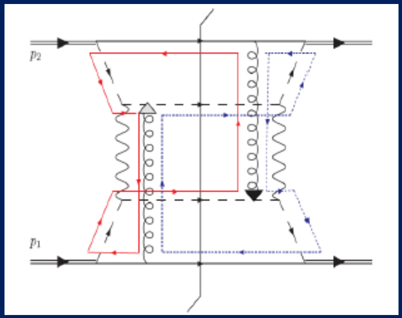
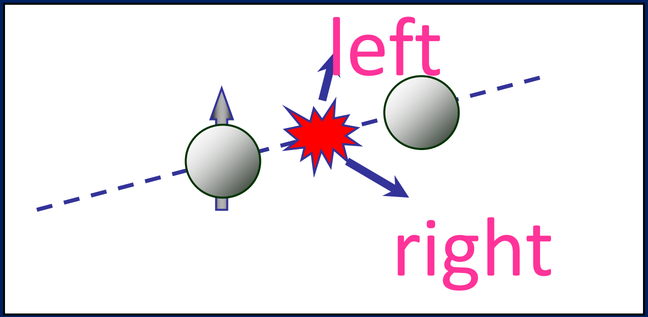
Spin-Momentum Correlations, Aharonov-Bohm, and Color Entanglement in Quantum Chromodynamics

Christine A. Aidala

University of Michigan





$$\psi(x)|P\rangle = e^{ig\int_x^{x'} ds_\mu A^\mu}\psi(x')|P\rangle$$

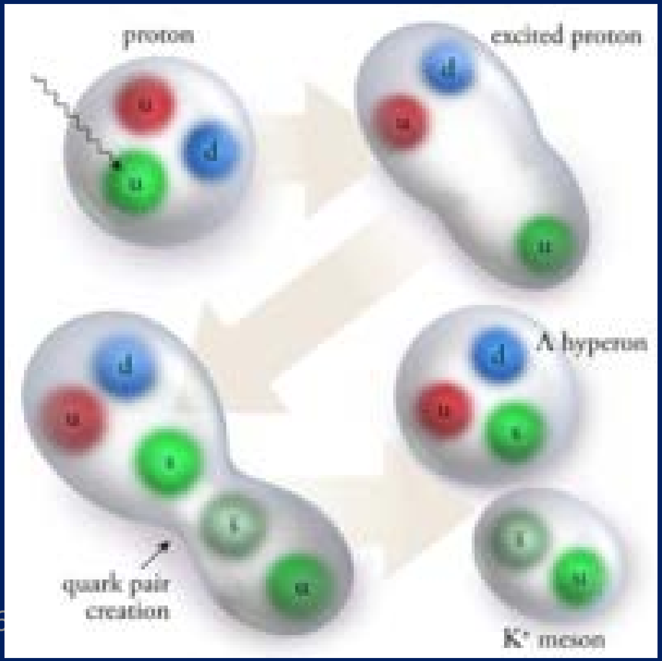
UCLA

October 17, 2016

Theory of strong interactions: Quantum Chromodynamics

- Fundamental field theory in hand since the early 1970s—BUT . . .
- Quark and gluon degrees of freedom in the theory cannot be observed or manipulated directly in experiment!

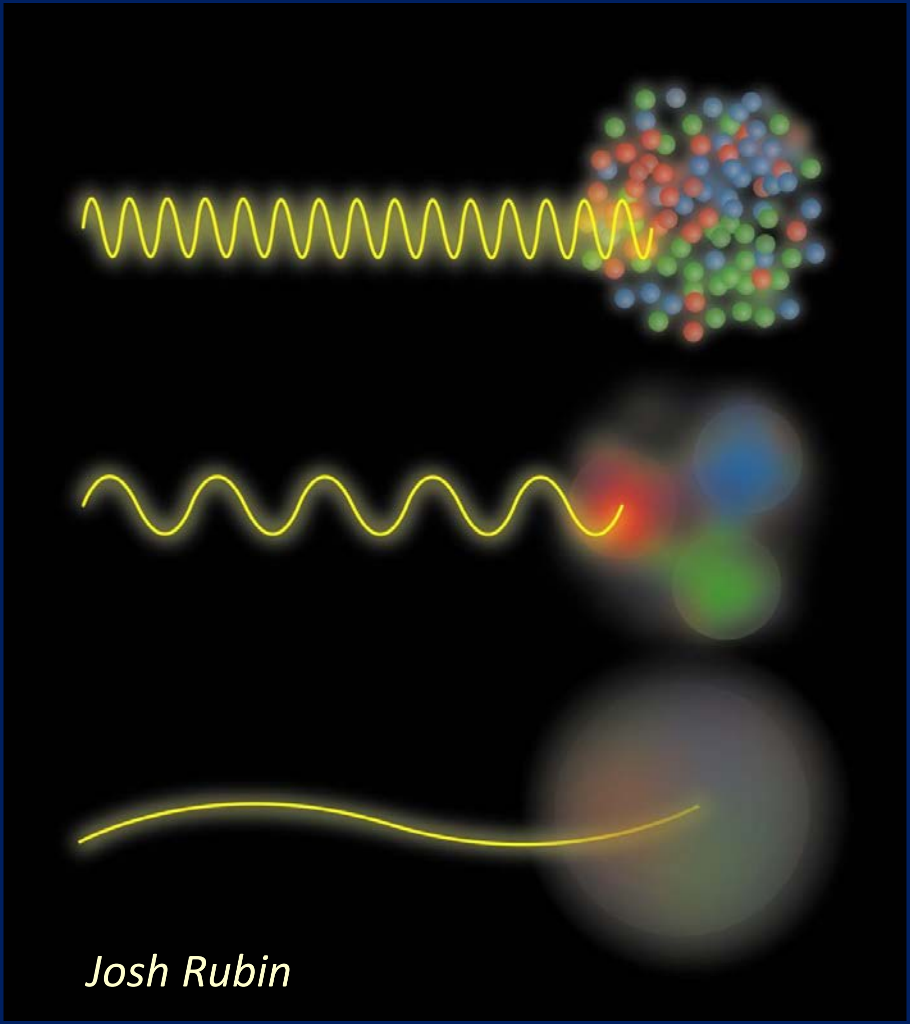
Color *confinement*—quarks and gluons are confined to color-neutral bound states



CLAS, PRL 113, 152004 (2014)
PRL Editor's Choice Oct. 2014

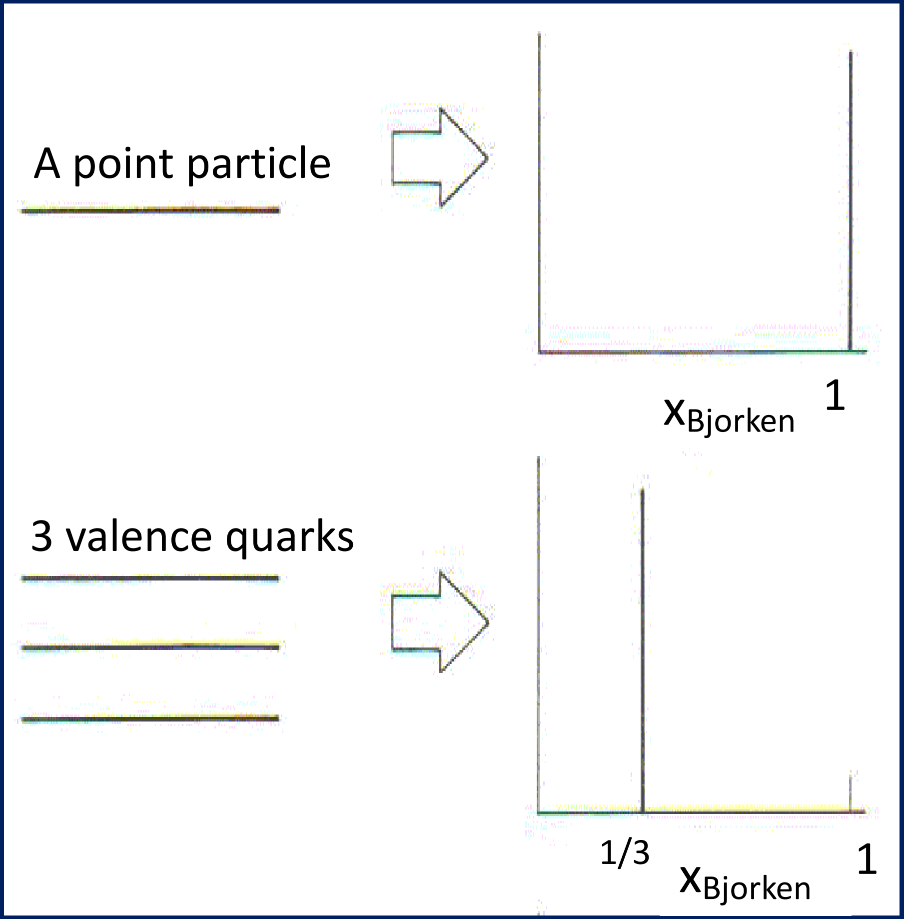
Quark and gluon structure of the nucleon

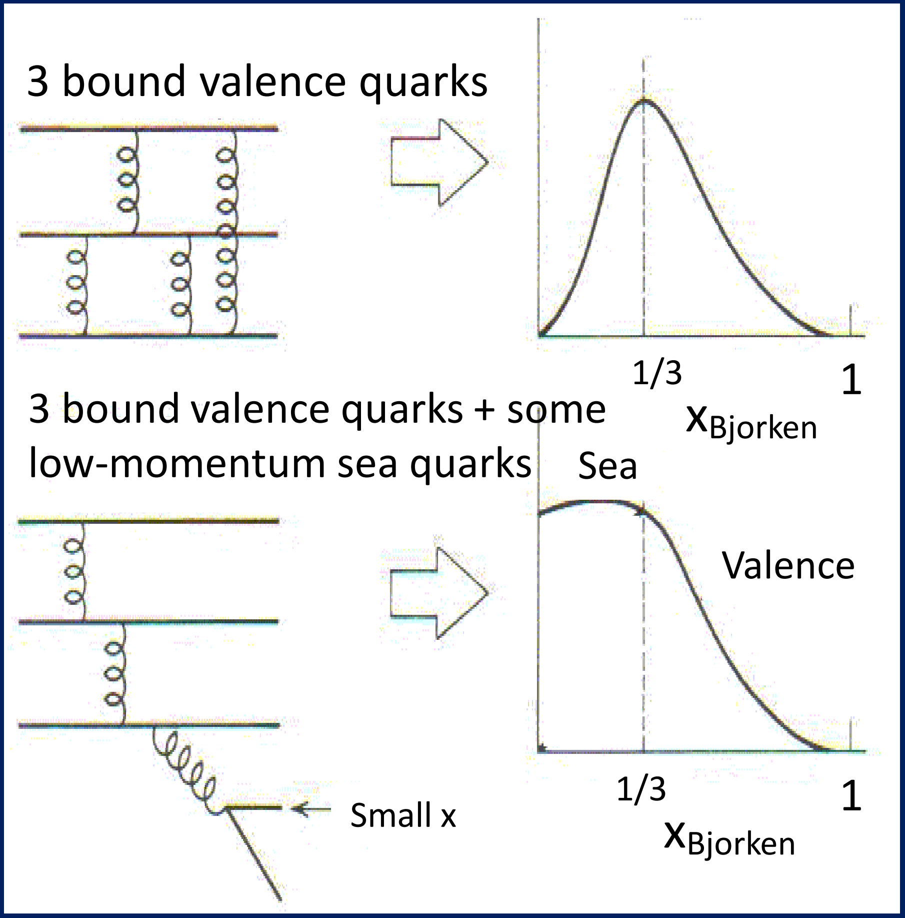
- Probing the proton at different energy scales offers information on different aspects of its internal structure



Parton distribution functions inside a nucleon: The language we've developed (so far!)

What momentum fraction would the scattering particle carry if the proton were made of …

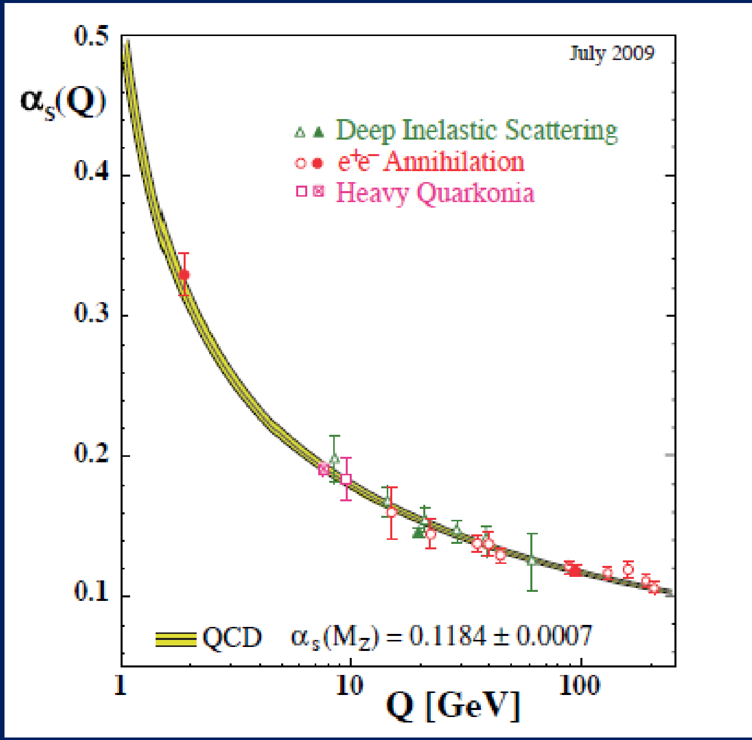




Halzen and Martin, "Quarks and Leptons", p. 201

Perturbative QCD

- Take advantage of running of the strong coupling constant with energy (*asymptotic freedom*)—weak coupling at high energies (short distances)
- Perturbative expansion as in quantum electrodynamics (but many more diagrams due to gluon self-coupling!!)



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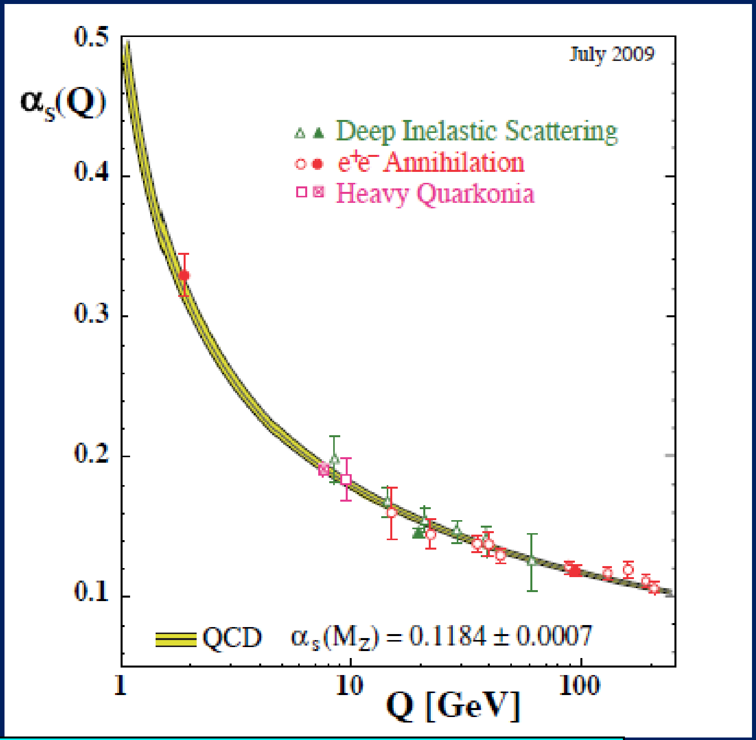
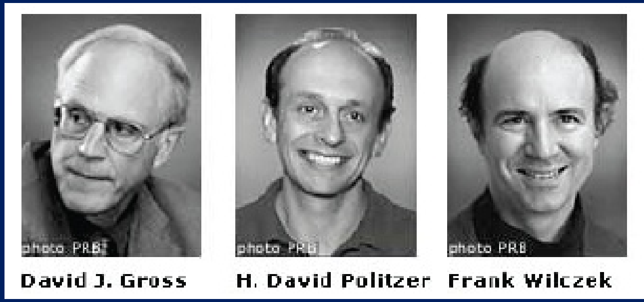


Provides a rigorous way of relating the fundamental field theory to a variety of physical observables!

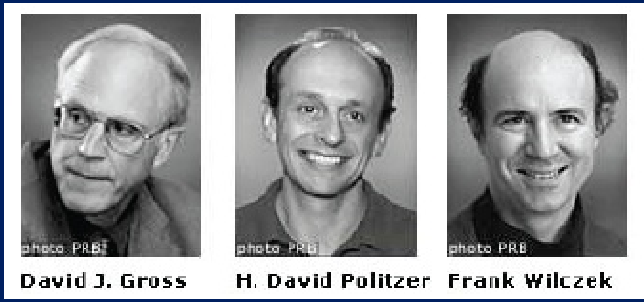
QCD: How far have we come?



- 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

QCD: How far have we come?



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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 *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 QCD bound states

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- Nonperturbative 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!

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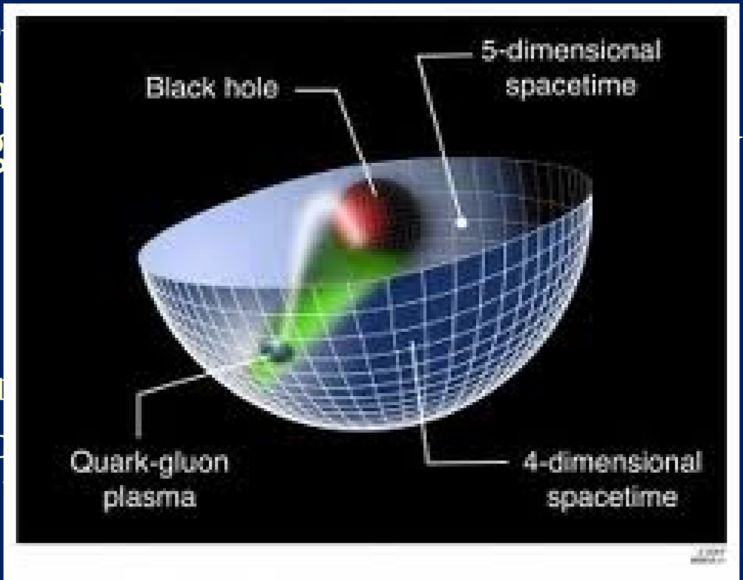

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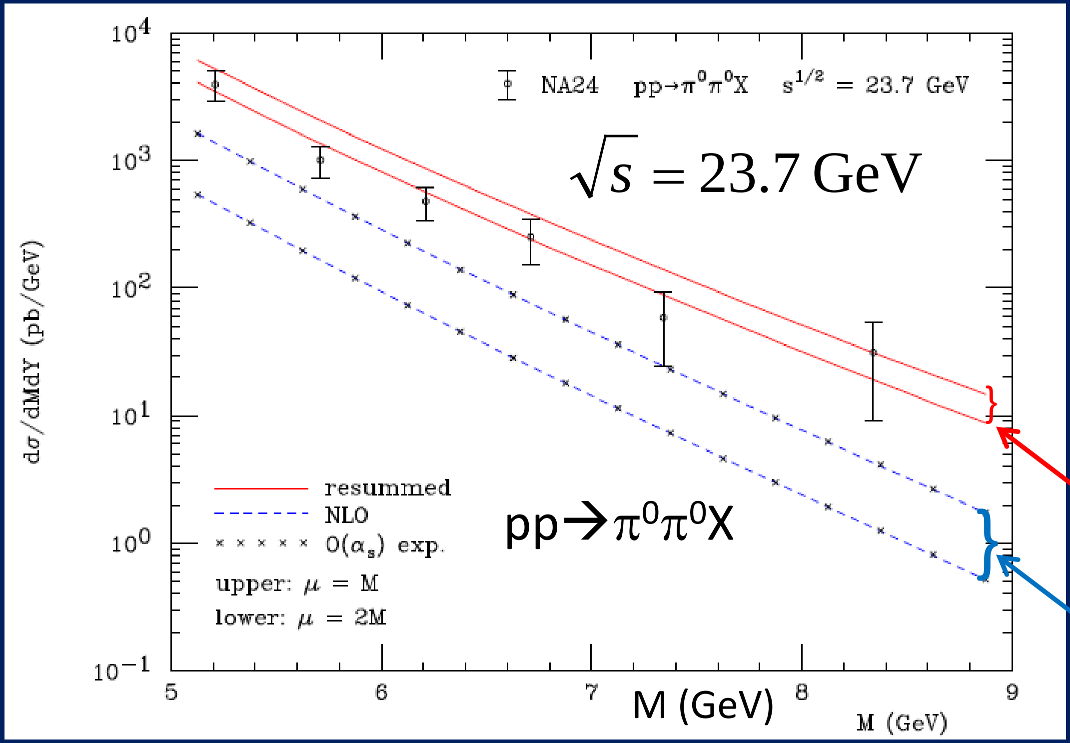
Effective field theories

- 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 symmetry breaking, . . .

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



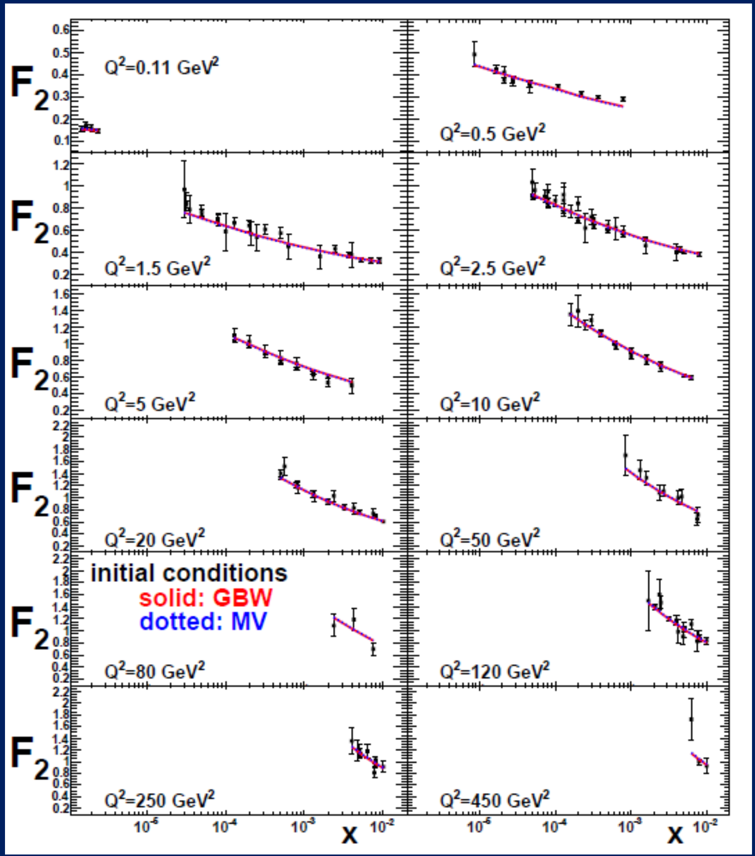
For observables with two different scales, sum logs of their ratio to all orders in the strong coupling constant

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



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!

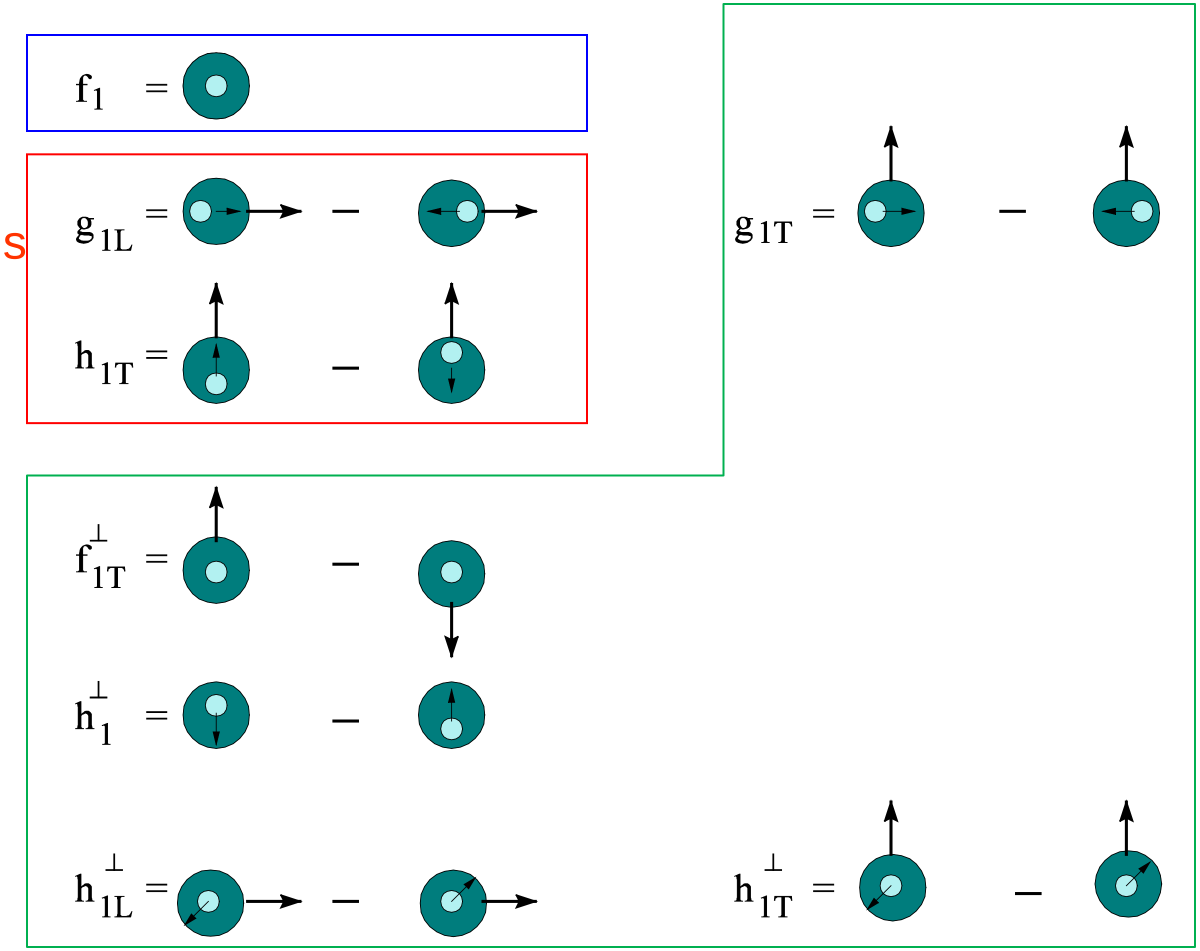
Example: Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

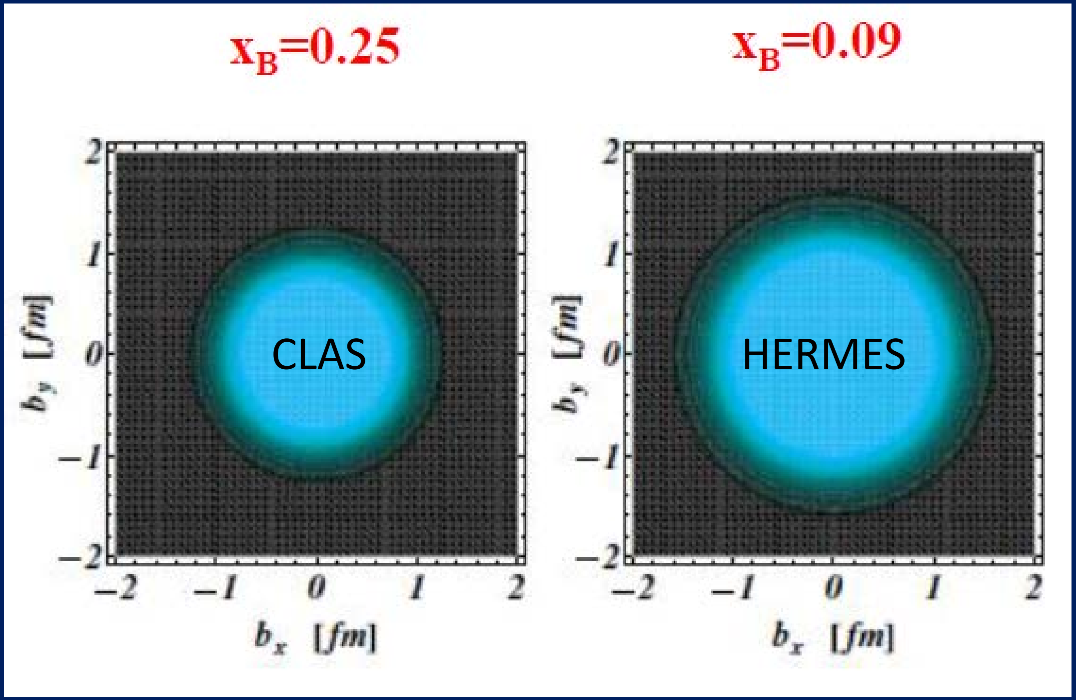
Spin-spin correlations

Spin-momentum correlations

$$S\bullet(p_1\times p_2)$$



Example: Exploring spatial distributions



Spatial charge densities measured via deeply virtual Compton scattering

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

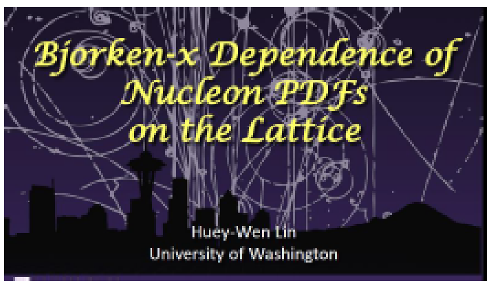
Example: Progress in lattice QCD

Recent progress in LQCD suggests the possibility to calculate the *x*-dependence of parton distributions

PRL **110,** 262002 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

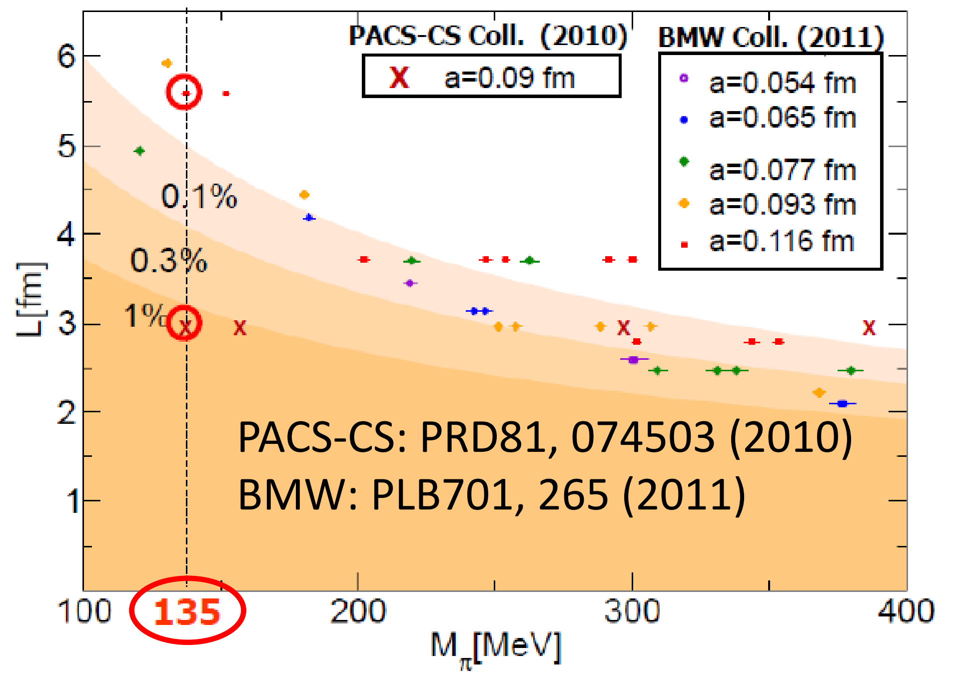
Parton Physics on a Euclidean Lattice

Xiangdong Ji[1,2]



The *x*-dependence of the quark and antiquark transversity distributions can be calculated (not just their moments)

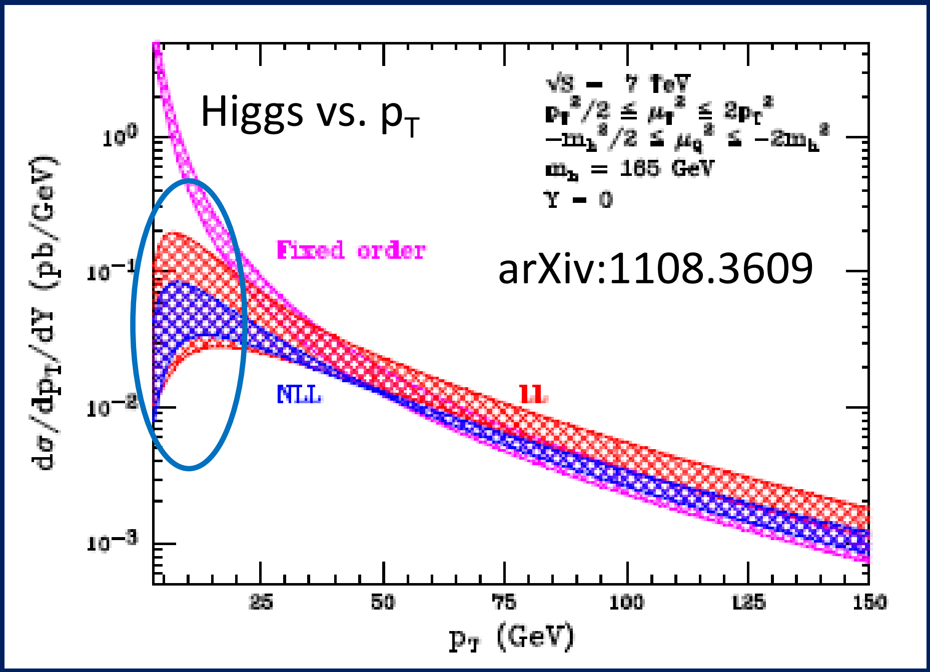
Slide from J.-C. Peng, Transversity 2014



First calculations at physical pion mass 135 MeV

Figure from T. Hatsuda, PANIC 2011

Example: Effective field theories



TRANSVERSE MOMENTUM DISTRIBUTIONS FROM EFFECTIVE FIELD THEORY

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Frank Petriello

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

Department of Physics & Astronomy, Northwestern University
Evanston, IL 60208, USA
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Soft Collinear Effective Theory
– Transverse momentum distribution for gluon+gluon→Higgs

Mapping out the partonic structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*

Mapping out the partonic structure of the proton

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- *Color*

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Vast majority of past four decades focused on *1-dimensional* momentum structure! Since 1990s starting to consider transverse components . . .

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Polarized protons first studied in 1980s. How angular momentum of quarks and gluons add up still not well understood!

Mapping out the partonic structure of the proton

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Good measurements of flavor distributions in valence region. Flavor structure at lower momentum fractions still yielding surprises!

Mapping out the partonic structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
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Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past decade.

Mapping out the partonic structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
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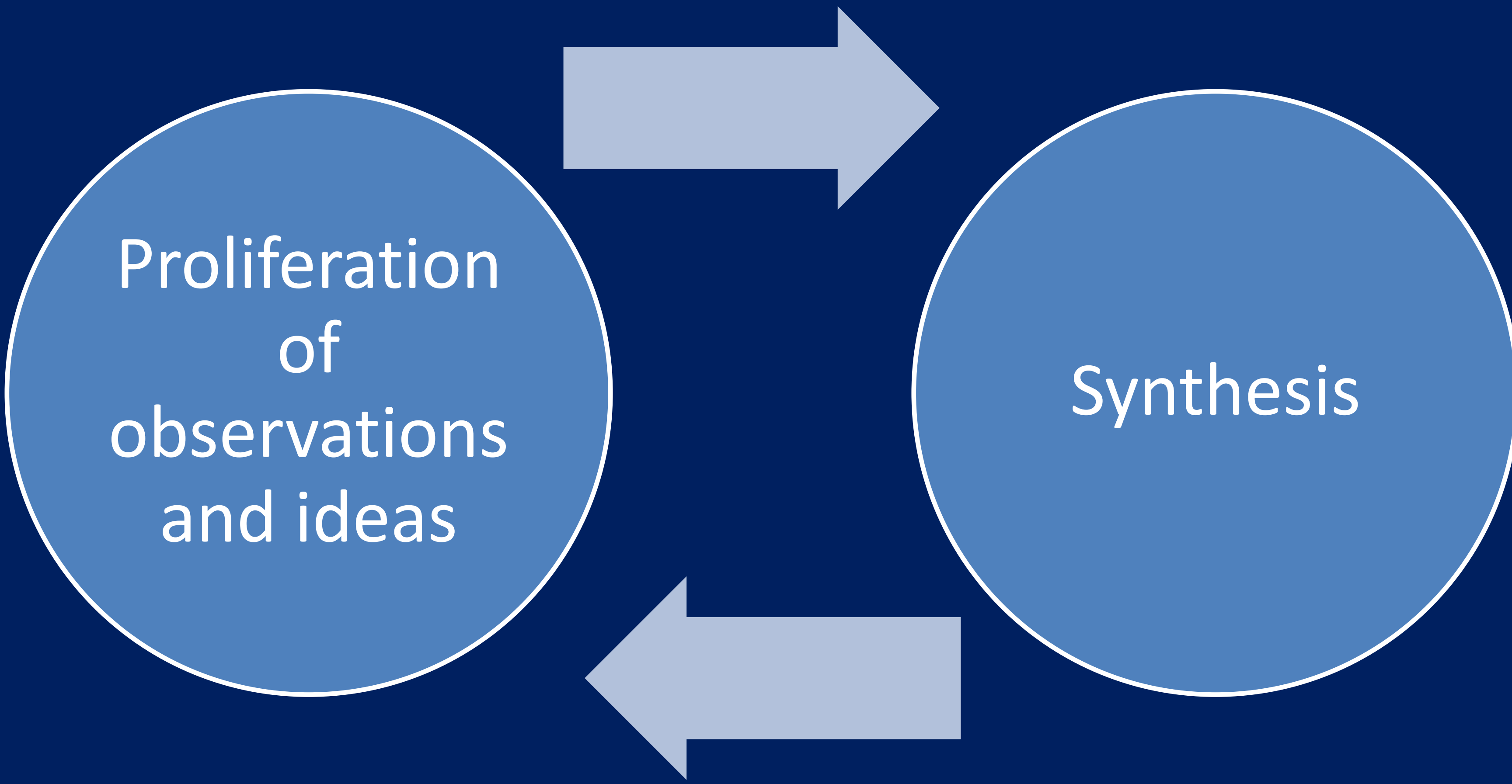
- *Color*

Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color have come to forefront in last few years . . .

A cyclical process



Factorization and universality in perturbative QCD

- Need to systematically *factorize* short- and long-distance physics—observable physical QCD processes always involve at least one long-distance scale (confinement)!
- Long-distance (i.e. not perturbatively calculable) functions need to be *universal* in order to be portable across calculations for many processes

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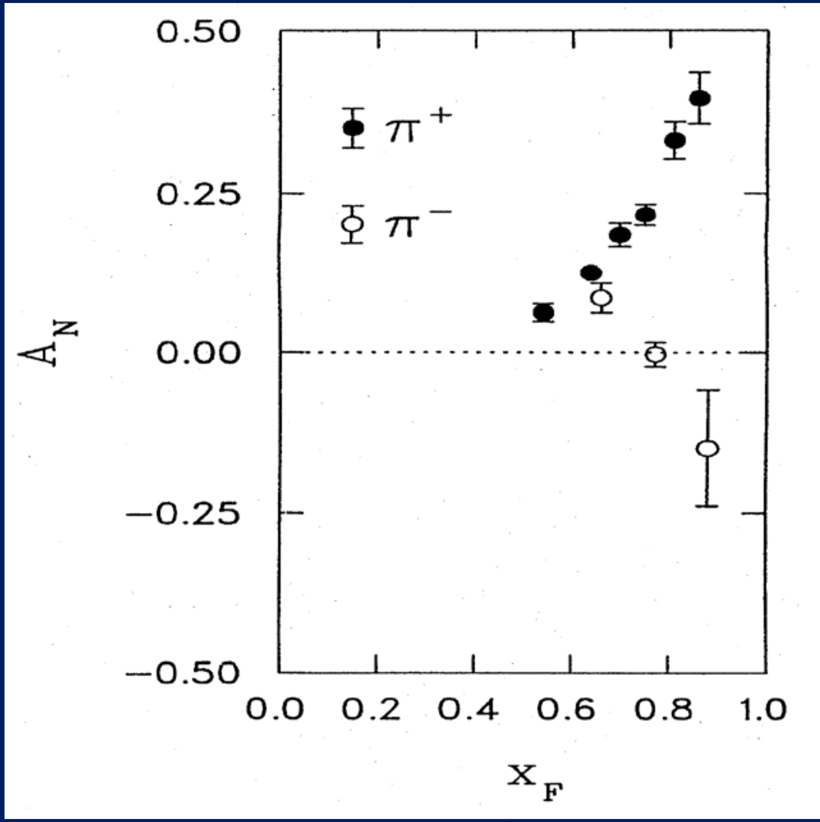
Measure nonperturbative parton distribution functions (pdfs) and fragmentation functions in many colliding systems over a wide kinematic range→constrain by performing *simultaneous fits to world data*

Spin-momentum correlations: 1976 discovery in p+p collisions

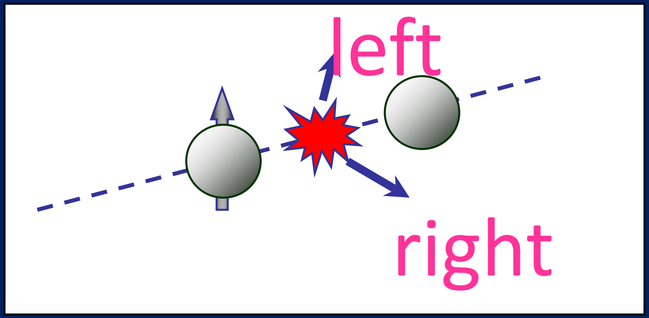
Argonne √s=4.9 GeV



W.H. Dragoset et al., PRL36, 929 (1976)

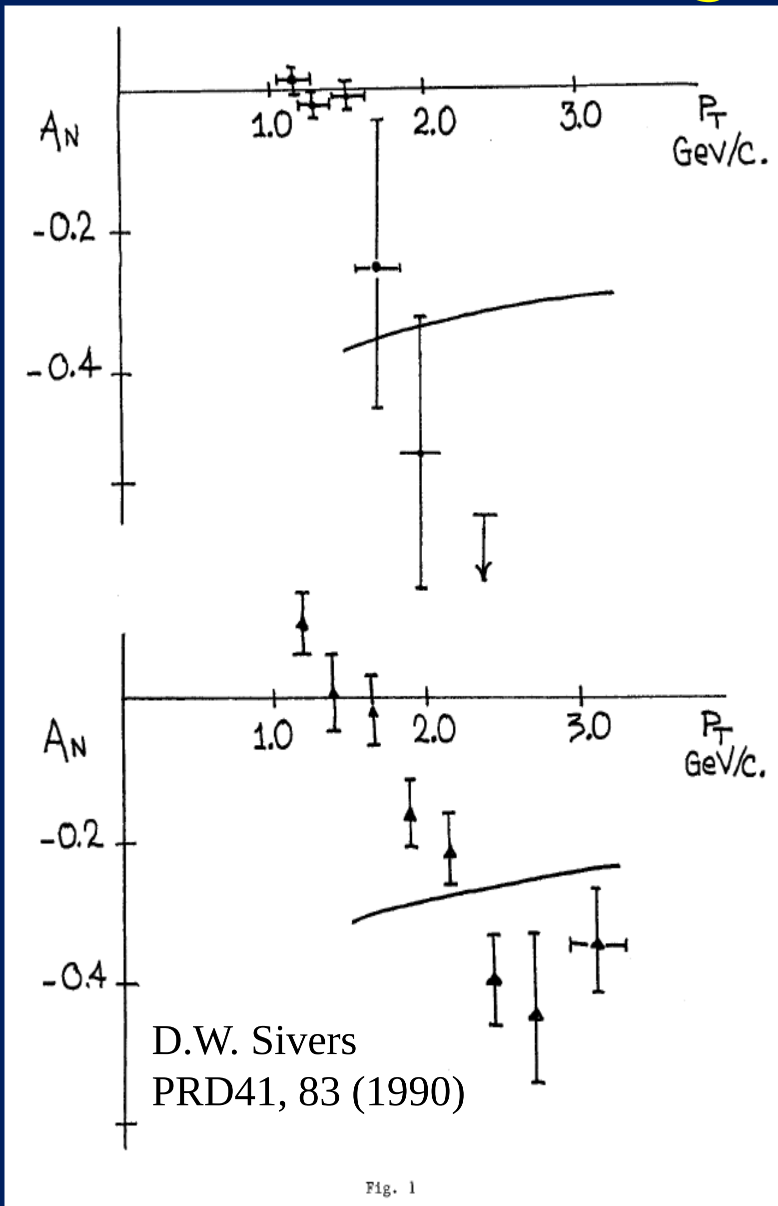
Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction—by up to 40%!!

Had to wait more than a decade for the birth of a new subfield in order to explore the possibilities . . .



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

Transverse-momentum-dependent distributions and single-spin asymmetries



D.W. Sivers
PRD41, 83 (1990)

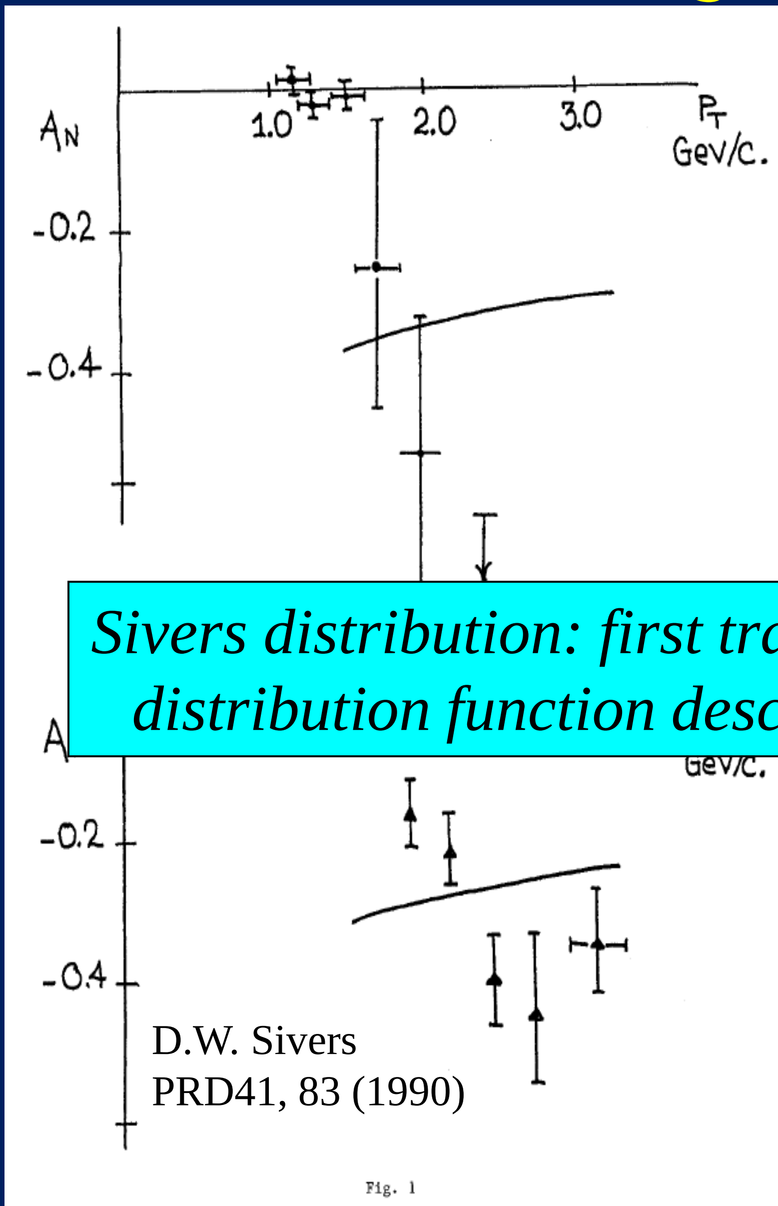
- 1990: “Sivers mechanism” proposed in attempt to understand observed asymmetries

- Departs from traditional *collinear* factorization assumption in pQCD and proposes correlation between the *intrinsic transverse motion* of the quarks and gluons and the proton’s spin

$$s \cdot (p_1 \times p_2)$$

Spin and momenta of partons and/or hadrons

Transverse-momentum-dependent distributions and single-spin asymmetries



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Sivers distribution: first transverse-momentum-dependent parton distribution function describing a spin-momentum correlation

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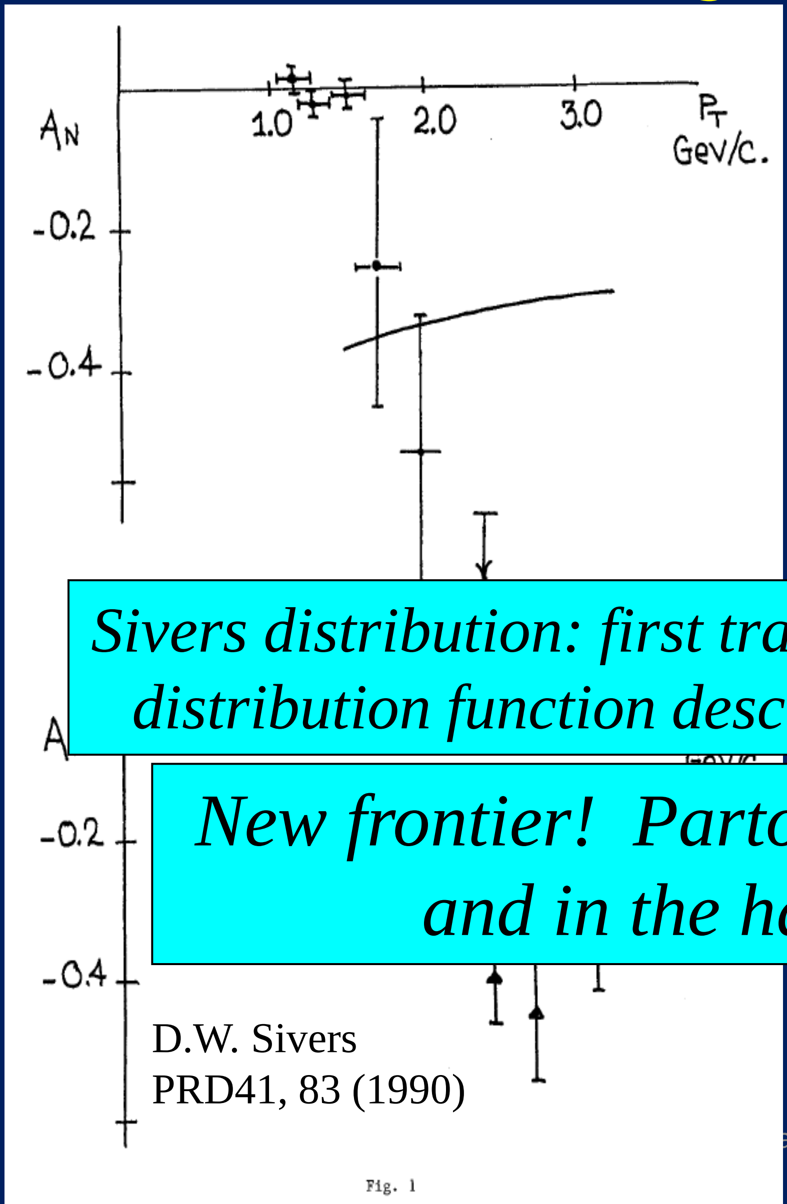

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*New frontier! Parton **dynamics** inside hadrons, and in the hadronization process*

$$s \cdot (p_1 \times p_2)$$

Spin and momenta of partons and/or hadrons

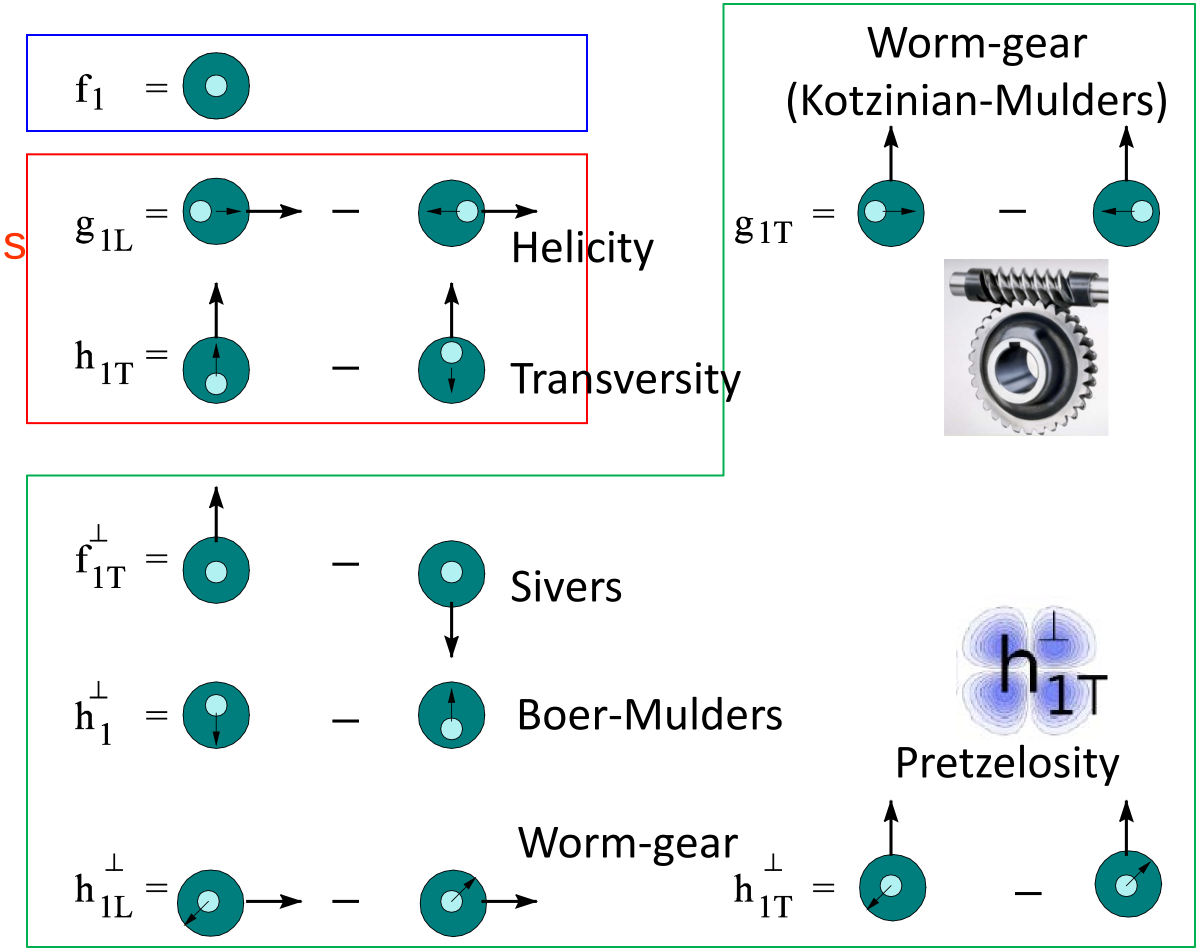
Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

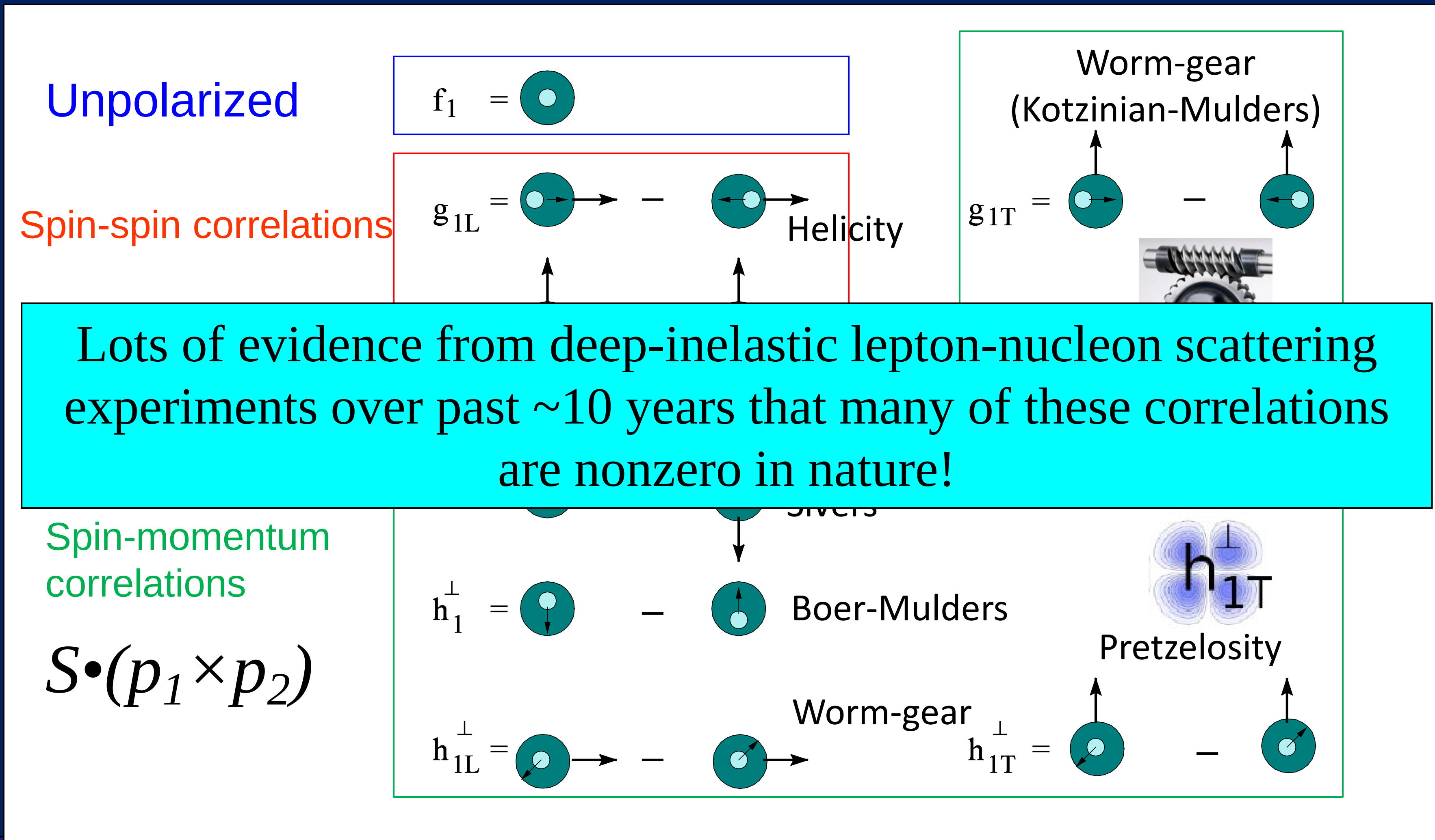
Spin-spin correlations

Spin-momentum correlations

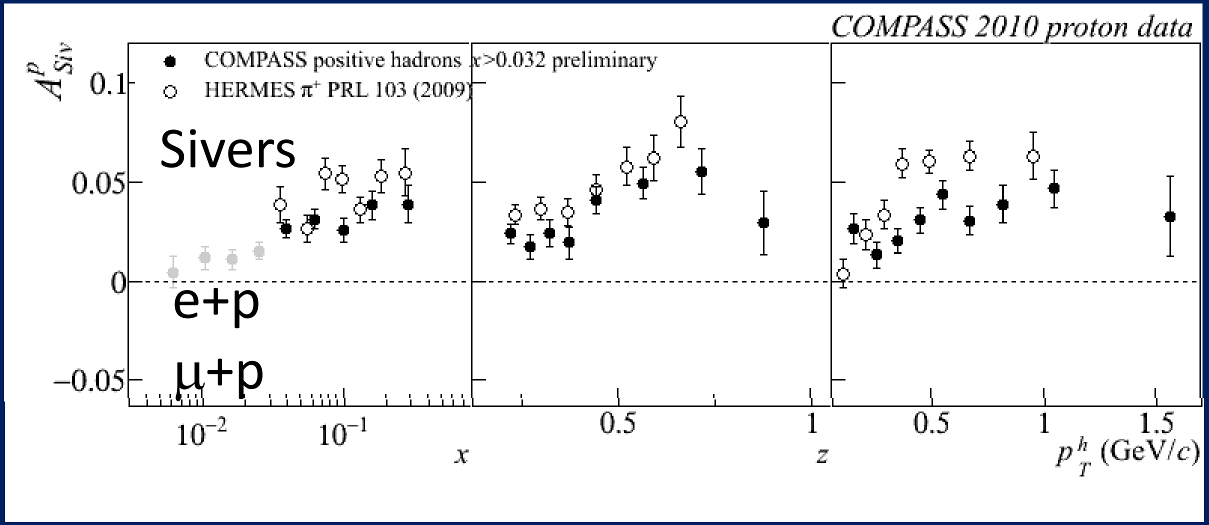
$S \bullet (p_1 \times p_2)$

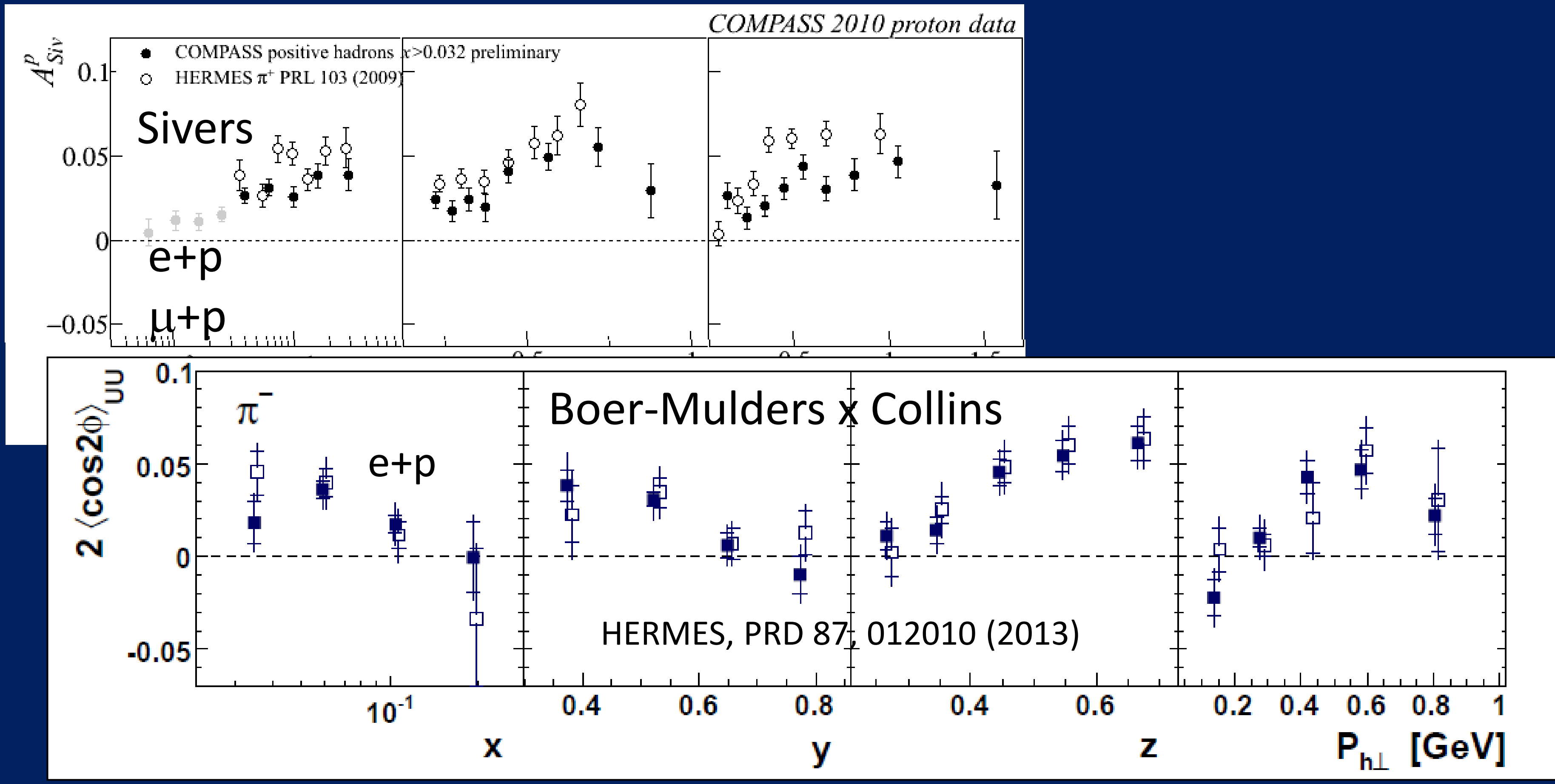


Spin-spin and spin-momentum correlations in QCD bound states



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


COMPASS 2010 proton data
A^p_{Siv}
COMPASS positive hadrons x>0.032 preliminary
HERMES π^+ PRL 103 (2009)
Sivers
e+p
μ+p
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)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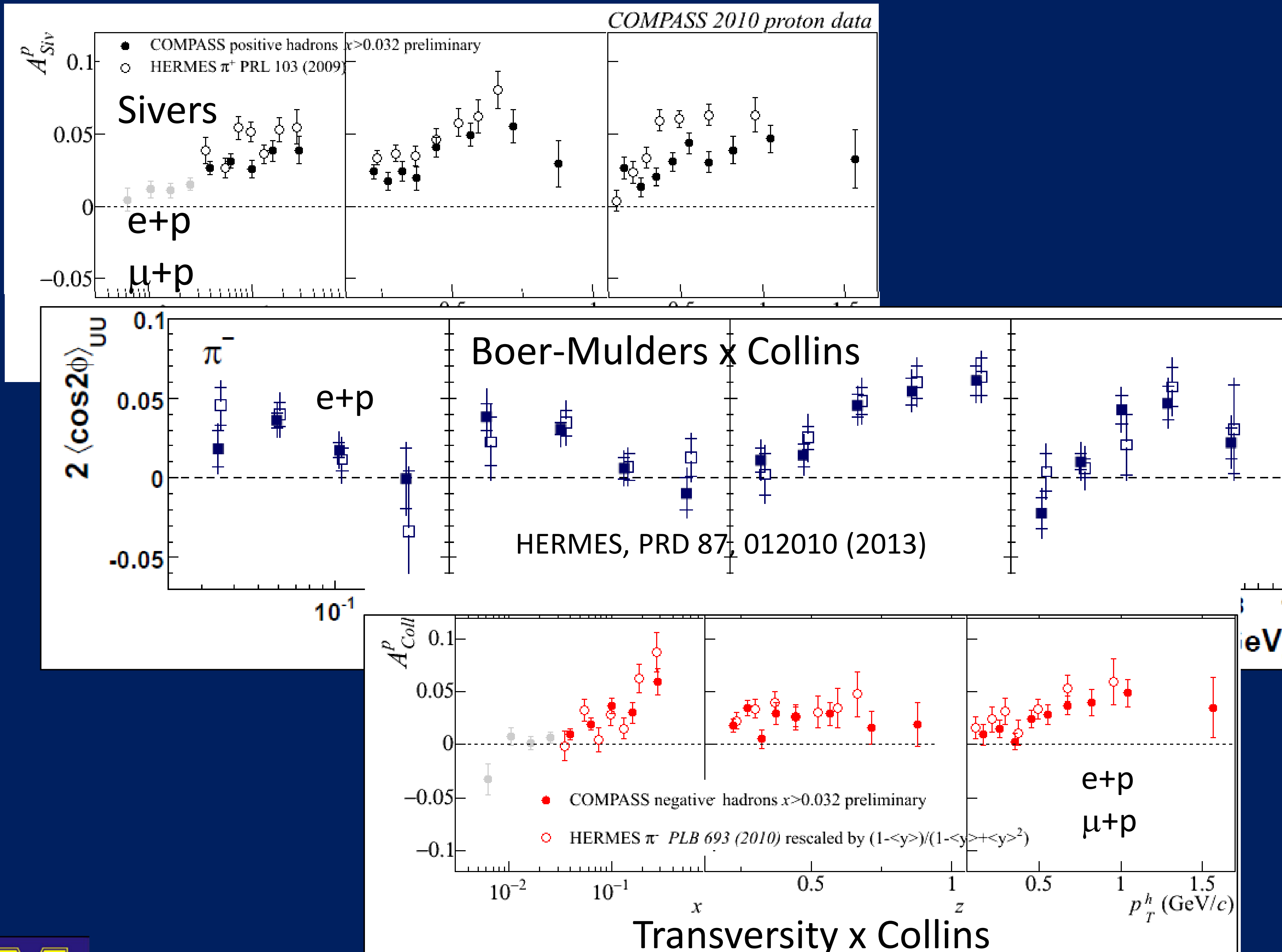
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COMPASS negative hadrons x>0.032 preliminary
HERMES π− PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>2)
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−0.05
−0.1
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10−1
x
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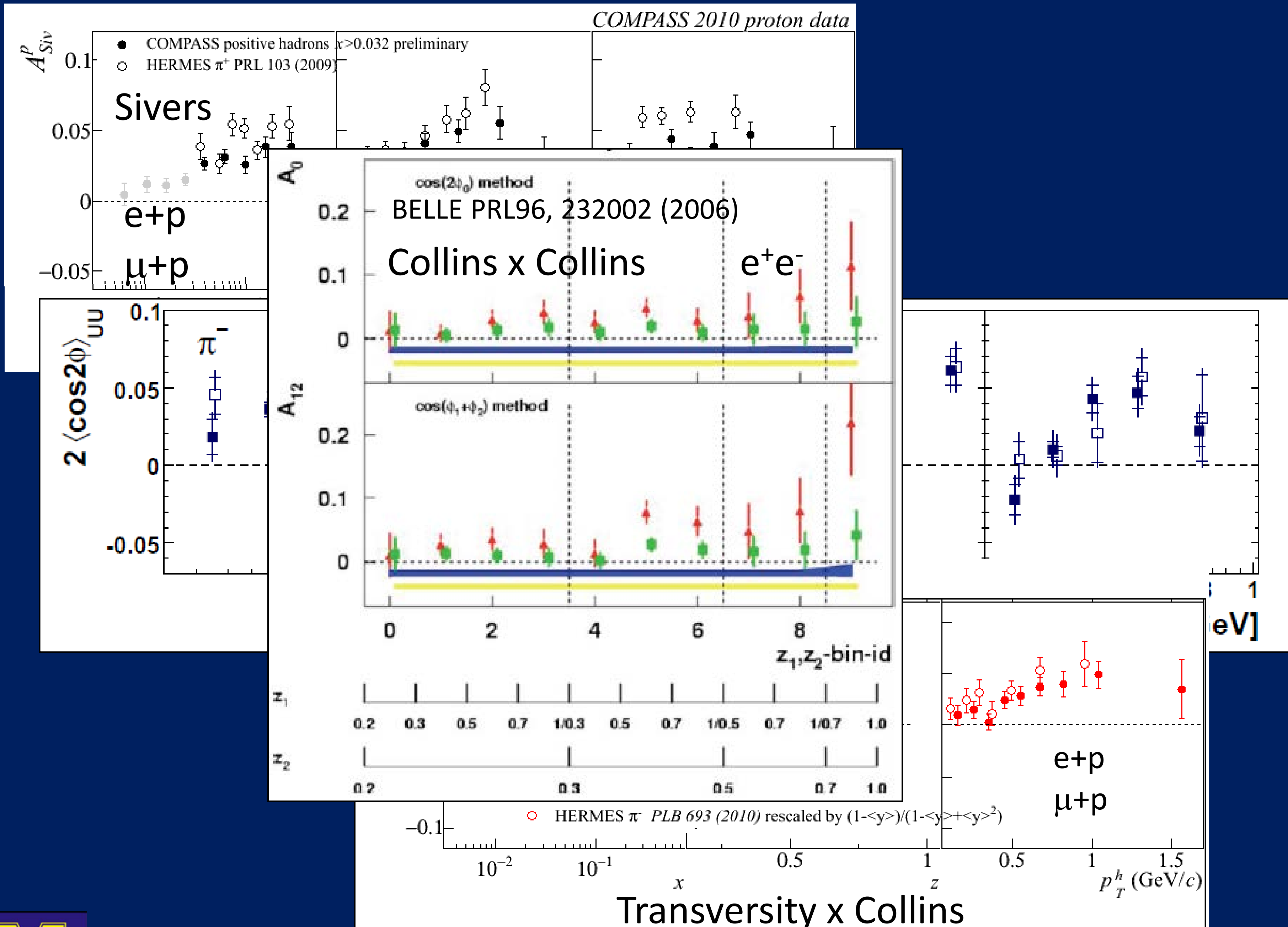
1
z
0.5
1
1.5
p^h_T (GeV/c)
Transversity x Collins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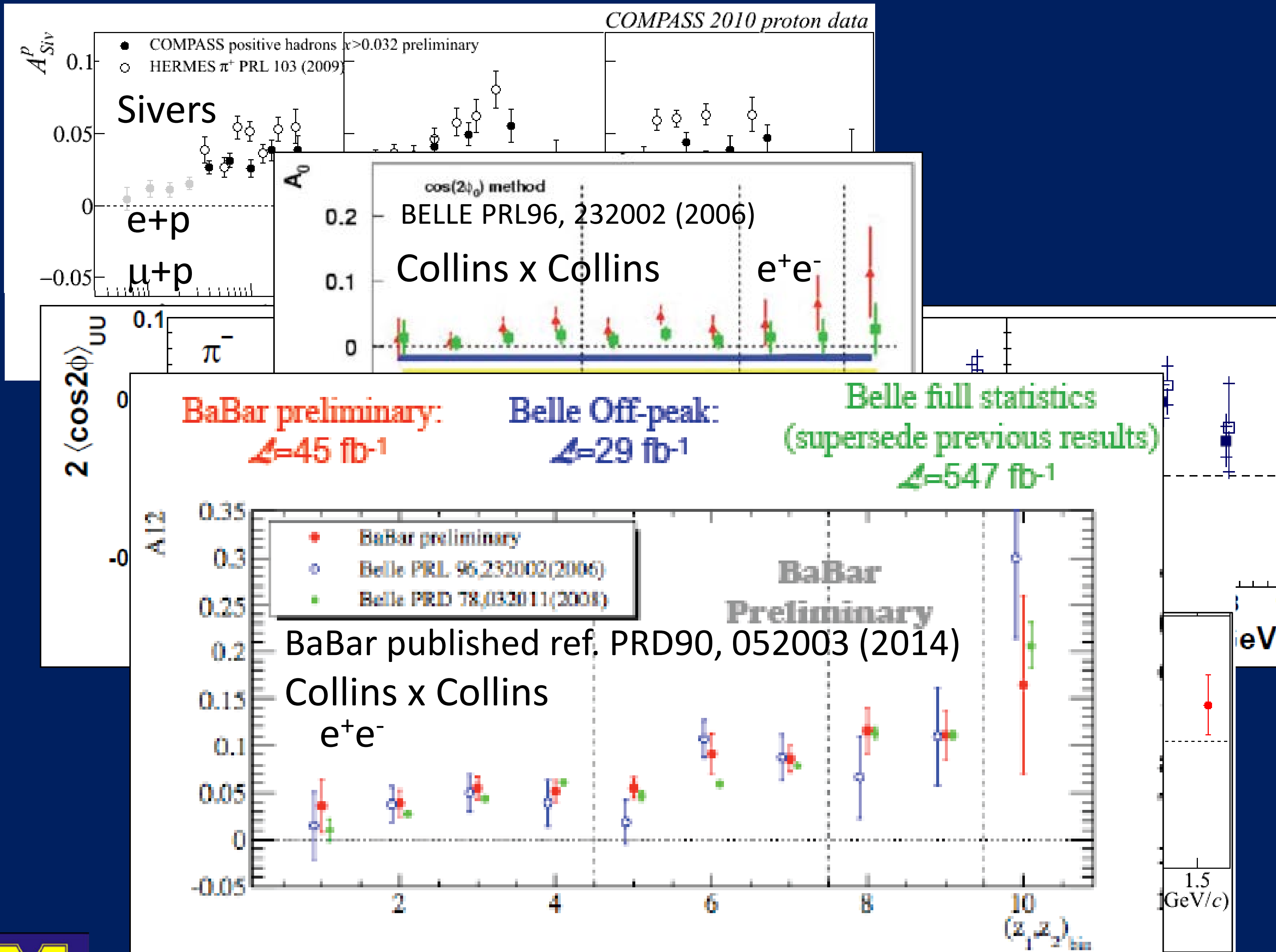
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
cos(2φ0) method
cos(φ1+φ2) method
z1,z2-bin-id
π-
HERMES π- PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>2)
e+p
μ+p
Transversity x Collins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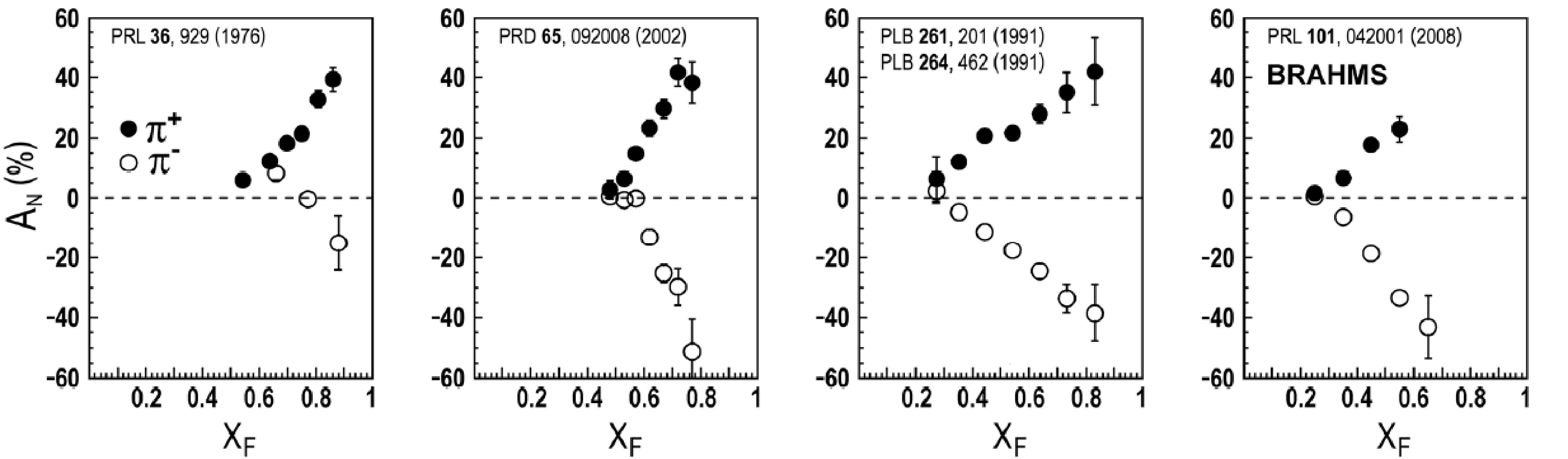
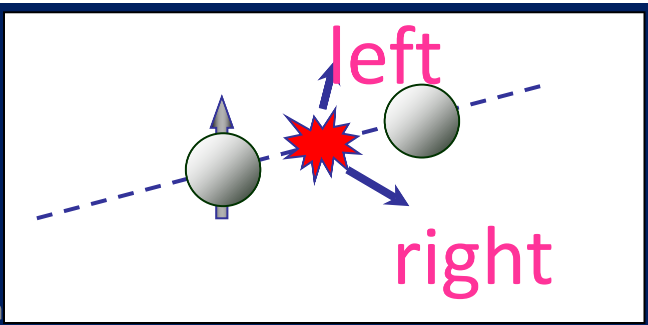
BaBar preliminary:
L=45 fb-1
Belle Off-peak:
L=29 fb-1
Belle full statistics
(supersede previous results)
L=547 fb-1
BaBar preliminary
Belle PRL 96,232002(2006)
Belle PRD 78,032011(2008)
BaBar
Preliminary
BaBar published ref. PRD90, 052003 (2014)
Collins x Collins
e+e-
A12
(z1,z2)bin

But what about proton-proton collisions?

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



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



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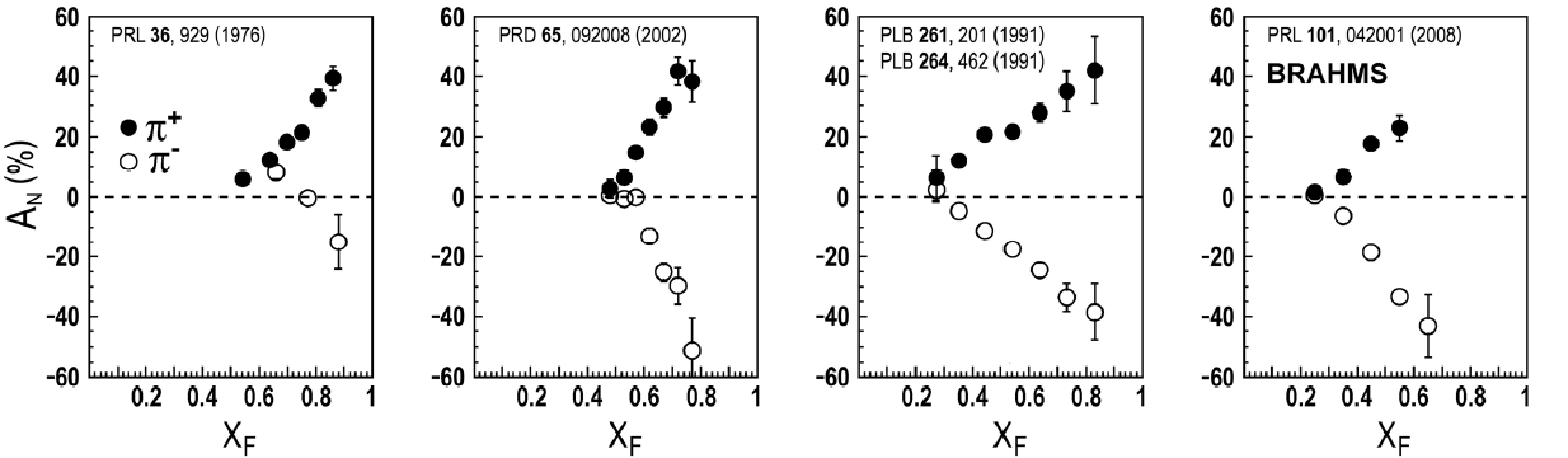
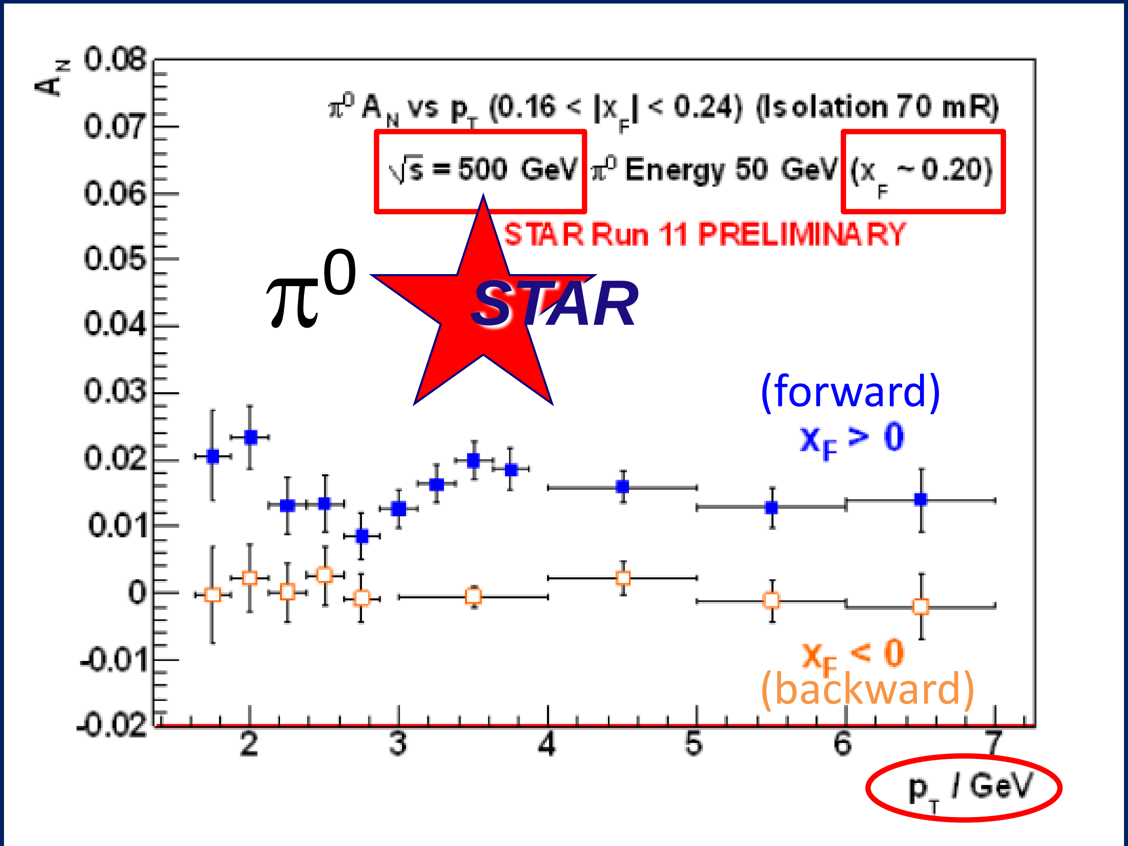


Strikingly similar effects across energies!

→ Continuum between nonperturbative/nonpartonic and perturbative/partonic descriptions of this <u>nonperturbative</u> structure?

Single-spin asymmetries in transversely polarized p+p collisions



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

p+p → hadron + X: Challenging to interpret

- Always huge effects!
- But in p+p → pion +X don't have enough information to separate initial-state (proton structure) from final-state (hadronization) effects

Properties of naïve-T-odd spin-momentum correlation functions

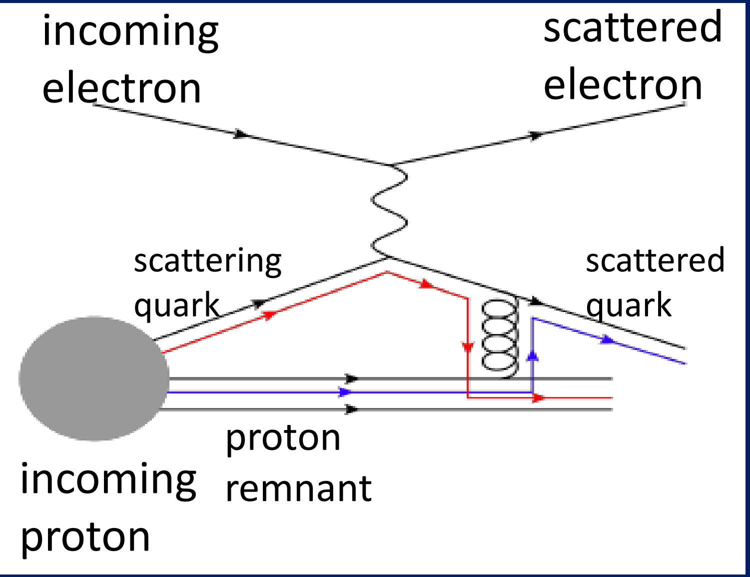
- Sivers transverse-momentum-dependent parton distribution function is odd under “naïve-time-reversal” (actually a PT transformation)
  - As is Boer-Mulders spin-momentum correlation

Properties of naïve-T-odd spin-momentum correlation functions

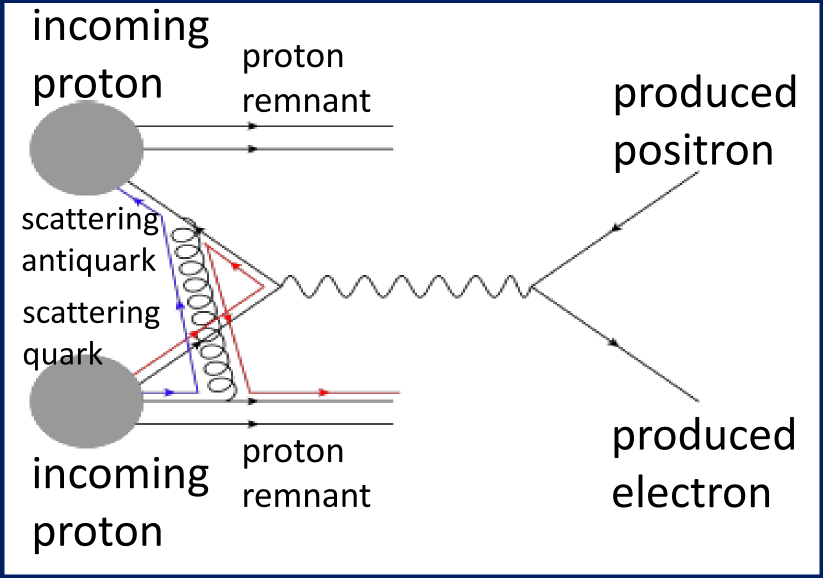
- Sivers transverse-momentum-dependent parton distribution function is odd under "naïve-time-reversal" (actually a PT transformation)
  - As is Boer-Mulders spin-momentum correlation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish
- Only realized in 2002 by Brodsky, Hwang, and Schmidt that could be nonvanishing if *phase interference effects due to color interactions* present

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

Deep-inelastic lepton-nucleon scattering: Final-state color exchange



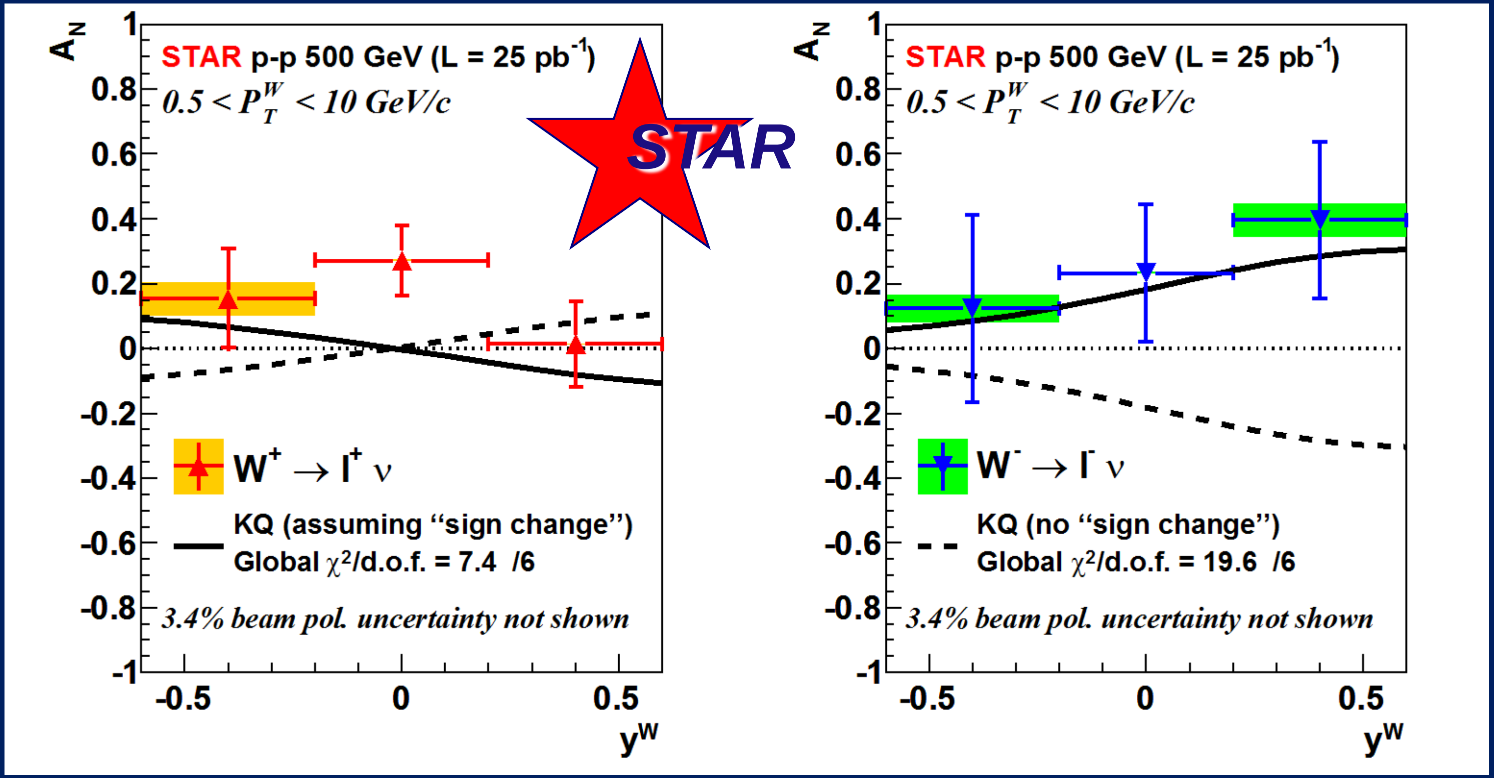
Quark-antiquark annihilation to leptons: Initial-state color exchange



As a result, get *opposite sign* for the Sivers transverse-momentum-dependent pdf when measure in semi-inclusive DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

Figures by J.D. Osborn

Modified universality: Hints but not yet conclusively tested



W boson measurement from STAR more consistent with sign change, but not yet conclusive. Will take more data in 2017. COMPASS experiment at CERN will also perform a measurement in next couple years.

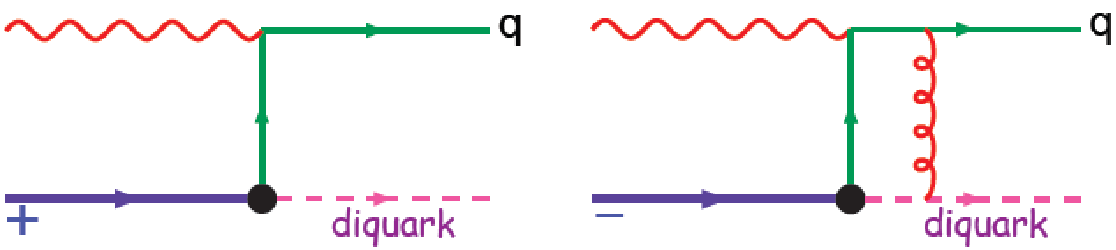
Modified universality requires full QCD: Gauge-invariant quantum field theory

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].

From 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."

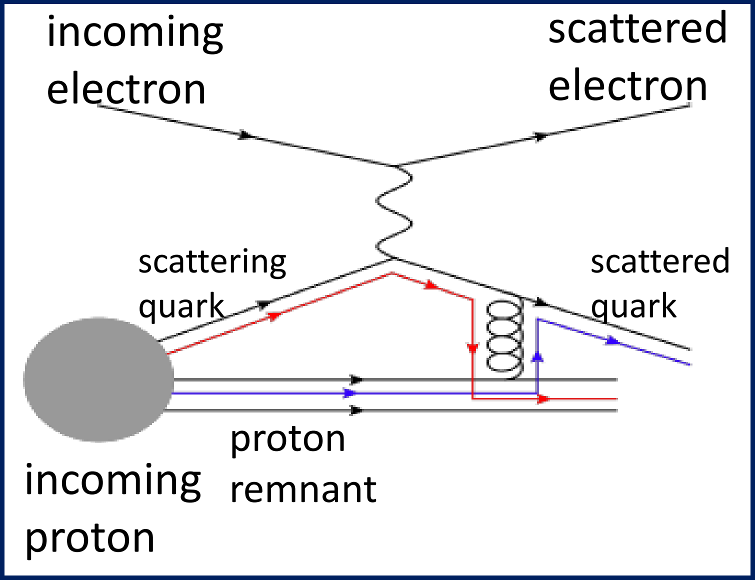
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

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: Final-state color exchange



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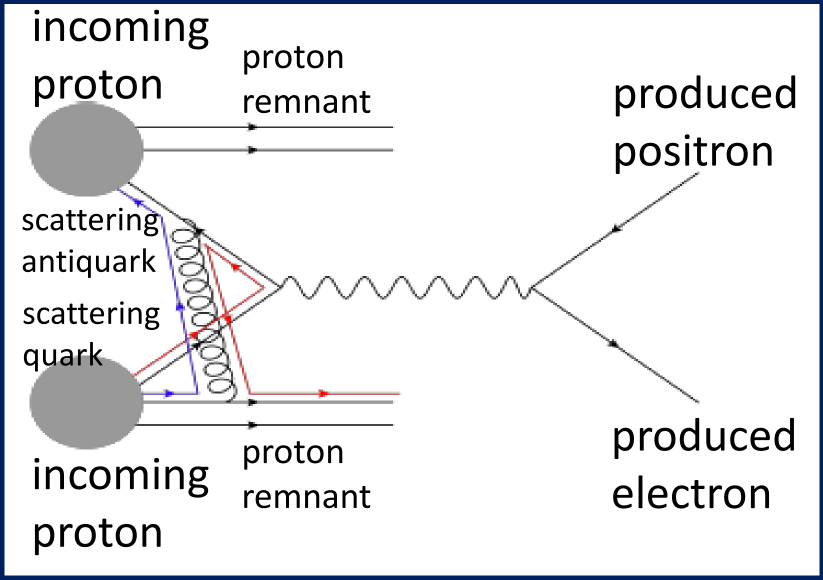

See e.g. Pijlman, hep-ph/0604226
or Sivers, arXiv:1109.2521

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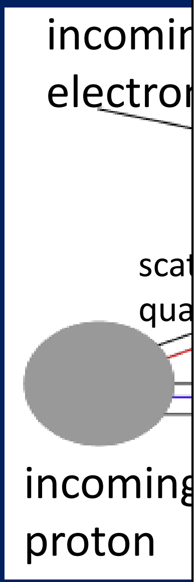
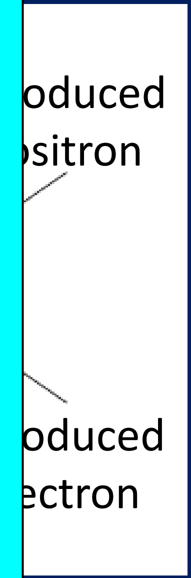


Simplicity of these two processes:
Abelian vs. non-Abelian nature of the gauge group doesn't play a major qualitative role.

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



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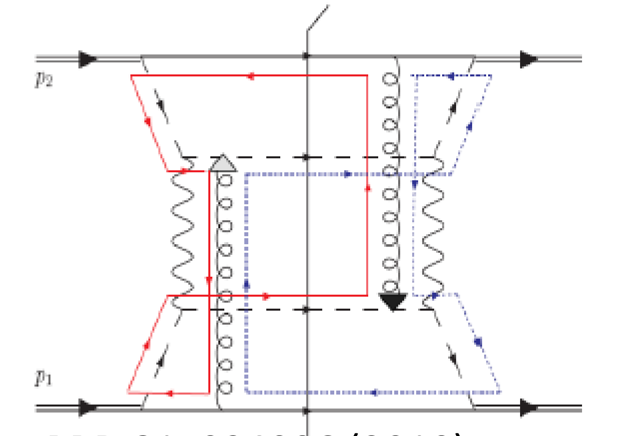
QCD Aharonov-Bohm effect: Color entanglement

- 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.

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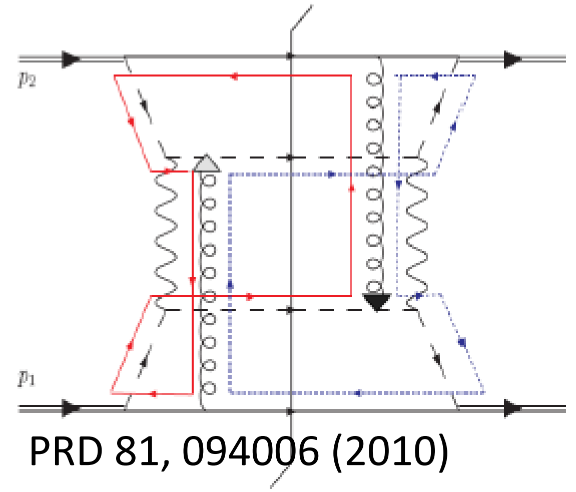

PRD 81, 094006 (2010)

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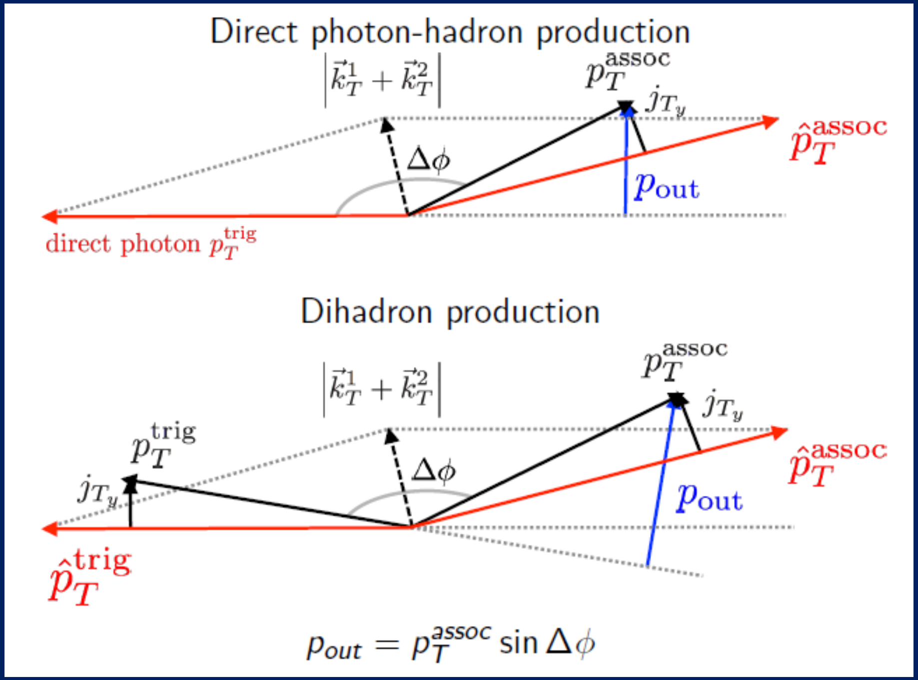
Huge transverse spin asymmetries in p+p a color entanglement effect??

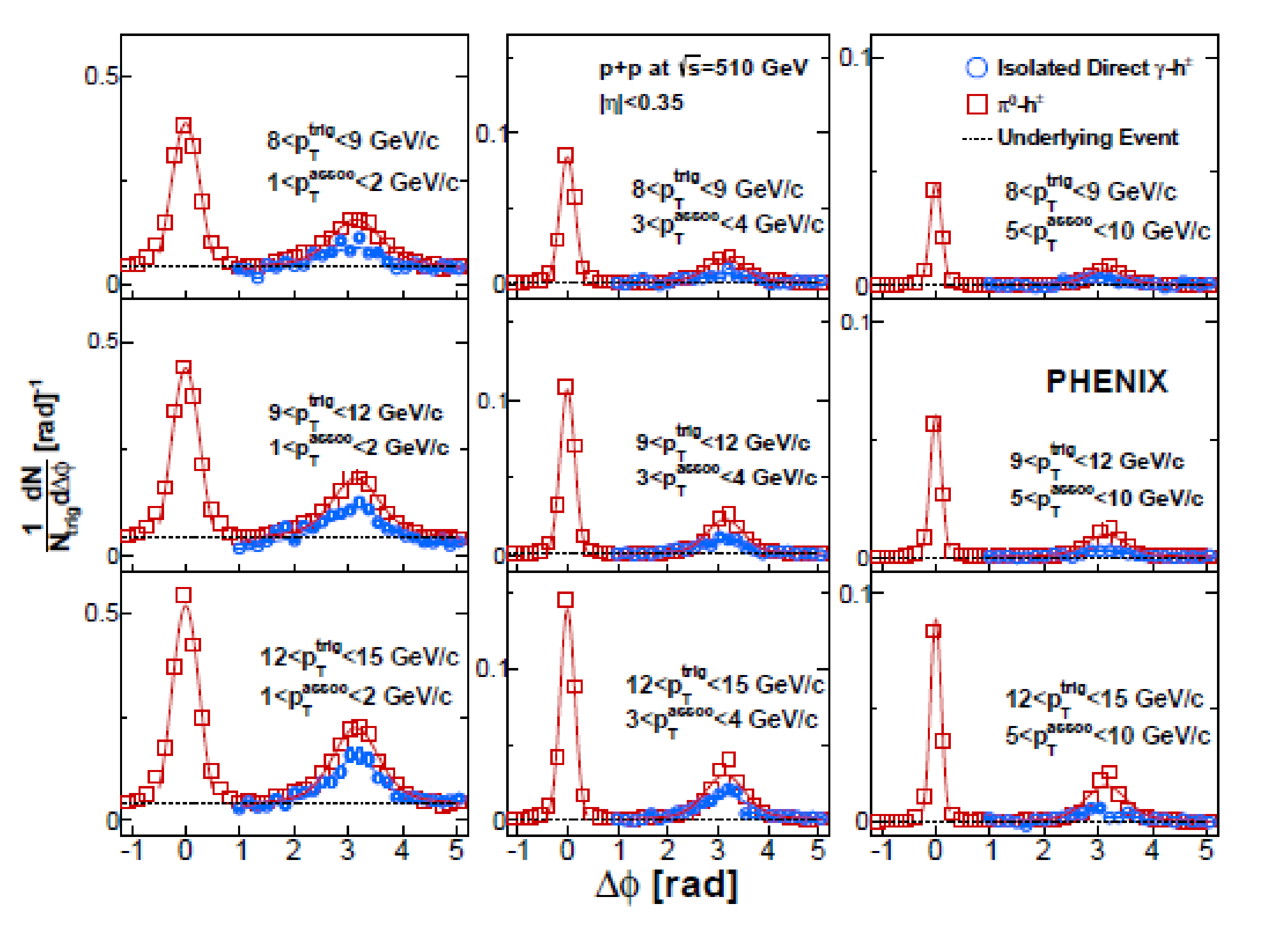
Searching for evidence of color entanglement at RHIC

- Need observable sensitive to a nonperturbative momentum scale
  - Nearly back-to-back particle production
- Need 2 initial-state hadrons
  - color exchange between a scattering parton and remnant of other proton
- And at least 1 final-state hadron
  - exchange between scattered parton and either remnant

→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production

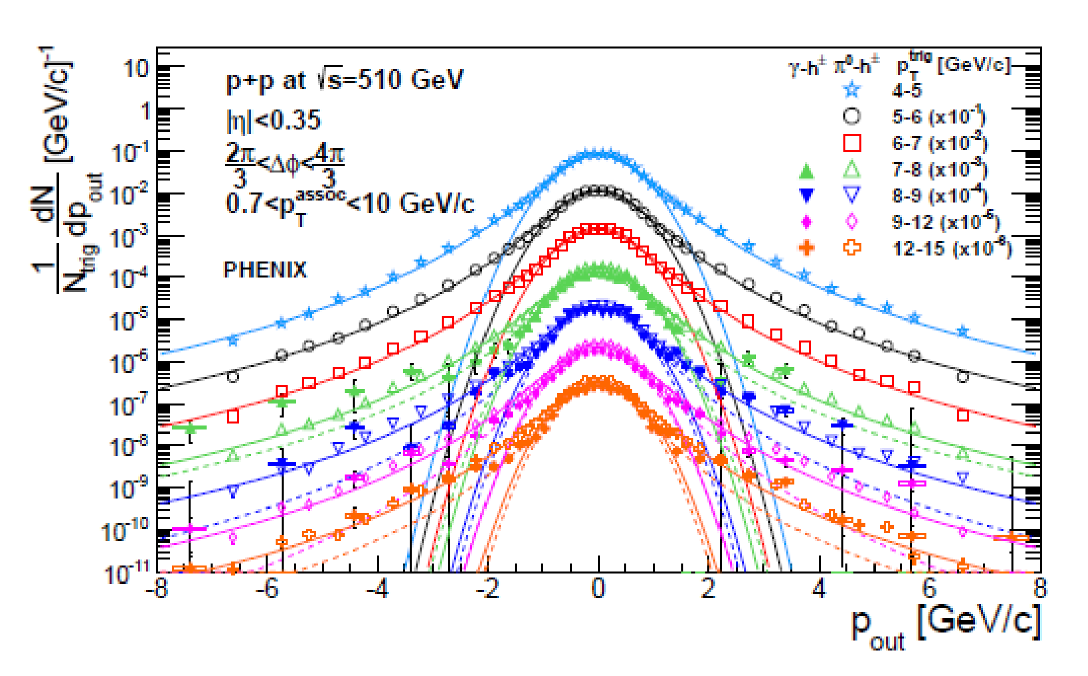


Two-particle correlation distributions show expected jet-like structure



Out-of-plane momentum component distributions

- Clear two-component distribution
  - Gaussian near 0—nonperturbative transverse momentum
  - Power-law at large p_{out}—kicks from hard (perturbative) gluon radiation
- Different colors → different bins in hard interaction scale



Curves are fits to Gaussian and Kaplan functions, not calculations!

*Look at **evolution** of nonperturbative transverse momentum widths with hard scale (Q^2)*

- Theoretical proof of factorization for transverse-momentum-dependent parton distribution functions directly predicts that nonpertubative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation

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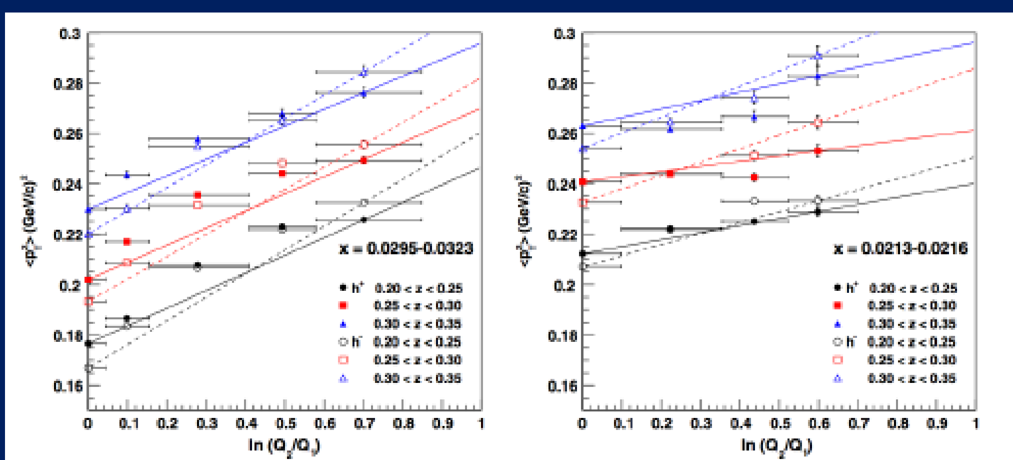
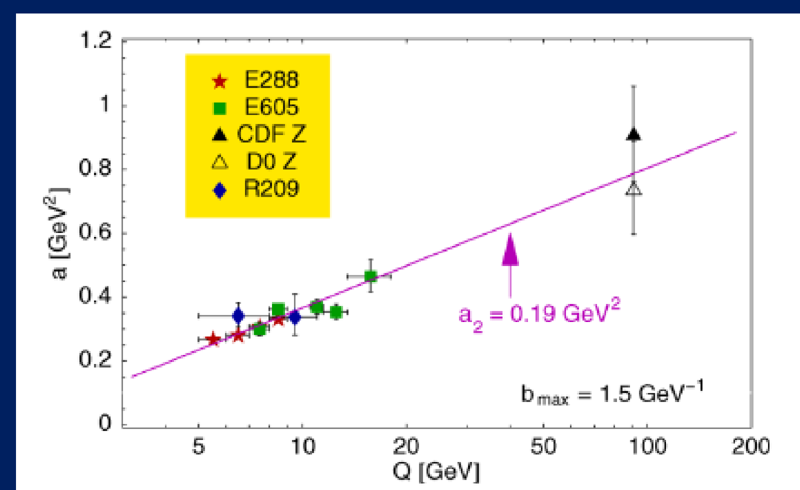
- Theoretical proof of factorization for transverse-momentum-dependent parton distribution functions directly predicts that nonpertubative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation
- Observed experimentally in semi-inclusive deep-inelastic lepton-nucleon scattering (left) and quark-antiquark annihilation to leptons (right)

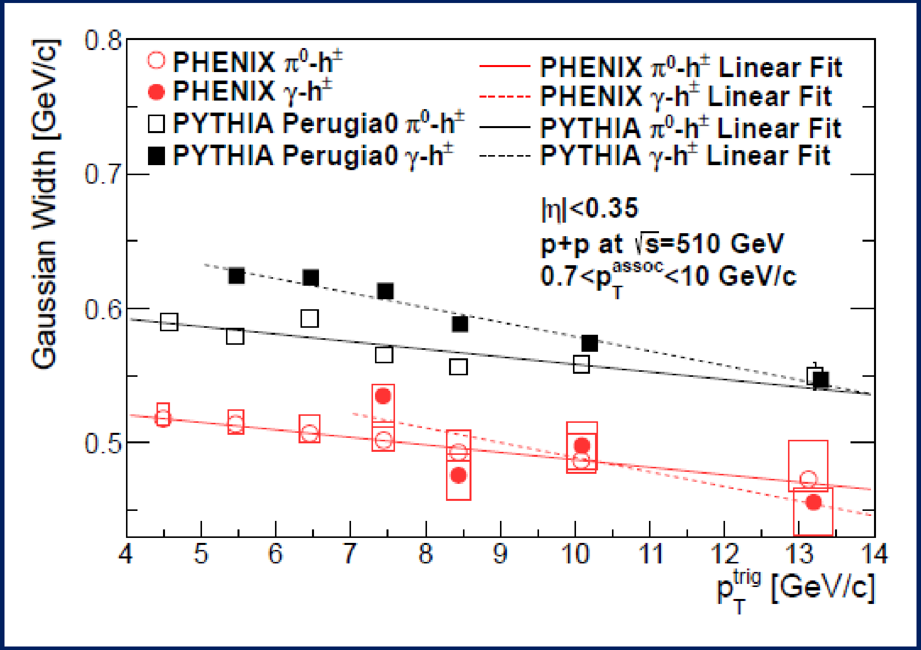


Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



Konychev + Nadolsky, Phys. Lett. B633, 710 (2006)

*Nonperturbative momentum widths **decrease** in processes where entanglement predicted*



PHENIX Collab., arXiv:1609.04769, Submitted to PRD

- Suggestive of quantum-correlated partons across colliding protons!
- However, have not yet completely ruled out kinematic effects

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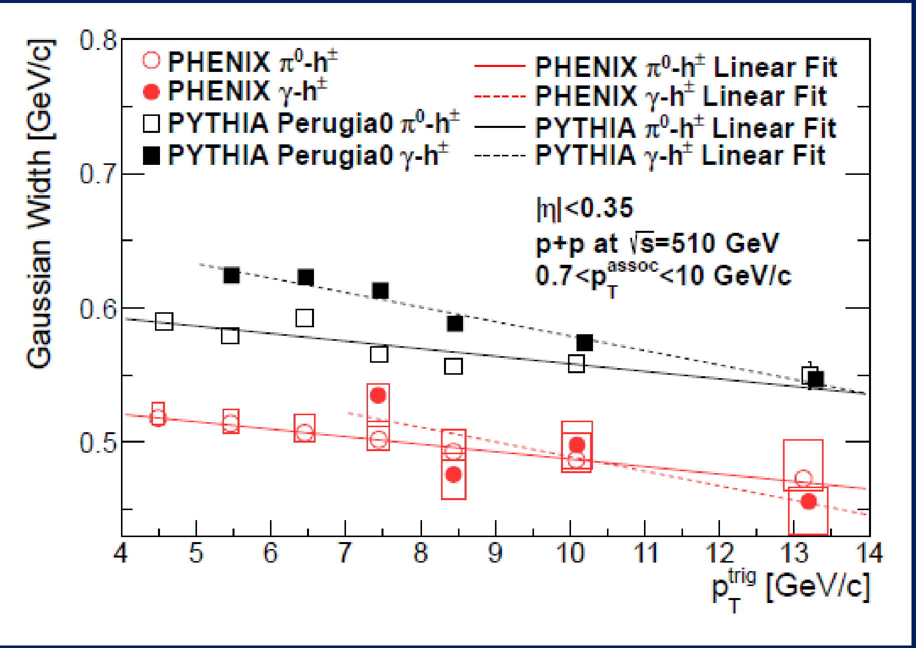
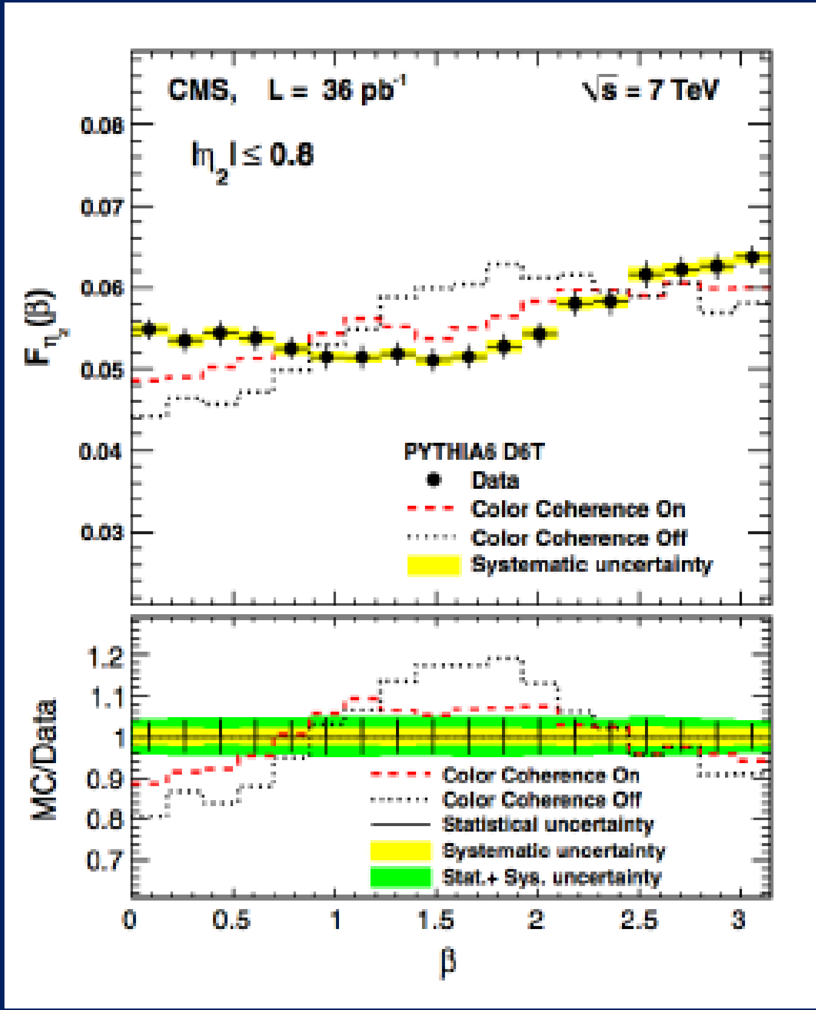


PHENIX Collab., arXiv:1609.04769, Submitted to PRD

- Suggestive of quantum-correlated partons across colliding protons!
- However, have not yet completely ruled out kinematic effects
- Slope of decrease for both photon-hadron and dihadron correlations reproduced ~exactly in PYTHIA p+p event generator—could this effect be in PYTHIA??
  - Effectively yes! Unlike analytic pQCD calculations, PYTHIA forces *entire event including remnants* to color neutralize, implemented via something they call "color reconnection"
- Discussions ongoing, and follow-up studies underway . . .

Possible links to "color coherence" at Tevatron and LHC?

- D0, CDF, CMS have all published on evidence for "color coherence effects"
  - CMS: EPJ C74, 2901 (2014)
  - CDF: PRD50, 5562 (1994)
  - D0: PLB414, 419 (1997)
- Few citations—relatively little-known work thus far. Need to get different communities talking to explore detailed color effects more in upcoming years!



Summary

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- Gradually shifting to think about QCD systems in new ways, focusing on topics/ideas/concepts that have long been familiar to the world of condensed matter physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems

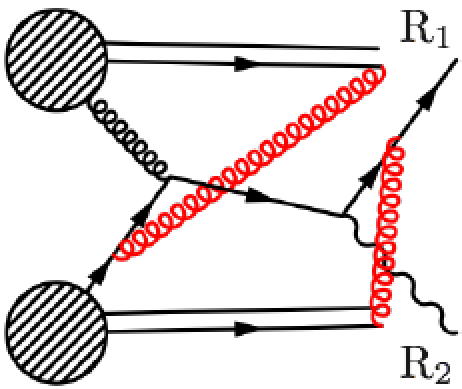
Summary

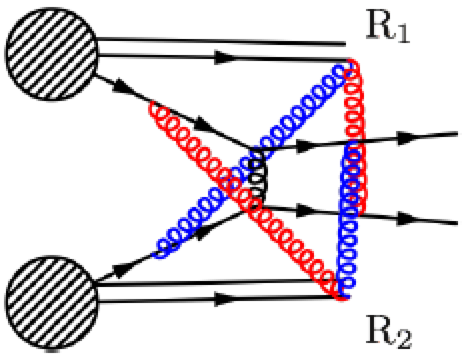
- Early years of rewarding new era of quantitative basic research in QCD!
- Gradually shifting to think about QCD systems in new ways, focusing on topics/ideas/concepts that have long been familiar to the world of condensed matter physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems
- Will be exciting to continue testing and exploring these ideas and phenomena in upcoming years . . .

Extra

$p+p \rightarrow \gamma+h+X$ vs. $p+p \rightarrow h+h+X$

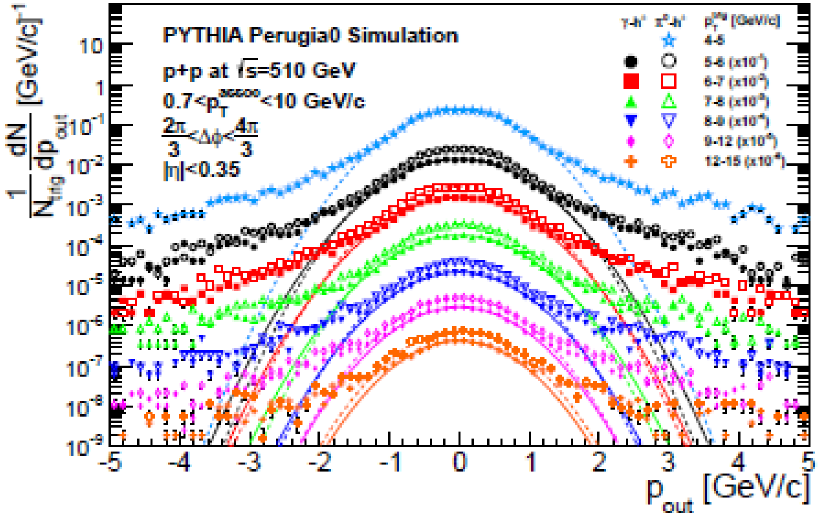
- Direct photon-hadron and dihadron correlations both predicted to be sensitive to factorization breaking effects in PHENIX
- Assuming factorization, direct photon-hadrons probe three nonperturbative functions, while dihadrons probe four
- Direct photons offer one less avenue for gluon exchange in the final-state: fewer/different effects?





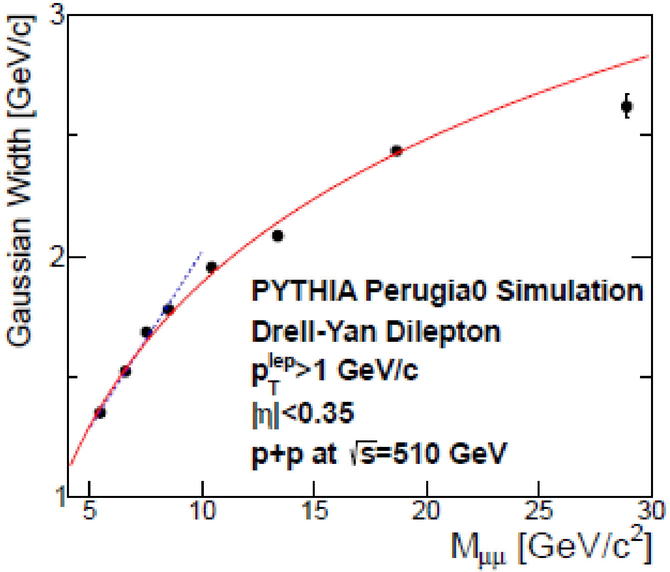
PYTHIA p_{out} distributions

- PYTHIA π^0-h$^\pm$ and isolated γ-h$^\pm$ correlations analyzed similarly to data
- PYTHIA exhibits similar characteristics to data: nonperturbative transitioning to perturbative region
- Initial and final state interactions possible in PYTHIA: all particles are forced to color neutralize



PYTHIA Drell-Yan

- Can check if PYTHIA also reproduces CSS evolution with DY dimuon production
- Construct same observable $p_{out} = p_T^{lep} \sin \Delta\phi$ between two nearly back-to-back leptons
- PYTHIA confirms expectation from CSS evolution for same observable

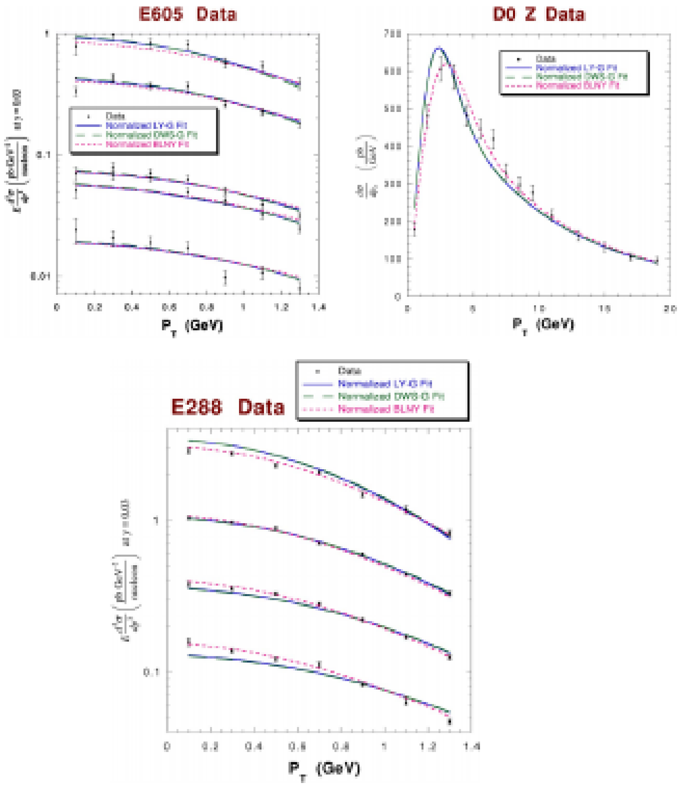


- Note rate of increase is significantly larger in magnitude also
- Red solid line shows log fit, blue dotted line shows linear fit

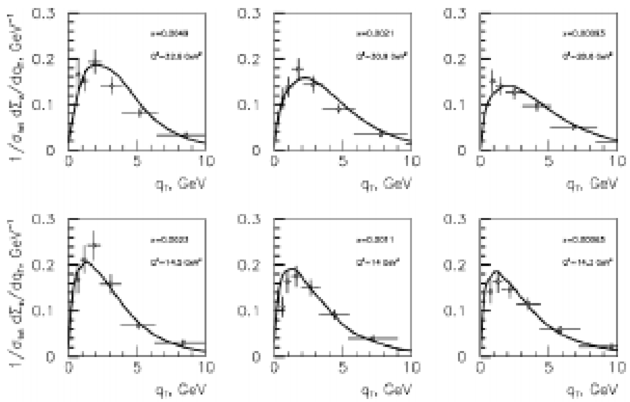
Nonperturbative momentum measurements in Drell-Yan and Z production

Other DY/Z and SIDIS Refs.

Phys. Rev. D 67, 073016 (2003)
(DY/Z)



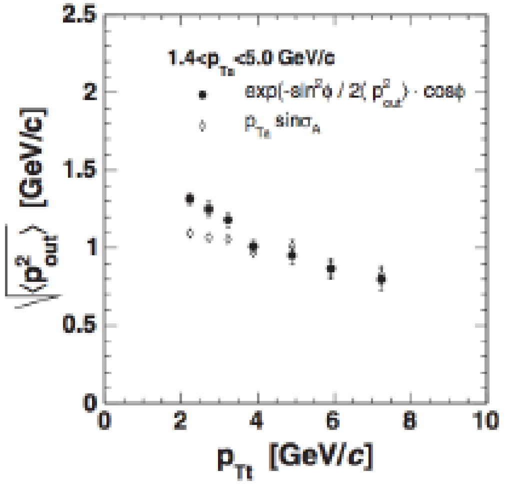
Phys. Rev. D 61, 014003 (2000)
(SIDIS)

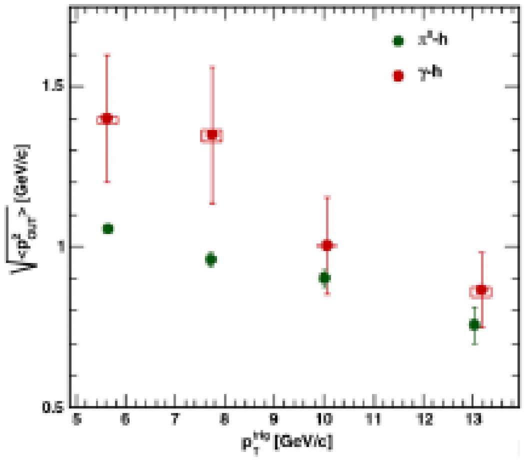


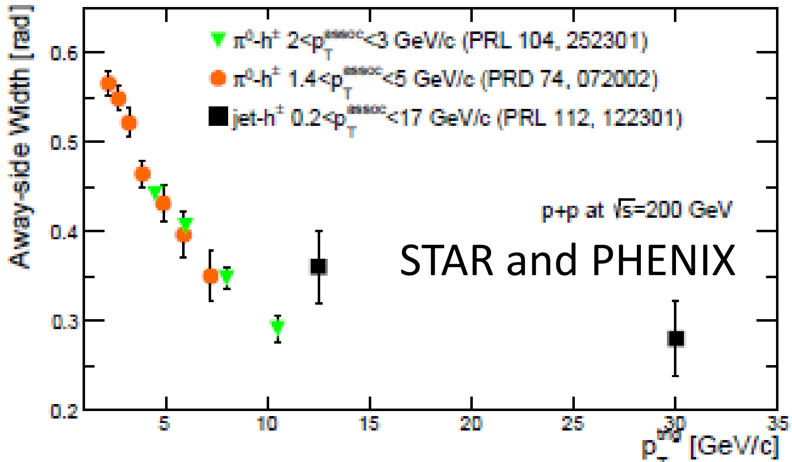
Other measurements showing decreasing nonperturbative momentum widths

- Other RHIC publications show the same effect in $\sqrt{\langle p_{out}^2 \rangle}$ and away-side width
- All previous analyses motivated by different physics goals: fragmentation functions, partonic energy loss in QGP, etc.

PRD 74, 072002 (2006) (PHENIX)



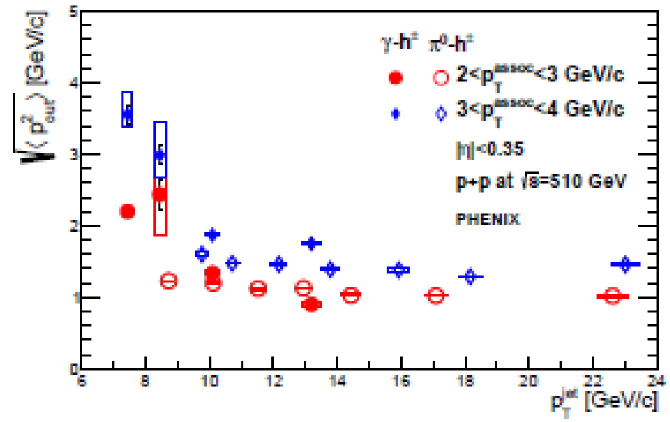


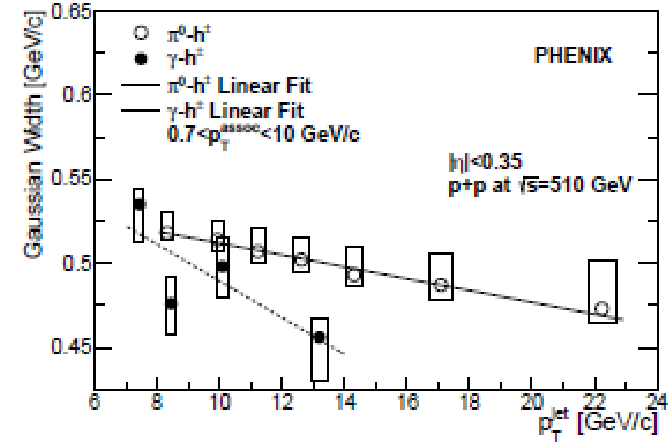


PRD 82, 072001 (2010) (PHENIX)

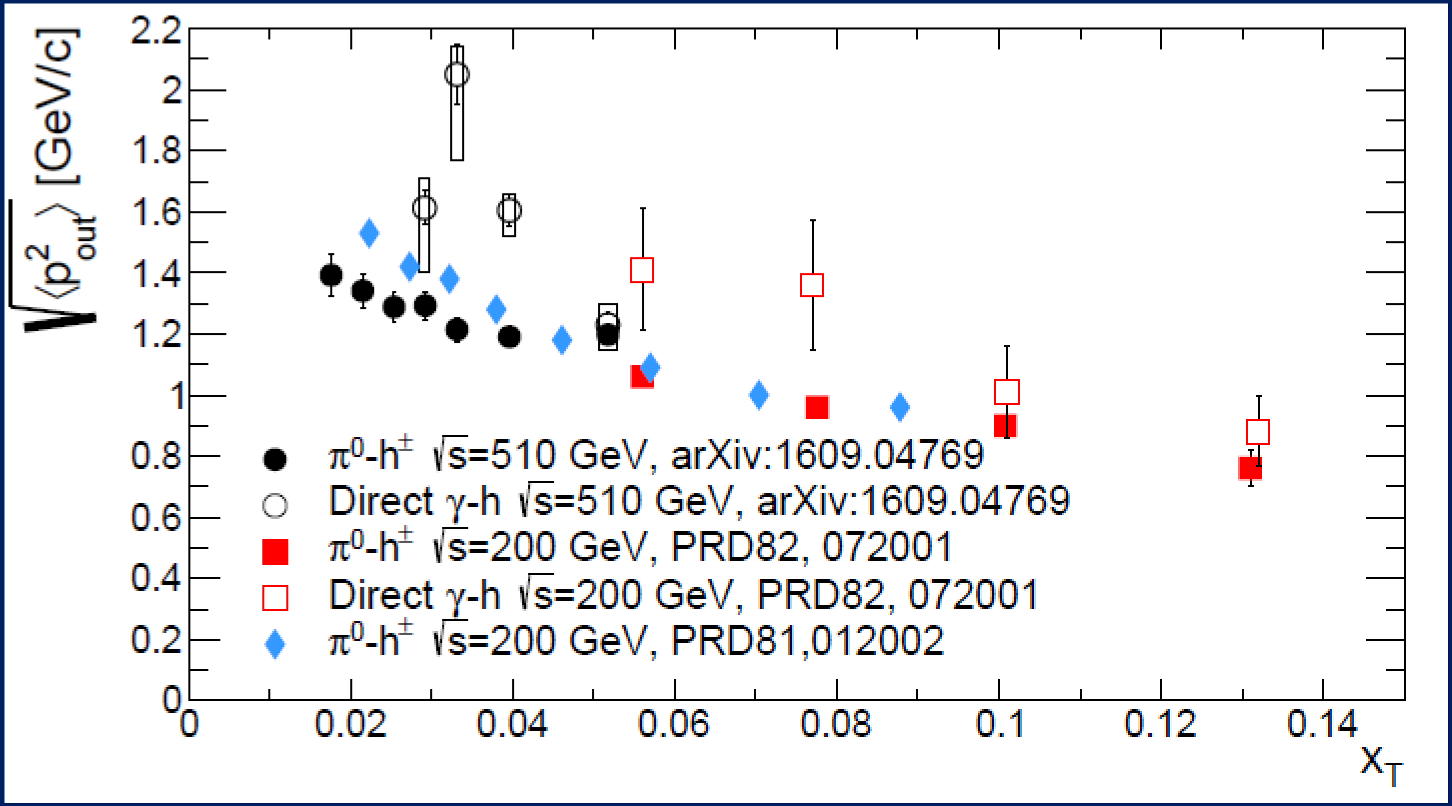
PYTHIA $\langle z_T \rangle$ Correction

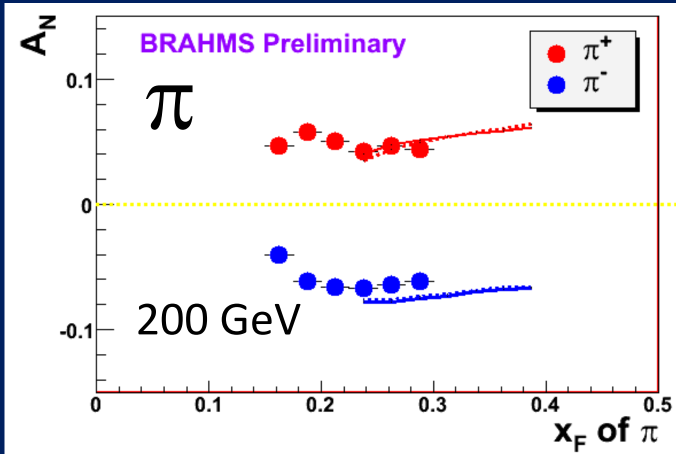
- Direct photons emerge directly from hard scattering, π^0s are a fragment
- Thus a more direct comparison is between p_T^{trig} for direct photon and jet p_T^{trig} for π^0
- Determine $\langle z_T \rangle = p_T^{\pi^0} / \hat{p}_T^{parton}$ using PYTHIA, "correct" π^0 p_T^{trig} to get $p_T^{jet} = p_T^{trig,\pi^0} / \langle z_T \rangle$



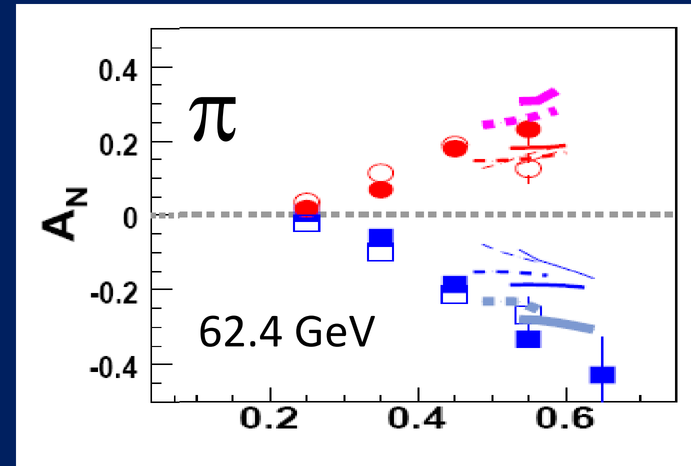


RMS p_{out} vs. x_T

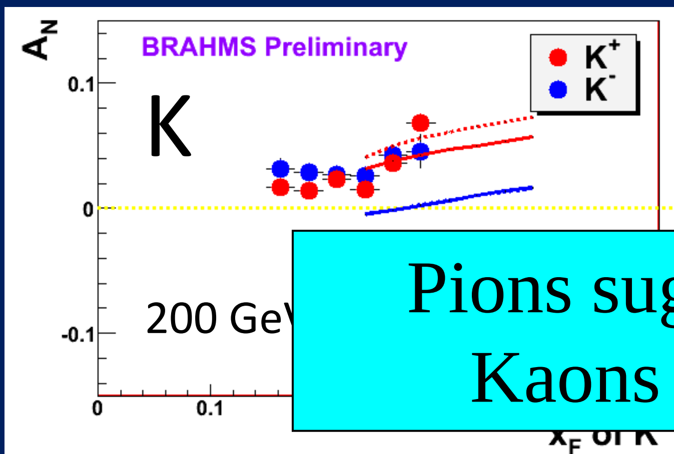




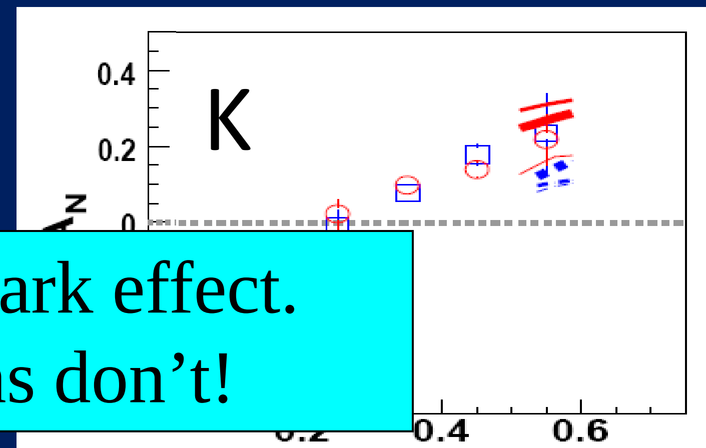
π, K, p at 200 and 62.4 GeV



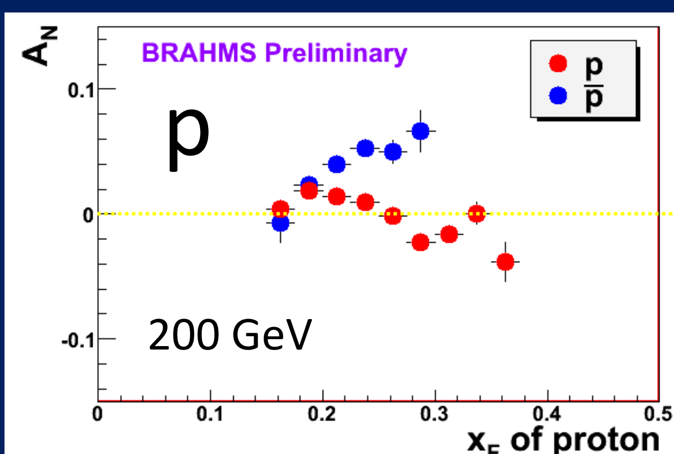
Note different scales



K- asymmetries underpredicted

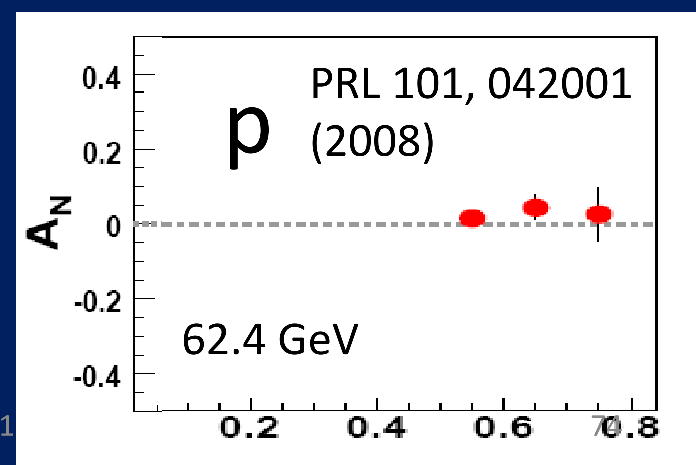


Pions suggest valence quark effect. Kaons and (anti)protons don't!

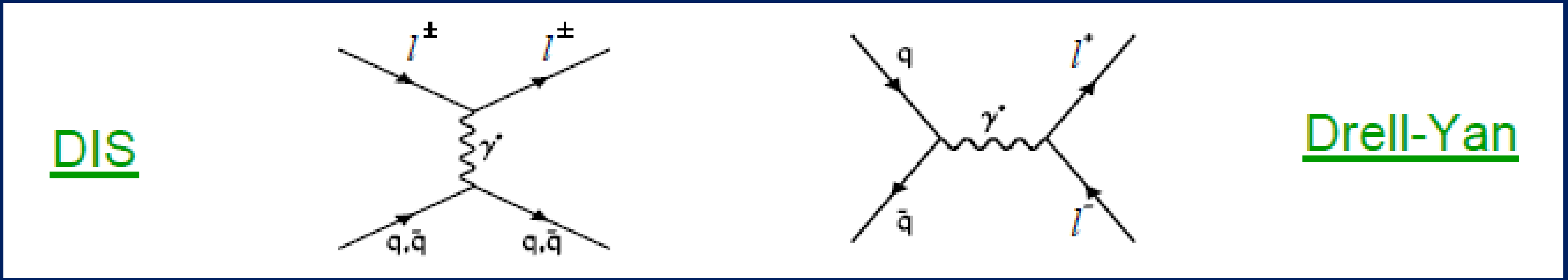


Large antiproton asymmetry??

Unfortunately no 62.4 GeV measurement

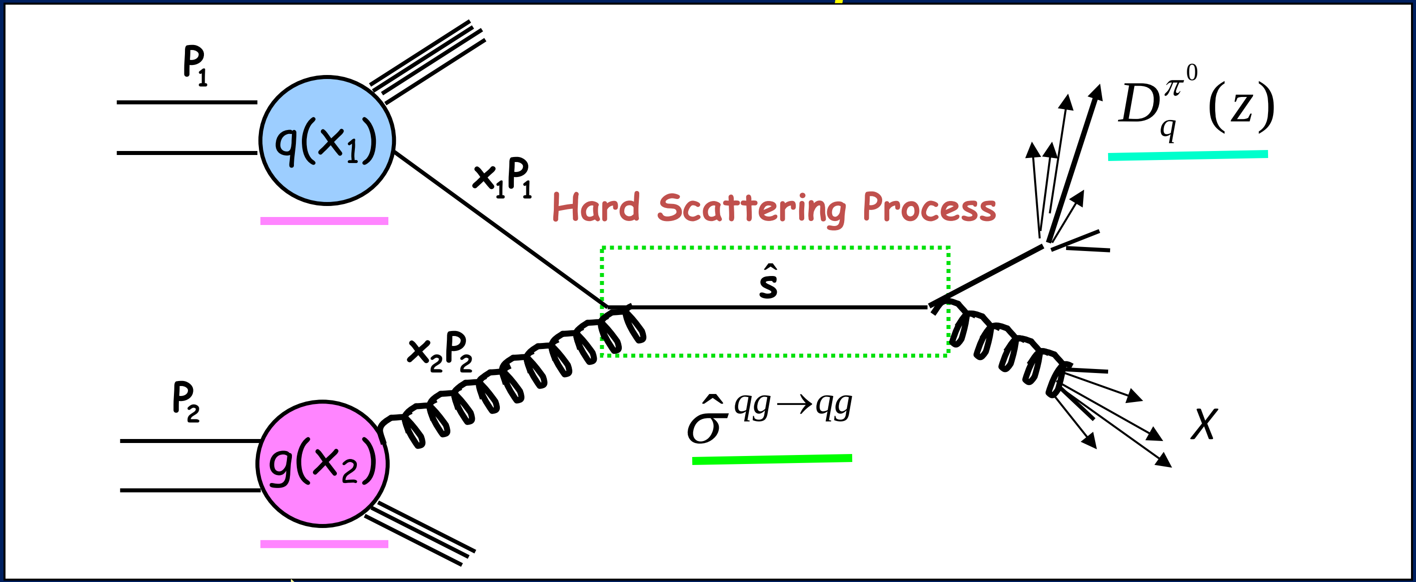


Complementarity of Drell-Yan and DIS



- Both deep-inelastic lepton-nucleon scattering (DIS) and quark-antiquark annihilation to leptons (Drell-Yan process) are tools to probe the quark and antiquark structure of hadrons

Parton distribution functions in perturbative QCD calculations of observables



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

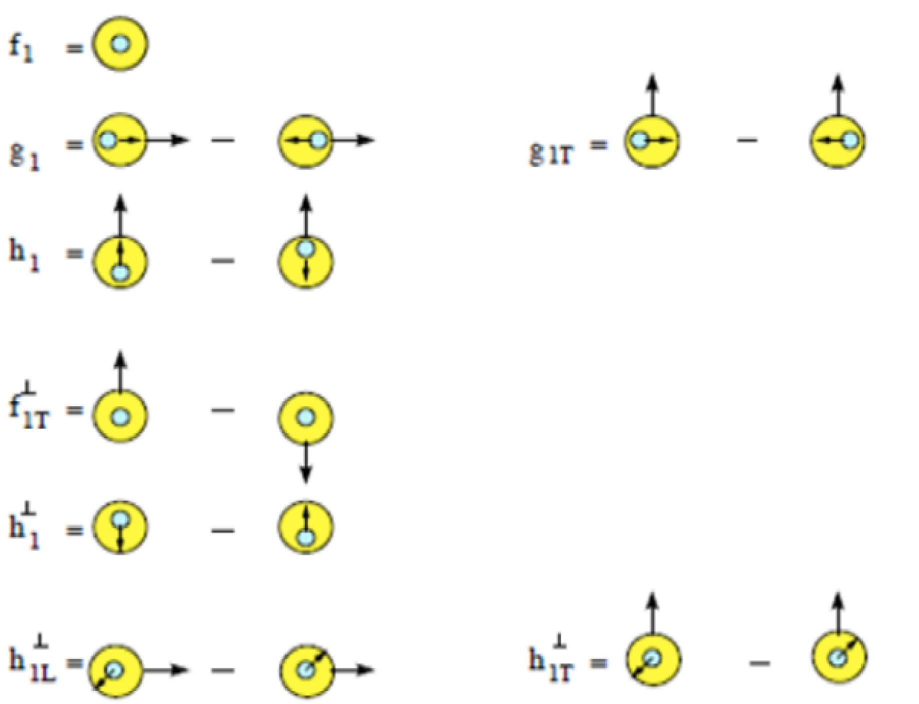
High-energy processes have predictable rates given:

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

} **Universal non-perturbative factors**

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

U = unpolarized L = longitudinally polarized T = transversely polarized
N = nucleon q = quark



N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Magnetic and electric A-B effects; Type-I and Type-II A-B effects

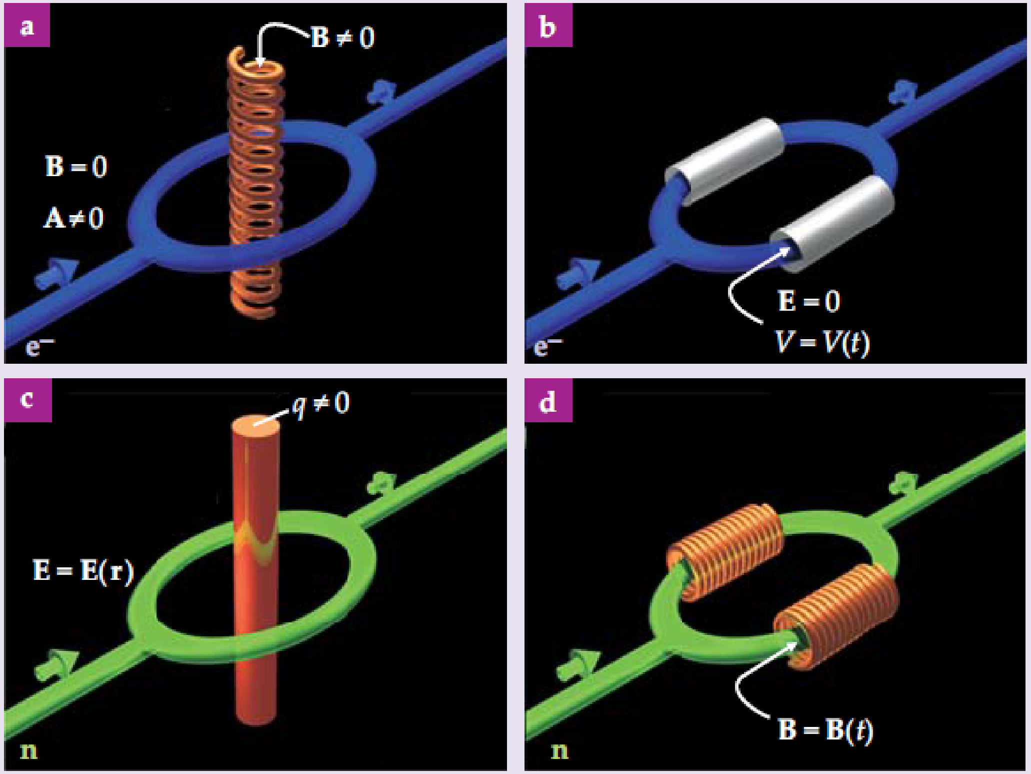
Box 1. Types and duals

Physics Today, September 2009

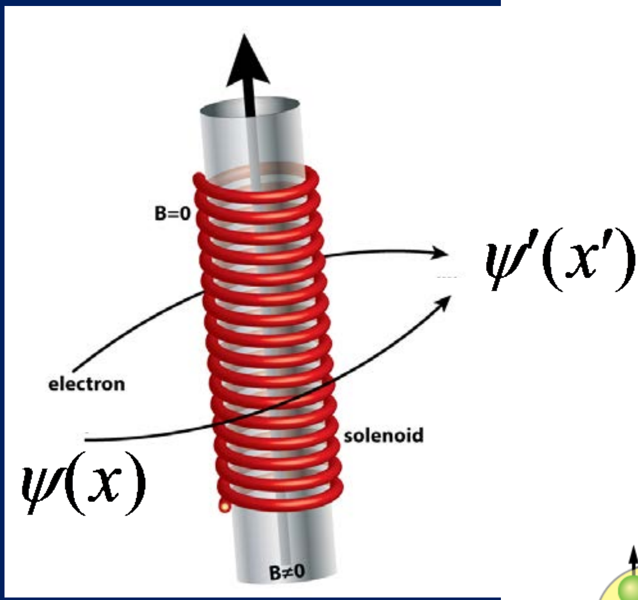
The original magnetic and electric Aharonov–Bohm effects (panels a and b) are type I effects in the sense that in an ideal experiment, the electron sees no **B** or **E** fields, though it does traverse different potentials **A** and *V*. In their respective dual effects—the Aharonov–Casher effect (panel c) and the so-called neutron-scalar AB effect (panel d)—polarized neutrons (neutral particles with magnetic dipole moments) replace unpolarized electrons, and electrostatic configurations change places with solenoids.[10] In panel c, a neutron interferometer encloses a line of charge, and in panel d, neutrons pass through pulsed solenoids. These duals are classified as type II effects because the neutron must traverse a nonvanishing **E** or **B** field.

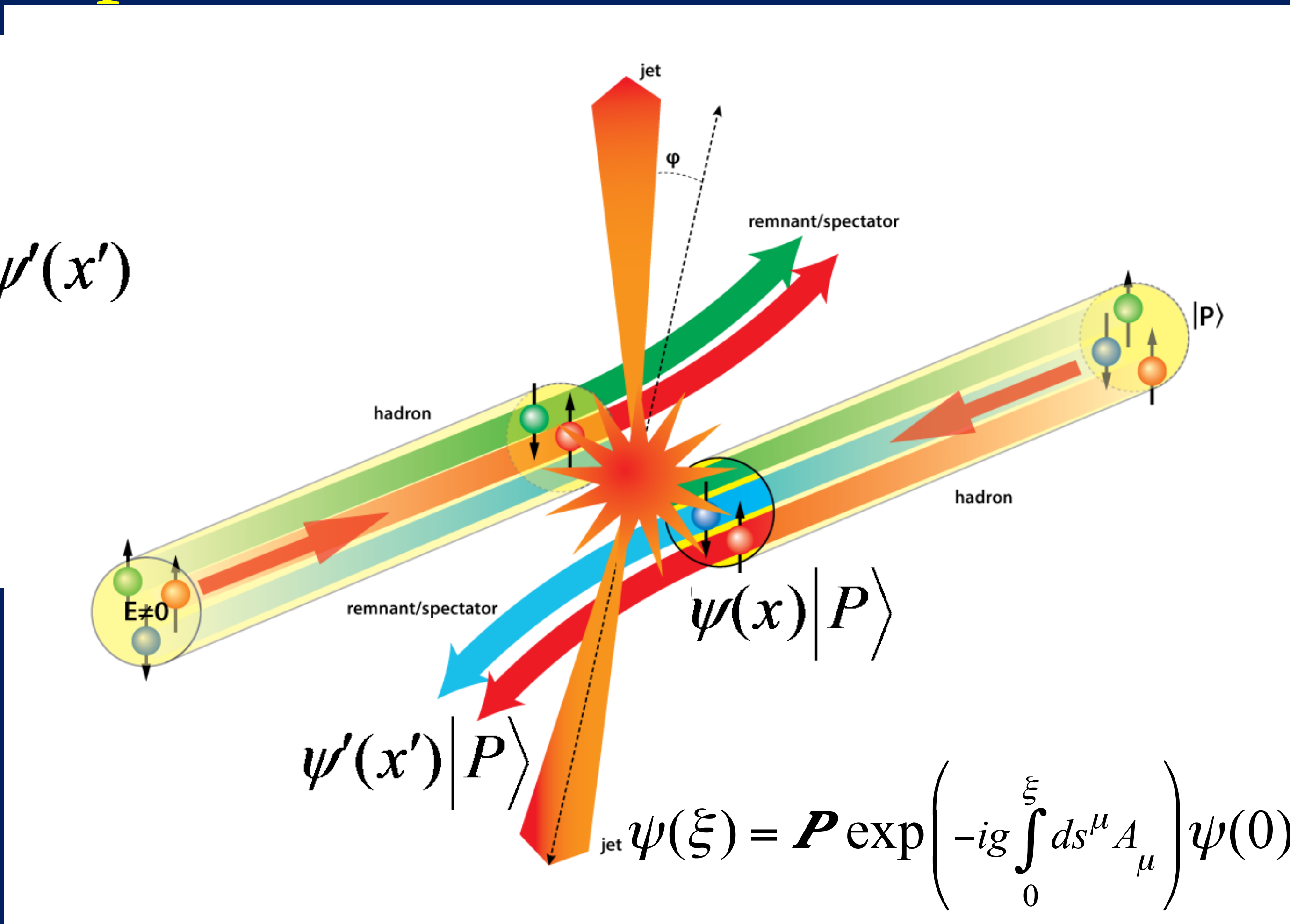
In either case, to acquire an AB phase shift, the electron or neutron must pass through a region of nonzero electromagnetic potential. That quantum mechanical result seems to elevate the status of the potentials to a physical reality absent from classical electromagnetism. Yakir Aharonov has pointed out that the potentials do overdetermine the experimental outcome; the phase shift need only be known modulo 2π. An alternative view is that the original magnetic AB effect shows electromagnetic fields acting nonlocally.[1]

For type II effects, the wavepackets can plow straight through force fields, and forces are allowed in the interaction. But the AB interpretation requires that the emerging wavepackets not be deflected or delayed in any way. Quantum mechanical descriptions generally circumvent the notion of forces. But one can use here an operational definition of forces that might be mimicking an AB effect: If the interaction has produced no deflection or delay, there were no forces.



Opportunities to see color-induced phases in QCD



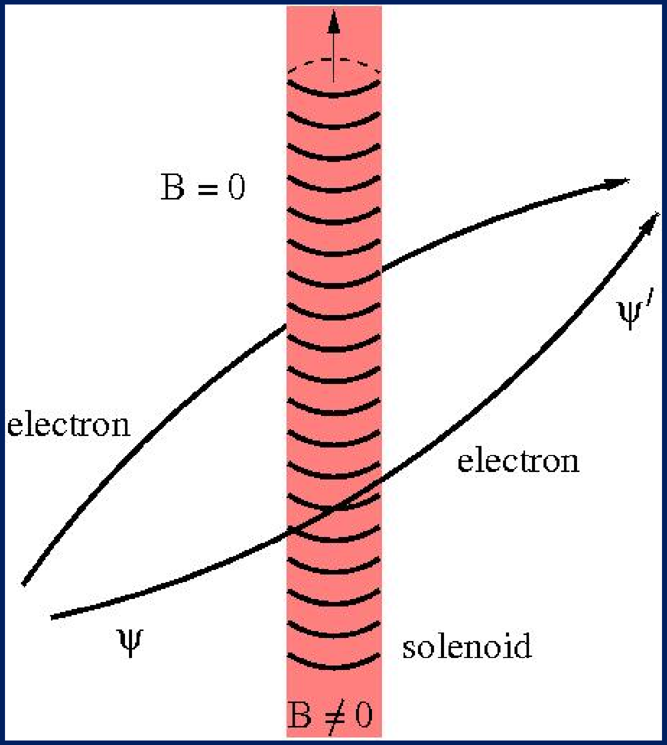


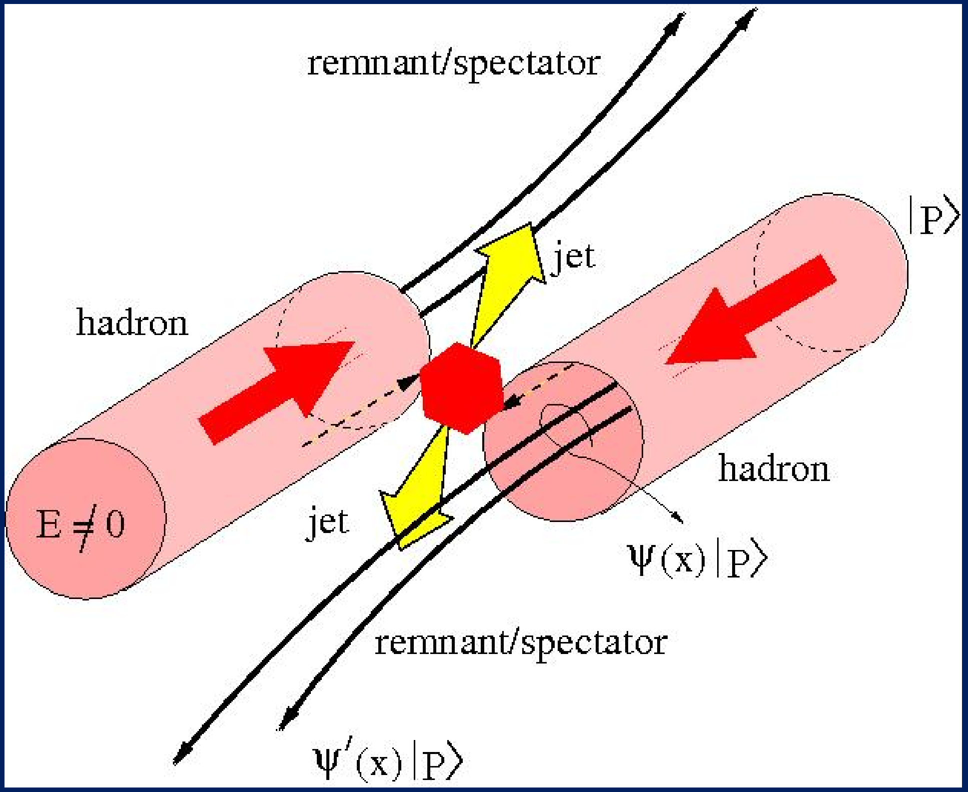
Slide from P. Mulders

Figures by Kees Huyser

Featuring: phases in gauge theories

Slide from P. Mulders





$$\psi' = P\, e^{ie\int ds.A}\, \psi$$

$$\psi_i(x)\left|P\right\rangle = P\, e^{-ig\int_x^{x'} ds_\mu A^\mu}\, \psi_i(x')\left|P\right\rangle$$

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)