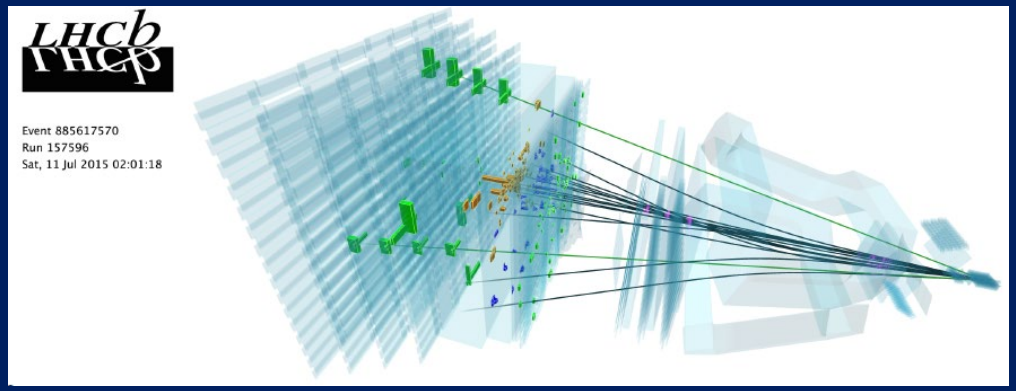
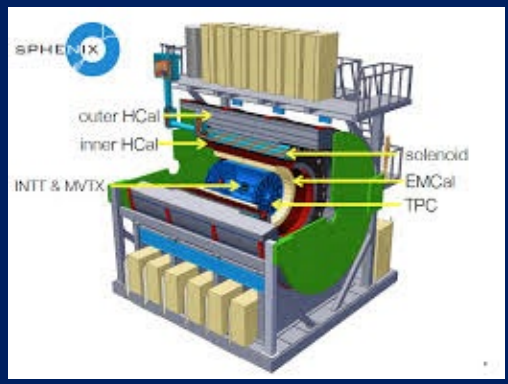


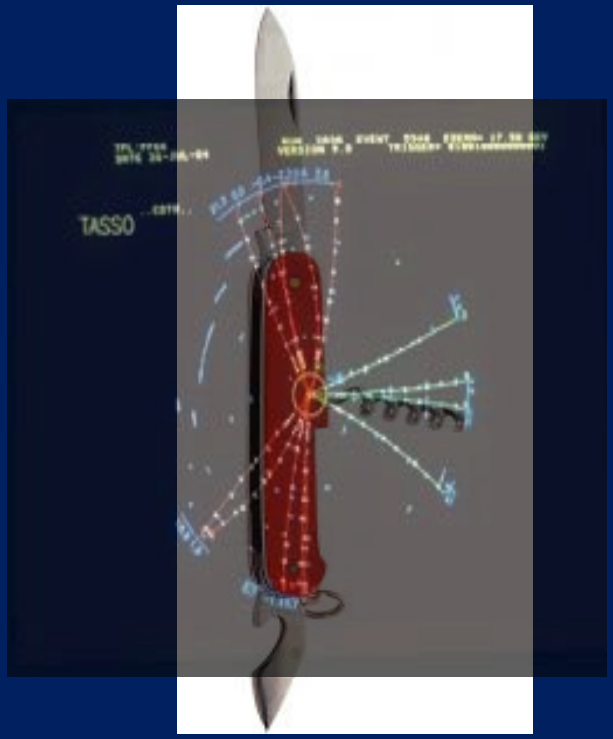
Jets as Jackknives: The Hadronization Tool

Christine A. Aidala
University of Michigan



Jets for 3D Imaging at the EIC Workshop
November 23-25, 2020


TASSO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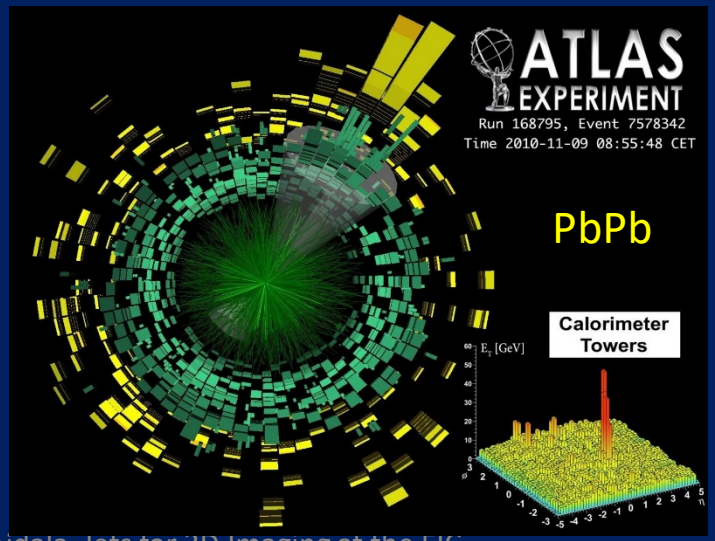
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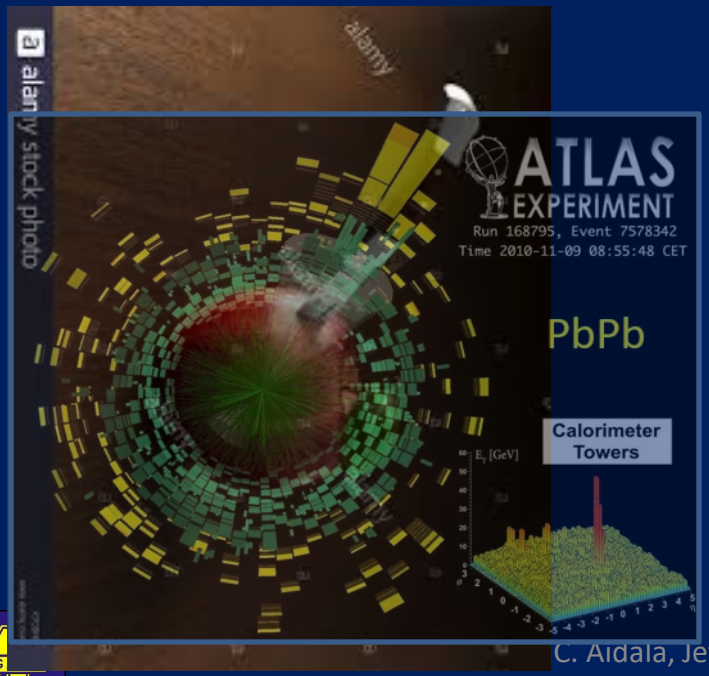
PbPb
Calorimeter Towers
E_T [GeV]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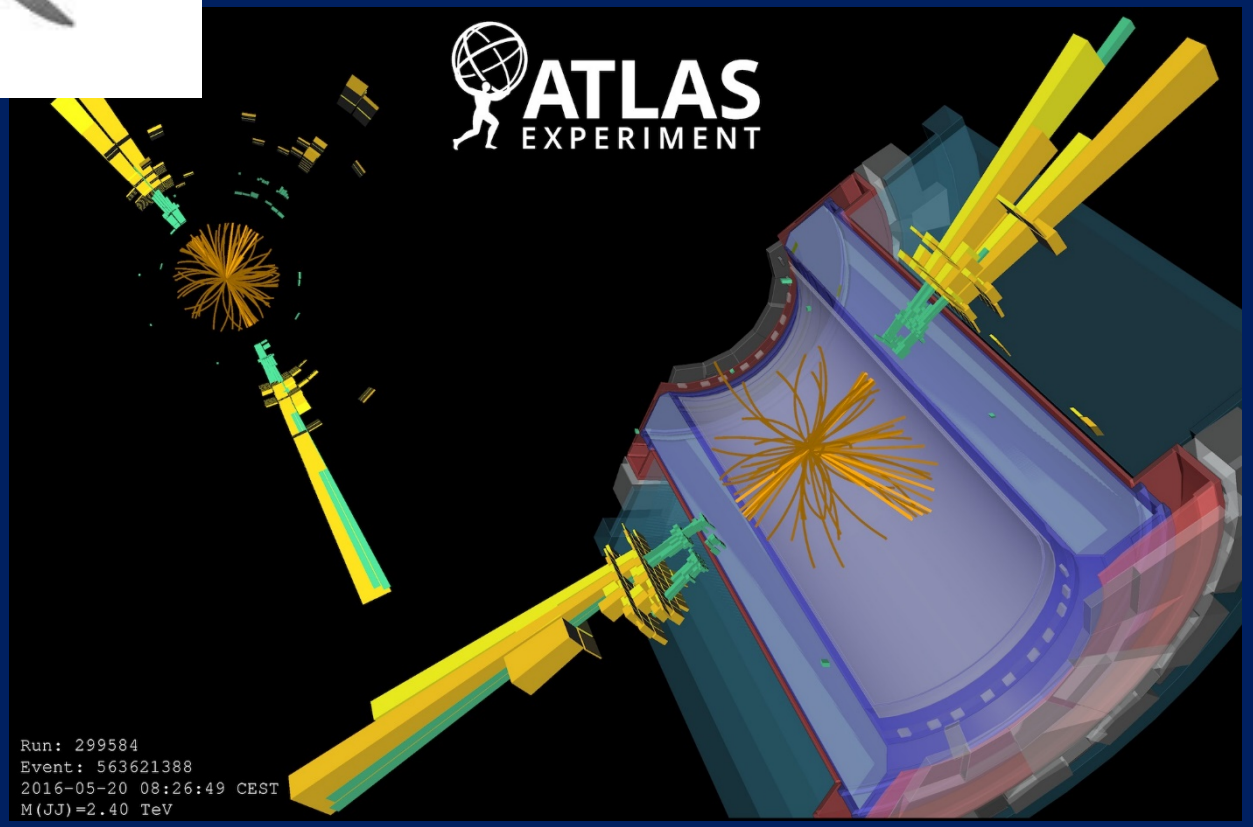
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EXPERIMENT
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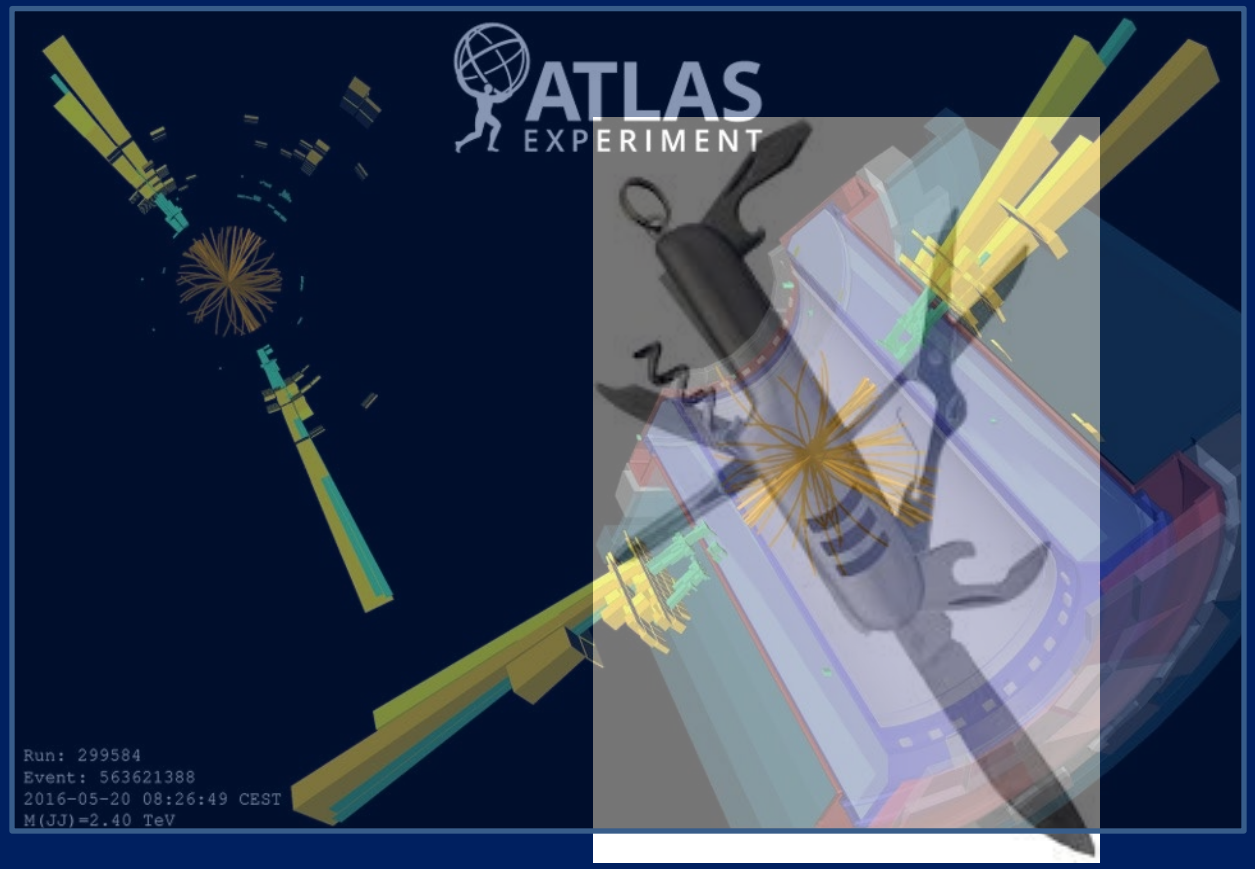
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ)=2.40 TeV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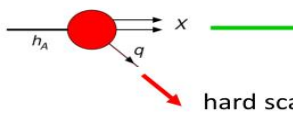
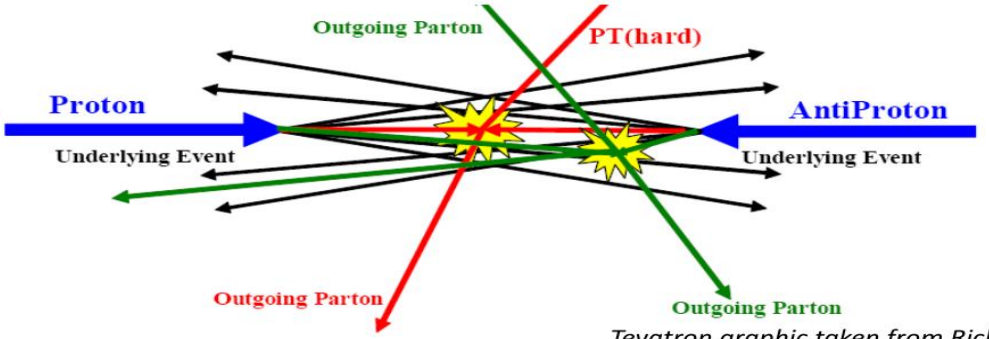
...+ multi-parton scattering +...

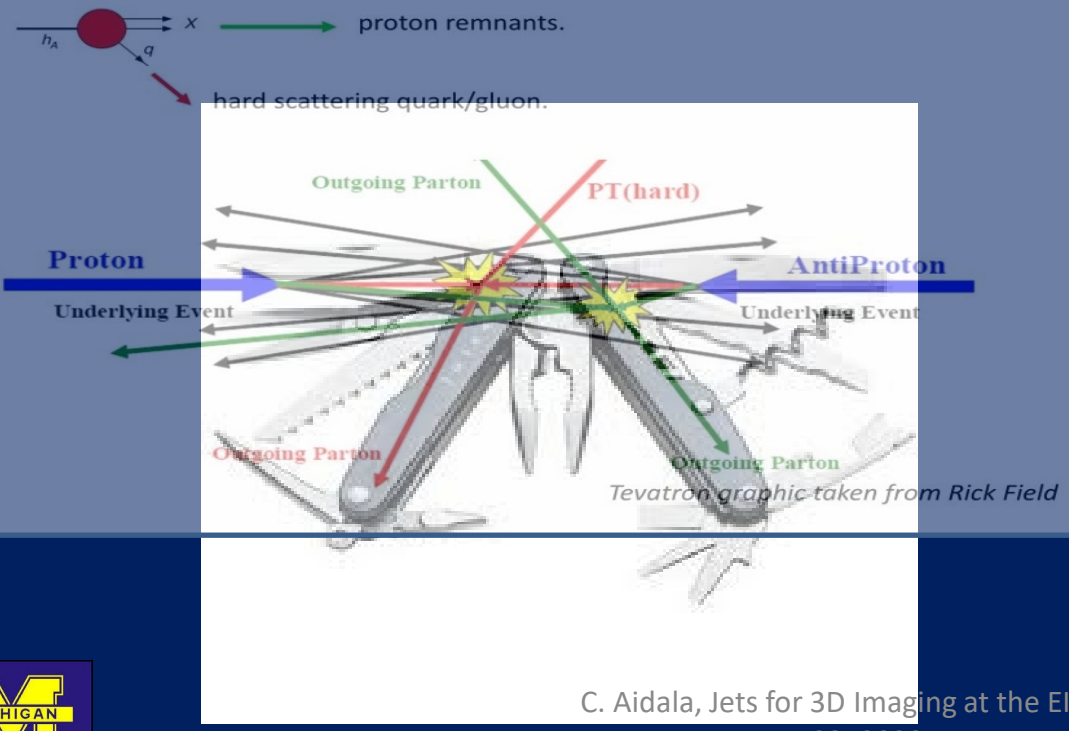




Tevatron graphic taken from Rick Field

From talk by Harald Ita

...+ multi-parton scattering +...



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Jets have become versatile tools!

- Anti-k_T jet reconstruction algorithm has opened up many new possibilities to make robust comparisons of jets between theory and experiment – Cacciari, Salam, Soyez, JHEP 04, 063 (2008)
- Lots of subsequent developments!
  - Healthy interplay between experiment and theory, in particular given the wealth of jet data from pp and heavy ion collisions at the LHC

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- Diffractive imaging of protons and nuclei
- …

Jets as jackknives: The hadronization tool?

- "Which" jets can teach us about hadronization??

Jets as jackknives: The hadronization tool?

- "Which" jets can teach us about hadronization??

- From an experimental point of view, where you don't have a jet if you don't reconstruct tracks and/or clusters, basically any jet can teach us something about hadronization, if that's what we choose to focus on!

Hadronization and confinement

- How do we relate the quark and gluon d.o.f. of QCD to the hadronic d.o.f. we observe in nature?
- Flip sides of the "confinement coin":
  - Hadron *structure*
  - Hadron *formation*

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- Flip sides of the "confinement coin":
  - Hadron *structure*
  - Hadron *formation*
- Much greater effort has been dedicated to studying hadron structure than hadron formation over the past half century
  - Nucleon structure in particular

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Hadronization offers an exciting frontier in QCD! The EIC will offer a wealth of opportunities to study hadronization, both within jets (see Wed talk by Joe Osborn) and more generally.

Hadronization in jets: Theory over the last decade

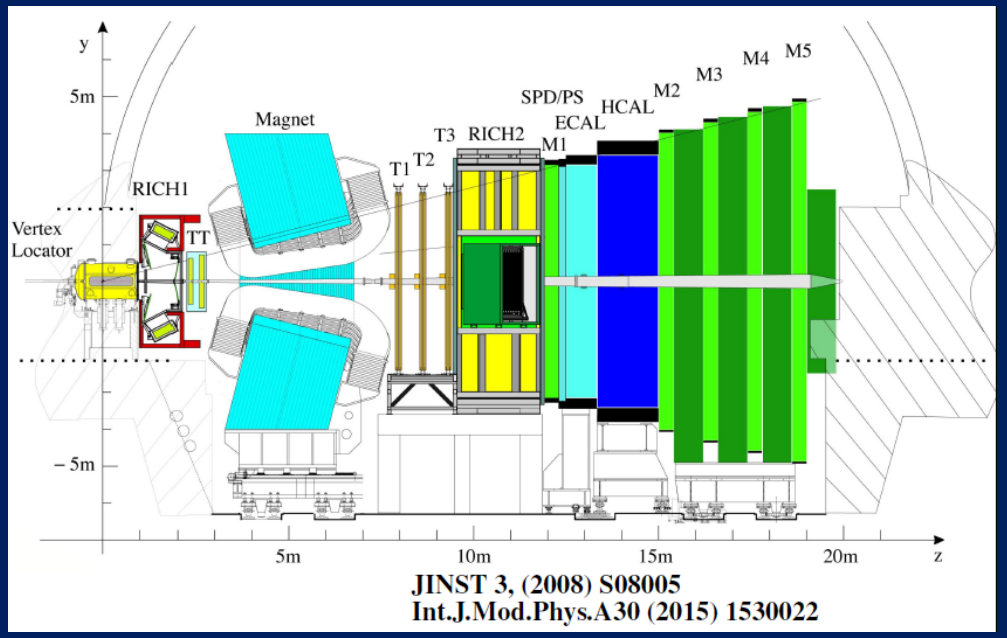
- Over the last decade, theory advances have made jets even more powerful tools to study hadronization, e.g.
  - Single hadron-in-jet FFs – introduced in Procura and Stewart, PRD81, 074009 (2010)
  - Fragmenting jet functions – introduced in Procura and Stewart, PRD81, 074009 (2010)
  - Jet substructure more generally – for a review see Larkoski, Moult, Nachman, arXiv:1709.04464.

LHCb: Opportunities for hadronization measurements in p+p

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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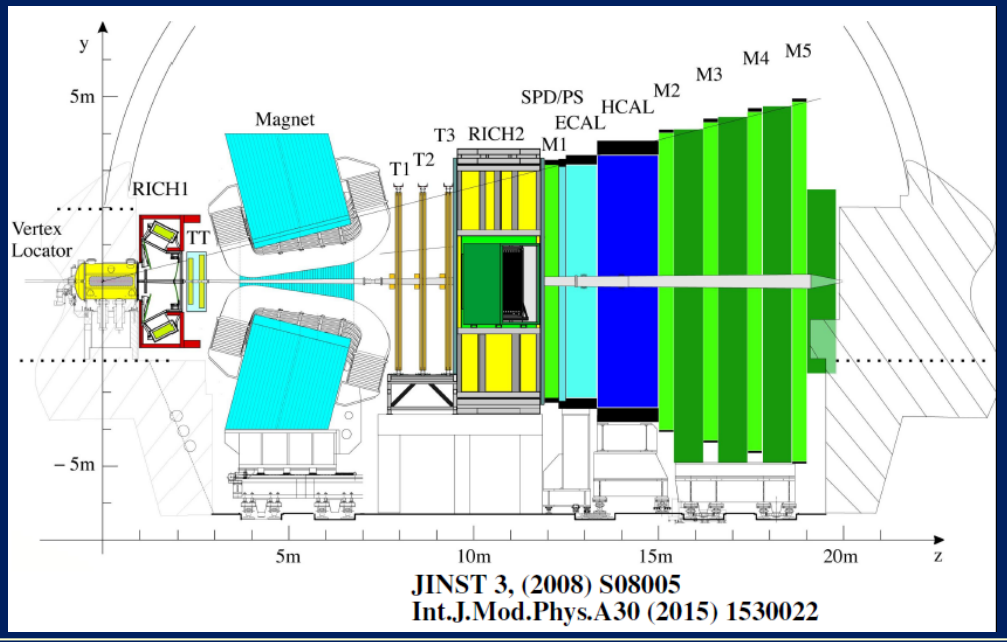


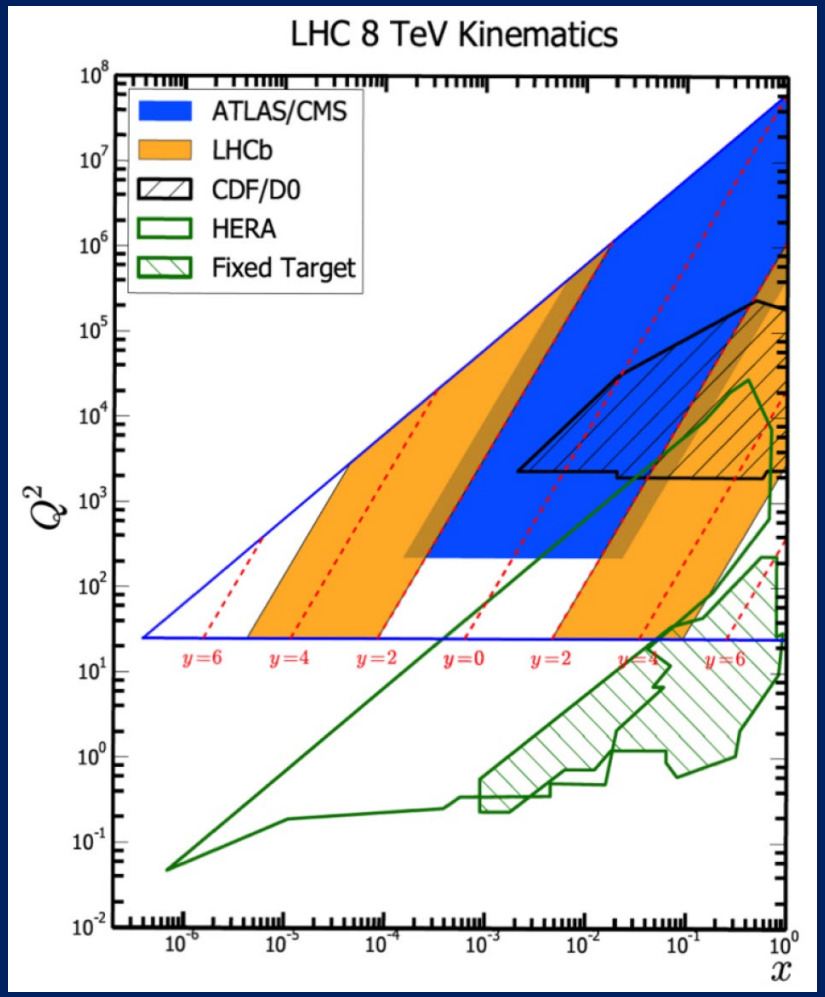
Some features specifically attractive for hadronization:

- 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!

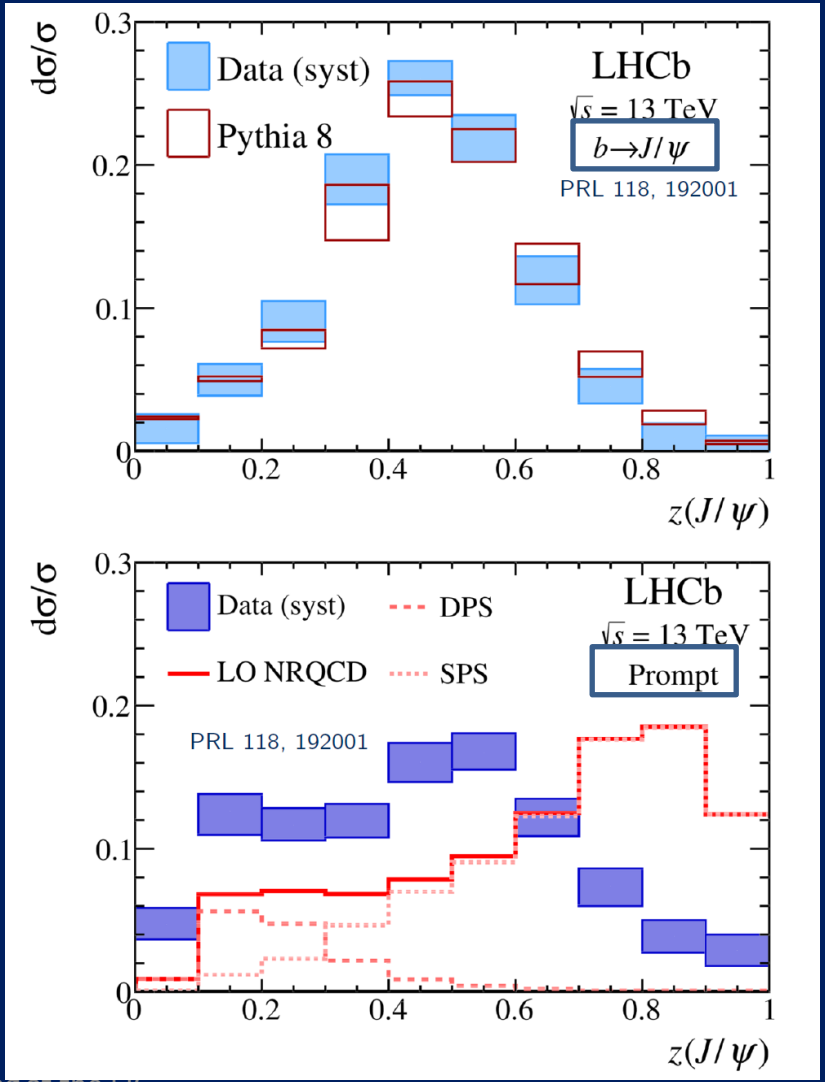
x-Q^2 coverage affects parton mix

- 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?



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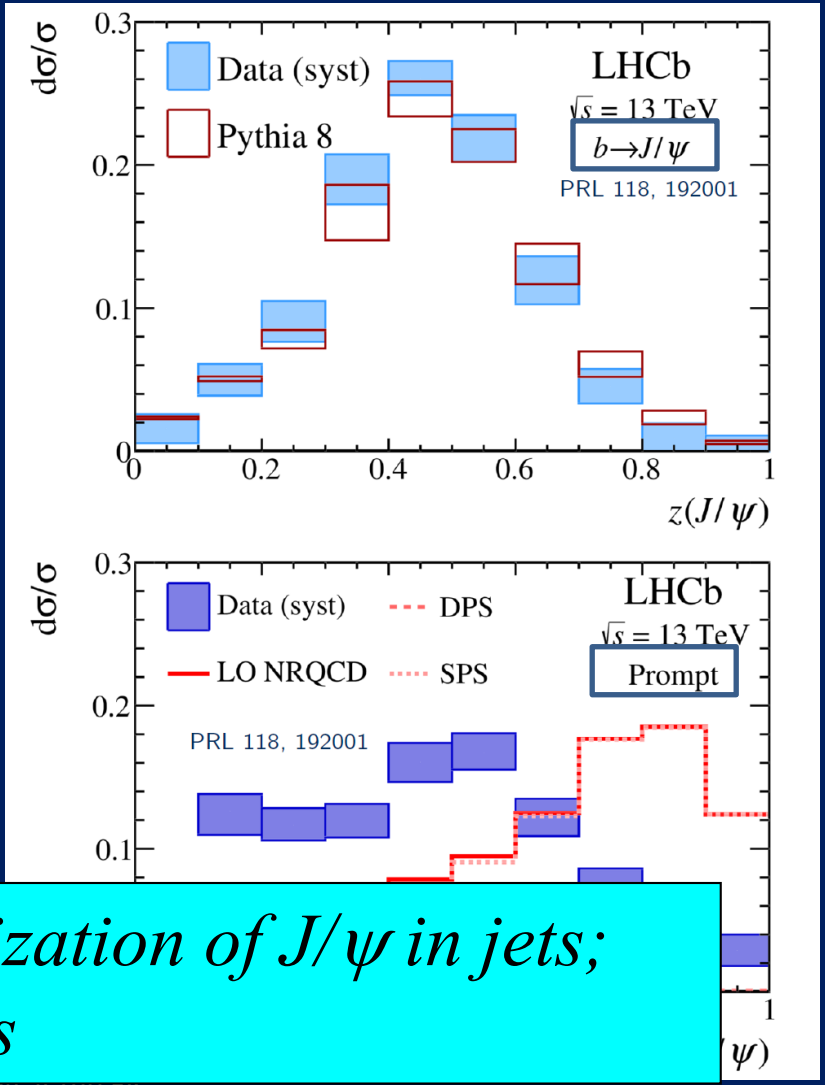
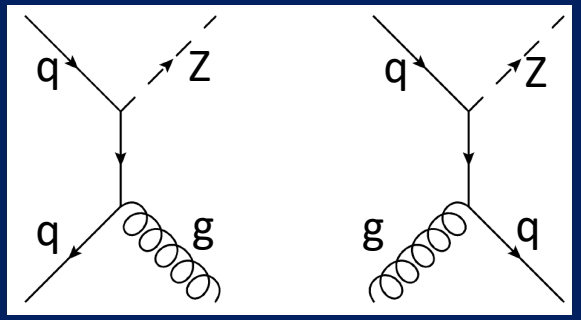
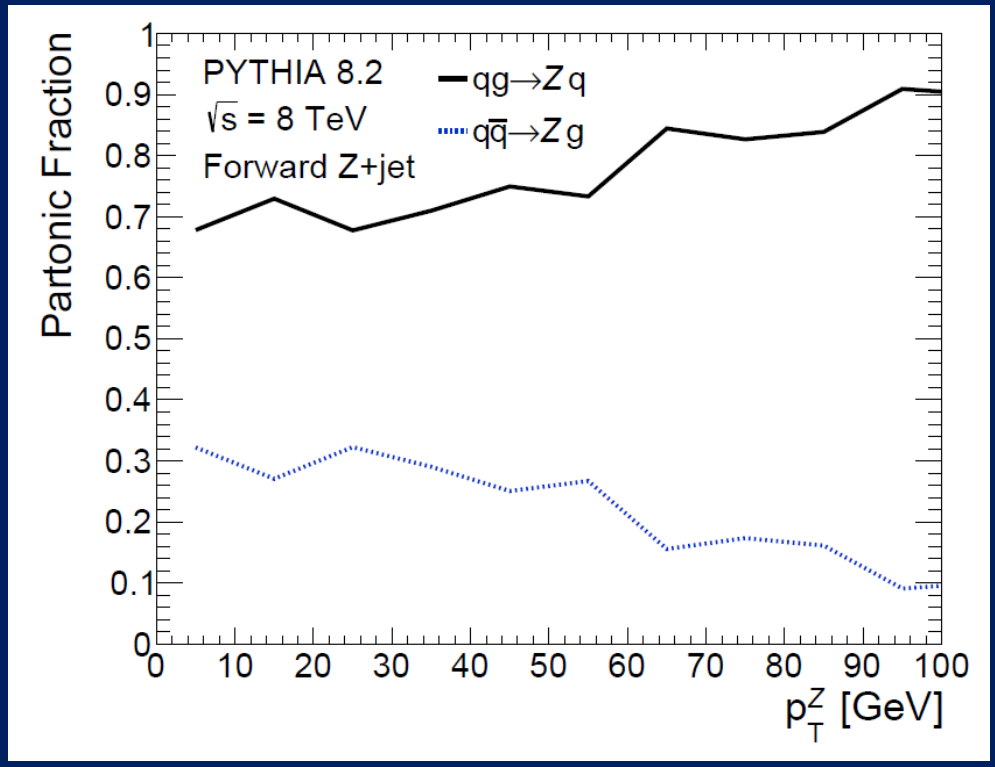


Underway at LHCb: Polarization of J/ψ in jets;
ϒ in jets

Forward Z+jet

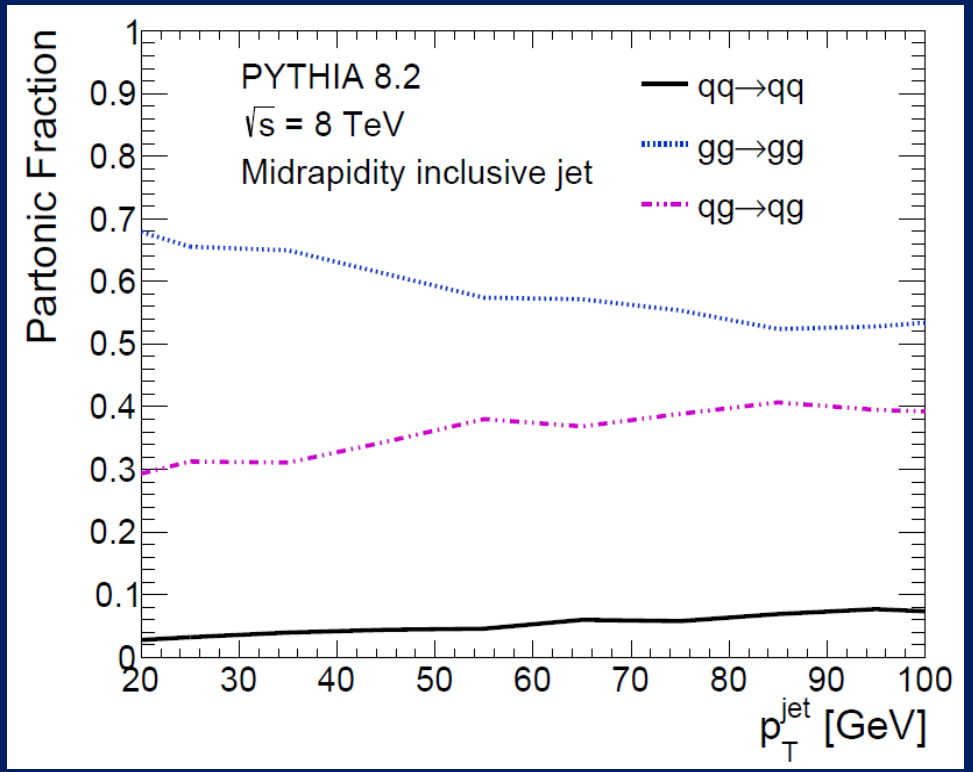


- Z+jet is predominantly sensitive to quark jets
- Forward kinematics increases fraction of light quark jets



Forward Z+jet – vs. midrapidity inclusive jets

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

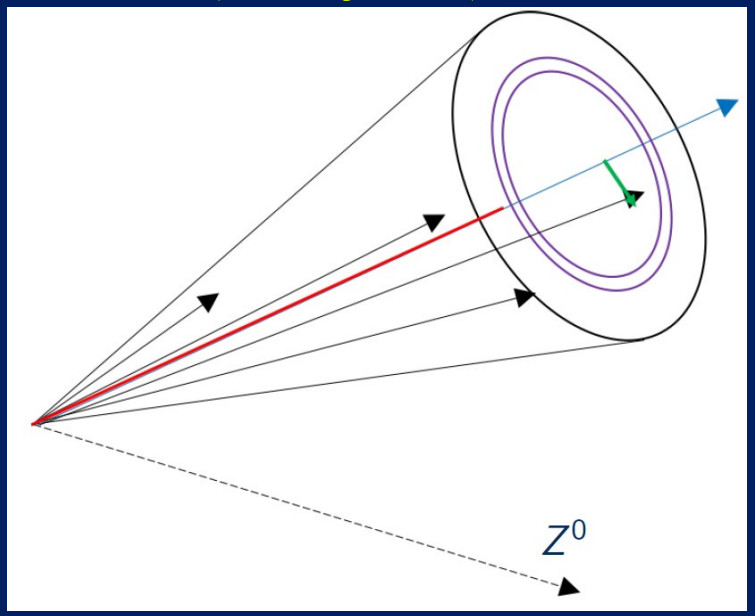


Charged hadrons in forward Z+jet: Observables measured (so far)

PRL 123, 232001 (2019)

- 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



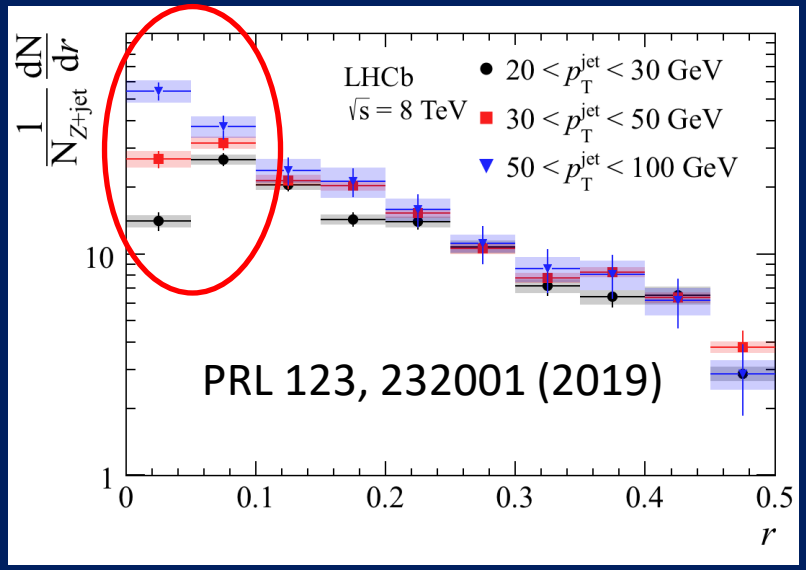
$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

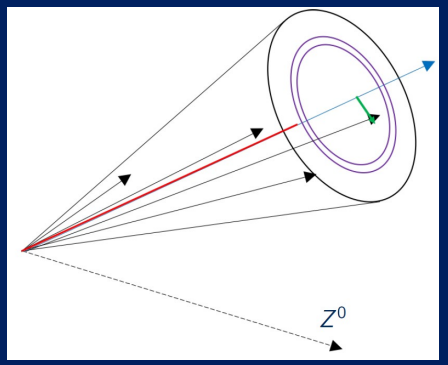
$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$

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

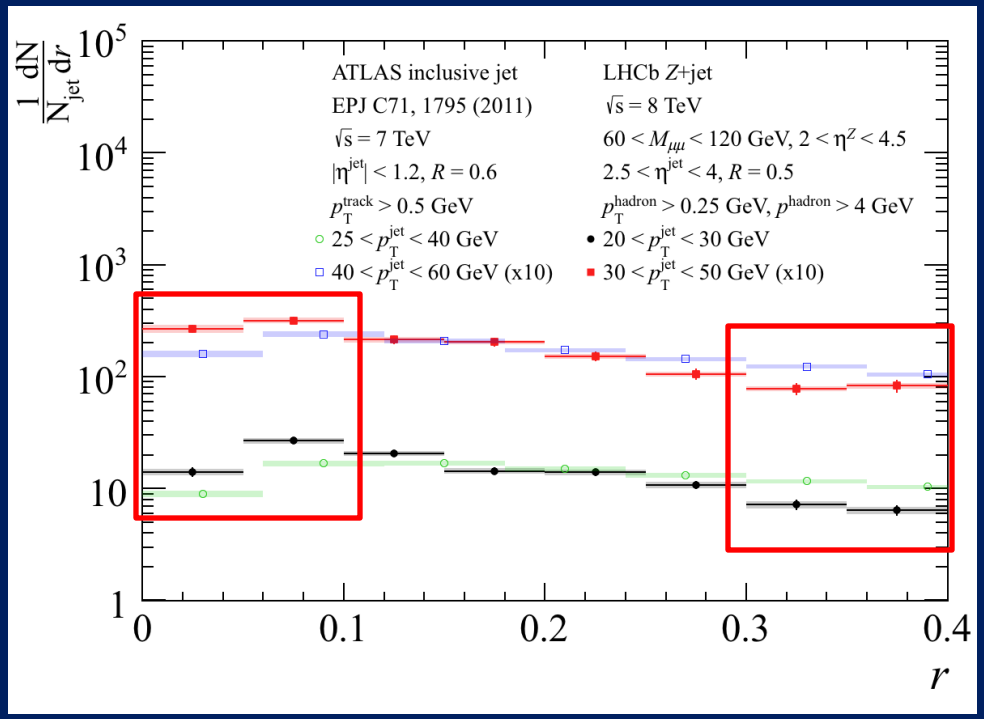
Results: Radial profiles

- 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





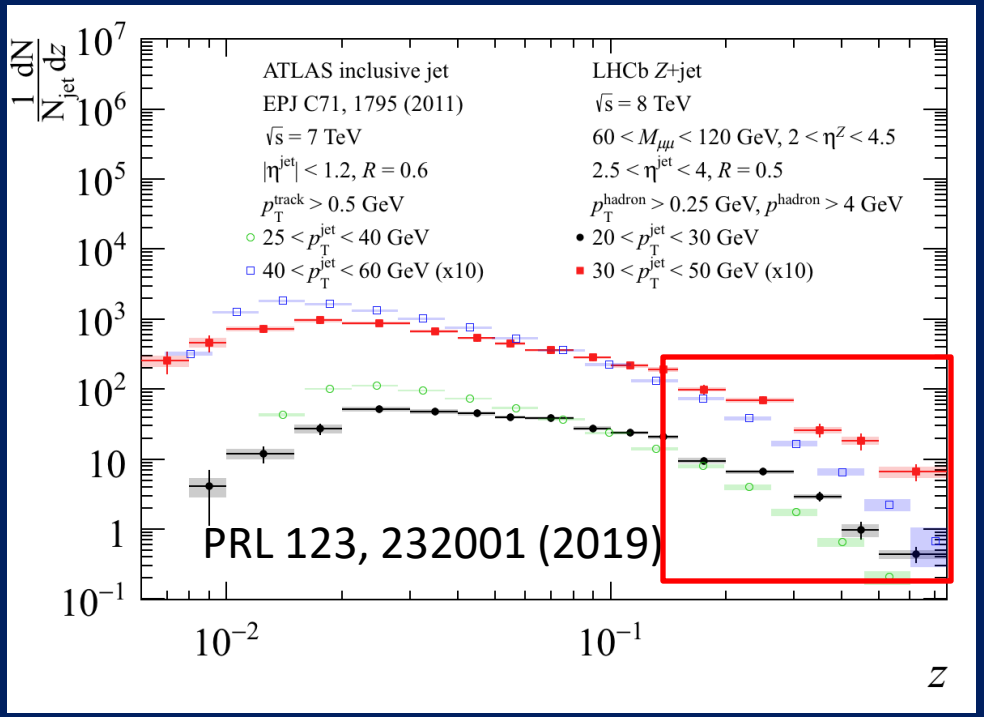
Differences between quark- and gluon-dominated jet samples: Radial profile



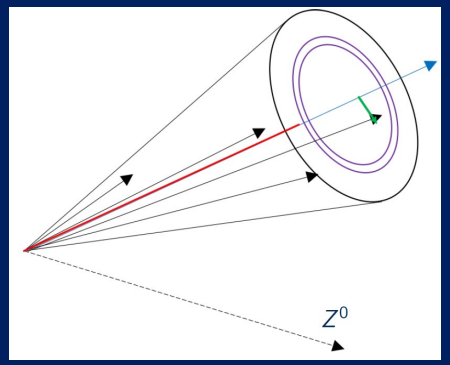
PRL 123, 232001 (2019)

- 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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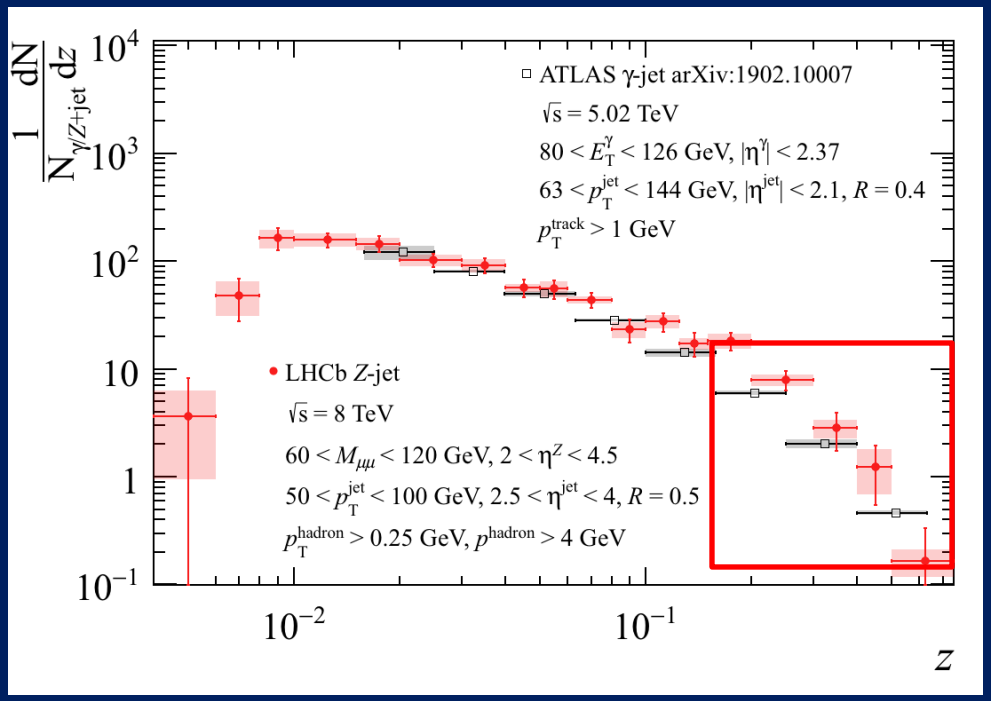

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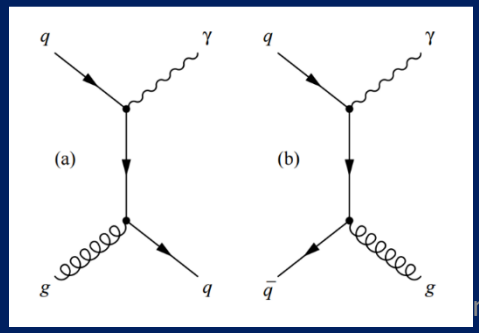
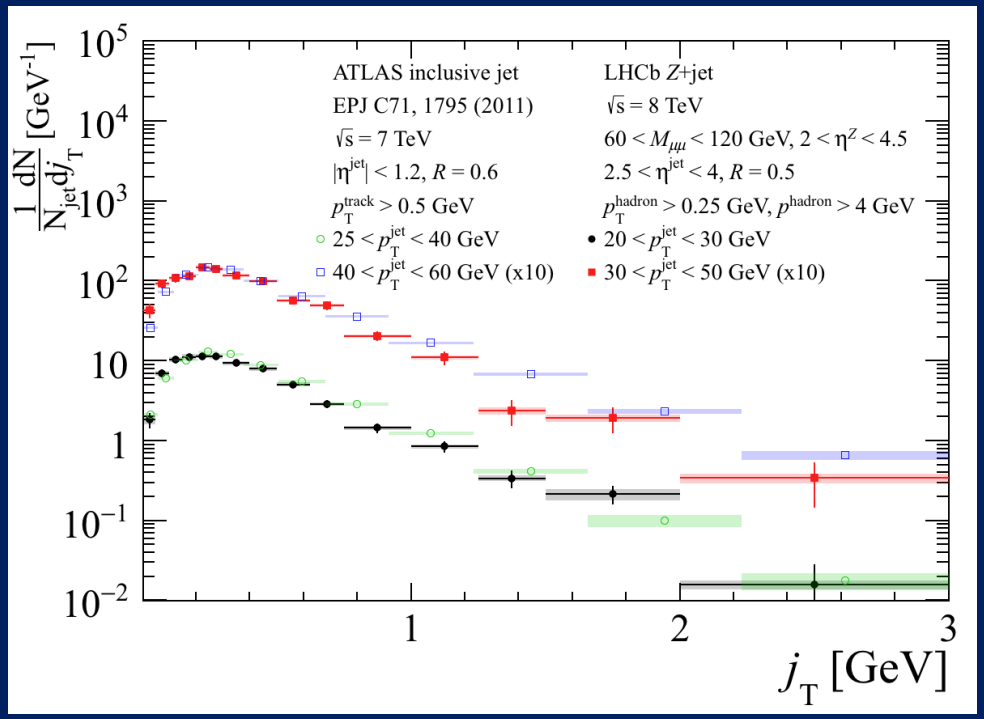


- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal momentum distributions are more similar
  - γ+jet, like Z+jet, enhances quark jet fraction
  - Further evidence that differences observed between LHCb results and ATLAS gluon-dominated results are due to differences in quark and gluon hadronization

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

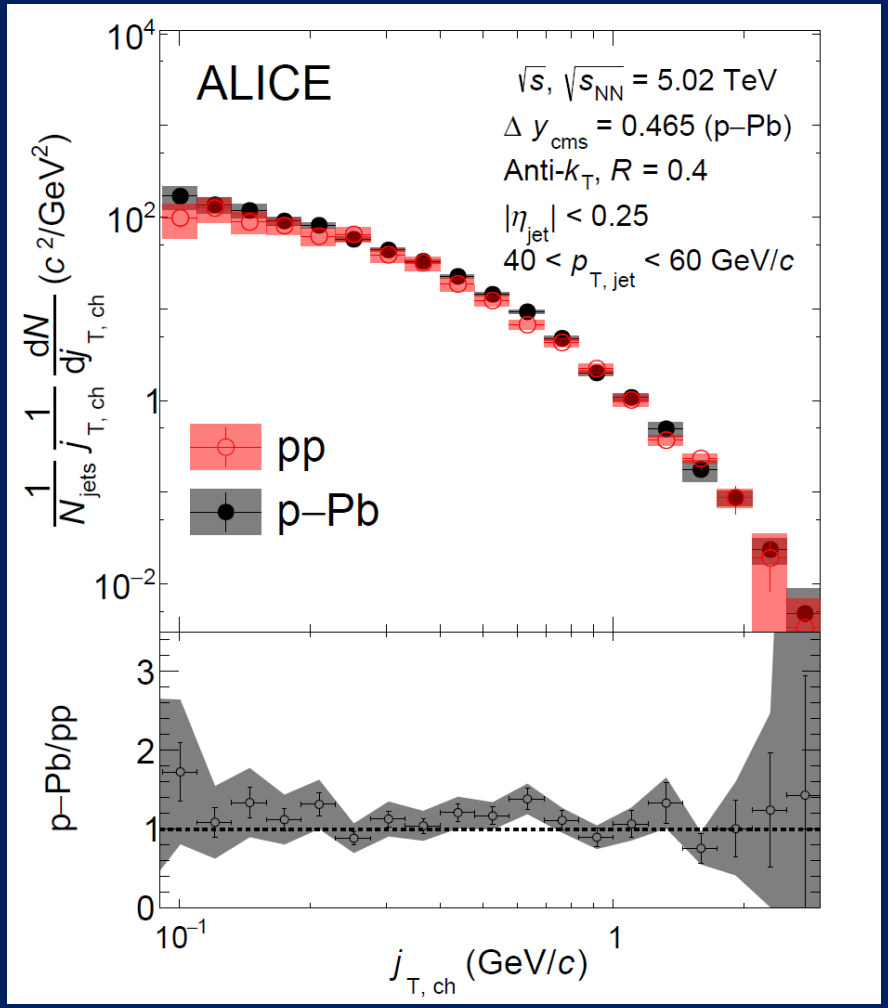
- Transverse momentum distributions similar but show slightly smaller $\langle j_T \rangle$ in Z+jet vs. inclusive jet at small j_T



PRL 123, 232001 (2019)

Transverse momentum distributions in pp and pPb jets from ALICE

- New j_T results from ALICE! arXiv:2011.05904
- No significant modification in j_T distribution of charged hadrons for pp vs. pPb
- (Note extra factor of $\frac{1}{j_T}$ w.r.t. LHCb and ATLAS results on previous slide, also logarithmic x-axis)



Other hadronization-in-jet measurements in progress or planned at LHCb

- Identified π, K, p distributions in Z+jet (light-quark dominated)
  - z, j_T, r
- Charge ratio vs. z in Z+jet (light-quark dominated)
  - Statistically test ideas about correlation between charge of leading hadron and charge of initiating quark

Other hadronization-in-jet measurements in progress or planned at LHCb

- Charged hadron distributions in heavy-flavor-tagged jets
  - Differences between light and heavy quark hadronization?
- Fragmentation of heavy flavor hadrons within jets
  - Build jet around the identified particle, as is done for quarkonium
- Identified strange-antistrange particle correlations within a jet

Making LHCb jet data available to a wider community

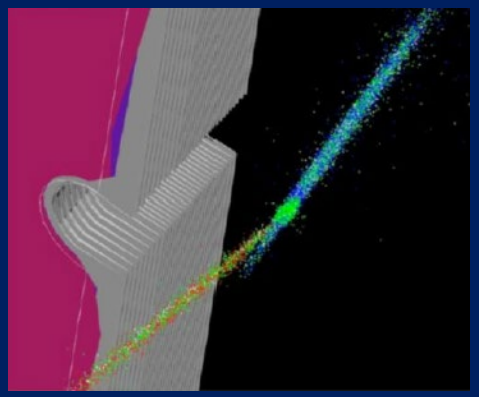
- In principle can do full jet reconstruction and identify ~every single particle in the jet at LHCb—wealth of possibilities to study in-jet correlated particle production for the hadronization of light and heavy quarks!
  - But so far very limited theory tools to describe correlated particle production within jets…
  - Want to make this unique LHCb data available for new analysis ideas into the future!

→Working on an open data set for research on hadronization within jets

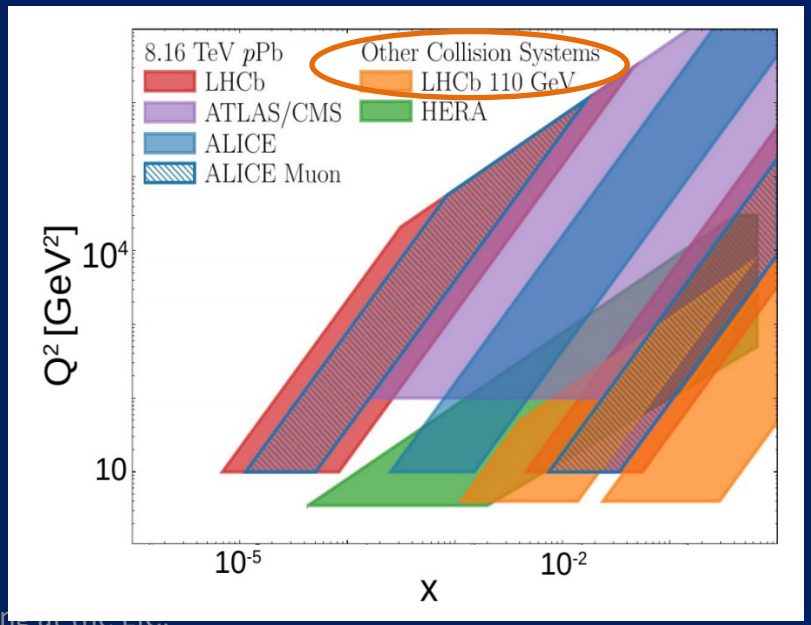
LHCb fixed-target capabilities

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

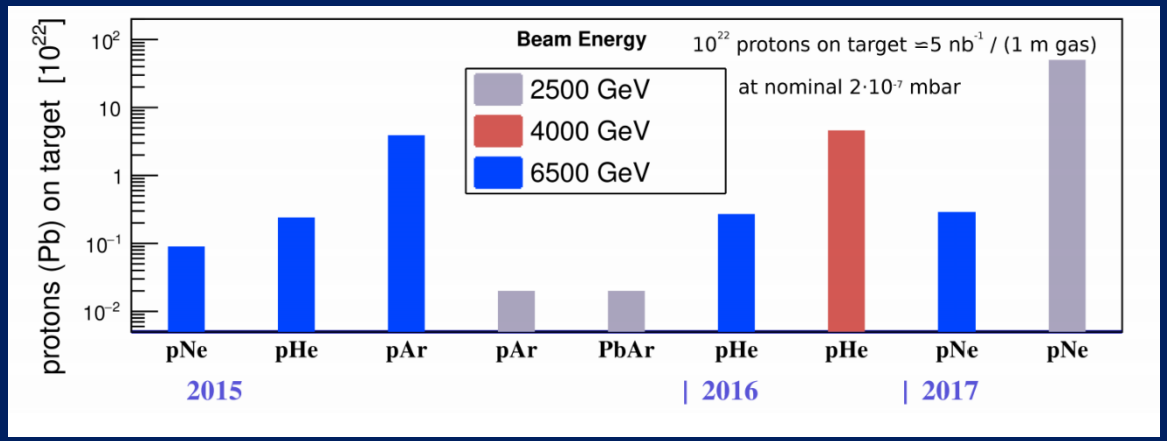
- System for Measuring Overlap with Gas (SMOG) allowed injection of small amounts of noble gas into LHC beam pipe around LHCb collision region. Luminosity up to 10^{30} cm^{-2} s^{-1}



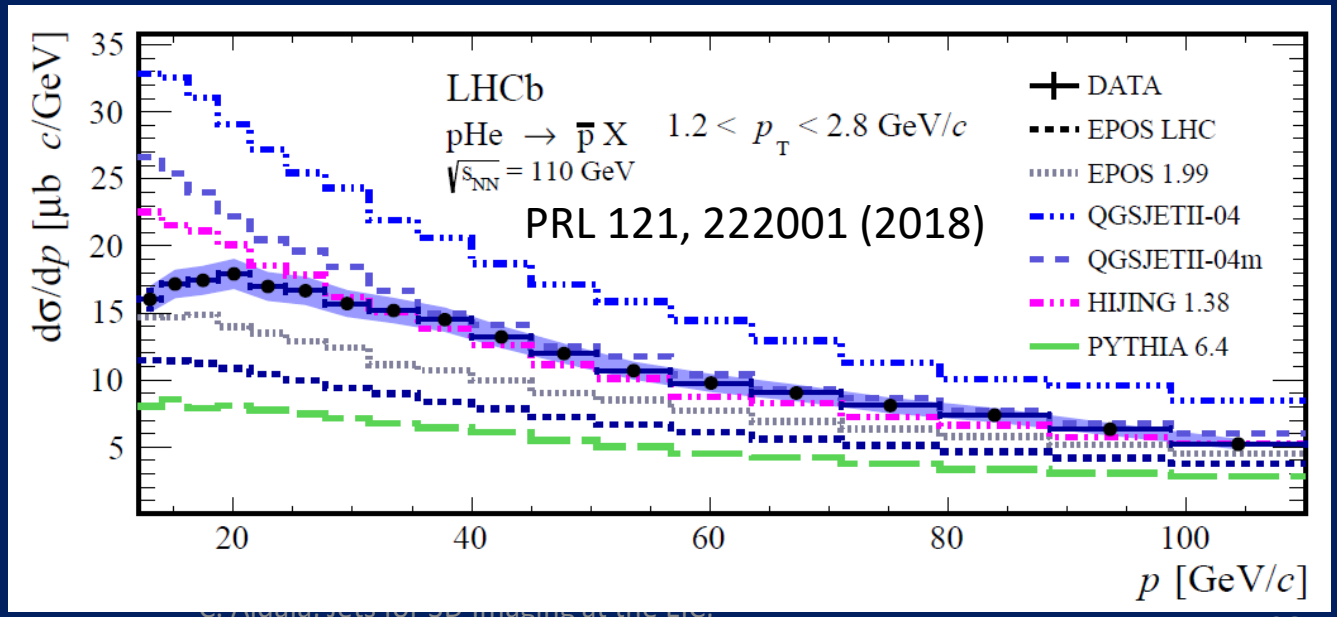
- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{beam}M_p}$ 41-110 GeV for E_{beam}= 0.9-6.5 TeV
  - Between SPS and top RHIC energies
- Overlap with EIC energies!



LHCb fixed-target capabilities



Forward antiproton production in pHe



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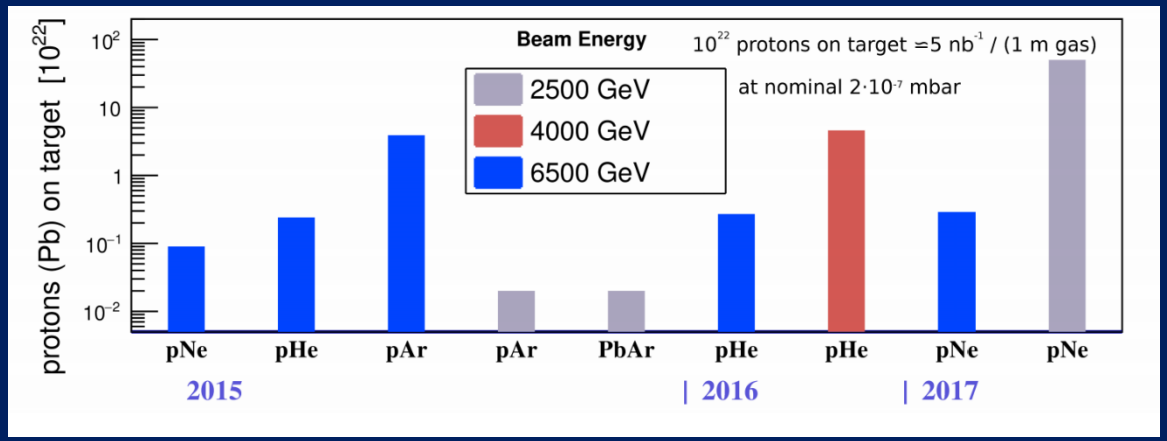
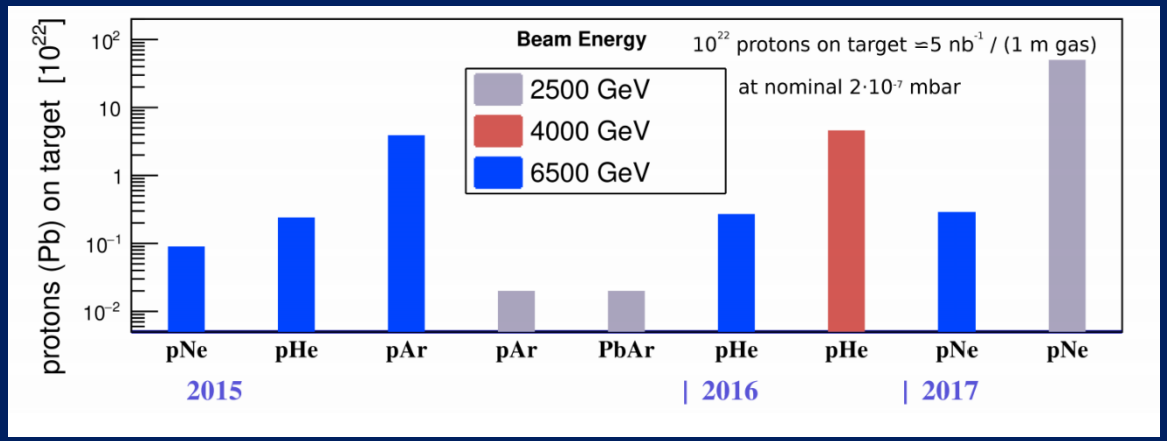


- Target storage cell installed 2020: For LHC Run 3, up to 2 orders of magnitude higher luminosity, improved lumi determination, reduced backgrounds, wider variety of target species:
  H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe

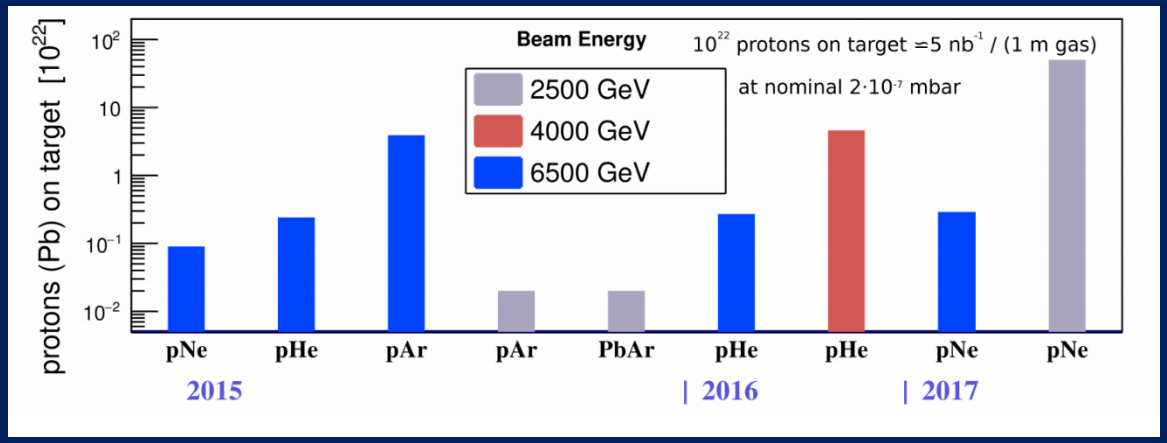
LHCb fixed-target capabilities



- Target storage cell installed 2020: For LHC Run 3, 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

- LHCSpin: Proposal for transversely polarized gas jet target at LHCb currently in R&D and technical evaluation
  → Would offer transversely polarized pp collisions in final years before EIC

LHCb fixed-target capabilities



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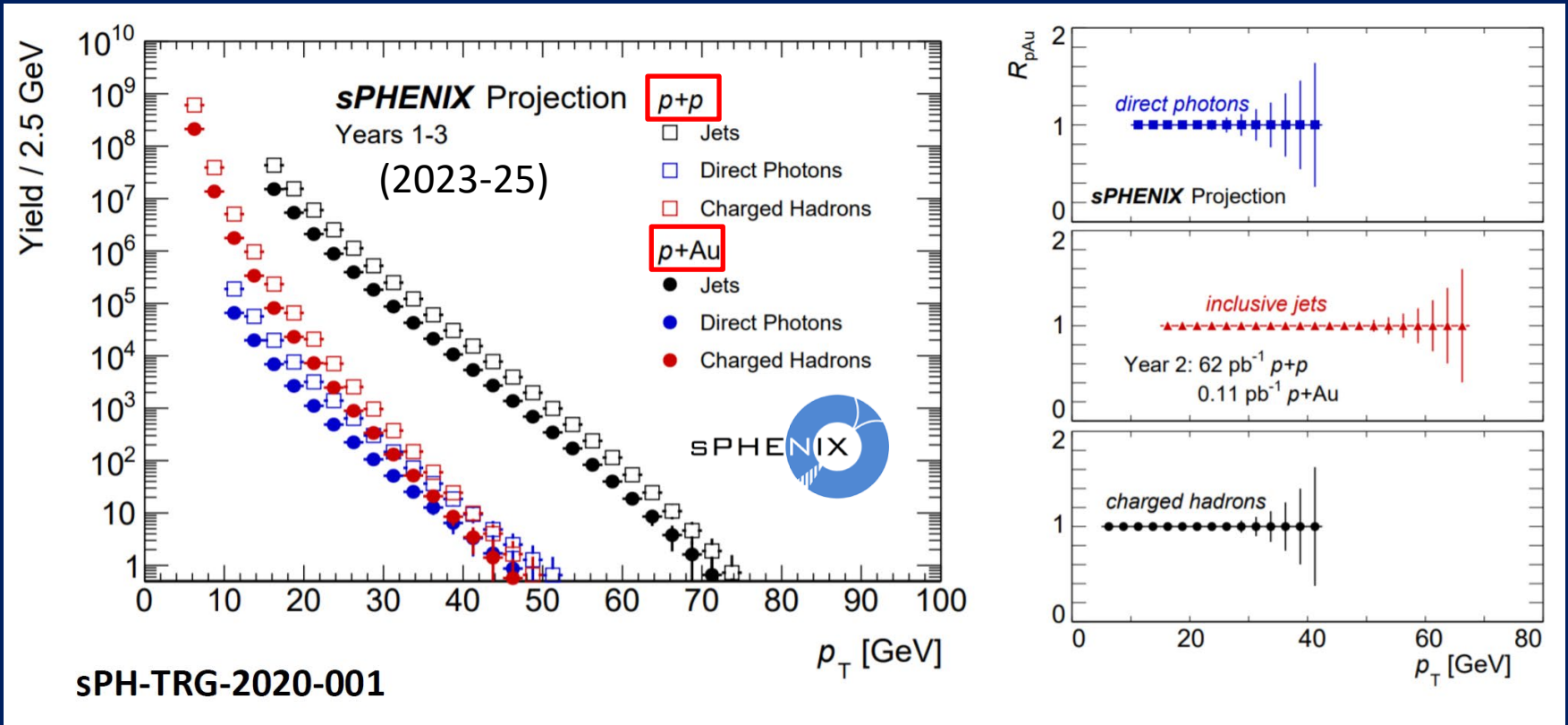
Fixed-target jet measurements possible at LHCb, but so far no one working on them…
Lots of opportunities at LHCb for new QCD groups to join!

C

Hadronization in jets at sPHENIX

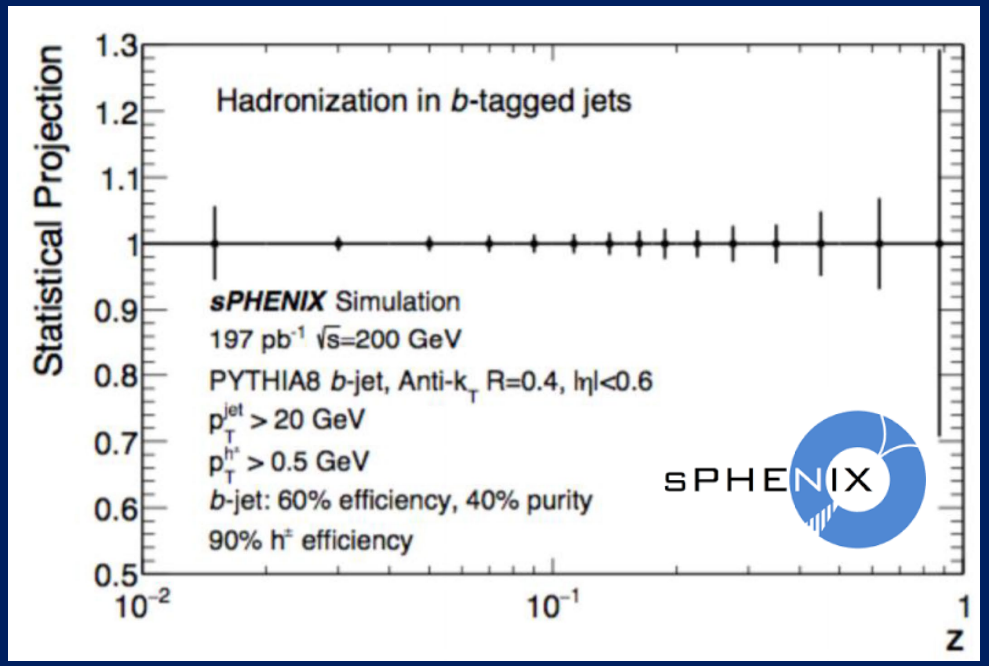


- Nuclear modification of hadron-in-jet distributions possible
  - Direct photons and charged hadrons up to p_T ~45 GeV
  - Jets up to ~70 GeV

Hadronization in jets at sPHENIX

Will also measure

- Hadronization in b-tagged jets
- Collins transverse-momentum-dependent fragmentation function
  - Transverse spin of scattered quark affects angular distribution of produced hadrons
  - See talk by Maria Zurek on Wed



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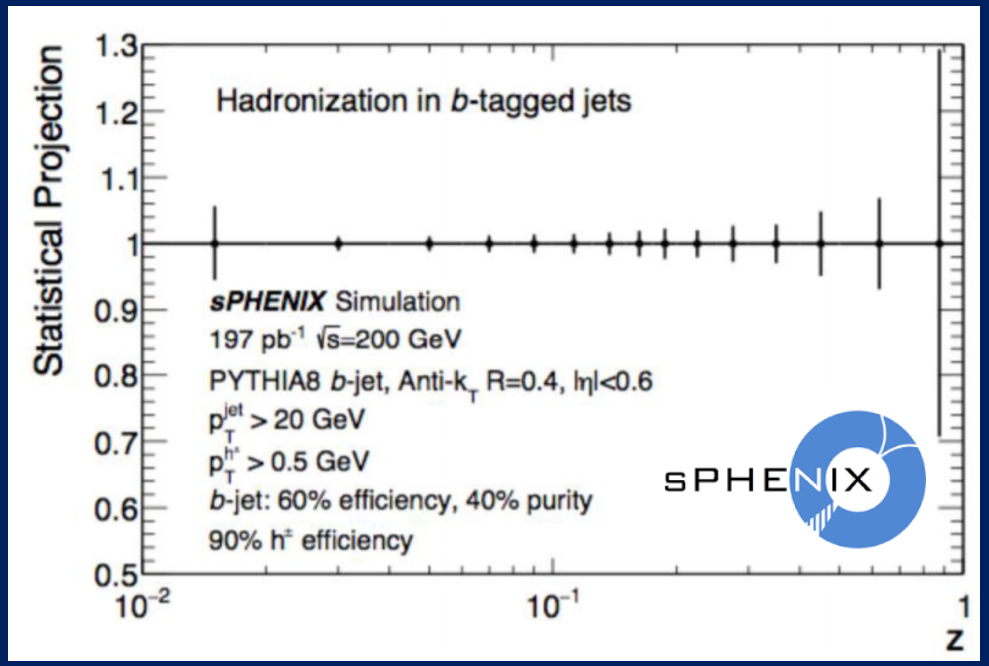

See dedicated talk on jets at sPHENIX by Dennis Perepelitsa later today

Conclusions

- Over the course of the past ~decade, jets have become extremely versatile tools in high-energy nuclear and particle physics!
  - To study hadronization as well as a wide variety of other physics

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Conclusions

- Over the course of the past ~decade, jets have become extremely versatile tools in high-energy nuclear and particle physics!
  - To study hadronization as well as a wide variety of other physics
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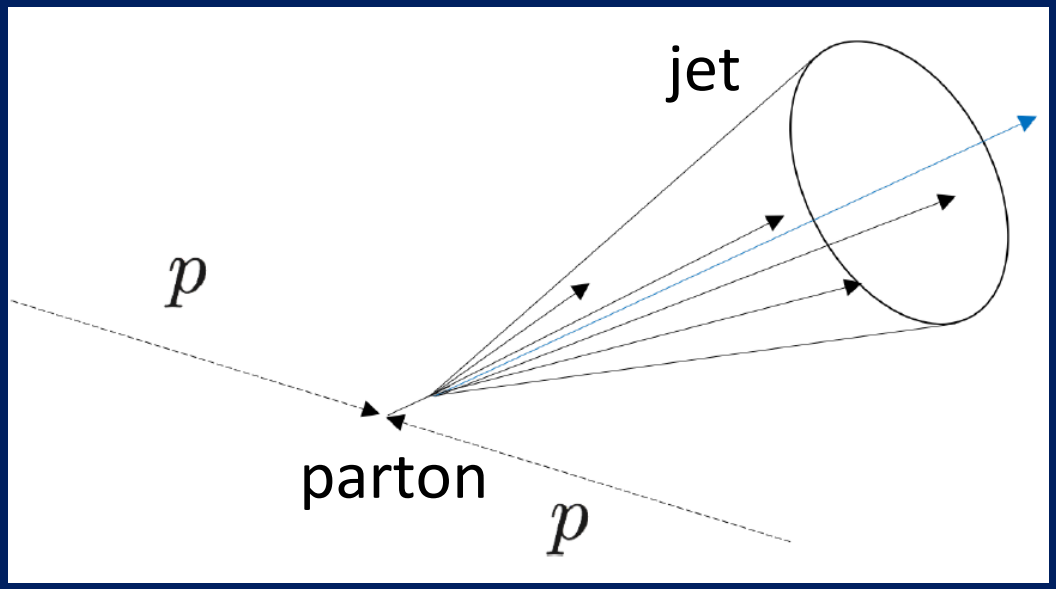
Extra

Hadronization: An open playing field in QCD

- The EIC will be well timed and well suited to make tremendous progress in our understanding of hadronization
  - Discussed less for the EIC than partonic structure of nucleons and nuclei because we still think much less about hadronization as a community…
  - Hadronization: "The Electron-Ion Collider is going to do so many things we have no idea about." – R. Ent

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

Understanding high-energy hadronization: A wish list



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

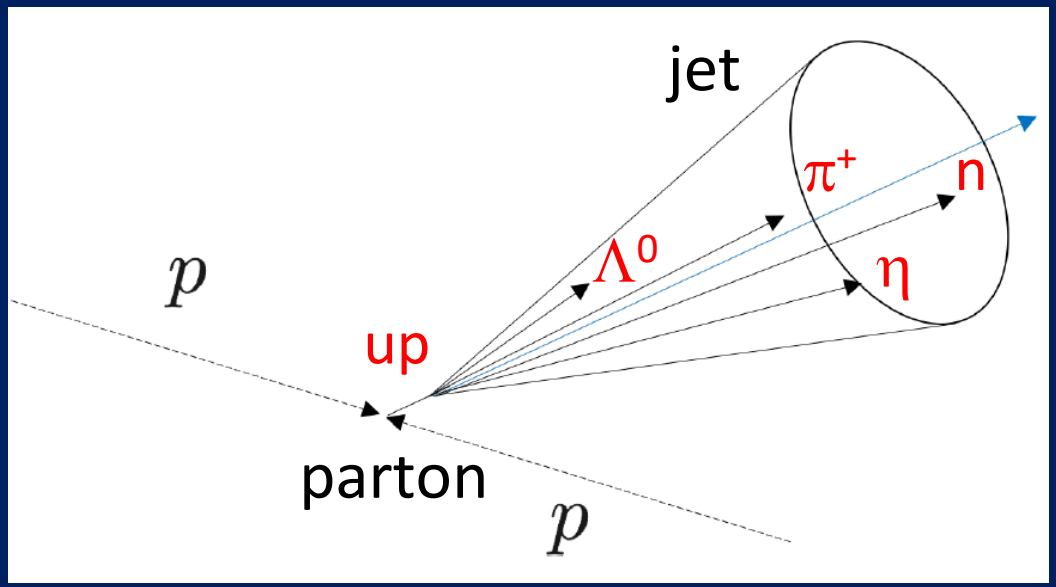
   - Jets, as a proxy for a parton, are a tool to connect the perturbative to nonperturbative

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

Understanding high-energy hadronization: A wish list



- 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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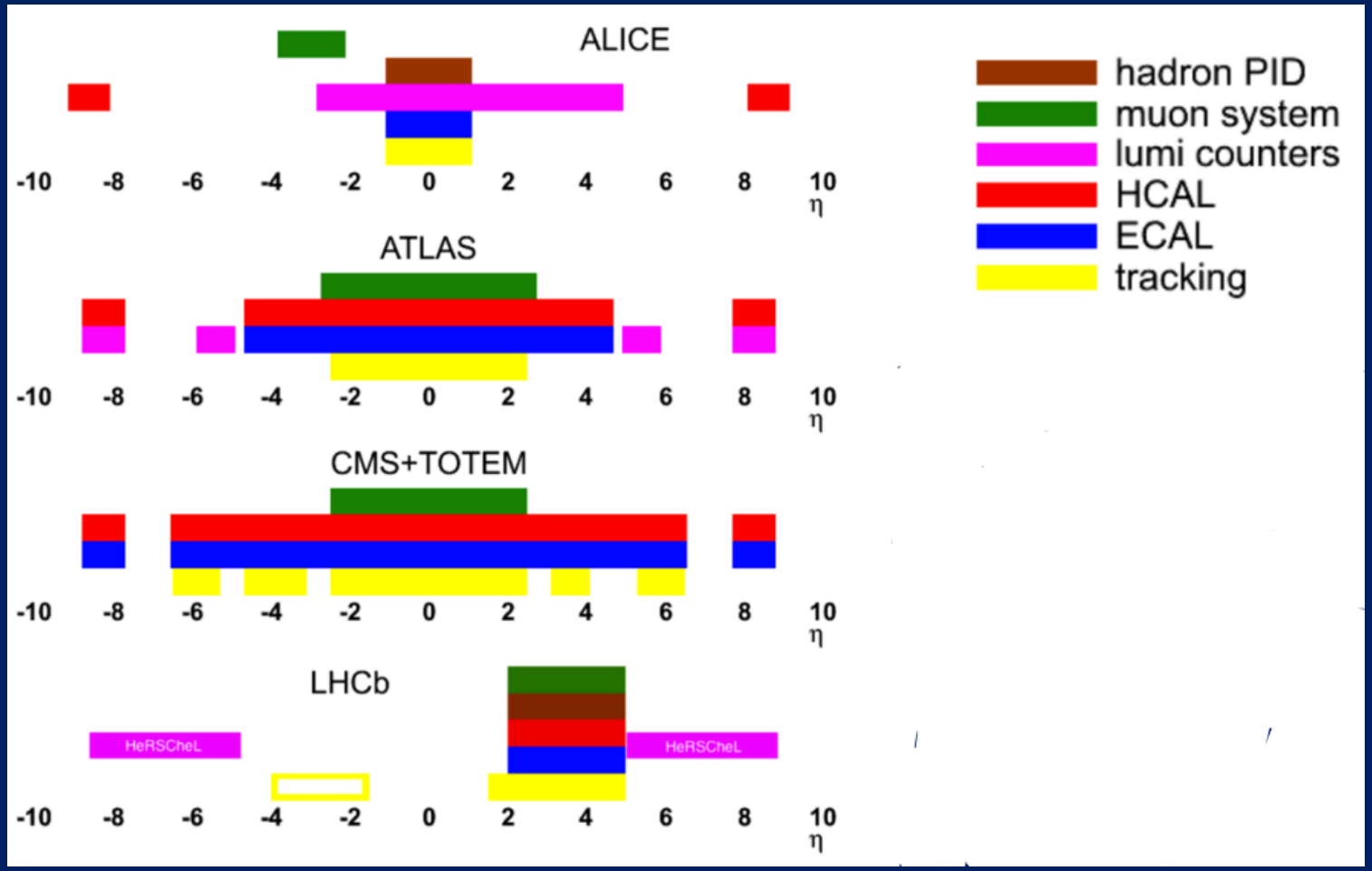
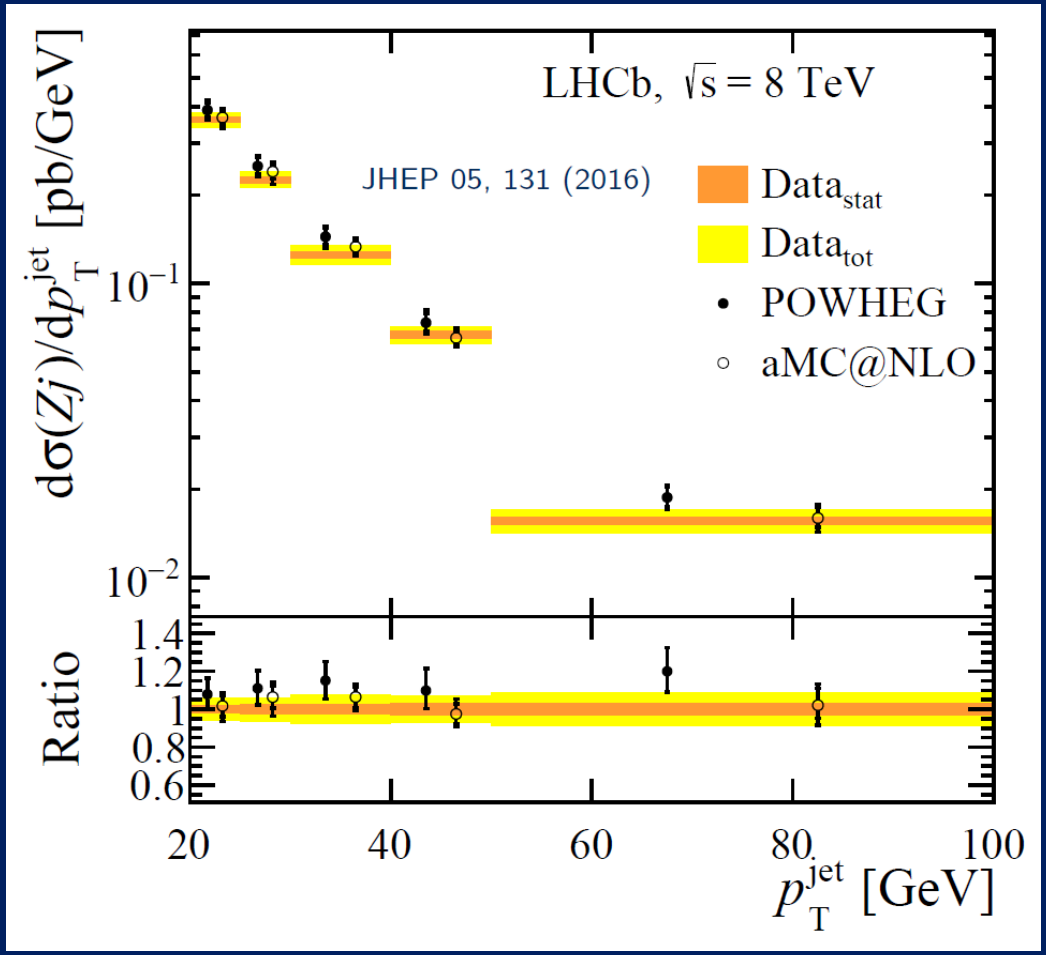
Pseudorapidity coverage at LHC



Forward Z+jet

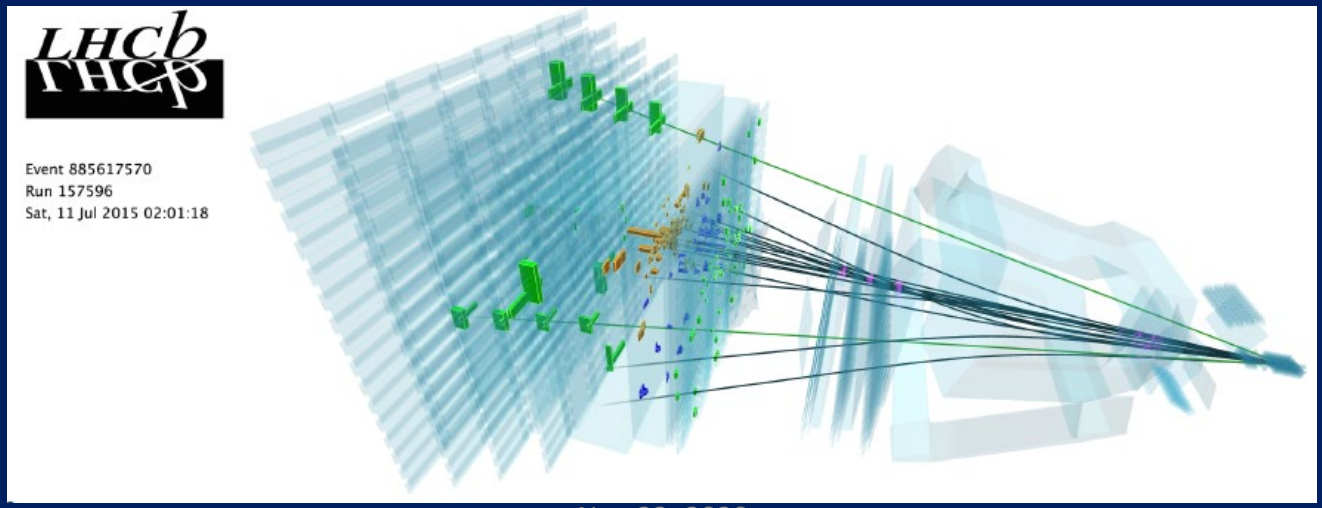
- LHCb previously measured the forward Z+jet cross section
  - JHEP 05, 131 (2016)
- Now have measured charged hadron distributions within the jet, in the same data set
  - PRL 123, 232001 (2019)
- First LHC measurement of charged hadrons within Z-tagged jets
- First LHC measurement of charged hadrons-in-jets at forward rapidity



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)

- $Z \to \mu^+\mu^-$ 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, $\Delta R < 0.5$



Ideas for further hadronization measurements at hadron colliders welcome!

At a single experiment or for comparison across multiple experiments.

- Particular observables as a function of jet constituent multiplicity, *R*, rapidity, p_T, mass, …?
- Particular correlations across dijets? Among multijets (ATLAS and CMS)?
- (Identified) Hadron distributions in the azimuthal region *between* Z-jet or dijets (the "underlying event")?
  - Learn more from comparison to (identified) hadron distributions in e+e- in the region perpendicular to the thrust axis?
- Measurements in p+A and A+A?
- Value of single-particle cross sections versus less inclusive measurements?
- What can the formation of nuclei/antinuclei/hypernuclei formed in A+A teach us about hadronization, or more generally about the relationship(s) between partons and nuclei?
- What can hadron spectroscopy (in p+p or other collision systems) teach us about mechanisms of hadron formation?

Hadronization: Recent advances

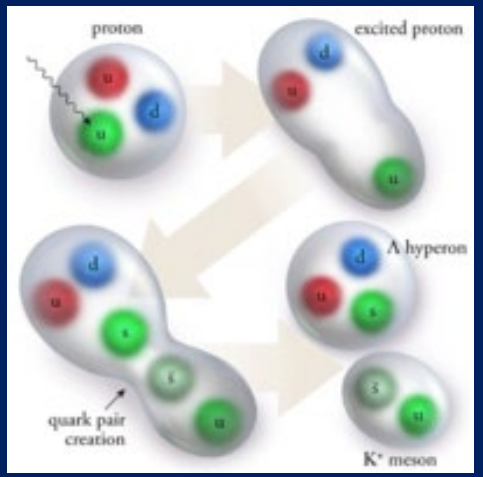
Have been starting to think about hadronization more over past ~10-15 years, going beyond collinear fragmentation of one parton to one hadron in vacuum.

See Metz and Vossen, Prog. Part. Nucl. Phys. 91, 136 (2016) for a review of parton FFs (collects 628 references!).

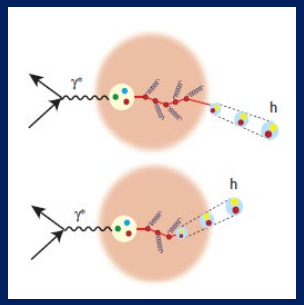
- Transverse-momentum-dependent FFs
  - Mainly Collins, unpolarized, and polarizing TMD FFs so far
  - Some recent discussion of universality properties of TMD FFs
- Twist-3 correlators describing hadronization – interference between hadronization of one parton and (parton + gluon)
- Dihadron FFs – one parton → 2 hadrons. Unpolarized; interference FF
- Two-parton FFs
- Heavy flavor FFs
- Fracture functions – describe target rather than current fragmentation region
- Nuclear modification of FFs

Different mechanisms of hadronization

- High-energy limit of "string-breaking" or "cluster" pictures
- Coalescence/recombination of partons nearby in phase space
- Soft hadron production from remnant (target fragmentation)
- Threshold production
- Production via decay from other hadrons
- …?



CLAS, PRL 113, 152004 (2014)



Hadronization at the EIC

EIC will be an extremely versatile and powerful facility to study hadronization!

- Lepton probe → Reconstruction of partonic kinematics
- Protons, light → heavy nuclei
  - Range of parton densities
  - Move hadronization inside/outside nucleus via range of nuclear sizes and scattered parton energies
- Polarization
- Separation of current and target fragmentation regions
- Hadron PID
- Charm measurements
- Jets
- Integrated luminosities allowing multidifferential measurements
- …