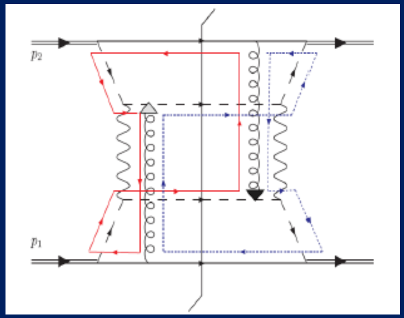
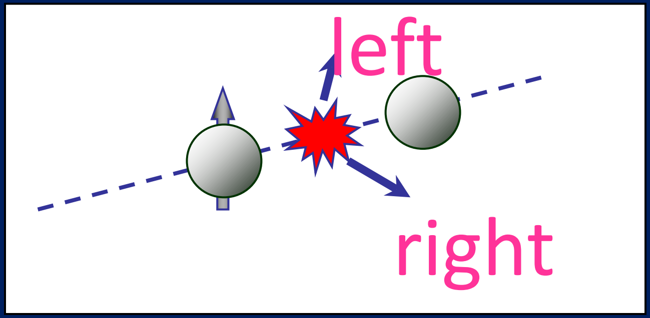
Spin-Momentum Correlations, Aharonov-Bohm, and Color Entanglement in Quantum Chromodynamics

Christine A. Aidala

University of Michigan





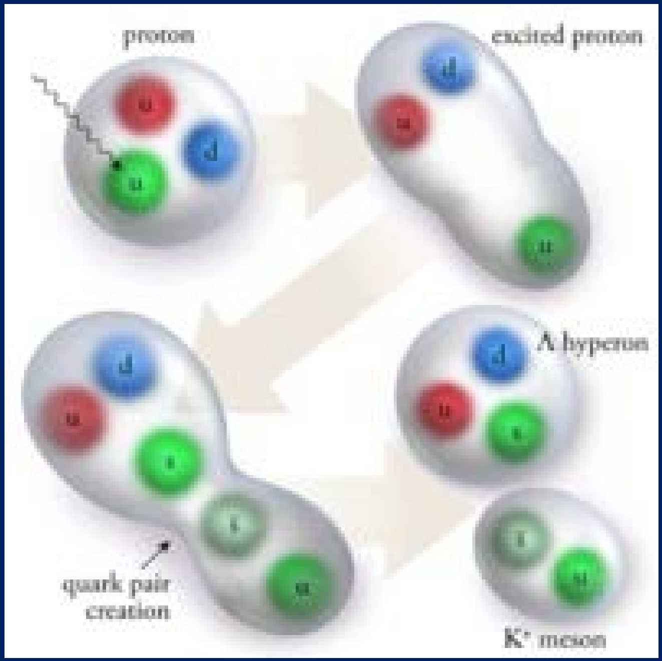
$$\psi(x)|P\rangle = e^{ig\int_x^{x'} ds_\mu A^\mu}\psi(x')|P\rangle$$

Jefferson Lab
January 30, 2015

Theory of strong interactions: Quantum Chromodynamics

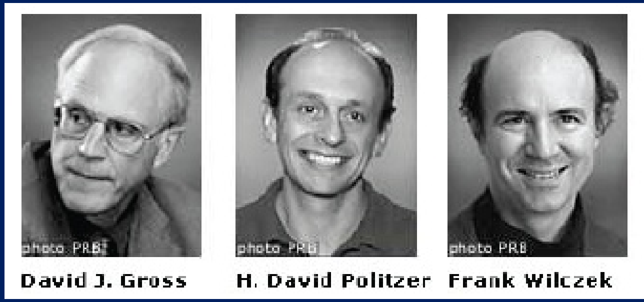
- Fundamental field theory in hand since the early 1970s—BUT . . .
- Quark and gluon degrees of freedom in the theory cannot be observed or manipulated directly in experiment!

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



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

QCD: How far have we come?



- QCD is challenging!!
- Three-decade period after initial birth of QCD dedicated to "discovery and development"

→ Symbolic closure: Nobel prize 2004 - Gross, Politzer, Wilczek for asymptotic freedom

Now early years of second phase: ***quantitative QCD**!*

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!

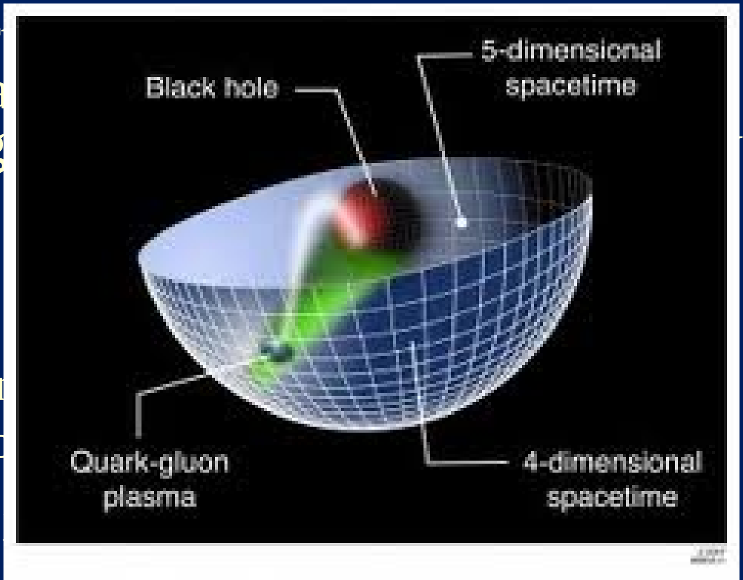
  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentum fractions
  - *Spin-spin* and *spin-momentum* correlations in QCD bound states
  - Techniques to handle *target-mass and "higher-twist" corrections*
  - *Spatial* distributions of partons in QCD bound states

- 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!

Advancing into the era of quantitative QCD: Theory has been forging ahead

- In perturbative QCD, since 1990s star *dynamics* that parts with traditional pa hadrons—and perform phenomenolog ideas/tools!

  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentu
  - *Spin-spin* and *spin-momentum* correlatio
  - Techniques to handle *target-mass and* "
  - *Spatial* distributions of partons in QCD

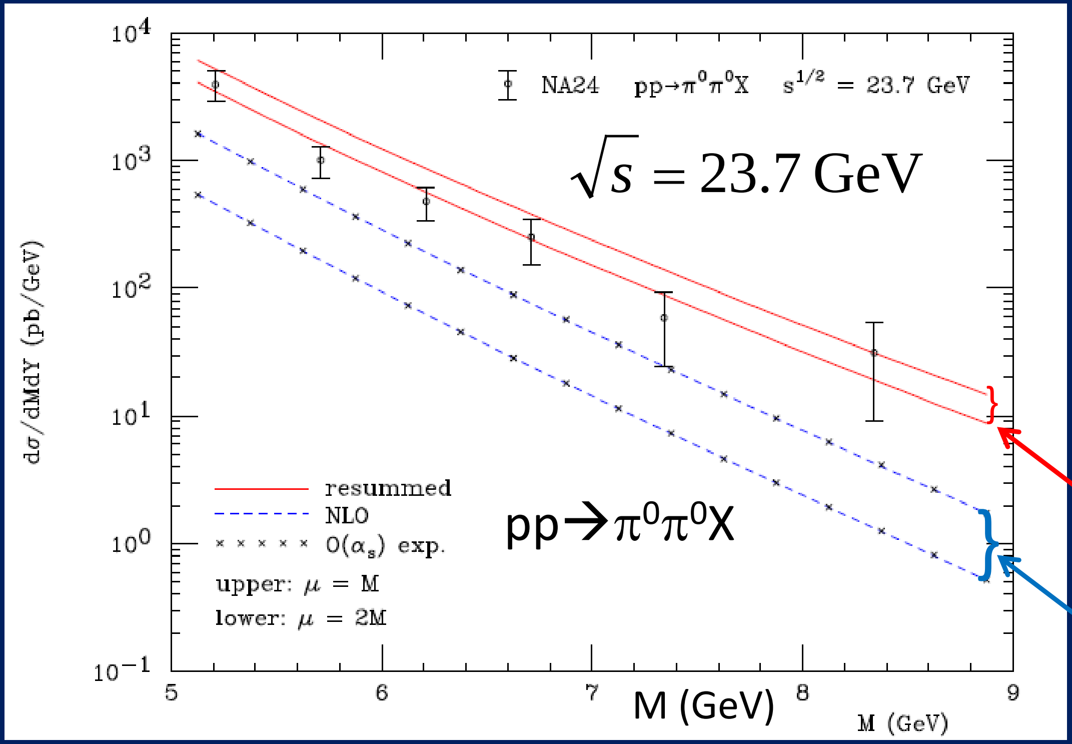


- Nonperturbative methods:
  - Lattice QCD less and less limited by computing resources—since 2010 starting to perform calculations at the physical pion mass (after 36 years!). Plus recent new ideas on how to calculate previously intractable quantities.
  - AdS/CFT "gauge-string duality" an exciting 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
  - Heavy Quark Effective Theory, Non-Relativistic QCD, . . .
  - Many effective theories for nonperturbative QCD – chiral symmetry breaking, . . .

Example: "Threshold resummation" Extending perturbative calculations to lower energies



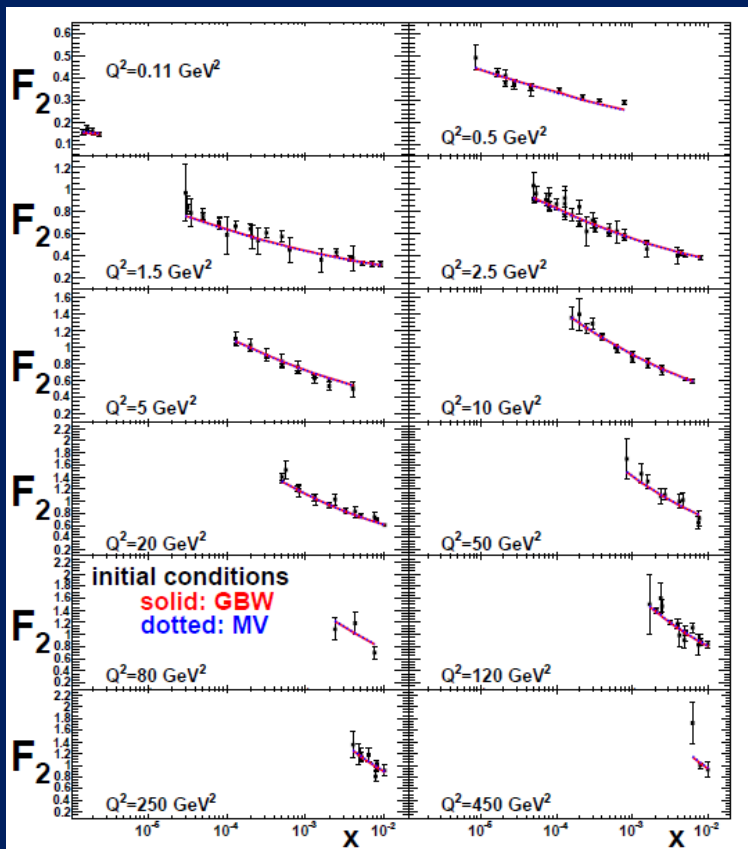
For observables with two different scales, sum logs of their ratio to all orders in the strong coupling constant

Next-to-leading-order in α_s + resum.

Next-to-leading-order in α_s

Almeida, Sterman, Vogelsang PRD80, 074016 (2009)

Example: Phenomenological applications of a non-linear gluon saturation regime



Fits to proton structure function data at low parton momentum fraction *x*.

Non-linear QCD meets data: A global analysis of lepton-proton scattering with running coupling BK evolution

Phys. Rev. D80, 034031 (2009)

Javier L. Albacete[1], Néstor Armesto[2], José Guilherme Milhano[3] and Carlos A. Salgado[2]

Basic framework for non-linear QCD, in which gluon densities are so high that there's a non-negligible probability for two gluons to combine, developed ~1997-2001. But had to wait until "running coupling BK evolution" figured out in 2007 to compare directly to data!

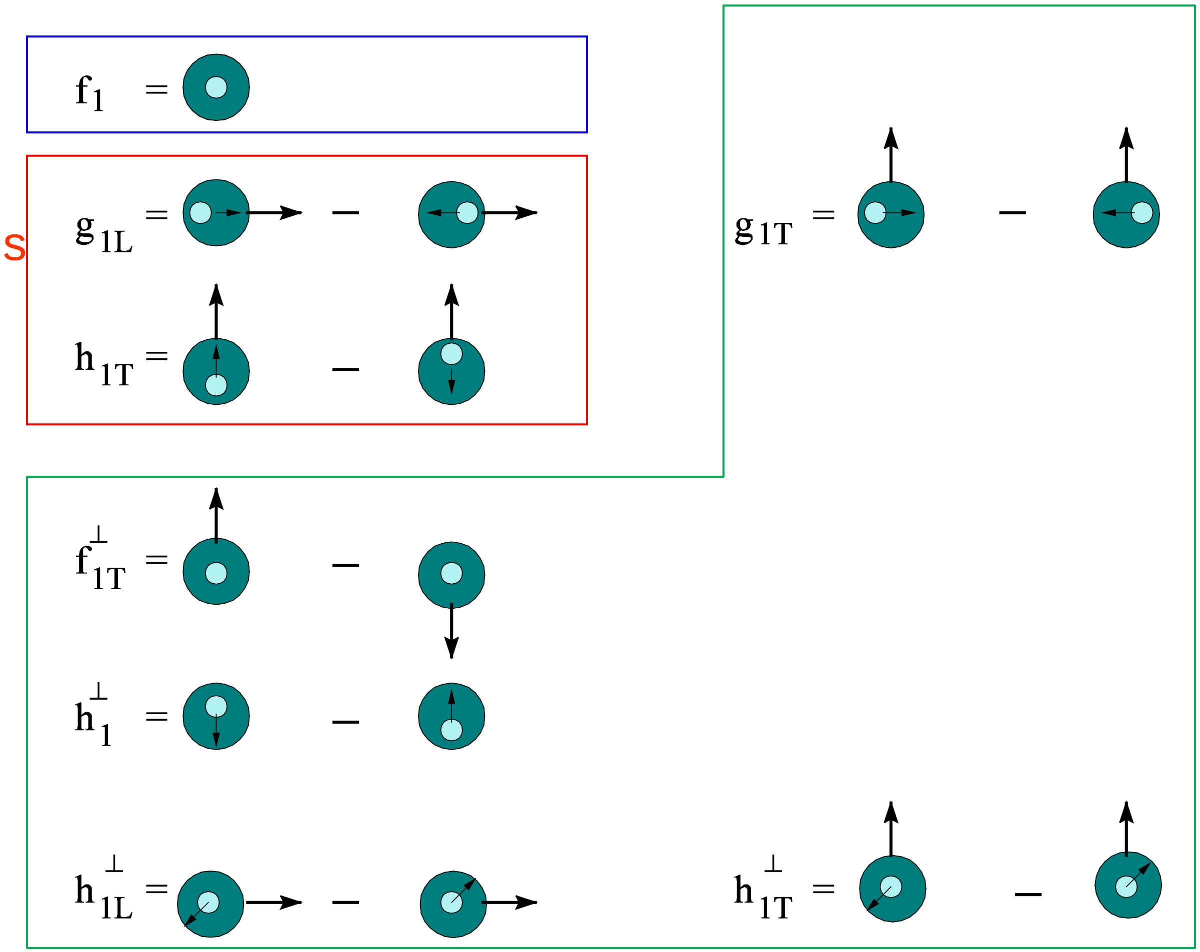
Example: Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

Spin-spin correlations

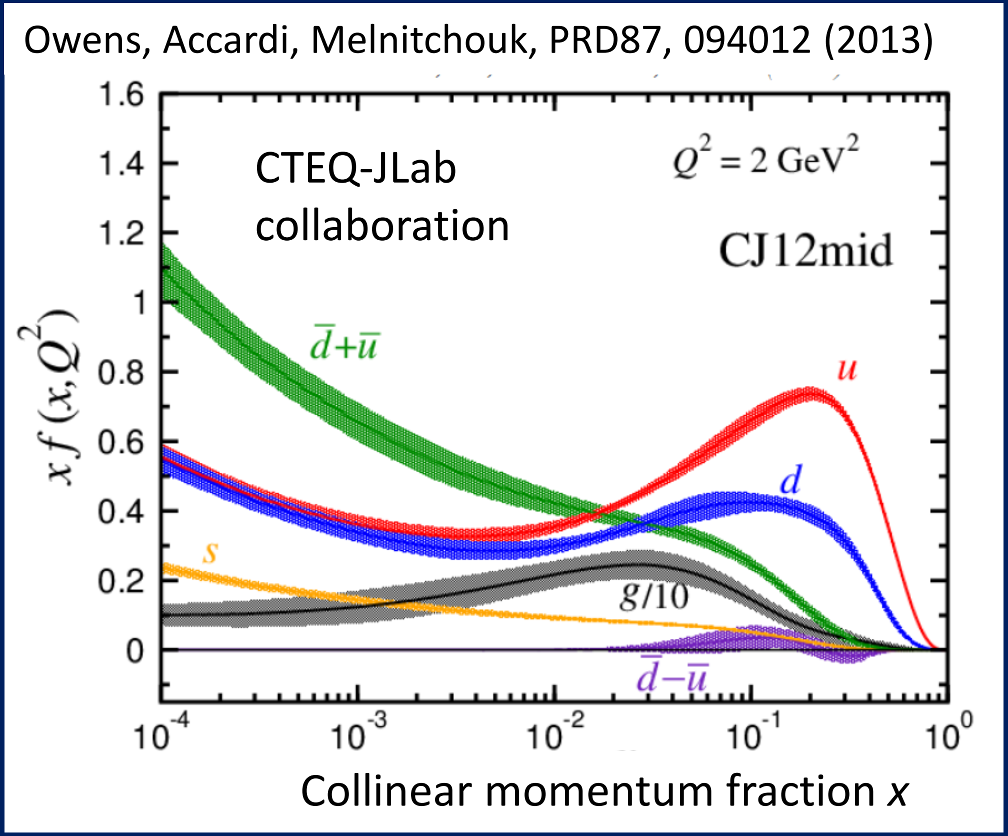
Spin-momentum correlations

$$S\bullet(p_1 \times p_2)$$

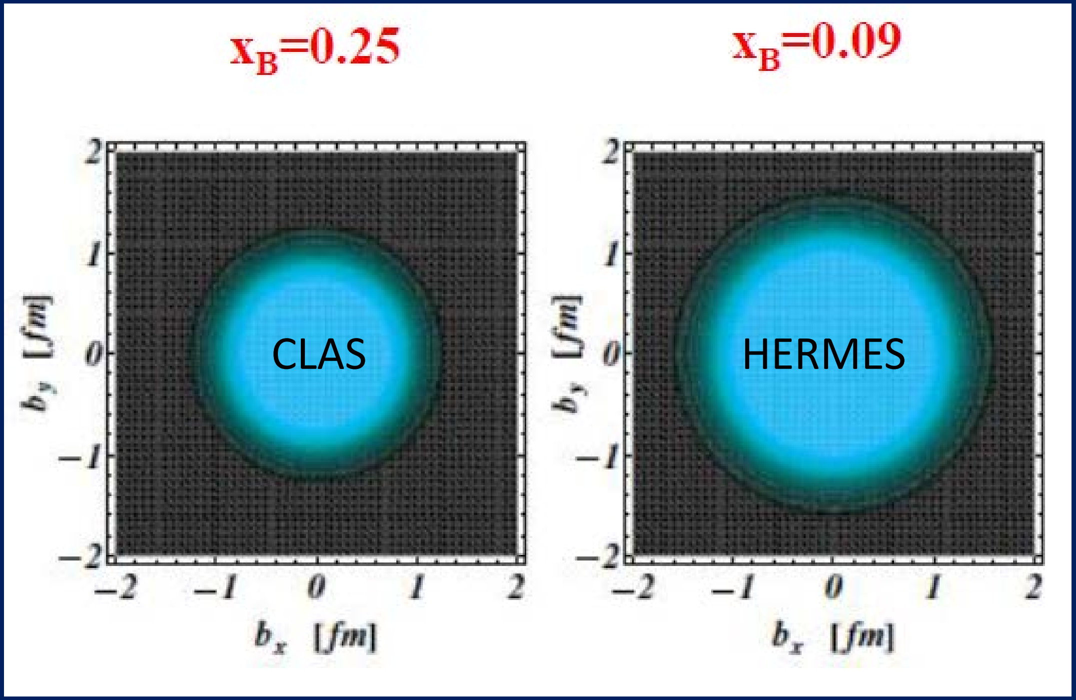


Example: Fits to quark and gluon distributions including much wider range of data

- Incorporate corrections for target mass, "higher-twist," and nuclear effects
- Can in turn make predictions for future measurements in extended kinematic regions



Example: Exploring spatial distributions



Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013) 066202

Spatial charge densities measured via deeply virtual Compton scattering

Initial evidence that quarks carrying larger momentum fractions (25% vs. 9%) in the nucleon are distributed over a smaller volume in space

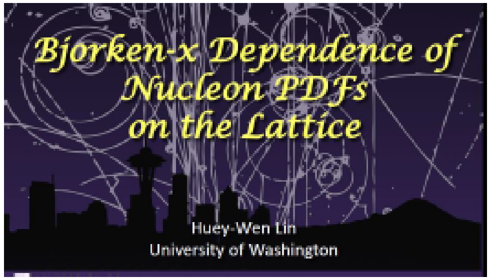
Example: Progress in lattice QCD

Recent progress in LQCD suggests the possibility to calculate the *x*-dependence of parton distributions

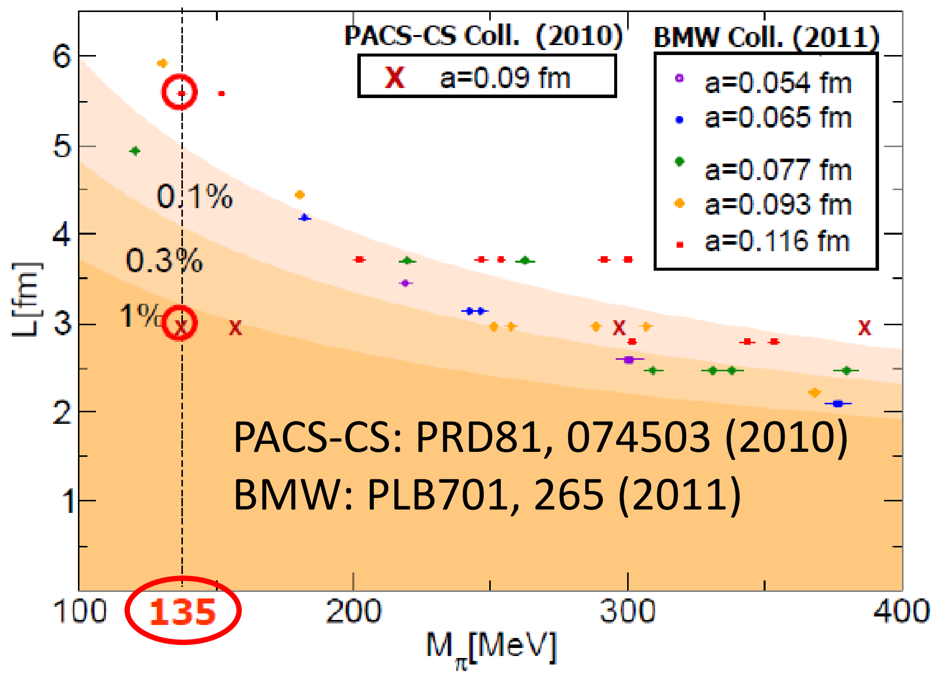
PRL 110, 262002 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Parton Physics on a Euclidean Lattice

Xiangdong Ji[1,2]



The *x*-dependence of the quark and antiquark transversity distributions can be calculated (not just their moments)

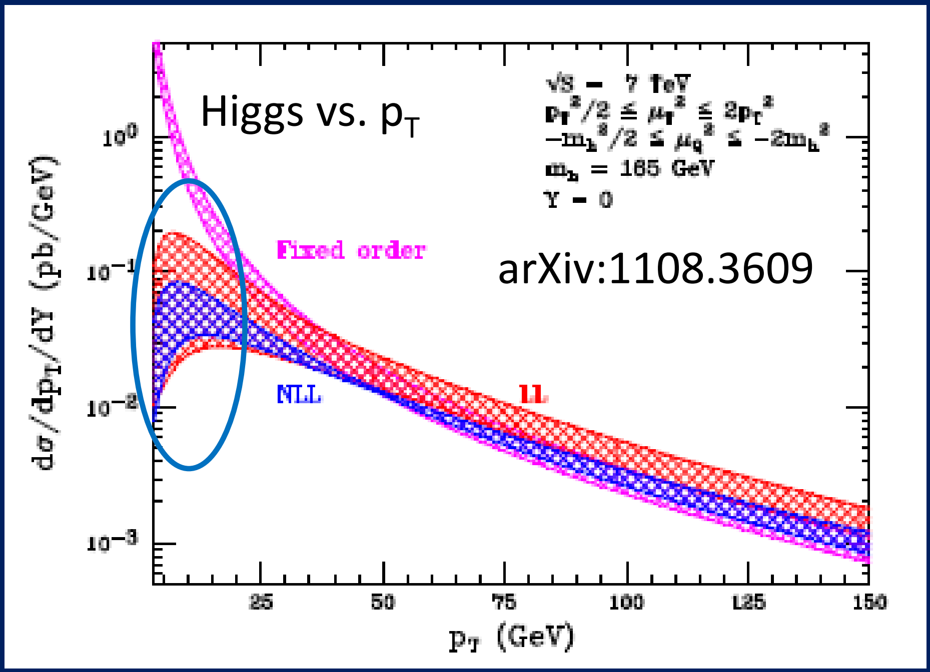


Slide from J.-C. Peng, Transversity 2014

First calculations at physical pion mass 135 MeV

Figure from T. Hatsuda, PANIC 2011

Example: Effective field theories



TRANSVERSE MOMENTUM DISTRIBUTIONS FROM EFFECTIVE FIELD THEORY

Sonny Mantry*

University of Wisconsin at Madison
Madison, WI 53706, USA
mantry147@gmail.com

Frank Petriello

High Energy Physics Division, Argonne National Laboratory
Argonne, IL 60439, USA

Department of Physics & Astronomy, Northwestern University
Evanston, IL 60208, USA
f-petriello@northwestern.edu

Soft Collinear Effective Theory

– Transverse momentum distribution for gluon+gluon→Higgs

Mapping out the partonic 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 . . .

Mapping out the partonic structure of the proton

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

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

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

Mapping out the partonic structure of the proton

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

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

Early measurements of flavor distributions in valence region. Flavor structure at lower momentum fractions still yielding surprises!

Mapping out the partonic structure of the proton

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

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

Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past decade.

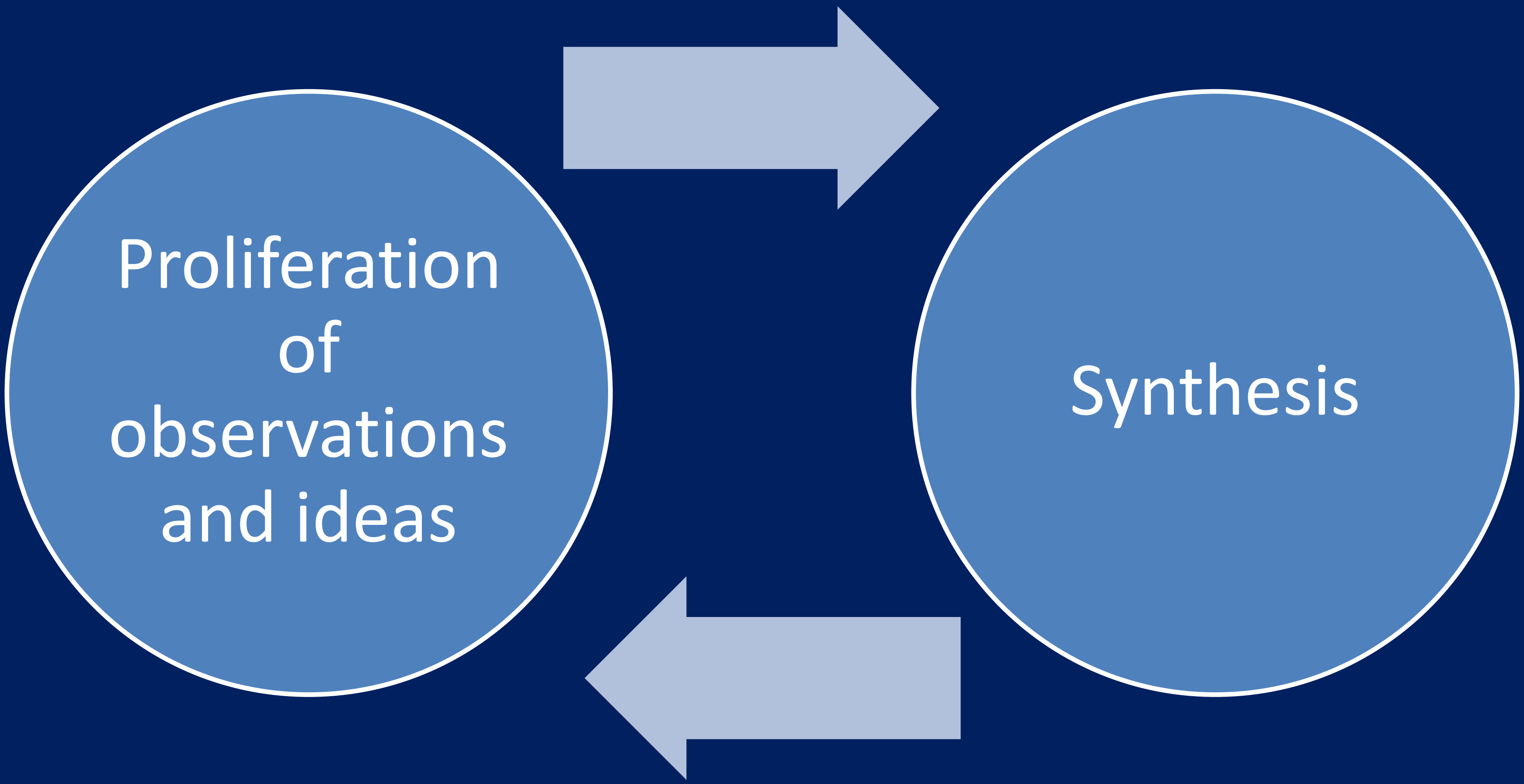
Mapping out the partonic structure of the proton

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

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

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

A cyclical process



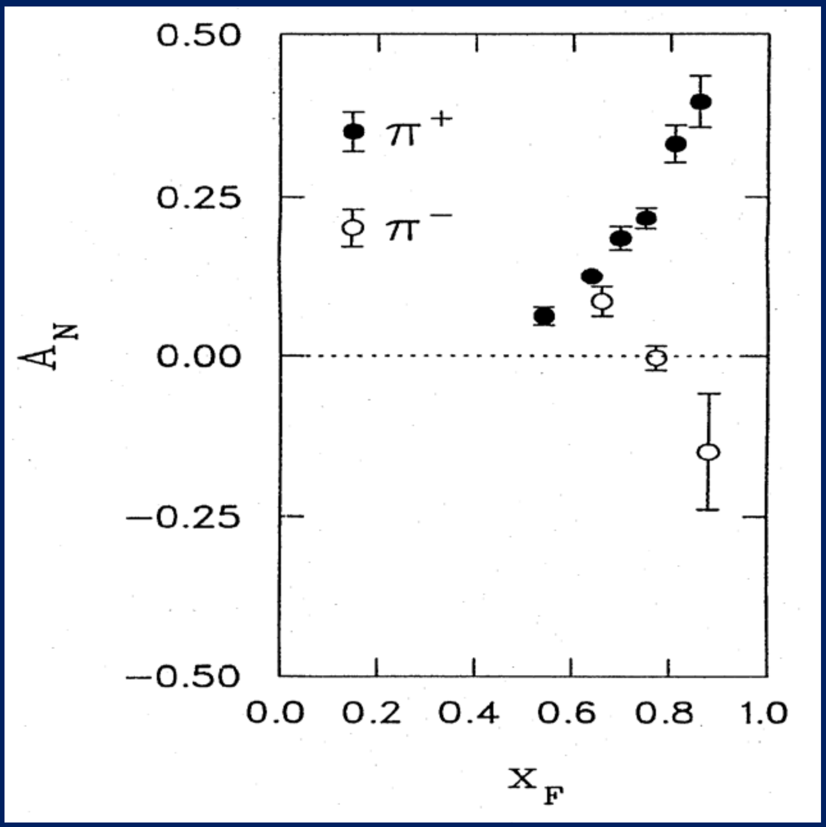
Factorization and universality in perturbative QCD

- Need to systematically *factorize* short- and long-distance physics—observable physical QCD processes always involve at least one long-distance scale (confinement)!
- Long-distance (i.e. nonperturbative) functions need to be *universal* in order to be portable across calculations for many processes

Measure nonperturbative parton distribution functions (pdfs) and fragmentation functions in many colliding systems over a wide kinematic range→constrain by performing *simultaneous fits to world data*

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

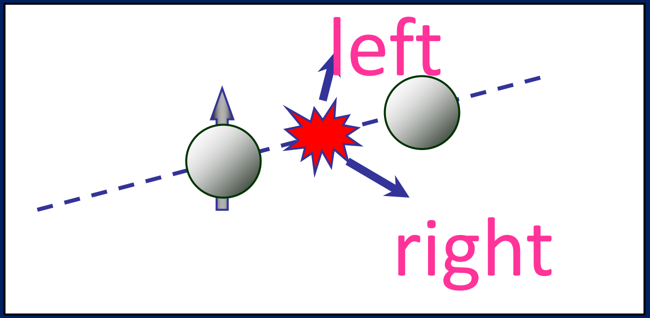
Argonne $\sqrt{s}$=4.9 GeV



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

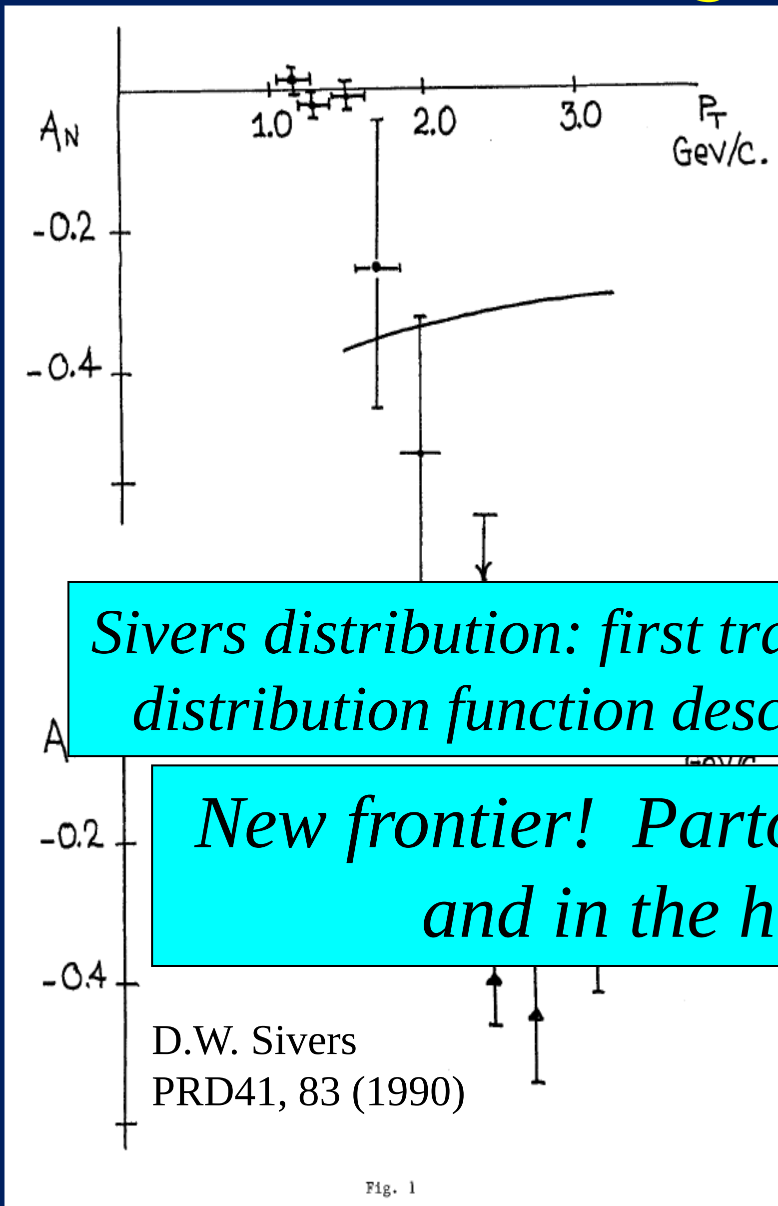
Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction—by up to 40%!!

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



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

Transverse-momentum-dependent distributions and single-spin asymmetries



D.W. Sivers
PRD41, 83 (1990)

- 1990: “Sivers mechanism” proposed in attempt to understand observed asymmetries
- 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

Sivers distribution: first transverse-momentum-dependent parton distribution function describing a spin-momentum correlation

New frontier! Parton ***dynamics*** *inside hadrons, and in the hadronization process*

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

Spin and momenta of partons and/or hadrons

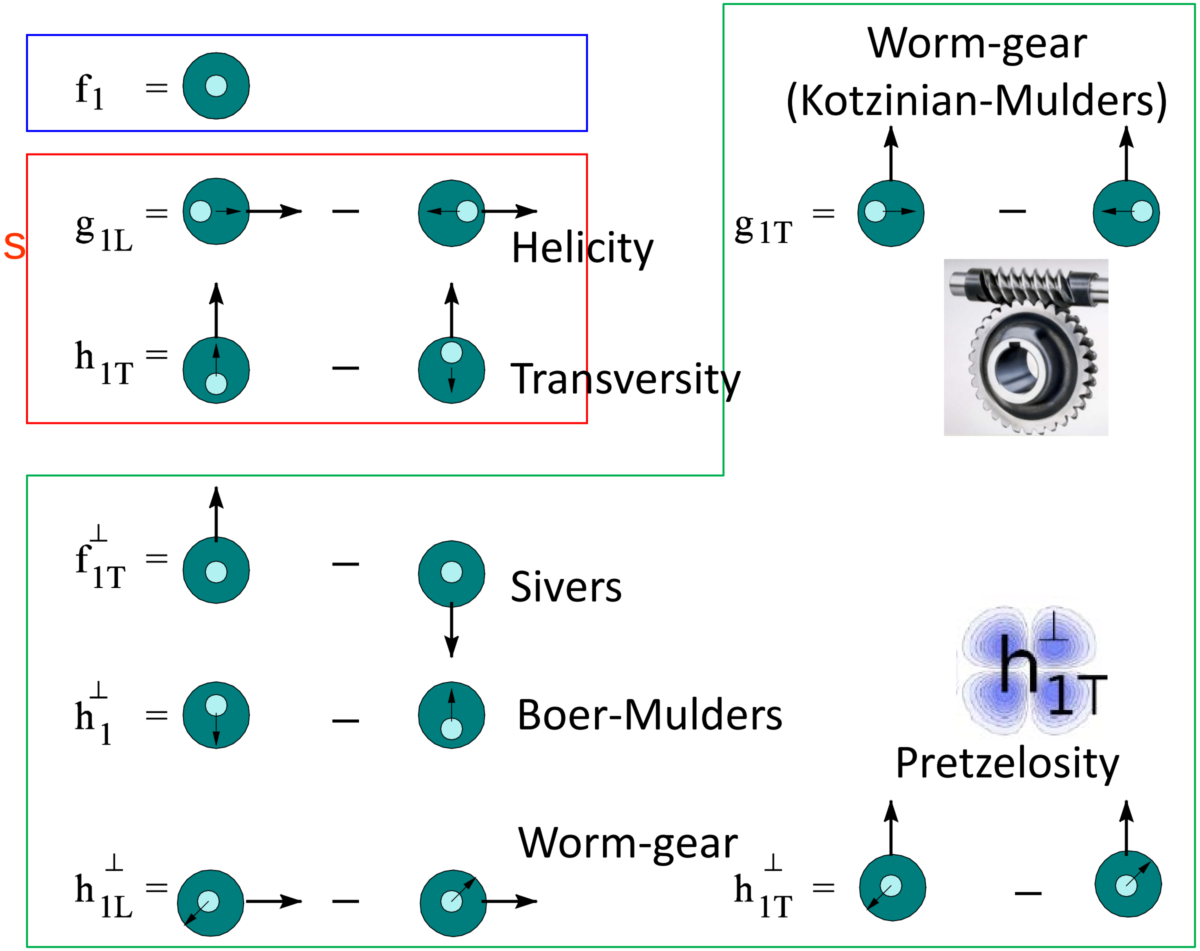
Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

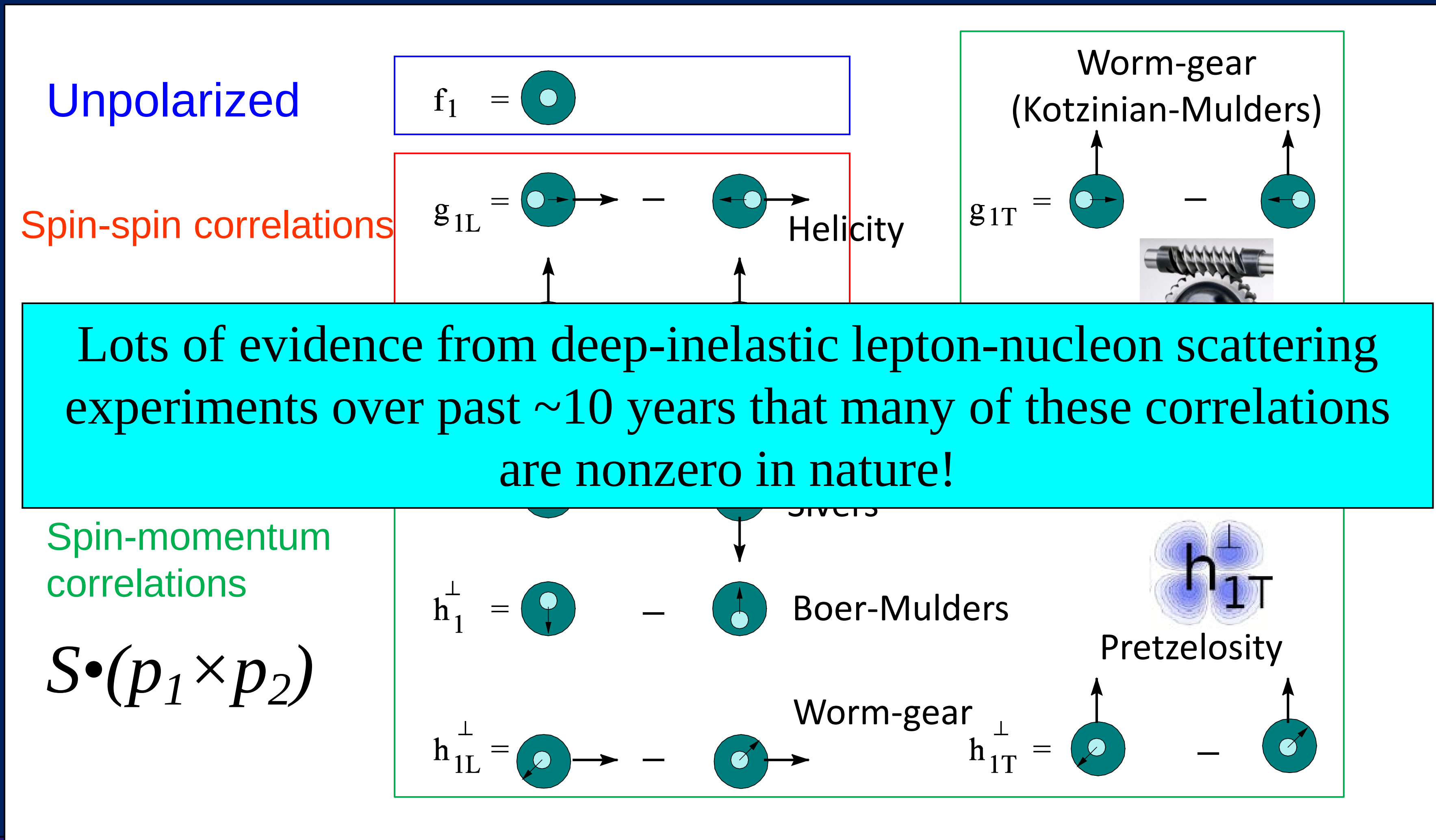
Spin-spin correlations

Spin-momentum correlations

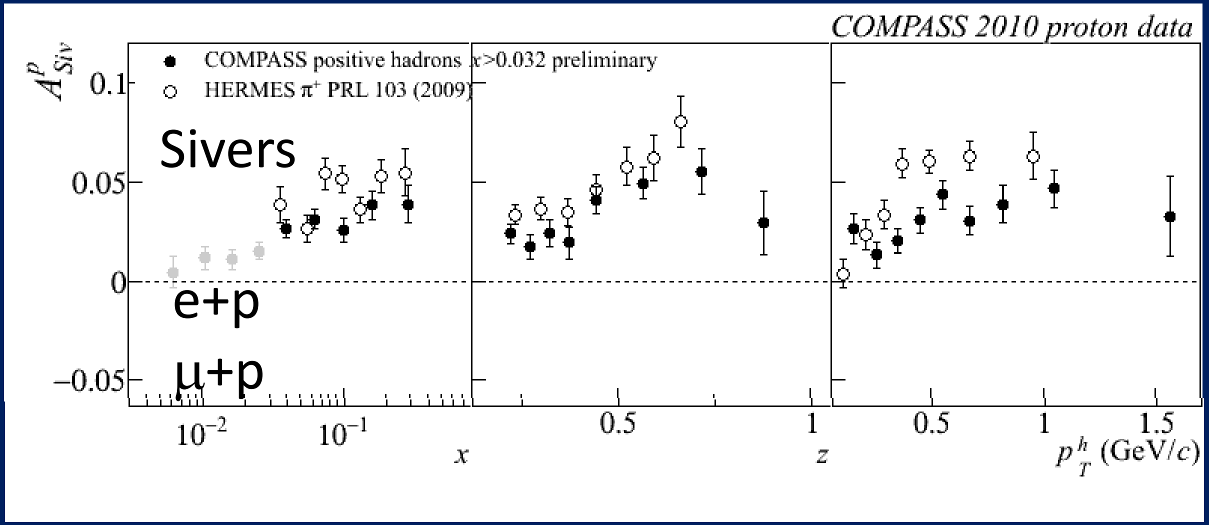
$$S \bullet (p_1 \times p_2)$$

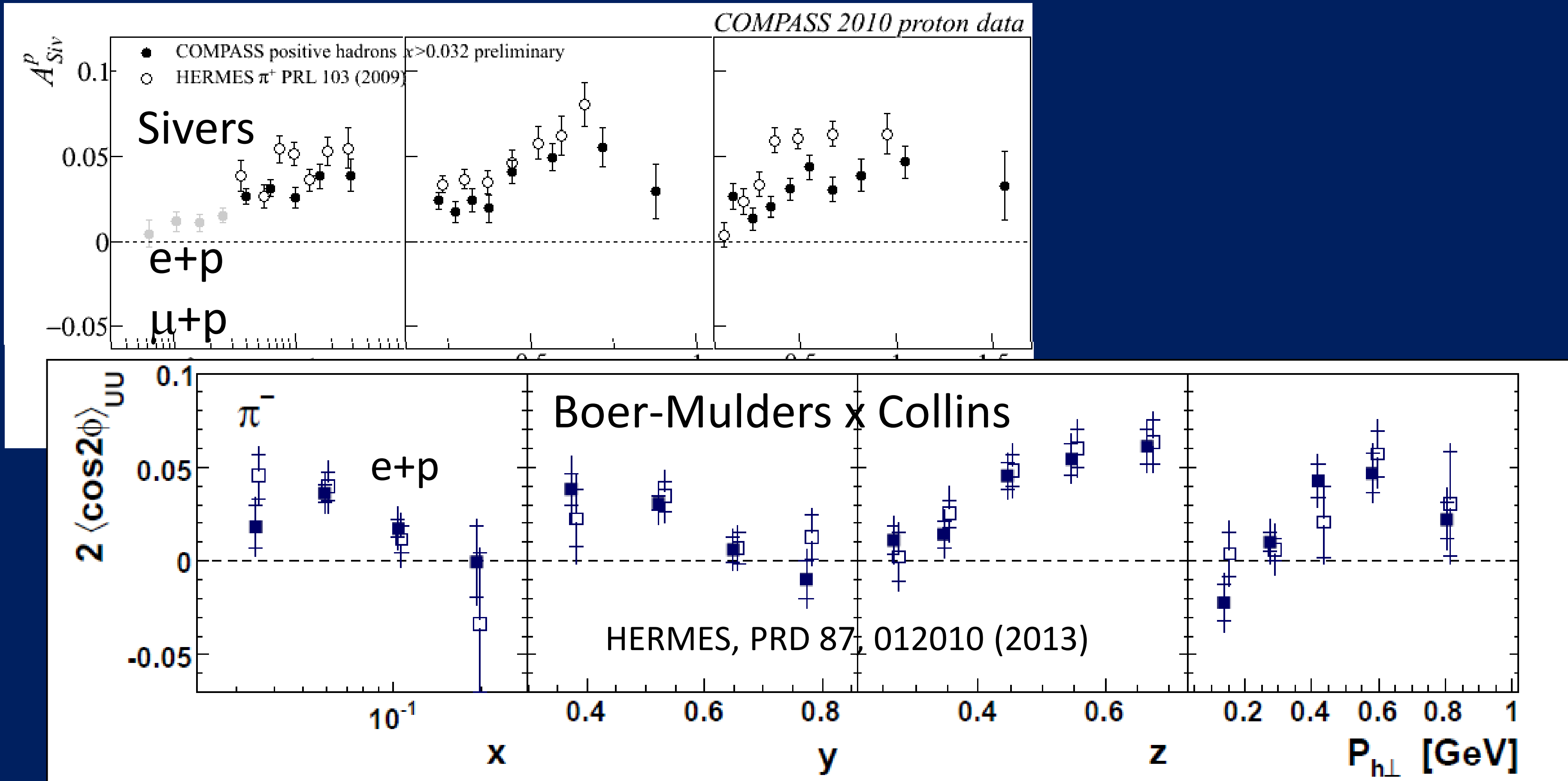


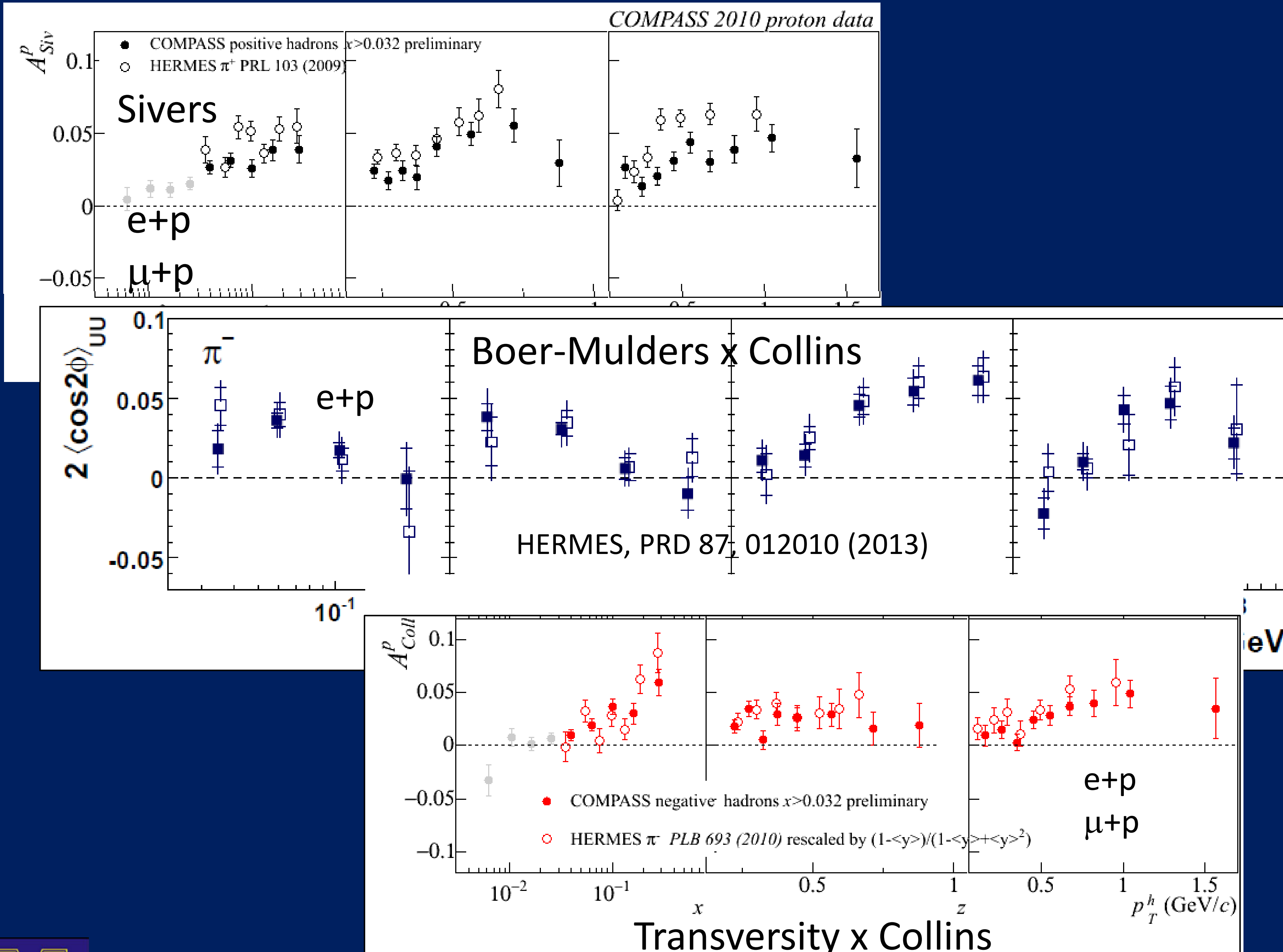
Spin-spin and spin-momentum correlations in QCD bound states

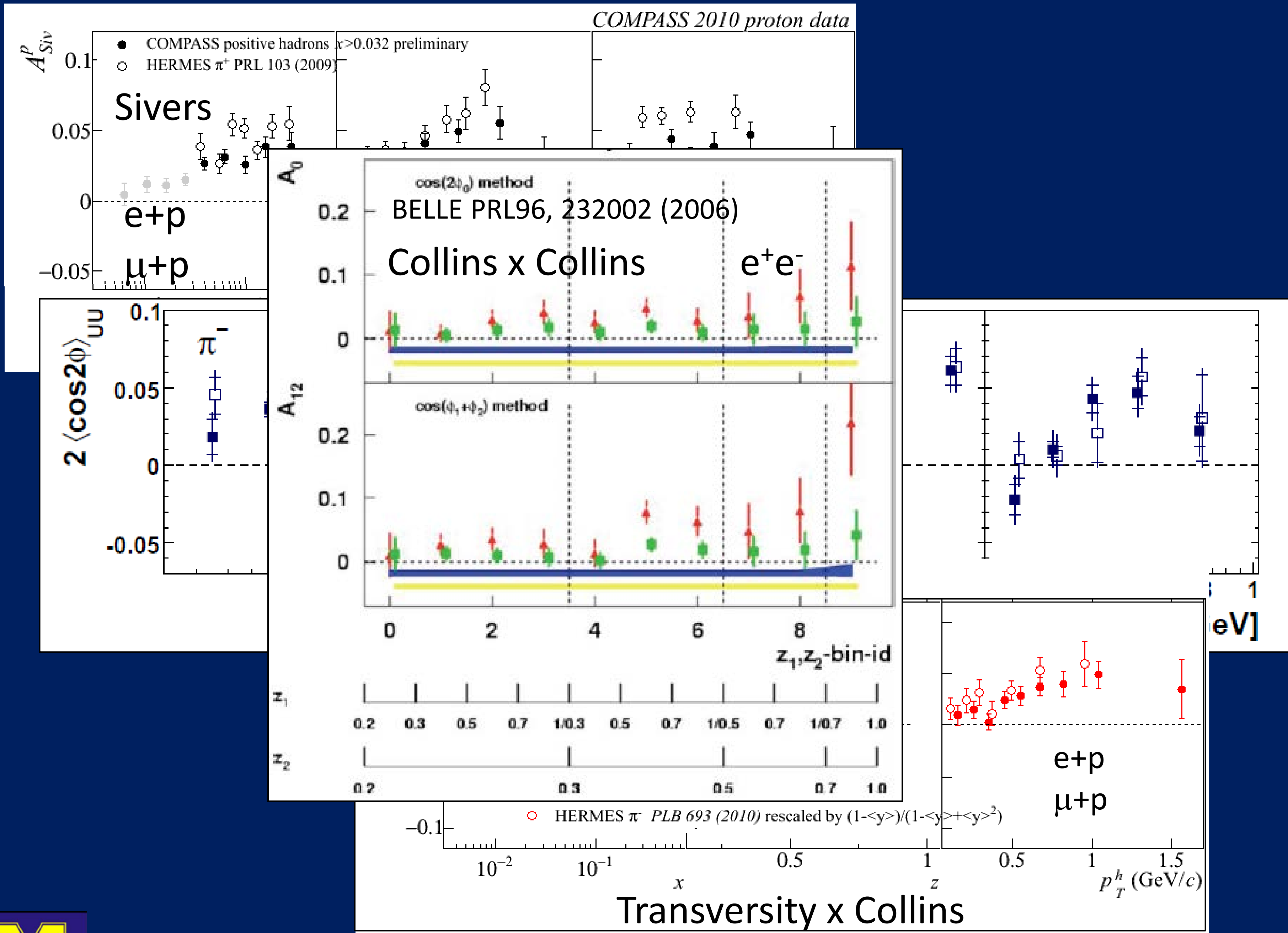


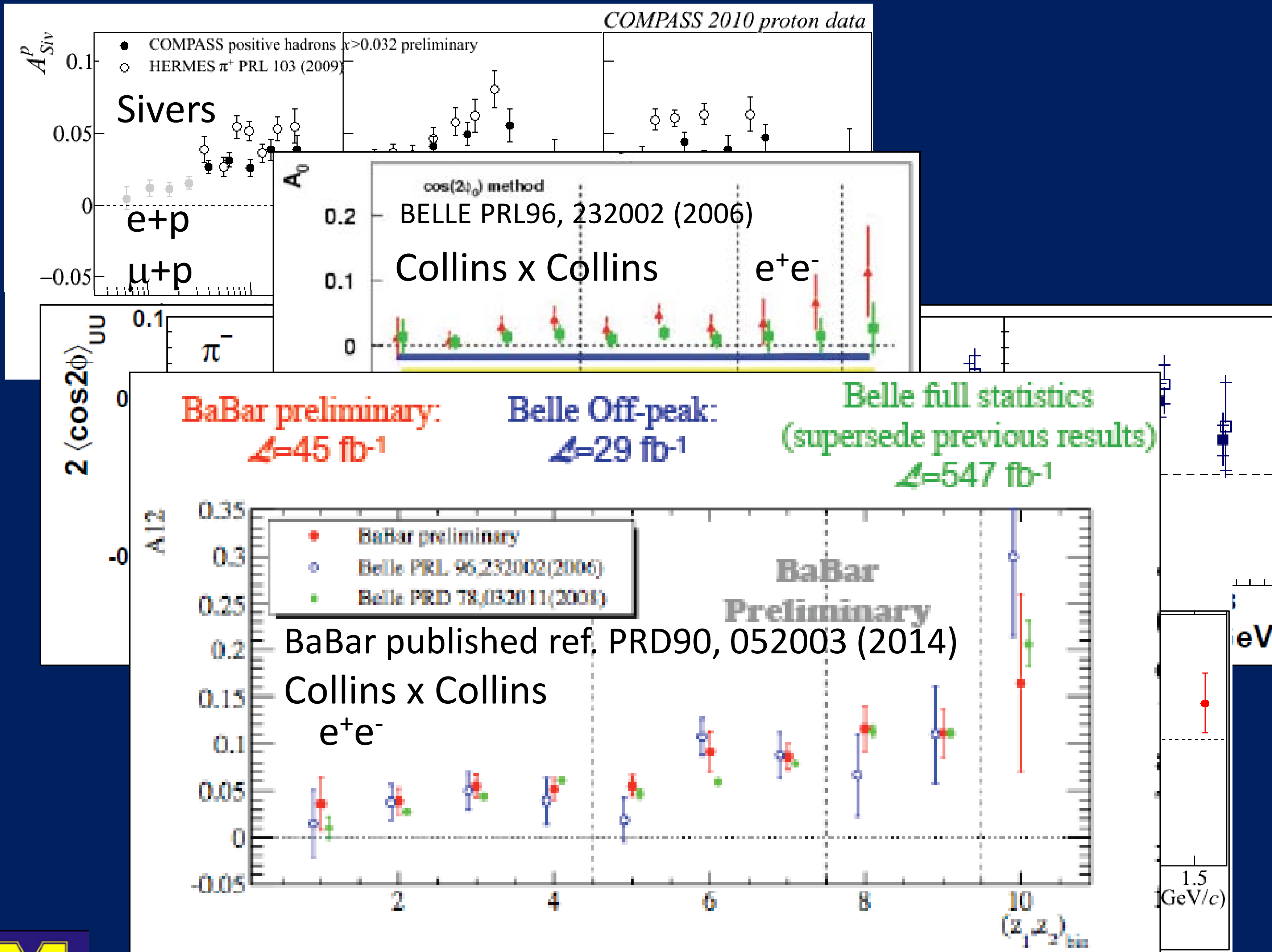
Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~10 years that many of these correlations are nonzero in nature!


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^{h}_{T} (GeV/c)

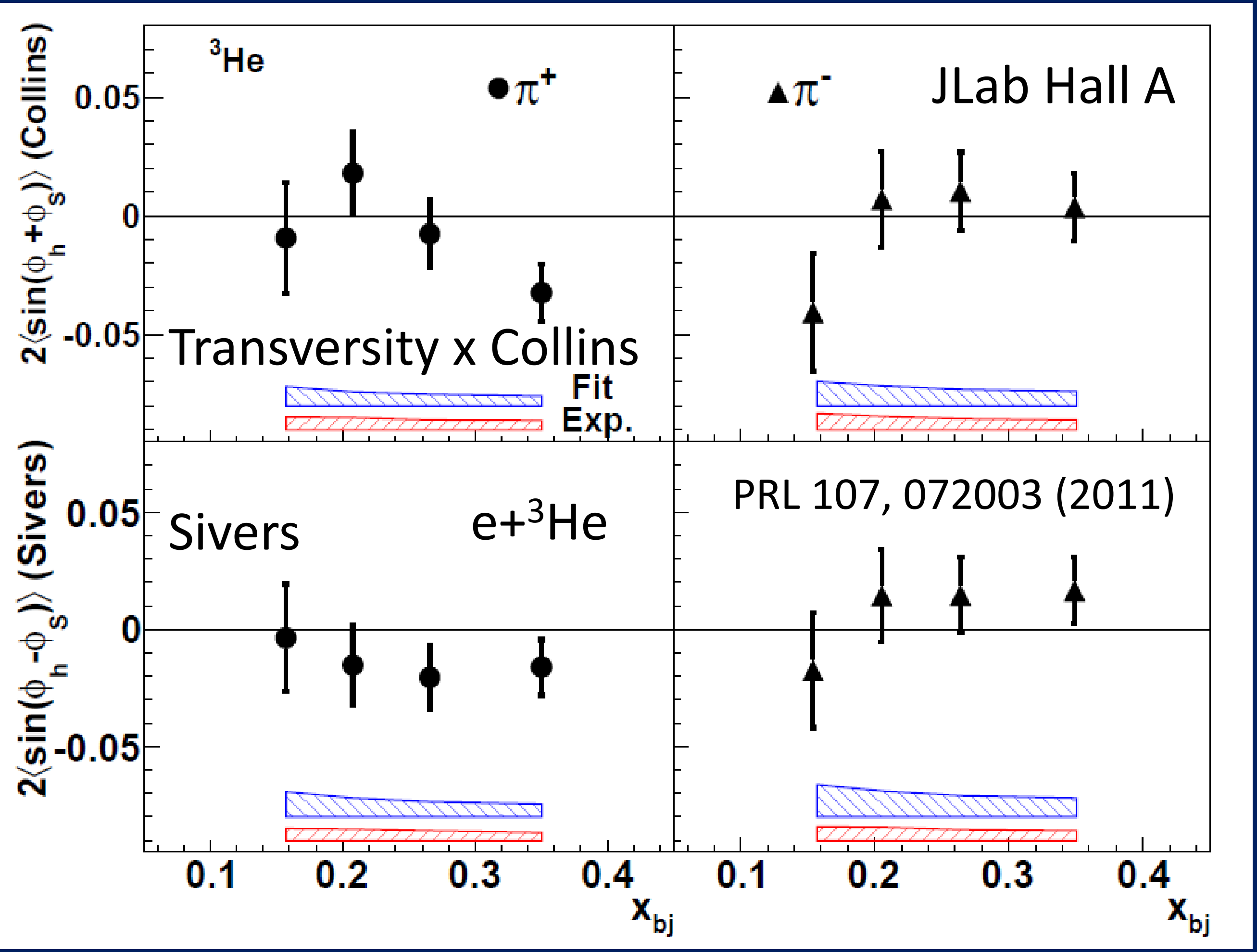

COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
A^{p}_{Siv}
0.1
0.05
0
−0.05
π−
e+p
Boer-Mulders x Collins
HERMES, PRD 87, 012010 (2013)
$2\langle\cos 2\phi\rangle_{UU}$
0.1
0.05
0
-0.05
10^{-1}
x
0.4
0.6
0.8
y
0.4
0.6
z
0.2
0.4
0.6
0.8
1
$P_{h\perp}$ [GeV]


COMPASS 2010 proton data
A^p_{Siv}
COMPASS positive hadrons x>0.032 preliminary
HERMES π^+ PRL 103 (2009)
Sivers
e+p
μ+p
$2\langle\cos 2\phi\rangle_{UU}$
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


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
π-
HERMES π- PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>^2)
e+p
μ+p
Transversity x Collins

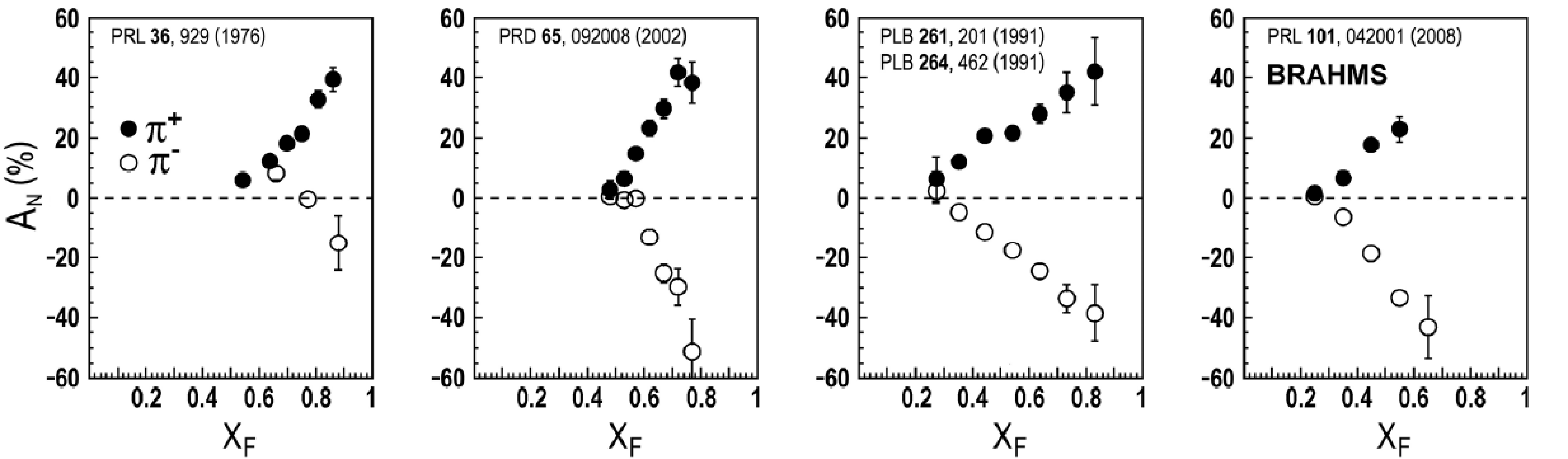

COMPASS 2010 proton data
COMPASS positive hadrons
HERMES π+ PRL 103 (2009)
x>0.032 preliminary
Sivers
e+p
μ+p
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
BaBar preliminary:
Belle Off-peak:
Belle full statistics
(supersede previous results)
BaBar preliminary
Belle PRL 96,232002(2006)
Belle PRD 78,032011(2008)
BaBar
Preliminary
BaBar published ref. PRD90, 052003 (2014)
Collins x Collins
e+e-

Hints from polarized ^3He

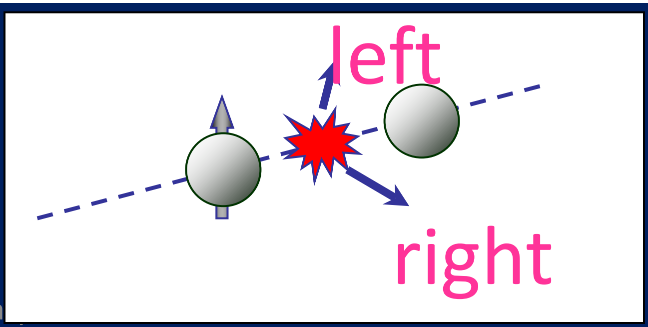


But what about proton-proton collisions?

ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV

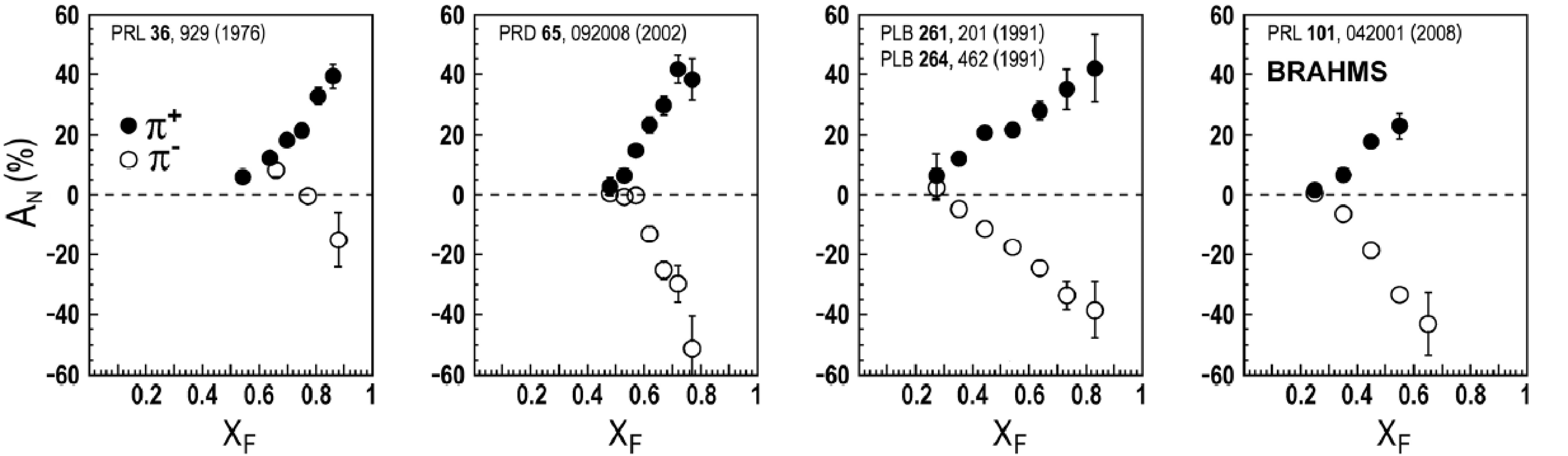


$$x_F = 2 p_{long} / \sqrt{s}$$



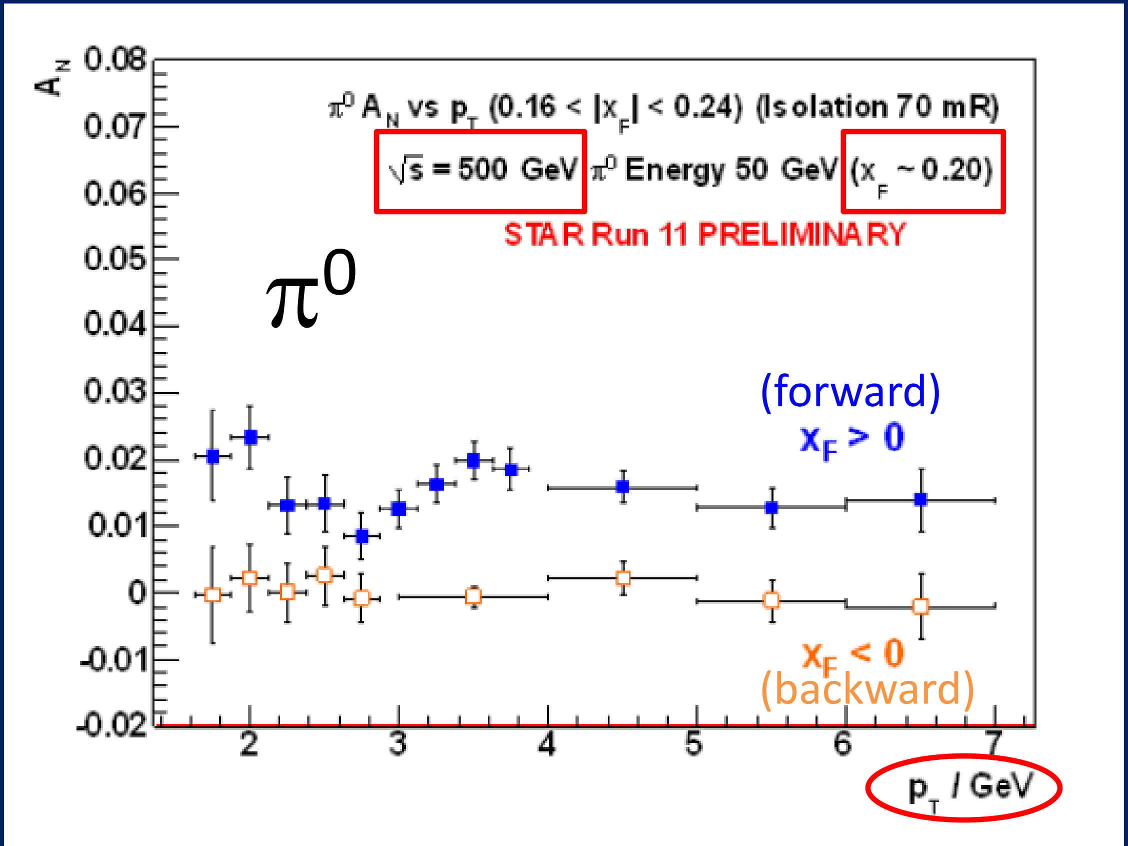
But what about proton-proton collisions?

ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV



Strikingly similar effects across energies!
→ Continuum between nonperturbative/nonpartonic and perturbative/partonic descriptions of this <u>nonperturbative</u> structure?

Single-spin asymmetries in transversely polarized p+p collisions



- Effects persist to kinematic regimes where perturbative QCD techniques clearly apply
- p_T = 7 GeV
  → Q^2 ~ 49 GeV^2!

p+p → hadron + X: Challenging to interpret

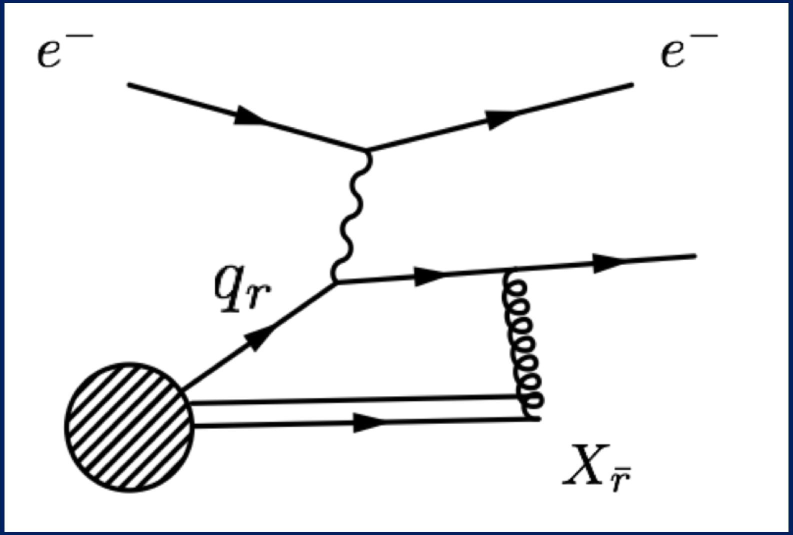
- Always huge effects!
- But in p+p → pion +X don't have enough information to separate initial-state (proton structure) from final-state (hadronization) effects

Properties of naïve-T-odd spin-momentum correlation functions

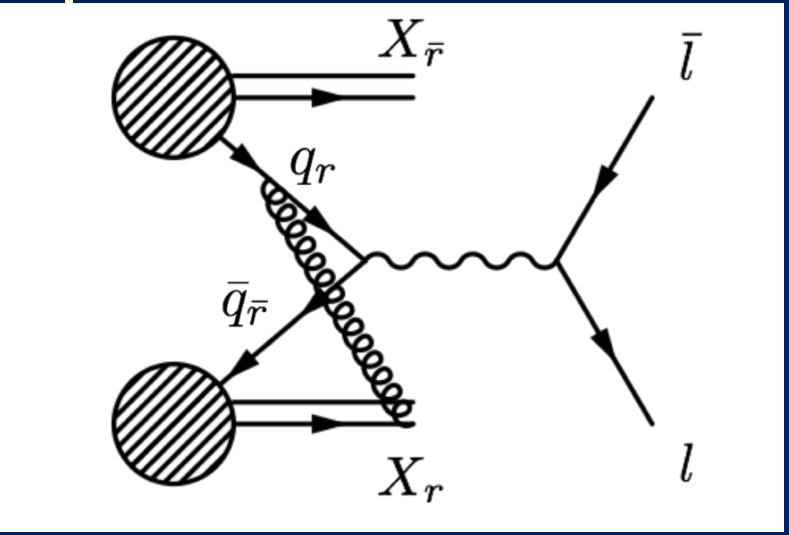
- Sivers transverse-momentum-dependent parton distribution function is odd under "naïve-time-reversal" (actually a PT transformation)
  - As is Boer-Mulders spin-momentum correlation
- In 1993, after original 1990 paper by D.W. Sivers, J.C. Collins claimed such functions must vanish
- Only realized in 2002 by Brodsky, Hwang, and Schmidt that could be nonvanishing if *phase interference effects due to color interactions* present

Modified universality of certain transverse-momentum-dependent distributions: Color in action!

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions

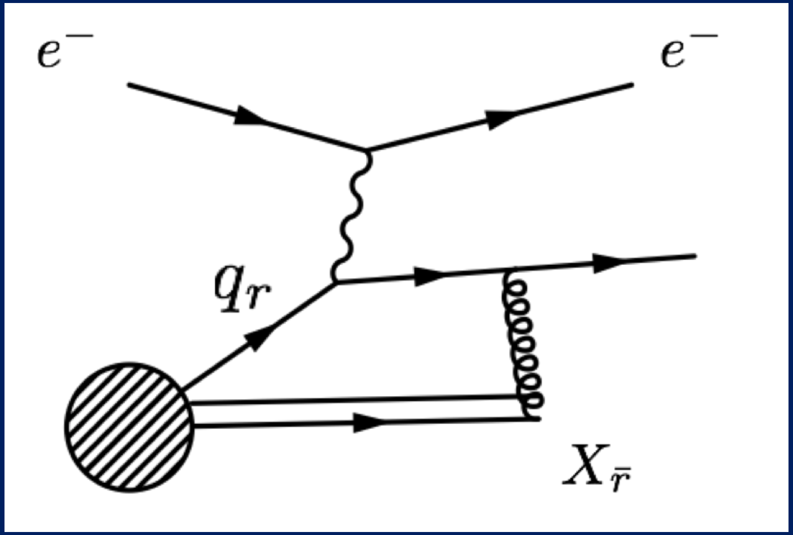


As a result, get *opposite sign* for the Sivers transverse-momentum-dependent pdf when measure in semi-inclusive DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

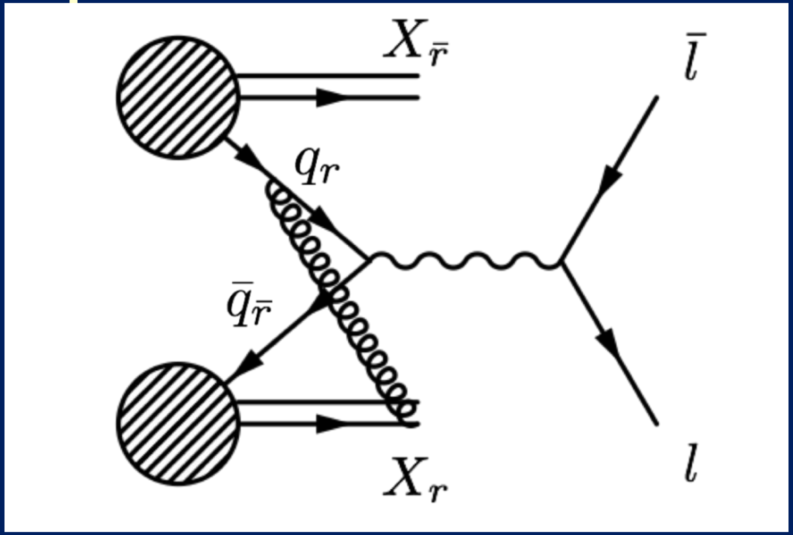
Figures by J.D. Osborn

Modified universality of certain transverse-momentum-dependent distributions: Color in action!

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



Still waiting for a polarized quark-antiquark annihilation measurement to compare to existing lepton-nucleon scattering measurements . . .

Figures by J.D. Osborn

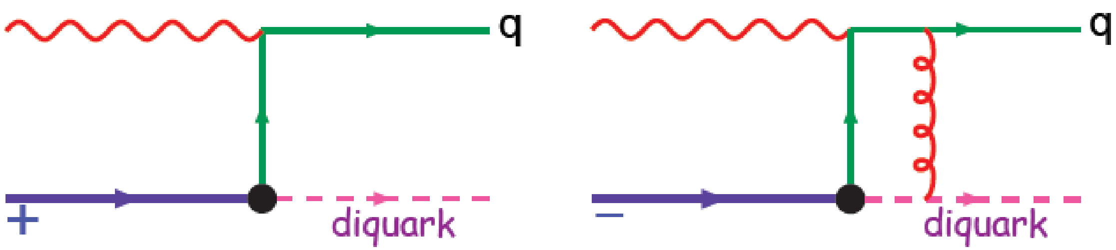
Modified universality requires full QCD: Gauge-invariant quantum field theory

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].

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

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

SIDIS final state interactions



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

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

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

Slide from M. Anselmino, Transversity 2014

Physical consequences of a gauge-invariant quantum theory: 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."

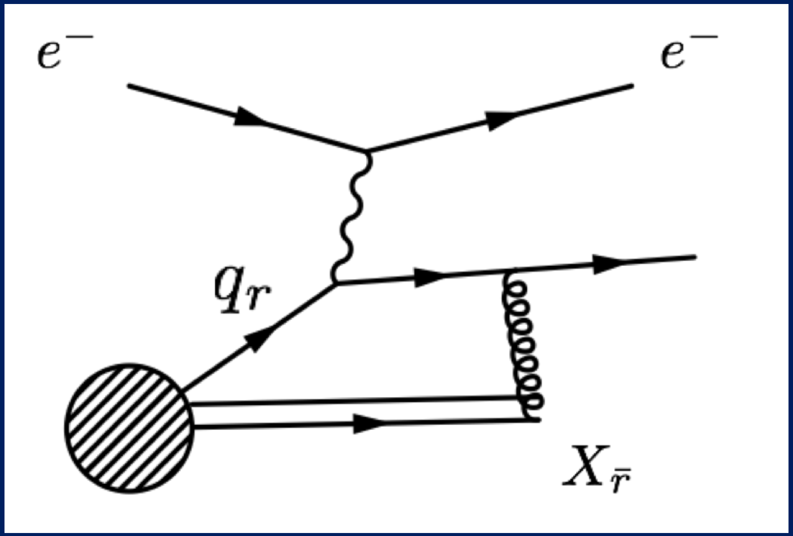
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

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

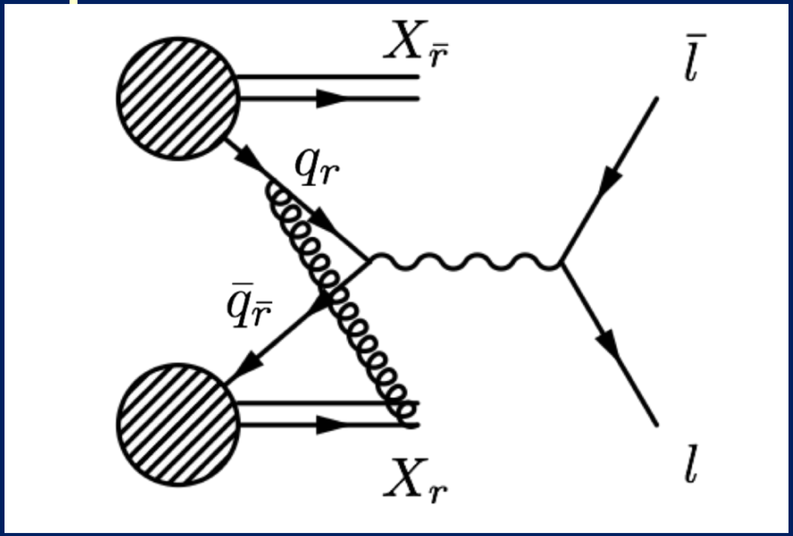
“Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories.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



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



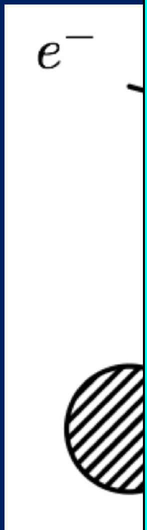
See e.g. Pijlman, hep-ph/0604226
or Sivers, arXiv:1109.2521

Figures by J.D. Osborn

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

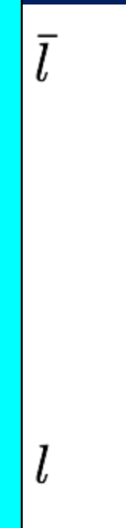
Deep-inelastic lepton-nucleon scattering:

Attrac



Quark-antiquark annihilation to leptons:

ctions



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

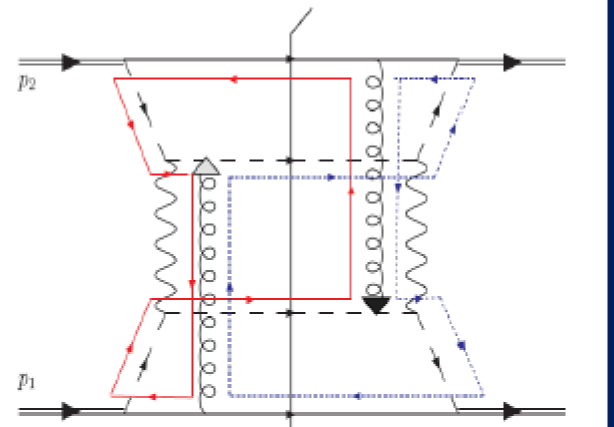
BUT: In QCD expect additional, new effects due to specific <u>non-Abelian</u> nature of the gauge group

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

Figures by J.D. Osborn

QCD Aharonov-Bohm effect: Color entanglement

- 2010: Rogers and Mulders predict *color entanglement* in processes involving p+p production of hadrons if quark transverse momentum taken into account
- Quarks become correlated *across* the two protons
- Consequence of QCD specifically as a ***non-Abelian*** gauge theory!



PRD 81, 094006 (2010)

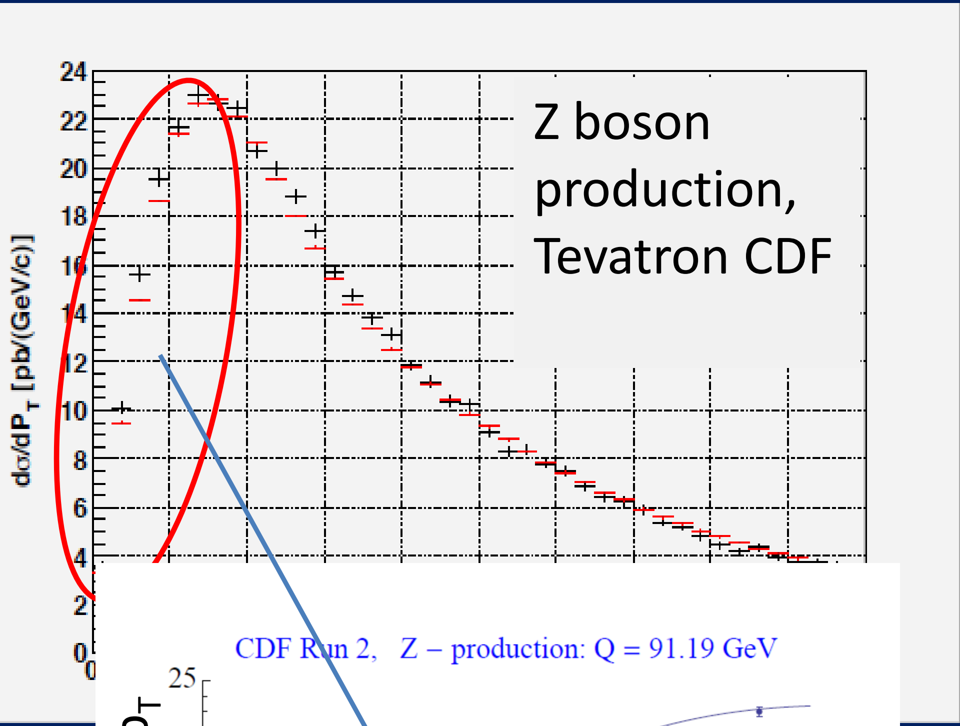
$$p+p \rightarrow h_1 + h_2 + X$$

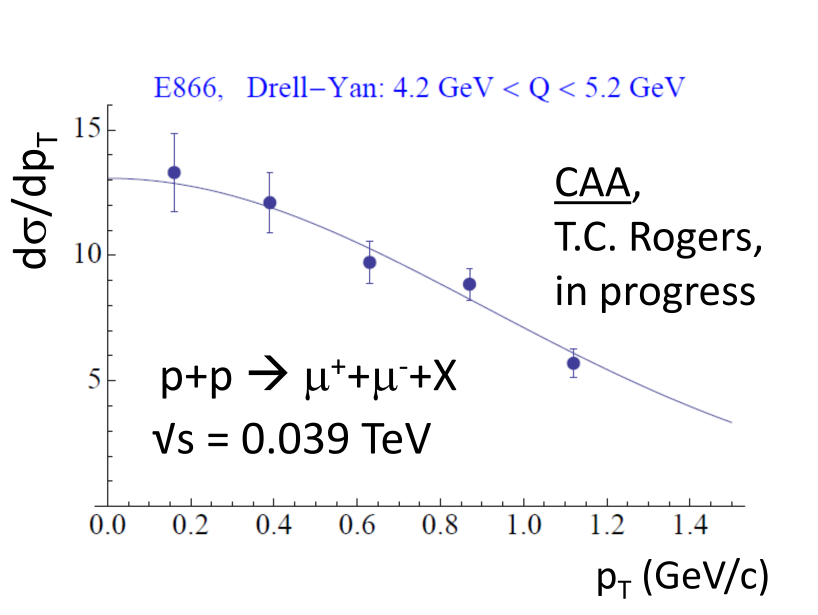
Color flow can't be described as flow in the two gluons separately. Requires simultaneous presence of both.

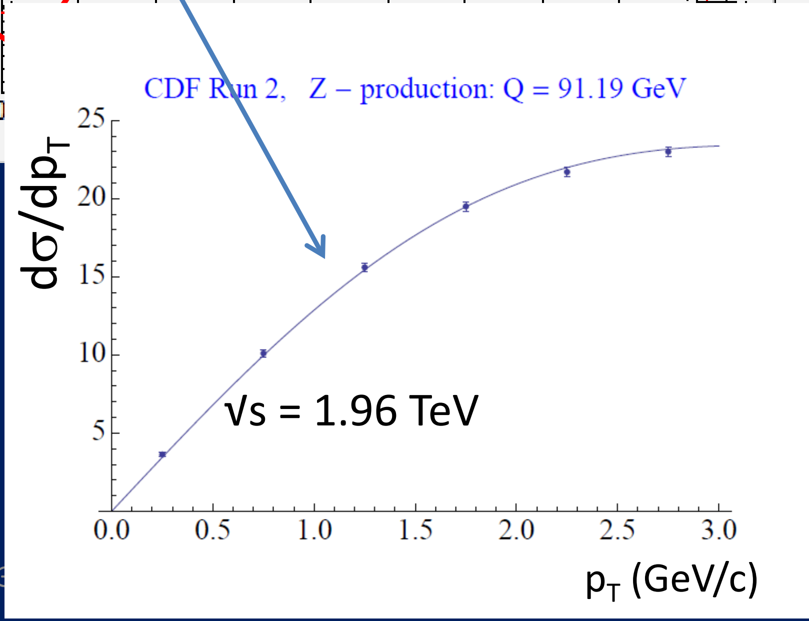
Huge transverse spin asymmetries in p+p a color entanglement effect??

Testing the Aharonov-Bohm effect in QCD as a non-Abelian gauge theory

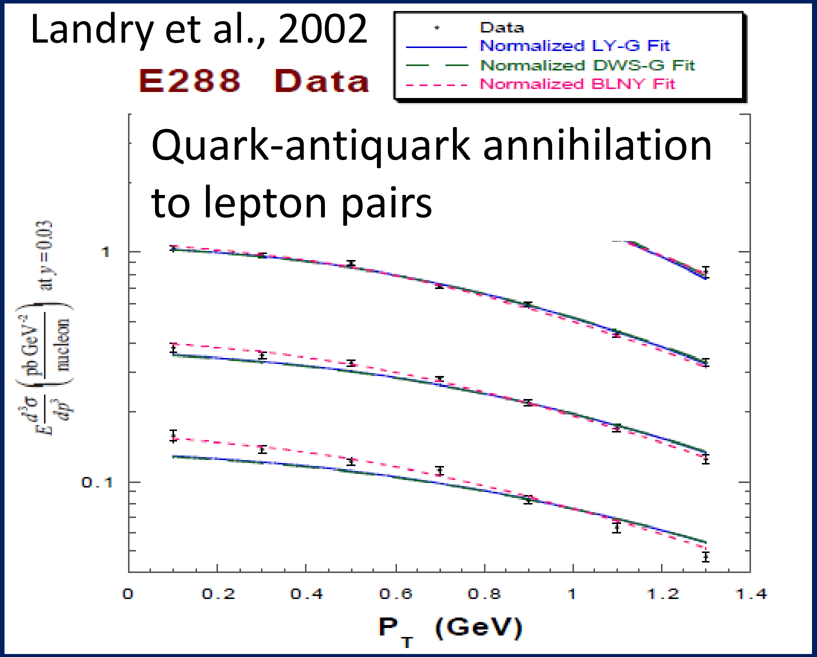
- Look for contradiction with predictions for the case of *no* color entanglement
- But first need to parameterize (unpolarized) transverse-momentum-dependent pdfs from world data
  - Can put better constraints on unpolarized predictions because of more available data







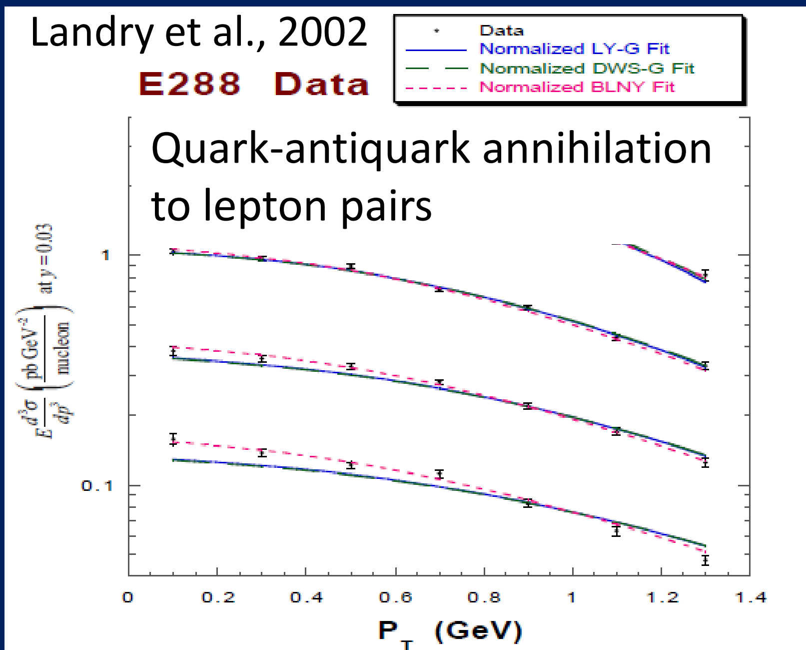
Testing the Aharonov-Bohm effect in QCD as a non-Abelian gauge theory



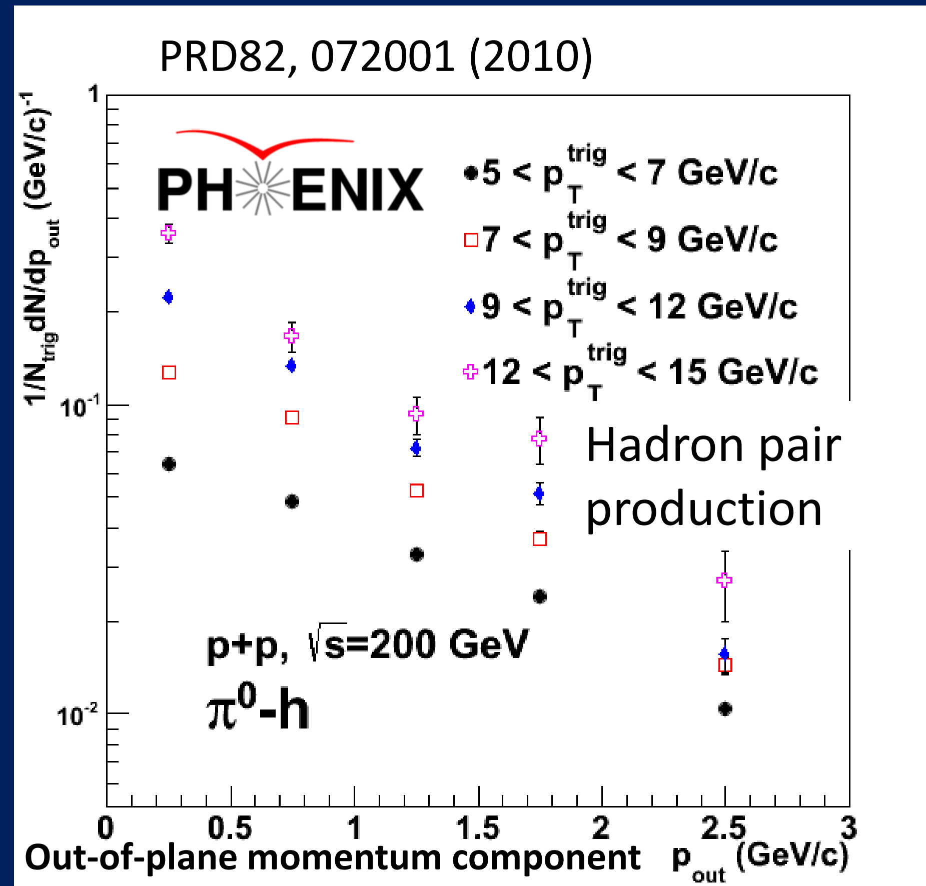
Get predictions from fits to data where no entanglement expected

$p+A \rightarrow \mu^+ + \mu^- + X$ for different invariant masses: No color entanglement expected

Testing the Aharonov-Bohm effect in QCD as a non-Abelian gauge theory



Get predictions from fits to data where no entanglement expected



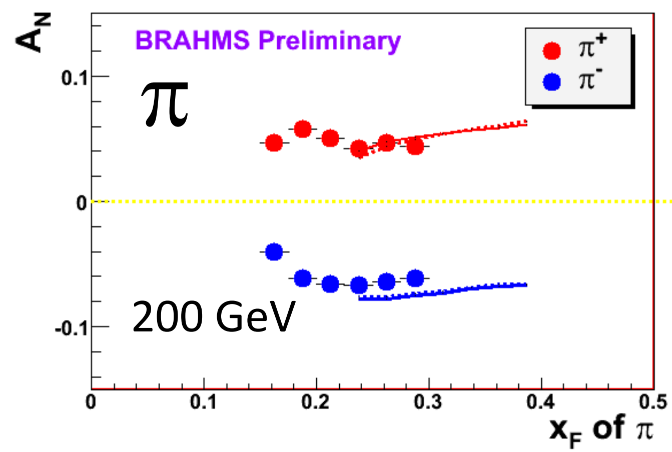
Make predictions for processes where entanglement *is* expected; look for deviation

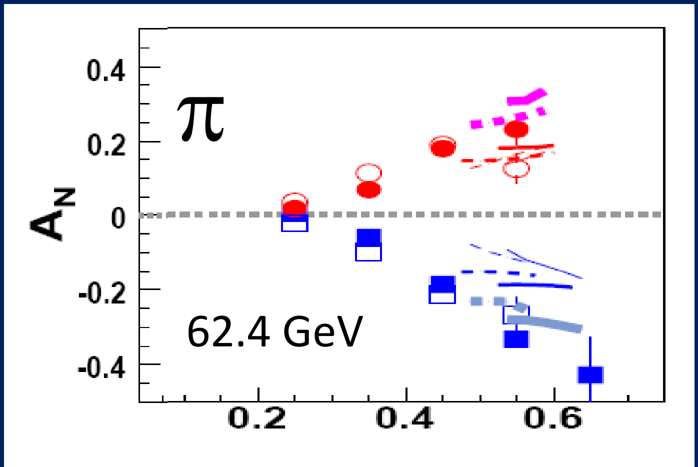
Summary

- Early years of rewarding new era of quantitative basic research in QCD!
- Gradually shifting to think about QCD systems in new ways, focusing on topics/ideas/concepts that have long been familiar to the world of condensed matter physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems
- Will be exciting to continue testing and exploring these ideas and phenomena in upcoming years . . .

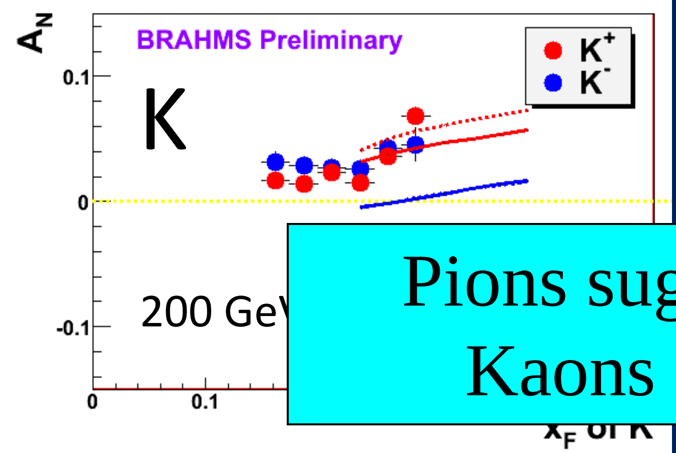
Extra

π, K, p
at 200 and
62.4 GeV

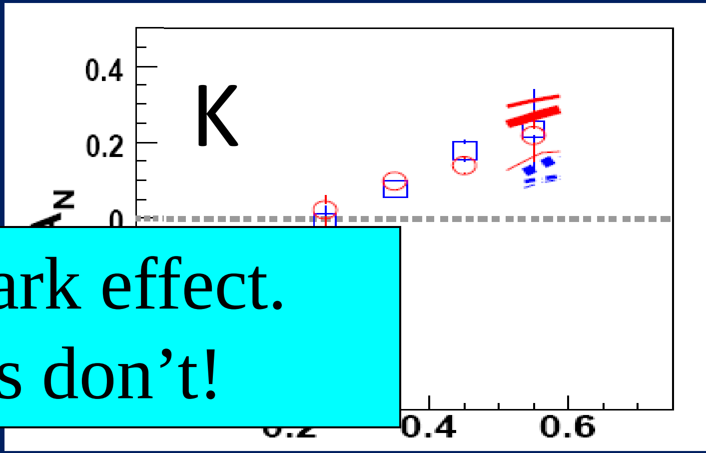




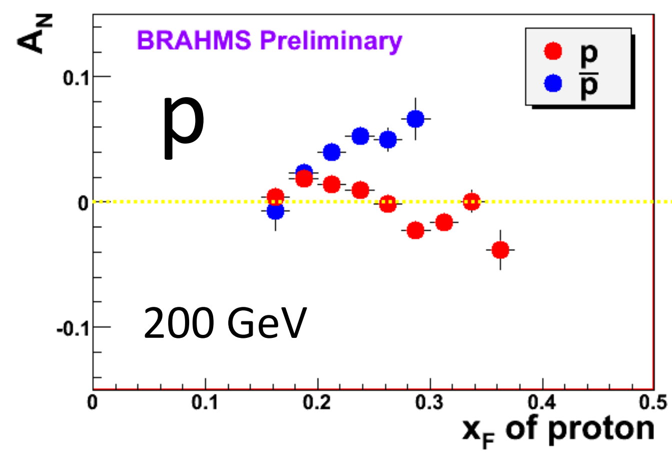
Note different scales

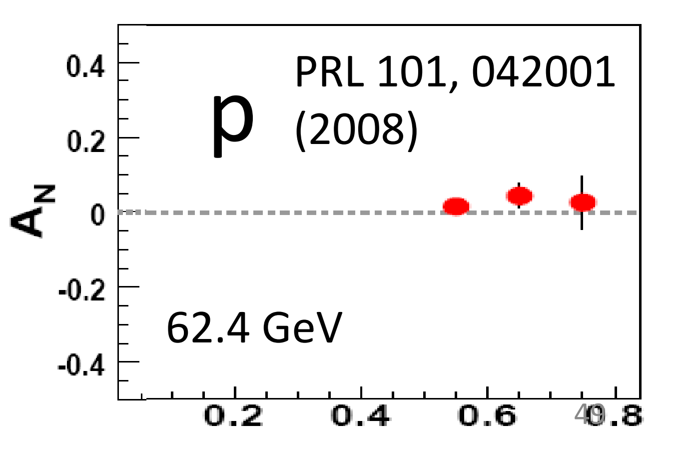


K- asymmetries underpredicted



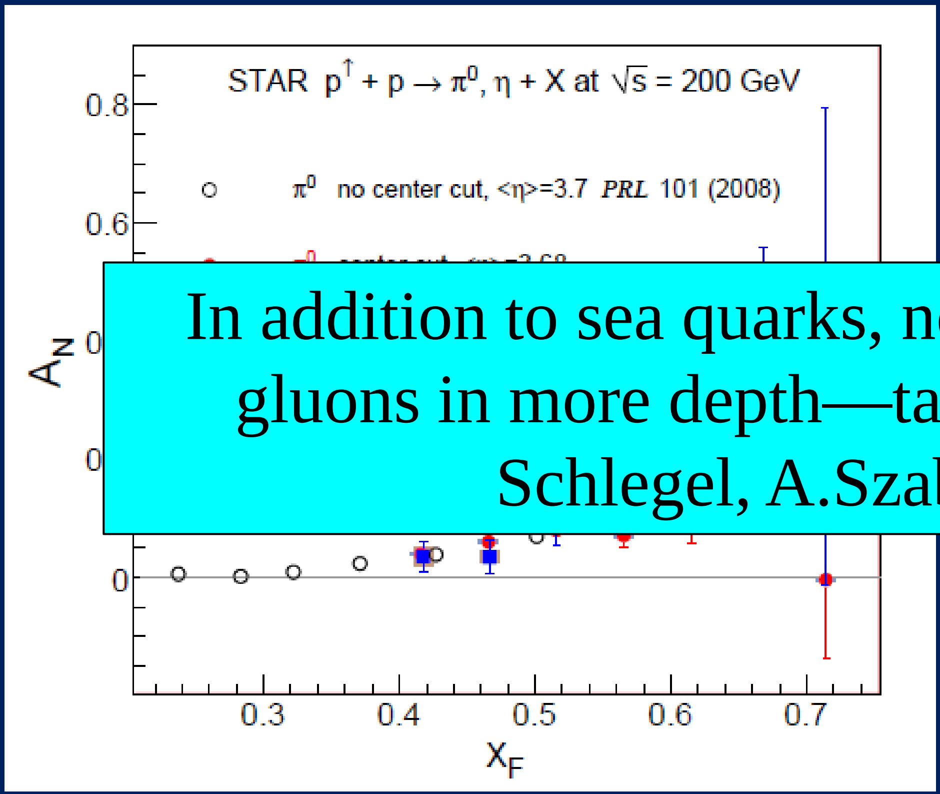
Pions suggest valence quark effect.
Kaons and (anti)protons don’t!

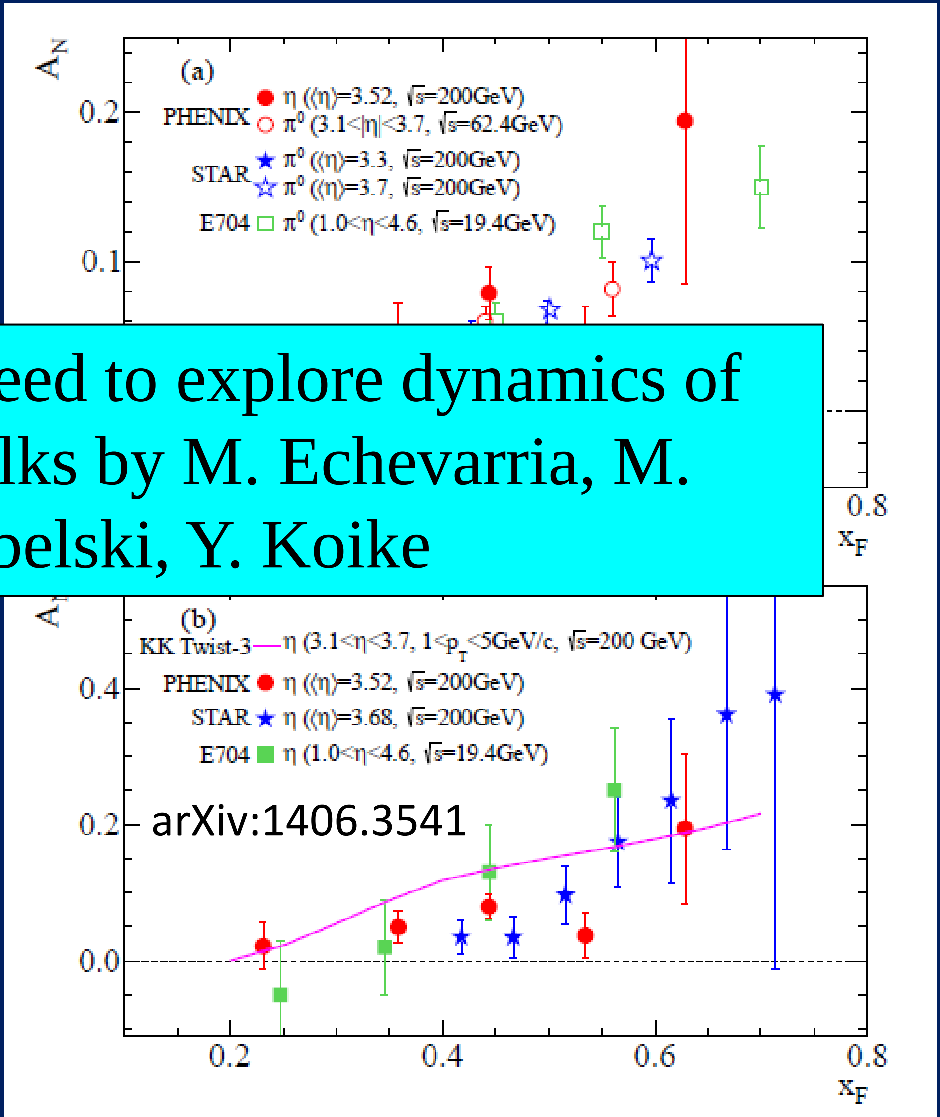




Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement

p+p η A_N larger than π^0?? Same?





In addition to sea quarks, need to explore dynamics of gluons in more depth—talks by M. Echevarria, M. Schlegel, A.Szabelski, Y. Koike

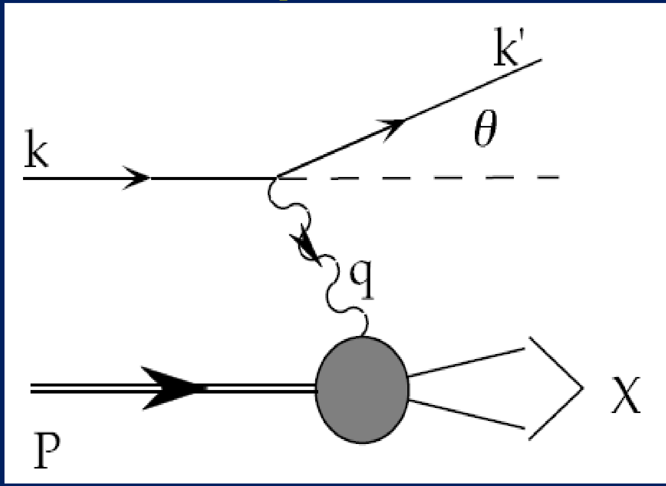
Related talks by L. Bland, D. Kleinjan, A. Vossen, A. Ogawa, Y. Koike, D. Pitonyak, C. Pisano

Hadronization

- Not as far along as nucleon structure—less of a focus in earlier years
- Recent advances via
  - TMD FFs
  - Collinear twist-3 functions to describe hadronization
  - Dihadron (interference) FF
  - Hadronization from nuclei

Related talks by M. Radici, A. Kotzinian, I. Garzia, M. Grosse Perdekamp, F. Giordano, M. Contalbrigo, Y. Guan, O. Eyser, A. Vossen, + other p+p talks and all SIDIS talks . . .

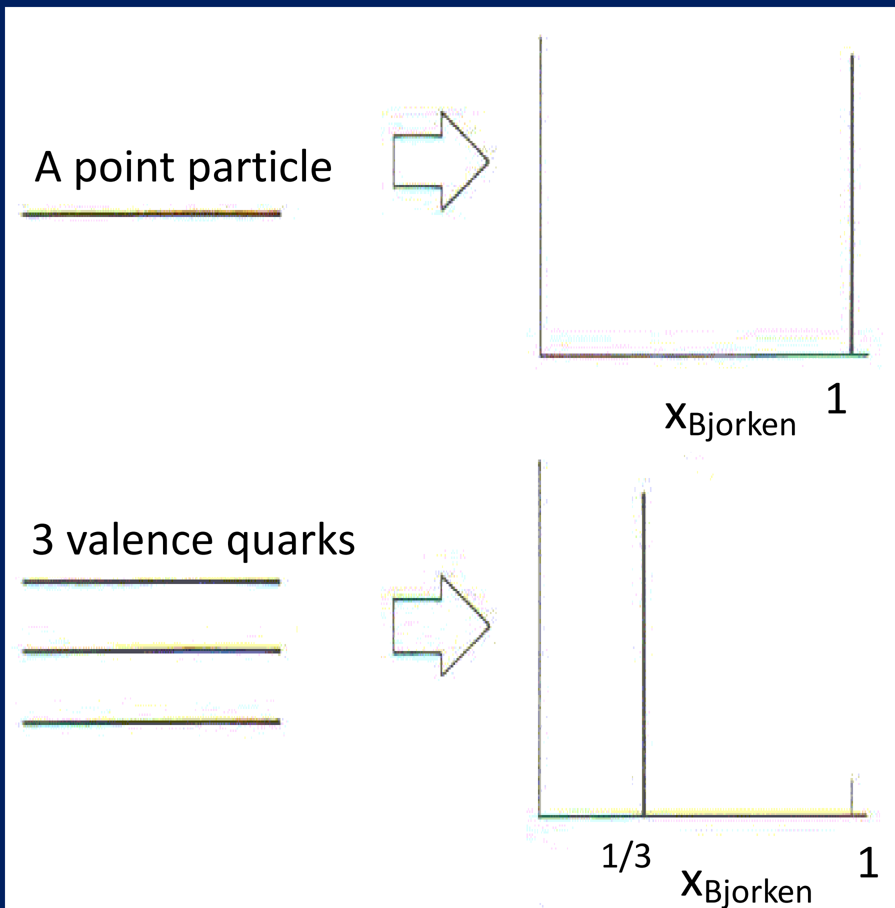
Deep-inelastic lepton-nucleon scattering: A tool of the trade

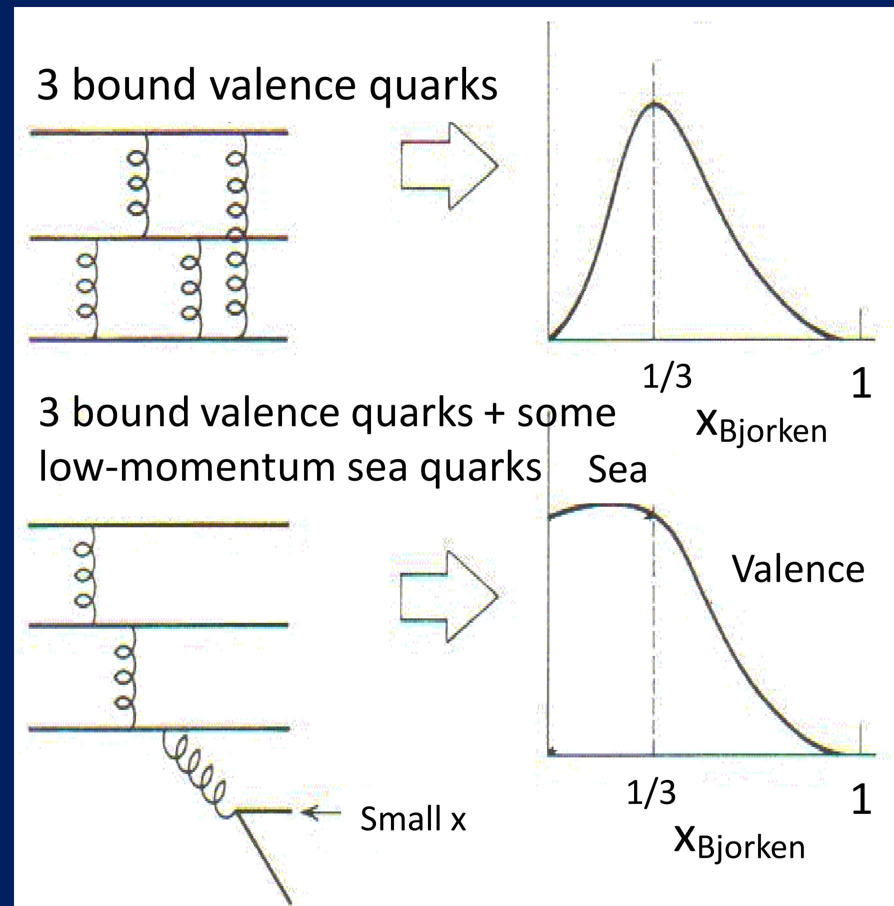


- Probe nucleon with an electron or muon beam
- Interacts electromagnetically with (charged) quarks and antiquarks
- "Clean" process theoretically—quantum electrodynamics well understood and easy to calculate!

Parton distribution functions inside a nucleon: The language we've developed (so far!)

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



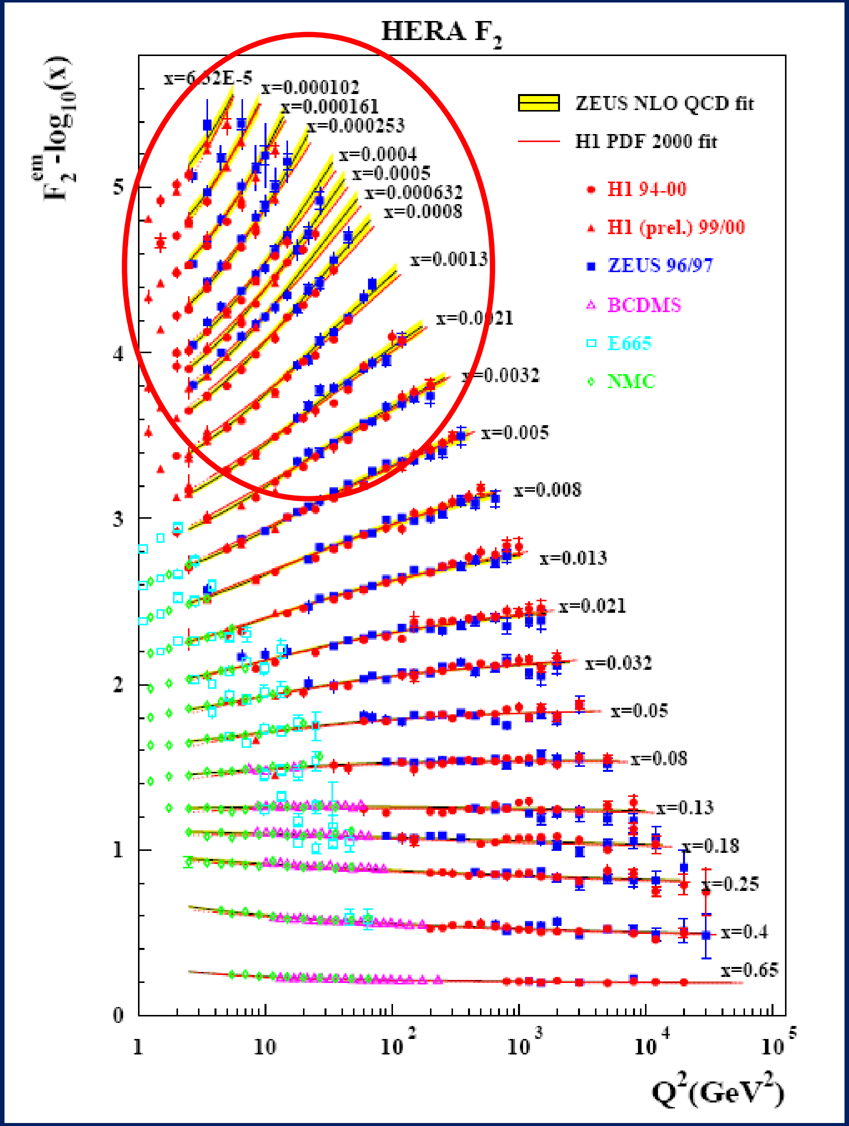


Halzen and Martin, "Quarks and Leptons", p. 201

Decades of deep-inelastic lepton-nucleon scattering data: What have we learned?

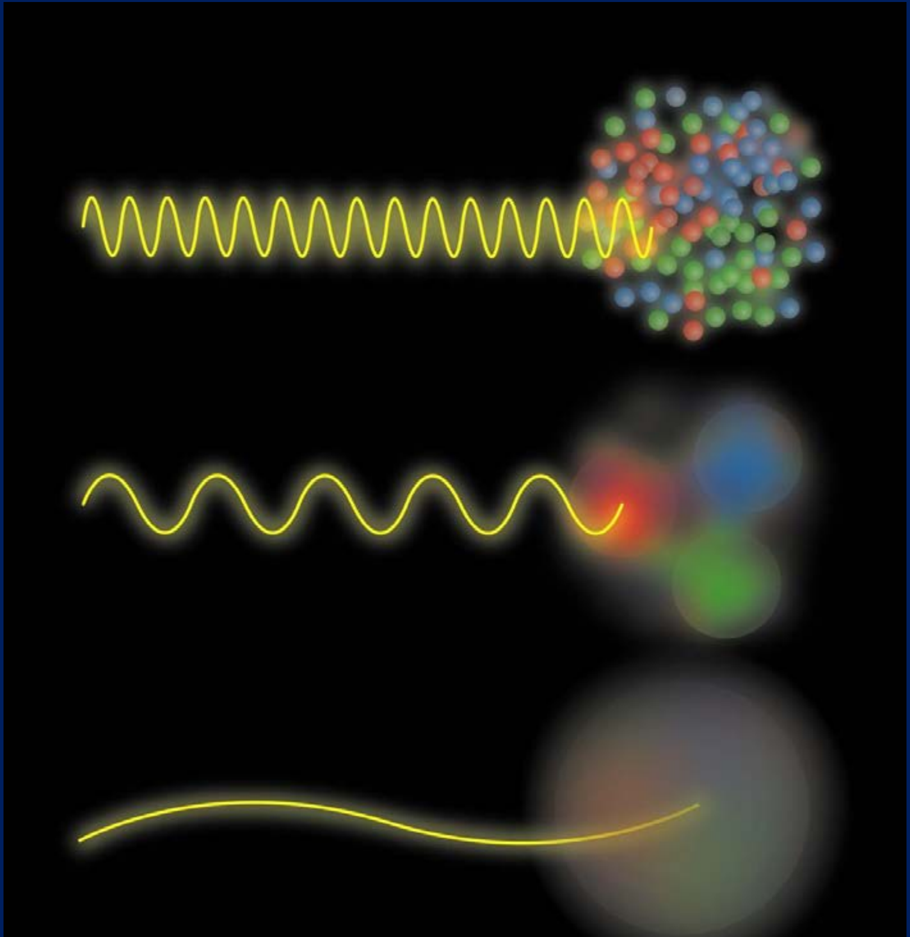
$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

- Wealth of data largely thanks to proton-electron collider, HERA, in Hamburg, which run 1992-2007
- Rich structure at low *x*
- Half proton’s linear momentum carried by gluons!



Partonic structure of the nucleon

- Probing the proton at different energy scales offers information on different aspects of partonic structure



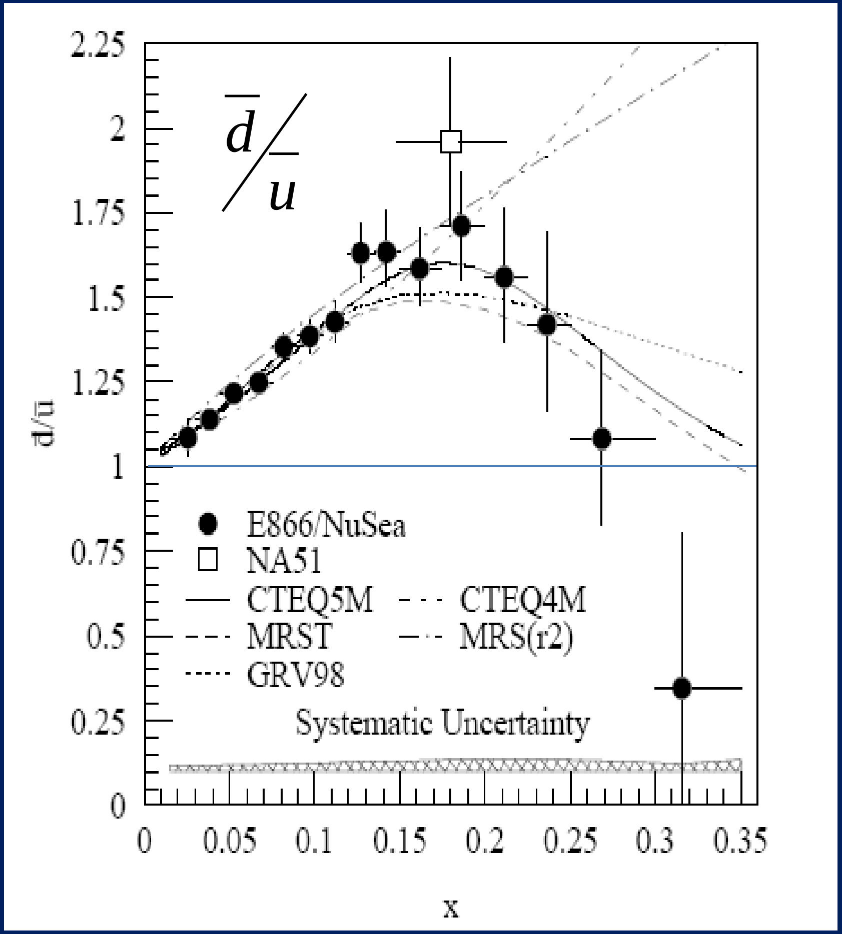
Graphic by Josh Rubin

And a (relatively) recent surprise from p+hydrogen, p+deuterium collisions

- Fermilab Experiment 866 used proton-hydrogen and proton-deuterium collisions to probe nucleon structure via the Drell-Yan process

$$q + \bar{q} \rightarrow \mu^+ + \mu^-$$

- Would expect anti-up/anti-down ratio of 1 if sea quarks are only generated dynamically by gluon splitting into quark-antiquark pairs
- Measured flavor asymmetry in the quark sea, with striking *x* behavior
- Indicates some kind of "primordial" sea quarks!

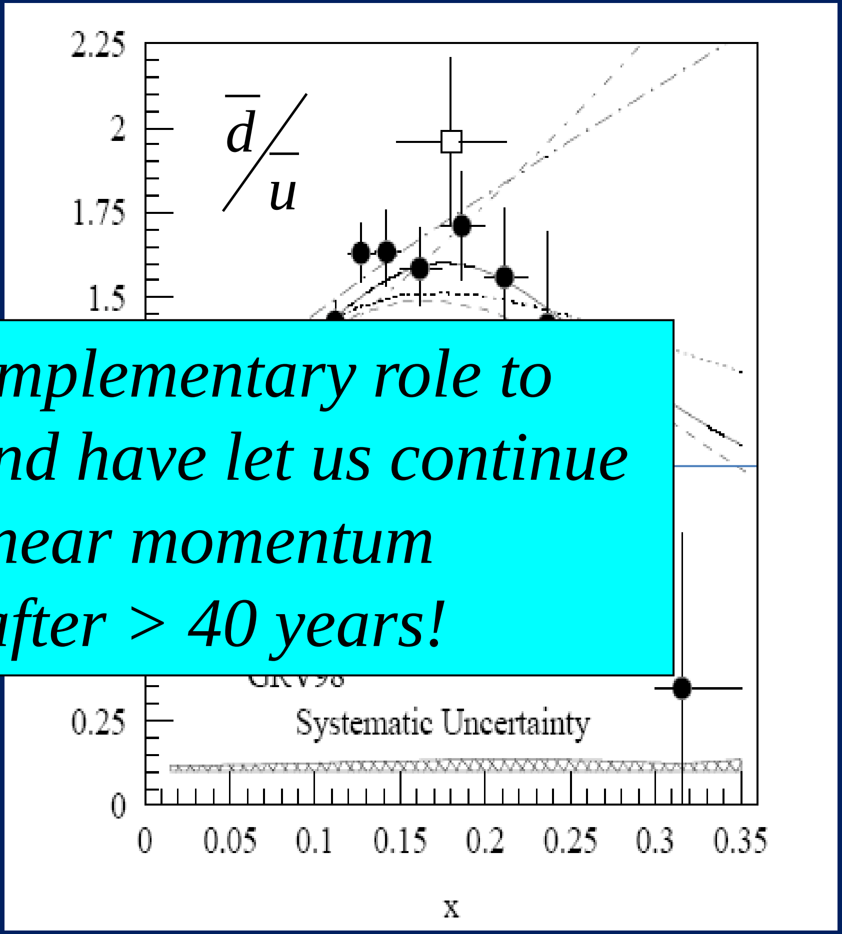


PRD64, 052002 (2001)

And a (relatively) recent surprise from p+hydrogen, p+deuterium collisions

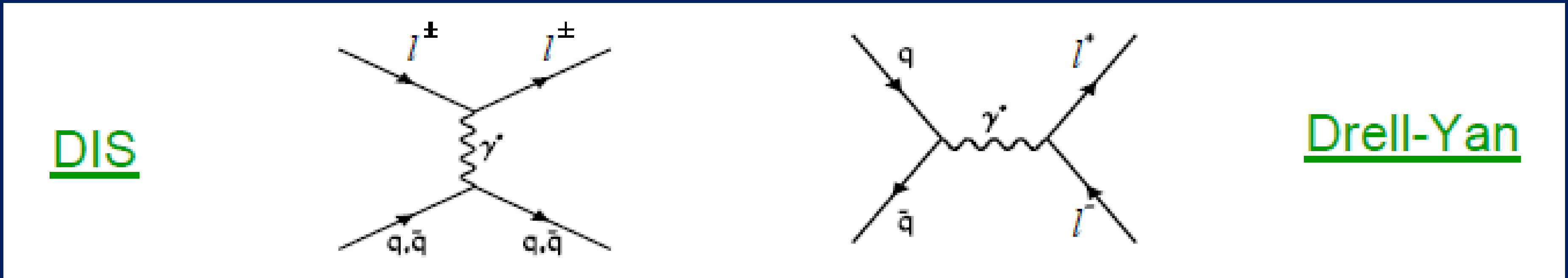
- Fermilab Experiment 866 used proton-hydrogen and proton-deuterium collisions to probe nucleon structure via the Drell-Yan process
- W
ra
ge
sp
pa
- Measured flavor asymmetry in the quark sea, with striking *x* behavior
- Indicates some kind of "primordial" sea quarks!

Hadronic collisions play a complementary role to electron-nucleon scattering and have let us continue to find surprises in the rich linear momentum structure of the proton, even after > 40 years!



PRD64, 052002 (2001)

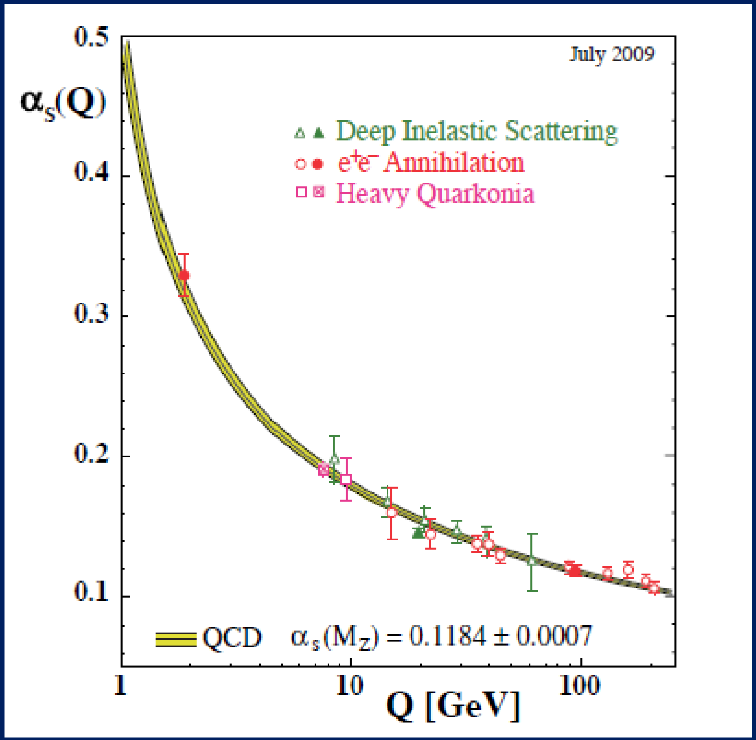
Complementarity of Drell-Yan and DIS



- Both deep-inelastic lepton-nucleon scattering (DIS) and quark-antiquark annihilation to leptons (Drell-Yan process) are tools to probe the quark and antiquark structure of hadrons

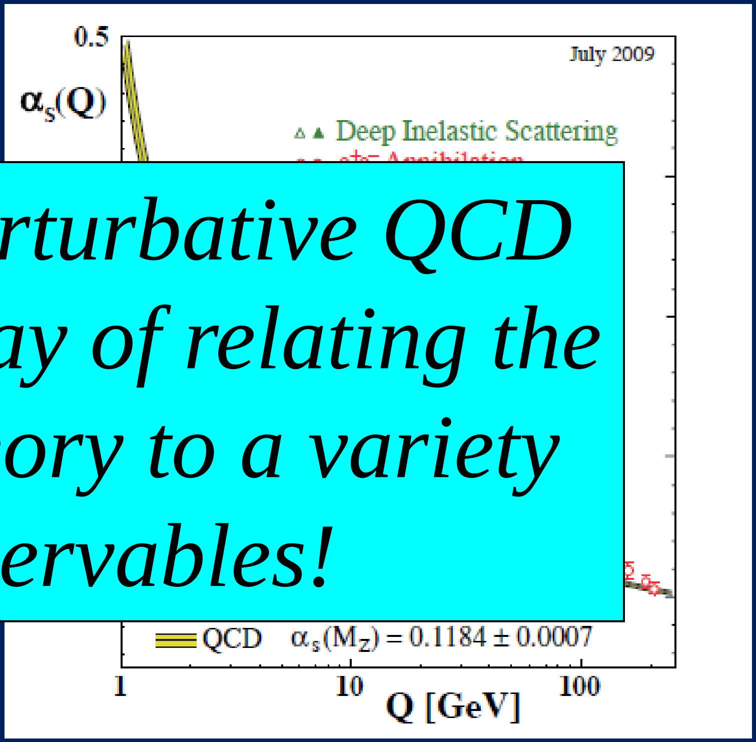
Perturbative QCD

- Take advantage of running of the strong coupling constant with energy (*asymptotic freedom*)—weak coupling at high energies (short distances)
- Perturbative expansion as in quantum electrodynamics (but many more diagrams due to gluon self-coupling!!)



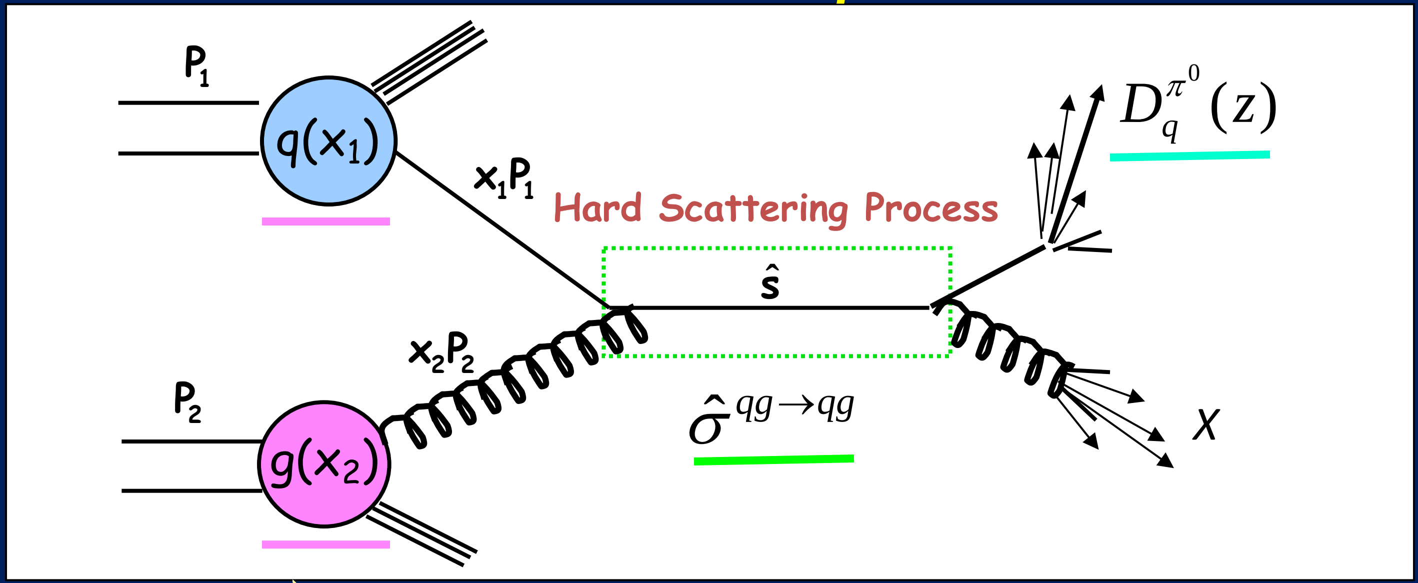
Perturbative QCD

- Take advantage of running of the strong coupling constant w
  fr
  hi
  di
- Pe
  quantum electrodynamics (but many more diagrams due to gluon self-coupling!!)



Most importantly: Perturbative QCD provides a rigorous way of relating the fundamental field theory to a variety of physical observables!

Parton distribution functions in perturbative QCD calculations of observables



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

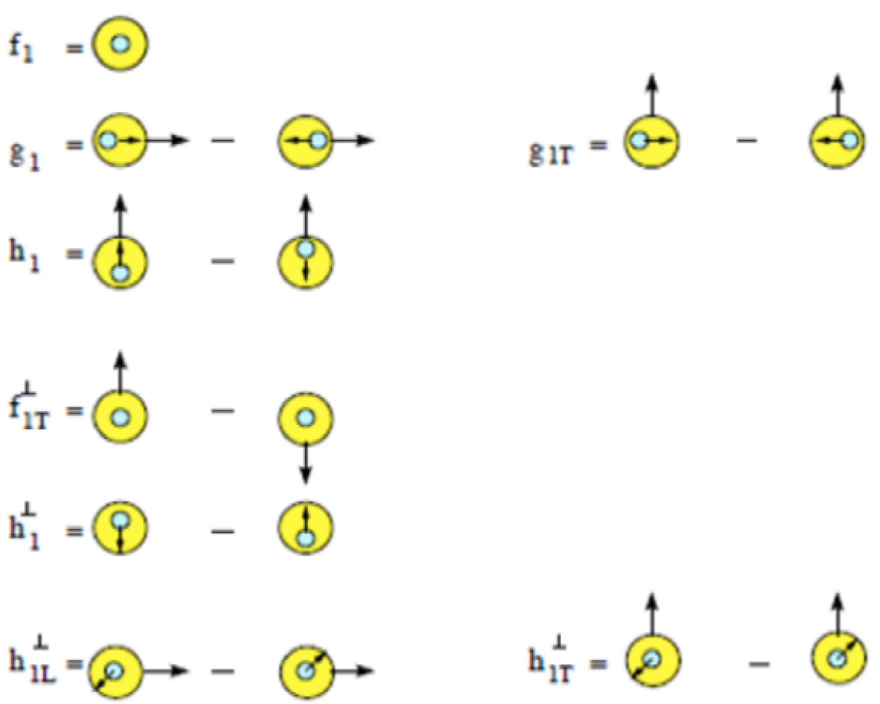
High-energy processes have predictable rates given:

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

Universal non-perturbative factors

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

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



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

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 <u>new</u> information on hadron structure

- <u>Leading</u> 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

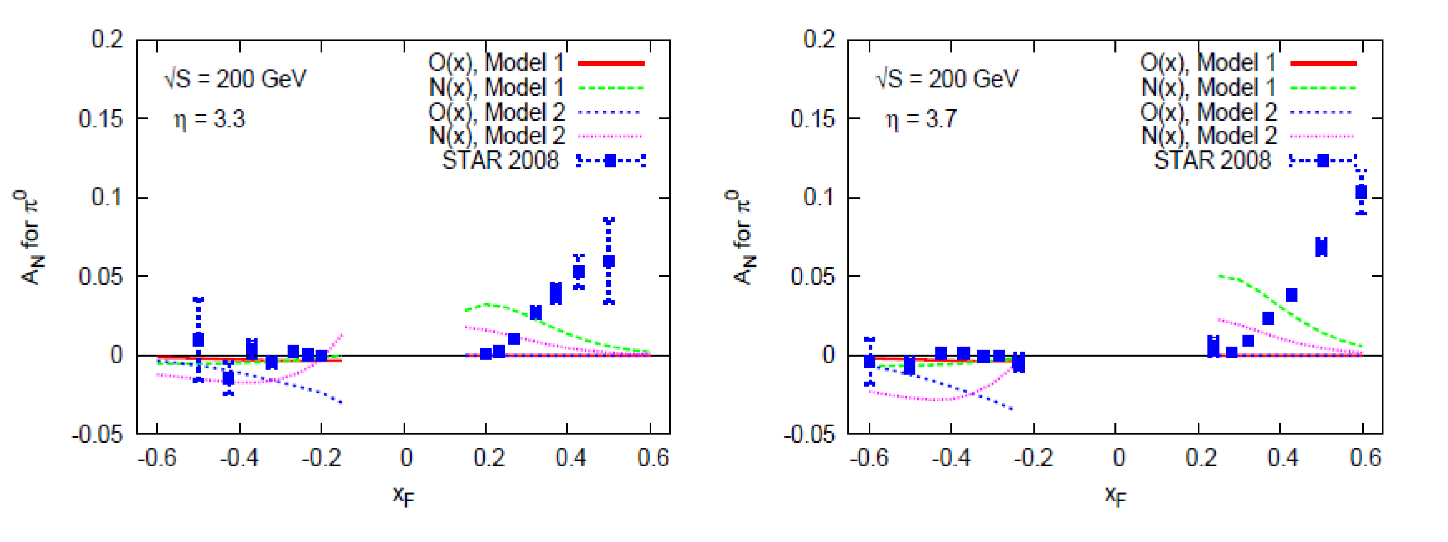
Multiparton correlations in hadronization

- 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

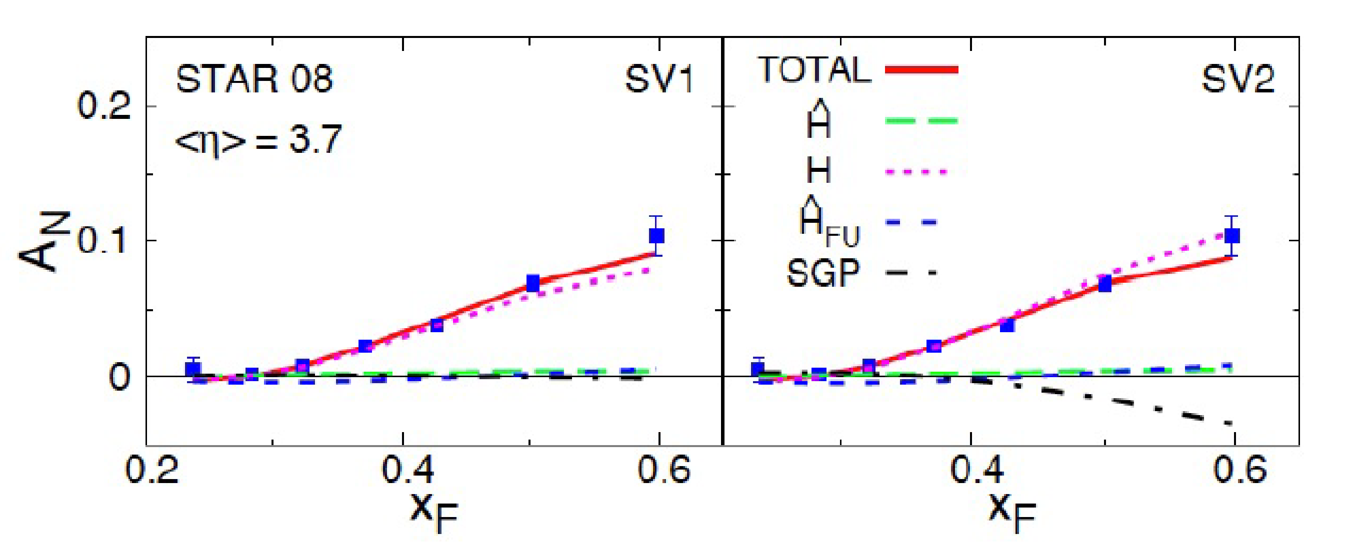
Transverse-momentum-dependent functions and twist-3 multiparton correlators

- Twist-3 (collinear) multiparton correlators believed to be related to k_T-moments of (twist-2)TMD pdfs and fragmentation functions
  - NPB667, 201 (2003); PRL97, 082002 (2006)
- To directly constrain TMD functions with experimental data, need *two* scales
  - Hard momentum
  - Observable sensitive to parton intrinsic momentum
  - Note: Original hadronic asymmetries only measured a single scale

Twist-3 multiparton correlations to interpret inclusive A_N data from RHIC



Making progress!

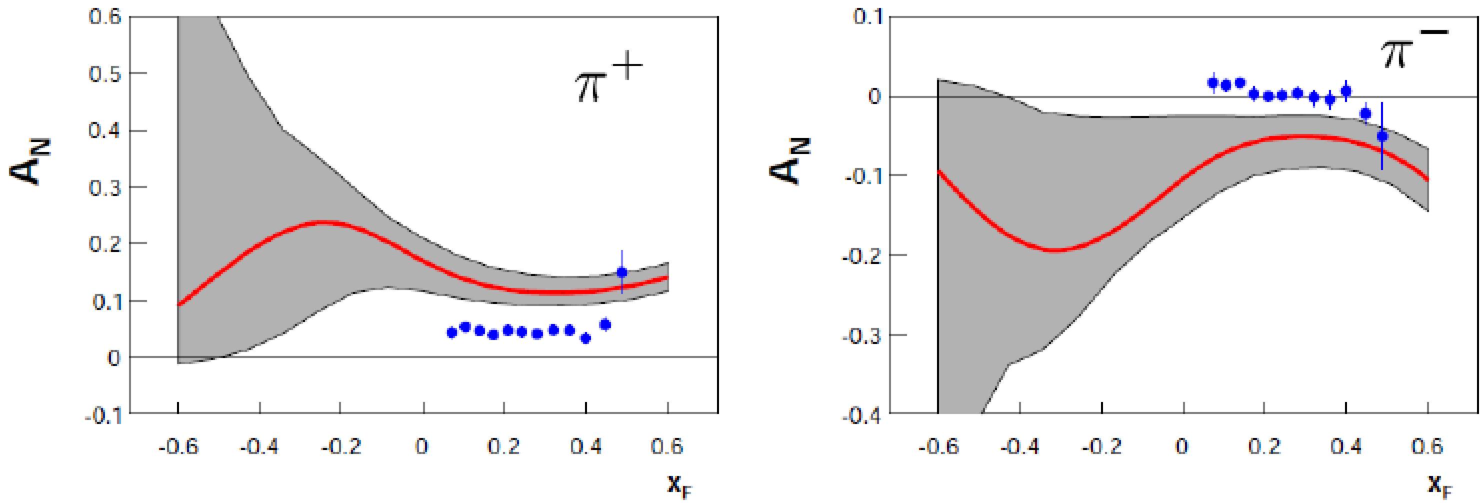


Inclusive hadron A_N in e+p

Phenomenology: twist-3

Gamberg, Kang, Metz, Pitonyak, AP (to appear)

$\hat{H}_{FU}^{h/q} = 0.$ allows for a comparison with TMD results directly



Collins contribution is not suppressed, Sivers dominates. $\pi^+\pi^-$ similar to TMD

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

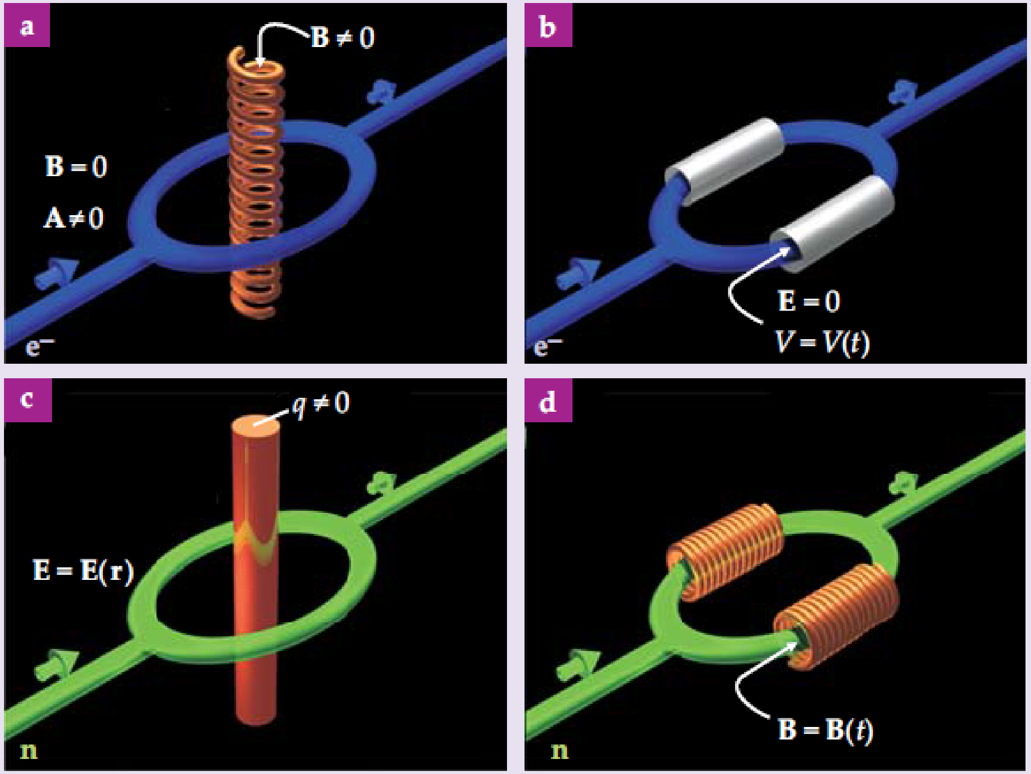
Box 1. Types and duals

Physics Today, September 2009

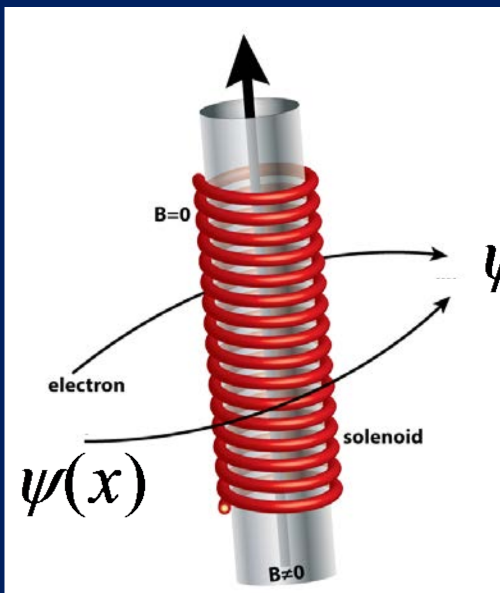
The original magnetic and electric Aharonov–Bohm effects (panels a and b) are type I effects in the sense that in an ideal experiment, the electron sees no **B** or **E** fields, though it does traverse different potentials **A** and *V*. In their respective dual effects—the Aharonov–Casher effect (panel 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]

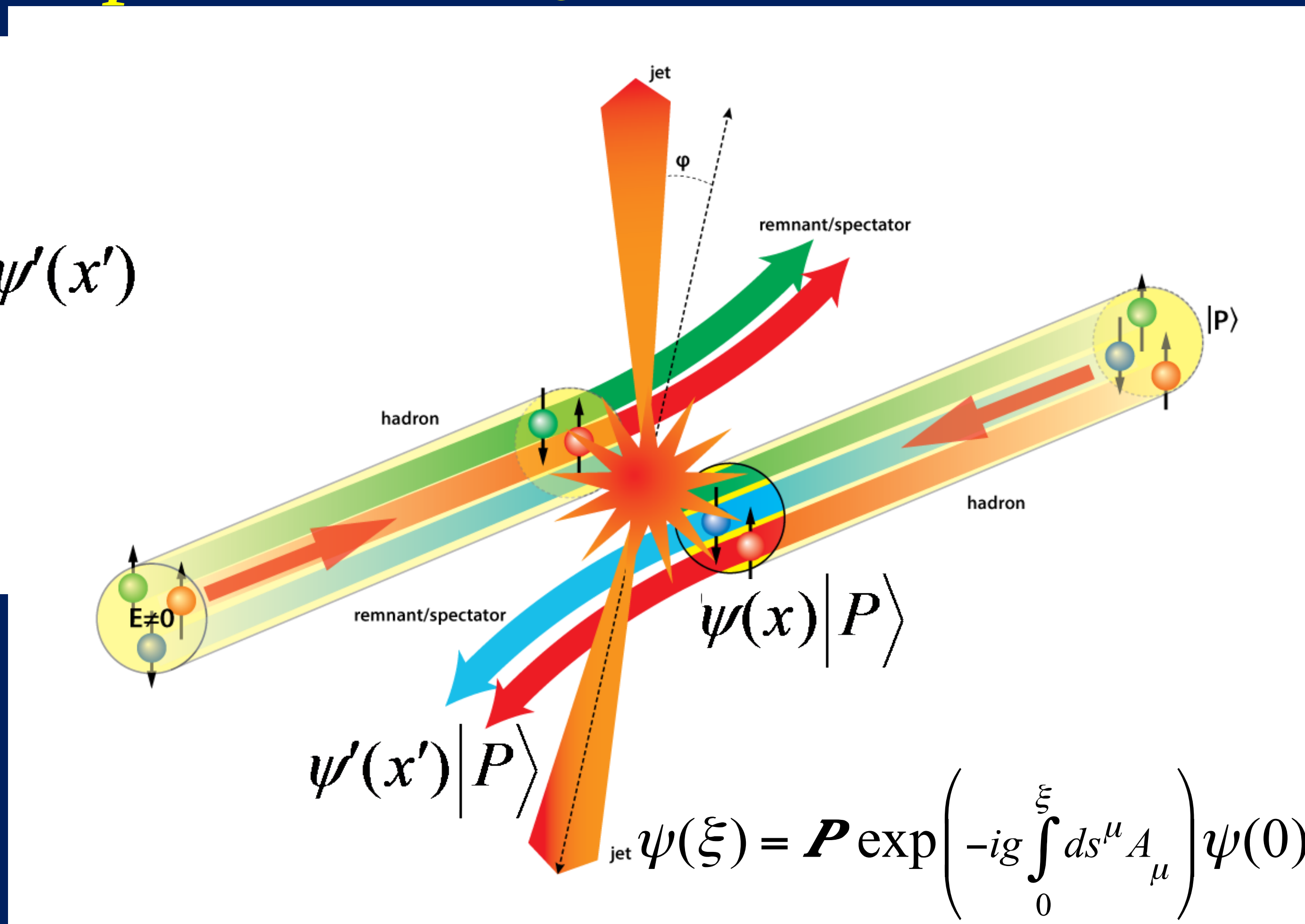
For type II effects, the wavepackets can plow straight through force fields, and forces are allowed in the interaction. But the AB interpretation requires that the emerging wavepackets not be deflected or delayed in any way. Quantum mechanical descriptions generally circumvent the notion of forces. But 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



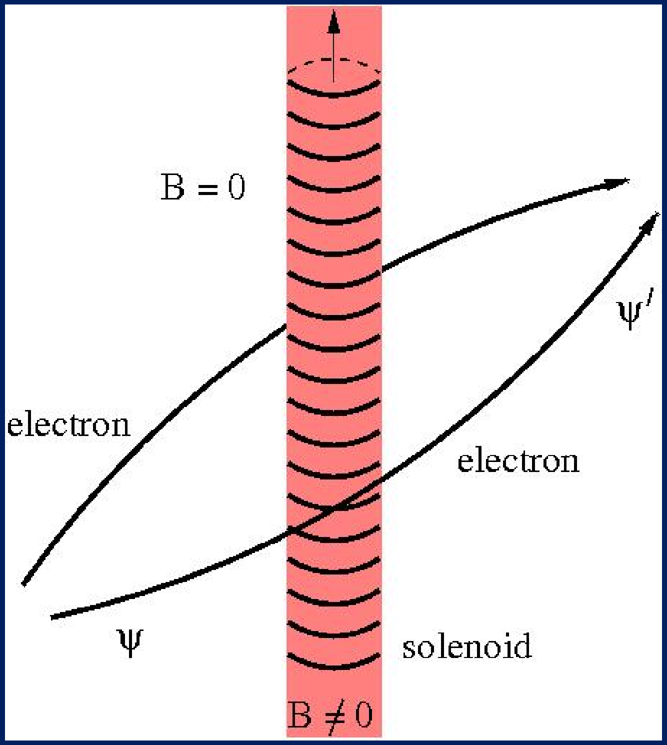
Slide from P. Mulders

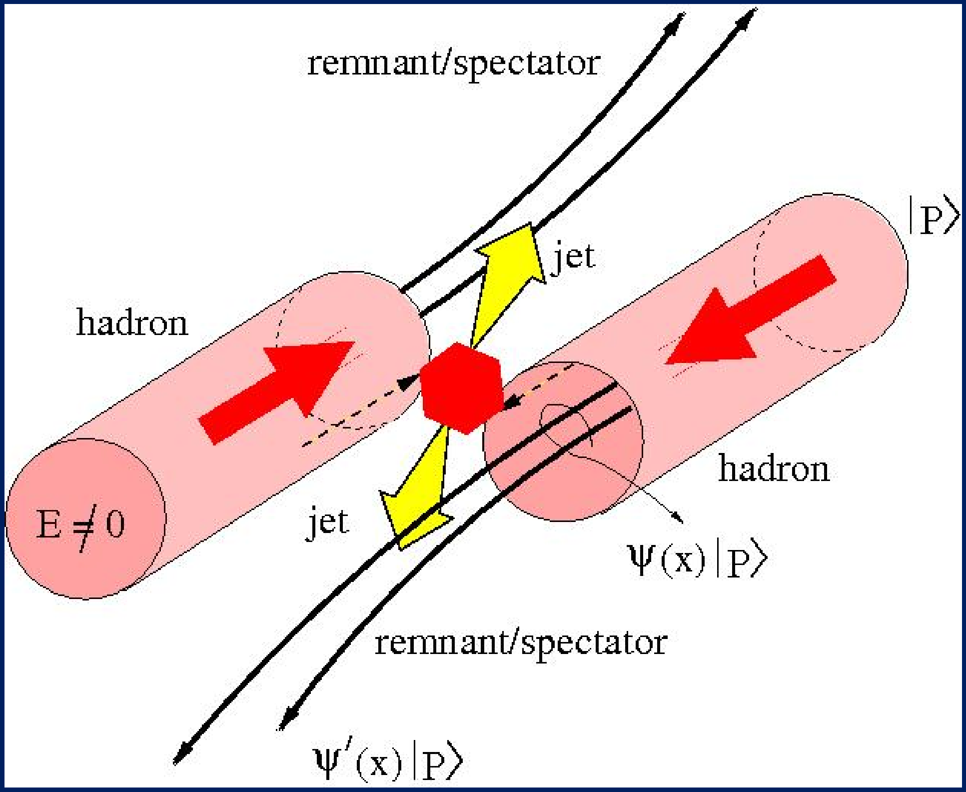


Figures by Kees Huyser

Featuring: phases in gauge theories

Slide from P. Mulders





$$\psi' = P\, e^{ie\int ds.A}\, \psi$$

$$\psi_i(x)\left|P\right\rangle = P\, e^{-ig\int_x^{x'} ds_\mu A^\mu}\, \psi_i(x')\left|P\right\rangle$$