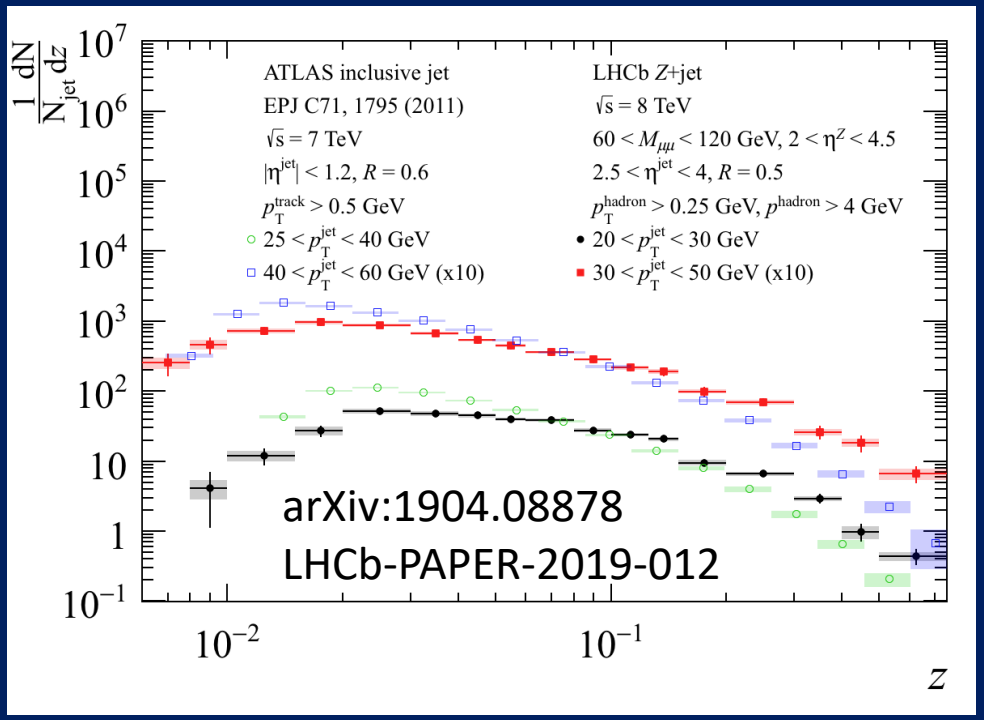
Results: Longitudinal momentum distributions



- Measurements in three p_T^{jet} bins, integrated over Z kinematics
- Longitudinal hadron-in-jet distributions independent of jet p_T at high z
- Distributions diverge at low z due to kinematic phase space available

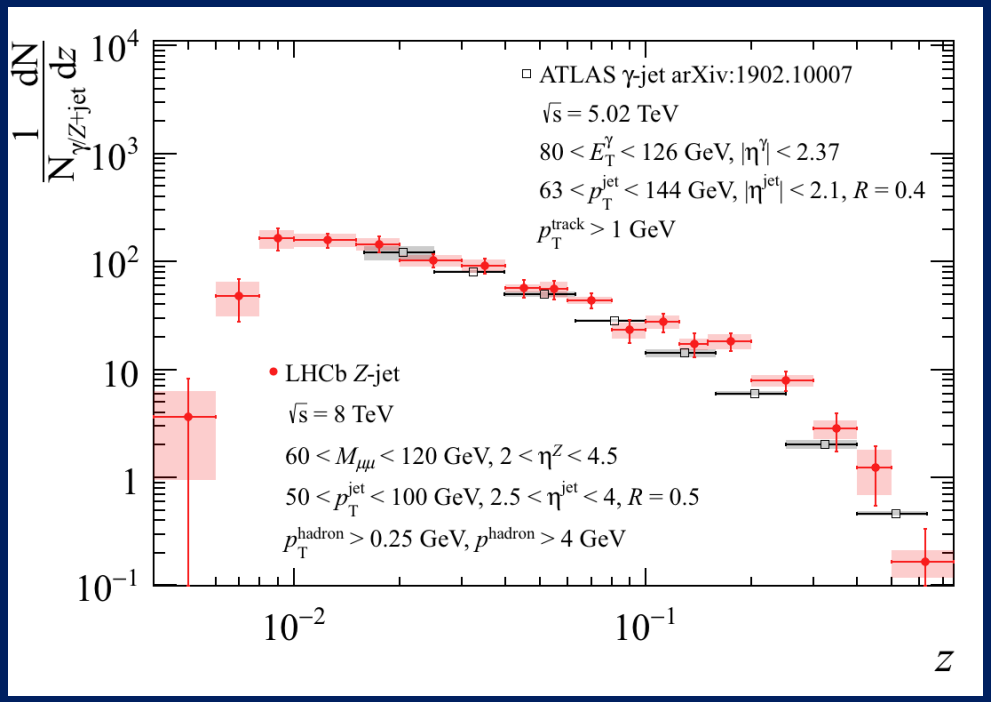


Longitudinal momentum distributions: Comparison to ATLAS inclusive jets



- Comparing ATLAS midrapidity inclusive jets to LHCb forward Z+jet shows longitudinal distributions in Z+jet "flatter" as a function of z
- Caveats – ATLAS/LHCb measurements can only be compared qualitatively due to different kinematics

Longitudinal momentum distributions: Comparison to ATLAS γ+jet

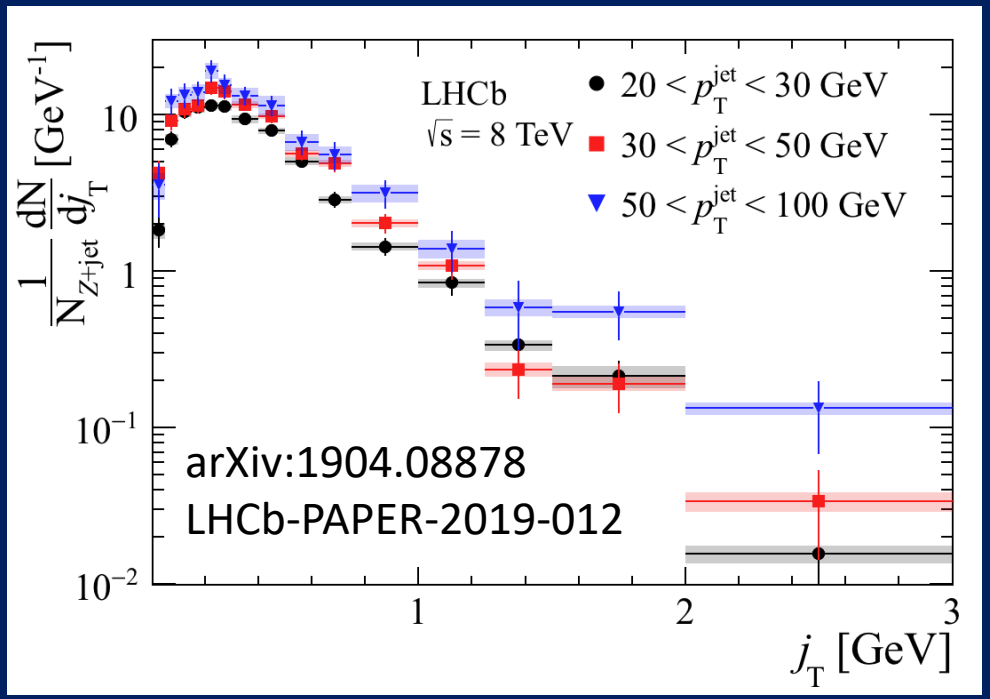


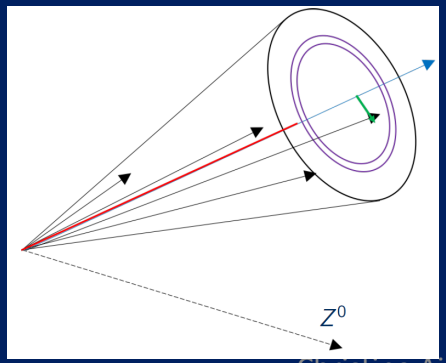
arXiv:1904.08878
LHCb-PAPER-2019-012

- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal distributions are instead very similar in the comparable jet p_T bin
  - γ+jet, like Z+jet, enhances quark jet fraction!
- Kinematic fiducial space similar but not exactly the same

Results: Transverse momentum distributions

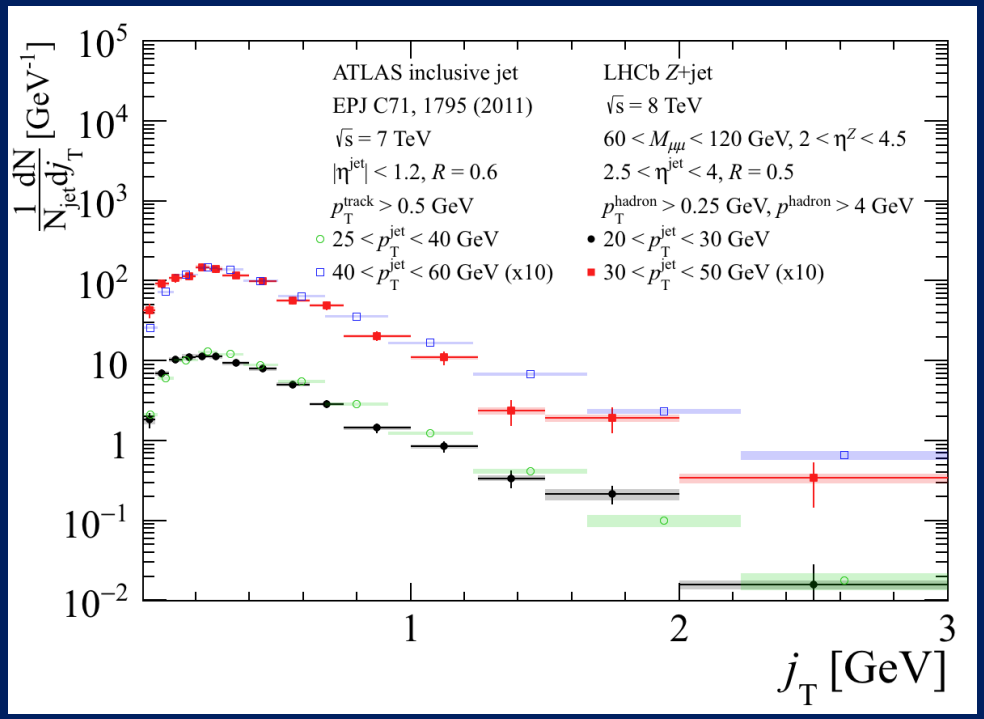
- Transverse momentum of hadron with respect to jet axis shows nonperturbative to perturbative transition
- Shapes very similar as function of p_T^{jet} – slight increase of $\langle j_T \rangle$ with p_T^{jet}





Transverse momentum distributions: Comparison to ATLAS inclusive jets

- Transverse momentum distributions show smaller $\langle j_T \rangle$ in Z+jet vs. inclusive jet at small j_T



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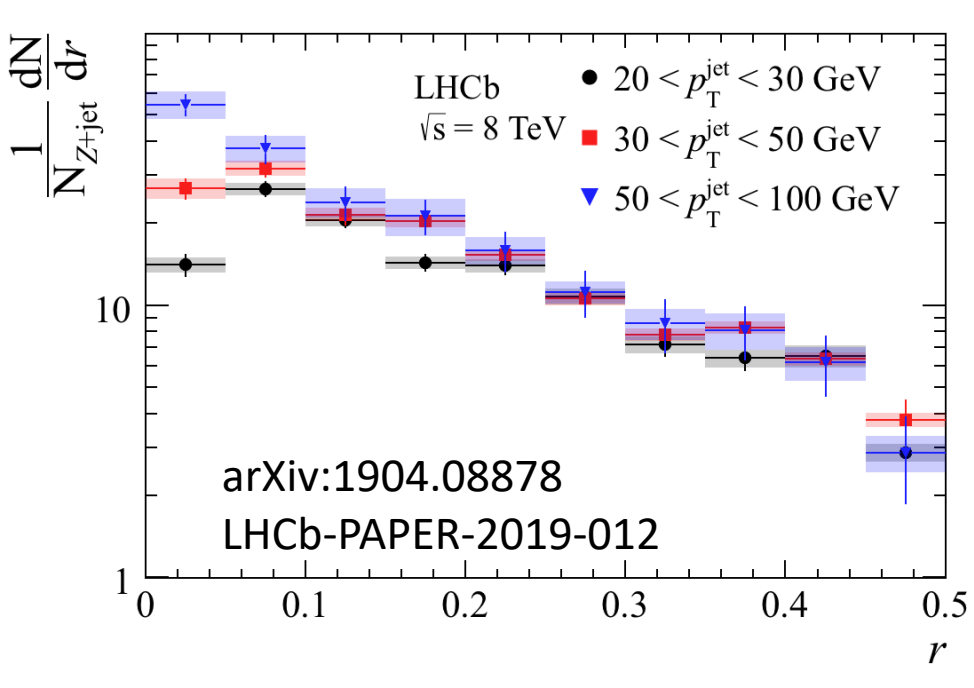
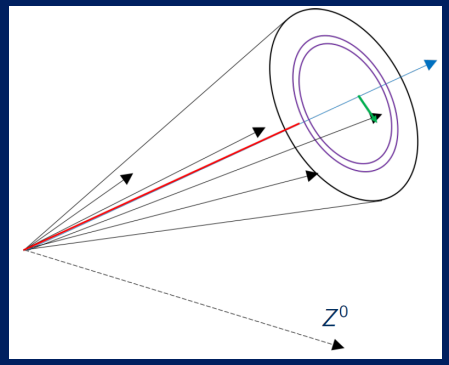
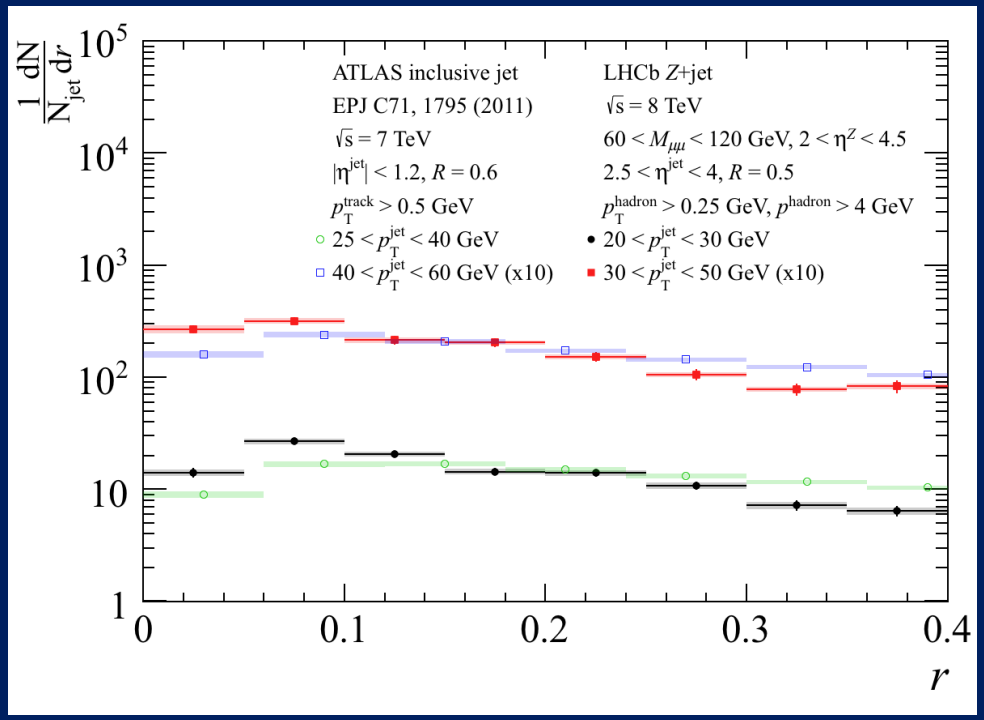
Results: Radial profiles





- Radial profiles largely independent of jet p_T away from the jet axis
- Multiplicity of hadrons along jet axis rises sharply with jet p_T

Radial profiles: Comparison to ATLAS inclusive jets



- Forward Z-tagged jets more collimated than midrapidity inclusive jets
  - I.e. more charged hadrons at small radii, fewer at large radii

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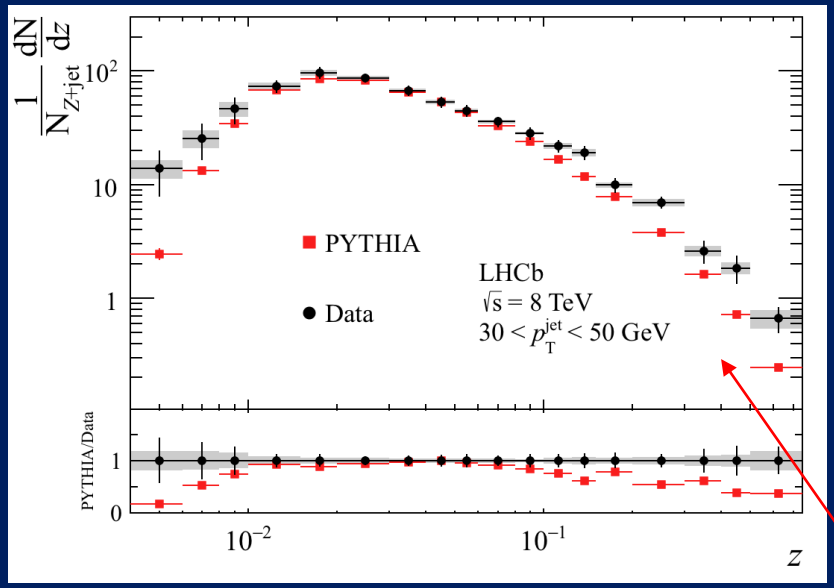
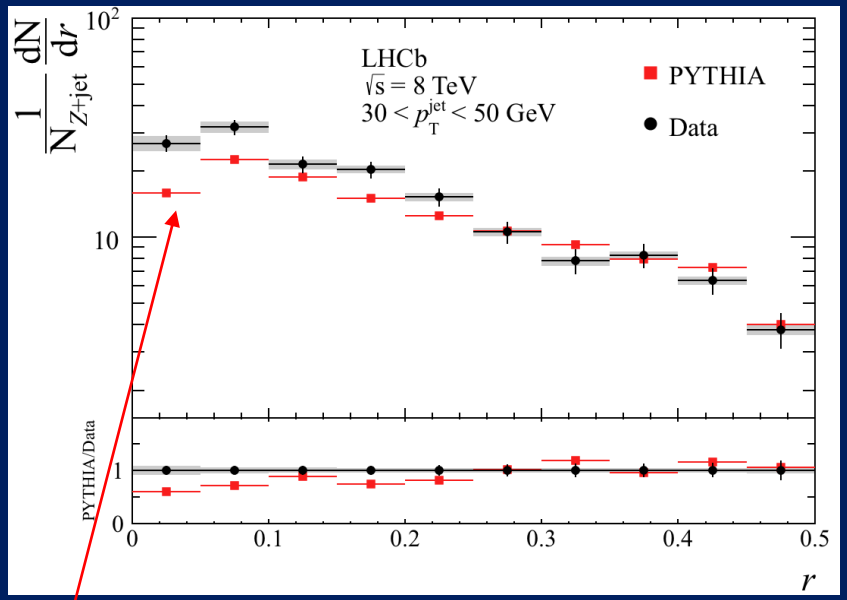
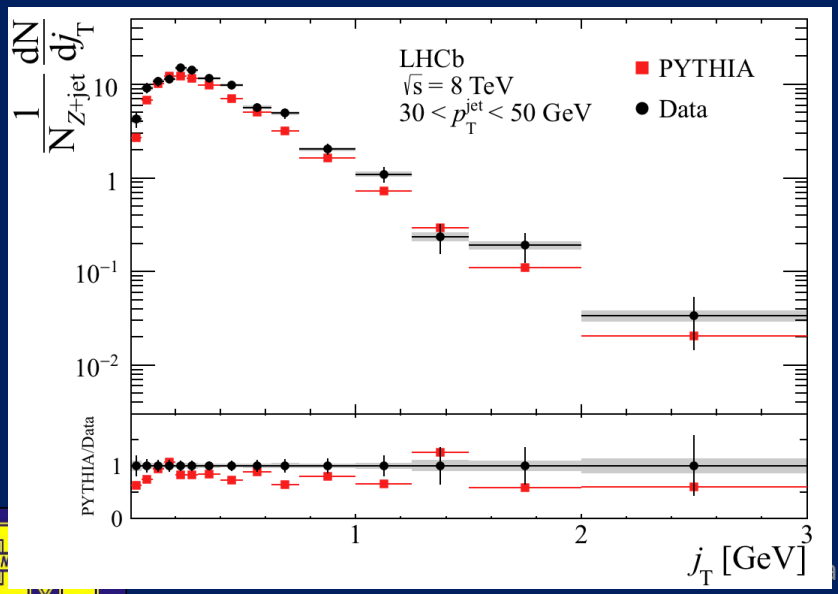
Comparisons with PYTHIA







PYTHIA generally underpredicts the number of high-momentum charged hadrons within Z-tagged jets, correlated with low radii

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LHCb-PAPER-2019-012

Hadronization in jets at LHCb—More in progress!

- Charged hadron distributions in b- and c-tagged jets
- Identified hadron ($\pi^{+/-}$, $K^{+/-}$) distributions in light quark, b- and c-tagged jets
- Beauty and charm hadron distributions in b- and c-tagged jets
- Baryon and meson distributions in jets
- More quarkonia in jets: Υ, ϕ, J/ψ polarization in jets

Summary

- LHCb has unique capabilities to study hadronization within jets, complementary to other LHC experiments
  - Forward acceptance
  - Particle ID
- Recent measurements of charged hadron distributions in forward Z+jet, in particular when compared with midrapidity inclusive jets and γ+jet, can provide information on quark vs. gluon hadronization
  - For full details, see

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/LHCb-PAPER-2019-012.html

- Stay tuned for more jet hadronization results in the near future!

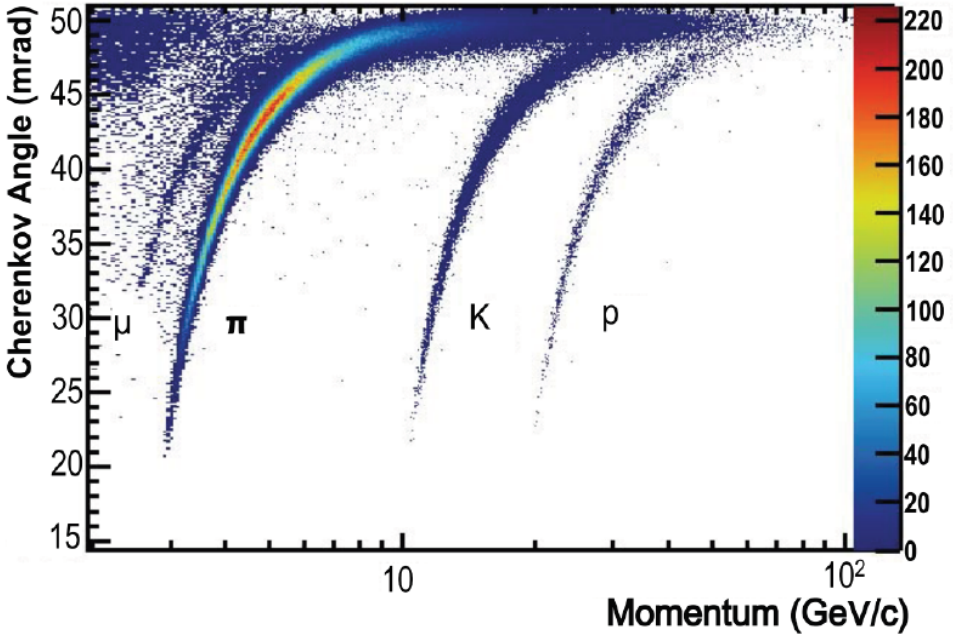
Extra

LHCb jet measurements

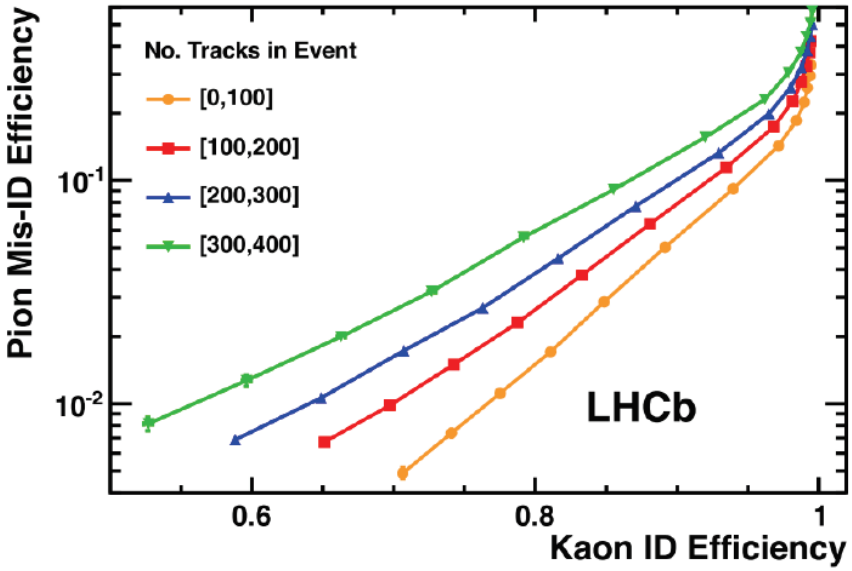
- W/Z+jet cross sections
  - JHEP 05, 131 (2016)
  - JHEP 01, 064 (2015)
  - JHEP 01, 33 (2014)
- Heavy flavor jets
  - PRL 118, 192001 (2017)
  - JINST 10, P06013 (2015)

The LHCb detector – Particle ID

Reconstructed Cherenkov angle for Isolated Tracks



Pion Mis-ID vs Kaon ID efficiencies for events with many tracks



Int. J. Mod. Phys. A **30**, 1530022 (2015)