PHENIX

CHARM 2015

Inclusive J/ψ Longitudinal Double Spin Asymmetry Measurements at Forward Rapidity in p+p Collisions at PHENIX

Haiwang Yu (Peking University) for PHENIX Collaboration

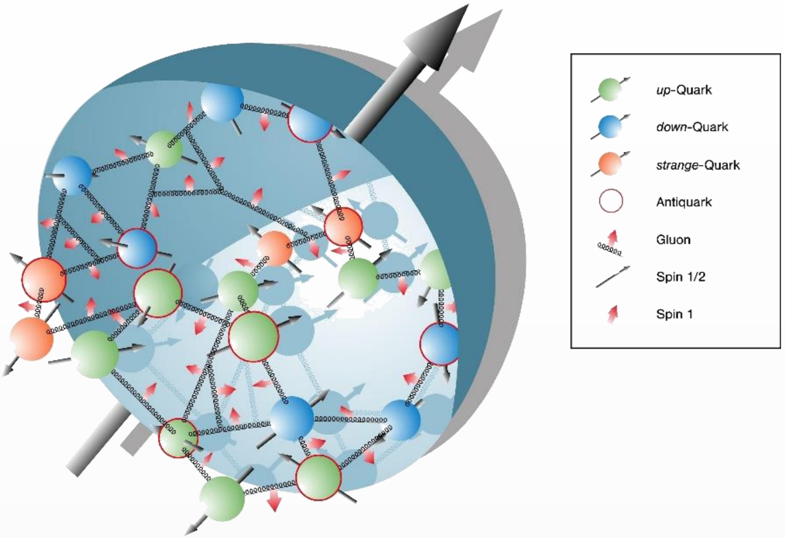
The 7th International Workshop on Charm Physics (CHARM 2015)
Wayne State University, Detroit, Michigan
May 18-22, 2015.

Outline

- Proton Spin Structure
- Gluon polarization of the RHIC Spin Program
- J/ψ double longitudinal asymmetry (A_{LL}) at forward rapidity

Proton Spin Structure

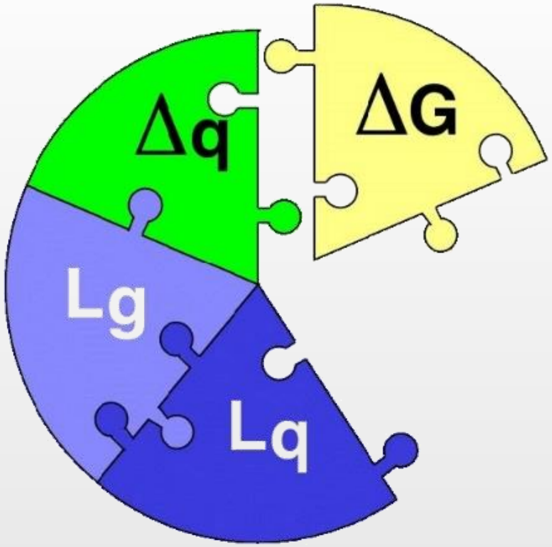
"Spin Puzzle"



Decomposition of the Proton Spin

Manohar-Jaffe sum rule:

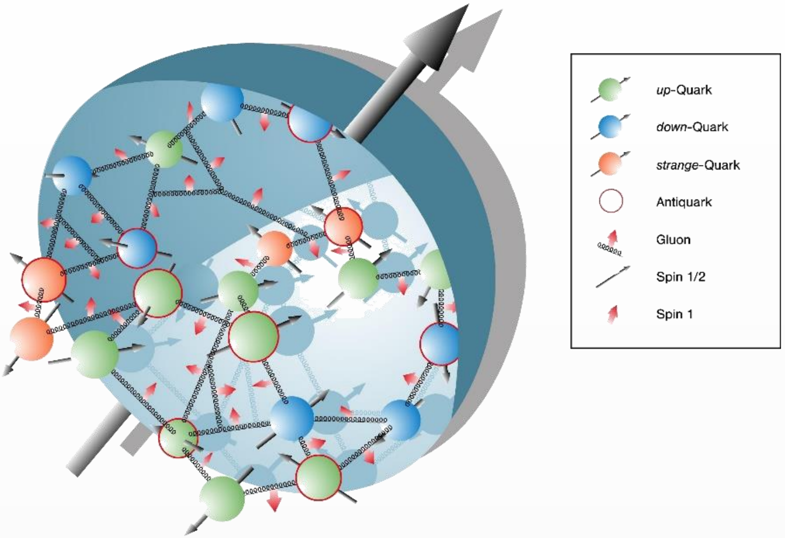
$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



In 1980's experiment by the European Muon Collaboration (EMC) discovered that quarks only carry a small portion of the proton spin.

Current knowledge from Polarized Deep Inelastic Scattering (DIS) and Semi-inclusive DIS (SIDIS) Measurements:
$\Delta\Sigma = \sim 30\%$

Proton Spin Structure
"Spin Puzzle"



Decomposition of the Proton Spin

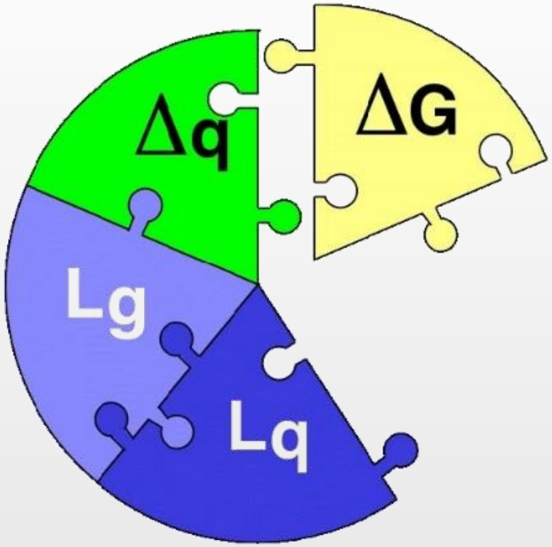
Manohar-Jaffe sum rule:

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Focus on this part today

In 1980's experiment by the European Muon Collaboration (EMC) discovered that quarks only carry a small portion of the proton spin.

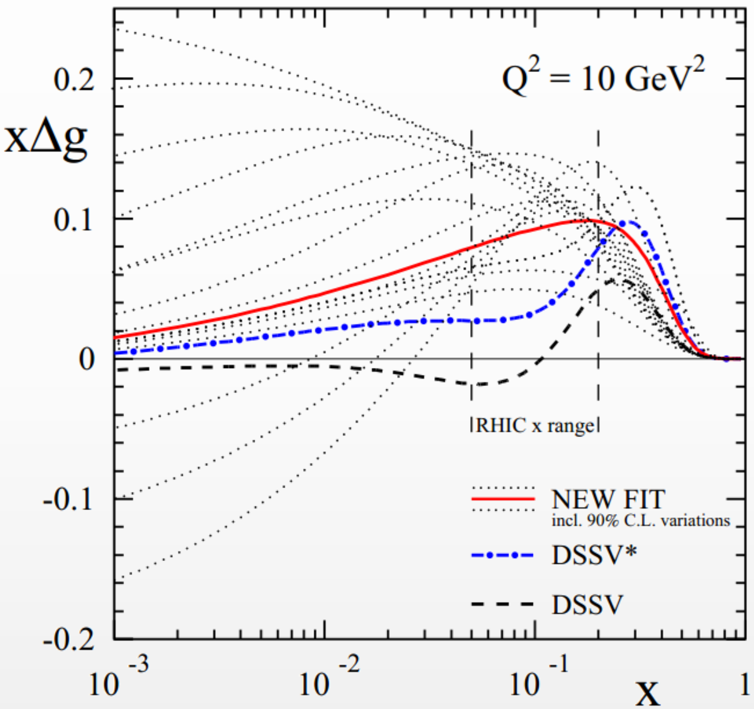
Current knowledge from Polarized Deep Inelastic Scattering (DIS) and Semi-inclusive DIS (SIDIS) Measurements:
$\Delta\Sigma = {\sim}30\%$



RHIC Spin Program
Gluon polarization

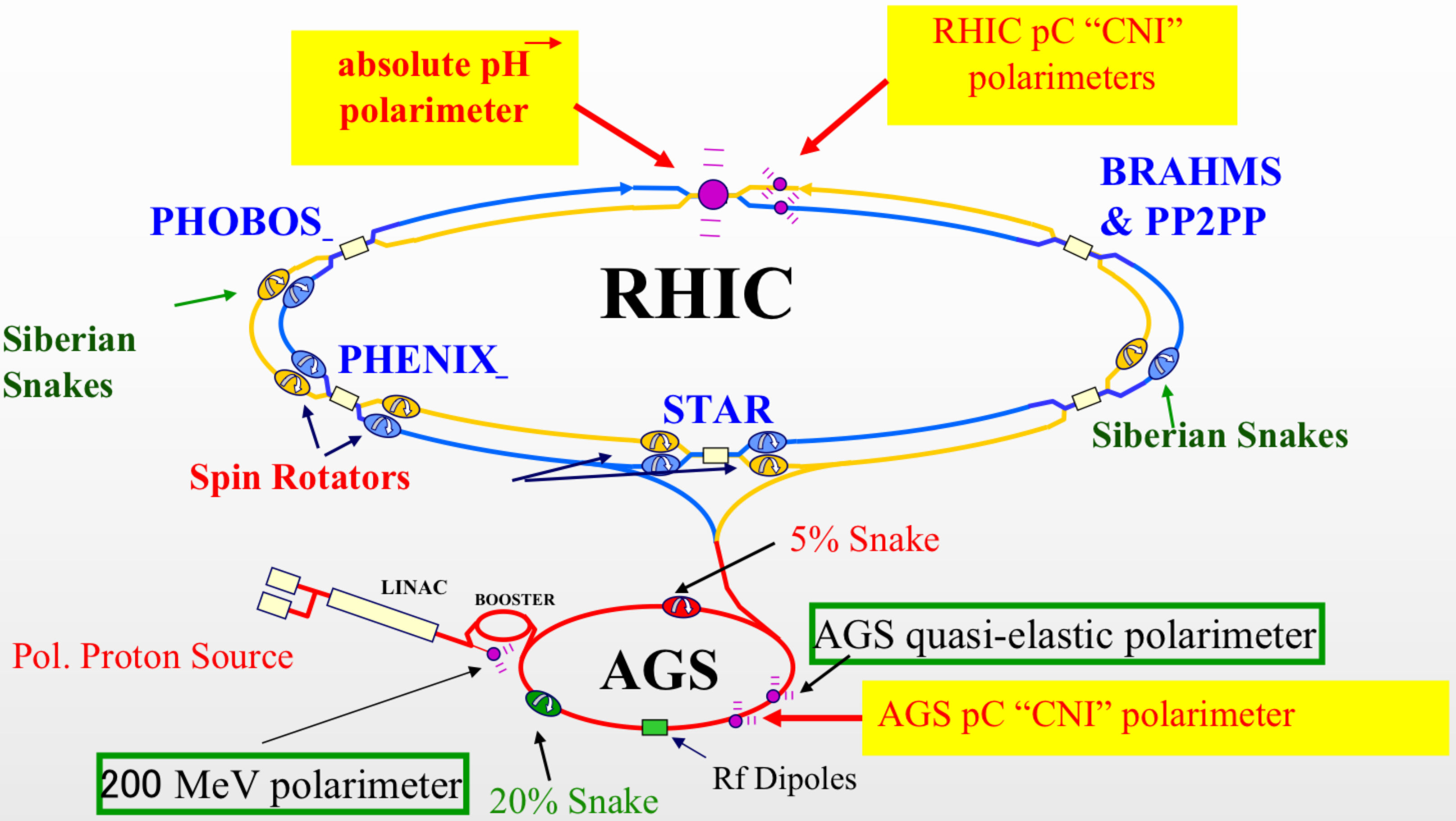
2014 DSSV Global Fit

- Including 2009 RHIC data sets, the 2014 DSSV global fit suggests non zero polarization of gluons in the proton at intermediate x range (0.05~0.2).
- Yet at low x range, the errors of DSSV are still poorly constrained
- Measurements from forward rapidity needed.

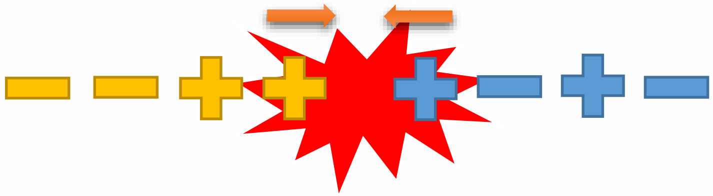


RHIC Spin Program

World's only polarized proton collider

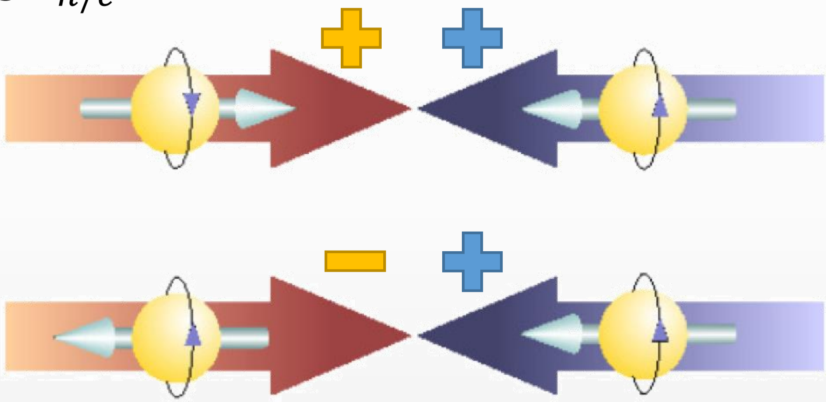


Double Longitudinal Asymmetry



Theoretically:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{h/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{h/c}}$$



Experimentally:

$$A_{LL} = \frac{1}{P_B P_Y} \frac{N^{++} - R\, N^{+-}}{N^{++} + R N^{+-}}$$

Where $P_{B,Y}$ is the polarization of Blue (Yellow) beam.

And R is the relative luminosity:

$$R = \frac{L^{++}}{L^{+-}}$$

RHIC Spin Program

Recent Longitudinal Runs

PHENIX Recent Longitudinal Runs:

Year	$\sqrt{s}$(GeV)	L(Pb^{-1})	P(%)	FoM(P^4L)
2003	200	0.35	27	0.0019
2004	200	0.12	40	0.0031
2005	**200**	**3.4**	**49**	**0.2**
2006	**200**	**7.5**	**57**	**0.79**
2006	62.4	0.08	48	0.0042
2009	500	10	40	0.26
2009	200	14	57	1.4
2011	500	16.7	48	0.88
2012	510	30.03	52	2.2
2013	**510**	**150**	**55**	**14**

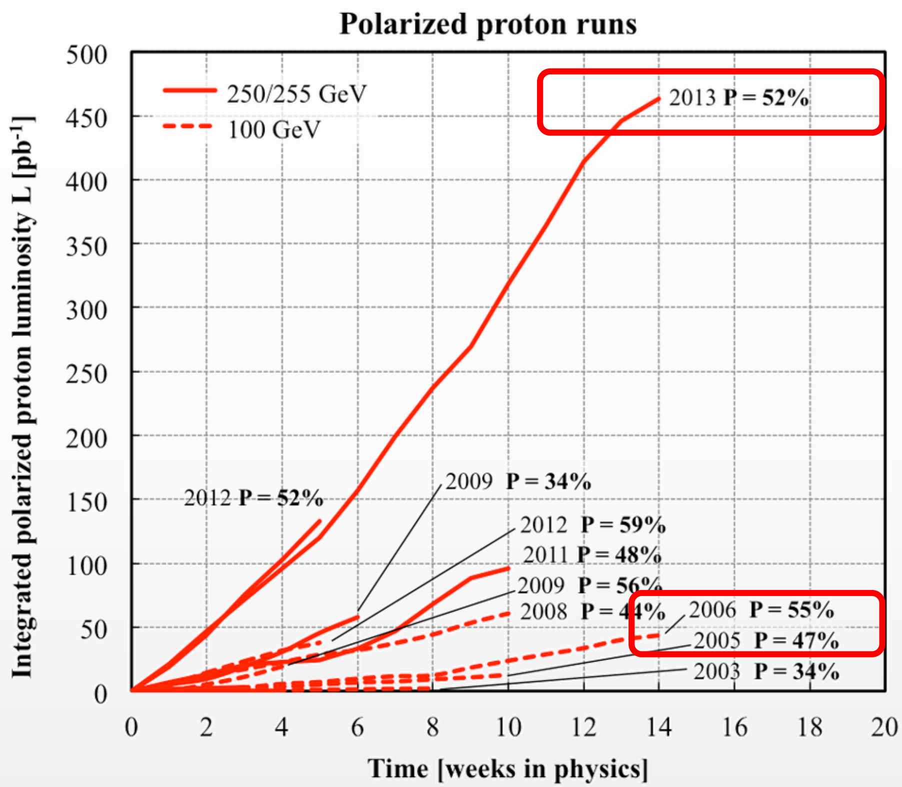


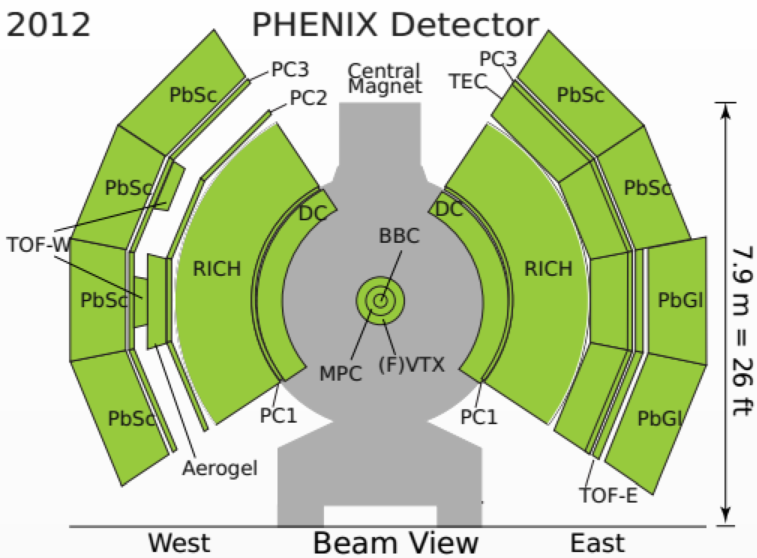
Figure of Merit:

High polarization is essential for effective asymmetry measurement:

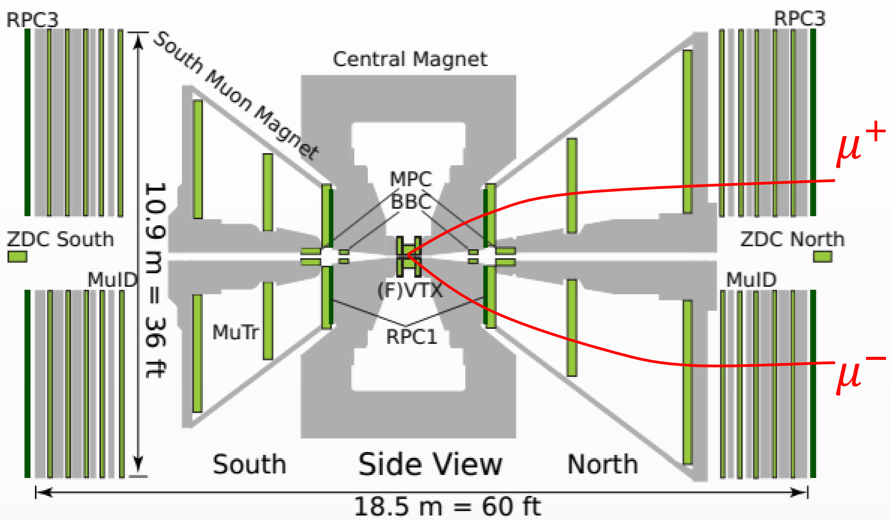
Single Spin Asymmetry: $L < P >^2$

Double Spin Asymmetry: $L < P >^4$

PHENIX Central Arm



Forward Muon Spectrometer



- Energy measured in EM Calorimeter (PbSc + PbGl)
- Momentum/Tracking in Drift Chamber (DC) + Silicon Barrel (VTX)
- PID with Ring Imaging Cherenkov Counter (RICH)
- $|\eta| < 0.35$, $\Delta\phi = 2 \times \frac{\pi}{2}$

- Silicon strip tracking and vertexing (FVTX)
- Momentum measured in cathode strip tracking chambers (MuTr)
- $\mu^{\pm}$ ID from Iarocci tubes interleaved with steel absorbers (MuID)
- $1.2 < |\eta| < 2.2$, $\Delta\phi = 2\pi$

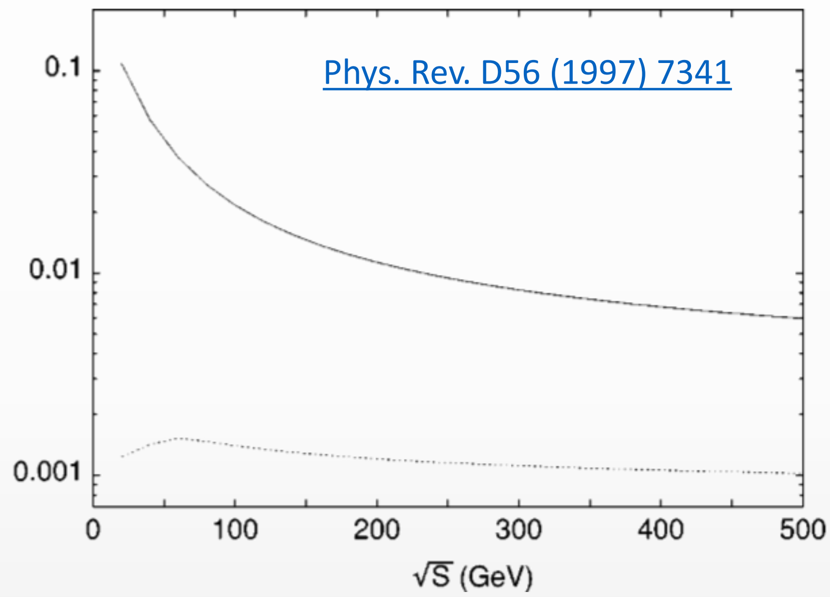
J/ψ A_{LL} @ forward rapidity

J/ψ production at RHIC

At RHIC energies J/ψ production is dominated by gluon-gluon fusion.

The A_{LL} for J/ψ can be written (LO):

$$A_{LL} = \frac{\Delta\sigma}{\sigma} \propto \frac{\Delta g(x1)}{g(x1)} \frac{\Delta g(x2)}{g(x2)}$$



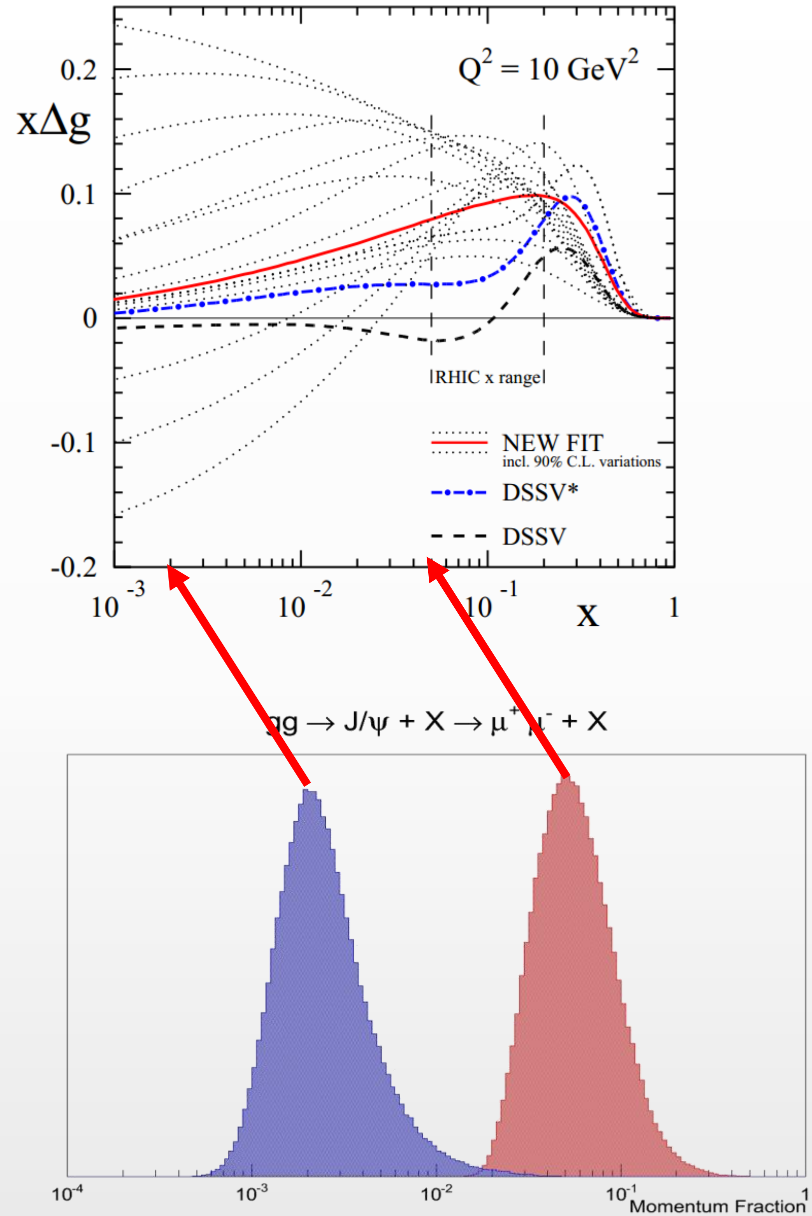
$q\bar{q}$ to gg ratios of unpolarized (solid) and polarized (dashed) processes

$J/\psi\ A_{LL}$ @ forward rapidity

Bjorken x range

Benefits of Forward Rapidity

- At forward rapidity the x distributions of the two gluons are at very different region
- Instead of probing $\sim(\Delta g/g)^2$ we are probing $\frac{\Delta g(x1)}{g(x1)}\frac{\Delta g(x2)}{g(x2)}$
- High-x gluon sits in the x-range where RHIC Run9 data already has constraints on the Δg
- Therefore, this forward $J/\psi \to \mu^+\mu^-\ A_{LL}$ gives sensitivity to possible sign change in Δg and cleanly accesses down to $x \sim 2 \times 10^{-3}$



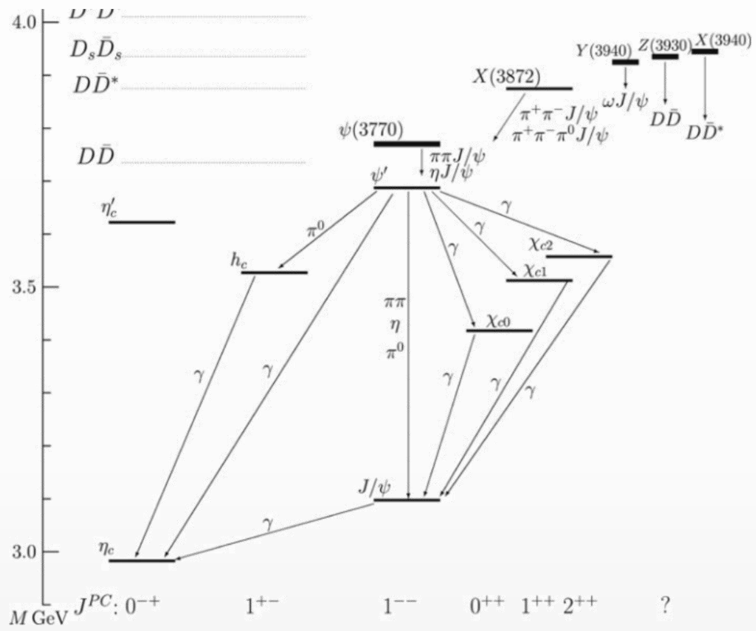
from Pythia simulation

J/ψ A_{LL} @ forward rapidity

Excited states feed-down

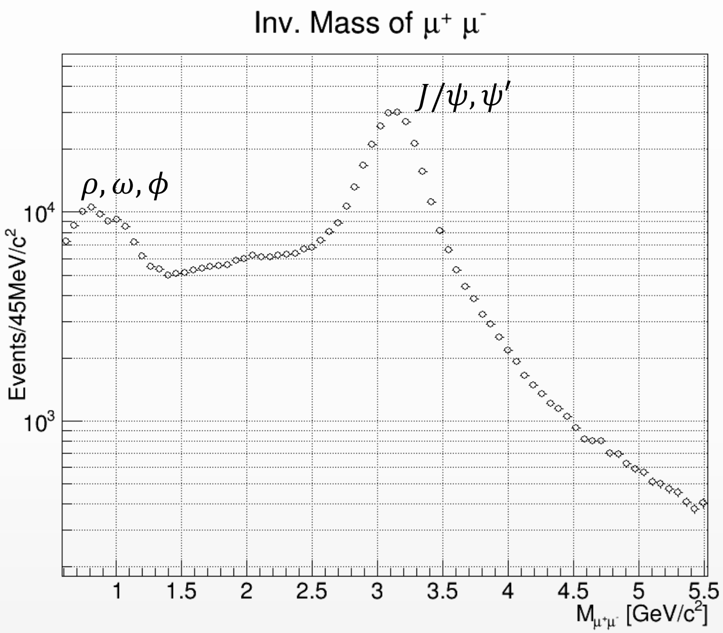
Charmonium

- Except for J/ψ's, excited charmonium states are also generated in RHIC p+p collisions
- χ_c and ψ' feed-down forms a sizable portion
    - Phys. Rev. D 85, 092004 (2012)
- ψ' overlaps with J/ψ
- Different calculating schemes gave different Δg depends for each excited states (Phys. Rev. D 56, 7341 (1997))
    - Good test bed for different aspects of NRQCD factorization and scaling



$J/\psi\ A_{LL}$ @ forward rapidity
Event and track selection

- Vertex selection: |BBC_Z|<30 cm
- common PHENIX muon tracks quality cuts including:
  - from same arm
  - track matching between muon tracker and identifier
  - penetrating muon candidates cuts
  - etc.
- RPC timing cut are applied to guarantee J/ψ's are from the right bunch crossing



$\mu^+\mu^-$ *inv. mass spectrum* after event and μ track selection
sideband region is used to estimate background asymmetry

$J/\psi\ A_{LL}$ @ forward rapidity

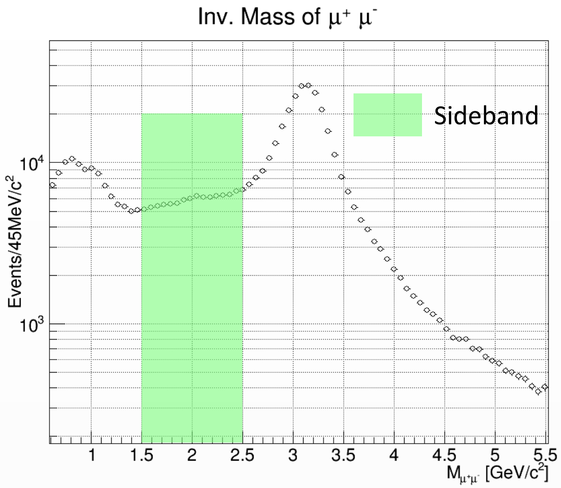
measurement procedure

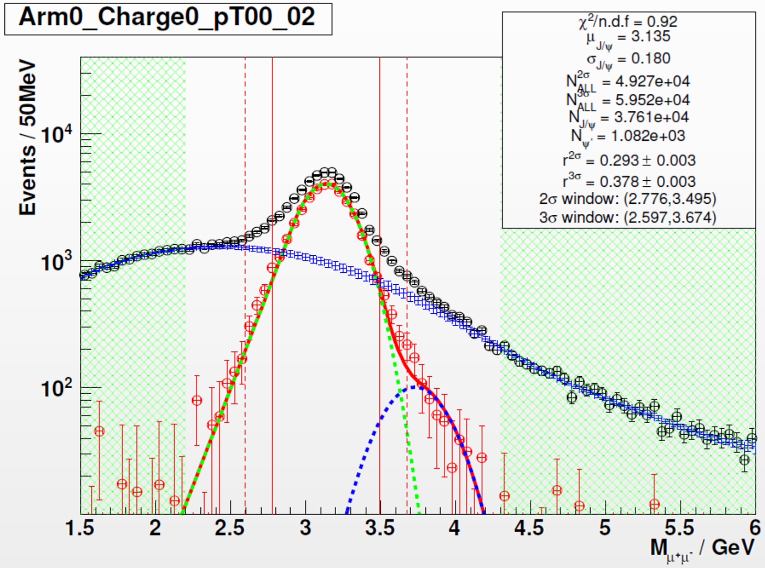
Outline

- Analyze south and north arm separately, and divide data from each arm into 3 p_T bins. So 6 subsets total.
- Fit each subsets for 2σ J/ψ mass window and background fraction "r".
  - CB shape for J/ψ, Gaussian for ψ'
  - Gaussian Process Regression (GPR) for background shape
- Sideband region is defined as $M_{\mu\mu} \in [1.5GeV, 2.5GeV]$
- Calculate $A_{LL}^{incl.}$ in the 2σ J/ψ mass window
- Estimate the background asymmetry from a sideband

$$A_{LL}^{J/\psi} = \frac{A_{LL}^{incl.} - r * A_{LL}^{BKG.}}{1-r}$$

$$\Delta A_{LL}^{J/\psi} = \frac{\sqrt{(\Delta A_{LL}^{incl.})^2 + r^2 * (\Delta A_{LL}^{BKG.})^2}}{1-r}$$

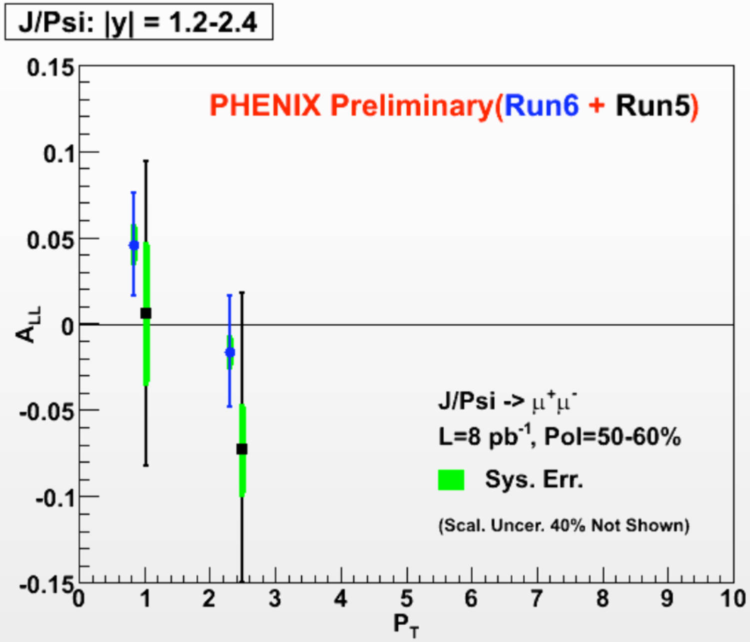




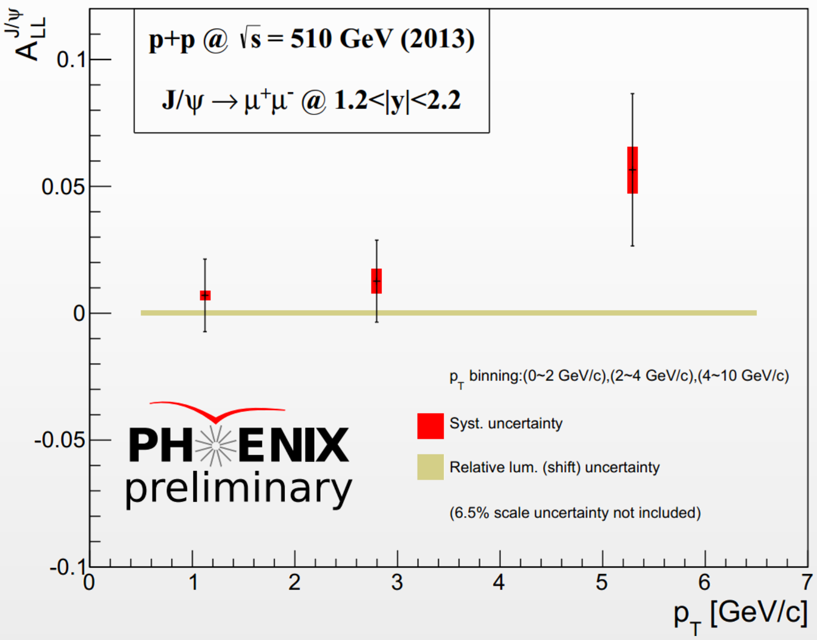
Gaussian Process Regression (GPR) background fraction extraction

$J/\psi\ A_{LL}$ @ forward rapidity
recent results

$$pp \to J/\psi + \mathrm{X} \to \mu^+ + \mu^- + X$$
$$@\sqrt{s} = 200GeV$$



$$pp \to J/\psi + \mathrm{X} \to \mu^+ + \mu^- + X$$
$$@\sqrt{s} = 510GeV$$



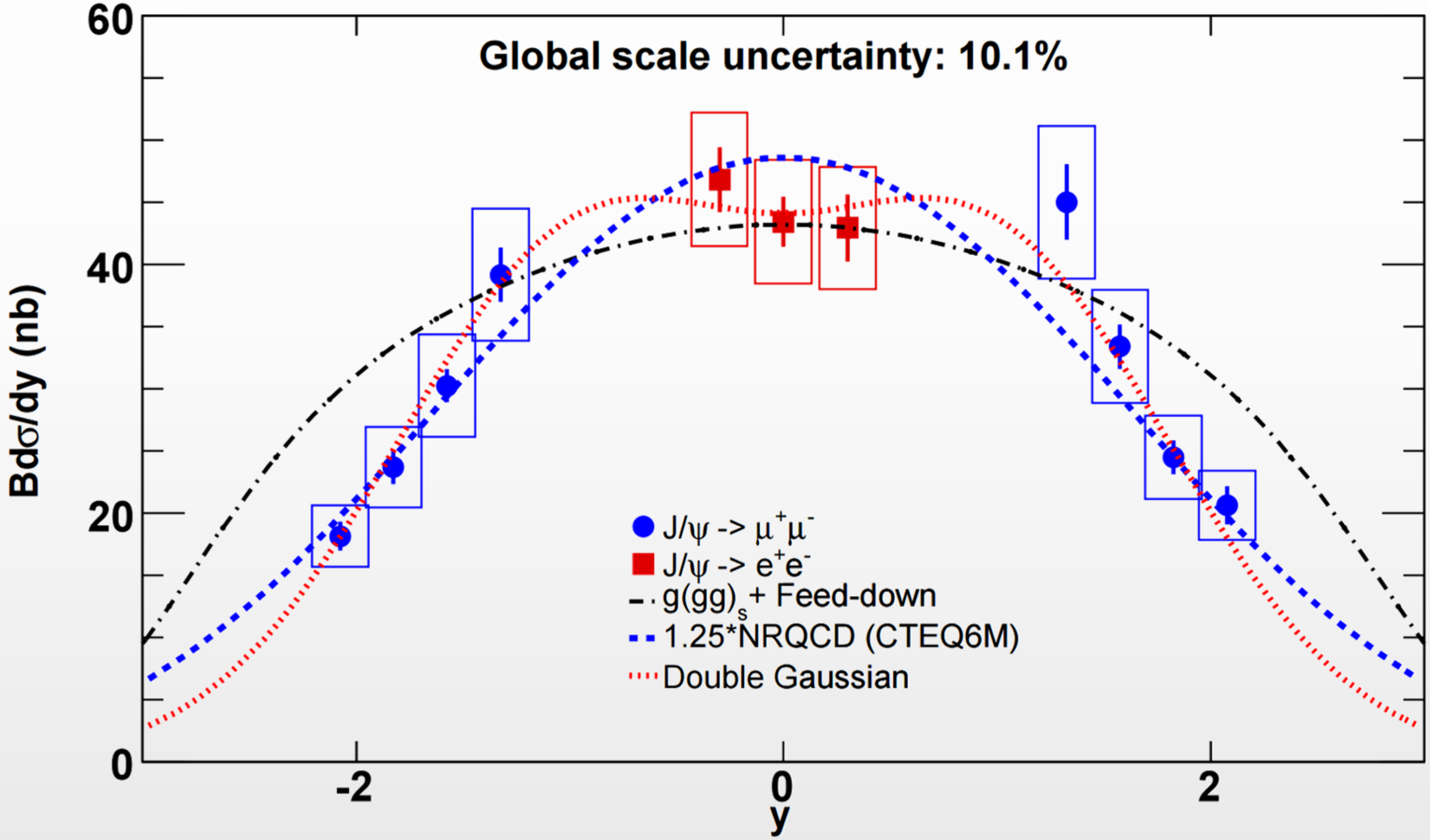
Summary & outlook

- Including data from RHIC spin program, the recent DSSV global analysis indicates non-zero ΔG for x larger than 0.05.
- We measured the J/ψ A_{LL} for 200GeV and 510GeV at forward rapidity which provides access to the small-x region (~10^{-3})
- We encourage theory community to incorporate this data in future NLO fits.
- The J/ψ cross-section measurement @ 510 GeV is undergoing.

Backup slides

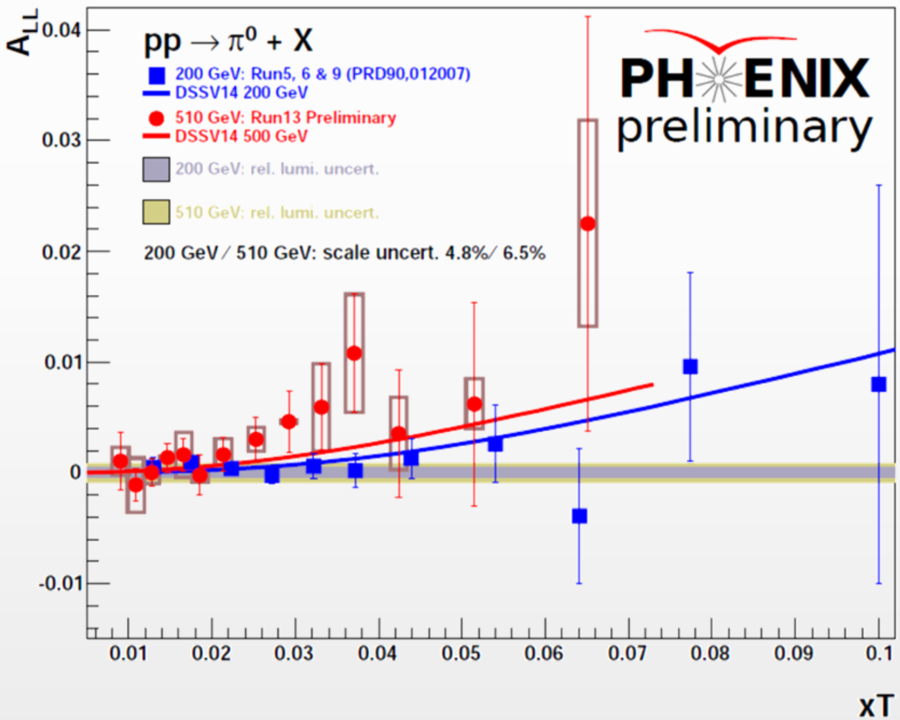
J/ψ production vs. rapidity at 200GeV

Phys. Rev. Lett. 98:232002, 2007



PHENIX 2013 pi0 A_{LL} Measurement

H. Guragain, DIS 2015



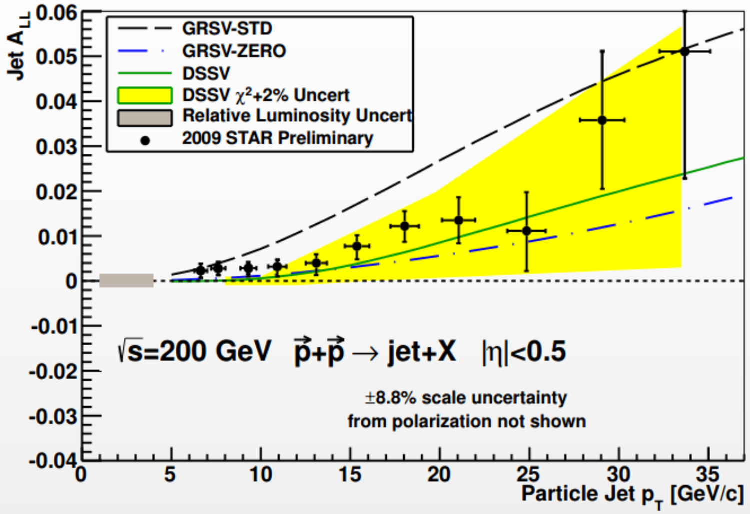
- Data gives larger asymmetry compared to previous results.
- Also, Data favor larger A_{LL} than the DSSV best fit predicts.

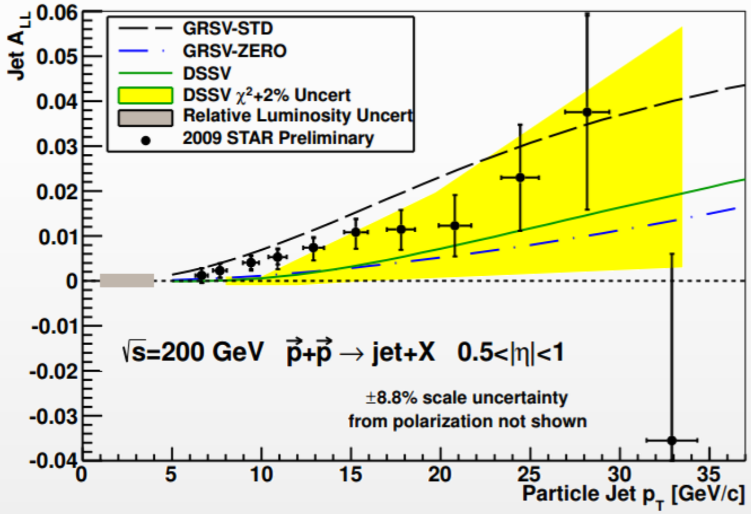
Here:

$$x_T = 2\frac{p_T}{\sqrt{s}}.$$

Star 2009 Inclusive Jet A_{LL} Measurement

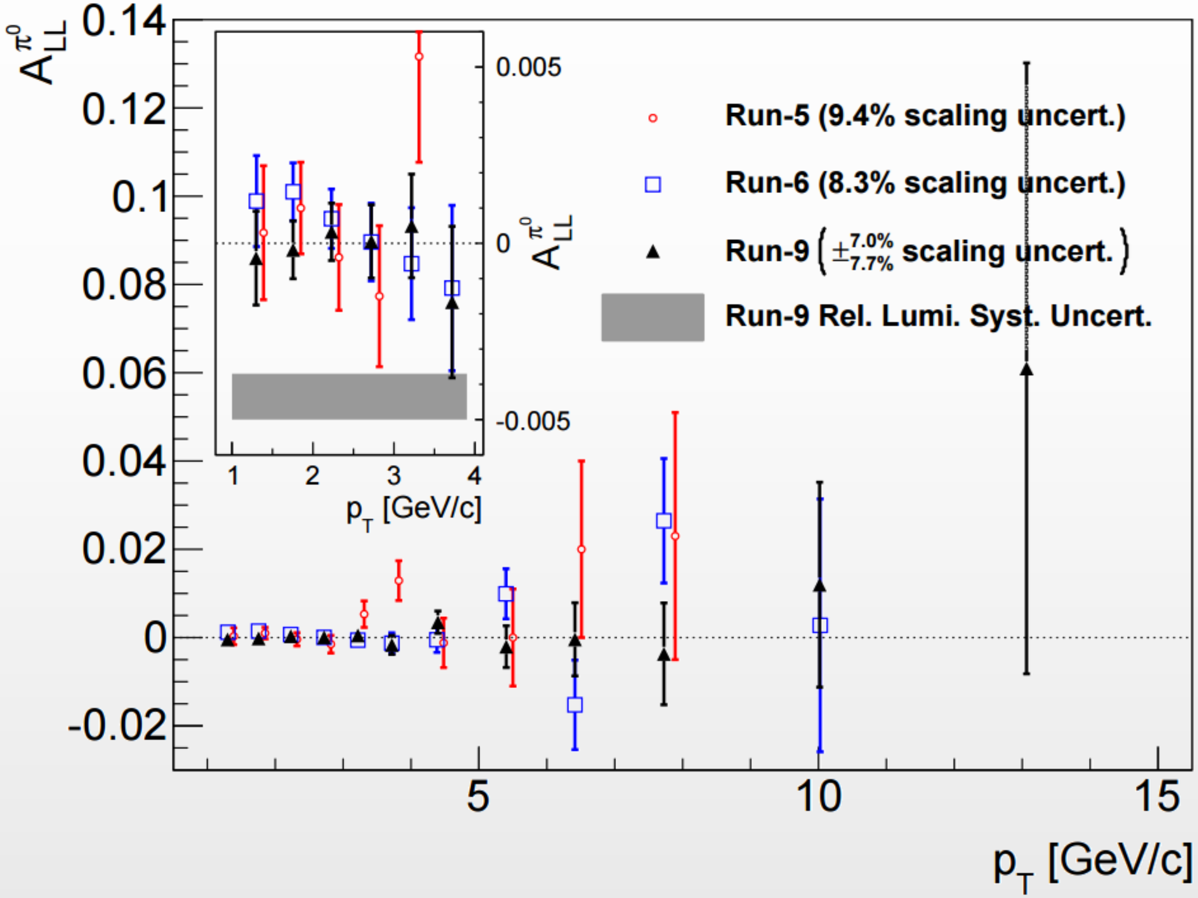
arXiv:1303.0543





PHENIX 2009 π^0 A_{LL} Measurement

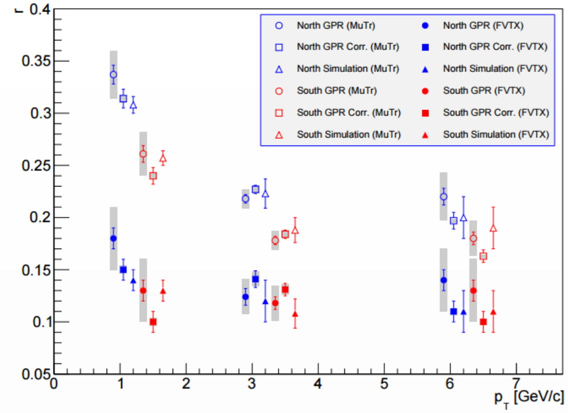
arXiv:1402.6296.

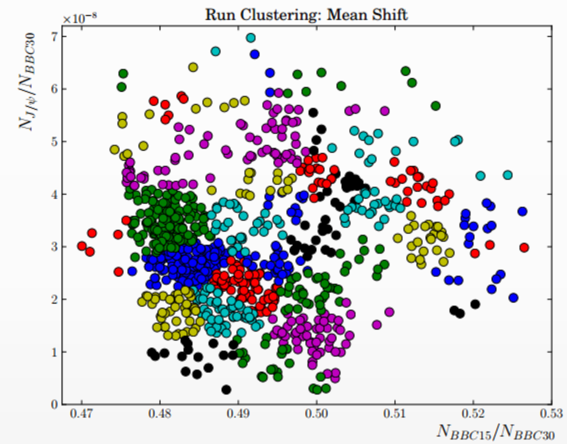


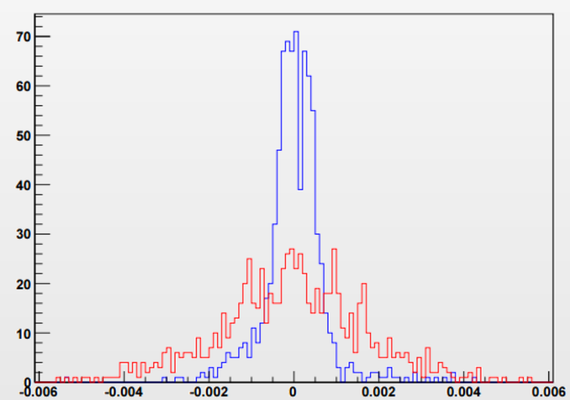
$J/\psi\ A_{LL}$ @ forward rapidity

Systematic uncertainty

- Background fraction "r", using different fitting method:
  - Gaussian Progress Regression
  - Simulation driven
  - Polynomial background etc.
- Different run clustering:
  - Luminosity and trigger eff. based clustering using mean shift algorithm
  - Fill-by-fill clustering
  - Sum all runs in one group
- Asymmetry from relative luminosity measurement

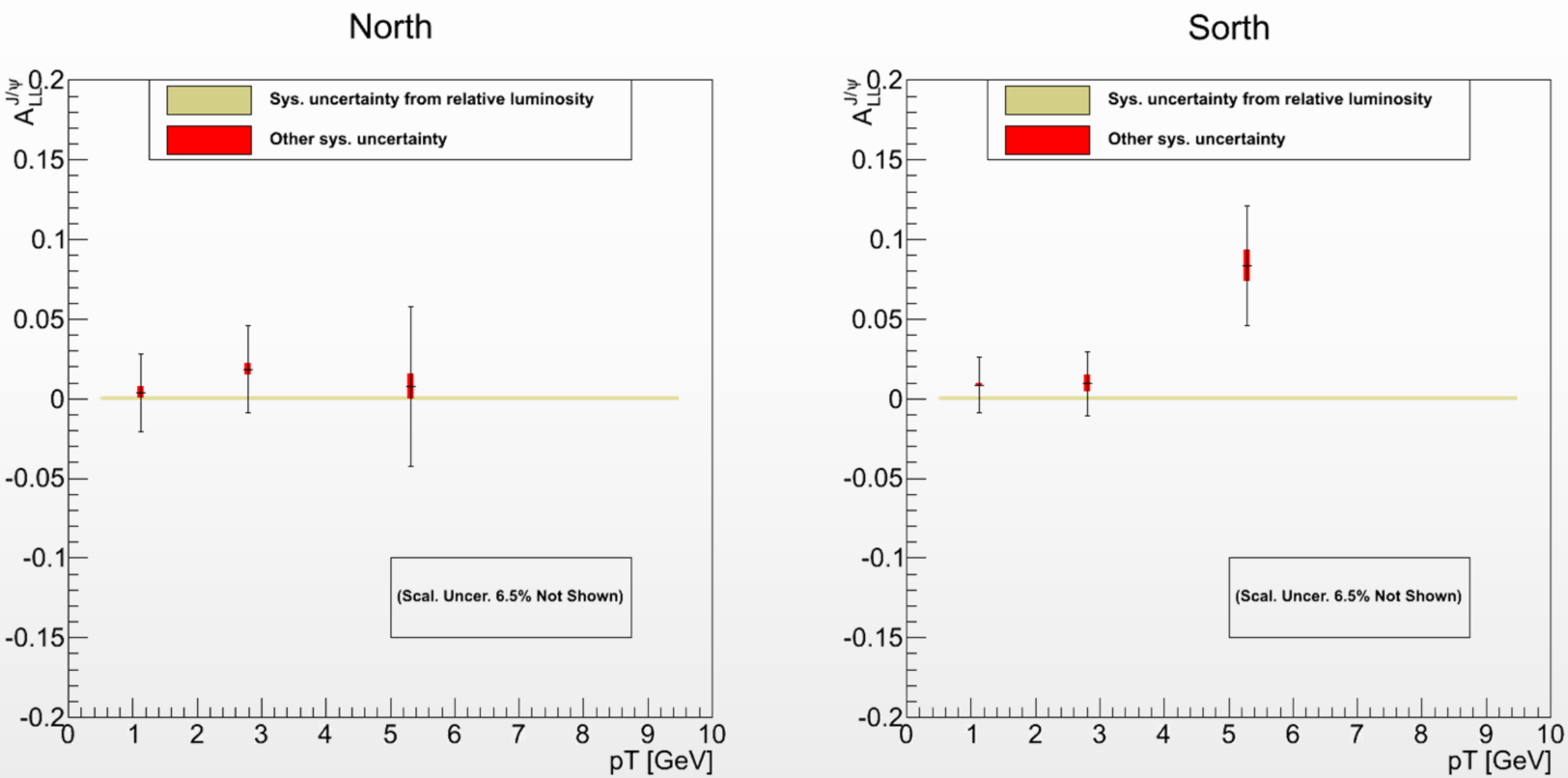






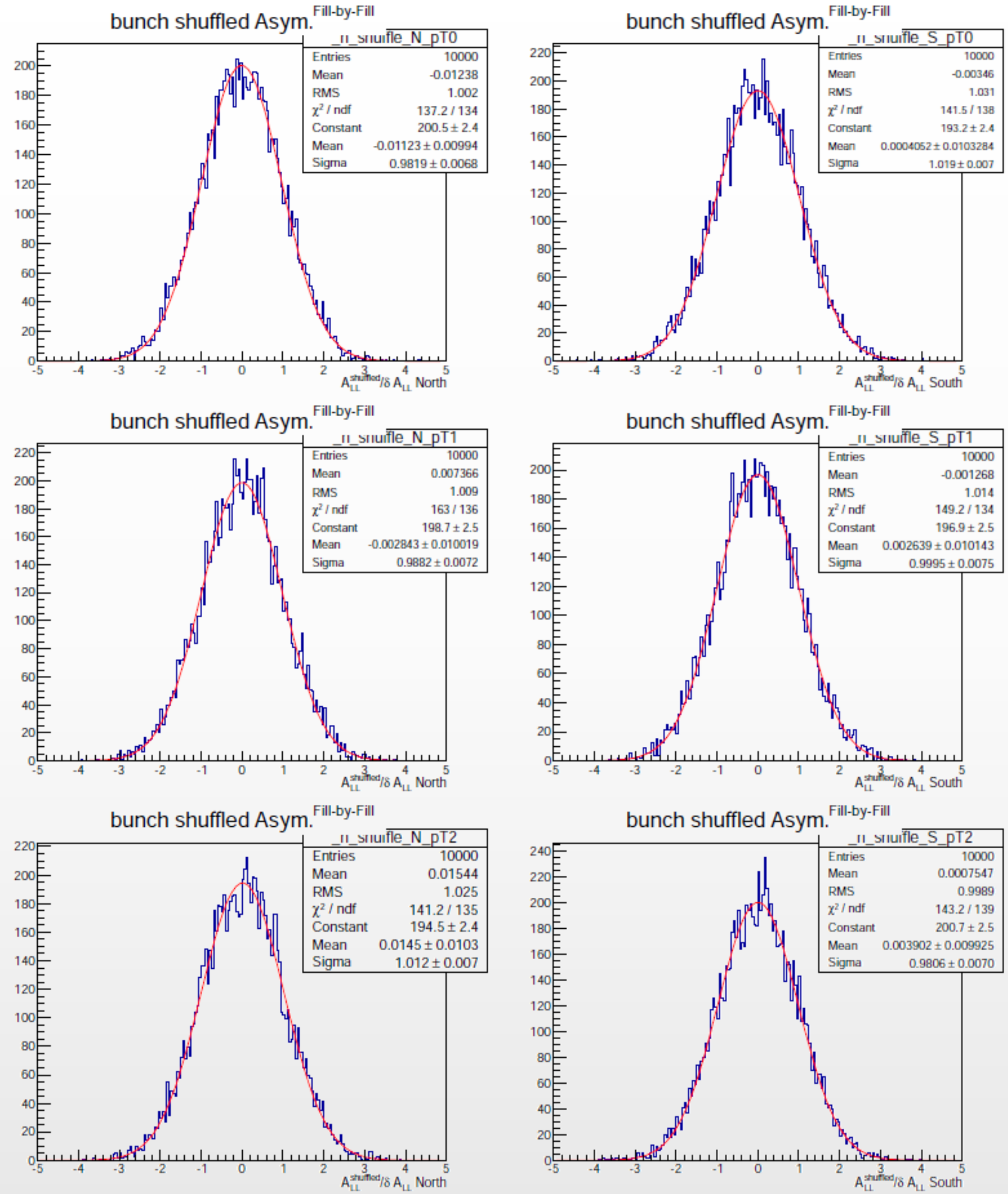
J/ψ A_{LL} result for North and South Muon arm separately

result based on 2013 RHIC 500GeV p+p run data set



bunch shuffling

The fact that the normalized RMS close to 1, indicates that all other non correlated bunch-to-bunch and fill-to-fill systematic errors are much smaller than the statistical errors.



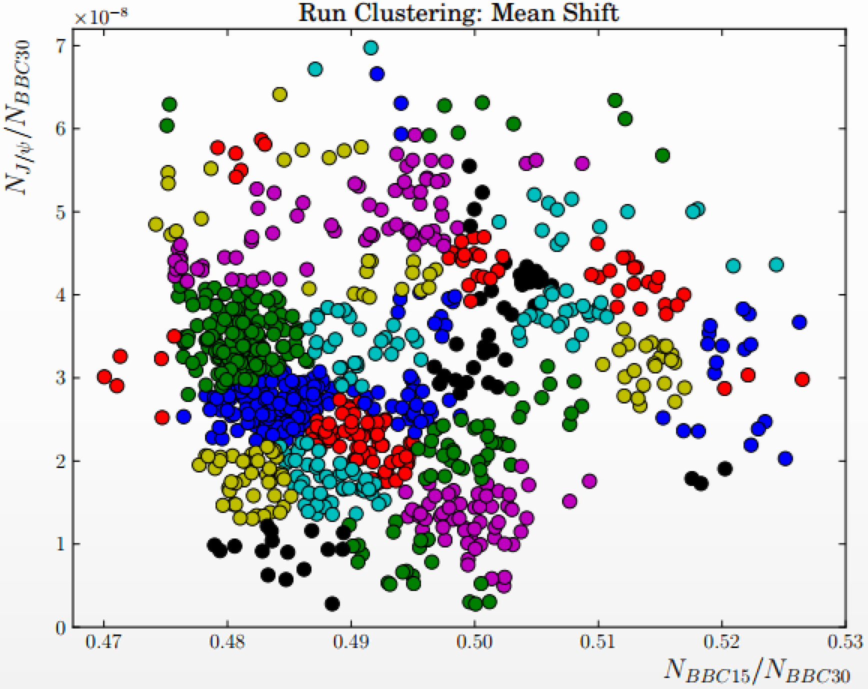
Run Clustering

Quantifying Stability

- Trigger: number of J/ψ candidates per minimum bias trigger
- Vertex: ratio of BBC15 and BBC30

Clustering

- Mean Shift algorithm
- Estimates number of feature sets and populations
- Use luminosity weighted average polarization for subset asymmetries



More information

D. Comaniciu, V. Ramesh, and P. Meer. Mean shift: A robust approach towards feature space analysis. IEEE Trans. on Pattern Analysis and Machine Intelligence, 24(5):603–619, 2002.

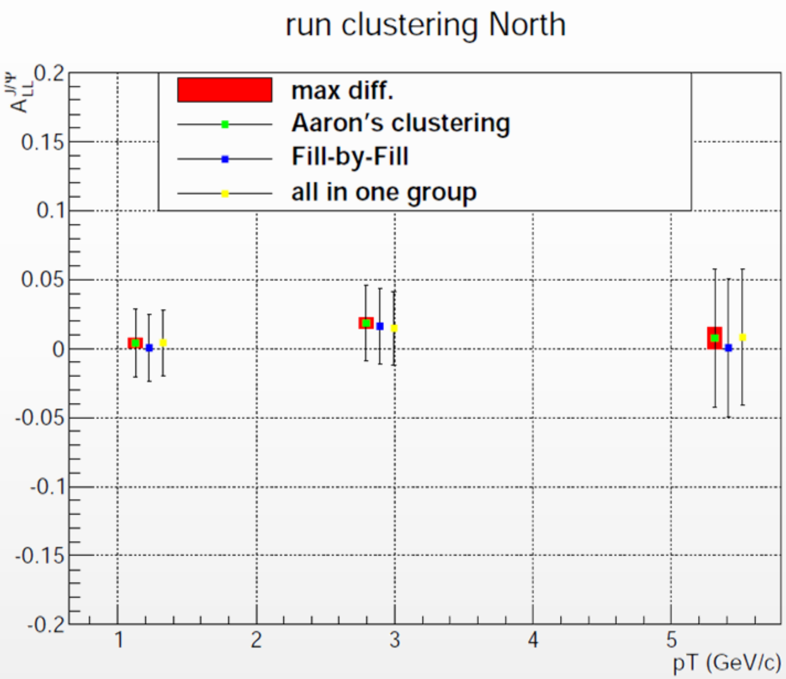
Ground and excited state charmonium production in p+p collisions at √s=200 GeV

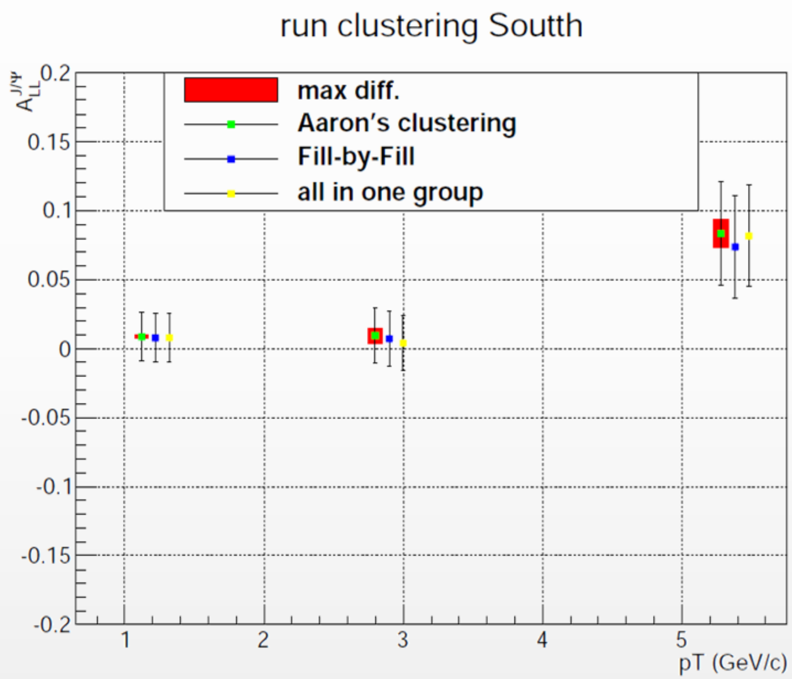
Phys. Rev. D **85**, 092004 (2012)

VII. SUMMARY AND CONCLUSIONS

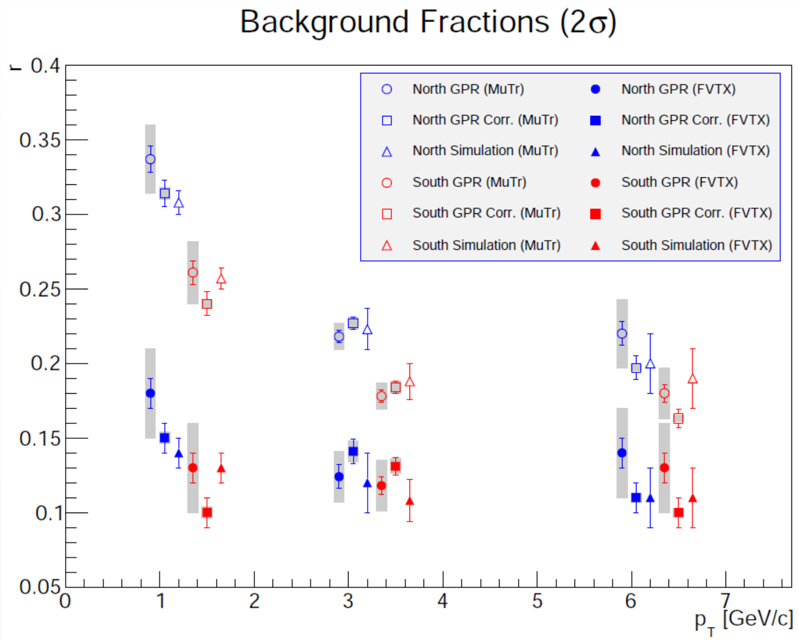
In conclusion, we have measured the yields of the three most important charmonium states in $p+p$ collisions at $\sqrt{s} = 200$ GeV, where gluon fusion is expected to be the dominant production process. The rapidity dependence of J/ψ supports the use of CTEQ6M to describe the gluon distribution in protons. The inclusive J/ψ yield is in agreement with current models which involve a initial formation of colored charmonium states, as in the CEM or the color octet states of the NRQCD models. The inclusive J/ψ yield observed at midrapidity is composed of $9.6 \pm 2.4\%$ of ψ' decays and $32 \pm 9\%$ of χ_c decays. This result is in agreement with what was observed in other experiments. Given the current large statistical uncertainties, no conclusion can be made about collision energy or p_T dependence of these fractions. Finally, this J/ψ cross section measurement and feed-down fractions will play an important role in current studies of cold nuclear matter and the hot, dense matter formed in heavy ion collisions.

Systematics Uncertainty from run clustering

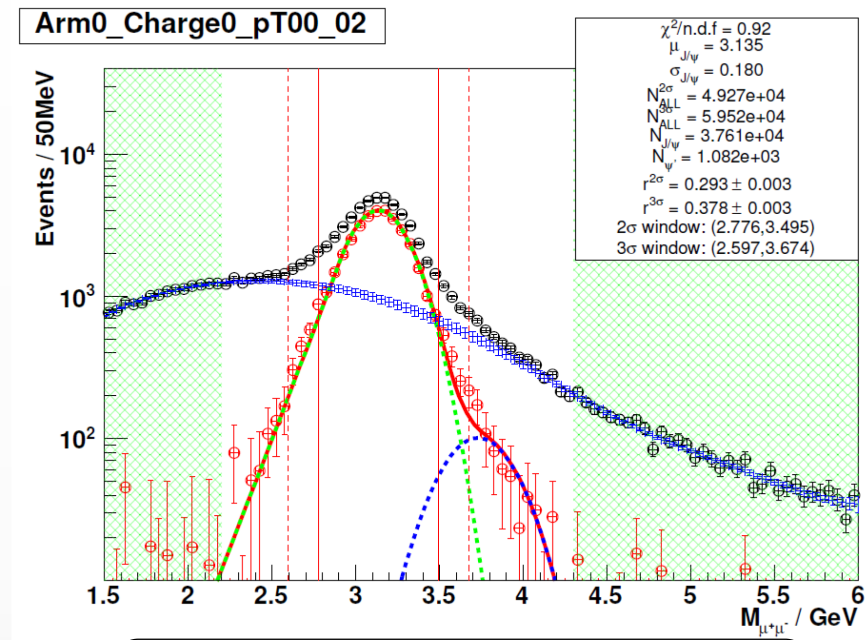




background fraction "r"



showing different fitting methods

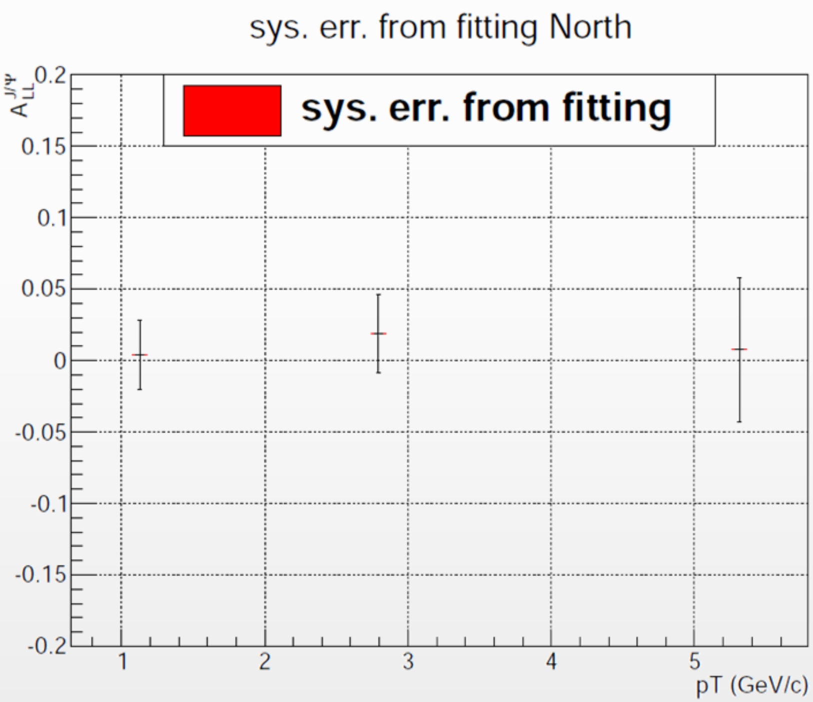


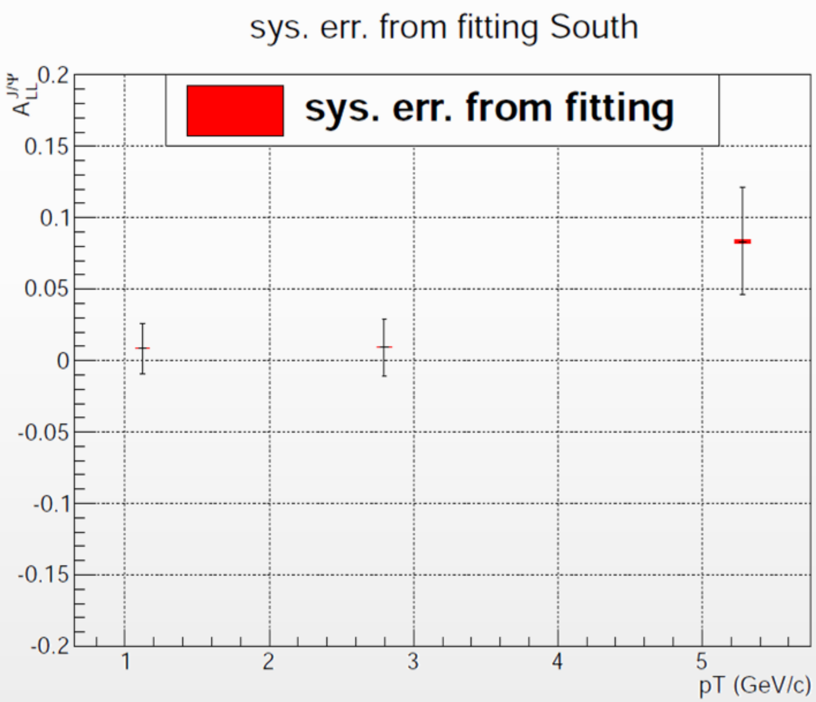
Showing one arm, one pT bin fitting for the Final result

The extraction of "r" has been done using several methods: GPR for the background, simulation driven, and the old fashion polynomial.

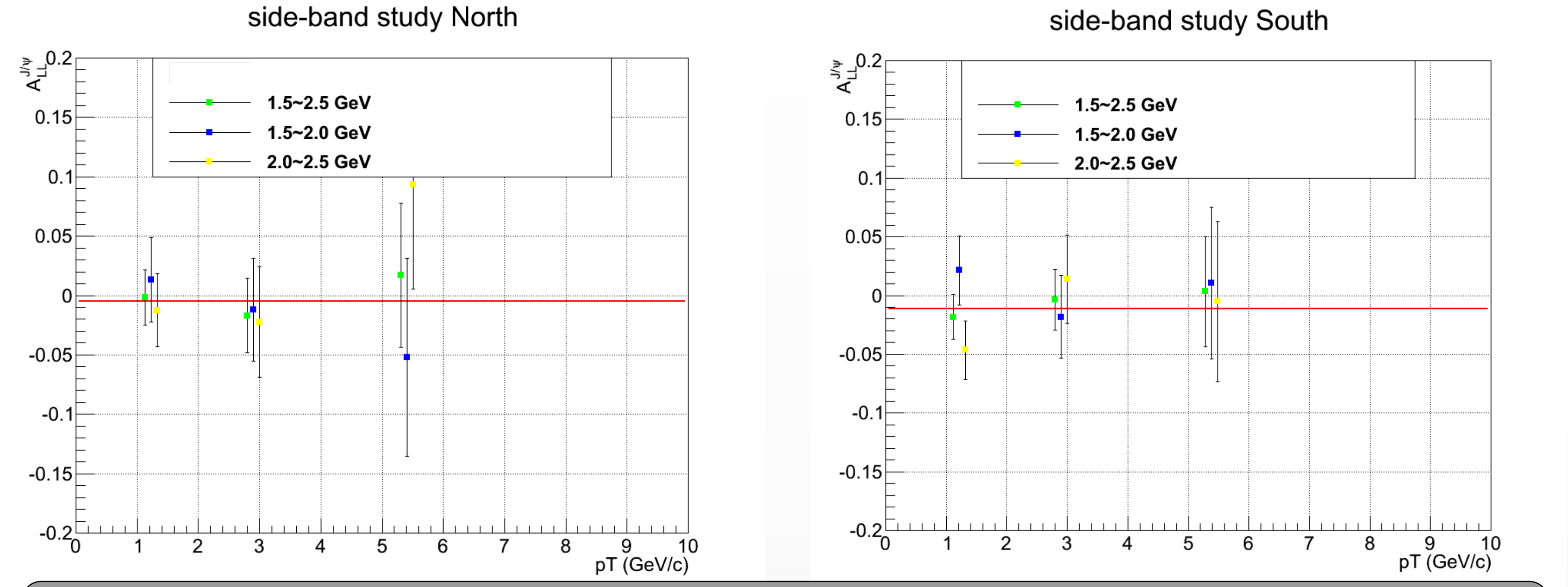
At the end, we took the GPR method as the central value and the difference as one systematic error.

Systematics Uncertainty from background fraction extraction





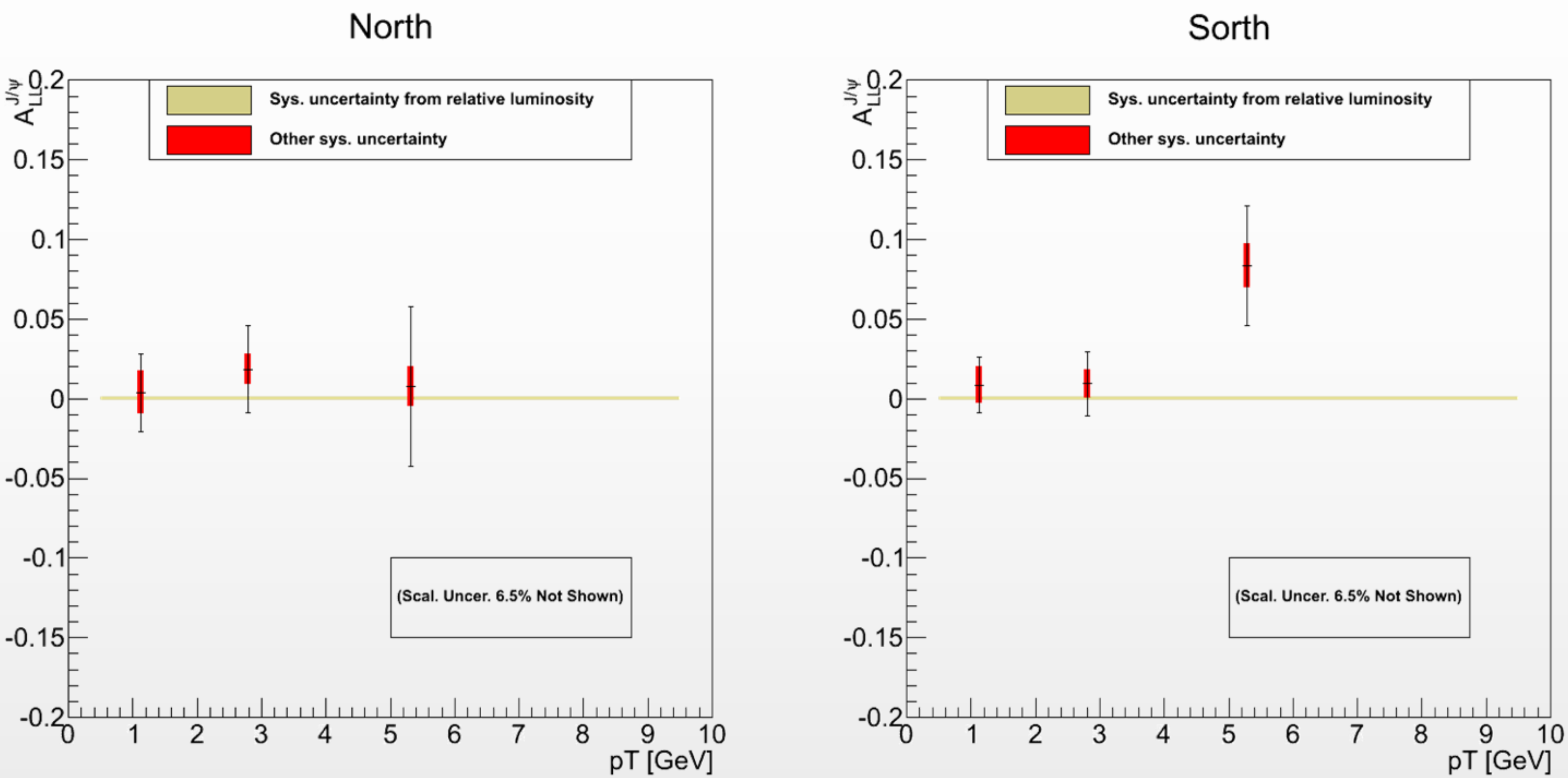
background Asymmetry $A_{LL}^{BKG.}$ Estimation



- AN1194 Figure 9:
    - showing the side-band asymmetry for different mass window

- We try to justify there is no obvious mass dependence of the asymmetry of the side band beyond the stat. err. can tell. So as we already assigned relatively large stat. err. to the background asymmetry, we ignored the sys. err. from this estimation method.

if use this very conservative sys. err. from side band estimation method:



Motivation

Gluon Polarization

For an A_{LL} measurement to be meaningful partonic level asymmetry must be reproduced at NLO accuracy

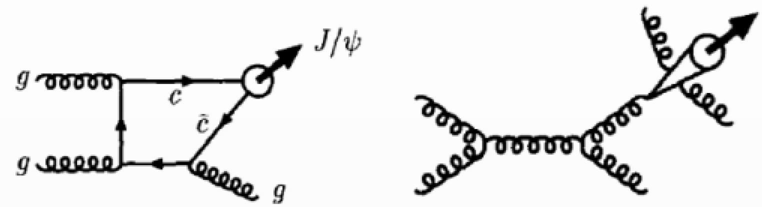
A_{LL} for J/Ψ production (LO)

$$A_{LL} = \frac{\Delta\sigma}{\sigma} \sim \frac{\Delta g(x_1)}{g(x_1)} \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to c\bar{c}}$$

The production mechanism for the J/ψ from the $c\bar{c}$ pair remains an open question

Bottom Line

- None of the models completely describe the data
- Measurement of J/ψ cross section at 510 GeV is an important intermediate data point in the production mechanism search

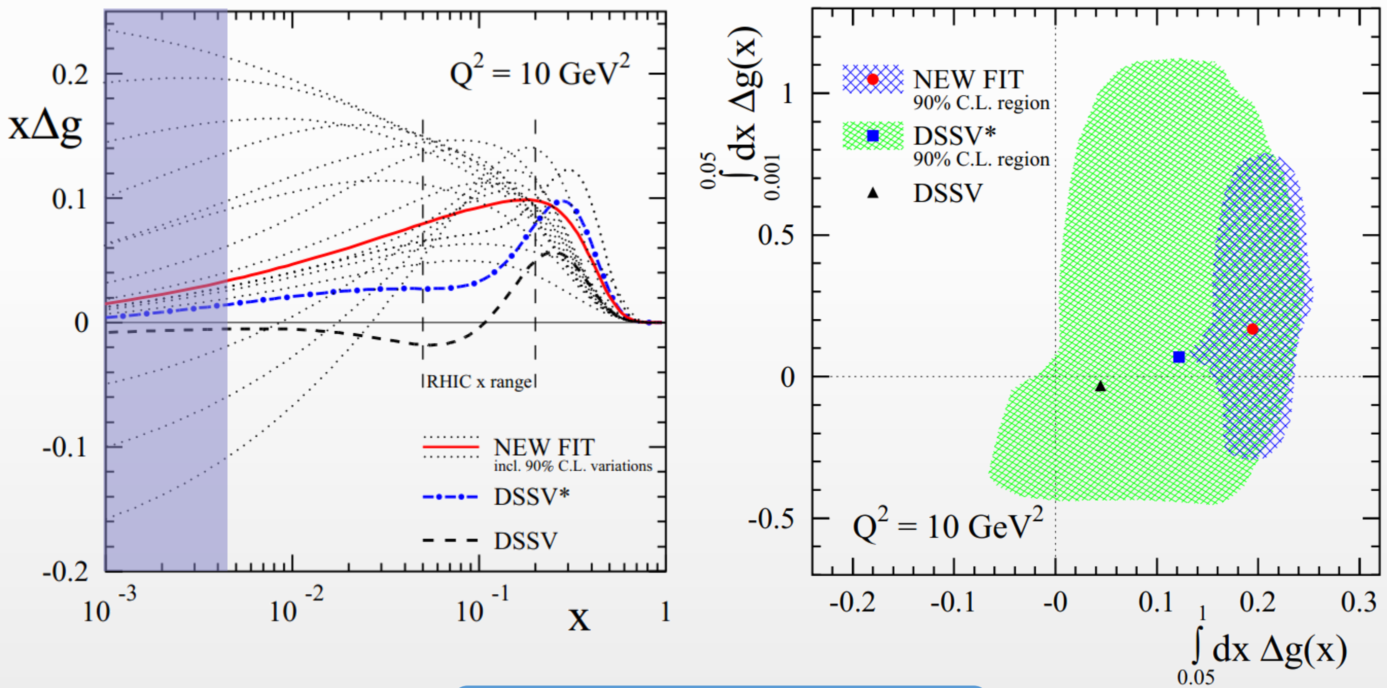


Color singlet diagrams for J/ψ production at LO (left) and from fragmentation (right)

Color octet diagrams for J/ψ production at LO (left) and from fragmentation (right)

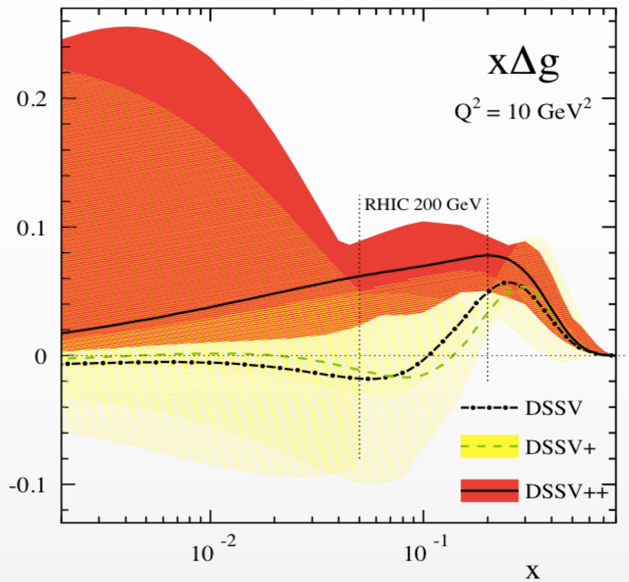
New global Fitting
2014 DSSV Global Fit

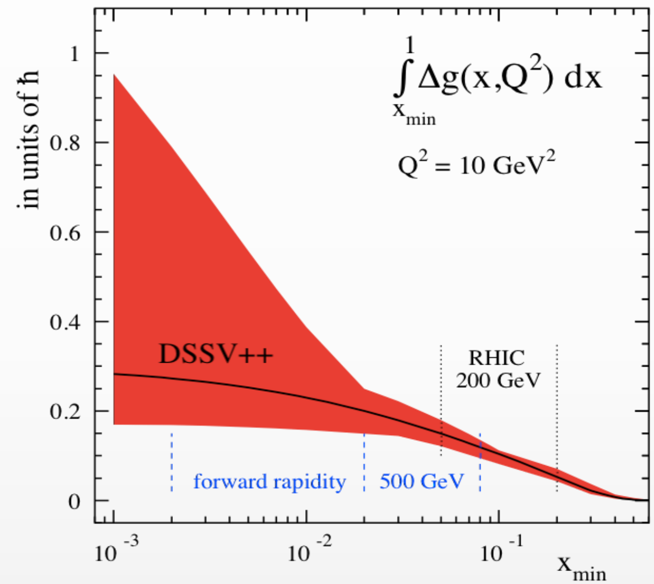
- Including 2009 RHIC data sets, the 2014 DSSV global fit suggests non zero polarization of gluons in the proton at intermediate x range (0.05~1).
- Yet at low x range, the errors of DSSV are still poorly constrained



[Phys. Rev. Lett. 113, 012001 (2014)]

Recent Results
Global Fit: DSSV++

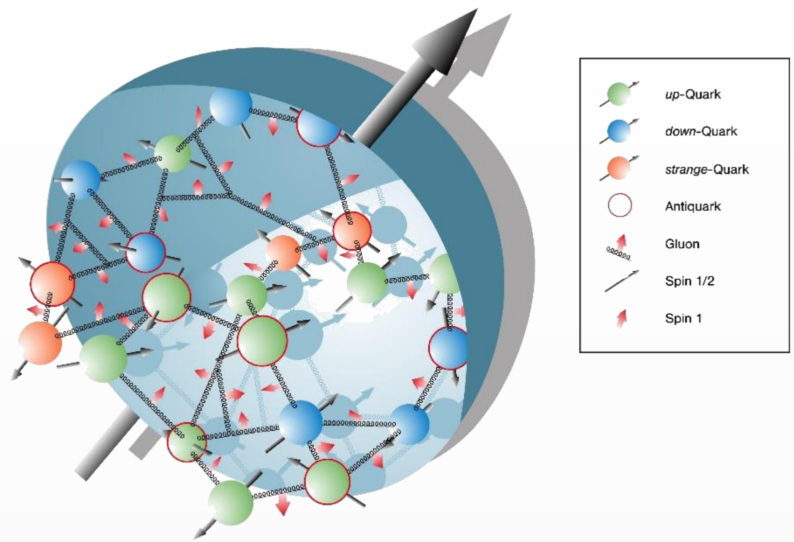




Outlook:

- Large uncertainties remain in both the shape and integral of Δg(x)
- Unconstrained in the low x range where currently no data is available
- Improvements forthcoming from ALL measurements at 510 GeV and forward rapidity

Proton Spin Structure
"Spin Puzzle"



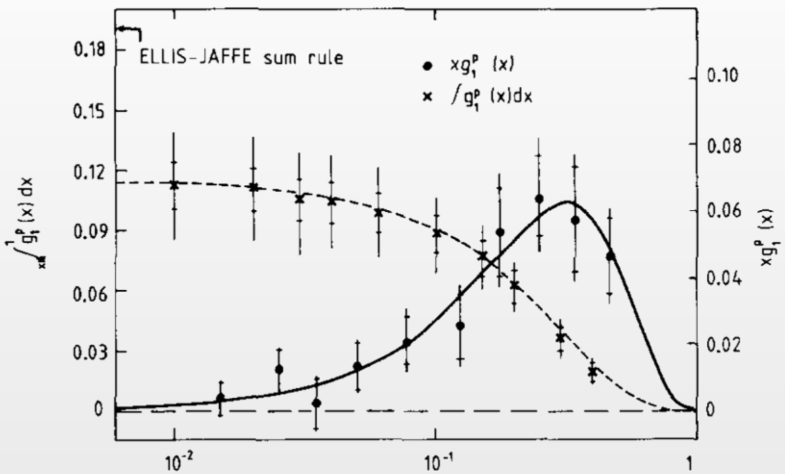
Decomposition of the Proton Spin

Manohar-Jaffe sum rule:

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

In 1980's experiment by the European Muon Collaboration (EMC) discovered that quarks only carry a small portion of the proton spin.

Current knowledge from Polarized Deep Inelastic Scattering (DIS) and Semi-inclusive DIS (SIDIS) Measurements:
$\Delta\Sigma = \sim 30\%$



[Phys. Lett. B206 364]

RHIC Spin Program

Gluon and sea quark polarization

Current status:

- Gluon polarization is largely unconstrained
- Large uncertainty in fragmentation functions leads to large uncertainty on sea quark polarization

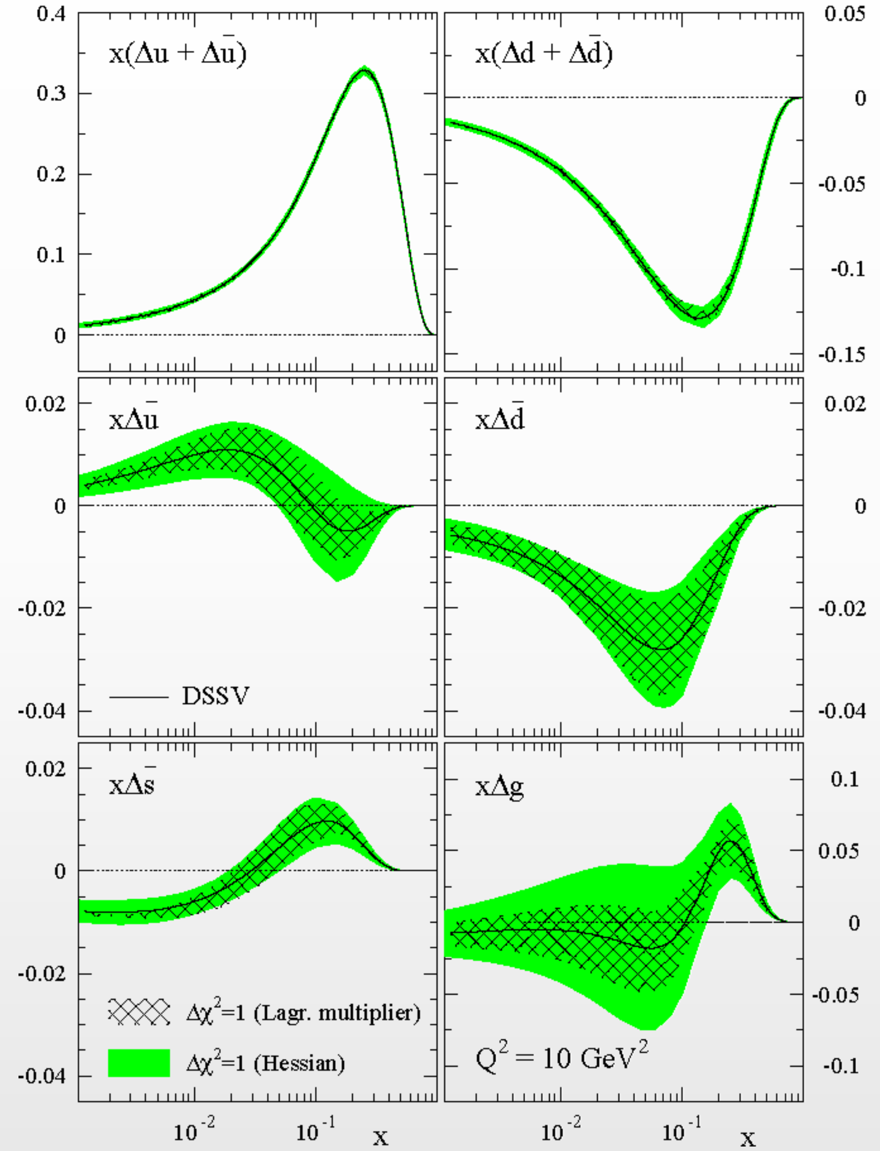
Access $\Delta G(x)$ @ LO:

- PHENIX π^0 measurements
- PHENIX J/ψ measurements
- Star inclusive Jet measurements

Sea quark polarization Measurement

- W measurements in lepton channel

Phys. Rev. D 80, 034030 (2009)



RHIC Spin Program

World's only polarized proton collider