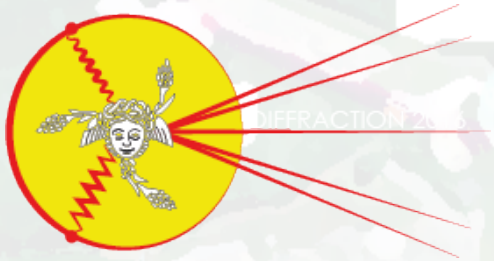
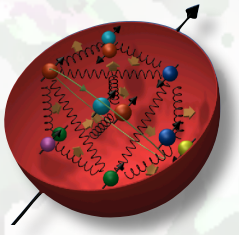
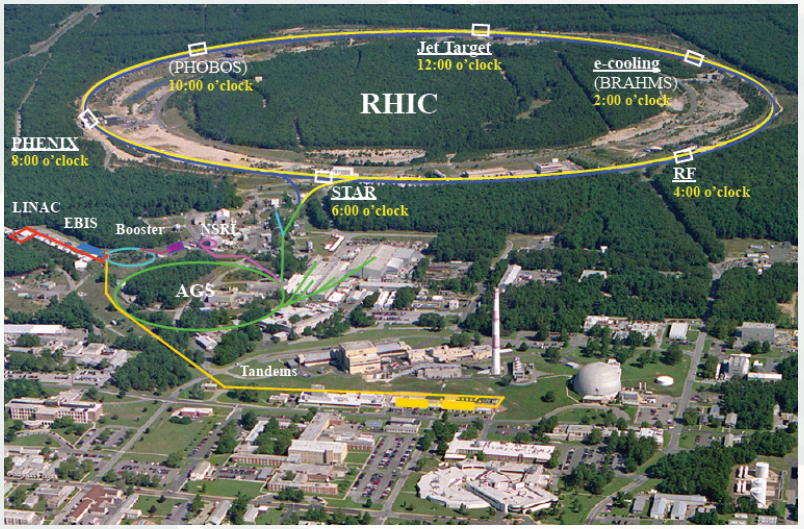
Recent results of the high-energy spin physics program at RHIC at BNL

Bernd Surrow
TEMPLE UNIVERSITY

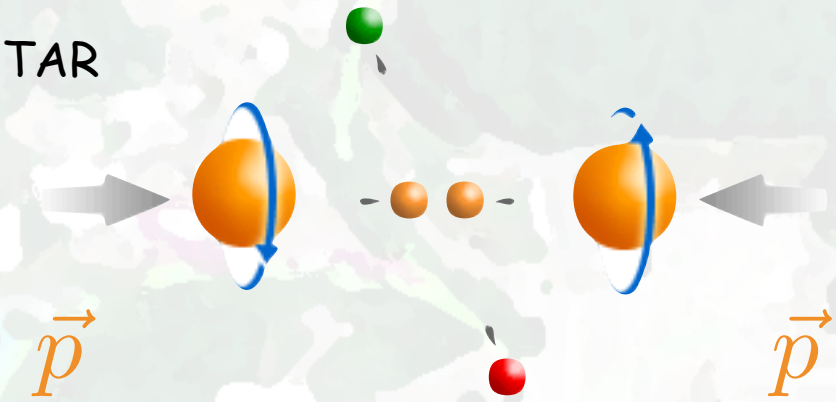




Outline

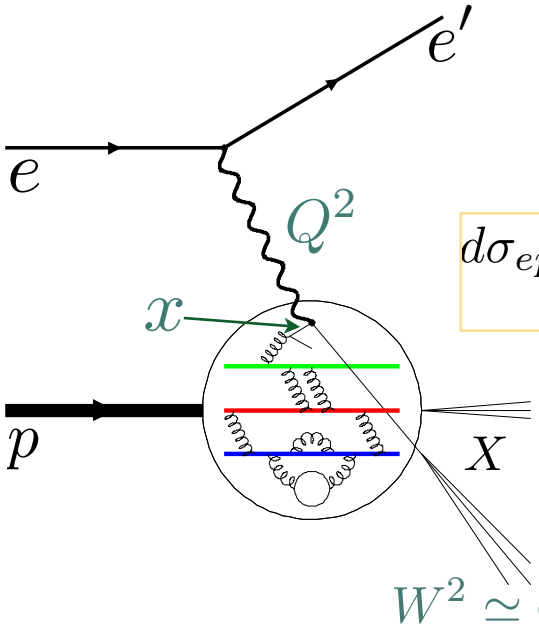


- Results / Status
  - Gluon related studies (Jet production): g / Δg
  - Quark / Anti-quark related studies (W / Z production): q / Δq
- Experimental aspects: RHIC / PHENIX / STAR
- Theoretical foundation
- Summary and Outlook



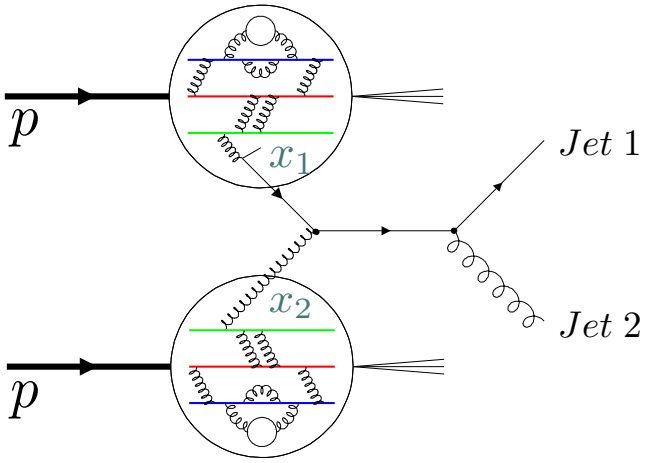
Theoretical foundation

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



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

Universality



$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

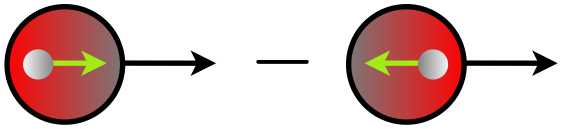
Factorization

Momentum contribution

$$f(x) =$$

$$f^+(x) + f^-(x)$$

$$\Delta f(x) =$$

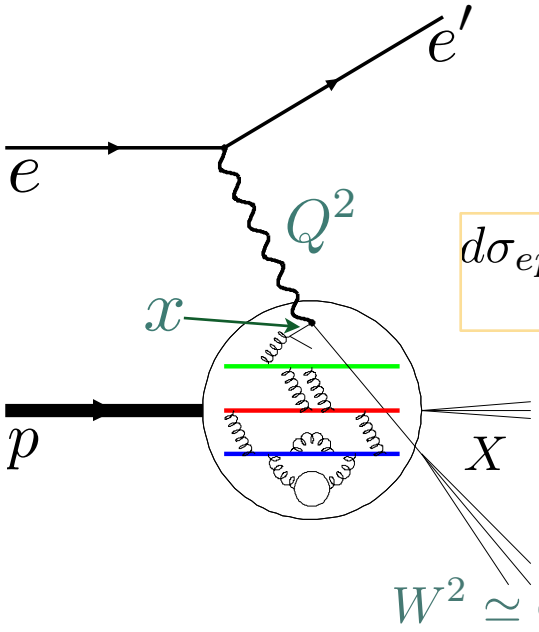


$$f^+(x) - f^-(x)$$

Spin contribution

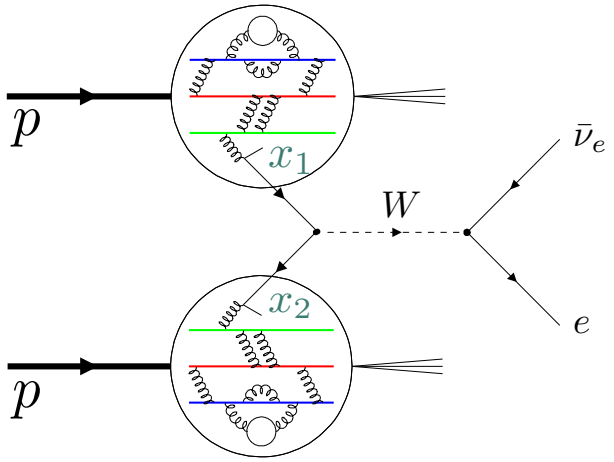
Theoretical foundation

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



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

Universality

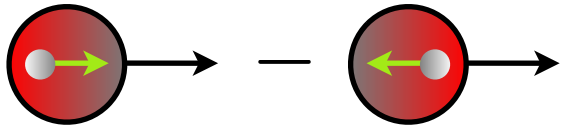


$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$ Factorization

Momentum contribution

$$f(x) = f^+(x) + f^-(x)$$

$$\Delta f(x) = f^+(x) - f^-(x)$$



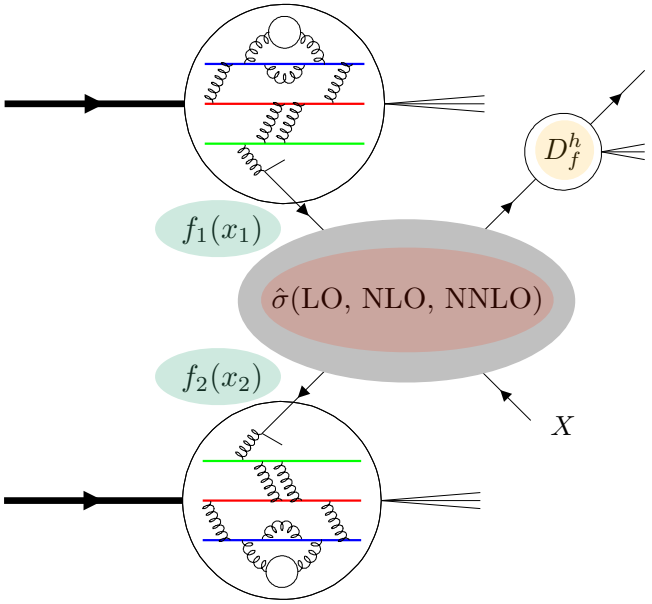
Spin contribution

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}

long-range short-range long-range

$$a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$$

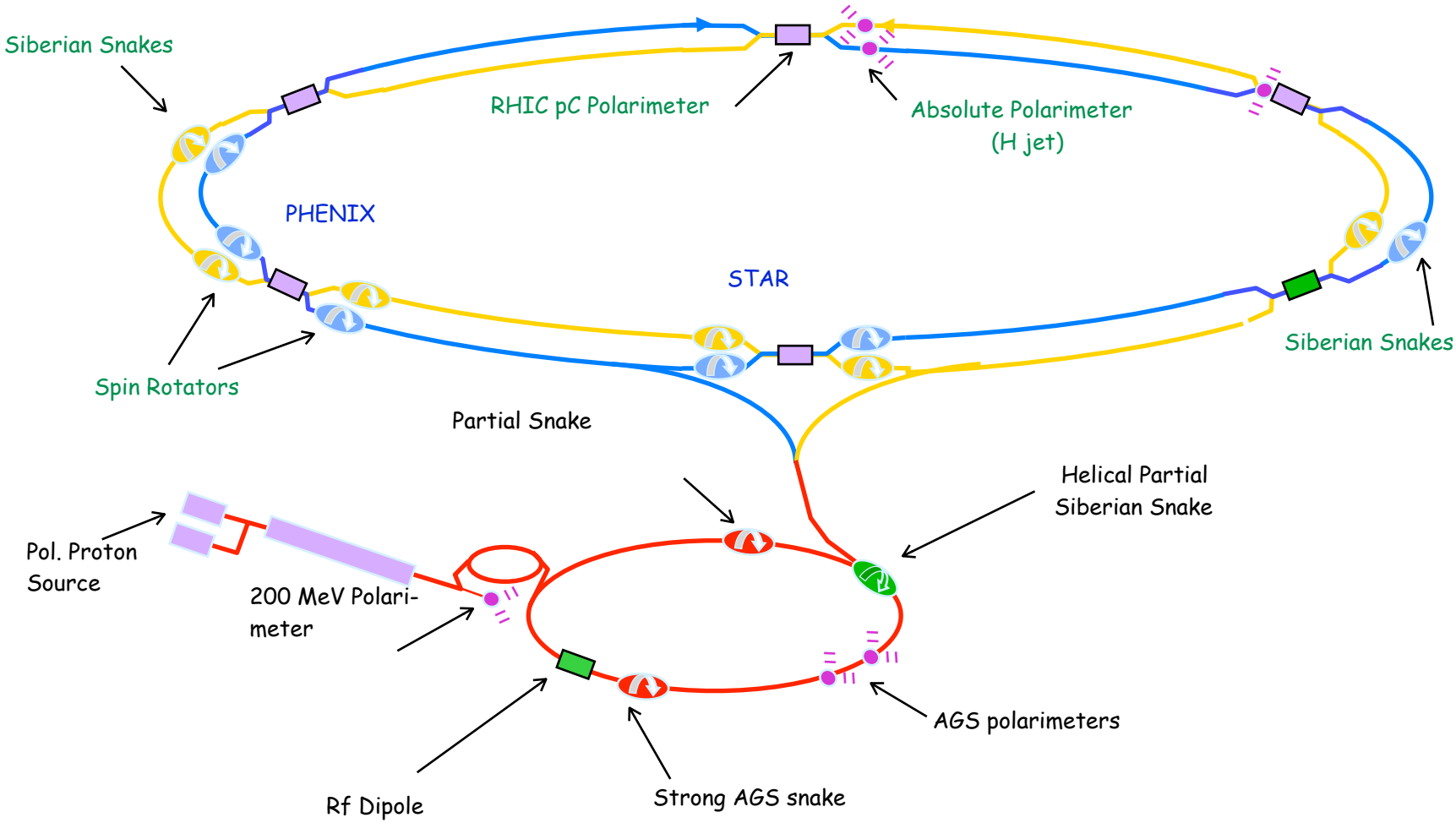
Input

Δf_1 Δf_2

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

Experimental aspects - RHIC

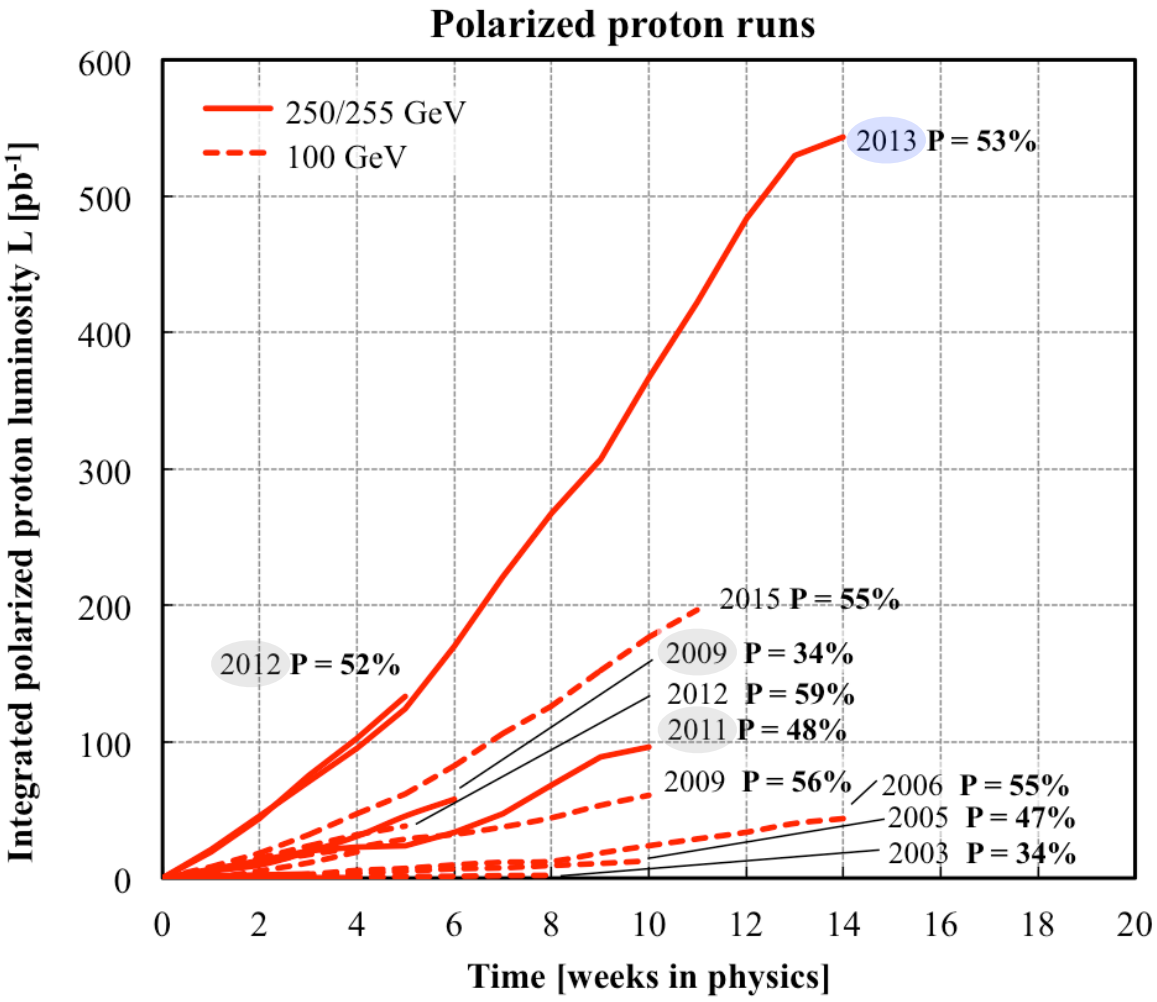
- The world's first polarized proton-proton collider



Experimental aspects - RHIC

- Polarized p-p collisions
  - Production runs at $\sqrt{s}$=500/510GeV (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^2L) (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

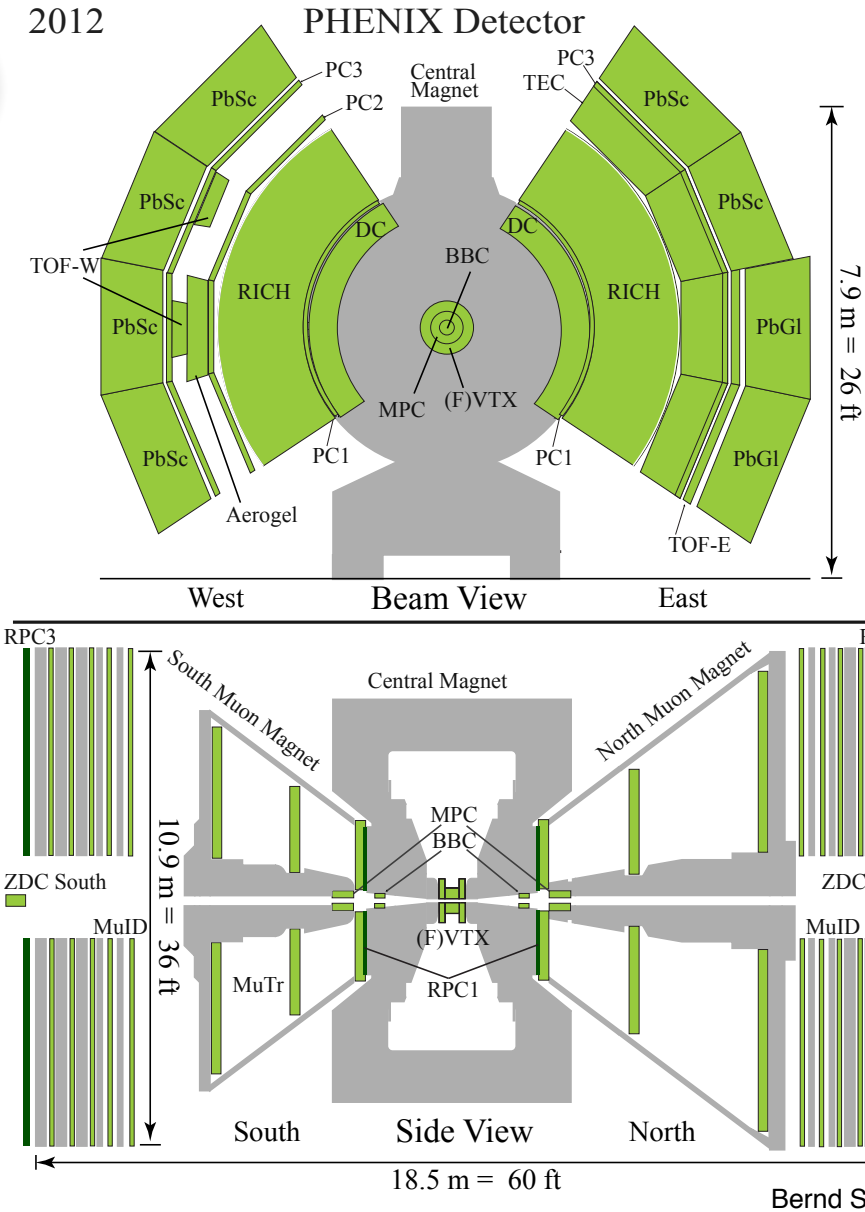


Experimental aspects - PHENIX

- Overview

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

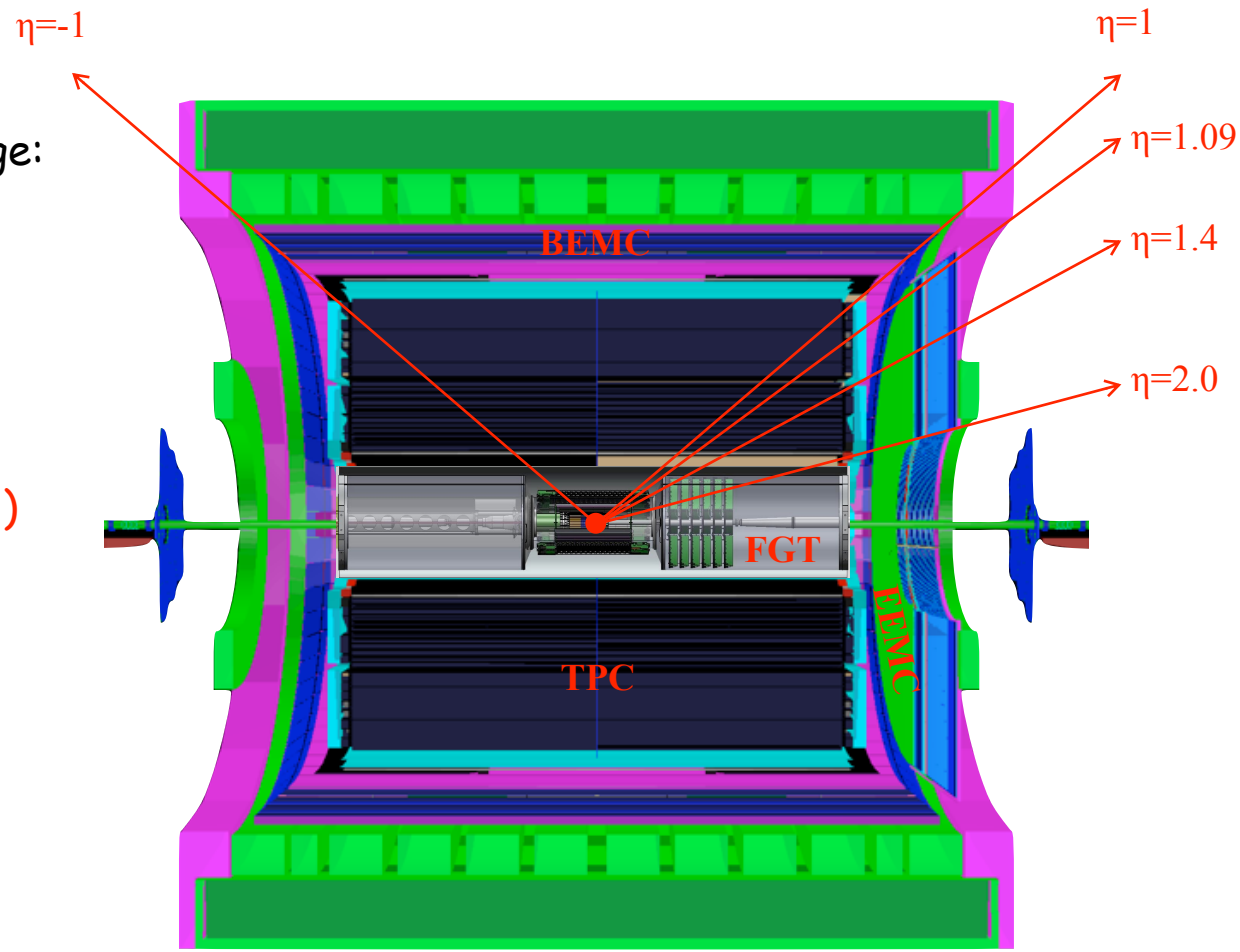
  - π^0, η, γ
    - Electromagnetic Calorimeter (PbSc/PbGl)
      ($|\eta| < 0.35$, $\varphi = 2 \times \pi/2$)
  - $\pi^{\pm}$, e, $J/\psi \rightarrow e^+e^-$
    - Drift Chamber (DC)
    - Ring Imaging Cherenkov Detector (RICH)
    - Electromagnetic Calorimeter (PbSc/PbGl)
  - μ, $J/\psi \rightarrow \mu^+\mu^-$
    - Muon Id/Muon Tracker ($1.2 < |\eta| < 2.4 + 2\pi$)
  - π^0, η
    - MPC ($3.1 < |\eta| < 3.9 + 2\pi$)
  - Relative Luminosity
    - Beam Beam Counter (BBC) ($3.0 < \eta < 3.9$)
    - Zero Degree Calorimeter (ZDC)



Experimental aspects - STAR

Overview

- Calorimetry system with 2π coverage: BEMC (-1<η<1) and EEMC (1<η<2)
- TPC: Tracking and particle ID (|η|<1.3)
- FGT: Forward GEM Tracker (Run 13) (1<η<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 / Δg(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)

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

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

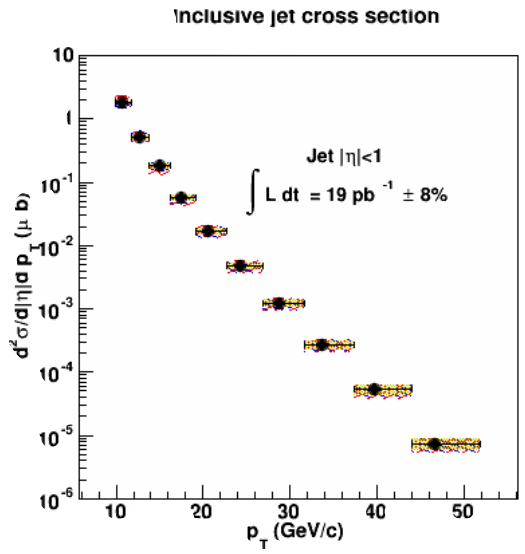
$$d = \min\left(\{D_{ij}, D_i\}\right)$$

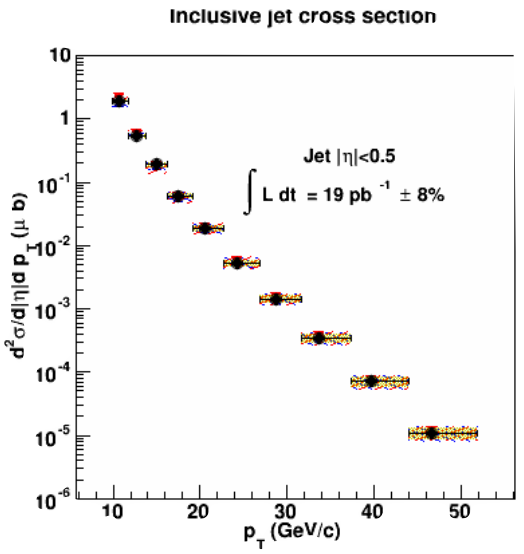
If $d = D_{ij}$: Combine jet i and jet j

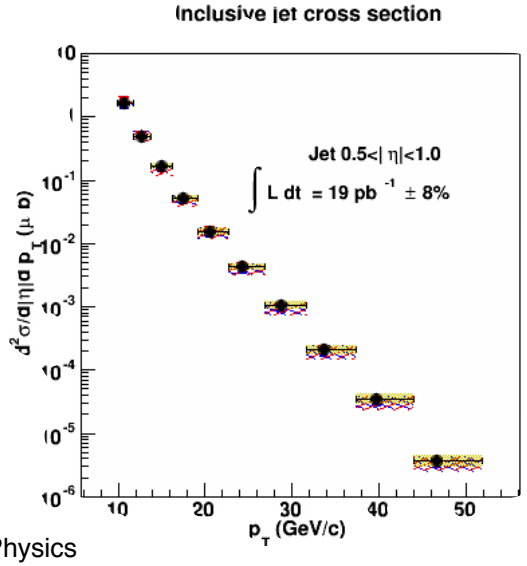
If $d = D_i$: Define jet i as final jet

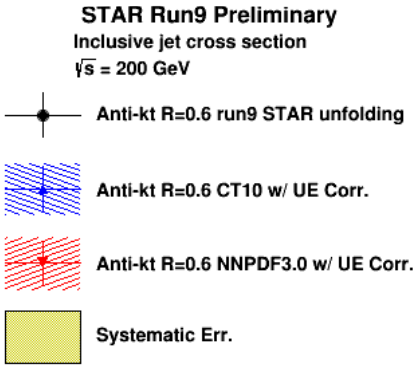
corrected to particle level for three different pseudo-rapidity regions of |η|<1, |η|<0.5 and 0.5<|η|<1.0

- 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









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

Results / Status - g / Δg(x) related studies

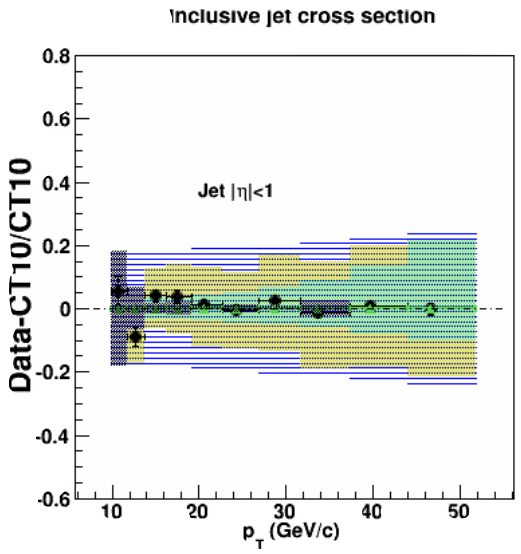
- STAR: Mid-rapidity Inclusive Jet cross-section measurement (Run 9) at 200GeV (2)
  - Quantitative comparison between data and theory of (Data-Theory)/ Theory showing

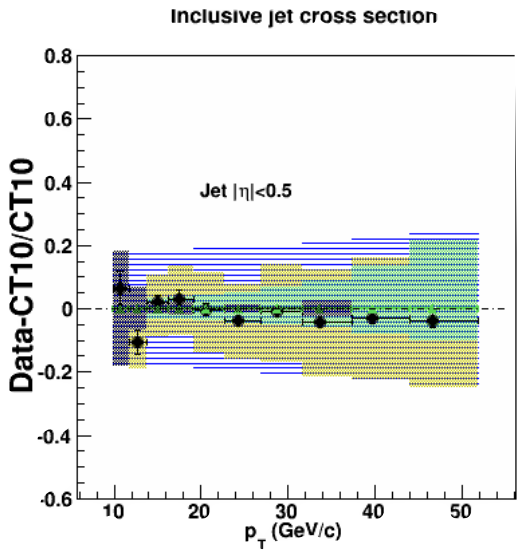
    UE/hadronization corrections applied to pure NLO calculations

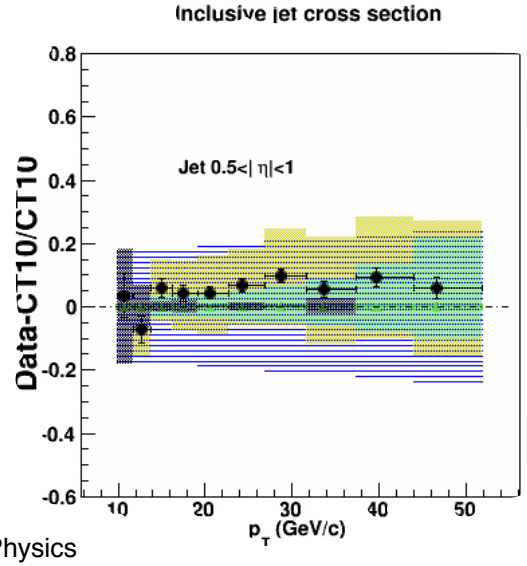
    Data systematic errors

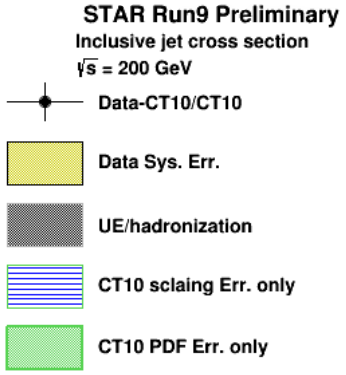
    CT10 scale uncertainties

    CT10 pdf uncertainites





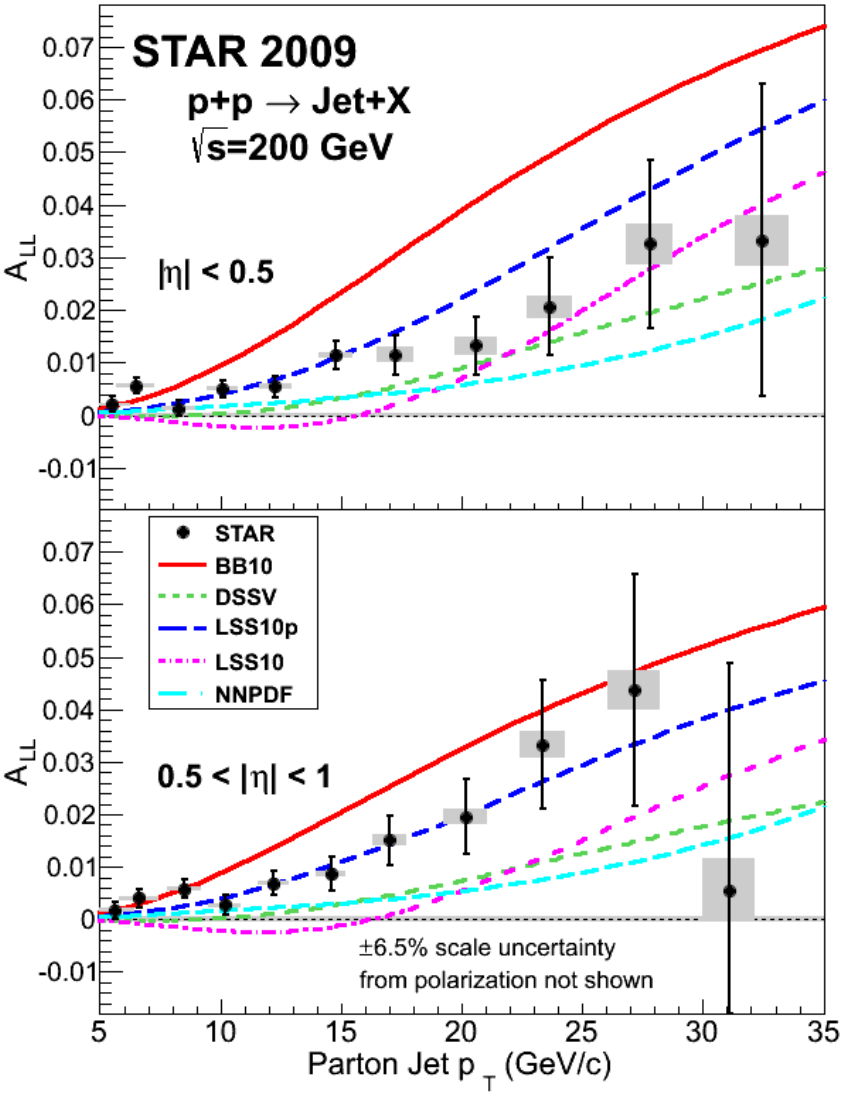




X. Li et al. (STAR Collaboration), DIS 2015.

Results / Status - g / Δg(x) related studies

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

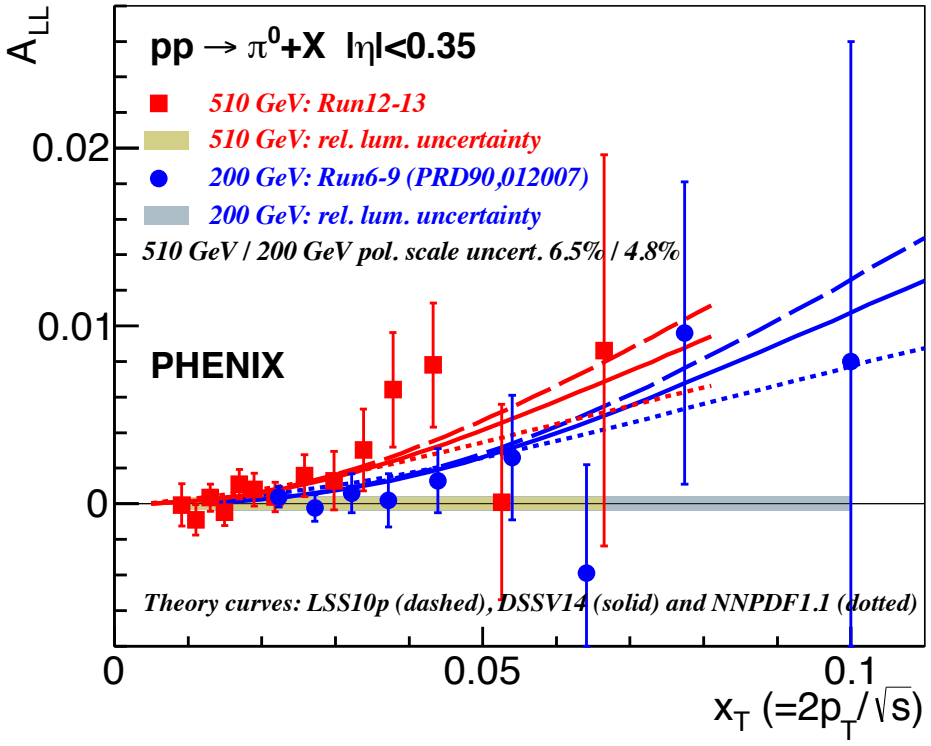


L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 115, (2015) 092002.

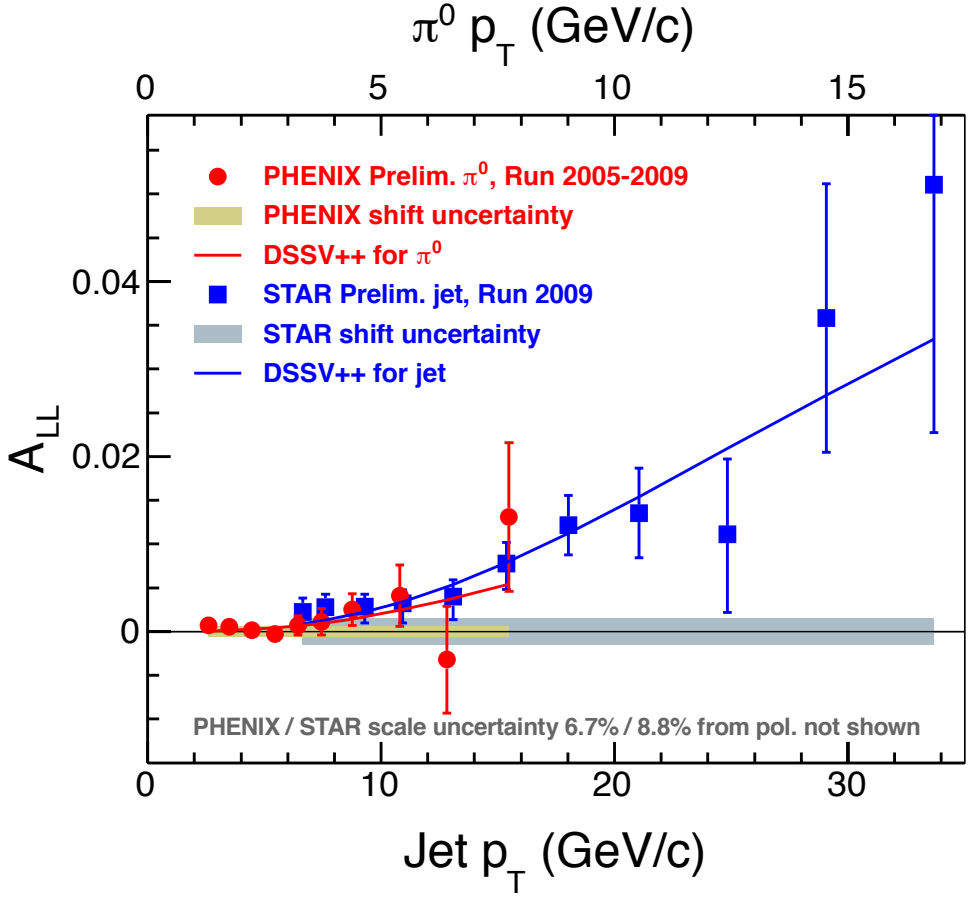
- Run 9 A_{LL} measurement between BB10 and DSSV / Clearly above zero at low p_T
- Larger asymmetry at low p_T suggests larger gluon polarization compared to DSSV
- With global analysis, A_{LL} jet result provides evidence for positive gluon polarization for $x > 0.05$

Momentum $q_i(x)$ and helicity distributions $\Delta q_i(x)$

- PHENIX: Mid-rapidity neutral pion



A. Adare et al. (PHENIX Collaboration), arXiv:1510/02317.

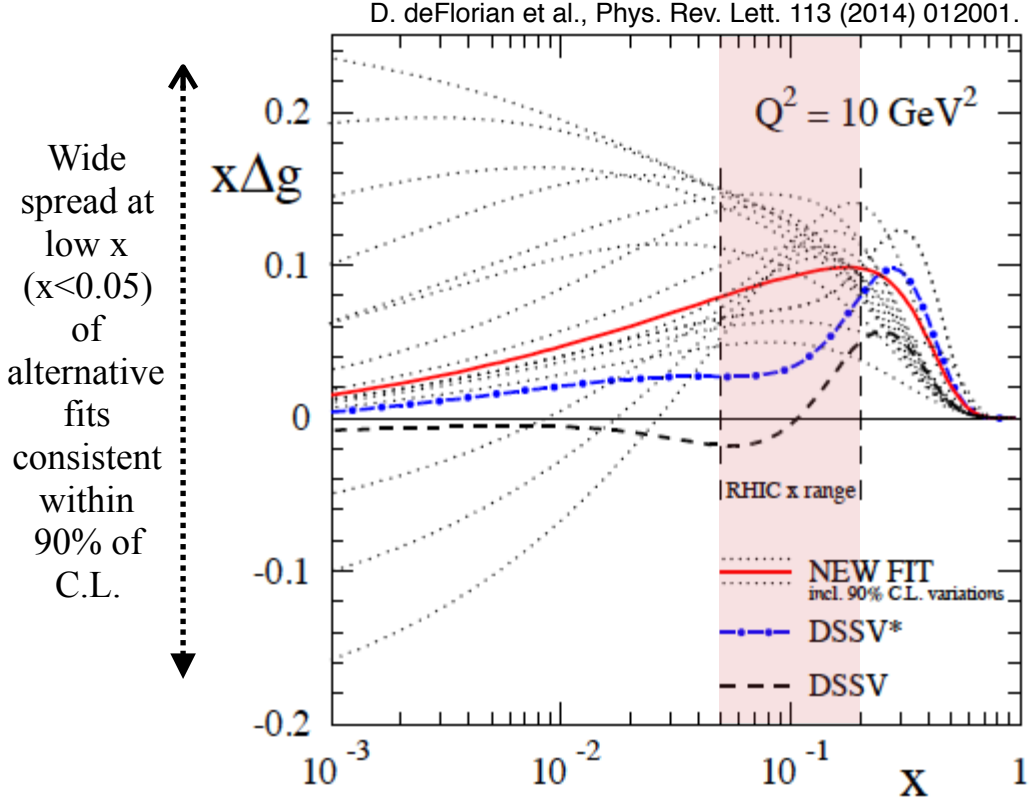


- Data are well described by NLO pQCD calculations
- New PHENIX Run 13 results at 510GeV
- Consistency between PHENIX and STAR results!

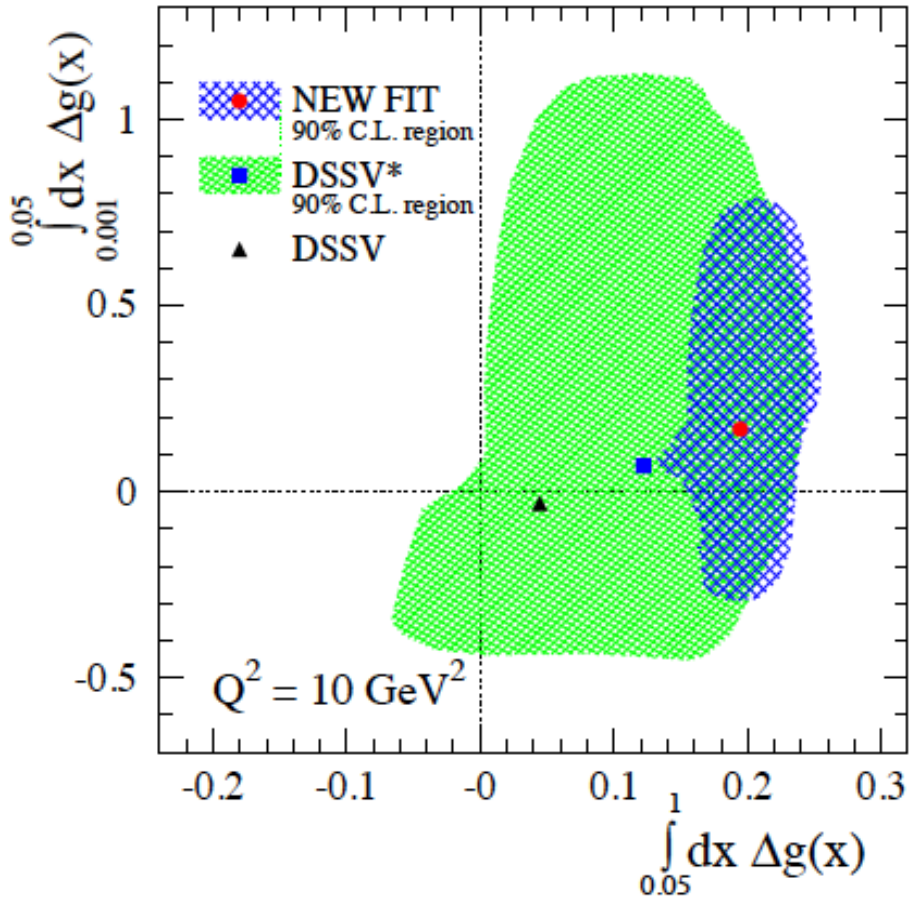
Results / Status - g / Δg(x) related studies

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 Δg(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 $0.05 < x < 0.5$

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

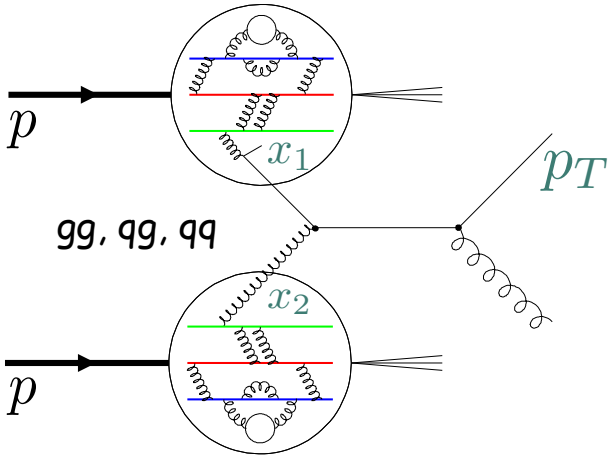
"...better small-x probes are badly needed."

Results / Status - Gluon related studies

RHIC Gluon polarization - Correlation Measurements

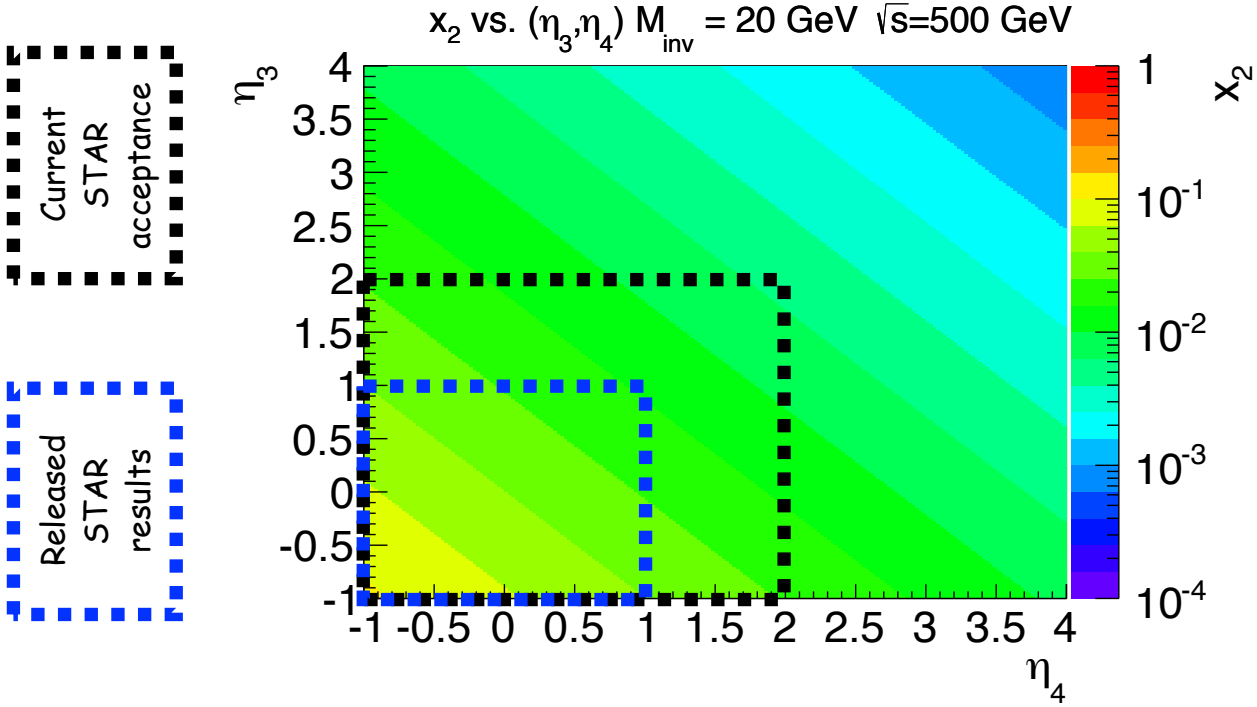
- Correlation measurements provide access to LO partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:

$$x_{1\,(2)} = \frac{1}{\sqrt{s}}\left(p_{T_3} e^{\eta_3(-\eta_3)} + p_{T_4} e^{\eta_4(-\eta_4)}\right)$$



Di-Jet production

- Bjorken x-coverage:

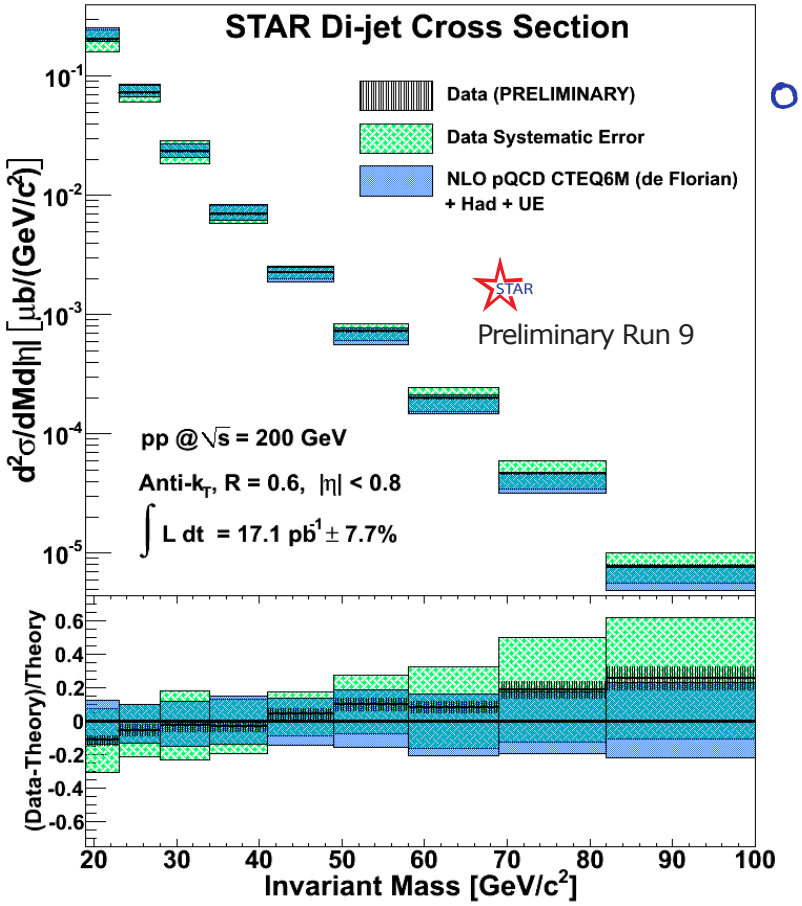


$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

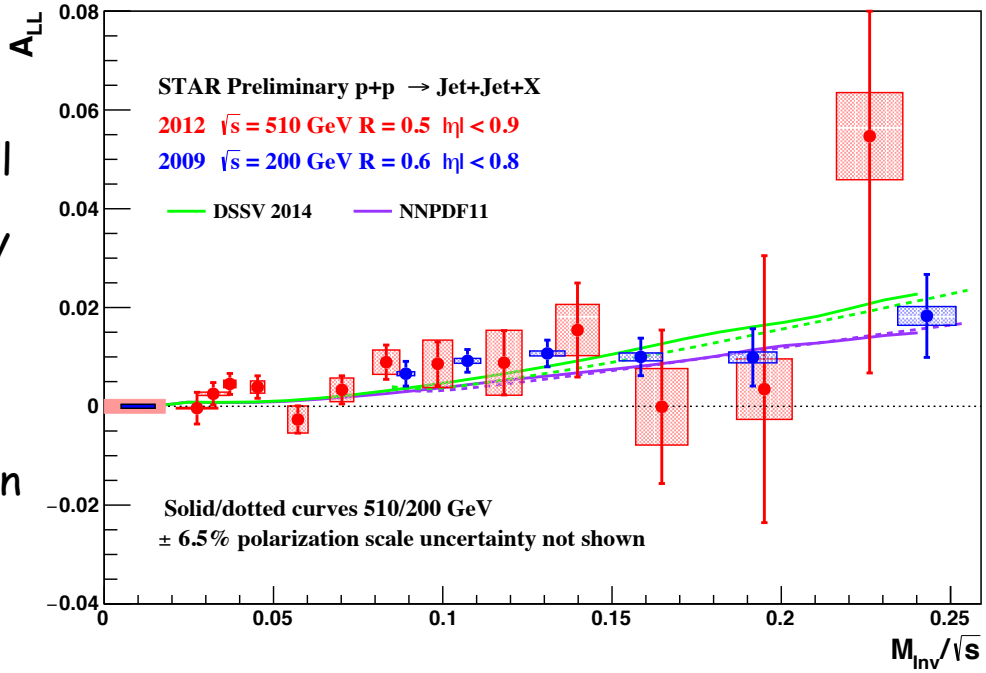
$$M = \sqrt{s}\sqrt{x_1 x_2}$$

Results / Status - Gluon related studies

- Mid-rapidity STAR Di-Jet cross-section (Run 9) and A_{LL} measurement (Run 9)



- Data are well described by NLO pQCD plus hadronization and underlying event corrections



- A_{LL} measurements consistent with DSSV2015 and NNPDF11 constrained by Run 9 data

$$M = \sqrt{s}\sqrt{x_1 x_2} \qquad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

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

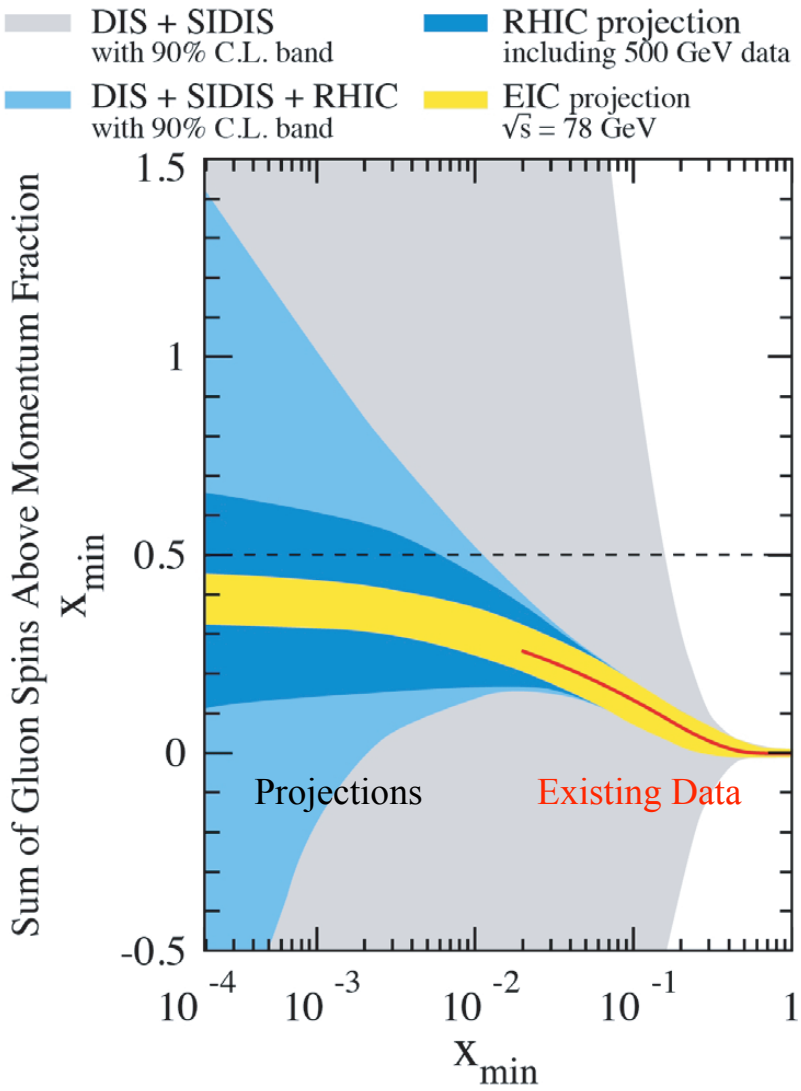
S. Rakmachandran et al. (STAR Collaboration), DIS 2016. (Run 12 / 500GeV)

Results / Status - g / Δg(x) related studies

- Impact on Δg from RHIC data / projections and future EIC facility
  - Integral of Δg (Q^2=10GeV^2) (Running integral) from x_{min} to 1 as a function of x_{min}

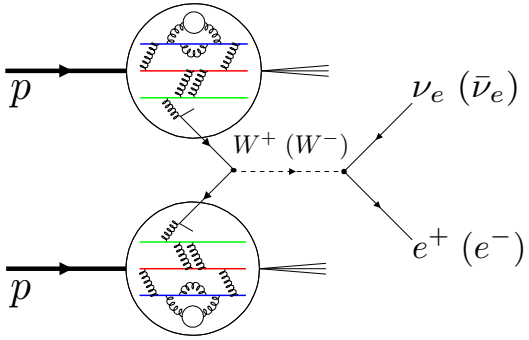
$$\Delta G(Q^2 = 10\,\mathrm{GeV}^2) = \int_{x_{min}}^{1} \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2)\, dx$$

  - 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 / qbar related studies

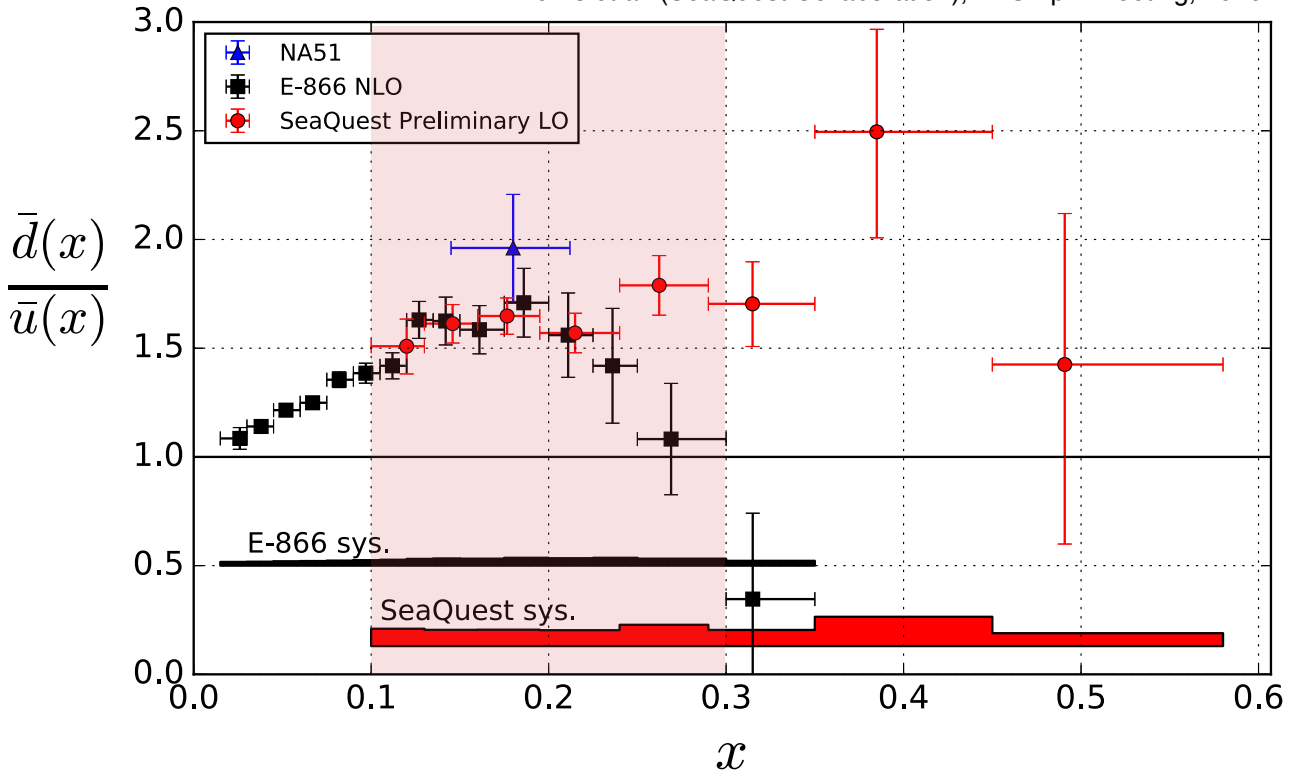
- STAR: Probing dbar / ubar ratio: QCD sea



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

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

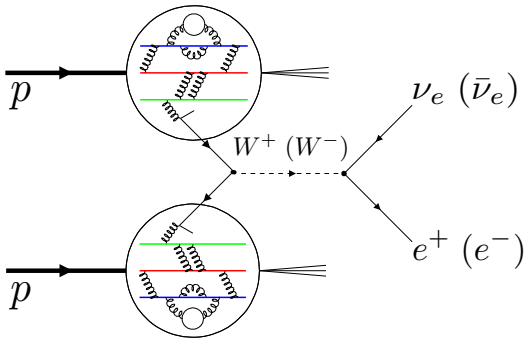
B. Kerns et al. (SeaQuest Collaboration), APS April Meeting, 2016.



- STAR coverage at mid-rapidity: 0.1 < x < 0.3 for -1 < η < 1
- Constraints on global fitting for dbar/ubar through W production at higher Q^2 compared E906
- Independent cross-check of Drell-Yan data

Results / Status - q / qbar related studies

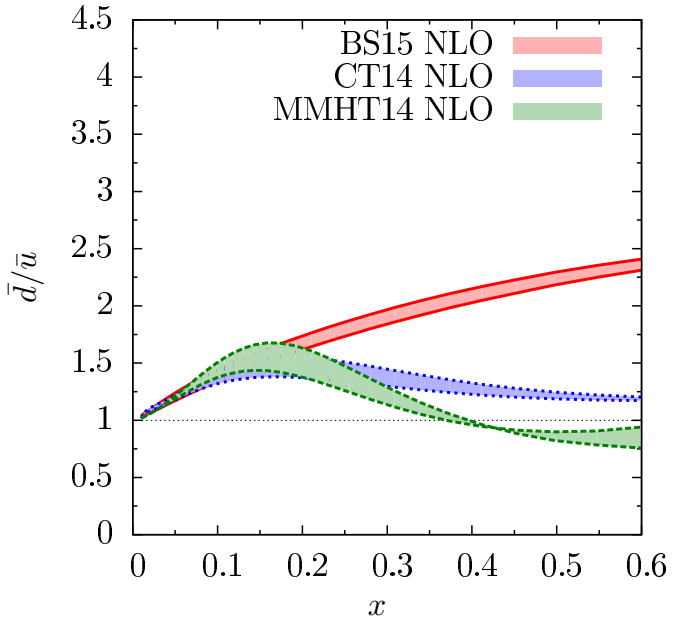
- STAR: Probing dbar / ubar ratio: QCD sea

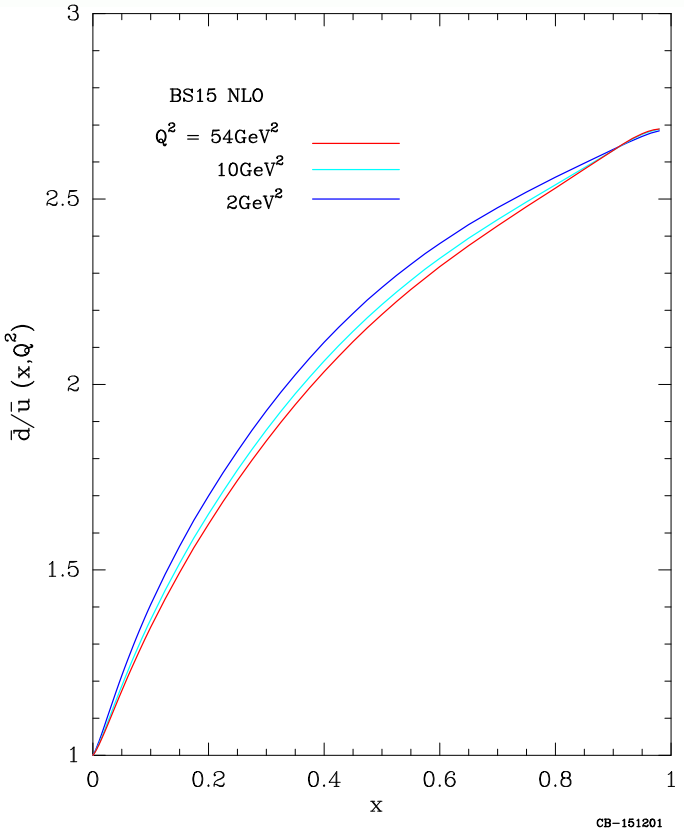


$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} =$$

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

C. Bourrely and J. Soffer (2013)

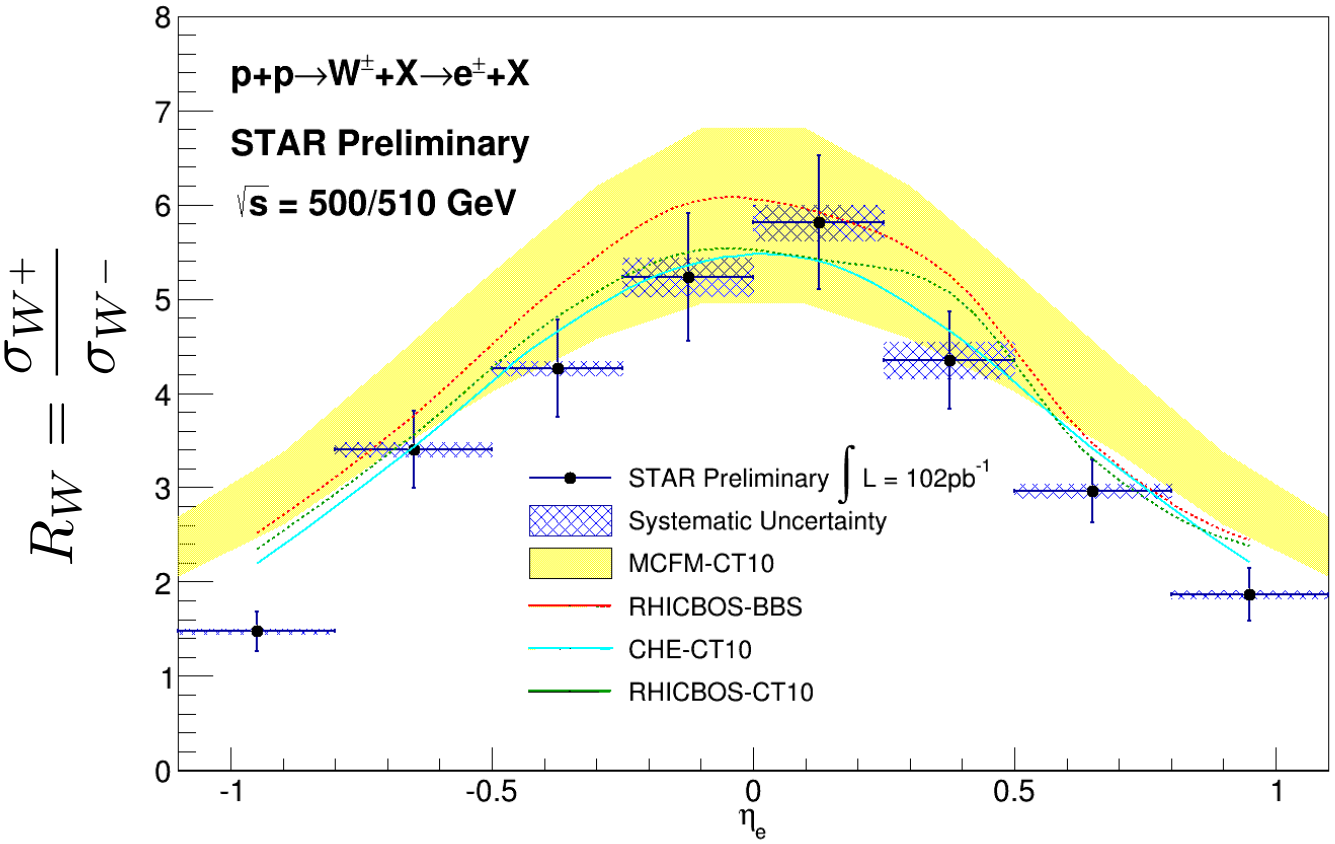




- STAR coverage at mid-rapidity: 0.1 < x < 0.3 for -1 < η < 1
- Constraints on global fitting for dbar/ubar through W production at higher Q^2 compared E906
- Independent cross-check of Drell-Yan data

Results / Status - q / qbar related studies

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

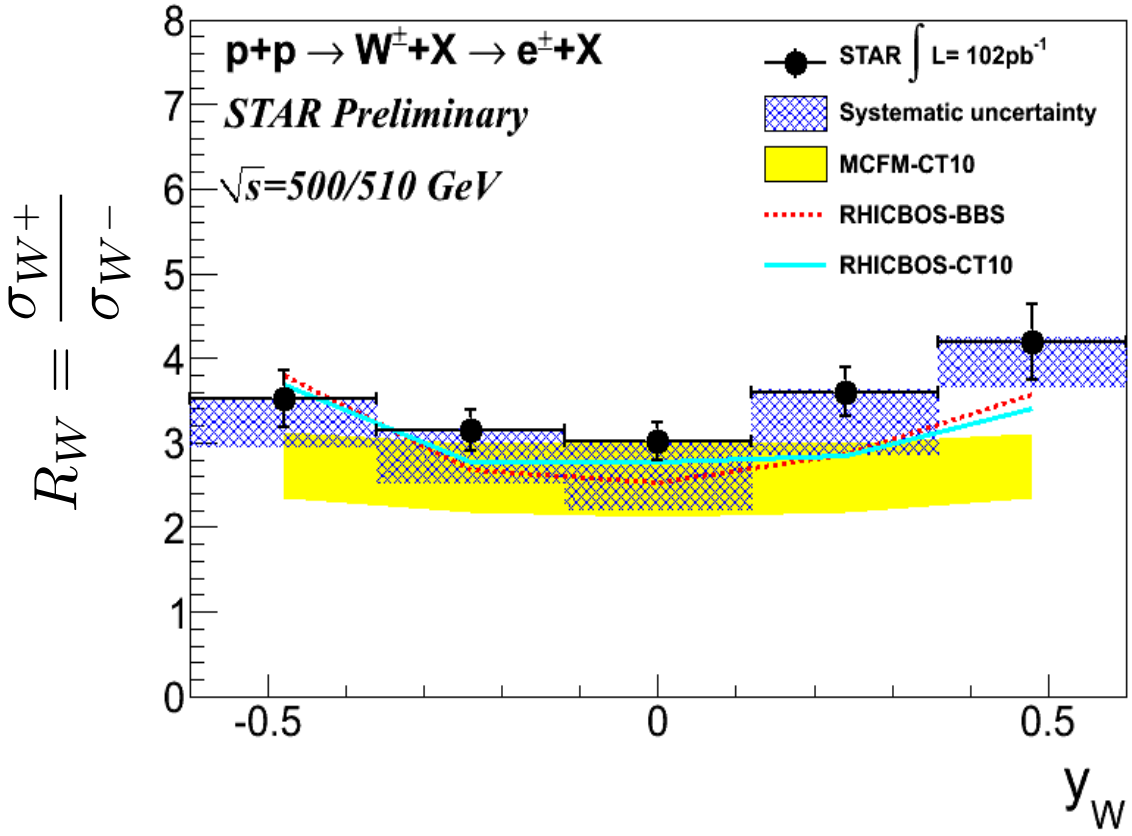


- Run 11 + Run 12 preliminary result: ~100pb^{-1}
- Run 13 data sample with ~300pb^{-1} will provide important improvement on precision
- Planned Run 17 data sample of ~400pb^{-1}

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

Results / Status - q / qbar related studies

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



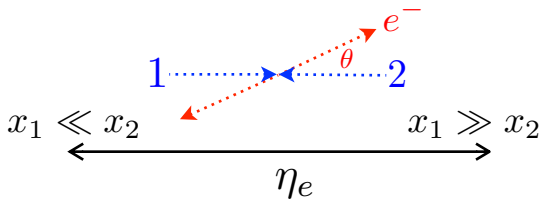
- W boson kinematics can be determined by reconstructing the W kinematics via its recoil
- Combination of data/MC simulations allows W boson rapidity reconstruction
- Critical for transverse single-spin asymmetry result of W production probing Sivers sign change

S. Fazio et al. (STAR Collaboration), DIS 2015.

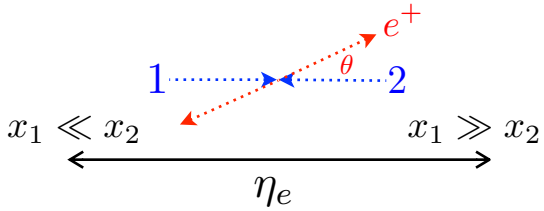
Results / Status - Δq / Δqbar related studies

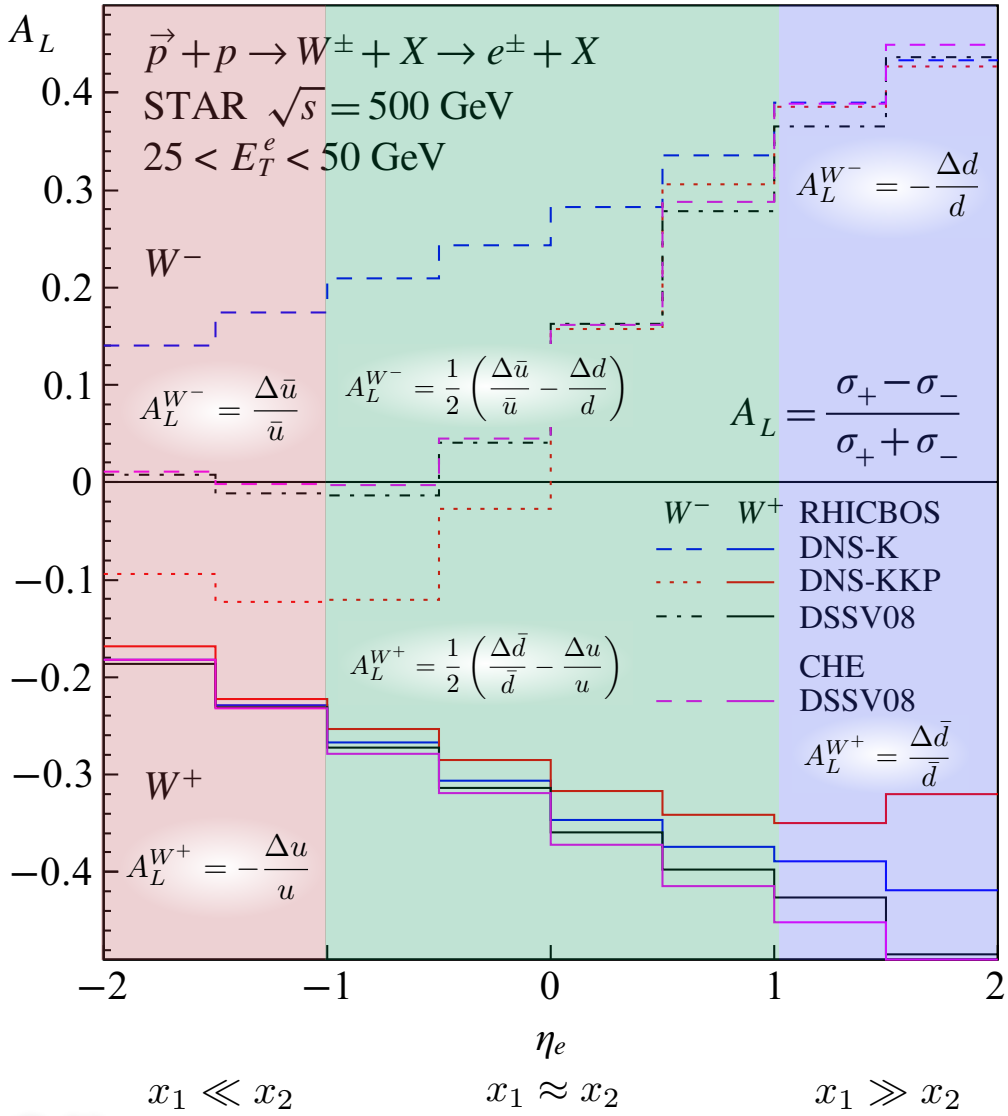
- RHIC Probing the quark flavor structure using W boson production

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



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





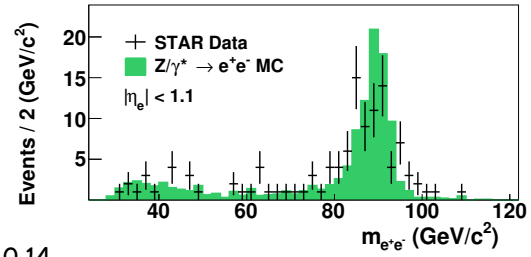
$\sqrt{s} = 500\,GeV$

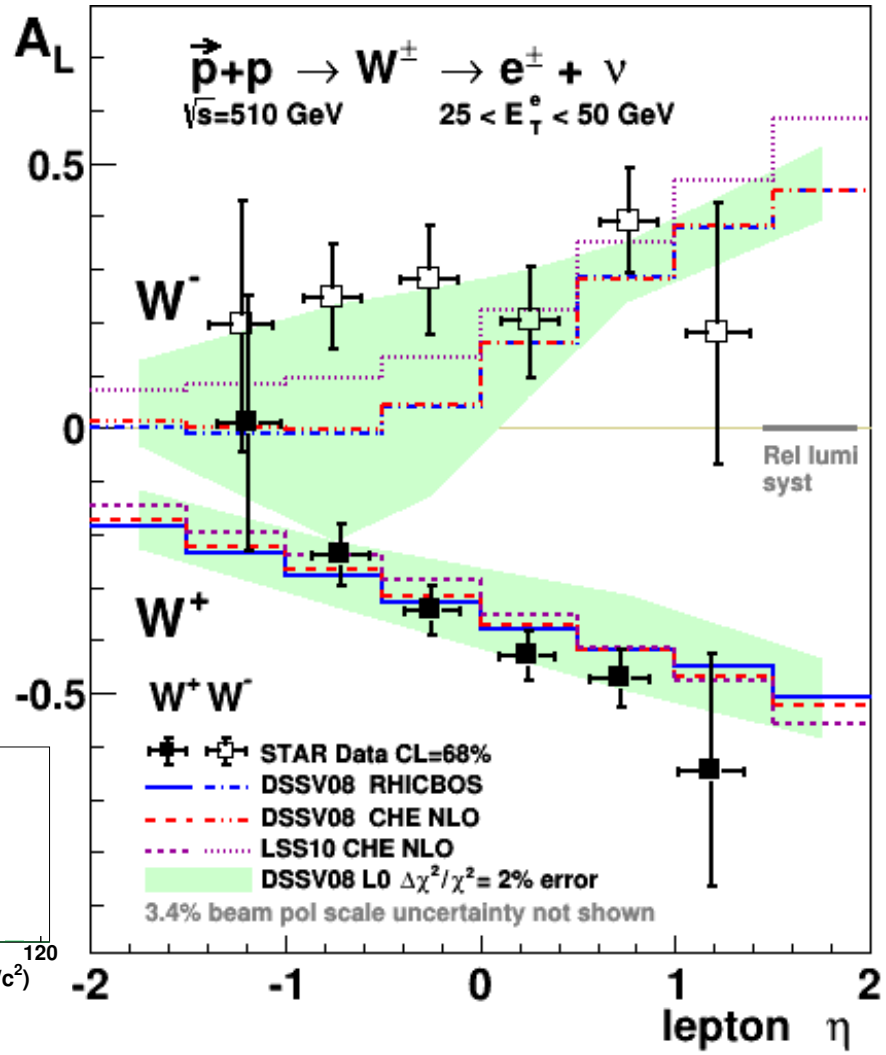
Results / Status - Δq / Δqbar related studies

- 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/γ^*) result: $A_L = -0.07^{+0.14}_{-0.14}$

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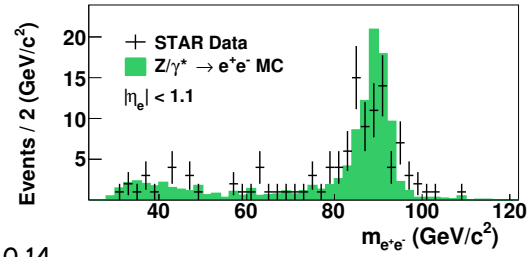

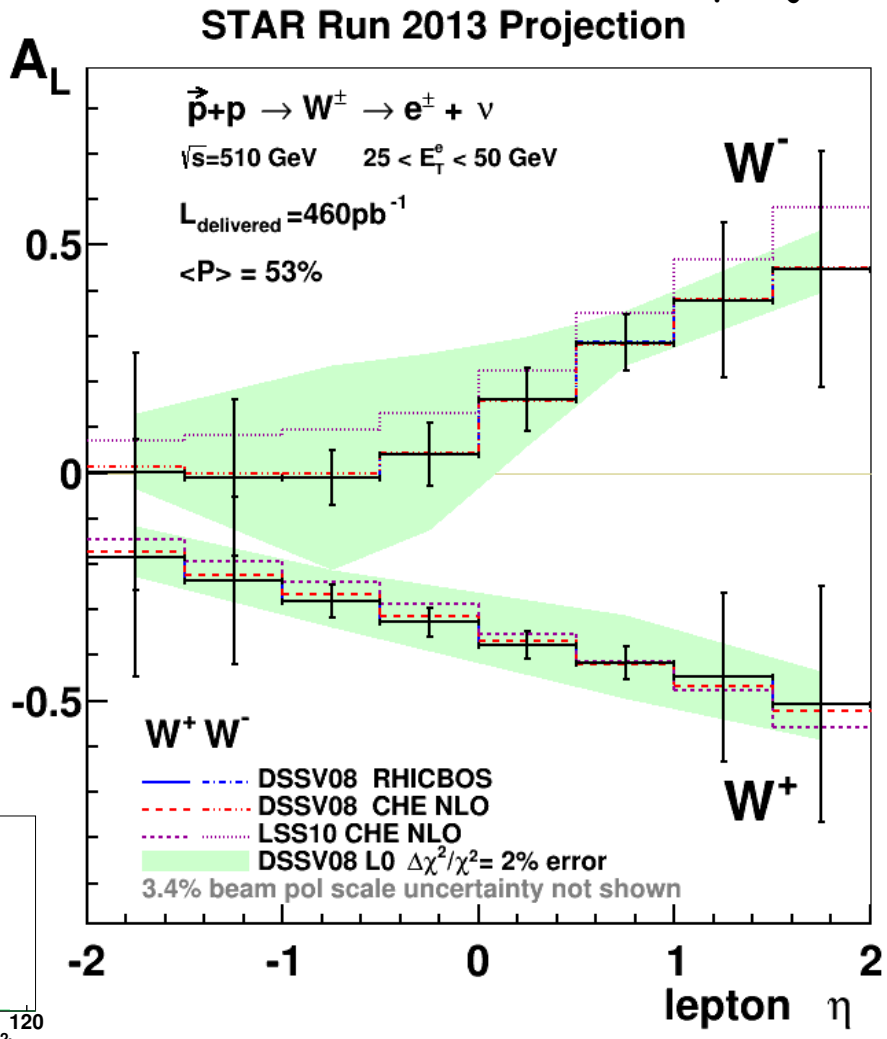

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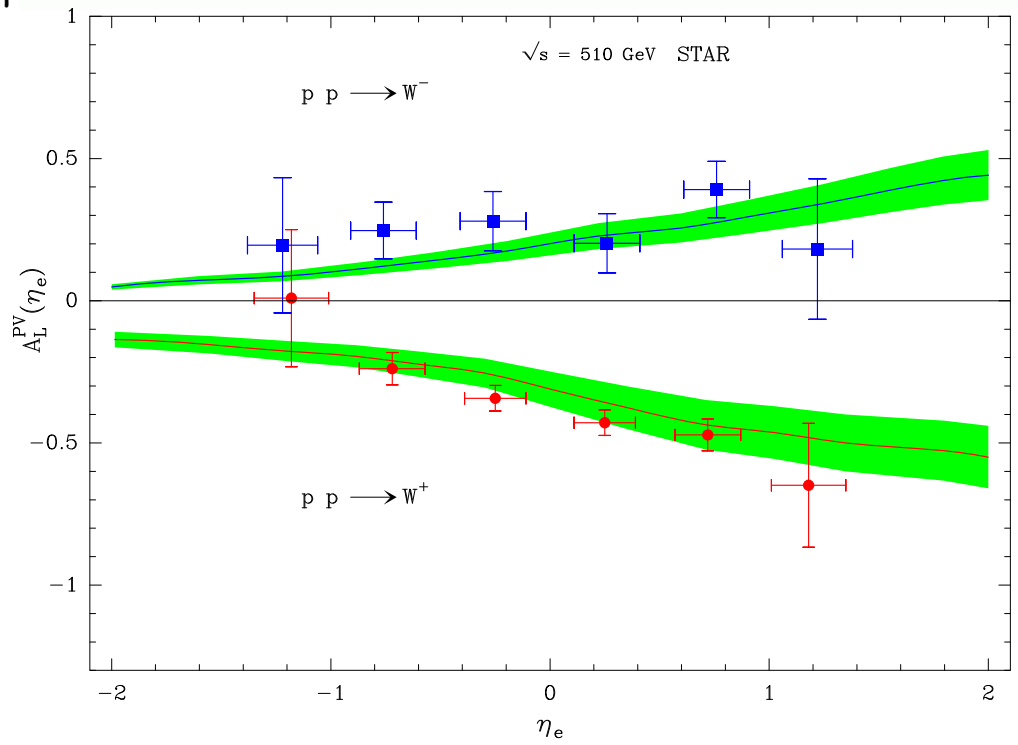

C. Bourrely and J. Soffer (2013)

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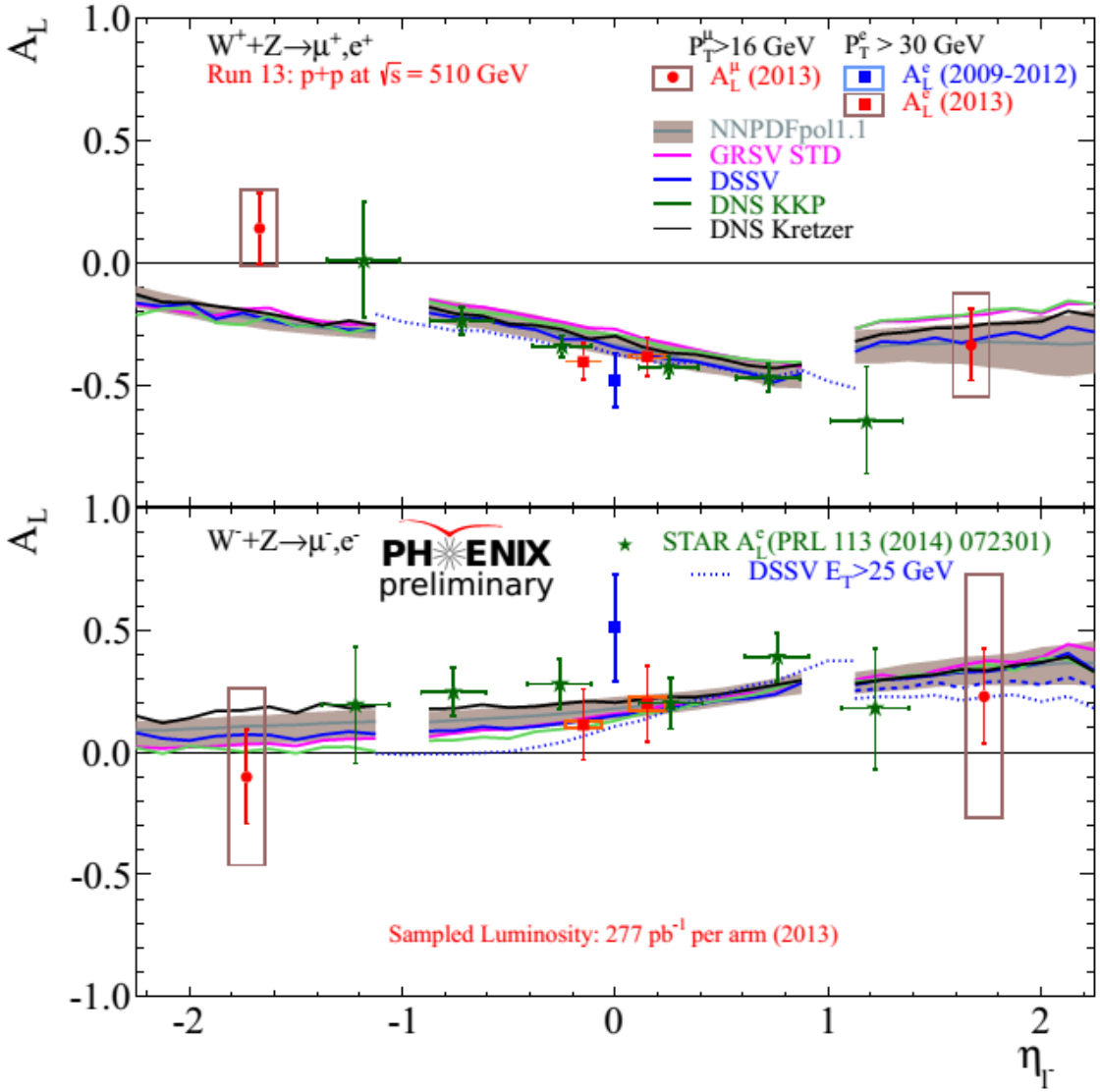
Results / Status - q / qbar related studies

- PHENIX: W A_L mid-rapidity and forward rapidity results

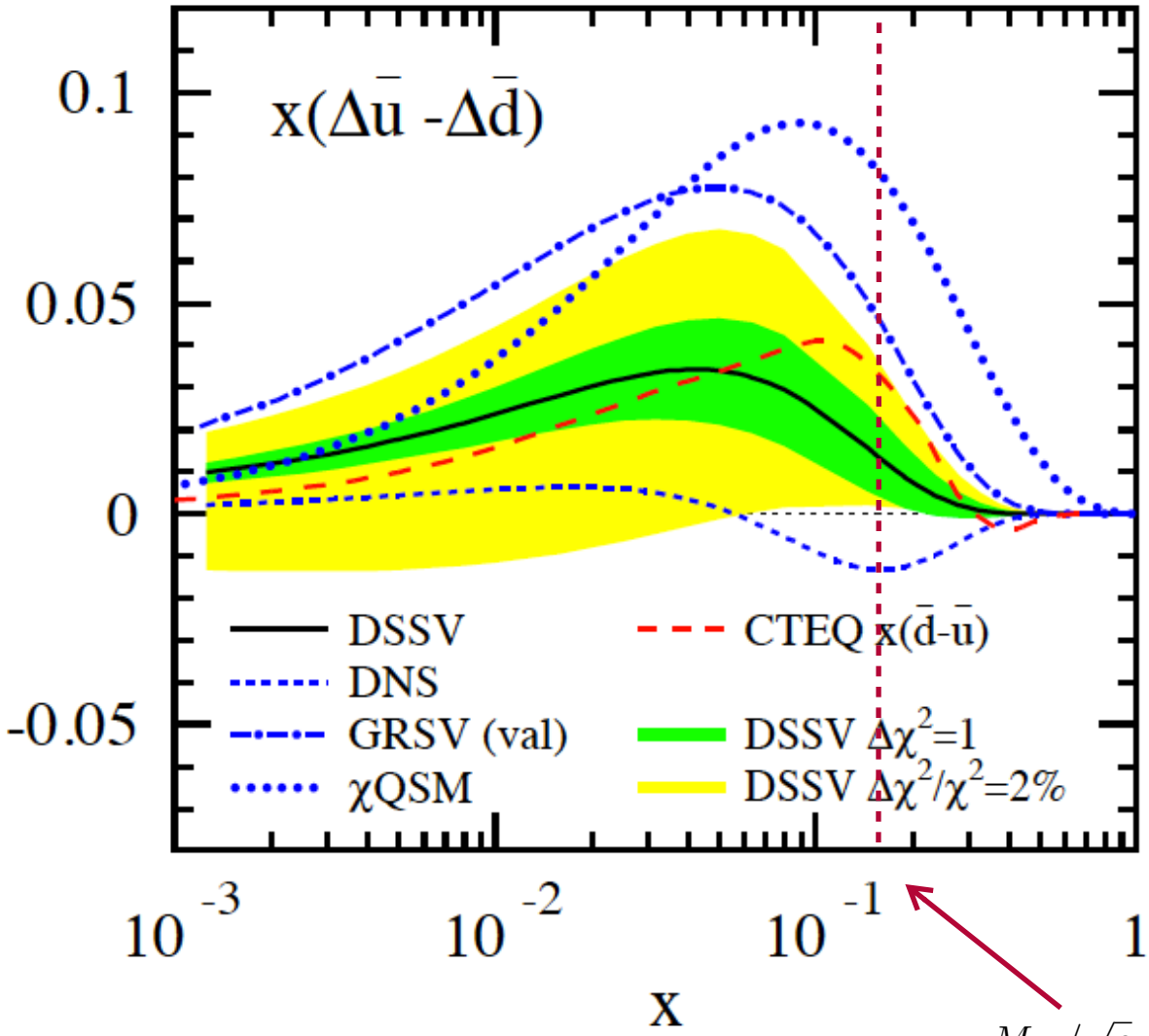


- Compilation of PHENIX Run 13 forward rapidity and mid-rapidity results together with STAR mid-rapidity results

Momentum $q_i(x)$ and helicity distributions $\Delta q_i(x)$

- DSSV global fit result

D. de Florian et al., Phys. Rev. Lett. 101 (2008) 072001



$M_W/\sqrt{s} = 0.16$

RHIC Spin Collaboration (2012)

- From recent DSSV++ result incl. STAR A_L data:

$$\int_{0.05}^{1} \Delta\bar{u}(x,Q^2)dx \approx 0.02$$

$$\int_{0.05}^{1} \Delta\bar{d}(x,Q^2)dx \approx -0.05$$

Summary / Outlook

- Gluon related studies: g / Δg
  - 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 / Δq
  - 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 dbar/ubar probe using W production complementary to SeaQuest / Substantial improvement with Run 13 data sample
  - Forward rapidity analysis requires completion of challenging FGT tracking analysis
- 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 dbar / ubar probe
  - Exciting long-term program beyond 2020 requiring forward detector upgrade (Cold QCD plan)

Cold QCD plan, arXiv: 1602.03922.