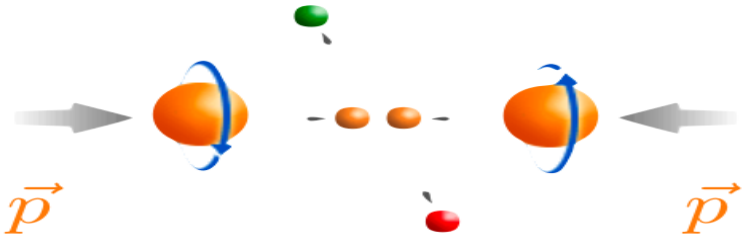
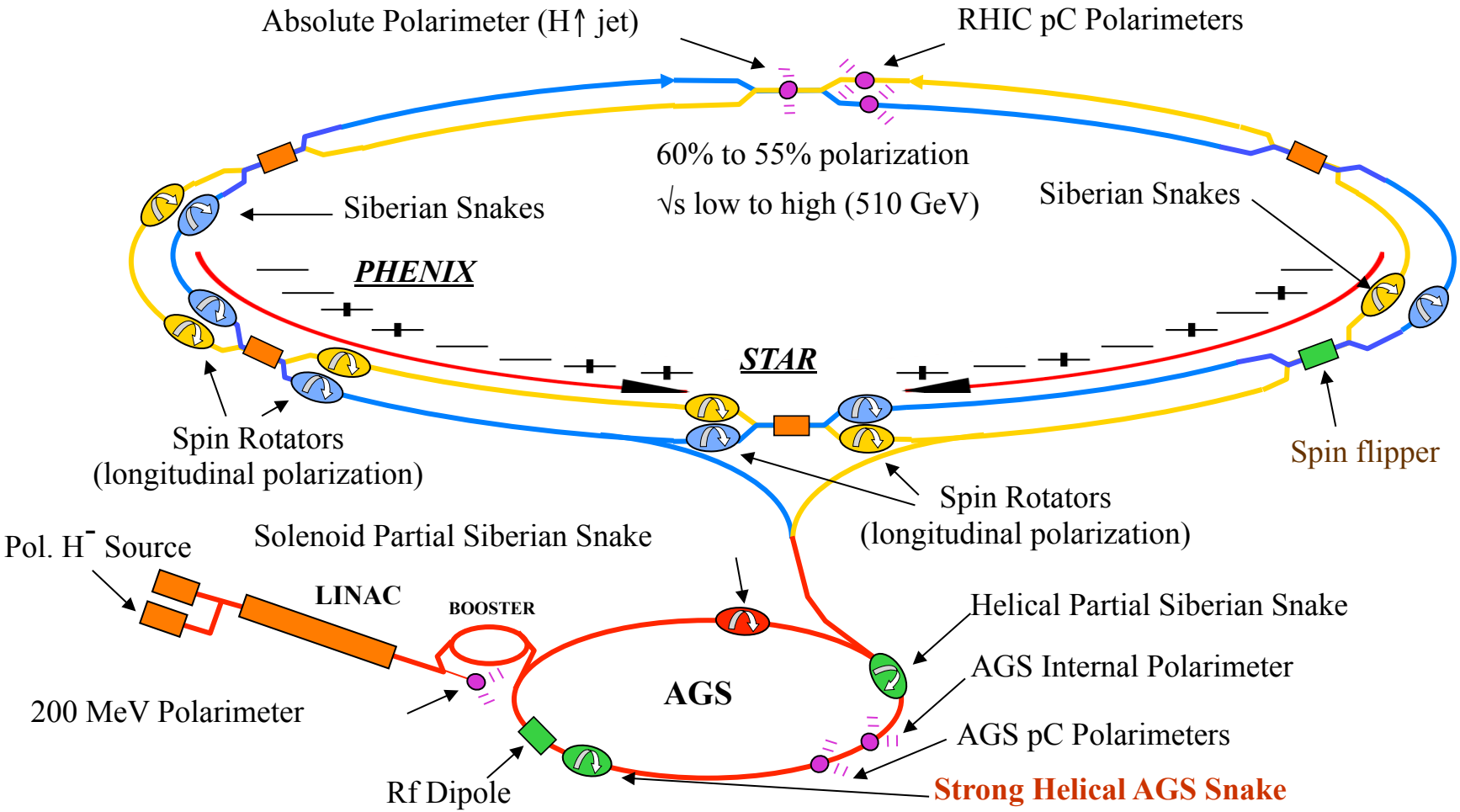
Recent spin results from STAR

Qinghua Xu(Shandong Uni.), *for the STAR Collaboration*

DSPIN2013，Dubna, October 9, 2013



RHIC- the first polarized pp collider in the world

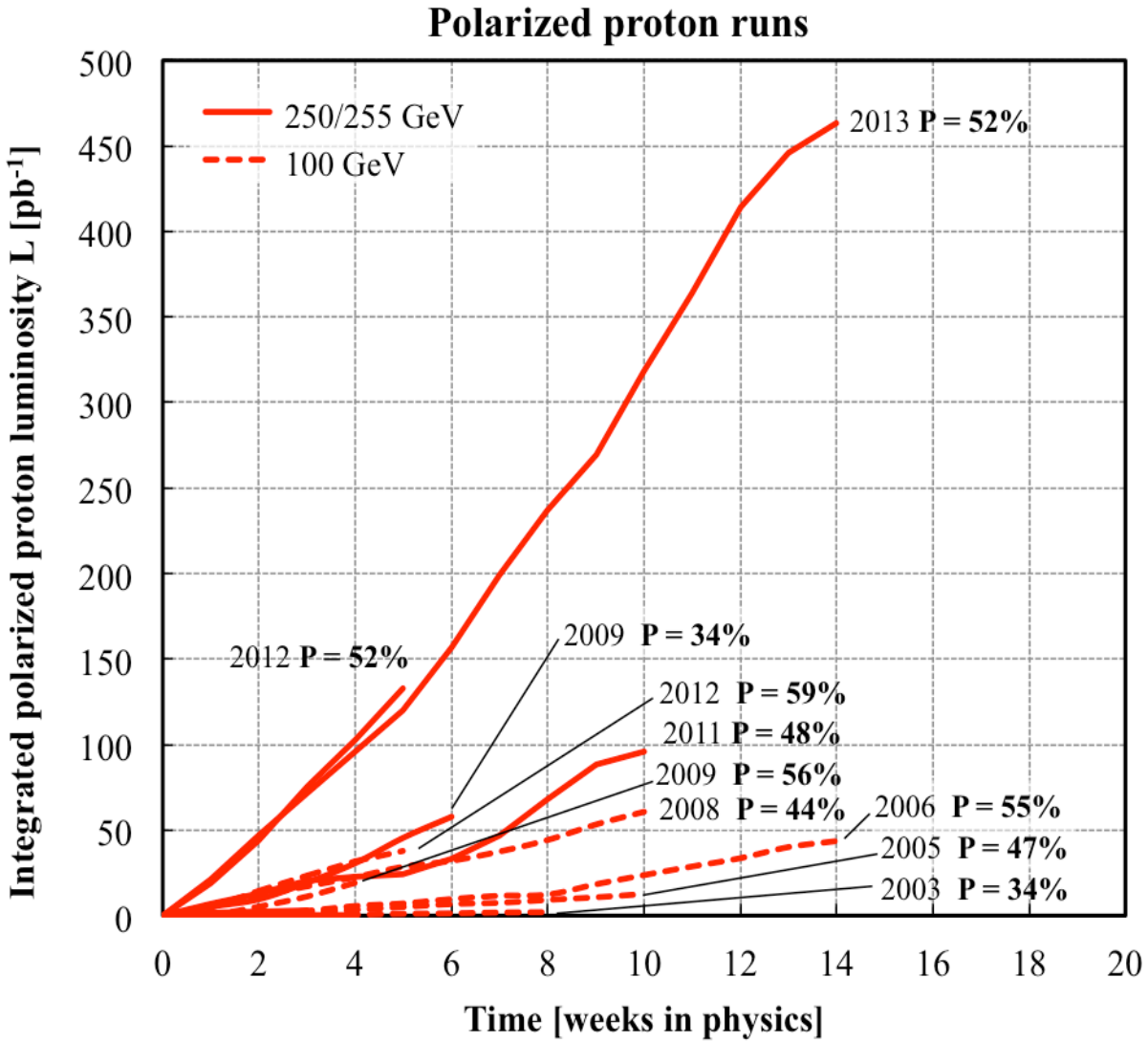


- Spin direction changes from bunch to bunch
- Spin rotators provide choice of spin orientation

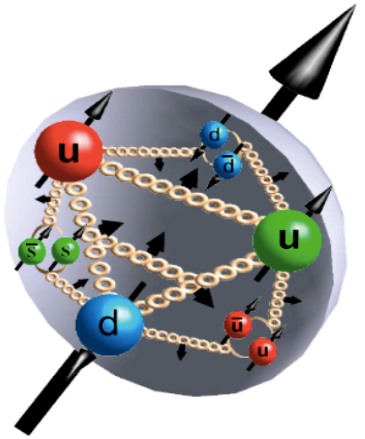
RHIC performance with pp collisions

- 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.

-at STAR



Spin structure of nucleon



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

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

Quark spin, (~30%)-DIS

Gluon spin, RHIC

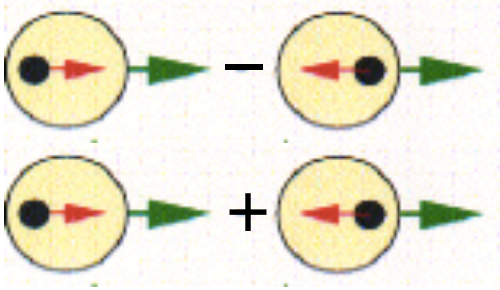
Orbital Angular Momenta Little known (DVCS)

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

- Polarized parton densities:

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

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



STAR - Solenoid Tracker At RHIC

Magnet

- 0.5 T Solenoid

Triggering & Luminosity Monitor

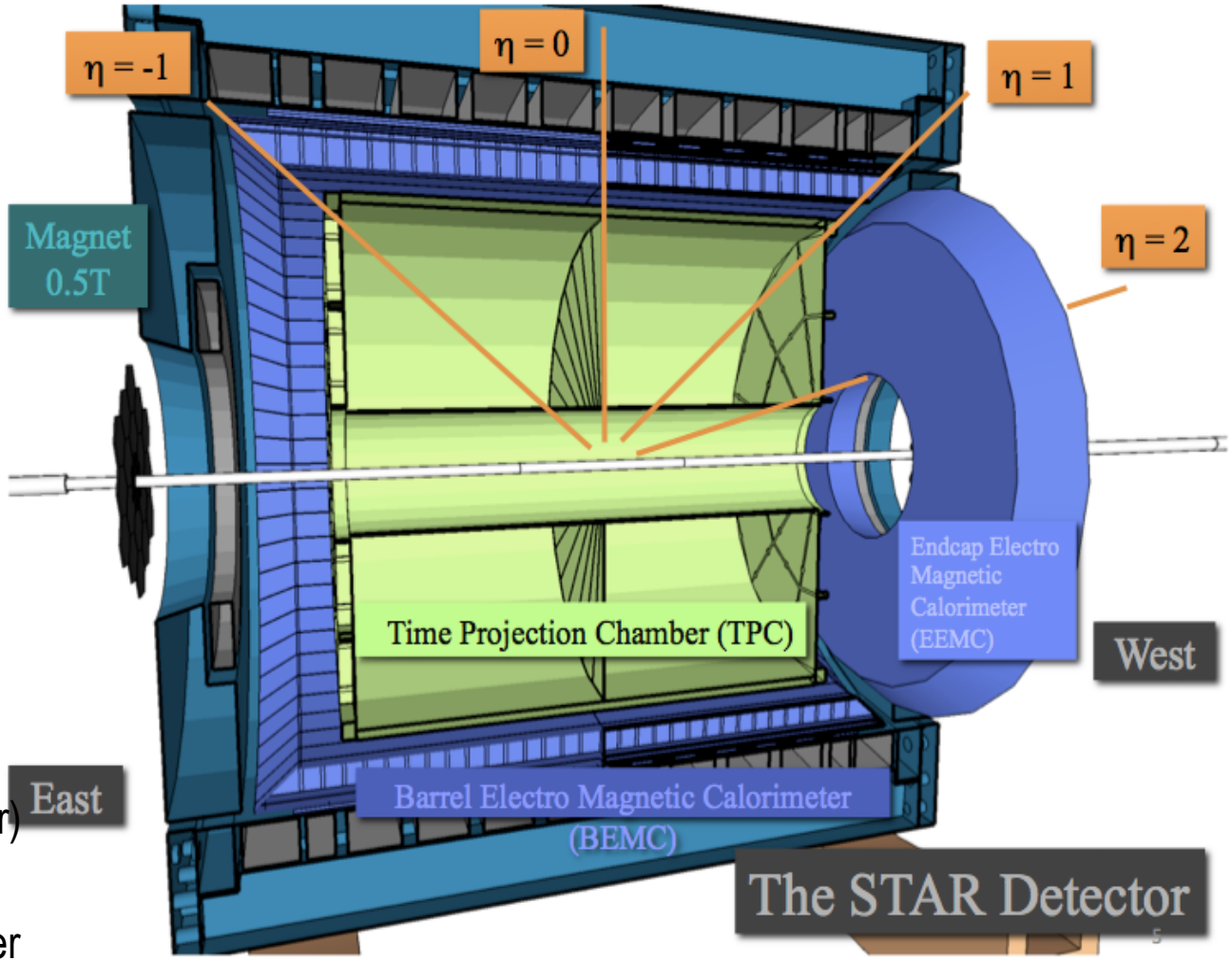
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters
- Vertex Position Detector

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
  - $2.5 < \eta < 4.0$



Tai Sakuma, Thesis, MIT (2010)

The STAR spin program

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

    -- inclusive jet, hadrons

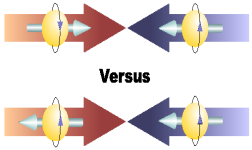
    -- di-jets, γ+jet
  - Flavor separation: quark & anti-quark polarization

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

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

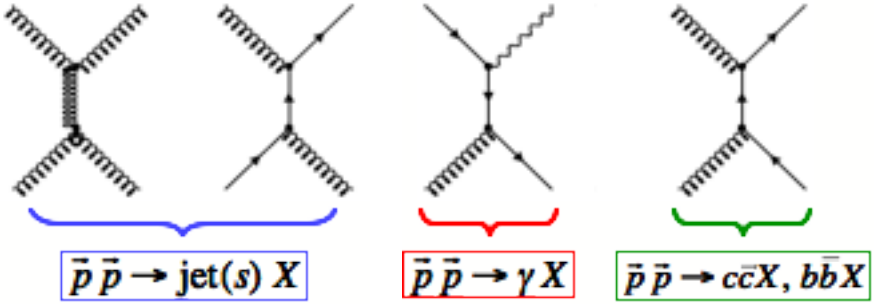
Accessing Δg(x) in pp collision

- Longitudinal spin asymmetry:

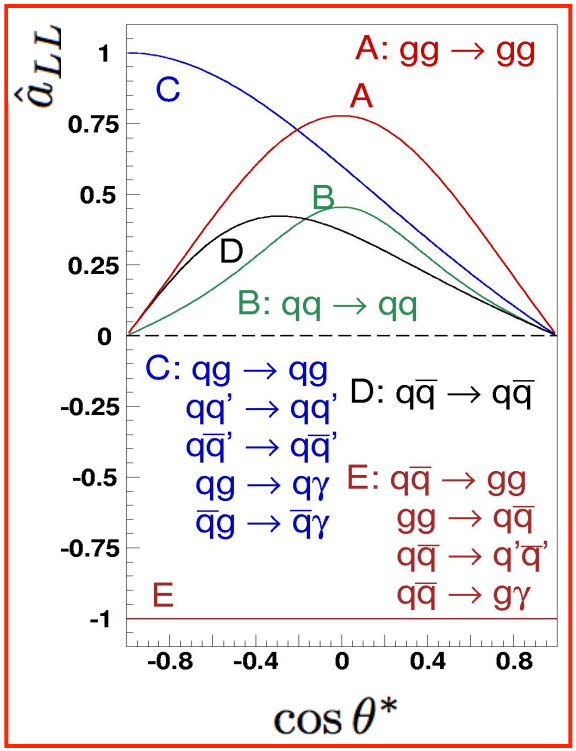


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

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

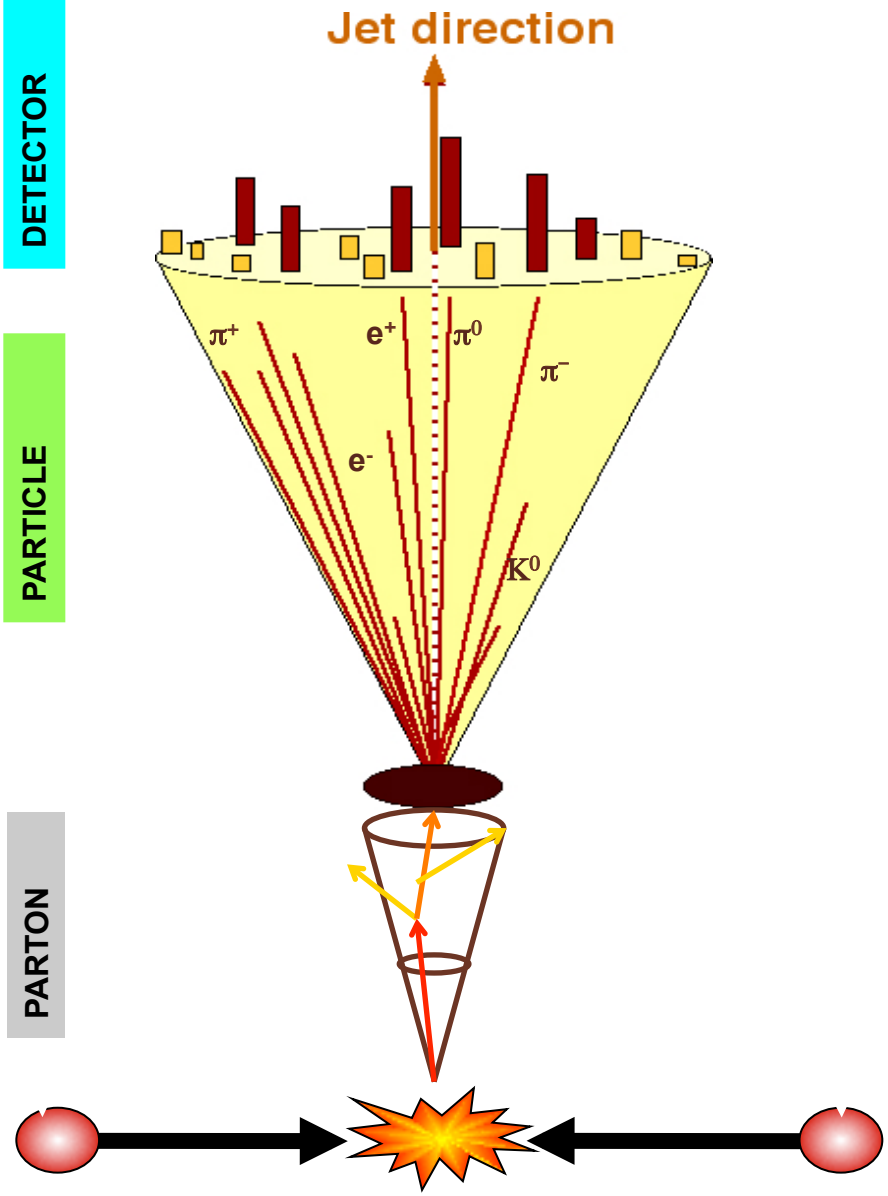


Jet Reconstruction in pp at STAR

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

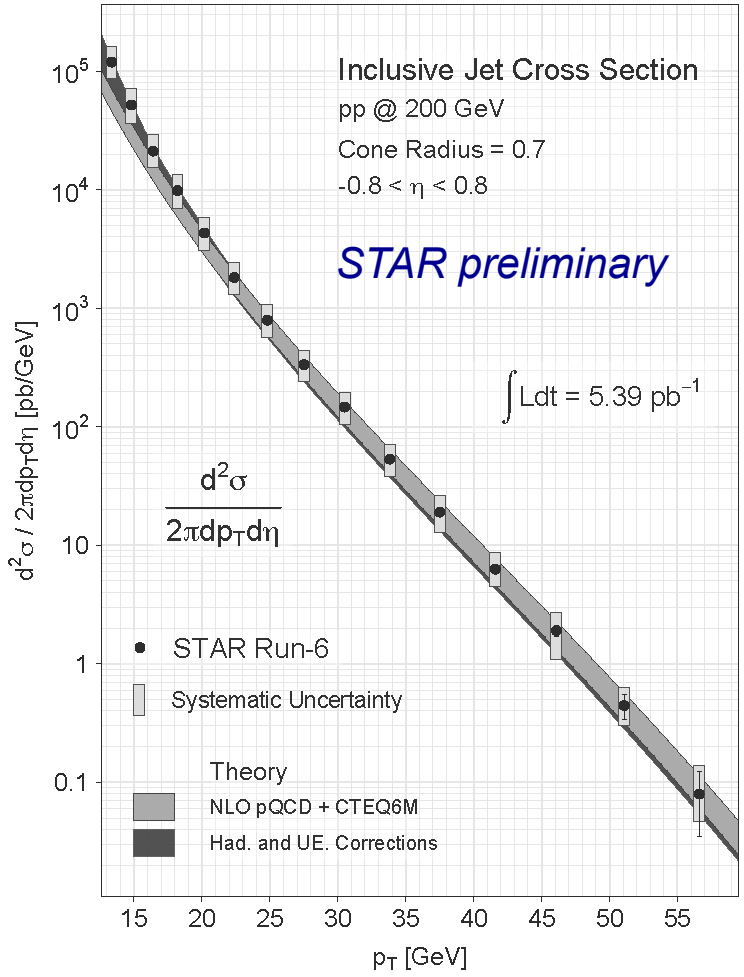
$$d_{ij} = \min\left(\frac{1}{k_{Ti}^2}, \frac{1}{k_{Tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

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

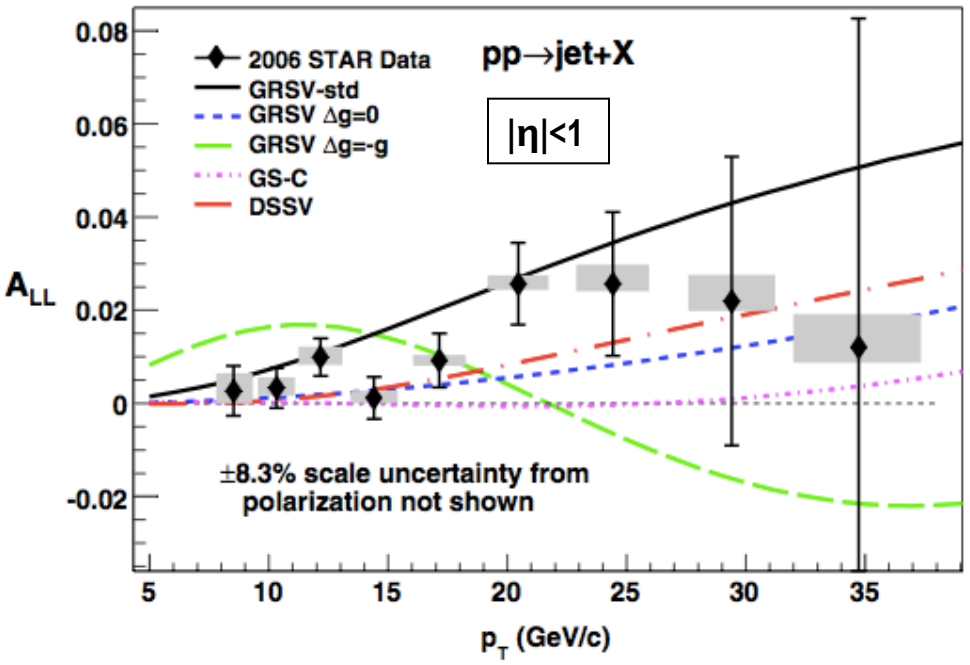
1) was used in previous years, now both methods are employed with 2) preferred.

STAR Run6 results on jet x-section and A_{LL}

- Cross section well described by NLO pQCD+Hadronization



STAR, PRD86, 32006(2012)

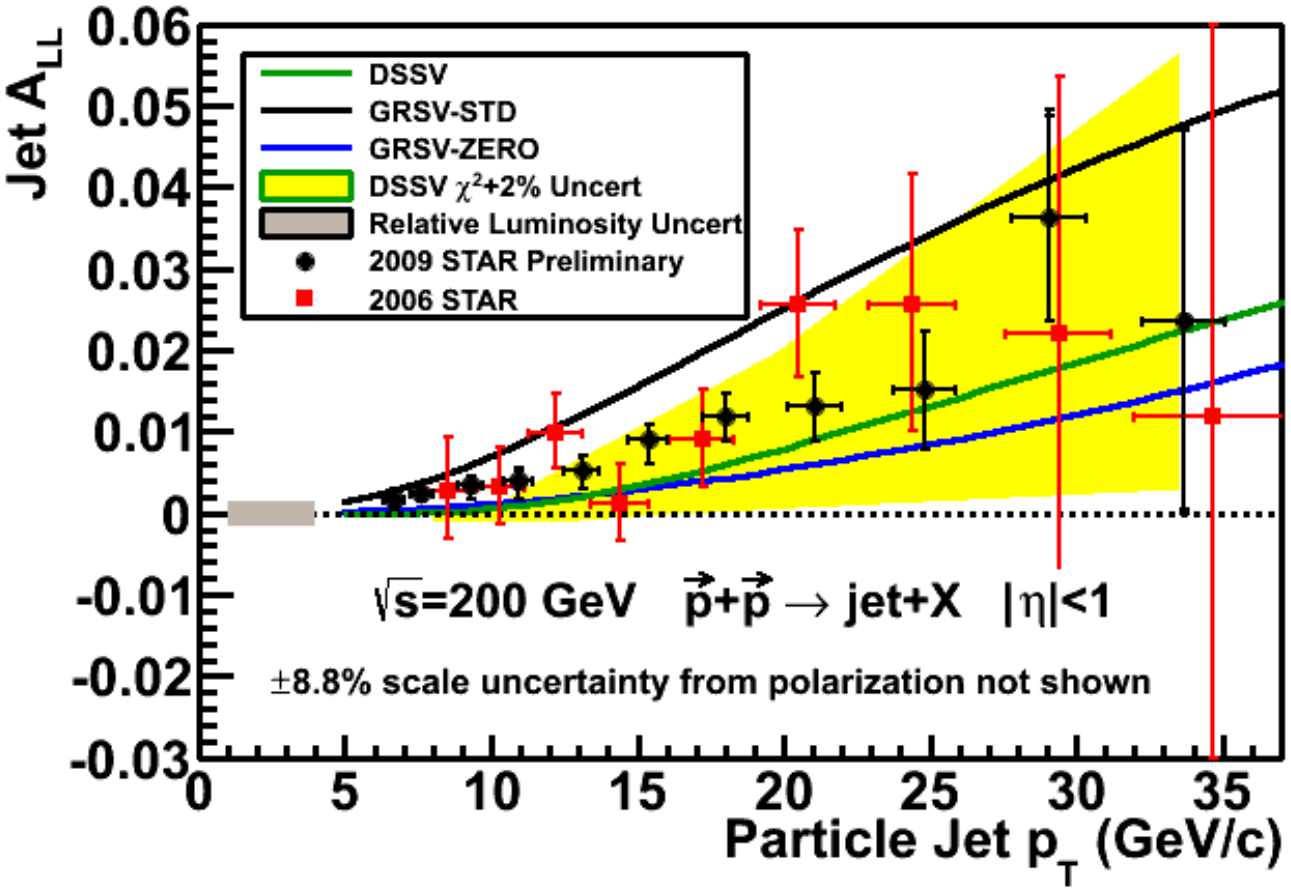


- STAR run6 data rule out several previous models of gluon polarization, and included in the DSSV global analysis together with PHENIX π^0 results.

$$\int_{0.05}^{0.2} \Delta g(x)dx = 0.005 \pm^{0.129}_{0.164}$$ at $Q^2 = 10\text{GeV}^2$

-arXiv:1304.0079

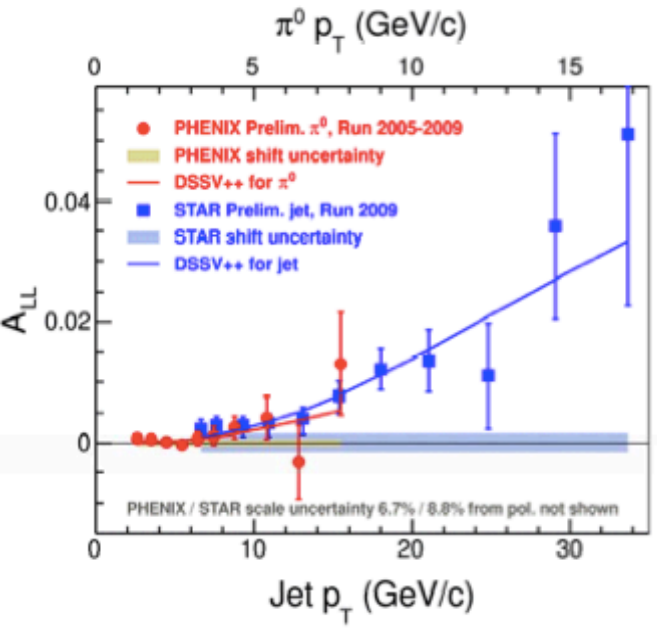
STAR inclusive jet A_{LL} from run9

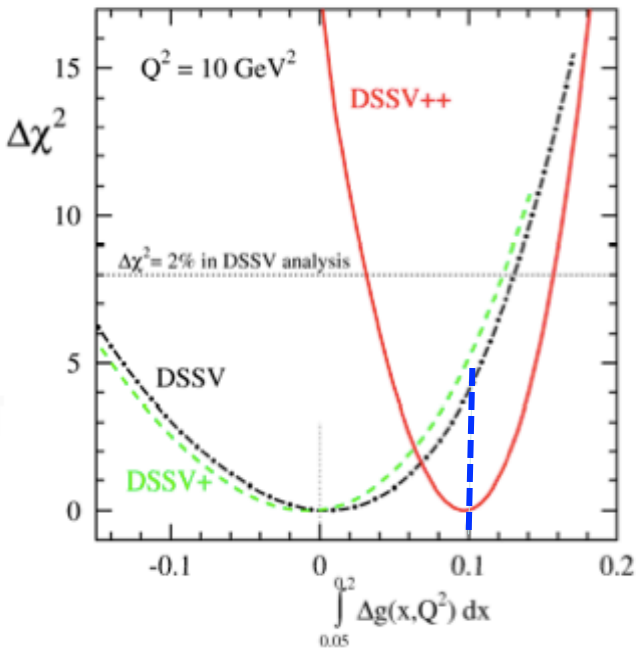


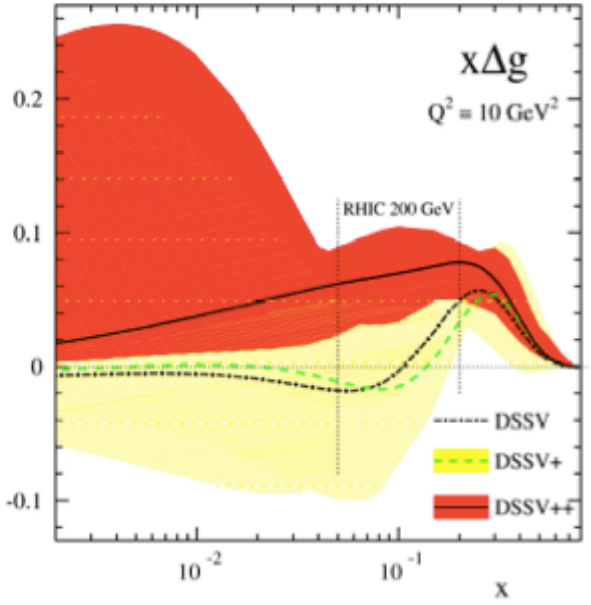
- 2009 STAR data is a factor of 4 more precise than 2006.
- The A_{LL} asymmetry is small, but clearly non-zero !
- Results fall between predictions from **DSSV** and **GRSV-STD**

New global analysis with 2009 RHIC data

arXiv:1304.0079







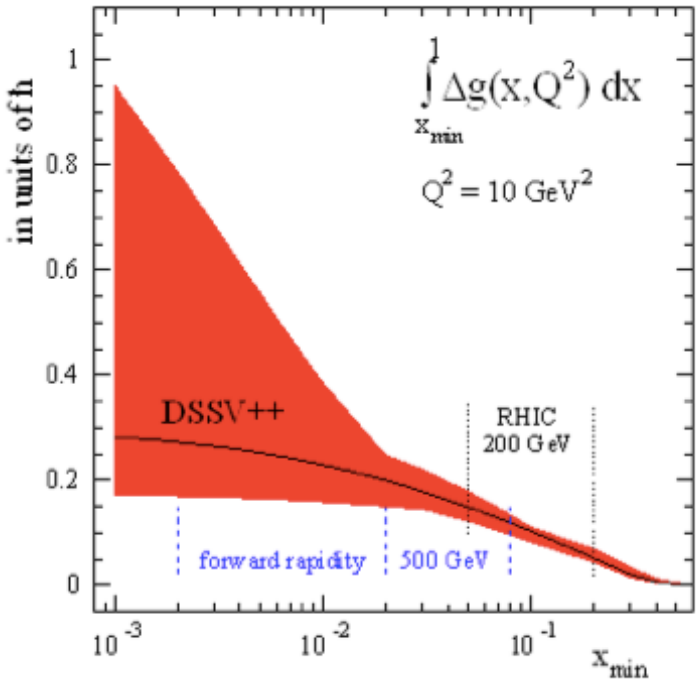
- DSSV++ is new global analysis from the DSSV group that include the preliminary 2009 A_{LL} results from STAR and PHENIX:

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

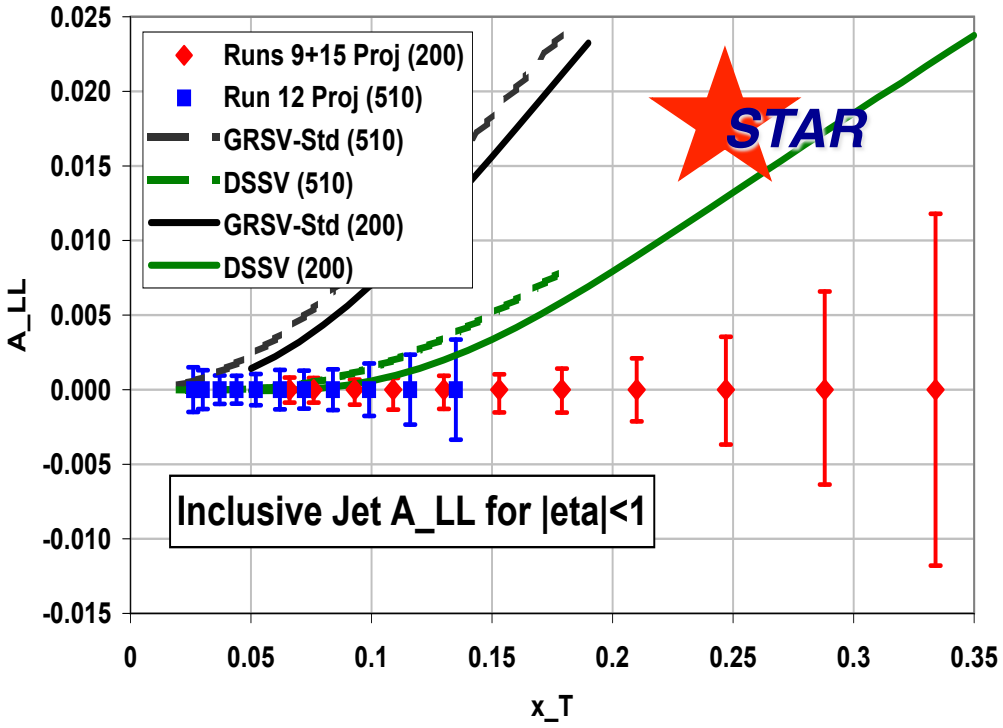
- First experimental evident of non-zero gluon polarization in the RHIC x range (0.05<x<0.2)

Projections with future jet measurements

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



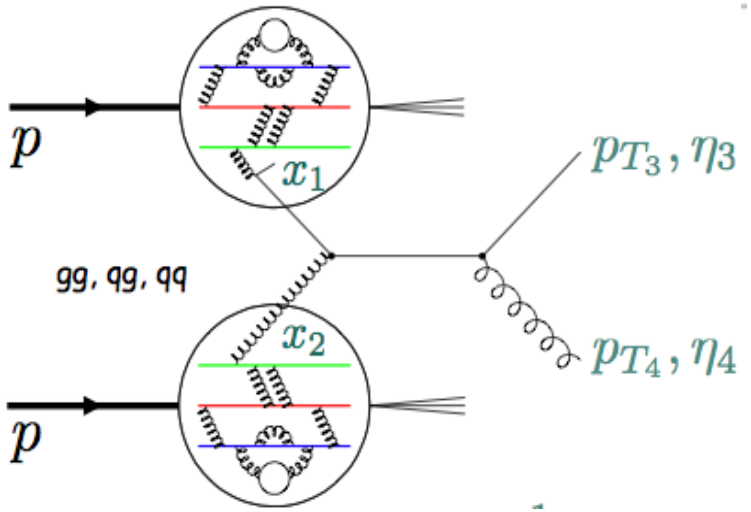
arXiv:1304.0079



- 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.

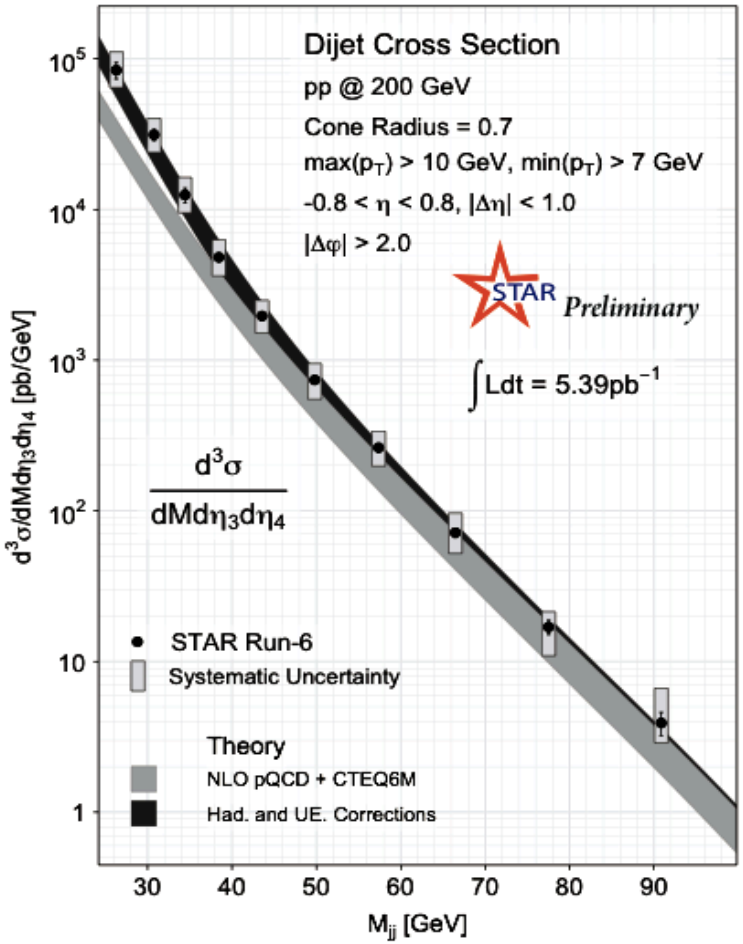
Correlation measurements with partonic kinematics

- Access to partonic kinematics through di-jet production

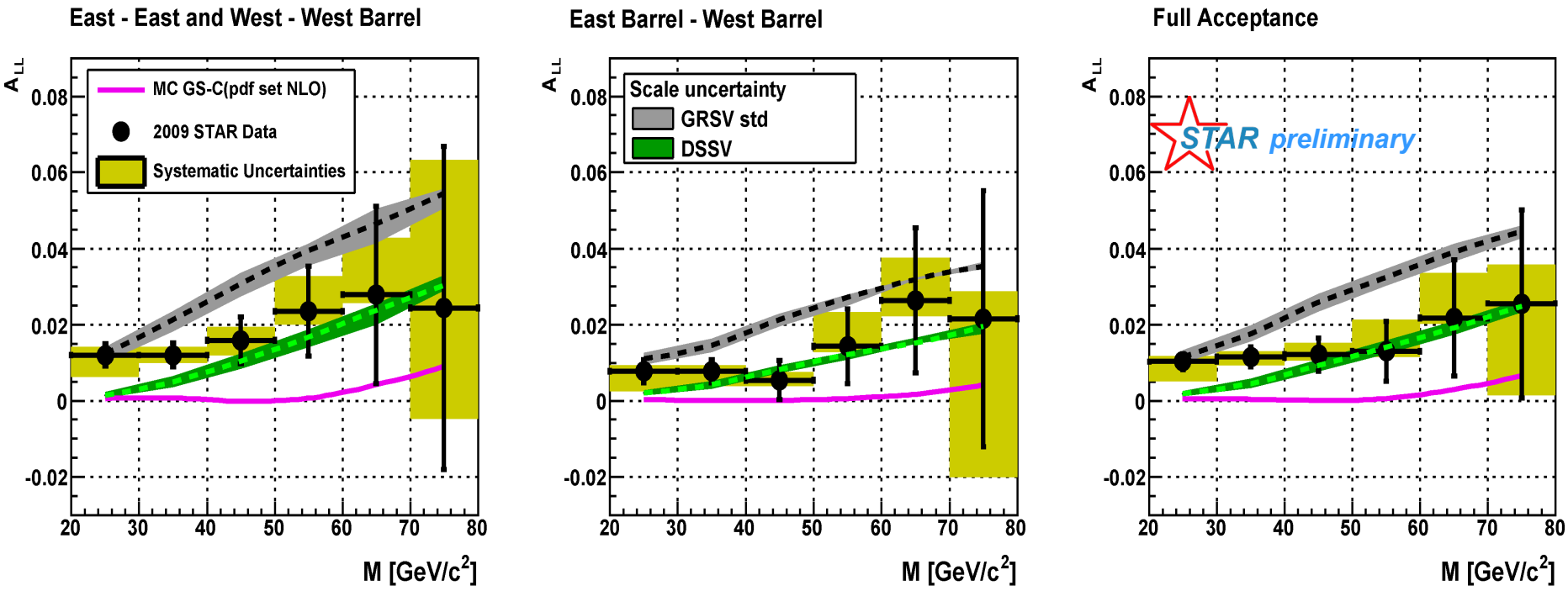


$$x_{1(2)} = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3(-\eta_3)} + p_{T4}e^{\eta_4(-\eta_4)}\right)$$

2006 di-jet cross section at 200 GeV



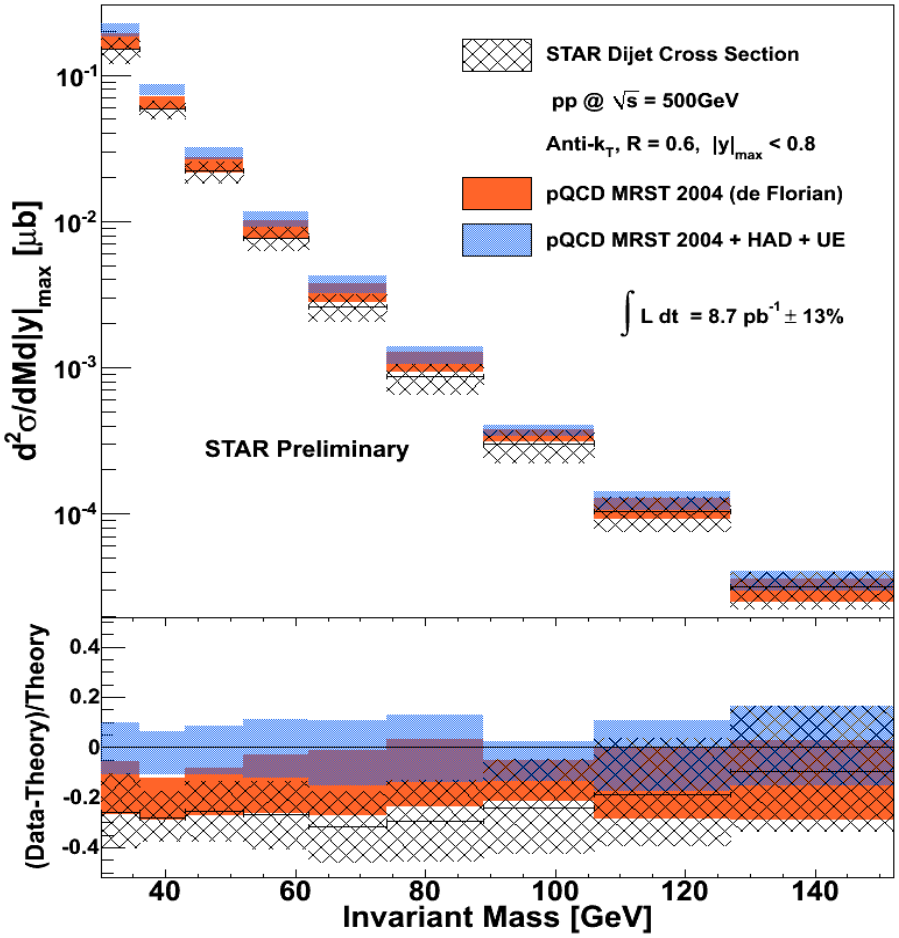
STAR di-jet A_{LL} from run9



- 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 $\Delta g(x)$.

Di-jet production at 500 GeV

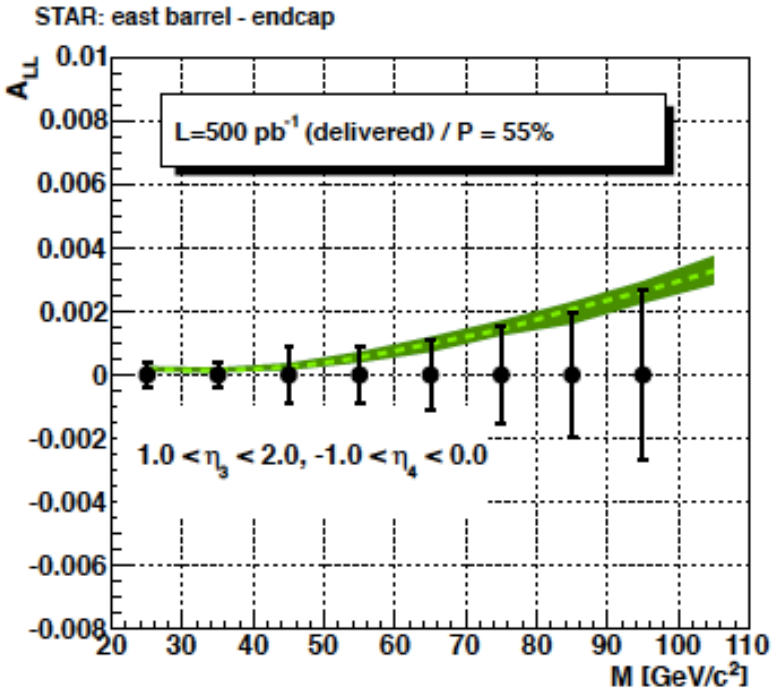
- Reach lower *x* to help constrain the integral of Δg-> 500 GeV

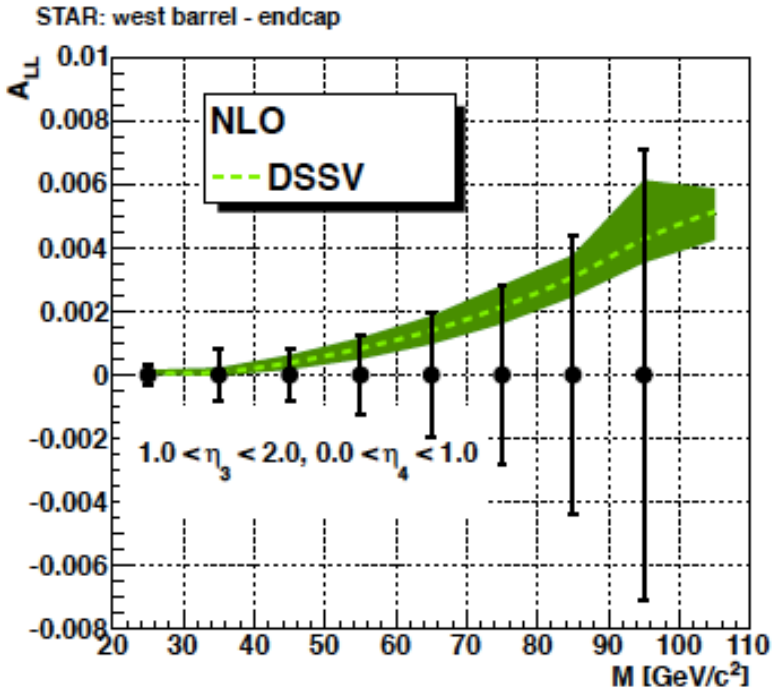


X-section is in agreement with pQCD evaluation within uncertainties. Next step is the A_{LL} measurement.

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

p+p→ jet+jet+X at 500 GeV

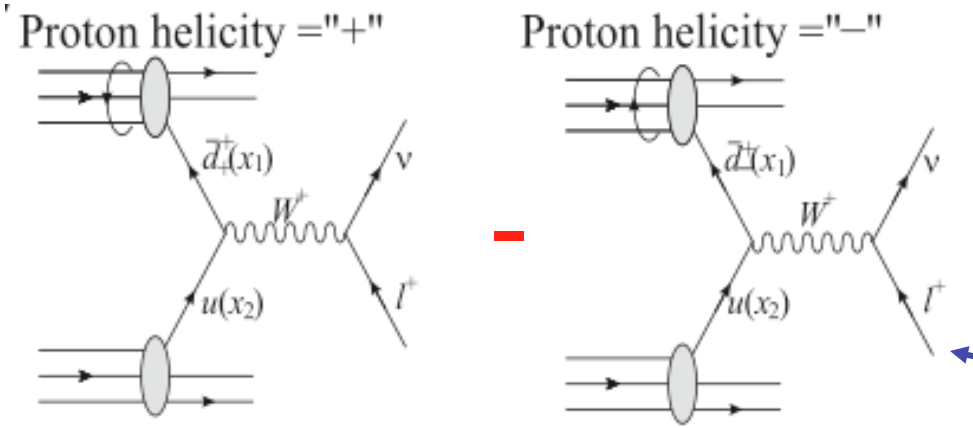




- Projections show expected sensitivity for 2012+2013 data.
- Higher energy accesses lower x_g ->Expect smaller A_{LL}

Probing sea quark pol. via W production

- Quark polarimetry with W-bosons:



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

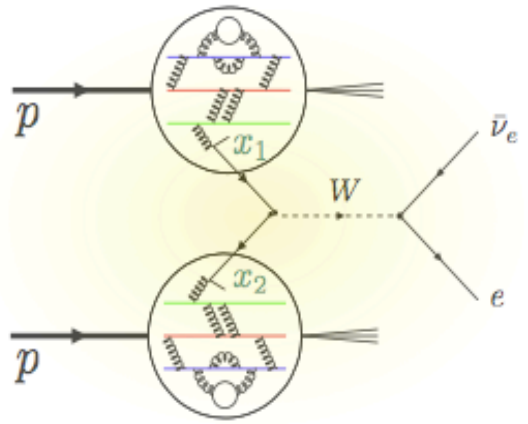
W-detection through high energy lepton

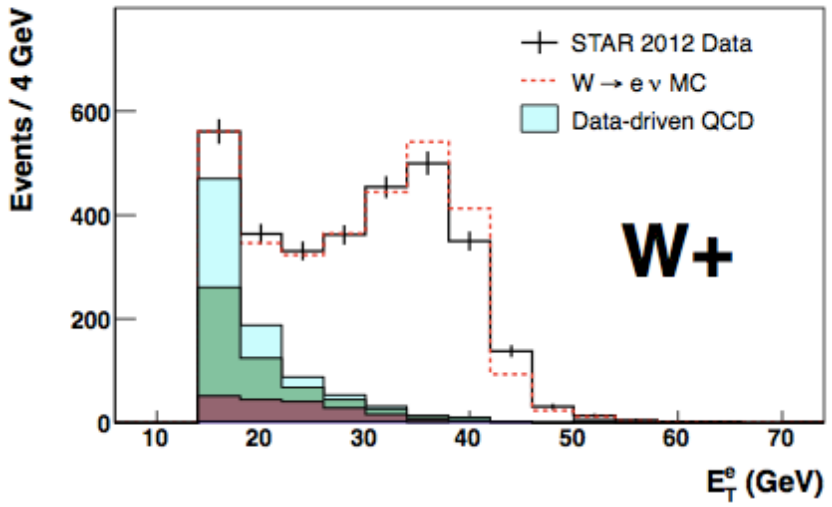
- Spin asymmetry measurements:

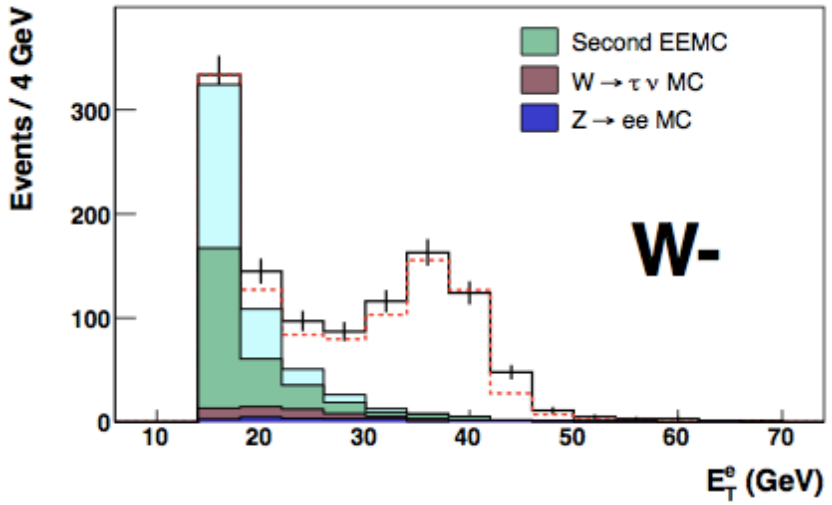
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} = \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

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

W selection : Jacobian peak

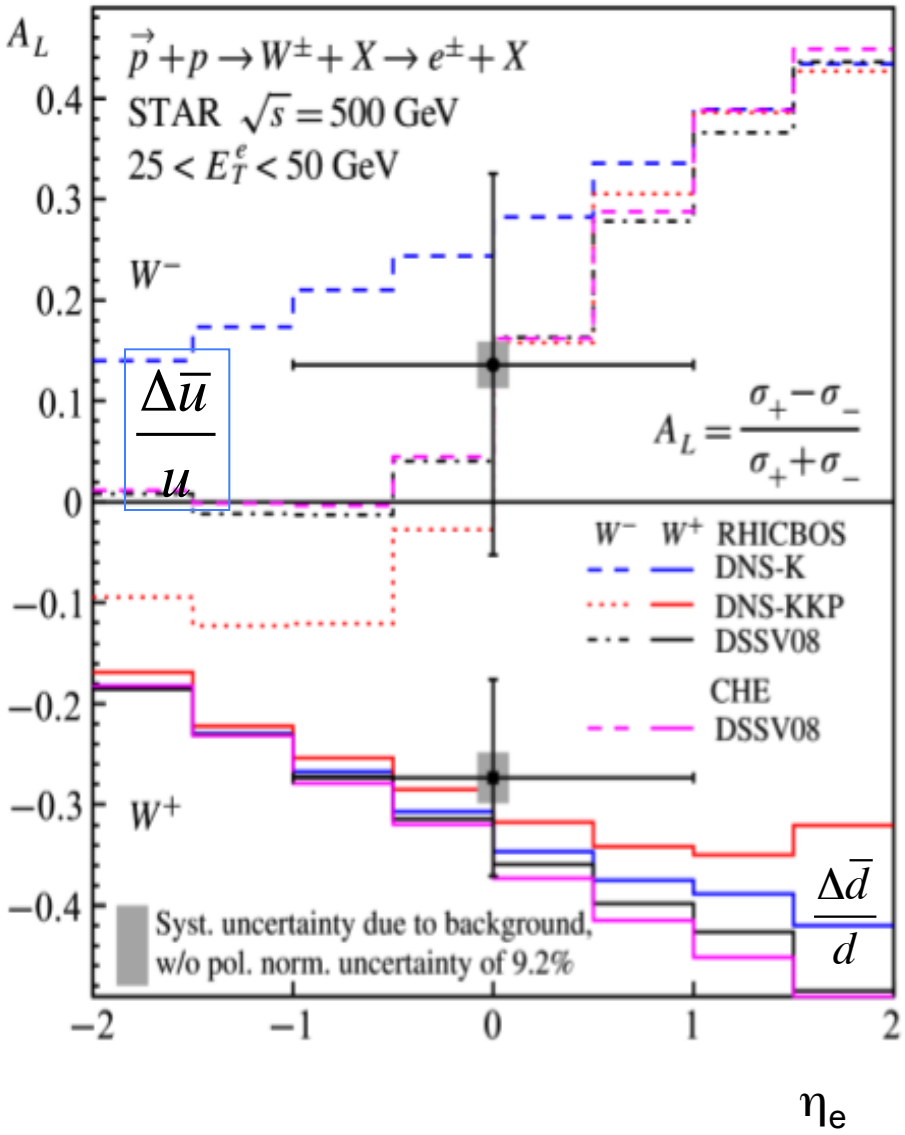






- Background dominated by QCD background, estimated with a data driven method. Also smaller fraction from $W \rightarrow \tau\upsilon$ decay, and Z^0 boson decay (MC estimate).

First STAR W A_L results (Run9)

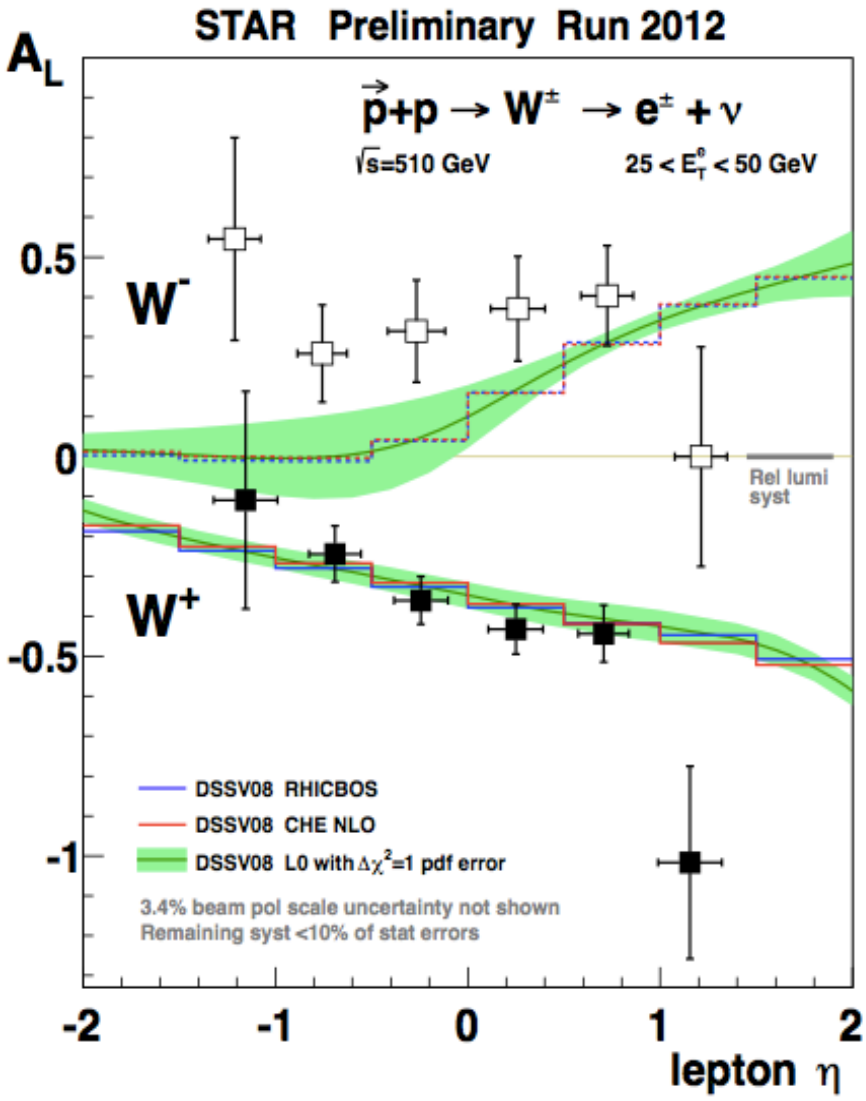


STAR: Phys. Rev. Lett. 106, 062002(2011)

- 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

STAR 2012 W A_L results



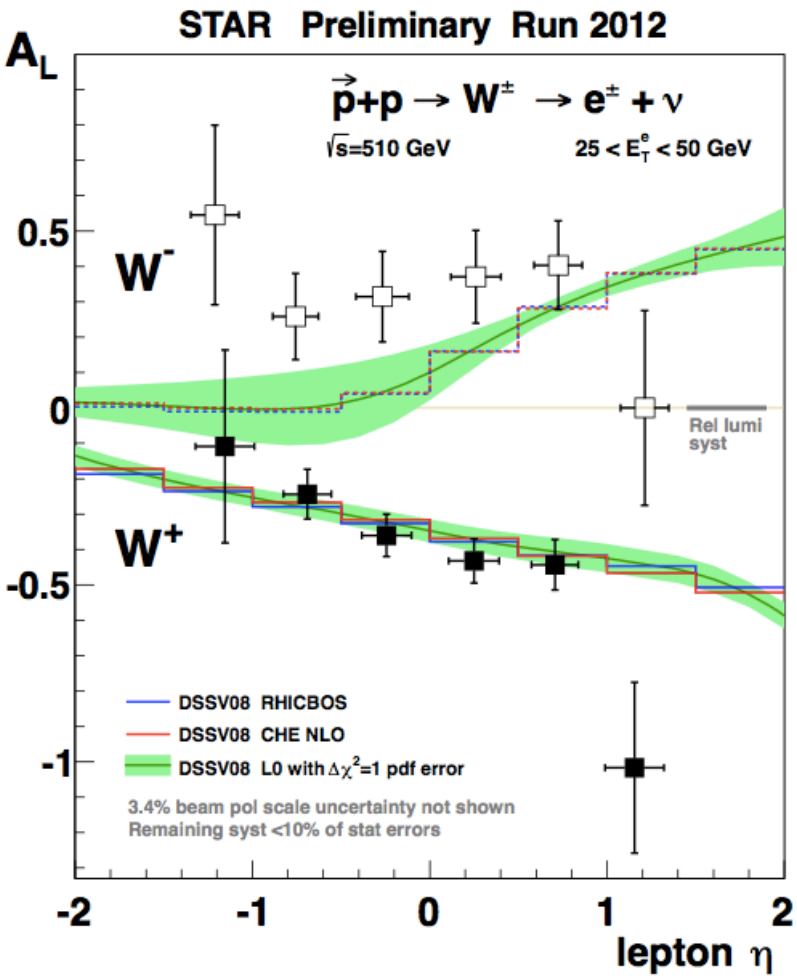
- A_L of W- shows indication that data is larger than the DSSV predictions

-> The enhancement at $\eta_e<0$ is sensitive to anti u-quark distribution

- A_L of W+ is consistent with theoretical predictions with DSSV pdf.

- The systematic uncertainties for A_L is well under control for $|\eta_{el}|<1.4$

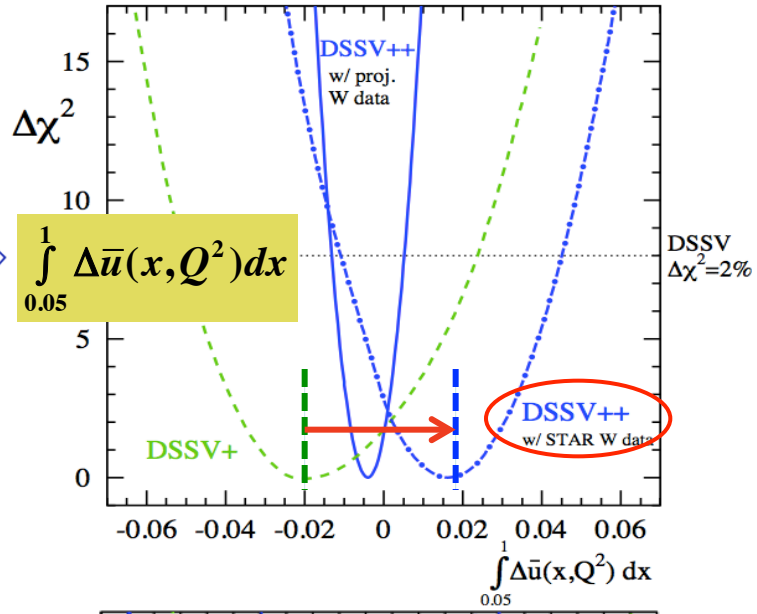
Global Analysis with STAR 2012 W results

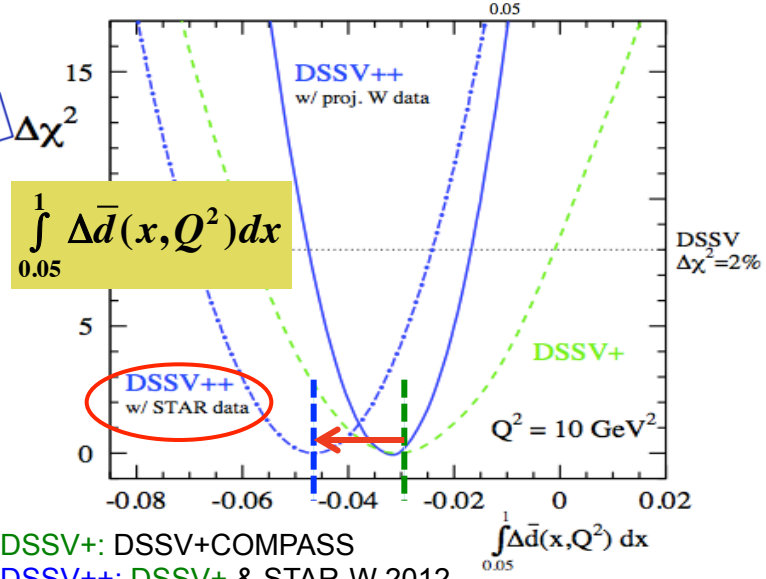


$\Delta\bar{u}$

$\Delta\bar{d}$

arXiv:1304.0079



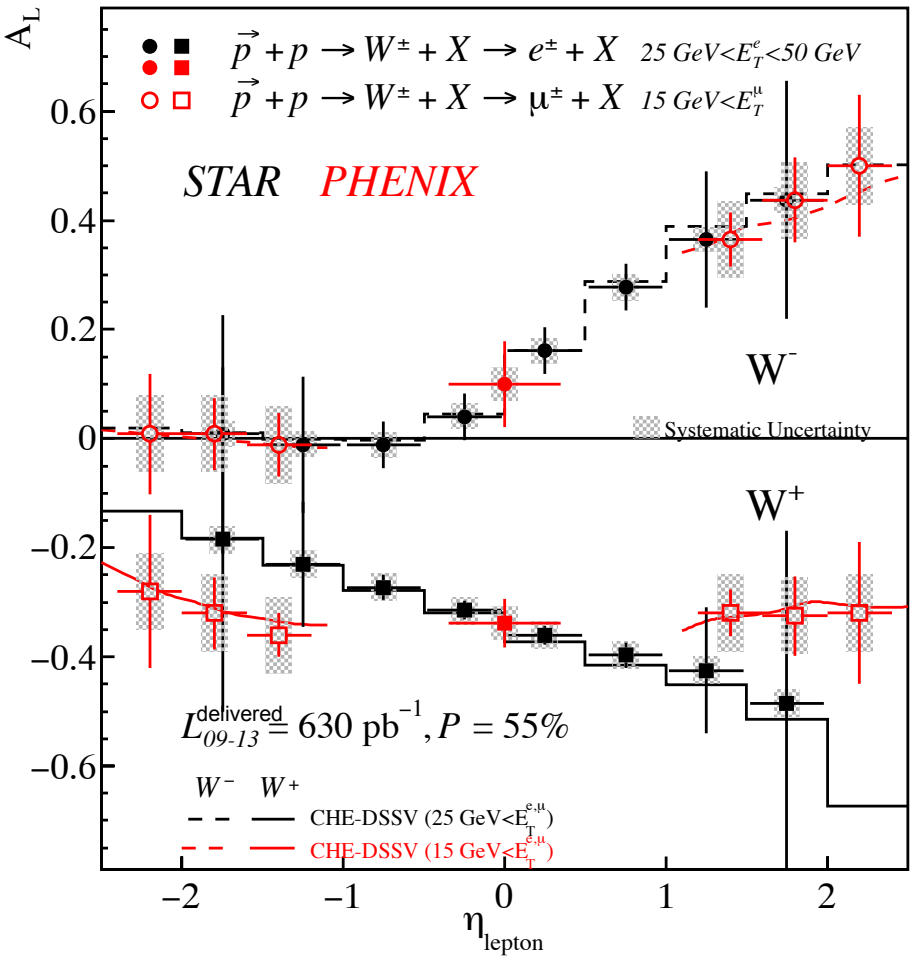


DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012

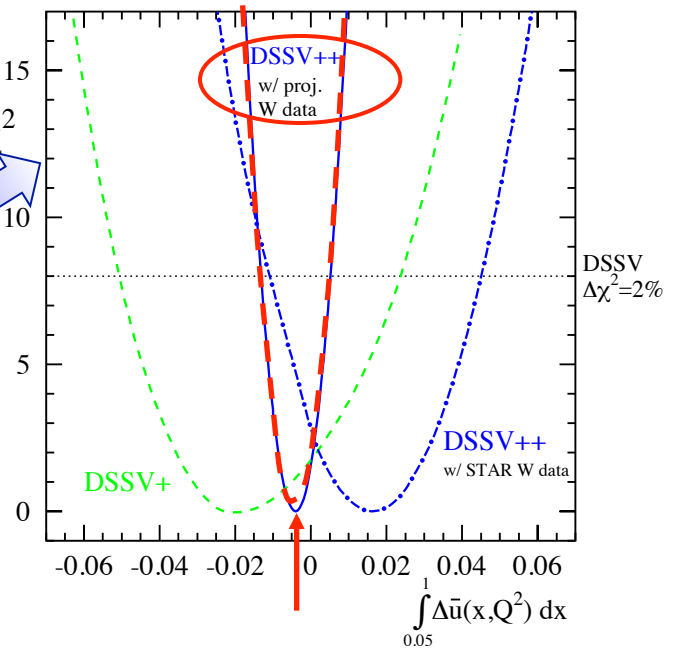
STAR 2012 W results provide significant constraints on $\Delta\bar{u}, \Delta\bar{d}$.

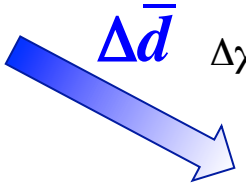
STAR Run 9-13 Projections at 500 GeV

arXiv:1304.0079
(pseudo-data randomized around DSSV)

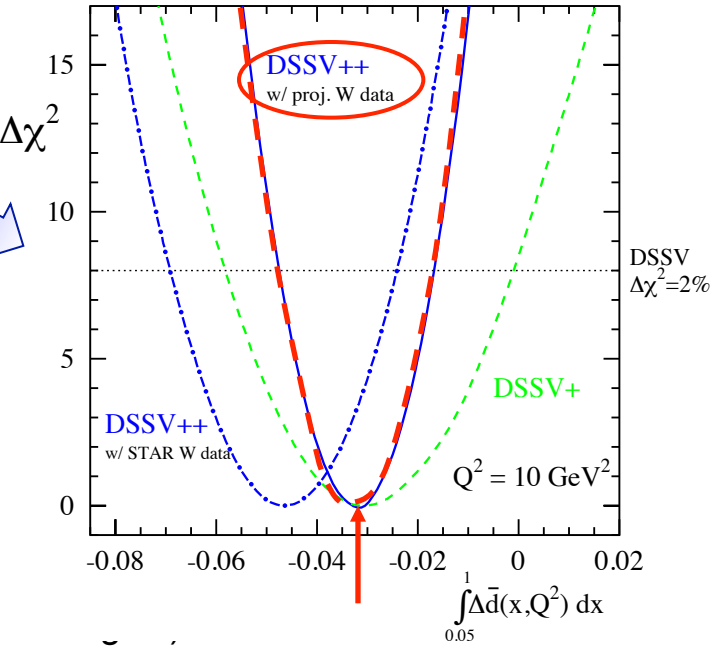


$\Delta\bar{u}$





$\Delta\bar{d}$



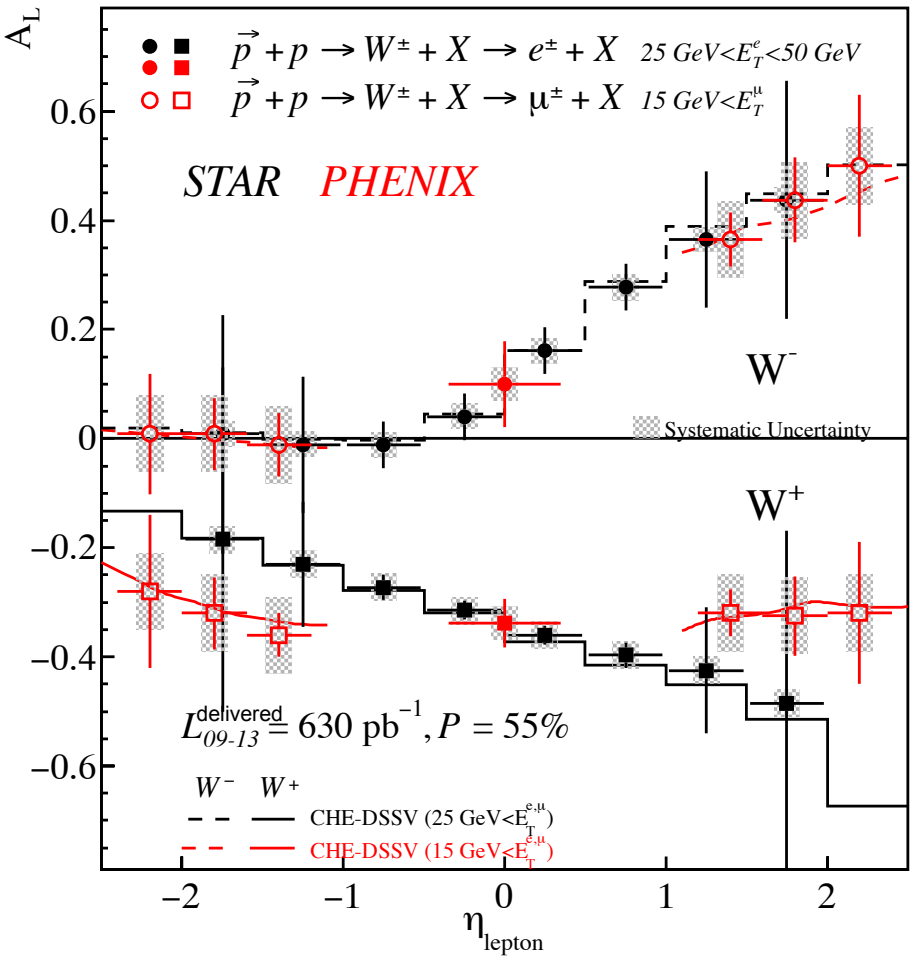
RHIC: $\int L_{09\text{-}13} = (50+100+120+475) = 745 pb^{-1}$

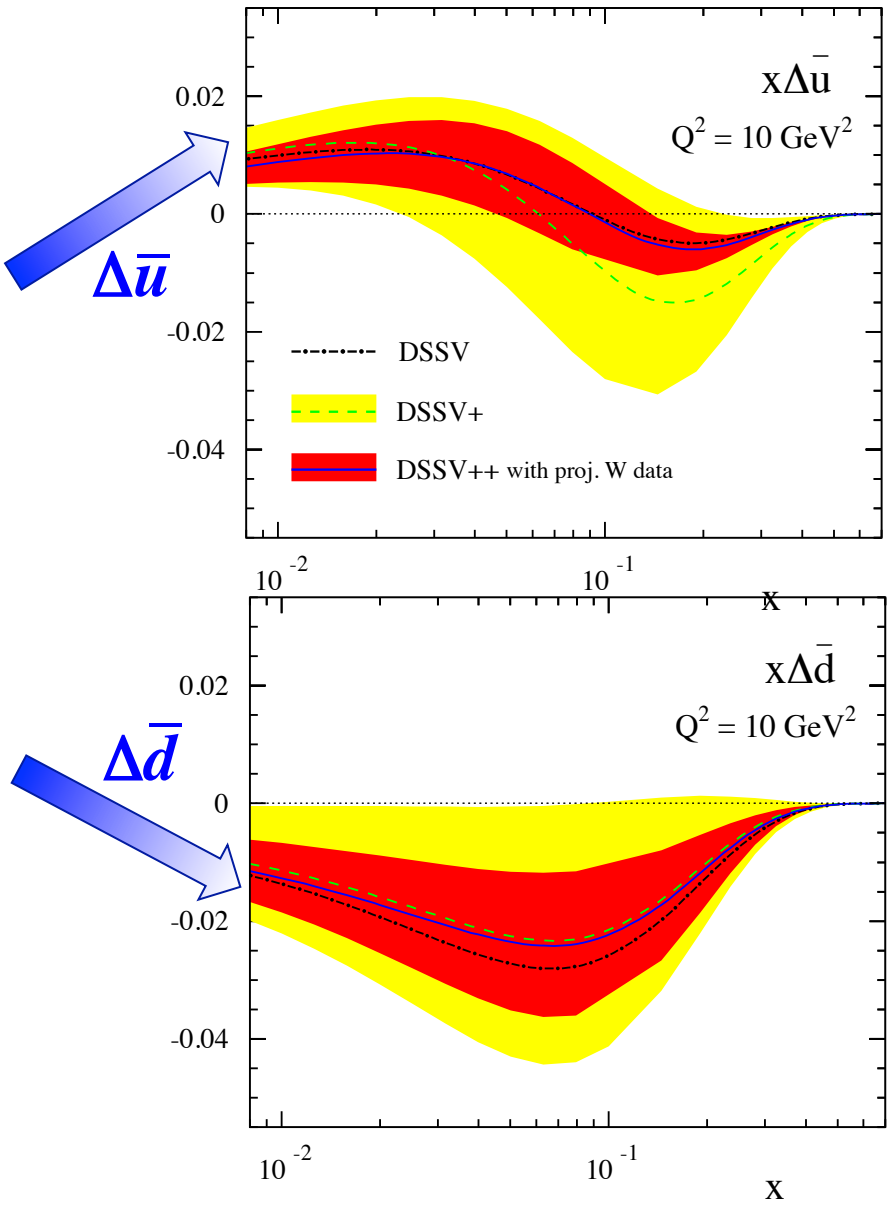
DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj.

-courtesy of E. Aschenauer

STAR Run 9-13 Projections at 500 GeV

arXiv:1304.0079
(pseudo-data randomized around DSSV)



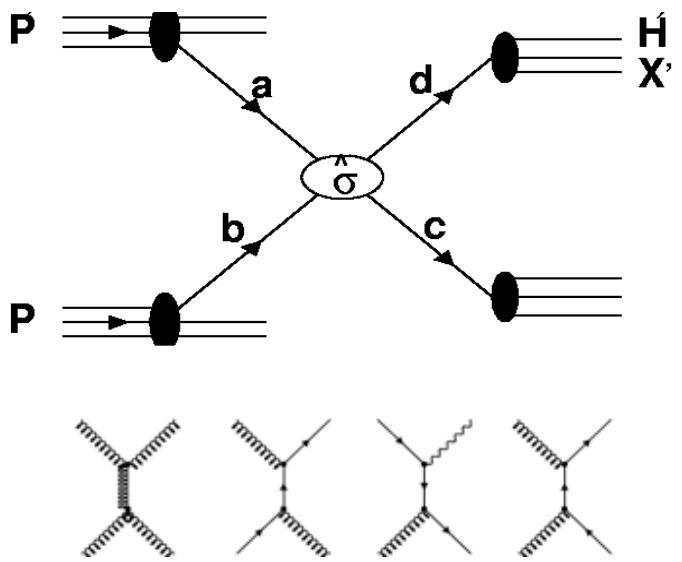


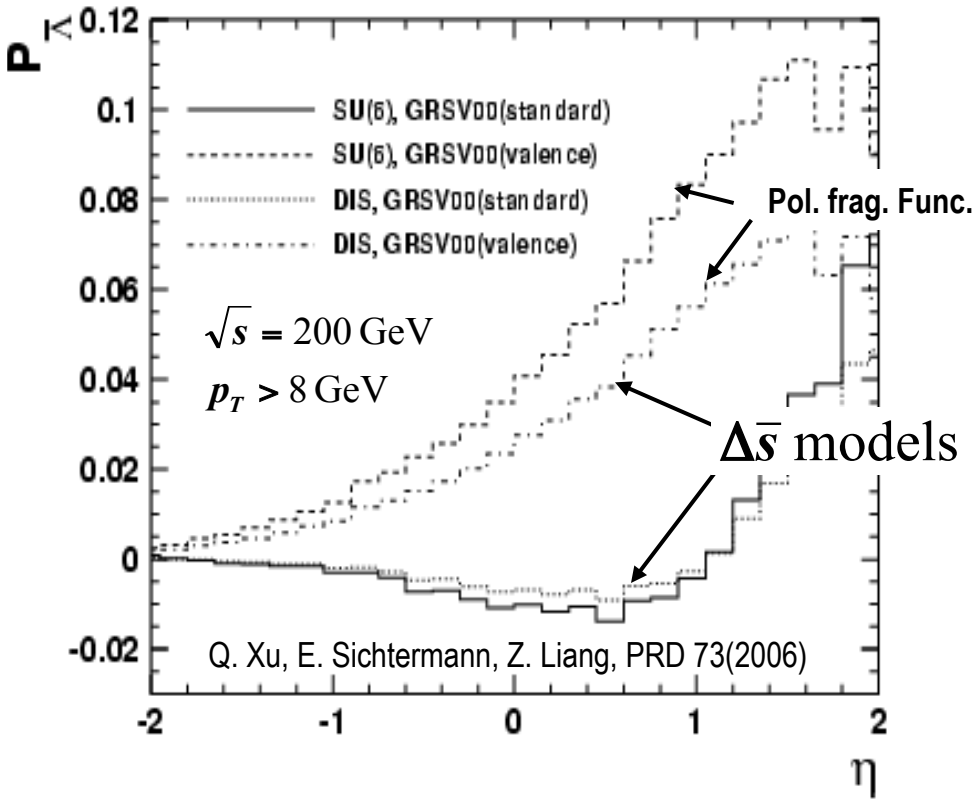
RHIC: $\int L_{09\text{-}13} = (50+100+120+475) = 745 pb^{-1}$

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

Hyperon spin transfer in pp collisions

- Hyperon spin transfer can provide sensitivity to strange quark polarization:



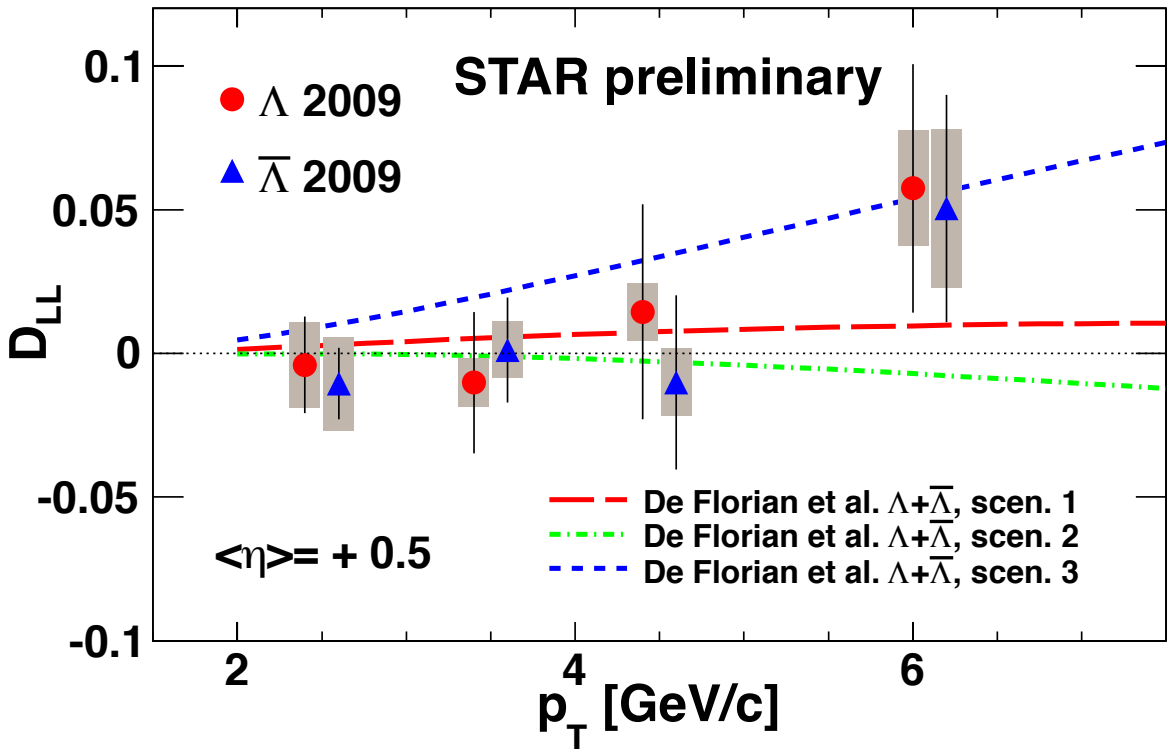


$$d\sigma \propto \int f_a(x_1)\cdot f_b(x_2) \otimes d\hat{\sigma} \otimes D^{\Lambda}(z)$$

- Longitudinal spin transfer D_{LL} of hyperons:

$$D_{LL} \equiv \frac{\sigma_{p^+p\to\bar{\Lambda}^+X} - \sigma_{p^+p\to\bar{\Lambda}^-X}}{\sigma_{p^+p\to\bar{\Lambda}^+X} + \sigma_{p^+p\to\bar{\Lambda}^-X}} = \frac{d\Delta\sigma}{d\sigma}$$

D_{LL} Results of STAR from 2009 data



D. de Florian, M. Stratmann, and W. Vogelsang, 1998. (updated calculation to low p_T)

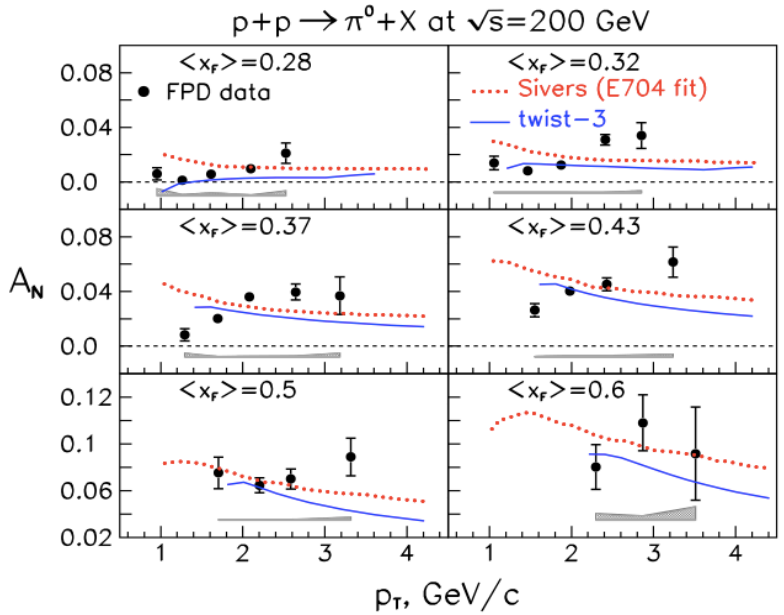
scen. 1: SU(6) picture.
scen. 2: DIS picture.
scen. 3: equal contribution.

- D_{LL} extended to p_T ~6.0 GeV with ~4% precision.
- D_{LL} for Lambda and Anti-Lambda are consistent with each other.
- The statistics are similar to the spread of different models.

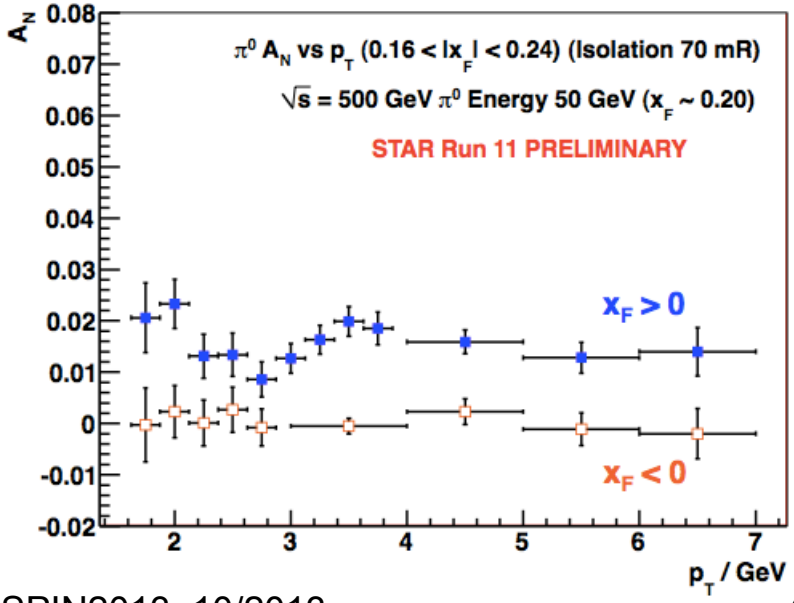
Recent results on transverse spin physics at STAR

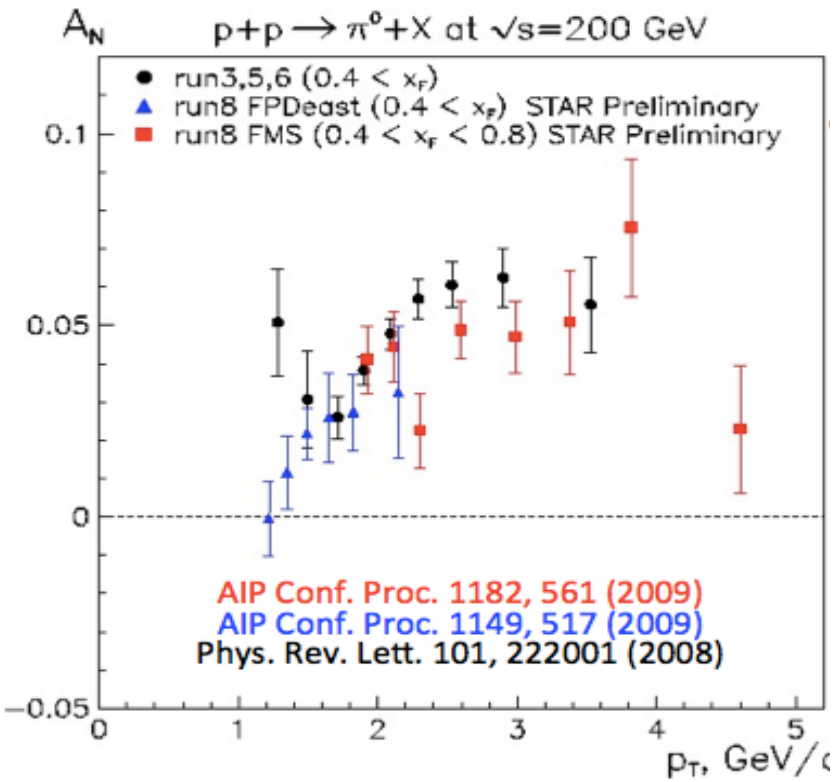
- Single spin asymmetries in the forward region
- Mid-rapidity hadron-jet correlations (Collins & Sivers)
- Di-hadron spin asymmetries (Transversity+IFF)

STAR π^0 A_N in the forward region



STAR, Phys. Rev. Lett 101,2008



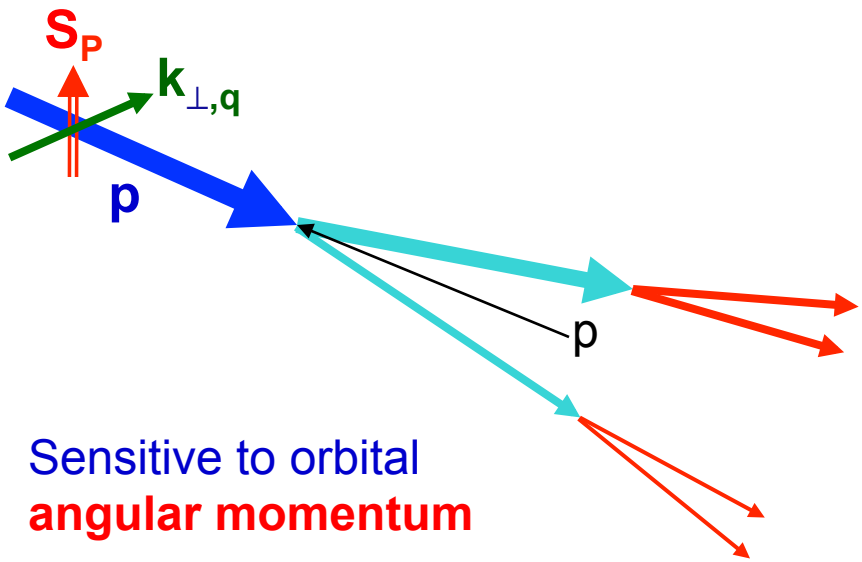


Asymmetries persist at high p_T seen from STAR Run3 to Run11 data at 200 and 500 GeV.

Studying Sivers and Collins effect at RHIC

- Sivers effect (*Sivers'90*):

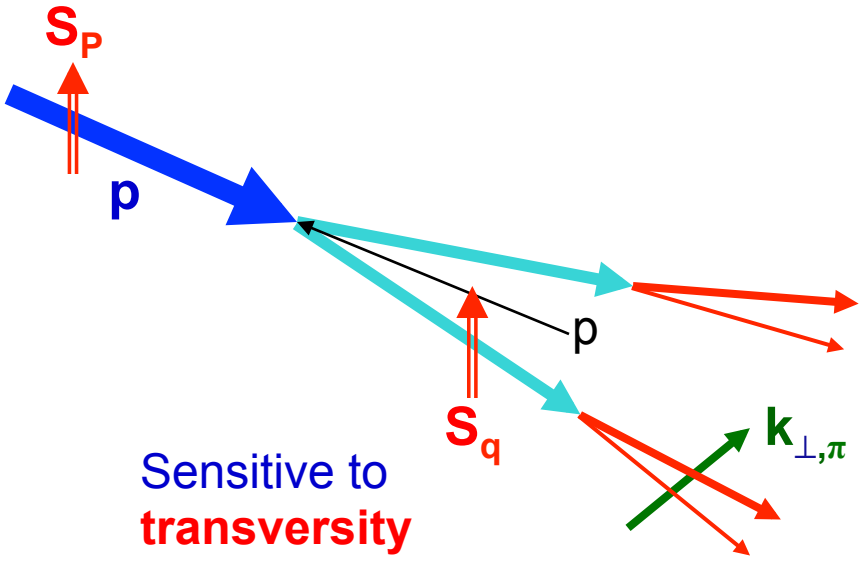
  parton spin and $k_\perp$ correlation in initial state (related to orbital angular momentum)



Sensitive to orbital **angular momentum**

- Collins effect (*Collins'93*):

  quark spin and $k_\perp$ correlation in fragmentation process (related to transversity)

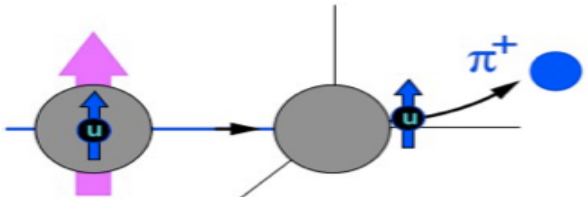


Sensitive to **transversity**

- For hadron SSA, both Sivers and Collins effects can contribute.
- Study of jet production can separate Collins & Sivers effects.

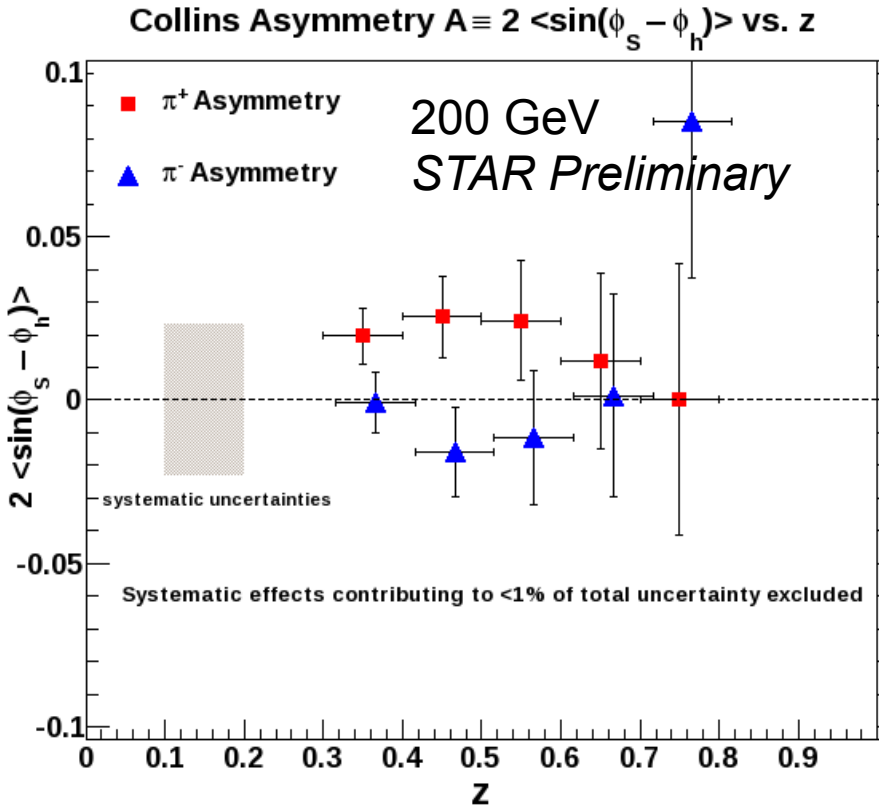
Mid-rapidity hadron-jet correlations

Study proton transversity through its coupling to Collins function:

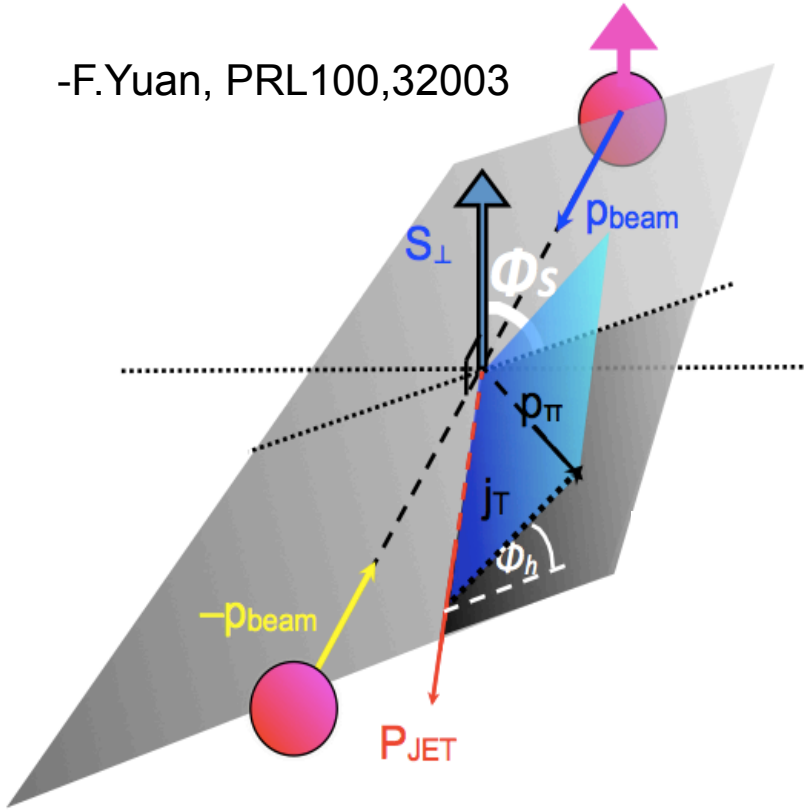


$$h_1(x) \otimes H_1^{\perp}(z, j_T)$$

- Collins asymmetries from STAR Run6:



-F.Yuan, PRL100,32003



Mid-rapidity hadron-jet correlations

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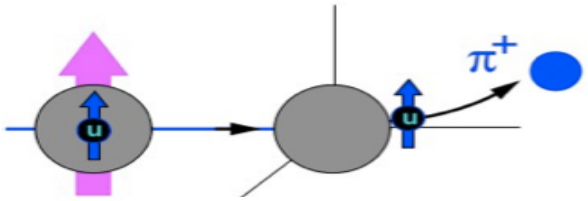

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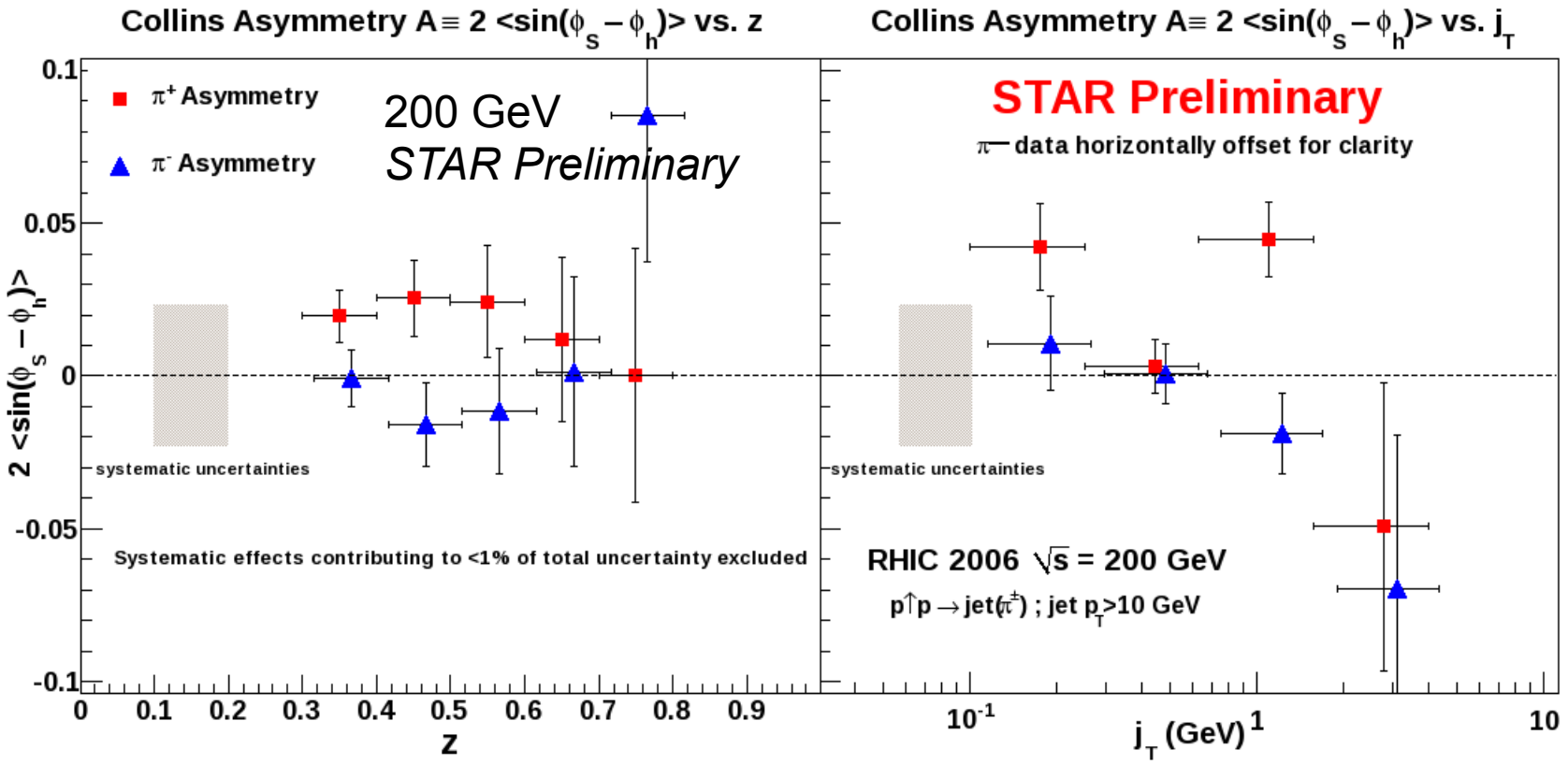
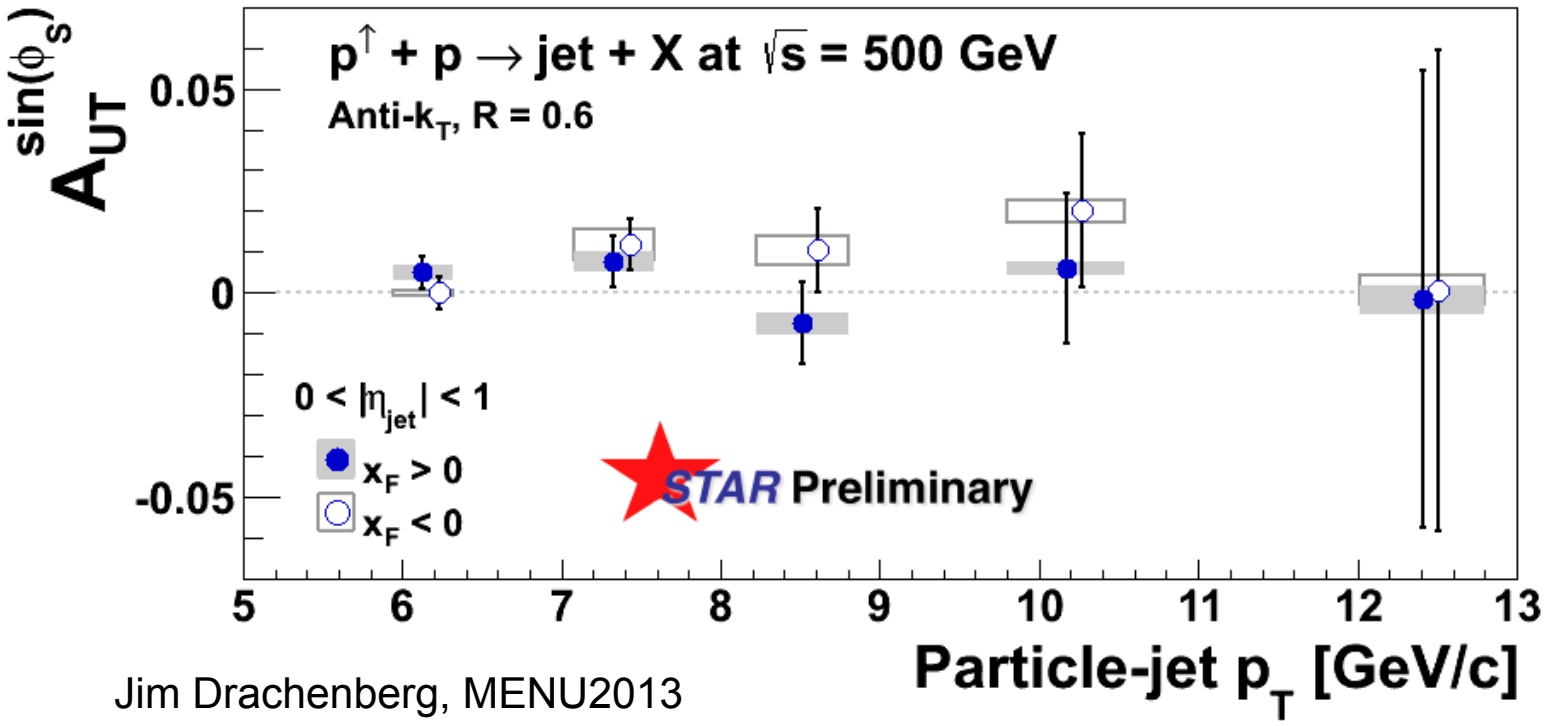


Sivers asymmetries- jet SSA

- New results on jet spin asymmetries at 500 GeV (Run 11):

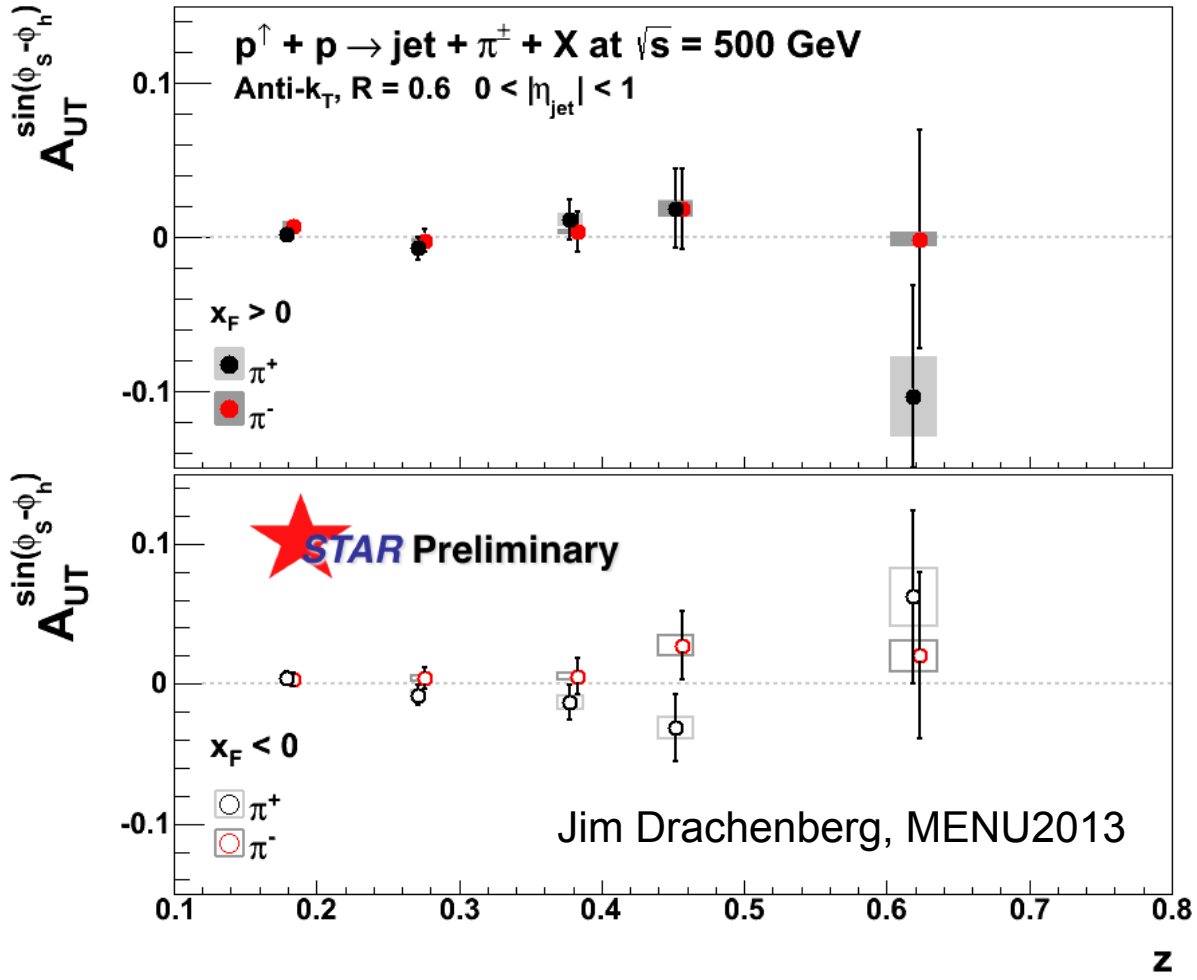


Jim Drachenberg, MENU2013

No sign of sizable azimuthal asymmetry in mid-rapidity jet production.

Collins asymmetries at 500 GeV

- New results on Collins asymmetries at 500 GeV (run11):



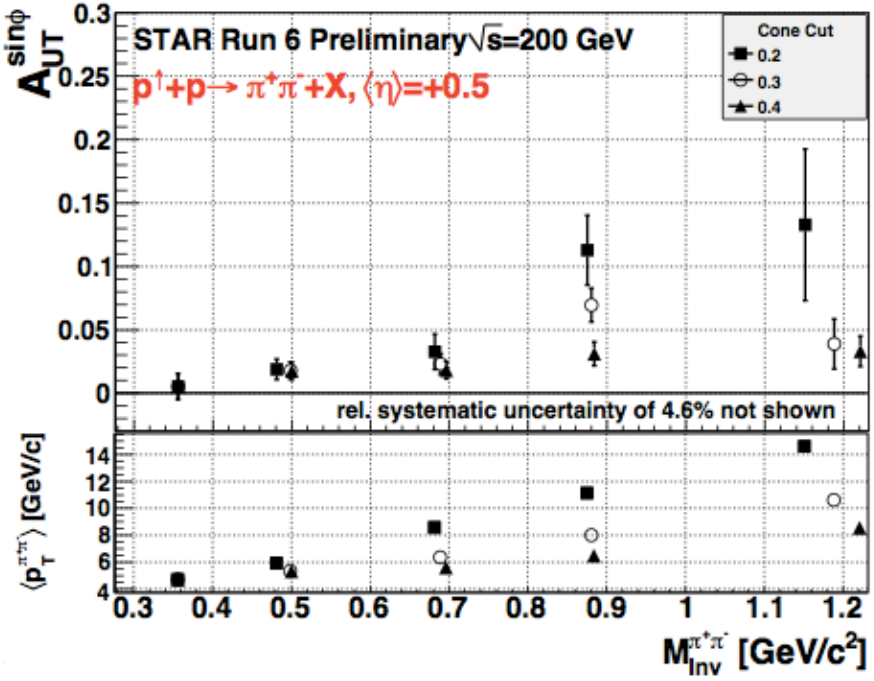
Limited statistics at high z. Consistent with zero within uncertainty.

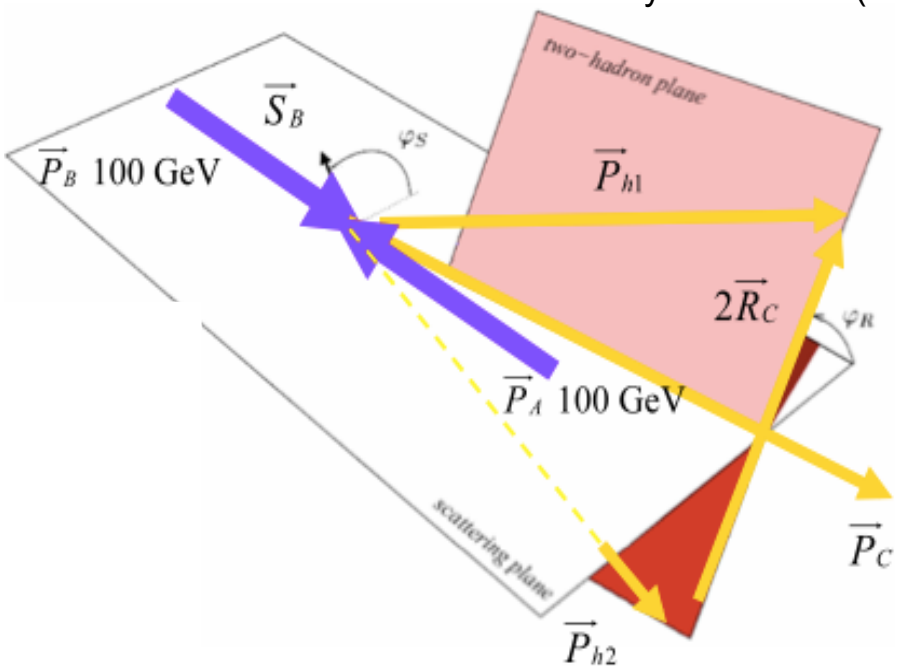
Di-hadron spin asymmetries at STAR

Di-hadron correlation provide access to IFF& transversity:

$$\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}(\Phi_S - \Phi_R) = A_{UT}^{\sin\Phi} \sin(\Phi_S - \Phi_R).$$

Bacchetta, Radici, Phys.Rev. D70 (2004)





Sign of non-zero signal for di-hadron transverse single spin asymmetries-> constraints on transversity!

Run12+15: opportunity for much higher precision.

Di-hadron spin asymmetries at STAR

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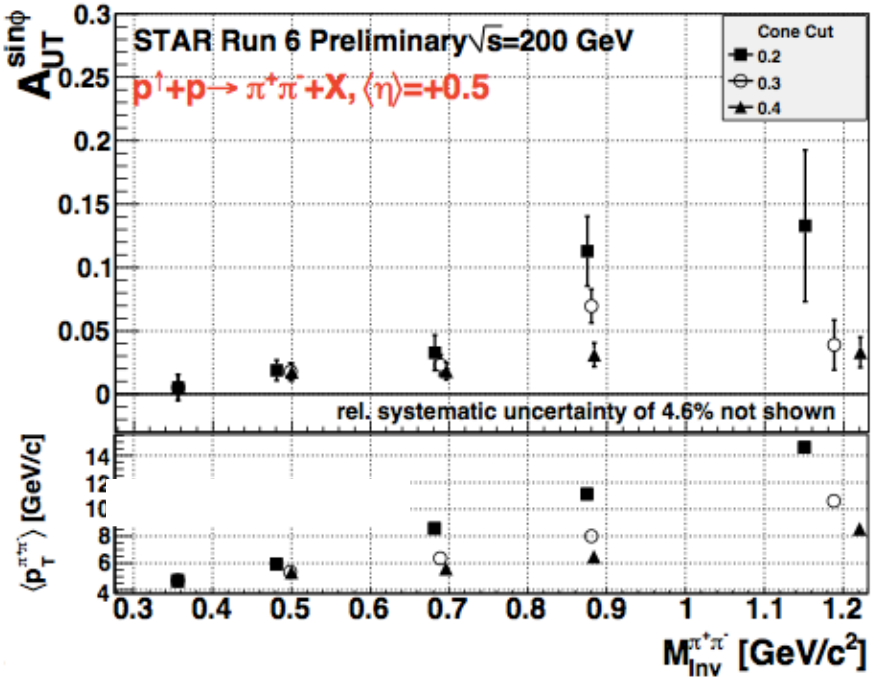

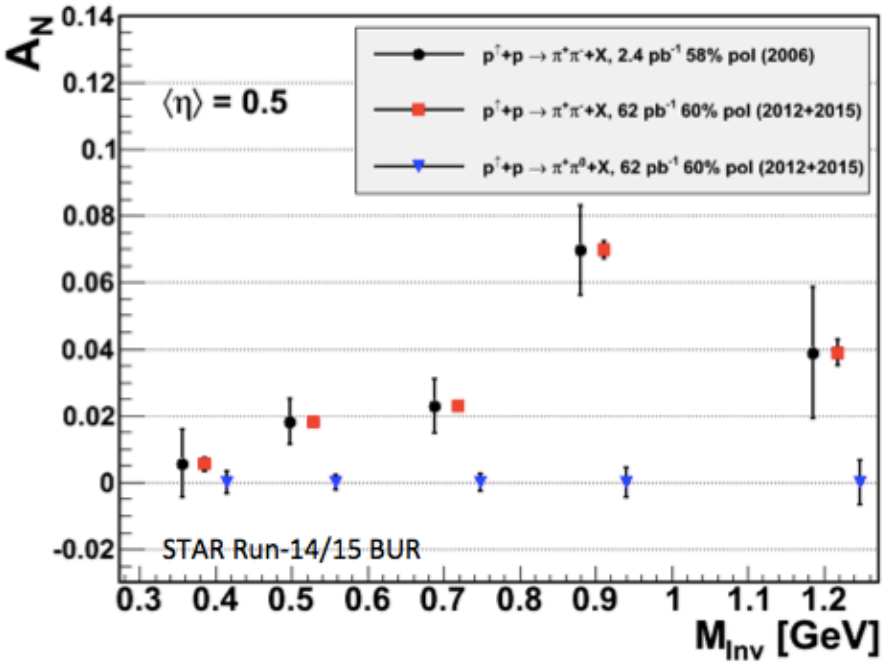

Sign of non-zero signal for di-hadron transverse single spin asymmetries-> constraints on transversity!

Run12+15: opportunity for much higher precision.

Summary & Outlook

Determination of gluon polarization ΔG at STAR:

- Currently probes with jets, 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

Probing sea quark polarization at STAR:

- STAR 2012 results on W-boson A_L provide new constraints on $\Delta\bar{u}, \Delta\bar{d}$.
- Hyperon spin transfer measurement->study strange quark pol.

Results on transverse spin physics at STAR:

- Single spin asymmetries in the forward region even at high p_T.
- Mid-rapidity hadron-jet correlations (Collins & Sivers).
- Non-zero di-hadron spin asymmetries (Transversity+IFF).

STAR Run 13 and future:

- A long 500 GeV pp run in 2013 -> L_{int}~300 pb^{-1}
- 200GeV pp/pA run in run15 and likely more 500GeV running in future.

Forward upgrade at STAR

The upgrade will extend the capabilities for jets, photons, leading particles at the forward region (>2015).