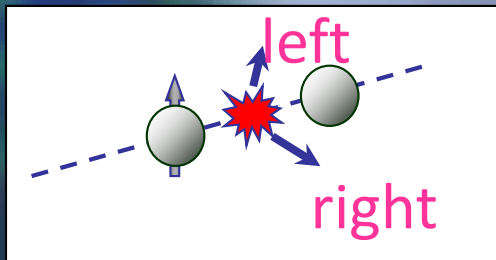


# *Spin-Momentum Correlations, Aharonov-Bohm, and Color Entanglement in Quantum Chromodynamics*

*Christine A. Aidala  
University of Michigan*



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

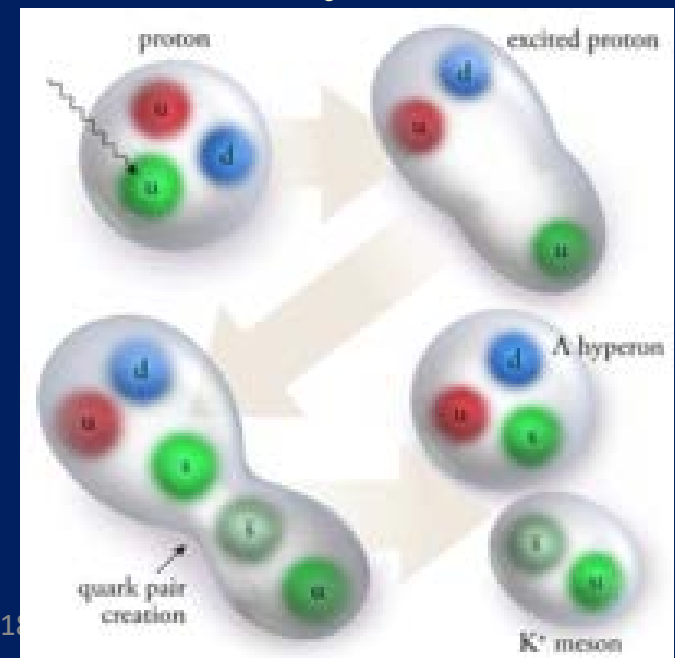
CENPA Seminar  
University of Washington  
February 1, 2018

# *Theory of strong nuclear interaction: 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



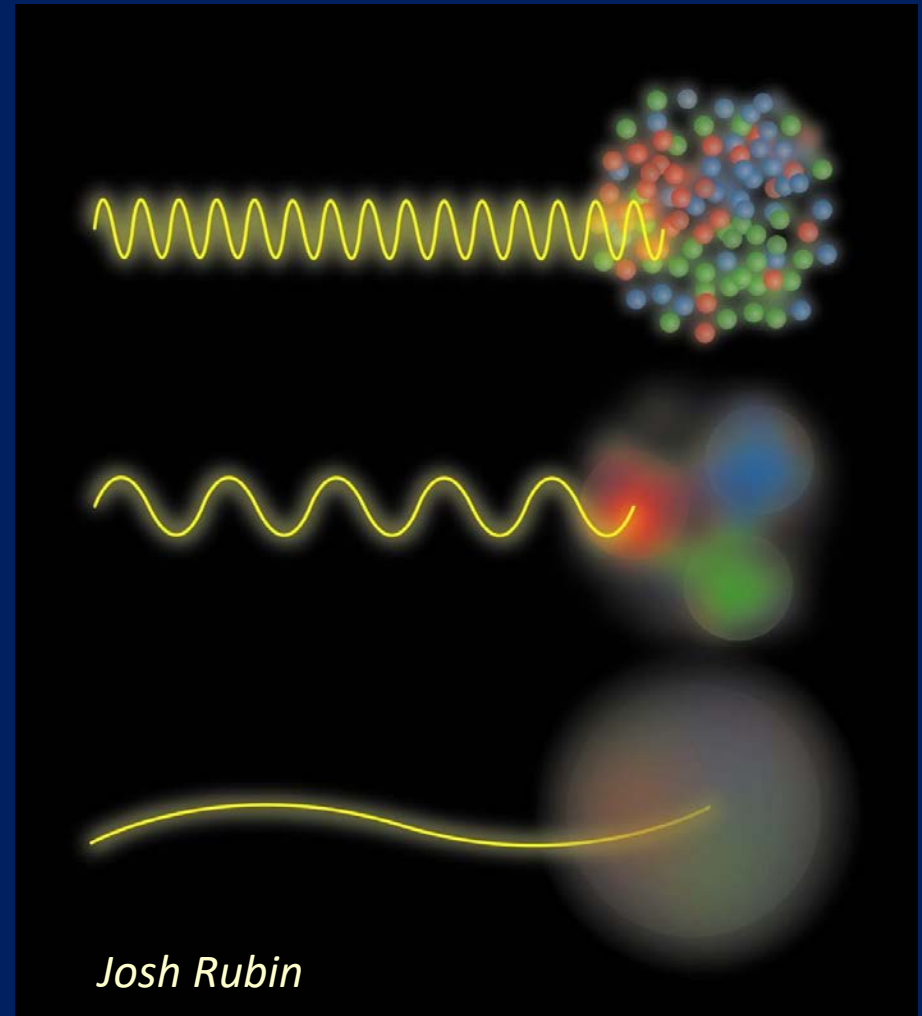
*How do we understand the visible matter  
in our universe in terms of the quark  
and gluon degrees of freedom of  
quantum chromodynamics?*

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



# *The proton as a “laboratory” for studying QCD*

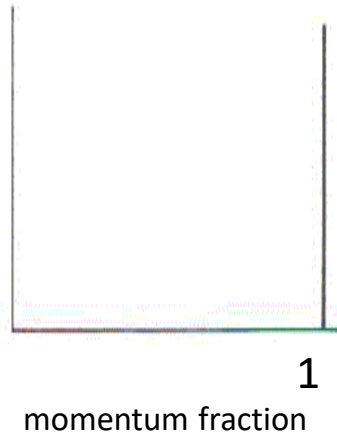
- Proton: simplest stable QCD bound state
- Different energy scales offer information on different aspects of proton internal structure



# *Quark distribution functions inside the proton: The language we've developed (so far!)*

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

A point-like  
particle



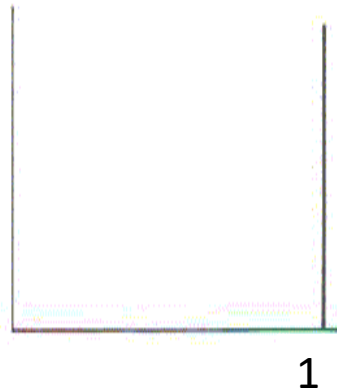
Halzen and Martin, "Quarks and Leptons", p. 201  
Christine Aidala, CENPA Seminar, 2/1/18



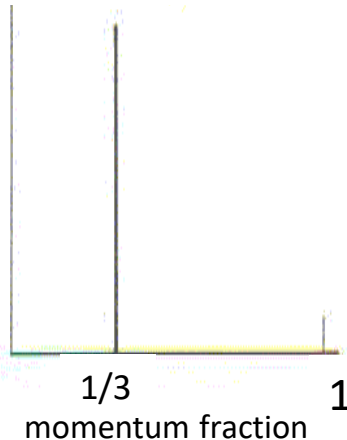
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3 valence quarks



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

Christine Aidala, CENPA Seminar, 2/1/18



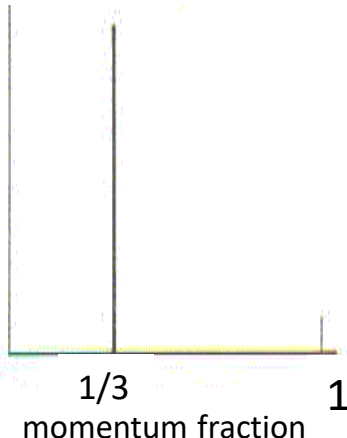
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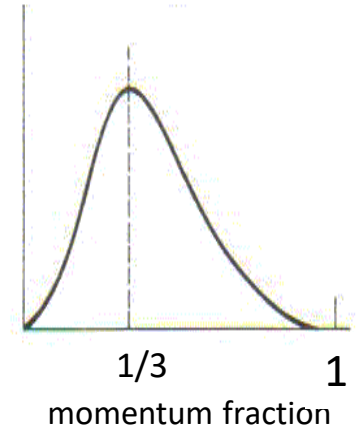
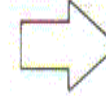
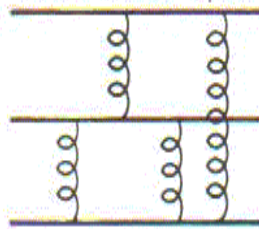
A point-like  
particle



3 valence quarks



3 bound valence quarks



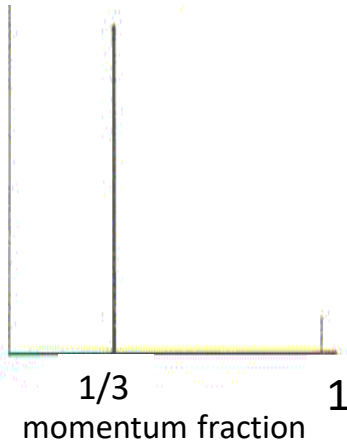
# Quark distribution functions inside the proton: The language we've developed (so far!)

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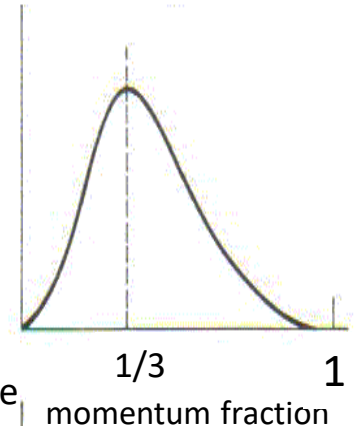
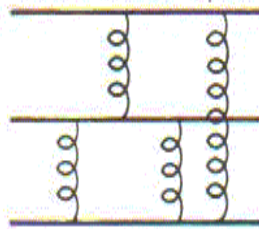
A point-like  
particle



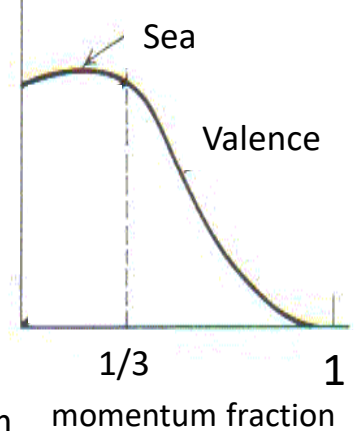
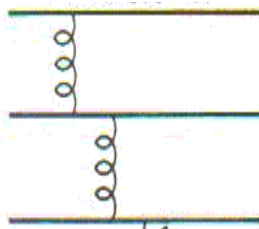
3 valence quarks



3 bound valence quarks



3 bound valence quarks + some  
low-momentum sea quarks

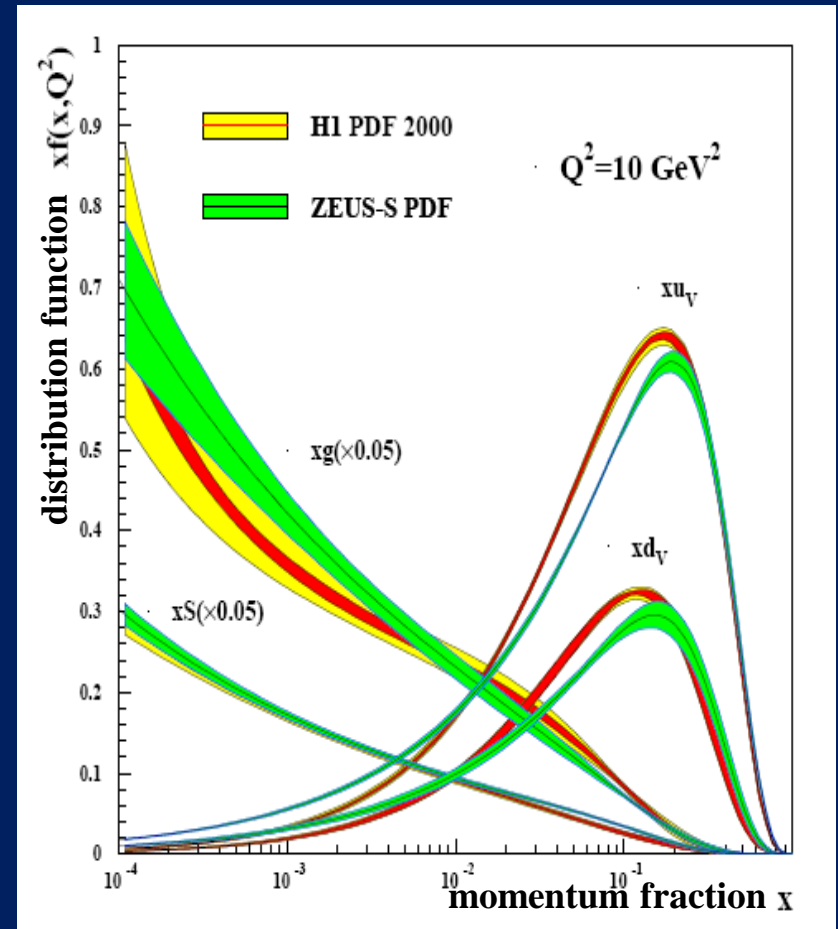
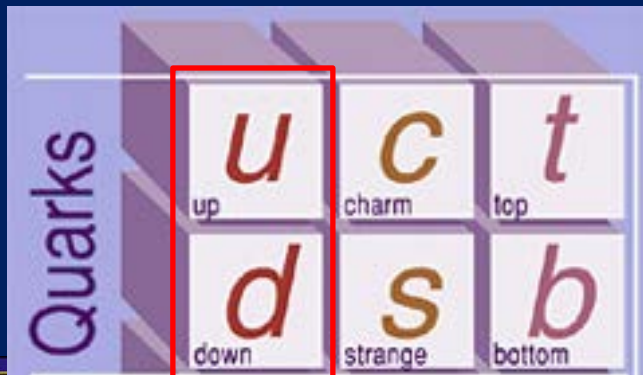


small  
momentum



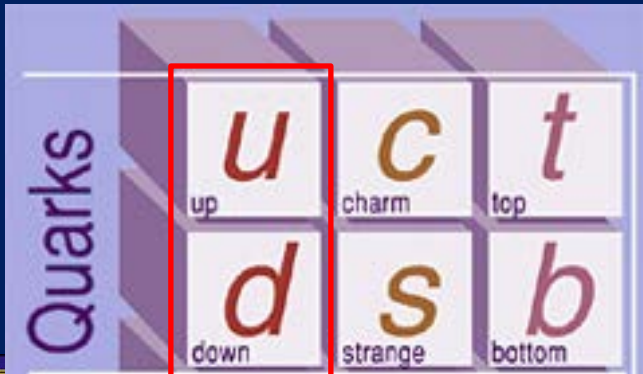
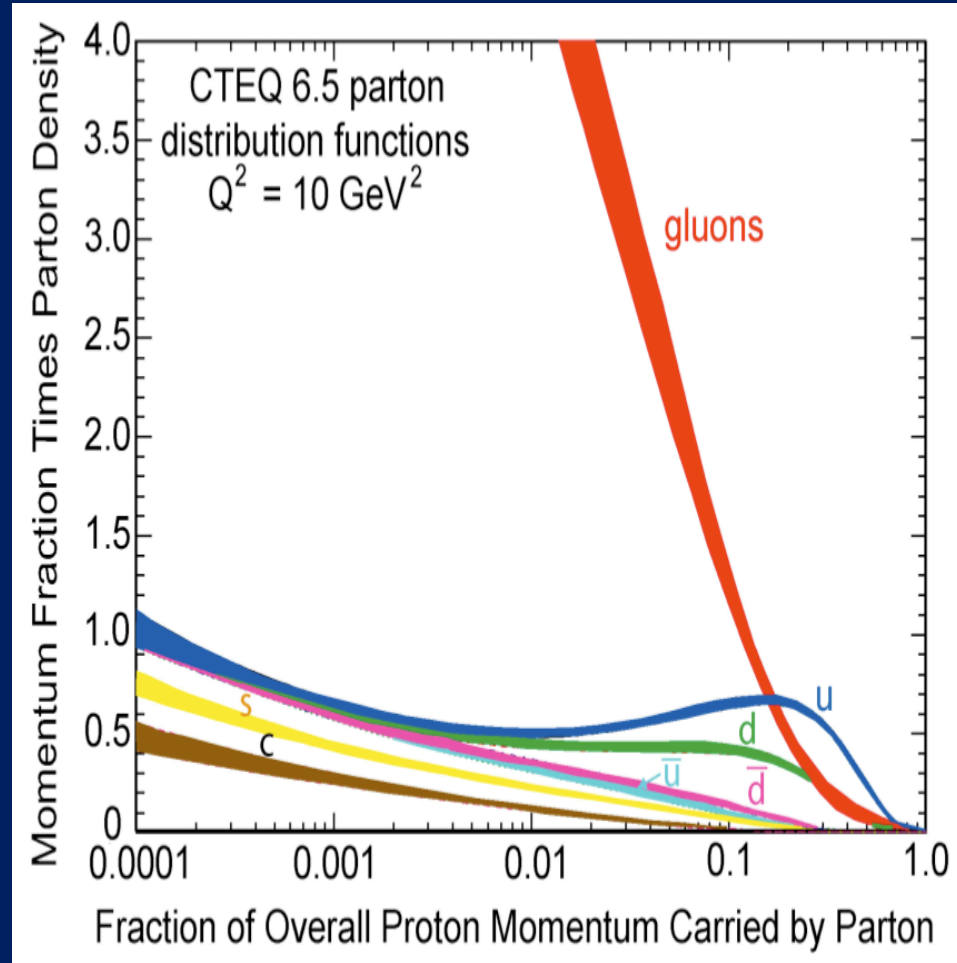
# *What have we learned in terms of this picture by now?*

- Up and down quark “valence” distributions peaked  $\sim 1/3$
- Lots of sea quark-antiquark pairs and even more gluons!



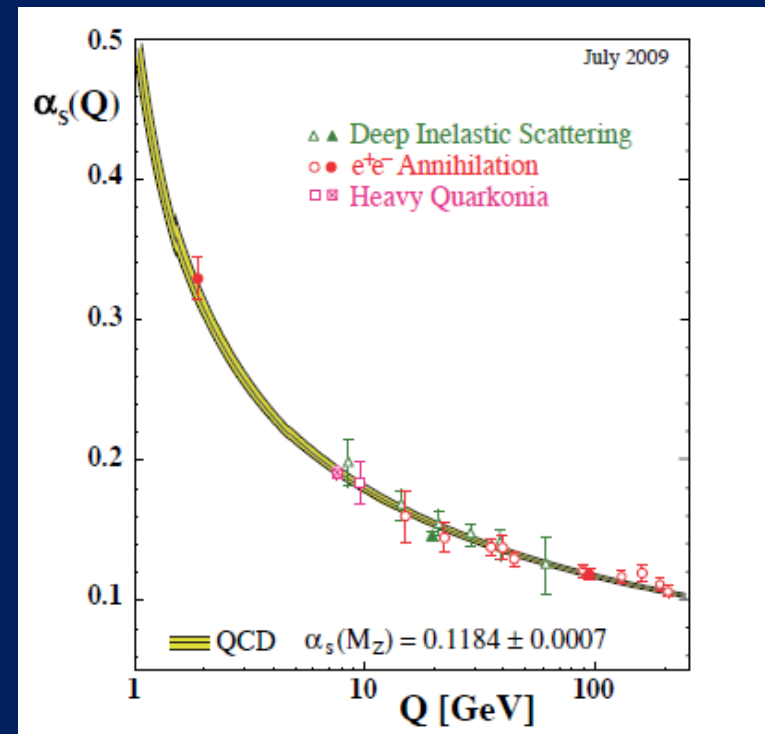
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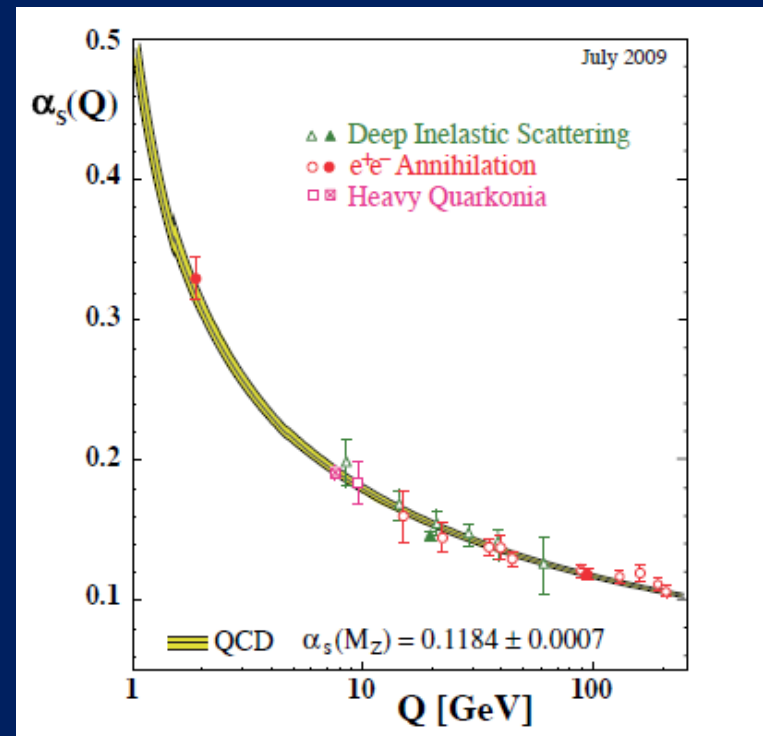
# Perturbative QCD

- Take advantage of running of 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!!)



# *Perturbative QCD*

- Take advantage of running of 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!!)



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

# *Factorization and universality in perturbative QCD*

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

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

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  - Physically meaningful description
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Note: Nonperturbative lattice QCD techniques have made tremendous progress toward *ab initio* calculations of proton structure in last  $\sim 5$  years!

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

# *Mapping out the quark-gluon structure of the proton*

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

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

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 quark-gluon 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!



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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 quark-gluon structure of the proton*

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

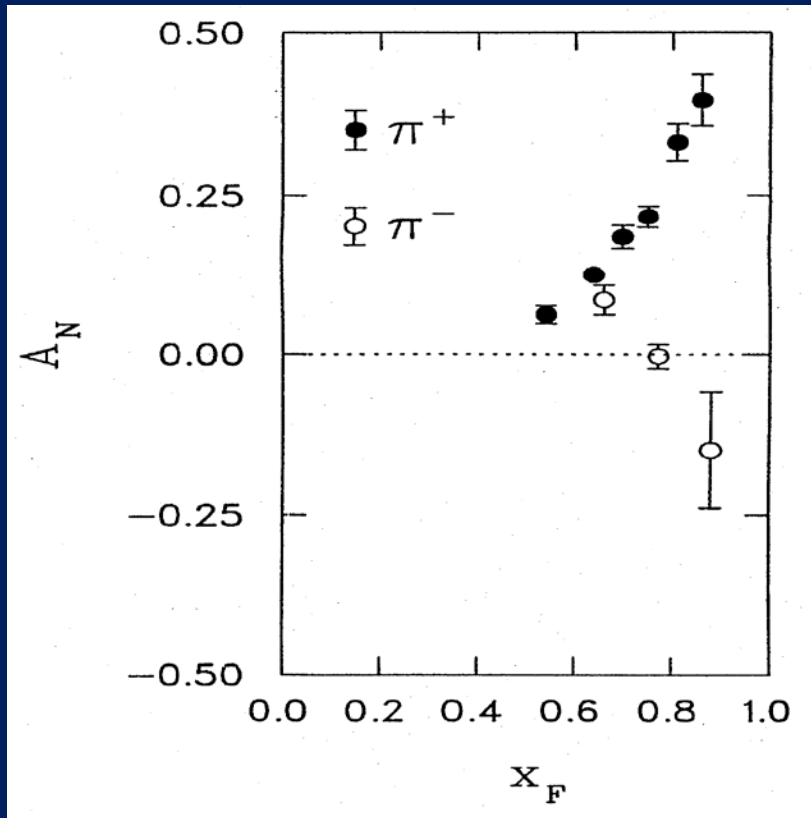
- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

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



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

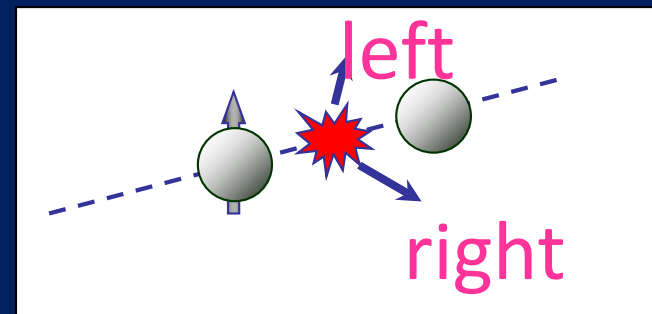
Argonne  $\sqrt{s}=4.9$  GeV



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 . . .



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

# Transverse-momentum-dependent distributions and single-spin asymmetries

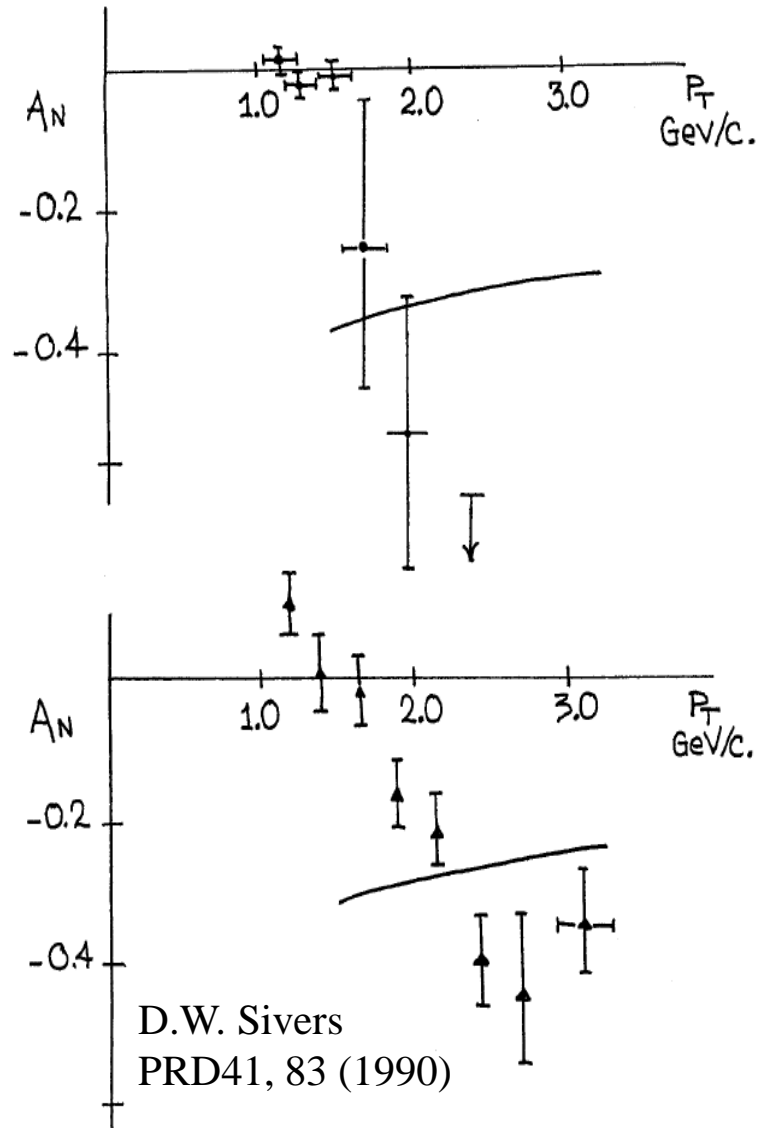


Fig. 1

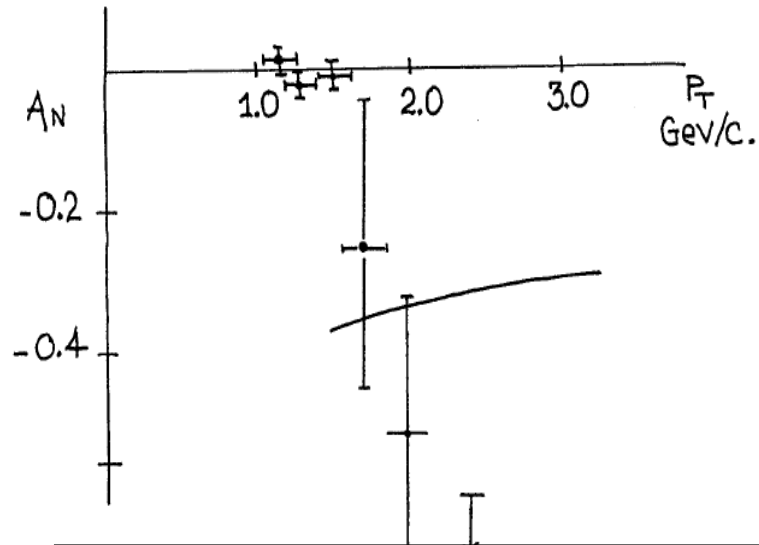
- 1990: D.W. Sivers departs from traditional *collinear* factorization assumption in pQCD and proposes correlation between the *intrinsic transverse motion* of the quarks and gluons and the proton's spin

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

Spin and momenta of  
quarks and/or bound states

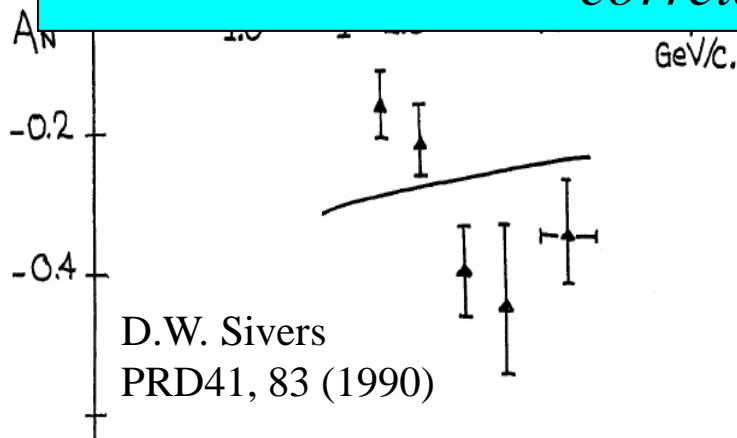


# Transverse-momentum-dependent distributions and single-spin asymmetries



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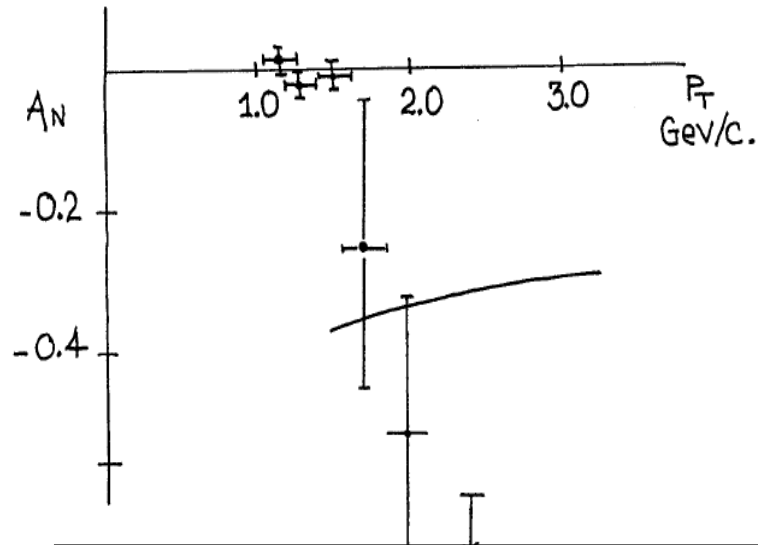
*First quark distribution function describing a spin-momentum correlation in the proton*



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

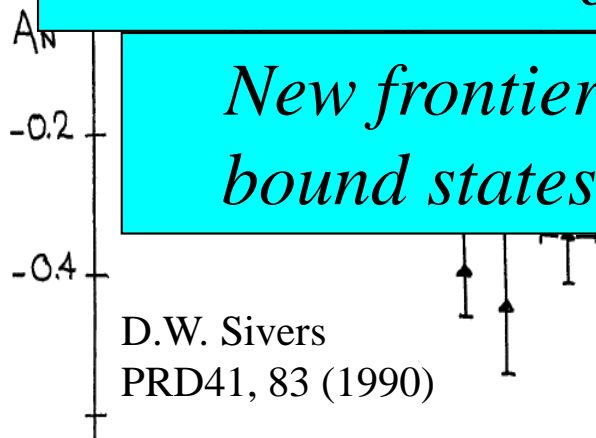
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*First quark distribution function describing a spin-momentum correlation in the proton*



D.W. Sivers  
PRD41, 83 (1990)

*New frontier! Quark dynamics inside QCD bound states, and in their formation process*

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

Spin and momenta of quarks and/or bound states

Fig. 1

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

Unpolarized

$$f_1 = \text{circle with a dot}$$

Spin-spin correlations

$$g_{1L} = \text{circle with dot and right arrow} - \text{circle with dot and left arrow}$$

$$h_{1T} = \text{circle with dot and up arrow} - \text{circle with dot and down arrow}$$

$$g_{1T} = \text{circle with dot and up arrow} - \text{circle with dot and left arrow}$$

Spin-momentum correlations

$$f_{1T}^{\perp} = \text{circle with dot and up arrow} - \text{circle with dot and down arrow}$$

$$h_1^{\perp} = \text{circle with dot and right arrow} - \text{circle with dot and left arrow}$$

$$h_{1L}^{\perp} = \text{circle with dot and up arrow} - \text{circle with dot and down arrow}$$

$$h_{1T}^{\perp} = \text{circle with dot and up arrow} - \text{circle with dot and right arrow}$$



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

Unpolarized


$$f_1 = \text{circle with a dot}$$

Spin-spin correlations

$$g_{1L} = \text{circle with dot and right arrow} - \text{circle with dot and left arrow} \quad \text{Helicity}$$

$$h_{1T} = \text{circle with dot and up arrow} - \text{circle with dot and down arrow} \quad \text{Transversity}$$

Worm-gear  
(Kotzinian-Mulders)

$$g_{1T} = \text{circle with dot and right arrow} - \text{circle with dot and left arrow}$$


Spin-momentum correlations

$$f_{1T}^{\perp} = \text{circle with up arrow} - \text{circle with down arrow} \quad \text{Sivers}$$

$$h_1^{\perp} = \text{circle with dot and up arrow} - \text{circle with dot and down arrow} \quad \text{Boer-Mulders}$$

$$h_{1L}^{\perp} = \text{circle with dot and up-right arrow} - \text{circle with dot and up-left arrow} \quad \text{Worm-gear} \quad h_{1T}^{\perp} = \text{circle with dot and right arrow} - \text{circle with dot and left arrow}$$

$$h_{1T}^{\perp}$$

Pretzelosity

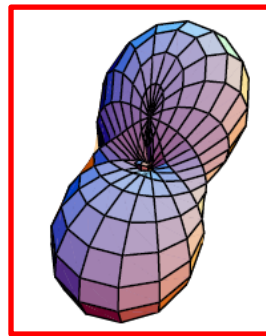
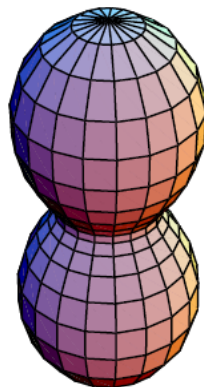
# Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

$$f_1 = \odot$$

Worm-gear  
(Kotzinian-Mulders)

case with  $\rho_L/\rho_U=3$  is shown in in Fig. 5. A pretzel form is obtained if  $\mathbf{n}$  is out of the page.



G.A. Miller, Phys. Rev. C68,  
022201 (2003)

FIG. 5. Shape of the proton coordinate space. Left:  $\mathbf{n} = \mathbf{s}$ , right:  $\mathbf{n}$  points out of the page  
correlations

$$h_1^\perp = \odot \downarrow$$

—



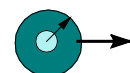
Boer-Mulders



Pretzelosity

$$h_{1L}^\perp = \odot \rightarrow$$

—



Worm-gear

$$h_{1T}^\perp = \odot \uparrow$$



—

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

Unpolarized

$$f_1 = \text{[Diagram: circle with a dot]}$$

Spin-spin correlations

$$g_{1L} = \text{[Diagram: two circles with arrows pointing right]} - \text{[Diagram: two circles with arrows pointing left]} \quad \text{Helicity}$$

Worm-gear  
(Kotzinian-Mulders)

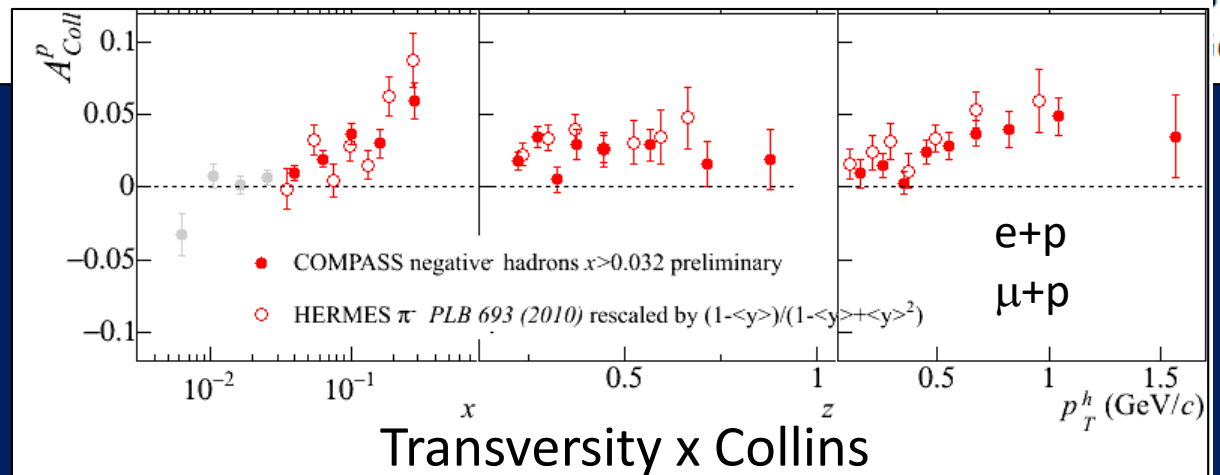
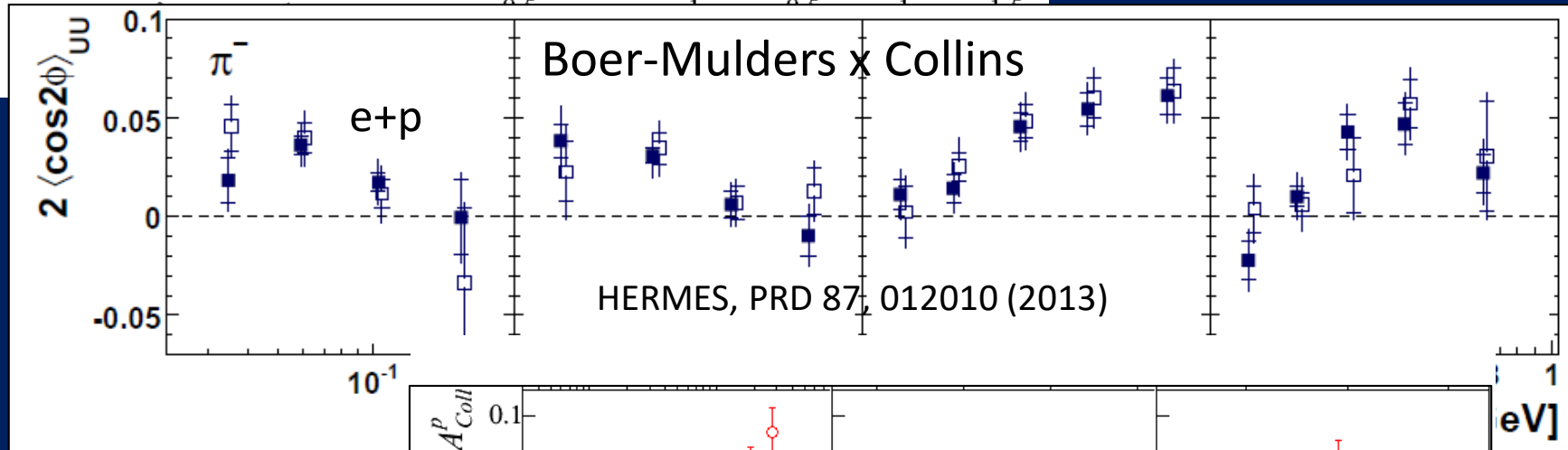
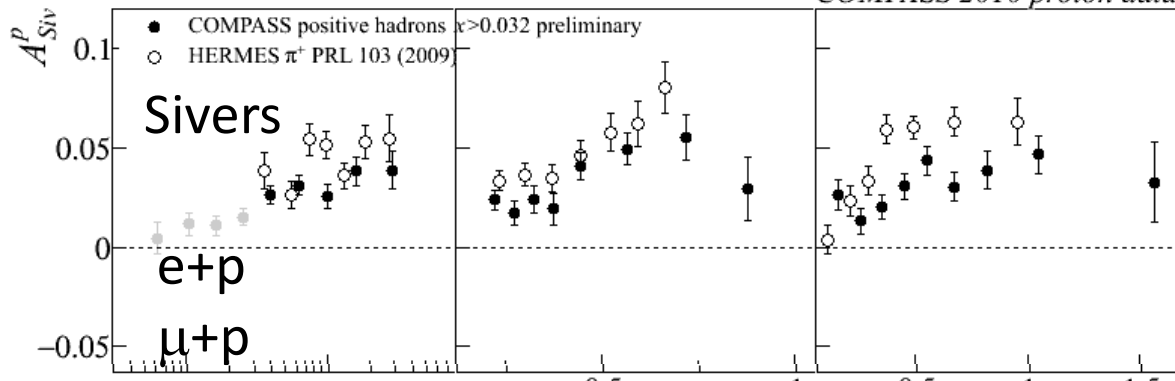
$$g_{1T} = \text{[Diagram: two circles with arrows pointing up]} - \text{[Diagram: two circles with arrows pointing down]} \quad \text{[Image: worm gear]$$

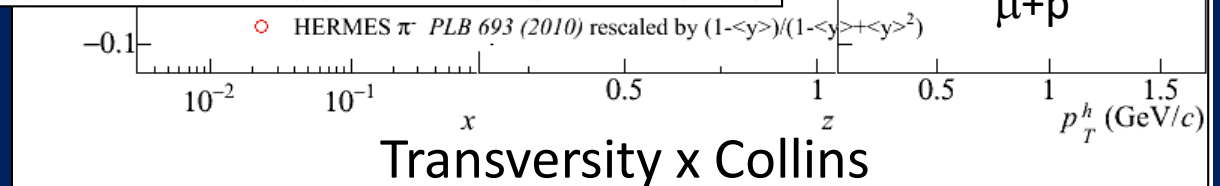
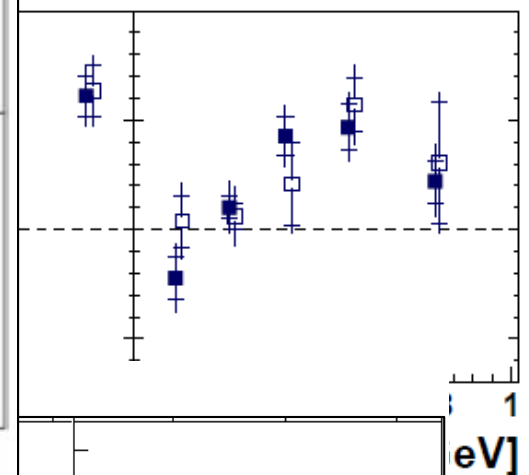
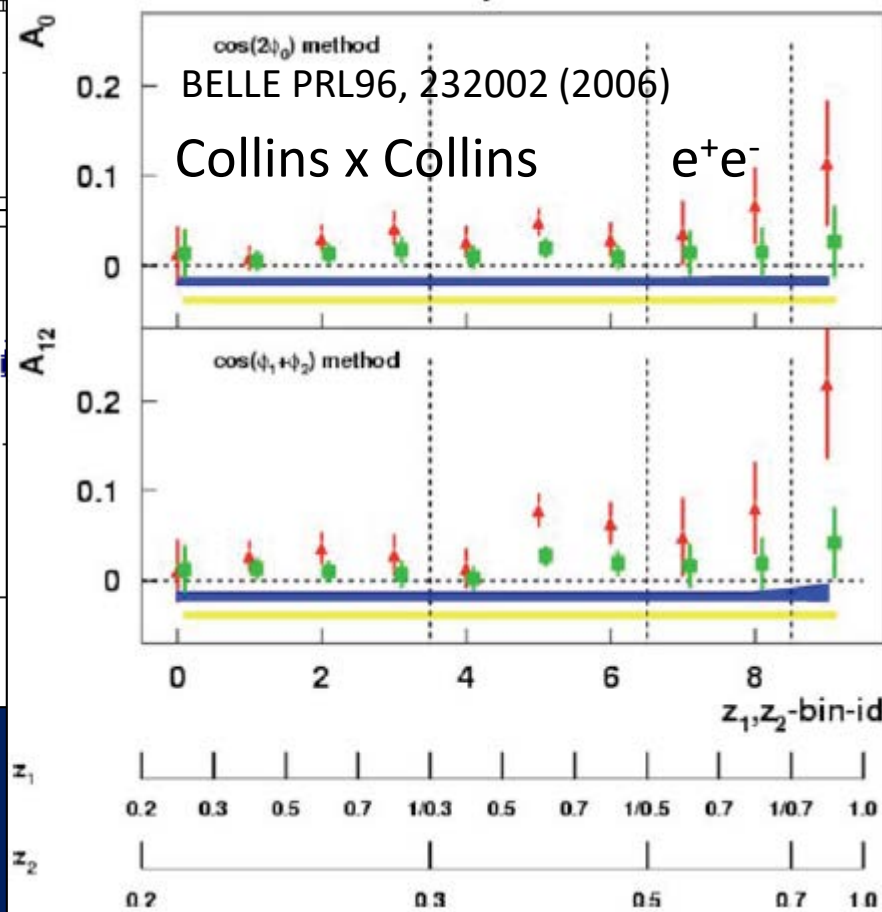
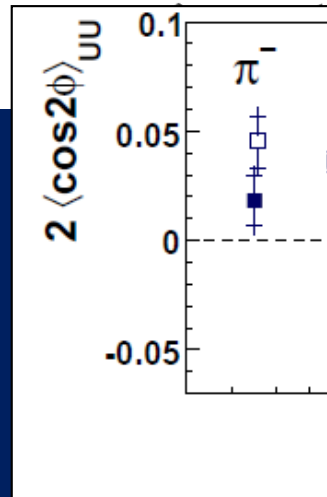
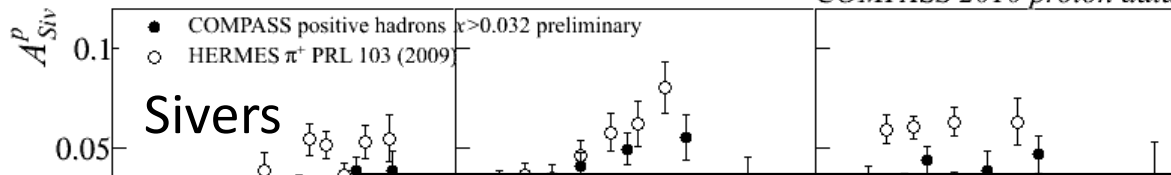
Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~12 years that many of these correlations are nonzero in nature!

Spin-momentum correlations

$$h_1^\perp = \text{[Diagram: circle with arrow pointing down]} - \text{[Diagram: circle with arrow pointing up]} \quad \text{Boer-Mulders}$$

$$h_{1L}^\perp = \text{[Diagram: circle with arrow pointing right]} - \text{[Diagram: circle with arrow pointing left]} \quad \text{Worm-gear} \quad h_{1T}^\perp = \text{[Diagram: circle with arrow pointing up]} - \text{[Diagram: circle with arrow pointing down]} \quad \text{Pretzelosity}$$





# *But what about proton-proton collisions?*

ANL

$\sqrt{s}=4.9$  GeV

BNL

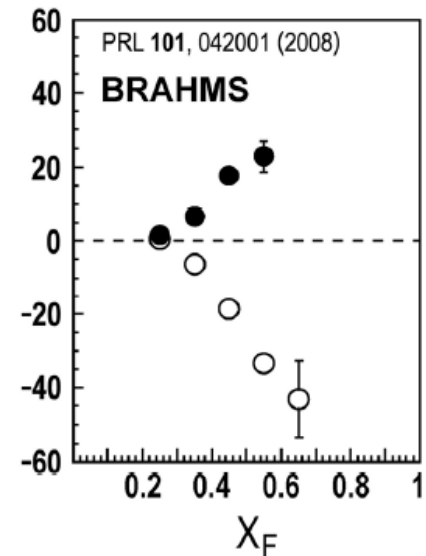
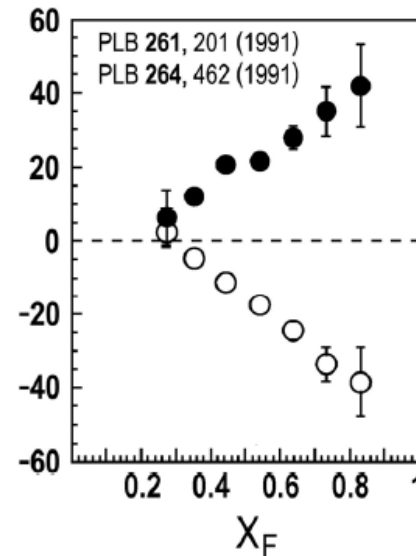
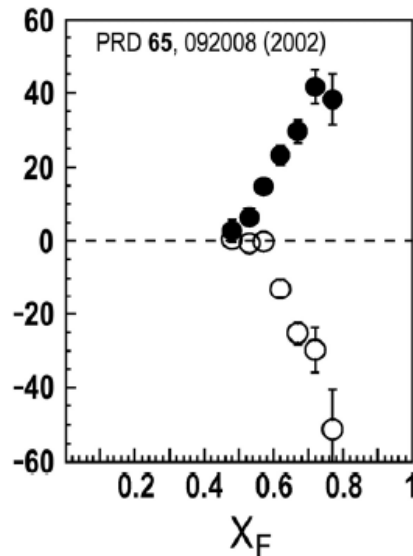
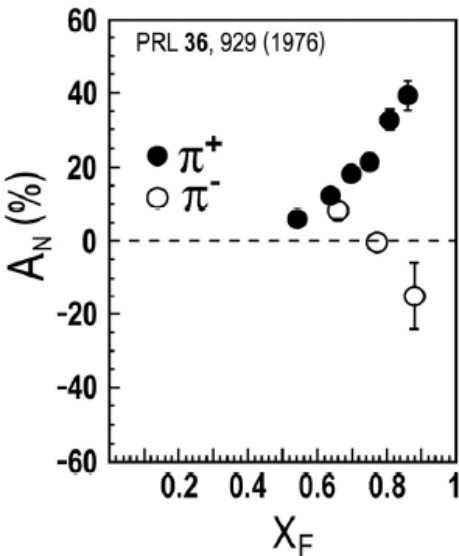
$\sqrt{s}=6.6$  GeV

FNAL

$\sqrt{s}=19.4$  GeV

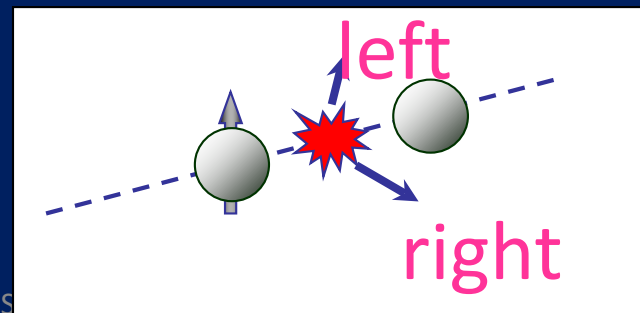
RHIC

$\sqrt{s}=62.4$  GeV



Aidala, Bass, Hasch, Mallot, RMP 85, 655 (2013)

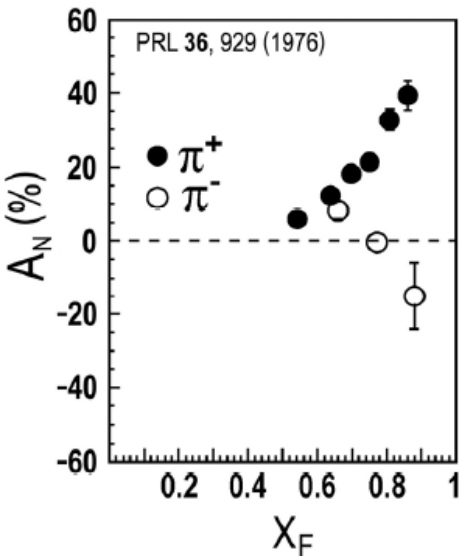
$$x_F = 2p_{long} / \sqrt{s}$$



# *But what about proton-proton collisions?*

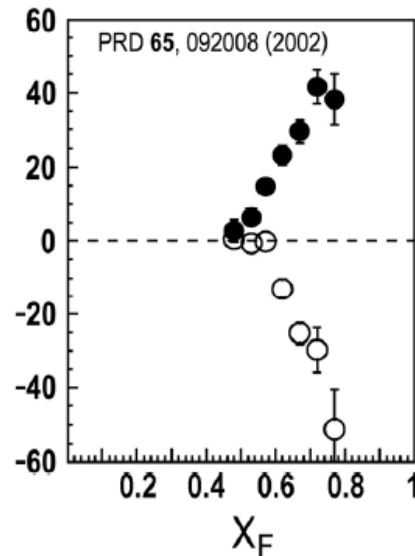
ANL

$\sqrt{s}=4.9$  GeV



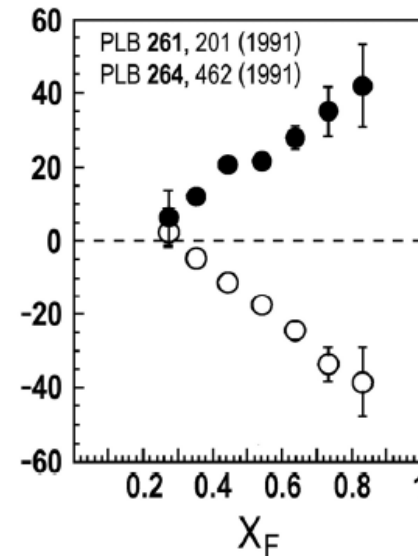
BNL

$\sqrt{s}=6.6$  GeV



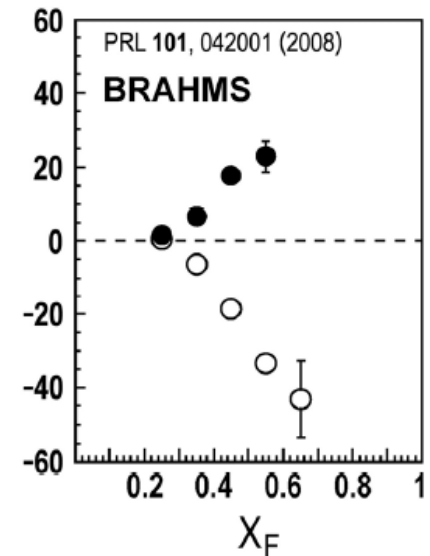
FNAL

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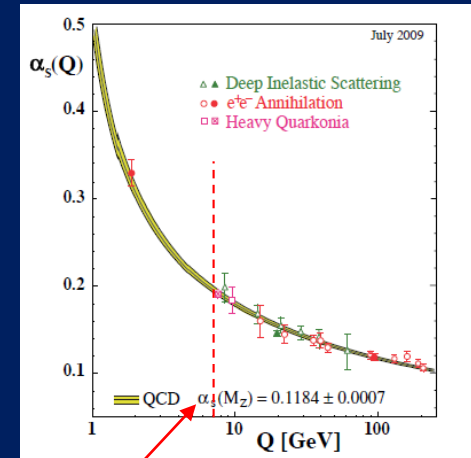
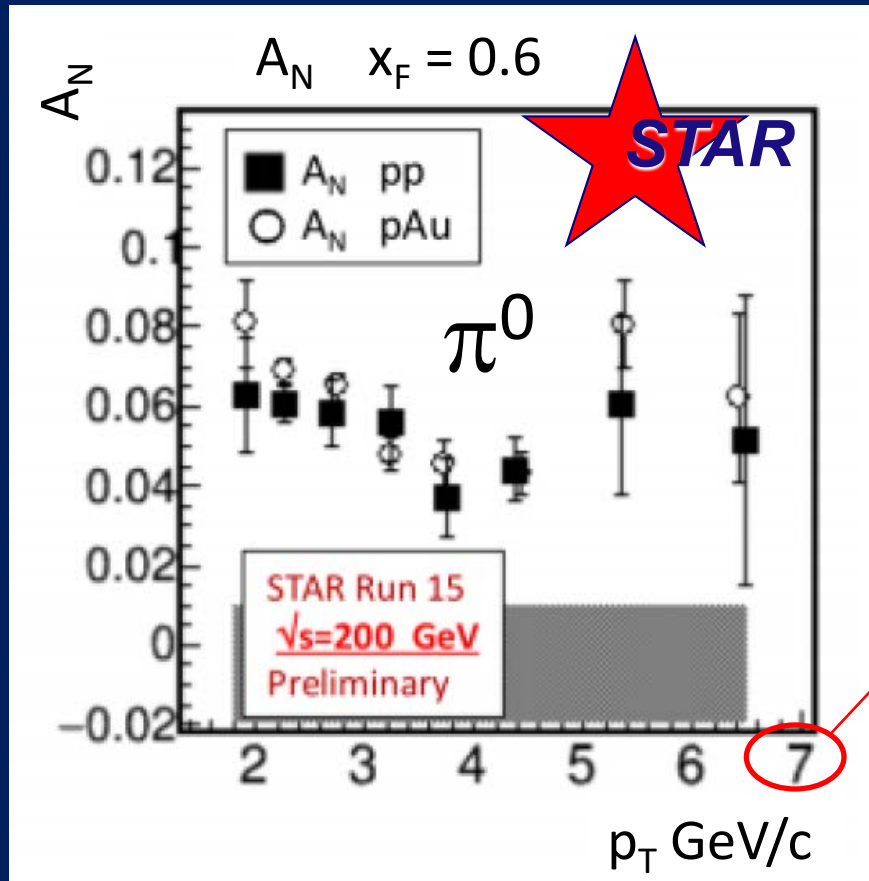
Al

Much larger spin-momentum correlations, and strikingly similar effects across energies!

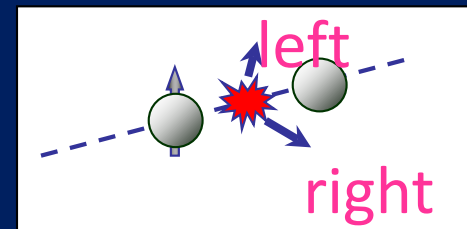
right



# Single-spin asymmetries in transversely polarized proton-proton collisions



Effects persist to kinematic regimes where perturbative QCD techniques clearly apply





*proton-proton  $\rightarrow$  pion + X:*  
*Challenging to interpret*

- Always huge effects!
- But in  $p+p \rightarrow \text{pion} + X$  don't have enough information to separate initial-state (proton structure) from final-state (pion formation) effects
- Need to think more carefully . . .



# *Different symmetry properties for different spin-momentum correlations*

- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation



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- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish



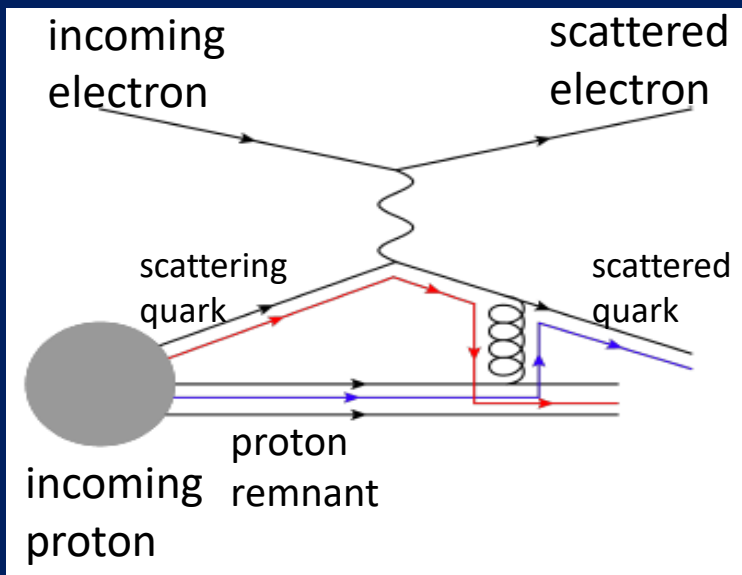
# *Different symmetry properties for different spin-momentum correlations*

- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation
- 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

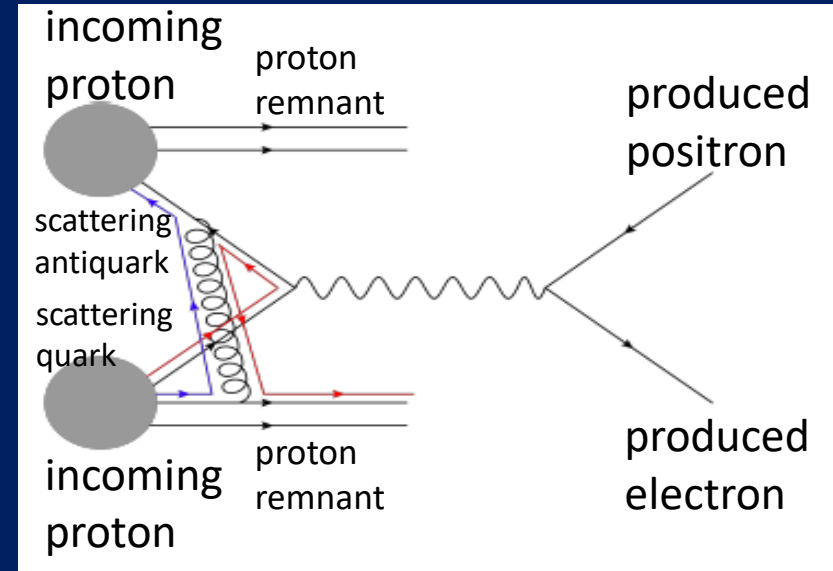


# Modified universality of $PT$ -odd correlations: *Color in action!*

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



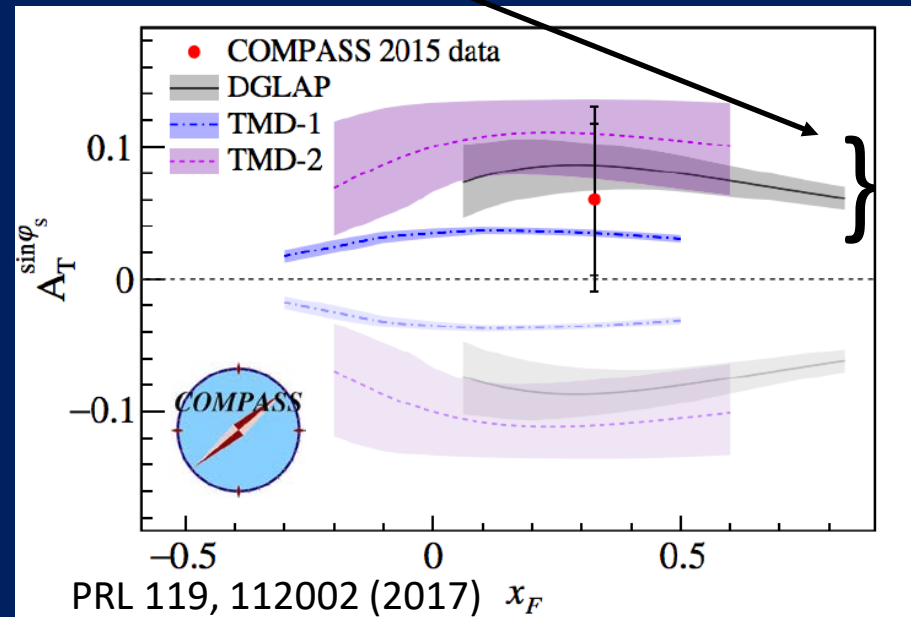
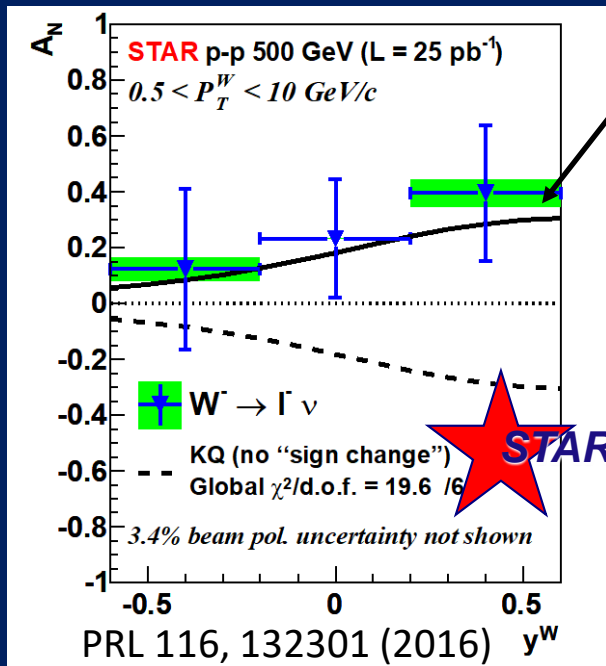
**Quark-antiquark annihilation to leptons: Initial-state color exchange**



***Opposite sign for  $PT$ -odd transverse-momentum-dependent distributions measured in these two processes:***  
***process-dependent! (Collins 2002)***

# Modified universality: Initial experimental hints

Predictions including  
sign change



*First measurements by STAR at RHIC and COMPASS at CERN  
 suggestive of predicted sign change in color-annihilation processes  
 compared to quark knock-out by an electron.  
 More statistics forthcoming . . .*

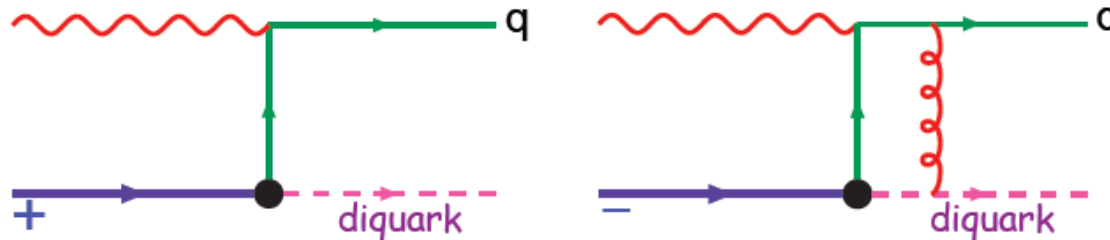
# Modified universality requires full QCD: Gauge-invariant quantum field theory

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 Sivvers function,

SIDIS final state interactions



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

An earlier proof that the Sivvers 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 Sivvers 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.

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

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 :**

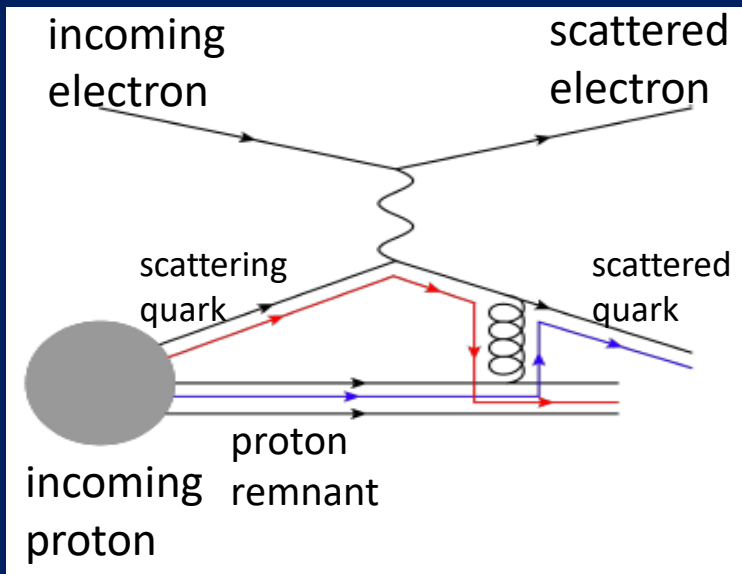
**The Aharonov–Bohm effects: Variations on a subtle theme,**  
by Herman Batelaan and Akira Tonomura.

“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.”

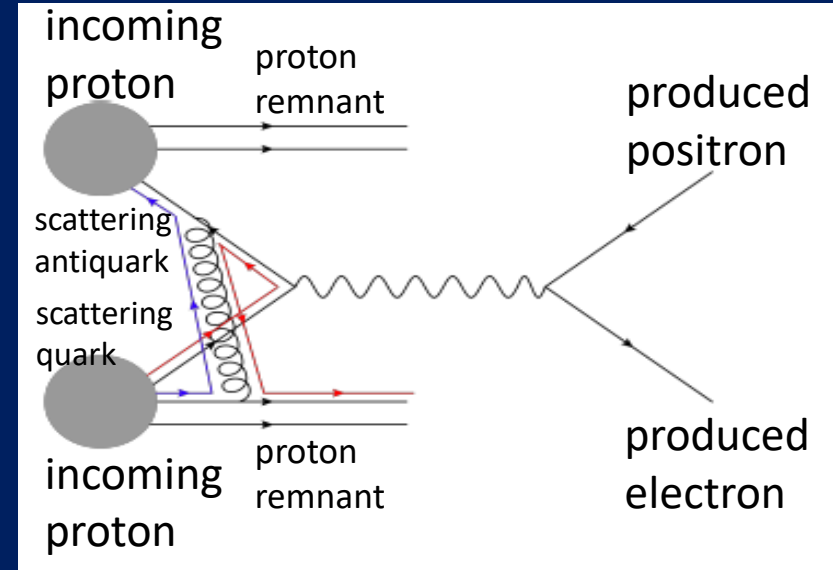


# *Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm effect in QCD!!*

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



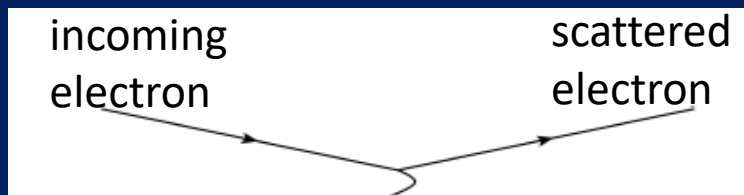
**Quark-antiquark annihilation to  
leptons: Initial-state color exchange**



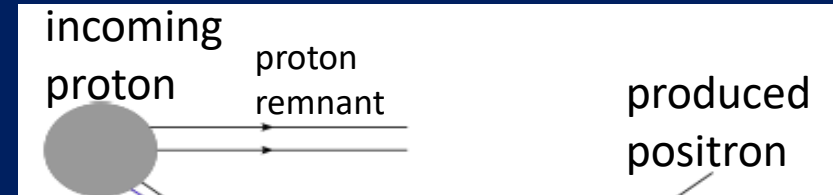
See e.g. Pijlman, hep-ph/0604226  
or Sivers, arXiv:1109.2521

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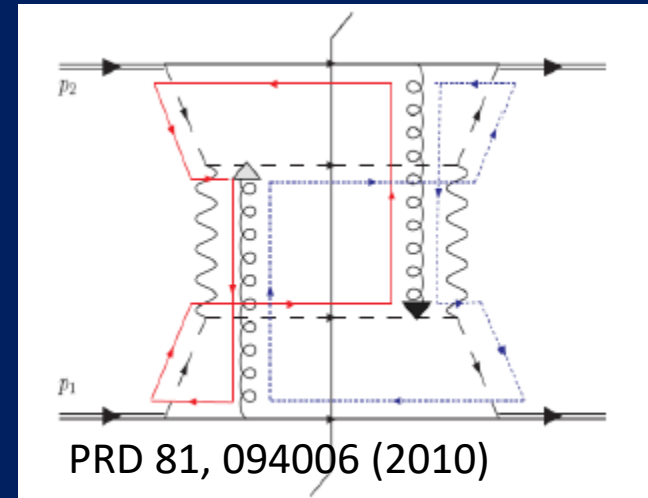
*Simplicity of these two processes:  
Abelian vs. non-Abelian nature of the gauge  
group doesn't play a role.*

*BUT: In QCD expect additional, new effects  
due to specific non-Abelian nature of the  
gauge group  $\rightarrow$  gluon self-coupling*

# *QCD Aharonov-Bohm effect:*

## *Color entanglement*

- 2010: T.C. Rogers and P. Mulders predict *color entanglement* in processes involving proton-proton production of QCD bound states if quark transverse momentum taken into account
- Quarks become correlated *across* the two colliding protons
- Consequence of QCD specifically as a *non-Abelian* gauge theory!



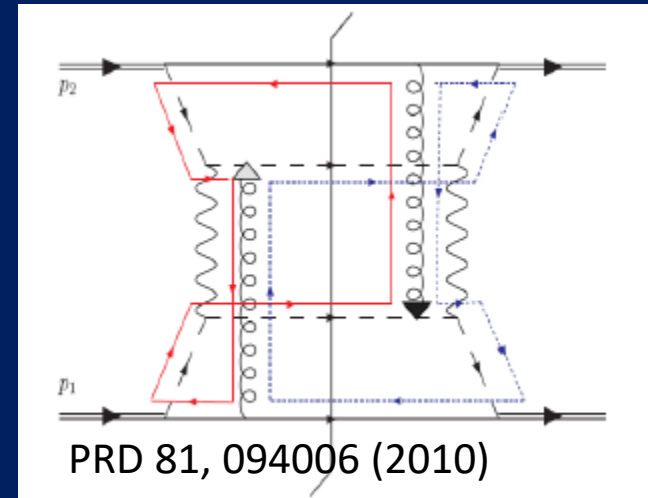
$$p + p \rightarrow h_1 + h_2 + X$$

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

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

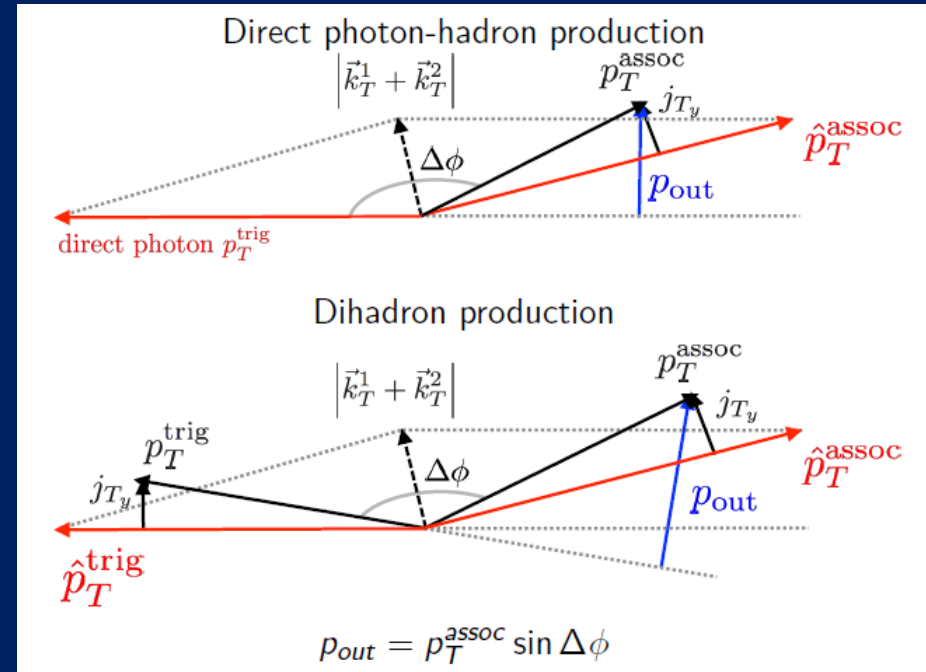
Color flow can't be described as flow in the two gluons separately. Requires presence of both.

*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 QCD bound states
  - color exchange between a scattering quark and remnant of other proton
- And at least 1 final QCD bound state
  - exchange between scattered quark and either remnant

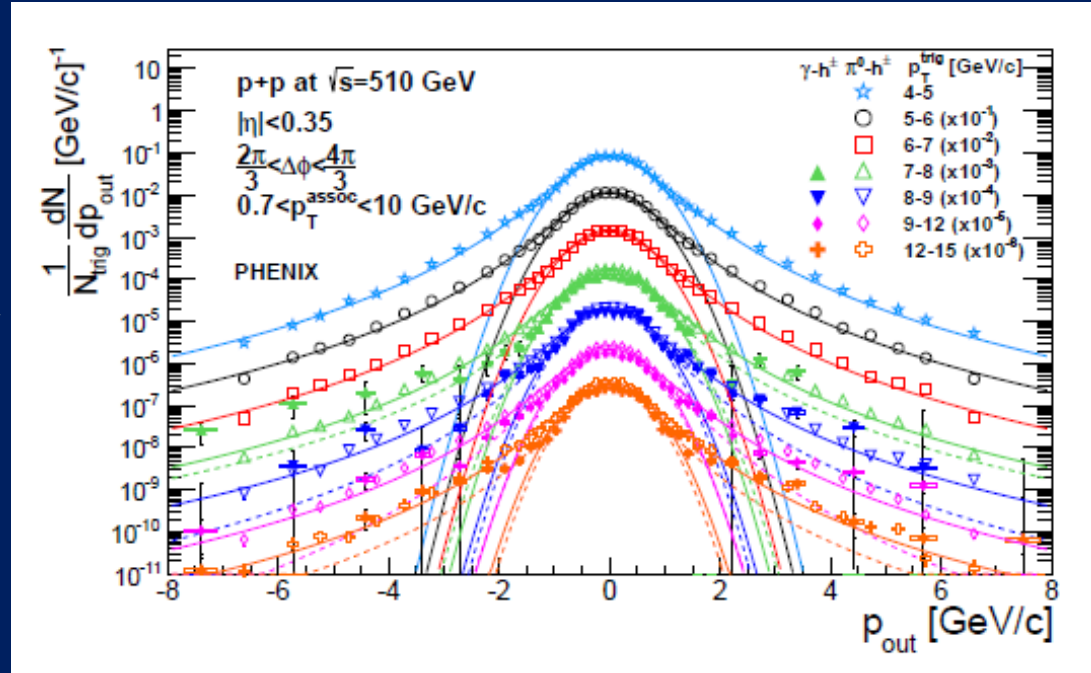
→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production



# Out-of-plane momentum component distributions

PRD95, 072002 (2017)

- Clear two-component distribution
  - Gaussian near 0—nonperturbative transverse momentum
  - Power-law at large  $p_{\text{out}}$ —kicks from hard (perturbative) gluon radiation
- Different colors  $\rightarrow$  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 ( $Q^2$ )*

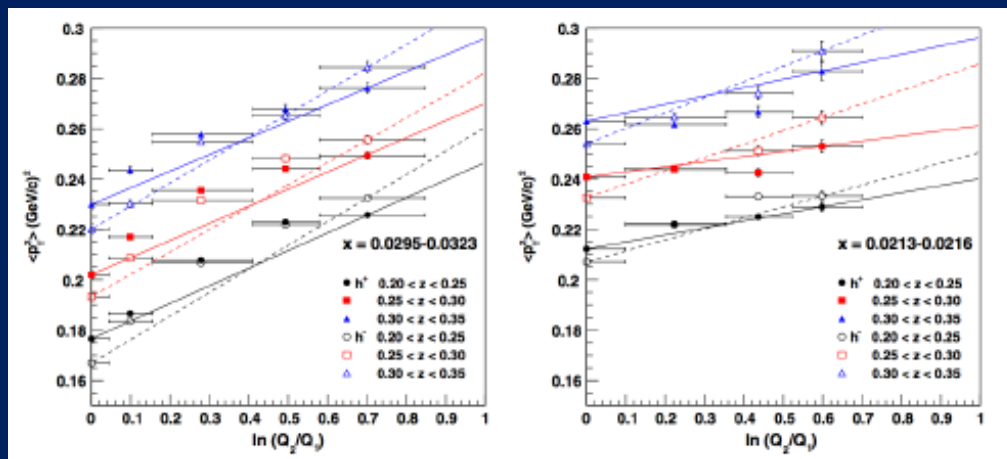
- Proof of factorization (i.e. no entanglement) for processes sensitive to nonperturbative transverse momentum directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation



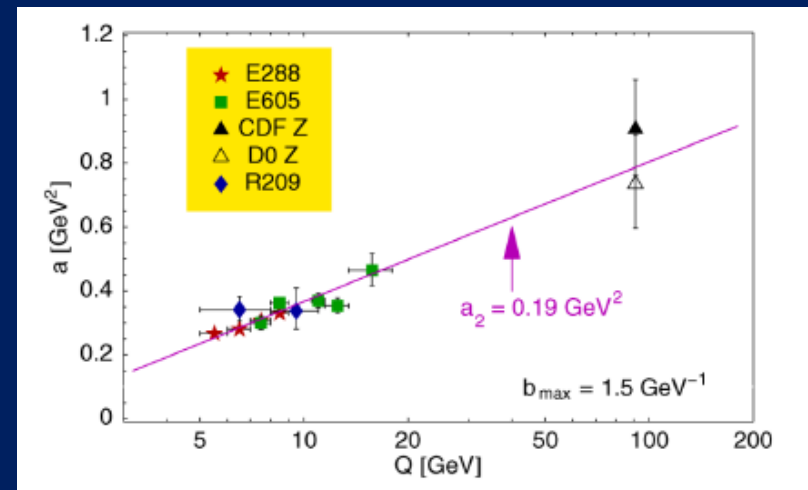


# Look at *evolution* of nonperturbative transverse momentum widths with hard scale ( $Q^2$ )

- Proof of factorization (i.e. no entanglement) for processes sensitive to nonperturbative transverse momentum directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation
- Confirmed experimentally in deep-inelastic lepton-nucleon scattering (left) and quark-antiquark annihilation to leptons (right)



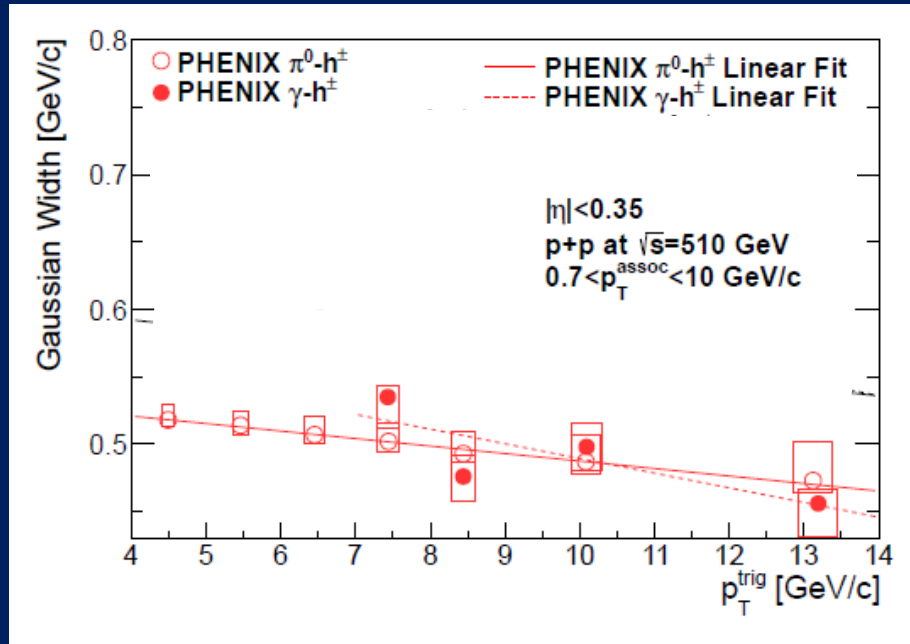
Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



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



# *Nonperturbative momentum widths may **decrease** in processes where entanglement predicted??*

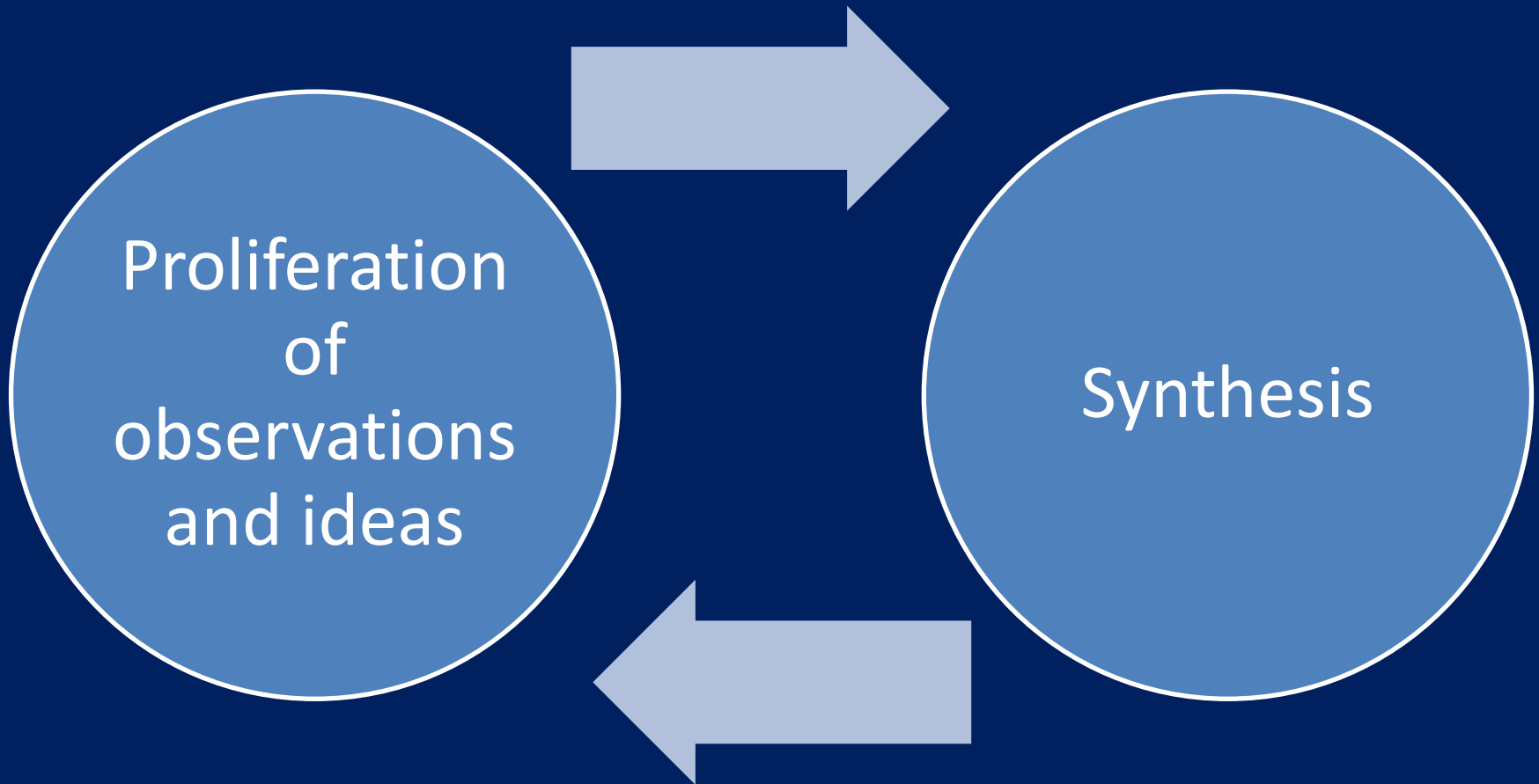


PHENIX Collab., PRD95, 072002 (2017)

- Measurements suggestive of quantum-correlated quarks across colliding protons?
- However, correlations among measured kinematic variables make results inconclusive ...
- Follow-up studies underway

*Discussions of other potential observables ongoing . . .*

# *A cyclical process*



# *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 that have long been familiar to the world of condensed matter and AMO physics
  - All sorts of correlations within systems and in their formation
  - Quantum mechanical phase interference effects
  - Quantum entangled systems



# Summary

- Early years of rewarding new era of quantitative basic research in QCD!
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  - All sorts of correlations within systems and in their formation
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*Will be exciting to continue testing and exploring these ideas and phenomena in upcoming years . . .*



*Afterword:*  
*QCD “versus” proton structure?*  
*A personal perspective*



*We shall not cease from exploration  
And the end of all our exploring  
Will be to arrive where we started  
And know the place for the first time.*

*T.S. Eliot*





# *Extra*



# *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
- 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!

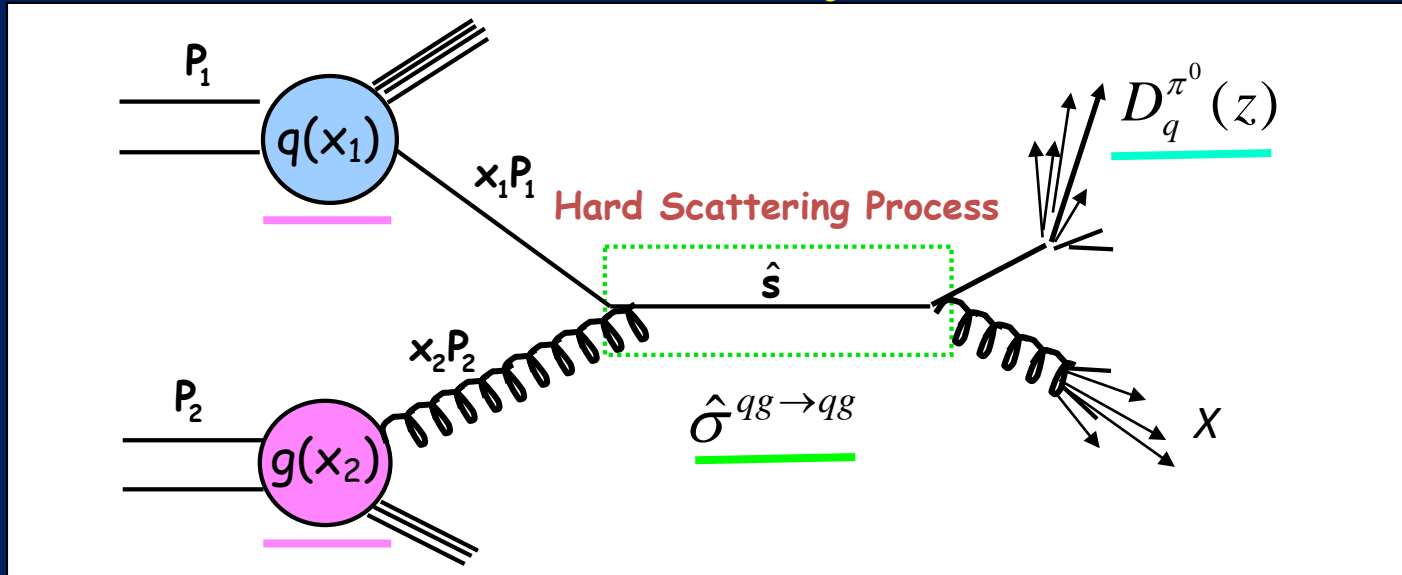


# *Effective field theories*

- 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
  - Chiral Effective Theory, Heavy Quark Effective Theory, Non-Relativistic QCD, . . .
  - Many effective theories for nonperturbative QCD – chiral symmetry breaking, . . .



# Parton distribution functions in perturbative QCD calculations of observables



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

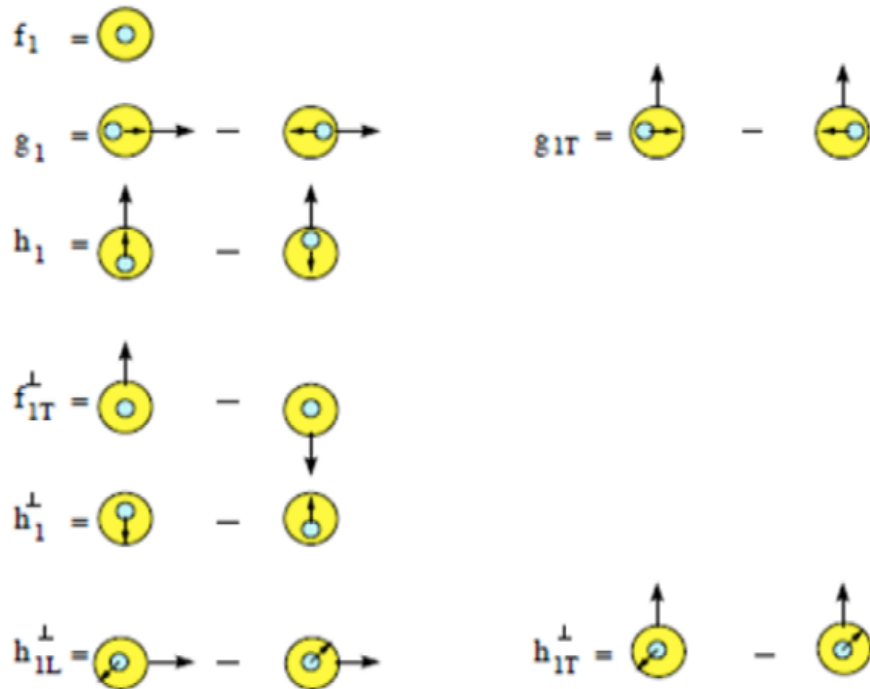
High-energy processes have predictable rates given:

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

} Universal non-perturbative factors

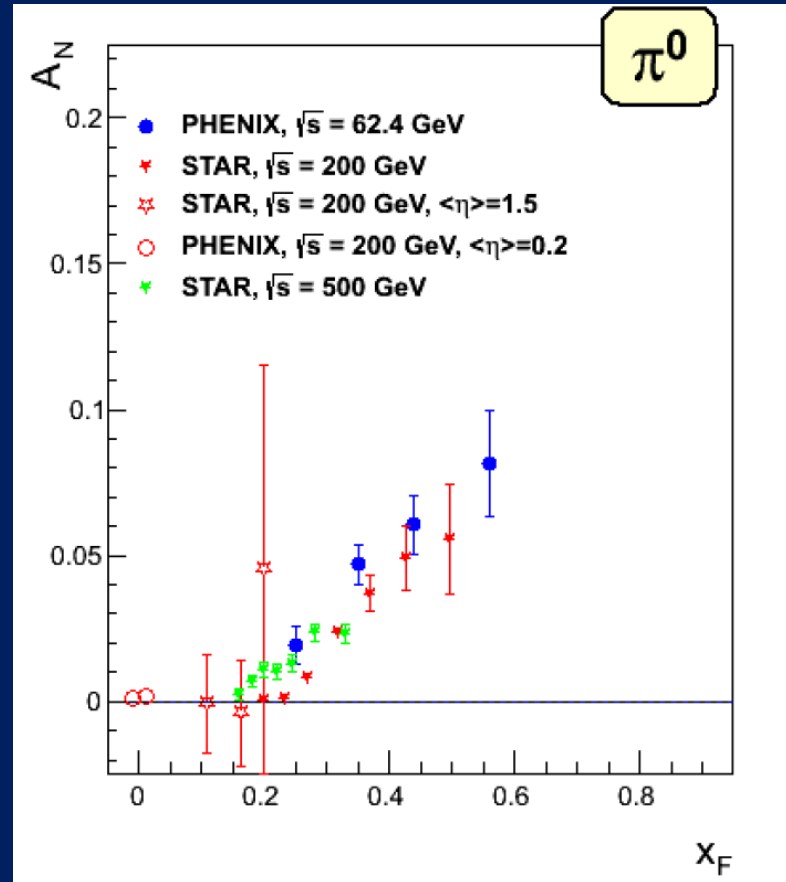
# Spin-spin and spin-momentum correlations in QCD bound states

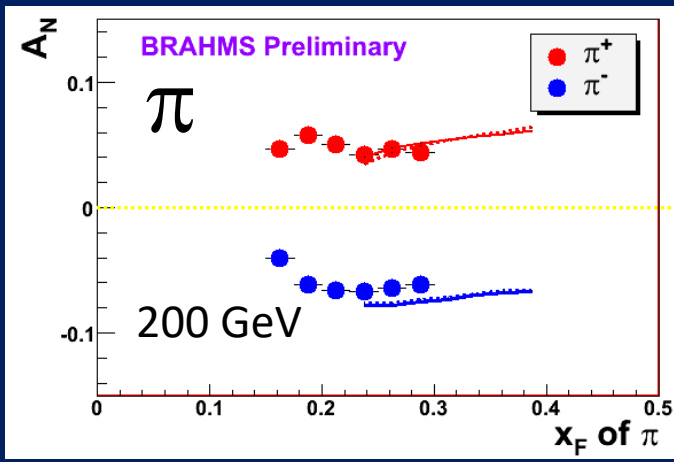
U = unpolarized      L = longitudinally polarized      T = transversely polarized  
N = nucleon      q = quark



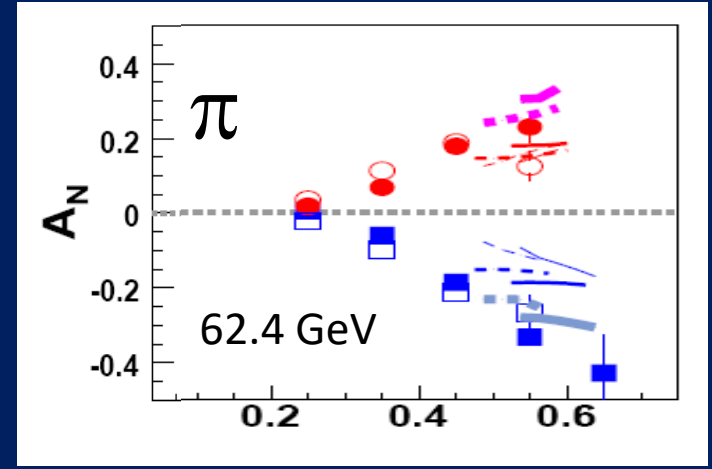
N \ q			
	U	L	T
U	$f_1$		$h_1^\perp$
L		$g_1$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}$	$h_1 h_{1T}^\perp$

# Forward transverse single-spin asymmetries for neutral pions

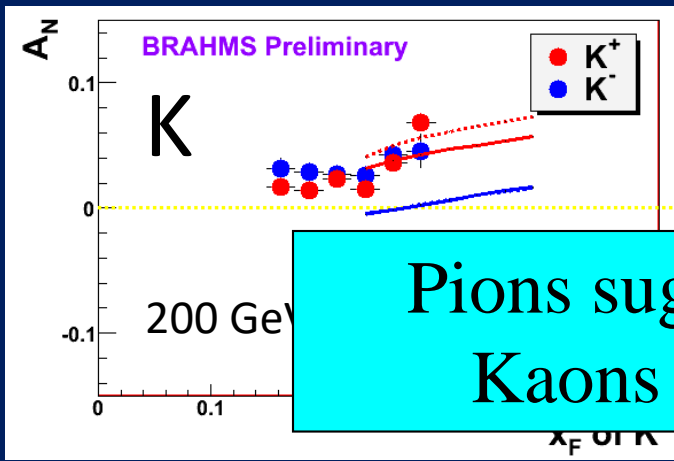




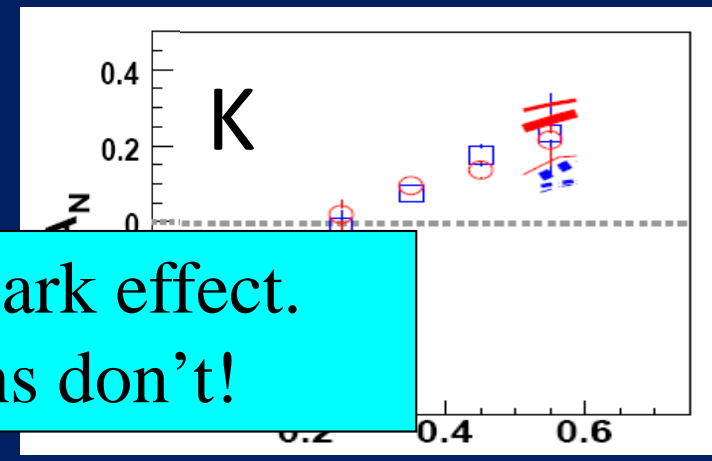
$\pi, K, p$   
at 200 and  
62.4 GeV



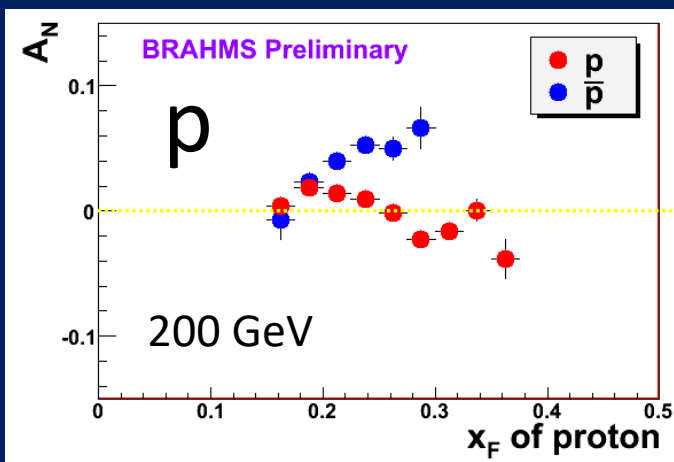
Note different scales



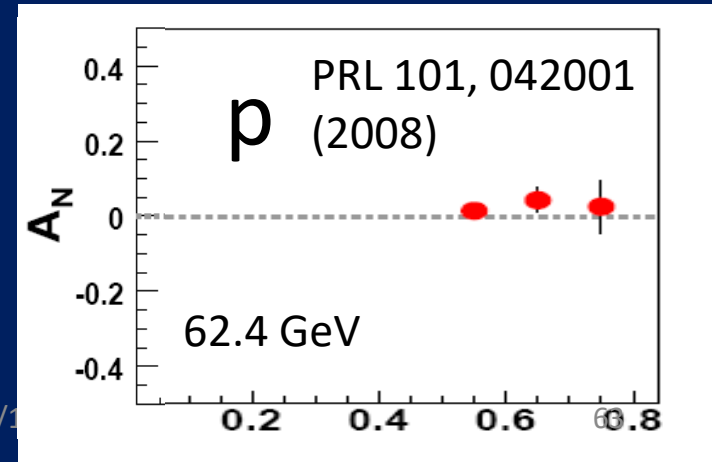
K- asymmetries  
underpredicted



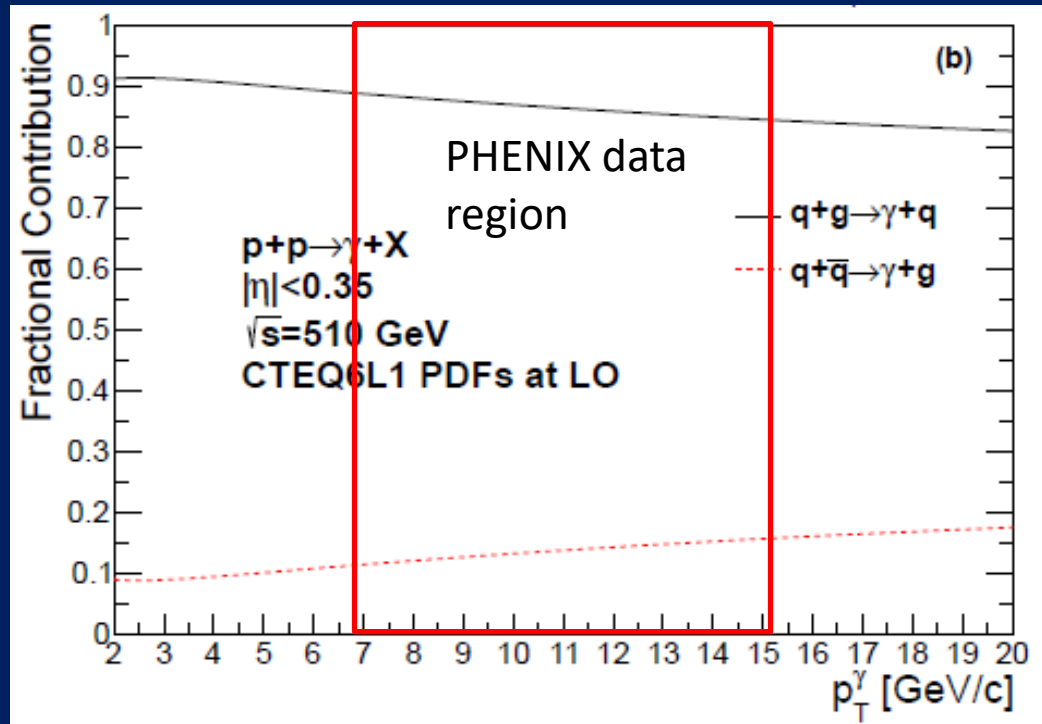
Pions suggest valence quark effect.  
Kaons and (anti)protons don't!



Large antiproton  
asymmetry??  
Unfortunately no 62.4  
GeV measurement



# Partonic process contributions for direct photon production



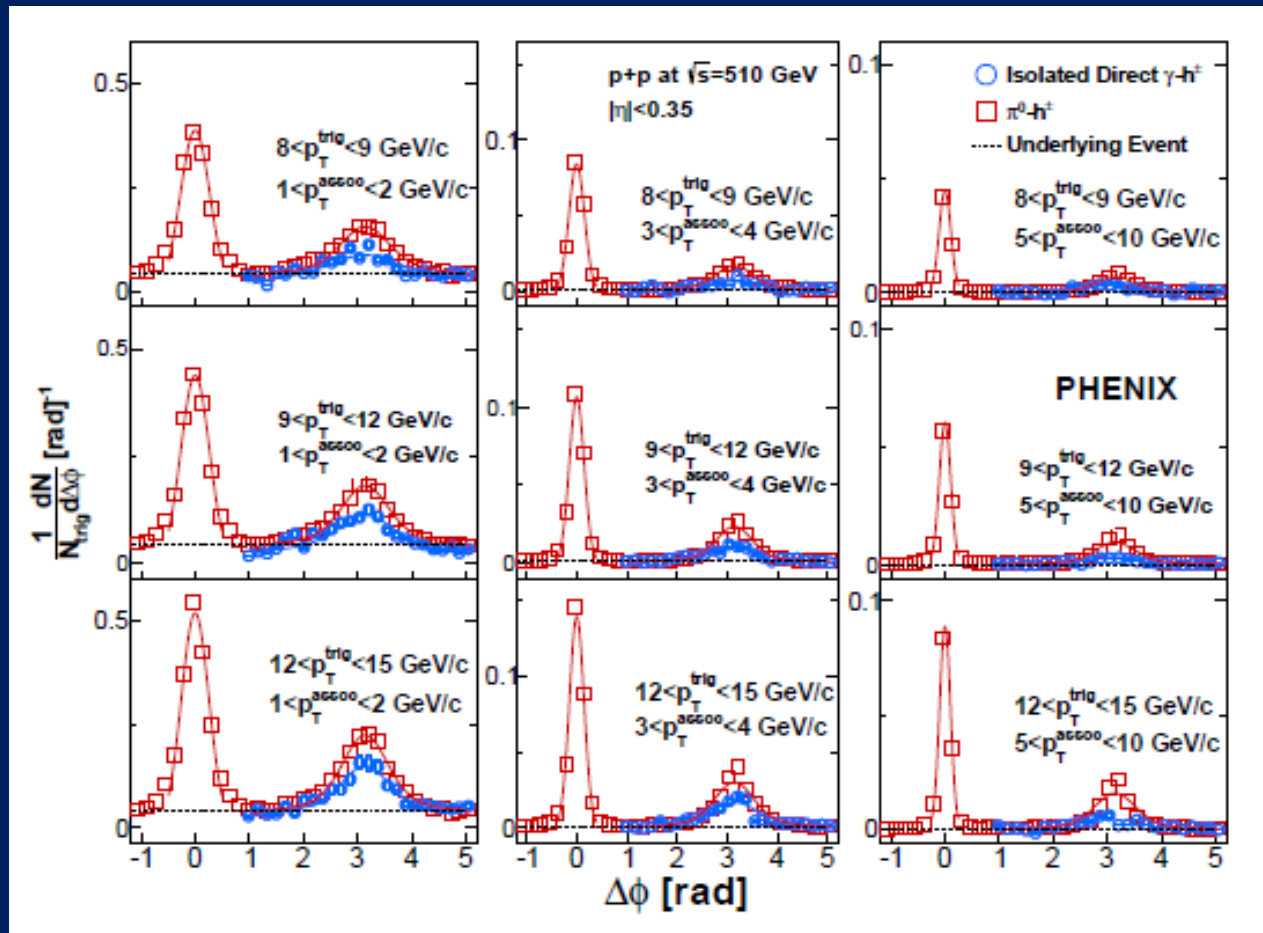
Quark-gluon Compton scattering still dominates at NLO - PLB140, 87 (1984)

PHENIX Collab., arXiv:1609.04769,  
Submitted to PRD.  
Calculation by T. Kaufmann





# Two-particle correlation distributions show expected jet-like structure



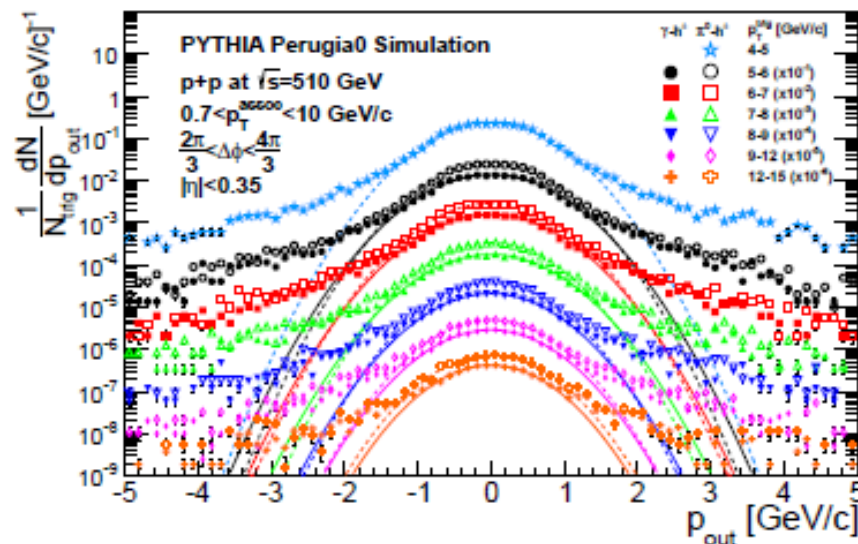
PRD95, 072002 (2017)

Christine Aidala, CENPA Seminar, 2/1/18



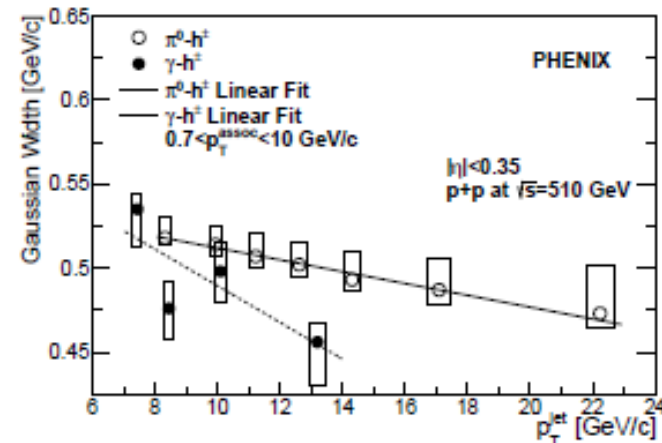
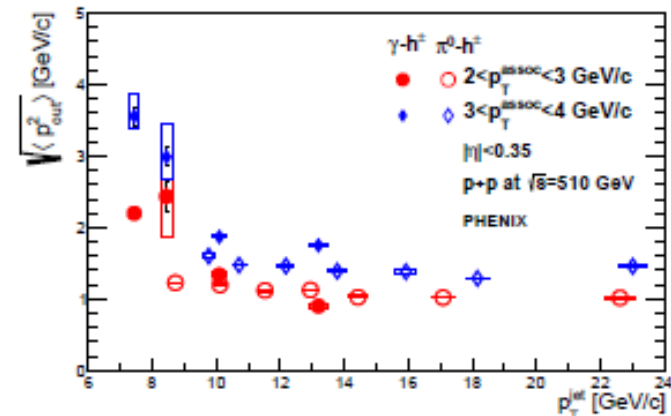
# PYTHIA $p_{out}$ distributions

- PYTHIA  $\pi^0$ - $h^\pm$  and isolated  $\gamma$ - $h^\pm$  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



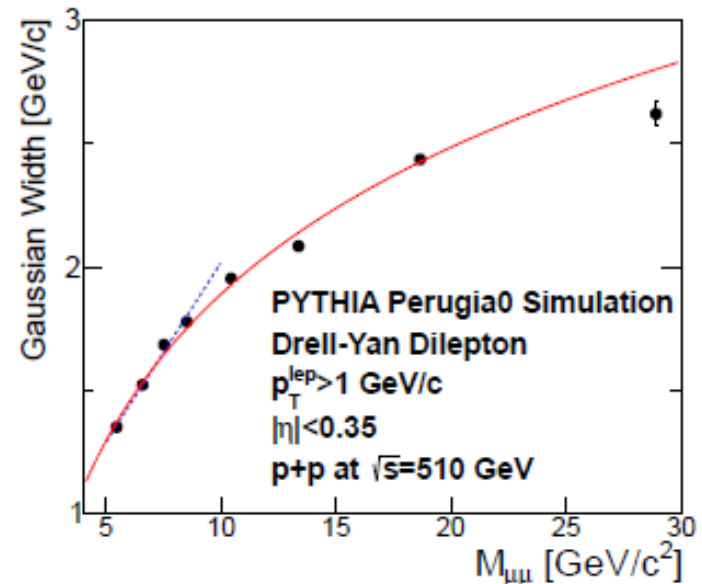
# PYTHIA $\langle z_T \rangle$ Correction

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



# 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

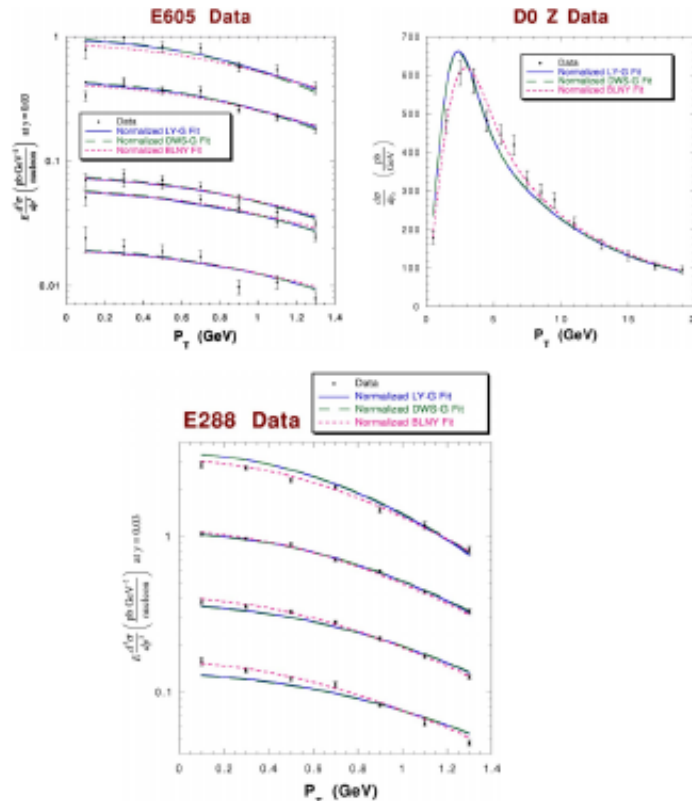


- Note rate of increase is significantly larger in magnitude also
- Red solid line shows log fit, blue dotted line shows linear fit

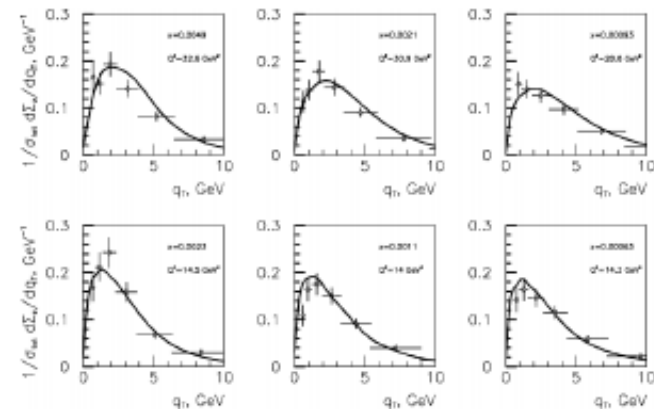
# Nonperturbative momentum measurements in Drell-Yan and Z production

Other DY/Z and SIDIS Refs.

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

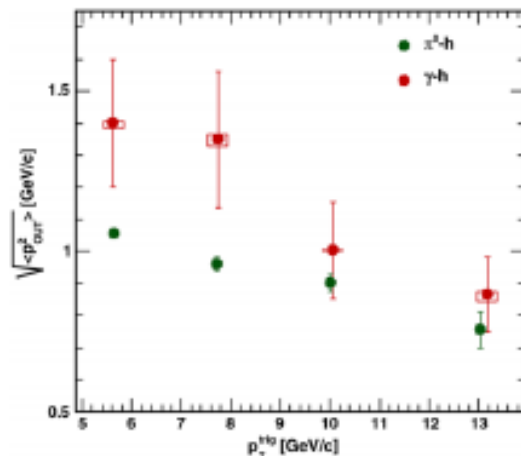


Phys. Rev. D 61, 014003 (2000)  
(SIDIS)



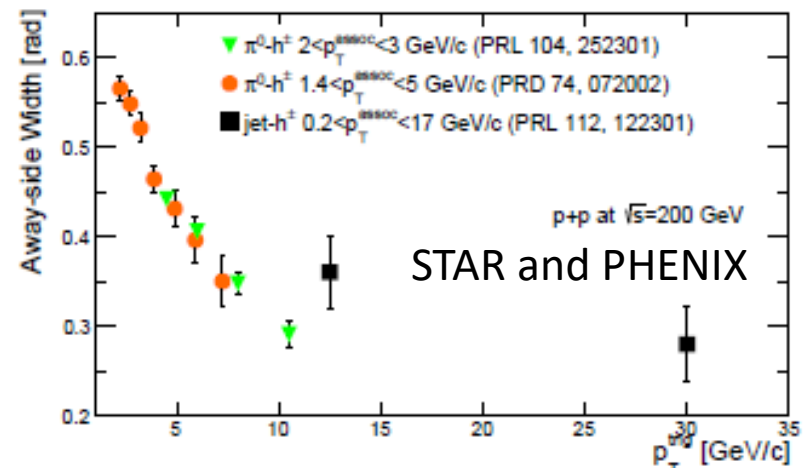
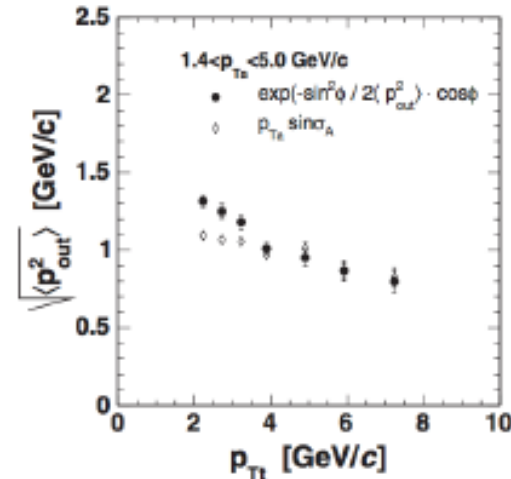
# Other measurements showing decreasing nonperturbative momentum widths

- 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 82, 072001 (2010) (PHENIX)

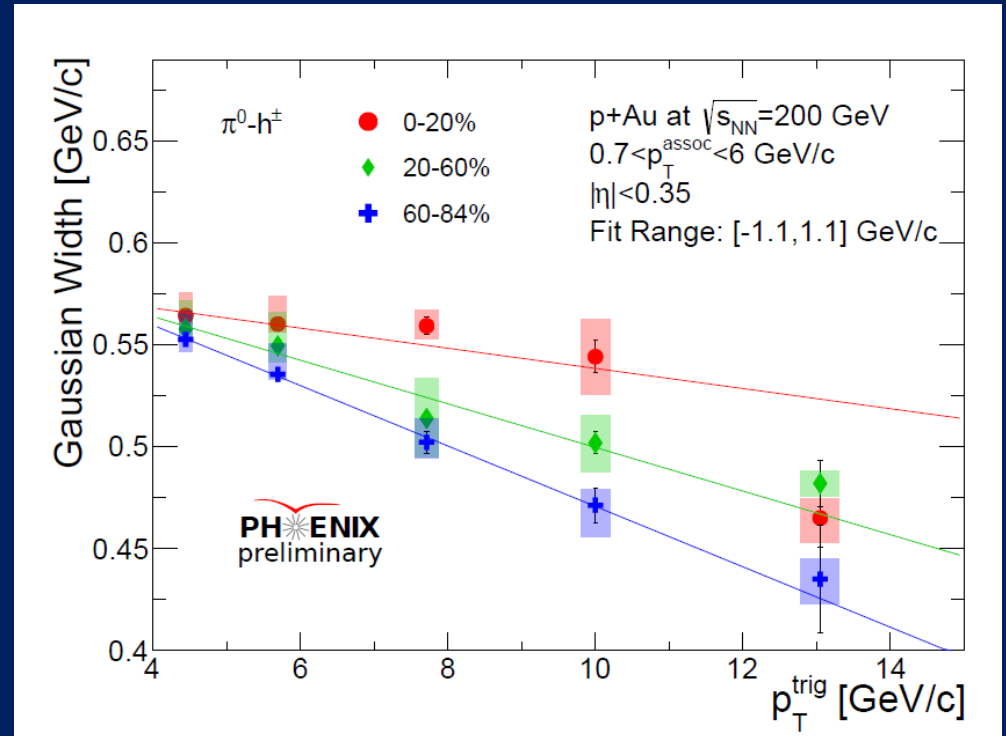
PRD 74, 072002 (2006) (PHENIX)





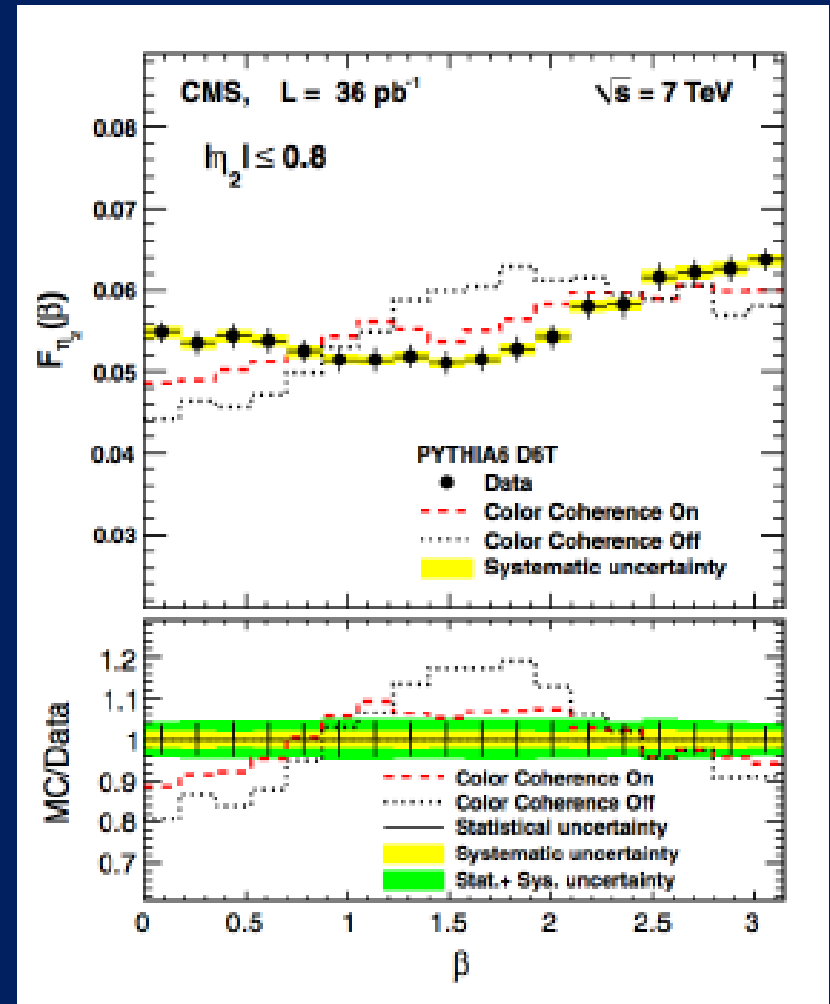
# Nuclear effects?

- Do stronger color fields lead to modified factorization breaking effects?
- p+Au shows steepest decreasing slope for most peripheral events—why??



# Links to “color coherence” at Tevatron and LHC?

- D0, CDF, CMS have all published 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!





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

## Box 1. Types and duals

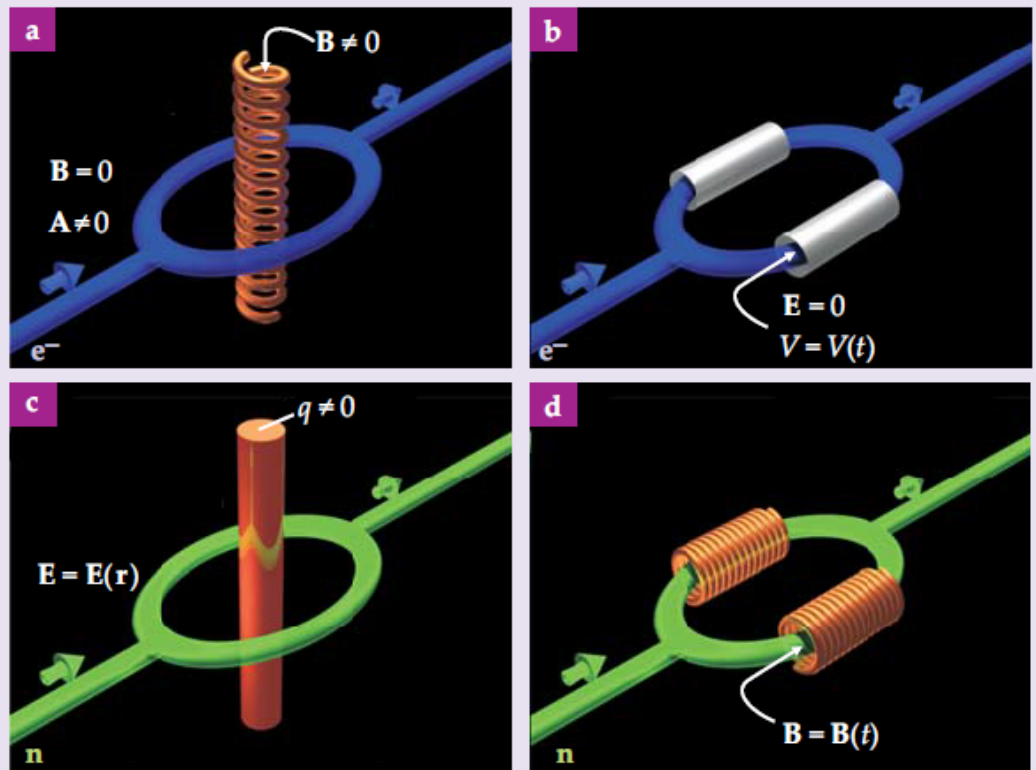
Physics Today, September 2009

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  $\mathbf{B}$  or  $\mathbf{E}$  fields, though it does traverse different potentials  $\mathbf{A}$  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.<sup>10</sup> 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  $\mathbf{E}$  or  $\mathbf{B}$  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  $2\pi$ . An alternative view is that the original magnetic AB effect shows electromagnetic fields acting nonlocally.<sup>1</sup>

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

