Studying Cold QCD with Hadron Colliders

Disclaimer: Much taken from soon-to-be-released draft cold QCD plan, but this is NOT an official report of the plan! Emphases in talk are my own choices.

Christine A. Aidala
University of Michigan

sPHENIX Collaboration Meeting, Rutgers University
December 11, 2015

References and resources (chronological order)

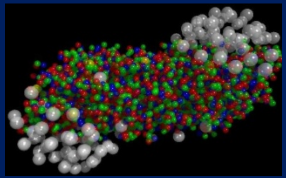
- *Future Opportunities in p+p and p+A Collisions at RHIC with the Forward sPHENIX Detector*, April 2014
  - https://indico.bnl.gov/getFile.py/access?resId=0&materialId=5&confId=764
- *The RHIC Spin Program: Achievements and Future Opportunities*, Jan 2015
  - arXiv:1501.01220
- *Physics Opportunities with STAR in 2020+*, Oct 2015
  - https://drupal.star.bnl.gov/STAR/files/STAR-2020-plan.pdf
- Forthcoming RHIC Cold QCD Plan
  - Draft to be released this month

Slide from sPHENIX talk, WWND2011 . . .

Why did we build RHIC in the first place?

- To study QCD!
- An accelerator-based program, but not at the energy (or intensity) frontier. More closely analogous to many areas of condensed matter research—create a system and study its properties!





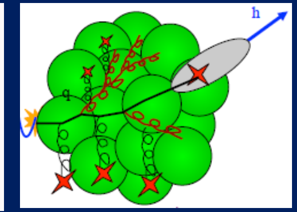
- What systems are we studying?
  - "Simple" QCD bound states—the proton is the simplest stable bound state in QCD (and conveniently, nature has already created it for us!)
  - Collections of QCD bound states (nuclei, also available out of the box!)
  - QCD deconfined! (QGP, some assembly required!)

eRHIC version of the slide, DNP 2012 . . .

eRHIC

- A facility to bring this new era of quantitative QCD to maturity!
- Study in detail
  - “Simple” QCD bound states: Nucleons
  - Collections of QCD bound states: Nuclei
  - Hadronization





Collider energies: Focus on sea quarks and *gluons* eRHIC version of the slide, DNP 2012 . . .

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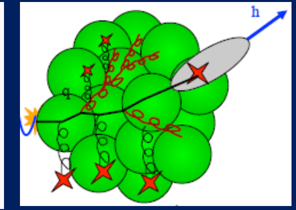

Collider energies: Focus on sea quarks and *gluons*

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- In the business of nuclear physics, you study your systems via scattering processes
  - Scattering process typically treated as a tool

- In recent years, QCD processes themselves becoming a focus, in addition to QCD systems

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"The good life is a process, not a state of being."
– Carl Rogers (20th century American psychologist)

QCD interactions

- QCD interactions in the form of parton dynamics within systems already a focus, e.g.
  – Spin-momentum correlations of partons in nucleon
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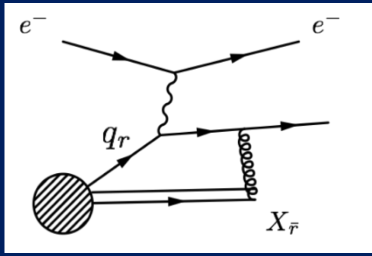
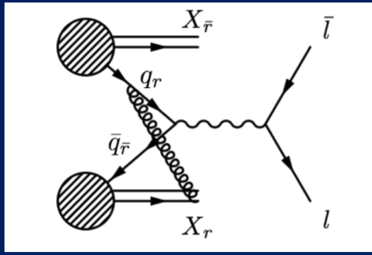
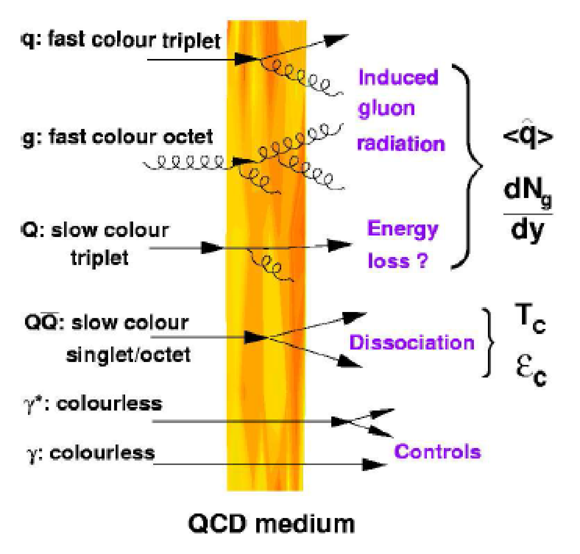




- Some observables provide interesting information on both structure *and* interactions, e.g.
  - Transverse single-spin asymmetries: due to e.g. Sivers pdf *plus* initial- or final-state gluon exchange in the interaction
  - Diffractive measurements for spatial imaging, and to probe universality of processes in e+p/A and hadronic collisions

QCD interactions



- QCD interactions themselves increasingly an explicit focus, e.g.
  - Parton energy loss traversing cold or hot QCD matter
  - Hadronization, in various environments
  - Quantum phase interference and phase shifts
  - Predicted color entanglement of partons *across* colliding protons
    - For hadronic final states sensitive to nonperturbative transverse momentum

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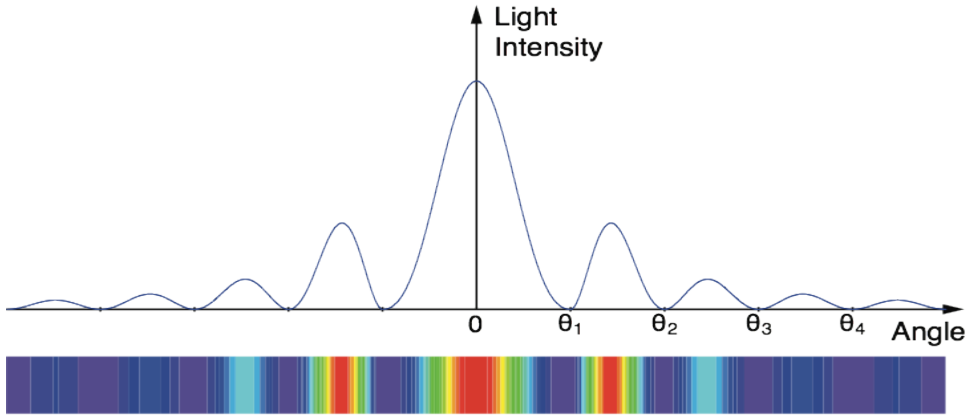
- As QCD research has matured, more in common with areas of research based on QED (condensed matter, AMO)
- But: (Sub-)nuclear distance scales require high energies → large accelerators
- And while we can *control* various aspects of the interactions (collision species → geometry, path length; energy; polarization), we have to *select out* many others (centrality, ultraperipheral events,…)
- Given short distance and time scales, also need to find clever ways for the interactions themselves to create our system probes

"Gamma-ray diffraction" to probe spatial structure of nuclei

Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius



From E. Aschenauer

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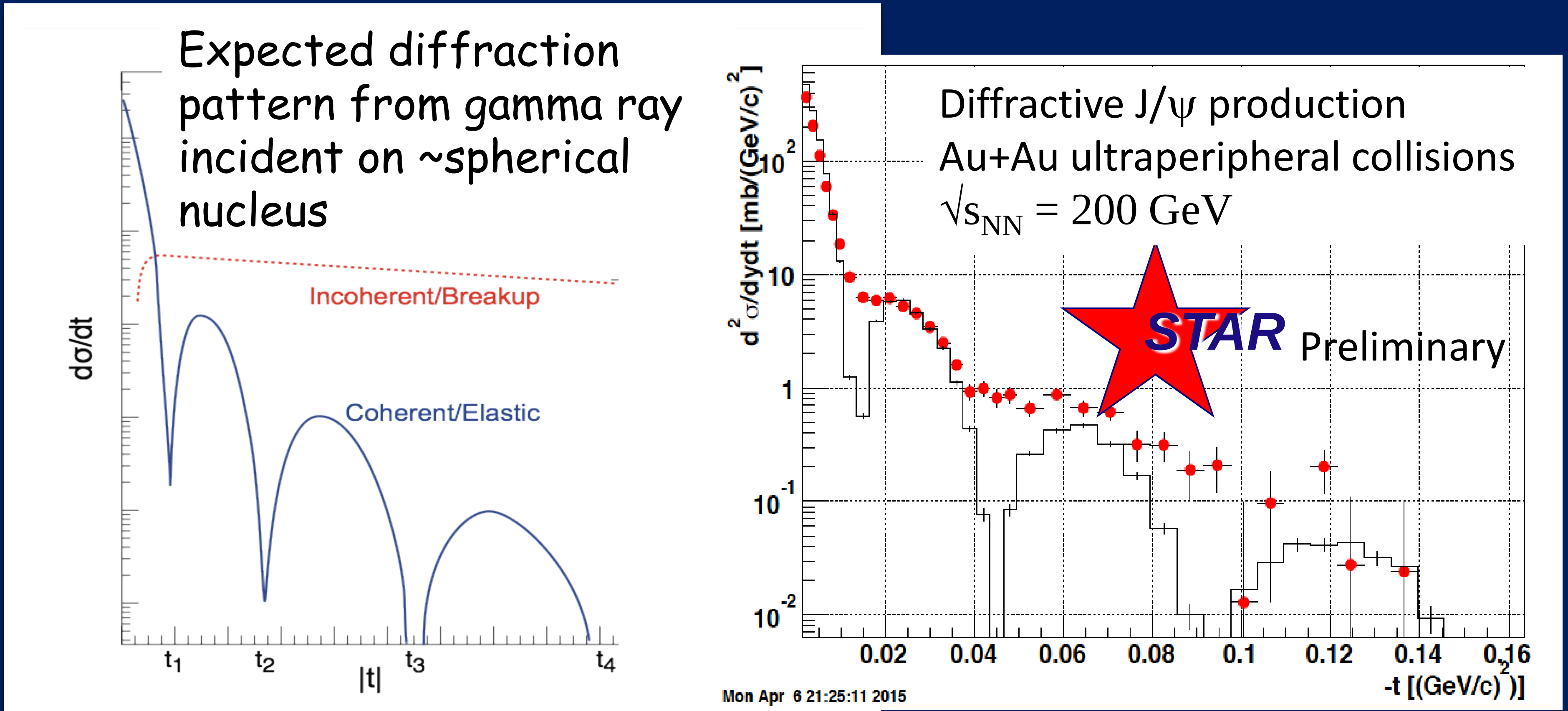

"Cold" QCD physics areas of focus (Many are linked to one another!)

- Diffraction
- Partonic structure of nuclei/nuclear pdfs
- Low-x/Saturation
- Spin-momentum correlations, interference effects and their process dependence
- Hadronization in different environments

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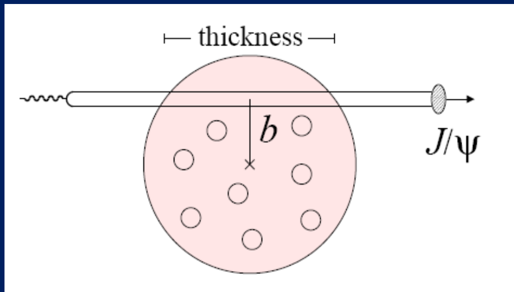
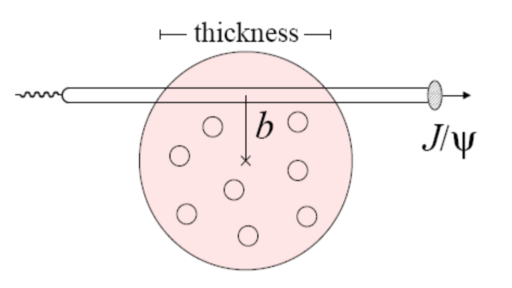
- At RHIC: focus on measurements in support of or complementary to future EIC physics program
  - Unique color interactions
  - Early measurements to gauge scale of effects/observables to be studied in depth at EIC
  - Draw larger community into physics and observables of EIC



Diffraction

- Lots of recent work/plans/ideas by STAR
  - J/Psi results in Au+Au—clear diffractive peaks!



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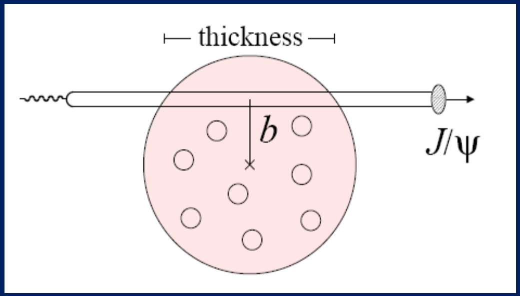

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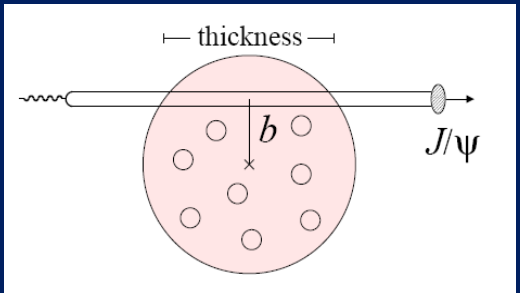

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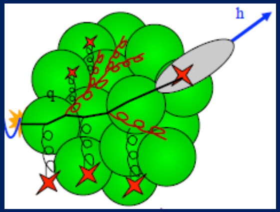
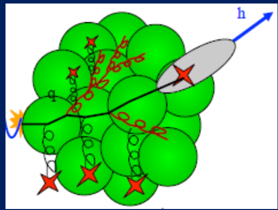
  - Diffractive J/Psi production in polarized p+A, for two different physics measurements!
    - Spatial imaging of gluon distribution in nucleus
    - Probe gluon OAM in polarized proton – Z^2 from A helps!



Hadronization

- Not as far along as nucleon structure—less of a focus in earlier years
- Recent advances via
  - Spin-momentum (and spin-spin) correlations in FFs



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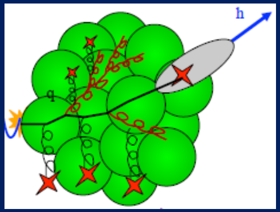

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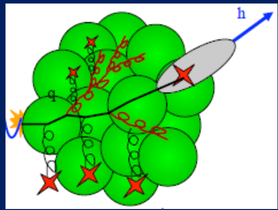

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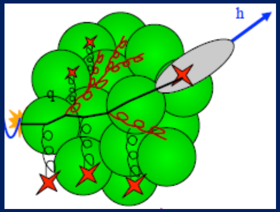

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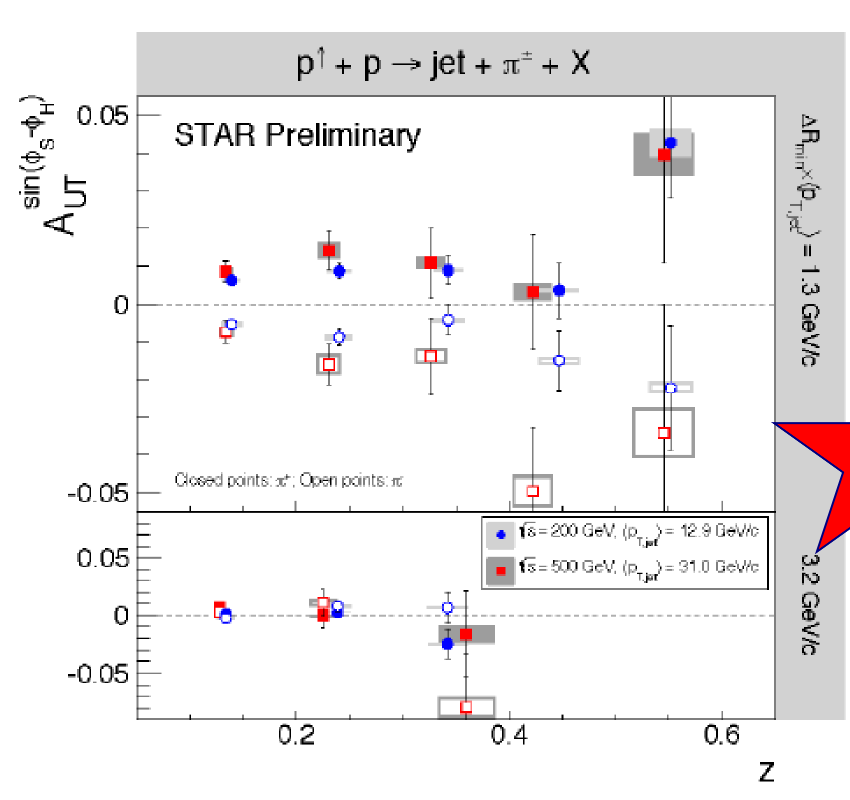
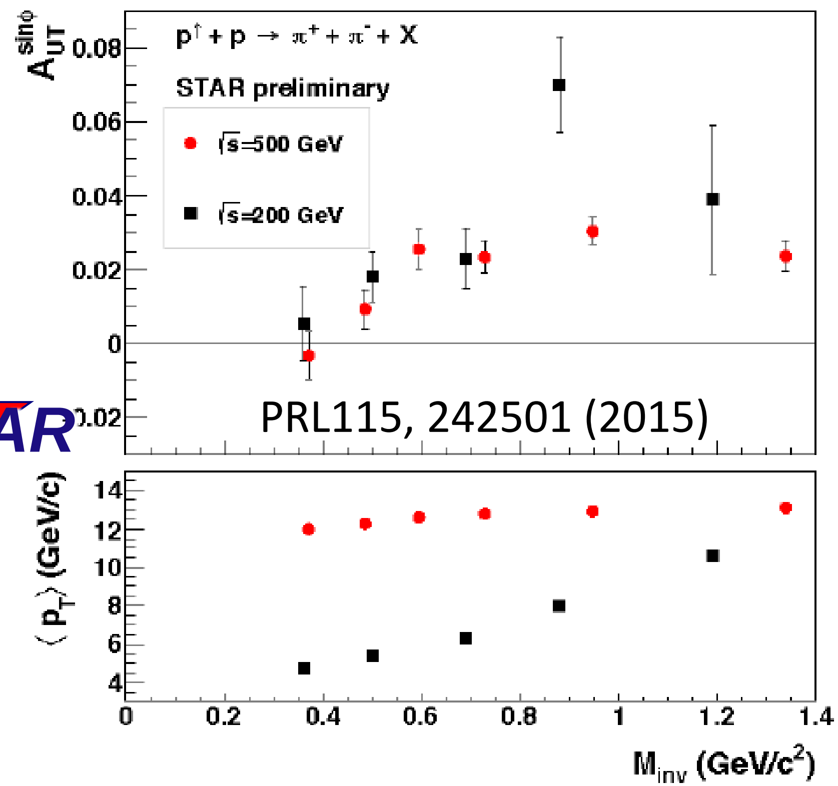
- Intense Trento workshop dedicated to hadronization late October—topic getting more attention these years!

STAR pushing forward studies of hadronization at RHIC:Clear spin-dependent hadronization observed



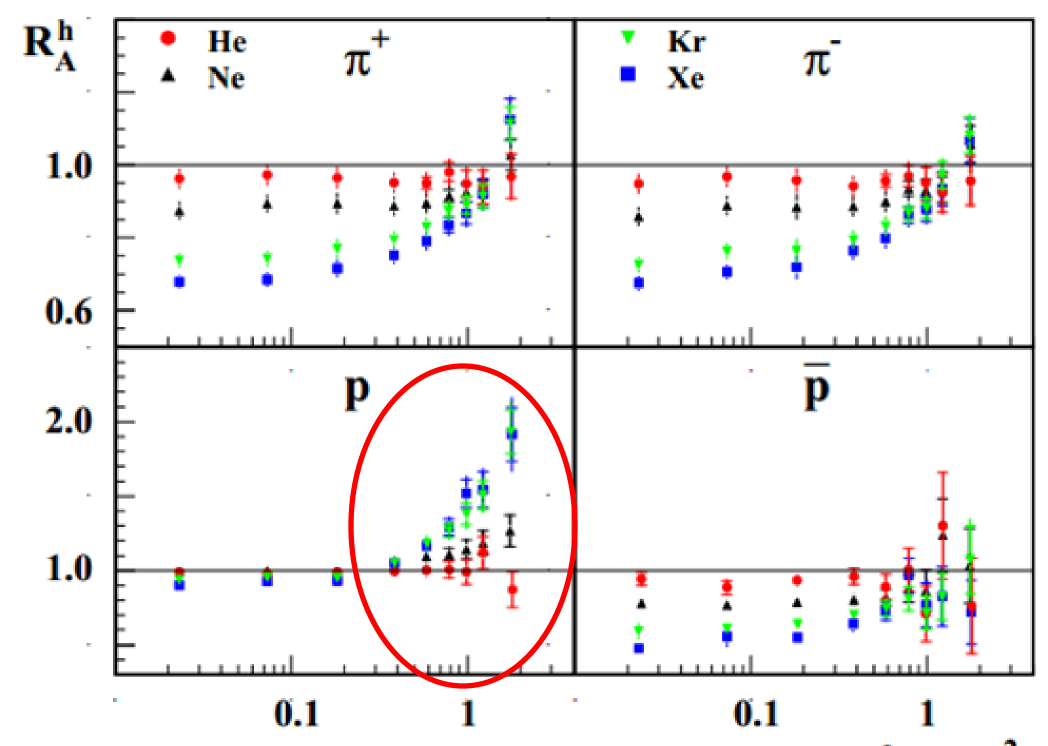
Charged pion in a reconstructed jet



Interference between two pions hadronizing from same parton

Hadronization in higher-density partonic environments

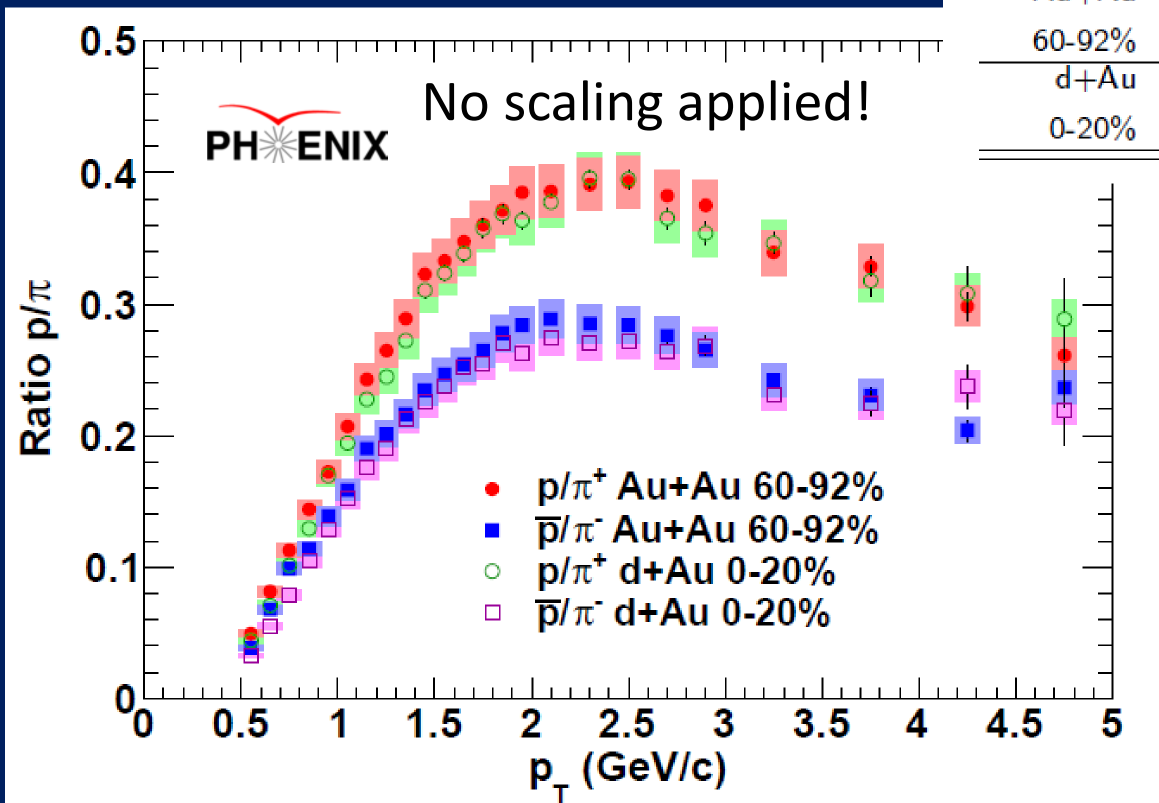
- Nuclear modification of particle production
  - Not fully explainable by nuclear pdfs
- Enhancement of protons compared to pions in e+A with respect to scaled e+p



HERMES, NPB780, 1 (2007)

Hadronization in higher-density partonic environments

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

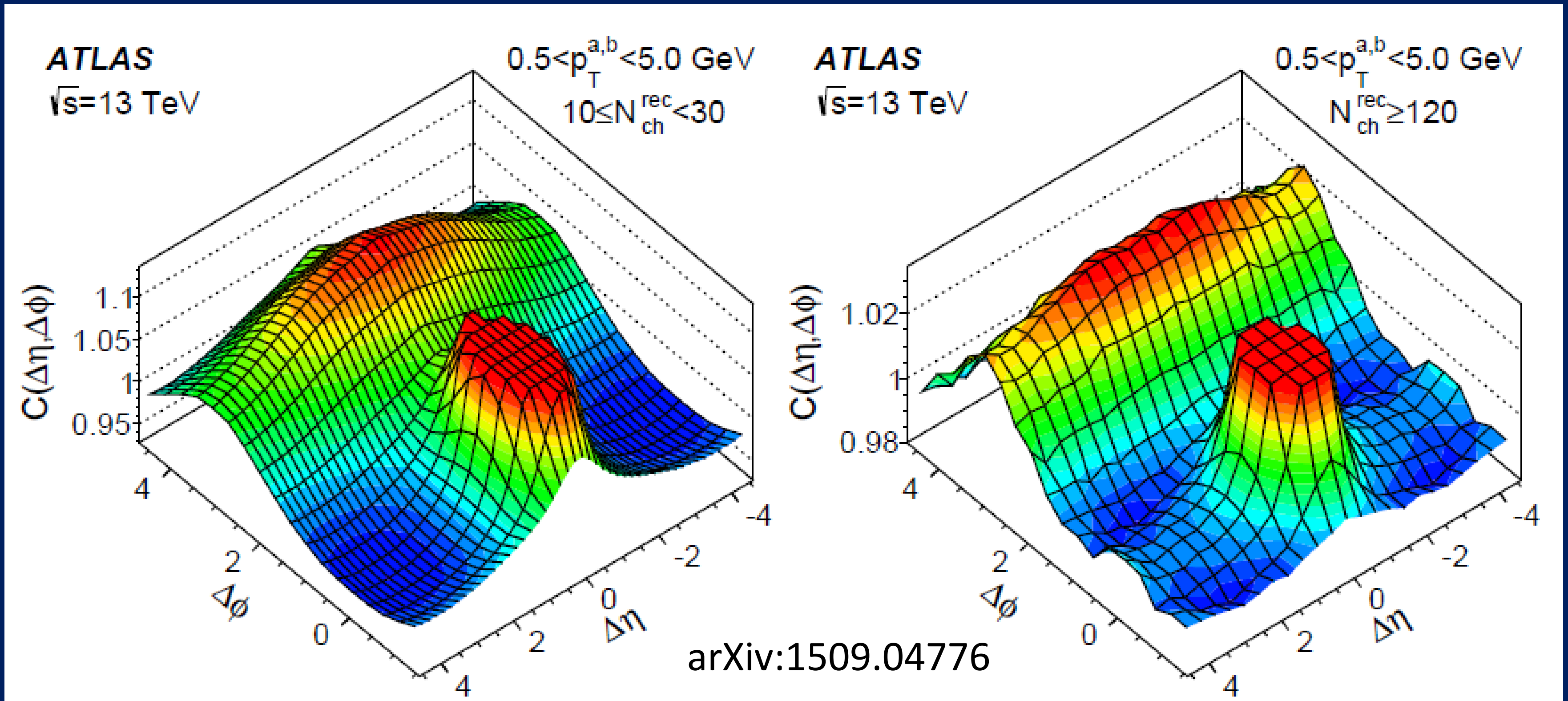


PRC88, 024906 (2013)

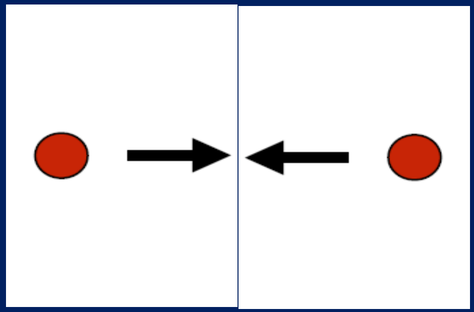
p/pi ratio for central d+Au and peripheral Au+Au—shape *and* magnitude identical!

Suggests common mechanism(s) for baryon production in the two systems

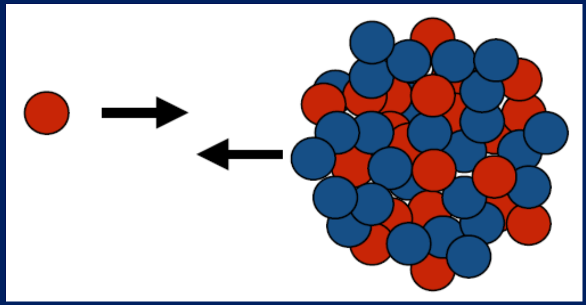
Links to collective behavior in high-multiplicity p+p, and in p+A?



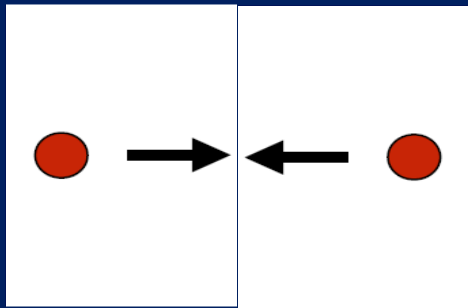
Lots of interesting behavior when extra partons come into play, whether it's "hot" or "cold" QCD



Outlook



- Cold QCD physics goals will continue taking shape over next year, influenced by
  - Run-15 p+A results
  - Run-15 forward direct photon measurements
  - STAR diffractive measurements
  - Increasing thought/ideas on hadronization
  - Input from all interested parties!



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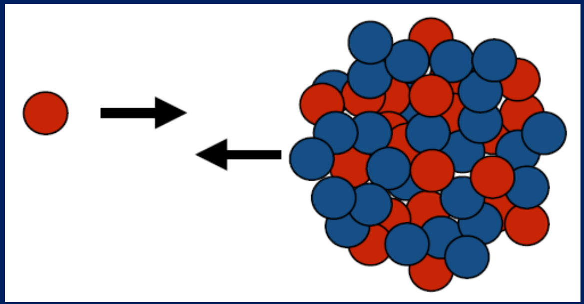

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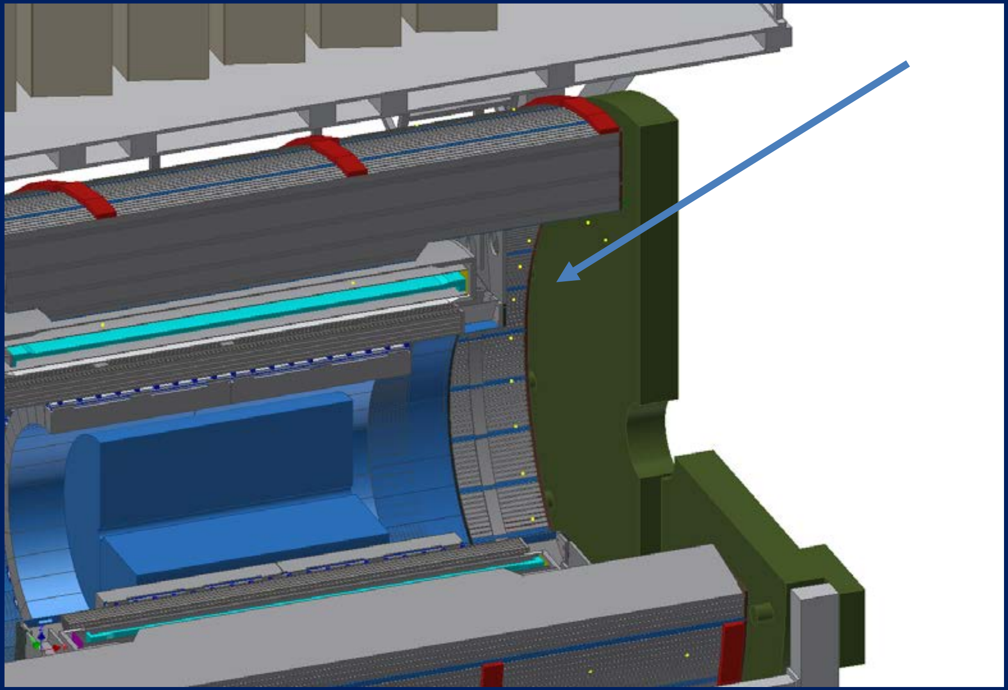
  - Input from all interested parties!
- Physics goals in turn define/refine detector needs—adding forward capabilities essential

Generic detector requirements

- Coverage approximately $1<\eta<4$
- Calorimetry (EM and HCal)
- Tracking
- Roman pots
- Hadron PID for hadronization measurements

- (Nearly all) new investments should be potentially reusable for eRHIC

fsPHENIX: Starting point for IP8 implementation



- sPHENIX flux return further back → now leaves room for future forward instrumentation!
- Important to preserve the envelope!

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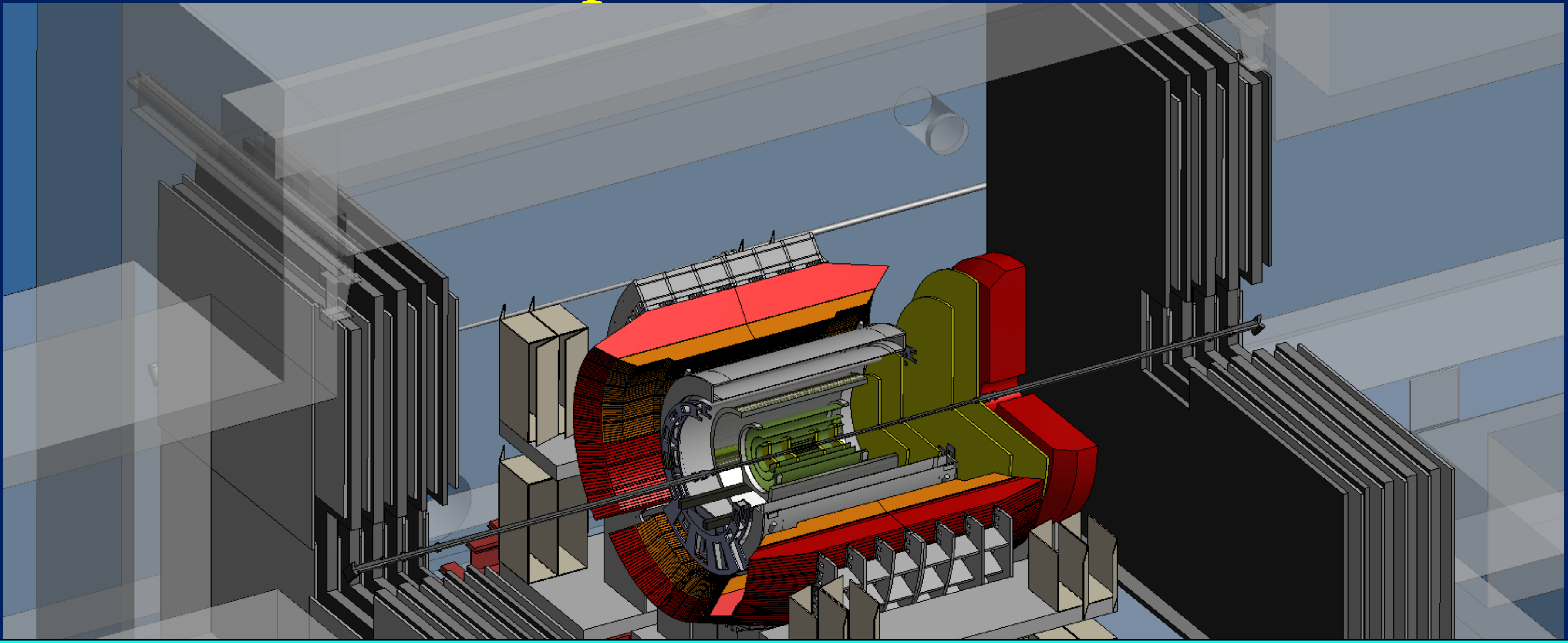

With sPHENIX in LRP and envelope in place, now the time to work on forward instrumentation design in earnest. Plenty to do for anyone interested!

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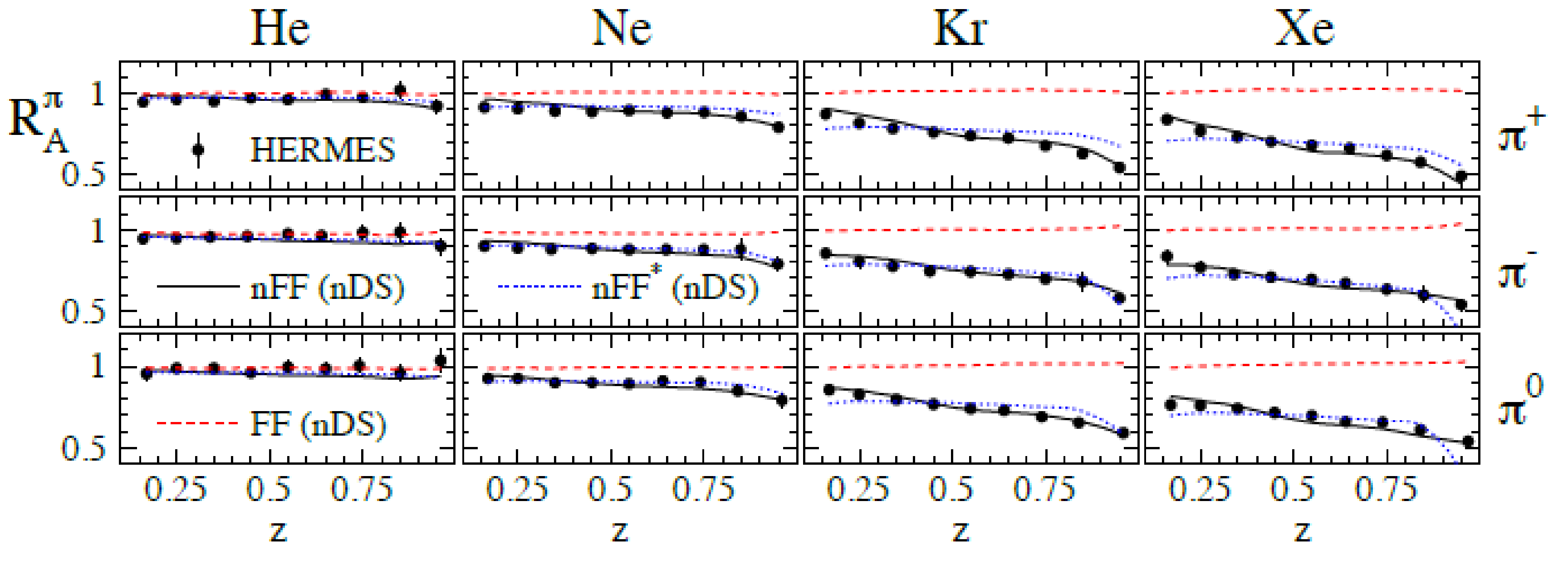
I look forward to seeing how we'll gain even more exquisite control and understanding as we continue to work with our "tabletop" experiment for giants!

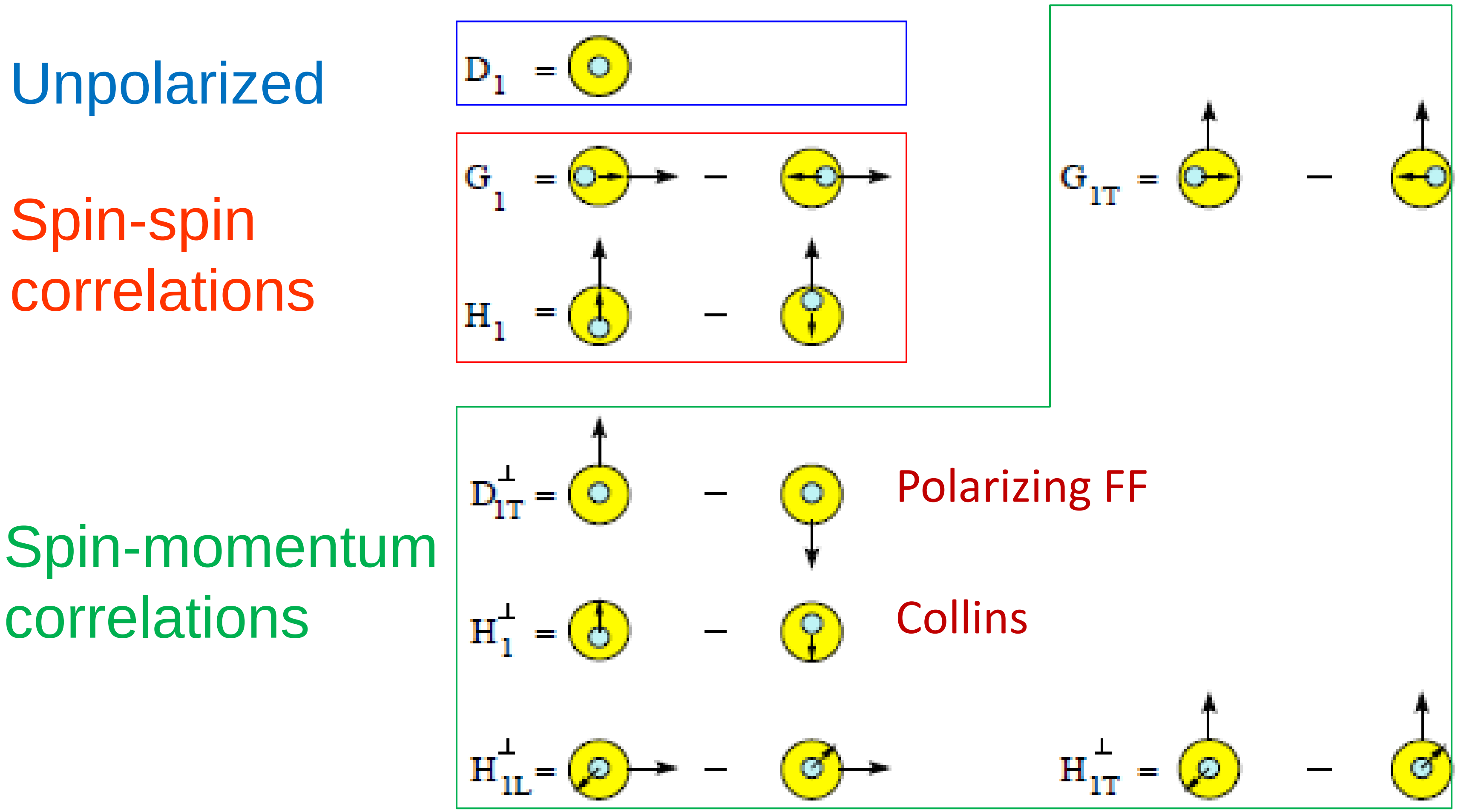
Extra

Nuclear modification of FFs at HERMES



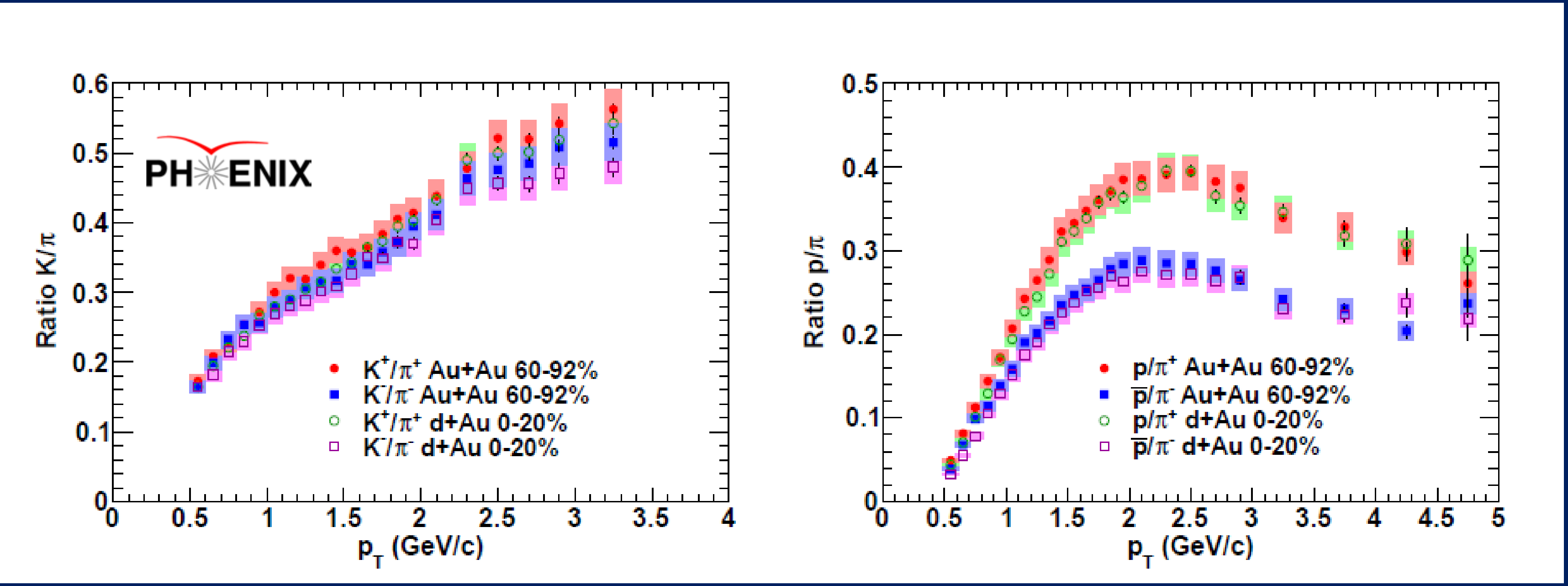
Nuclear pdfs aren't enough to explain modification of pion production in nuclear SIDIS!

Twist-2 fragmentation functions



Comparing central d+Au with peripheral Au+Au

PRC88, 024906 (2013)



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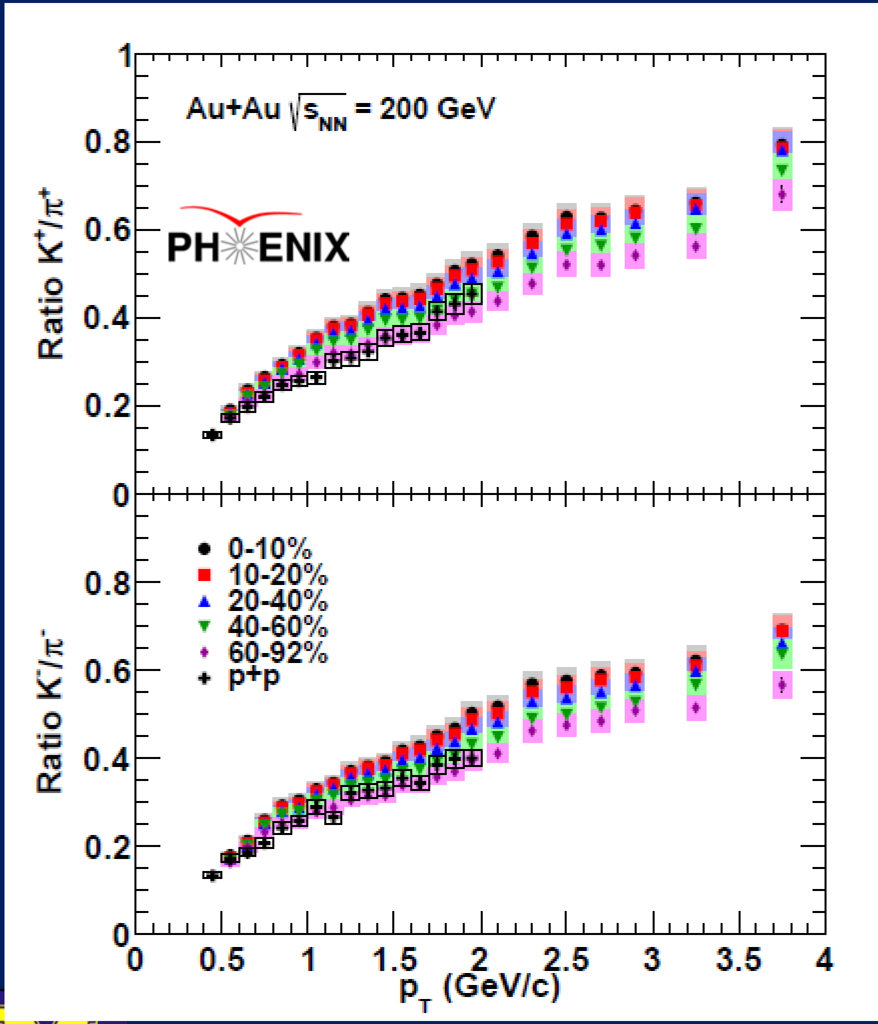
Enhancement of strange meson production in central Au+Au



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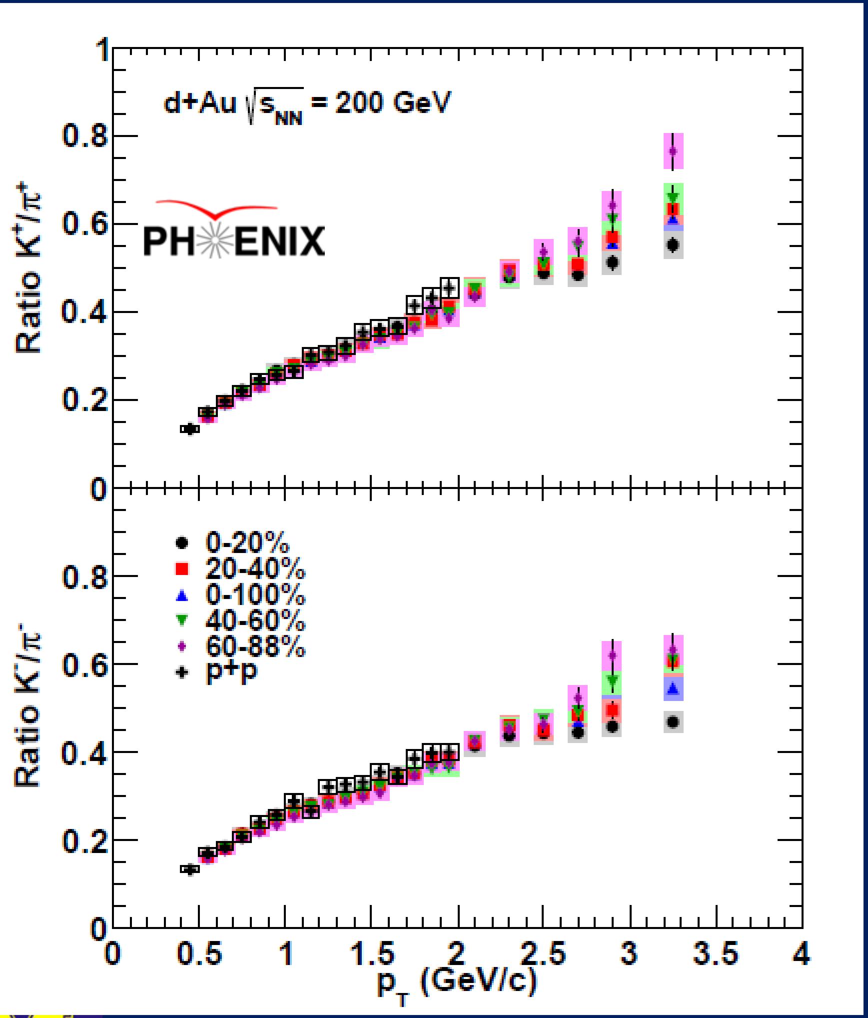
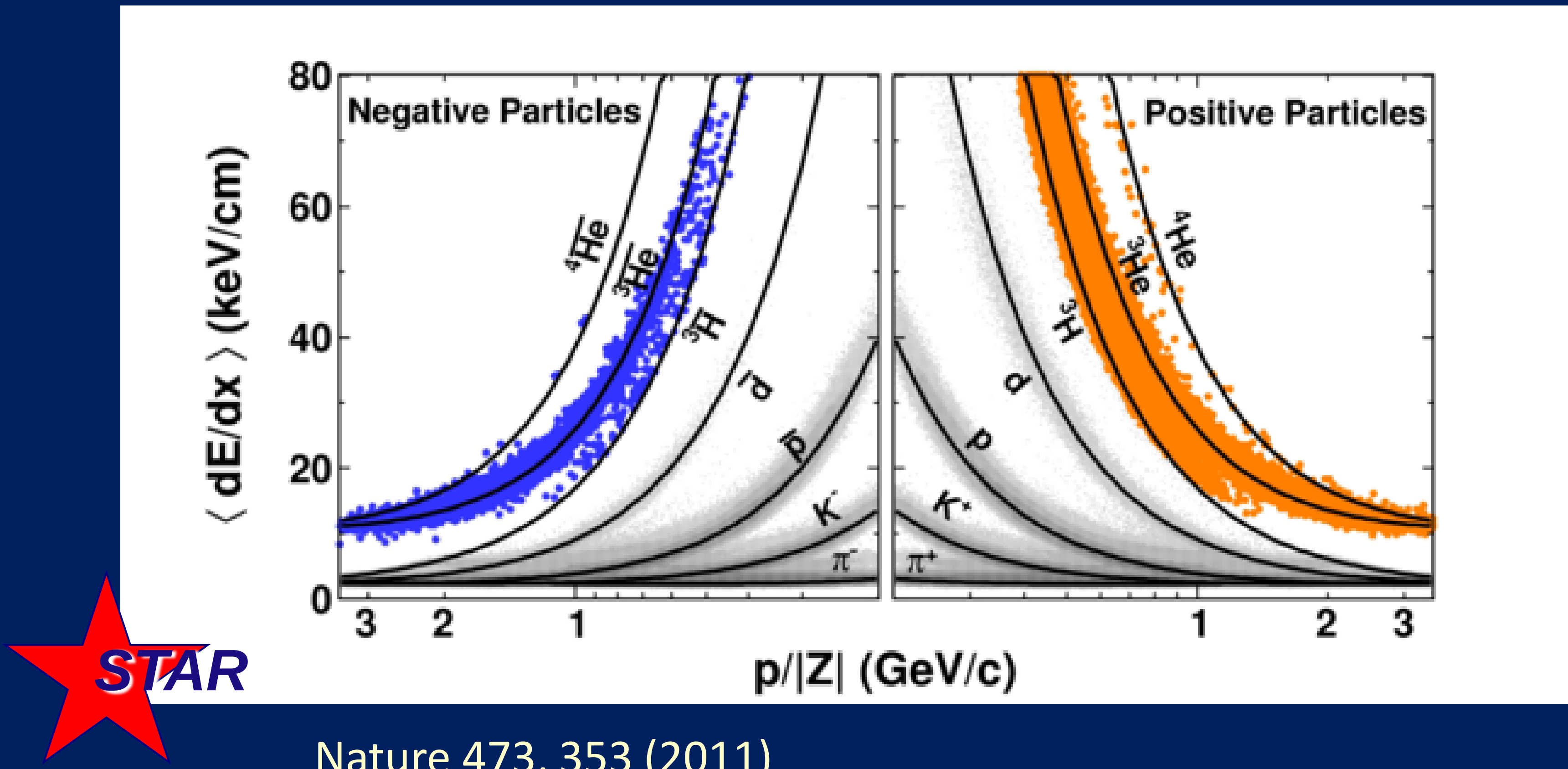


- K/π ratio higher in more central Au+Au than p+p, increases with centrality
- K/π ratio in d+Au same as p+p for all centralities

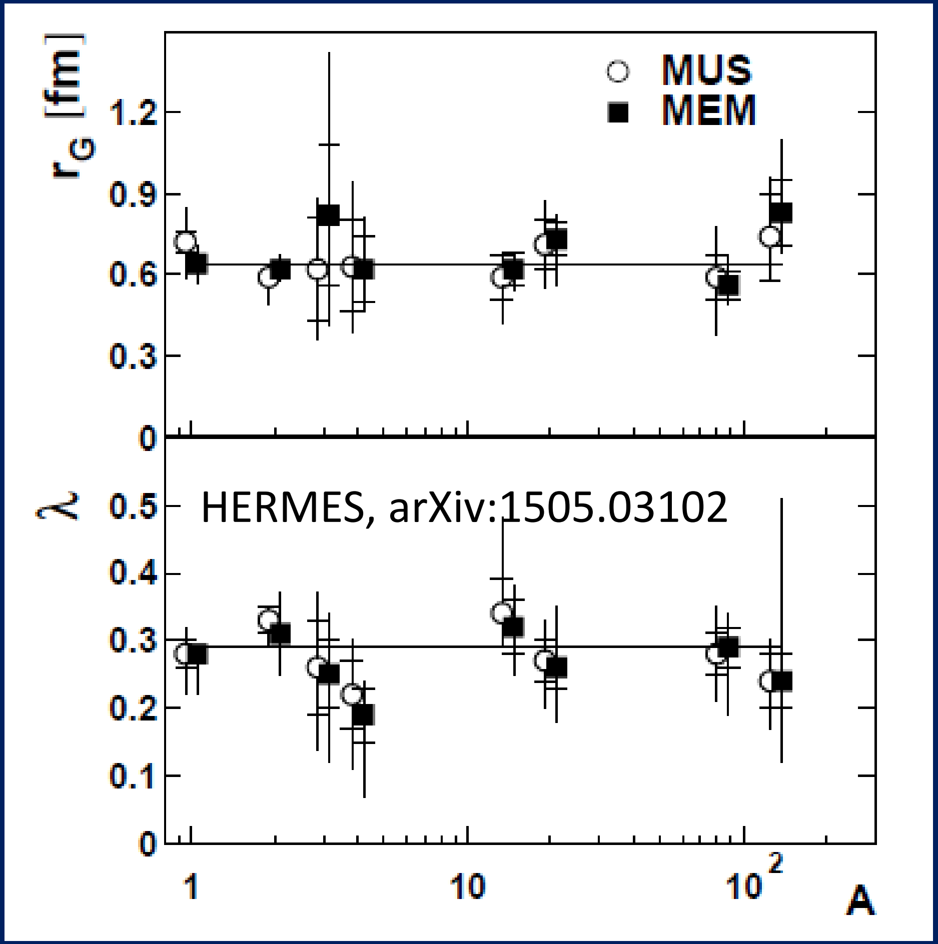
Bound states of hadronic bound states: Creating nuclei!



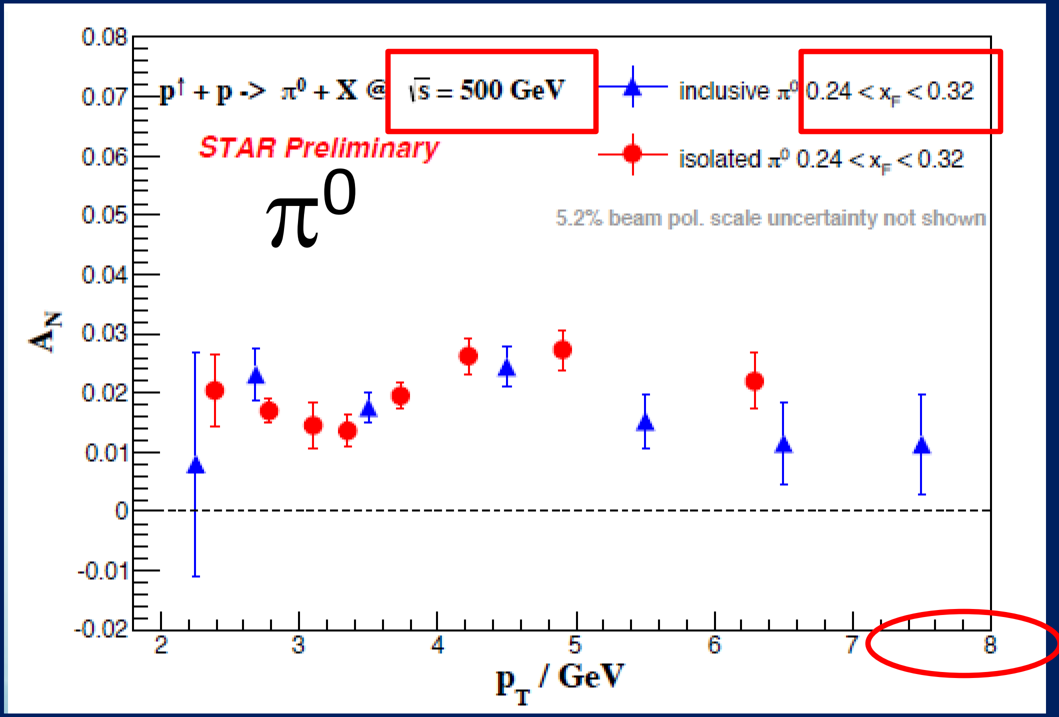
Nature 473, 353 (2011)

Bose-Einstein correlations for nuclear semi-inclusive DIS

- Sensitive to spatial separation of production of the two particles
- No nuclear dependence found within uncertainties



p+p → hadron asymmetries persist up to $\sqrt{s}$=0.5 TeV and p_T = 7 GeV!



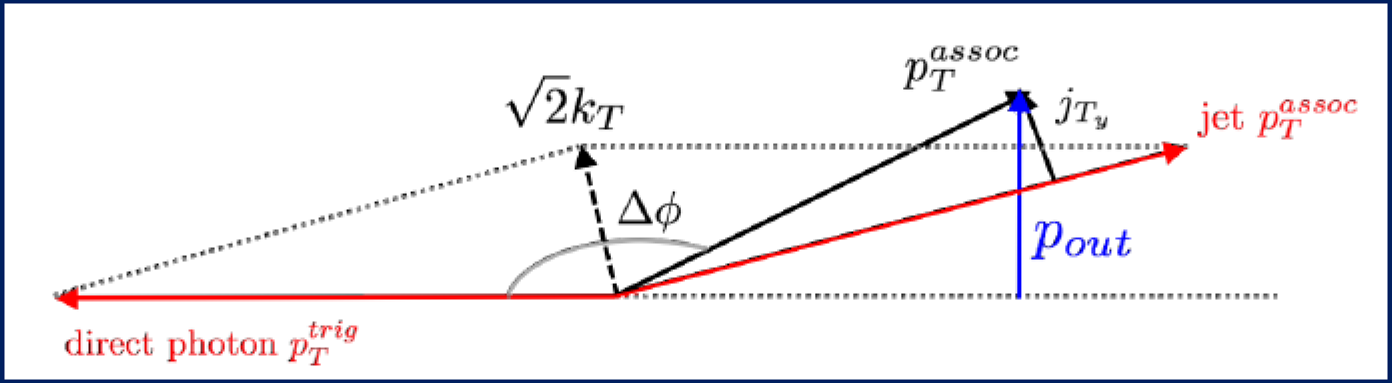
- Effects persist to kinematic regimes where perturbative QCD techniques clearly apply
- p_T = 8 GeV
  → $Q^2 \sim 64$ GeV^2!

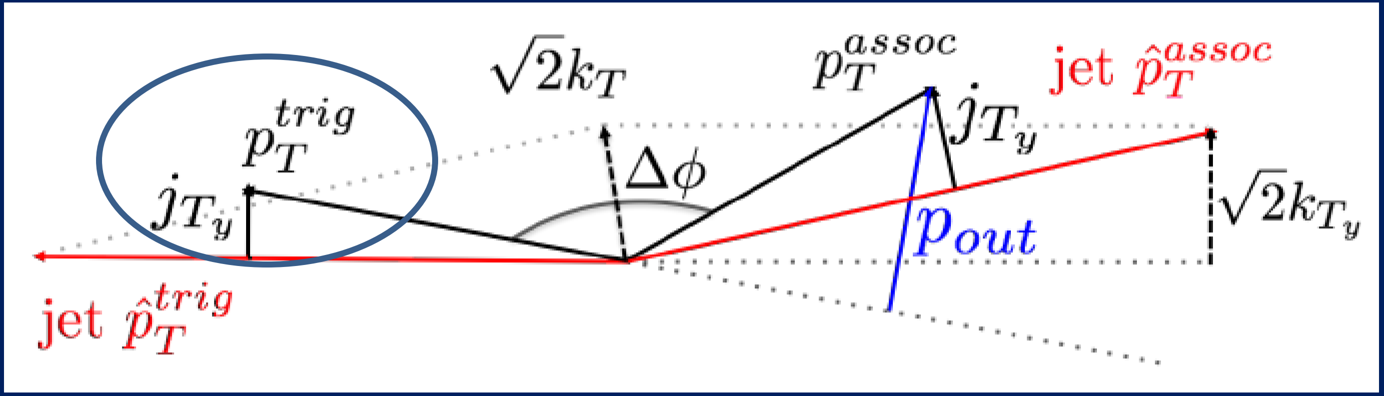
Note x_F = 0.24-0.32 here, where asymmetries approached zero on lower-energy plots—need more-forward measurements at high energies!

Testing TMD-factorization breaking/ color entanglement: p+p → hadrons

- 2010 prediction by Rogers and Mulders that nonperturbative objects no longer factorize from one another when have p+p → hadrons and observable sensitive to nonperturbative transverse momentum
  - PRD 81, 094006 (2010)
- Try to test by measuring out-of-plane momentum component in nearly back-to-back particle production in p+p

Direct photon – hadron and π^0 – hadron correlations in p+p

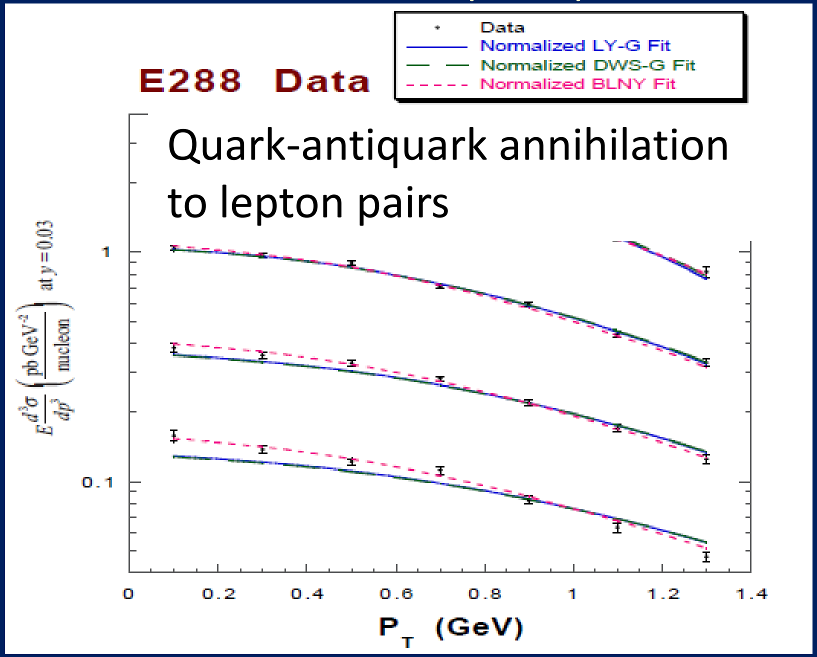




Additional nonperturbative transverse momentum in π^0 – charged hadron correlations

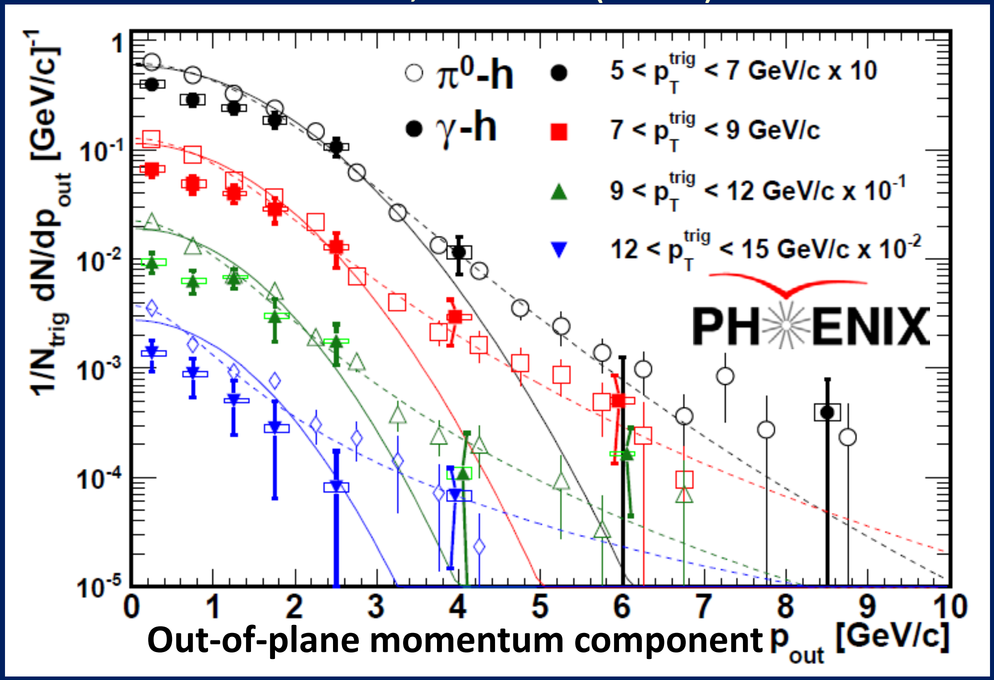
Testing TMD-factorization breaking/ color entanglement: p+p → hadrons

PRD 67, 073016 (2003)



Drell-Yan p_T for different hard scales: no entanglement expected

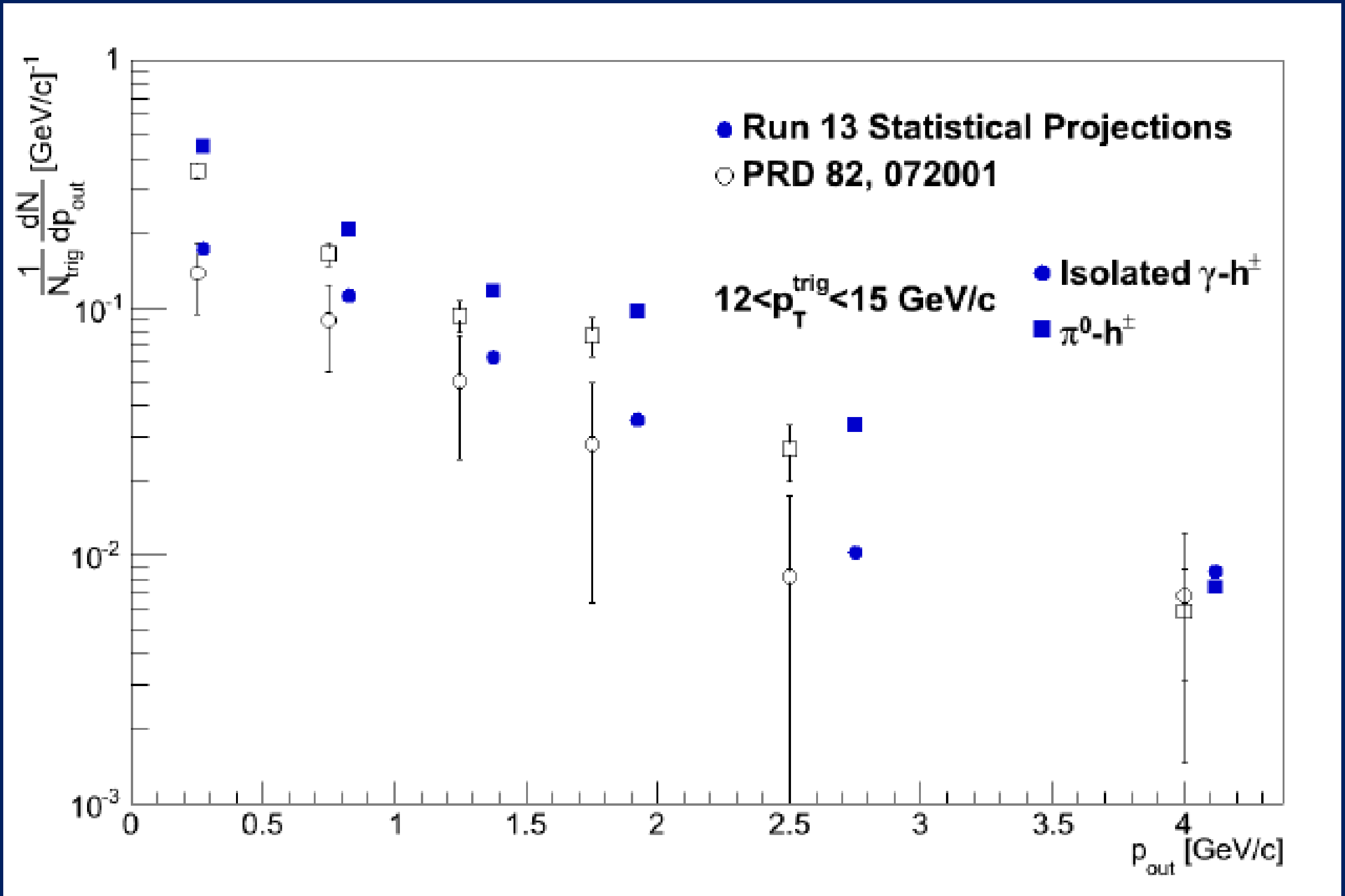
PRD82, 072001 (2010)



π^0-charged hadron and γ-charged hadron correlations for different hard scales: entanglement expected. Gaussian shape at low p_{out}

Look for different evolution with hard scale. . . In progress!

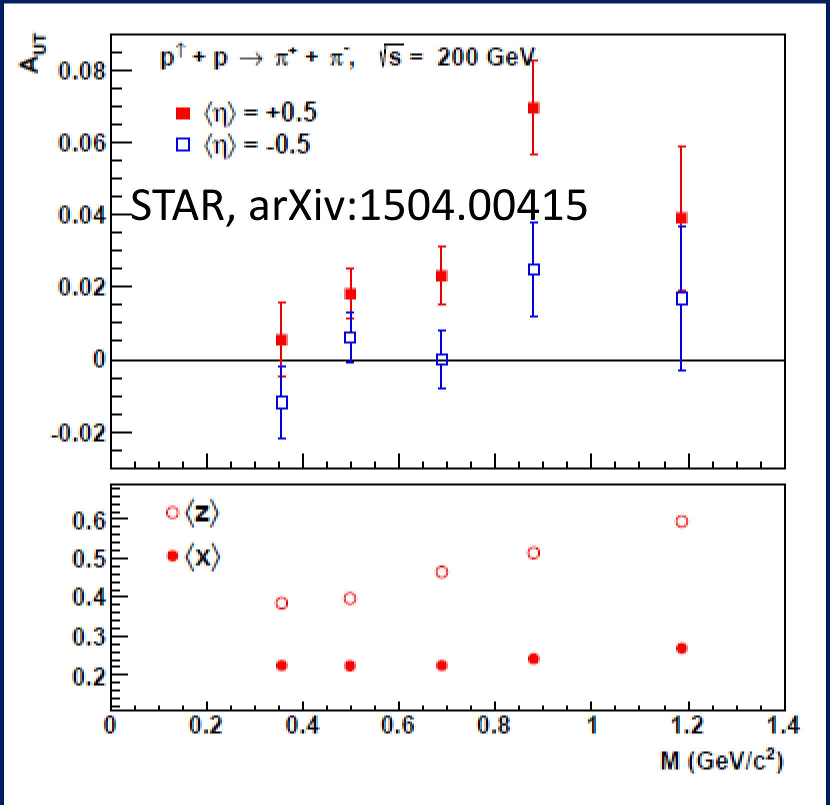
Much better data coming soon from 510 GeV p+p

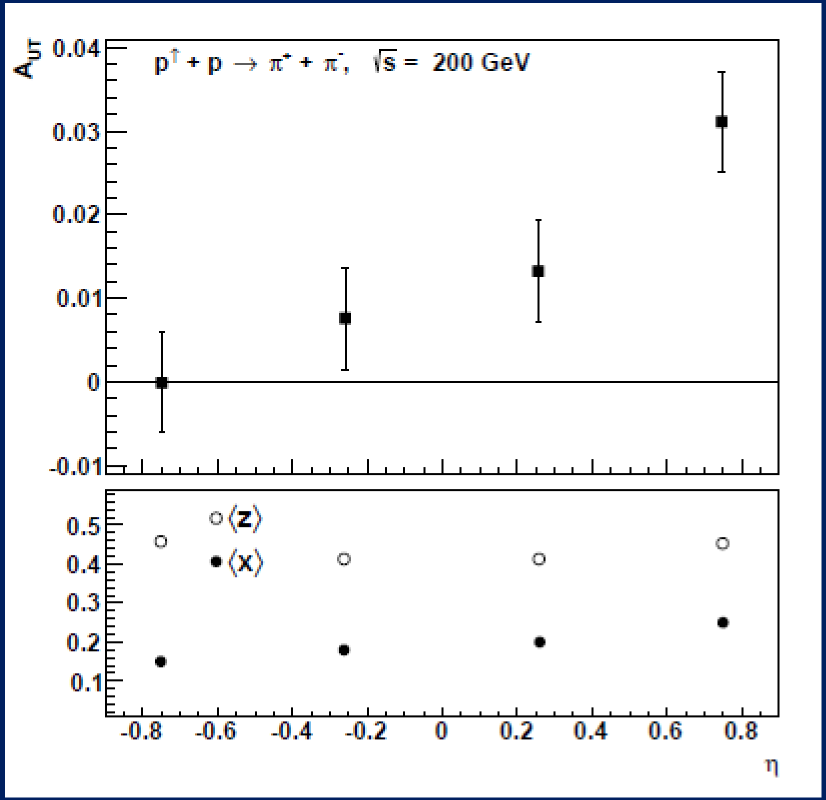


Collinear, twist-3 multiparton correlations in hadronization

- 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

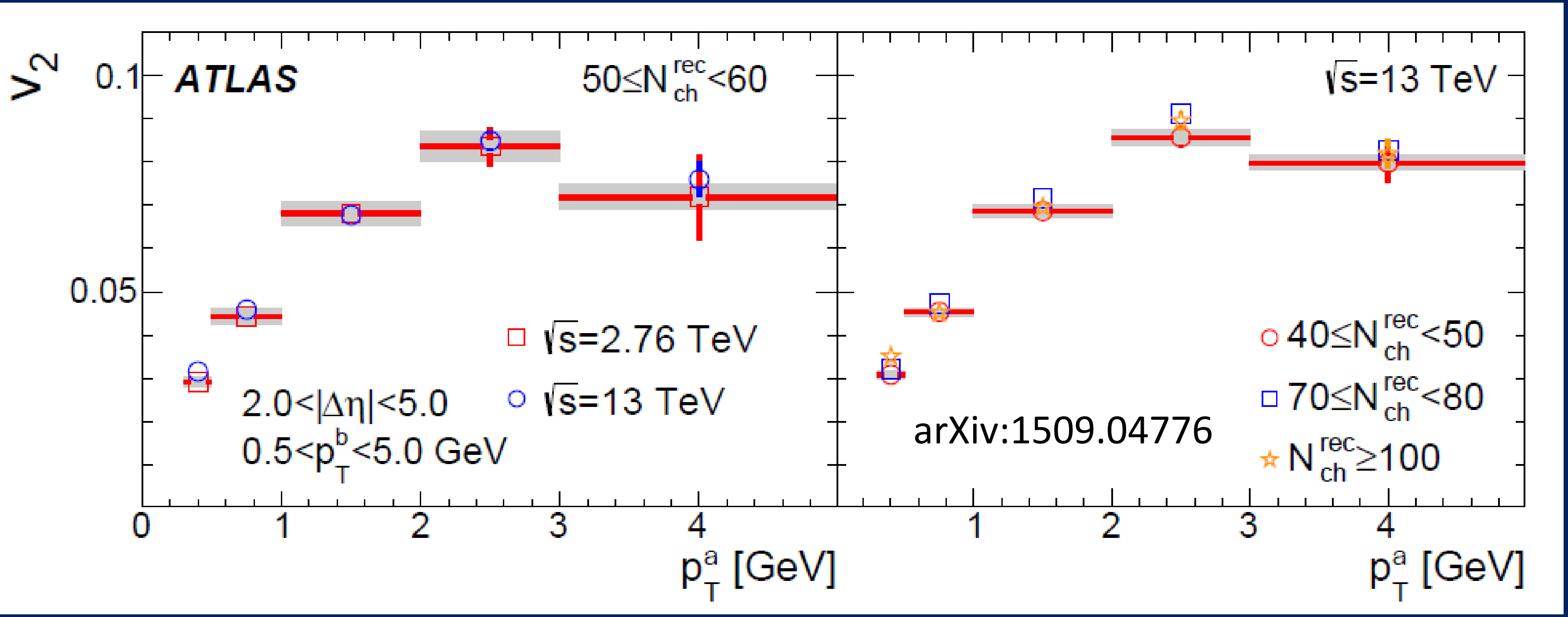
Transverse single-spin asymmetry in dihadron production, 200 GeV p+p





- 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
- Clear nonzero asymmetry observed; pseudorapidity dependence
- Sensitive to transversity x IFF

High-multiplicity p+p: p_T-dependent cos 2ϕ modulation



- v_2 = amplitude of cos 2ϕ modulation
- Heavy ion community thinks of hydrodynamic flow . . .
- Proton structure community thinks of spin-momentum correlations such as Boer-Mulders . . .