QCD and Baryon Polarization

Lecture 3:
Hadronization

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Outline of lectures

1. Introduction; collinear and TMD nucleon structure
2. Spin-momentum correlations in the nucleon in terms of TMD PDFs and collinear twist-3 multiparton correlations
3. *Hadronization: collinear and TMD fragmentation functions, collinear twist-3 correlations; dihadron FFs; different hadronization mechanisms/pictures*
4. Hadron structure and hadronization: Sea quarks/non-valence quarks
5. Hyperon and heavy flavor baryon polarization I
6. Hyperon and heavy flavor baryon polarization II

Confinement

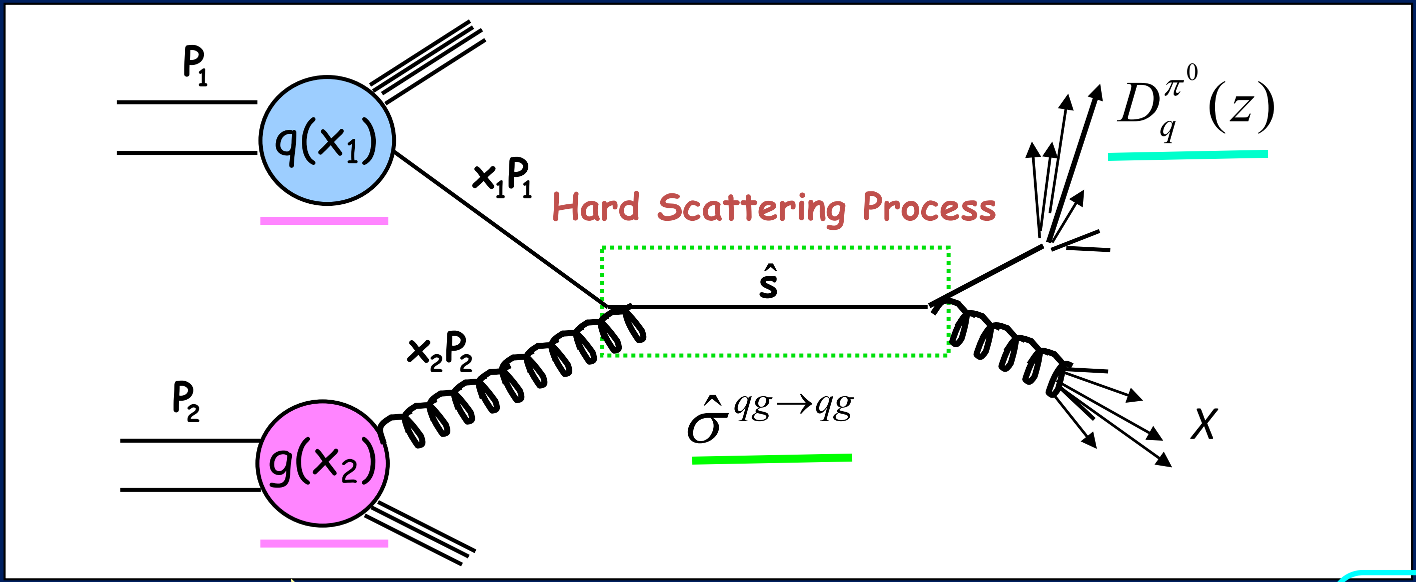
- How do we relate the quark and gluon d.o.f. of QCD to the hadronic d.o.f. we observe in nature?
- Flip sides of the "confinement coin":
  - Hadron *structure*
  - Hadron *formation*
- <u>Much</u> greater effort has been dedicated to studying hadron structure than hadron formation over the past half century
  - Proton structure in particular

Recall: Factorization and universality in perturbative QCD

- Systematically *factorize* short- and long-distance physics
  - Observable physical QCD processes always involve at least one "long-distance" scale of $\sim 10^{-15}$ m describing bound-state structure (confinement)!
- Long-distance (i.e. not perturbatively calculable) functions describing structure need to be *universal*
  - Physically meaningful descriptions
  - Portable across calculations for many processes

Constrain functions describing ~~proton structure~~ hadron formation by measuring scattering cross sections in many colliding systems over wide kinematic range and performing *simultaneous fits to world data*

Factorized pQCD calculations of observables



$$\sigma\left(pp \to \pi^0 X\right) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg\to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

High-energy processes have predictable rates given:

- Partonic hard scattering rates (calculable in pQCD)
- Parton distribution functions (experiment)
- Fragmentation functions (experiment)

} Universal non-perturbative factors

Fragmentation functions

- Can think of intuitively as probability that a particular high-energy outgoing parton will produce a particular species of hadron
- Traditionally parametrized as a function of the momentum fraction (z) of the parton carried by the produced hadron
- $e^+e^- \rightarrow q\bar{q}$ provides “clean” information on single-parton hadronization
  - BUT – no way to flavor-separate light quarks, antiquarks, and can’t constrain gluon hadronization

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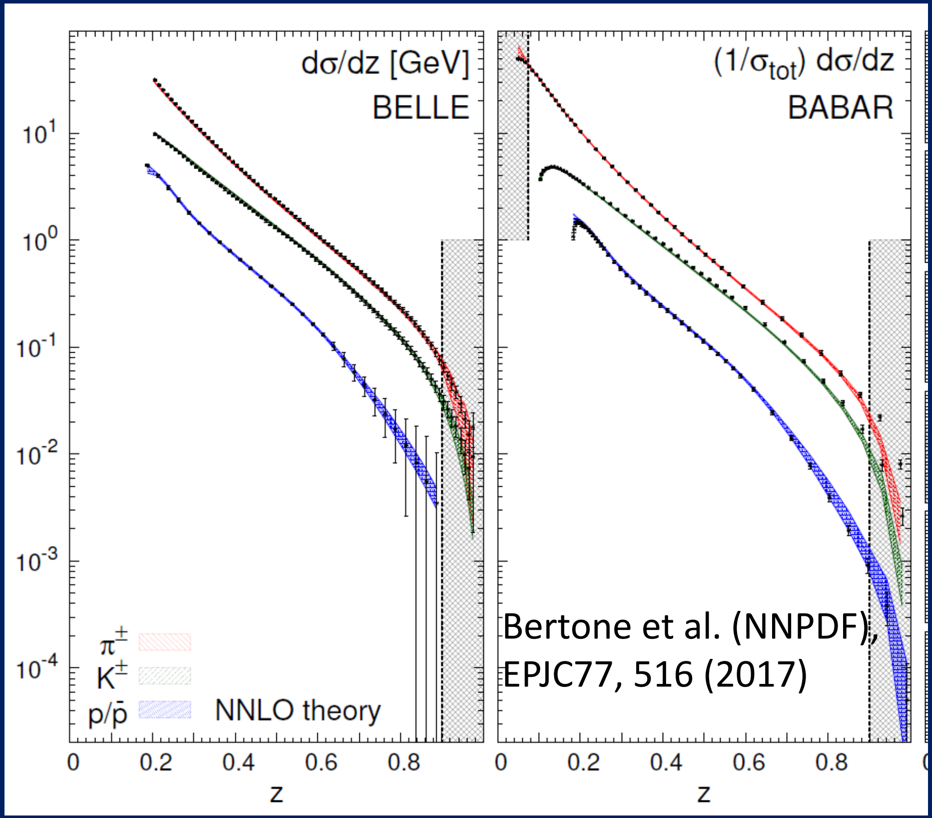
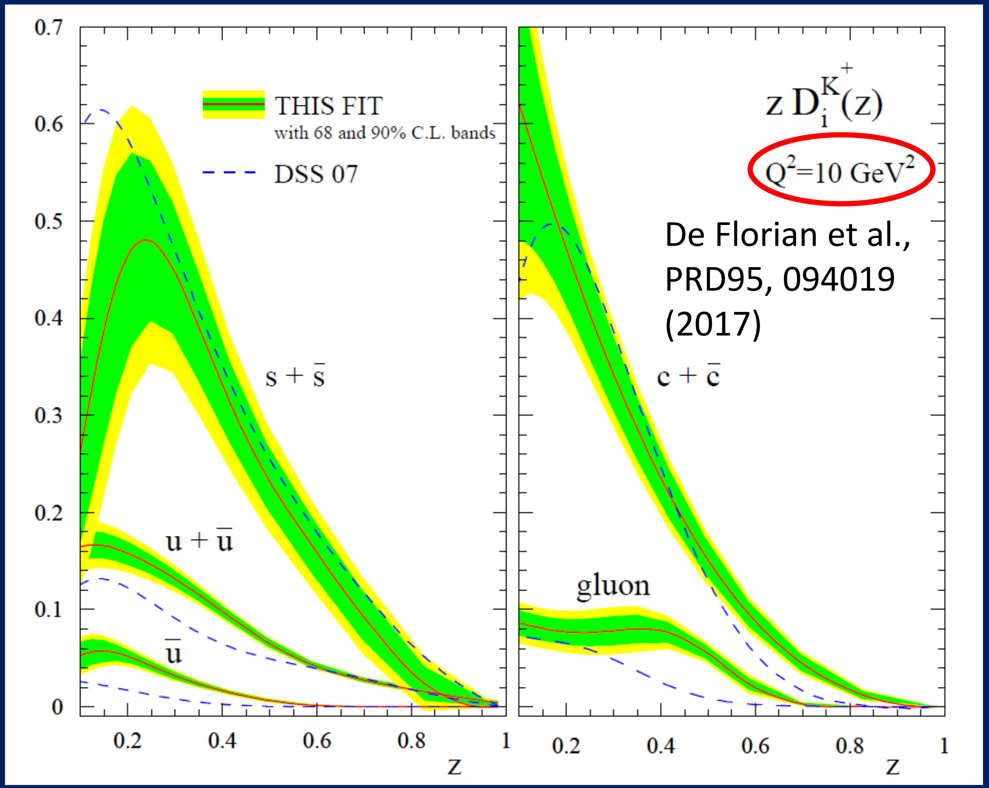


NNLO fit of world e+e- data for identified pion, kaon, and proton production (9 experiments included)

Flavor separation + gluons from hadronic data

- NLO fit to kaon production in e+e-, semi-inclusive DIS, and p+p
  - Get flavor separation and constraints on gluon fragmentation
  - Shown for $K^+ = u\bar{s}$. Note that a single parametrization is assumed for all "disfavored" fragmentation, since the data can't discriminate further ($\bar{u} = d = \bar{d} = s$)



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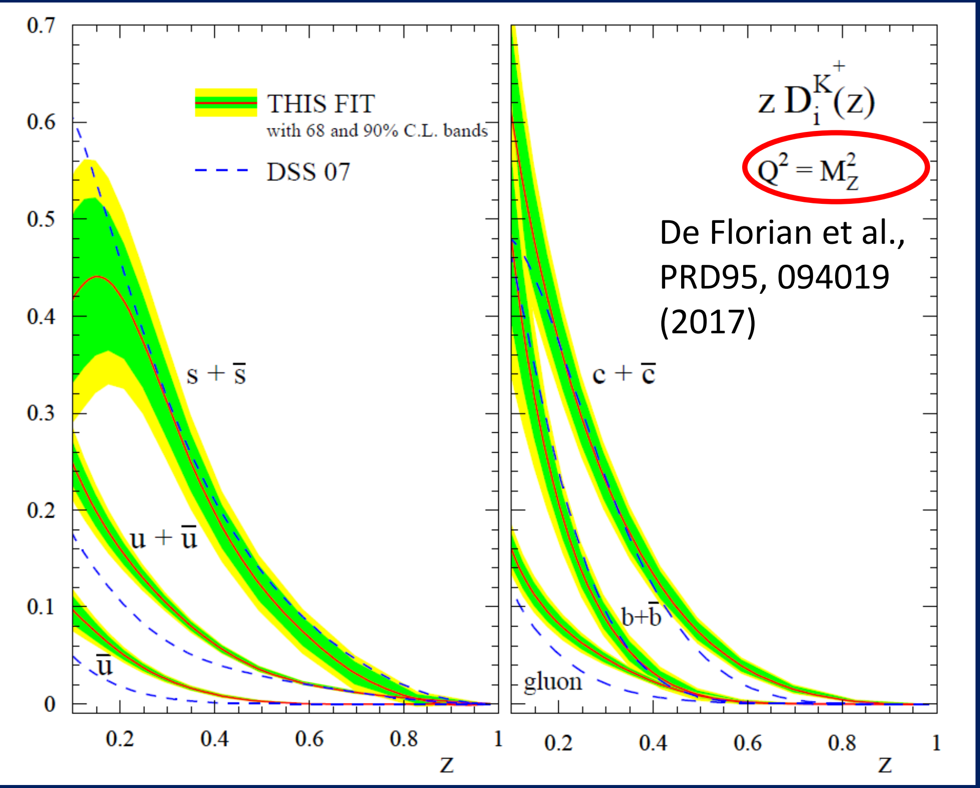
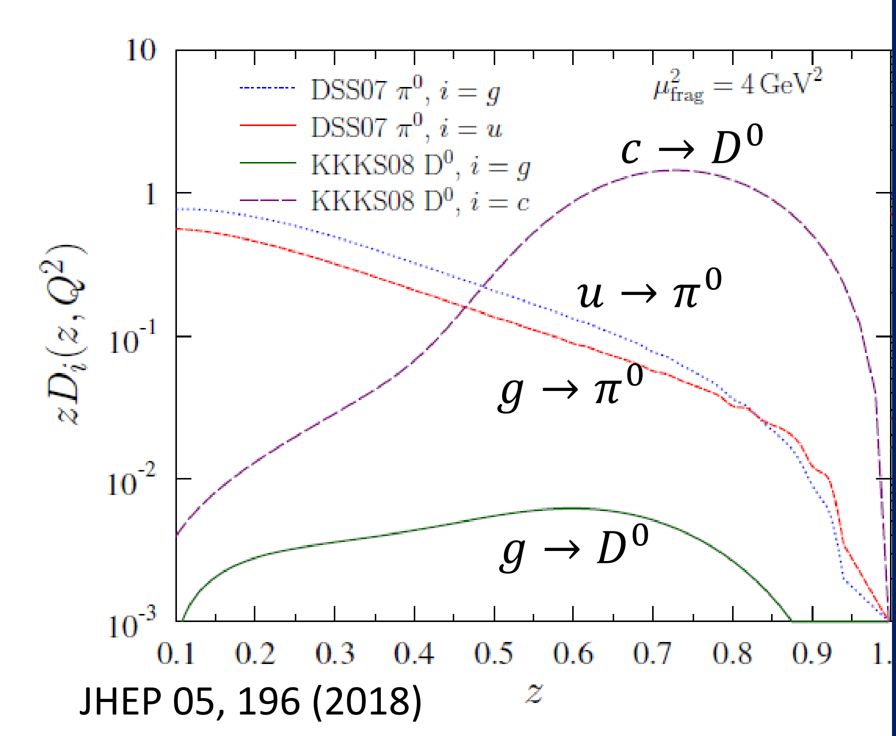


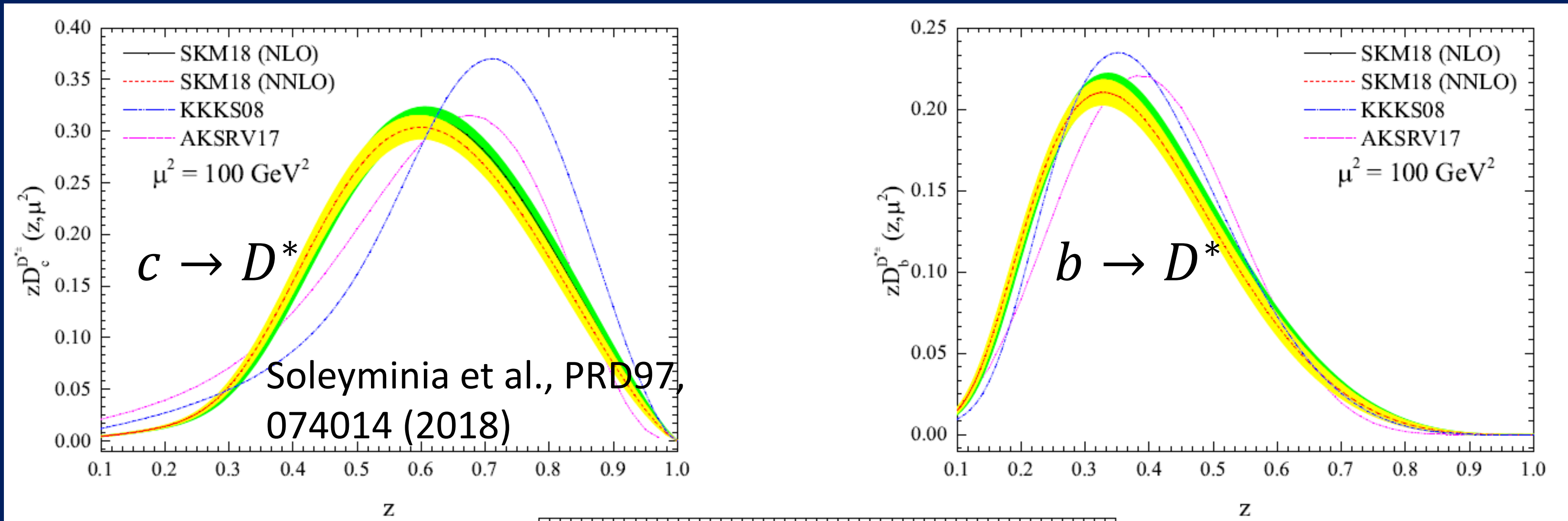
FFs depend on hard interaction scale (Q), similarly to PDFs

Heavy flavor hadron FFs

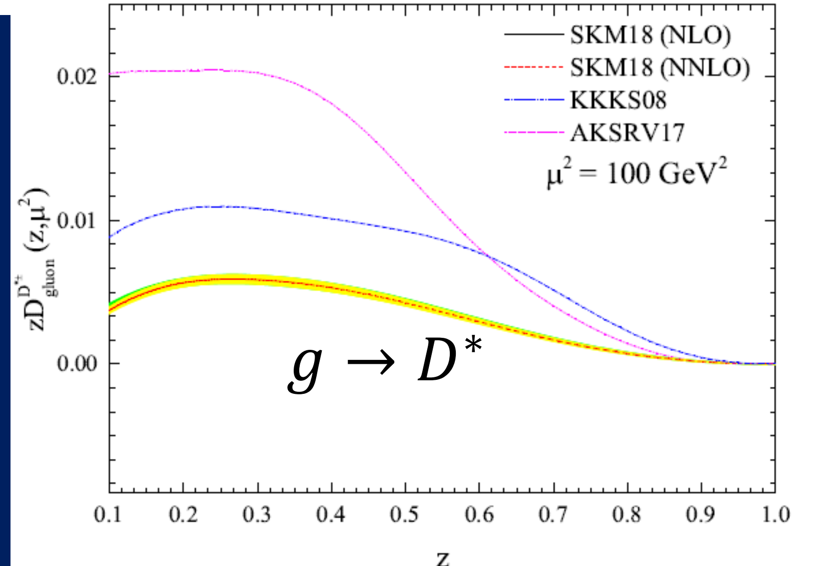
- Theory considerations typically different due to mass of c or b quark being larger than Λ_{QCD}
- Much less data available than e.g. π, K, p
- Heavy quark FF to heavy flavor hadron peaked at higher momentum fraction *z* than for light flavor hadrons



D fragmentation functions*



Sharply peaked contributions from b and c quarks, but b contributions shifted to lower momentum fractions



Significant disagreement among parametrizations for $g \to D^*$

Recall: Transverse single-spin asymmetries

- General form for transverse single-spin asymmetries: $S \cdot (p_1 \times p_2)$
  - Collinear momenta would produce no effect
  - Thus importance of transverse momentum dependence
- Spin could be of initial proton, struck quark, fragmenting quark, produced hadron
- Possible momentum vectors include initial proton momentum, final-state particle or jet momentum, k_T of parton within proton, j_T of final-state particle with respect to jet axis
- Lots of combinations possible!

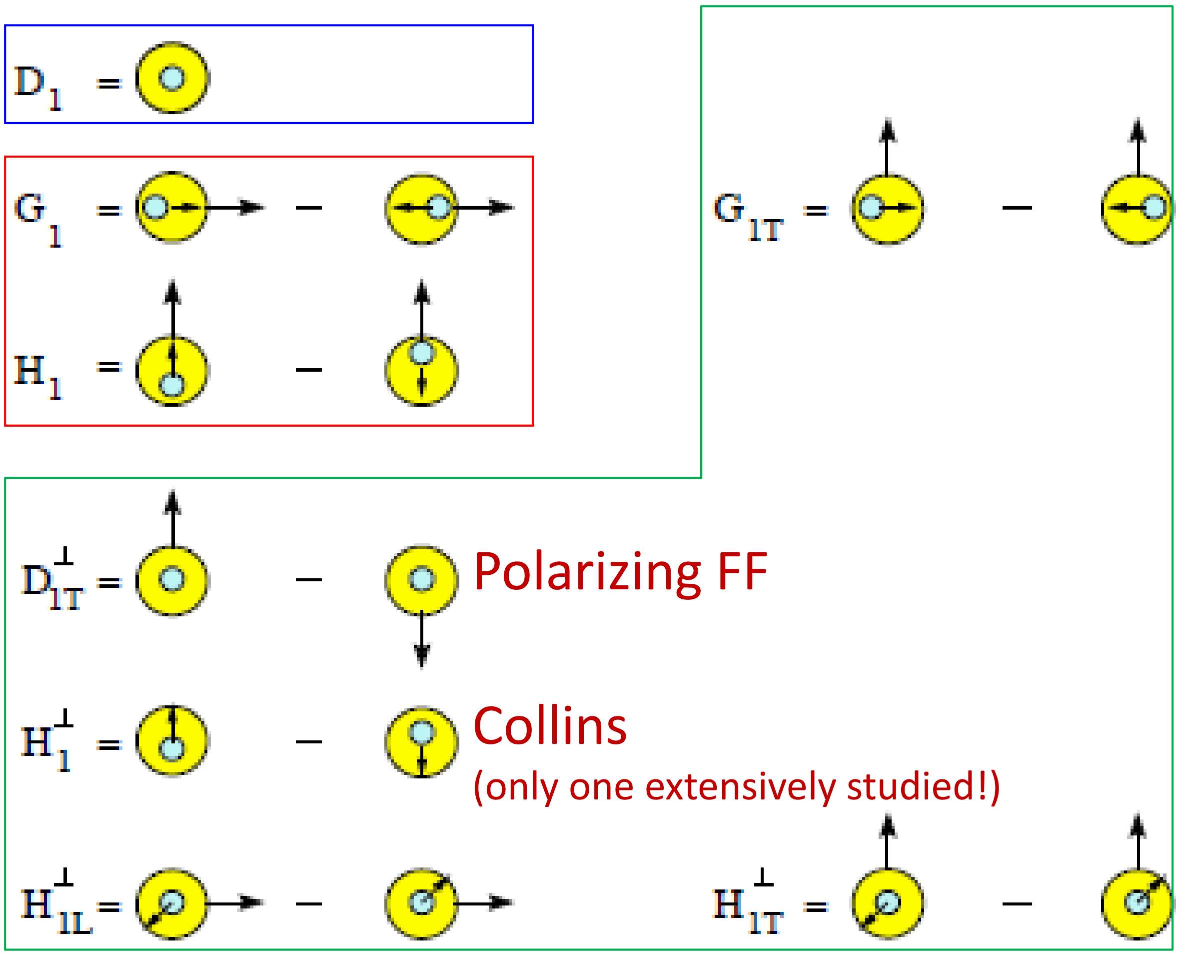
Spin-spin and spin-momentum correlations in hadronization

Unpolarized

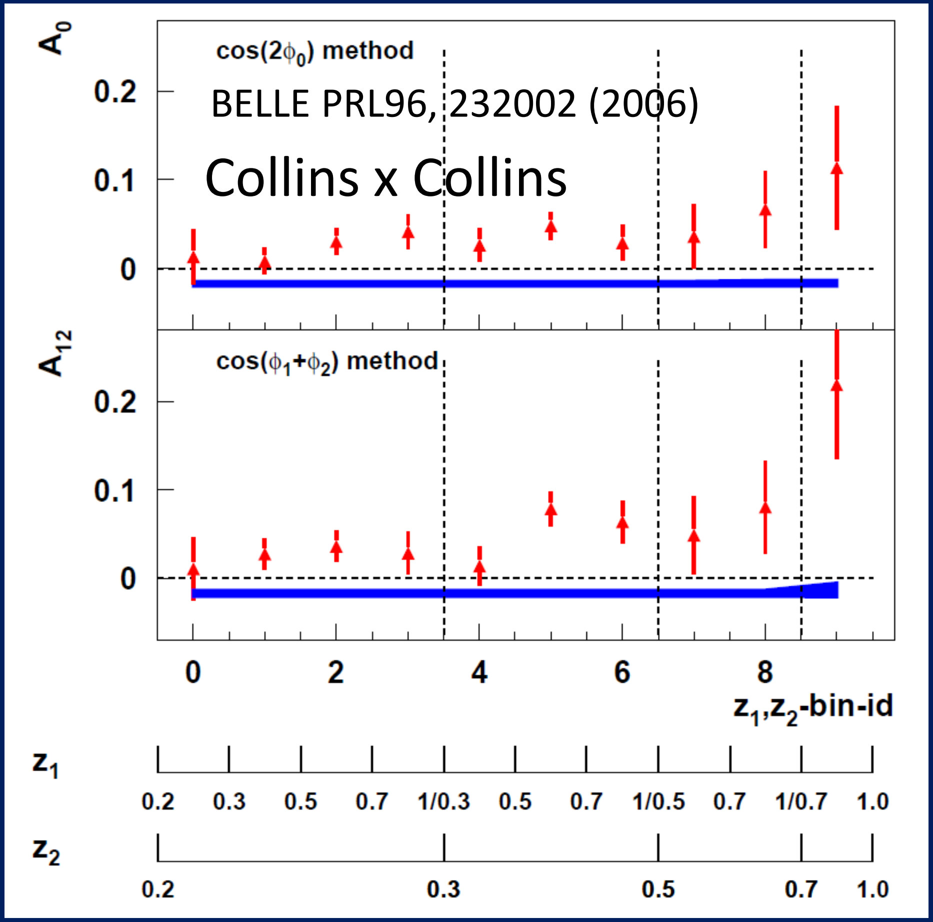
Spin-spin correlations

Spin-momentum correlations

Transverse-momentum-dependent FFs

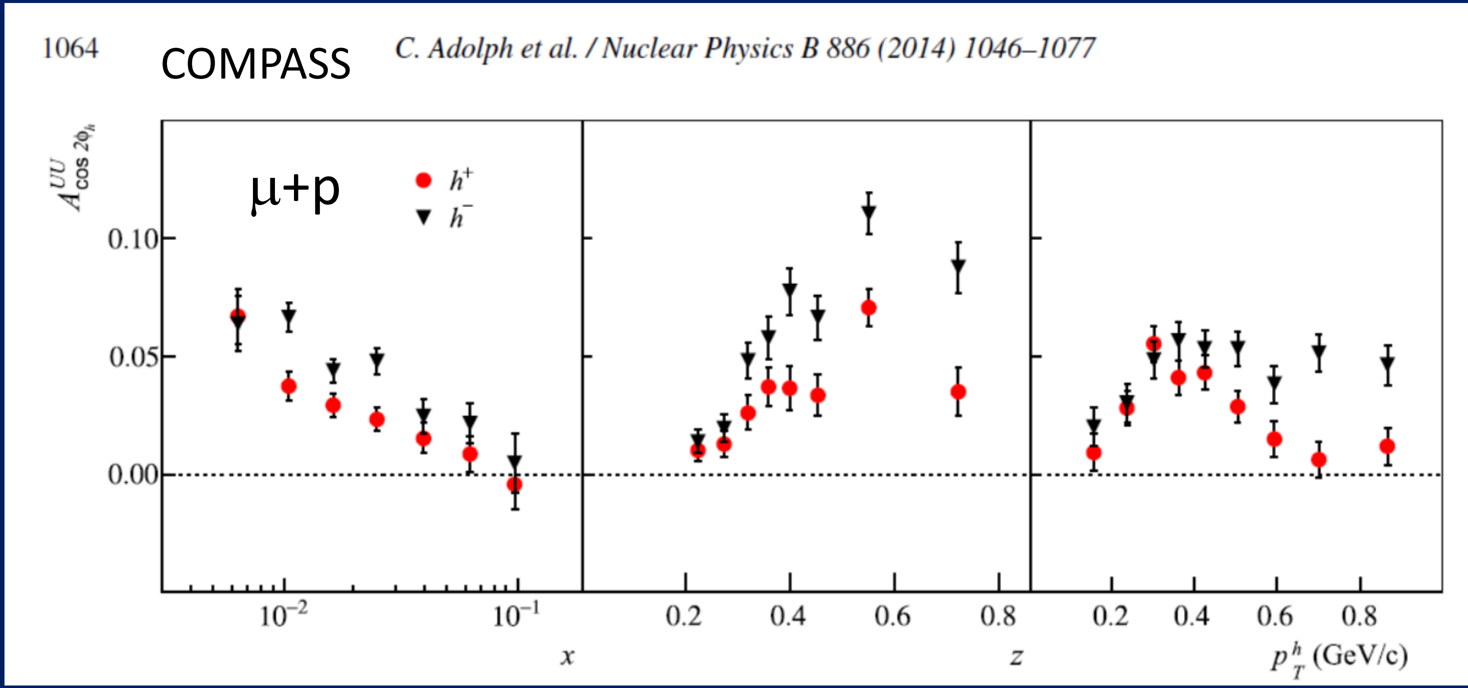


Spin-momentum correlations in hadronization: Collins TMD FF



- Correlation between transverse spin of outgoing (anti-)quark and angular distribution of produced hadrons
- 5-10% effect measured by Belle and BaBar
  - Spin of produced q and $\bar{q}$ correlated. Measure *relative* angular distributions of pions in one hemisphere with respect to other
- Collins TMD FF x Collins TMD FF
  - Chiral-odd, so need convolution of two chiral-odd functions

Recall: Boer-Mulders TMD PDF ×Collins TMD FF asymmetry from semi-inclusive DIS



- Boer-Mulders TMD PDF – correlation between quark transverse spin and its own transverse momentum. Chiral-odd. Zero if orbital angular momentum zero.
- Chiral-odd → need another chiral-odd function to measure it. Here the Collins TMD FF
- Clearly nonzero for positive and negative hadrons
- Also measured by HERMES – PRD87, 012010 (2013) (see backup)

Higher-twist multiparton correlations in hadronization

- Extend our ideas about (single-parton) ~~PDFs~~ FFs to correlation functions that can't be associated with a single parton
- Non-perturbative structure → matrix elements involving the quantum mechanical *interference* between ~~scattering off~~ hadronization of a (quark+gluon) and ~~scattering off~~ hadronization of a single quark (of the same flavor and at the same x)
  - Can also have interference between (gluon+gluon) and single gluon
  - No explicit dependence on partonic transverse momentum
  - Kanazawa and Koike, 2000

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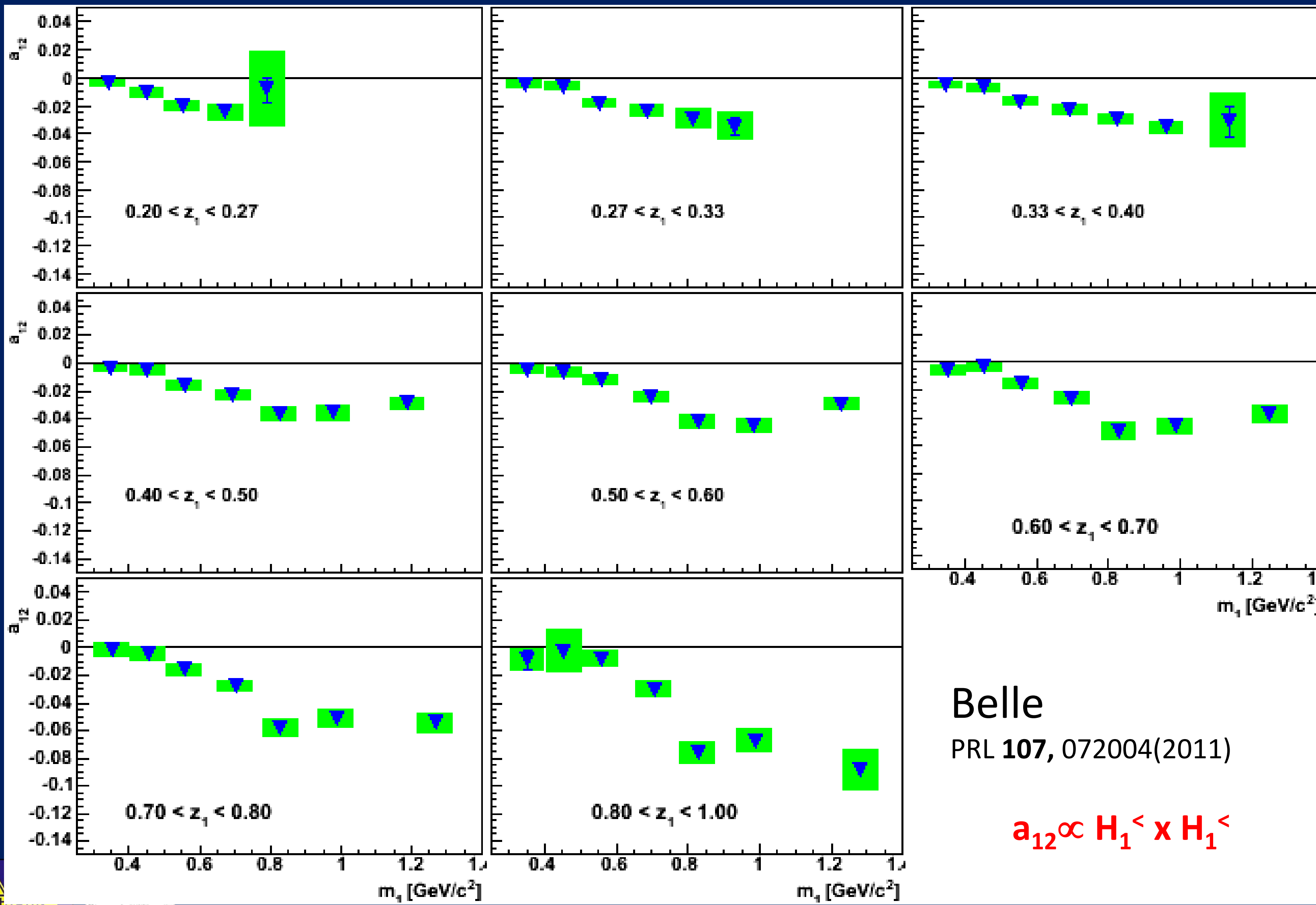
See Metz + Vossen, Prog. Part. Nucl. Phys. 91, 136 (2016) for a review of parton FFs (collects 628 references!).

Dihadron *fragmentation functions*

- Describe single parton fragmenting into *two* hadrons
  - Collinear, leading-twist
- Unpolarized or for transversely polarized quark
- Transversely polarized quark: “dihadron interference FF”
  - Interference between s and p waves, so far measured for pion pair production
  - Large effects observed by Belle

Dihadron Interference Fragmentation Function

$$H_1^{\angle}(q^{\uparrow} \rightarrow \pi^+\pi^-)$$



Belle

PRL **107,** 072004(2011)

$a_{12} \propto H_1^< \times H_1^<$

Hadronization within jets

- Would ideally want to go beyond single- and dihadron FFs to understand correlations among *all* hadrons produced by a high-energy fragmenting parton → hadronization in a jet
  - LHCb can measure fully reconstructed jets and identify every single particle within them → new opportunities!
  - Still far from such a theoretical description within a pQCD framework
    - MC event generators of course try to describe the full event, tuned based on data

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    - MC event generators of course try to describe the full event, tuned based on data
- 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)
  - Single hadron-in-jet FFs – introduced in Procura and Stewart, PRD81, 074009 (2010)
  - Fragmenting jet functions – introduced in Procura and Stewart, PRD81, 074009 (2010)

Different mechanisms of hadronization

- High-energy limit of "string-breaking" or "cluster" pictures

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- Coalescence/recombination of partons nearby in phase space

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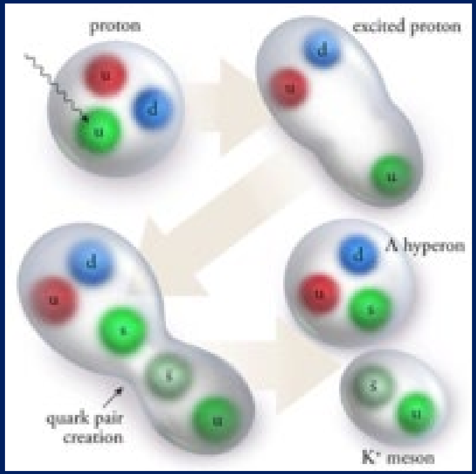
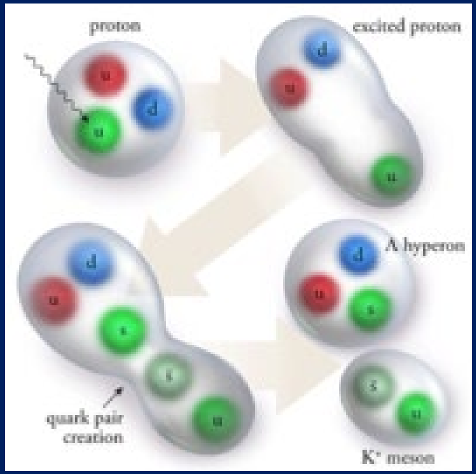
- Coalescence/recombination of partons nearby in phase space
- Threshold production



CLAS, PRL 113, 152004 (2014)

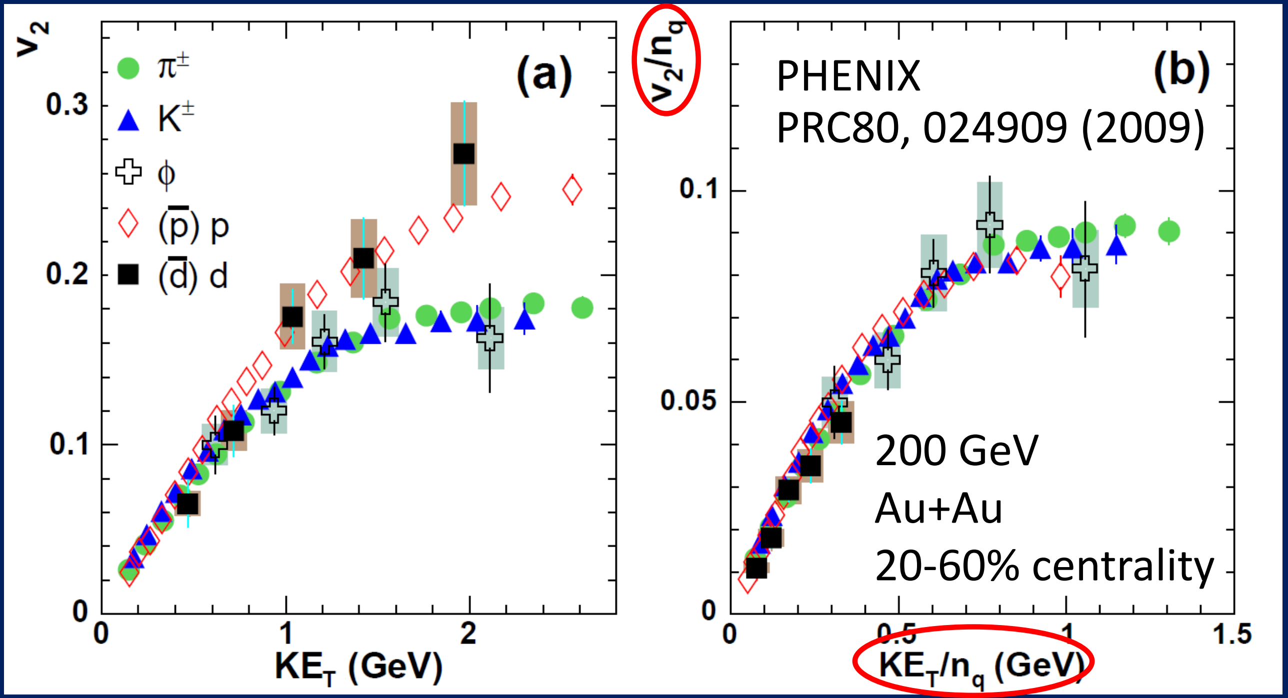
Different mechanisms of hadronization

- 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)

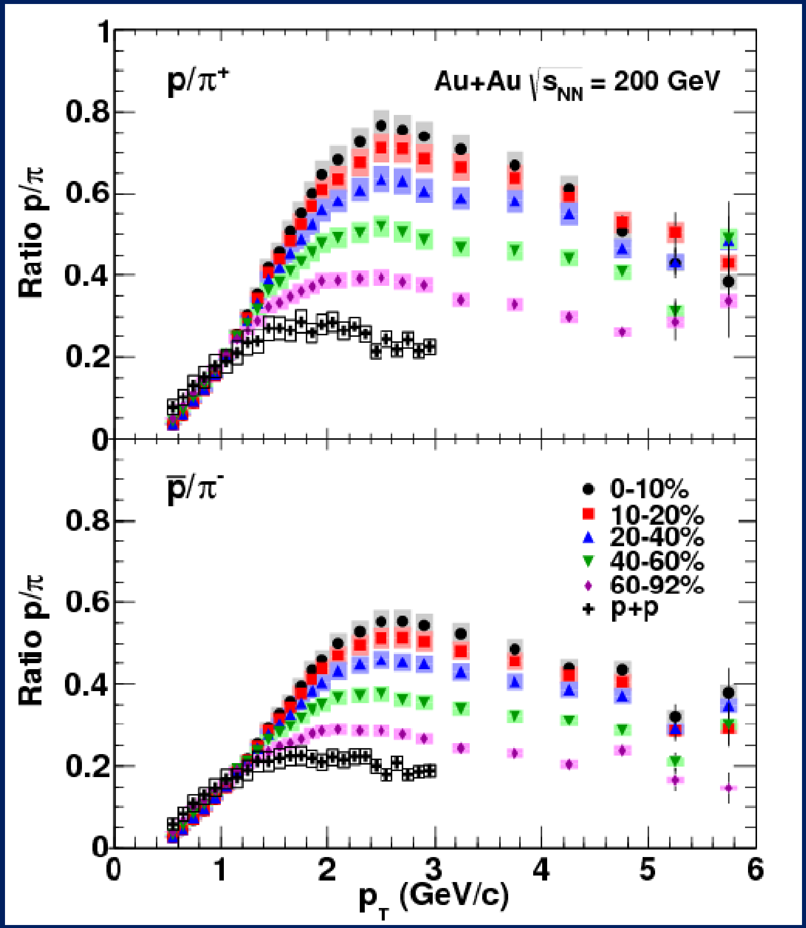
Scaling of elliptic flow in heavy ion collisions based on number of constituent quarks



Elliptic flow (2nd Fourier coefficient wrt event plane) as a function of transverse kinetic energy (left), and scaled by the number of constituent quarks (right)

- When normalized by number of constituent quarks, universal behavior observed for mesons, protons, and deuterons.
- Strong evidence for hadronization via recombination!

Baryon enhancement in heavy ion collisions with respect to p+p



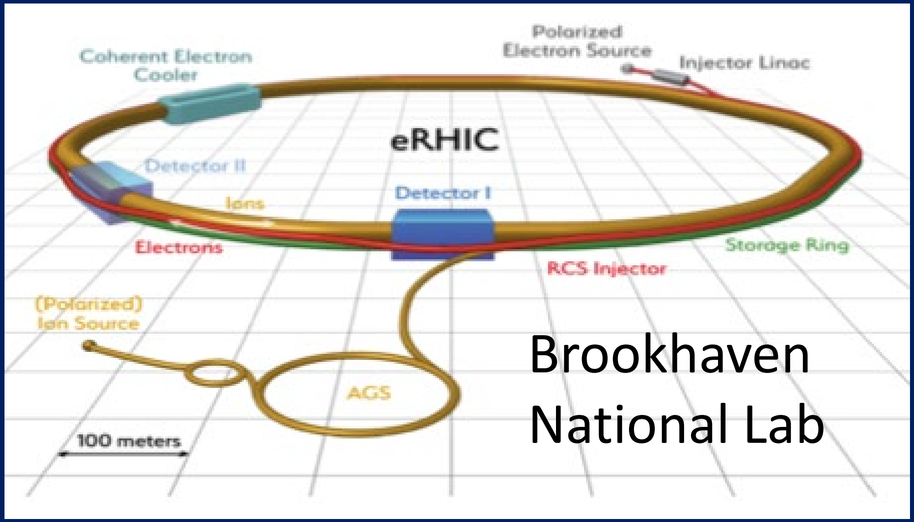
PHENIX, PRC88, 024906 (2013)

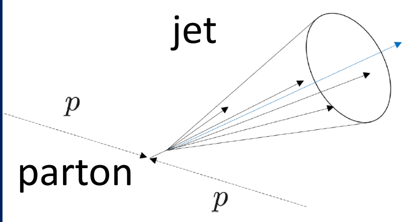
- If a deconfined medium is created and recombination is dominant hadronization mechanism, expect baryons to have higher mean p_T than mesons

Next-generation QCD facility: The Electron-Ion Collider

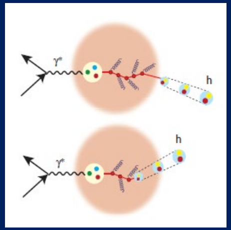
- Polarized electrons on polarized protons up to $\sqrt{s}$ =140 GeV
- Light and heavy nuclear beams
- Broad QCD physics program to study
  - spin-momentum correlations in the nucleon
  - partonic structure of nuclei
  - high-density gluon regime
  - hadronization
  - …
- First data anticipated 2030

Project approval ("Critical Decision 0") and site selection at Brookhaven National Lab announced Jan 9, 2020





Summary: Lecture 3



- Hadron structure and hadronization are flip sides of the "confinement coin"
- Hadronization remains much less explored than nucleon structure
  - Most existing efforts have been focused on the high-energy limit of single parton fragmentation, considering inclusive production of single observed particles
  - Hadronization to heavy flavor hadrons requires different treatment than light hadrons

- Striking spin-momentum correlations (up to ~10%) in hadronization have been clearly observed in e+e- annihilation

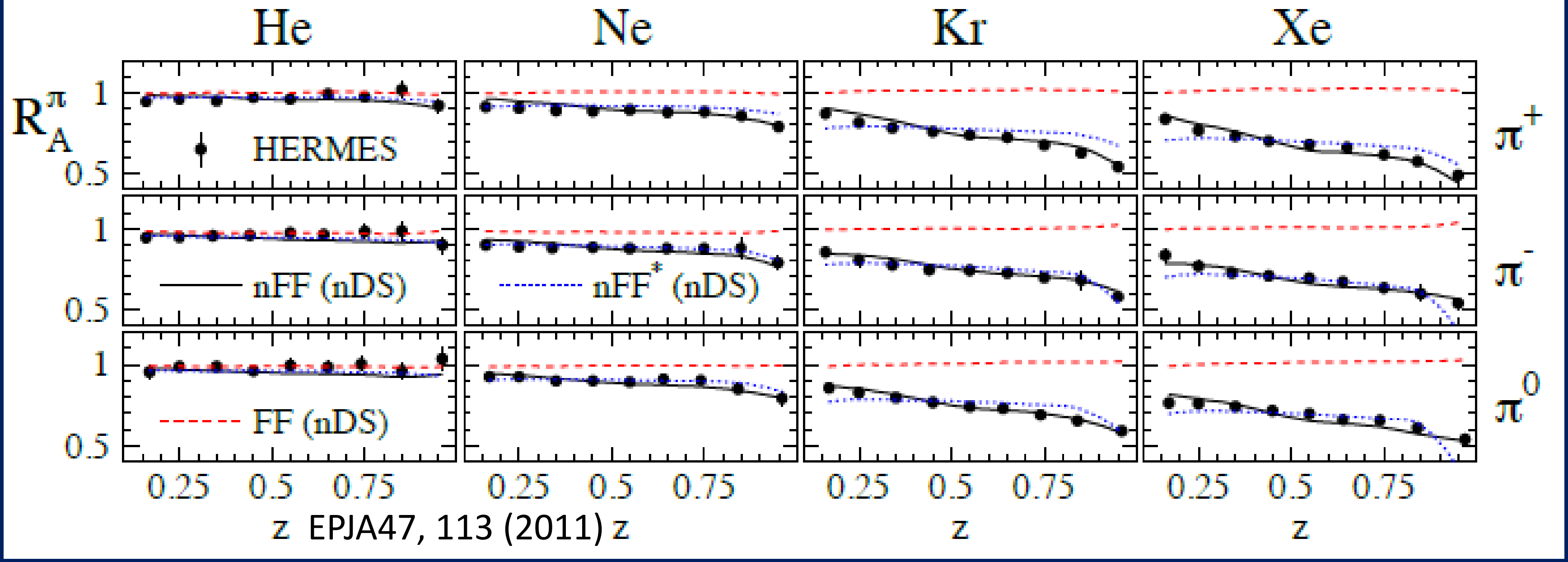
- The theoretical frameworks within perturbative QCD of transverse-momentum-dependent fragmentation functions and twist-3 multiparton correlators can characterize these nonperturbative spin-momentum correlations in hadronization

- Collisions involving nuclei offer opportunities to study recombination mechanisms of hadronization

Extra

Hadronization in higher-density partonic environments

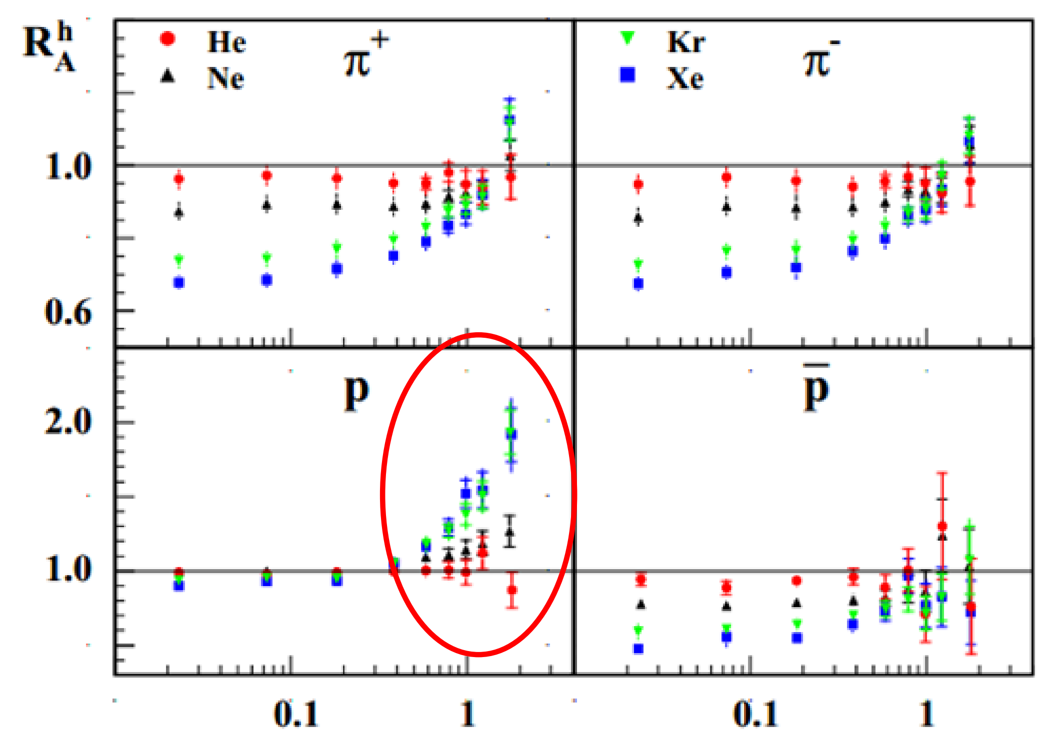
- No longer (only) "vacuum" fragmentation
- Nuclear modification of FFs observed in e+nucleus collisions with respect to e+p, e.g. pion suppression



EPJA47, 113 (2011)

Hadronization in higher-density partonic environments

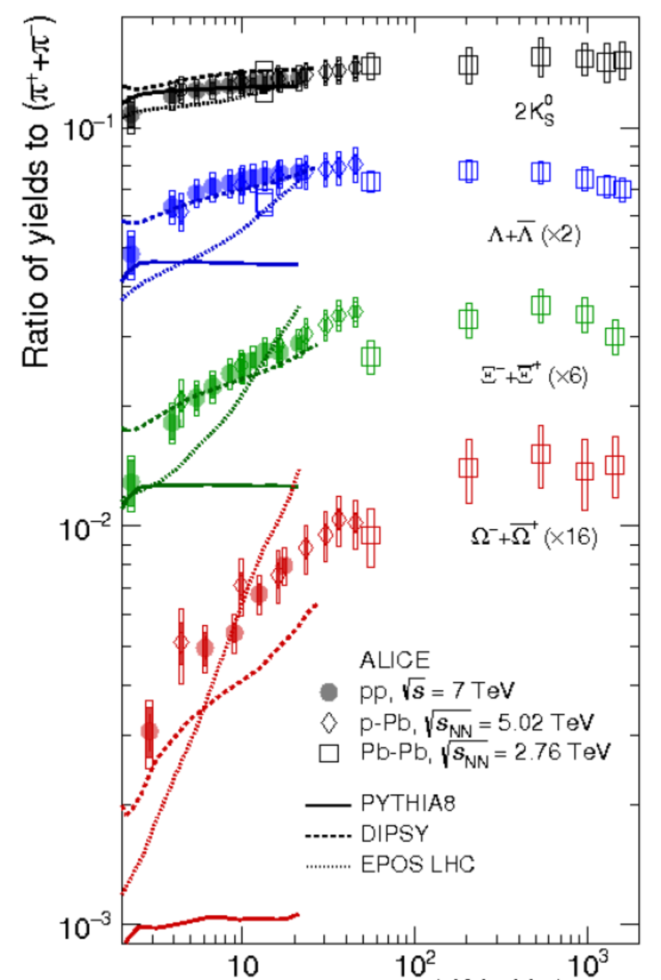
- Pion *suppression* observed in e+A compared to e+, but proton *enhancement* in certain p_T range (antiprotons unclear)
  - Related to baryon enhancement observed in p+A and A+A, believed to be due to recombination?



HERMES, NPB780, 1 (2007)

Strangeness enhancement with track multiplicity

- Strangeness enhancement observed in heavy ion collisions
  - Stronger for hadrons with greater strangeness content
  - Suggests deconfined medium and recombination
- But actually turns on rapidly as a function of charged track multiplicity, already in p+p collisions
  - Sign of deconfined medium produced in p+p?
  - Other effects of higher density partonic/color environment?



Nature Phys. 13, 535 (2017)