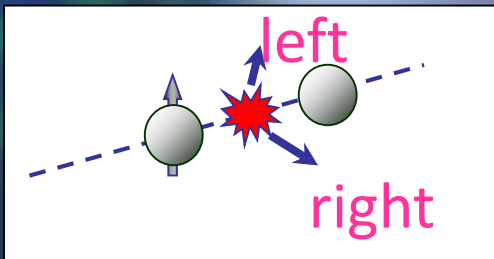


# *Spin-Momentum Correlations, Aharonov-Bohm, and Color Entanglement in Quantum Chromodynamics*

*Christine A. Aidala  
University of Michigan*



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

Colloquium  
University of Pavia  
January 30, 2020

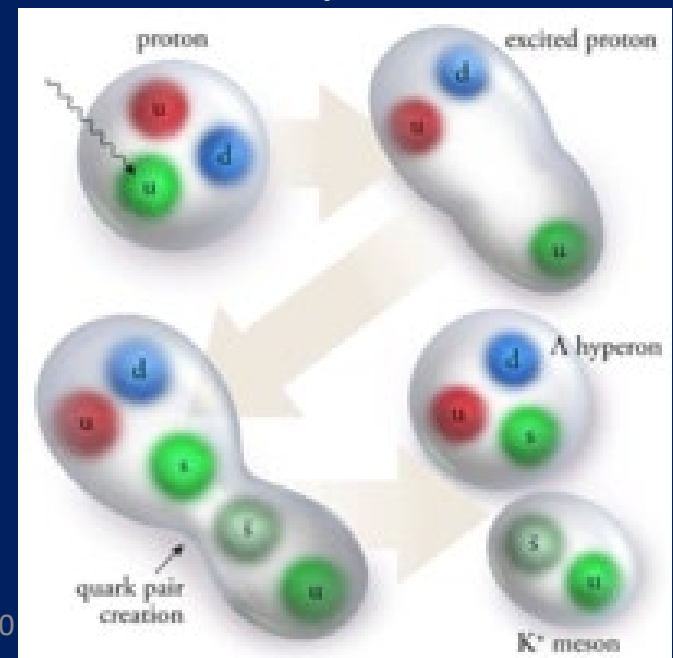
# *Theory of strong nuclear interaction: Quantum Chromodynamics*

- 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

Christine Aidala, Pavia, 30 Jan 2020



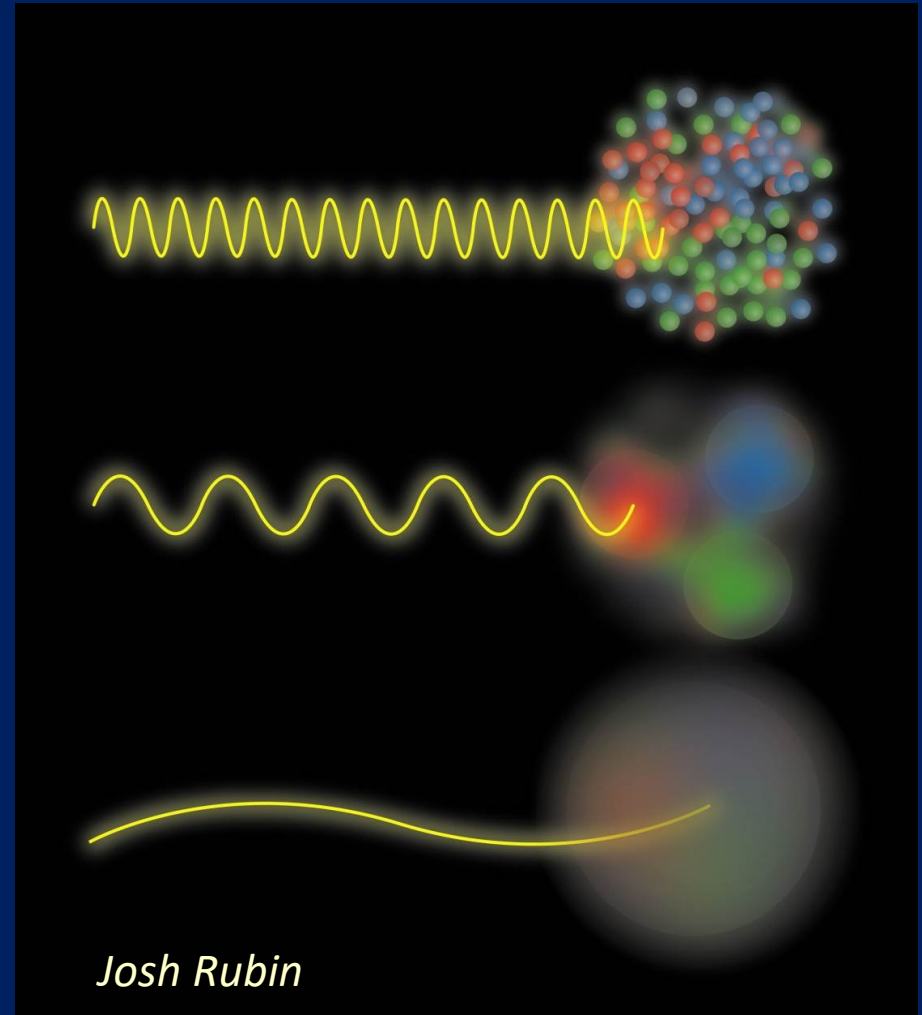
*How do we understand the visible matter  
in our universe in terms of the quark  
and gluon degrees of freedom of  
quantum chromodynamics?*

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



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

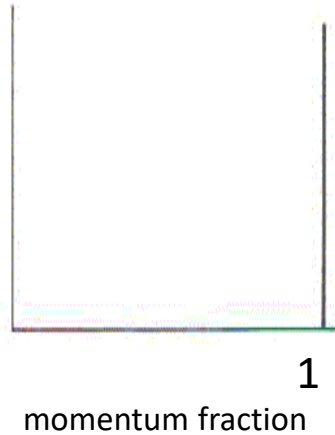
- Proton: simplest stable QCD bound state
- Different energy scales offer information on different aspects of proton internal structure



# *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

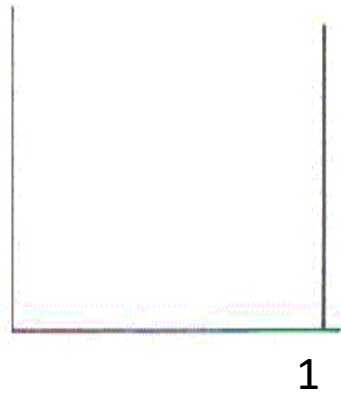


Halzen and Martin, "Quarks and Leptons", p. 201  
Christine Aidala, Pavia, 30 Jan 2020

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

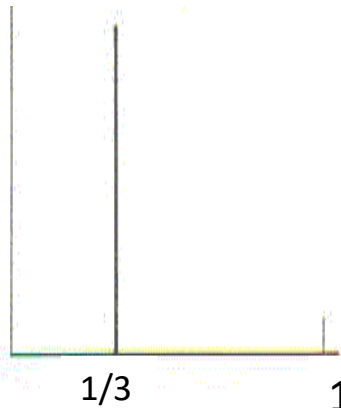
What momentum fraction would the scattering particle carry if the proton were made of ...

A point-like  
particle



momentum fraction

3 valence quarks



momentum fraction

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

Christine Aidala, Pavia, 30 Jan 2020

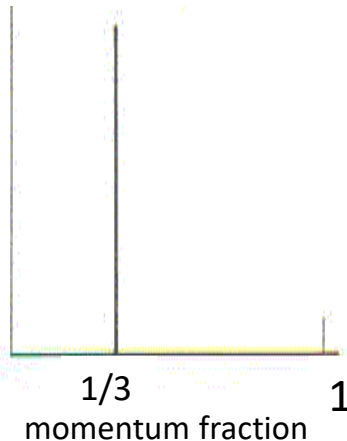
# *Quark distribution functions inside the proton: The language we've developed (so far!)*

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

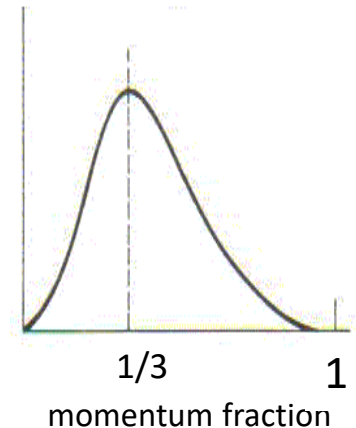
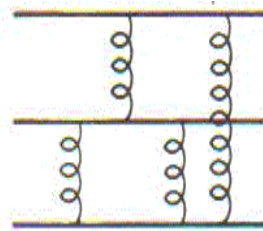
A point-like  
particle



3 valence quarks



3 bound valence quarks



# 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



1

momentum fraction

3 valence quarks

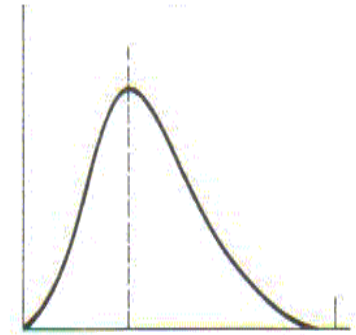
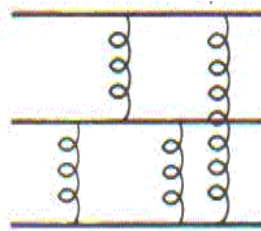


1/3

momentum fraction

1

3 bound valence quarks

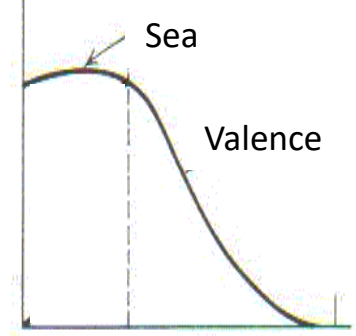
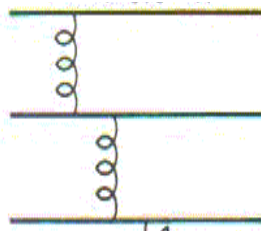


1/3

1

momentum fraction

3 bound valence quarks + some  
low-momentum sea quarks



1/3

1

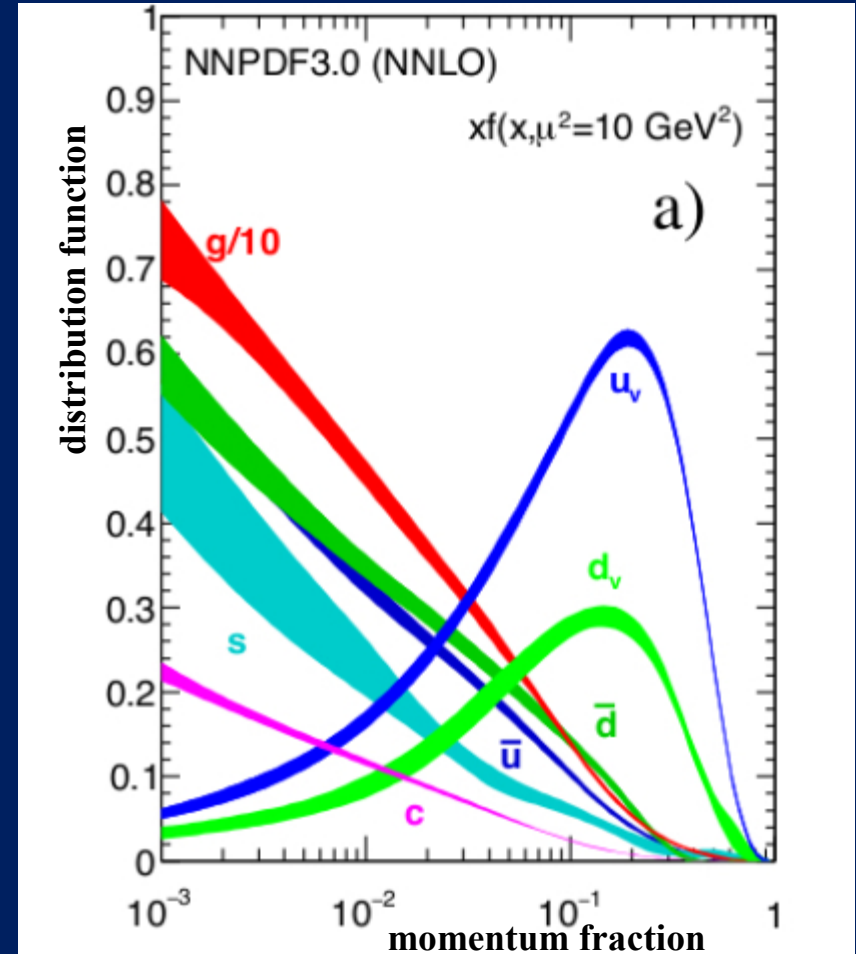
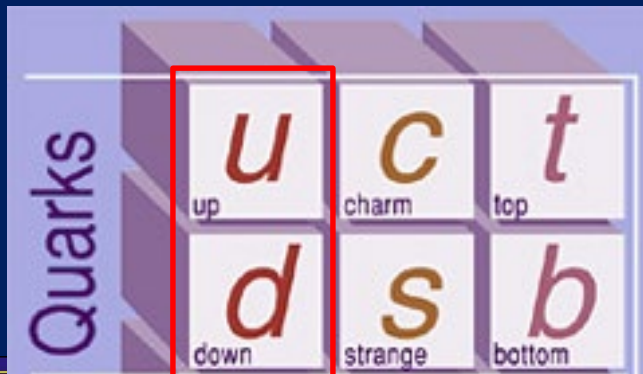
momentum fraction

small  
momentum



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

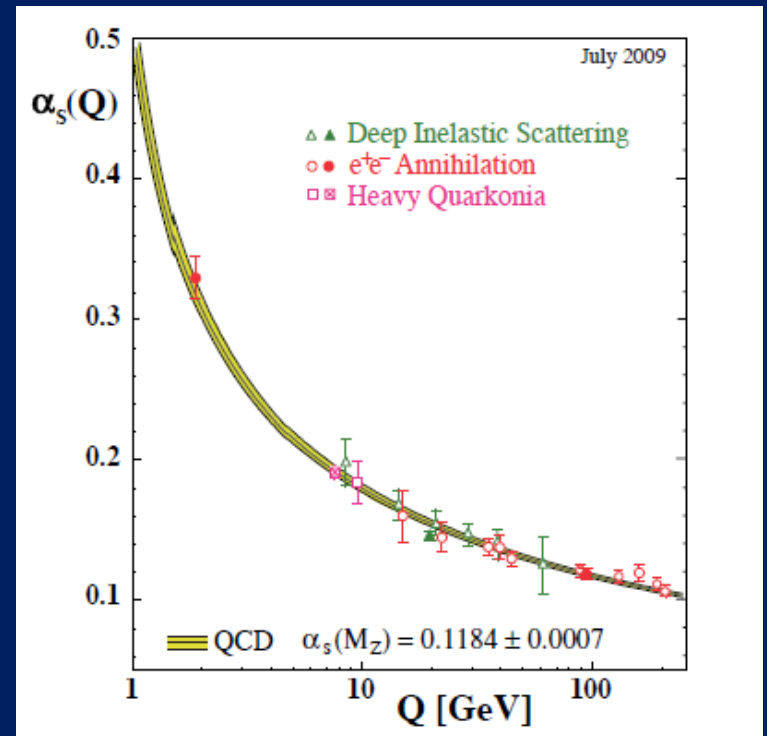
- Up and down quark “valence” distributions peaked  $\sim 1/3$
- Lots of sea quark-antiquark pairs and even more gluons!



EPJ C76, 647 (2016)

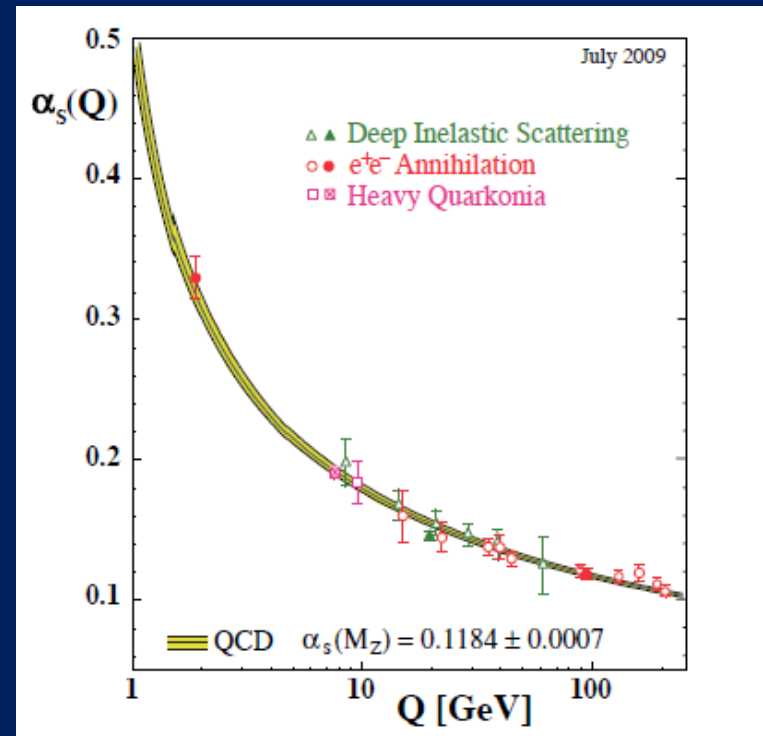
# Perturbative QCD

- 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*

# *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 perturbative) functions describing structure need
  - Physically meaningful description
  - Portable across calculations for many processes

Note: Nonperturbative lattice QCD techniques have made tremendous progress toward *ab initio* calculations of proton structure in last  $\sim 7$  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 five decades focused on *1-dimensional* momentum structure. Since 1990s starting to consider transverse components . . .



# *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*

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*

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

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

Good measurements of flavor distributions in valence region. Flavor structure for sea quarks still yielding surprises.





# *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*

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*

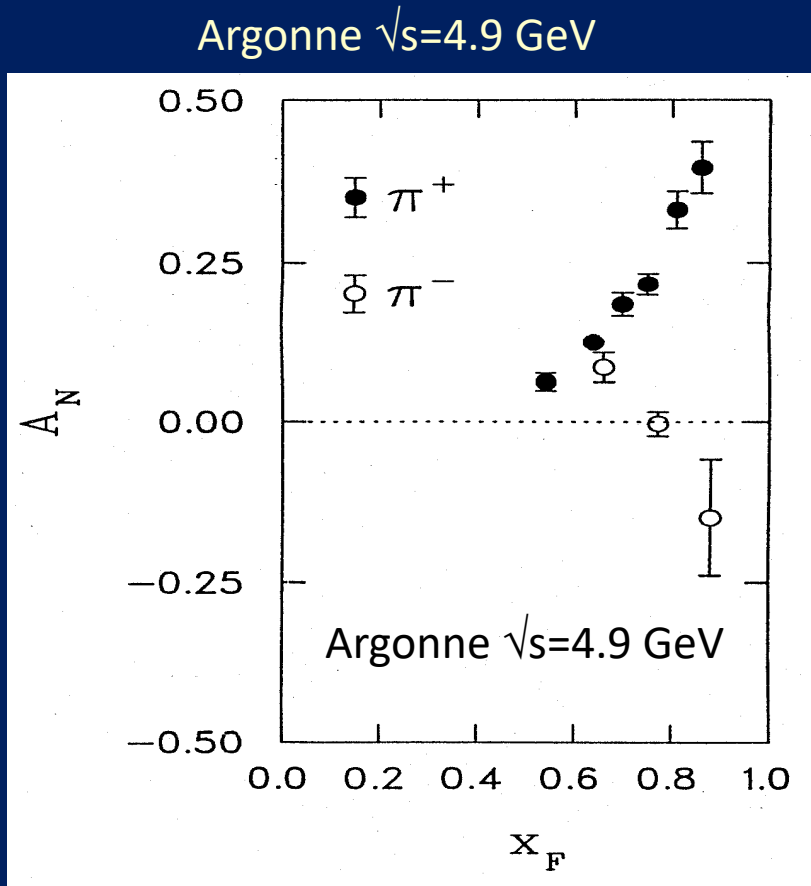
What does the proton look like in terms of the quarks and gluons inside it?

- *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 decade . . .



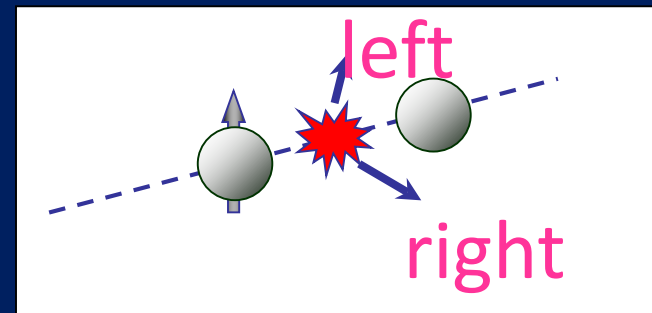
# Spin-momentum correlations: 1976 discovery in $p+p$ collisions



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

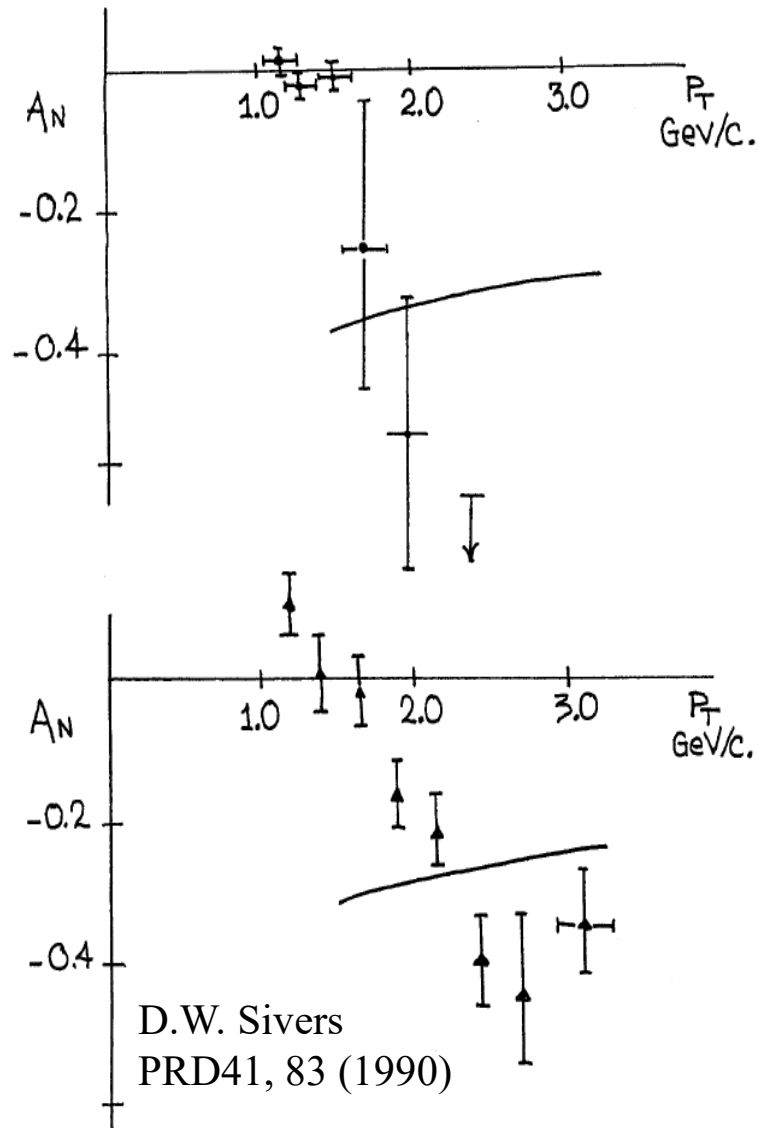


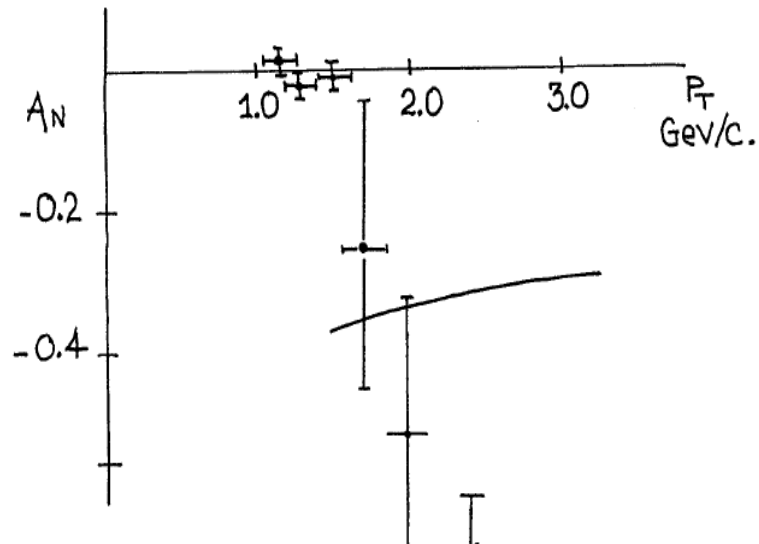
Fig. 1

- 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

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

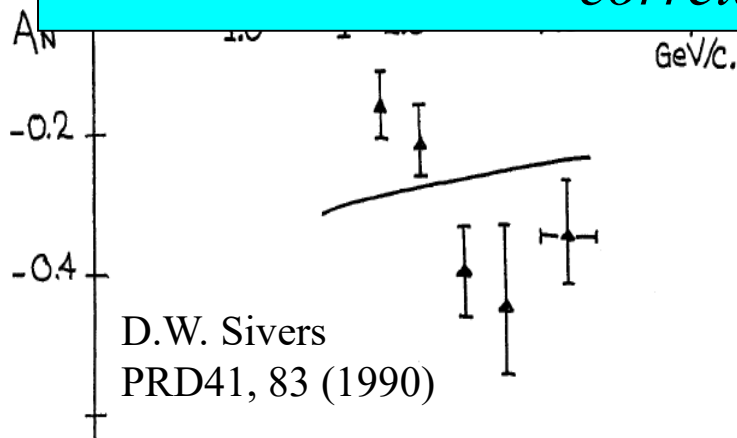
Spin and momenta of  
quarks and/or bound states

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



- 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

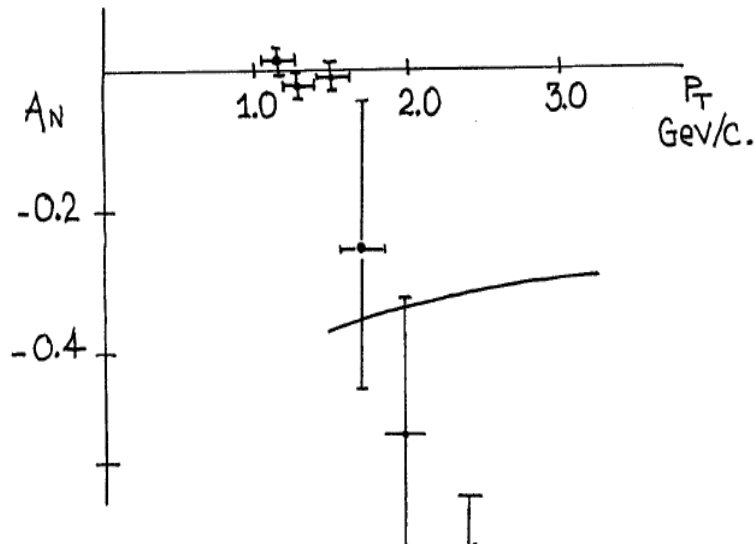
*First quark distribution function describing a spin-momentum correlation in the proton*



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

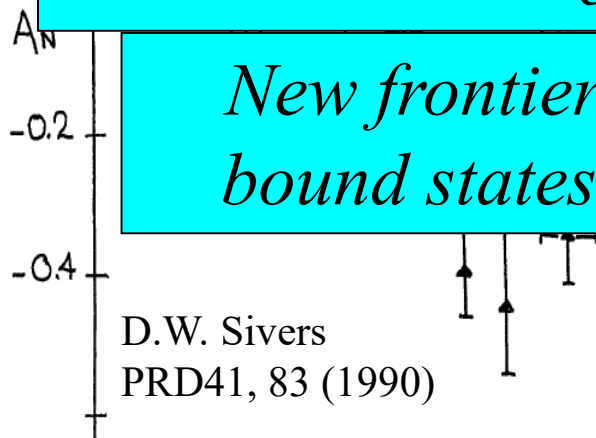
Spin and momenta of  
quarks and/or bound states

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



- 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

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



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

D.W. Sivers  
PRD41, 83 (1990)

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

Spin and momenta of  
quarks and/or bound states

# 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

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

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

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

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

# 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

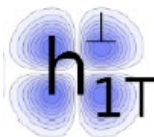
$$f_{1T}^{\perp} = \text{circle with up arrow} - \text{circle with down arrow} \quad \text{Sivers}$$

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

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

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

Pretzelosity





# 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)

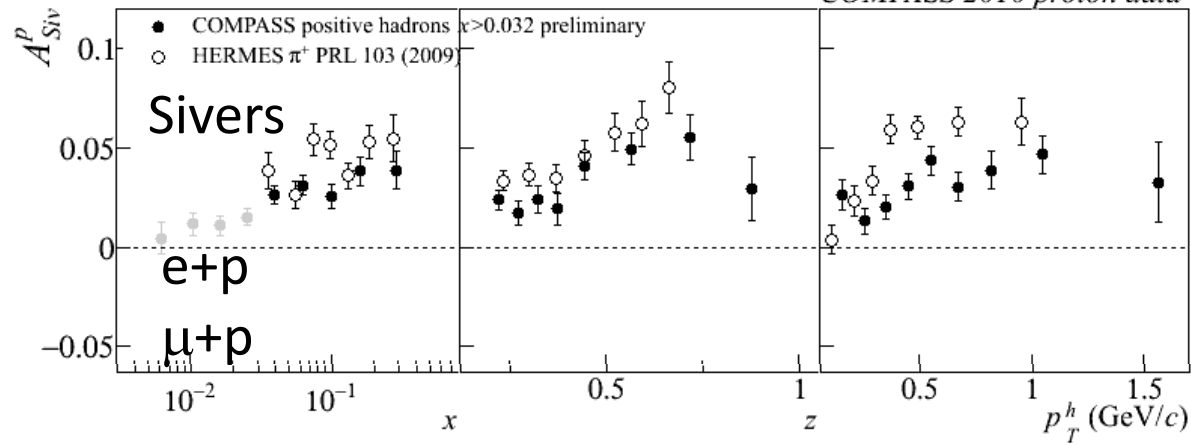
$$g_{1T} = \text{[Diagram: two circles with arrows pointing up]} - \text{[Diagram: two circles with arrows pointing down]} \quad \text{[Image: worm gear]$$

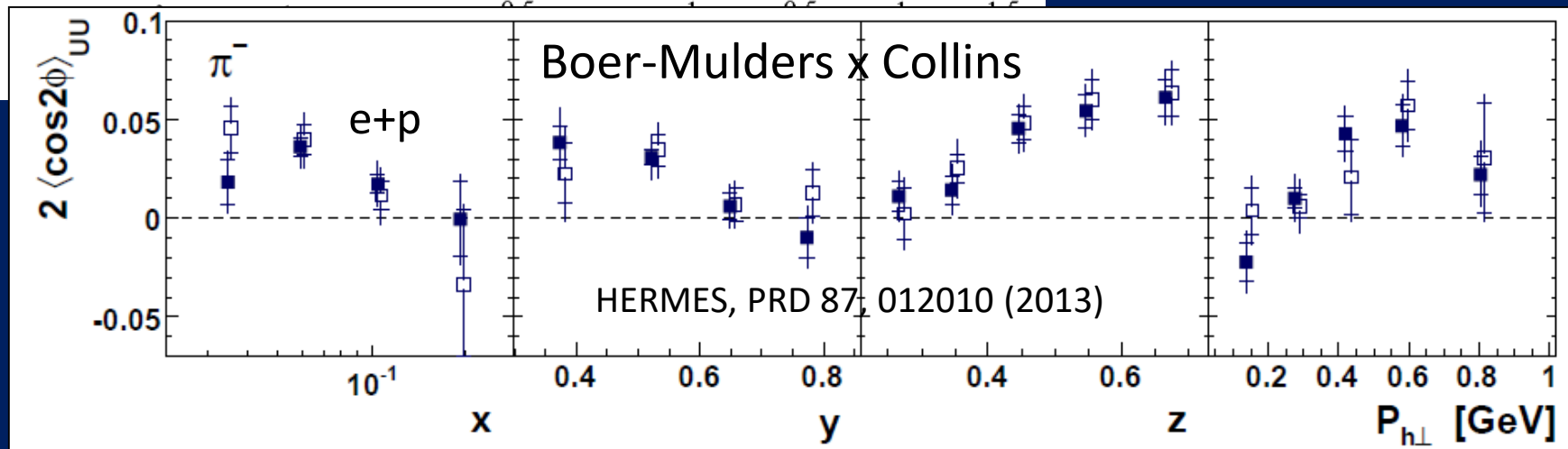
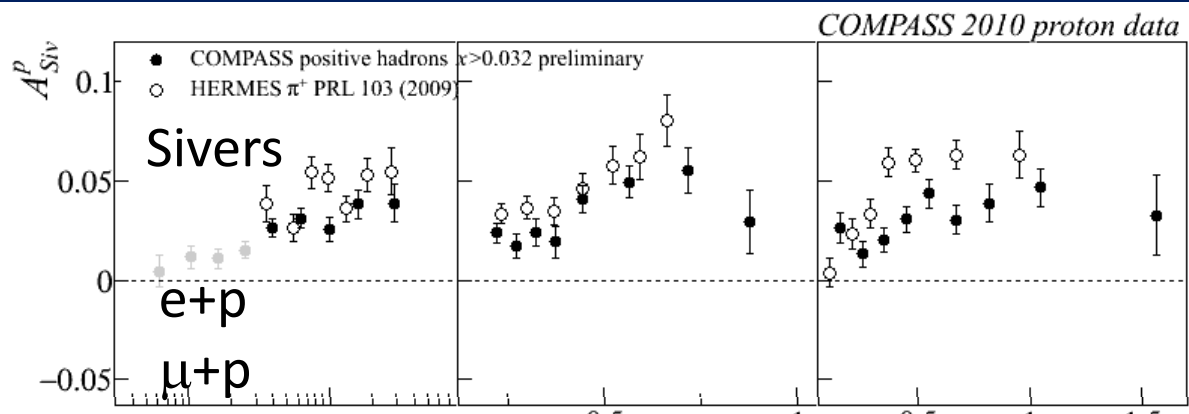
Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~15 years that many of these correlations are nonzero in nature!

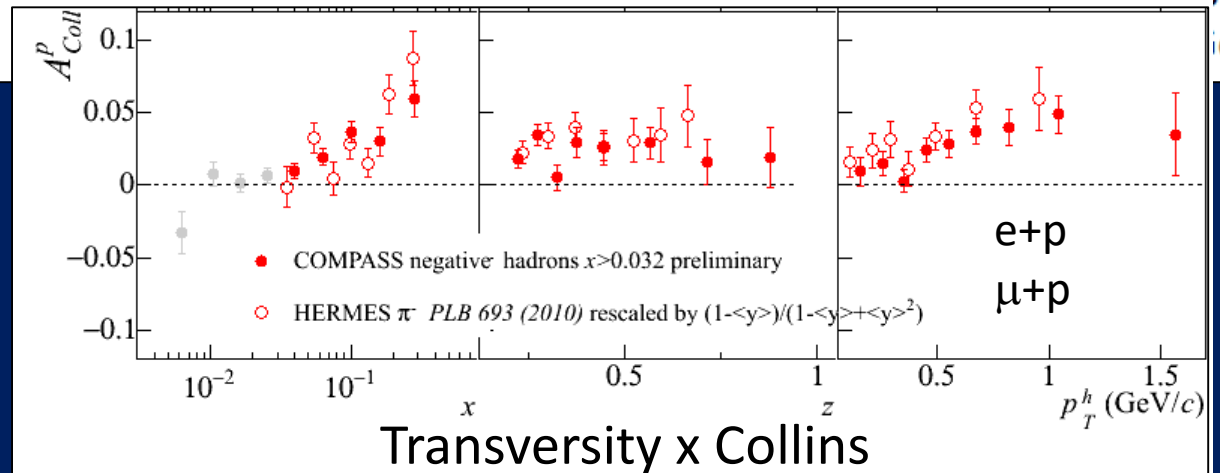
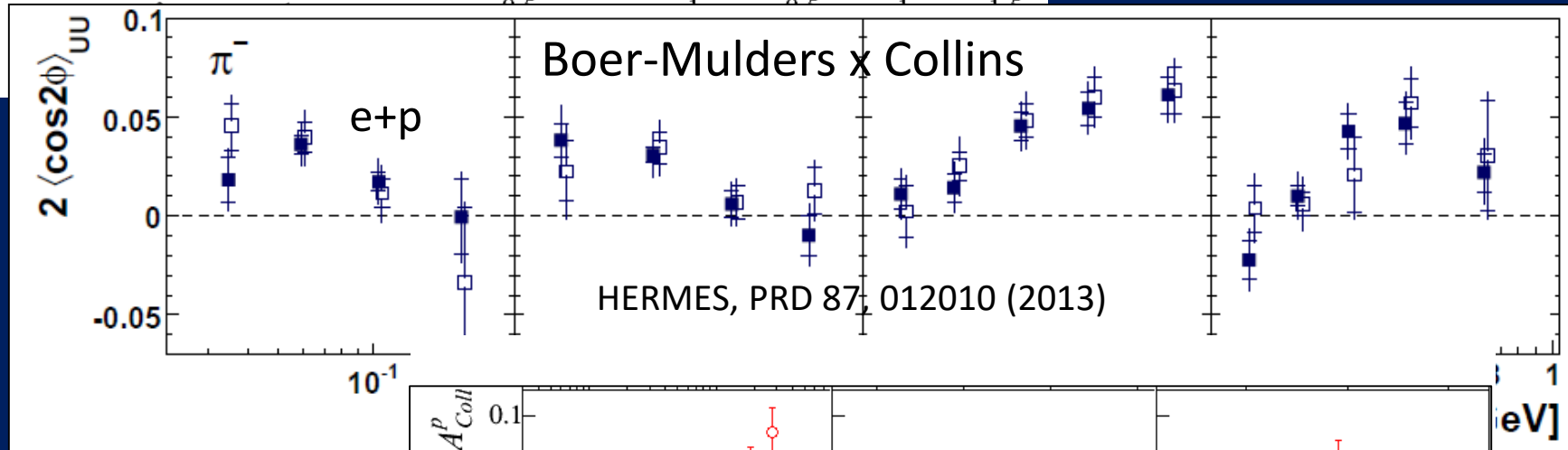
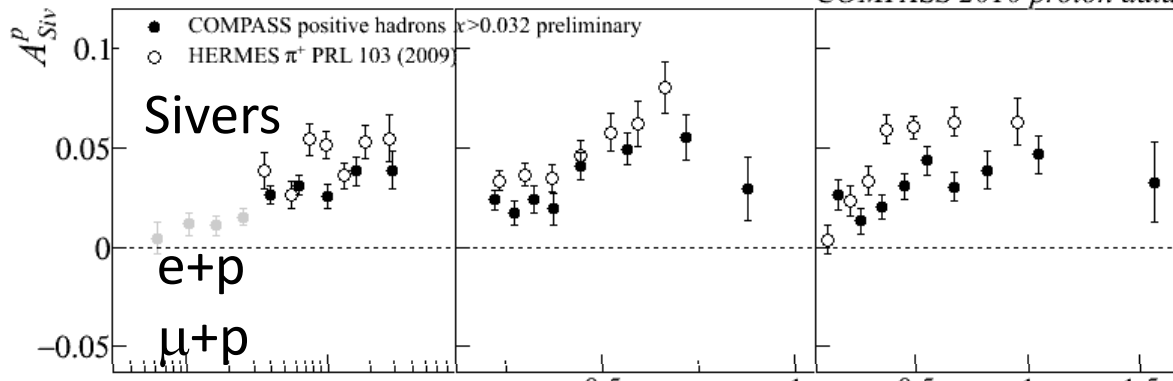
Spin-momentum correlations

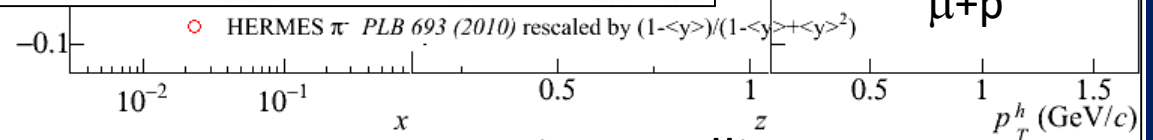
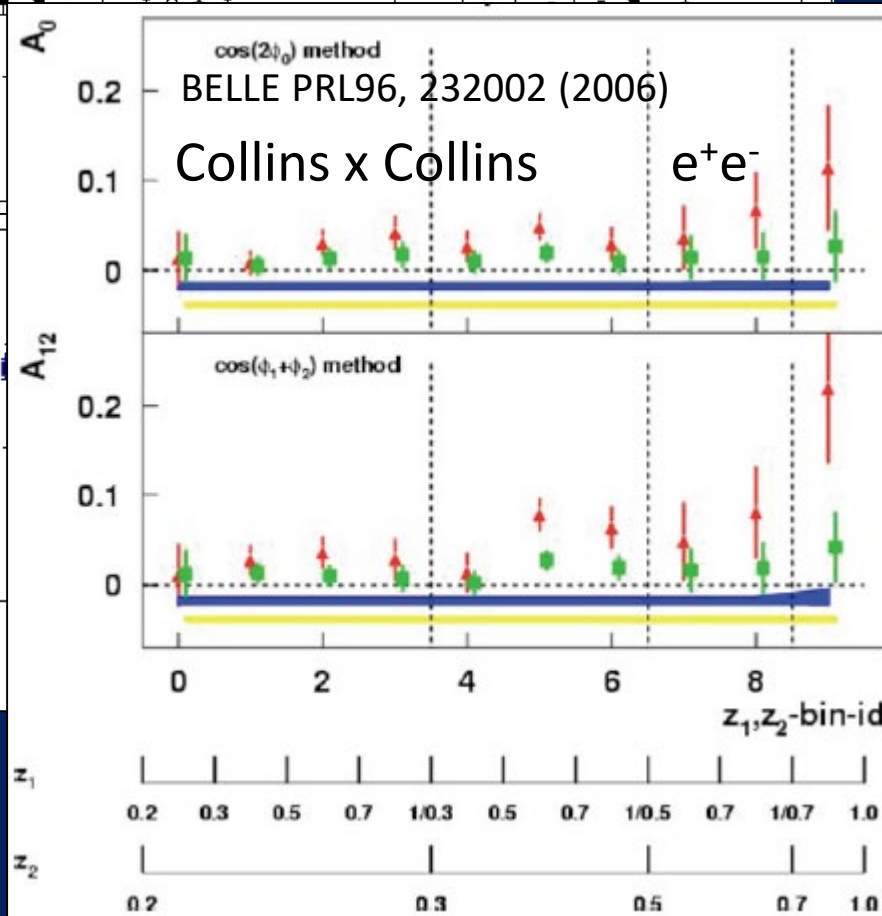
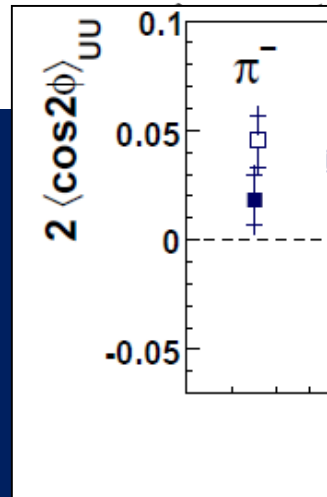
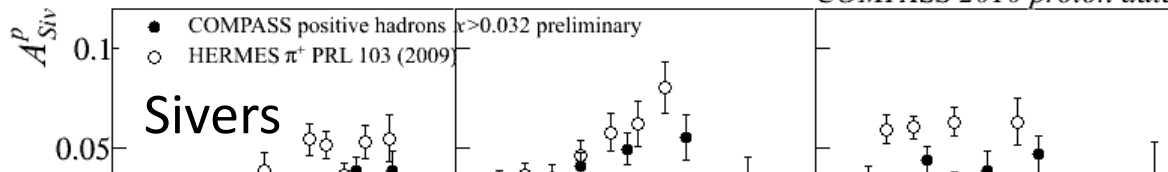
$$h_1^\perp = \text{[Diagram: circle with arrow pointing down]} - \text{[Diagram: circle with arrow pointing up]} \quad \text{Boer-Mulders}$$

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









Transversity x Collins

# First Extraction of Transversity from a Global Analysis of Electron-Proton and Proton-Proton Data

Marco Radici<sup>1,\*</sup> and Alessandro Bacchetta<sup>2,1,†</sup>

<sup>1</sup>INFN Sezione di Pavia, Via Bassi 6, I-27100 Pavia, Italy

<sup>2</sup>Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy

Physics Letters B 797 (2019) 134850

Contents lists available at ScienceDirect

Physics Letters B

[www.elsevier.com/locate/physletb](http://www.elsevier.com/locate/physletb)

ELSEVIER

Azimuthal asymmetries in unpolarized SIDIS and Drell-Yan processes: A case study towards TMD factorization at subleading twist

Alessandro Bacchetta<sup>a,b</sup>, Giuseppe Bozzi<sup>a,b</sup>, Miguel G. Echevarria<sup>b,\*</sup>, Cristian Pisano<sup>c,d</sup>, Alexei Prokudin<sup>e,f</sup>, Marco Radici<sup>b</sup>

<sup>a</sup> Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy

<sup>b</sup> INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy

<sup>c</sup> Dipartimento di Fisica, Università di Cagliari, Cittadella Universitaria, I-09042 Monserrato, CA, Italy

<sup>d</sup> INFN Sezione di Pavia, Cittadella Universitaria, I-09042 Monserrato, CA, Italy

<sup>e</sup> Science Division, Penn State University Berks, Reading, PA 19610, USA

<sup>f</sup> Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, USA

Transverse-momentum-dependent parton distributions up to N<sup>3</sup>LL from Drell-Yan data

PHYSICAL REVIEW D **100**, 054039 (2019)

Alessandro Bacchetta<sup>a,b</sup>, Valerio Bertone<sup>a,b</sup>, Chiara Bissolotti<sup>a,b</sup>, Giuseppe Bozzi<sup>c</sup>, Filippo Delcarro<sup>c</sup>, Fulvio Piacenza<sup>a,b</sup> and Marco Radici<sup>b</sup>

<sup>a</sup> Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia

<sup>b</sup> INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy

<sup>c</sup> Jefferson Lab, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA

E-mail: [alessandro.bacchetta@unipv.it](mailto:alessandro.bacchetta@unipv.it), [valerio.bertone@cern.ch](mailto:valerio.bertone@cern.ch), [chiara.bissolotti101@universitadipavia.it](mailto:chiara.bissolotti101@universitadipavia.it), [giuseppe.bozzi@unipv.it](mailto:giuseppe.bozzi@unipv.it), [delcarro@jlab.org](mailto:delcarro@jlab.org), [fulvio.piacenza01@universitadipavia.it](mailto:fulvio.piacenza01@universitadipavia.it), [marco.radici@pv.infn.it](mailto:marco.radici@pv.infn.it)

Revisiting model relations between  $T$ -odd transverse-momentum-dependent parton distributions and generalized parton distributions

Barbara Pasquini<sup>⊗,\*</sup>, Simone Rodini<sup>⊗,†</sup> and Alessandro Bacchetta<sup>‡</sup>

Dipartimento di Fisica, Università degli Studi di Pavia, I-27100 Pavia, Italy and Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, I-27100 Pavia, Italy



# *But what about proton-proton collisions?*

ANL

$\sqrt{s}=4.9$  GeV

BNL

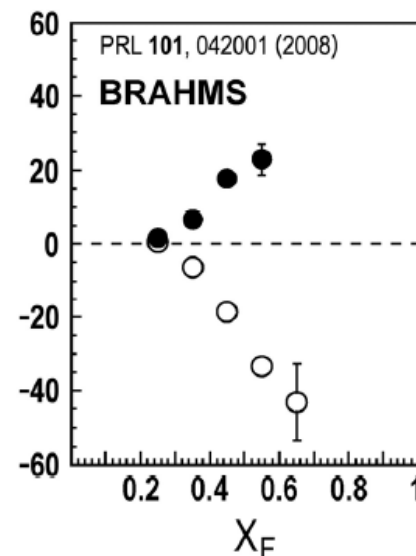
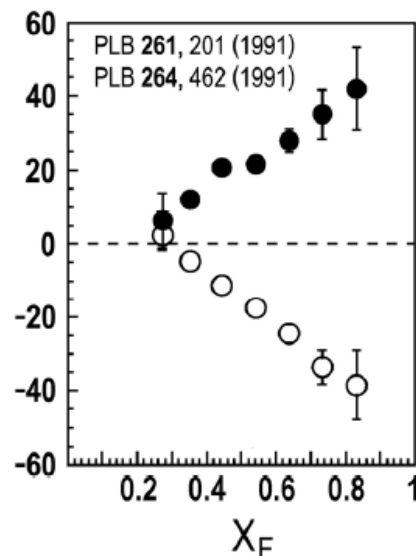
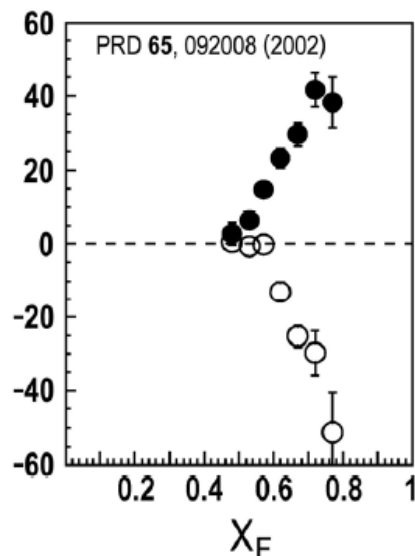
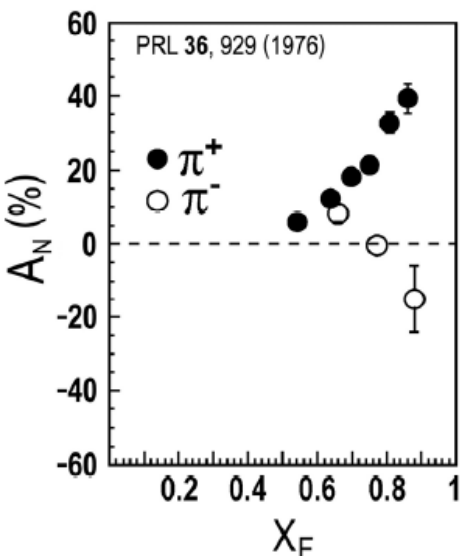
$\sqrt{s}=6.6$  GeV

FNAL

$\sqrt{s}=19.4$  GeV

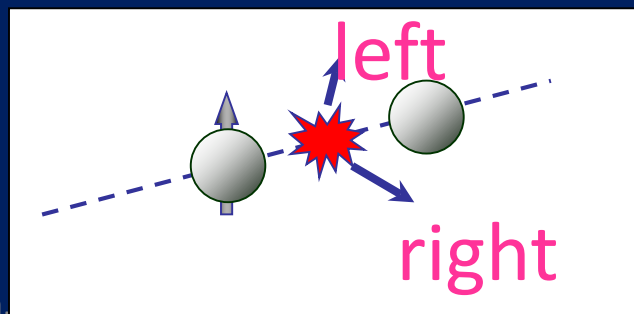
RHIC

$\sqrt{s}=62.4$  GeV



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

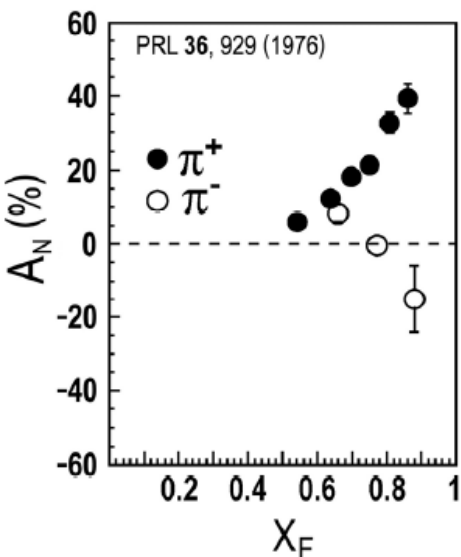
$$x_F = 2p_{long} / \sqrt{s}$$



# *But what about proton-proton collisions?*

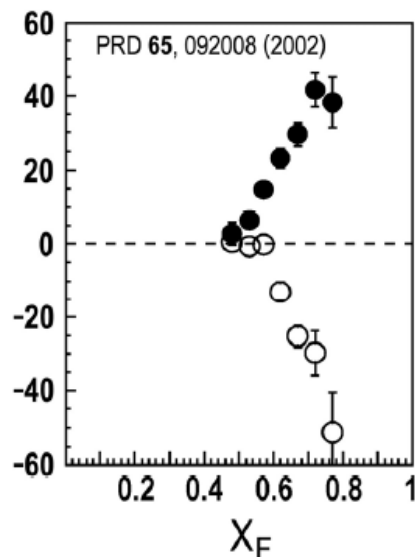
ANL

$\sqrt{s}=4.9$  GeV



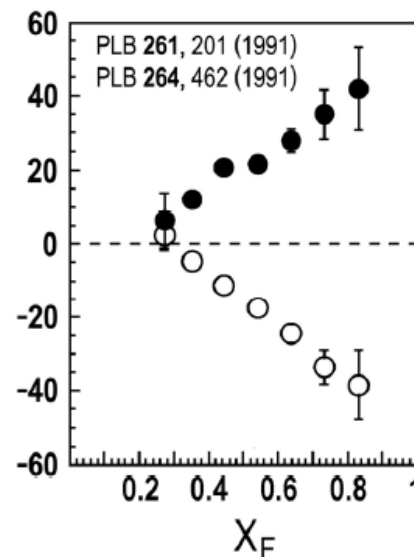
BNL

$\sqrt{s}=6.6$  GeV



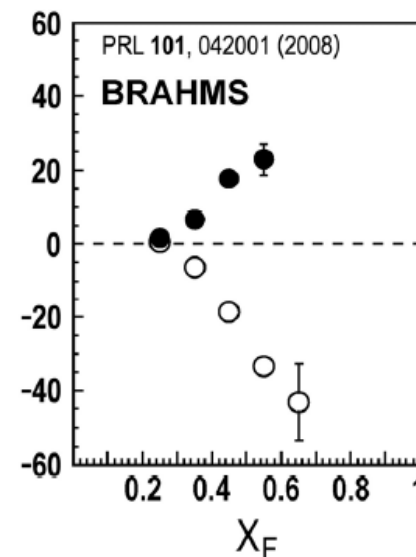
FNAL

$\sqrt{s}=19.4$  GeV



RHIC

$\sqrt{s}=62.4$  GeV



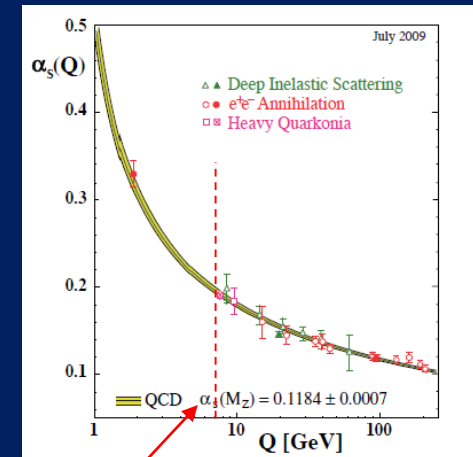
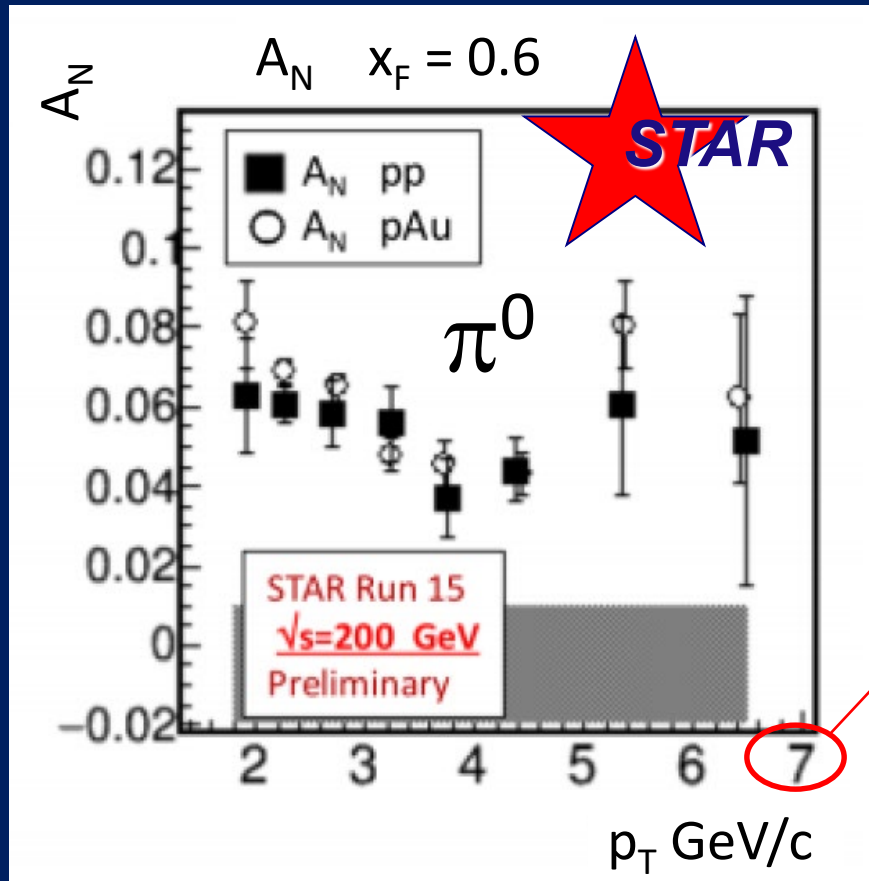
A

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

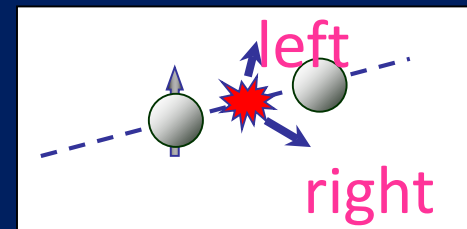
right



# 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 quark distribution functions odd under a parity- and time-reversal (PT) transformation



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

- Some transverse-momentum-dependent quark 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



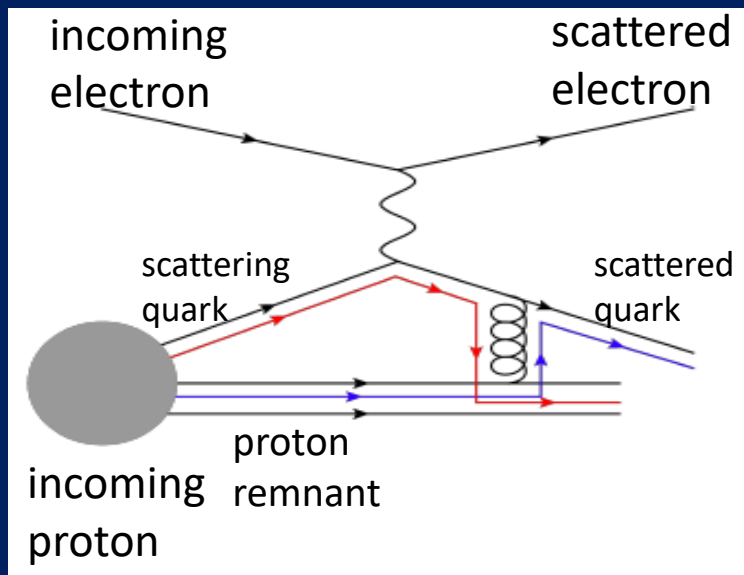
# *Different symmetry properties for different spin-momentum correlations*

- Some transverse-momentum-dependent quark 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

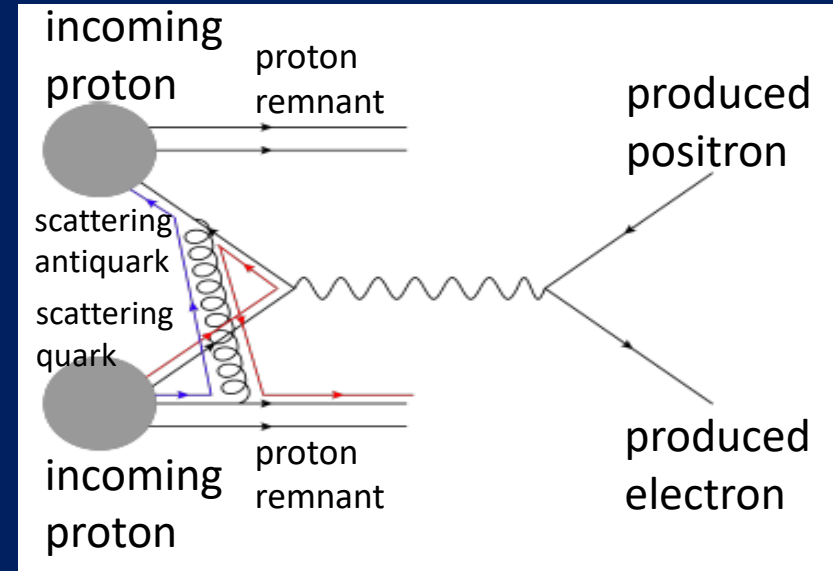


# Modified universality of $PT$ -odd correlations: *Color in action!*

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



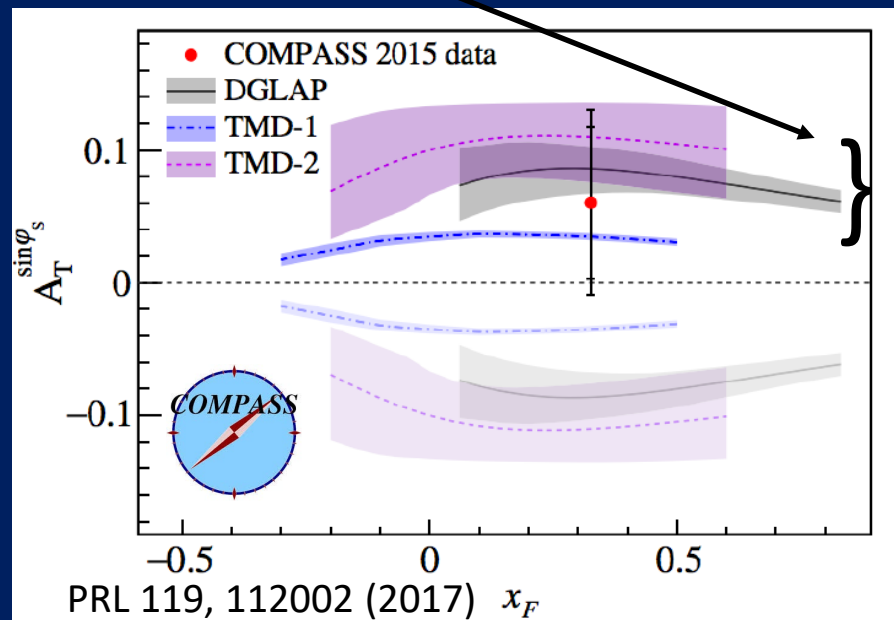
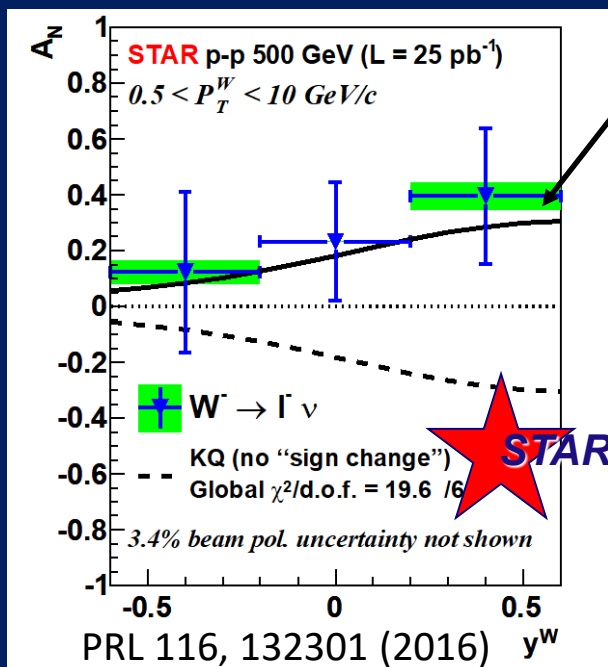
**Quark-antiquark annihilation to leptons: Initial-state color exchange**



***Opposite sign* for  $PT$ -odd spin-momentum correlations in the proton measured in these two processes:  
*process-dependent!* (Collins 2002)**

# Modified universality: Initial experimental hints

Predictions including  
sign change



*First measurements by STAR at the Relativistic Heavy Ion Collider and COMPASS at CERN suggestive of predicted sign change in color-annihilation processes compared to quark knock-out by a lepton.  
 More statistics forthcoming . . .*

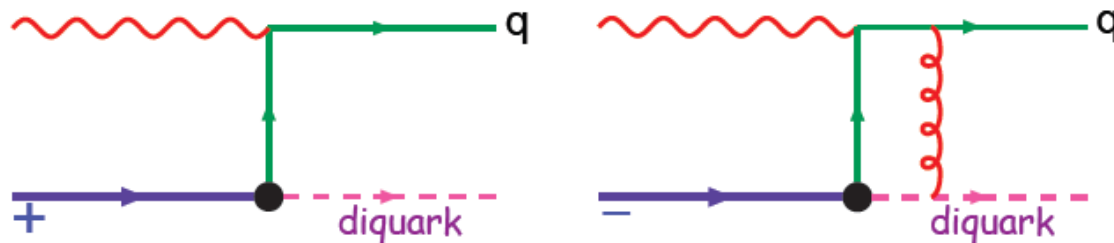
# Modified universality requires full QCD: Gauge-invariant quantum field theory

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 :**

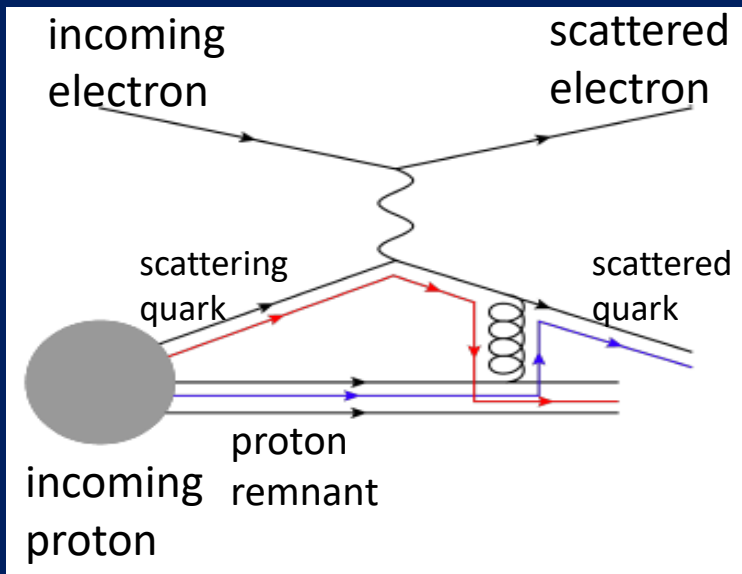
**The Aharonov–Bohm effects: Variations on a subtle theme,**  
by Herman Batelaan and Akira Tonomura.

“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.”

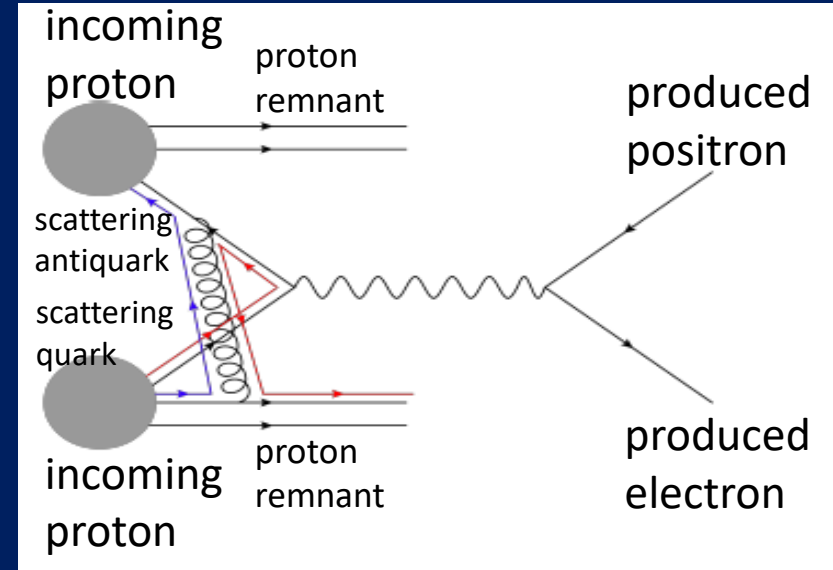


# *Physical consequences of a gauge-invariant quantum theory: an Aharonov-Bohm effect in QCD!*

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



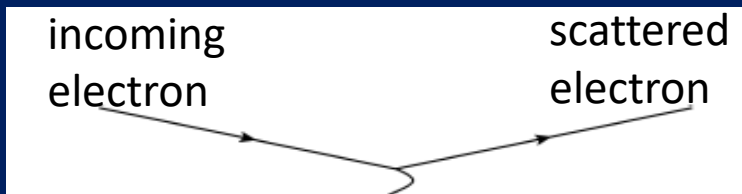
**Quark-antiquark annihilation to  
leptons: Initial-state color exchange**



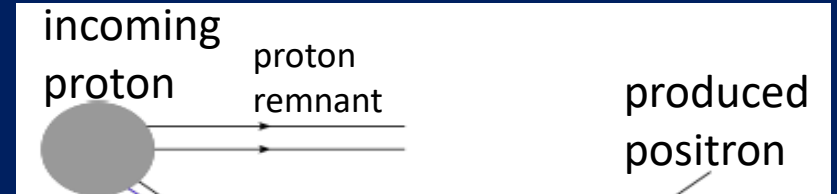
See e.g. Pijlman, hep-ph/0604226  
or Sivers, arXiv:1109.2521

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

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



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

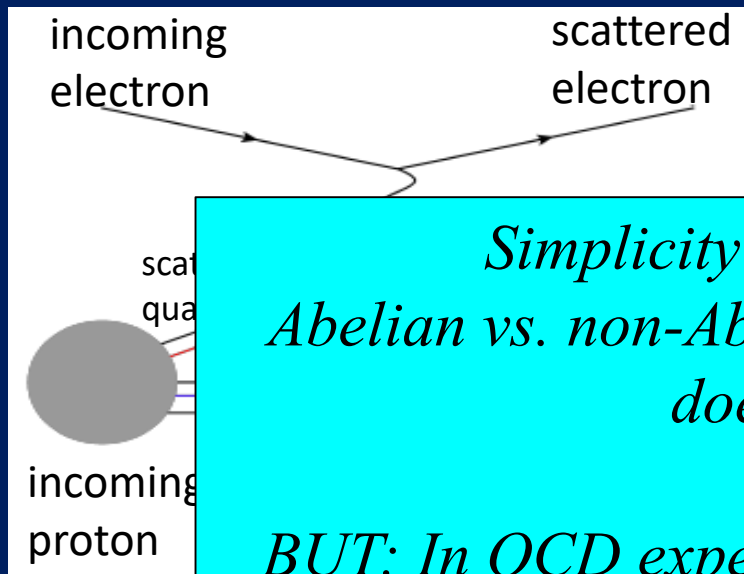


*Simplicity of these two processes:  
Abelian vs. non-Abelian nature of the gauge group  
doesn't play a role.*

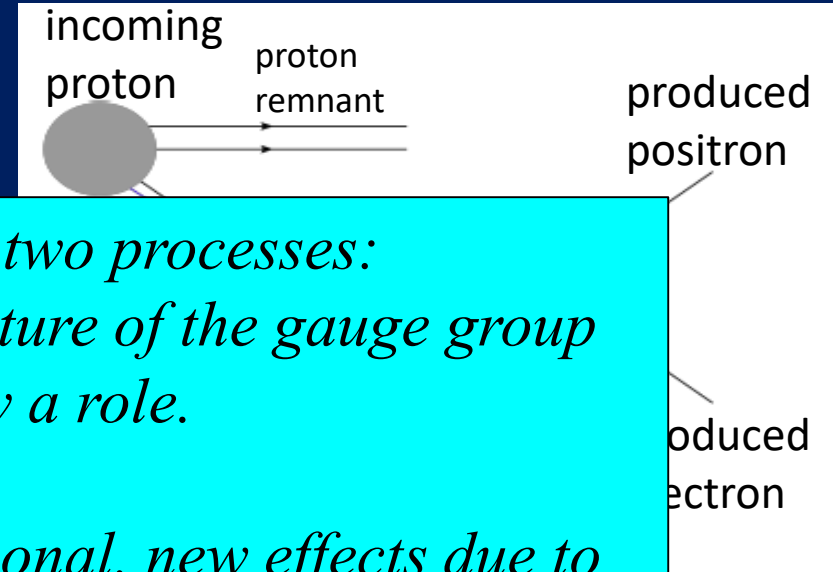
*Currently pursuing QED analog calculations with  
Dylan Manna, for PT-odd spin-momentum  
correlations in (boosted) hydrogen probed via elastic  
scattering vs. annihilation processes.*

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

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



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



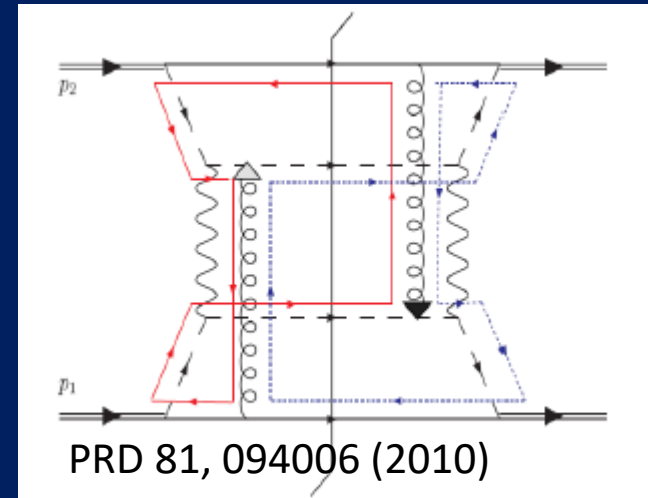
*Simplicity of these two processes:  
Abelian vs. non-Abelian nature of the gauge group  
doesn't play a role.*

*BUT: In QCD expect additional, new effects due to  
specific non-Abelian nature of the gauge group →  
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
  - Novel QCD state!
- Consequence of QCD specifically as a *non-Abelian* gauge theory



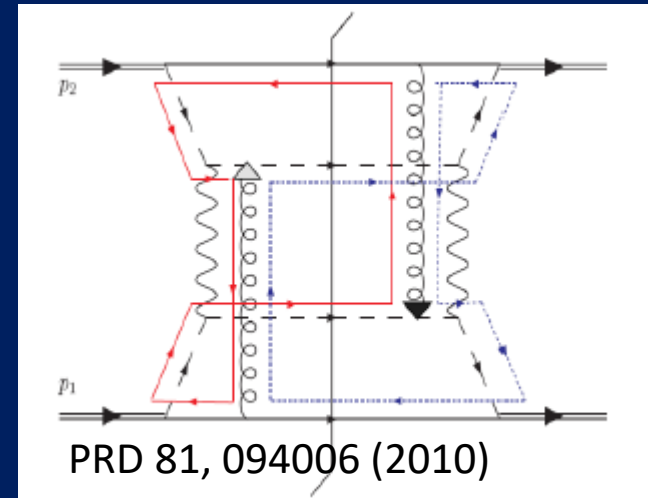
$$p + p \rightarrow h_1 + h_2 + X$$

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

# *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
  - Novel QCD state!
- Consequence of QCD specifically as a *non-Abelian* gauge theory



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

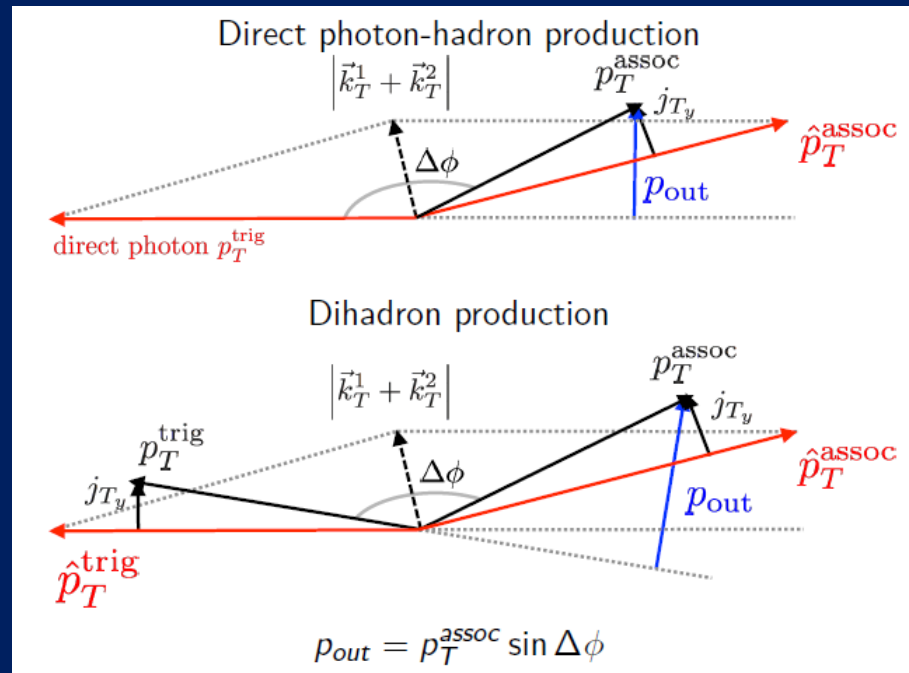
Color flow can't be described as flow in the two gluons separately. Requires presence of both.

*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



PHENIX Collaboration:  
 PRD95, 072002 (2017)  
 PRD98, 072004 (2018)  
 PRC99, 044912 (2019)

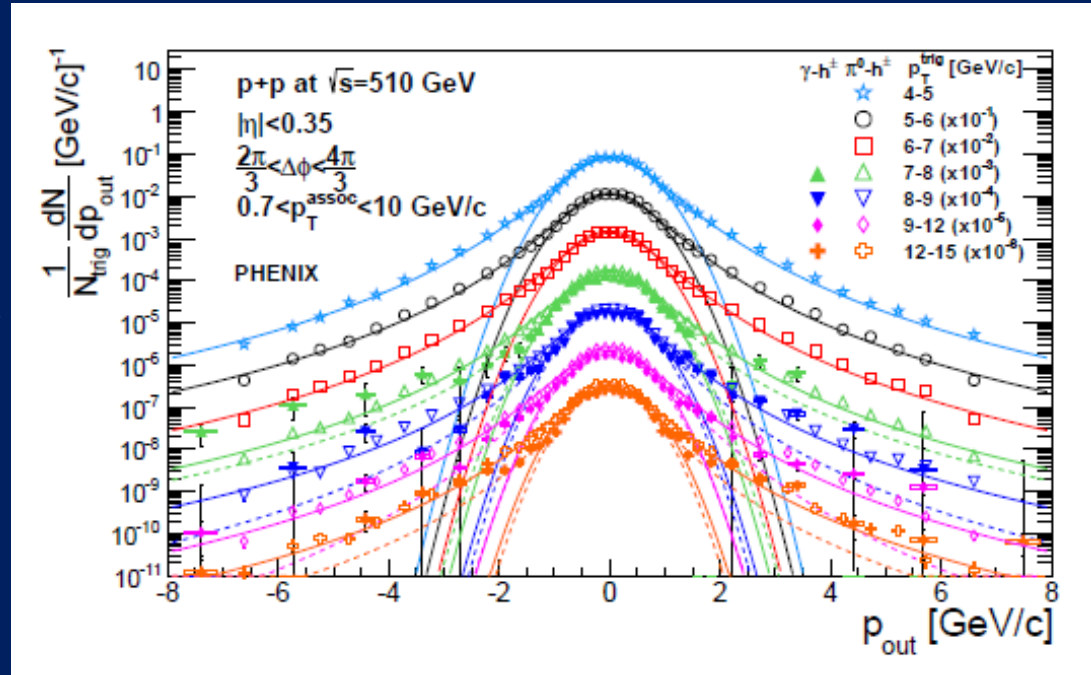




# Out-of-plane momentum component distributions

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

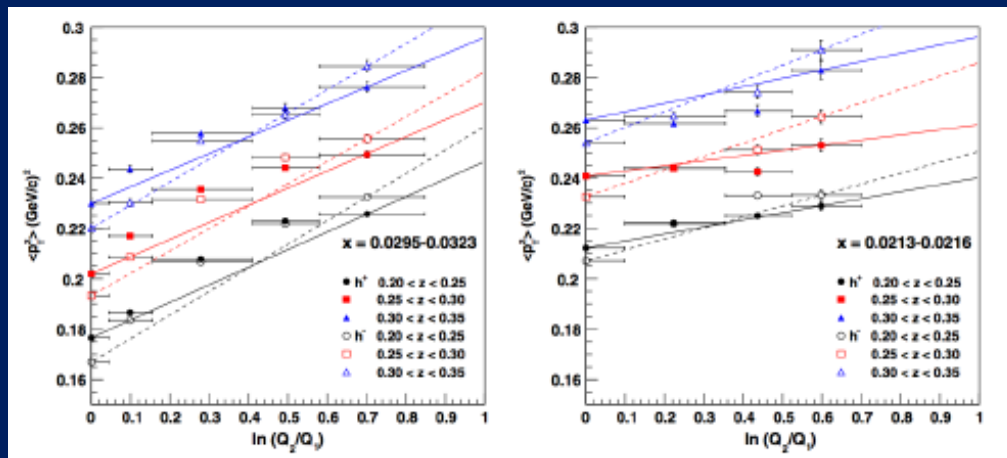
# *Look at **evolution** of nonperturbative transverse momentum widths with hard scale ( $Q^2$ )*

- Proof of factorization (i.e. no entanglement) directly predicts that nonperturbative transverse momentum widths *increase* with hard scattering energy scale
  - Increased phase space for gluon radiation

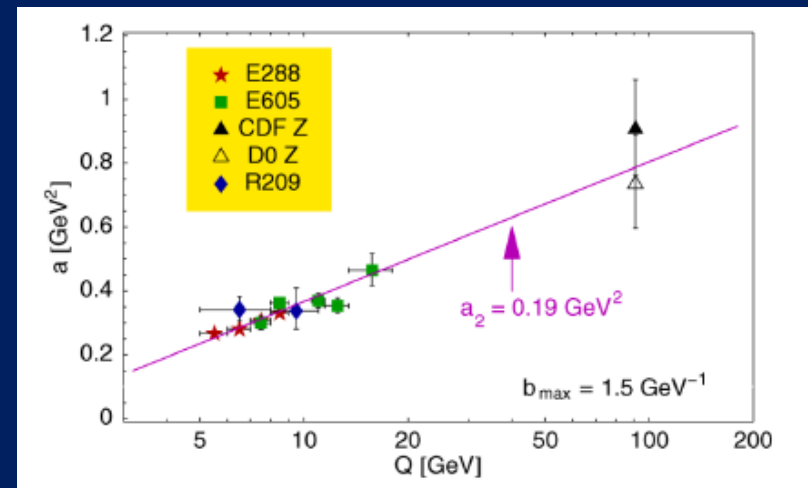


# Look at *evolution* of nonperturbative transverse momentum widths with hard scale ( $Q^2$ )

- Proof of factorization (i.e. no entanglement) directly predicts that nonperturbative transverse momentum widths *increase* with 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)

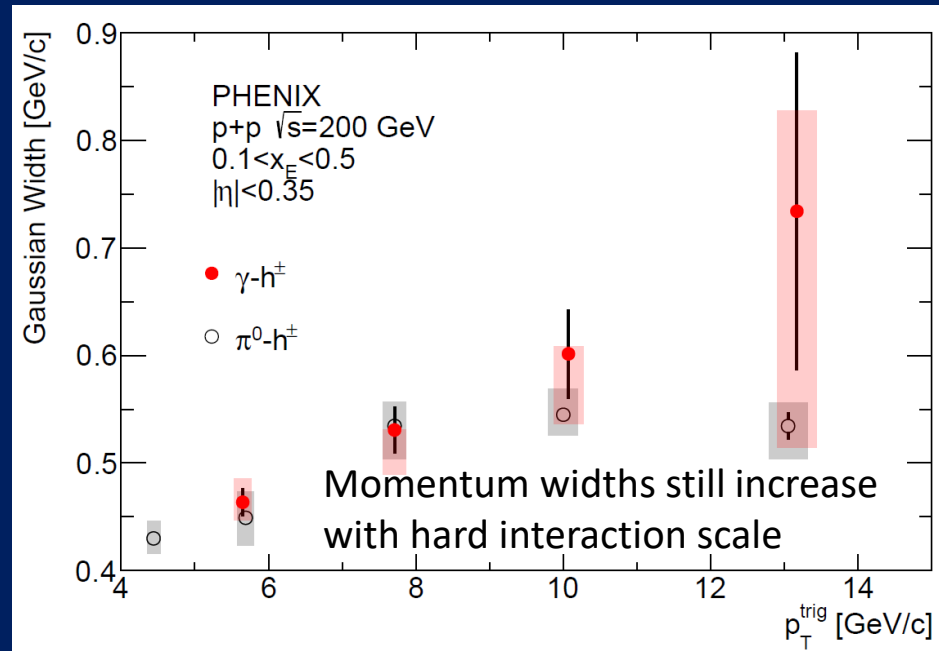


Konychev + Nadolsky, Phys. Lett. B633, 710 (2006)



# *So far see qualitatively similar trend where factorization predicted to be broken*

- Phenomenological calculations assuming factorization holds recently started here at Pavia
  - Search for *quantitative* deviations . . .
- Goal is to study factorization breaking and non-Abelian phenomena in a controlled way



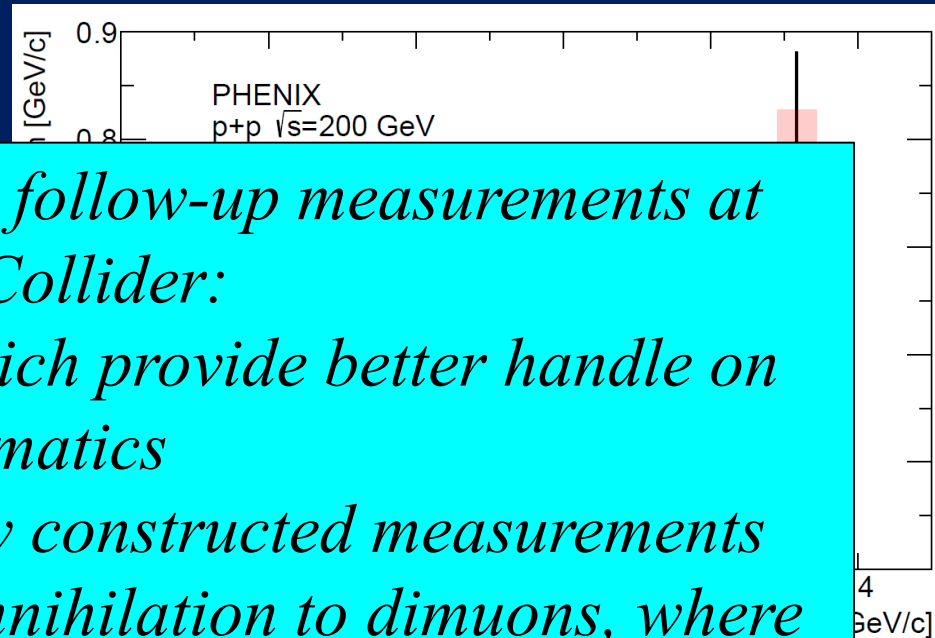
Don't reconstruct jets, so use  $x_E$  as a proxy for fraction of jet momentum carried by hadron:

$$x_E \equiv -\frac{p_T^{\text{trig}} \cdot p_T^{\text{assoc}}}{|p_T^{\text{trig}}|^2} = -\frac{|p_T^{\text{assoc}}|}{|p_T^{\text{trig}}|} \cos \Delta\phi$$

PRD98, 072004 (2018)

*So far see **qualitatively** similar trend where factorization predicted to be broken*

- Phenomenological calculations assuming factorization holds

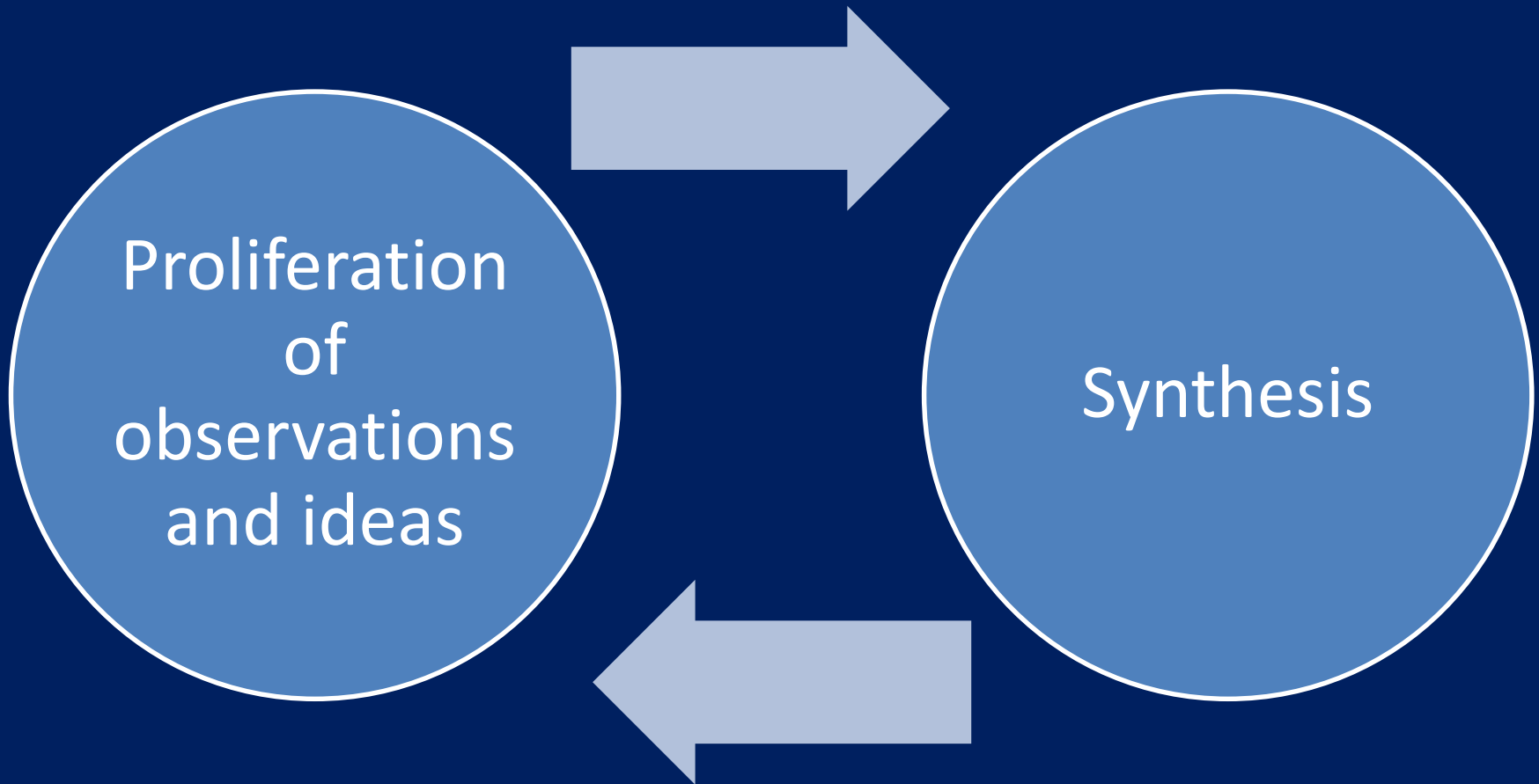


*In the meantime, performing follow-up measurements at LHCb at the Large Hadron Collider:*

- *Z-jet correlations, which provide better handle on quark and gluon kinematics*
- *As a control, similarly constructed measurements of quark-antiquark annihilation to dimuons, where no color entanglement is predicted*

*Discussions of other potential observables ongoing . . .*

# *A cyclical process*

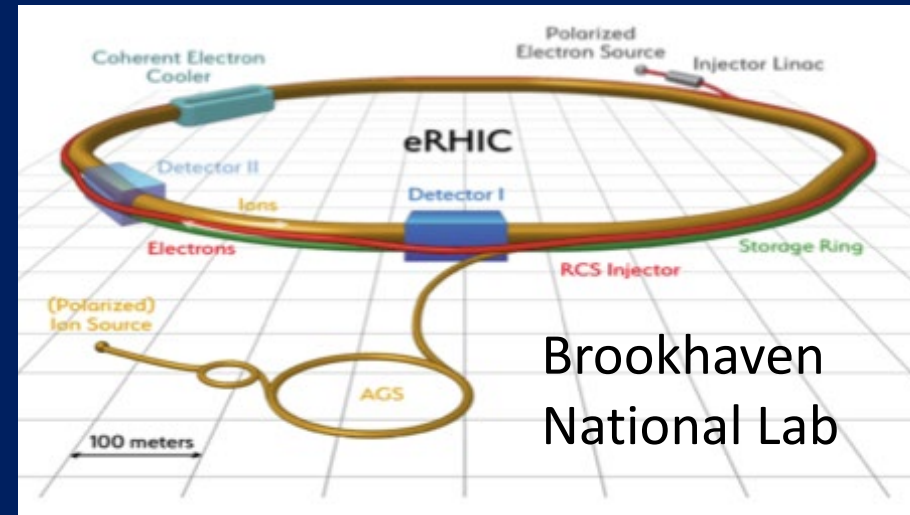


# *Next-generation QCD facility: The Electron-Ion Collider*

Key science questions:

- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent properties of dense systems of gluons?*

Project approval (“Critical Decision 0”) and site selection at Brookhaven National Lab announced Jan 9, 2020!



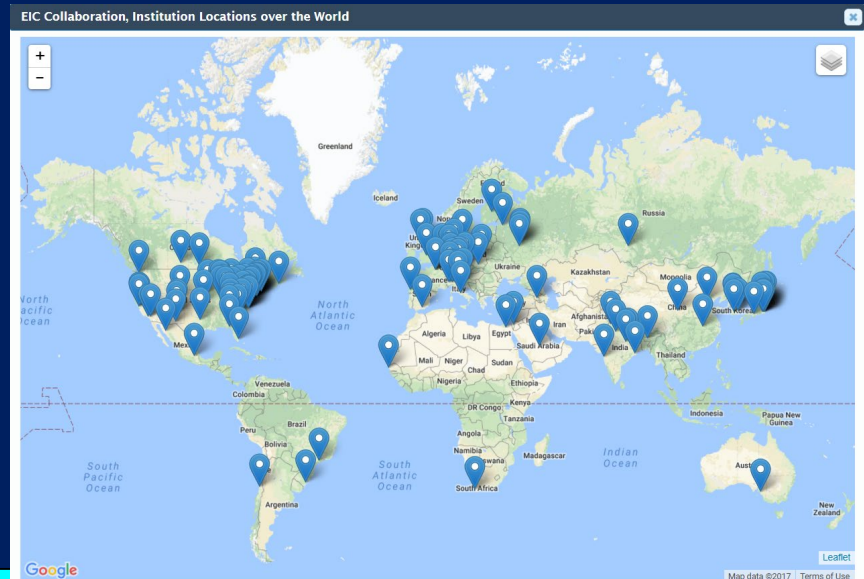


# *Next-generation QCD facility: The Electron-Ion Collider*

Key science questions:

- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent*

Project approval (“Critical Decision 0”) and site selection at Brookhaven National Lab announced Jan 9, 2020!

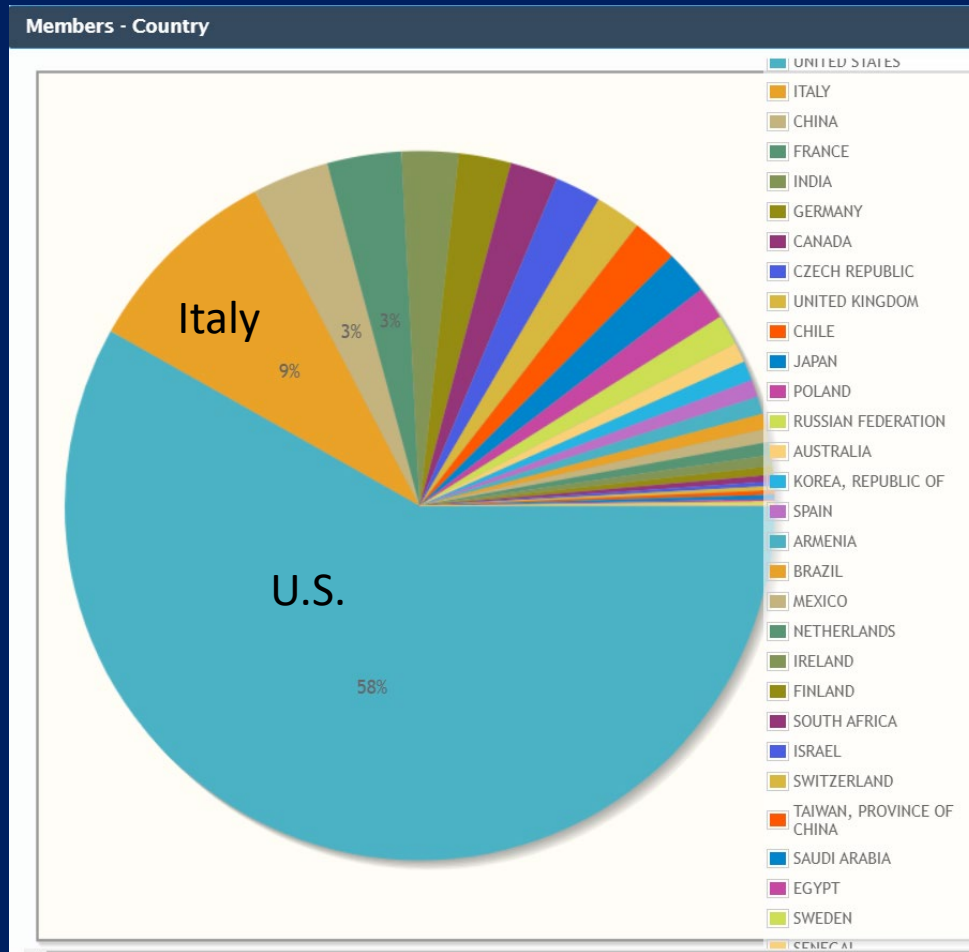


*Electron-Ion Collider User Group: Currently  
1007 members from 207 institutions in 30  
countries*

[www.eicug.org](http://www.eicug.org)



# *Next-generation QCD facility: The Electron-Ion Collider*



- Italy has largest number of member scientists in EIC User Group after the U.S.
- Leadership roles by Marco Radici, Barbara Pasquini, and Alessandro Bacchetta here at Pavia

[www.eicug.org](http://www.eicug.org)



# *Summary*

- Early years of a new era of research in quantum chromodynamics!



# *Summary*

- Early years of a new era of research in quantum chromodynamics!
- 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, atomic, and optical physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems



# Summary

- Early years of a new era of research in quantum chromodynamics!
- 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, atomic, and optical 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 at existing facilities as well as at the future Electron-Ion Collider . . .*

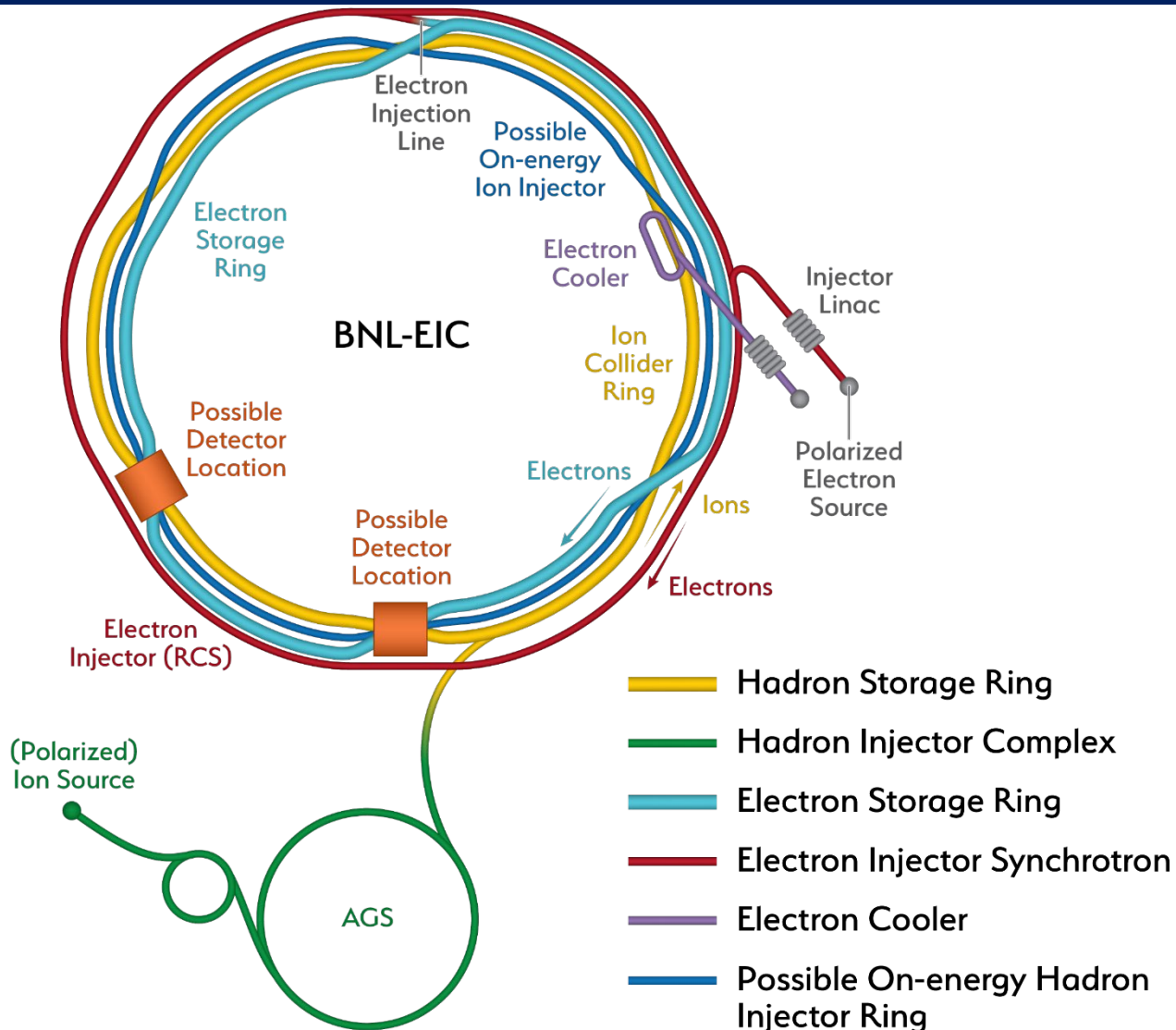
# *Extra*



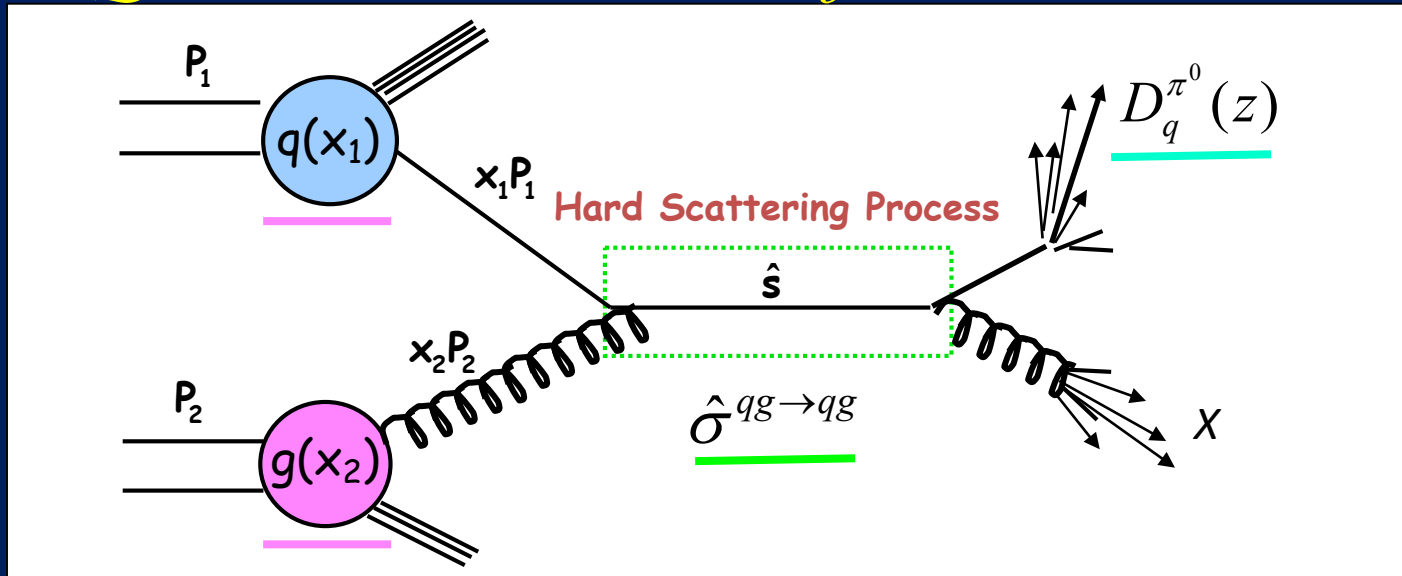
Christine Aidala, Pavia, 30 Jan 2020



# *How RHIC is transformed into an EIC*



# Parton distribution functions in perturbative QCD calculations of observables



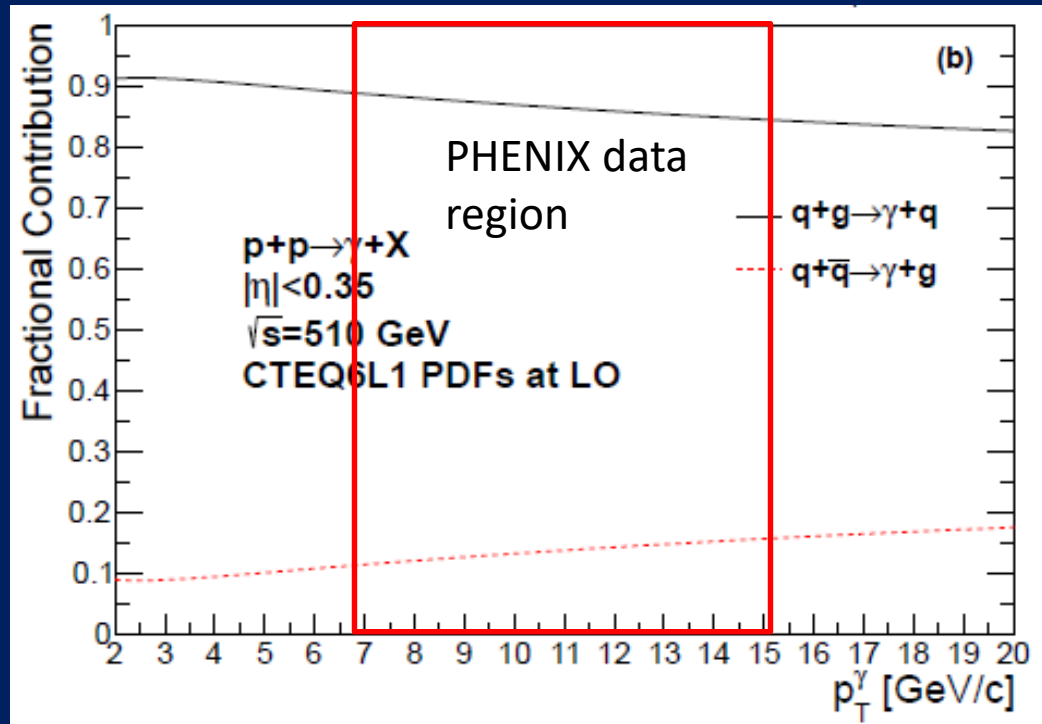
$$\sigma(pp \rightarrow \pi^0 X) \propto \underline{q(x_1)} \otimes \underline{g(x_2)} \otimes \underline{\hat{\sigma}^{qg \rightarrow qg}(\hat{s})} \otimes \underline{D_q^{\pi^0}(z)}$$

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

# Partonic process contributions for direct photon production

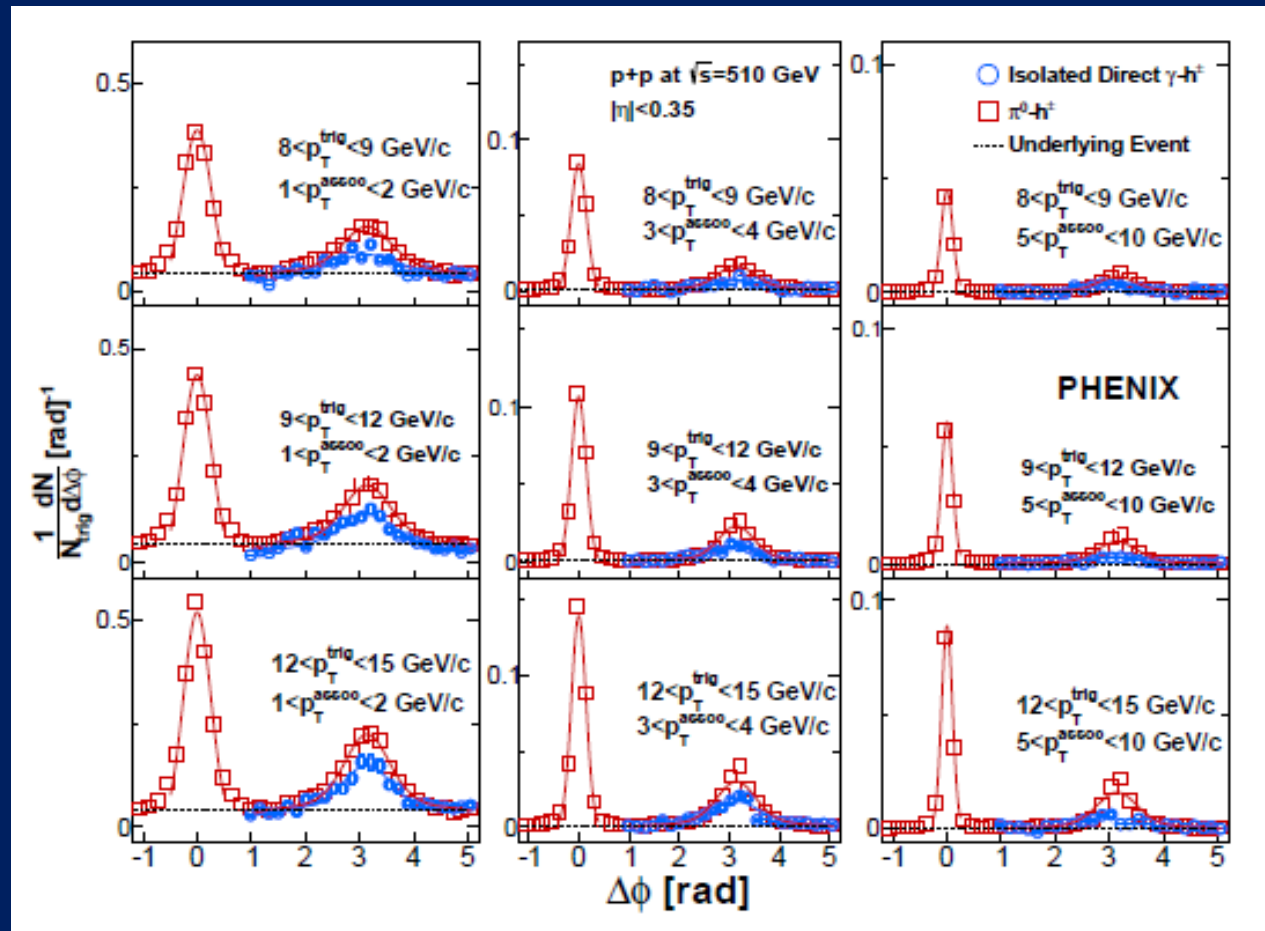


Quark-gluon Compton scattering still dominates at NLO - PLB140, 87 (1984)

PHENIX Collab., Phys. Rev. D95, 072002 (2017).  
Calculation by T. Kaufmann



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



PRD95, 072002 (2017)

Christine Aidala, Pavia, 30 Jan 2020

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

## Box 1. Types and duals

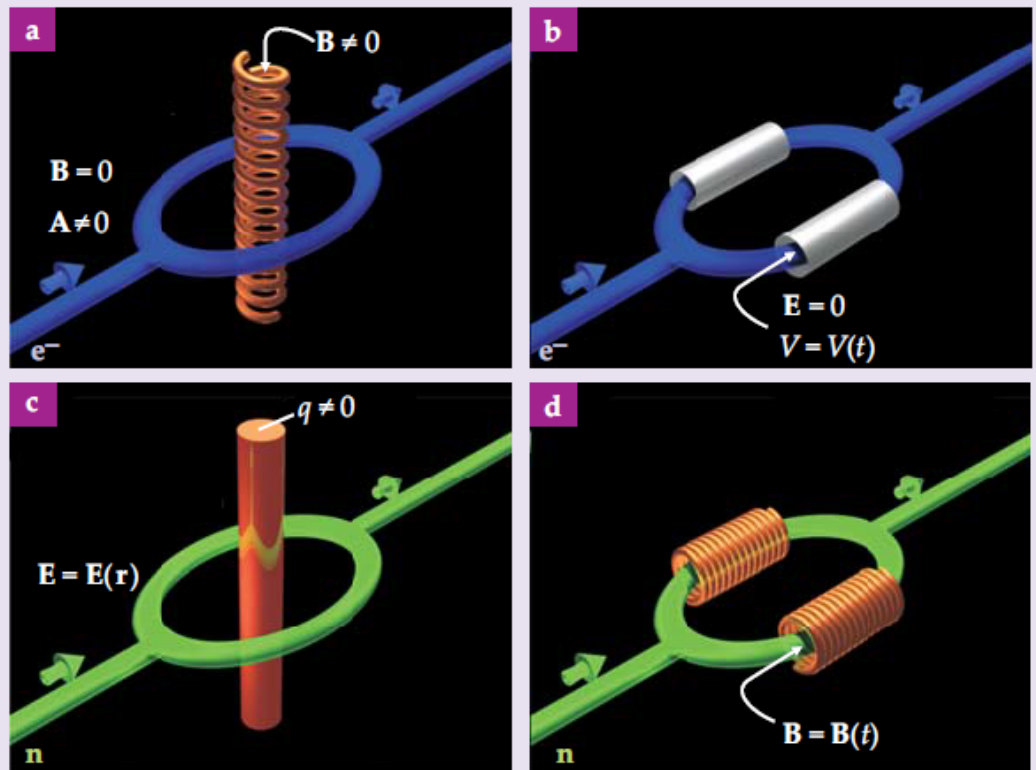
Physics Today, September 2009

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.



# *Exploring the role of color interactions in QCD*

- Process-dependent sign change for PT-odd TMD functions and TMD-factorization breaking prediction both due to color flow in hadronic interactions
- Renewed/increasing interest in color interactions in recent years! Various motivations. Some examples of recent papers (not by any means comprehensive!) . . .



# *Further discussions of color entanglement*

- A. Schaefer + J. Zhou PRD90, 094012 (2014) – “Color entanglement for gamma-jet in polarized p+A collisions”
  - “...the new gluon distribution function  $G_4(x, k_T)$  generated by color entanglement”
  - Entanglement “can be seen not as a nuisance, but as a chance to explore the nontrivial interplay of color flow in local non-Abelian gauge theories”
- J. Zhou PRD96, 114001 (2017) – “Color entanglement like effect in collinear twist-3 factorization”



# *Quarkonium suppression in $p+A$ ; Collective behavior in high-multiplicity $p+p$*

- Ma, Venugopalan, Watanabe, Zhang PRC97, 014909 (2018) – “Psi(2S) versus J/Psi suppression in proton-nucleus collisions from factorization violating soft color exchanges”
- Ortiz Velasquez, Christiansen, Cuautle Flores, Maldonado Cervantes, Paic PRL 111, 042001 (2013) – “Color reconnection and flowlike patterns in pp collisions”
- Ortiz, Palomo arXiv:1809.01744 - “Probing color reconnection with underlying event observables at the LHC energies”



# *“Color coherence” in $e^+e^-$ , $p(\text{bar})p$*

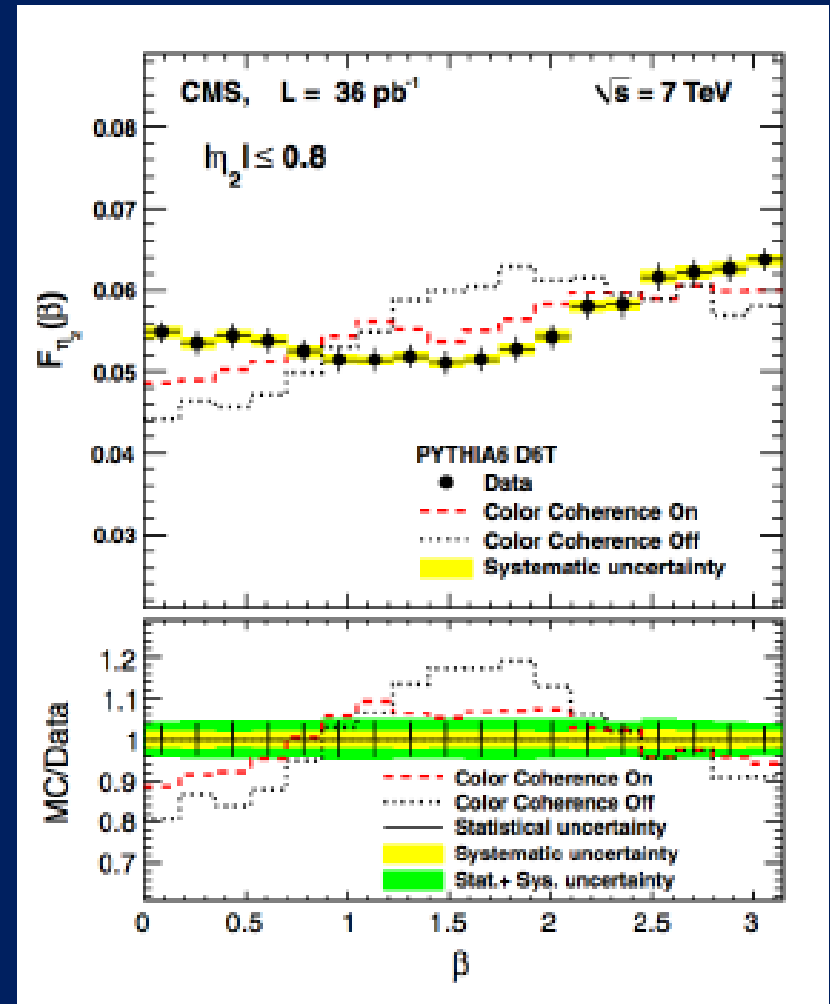
- “Color coherence” ideas about increased soft radiation between color-connected partons/remnants go back to  $e^+e^-$  measurements in the 1980s, e.g.
  - TPC/2g Collaboration, “Comparison of the Particle Flow in  $q\text{-}q\text{bar}\text{-}g$  and  $q\text{-}q\text{bar}\text{-}\gamma$  Events in  $e^+e^-$  Annihilation”, Phys. Rev. Lett. 57, 945 (1986)
  - MARK2 Collaboration, “Comparison of the particle flow in Three-Jet and radiative Two-Jet Events from  $e^+e^-$  Annihilation at  $E_{\text{c.m.}} = 29$  GeV”, Phys. Rev. Lett. 57, 1398 (1986)
  - OPAL Collaboration, “A study of coherence of soft gluons in hadron jets”, Phys. Lett. B247, 617 (1990)
  - L3 Collaboration, “Evidence for gluon interference in hadronic Z decays”, Phys. Lett. B353, 145 (1995)
- In 3-jet events in hadronic collisions, color coherence predicts that gluon radiation leading to lowest- $p_T$  jet more likely to be in plane defined by emitting hard-scattered parton, i.e. “second” jet, and beam remnant, with stronger effects expected when second jet is closer to beam rapidity.





# “Color coherence” in $e^+e^-$ , $p(\bar{p})p$

- D0, CDF, CMS have all published evidence for “color coherence effects”
  - CDF: PRD50, 5562 (1994) – “Evidence for color coherence in pp collisions at  $\sqrt{s} = 1.8$  TeV”
  - D0: PLB414, 419 (1997) – “Color coherent radiation in multijet events from pp collisions at  $\sqrt{s} = 1.8$  TeV”
  - CMS: EPJ C74, 2901 (2014) – “Probing color coherence effects in pp collisions at  $\sqrt{s} = 7$  TeV”



# *“Color coherence” in $e^+e^-$ , $p(\bar{p})p$*

- ATLAS NPB918, 257 (2017) – “High- $E_T$  isolated-photon plus jets production in pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector”
  - Measured isolated photon+(1, 2, or 3) jets – enhancements in QCD radiation “observed around the leading jet with respect to the photon in the directions towards the beams”





# *Using color correlations to reduce background in beyond-the-SM searches*

- Gallicchio + Schwartz PRL 105, 022001 (2010) – “Seeing in Color: Jet Superstructure”
  - “the radiation on each end of a color dipole is being pulled towards the other end of the dipole”
  - Define “jet pull” observable based on color connection ideas

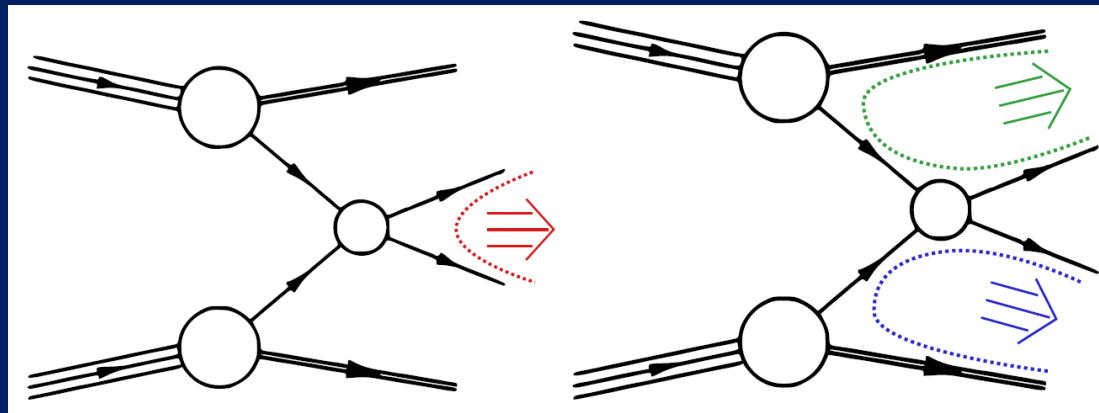


FIG. 1: Possible color connections for signal ( $pp \rightarrow H \rightarrow b\bar{b}$ ) and for background ( $pp \rightarrow g \rightarrow b\bar{b}$ ).

# *Using color correlations to reduce background in beyond-the-SM searches*

- ATLAS proof-of-principle measurement using Gallicchio-Schwartz proposal: PLB 750, 475 (2015) – “Measurement of colour flow with the jet pull angle in  $t\bar{t}$  events using the ATLAS detector at  $\sqrt{s} = 8$  TeV”
  - “The jet pull angle is found to correctly characterise the W boson as a colour singlet”

