



Nucleon Structure from High-Energy Polarized Proton Collisions

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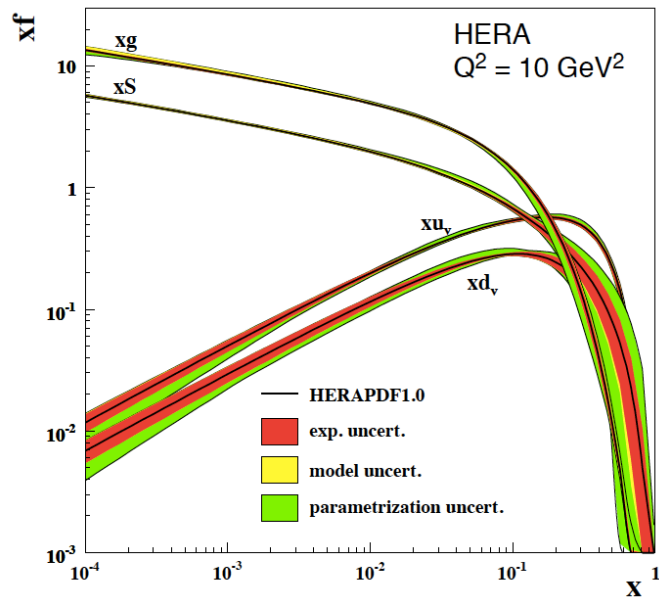
Outline

- Introduction
- Longitudinal spin structure
- Transverse spin structure

Why do we study the proton spin?

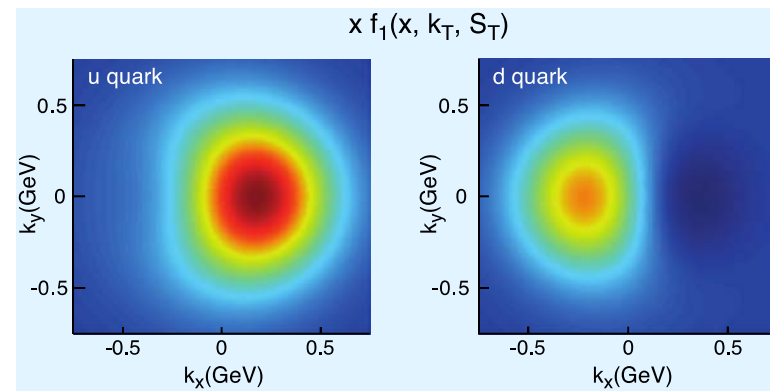
- Spin is an fundamental quantum mechanical property of all matter
- Exploring spin has revealed many surprises
 - Anomalous magnetic moment of the proton
 - The proton is not elementary; it has substructure
 - Proton “spin crisis”
 - Quarks contribute much less than naïve expectations
 - ...
- In QCD, the proton spin arises from a complex interplay between the intrinsic properties and interactions of quarks and gluons
 - A window to elucidate quark-gluon interactions at the confinement scale
- **An essential step toward understanding QCD**

Fundamental questions

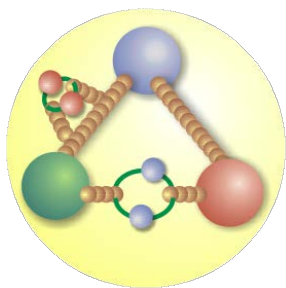
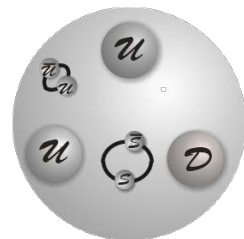
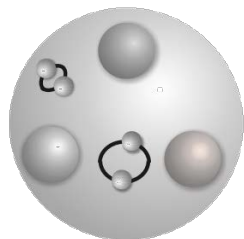


- How do quarks and gluons conspire to provide the proton's spin $\frac{1}{2}$?
 - What is the role of gluons?
 - Reminder – gluons contribute 50% of the proton's momentum
 - What is the role of sea quarks?
 - How much orbital angular momentum is needed?
- What is the dynamic structure of the proton?

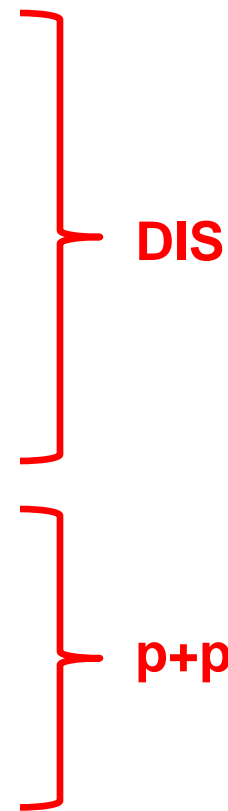
- How do we go beyond longitudinal parton distribution functions to a 2D+1 picture in coordinate and momentum space?
- Can we visualize color interactions in QCD?



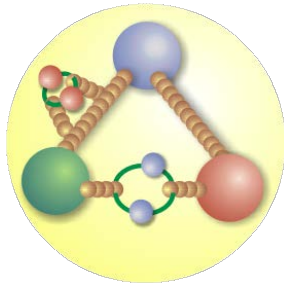
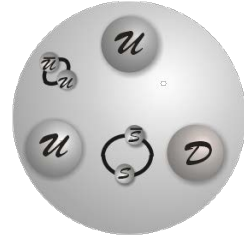
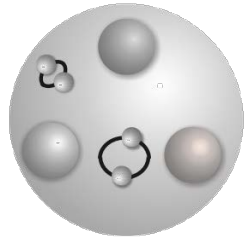
Complementarity of DIS and p+p



- Electromagnetic interactions
 - Sensitive to charge²
 - Insensitive to color
- Weak interactions
 - Sensitive to weak charge (~flavor)
 - Insensitive to color
- Strong interactions
 - Sensitive to color charge
 - Unique sensitivity to gluons
 - Insensitive to flavor
- **Need both for a complete picture**



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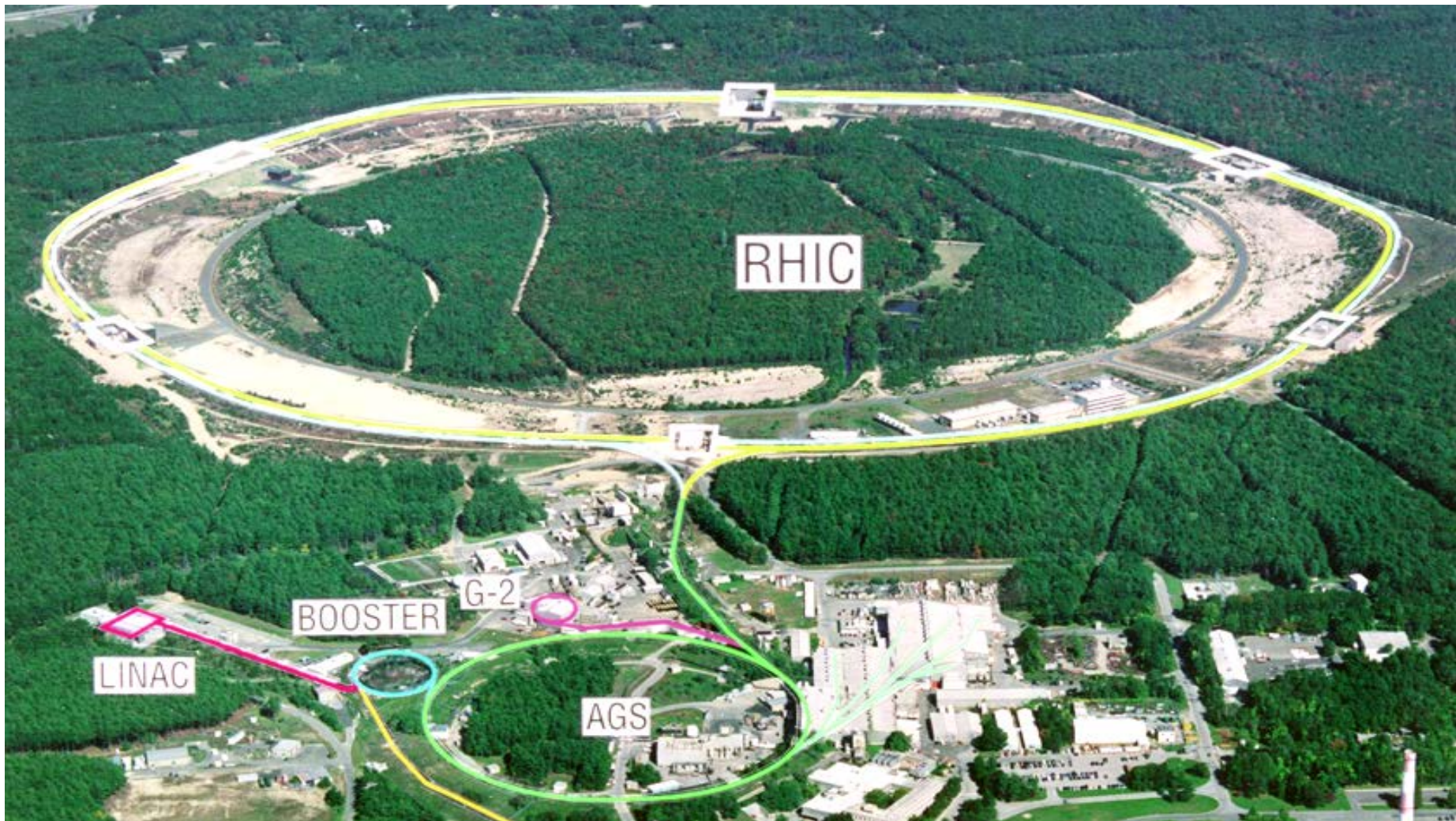
DIS

p+p

- **Need both for a complete picture**

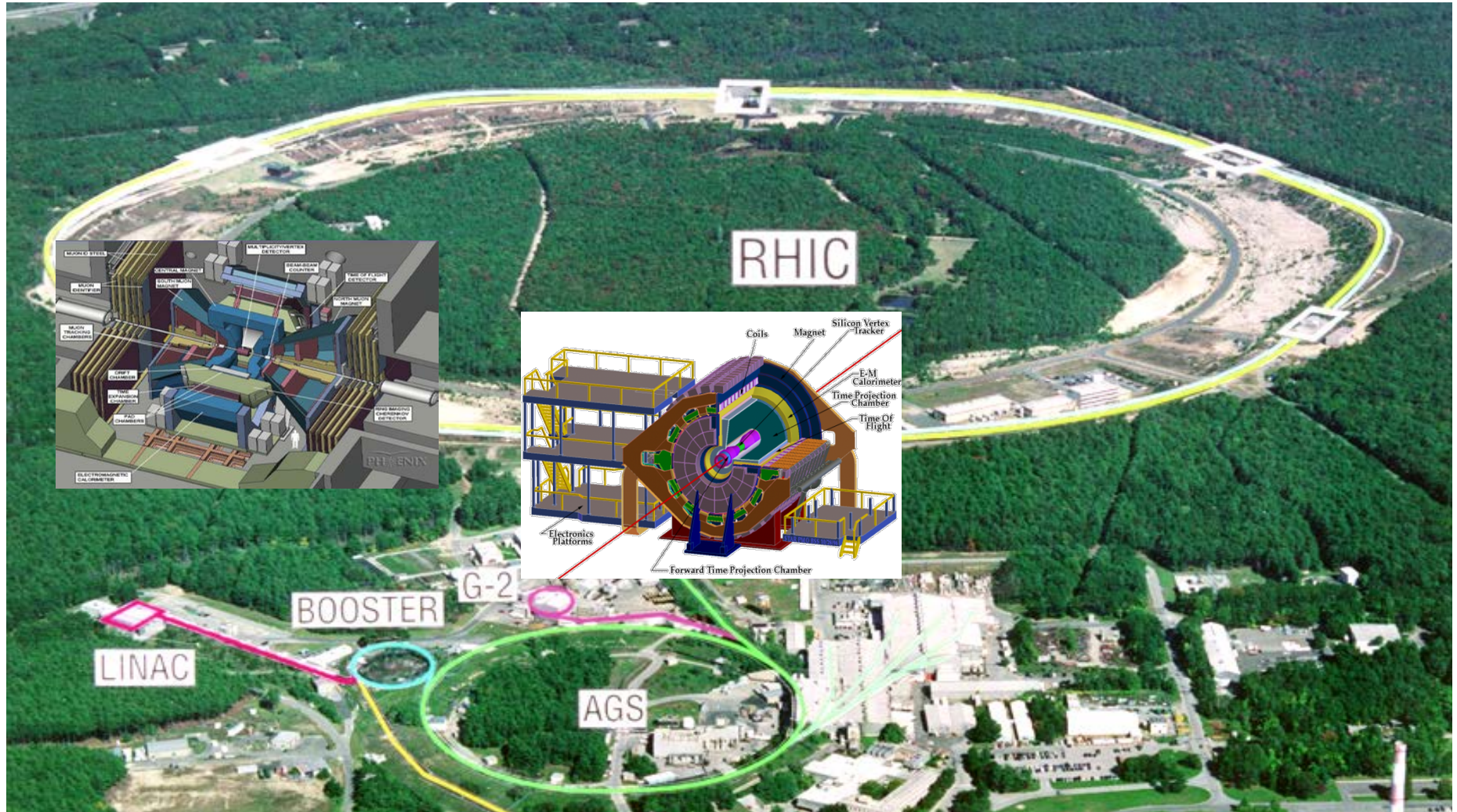
- **Combine DIS and p+p** to explore **universality** and separate **interaction-dependent phenomena** from **intrinsic properties**

RHIC: the Relativistic Heavy Ion Collider



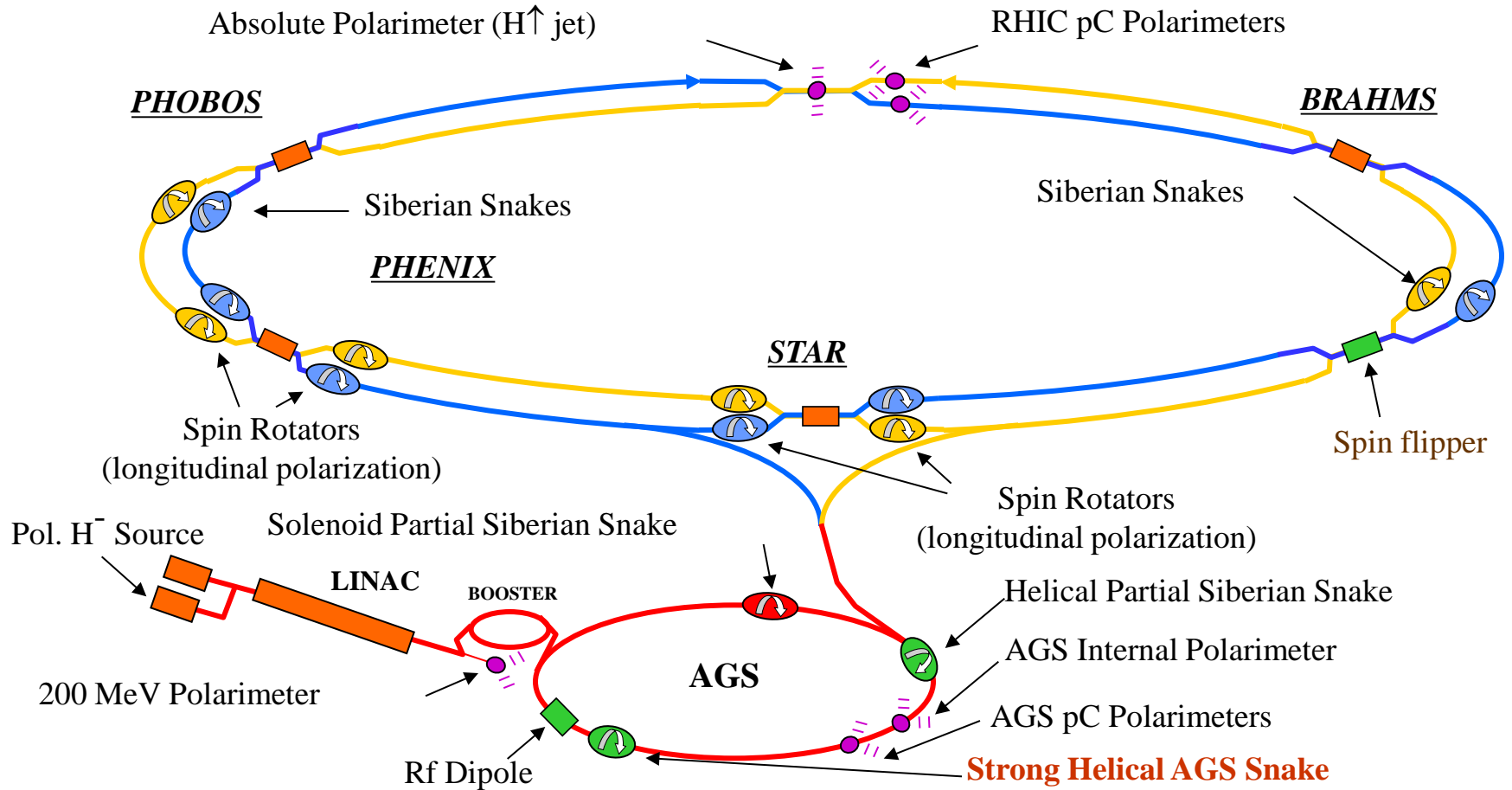
- Search for and study the Quark-Gluon Plasma
- **Explore the partonic structure of the proton**
- Determine the partonic structure of nuclei

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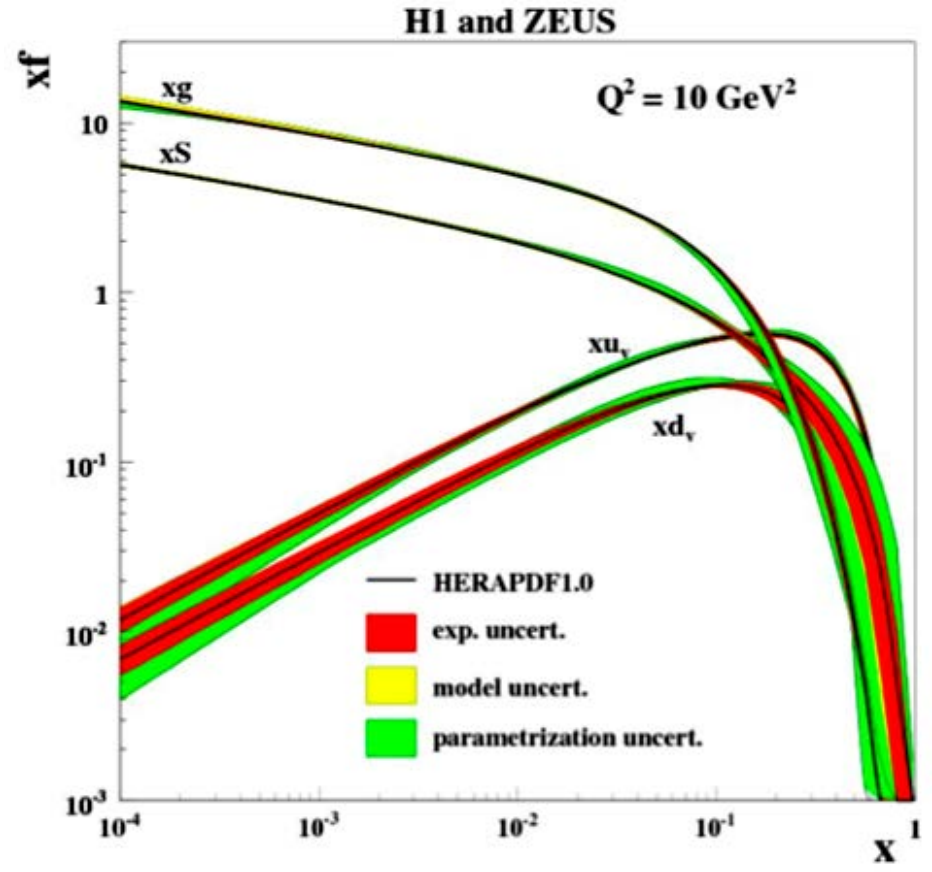
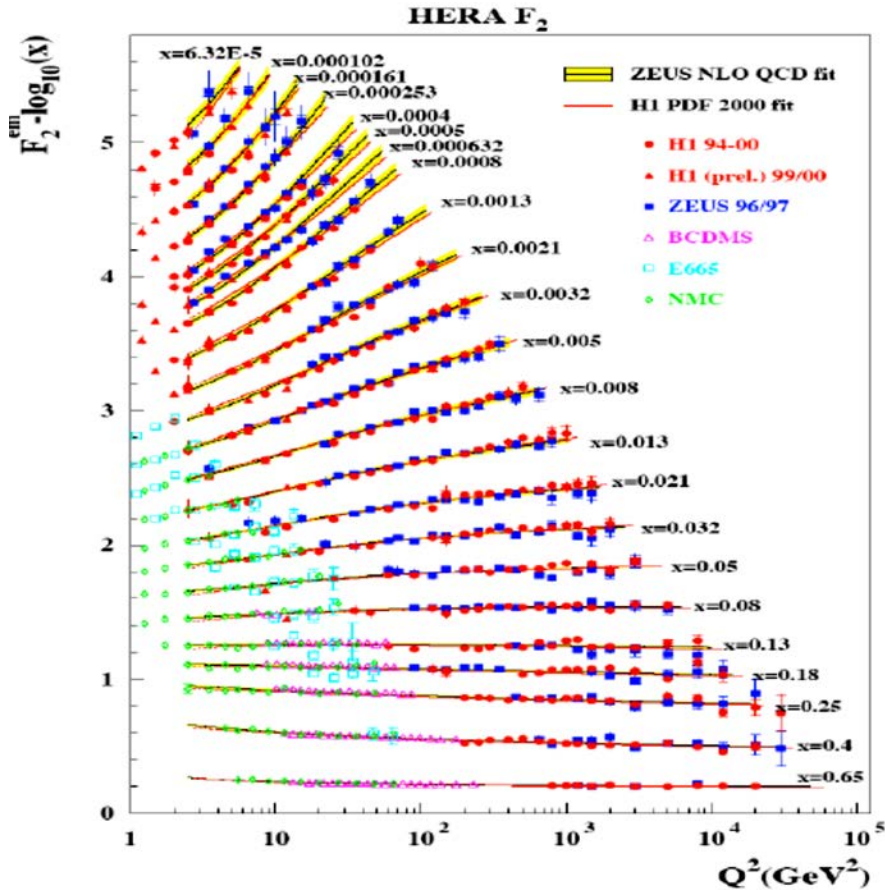
RHIC: the world's first (and only!) polarized hadron collider



- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

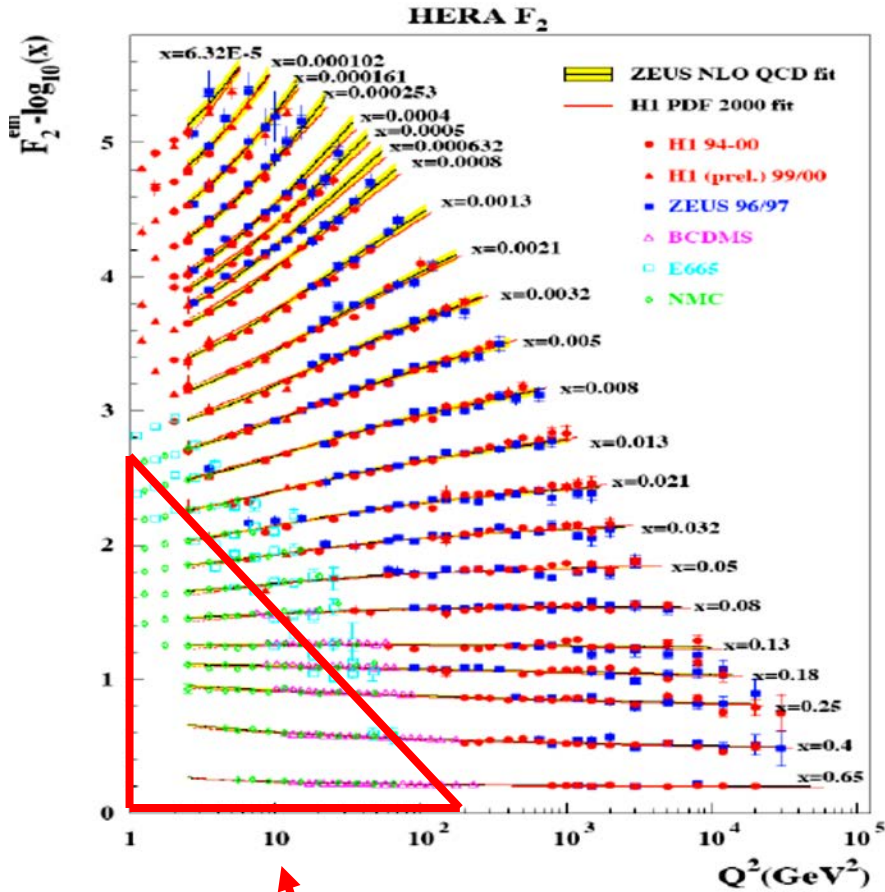
Longitudinal spin structure

Parton distribution functions

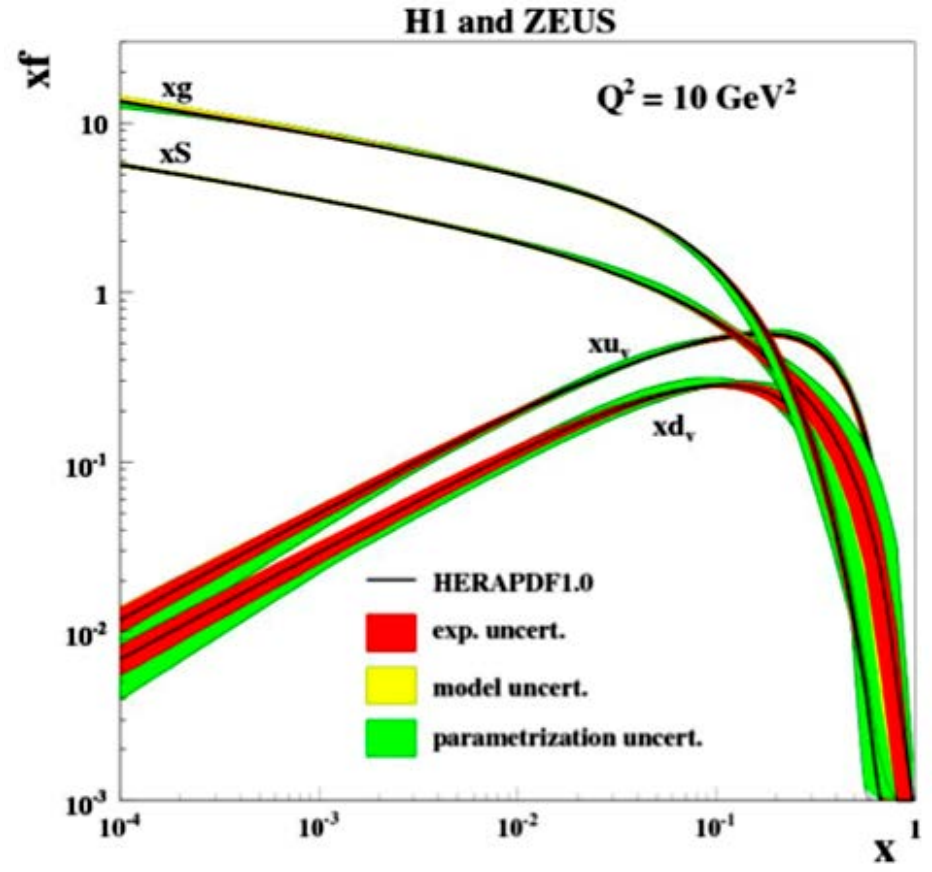


- Unpolarized PDF fits have access to a **huge body of data**
- Data for polarized PDF fits are far more limited

Parton distribution functions



Kinematic region of **polarized** measurements



- Unpolarized PDF fits have access to a **huge body of data**
- Data for polarized PDF fits are far more limited

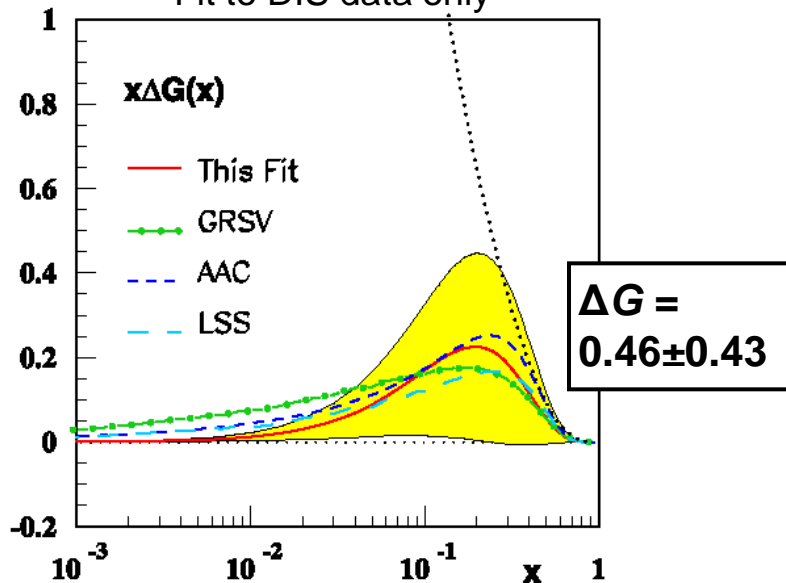
Gluon polarization **without** RHIC data

$$S_z = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + \langle L_z \rangle$$

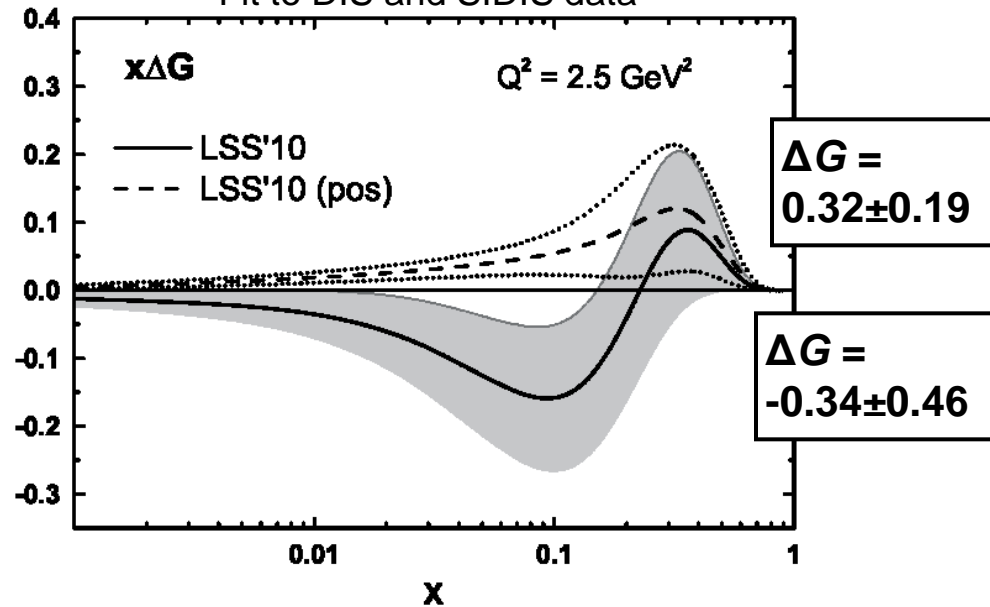
Polarized DIS: ~ 0.3

Poorly constrained by DIS

Blümlein & Böttcher, NPB 841, 205 (2010)
Fit to DIS data only



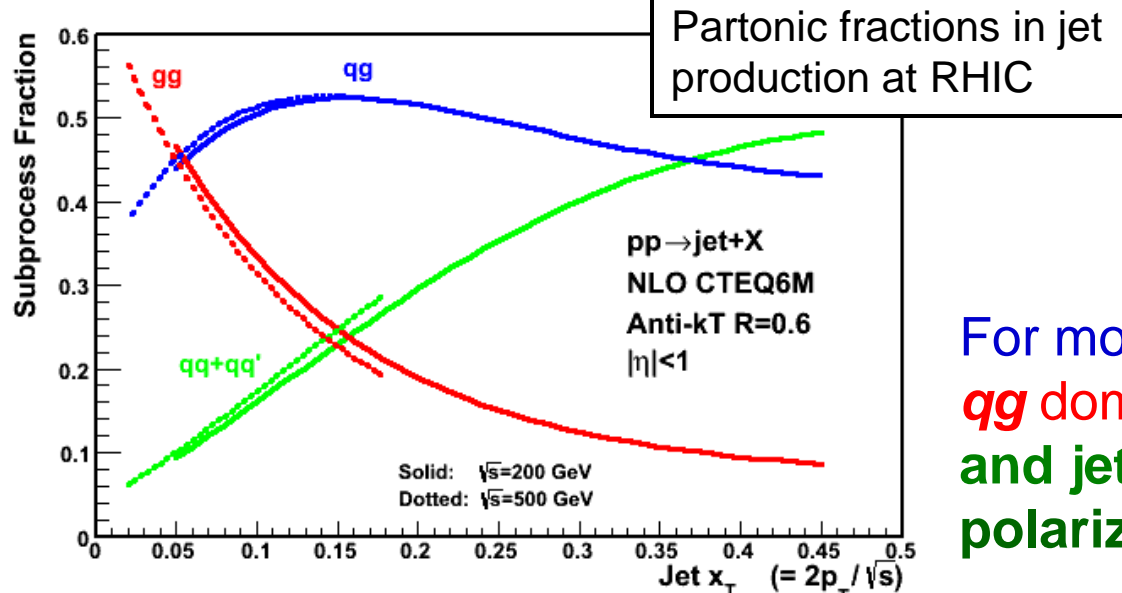
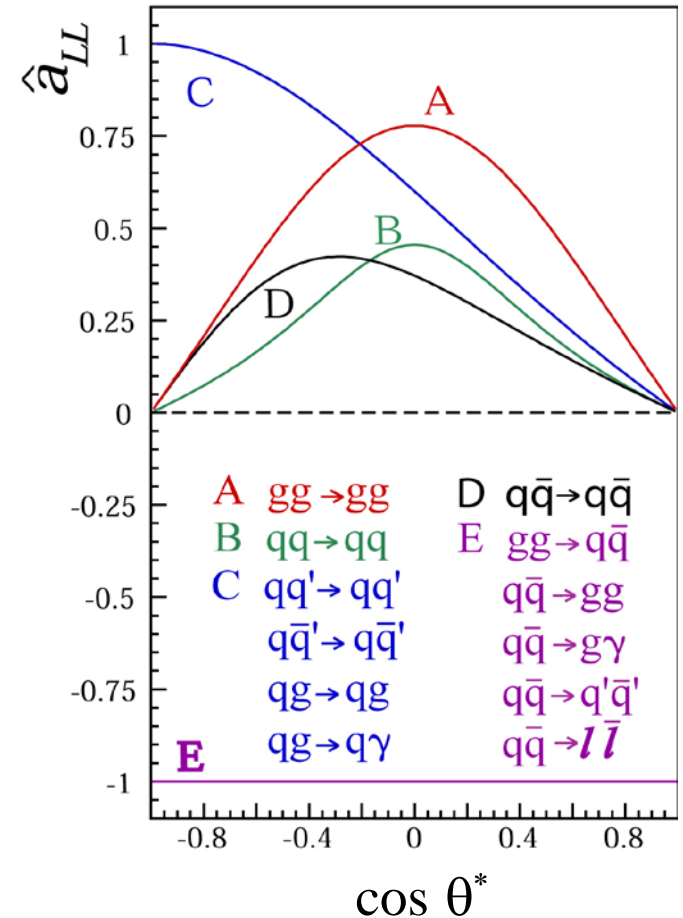
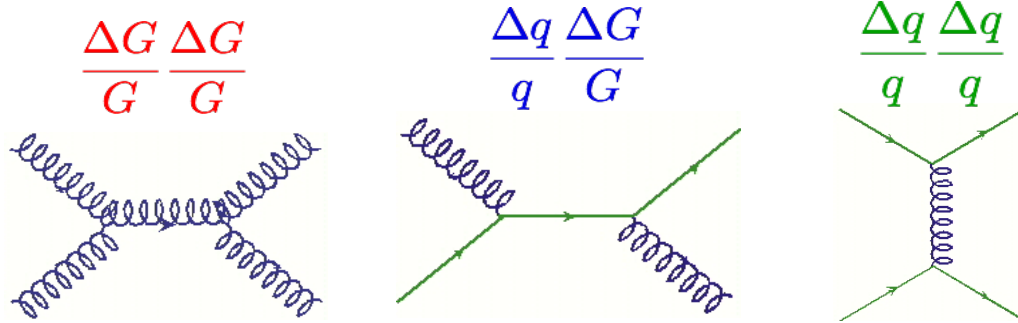
Leader et al, PRD 82, 114018 (2010)
Fit to DIS and SIDIS data



Exploring gluon polarization at RHIC

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

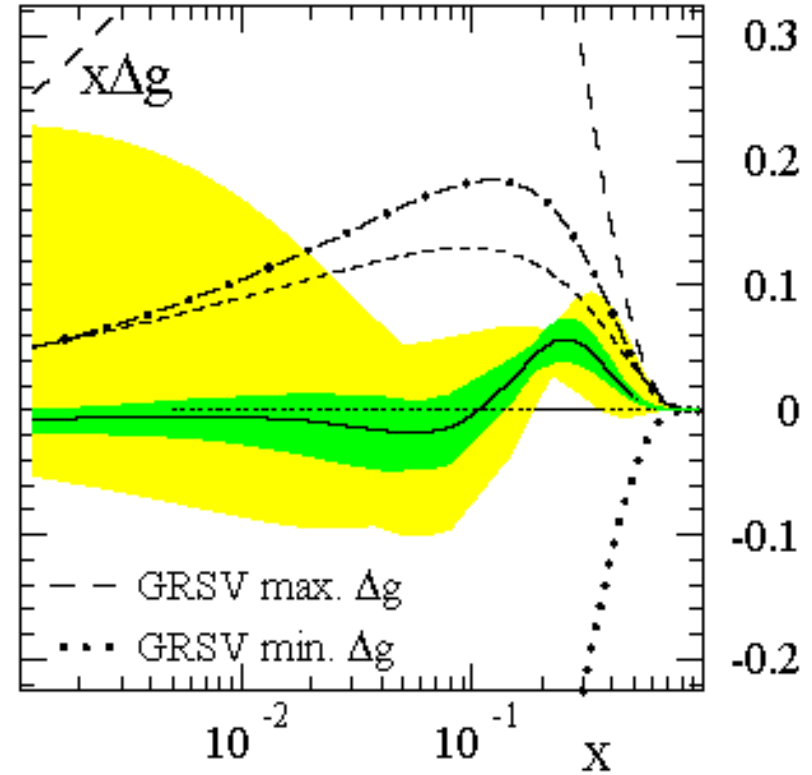
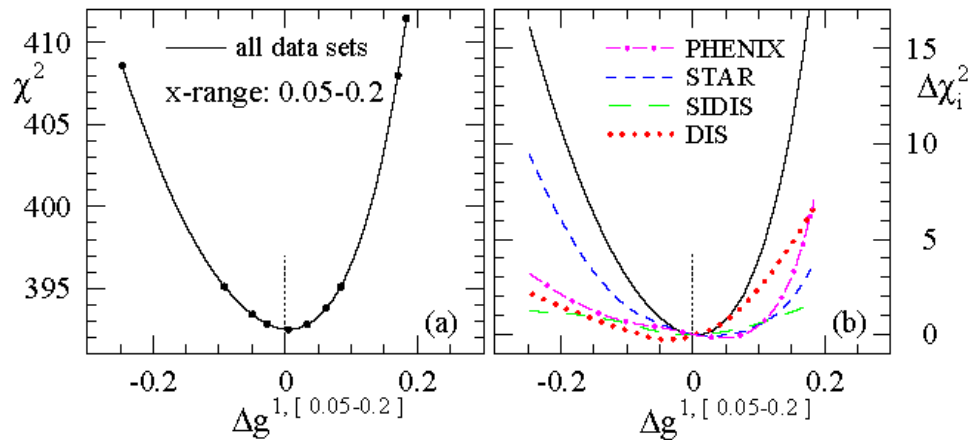
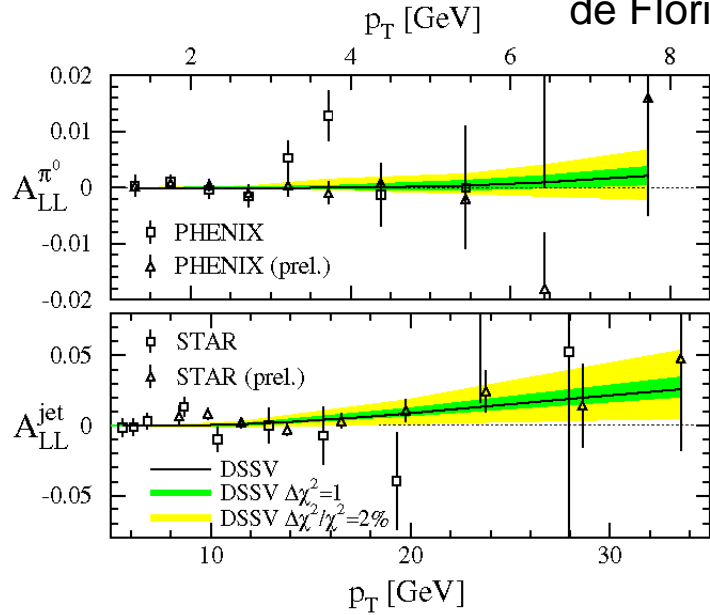
Δf : polarized parton distribution functions



For most RHIC kinematics, **gg** and **qq** dominate, making A_{LL} for pions and jets sensitive to gluon polarization.

First global NLO analysis with RHIC pp data

de Florian et al., PRL 101, 072001

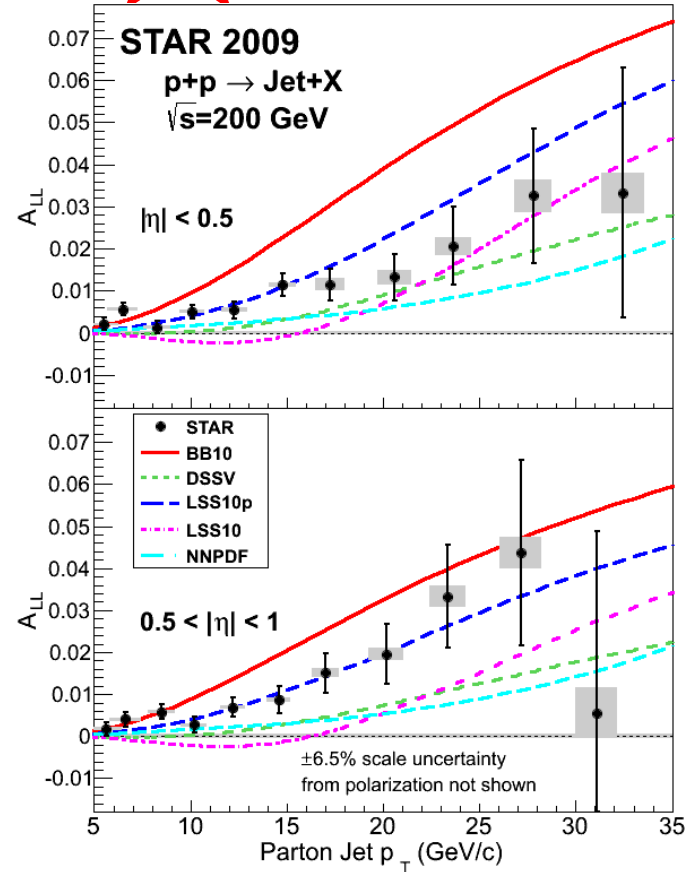
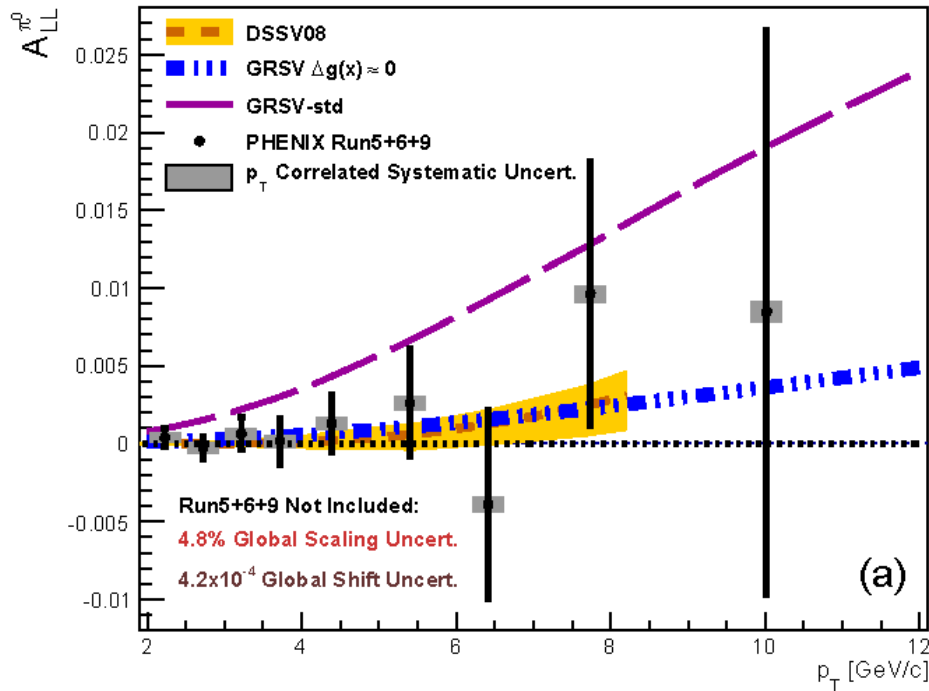


- DSSV'08 was the first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing

Precision measurements from the 2009 run

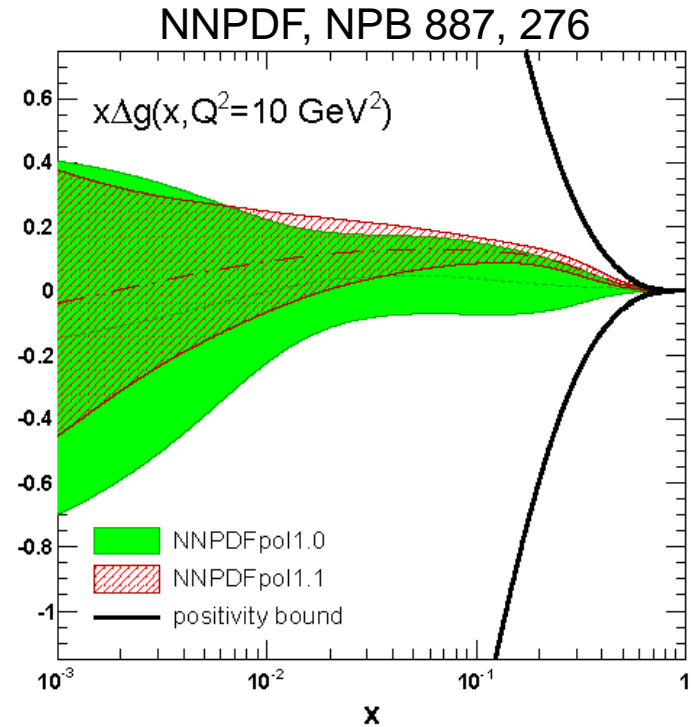
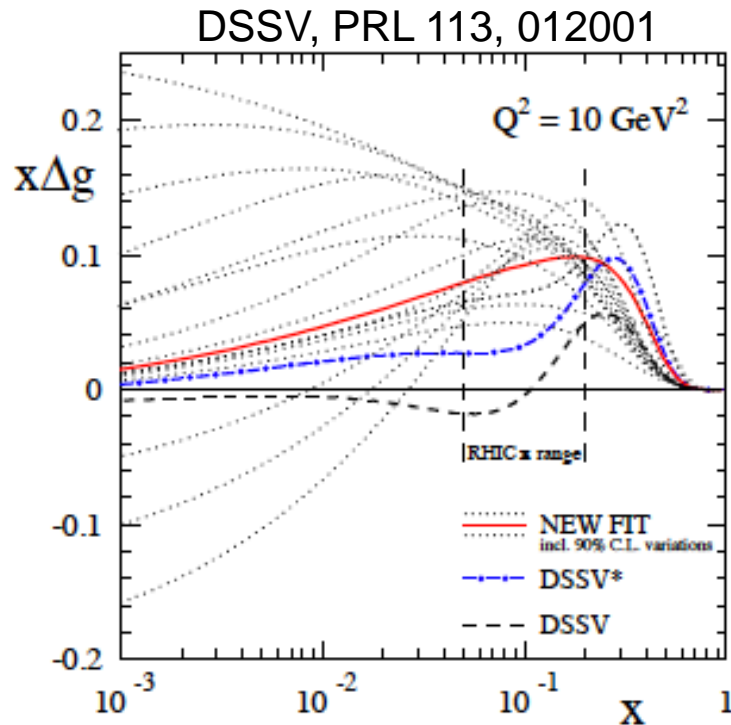


PHENIX PRD 90, 012007



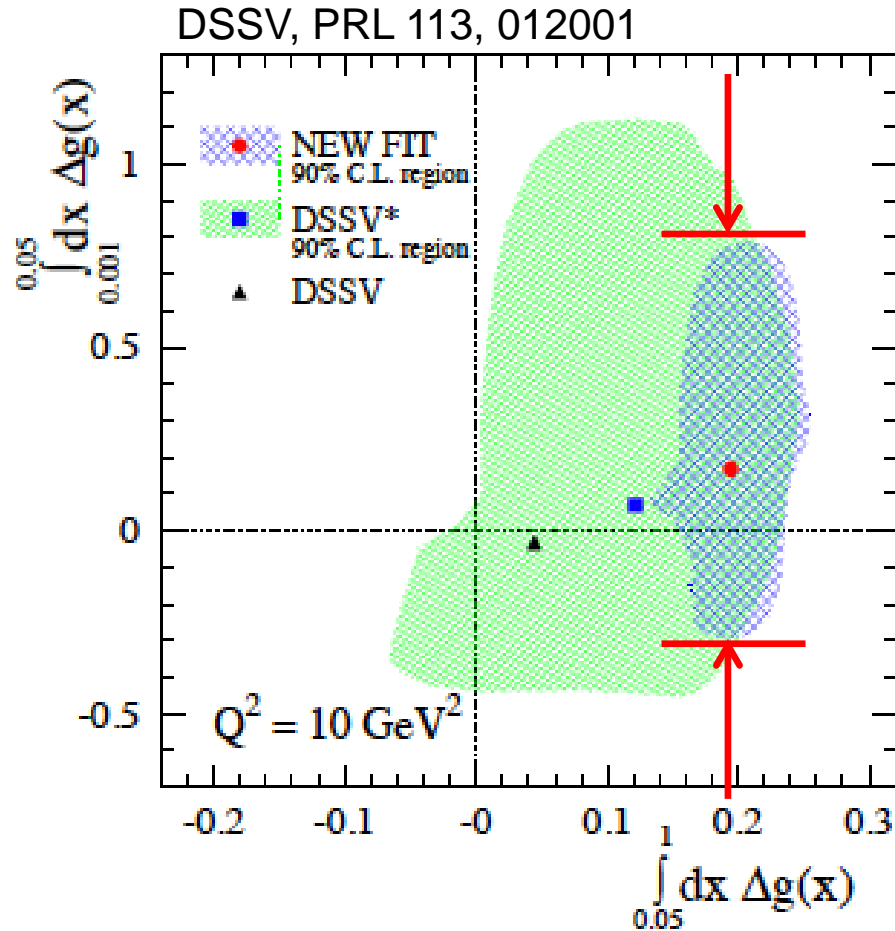
- Both PHENIX (π^0) and STAR (jets) released final results from the 2009 RHIC run in 2014
- Substantially more precise than results from 2005+'06

Gluon polarization with RHIC data



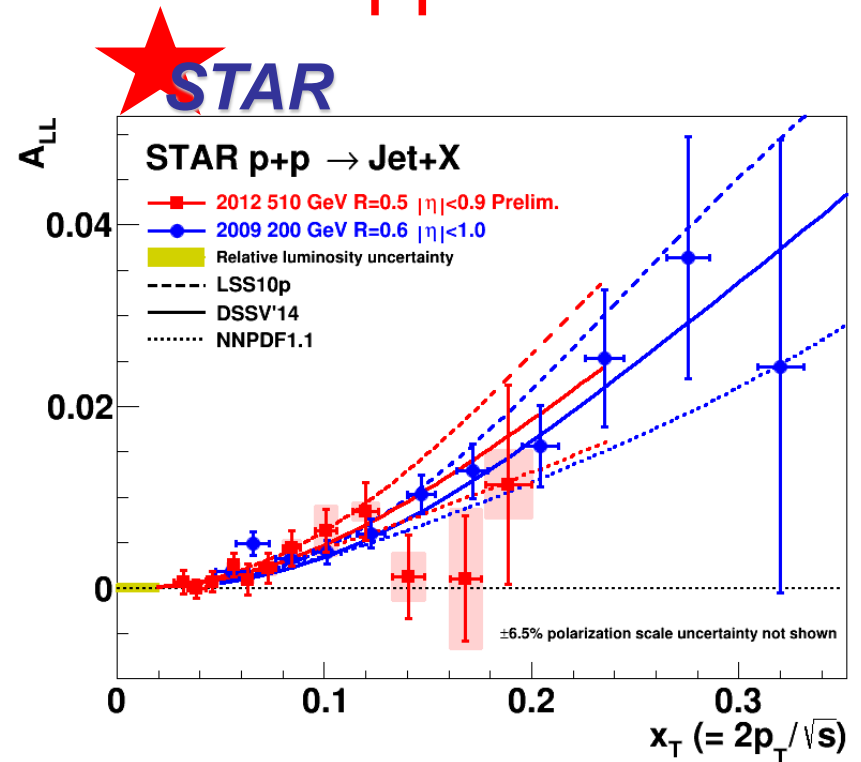
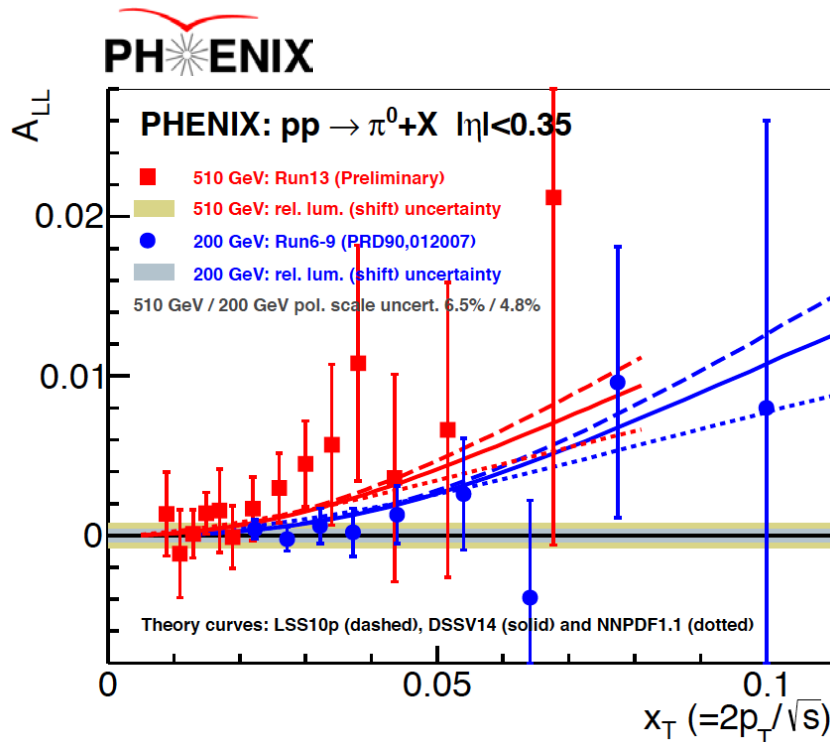
- Both DSSV and NNPDF have released new polarized PDF fits
- Both find the **2009 RHIC results provide significantly tighter constraints on gluon polarization** than previous measurements
- Both find **evidence for positive gluon polarization** in the region $x > 0.05$
 - **DSSV: $0.19^{+0.06}_{-0.05}$ at 90% c.l. for $0.05 < x$**
 - **NNPDF: 0.23 ± 0.07 for $0.05 < x < 0.5$**

Where to from here?



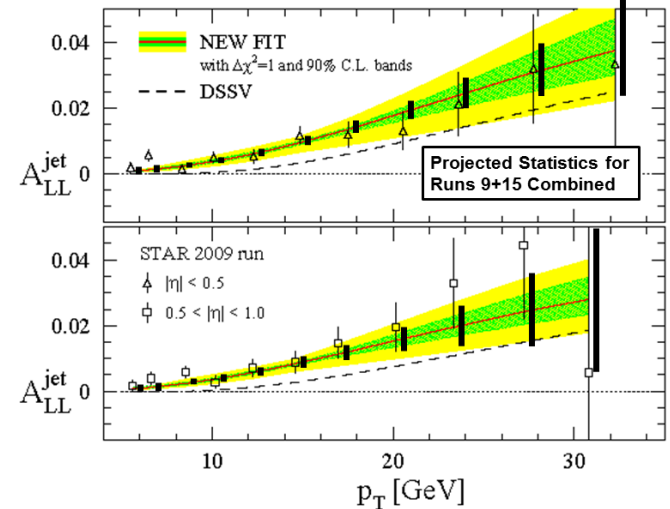
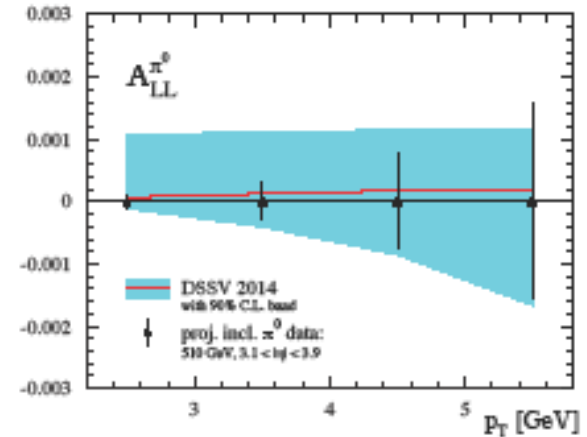
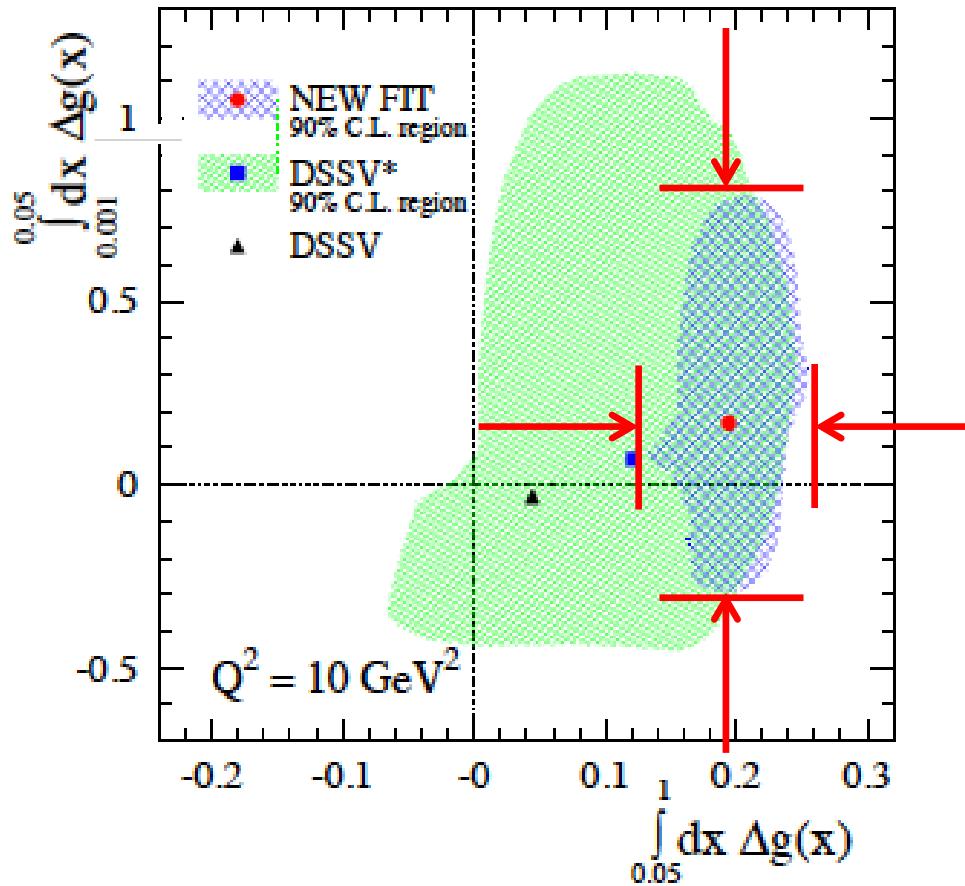
- Need to extend sensitivity to lower x_g where current extrapolations have very large uncertainties

First A_{LL} results from 510 GeV pp collisions



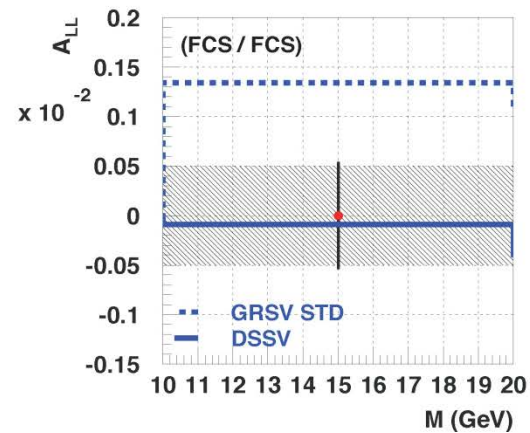
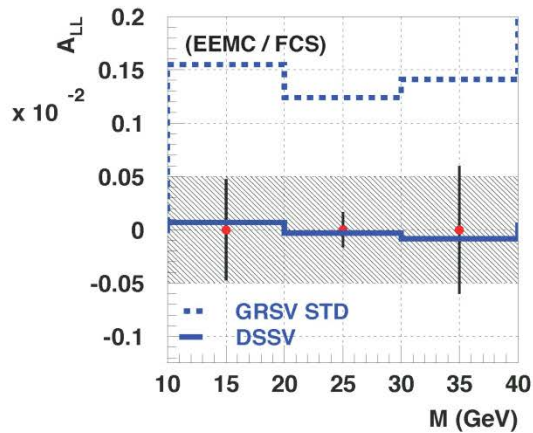
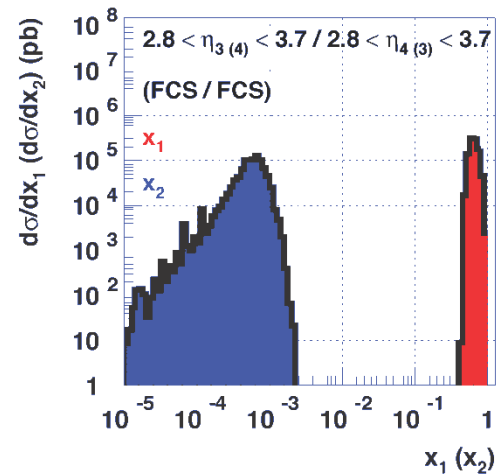
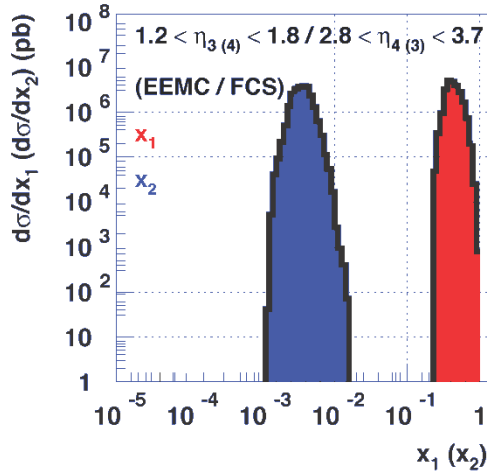
- RHIC had very successful runs with 510 GeV pp collisions during 2012 and 2013
 - Higher center-of-mass energies probe **lower x partons**
- PHENIX (pions) and STAR (jets) both released preliminary A_{LL} results at SPIN 2014 last October
- **New results are well described by global fits** that previously gave a good description of the 2009 measurements at 200 GeV

Additional future measurements



- Forward rapidity measurements provide an alternative path to lower x_g
- Increased precision in the currently sampled region to consolidate the observation of non-zero gluon polarization

Further future

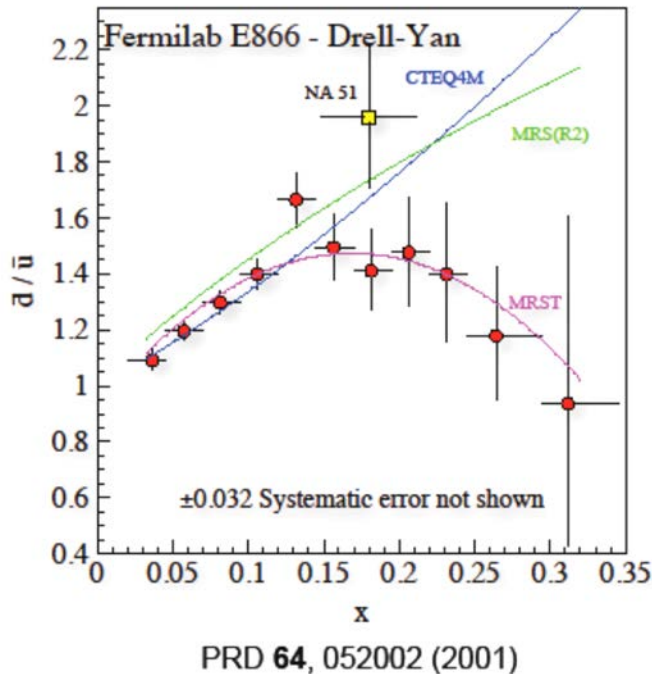


- Both PHENIX and STAR are proposing significant upgrades at forward rapidity in 2020+, motivated by spin and p+A measurements
- Forward di-jets will provide direct sensitivity to $\Delta g(x)$ down to $x \sim 10^{-3}$

Why is $\Delta\Sigma$ so small?

$$\Delta\Sigma = \int_0^1 (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}) dx$$

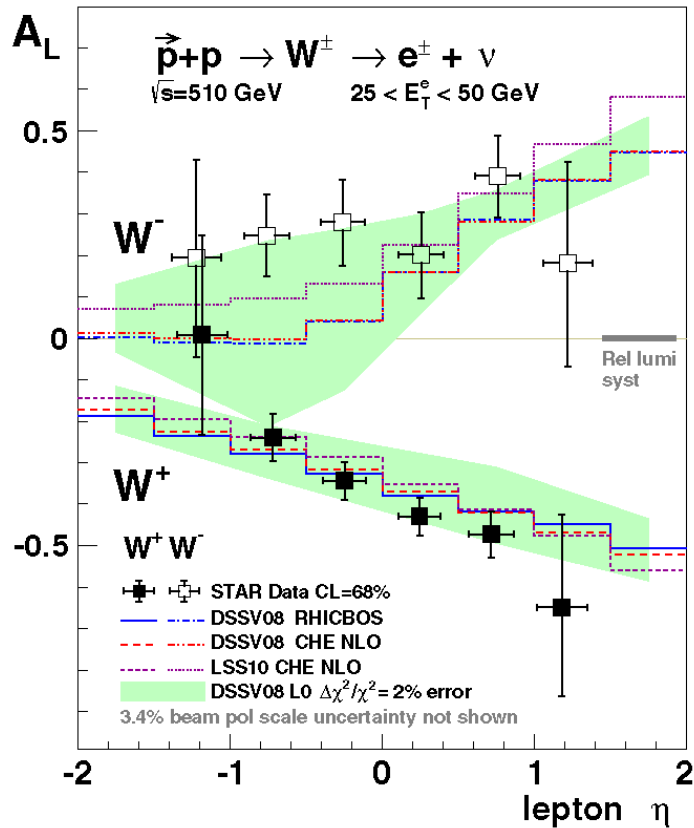
- Polarized inclusive DIS data measure $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$
- Polarized semi-inclusive DIS data provide flavor separation, but uncertainties remain large
 - FNAL E866 found surprising structure in the unpolarized antiquark distributions



- **Might the polarized antiquark distributions also contain surprises?**
- **Can separate polarized quark and antiquark flavors with W production**
 - Only left-handed quarks and right-handed anti-quarks participate
 - Complementary to semi-inclusive DIS
 - No fragmentation function uncertainties
 - Extremely clean theoretically

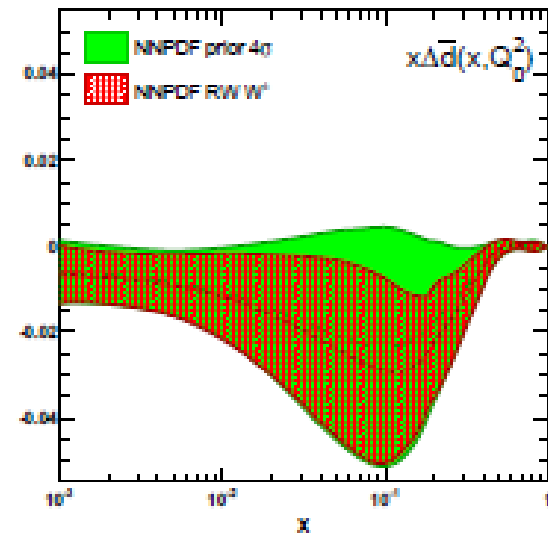
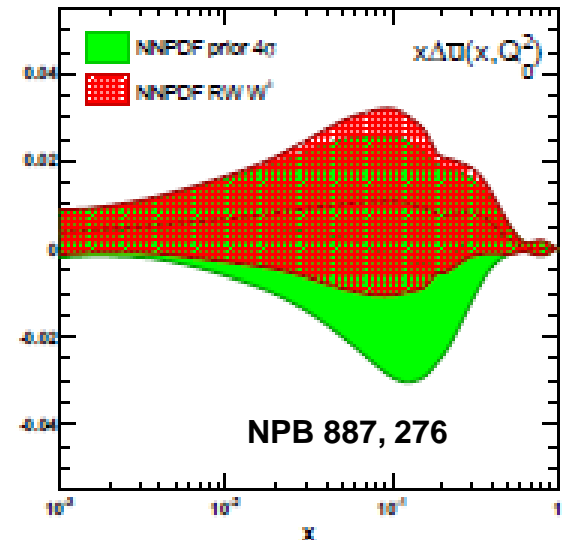
RHIC results already make an impact

 STAR PRL 113, 072301



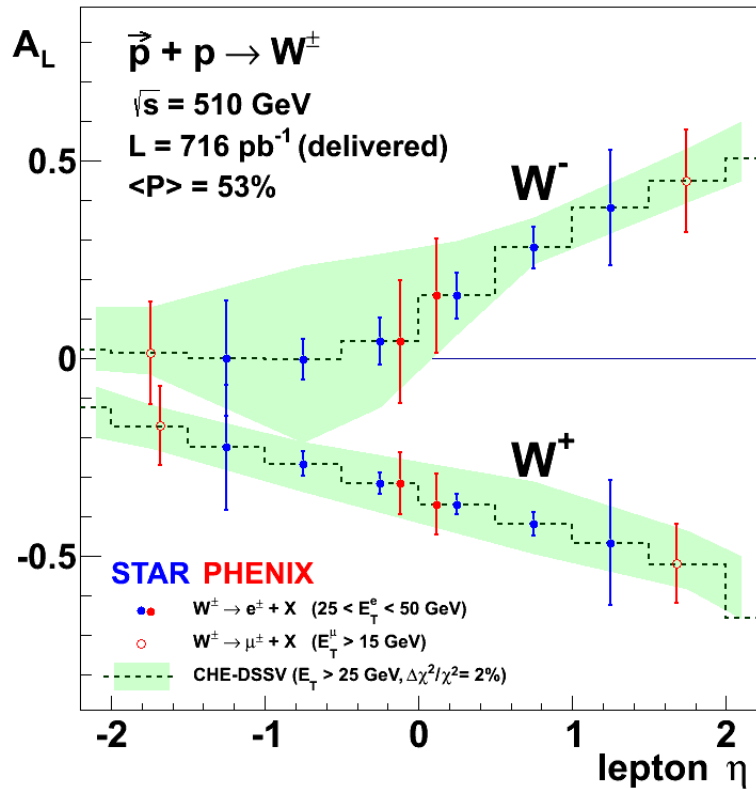
$\Delta\bar{u}$

$\Delta\bar{d}$

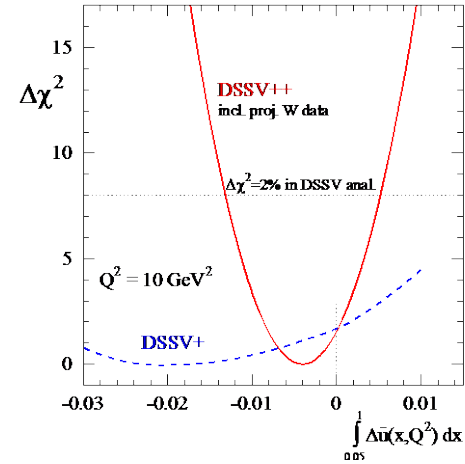
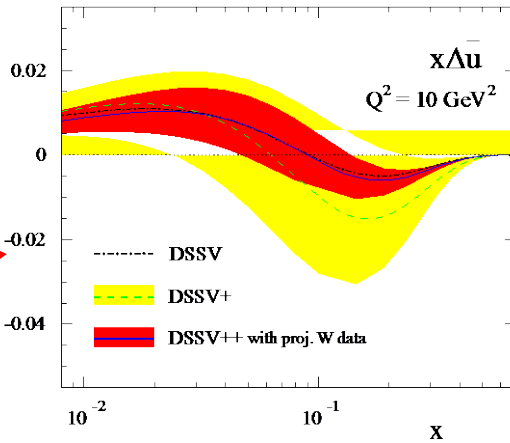


- The unpolarized distributions indicate $\bar{d} > \bar{u}$
- The RHIC results point toward $\Delta\bar{u} > \Delta\bar{d}$

Additional precision coming soon

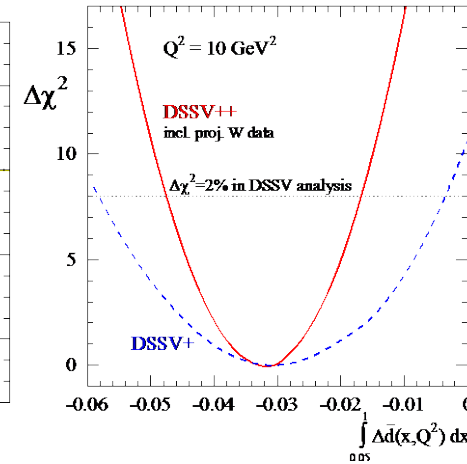
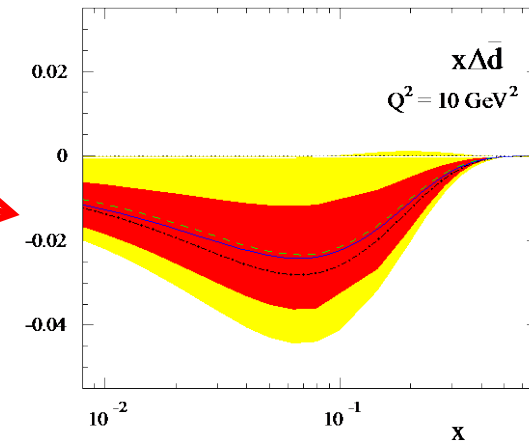


$\Delta\bar{u}$



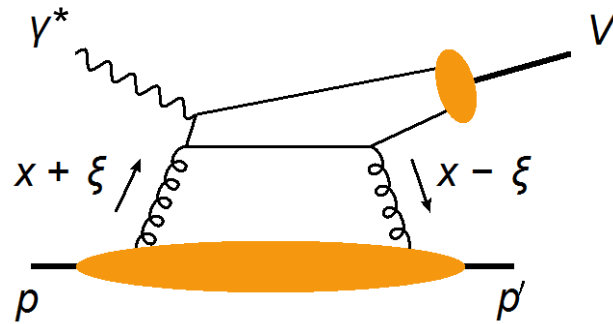
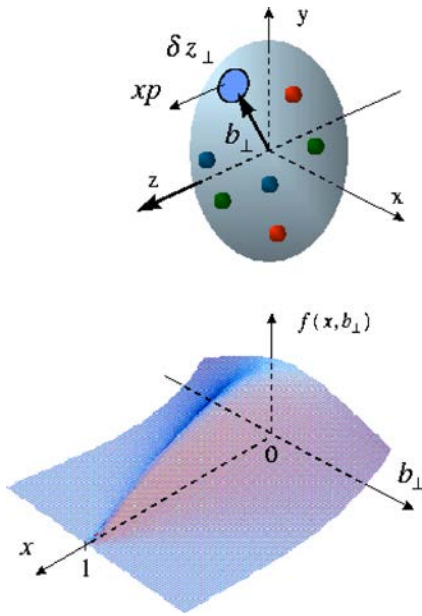
arXiv:1304.0079

$\Delta\bar{d}$



- Combined RHIC results from 2009-13 will provide **strong constraints on anti-quark polarizations**
- Uncertainties remain statistics dominated → **room for greater precision with additional data in the future**

What about orbital angular momentum?



$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2} \Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

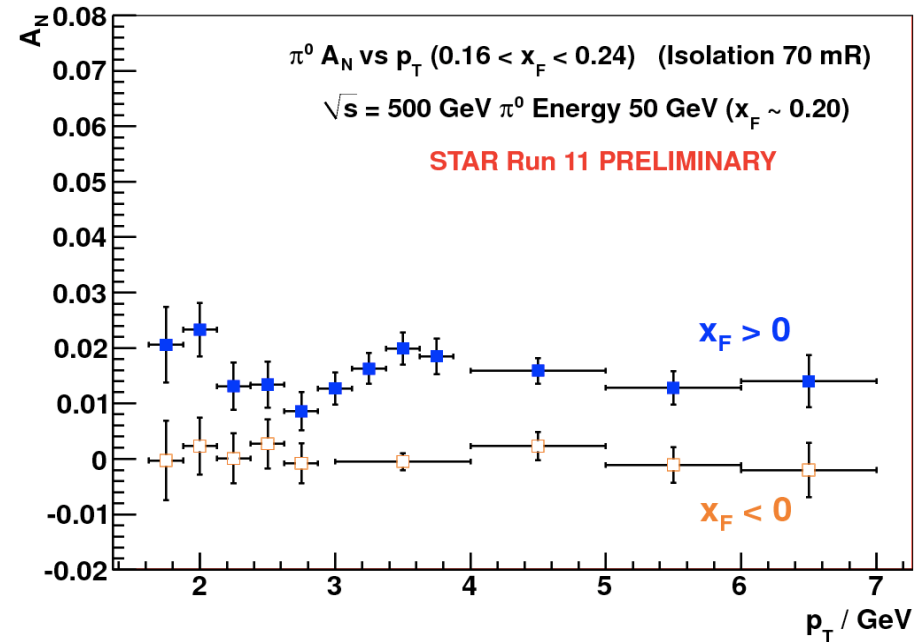
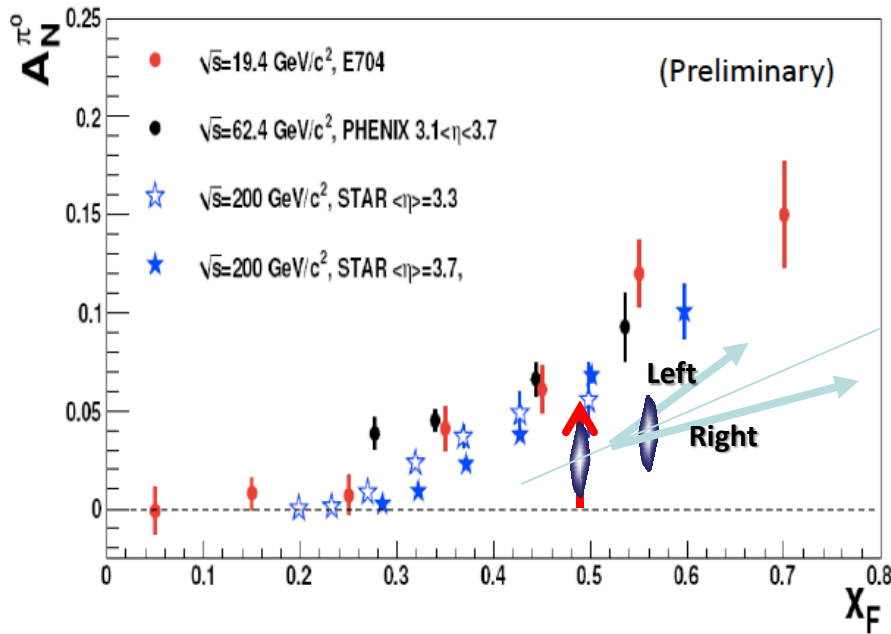
quark contribution

$$J_{q,g}^z = \frac{1}{2} \left(\int_{-1}^1 x dx \left(H^{q,g} + E^{q,q} \right) \right)_{t \rightarrow 0}$$

- Generalized parton distributions (GPDs), measured via exclusive reactions, provide **access to L_q and L_g**
- Exclusive J/ψ production in ultra-peripheral collisions with transversely polarized p+p and p+Au provides access to the GPD E_g
 - The GPD E is responsible for orbital angular momentum
 - **Only access world-wide to E_g before EIC**
- First measurements are starting now, enabled by the Roman Pot phase II* upgrade to STAR

Transverse spin structure

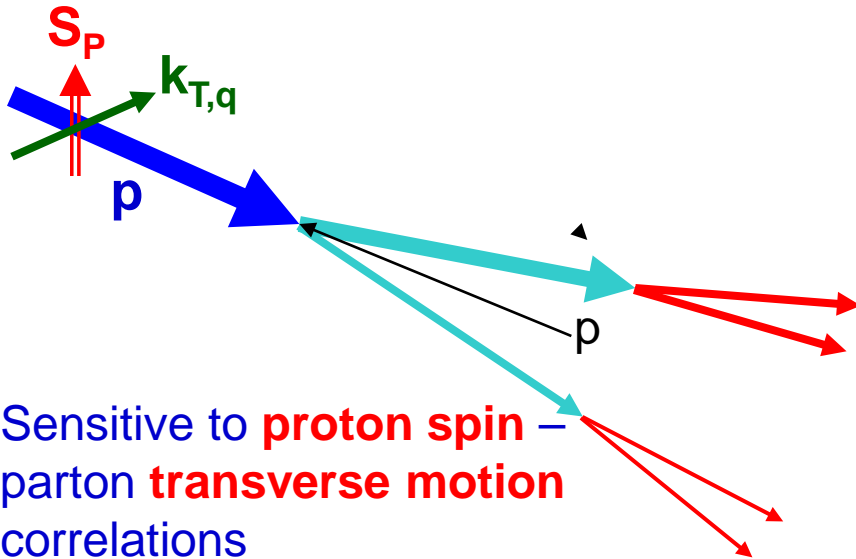
Transverse spin asymmetries in high energy p+p



- Large transverse single-spin asymmetries over a very wide range of \sqrt{s}
- Naïve collinear pQCD predicts $A_N \sim \alpha_s m_q / \sqrt{s} \sim 0.001$
- May arise from
 - Sivers effect / twist-3
 - Transversity + Collins fragmentation function
- No evidence to date of a fall-off at high p_T
 - Something we haven't thought of yet ?

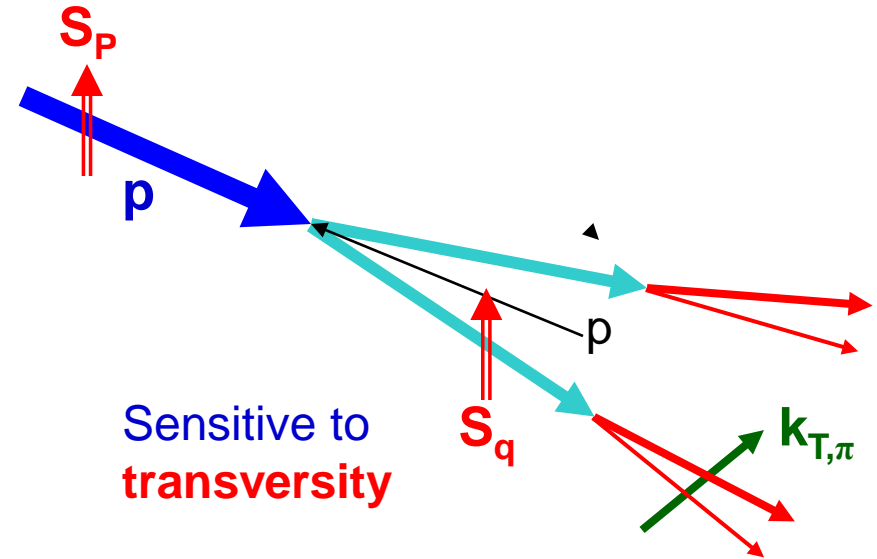
Initial- and final-state effects in pp collisions

Sivers or twist-3 mechanisms:
asymmetry in jet or γ production



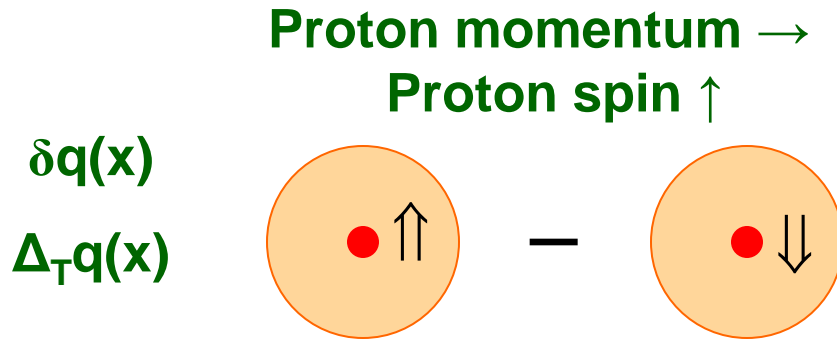
- Signatures:
 - A_N for jets or direct photons
- **NOT universal**
 - Sign change from SIDIS to Drell-Yan

Collins or novel FF mechanisms:
asymmetry in jet fragmentation

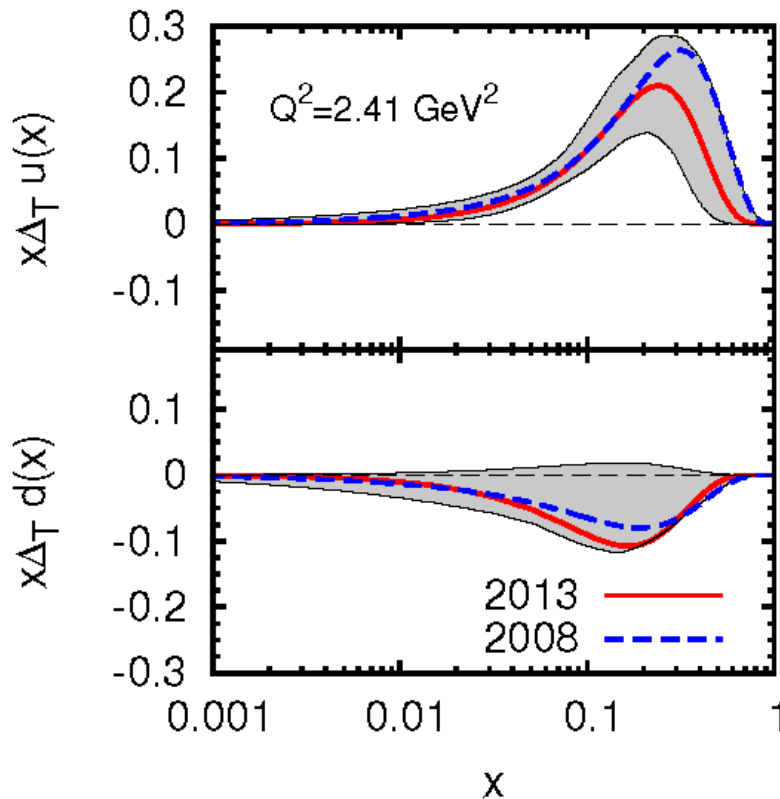


- Signatures:
 - Collins effect
 - Interference fragmentation functions
- **Believed to be universal**

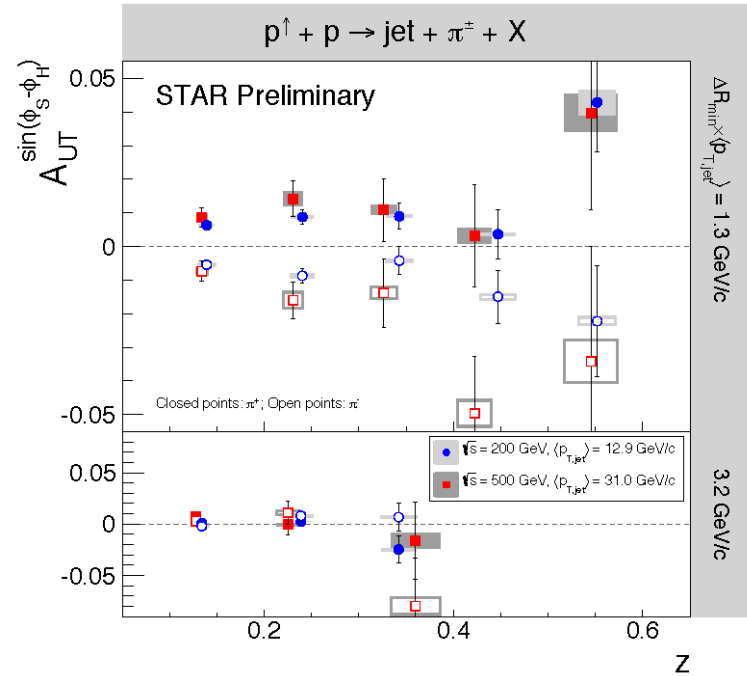
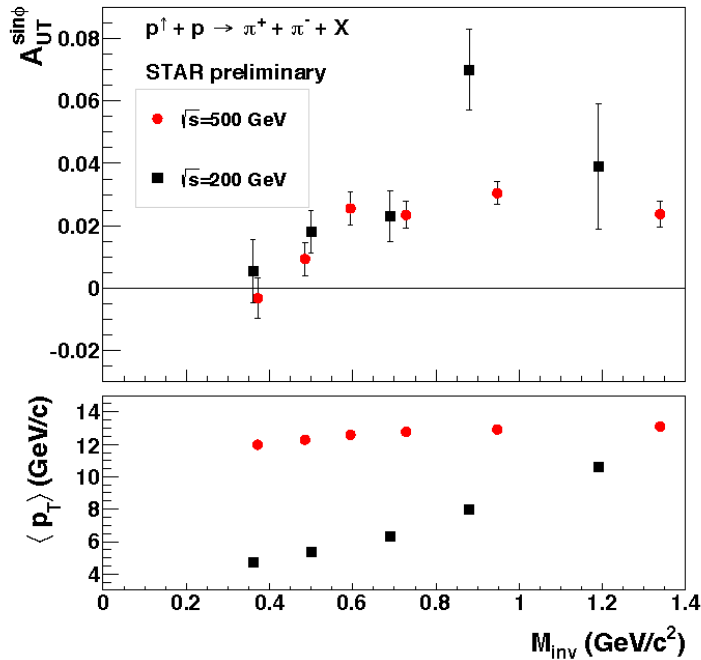
Transversity



- Quark polarization along spin of a transversely polarized proton
 - Third collinear, leading twist distribution
 - Chiral odd
- To date, only observed in SIDIS combined with e^+e^-
- Much less data than for helicity
- Global analyses:
 - Collins effect: PRD 87, 094019
 - Interference fragmentation functions (IFF): JHEP 1303, 119

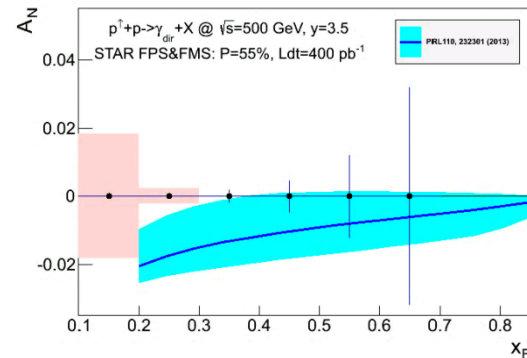
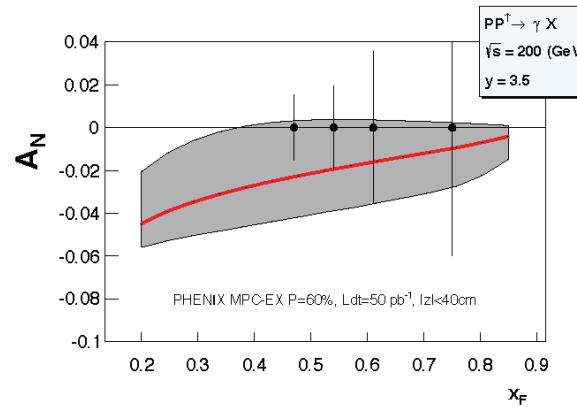
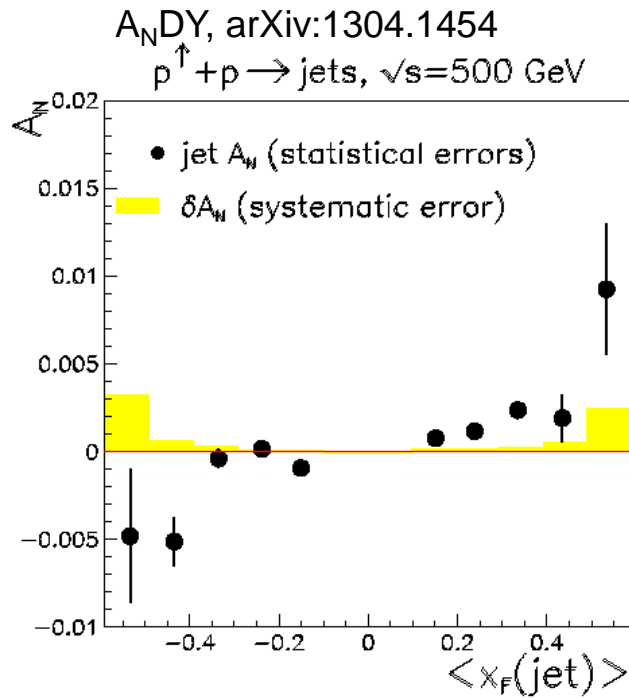


Observations of transversity in pp collisions



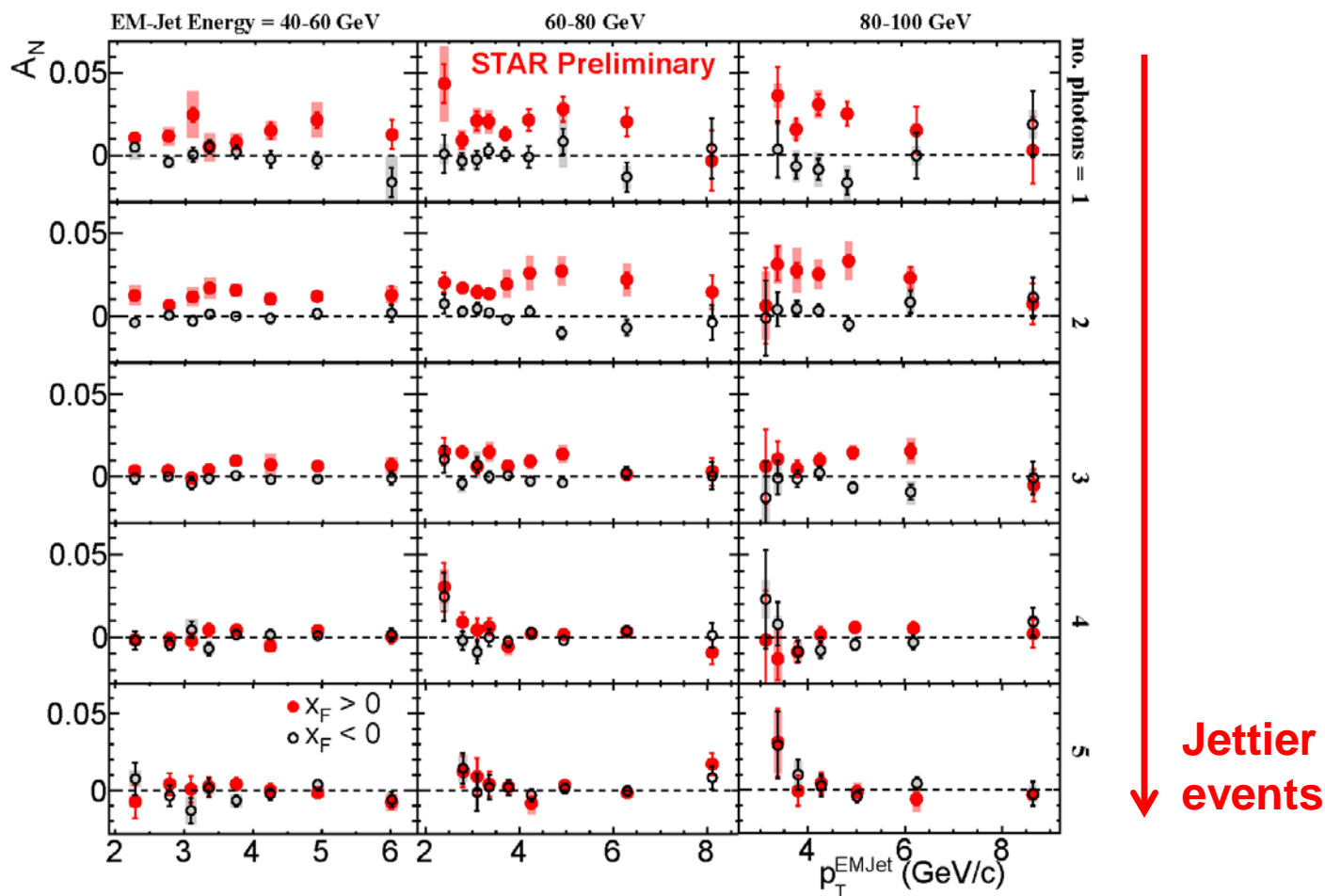
- IFFs and the Collins effect provide complementary ways to sample transversity
 - IFFs are collinear and follow DGLAP evolution
 - Collins effect involves transverse momentum dependent fragmentation
- Comparable signals are seen in both channels, in both 200 and 500 GeV pp collisions
 - Powerful test of universality and evolution effects
- First observations of transversity in pp collisions

Isolating initial state contributions to forward A_N



- Measuring jets or direct photons eliminates final-state contributions
 - Isolate the Sivers/twist-3 contribution
- A_N DY finds A_N for forward jets is an order of magnitude smaller than that for π^0
- This week, PHENIX and STAR are beginning measurements of A_N for forward direct photons in 200 GeV pp collisions

Or maybe something completely different?



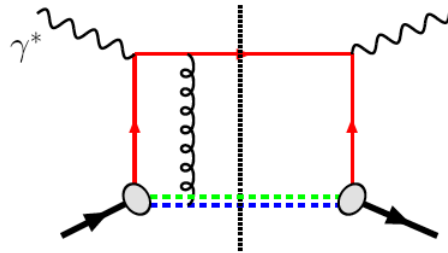
- A_N decreases as EM jets become jettier. Also is much smaller when there is a coincident jet at mid-rapidity
 - Raises serious questions how much of the large forward π^0 A_N arises from $2 \rightarrow 2$ parton scattering

Color interactions in QCD

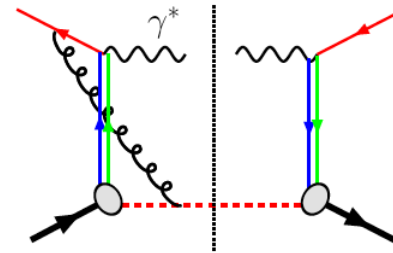
Non-universality of the Sivers function

QCD:

DIS:
attractive FSI



Drell-Yan:
repulsive ISI



$$\text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{DY}} \text{ or } \text{Sivers}_W \text{ or } \text{Sivers}_{z_0}$$

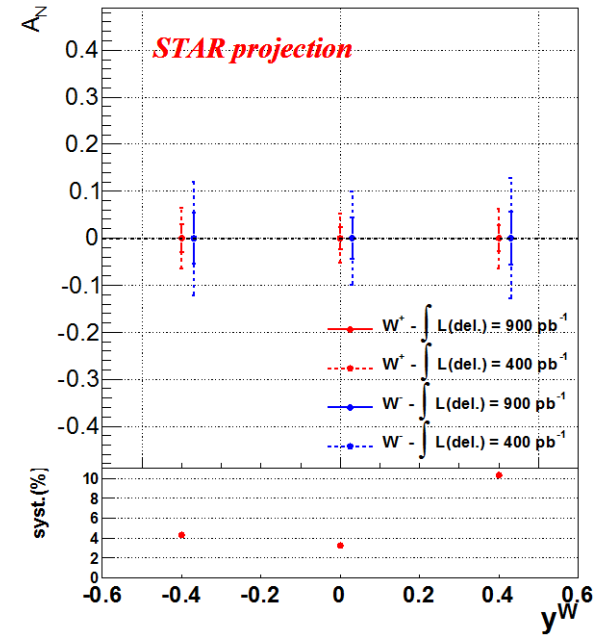
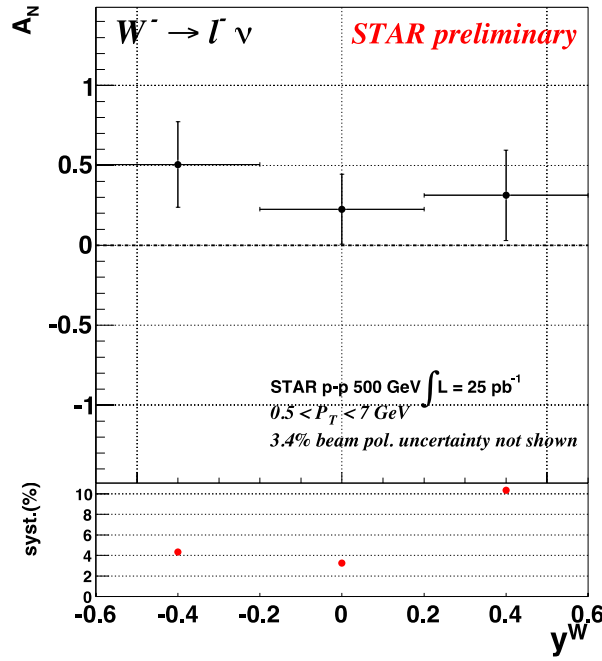
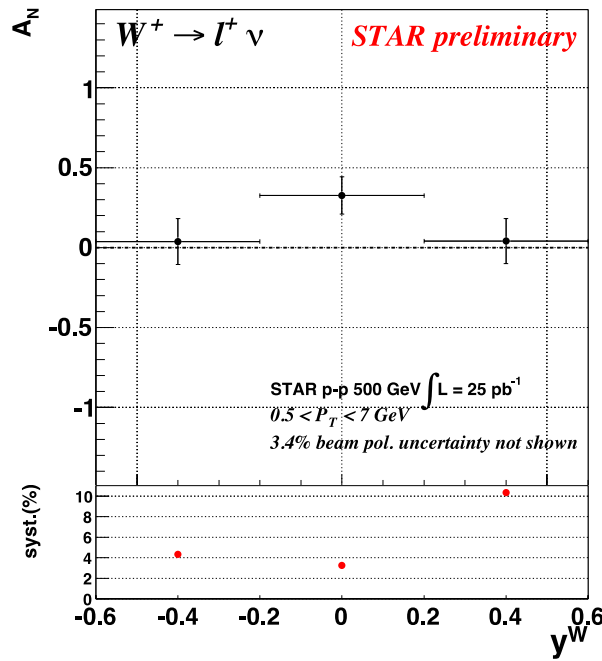
A_N for direct photon also has sign change in twist-3

Critical test for our understanding of TMD's and TMD factorization

**Can explore all of these observables
in 500 GeV pp collisions at RHIC**

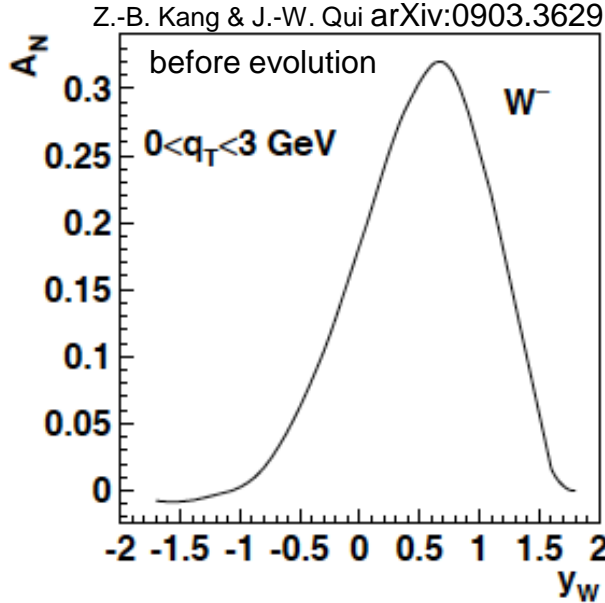
Both PHENIX and STAR have installed upgrades for 2015 to enable direct photon detection at forward rapidity

A_N for W production

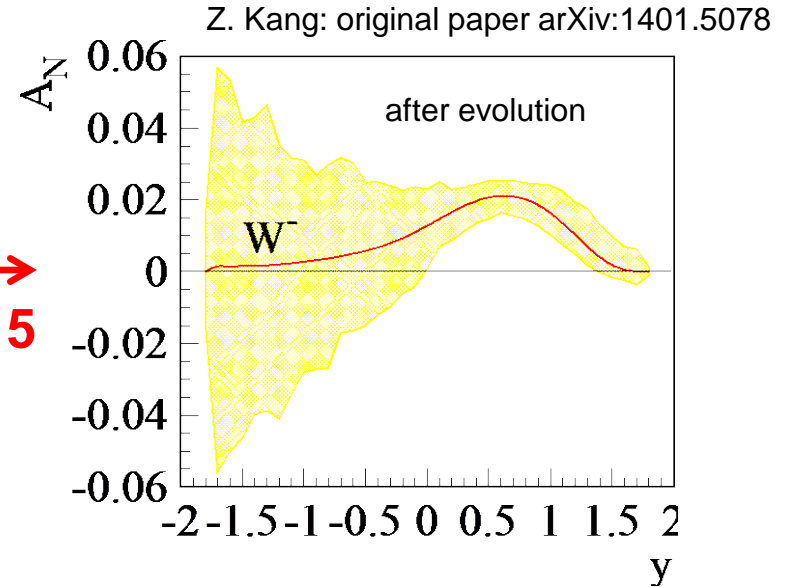


- STAR performed an exploratory measurement of A_N for W production with a small data set recorded in 2011
 - W kinematics fully reconstructed, not just decay electron
- Similar measurements of A_N for Z^0 are very clean, but statistics challenged
- Need more data to explore **TMD evolution** and the **Sivers sign change**
 - Proposed for 2016

TMD evolution: a possible new discovery?

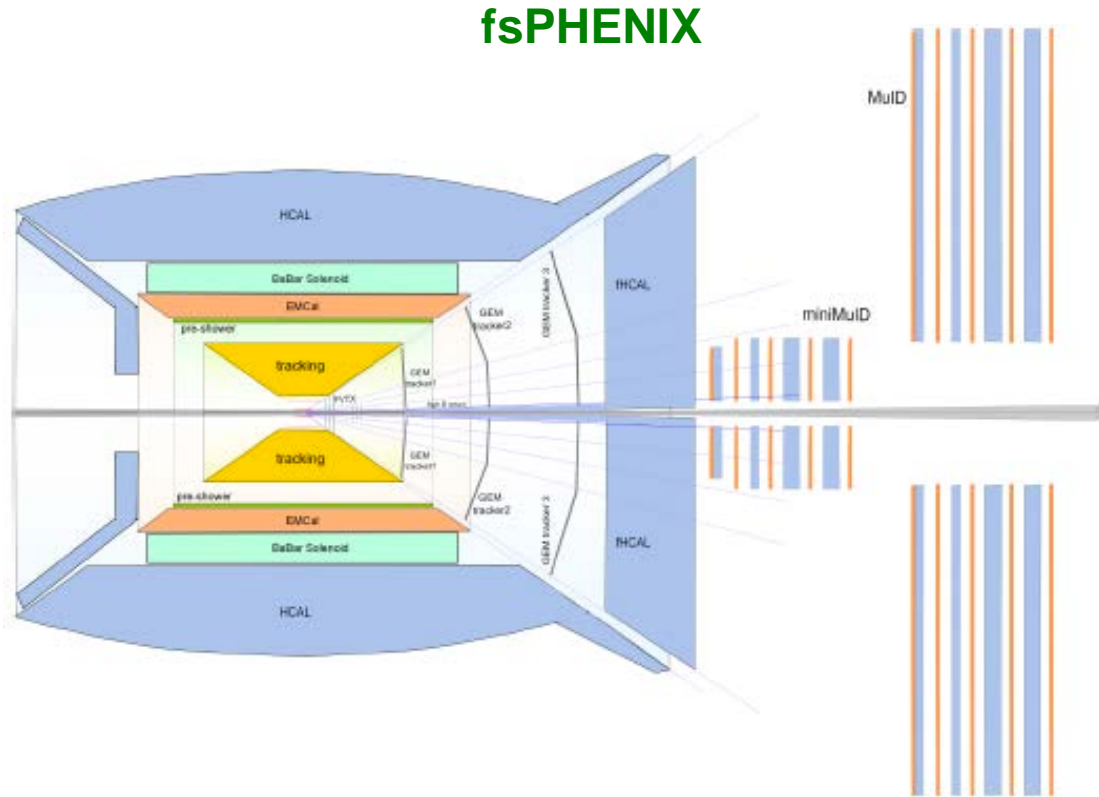
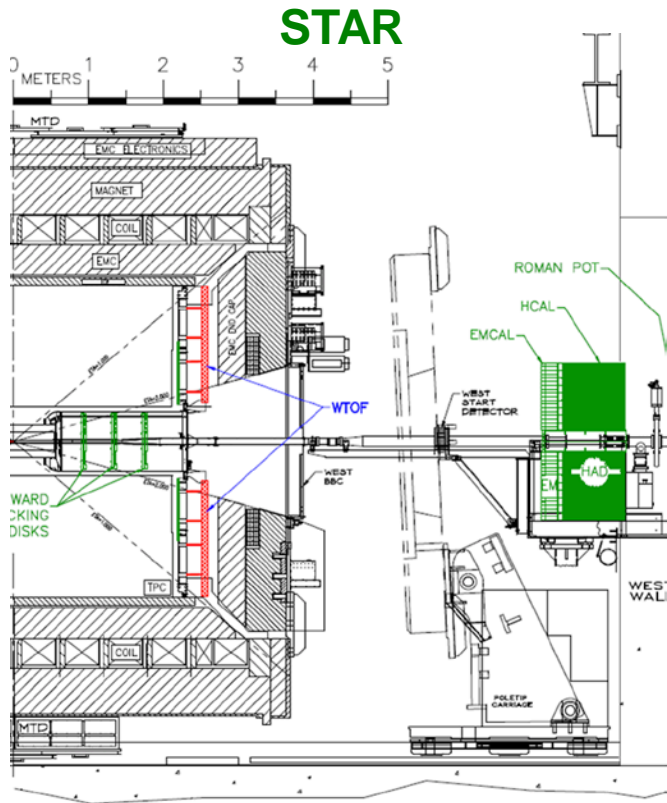


Factor of ~15



- TMD evolution may be much stronger than any other known evolution effects (or not !)
 - Needs new data to constrain the non-perturbative part of the evolution
 - Must access similar observables at comparable x but very different Q^2
 - Direct photon A_N for $\sqrt{s} = 200$ and 500 GeV
 - W A_N at 500 GeV
 - In the further future, Drell-Yan at 500 GeV

Forward upgrades for PHENIX and STAR



- Forward di-jets will extend gluon polarization to $x < \sim 10^{-3}$
- Transverse spin phenomena:
 - Precision TMDs through jets at forward rapidity
 - Precision A_N (Drell-Yan) to complete the Sivers measurements
- Also an extensive suite of measurements in p+A collisions

Conclusions

- **RHIC Spin has already:**
 - Found evidence for positive gluon polarization in the region $x > 0.05$
 - Found indications of an asymmetry in the polarized anti-quark sea
 - Made the first observation of transversity in pp collisions
- **During the next decade, RHIC Spin will:**
 - Measure gluon polarization down to $x \sim 10^{-3}$
 - Place strong constraints on anti-quark polarizations
 - Provide a first look at gluon orbital angular momentum
 - Find the origin of the large transverse single-spin asymmetries
 - Observe color interactions in QCD
 - Test TMD evolution with a very broad Q^2 lever arm
 - ...
- Spin asymmetries in **polarized p+A collisions** will provide a unique probe of the saturation scale in heavy nuclei
- **RHIC Spin provides a bridge between the physics of RHIC and the physics of the EIC**