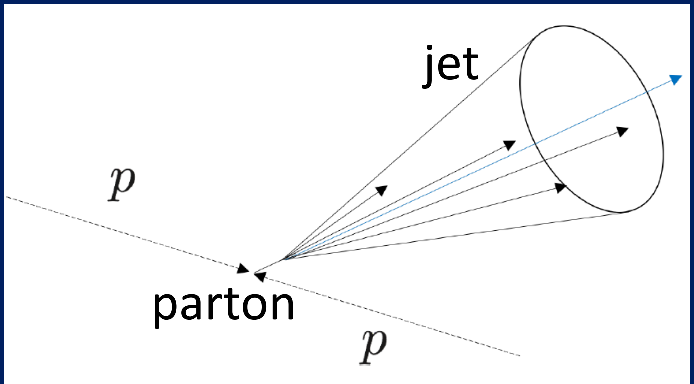
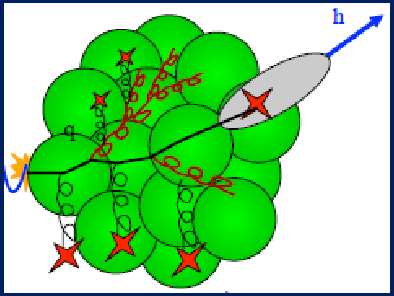
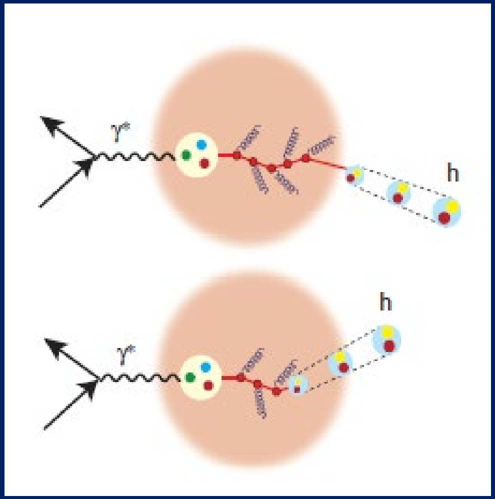
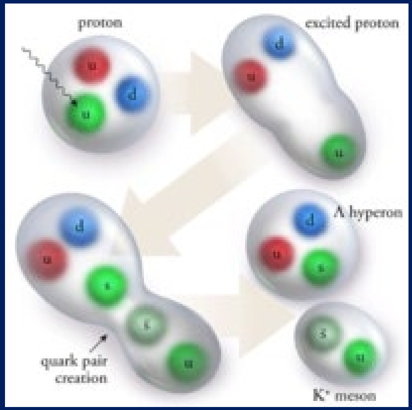



# *Advancing Hadronization: From Inclusive Production to Multiparticle Correlations*

*Christine A. Aidala*
*University of Michigan*
*and*
*University of Pavia*




*CPHI*
*CERN*
*February 3-7, 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

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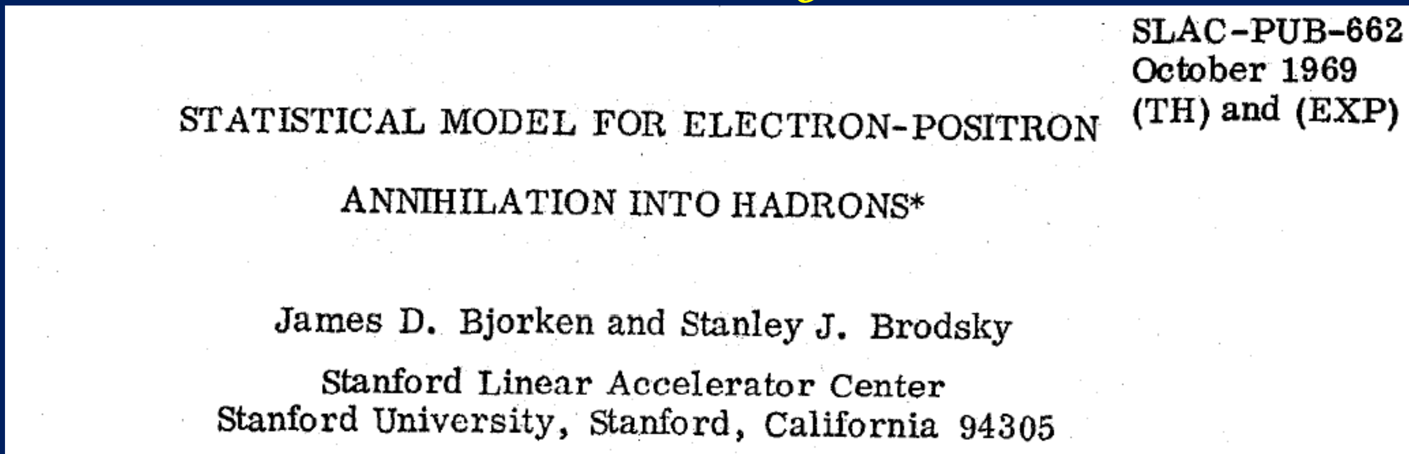

SLAC-PUB-662
October 1969
(TH) and (EXP)

STATISTICAL MODEL FOR ELECTRON-POSITRON ANNIHILATION INTO HADRONS*

James D. Bjorken and Stanley J. Brodsky

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

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SLAC-PUB-1930
April 1977
(T/E)

HADRON PRODUCTION IN NUCLEAR COLLISIONS – A NEW PARTON MODEL APPROACH*

Stanley J. Brodsky
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

John F. Gunion
Department of Physics
University of California, Davis, California 95616

J. H. Kühn
Max Planck Institut für Physik und Astrophysik
München 40, Germany

# *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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  - Mainly Collins, unpolarized, and polarizing TMD FFs so far
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**Monte Carlo Implementation of Polarized Hadronization**

Hrayr H. Matevosyan,[1,*] Aram Kotzinian,[2,3,†] and Anthony W. Thomas[1,‡]

[1] *ARC Centre of Excellence for Particle Physics at the Tera-scale, and CSSM, School of Chemistry and Physics, The University of Adelaide, Adelaide SA 5005, Australia*
*http://www.physics.adelaide.edu.au/cssm*
[2] *Yerevan Physics Institute, 2 Alikhanyan Brothers St., 375036 Yerevan, Armenia*
[3] *INFN, Sezione di Torino, 10125 Torino, Italy*

2016

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**Semi-inclusive production of two back-to-back hadron pairs in $e^+e^-$ annihilation revisited**

2018

Hrayr H. Matevosyan,[1,*] Alessandro Bacchetta,[2,3,†] Daniël Boer,[4,‡] Aurore Courtoy,[5,§] Aram Kotzinian,[6,7,¶] Marco Radici,[3,**] and Anthony W. Thomas[1,††]

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2018

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UNIVERSITÀ DI PAVIA

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**SIDIS in the target fragmentation region: polarized and transverse momentum dependent fracture functions**

2011

M. Anselmino[a], V. Barone[b], A. Kotzinian[a,c]

- Two-parton FFs
- Heavy flavor FFs
- Fracture functions
region

**Double hadron lepto-production in the current and target fragmentation regions**

2011

M. Anselmino[a], V. Barone[b], A. Kotzinian[a,c]

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**Using Nuclei to Probe Hadronization in QCD**

STANLEY J. BRODSKY*

*Stanford Linear Accelerator Center*
*Stanford University*
*Stanford, California 94305*
and
*Institute for Theoretical Physics*
*University of California*
*Santa Barbara, California 93106*

A.H. MUELLER†

*Physics Department*
*Columbia University*
*New York, NY 10027*
and
*Institute for Theoretical Physics*
*University of California*
*Santa Barbara, California 93106*

1988

The Nucleus as a Color Filter in QCD:
Hadron Production in Nuclei*

STANLEY J. BRODSKY

*Stanford Linear Accelerator Center*
*Stanford University, Stanford, California 94309*

and

PAUL HOYER

*Department of High Energy Physics*
*University of Helsinki, SF-00170 Helsinki, Finland*

1989

# *Hadronization: Recent advances*

- 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)
  - 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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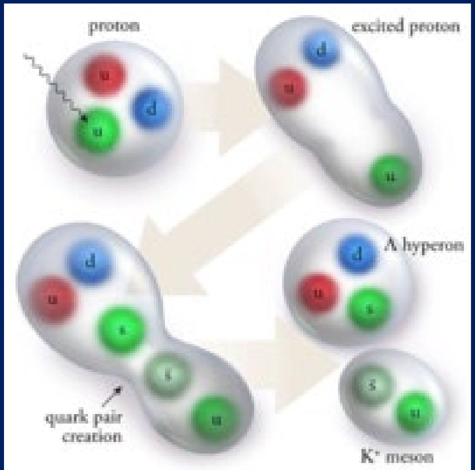


CLAS, PRL 113, 152004 (2014)

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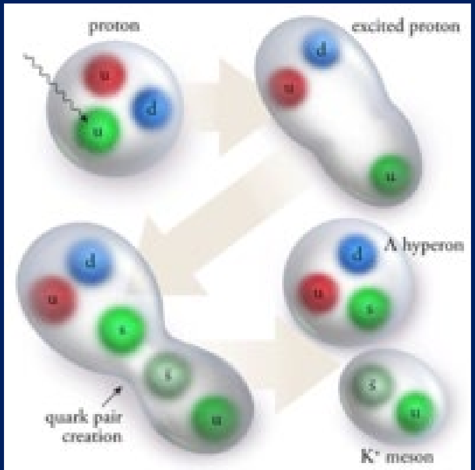
- Threshold production
- Production via decay from other hadrons
- …?

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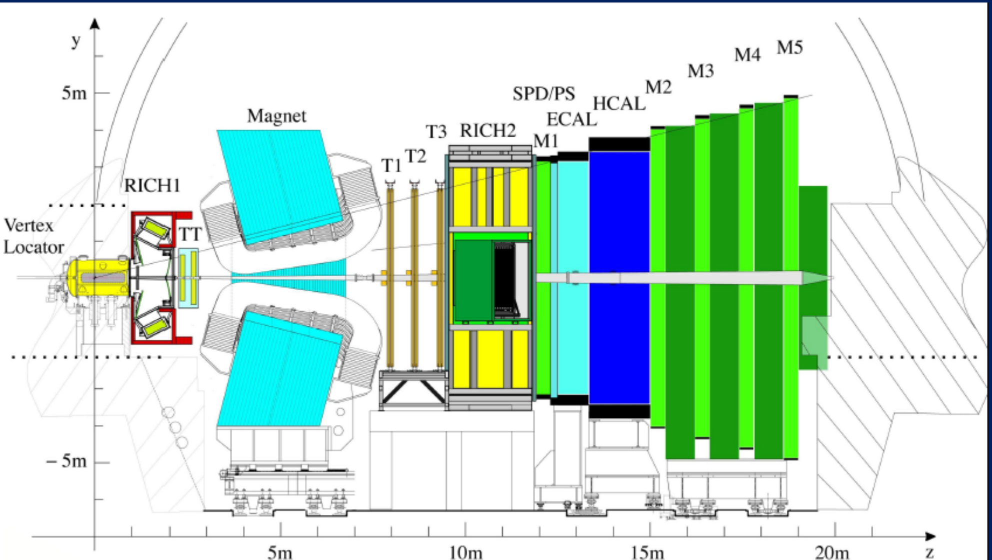
# *LHCb: Opportunities for hadronization measurements in p+p*

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
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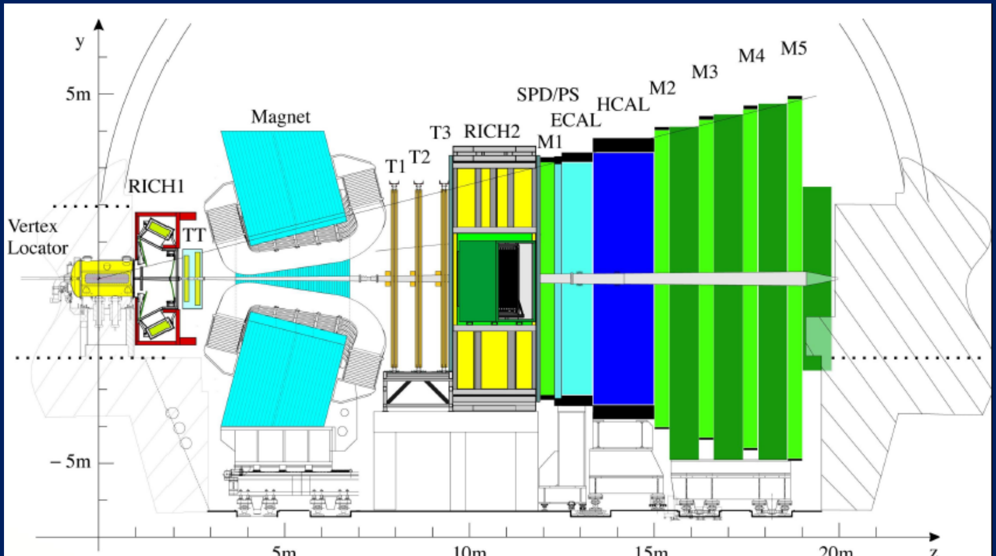


JINST 3, (2008) S08005
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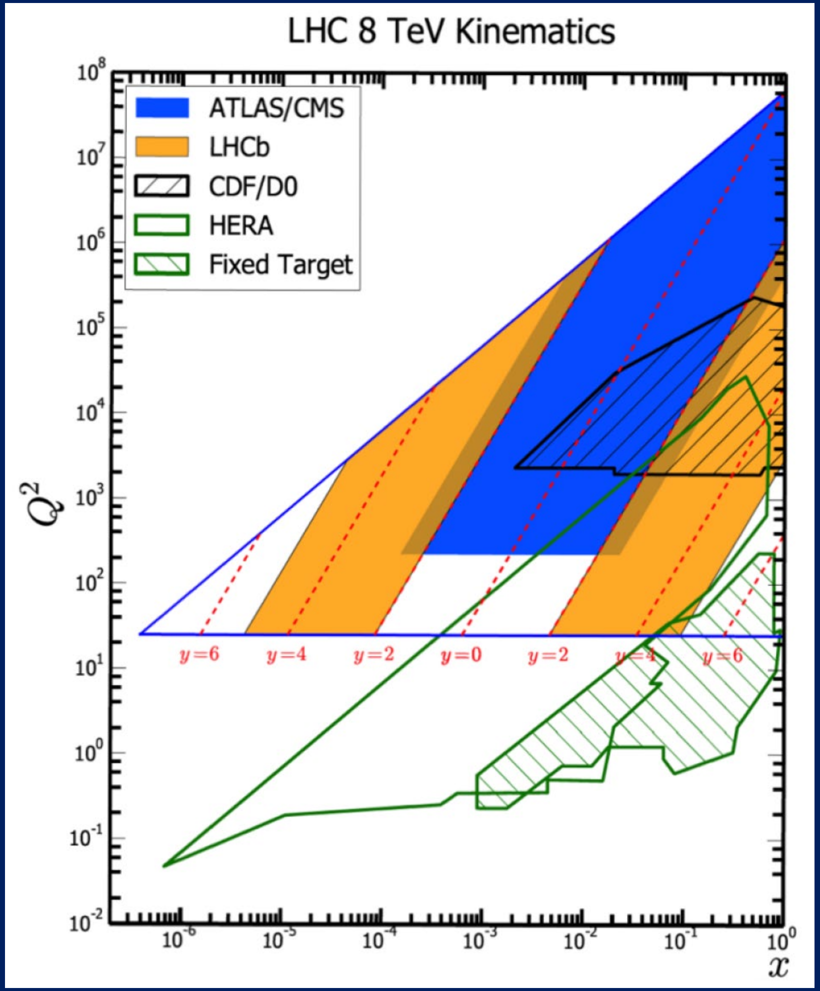
Some features specifically attractive for hadronization:

- 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!

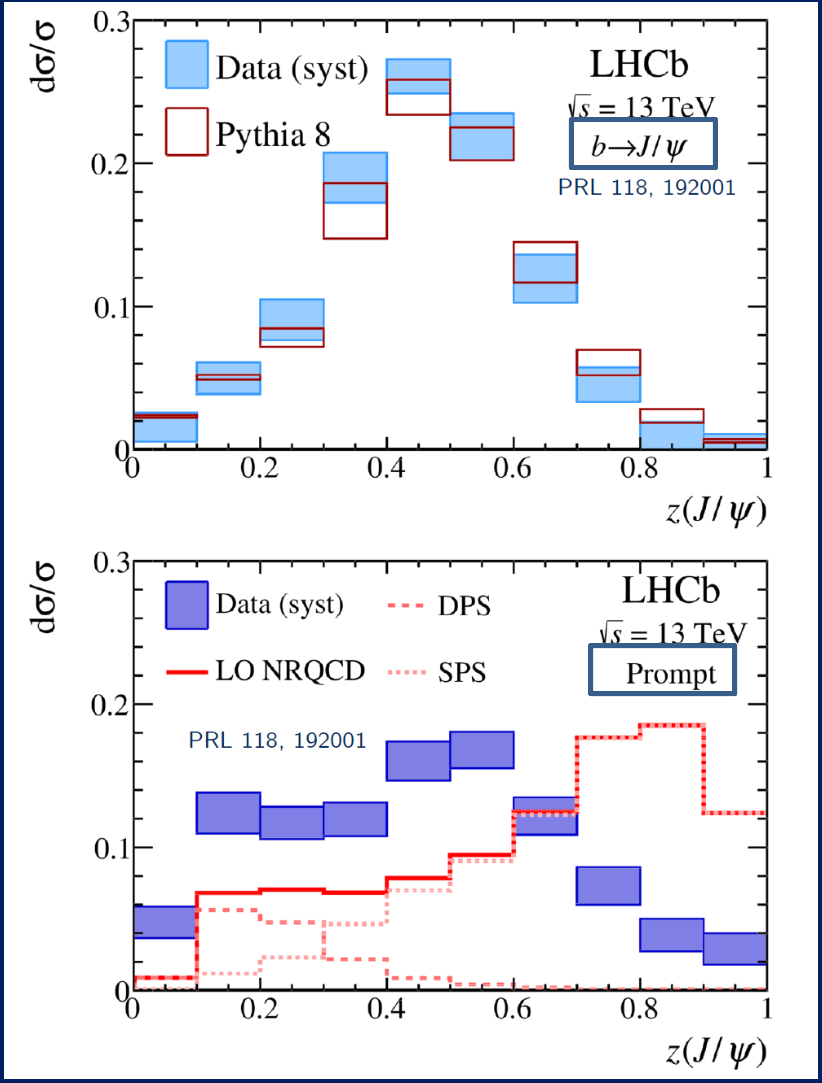
# *x-$Q^2$ coverage affects parton mix*

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

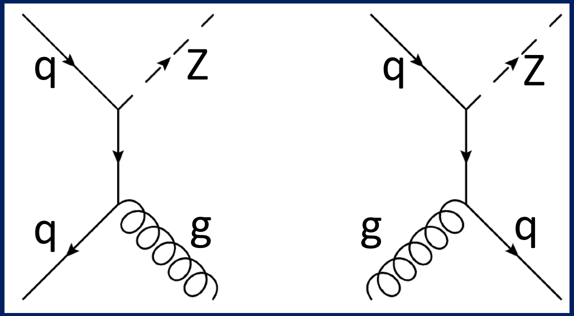


# J/Ψ production in jets at LHCb

- 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?

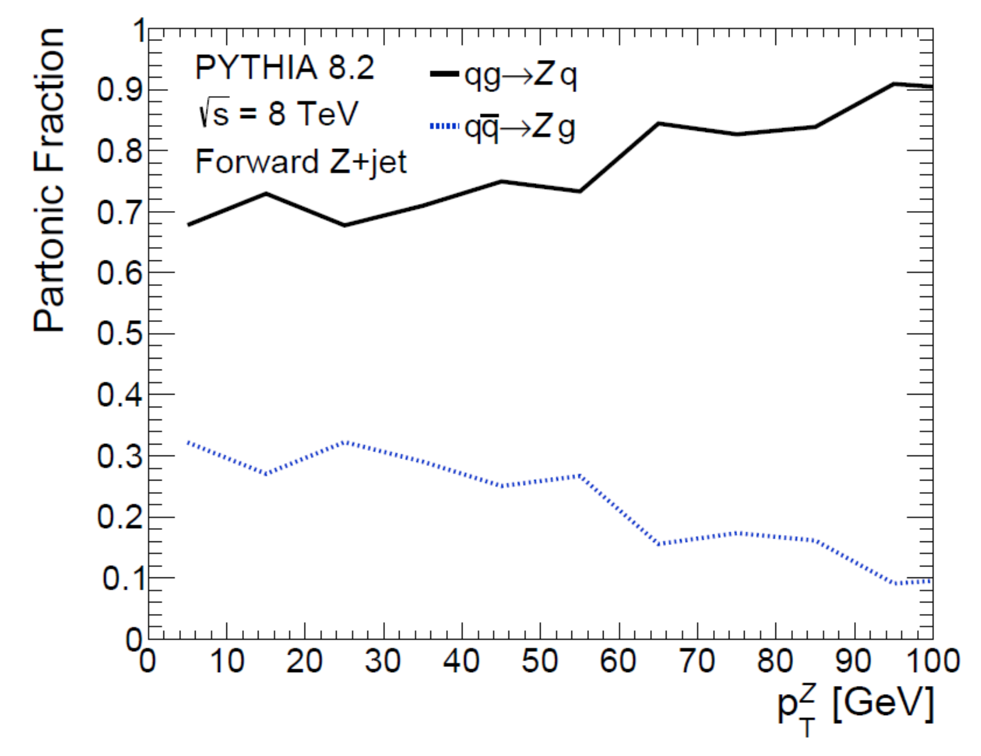


# *Forward Z+jet*



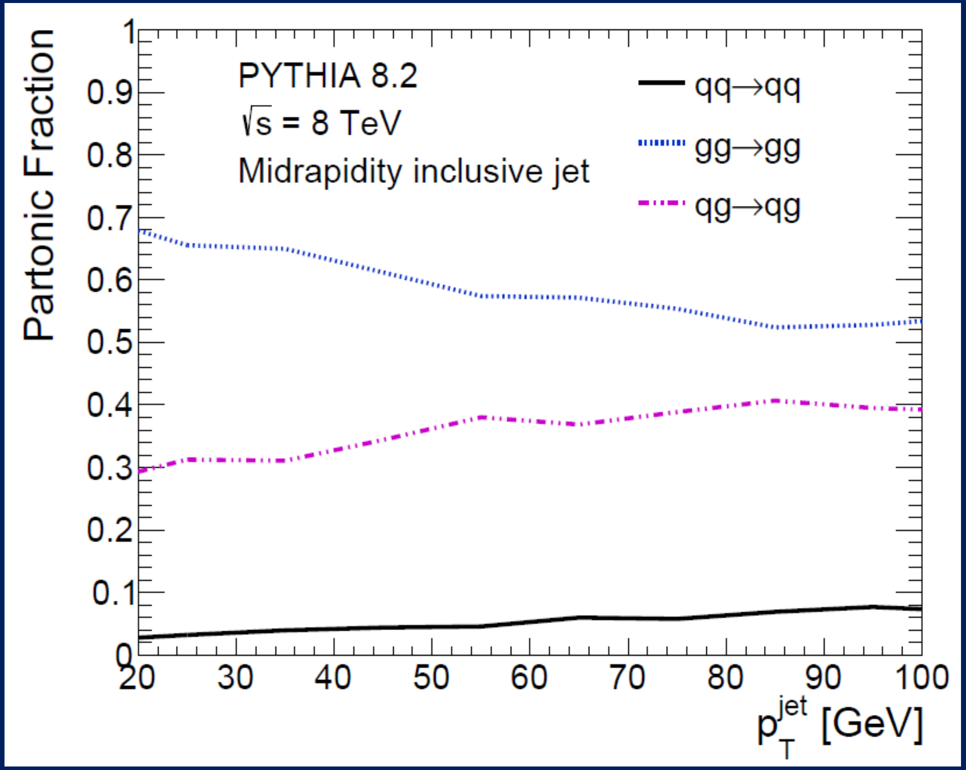

- Z+jet is predominantly sensitive to quark jets

- Forward kinematics increases fraction of light quark jets



# *Forward Z+jet*

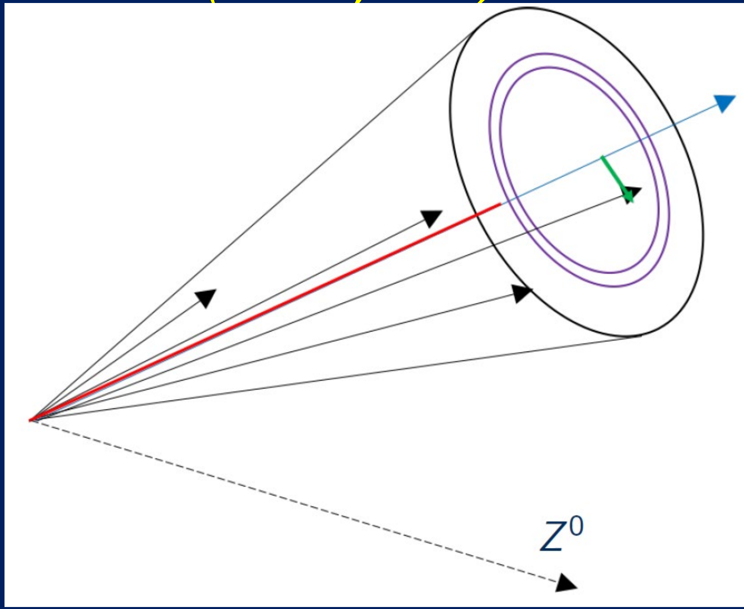
- In contrast to midrapidity inclusive jets, dominated by gluons
- Opportunity to study light quark vs. gluon jets
  - Hadronization dynamcs
  - Jet properties



# *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

PRL 123, 232001 (2019)




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

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

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

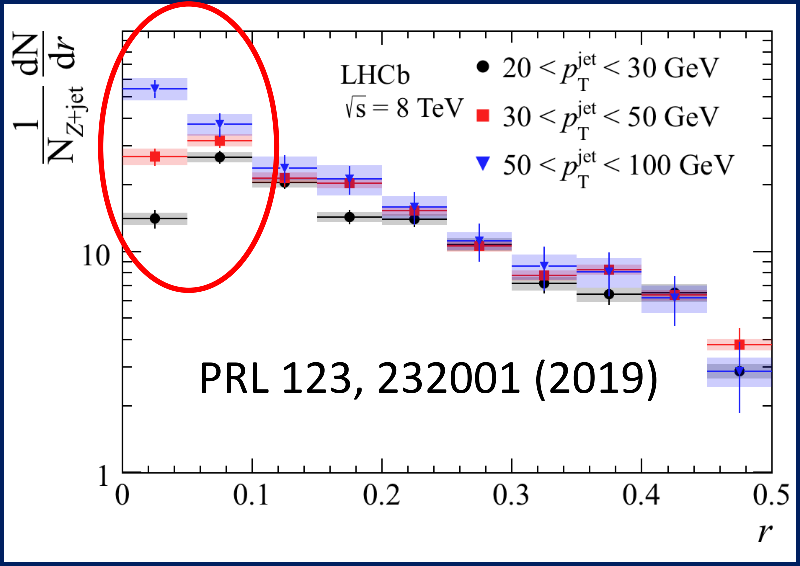
Lays the foundation for a broader hadronization program at LHCb utilizing

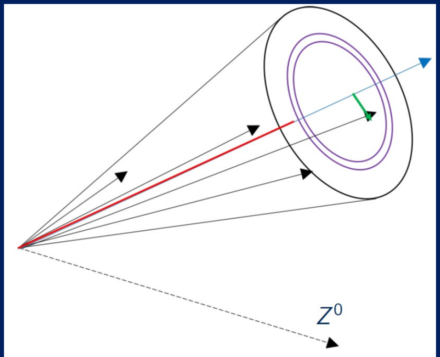
- Particle ID
- Heavy flavor jet tagging
- Resonance production within jets
- Correlations with flavor ID
- Baryon vs. meson production
- Multiplicity-dependent hadronization
- Forward hyperon polarization
- …

# Results: Radial profiles

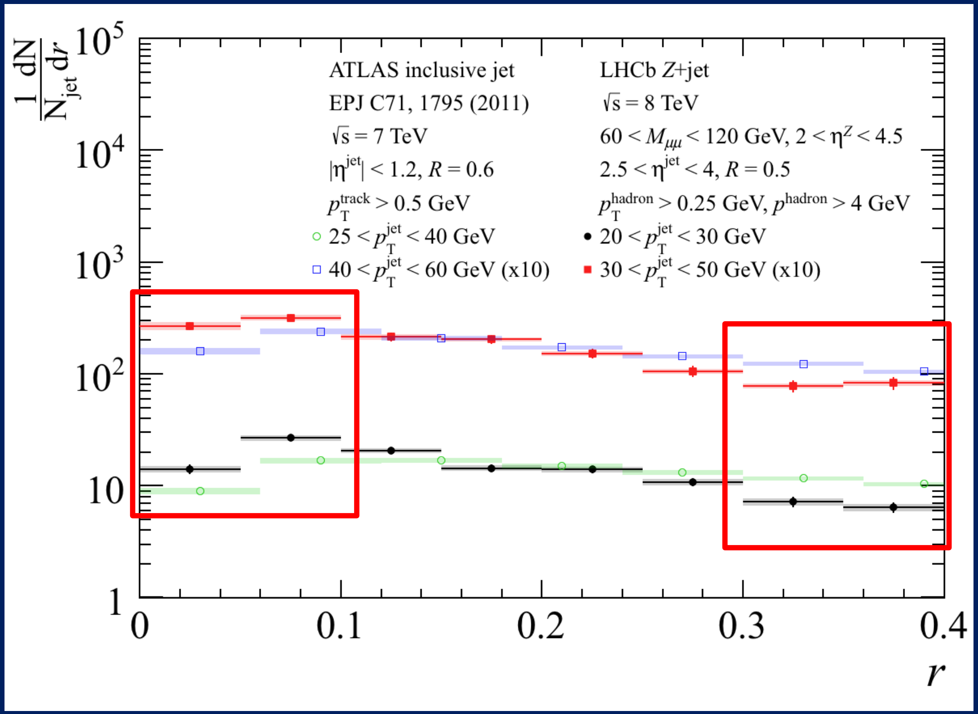
- Observe that the greater energy available in higher transverse momentum jets leads to more hadrons produced (logical)

- 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



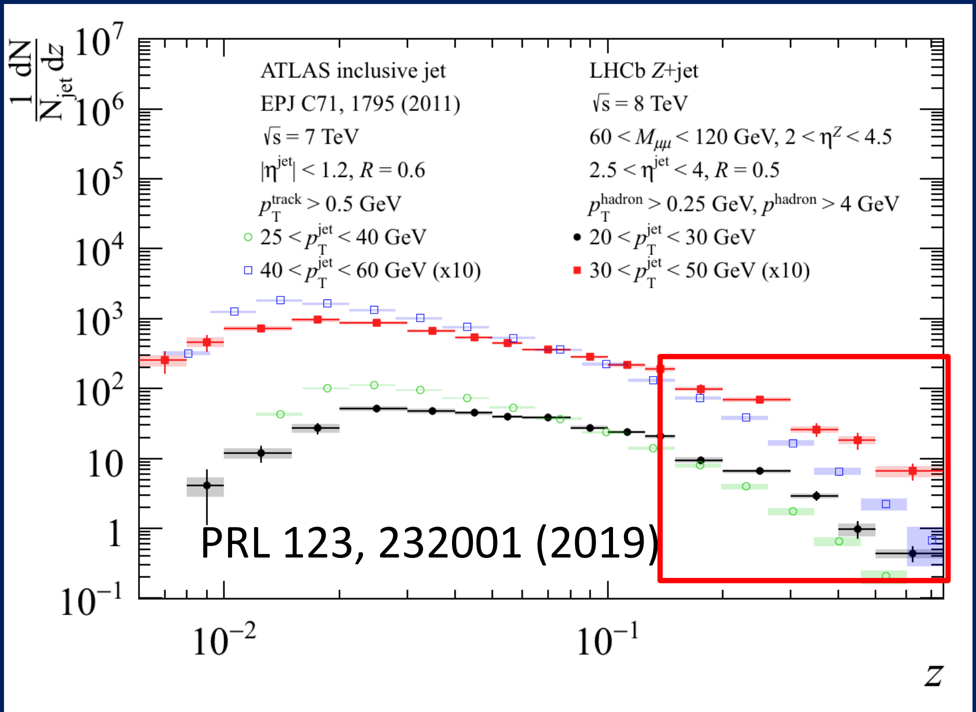
# Differences between quark- and gluon-dominated jet samples: Radial profile




PRL 123, 232001 (2019)

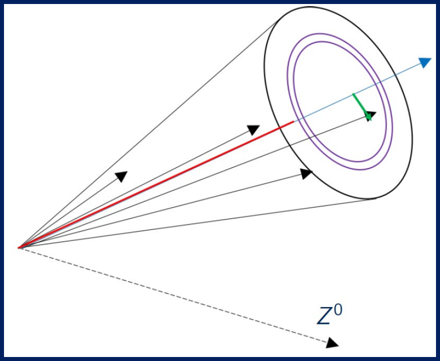
- Quark-dominated jets more collimated than gluon-dominated jets measured by ATLAS
  - I.e. more charged hadrons at small radii, fewer at large radii
  - Qualitatively agrees with conventional expectations, but this shows clear and quantitative evidence from data

# *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

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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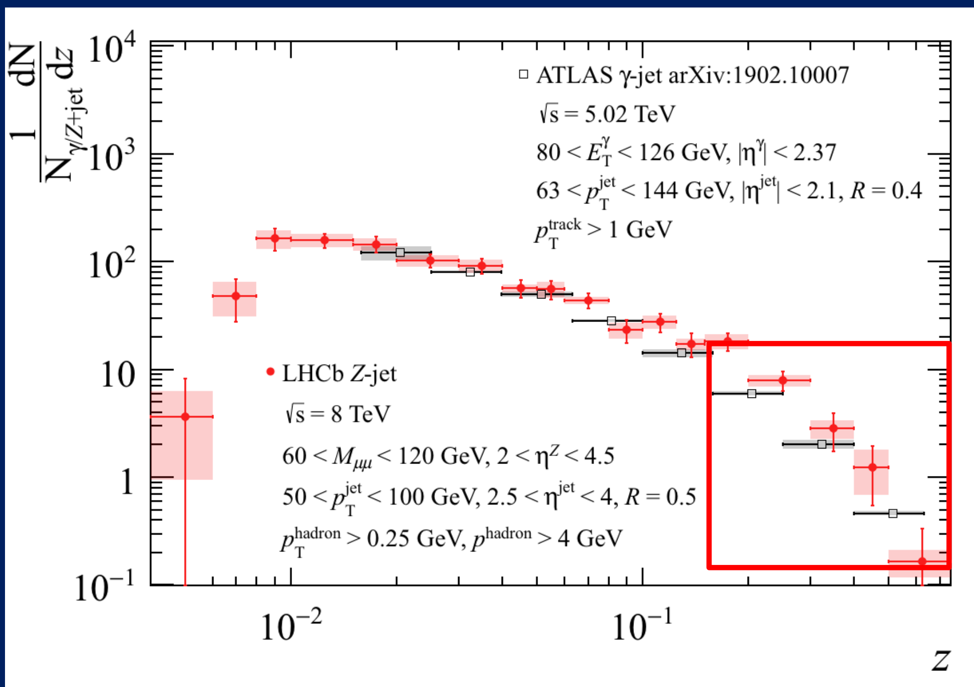


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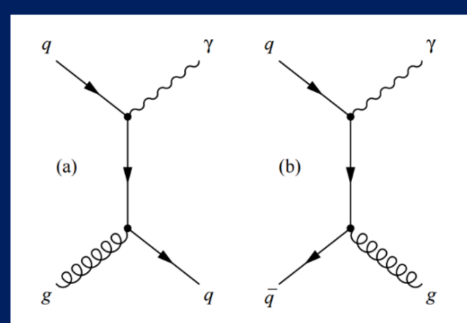
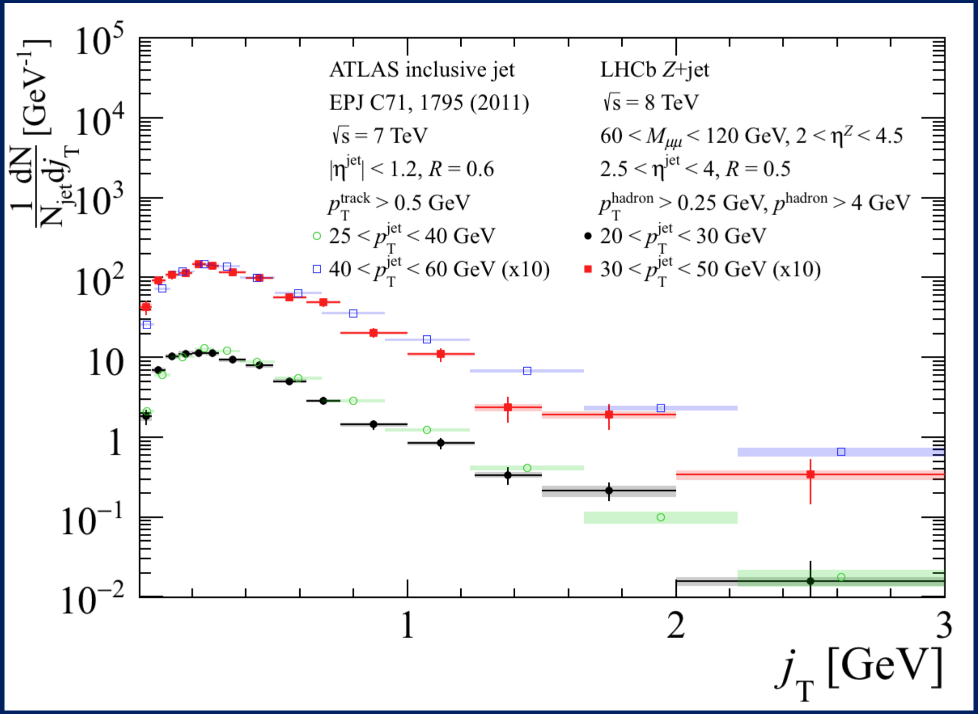



- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal momentum distributions are more similar
  - γ+jet, like Z+jet, enhances quark jet fraction
  - Further evidence that differences observed between LHCb results and ATLAS gluon-dominated results are due to differences in quark and gluon hadronization

# *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 $j_T$

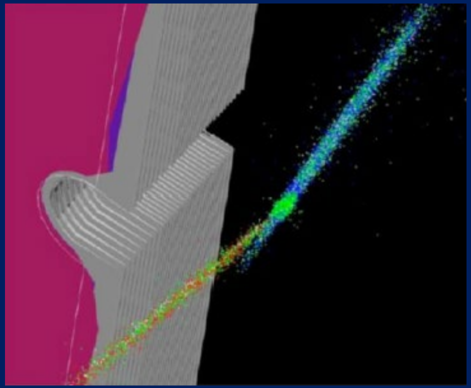


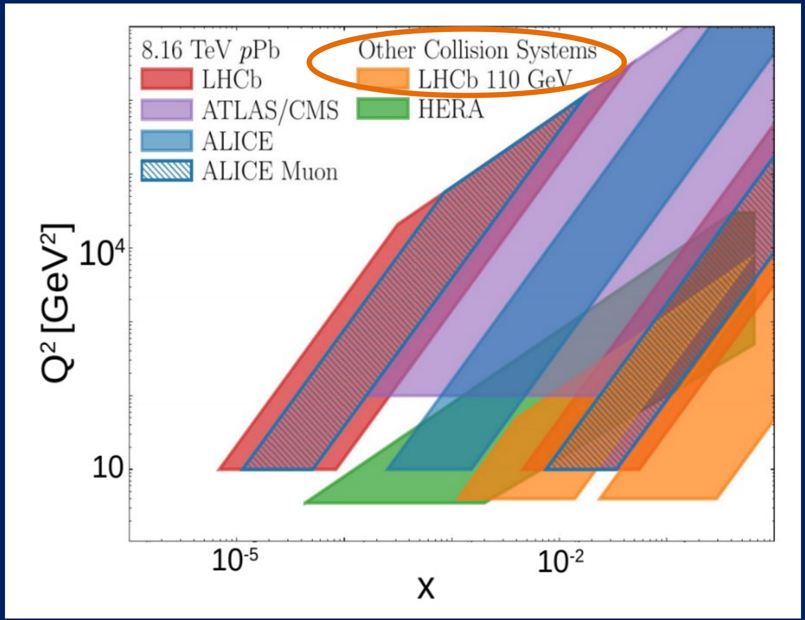

PRL 123, 232001 (2019)

# LHCb fixed-target capabilities

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

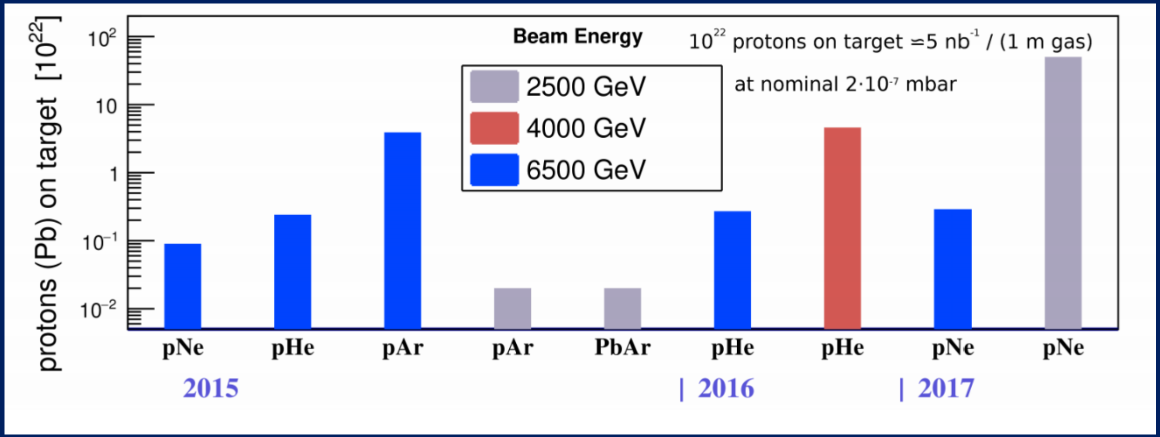
- System for Measuring Overlap with Gas (SMOG) allowed injection of small amounts of noble gas into LHC beam pipe around LHCb collision region. Luminosity up to $10^{30}$ cm$^{-2}$ s$^{-1}$



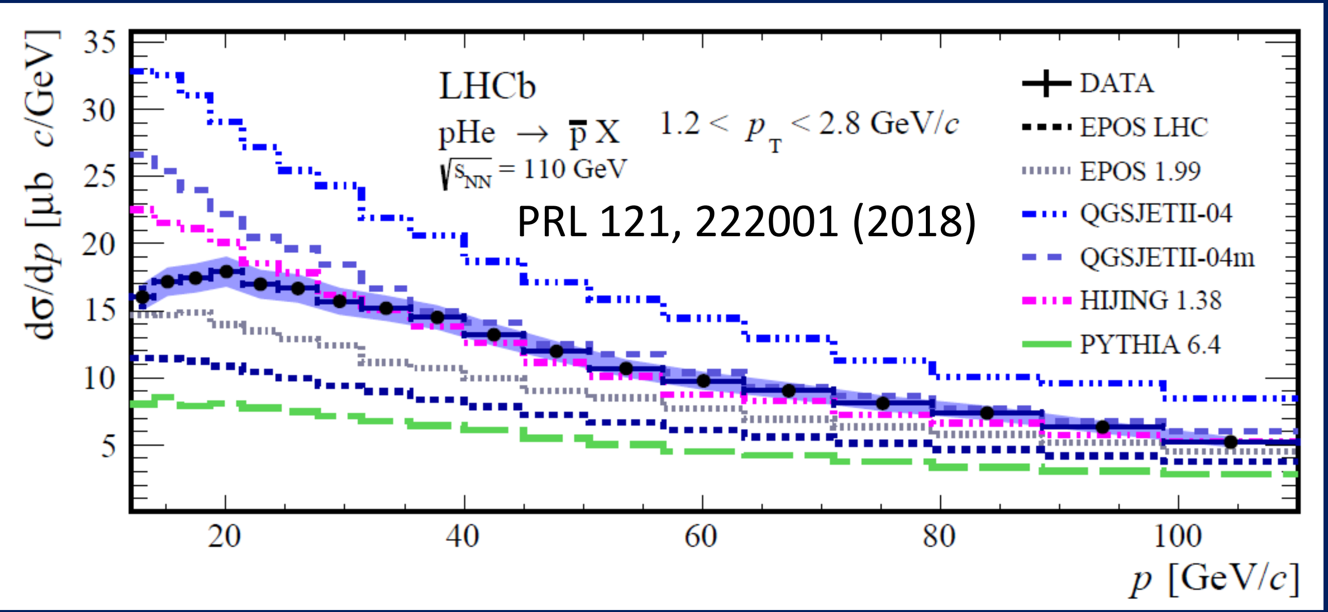



- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{beam}M_p}$ 41-110 GeV for $E_{beam}$= 0.9-6.5 TeV
  - Between SPS and top RHIC energies
- Overlap with EIC energies

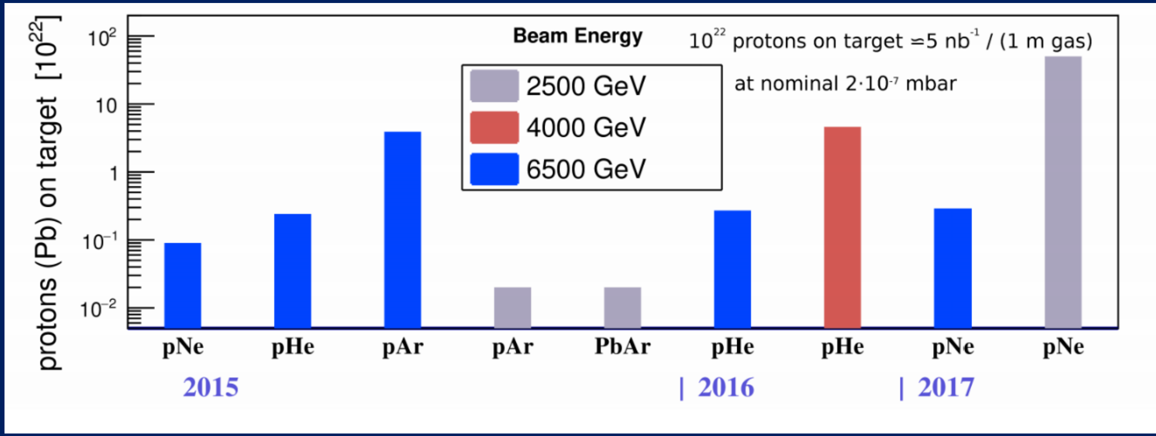
# LHCb fixed-target capabilities




Forward antiproton production in pHe

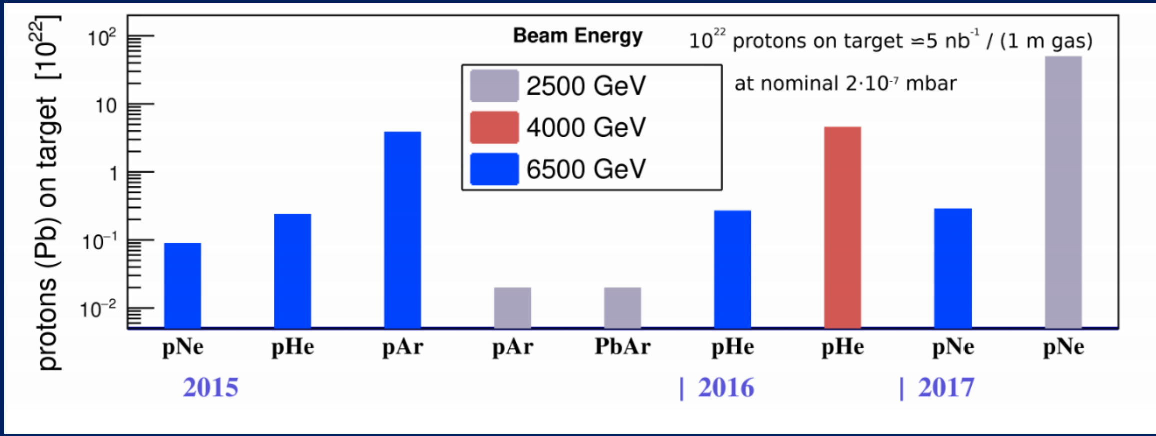


# LHCb fixed-target capabilities




- Target storage cell to be installed Mar 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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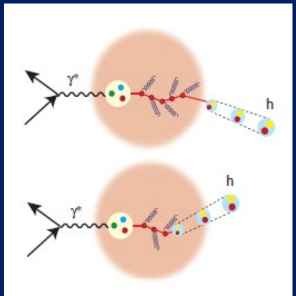
- LHCSpin: Proposal for transversely polarized gas jet target at LHCb currently in R&D and technical evaluation

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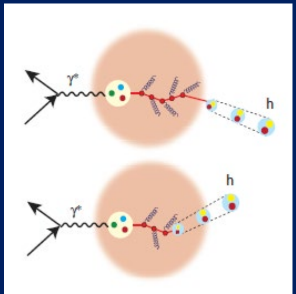


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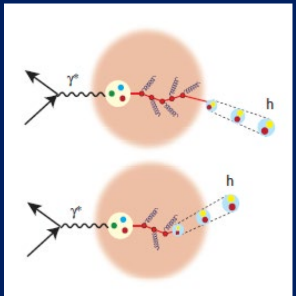


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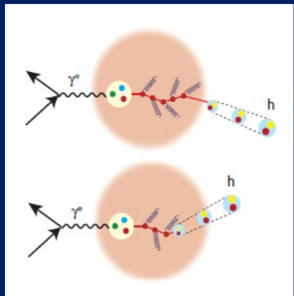


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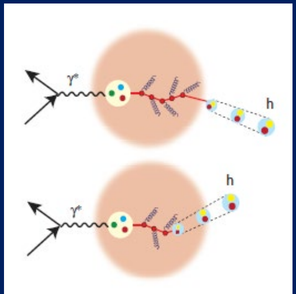


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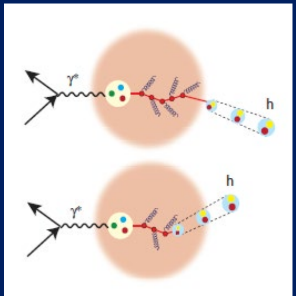


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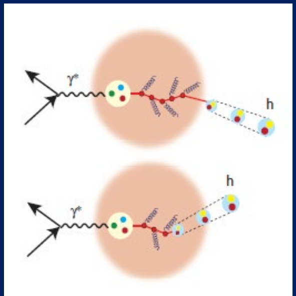


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- Jets
- Integrated luminosities allowing multidifferential measurements
- …

# *Final remarks*

- Efforts on hadronization starting to ramp up!
- Hadronization is closely tied to confinement and to hadron mass generation

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- Moving toward more multiparticle correlation measurements will deepen our understanding of the inherently dynamical process of color neutralization

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*We should keep performing complementary measurements at Belle, Belle II, JLab, COMPASS, AMBER, RHIC, and the LHC throughout the 2020s to ensure that we are positioned to take full advantage of the EIC's potential for hadronization!*

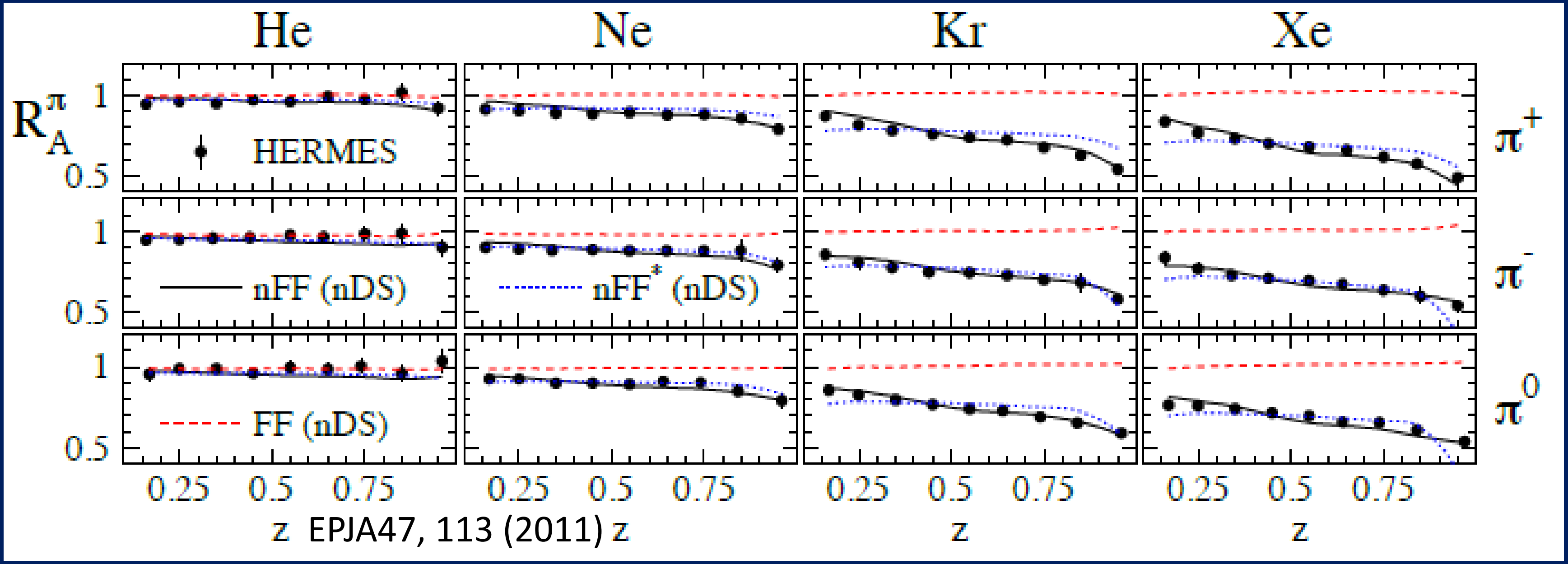
*Back-and-forth between experimentalists and theorists will be crucial to advance.*

# *Extra*

# *Hadronization in higher-density partonic environments*

- No longer (only) “vacuum” fragmentation

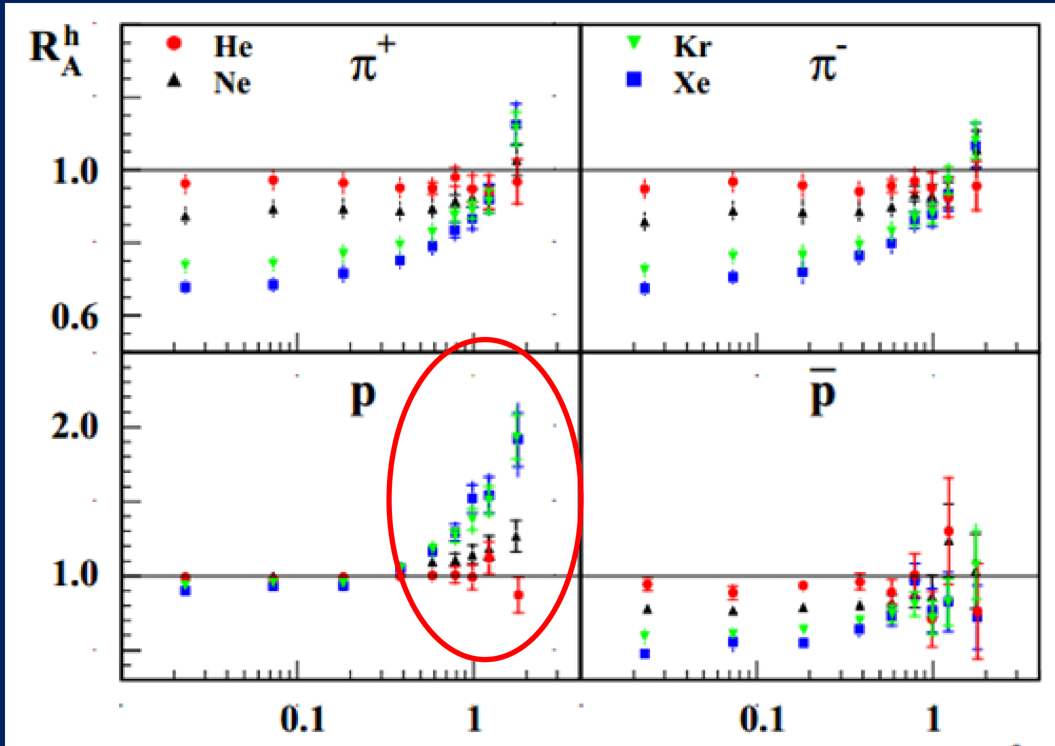
- Nuclear modification of FFs observed in e+A collisions, e.g. pion suppression




EPJA47, 113 (2011)

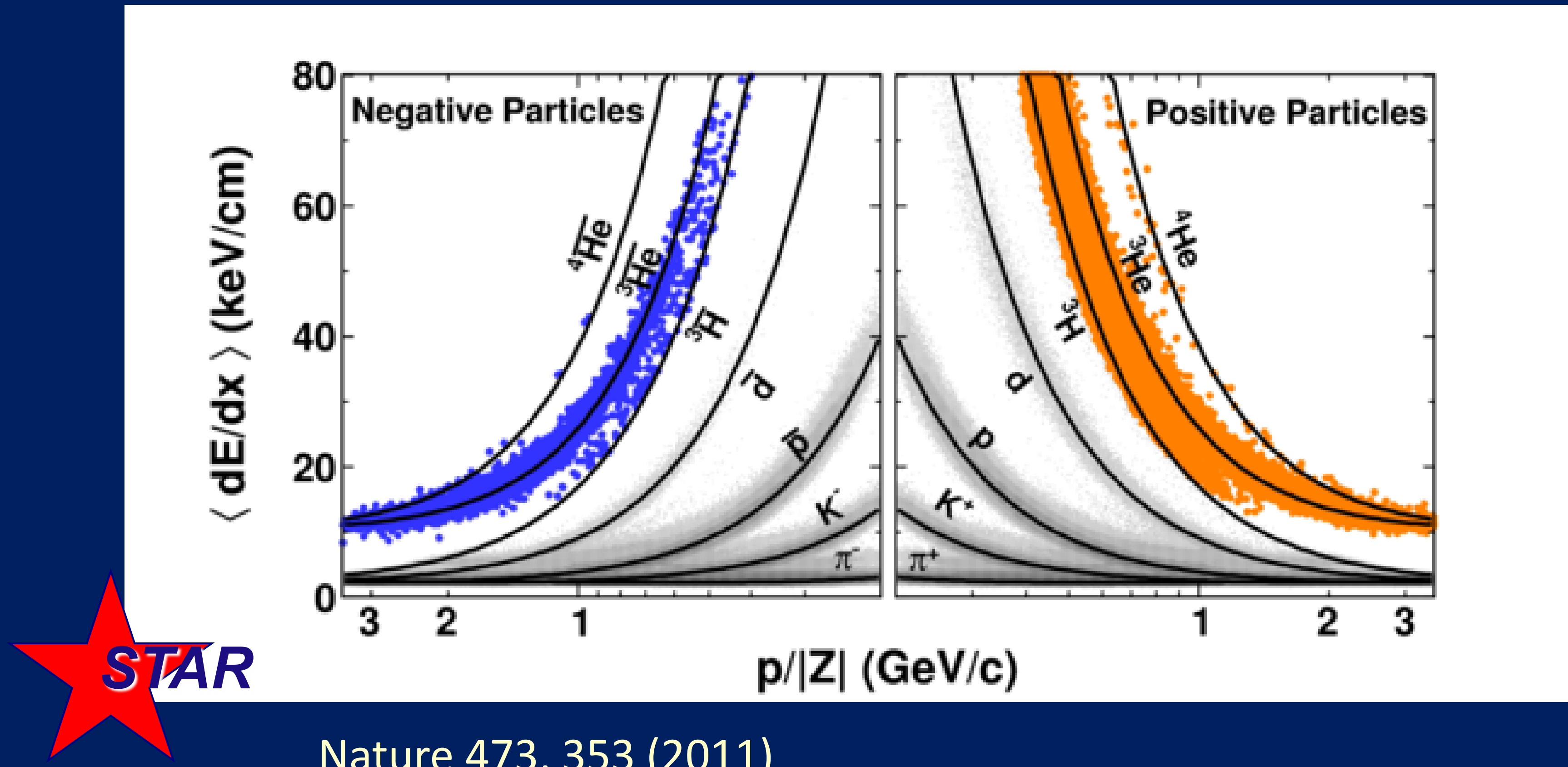
# *Hadronization in higher-density partonic environments*

- 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??

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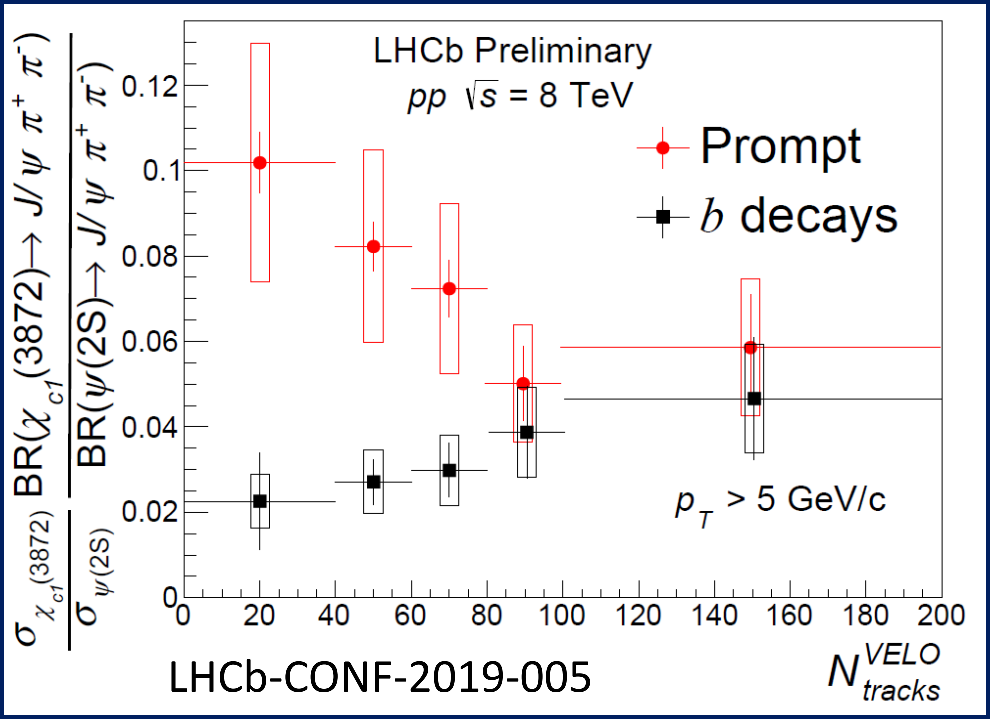
- Do we understand enough by now about QCD bound states—and nucleons specifically—to start to think more about going from first principles to the “van der Waals” forces that bind color-neutral nucleons into nuclei??

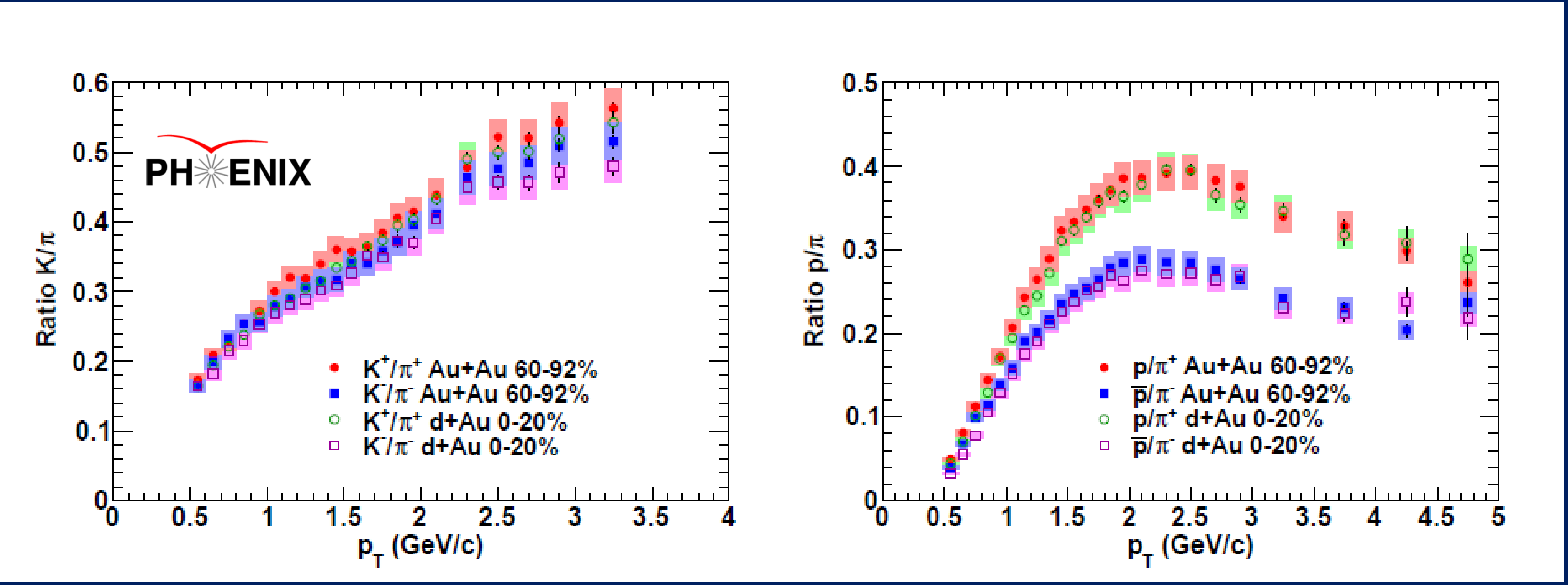
- Can we possibly learn anything from tetraquarks about bound states of hadrons??




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

# Comparing central d+Au with peripheral Au+Au

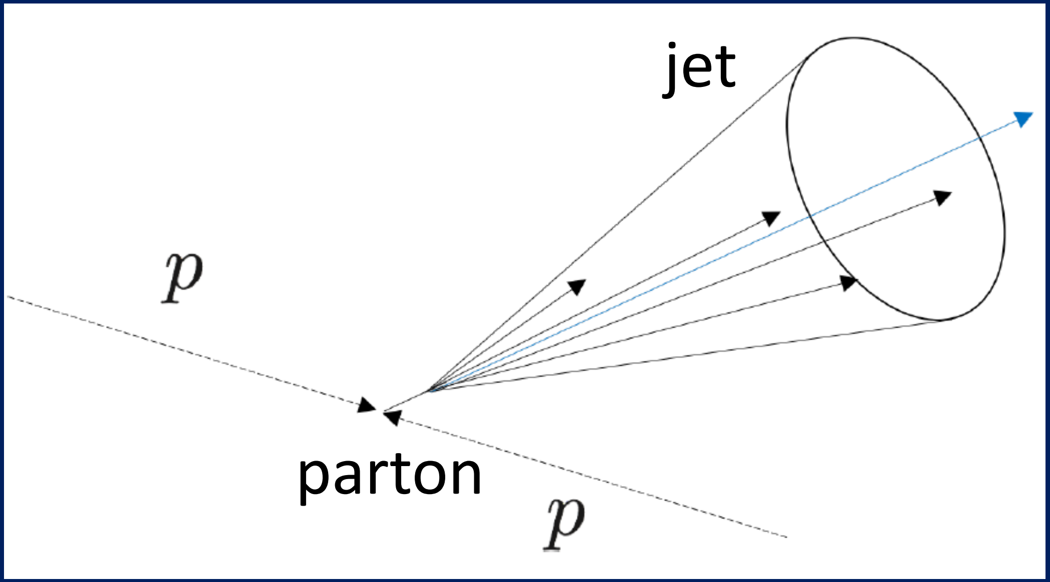
PRC88, 024906 (2013)




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

Both shape and magnitude identical!

# *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

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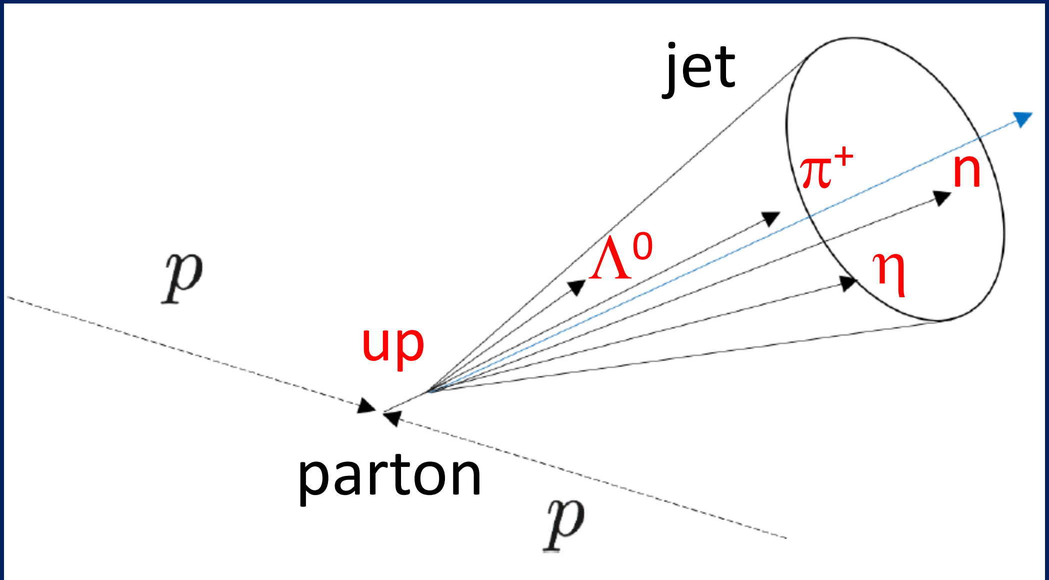


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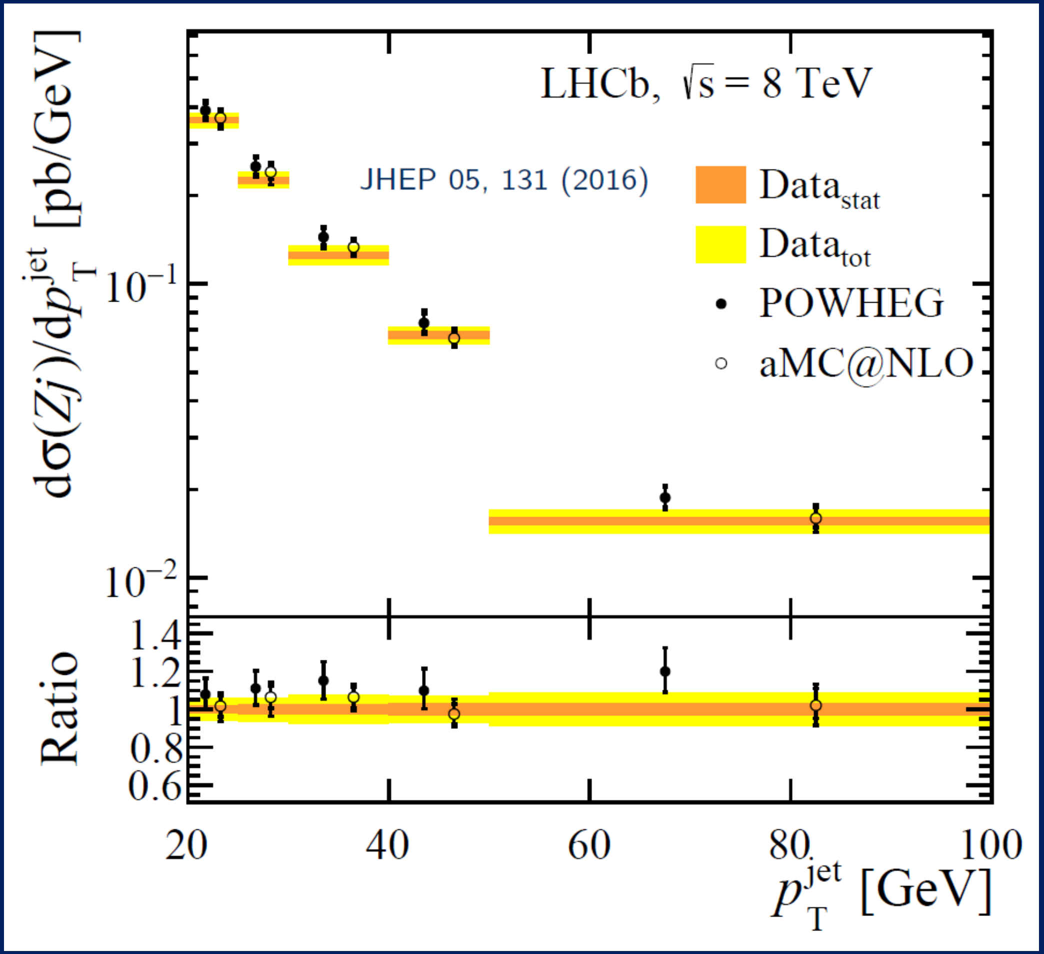
- Baryon vs. meson
- Correlations (e.g. strangeness, heavy flavor)
- Resonance production ($\phi$, $J/\psi$, $\Upsilon$)
- Increase projectile/target size (hadronization in medium)
- …

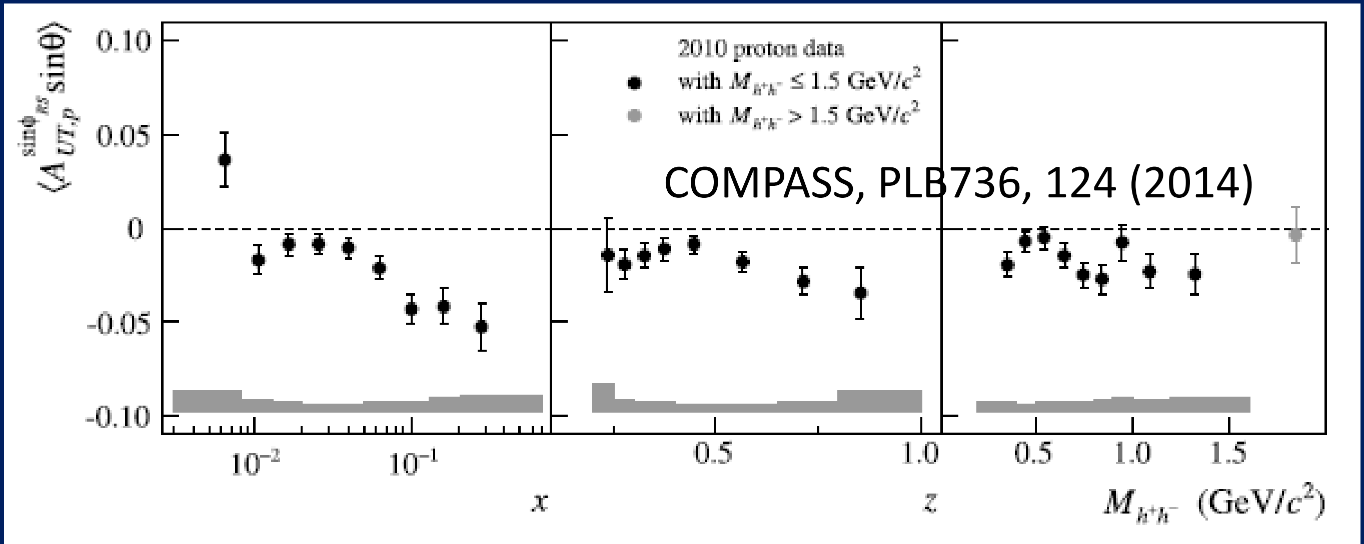
Courtesy Joe Osborn

# *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*

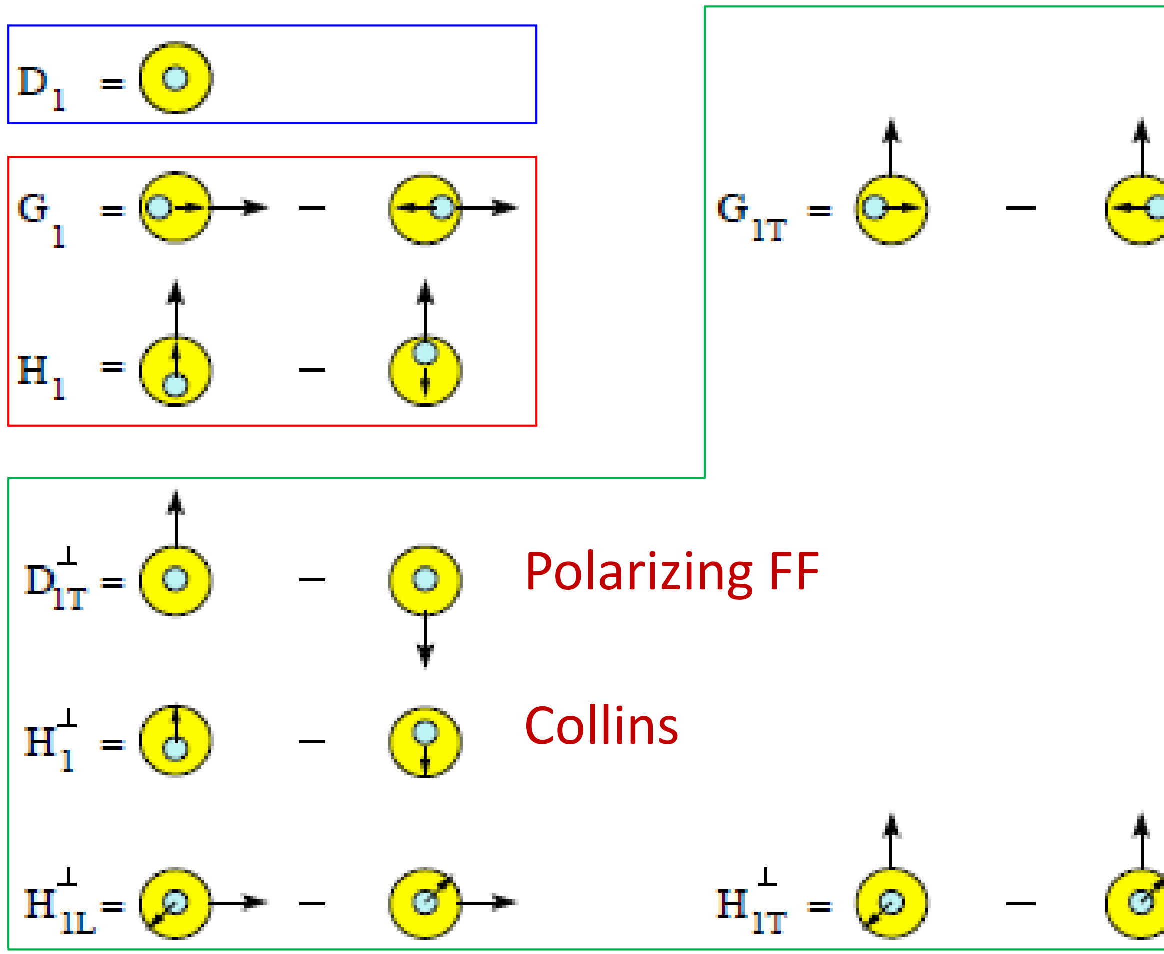
- Interference between a (quark+gluon) hadronizing and only a quark
- Similarly, interference between (gluon+gluon) and only a single gluon
- Can generate transverse single-spin asymmetries
- Increasing phenomenology efforts in recent years . . .

# *Twist-2 fragmentation functions*

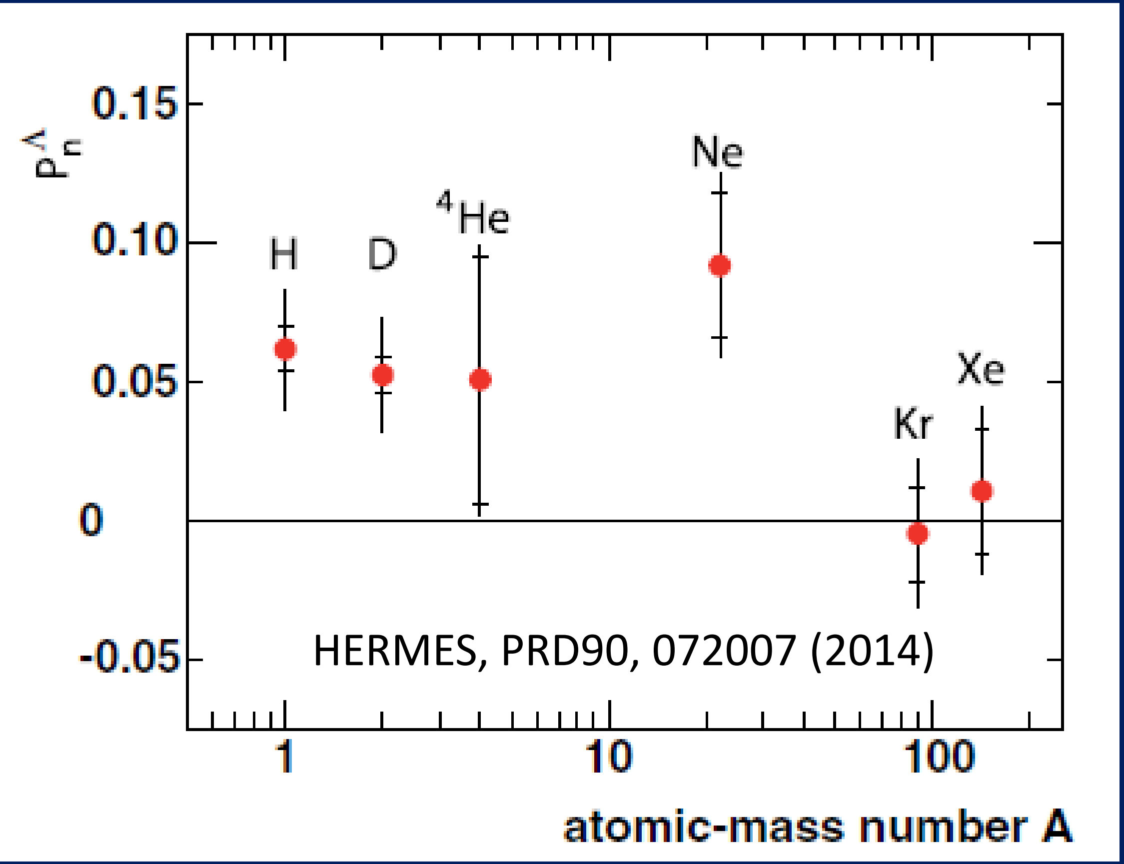
Unpolarized

Spin-spin correlations

Spin-momentum correlations

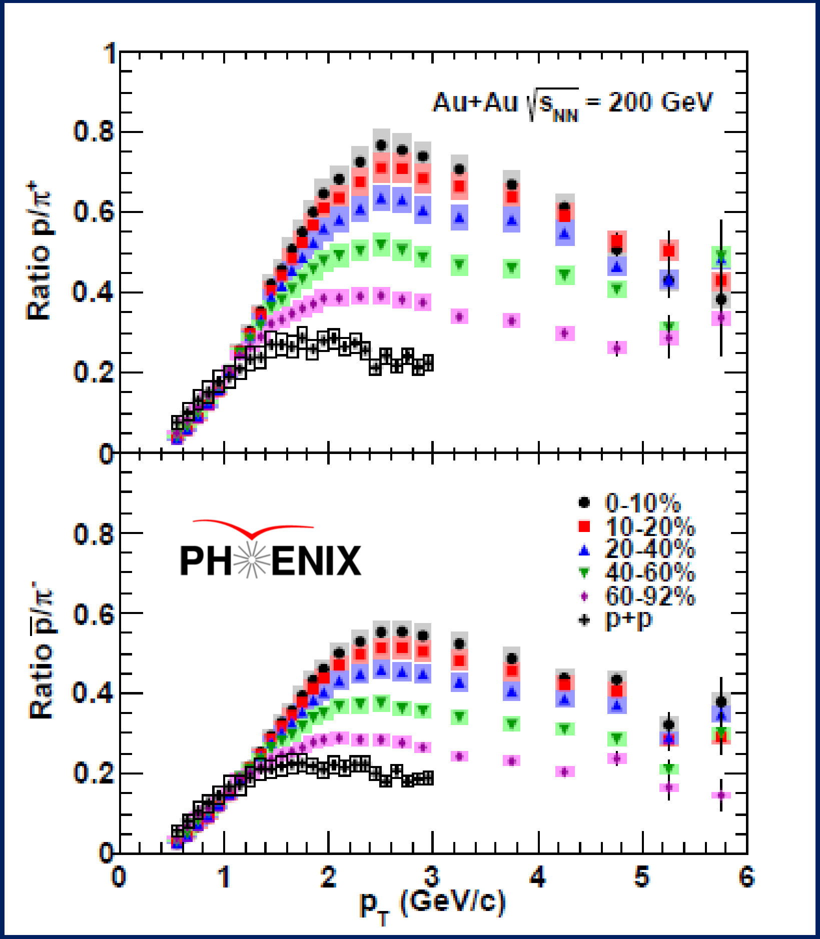


# *Lambda polarization observed in semi-inclusive DIS*




- Nonzero in both forward and backward directions

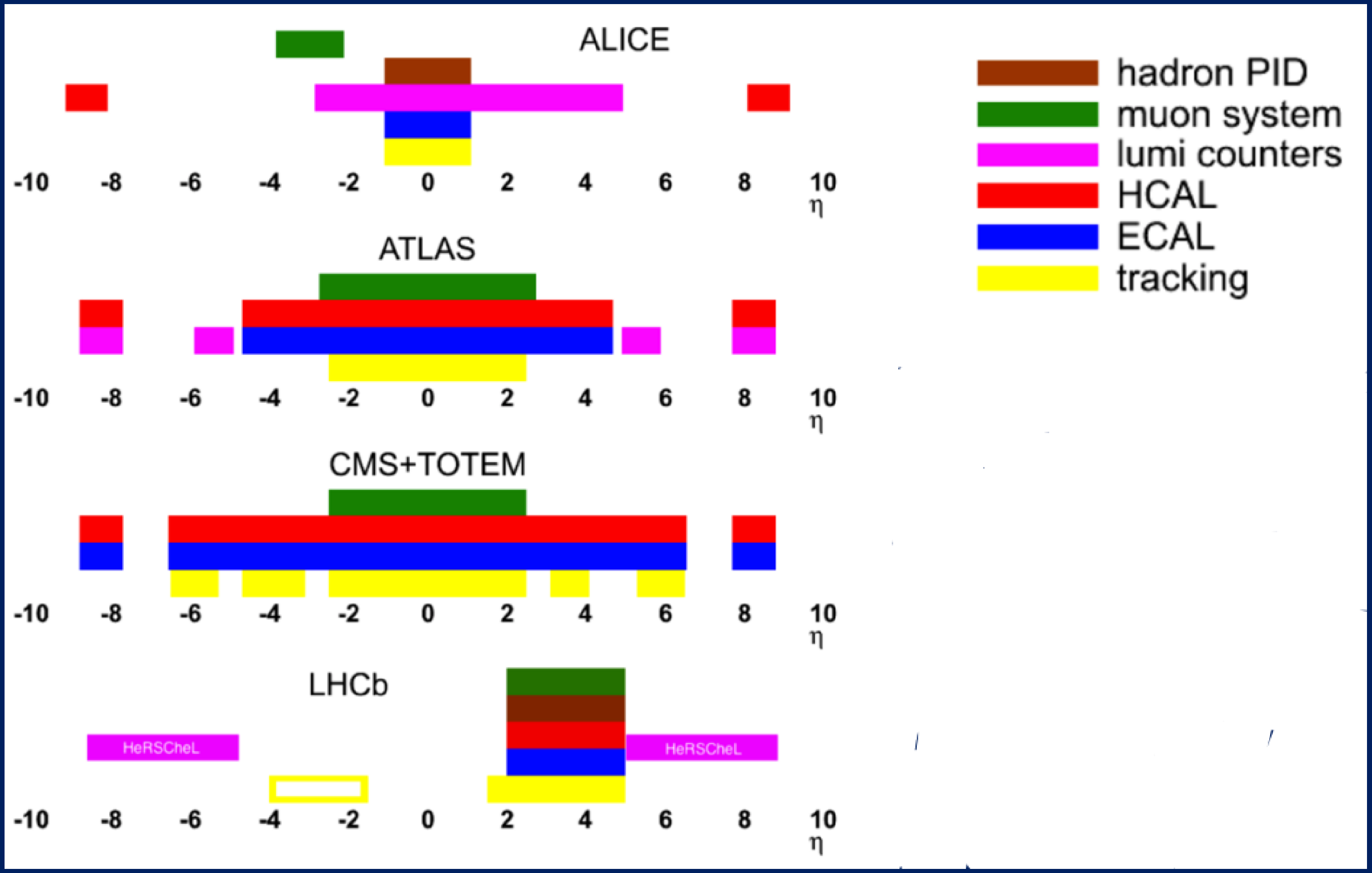
# *Centrality-dependent baryon enhancement in d+Au compared to p+p*




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*

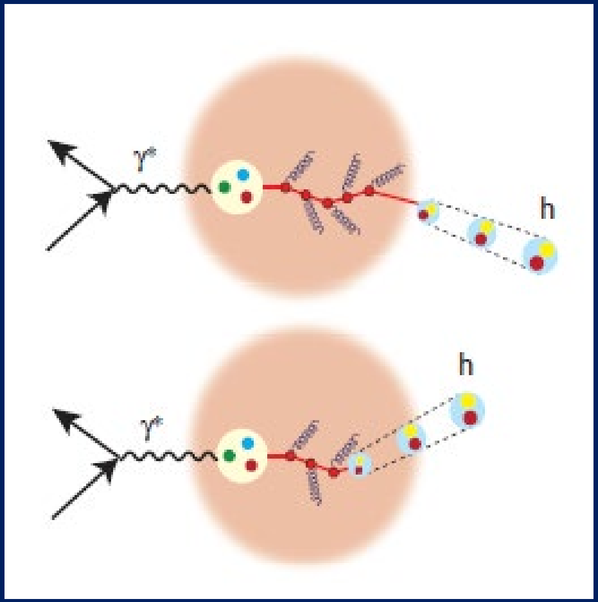


# *Actually, what's going on with baryons in general?*

- 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



# *Hadronization: An open playing field in QCD*

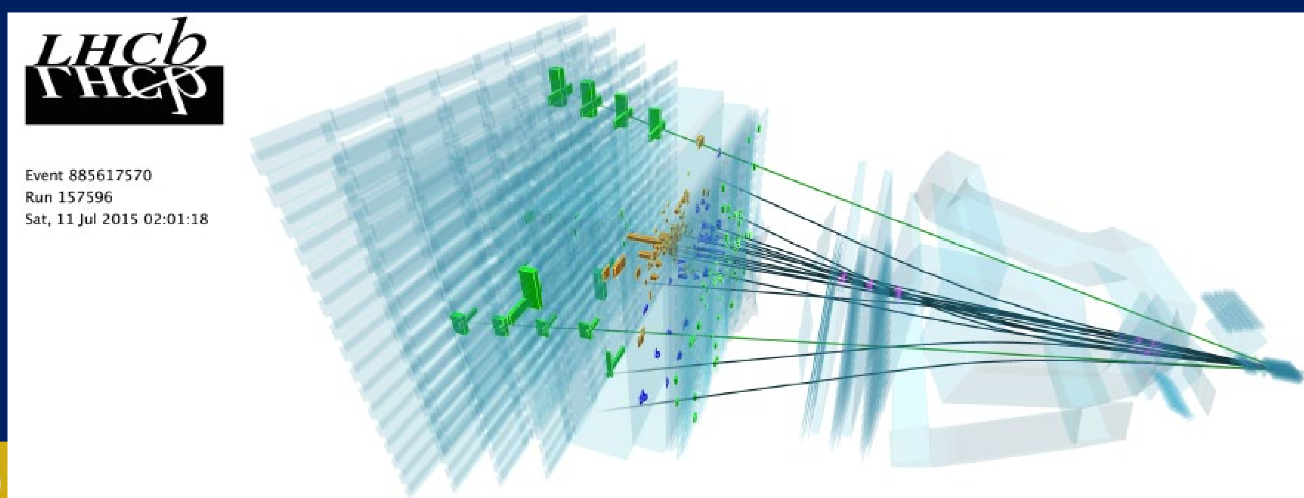
- The EIC will be well timed and well suited to make tremendous progress in our understanding of hadronization
  - Discussed less for the EIC than partonic structure of nucleons and nuclei because we still think much less about hadronization as a community…
  - Hadronization: "The Electron-Ion Collider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

PRL 123, 232001 (2019)

# *Analysis details*

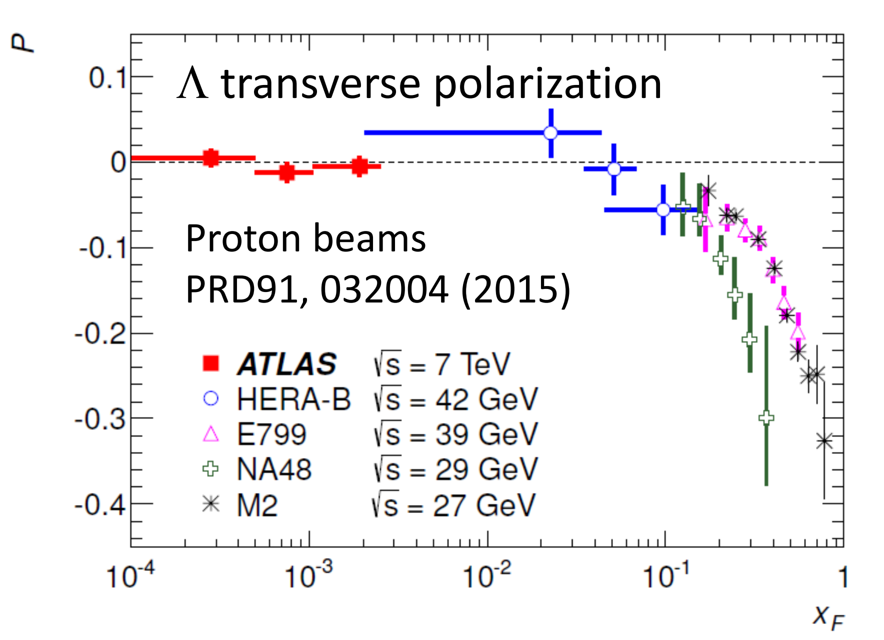
- Follow similar analysis strategy to ATLAS and previous LHCb papers
  - ATLAS: EPJC 71, 1795 (2011), NPA 978, 65 (2018)
  - LHCb: PRL 118, 192001 (2017)

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



# 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
- Forward lambda and other hyperon polarization measurements



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At a single experiment or for comparison across multiple experiments.

- Particular observables as a function of jet constituent multiplicity, *R*, rapidity, $p_T$, mass, …?

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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*