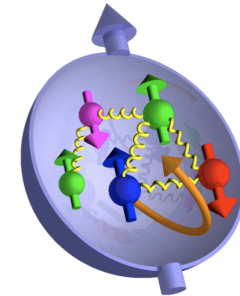




# Exploring Nucleon Spin Structure with Colliders

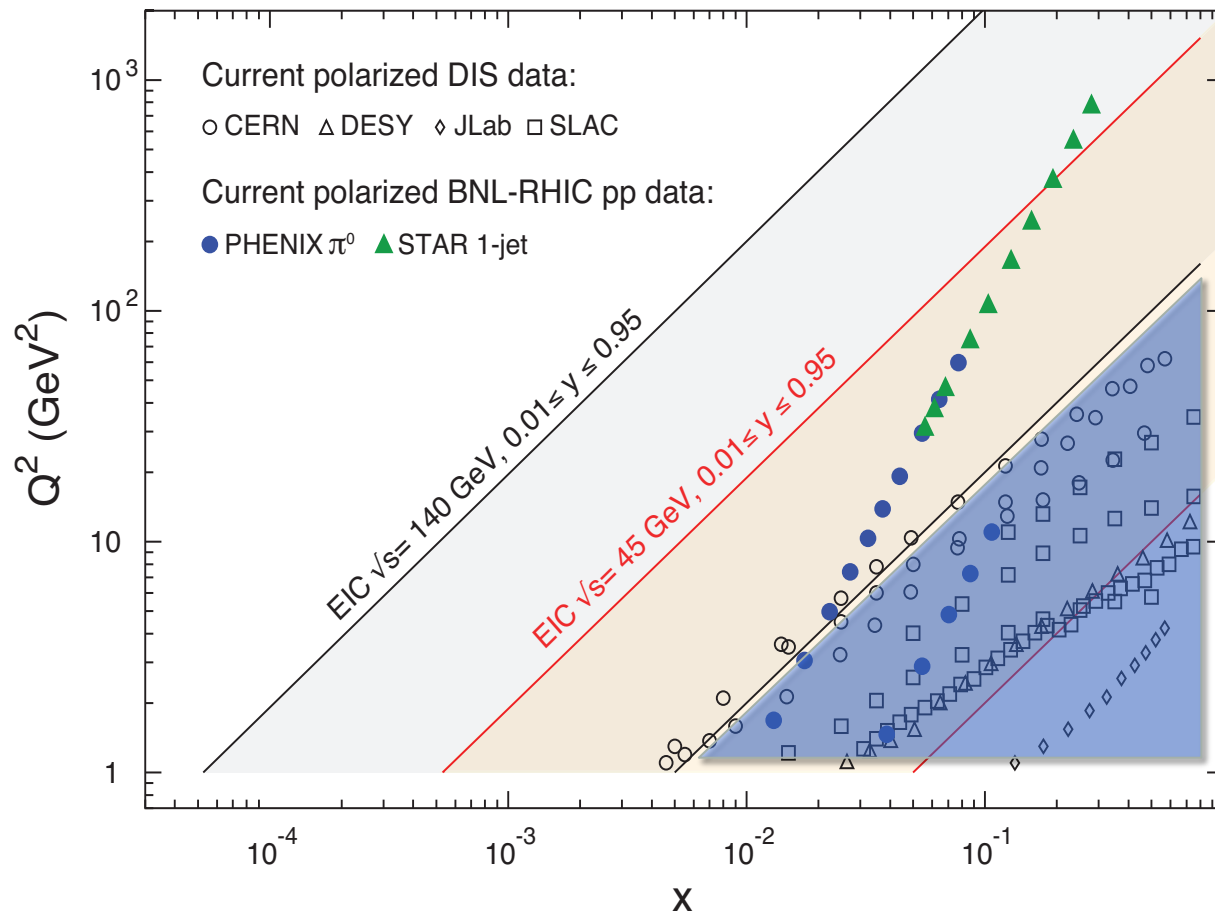


Why Collider? Advantages & complementarity

RHIC Spin program (polarized p-p) at BNL & recent results

Future Electron Ion Collider (EIC polarized e-p): science and status

# Complementary kinematic regions of Collider vs. fixed target experiments

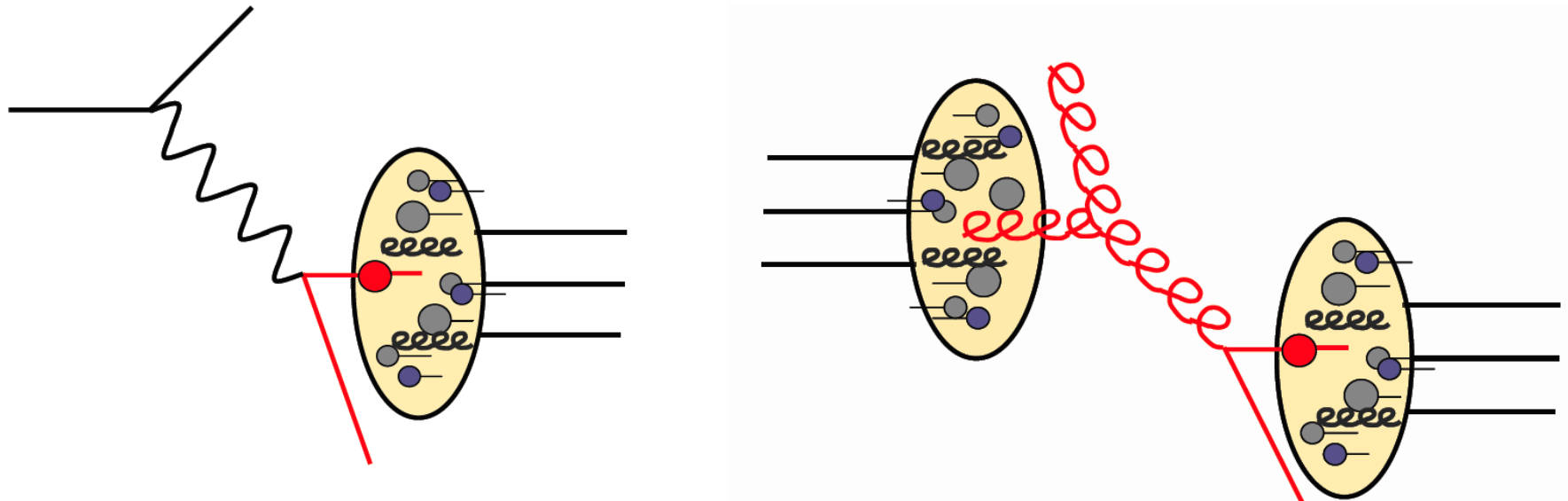


$$Q^2 = Sxy$$

$$S = \sqrt{4 \cdot E_1 \cdot E_2}$$

**Colliders enable significant enhancement in x and Q<sup>2</sup> reach of any measurement**

# Complementary techniques



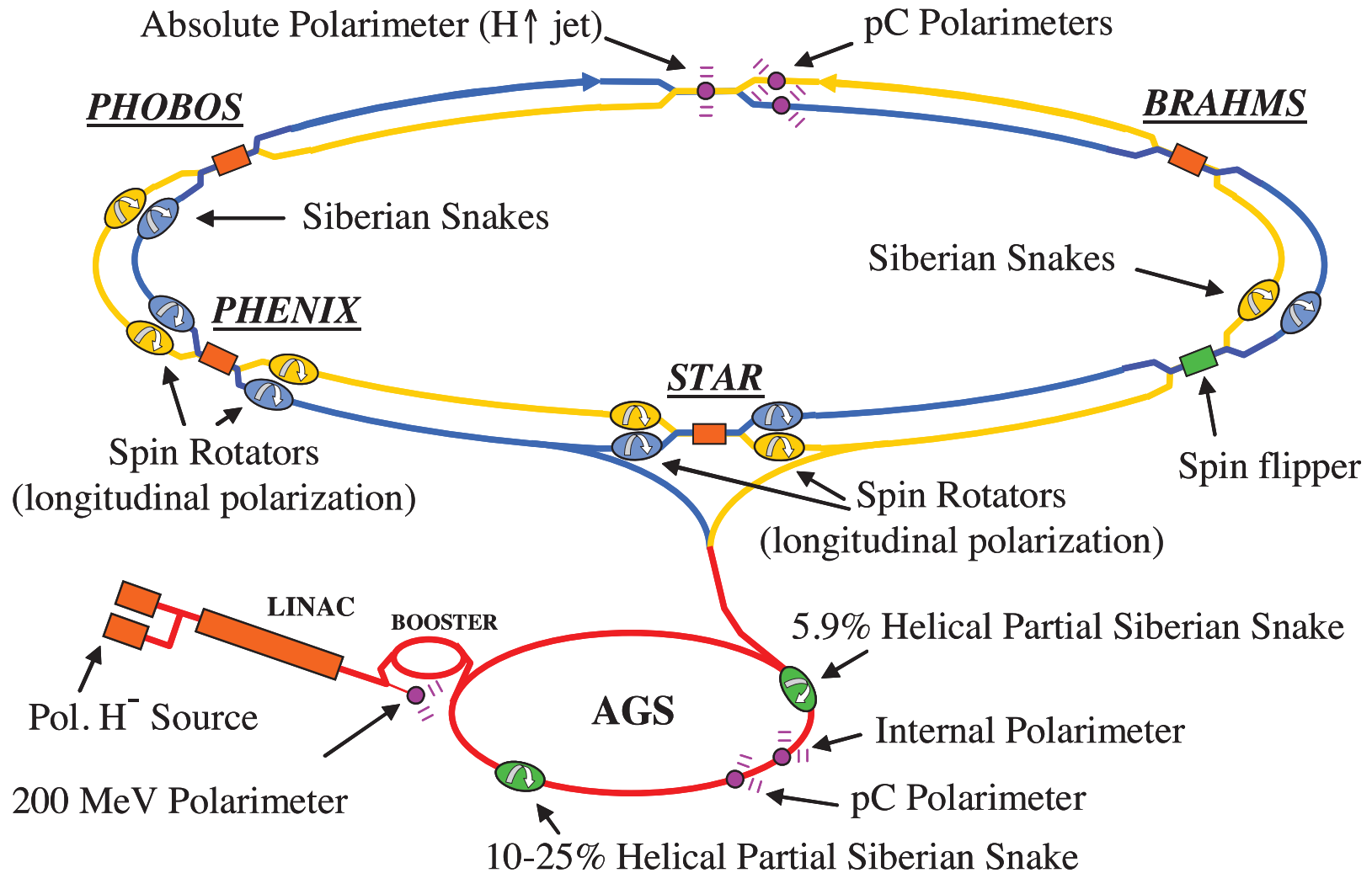
Photons colorless: forced to interact at NLO with gluons

Can't distinguish between quarks and anti-quarks

Why not use polarized quarks and gluons abundantly available in protons as probes ?

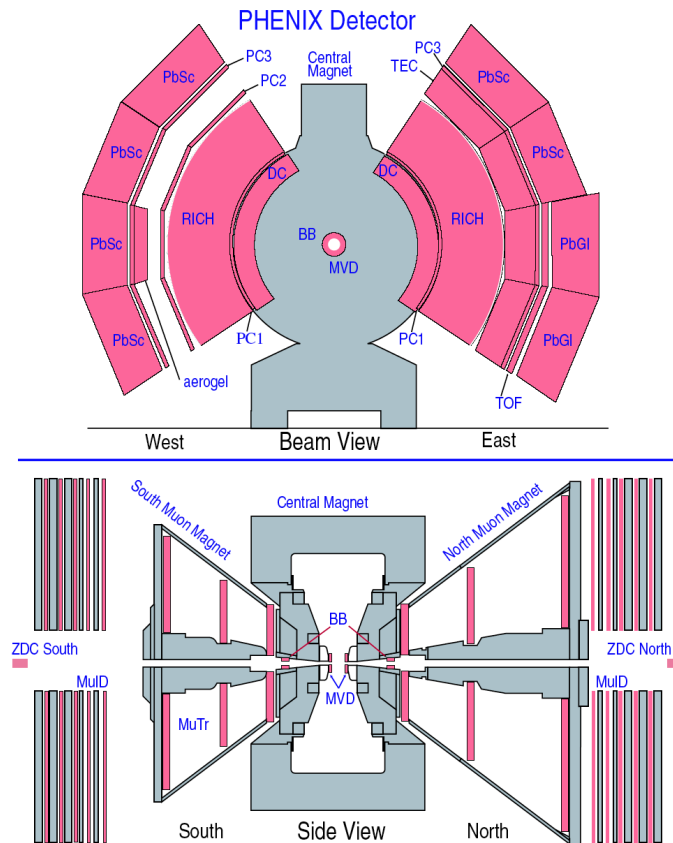
Precise kinematic reconstruction difficult in inclusive measurements

# RHIC as a Polarized p-p Collider



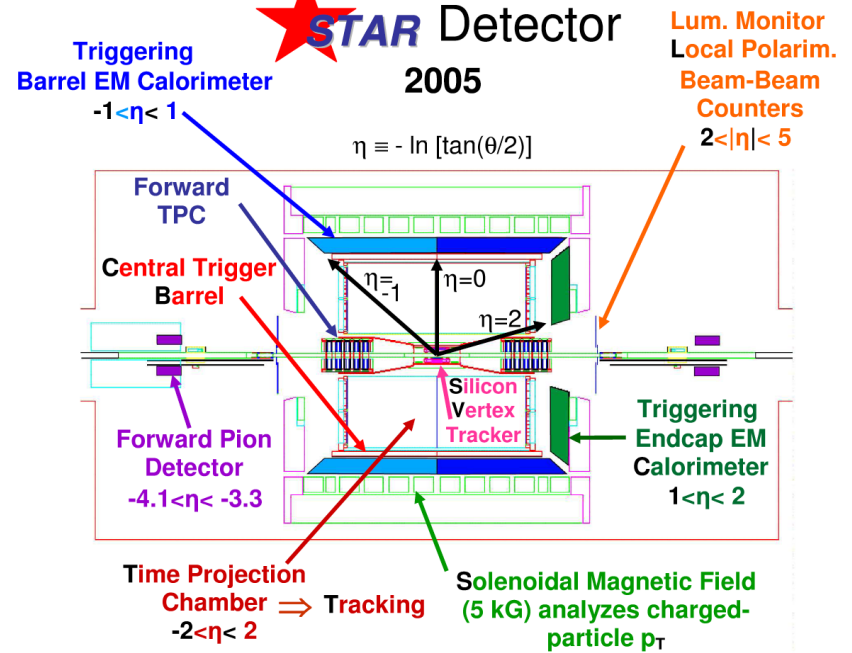
# Two major collider detectors

## PHENIX Detector



EM Calorimetry  $|\eta| < 0.35$  &  $2.0 < \eta < 3.6$   
 MuID/Tracking  $1.2 < \eta < 2.4$

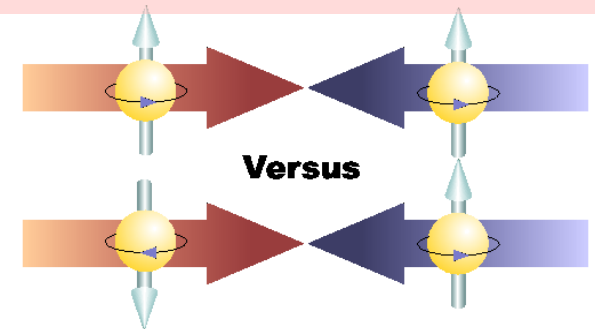
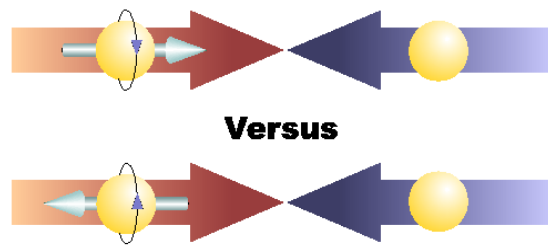
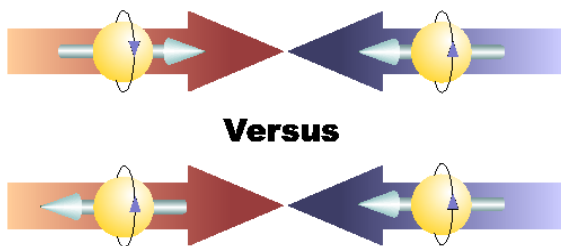
## STAR Detector 2005



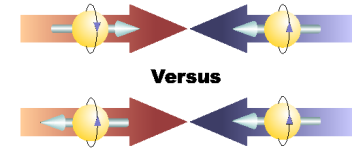
EM Calorimetry  $-1 < \eta < 2$   
 Tracking & PID  $-1 < \eta < 1$

# RHIC Spin Program $\frac{1}{2} = \left[ \frac{1}{2} \Delta\Sigma + L_Q \right] + [\Delta g + L_G]$

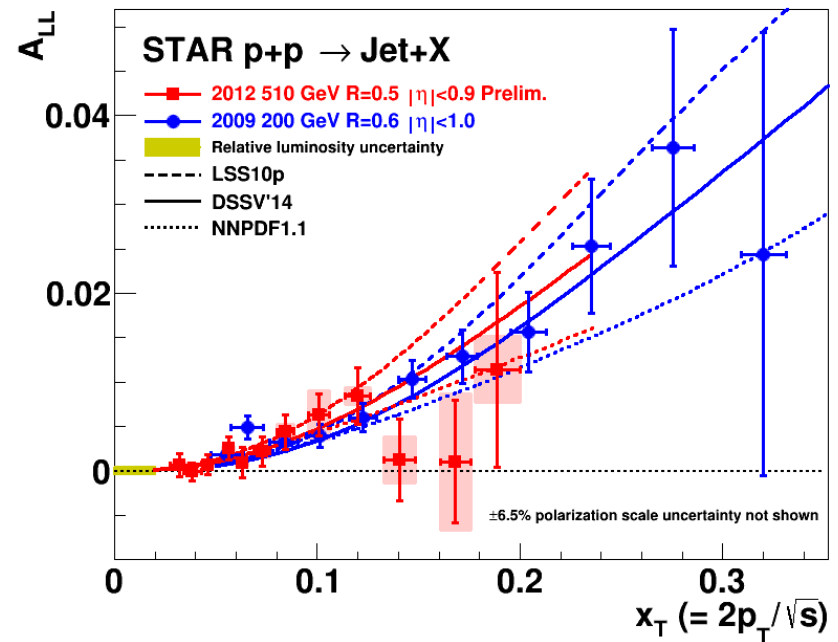
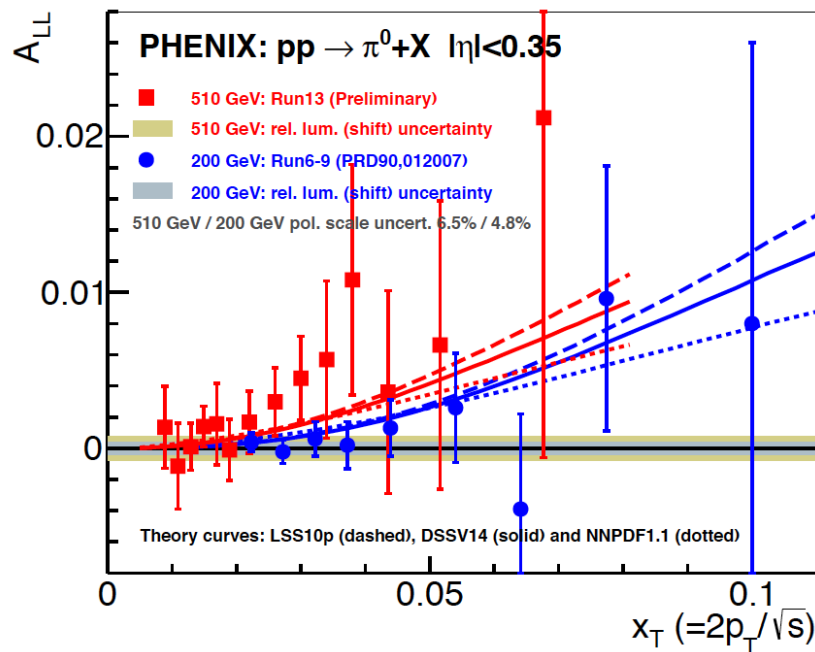
<p style="text-align: center;">Gluon Polarization</p> <p style="text-align: center;"><math>\Delta G</math></p>	<p style="text-align: center;">Anti-Quark Polarization</p> <p style="text-align: center;"><math>\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}</math></p>	<p style="text-align: center;">Transverse single/double Spin effects</p>
<p style="text-align: center;"><math>\pi^{0,\pm}</math> Production <math>A_{LL}(gg, gq \rightarrow \pi^{0,\pm} + X)</math></p> <p style="text-align: center;">Heavy Flavors <math>A_{LL}(gg \rightarrow c\bar{c}, b\bar{b} + X)</math></p> <p style="text-align: center;">Prompt Photon <math>A_{LL}(aa \rightarrow \gamma + X)</math></p>	<p style="text-align: center;">W physics <math>A_L(u + \bar{d} \rightarrow W^+ \rightarrow l^+ + \nu_l)</math> <math>A_L(\bar{u} + d \rightarrow W^- \rightarrow l^- + \bar{\nu}_l)</math></p> <p style="text-align: center;">Longitudinal single spin physics</p> <p style="text-align: center;">500 GeV CM</p>	<p style="text-align: center;">Transversity: Sivers vs. Collins effects &amp; physics of higher twists; Pion interf. Fragmentation</p> <p style="text-align: center;">Transverse single spin physics Phenix-Local Polarimetry</p>



# $A_{LL}$ proportional to $\Delta g$



50%-65% Beam polarization  
At 250 & 100 GeV p beams

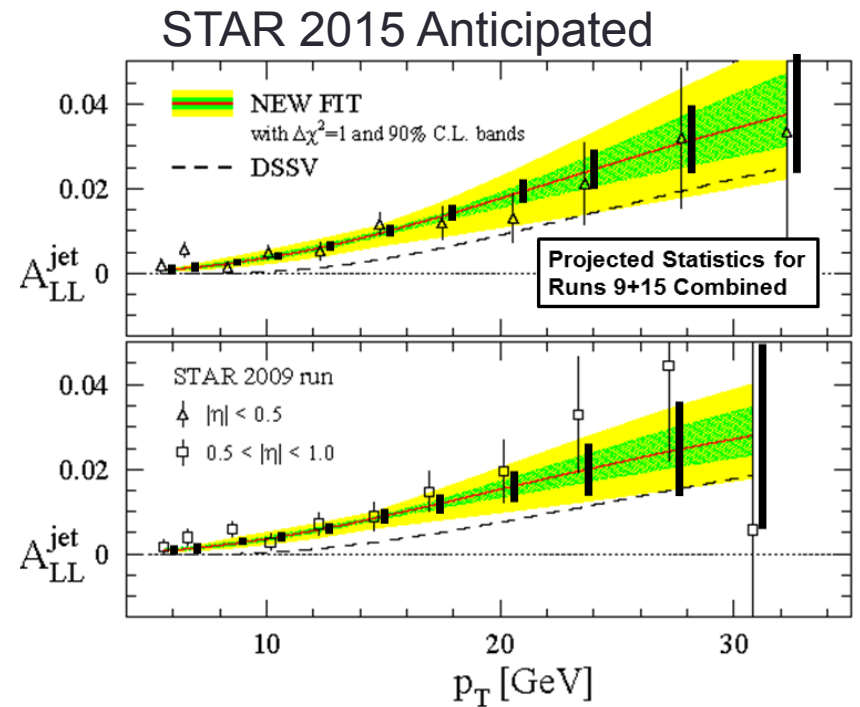
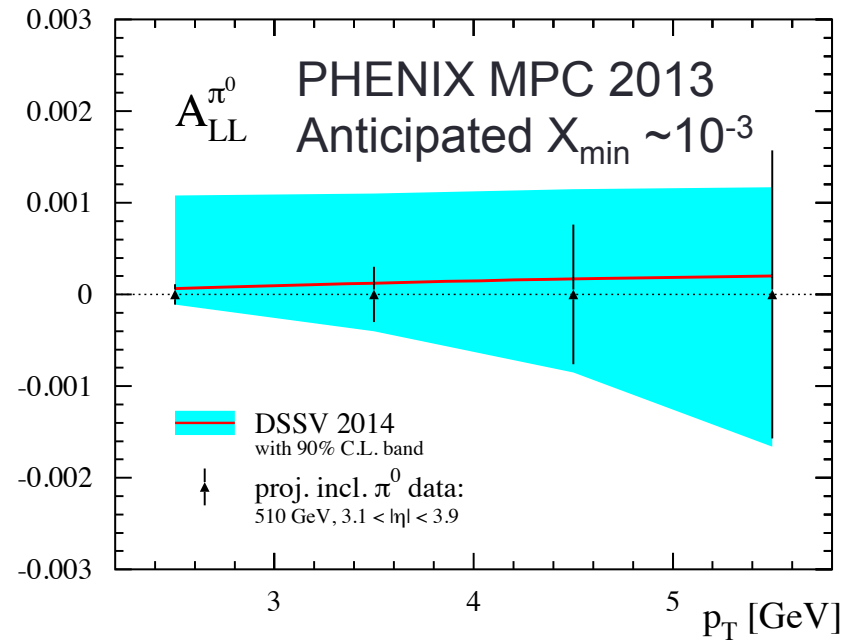
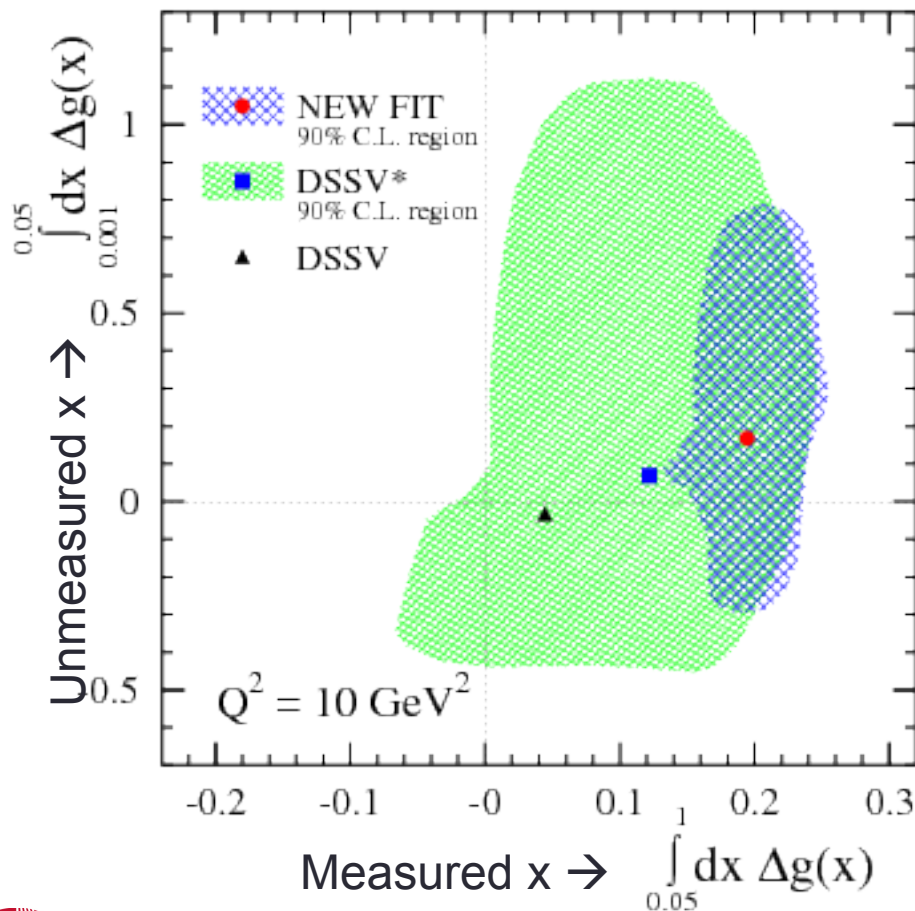


Principle data sets to be included in the Next-to-Leading-Order (NLO) calculations  
By theorists (DSSV) DeFlorian, Sassot, Stratmann & Vogelsang (2008-2014)  
Leader et al. (LSS), and recently neural network in to PDFs (NNPDF)

# $\Delta g$ @ RHIC Current status:

$0.05 < x < 0.2$

Difficult to go below  $\langle x \rangle = 0.01$ ,  $x_{min} < 0.001$





## Status of $\Delta g$ & $\Delta\Sigma$

$$\frac{1}{2} = \left[ \frac{1}{2} \Delta\Sigma + L_Q \right] + [\Delta g + L_G]$$

$$\int_{0.001}^1 \Delta\Sigma(x) dx = 0.366 \pm_{0.062}^{0.042} \quad \int_{0.05}^{0.2} \Delta g(x) dx = 0.1 \pm_{0.07}^{0.06}$$

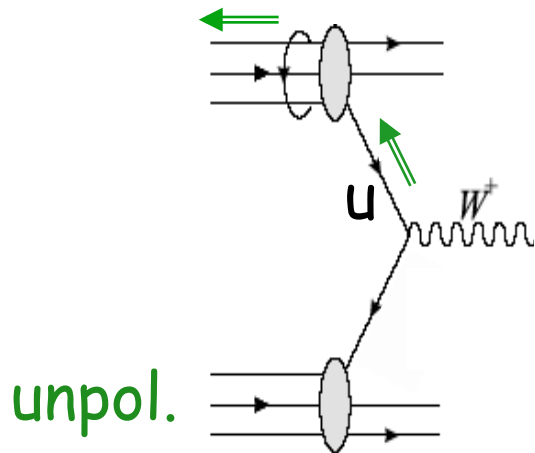
After RHIC-Spin Program:

$\Delta g \sim 1.0 \pm 1.5$  before RHIC

- Confidence in  $\Delta\Sigma$
- $\Delta g$  needs significant broadening in x-range to make it more precise
- No measurements of  $L_G$ ,  $L_Q$

*Leads directly to the future Electron Ion Collider (EIC)*

# Anti-Quark Polarization measurement via $W$ production and decay



$$\sqrt{s} = 500 \text{ GeV}$$

- Large parity violating effect anticipated

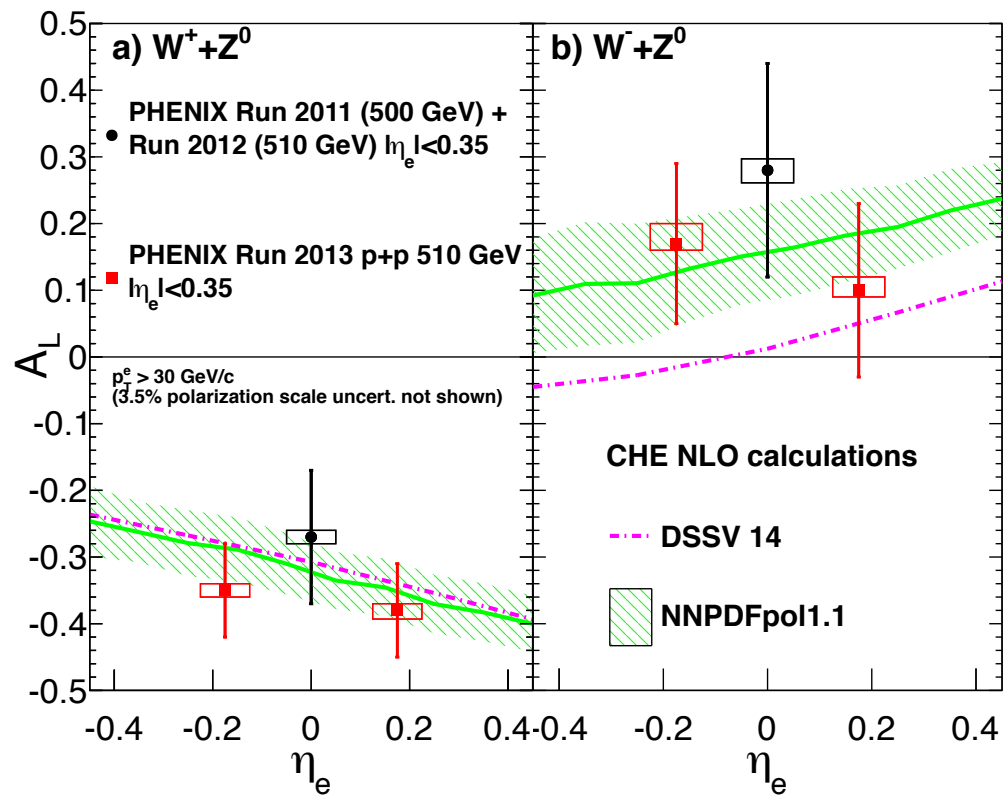
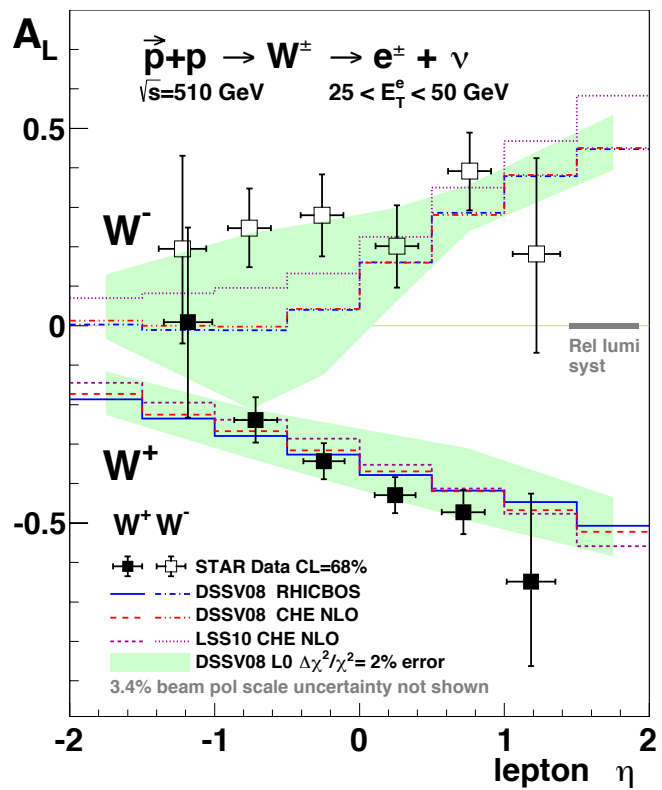
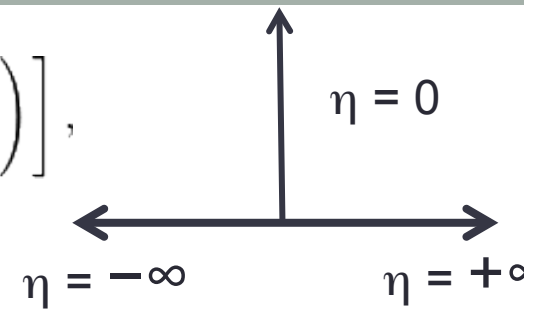
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$

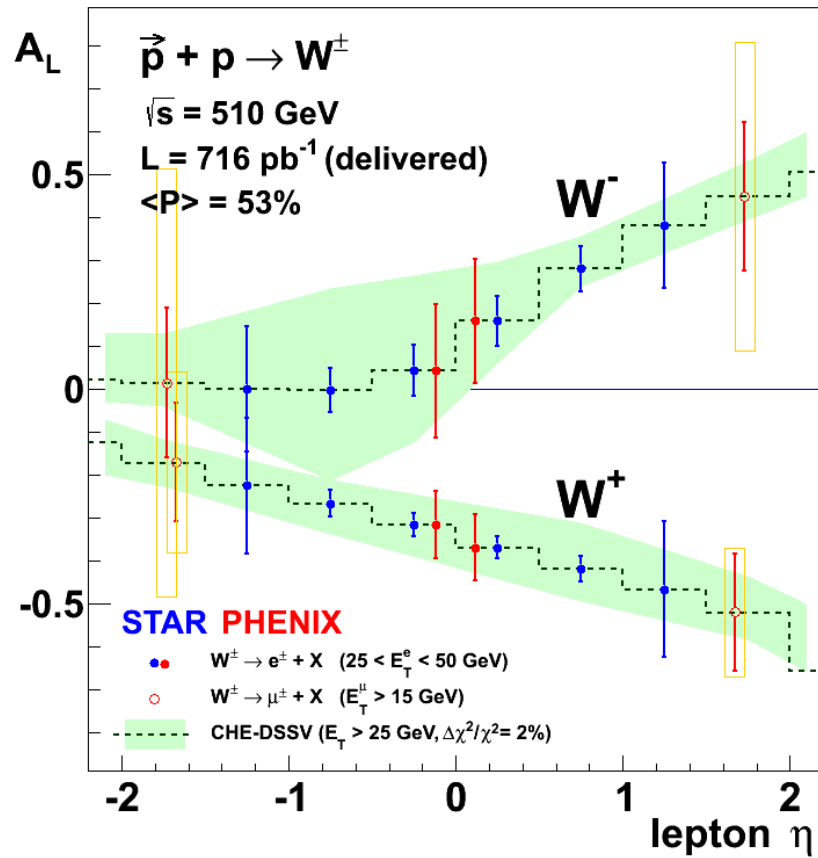
- Measurement complimentary to SIDIS, but devoid of fragmentation function makes it cleaner!
- NLO analyses about now available

“ $W^{+/-} \rightarrow e^{+/-}$ ”

STAR ( $|\eta| < 1.2$ ) & PHENIX ( $|\eta| < 0.35$ )

$$\eta \equiv -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right],$$



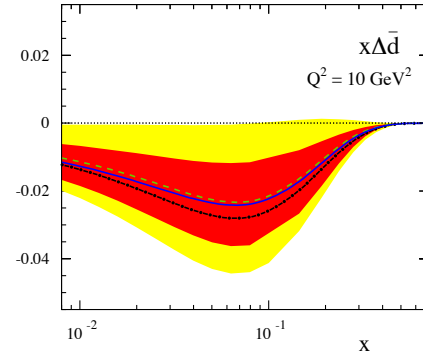
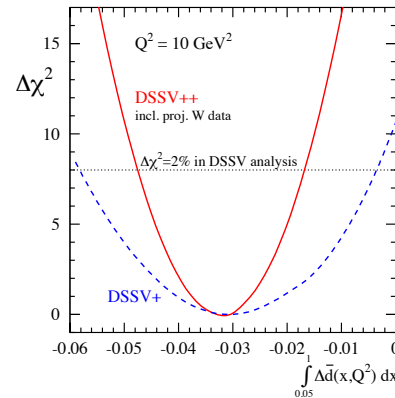
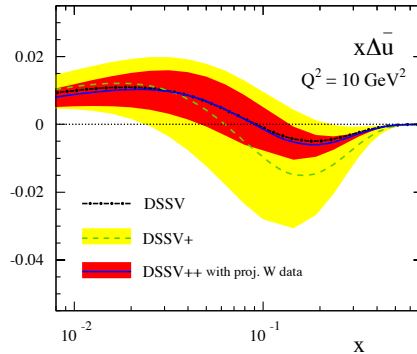
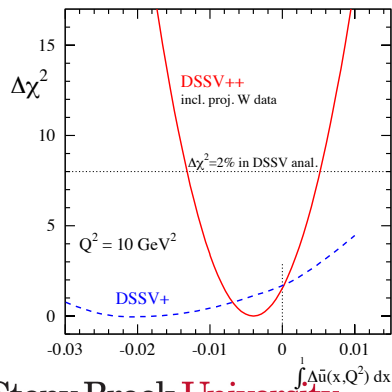


# Anti-Quark polarization.... $W^{+/-}$ production @ 500 GeV

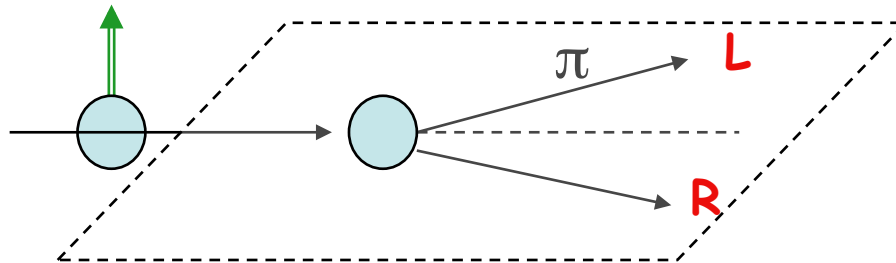
## Anticipated results & their impact

$u$

$\bar{d}$



# Transverse spin introduction



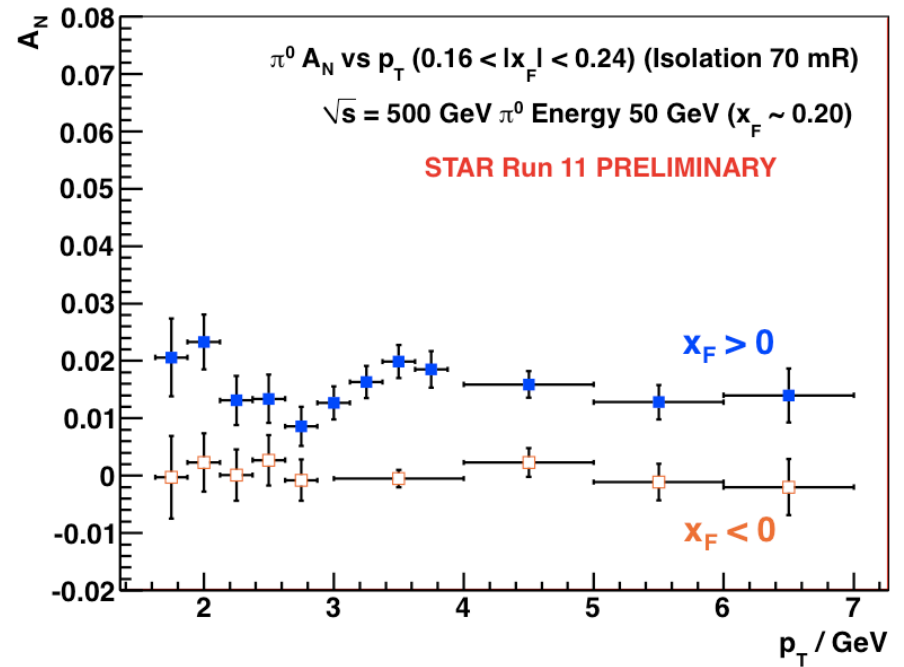
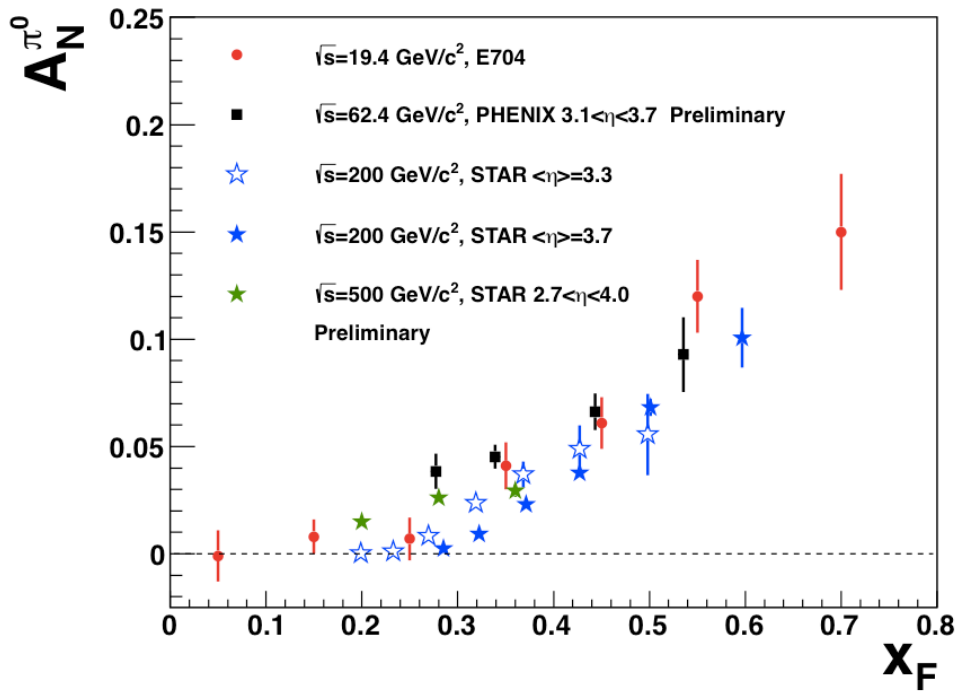
$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

$$A_N \sim \frac{m_q}{p_T} \alpha_S$$

Kane, Pumplin, Repko 1978

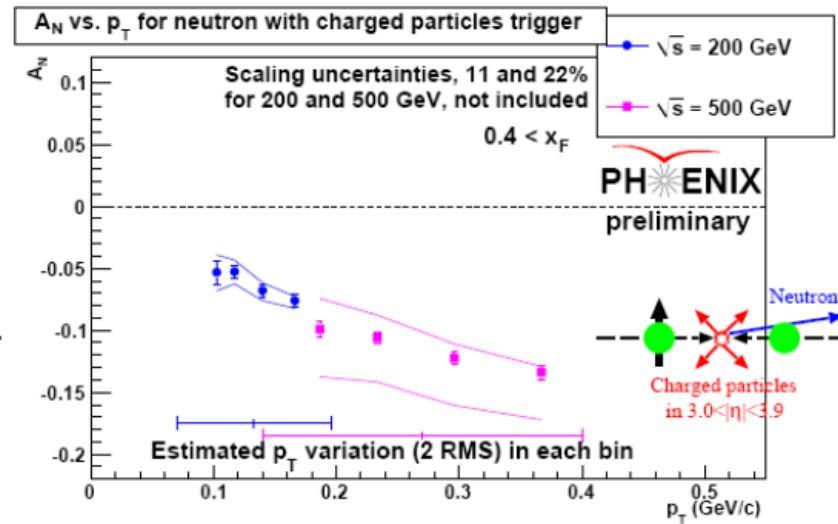
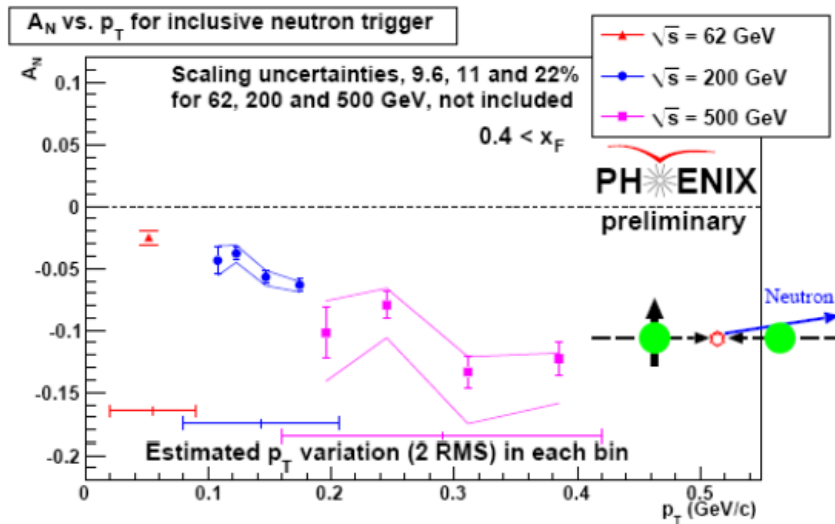
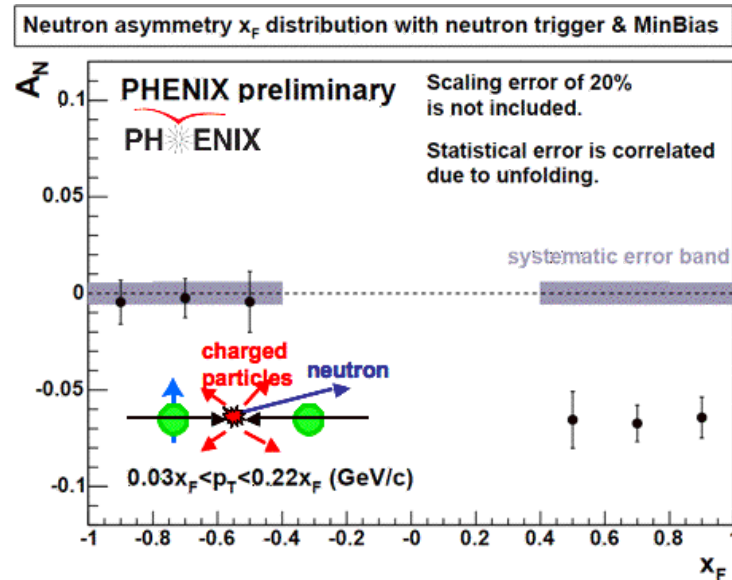
- Since people started to measure effects at high  $p_T$  to interpret them in pQCD frameworks, this was “neglected” as it was expected to be small..... However....
- Pion production in single transverse spin collisions showed us something different....

# Transverse spin asymmetries @ RHIC

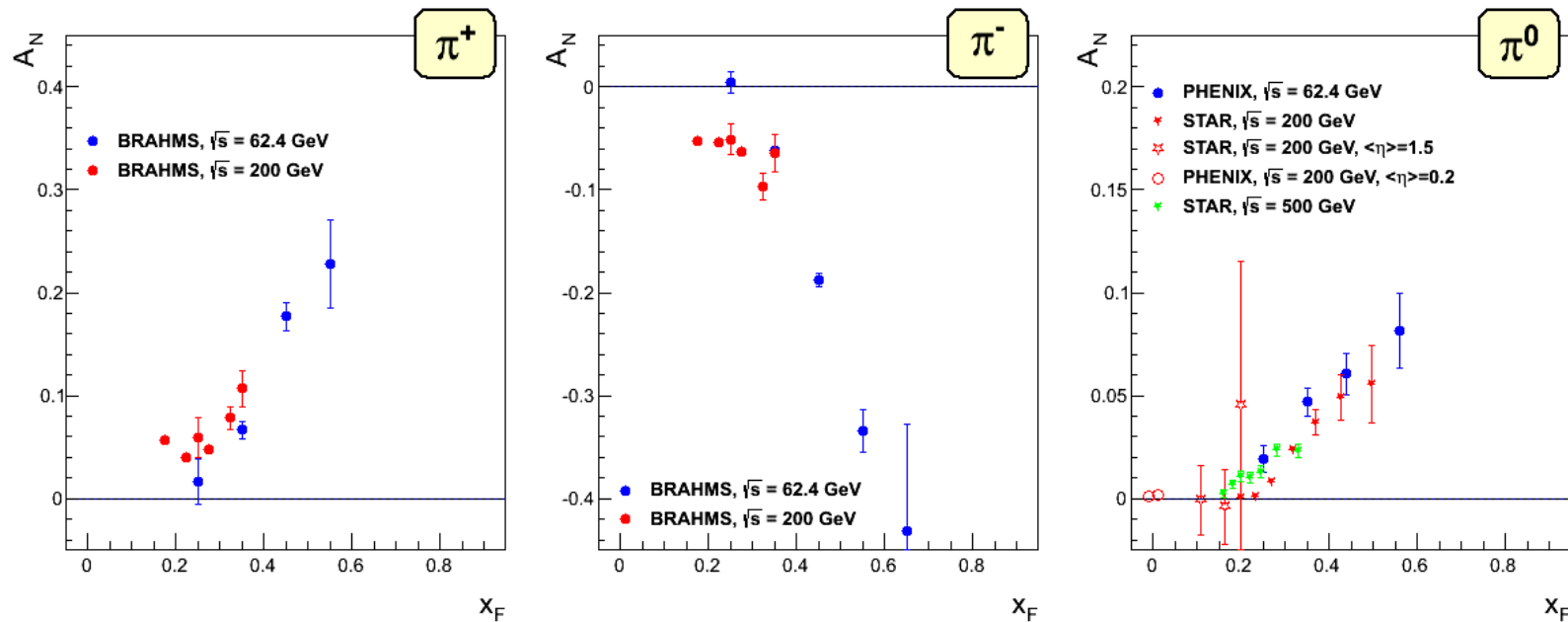


# Other unexpected discoveries...

- Large very forward neutron asymmetry found at RHIC.
- Center of Mass &  $p_T$  dependence studied
- **Not understood how it arises: a challenge to theorist**



# Transverse spin data @ RHIC:



Large transverse spin asymmetries at high Center of Mass  $\rightarrow$   
 Surprise! Various questions being studied...

What is the underlying mechanism?

Observed  $p_T$  dependence  $A_N$  consistent with expectations?

Can TMD evolution be seen in RHIC data?

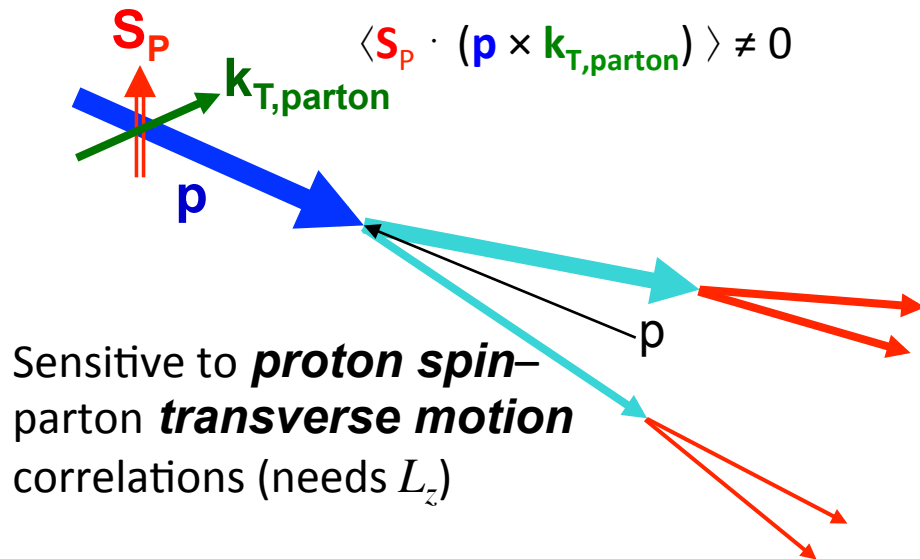
Can we study factorization breaking using RHIC p+p data?



# Possible origins of transverse spin effects:

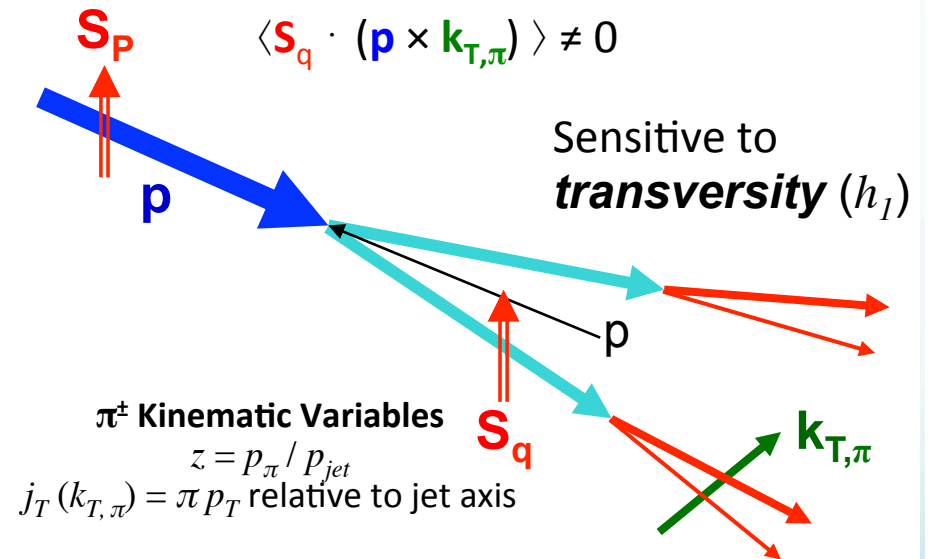
**Sivers mechanism:** asymmetry in the forward jet or  $\gamma$  *production*

D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)



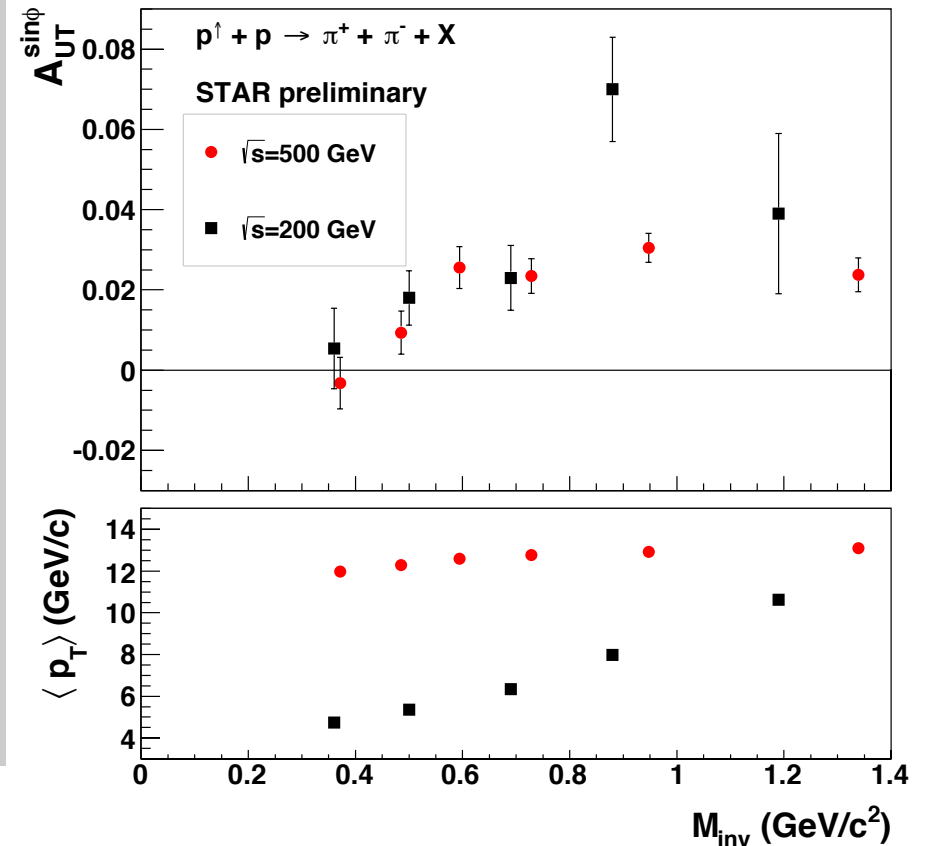
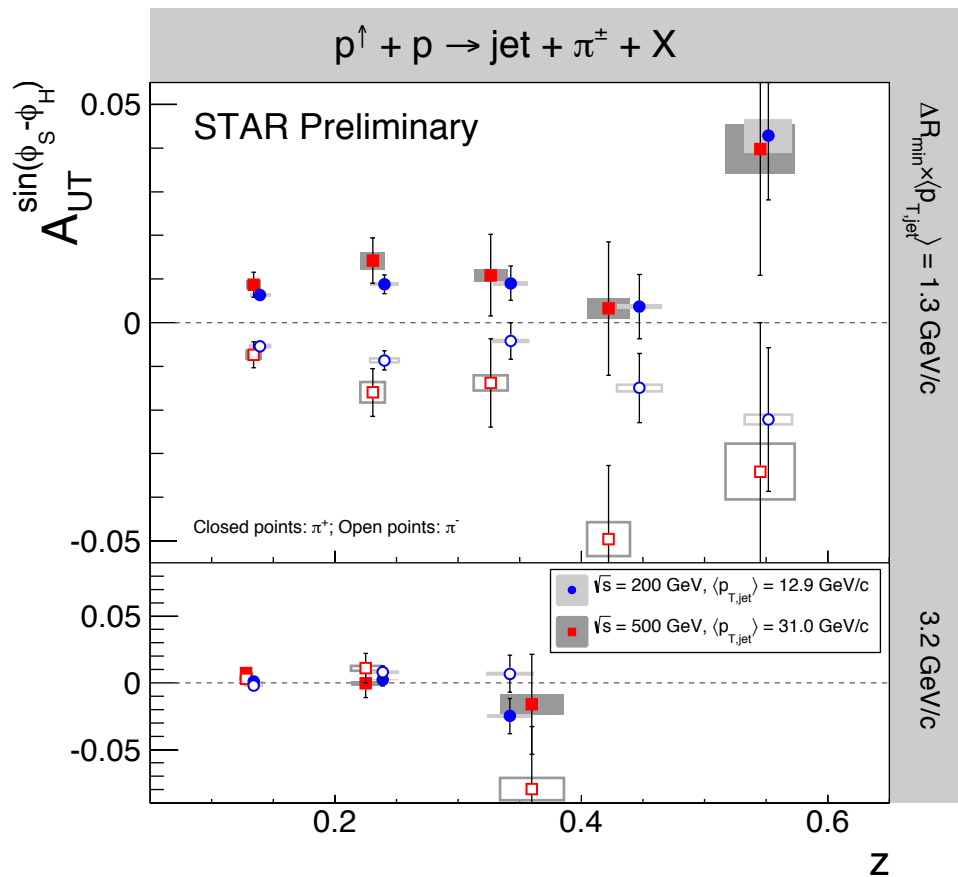
**Collins mechanism:** asymmetry in the forward jet *fragmentation*

J. Collins, NP B396, 161 (1993)

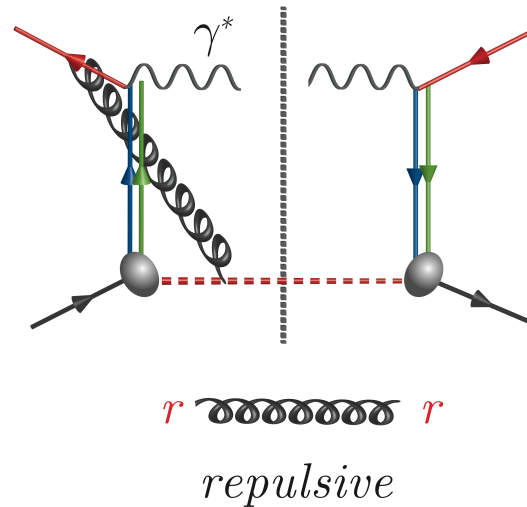
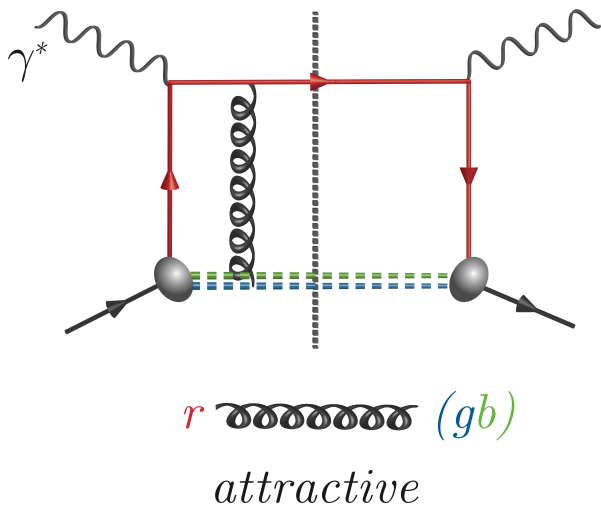


In p-p scattering you will always see a combination of both.  
 → *Fragmentation functions need to be measured in e+e- to disentangle various observed effects: now underway*

# STAR: jet + $\pi^{+/-} + X$ and $\pi^+ + \pi^- + X$ transversity $\times$ fragmentation function $\neq 0$



# Between now and 2017/2018



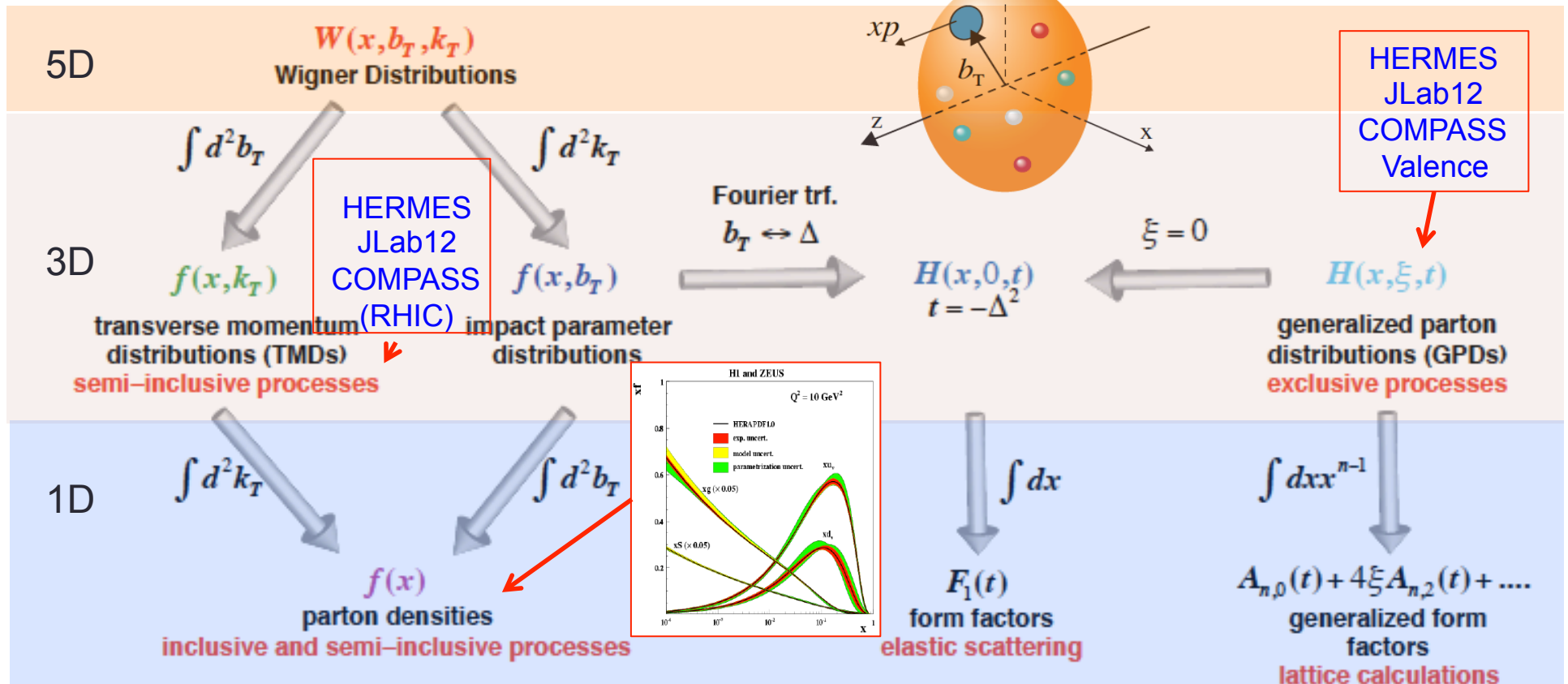
Experimental Observation of This sign change  
 → Factorization understood  
 → Otherwise?

<p>200 GeV <math>p^\uparrow + A</math></p>	<p>Unravel underlying sub-processes for <math>A_N</math>, <math>A_{UT}</math> for excl. <math>J/\Psi \rightarrow GPD E</math></p>	<p>STAR inner TPC pad row upgrade</p>
<p>500 GeV <math>p^\uparrow + p</math></p>	<p>First measurement of PHENIX: <math>A_N(DY)</math>, STAR: <math>A_N(W/Z)</math></p>	
<p>500 GeV <math>\bar{p} + \bar{p}</math></p>	<p>Unravel underlying sub-processes for <math>A_N</math>  <math>\Delta g(x)</math> at low-<math>x</math>, sea antiquark polarizations</p>	

Could continue these studies with focus on high  $h$  should the EIC get delayed: with PHENIX and STAR detector Upgrades

# Unified view of the Nucleon Structure

## Wigner distributions



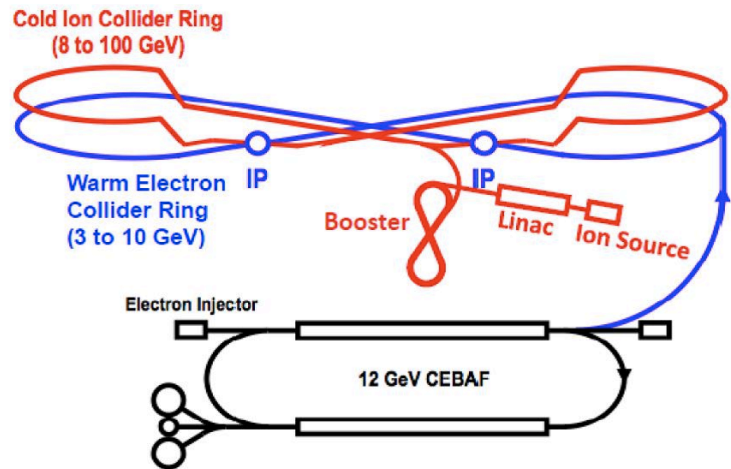
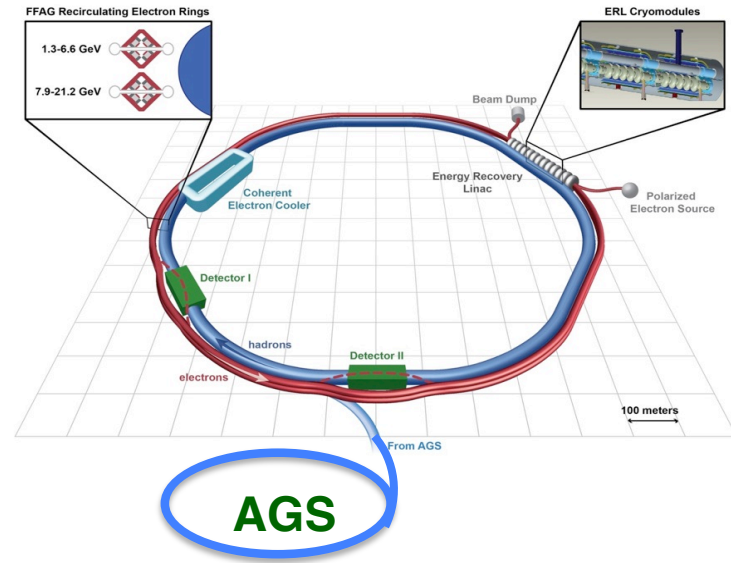
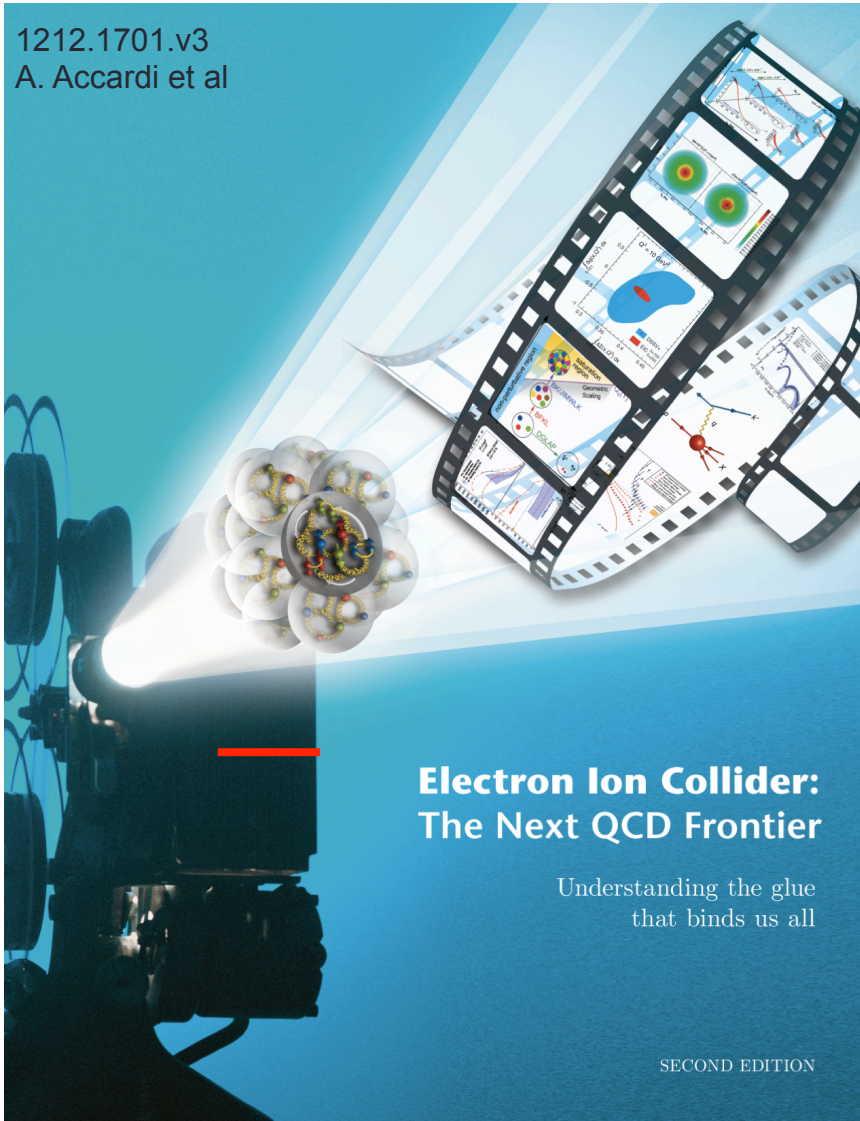
## (2+1)D imaging Quarks (Jlab/COMPASS), Gluons (COMPASS/EIC)

✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)

✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS & diffraction)

# The Electron Ion Collider

## Two proposals for realization of the Science Case



# The Electron Ion Collider

## Two proposals for realization of the Science Case

### For e-N collisions at the EIC:

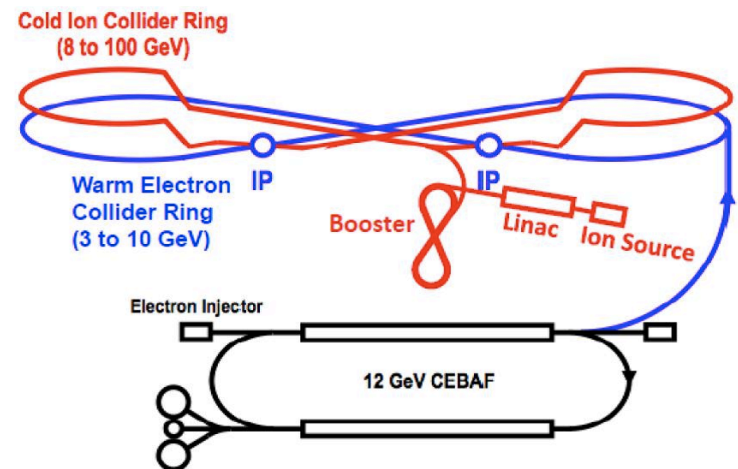
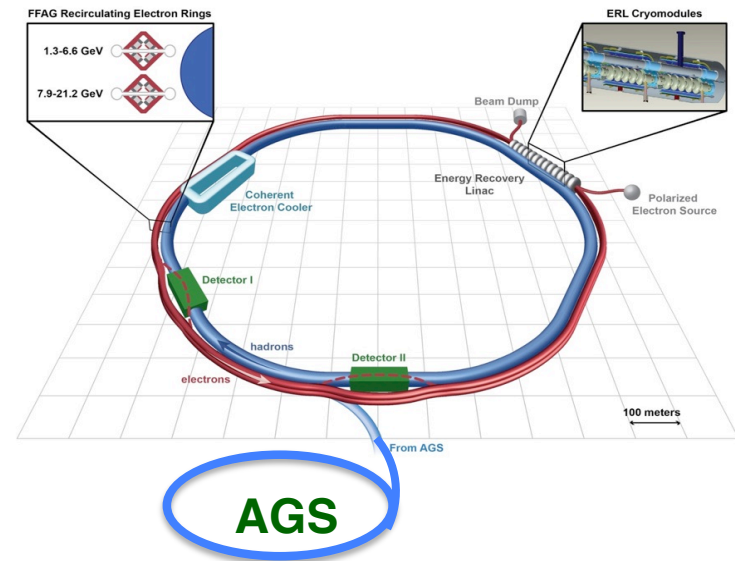
- ✓ Polarized beams: e, p, d/<sup>3</sup>He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity  $L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{sec}^{-1}$   
100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

### For e-A collisions at the EIC:

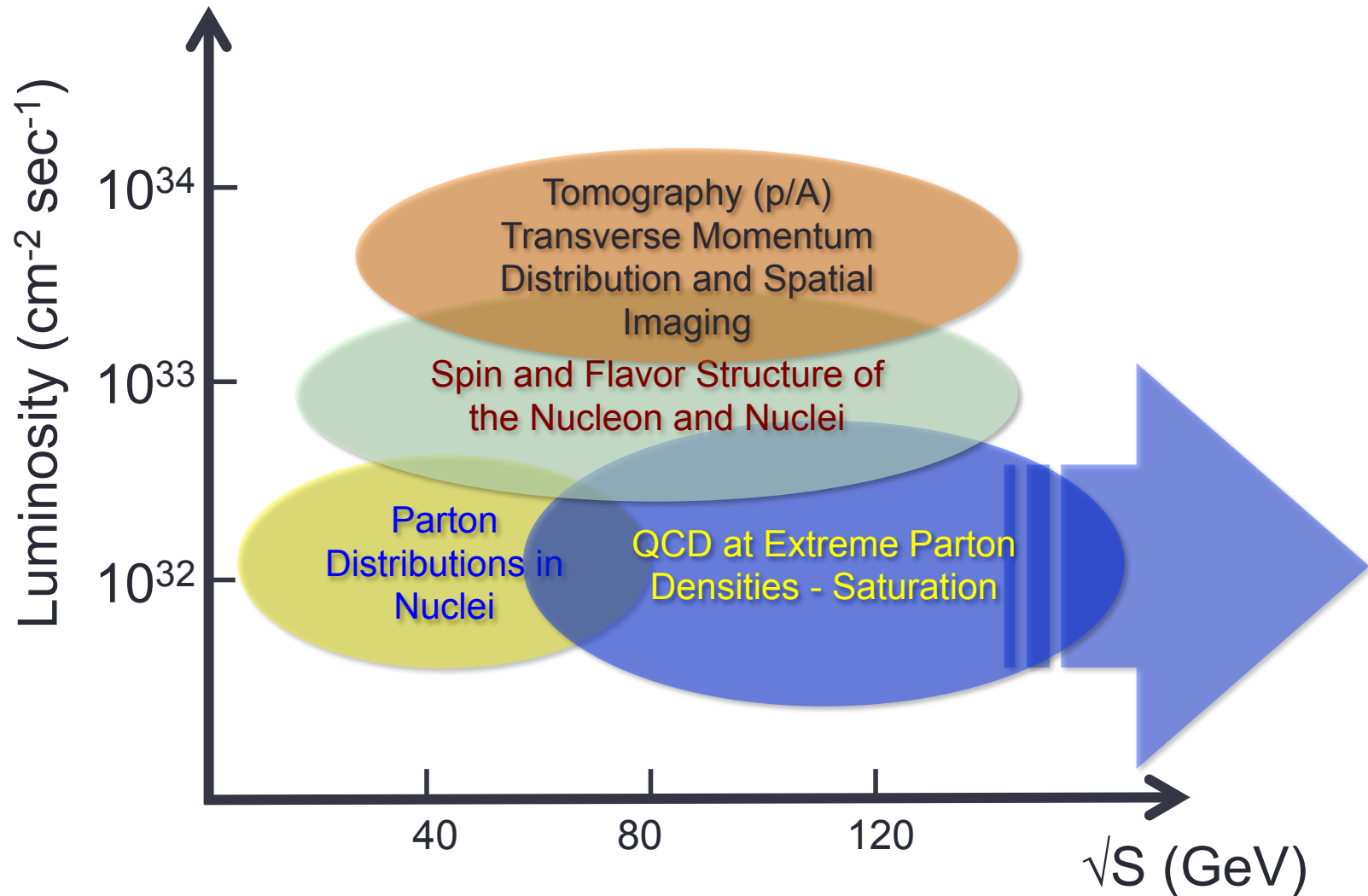
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

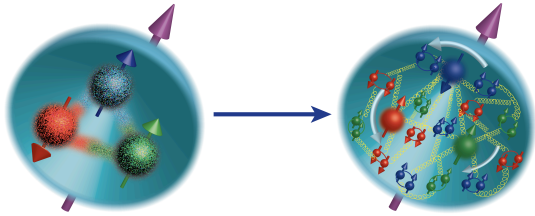
World's first  
Polarized electron-proton/light ion  
and electron-Nucleus collider

Both designs use DOE's significant  
investments in infrastructure

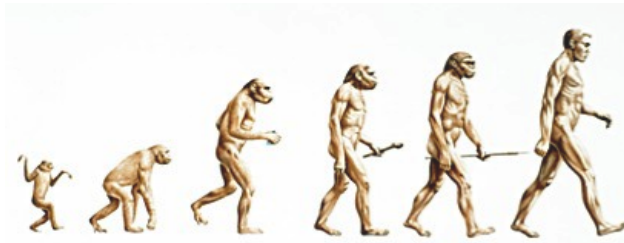


# Physics vs. Luminosity & Energy





# Our Understanding of Nucleon Spin



$$\frac{1}{2} = \left[ \frac{1}{2} \Delta\Sigma + L_Q \right] + [\Delta g + L_G]$$

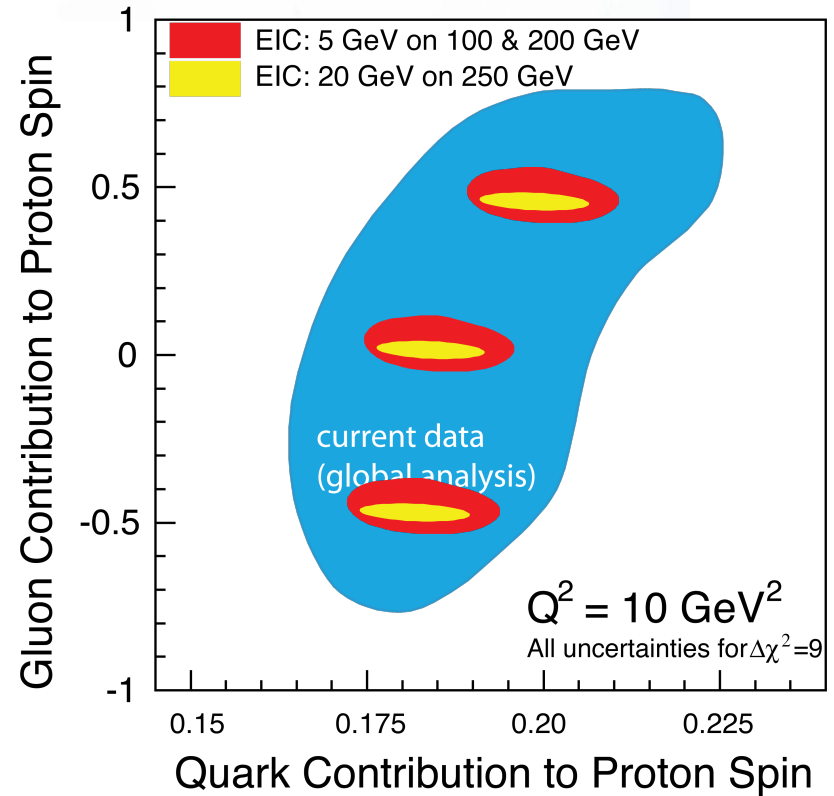
$\Delta\Sigma/2$  = Quark contribution to Proton Spin

$L_Q$  = Quark Orbital Ang. Mom

$\Delta g$  = Gluon contribution to Proton Spin

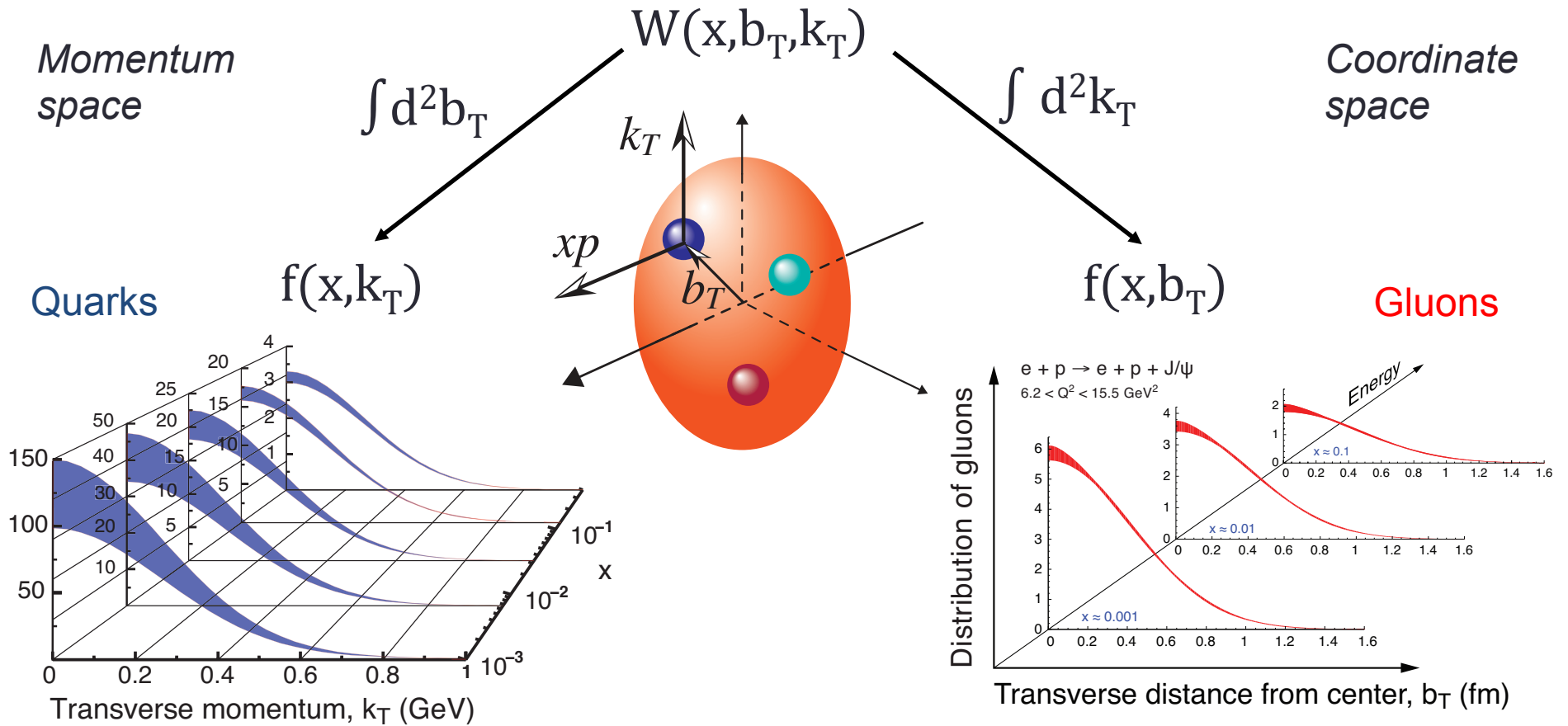
$L_G$  = Gluon Orbital Ang. Mom

Precision in  $\Delta\Sigma$  and  $\Delta g \rightarrow$  A clear idea  
Of the magnitude of  $L_Q + L_G$





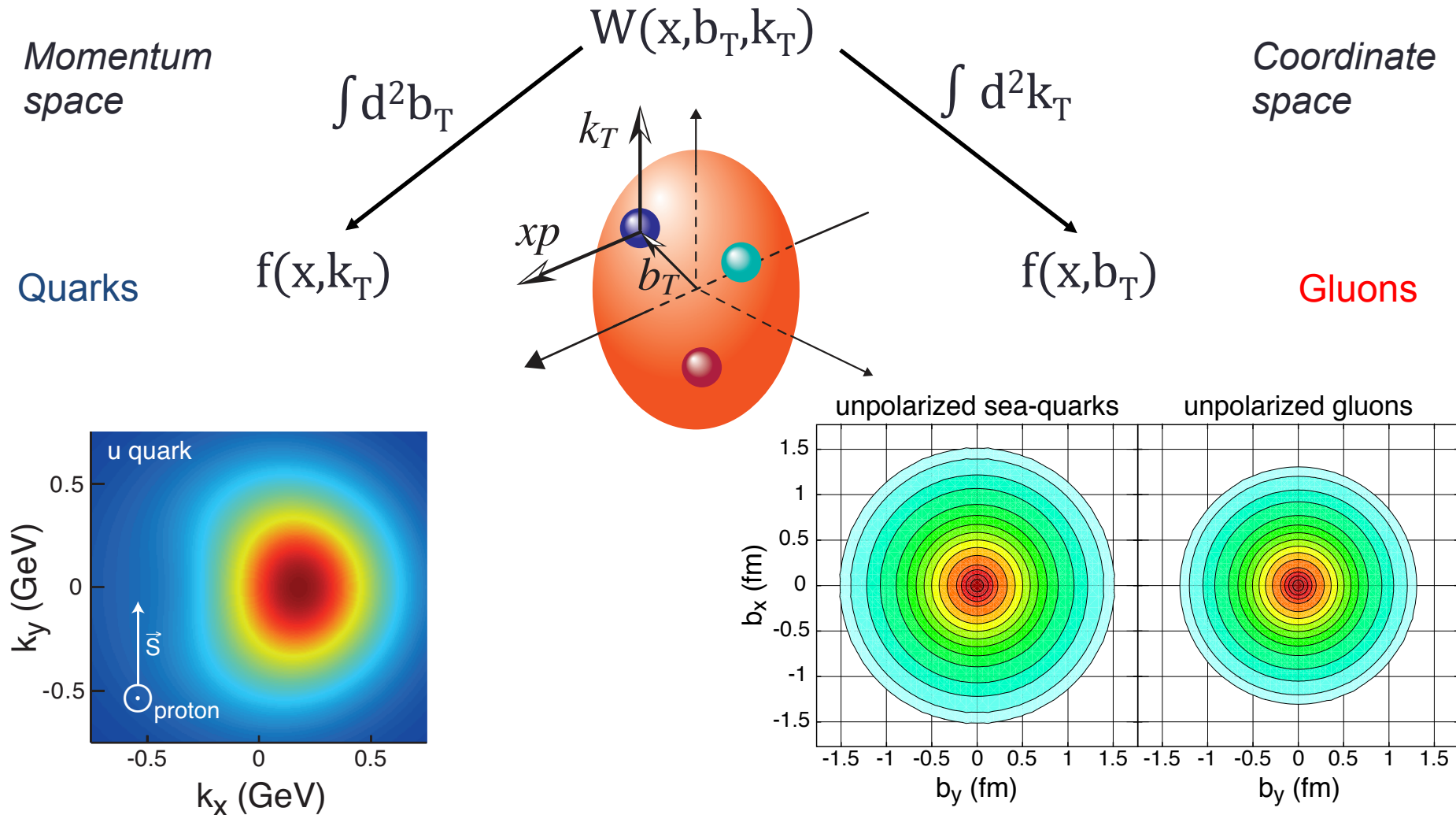
# 3-Dimensional Imaging Quarks and Gluons



Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images from exclusive scattering

# 3-Dimensional Imaging Quarks and Gluons



Position  $r$  X Momentum  $p \rightarrow$  Orbital Motion of Partons

# Prospect of direct comparison with lattice QCD

## ➤ Quark GPDs and its orbital contribution to the proton spin:

$$J_q = \frac{1}{2} \lim_{t \rightarrow 0} \int dx x \text{ (General. Parton Dist.s H,E) } = \frac{1}{2} \Delta q + L_q$$

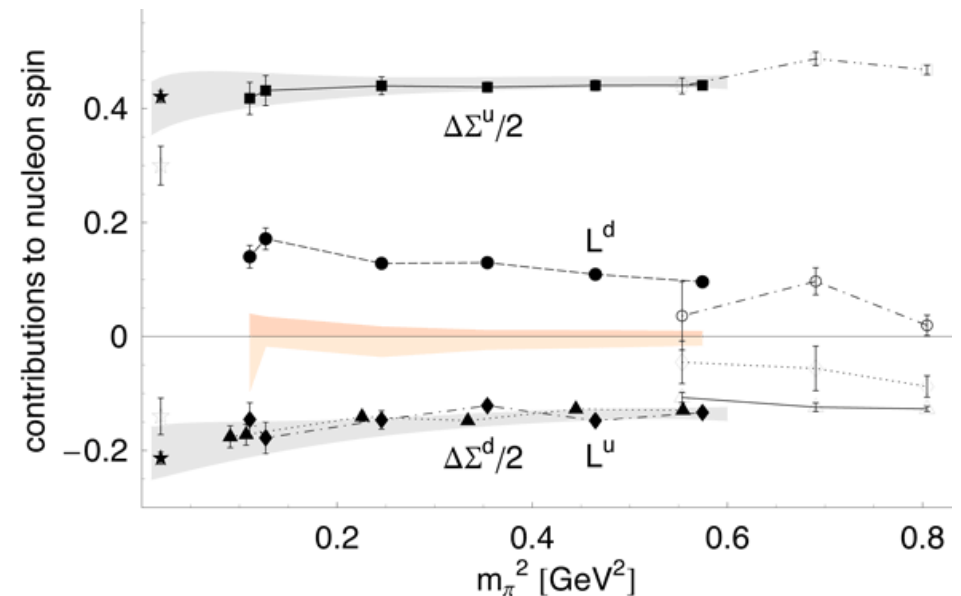
The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab12/COMPASS

## $J_q$ , calculated on Lattice QCD:

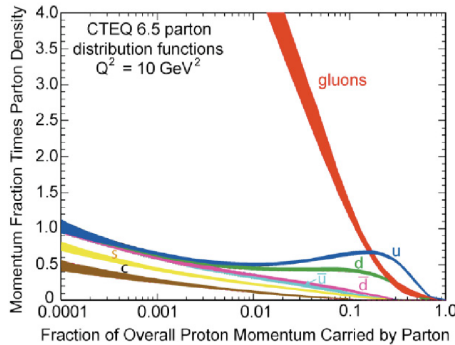
Future:

*New developments on LQCD calculating parton distributions including gluon distributions:*

X. Ji et al. PRL 111 (2013) 112002  
Y. Hatta, PRD89 (2014) 8, 085030  
& Y.-Q. Ma, J.-W. Qiu 1404.6860

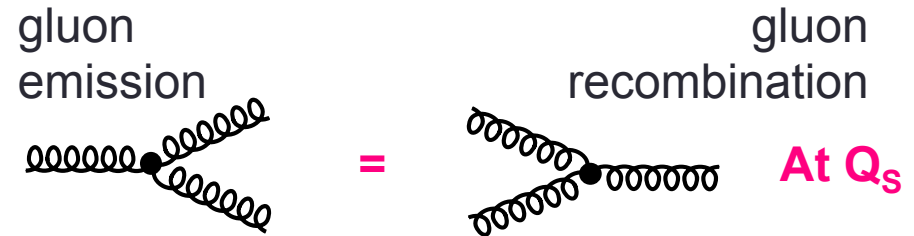
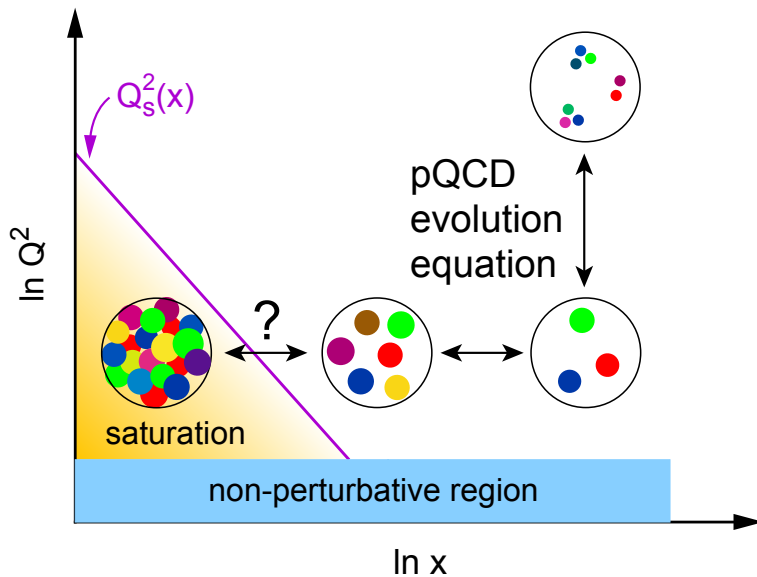


# What do we learn from low-x studies?



## What tames the low-x rise?

- New evolution eqn.s @ low x & moderate  $Q^2$
- Saturation Scale  $Q_s(x)$  where gluon emission and recombination comparable



First observation of gluon recombination effects in nuclei:  
 → leading to a **collective gluonic system!**

First observation of g-g recombination in **different** nuclei  
 → Is this a **universal property?**

→ Is the **Color Glass Condensate** the correct effective theory?

# Status and prospects of US EIC

- EIC part of the 2015 Long Range Planning Discussion
  - Will be released October 15, 2015 by the Nuclear Science Advisory Committee
    - All indications are positive, but we need to wait and see
  - EIC User Group is being formed (contact me if you are interested)
    - 1<sup>st</sup> Official User Group Meeting at Stony Brook U. June 2014
    - 2<sup>nd</sup> meeting planned at Berkeley, January 6-9, 2016 (INVITATION)
  - EIC Detector R&D Funding available
    - ~140 physicists, 31 institutes (5 Labs, 22 Universities, 9 Non-US Institutions) 15+ detector consortia exploring novel technologies for tracking, particle ID, calorimetry
    - [https://wiki.bnl.gov/conferences/index.php/EIC\\_R%25D](https://wiki.bnl.gov/conferences/index.php/EIC_R%25D)
- There is need and there is opportunity for YOU to join and contribute

# Summary:

- DIS, p-p, and ee contributed complementarily to the development of SM of High Energy Physics → Same true for Spin Physics and QCD [RHIC, polarized DIS, polarized e+e- at Belle for fragmentation studies]
- RHIC addressed  $\Delta g$  significantly (limited x), Anti-Quarks, and systematically explores transverse spin phenomena
  - Enormous richness of 3D structure of the proton emphasized
- Spin physics program at the future polarized EIC will address all of this and provide the concrete answers to those open questions and more...

# Thank You

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Abhay Deshpande

Stony Brook University

September 17, 2015

Erice, 37<sup>th</sup> School at the Ettore Majorana Center

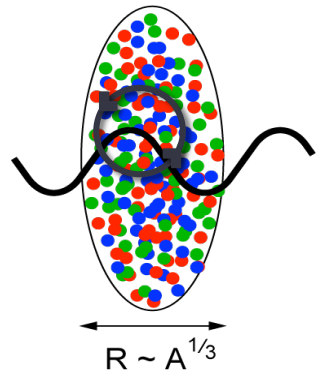
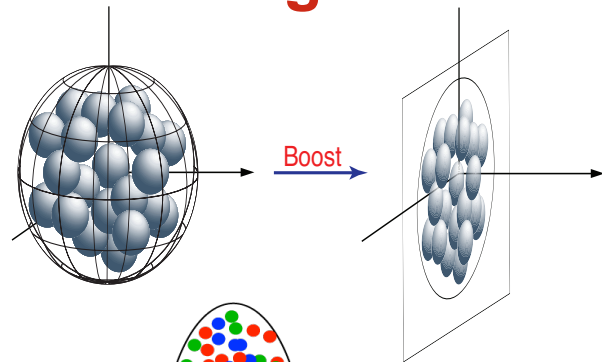




# How to explore/study this new phase of matter?

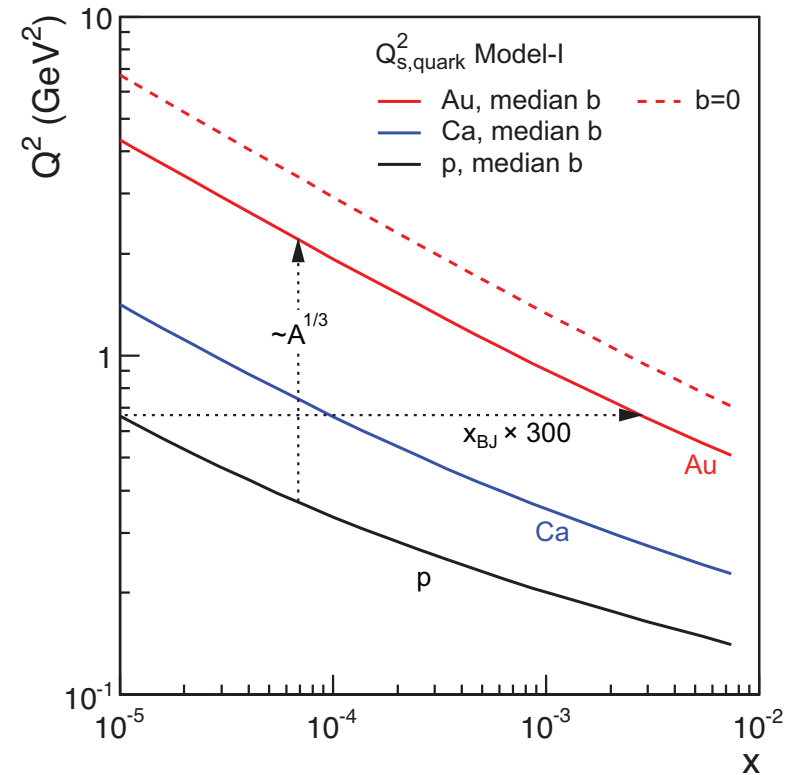
(multi-TeV) e-p collider (LHeC) **OR** a (multi-10s GeV) e-A collider

## Advantage of nucleus →



$$(Q_s^A)^2 \approx c Q_0^2 \left[ \frac{A}{x} \right]^{1/3}$$

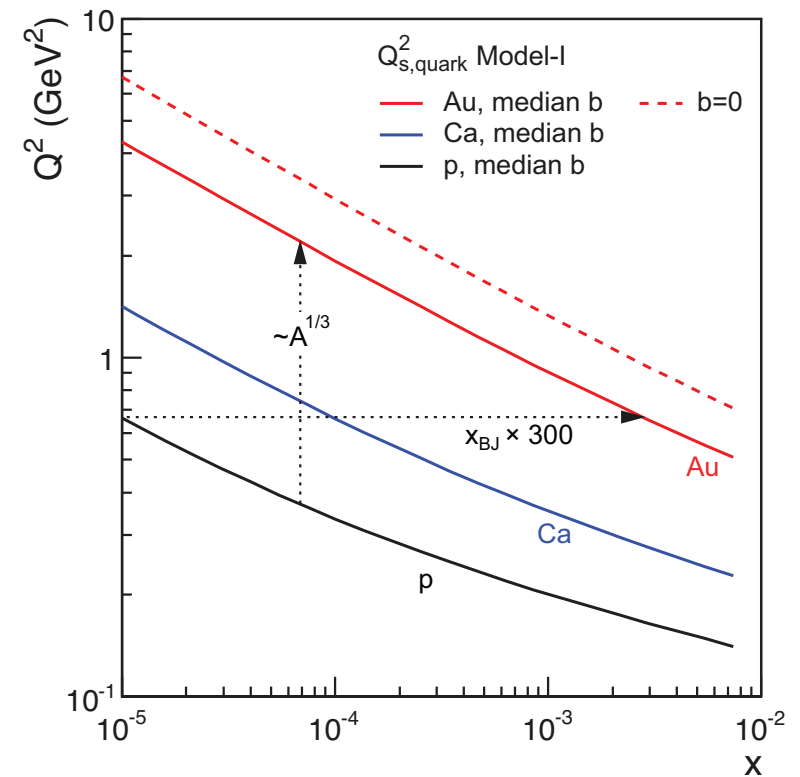
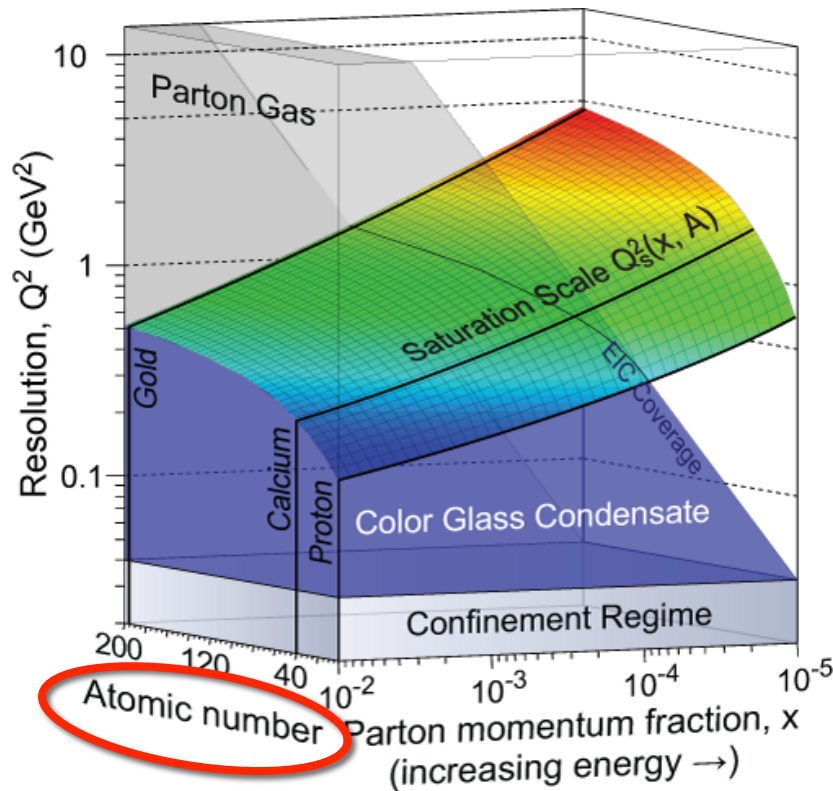
$$L \sim (2m_N x)^{-1} > 2 R_A \sim A^{1/3}$$



Enhancement of  $Q_s$  with  $A$ :  
 Saturation regime reached at significantly lower energy (read: “cost”) in nuclei

# How to explore/study this new phase of matter? (multi-TeV) e-p collider (LHeC) OR a (multi-10s GeV) e-A collider

## Advantage of nucleus →



Enhancement of  $Q_s$  with  $A$ :  
 Saturation regime reached at significantly lower energy (read: “cost”) in nuclei

## Final vote on Long Range Plan US NSAC: EIC Part of this plan (to be released October 15, 2015)

An active Generic Detector R&D Program for EIC underway, (supported by DOE, administered by BNL):

~140 physicists, 31 institutes (5 Labs, 22 Universities, 9 Non-US Institutions) 15+ detector consortia exploring novel technologies for tracking, particle ID, calorimetry

→ [https://wiki.bnl.gov/conferences/index.php/EIC\\_R%25D](https://wiki.bnl.gov/conferences/index.php/EIC_R%25D)

**Invitation: Ample opportunities for your contributions**

The EIC Users Meeting at Stony Brook, June 2014:

~180 participants from all over the world (Europeans and Asian QCD group representatives participated actively) :

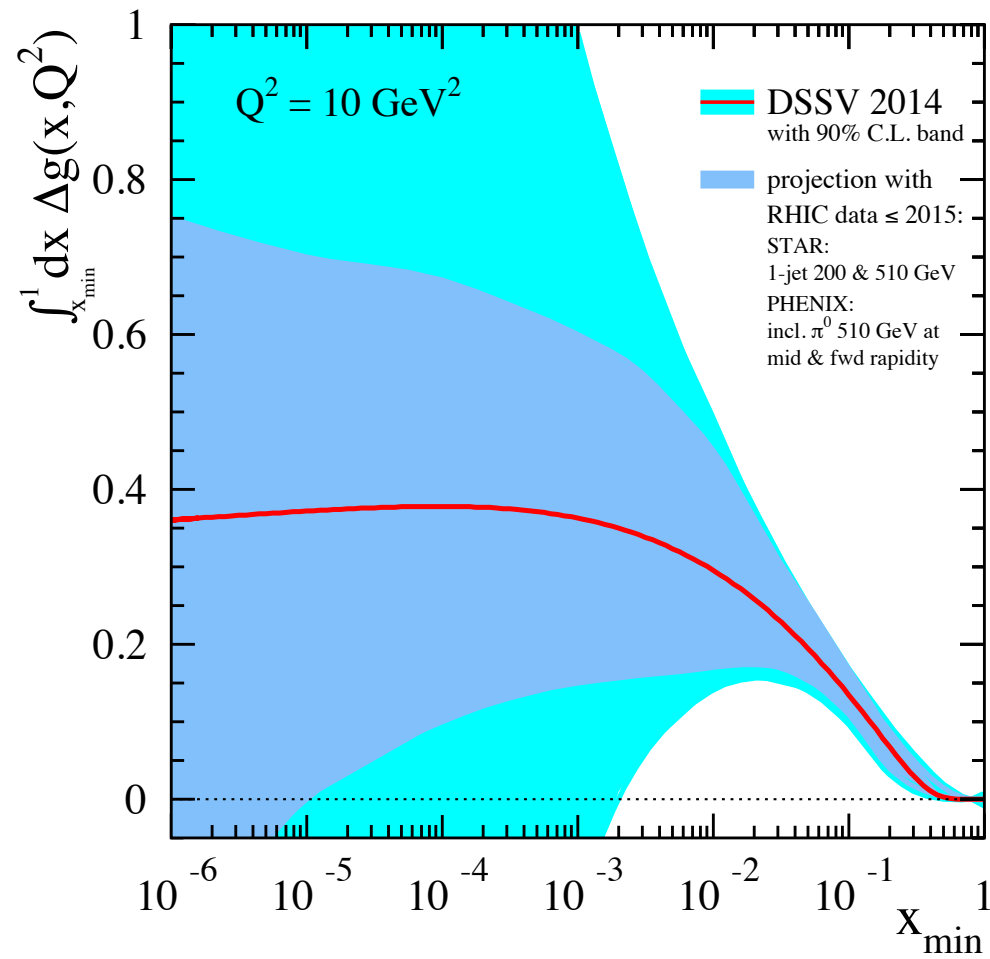
→ <http://skipper.physics.sunysb.edu/~eicug/meetings/SBU.html>

**Next Meeting of the EIC User Group: January 6-9, 2016  
University of California @ Berkeley**

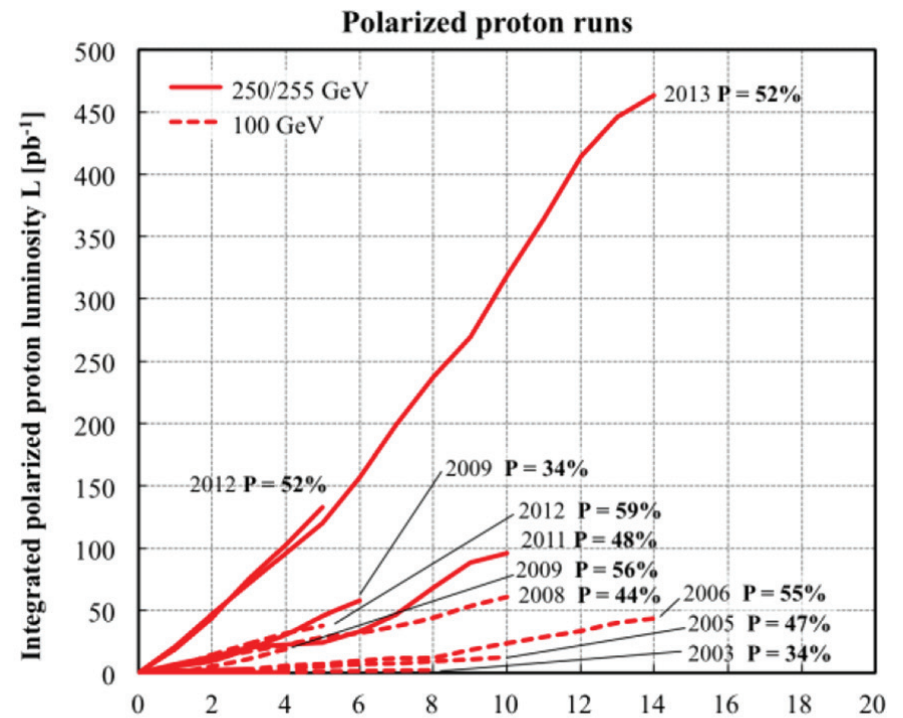
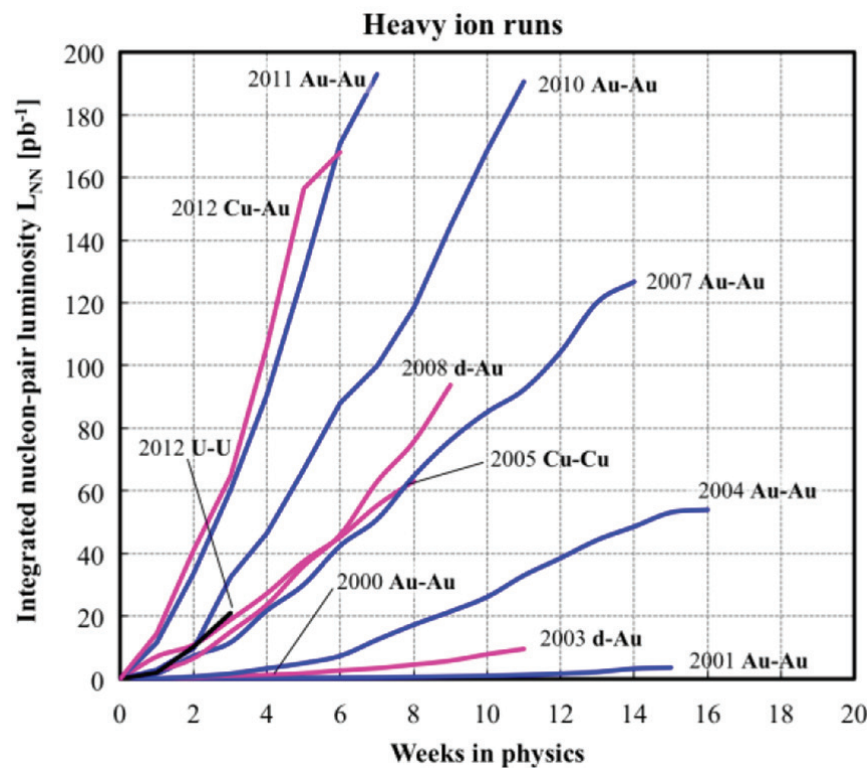
# The RHIC Spin Program (early 2000)

$$\frac{1}{2} = \left[ \frac{1}{2} \Delta\Sigma + L_Q \right] + [\Delta g + L_G]$$

- Direct determination of polarized gluon distribution (and contribution to) in the polarized proton
  - Polarized fixed target experiments and NLO global analyses suggested  $\Delta\Sigma \sim 0.25 \pm 0.05$  &  $\Delta g \sim 1.0 \pm 1.5$
- Direct determination of anti-quark polarization via using the maximal parity violating electro-weak ( $W^{+/-}$ ) probes
  - SIDIS: questions regarding contamination from **high-twist and large uncertainties in polarized fragmentation functions**
- Systematic study of transverse spin phenomena
  - **Many un-understood single spin asymmetries** observed but none expected

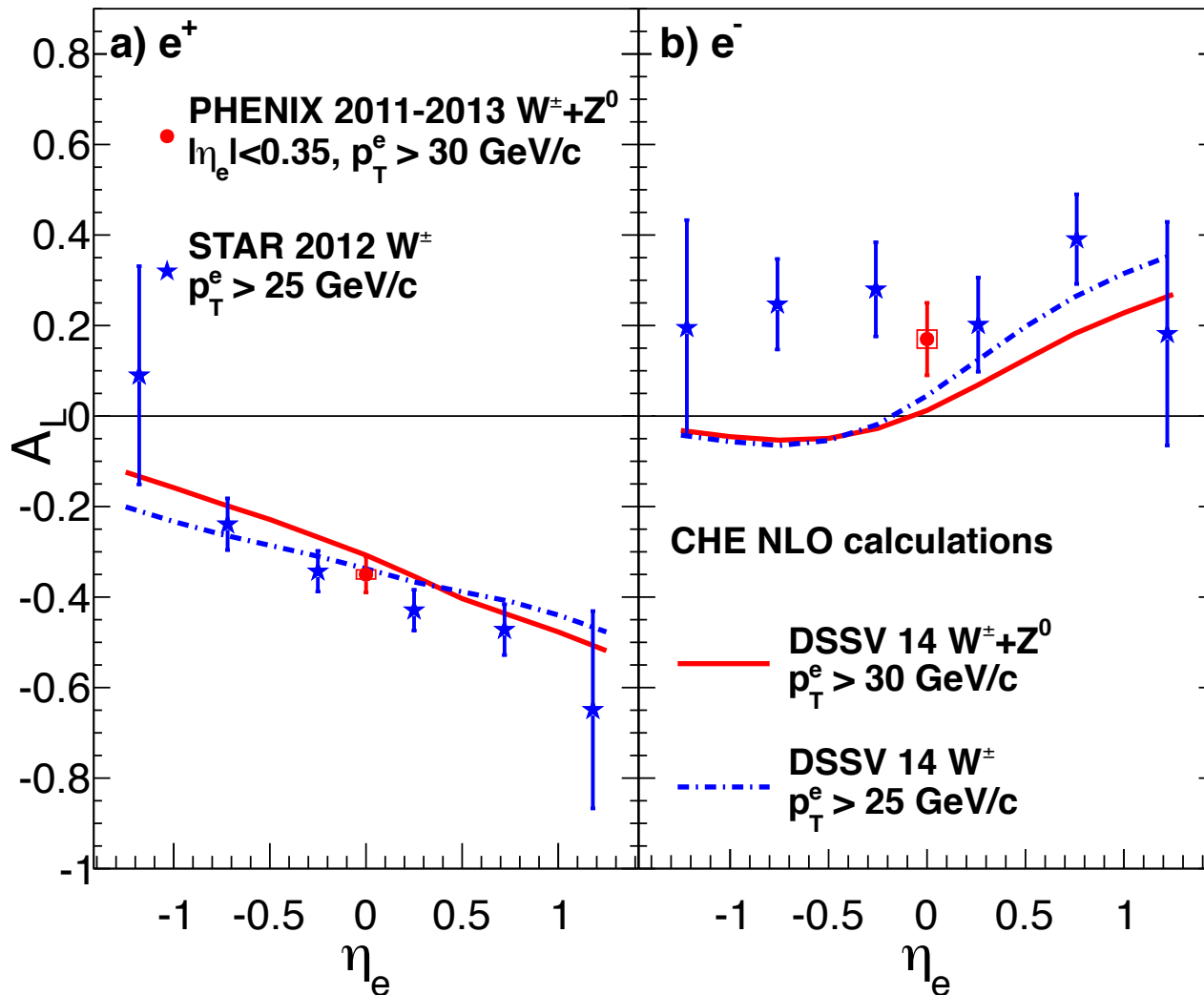


# RHIC: The most versatile collider yet



1504.07451v1 to be published PRD

# RHIC $W \rightarrow e$ Combined results 2011-2013

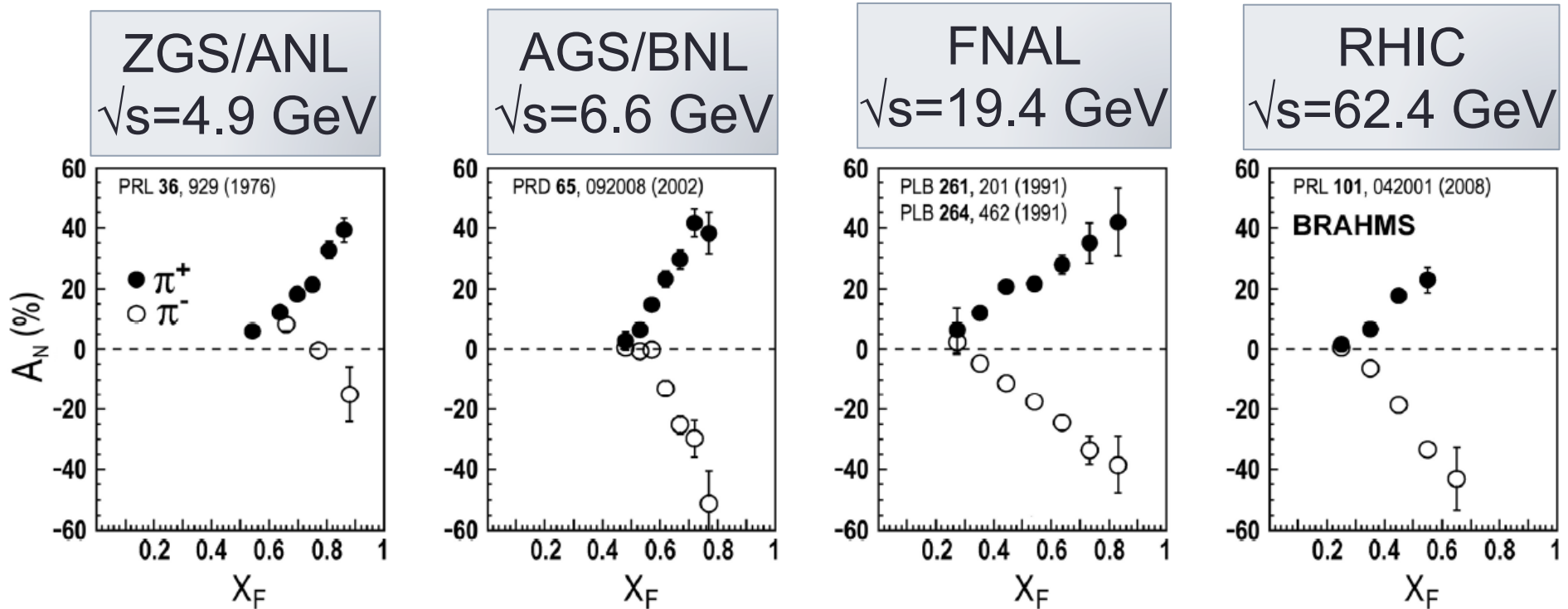


High  $|\eta|$   $W \rightarrow \mu$   
 data anticipated  
 in near future

When its  
 there...

# Pion asymmetries: at most CM energies!

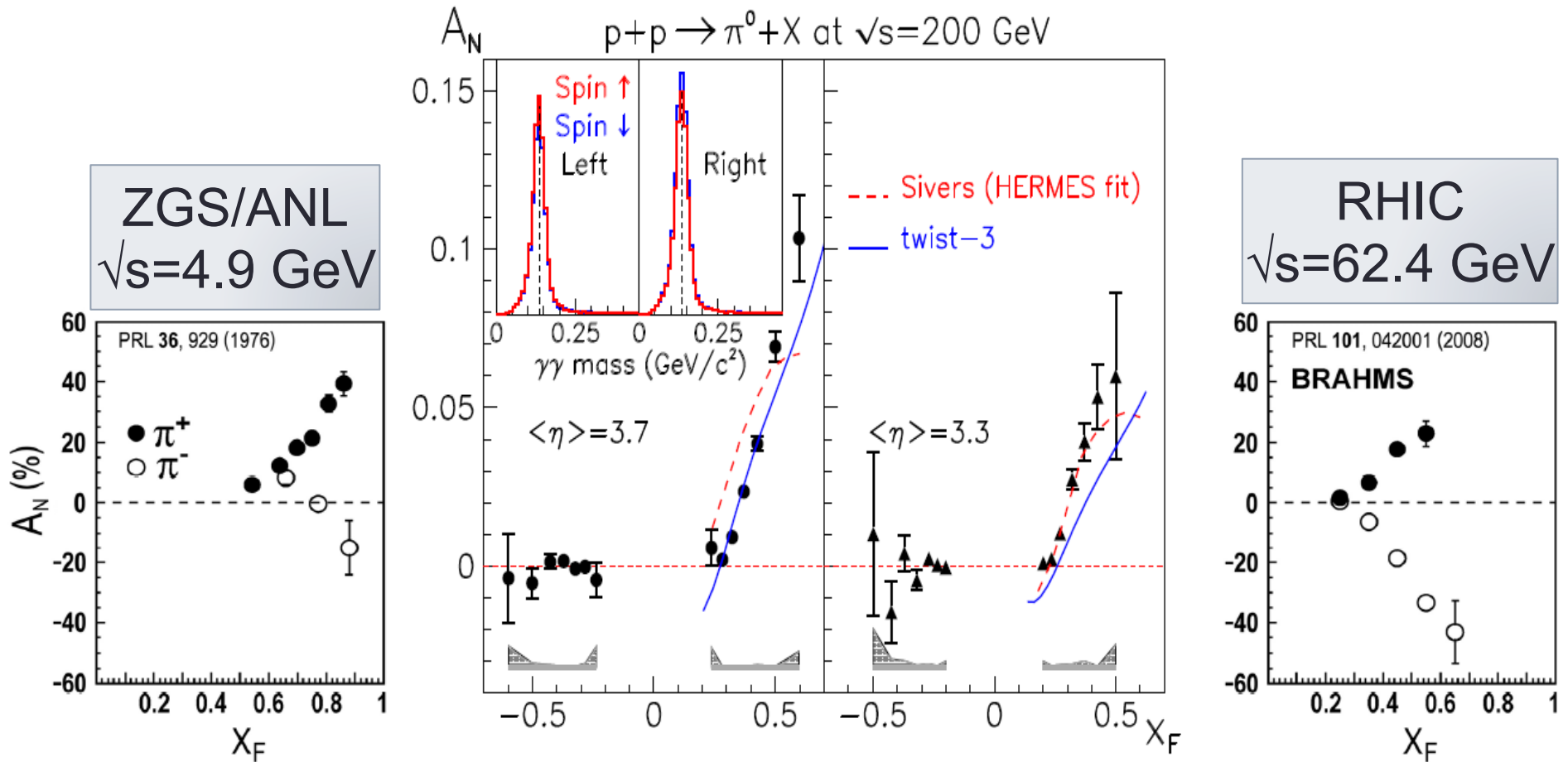
$$x_F = P_L / P_L^{\max} = 2P_L / \sqrt{s}$$



Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

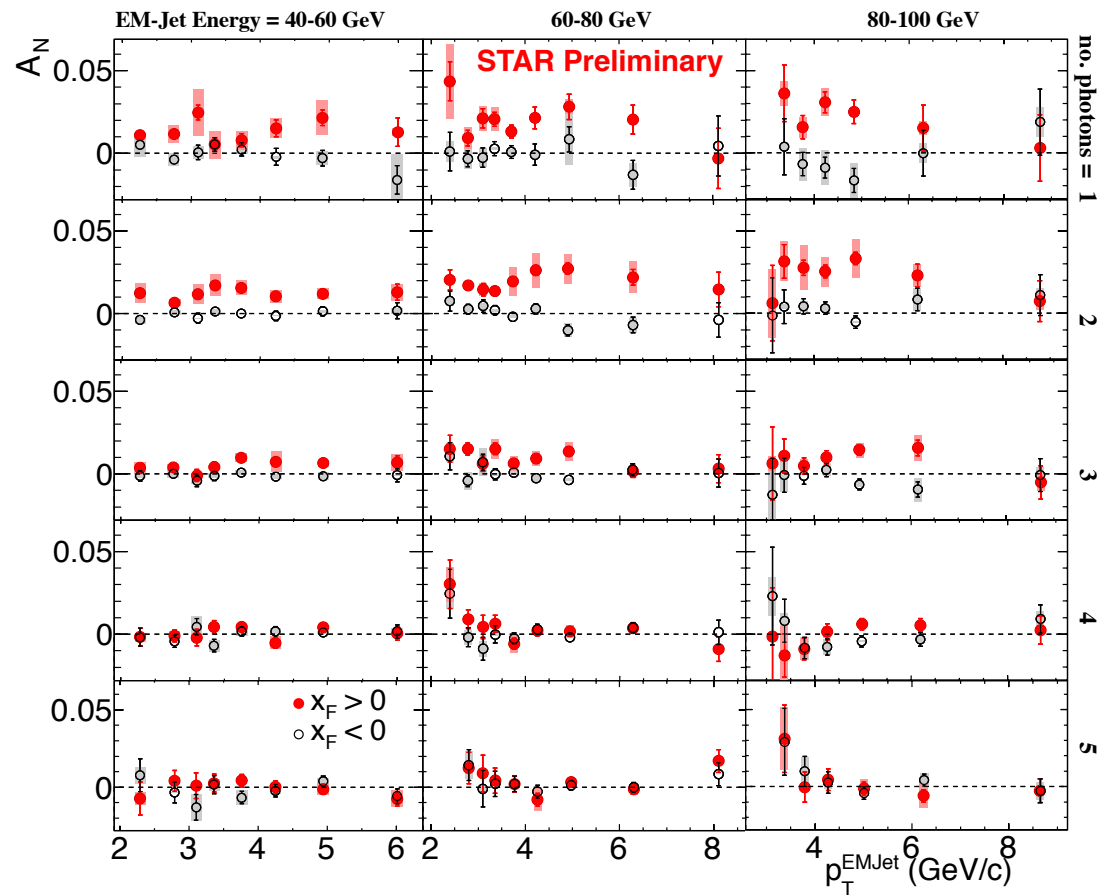


# Pion asymmetries: at most CM energies!

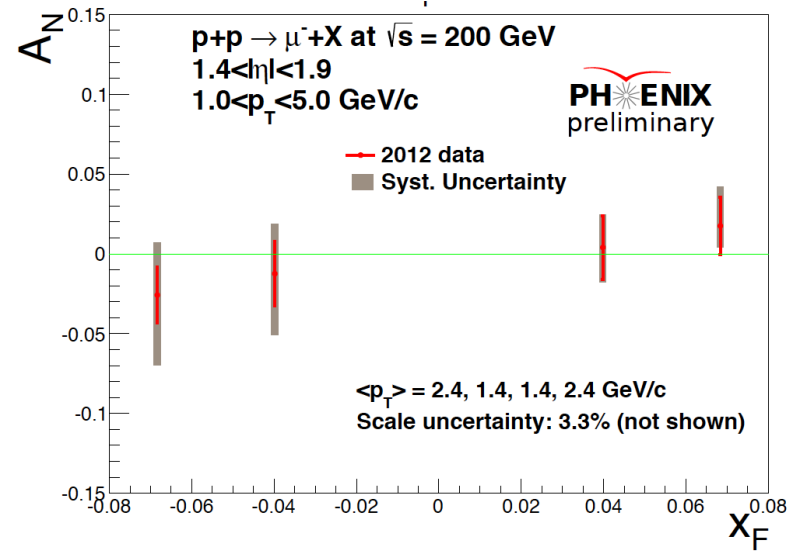
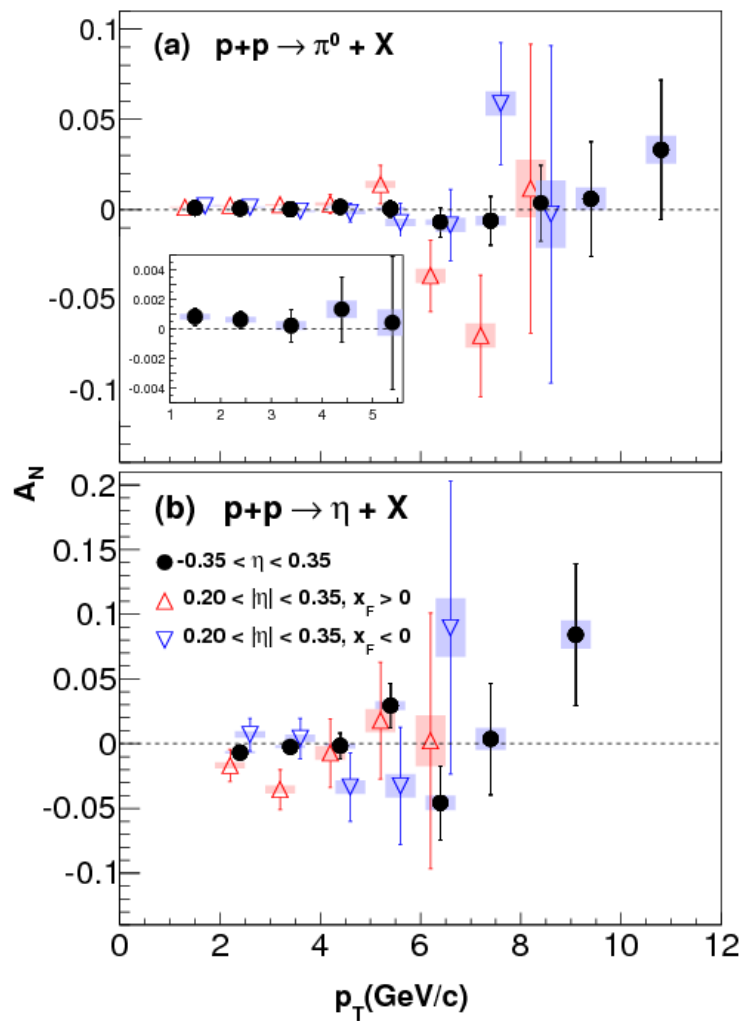


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

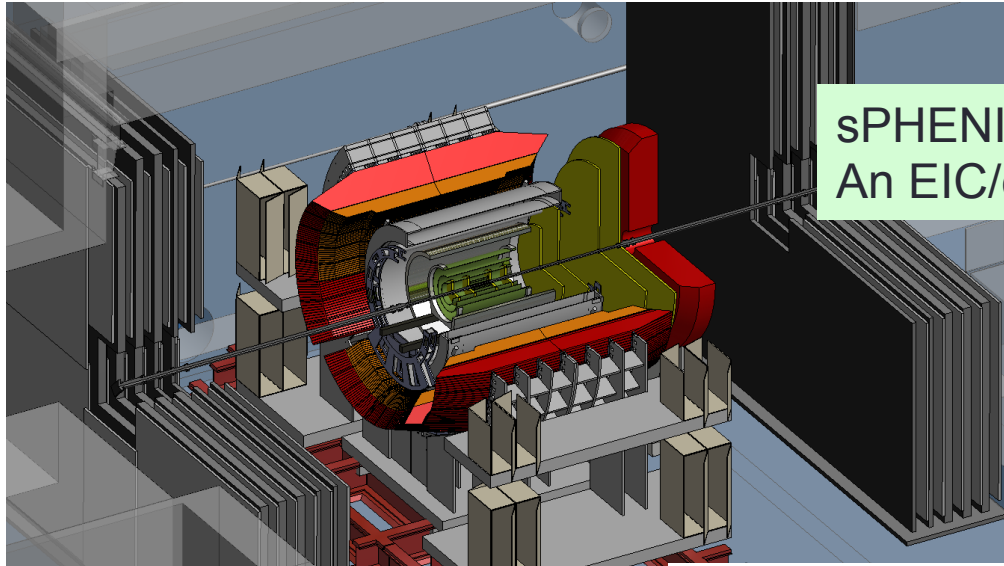
# STAR EM Jets high $\eta$



# Recent PHENIX results

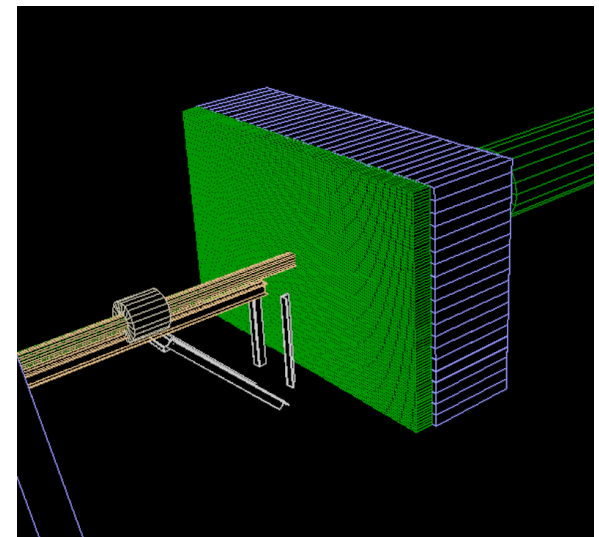
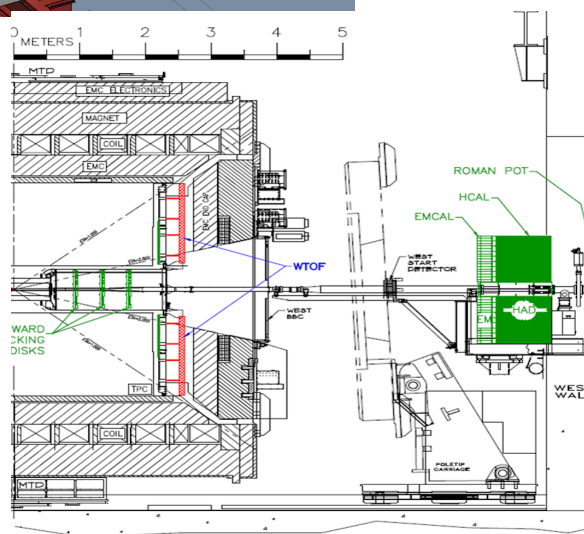


# Near term RHIC Detector Upgrades Spin and non-spin physics programs

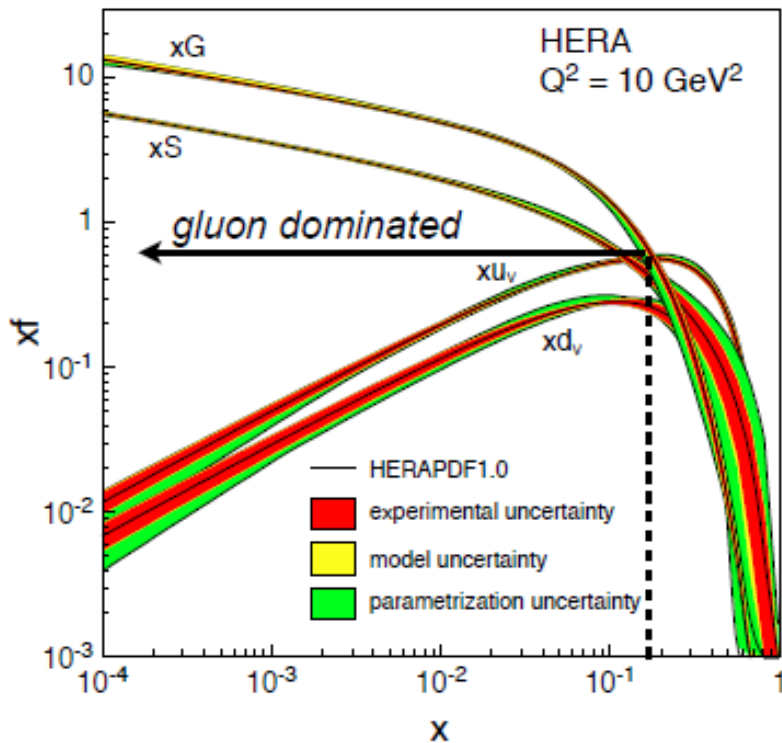


sPHENIX → forward sPHENIX →  
An EIC/eRHIC detector (not shown)

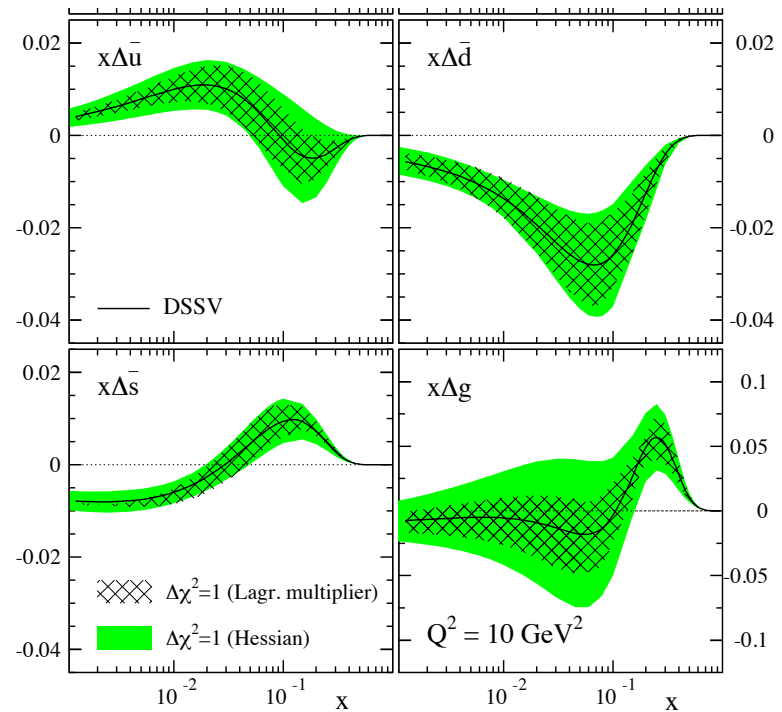
STAR upgrade:  
Forward Calorimeter  
System (FCS)



# What does a proton look like? Un-polarized & polarized



**We only have a 1-dimensional picture!**



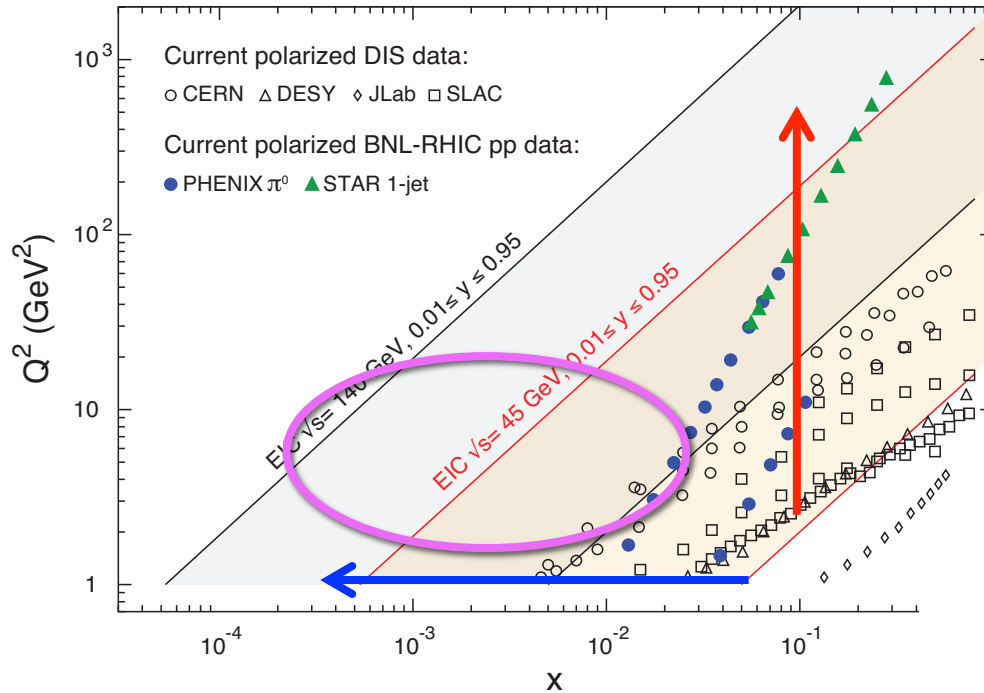
**Need to go beyond 1-dimension!**

**Need 3D Images of nucleons in Momentum & Position space**

**Could they give us clues on orbital motion of partons?**

**→ Finally help solve the spin puzzle?**

# US EIC: Kinematic reach & properties



## For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/<sup>3</sup>He
- ✓ Variable center of mass energy
- ✓ Wide  $Q^2$  range → evolution
- ✓ Wide x range → spanning valence to low-x physics

## For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)

