Probing Gluon and Sea Quark Polarization with PHENIX

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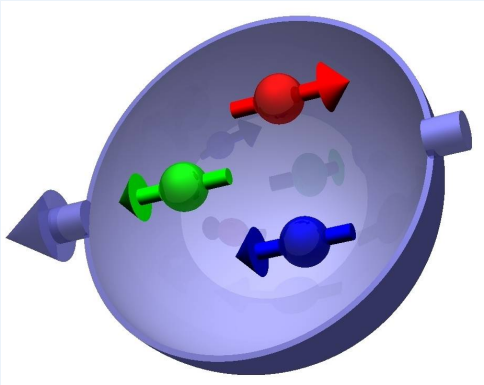
RHIC Spin

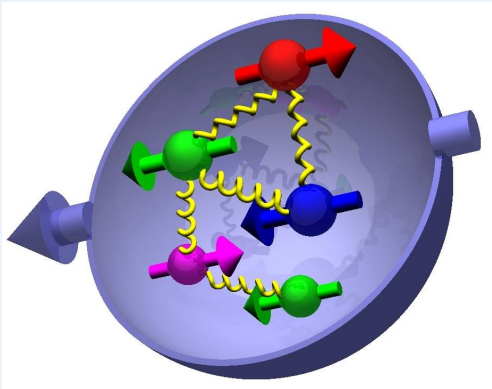
RHIC Spin is a unique program
PHENIX and STAR are truly complementary

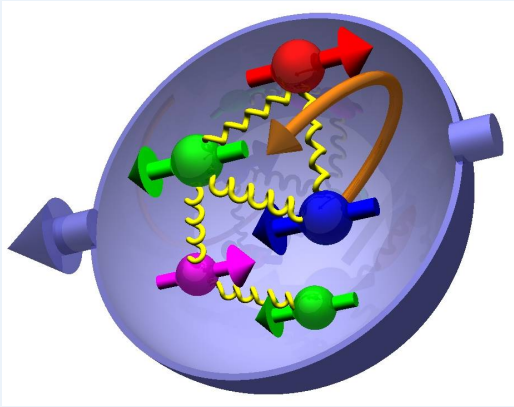
arXiv: 1501.01220
The RHIC Spin Program
Achievements and Future Opportunities

Instead of presenting only PHENIX results I'll give you a more complete and coherent picture of Spin results from RHIC, with focus on longitudinal spin (helicity) measurements

Nucleon Helicity Structure







Naïve parton model:

$$\frac{1}{2} = \frac{1}{2}\left(\Delta u_v + \Delta d_v\right)$$

1989 EMC (CERN):
$\Delta\Sigma$=0.12±0.09±0.14

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}$$

$\Rightarrow$ Spin Crisis

$\Rightarrow$ Gluons are polarized (ΔG)
$\Rightarrow$ Sea quarks are polarized:

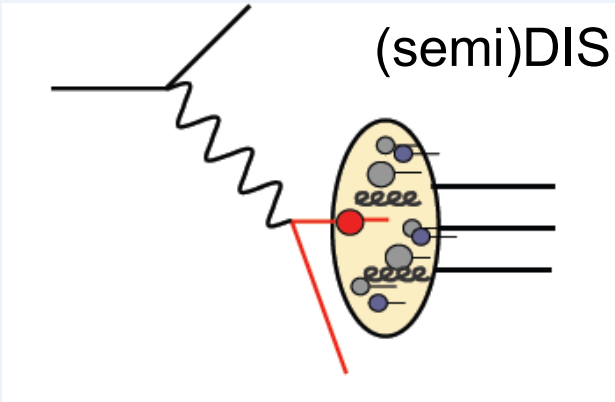
$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta\bar{q}\right) + \Delta G$$

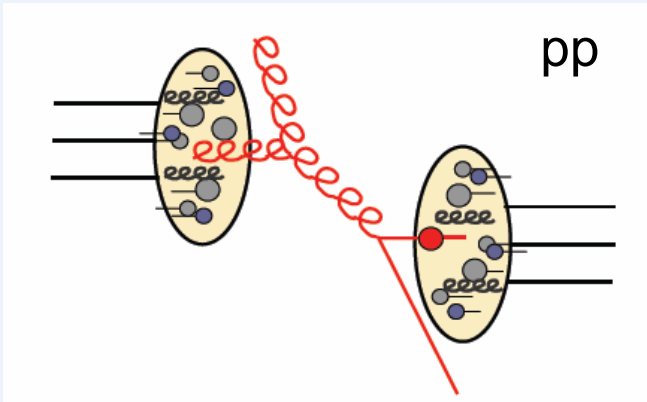
For complete description include parton orbital angular momentum L_z:

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta\bar{q}\right) + \Delta G + L_Z$$

Determination of ΔG and Δq-bar has been the main goal of longitudinal spin program at RHIC

From DIS to pp:





Probes ΔG:

- Q^2 dependence of quark PDFs
- Photon-gluon fusion

(Anti-)quark flavor separation:

- Through fragmentation processes

Probes ΔG:

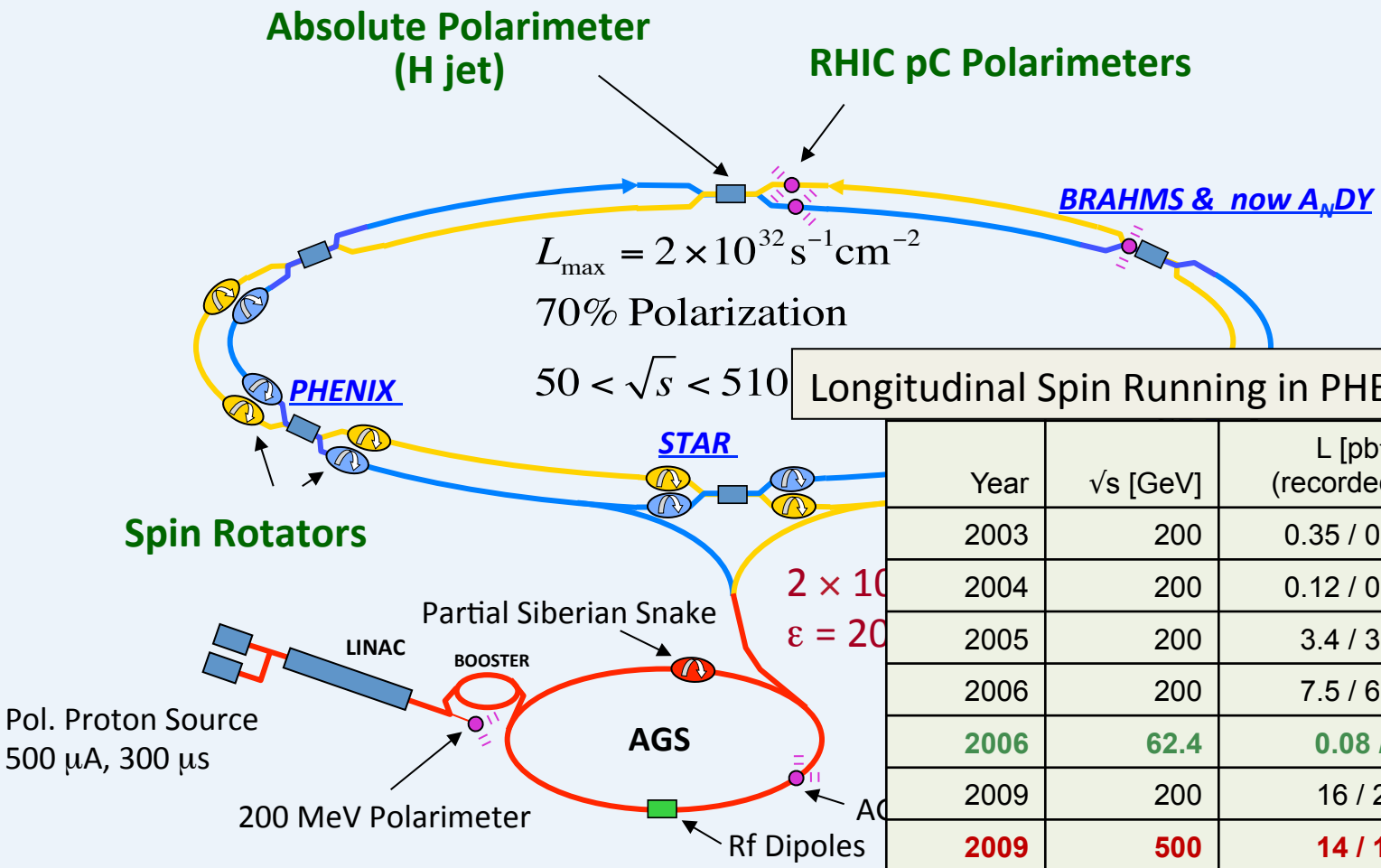
- Directly from *gg* and *qg* scattering

(Anti-)quark flavor separation:

- Through $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$

Complementary approaches

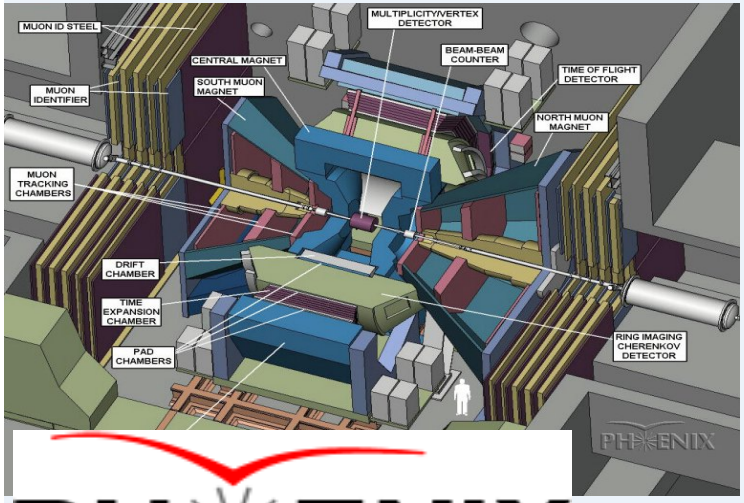
RHIC as polarized proton collider



Longitudinal Spin Running in PHENIX/STAR

Year	√s [GeV]	L [pb^{-1}] (recorded)	Pol. [%]
2003	200	0.35 / 0.3	27
2004	200	0.12 / 0.3	40
2005	200	3.4 / 3.1	49
2006	200	7.5 / 6.8	57
2006	62.4	0.08 / -	48
2009	200	16 / 25	55
2009	500	14 / 10	39
2011	500	18 / 12	48
2012	510	32 / 82	53
2013	510	155 / 300	53

PHENIX and STAR

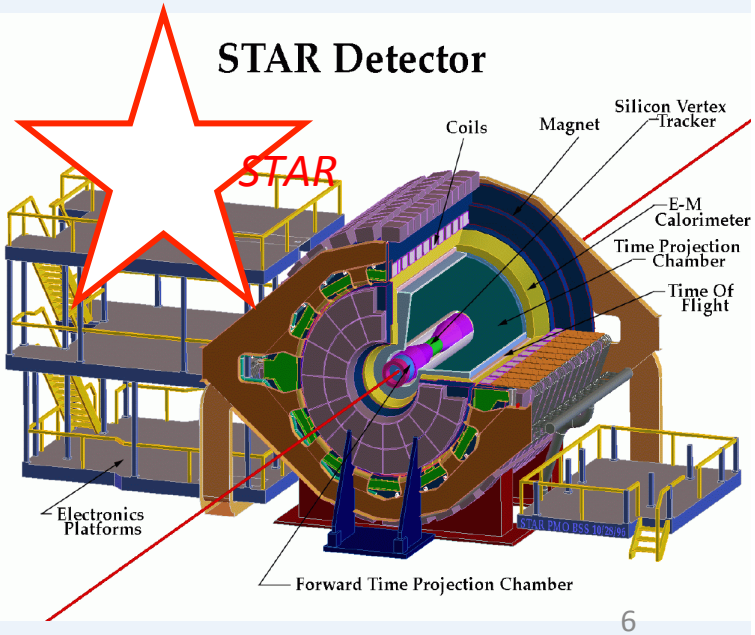


PHENIX:

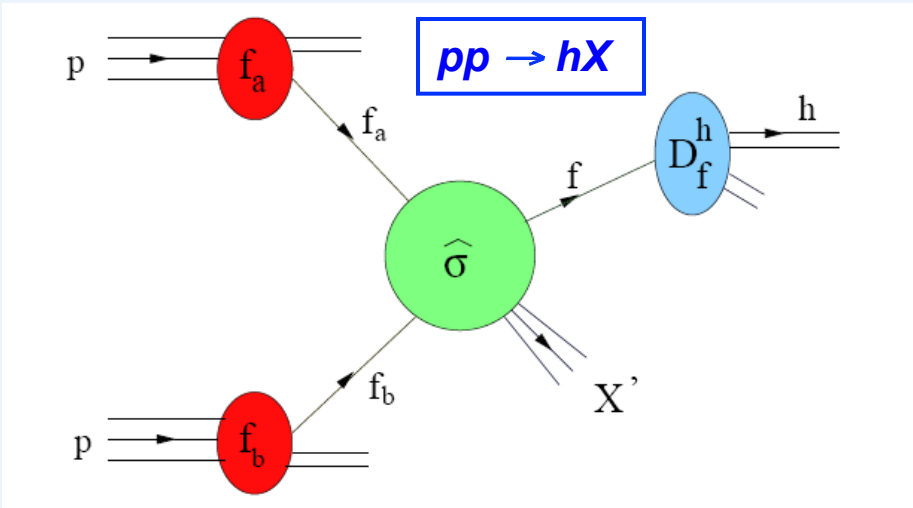
High rate capability
High granularity
Good mass resolution and PID
Limited acceptance
Upgraded to forward capabilities, inner tracking

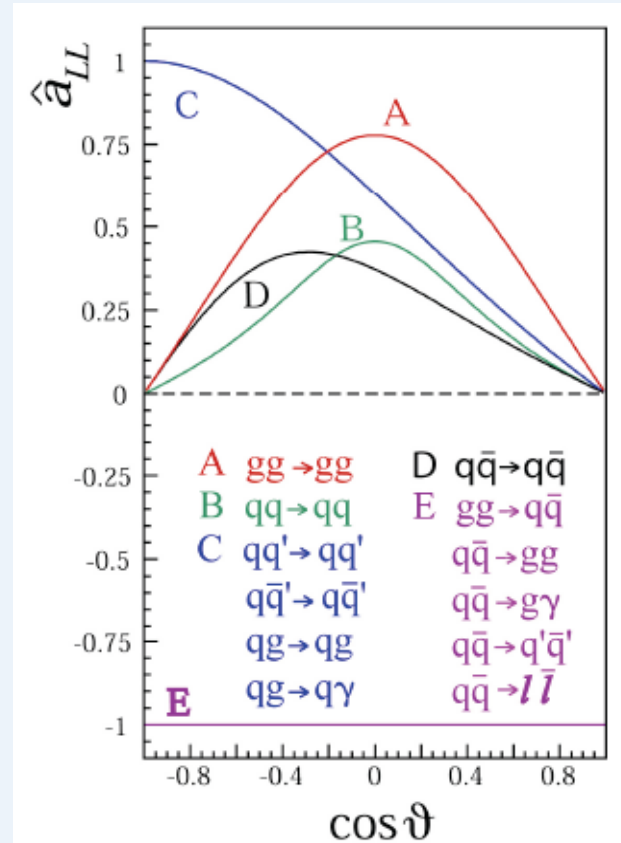
STAR:

Large acceptance with azimuthal symmetry
Good tracking and PID
Central and forward calorimetry
Upgrades to higher rate capabilities,
Inner tracking

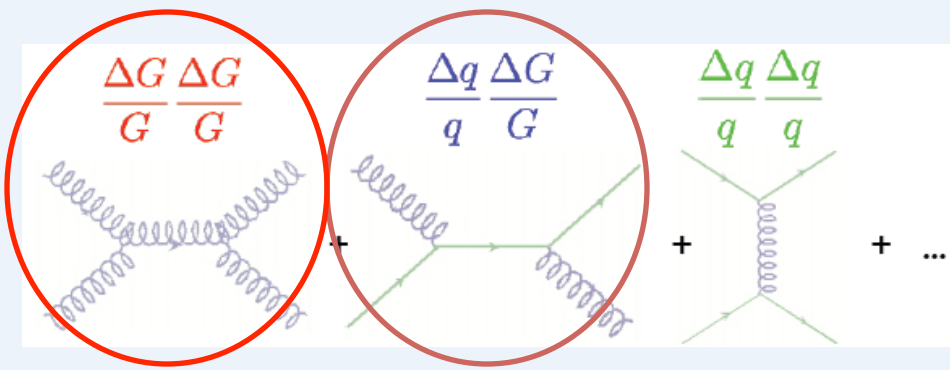


Probing ΔG in pol. pp collisions



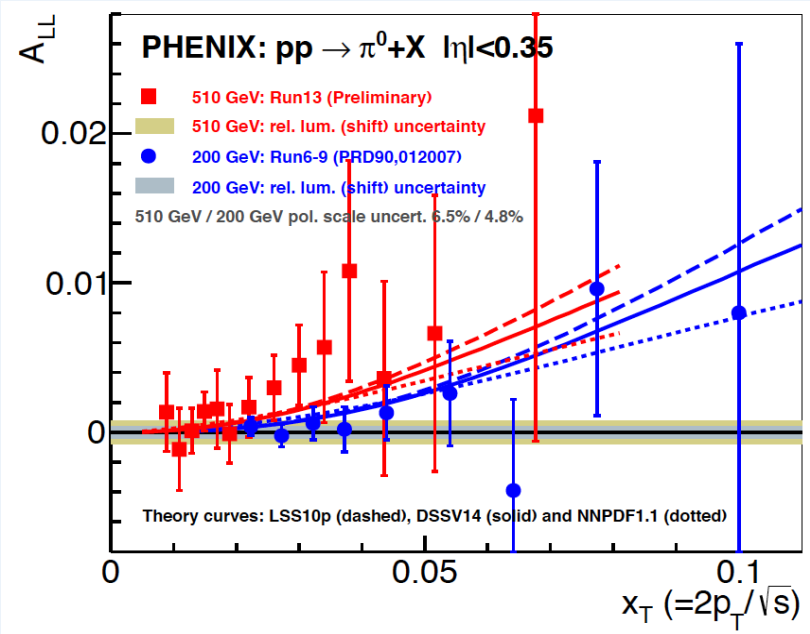


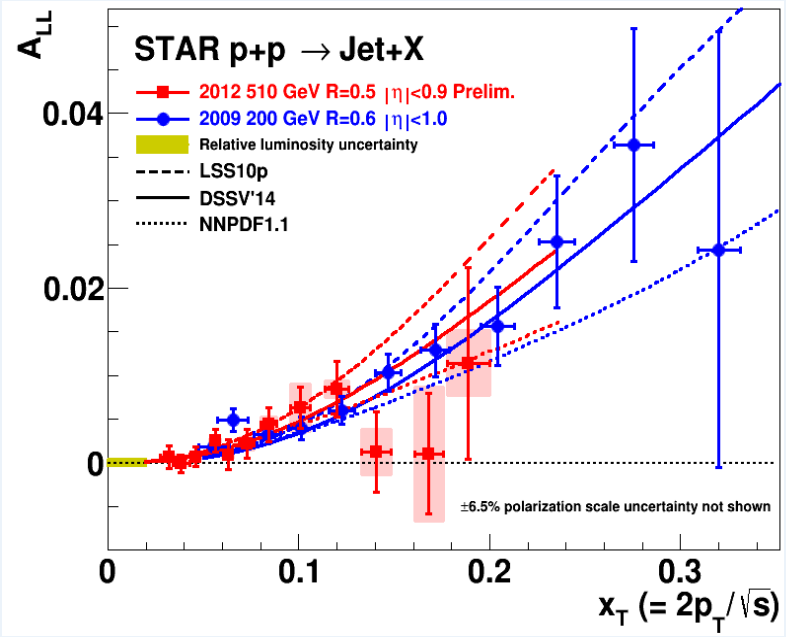
$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$



Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

ΔG: π0 and jet A_{LL}

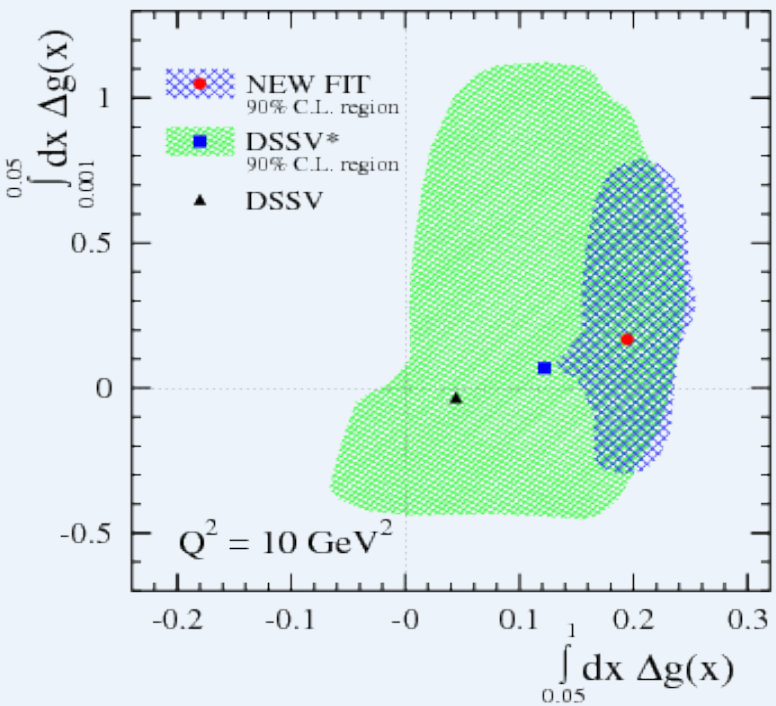




First observation of non-zero A_{LL} associated with non-zero ΔG !

ΔG: DIS+pp global QCD fit

DSSV:
D. de Florian
R. Sassot
M. Stratmann
W. Vogelsang



DSSV: Phys Rev Lett, 101, 072001 (2008)
Data from up to 2006

New DSSV: Phys Rev Lett, 113, 012001 (2014)
Data from up to 2009

$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07}$$

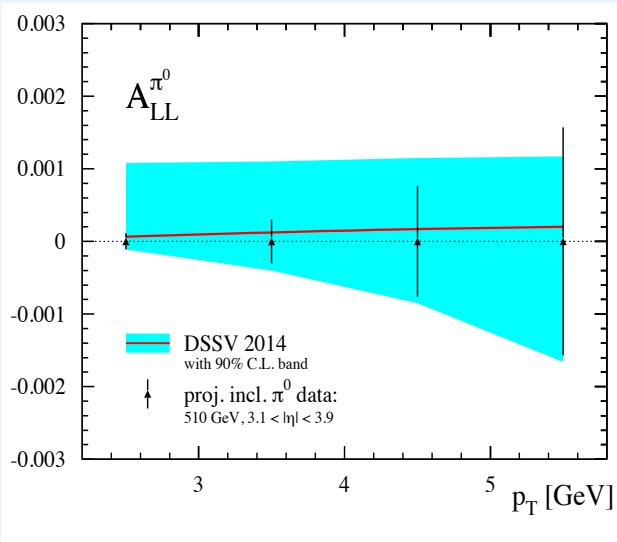
Significant non-zero Δg(x) in the kin. region probed by RHIC

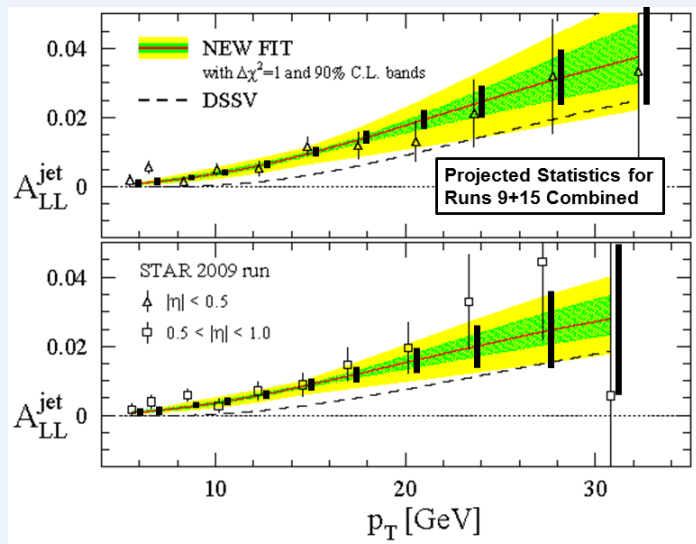
Similar result from another global fit NNPDF

Still huge uncertainty in unmeasured region (x<0.05)

=> Measurements at higher √s and forward rapidity

ΔG: Near Term Projections





π0 in forward region at √s=510 GeV (PHENIX):

Based on collected 2013 data

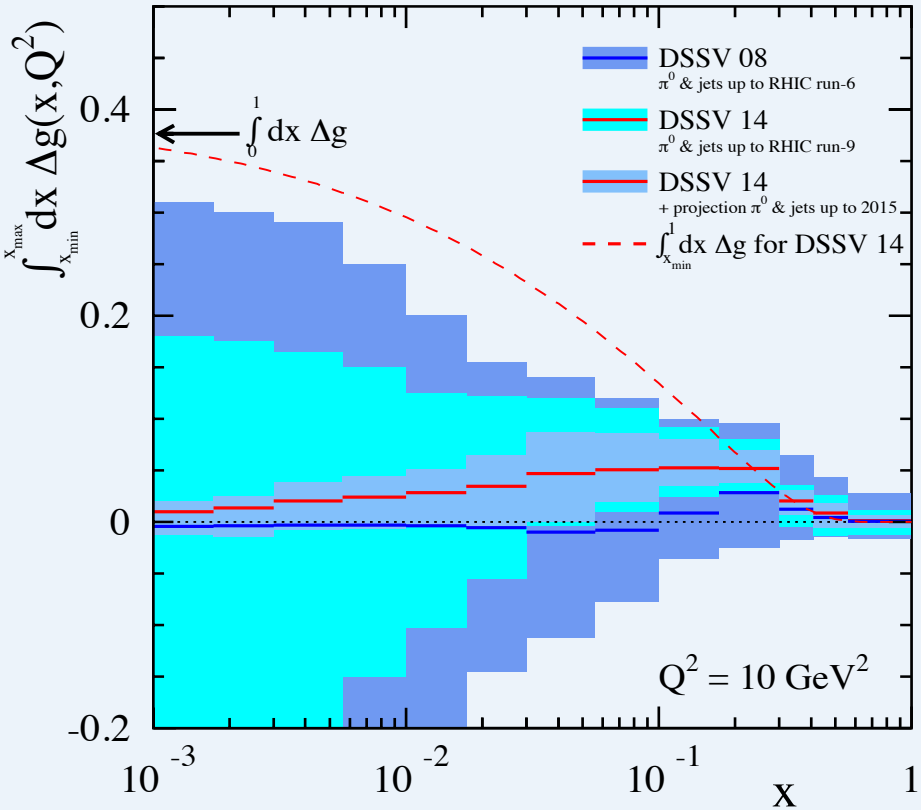
Probes lower x down to ~10^{-3}

Inc. Jet at √s=200 GeV (STAR):

Based on 2009/15 data

Considerably improve exp. precisions

ΔG: Near Term Projections



ΔG fit in each x bin

Innermost band: after inclusion of projected data up to 2015

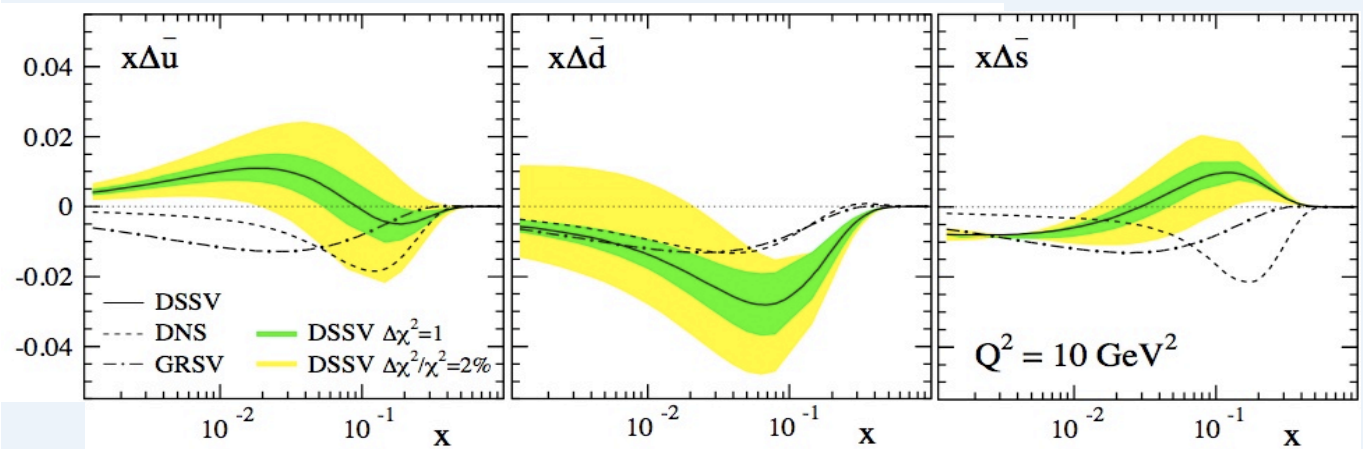
x>0.01 mainly from central rap. data
x<0.01 mainly from forward rap. data

Significant improvement expected soon, particularly at x<0.03

Other channels are also being measured
γ, η, π±, h±, heavy flavor through e and μ
jet-jet, h-h, γ-jet, γ-h
Will serve for syst. effects study in Δg(x) fit

(Anti)quark flavor separation

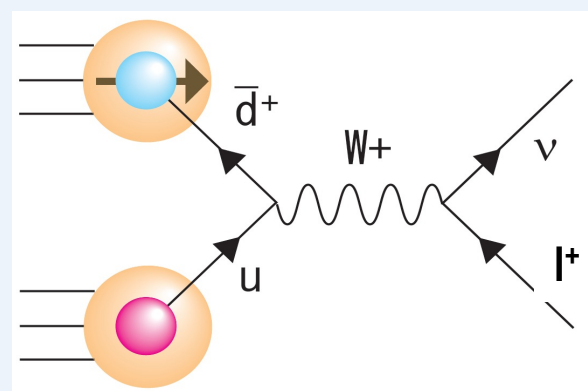
DSSV: PRL 101, 072001 (2008)



Mainly from SIDIS:

Fragmentation functions to tag (anti)quark flavor

$p+p \rightarrow W^{\pm} \rightarrow (e/\mu)^{\pm} + \nu$



- Parity violating W production:

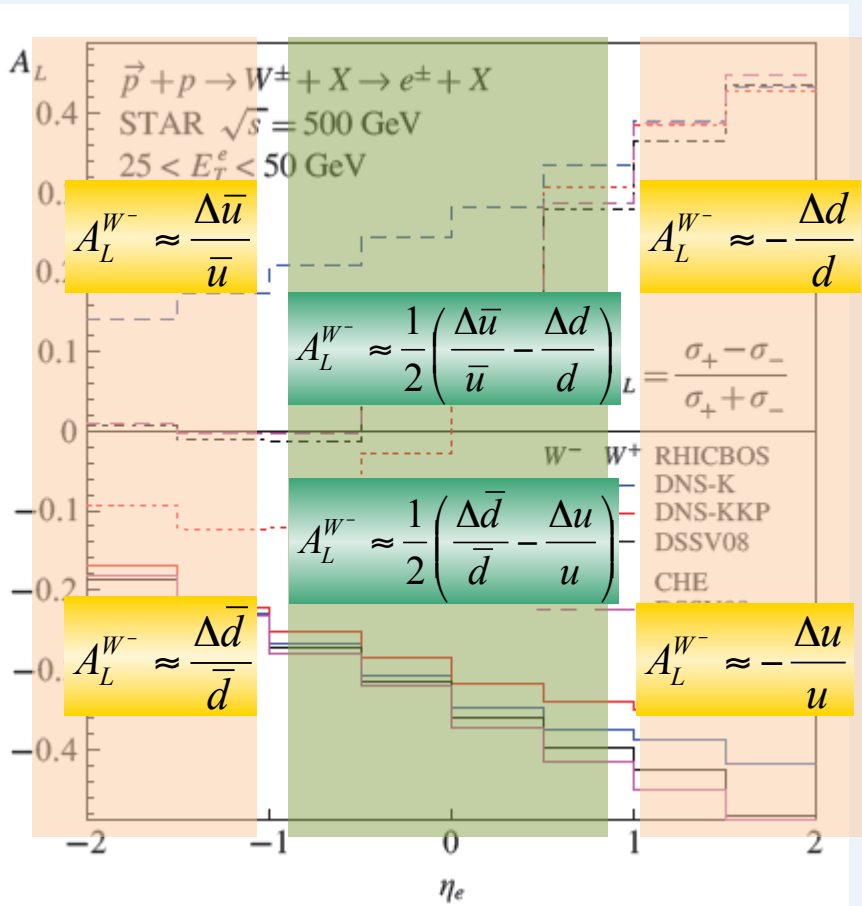
  Fixes quark helicity and flavor:

  $d_L \bar{u}_R \rightarrow W^-$ $\quad u_L \bar{d}_R \rightarrow W^+$
- No fragmentation involved
- High Q^2 (set by W mass)

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

W: A_L vs η

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



STAR

Central (barrel) region (W→e±, |η|<1)

- Data from 2009: **PRL106, 062002 (2011)**
- Data from 2011/12: **PRL113, 072301 (2014)**

Forward (endcup) region (W→e±, 1<|η|<2) :

- Forward tracker upgrade, first data from 2013

PHENIX

Central Arms (W→e±, |η|<0.35)

- 2009 data: **PRL106, 062001 (2011)**
- 2011-13 data: **"Preliminary"**

Forward Arms (W→μ±, 1.2<|η|<2.4) :

- 2011-13 data: **"Preliminary"**

Crucial to measure in wide rapidity range

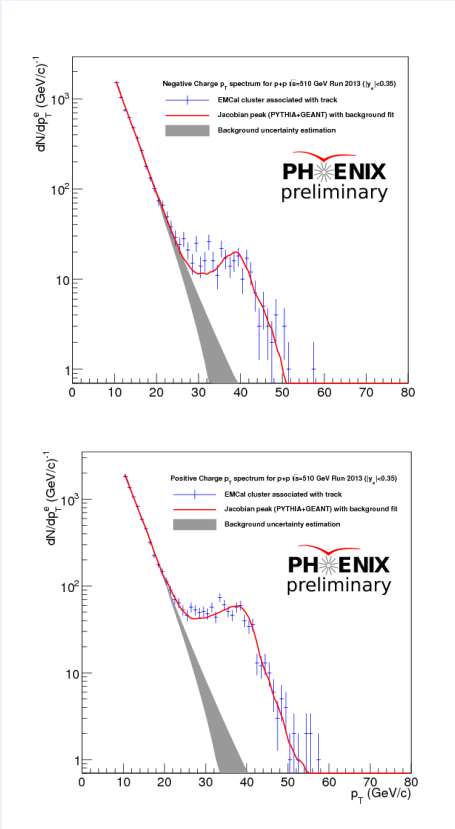
Central region: $W^{\pm} \rightarrow e^{\pm}$

- Triggered by energy in EMCal
- Momentum from energy in EMCal
- Charge from tracking in B field

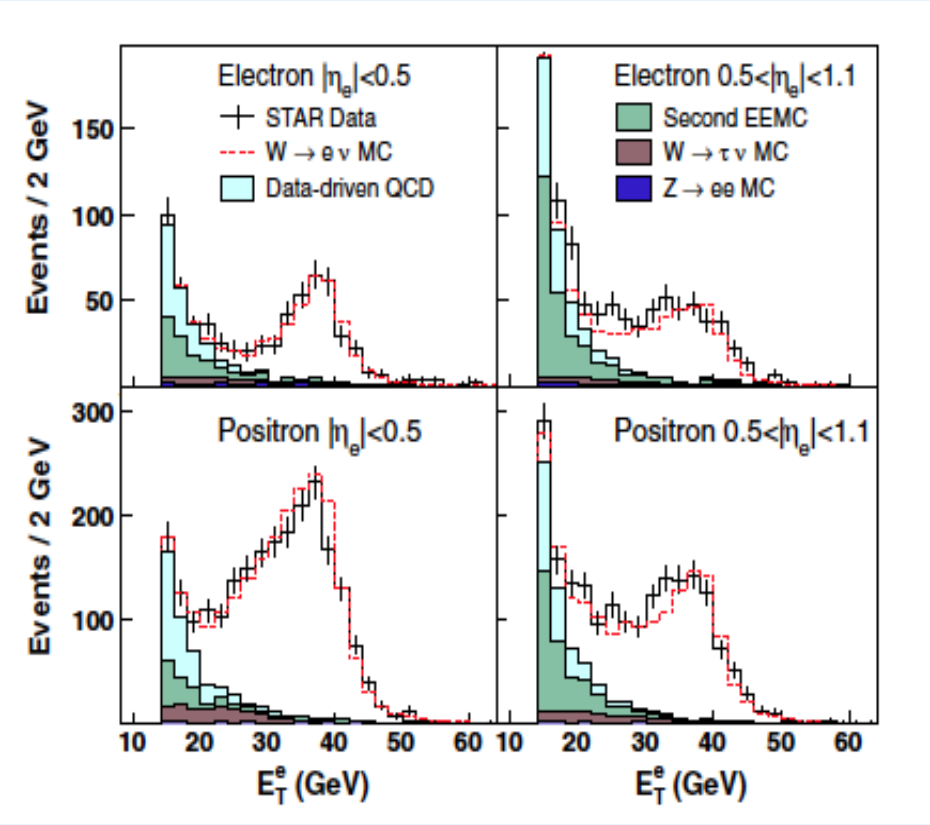
PHENIX: $|\eta|<0.35$

$W^{-} \rightarrow e^{-}$

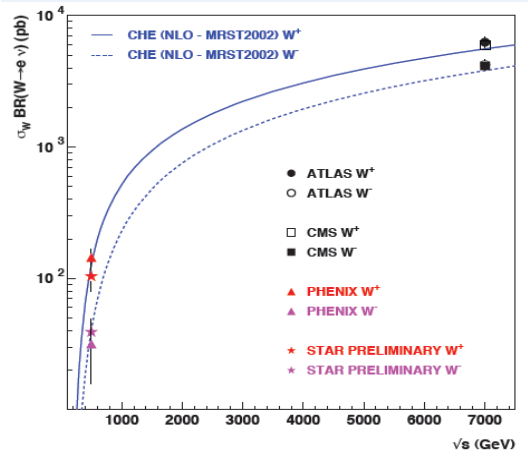
$W^{+} \rightarrow e^{+}$



STAR: $|\eta|<0.5$ STAR: $0.5<|\eta|<1.1$

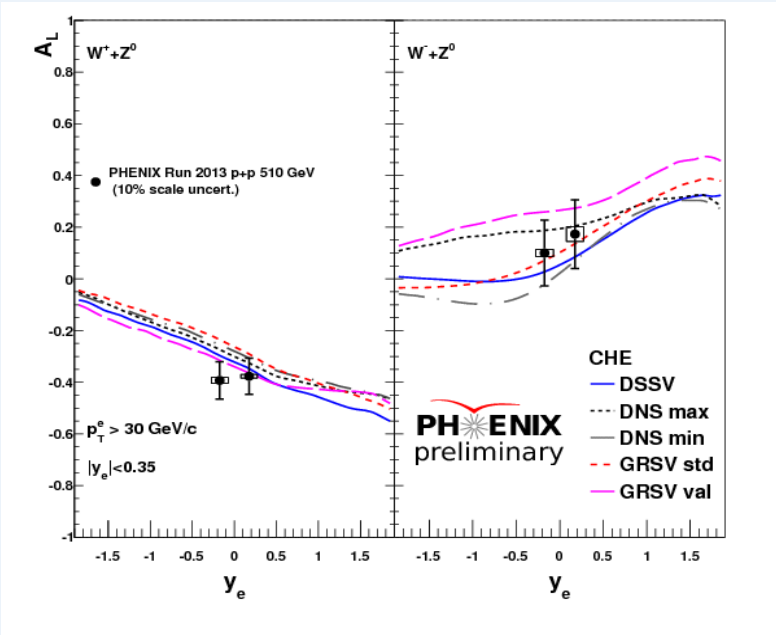


Cross section

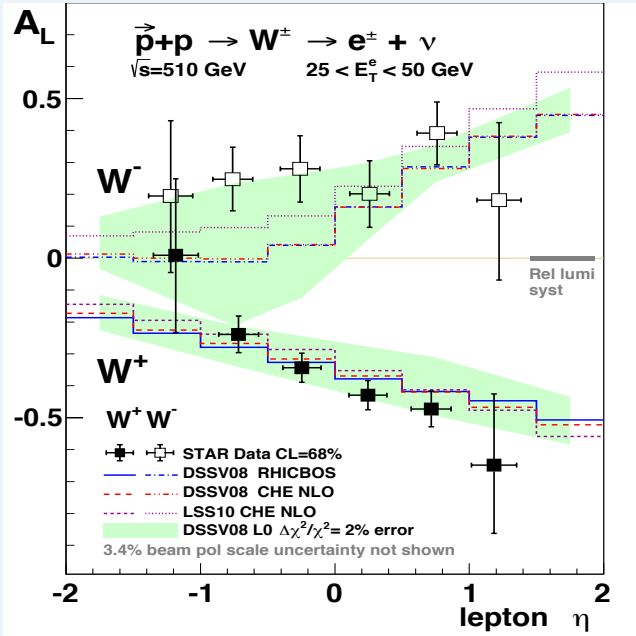


Central region: $W^{\pm} \rightarrow e^{\pm}$

PHENIX: 2011-13



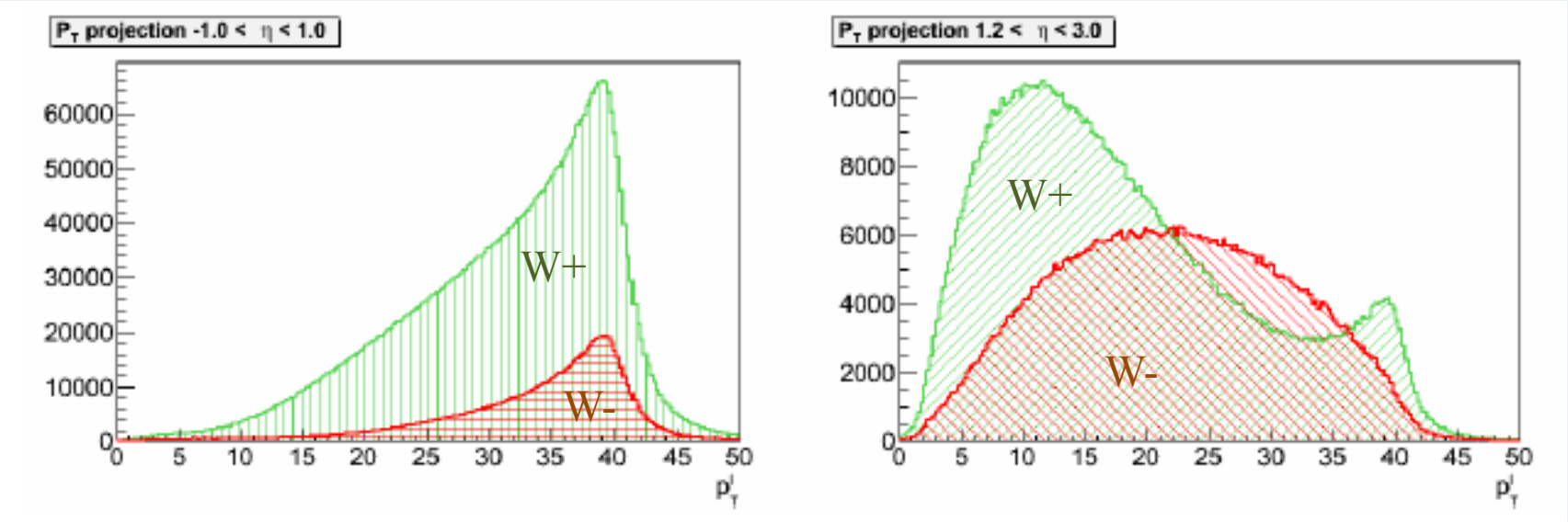
STAR: 2011/12



Δu-bar tends to be more positive

Symmetry breaking in polarized quarks?

W: Central vs Forward region

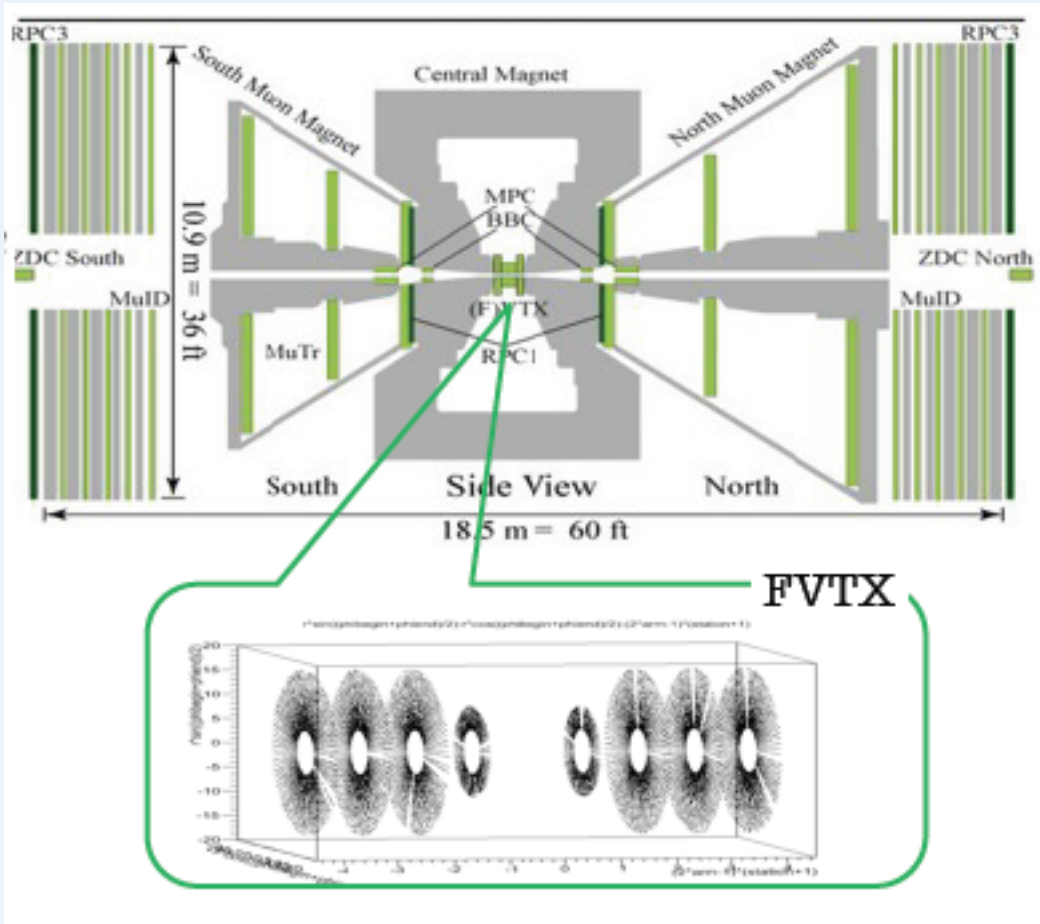


Clear Jacobian peak
at central rapidities

Suppressed/No Jacobean peak
at forward rapidities

Forward region: $W^{\pm} \rightarrow \mu^{\pm}$

PHENIX



Muon Arms: 1.2<|η|<2.4 Δφ=2π

Muon Tracker (MuTr)

- Tracking, Momentum

Muon Identifier (MuID)

- μ/h separation

Resistive Plate Chamber (RPC)

- Timing, background rejection

Forward Vertex Detector (FVTX)

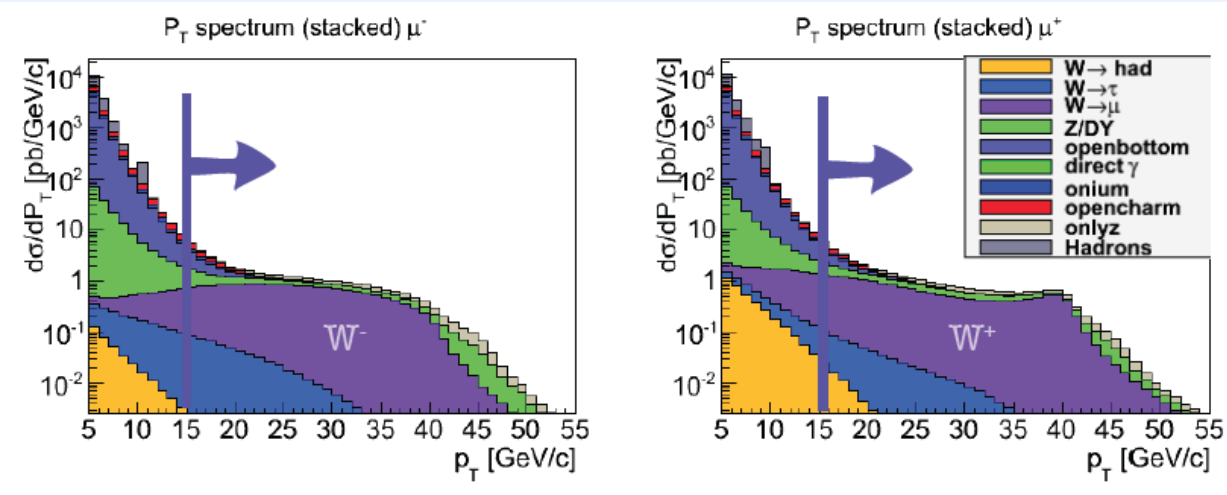
- More precise tracking, background rejection

Dedicated Trigger

- Based on MuTr and RPC
- To tag high pT muons

Forward region: $W^{\pm} \rightarrow \mu^{\pm}$

PHENIX

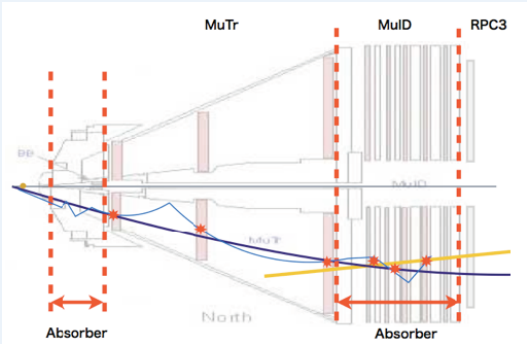


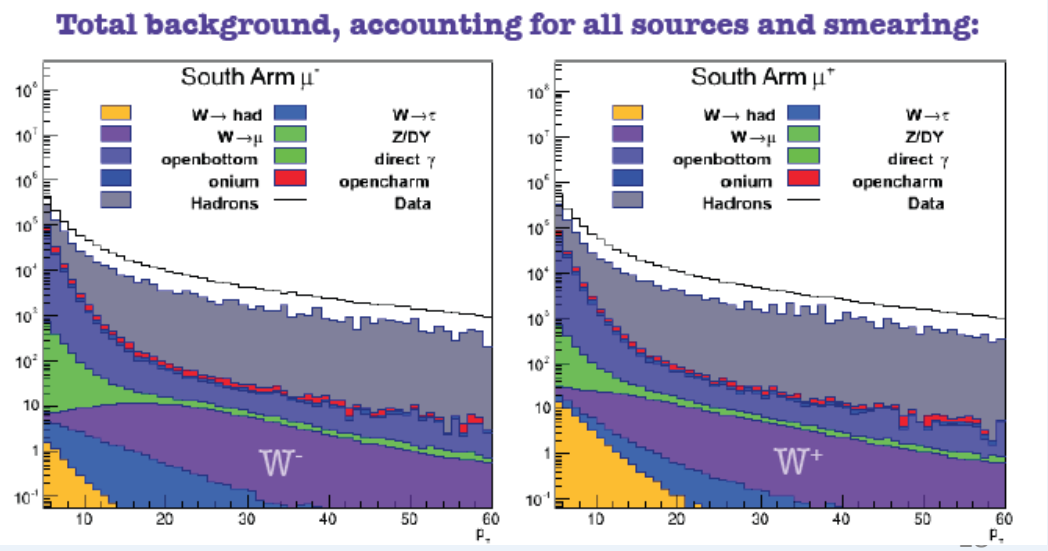
Muon background:

- Heavy flavor
- Quarkonia
- Decay muons
- Z/DY
- Etc.

Not significant at >15 GeV/c

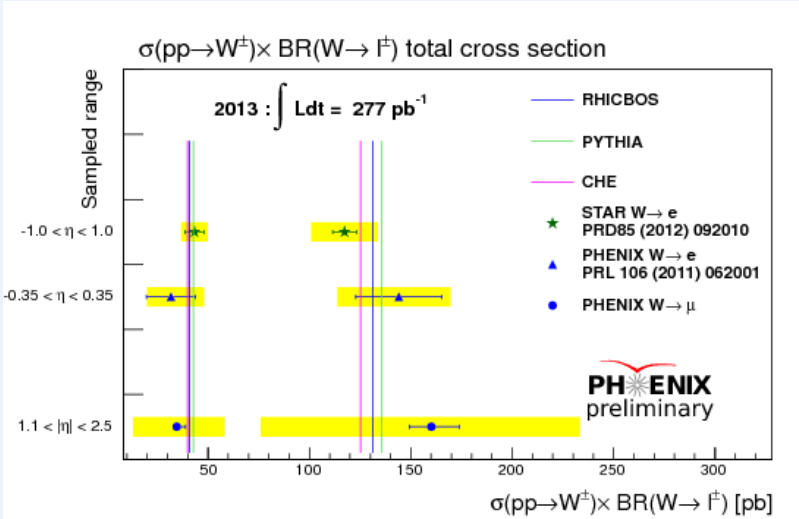
If include hadrons (misidentified as μ), h→μ (fake high pT) and pT smearing



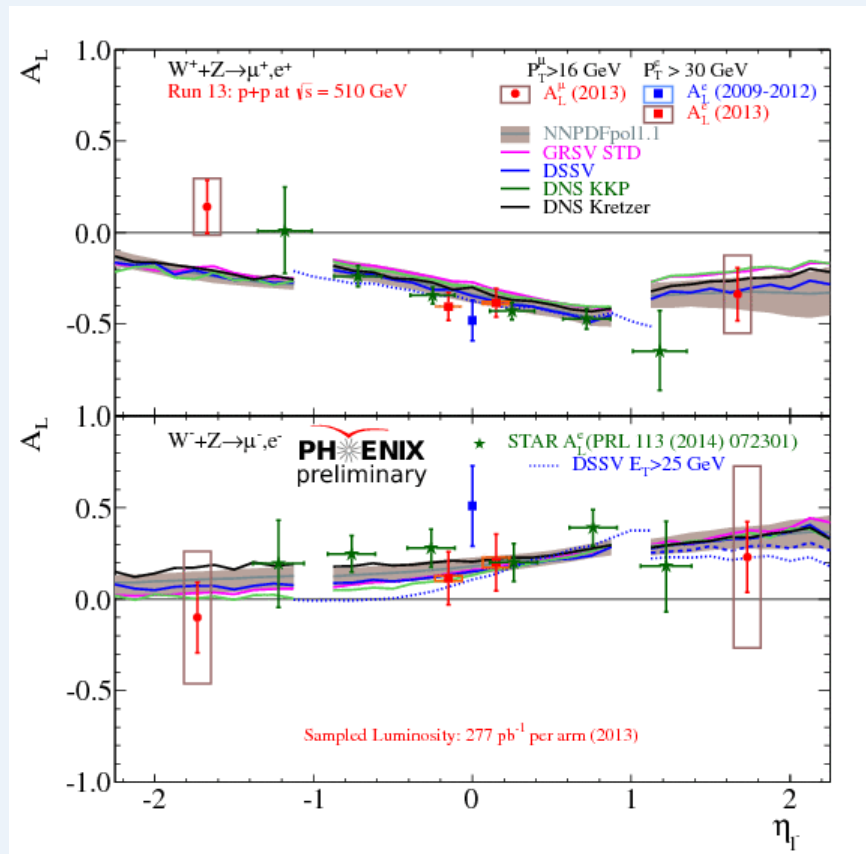


Forward region: $W^{\pm} \rightarrow \mu^{\pm}$

PHENIX



S/B = 0.2−1 depending on η

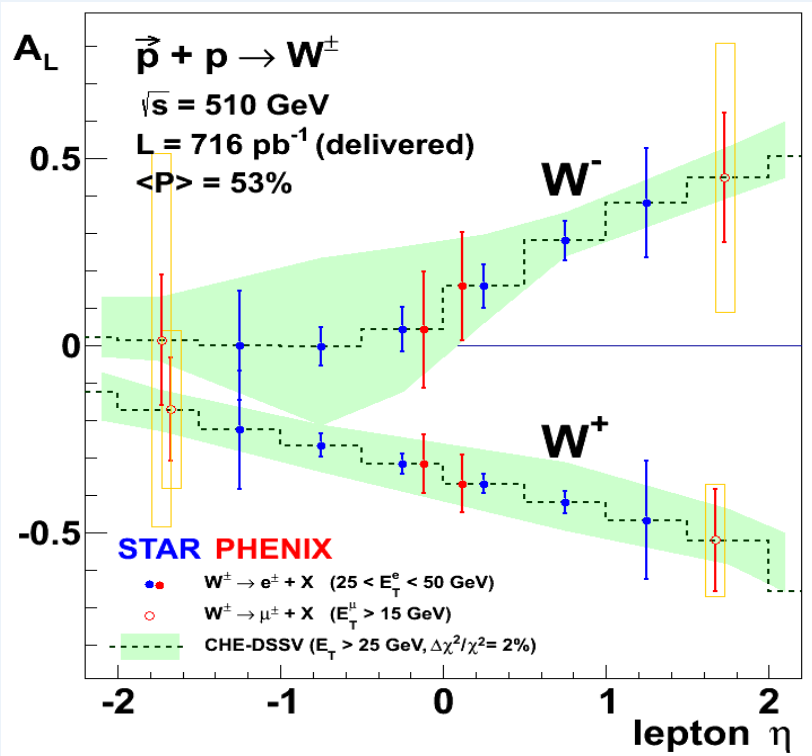


Measured cross section agrees with calculations within large uncertainties

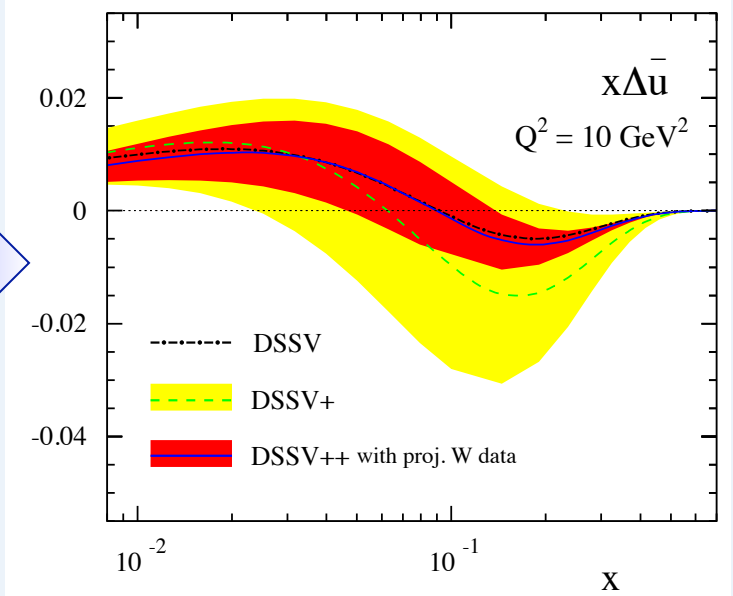
A_L uncertainties are still large

- Improve S/B
- Tracking alignment → reduce momentum smearing and improve charge reco

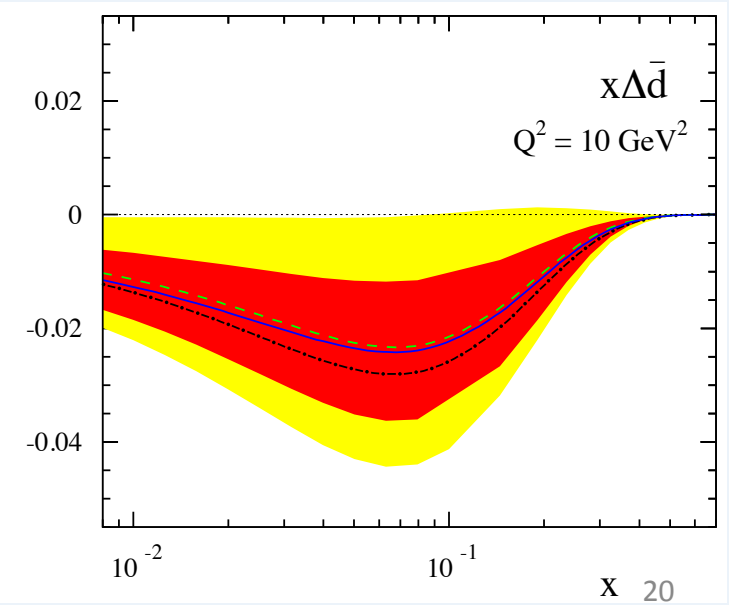
W: projection



$\Delta\bar{u}$



$\Delta\bar{d}$



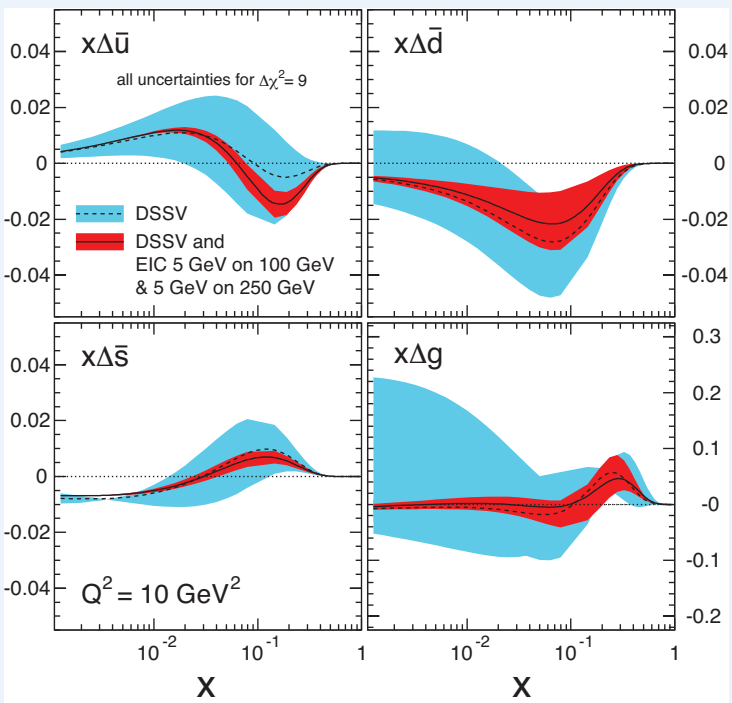
RHIC W-data will give a significant constraint on anti-quark polarization in the proton

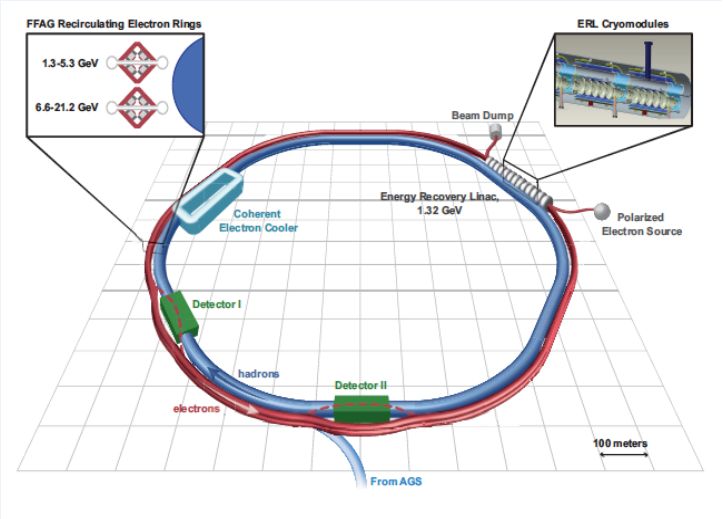
RHIC -> eRHIC

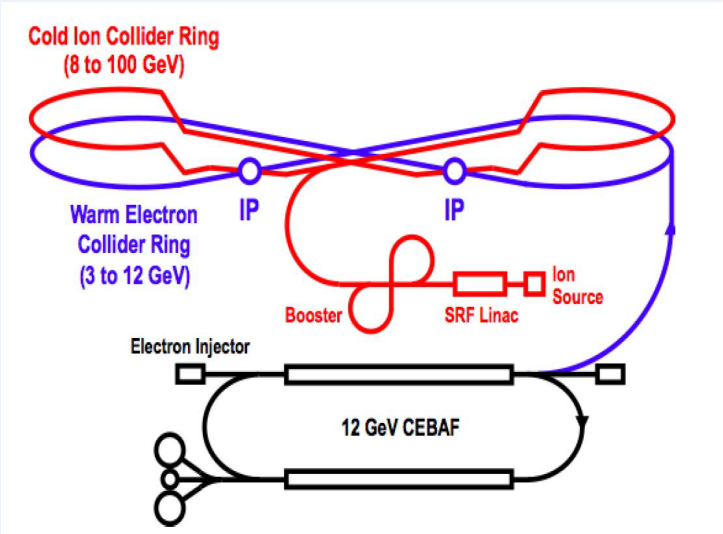
Electron – Ion Collider

Add electron ring to existing RHIC proton/heavy_ion ring or
Add proton/heavy_ion ring to existing electron ring

Back to DIS but at much higher luminosity
(x100-1000 as HERA)
And much higher √s (with both beams polarized)







Summary

RHIC Longitudinal Spin program:

How do gluon contribute to the proton Spin

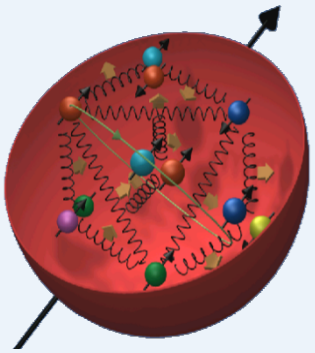
- Non-zero (in the limitted x-range) and comparable to quark contribution
- Plan to study lower x (data already collected!)

What is the flavor structure of polarized sea in the proton

- Δu-bar tends to be positive, Δd-bar tends to be negative
- Will see the more precise conclusion very soon

Backup

Outlook



Proton Spin

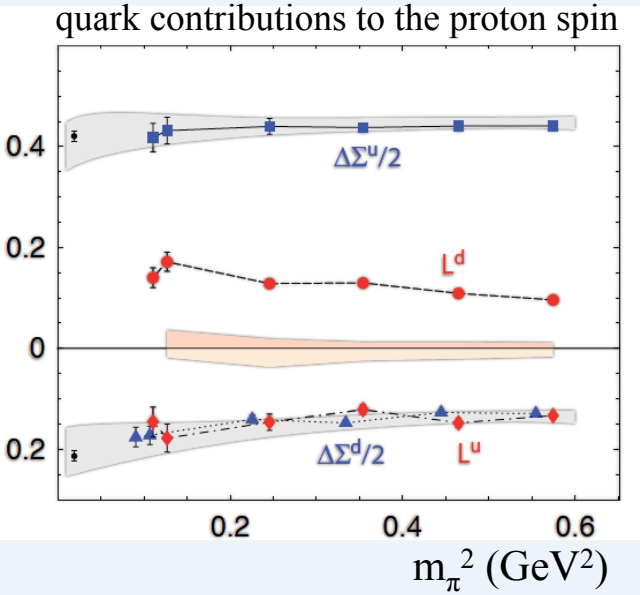
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

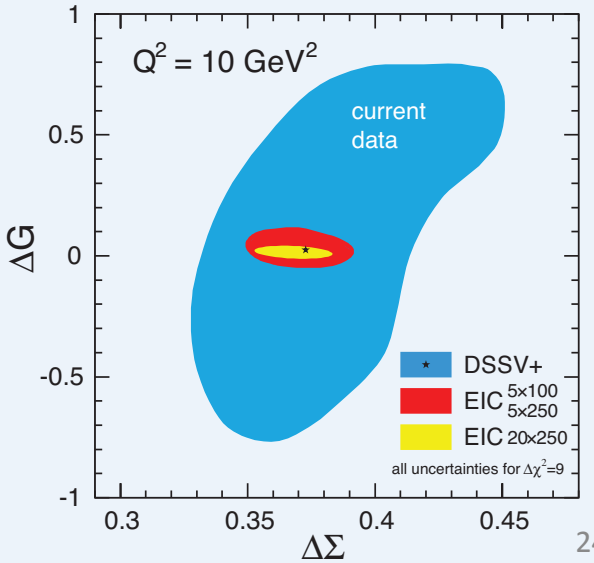
(Anti)quark Contribution: 0.15-0.20

Gluon Contribution: 0.1 in 0.05<x<0.2

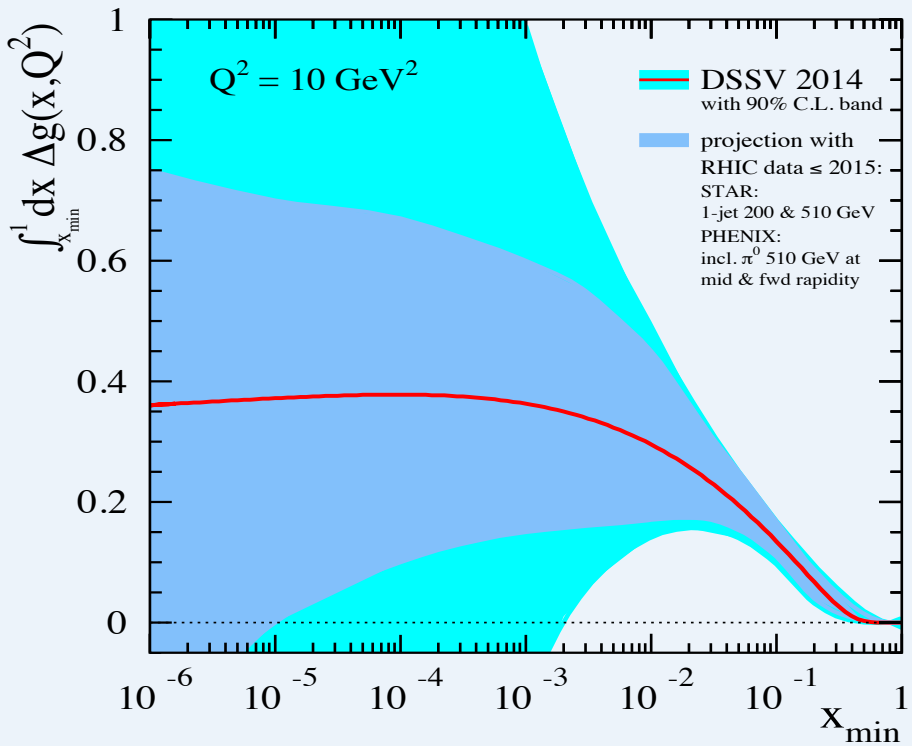
Parton Orbital Momentum: ???

Lattice QCD: quark contributions to the proton spin



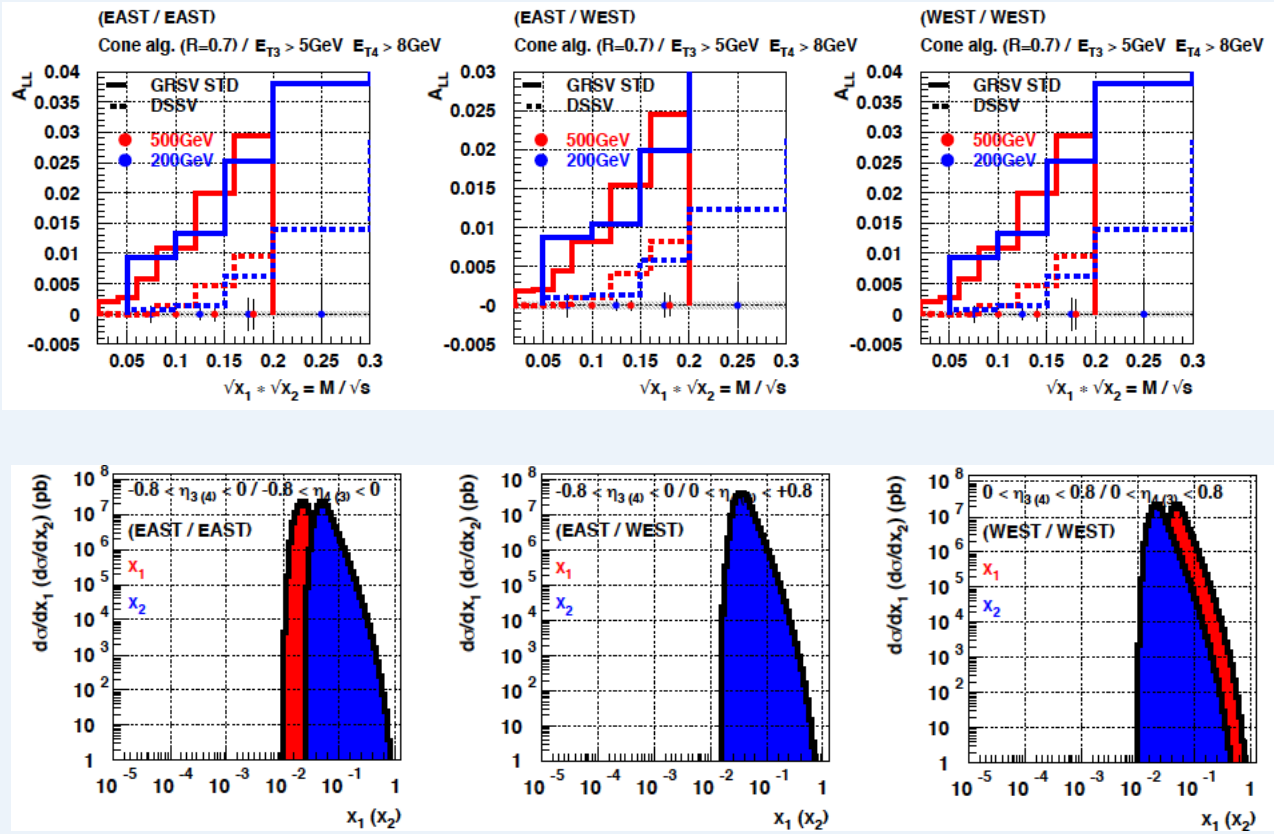


ΔG: Near Term Projections

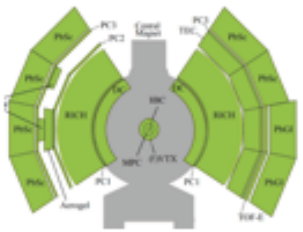


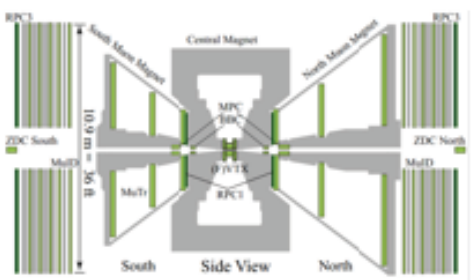
ΔG: Near Term Projections

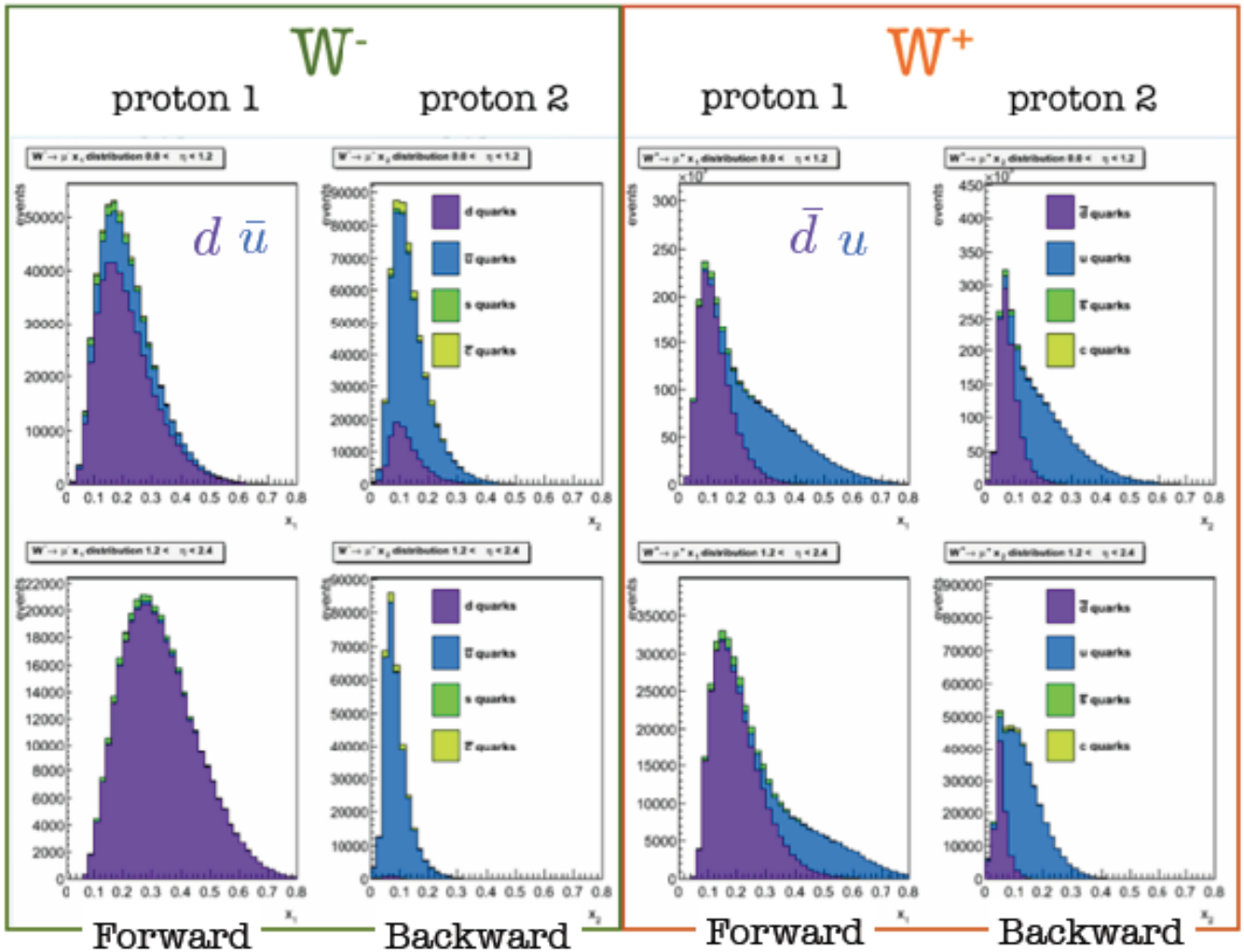
Di-Jet projections in STAR



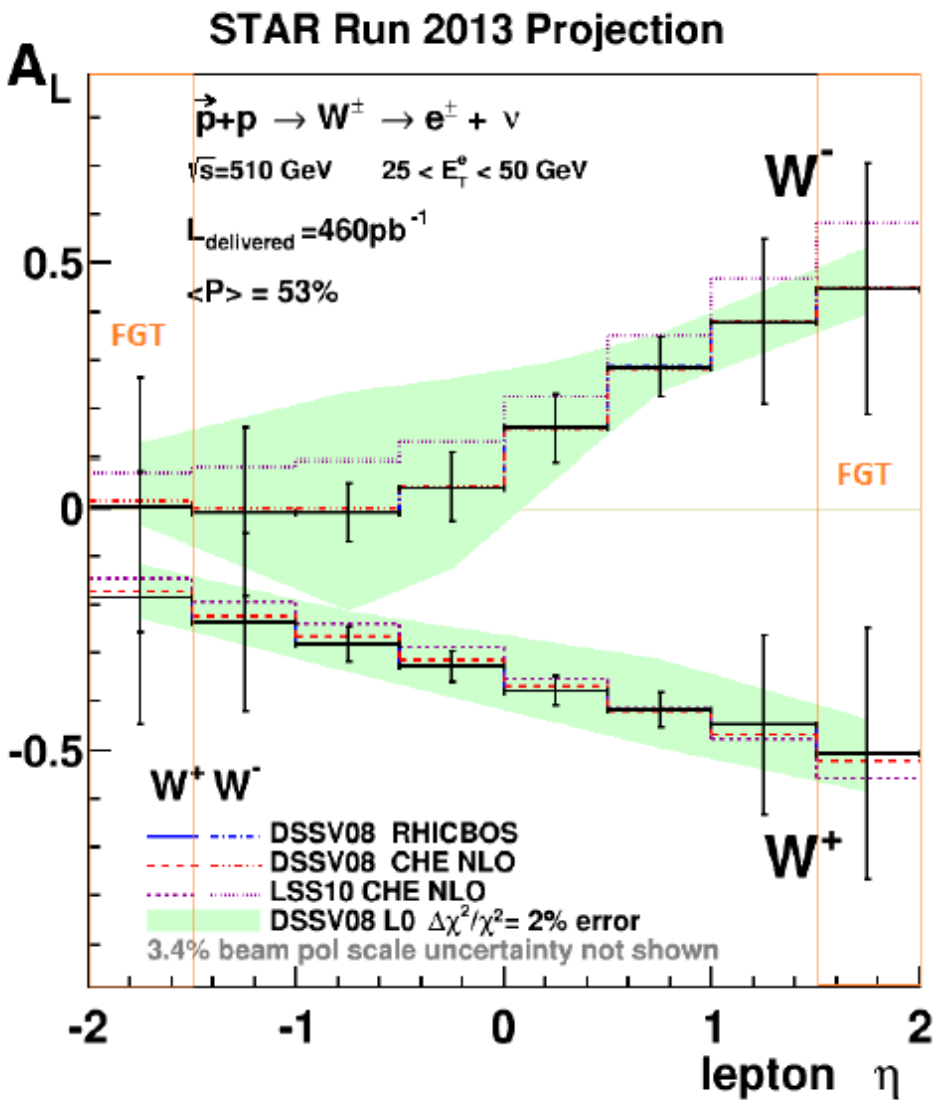
W: Decay lepton kinematics

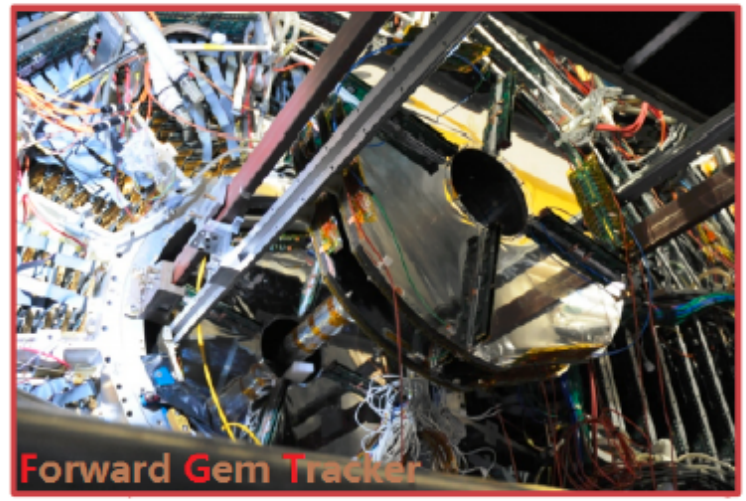






W: STAR Projection

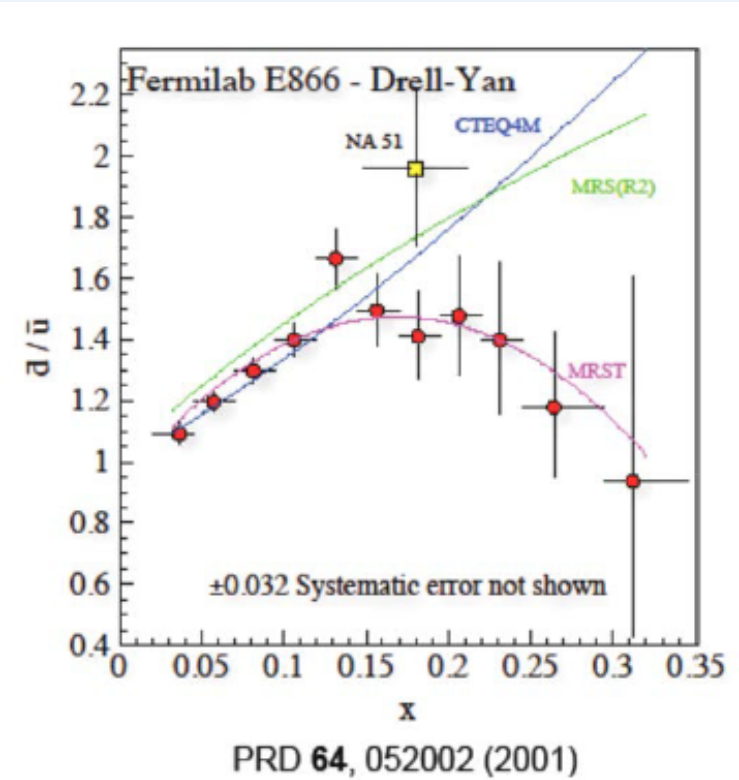




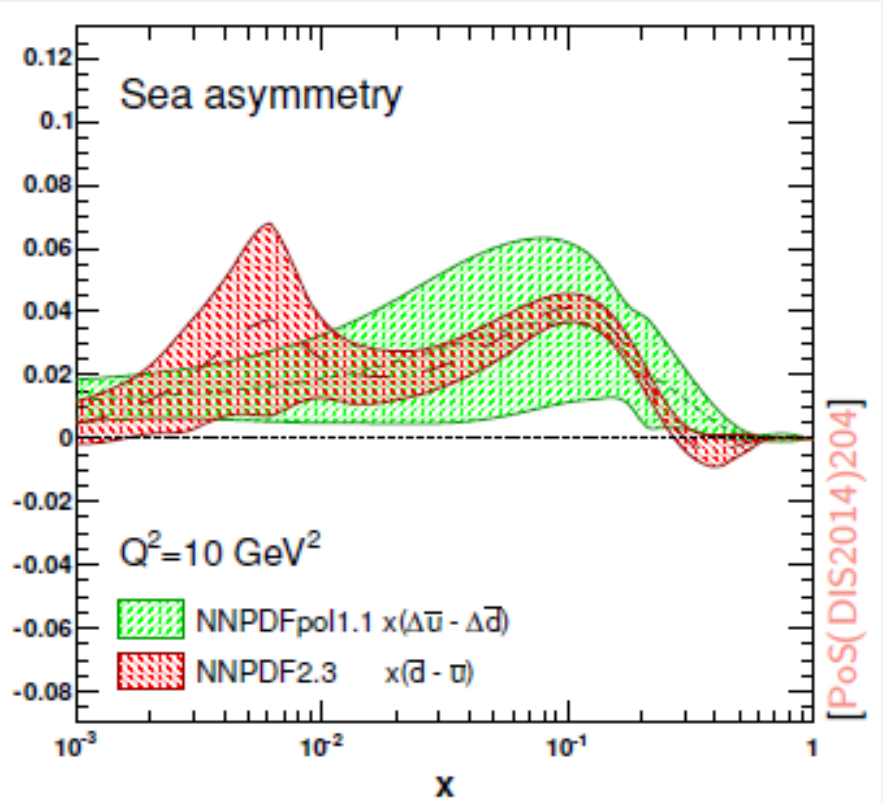
FGT was fully installed for Run13

- Extension of backward and forward acceptance enhances sensitivity to $\bar{u}$ and $\bar{d}$ quark polarization
- Higher precision result is expected from much larger statistics of run13 database (being analyzed).

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



PRD **64**, 052002 (2001)

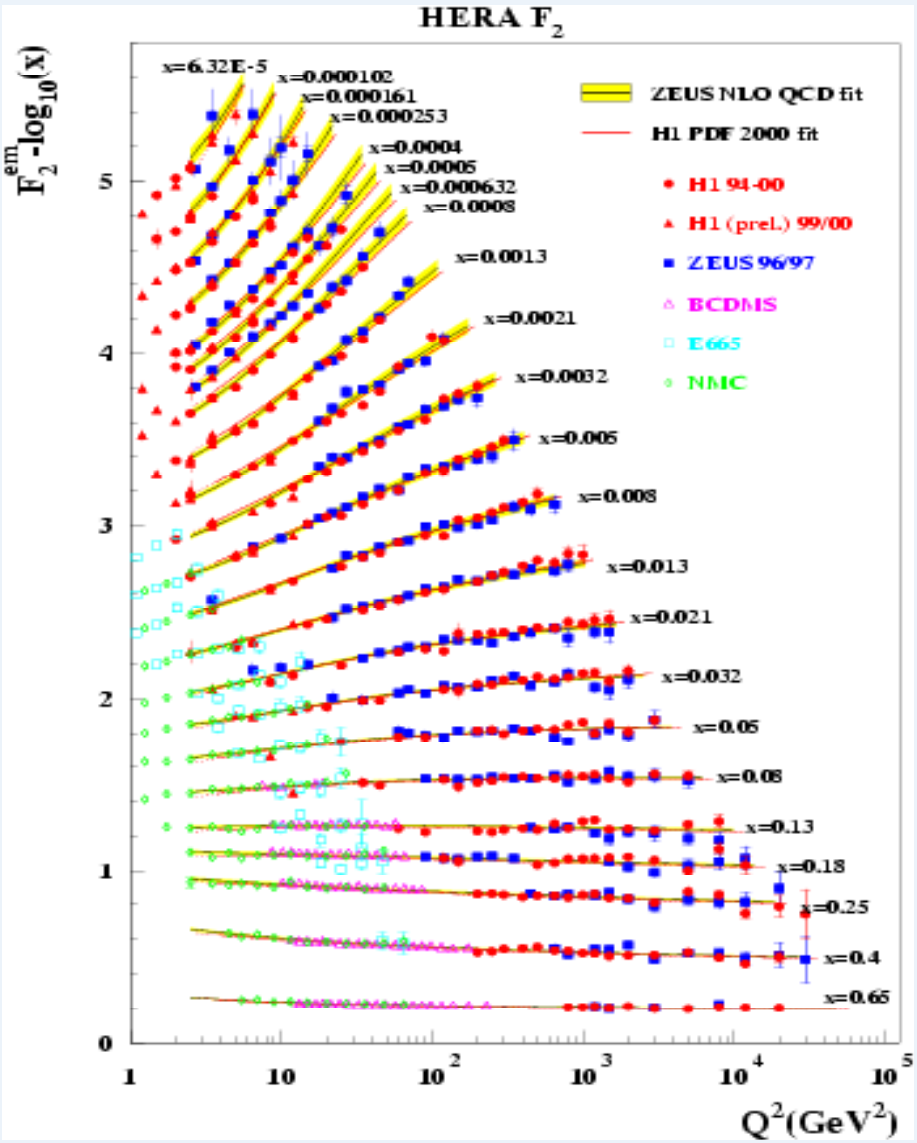


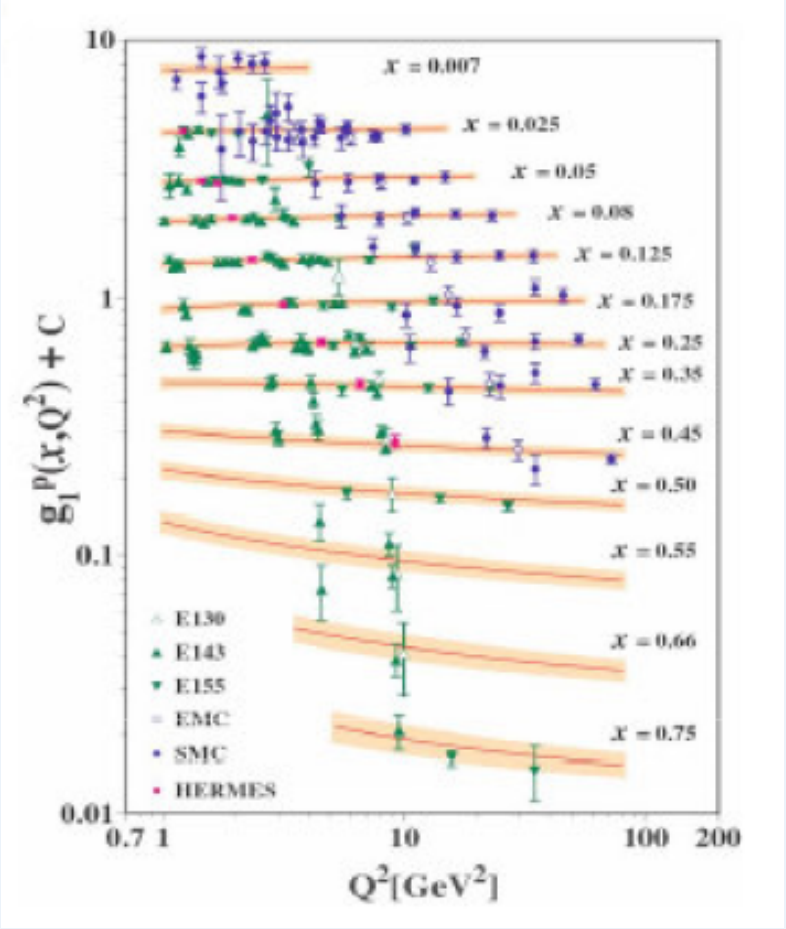
[PoS(DIS2014)204]

Unpolarized sea is not symmetric

Symmetry breaking in polarized sea?

From Inclusive Pol. DIS

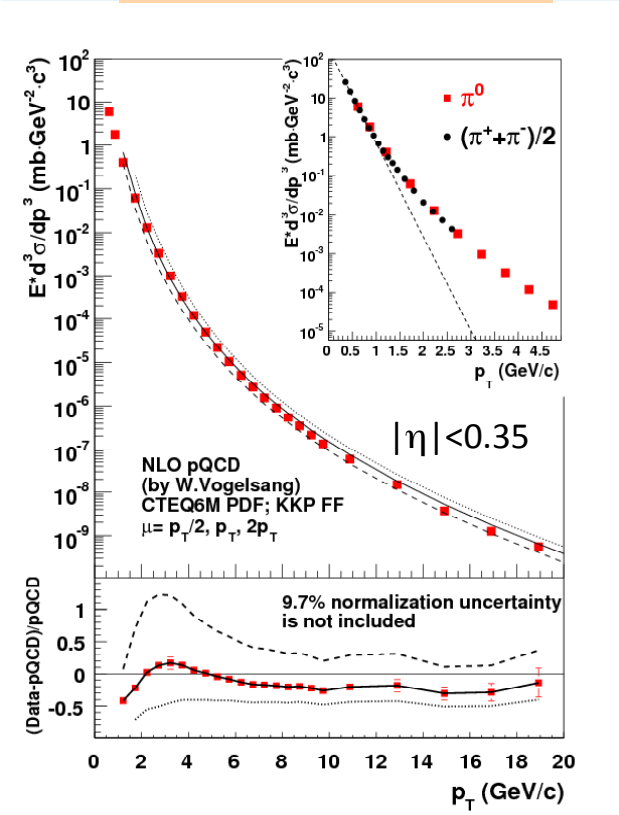




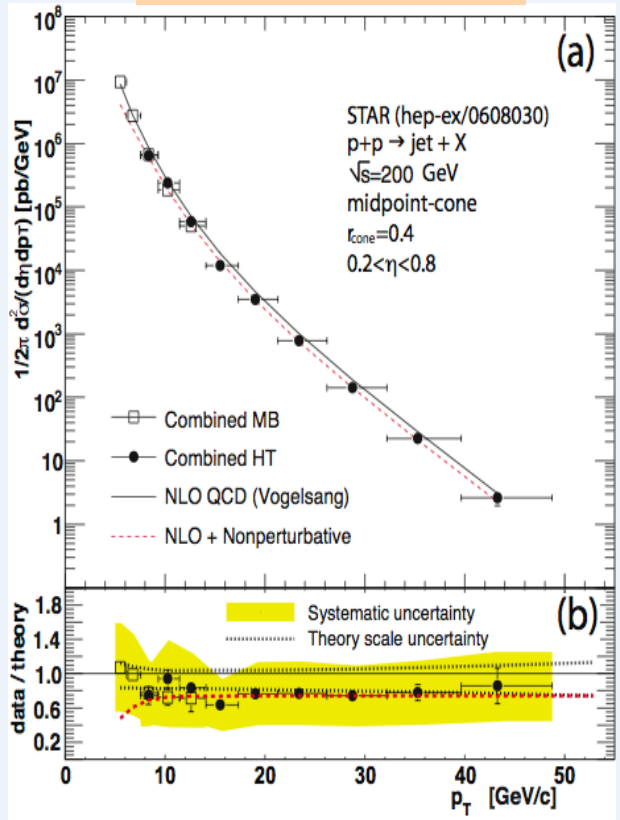
$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta q\\ \Delta g\end{pmatrix}=\begin{pmatrix}\Delta P_{qq} & \Delta P_{qg}\\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q\\ \Delta g\end{pmatrix}$$

Unpol. Cross Section and pQCD in pp

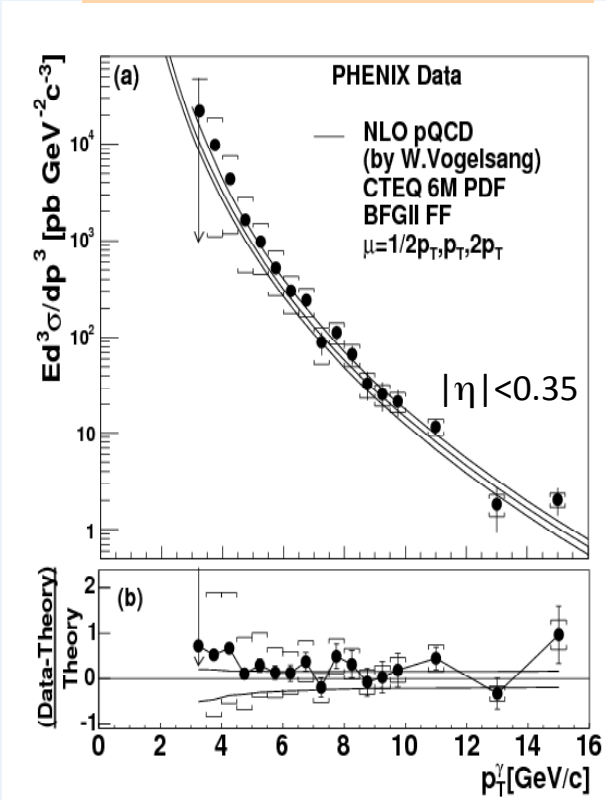
PHENIX pp→ π^0 X
PRD76, 051106



STAR: pp→jet X
PRL 97, 252001

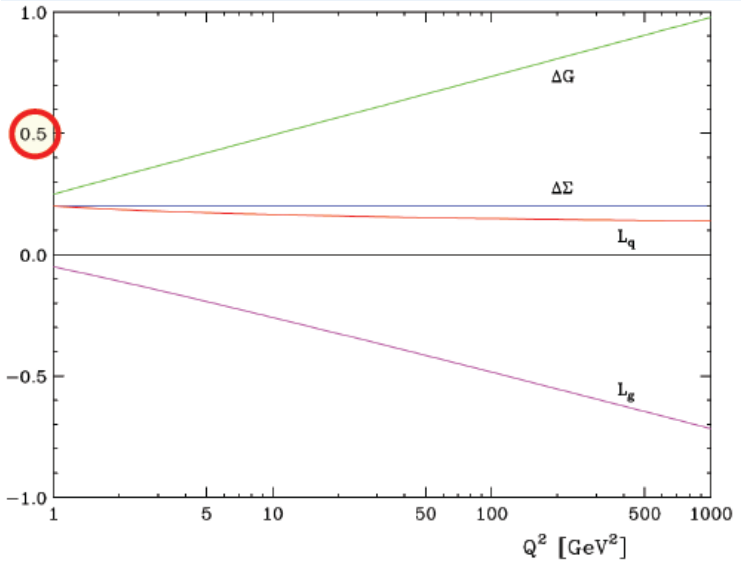


PHENIX pp→γ X
PRL 98, 012002



Good agreement between NLO pQCD calculations and data ⇒ pQCD can be used to extract spin dependent pdf's from RHIC data.

Q2 dependence



ΔG is dynamic value – Q^2 dependent
ΔG can be large at large Q^2 (and can be >>1/2) no matter how small it is at some low Q^2
Large ΔG at large Q^2 is compensated by L_g

$$\frac{1}{2}^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

$$\frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\frac{3n_f}{3n_f + 16} = 0.18$$

$$\Delta g + L_g = \frac{1}{2}\frac{16}{3n_f + 16} = 0.32$$