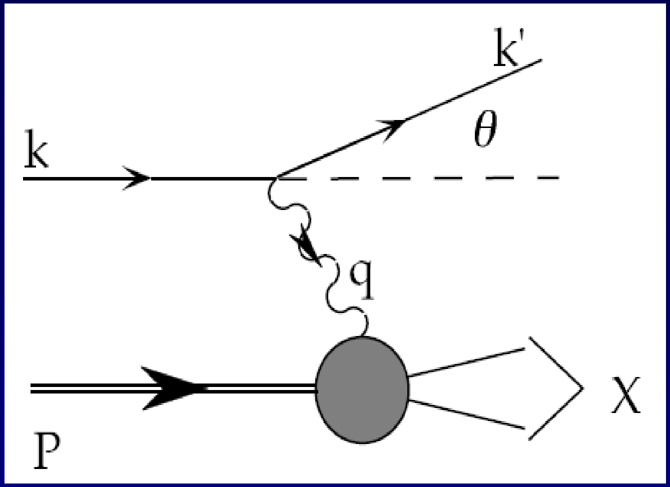
Investigating Proton Structure at the Relativistic Heavy Ion Collider

Christine Aidala
University of Michigan

Southern Methodist University
December 1, 2014

How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of quantum chromodynamics?

Deep-Inelastic Scattering: A Tool of the Trade

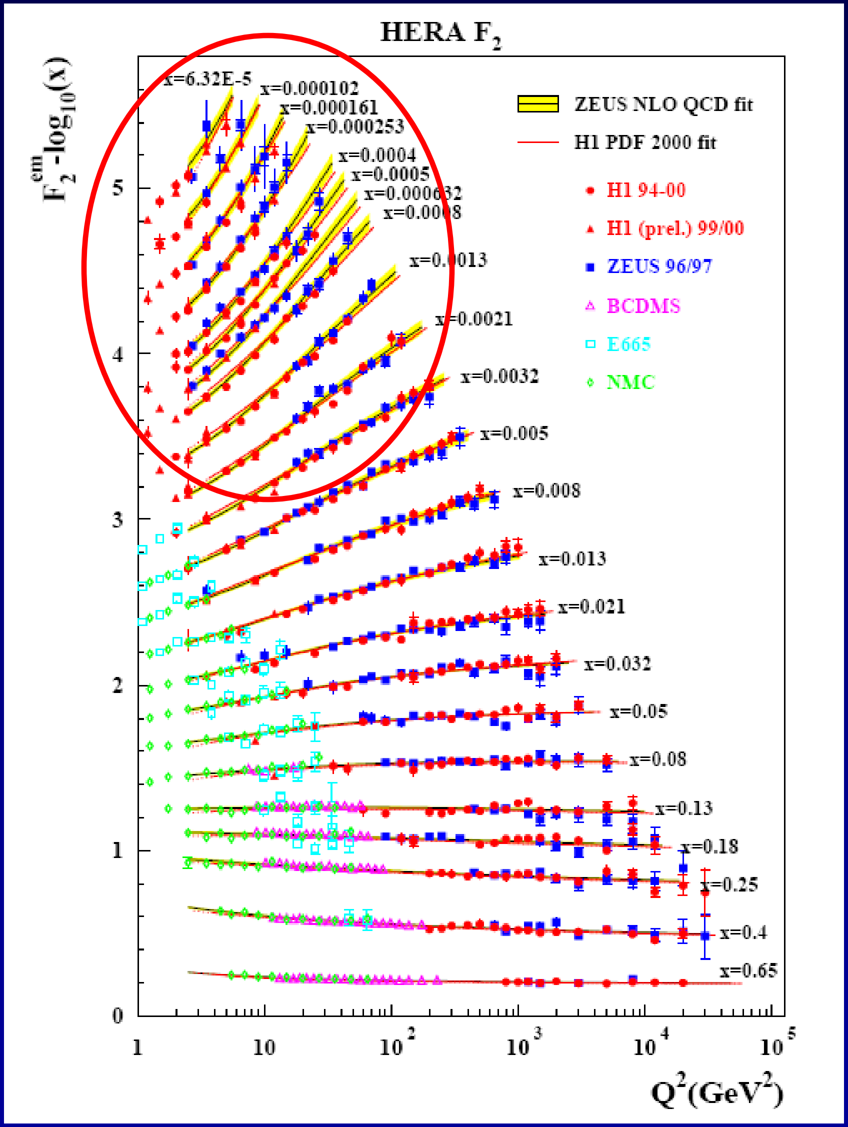


- Probe nucleon with an electron or muon beam
- Interacts electromagnetically with (charged) quarks and antiquarks
- "Clean" process theoretically—quantum electrodynamics well understood and easy to calculate
- Technique that originally discovered the parton structure of the nucleon in the 1960s

Decades of DIS data: What have we learned?

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

- Wealth of data largely from HERA e+p collider
- Rich structure at low *x*
- Half proton's linear momentum carried by gluons!



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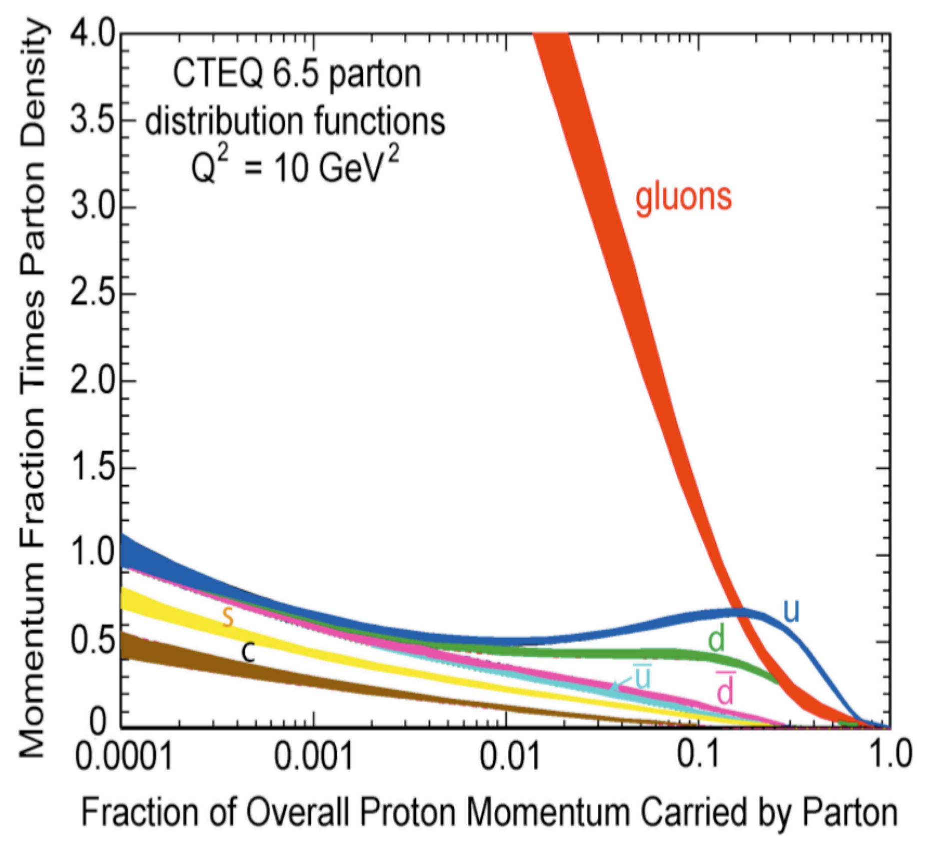
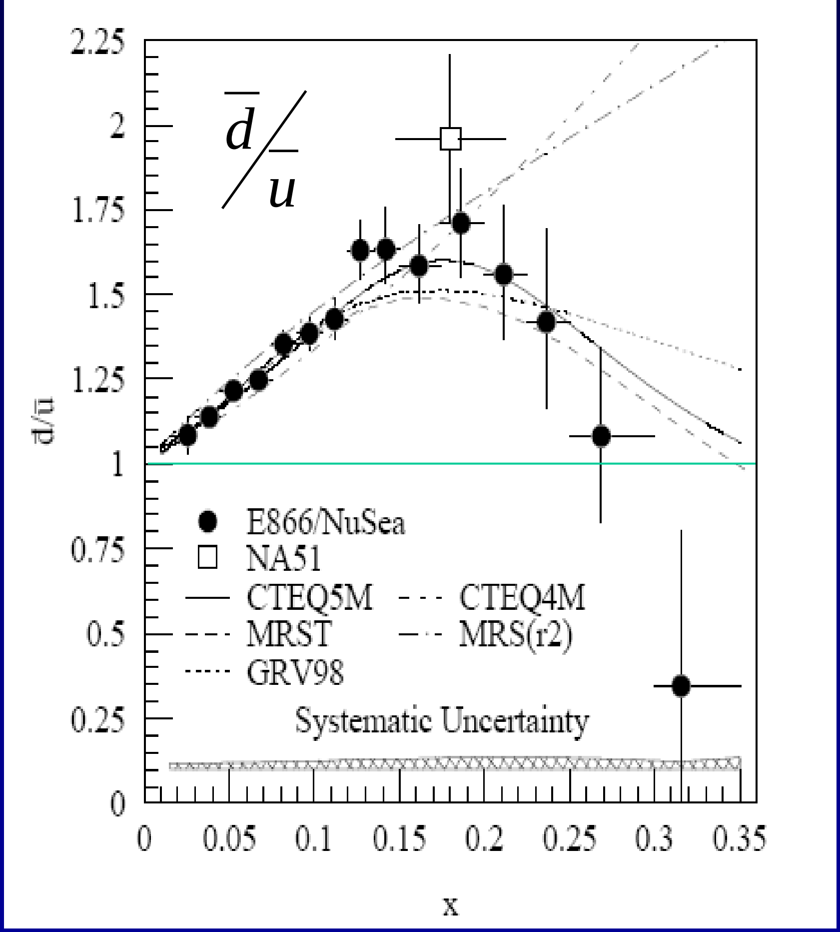


And a (relatively) recent surprise from p+p, p+d collisions

- 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-down/anti-up 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—still not well understood



PRD64, 052002 (2001)

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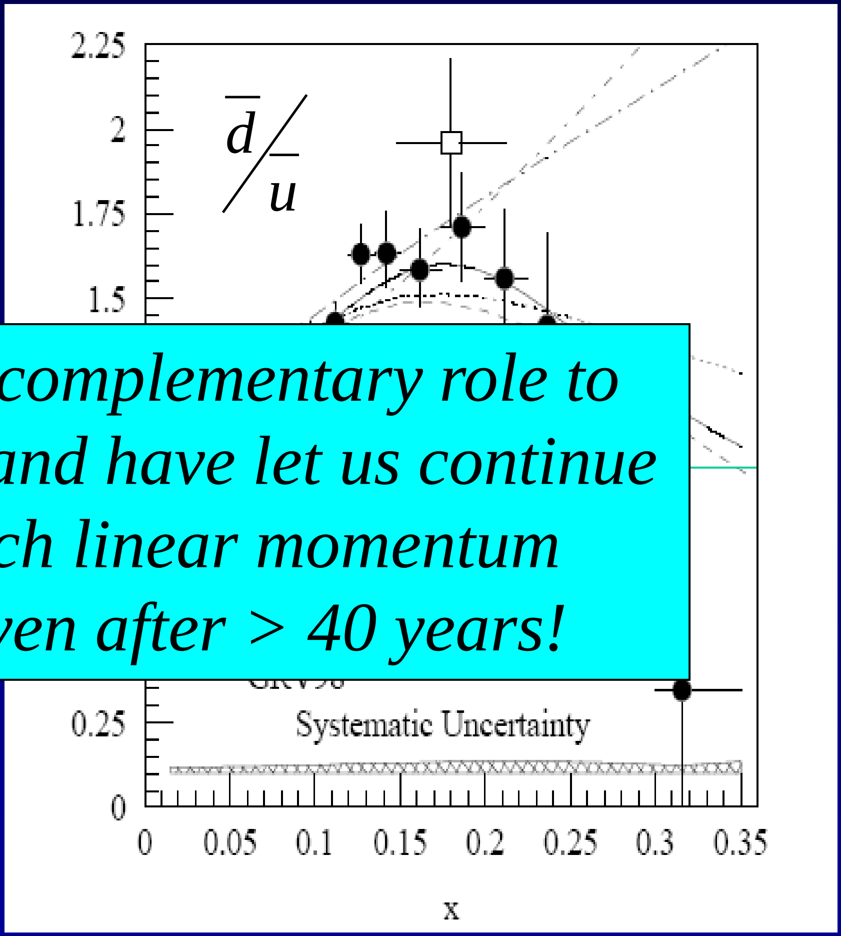
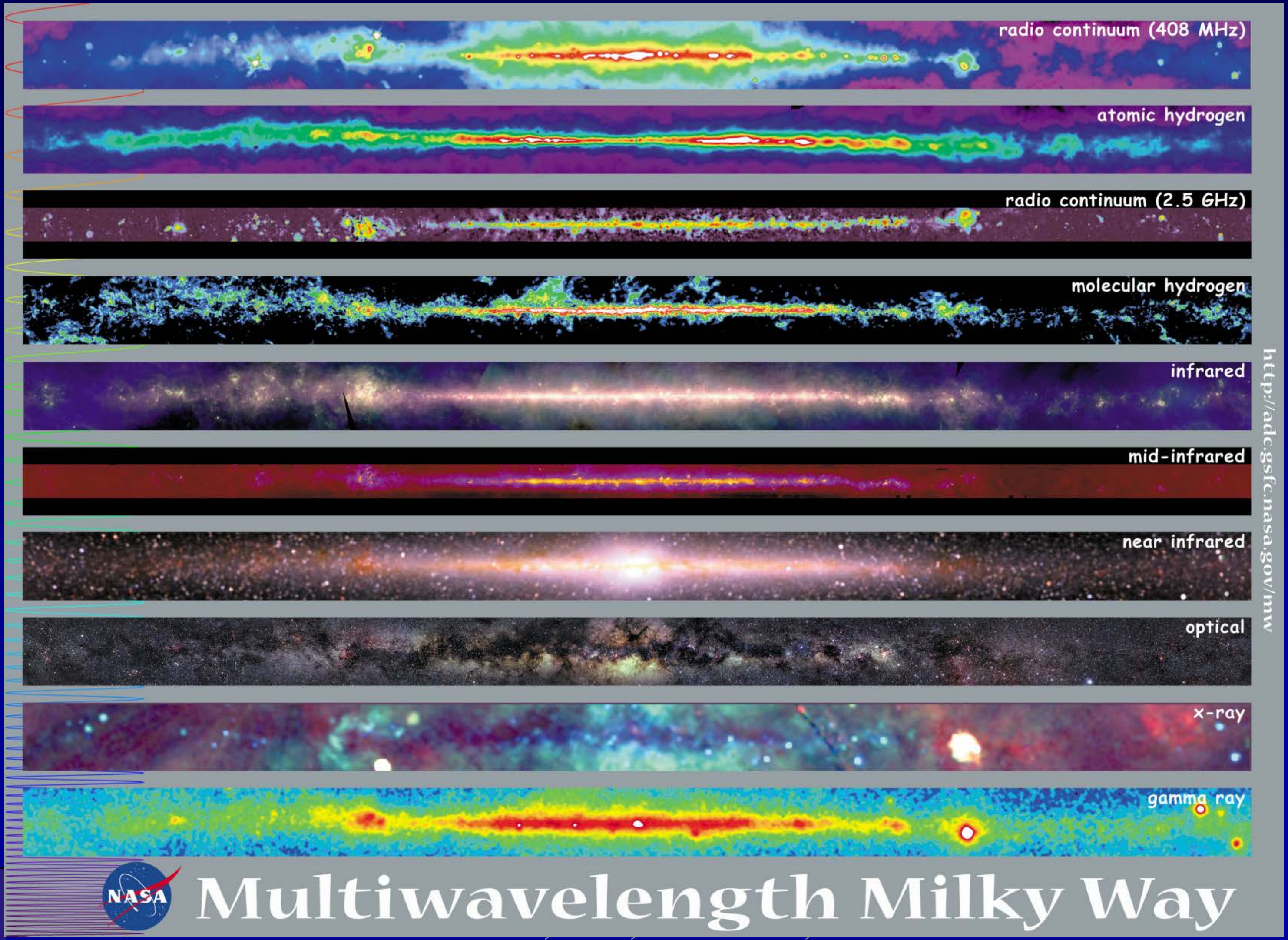
- Measured flavor asymmetry in the quark sea, with striking x behavior—still not well understood

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!

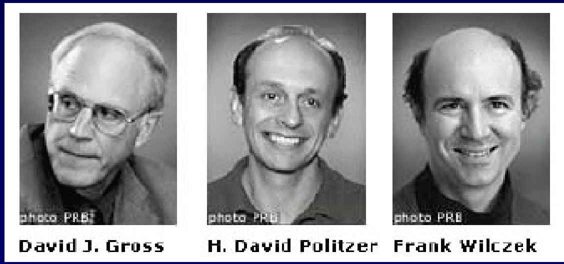


PRD64, 052002 (2001)

Observations with different probes allow us to learn different things!

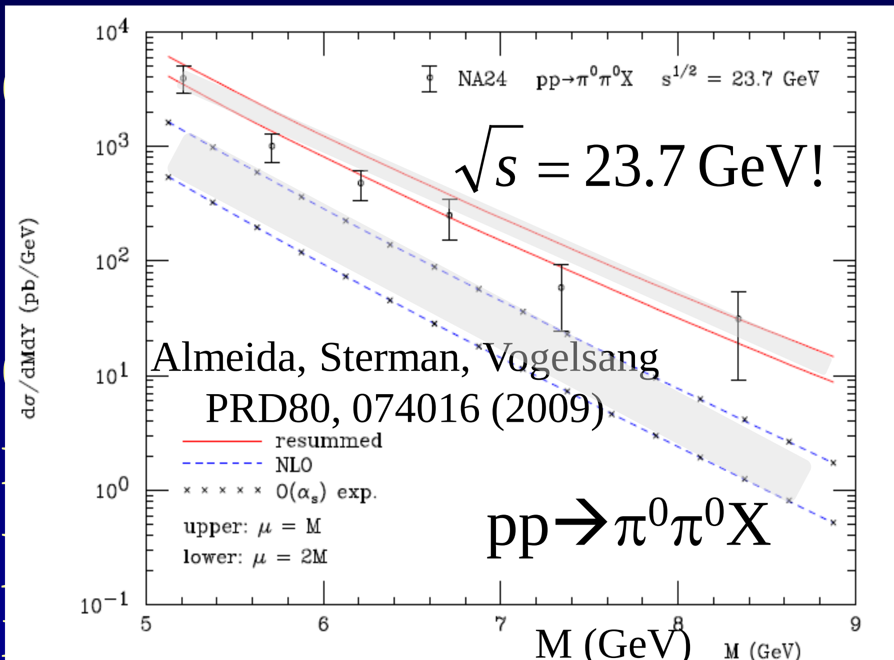


The nascent era of quantitative QCD!



- QCD: Discovery and development
  - 1973 → ~2004
- Since 1990s starting to consider detailed internal QCD *dynamics*, going beyond traditional parton model ways of looking at hadrons—and perform phenomenological calculations using these new ideas/tools!

The nascent era of quantitative QCD!

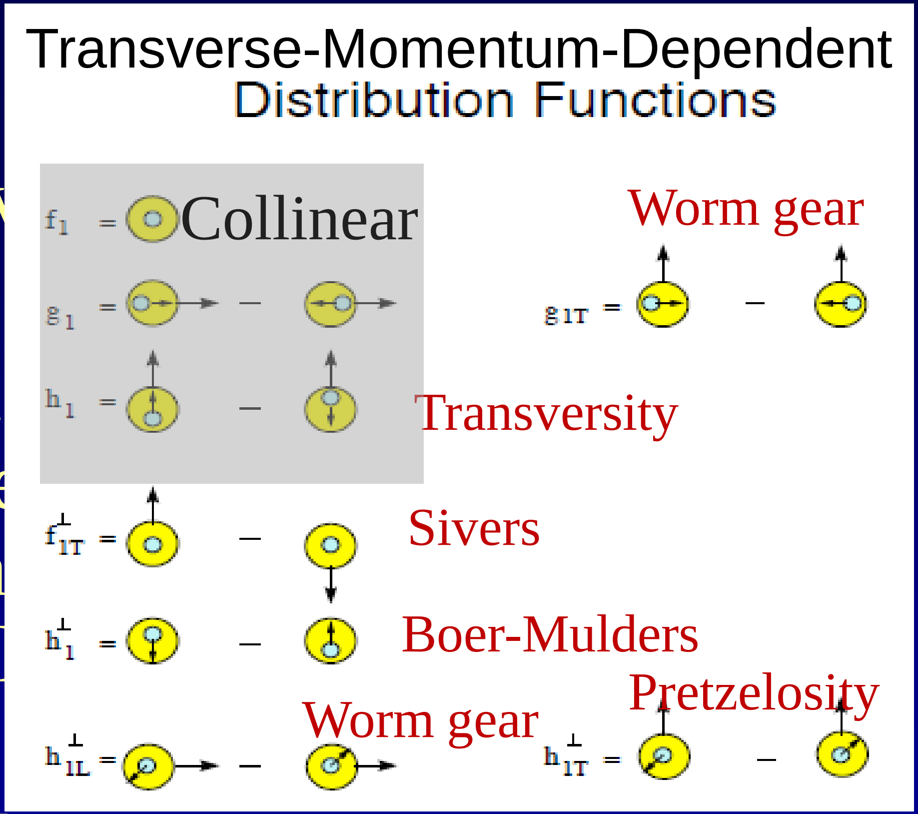


- … pment
- … ider detailed internal … nd traditional parton … drons—and perform … ons using these new
  - Various *resummation* techniques

The nascent era of quantitative QCD!

Mulders & Tangerman,
NPB 461, 197 (1996)

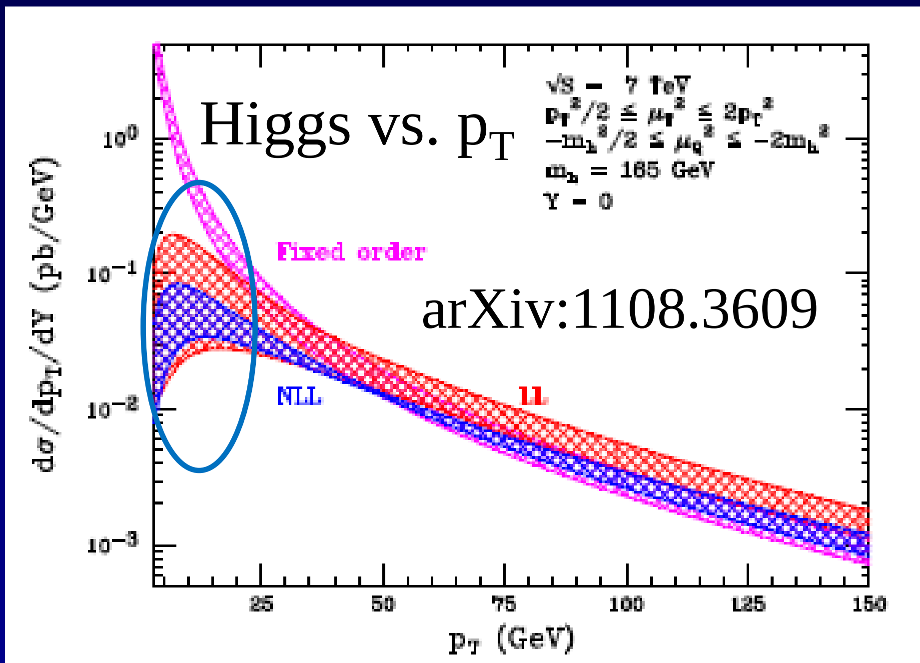
- Since 1990s starting to c… QCD *dynamics*, going be… model ways of looking a… phenomenological calcul… ideas/tools!
  - Various *resummation* techniques
  - *Non-collinearity* of partons with parent hadron

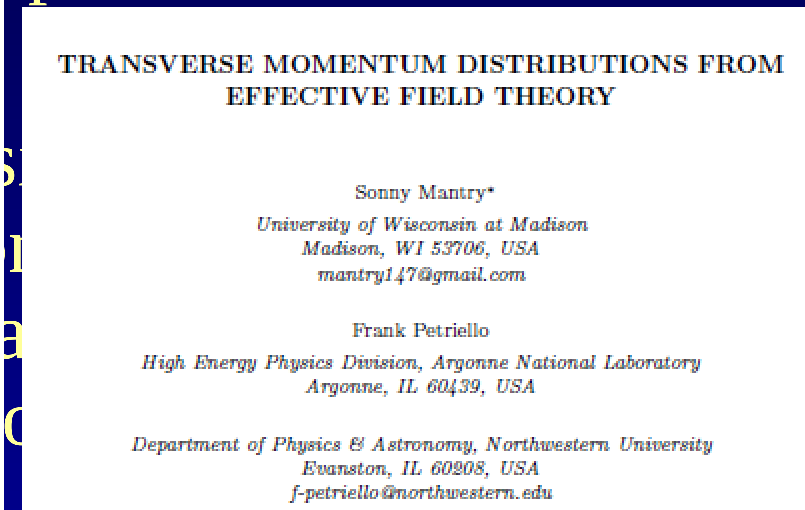


The nascent era of quantitative QCD!

- opment

- ideas/tools:





TRANSVERSE MOMENTUM DISTRIBUTIONS FROM EFFECTIVE FIELD THEORY

Sonny Mantry*

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

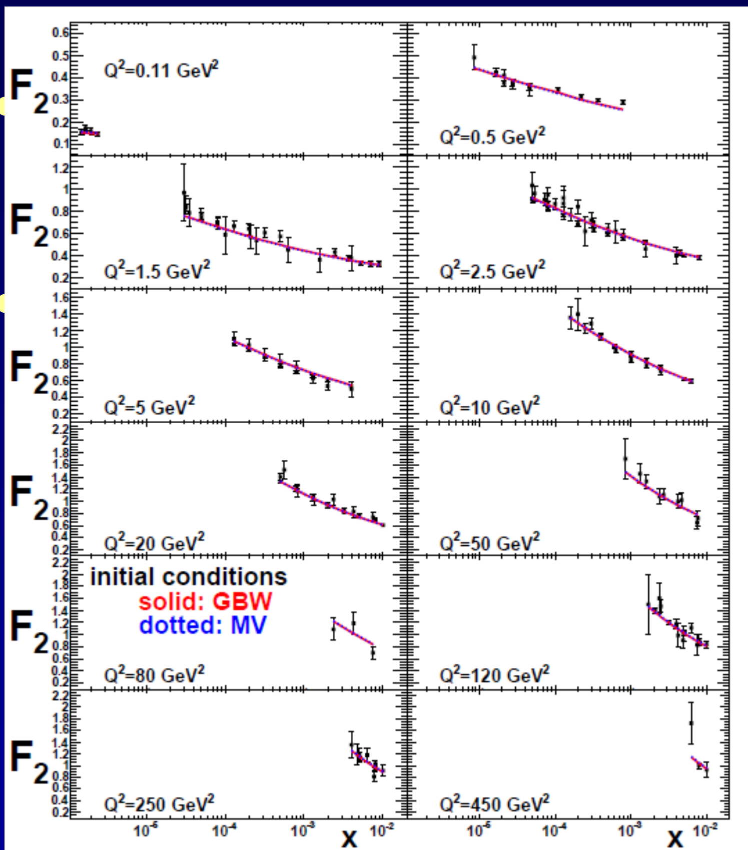
Frank Petriello

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

  - Various *resummation* techniques
  - *Non-collinearity* of partons with parent hadron
  - Various *effective field theories*, e.g. Soft-Collinear Eff. Th.

The nascent era of quantitative QCD!



- … development

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

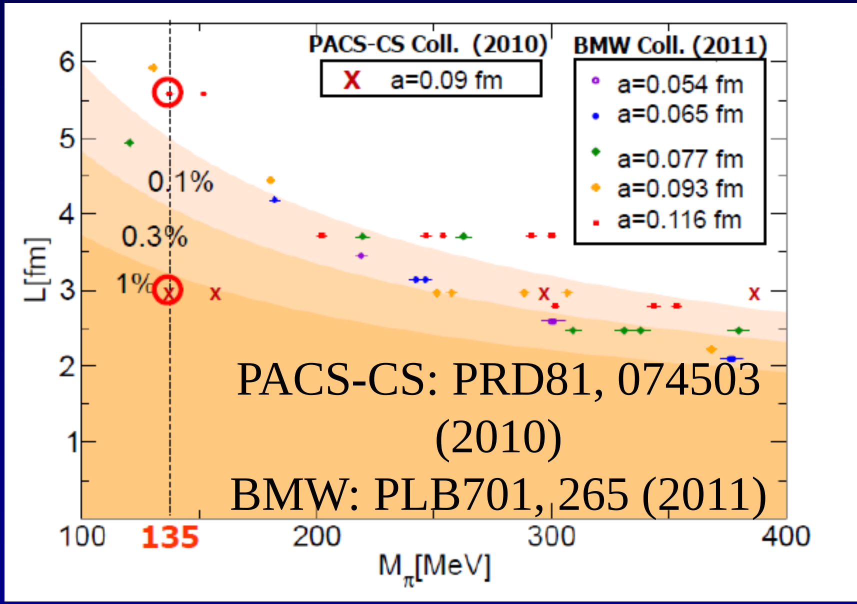
PRD80, 034031 (2009)

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

- … lculations using these new … techniques
  - … artons with parent hadron
  - Various *effective field theories*, e.g. Soft-Collinear Eff. Th.
  - *Non-linear* evolution at small momentum fractions

Additional recent theoretical progress in QCD

- Progress in non-perturbative methods:
  - Lattice QCD starting to perform calculations at physical pion mass!
  - AdS/CFT "gauge-string duality" an exciting recent development as first fundamentally new handle to try to tackle QCD in decades!



PACS-CS: PRD81, 074503 (2010)
BMW: PLB701, 265 (2011)

T. Hatsuda, PANIC 2011

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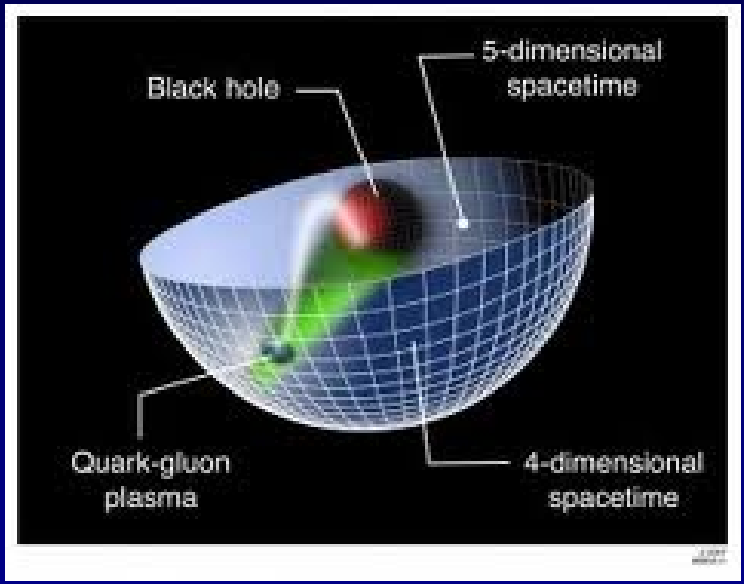

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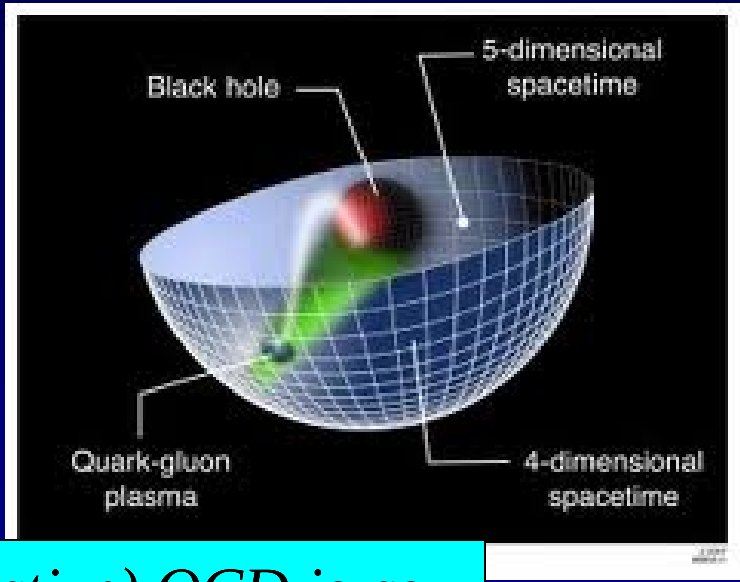
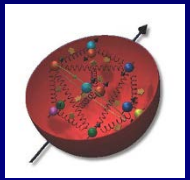
  - AdS/CFT “gauge-string

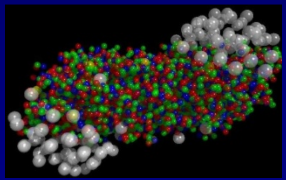


“Modern-day ‘testing’ of (perturbative) QCD is as much about pushing the boundaries of its applicability as about the verification that QCD is the correct theory of hadronic physics.”
– G. Salam, hep-ph/0207147 (DIS2002 proceedings)

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

- A great place to be to study QCD!
- A collider-based program, but not designed to be at the energy (or intensity) frontier. More closely analogous to many areas of condensed matter research—create a system and study its properties





- What systems are we studying?
  - "Simple" QCD bound states—the proton is the simplest stable bound state in QCD (and conveniently, nature has already created it for us!)
  - Collections of QCD bound states (nuclei, also available out of the box!)
  - QCD deconfined! (quark-gluon plasma, some assembly required!)

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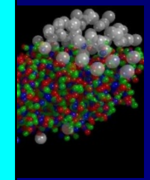

Understand more complex QCD systems within the context of simpler ones

→RHIC was designed from the start as a single facility capable of nucleus-nucleus, proton-nucleus, and proton-proton collisions

Mapping out the proton

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

- *Position*
- *Momentum*
- *Spin*

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

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

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

Mapping out the proton

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

- *Position*
- *Momentum*
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- *Color*

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

Mapping out 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.

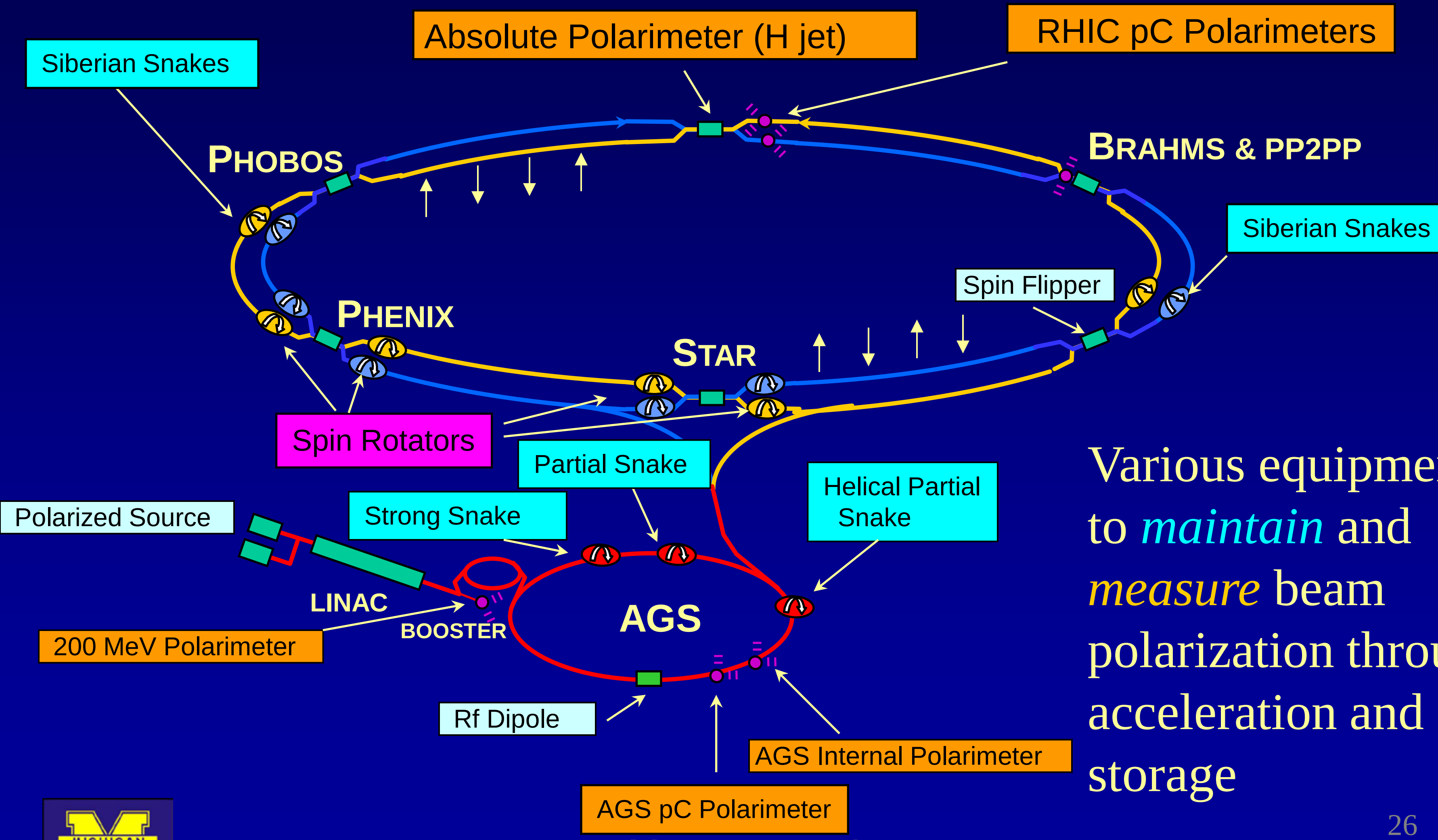
Mapping out the proton

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

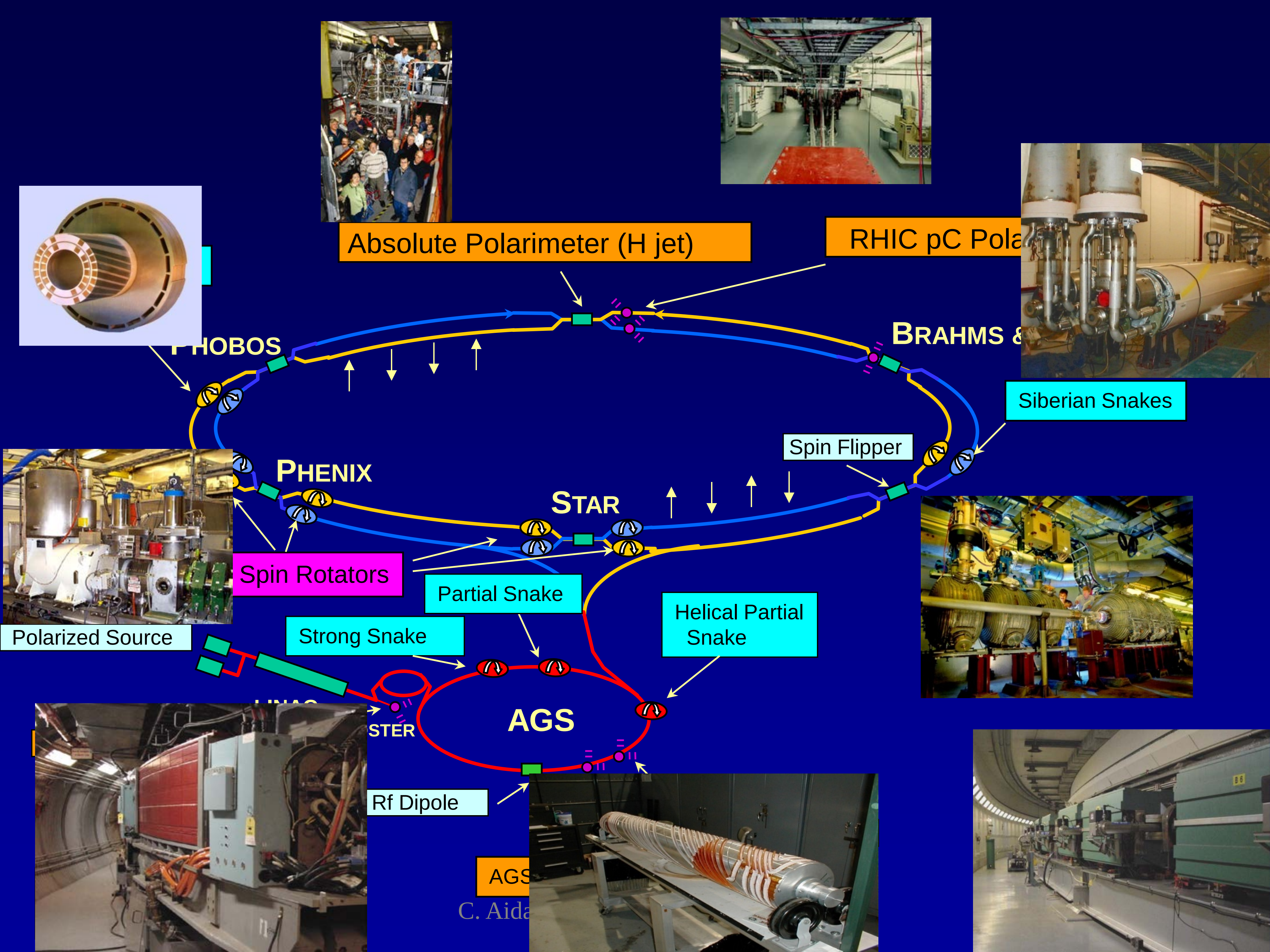
- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

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

RHIC as a polarized p+p collider

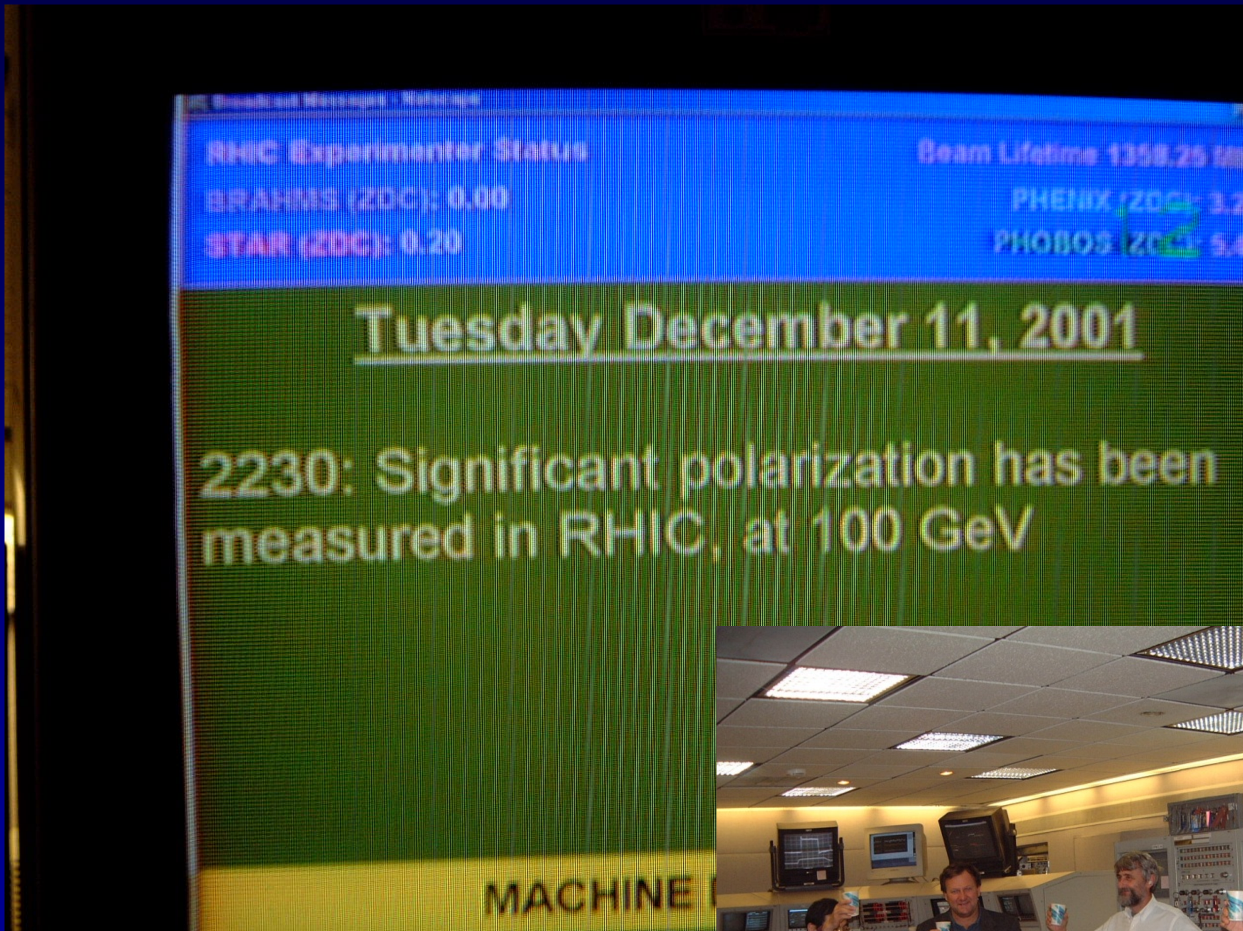


Various equipment to *maintain* and *measure* beam polarization through acceleration and storage



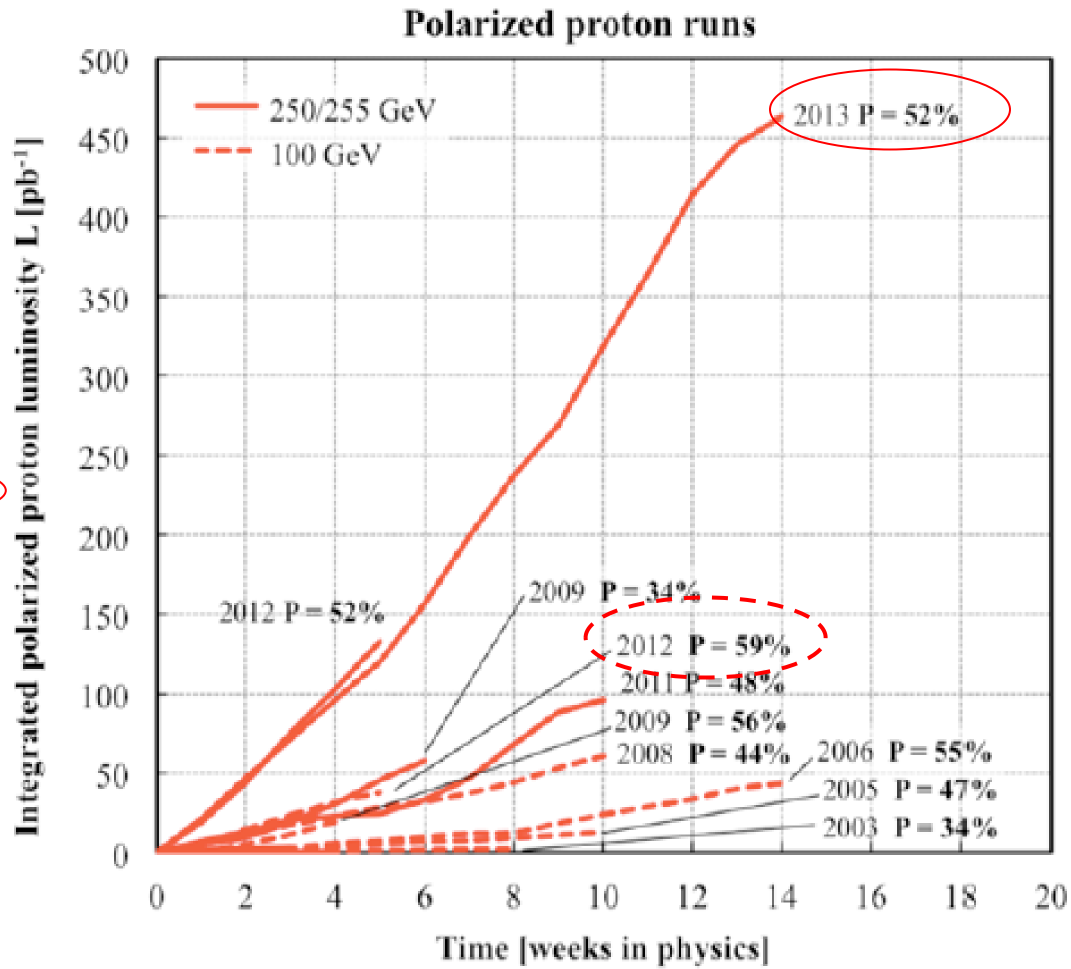
Absolute Polarimeter (H jet)
RHIC pC Pola
HOBOS
BRAHMS &
Siberian Snakes
Spin Flipper
PHENIX
STAR
Spin Rotators
Partial Snake
Helical Partial Snake
Polarized Source
Strong Snake
AGS
STER
Rf Dipole
AGS
C. Aida

December 2001: News to celebrate

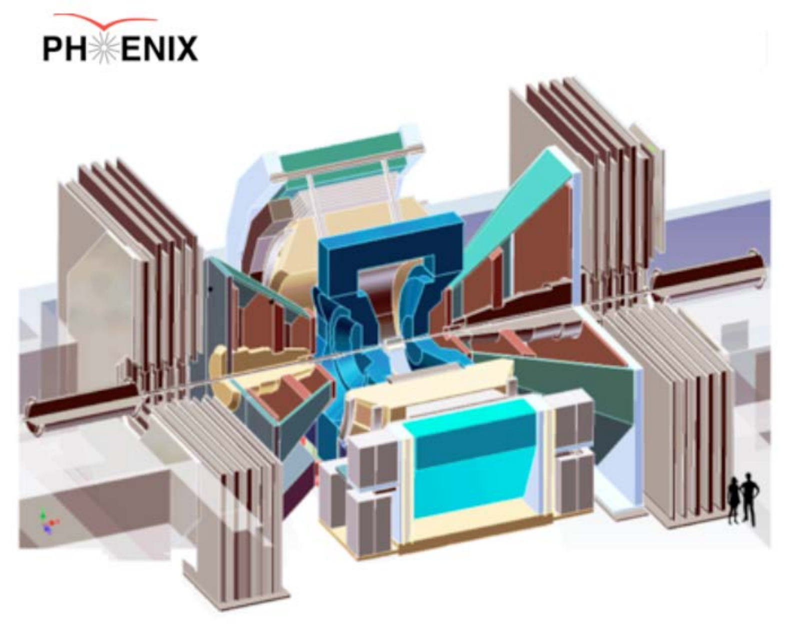


RHIC performance for polarized protons

Longitudinal data	STAR
$\sqrt{s}$ = **200 GeV**	
2005	3 pb^{-1}
2006	7 pb^{-1}
2009 (2015)	35 pb^{-1} (50 pb^{-1})
$\sqrt{s}$ = **500 GeV**	
2009	10 pb^{-1}
2011	12 pb^{-1}
2012	82 pb^{-1}
2013	300 pb^{-1}
Transverse data	
$\sqrt{s}$ = **200 GeV**	
2006	9 pb^{-1}
2008	8 pb^{-1}
2012 (2015)	22 pb^{-1} (50 pb^{-1})
$\sqrt{s}$ = **500 GeV**	
2011 (2016)	25 pb^{-1} (400 pb^{-1})

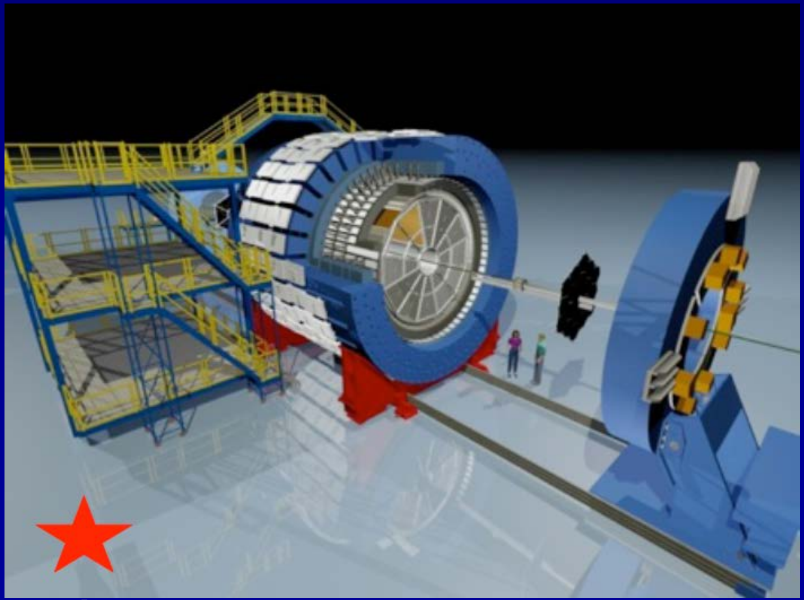


RHIC's current main experiments



PHENIX:

- High resolution; high rate capabilities for rare probes
- Central arms $|\eta|<0.35$, $\Delta\phi\sim2\pi$ with key strength measuring EM probes
- Muon arms $1.2<|\eta|<2.4$
- Forward EM calorimetry

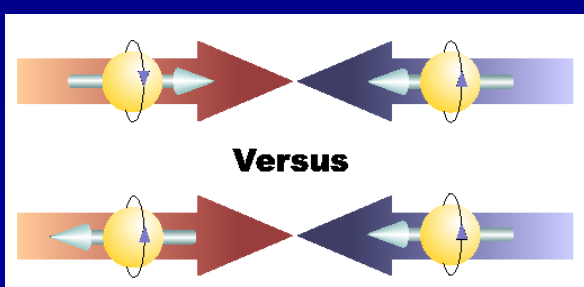


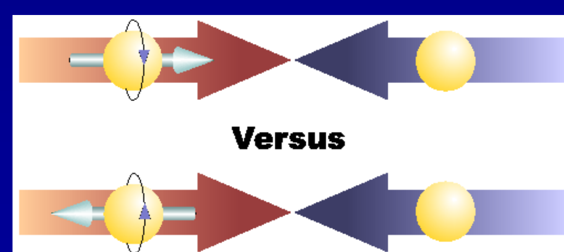
STAR:

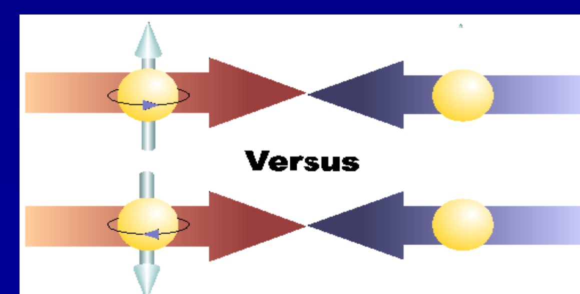
- Key strengths jets + correlations
- Full acceptance including PID for $|\eta|< 1$, $\Delta\phi\sim2\pi$
- Forward EM calorimetry

Proton spin structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse spin and spin-momentum correlations
π, Jets $A_{LL}(gg, gq \to \pi + X)$ Back-to-Back Correlations	W Production $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	Transverse-momentum-dependent distributions Single-Spin Asymmetries







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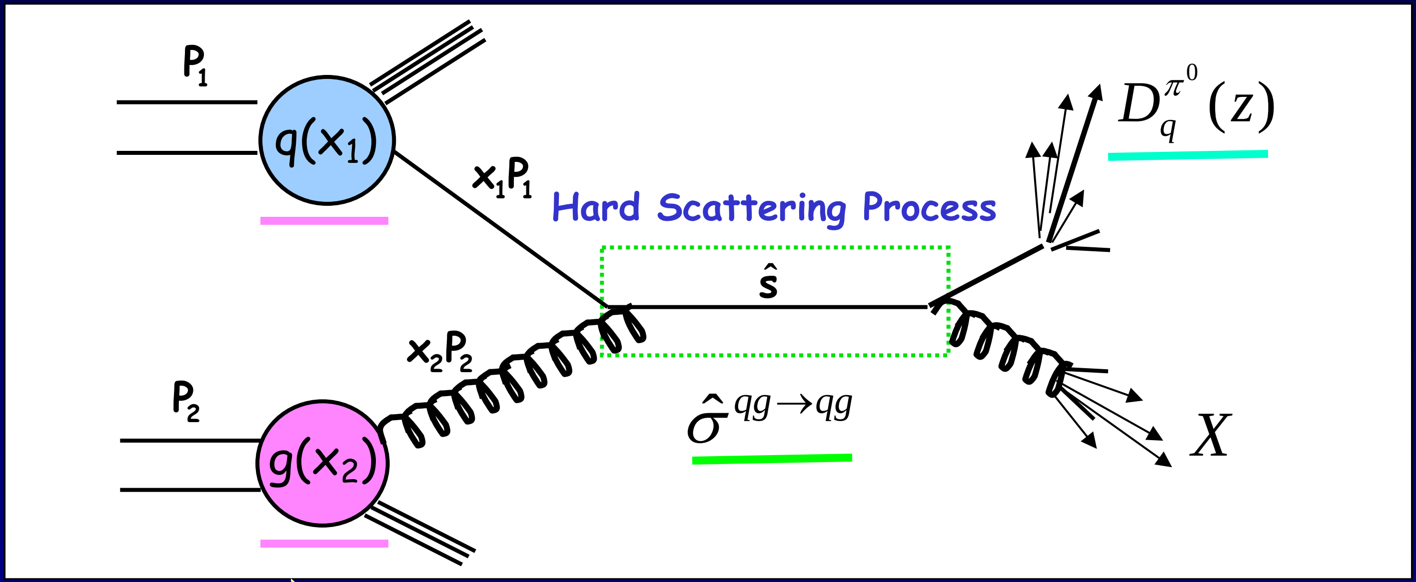
Advantages of a polarized *proton-proton collider*:
- Hadronic collisions → Leading-order access to gluons
- High energies → Applicability of perturbative QCD
- High energies → Production of new probes: W bosons

Reliance on input from simpler systems

- Disadvantage of hadronic collisions: much "messier" than deep-inelastic scattering! → *Rely on input from simpler systems*
  - Just as the heavy ion program at RHIC relies on information from simpler collision systems

- The more we know from simpler systems such as deep-inelastic scattering and e+e- annihilation, the more we can in turn learn from hadronic collisions

Predictive power of pQCD



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

High-energy processes have predictable rates given:

Partonic hard scattering rates (calculable in pQCD)

– Parton distribution functions (need experimental input)

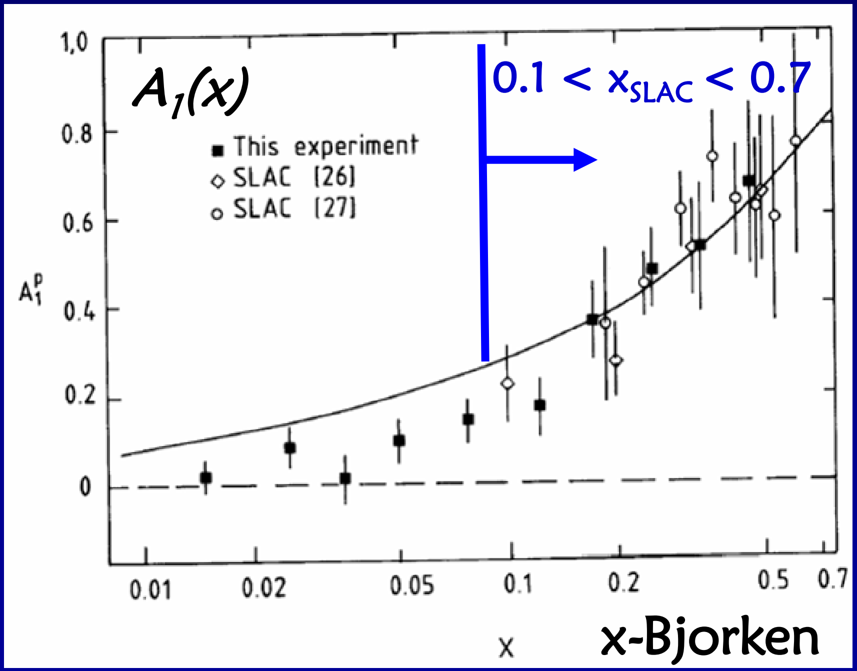
– Fragmentation functions (need experimental input)

} **Universal non-perturbative factors**

Proton "spin crisis"

SLAC: *0.10 < x <0.7*

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



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

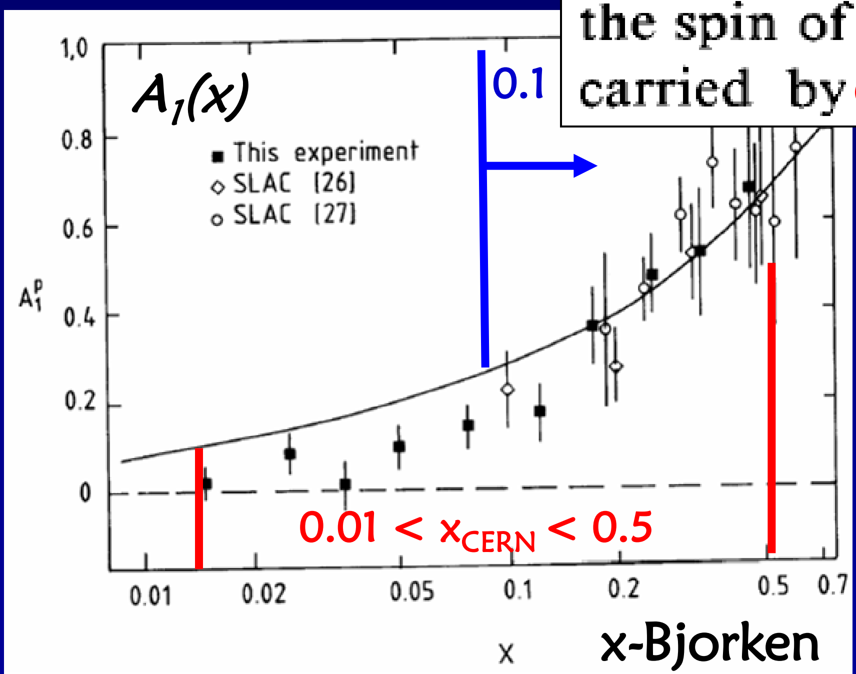
E130, Phys.Rev.Lett.51:1135 (1983)
472 citations

Proton "spin crisis"

SLAC: *0.10 < x <0.7*
CERN: *0.01 < x <0.5*

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

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

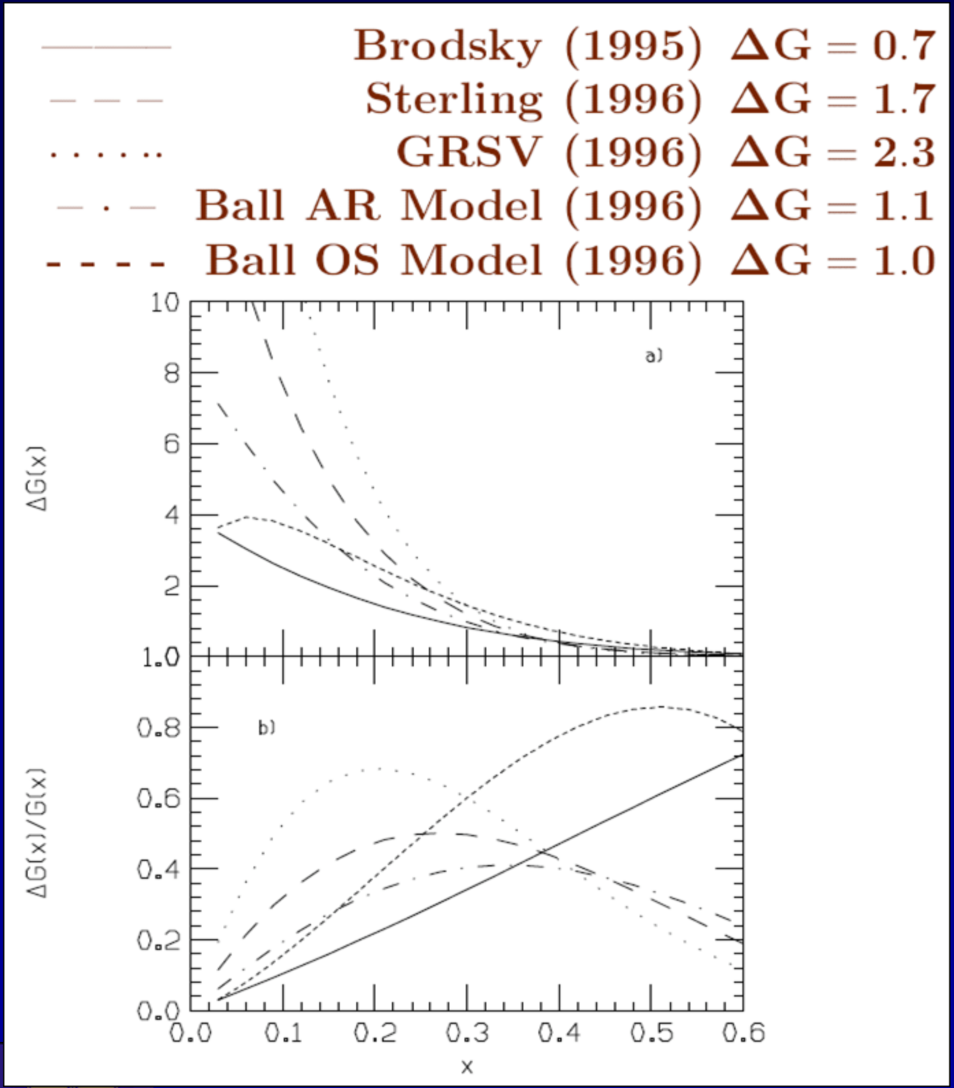


These haven't been easy to measure!

EMC (CERN), Phys.Lett.B206:364 (1988)
1759 citations!

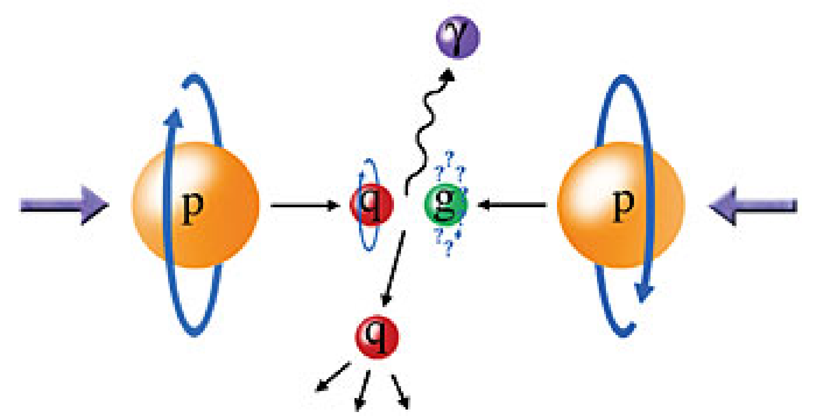
"Proton Spin Crisis"

Quest for ΔG, the gluon spin contribution to the spin of the proton



- With experimental evidence indicating that only about 30% of the proton's spin is due to the spin of the quarks, in the 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.

Probing the helicity structure of the nucleon with p+p collisions



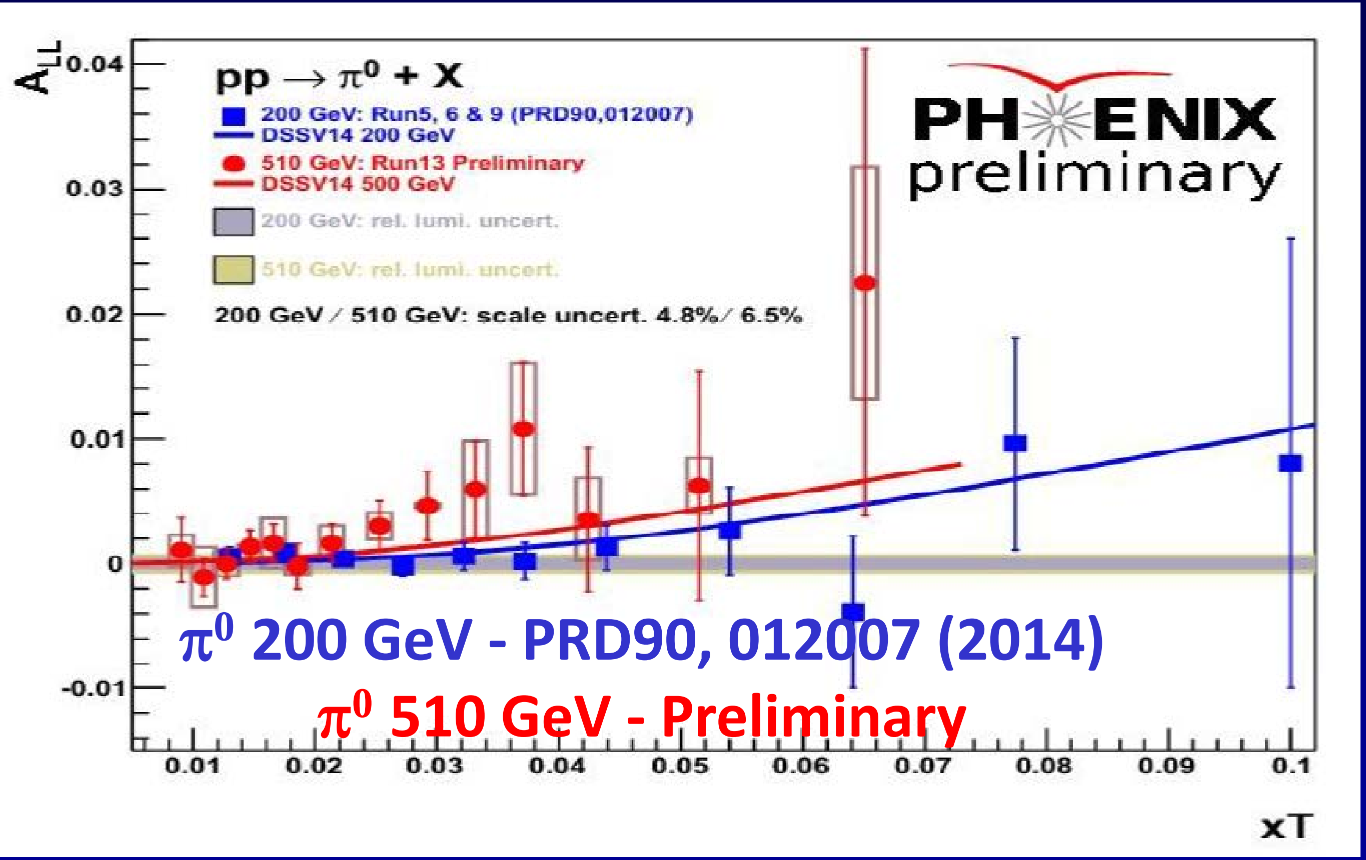
$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1P_2|}\frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

Study difference in particle production rates for same-helicity vs. opposite-helicity proton collisions

$$\Delta\sigma(pp \to \pi^0 X) \propto \underbrace{\Delta q(x_1)}_{\text{DIS}} \otimes \underbrace{\Delta g(x_2)}_{?} \otimes \underbrace{\Delta\hat{\sigma}^{qg\to qg}(\hat{s})}_{\text{pQCD}} \otimes \underbrace{D_q^{\pi^0}(z)}_{\text{e+e-}}$$

Leading-order access to gluons → ΔG

RHIC measurements sensitive to gluon polarization

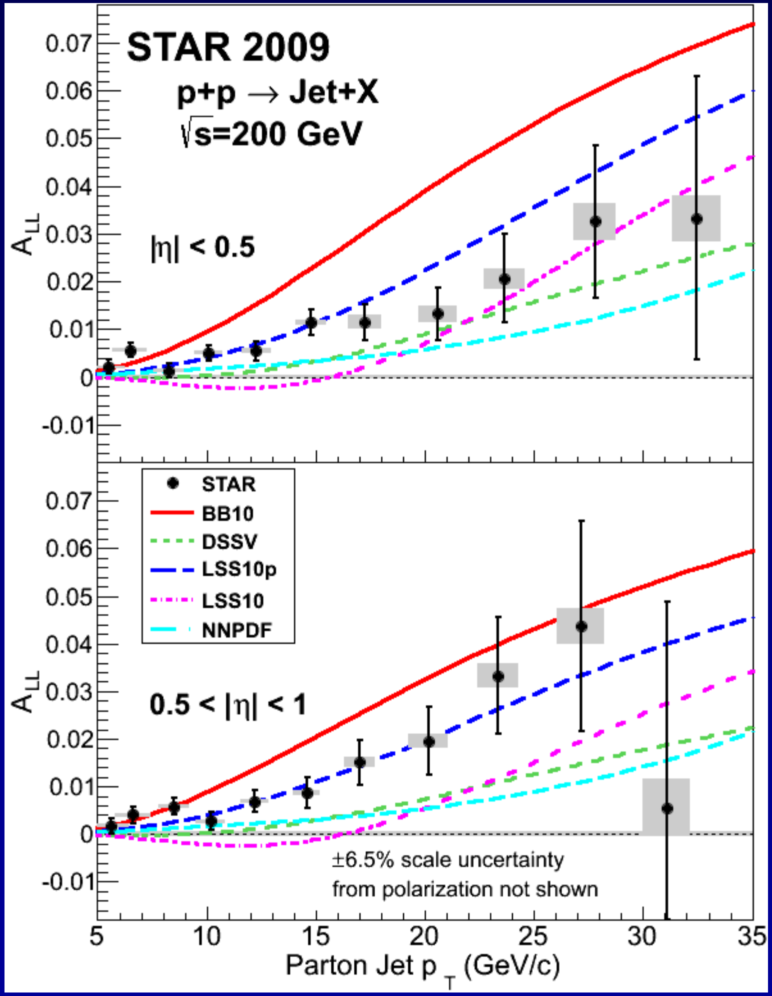


Neutral pion double-helicity asymmetries

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

RHIC measurements sensitive to gluon polarization

arXiv:1405.5134

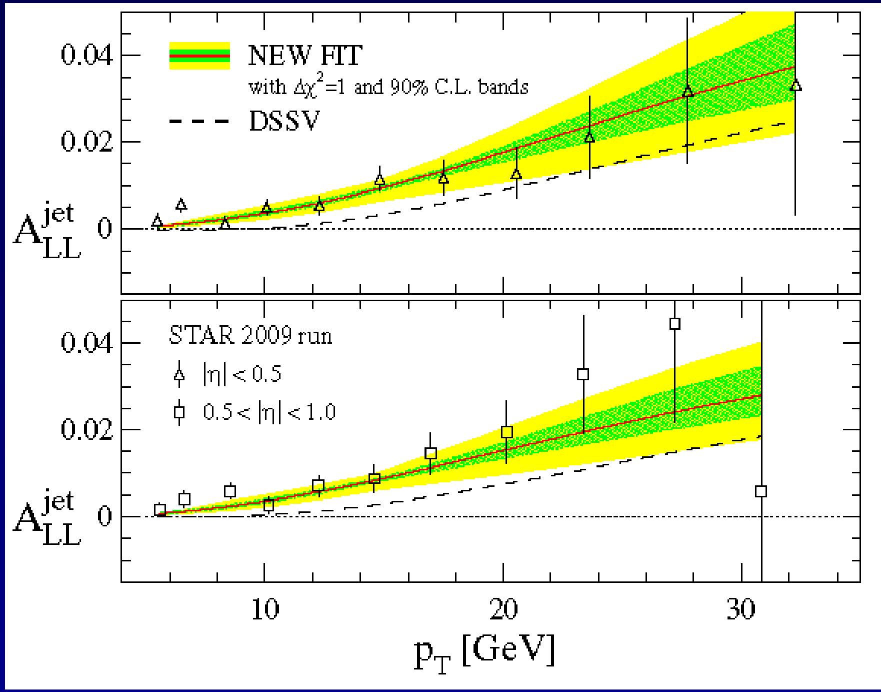


- Clear nonzero asymmetry seen in STAR jet measurements from 2009 data!
- PHENIX π^0 data consistent

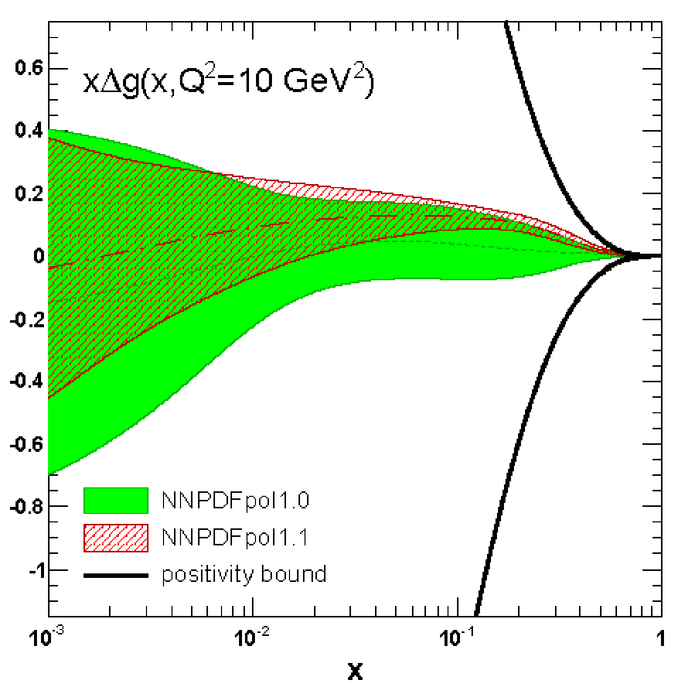
$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

Two new helicity pdf fits

DSSV, PRL 113, 012001 (2014)

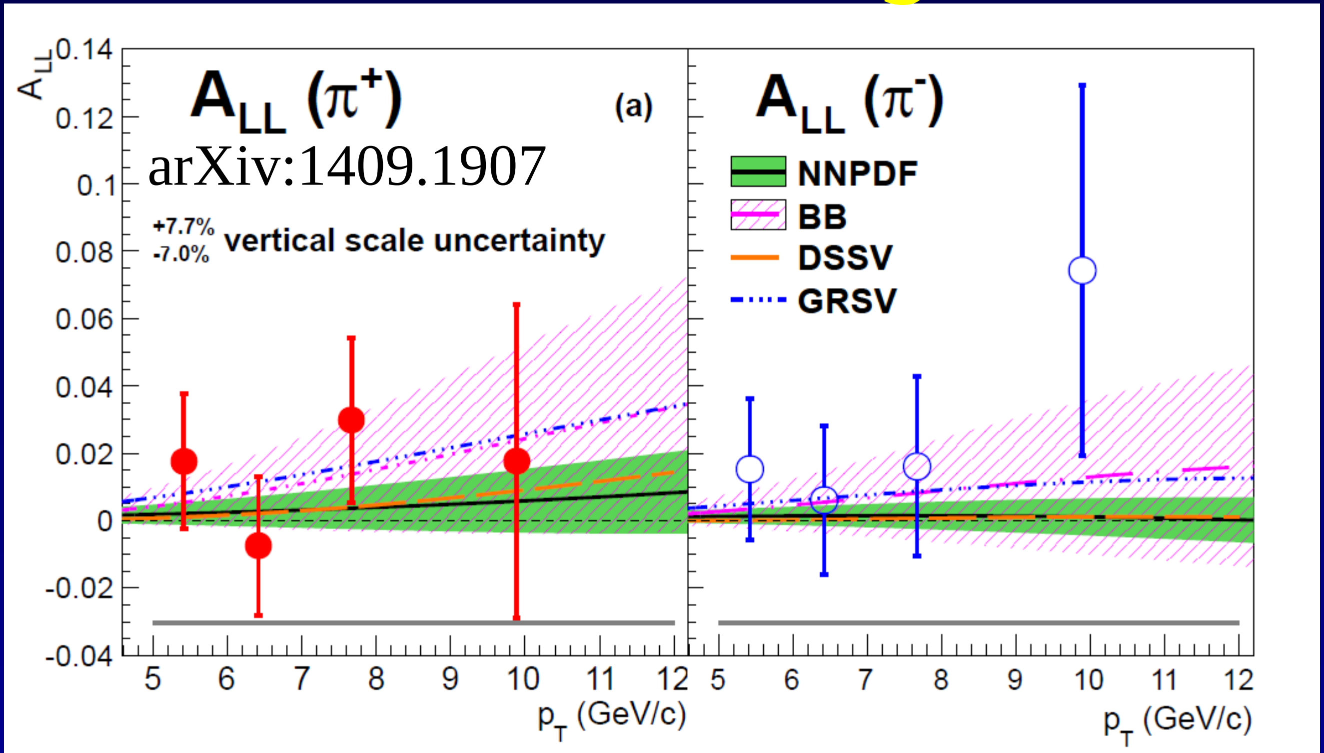


NNPDF, NPB 887.276 (2014)

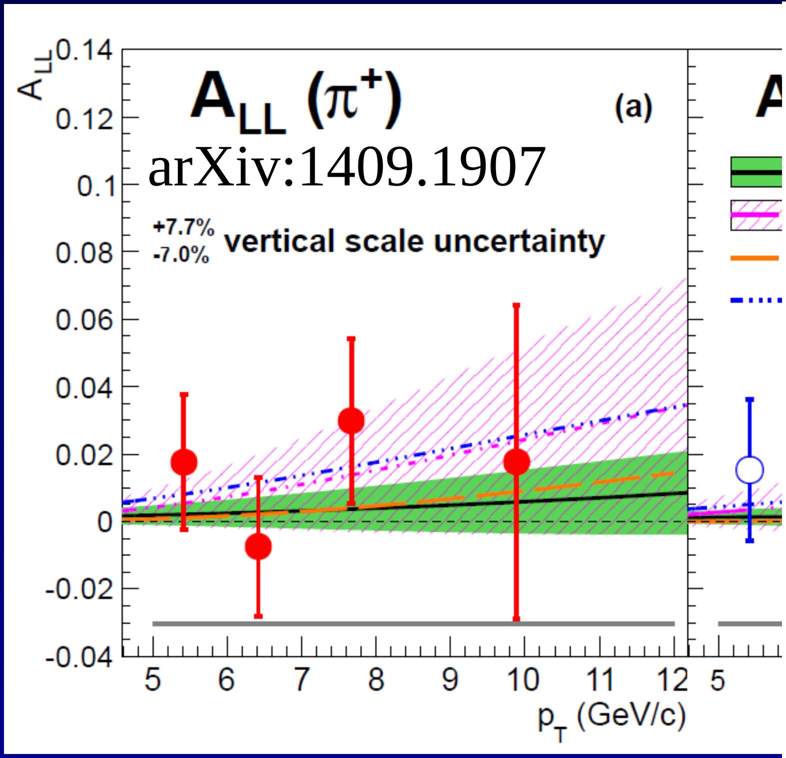


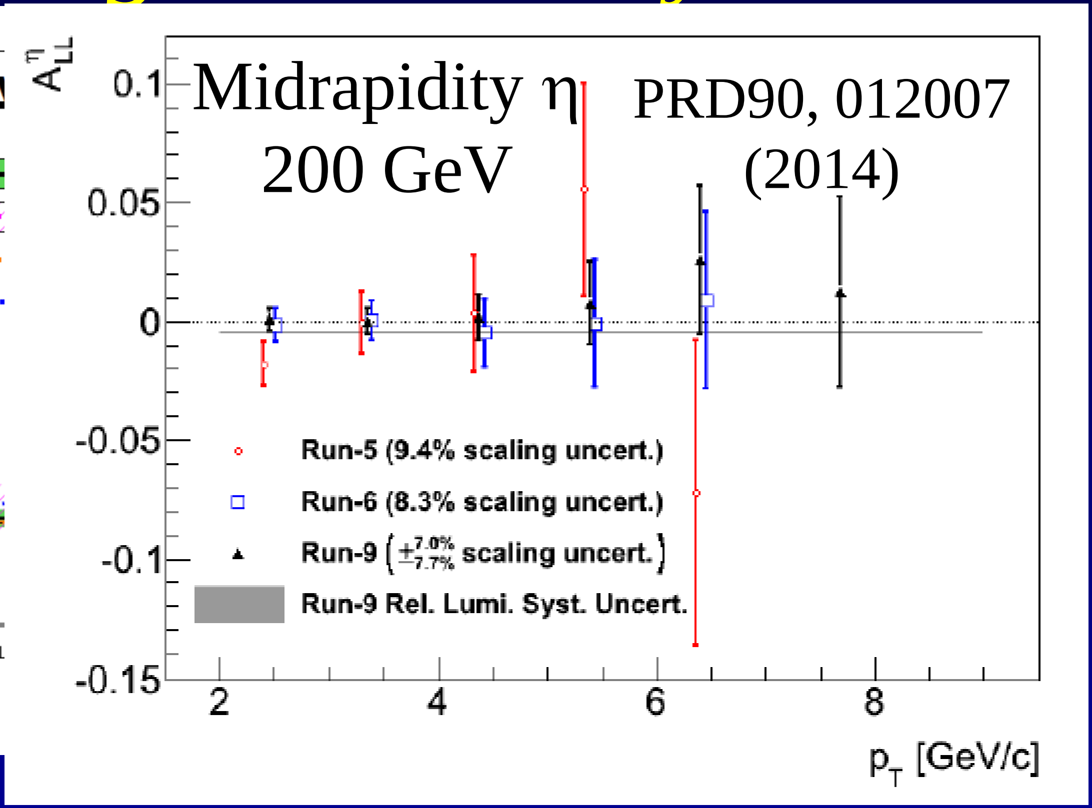
- DSSV and NNPDF have released new polarized pdf fits including RHIC data
- 2009 STAR jet A_{LL} results in particular provide significantly tighter constraints on gluon polarization than previous measurements
- Both find evidence for positive gluon polarization in the region x > 0.05, but looks like orbital angular momentum will still be needed to account for total spin

Other recently measured probes sensitive to gluon helicity

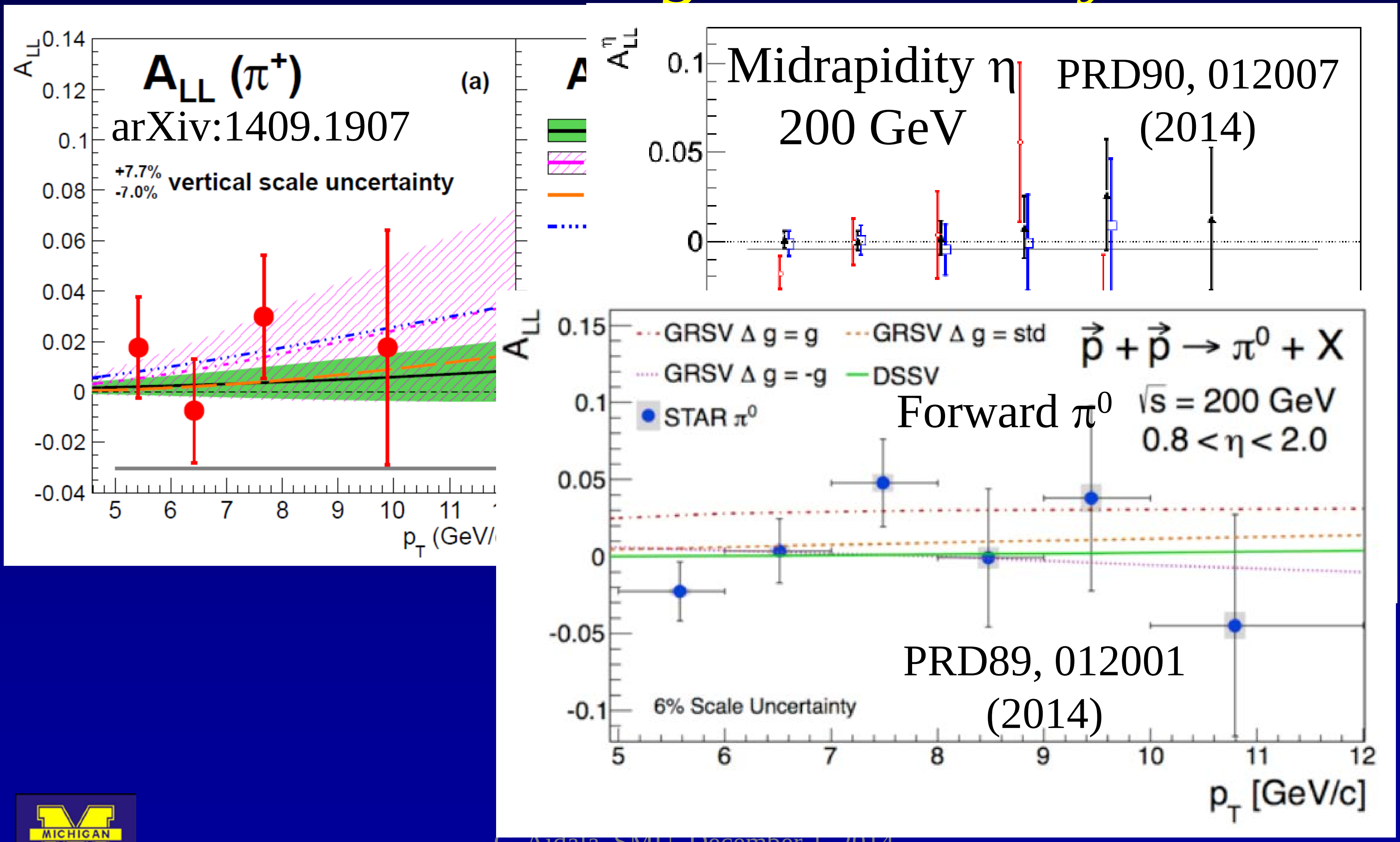


Other recently measured probes sensitive to gluon helicity

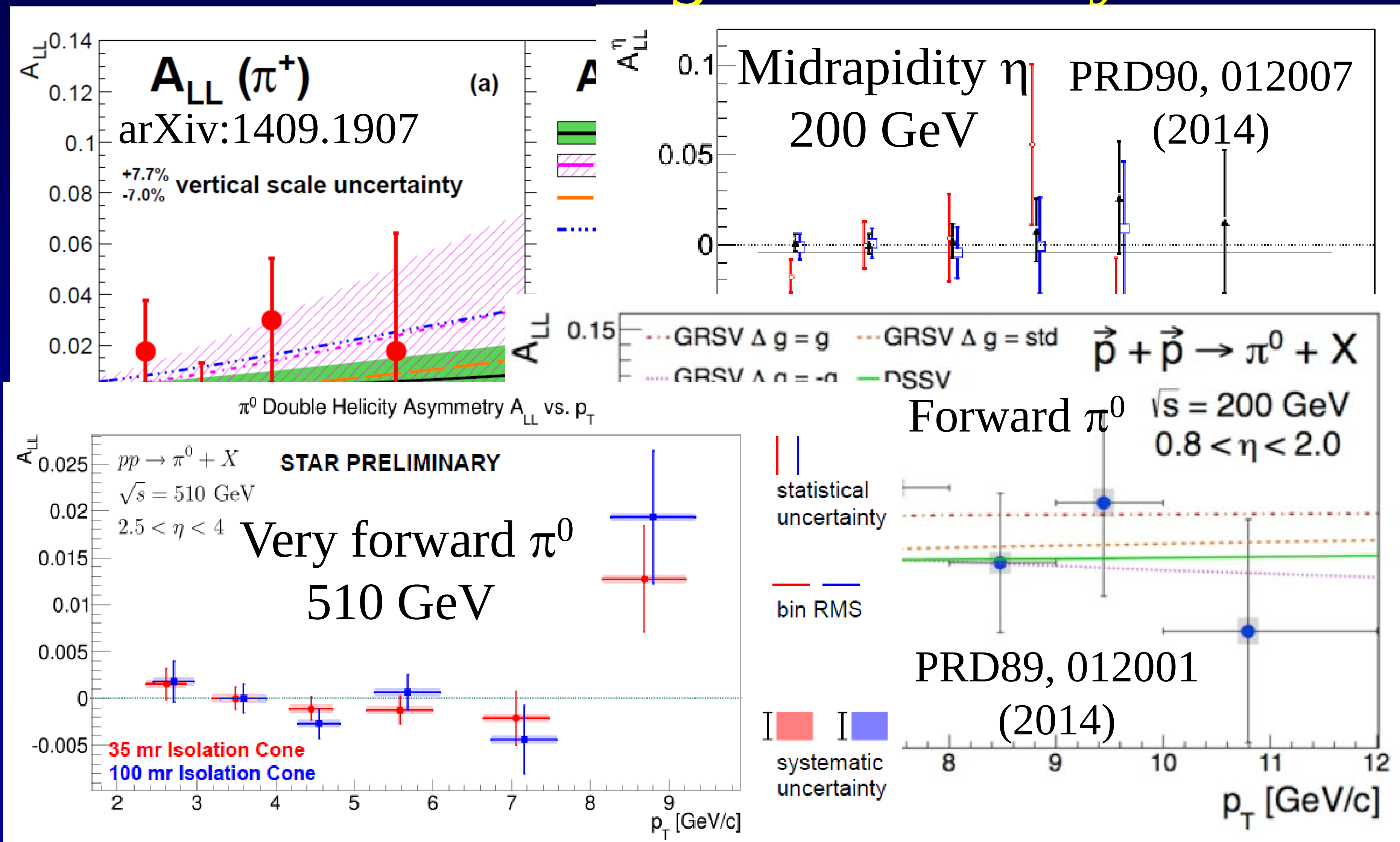




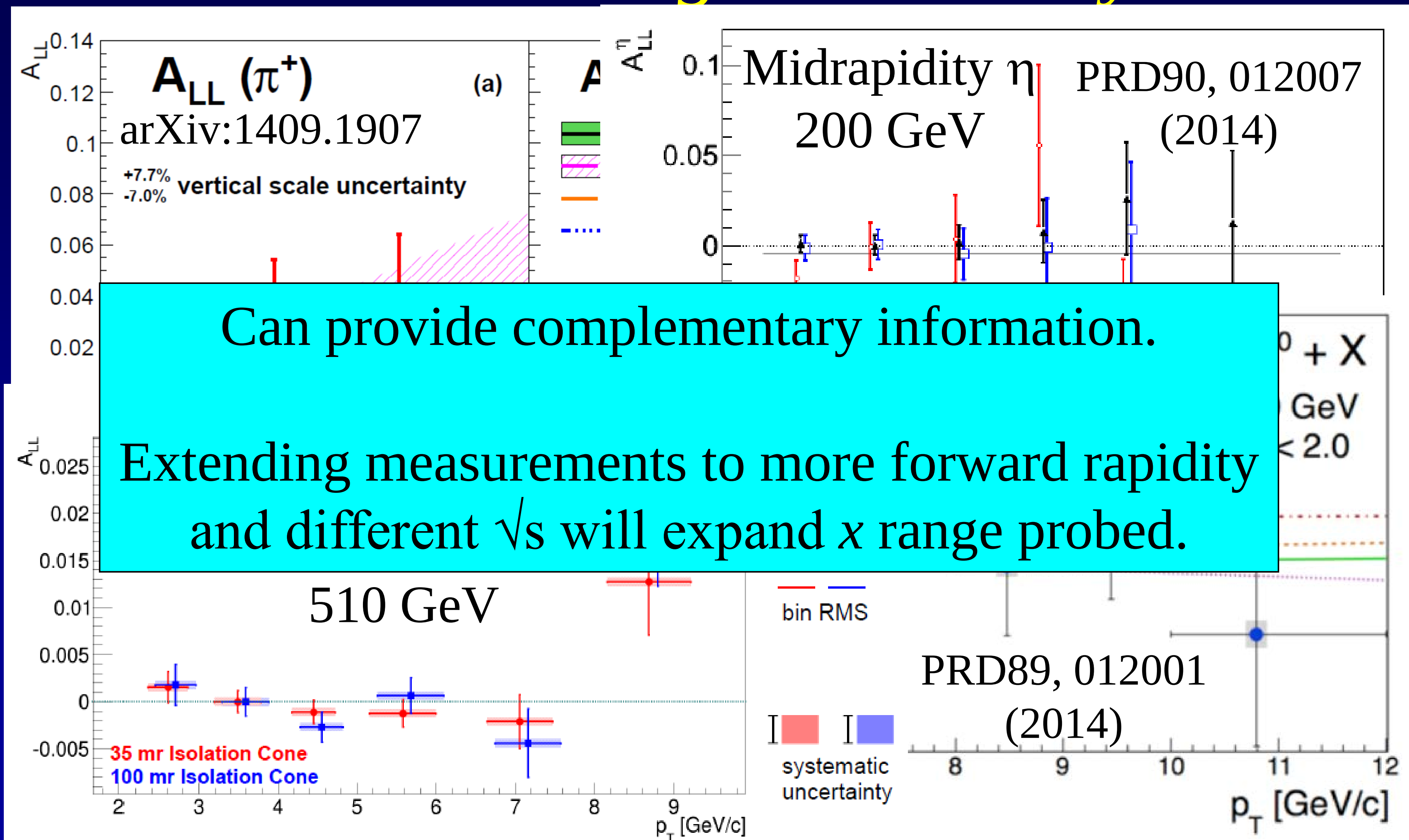
Other recently measured probes sensitive to gluon helicity



Other recently measured probes sensitive to gluon helicity



Other recently measured probes sensitive to gluon helicity

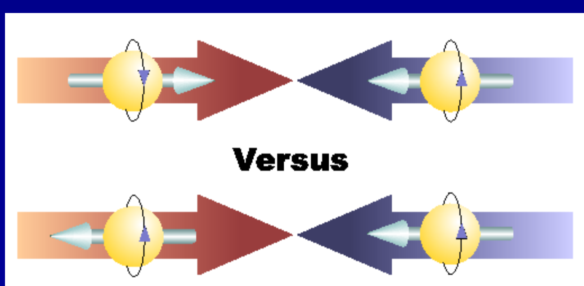


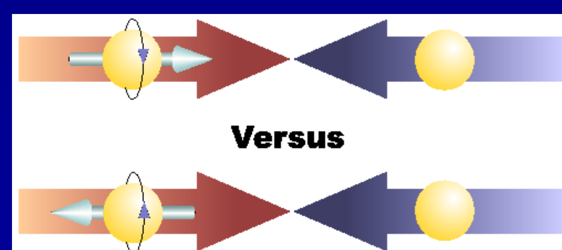
Can provide complementary information.

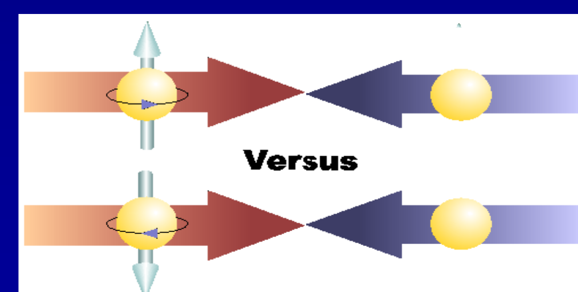
Extending measurements to more forward rapidity and different √s will expand *x* range probed.

Proton spin structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse spin and spin-momentum correlations
π, Jets $A_{LL}(gg, gq \to \pi + X)$ Back-to-Back Correlations	W Production $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	Transverse-momentum-dependent distributions Single-Spin Asymmetries



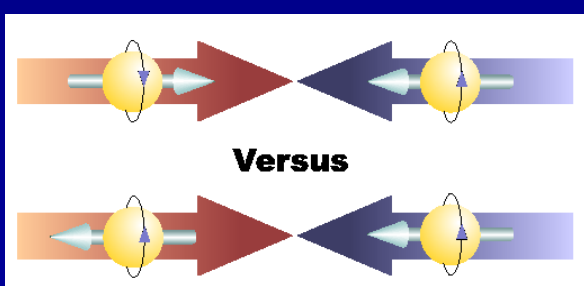


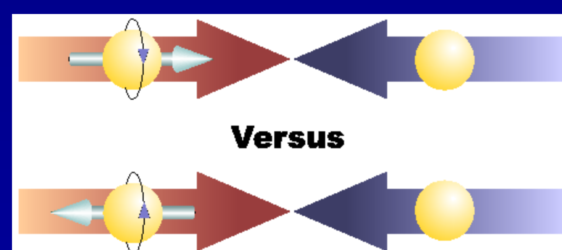


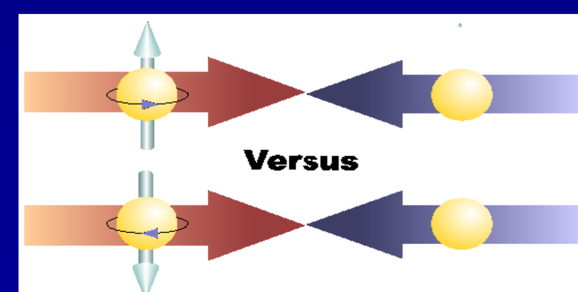
Proton spin structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse spin and spin-momentum correlations
π, Jets Back-t		um- ions es

Not expected to resolve spin crisis, but of particular interest given surprising isospin-asymmetric structure of the unpolarized sea discovered by E866 at Fermilab.





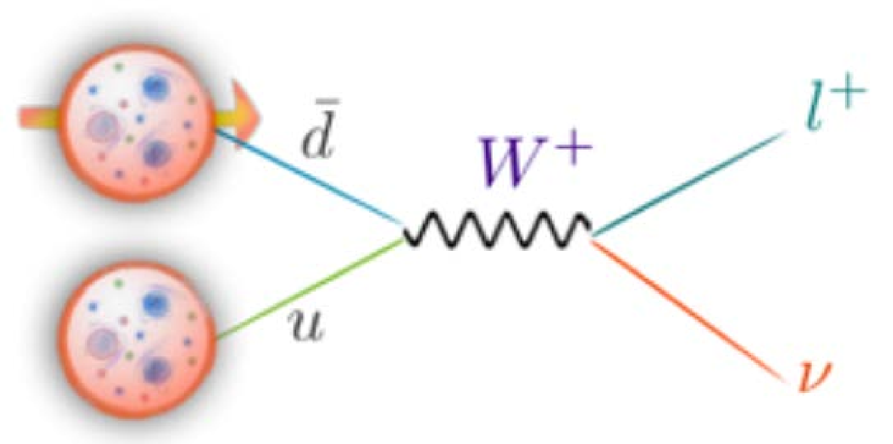


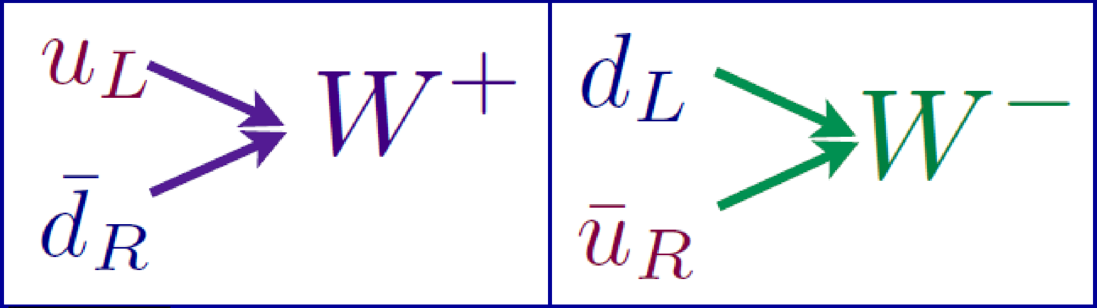
Flavor-separated sea quark helicities through W production

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

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

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





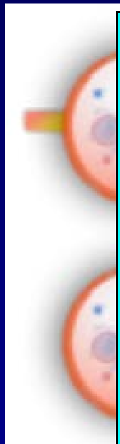
Parity violation of weak interaction + control over proton spin orientation gives access to *flavor*-spin structure of proton

Flavor-separated sea quark helicities through W production

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

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

$$\ldots)d(x_2) \quad / \quad \ldots d(x_2)$$

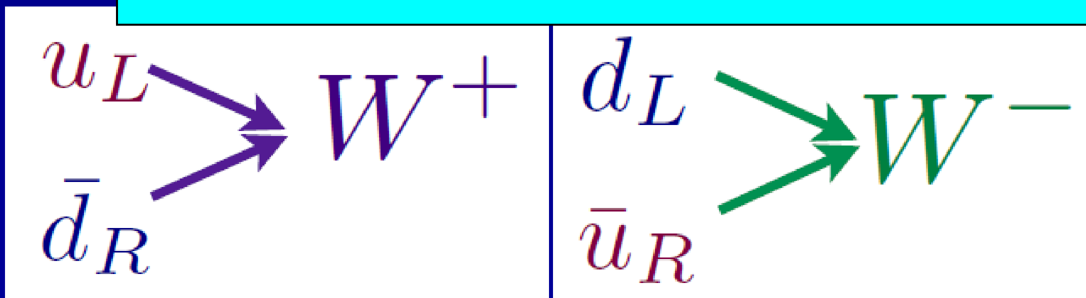


Flavor separation of the polarized sea quarks with ***no reliance on fragmentation functions,*** *and at* ***much higher scale*** *than previous fixed-target experiments.*

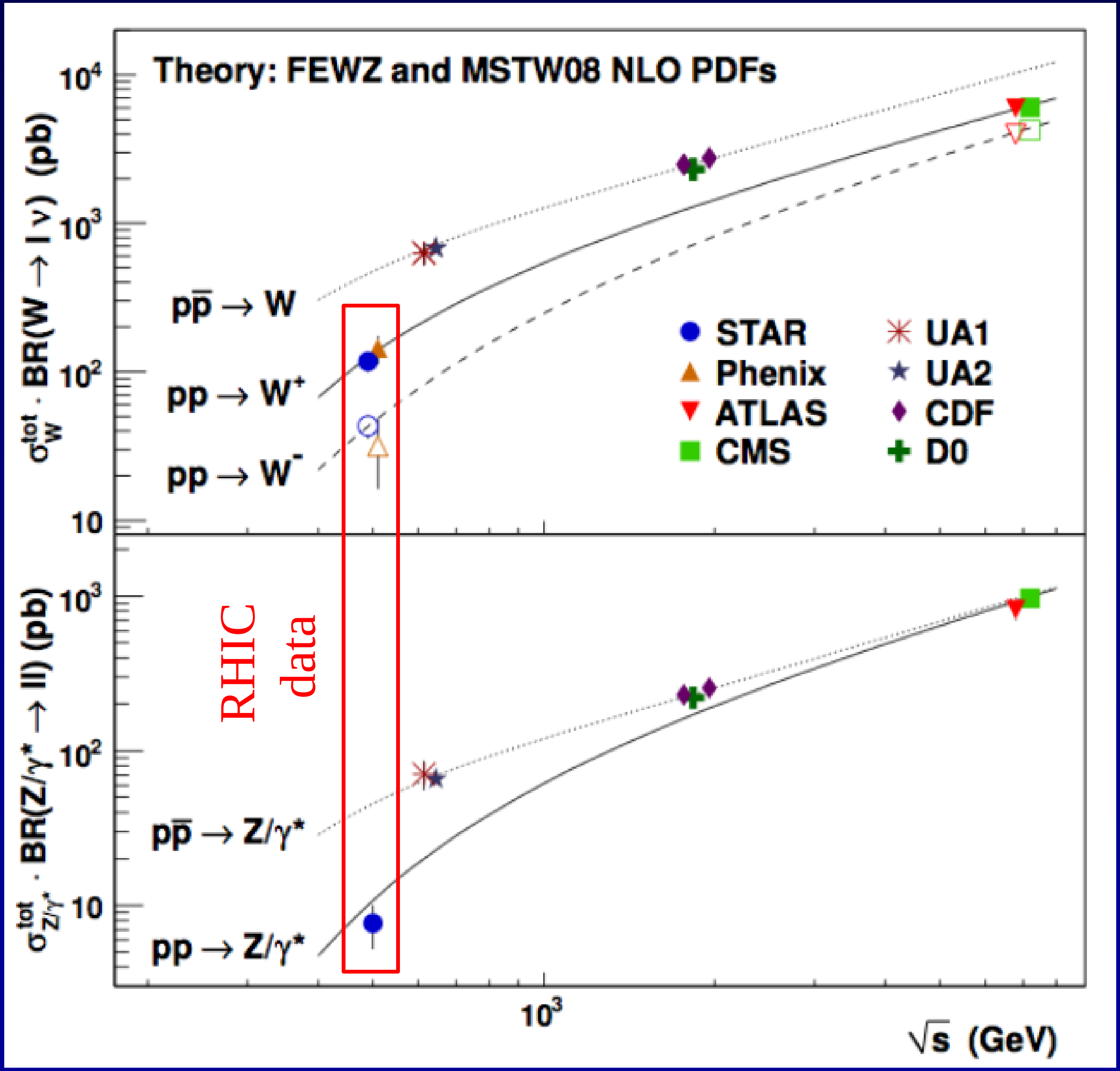
Complementary *to semi-inclusive DIS measurements.*

...eak

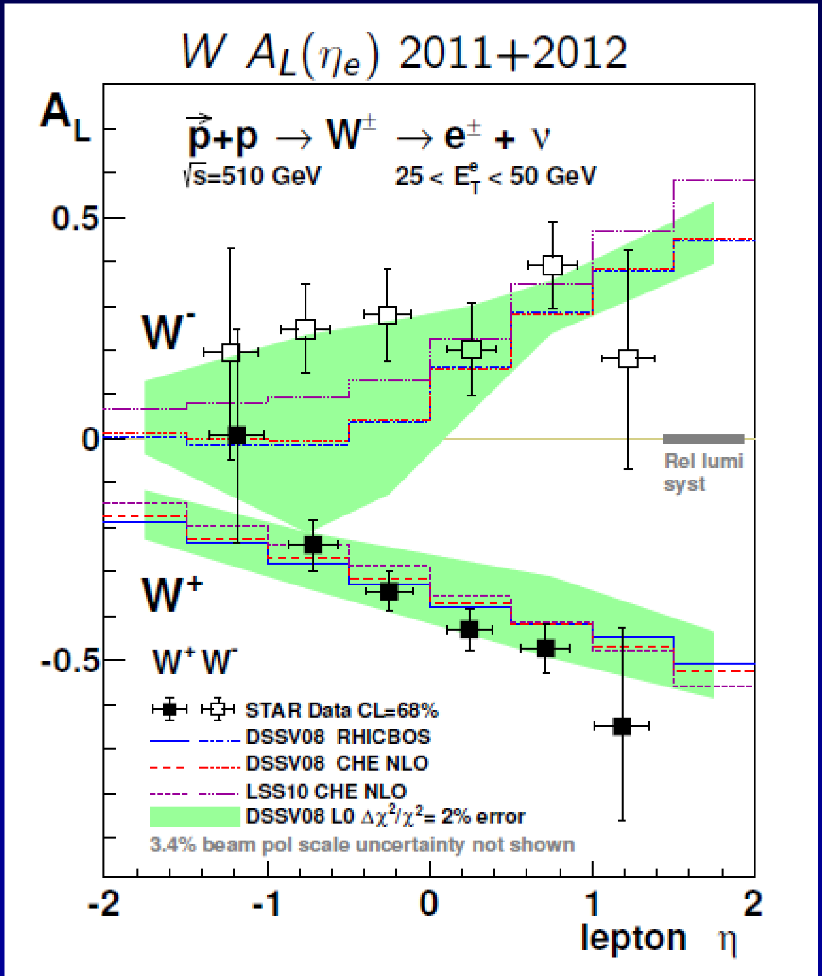
...spin orientation gives access to *flavor*-spin structure of proton



World W cross section measurements



Large parity-violating single-helicity asymmetries

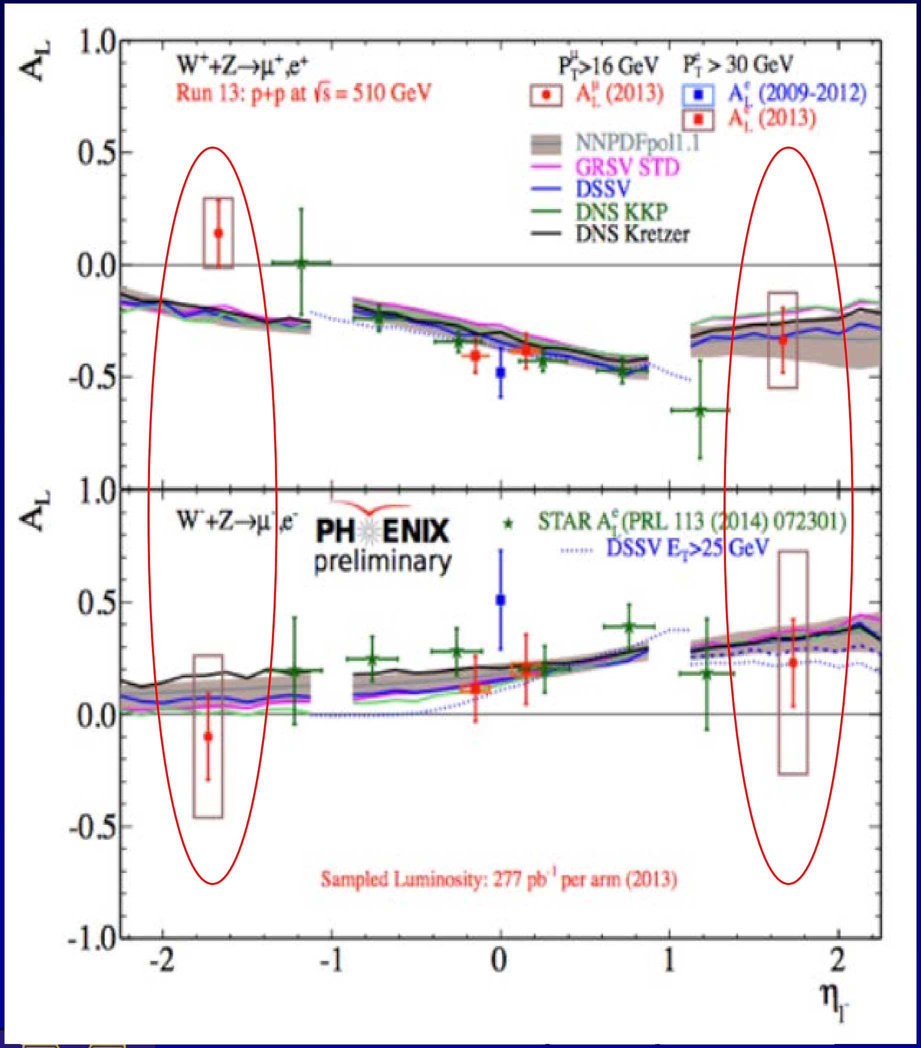


PRL 113, 072301 (2014)

- Improve constraints on light antiquark helicity distributions

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

Large parity-violating single-helicity asymmetries

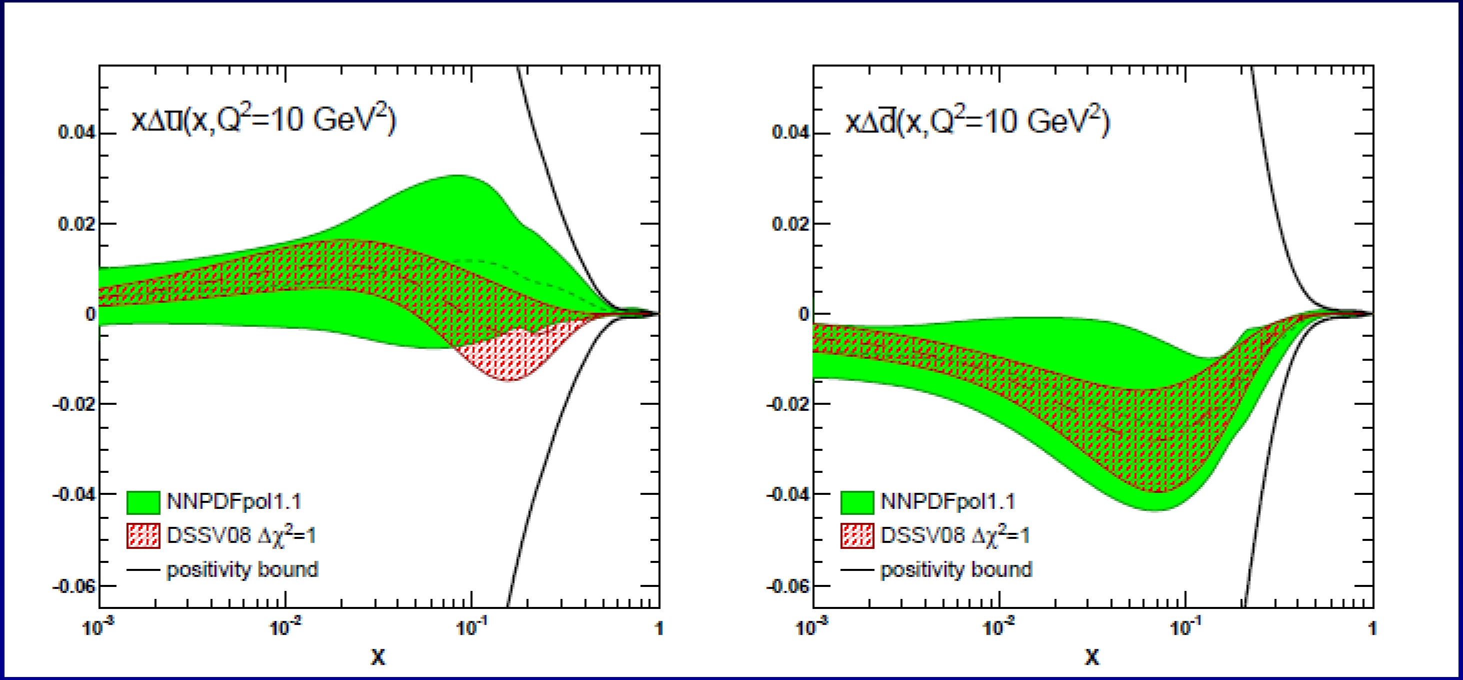


- Improve constraints on light antiquark helicity distributions
- New preliminary PHENIX muon results extend rapidity range

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

Flavor-separated sea quark helicities through W production

NNPDF, NPB 887.276 (2014)

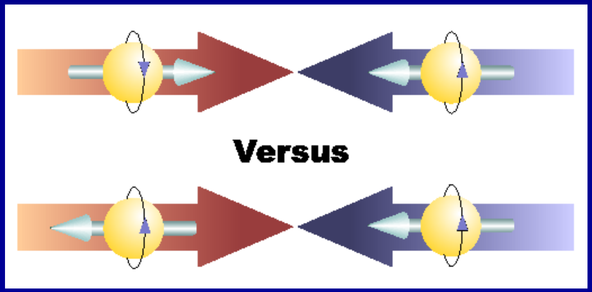


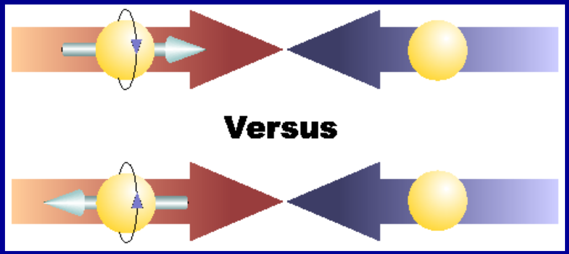
(DSSV08: Before RHIC W data)

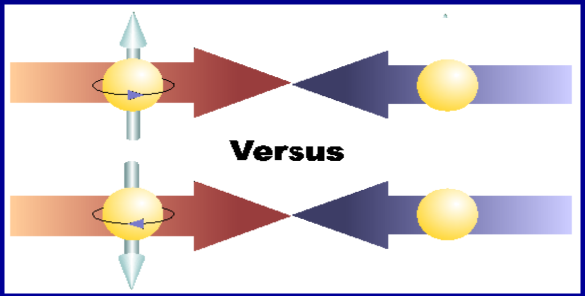
Latest NNPDF fit to helicity distributions, including RHIC W data: Indication of SU(3) breaking in the polarized quark sea (as in the unpolarized sea), but still relatively large uncertainties on helicity distributions of anti-up and anti-down quarks

Proton spin structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse spin and spin-momentum correlations
π, Jets $A_{LL}(gg, gq \rightarrow \pi + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \rightarrow W^+ \rightarrow \ell^+ + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^- \rightarrow \ell^- + \bar{\nu}_l)$	**Transverse-momentum-dependent distributions** Single-Spin Asymmetries



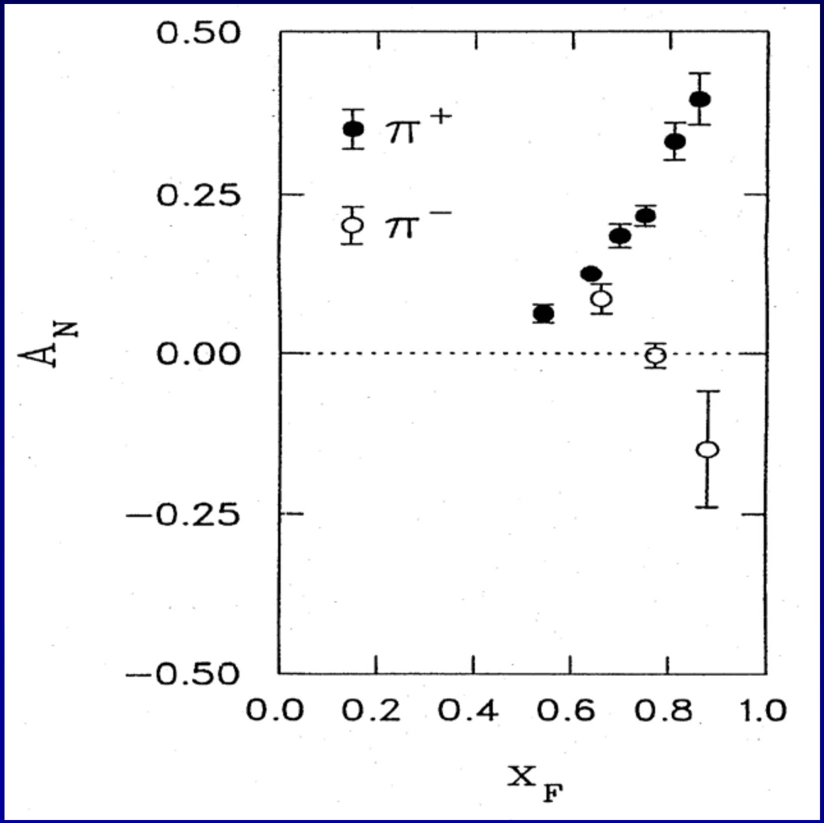




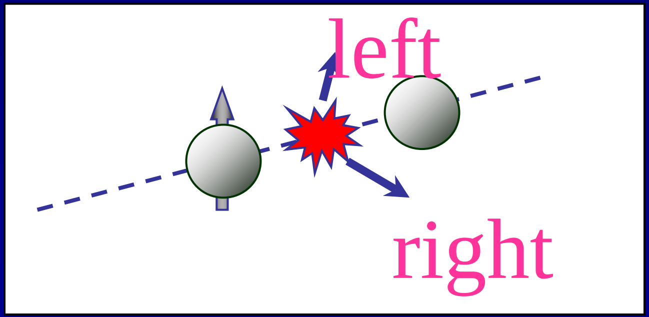
1976: Discovery in p+p collisions!

Huge transverse single-spin asymmetries

Argonne √s=4.9 GeV



Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction



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

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

1976: Discovery in p+p collisions!

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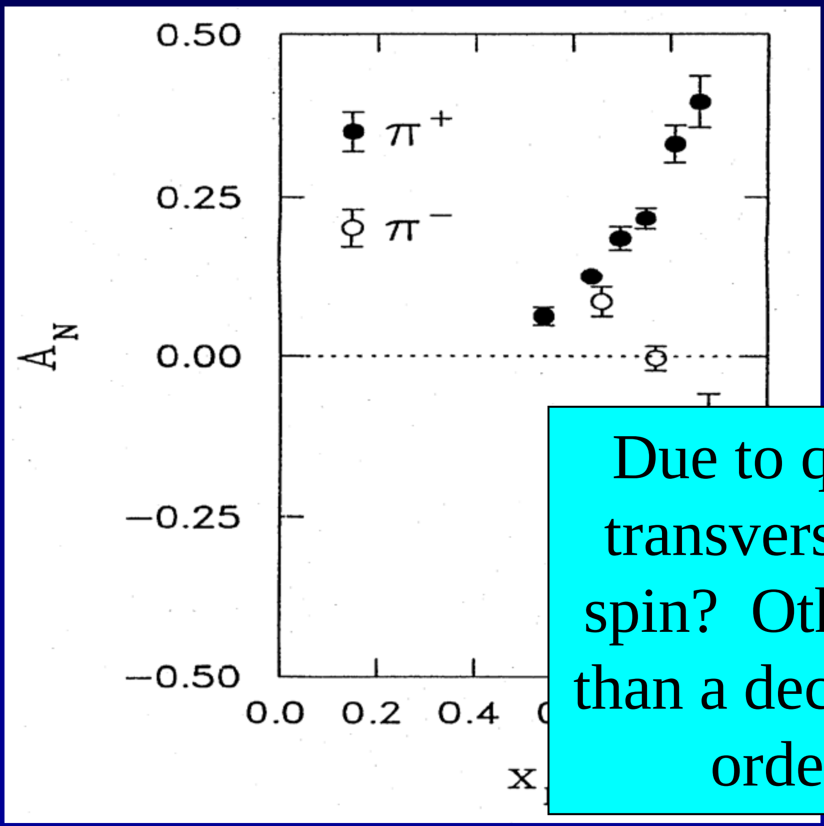


Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction

Due to quark transversity, i.e. correlation of transverse quark spin with transverse proton spin? Other effects? We'll need to wait more than a decade for the birth of a new subfield in order to explore the possibilities . . .

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

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

Transverse-momentum-dependent distributions and single-spin asymmetries

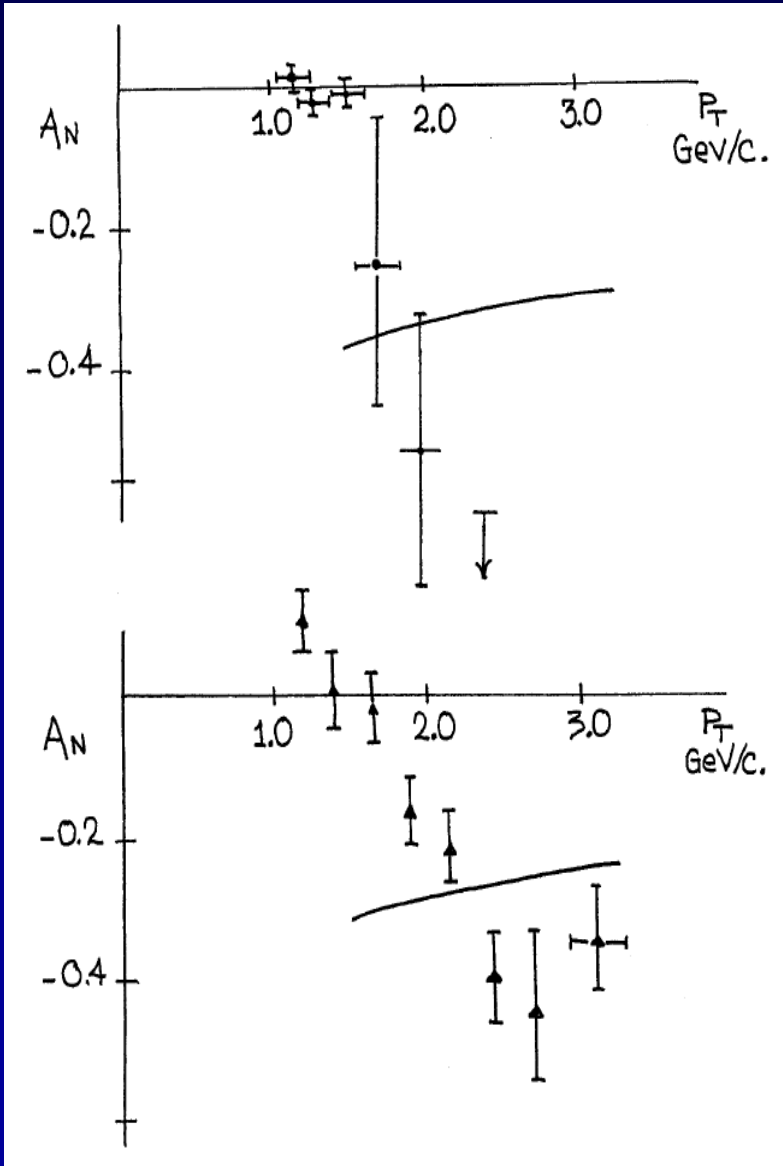


Fig. 1

1989: The "Sivers mechanism" is proposed in an attempt to understand the observed asymmetries.

D.W. Sivers, PRD41, 83 (1990)

Departs from the traditional *collinear* factorization assumption in pQCD and proposes a 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 can be of partons or hadrons

Transverse-momentum-dependent distributions and single-spin asymmetries

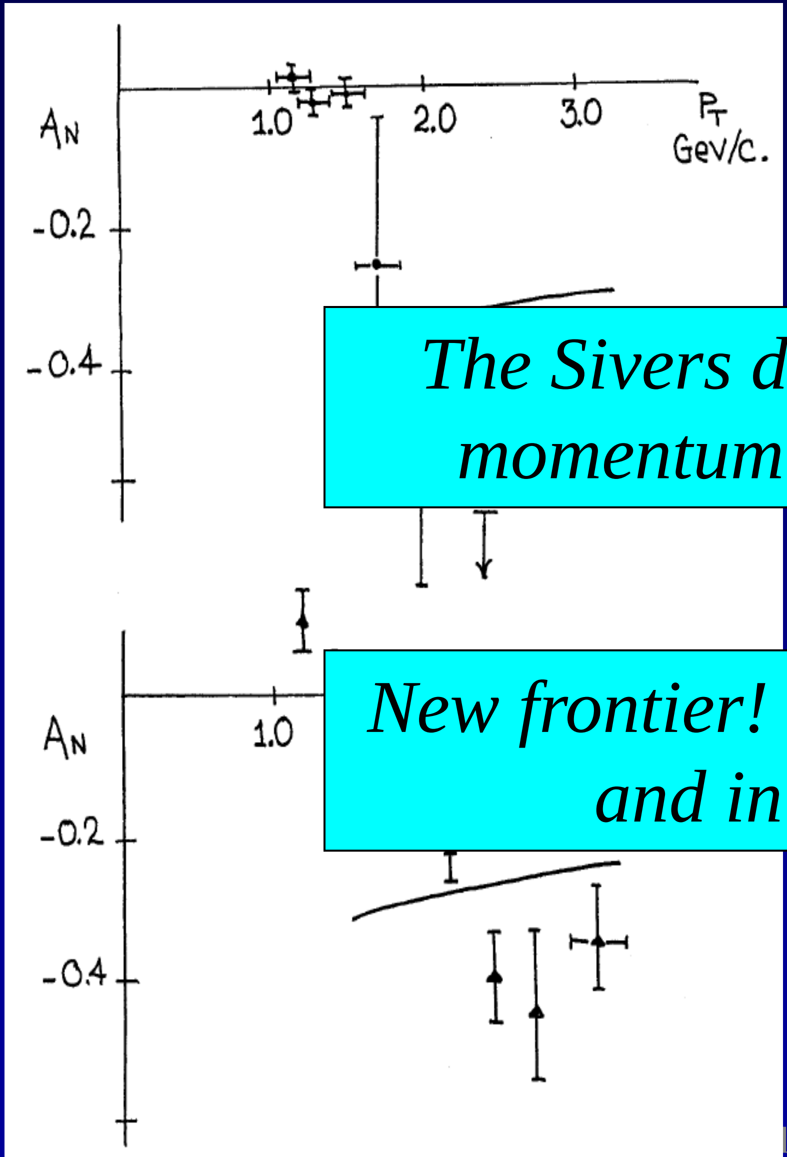


Fig. 1

1989: The "Sivers mechanism" is proposed in an attempt to understand the observed asymmetries.

The Sivers distribution: the first transverse-momentum-dependent distribution (TMD)

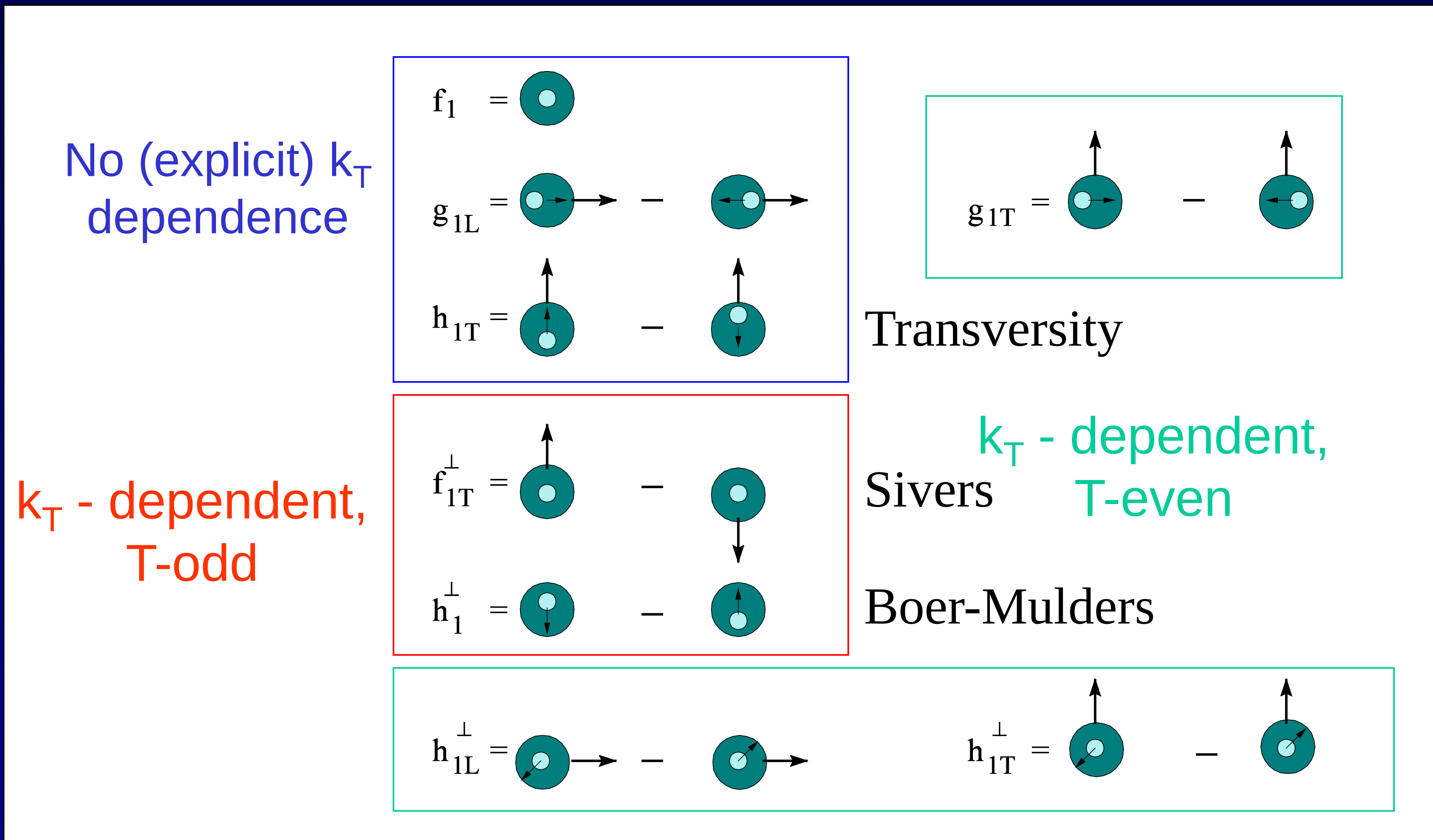
factorization assumption in pQCD and proposes a correlation between the

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

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

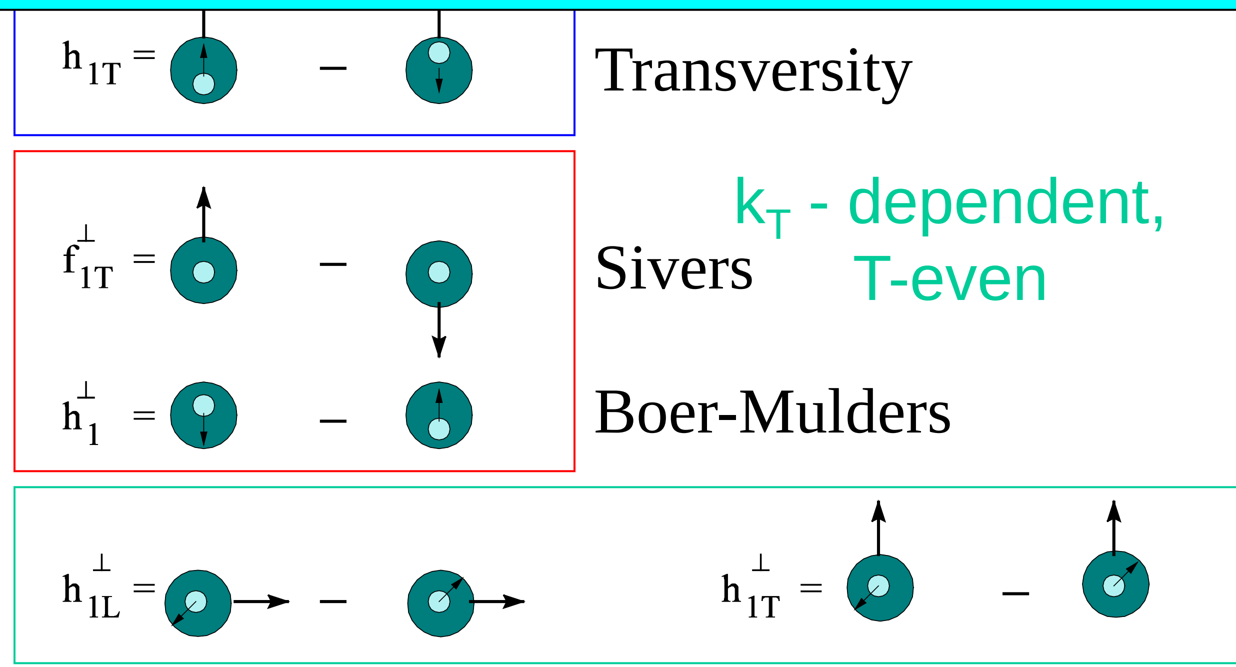
Spin and momenta can be of partons or hadrons

Quark distribution functions



Quark distribution functions

Similarly, can have k_T-dependent fragmentation functions (FFs). One example: the chiral-odd Collins FF, which provides one way of accessing transversity distribution (also chiral-odd).



Transversity

Sivers

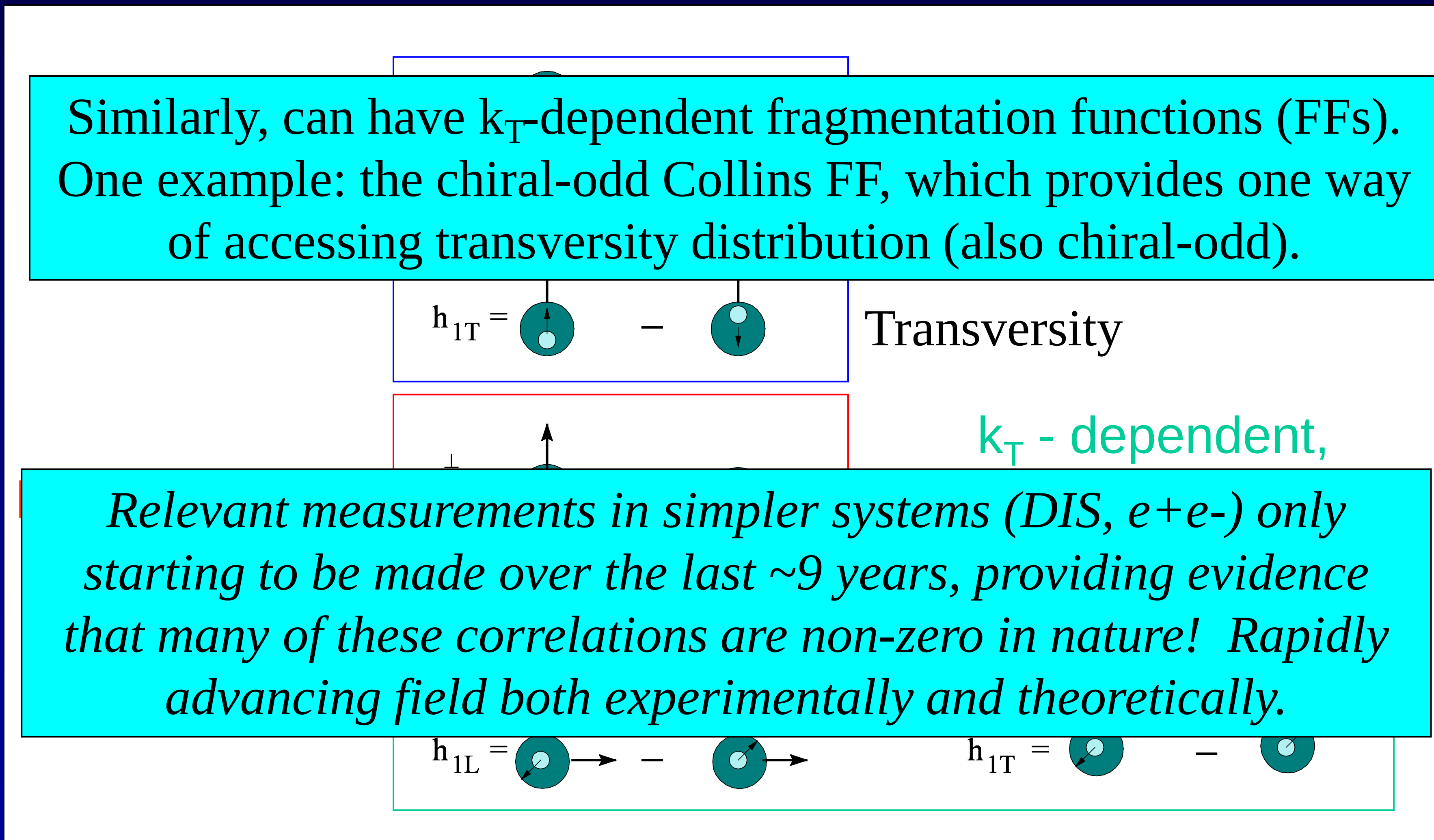
Boer-Mulders

k_T - dependent, T-odd

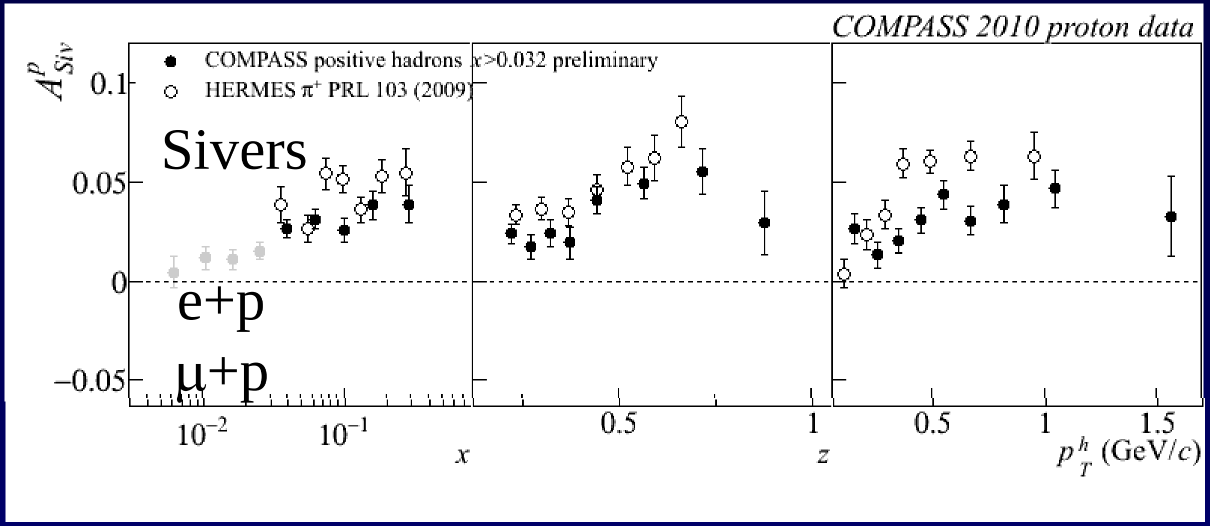
k_T - dependent, T-even

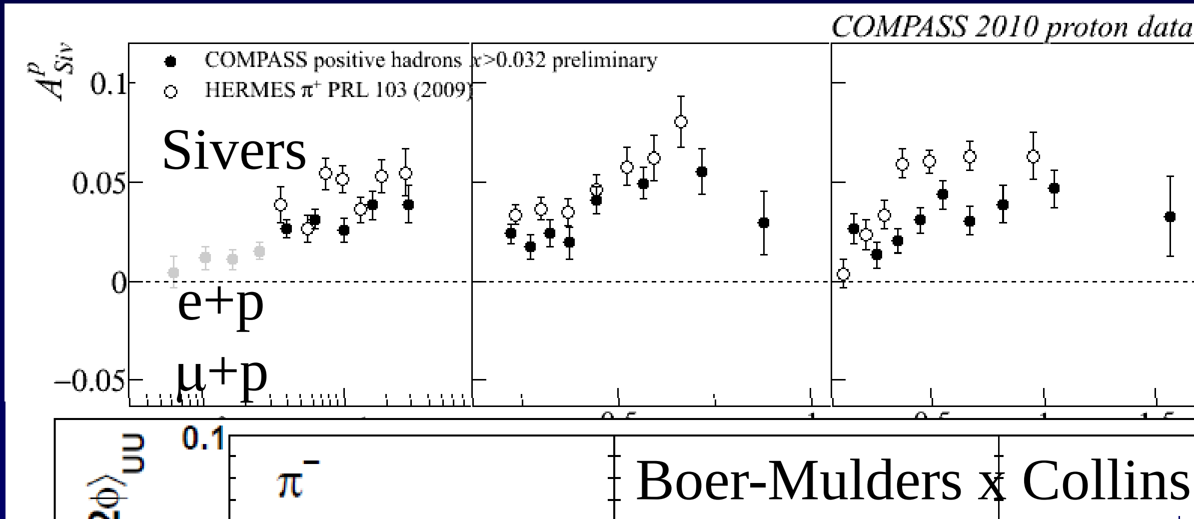
Quark distribution functions

Similarly, can have k_T-dependent fragmentation functions (FFs). One example: the chiral-odd Collins FF, which provides one way of accessing transversity distribution (also chiral-odd).



Relevant measurements in simpler systems (DIS, e+e-) only starting to be made over the last ~9 years, providing evidence that many of these correlations are non-zero in nature! Rapidly advancing field both experimentally and theoretically.


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
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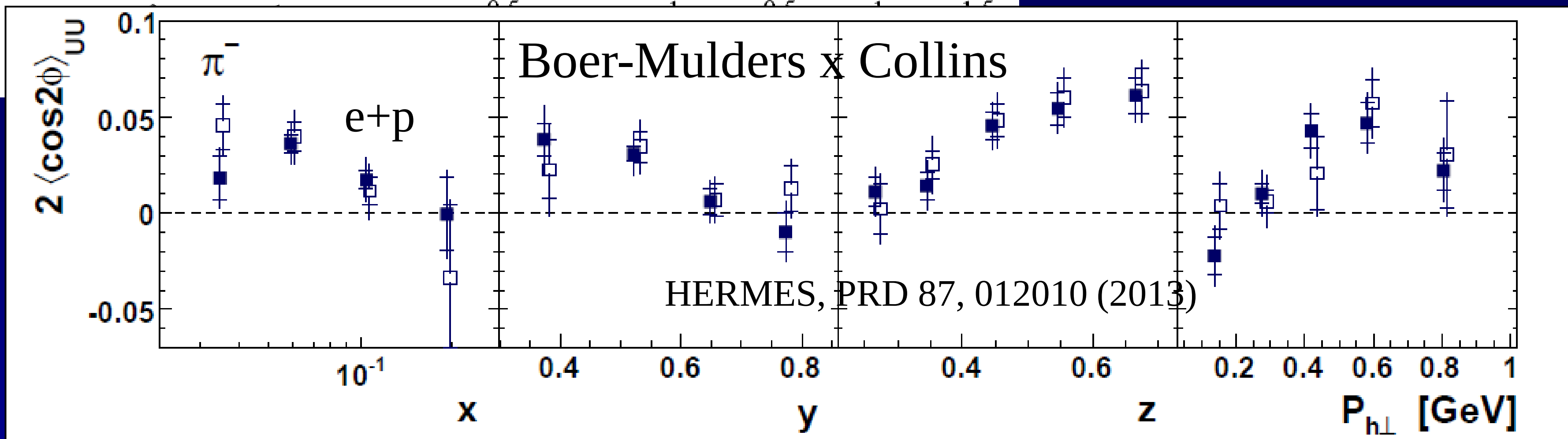
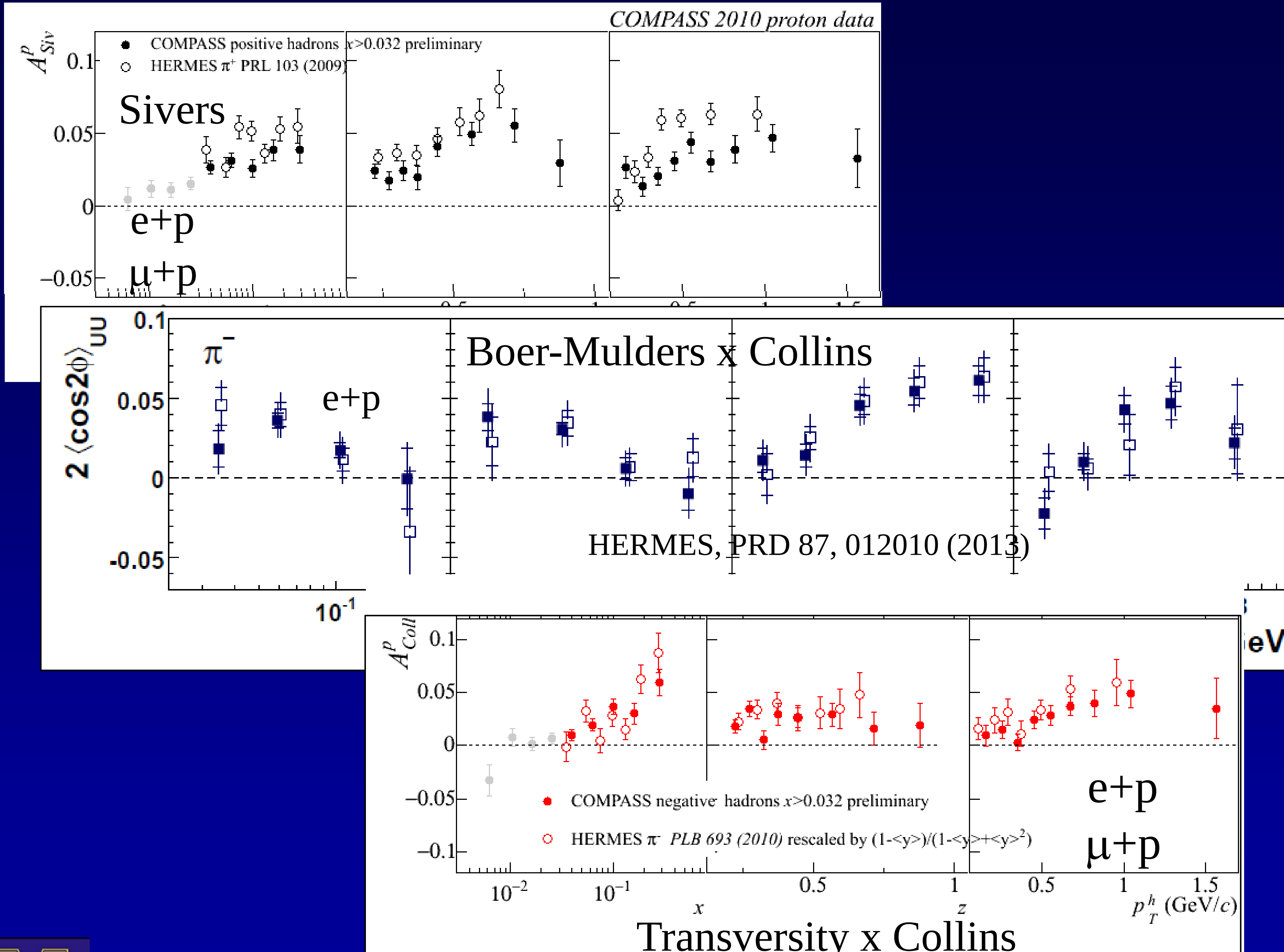
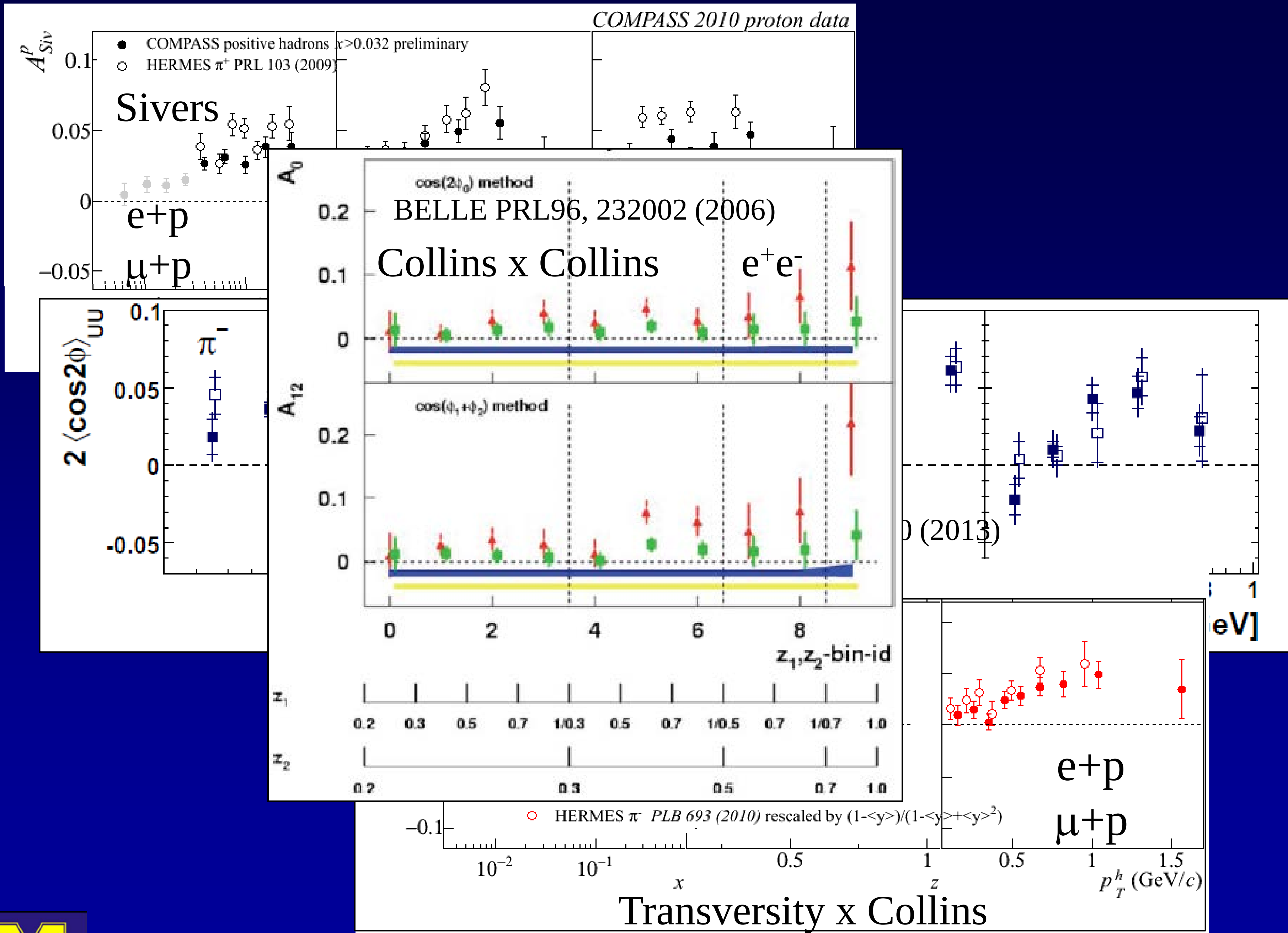
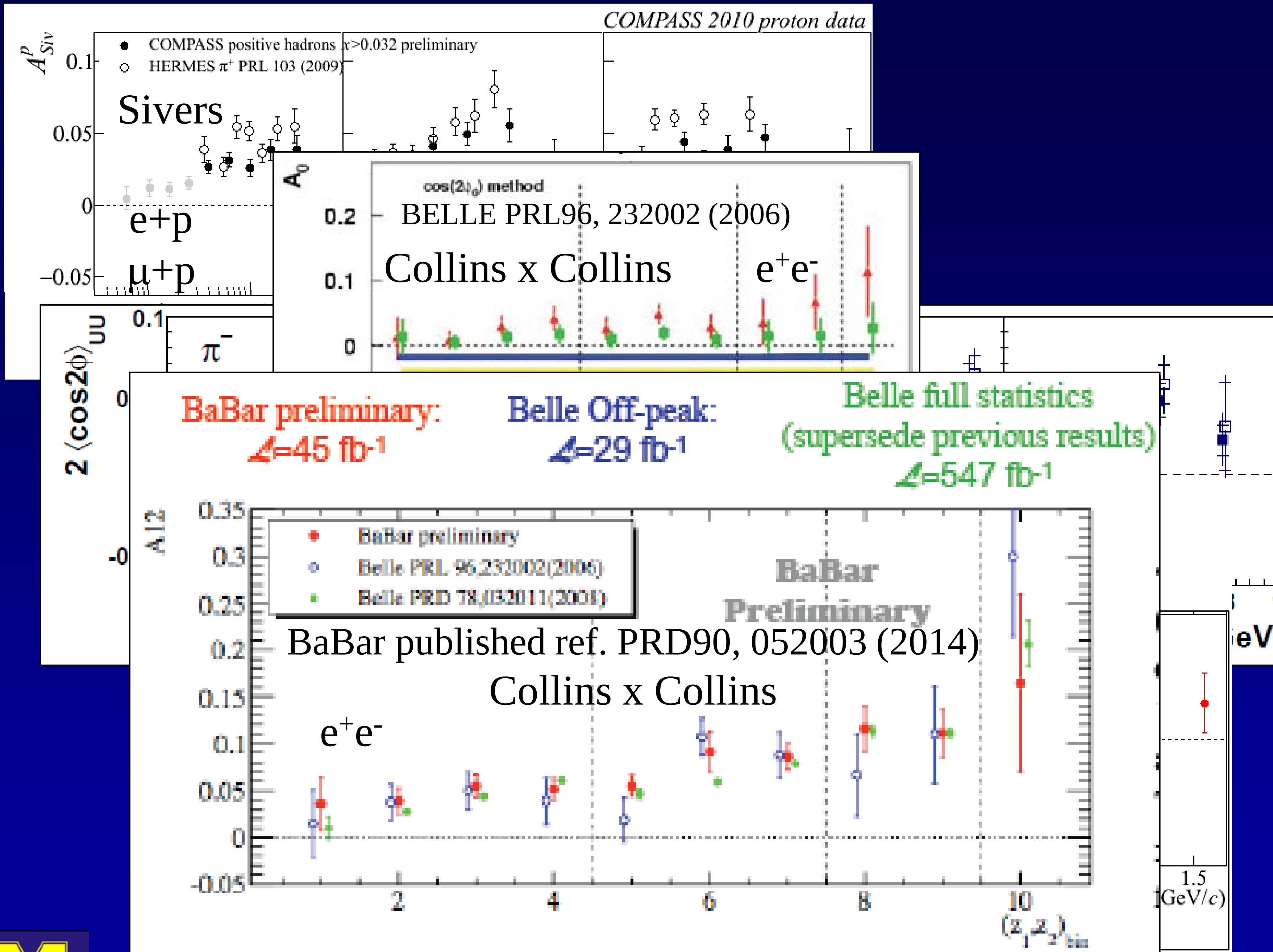

Boer-Mulders x Collins
π−
e+p
HERMES, PRD 87, 012010 (2013)
2 ⟨cos2ϕ⟩UU
0.1
0.05
0
-0.05
10−1
x
0.4
0.6
0.8
y
0.4
0.6
z
0.2
0.4
0.6
0.8
1
Ph⊥ [GeV]



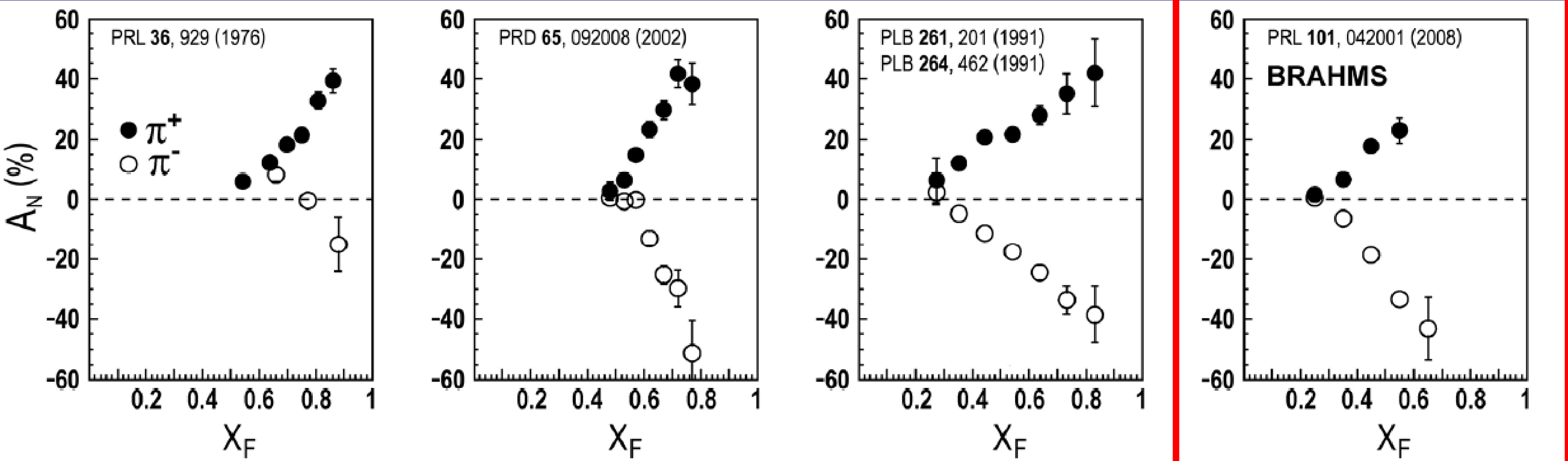
COMPASS 2010 proton data
A^p_{Siv}
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
$2\langle\cos 2\phi\rangle_{UU}$
π−
e+p
Boer-Mulders x Collins
HERMES, PRD 87, 012010 (2013)
A^p_{Coll}
COMPASS negative hadrons x>0.032 preliminary
HERMES π− PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
e+p
μ+p
x
z
p_T^h (GeV/c)
Transversity x Collins


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 ⟨cos2ϕ⟩UU
π−
(2013)
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
cos(2ϕ0) method
cos(ϕ1+ϕ2) method
A0
A12
z1,z2-bin-id
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

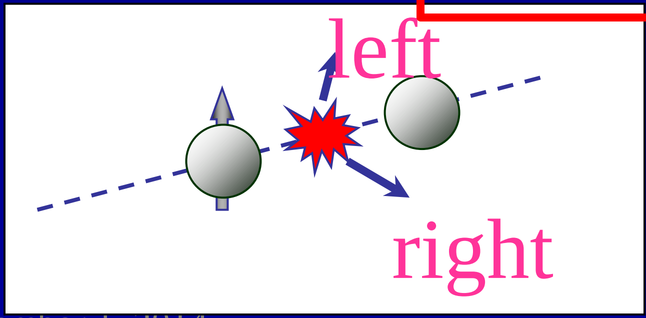

COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
cos(2φ0) method
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
BaBar preliminary:
ℒ=45 fb-1
Belle Off-peak:
ℒ=29 fb-1
Belle full statistics
(supersede previous results)
ℒ=547 fb-1
BaBar preliminary
Belle PRL 96,232002(2006)
Belle PRD 78,032011(2008)
BaBar
Preliminary
BaBar published ref. PRD90, 052003 (2014)
Collins x Collins
e+e-
A12
(z1,z2)bin

Transverse single-spin asymmetries: From low to high energies!

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



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



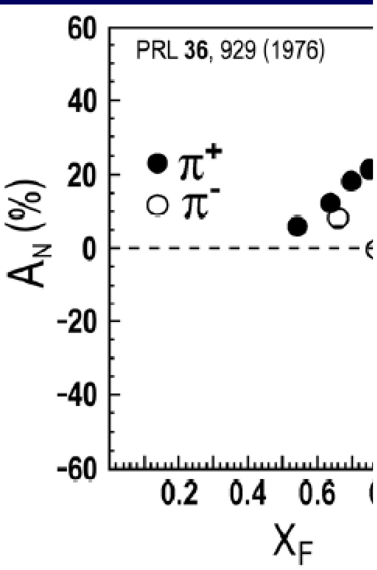
Transverse single-spin asymmetries: From low to high energies!

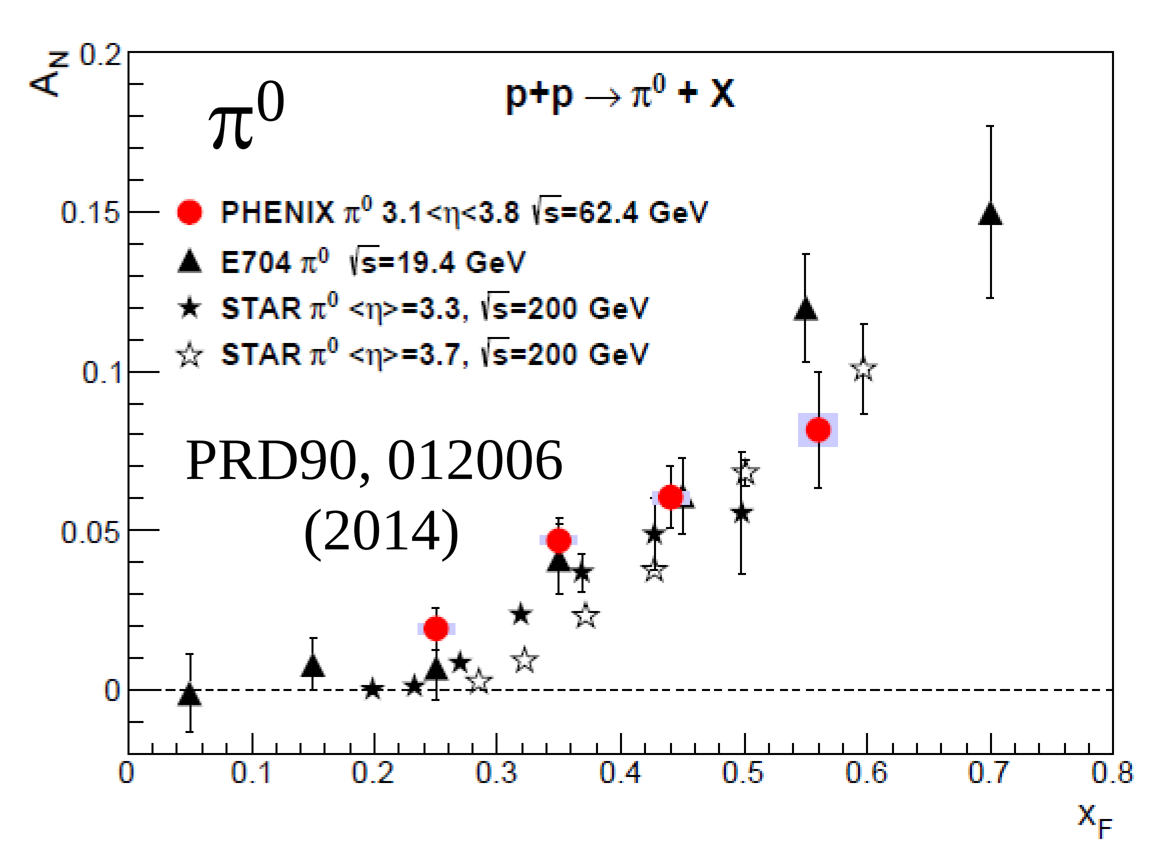
ANL $\sqrt{s}$=4.9 Ge

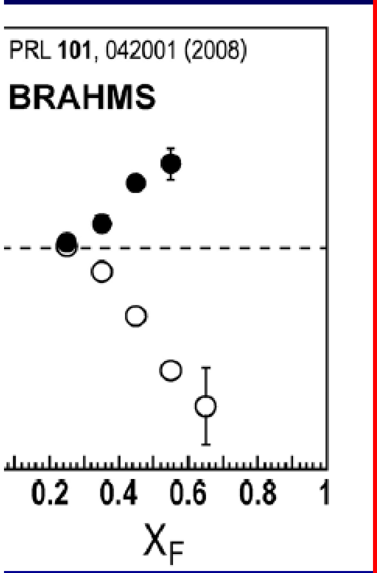
BNL

FNAL

RHIC $\sqrt{s}$=62.4 GeV



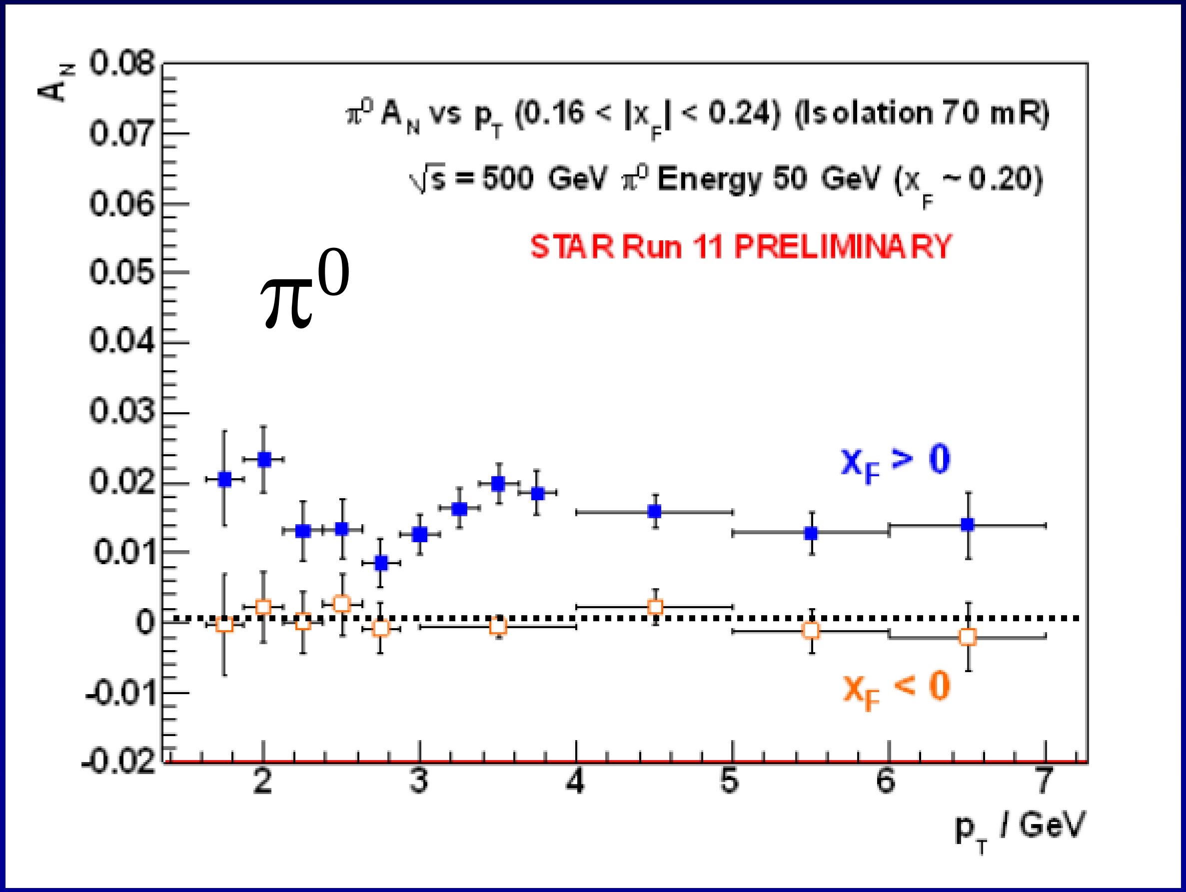




$x_F =$

right

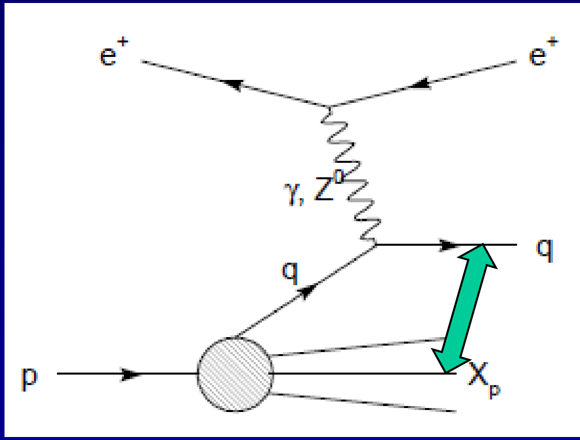
Effects persist up to transverse momenta of 7(!) GeV/c at $\sqrt{s}$=500 GeV



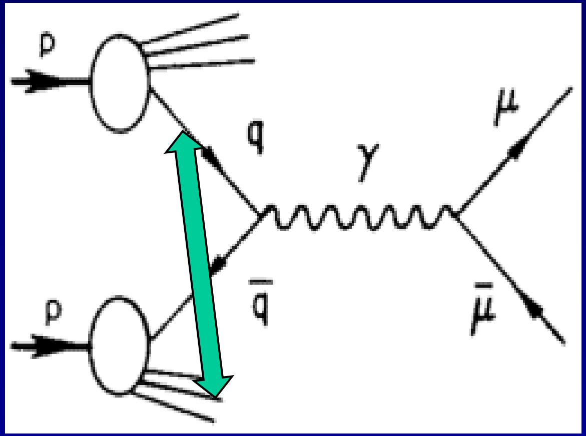
- Can try to interpret these non-perturbative effects within the framework of perturbative QCD.
- Haven't yet disentangled all the possible contributing effects to the (messy) process of p+p to pions

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

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



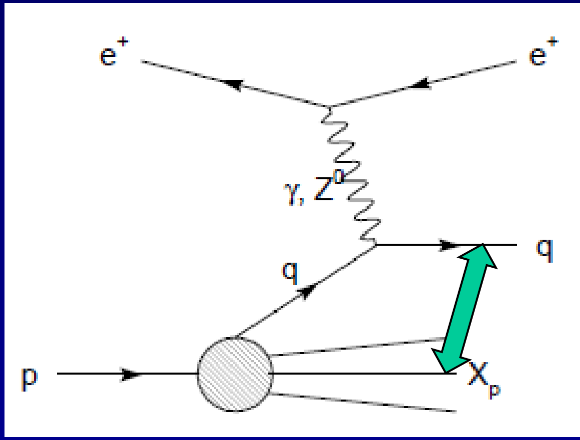
Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



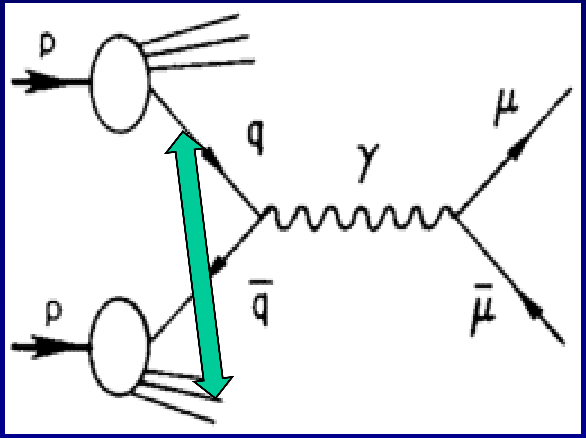
As a result, get *opposite sign* for the Sivers transverse-momentum-dependent pdf when measure in semi-inclusive DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

Modified universality of T-odd 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

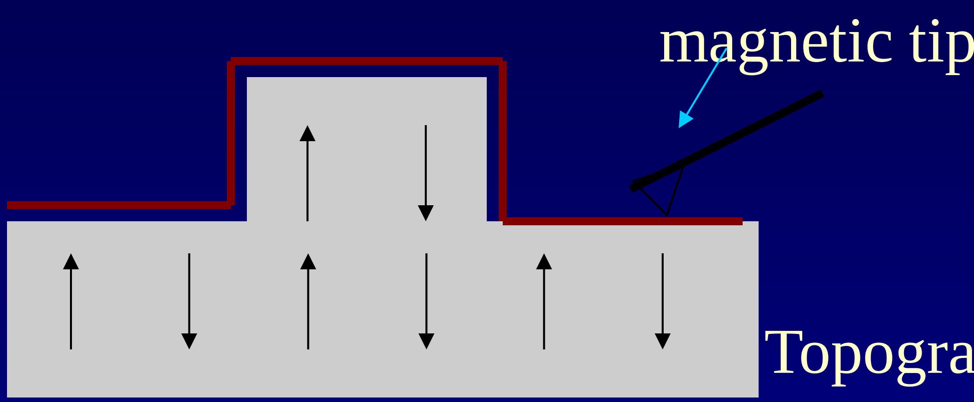


Still waiting for a polarized quark-antiquark annihilation measurement to compare to existing lepton-nucleon scattering measurements . . .

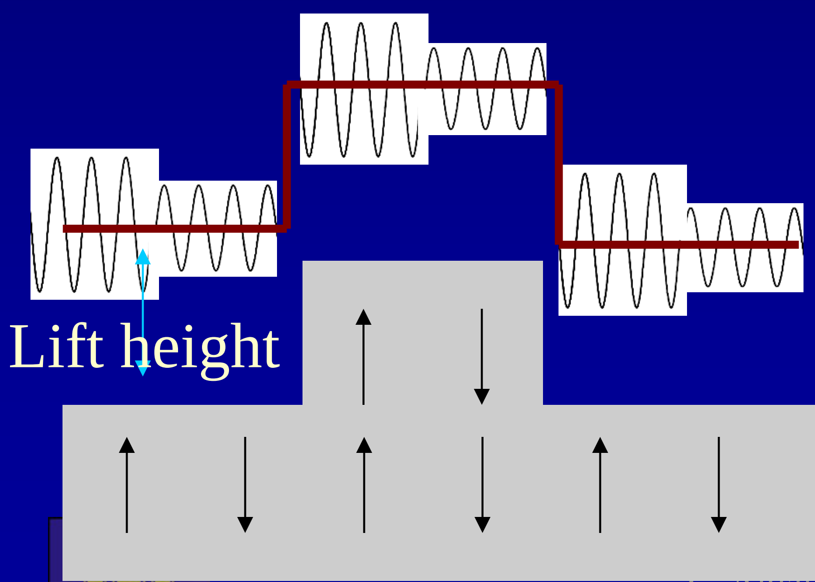
What things "look" like depends on how you "look"!

Slide courtesy of K. Aidala

Magnetic Force Microscopy

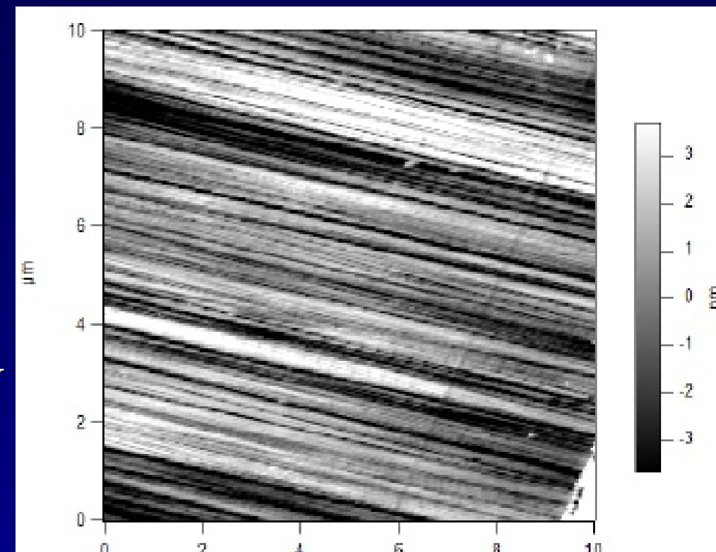


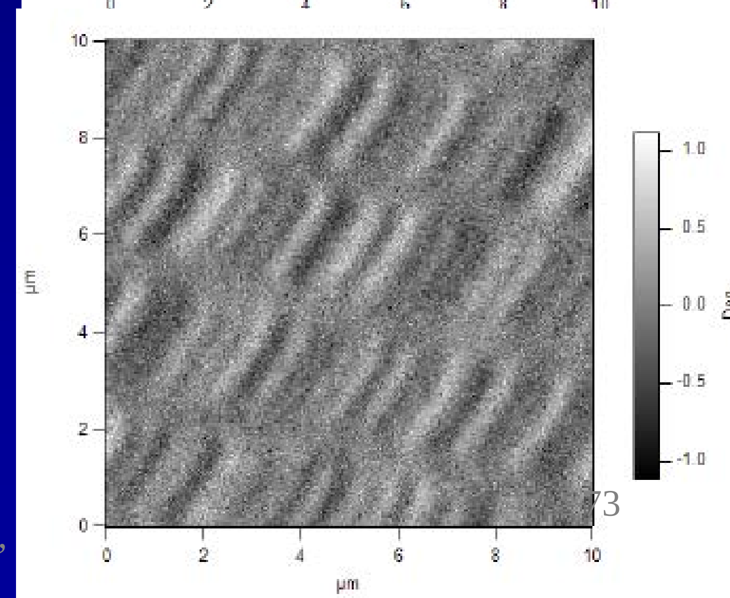
Topography



Magnetism

Computer Hard Drive





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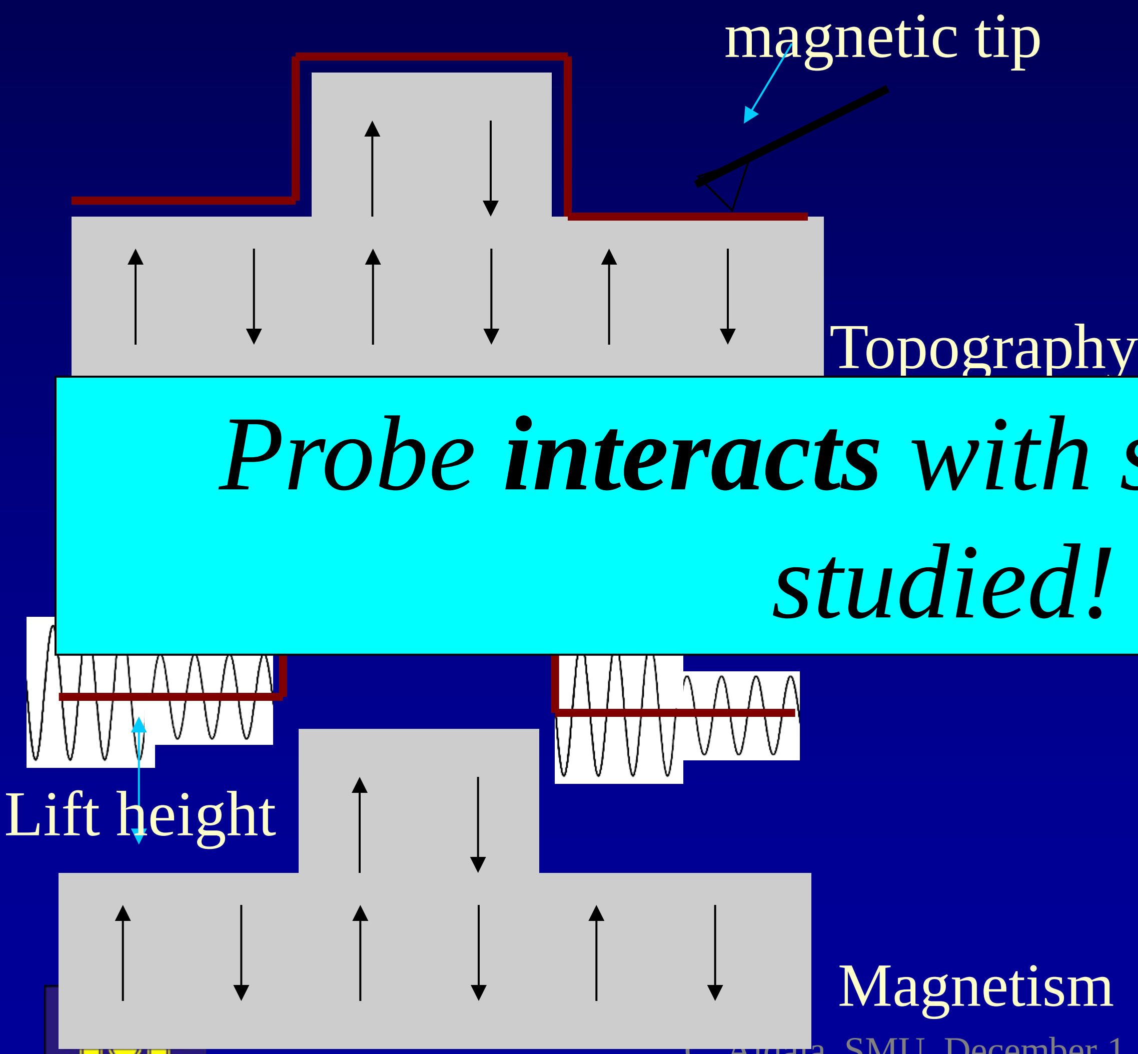
Magnetic Force Microscopy



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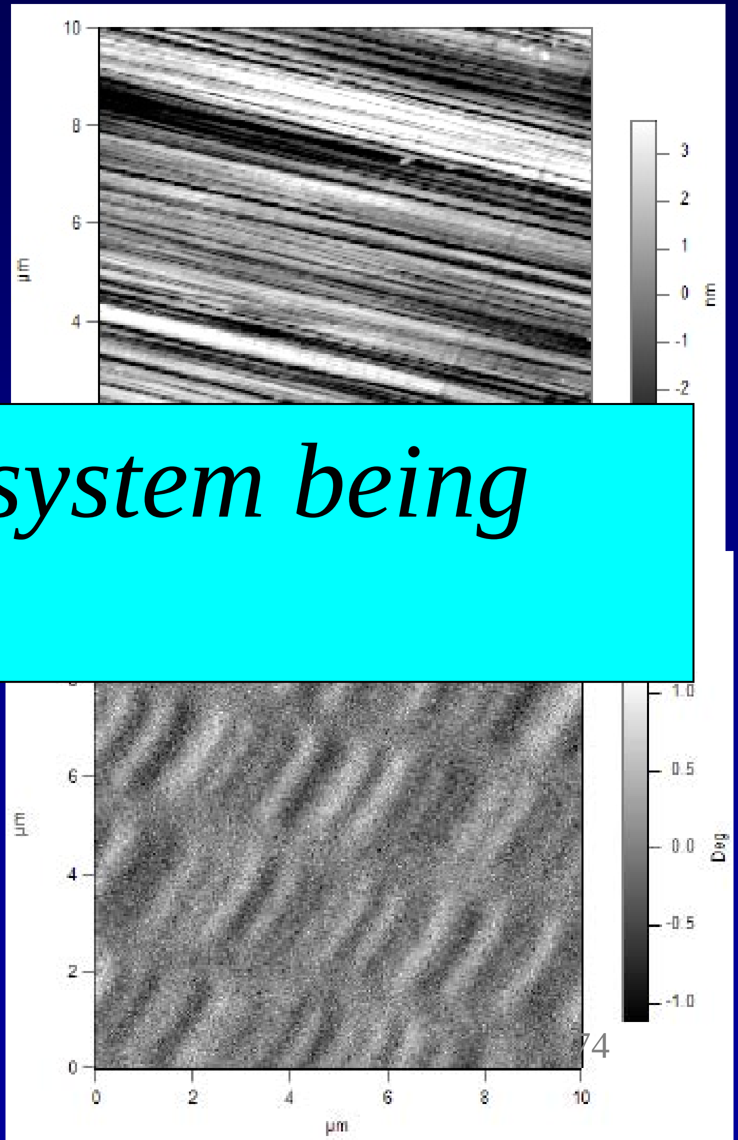


*Probe **interacts** with system being studied!*

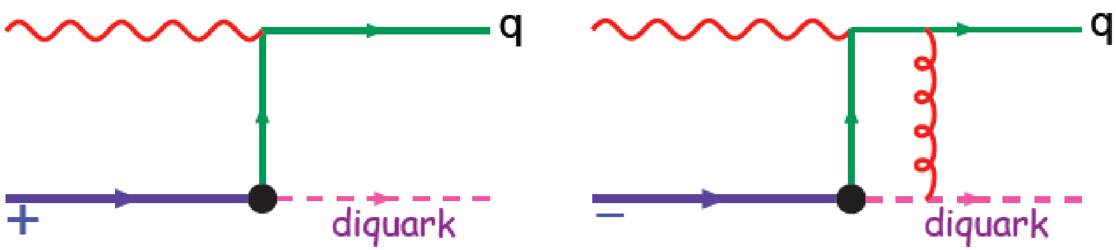
Modified universality requires full QCD: Gauge-invariant quantum field theory

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].

Collins, 1993

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.

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

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)

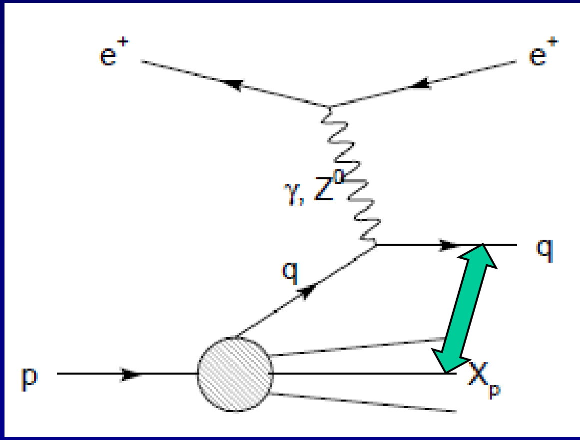
Physics Today, September 2009 :
The Aharonov–Bohm effects: Variations on a subtle theme,
by Herman Batelaan and Akira Tonomura.

“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.”

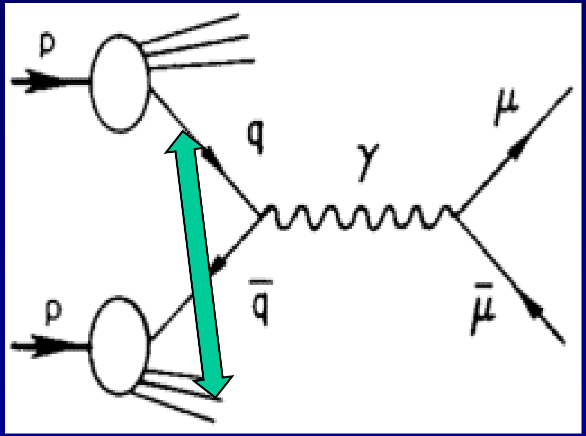
See e.g. Pijlman, hep-ph/0604226 or Sivers, arXiv:1109.2521

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

Deep-inelastic lepton-nucleon scattering:
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)

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:
Attractive final-state interactions

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

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 non-Abelian nature of the gauge group

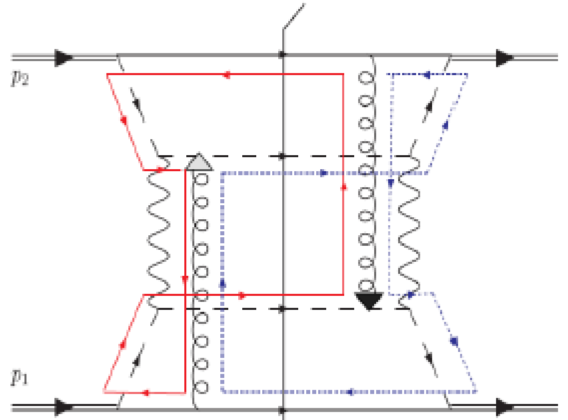
As

mo **ive**

DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

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!



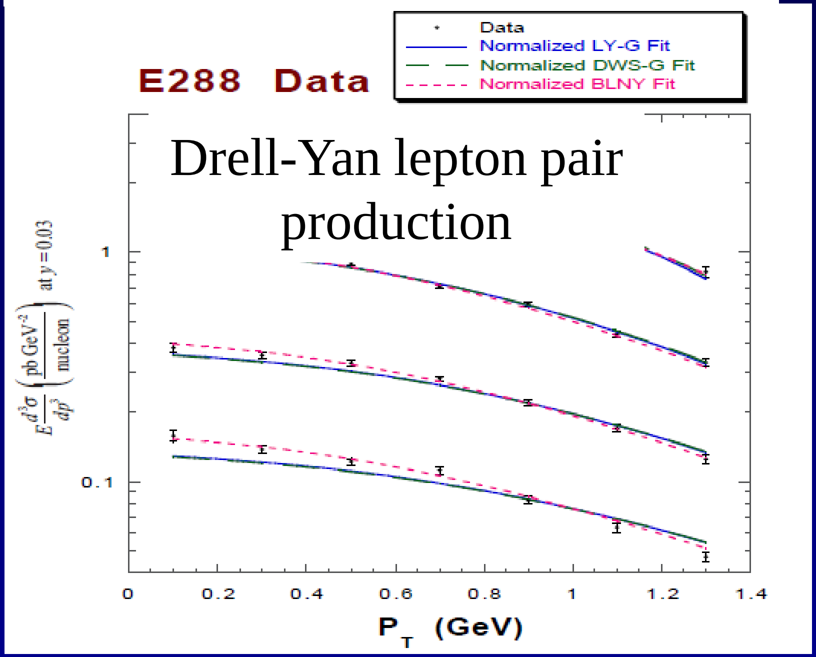
PRD 81:094006 (2010)

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

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

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

Landry, Brock, Nadolsky, Yuan, 2002

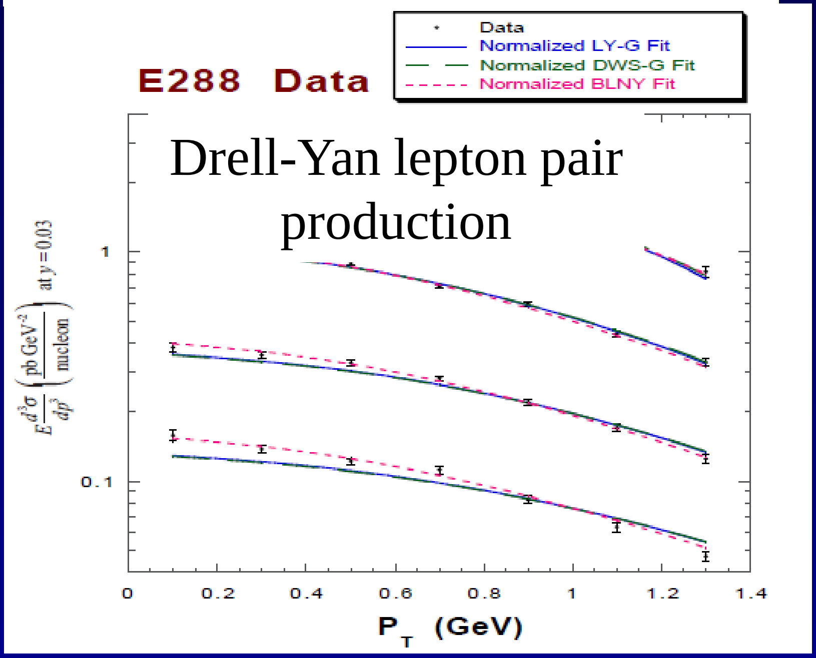


p+A → $\mu^+ + \mu^- + X$ for different invariant masses: No color entanglement expected

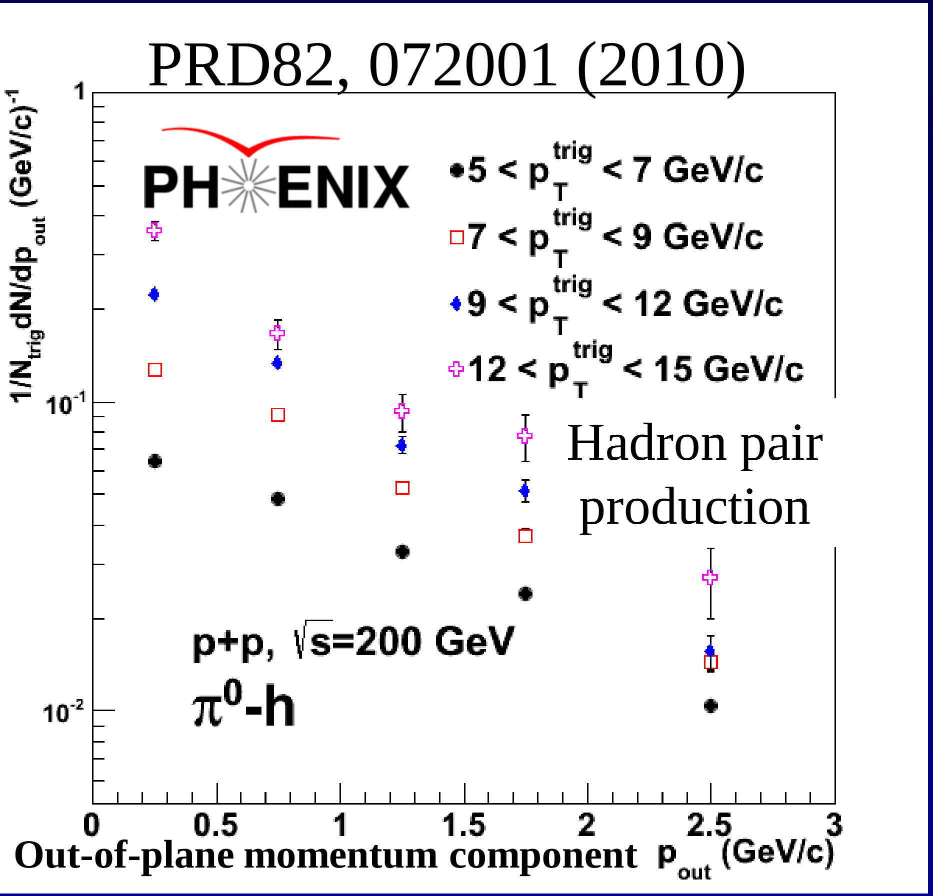
Get predictions from fits to data where no entanglement expected

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

Landry, Brock, Nadolsky, Yuan, 2002



Get predictions from fits to data where no entanglement expected



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

Summary and outlook

- We still have a ways to go from the quarks and gluons of QCD to full descriptions of the protons and nuclei of the world around us!
- After an initial "discovery and deveopment" period lasting ~30 years, we're now taking early steps into an exciting new era of *quantitative QCD!*
- Work related to the intrinsic transverse momentum of quarks within the proton has opened up a whole new research area focused on spin-momentum correlations and parton dynamics in QCD, and brought to light fundamental predictions of process-dependent pdfs and color entanglement across QCD bound states

Summary and outlook

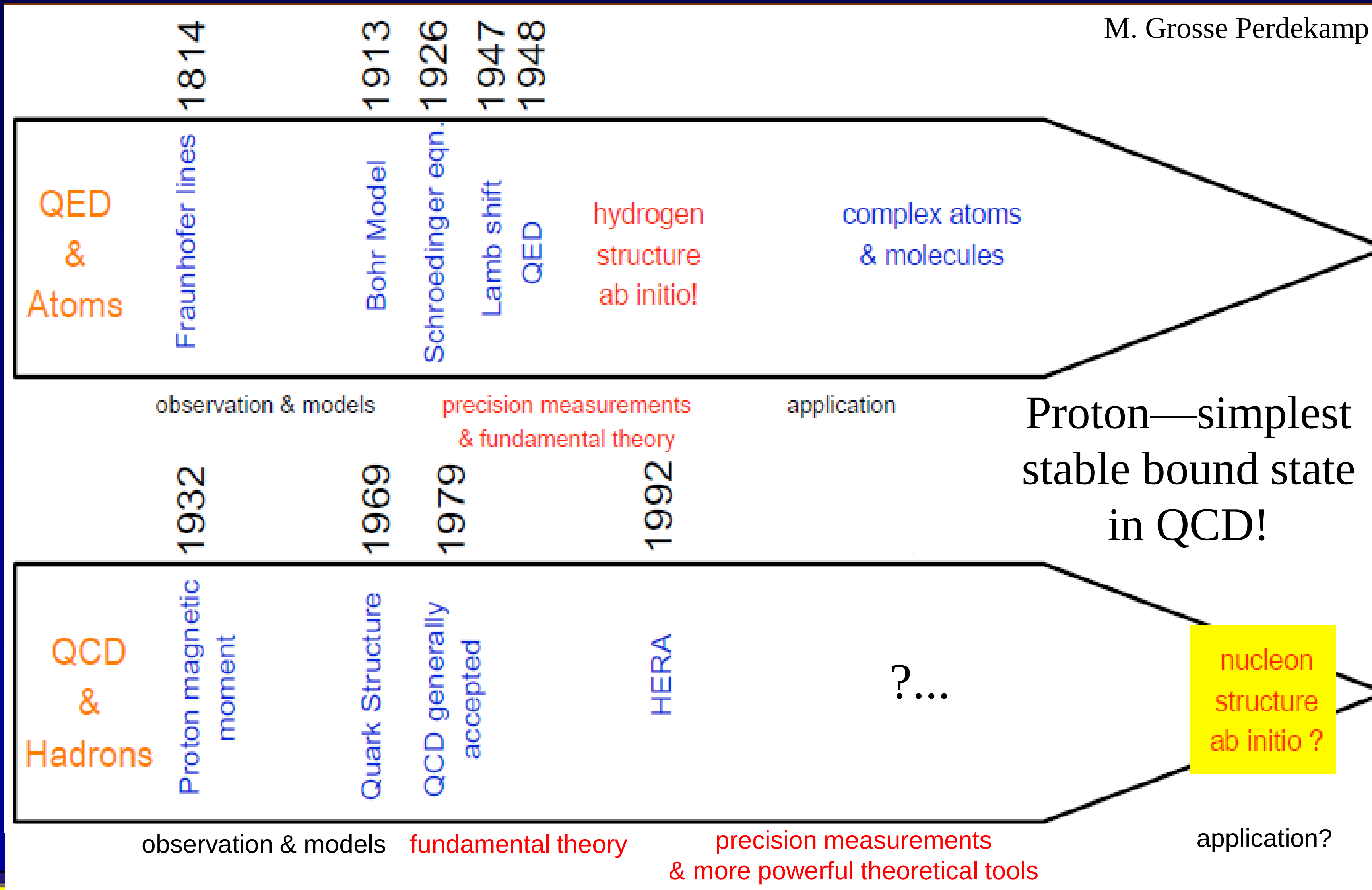
- We still have a ways to go from the quarks and gluons

There's a large and diverse community of people—at RHIC and complementary facilities—driven to continue coaxing the secrets out of one of the most fundamental building blocks of the world around us.

- quarks within the proton has opened up a whole new research area focused on spin-momentum correlations and parton dynamics in QCD, and brought to light fundamental predictions of process-dependent pdfs and color entanglement across QCD bound states

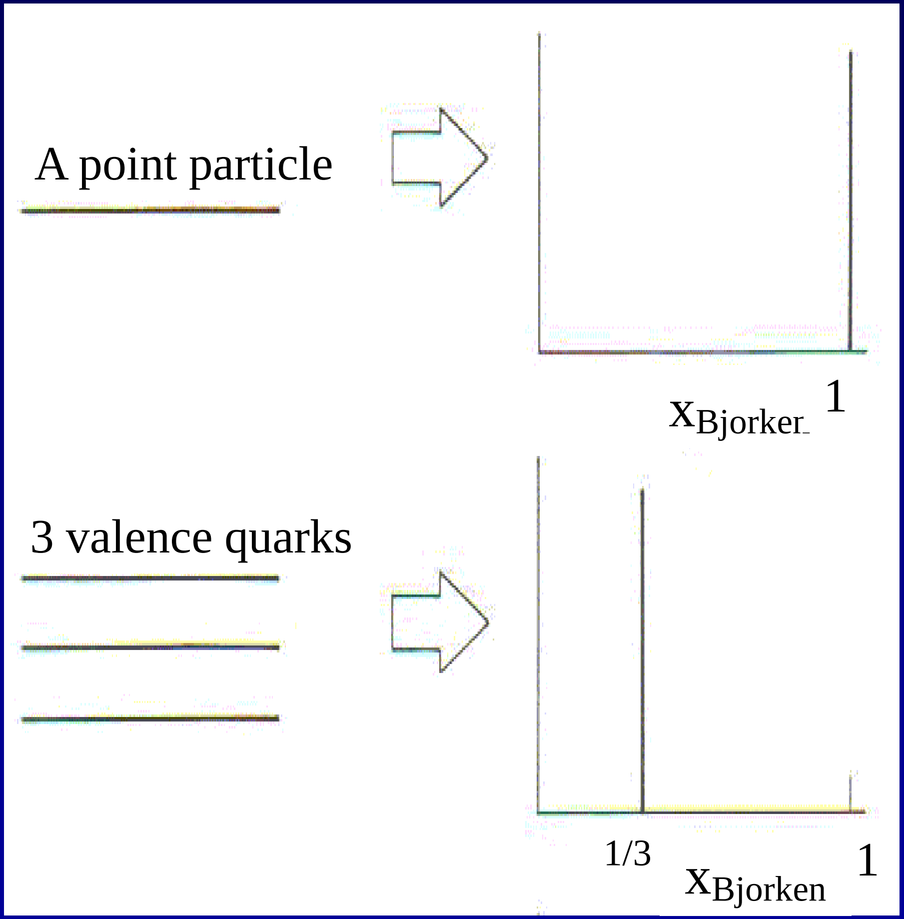
Additional Material

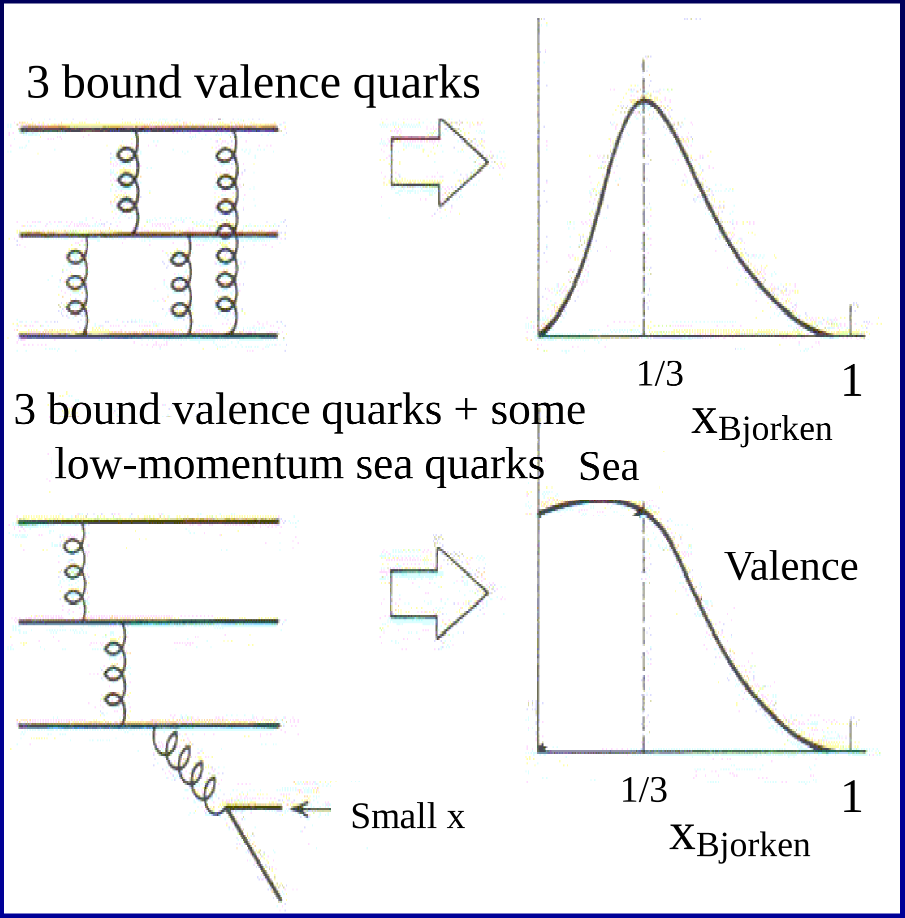
The proton as a QCD "laboratory"



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

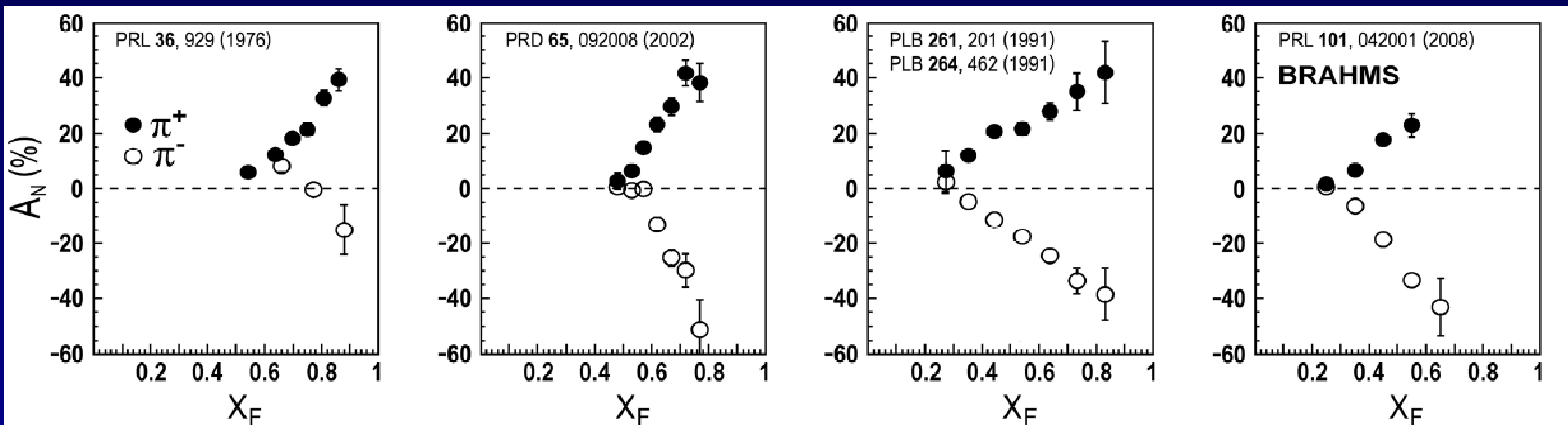
What momentum fraction would the scattering particle carry if the proton were made of …





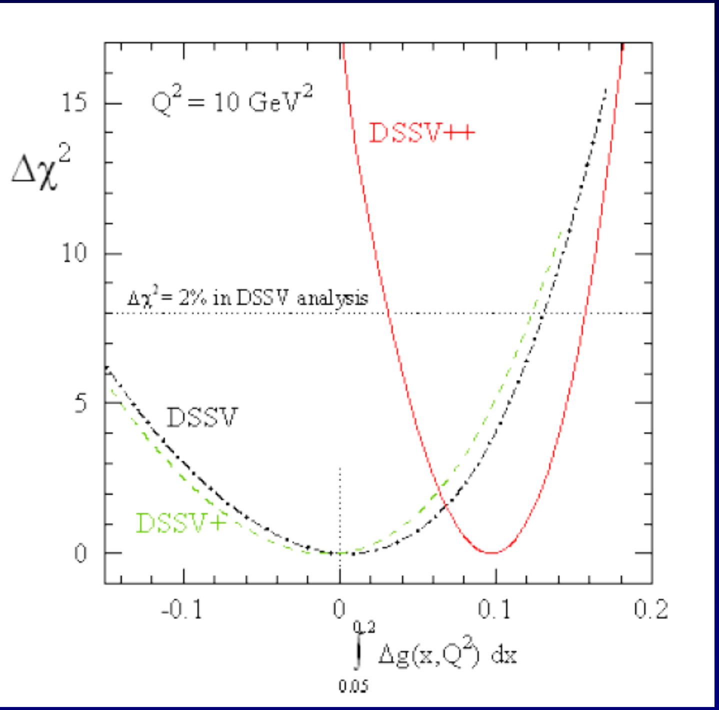
Halzen and Martin, "Quarks and Leptons", p. 201

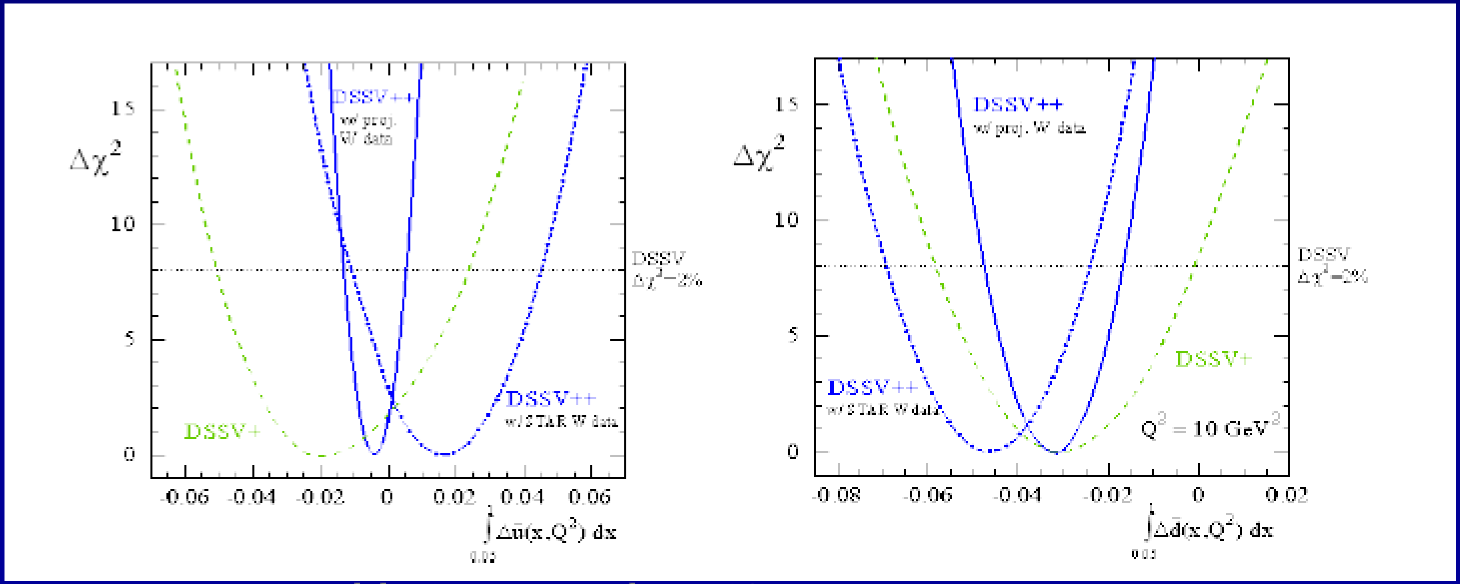
Consequences of QCD as a non-Abelian gauge theory: New predictions emerging



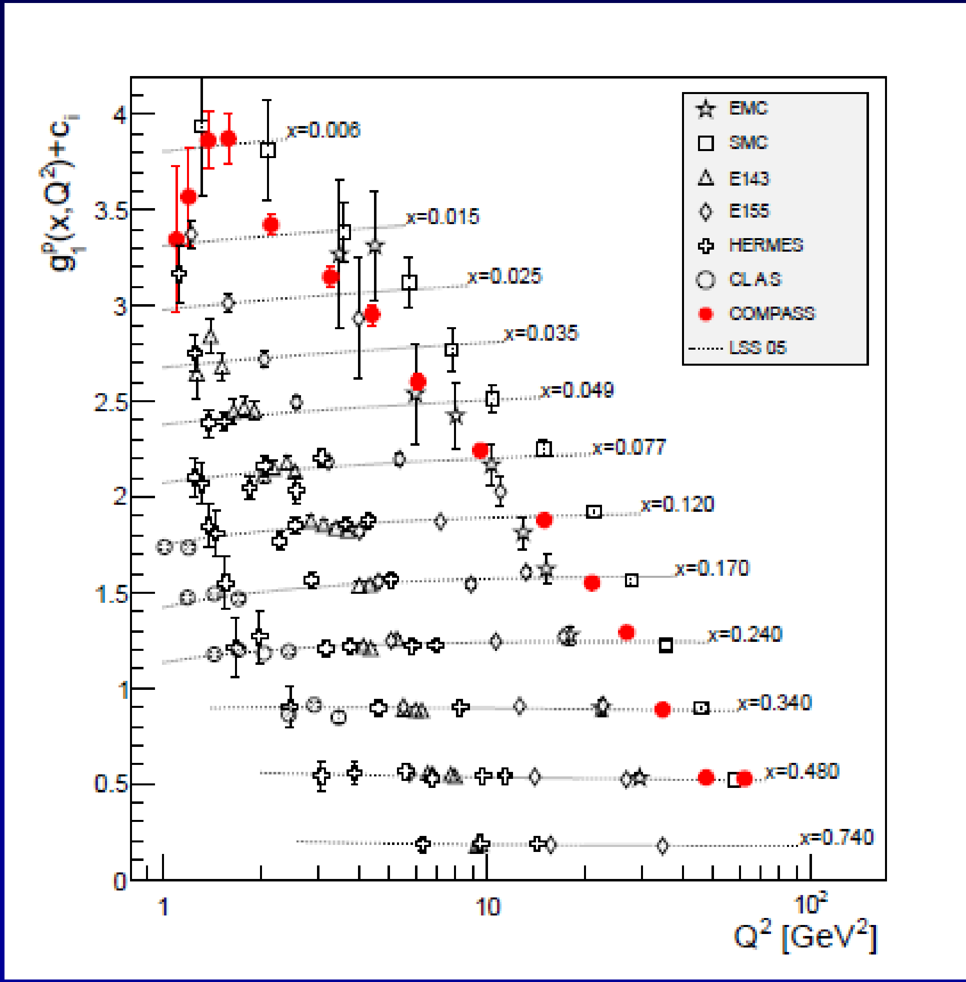
on the right track?

Improvements in knowledge of gluon and sea quark spin contributions from RHIC data

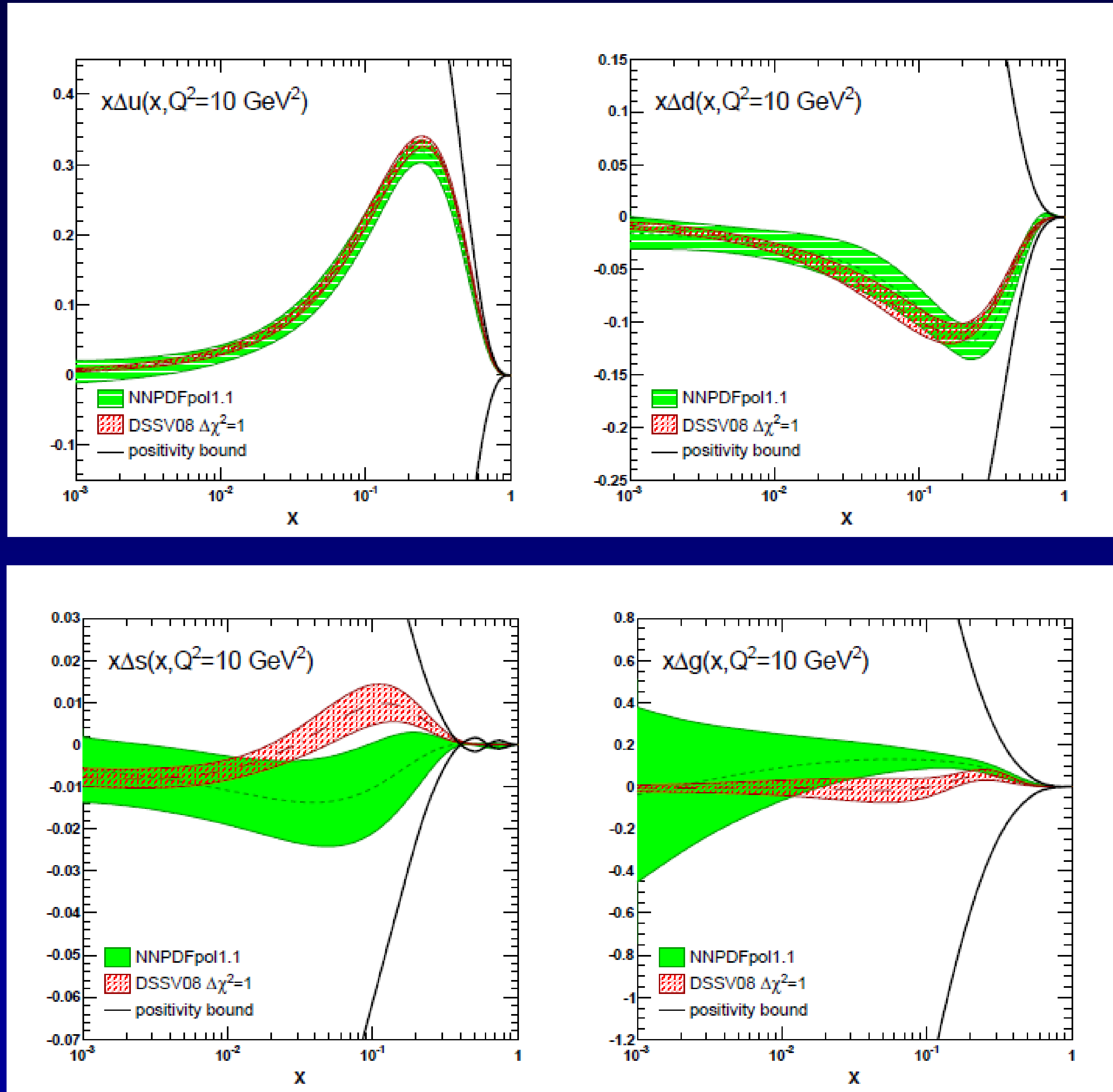




World data on polarized proton structure function

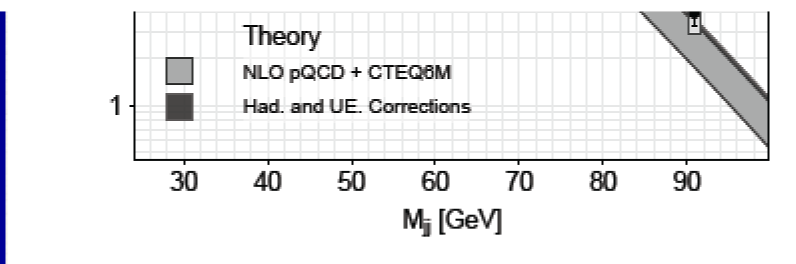


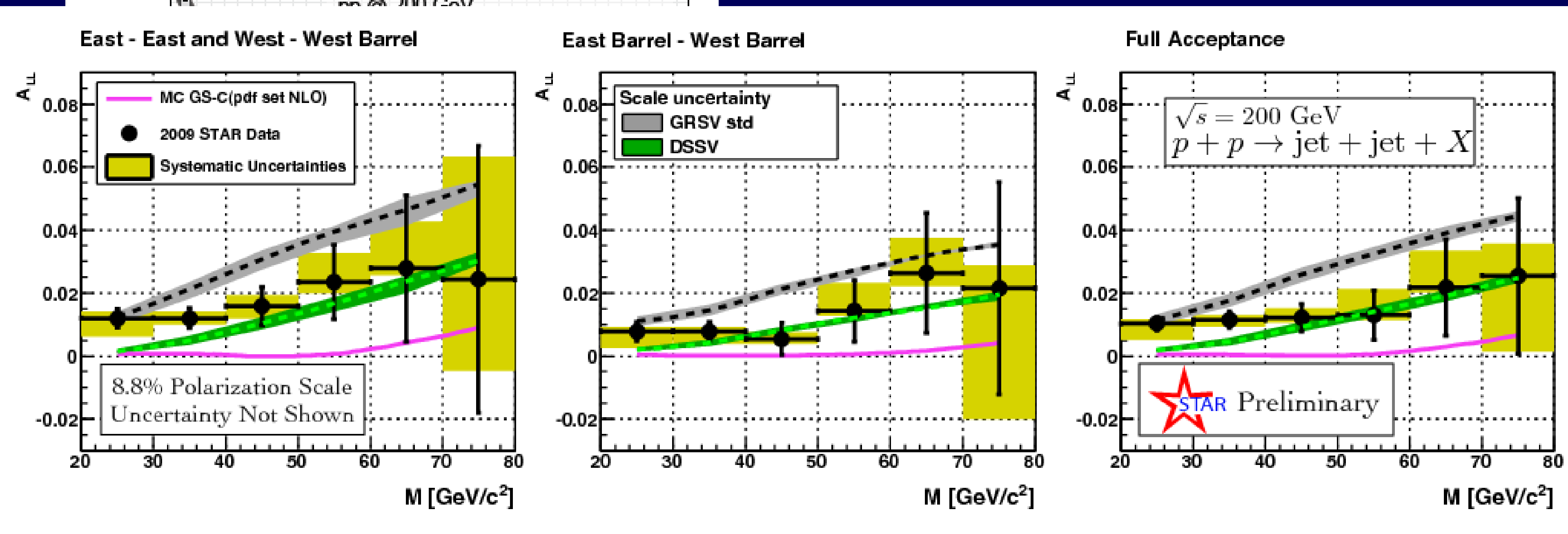
NNPDF, NPB 887.276 (2014)



Dijet Cross Section and Double Helicity Asymmetry

- Dijets as a function of

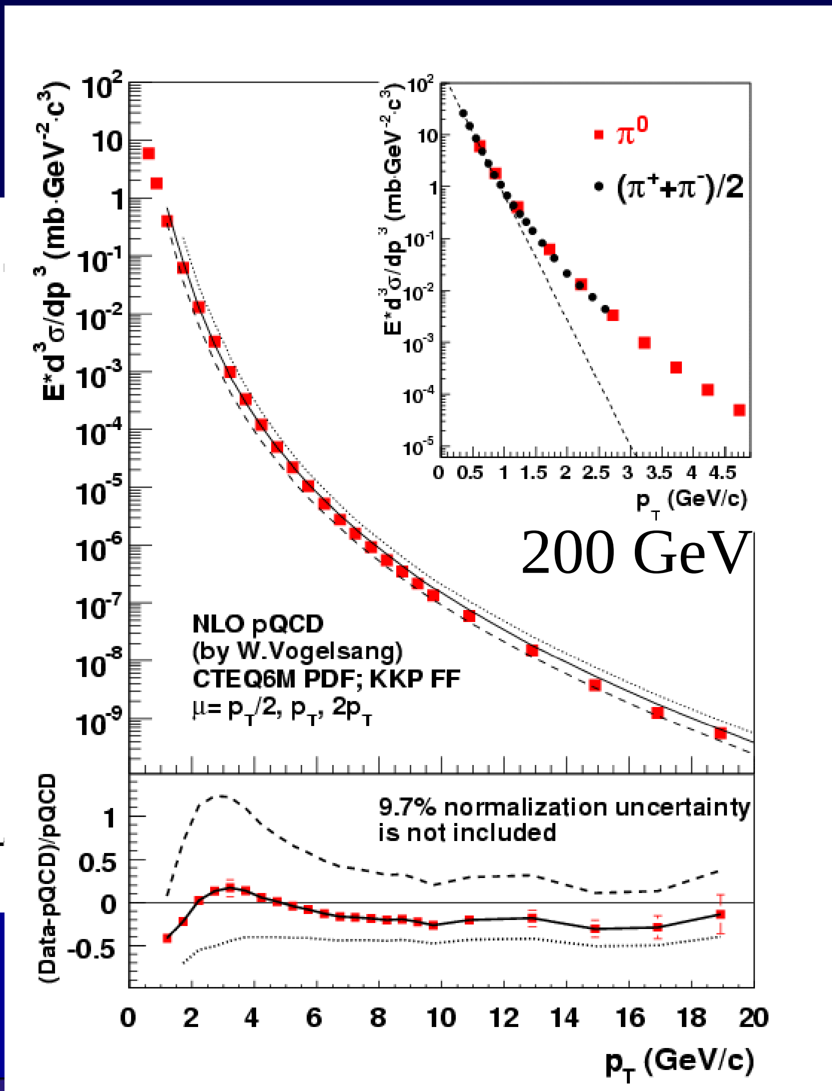




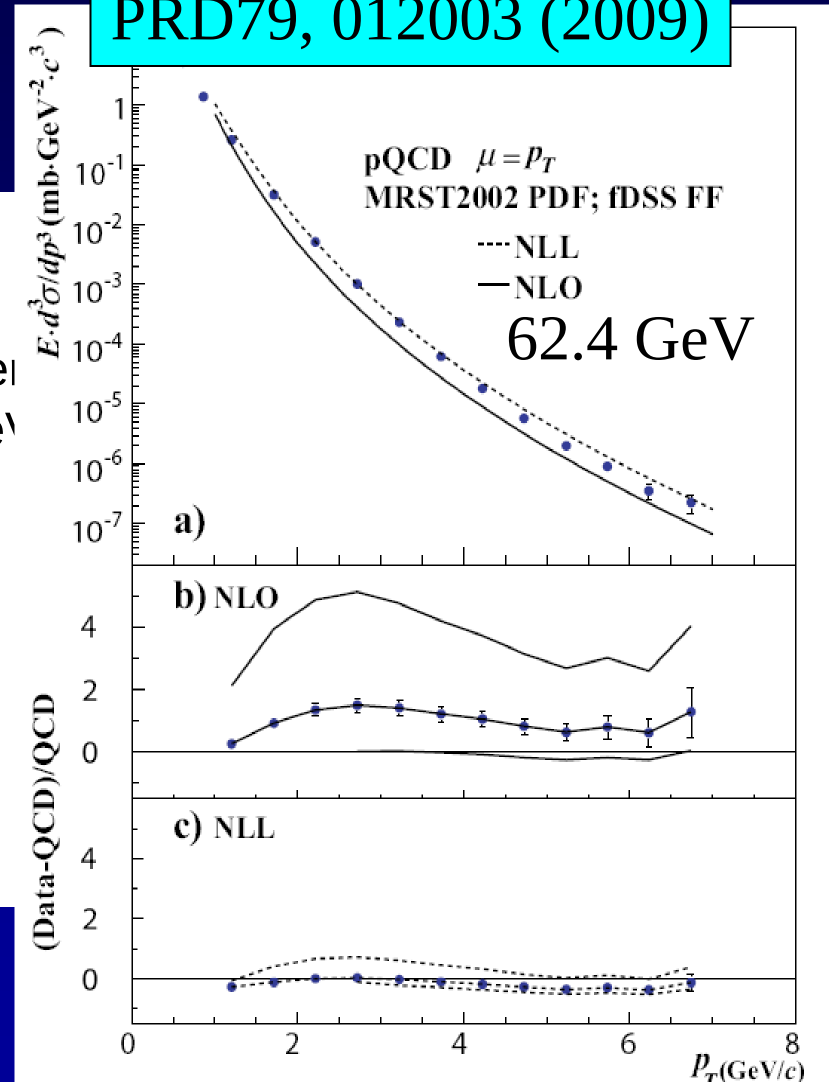
Fragmentation Functions (FF's): Improving Our Input for Inclusive Hadronic Probes

- FF's not directly calculable from theory—need to be measured and fitted experimentally
- The better we know the FF's, the tighter constraints we can put on the polarized parton distribution functions!
- Traditionally from e+e- data—clean system!
- Framework now developed to extract FF's using all available data from deep-inelastic scattering and hadronic collisions as well as e+e-
  - de Florian, Sassot, Stratmann: PRD75:114010 (2007) and arXiv:0707.1506

Extending x Coverage

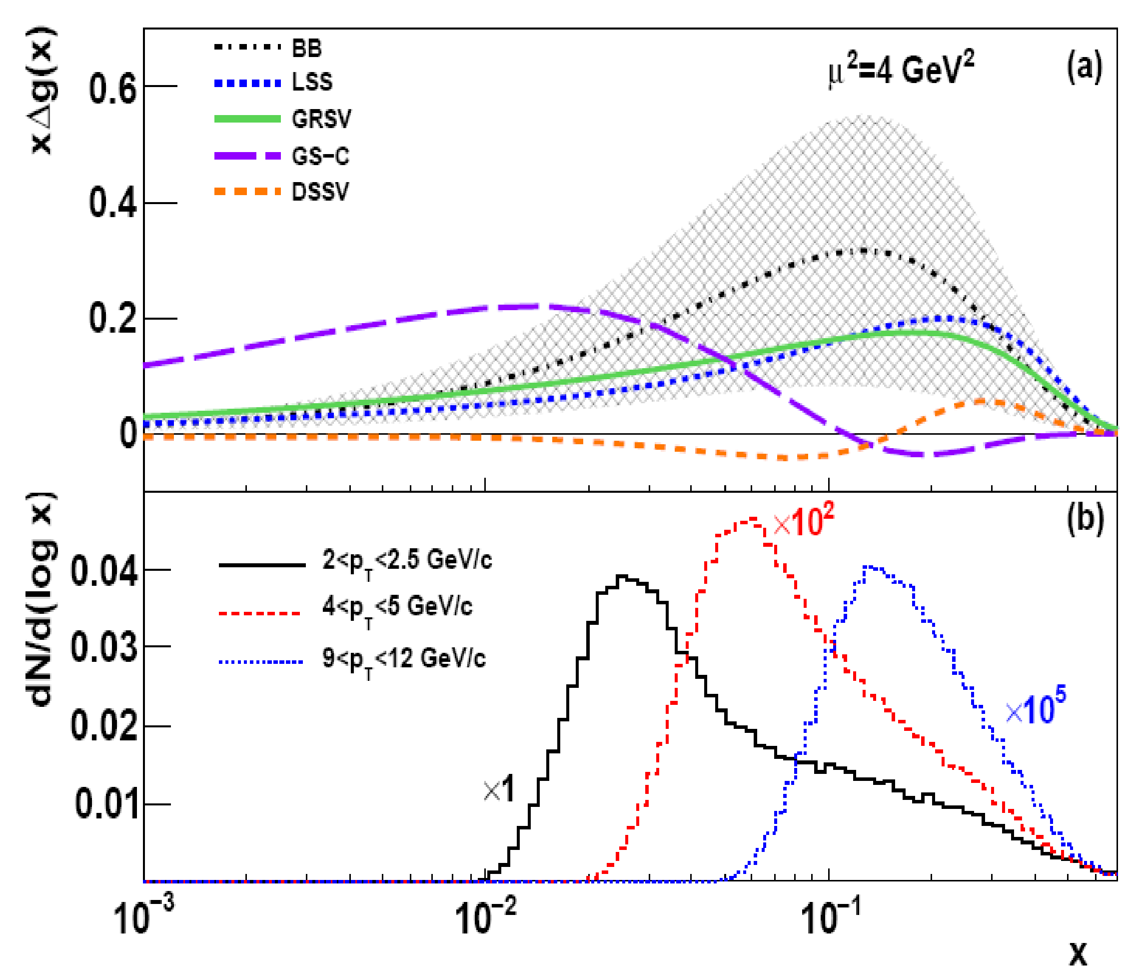


PRD79, 012003 (2009)



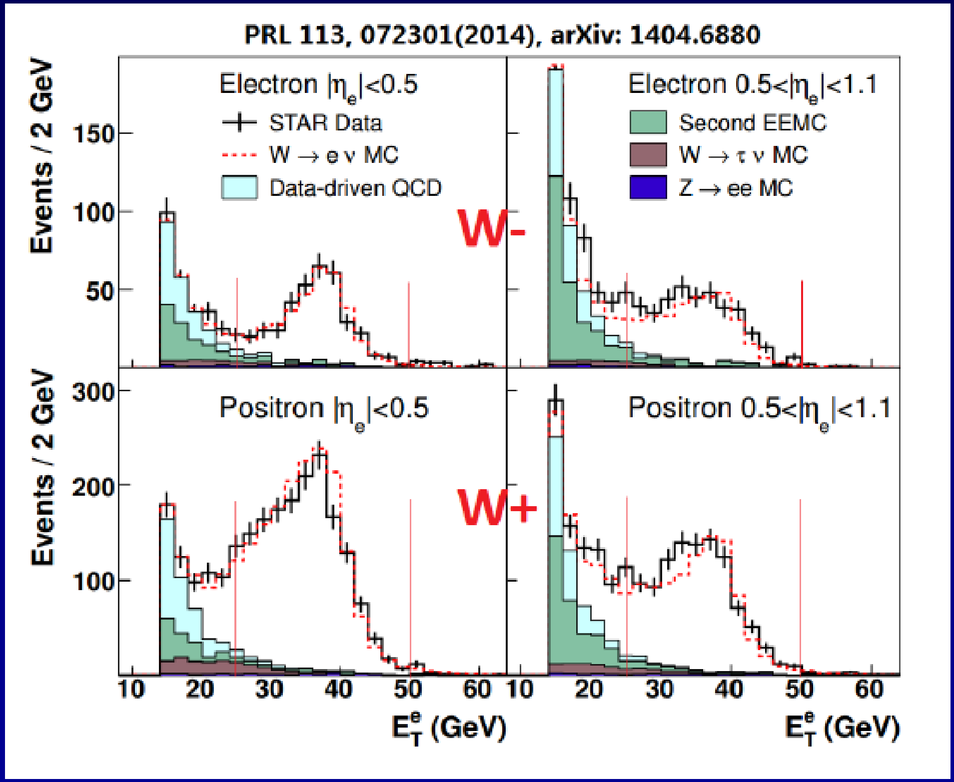
Sampling the Integral of ΔG: π^0 p_T vs. x_{gluon}

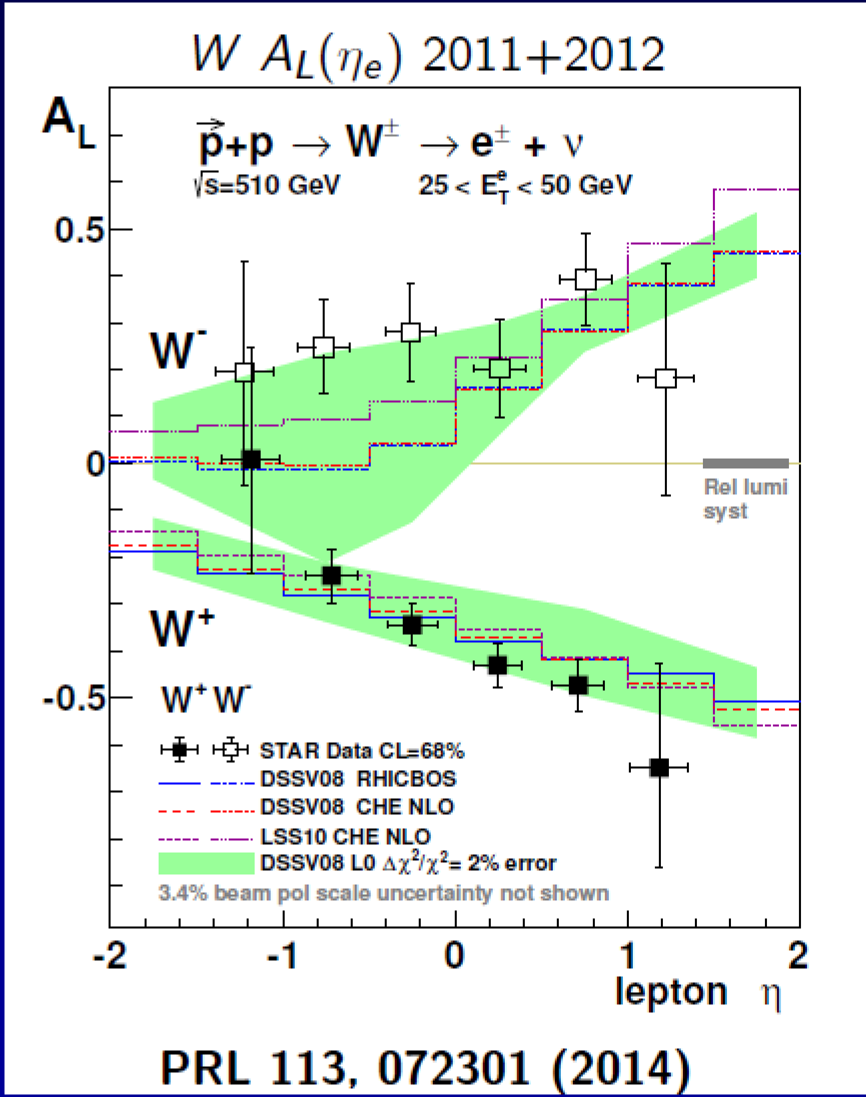
Inclusive asymmetry measurements in p+p collisions sample from wide bins in *x*—sensitive to (truncated) integral of ΔG, not to functional form vs. *x*



Based on simulation using NLO pQCD as input

PRL 103, 012003 (2009)

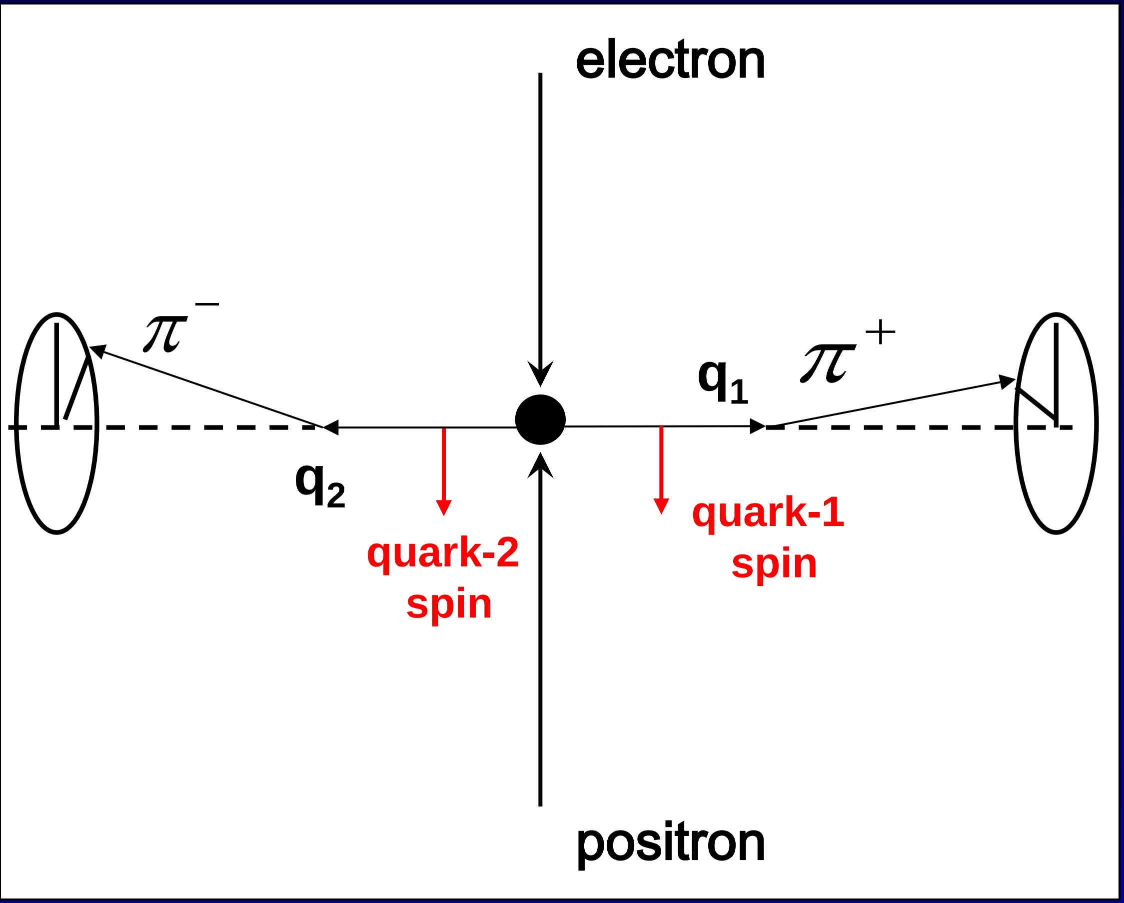

PRL 113, 072301(2014), arXiv: 1404.6880
Electron $|\eta_e|<0.5$
STAR Data
$W \to e\nu$ MC
Data-driven QCD
Electron $0.5<|\eta_e|<1.1$
Second EEMC
$W \to \tau\nu$ MC
$Z \to ee$ MC
W-
Positron $|\eta_e|<0.5$
Positron $0.5<|\eta_e|<1.1$
W+
Events / 2 GeV
E_T^e (GeV)


$W\ A_L(\eta_e)$ 2011+2012
A_L
$\vec{p}+p \to W^\pm \to e^\pm + \nu$
$\sqrt{s}$=510 GeV
$25 < E_T^e < 50$ GeV
W^-
W^+
Rel lumi syst
$W^+ W^-$
STAR Data CL=68%
DSSV08 RHICBOS
DSSV08 CHE NLO
LSS10 CHE NLO
DSSV08 L0 $\Delta\chi^2/\chi^2$= 2% error
3.4% beam pol scale uncertainty not shown
lepton η
PRL 113, 072301 (2014)

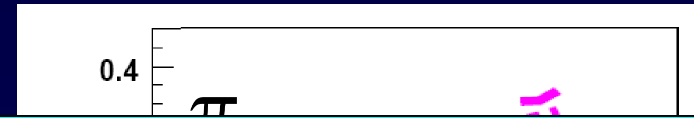
Longitudinal (Helicity) vs. Transverse Spin Structure

- Transverse spin structure of the proton cannot be deduced from longitudinal (helicity) structure
  - Spatial rotations and Lorentz boosts don't commute!
  - Only the same in the non-relativistic limit
- Transverse structure linked to intrinsic parton transverse momentum (k_T) and orbital angular momentum!

The Collins Effect Must be Present In e^+e^- Annihilation into Quarks!

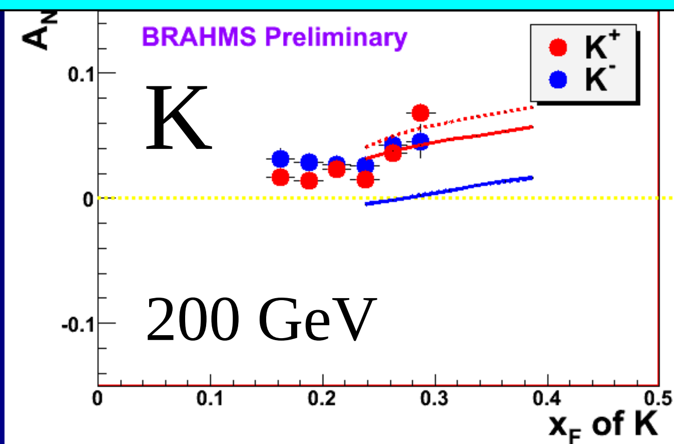


Collins effect in e+e-
Quark fragmentation
will lead to effects
in di-hadron correlation
measurements!

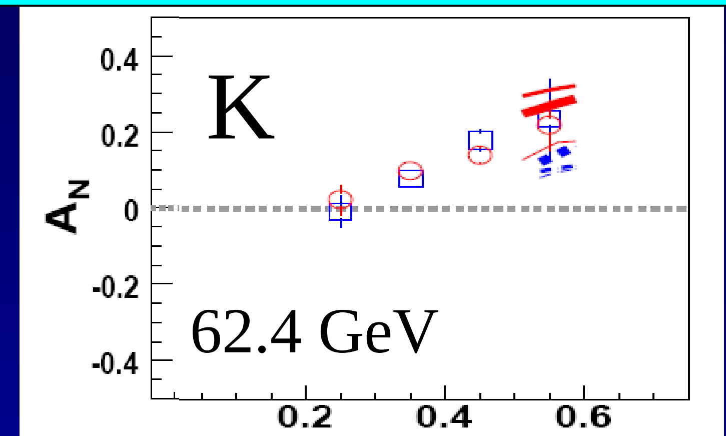


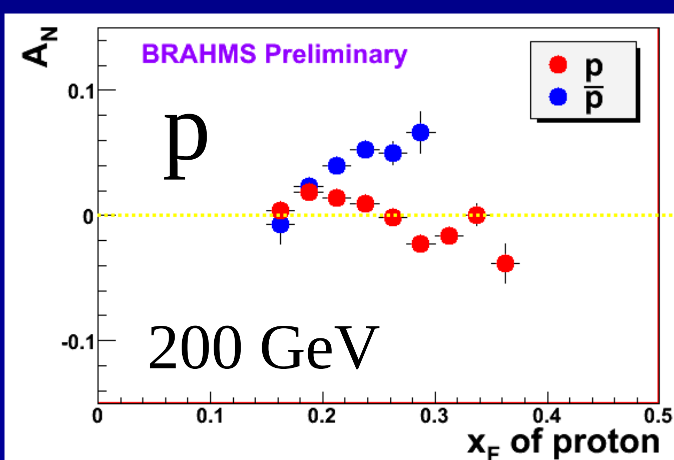
Pattern of pion species asymmetries in the forward direction → valence quark effect.

But this conclusion confounded by kaon and antiproton asymmetries!

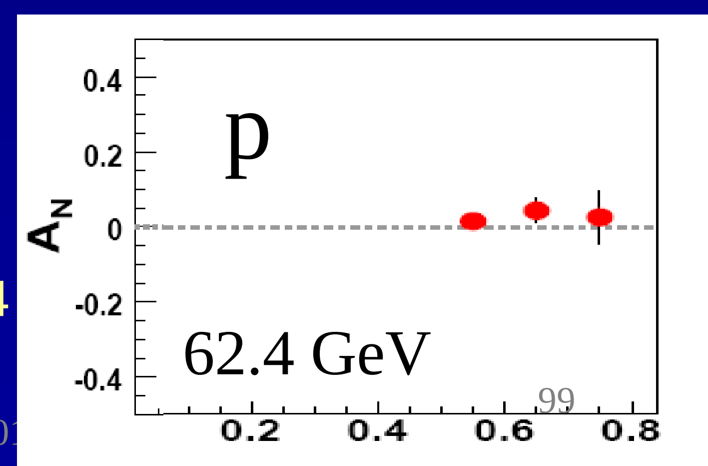


K- asymmetries underpredicted





Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement



Another Surprise: Transverse Single-Spin Asymmetry in Eta Meson Production

$$p^{\uparrow} + p \rightarrow \eta + X \quad \sqrt{s} = 200\ \text{GeV}$$

$\eta \rightarrow$

Larg

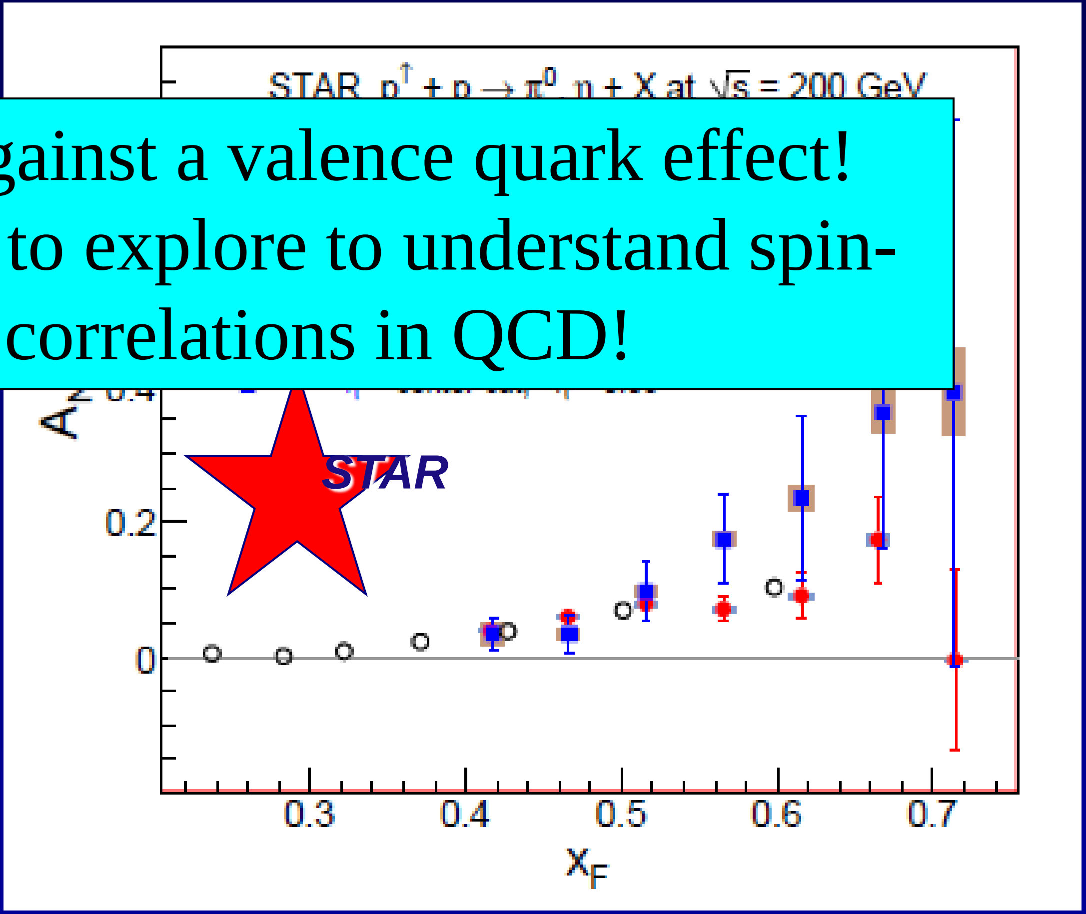
$.55 < x_F < .75$

$$\langle A_N \rangle_{\eta} = 0.361 \pm 0.064$$

$$\langle A_N \rangle_{\pi} = 0.078 \pm 0.018$$

$$\pi^0 \equiv \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$

$$\eta \equiv \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$$

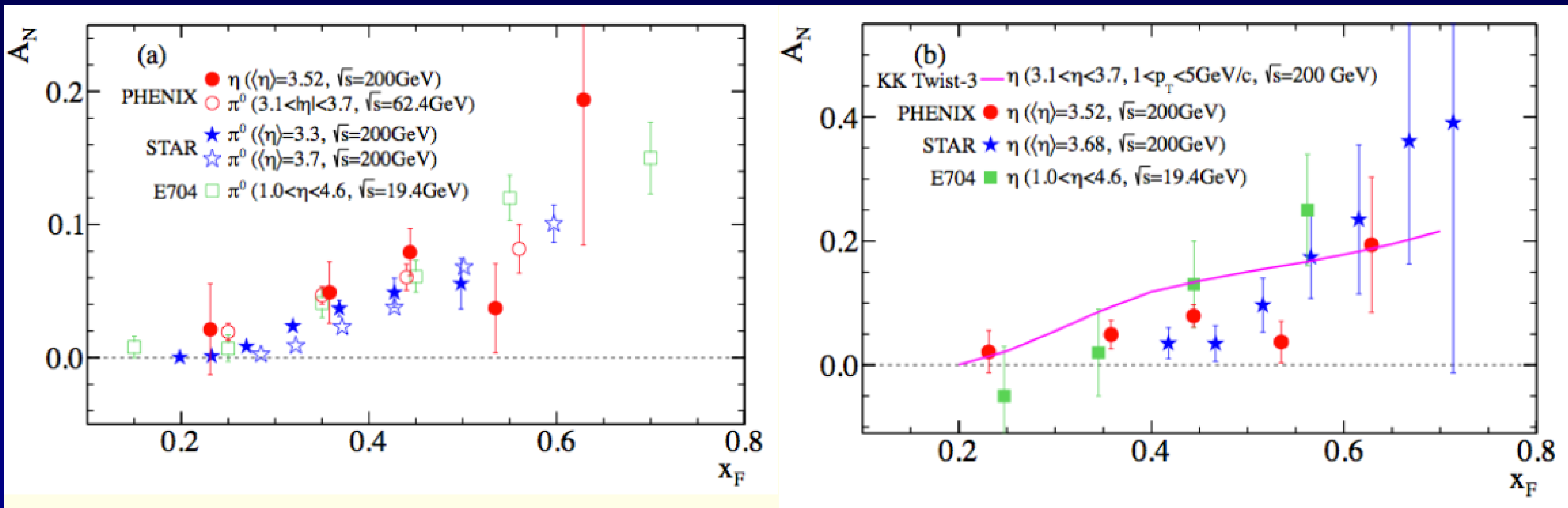


Further evidence against a valence quark effect!
Lots of territory still to explore to understand spin-momentum correlations in QCD!

PRD 86:051101 (2012)

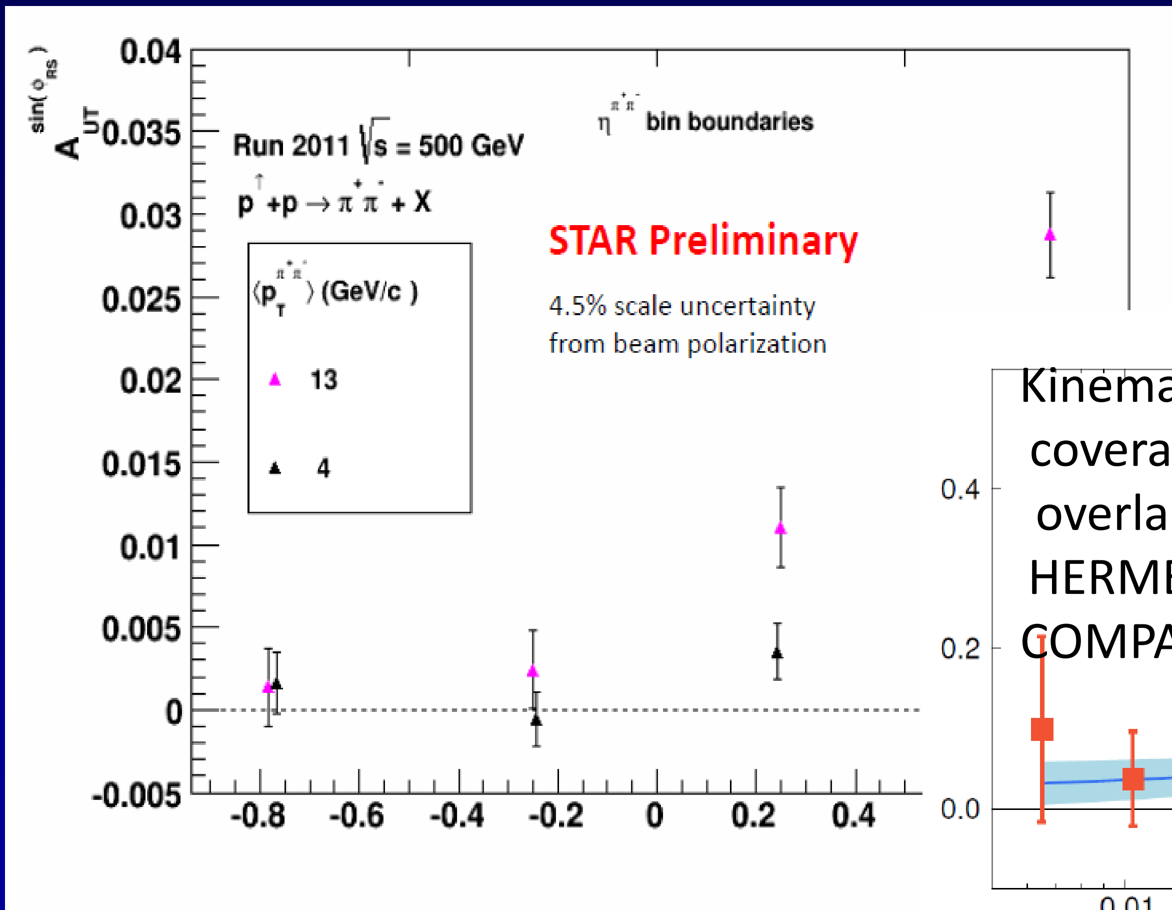
New eta A_N from PHENIX

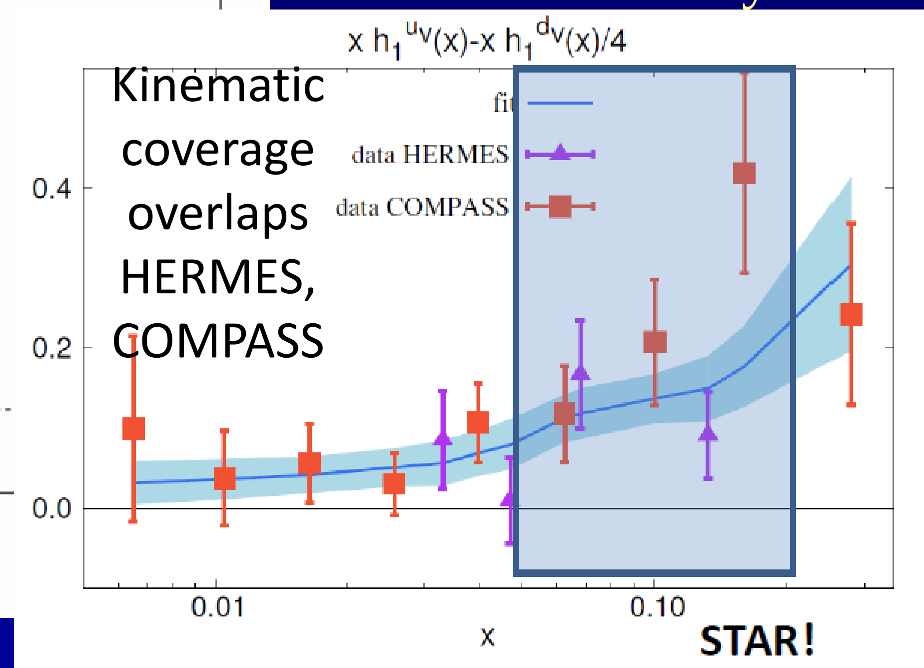
PRD90, 072008 (2014)



- Large η A_N observed by STAR and PHENIX (and E704), similar in magnitude to π^0
- Expect to measure forward *direct photons* from 2015 data for p+p, p+A with transverse proton polarization—minimal sensitivity to final-state effects
  - PHENIX MPC-EX forward preshower upgrade

Transverse single-spin asymmetry in dihadron production from STAR

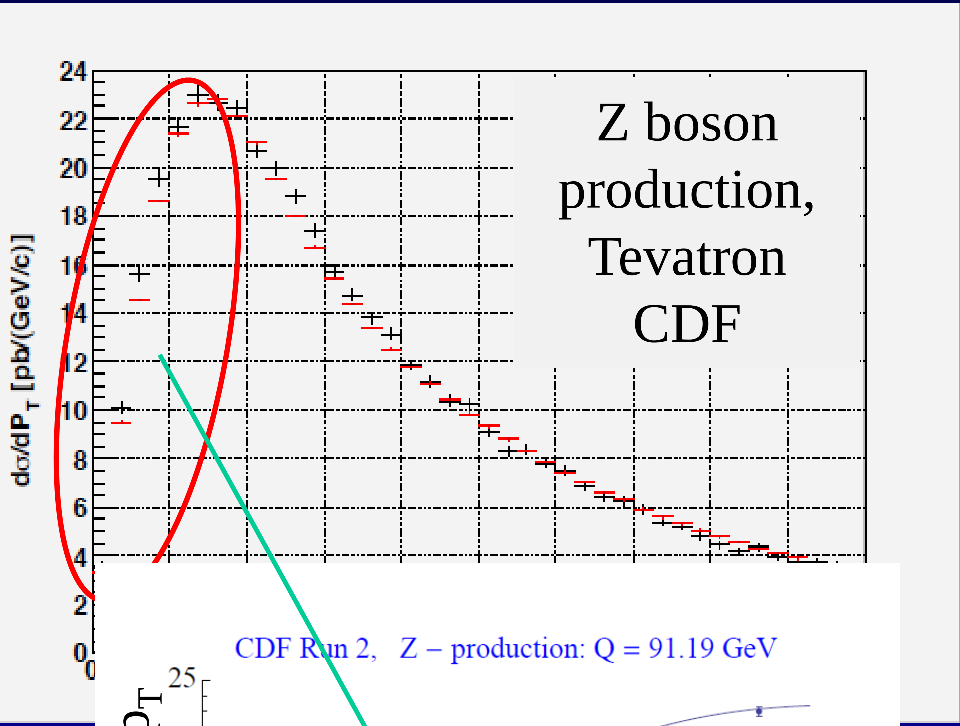


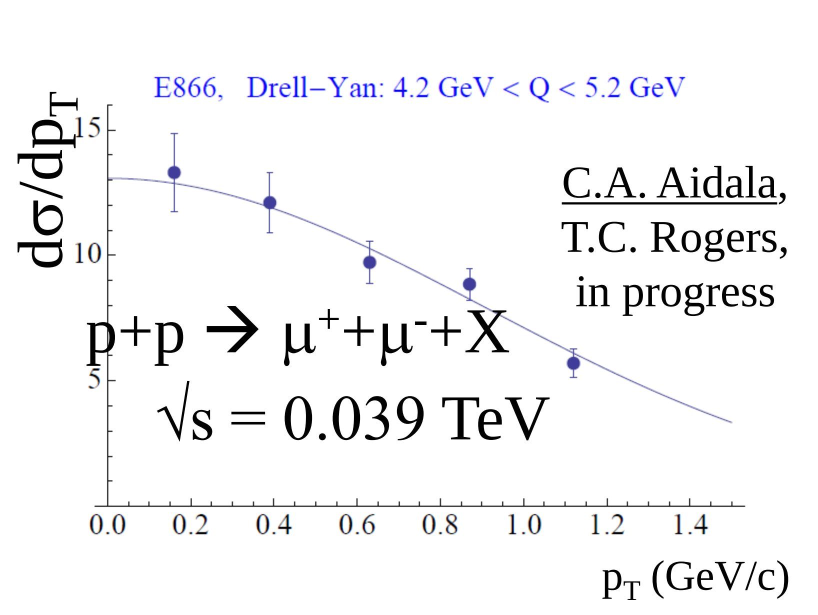


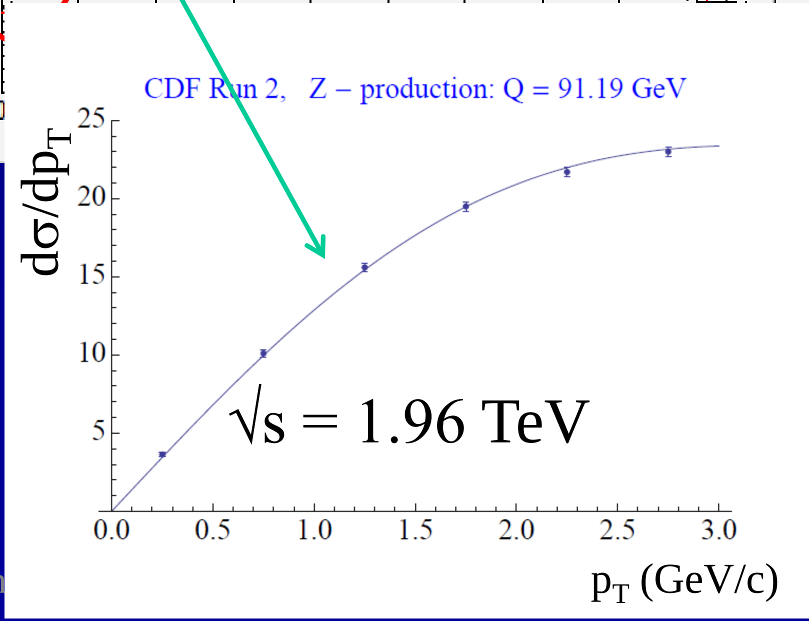
- Nonzero result observed in 200 GeV
- Collinear process—should be cleanly

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

- Don't know what to expect from color-entangled quarks → Look for contradiction with predictions for the case of *no* color entanglement
- But first need to parameterize (unpolarized) transverse-momentum-dependent parton distribution functions from world data—never looked at before!

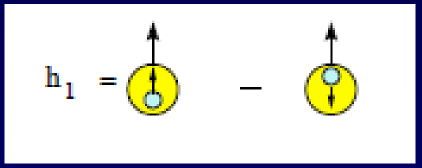






Spin-momentum correlations and the proton as a QCD "laboratory"

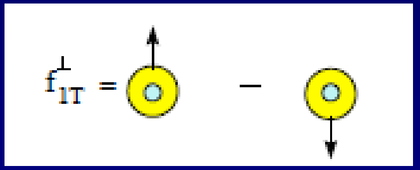
"Transversity" pdf:



Correlates *proton transverse spin* and *quark transverse spin*

S_p-S_q *coupling*

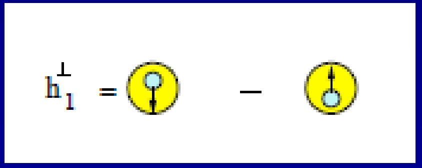
"Sivers" pdf:



Correlates *proton transverse spin* and *quark transverse momentum*

S_p-L_q *coupling*

"Boer-Mulders" pdf:



Correlates *quark transverse spin* and *quark transverse momentum*

S_q-L_q *coupling*