Transverse-Momentum-Dependent Factorization, Color Flow, and Entanglement in QCD

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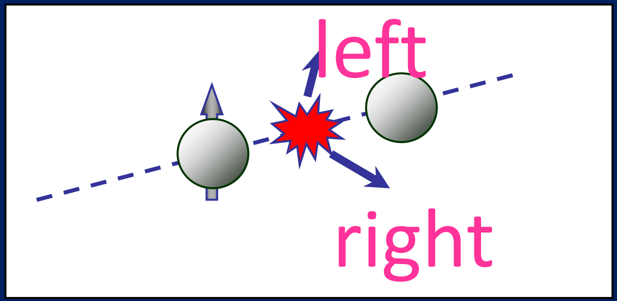
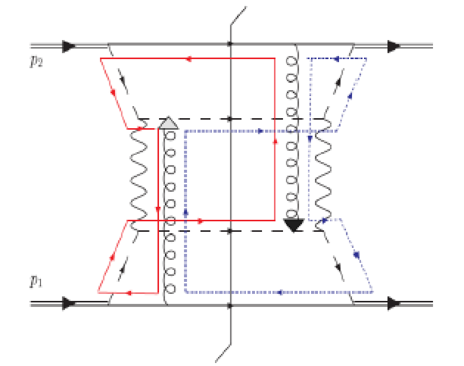
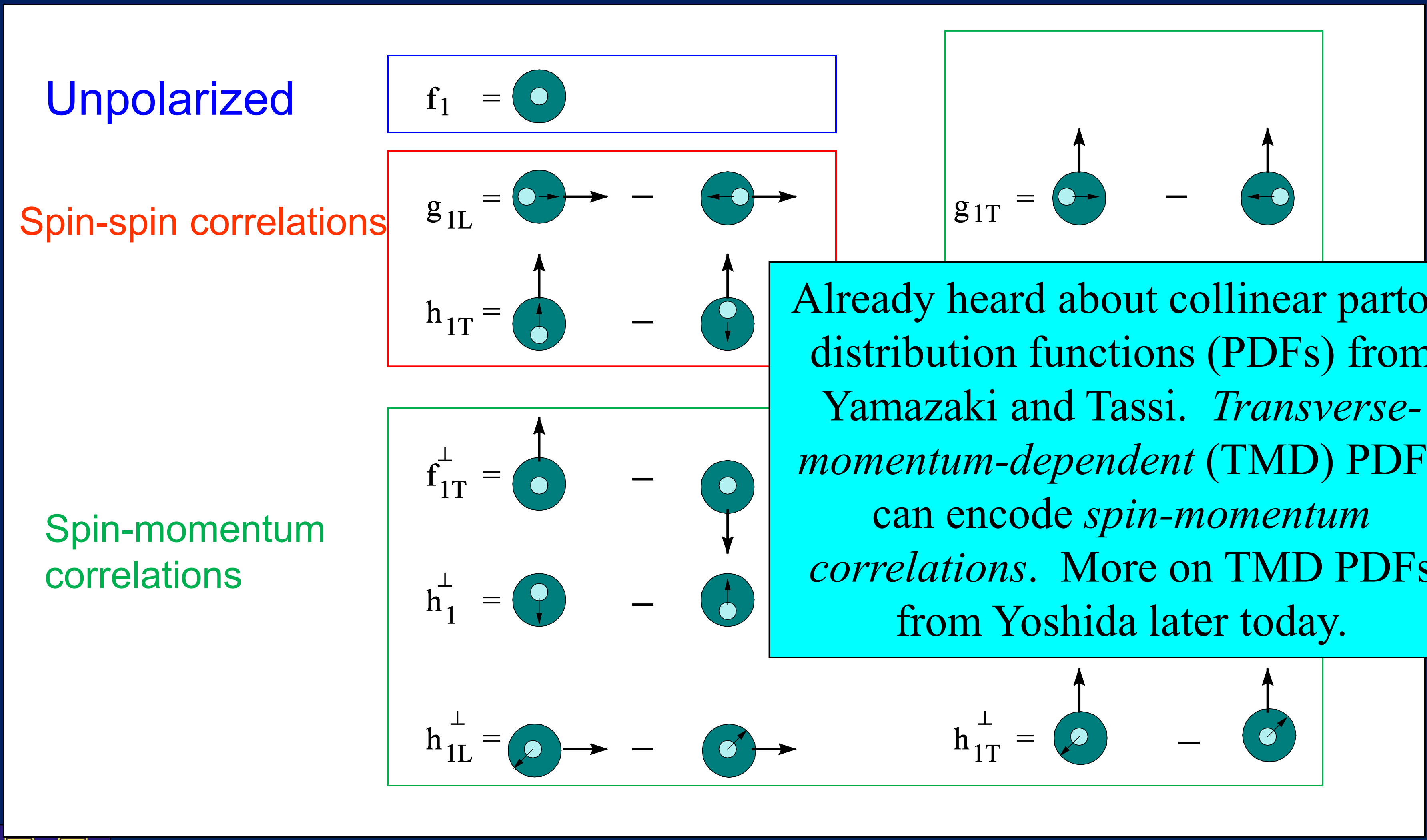
University of Michigan





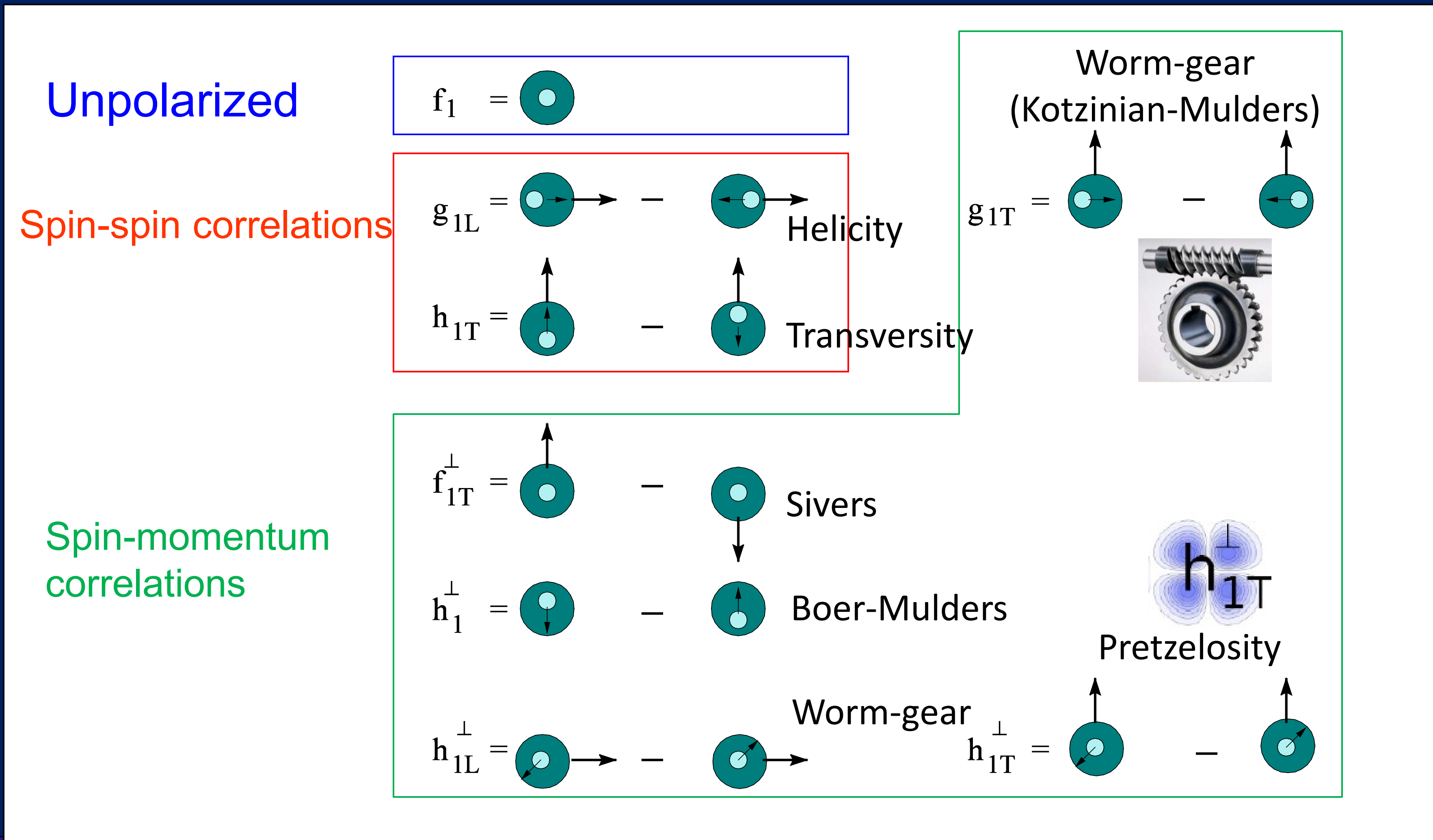
New Particle and Nuclear Physics Developing in EIC
University of Tokyo
May 30, 2024

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

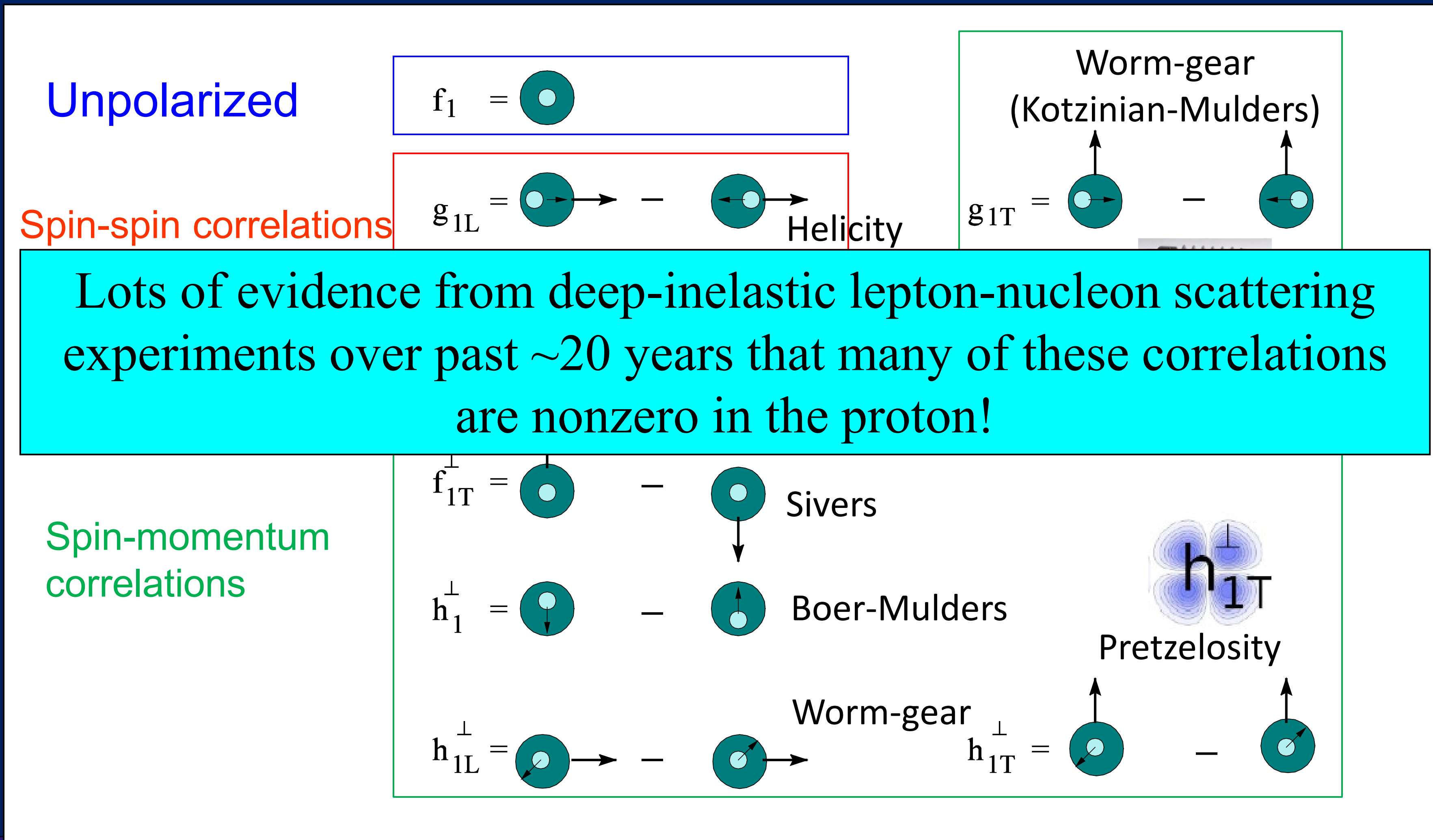


Already heard about collinear parton distribution functions (PDFs) from Yamazaki and Tassi. *Transverse-momentum-dependent* (TMD) PDFs can encode *spin-momentum correlations*. More on TMD PDFs from Yoshida later today.

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

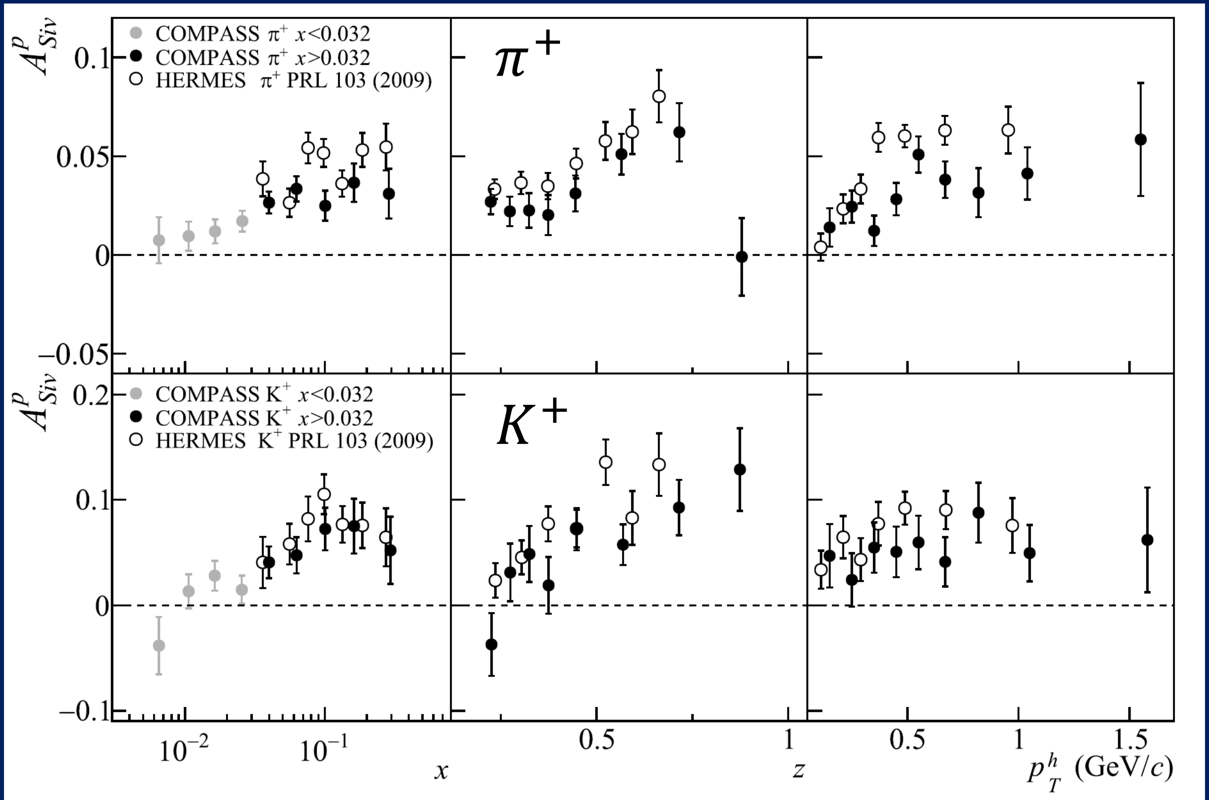


Spin-spin and spin-momentum correlations in QCD bound states



Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~20 years that many of these correlations are nonzero in the proton!

Measured asymmetries due to motion of unpolarized quarks in transversely polarized protons (Sivers TMD PDF)



5-10% spin asymmetries observed in the production of pions and kaons via semi-inclusive deep-inelastic scattering with muon (COMPASS) or electron (HERMES) beams on transversely polarized protons.

PLB 744, 250 (2015)

Different symmetry properties for different spin-momentum correlations

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

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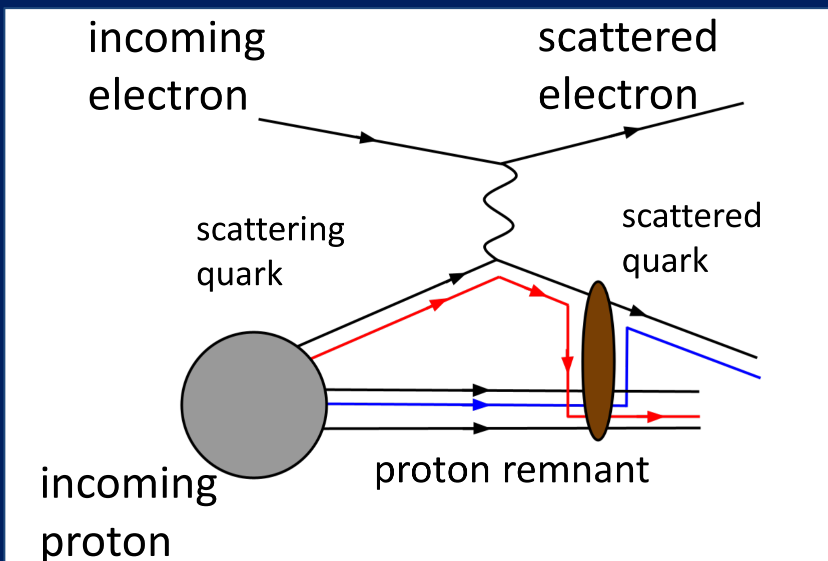
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish

Different symmetry properties for different spin-momentum correlations

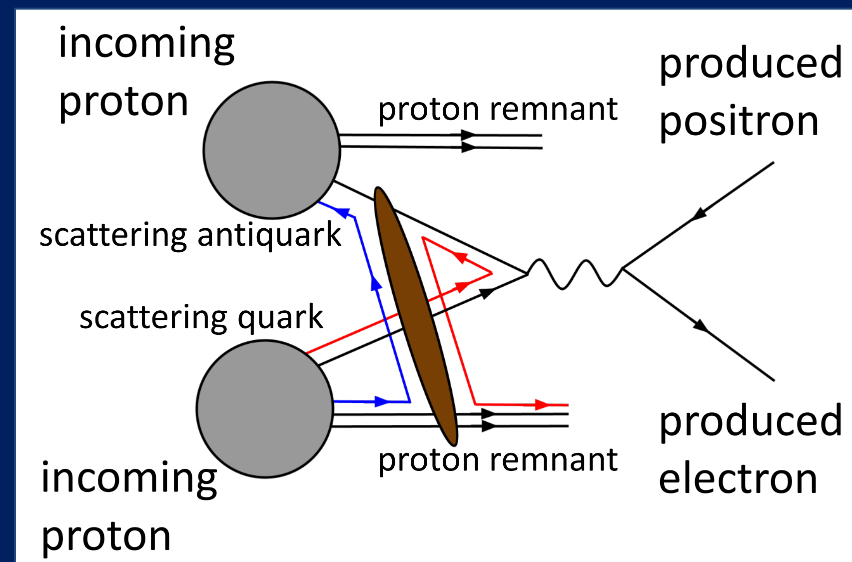
- Some transverse-momentum-dependent quark distribution functions odd under a parity- and time-reversal (PT) transformation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish
- Only realized in 2002 by Brodsky, Hwang, and Schmidt that could be nonvanishing 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



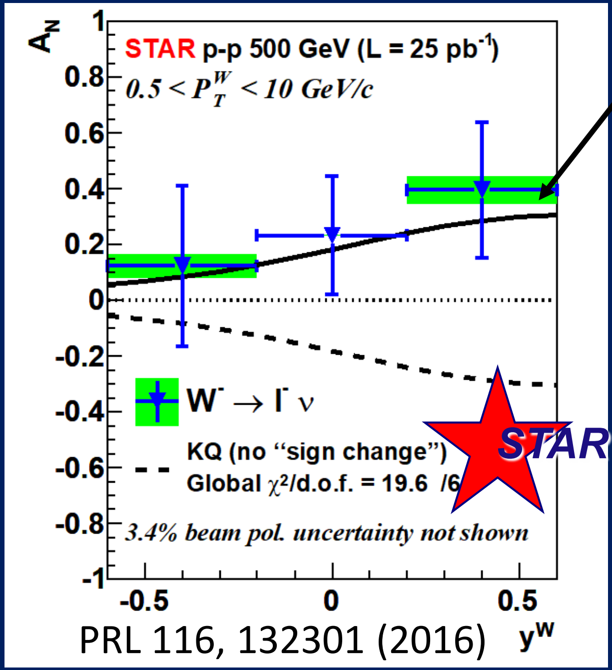
Quark-antiquark annihilation to leptons: Initial-state color exchange

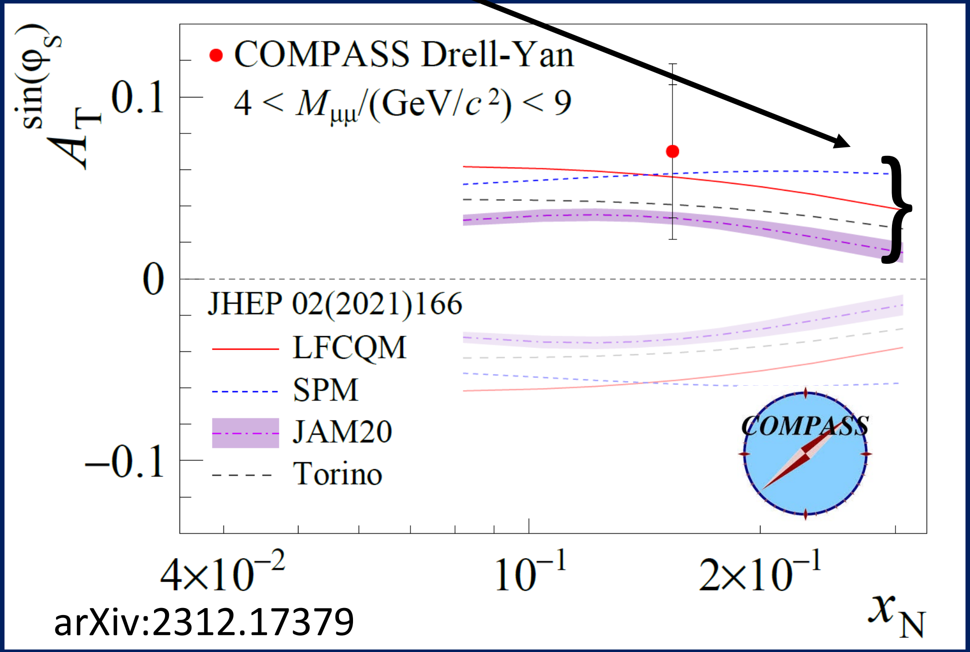


Opposite sign **for PT-odd spin-momentum correlations in the proton measured in these two processes:**
***process-dependent*!** **(Collins 2002)**
Due to *differences in color flow* between the two processes.

Modified universality: Initial experimental hints

Predictions including sign change





First measurements by STAR at the Relativistic Heavy Ion Collider and final results from COMPASS at CERN hint at predicted sign change in color-annihilation processes compared to semi-inclusive deep-inelastic lepton-nucleon scattering. More statistics from STAR coming …

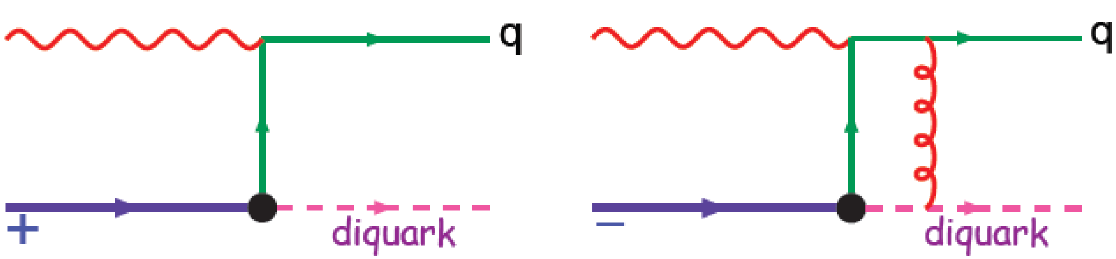
Modified universality requires full QCD: Gauge-invariant quantum field theory

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

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

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

SIDIS final state interactions



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

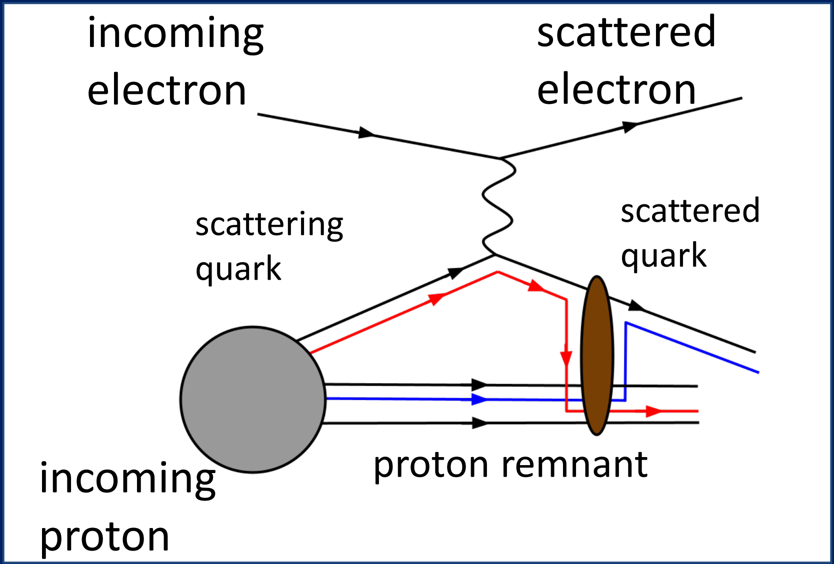
An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced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

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

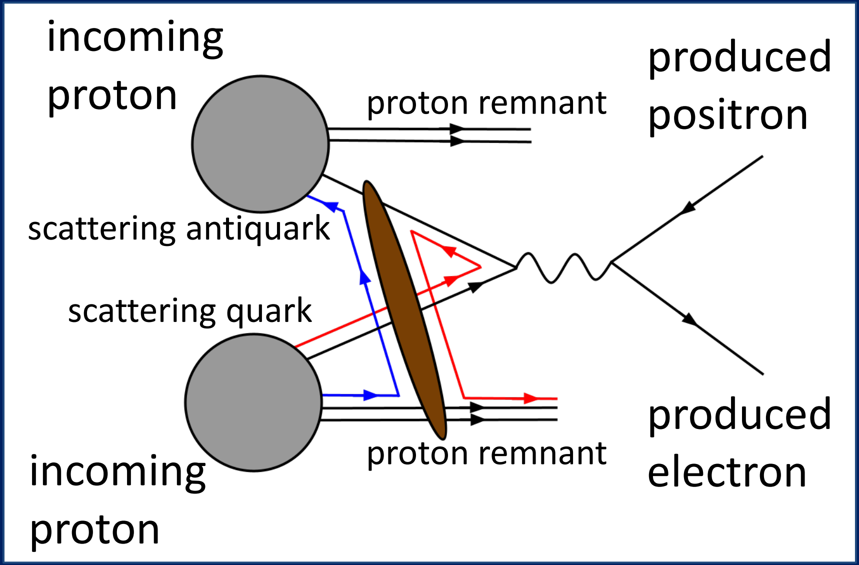
Slide from M. Anselmino, Transversity 2014

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

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



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



Can think of the parton getting its phase shifted by passing through the potential field of the proton remnant.

Relative phase shift difference of π between the two processes.

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

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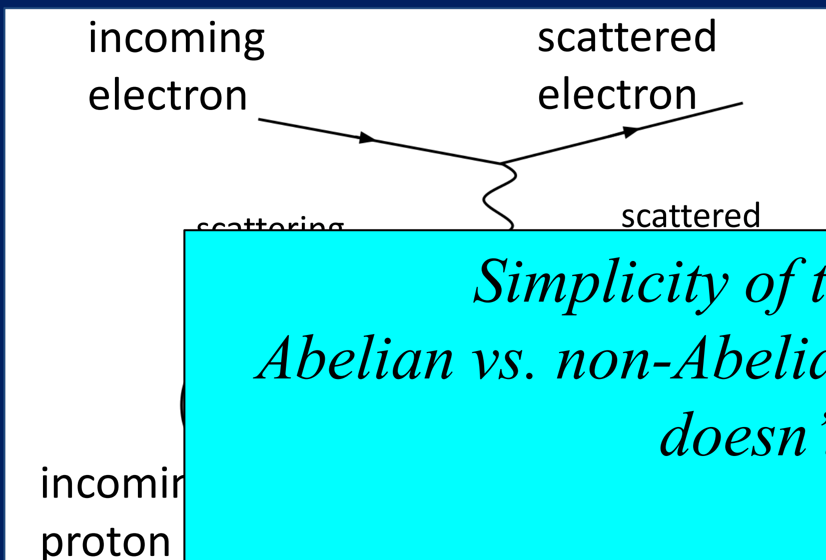

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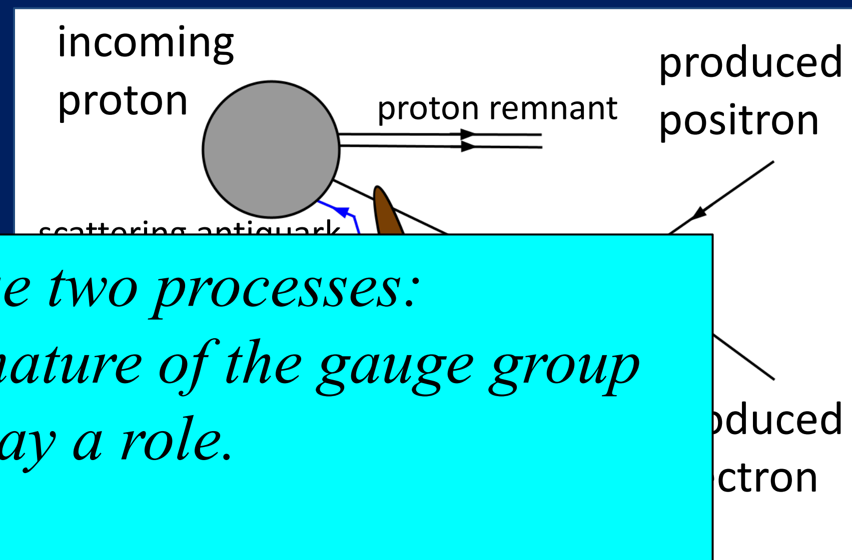


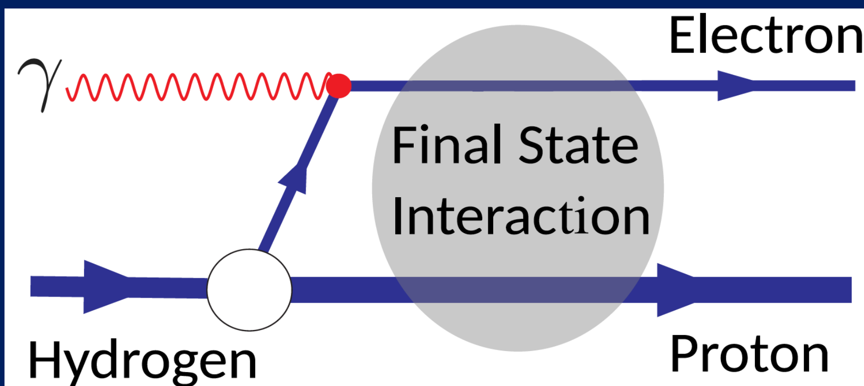
Simplicity of these two processes:
Abelian vs. non-Abelian nature of the gauge group doesn't play a role.

Therefore should expect similar process-dependent effects when probing PT-odd spin-momentum correlations in QED bound states (atoms)…

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

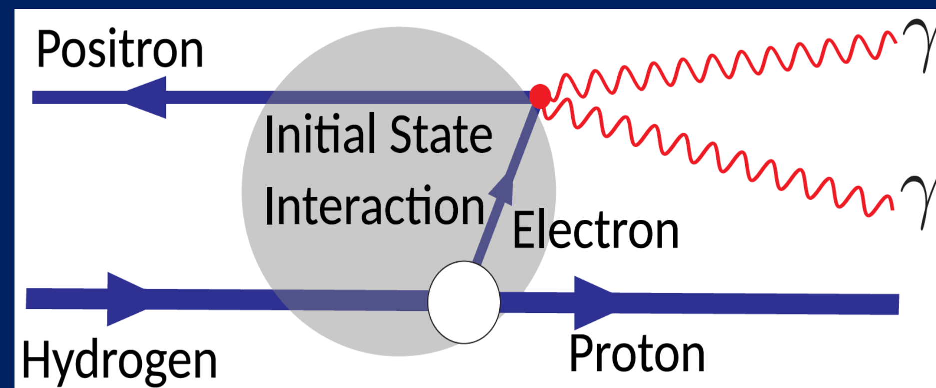
*Process-dependent PT-odd spin-momentum correlations in **atomic** bound states*

Photo-ionization: Final-state photon exchange



Measure angular distribution of scattered photon and ionization electron with respect to angular momentum $\vec{J}$ of atom

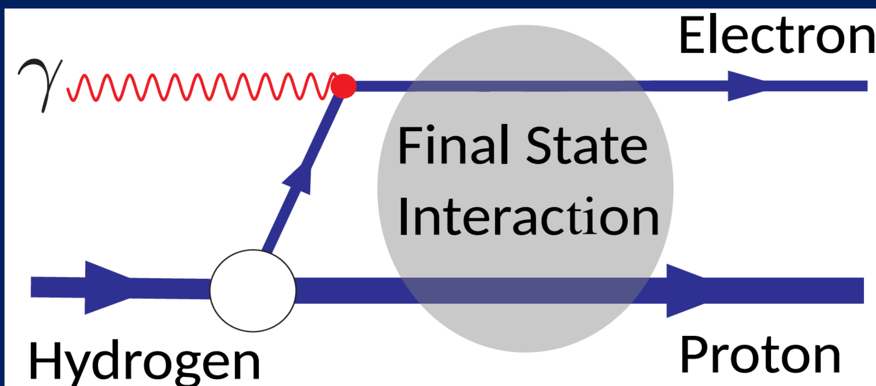
Annihilation to photons: Initial-state photon exchange



Measure angular distribution of photon pair with respect to angular momentum $\vec{J}$ of atom

*Process-dependent PT-odd spin-momentum correlations in **atomic** bound states*

Photoionization: Final-state photon exchange



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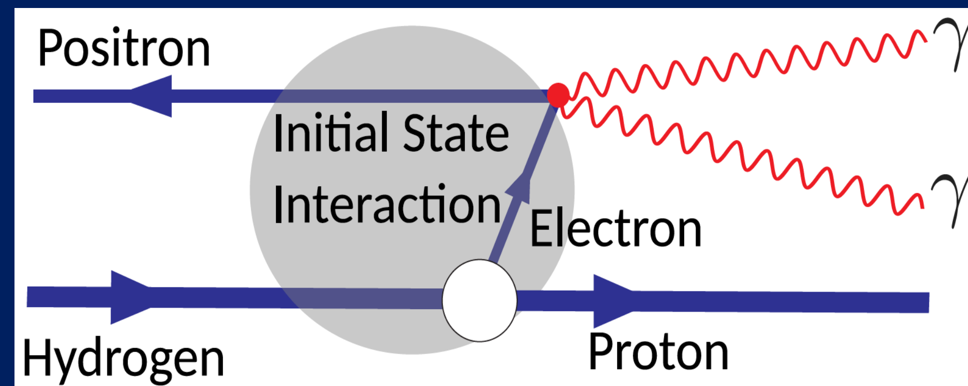

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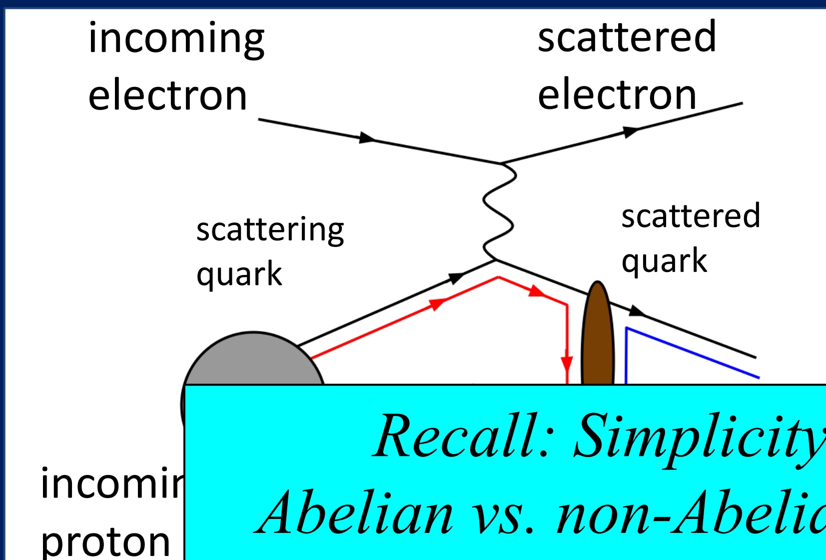
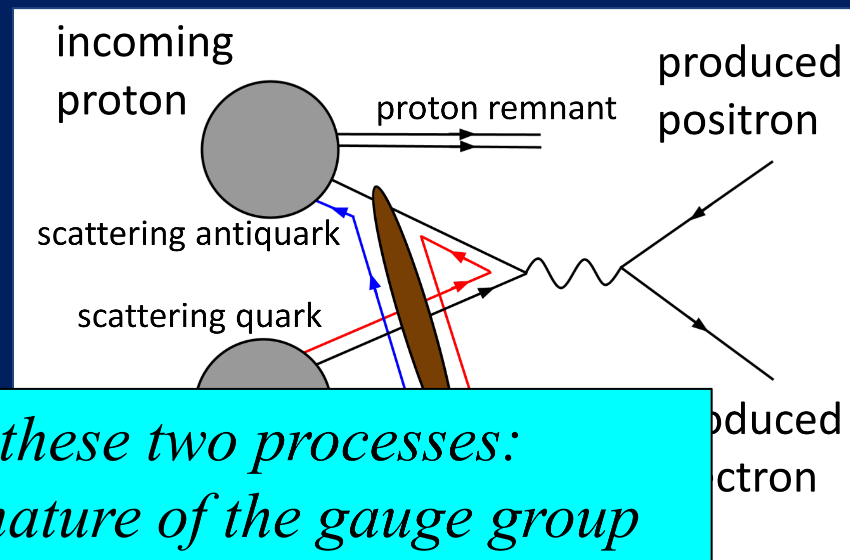
Currently pursuing QED analog calculations with Dylan Manna and Andrea Signori, for PT-odd spin-momentum correlations in singly ionized helium probed via photoionization vs. annihilation processes.

Recall: 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

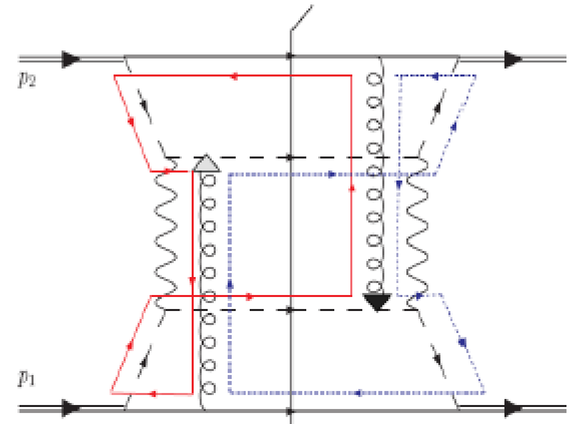


Recall: Simplicity of these two processes:
Abelian vs. non-Abelian nature of the gauge group doesn't play a role.

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 hadrons 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



PRD 81, 094006 (2010)

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

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

Factorization and factorization breaking

- Factorization generally refers to two things in QCD processes with a hard scale
  - Factorization of short-distance (i.e. perturbative) from long-distance (i.e. nonperturbative) physics
  - Factorization of nonperturbative functions from one another, e.g. into separate PDFs and fragmentation functions for each hadron involved in a process

Factorization and factorization breaking

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  - Factorization of short-distance (i.e. perturbative) from long-distance (i.e. nonperturbative) physics
  - Factorization of nonperturbative functions from one another, e.g. into separate PDFs and FFs for each hadron involved in a process

- Factorization of short-distance from long-distance physics believed to hold
- Factorization of nonperturbative functions predicted to be broken in TMD processes involving p+p → hadrons
  - Would need e.g. a single nonperturbative function to describe *quantum correlated partons across the two protons*

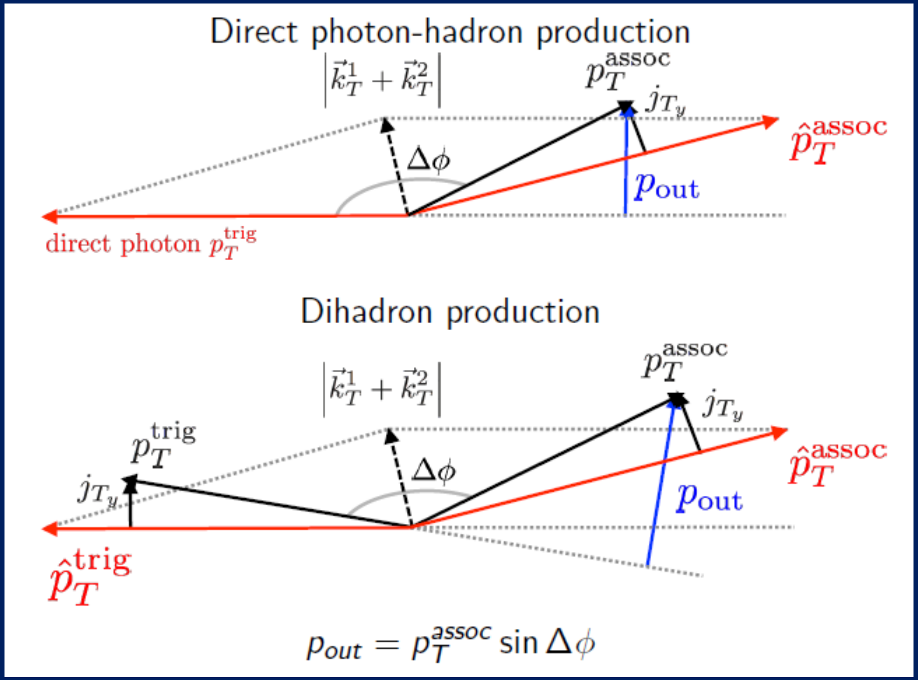
How can we search for color entanglement effects?

- Need processes where gluons can be exchanged in *both* the initial and final states
  - Hadron-hadron collisions
  - At least one hadron in the final state (gluon can be exchanged with remnant of initial-state hadron)
- Need processes sensitive to nonperturbative transverse momentum

Searching for evidence of color entanglement at the Relativistic Heavy Ion Collider

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

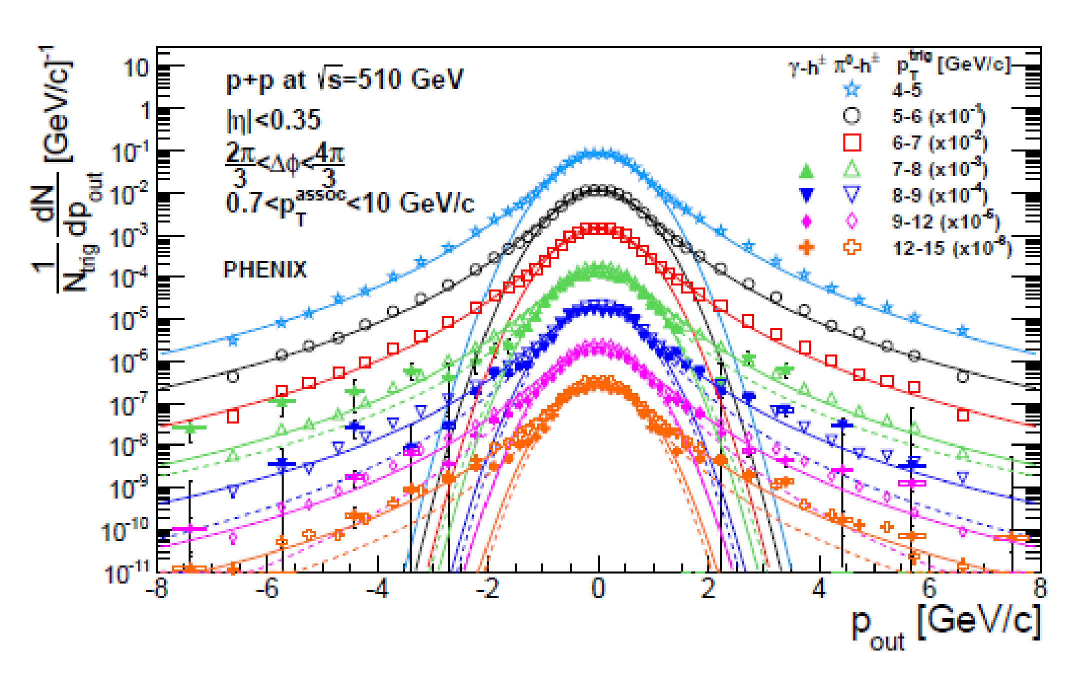


PHENIX Collaboration:
PRD95, 072002 (2017)
PRD98, 072004 (2018)
PRC99, 044912 (2019)

Out-of-plane momentum component distributions

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

PRD95, 072002 (2017)



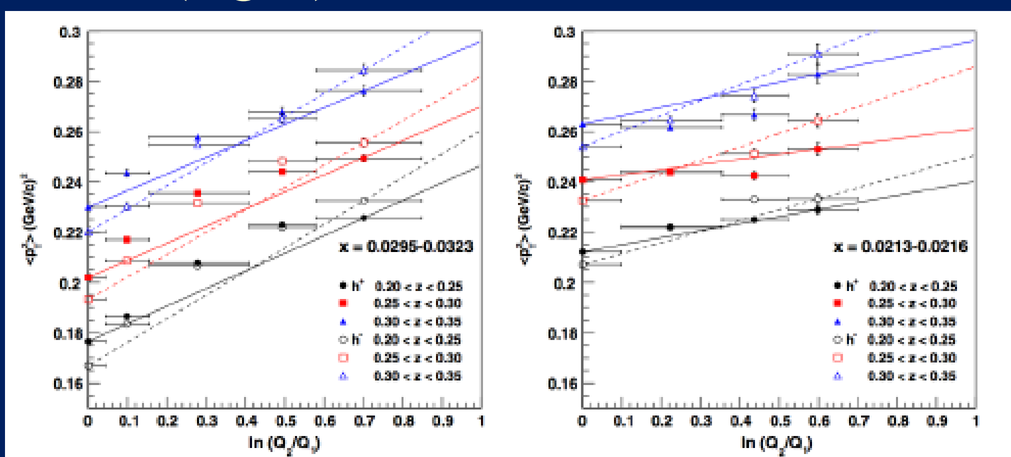
Curves are fits to Gaussian and Kaplan functions, *not* calculations

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

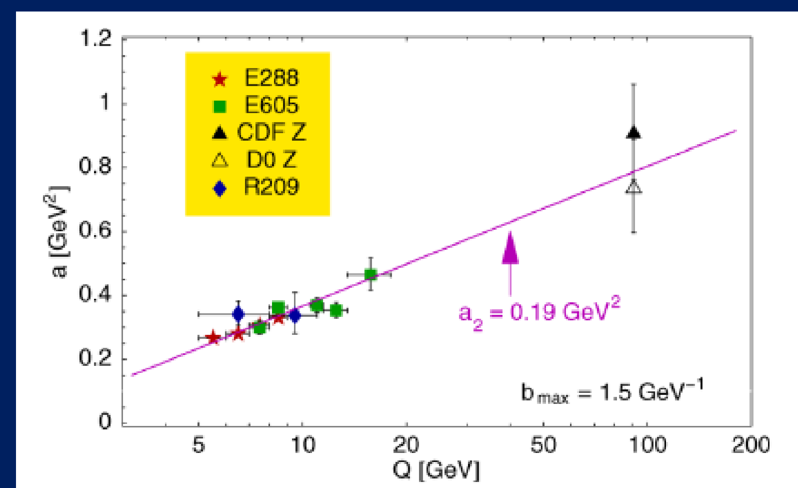
- Proof of TMD-factorization (i.e. no entanglement) directly predicts that nonperturbative transverse momentum widths *increase* with hard scattering energy scale
  - Increased phase space for gluon radiation

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

- Proof of TMD-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)

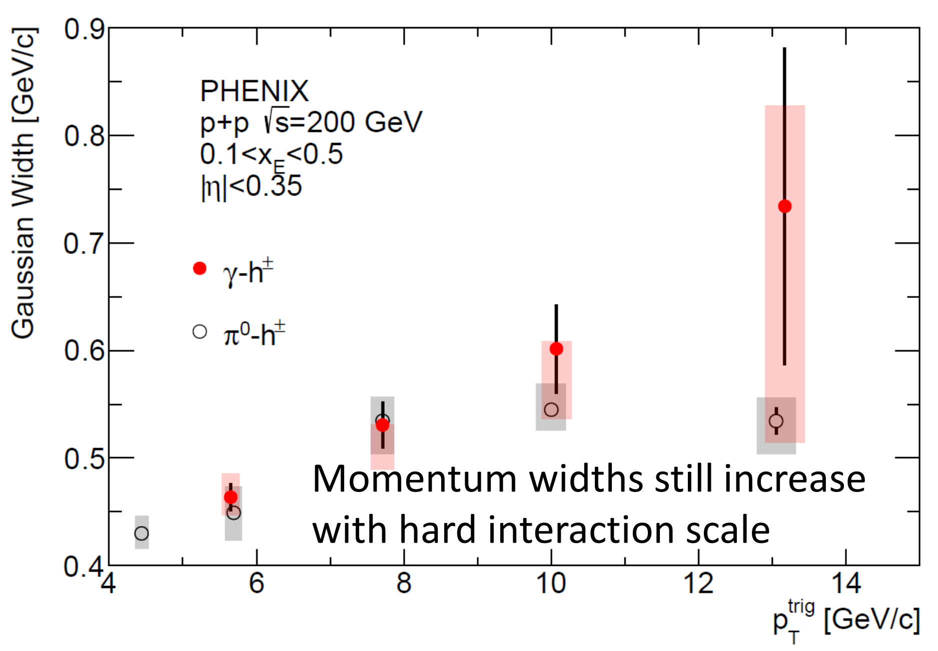


Konychev + Nadolsky, Phys. Lett. B633, 710 (2006)

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

- With future phenomenological calculations assuming factorization holds, can search for *quantitative* deviations

- Goal is to study factorization breaking and non-Abelian phenomena in a controlled way



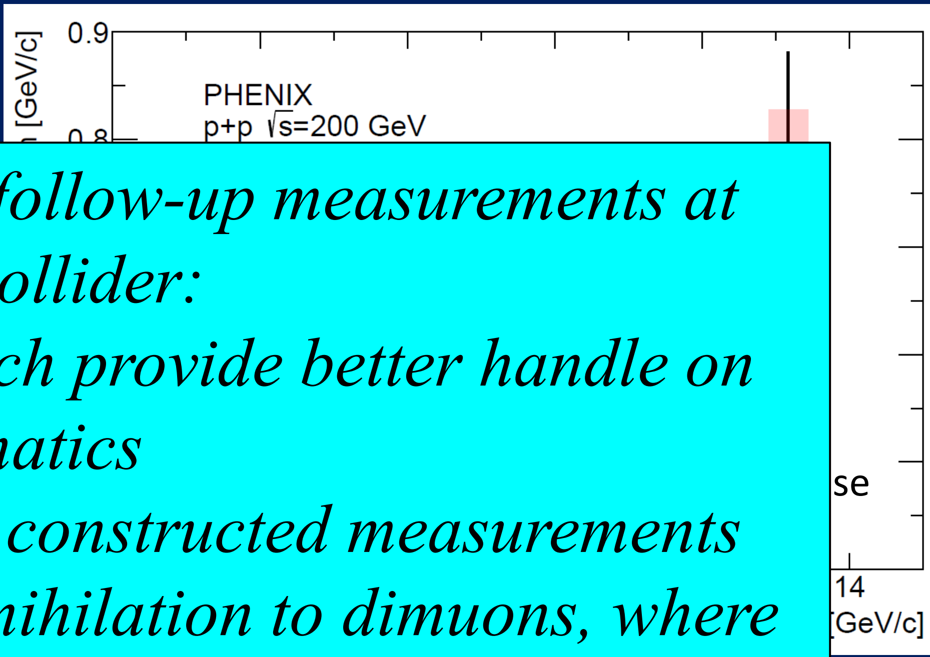
Don't reconstruct jets, so use x_E as a proxy for fraction of jet momentum carried by hadron:

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

PRD98, 072004 (2018)

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

- With future phenomenological calculations assuming



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 . . .

Possible to study TMD-factorization breaking at the EIC??

- Need to be able to exchange color in both the initial and final state
  - Final-state gluon exchange between a scattered quark and the remnant of the proton no problem
  - But can't attach a gluon to an incoming electron!
- Possible to set up color entanglement if virtual photon fluctuates into a $q\bar{q}$ pair??
  - Need further discussion with theorists

Probing factorization breaking, entanglement, and color flow

(Controlled) factorization breaking, effects of entanglement, and color flow are areas of growing interest

- See backup slides for more details

- "Color coherence" ideas about increased soft radiation between color-connected partons/remnants go back to e+e- measurements in the 1980s and have seen renewed interest recently
- Studying color correlations proposed to reduce backgrounds in searches for beyond-the-Standard-Model physics
- "Color reconnection" proposed to explain observed collective behavior in high-multiplicity p+p collisions
- …

"Entanglement entropy" in deep-inelastic lepton-proton scattering

Deep inelastic scattering as a probe of entanglement

Dmitri E. Kharzeev (RIKEN BNL and SUNY, Stony Brook), Eugene M. Levin (Santa Maria U., Valparaiso and Tel Aviv U.)

Feb 12, 2017

12 pages
Published in: *Phys.Rev.D* 95 (2017) 11, 114008
Published: Jun 13, 2017
e-Print: 1702.03489 [hep-ph]
DOI: 10.1103/PhysRevD.95.114008
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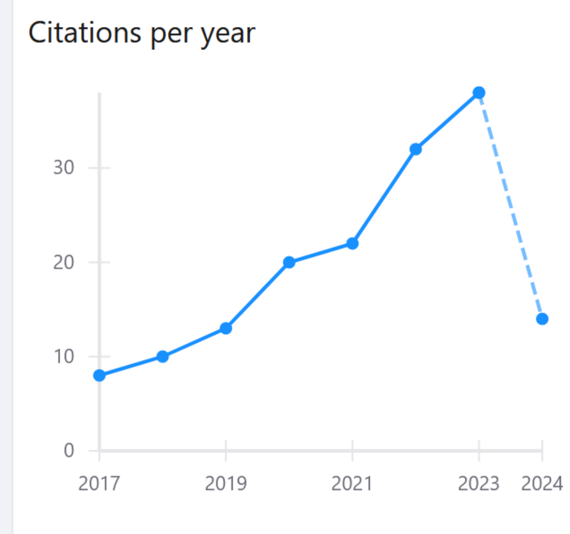


"We interpret the result as the entropy of entanglement between the spatial region probed by deep inelastic scattering and the rest of the proton."

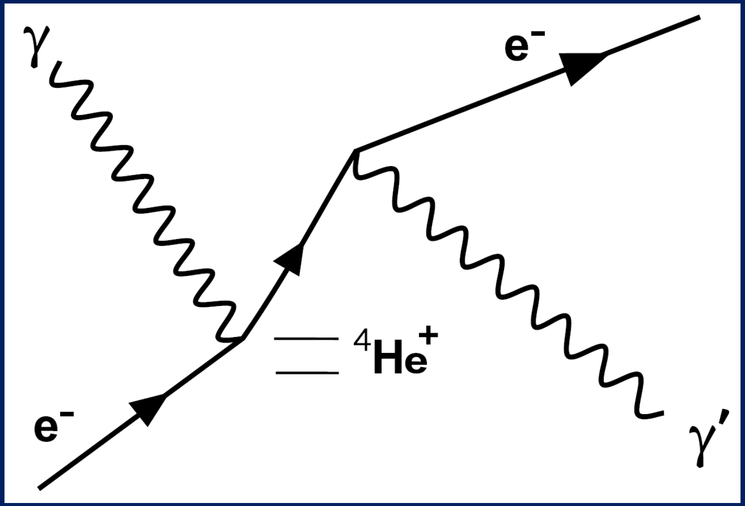
Summary

- *Processes and interactions* in QCD are becoming a focus on their own, independent of their use as tools to study hadron structure
- Studies related to transverse-momentum-dependent PDFs and fragmentation functions are bringing to light fundamental aspects of QCD as a gauge-invariant quantum field theory, and specifically as a non-Abelian one
- Complementary measurements in p+p, e+p, and $e^+ + e^-$ in the upcoming years will allow us to investigate processes with different color flow patterns, probe the limits of factorization and universality, and explore different types of entanglement in QCD systems

Extra

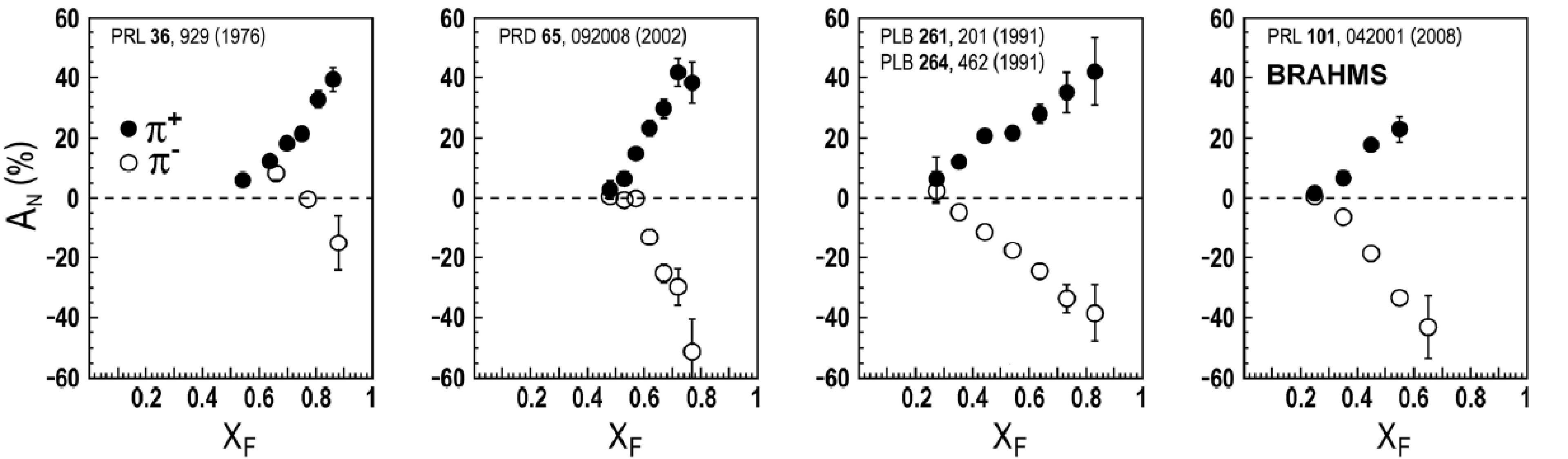
Atomic "semi-inclusive deep-inelastic scattering" calculations

- Photoionization of singly ionized 4He+
- 4He a scalar (spin-0) nucleus
- Treat as perturbed Compton scattering
- Use wavefunctions of hydrogen-like atoms in momentum space (B. Podolsky + L. Pauling, Phys. Rev. 34:109, 1929)



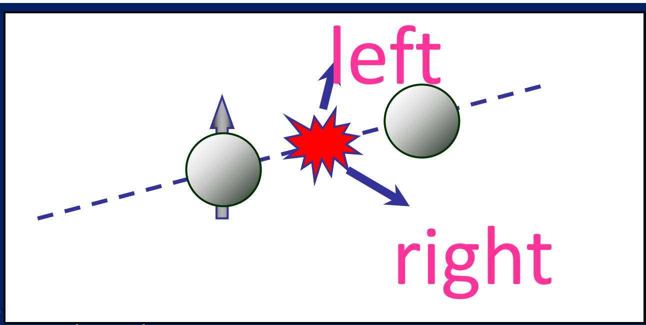
***Huge** spin asymmetries in p+p → hadrons: Does color entanglement play a role??*

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



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

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

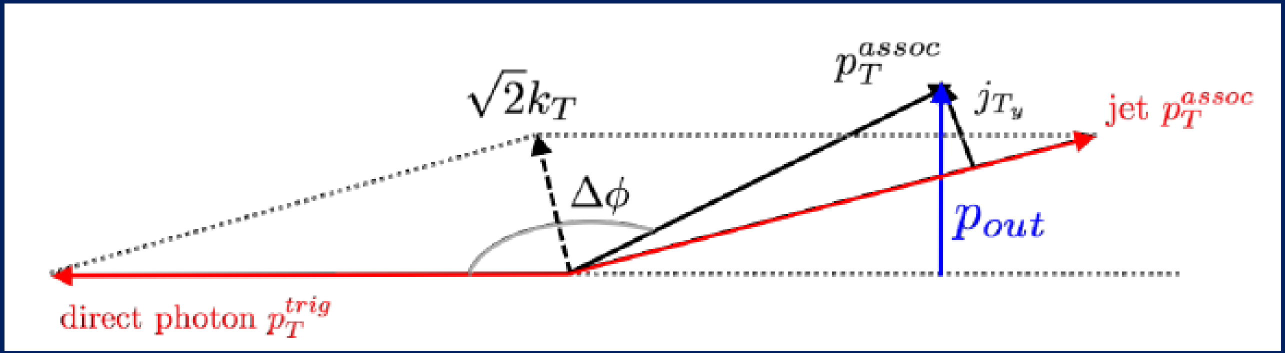


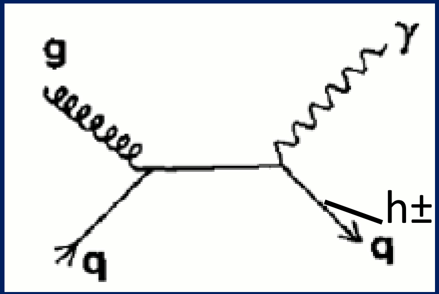
Recall: Modified universality of PT-odd TMD PDFs

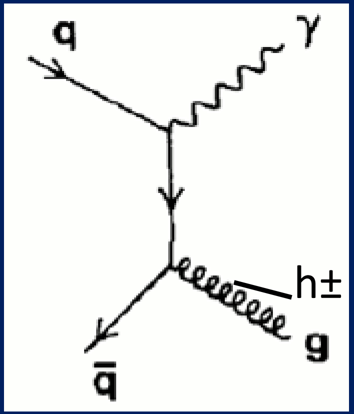
- Gluon exchange between a parton involved in the hard scattering and a remnant can (and presumably does) always take place

- What's special about processes involving PT-odd TMD PDFs: *Can't get rid of such gluon exchanges via a gauge transformation*

Direct photon – hadron correlations in p+p

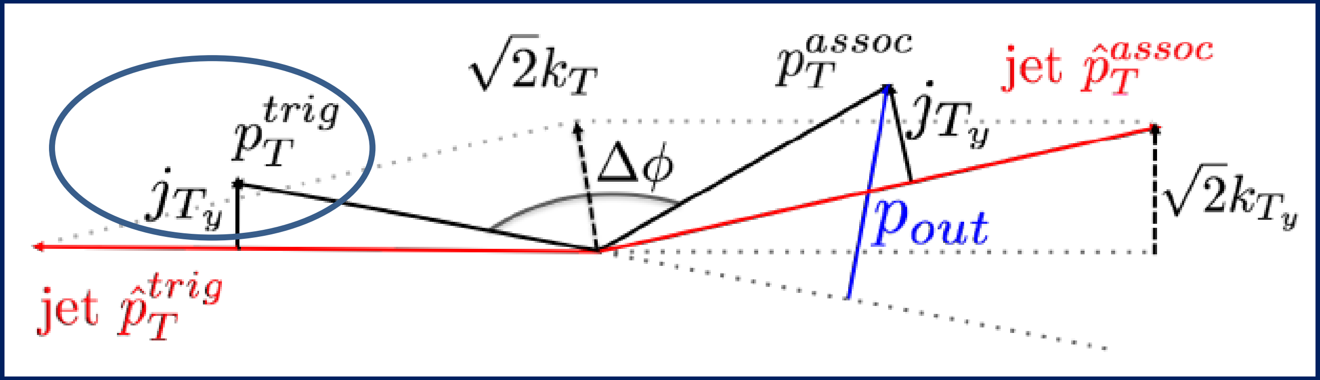






- "Direct" photon – produced directly in hard scattering
- ~85% quark-gluon Compton scattering (top diagram) in our kinematics
- Measure out-of-plane momentum component p_{out} of one particle with respect to other
- Unpolarized – effects predicted for polarized and unpolarized; more data available for unpolarized

Also π^0 – hadron correlations in p+p

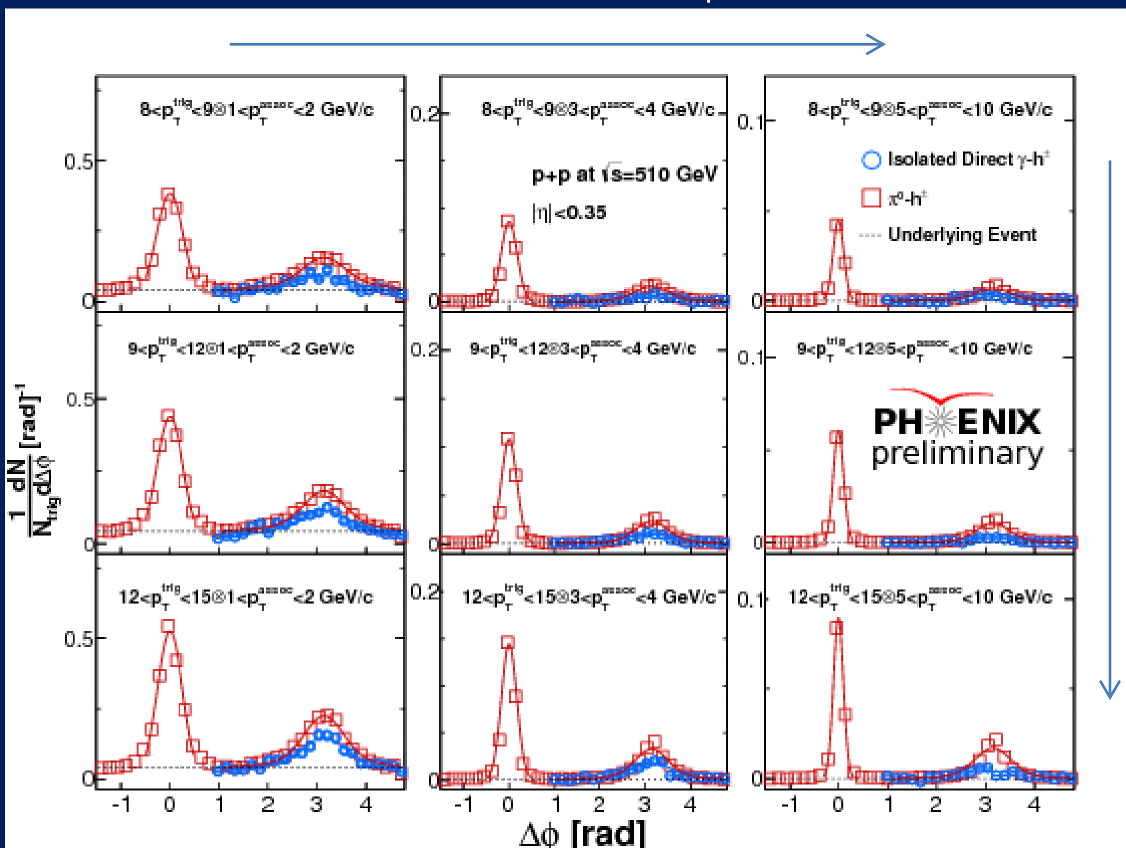


- Additional place for gluon to attach in π^0 – charged hadron correlations compared to direct photon – charged hadron correlations
- Additional nonperturbative transverse momentum from pion fragmentation

- Both measurements at $\sqrt{s}$ = 510 GeV, midrapidity

Two-particle azimuthal angular correlations

Associated charged hadron p_T increasing



Trigger photon or pion p_T increasing

- Angular distribution of "associated" charged hadrons around a "trigger" photon or π^0
- Two-jet structure seen for pion-hadron correlations
- Away-side jet structure seen for direct photon – hadron correlations
  - Isolation cut on near side
- Trigger particle p_T shown here ranges from 8-15 GeV/c → hard scale

Terminology

- "TMD-factorization breaking"
- "Color entanglement"
- "Correlated partons across colliding protons"

- All refer to same predicted phenomenon

Entanglement

- Consider familiar case of spins of two-electron system
- Non-entangled cases, e.g.

$$|\uparrow\rangle\,|\downarrow\rangle$$

$$|\uparrow\rangle\,|\downarrow\rangle + |\downarrow\rangle\,|\downarrow\rangle = (|\uparrow\rangle + |\downarrow\rangle)|\downarrow\rangle$$

- Entangled cases, e.g.

$$|\uparrow\rangle\,|\uparrow\rangle + |\downarrow\rangle\,|\downarrow\rangle$$

$$|\uparrow\rangle\,|\downarrow\rangle - |\downarrow\rangle\,|\uparrow\rangle$$

- In entangled cases the two spins are correlated
  - Don't factorize from one another
  - Any interactions are with the two-electron system as a whole

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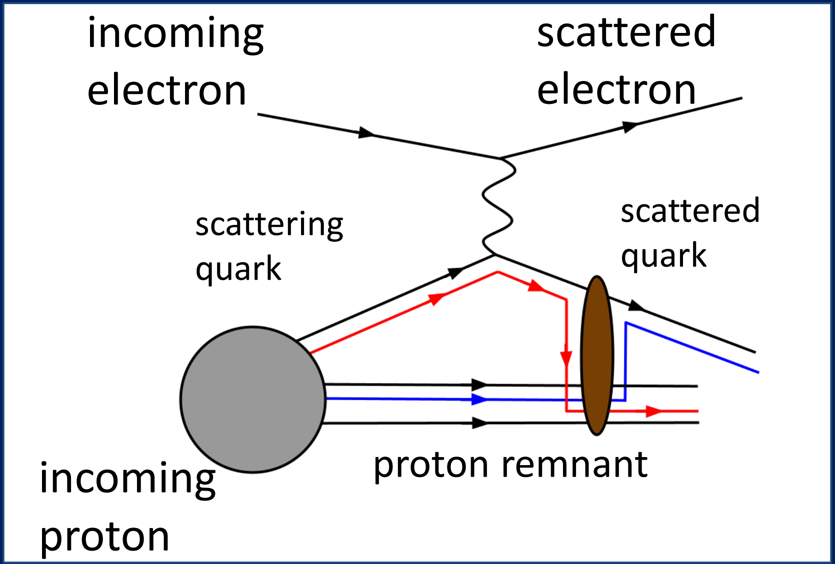
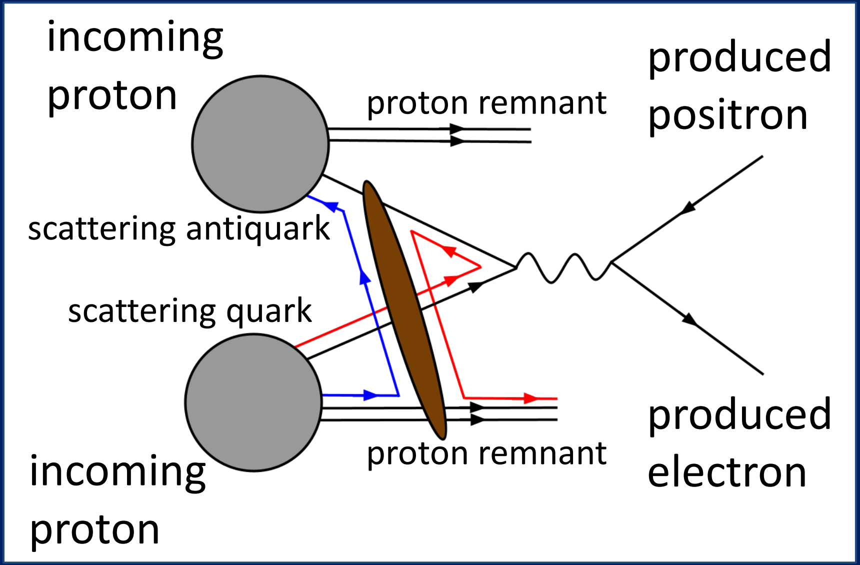
Deep-inelastic lepton-nucleon scattering: Final-state color exchange



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



Can think of the parton getting its phase shifted by passing through the potential

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

field of the proton remnant. Relative phase shift difference of π between the two processes. See e.g. Pijlman, hep-ph/0604226 or Sivers, arXiv:1109.2521.

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"

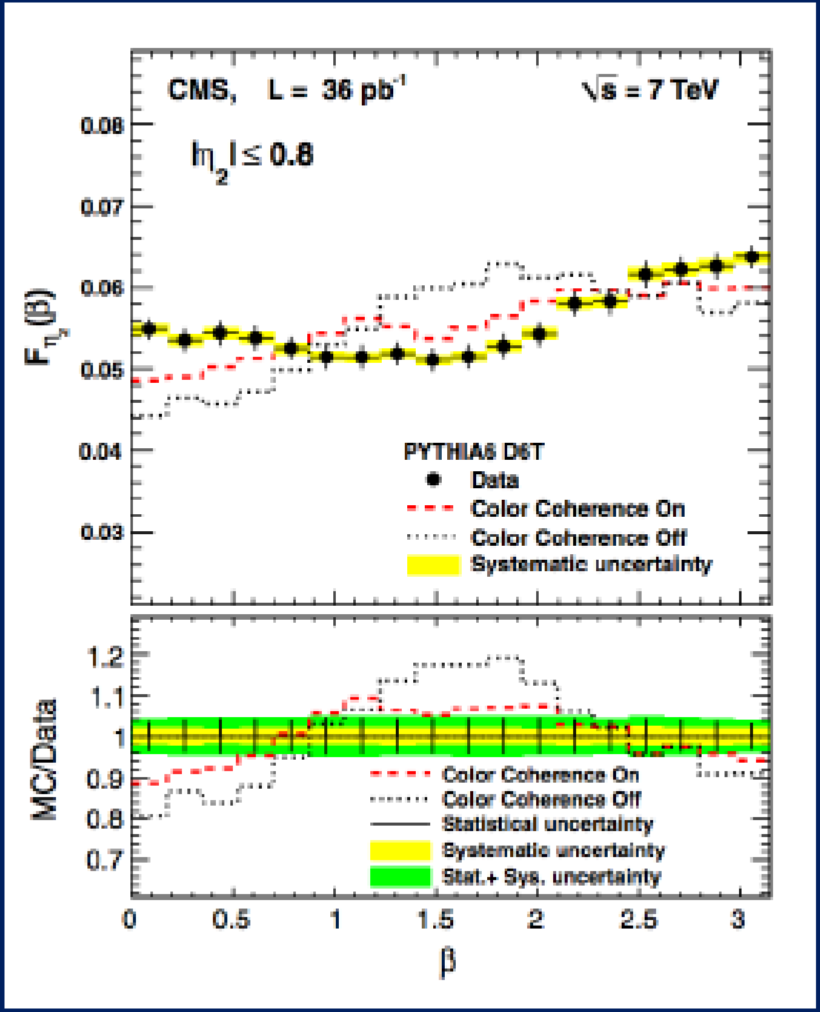
"Color coherence" in e+e-, p(bar)p

- "Color coherence" ideas about increased soft radiation between color-connected partons/remnants go back to e+e- measurements in the 1980s, e.g.
  - TPC/2*g* Collaboration, "Comparison of the Particle Flow in q-qbar-g and q-qbar-γ 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 $E_{c.m.}$ = 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

- 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

- 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

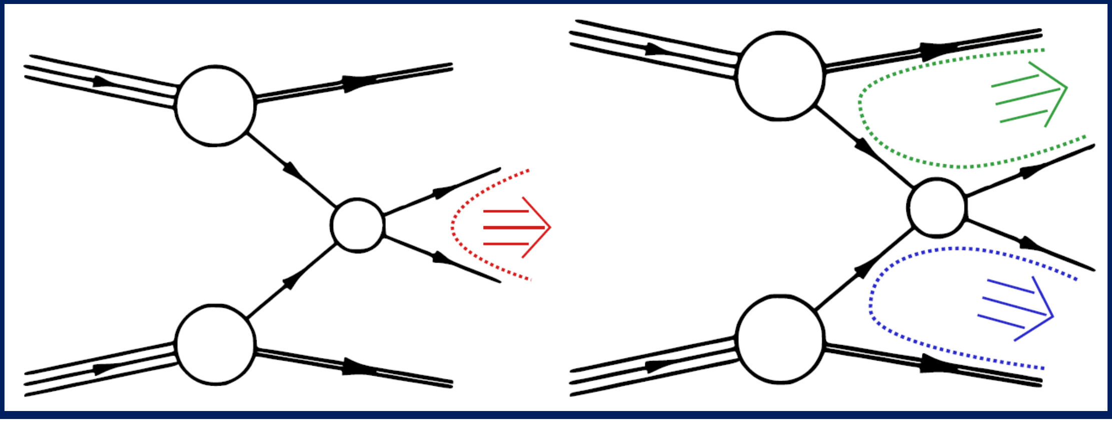


FIG. 1: Possible color connections for signal ($pp \to H \to b\bar{b}$) and for background ($pp \to g \to b\bar{b}$).

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 ttbar 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"