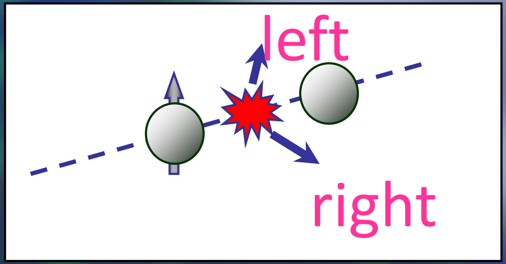
Spin-Momentum Correlations, Aharonov-Bohm, and Color Entanglement in Quantum Chromodynamics

Christine A. Aidala

University of Michigan



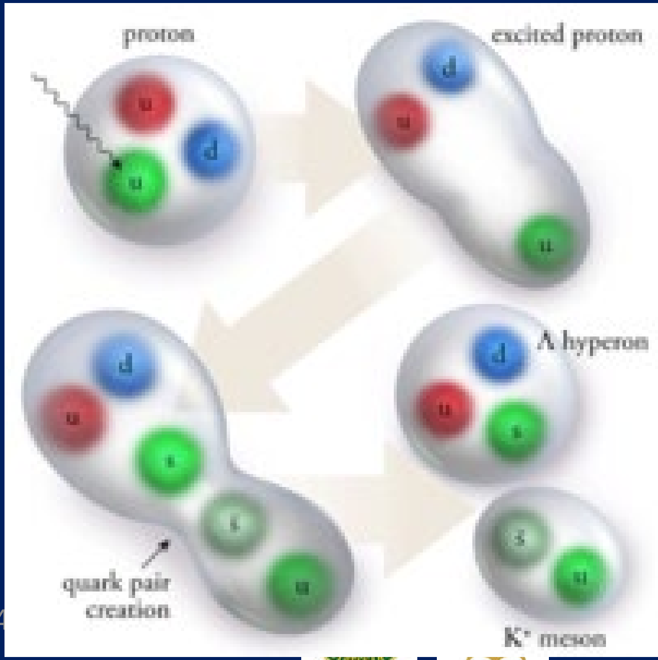
$$\psi(x)|P\rangle = e^{ig\int_x^{x'} ds_\mu A^\mu}\psi(x')|P\rangle$$

HEP Seminar
Argonne National Lab
April 24, 2019

Theory of strong nuclear interaction: Quantum Chromodynamics

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

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



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

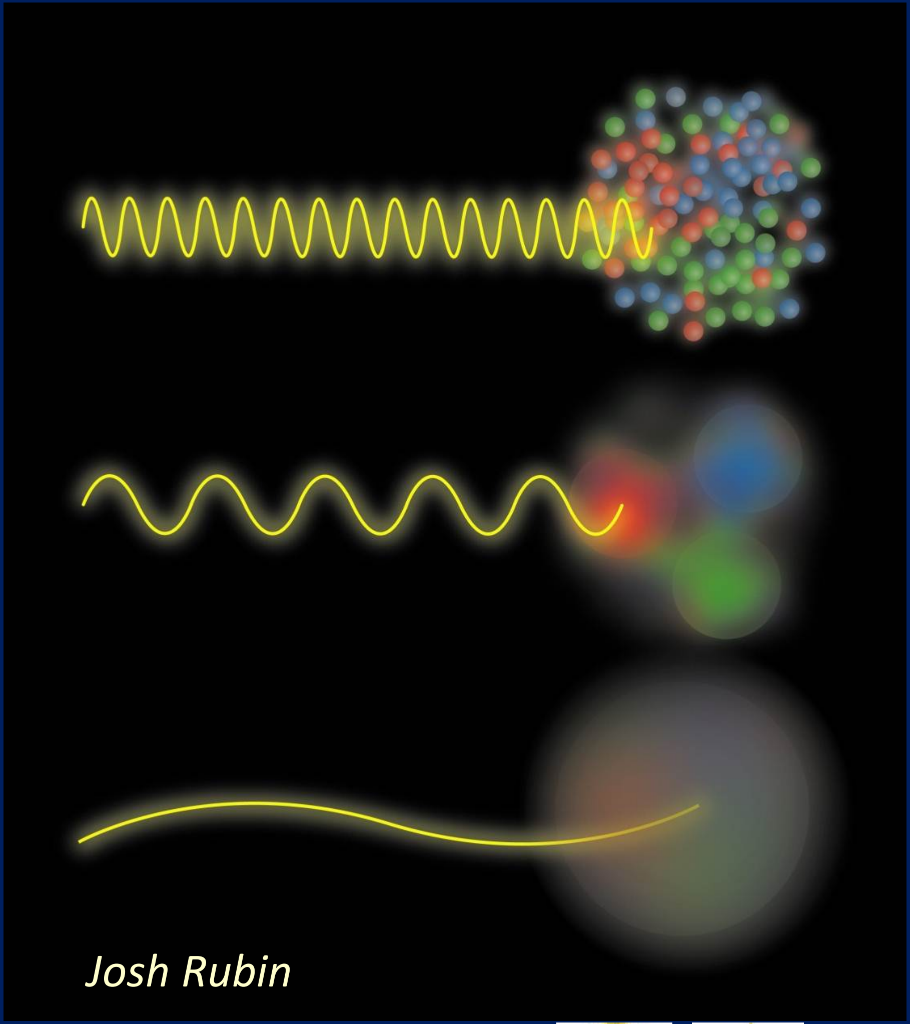
How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

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

The proton as a "laboratory" for studying QCD

- Proton: simplest stable QCD bound state

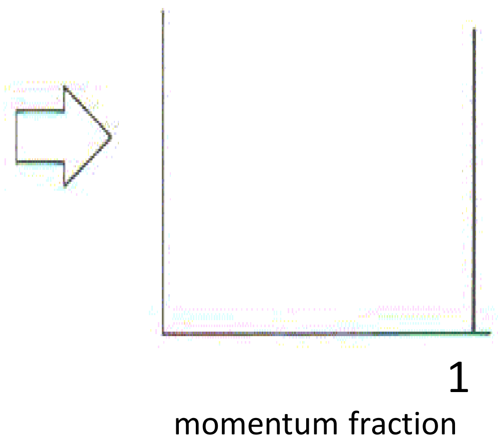
- Different energy scales offer information on different aspects of proton internal structure



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

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

A point-like particle



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

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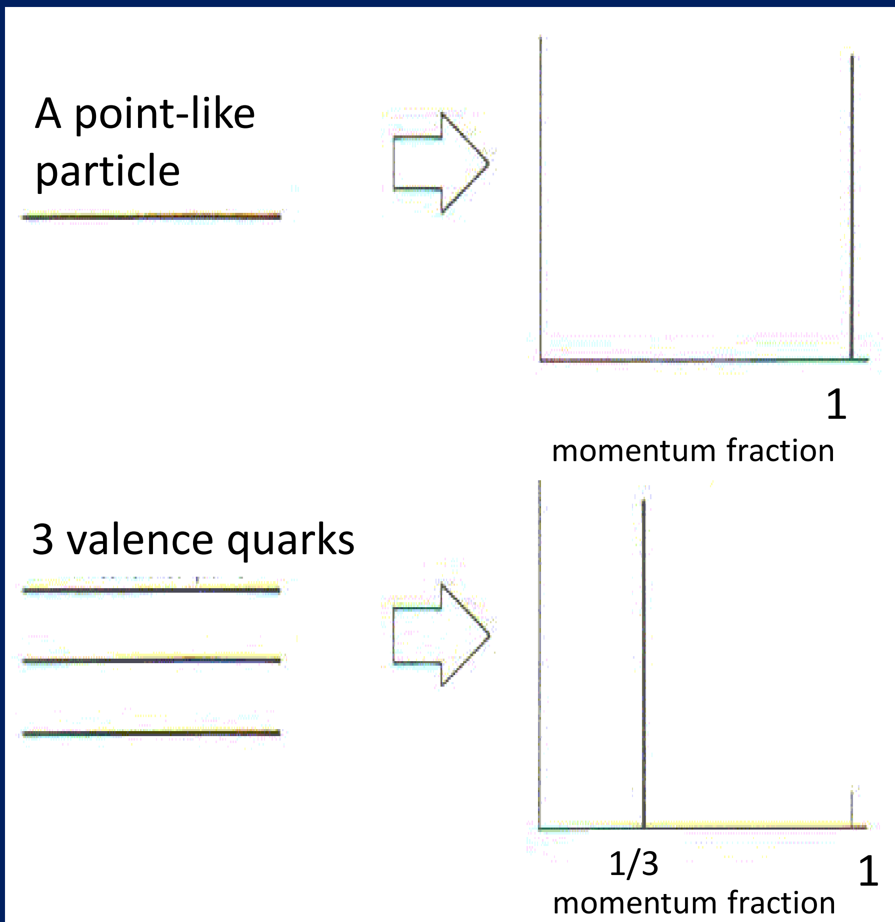

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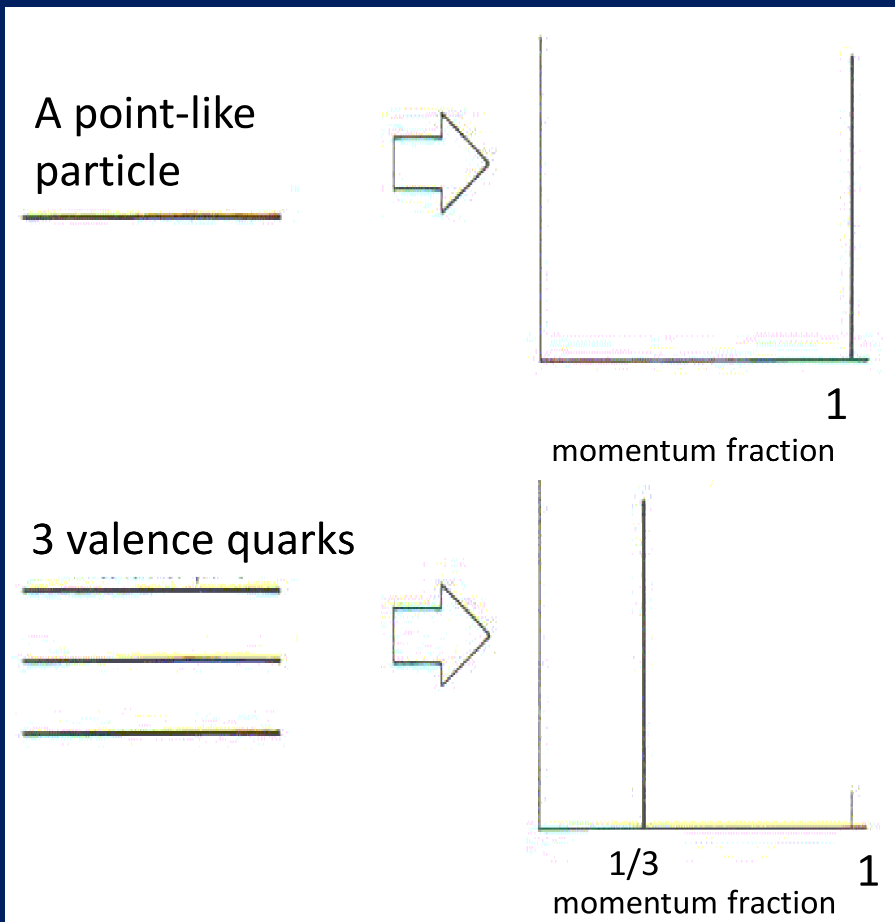

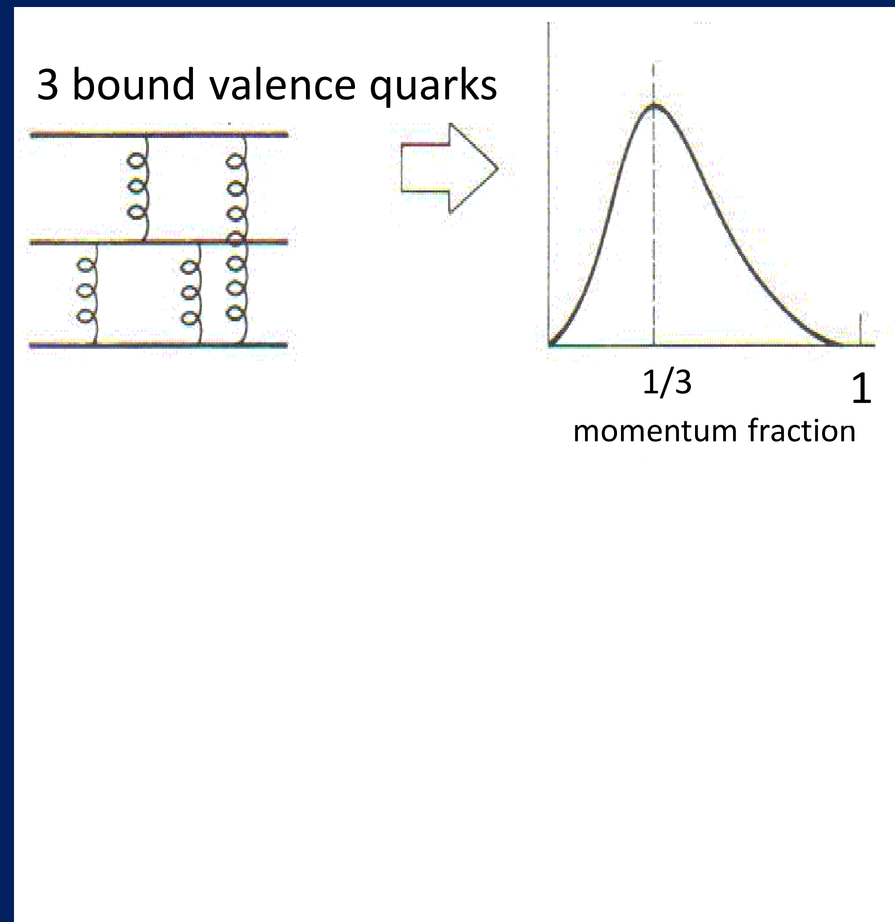

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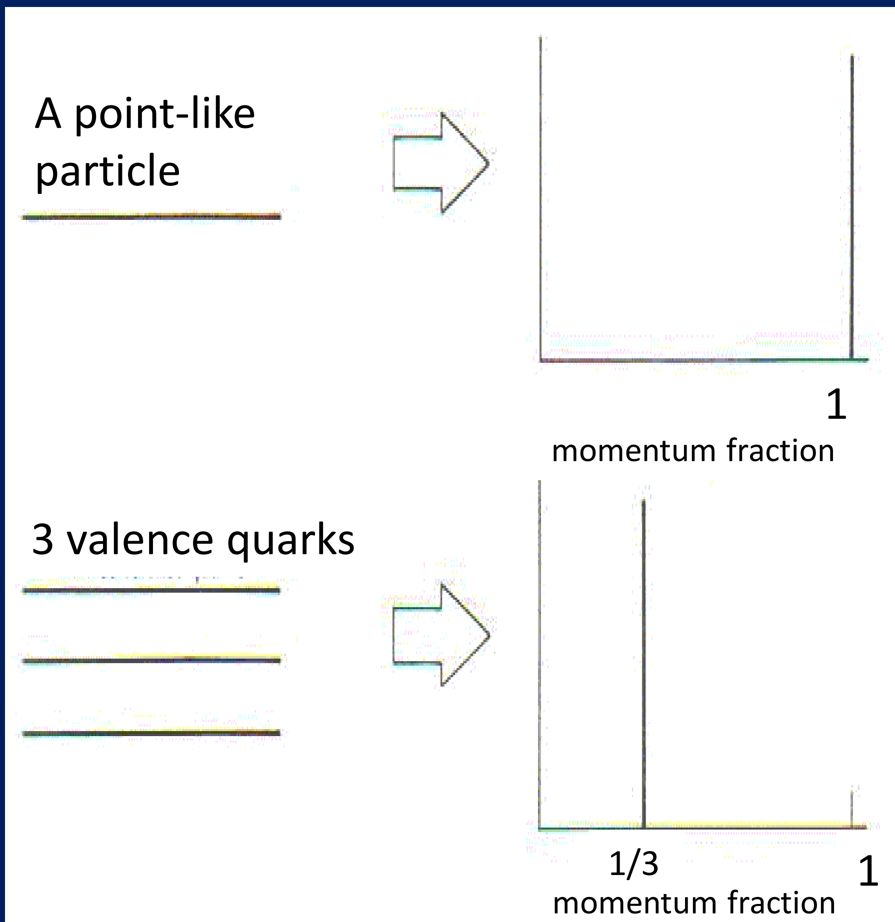
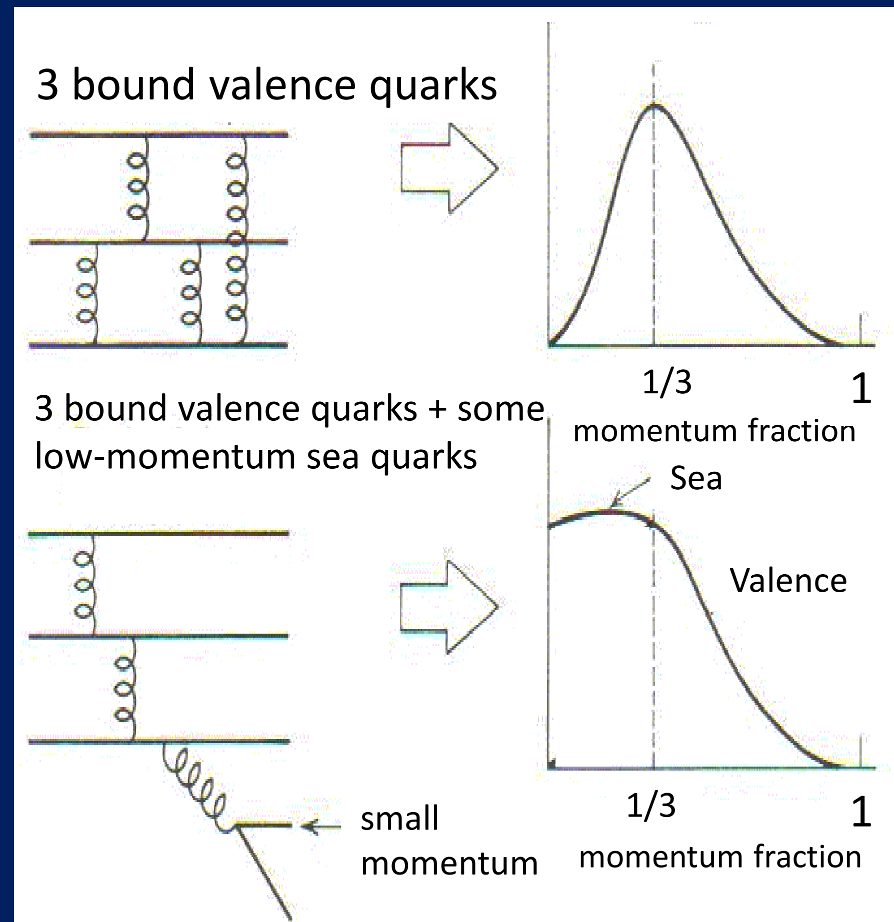
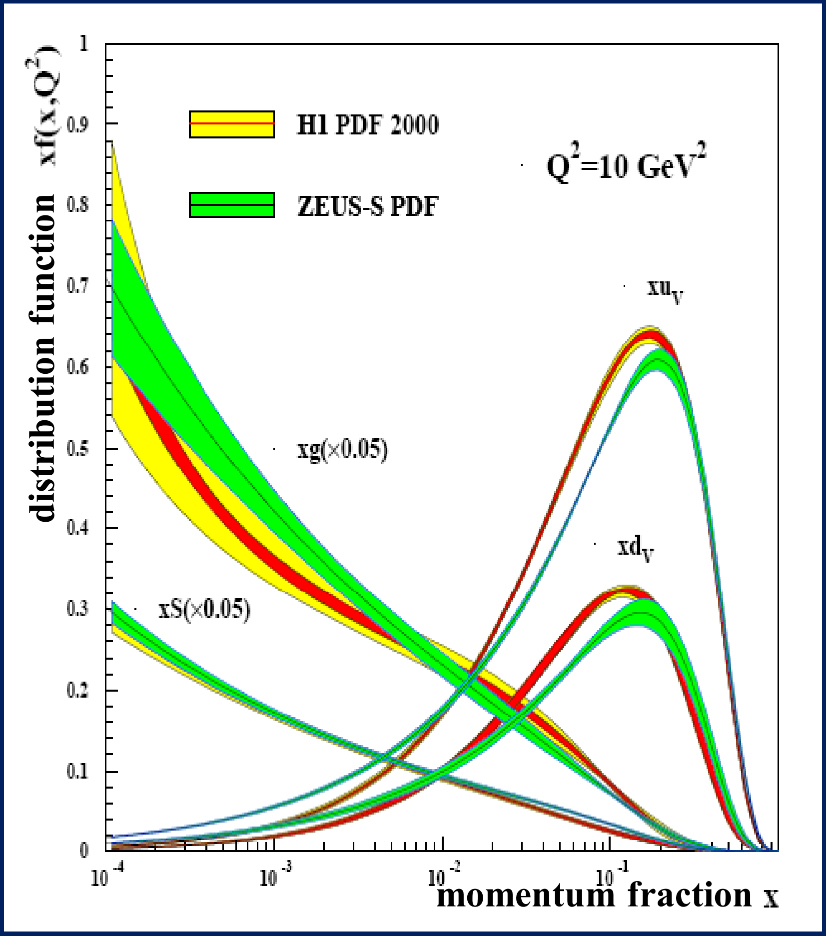


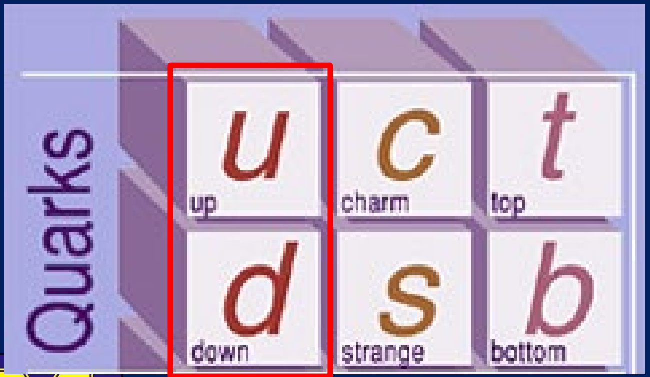


Halzen and Martin, "Quarks and Leptons", p. 201

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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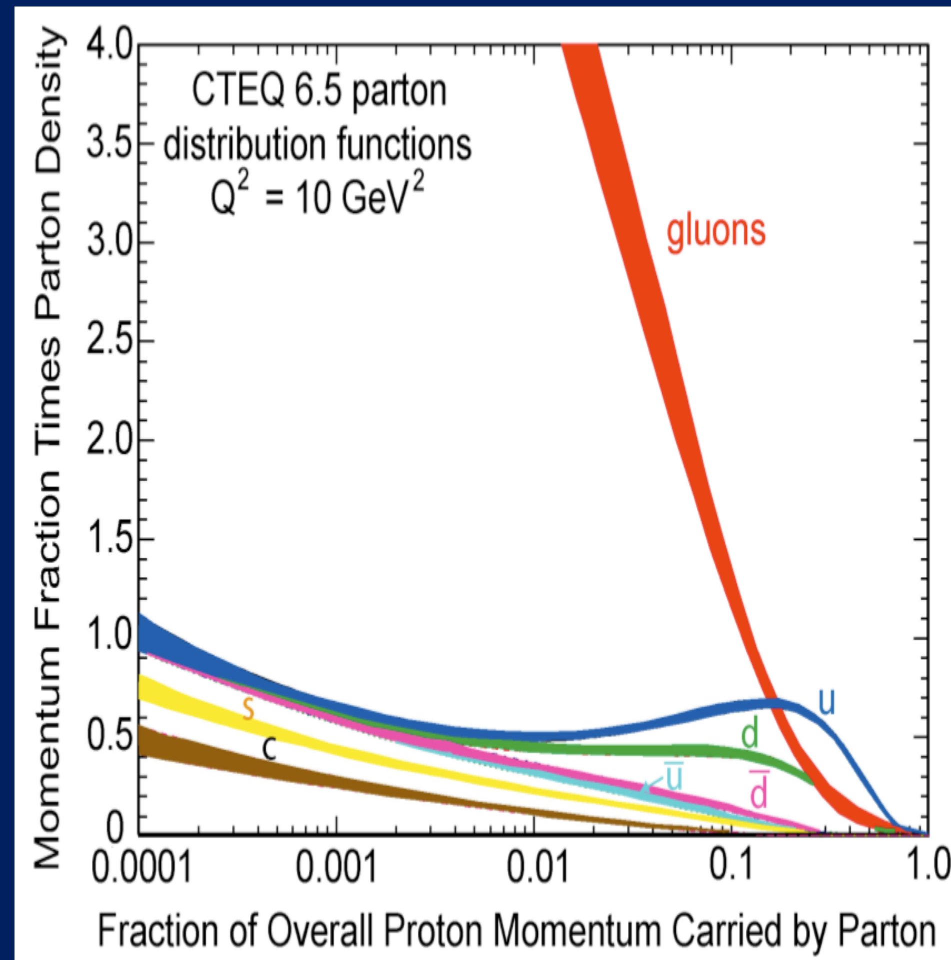
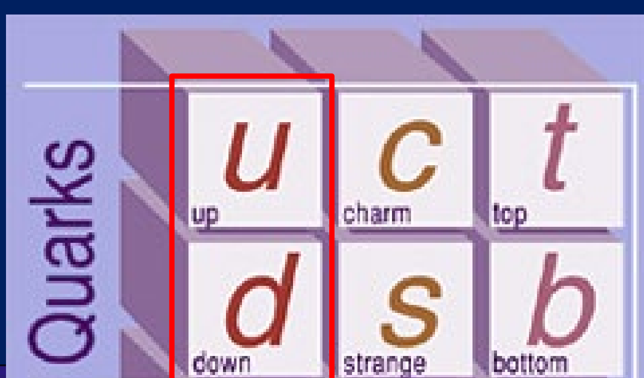
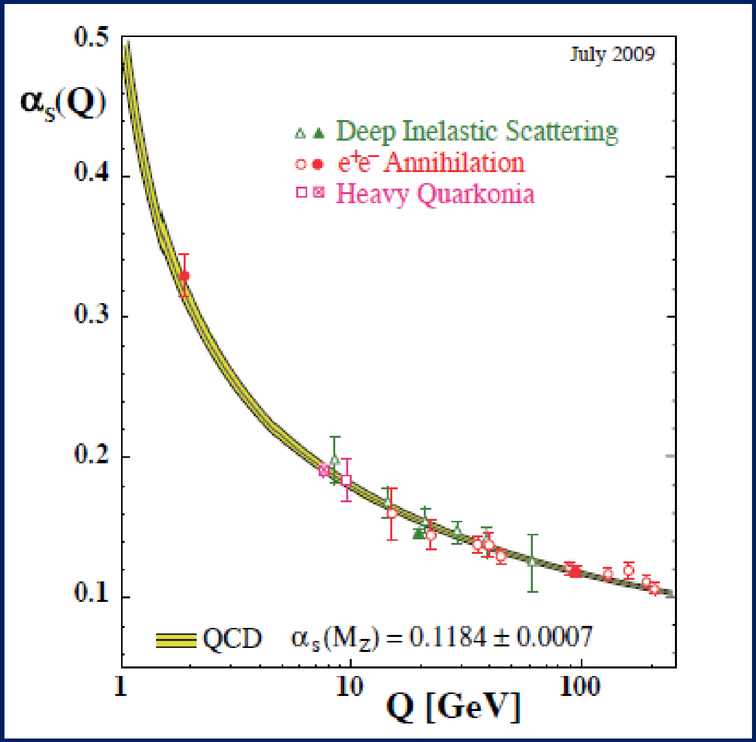




Perturbative QCD

- 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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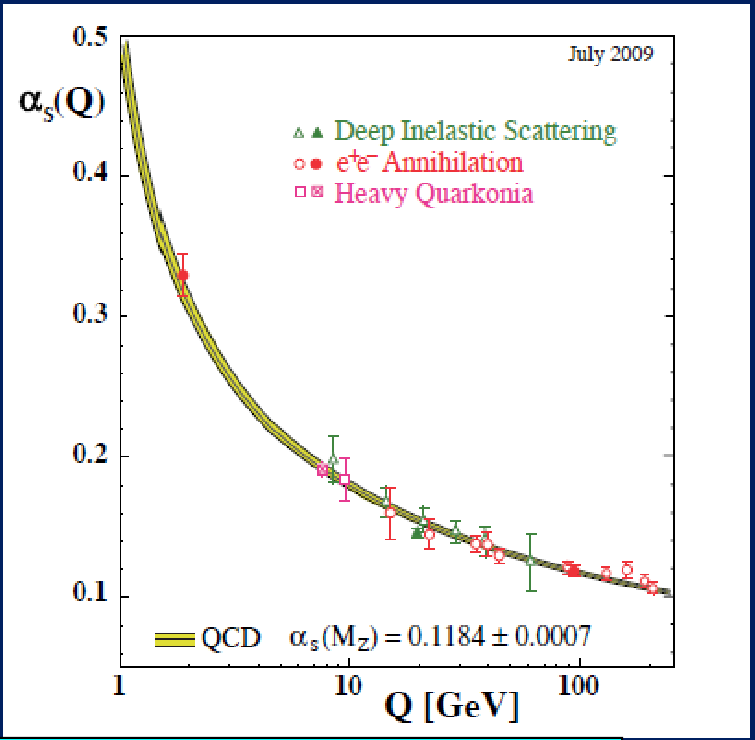

Provides one rigorous way of relating the fundamental field theory to a variety of physical observables

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 $\sim 10^{-15}$ m describing bound-state structure (confinement)!
- Long-distance (i.e. not perturbatively calculable) functions describing structure need to be *universal*
  - Physically meaningful descriptions
  - Portable across calculations for many processes

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

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Note: Nonperturbative lattice QCD techniques have made tremendous progress toward *ab initio* calculations of proton structure in last ~6 years!

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

Mapping out the quark-gluon structure of the proton

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

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

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

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

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Good measurements of flavor distributions in valence region. Flavor structure for sea quarks 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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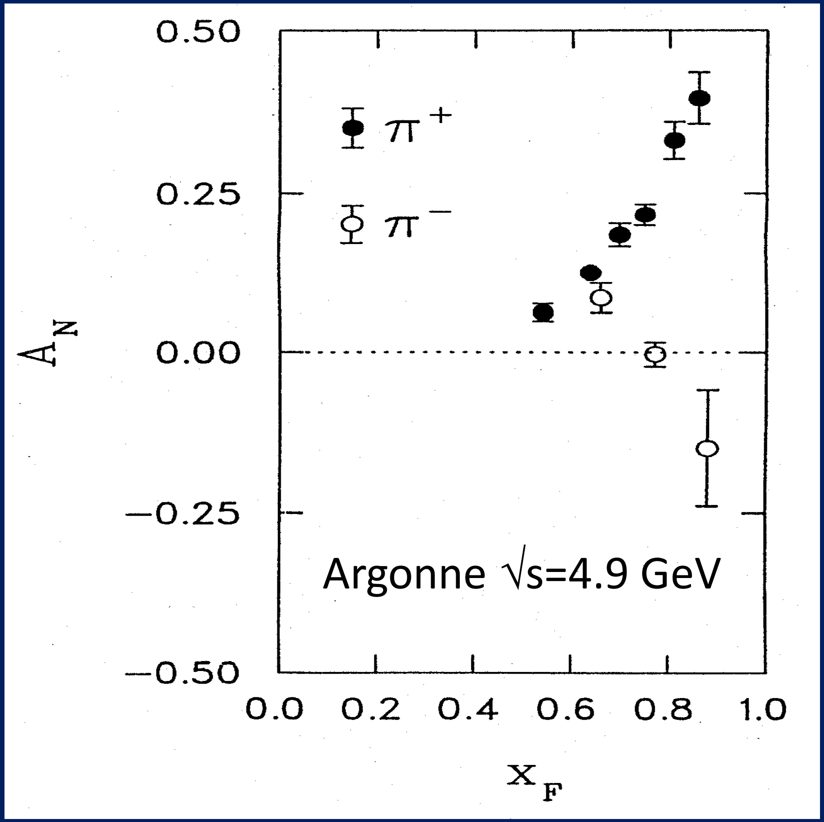
Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color flow have come to forefront in last few years . . .

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

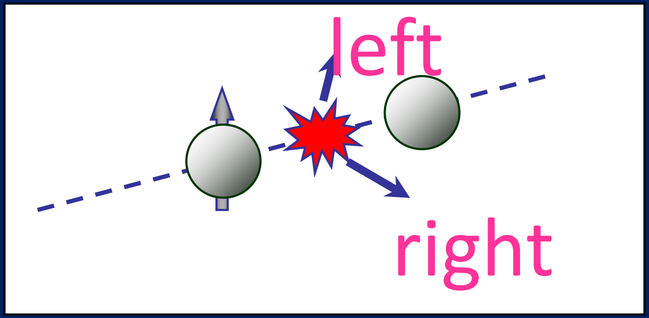
At Argonne Zero Gradient Synchrotron



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

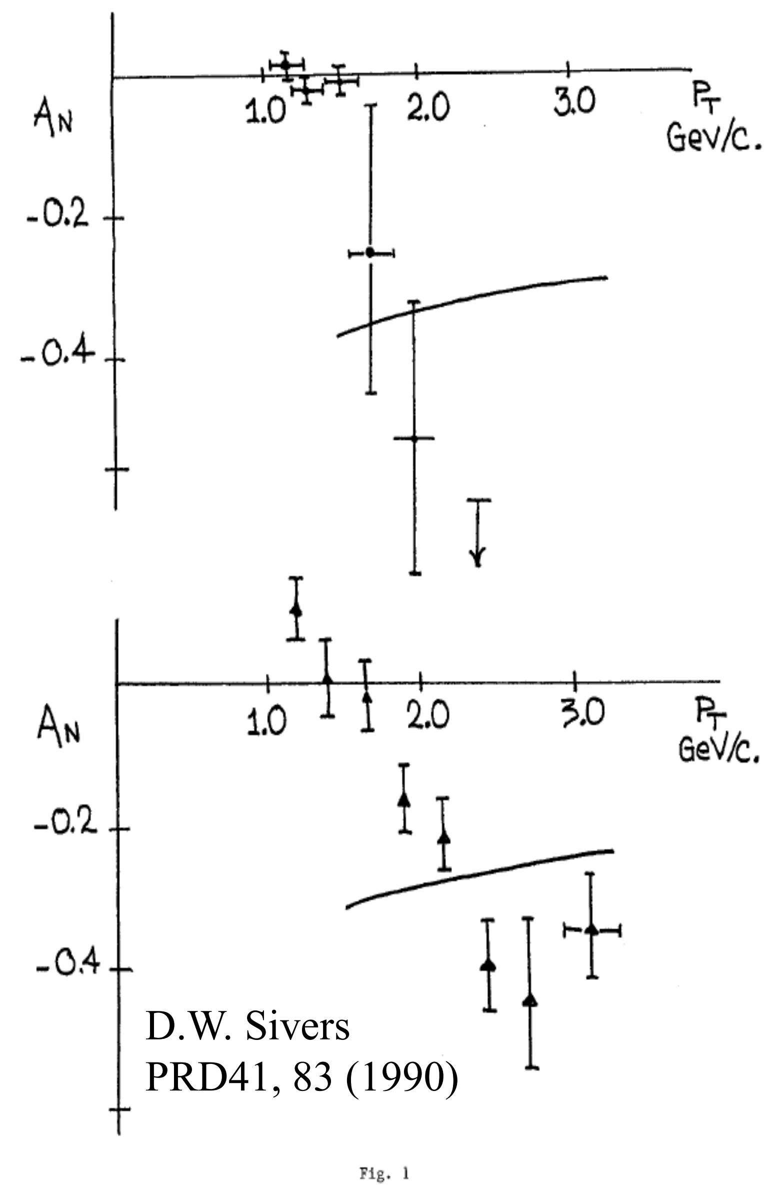
Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction—by up to 40%!!

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



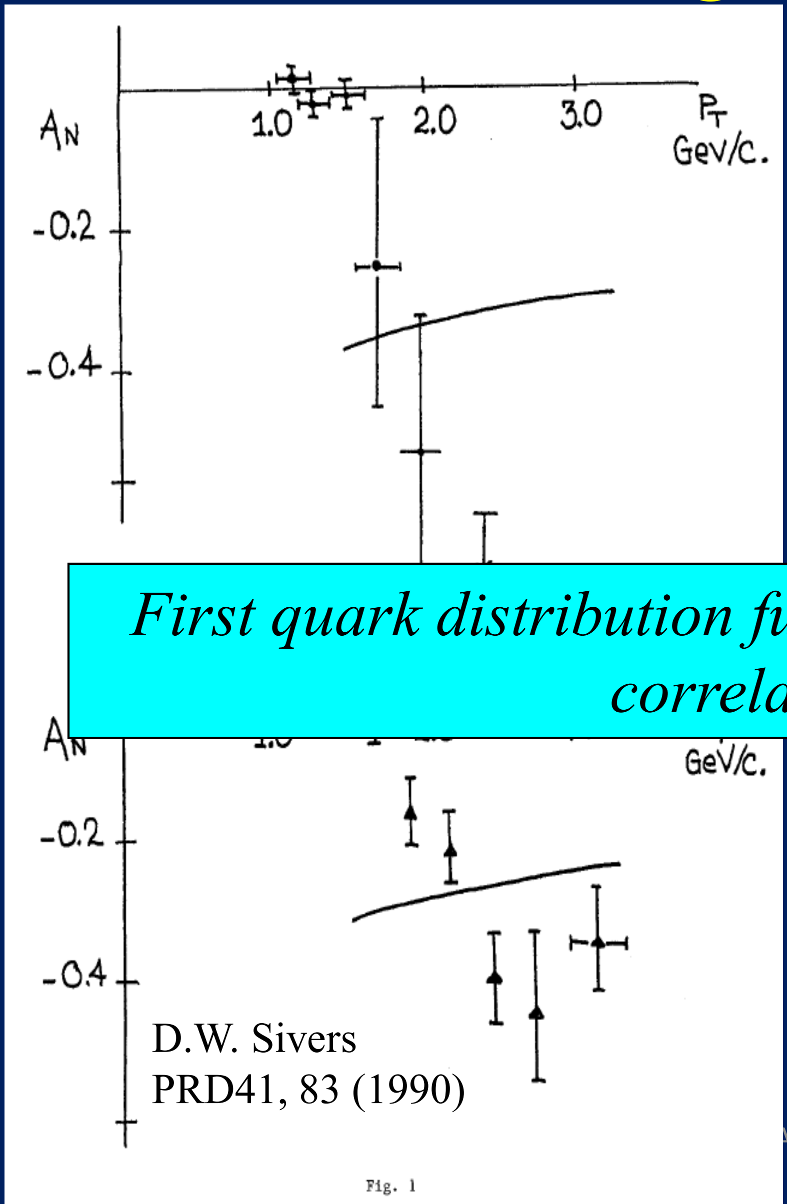
D.W. Sivers
PRD41, 83 (1990)

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

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

Spin and momenta of quarks and/or bound states

Transverse-momentum-dependent distributions and single-spin asymmetries



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

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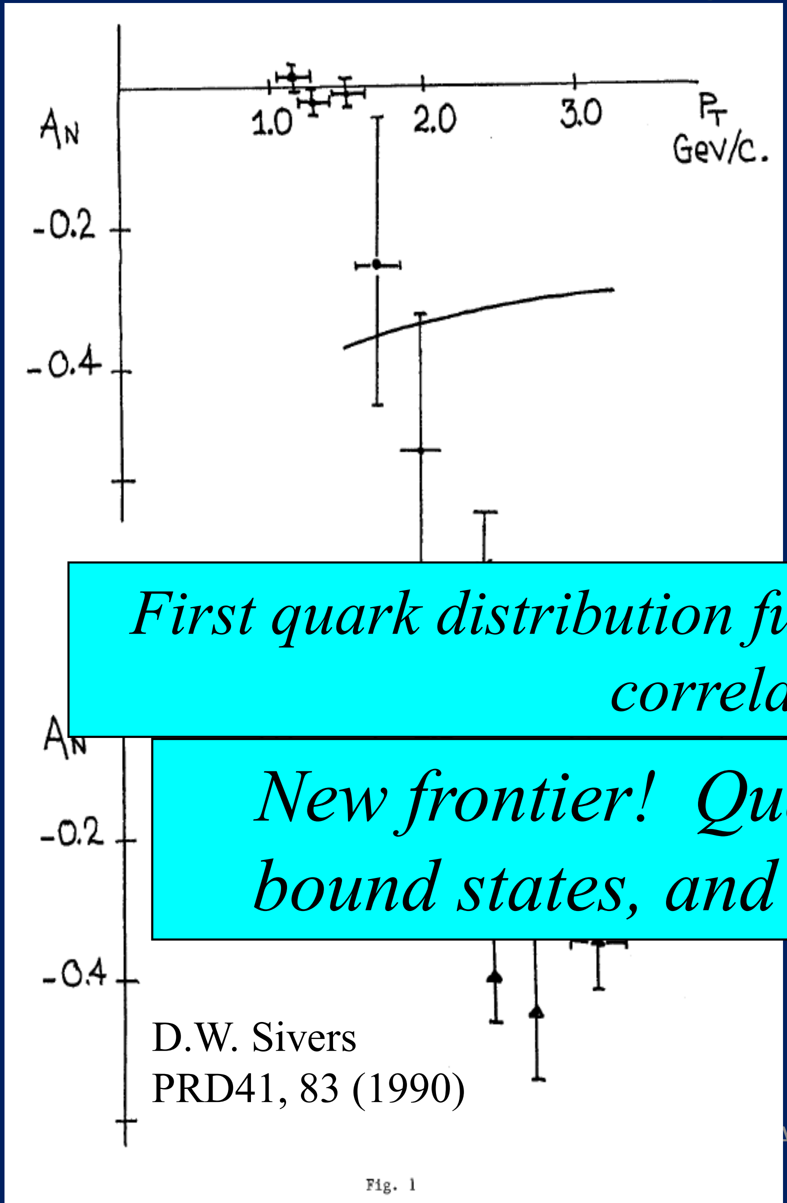

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First quark distribution function describing a spin-momentum correlation in the proton

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

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

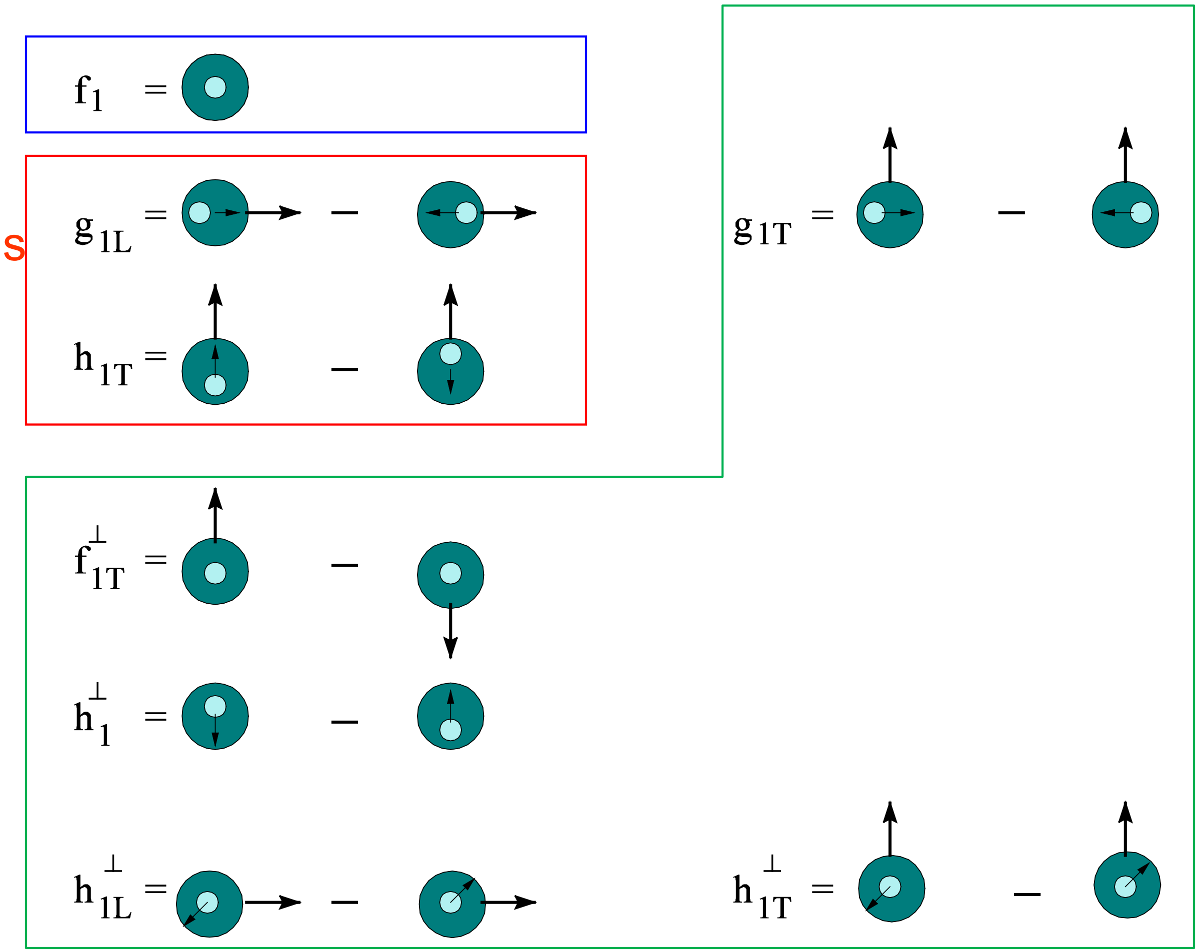
Spin and momenta of quarks and/or bound states

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

Unpolarized

Spin-spin correlations

Spin-momentum correlations



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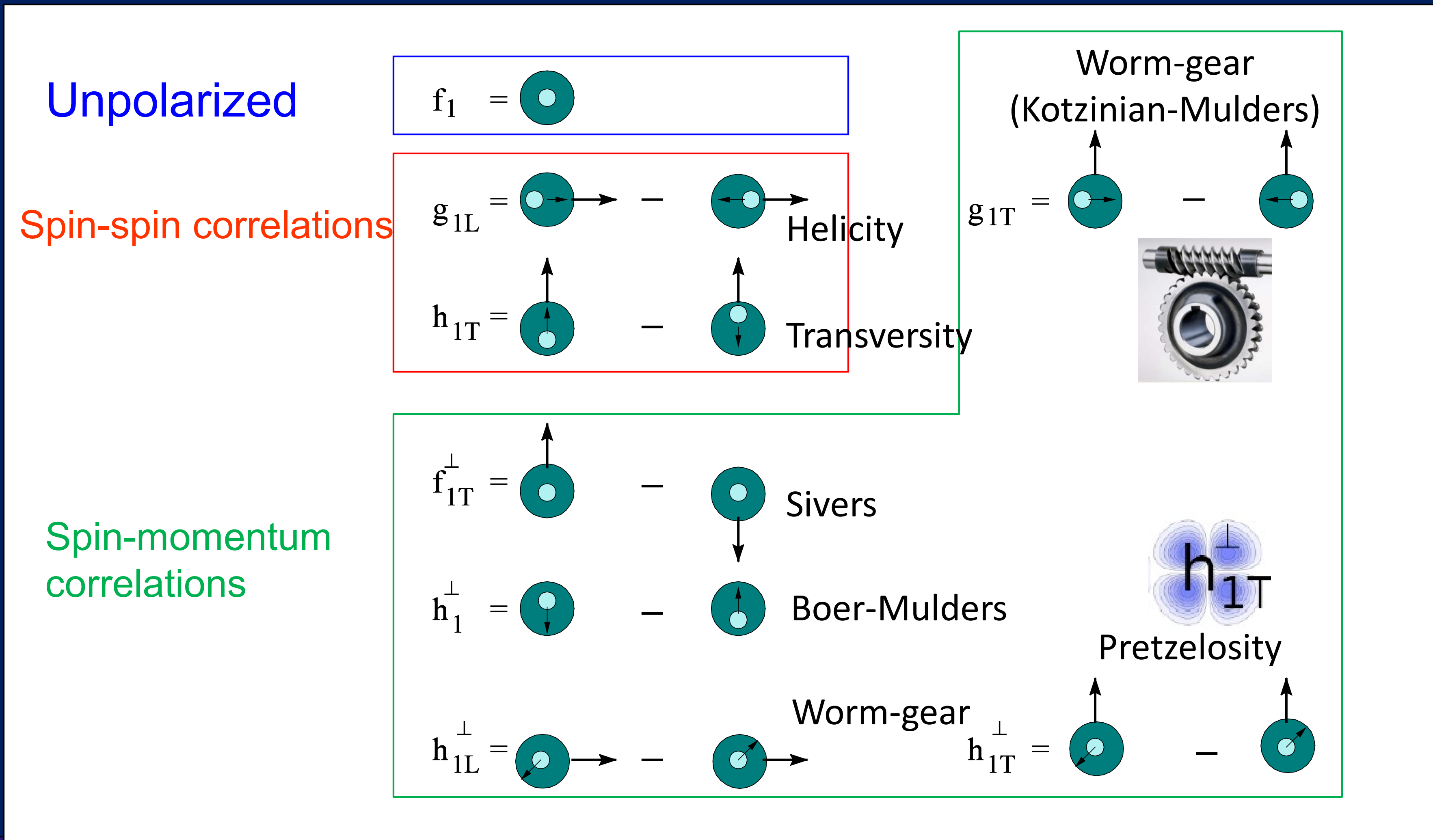

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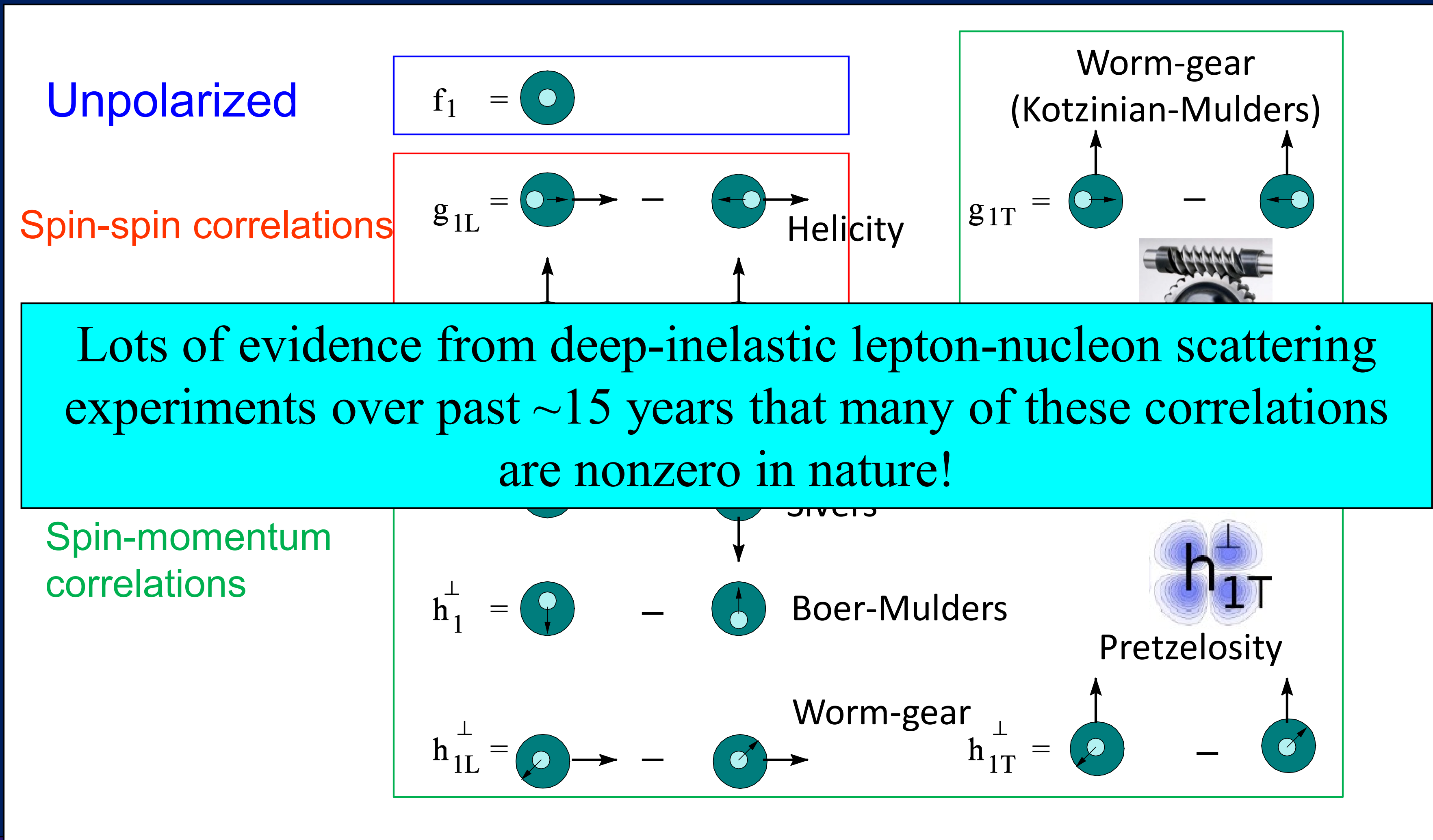
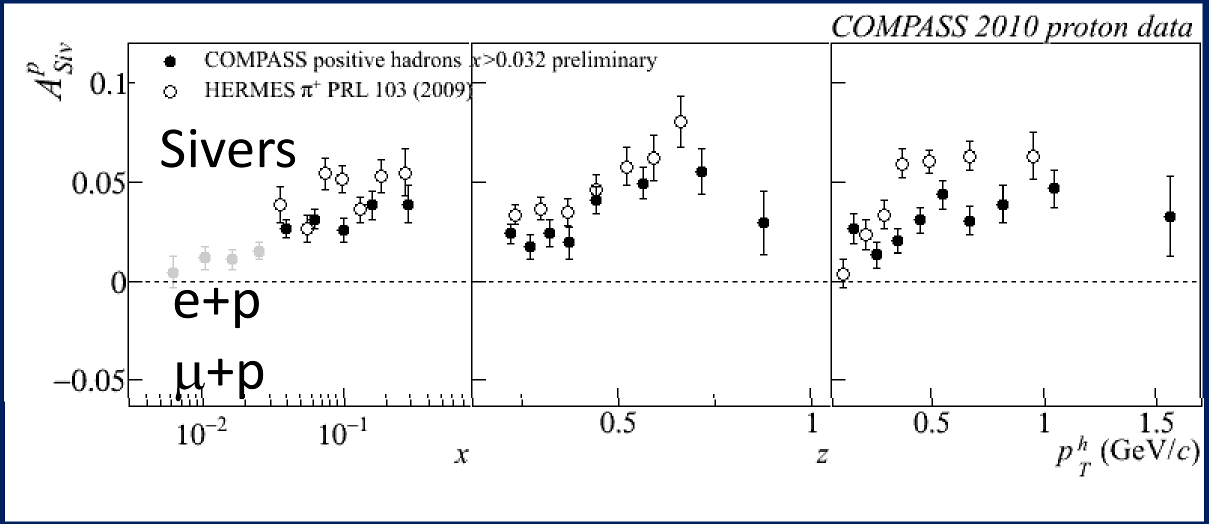
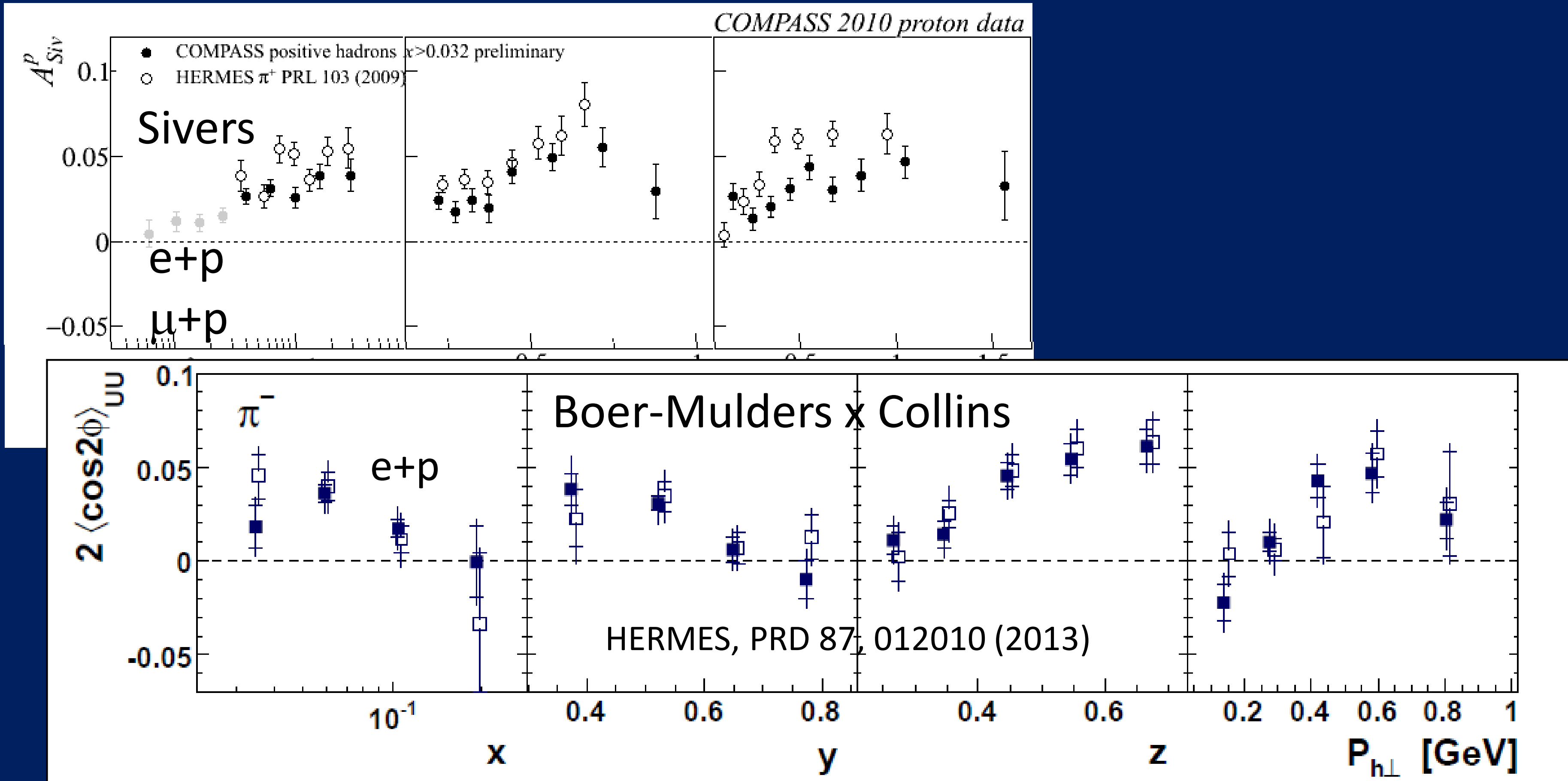


Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~15 years that many of these correlations are nonzero in nature!


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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e+p
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0.1
0.05
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π−
e+p
Boer-Mulders x Collins
HERMES, PRD 87, 012010 (2013)
2 ⟨cos2ϕ⟩UU
0.1
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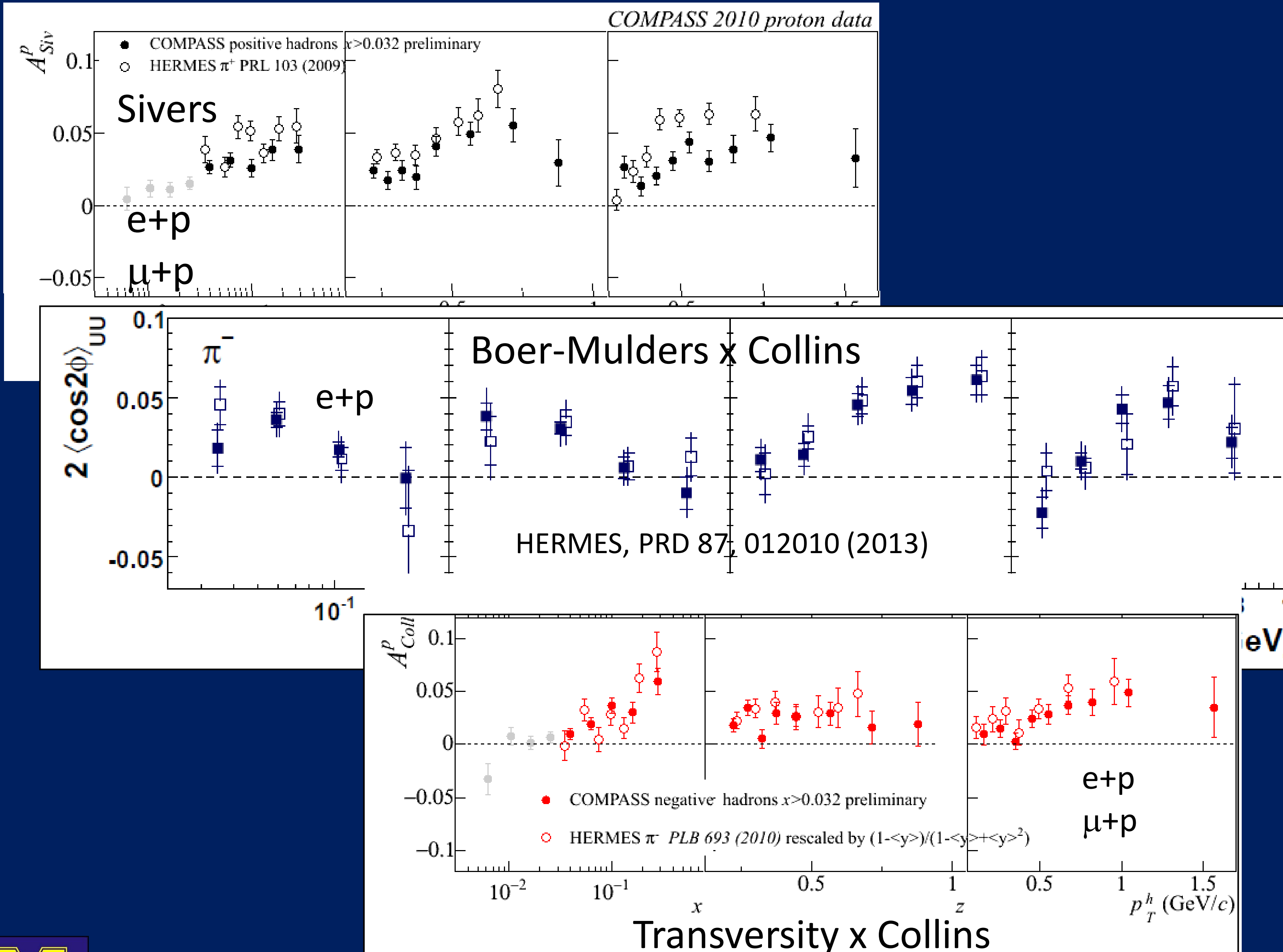
0.4
0.6
0.8
0.2
1
x
y
z
Ph⊥ [GeV]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e+p
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π−
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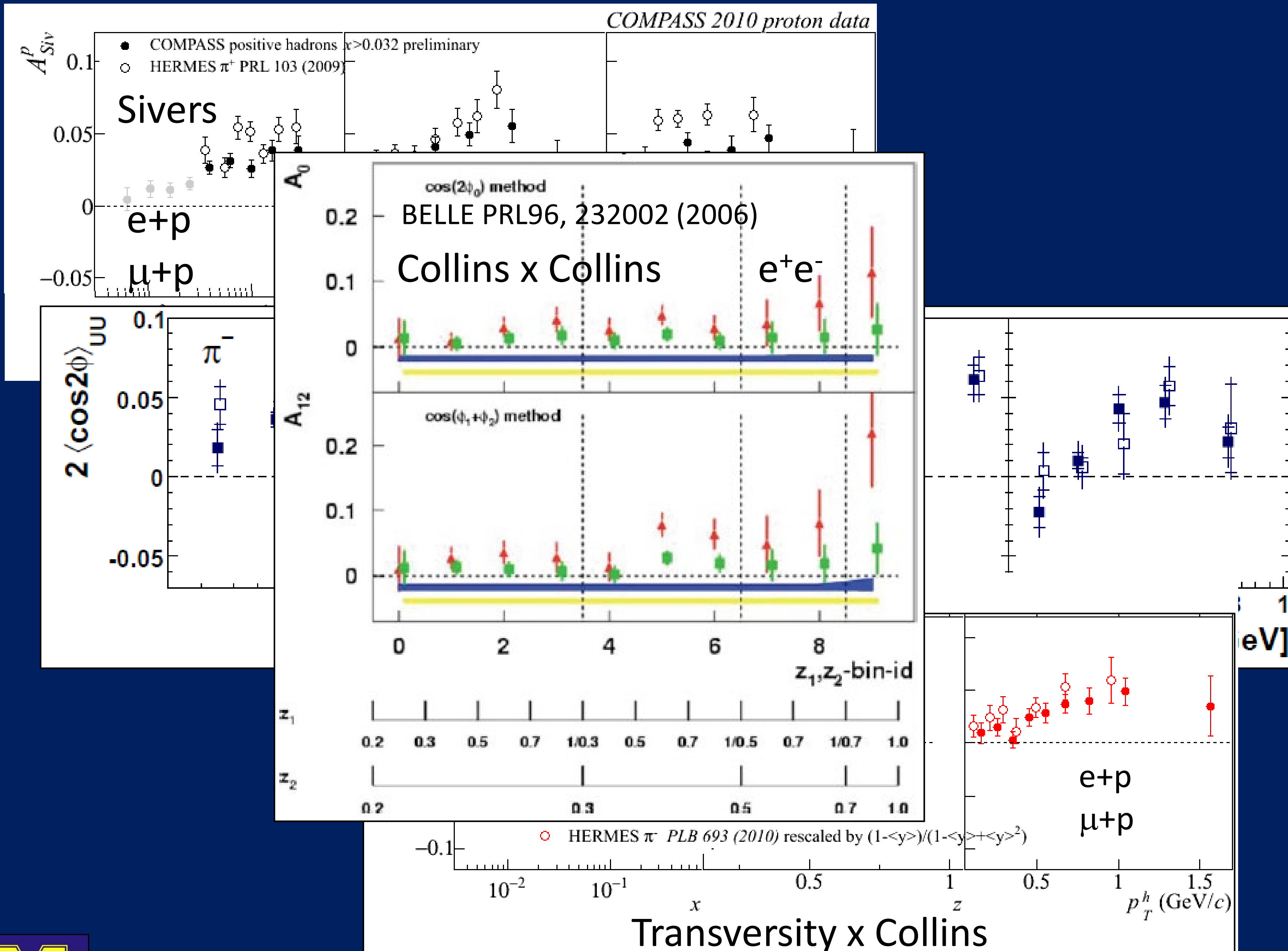
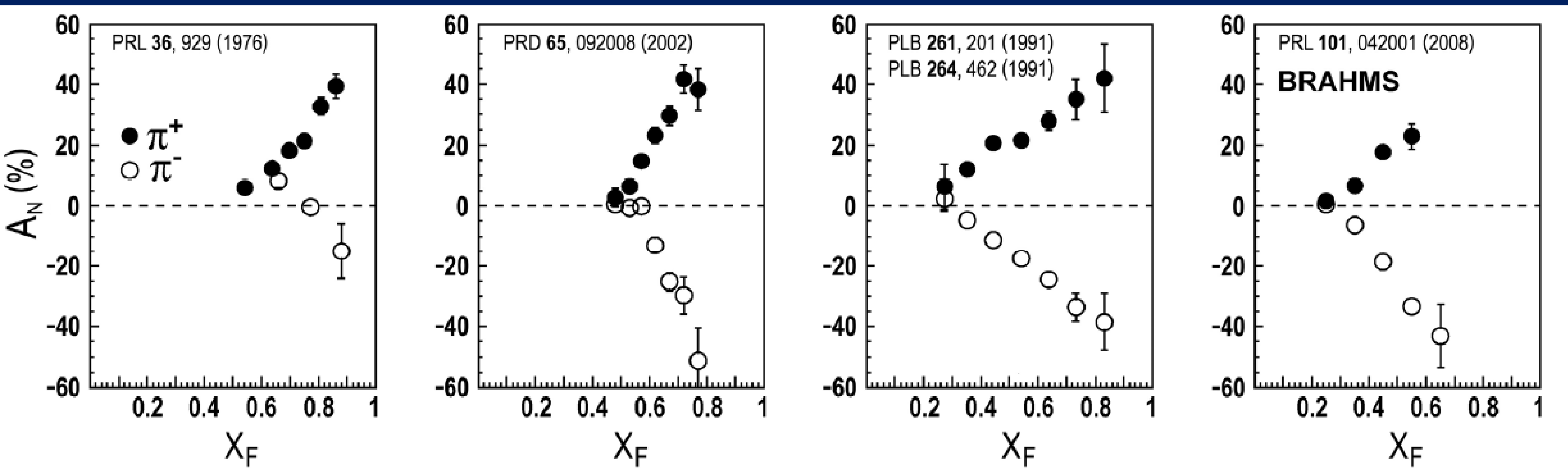
HERMES, PRD 87, 012010 (2013)
COMPASS negative hadrons x>0.032 preliminary
HERMES π− PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
e+p
μ+p
x
z
p_T^h (GeV/c)
Transversity x Collins


COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
cos(2φ0) method
cos(φ1+φ2) method
z1,z2-bin-id
2 ⟨cos2φ⟩UU
π-
HERMES π- PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>^2)
e+p
μ+p
Transversity x Collins

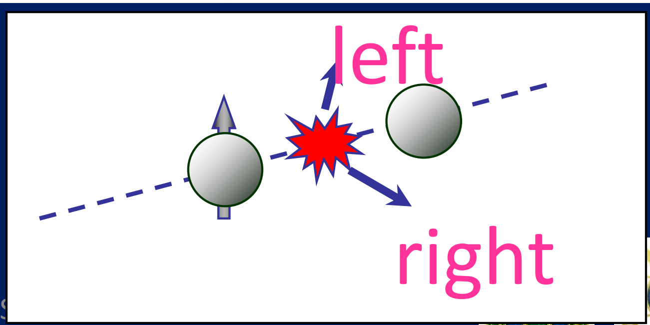
But what about proton-proton collisions?

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



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

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



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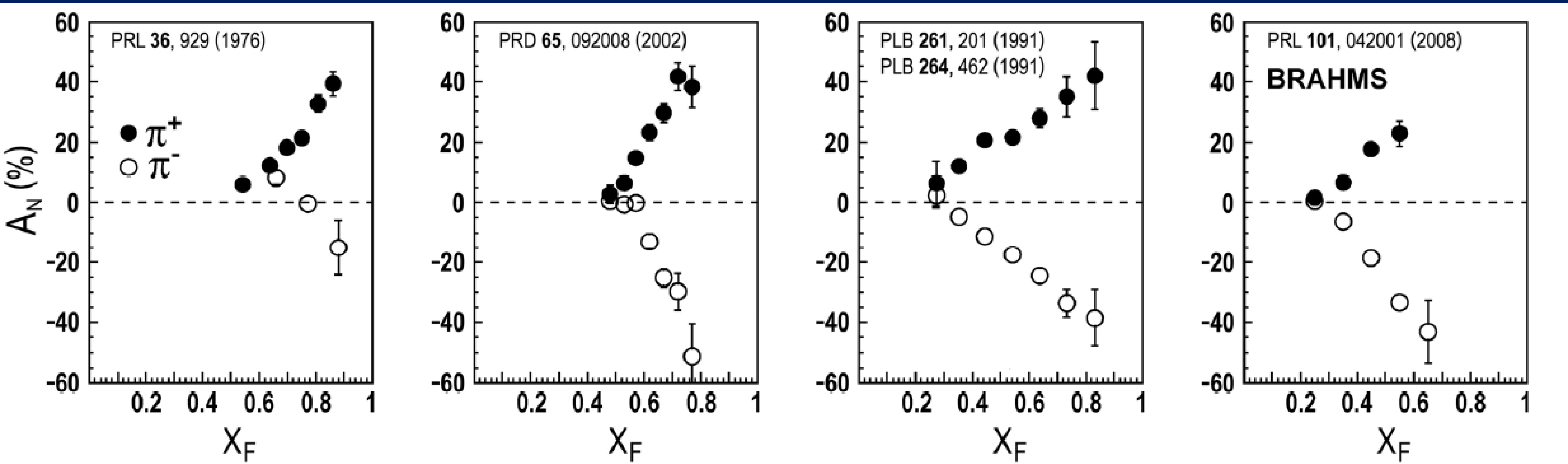
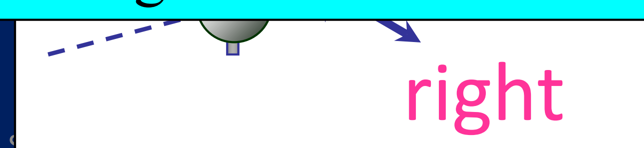
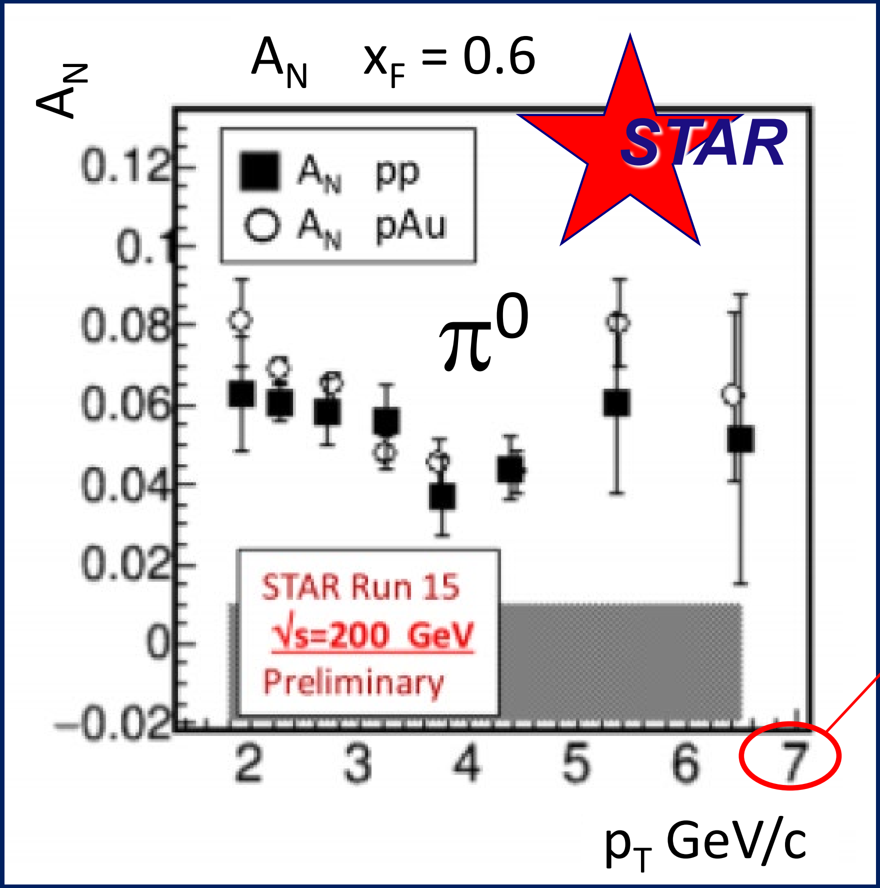


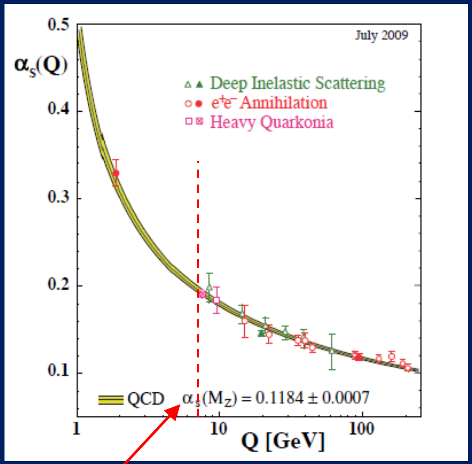
Ai

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

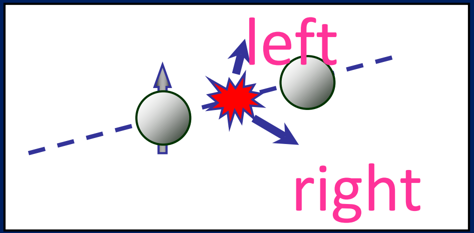


Single-spin asymmetries in transversely polarized proton-proton collisions





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

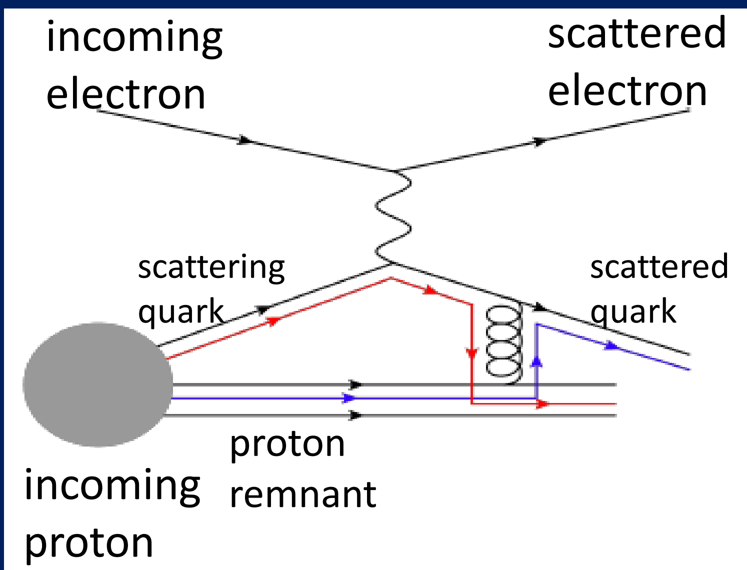
- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish

Different symmetry properties for different spin-momentum correlations

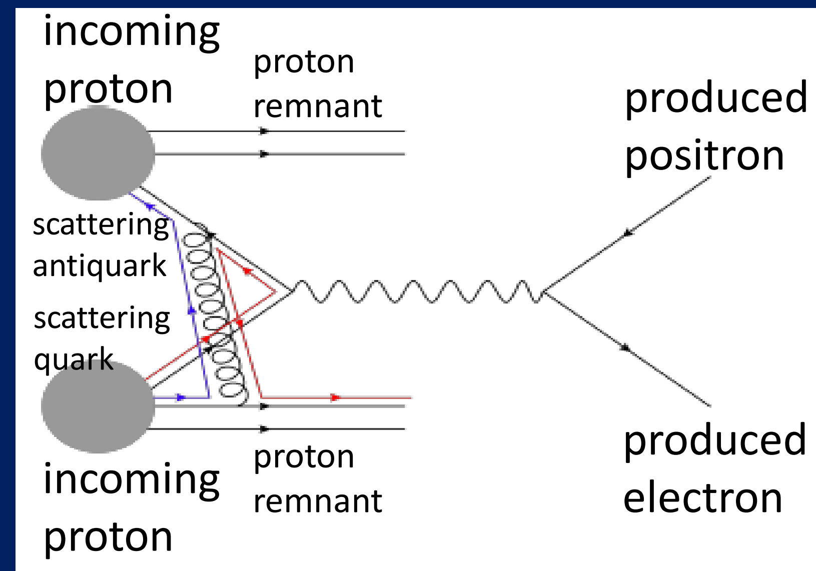
- Some transverse-momentum-dependent parton distribution functions odd under a parity- and time-reversal (PT) transformation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish
- Only realized in 2002 by Brodsky, Hwang, and Schmidt that could be nonvanishing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

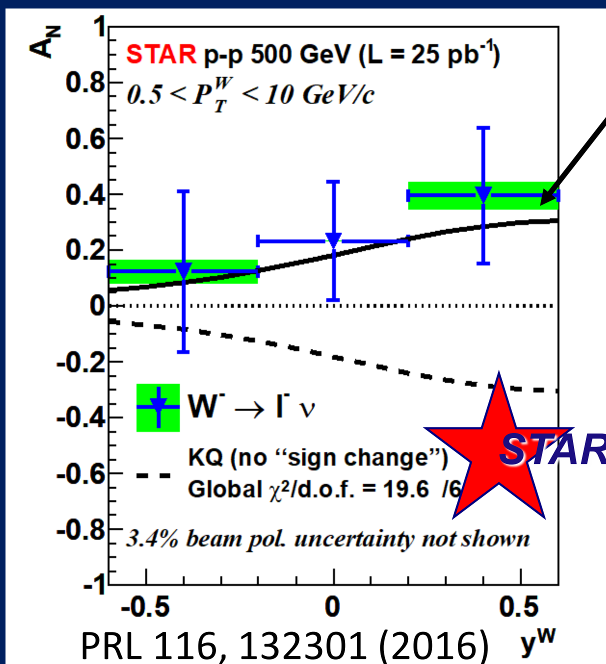


***Opposite sign* for PT-odd transverse-momentum-dependent distributions measured in these two processes: *process-dependent*! (Collins 2002)**

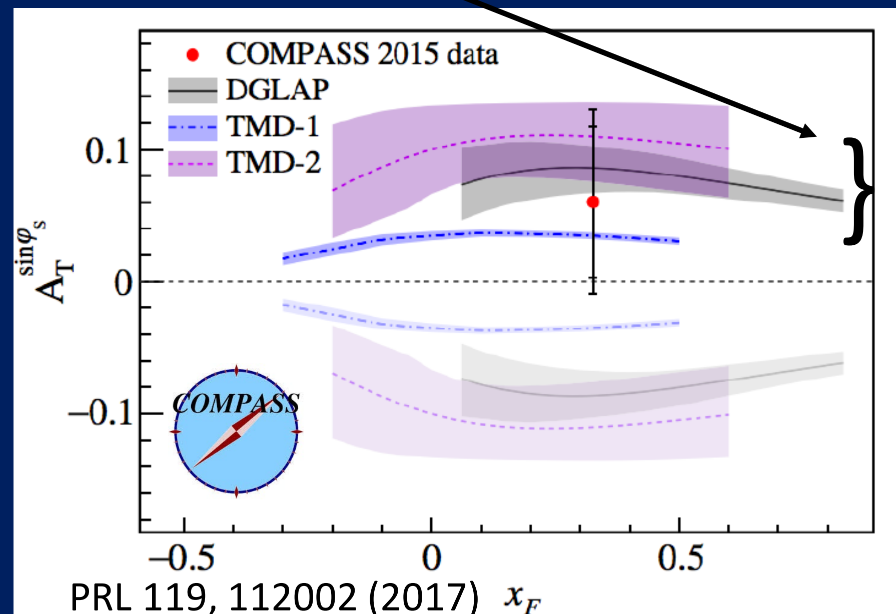
Figures by J.D. Osborn

Modified universality: Initial experimental hints

Predictions including sign change



PRL 116, 132301 (2016)



PRL 119, 112002 (2017)

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 a lepton.
More statistics forthcoming . . .

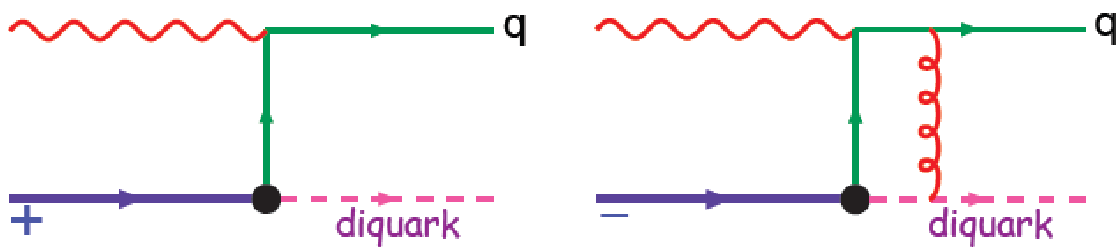
Modified universality requires full QCD: Gauge-invariant quantum field theory

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 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."

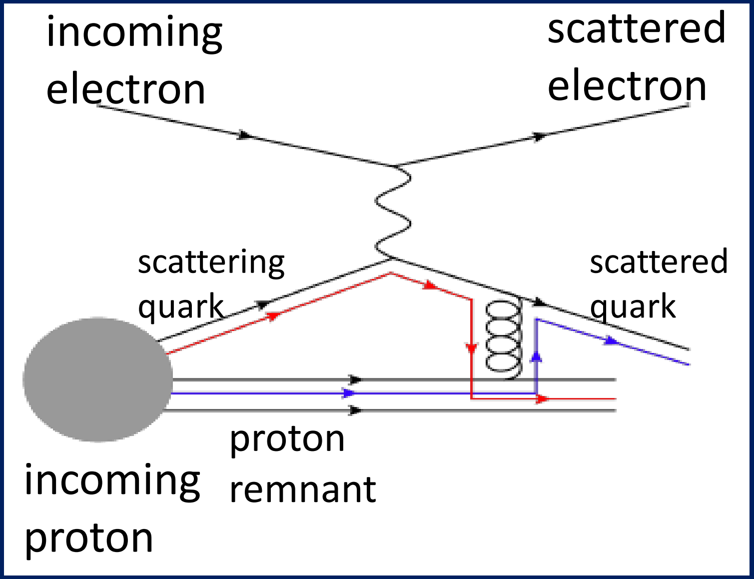
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

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

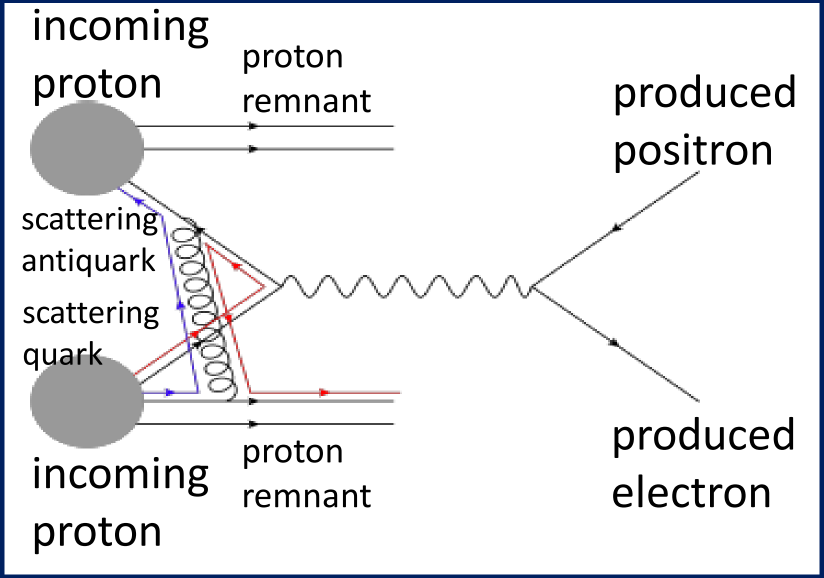
"Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories.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



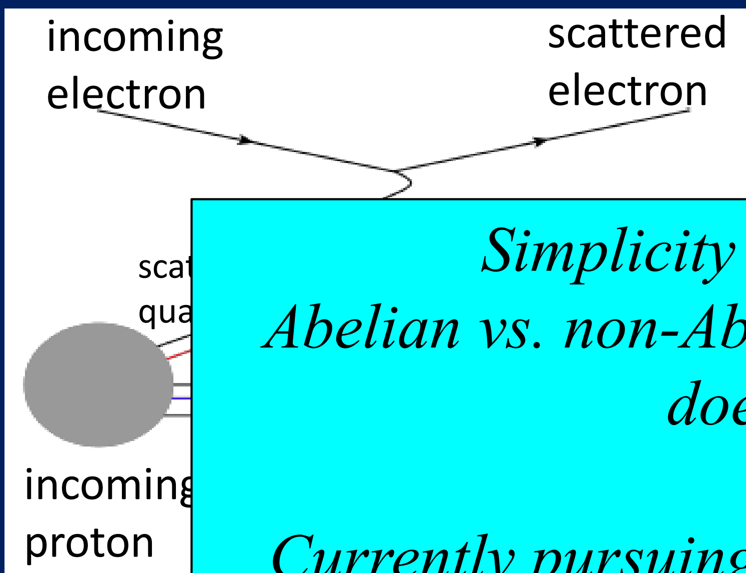
Quark-antiquark annihilation to leptons: Initial-state color exchange



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!!

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



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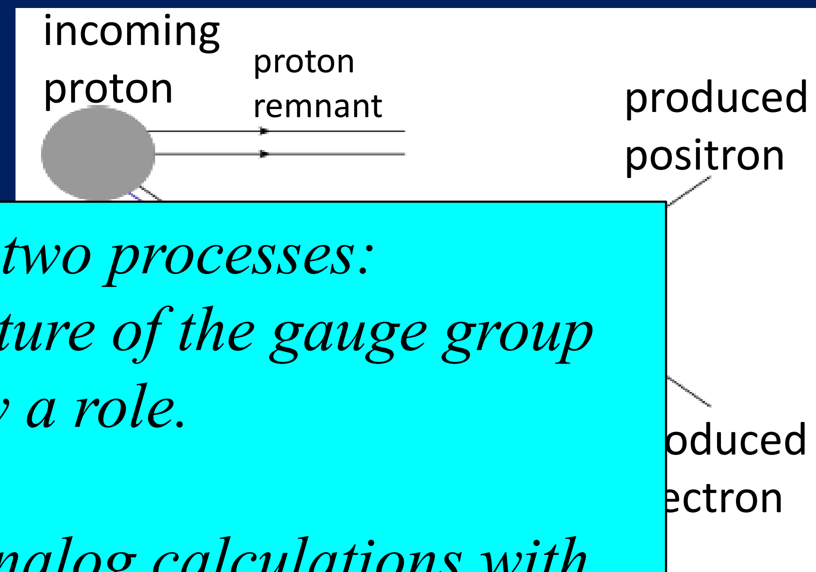
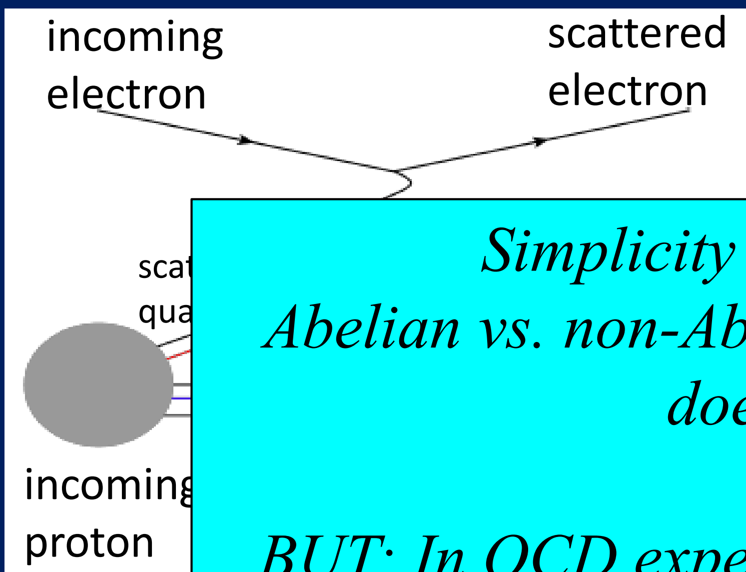


Simplicity of these two processes:
Abelian vs. non-Abelian nature of the gauge group doesn't play a role.

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: Aharonov-Bohm effect in QCD!!

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



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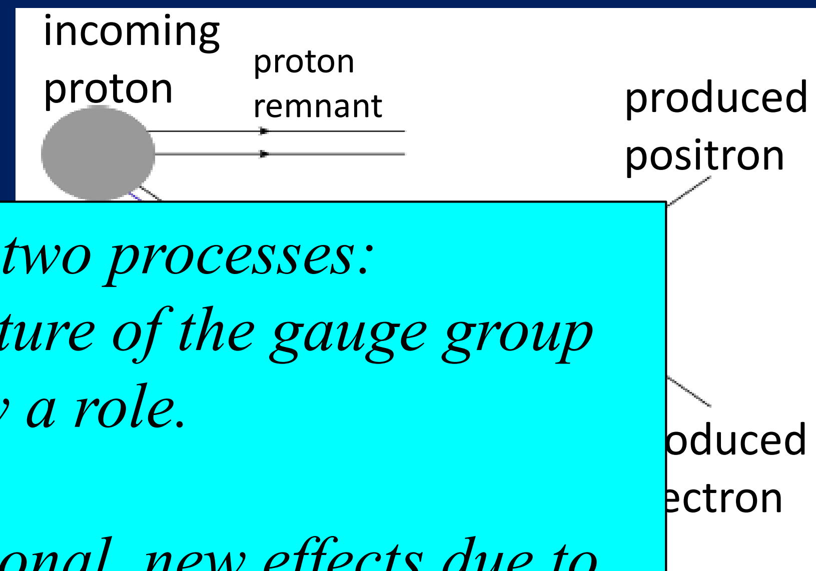
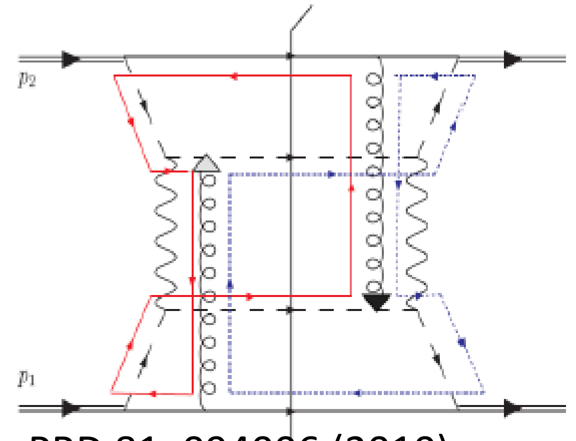


Simplicity of these two processes:
Abelian vs. non-Abelian nature of the gauge group doesn't play a role.

BUT: In QCD expect additional, new effects due to specific <u>*non-Abelian*</u> *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
- Factorization is broken, and 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.

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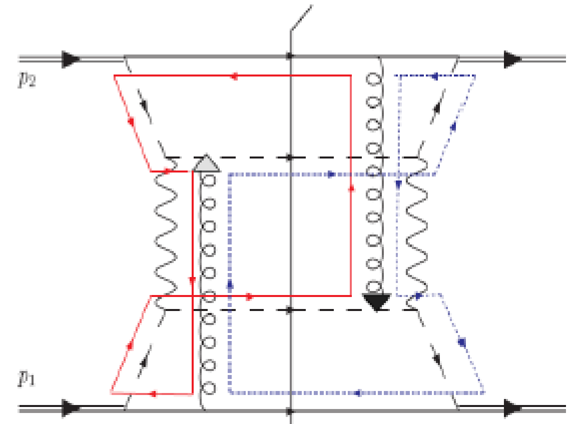

PRD 81, 094006 (2010)

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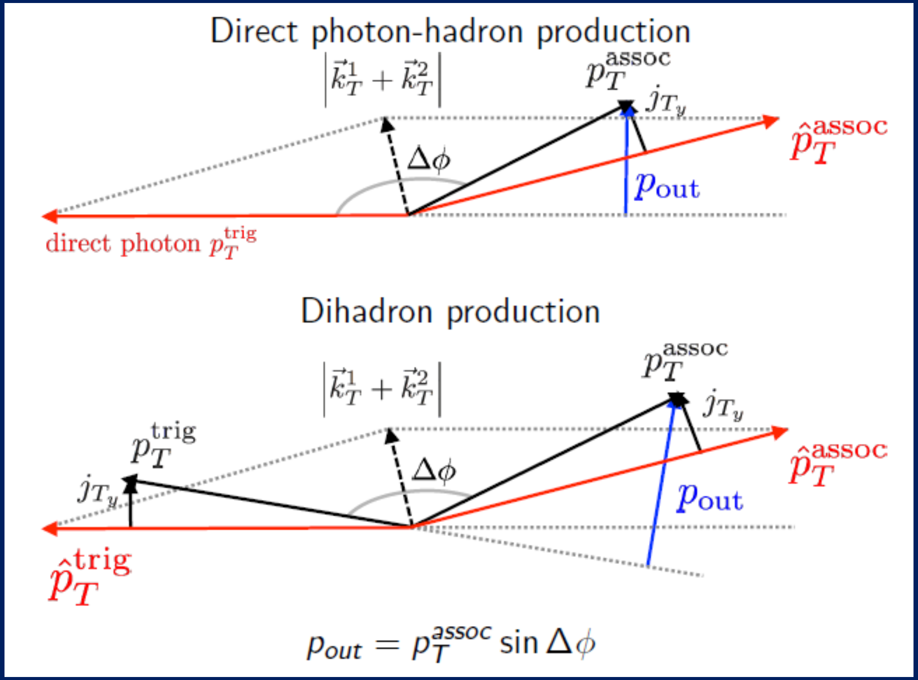
Color flow can't be described as flow in the two gluons separately. Requires presence of both.

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

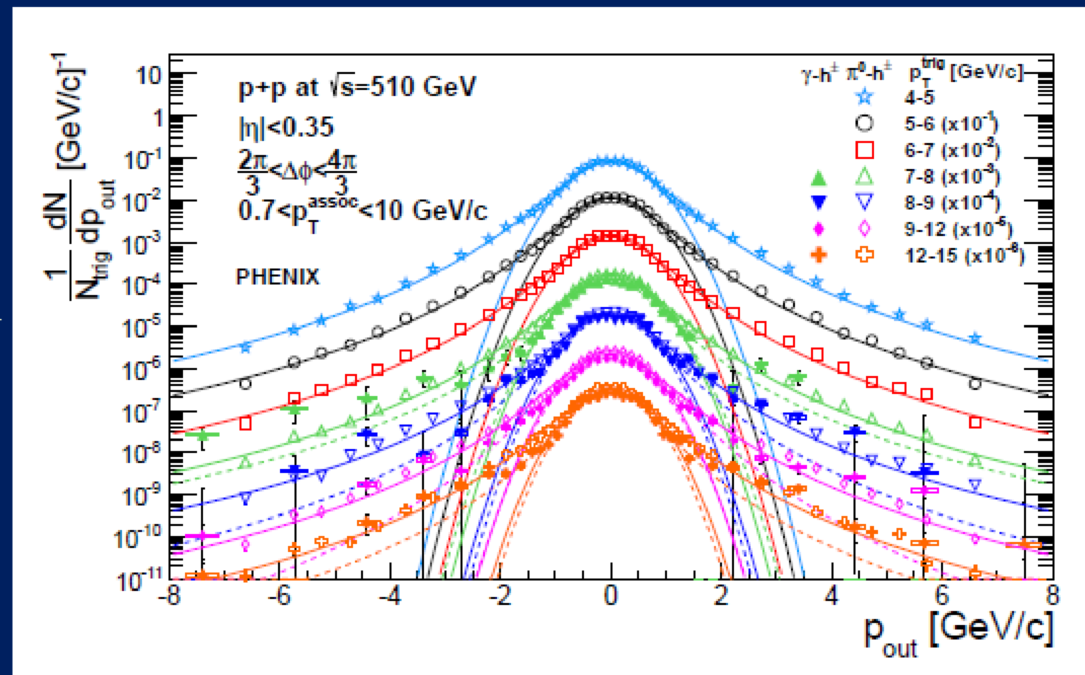


PHENIX Collaboration:
PRD95, 072002 (2017)
PRD98, 072004 (2018)
PRC99, 044912 (2019)

Out-of-plane momentum component distributions

- 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)



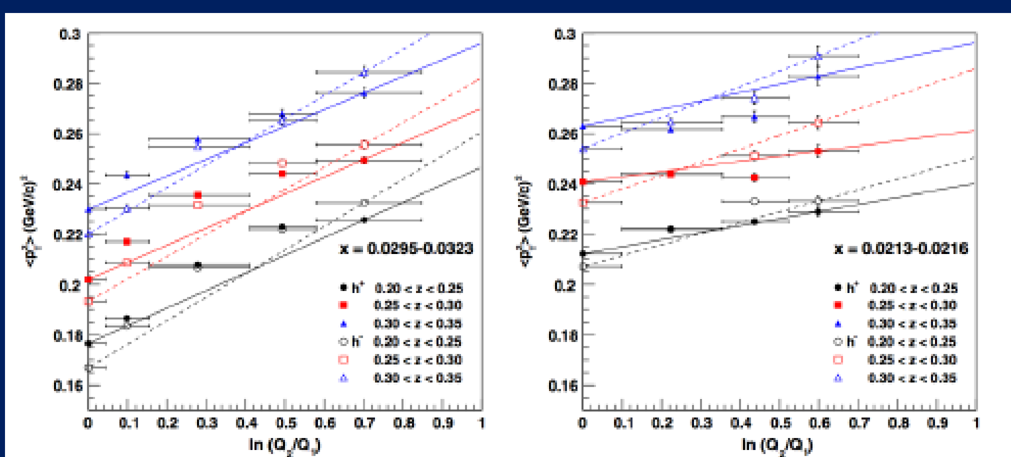
Curves are fits to Gaussian and Kaplan functions, not calculations!

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

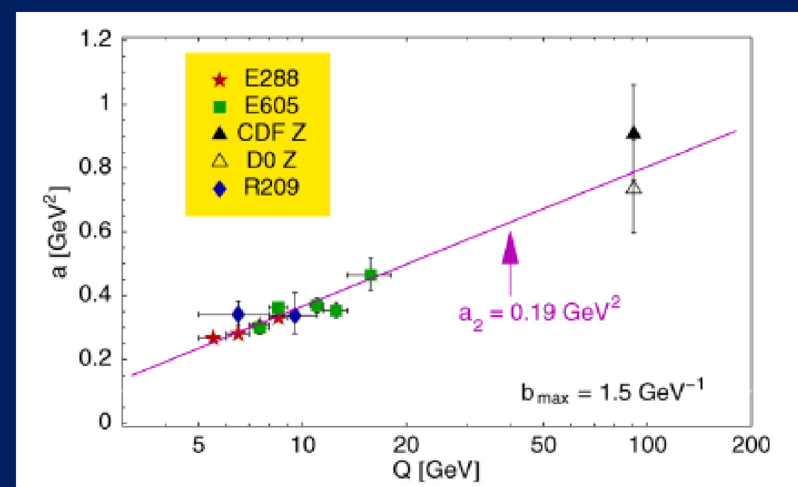
- Proof of factorization (i.e. no entanglement) for processes sensitive to nonperturbative transverse momentum directly predicts that nonperturbative transverse momentum widths *increase* as a function of the hard scattering energy scale
  - Increased phase space for gluon radiation

*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)



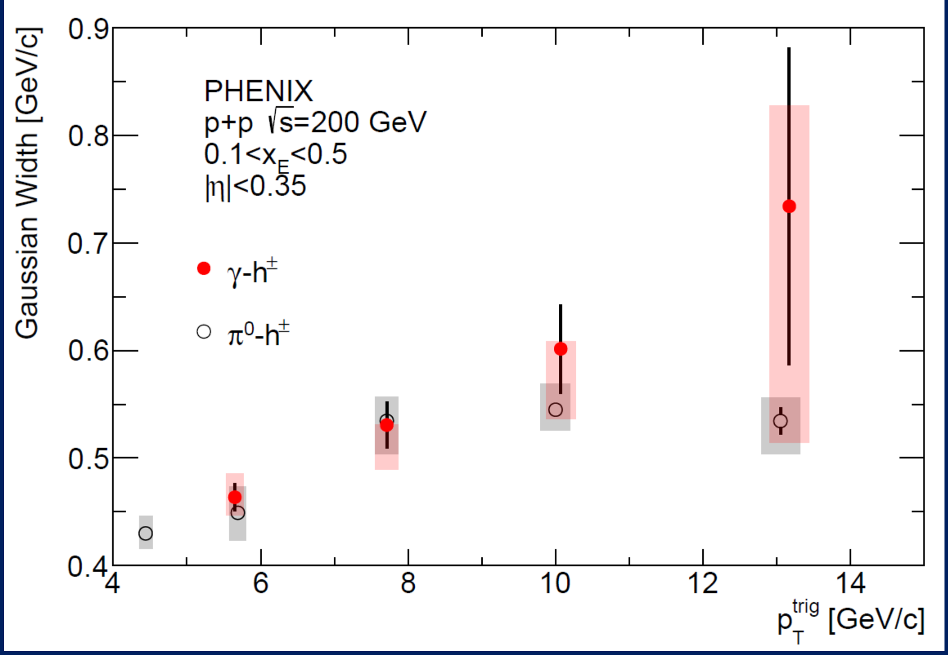
Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



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

*When control for kinematics of hadronization, see **qualitatively** similar trend where factorization predicted to be broken*

- Still waiting for phenomenological calculations assuming factorization holds, to search for quantitative deviations . . .
- Goal is to study factorization breaking and non-Abelian phenomena in a controlled way



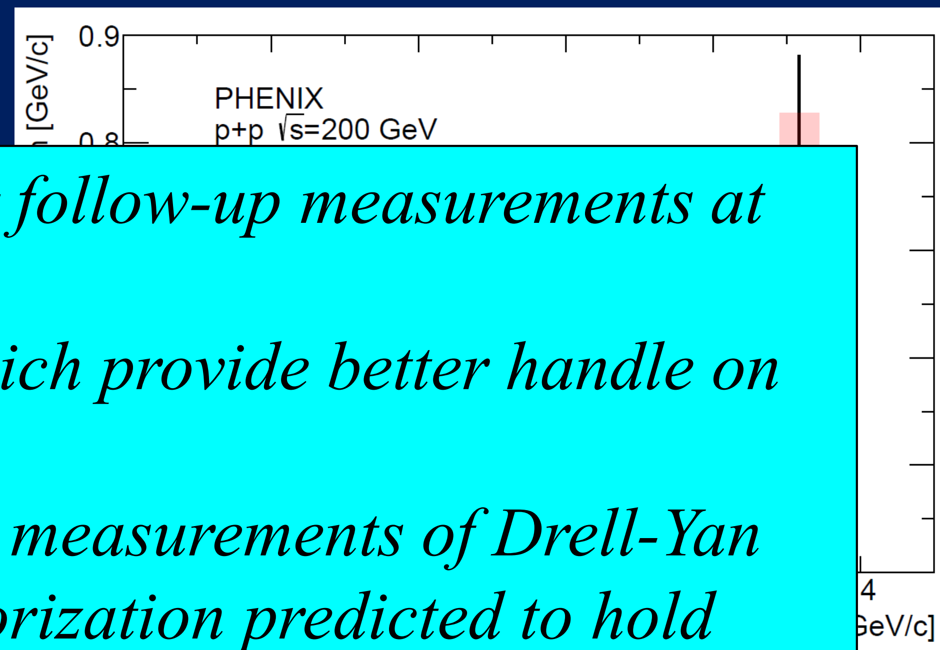
Don't reconstruct jets, so use x_E as a proxy for fraction of jet momentum carried by hadron:

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

PRD98, 072004 (2018)

*When control for kinematics of hadronization, see **qualitatively** similar trend where factorization predicted to be broken*

- Still waiting for phenomenological calculations



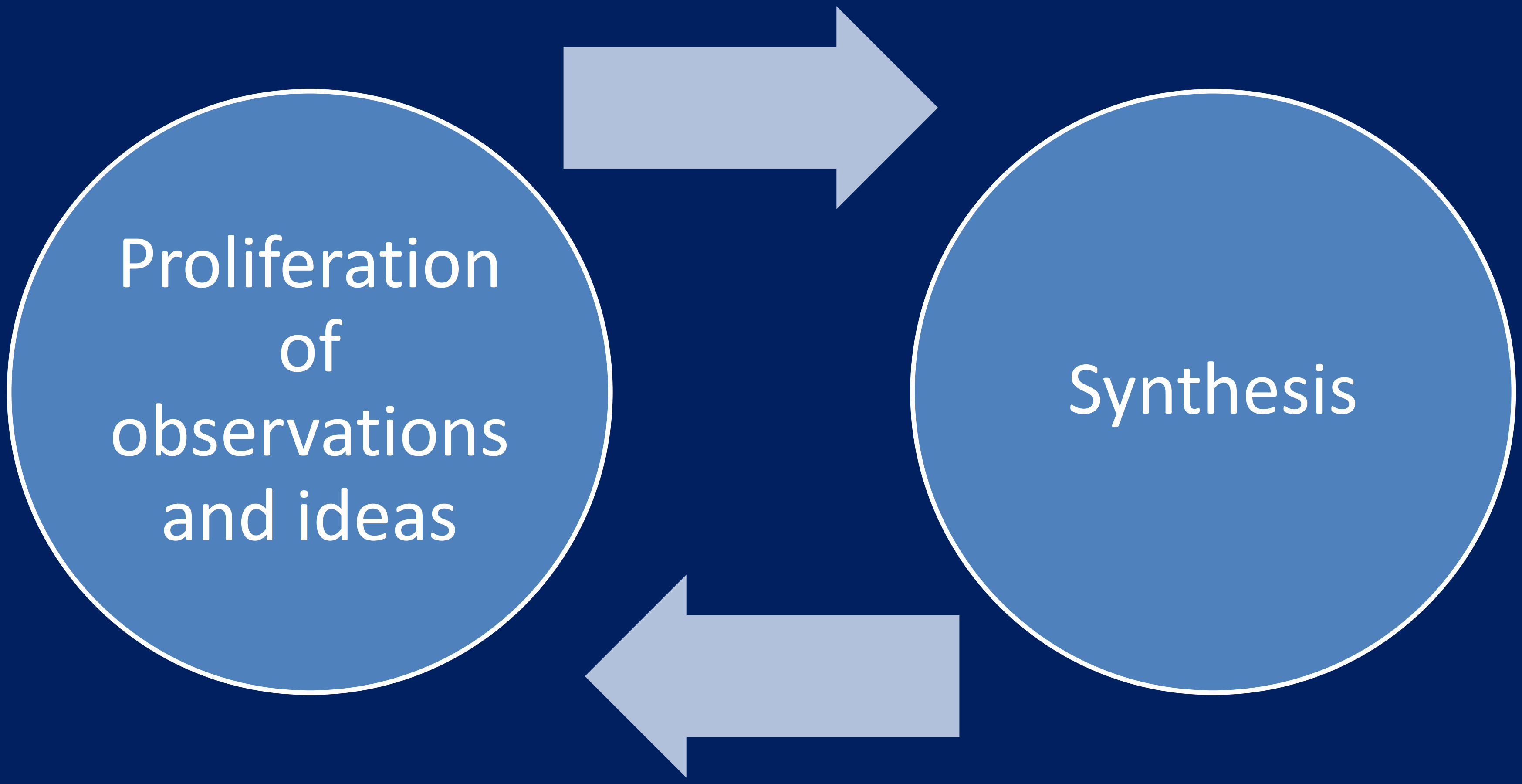
In the meantime, performing follow-up measurements at LHCb:

- *Z-jet correlations, which provide better handle on parton kinematics*
- *Similarly constructed measurements of Drell-Yan dileptons, where factorization predicted to hold*

Discussions of other potential observables ongoing . . .

PRD98, 072004 (2018)

A cyclical process



Synthesis across fields of physics: Assumptions of Physics project

- In a project completely separate (so far) from my QCD research, I'm aiming to identify a handful of physical assumptions from which the basic laws of the various branches of physics can be rigorously derived
  - With Gabriele Carcassi (Michigan)

http://assumptionsofphysics.org/

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- To do that we want to develop a general mathematical theory of experimental science: the theory that studies scientific theories
  - A formal framework that forces us to clarify our assumptions
  - From those assumptions the mathematical objects are derived
  - Each mathematical object has a clear physical meaning and no object is unphysical

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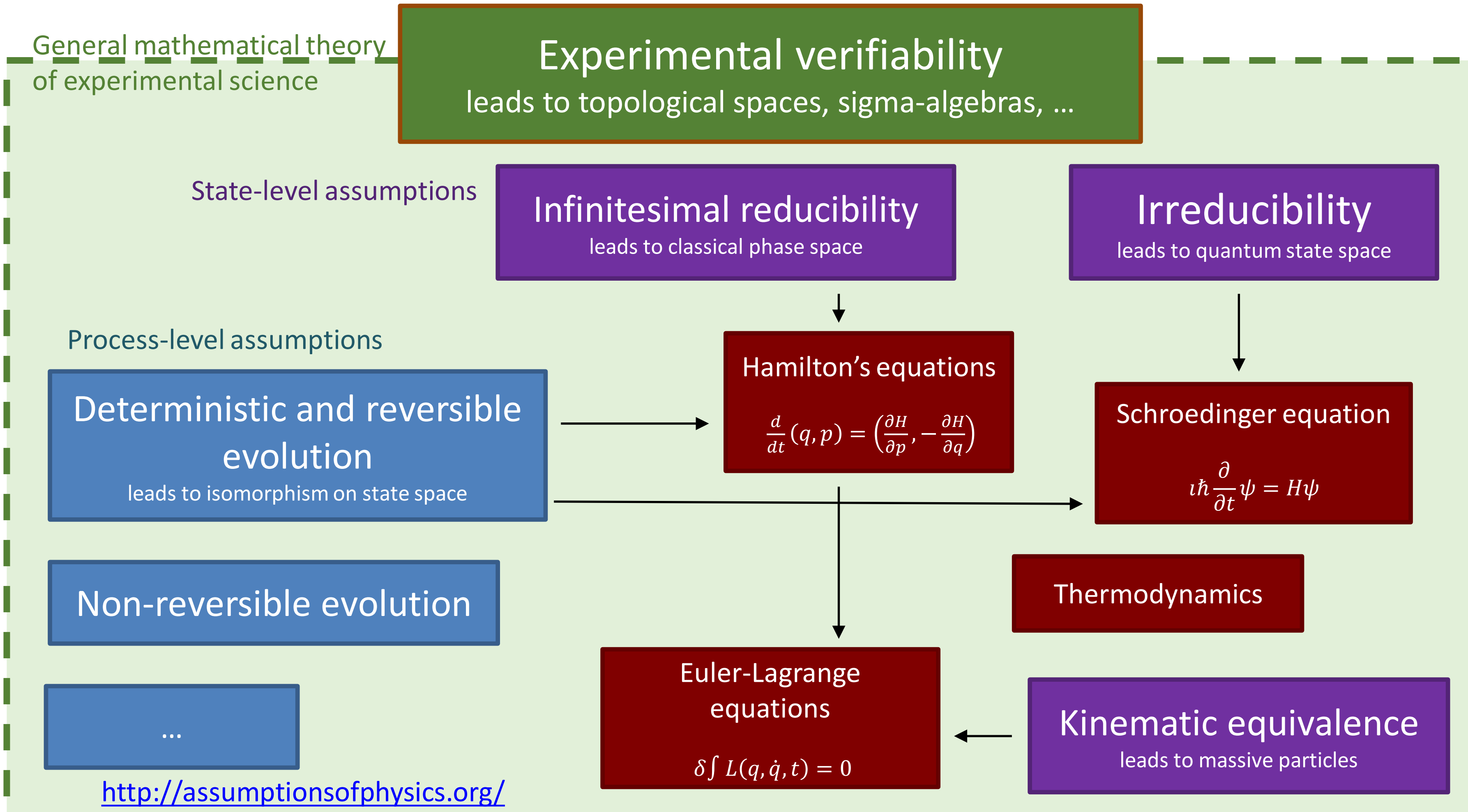
  - From those assumptions the mathematical objects are derived
  - Each mathematical object has a clear physical meaning and no object is unphysical
  - Gives us concepts and tools that span across different disciplines
  - Gives us a better understanding of what the laws of physics are and what they represent

http://assumptionsofphysics.org/


General mathematical theory of experimental science
Experimental verifiability
leads to topological spaces, sigma-algebras, …
State-level assumptions
Infinitesimal reducibility
leads to classical phase space
Irreducibility
leads to quantum state space
Process-level assumptions
Deterministic and reversible evolution
leads to isomorphism on state space
Hamilton's equations
$\frac{d}{dt}(q,p) = \left(\frac{\partial H}{\partial p}, -\frac{\partial H}{\partial q}\right)$
Schroedinger equation
$\imath\hbar\frac{\partial}{\partial t}\psi = H\psi$
Non-reversible evolution
Thermodynamics
…
Euler-Lagrange equations
$\delta\int L(q,\dot{q},t) = 0$
Kinematic equivalence
leads to massive particles
http://assumptionsofphysics.org/

Summary

- Color flow and color interactions in high-energy collisions have drawn increased interest in recent years

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- QCD offers unique opportunities to explore non-Abelian quantum field theories
- Insight can be gained by examining analog processes and phenomena across the different quantum field theories of the Standard Model

Will be exciting to continue testing and exploring these ideas and phenomena at existing facilities as well as at a future Electron-Ion Collider . . .

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 <u>phenomenological calculations</u> using these new ideas/tools!

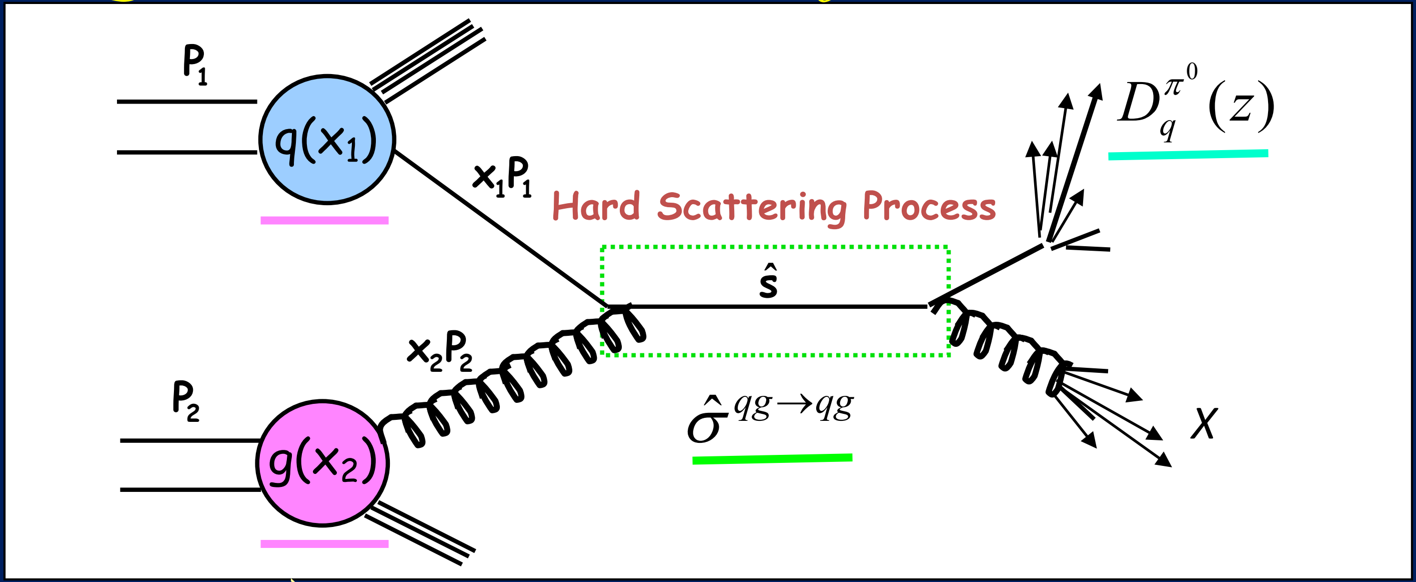
  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentum fractions
  - *Spin-spin* and *spin-momentum* correlations in QCD bound states
  - *Spatial* distributions of partons in QCD bound states

- 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



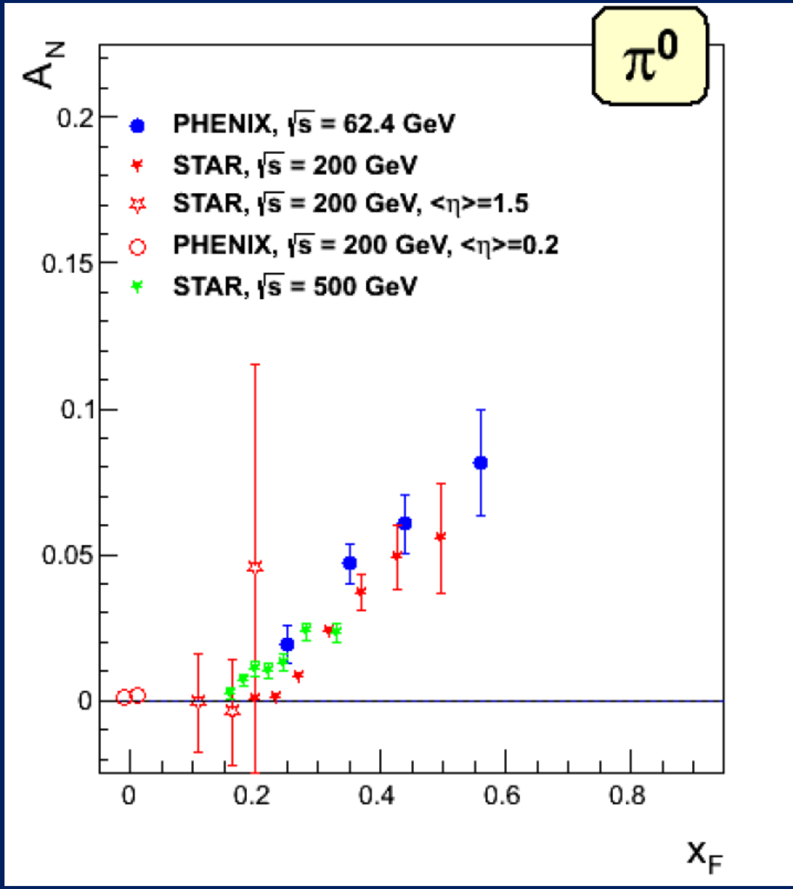
$$\sigma\left(pp\to\pi^0X\right)\propto q\left(x_1\right)\otimes g\left(x_2\right)\otimes\hat{\sigma}^{qg\to qg}\left(\hat{s}\right)\otimes D_q^{\pi^0}\left(z\right)$$

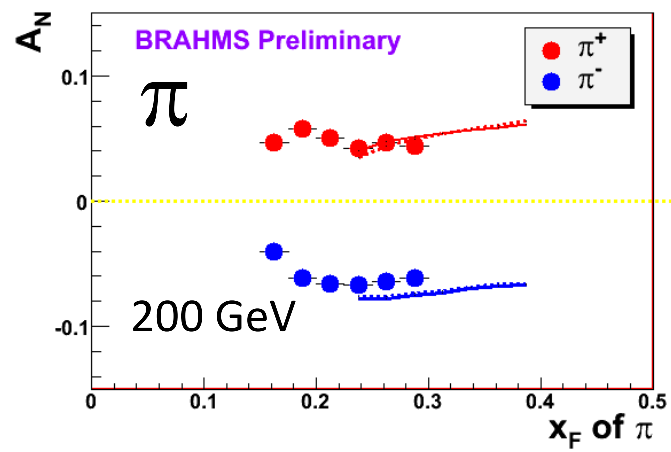
High-energy processes have predictable rates given:

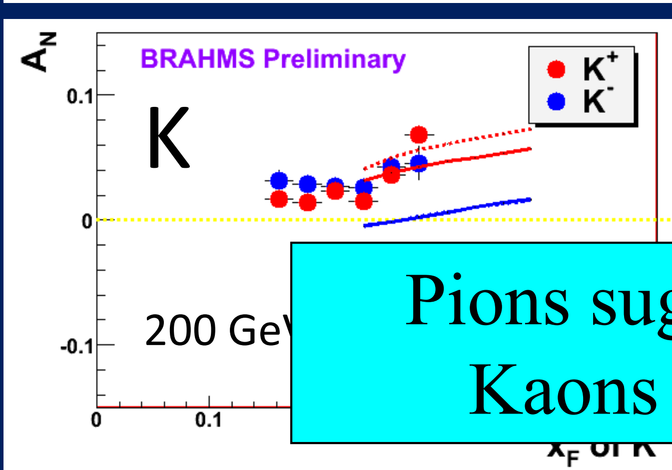
- Partonic hard scattering rates (calculable in pQCD)
- Parton distribution functions (experiment or lattice)
- Fragmentation functions (experiment or lattice)

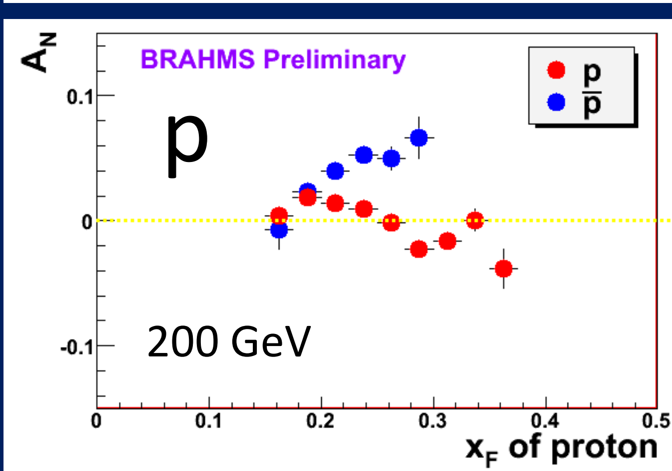
} Universal non-perturbative factors

Forward transverse single-spin asymmetries for neutral pions

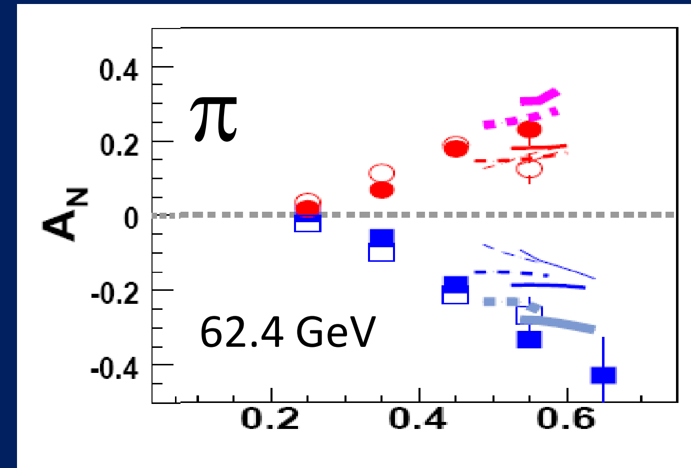




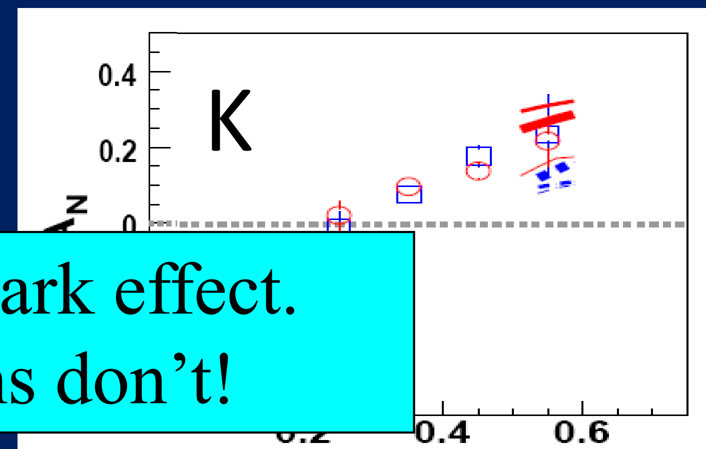




π, K, p
at 200 and
62.4 GeV

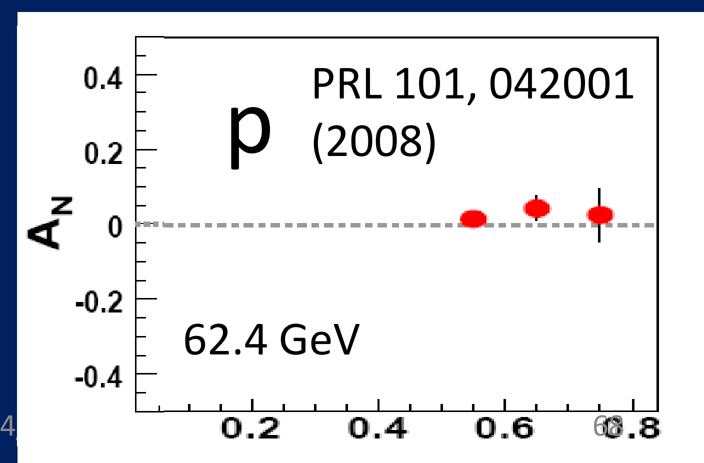


Note different scales



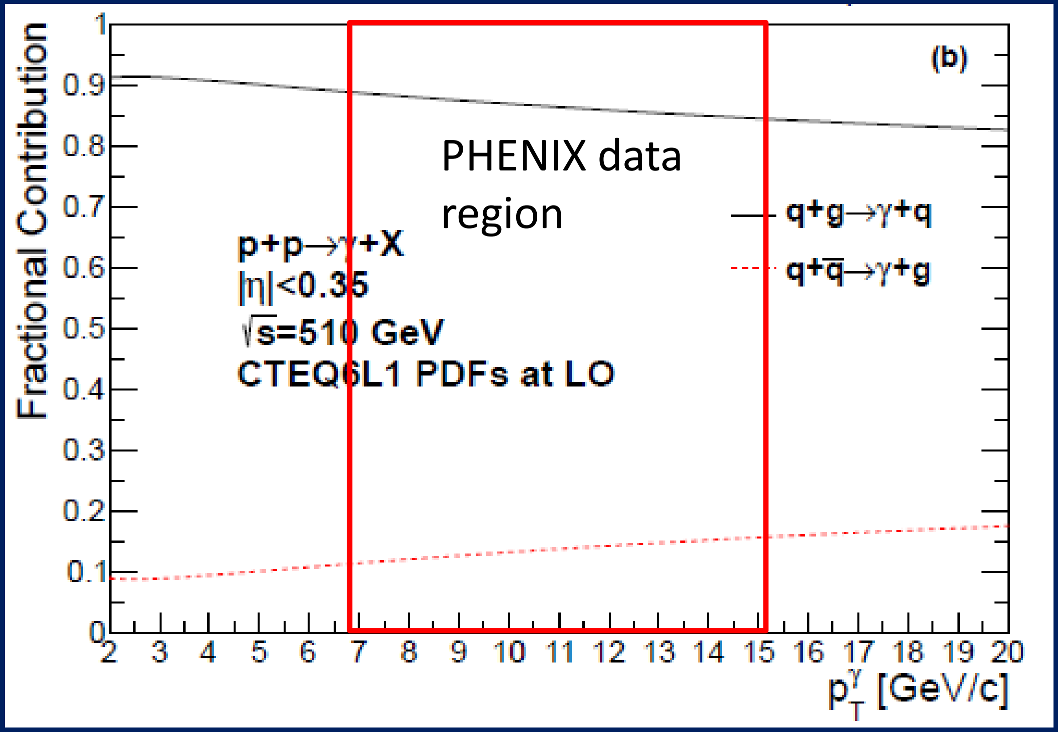
K- asymmetries underpredicted

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



Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement

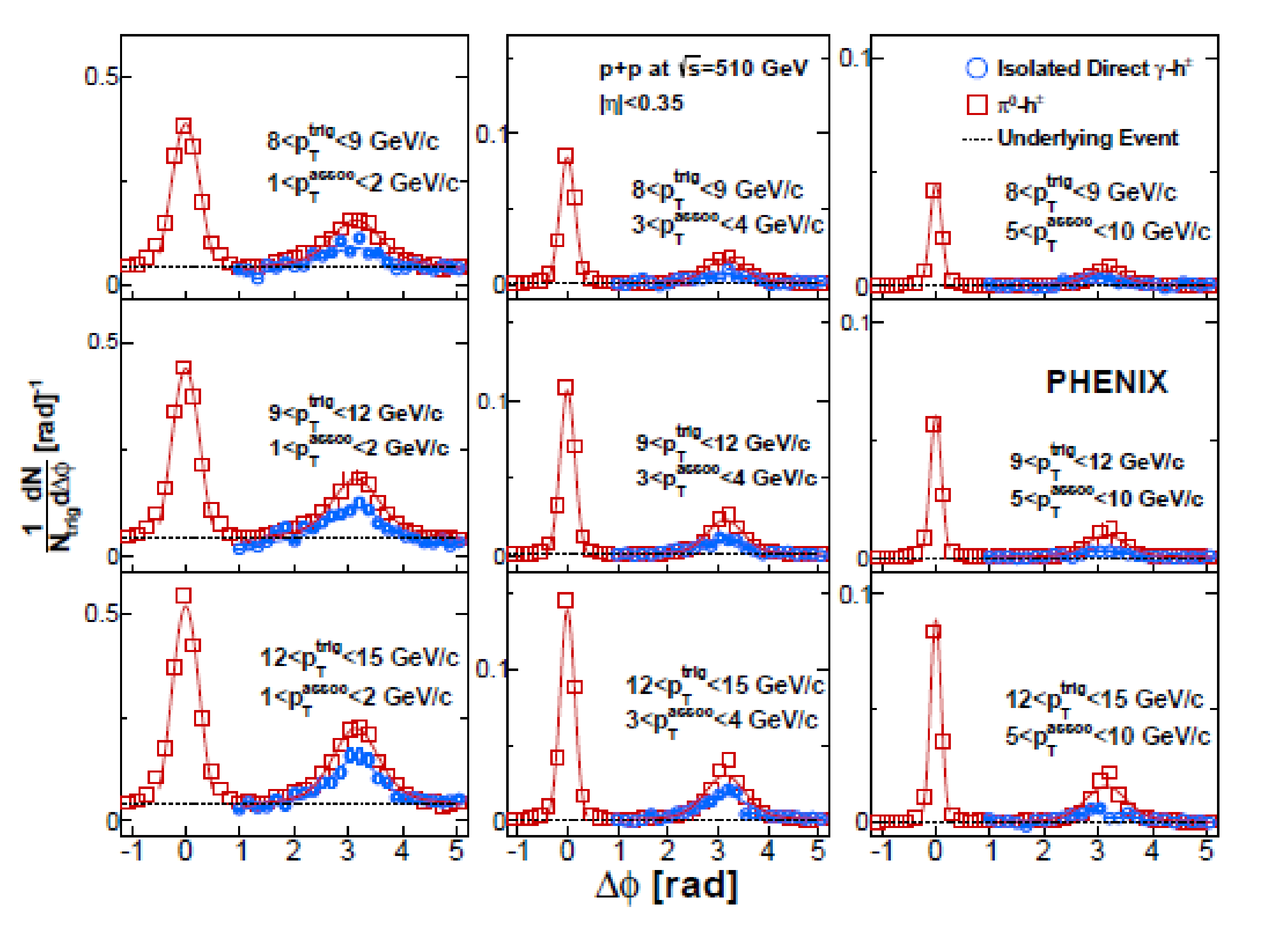
Partonic process contributions for direct photon production



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

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

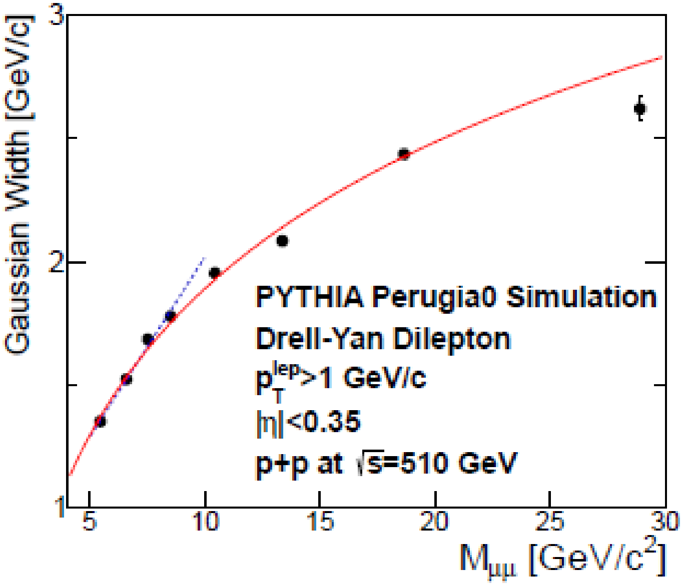
Two-particle correlation distributions show expected jet-like structure



PRD95, 072002 (2017)

PYTHIA Drell-Yan

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

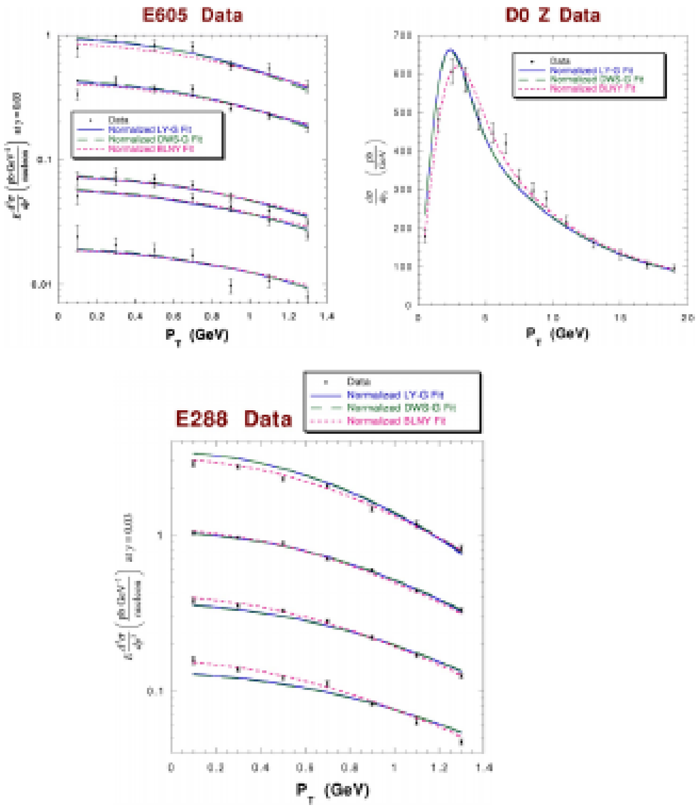


- Note rate of increase is significantly larger in magnitude also
- Red solid line shows log fit, blue dotted line shows linear fit

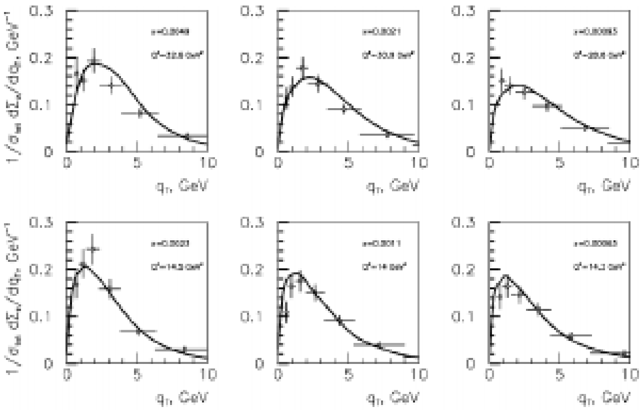
Nonperturbative momentum measurements in Drell-Yan and Z production

Other DY/Z and SIDIS Refs.

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



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



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

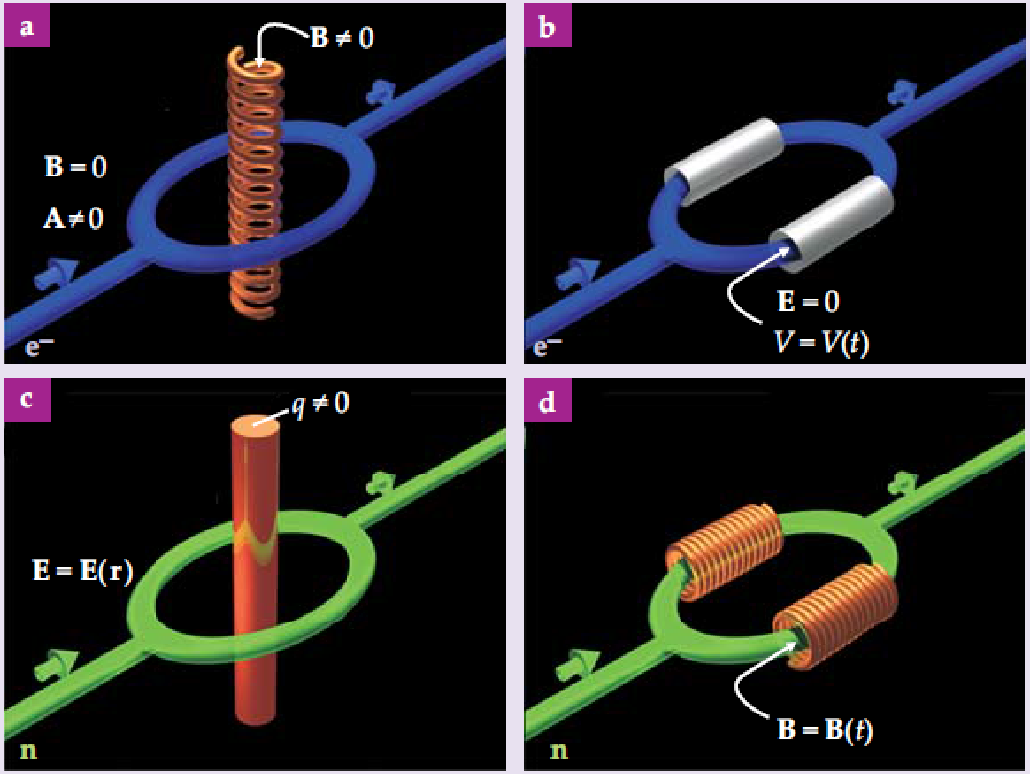
Box 1. Types and duals

Physics Today, September 2009

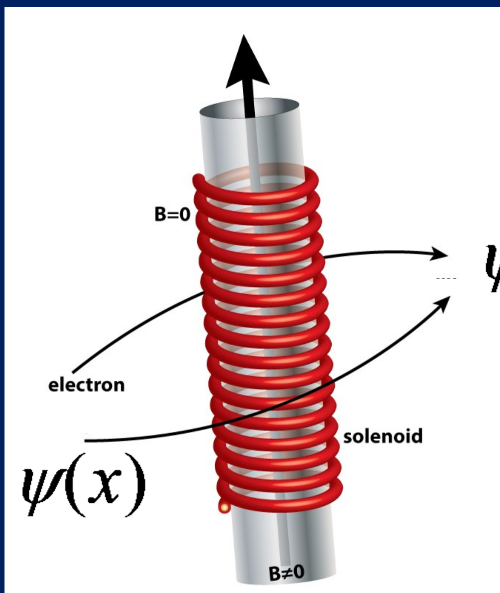
The original magnetic and electric Aharonov–Bohm effects (panels a and b) are type I effects in the sense that in an ideal experiment, the electron sees no **B** or **E** fields, though it does traverse different potentials **A** and *V*. In their respective dual effects—the Aharonov–Casher effect (panel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

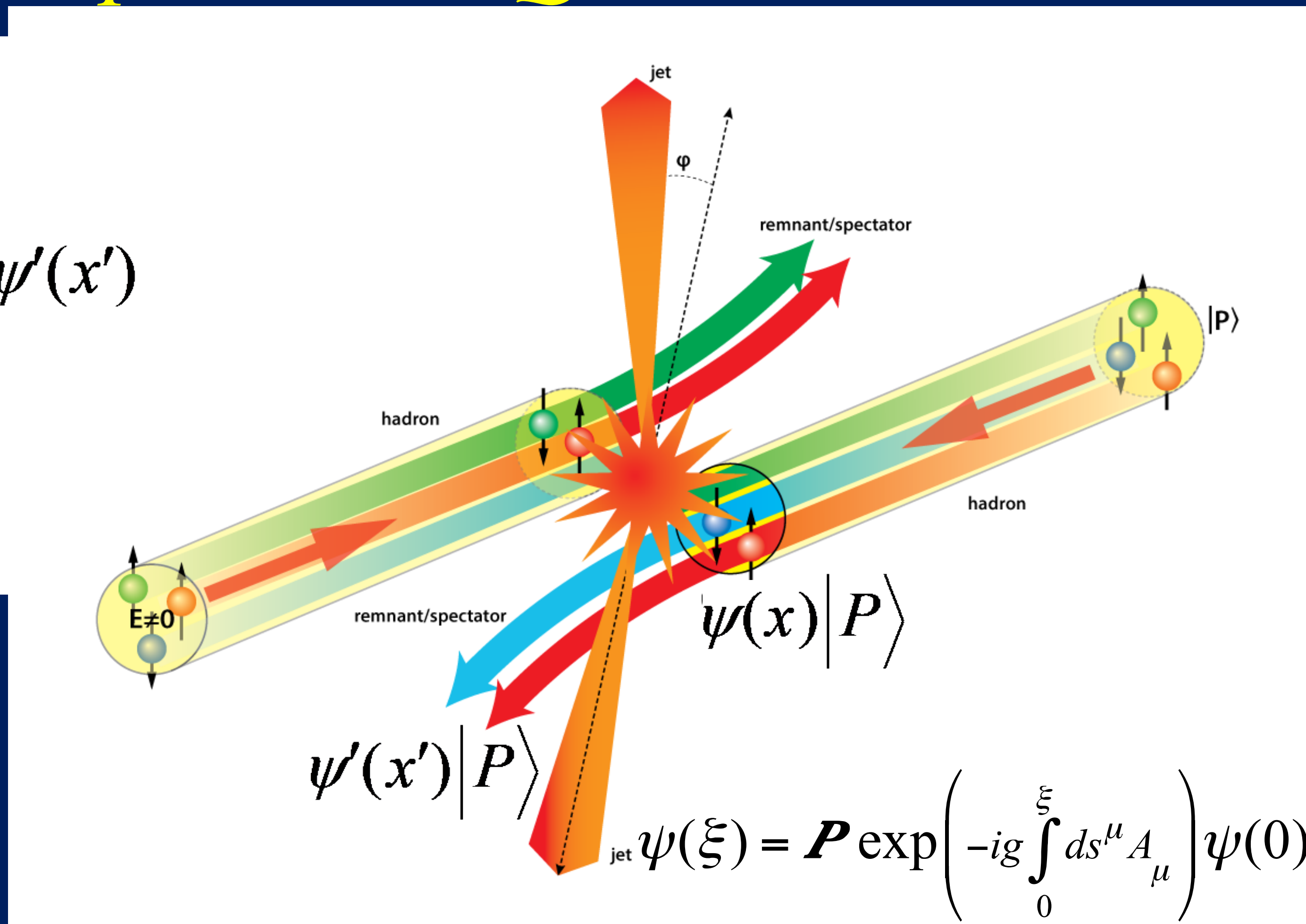
In either case, to acquire an AB phase shift, the electron or neutron must pass through a region of nonzero electromagnetic potential. That quantum mechanical result seems to elevate the status of the potentials to a physical reality absent from classical electromagnetism. Yakir Aharonov has pointed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

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



Opportunities to see color-induced phases in QCD





Slide from P. Mulders

Figures by Kees Huyser

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"

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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"

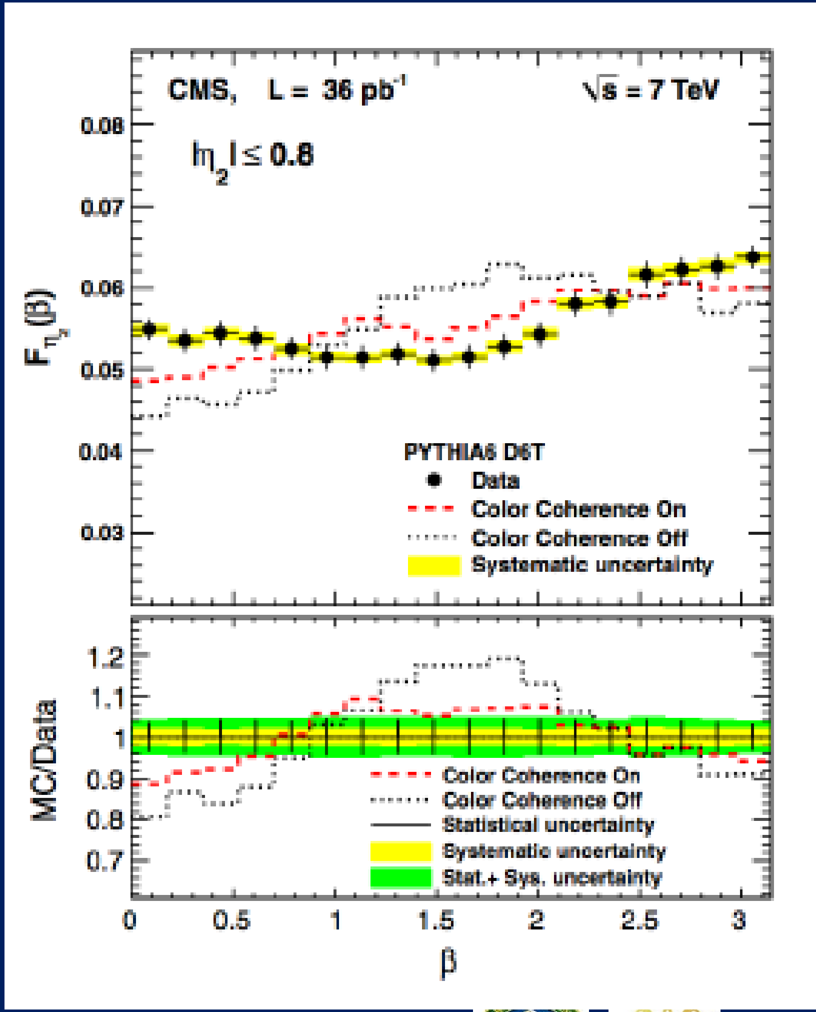
“Color coherence” in e+e-, p(bar)p

- “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

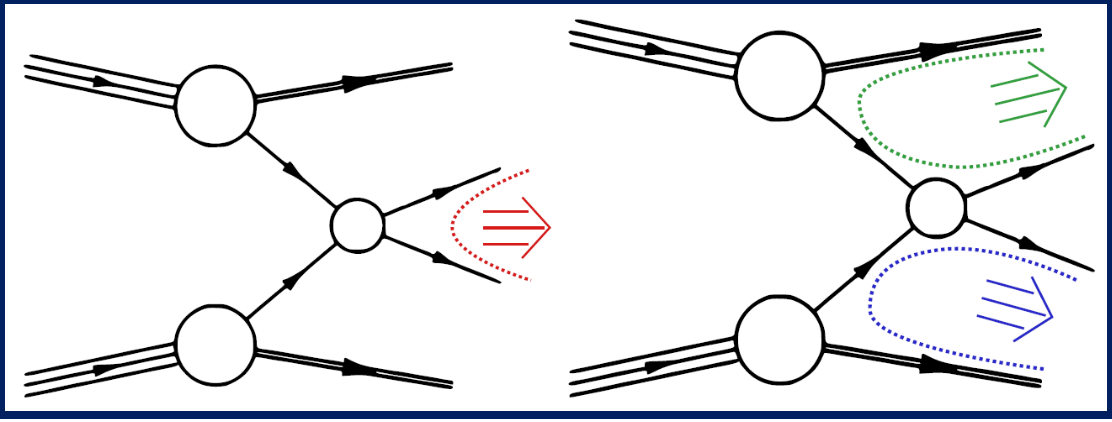


FIG. 1: Possible color connections for signal ($pp \to H \to b\bar{b}$) and for background ($pp \to g \to b\bar{b}$).

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

- ATLAS 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"
  - A "proof-of-principle" measurement by ATLAS