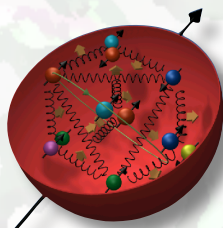


Recent results of the high-energy spin physics program at RHIC at BNL

Bernd Surrow



(On behalf on the STAR Collaboration)

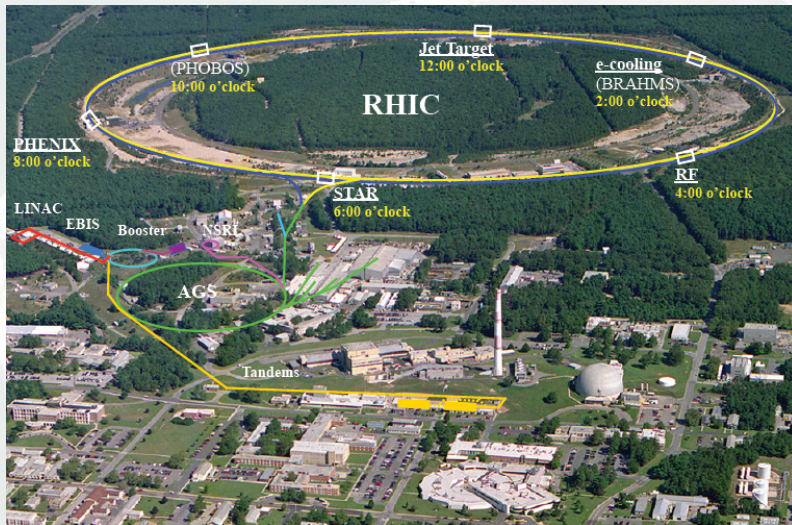


**38th INTERNATIONAL CONFERENCE
ON HIGH ENERGY PHYSICS**

AUGUST 3 - 10, 2016
CHICAGO



Outline

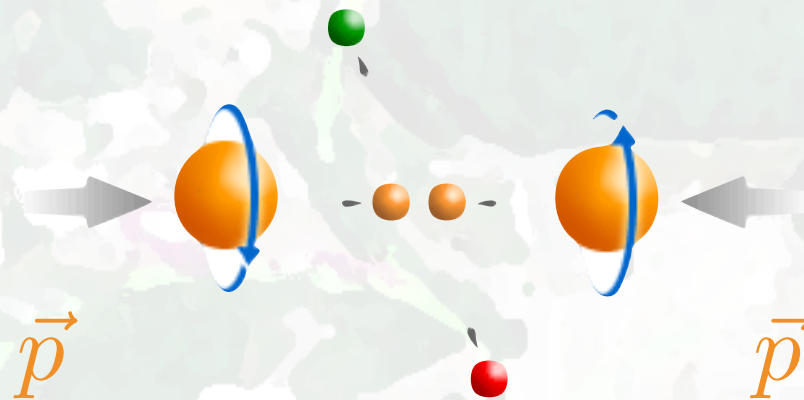


Results / Status

- Gluon related studies (Jet production): $g / \Delta g$
- Quark / Anti-quark related studies (W / Z production): $q / \Delta q$
- Transverse spin dynamics (W / Z production):
Sivers function

Experimental aspects: RHIC / STAR

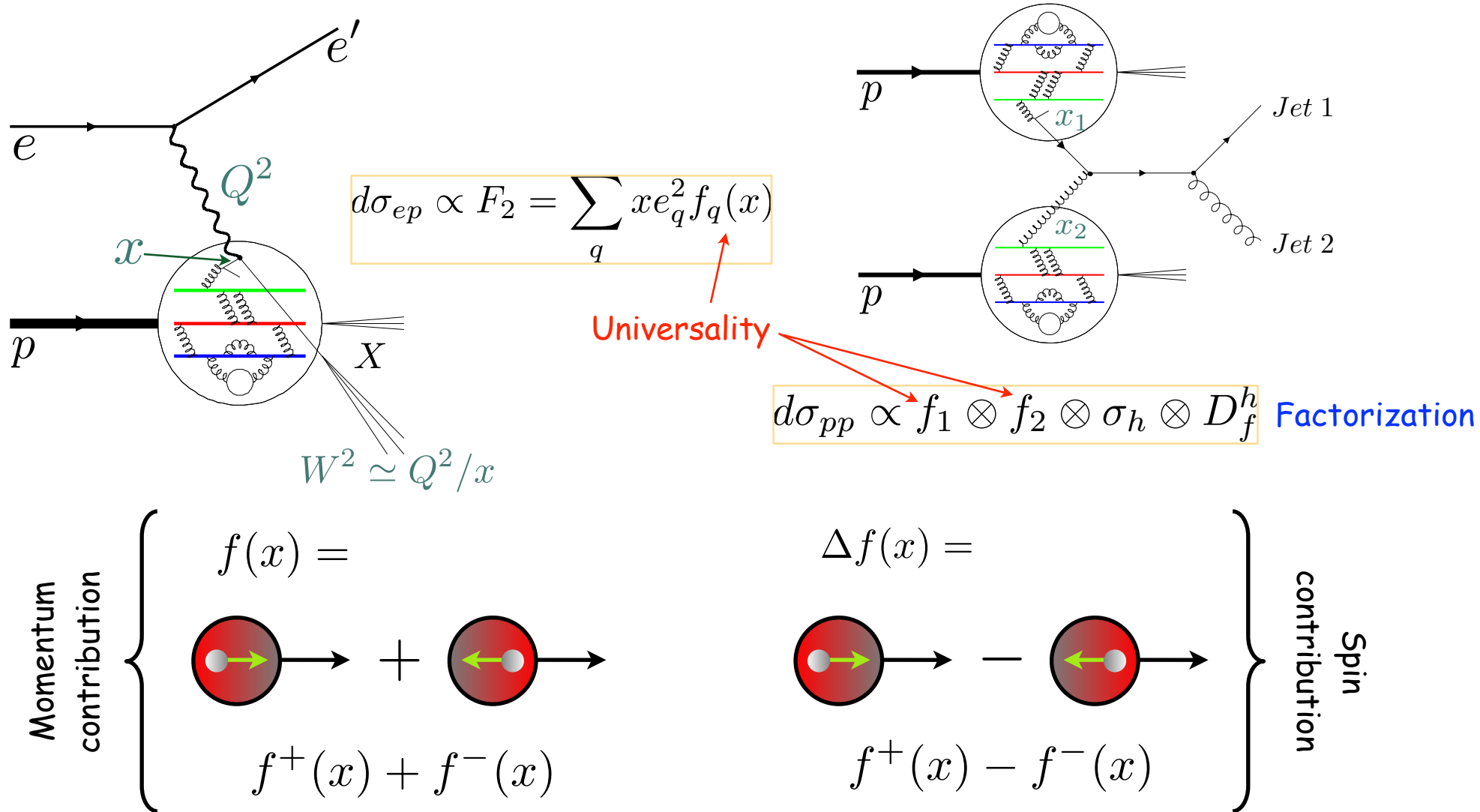
Theoretical foundation



Summary and Outlook

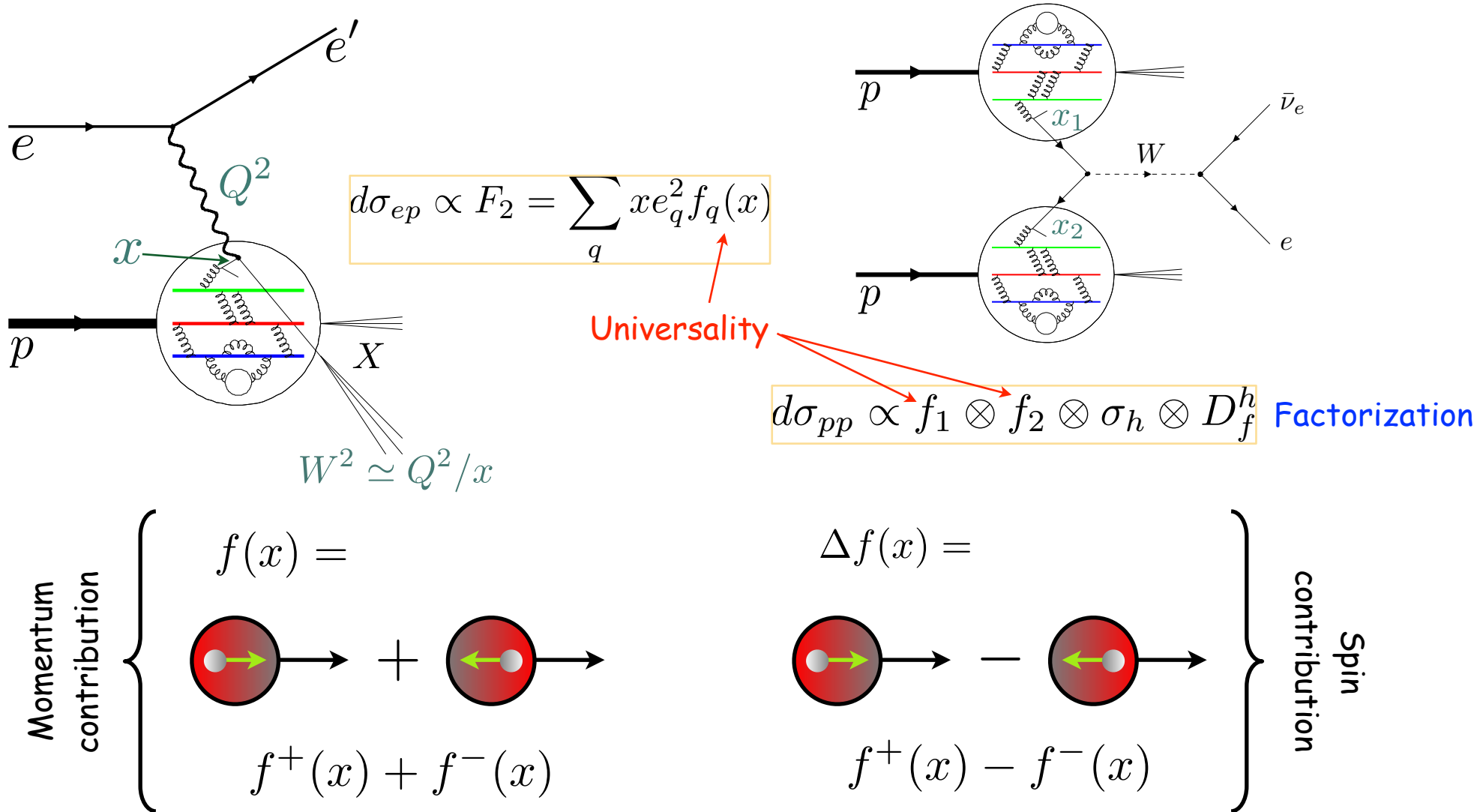
Theoretical foundation

- How do we probe the structure and dynamics of matter in ep vs. pp scattering?



Theoretical foundation

- How do we probe the structure and dynamics of matter in ep vs. pp scattering?



Theoretical foundation

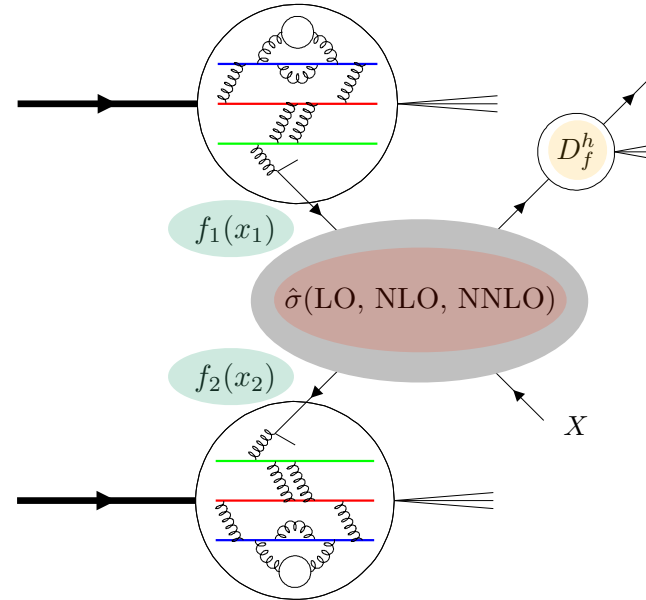
□ Proton spin structure using high-energy polarized p+p collisions: Helicity

○ Observable: Quark/Anti-quark polarization (W production)

- Longitudinal single-spin asymmetry A_L

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

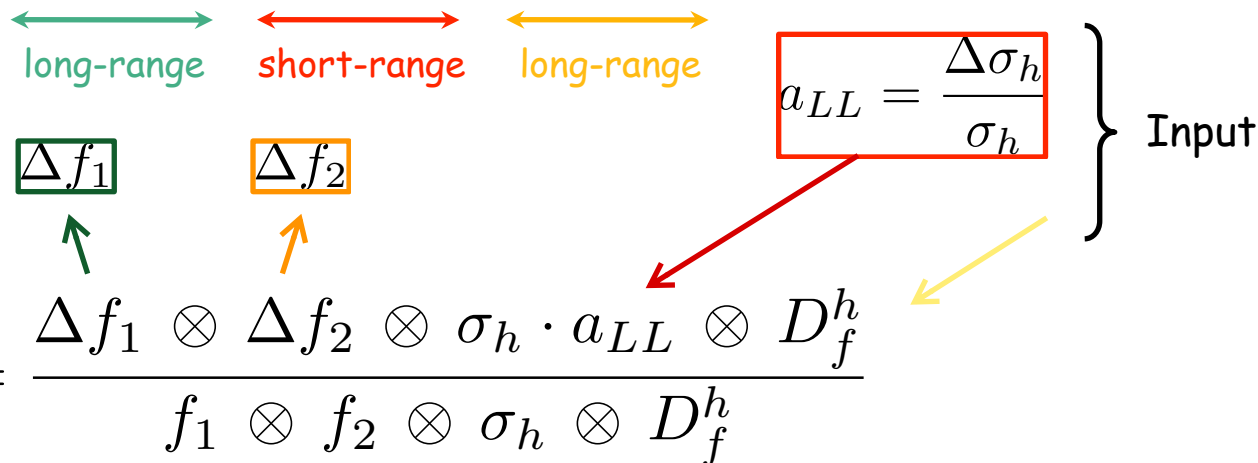
- Parity (Spatial inversion) violating for W production!



○ Observable: Gluon polarization (Jet/Hadron production)

- Double longitudinal single-spin asymmetry A_{LL}

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$



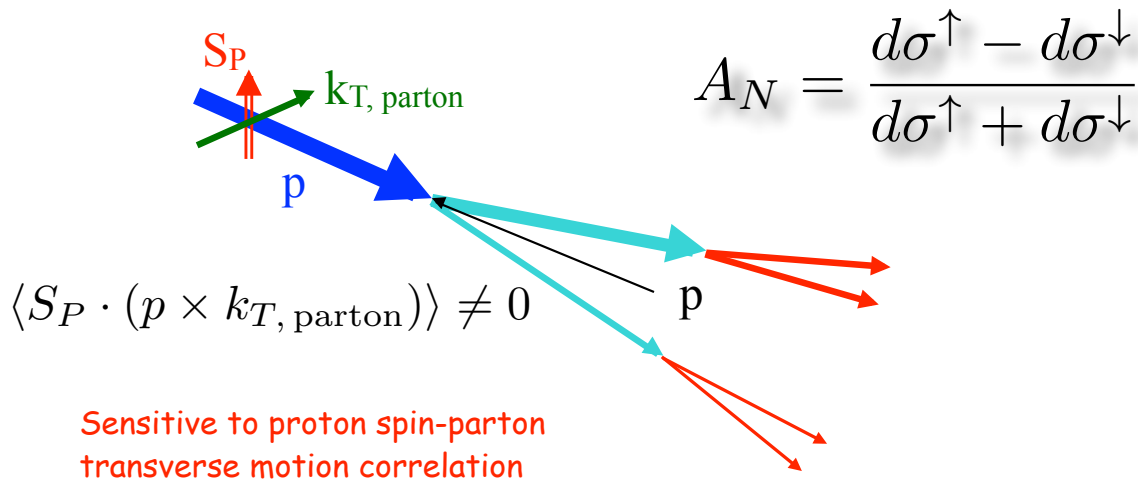
Theoretical foundation

□ Proton spin structure using high-energy polarized p+p collisions: Trans. spin dynamics

○ Transverse momentum dependent (TMD) PDFs and FFs

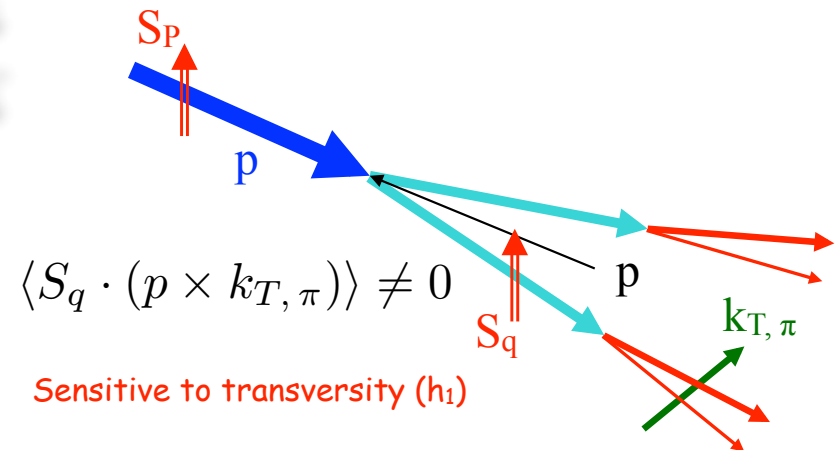
Sivers mechanism: Asymmetry in forward jet or γ production

D. Sivers, Phys. Rev. D 41, (1990) 83.
D. Sivers, Phys. Rev. D 43, (1991) 261.

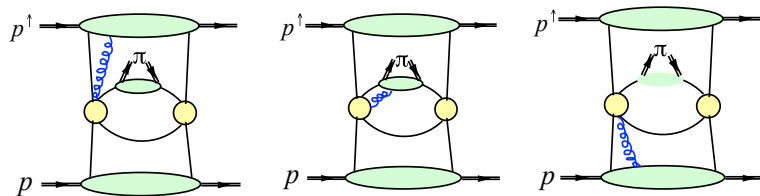


Collins mechanism: Asymmetry in forward jet fragmentation

J. Collins, Nucl. Phys. B396, (1993) 161.



○ Transverse momentum dependent (TMD) PDFs and FFs



Non-zero asymmetry from multi-parton correlation functions

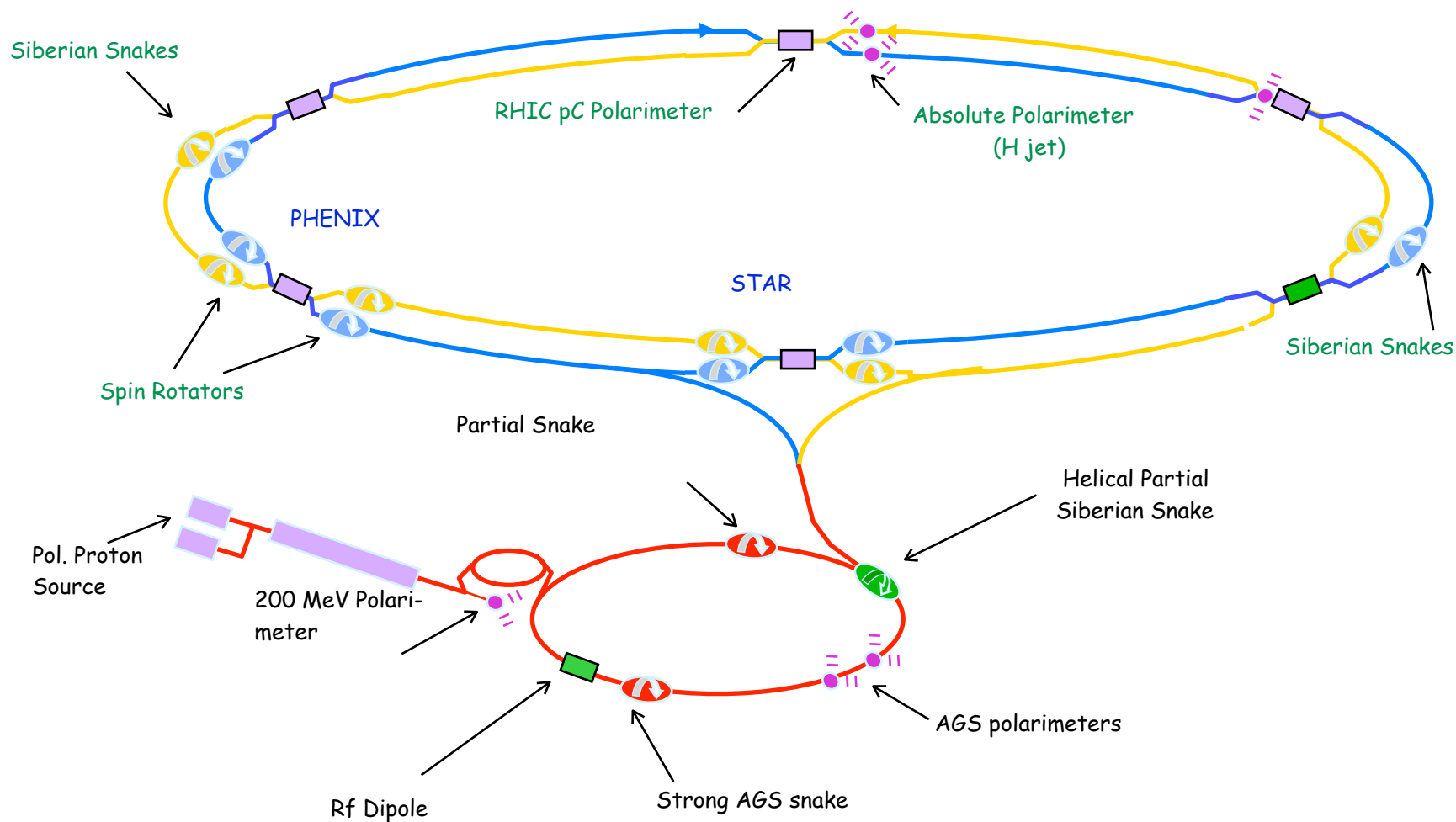
J. Qiu and G. Sterman, Phys. Rev. Let. 67 (1991) 2264.
J. Qiu and G. Sterman, Phys. Rev. D59 (1998) 014004.

Correlators closely related to k_T moments of TMDs

D. Boer, P. Mulders and F. Pijlman, Nucl. Phys. B 667 (2003) 201.

Experimental aspects - RHIC

- The world's first polarized proton-proton collider

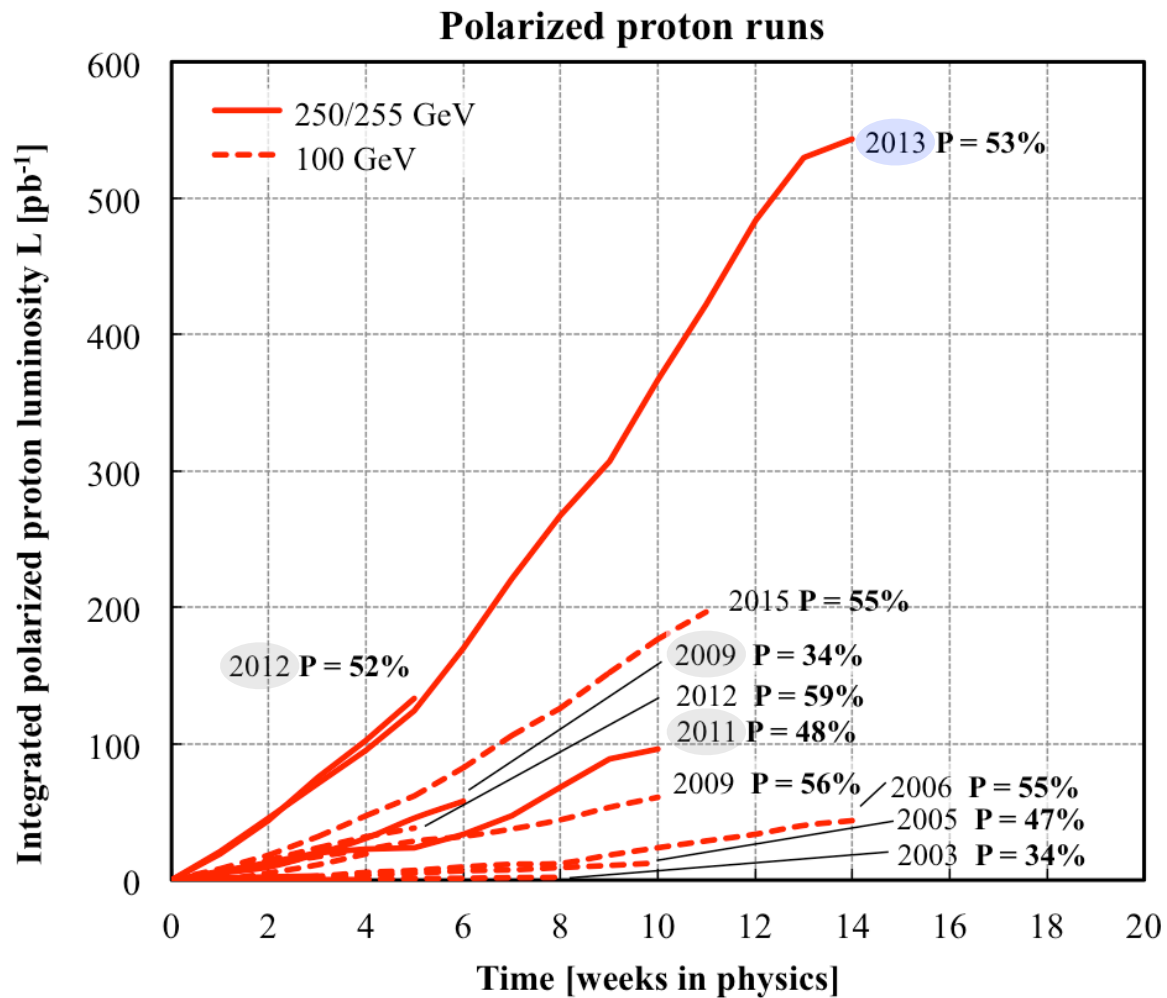


Experimental aspects - RHIC

□ Polarized p-p collisions

- Production runs at $\sqrt{s}=500/510\text{ GeV}$ (long. polarization) in 2009, 2011, 2012 and 2013: [W production \(Quark polarization\)](#) / [Jet and Hadron production \(Gluon polarization\)](#)

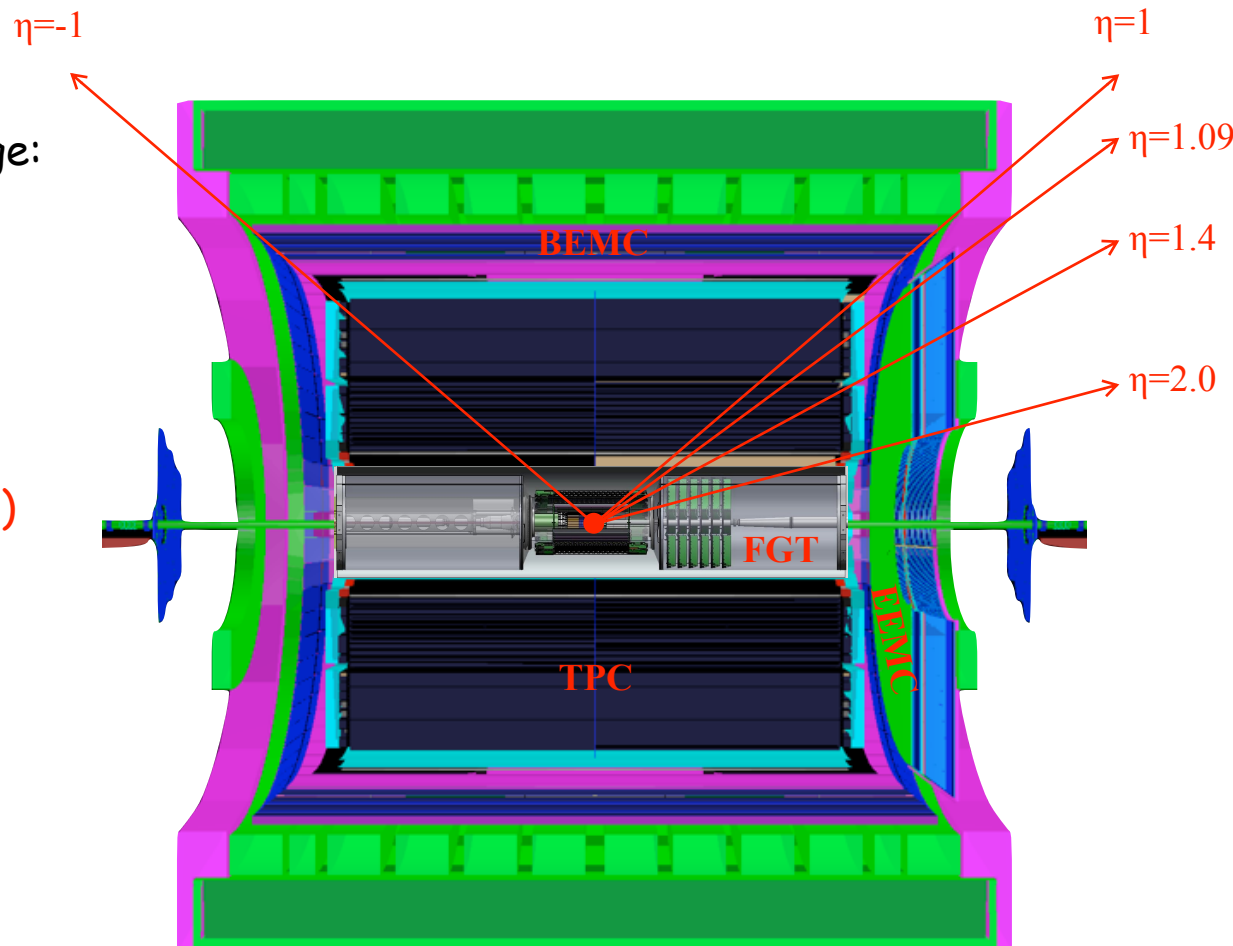
Run	L (pb ⁻¹)	P (%)	FOM (P ² L) (pb ⁻¹)
Run 9	12	0.38	1.7
Run 11	9.4	0.49	2.3
Run 12	72	0.56	24
Run 13	~300	0.54	~87



Experimental aspects - STAR

□ Overview

- Calorimetry system with 2π coverage:
BEMC ($-1 < \eta < 1$) and EEMC ($1 < \eta < 2$)
- TPC: Tracking and particle ID
($|\eta| < 1.3$)
- FGT: Forward GEM Tracker (Run 13)
($1 < \eta < 2$)
- ZDC: Relative
luminosity and local
polarimetry
- BBC: Relative
luminosity and
Minimum bias trigger



$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right)$$

Results / Status - g / $\Delta g(x)$ related studies

□ STAR: Mid-rapidity Inclusive Jet cross-section measurement (Run 9) at 200GeV (1)

- Unfolded inclusive jet cross-section using anti- k_T algorithm ($R=0.6$) (Smaller dependence on underlying event (UE) and Pile-up)

$$D_{ij} = \min \left(\frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2} \right) \frac{\Delta R_{ij}^2}{R}$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \quad D_i = \frac{1}{k_{T,i}^2}$$

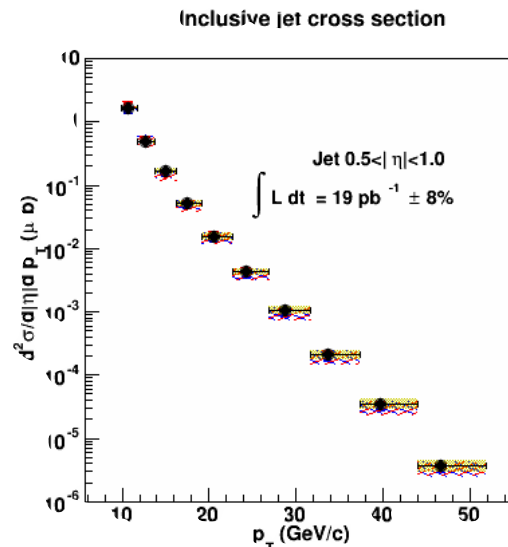
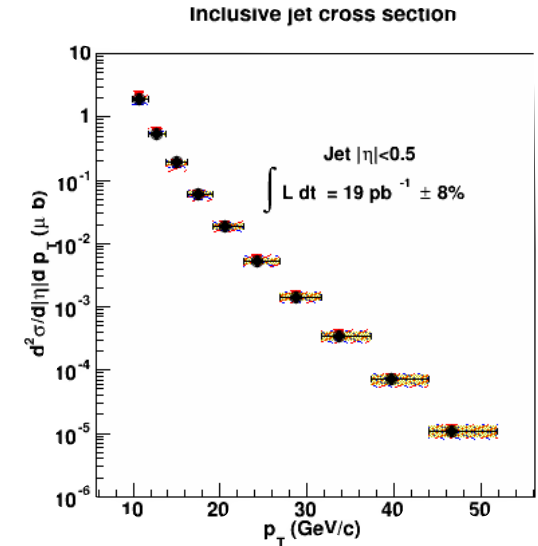
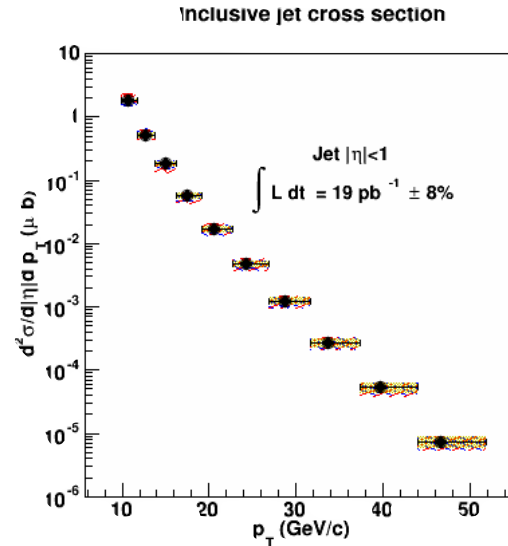
$$d = \min(\{D_{ij}, D_i\})$$

If $d = D_{ij}$: Combine jet i and jet j

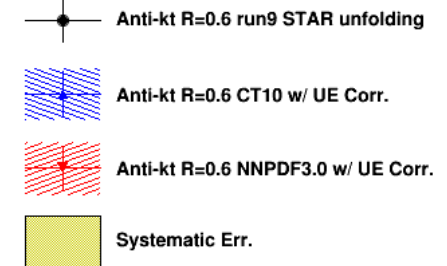
If $d = D_i$: Define jet i as final jet

corrected to particle level for three different pseudo-rapidity regions of $|\eta| < 1$, $|\eta| < 0.5$ and $0.5 < |\eta| < 1.0$

- Hadronization and UE corrections evaluated using PYTHIA applied to NLO calculations applied to pure NLO calculations for data comparison
- Comparison to NLO calculations for CT10, NNPDF3.0 and MRST-W2008 with a preference for CT10



STAR Run9 Preliminary
Inclusive jet cross section
 $\sqrt{s} = 200 \text{ GeV}$



X. Li et al. (STAR Collaboration), DIS 2015.

Bernd Surrow

Results / Status - $g / \Delta g(x)$ related studies

□ STAR: Mid-rapidity Inclusive Jet cross-section measurement (Run 9) at 200GeV (2)

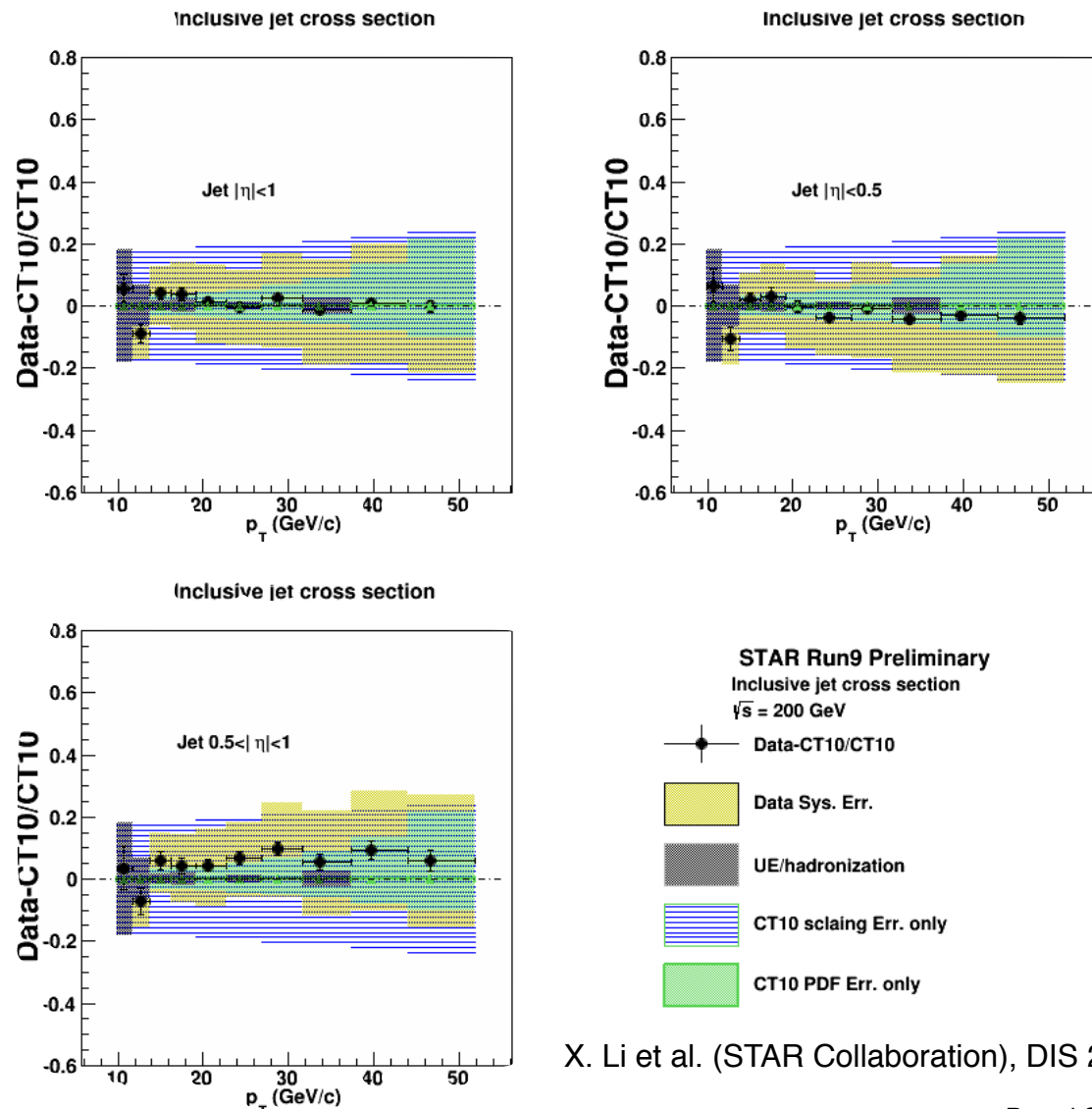
- Quantitative comparison between data and theory of (Data-Theory)/Theory showing

UE/hadronization corrections applied to pure NLO calculations

Data systematic errors

CT10 scale uncertainties

CT10 pdf uncertainties



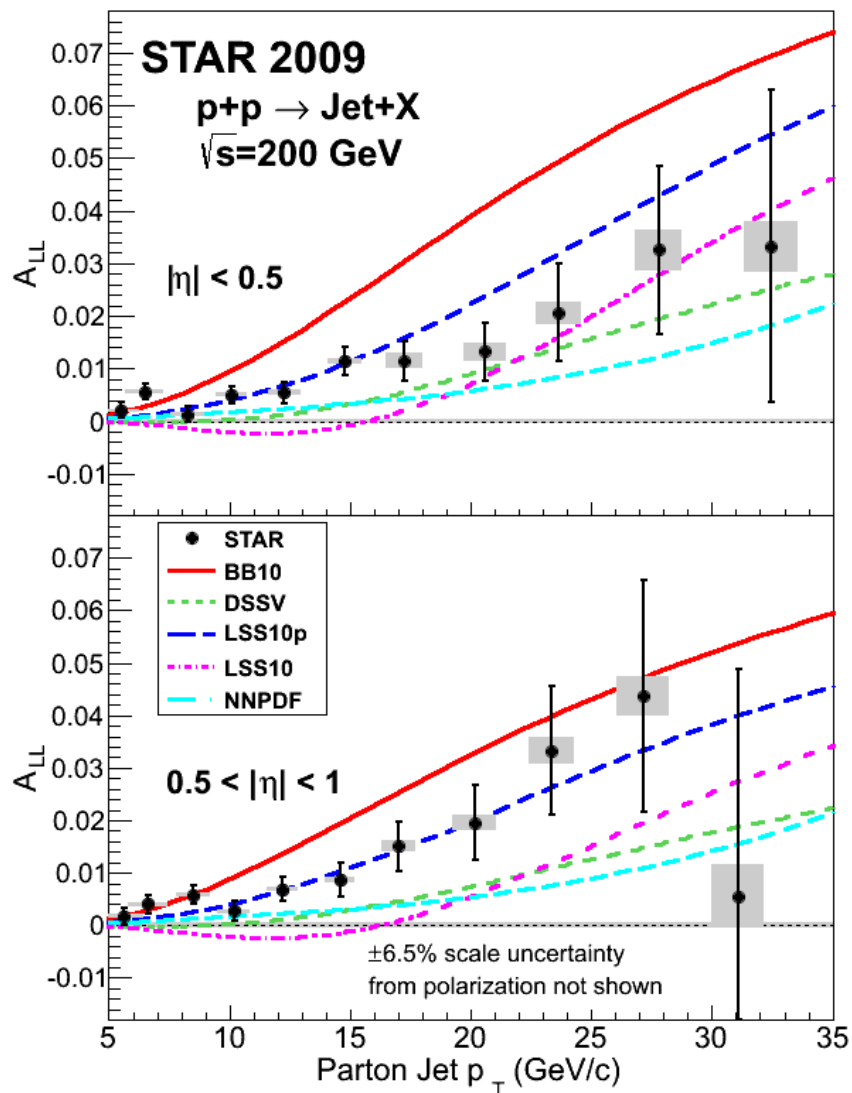
X. Li et al. (STAR Collaboration), DIS 2015.

Bernd Surrow

Results / Status - $g / \Delta g(x)$ related studies

STAR: Mid-rapidity Inclusive Jet A_{LL} measurement (Run 9) at 200GeV

L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 115, (2015) 092002.

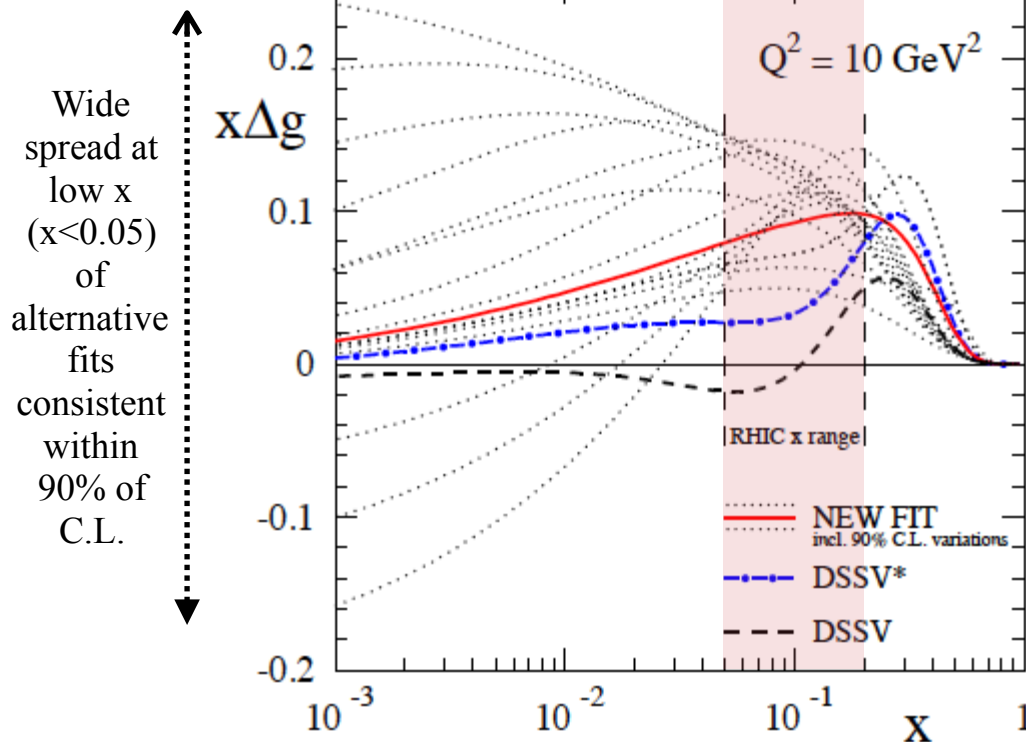


- Run 9 A_{LL} measurement between **BB10** and **DSSV** / Clearly **above** zero at low p_T
- Larger asymmetry at low p_T suggests larger gluon polarization compared to **DSSV**
- With global analysis, A_{LL} jet result provides evidence for positive gluon polarization for $x > 0.05$

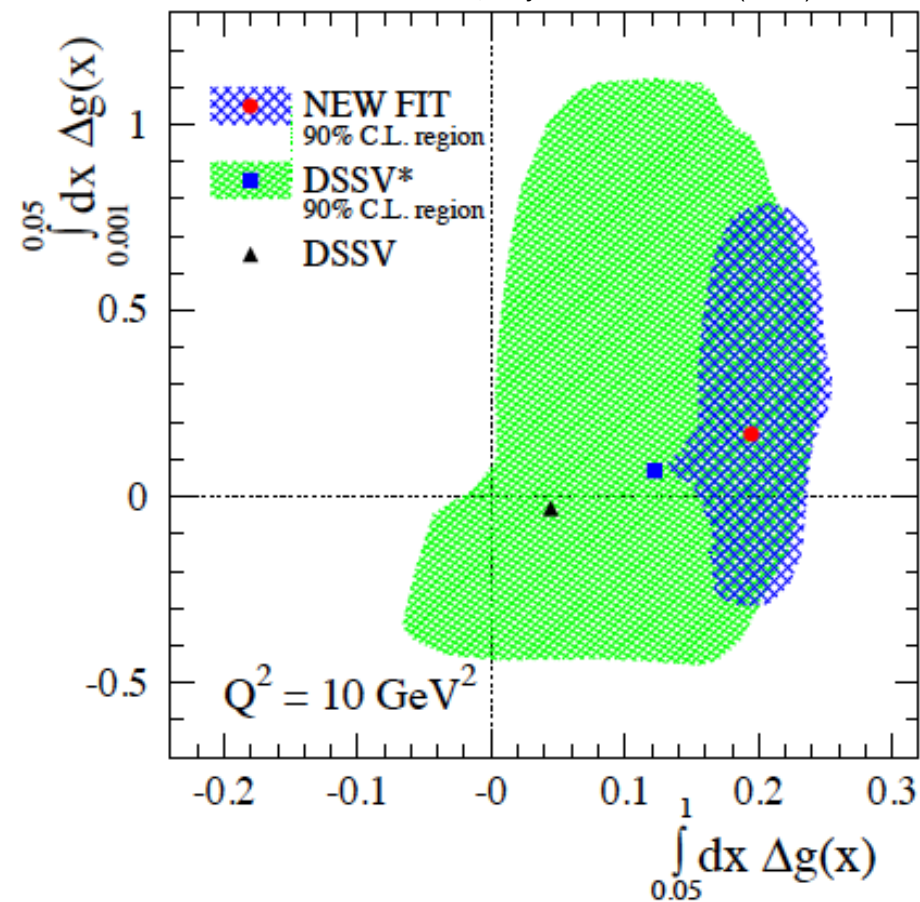
Results / Status - $g / \Delta g(x)$ related studies

Impact on Δg from RHIC data

D. deFlorian et al., Phys. Rev. Lett. 113 (2014) 012001.



D. deFlorian et al., Phys. Rev. Lett. 113 (2014) 012001.



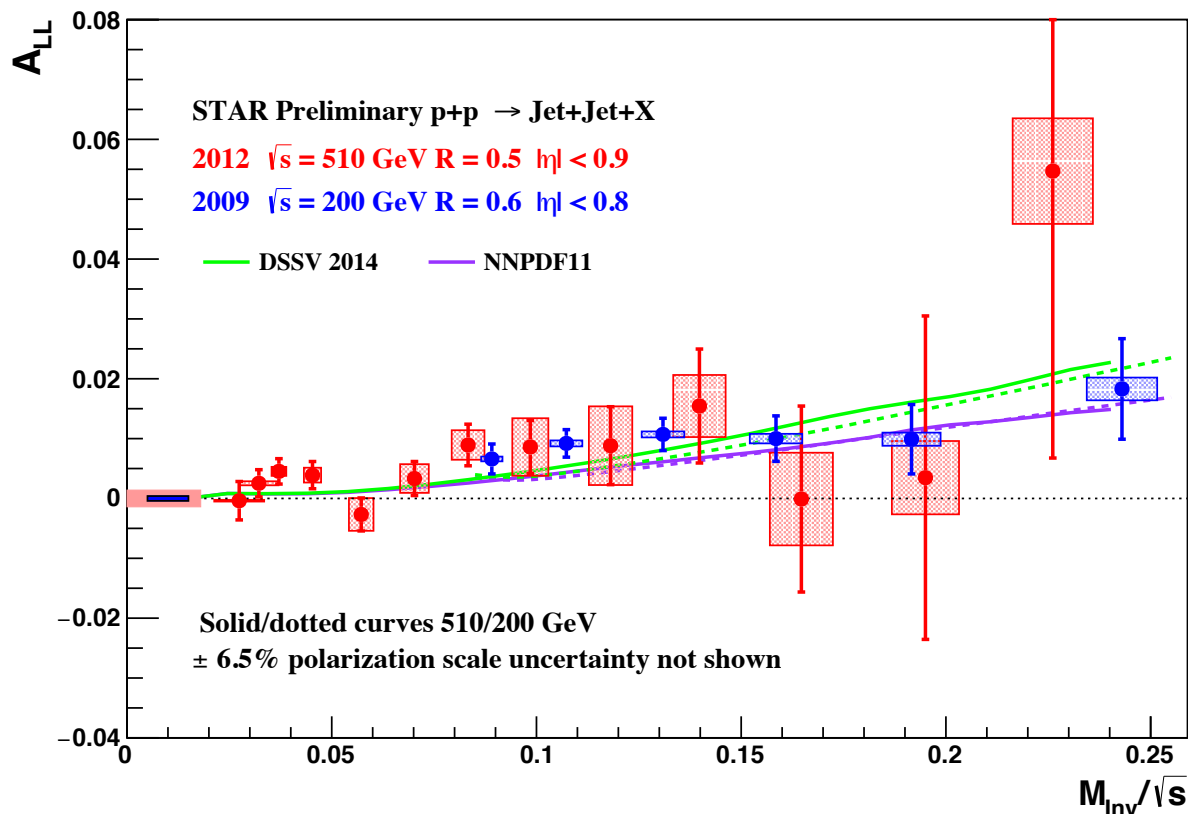
- DSSV: Original global analysis incl. first RHIC results (Run 5/6)
- DSSV*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates
- DSSV - NEW FIT: Strong impact on $\Delta g(x)$ with RHIC run 9 results: $0.20^{+0.06}_{-0.07}$ 90% C.L. for $0.05 < x$
- Similar conclusion by independent global analysis of NNPDF: $0.23^{+0.07}_{-0.07}$ for $0.05 < x < 0.5$

"...better small- x probes are badly needed."

E. R. Nocera et al., Nucl. Phys. B887 (2014) 276.

Results / Status - $g / \Delta g(x)$ related studies

- STAR: Mid-rapidity Di-Jet Jet A_{LL} measurement (Run 9 / 200GeV) (Run 12 / 500GeV)



- A_{LL} measurements consistent with

DSSV2015 and NNPDF11

constrained by Run 9 data

- Sensitivity to partonic kinematics (2-2 process, LO):

$$M = \sqrt{s} \sqrt{x_1 x_2}$$

$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

B. Paige et al. (STAR Collaboration), Moriond 2016. (Run 9 / 200GeV)

S. Rakmachandran et al. (STAR Collaboration), DIS 2016. (Run 12 / 500GeV)

Results / Status - g / $\Delta g(x)$ related studies

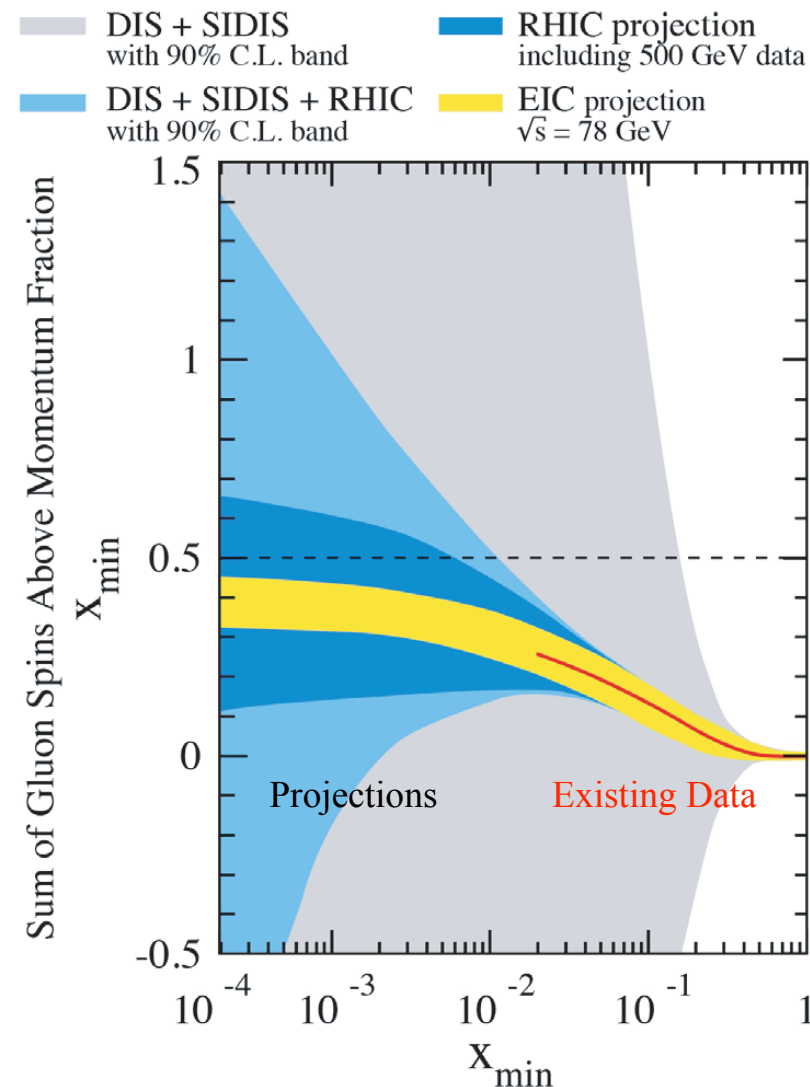
□ Impact on Δg from RHIC data / projections and future EIC facility

- Integral of Δg ($Q^2=10\text{GeV}^2$) (Running integral) from x_{\min}

to 1 as a function of x_{\min}

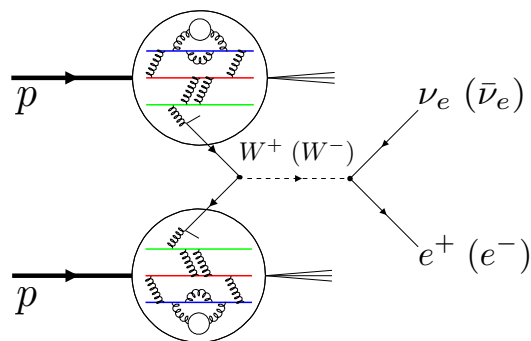
$$\Delta G(Q^2 = 10 \text{ GeV}^2) = \int_{x_{\min}}^1 \Delta g(x, Q^2 = 10 \text{ GeV}^2) dx$$

- Uncertainties shown on running integral!
- Important constraint from high-statistics 200GeV data (Run 9 / Published and Run 15) together with 500GeV data (Run 12 and Run 13) and forward rapidity measurements at RHIC prior to EIC - critical for low- x coverage!



Results / Status - q / \bar{q} related studies

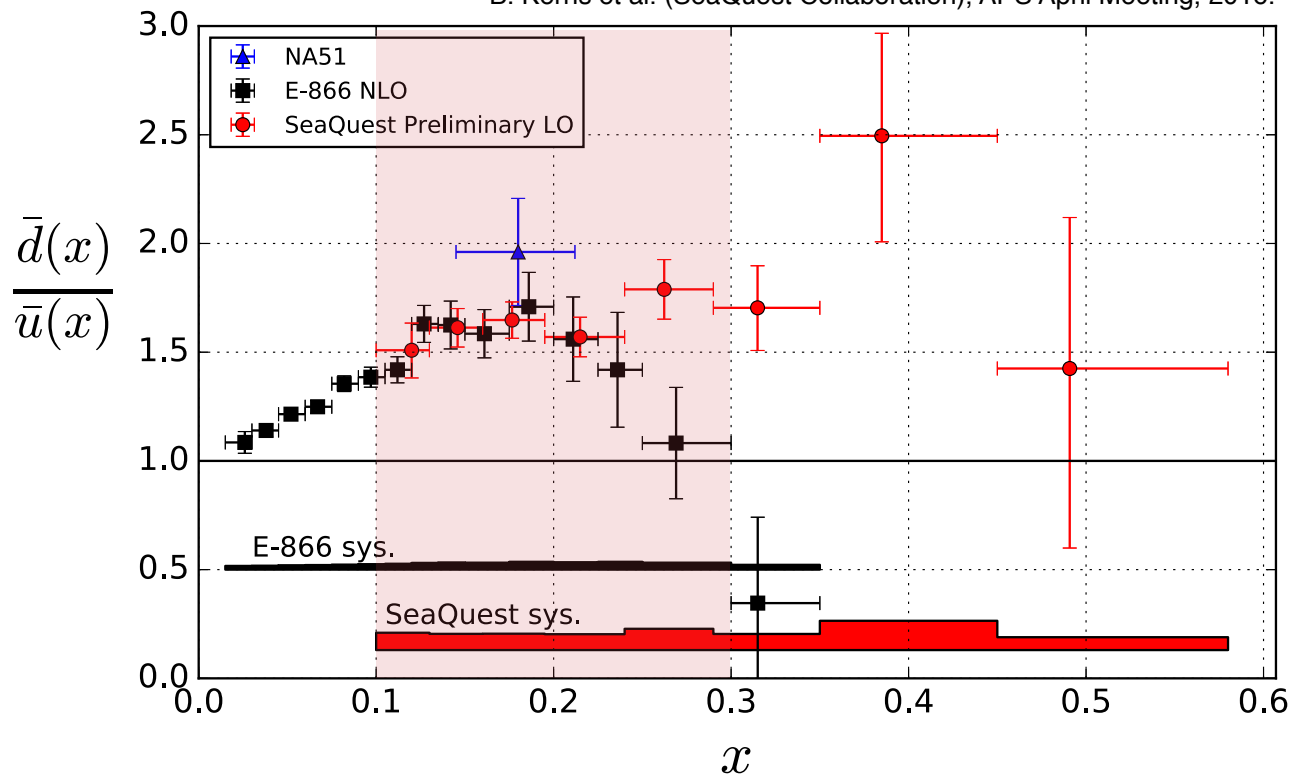
□ STAR: Probing $d\bar{q} / u\bar{q}$ ratio: QCD sea



$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} =$$

$$\frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

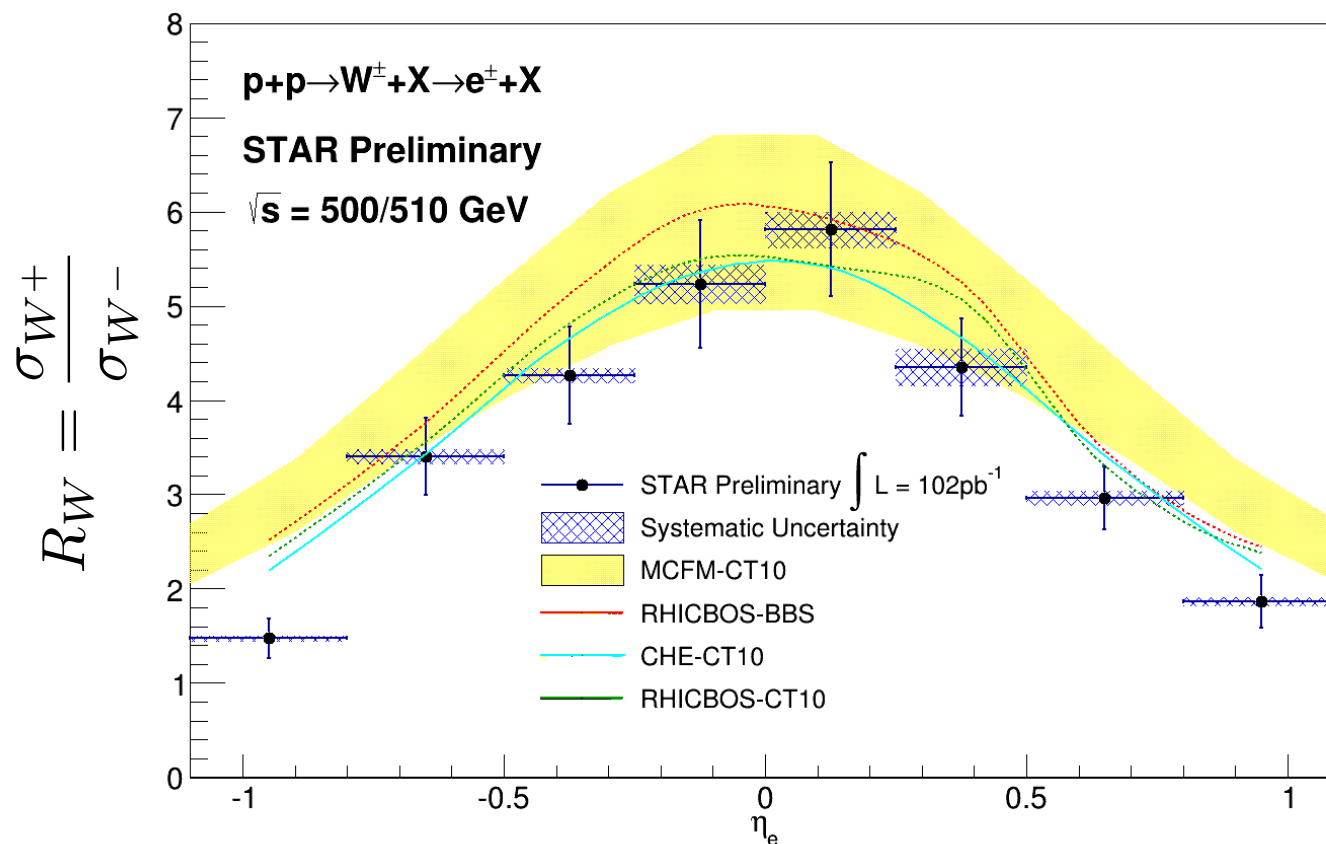
B. Kerns et al. (SeaQuest Collaboration), APS April Meeting, 2016.



- STAR coverage at mid-rapidity: $0.1 < x < 0.3$ for $-1 < \eta < 1$
- Constraints on global fitting for $d\bar{q}/u\bar{q}$ through W production at higher Q^2 compared E906
- Independent cross-check of Drell-Yan data

Results / Status - q / \bar{q} related studies

- STAR: W cross-section ratio measurements (Run 11 / 500GeV) (Run 12 / 510GeV)

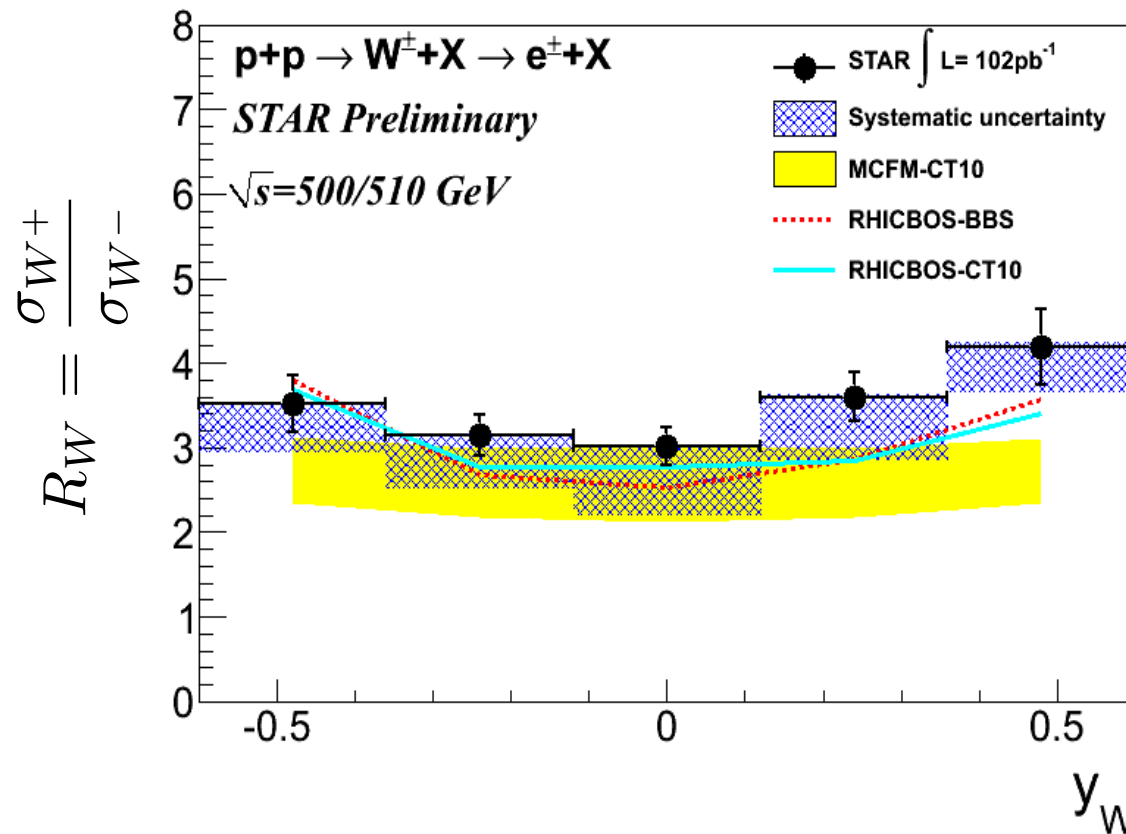


- Run 11 + Run 12 preliminary result: $\sim 100 \text{ pb}^{-1}$
- Run 13 data sample with $\sim 300 \text{ pb}^{-1}$ will provide important improvement on precision
- Planned Run 17 data sample of $\sim 400 \text{ pb}^{-1}$

M. Posik et al. (STAR Collaboration), DIS 2015.

Results / Status - q / \bar{q} related studies

- STAR: W cross-section ratio measurements at (Run 11 / 500GeV) (Run 12 / 510GeV)

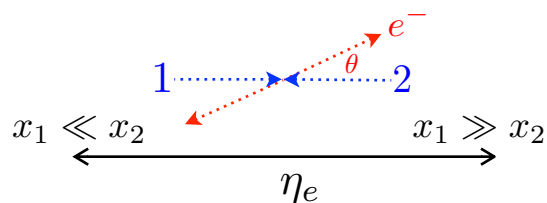


- W boson kinematics can be determined by reconstructing the W kinematics via its recoil
- Combination of data/MC simulations allows W boson rapidity reconstruction
- Critical for transverse single-spin asymmetry result of W production probing Siverts sign change

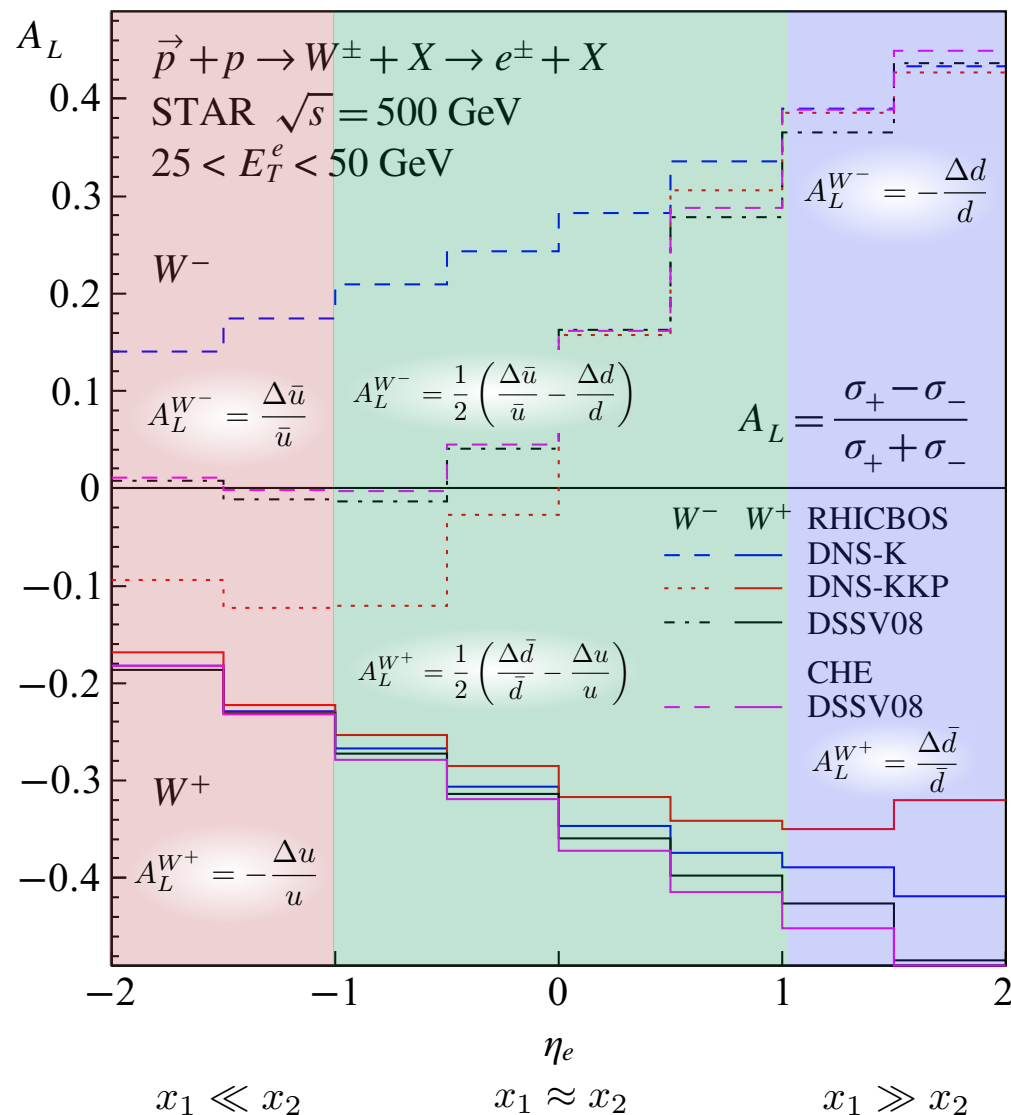
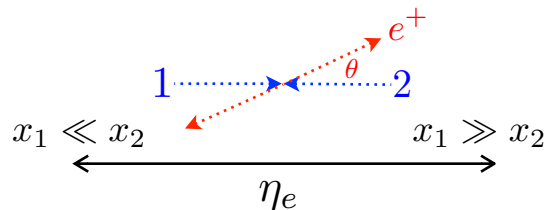
Results / Status - Δq / Δq_{bar} related studies

□ RHIC Probing the quark flavor structure using W boson production

$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1, x_2)} [\Delta \bar{u}(x_1) d(x_2) (1 - \cos \theta)^2 - \Delta d(x_1) \bar{u}(x_2) (1 + \cos \theta)^2]}{\int_{\otimes(x_1, x_2)} [\bar{u}(x_1) d(x_2) (1 - \cos \theta)^2 + d(x_1) \bar{u}(x_2) (1 + \cos \theta)^2]}$$



$$A_L^{e^+} \approx \frac{\int_{\otimes(x_1, x_2)} [\Delta \bar{d}(x_1) u(x_2) (1 + \cos \theta)^2 - \Delta u(x_1) \bar{d}(x_2) (1 - \cos \theta)^2]}{\int_{\otimes(x_1, x_2)} [\bar{d}(x_1) u(x_2) (1 + \cos \theta)^2 + u(x_1) \bar{d}(x_2) (1 - \cos \theta)^2]}$$



Results / Status - Δq / Δq_{bar} related studies

- STAR: W A_L measurements (Run 11 / 500GeV) (Run 12 / 510GeV) and Run 13 proj.

L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 113, (2014) 072301.

- Measured asymmetries constrain anti-quark

polarizations: Larger asymmetry for W^- suggest

large anti-u quark polarization!

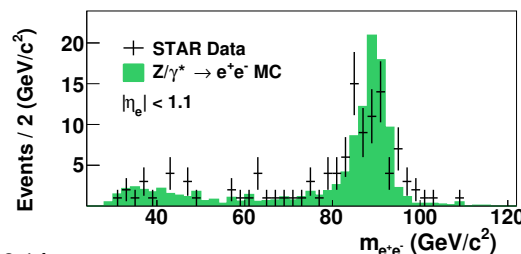
- Critical: Measurement of W^+ and W^-

asymmetries as a function η_e

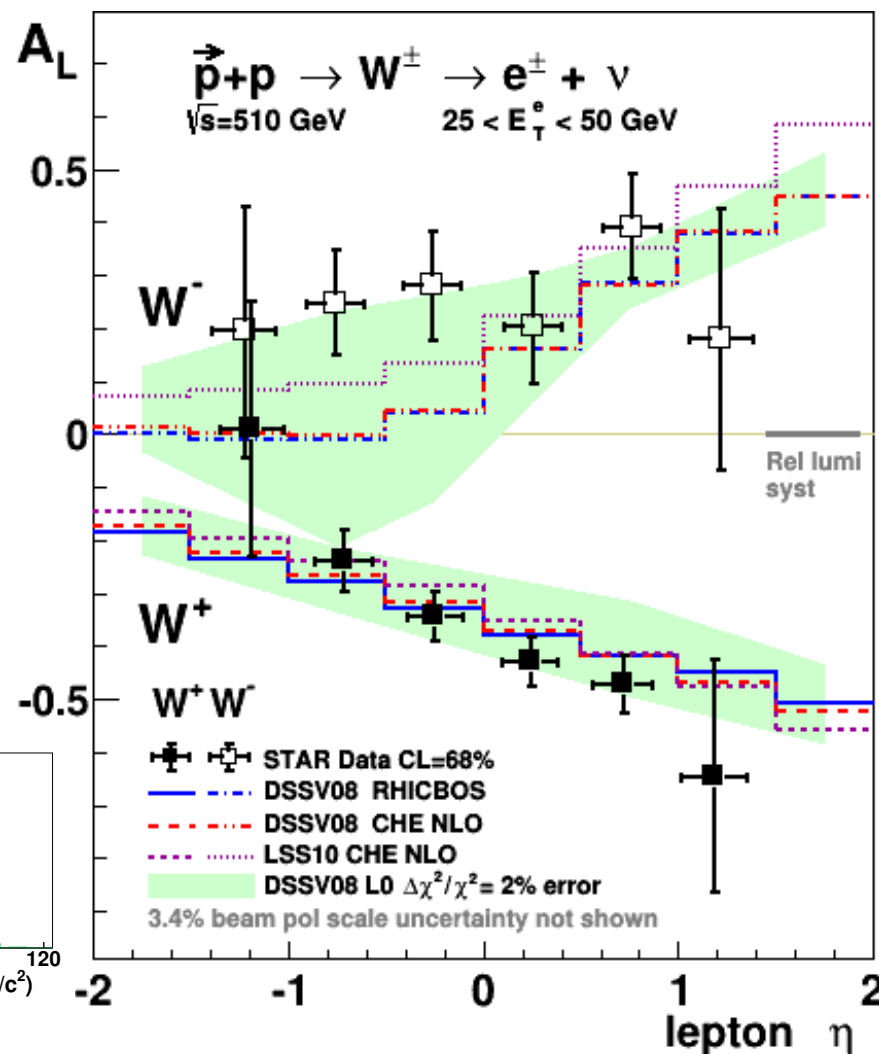
- Extension of backward / forward η_e

acceptance enhances sensitivity to anti-u /

anti-d quark polarization



- $A_L(Z/\gamma^*)$ result: $A_L = -0.07^{+0.14}_{-0.14}$



Results / Status - Δq / Δq_{bar} related studies

- STAR: W A_L measurements (Run 11 / 500GeV) (Run 12 / 510GeV) and Run 13 proj.
STAR Run 2013 Projection

- Measured asymmetries constrain anti-quark

polarizations: Larger asymmetry for W^- suggest

large anti-u quark polarization!

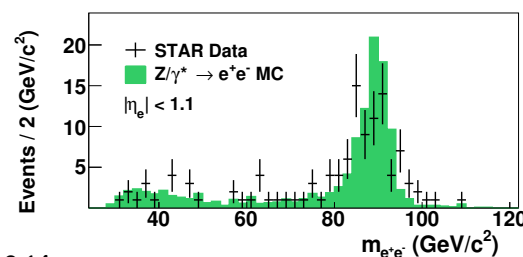
- Critical: Measurement of W^+ and W^-

asymmetries as a function η_e

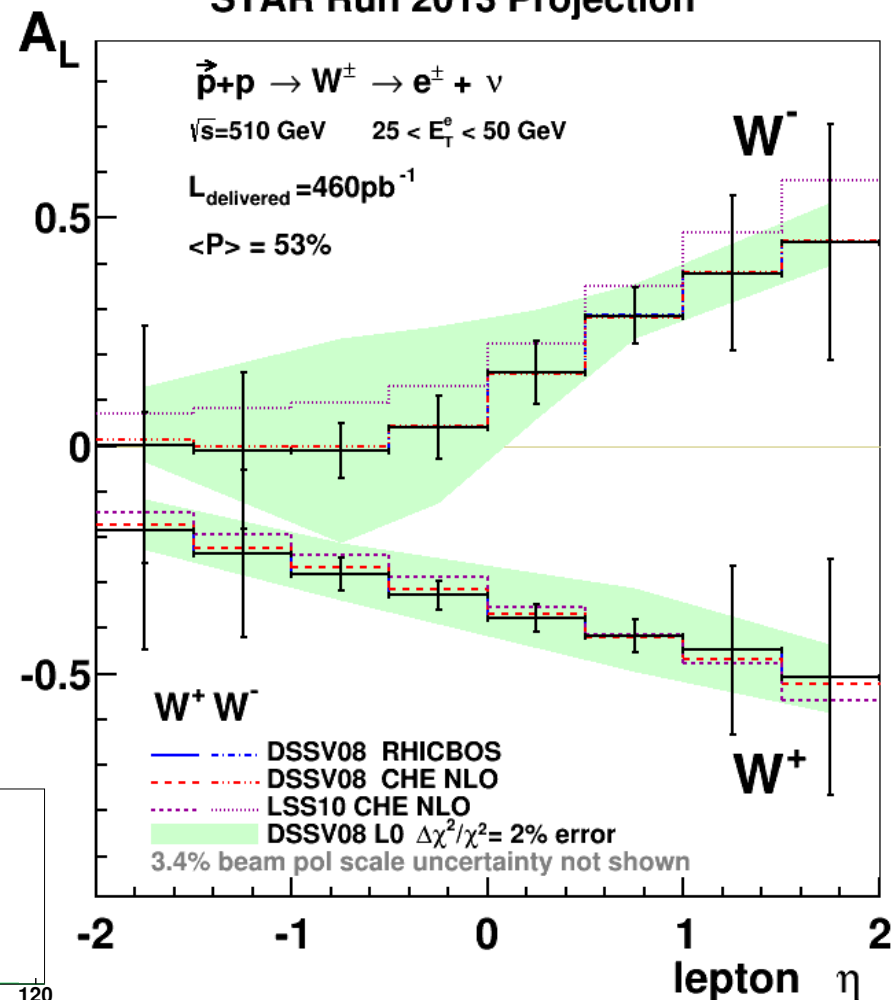
- Extension of backward / forward η_e

acceptance enhances sensitivity to anti-u /

anti-d quark polarization

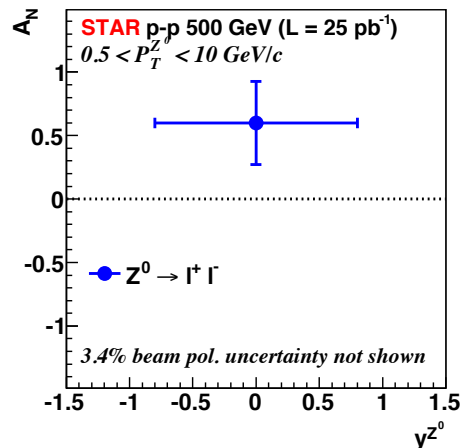


- $A_L(Z/\gamma^*)$ result: $A_L = -0.07^{+0.14}_{-0.14}$

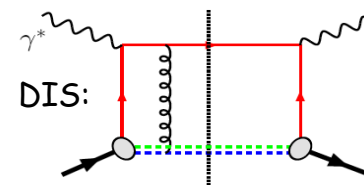


Results / Status - Transverse spin related studies

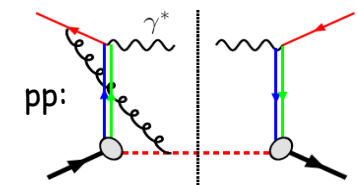
□ STAR: W / Z A_N measurements (Run 11 / 500GeV)



- Sivers function quantifies correlation between transverse parton momentum and transverse proton spin
- Fundamental prediction of QCD gauge invariance:



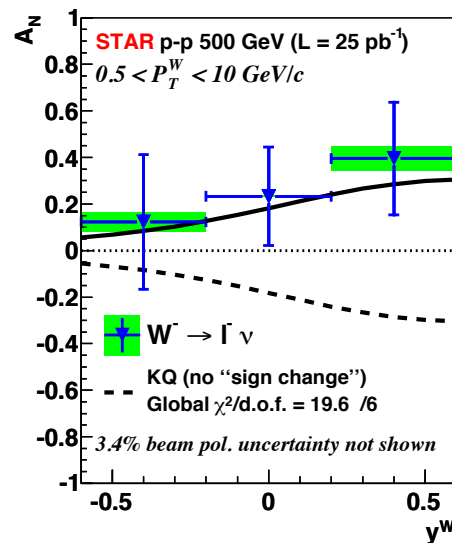
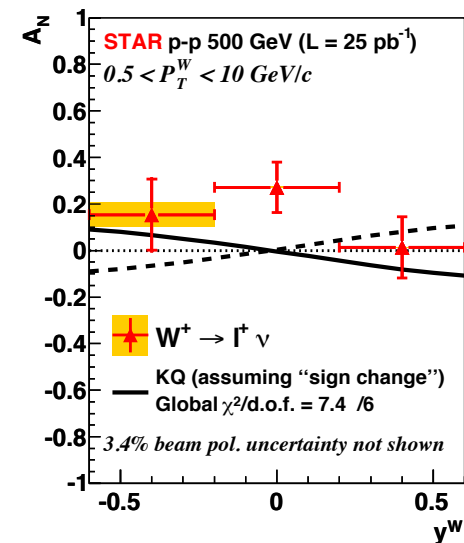
Attractive FSI



Repulsive ISI

$$\text{Sivers}_{\text{DIS}} = - \text{Sivers}(\text{DY} / \text{W} / \text{Z})$$

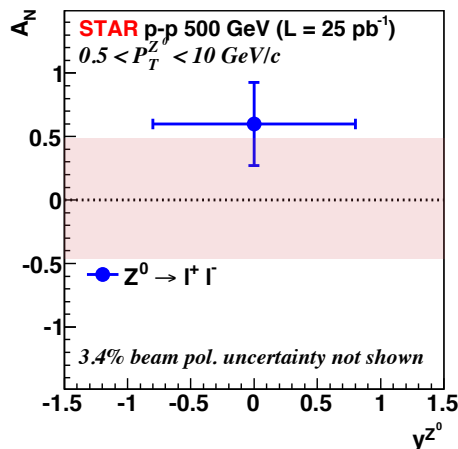
- Active experimental programs at COMPASS (DY) and RHIC (W production)
- First measurement of A_N for W/Z production using fully reconstructed gauge bosons at 500GeV (Run 11 / 25pb⁻¹)
- Sivers-Sign sign-change scenario ($\chi^2/\text{n.d.f.}=7.4/6$) preferred over no-sign change scenario ($\chi^2/\text{n.d.f.}=19.6/6$)
- Precise measurement of A_N (W) in Run 17 (~400pb⁻¹ - X 16 of L_{Run 11}) in bins of p_T and rapidity and $A_N(\text{Z})$



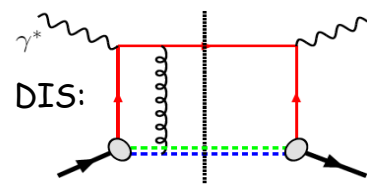
L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 116, (2016) 132301.

Results / Status - Transverse spin related studies

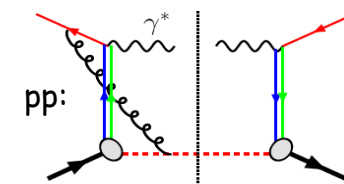
□ STAR: W / Z A_N measurements (Run 11 / 500GeV)



- Sivers function quantifies correlation between transverse parton momentum and transverse proton spin
- Fundamental prediction of QCD gauge invariance:



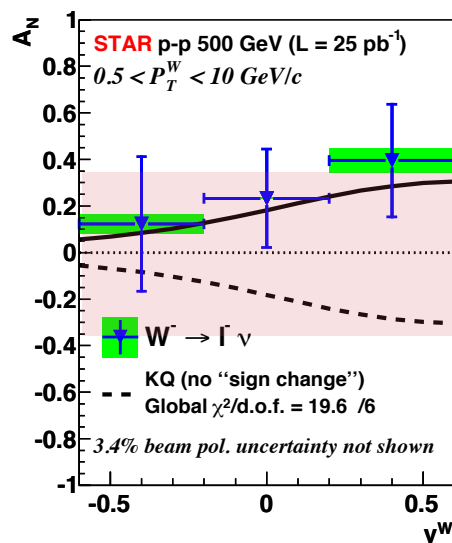
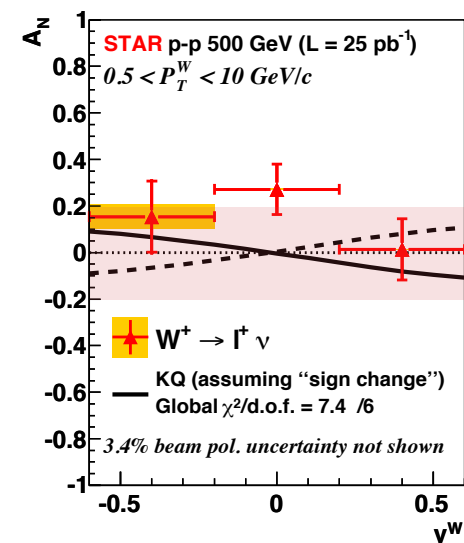
Attractive FSI



Repulsive ISI

$$\text{Sivers}_{\text{DIS}} = - \text{Sivers}(\text{DY} / \text{W} / \text{Z})$$

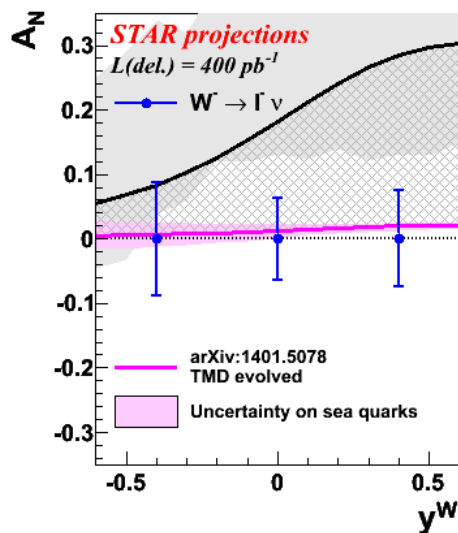
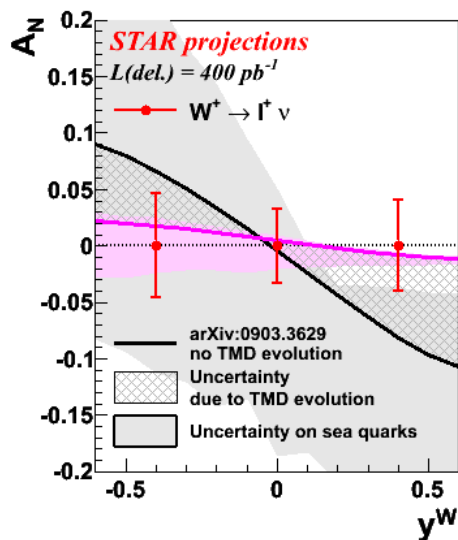
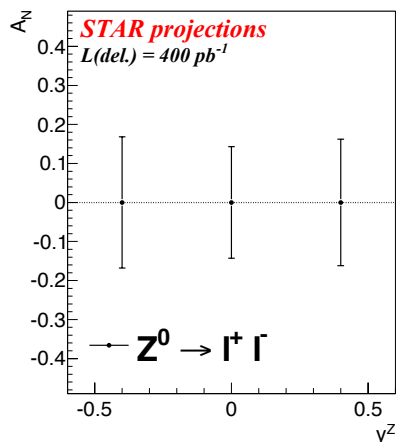
- Active experimental programs at COMPASS (DY) and RHIC (W production)
- First measurement of A_N for W/Z production using fully reconstructed gauge bosons at 500GeV (Run 11 / 25pb⁻¹)
- Sivers-Sign sign-change scenario ($\chi^2/\text{n.d.f.}=7.4/6$) preferred over no-sign change scenario ($\chi^2/\text{n.d.f.}=19.6/6$)
- Precise measurement of A_N (W) in Run 17 ($\sim 400\text{pb}^{-1}$ - X 16 of L_{Run 11}) in bins of p_T and rapidity and $A_N(\text{Z})$



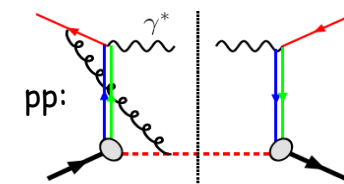
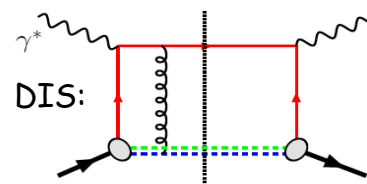
L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 116, (2016) 132301.

Results / Status - Transverse spin related studies

□ STAR: W / Z A_N measurements (Run 11 / 500GeV)



- Sivers function quantifies correlation between transverse parton momentum and transverse proton spin
- Fundamental prediction of QCD gauge invariance:



Attractive FSI

Repulsive ISI

$$\text{Sivers}_{\text{DIS}} = - \text{Sivers}(\text{DY} / \text{W} / \text{Z})$$

- Active experimental programs at COMPASS (DY) and RHIC (W production)
- First measurement of A_N for W/Z production using fully reconstructed gauge bosons at 500GeV (Run 11 / 25pb⁻¹)
- Sivers-Sign sign-change scenario ($\chi^2/\text{n.d.f.}=7.4/6$) preferred over no-sign change scenario ($\chi^2/\text{n.d.f.}=19.6/6$)
- Precise measurement of $A_N(W)$ in Run 17 ($\sim 400\text{pb}^{-1}$ - X 16 of $L_{\text{Run 11}}$) in bins of p_T and rapidity and $A_N(Z)$

Projections for $A_N(W/Z)$ in Run 17 based on 400pb⁻¹!

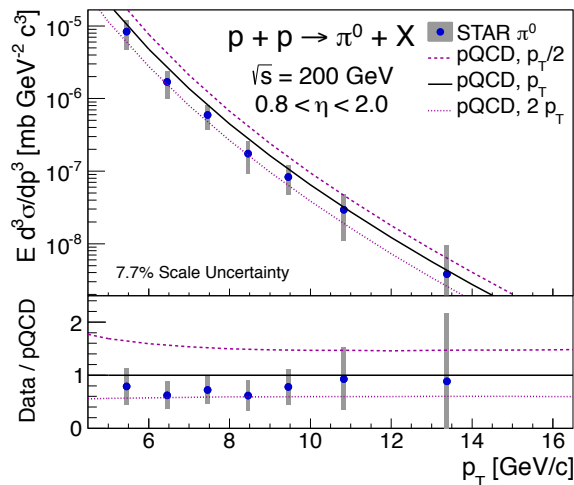
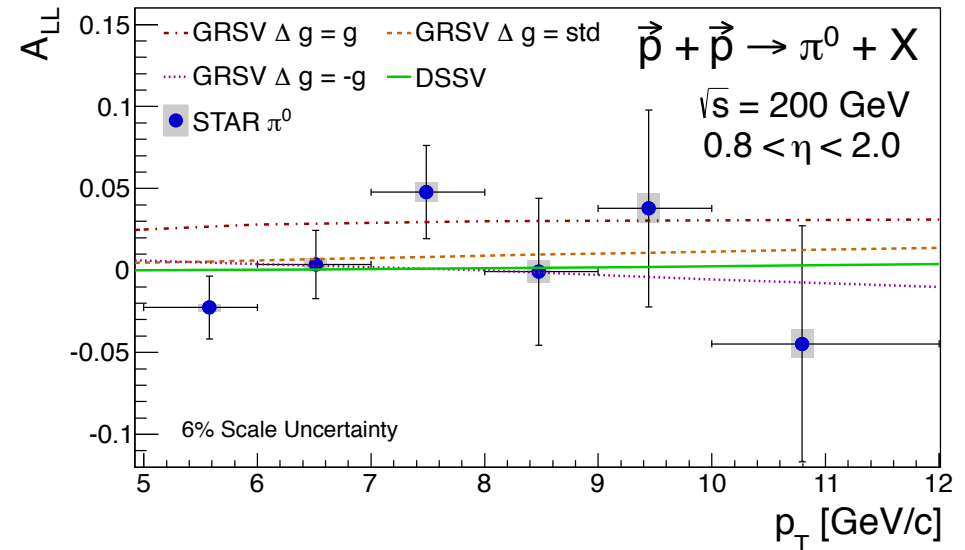
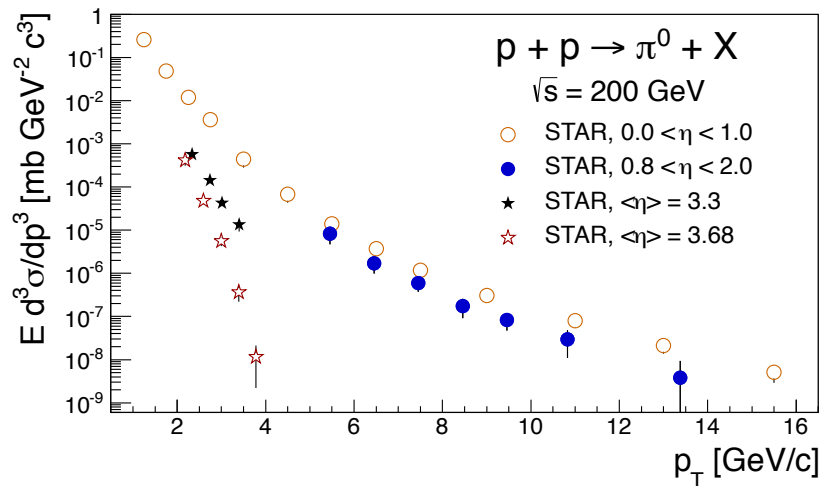
Summary / Outlook

- Gluon related studies: $g / \Delta g$
 - Precise Run 9 A_{LL} measurement: **Non-zero ΔG of similar magnitude as quark polarization!**
 - First Di-Jet measurement opens the path to **constrain the shape of Δg**
 - New inclusive jet cross-section: **Important constraint for unpol. gluon distribution at high x**
- Quark / Anti-quark related studies: $q / \Delta q$
 - Mid-rapidity (Run 11/12): Published W asymmetry results suggest large anti-u quark polarization along with **broken QCD sea** / Substantial improvement with Run 13 data sample
 - New prelim. result of cross-section ratio measurement (Run 11/12): **Strong physics case of unpolarized $d\bar{b}/u\bar{b}$ probe** using W production complementary to SeaQuest / Substantial improvement with Run 13 data sample
 - Forward rapidity analysis requires completion of challenging FGT tracking analysis
- First fully reconstructed $W A_N$ asymmetry: Sign-change preferred!
- Future
 - **Long 510GeV run in 2017** (Run 17) at transverse spin polarization of about 400pb^{-1} : $W A_N$ / Unpol. QCD sea
 - **Unpolarized program for Run 17**: Cross-section ratio measurements of W^+/W^- Unpolarized $d\bar{b}/u\bar{b}$ probe
 - **Exciting long-term program beyond 2020** requiring **forward detector upgrade** (Cold QCD plan)

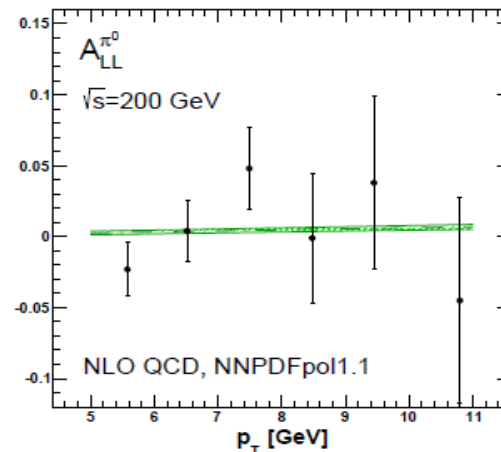
Cold QCD plan, arXiv: 1602.03922.

Backup

□ STAR: Neutral Pion A_{LL} measurement at 200 GeV for $0.8 < \eta < 2.0$



NNPDFpol1.1 prediction with STAR 200 GeV data
 ($0.8 < \eta < 2.0$)

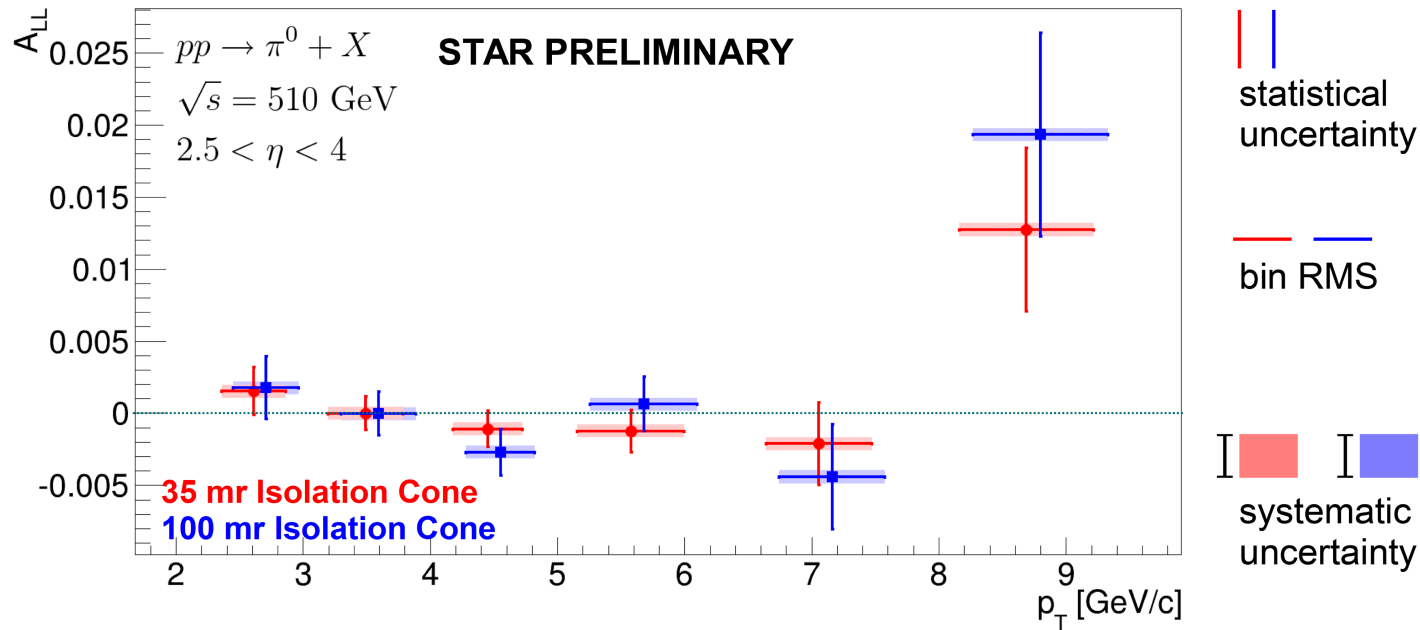


- Need more precise results to constrain PDF's at low x
- STAR 2012 510 GeV data sample is being analyzed

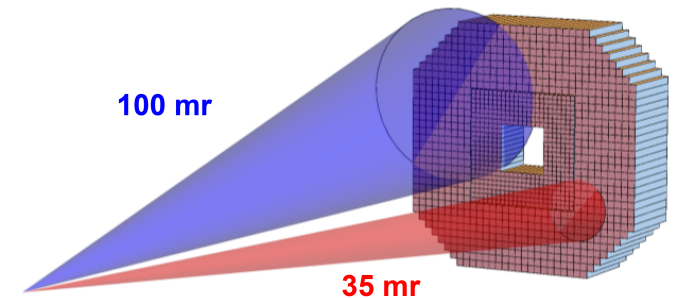
L. Adamczyk et al. (STAR Collaboration), Phys. Rev. D89, (2014) 012001.

Backup

□ STAR: Neutral Pion A_{LL} measurement at 510GeV for $2.5 < \eta < 4.0$



- Measurement in FMS at $2.5 < \eta < 4.0$ by using 2012 and 2013 510GeV data
- Isolated π_0 measured by 2 isolation cone with cone radius 35mrard and 100mard
- A_{LL} does not depend on isolation cone cut
- Isolated π_0 A_{LL} is consistent with zero



C. Dilks et al. (STAR Collaboration), SPIN 2014.

Bernd Surrow