Nucleon Structure and the Electron-Ion Collider

Lecture 1: Nucleon Structure and QCD

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GRK Retreat

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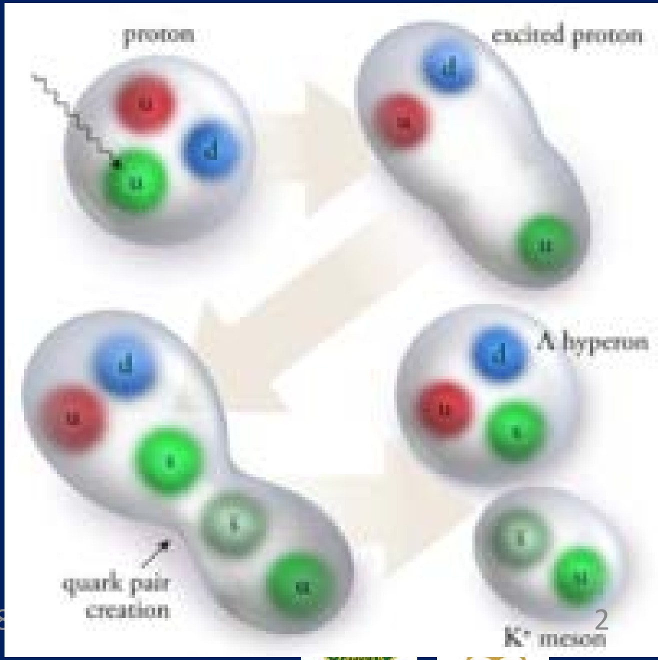
Theory of strong nuclear interactions: Quantum Chromodynamics

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

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



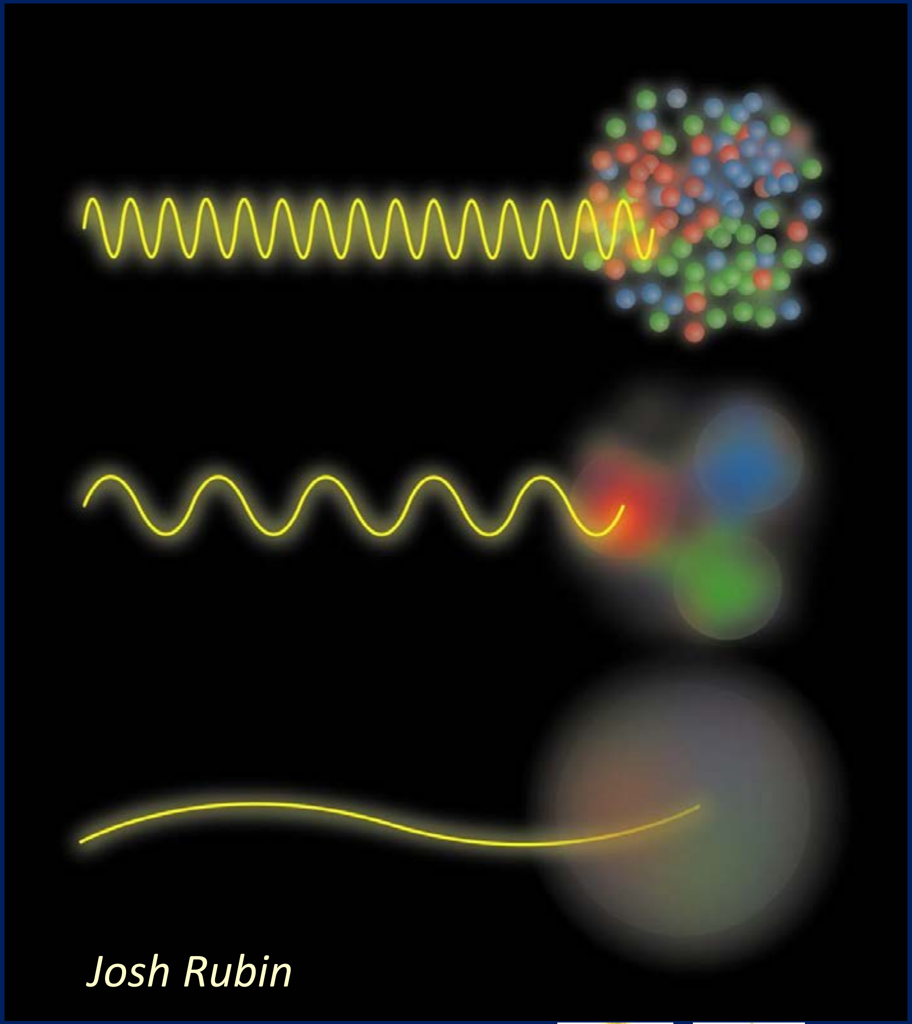
CLAS, PRL 113, 152004 (2014)
PRL Editor's Choice Oct. 2014

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?

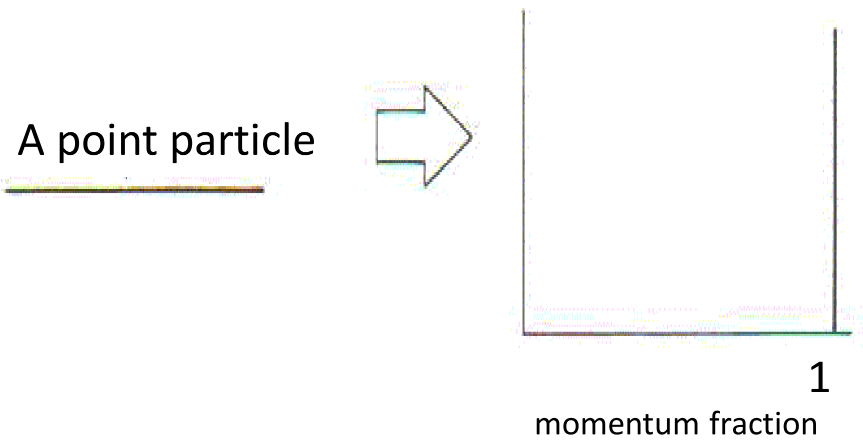
The proton as a "laboratory" for studying QCD

- 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 …



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

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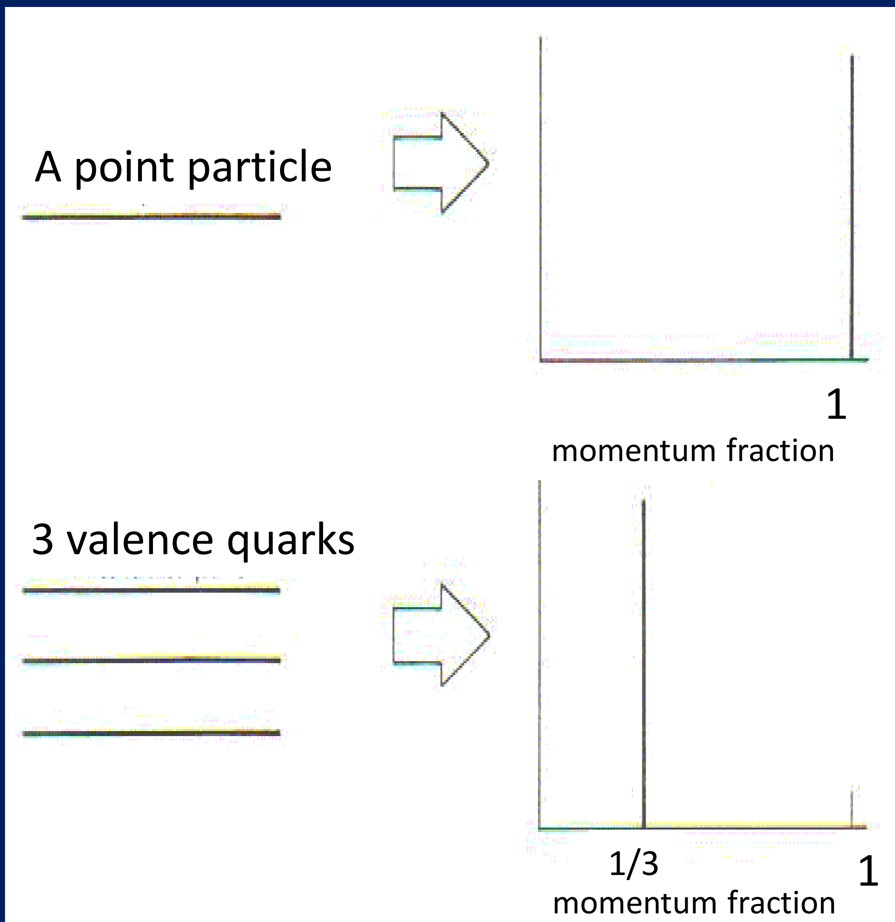

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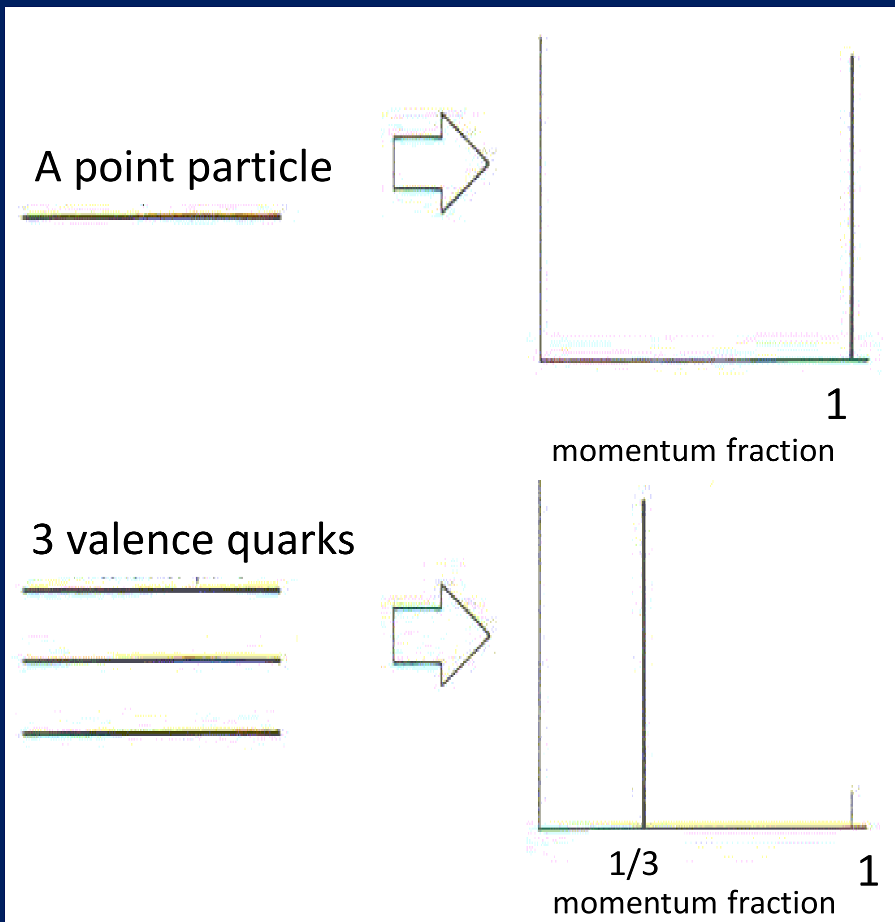

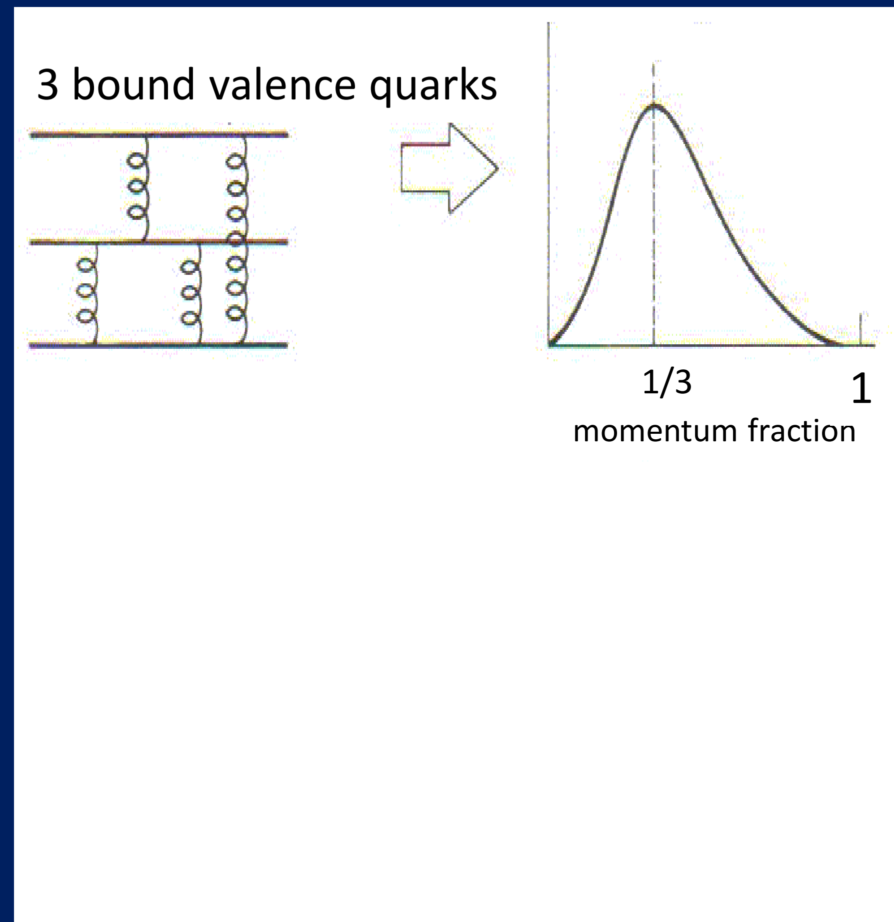

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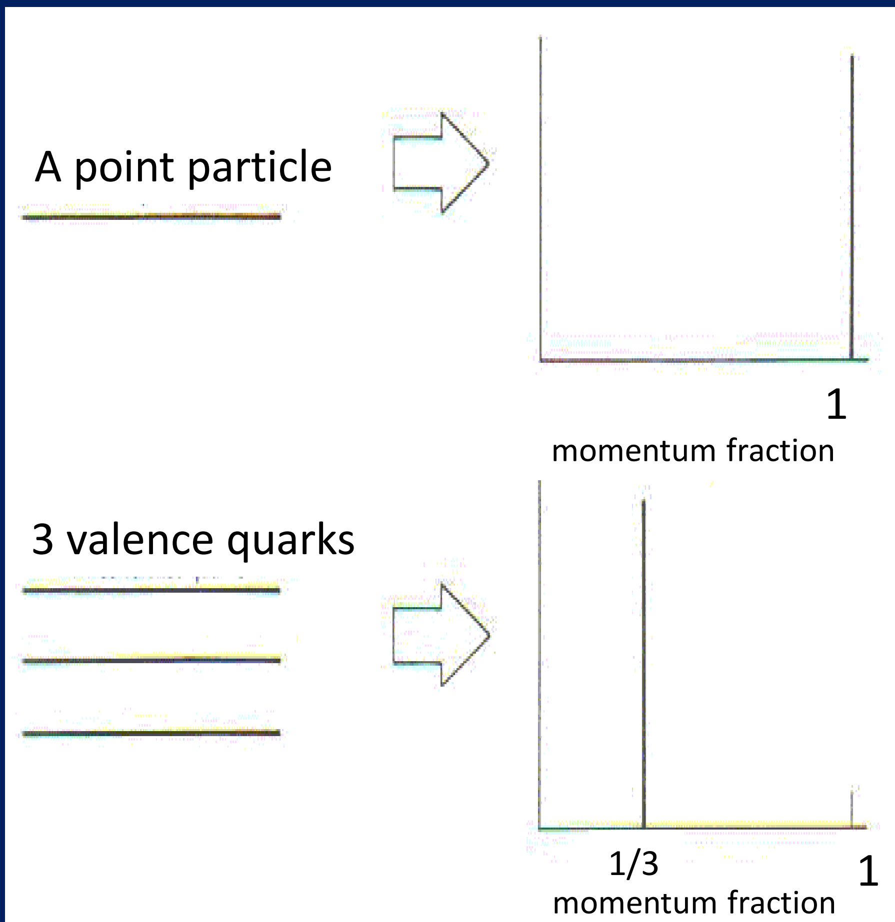

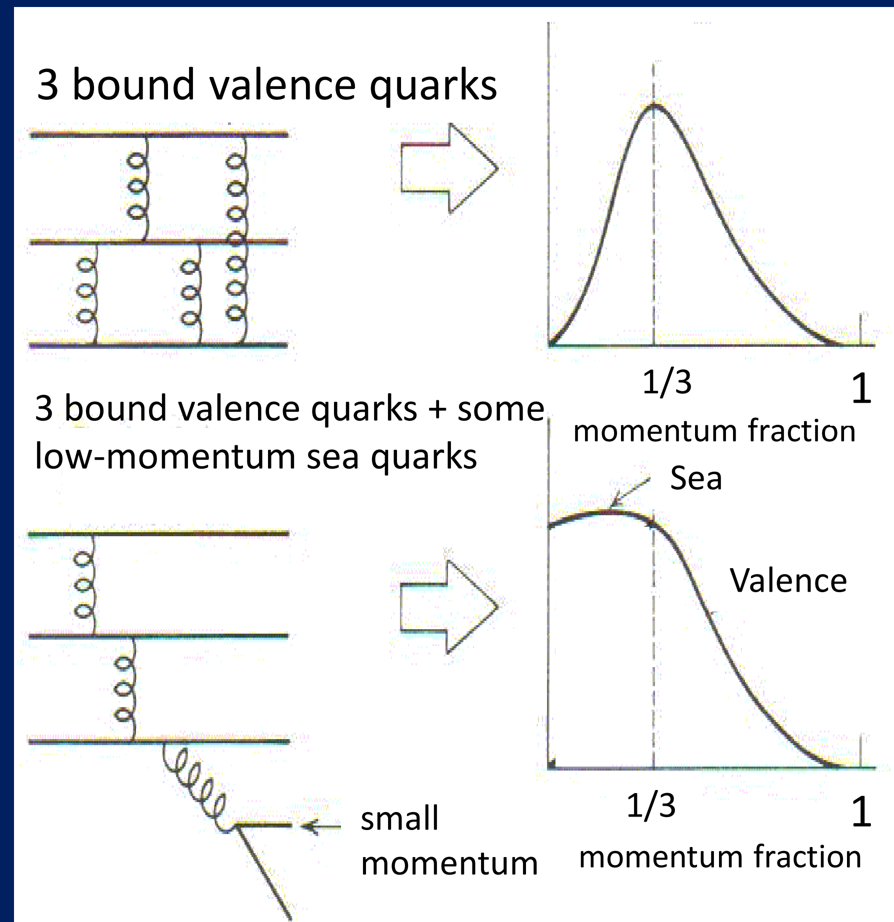

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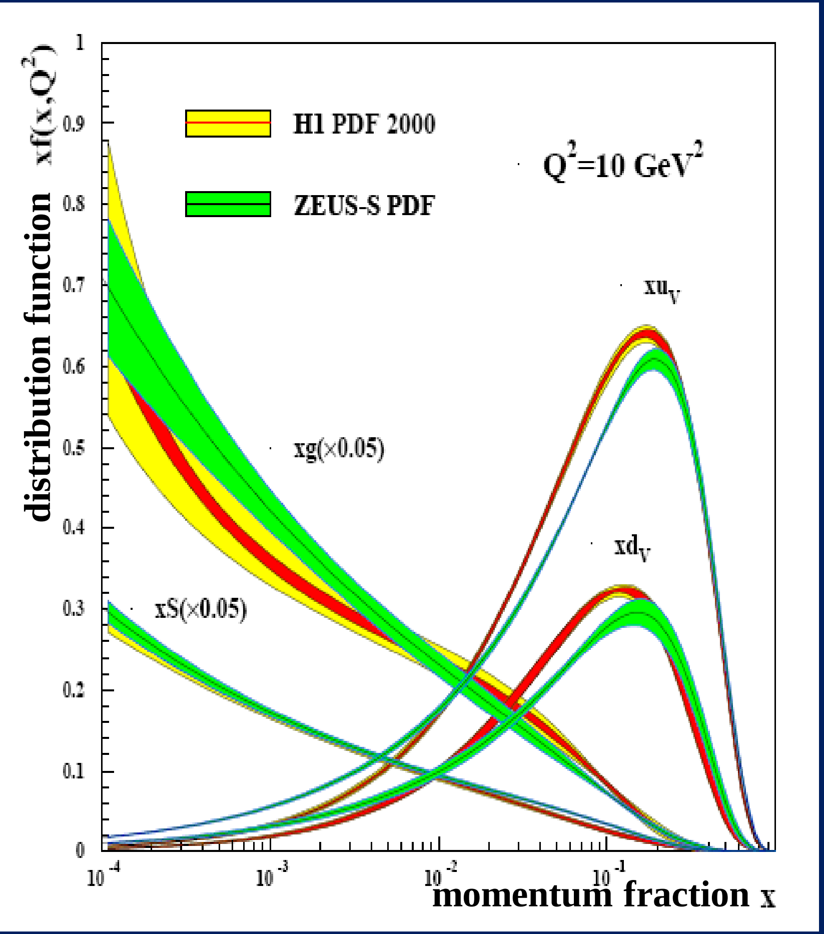
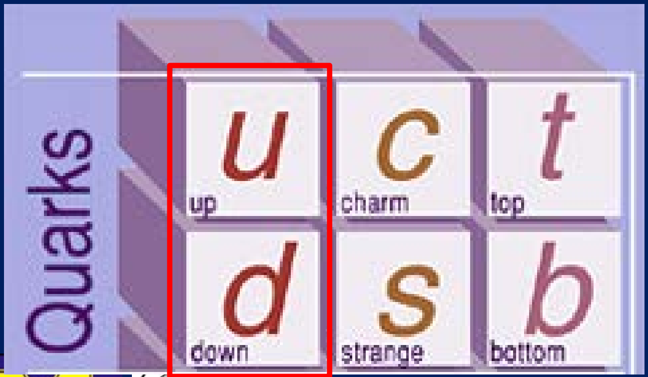
What have we learned in terms of this picture by now?

- Up and down quark "valence" distributions peaked ~1/3
- Lots of sea quark-antiquark pairs and even more gluons!





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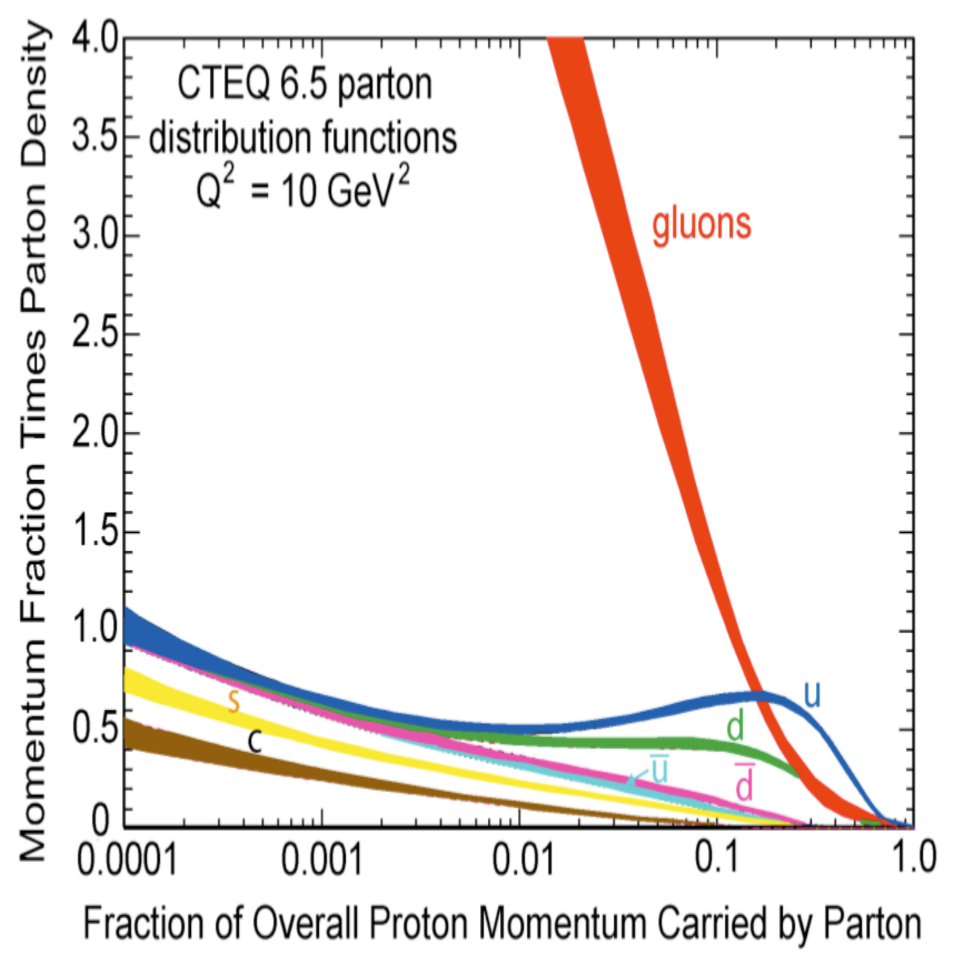
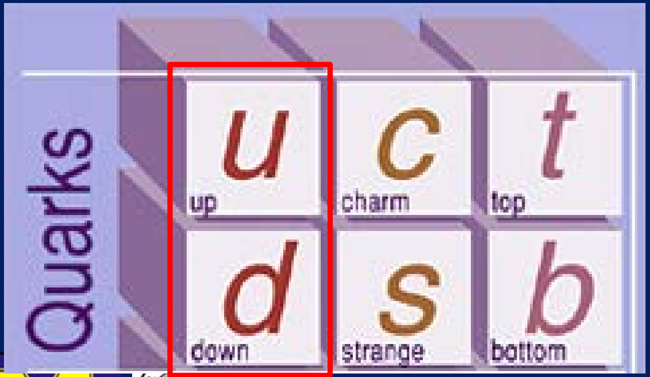
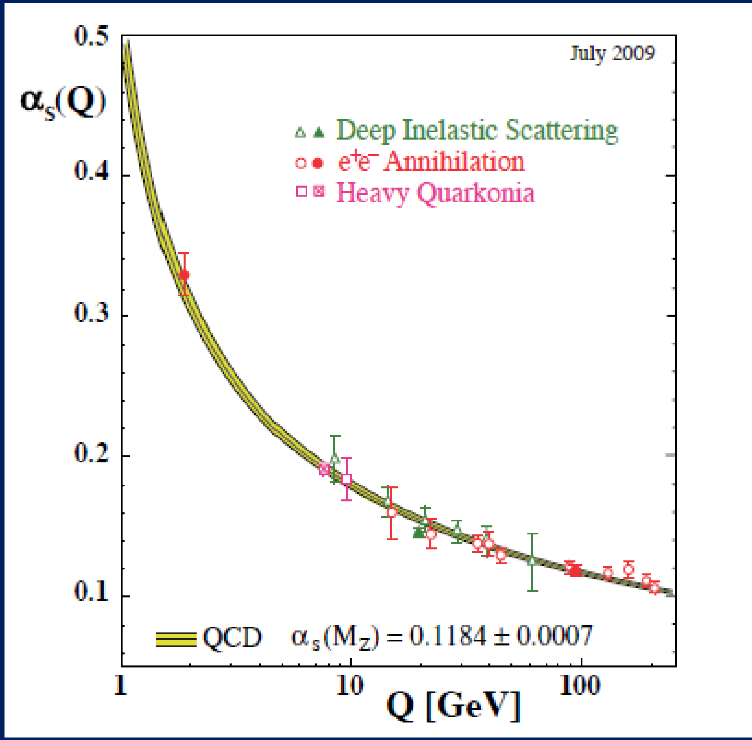




Perturbative QCD

- 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!!)



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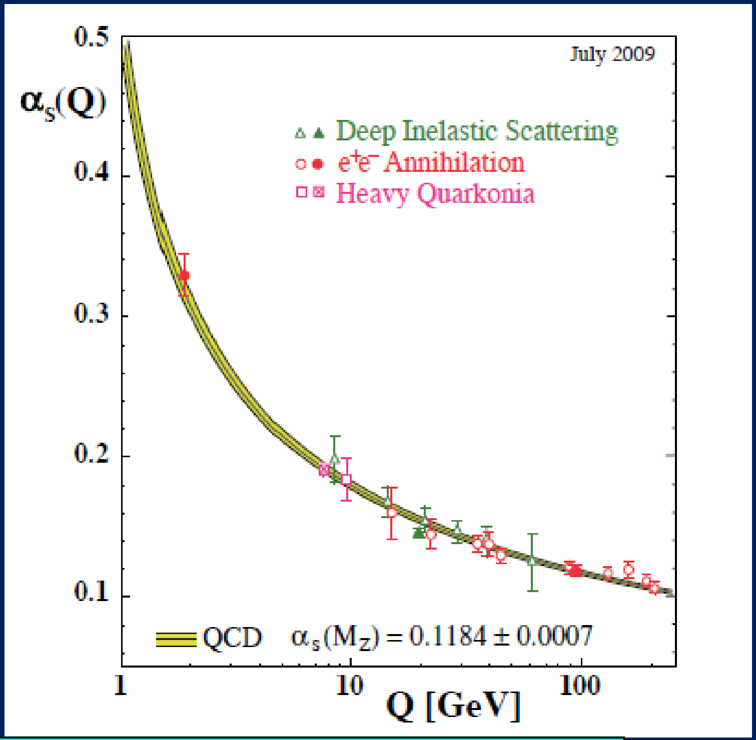

Provides one rigorous way of relating the fundamental field theory to a variety of physical observables!

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 ~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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  functions describing structure n
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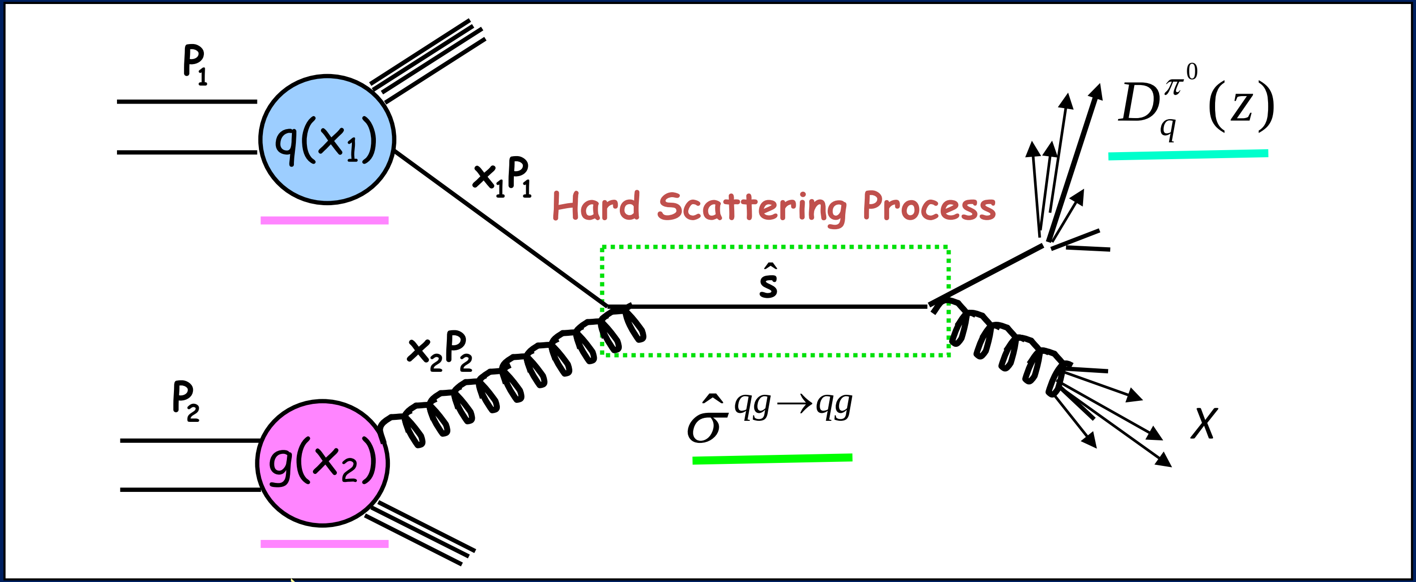
Note: Nonperturbative lattice QCD techniques have made tremendous progress toward *ab initio* calculations of proton structure in last ~5 years!

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*

PDFs and FFs in pQCD calculations of observables



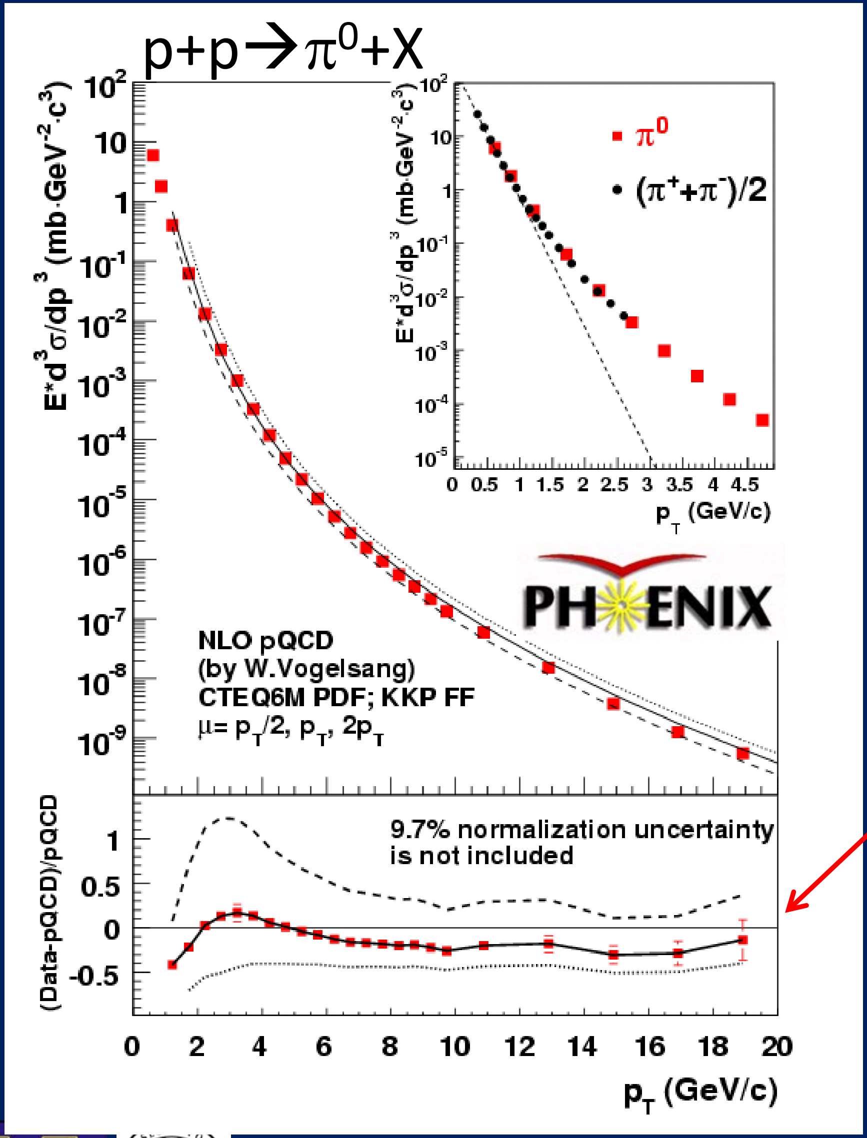
$$\sigma\left(pp \to \pi^0 X\right) \propto \underline{q(x_1) \otimes g(x_2)} \otimes \underline{\hat{\sigma}^{qg\to qg}(\hat{s})} \otimes \underline{D_q^{\pi^0}(z)}$$

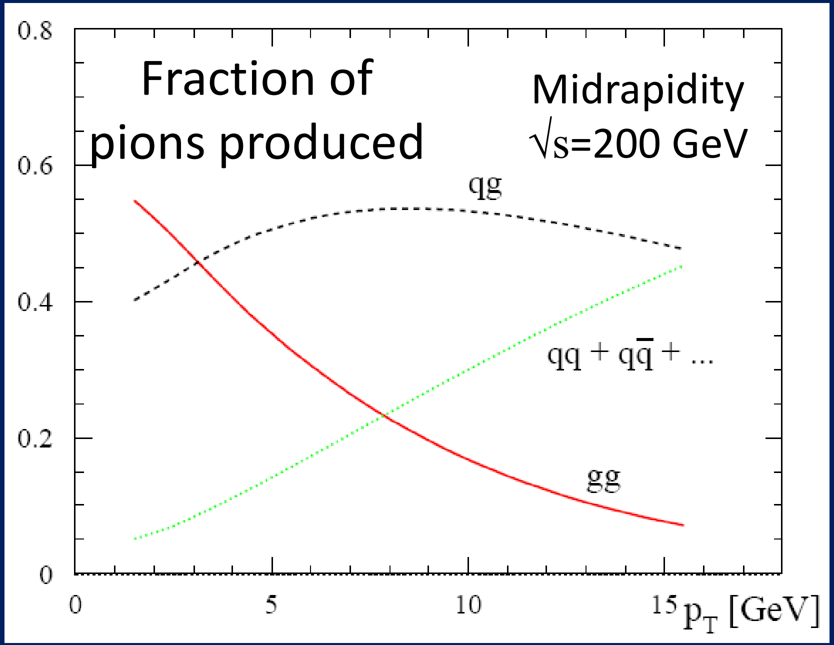
High-energy processes have predictable rates given:

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

} Universal non-perturbative factors

pQCD in action at $\sqrt{s}$=200 GeV





Systematic uncertainty on calculation due to factorization, renormalization, and fragmentation scale dependence. All three scales taken as equal and varied from $p_T/2$ to $2p_T$.
Cross section prediction varies by tens of percent here.

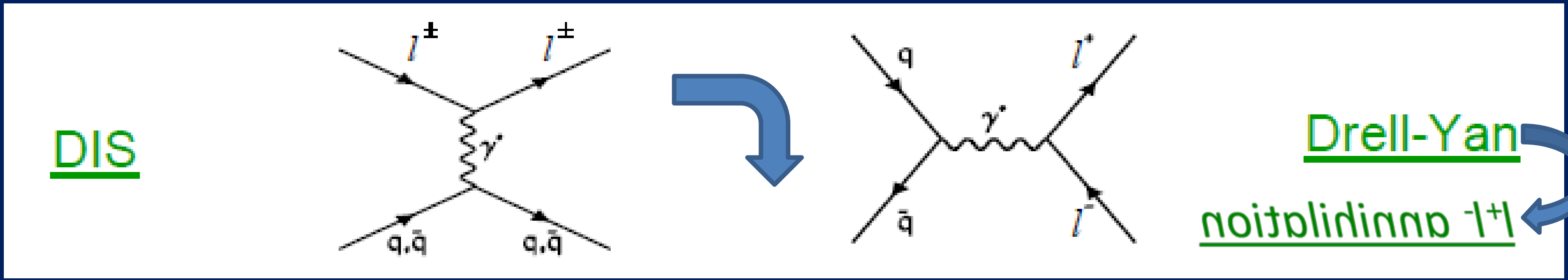
Complementary scattering systems

- Learn from p+p results in conjunction with information from simpler systems
  - Many subprocesses contribute to (e.g.) inclusive hadron production in p+p collisions—couldn't disentangle them with p+p data alone
  - (A few processes are simpler, e.g. Drell-Yan process of quark-antiquark annihilation to leptons)

- Most knowledge of PDFs from deep-inelastic lepton-nucleon scattering (DIS)

- Most knowledge of fragmentation functions from e+e- annihilation to qqbar

Complementary scattering systems



- Note that Drell-Yan, DIS, and e+e- are all *QED* processes involving hadrons
- Once you have reasonably constrained PDFs and/or FFs, can use p+p data to further refine those constraints
  - Hadronic collisions have been important in constraining *gluons*—interact at leading order. E.g. pion production results 2 slides ago have improved constraints on gluon → pion FFs
  - Hadronic collisions also open up opportunities to explore unique aspects of QCD…

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!

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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.

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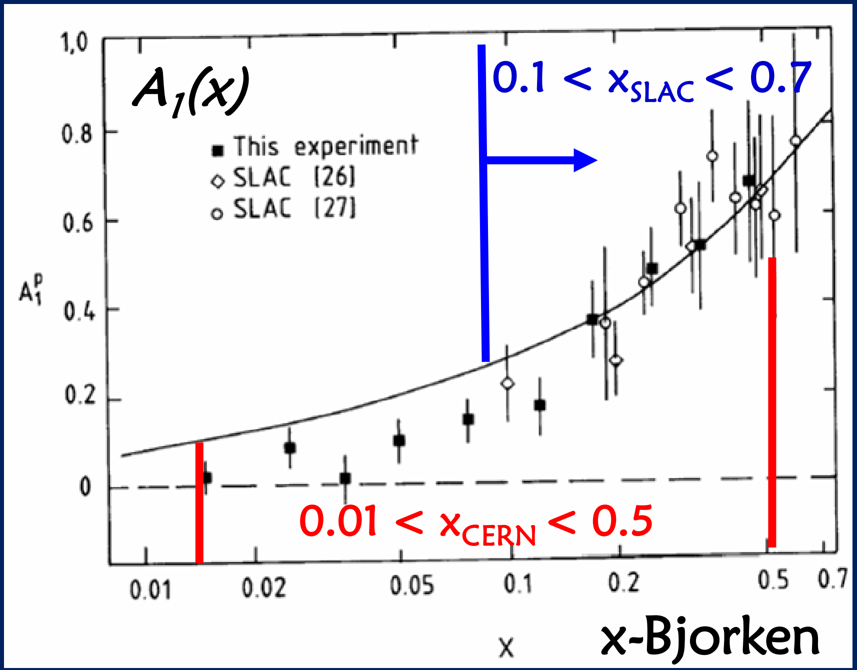
Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color flow have come to forefront in last few years . . .

Spin-spin correlations: Proton "spin crisis"

SLAC: *0.10 < x <0.7*

CERN: *0.01 < x <0.5*

$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$



$\Delta\Sigma_{SLAC} \sim 0.6$ Quark–Parton Model expectation

E130, Phys.Rev.Lett.51:1135 (1983)
518 citations

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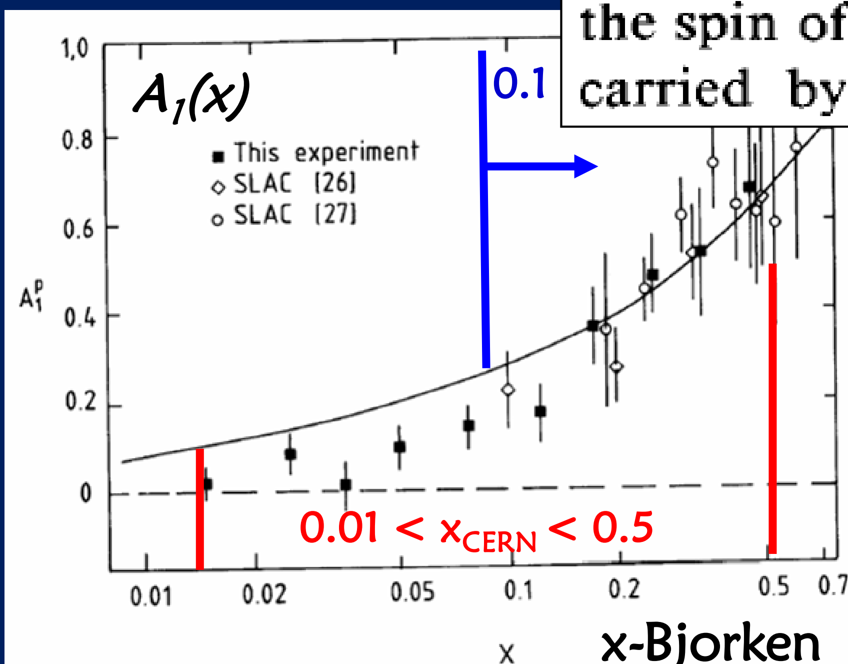
$$\frac{1}{2} = \frac{1}{2}\cdot\Delta\Sigma + \Delta G + L_{G+q}$$

Hence (14 ± 9 ± 21)% of the proton spin is carried by the spin of the quarks. The remaining spin must be carried by gluons or orbital angular momentum



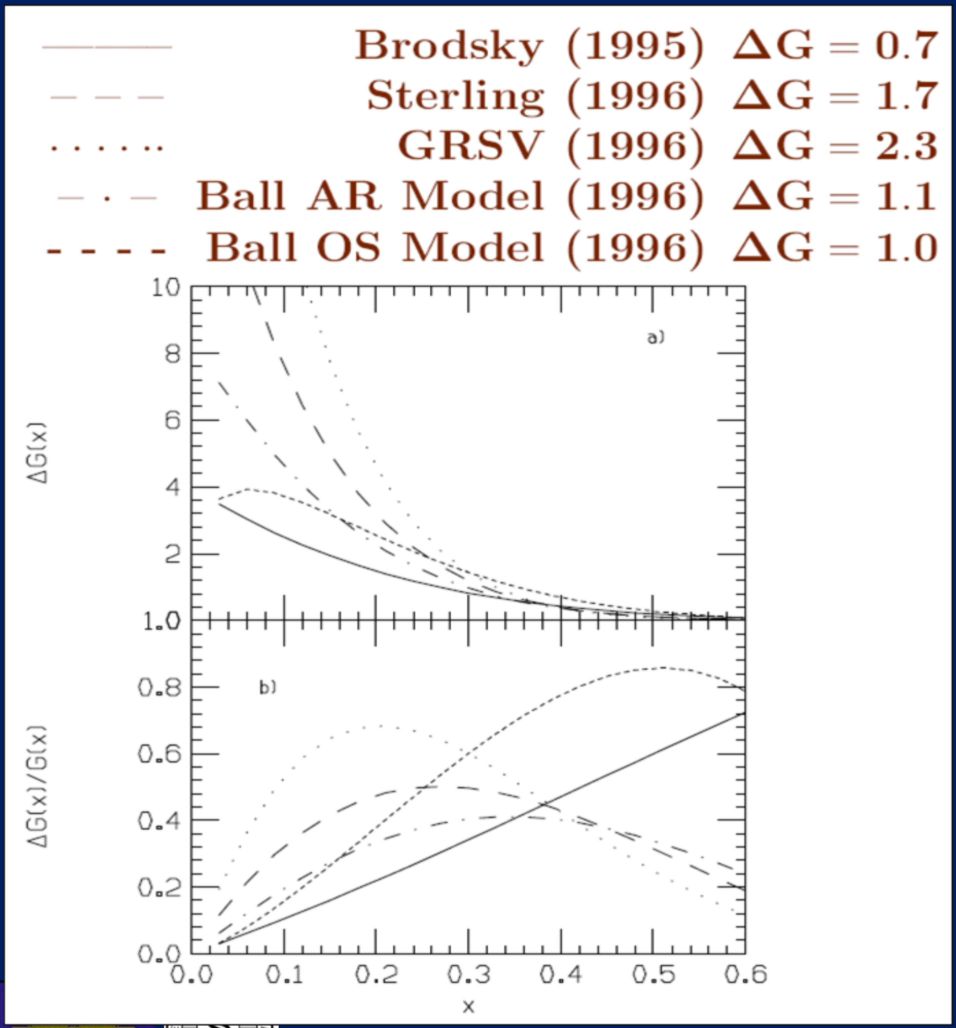
These haven't been easy to measure!

EMC (CERN), Phys.Lett.B206:364 (1988)

2057 citations!

"Proton Spin Crisis"

Quest for ΔG, gluon spin contribution to spin of proton



- In mid-1990s predictions for the integrated gluon spin contribution to proton spin ranged from 0.7 – 2.3!
  - Many models hypothesized large gluon spin contributions to screen the quark spin, but these would then require large orbital angular momentum in the opposite direction

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July 2014

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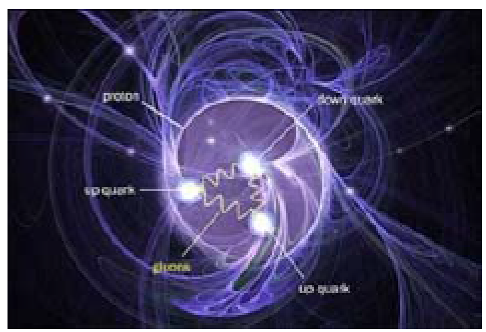
Proton Spin Mystery Gains a New Clue

Physicists long assumed a proton's spin came from its three constituent quarks. New measurements suggest particles called gluons make a significant contribution

By Clara Moskowitz | July 21, 2014



Brookhaven National Laboratory

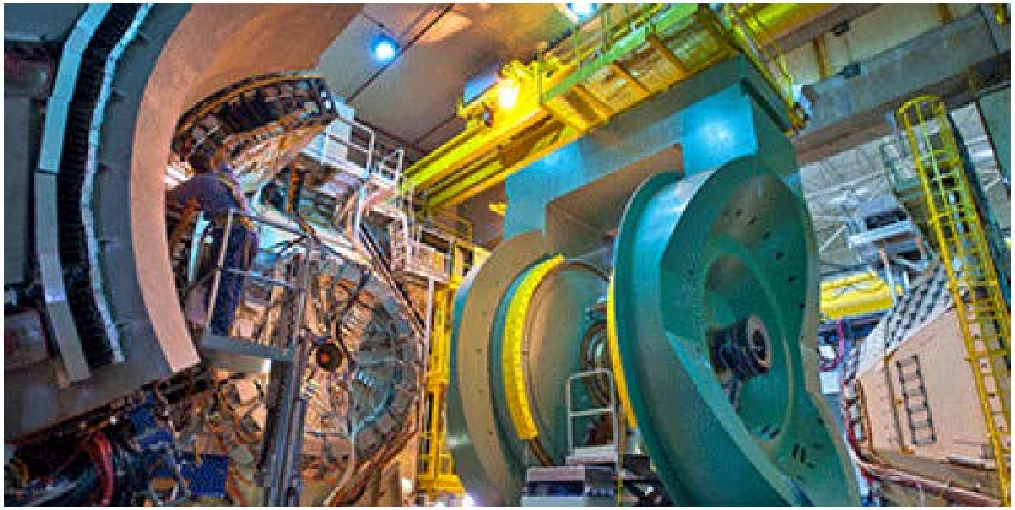
Protons have a constant spin that is an intrinsic particle property like mass or charge. Yet where this spin comes from is such a mystery it's dubbed the "proton spin crisis." Initially physicists thought a proton's spin was the sum of the spins of its three constituent quarks. But a 1987 experiment showed that quarks can account for only a small portion of a proton's spin, raising the question of where the rest arises. The quarks inside a proton are held together by gluons, so scientists suggested perhaps they contribute spin. That idea now has support from a pair of studies analyzing the results of proton collisions inside the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, N.Y.

Physics

Synopsis: Gluons Chip in for Proton Spin

July 2, 2014

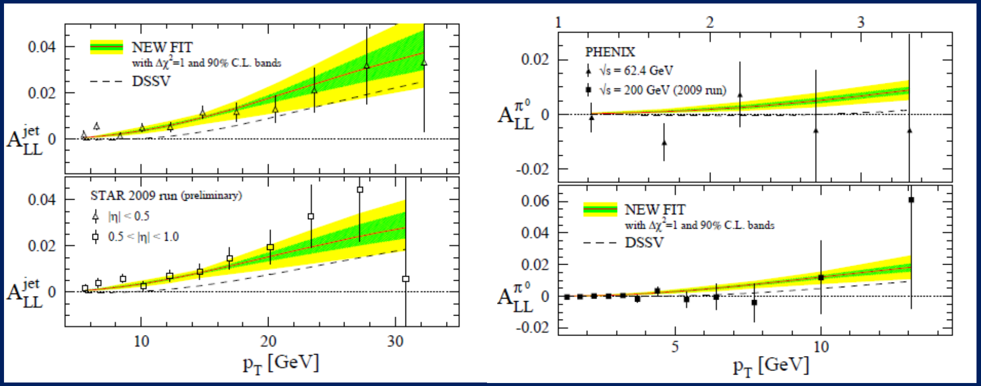
A new analysis of high-energy data shows that gluons may provide some of the proton's missing spin.

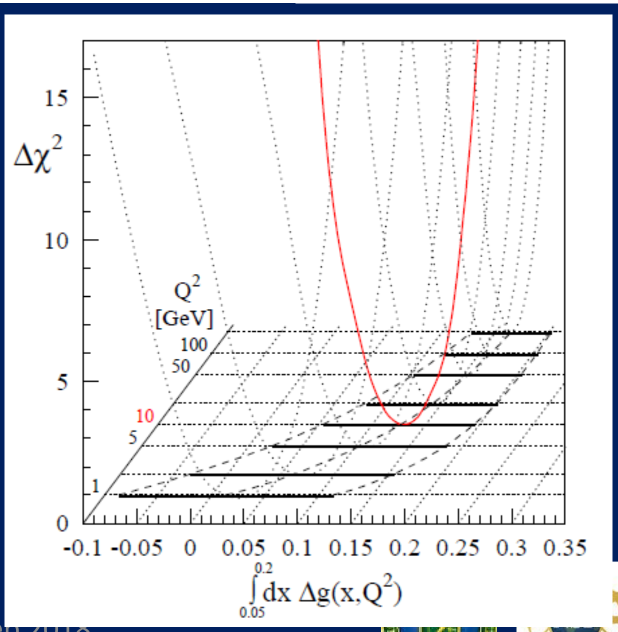


Brookhaven National Laboratory

First evidence for nonzero gluon polarization in proton

- Suite of RHIC measurements sensitive to gluon spin, using different final-state observables
  - Jets – STAR, PRD86, 032006; PRL 115, 092002
  - Neutral pions – PHENIX, PRD90, 012007





de Florian, Sassot, Stratmann, Vogelsang, PRL 113, 012001

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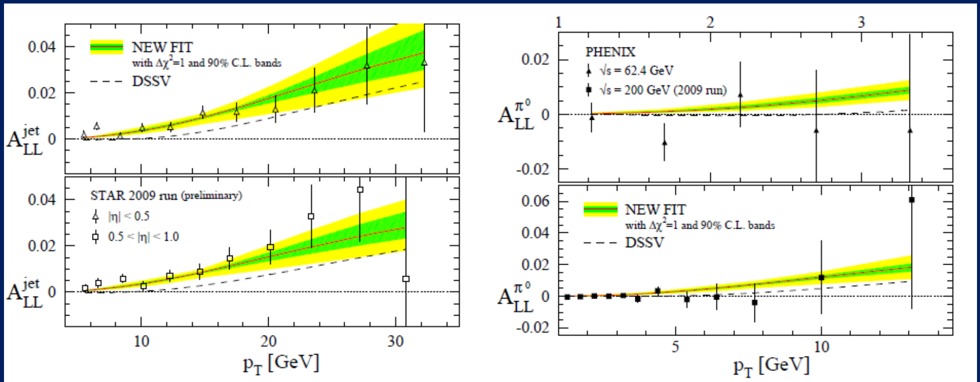
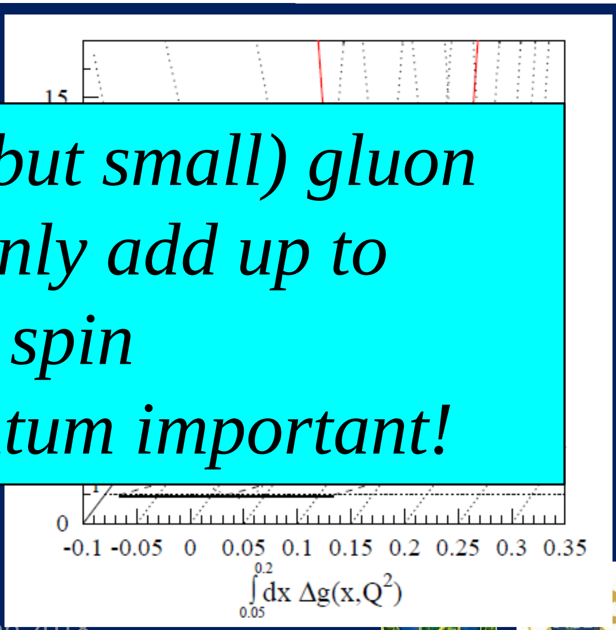


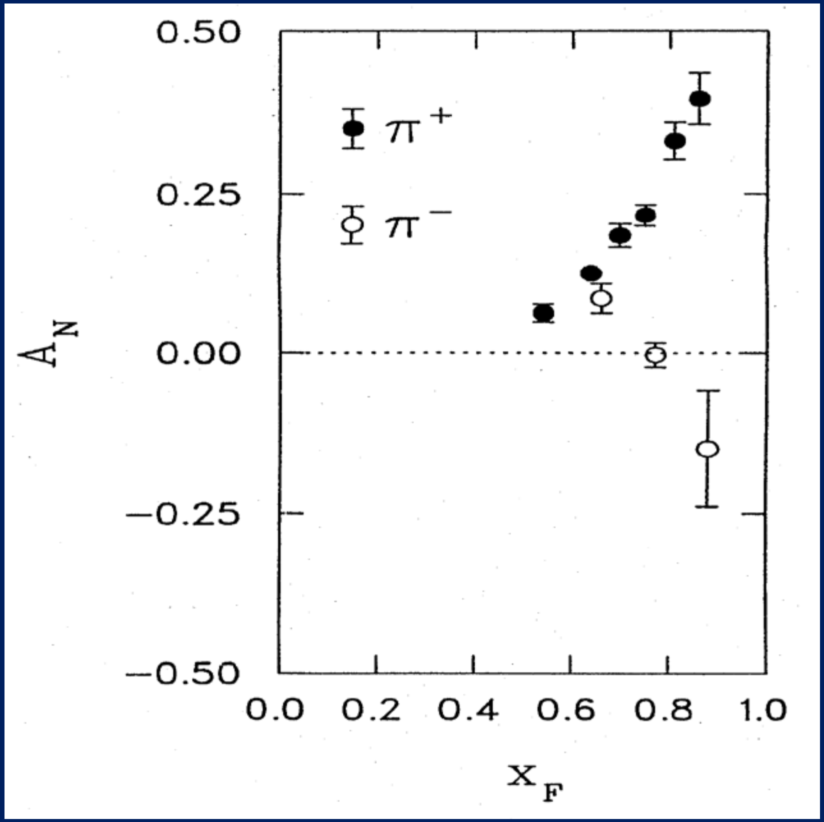
But quark spin + (nonzero but small) gluon spin contributions still only add up to ~50% of proton spin
→ Orbital angular momentum important!



de Florian, Sassot, Stratmann, Vogelsang, PRL 113, 012001

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

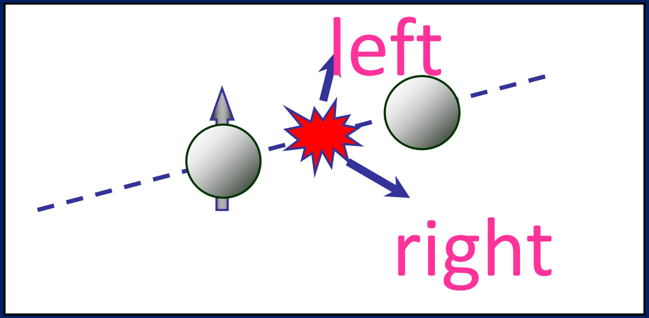
Argonne √s=4.9 GeV



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

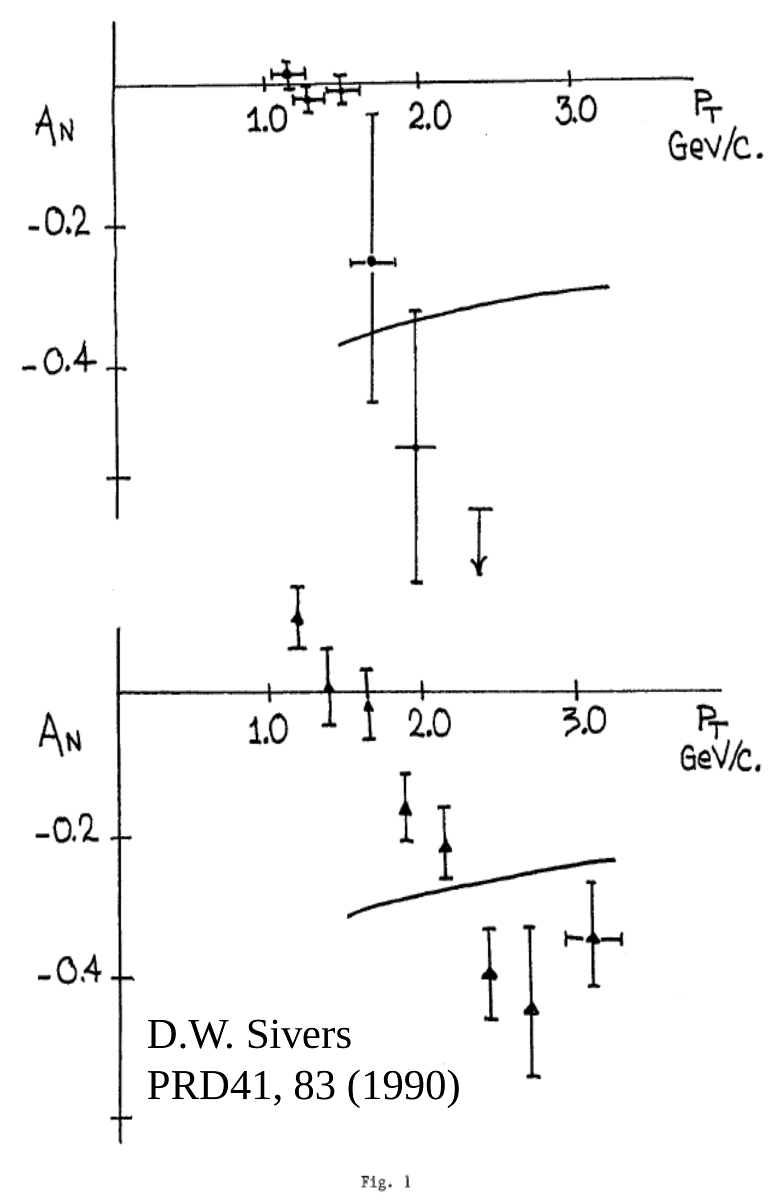
Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction—by up to 40%!!

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



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

Transverse-momentum-dependent distributions and single-spin asymmetries



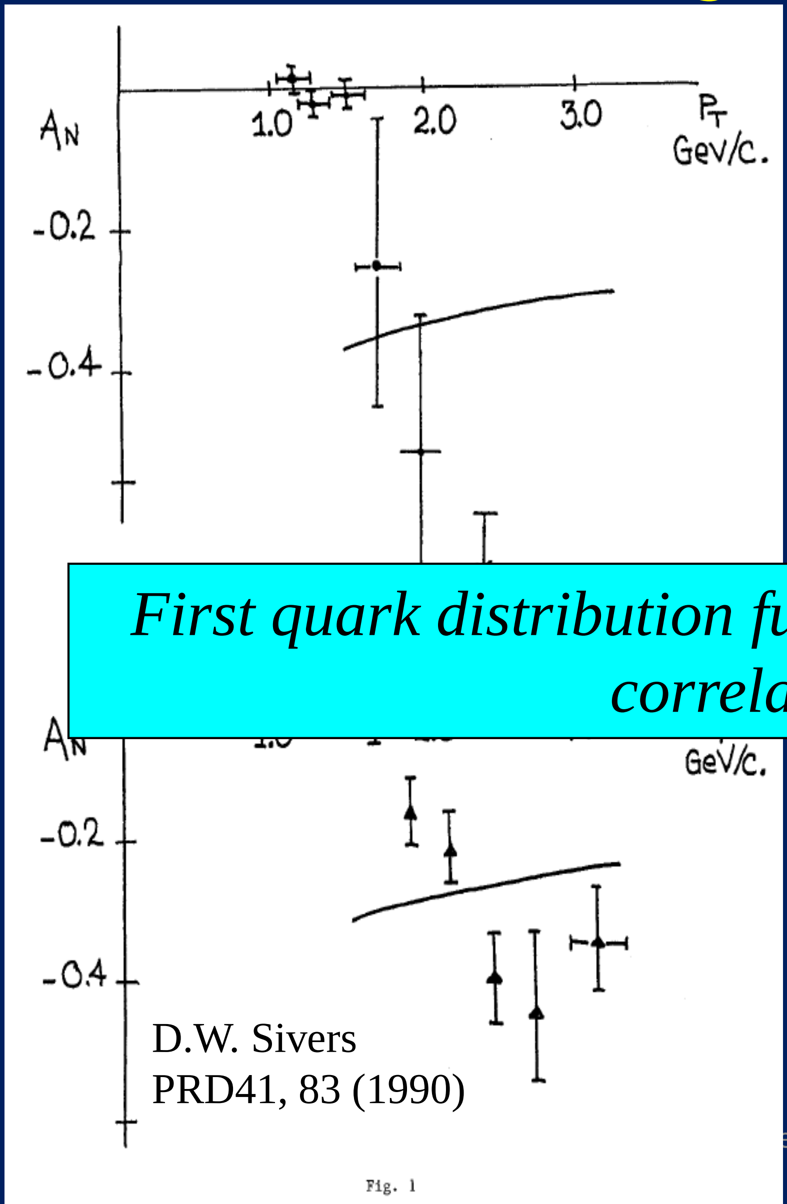
D.W. Sivers
PRD41, 83 (1990)

- 1990: 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

$$\boxed{s \cdot (p_1 \times p_2)}$$

Spin and momenta of quarks and/or bound states

Transverse-momentum-dependent distributions and single-spin asymmetries



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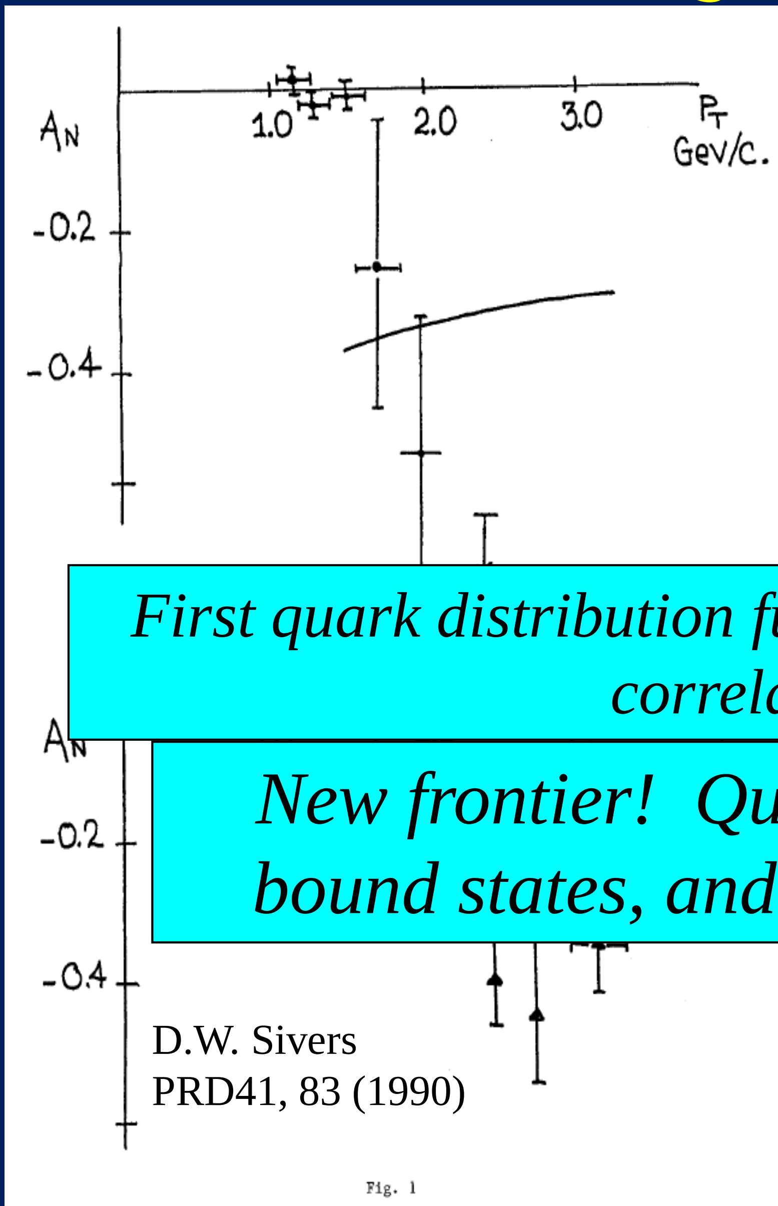

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*New frontier! Quark **dynamics** inside QCD bound states, and in their formation process*

$$\boxed{s \cdot (p_1 \times p_2)}$$

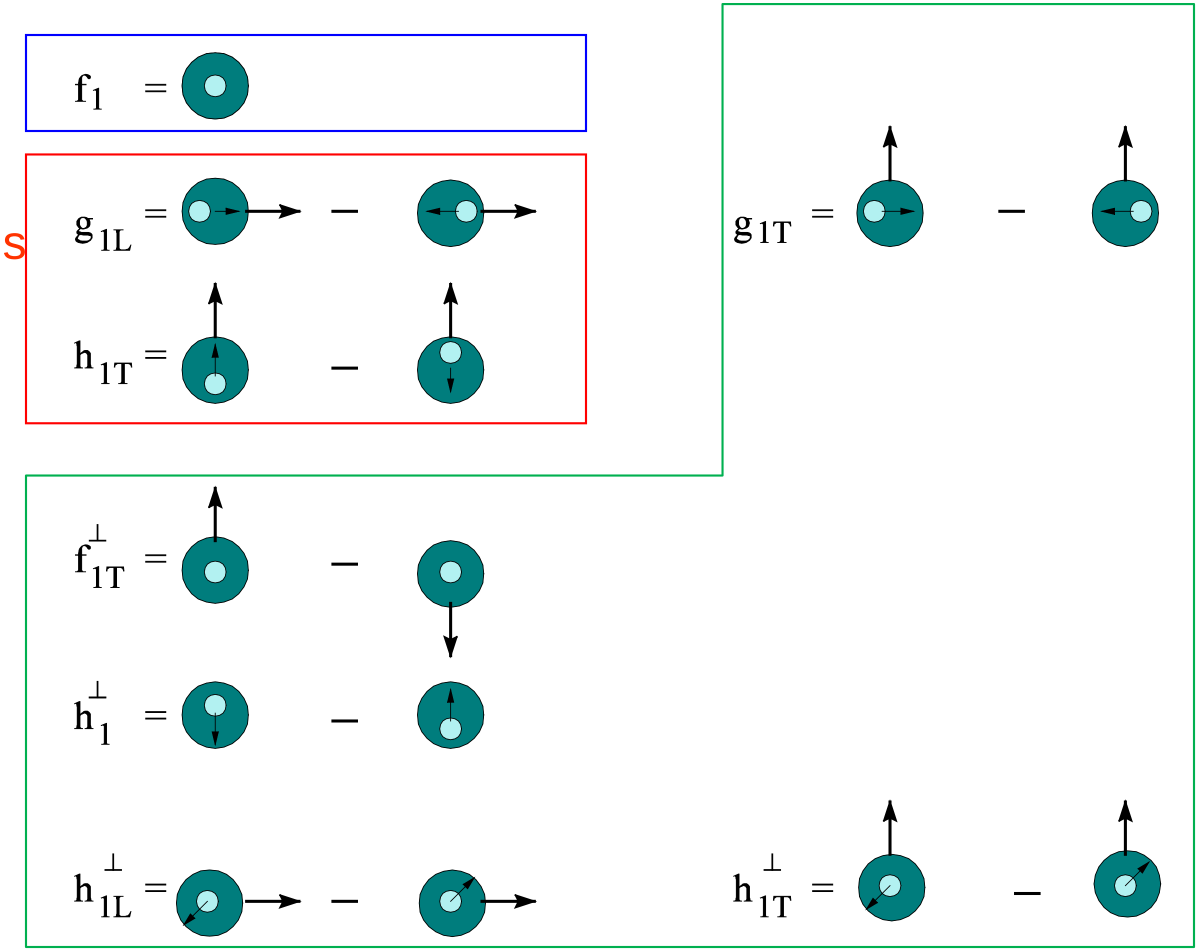
Spin and momenta of quarks and/or bound states

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

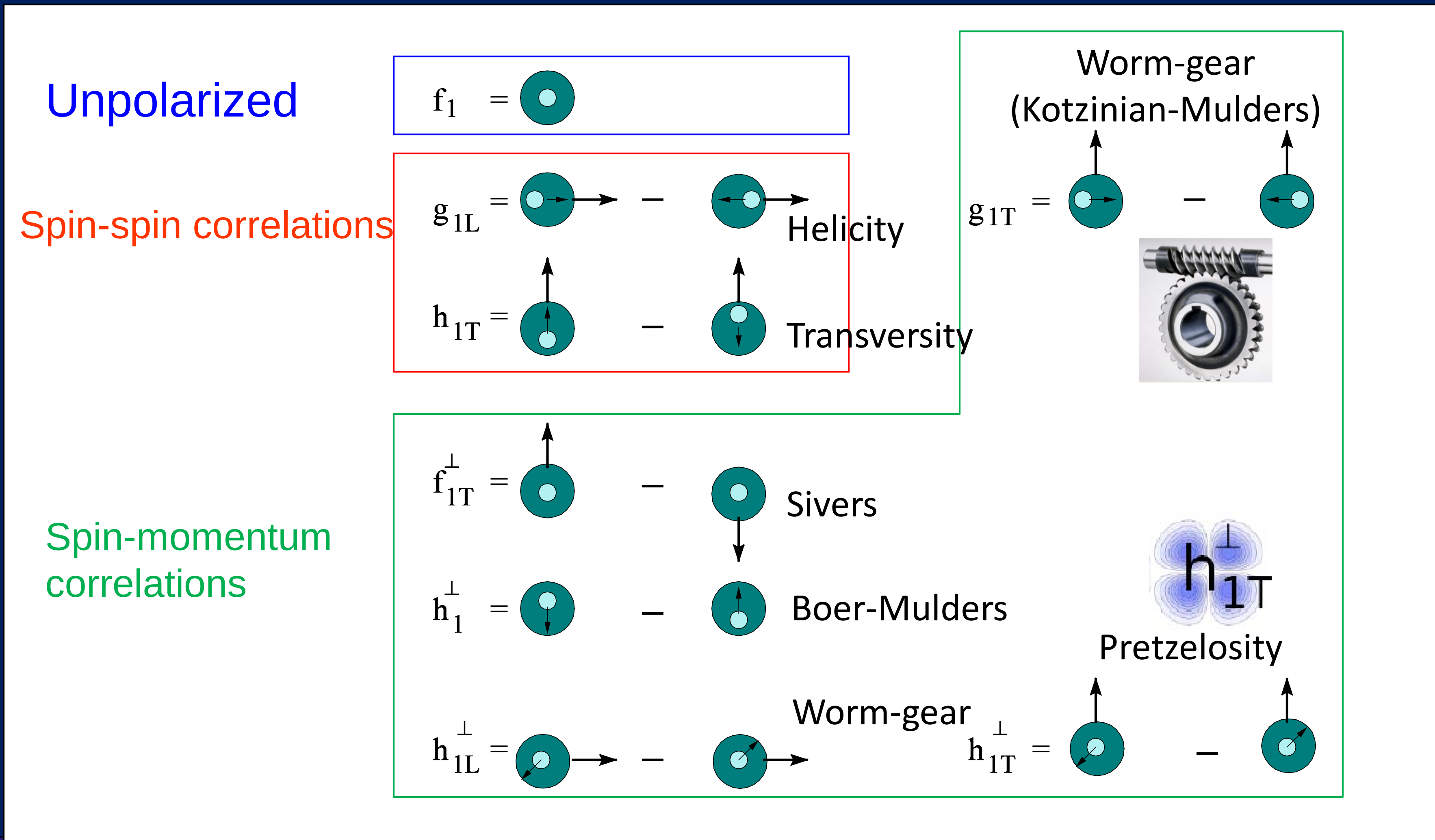
Unpolarized

Spin-spin correlations

Spin-momentum correlations



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



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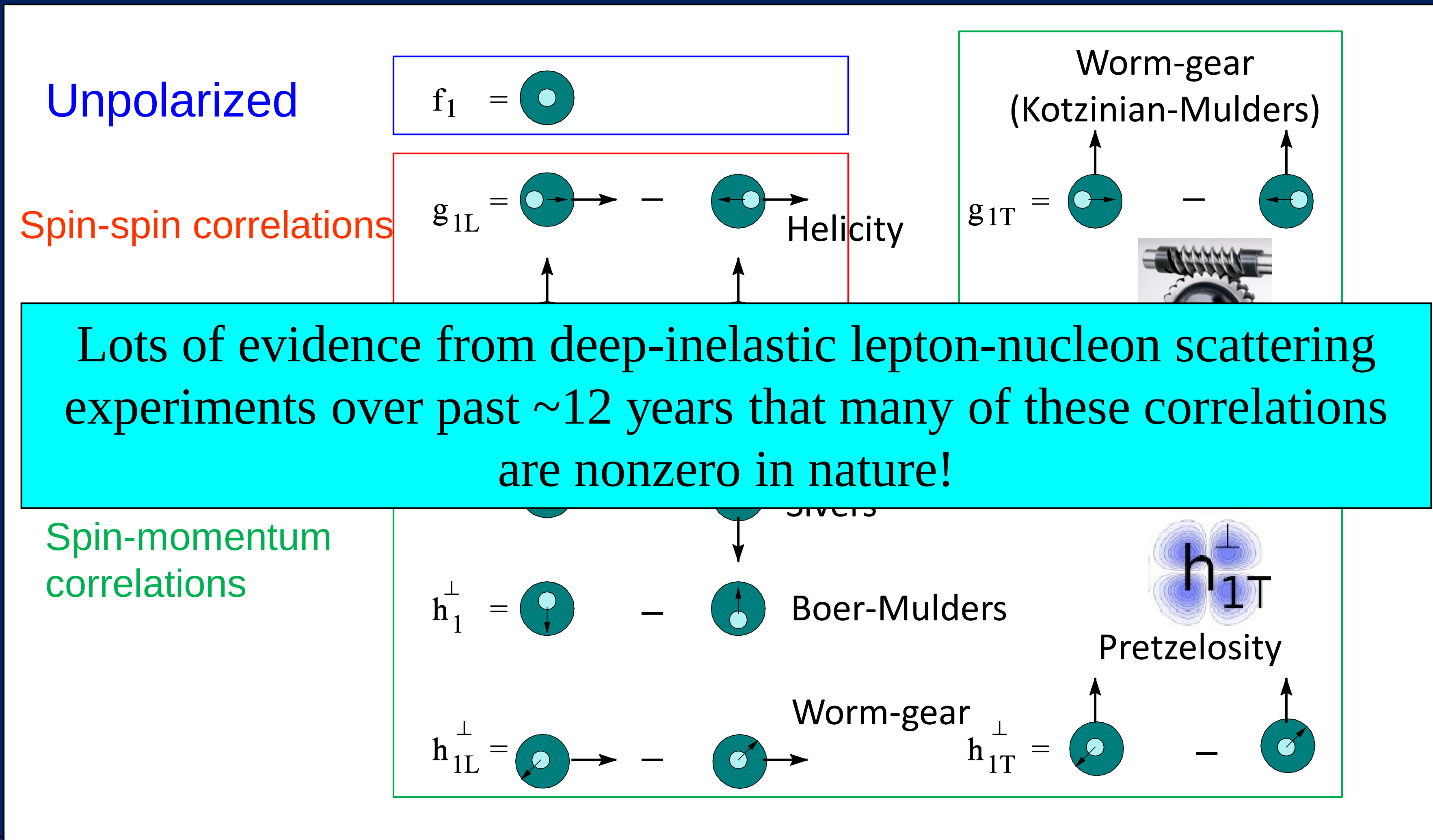
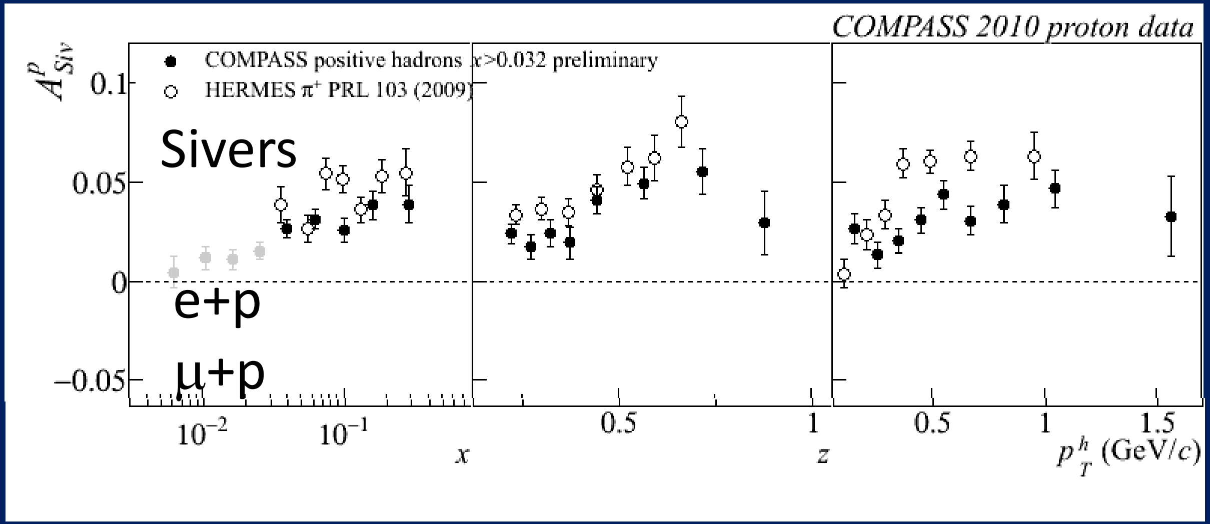
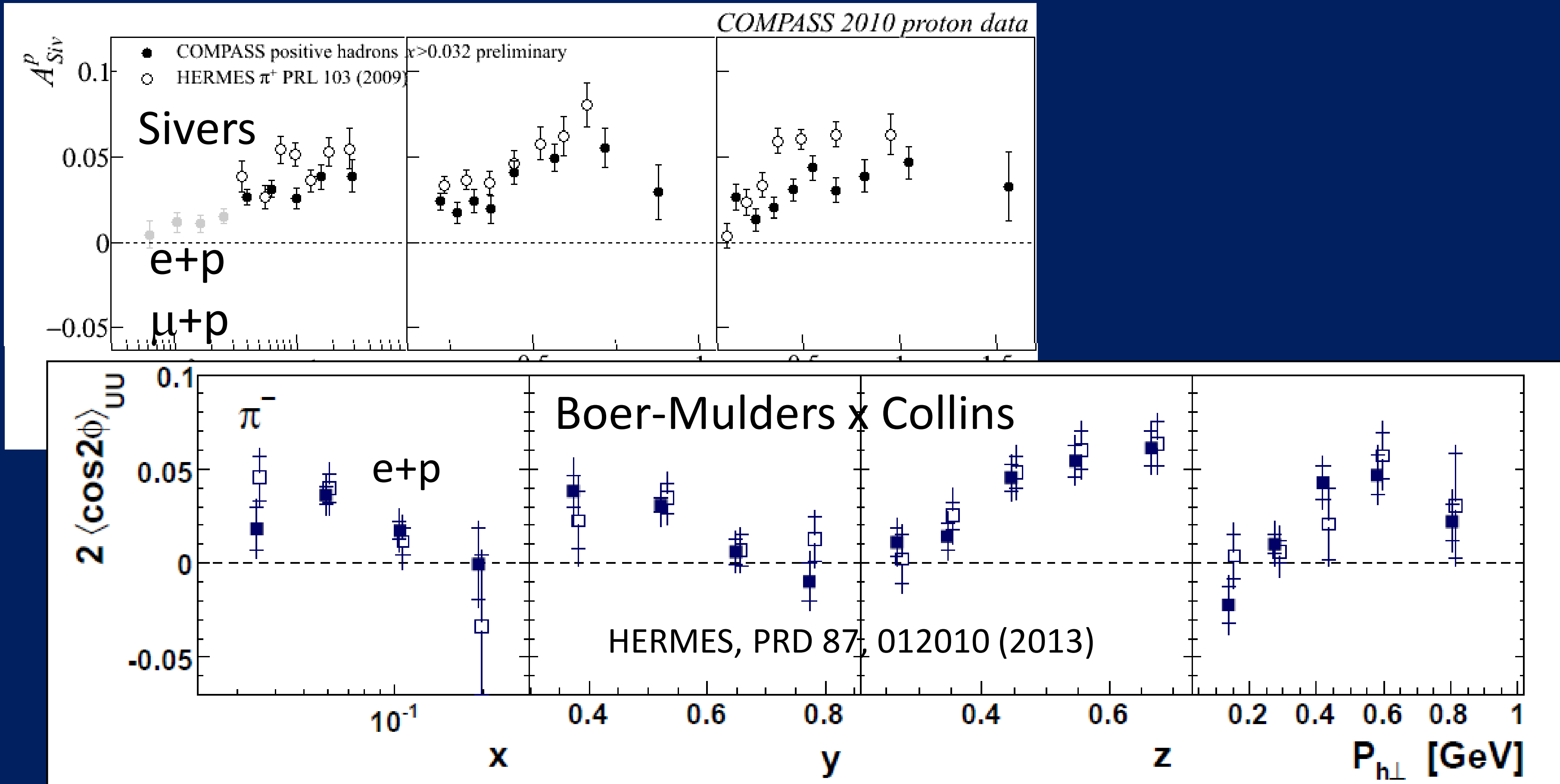


Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~12 years that many of these correlations are nonzero in nature!


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



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Boer-Mulders x Collins
π−
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HERMES, PRD 87, 012010 (2013)
2 ⟨cos2ϕ⟩UU
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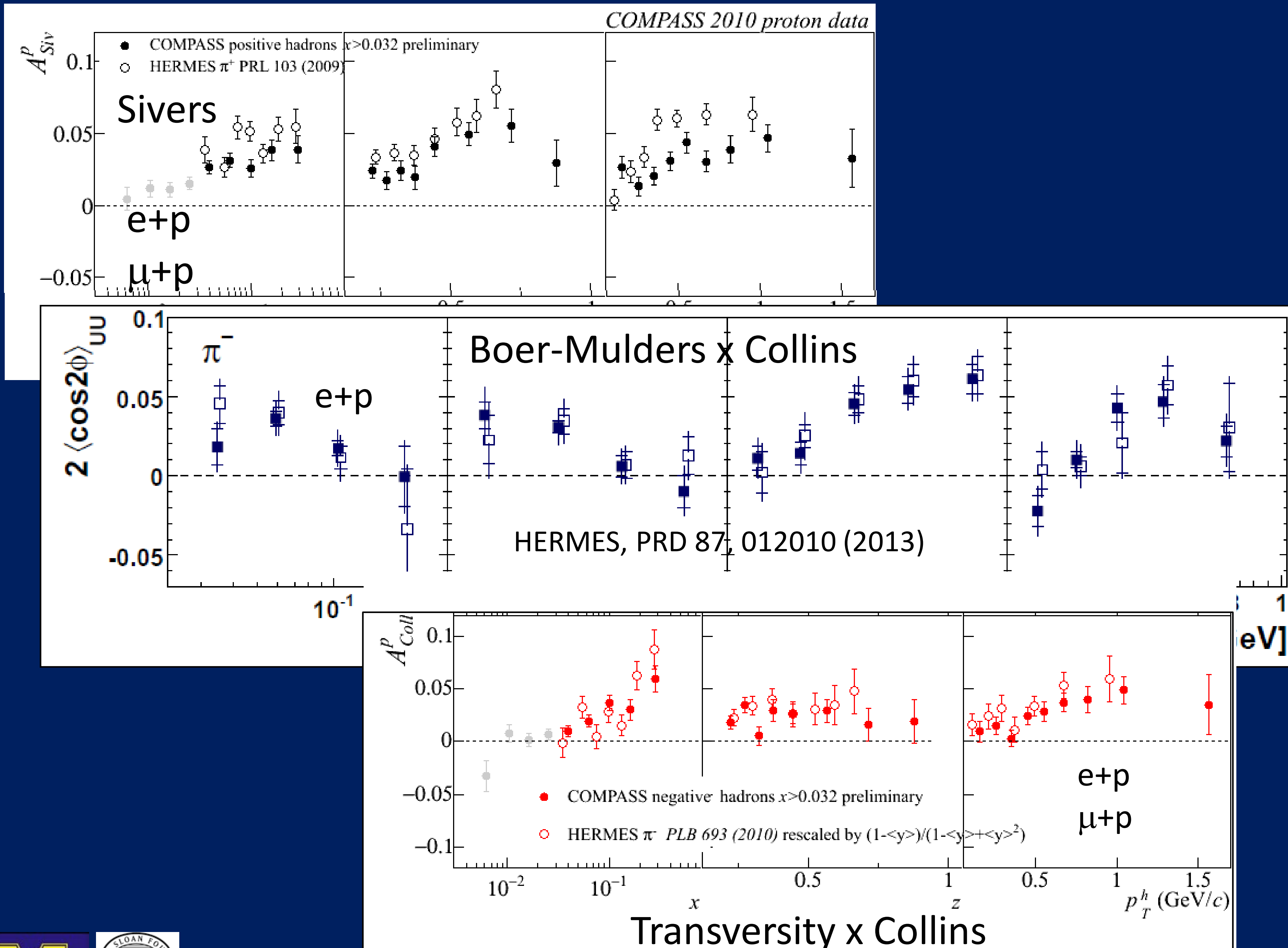
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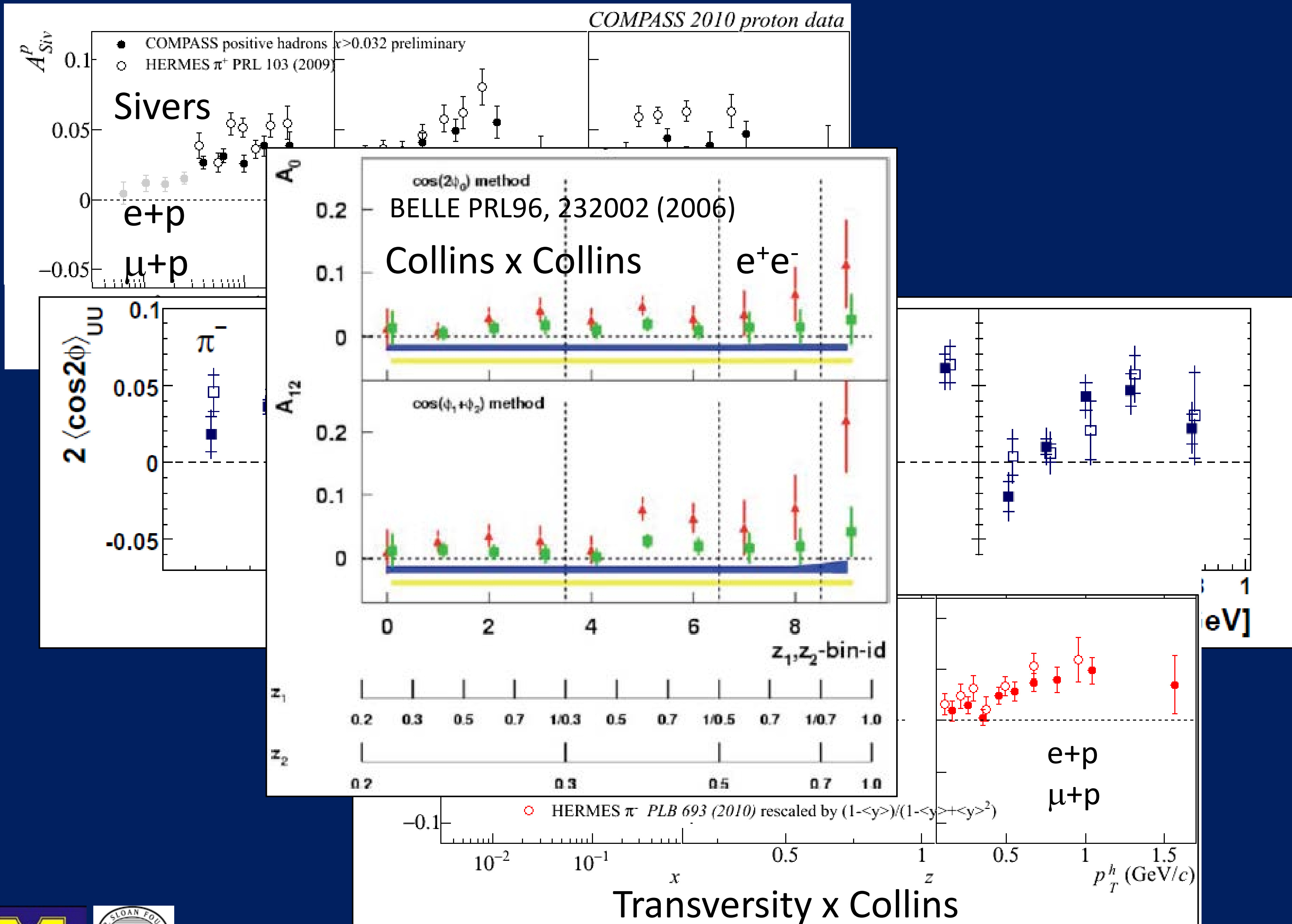
π−
e+p
Boer-Mulders x Collins
HERMES, PRD 87, 012010 (2013)
A^p_{Coll}
COMPASS negative hadrons x>0.032 preliminary
HERMES π− PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>2)
e+p
μ+p
x
z
p^h_T (GeV/c)
Transversity x Collins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HERMES π+ PRL 103 (2009)
Sivers
e+p
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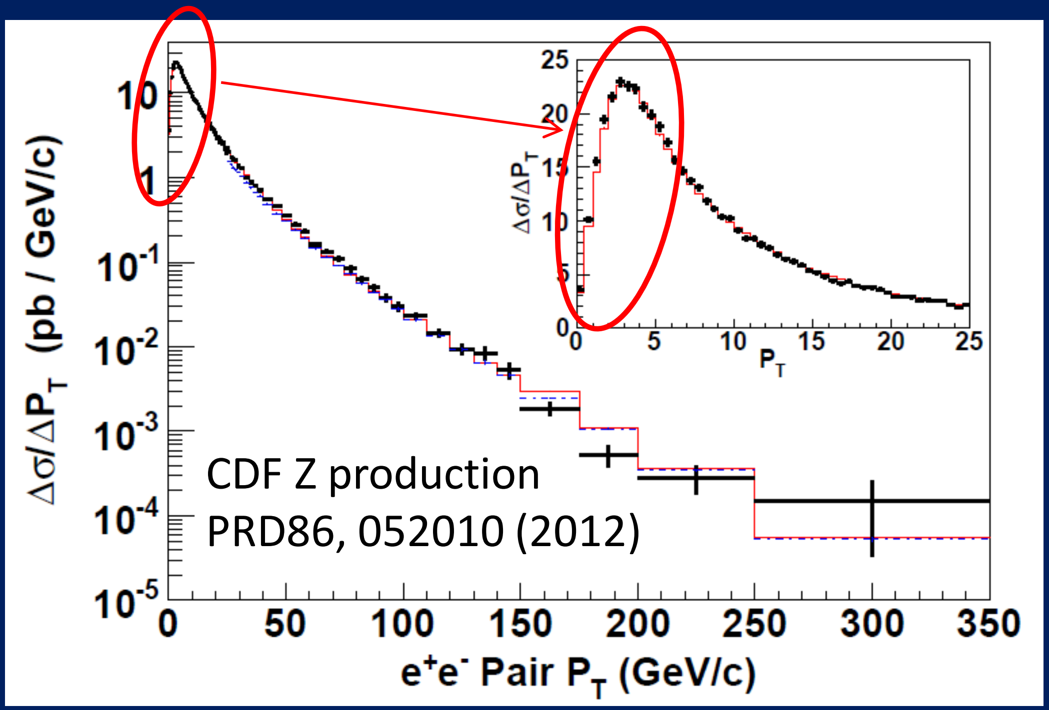
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
cos(2φ0) method
cos(φ1+φ2) method
z1,z2-bin-id
2 ⟨cos2Φ⟩UU
π-
HERMES π- PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>2)
e+p
μ+p
Transversity x Collins

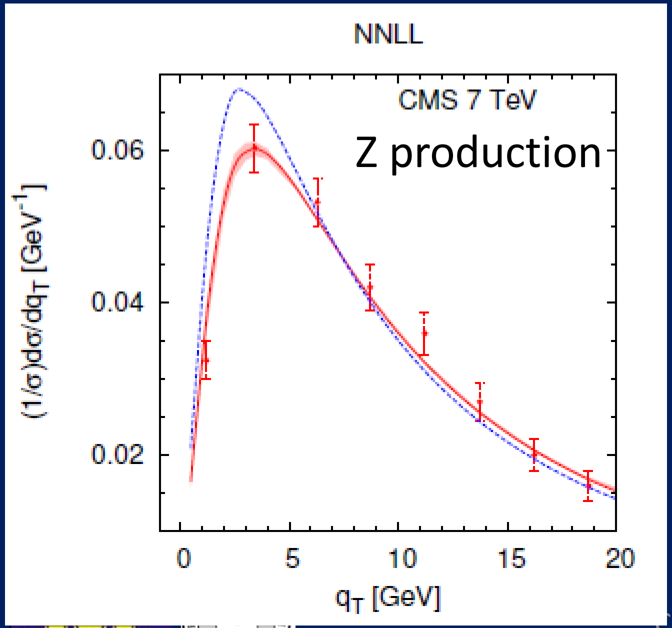
What about unpolarized TMD functions? Unpolarized TMD PDFs

- Can access via transverse-momentum-dependent Drell-Yan, Z, and W boson production
  - Isolate initial state, i.e. access PDFs without FFs
  - Transverse momentum of the final-state Drell-Yan lepton pair, Z, or W for small (nonperturbative) transverse momentum values due to initial-state k_T of the interacting quark and antiquark
    - Larger final-state transverse momenta generated perturbatively via gluon radiation

Unpolarized quark TMD PDFs

- p_T of Z in this region due to k_T vectors of annihilating quark and antiquark
- Perturbatively generated tail out to hundreds of GeV

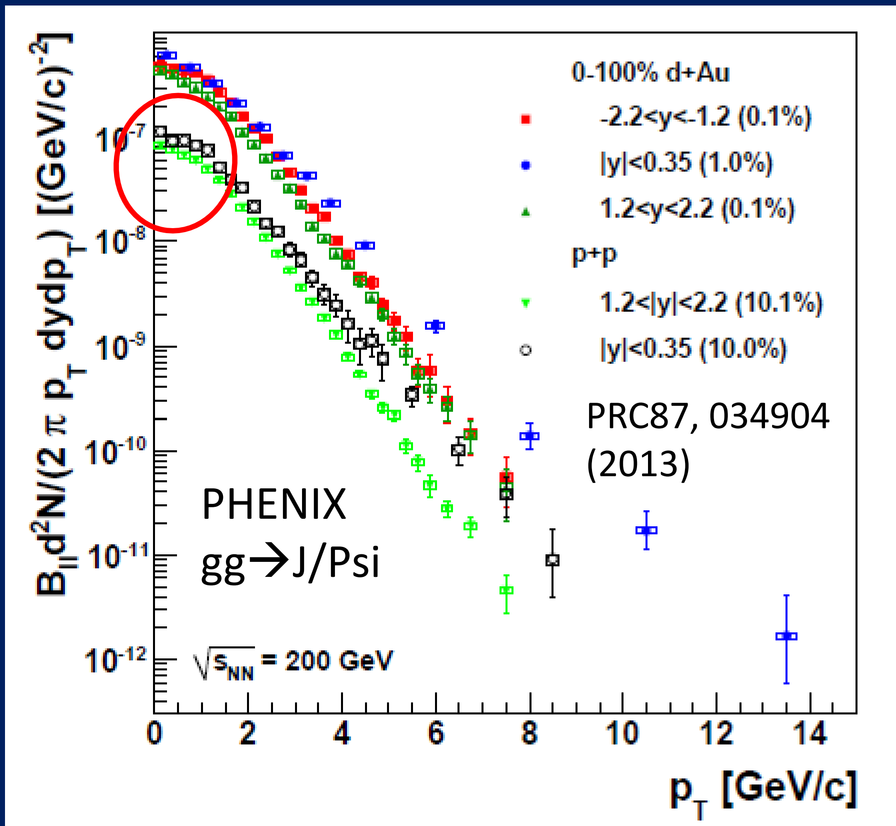


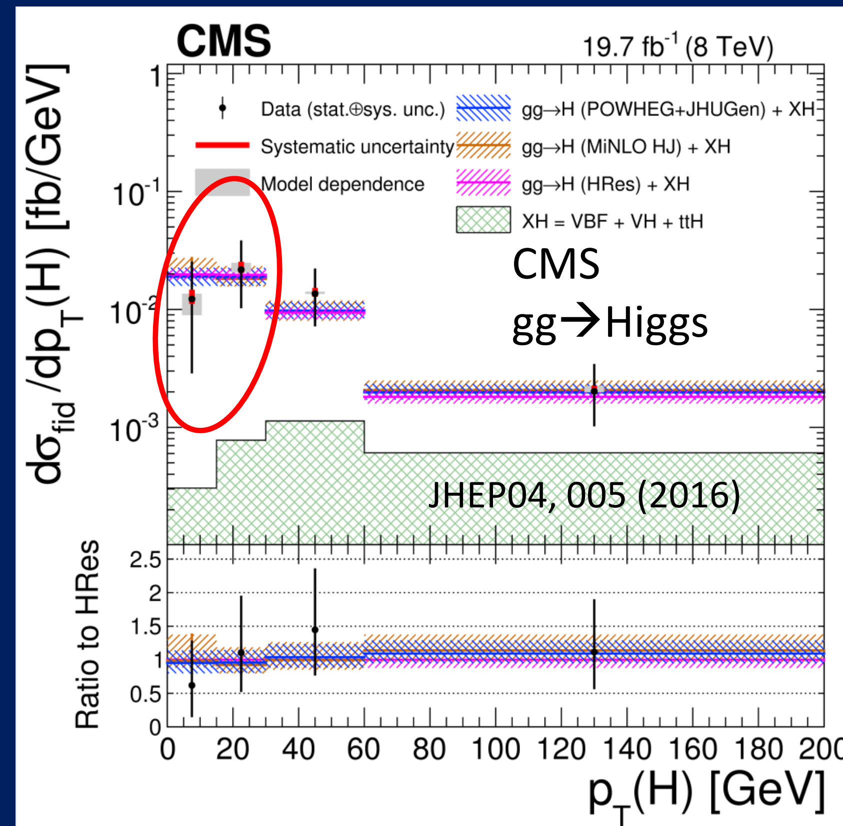


D'Alesio, Echevarria, Melis, Scimemi
JHEP 1411 (2014) 098

Need nonperturbative input to describe Z production at low transverse momentum (here using Soft Collinear Effective Theory, which can be related to the TMD formalism)

Unpolarized gluon TMD PDFs





- Need more data, but same idea as for Drell-Yan and Z boson production
- k_T vectors of fusing gluons lead to nonperturbative p_T of J/Psi or Higgs; then long perturbative tail

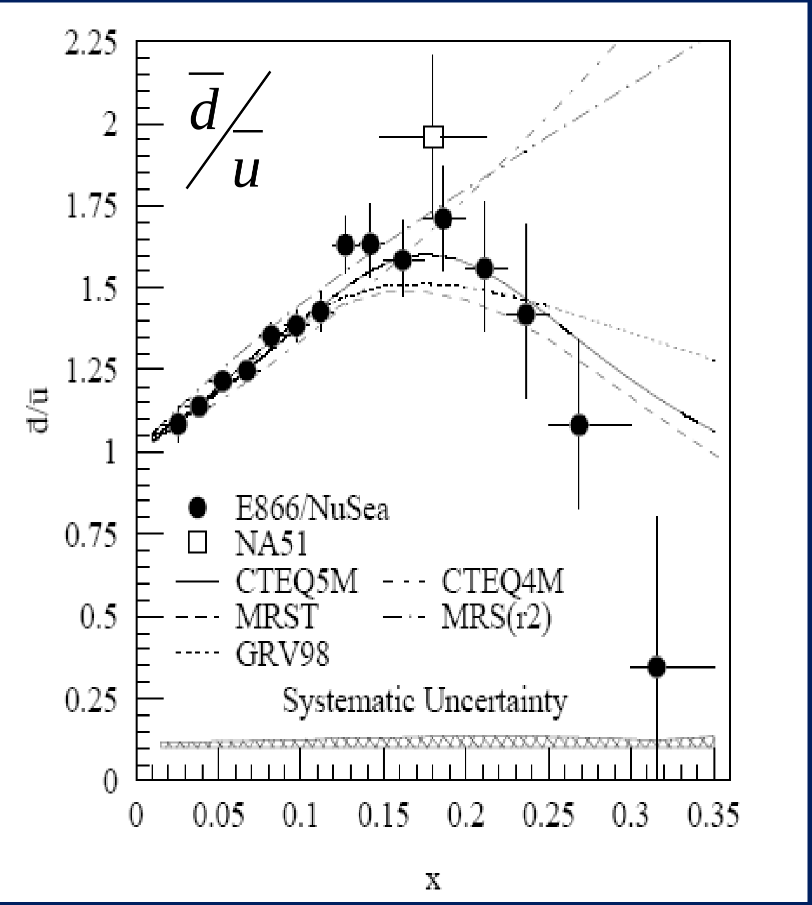
Sea quarks and sea quark dynamics

- Proton-hydrogen and proton-deuterium collisions

$$\frac{\sigma^{pd}(x_t)}{2\sigma_{pp}(x_t)} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]^*$$

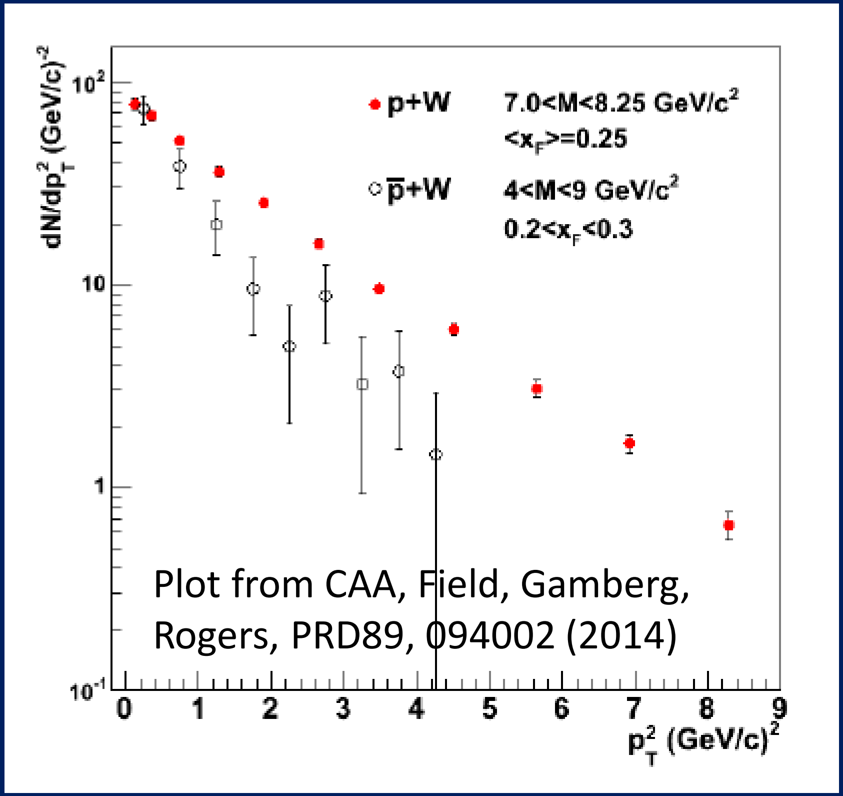
*simplest leading-order expression

- Expect anti-down/anti-up ratio of 1 if sea quarks only generated by gluon splitting
- Indicates additional mechanism to generate sea quarks—still not well understood
  - Recent review: Chang and Peng, Prog. Part. Nucl. Phys. 79, 95 (2014)



Fermilab E866 data: PRD64, 052002 (2001)
CERN NA51 data: PLB332, 244 (1994)

Sea quarks—many hints of interesting behavior already!



Data from E537 (pbar+W): PRD38, 1377 (1988)
E439: (p+W): AIP Conf. Proc. 45, 93 (1978)

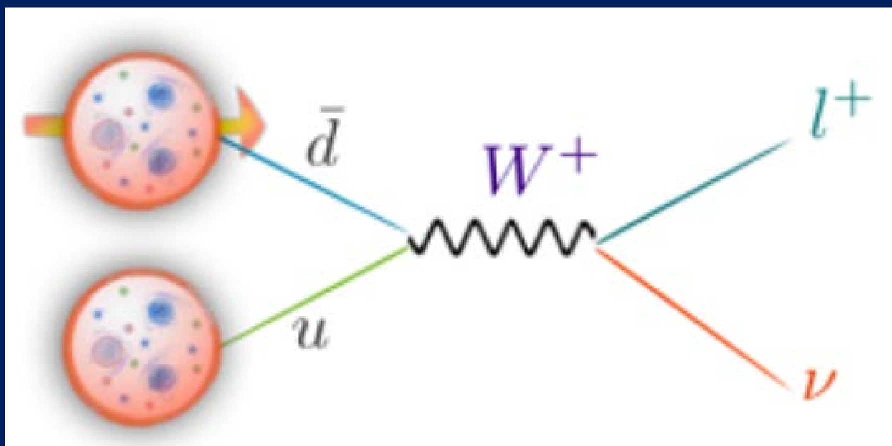
- p+W: (Valence) quark from p, (sea) antiquark from W
- pbar+W: (Valence) quark from W, (valence) antiquark from pbar
- (Valence × sea) spectrum harder → Larger mean k_T for sea than valence quarks?
  - Agrees with chiral soliton model predictions (e.g. Schweitzer, Strikman, Weiss 2013)
  - Consistent with work by Bacchetta et al.

Sea quark spin-spin correlations (helicity distributions)

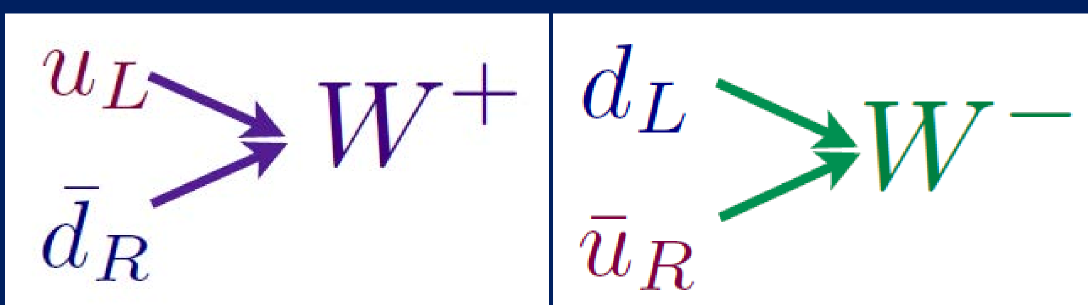
$$\Delta q(x), \Delta\bar{q}(x)$$

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) - \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) - \bar{u}(x_1)d(x_2)}$$



Parity violation of weak interaction + control over proton spin orientation gives access to *flavor*-spin structure of proton



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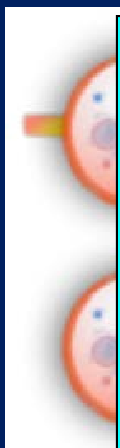
$)d(x_2)$

$d(x_2)$



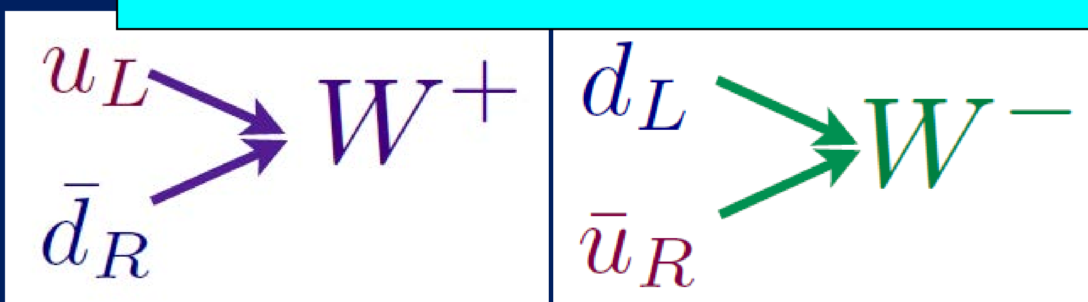
Flavor separation of the polarized sea quarks with ***no reliance on fragmentation functions,*** *and at* ***much higher scale*** *than previous fixed-target experiments.*

Complementary *to semi-inclusive DIS measurements.*

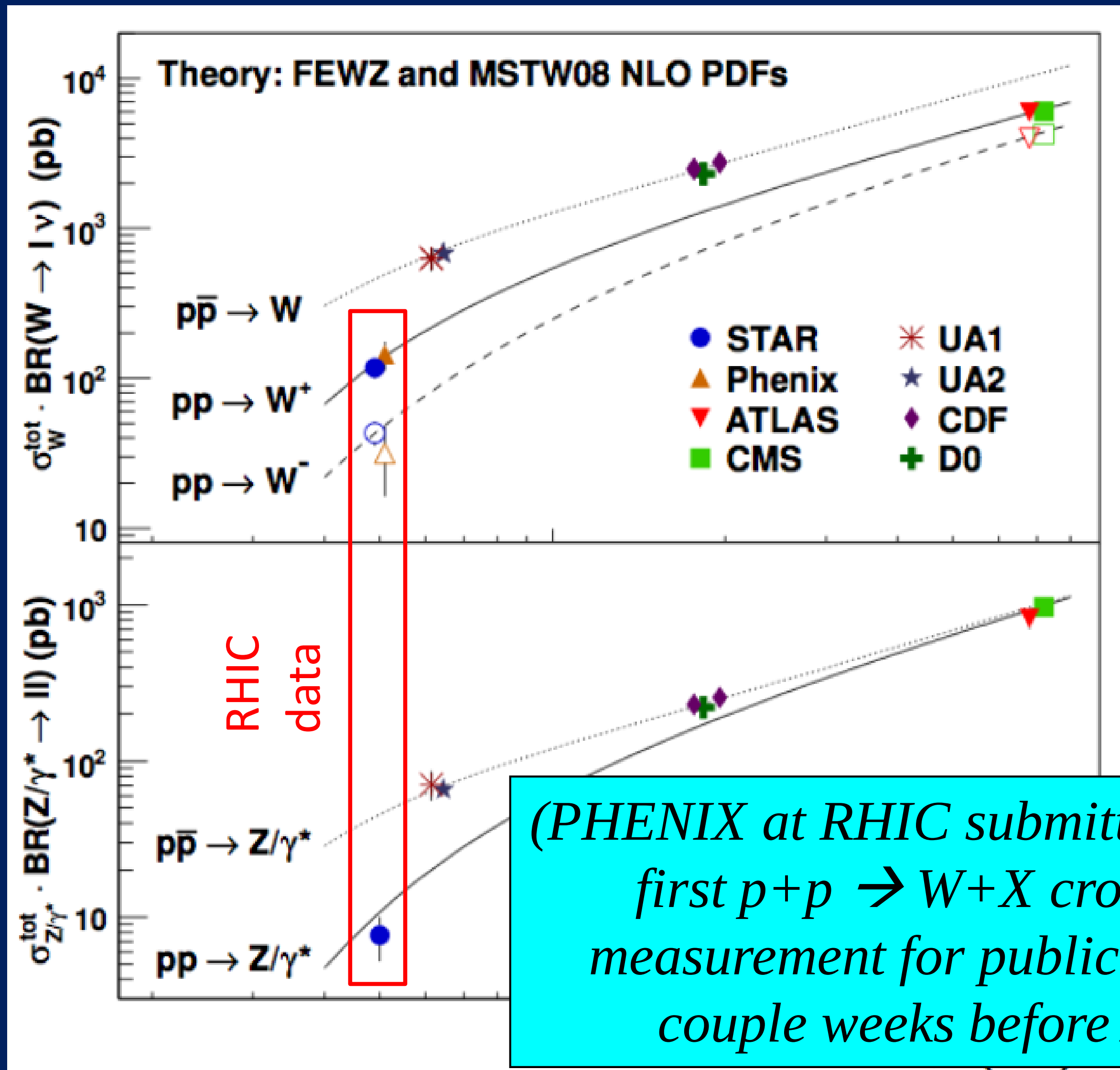
proton

ss to

ton

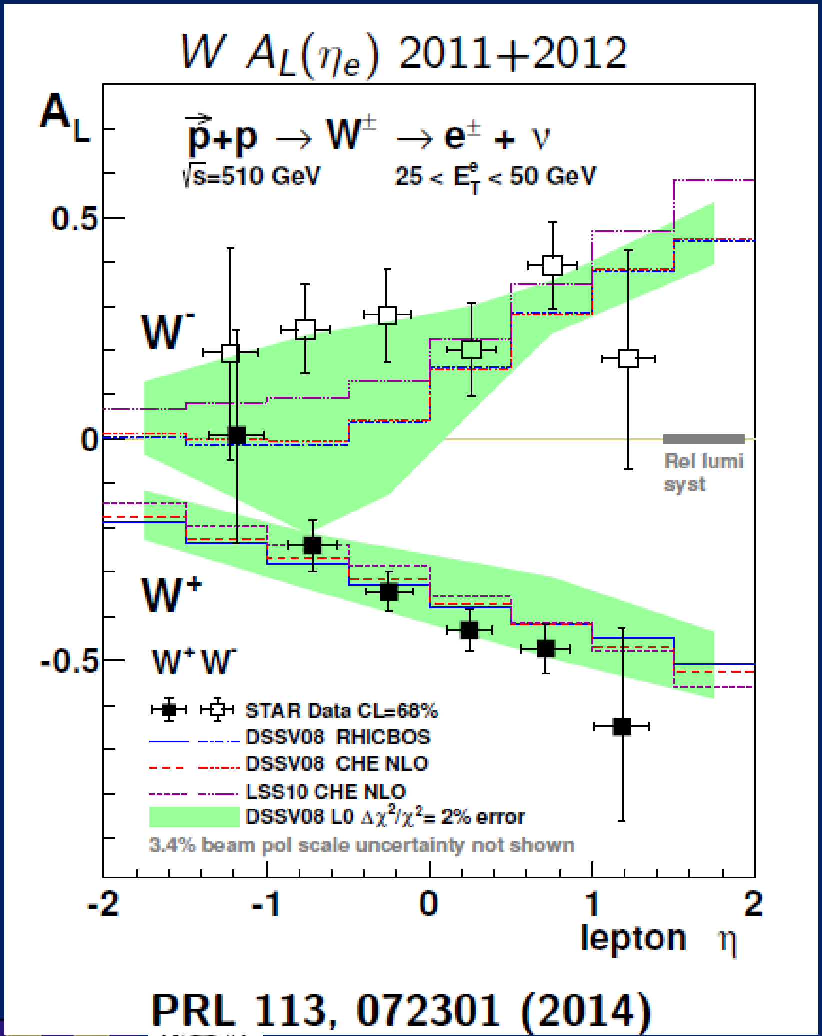


World W cross section measurements



(PHENIX at RHIC submitted the world's first p+p → W+X cross section measurement for publication, just a couple weeks before ATLAS!)

Large parity-violating single-helicity asymmetries

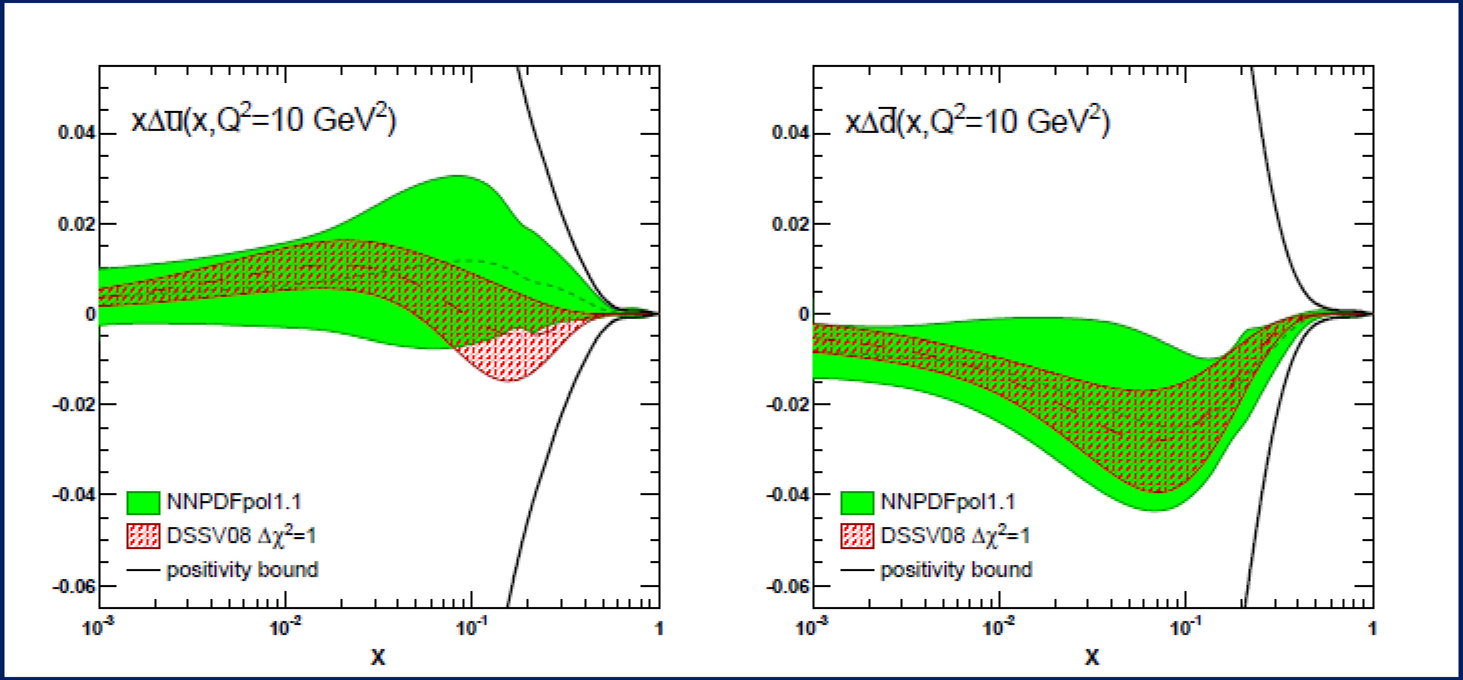


- Improve constraints on light antiquark helicity distributions

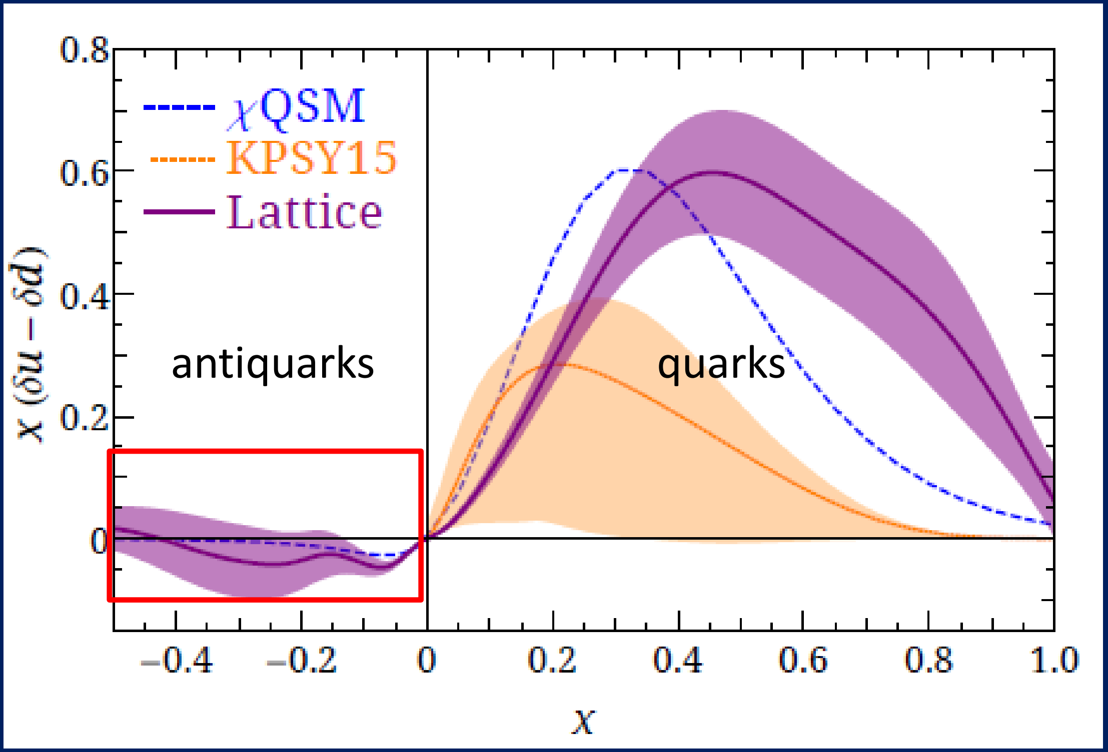
$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

Flavor asymmetry in the sea helicity distributions

NNPDF, NPB 887.276 (2014)



Transverse *spin-spin correlation for sea quarks also nonzero and flavor-asymmetric?*



$\delta\bar{q}(x) = -\delta q(-x)$

Initial lattice calculation finds "transversity" for sea nonzero and flavor-asymmetric! Chen et al., arXiv:1603.06664

Also chiral quark soliton model Schweitzer et al., PRD64, 034043 (2001)

No constraining measurements yet

Spin-spin correlations (collinear or TMD): Helicity vs. transverse spin structure

- Transverse spin structure of the proton cannot be deduced from helicity structure
  - Spatial rotations and Lorentz boosts don't commute
  - Relationship between longitudinal and transverse structure provides information on the relativistic nature of partons in the proton
  - Even collinear transverse spin structure (transversity) should thus be linked to parton k_T

Spin-spin correlations in terms of helicity

Elastic proton-quark scattering

(related to inelastic scattering through optical theorem)

Three independent pdfs corresponding to following helicity states in scattering:

$$\begin{array}{cccccc}
\frac{1}{2} & \frac{1}{2} & \longrightarrow & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & \frac{1}{2} & -\frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & -\frac{1}{2} & \frac{1}{2}
\end{array}$$

Helicity basis not "natural" for transversity

Corresponds to difference in probability of scattering off of transversely polarized quark within transversely polarized proton with quark spin parallel vs. antiparallel to proton's

Take linear combinations to form familiar collinear pdfs:

$$q \longleftrightarrow \left(\frac{1}{2}\ \frac{1}{2} \rightarrow \frac{1}{2}\ \frac{1}{2}\right) + \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow \frac{1}{2}\ -\frac{1}{2}\right)$$

$$\Delta q \longleftrightarrow \left(\frac{1}{2}\ \frac{1}{2} \rightarrow \frac{1}{2}\ \frac{1}{2}\right) - \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow \frac{1}{2}\ -\frac{1}{2}\right)$$

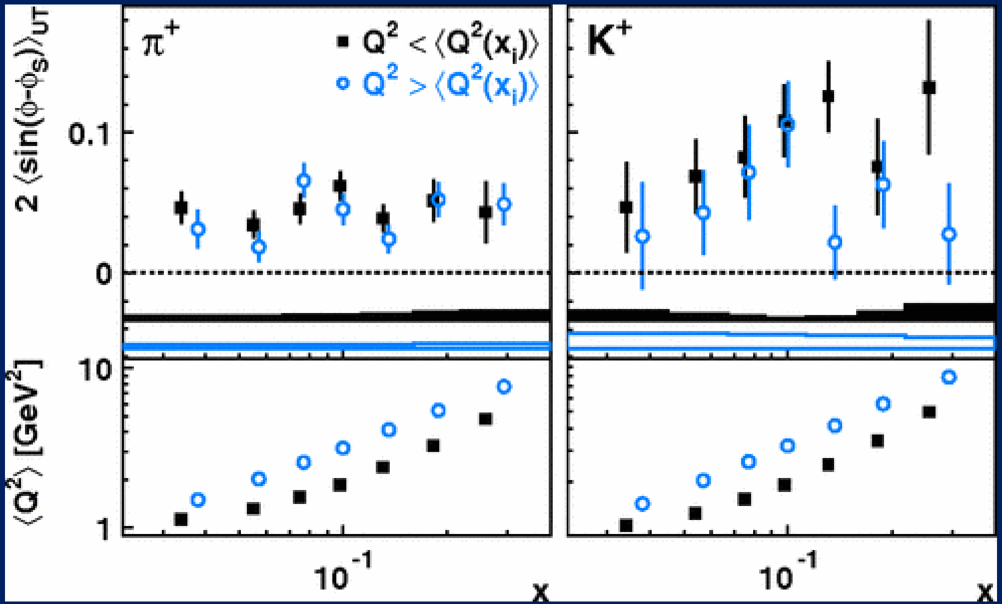
$$\boxed{\delta q \longleftrightarrow \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow -\frac{1}{2}\ \frac{1}{2}\right)}$$

Helicity average (unpolarized pdf)

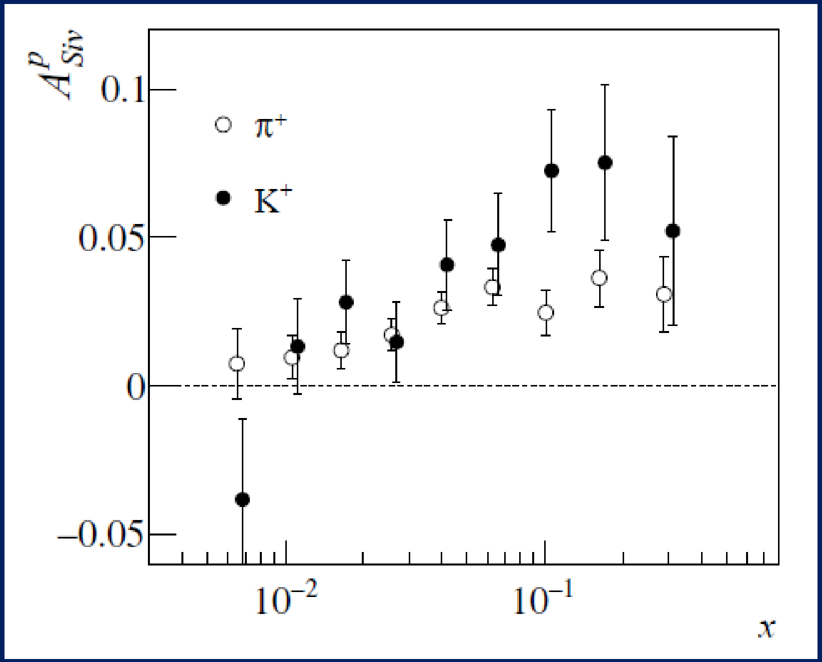
Helicity difference (helicity pdf)

Helicity flip (transversity pdf)

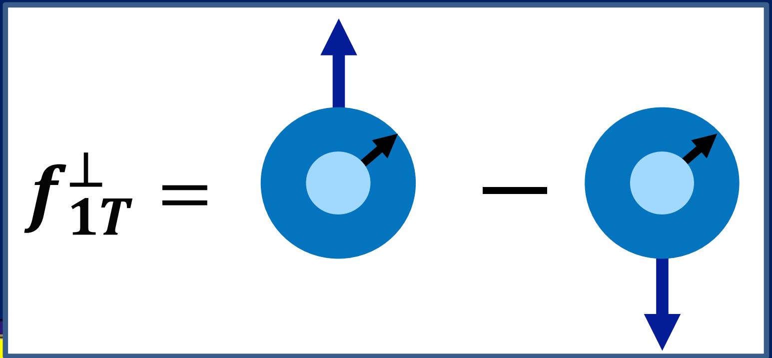
Semi-inclusive DIS "Sivers" spin-momentum correlations larger for K^+ than π^+



HERMES, PRL103, 152002 (2009)



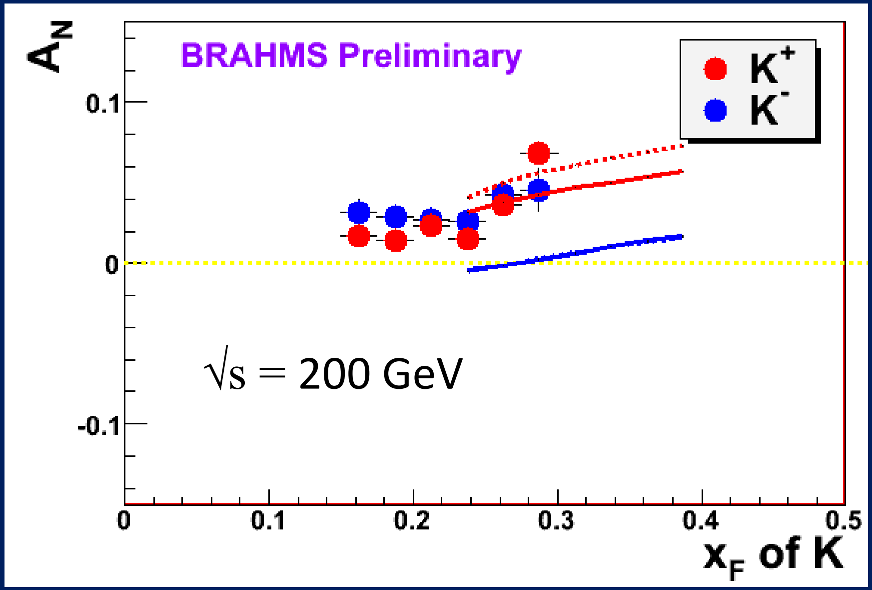
COMPASS, PLB744, 250 (2015)

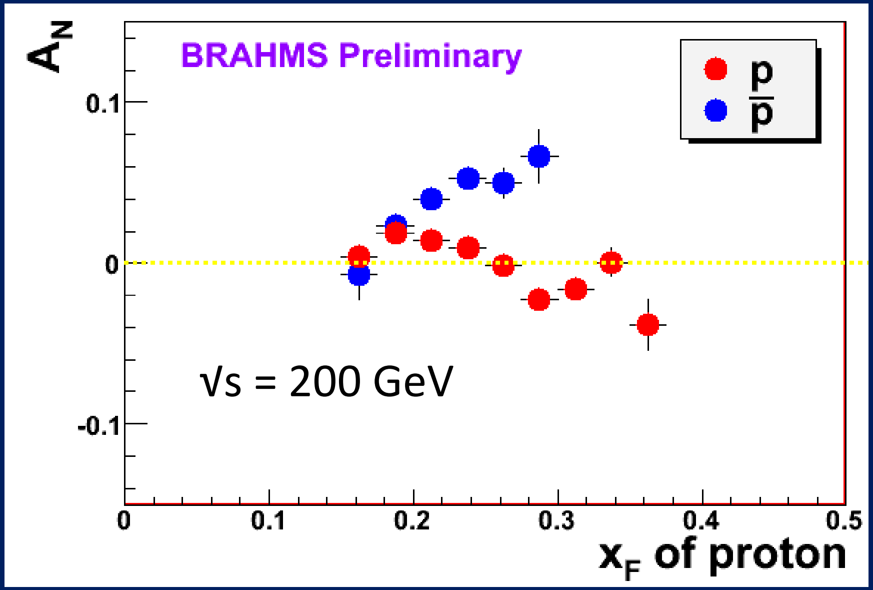


Due to strangeness?

K+ : $u\bar{s}$ π+ : $u\bar{d}$

Large K^- and antiproton transverse single-spin asymmetries in p+p at RHIC



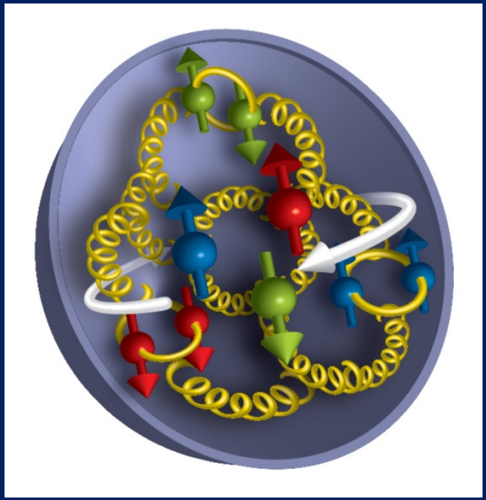


BRAHMS

We have a lot to learn about the nucleon sea!

Need more data for sea quarks!

- And with more measurements to provide meaningful constraints, will need consistent treatment of sea quarks in theory/phenomenology



- Understanding the *dynamics* of sea quarks, which probe beyond static pictures of antiquarks in the nucleon, will be crucial to understanding how the nucleon sea is generated (and what in fact it is!)

Relationship between gluons and sea quarks

- What can be learned about gluons from sea quark distributions, and vice-versa, for
  - unpolarized, collinear PDFs?
  - helicity PDFs?
  - transversity PDFs and linearly polarized gluons?
  - TMD PDFs?

- Perturbative vs. nonperturbative interplay between sea quarks and gluons?
  - Do the nonperturbative mechanisms that must be generating the flavor asymmetry observed in the unpolarized, collinear sea affect gluon distributions at all?
  - In the low-x regime, is the relationship between gluons and sea quarks straightforward?

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- What role does Q^2 evolution play in the relationship?
  - Is this role exactly the same for DGLAP vs. CSS evolution, i.e. are collinear and TMD PDFs affected differently?
  - What about evolution of the transversity distributions?

- Recent work on gluons in nuclei that aren't associated with a single nucleon. Does this have implications for sea quarks not associated with a single nucleon?
  - Any relationship to pion exchange models? (See next lecture for more on nuclear PDFs)

Proton vs. neutron sea

- Isospin symmetry between proton and neutron ultimately an approximation
- Different masses
  - Well, okay, only a 0.1% difference here.
- What about different magnitudes of electromagnetic charges of valence quarks?
  - Thinking in particular of a “dilute” picture of a nucleon, could this affect parton spin-momentum correlations or other dynamics?

Baryon vs. meson sea

- Would naively expect dynamics of valence quarks in baryons vs. mesons to be different. Also dynamics of sea quarks?
  - Three-(anti)quark system vs. quark-antiquark pair
  - Baryons as fermions vs. mesons as bosons—different spins

- Is strangeness suppressed in the sea of the phi meson through Pauli blocking? Charm suppressed in the sea of the J/Psi? Does it even make sense to think of these resonances as having a "sea"?

- Do different binding energies e.g of different heavy quarkonium states lead to different dynamics in the sea, or of the valence quarks?

What do we really mean by “valence” and “sea” anyway??

- At any given instant, the proton has a net up content of 2 and net down content of 1, which determines the +1 charge.
- It also determines the total spin somehow . . .

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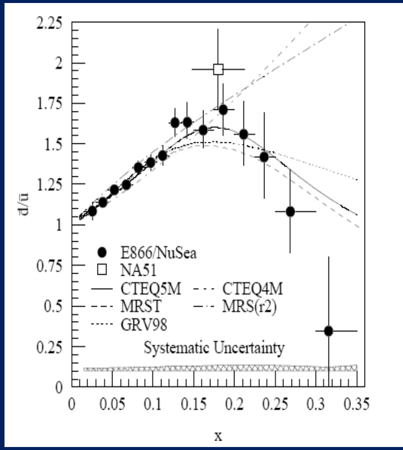
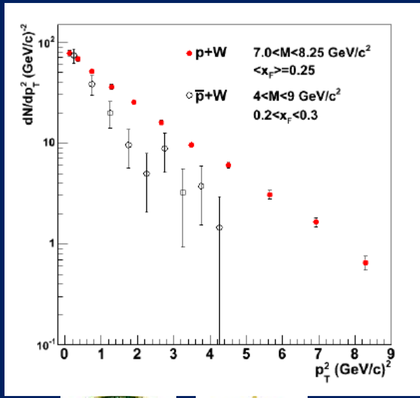
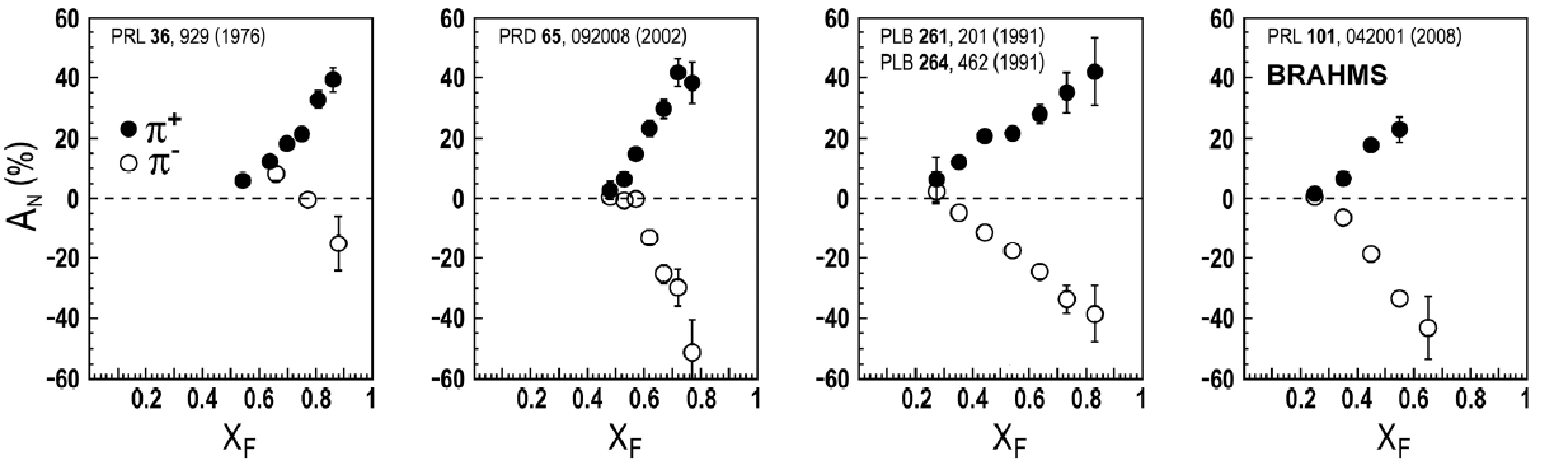


- We talk about "the valence quarks" being at large x, but e.g. Drell-Yan experiments have already measured (sea) antiquarks up to 0.35. Is it meaningful to think also of sea *quarks* at these high x values, i.e. up or down sea quarks rather than antiup or antidown?
  - If we measure an up or down quark at x~0.35, we call it "valence."
  - So what do hints of different dynamics for sea quarks than "valence" quarks mean? Should what we call "valence" vs. "sea" be associated with different processes/behavior within the proton?



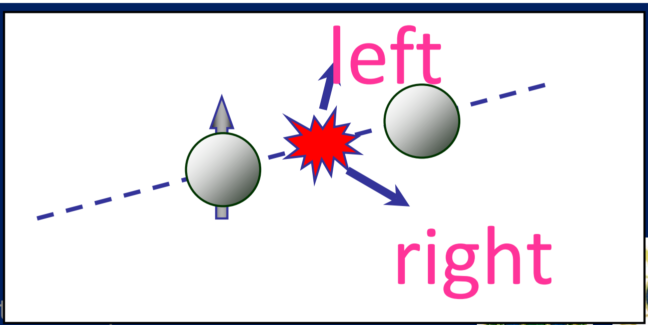
Back to those huge spin-momentum correlations in proton-proton collisions…

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)

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



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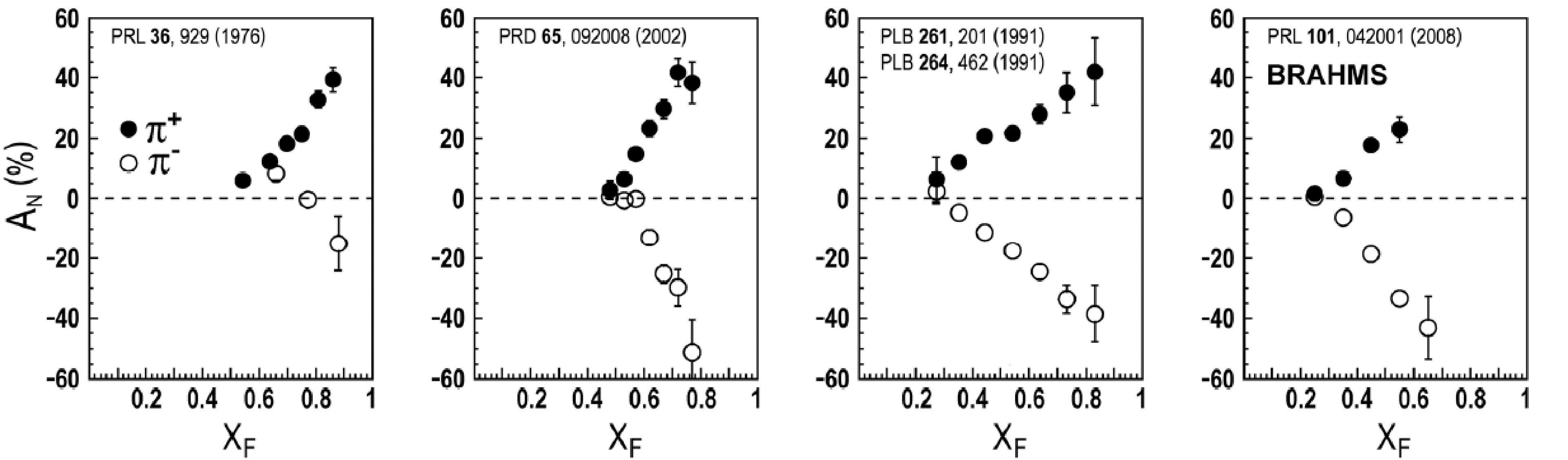
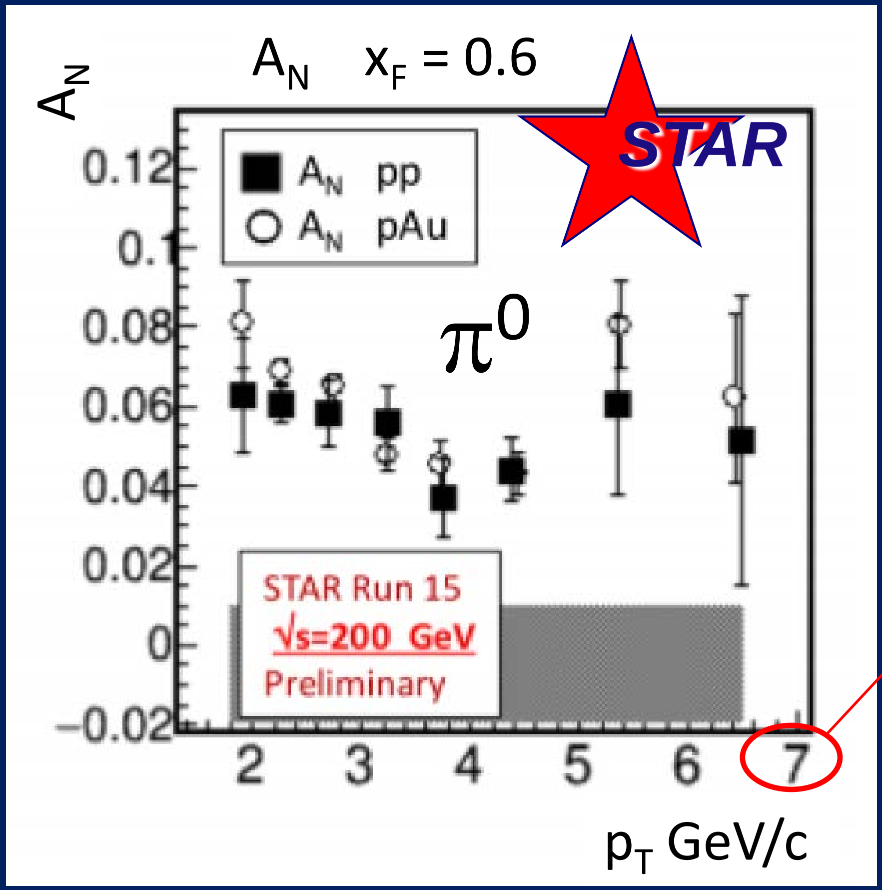
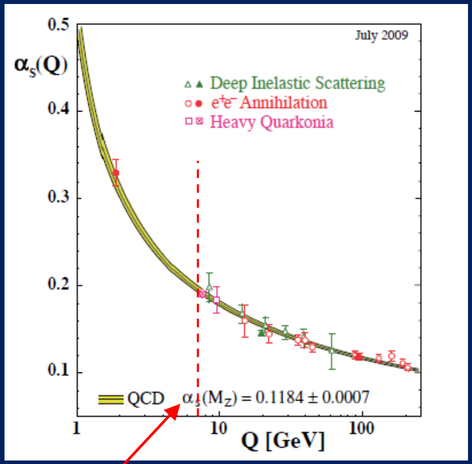


Ai

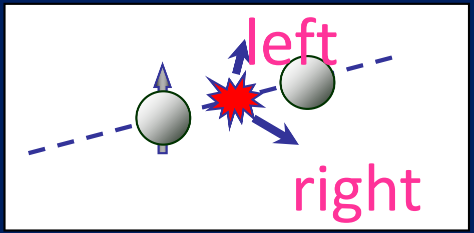
Much larger spin-momentum correlations, and strikingly similar effects across energies!

Single-spin asymmetries in transversely polarized proton-proton collisions





Effects persist to kinematic regimes where perturbative QCD techniques clearly apply



proton-proton → pion + X: Challenging to interpret

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

Different symmetry properties for different spin-momentum correlations

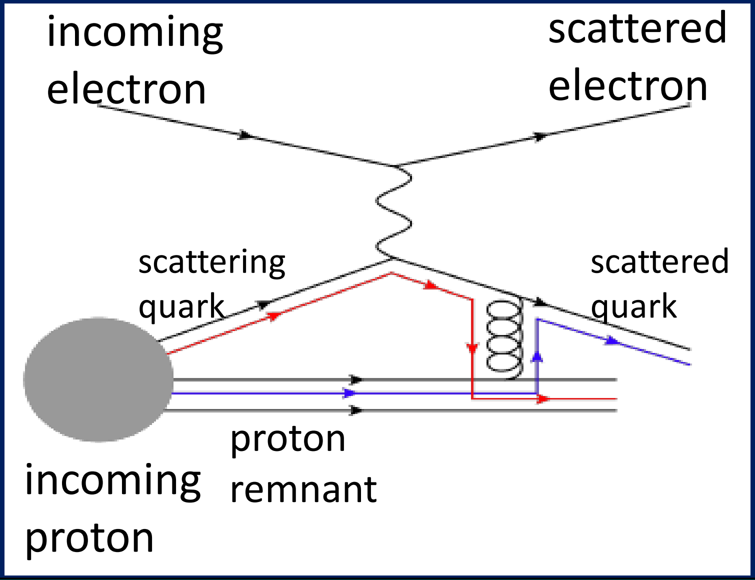
- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish

Different symmetry properties for different spin-momentum correlations

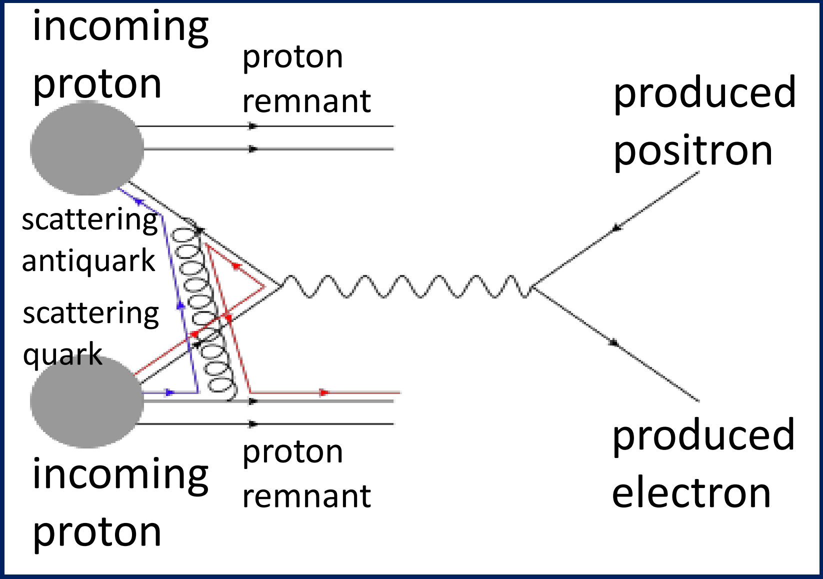
- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish
- Only realized in 2002 by Brodsky, Hwang, and Schmidt that could be nonvanishing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

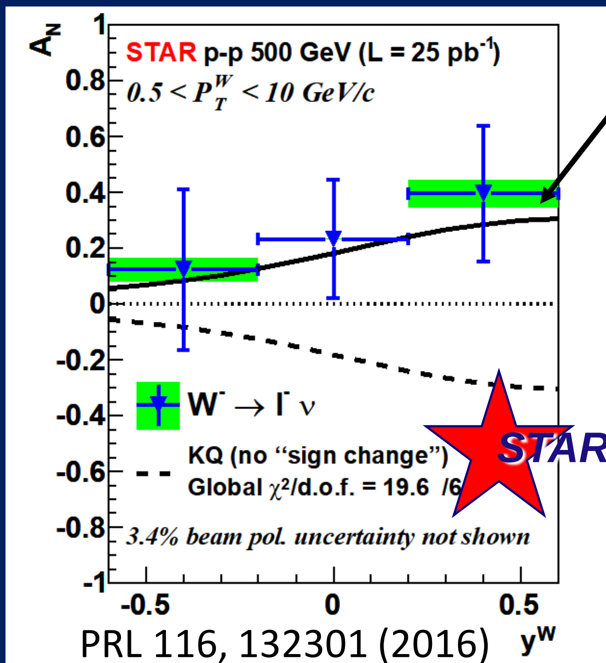


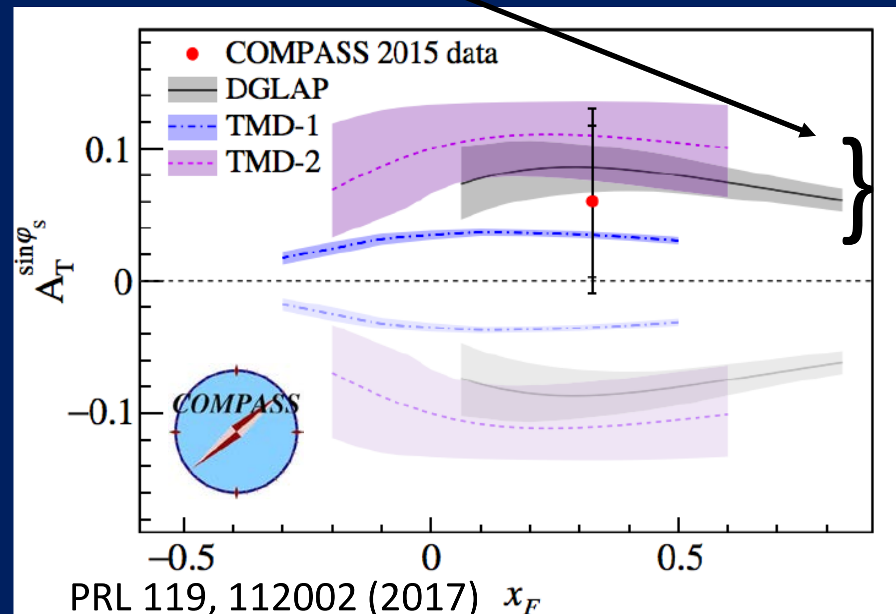
Opposite sign **for PT-odd transverse-momentum-dependent distributions measured in these two processes:**
process-dependent**!** **(Collins 2002)**

Figures by J.D. Osborn

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 . . .

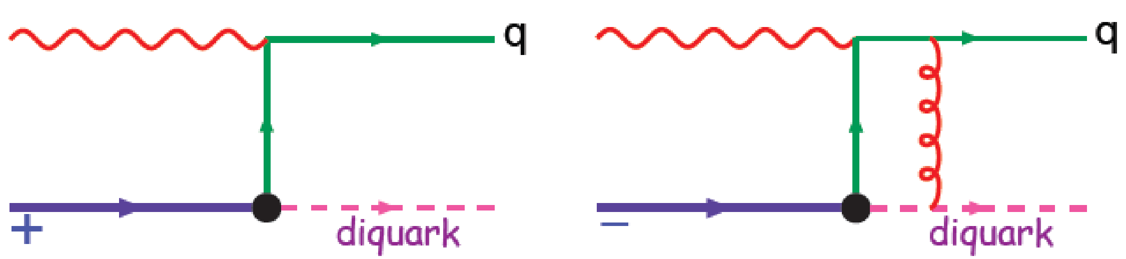
Modified universality requires full QCD: Gauge-invariant quantum field theory

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 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.

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

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."

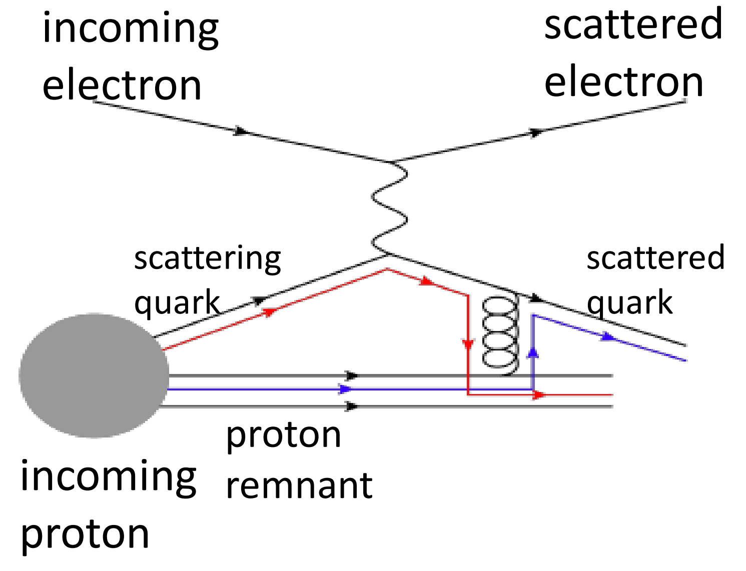
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

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

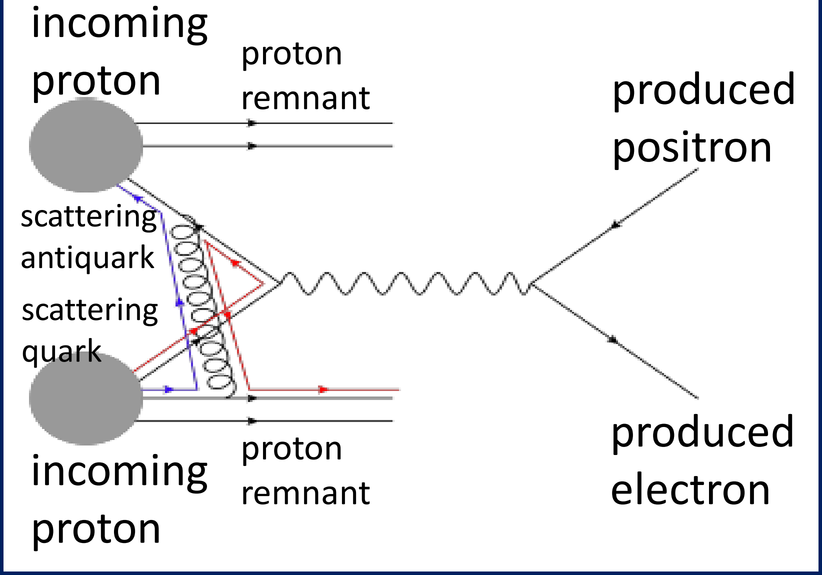
“Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories. 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!!

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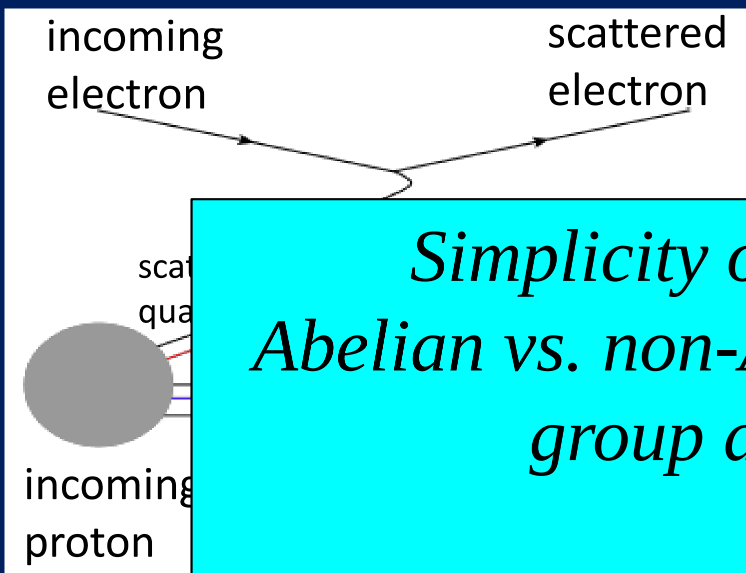

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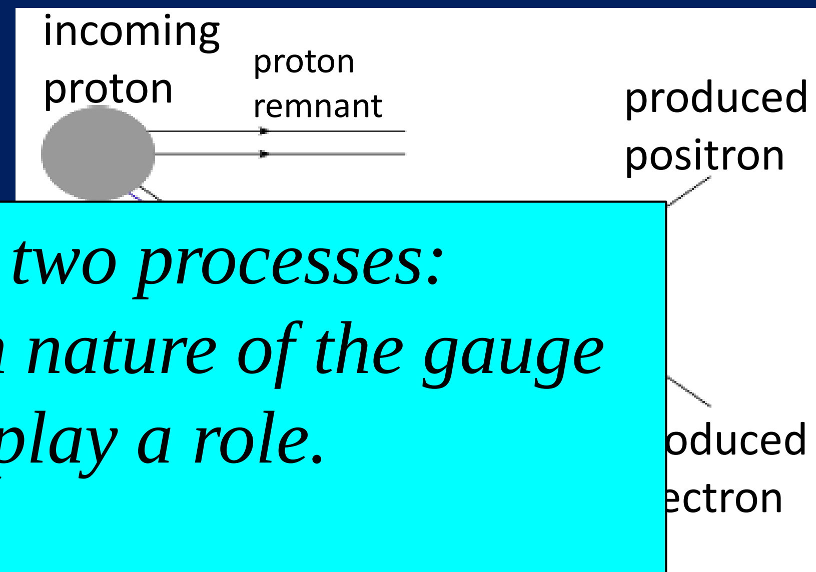
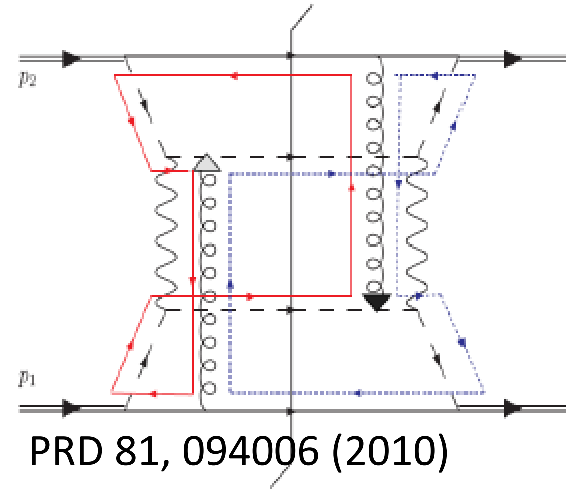


Simplicity of these two processes: Abelian vs. non-Abelian nature of the gauge group doesn't play a role.

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

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!



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.

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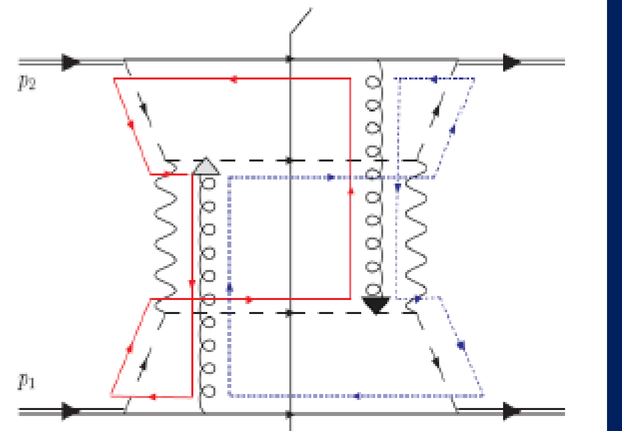

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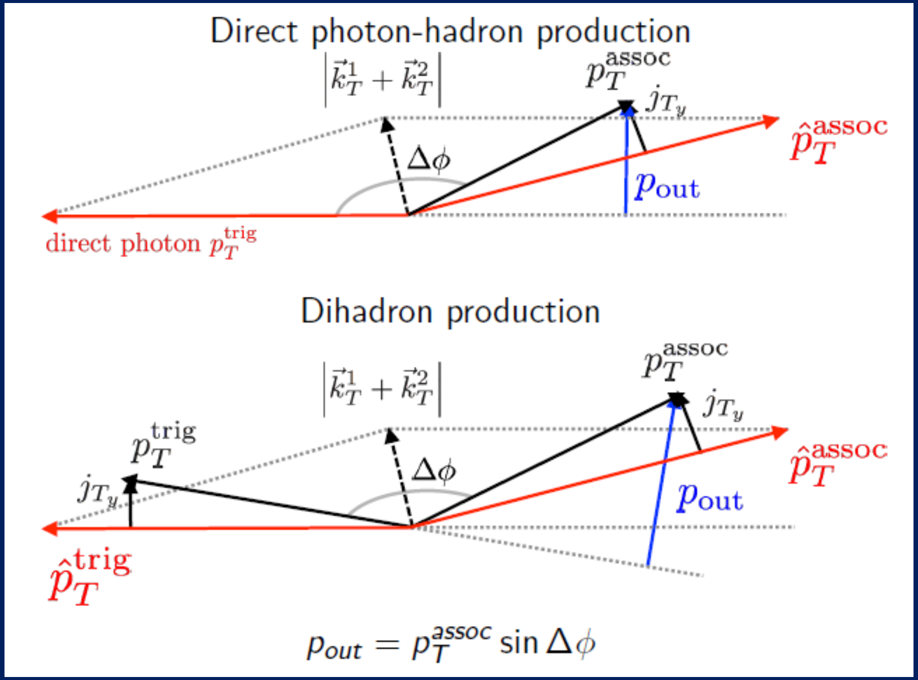
Huge transverse spin asymmetries in p+p a color entanglement effect??

Searching for evidence of color entanglement at RHIC

- Need observable sensitive to a nonperturbative momentum scale
  - Nearly back-to-back particle production
- Need 2 initial 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

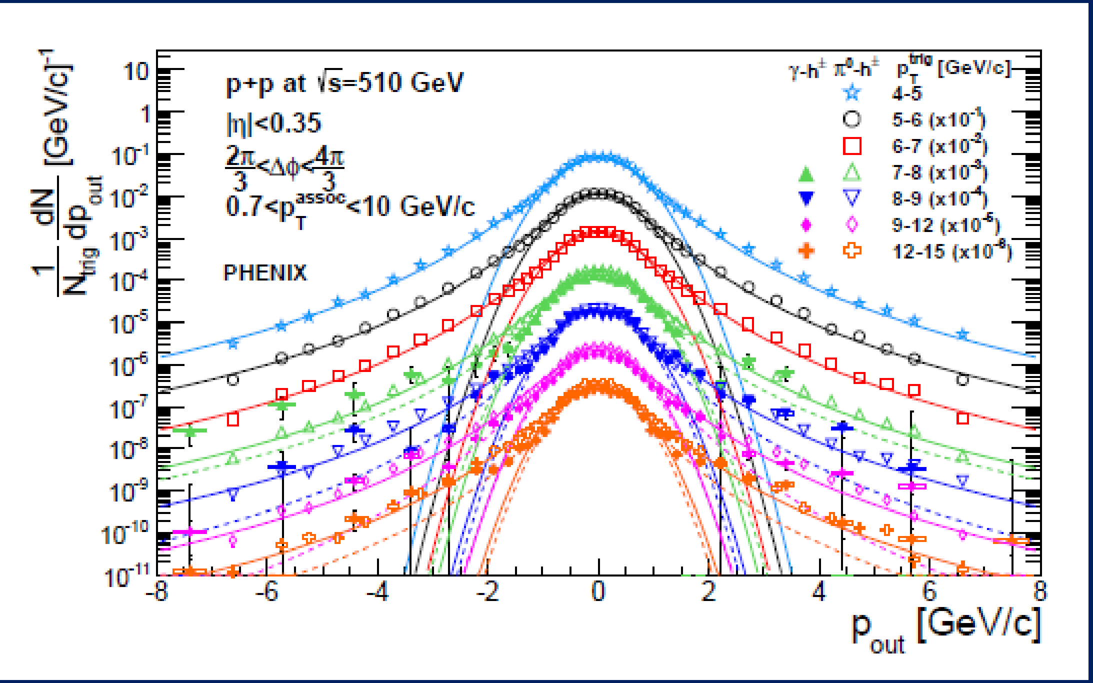


→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production

Out-of-plane momentum component distributions

- 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)



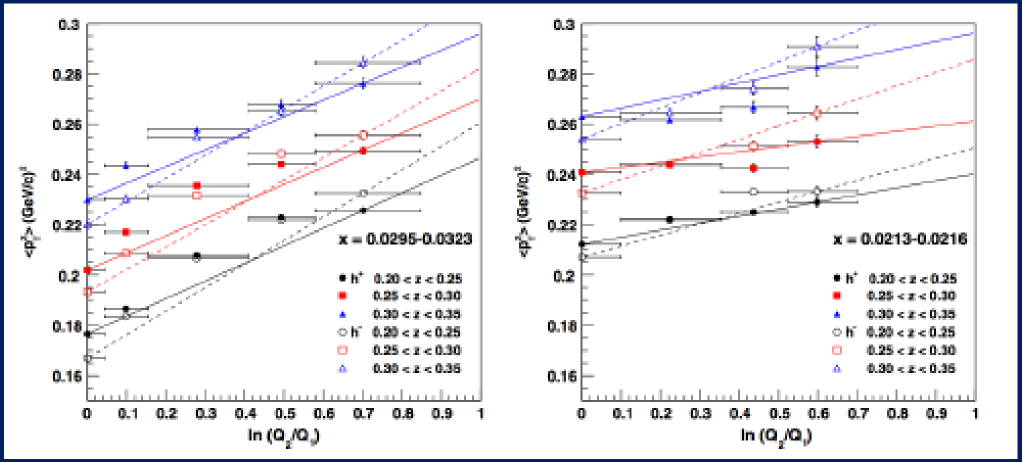
Curves are fits to Gaussian and Kaplan functions, not calculations!

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

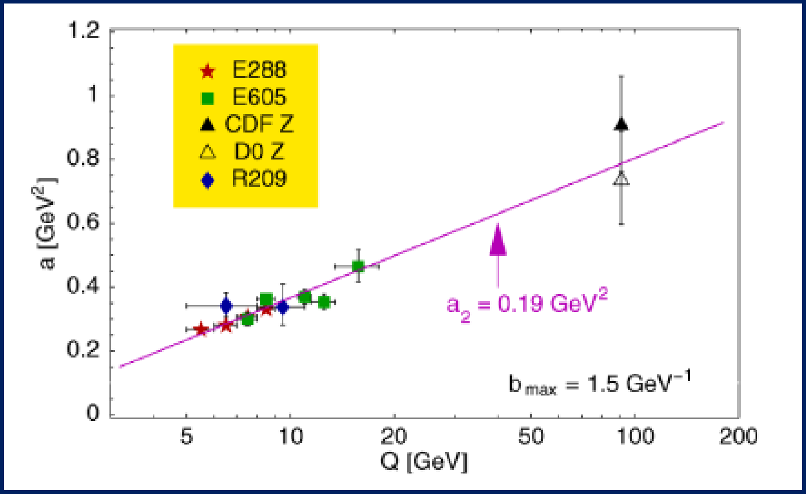
- Proof of factorization (i.e. no entanglement) for processes sensitive to nonperturbative transverse momentum directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation

*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)



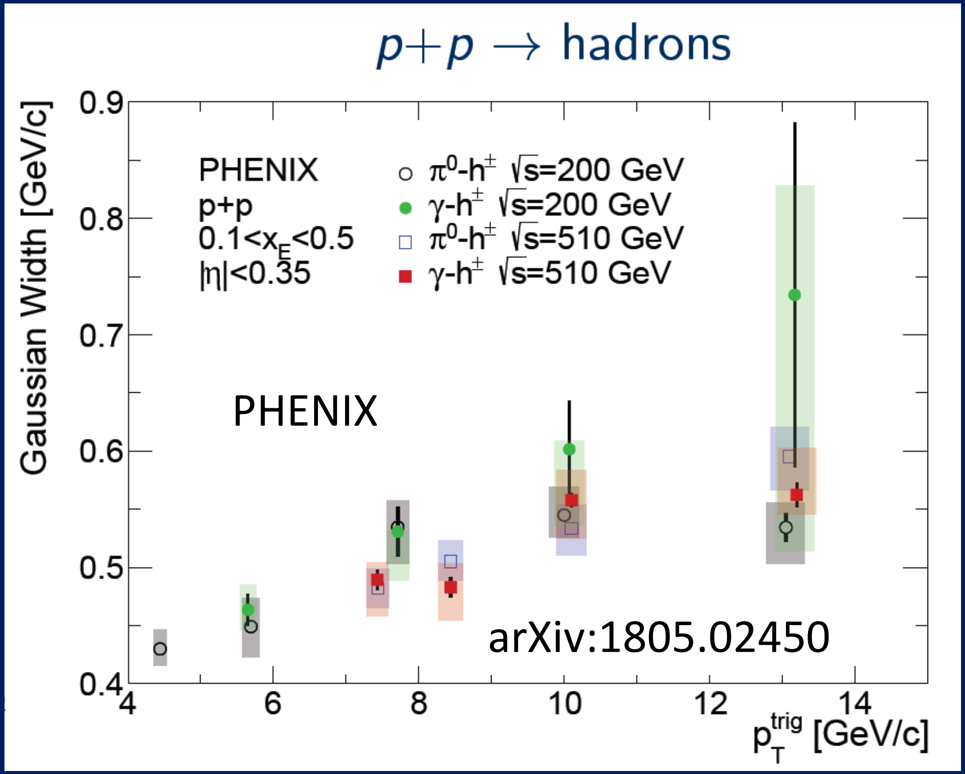
Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



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

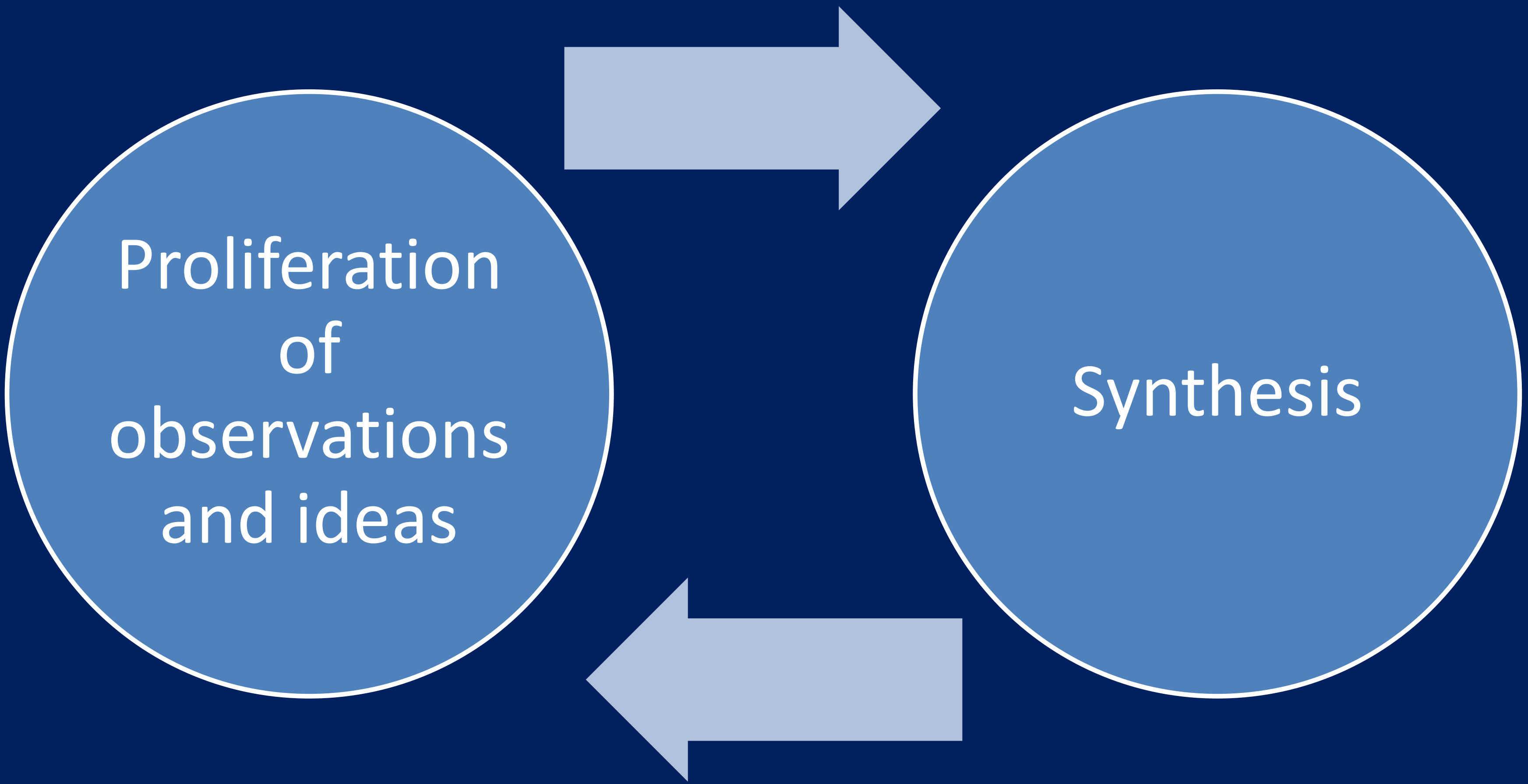
Evolution of nonperturbative momentum widths in processes where entanglement predicted

- No clear qualitative difference observed. Will need *quantitative* calculations from theorists to draw a conclusion.
  - Perform calculations assuming factorization holds, and look for discrepancies with measurement.
  - Currently no idea how to perform calculations for partons entangled across colliding protons!



Stay tuned! Discussions of other potential observables ongoing . . .

A cyclical process



Summary

- The proton as the simplest stable QCD bound state serves as a “laboratory” to study the behavior of quarks and gluons confined in color-neutral states
  - But should keep in mind that what we learn about the internal structure and dynamics of the proton won’t represent all QCD bound states
    - E.g. spin-1/2 fermion vs. pseudoscalar vs. vector bosons—partitioning of angular momentum must be different
    - Isospin mapping from proton to neutron not exact

- Puzzles remain
  - How exactly is the proton spin generated from its constituents, and how should we think about orbital angular momentum in confined systems more generally?
  - What generates the 40% asymmetries in spin-momentum correlations in p+p → hadrons??

Summary

- And there is much still to be learned
  - How can we relate partonic pictures of hadrons in the high-energy limit to internal dynamics at lower energies, where a partonic picture shouldn't apply?
    - p+p → h+X transverse single-spin asymmetries show remarkably similar behavior across a huge range of energies
  - What are the nonperturbative dynamics governing sea quarks?
  - What are the spatial distributions of quarks and gluons around the charge center of the proton? (See next lecture)
  - How is the behavior or quarks and gluons modified in a nucleus compared to a nucleon? (See next lecture)
  - Is there a universal state of hadronic matter when considering the smallest parton momentum fractions, i.e. gluon saturation? (See next lecture)

Summary

- 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 atomic, molecular, and optical physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems

- These new ways of thinking will help deepen our understanding of QCD as a non-Abelian quantum gauge theory

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!

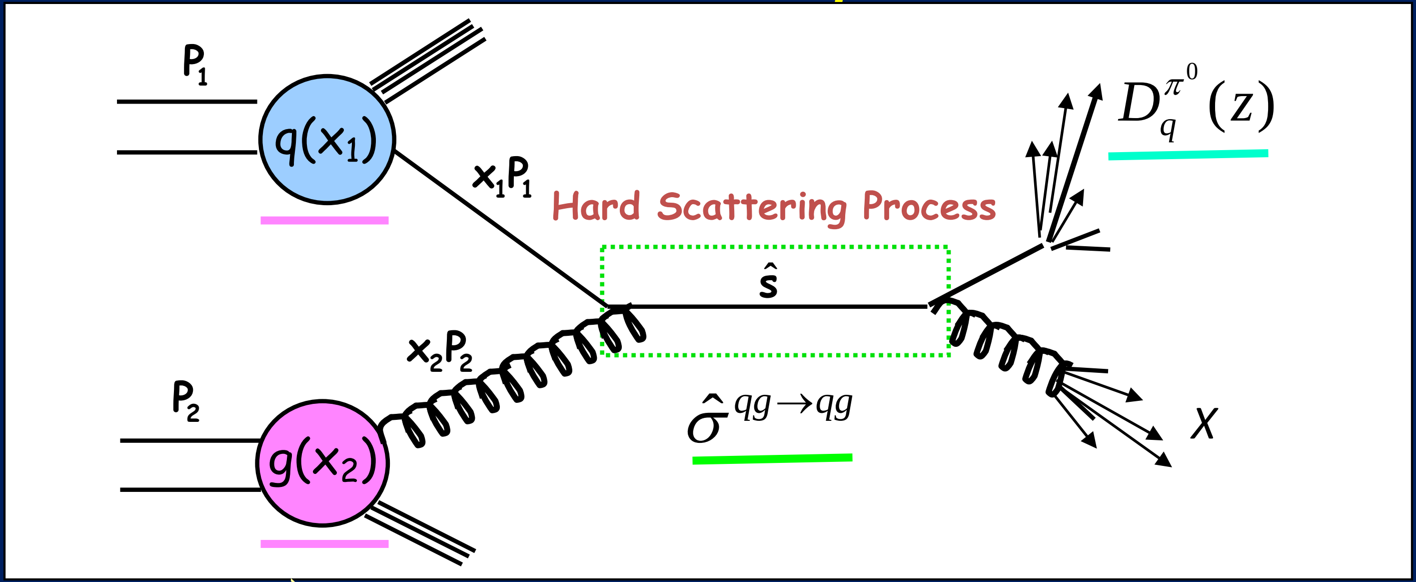
  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentum fractions
  - *Spin-spin* and *spin-momentum* correlations in QCD bound states
  - *Spatial* distributions of partons in QCD bound states

- 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



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

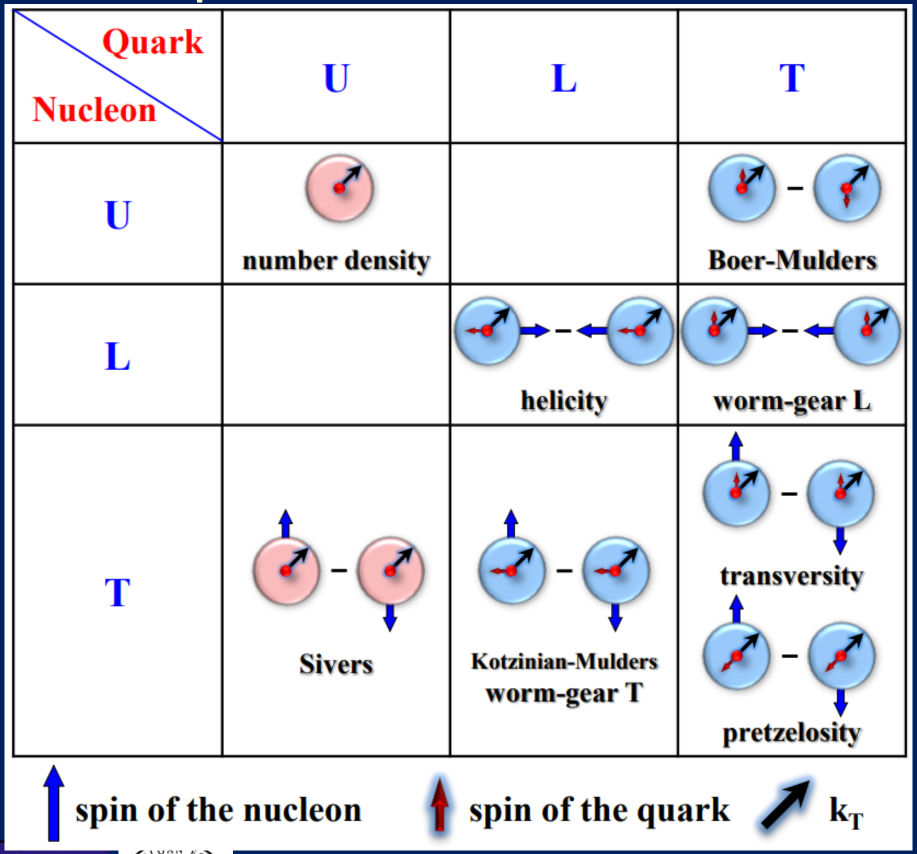
High-energy processes have predictable rates given:

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

} Universal non-perturbative factors

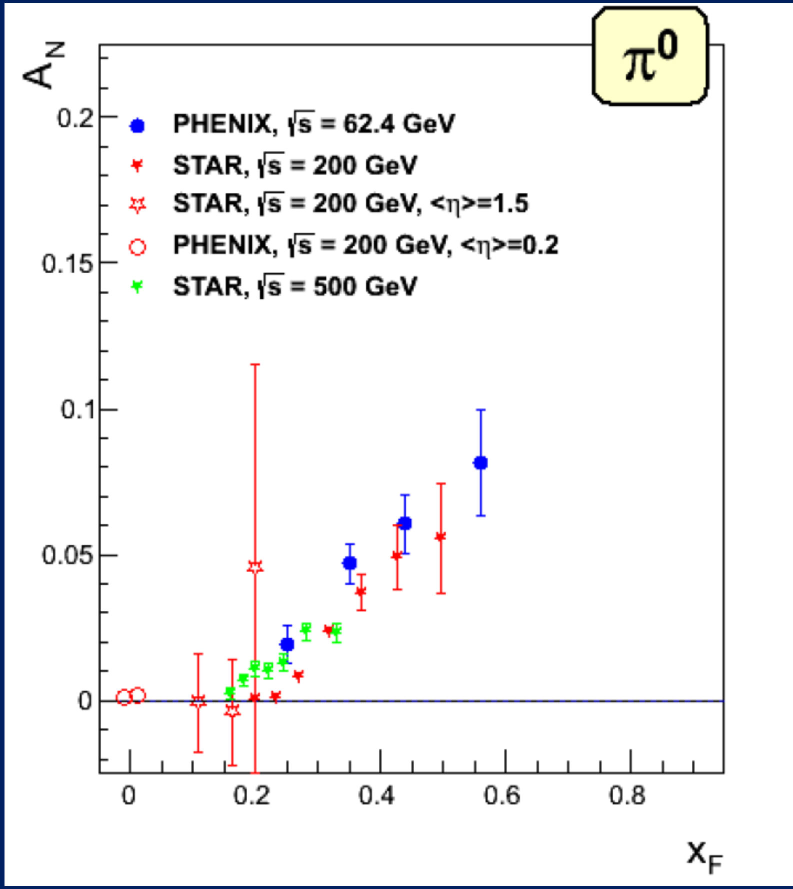
Transverse Momentum Dependent Nonperturbative Functions

Transverse Momentum Dependent Quark PDFs:

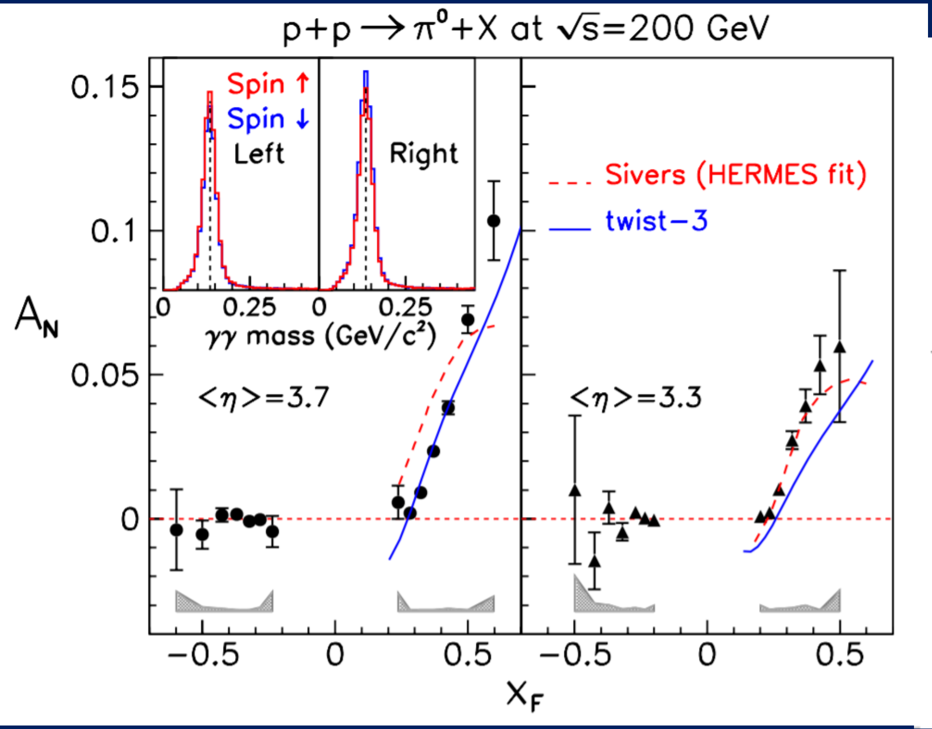


- Also TMD PDFs for gluons, except they can't be transversely polarized
- Corresponding TMD Fragmentation Functions
- Collins-Soper-Sterman evolution equations

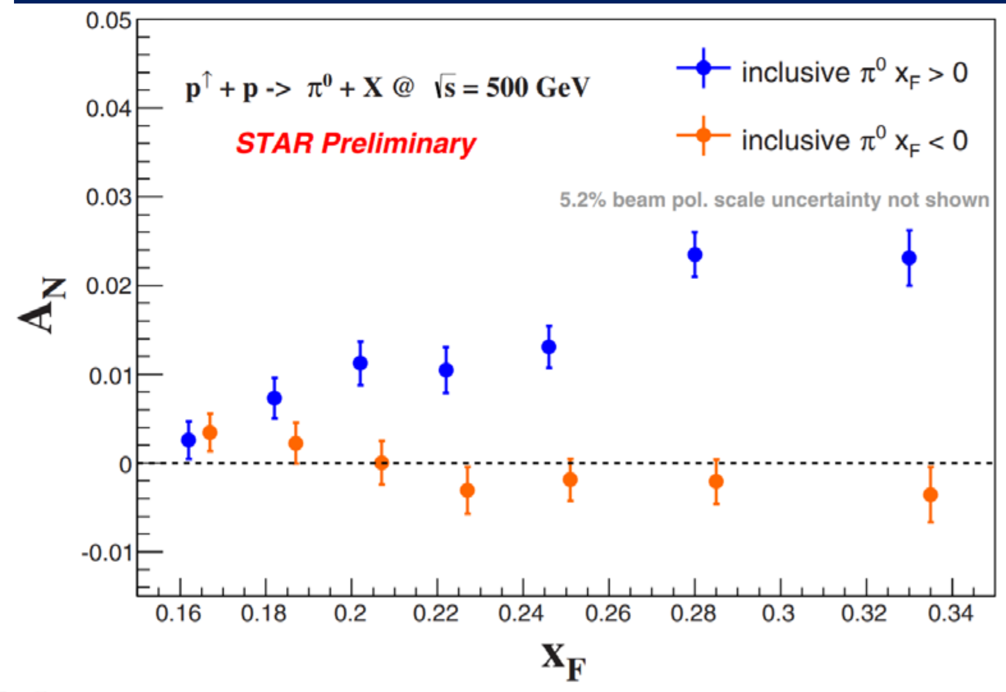
Forward transverse single-spin asymmetries for neutral pions



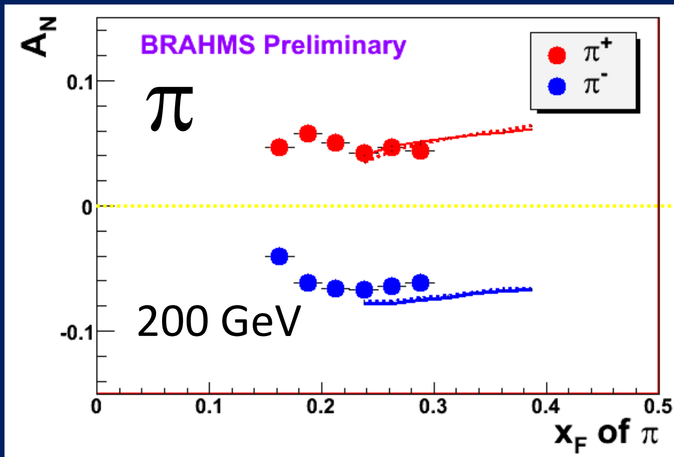
TSSA at Higher Energies



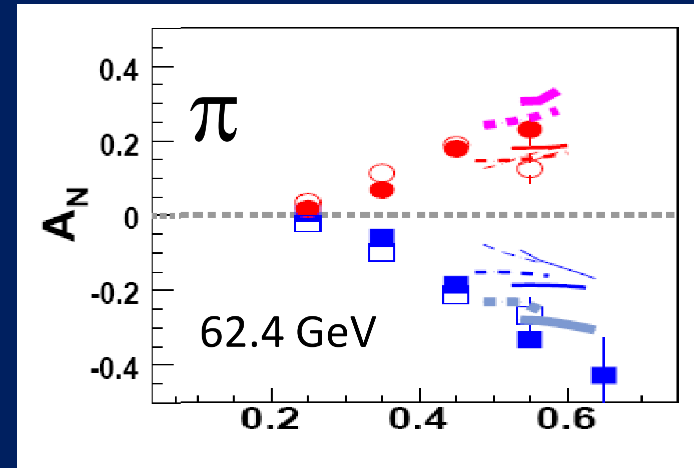
(STAR Collaboration) *Phys. Rev. Lett.* **101**, 222001 (2008)



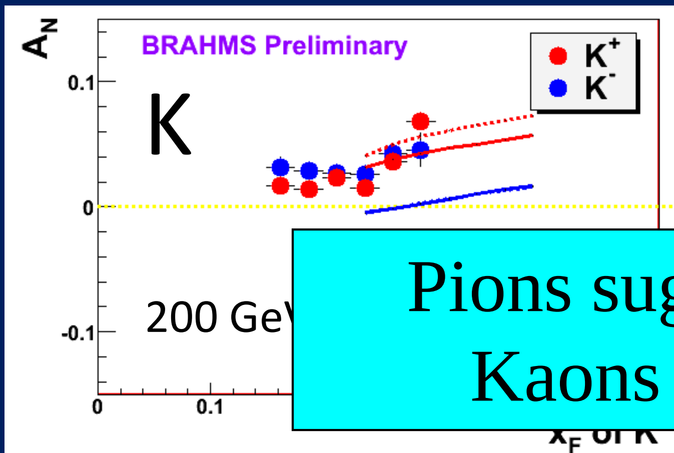
Yuxi Pan for the STAR Collaboration
International Journal of Modern Physics: Conference Series **40**, 1660037 (2016)



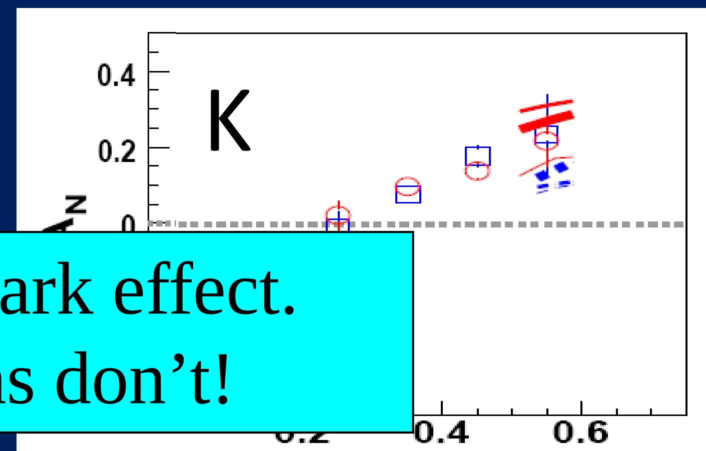
π, K, p at 200 and 62.4 GeV



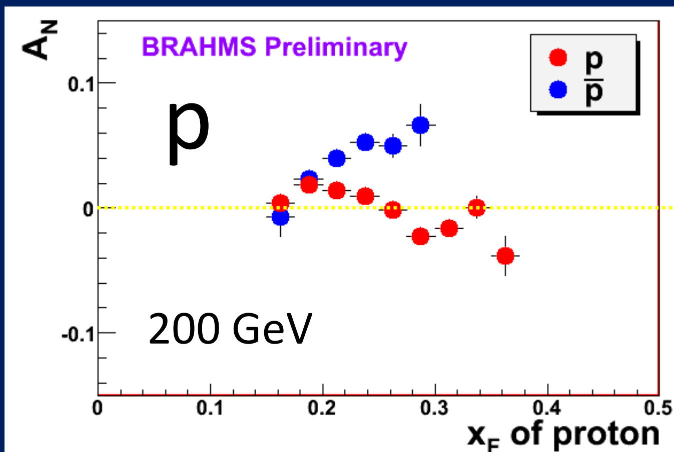
Note different scales



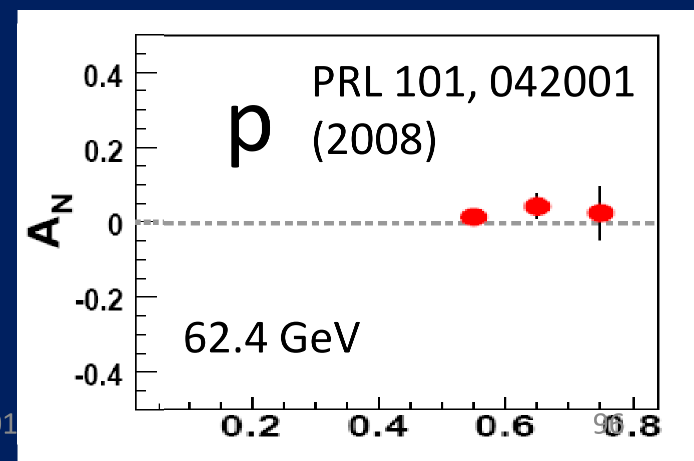
K- asymmetries underpredicted



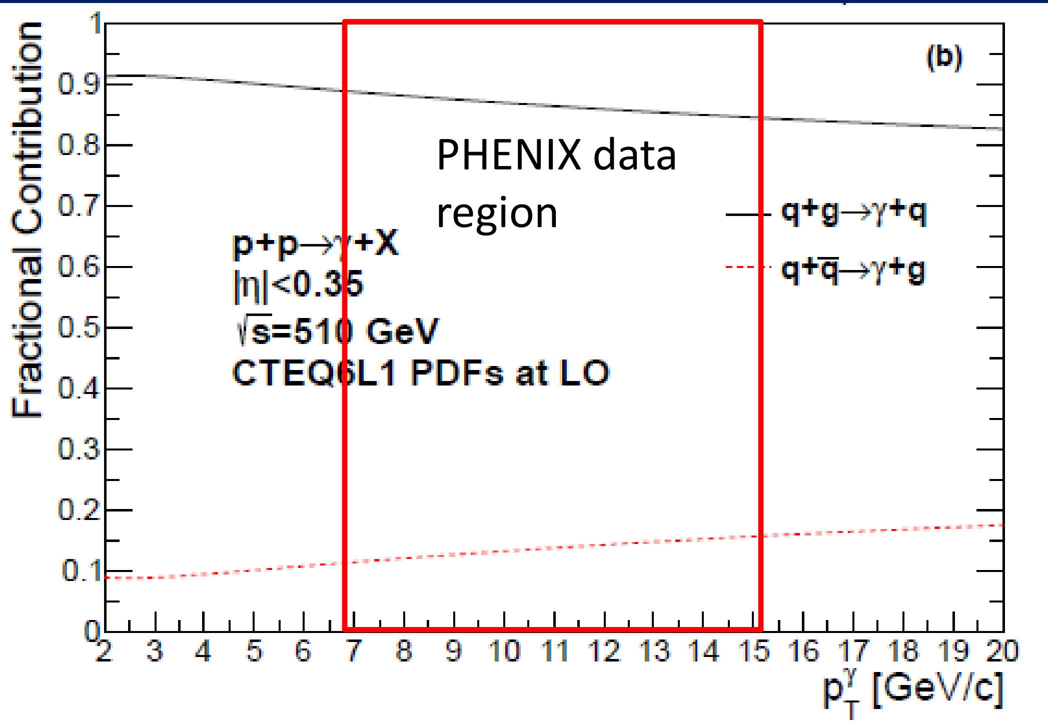
Pions suggest valence quark effect.
Kaons and (anti)protons don't!



Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement



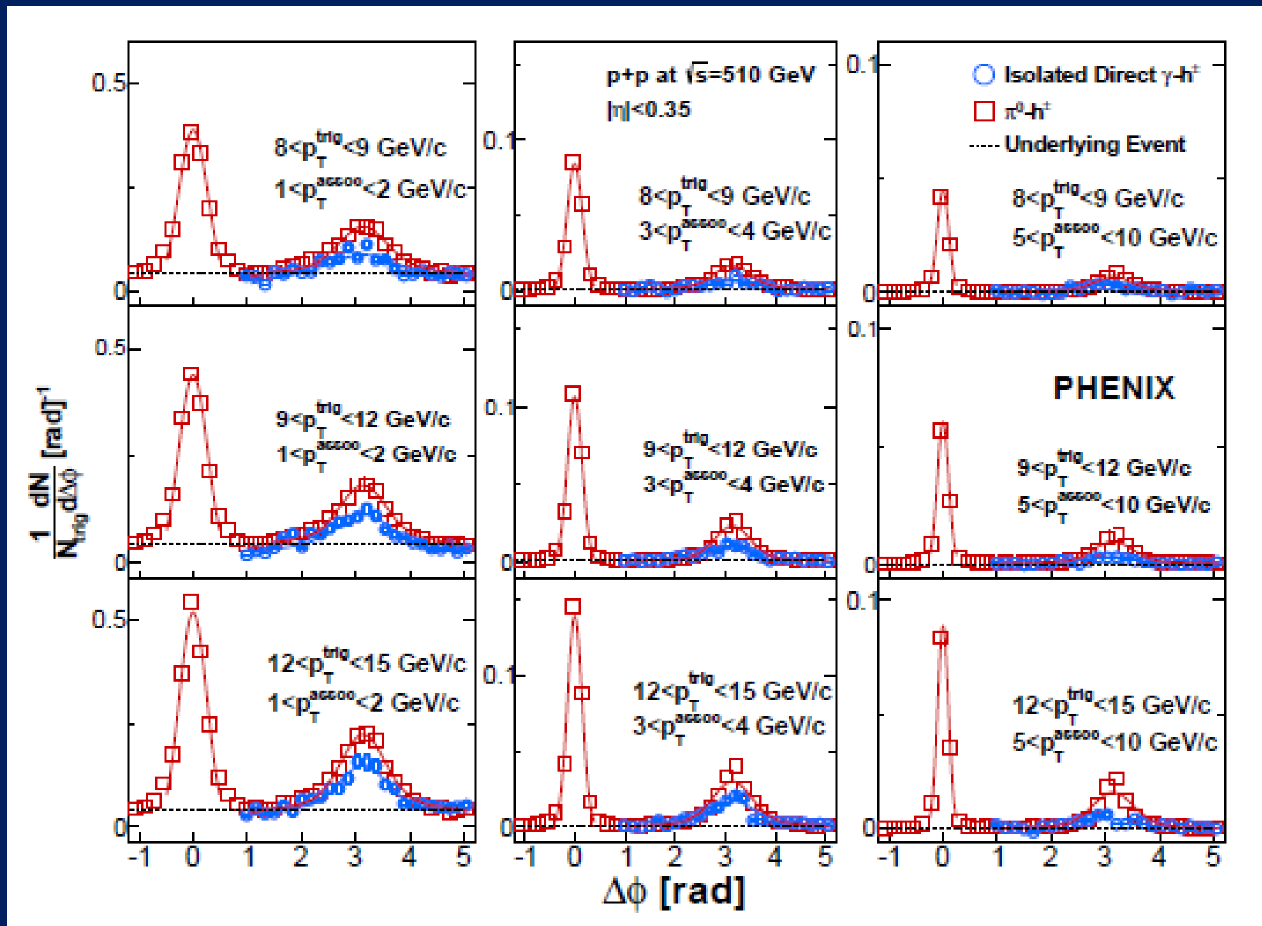
Partonic process contributions for direct photon production



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

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

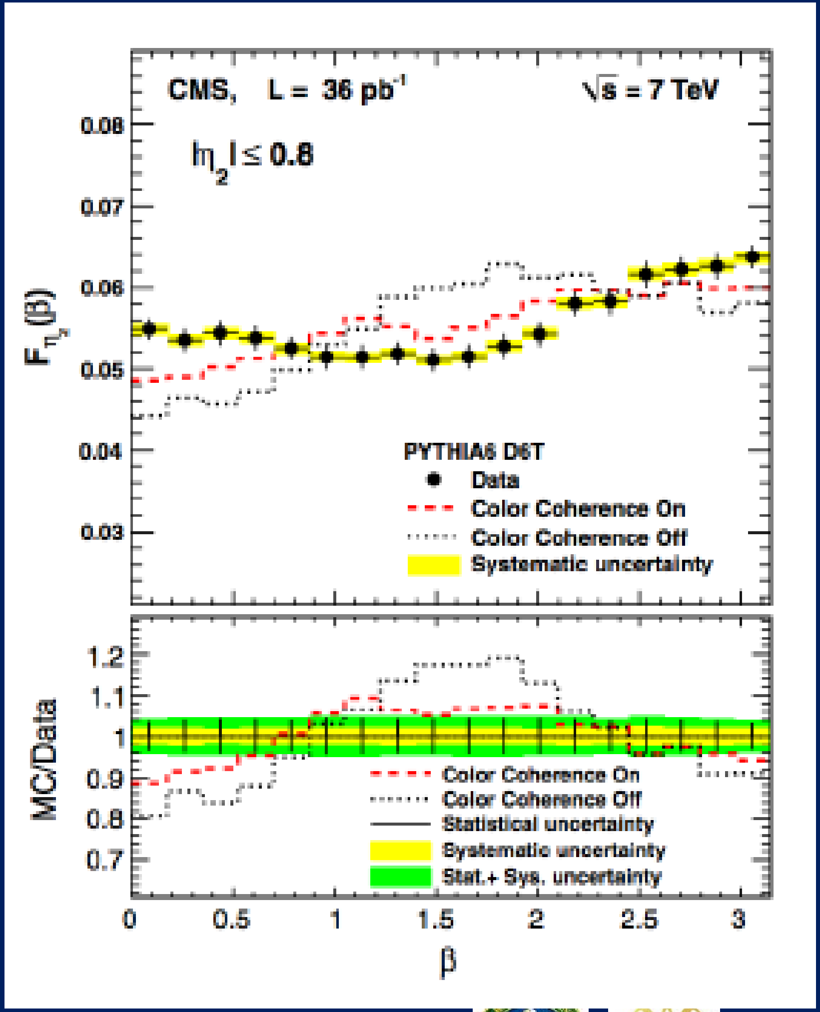
Two-particle correlation distributions show expected jet-like structure



PRD95, 072002 (2017)

Links to "color coherence" at Tevatron and LHC?

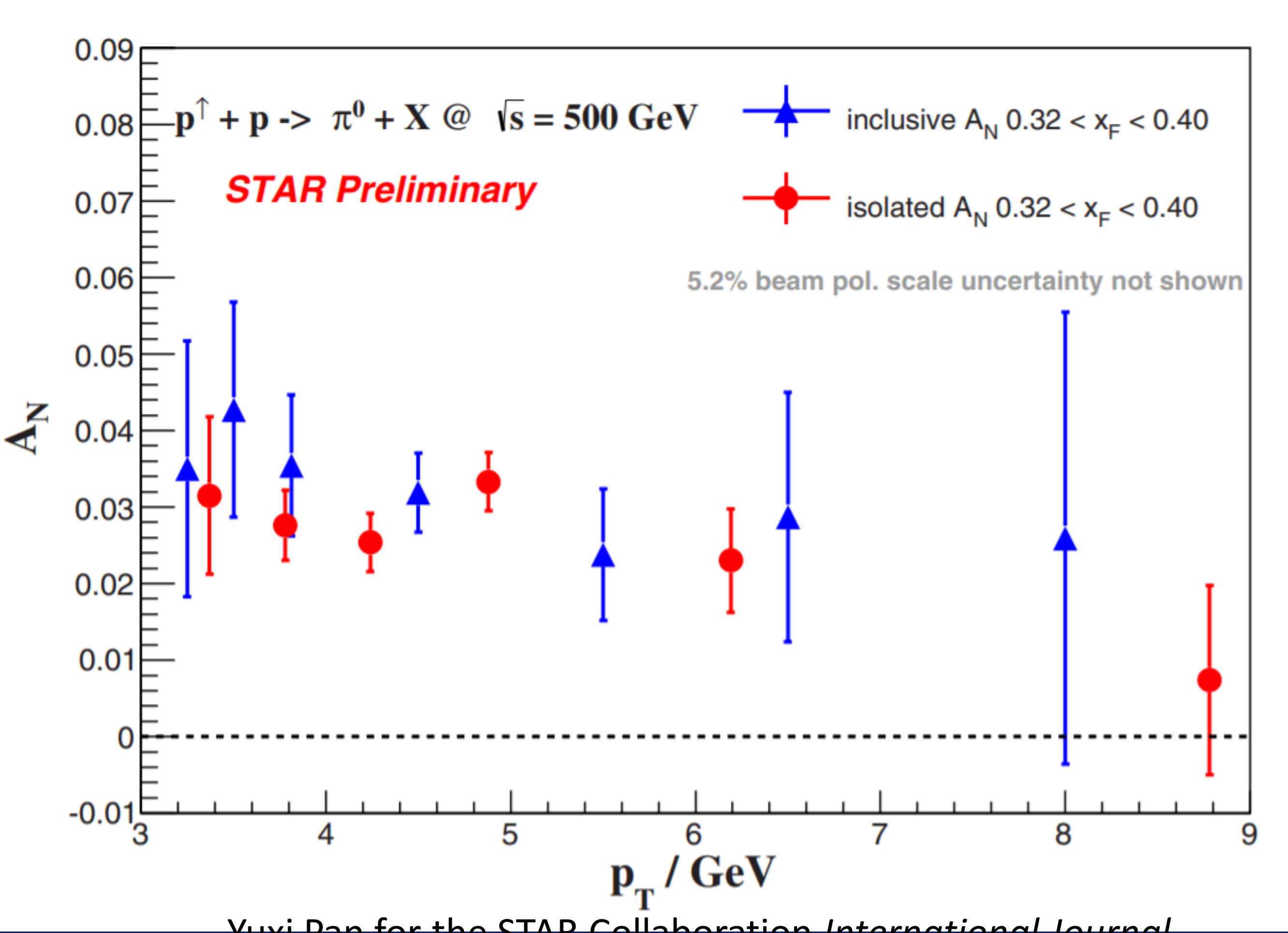
- D0, CDF, CMS have all published evidence for "color coherence effects"
  - CMS: EPJ C74, 2901 (2014)
  - CDF: PRD50, 5562 (1994)
  - D0: PLB414, 419 (1997)
- Few citations—relatively little-known work thus far. Need to get different communities talking to explore detailed color effects more in upcoming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



TSSAs in $p^{\uparrow} + p$

Large TSSA in $p^{\uparrow} + p \rightarrow h + X$

- Uncovered the need for a TMD framework
- Not sensitive to soft scale k_T $\rightarrow$ Only one (hard) scale available: p_T



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Multiparton correlations in hadronization

- Traditional fragmentation functions describe probability of single parton to hadronize into particular hadron, as function of momentum fraction (z) of parton carried by the final hadron
- Can have matrix elements describing *multiparton correlations in hadronization*
  - Interference between a (quark+gluon) hadronizing and only a quark
  - Similarly, interference between (gluon+gluon) and only a single gluon
  - Kanazawa+Koike, 2000

Summary of spin-momentum correlation results

- Clear empirical evidence for nonzero
  - Sivers TMD pdf – correlation between proton transverse spin and quark transverse momentum
    - SIDIS
  - Collins TMD FF – correlation between quark transverse spin and transverse momentum of produced hadron
    - e+e-, SIDIS
  - Boer-Mulders TMD pdf – correlation between quark transverse spin and quark transverse momentum
    - Drell-Yan, SIDIS
- Hints from SIDIS measurements (in backup) of nonzero
  - Worm gear TMD pdf – correlation between proton transverse spin, quark longitudinal spin, quark transverse momentum
  - Pretzelosity TMD pdf – correlation between proton transverse spin, perpendicular quark transverse spin, quark transverse momentum
- Also clear evidence for nonzero helicity and transversity collinear pdfs from SIDIS and p+p, collinear dihadron interference FF from e+e-, SIDIS, p+p

High-energy QCD: Thinking in terms of individual partons

- PDFs are *single-parton* functions in *single* nucleons
  - Or in nuclei, but typically still think of partons in individual nucleons within nucleus

- Can we go beyond this single-parton picture while staying in the hard (short-distance) limit of perturbative QCD?

An alternative approach to describing the large single-spin asymmetries: Higher-twist multiparton correlations

- Extend our ideas about (single-parton) pdfs to correlation functions that can't be associated with a single parton
- Non-perturbative structure → matrix elements involving the quantum mechanical *interference* between scattering off of a (quark+gluon) and scattering off of a single quark (of the same flavor and at the same *x*)
  – Can also have interference between (gluon+gluon) and single gluon
  – No explicit dependence on partonic transverse momentum
  – Efremov+Teryaev 1981, 84; Qiu+Sterman 1991, 98

Beware: Two common usages of the term "twist"

- Formal definition of twist: "mass dimension minus spin" of the operator in a matrix element within the Operator Product Expansion
  - "Leading twist" is twist-2
  - Twist-n *matrix element* carries a factor of $1/Q^{(n-2)}$

- But – *observables* with measurable contributions from terms suppressed by a factor of $1/Q^{(n-2)}$ often referred to as sensitive to "twist-n" contributions
  - Never measure a matrix element, only matrix elements squared!
  - To get 1/Q term describing an *observable*, need interference term in the square modulus:
    - A = order 1 + order 1/Q + order $1/Q^2$ + …
    - $|A|^2$ = $|\text{order } 1|^2$ + $|\text{order } 1/Q|^2$ + (order 1)(order 1/Q)* + (order 1)*(order 1/Q) + …
  - So twist-3 term in matrix element times *twist-2* term gives 1/Q
  - Square modulus of *twist-3* term gives $1/Q^2$, sometimes referred to as "twist-4"

Transverse single-spin asymmetries provide new information on hadron structure

- Leading contribution to transverse single-spin asymmetries comes from *either*:
  - Convolution of two twist-2 *transverse-momentum-dependent* parton distribution functions and/or fragmentation functions, or . . .
  - Convolution of one twist-2 collinear pdf or fragmentation function and one twist-3 (collinear) *multiparton correlation* matrix element