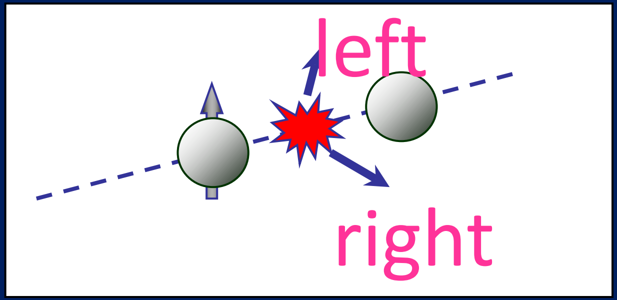
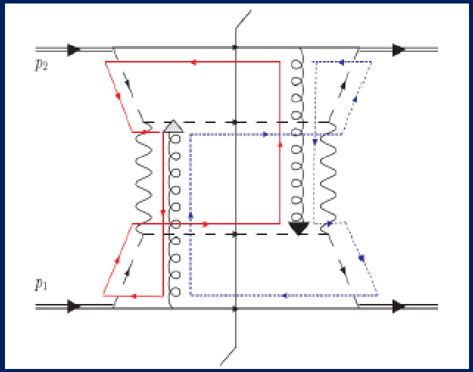
Transverse-Momentum-Dependent Distributions and Color Entanglement in QCD

Lecture 6 – Connections to Other Subfields and Outlook

Christine A. Aidala

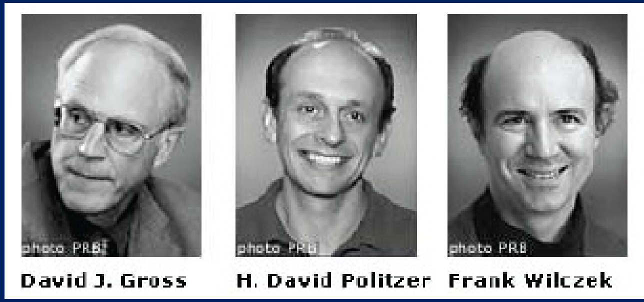
University of Michigan





Hampton University Graduate Studies Program
Jefferson Lab
June 2016

QCD: How far have we come?



- QCD is challenging!!
- Three-decade period after initial birth of QCD dedicated to "discovery and development"

→ Symbolic closure: Nobel prize 2004 - Gross, Politzer, Wilczek for asymptotic freedom

Now early years of second phase:
quantitative QCD!

Advancing the era of quantitative QCD: Theory has been forging ahead!

- In perturbative QCD, since 1990s starting to consider detailed internal QCD dynamics that parts with traditional parton model ways of looking at hadrons—and perform <u>phenomenological calculations</u> using these new ideas/tools!

  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentum fractions
  - *Spin-spin* and *spin-momentum* correlations in QCD bound states
  - *Spatial* distributions of partons in hadrons
- Non-perturbative methods:
  - Lattice QCD less and less limited by computing resources—since 2010 starting to perform calculations at the physical pion mass (after 36 years!). Plus recent new ideas on how to calculate previously intractable quantities.

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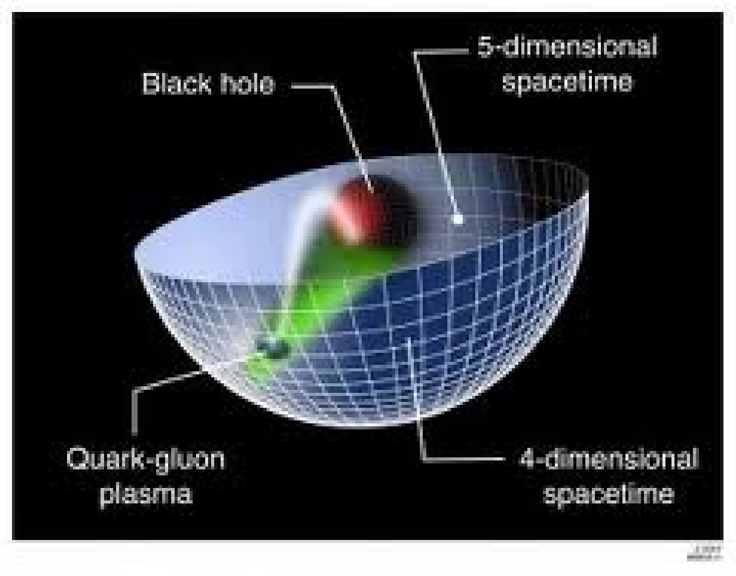

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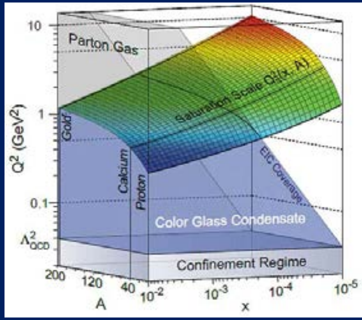
  - Lattice QCD less and less limited by computing resources—since 2010 starting to perform calculations at the physical pion mass (after 36 years!). Plus recent new ideas on how to calculate previously intractable quantities.
  - AdS/CFT "gauge-string duality" an exciting recent development as first fundamentally new handle to try to tackle QCD in decades!

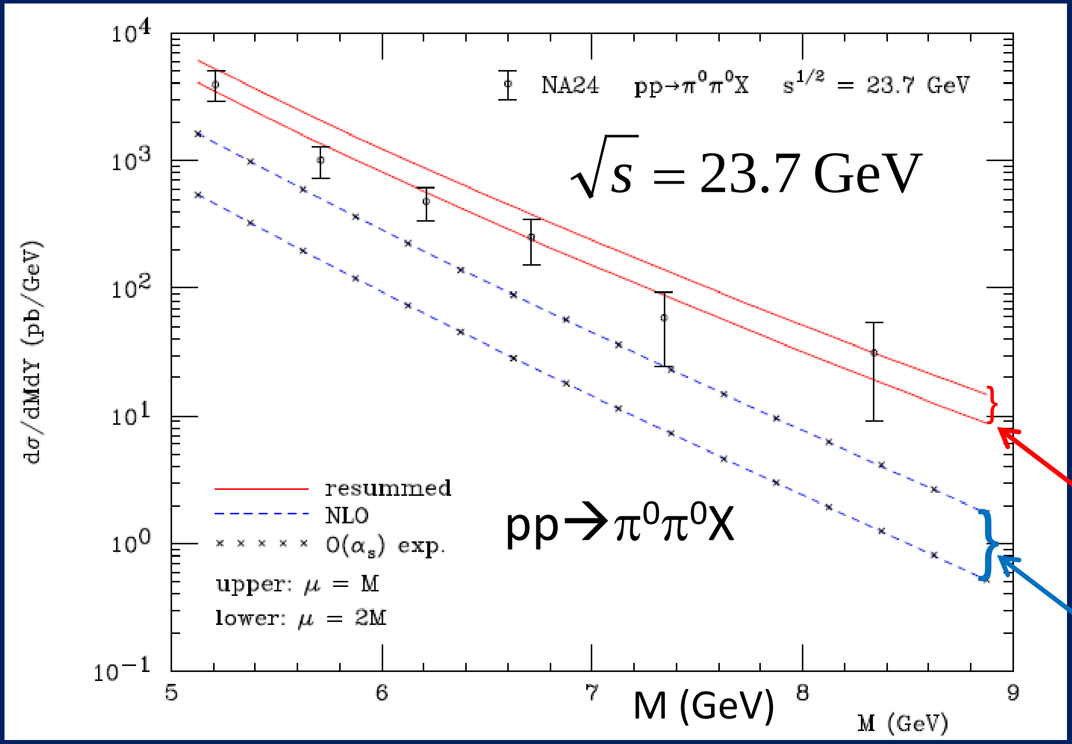
Lectures by Emilie Passemar

Effective field theories



- QCD exhibits different behavior at different scales—effective field theories are useful approximations within these different regimes
  - Color Glass Condensate – high energies, high densities
  - Soft-Collinear Effective Theory – new insights into performing complicated perturbative calculations very quickly
  - Heavy Quark Effective Theory, Non-Relativistic QCD, . . .
  - Many effective theories for nonperturbative QCD – chiral perturbation theory, . . .

Example: "Threshold resummation" Extending perturbative calculations to lower energies



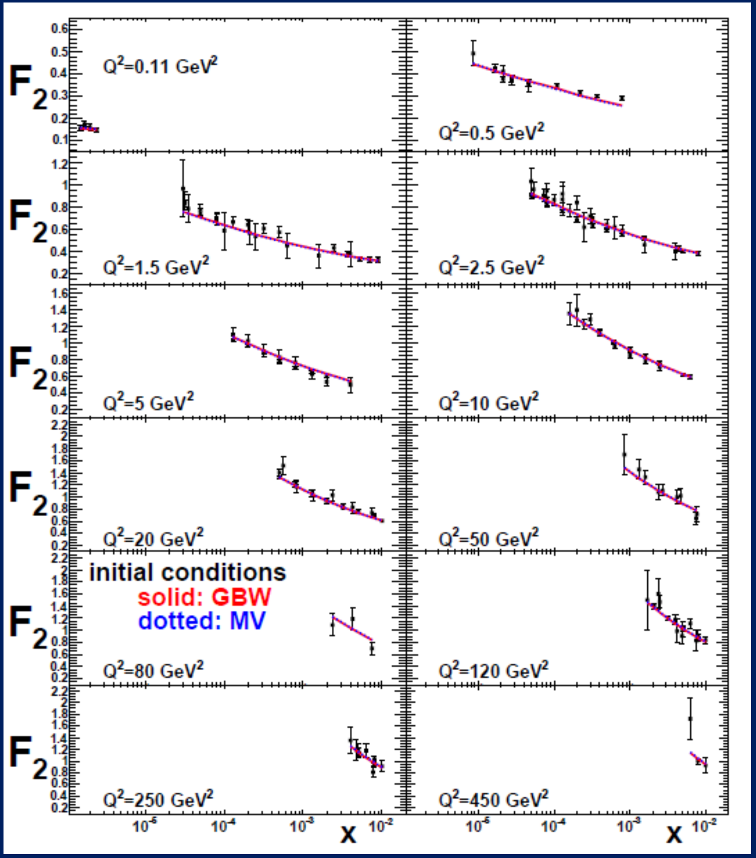
For observables with two different scales, sum logs of their ratio to all orders in the strong coupling constant

Next-to-leading-order in α_s + resum.

Next-to-leading-order in α_s

Almeida, Sterman, Vogelsang PRD80, 074016 (2009)

Example: Phenomenological applications of a non-linear gluon saturation regime at low x



Fits to proton structure function data at low parton momentum fraction *x*.

Non-linear QCD meets data: A global analysis of lepton-proton scattering with running coupling BK evolution

Phys. Rev. D80, 034031 (2009)

Javier L. Albacete[1], Néstor Armesto[2], José Guilherme Milhano[3] and Carlos A. Salgado[2]

Basic framework for non-linear QCD, in which gluon densities are so high that there's a non-negligible probability for two gluons to combine, developed ~1997-2001. But had to wait until "running coupling BK evolution" figured out in 2007 to compare directly to data!

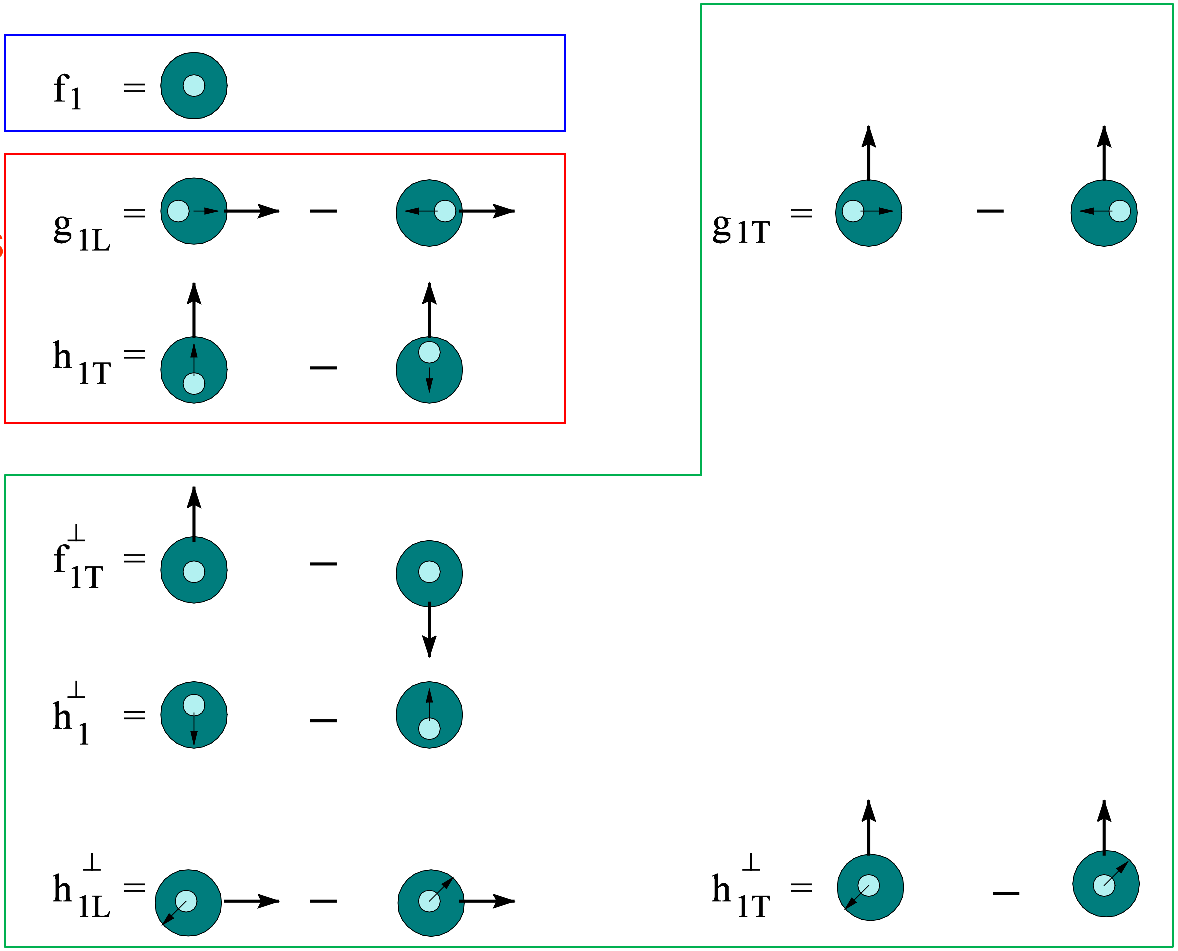
Example: Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

Spin-spin correlations

Spin-momentum correlations

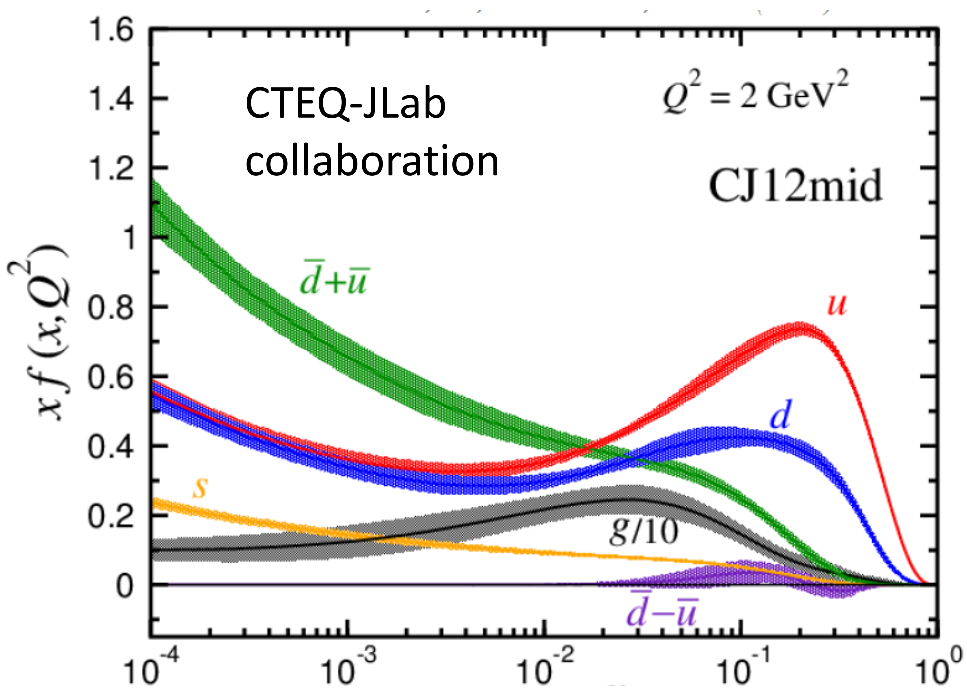
$S\bullet(p_1 \times p_2)$



Example: Fits to quark and gluon distributions including much wider range of data

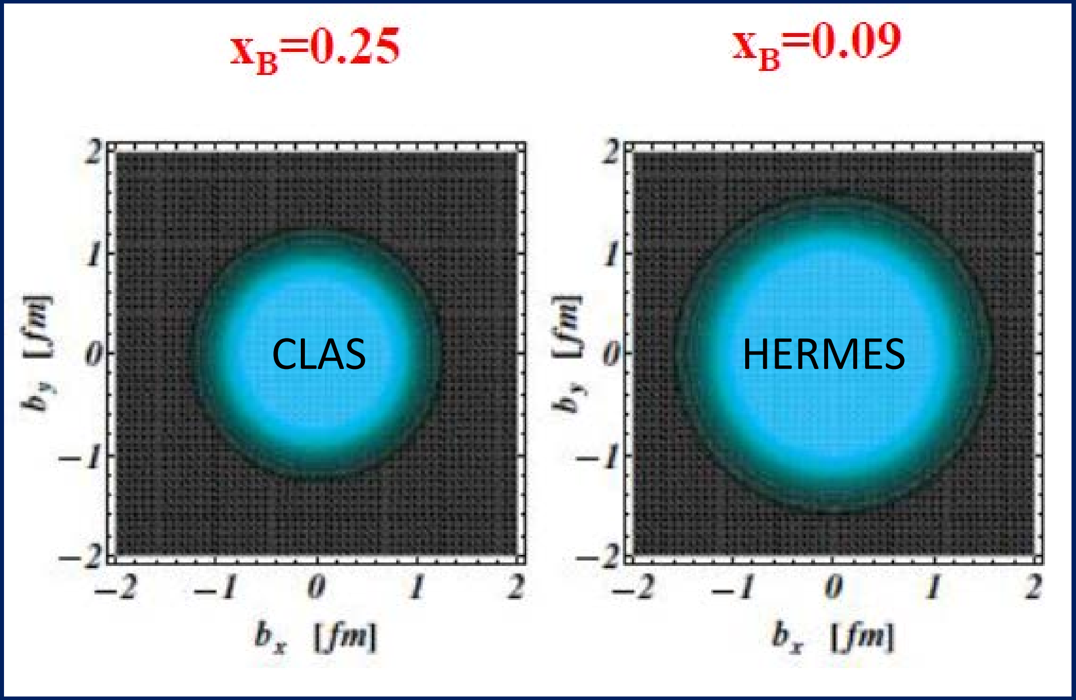
- Incorporate corrections for target mass, higher twist, and nuclear effects
- Can in turn make predictions for future measurements in extended kinematic regions

Owens, Accardi, Melnitchouk, PRD87, 094012 (2013)



Collinear momentum fraction *x*

Example: Exploring spatial distributions

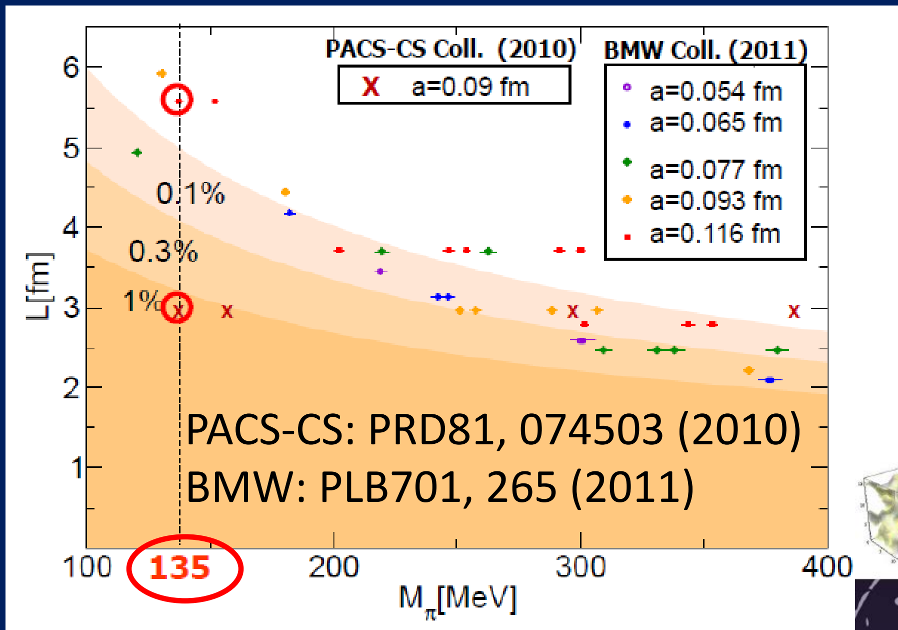


Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013) 066202

Spatial charge densities measured via deeply virtual Compton scattering

Initial evidence that quarks carrying larger momentum fractions (25% vs. 9%) in the nucleon are distributed over a smaller volume in space

Example: Progress in lattice QCD

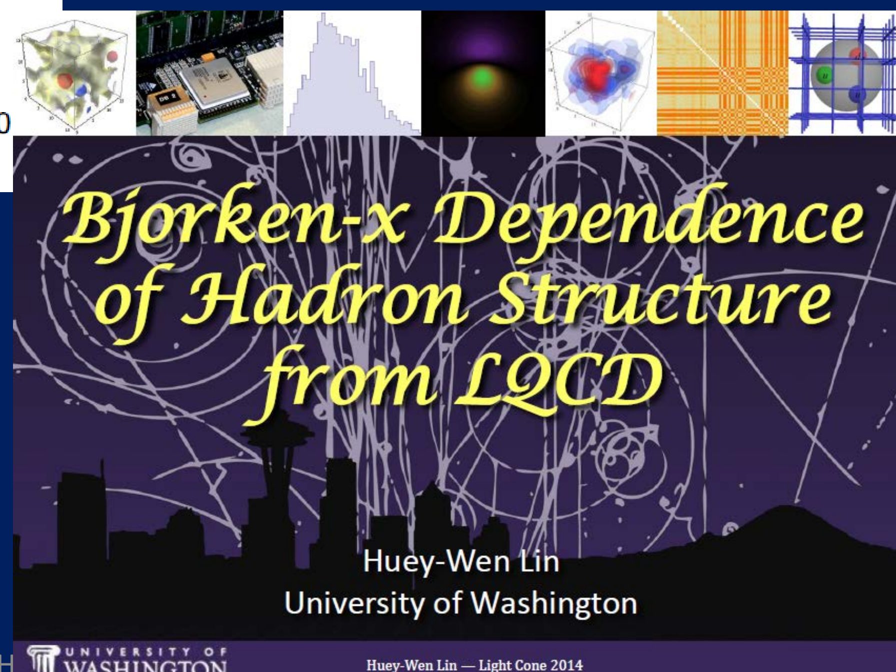


First calculations at physical pion mass 135 MeV

Figure from T. Hatsuda, PANIC 2011

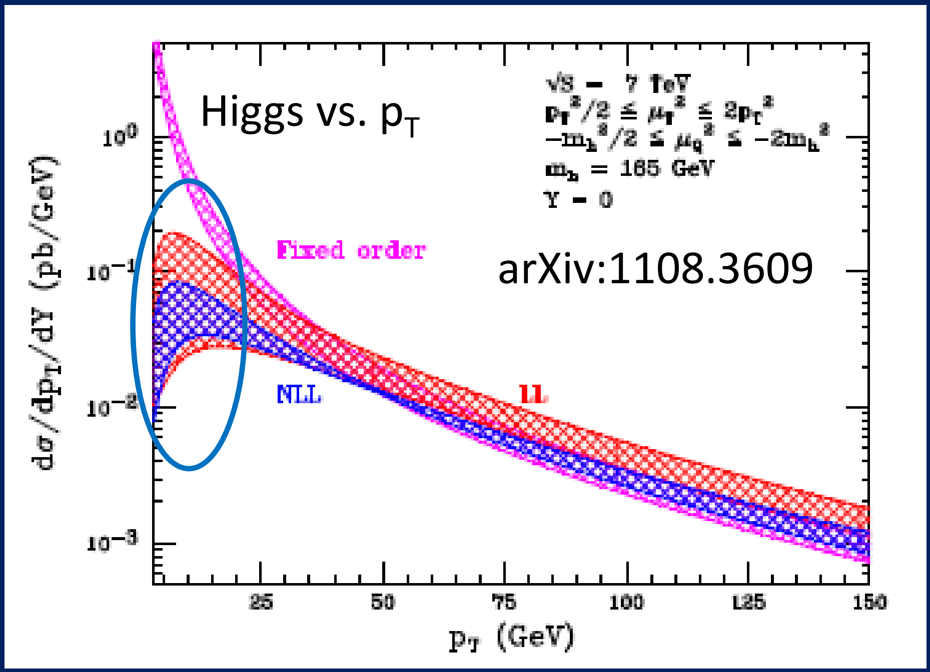
Since 2013, possibility to calculate x dependence of parton distribution functions

Slide from Huey-Wen Lin, Light Cone 2014



Example: Effective field theories

Soft Collinear Effective Theory – p_T distribution for gg→Higgs



TRANSVERSE MOMENTUM DISTRIBUTIONS FROM EFFECTIVE FIELD THEORY

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"Modern-day 'testing' of (perturbative) QCD is as much about pushing the boundaries of its applicability as about the verification that QCD is the correct theory of hadronic physics."
– G. Salam, hep-ph/0207147 (DIS2002 proceedings)

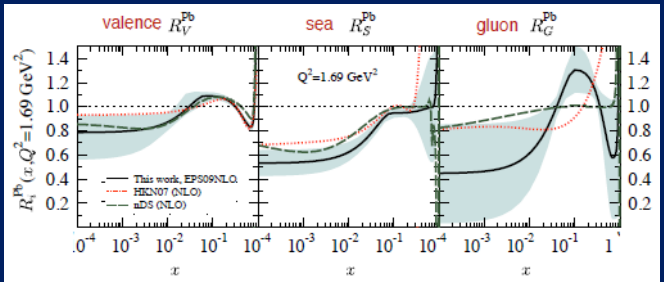
Experimental advances

- More sophisticated observables
  - E.g. angular distributions, spin dependence, multiparticle final states, . . .
  - Often sensitive to parton *dynamics*
- Multidifferential measurements
  - E.g. simultaneously in x, Q^2, p_T

→ Demand more of theoretical calculations!

Increasing connections among historically disparate areas of QCD

As we advance, we're building more connections among the various areas of QCD—and to other fields . . .



- Nucleon structure and heavy ion communities
  - Greater focus on initial-state (cold) nuclear effects
  - Parton distribution functions in the proton vs. nuclei
  - Hadronic vs. partonic degrees of freedom
  - In 2015 RHIC ran polarized protons on gold! Use polarization to help search for gluon saturation physics
  - Ultraperipheral heavy ion collisions and Generalized Parton Distributions for spatial imaging; impact-parameter-dependent nuclear distributions and collision geometry in heavy ion physics

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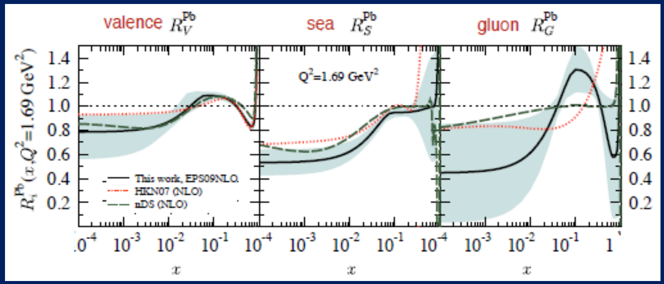

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  - "String fragmentation" vs. binding of nearby partons in phase space
  - Modified hadronization in hot or cold nuclear matter

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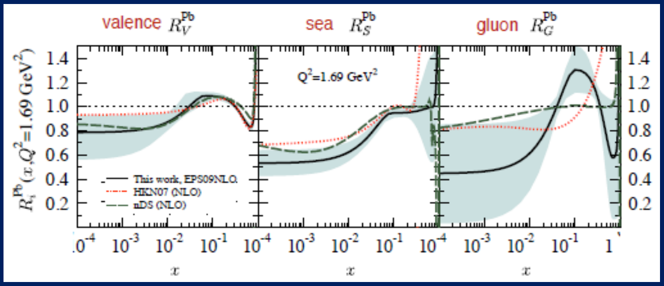

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- Heavy ion and stellar structure communities
  - Quark-gluon plasma and neutron stars: different corners of QCD phase diagram
- Heavy ion and low-energy nuclear reaction, cosmology communities
  - "Little Bang Nucleosynthesis" up to helium-4 (and antihelium-4!) in heavy ion collisions

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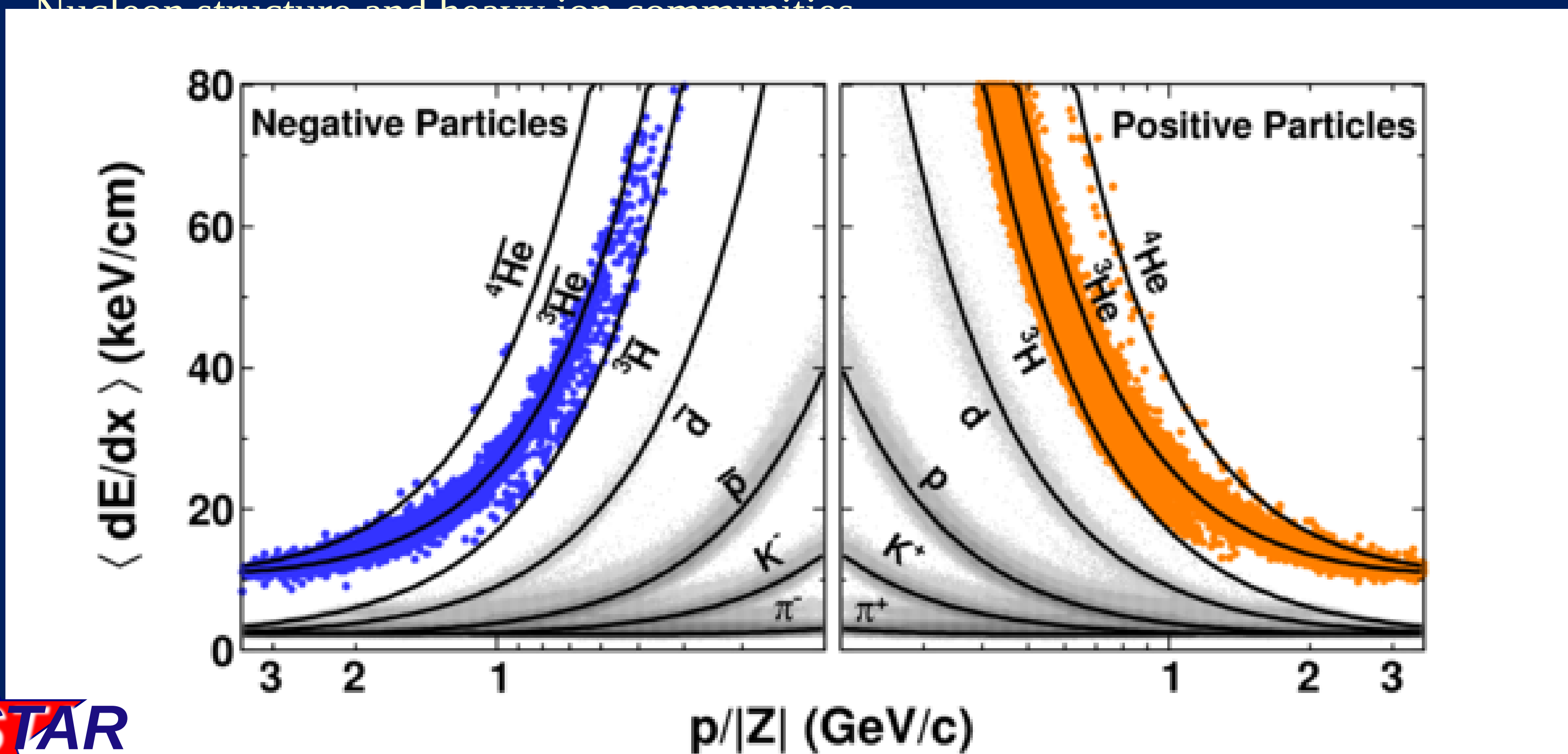
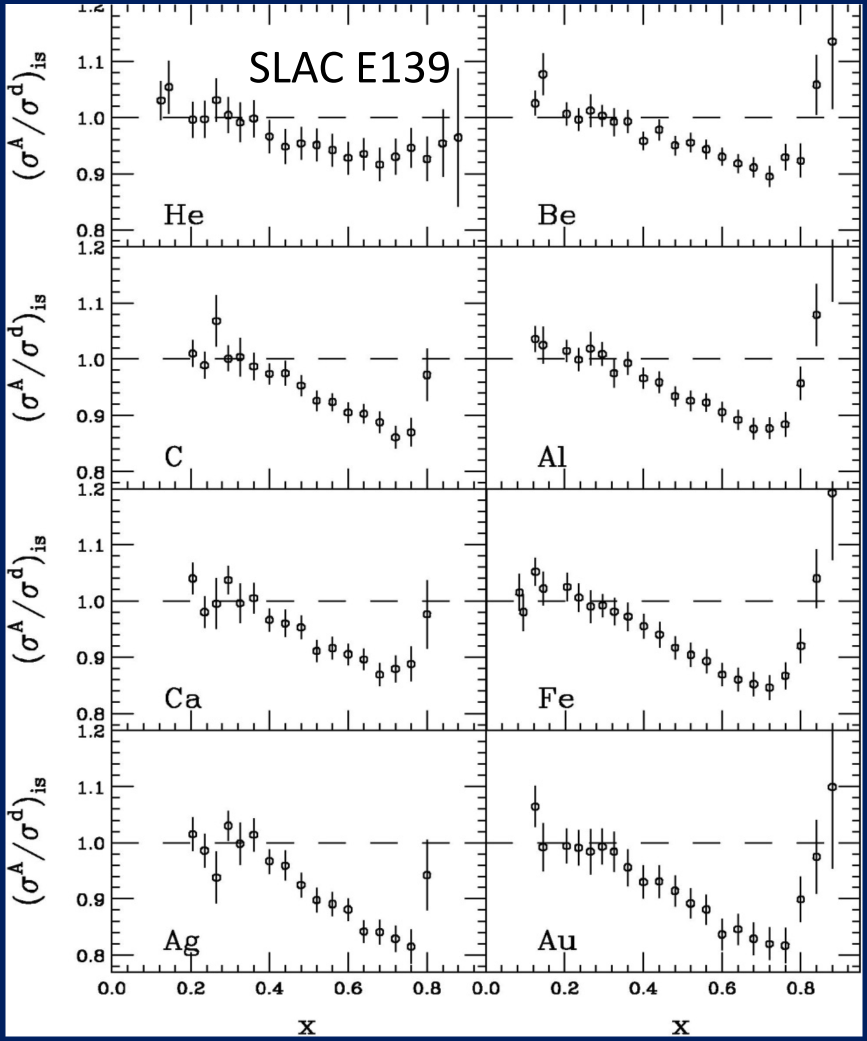


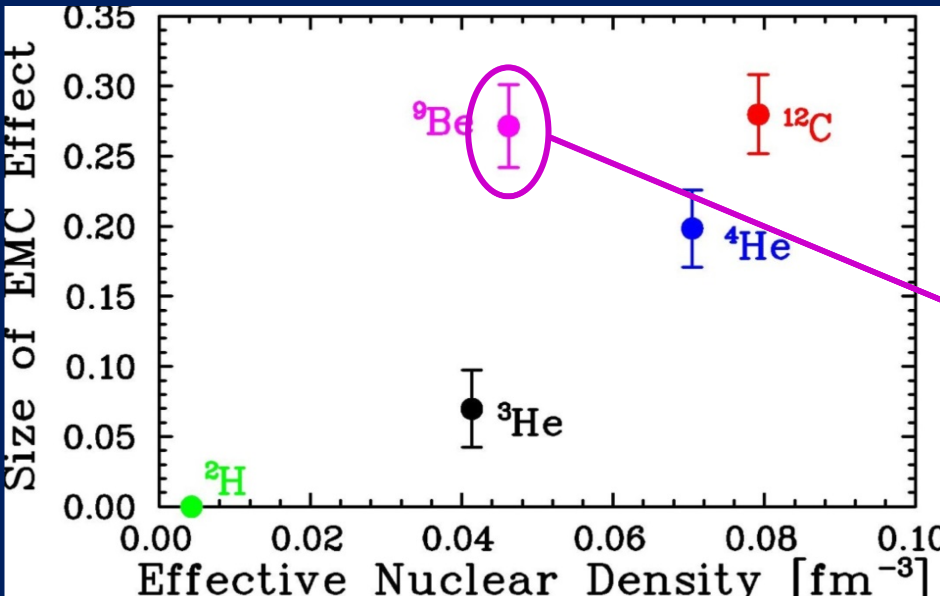
Nature 473, 353 (2011)

Nuclear modification of structure functions and the "EMC effect"

- DIS on nuclei, take ratio to DIS on deuterium
- Shows nuclear modification of structure functions
- Evidence for collective effects in nuclei



Links between partonic and nucleonic pictures of nuclei!

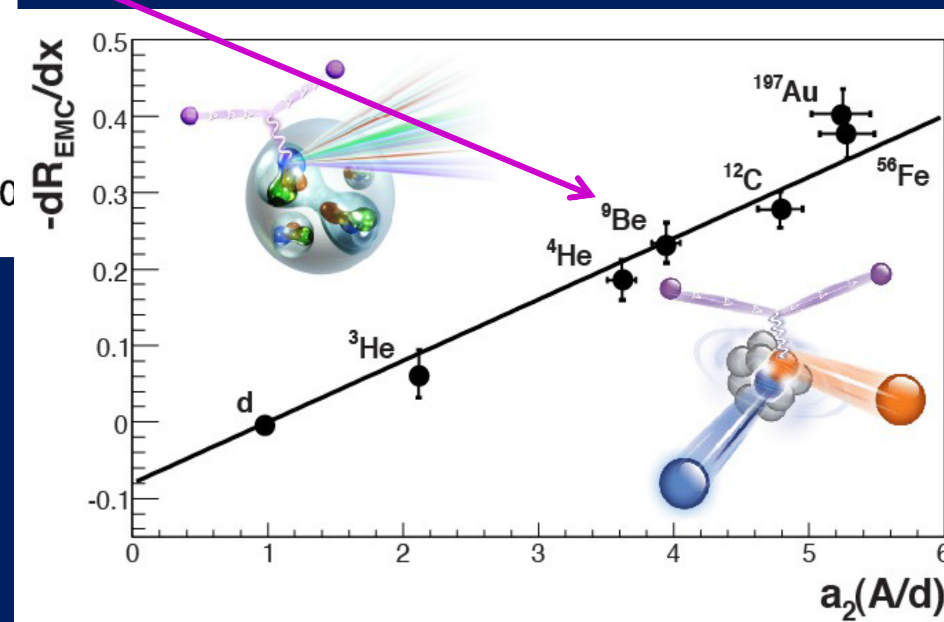


J. Seely, et al., PRL103, 202301 (2009)

N. Fomin, et al., PRL 108, 092052 (2012)

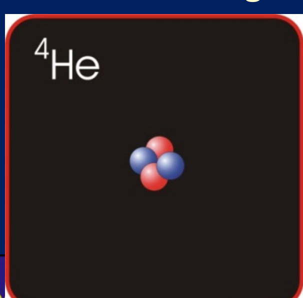
JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204

EMC effect of nuclear modification of DIS structure functions seems to be related to *local*, not average, density of nucleons

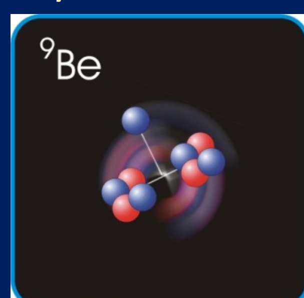


O. Hen, et al, PRC 85, 047301 (2012)

L. Weinstein, et al., PRL 106, 052301 (2011)



Credit: P. Mueller



Increasing connections between nuclear and particle physics

- Low-x/gluon saturation physics
  - Onset expected in higher-energy p+p collisions, lower-energy heavy ion collisions
- Transverse-momentum-dependent parton distribution functions, Q_T resummation, Soft-Collinear Effective Theory
  - Determine transverse momentum distribution for Higgs, Z/W, Drell-Yan at low p_T

Probing Gluonic Spin-Orbit Correlations in Photon Pair Production

Jian-Wei Qiu[1,2], Marc Schlegel[3] and Werner Vogelsang[3]
[1] *Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA and*
[3] *Institute for Theoretical Physics, Tübingen University, Auf der Morgenstelle 14, D-72076 Tübingen, Germany*
(Dated: July 27, 2011)

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  - Gluon vs. quark jets and hadronization
  - Search for beyond the SM physics
  - Measure parton spin-momentum correlations in hadronization via angular distributions of particles within jet
  - Understand jet modification and energy redistribution in nuclear medium
- Underlying event
  - Soft QCD physics in p+p, nuclear collisions
- Collectivity in high-multiplicity systems, regardless of system size

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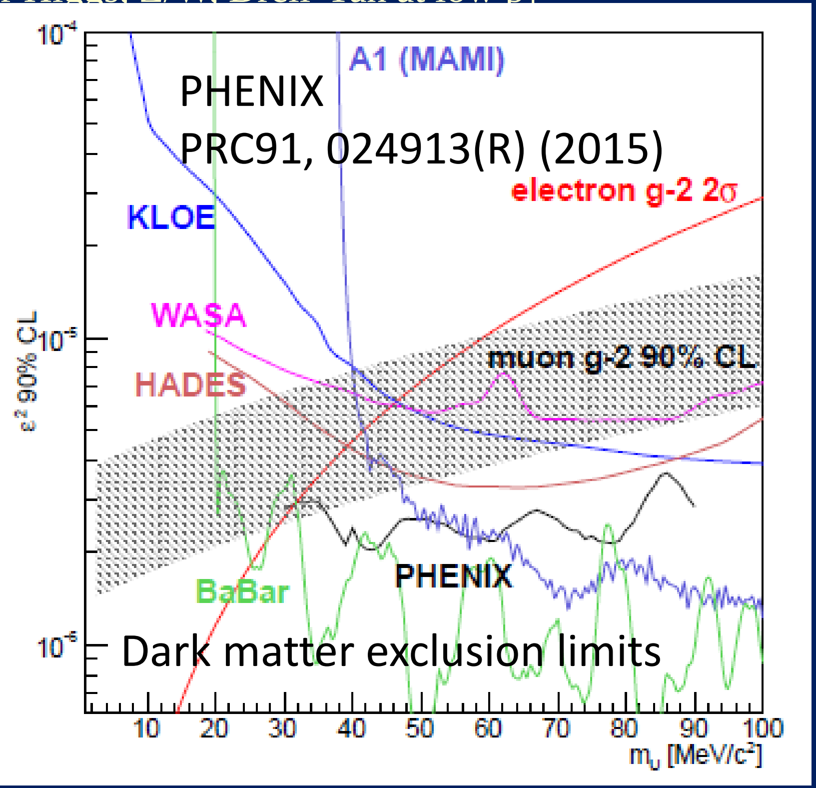


Color entanglement linked to "color coherence"??

PHYSICAL REVIEW D VOLUME 50, NUMBER 9 1 NOVEMBER 1994

CDF Collaboration

Evidence for color coherence in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

Color coherent radiation in multijet events from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

DØCollaboration PLB414, 419 (1997)

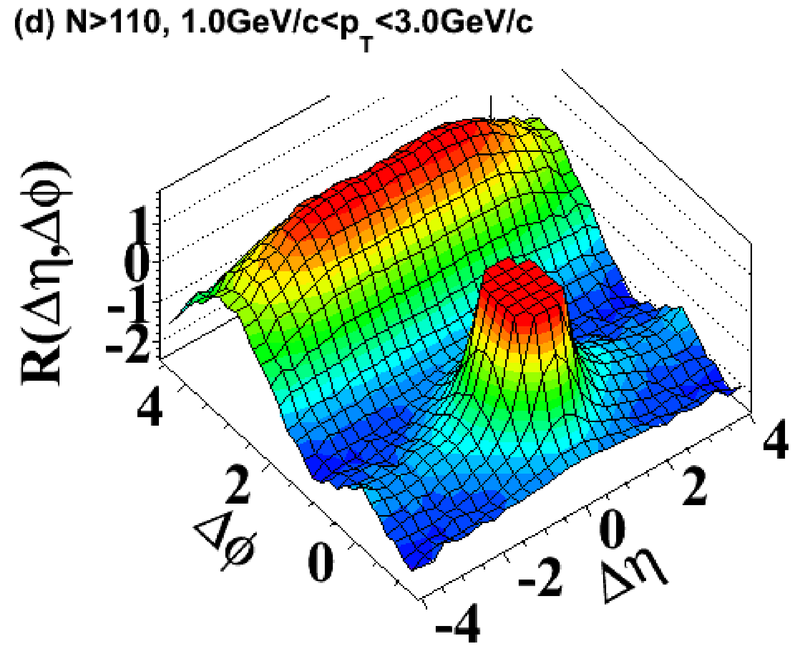
Probing color coherence effects in pp collisions at $\sqrt{s} = 7$ TeV

EPJ C74, 2901 (2014)

The CMS Collaboration*

Communities haven't been aware of each other's work …

Color entanglement implies long-distance parton correlations



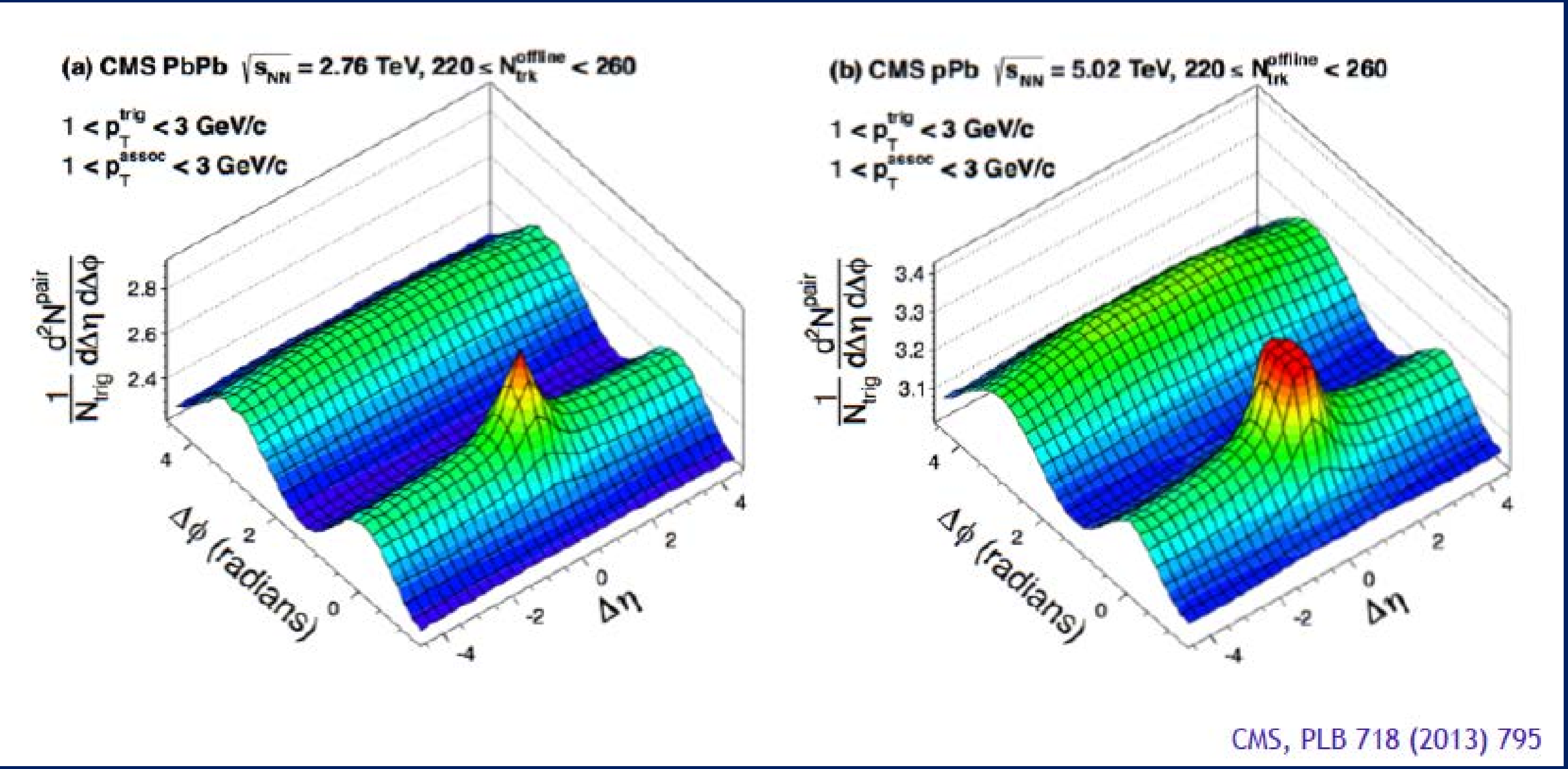
CMS JHEP 09 (2010), 091

Long-range correlations in high-multiplicity p+p at 7 TeV

- Surprising collectivity observed in high-multiplicity hadronic systems, regardless of size
  - Related to color entanglement effects??

- See Rogers, PRD88, 014002 (2013) for discussion of possible links between color entanglement and a variety of existing experimental observations

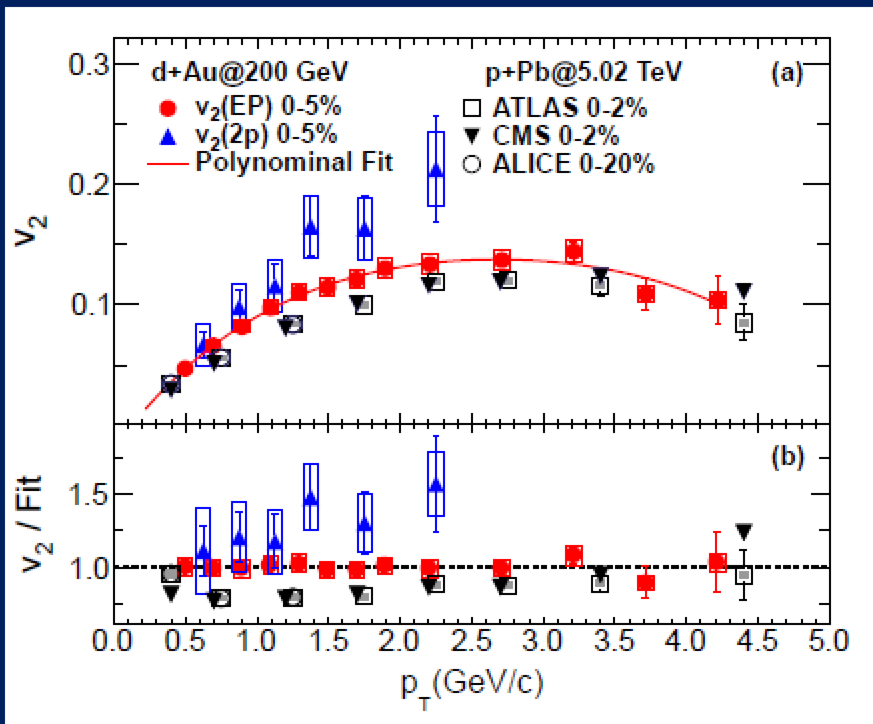
Surprising collectivity in high-multiplicity systems, regardless of size

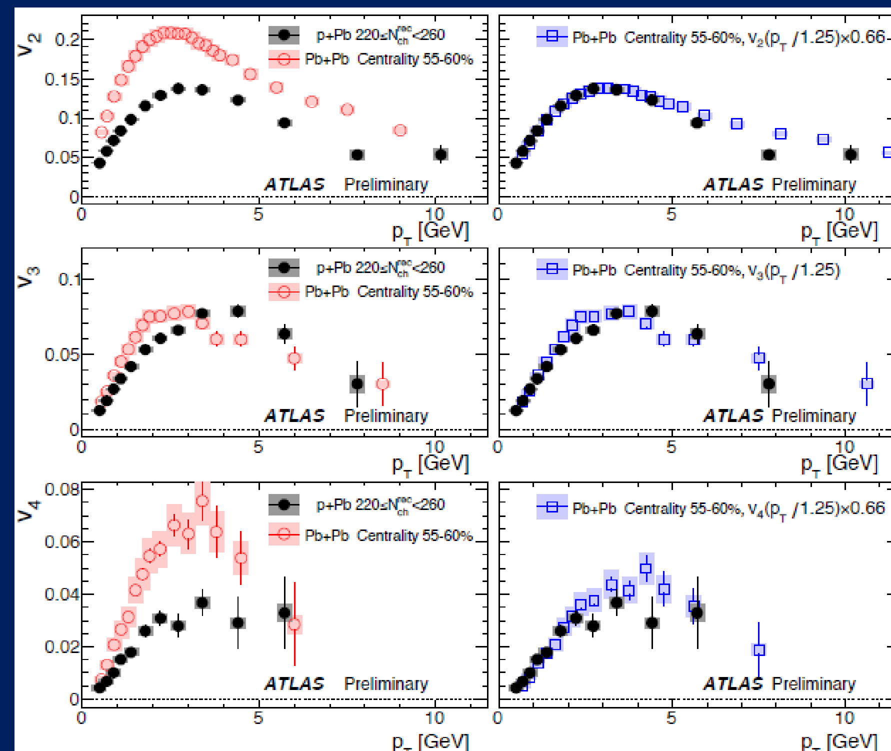


Pb+Pb at 2.76 TeV and high-multiplicity p+Pb at 5.02 TeV.
In Pb+Pb (and RHIC Au+Au) understood to be due to hydrodynamic flow of equilibrated quark-gluon plasma. What's going on in high-multiplicity p+p, p+Pb, d+Au?

Collectivity in high-multiplicity systems: Fourier amplitudes

PHENIX: PRL 114, 192301 (2015)



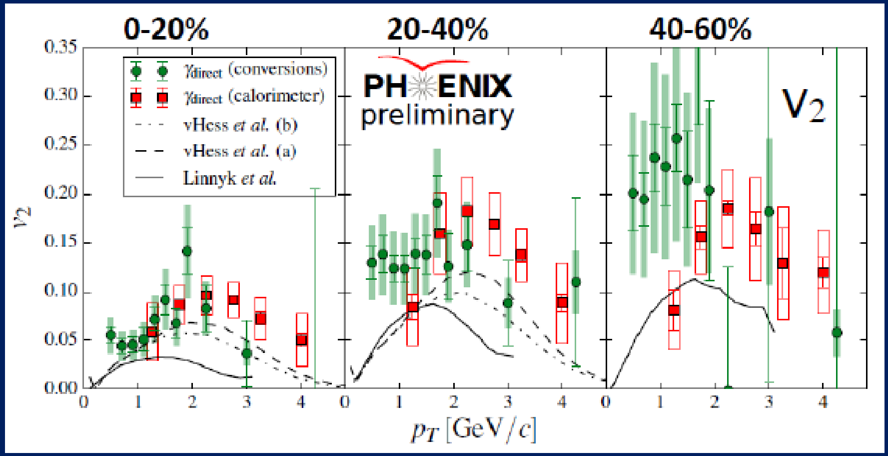


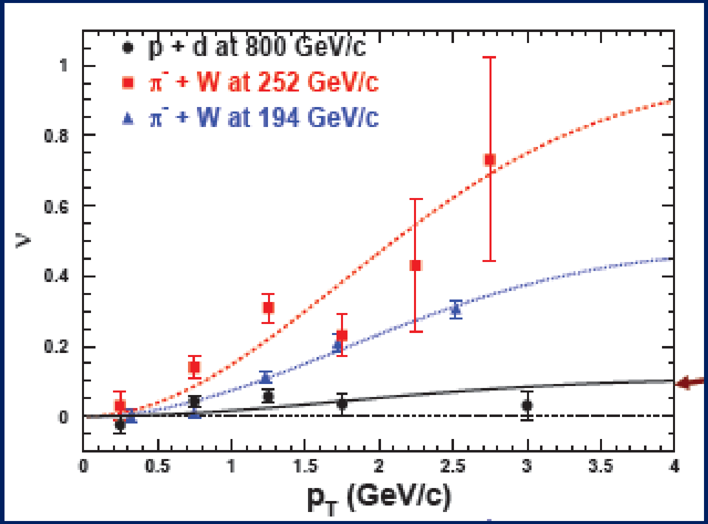
Large cos 2ϕ modulation in d+Au at 200 GeV, p+Pb at 5.02 TeV

Higher Fourier harmonics also large in high-multiplicity p+Pb. Empirical scaling shows similarity between p+Pb and Pb+Pb.

How many ways can a cos 2ϕ modulation be generated in hadronic collisions??

- Large modulation in direct photon production in 200 GeV Au+Au collisions
  – Not well understood
- *Huge* modulation in pion-induced Drell-Yan
  – Understood as due to spin-momentum correlations of partons inside (unpolarized) hadrons

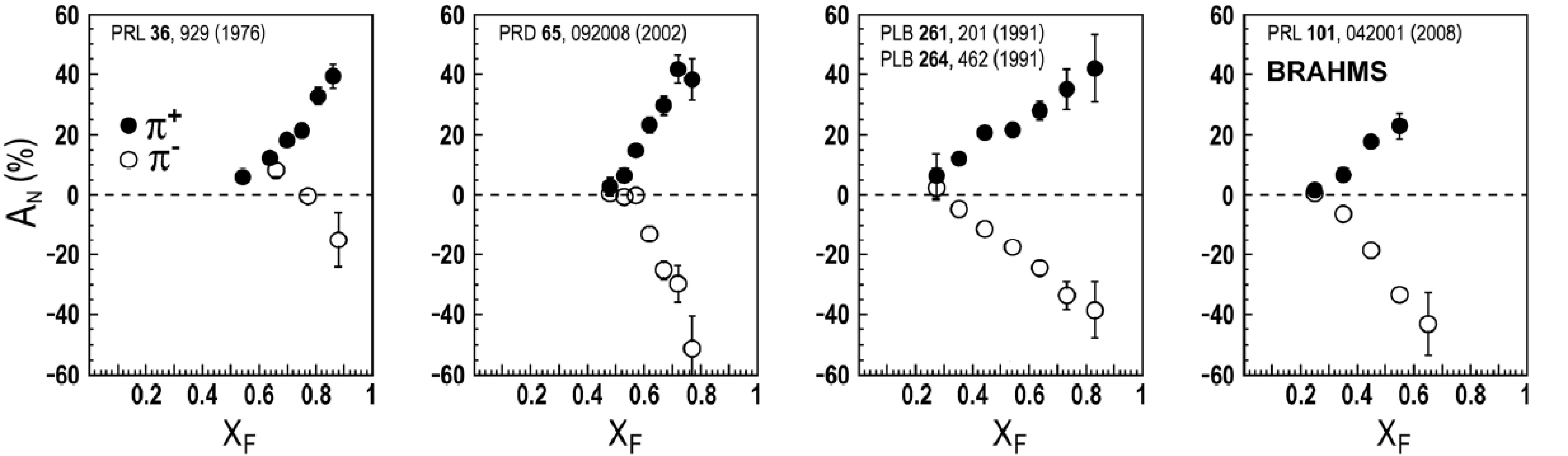




E866, PRL 99, 082301 (2007)
E615, PRD39, 92 (1989)
NA10, ZPC31, 513 (1986)

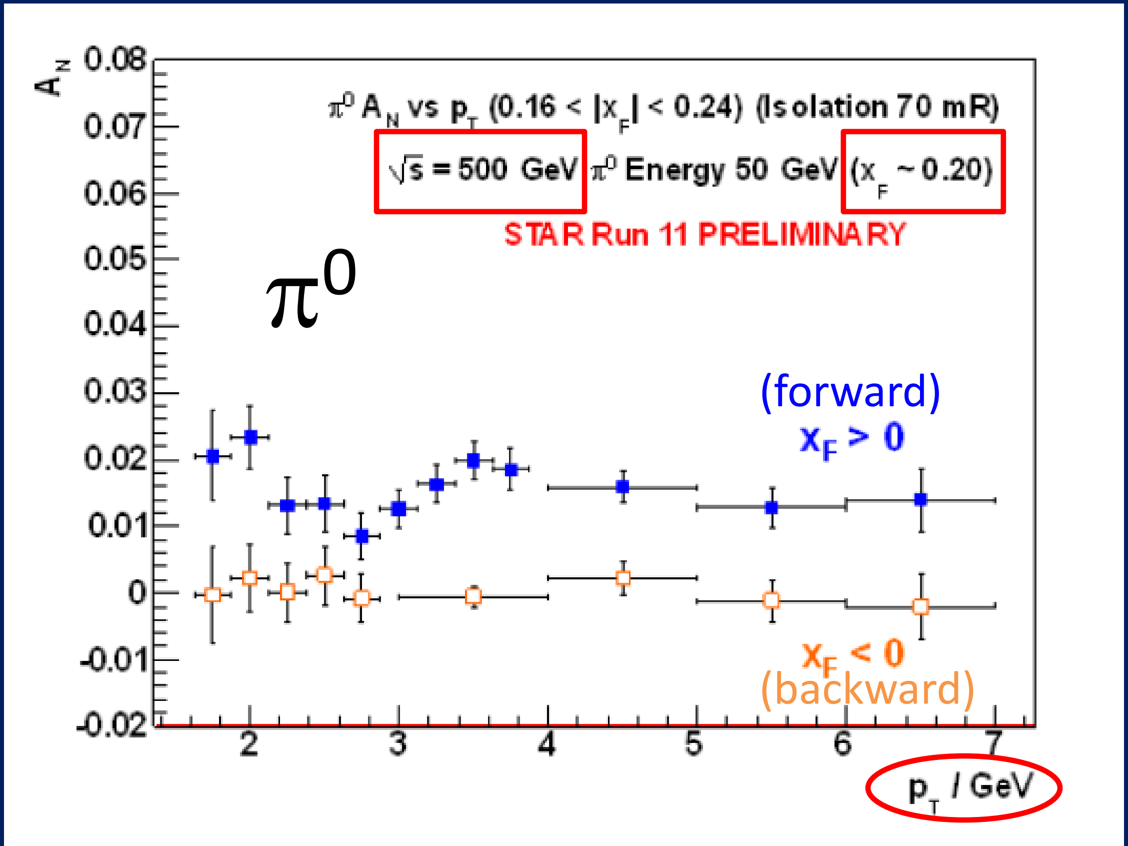
Huge transverse single-spin asymmetries in proton-proton collisions related to color entanglement effects?

ANL	BNL	FNAL	RHIC
√s=4.9 GeV	√s=6.6 GeV	√s=19.4 GeV	√s=62.4 GeV



Strikingly similar effects across energies!
→ Continuum between nonperturbative/nonpartonic and perturbative/partonic descriptions of this <u>nonperturbative</u> structure?

Don't seem to fall off with hard scale

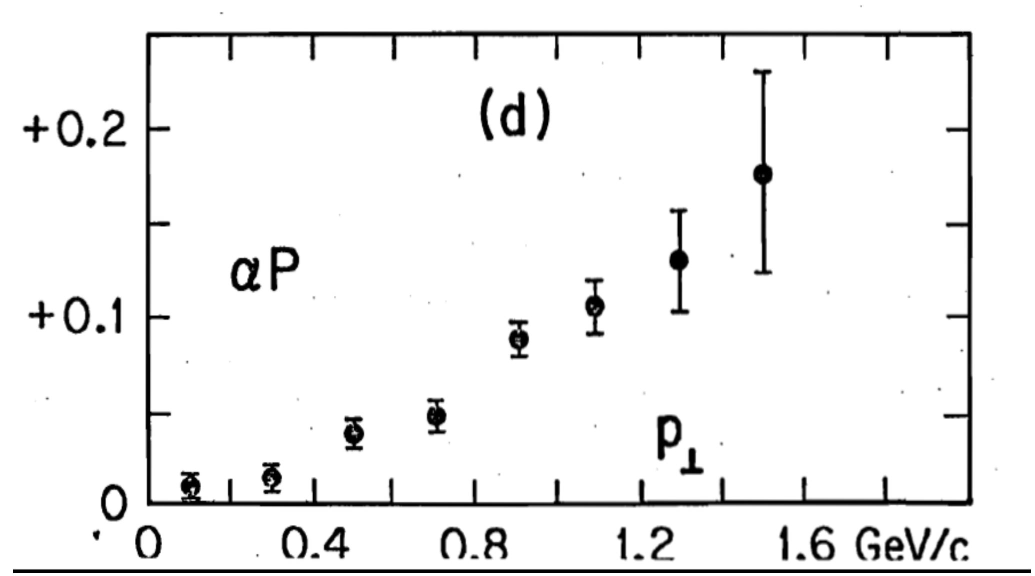


- Effects persist to kinematic regimes where perturbative QCD techniques clearly apply
- And don't seem to fall off with hard scale, as would be expected
- p_T = 7 GeV
  → Q^2 ~ 49 GeV^2!

Hyperon polarization from unpolarized collisions

Λ^c Hyperon Polarization in Inclusive Production by 300 GeV Protons on Beryllium

PRL36, 1113 (1976)



- Polarization transverse to production plane up to ~20% for forward-angle lambda production
- Confirmed by various proton-nucleus and proton-proton experiments
- Polarizing TMD FF?? Color entanglement effects??

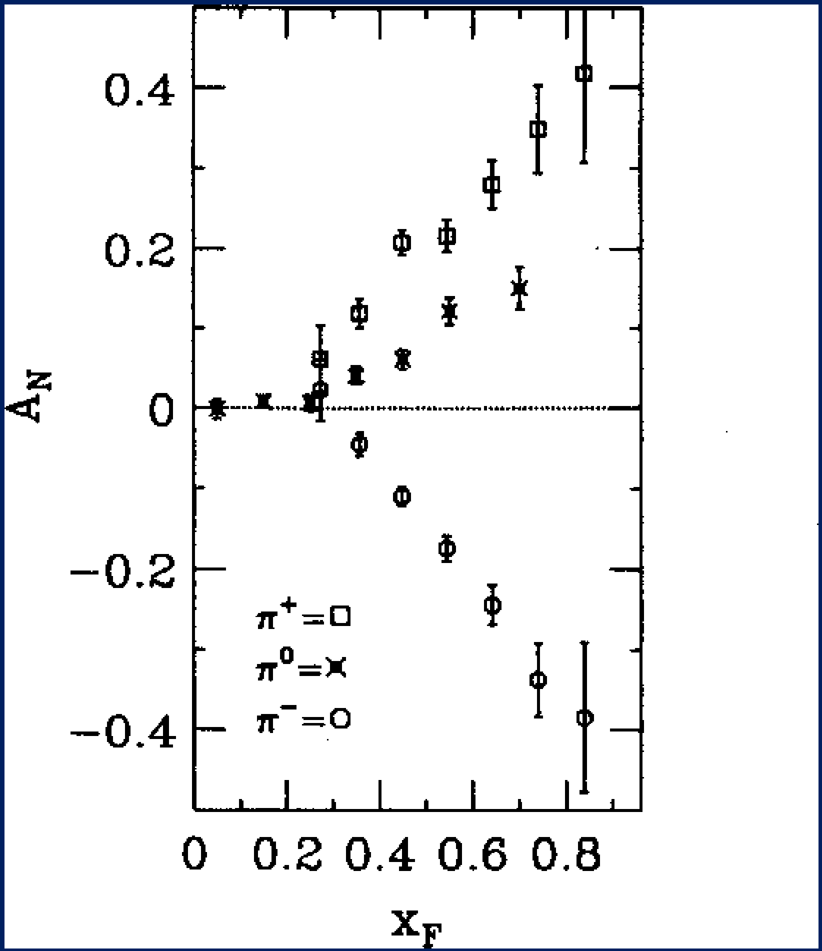
The "physics" vs. the "tools"

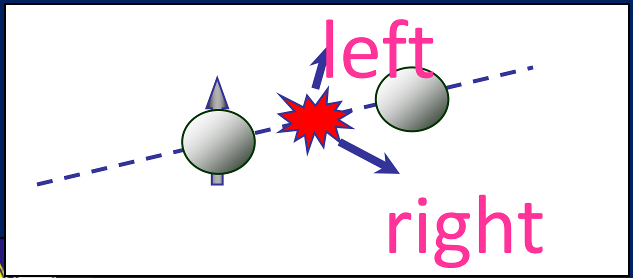
- "Heavy ion physics"—heavy ions (nuclei) tools to study
  - Hot, dense QCD systems (quark-gluon plasma)
  - QCD phase diagram
  - Low-x physics/gluon saturation
  - Parton energy loss in cold/hot nuclear matter
  - Partonic structure of nuclei
  - Collective phenomena in high-multiplicity partonic/hadronic states
  - …
- Not limited to heavy nuclei as the only relevant tools
  - Light nuclei, collisions of light on heavy nuclei, even p+p!
  - e+p, e+A also useful tools for several of the above

The "physics" vs. the "tools"

- Transverse single-spin asymmetry measurements at Fermilab used spontaneous lambda polarization to create transversely polarized beams of protons and antiprotons!

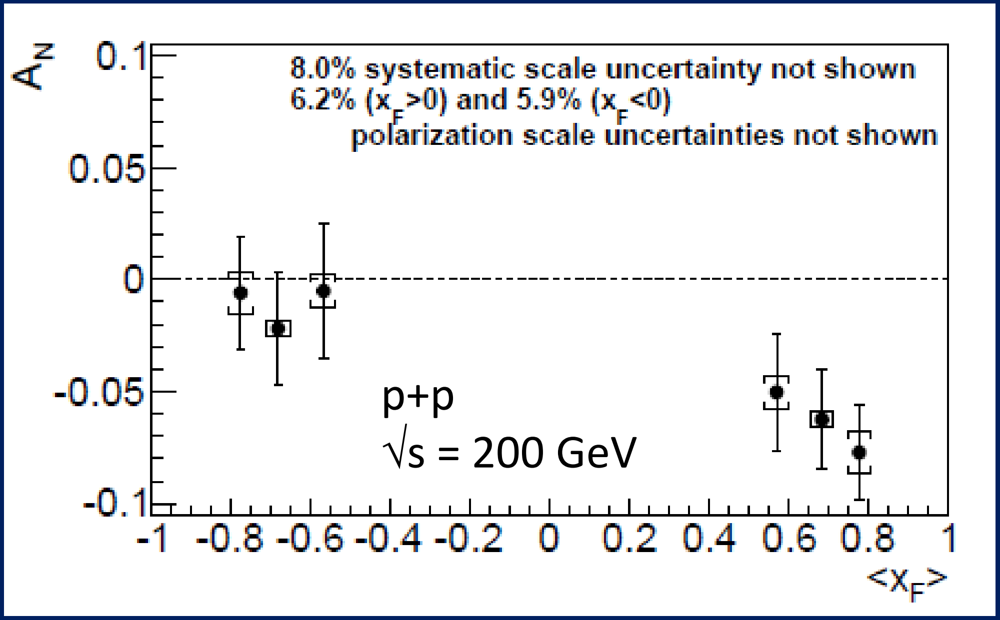
E704 at Fermilab at $\sqrt{s}$=19.4 GeV, p_T=0.5-2.0 GeV/c:





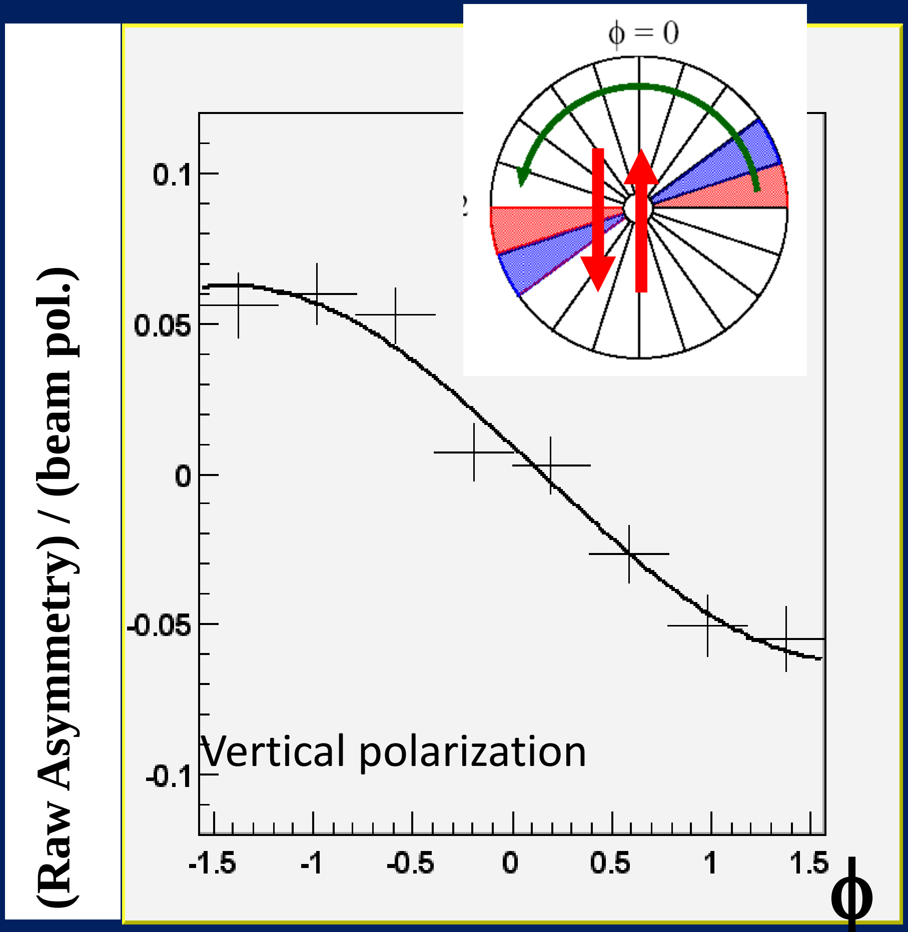
The "physics" vs. the "tools"

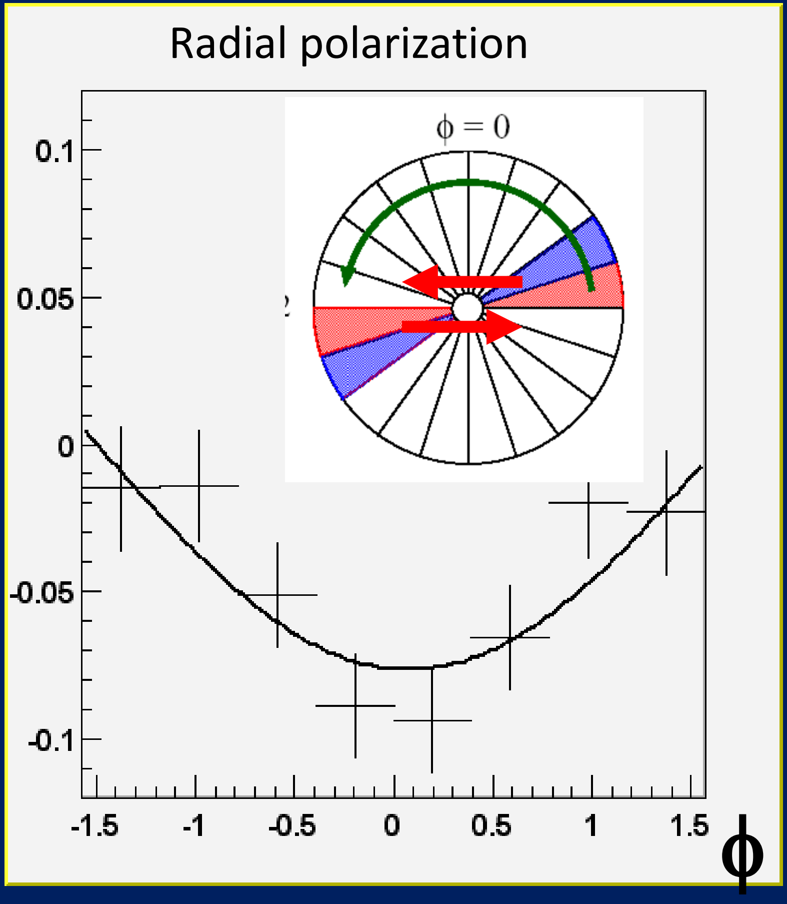
- Large negative transverse single-spin asymmetry observed in forward neutron production in p+p
- Not in perturbative regime (no hard scale)
- Interference between spin-flip amplitude due to pion exchange and nonflip amplitude from other Reggeon exchanges?
- Other effects relevant in this spin-momentum correlation?



PHENIX, PRD88, 032006 (2013)

The "physics" vs. the "tools"

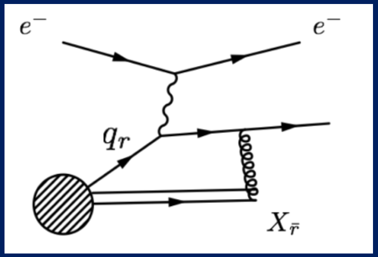


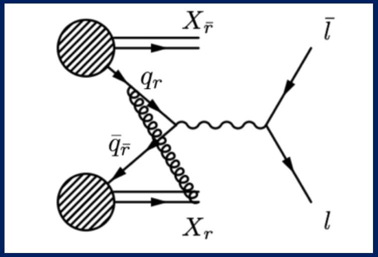


Use neutron asymmetry to confirm beam polarization direction at PHENIX, even if physics not completely understood!

The "physics" vs. the "tools": QCD <u>interactions</u>

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





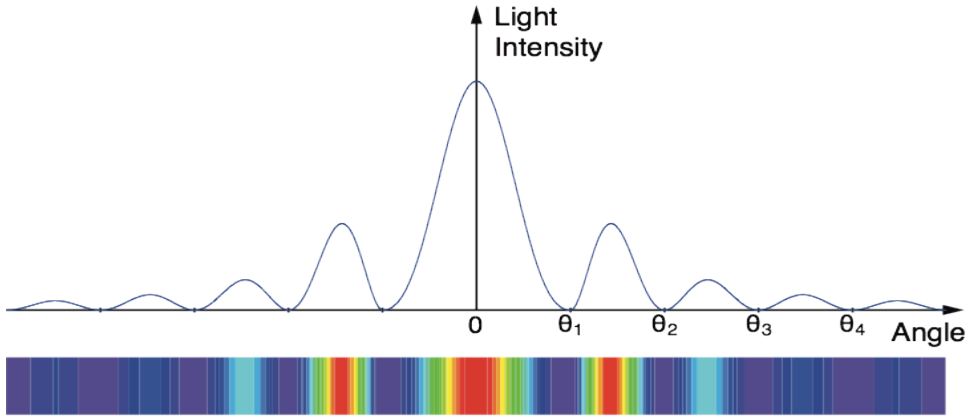
- Some observables provide interesting information on both structure *and* interactions, e.g.
  - Transverse single-spin asymmetries: due to e.g. Sivers pdf *plus* initial- or final-state gluon exchange in the interaction
  - Diffractive measurements for spatial imaging, and to probe universality of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

Manipulating QCD systems and their interactions

- As QCD research has matured, more in common with areas of research based on QED (condensed matter, atomic-molecular-optical)
- 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

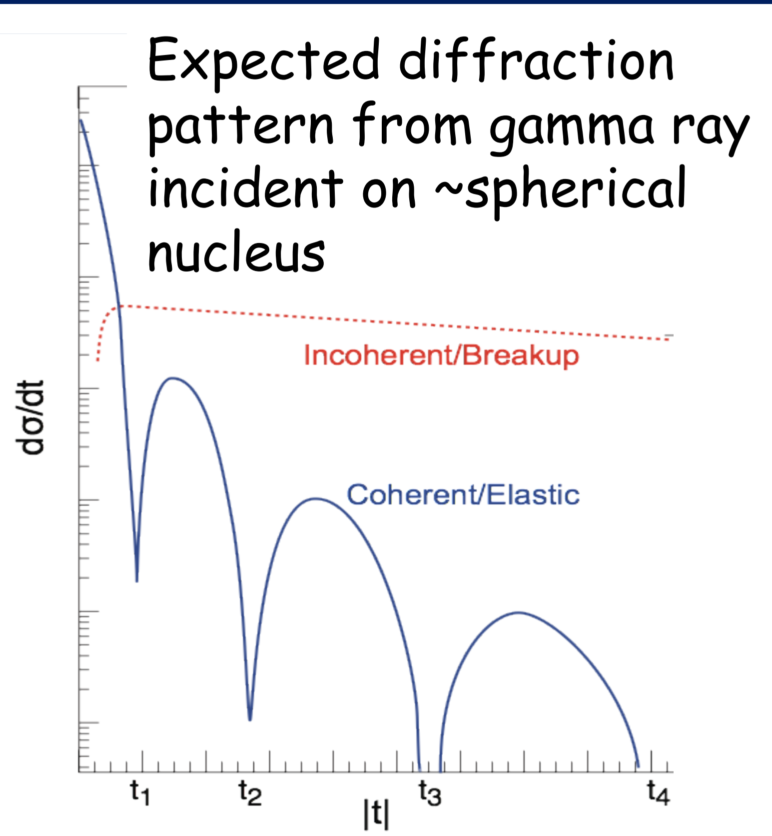
"Gamma-ray diffraction" to probe spatial structure of nuclei

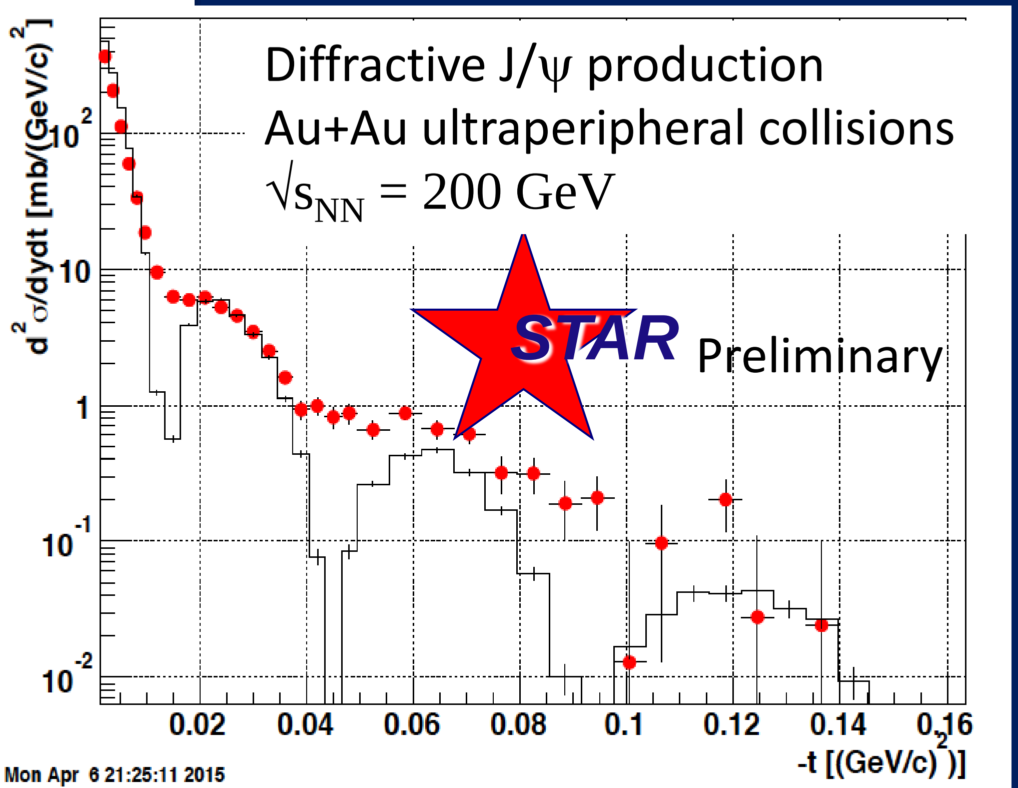
Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius



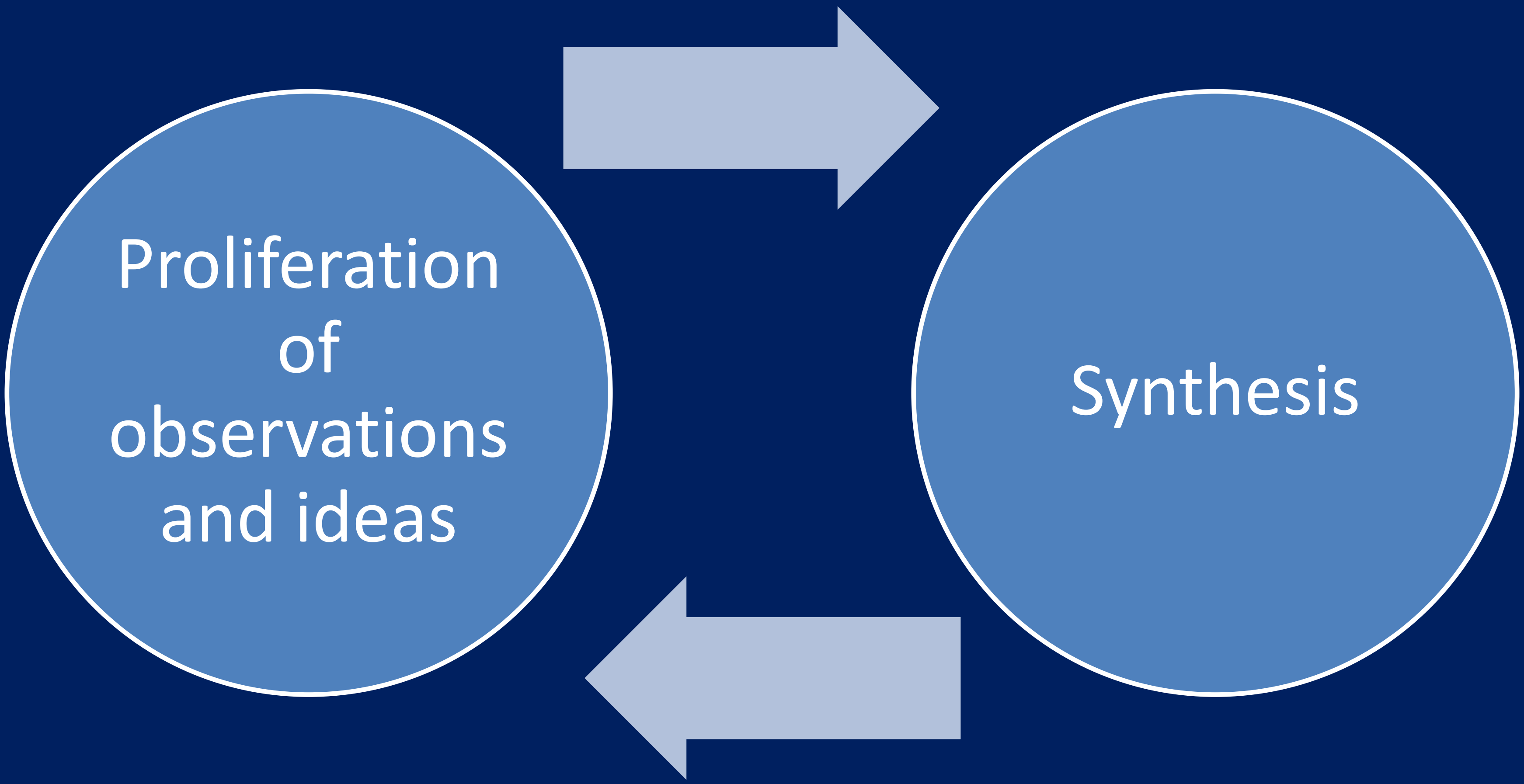
From E. Aschenauer

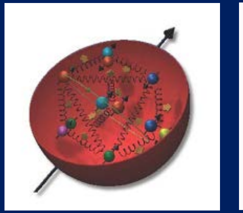
"Gamma-ray diffraction" to probe spatial structure of nuclei



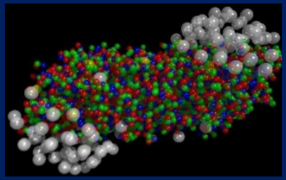
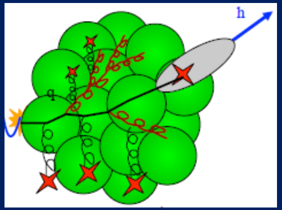


A cyclical process

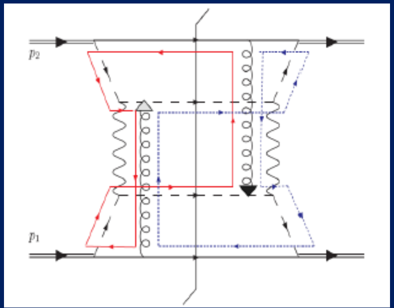





Summary

- Early years of rewarding new era of *quantitative basic research* in QCD!
- Gradually shifting to think about QCD systems in new ways, focusing on topics/ideas/concepts long familiar to the world of condensed matter physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems



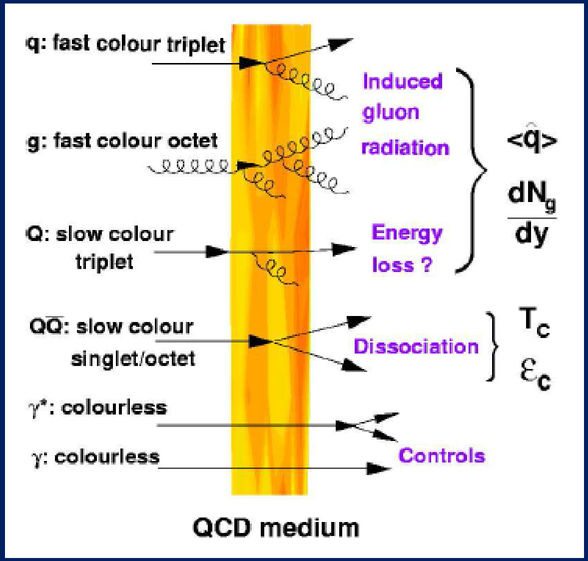
- Disparate subfields within QCD and within particle and nuclear physics starting to converge over last ~15 years

Taking small, initial steps along the path toward "grand unification" of QCD across different scales, from partons to neutron stars . . .

Extra

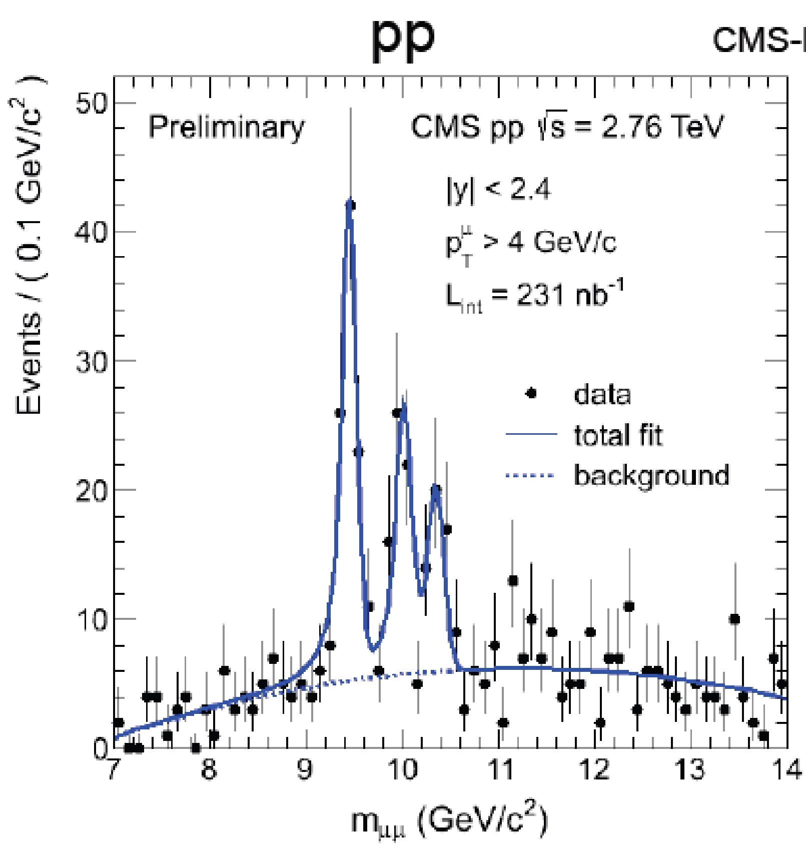
QCD interactions

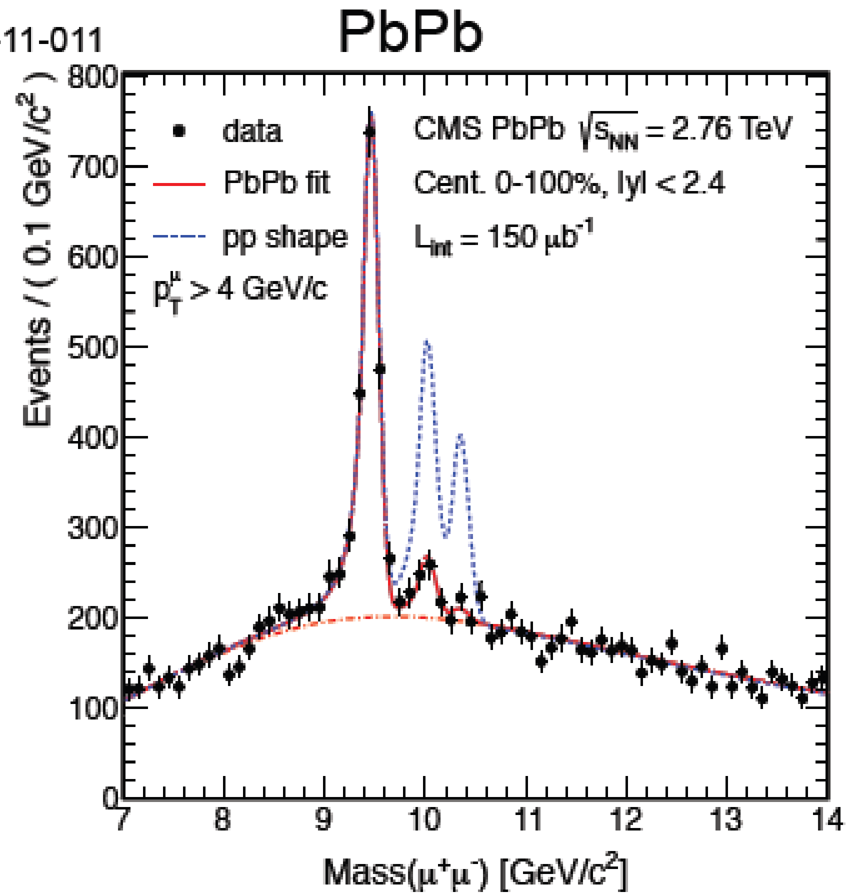
- QCD interactions themselves increasingly an explicit focus, e.g.
  - Parton energy loss traversing cold or hot QCD matter
  - Hadronization, in various environments
  - Quantum phase interference and phase shifts
  - Predicted color entanglement of partons *across* colliding protons
    - For hadronic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



Bottomonium in heavy ion collisions

CMS-HIN-11-011



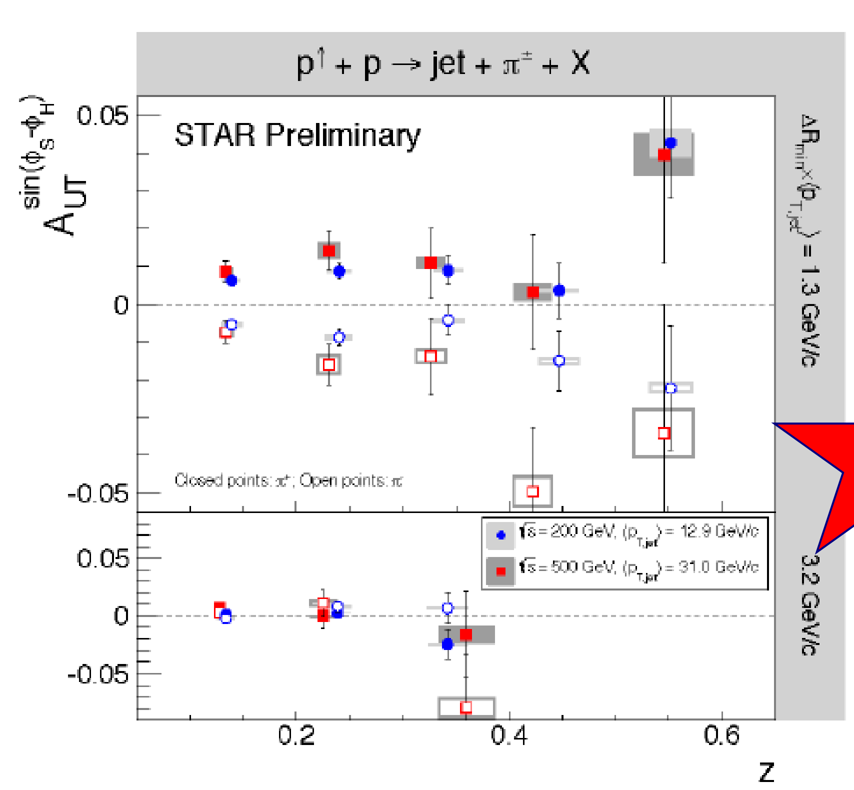


$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

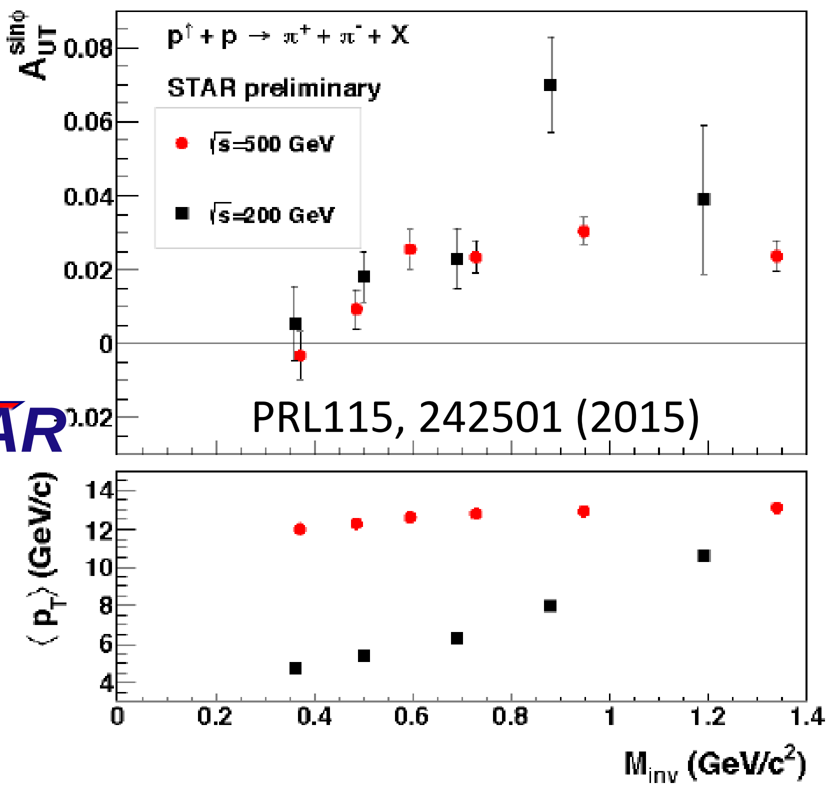
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

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

Overlapping tools and techniques

- HEP, nucleon structure, and heavy ion communities sharing an increasing number of tools/techniques
  - Jets—to study parton energy loss in quark-gluon plasma, in-medium modification of fragmentation functions, gluon spin contribution to spin of proton, . . .

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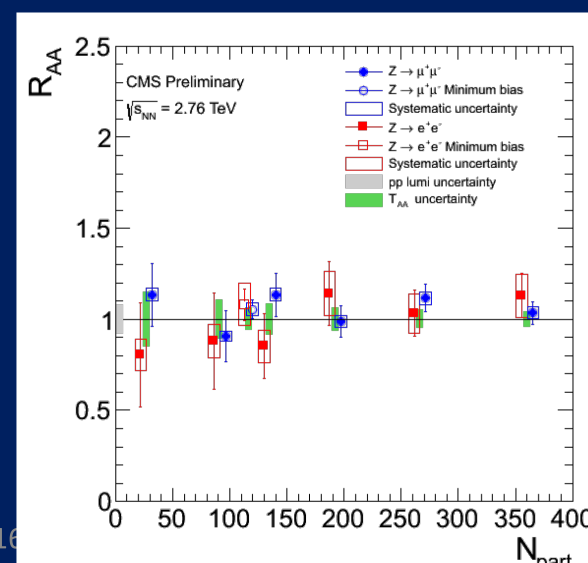
  - W/Z bosons—to calibrate parton energy loss in quark-gluon plasma, to study flavor-separated light sea quark helicity distributions, to test quantum phase interference effects due to gauge structure of QCD, . . .

Ratio of Z production in Pb+Pb to scaled p+p
→ No modification



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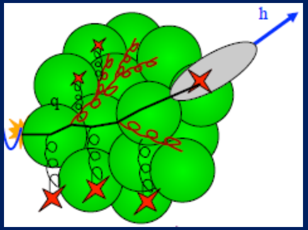
  - Bose-Einstein interferometry (Hanbury-Brown – Twiss)—to study properties and spatial extent of sources emitting radiation and particles—astronomy, heavy ions, e^+e^-, e+p, p+pbar, p+p

Hadronization: A lot to learn, from a variety of collision systems



What are the ways in which partons can turn into hadrons?

- Spin-momentum correlations in hadronization?
  - Correlations now measured definitively in e+e-! (BELLE, BABAR)
- Gluons vs. quarks?
  - Gluon vs. quark jets a hot topic in the LHC p+p program right now
  - Go back to clean e+e- with new jet analysis techniques in hand?
- In “vacuum” vs. cold nuclear matter vs. hot + dense QCD matter?
  - Use path lengths through nuclei to benchmark hadronization times → e+A
- Hadronization via “fragmentation” (what does that really mean?), “freeze-out,” “recombination,” . . .?
  - Soft hadron production from thermalized quark-gluon plasma—different mechanism than hadronization from hard-scattered q or g?
- Light atomic nuclei and antinuclei also produced in heavy ion collisions at RHIC!
  - How are such “compound” QCD systems formed from partons? Cosmological implications??
- …

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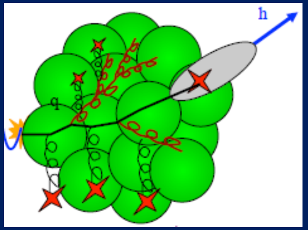

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-
-

In my opinion, hadronization has been a largely neglected area over the past decades of QCD—lots of progress to look forward to in upcoming years, with e+A, p+p, and A+A all playing a role along with e^+e^-!

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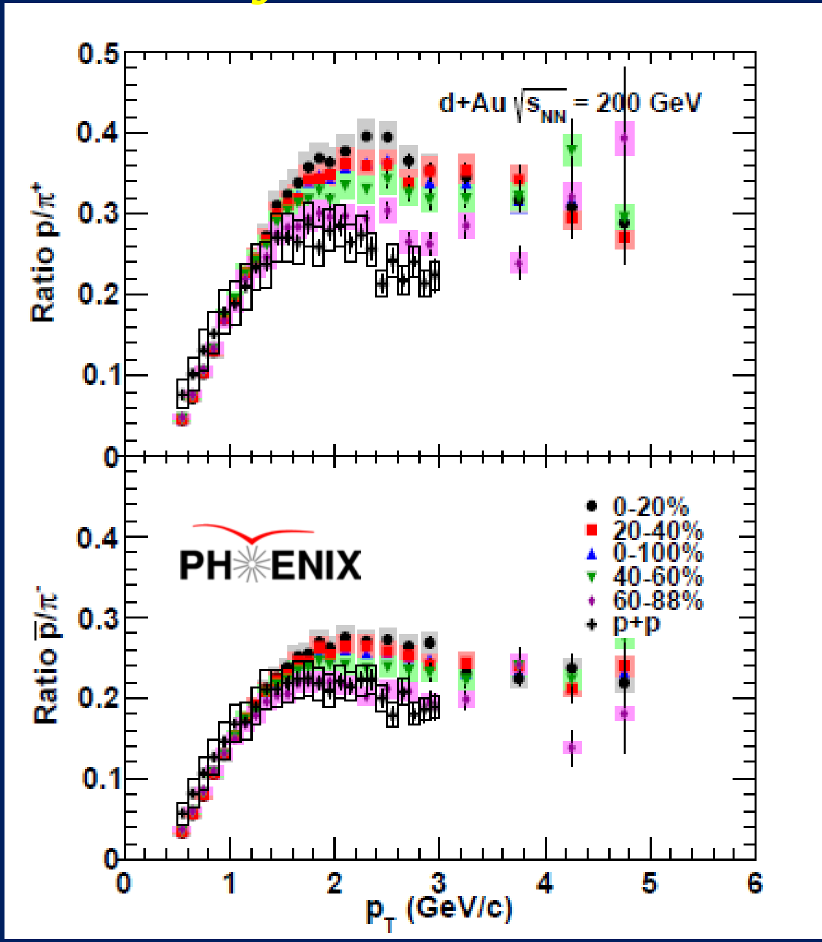
Mechanisms of hadronization other than "fragmentation": Baryon enhancement in d+Au and Au+Au

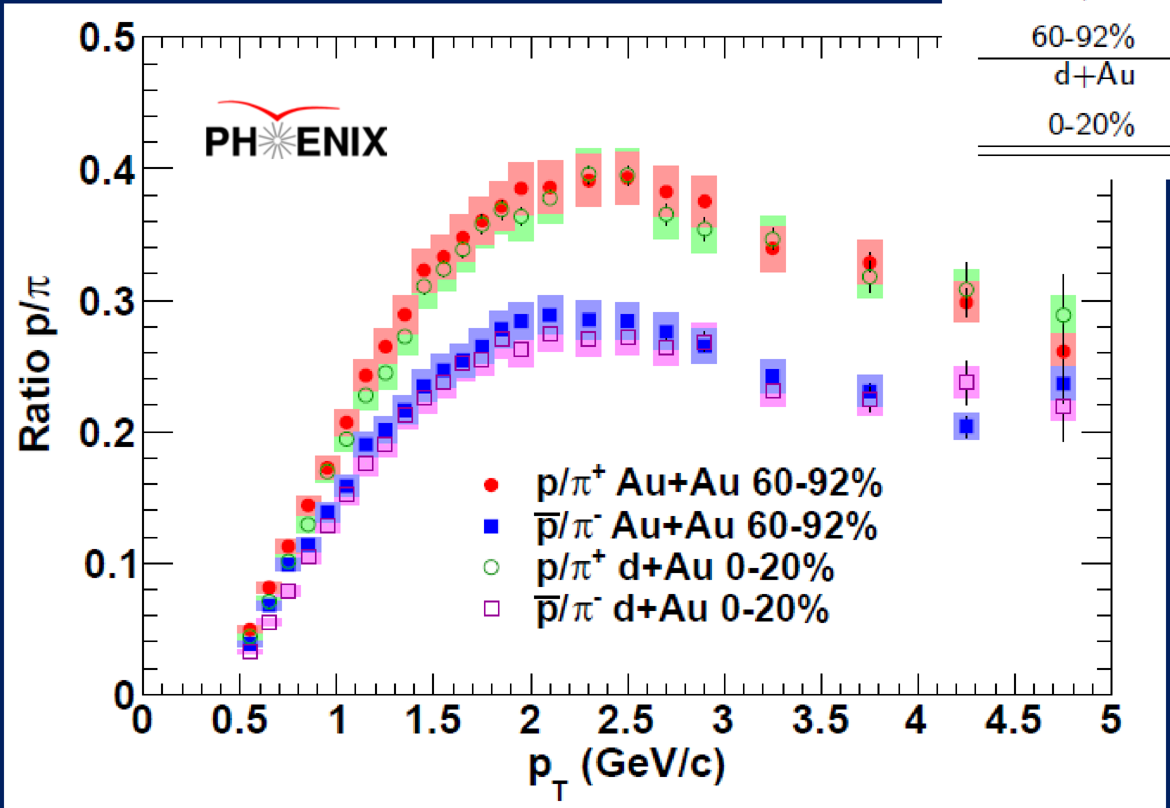


- Precision d+Au data for identified charged hadrons in bins of centrality
- New hadron production mechanism enabled by presence of additional partons/nucleons
  - Parton recombination?
- Strong centrality dependence despite small range of # participants
- Well-known centrality-dependent baryon enhancement in Au+Au
  - Previously explained by recombination of thermalized partons

PRC88, 024906 (2013)

Comparing central d+Au with peripheral Au+Au

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)

Both shape and magnitude identical!

Suggests common mechanism(s) for baryon production in the two systems—partons nearby in phase space bind? Don't need thermalized medium