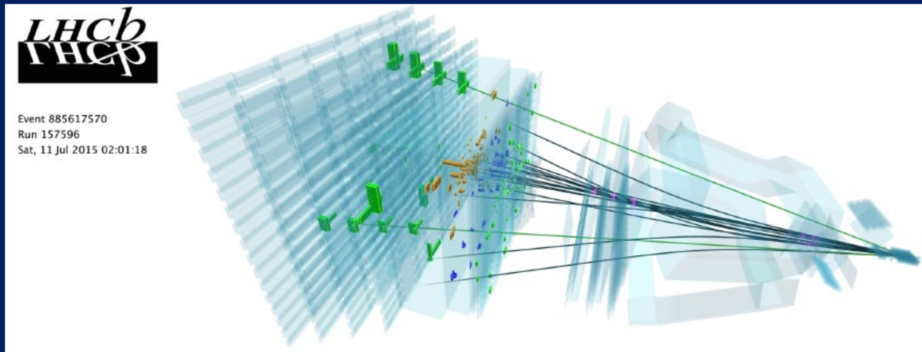
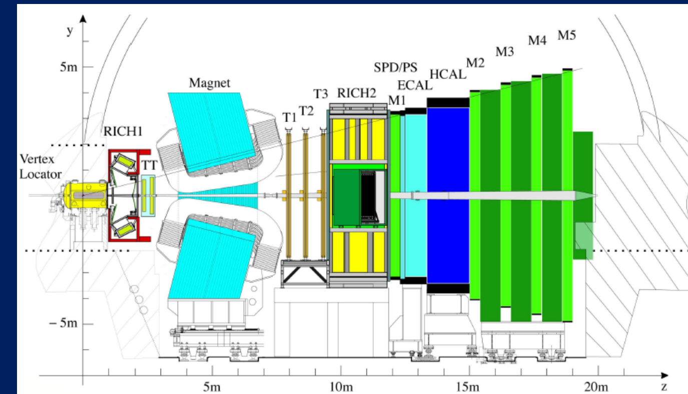
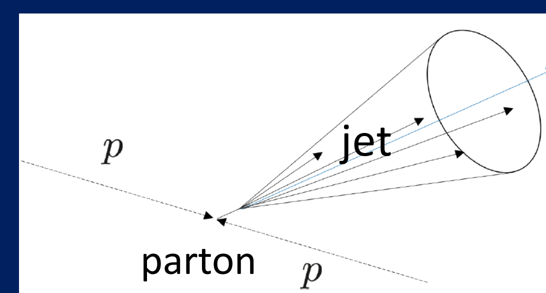




JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

Studying Parton Showers and Hadronization in Jets at LHCb

Christine A. Aidala
University of Michigan



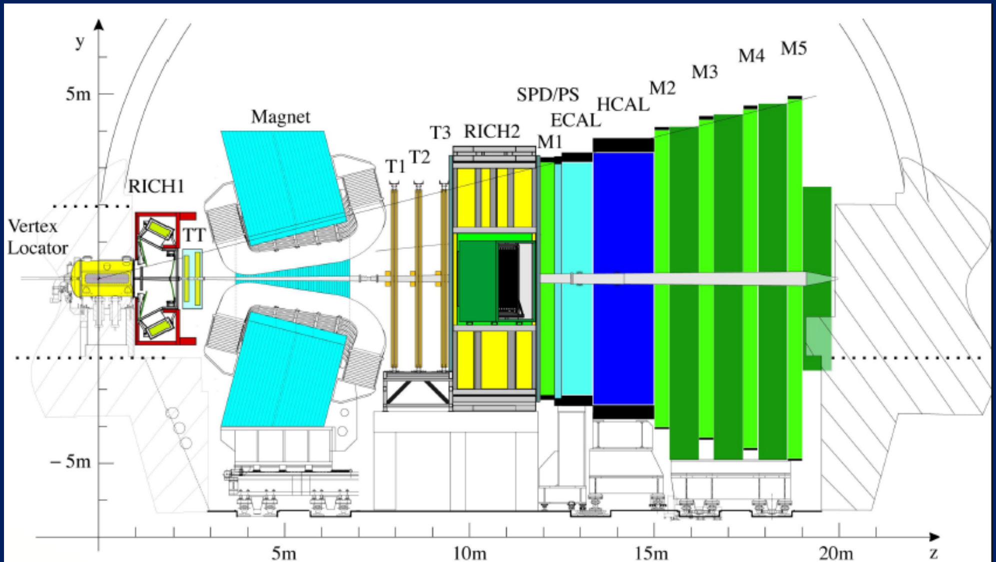
Flowing into the Future
Simons Center, Stony Brook
March 23, 2022

LHCb: Opportunities for hadronization measurements in jets

LHCb is the experiment devoted to flavor physics 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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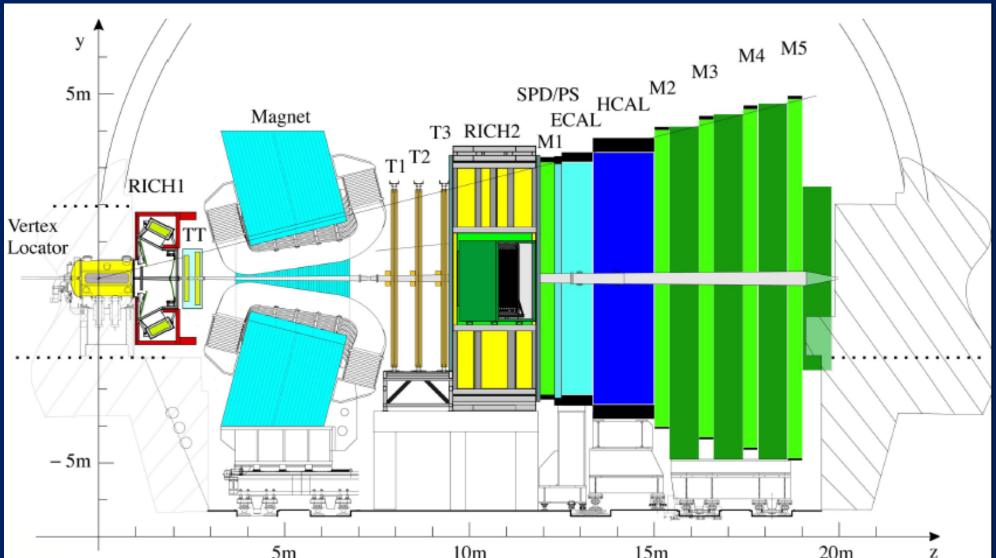


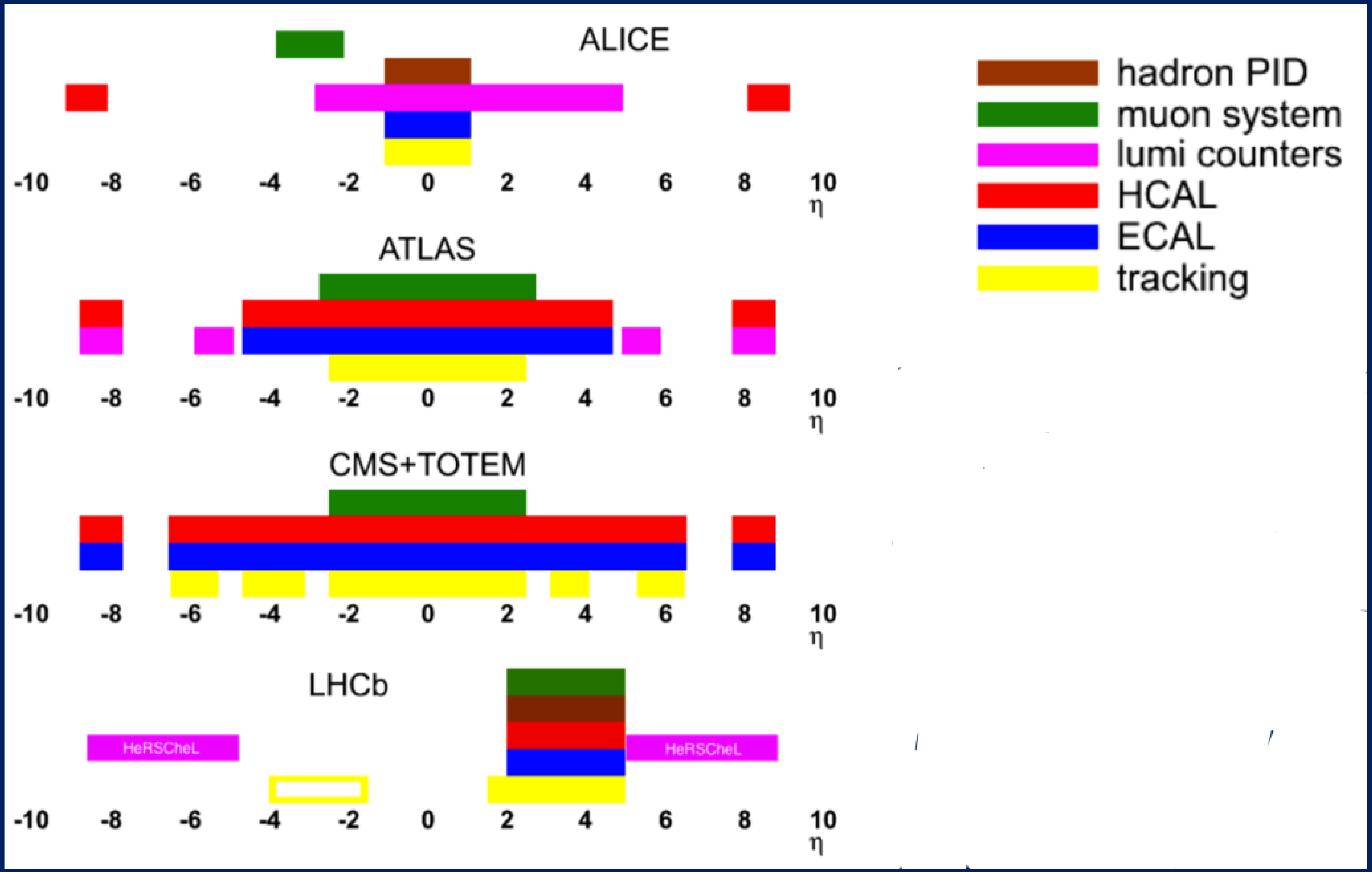
JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

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

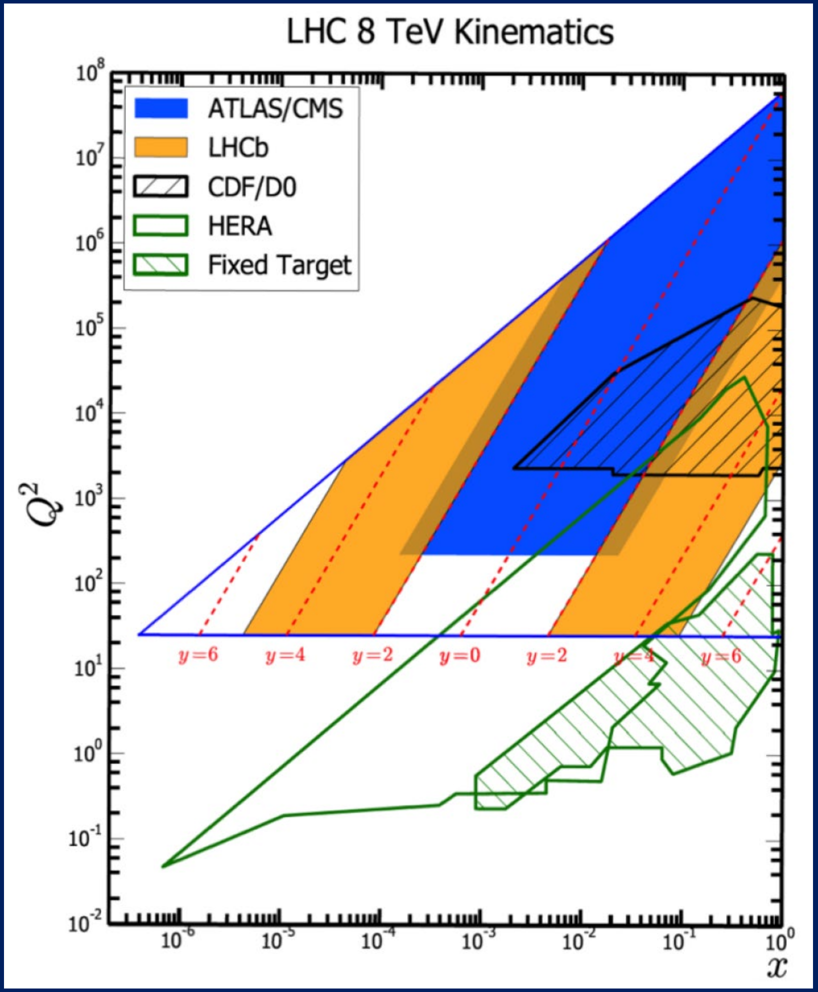
Can study identified particle distributions within jets!

Pseudorapidity coverage at LHC



x-Q^2 coverage affects parton mix

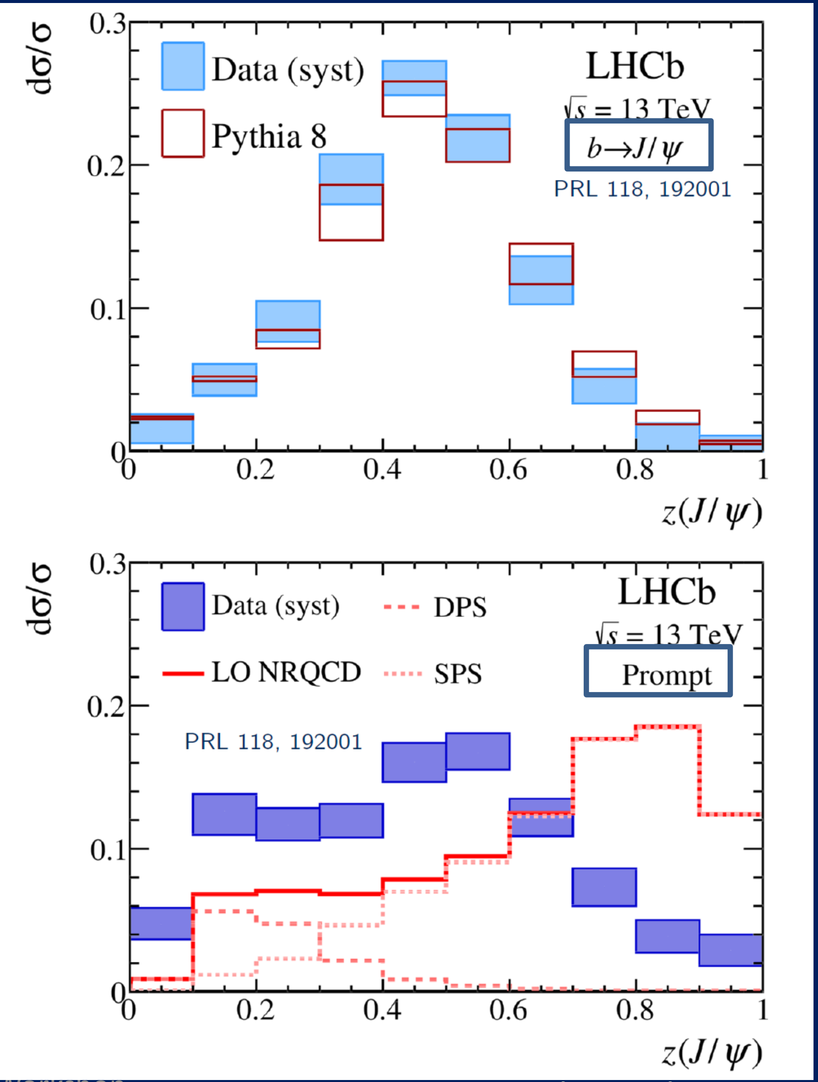
- LHCb also has unique x-Q^2 coverage
  - Enhanced light quark jet fraction in forward region



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).
  - See e.g. PRL 119, 032002 (2017) for NRQCD calculations using fragmenting jet functions that agree better with the prompt data

$$z \equiv \frac{p_T^{J/\psi}}{p_T^{jet}}$$

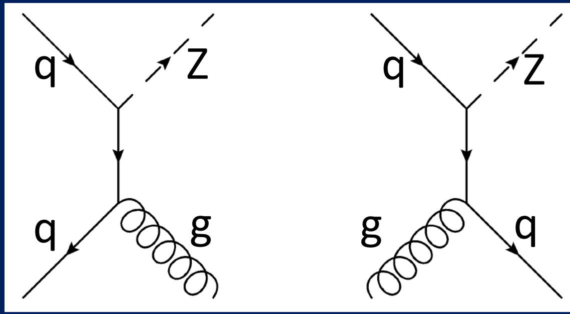


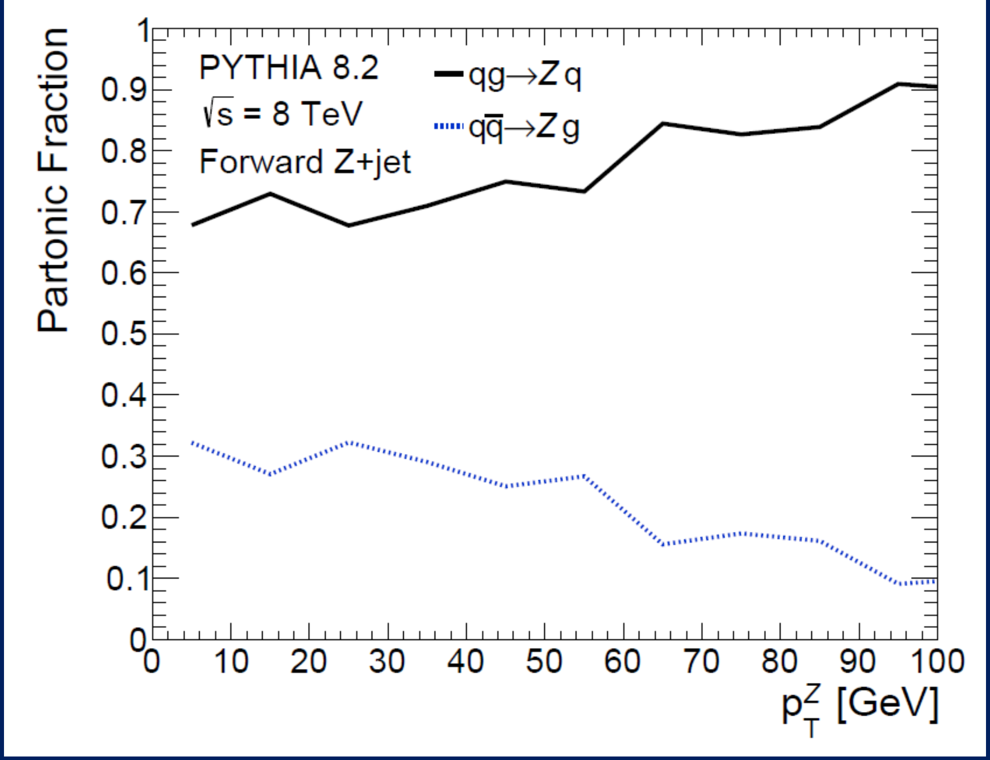
PRL 118, 192001 (2017)

Forward Z+jet

- Z+jet is predominantly sensitive to quark jets

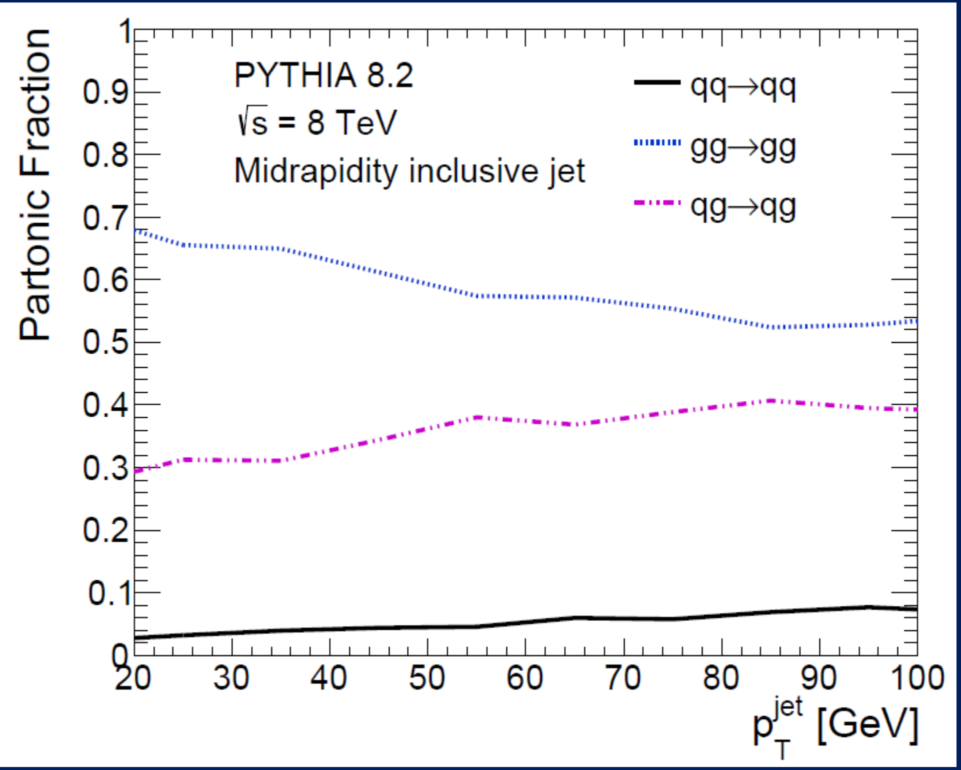
- Forward kinematics increases fraction of light quark jets





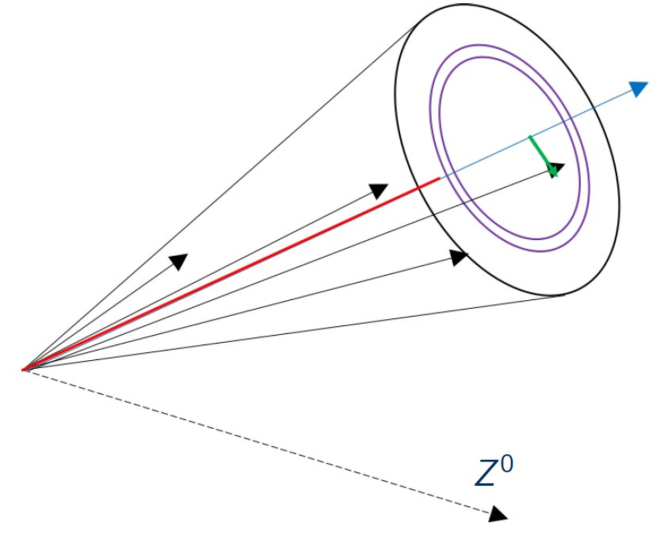
Forward Z+jet

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



Charged hadrons in forward Z+jet: Observables measured

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



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

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

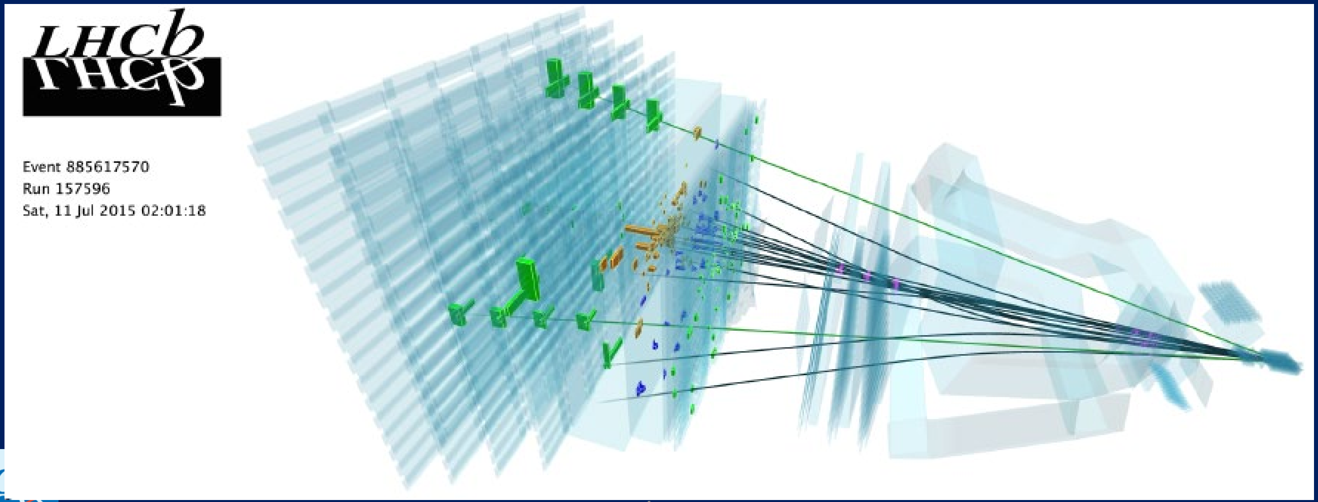
$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}$$

PRL 123, 232001 (2019)

Analysis details

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

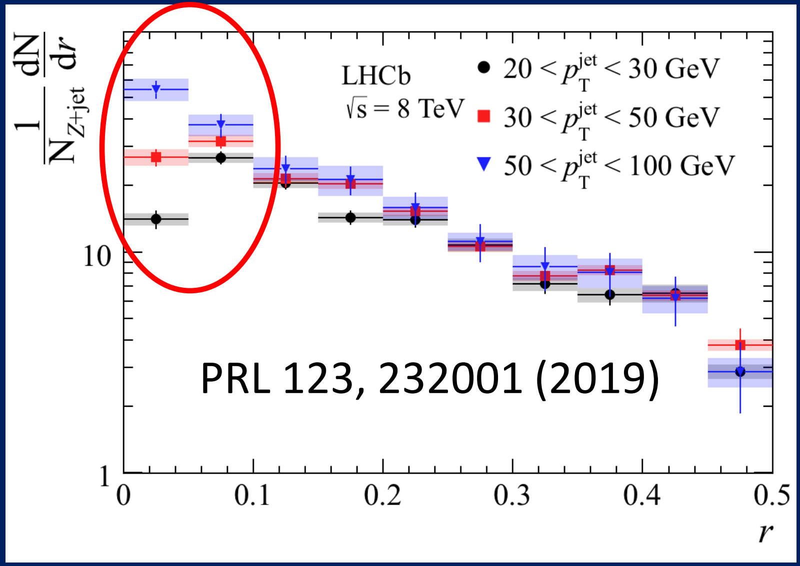
- $Z \rightarrow \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-k_T jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2 < \eta < 4.5$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects 2→2 event topology
- Charged hadrons selected with $p_T > 0.25$ GeV, $p > 4$ GeV,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

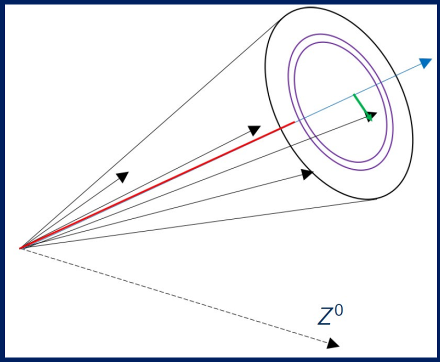


Results: Radial profiles

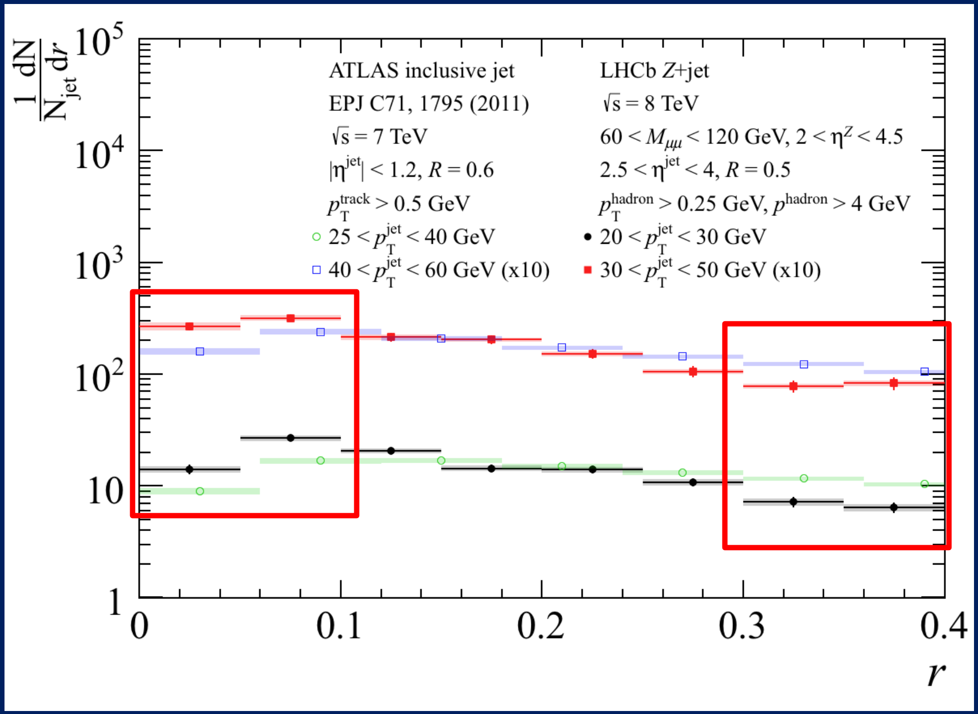
- Observe that the greater energy available in higher transverse momentum jets leads to more hadrons produced (logical)

- Note: ~All of the additional particles are produced close to the jet axis, and go from a depletion close to the axis to an excess





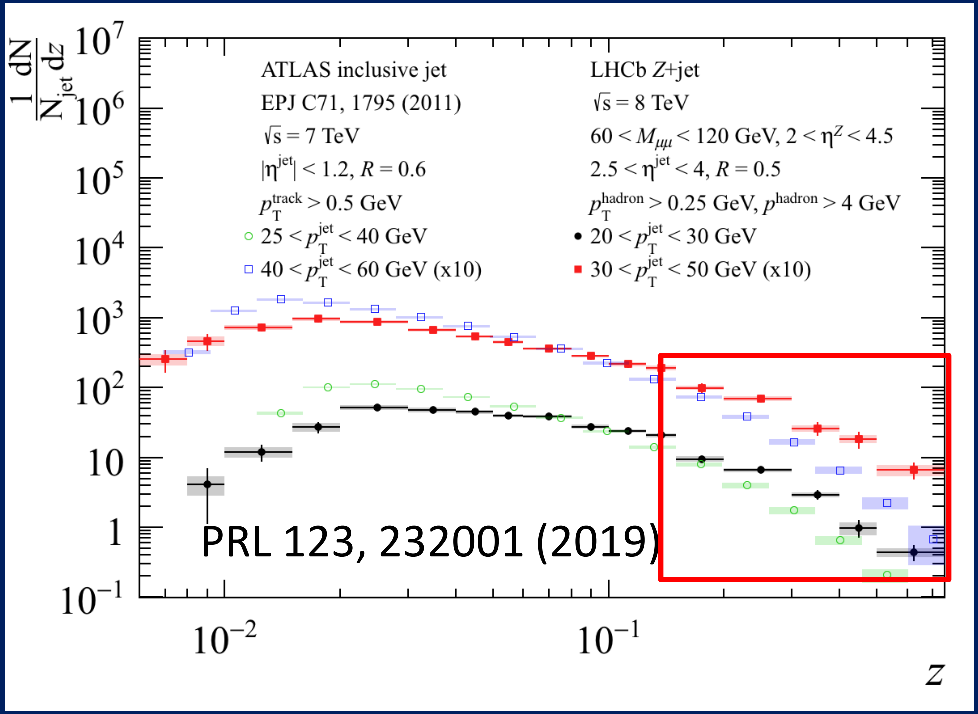
Differences between quark- and gluon-dominated jet samples: Radial profile



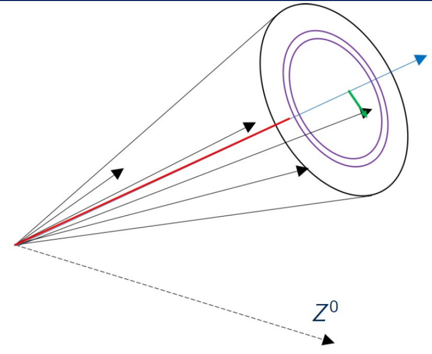
PRL 123, 232001 (2019)

- Quark-dominated jets more collimated than gluon-dominated jets measured by ATLAS
  - I.e. more charged hadrons at small radii, fewer at large radii
  - Qualitatively agrees with conventional expectations, but this shows clear and quantitative evidence from data

Differences between quark- and gluon-dominated jet samples: Longitudinal profile



- Quark-dominated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-dominated jets



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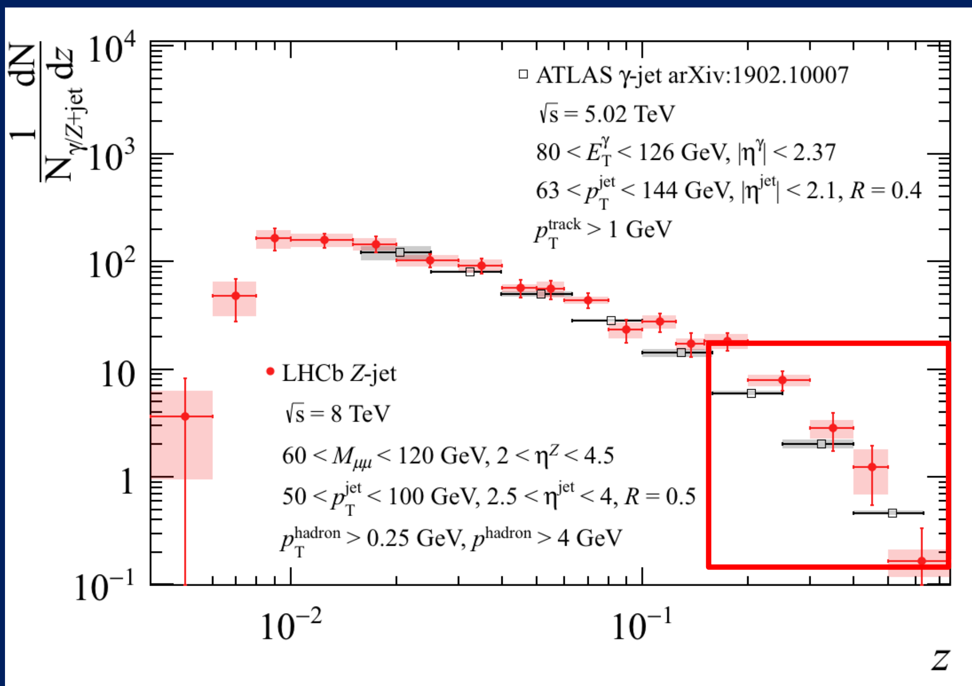
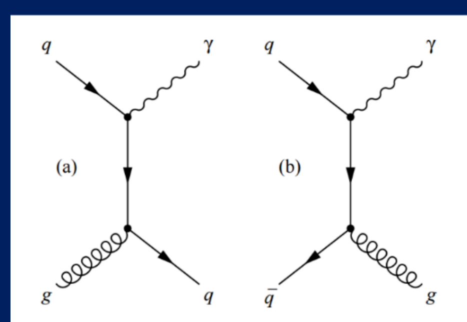


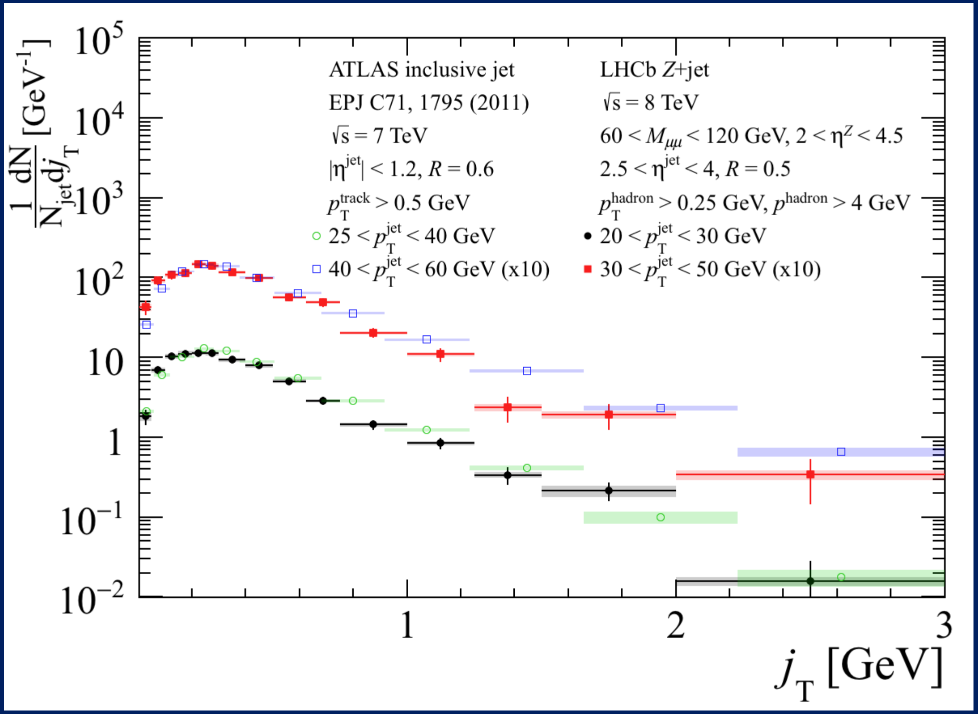
PRL 123, 232001 (2019)



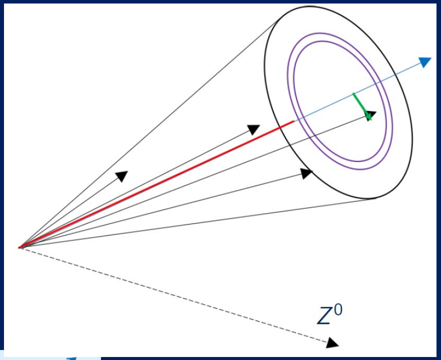
- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal momentum distributions are more similar
  - γ+jet, like Z+jet, enhances quark jet fraction
  - Further evidence that differences observed between LHCb results and ATLAS gluon-dominated results are due to differences in quark and gluon hadronization

Differences between quark- and gluon-dominated jet samples: Transverse momentum distributions

- Transverse momentum distributions similar in quark- and gluon-dominated jet samples

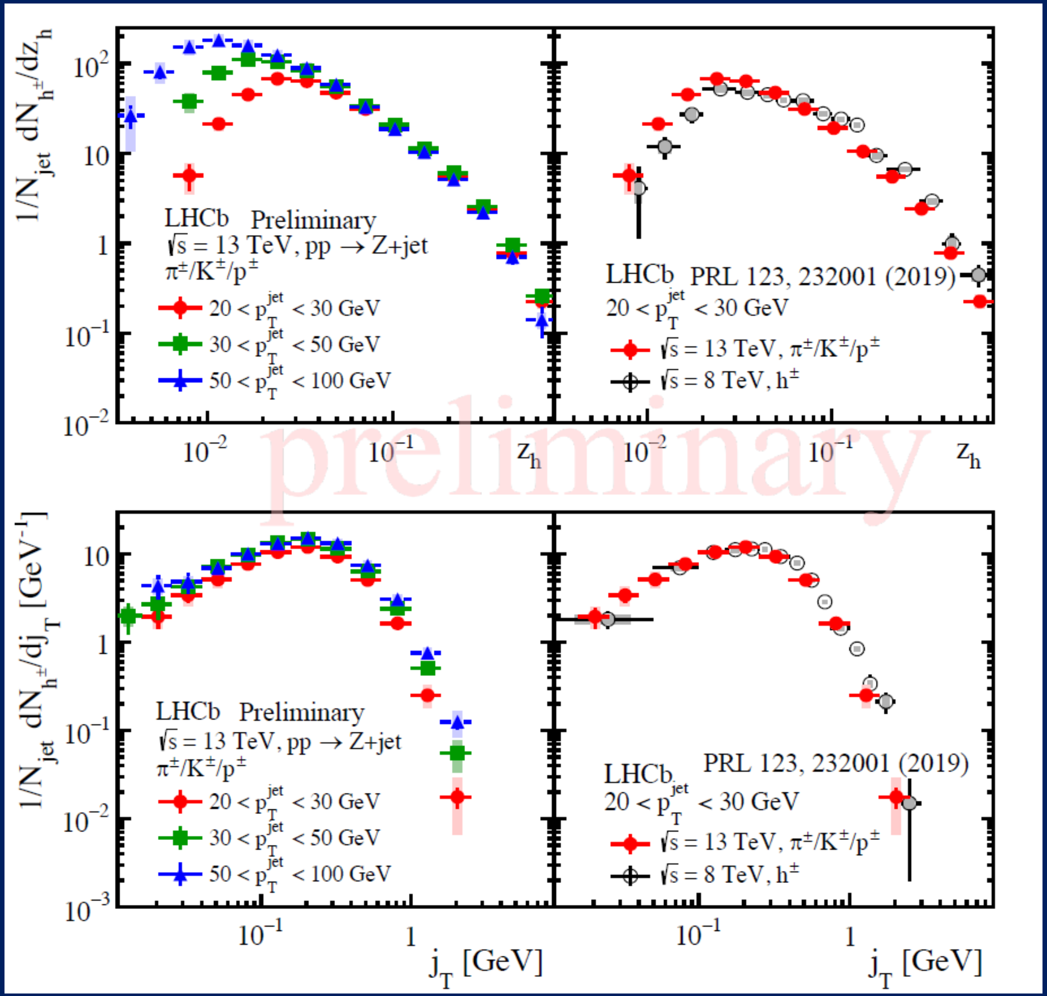


PRL 123, 232001 (2019)

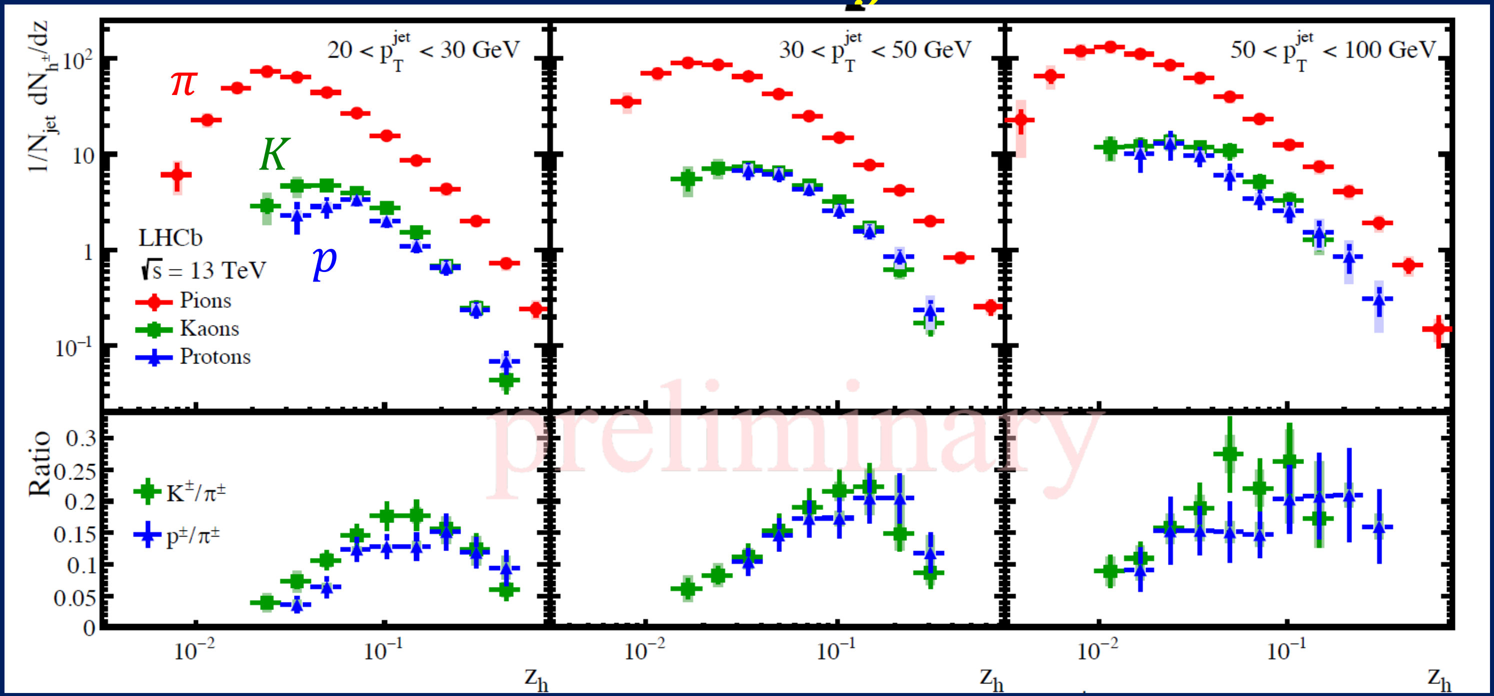


New! $h^{\pm}$ distributions in Z+jet at 13 TeV and comparison to 8 TeV

- Left: 13 TeV results in z (top) and j_T (bottom) for three jet p_T bins
  - Increased particle production for higher p_T^{jet}
    - Primarily at low z
    - But spread across all j_T with greater relative enhancement at larger j_T
- Right: 13 vs. 8 TeV: z (top) and j_T (bottom) distributions very similar at 13 and 8 TeV

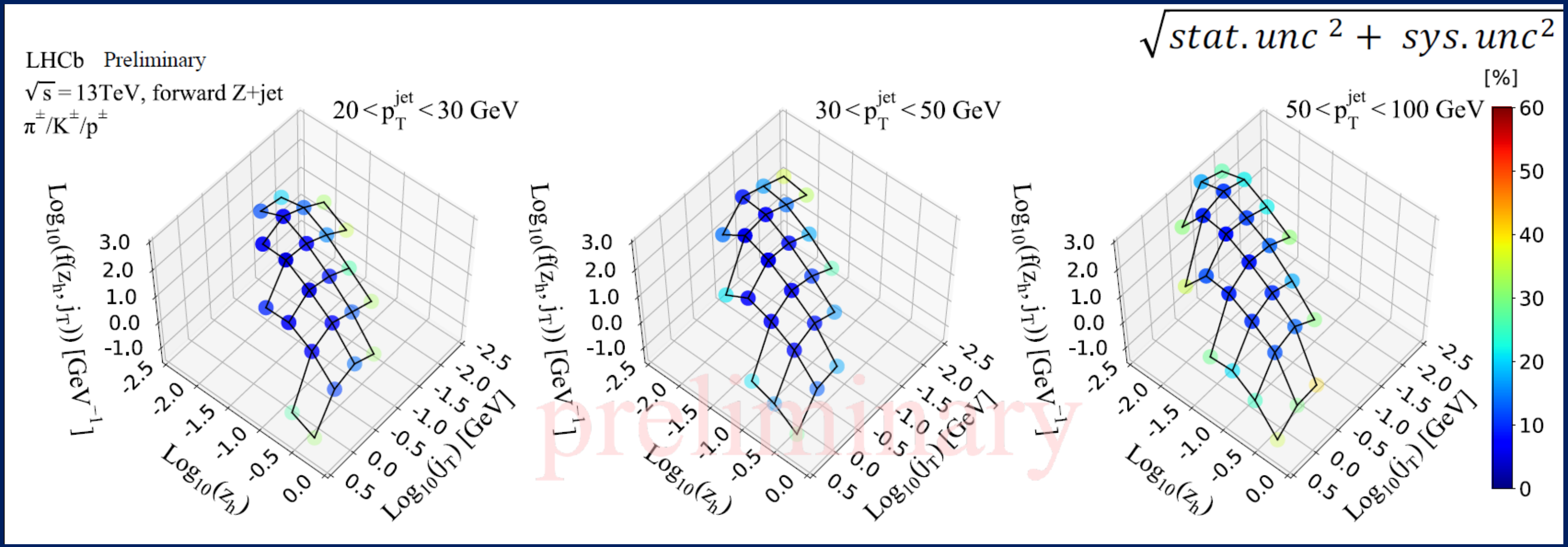


New! Identified $\pi^{\pm}, K^{\pm}, p^{\pm}$ distributions in Z+jet at 13 TeV



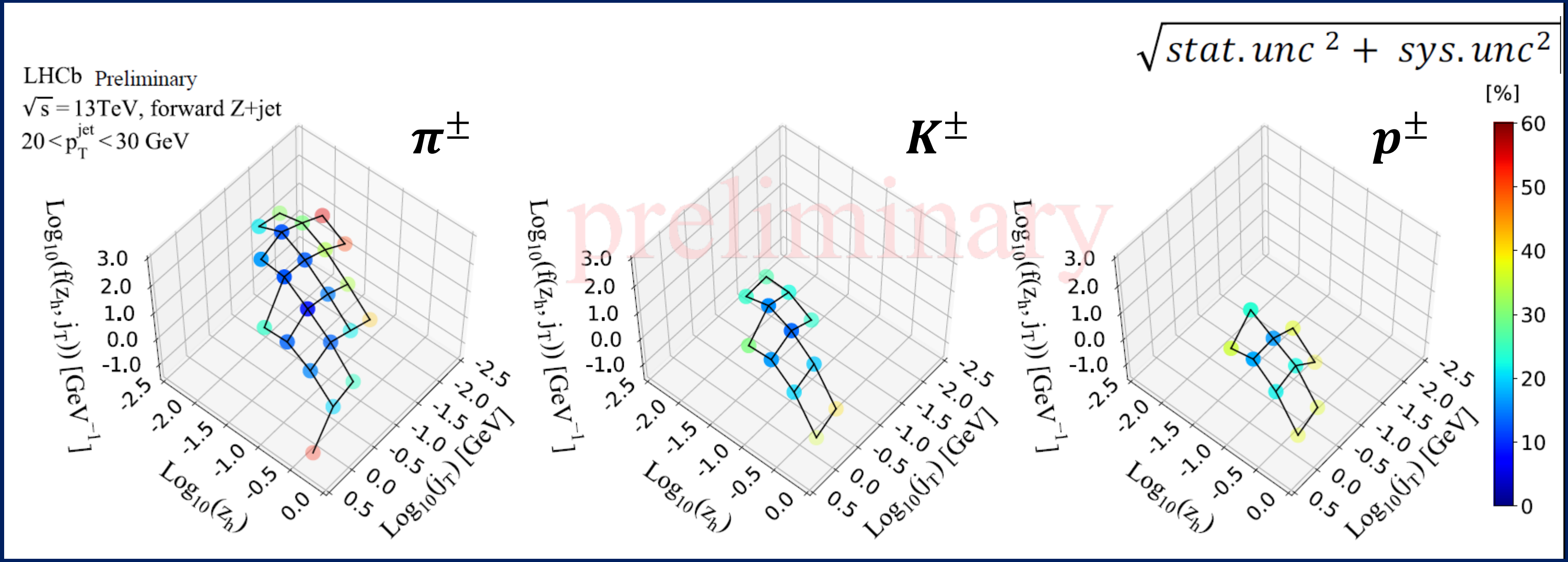
- Kaon and proton production rates similar, but kaons go down to lower *z* (mass effect)
- If assume larger *z* corresponds to earlier in the parton shower, observe
  - harder jets provide more energy to produce heavier hadrons later in the shower (more kaons and protons down to lower *z* for higher p_T jets)
  - hint that kaon production more suppressed earlier in the shower than proton production? (protons cross above kaons at high *z*?)

New! Joint z-j_T distributions for $h^{\pm}$ in Z+jet at 13 TeV



- Hadrons carrying large momentum fraction along jet axis tend to have large transverse momentum w.r.t. jet axis
- Centroid of harder jets shifted toward smaller *z* (soft particle production) and larger j_T (increased j_T for given *z*)

New! Joint z-j_T distributions for identified $\pi^\pm, K^\pm, p^\pm$ in Z+jet at 13 TeV



- Single jet p_T bin ($20 < p_T^{jet} < 30$ GeV)
- Heavier hadrons produced by harder partons, i.e. larger j_T as well as larger z

*Other **ongoing** and potential measurements of jet substructure at LHCb*

- **Charged hadron distributions in b- and c-tagged jets**

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  - Also look at ϕ?

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- Charge ratio as a function of z in light quark, b- and c-tagged jets, to test ideas about "leading hadrons" and jet flavor tagging
- Correlated particle production within jets, e.g. $\pi^{\pm}K^{\mp}$, $K^{\pm}K^{\mp}$, $p\bar{p}$

*Other **ongoing** and potential measurements of jet substructure at LHCb*

- **Comparison of Lund plane in b-tagged, c-tagged, and light quark jets (Z+jet), looking for dead cone effect**
  - Could also use explicitly reconstructed b or c hadrons for the heavy flavor jets rather than secondary-vertex tagging
- Other ideas??
  - Manpower limited, so . . .

LHCb open data set for jet physics forthcoming

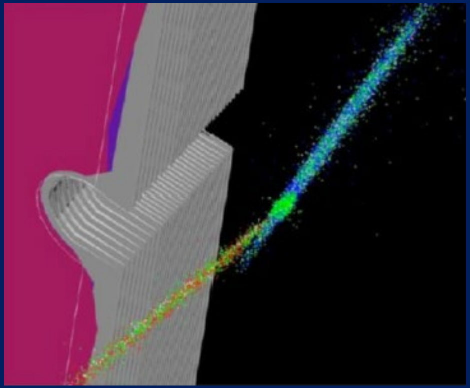
- With LHCb's beautiful hadron PID capabilities, full jet reconstruction, and low pile-up (can associate neutrals with a specific jet), can provide jet samples with complete 4-vector of every constituent → full information about jet structure!
- Plan to "publish" as an open data set on CERN Open Data Portal later this year

LHCb beyond pp

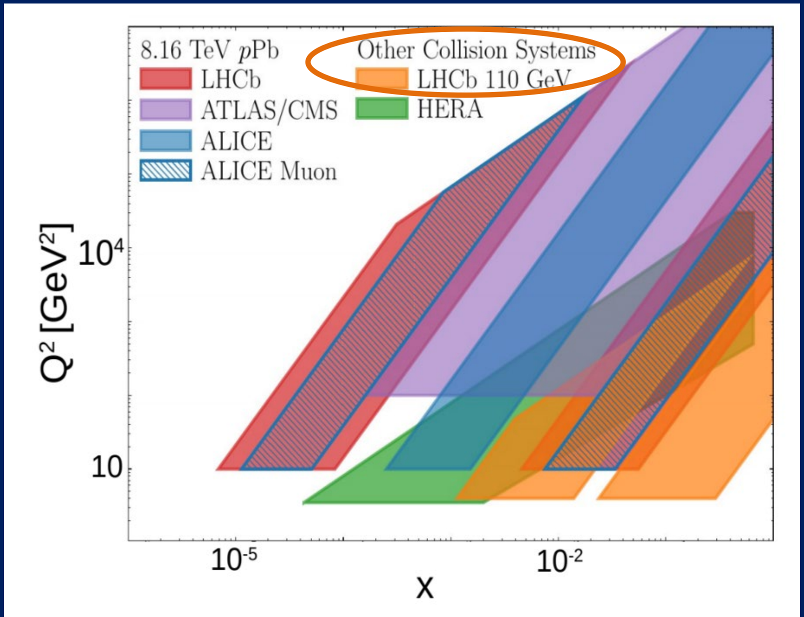
- So far only have jet measurements in pp, but data available and more data planned for pPb, Pbp, and fixed-target running . . .

LHCb fixed-target capabilities

"Fixed-target-like" geometry well suited for . . . fixed-target physics!

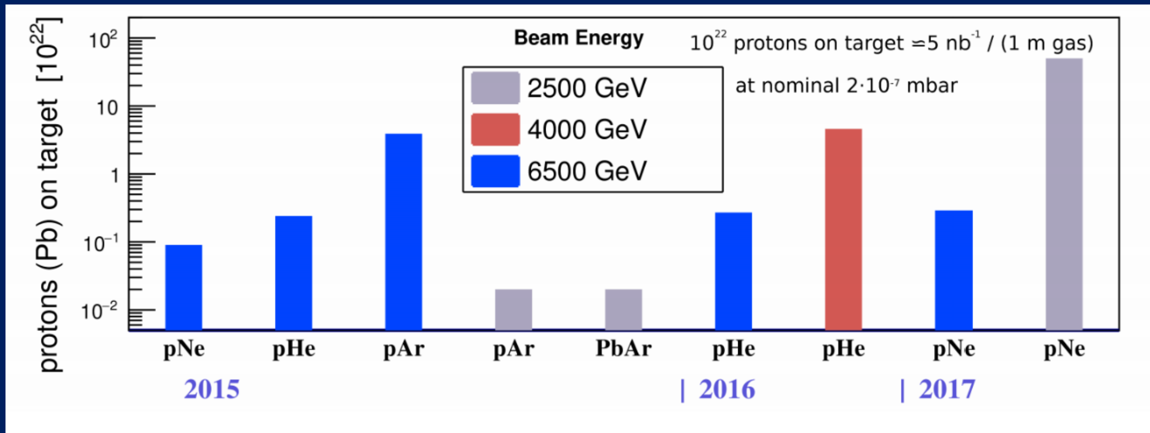


- System for Measuring Overlap with Gas (SMOG) allowed injection of small amounts of noble gas into LHC beam pipe around LHCb collision region. Luminosity up to 10^{30} cm^{-2} s^{-1}

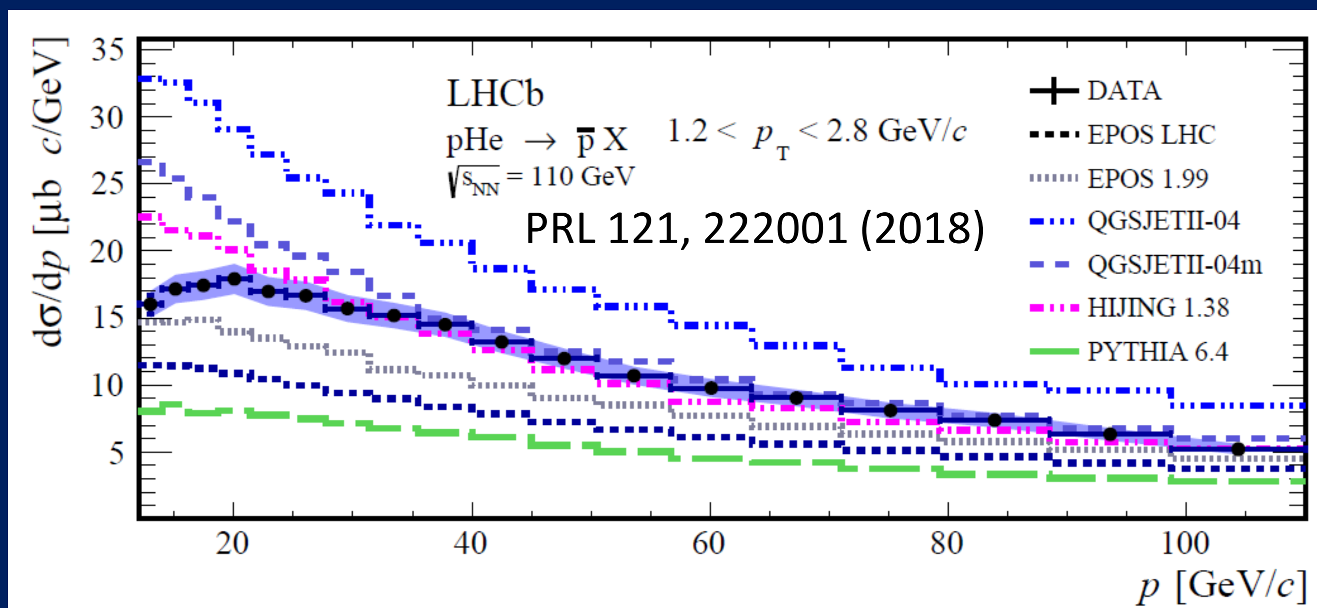


- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{beam}M_p}$ 41-110 GeV for E_{beam}= 0.9-6.5 TeV
  - Between SPS and top RHIC energies
- Overlap with EIC energies

LHCb fixed-target capabilities



Forward antiproton production in pHe



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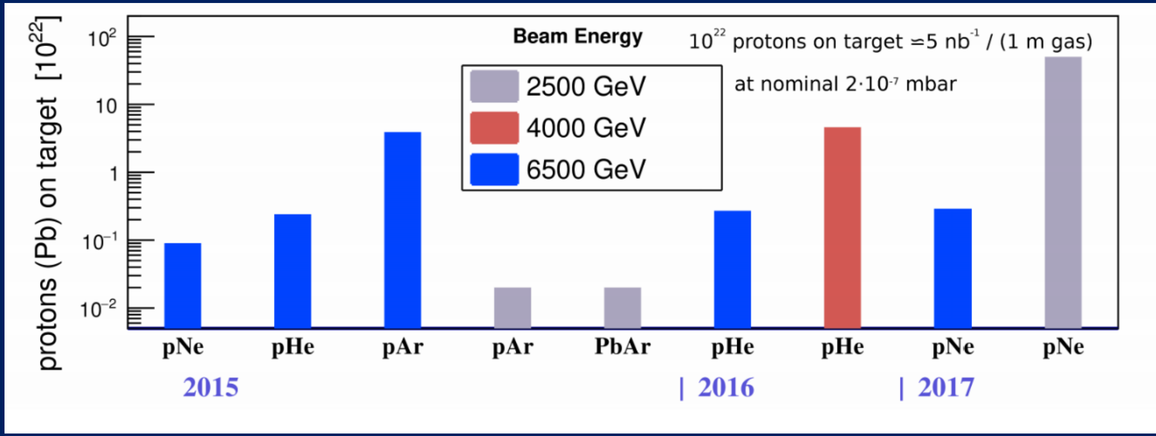
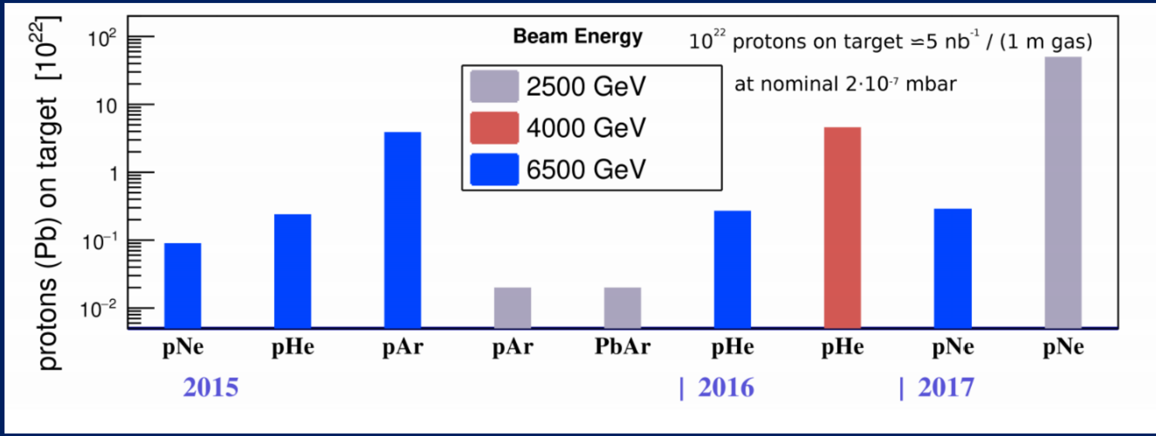


- Target storage cell installed Aug 2020: Up to 2 orders of magnitude higher luminosity, improved lumi determination, reduced backgrounds, wider variety of target species: H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe

LHCb fixed-target capabilities



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- LHCSpin: Proposal for transversely polarized gas jet target at LHCb currently in R&D and technical evaluation

Summary

- A more extensive jet substructure and hadronization program at LHCb is just getting underway
- To progress efficiently over the next decade, close interactions between theorists and experimentalists will be crucial
  - What sets of observables can teach us the most?
- Limited LHCb manpower focused on jets, but forthcoming open data set aimed at jet studies will allow others to pursue additional observables

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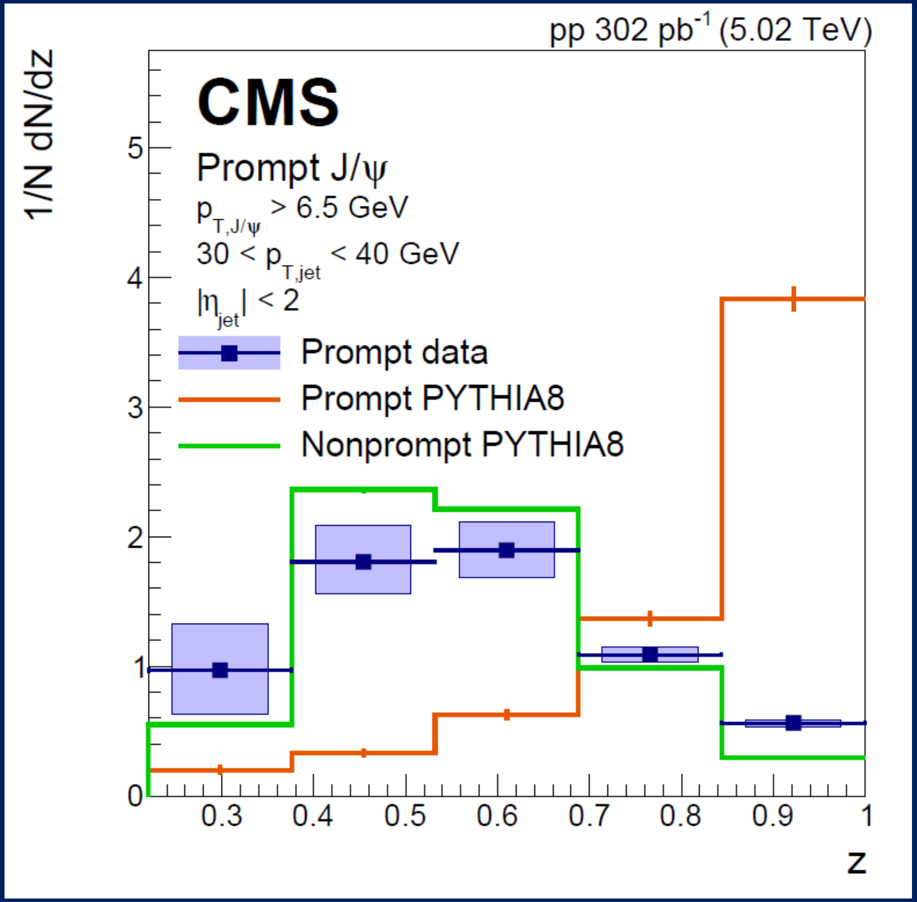
  - What sets of observables can teach us the most?
- Limited LHCb manpower focused on jets, but forthcoming open data set aimed at jet studies will allow others to pursue additional observables

LHCb offers a wealth of unique opportunities for jet physics, thanks to its
- *kinematic coverage*
- *full hadron PID*
- *low pile-up*
- *fixed-target program*

Extra

Prompt J/ψ in jet from CMS 5.02 TeV pp

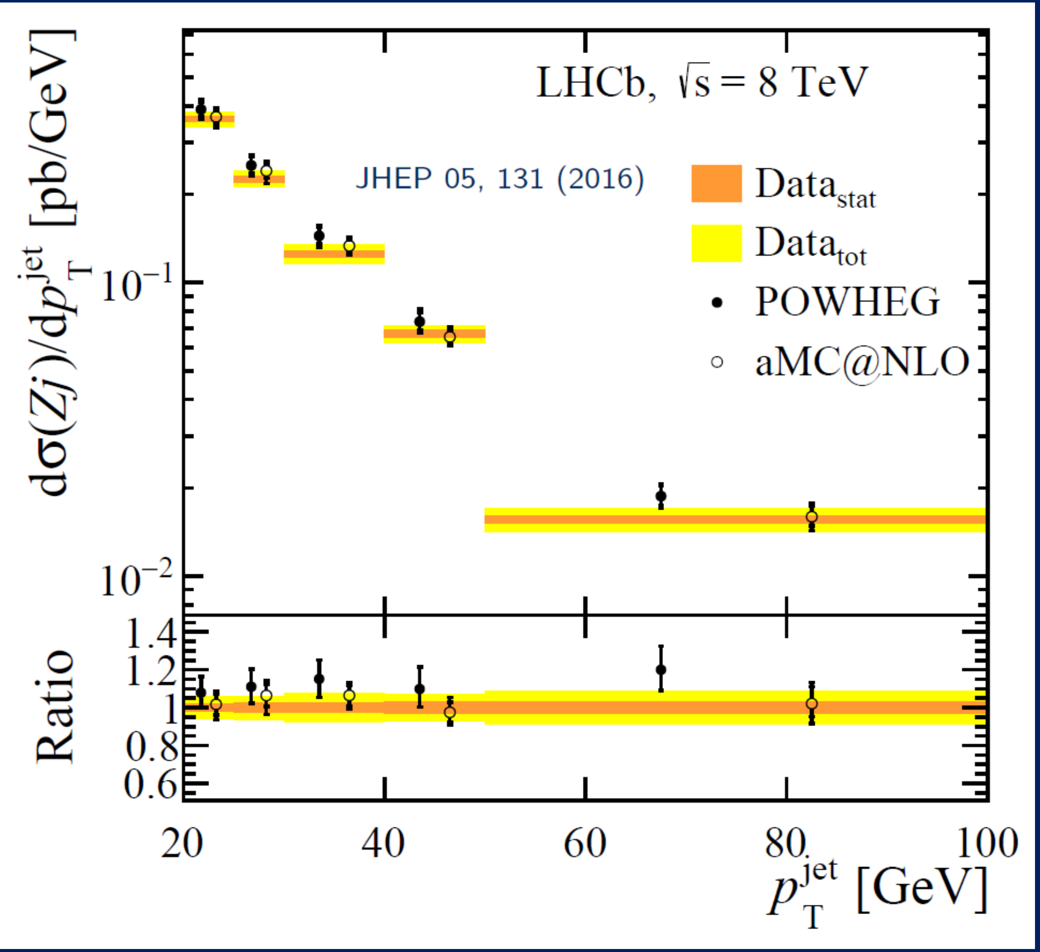
Phys.Lett.B 825 (2022) 136842



See also CMS, *Phys. Lett. B* 804 (2020) 135409

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
  - PRL 123, 232001 (2019)
- First LHC measurement of charged hadrons within Z-tagged jets
- First LHC measurement of charged hadrons-in-jets at forward rapidity



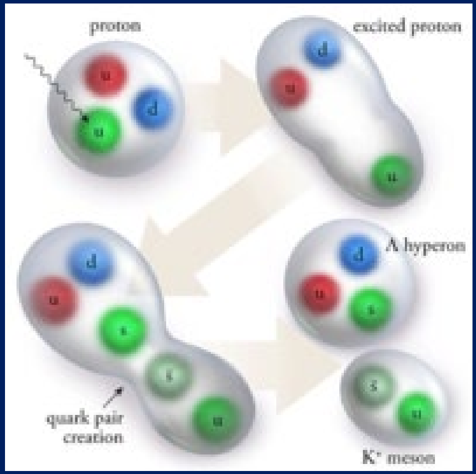
13 TeV identified hadron-in-jet analysis

Dataset & Selections

- MC : Reco16 Sim09j
  - Generation Code : 42112001
  - Generator level cuts : $p_T(\mu)$ > 4 GeV/c, $\eta(\mu)$> 1.6 and $m_{\mu\mu}$>40 GeV/c^2
- Data: Run II 2016 p+p data
- Stripping line : 'Z02MuMuLine' in Stripping28r2
- Trigger :
  - L0MuonEWDecision & Hlt1SingleMuonHighPTDecision & Hlt2EWSingleMuonVHighPtDecision
- Event requirement :
  - nPV=1
- Z selection:
  - $p_T(\mu)$ > 20 GeV/c, 2 < $\eta(\mu)$ < 4.5
  - $\frac{\sigma_p}{p}$ < 0.1, P(χ^2) > 0.1%, isMuon
  - 60 < $m_{\mu\mu}$ < 120 GeV/c^2
- Jet selection:
  - StdJets, p_T(jet) > 20 [15] GeV/c, 2.5 < η(jet) <4.0, deltaR(jet)=0.5
  - $\Delta\phi$(jet-μ) > 0.4
  - $\Delta\phi$ (Z-jet)> $\frac{7}{8}\pi$
- Track selection
  - Track χ^2/ndf < 3
  - 4 < p < 1000 GeV/c
  - p_T > 0.25 GeV/c

Different mechanisms of hadronization

- High-energy limit of “string-breaking” or “cluster” pictures
- Coalescence/recombination of partons nearby in phase space
- Threshold production
- Production via decay from other hadrons
- …?



CLAS, PRL 113, 152004 (2014)

Hadronization: An open playing field in QCD

- The future Electron-Ion Collider will be well timed and well suited to make tremendous progress in our understanding of hadronization in the 2030s
  - Discussed less for the EIC than partonic structure of nucleons and nuclei because we still think much less about hadronization as a community

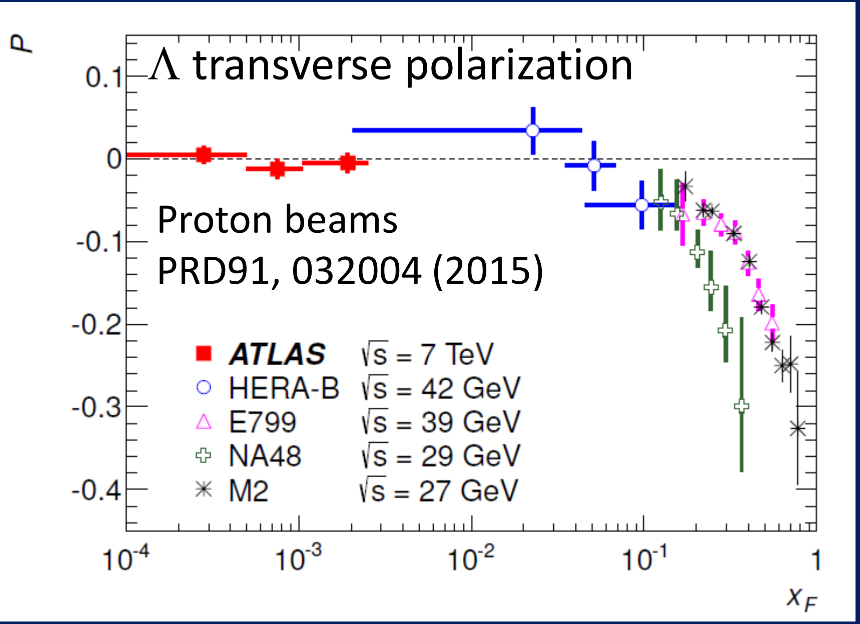
- We should use the 2020s to ensure that we are positioned to take full advantage of the EIC's potential for hadronization!

- LHCb offers a number of opportunities over the next decade
  . . .

Other ongoing hadronization studies at LHCb

- Multiplicity-dependent identified particle production in p+p and p+A (not in jets), with comparison of
  - meson vs. baryon production - sensitivity to parton coalescence/recombination
  - strangeness enhancement – sensitivity to collective effects in small systems

- Forward lambda and other hyperon polarization measurements



Actually, what's going on with baryons in general?

- Are we satisfied with our "vacuum fragmentation" picture for high-p_T baryon production?
- For high-p_T mesons usually think of single scattered quark, with partner coming from q-qbar pair
- Can thinking about gluon fragmentation to mesons help us think about baryon production?