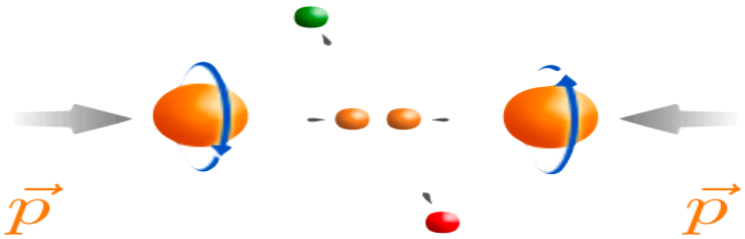
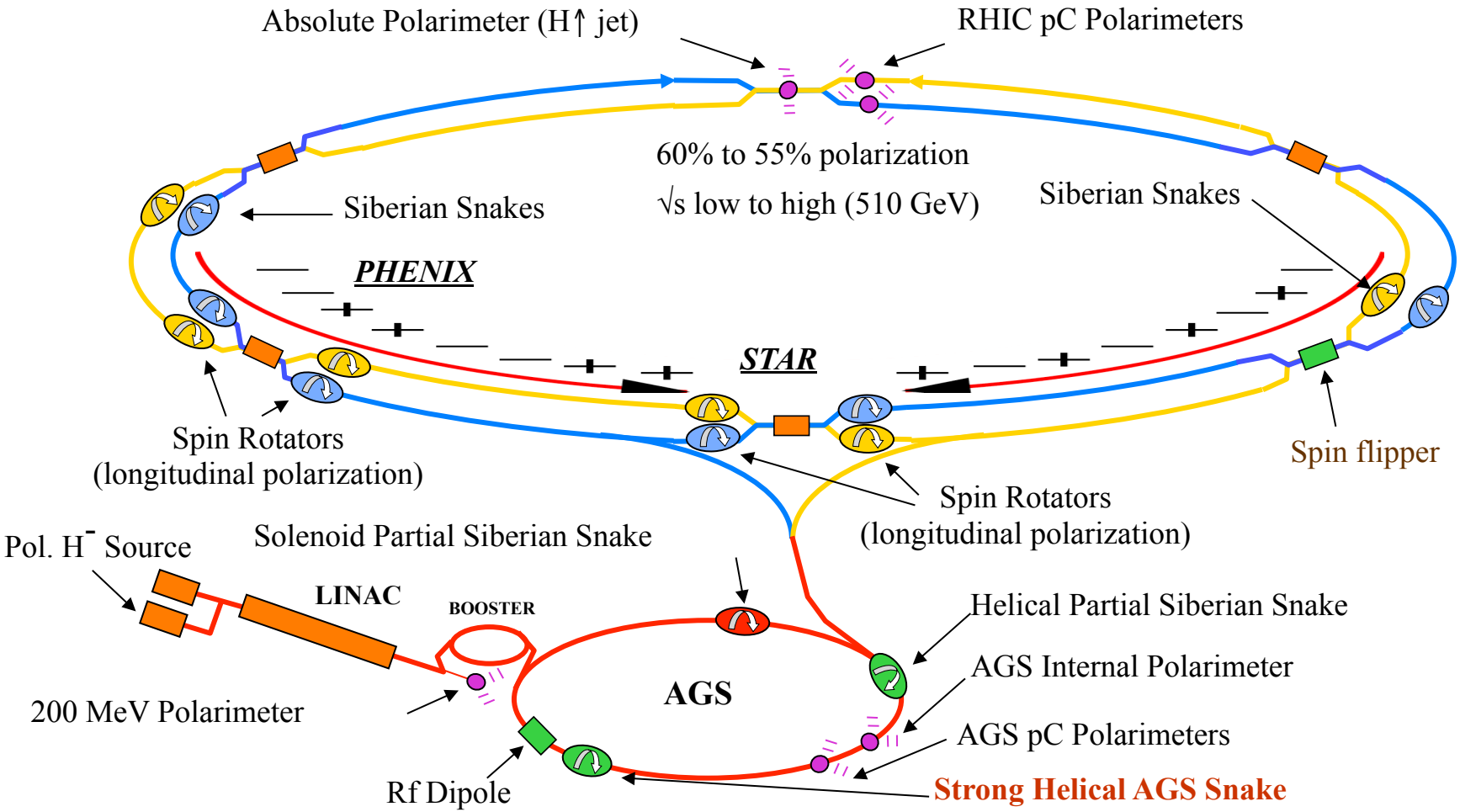
Recent results on nucleon spin structure study at RHIC

Qinghua Xu, Shandong University

6th workshop on "Hadron Physics in China and Opportunities in US" , Lanzhou, July 2014

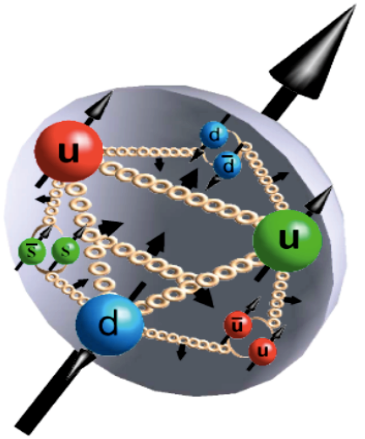


RHIC- the first polarized pp collider in the world



- Spin direction changes from bunch to bunch
- Spin rotators provide choice of spin orientation

Spin structure of nucleon



- Spin sum rule (longitudinal case, *X. Ji*):

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + < L_{q,g} >$$

Quark spin, (~30%)-DIS

Gluon spin, RHIC

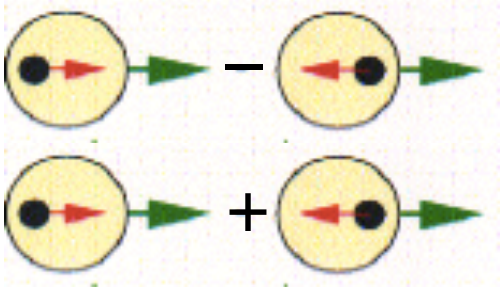
Orbital Angular Momenta Little known (DVCS)

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \qquad [\Delta q = \int_0^1 \Delta q(x)\,dx]$$

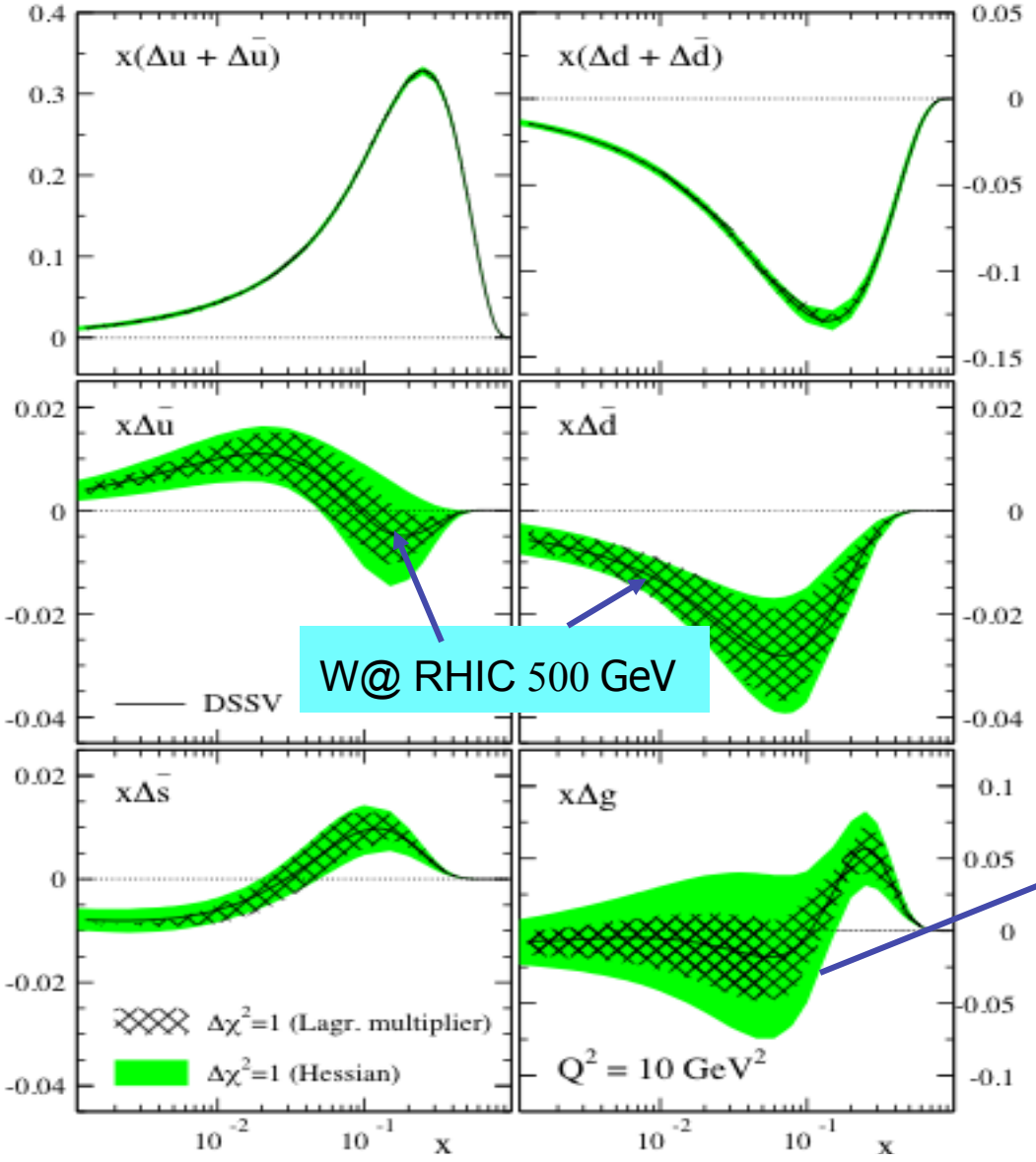
- Polarized parton densities:

$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

$$q(x,Q^2) = q^+(x,Q^2) + q^-(x,Q^2)$$



Detailed knowledge on $\Delta q(x)$, $\Delta g(x)$- global fit using DIS and pp data



D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)

The RHIC spin program

- Longitudinal spin program: determination of helicity distributions:
  - Gluon polarization $\Delta g(x)$ in the nucleon

    -- inclusive jet, hadrons

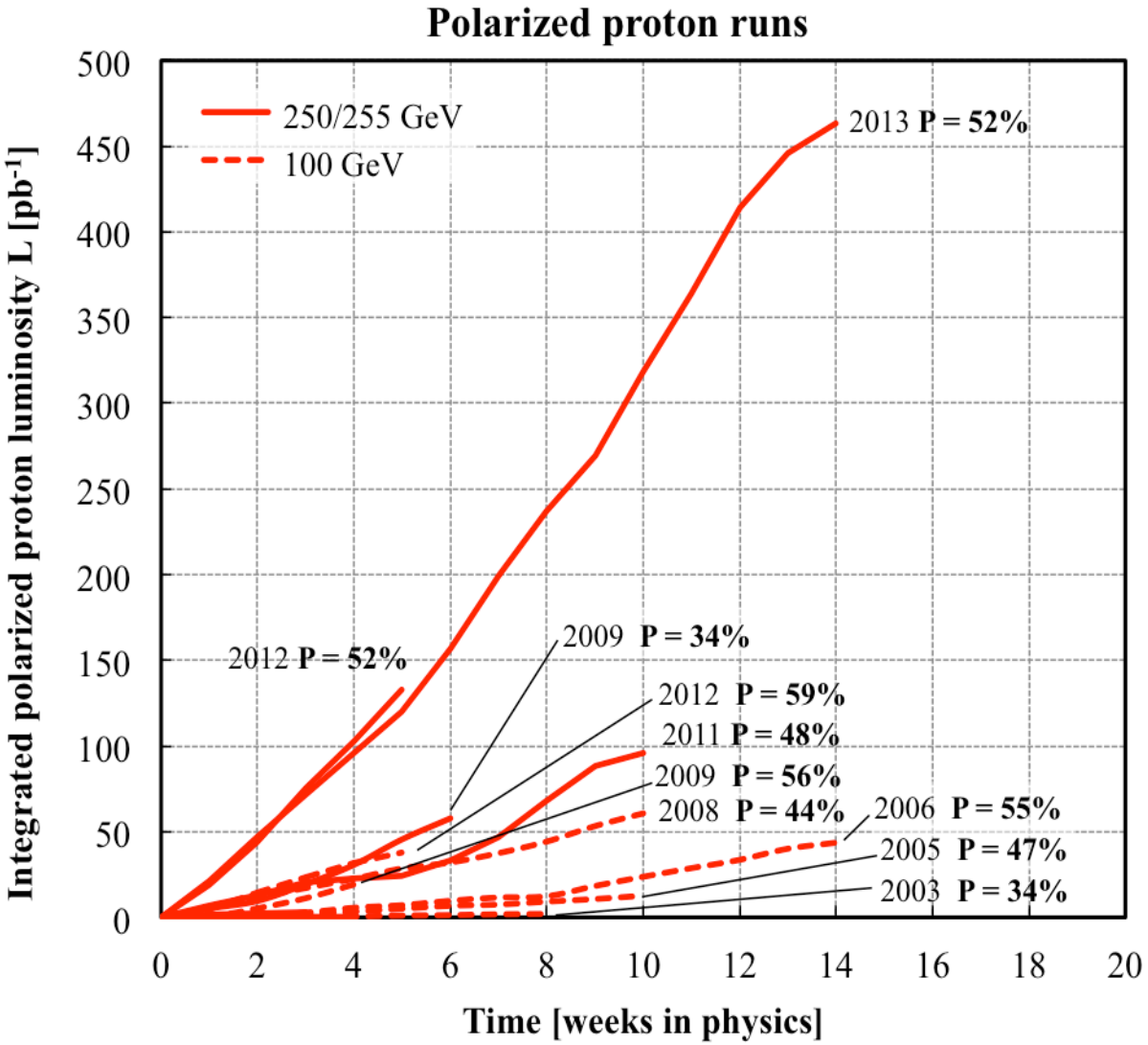
    -- di-jets, γ+jet
  - Flavor separation: quark & anti-quark polarization

    -- RHIC 500 GeV program ($W^{\pm}$ production)

- Transverse spin program: (Transversity, Sivers, Collins)
  - Single spin asymmetry A_N (SSA) on π^0, jet, W
  - Azimuthal correlations of hadron & jet (jet+$\pi^{\pm}$)
  - Di-hadron correlations within a jet (IFF)

RHIC performance with pp collisions

- Long runs with long. polarization at 200 GeV in 2005, 2006, 2009.
- Collisions at 500 GeV with long. pol. in 2009, 2012 and 2013.
- Long runs with trans. pol. in 2006, 2008, 2012 at 200GeV and 2011 at 500 GeV.



STAR - Solenoid Tracker At RHIC

Magnet

- 0.5 T Solenoid

Triggering & Luminosity Monitor

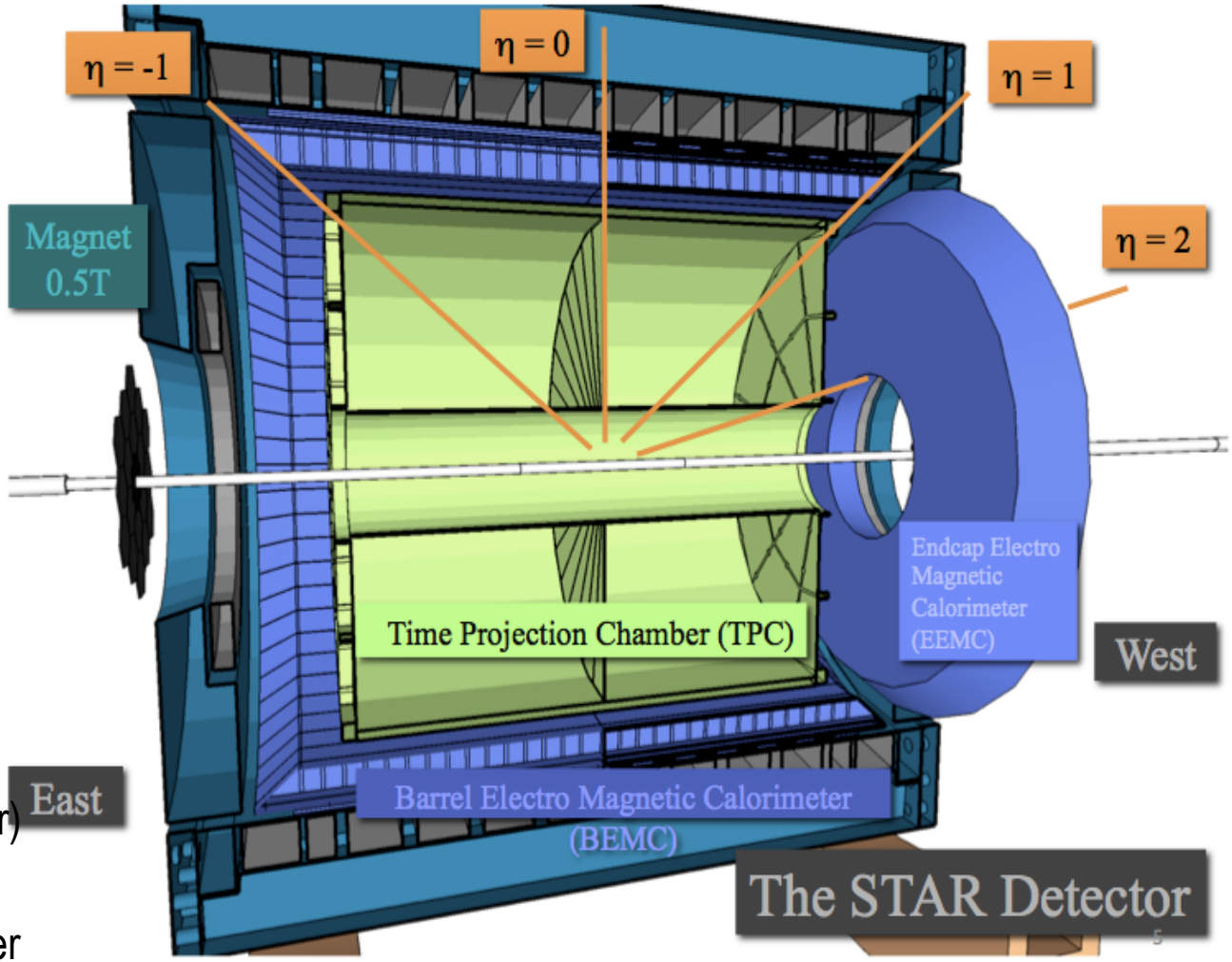
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters
- Vertex Position Detector

Central Tracking

- Large-volume TPC
  - $|\eta| < 1.3$

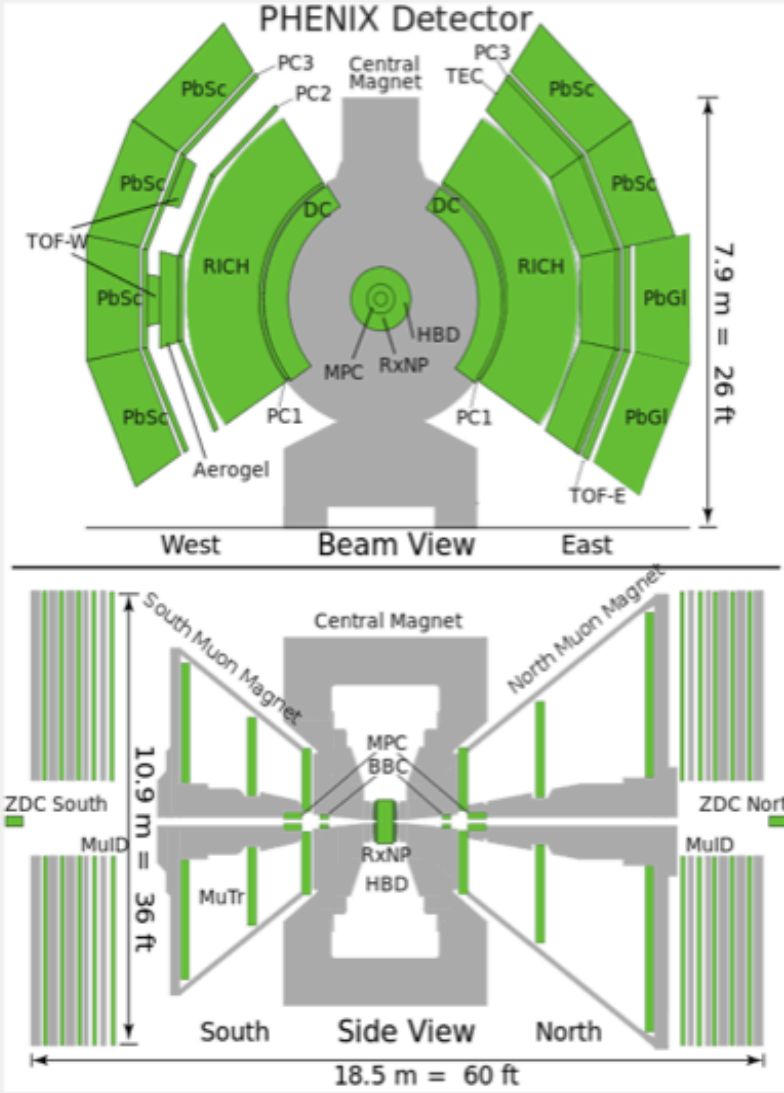
Calorimetry

- Barrel EMC (Pb/Scintilator)
  - $|\eta| < 1.0$
- Endcap EMC (Pb/Scintillator)
  - $1.0 < \eta < 2.0$
- Forward Meson Spectrometer
  - $2.5 < \eta < 4.0$



The PHENIX Experiment at RHIC

- **Central arms**
  - $|\eta| < 0.375$, $\Delta\varphi = (\pi/2) \times 2$
  - Tracking
    - Drift Chamber (Multi-Wire Proportional)
    - Pad Chambers
  - Particle ID
    - Ring Imaging Cherenkov detector
    - Hadron Blind Detector (Gas Electron Multiplier) in '09 and '10
  - EM Calorimetry
    - Two separate technologies for cross-check
    - Lead-Scintillator (**PbSc**)
      - sampling calorimeter
    - Lead-Glass (**PbSc**)
      - Cherenkov radiation calorimeter
- **Forward arms**
  - Tracking, Calorimetry, Muon Identification
  - Minbias detectors
    - Zero Degree Calorimeter:
    - $|\Delta\eta| = > 6$, $|z| = 18$m
      - outside of bending field, sees neutrals
    - Beam-Beam Counter: $\Delta\eta = \pm(3.1 \text{ to } 3.9)$, $|z| = 1.4$m
      - reconstruct collision z-vertex online with ~5cm



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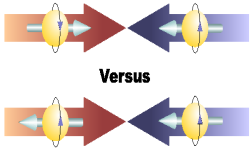
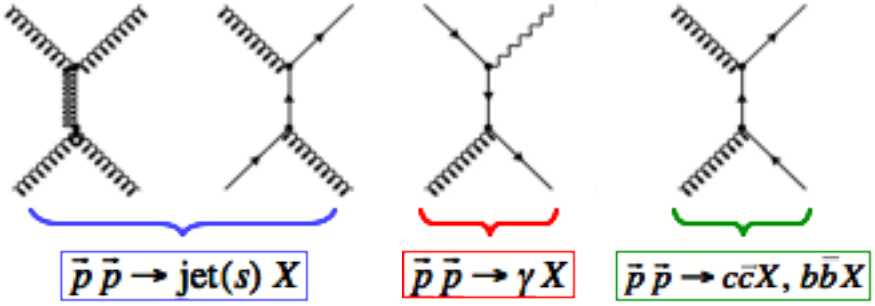
Accessing Δg(x) in pp collision

- Longitudinal spin asymmetry:

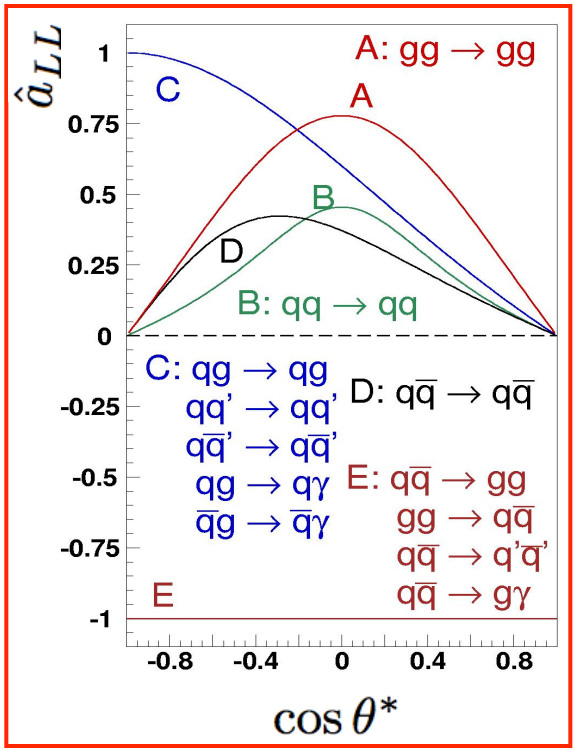


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

Δf_1 Δf_2 $\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}$ D_f^{π}

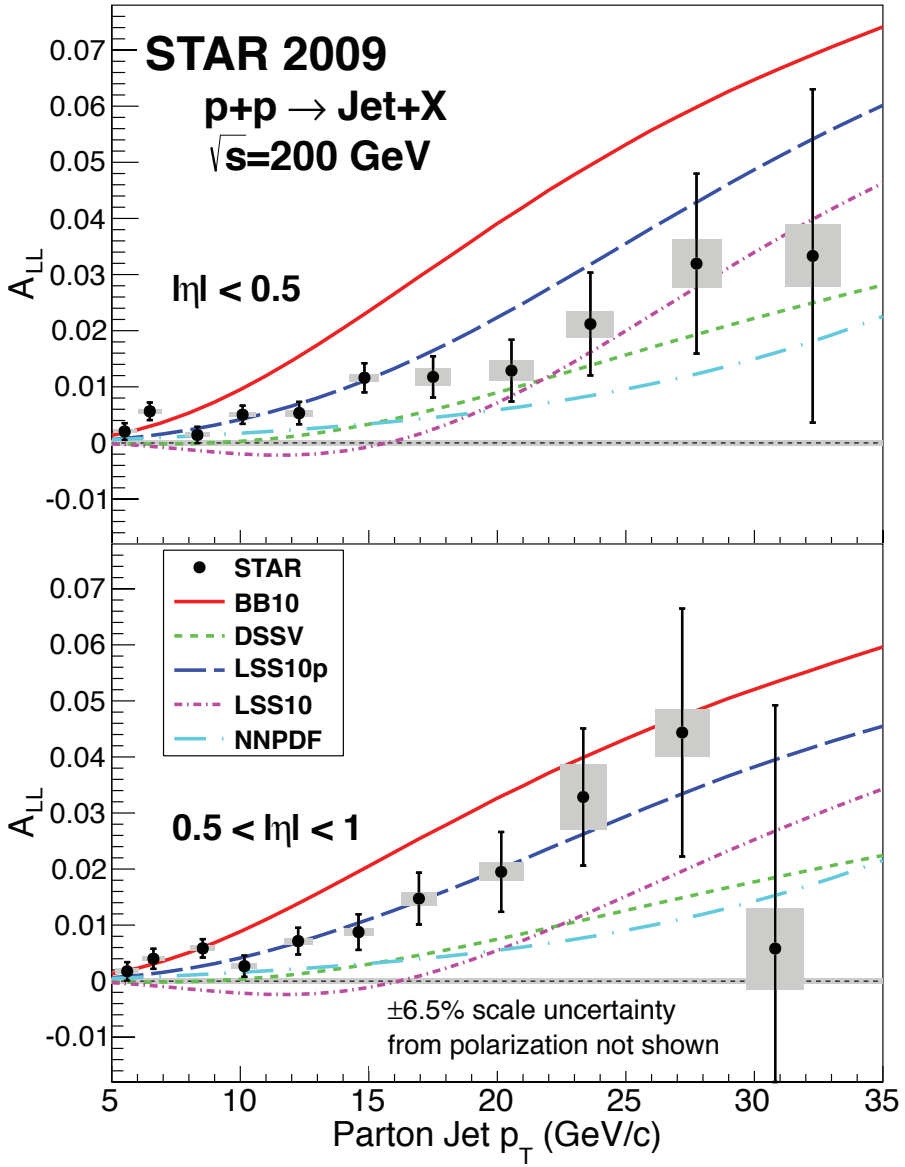


$\vec{p}\vec{p} \to jet + X$	No D_f^{π}. Average over partonic kinematics
$\vec{p}\vec{p} \to jet + jet$	No D_f^{π}. Reconstruct partonic kinematics.
$\vec{p}\vec{p} \to \pi^{+/-} + X$ $\vec{p}\vec{p} \to \pi^{0} + X$	Requires D_f^{π} for interpretation

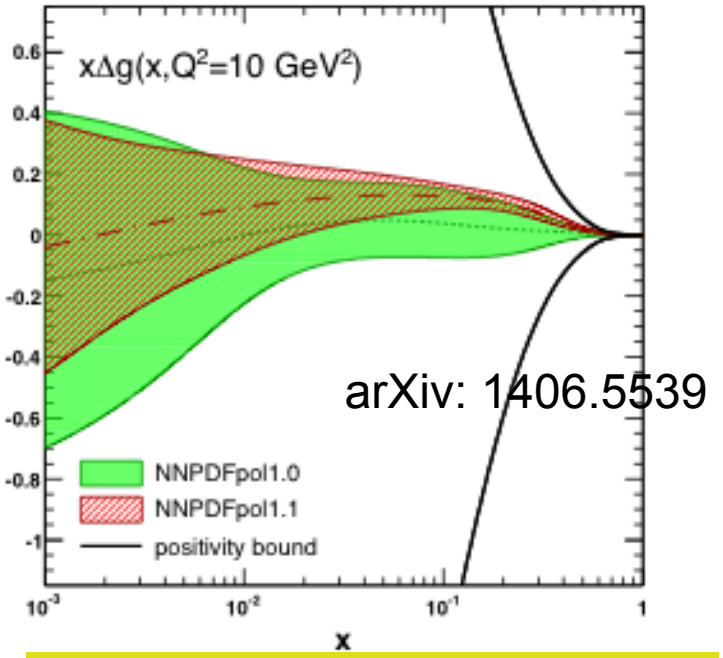


STAR inclusive jet A_{LL} from run9

STAR, arXiv:1405.5134



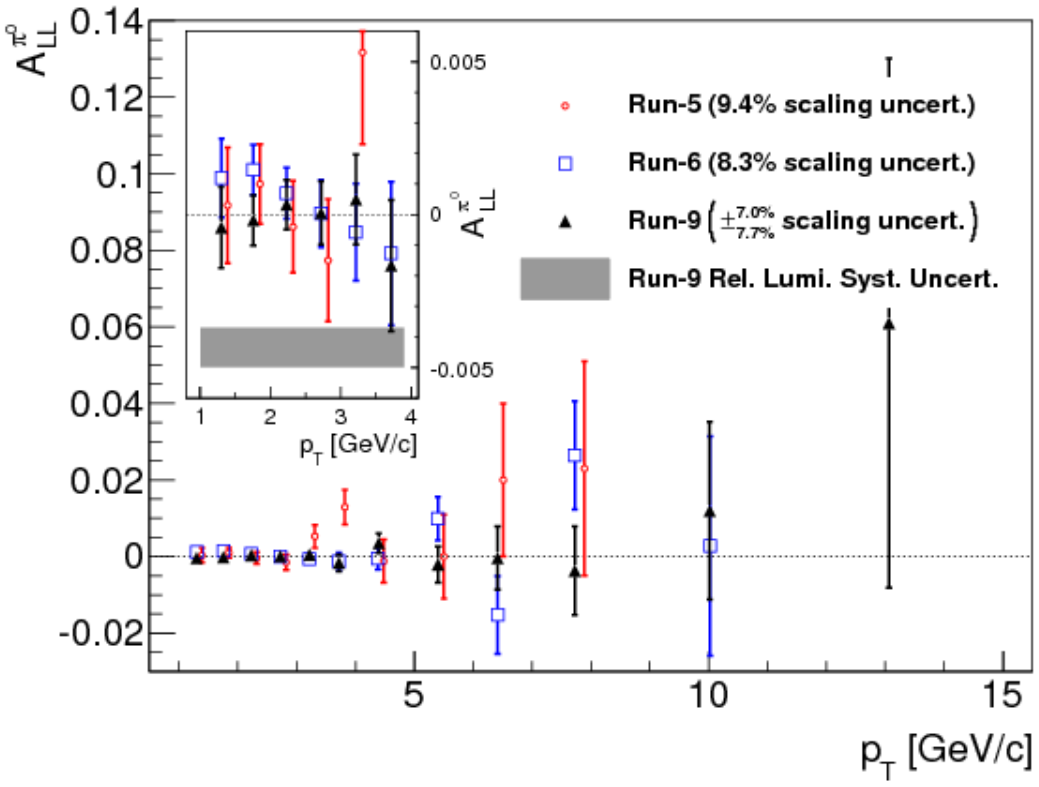
- 2009 STAR data is a factor of 4 more precise than 2006.
- The A_{LL} asymmetry is small, but clearly non-zero !
- Impact of STAR data in NNPDF



$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10 GeV^2) dx = 0.17 \pm 0.06$$

PHENIX results on π^0 A_{LL}

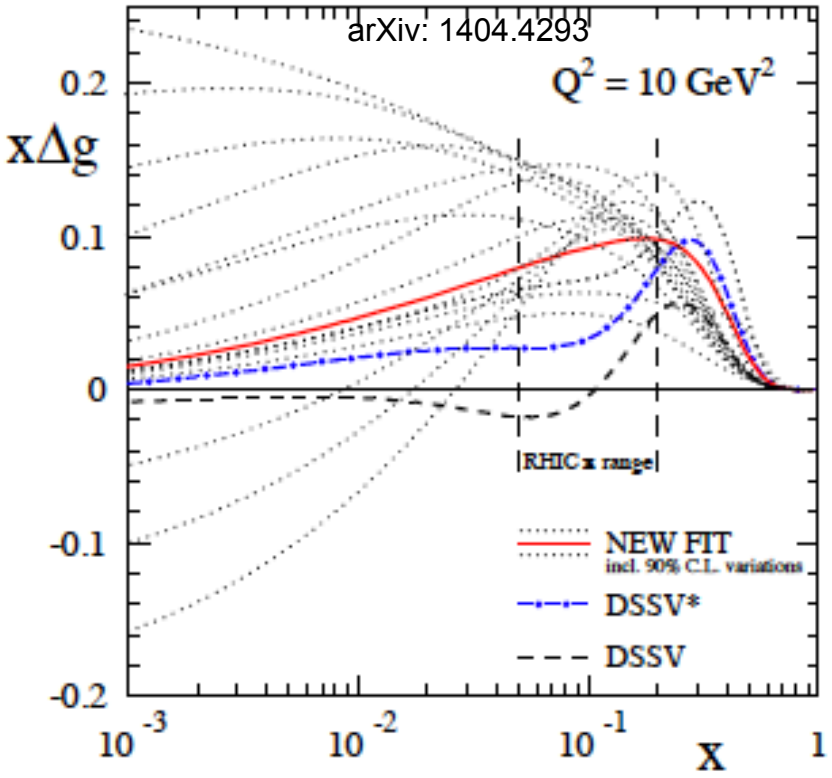
PHENIX- arXiv:1402.6296

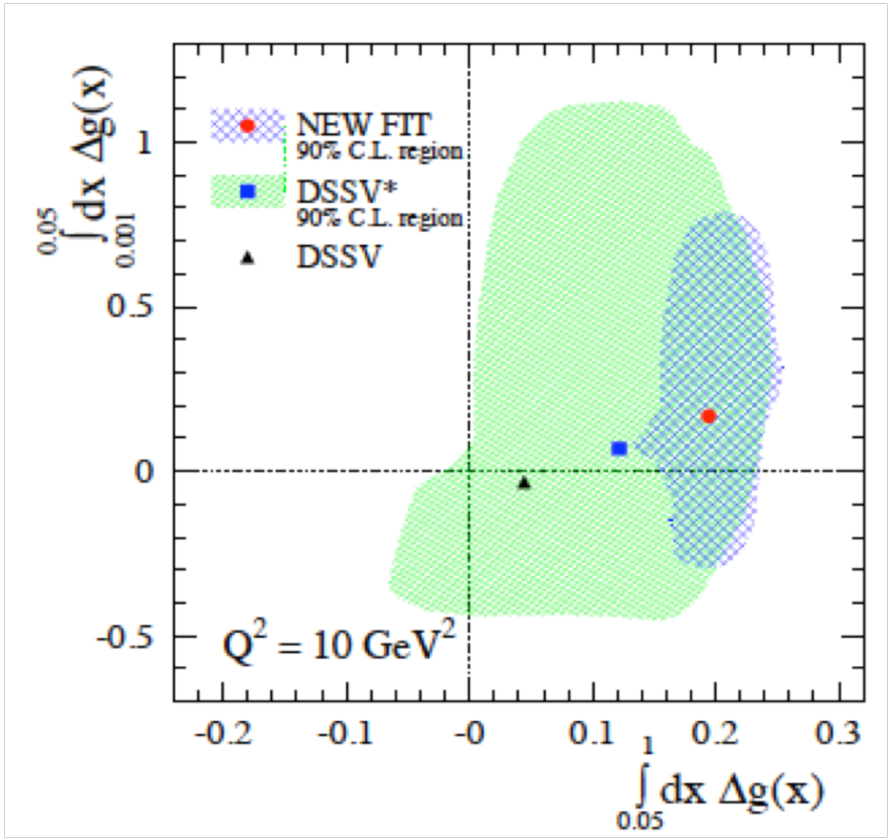


- High precision measurement at mid-rapidity
- Results are consistent with zero within uncertainty

DSSV global analysis including both STAR & PHENIX data -Observation of gluon polarization

DSSV, PRL113,12001(2014)





DSSV: arXiv:0904.3821
DSSV*: DSSV + all new (SI)DIS
DSSV: DSSV* & RHIC 2009

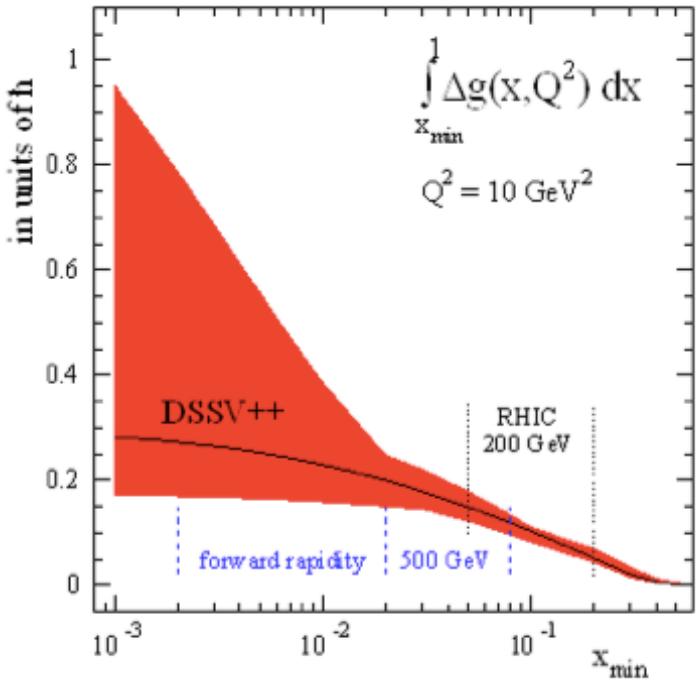
$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ GeV^2$$

To further constrain Δg(x), need to go to lower x

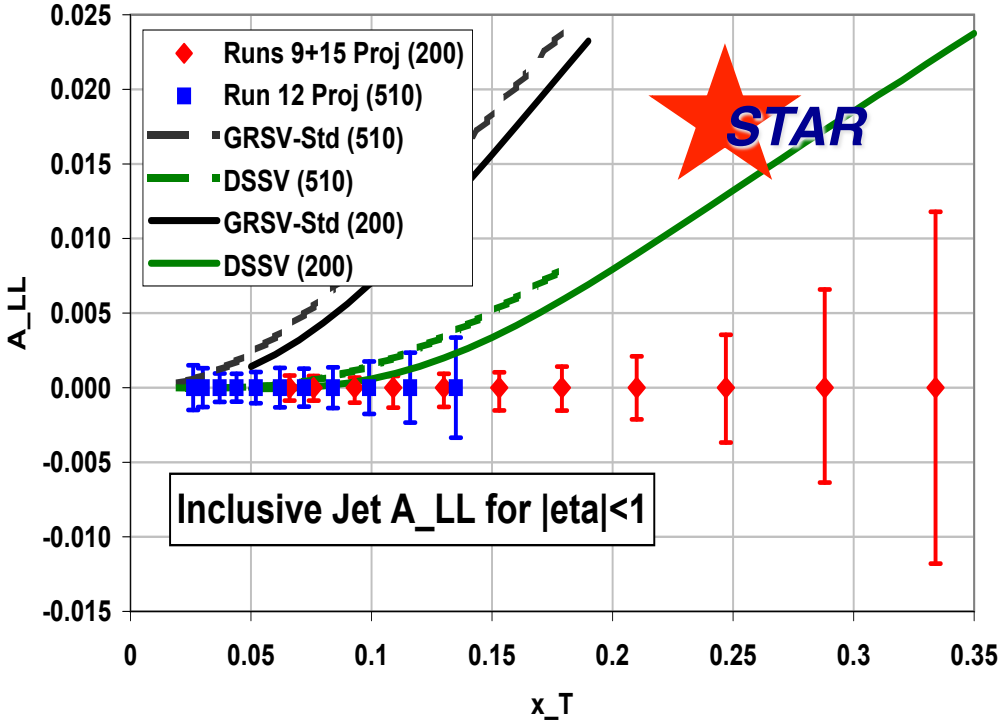
-> higher energy, forward di-jets

Projections with future jet measurements

- *Can we further improve our knowledge on Δg(x)? Yes!*



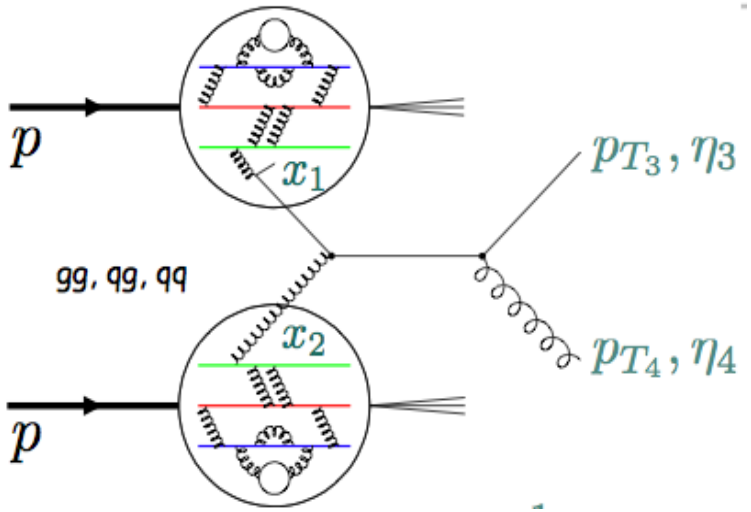
arXiv:1304.0079



- Measure inclusive jet A_{LL} with STAR 2012(+2013) of 510 GeV collision.
- STAR expects to double the existing 200 GeV data sample during the 2015 RHIC run.

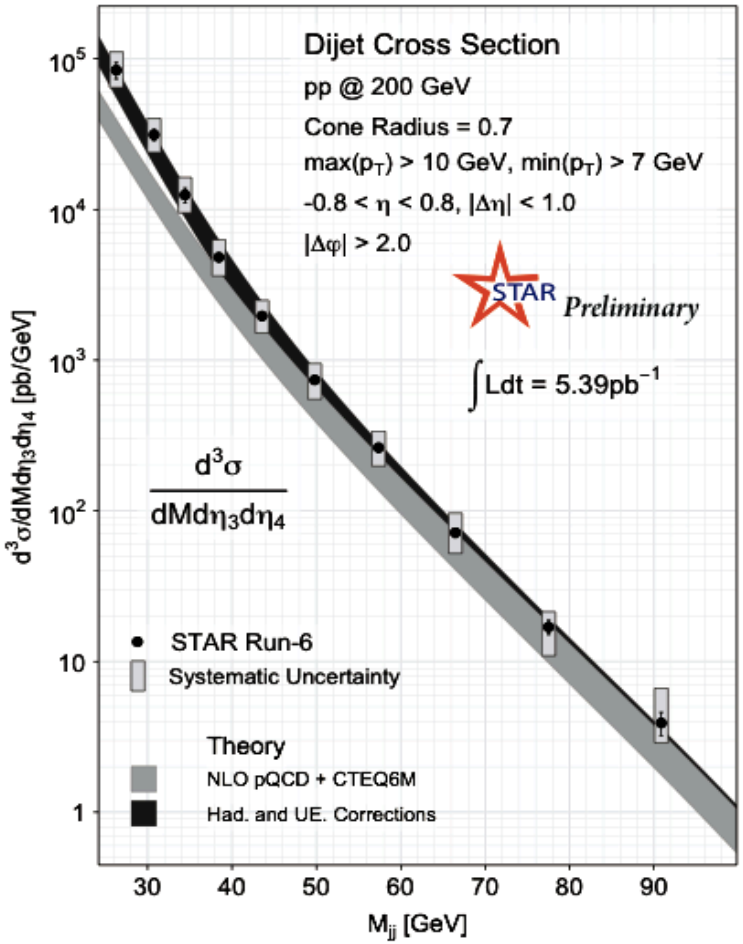
Correlation measurements with partonic kinematics

- Access to partonic kinematics through di-jet production

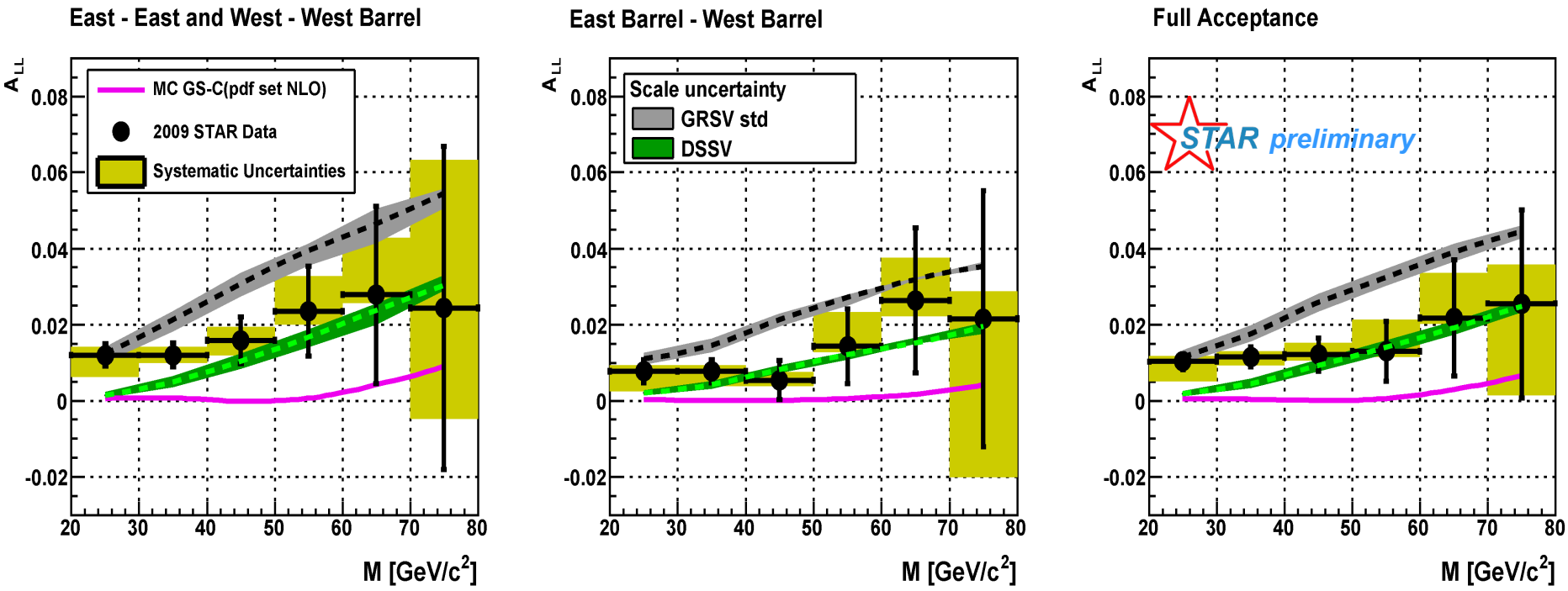


$$x_{1(2)} = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3(-\eta_3)} + p_{T4}e^{\eta_4(-\eta_4)}\right)$$

2006 di-jet cross section at 200 GeV



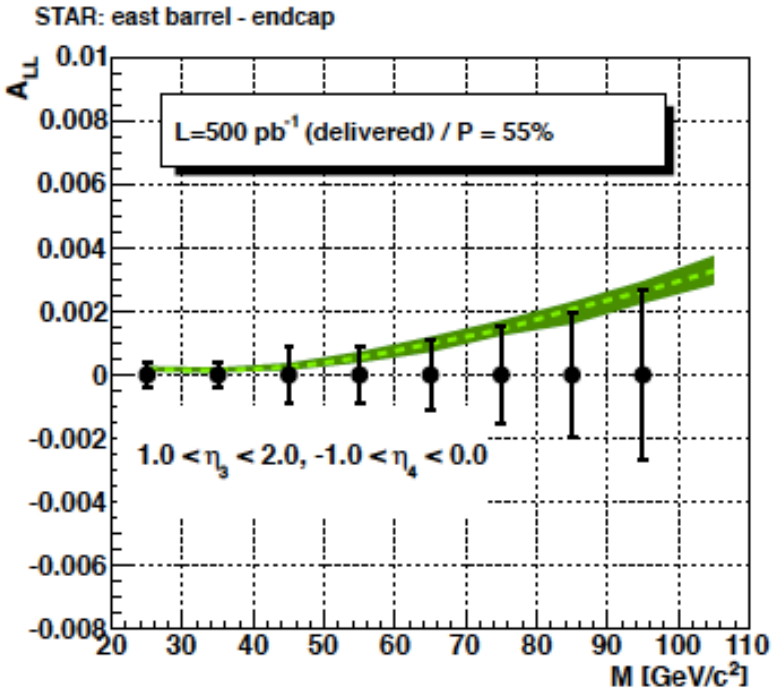
STAR di-jet A_{LL} from run9

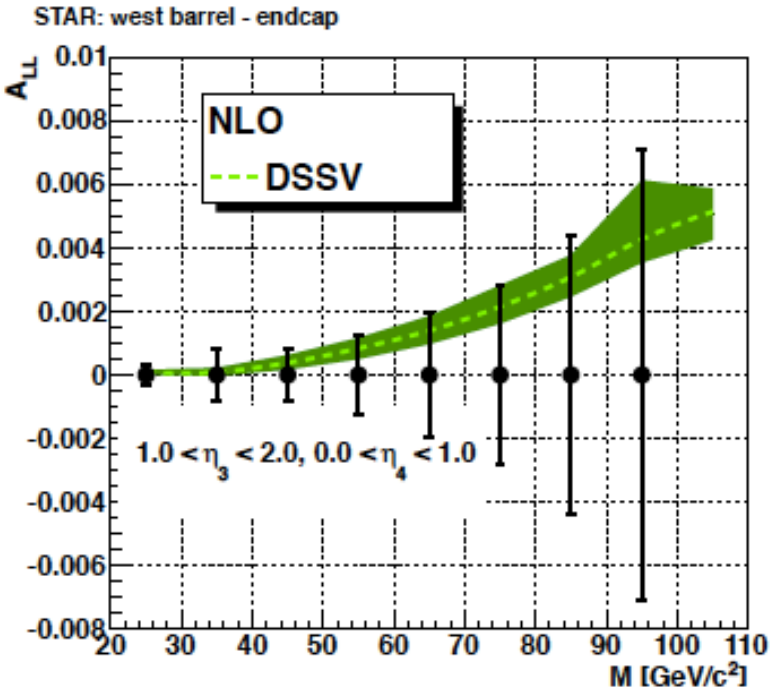


- For fixed M, different kinematic regions sample different *x* ranges
  - East-east and west-west sample higher x_1, lower x_2, and smaller $|\cos(\theta^*)|$
  - East-west samples lower x_1, higher x_2, and larger $|\cos(\theta^*)|$
- Di-jet allows for constraints on the shape of $\Delta g(x)$.

Projections of di-jet A_{LL} at 500 GeV

p+p→ jet+jet+X at 500 GeV

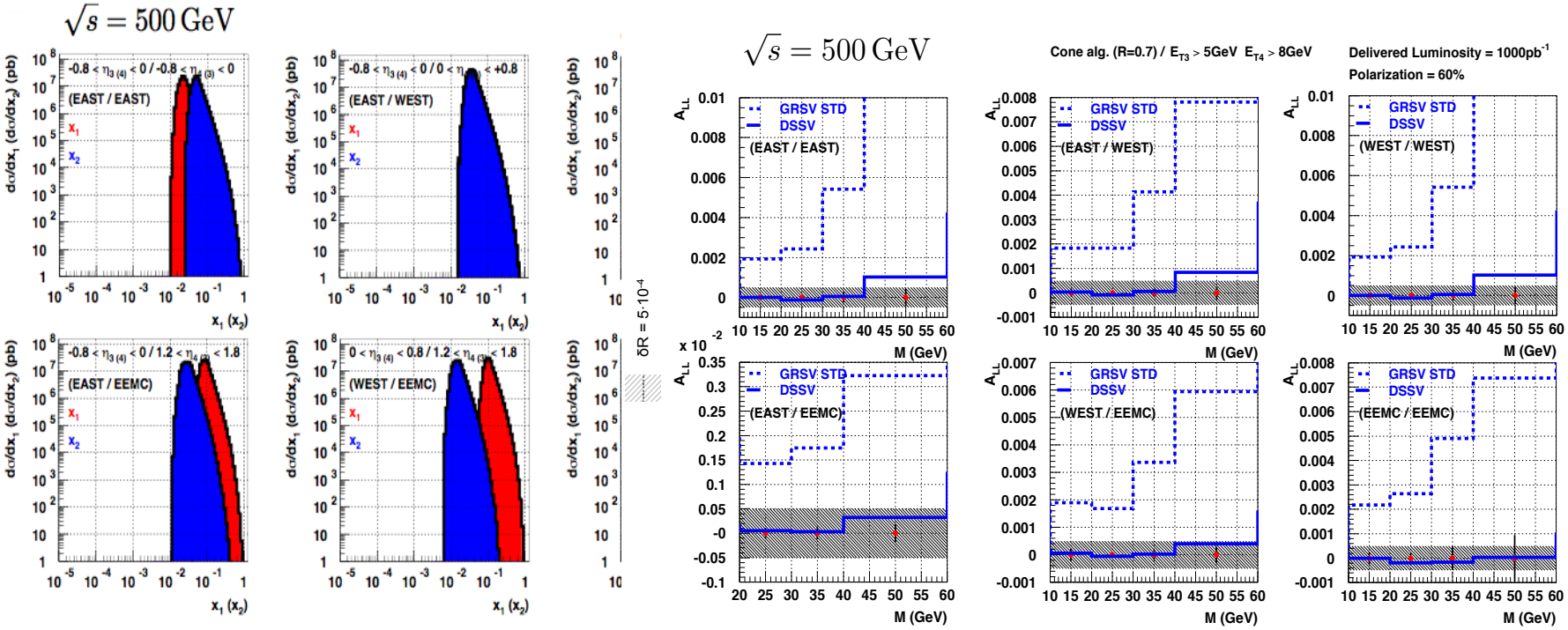




- Projections show expected sensitivity for 2012+2013 data.
- Higher energy accesses lower x_g ->Expect smaller A_{LL}

Projections of di-jet A_{LL} at 500 GeV (2020+)

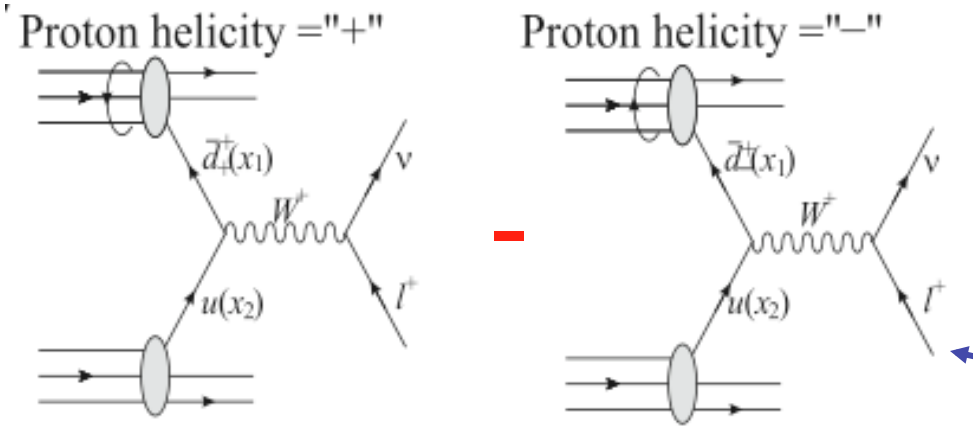
p+p→ jet+jet+X at 500 GeV



- This will be the measurement to constrain Δg(x) at lowest *x* before EIC.

Probing sea quark pol. via W production

- Quark polarimetry with W-bosons:



$$\propto \Delta\bar{d}(x)u(x)$$

W-detection through high energy lepton

- Spin asymmetry measurements:

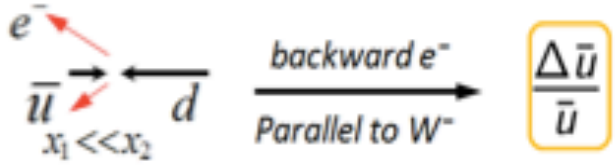
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} = \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

$$A_L^{W^-} = \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \end{cases}$$

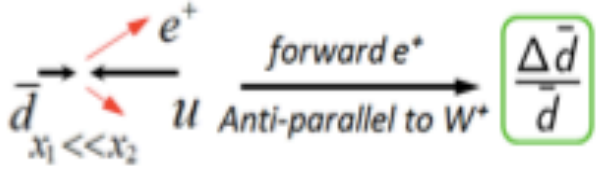
Expectation of W A_L

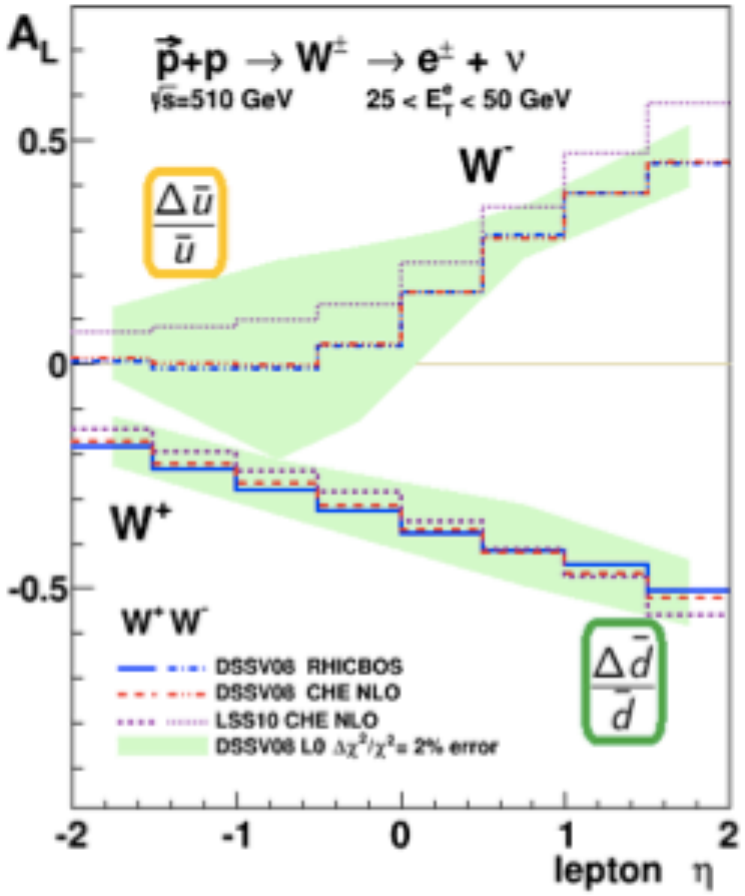
- Large parity-violating asymmetries expected
- Simplified interpretation at forward and backward Rapidity.

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



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



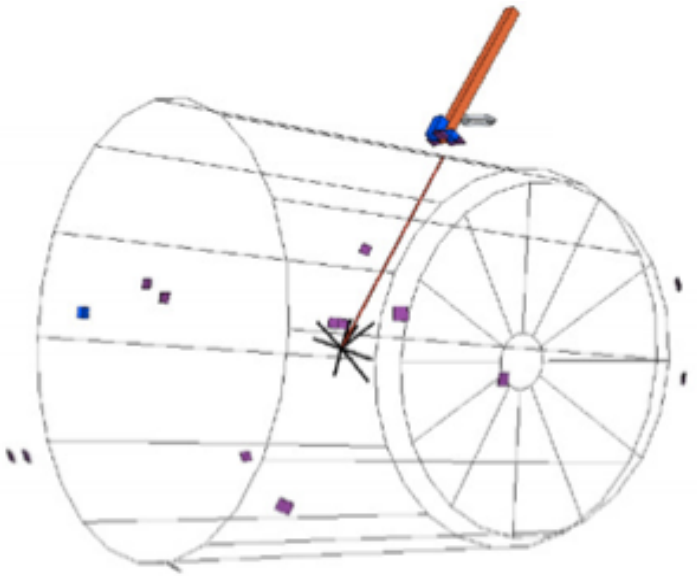


*Charged lepton tends to emitted parallel (anti-parallel) to $W^-(W^+)$ due to the handedness of produced neutrino.

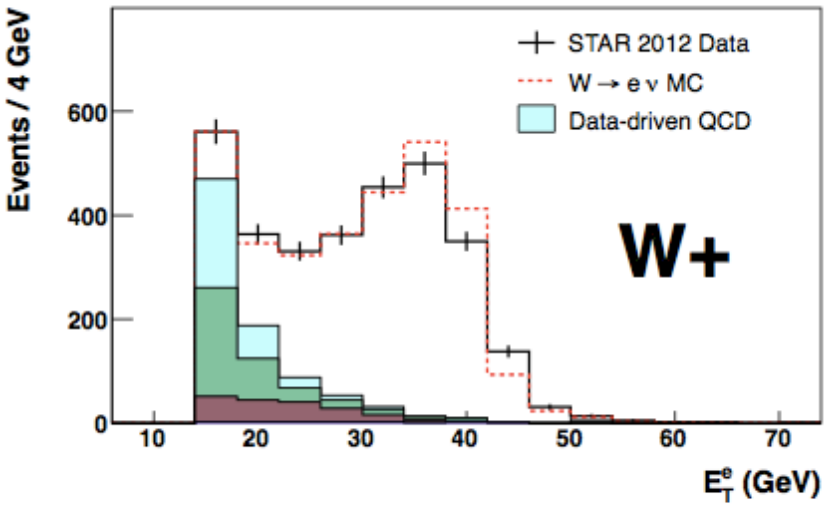
W selection at STAR : Jacobian peak

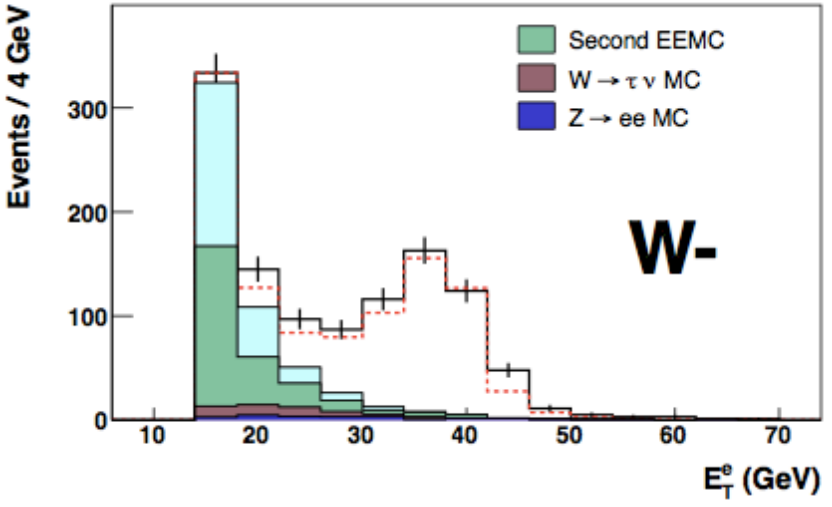
$W \rightarrow e + \nu$ Candidate Event:

- Isolated track pointing to isolated EM cluster in calorimeter
- Large "missing energy" opposite the electron candidate



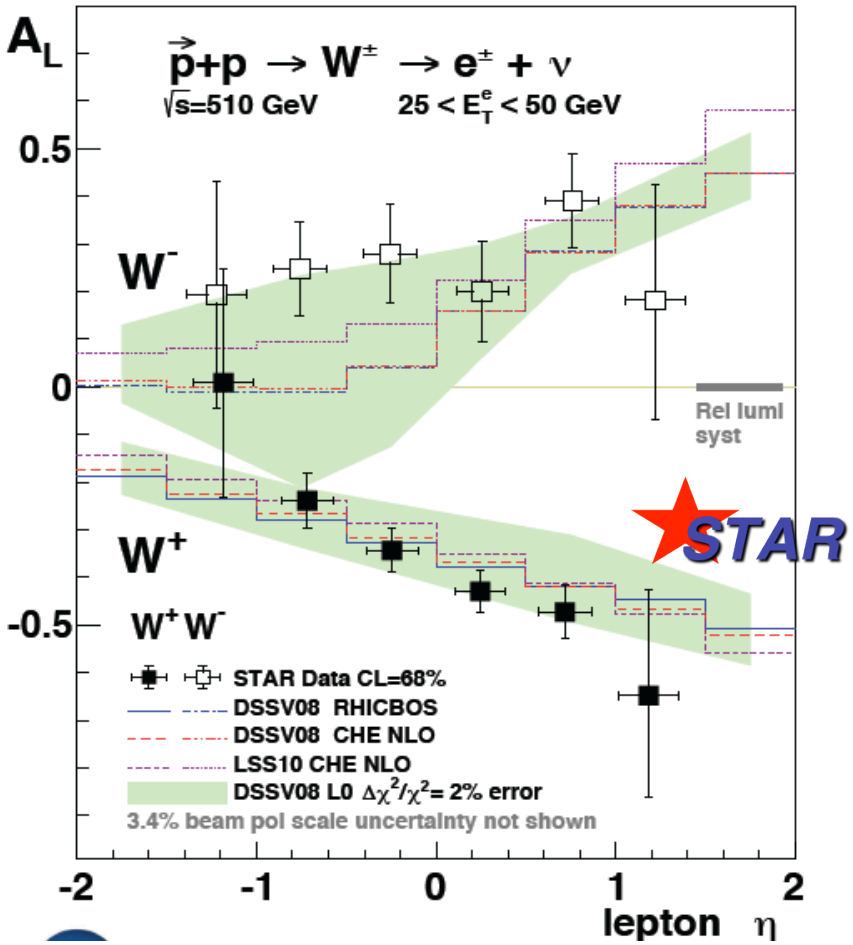
Signal of Jacobian peak with E_T distribution:





NEW RHIC 2012 W A_L results

arXiv:1404.6880, to appear in PRL



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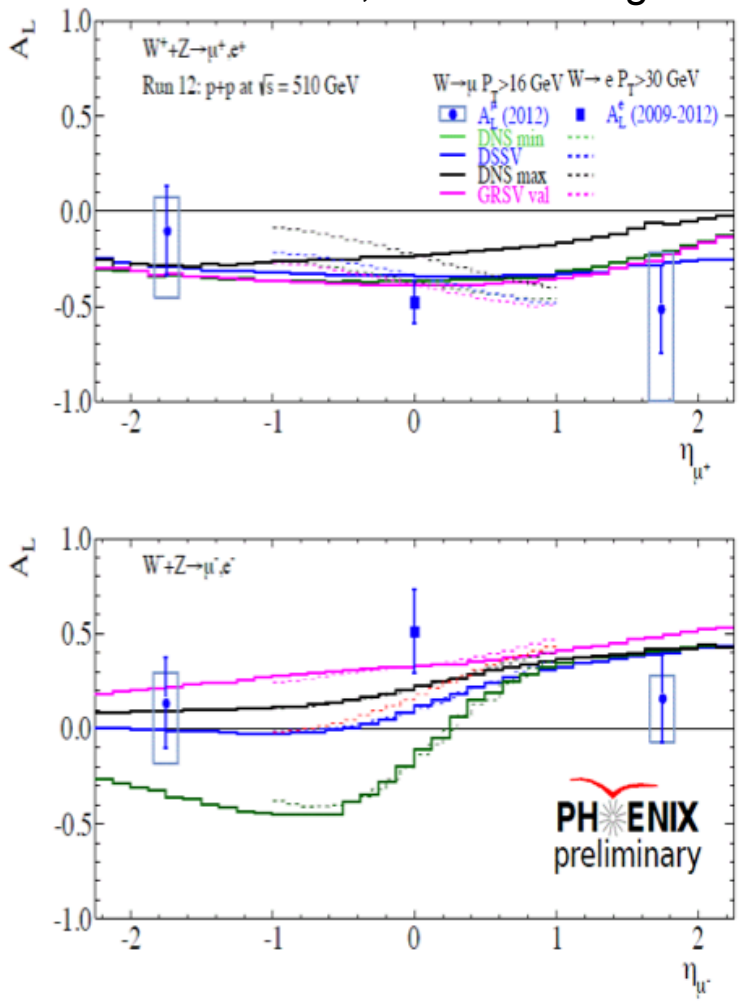


- A_L of W- shows indication that data is larger than the DSSV predictions
- A_L of W+ is consistent with theoretical predictions with DSSV pdf.

W A_{LL} results from STAR

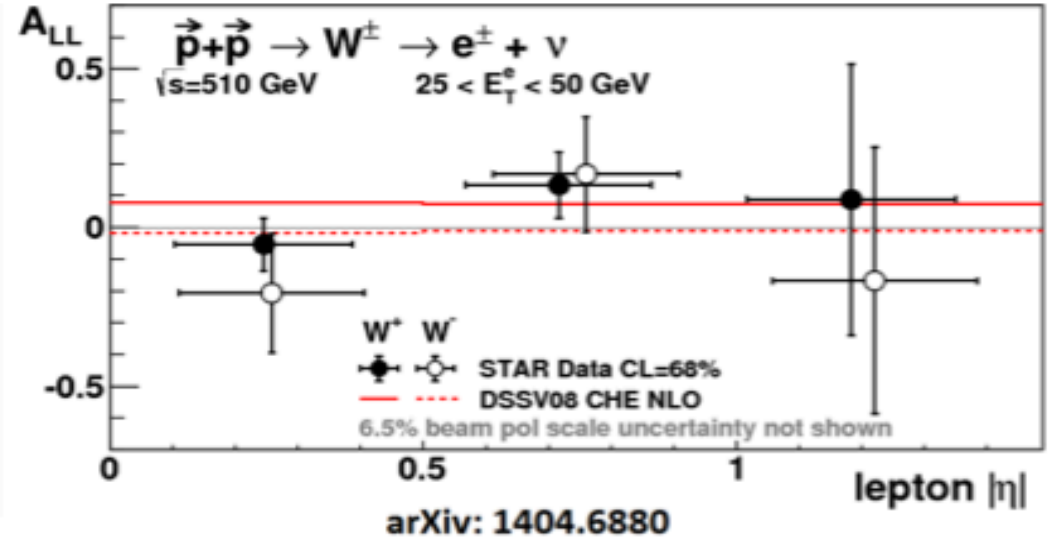
Measure double spin asymmetry:

$$A_{LL} = \frac{(\sigma^{++}+\sigma^{--})-(\sigma^{+-}+\sigma^{-+})}{(\sigma^{++}+\sigma^{--})+(\sigma^{+-}+\sigma^{-+})}$$

- Probes different combination of quark polarizations

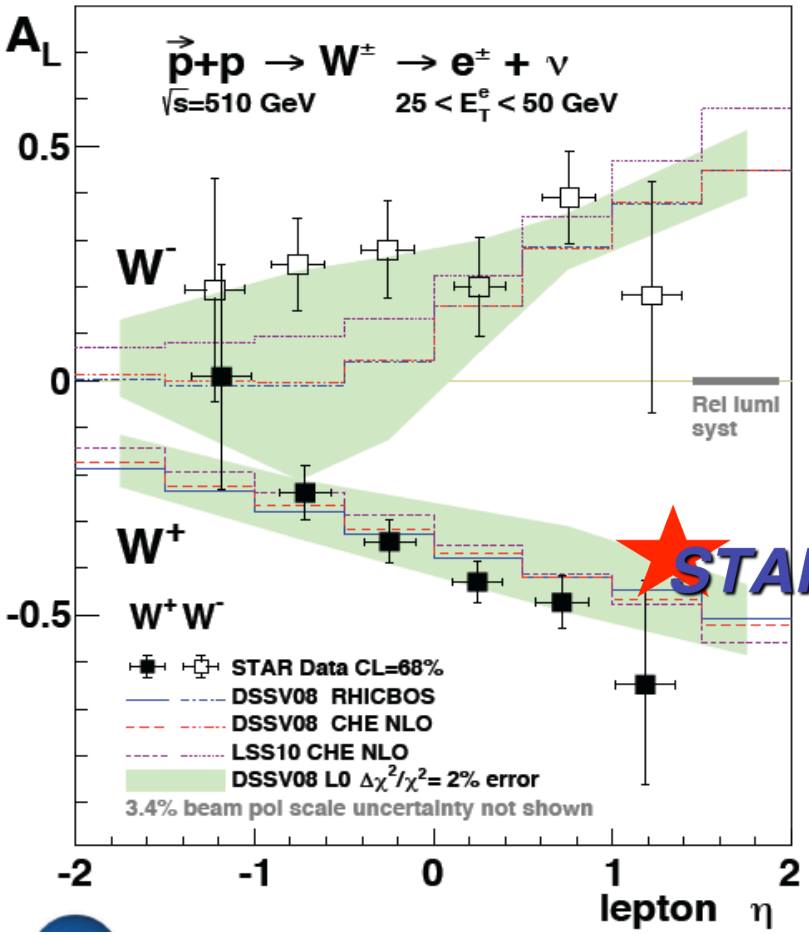
$$A_{LL}^{W^+} \sim \frac{\Delta u}{u}\frac{\Delta \bar{d}}{\bar{d}} \qquad A_{LL}^{W^-} \sim \frac{\Delta d}{d}\frac{\Delta \bar{u}}{u}$$

- Proposed to test positivity constraints using a combination of A_L and A_{LL}
- First measurement is consistent with predictions from DSSV



Global Analysis with STAR 2012 W results

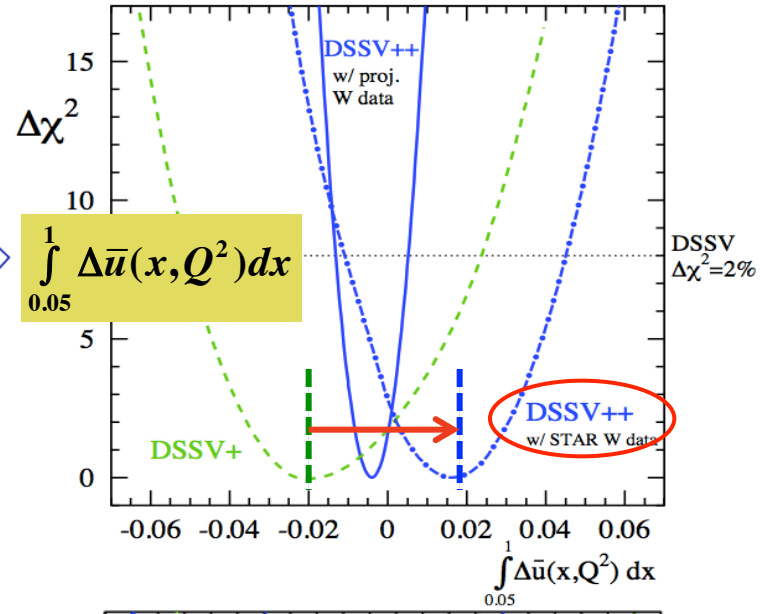
arXiv:1404.6880, to appear in PRL

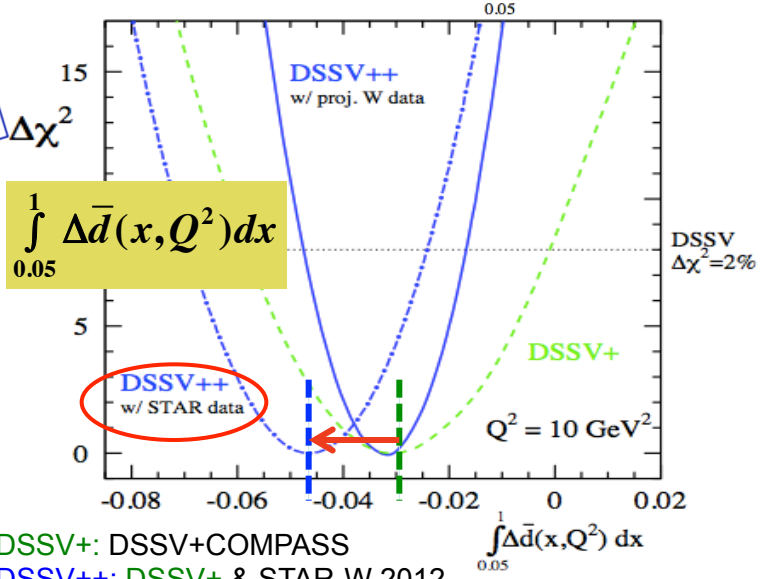


$\Delta\bar{u}$

$\Delta\bar{d}$

arXiv:1304.0079



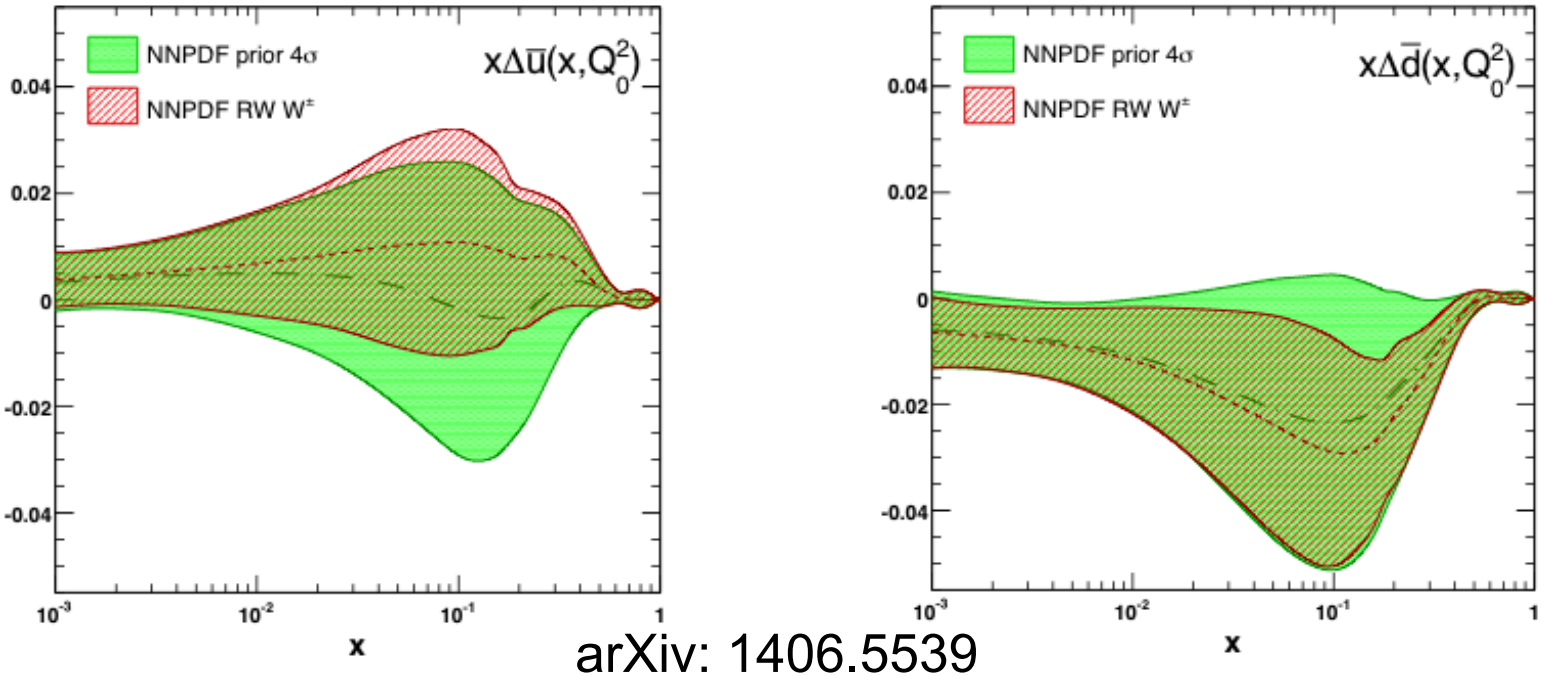


STAR 2012 W results provide significant constraints on $\Delta\bar{u}, \Delta\bar{d}$.

DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012

Global Analysis with RHIC 2012 W results

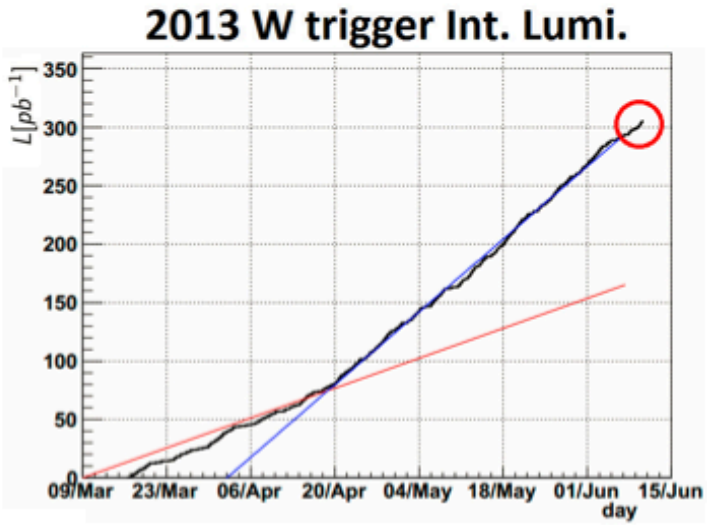
Big impact from NNPDFpol1.1 global analysis before and after including new RHIC/STAR data:

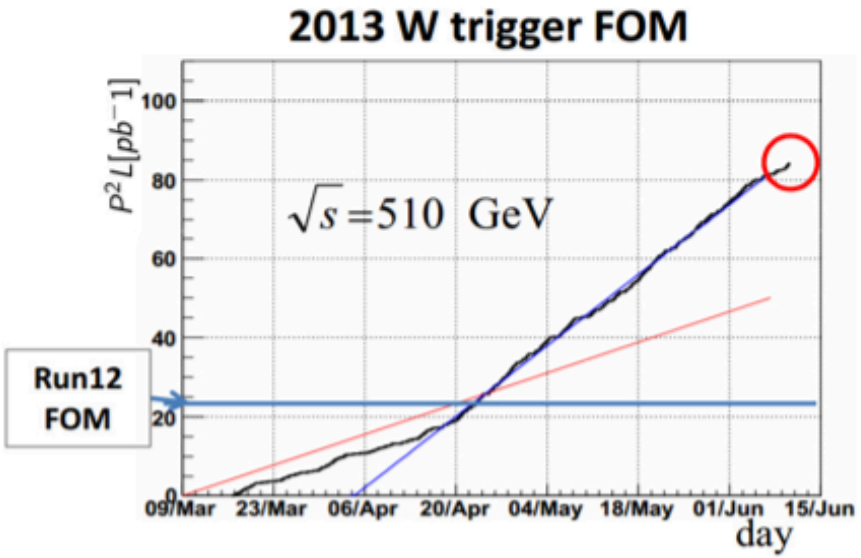


arXiv: 1406.5539

NNPDF1.0: only DIS data used.
NNPDF1.1: pol1.0+RHIC data +COMPASS open charm.
*No semi-inclusive DIS data and RHIC pi0 data to avoid uncertainty from frag. func.

STAR Run13 dataset- factor of 4 times bigger!



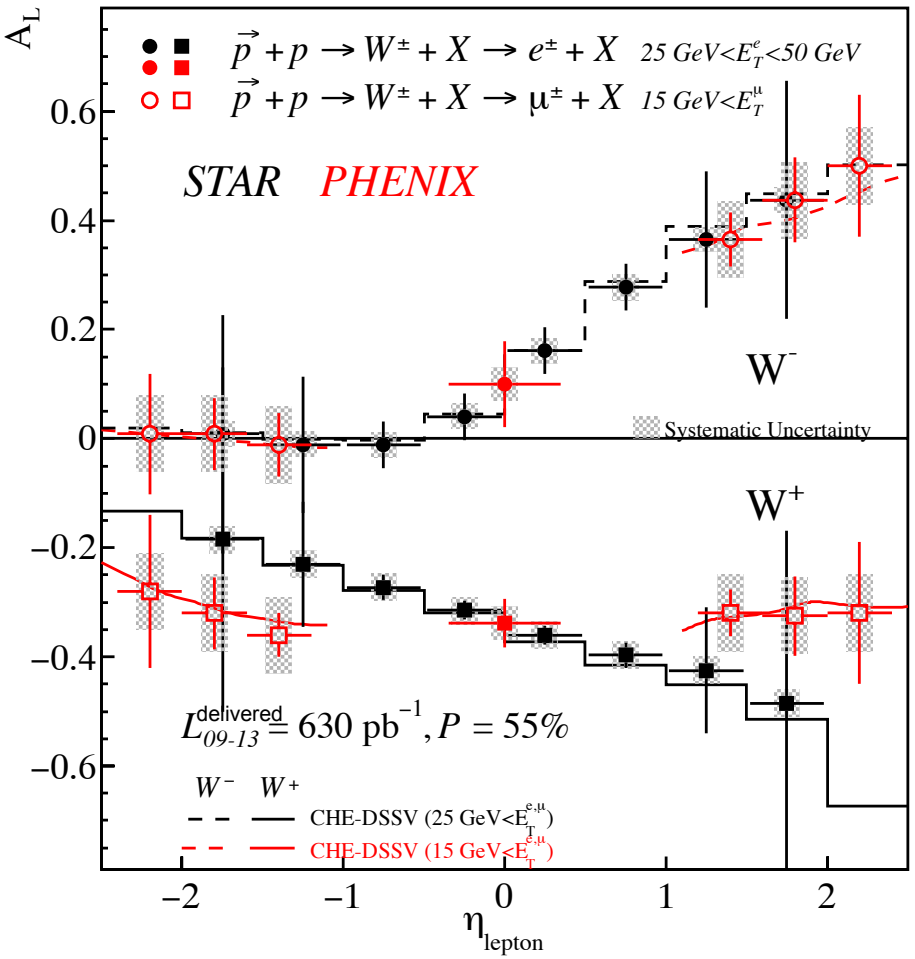


STAR pp500 Longitudinal			
Run	L (pb^{-1})	P	P^2L (pb^{-1})
2009	12	0.38	1.7
2011	9.4	0.49	2.3
2012	77	0.56	24
2013	**$\sim$300**	**$\sim$ 0.53**	**$\sim$84**

- In 2013, STAR collected an integrated luminosity of $\sim$300 pb^{-1} at $\sqrt{s} = 510$ GeV with an average beam polarization of $\sim$53%, which is 3 times greater than total of previous years in FOM.

STAR Run 9-13 Projections at 500 GeV

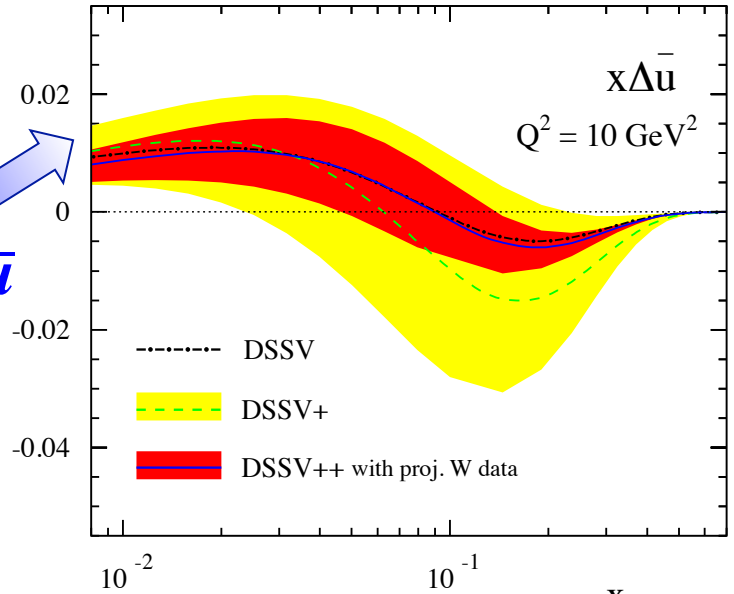
arXiv:1304.0079
(pseudo-data randomized around DSSV)



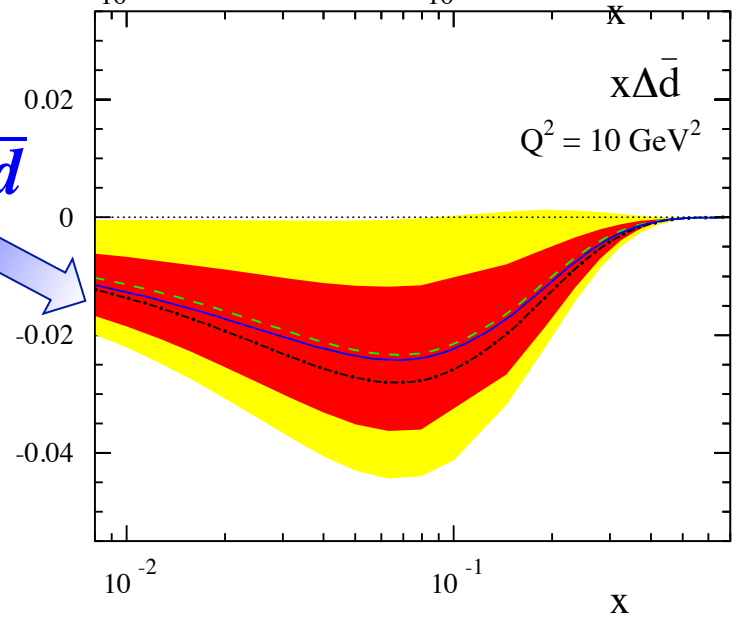
RHIC: $\int L_{09\text{-}13} = (50+100+120+475) = 745\text{pb}^{-1}$

DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj.

$\Delta\bar{u}$



$\Delta\bar{d}$



Summary & Outlook

- Observation of positive gluon polarization from RHIC:
  - Probes with jets and pion, are providing important constraints on ΔG.
    Global analysis indicates non-zero gluon polarization (0.05<x<0.2).
  - Correlation measurements (di-jet) with access to partonic kinematics

- Unique probe of sea quark polarization via W production:
  - RHIC/STAR 2012 results on W A_L provide important constraints on $\Delta\bar{u}, \Delta\bar{d}$.

- Future measurements at RHIC will provide better constraints and wider *x*-coverage for gluon and sea quark polarization.

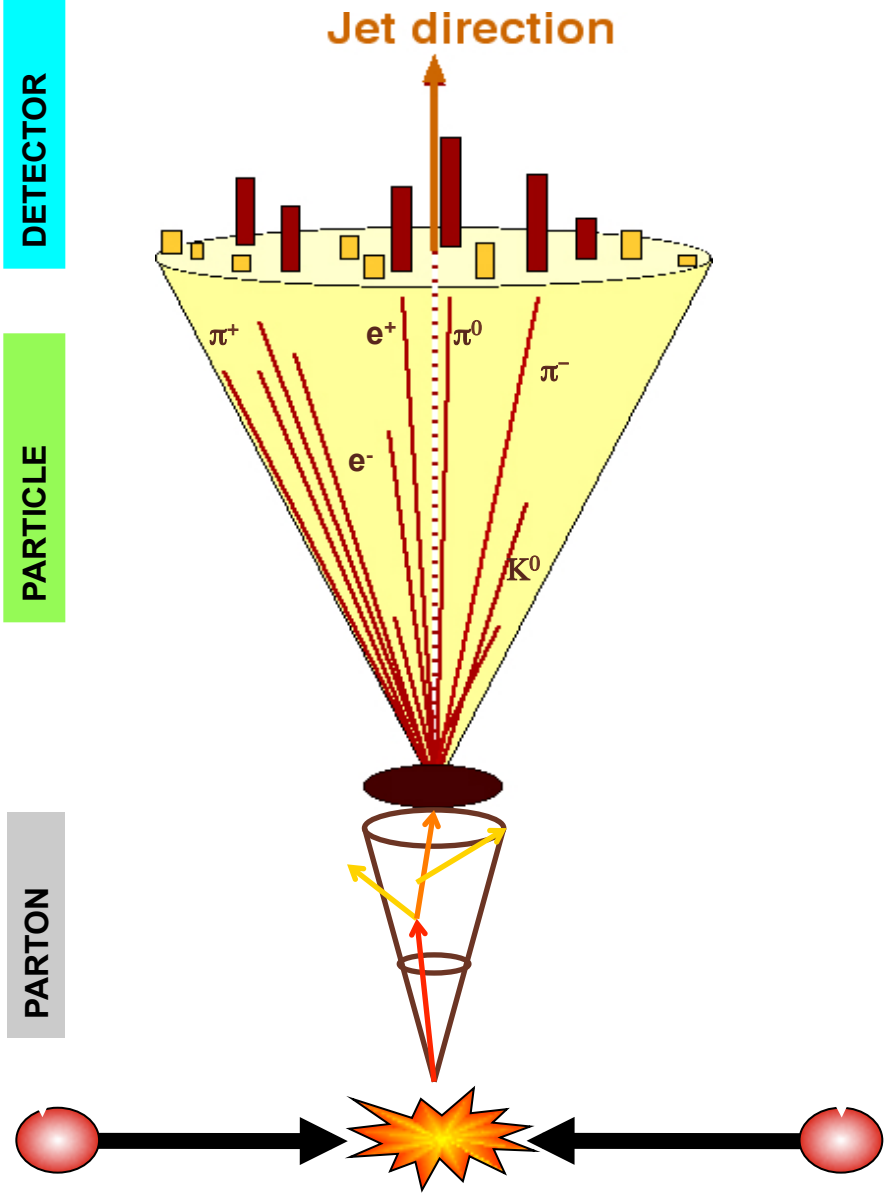
Backup Slides

Jet Reconstruction in pp at STAR

DETECTOR

PARTICLE

PARTON



1) Midpoint cone algorithm

(Adapted from Tevatron II - hep-ex/0005012)

- Seed energy E_T^{seed} = 0.5 GeV
- Cone radius R = $\sqrt{\Delta\eta^2+\Delta\varphi^2}$ = 0.7
- Split/merge fraction f = 0.5

2) Anti-K_T algorithm

([arXiv:0802.1189])

- Successive Combination
- Radius R = 0.6

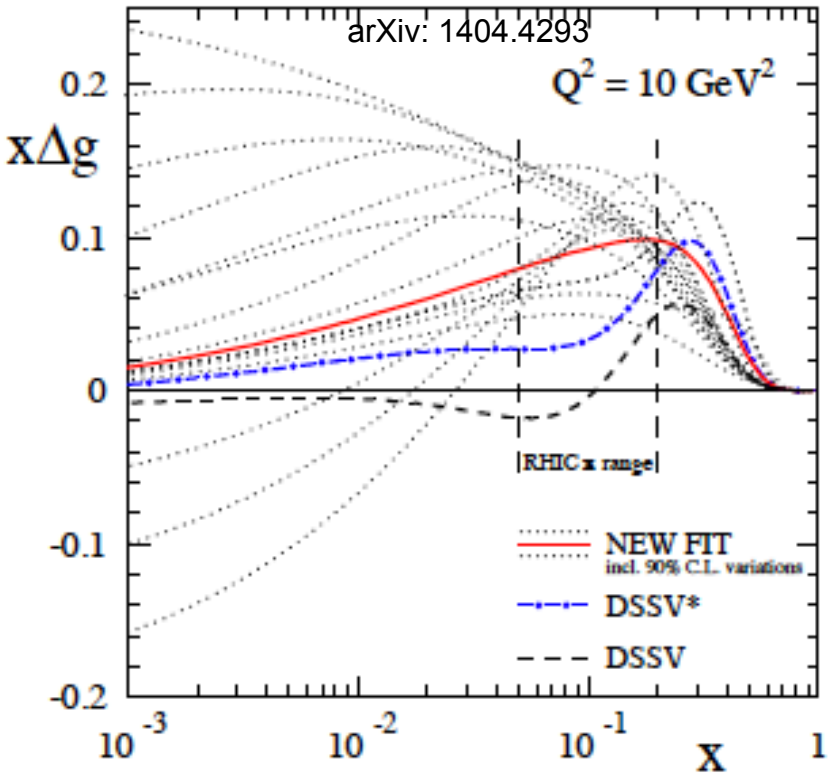
$$d_{ij} = \min\left(\frac{1}{k_{Ti}^2}, \frac{1}{k_{Tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

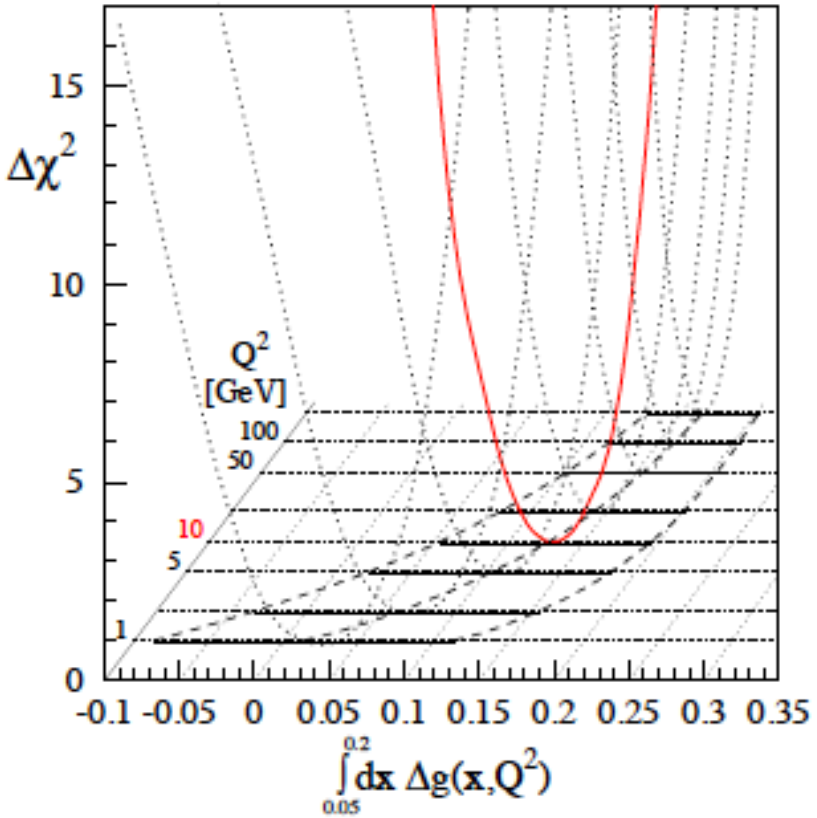
$$d_{iB} = \frac{1}{k_{Ti}^2}$$

1) was used in previous years, now both methods are employed with 2) preferred.

DSSV global analysis including both STAR & PHENIX data -Observation of gluon polarization

DSSV, PRL113,12001(2014)



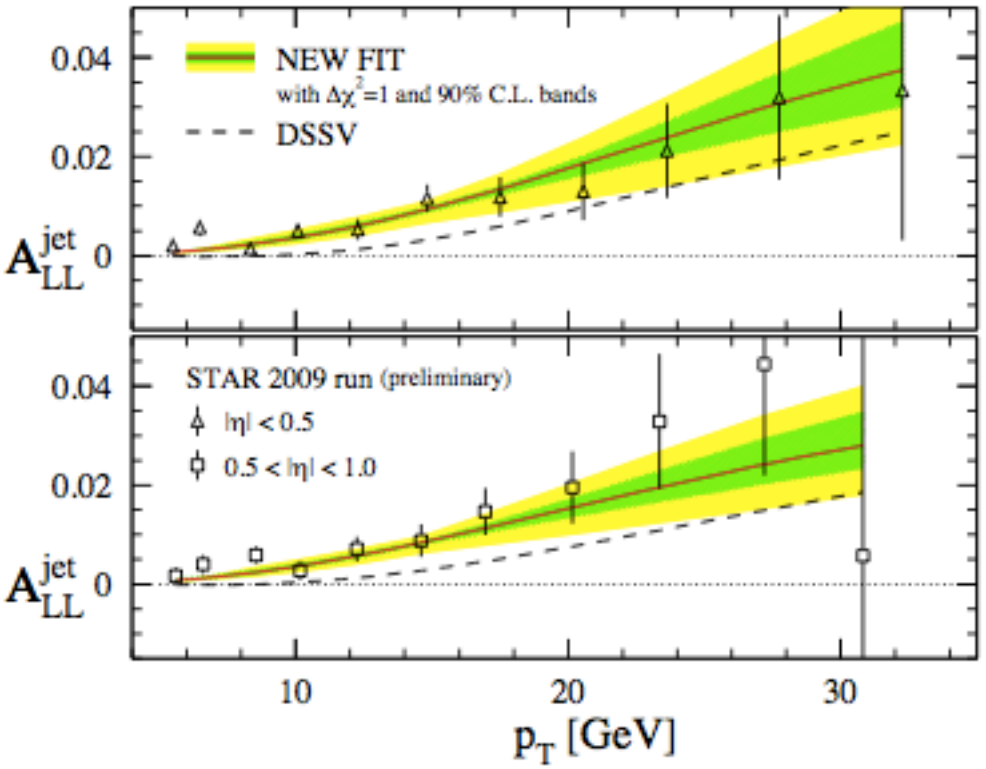


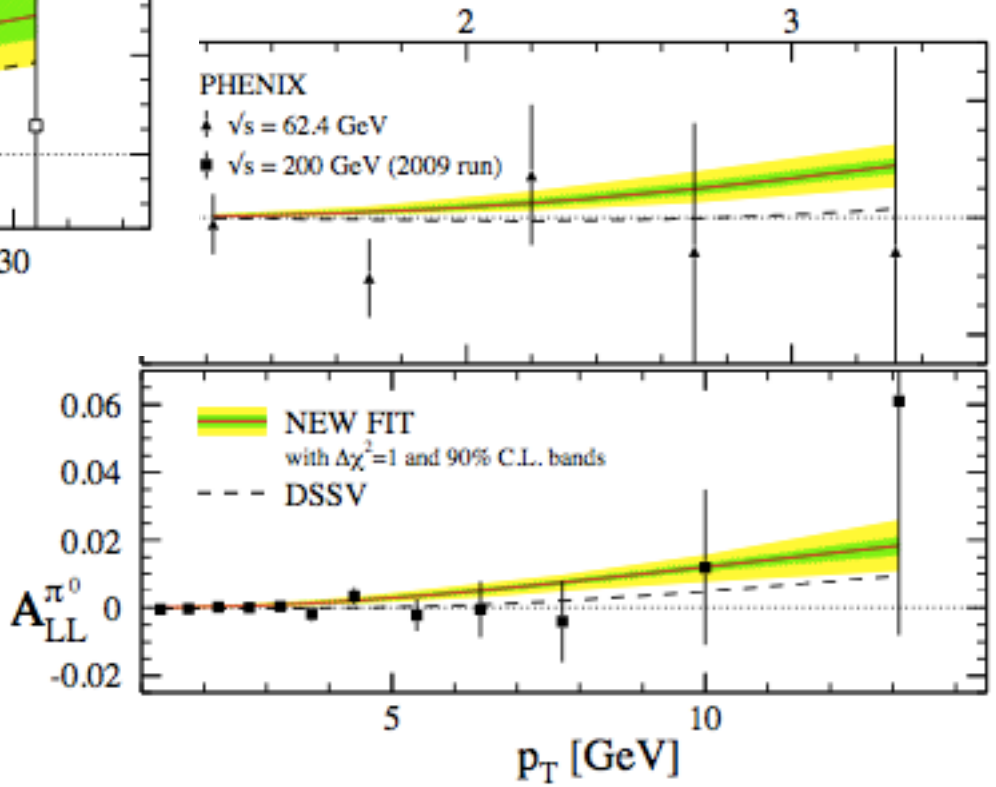
DSSV: arXiv:0904.3821
DSSV*: DSSV + all new (SI)DIS
DSSV: DSSV* & RHIC 2009

$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ GeV^2$$

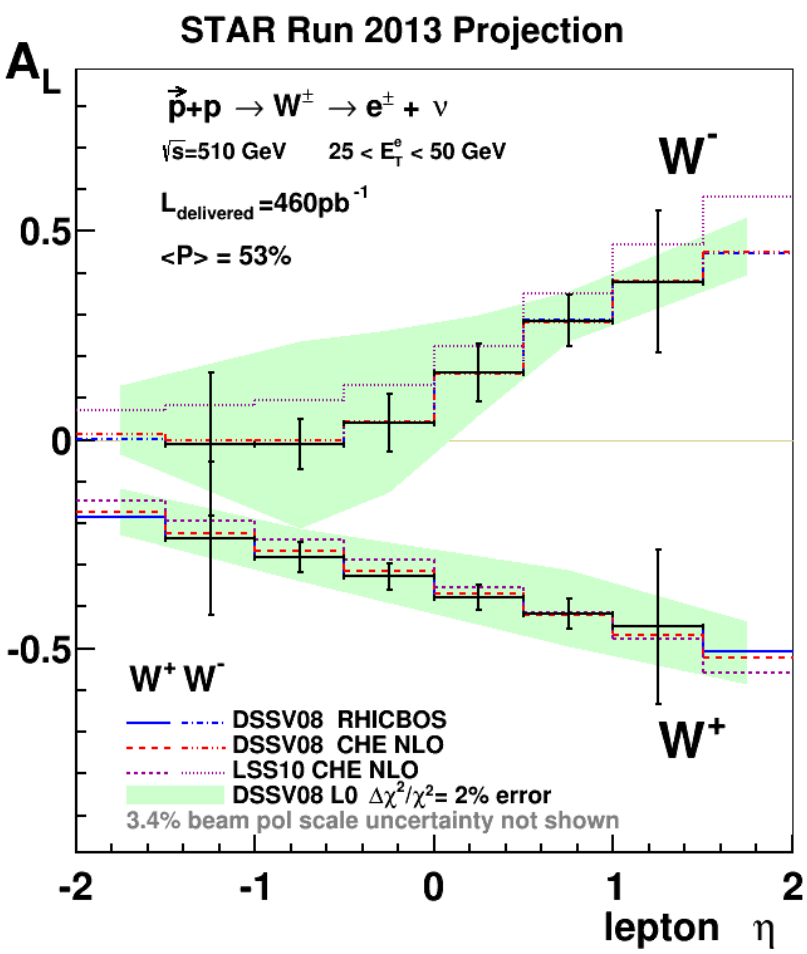
Scale evolution- integral of $\Delta g(x)$ increase with Q^2

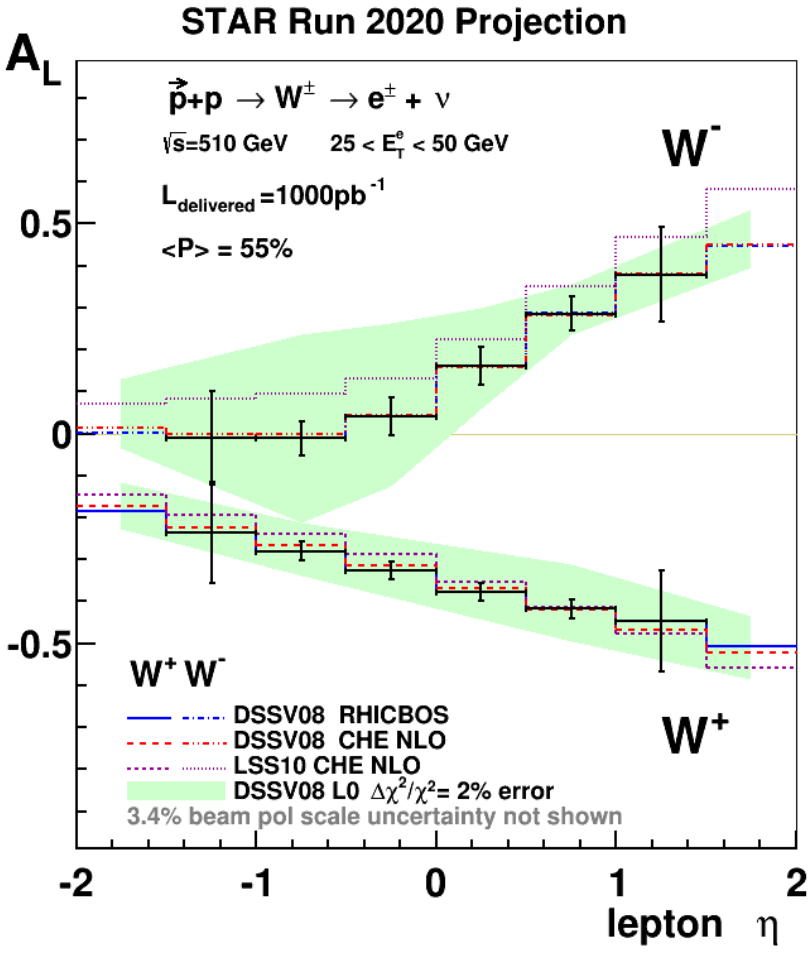
-> consistency of STAR & PHENIX


NEW FIT
with $\Delta\chi^2$=1 and 90% C.L. bands
DSSV
A_{LL}^{jet}
STAR 2009 run (preliminary)
$|\eta| < 0.5$
$0.5 < |\eta| < 1.0$
p_T [GeV]


PHENIX
$\sqrt{s}$ = 62.4 GeV
$\sqrt{s}$ = 200 GeV (2009 run)
NEW FIT
with $\Delta\chi^2$=1 and 90% C.L. bands
DSSV
$A_{LL}^{\pi^0}$
p_T [GeV]

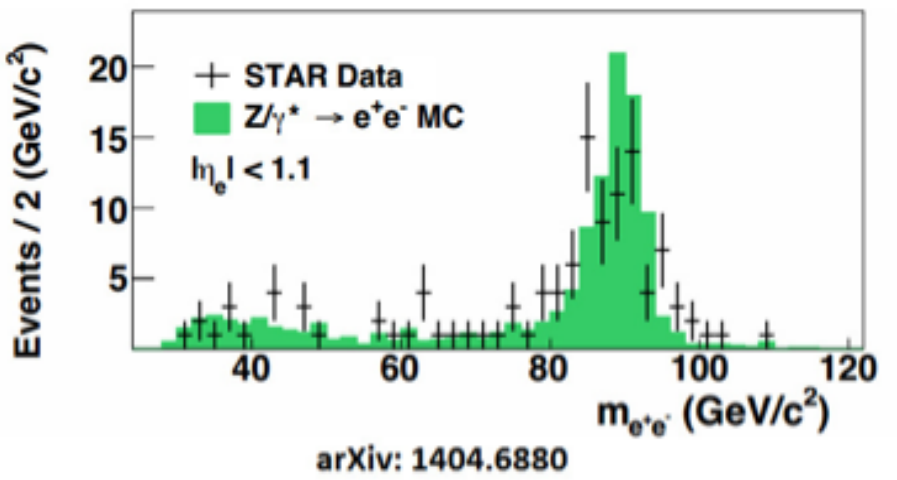
Projections of W measurement at STAR

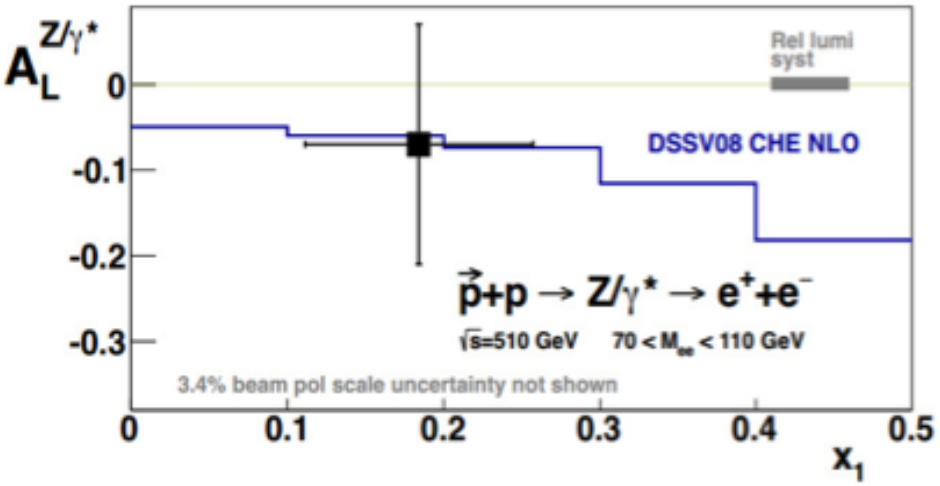




Theoretically cleanest way to constrain $\Delta q(x,Q^2)$ at medium/high x
no target mass & higher twist corrections or FF uncertainties
as in SIDIS

Z A_L results from STAR





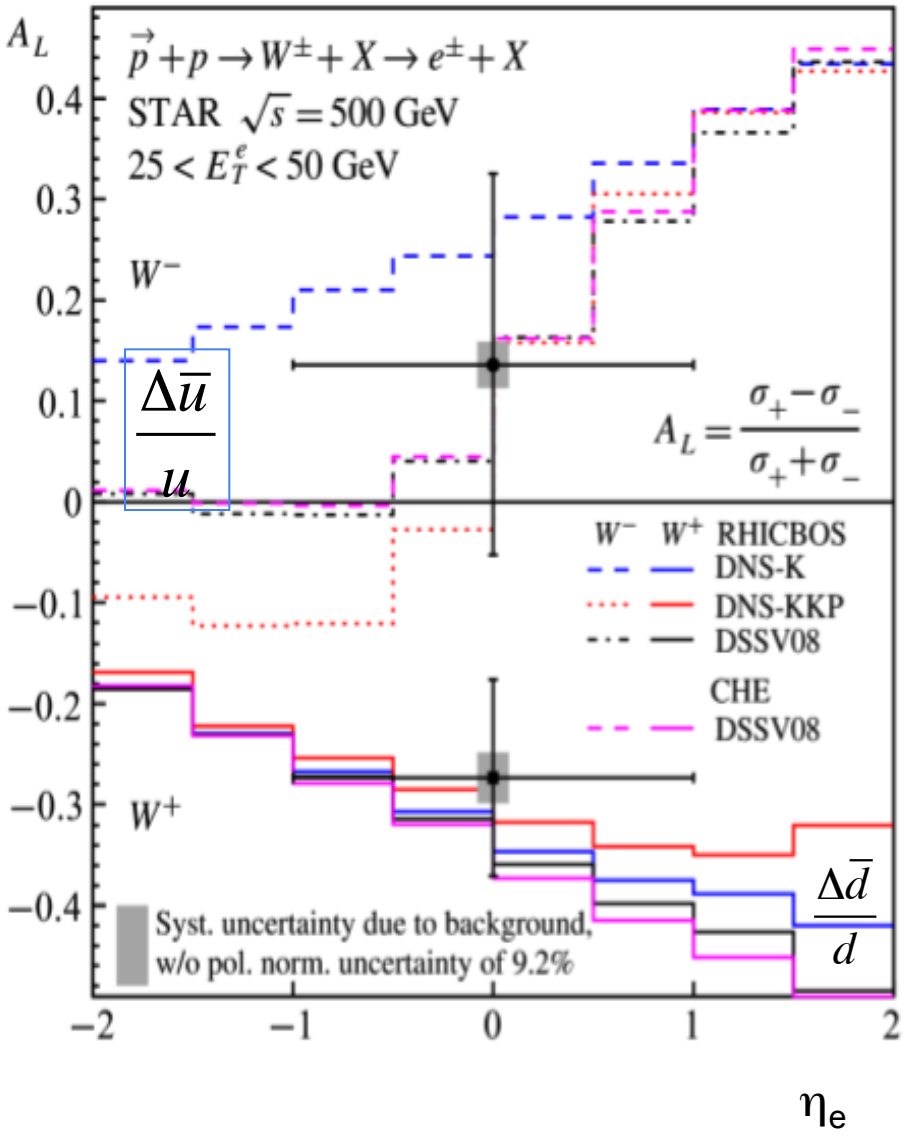
- Reconstruct initial state kinematics at leading order:

$$x_{1(2)} = \frac{M_{ee}}{\sqrt{s}} e^{\pm yZ}$$

- A_L^Z is sensitive to the combination of $u, \bar{u}, d$ and $\bar{d}$ polarizations

- Consistent with theoretical predictions within the large uncertainty.

First STAR W A_L results (Run9)



STAR: Phys. Rev. Lett. 106, 062002(2011)

- The first W A_L asymmetries are in agreement with theory evaluation using pol. pdf (DSSV) constrained by pol. DIS data.
- Statistics improvement from Run 9 to Run 12:

	L (pb^{-1})	P	P^2L (pb^{-1})
Run 9	12	0.40	1.9
Run 12	72	0.56	22.6