Longitudinal Spin at RHIC

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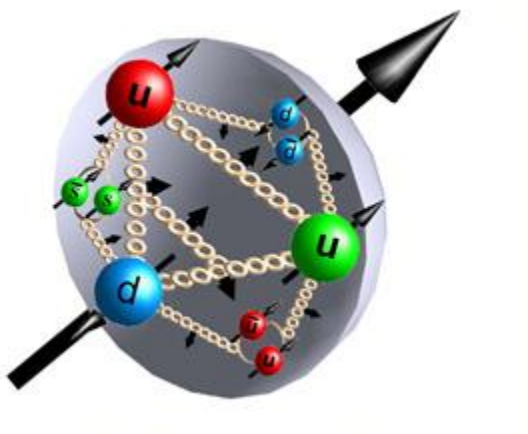
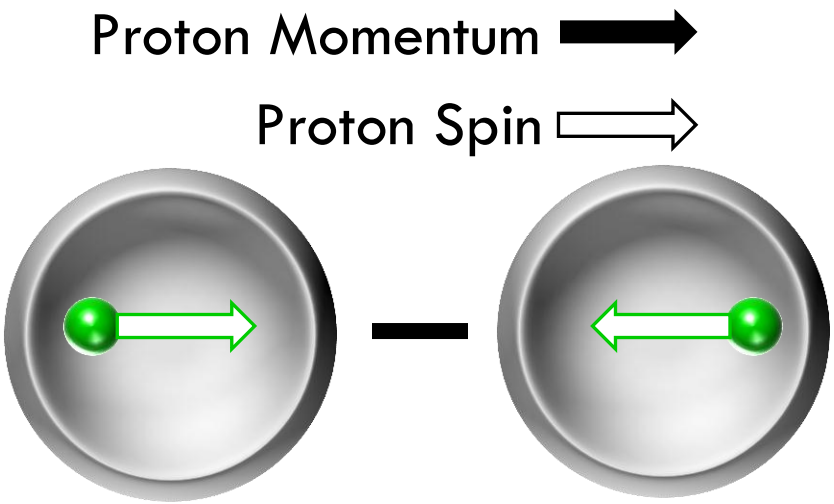
From the RHIC Spin white paper (2012):

Helicity parton density functions (PDFs) carry vital information on the extent to which quarks and gluons with a given momentum fraction x have their spins aligned with the spin direction of a fast moving nucleon in a helicity eigenstate. The corresponding integrals over all x relate to one of the most fundamental, but not yet satisfactorily answered questions in hadronic physics: how is the spin of the proton distributed among its constituents?

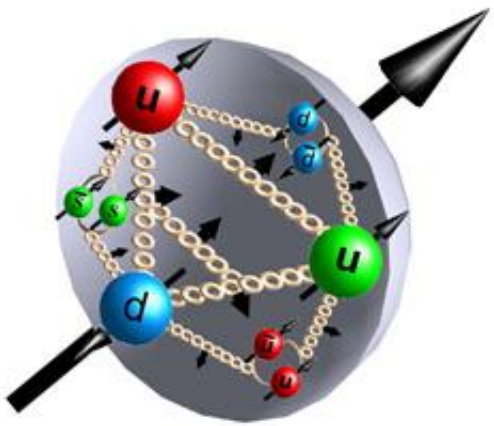


Helicity
$\Delta q(x,Q^2)$
$\Delta g(x,Q^2)$



$\Delta f(x) = f^{+}(x) - f^{-}(x)$, where superscript +(-) indicates parton spin aligned (anti-aligned) with proton spin

Where does the proton's spin of ½ come from?



$\Rightarrow$ Total Quark Spin :

$$\Delta\Sigma = \sum_{q,\bar{q}} \int_{x=0}^{x=1} \Delta q(\mathrm{x})\mathrm{dx}$$

$\Rightarrow$ Total Gluon Spin :

$$\Delta G = \int_{x=0}^{x=1} \Delta g(\mathrm{x})\mathrm{dx}$$

RHIC longitudinal spin aims: ΔG and sea quark contribution to ΔΣ

$\Rightarrow$ Total Orbital Angular Momentum of Quarks and Gluons : $\mathrm{L_Z}$

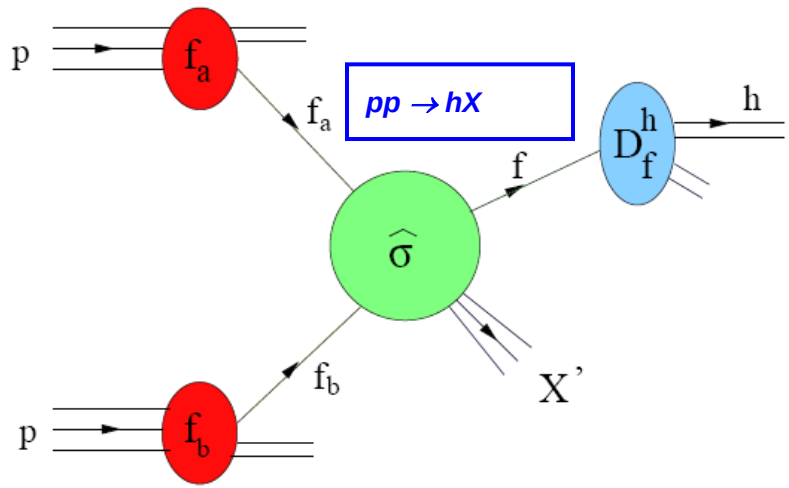
Proton spin:

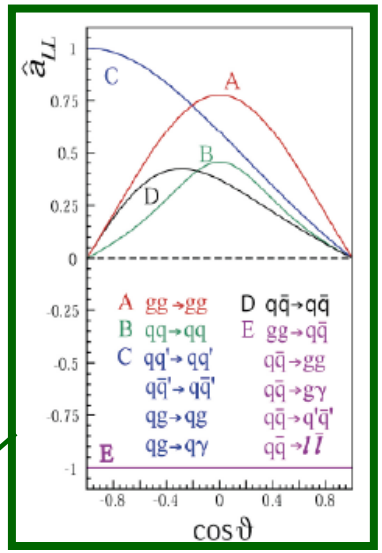
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Outline

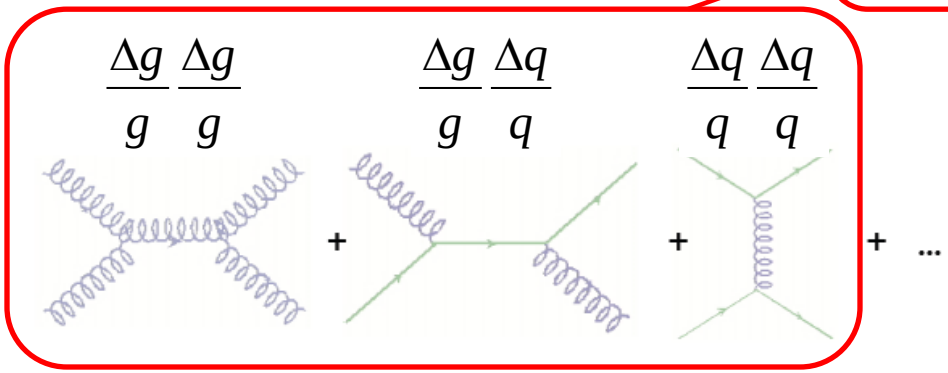
- **ΔG at RHIC**
  - Accessing ΔG with double longitudinal spin asymmetries, A_{LL}
  - Measuring A_{LL} at RHIC
  - ΔG from A_{LL}: Global analysis (by DSSV) with RHIC data
    - Impact of recent results from PHENIX+STAR
    - Next steps
- **Sea quark polarization at RHIC: the W program**
  - Physics motivation: sea-quark polarization from A_L^W
  - Recent A_L^W results from STAR and PHENIX
  - Contribution of current and future data to DSSV global analysis

Factorization: can break down cross section into pQCD-calculable hard scattering and pQCD-incalculable PDFs and fragmentation functions





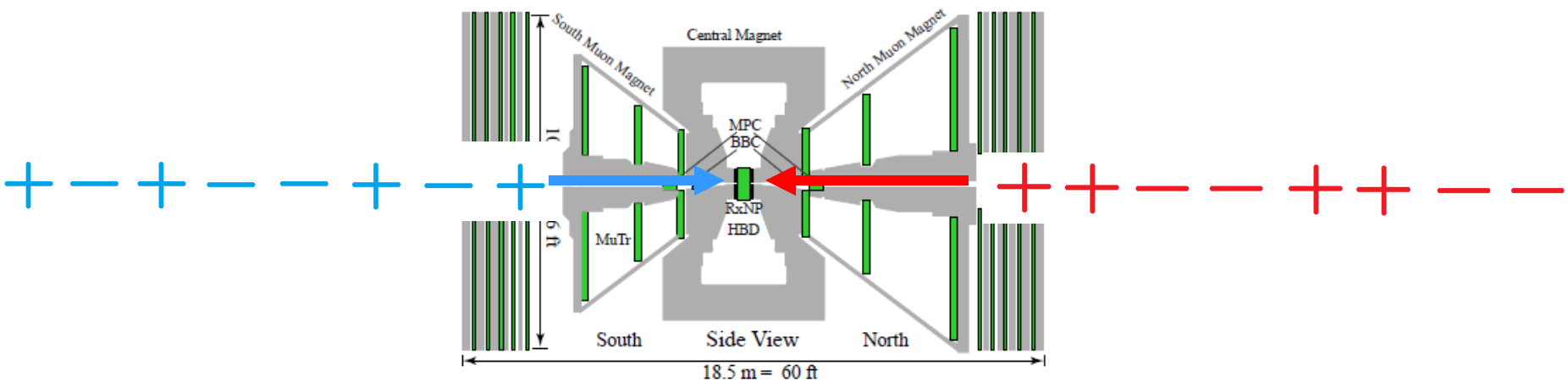
$$A_{LL}^{\pi^0} = \frac{\Delta\sigma^{p+p\to\pi^0+X}}{\sigma^{p+p\to\pi^0+X}} = \sum_{a,b,c,d=q,\bar{q},g} \frac{\Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma}^{a+b\to c+d} \otimes D_{c,d\to\pi^0}}{f_a \otimes f_b \otimes \hat{\sigma}^{a+b\to c+d} \otimes D_{c,d\to\pi}}$$



Double longitudinal spin asymmetry is sensitive to Δg and Δq

Measuring A_{LL} at RHIC

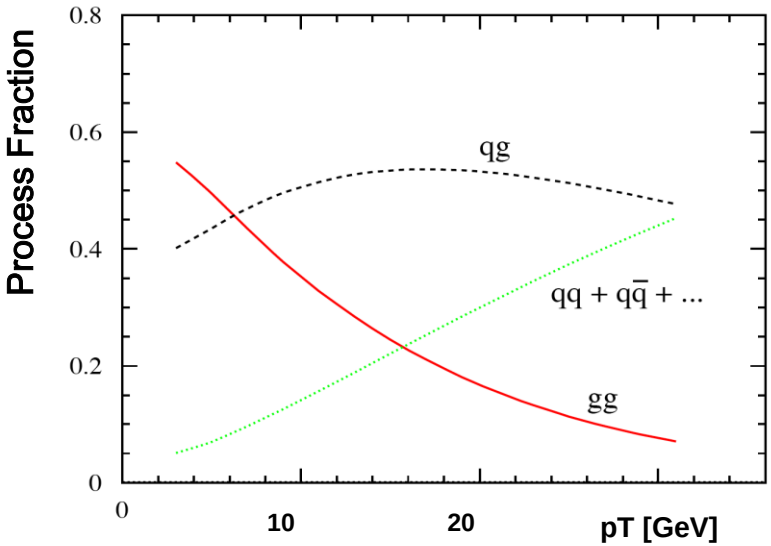
- A_{LL} is measured by determining difference in particle yields between ++ and +- crossings (with an additional factor to normalize luminosities for crossing types)
- Bunch spin patterns include ++,+-, -+, and -- crossings in each fill



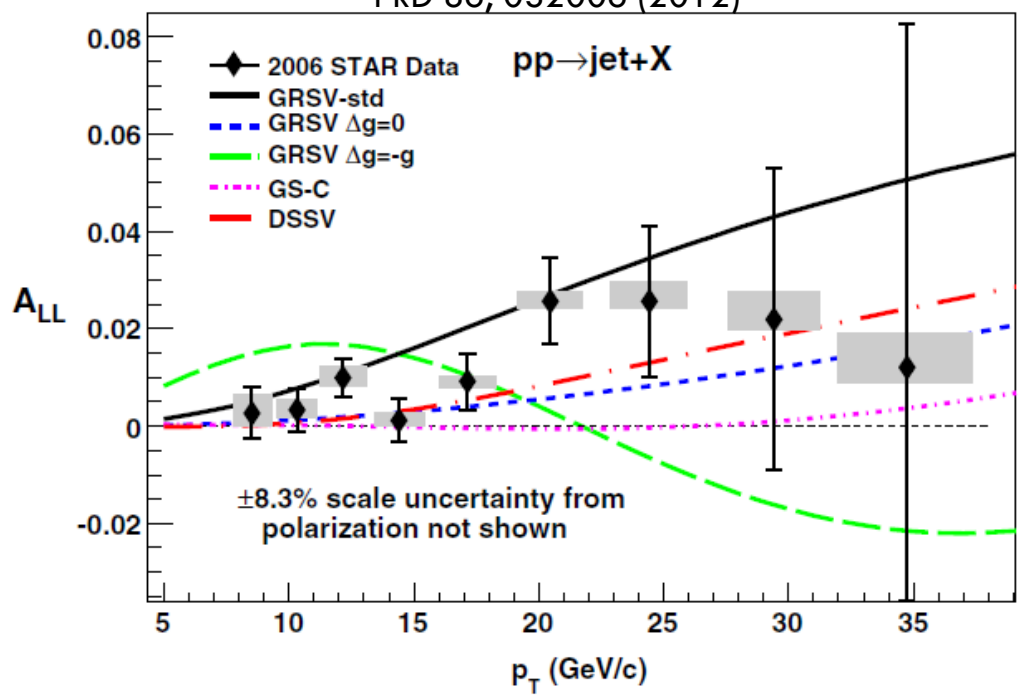
$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{1}{< P_B P_Y >} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}} \qquad R = \frac{L^{++}}{L^{+-}}$$

- N is the yield of the final state measured
  - e.g. $\pi^0, \pi^{+/-}, \eta, e^{+/-}$, jets, di-hadron or di-jet states

Measuring A_{LL} at RHIC: A_{LL} for Inclusive Jets at STAR



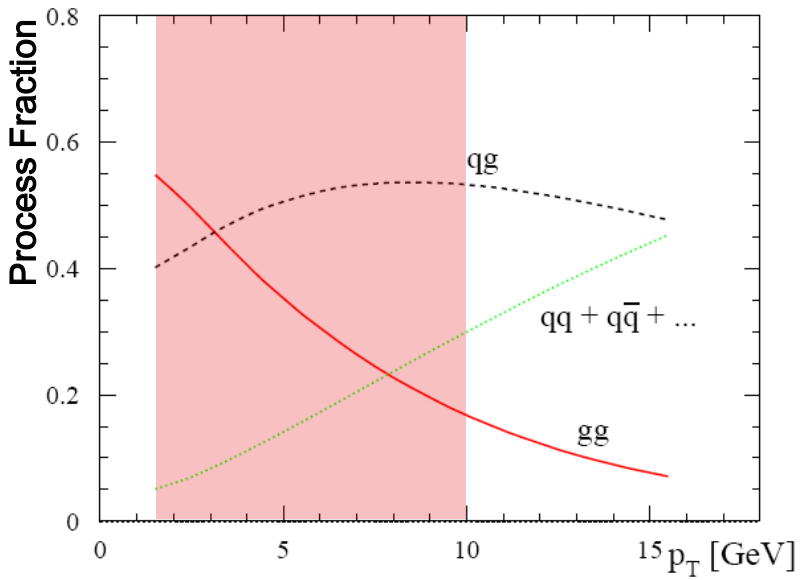
STAR Run 6 inclusive jet A_{LL}
Mid-rapidity, $\sqrt{s}$=200 GeV
PRD 86, 032006 (2012)



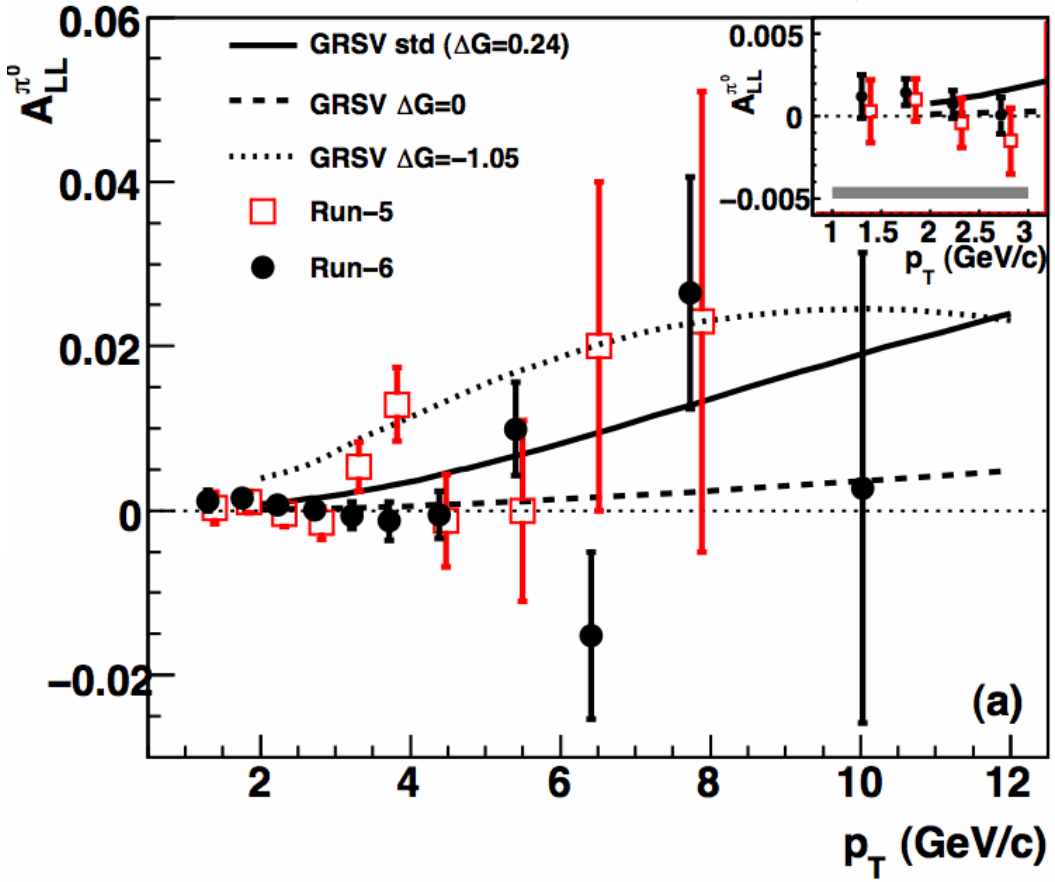
- STAR inclusive jet measurements at mid-rapidity have most statistics where qg processes dominate→sensitive to sign of Δg

Good discriminative power between calculations with different assumptions for ΔG

Measuring A_{LL} at RHIC: A_{LL} for Inclusive π^0 at PHENIX



PHENIX Run5+6 $\sqrt{s}$ = 200 GeV: PRL103, 012003



- PHENIX A_{LL} for inclusive π^0 covers a scaled-down p_T range compared to STAR—π^0's carry a fraction of jet momentum
- Smallest statistical uncertainty where process fraction for gg ≈ qg→weaker constraint on negative Δg, better constraints on positive Δg

ΔG from A_{LL}: QCD Global Analysis

- DSSV (de Florian, Sassot, Stratmann, Vogelsang): global NLO analysis including polarized data from inclusive DIS, SIDIS, and RHIC pp collisions
  - Phys.Rev.Lett.101:072001, 2008 and Phys.Rev.D80:034030,2009.

	experiment	data type	data point fitted
Inclusive DIS data: routinely used for PDF fits $\rightarrow \Delta q + \Delta\bar{q}$	EMC, SMC	DIS	34
	COMPASS	DIS	15
	E142, E143, E154, E155	DIS	123
	HERMES	DIS	39
	HALL-A	DIS	3
	CLAS	DIS	20
Semi-inclusive DIS data: previously used only in DNS fit $\rightarrow$ flavor separation	SMC	SIDIS, $h^{\pm}$	48
	HERMES	SIDIS, $h^{\pm}$	54
		SIDIS, $\pi^{\pm}$	36
		SIDIS, $K^{\pm}$	27
	COMPASS	SIDIS, $h^{\pm}$	24
First RHIC polarized pp data: first fit by DSSV $\rightarrow \Delta g$	PHENIX (in part prel.)	200 GeV pp, π^0	20
	PHENIX (prel.)	62 GeV pp, π^0	5
	STAR (in part prel.)	200 GeV pp, jet	19
	TOTAL:		467

467 data points in total (10% from RHIC)

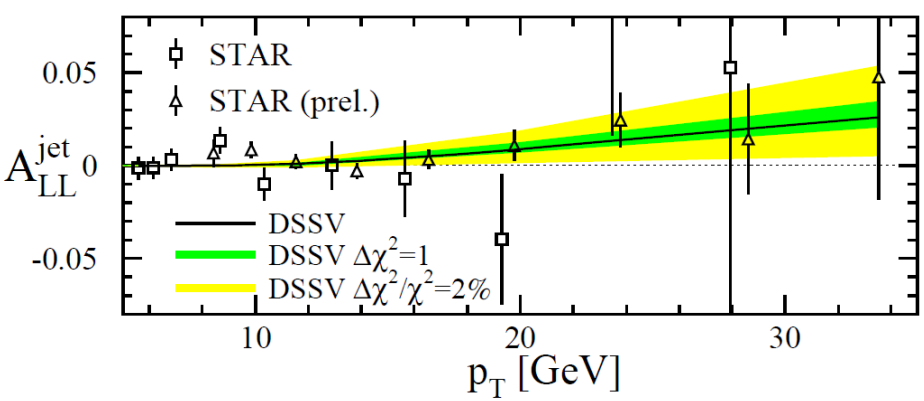
- **Methodology Overview:**
  - Parameterize distributions $\Delta f_i(x, {Q_0}^2 = 1\ GeV^2)$ for quarks and gluons
  - Impose additional physics-based constraints (e.g. $|\Delta f| < f$)
  - Evolve distributions from the input scale to the various Q^2 of experimental data
  - Find corresponding observables as a function of kinematic variable (p_T for pp, x for DIS)
  - Minimize χ^2 of fit of calculated observables to data

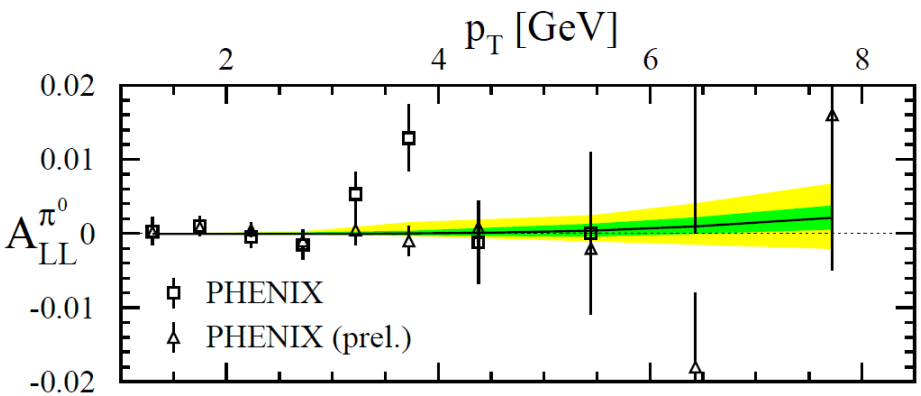
- **Methodology Overview:**

Parameterize distributions…

$$x\Delta f_j(x, Q_0^2) = N_j x^{\alpha_j}(1-x)^{\beta_j}(1+\gamma_j\sqrt{x}+\eta_j x)$$

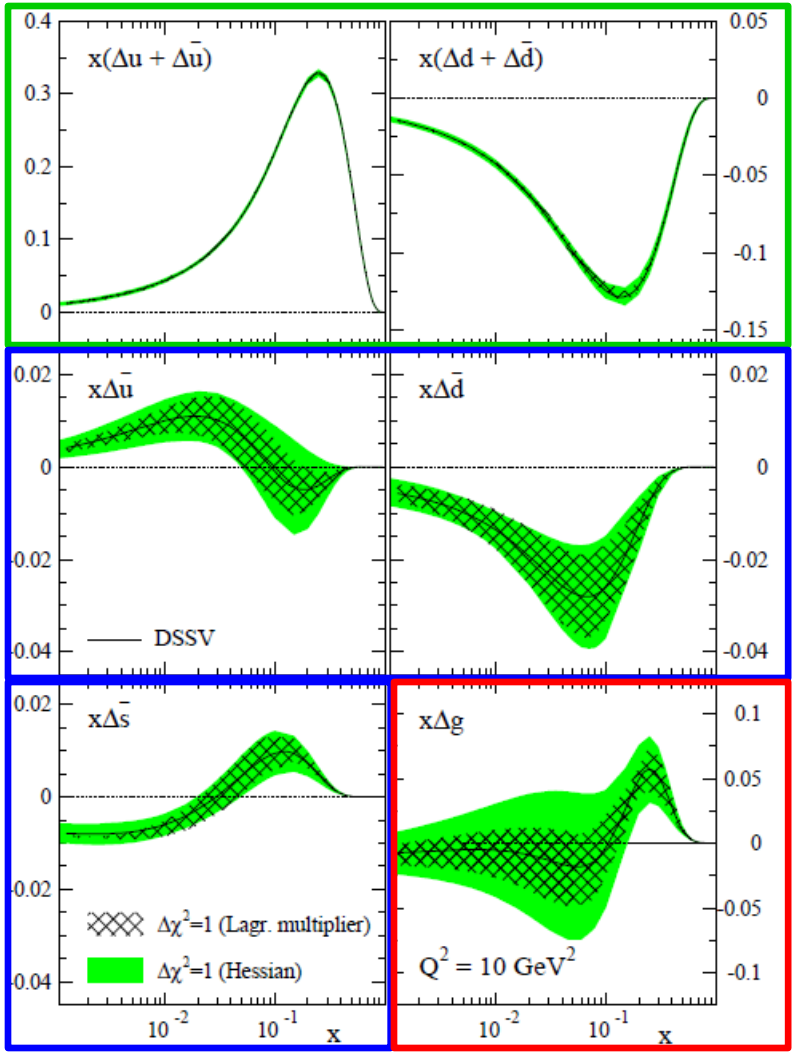
…calculate observables and fit to data
(STAR and PHENIX Run 5 + Run 6 data shown).





DSSV: Phys.Rev.Lett.101:072001, 2008

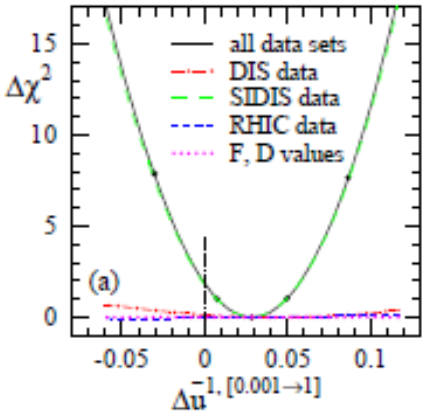
ΔG from A_{LL}: DSSV Results



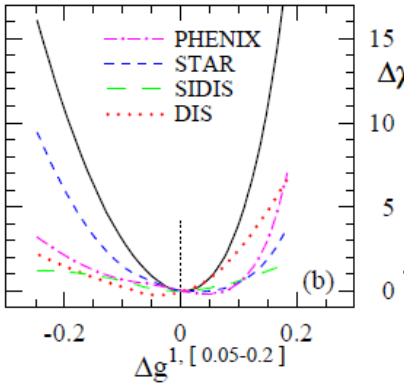
de Florian, Sassot, Stratmann, Vogelsang
Phys.Rev.D80:034030,2009

Well-determined by DIS

$$\int_{0.001}^{1} \Delta\Sigma(x, Q^2 = 10\ GeV^2)dx = 0.366^{+0.042}_{-0.062}$$



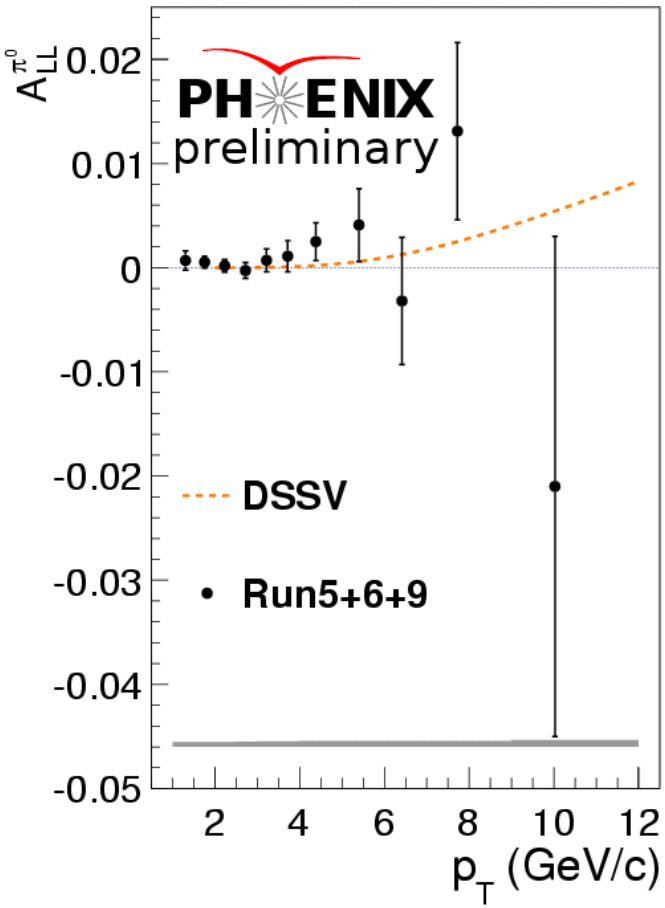
Main constraints to sea quarks from SIDIS (and DIS for strange quark)

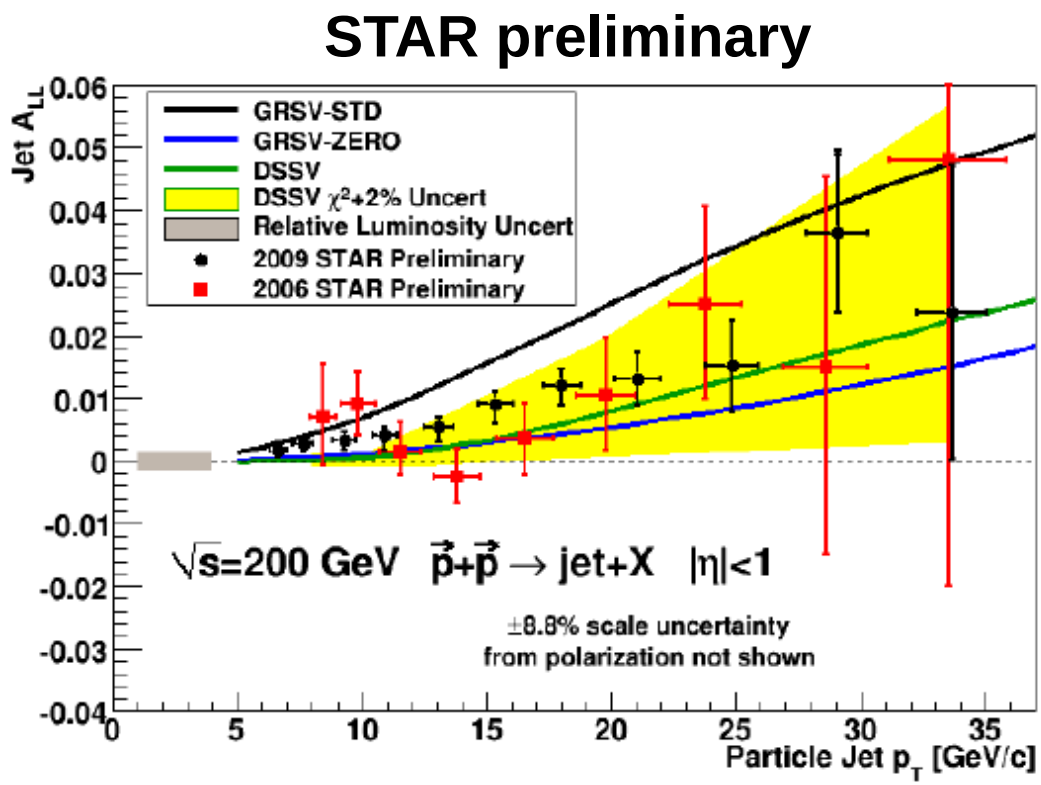


Best constraints for ΔG now provided by RHIC

$$\int_{0.05}^{0.2} \Delta g dx = 0.005^{+0.129}_{-0.164}$$

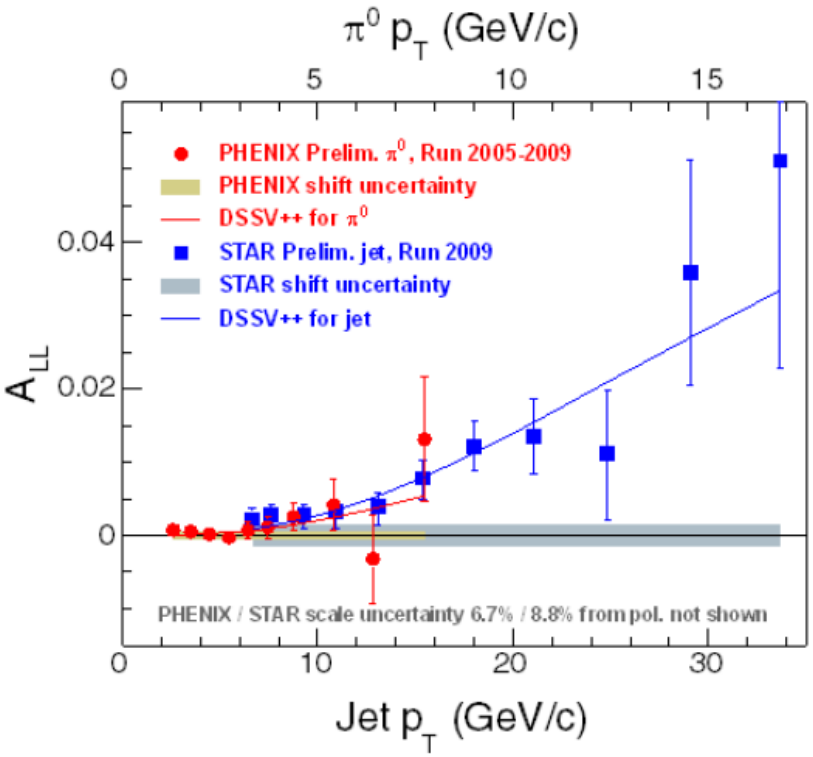
ΔG from A_{LL}: Run 9 A_{LL} Measurements at RHIC

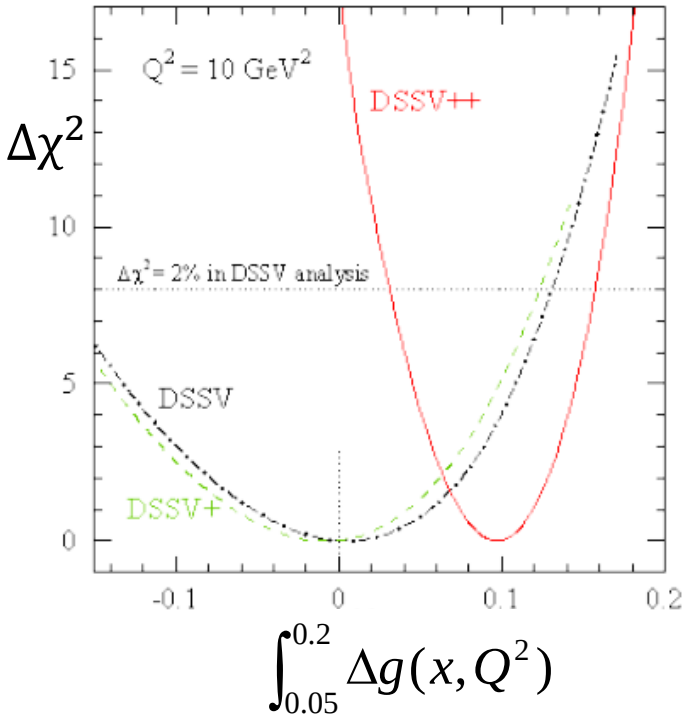




- Substantially larger figure of merit (P^4L) from Run 9 than in all previous runs combined.

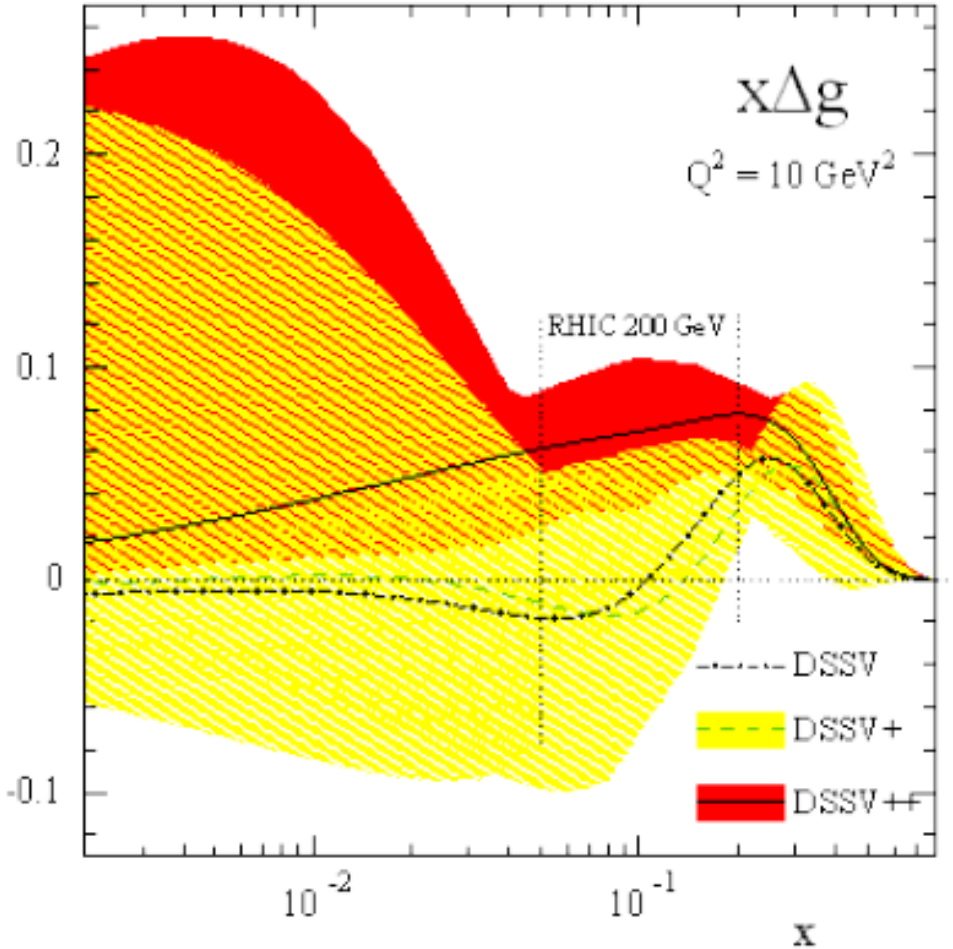
ΔG from A_{LL}: DSSV with Run 9 Data





- DSSV++ is a new, preliminary global analysis from the DSSV group that includes 2009 A_{LL} measurements from PHENIX and STAR
- **First experimental evidence of non-zero gluon polarization in the RHIC range (0.05 < x< 0.2)!**

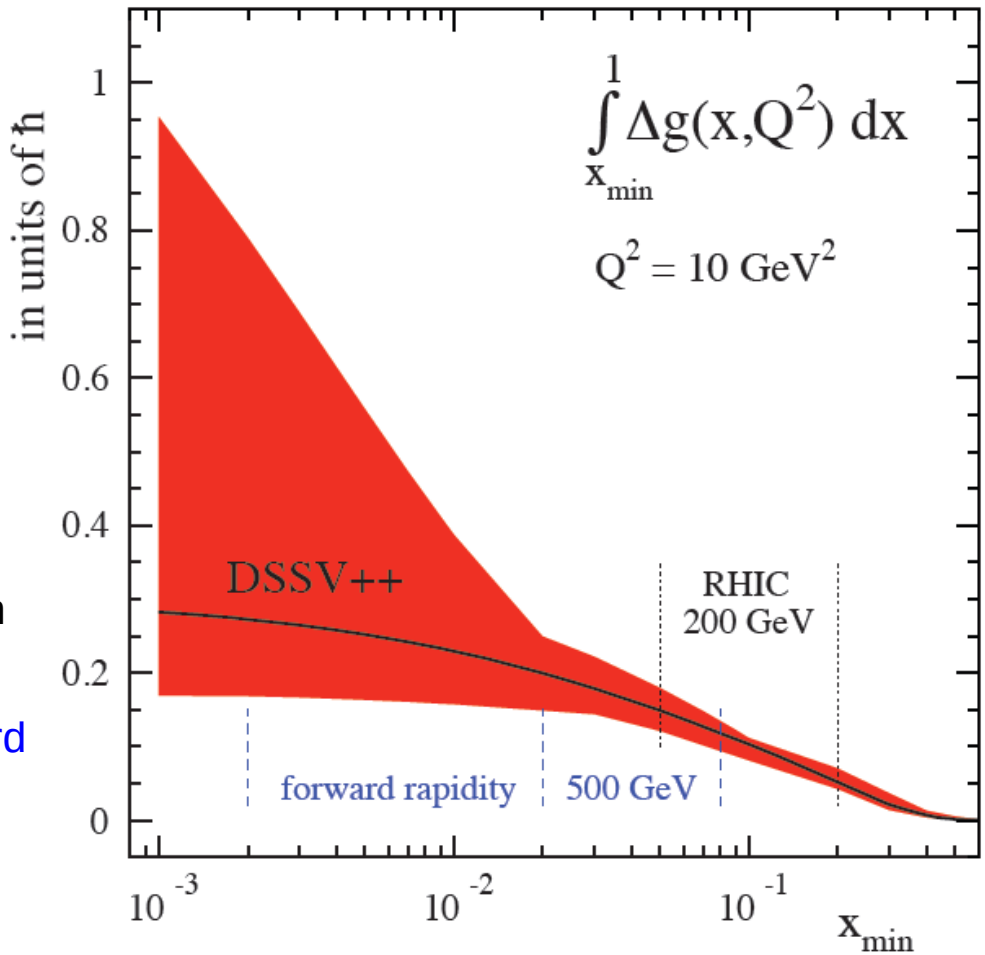
ΔG from A_{LL}: DSSV with Run 9 Data



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

ΔG at RHIC: Next Steps

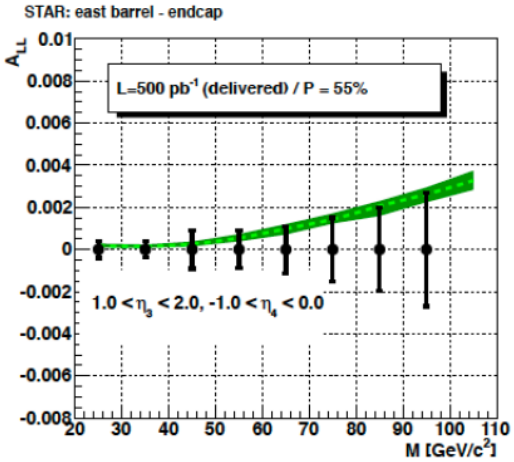
- **Large uncertainty still remains in both the shape of Δg(x) and its integral, particularly for small x region not yet accessed by RHIC data**
- **RHIC will continue to improve constraints through the following:**
  - Reduced statistical and systematic uncertainties for all A_{LL} channels
  - Better handle on measured x through correlation measurements
  - Access lower x region through forward measurements and $\sqrt{s} = 500\ GeV$

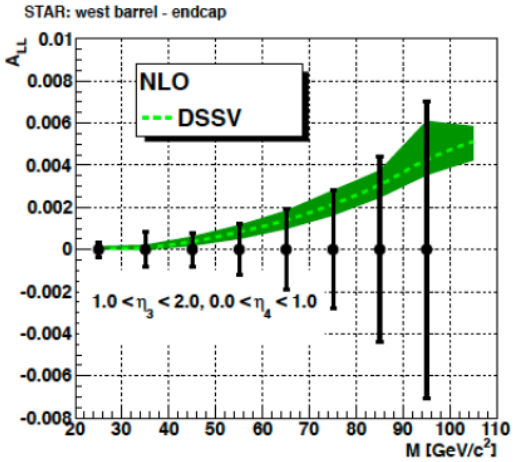


ΔG at RHIC: Next Steps: Correlation Measurements

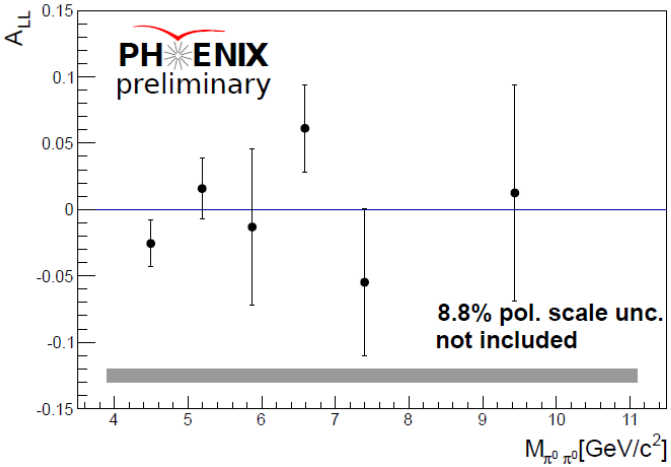
$$x_1 = \frac{p_T}{\sqrt{s}}(e^{y_3} + e^{y_4})$$
$$x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$

Measure two jets or jet tags to constrain event kinematics; provides data on shape of $\Delta g(x)$





STAR di-jet projections;
one jet at forward rapidity ($1<|\eta|<2$) to push down x_2



A_{LL} for back-to-back π^0's at mid-rapidity—more data needed!

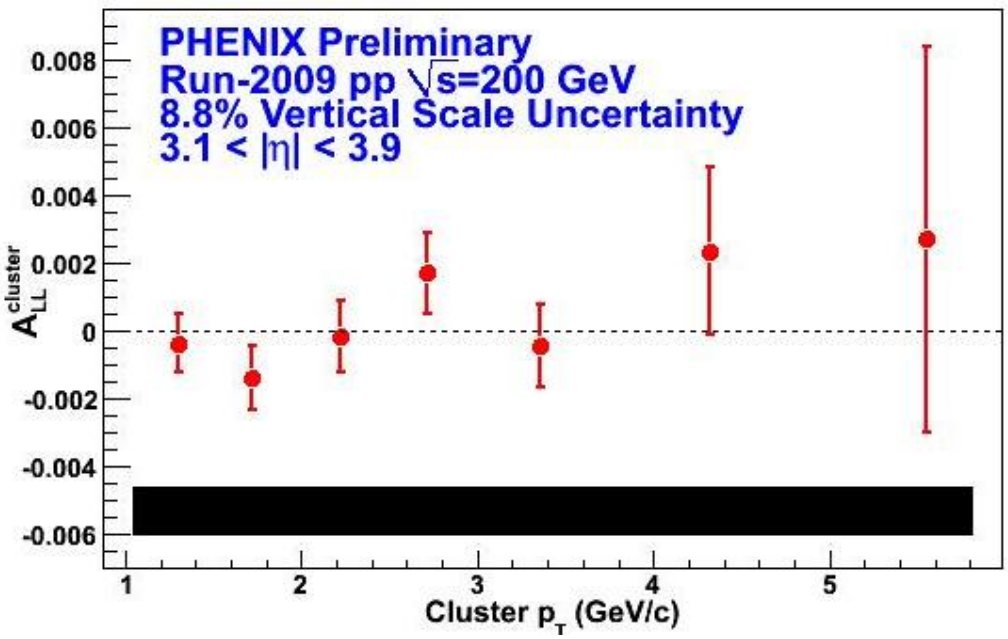
ΔG at RHIC: Next Steps: Low x with the MPC in PHENIX

$$x_1 = \frac{p_T}{\sqrt{s}}(e^{y_3} + e^{y_4})$$

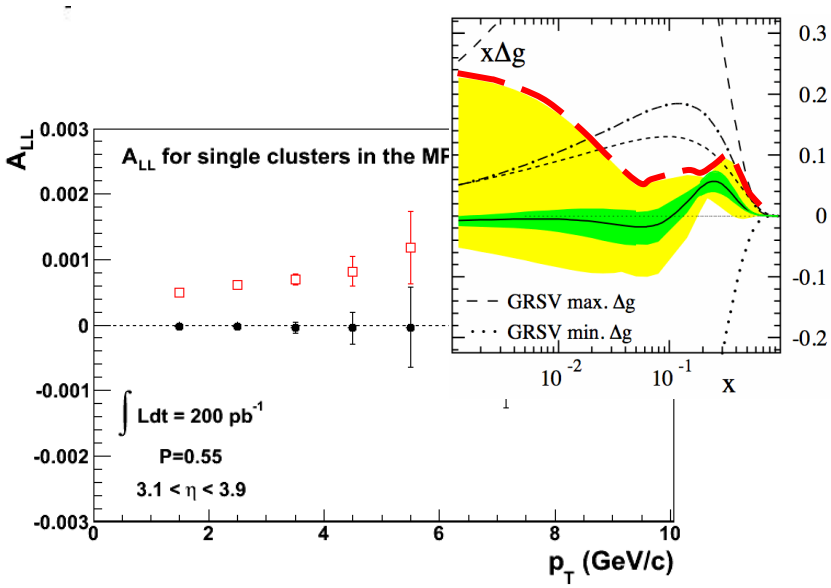
$$x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$

Larger η → smaller x_2

MPC: 3.1<|η|<3.9



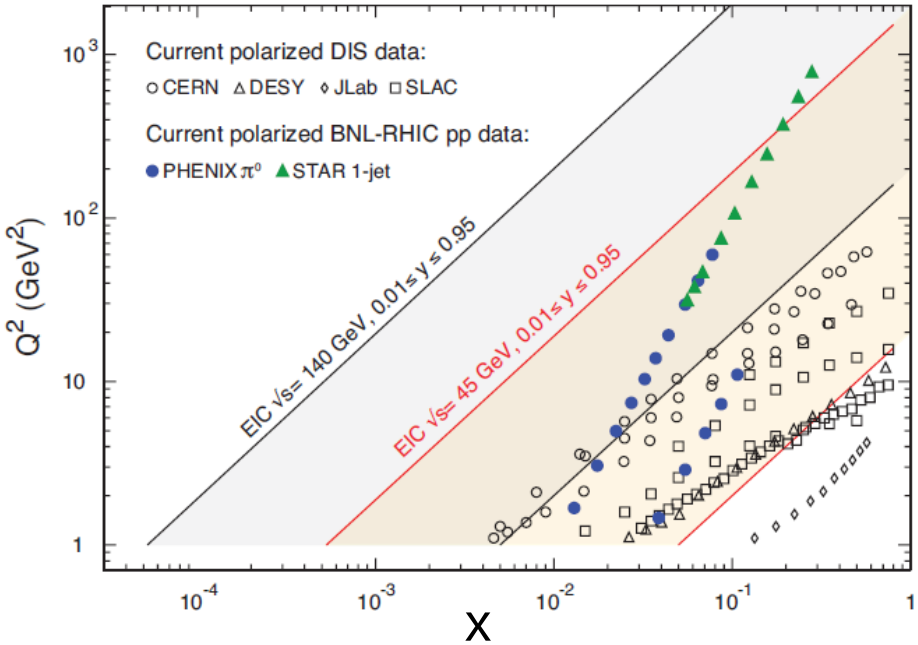
First PHENIX forward measurement of A_{LL} for merged EM clusters (~80% π^0)

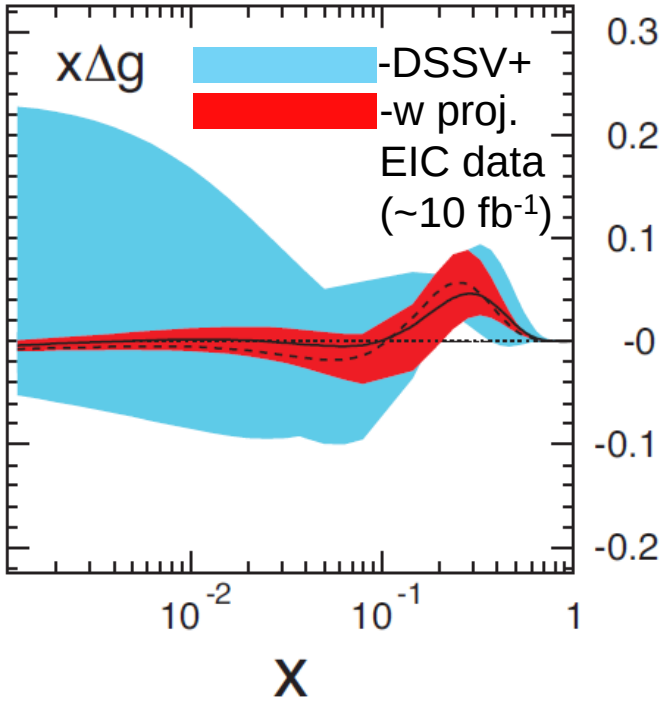


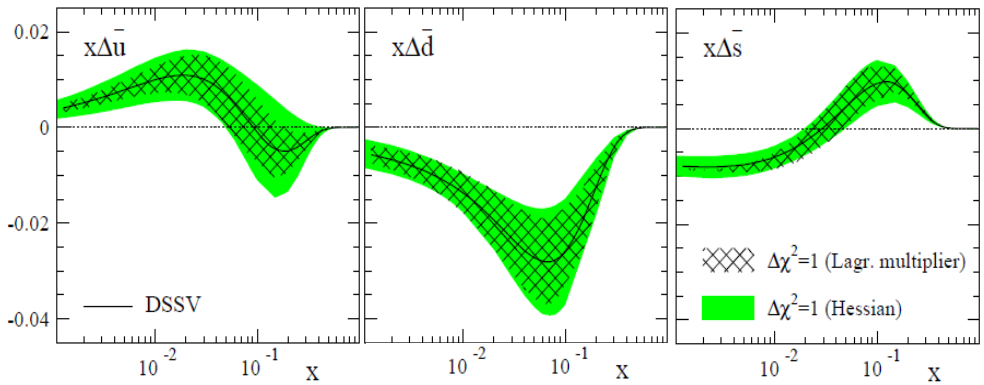
Projections of cluster A_{LL} with Run 13 for 2009 DSSV **best fit** and Δg upper uncertainty band

ΔG at RHIC: Next Next Steps: Electron-Ion Collider

- **Proposed electron-ion collider could greatly enhance our knowledge of ΔG beyond current capabilities of RHIC**
  - Polarization of both electron (~80%) and proton beam (70%)
  - Very high luminosity (~10 fb^{-1} used for projection below achievable in 1-2 months of running)
  - Broad coverage in Q^2 and x allows precise determination of Δg(x) through scaling violation

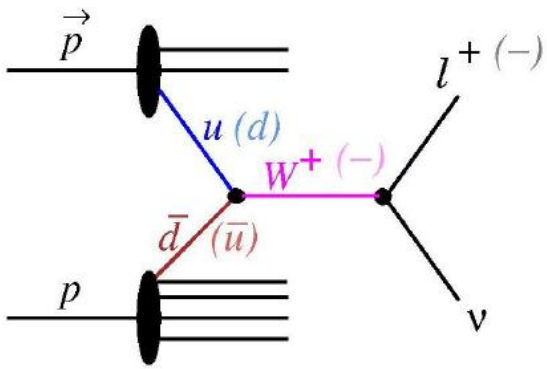






Previously constrained by SIDIS:
Large uncertainties from fragmentation functions and lack of data

- **Measurement of parity-violating W production at RHIC complements SIDIS data**
  - Leptonic final state→no FF dependence
  - Large $Q^2 \sim M_W^2$
  - W couples only to left-handed quarks and right-handed anti-quarks→fixes quark helicity and flavor



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

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

- **Selecting kinematic ranges allows sensitivity to specific quark/anti-quark helicities; upgrades allow lepton measurements at forward rapidity**

STAR

Central (barrel) region ($W \rightarrow e\pm$, $|\eta|<1$)

First data from 2009: PRL106, 062002 (2011)

Forward (endcap) region ($W \rightarrow e\pm$, $1<|\eta|<2$) :

Forward tracker upgrade, first data in 2012

Forward Gem Tracker

PHENIX

Central Arms ($W \rightarrow e\pm$, $|\eta|<0.35$)

First data from 2009: PRL106, 062001 (2011)

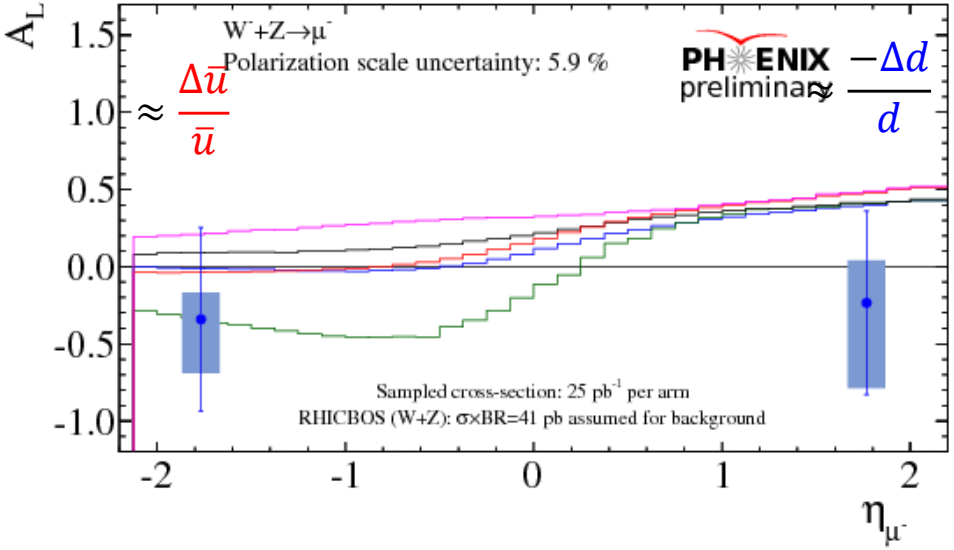
Forward Arms ($W \rightarrow \mu\pm$, $1.2<|\eta|<2.4$) :

Trigger upgraded, first data from 2011

RPC-1 North and RPC-3 North

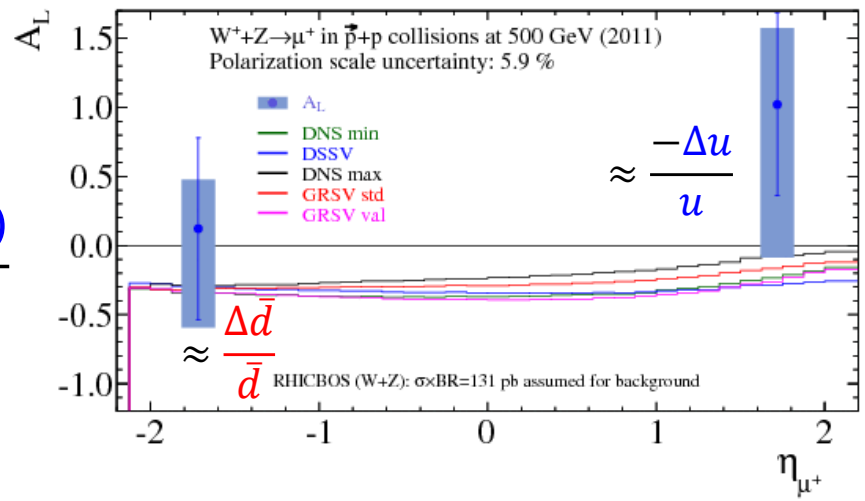
- **First measurement of $W \rightarrow \mu$ by PHENIX in 2011 ($1.2 < |\eta_\mu| < 2.4$)**

$\vec{p}$ ⟶ (towards +η)

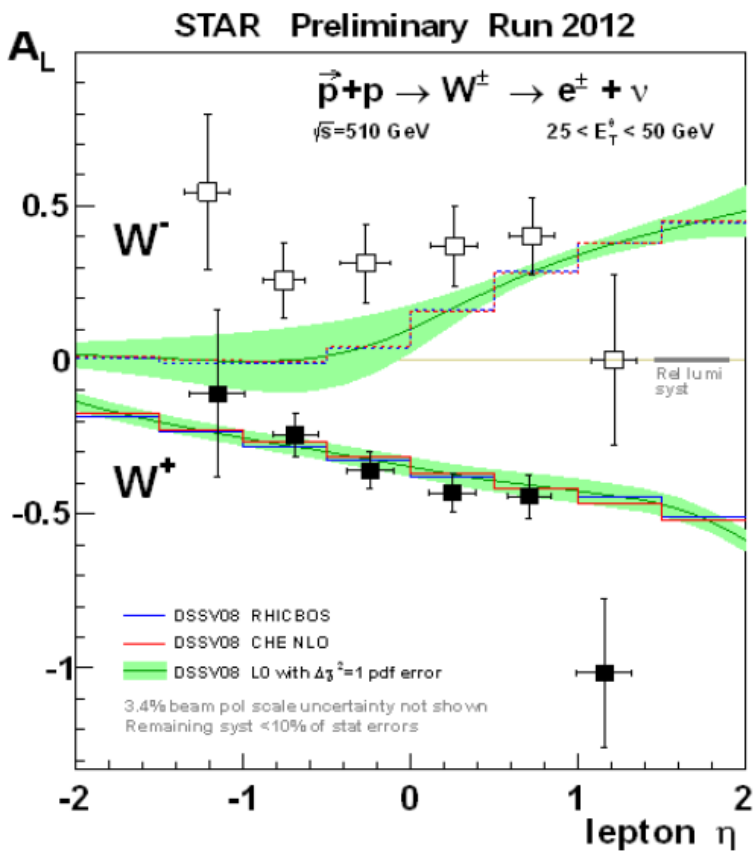


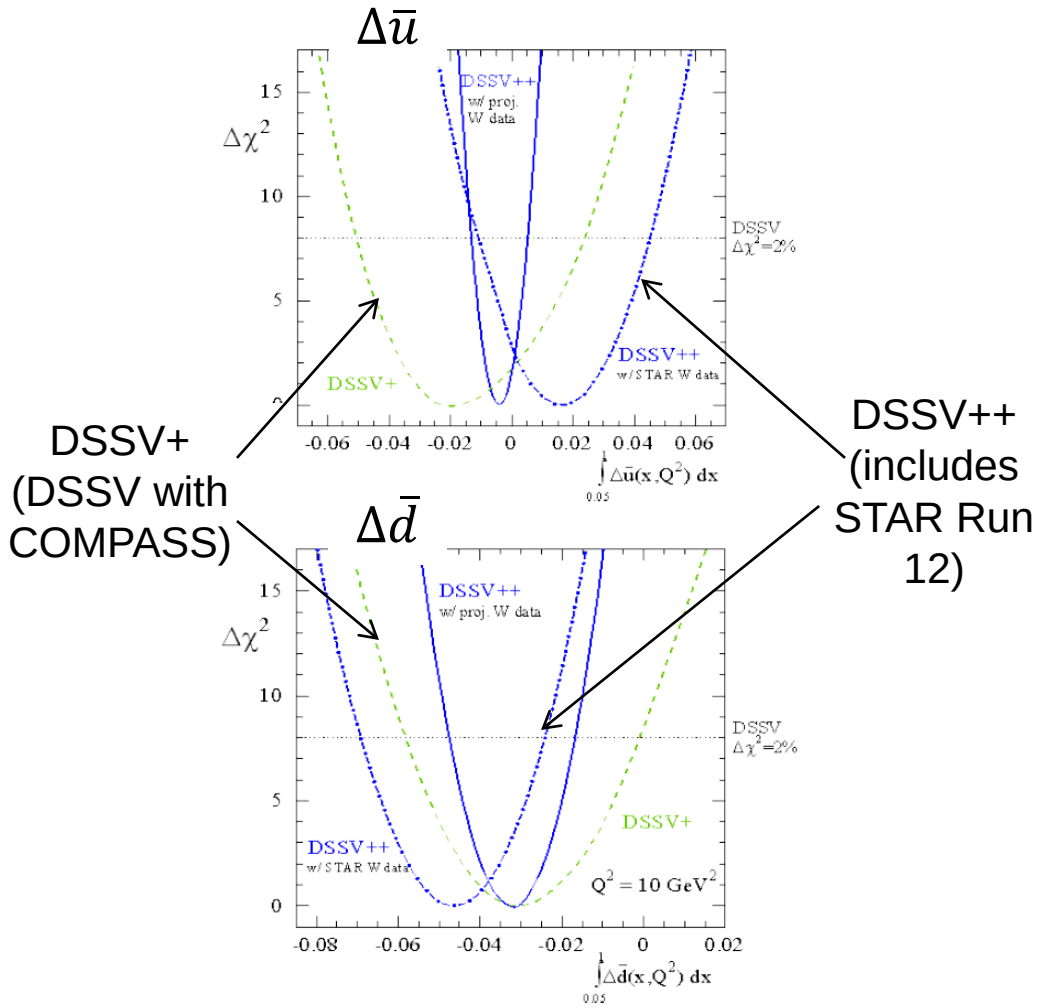
$$A_L{}^{W^-} = \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

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



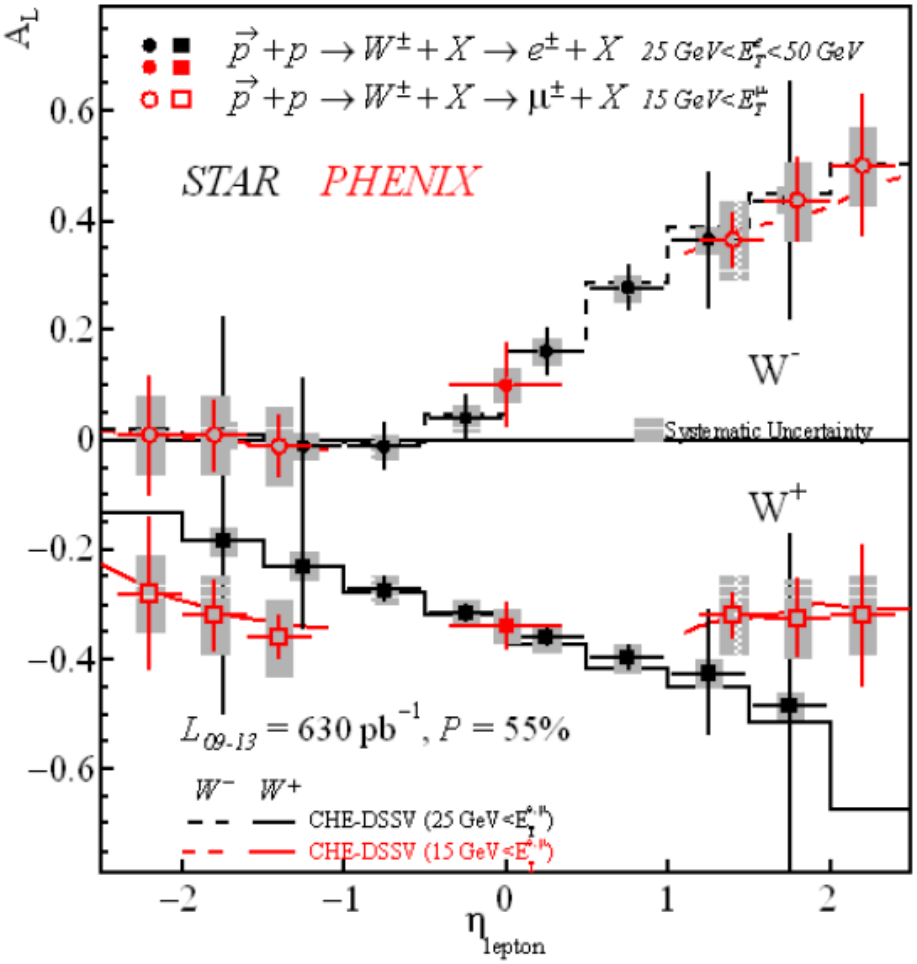
- **STAR preliminary A_L for Run 12 already has sizeable effect on DSSV fits**

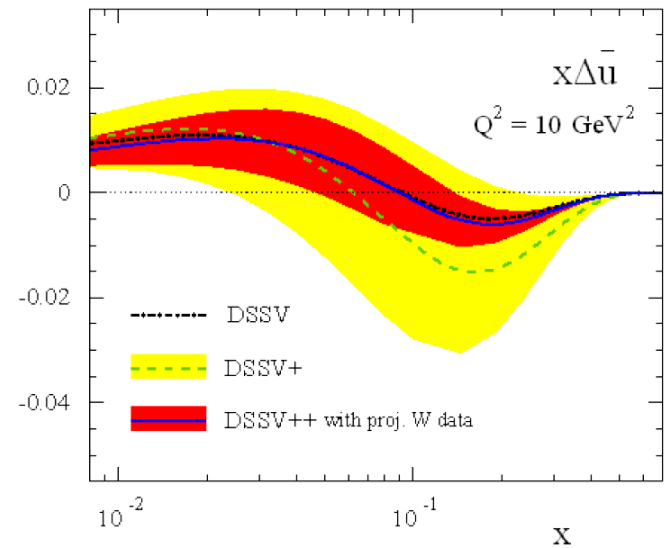


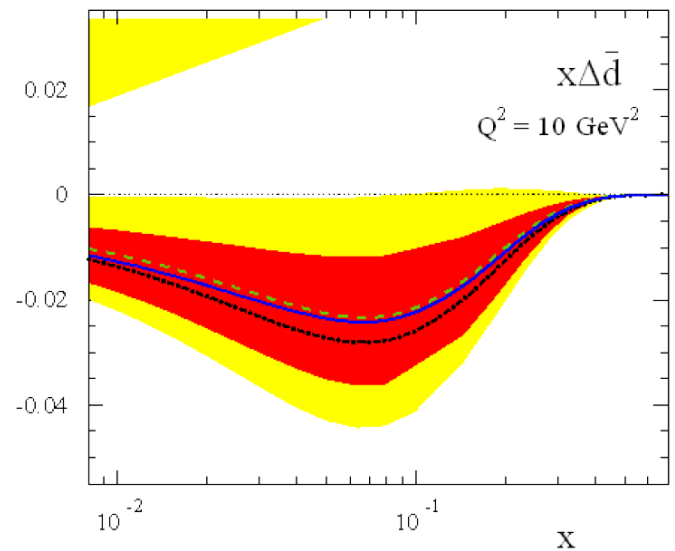


- **Run 13 goal: finish W program by reaching total $\int Ldt = 630\ pb^{-1}$**

Projections including expected data in 2013





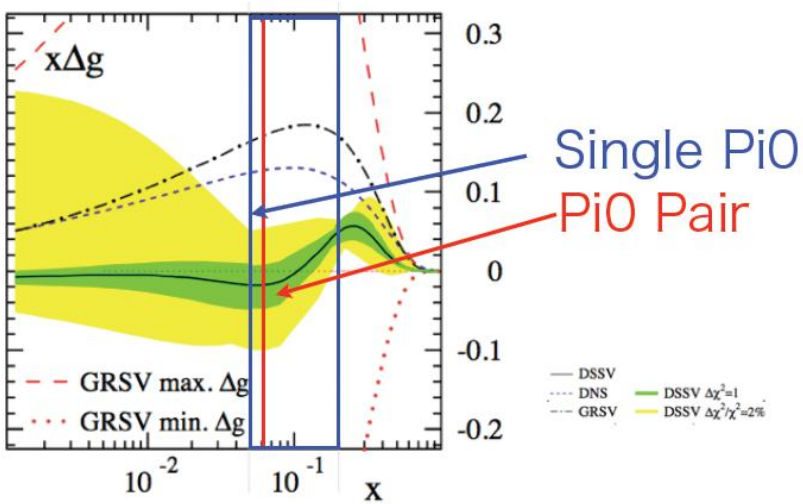


- **The PHENIX and STAR collaborations are making important contributions to our understanding of the helicity structure of the nucleon**

- **A_{LL} measurements provide best constraints to ΔG for QCD analyses**
  - For the first time we see evidence of a **non-zero gluon polarization**
  - Large dataset from Run 13 at $\sqrt{s}$ of 510 GeV will lead to precise measurement of ΔG at 0.05 < x < 0.2
  - A_{LL} for correlations and at forward rapidity will reduce uncertainties in the shape and integral of Δg(x) while broadening the coverage in x down to ~10^{-3}

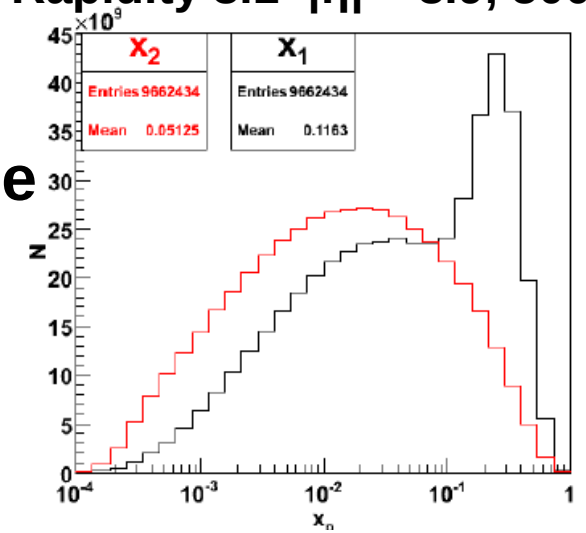
- **W program at RHIC will lead to substantial improvement in the understanding of the sea quark polarization in the near term with the expected statistics from Run 13**
  - The STAR A_L from Run 12 has already provided DSSV with a stronger constraint on the sea quark polarization

Backup

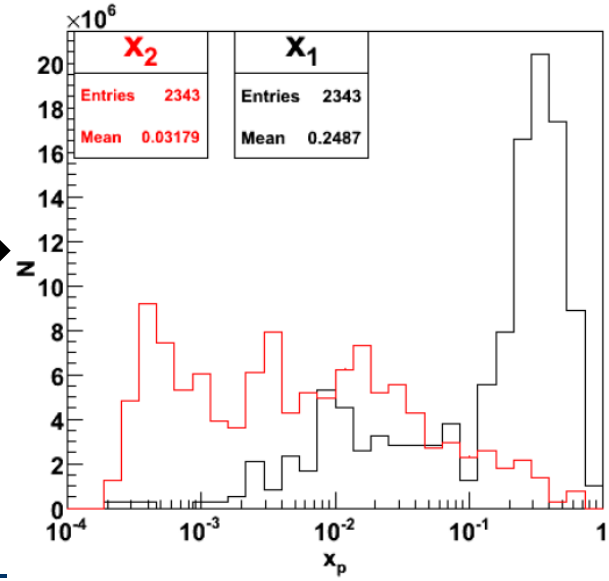


Fwd–Rapidity 3.1<|η| < 3.9, 500 GeV

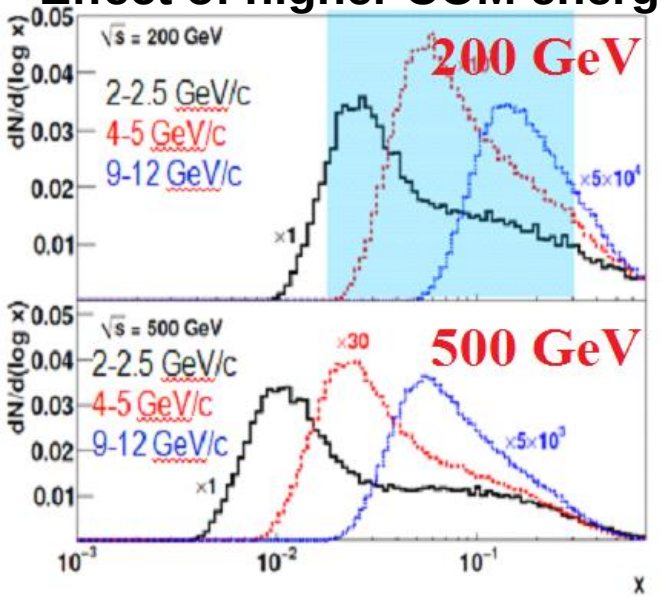
Single π^0→



Di-π^0→

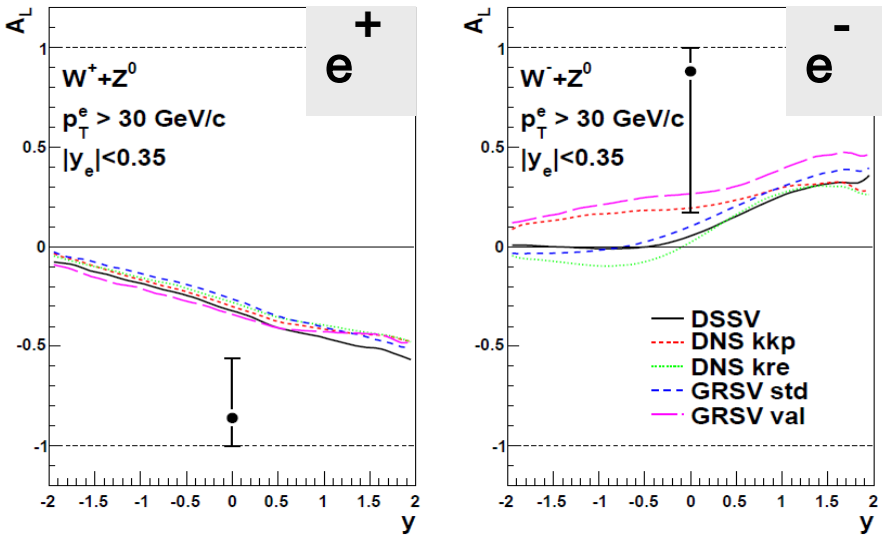


Effect of higher COM energy

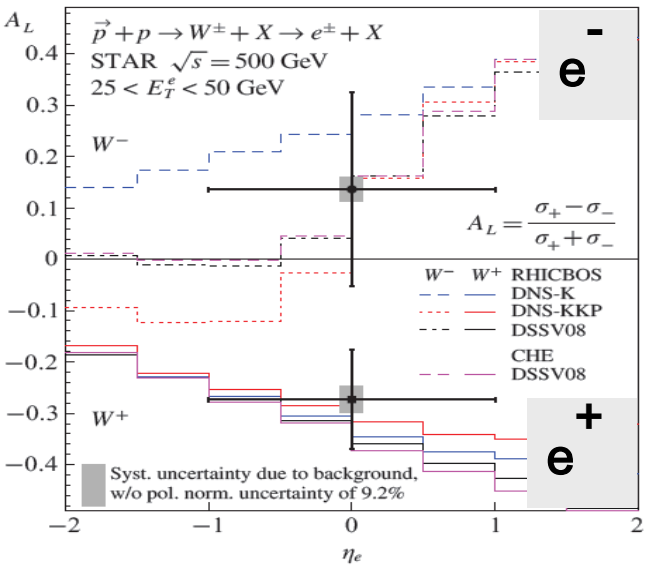


Central region: $W^{\pm} \rightarrow e^{\pm}$ from Run9

PHENIX $A_L^{e+/e-}$



STAR $A_L^{e+/e-}$



P=0.39 L=8.6/12 pb-1 in PHENIX/STAR

PHENIX: PRL106, 062001 (2011)
STAR: PRL106, 062002 (2011)