

2012

The RHIC SPIN Program

Achievements and Future Opportunities

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Carl Gagliardi

Texas A&M University

on behalf of the RHIC Spin Collaboration

What contributes to the proton spin?

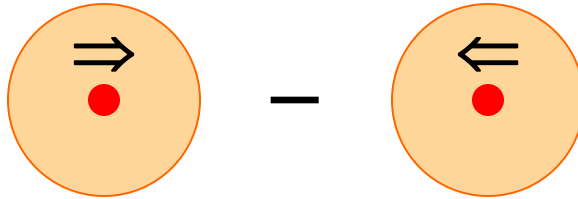
Consider a proton moving toward the right

Helicity

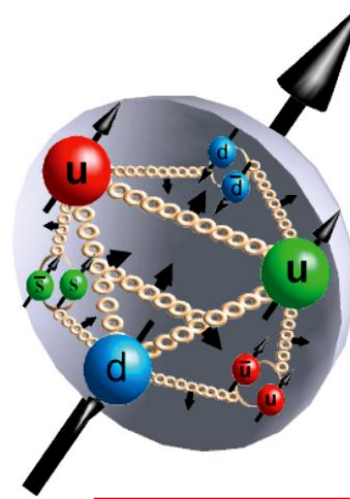
$\Delta q(x)$

$\Delta g(x)$

Proton spin \Rightarrow



Polarized DIS: ~ 0.3



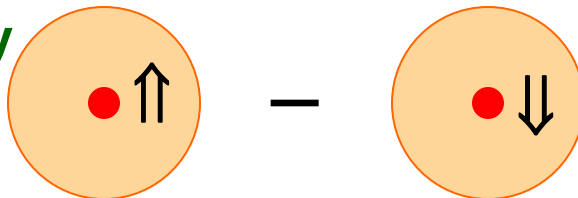
Poorly constrained

Spin sum rule: $\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L \rangle$

Transversity

$\delta q(x)$

Proton spin \Uparrow

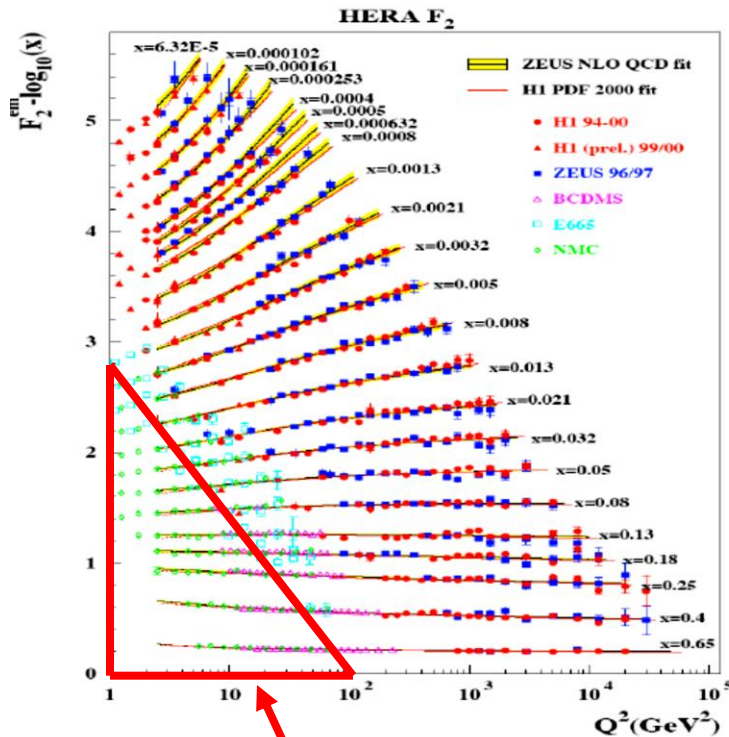


Chiral odd; very little data

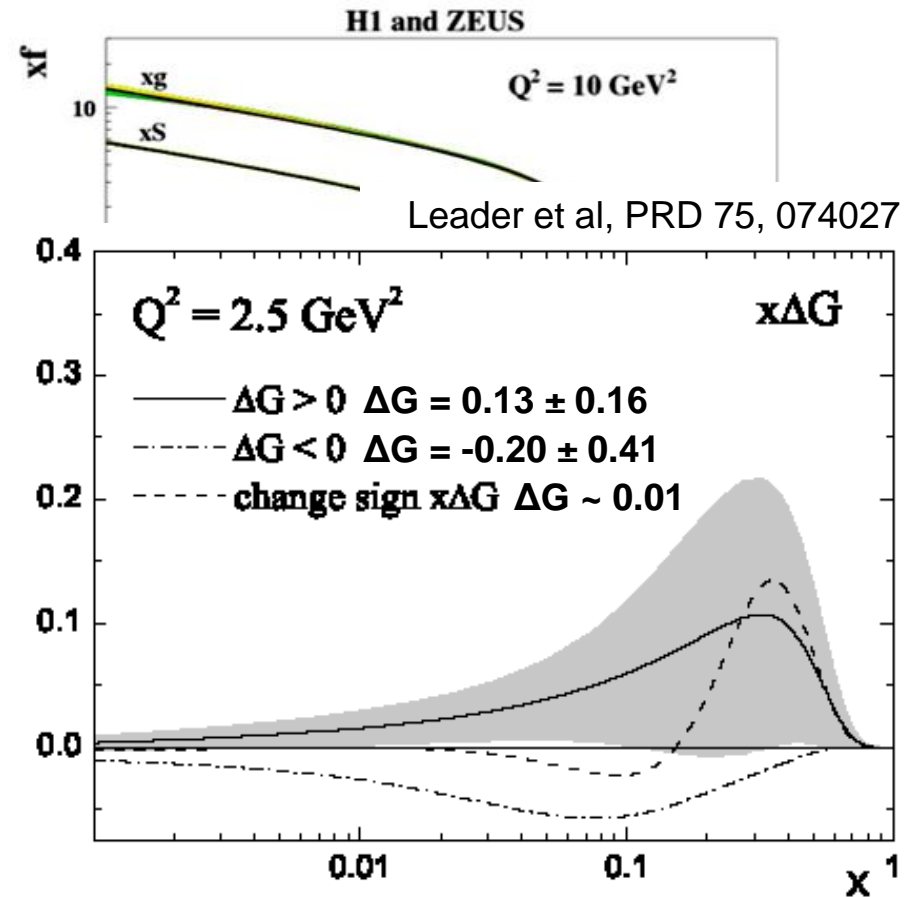
RHIC spin program:

- What is ΔG ?
- Role of antiquarks in $\Delta \Sigma$?
- How large is transversity?
- Move toward a 2- or 3-D picture of the proton?

Gluon polarization before RHIC data



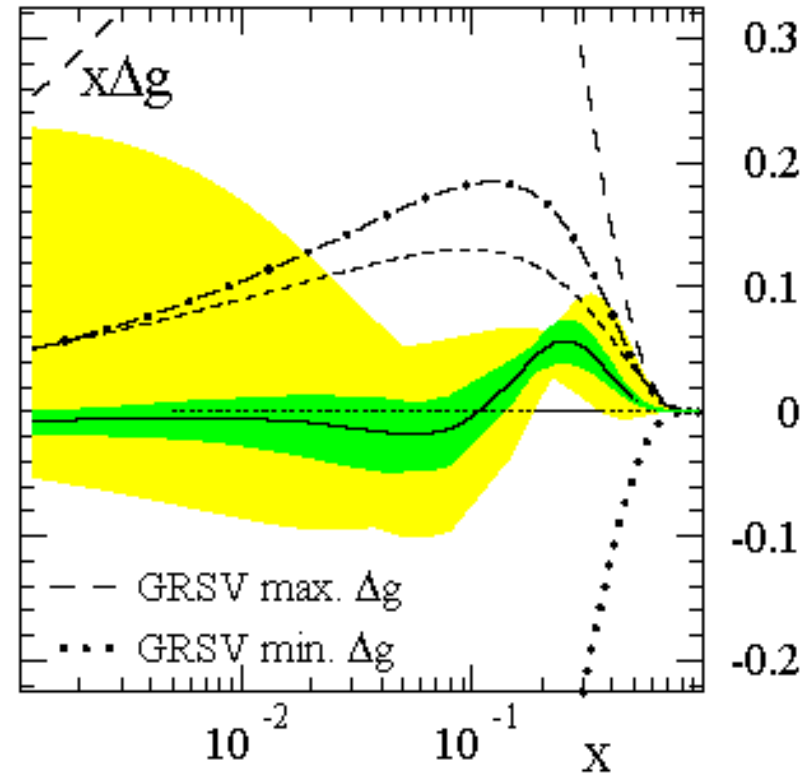
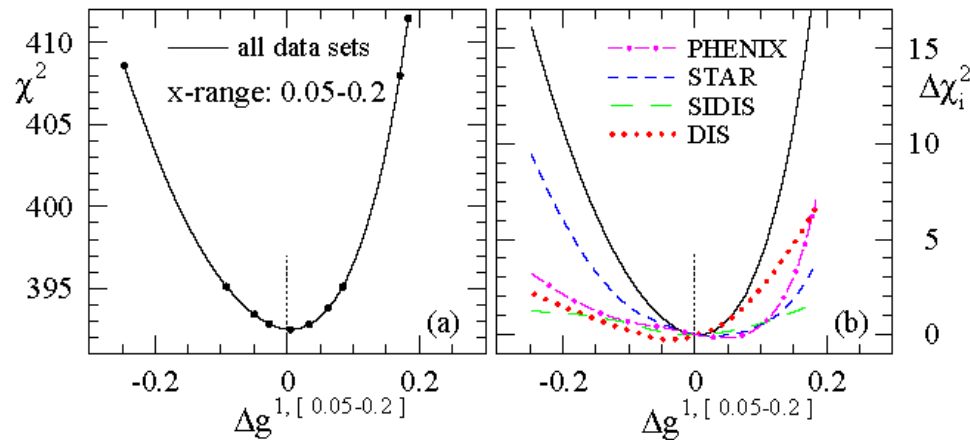
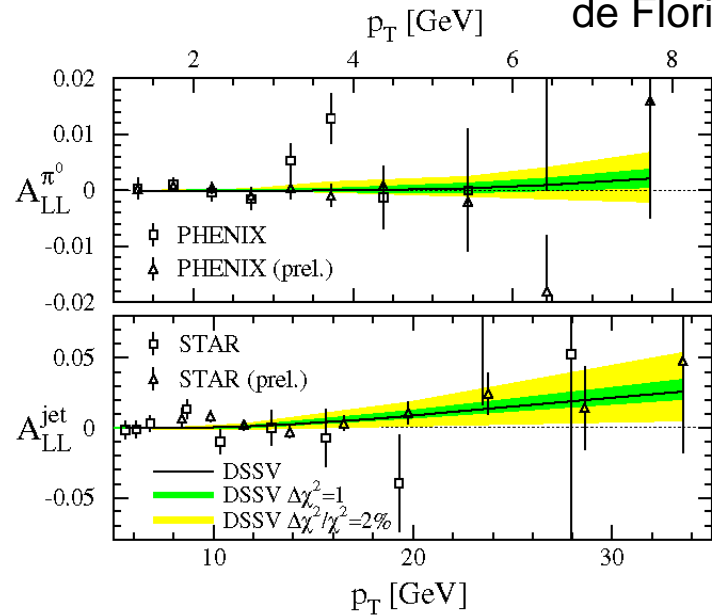
Kinematic region of **polarized** measurements



- Unpolarized parton distributions are determined precisely from DIS
 - Gluon distribution obtained indirectly from Q^2 dependence
- Kinematics of polarized DIS measurements far more limited
 - Q^2 lever arm provides only weak constraints on $\Delta g(x)$

DSSV – first global NLO analysis with RHIC pp data

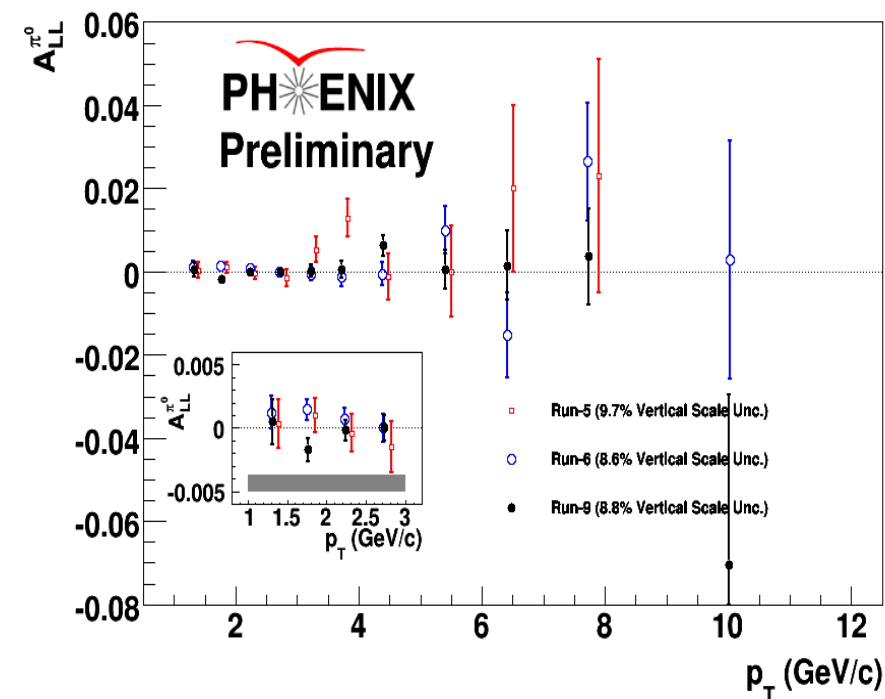
de Florian et al., PRL 101, 072001



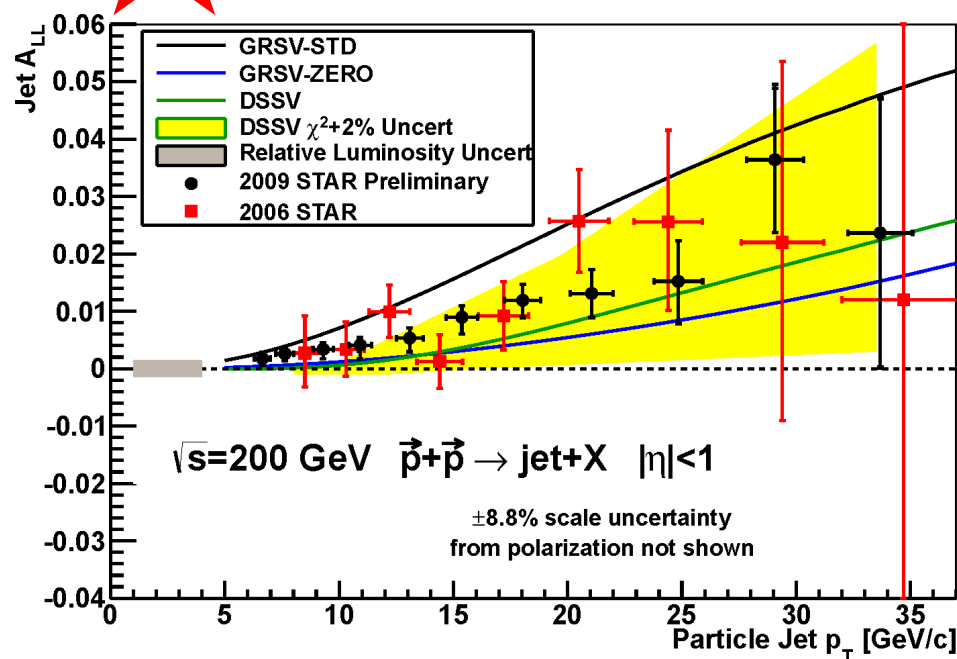
- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing

Improved precision from 2006 to 2009

PHENIX



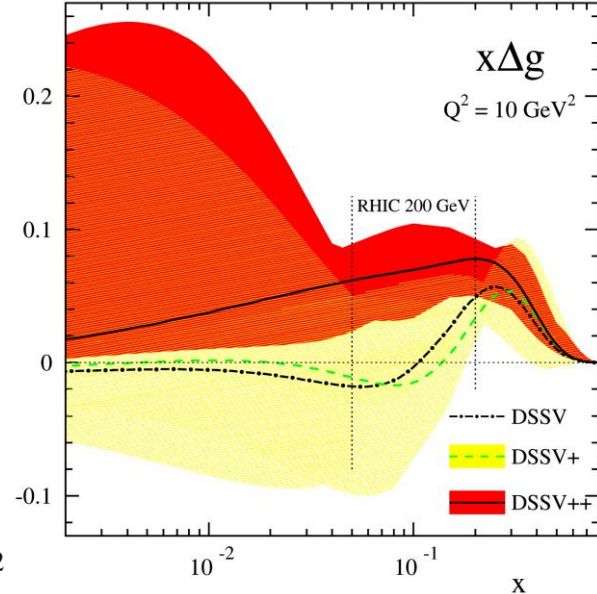
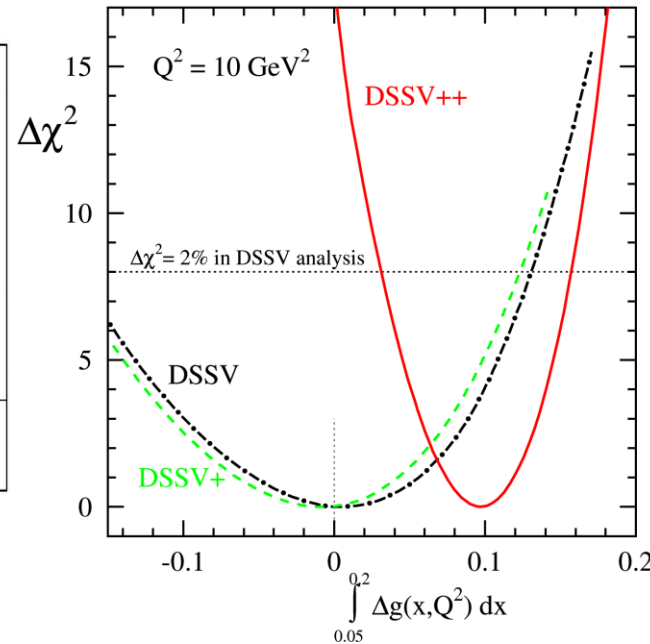
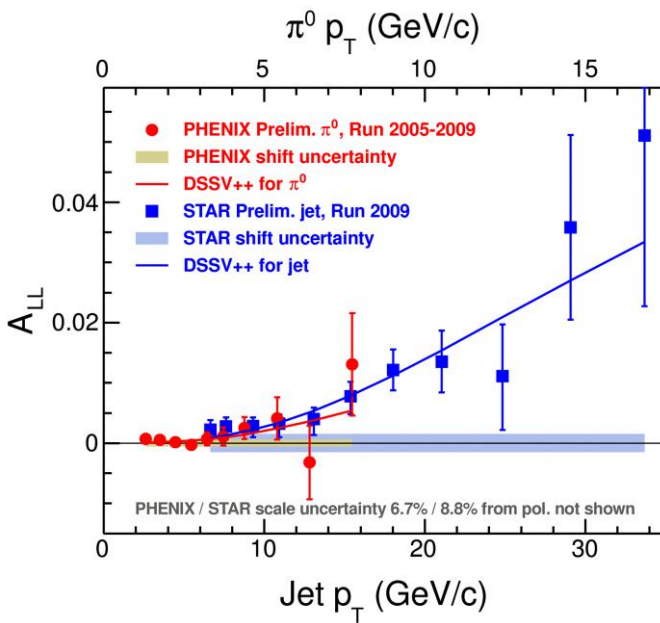
STAR



- Substantially larger figure of merit ($P^4 \times L$) than in all previous runs combined

New global analysis with 2009 RHIC data

Special thanks to the DSSV group!

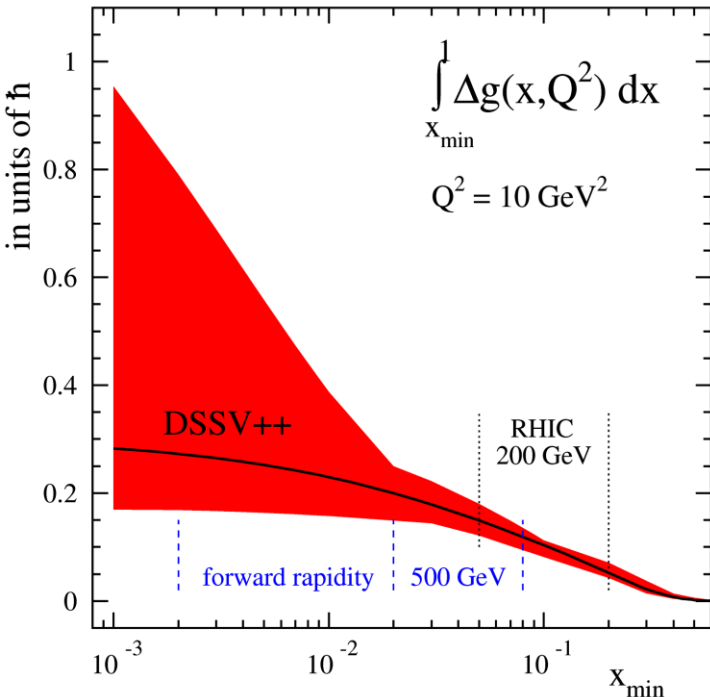


- DSSV++** is a new, preliminary global analysis from the DSSV group that includes 2009 A_{LL} measurements from PHENIX and STAR

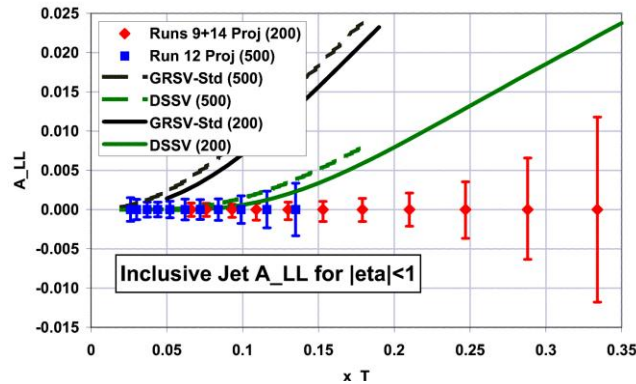
$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10 \text{ GeV}^2) dx = 0.10^{+0.06}_{-0.07}$$

- First experimental evidence of **non-zero gluon polarization** in the RHIC range ($0.05 < x < 0.2$)

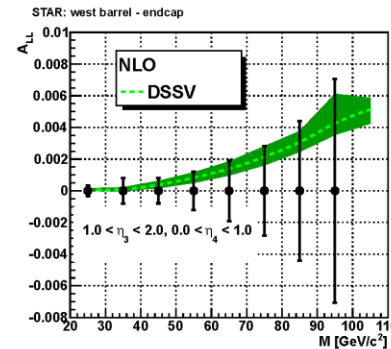
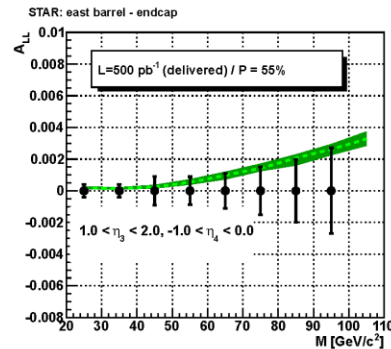
Where from here?



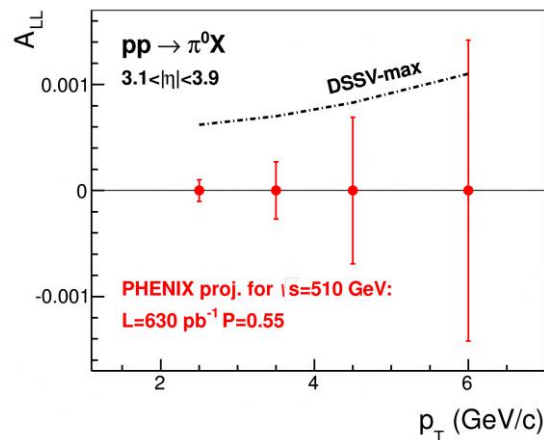
Extrapolation of ΔG over all x gives **~60% of proton spin**, but with **huge uncertainties**



Increased precision for inclusive π^0 and jets, including **510 GeV**



Di-jets and di-hadrons will constrain the functional form of $\Delta g(x)$

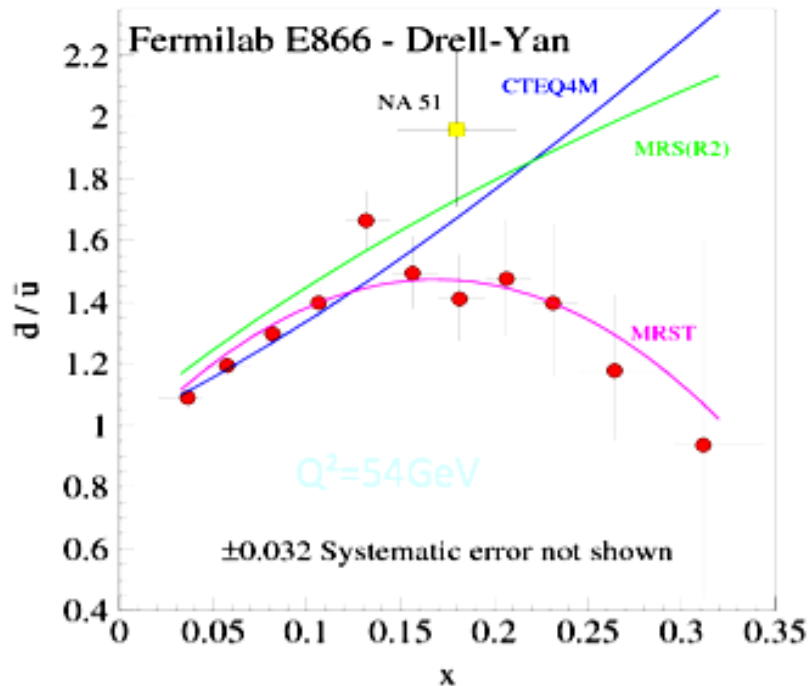


Forward rapidity measurements sensitive to lower x

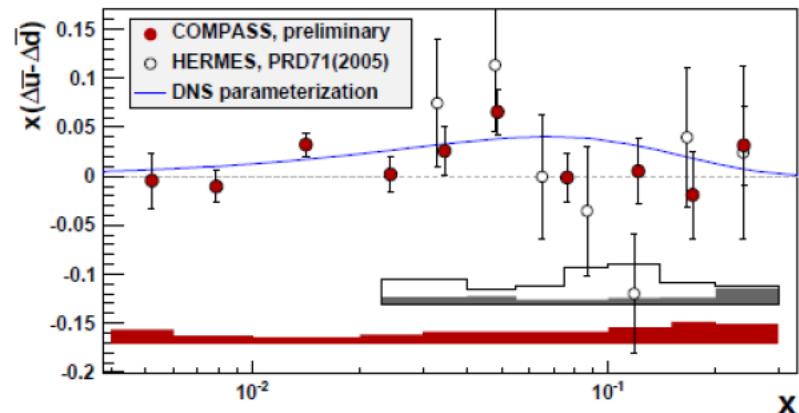
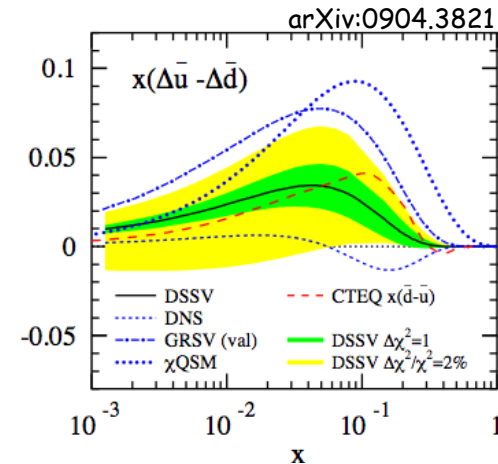
Toward end of decade, upgrades will enable **di-jets at forward rapidity**

What about the sea quarks?

What role do antiquarks play in determining the proton properties?

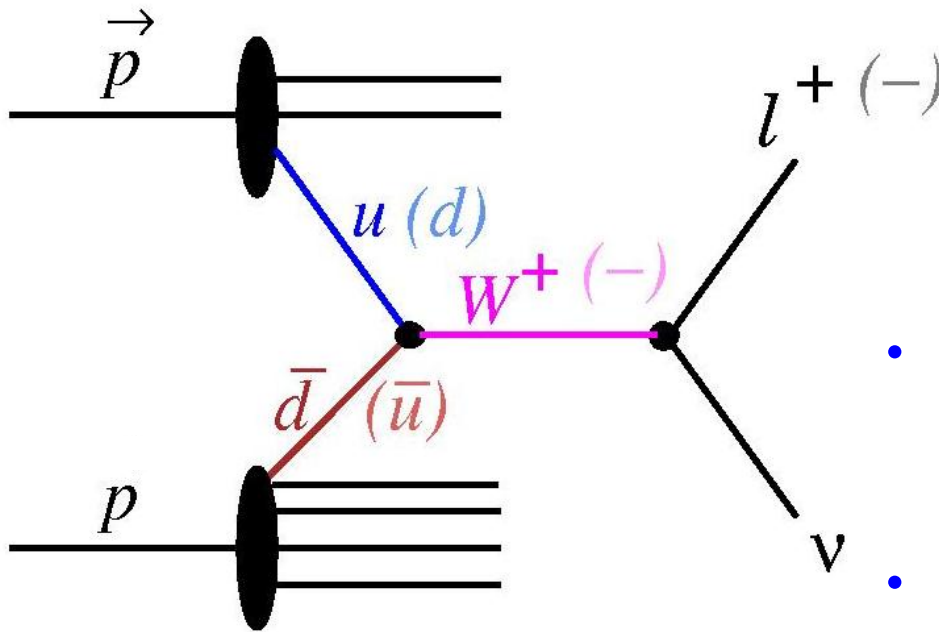


- Large flavor asymmetry in the antiquark sea of the nucleon



- Many models that describe the flavor asymmetry also predict a **spin asymmetry in the antiquark sea**

Probing sea quark polarization through Ws



$$u + \bar{d} \rightarrow W^+ \rightarrow l^+ + \nu$$

$$\bar{u} + d \rightarrow W^- \rightarrow l^- + \bar{\nu}$$

- Weak interaction process
 - Only left-handed quarks
 - Only right-handed anti-quarks
- Perfect spin separation

Parity violating single helicity asymmetry A_L

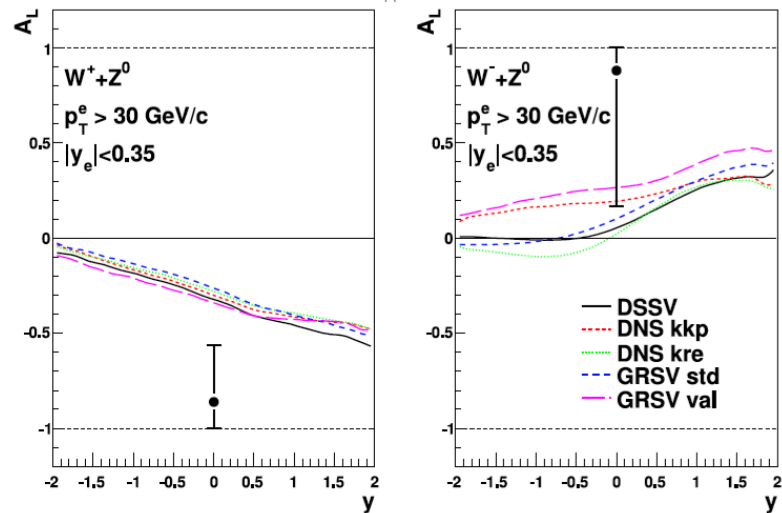
$$A_L^{W^-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2) \quad A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)$$

- **Complementary to SIDIS measurements**
 - High $Q^2 \sim M_W^2$
 - No fragmentation function effects

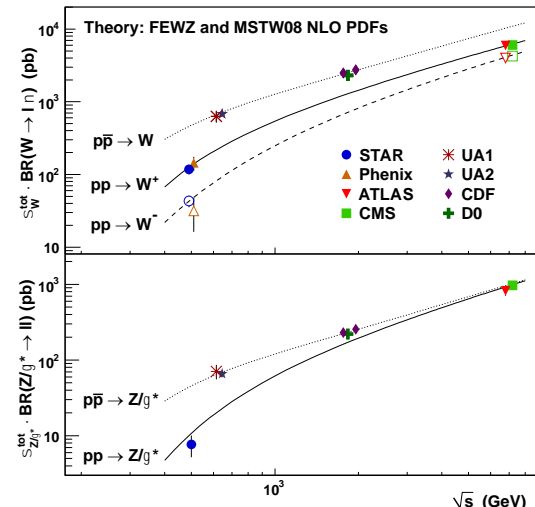
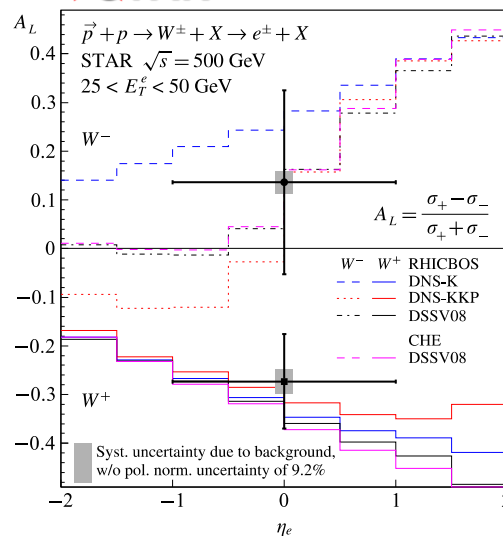
W measurements through 2011 RHIC run

2009 run

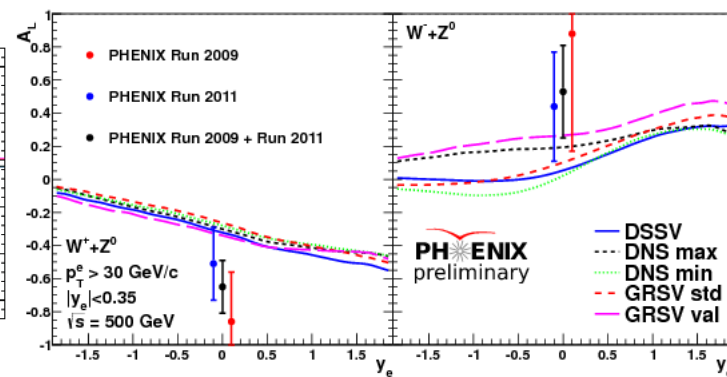
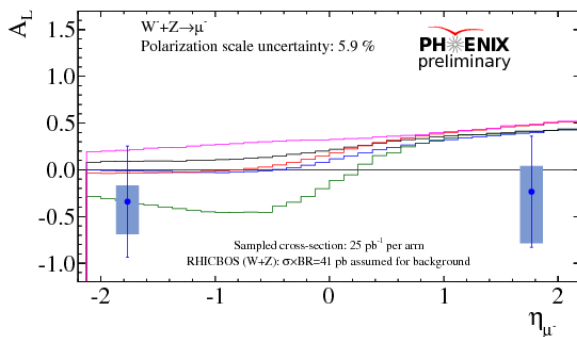
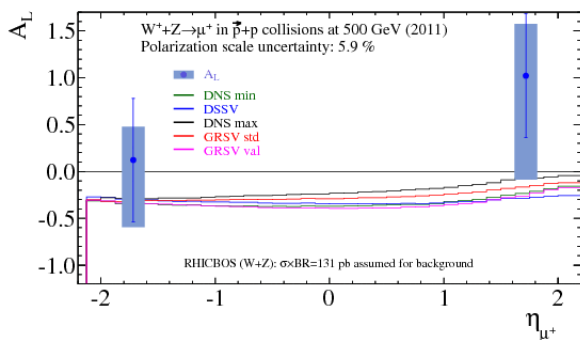
PHENIX



STAR

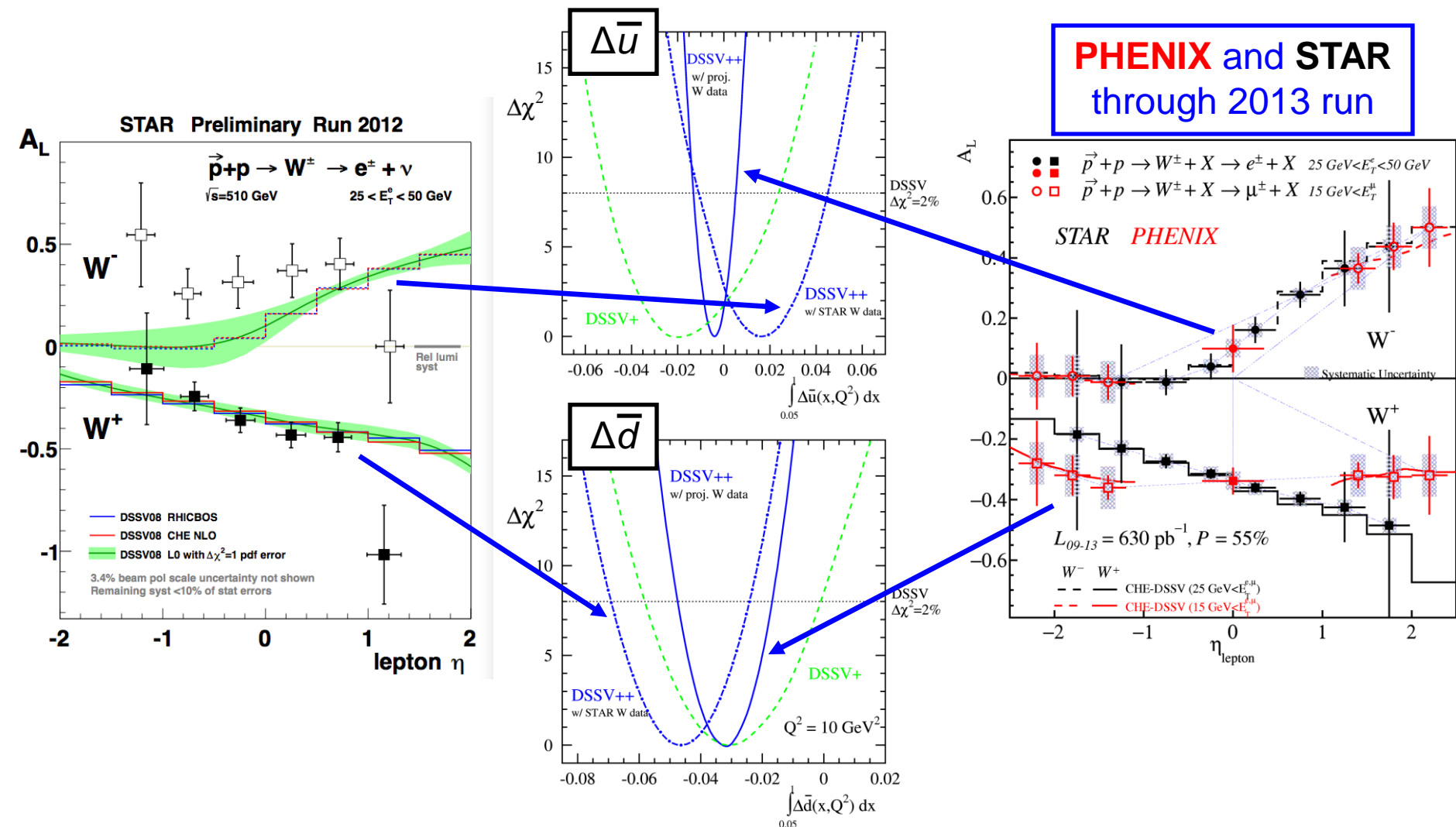


2011 run



- Important proof-of-principle studies

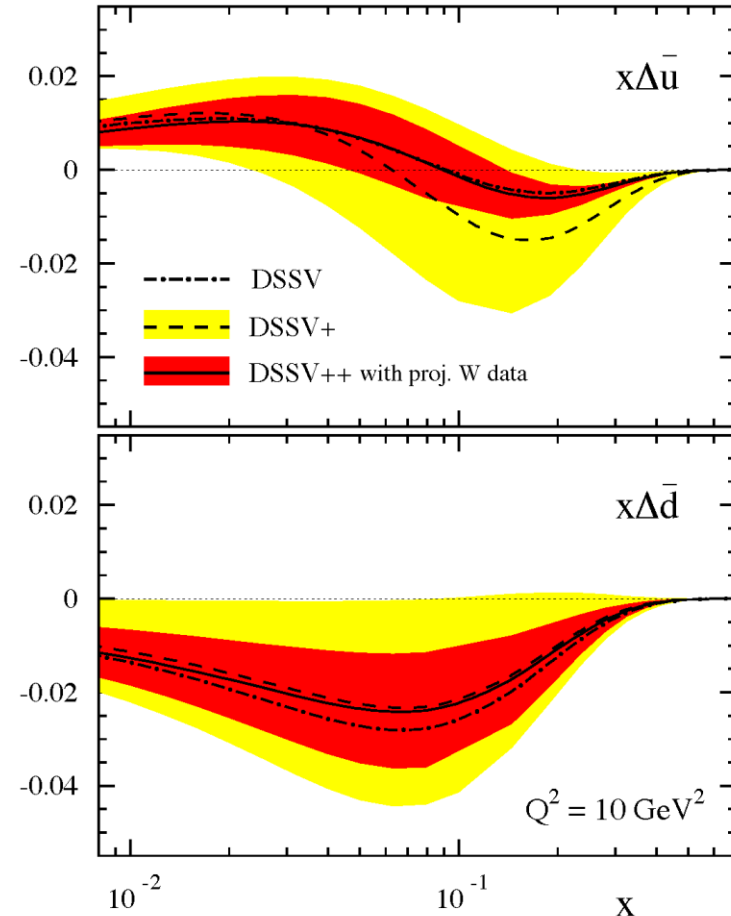
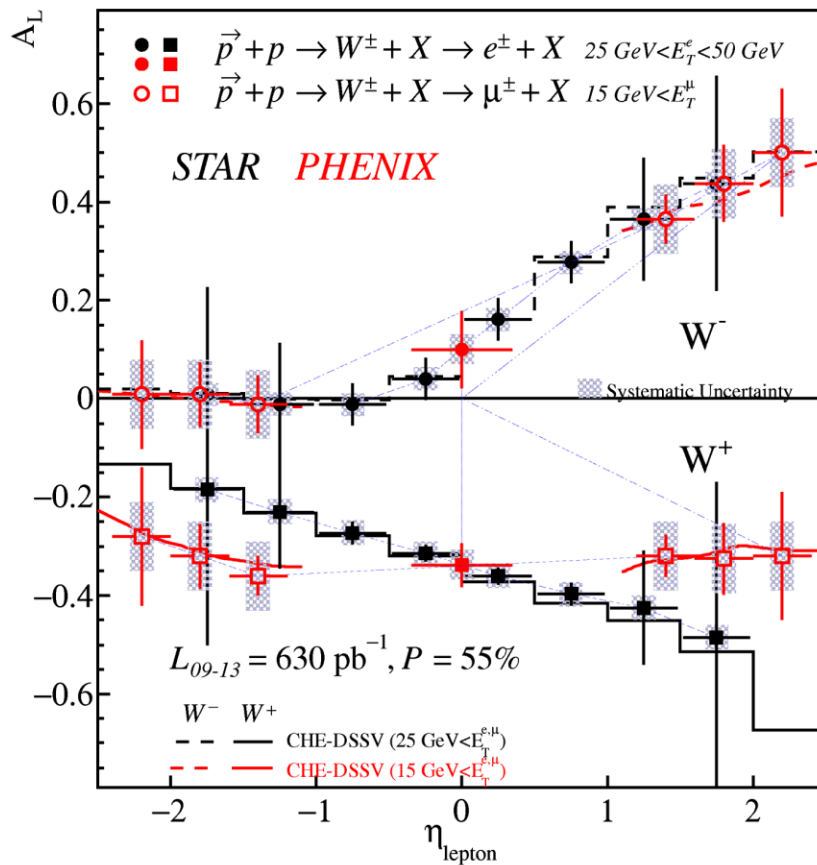
High precision W asymmetry era



- First preliminary results from 2012 already provide substantial sensitivity
- Future results will provide a dramatic reduction in the uncertainties

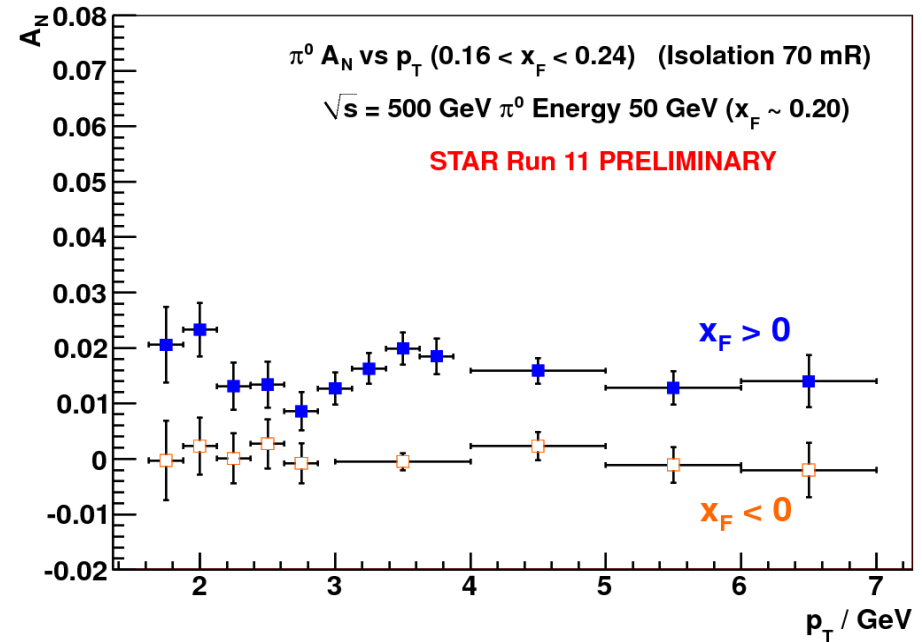
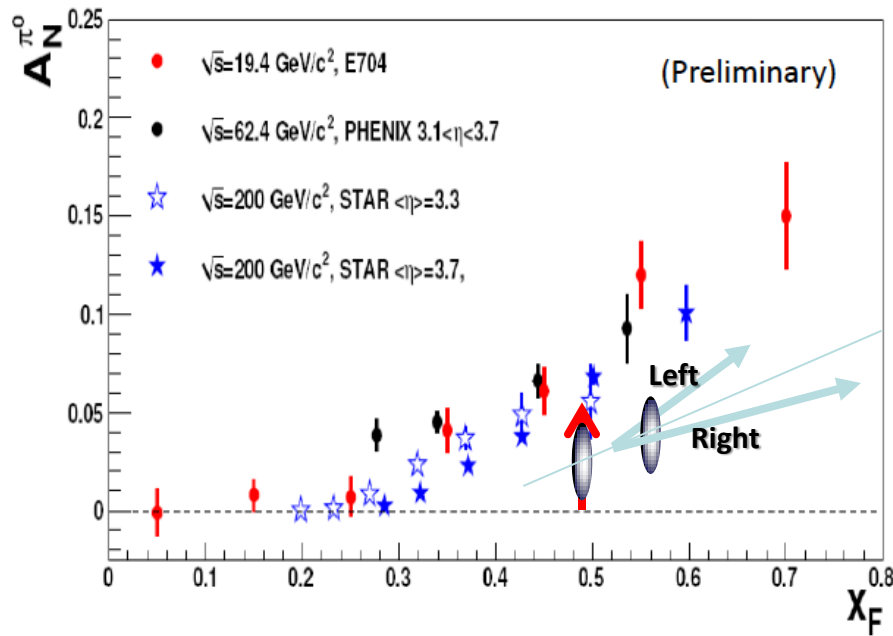
Implications for antiquark polarizations

PHENIX and **STAR**
through 2013 run



- W asymmetry measurements from RHIC will provide a substantial reduction in the current uncertainties for the antiquark polarizations

Transverse spin asymmetries in high energy p+p

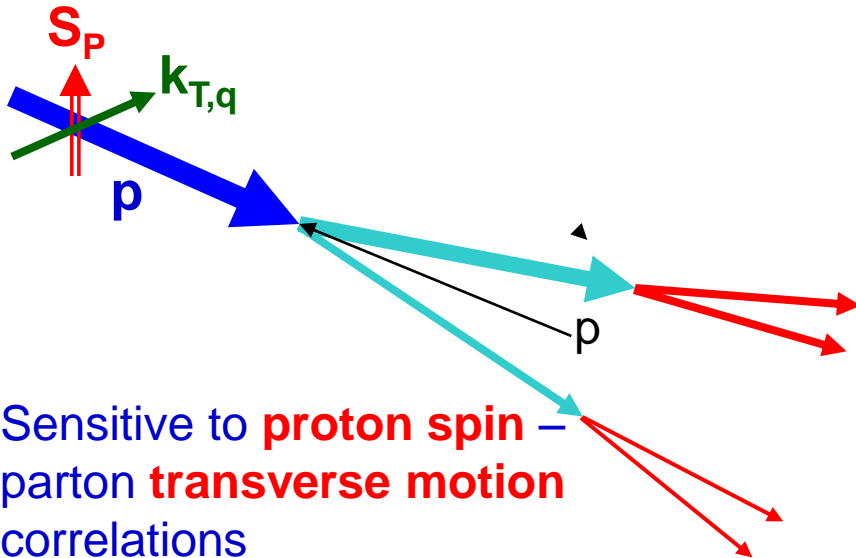


- Large transverse single-spin asymmetries over a very wide range of \sqrt{s}
- Naïve collinear pQCD predicts $A_N \sim \alpha_s m_q / \sqrt{s} \sim 0$
- May arise from
 - Sivers effect / twist-3
 - Transversity + Collins fragmentation function
- No evidence to date of a fall-off at high p_T
 - Something we haven't thought of yet ?

Sivers and Collins effects in pp collisions

Sivers/twist-3 mechanism:

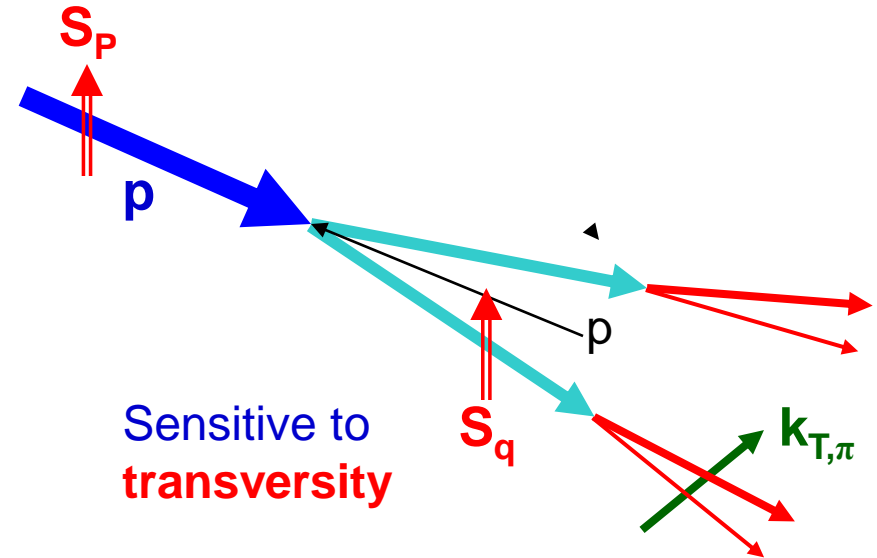
asymmetry in jet or γ production



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

Collins mechanism:

asymmetry in jet fragmentation



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

Isolating the underlying dynamics

SIVERS

Transversity x Collins

Rapidity dependence of

A_N for π^0 and eta with increased p_t coverage

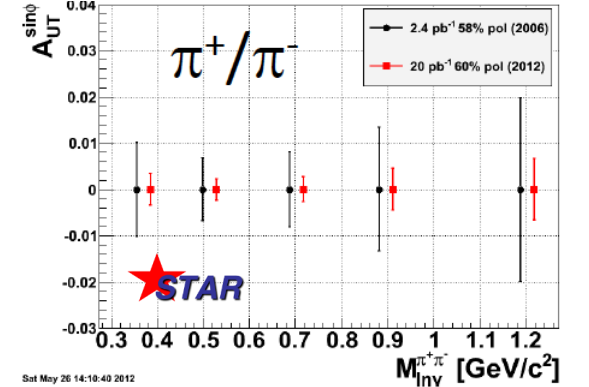
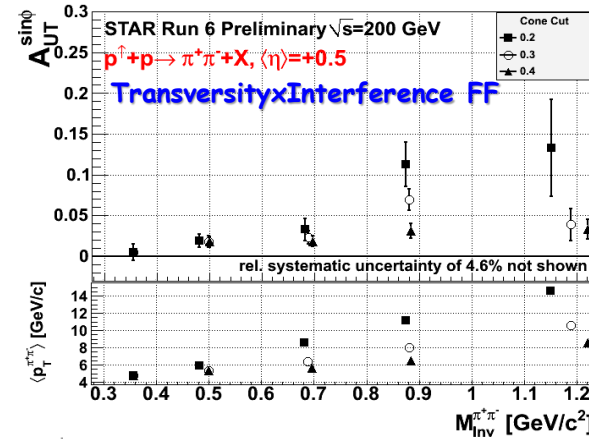
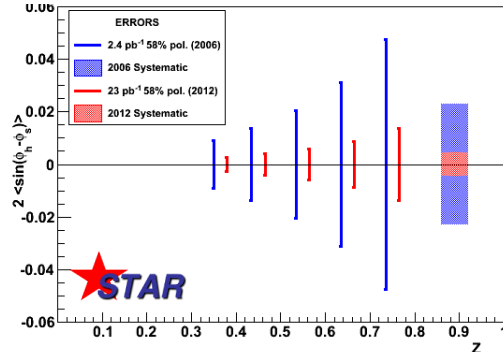
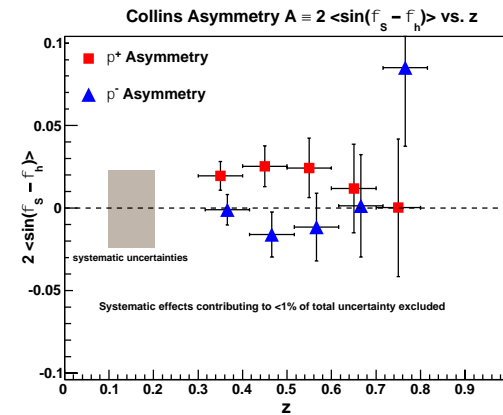
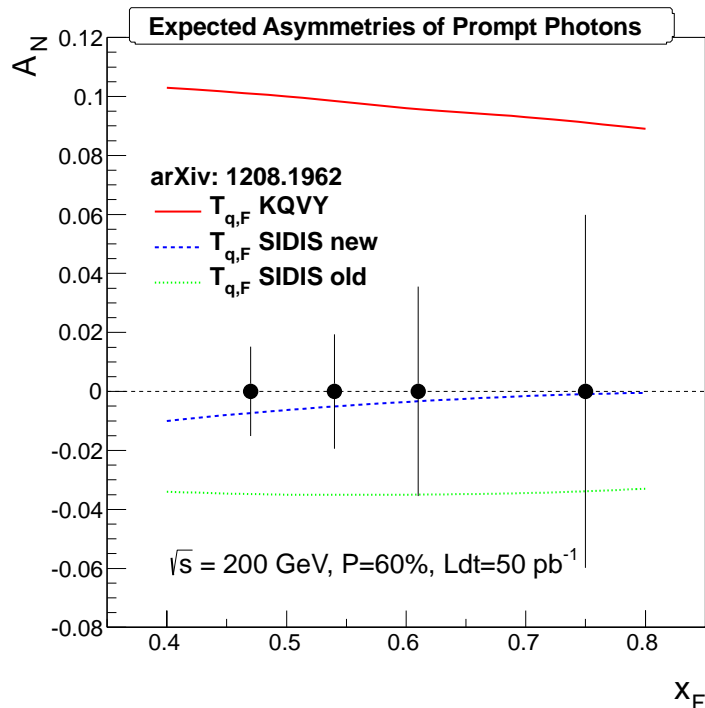
A_N for jets

A_N for direct photons

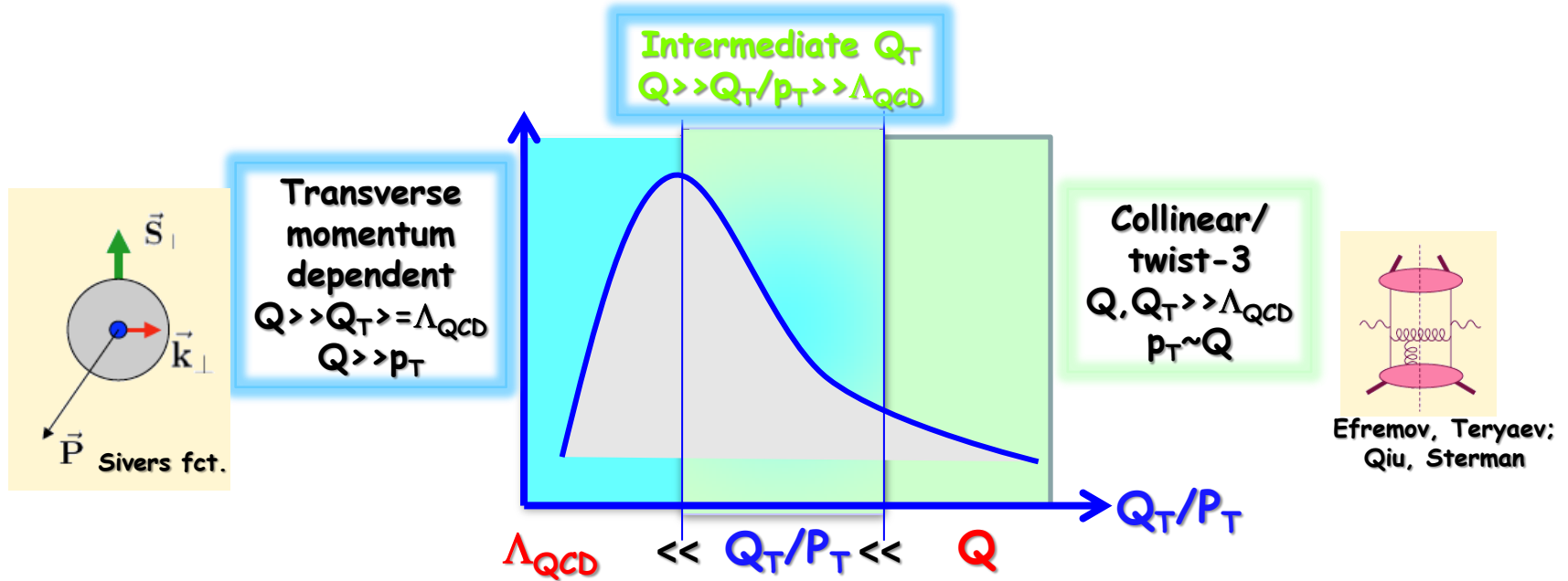
A_N for heavy flavor \rightarrow gluon

$\pi^{+/-} \pi^0$ azimuthal distribution in jets

Interference fragmentation function



Sivers effect sign change

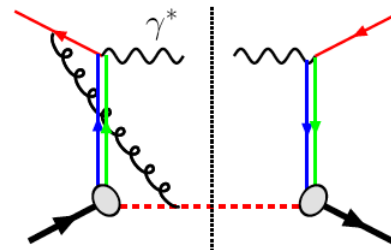
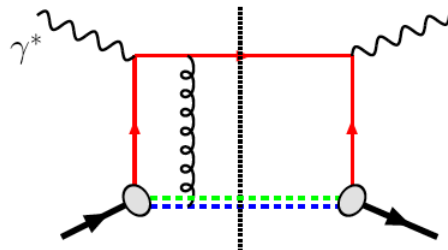


Critical test for our understanding of TMD's and TMD factorization

QCD:

DIS:
attractive FSI

Drell-Yan:
repulsive ISI



$$\text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{DY}} \text{ or } \text{Sivers}_W \text{ or } \text{Sivers}_{Z_0}$$

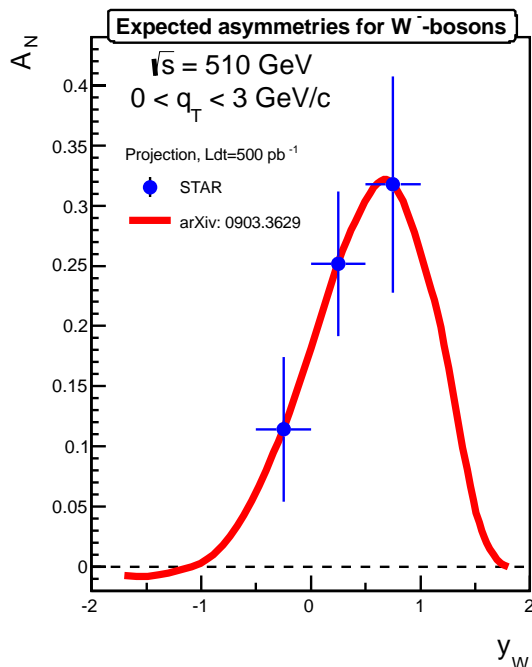
What can RHIC do *today* ?

Delivered luminosity of 500pb^{-1} with existing detectors

STAR $A_N(W)$:

$-1.0 < y < 1.5$

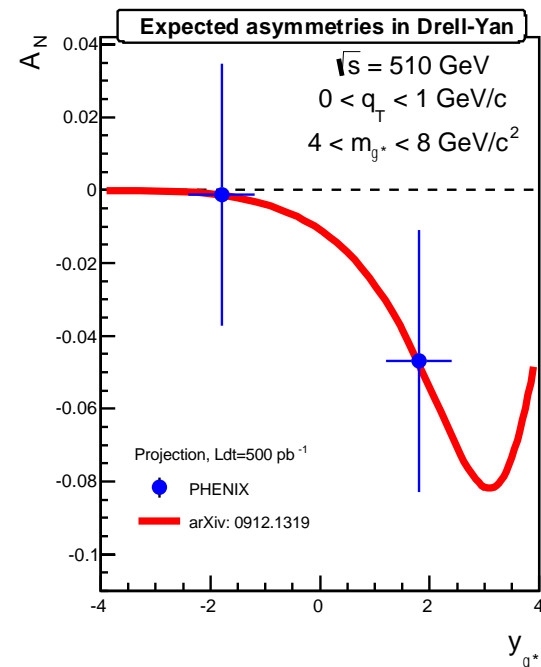
W-fully reconstructed



PHENIX $A_N(DY)$:

$1.2 < |y| < 2.4$

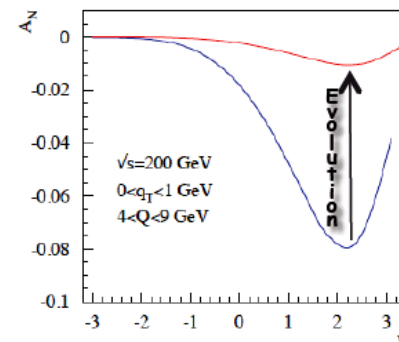
Muon-Arms+FVTX \rightarrow S/B ~ 0.2



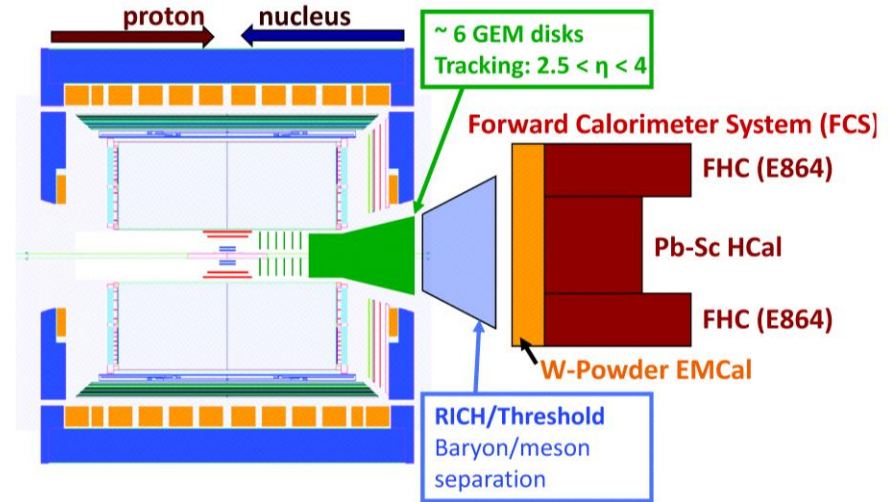
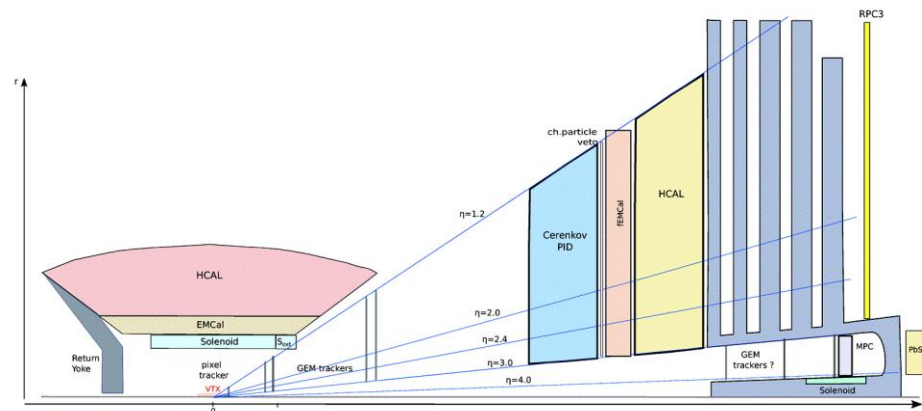
**Plus extremely clean measurement of $A_N(Z0)$
 to $\pm 10\%$ for $\langle y \rangle \sim 0$**

Caveat:

**potentially large evolution effects on A_N for DY, W, Z0
 not yet theoretically full under control and accounted for**



Forward upgrades late in the decade



- Both PHENIX and STAR are planning substantial forward upgrades
- Full suite of forward photon, hadron, jet, and Drell-Yan measurements
 - High precision measurements where transverse spin effects are the largest
 - Only opportunity to measure the Sivers sign change if evolution is as rapid as some calculations imply
 - $\Delta g(x)$ down to $x \sim 0.001$ with fully reconstructed di-jets

Additional measurements in write-up

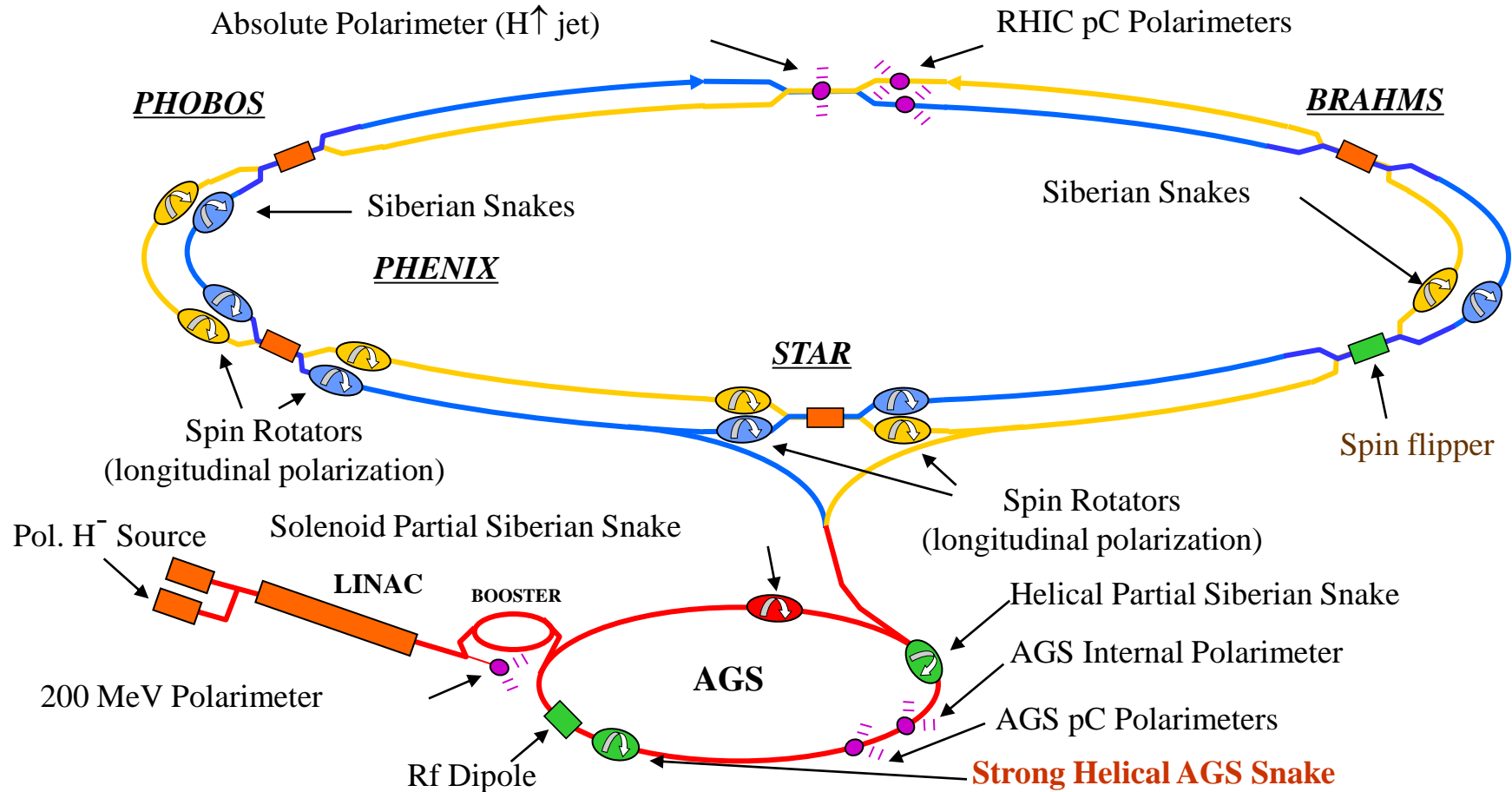
- Polarized p+A
 - TMDs are closely related to unintegrated parton distributions like $xg(x, k_T)$
 - Transverse asymmetries vs. A and p_T provide an alternative method to determine the saturation scale
 - See next talk (John Lajoie)
- Generalized parton distribution E_g
 - Sensitive to gluon spin-orbit correlations
 - Measured via transverse spin dependence of exclusive J/ψ production in ultra-peripheral p+A collisions
- Polarized ^3He
 - Access to polarized neutrons
 - Tagging spectator protons will enhance signal:background
 - Determine the flavor dependence of transverse spin asymmetries

Conclusions

- **RHIC is making unique contributions** to our understanding of the proton spin
 - Gluon polarization
 - Flavor-separated quark and anti-quark polarizations
 - Transversity
 - TMDs and twist-3 correlations
- The rest of this decade will bring **further substantial improvements in all of these**

Years	Beam Species and Energies	Science Goals	New Systems Commissioned/Required
2013	500 GeV $\bar{p}+p$	Sea antiquark and gluon polarization	Electron lenses upgraded pol'd source
2014	200 GeV $p^\uparrow+p$ 200 GeV $\bar{p}+p$	Unravel underlying sub-processes for A_N Improve precision on $\Delta g(x)$	PHENIX Muon Piston Calorimeter Extension
2015- 2017	200 GeV $p^\uparrow+A$ 500 GeV $p^\uparrow+p$ 500 GeV $\bar{p}+p$	Unravel underlying sub-processes for A_N , GPD E, First measurement of PHENIX: $A_N(DY)$, STAR: $A_N(W/Z)$ Unravel underlying sub-processes for A_N $\Delta g(x)$ at low- x , sea antiquark polarizations	STAR inner TPC pad row upgrade
>2018	200 GeV $p^\uparrow+A$ 500 GeV $p^\uparrow+p$	Unravel underlying sub-processes for A_N , GPD E Precision measurements of transversity, Sivers, IFF, and $A_N(DY)$	sPHENIX STAR forward physics upgrade Polarized He-3 beams

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



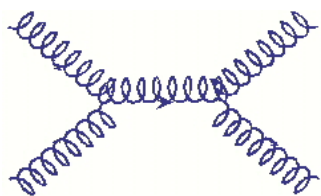
- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

Exploring gluon polarization at RHIC

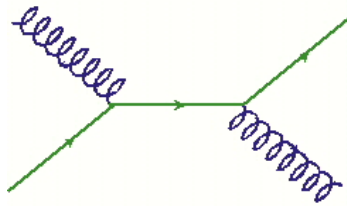
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf : polarized parton distribution functions

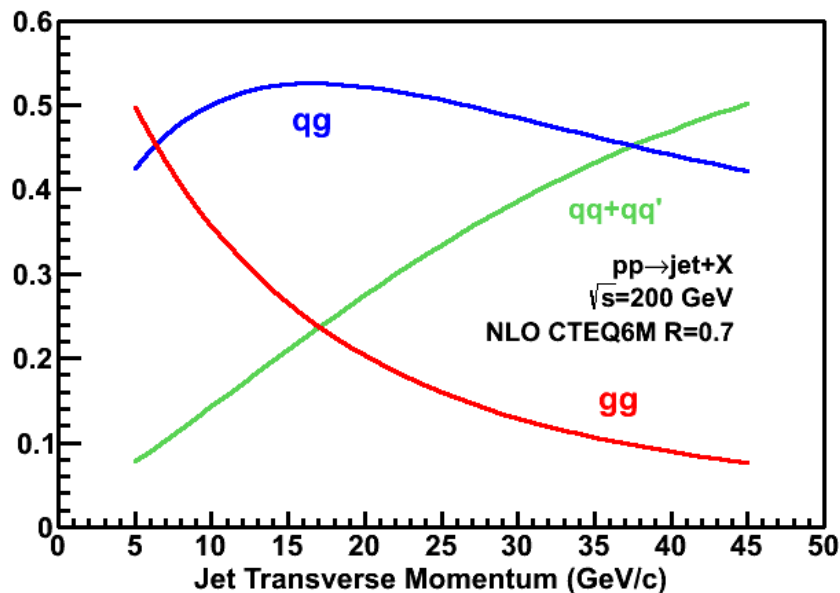
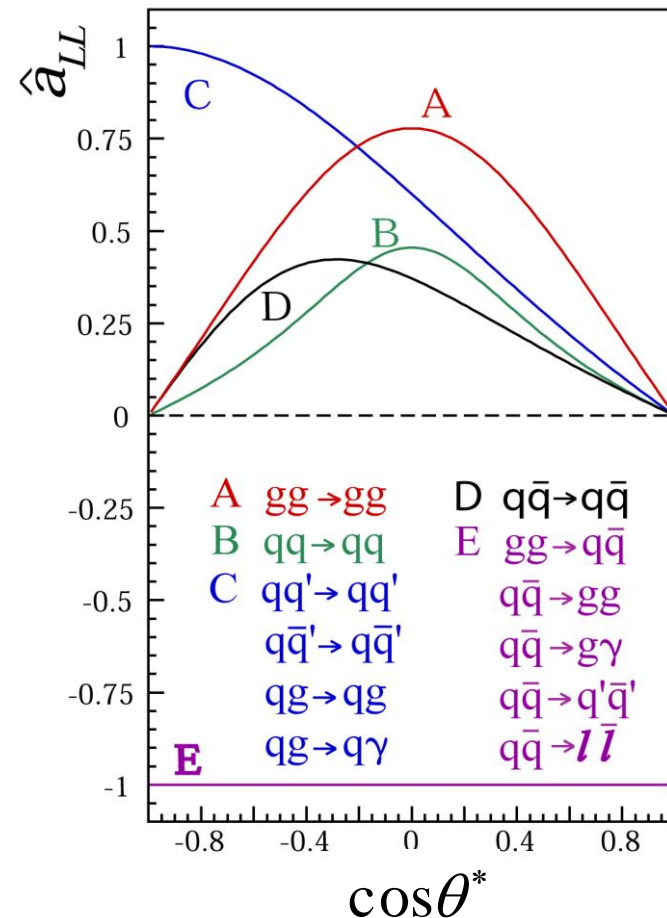
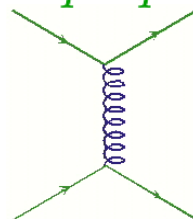
$$\frac{\Delta G}{G} \frac{\Delta G}{G}$$



$$\frac{\Delta q}{q} \frac{\Delta G}{G}$$



$$\frac{\Delta q}{q} \frac{\Delta q}{q}$$



For most RHIC kinematics, **gg** and **qg** dominate, making A_{LL} for π^0 and jets sensitive to **gluon polarization**.