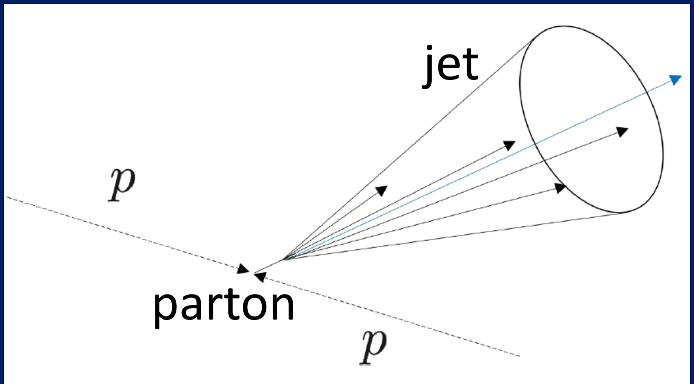
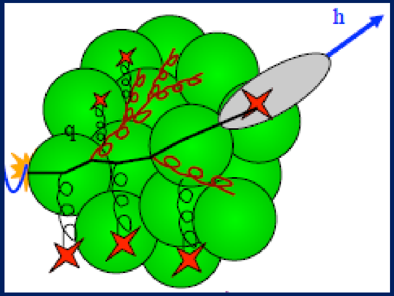
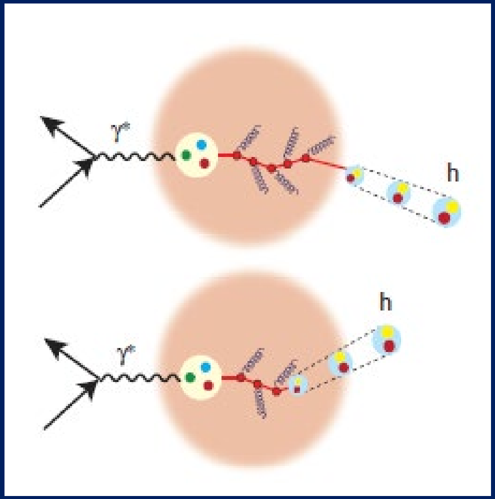
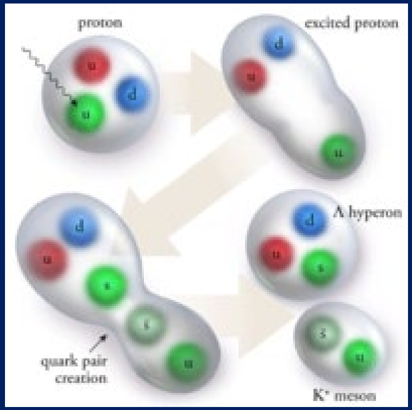




Setting the Stage for Hadronization Studies at the EIC



Christine A. Aidala
University of Michigan
and
University of Pavia



QCD with EIC
IIT Bombay
January 4-7, 2020

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*
- <u>Much</u> greater effort has been dedicated to studying hadron structure than hadron formation over the past half century
  - Nucleon structure in particular

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!).

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- Hadronization connected to jets
  - 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)

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  - Single hadron-in-jet FFs – introduced in Procura and Stewart, PRD81, 074009 (2010)
    - See talk by Felix Ringer
  - 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.

Different mechanisms of hadronization

- High-energy limit of “string-breaking” or “cluster” pictures

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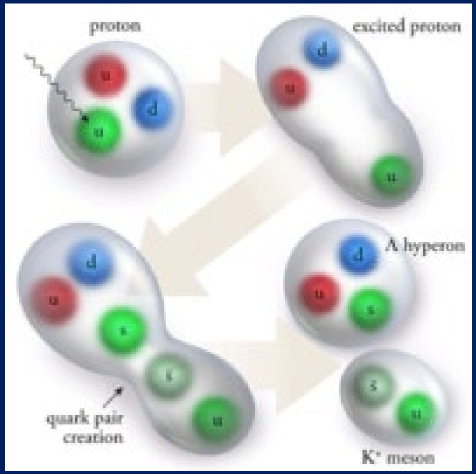
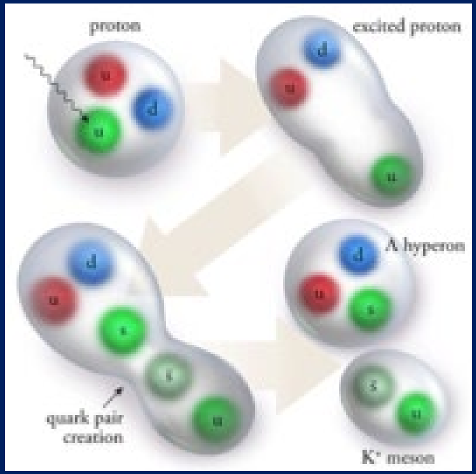


CLAS, PRL 113, 152004 (2014)

Different mechanisms of hadronization

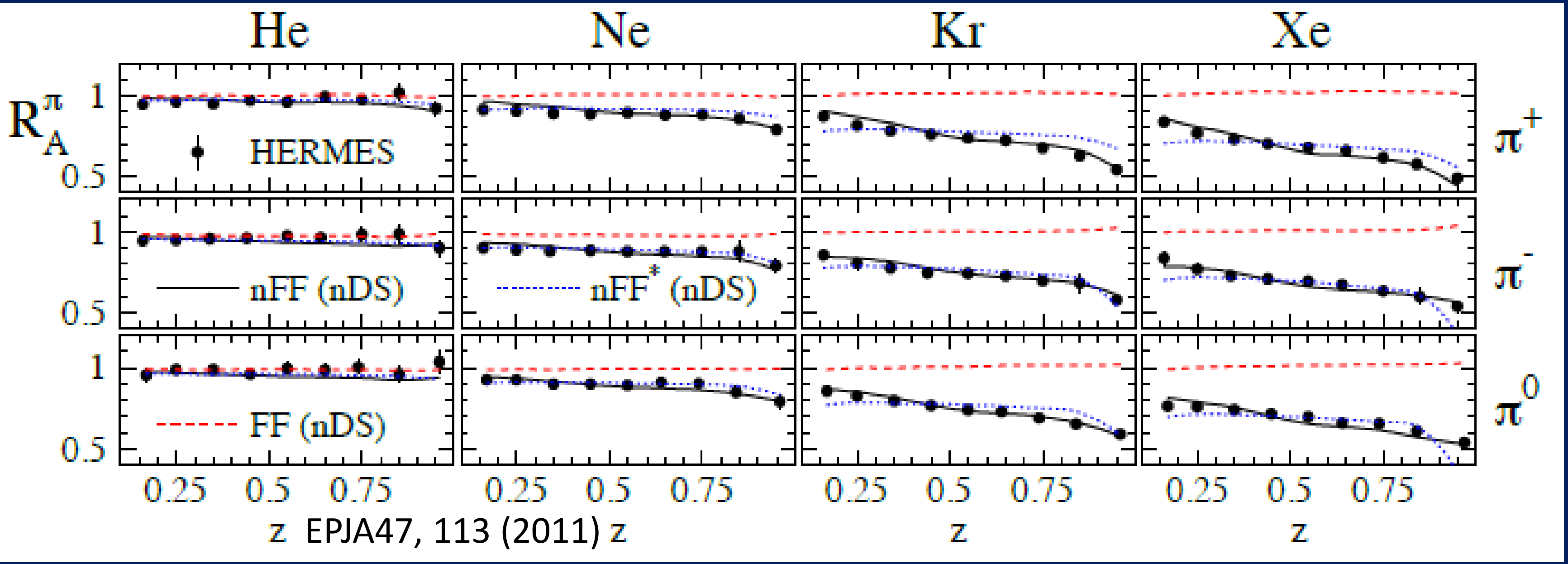
- High-energy limit of “string-breaking” or “cluster” pictures
- Coalescence/recombination of partons nearby in phase space
- Threshold production
- Production via decay from other hadrons
- …?



CLAS, PRL 113, 152004 (2014)

Hadronization in higher-density partonic environments

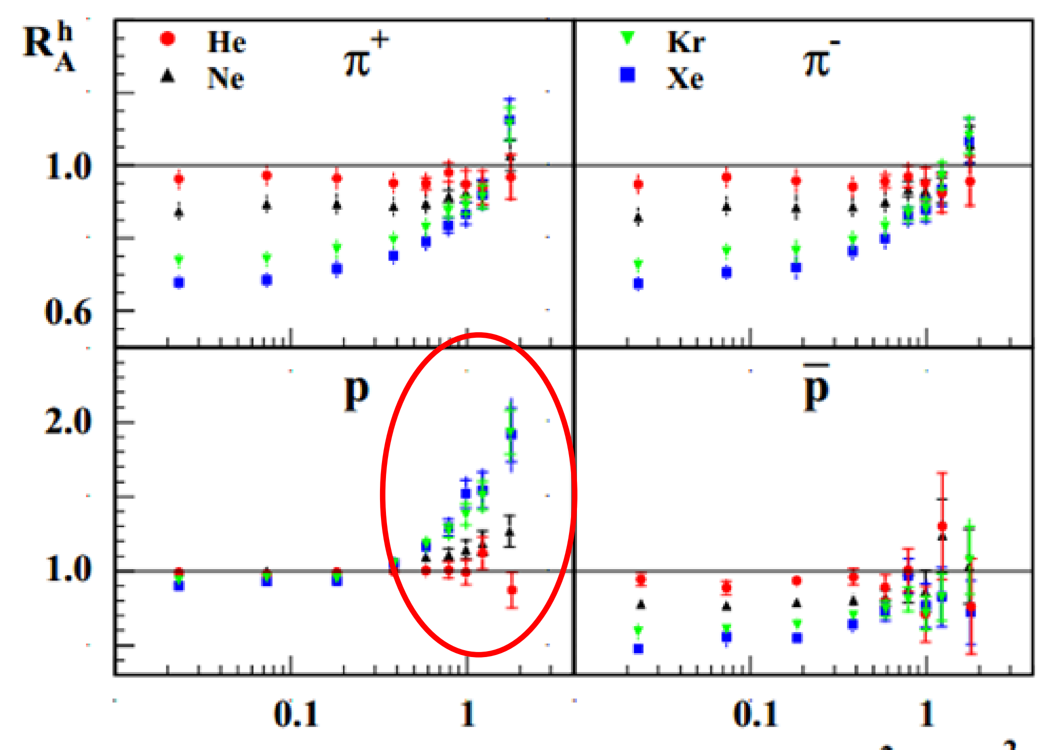
- No longer (only) "vacuum" fragmentation
- Nuclear modification of FFs observed in e+A collisions, e.g. pion suppression



EPJA47, 113 (2011)

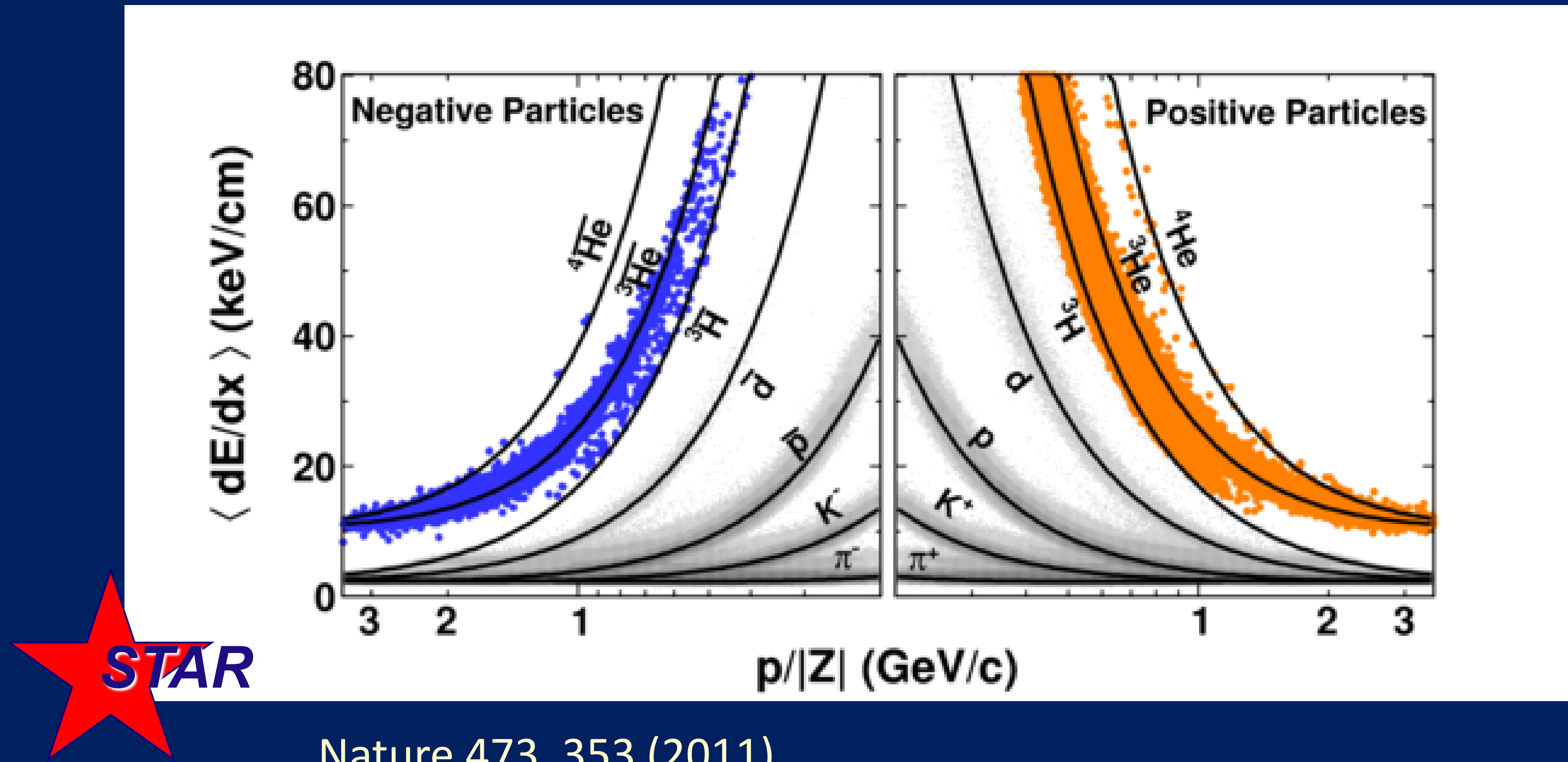
Hadronization in higher-density partonic environments

- But proton *enhancement* observed in e+A compared to scaled e+p in certain p_T range (antiprotons unclear)
  - Related to baryon enhancement observed in p+A and A+A, believed to be due to recombination?



HERMES, NPB780, 1 (2007)

Bound states of hadronic bound states: Creating (anti)nuclei!



Nature 473, 353 (2011)

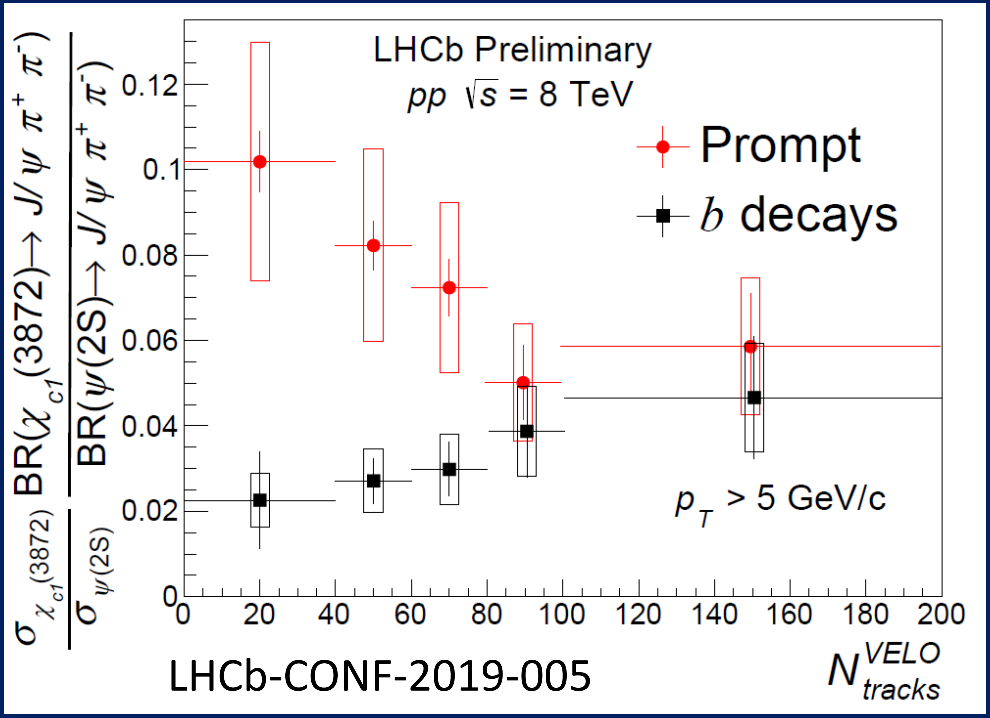
Bound states of hadronic bound states: Creating (anti)nuclei!

- Heavy ion collisions let us create nuclei—and antinuclei!—up to ^{4}He

- Do we understand enough by now about QCD bound states—and nucleons specifically—to start to think more about going from first principles to the "van der Waals" forces that bind color-neutral nucleons into nuclei??

Bound states of hadronic bound states: Creating (anti)nuclei!

- Heavy ion collisions let us create nuclei—and antinuclei!—up to ^{4}He
- Do we understand enough by now about QCD bound states—and nucleons specifically—to start to think more about going from first principles to the "van der Waals" forces that bind color-neutral nucleons into nuclei??
- Can we possibly learn anything from tetraquarks about bound states of hadrons??



Relative decrease in ratio of promptly produced χ_{c1}(3872) to ψ(2S) as a function of track multiplicity suggests a weakly bound state, such as a $D^0\overline{D}^{*0}$ molecule.

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

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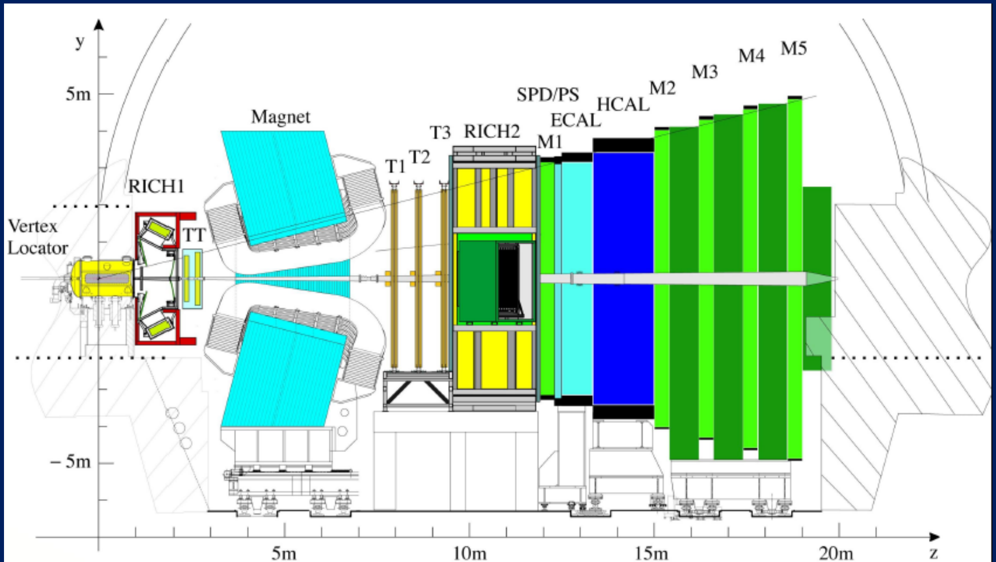
- We should use the 2020s to ensure that we are positioned to take full advantage of the EIC's potential for hadronization!

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



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

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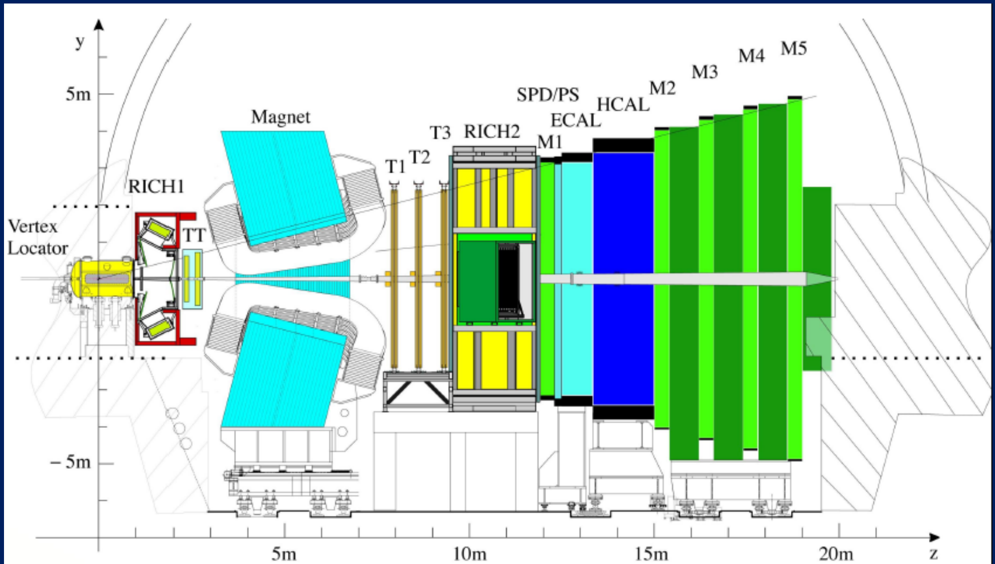

JINST 3, (2008) S08005
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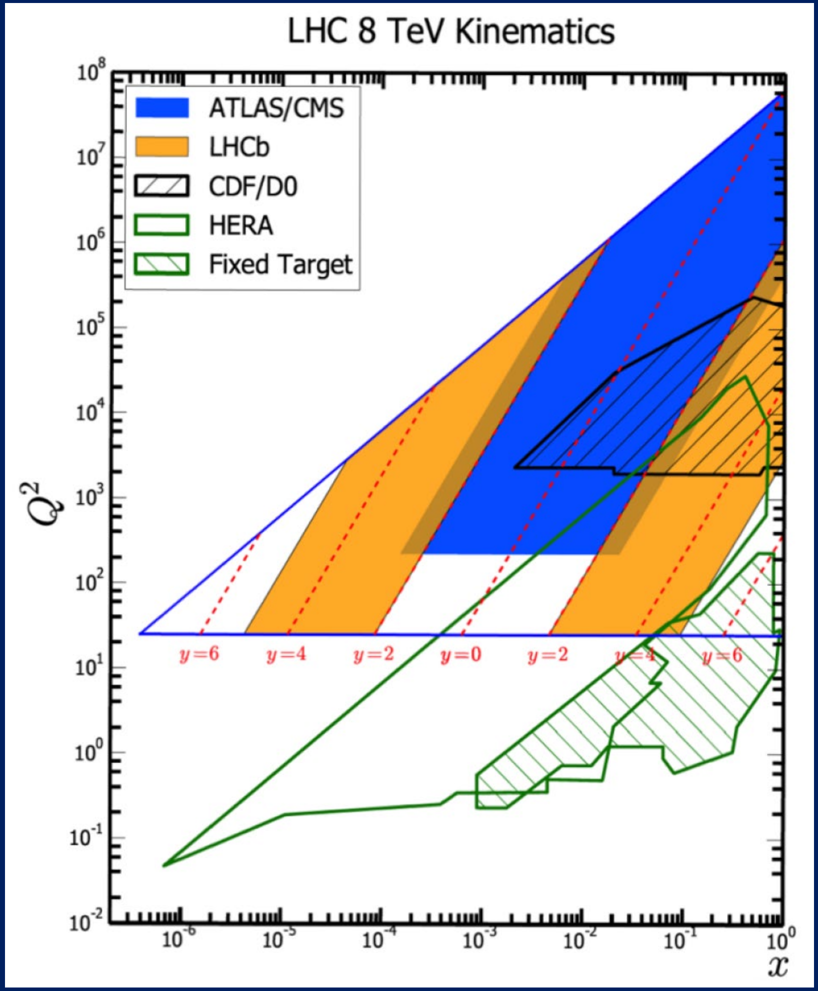
Some features specifically attractive for hadronization:

- 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!

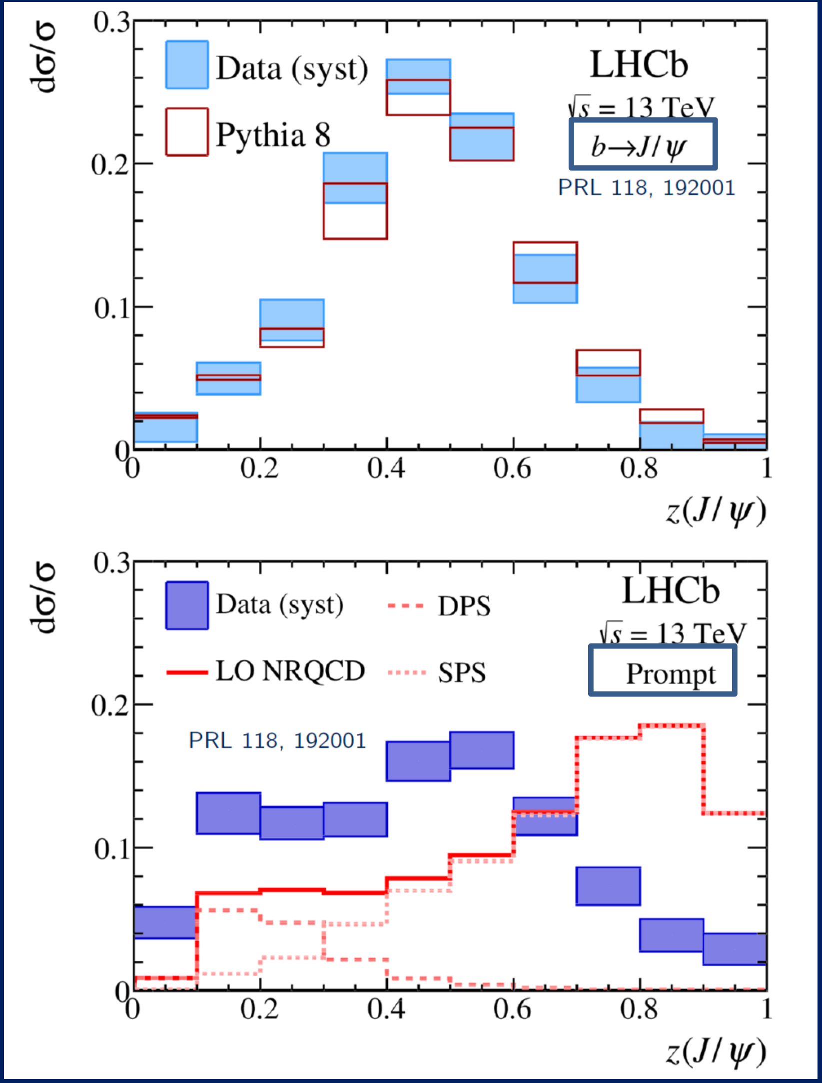
x-Q^2 coverage affects parton mix

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



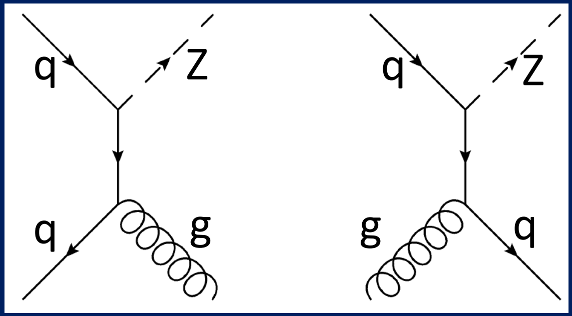
J/Ψ production in jets at LHCb

- 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?



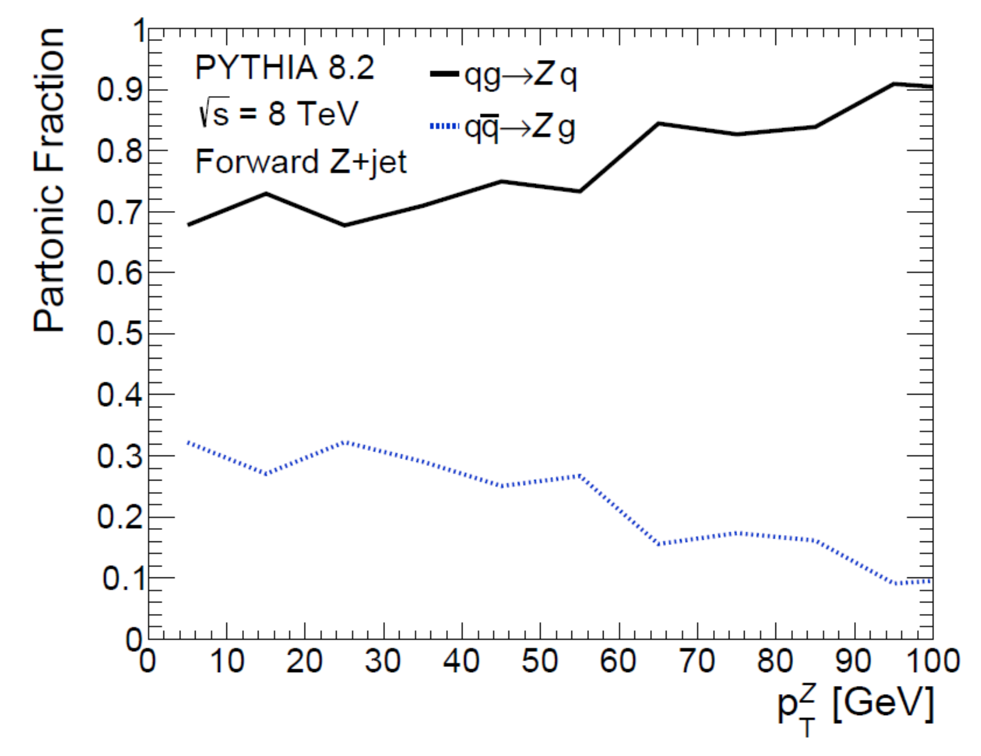
MICHIGAN UNIVERSITÀ DI PAVIA

Forward Z+jet



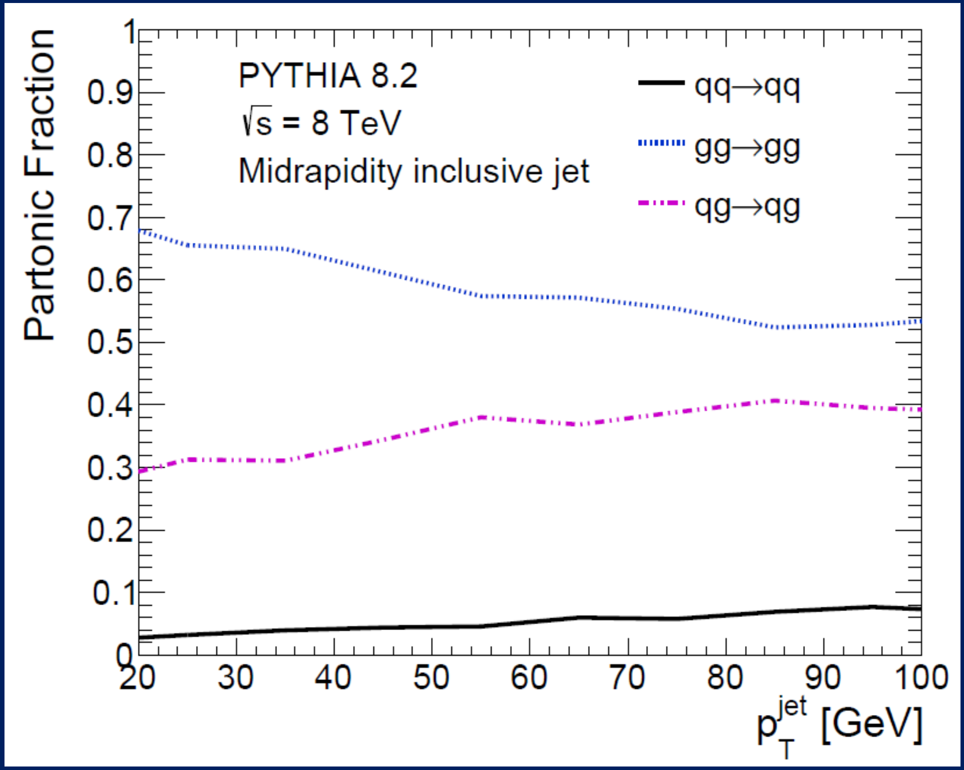
- Z+jet is predominantly sensitive to quark jets

- 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

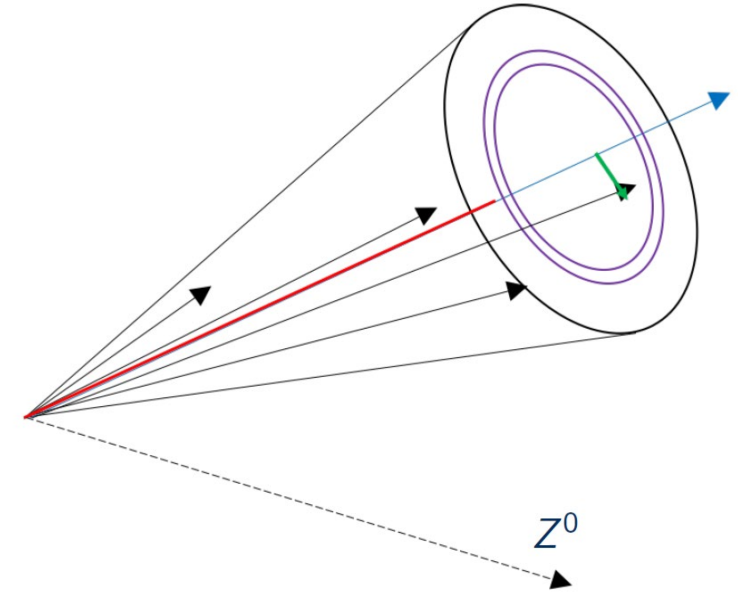


Charged hadrons in forward Z+jet: Observables measured (so far)

- 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



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

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

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

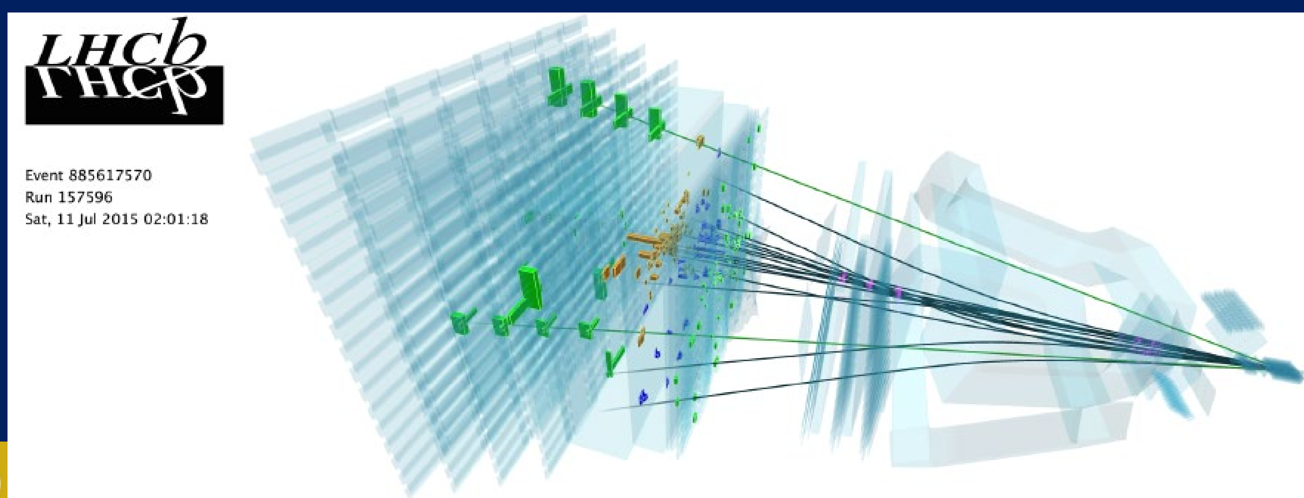
PRL 123, 232001 (2019)

PRL 123, 232001 (2019)

Analysis details

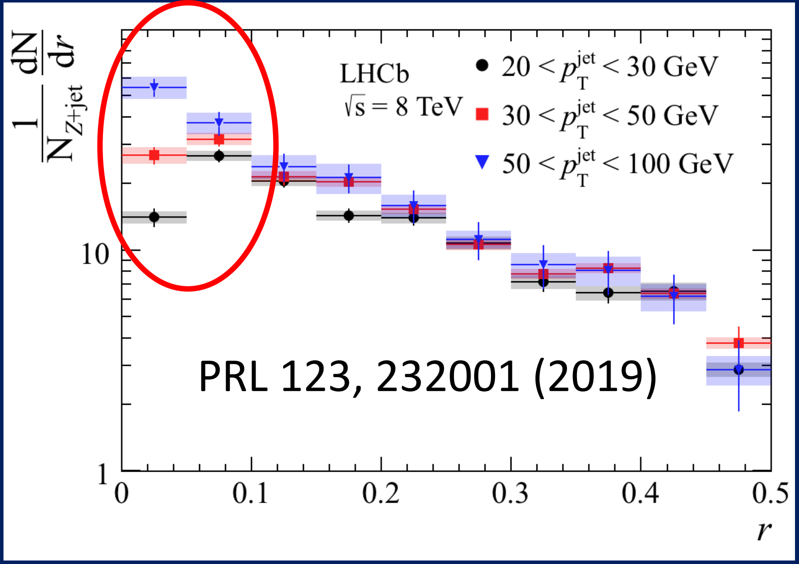
- Follow similar analysis strategy to ATLAS and previous LHCb papers
  - ATLAS: EPJC 71, 1795 (2011), NPA 978, 65 (2018)
  - LHCb: PRL 118, 192001 (2017)

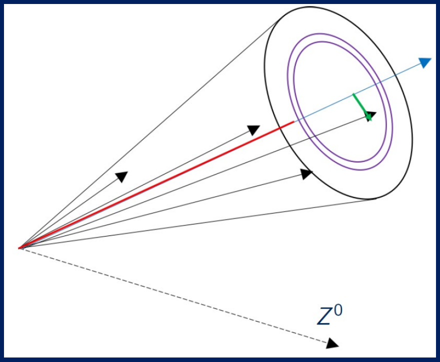
- $Z \to \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-k_T jets are measured with $R = 0.5$, $p_T^{jet} > 20$ GeV, in $2 < \eta < 4.5$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects 2→2 event topology
- Charged hadrons selected with $p_T > 0.25$ GeV, $p > 4$ GeV, $\Delta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



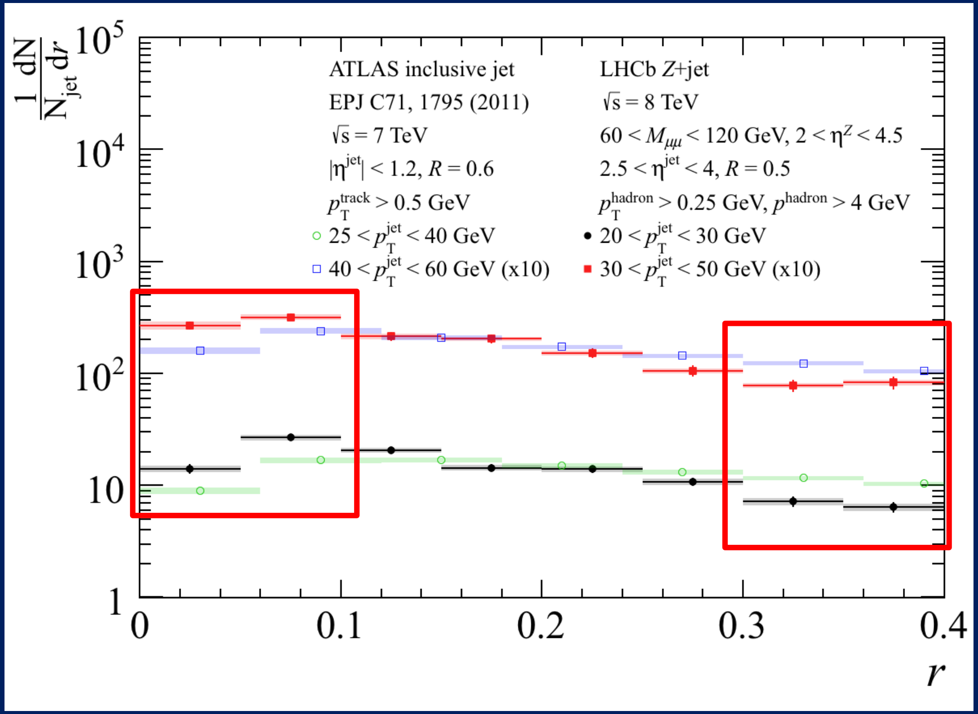
Results: Radial profiles

- Observe that the greater energy available in higher transverse momentum jets leads to more hadrons produced (logical)
- New: ~All of the additional particles are produced close to the jet axis, and go from a depletion close to the axis to an excess





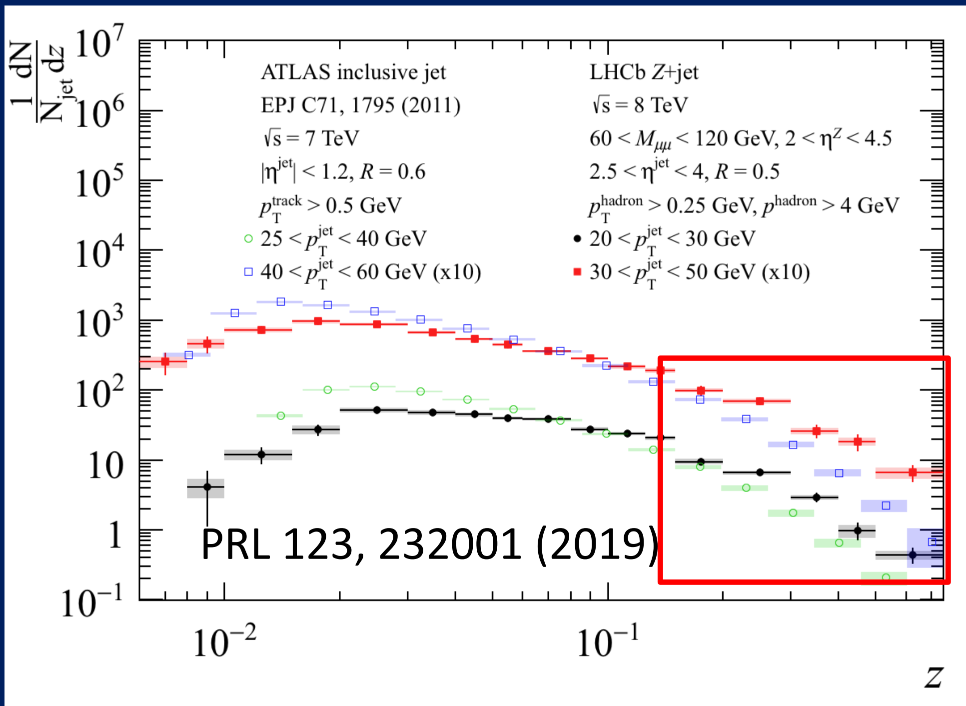
Differences between quark- and gluon-dominated jet samples: Radial profile



PRL 123, 232001 (2019)

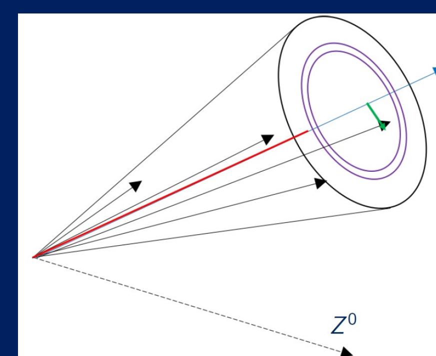
- Quark-dominated jets more collimated than gluon-dominated jets measured by ATLAS
  - I.e. more charged hadrons at small radii, fewer at large radii
  - Qualitatively agrees with conventional expectations, but this shows clear and quantitative evidence from data

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

Will be interesting to follow up with an identified particle measurement. Do the hadrons produced at large momentum fractions in quark-dominated jets tend to contain a quark of the same flavor as the one that initiated the jet?



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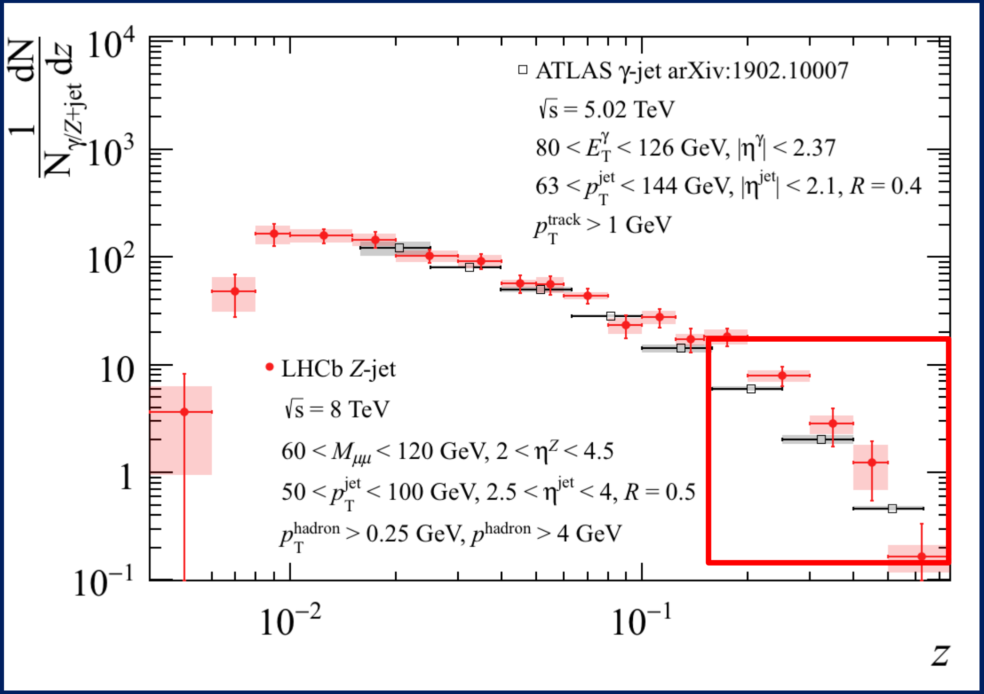
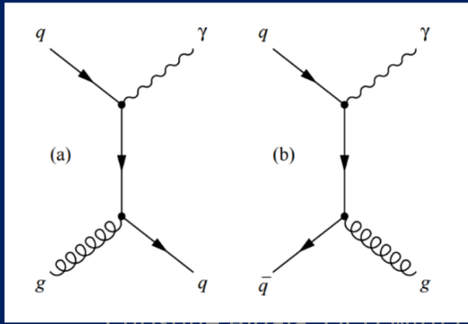


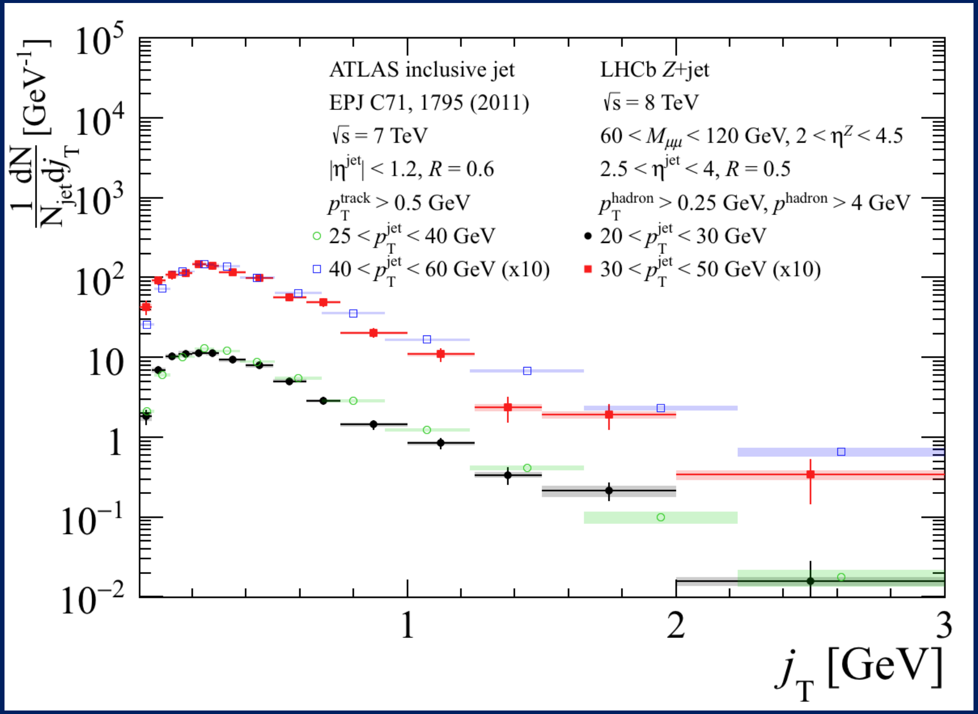
PRL 123, 232001 (2019)



- 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 show slightly smaller <j_T> in Z+jet vs. inclusive jet at small j_T



PRL 123, 232001 (2019)

Other ongoing and potential measurements of hadronization in jets at LHCb

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

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  - Observe the particles formed from ssbar pair production?
- More quarkonia in jets, including polarization: Υ, ϕ, J/ψ

Other 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 in particular
  - Potential sensitivity to parton coalescence/recombination

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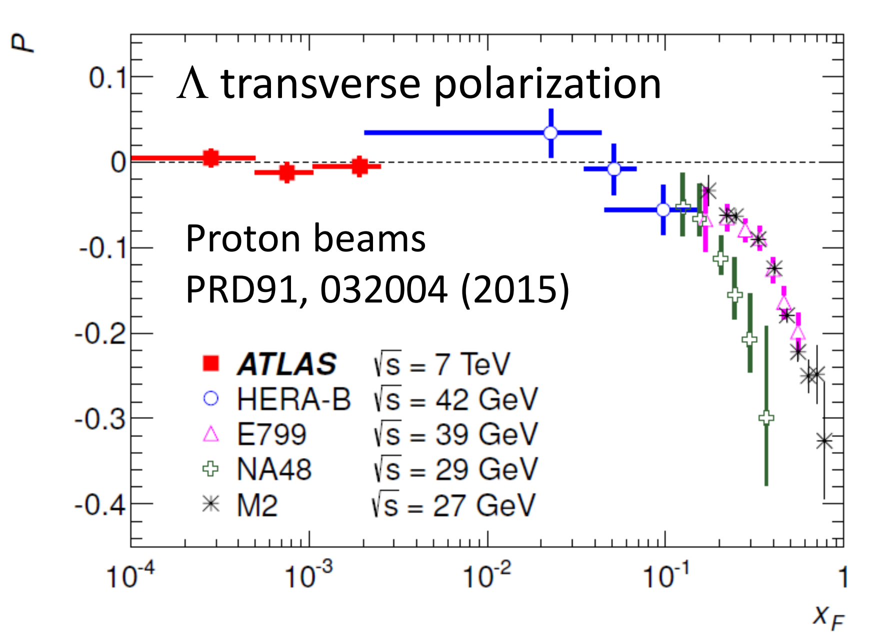
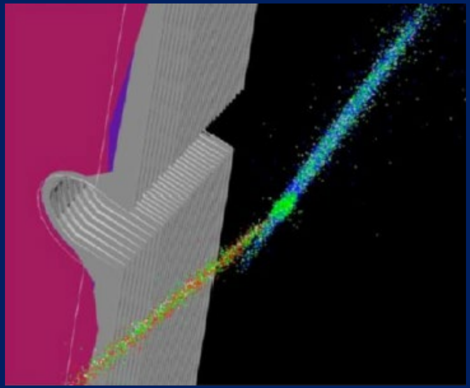
  - Potential sensitivity to parton coalescence/recombination
- Forward lambda and other hyperon polarization measurements

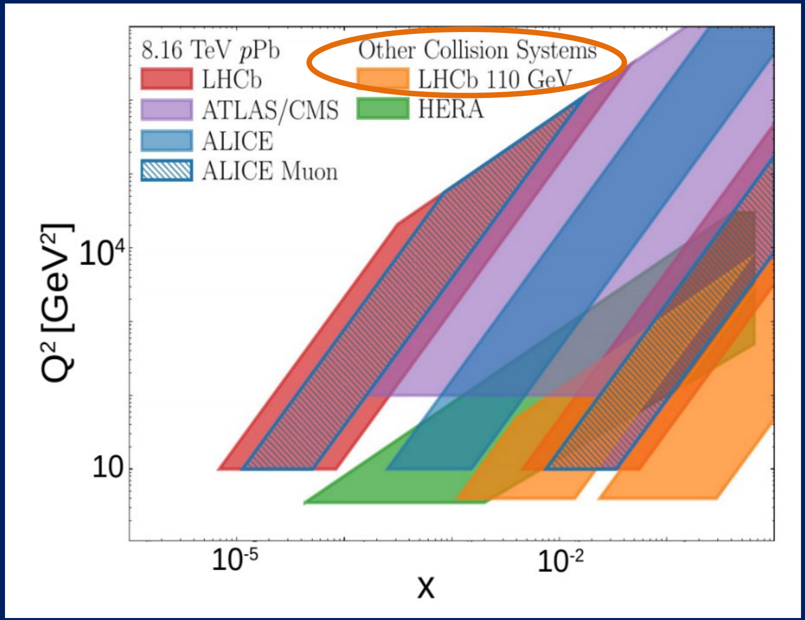


LHCb fixed-target capabilities

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

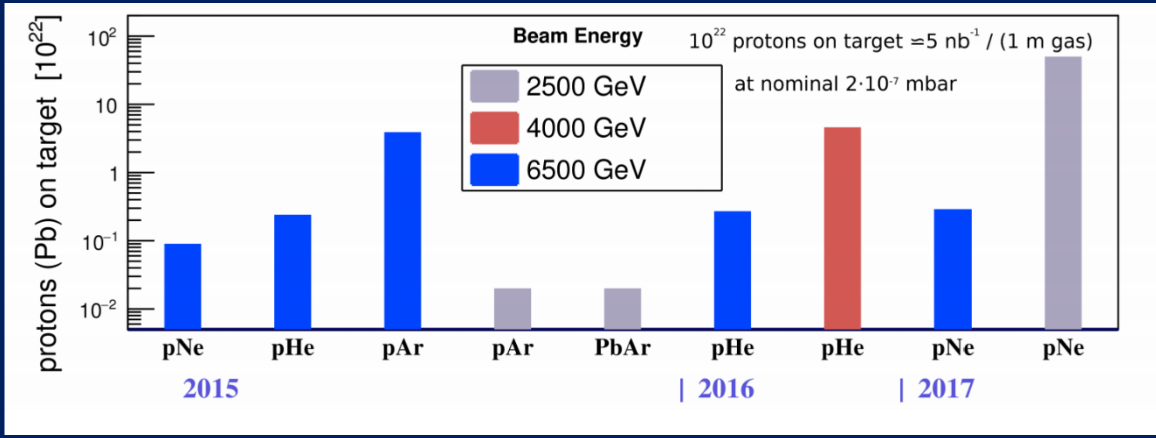


- System for Measuring Overlap with Gas (SMOG) allowed injection of small amounts of noble gas into LHC beam pipe around LHCb collision region. Luminosity up to 10^{30} cm^{-2} s^{-1}

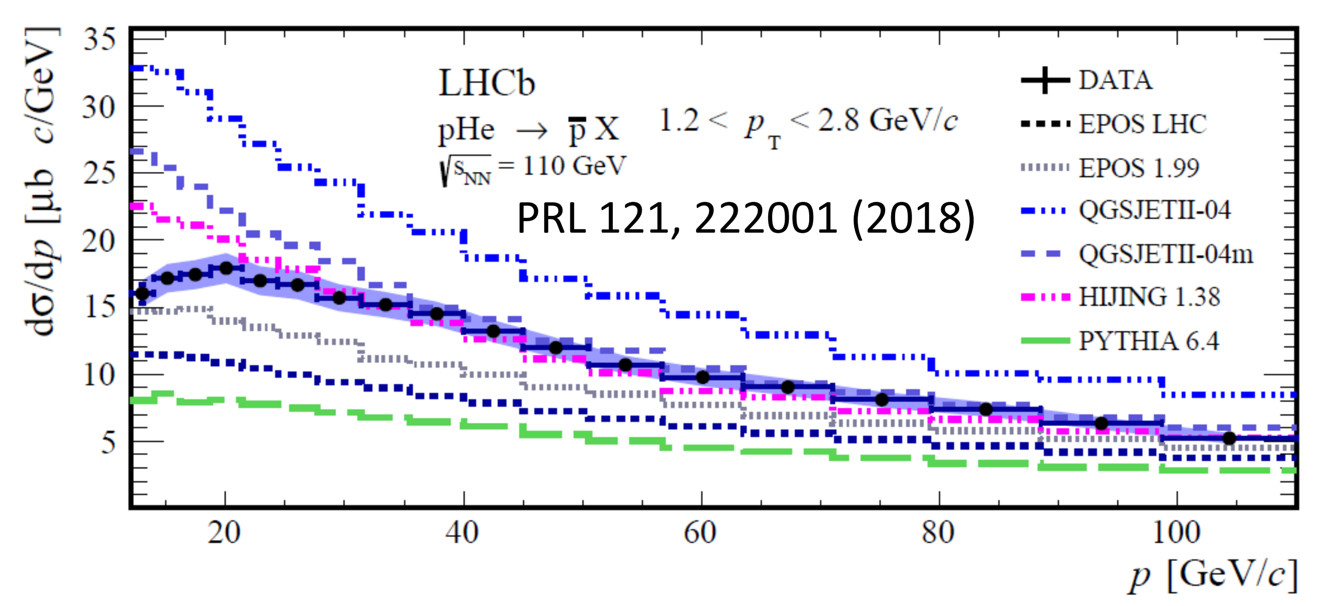


- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{beam}M_p}$ 41-110 GeV for E_{beam}= 0.9-6.5 TeV
  - Between SPS and top RHIC energies
- Overlap with EIC energies

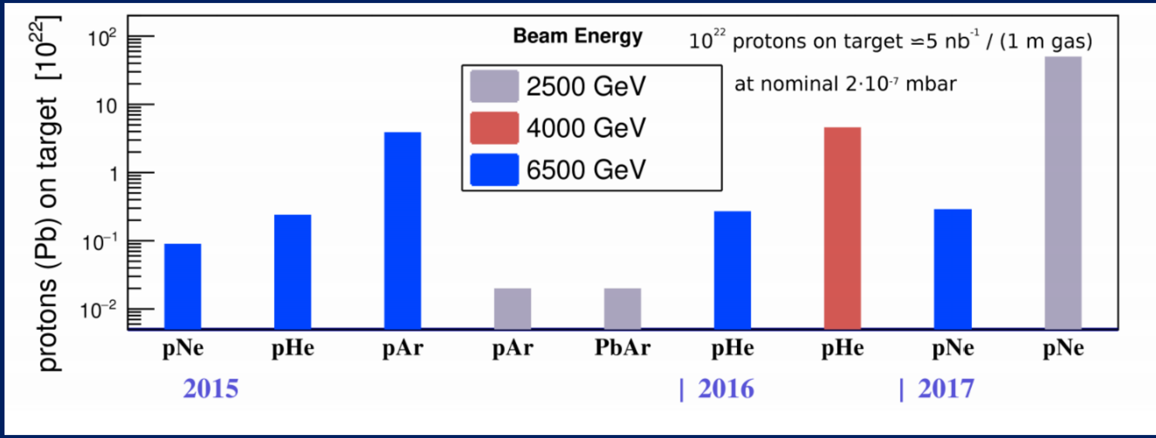
LHCb fixed-target capabilities



Forward antiproton production in pHe



LHCb fixed-target capabilities



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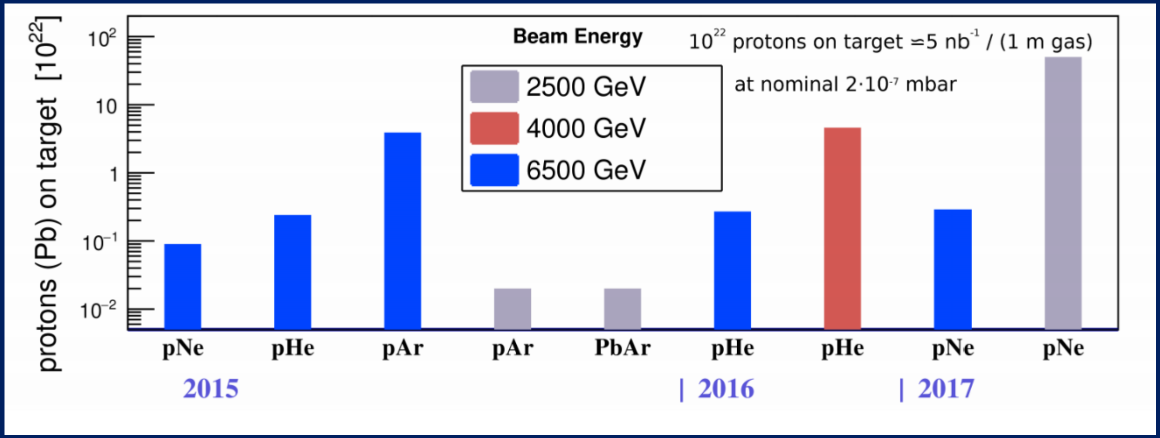

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- LHCSpin: Proposal for transversely polarized gas jet target at LHCb currently undergoing technical review

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At a single experiment or for comparison across multiple experiments.

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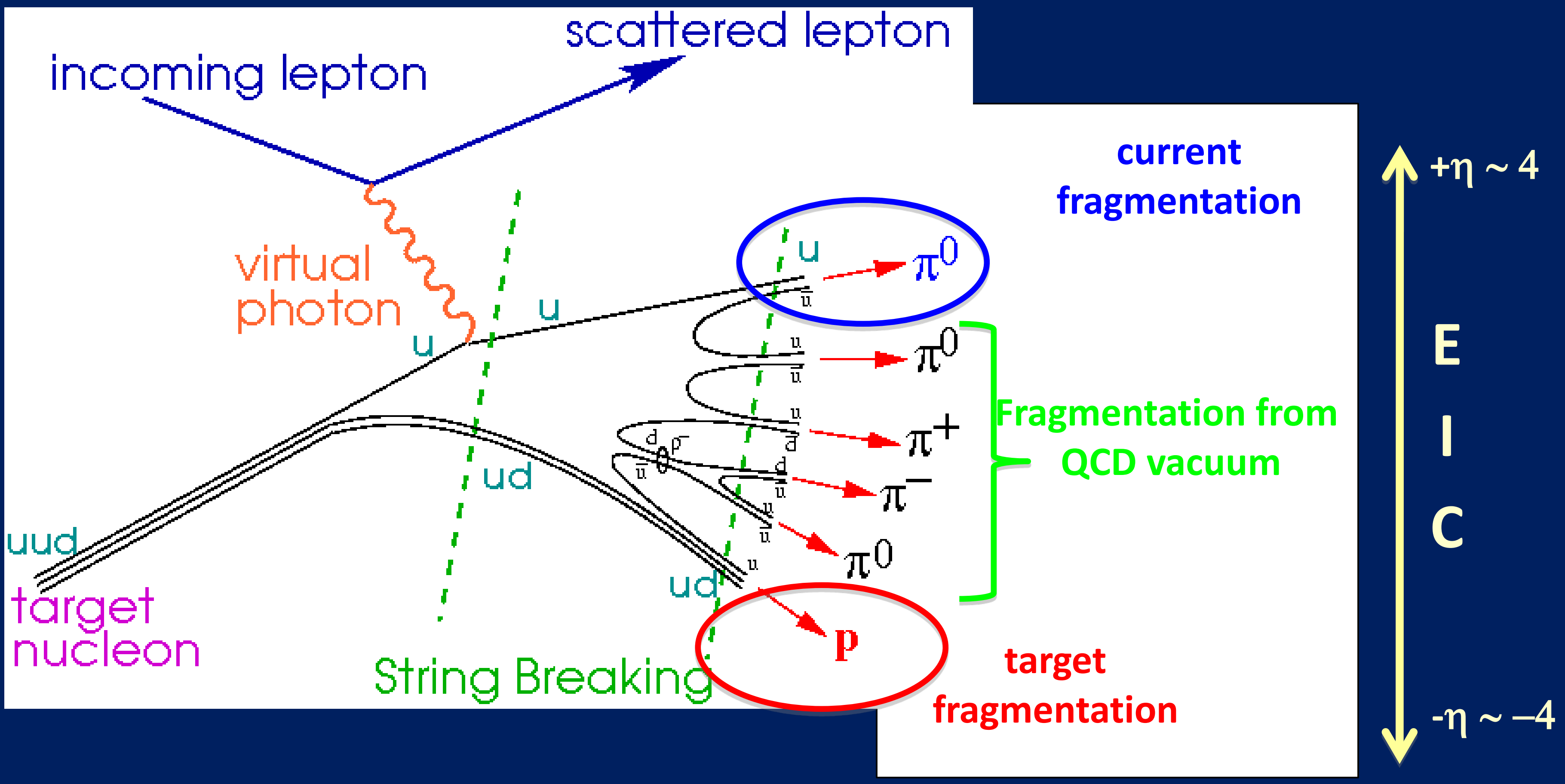
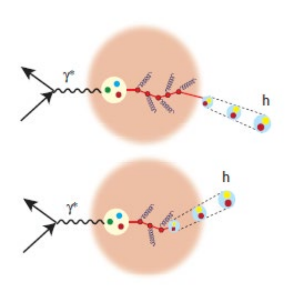
- What can hadron spectroscopy (in p+p or other collision systems) teach us about mechanisms of hadron formation?

Hadronization at the EIC





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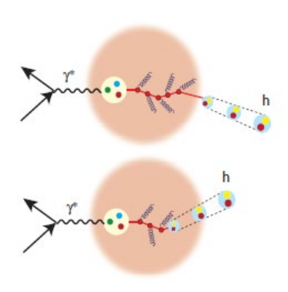

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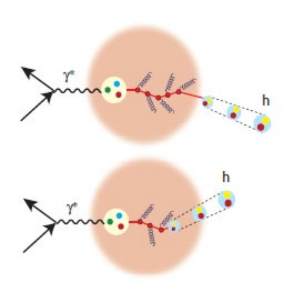

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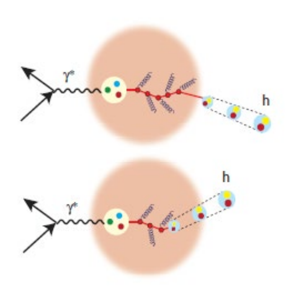

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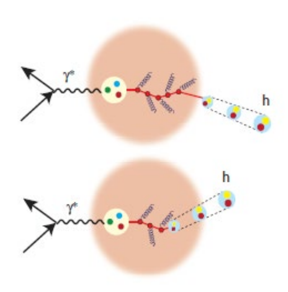

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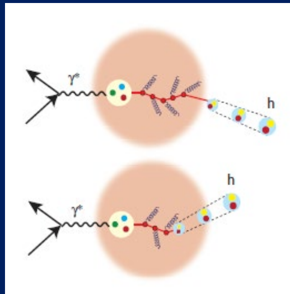

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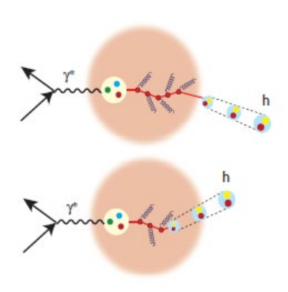

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- Integrated luminosities allowing multidifferential measurements
- …

Final remarks

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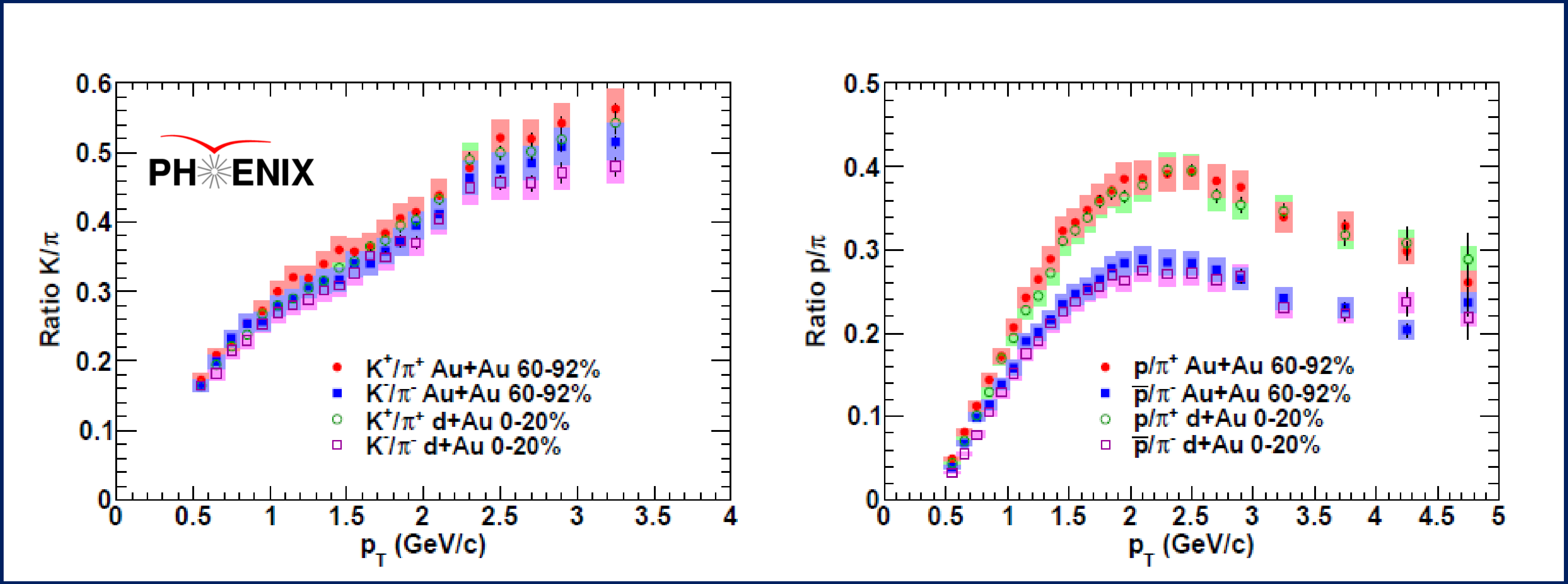
We should use the 2020s to ensure that we are positioned to take full advantage of the EIC's potential for hadronization!

DI PAVIA

Extra

Comparing central d+Au with peripheral Au+Au

PRC88, 024906 (2013)

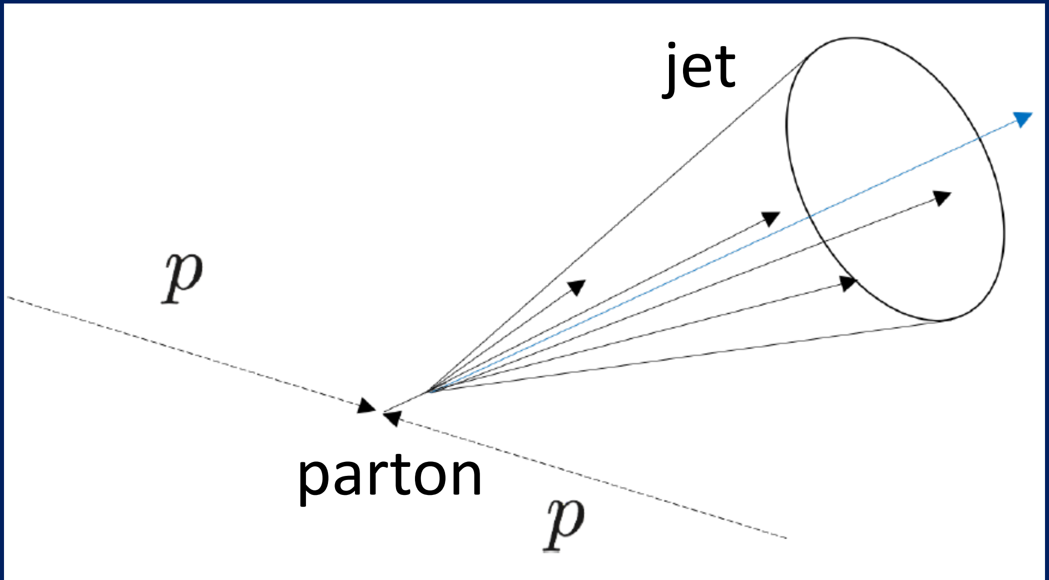


Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au 60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au 0-20%	15.1 ± 1.0	15.3 ± 0.8

Both shape and magnitude identical!

MICHIGAN
UNIVERSITÀ DI PAVIA

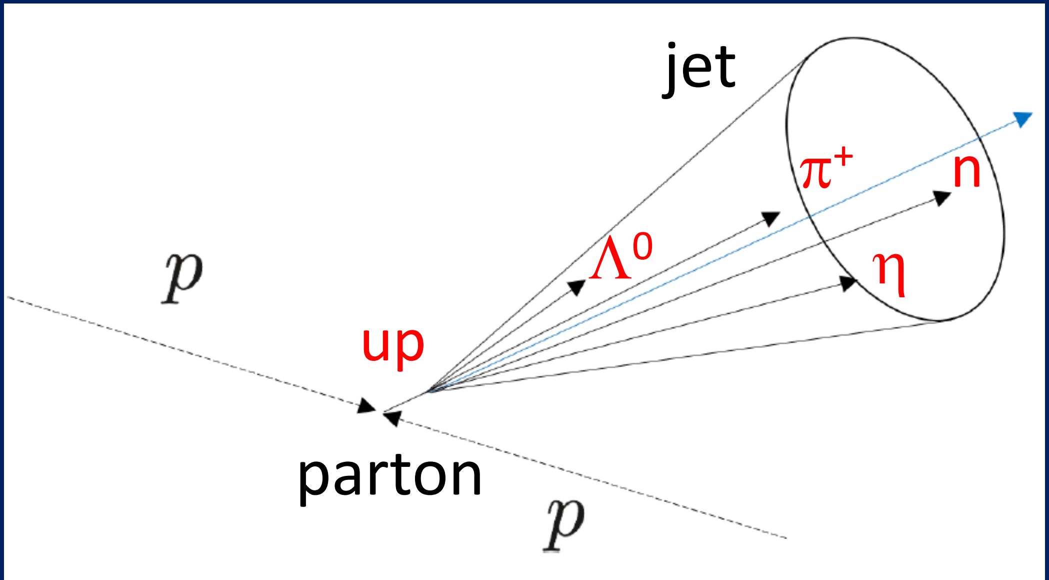
Understanding high-energy hadronization: A wish list



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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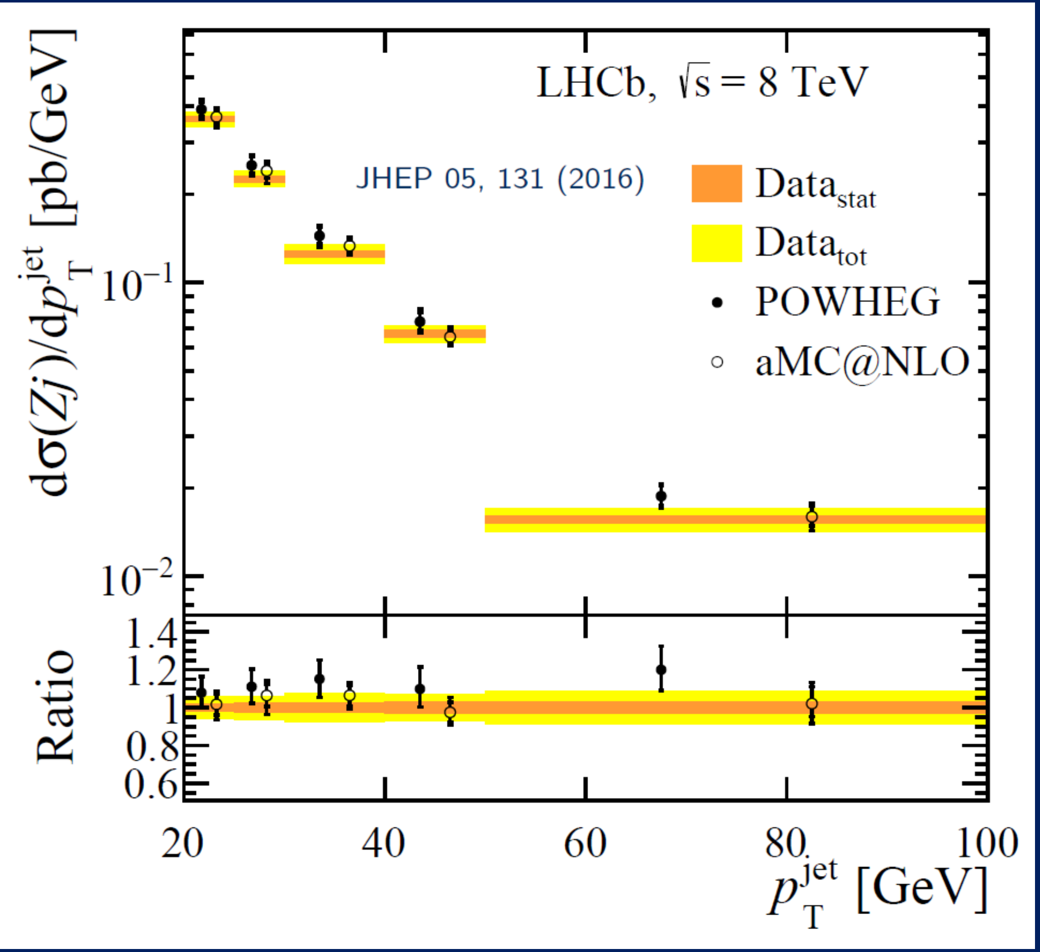
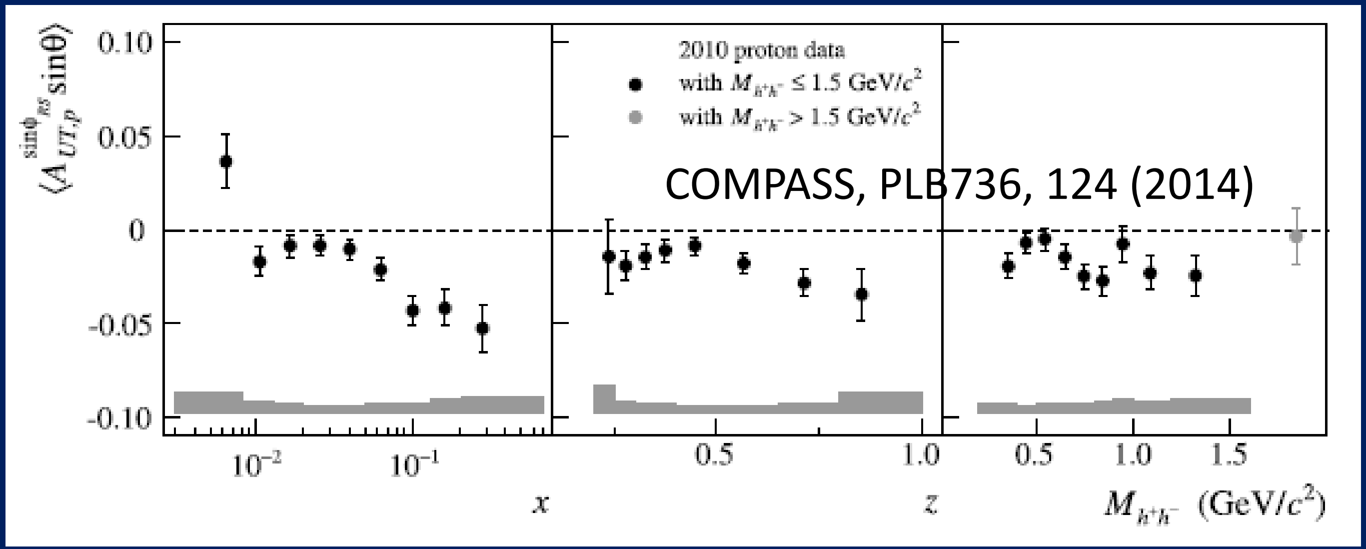
Forward Z+jet

- 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



Dihadron interference FF



- Pion pair hadronizes from same quark; correlation with quark transverse spin; chiral-odd
- Clear nonzero effects in e+e- and semi-inclusive DIS
  - Transversity x IFF in SIDIS

Collinear, twist-3 multiparton correlations in hadronization

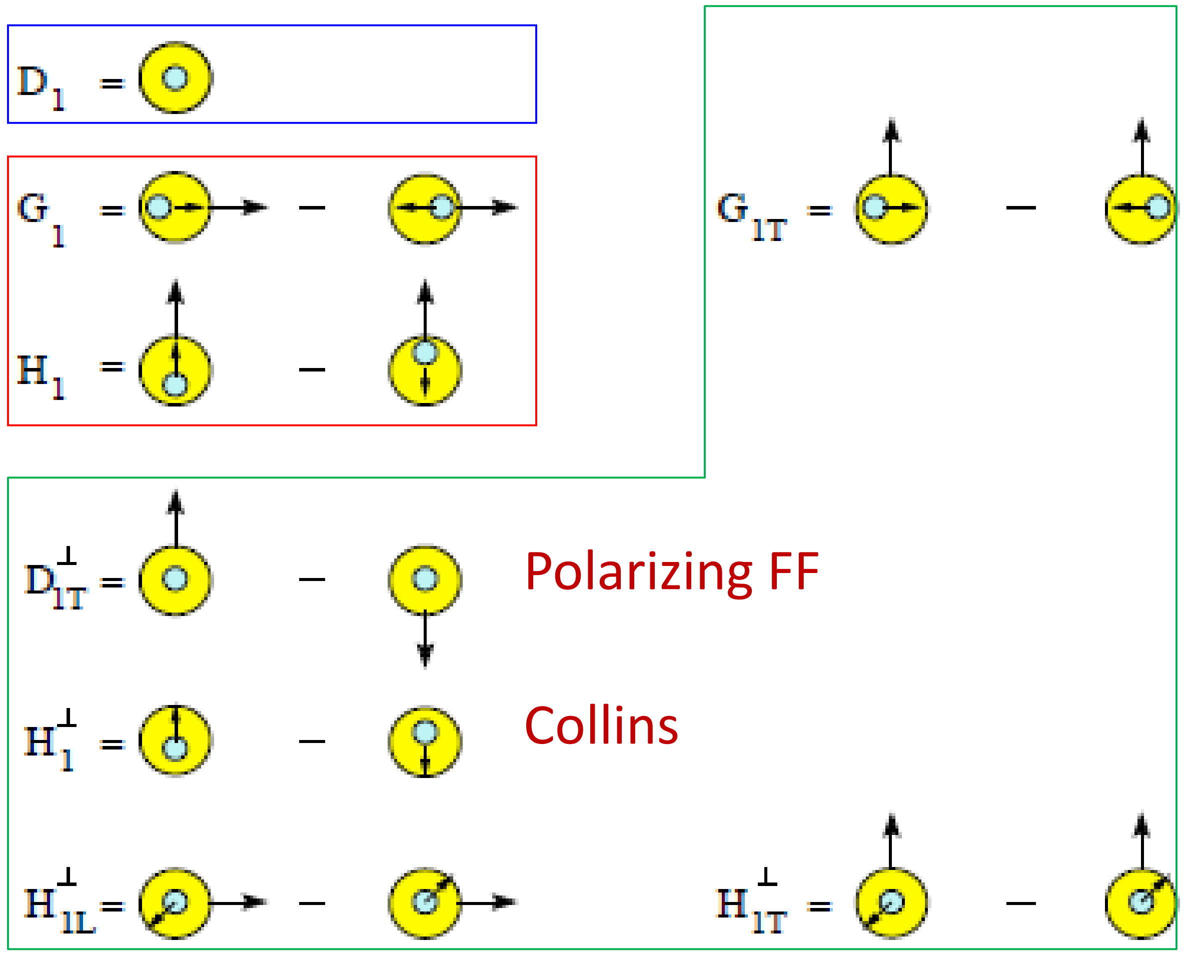
- Interference between a (quark+gluon) hadronizing and only a quark
- Similarly, interference between (gluon+gluon) and only a single gluon
- Can generate transverse single-spin asymmetries
- Increasing phenomenology efforts in recent years . . .

Twist-2 fragmentation functions

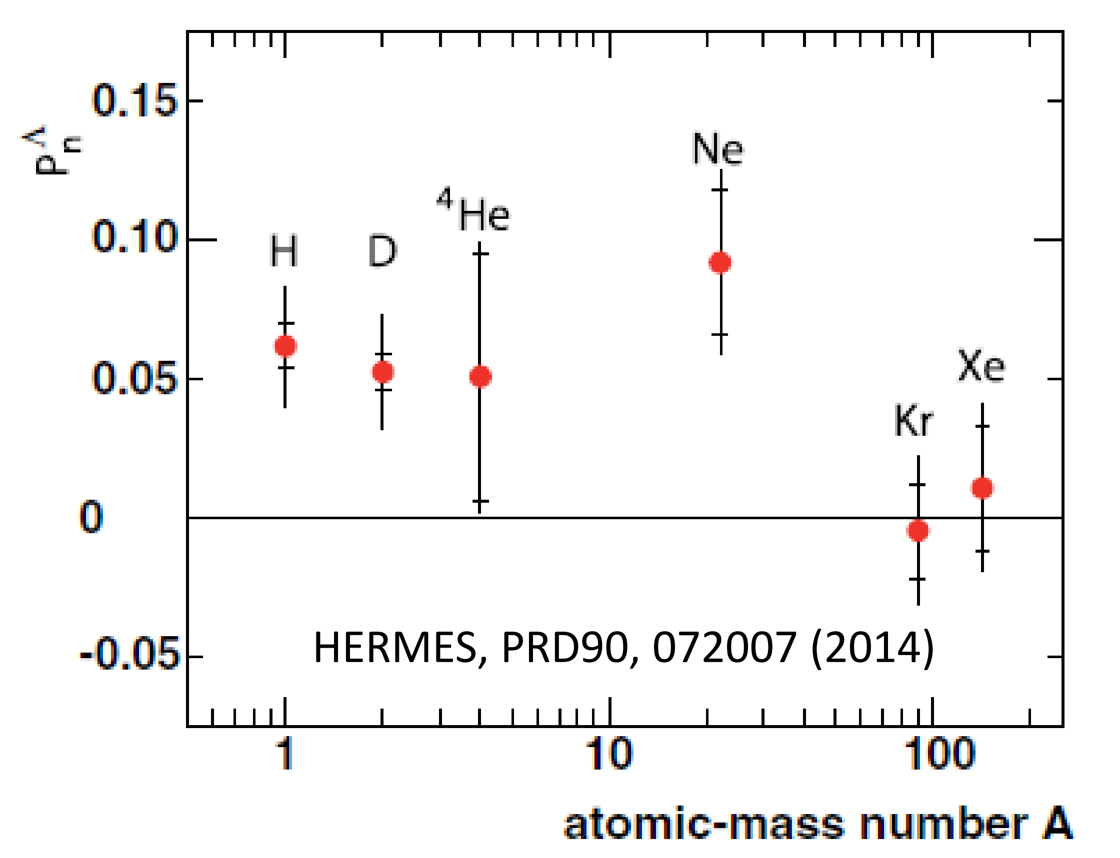
Unpolarized

Spin-spin correlations

Spin-momentum correlations

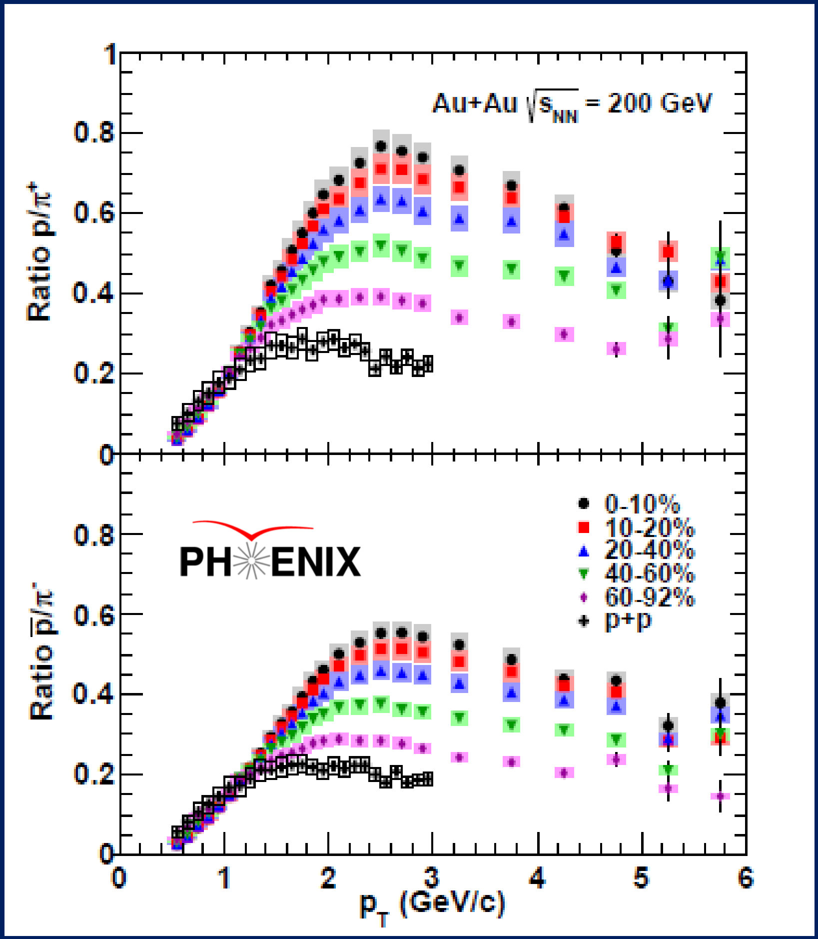


Lambda polarization observed in semi-inclusive DIS



- Nonzero in both forward and backward directions

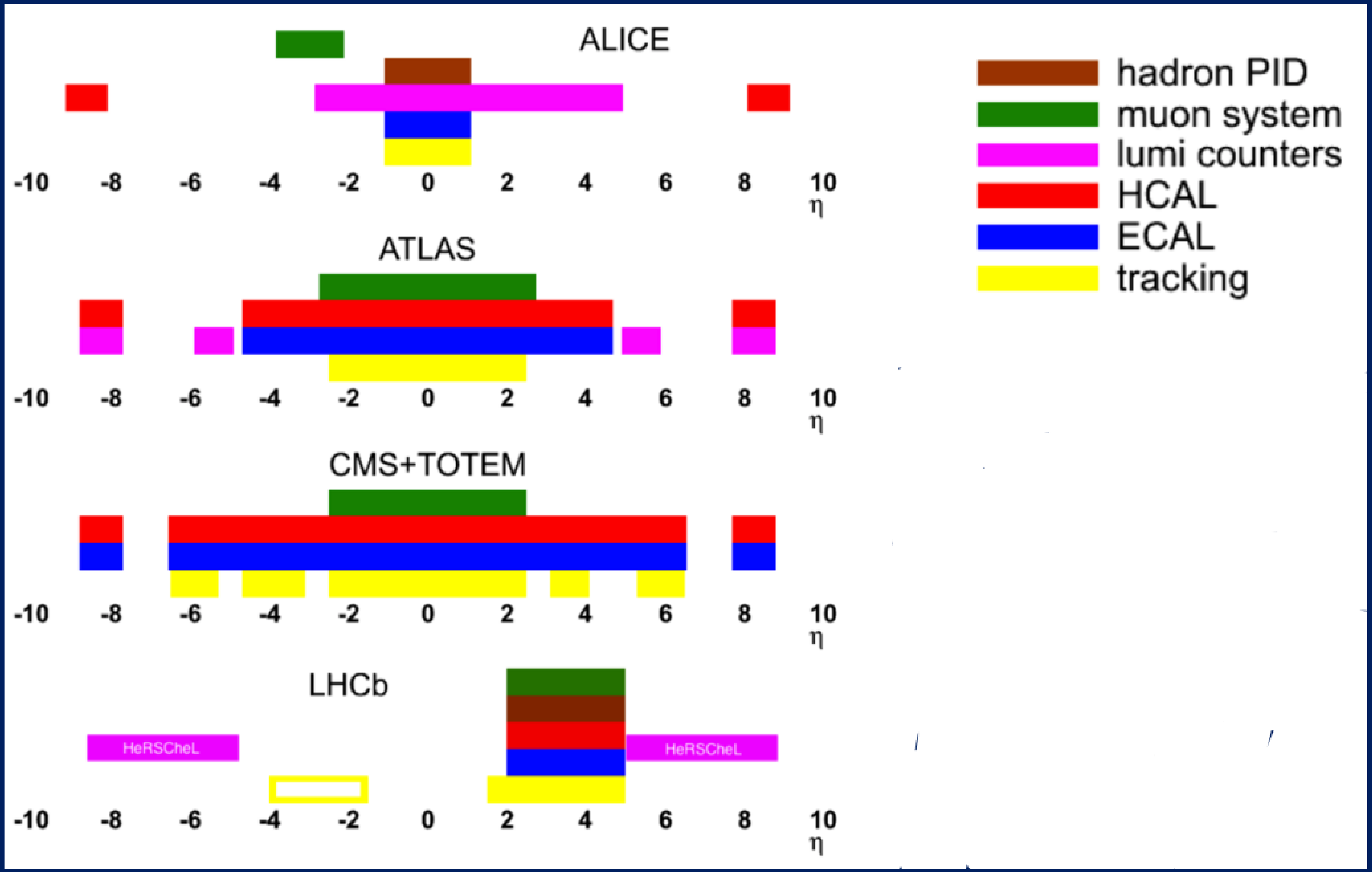
Centrality-dependent baryon enhancement in d+Au compared to p+p



PRC88, 024906 (2013)

- Precision d+Au data for identified charged hadrons in bins of centrality
- New hadron production mechanism enabled by presence of additional partons/ nucleons
  - Parton recombination?
- Strong centrality dependence despite small range of N_{part} and N_{coll} values in d+Au
- Well-known centrality-dependent baryon enhancement in Au+Au

Pseudorapidity coverage at LHC



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?

Formation of QCD bound states: Hadronization at EIC

- Use nuclei as femtometer-scale detectors of the hadronization process!
- Wide range of scattered parton energy; small to large nuclei
  - Move hadronization inside/outside nucleus
  - Distinguish energy loss and attenuation