Advancing the Era of Quantitative QCD: Experiment

(Why I think it's a really neat time to be a QCD experimentalist)

Christine A. Aidala
University of Michigan

DPF, Ann Arbor, MI
August 5, 2015

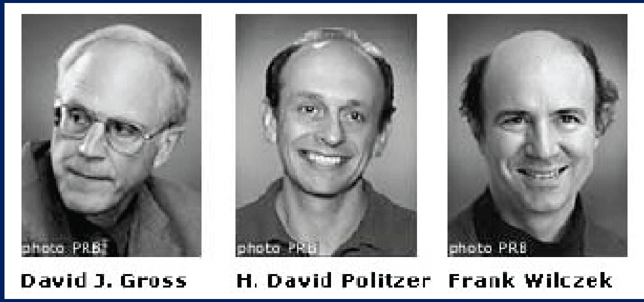
How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

QCD: How far have we come?

- Three-decade period after initial birth of QCD dedicated to “discovery and development”

QCD: How far have we come?



- 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 into 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 phenomenological calculations using these new ideas/tools!

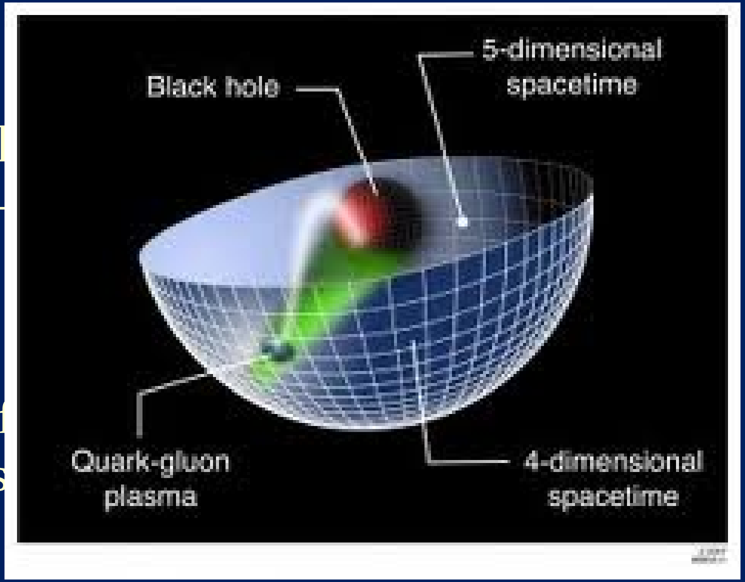
  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentum fractions
  - *Spin-spin* and *spin-momentum* correlations in QCD bound states
  - *Spatial* distributions of partons in hadrons

Advancing into 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 phenomenological calculations 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.

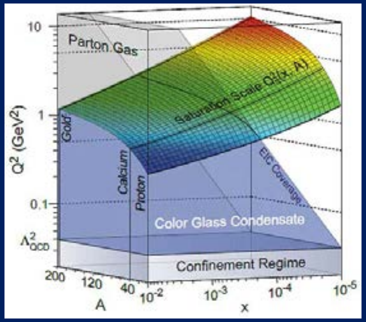
Advancing into the era of quantitative QCD: Theory has been forging ahead!



- In perturbative QCD, since 1990s starting
  QCD dynamics that parts with traditional
  hadrons—and perform <u>phenomenological</u>
  ideas/tools!

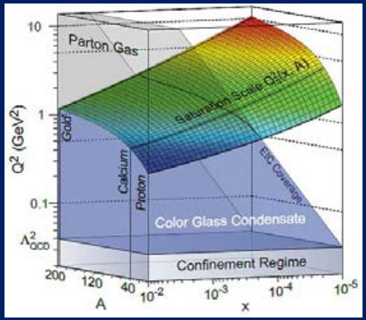
  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentum f
  - *Spin-spin* and *spin-momentum* correlations
  - *Spatial* distributions of partons in hadrons
- Non-perturbative methods:
  - Lattice QCD less and less limited by computing resources—since 2010 starting to perform calculations at the physical pion mass (after 36 years!). Plus recent new ideas on how to calculate previously intractable quantities.
  - AdS/CFT "gauge-string duality" an exciting recent development as first fundamentally new handle to try to tackle QCD in decades!

Effective field theories



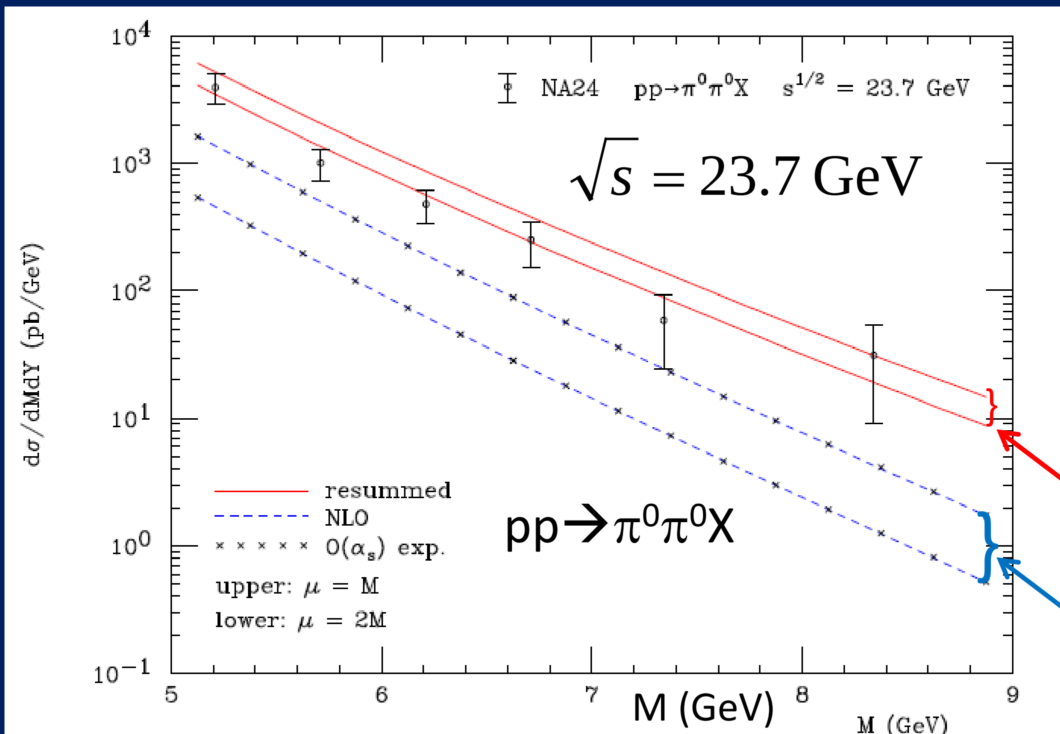
- QCD exhibits different behavior at different scales—effective field theories are useful approximations within these different regimes
  - Color Glass Condensate – high energies, high densities
  - Soft-Collinear Effective Theory – new insights into performing complicated perturbative calculations very quickly

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



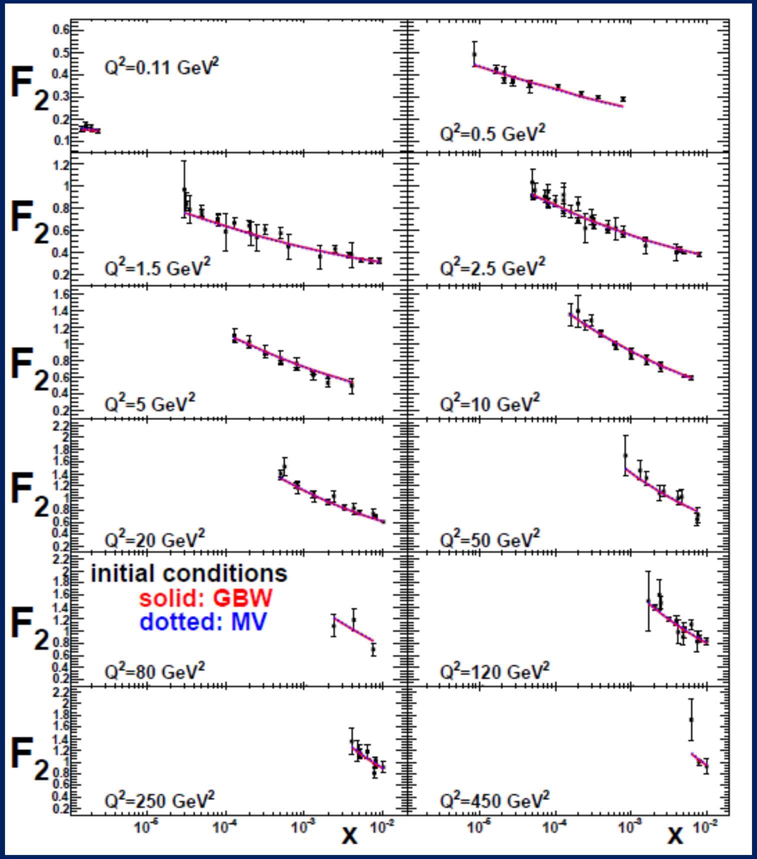
For observables with two different scales, sum logs of their ratio to all orders in the strong coupling constant

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!

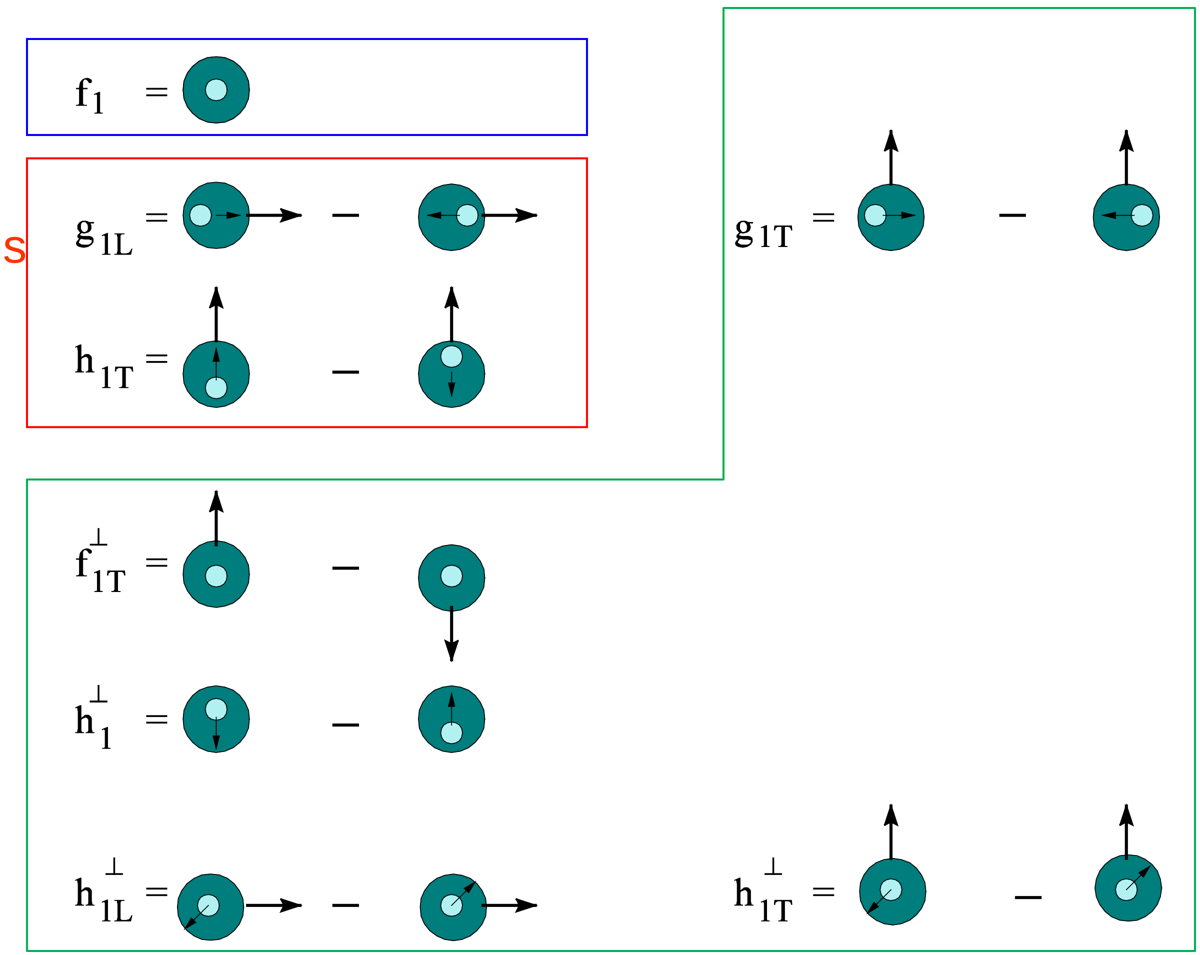
Example: Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

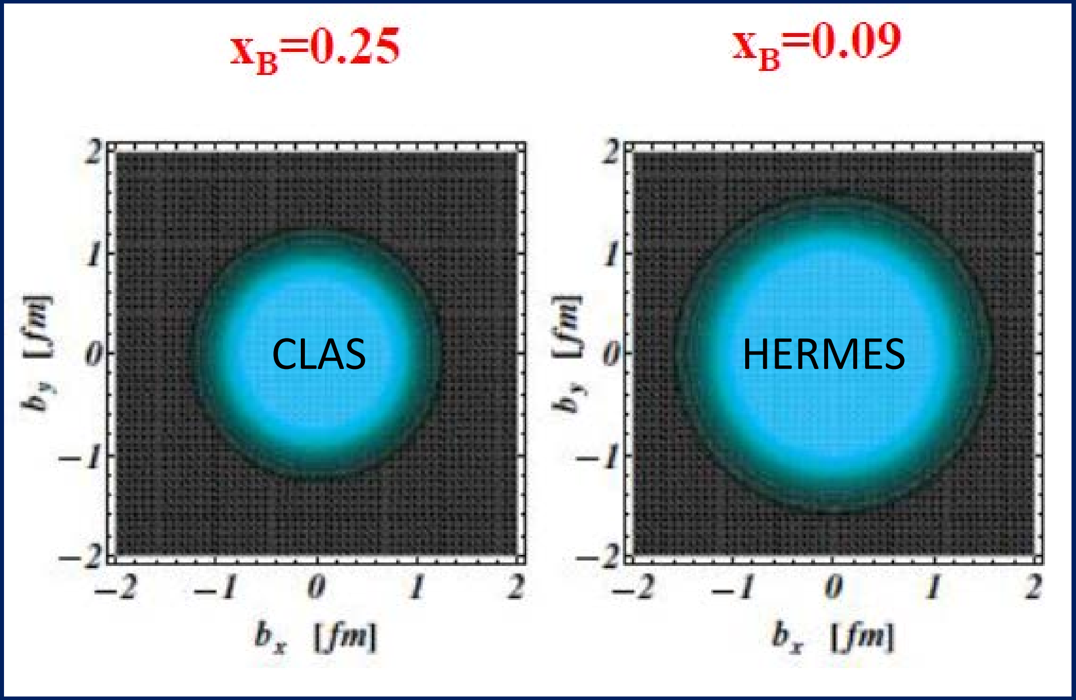
Spin-spin correlations

Spin-momentum correlations

$S \bullet (p_1 \times p_2)$



Example: Exploring spatial distributions



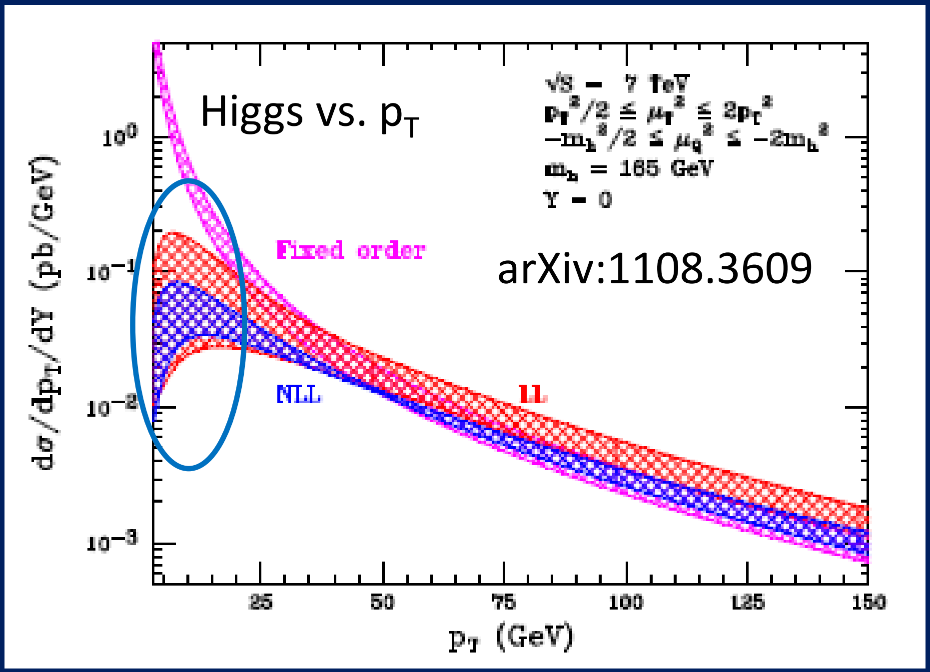
Spatial charge densities measured via deeply virtual Compton scattering in e+p

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

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

Example: Effective field theories

Soft Collinear Effective Theory – p_T distribution for gg→Higgs



TRANSVERSE MOMENTUM DISTRIBUTIONS FROM EFFECTIVE FIELD THEORY

Sonny Mantry*

University of Wisconsin at Madison
Madison, WI 53706, USA
mantry147@gmail.com

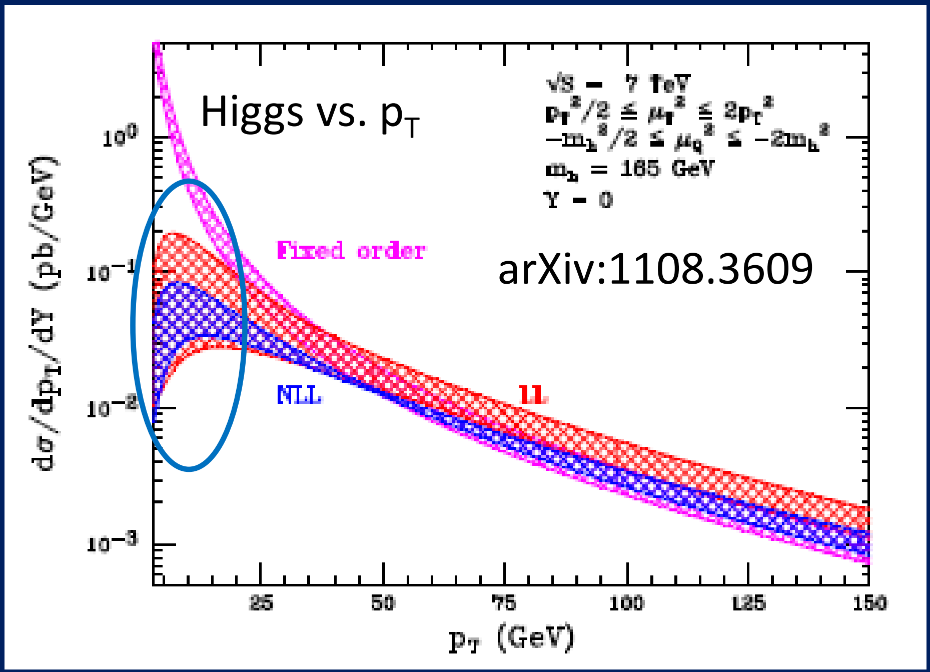
Frank Petriello

High Energy Physics Division, Argonne National Laboratory
Argonne, IL 60439, USA

Department of Physics & Astronomy, Northwestern University
Evanston, IL 60208, USA
f-petriello@northwestern.edu

Example: Effective field theories

Soft Collinear Effective Theory – p_T distribution for $gg \rightarrow$ Higgs



TRANSVERSE MOMENTUM DISTRIBUTIONS FROM EFFECTIVE FIELD THEORY

Sonny Mantry*

University of Wisconsin at Madison
Madison, WI 53706, USA
mantry147@gmail.com

Frank Petriello

High Energy Physics Division, Argonne National Laboratory
Argonne, IL 60439, USA

Department of Physics & Astronomy, Northwestern University
Evanston, IL 60208, USA
f-petriello@northwestern.edu

"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

- Ability to systematically vary collision species, energy

Experimental advances

- Ability to systematically vary collision species, energy
- Ability to maintain high-energy polarized proton beams

Experimental advances

- Ability to systematically vary collision species, energy
- Ability to maintain high-energy polarized proton beams
- High-luminosity facilities enable multidifferential measurements
  - E.g. simultaneously in parton momentum fraction x, rapidity, p_T, Q^2, z, . . .

Experimental advances

- Ability to systematically vary collision species, energy
- Ability to maintain high-energy polarized proton beams
- High-luminosity facilities enable multidifferential measurements
  - E.g. simultaneously in parton momentum fraction x, rapidity, p_T, Q^2, z, . . .
- More sophisticated observables
  - E.g. angular distributions, multiparticle final states, various correlations, spin dependence, . . .
  - Contain more information! Often sensitive to parton *dynamics*

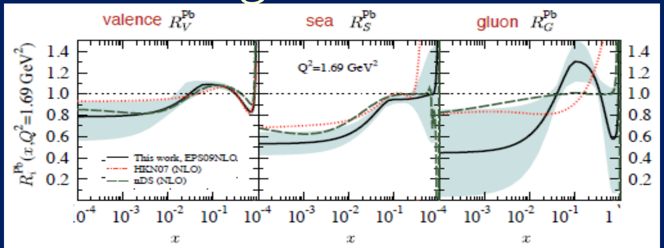
Experimental advances

- Ability to systematically vary collision species, energy
- Ability to maintain high-energy polarized proton beams
- High-luminosity facilities enable multidifferential measurements
  - E.g. simultaneously in parton momentum fraction x, rapidity, p_T, Q^2, z, . . .
- More sophisticated observables
  - E.g. angular distributions, multiparticle final states, various correlations, spin dependence, . . .
  - Contain more information! Often sensitive to parton *dynamics*

→ Demand more of theoretical calculations!

Increasing connections among historically disparate areas of QCD

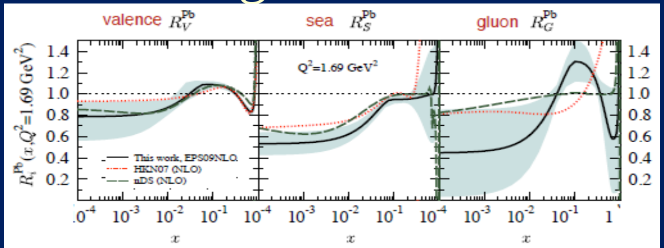
As we advance, we're building more connections among the various areas of QCD—and to other fields . . .



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

Increasing connections among historically disparate areas of QCD

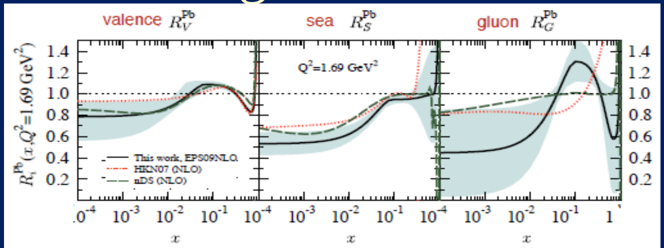
As we advance, we're building more connections among the various areas of QCD—and to other fields . . .



- Nucleon structure and heavy ion communities
  - Greater focus on initial-state (cold) nuclear effects
  - Parton distribution functions in the proton vs. nuclei
  - RHIC just ran *polarized* protons on gold! Use polarization to help search for gluon saturation physics
  - Ultraperipheral heavy ion collisions for spatial imaging; impact-parameter-dependent nuclear distributions and collision geometry in heavy ion physics
- Hadron spectroscopy and hadronization (nucleon structure) communities
  - B factories as common facilities

Increasing connections among historically disparate areas of QCD

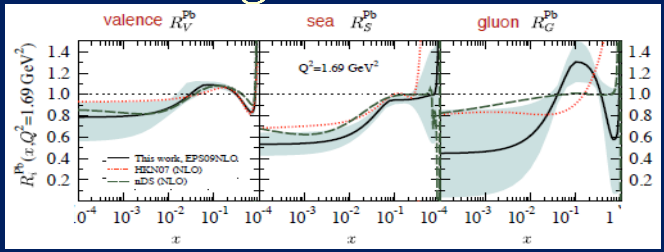
As we advance, we're building more connections among the various areas of QCD—and to other fields . . .



- Nucleon structure and heavy ion communities
  - Greater focus on initial-state (cold) nuclear effects
  - Parton distribution functions in the proton vs. nuclei
  - RHIC just ran *polarized* protons on gold! Use polarization to help search for gluon saturation physics
  - Ultraperipheral heavy ion collisions for spatial imaging; impact-parameter-dependent nuclear distributions and collision geometry in heavy ion physics
- Hadron spectroscopy and hadronization (nucleon structure) communities
  - B factories as common facilities
- Heavy ion and hadronization (nucleon structure) communities
  - "String fragmentation" vs. binding of nearby partons in phase space
  - Modified hadronization in hot or cold nuclear matter

Increasing connections among historically disparate areas of QCD

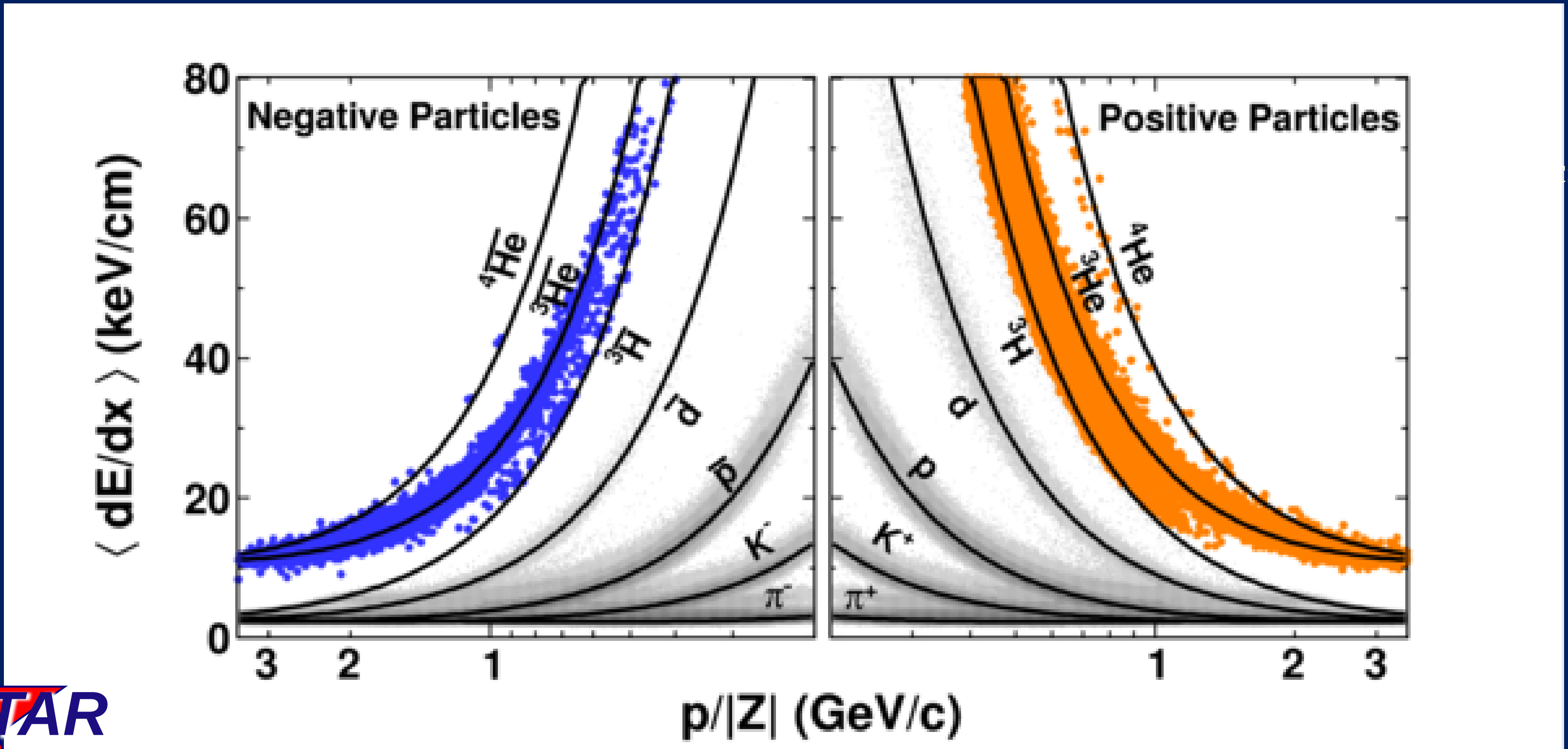
As we advance, we're building more connections among the various areas of QCD—and to other fields . . .



- Nucleon structure and heavy ion communities
  - Greater focus on initial-state (cold) nuclear effects
  - Parton distribution functions in the proton vs. nuclei
  - RHIC just ran *polarized* protons on gold! Use polarization to help search for gluon saturation physics
  - Ultraperipheral heavy ion collisions for spatial imaging; impact-parameter-dependent nuclear distributions and collision geometry in heavy ion physics
- Hadron spectroscopy and hadronization (nucleon structure) communities
  - B factories as common facilities
- Heavy ion and hadronization (nucleon structure) communities
  - "String fragmentation" vs. binding of nearby partons in phase space
  - Modified hadronization in hot or cold nuclear matter
- 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

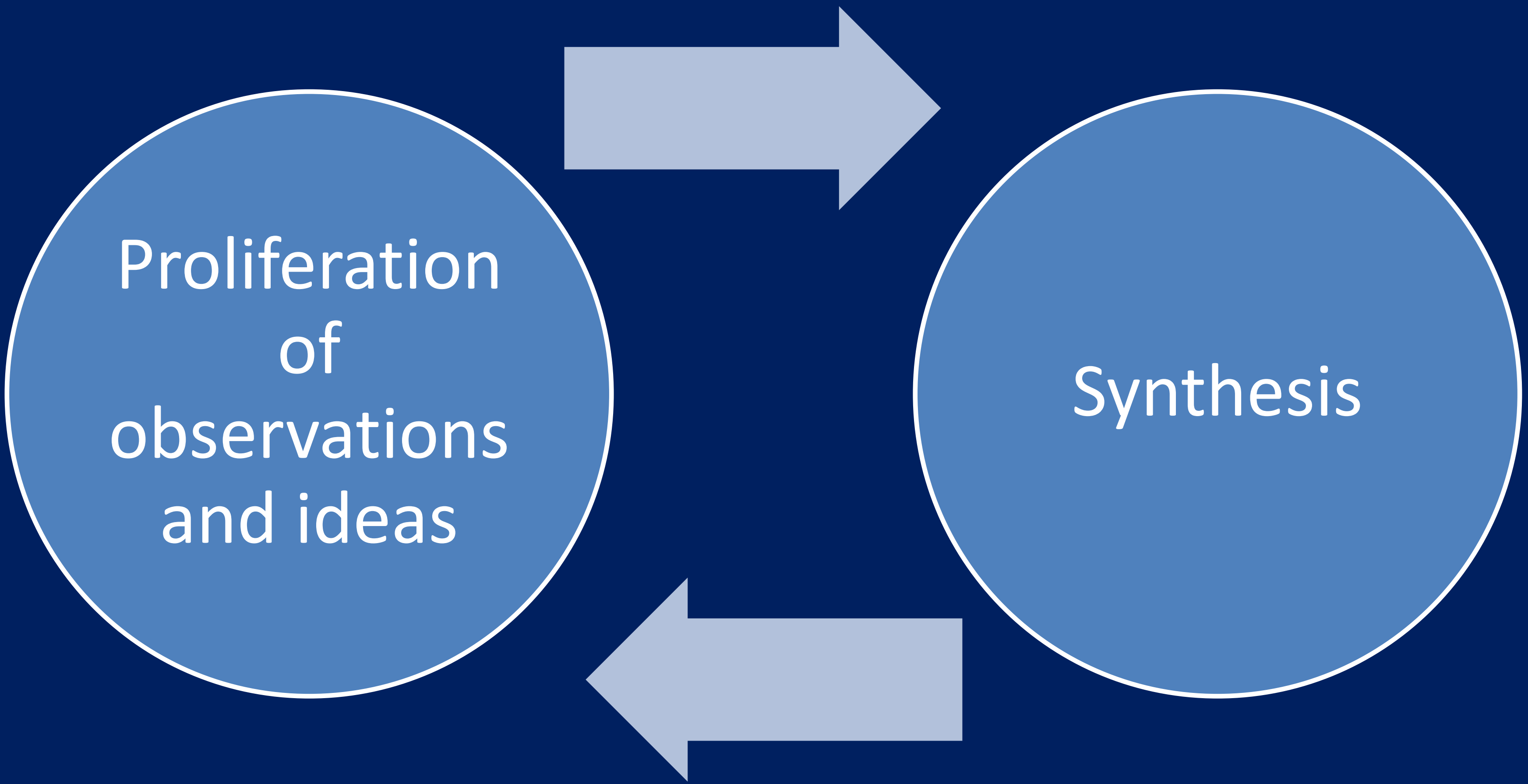
Increasing connections among historically disparate areas of QCD

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



Nature 473, 353 (2011)

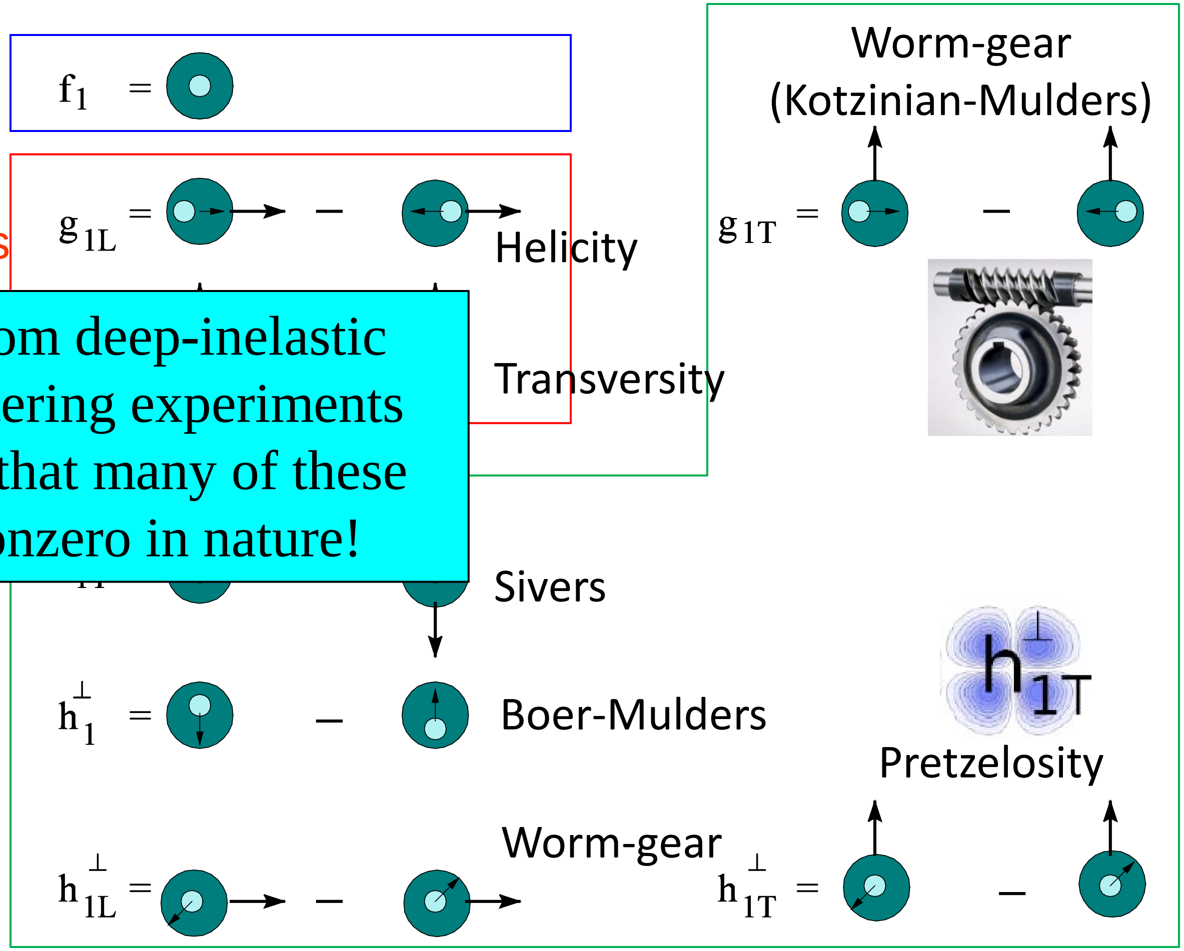
A cyclical process



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

Unpolarized

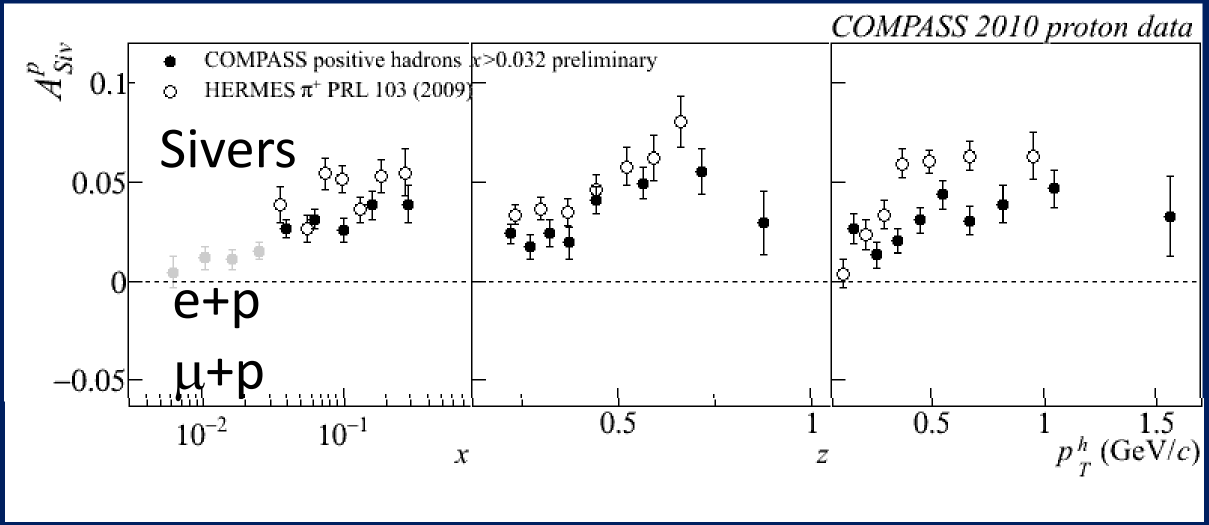
Spin-spin correlations

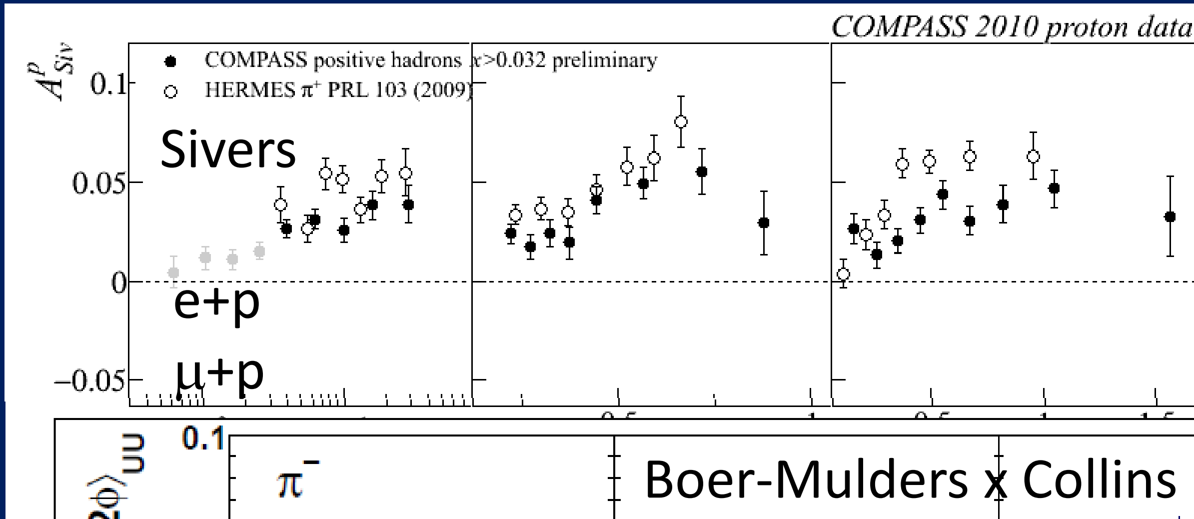


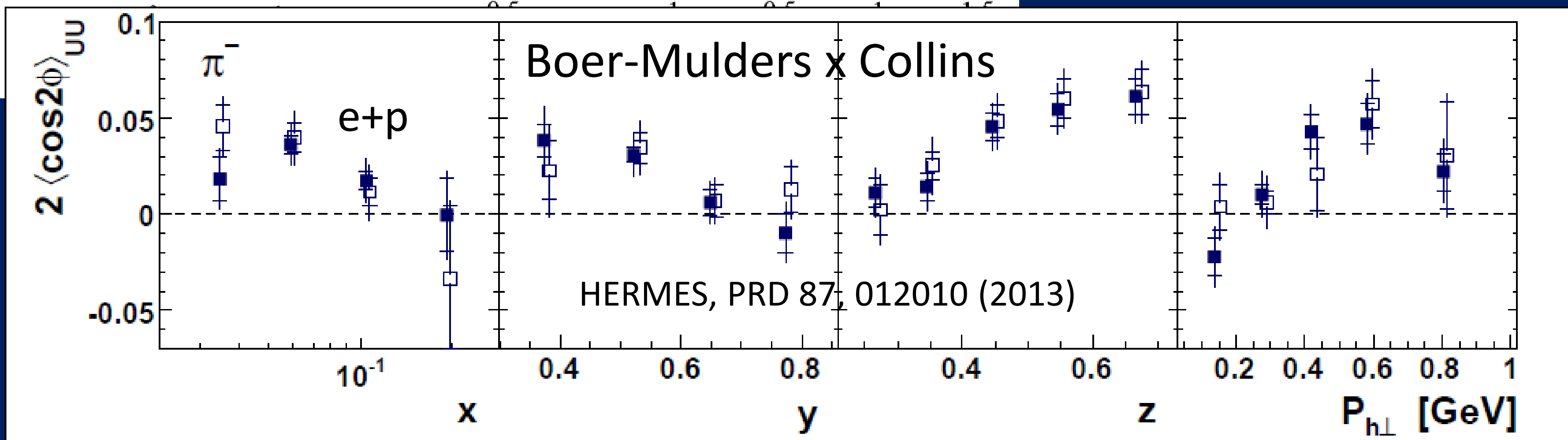
Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~10 years that many of these correlations are nonzero in nature!

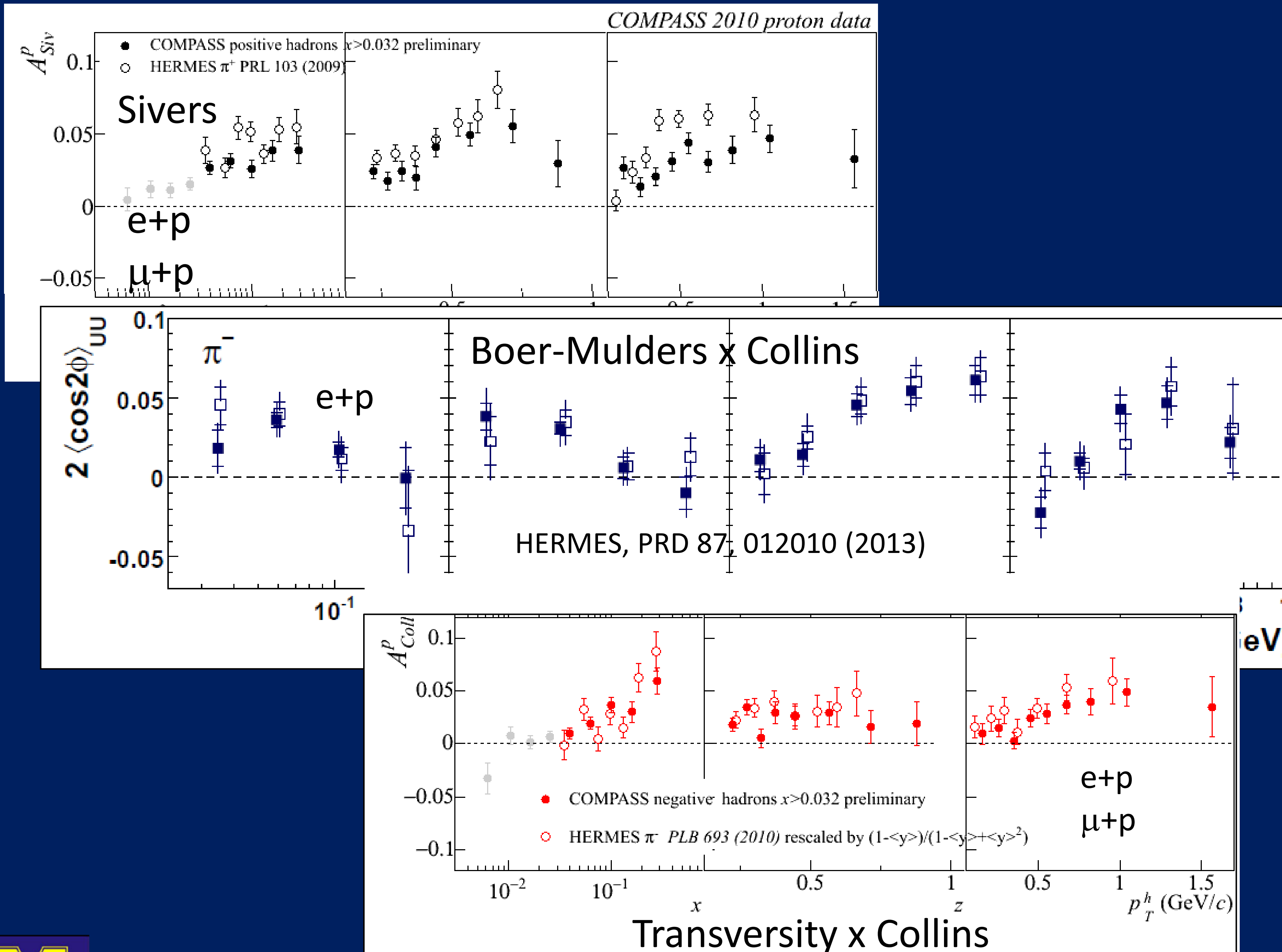
Spin-momentum correlations

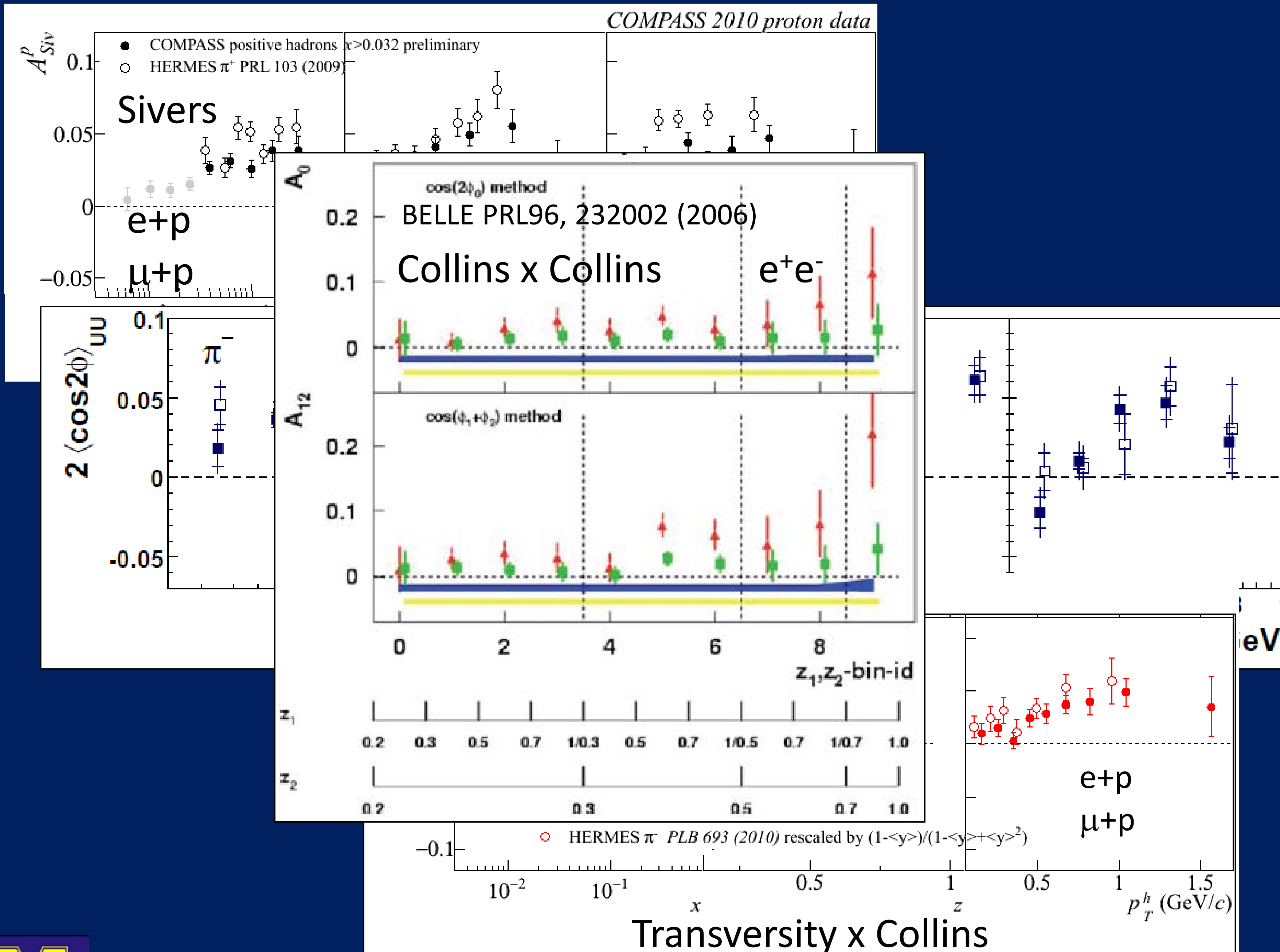
$S\bullet(p_1 \times p_2)$

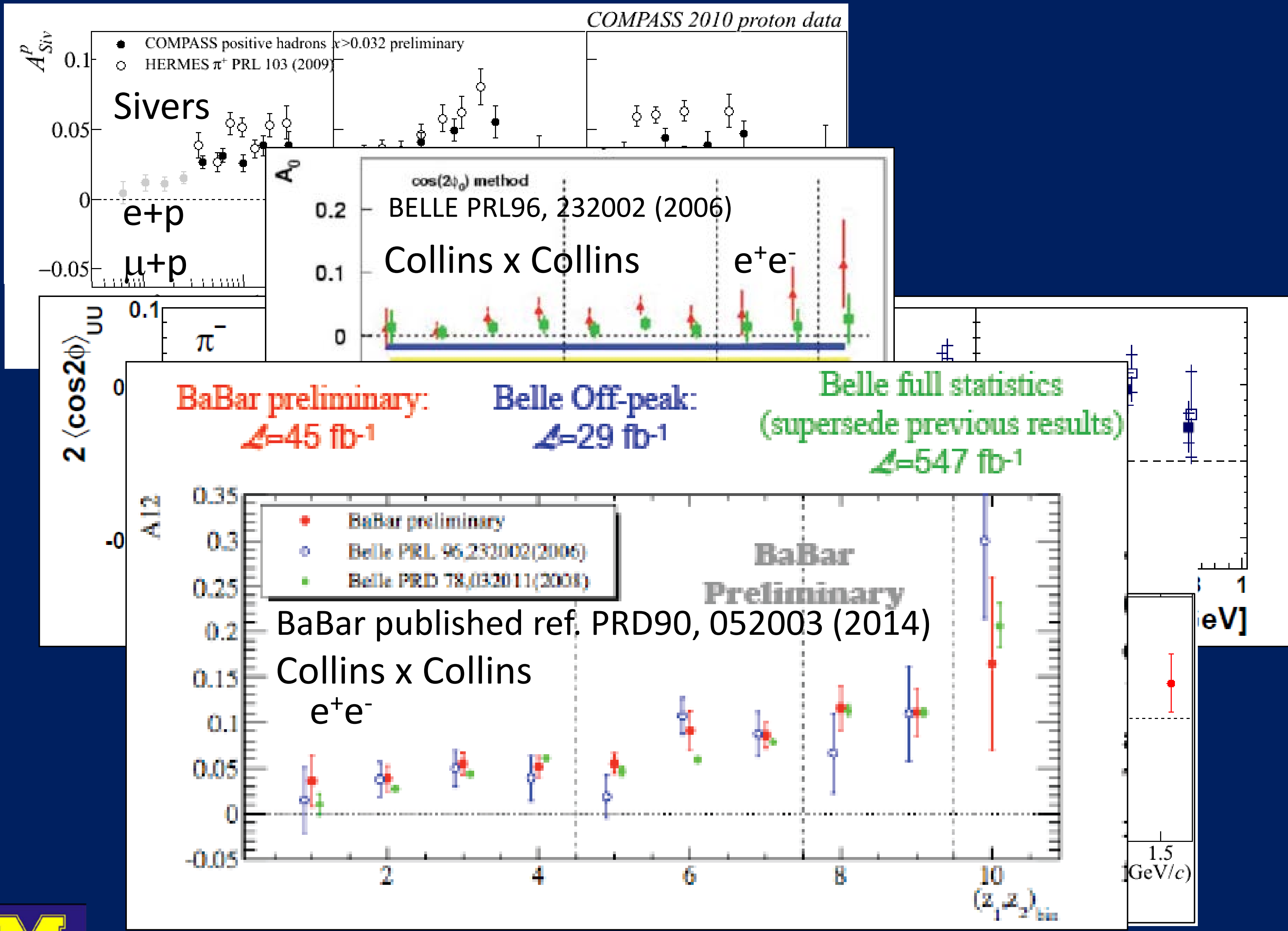

COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
A^p_{Siv}
0.1
0.05
0
−0.05
10^{-2}
10^{-1}
x
0.5
1
z
0.5
1
1.5
p_T^h (GeV/c)


COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p


Boer-Mulders x Collins
π−
e+p
HERMES, PRD 87, 012010 (2013)
2 ⟨cos2φ⟩UU
x
y
z
Ph⊥ [GeV]


COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
Boer-Mulders x Collins
π−
e+p
HERMES, PRD 87, 012010 (2013)
2 ⟨cos2ϕ⟩UU
COMPASS negative hadrons x>0.032 preliminary
HERMES π− PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
e+p
μ+p
x
z
p_T^h (GeV/c)
Transversity x Collins


COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
cos(2φ0) method
cos(φ1+φ2) method
z1,z2-bin-id
π-
2 ⟨cos2φ⟩UU
HERMES π- PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>2)
e+p
μ+p
Transversity x Collins


COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
cos(2φ0) method
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
BaBar preliminary:
ℒ=45 fb-1
Belle Off-peak:
ℒ=29 fb-1
Belle full statistics
(supersede previous results)
ℒ=547 fb-1
BaBar preliminary
Belle PRL 96,232002(2006)
Belle PRD 78,032011(2008)
BaBar
Preliminary
BaBar published ref. PRD90, 052003 (2014)
Collins x Collins
e+e-
A12
(z1,z2)bin

“Naïve-T-odd” spin-momentum correlations require phase interference

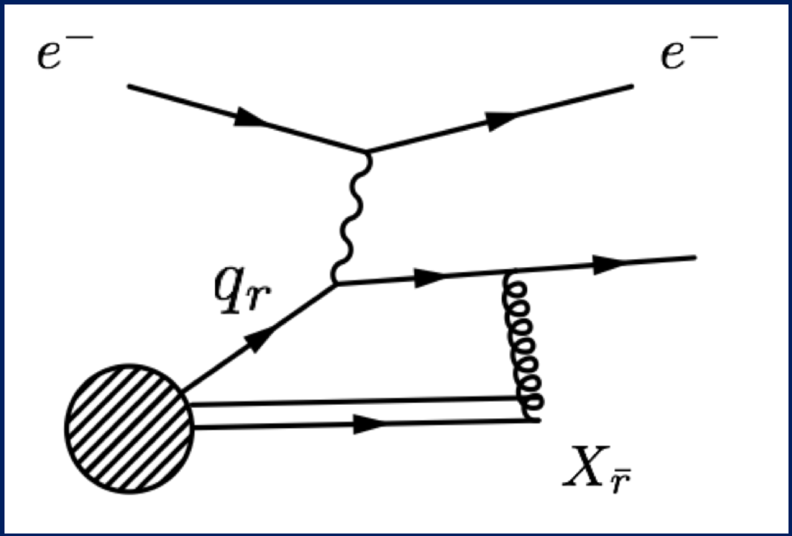
- Some transverse-momentum-dependent parton distribution functions odd under “naïve-time-reversal” (actually a PT transformation)

- 1990 – proposed by D.W. Sivers
- 1993 – Claimed forbidden by J.C. Collins

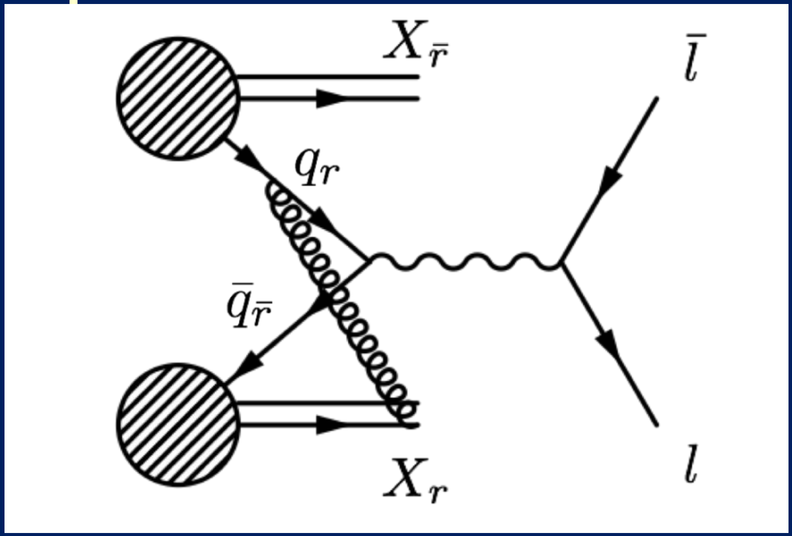
- 2002 – Demonstrated nonvanishing by Brodsky, Hwang, Schmidt if *phase interference effects due to color interactions* present

Color in action! <u>Modified universality</u> of certain transverse-momentum-dependent distributions

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions

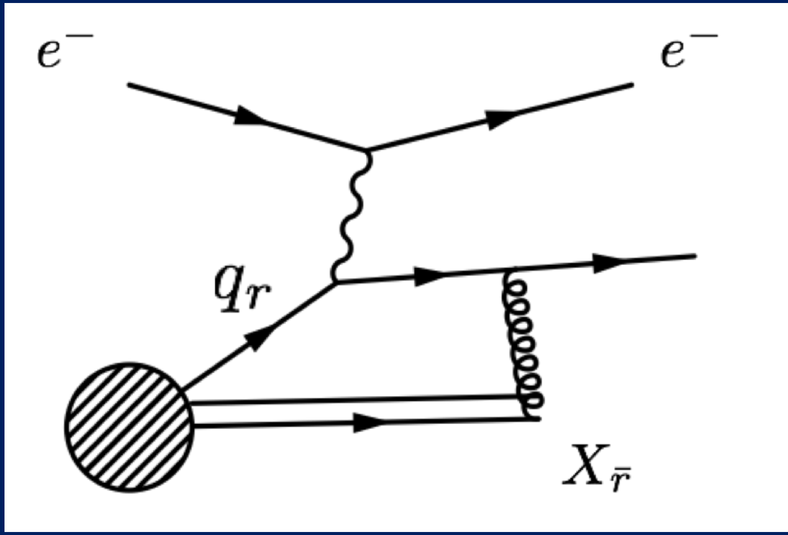


Get *opposite sign* for Sivers transverse-momentum-dependent pdf in semi-inclusive DIS versus Drell-Yan:
***process-dependent* pdf**! (Collins 2002)

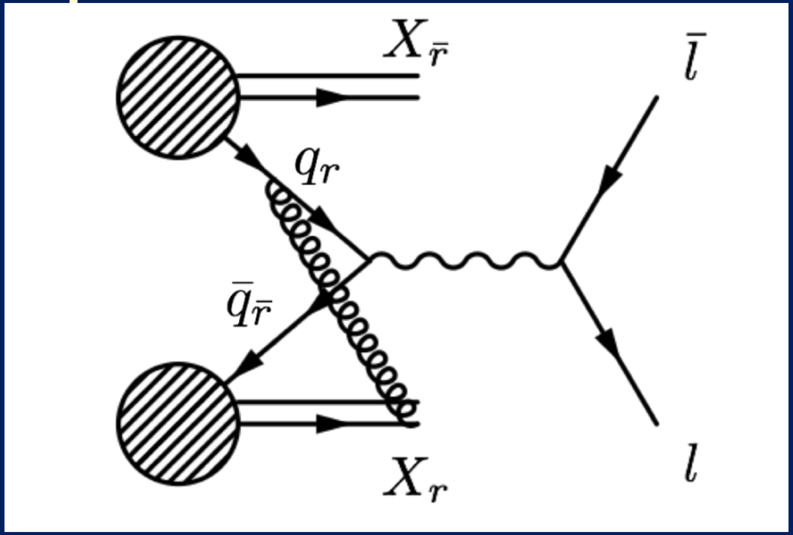
Figures by J.D. Osborn

Color in action! Modified universality of certain transverse-momentum-dependent distributions

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



Still waiting for a polarized quark-antiquark annihilation measurement to compare to existing lepton-nucleon scattering measurements . . .

Figures by J.D. Osborn

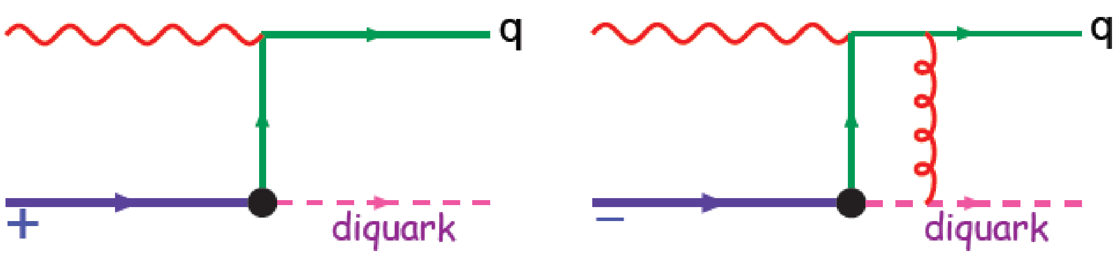
Modified universality requires full QCD: Gauge-invariant quantum field theory

We have ignored here the subtleties needed to make this a gauge invariant definition: an appropriate path ordered exponential of the gluon field is needed [18].

1993 claim by J.C. Collins that such processes must vanish

gauge links have physical consequences;
quark models for non vanishing Sivers function,

SIDIS final state interactions



Brodsky, Hwang, Schmidt, PL B530 (2002) 99 - Collins, PL B536 (2002) 43

An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced hard processes (e.g., Drell-Yan), thereby violating naive universality of parton densities. Previous phenomenology with time-reversal-odd parton densities is therefore validated.

$$[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}$$

Slide from M. Anselmino, Transversity 2014

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

Wikipedia:

"The Aharonov–Bohm effect is important conceptually because it bears on three issues apparent in the recasting of (Maxwell's) classical electromagnetic theory as a gauge theory, which before the advent of quantum mechanics could be argued to be a mathematical reformulation with no physical consequences. The Aharonov–Bohm thought experiments and their experimental realization imply that the issues were not just philosophical.

The three issues are:

- whether potentials are "physical" or just a convenient tool for calculating force fields;
- whether action principles are fundamental;
- the principle of locality."

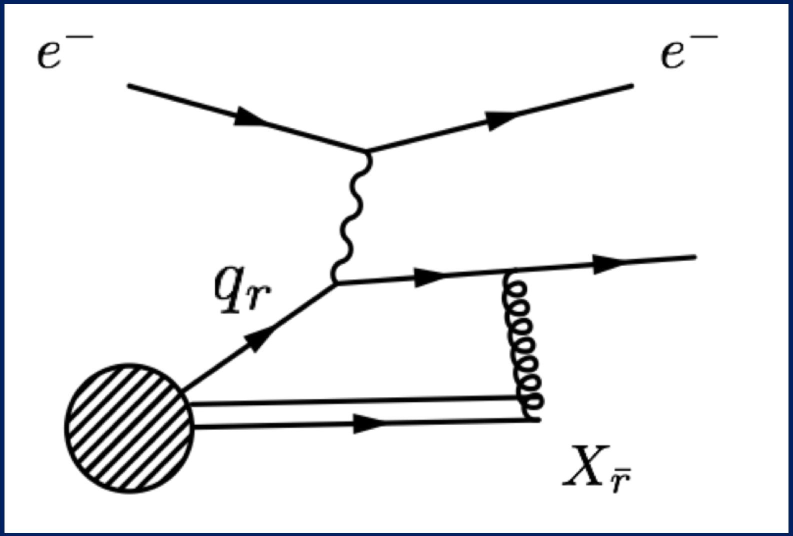
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

Physics Today, September 2009 :
The Aharonov–Bohm effects: Variations on a subtle theme,
by Herman Batelaan and Akira Tonomura.

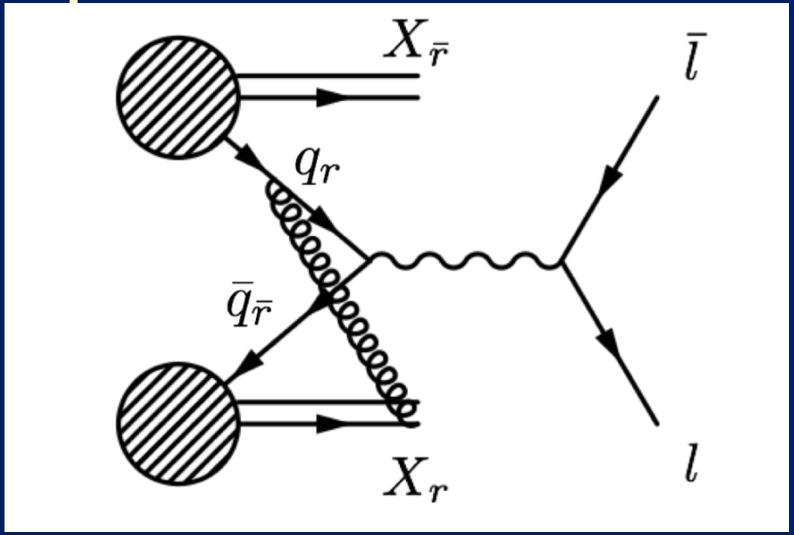
"Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories. So one may expect that particle-physics experimenters will be looking for new AB effects in new domains."

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm effect in QCD!!

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



See e.g. Pijlman, hep-ph/0604226
or Sivers, arXiv:1109.2521

Figures by J.D. Osborn

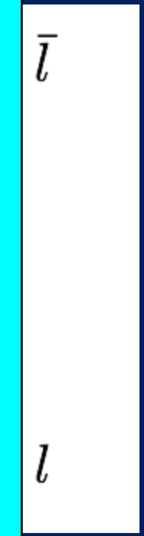
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm effect in QCD!!

Deep-inelastic lepton-nucleon scattering:

Attrac

Quark-antiquark annihilation to leptons:

ctions



Simplicity of these two processes:
Abelian vs. non-Abelian nature of the gauge group doesn't play a major qualitative role.

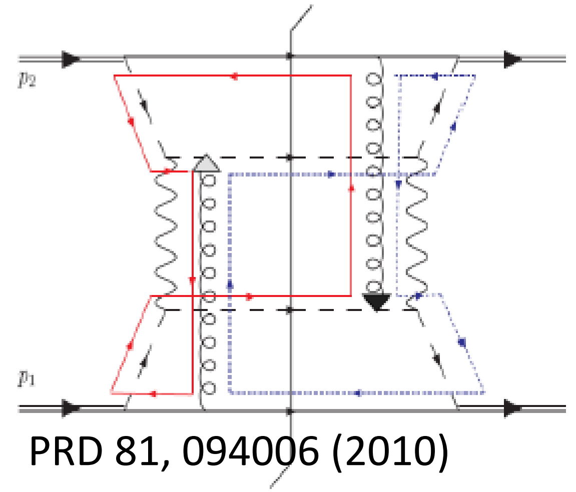
BUT: In QCD expect additional, new effects due to specific <u>non-Abelian</u> nature of the gauge group

See e.g. Pijlman, hep-ph/0604226
or Sivers, arXiv:1109.2521

Figures by J.D. Osborn

QCD Aharonov-Bohm effect: Color entanglement

- 2010: Rogers and Mulders predict *color entanglement* in processes involving p+p production of hadrons if quark transverse momentum taken into account
- Quarks become correlated *across* the two protons
- Consequence of QCD specifically as a ***non-Abelian*** gauge theory!



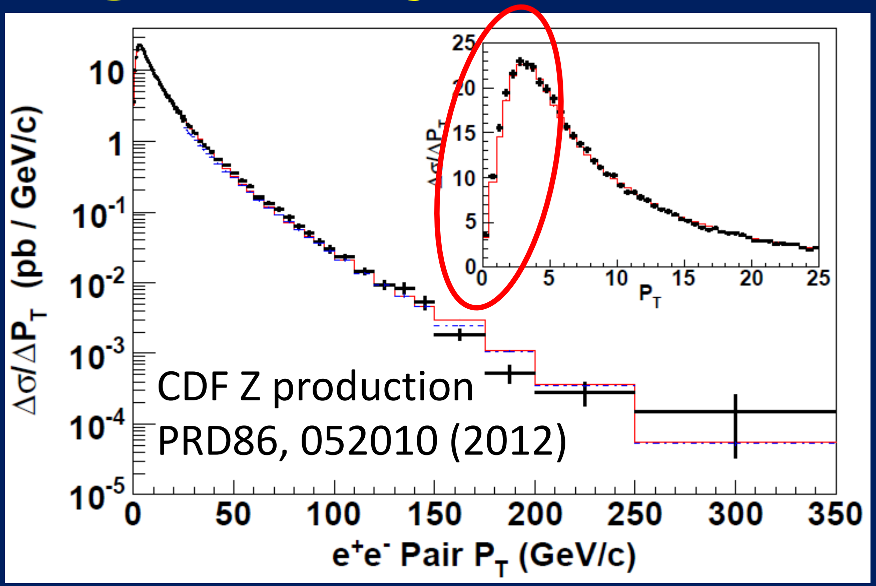
PRD 81, 094006 (2010)

$$p + p \rightarrow h_1 + h_2 + X$$

Color flow can't be described as flow in the two gluons separately. Requires simultaneous presence of both.

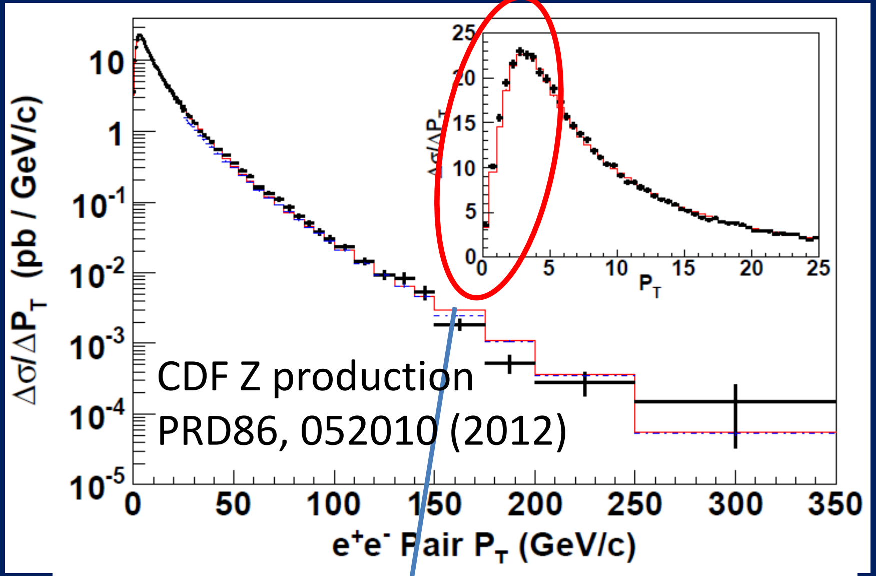
Testing Aharonov-Bohm effect in QCD as a non-Abelian gauge theory

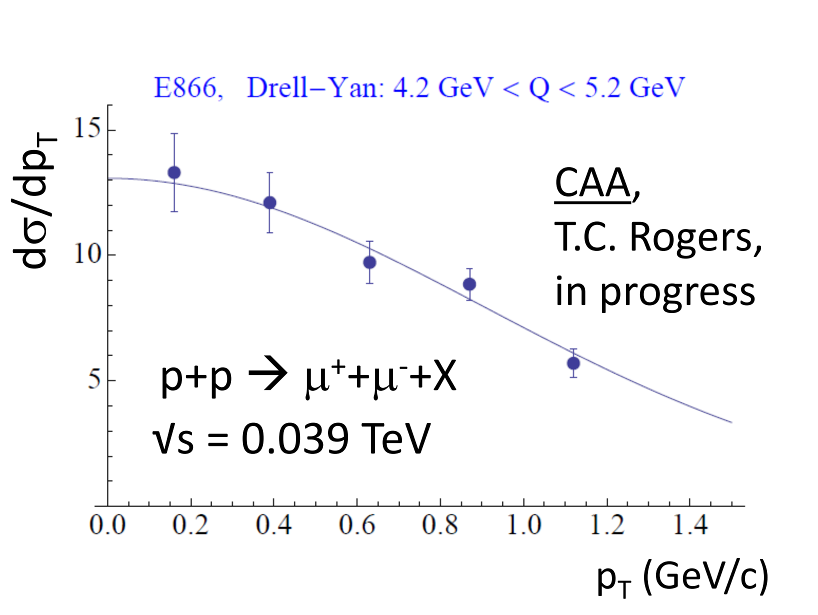
- Look for contradiction with predictions for the case of *no* color entanglement
- But first need to parameterize (unpolarized) transverse-momentum-dependent pdfs from world data
  - Better constraints on unpolarized predictions because more available data

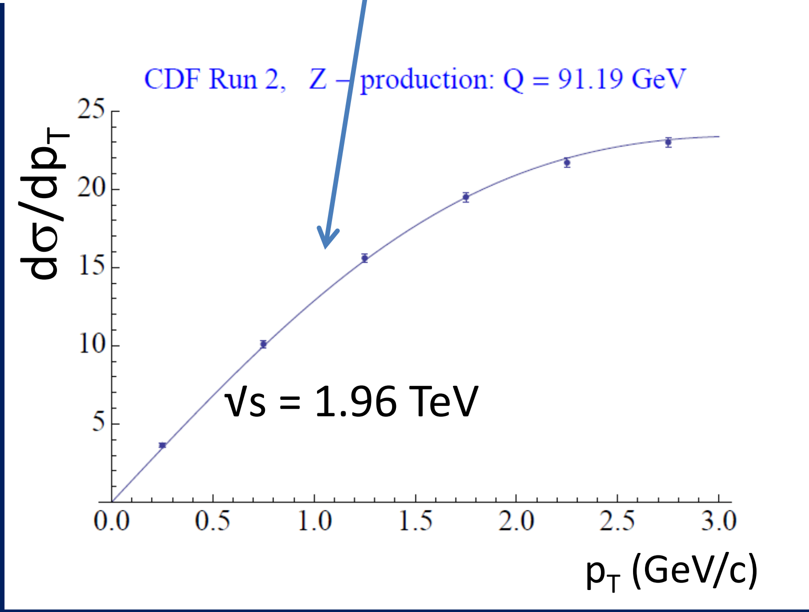


Testing Aharonov-Bohm effect in QCD as a non-Abelian gauge theory

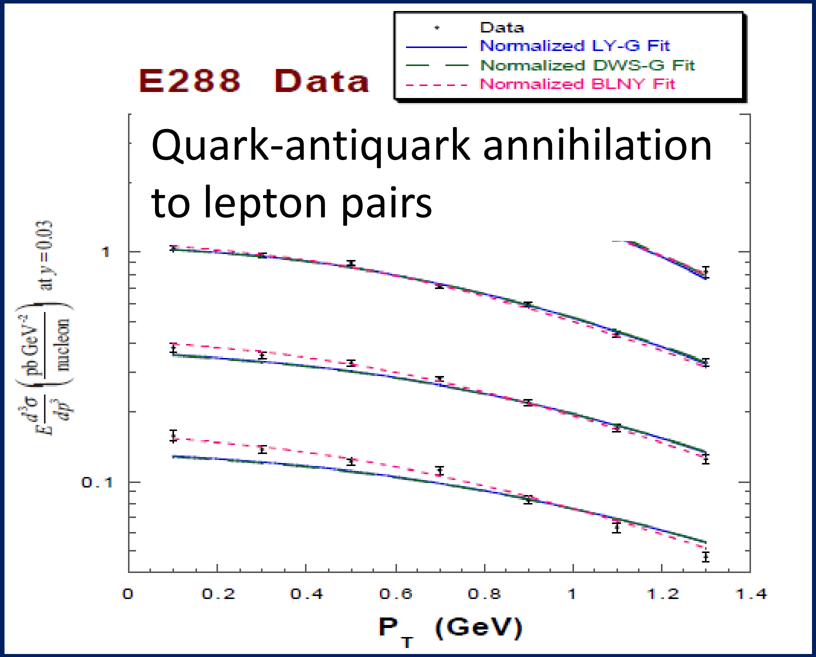
- Look for contradiction with predictions for the case of *no* color entanglement
- But first need to parameterize (unpolarized) transverse-momentum-dependent pdfs from world data
  - Better constraints on unpolarized predictions because more available data







Testing the Aharonov-Bohm effect in QCD as a non-Abelian gauge theory

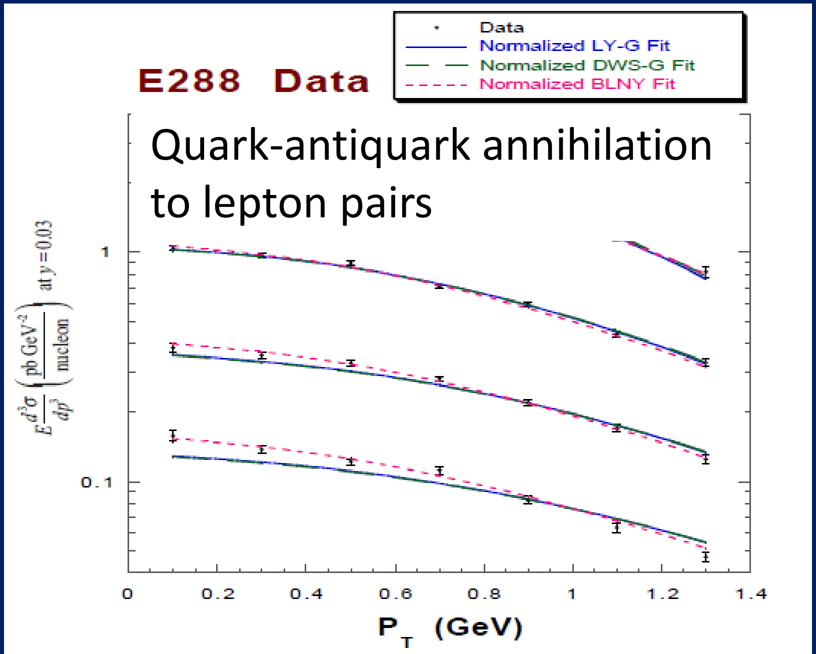


Landry, Brock, Nadolsky, Yuan, PRD 67, 073016 (2003)

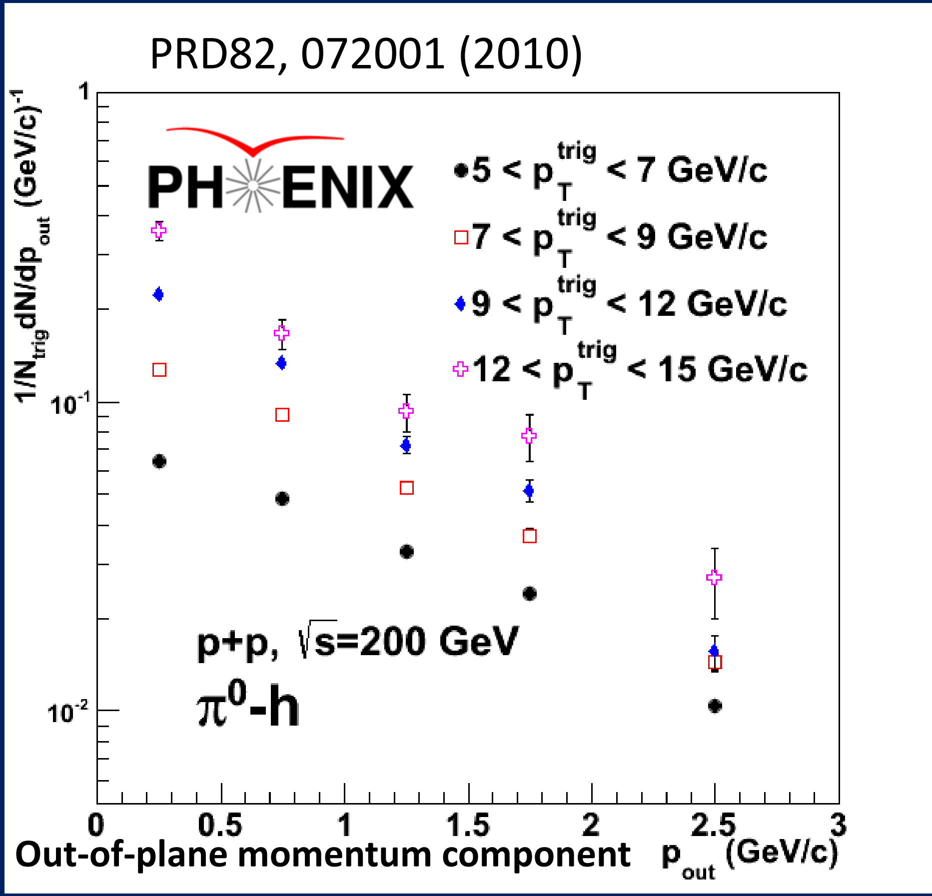
Get predictions from fits to data where no entanglement expected

$p+A \rightarrow \mu^+ + \mu^- + X$ for different invariant masses: No color entanglement expected

Testing the Aharonov-Bohm effect in QCD as a non-Abelian gauge theory



Landry, Brock, Nadolsky, Yuan, PRD 67, 073016 (2003)

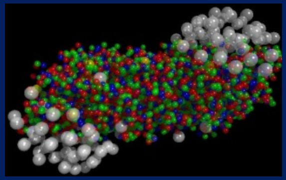
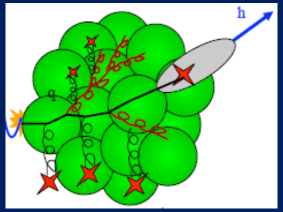


Get predictions from fits to data where no entanglement expected

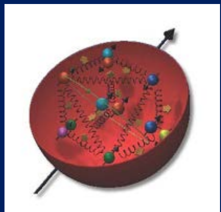
In progress . . .!

Make predictions for processes where entanglement *is* expected; look for deviation

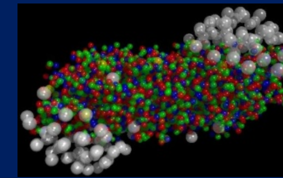
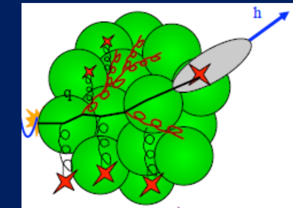

Summary

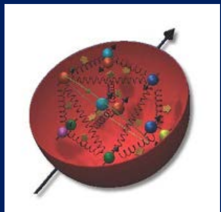
- Early years of rewarding new era of *quantitative basic research* in QCD!



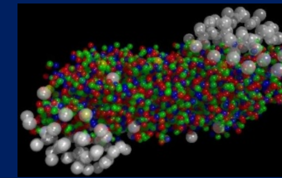
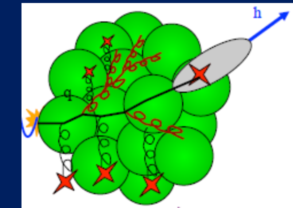

Summary

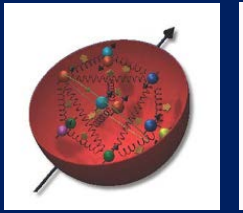
- Early years of rewarding new era of *quantitative basic research* in QCD!
- Gradually shifting to think about QCD systems in new ways, focusing on topics/ideas/concepts long familiar to the world of condensed matter physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference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



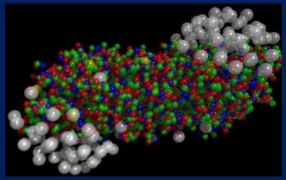
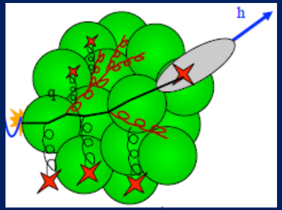

Summary

- 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




Summary

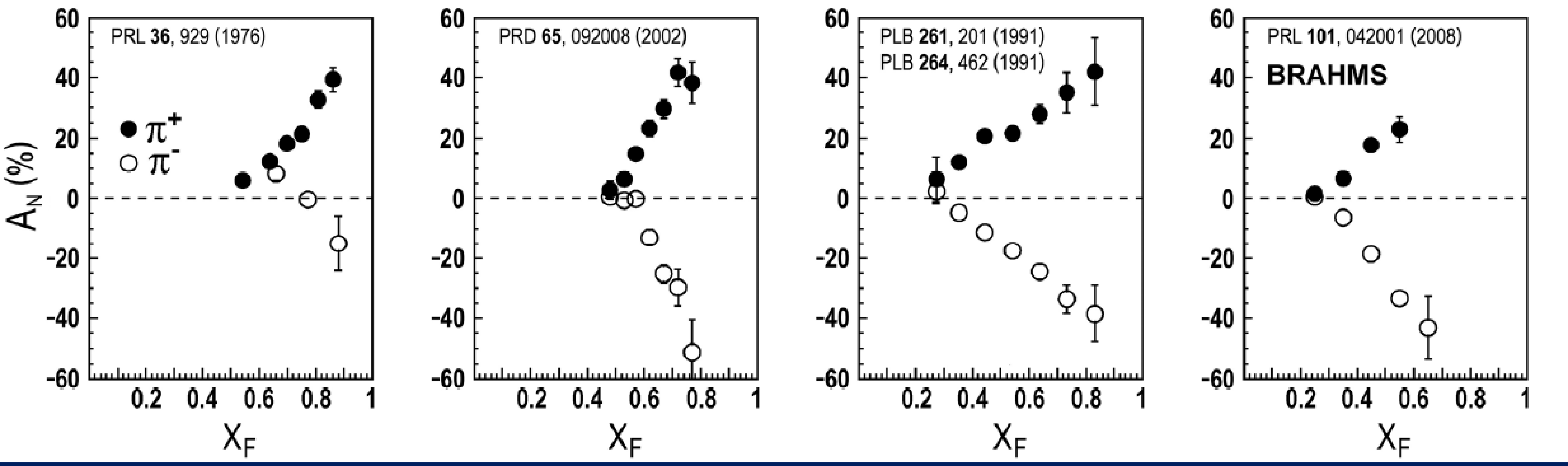
- Early years of rewarding new era of *quantitative basic research* in QCD!
- Gradually shifting to think about QCD systems in new ways, focusing on topics/ideas/concepts long familiar to the world of condensed matter physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference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

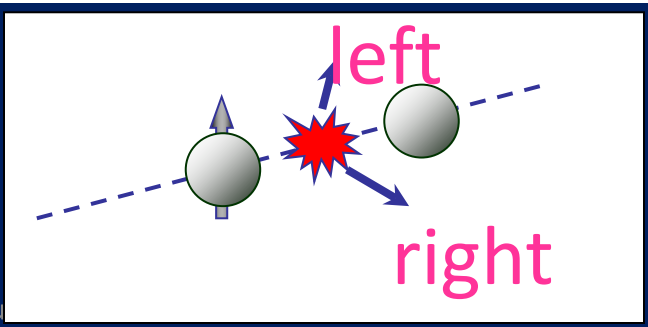
Extra

Huge *spin asymmetries in p+p → hadrons: Due to color entanglement??*

ANL $\sqrt{s}$=4.9 GeV	BNL $\sqrt{s}$=6.6 GeV	FNAL $\sqrt{s}$=19.4 GeV	RHIC $\sqrt{s}$=62.4 GeV

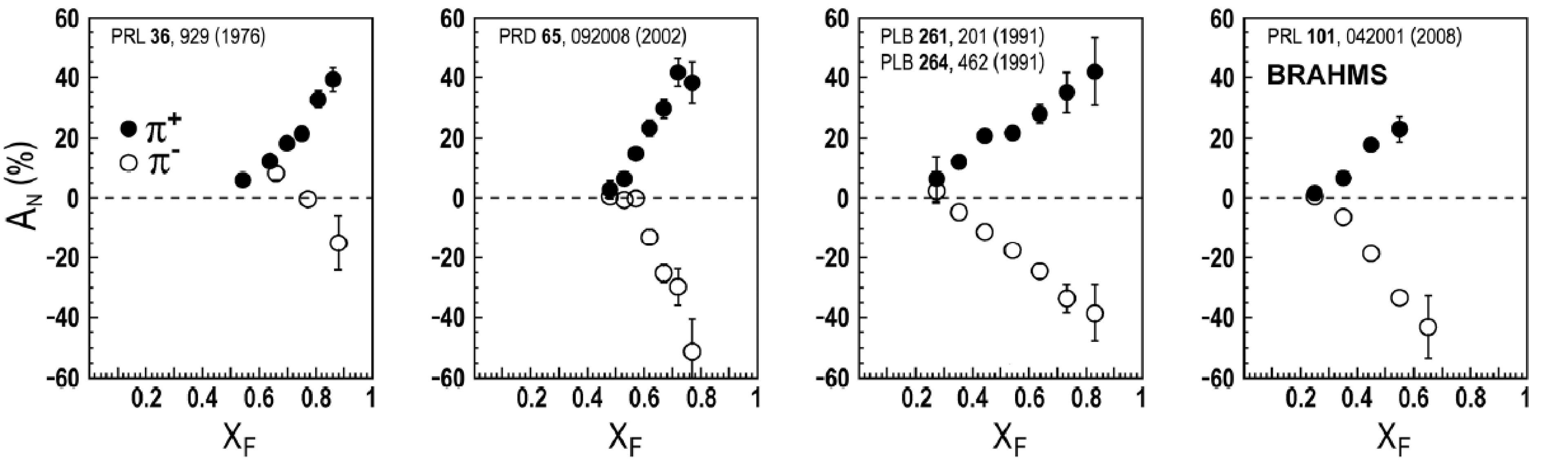


$$x_F = 2p_{long} / \sqrt{s}$$



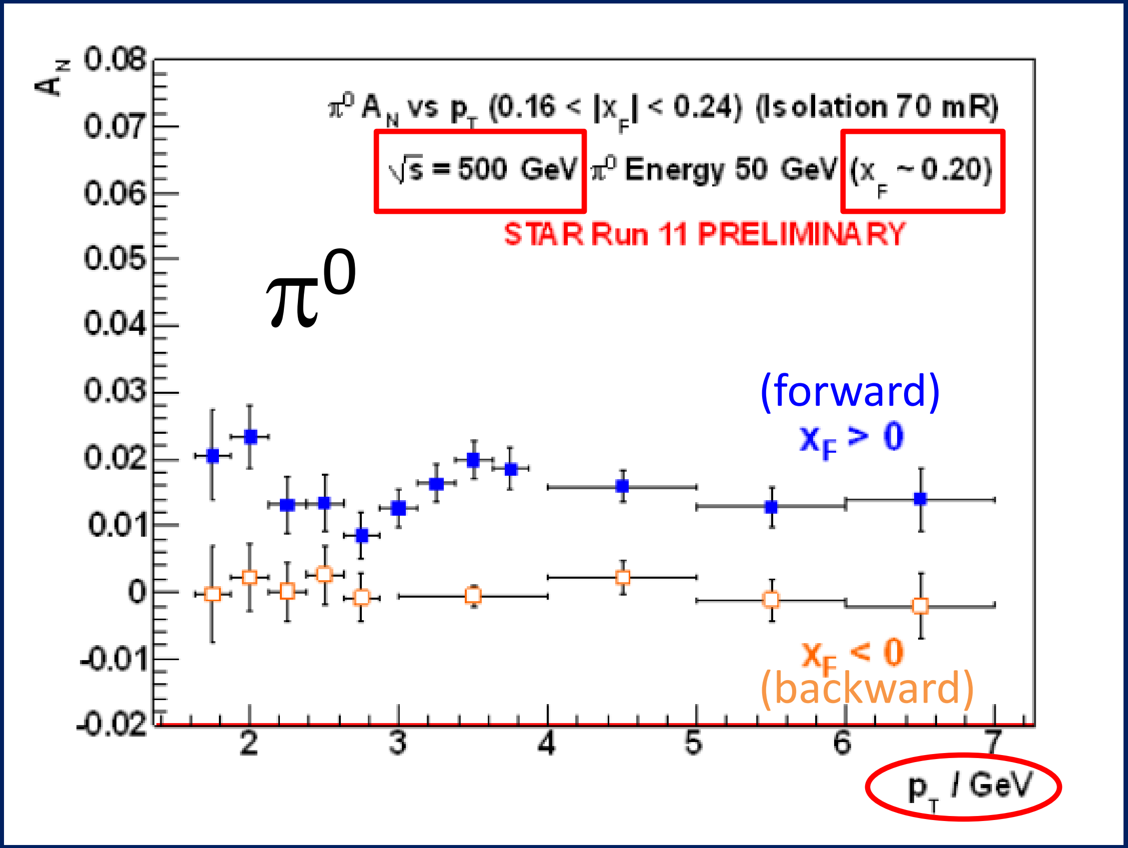
Huge *spin asymmetries in p+p → hadrons: Due to color entanglement??*

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 nonperturbative structure?

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

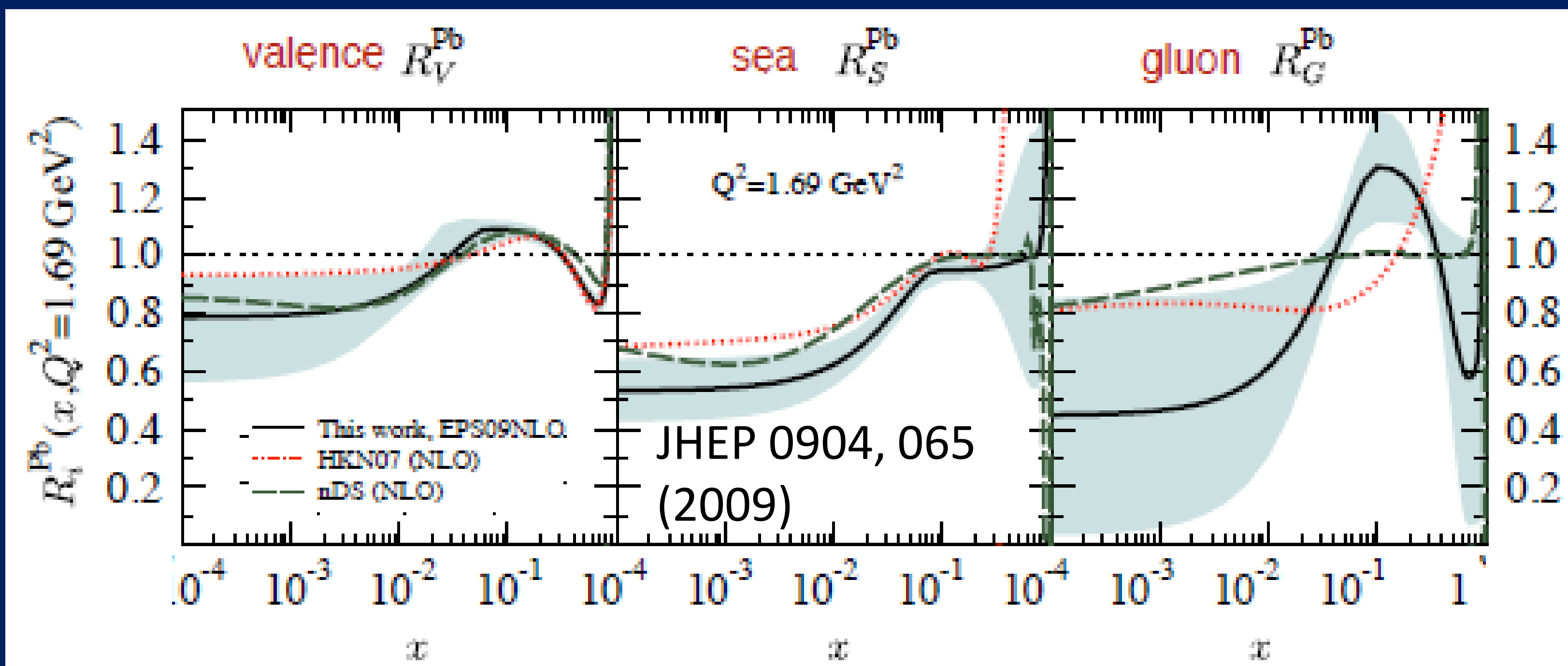


- Effects persist to kinematic regimes where perturbative QCD techniques clearly apply
- p_T = 7 GeV → $Q^2 \sim 49$ GeV^2!

Note x_F = 0.2 here, where asymmetries approached zero on lower-energy plots—need more-forward measurements at high energies!

Recent renaissance in nuclear pdfs

- Renaissance in nuclear pdfs
  - EPS09 483 citations!



Increasing connections between heavy ion or nucleon structure physics 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)

Increasing connections between heavy ion or nucleon structure physics 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
- B factories
  - Flavor physics and CP violation
  - Spin-momentum correlations in hadronization
  - Dihadron fragmentation functions—observe two particles fragmenting from single parton

Increasing connections between heavy ion or nucleon structure physics 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
- B factories
  - Flavor physics and CP violation
  - Spin-momentum correlations in hadronization
  - Dihadron fragmentation functions—observe two particles fragmenting from single parton
- Jets and jet substructure
  - Gluon vs. quark jets and hadronization
  - Search for BSM physics
  - Measure parton spin-momentum correlations in hadronization via angular distributions of particles within jet
  - Understand jet modification and energy redistribution in nuclear medium

Increasing connections between heavy ion or nucleon structure physics and particle physics

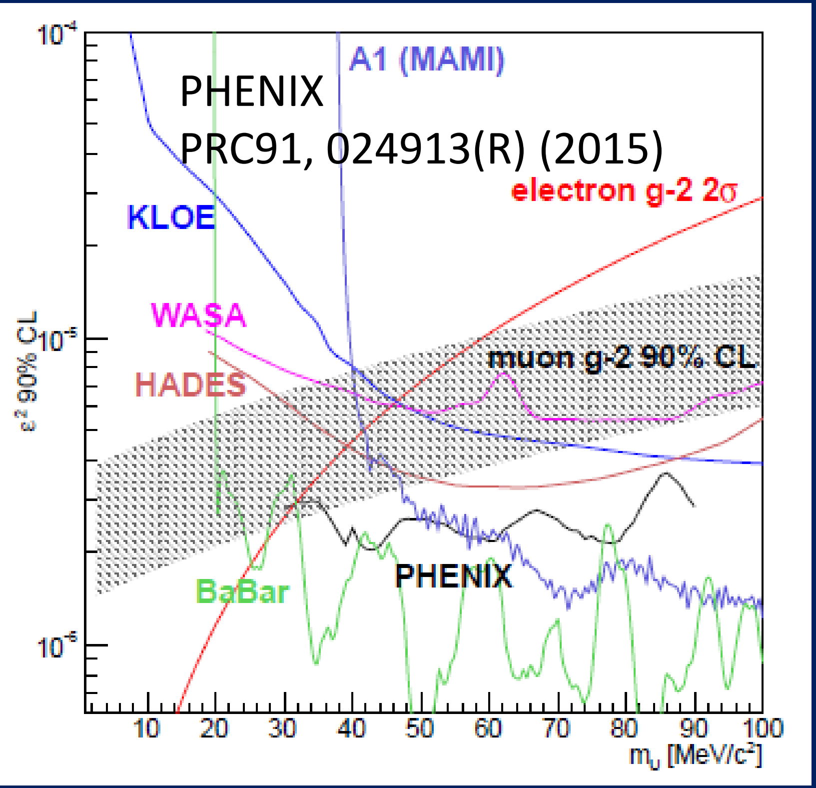
- Low-x/gluon saturation physics
  - Onset expected in higher-energy p+p collisions, lower-energy heavy ion collisions
- Transverse-momentum-dependent parton distribution functions, Q_T resummation, Soft-Collinear Effective Theory
  - Determine transverse momentum distribution for Higgs, Z/W, Drell-Yan at low p_T
- B factories
  - Flavor physics and CP violation
  - Spin-momentum correlations in hadronization
  - Dihadron fragmentation functions—observe two particles fragmenting from single parton
- Jets and jet substructure
  - Gluon vs. quark jets and hadronization
  - Search for BSM physics
  - Measure parton spin-momentum correlations in hadronization via angular distributions of particles within jet
  - Understand jet modification and energy redistribution in QCD medium
- Underlying event
  - Soft QCD physics in p+p, nuclear collisions

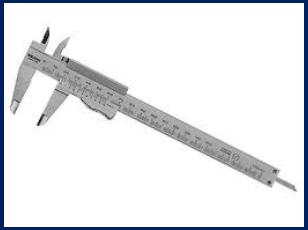
Increasing connections between heavy ion or nucleon structure physics and particle physics

- 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
- B factories
  - Flavor physics and CP violation
  - Spin-momentum correlations in hadronization
  - Dihadron fragmentation functions—observe two particles fragmenting from single parton
- Jets and jet substructure
  - Gluon vs. quark jets and hadronization
  - Search for BSM 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
- Searching for dark matter in heavy ion collisions

Increasing connections between heavy ion or nucleon structure physics 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 fo
- B factories
  - Flavor physics and CP violation
  - Spin-momentum correlations in hadronization
  - Dihadron fragmentation functions—observe two
- Jets and jet substructure
  - Gluon vs. quark jets and hadronization
  - Search for BSM physics
  - Measure parton spin-momentum correlations in particles within jet
  - Understand jet modification and energy redistrib
- Underlying event
  - Soft QCD physics in p+p, nuclear collisions
- Collectivity in high-multiplicity systems, reg
- Searching for dark matter in heavy ion collis





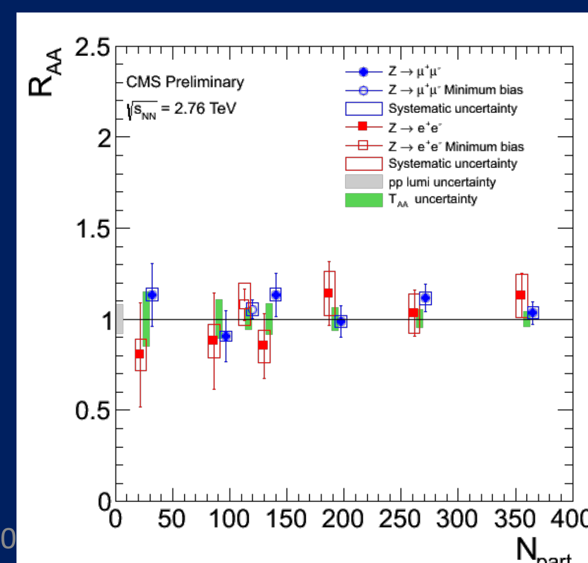
Overlapping tools and techniques

- 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, . . .

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, . . .
  - 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



Overlapping tools and techniques

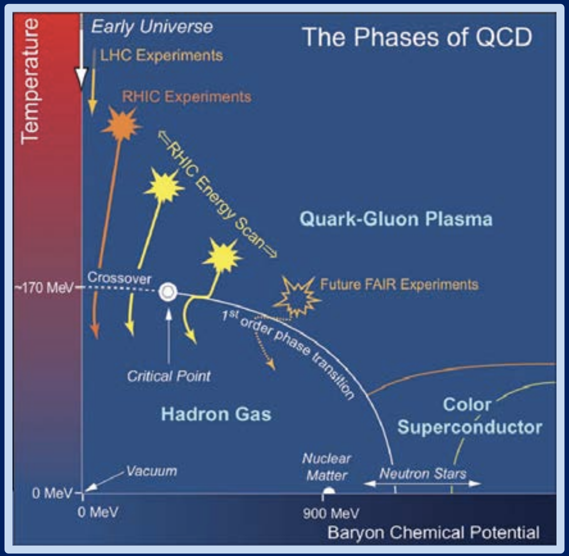
- HEP, nucleon structure, and heavy ion communities sharing an increasing number of tools/techniques
  - Jets—to study parton energy loss in quark-gluon plasma, in-medium modification of fragmentation functions, gluon spin contribution to spin of proton, . . .
  - W/Z bosons—to calibrate parton energy 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, . . .
  - Heavy flavor/quarkonia—to probe temperature of quark-gluon plasma, color screening effects, hadron production mechanisms, spin-dependent tri-gluon correlation functions, . . .

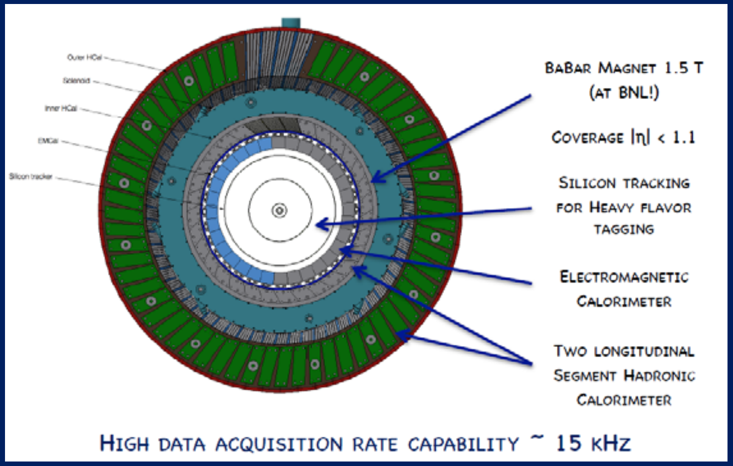
Overlapping tools and techniques

- 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, . . .
  - 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, . . .
  - Heavy flavor/quarkonia—to probe temperature of quark-gluon plasma, color screening effects, hadron production mechanisms, spin-dependent tri-gluon correlation functions, . . .
  - 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

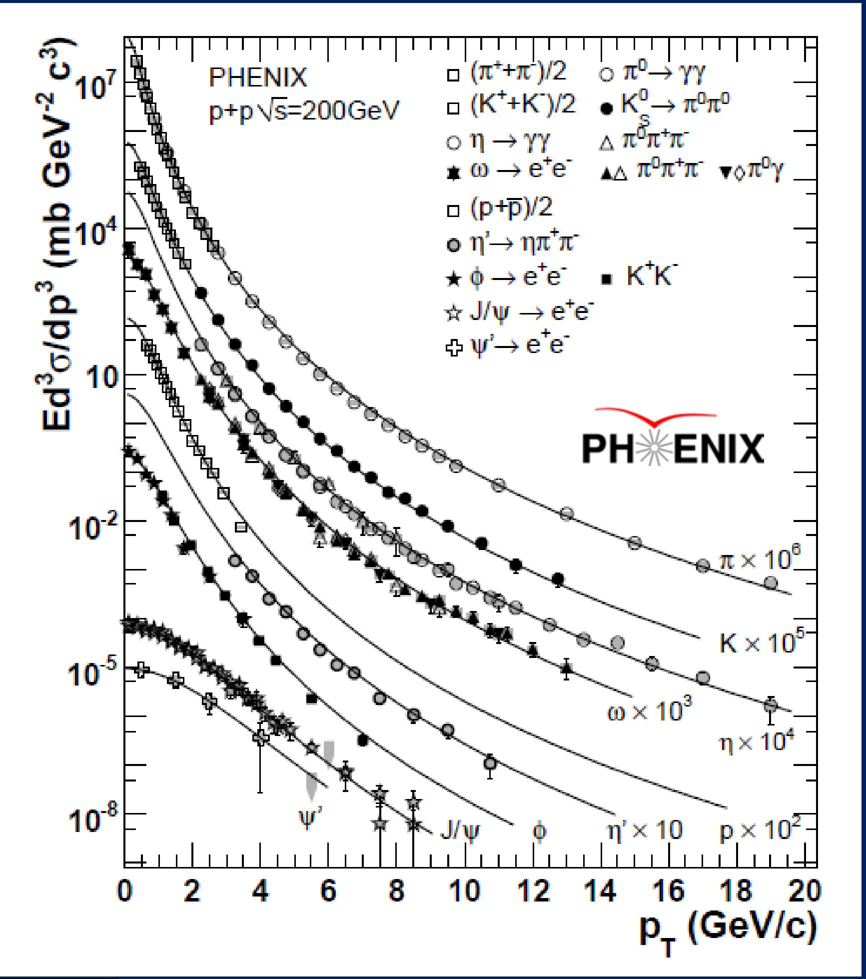
Coming up at RHIC

- RHIC Beam Energy Scan II
  - Search for QCD critical end point
- sPHENIX
  - Proposed new detector at RHIC focused on jets, jet correlations, upsilons
- Many more results from recent data sets: ^{3}He+Au, Cu+Au, U+U, $p^{\uparrow}$+Au, $p^{\uparrow}$+Al, $p^{\uparrow}+p^{\uparrow}$, . . .





Hadronization: Eventually even "more global" global fits of fragmentation functions?

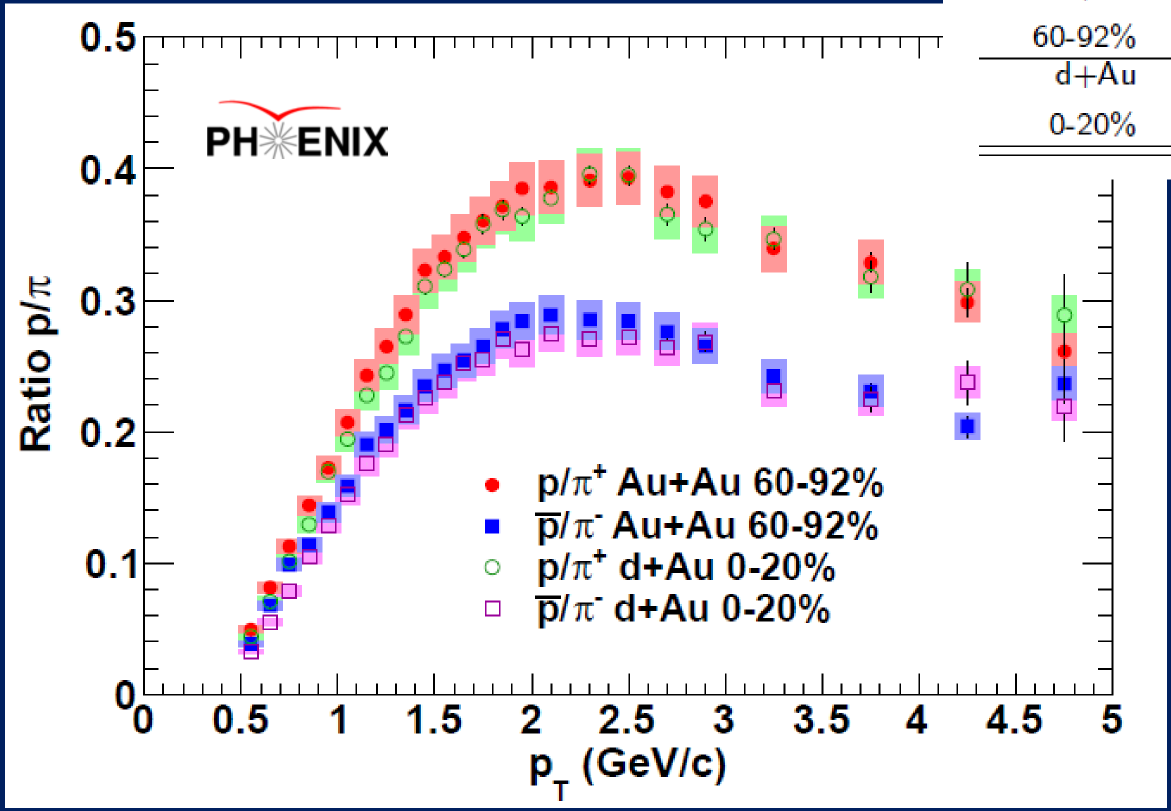


PRD83, 052004 (2011)

- Perform fragmentation function parameterizations for even more particles simultaneously?
  - Will constrain relative normalizations well
- Ultimate goal: Measure jet and all particles within it!
- Fit pdfs and FFs simultaneously . . .

Additional hadronization mechanisms in the presence of many partons?

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

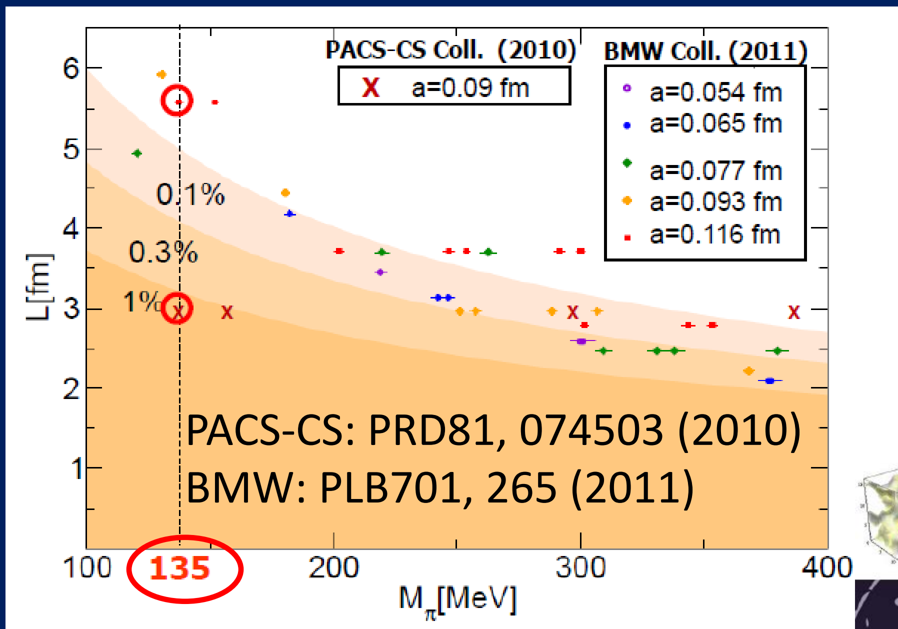


PRC88, 024906 (2013)

Both shape and magnitude of p/π ratio in d+Au and peripheral Au+Au identical!

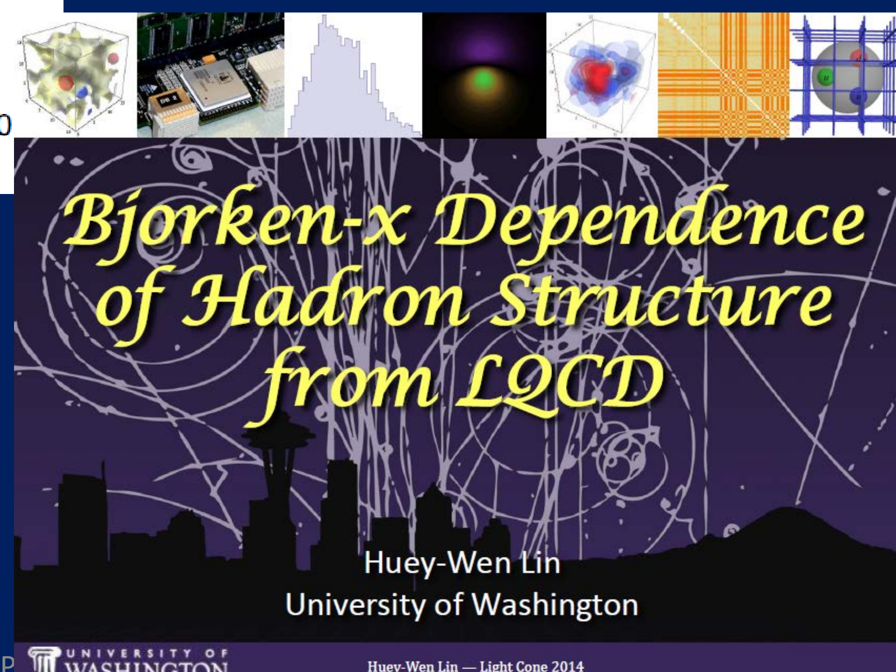
Suggests common mechanism(s) for baryon production in the two systems—partons nearby in phase space bind?

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