Selected results and future prospects of the high-energy polarized p+p program at RHIC at BNL

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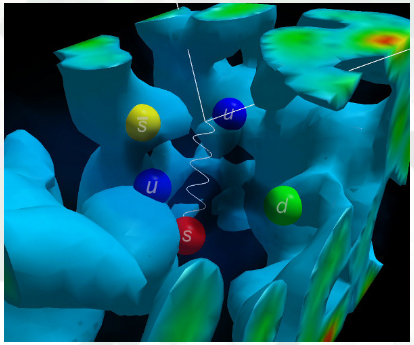
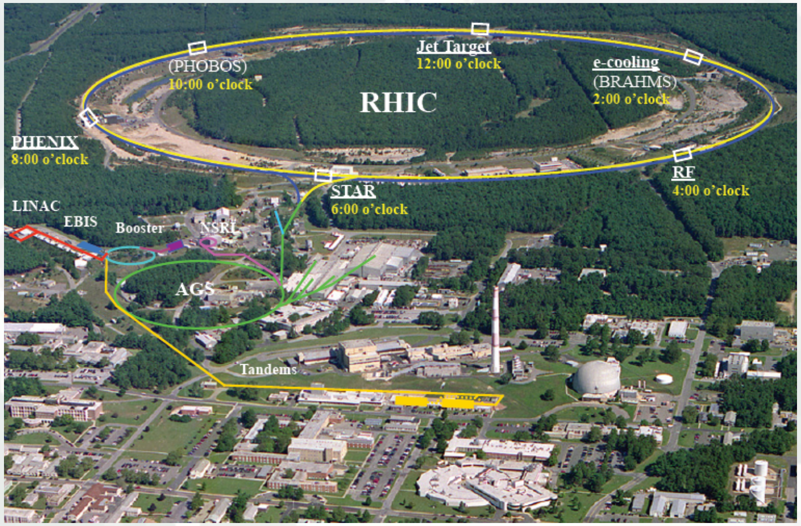
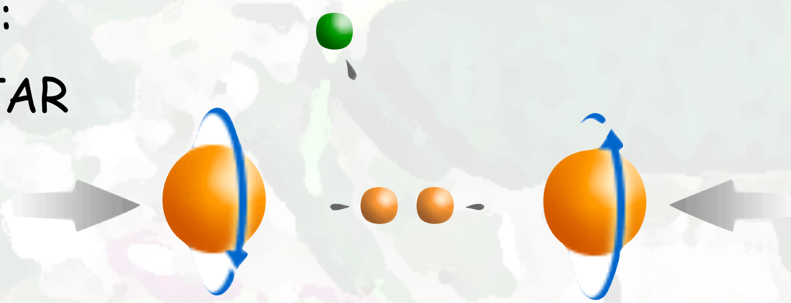


Outline



- Selected results and future prospects
  - Gluon related studies
  - Quark / Anti-quark related studies

- Experimental aspects: RHIC / PHENIX / STAR



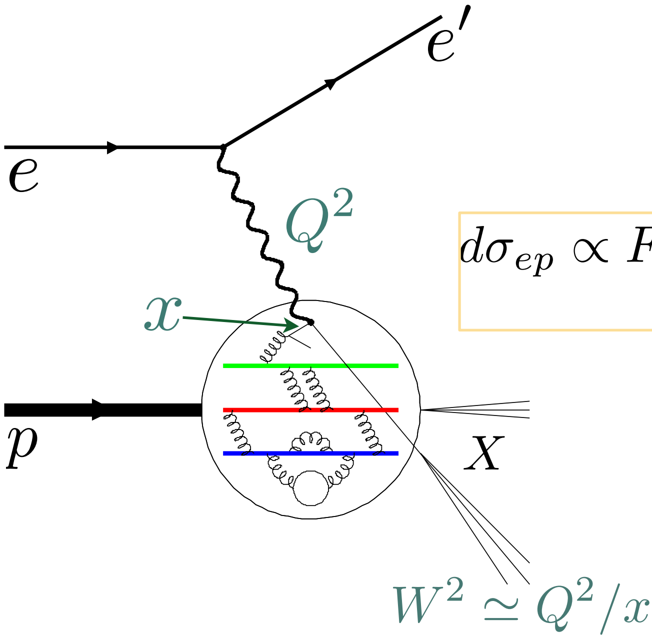
$\vec{p}$ $\vec{p}$

- Theoretical foundation

- Summary and Outlook

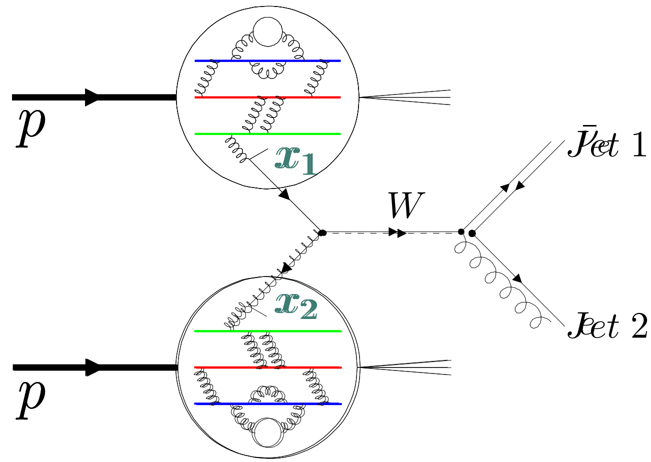
Theoretical foundation

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



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

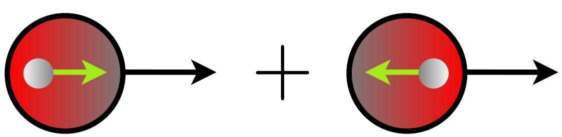
Universality



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

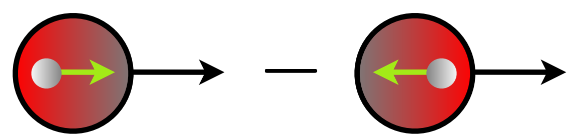
Momentum contribution

$$f(x) =$$



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

$$\Delta f(x) =$$



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

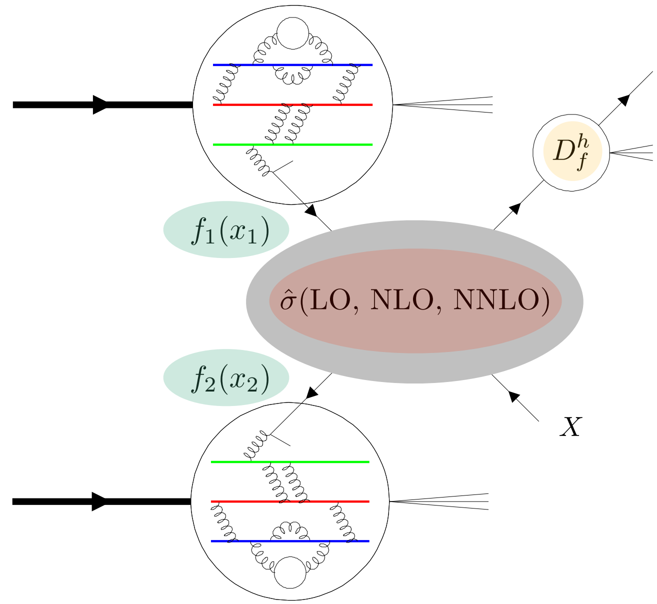
Spin contribution

Theoretical foundation

- Explore 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

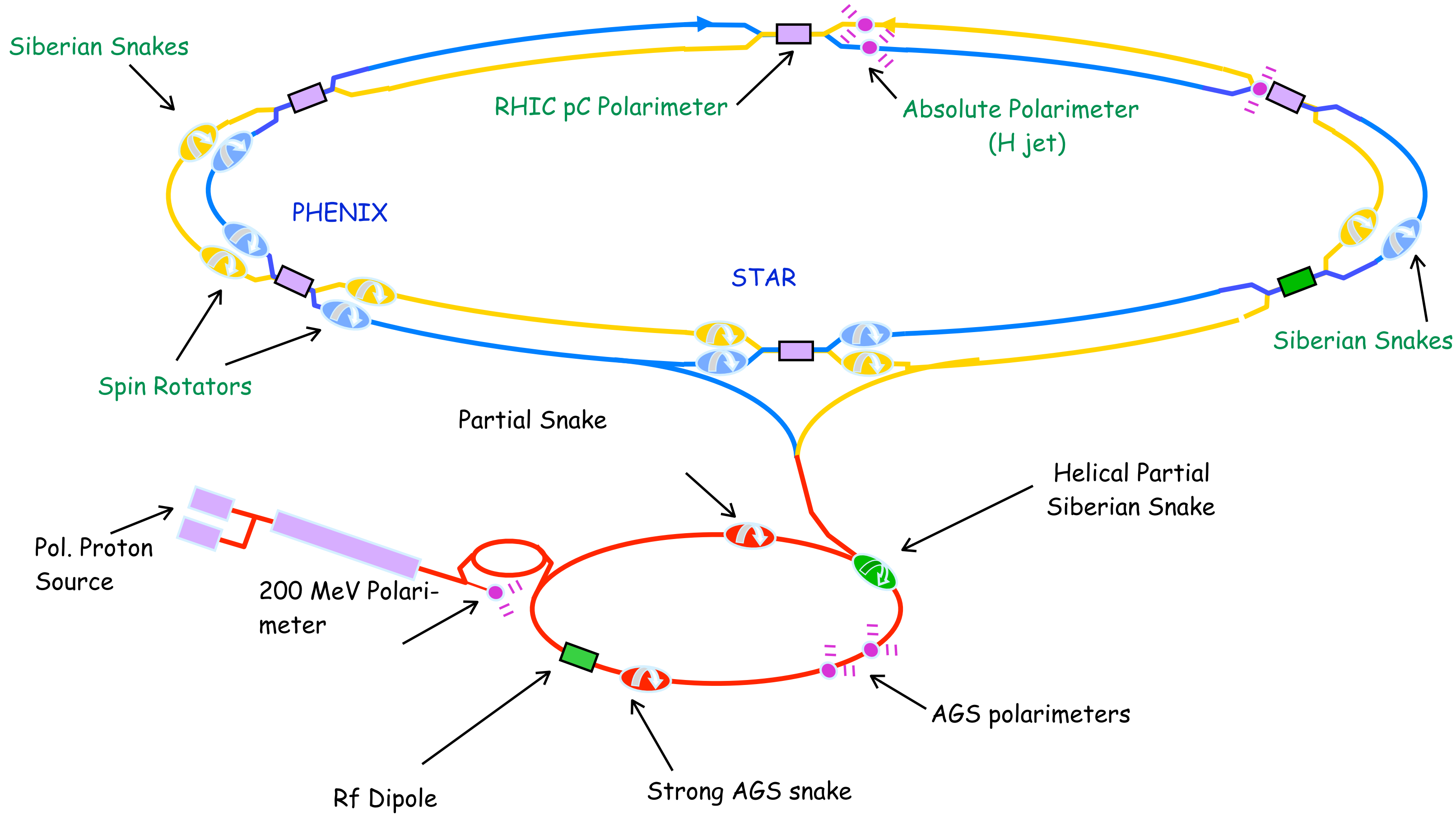
$\boxed{\Delta f_1}$ $\boxed{\Delta f_2}$

$$\boxed{a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}} \Bigg\} \text{ Input}$$

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

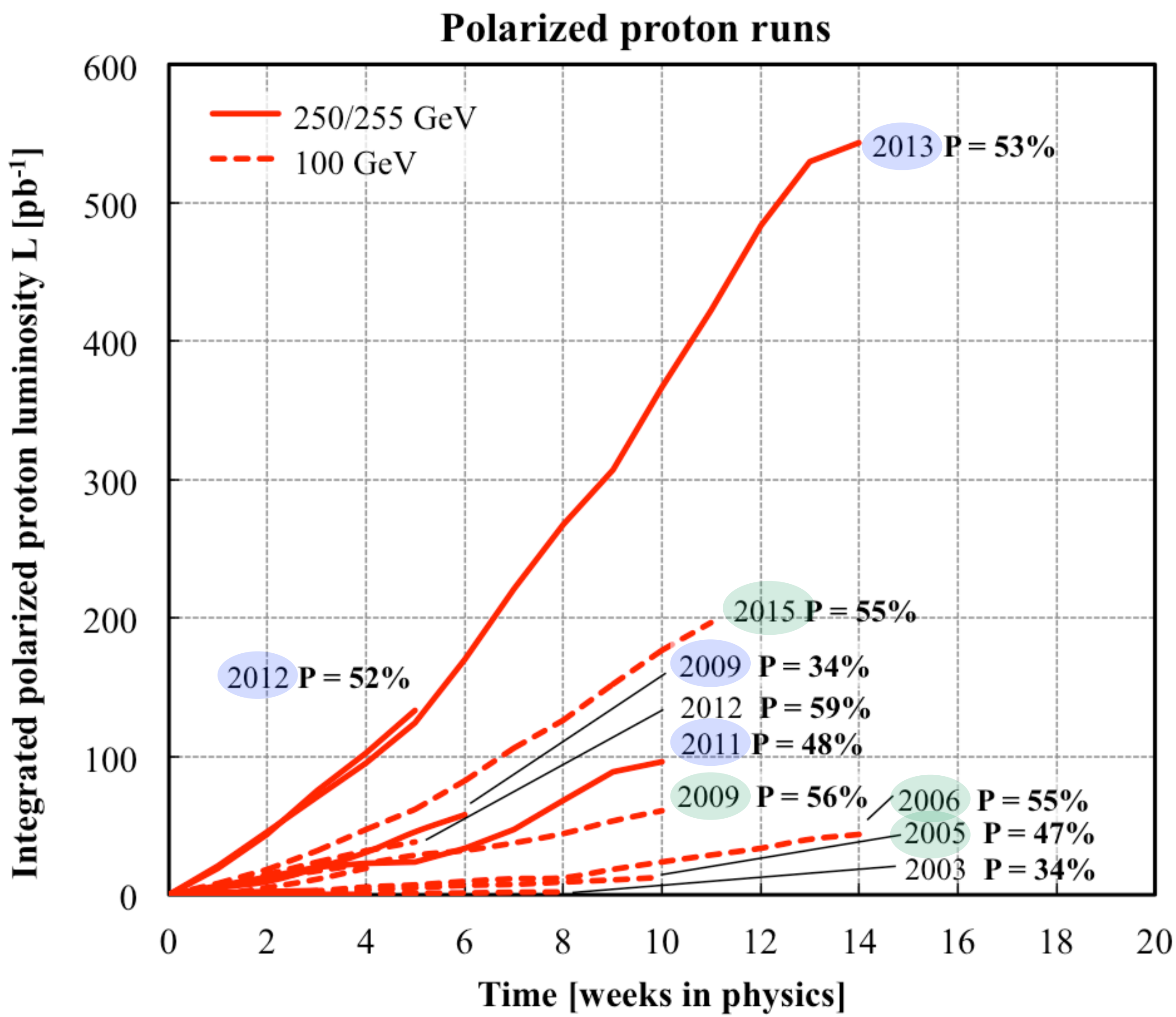
Experimental aspects - RHIC

- The world's first polarized proton-proton collider



Experimental aspects - RHIC

- Polarized p-p collisions
  - Production runs at √s=200GeV (long. polarization) in 2005, 2006, 2009 and 2015: Jet and Hadron production (Gluon polarization)
  - Production runs at √s=500GeV (long. polarization) in 2009, 2011, 2012 and 2013: W production (Quark polarization) / Jet and Hadron production (Gluon polarization)

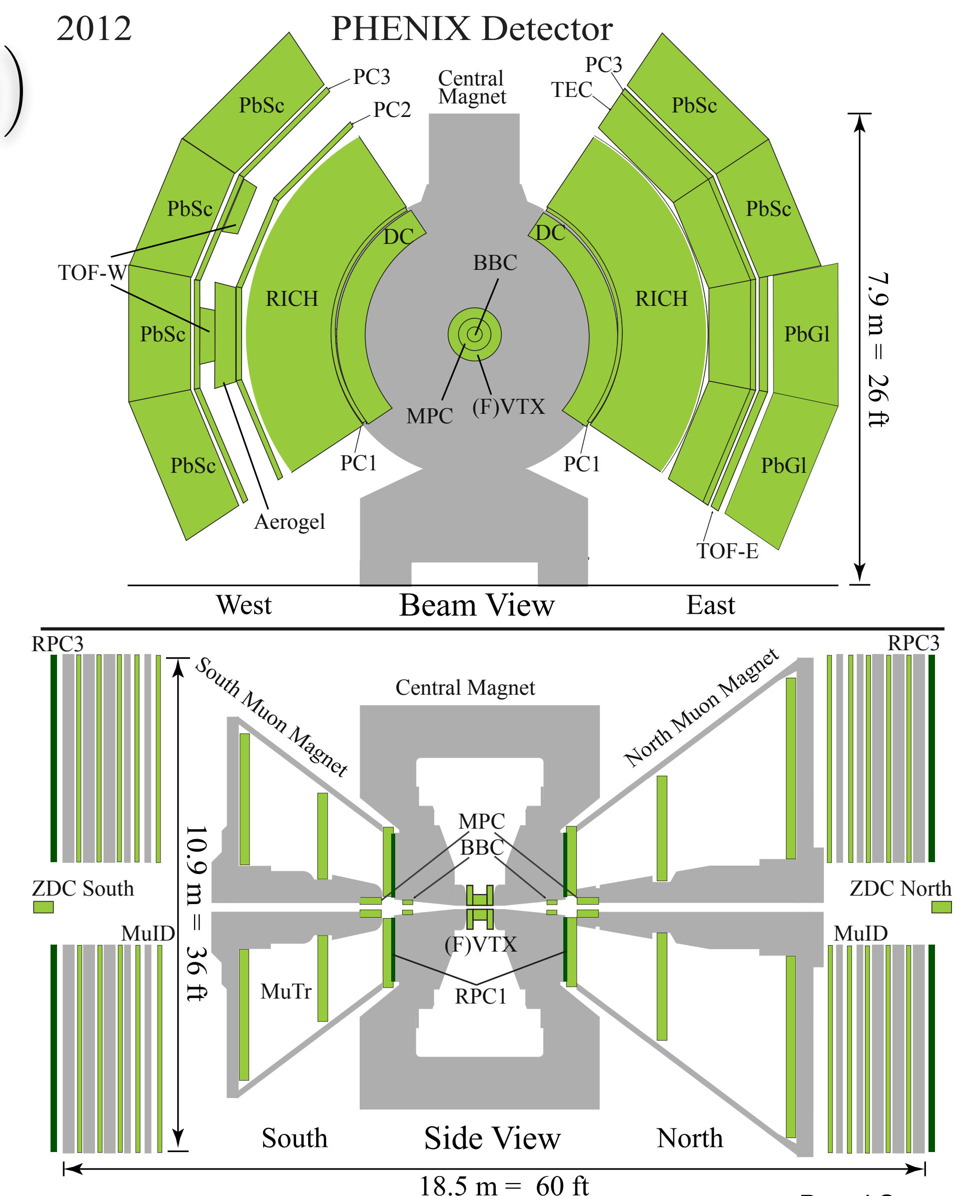


Experimental aspects - PHENIX

- Overview

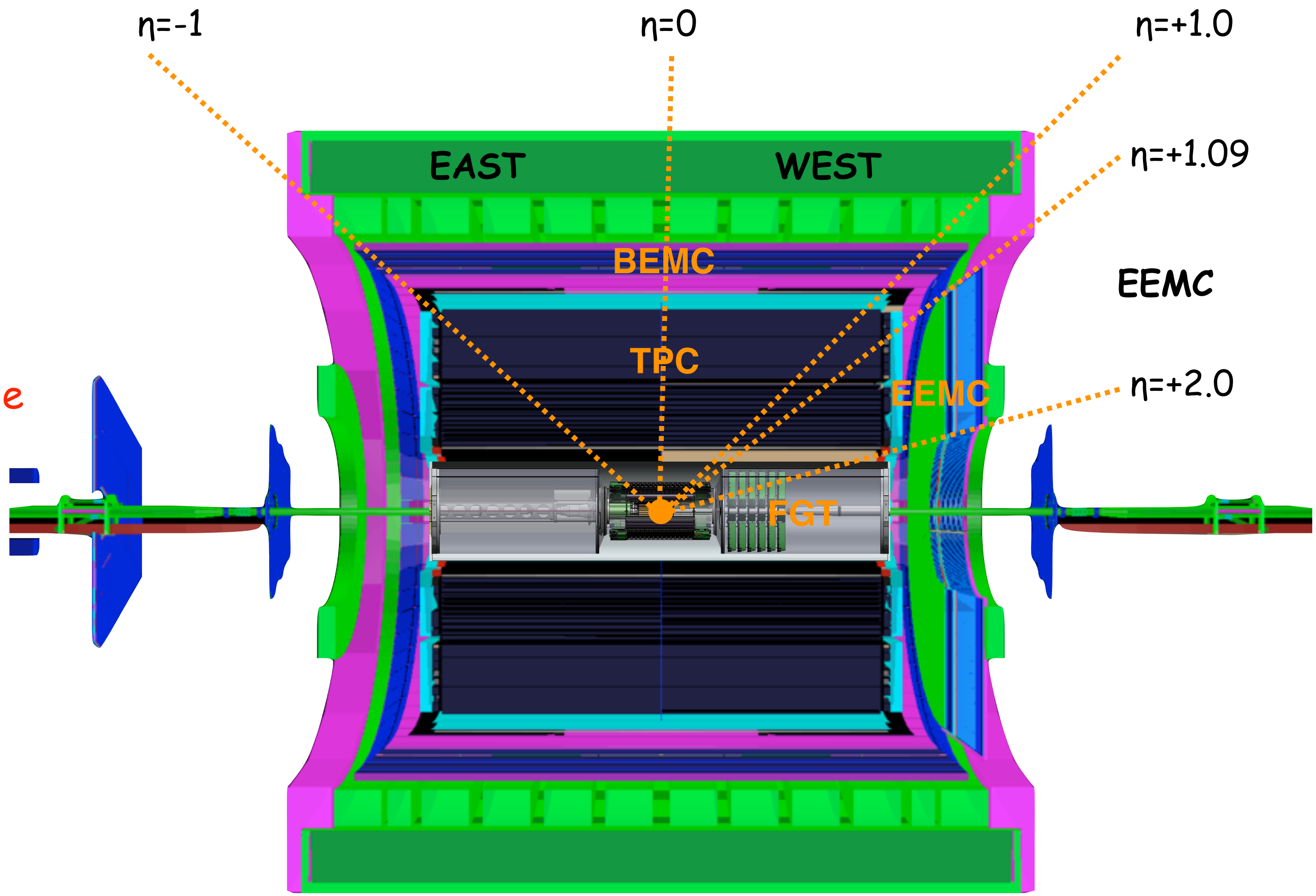
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- 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 ($1.2 < |\eta| < 2.4$ + 2π)
- π^0, η
  - MPC ($3.1 < |\eta| < 3.9$ + 2π)
- Relative Luminosity
  - Beam Beam Counter (BBC) ($3.0 < \eta < 3.9$)
  - Zero Degree Calorimeter (ZDC)



Experimental aspects - STAR

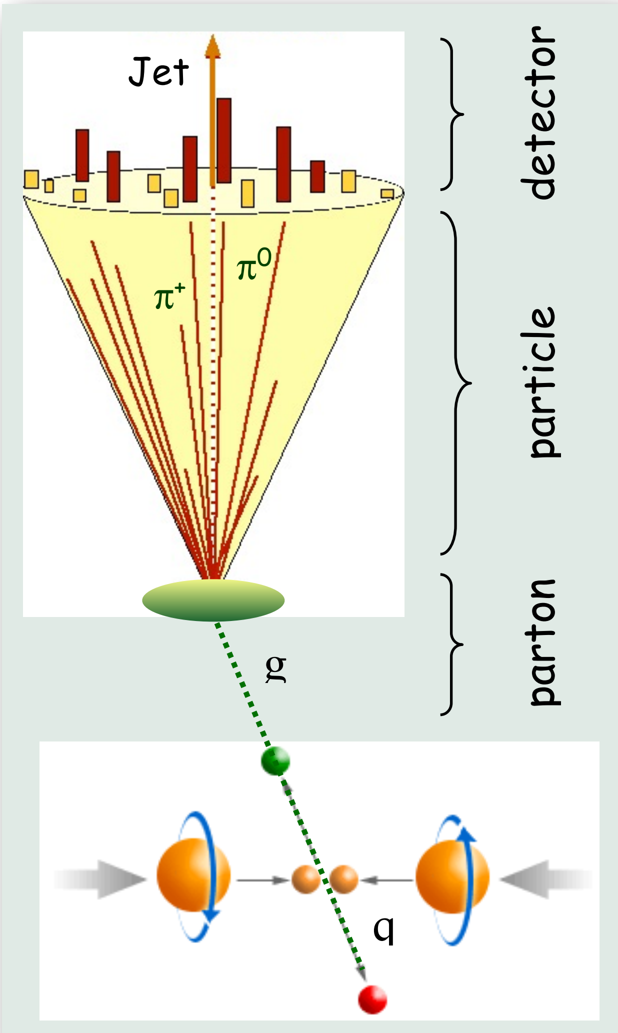
- Overview
  - Calorimetry system with 2π coverage: BEMC ($-1<\eta<1$) and EEMC ($1.09<\eta<2$)
  - TPC: Tracking and particle ID ($-1.3<\eta<1.3$)
  - FGT: Tracking ($1<\eta<2$)
  - ZDC: Relative luminosity and local polarimetry (500GeV)
  - BBC: Relative luminosity and Minimum bias trigger

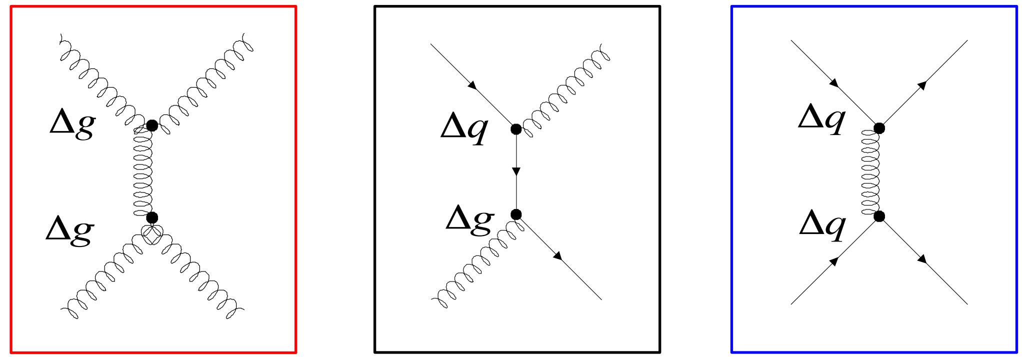


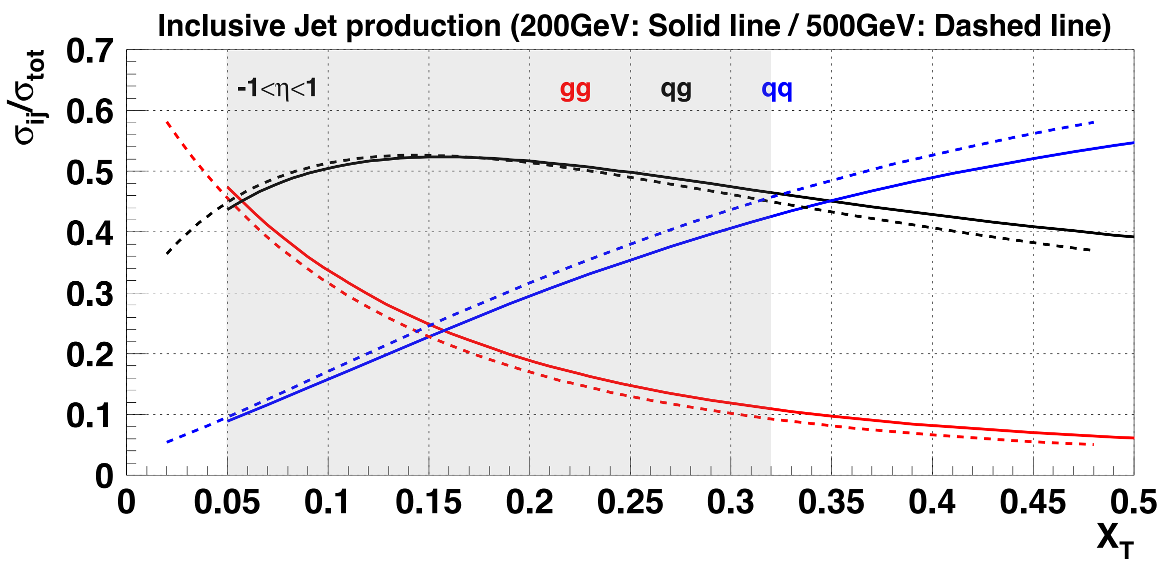
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Results / Status - Gluon related studies

- RHIC Gluon studies: Jet-type measurements



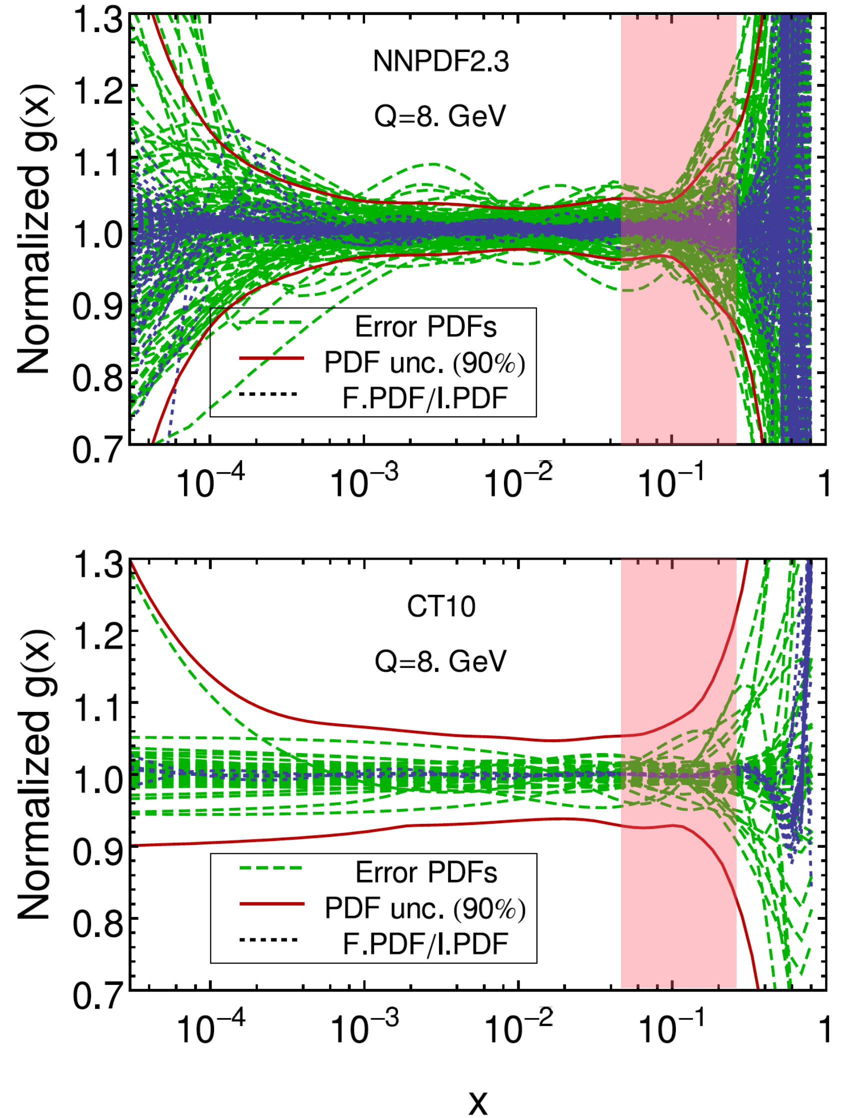




$$x_T = \frac{2p_T}{\sqrt{s}} \qquad \text{(x value at } \eta = 0\text{)}$$

Results / Status - Gluon related studies

- Uncertainty of unpolarized gluon distribution function g(x)
  - Large uncertainties of unpolarized gluon distribution function for x > 0.1 / Challenging to provide additional constraint from LHC experiments
  - RHIC mid-rapidity jet production probes x-range around x=0.1 of approximately 0.05 < x < 0.3
  - New STAR Inclusive Jet cross-section measurement using anti-kT algorithm with improved statistical precision and reduced systematic uncertainties will provide important and needed constraint on g(x) at high x



Results

Mid-rapidity Inclusive Jet cross-section measurement (1)

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

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

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

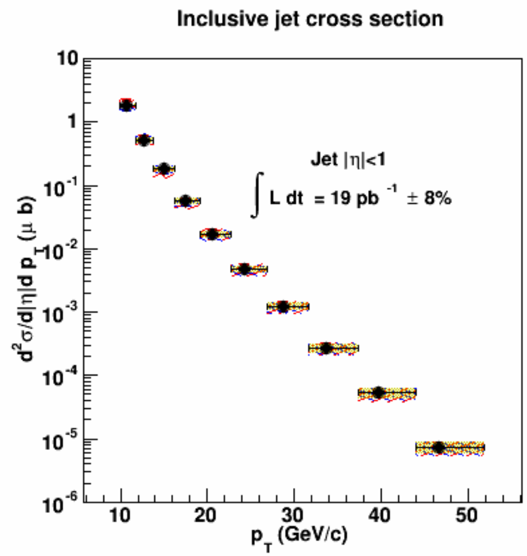
$$d = \min\left(\{D_{ij}, D_i\}\right)$$

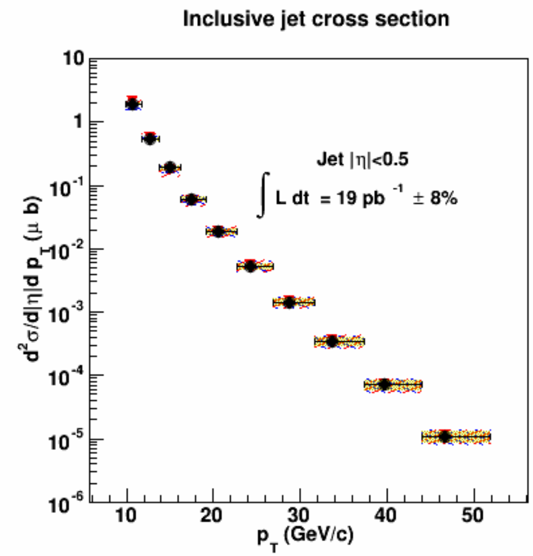
If $d = D_{ij}$: Combine jet i and jet j

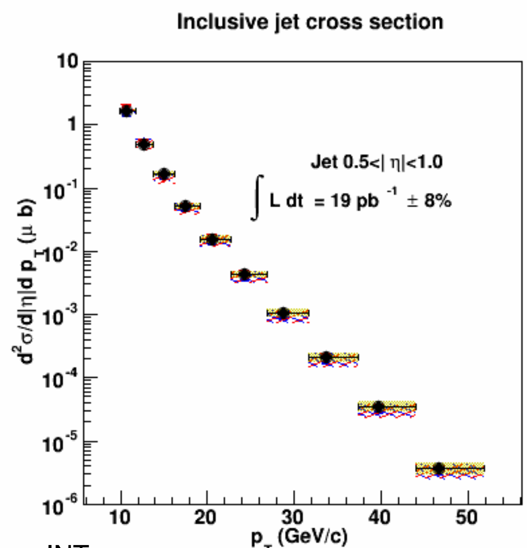
If $d = D_i$: Define jet i as final jet

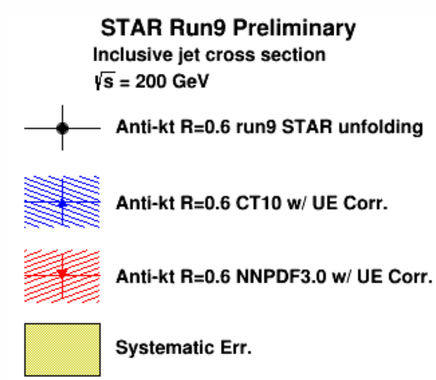
corrected to particle level for three different pseudo-rapidity regions of |η|<1, |η|<0.5 and 0.5<|η|<1.0

- 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









Results / Status - Gluon related studies

- STAR: Mid-rapidity Inclusive Jet cross-section measurement (Run 9) (2)

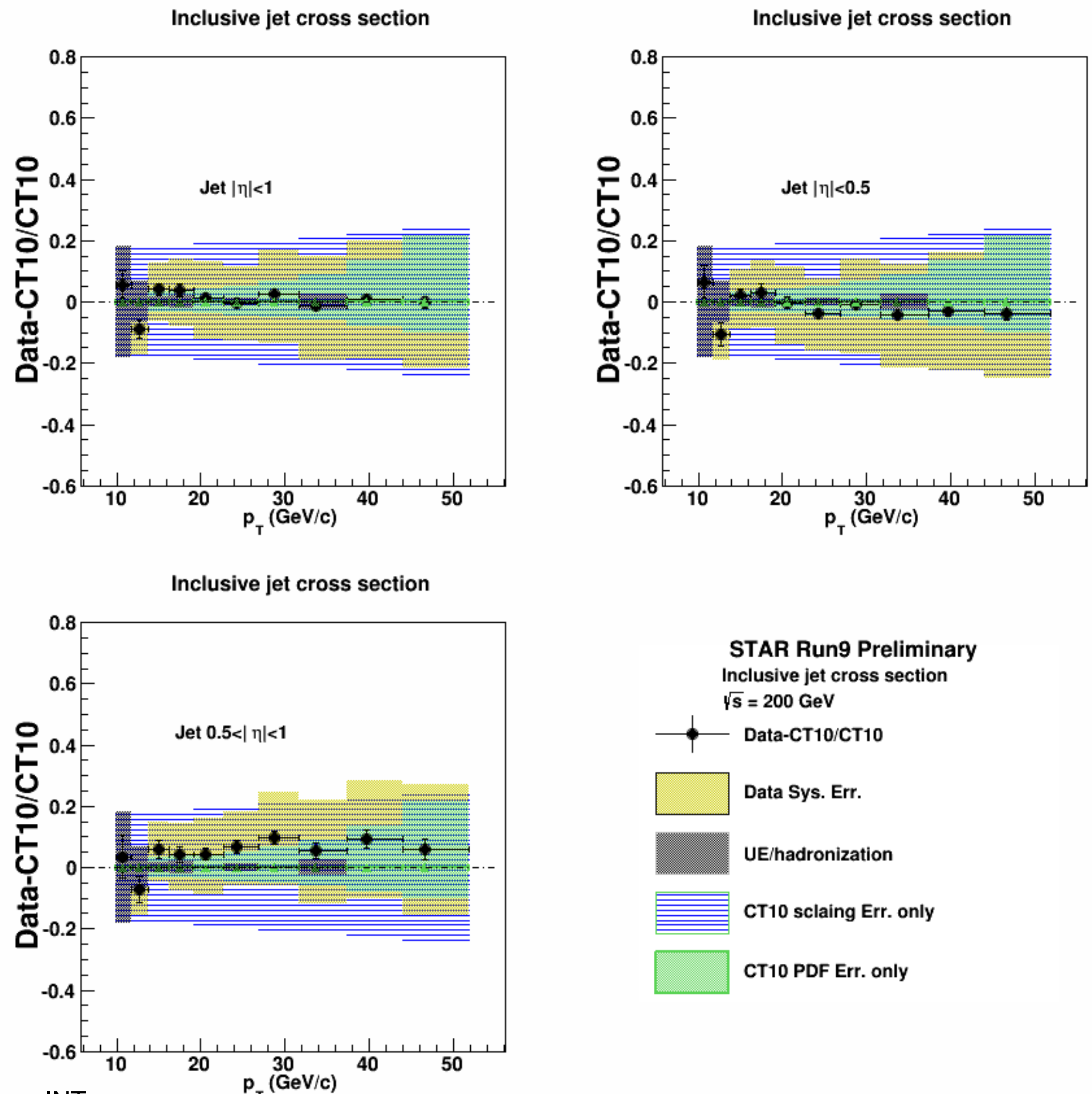
  - Quantitative comparison between data and theory of (Data-Theory)/ Theory showing

  UE/hadronization corrections applied to pure NLO calculations

  Data systematic errors

  CT10 scale uncertainties

  CT10 pdf uncertainites



Results / Status - Gluon related studies

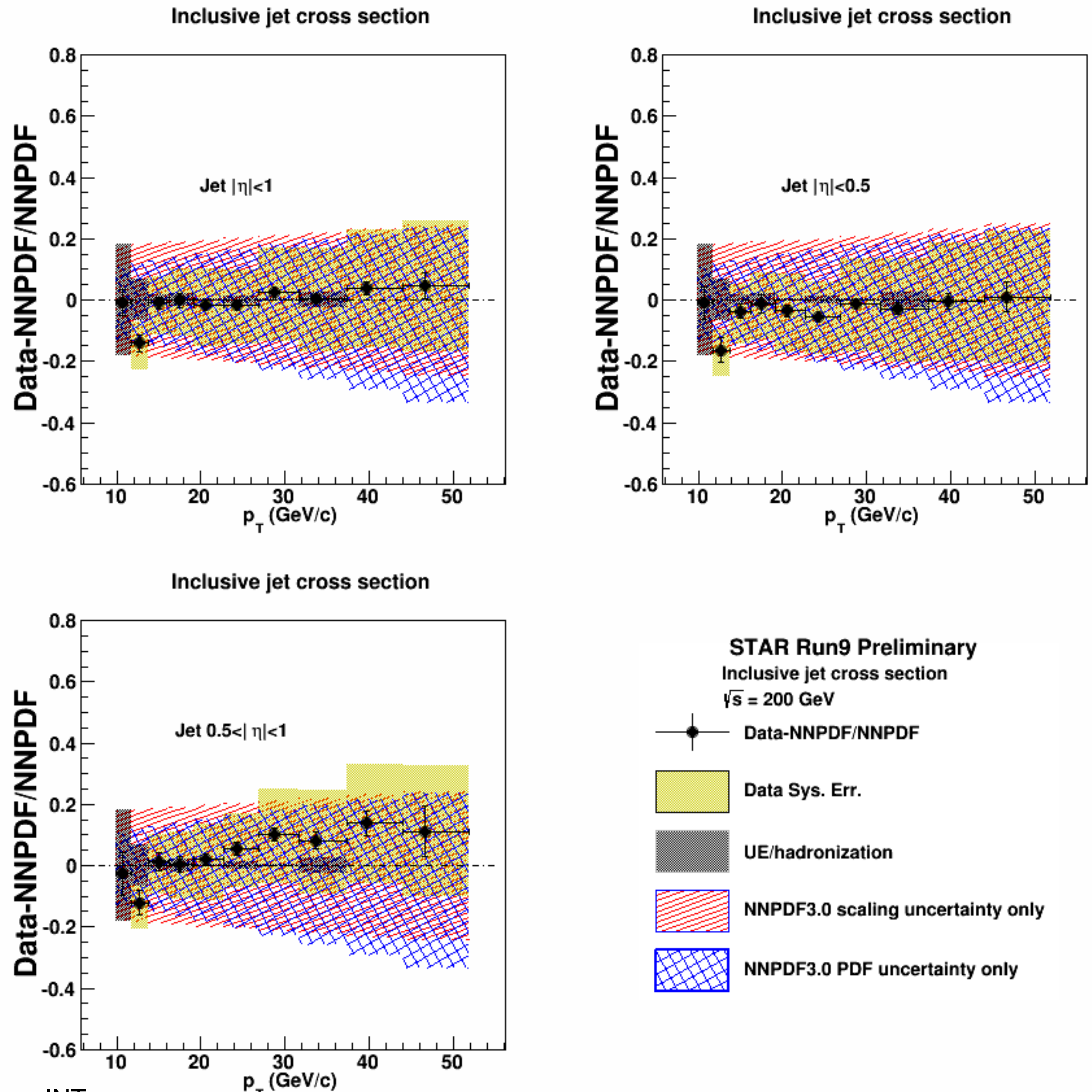
- STAR: Mid-rapidity Inclusive Jet cross-section measurement (Run 9) (3)
  - Quantitative comparison between data and theory of (Data-Theory)/ Theory showing

UE/hadronization corrections applied to pure NLO calculations

Data systematic errors

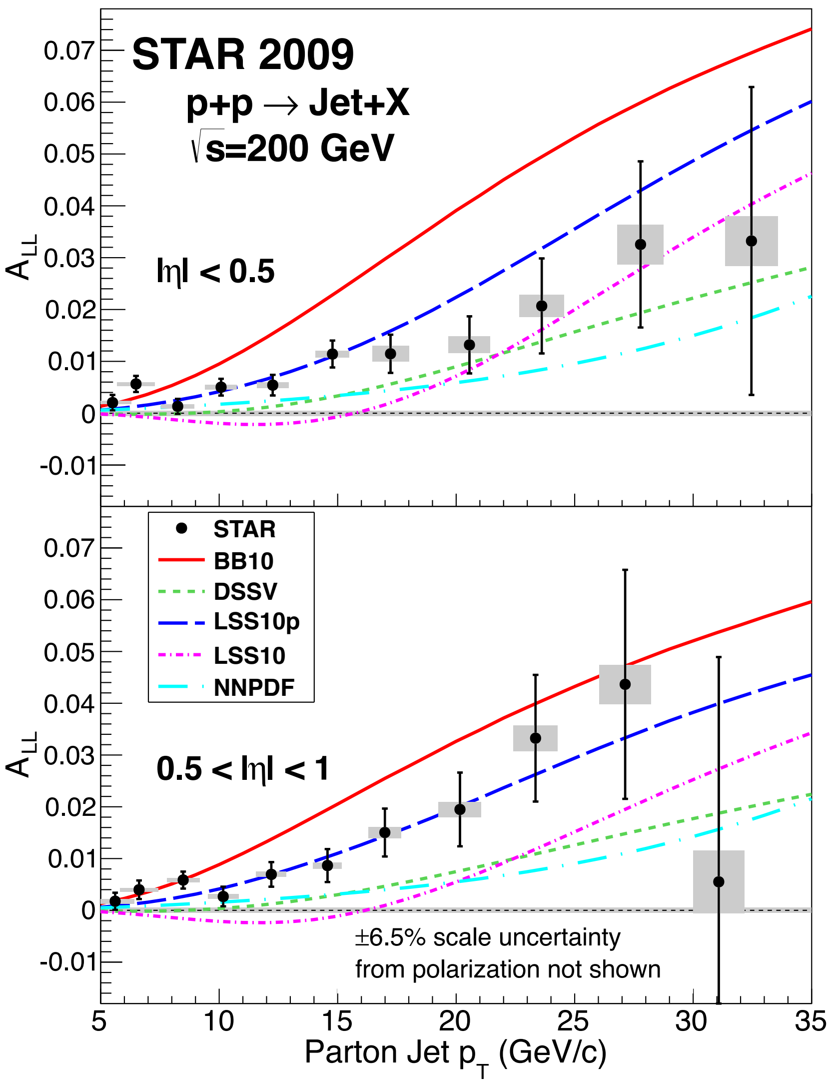
CT10 scale uncertainties

CT10 pdf uncertainites



Results / Status - Gluon related studies

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

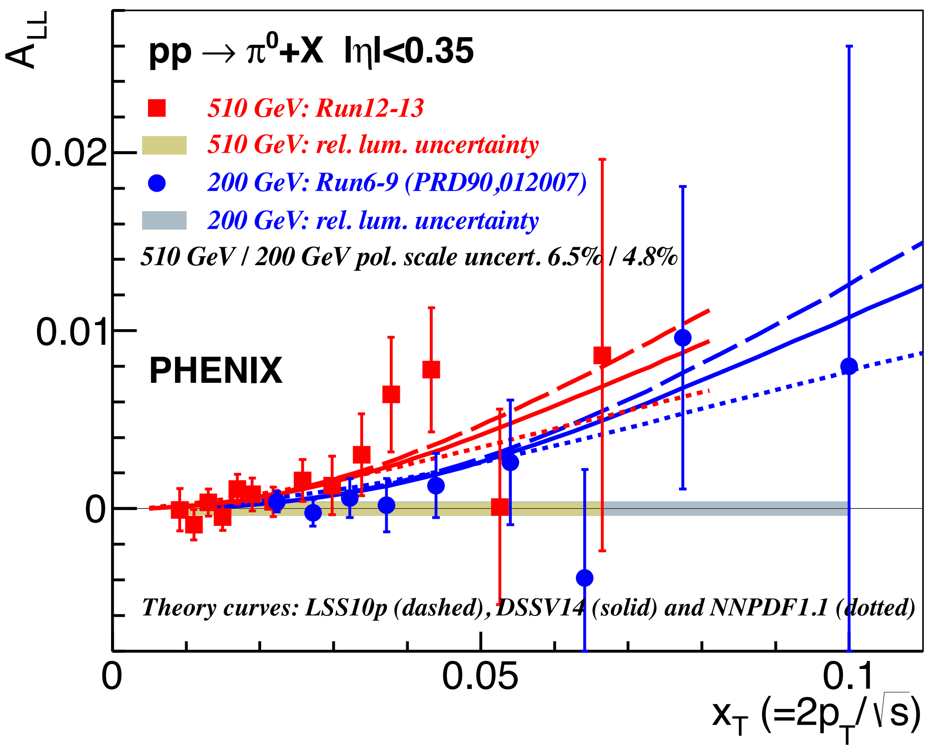


L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 115, (2015) 092002.

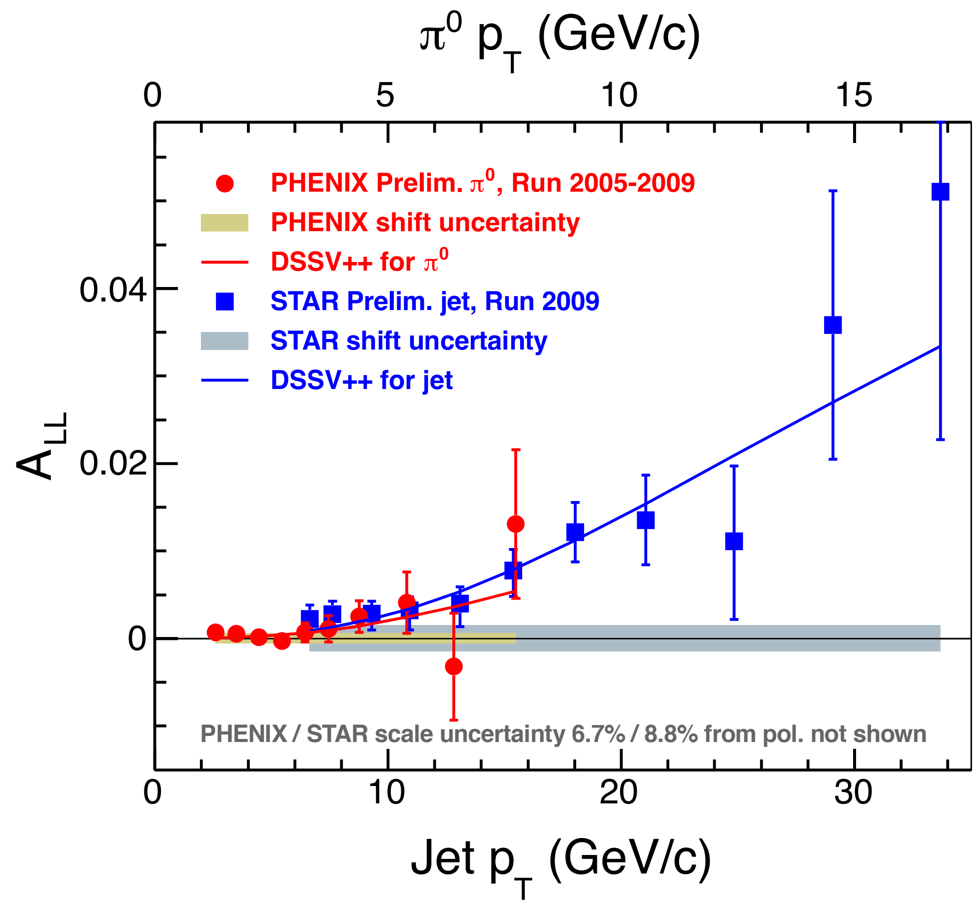
- Run 9 A_{LL} measurement between BB10 and DSSV / Clearly above zero at low p_T
- Larger asymmetry at low p_T suggests larger gluon polarization compared to DSSV
- With global analysis, A_{LL} jet result provides evidence for positive gluon polarization for $x > 0.05$

Results / Status - Gluon related studies

- PHENIX: Mid-rapidity neutral pion A_{LL} measurement



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



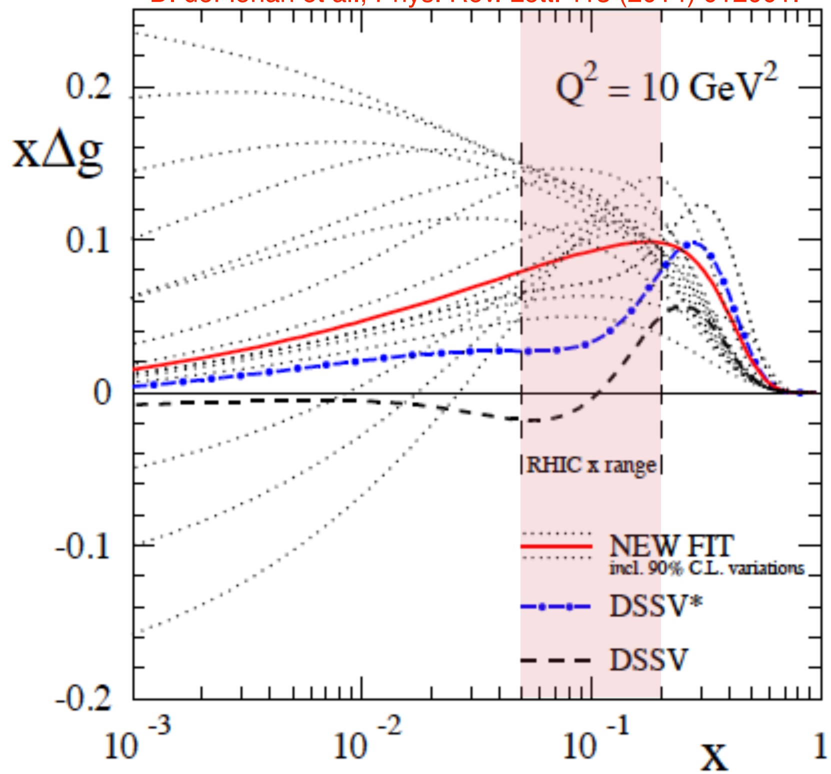
- Data are well described by NLO pQCD calculations
- New PHENIX Run 13 results at 510GeV
- Consistency between PHENIX and STAR results!

Results / Status - Gluon polarization program

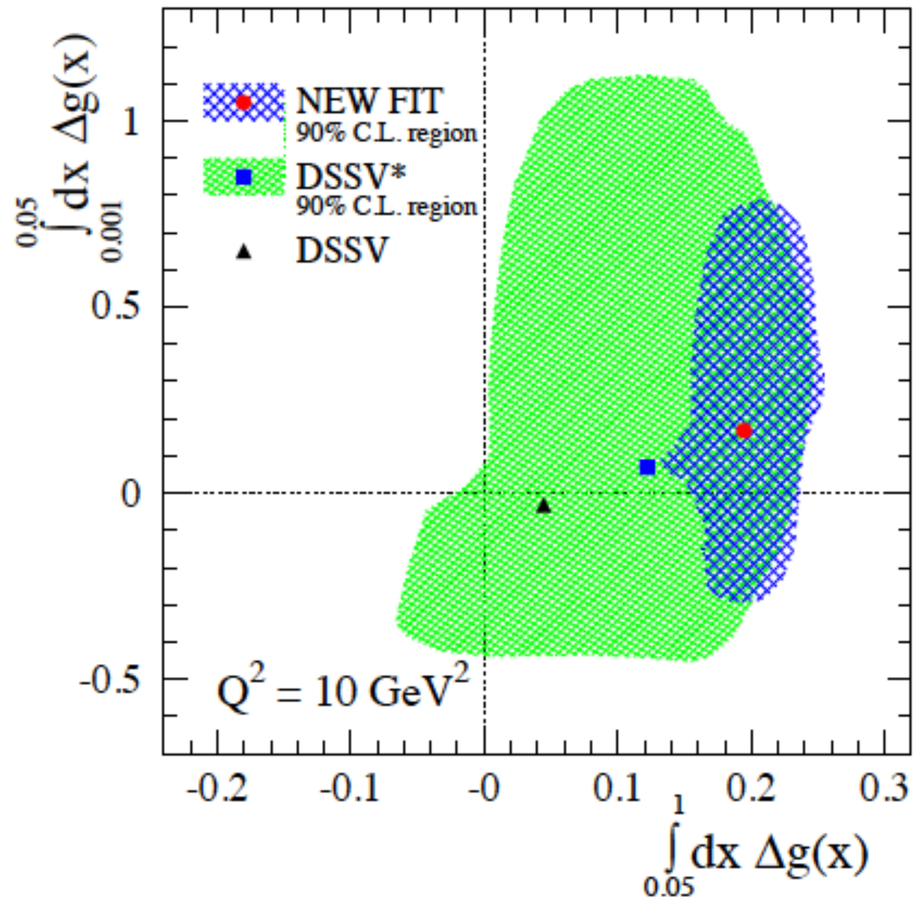
- Impact on Δg from RHIC data

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

Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.



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



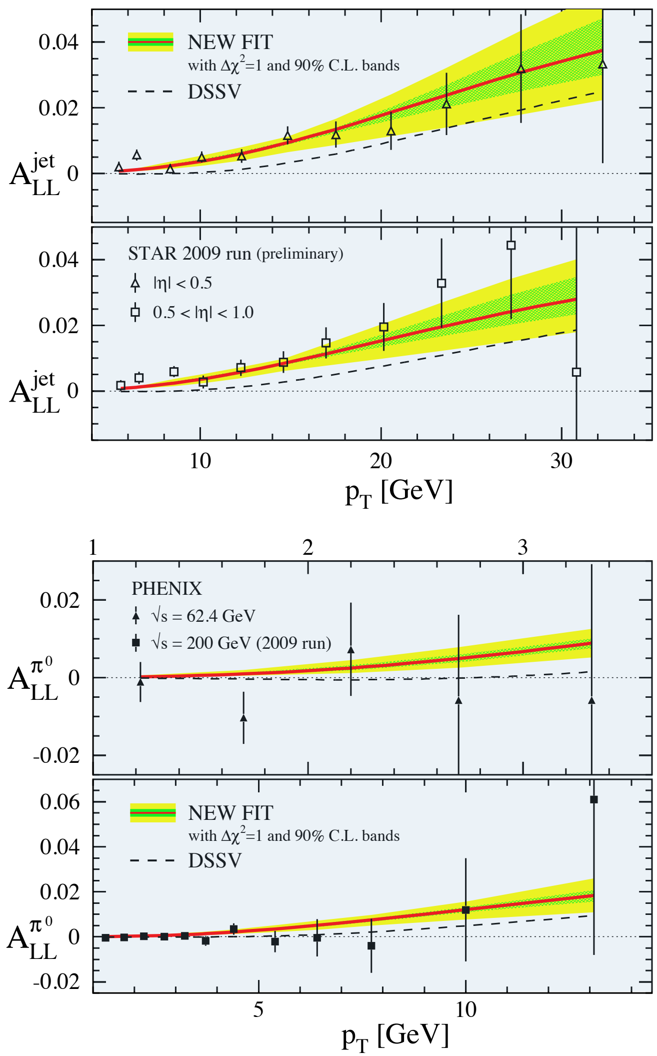
- DSSV: Original global analysis incl. first RHIC results (Run 5/6)
- DSSV*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates
- DSSV - NEW FIT: Strong impact on Δg(x) with RHIC run 9 results: $0.20^{+0.06}_{-0.07}$ 90% C.L. for $0.05 < x$
- Similar conclusion by independent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

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

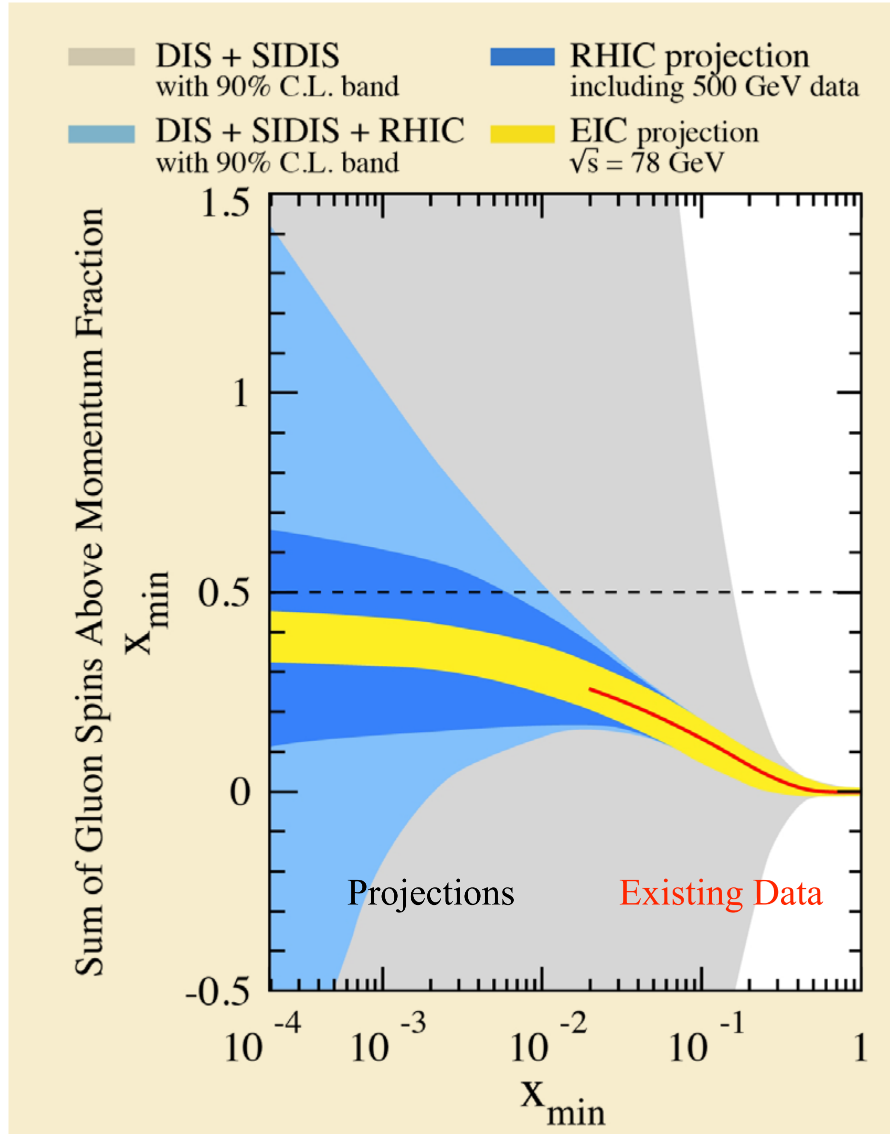
E. R. Nocera et al., Nucl. Phys. B887 (2014) 276.

Results / Status - Gluon related studies

- Impact on Δg from RHIC data

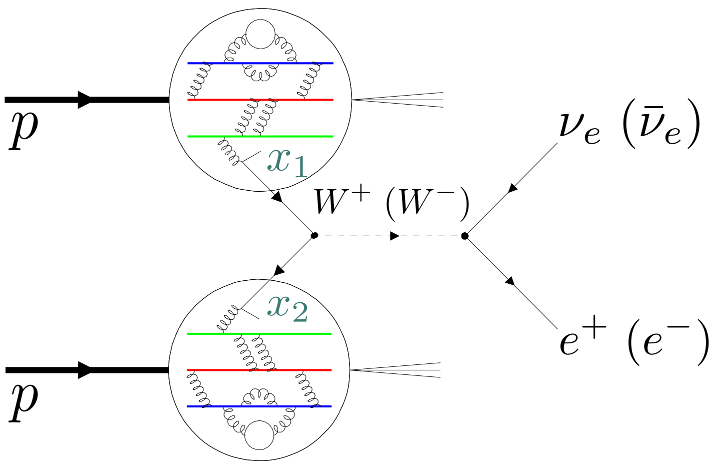


- Important constraint from 500GeV and forward rapidity measurements at RHIC



Results / Status - q / qbar related studies

- Probing the quark flavor structure: W boson production (1)



$$y_l = y_W + \underbrace{\frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*}}_{y_l^*}$$

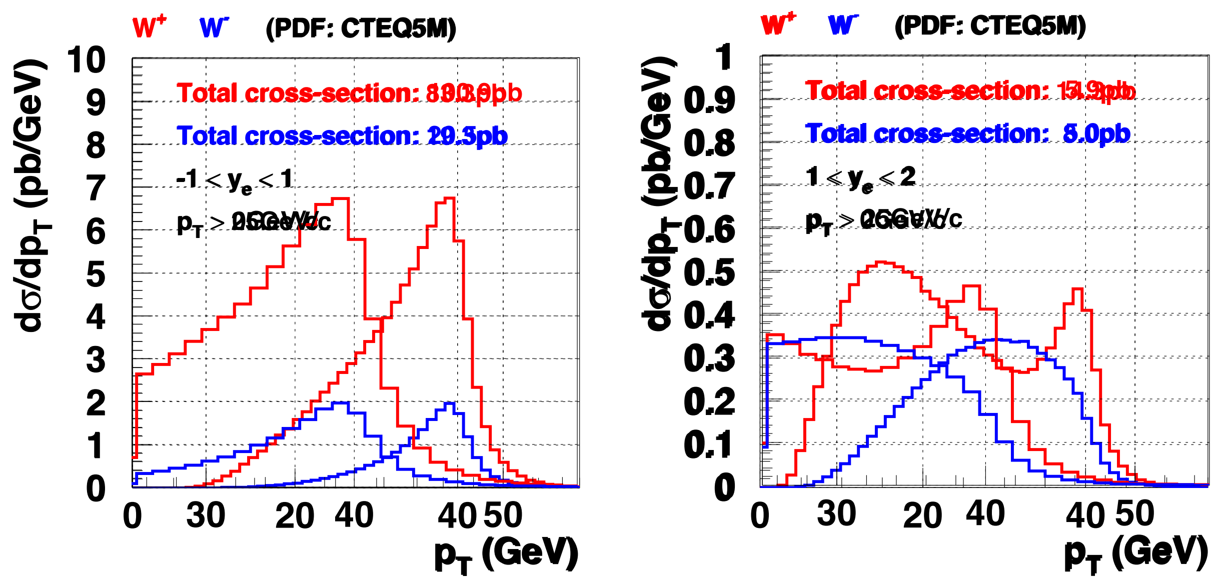
$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}$$

$$x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

$$p_T = p_T^* = \frac{M_W}{2}\sin\theta^*$$

$$\frac{M_W}{\sqrt{s}} = 0.16$$

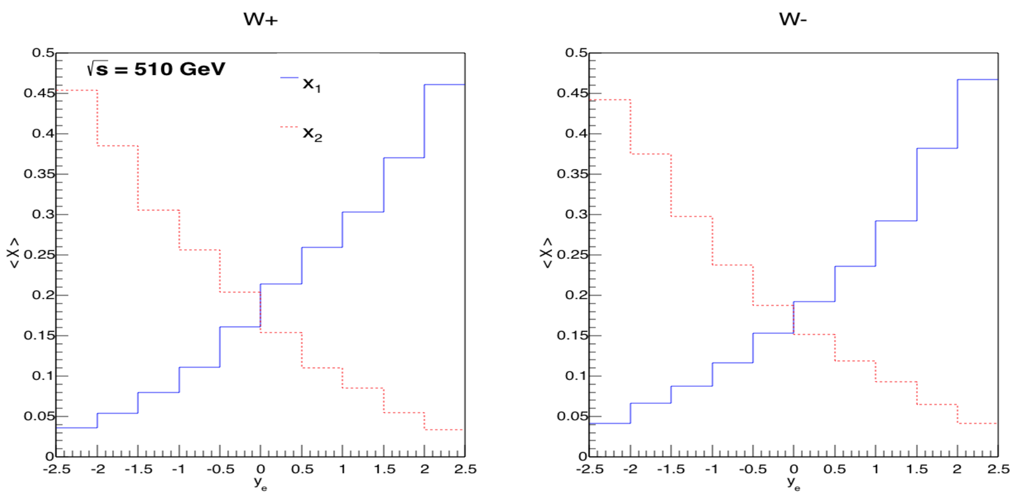
- Key signature: High p_T lepton (e^-/e^+)(Max. $M_W/2$) - Selection of W^+/W^- : Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination

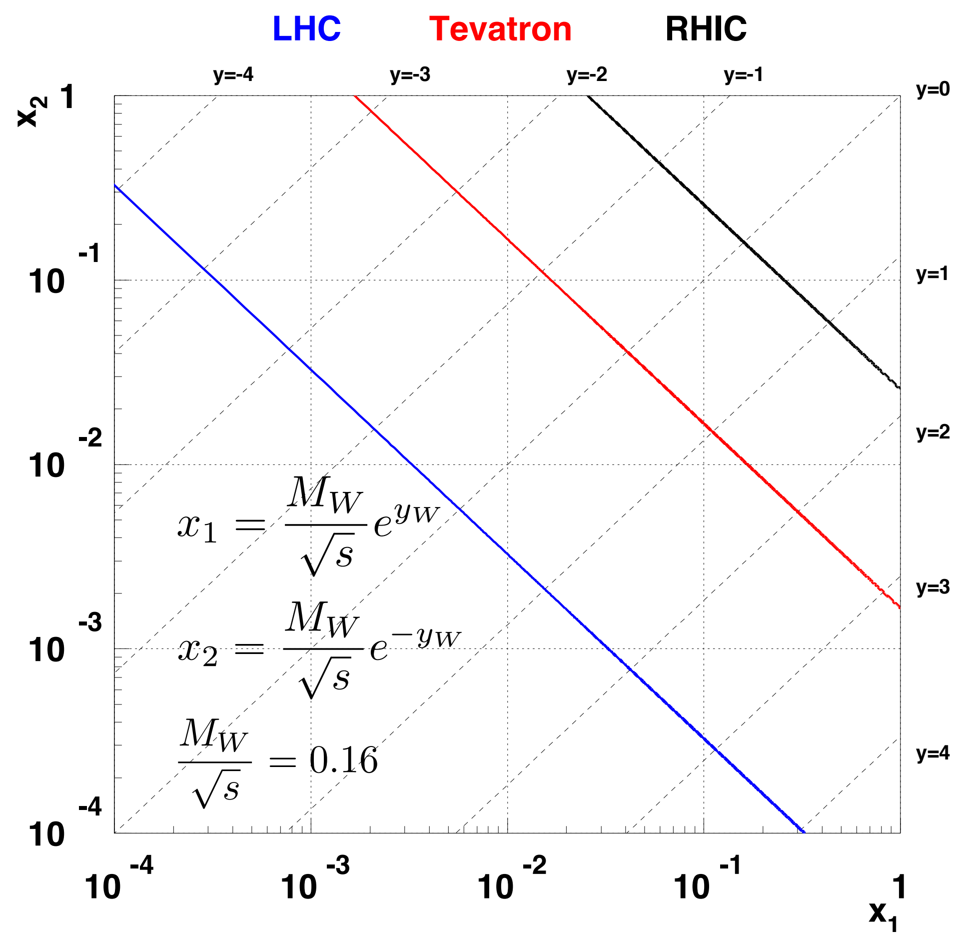


Total ($\sqrt{s}$=500GeV) $\sigma(W^+)$=135pb and $\sigma(W^-)$=42pb

Results / Status - q / qbar related studies

- Probing the quark flavor structure: W boson production (2)





$e^{+/-}$ pseudo-rapidity

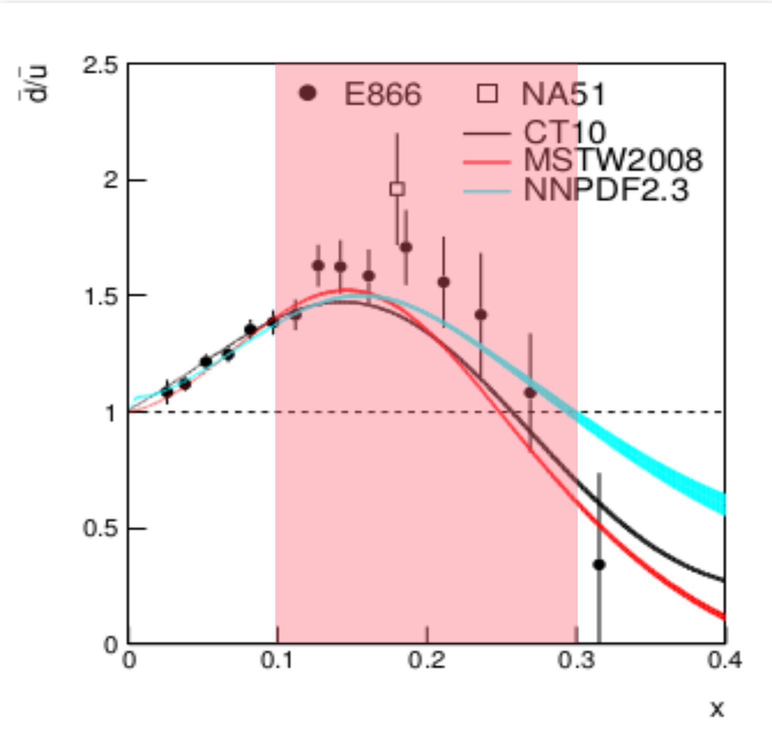
- Approximate kinematic range at RHIC:

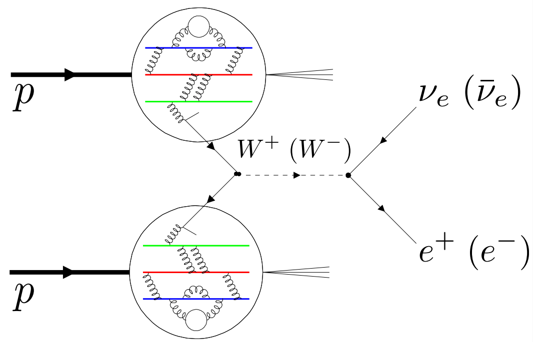
  $0.06 < x < 0.4$ for $-2 < \eta < 2$

- Measurement at LHC in high-x range would require very forward measurements

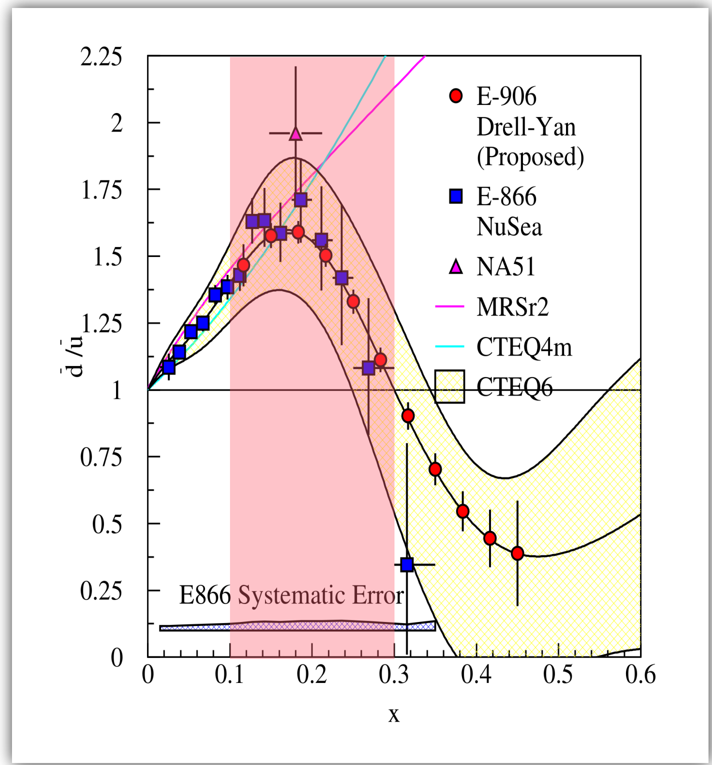
Results / Status - q / qbar related studies

- Probing dbar / ubar ratio ar RHIC: QCD sea





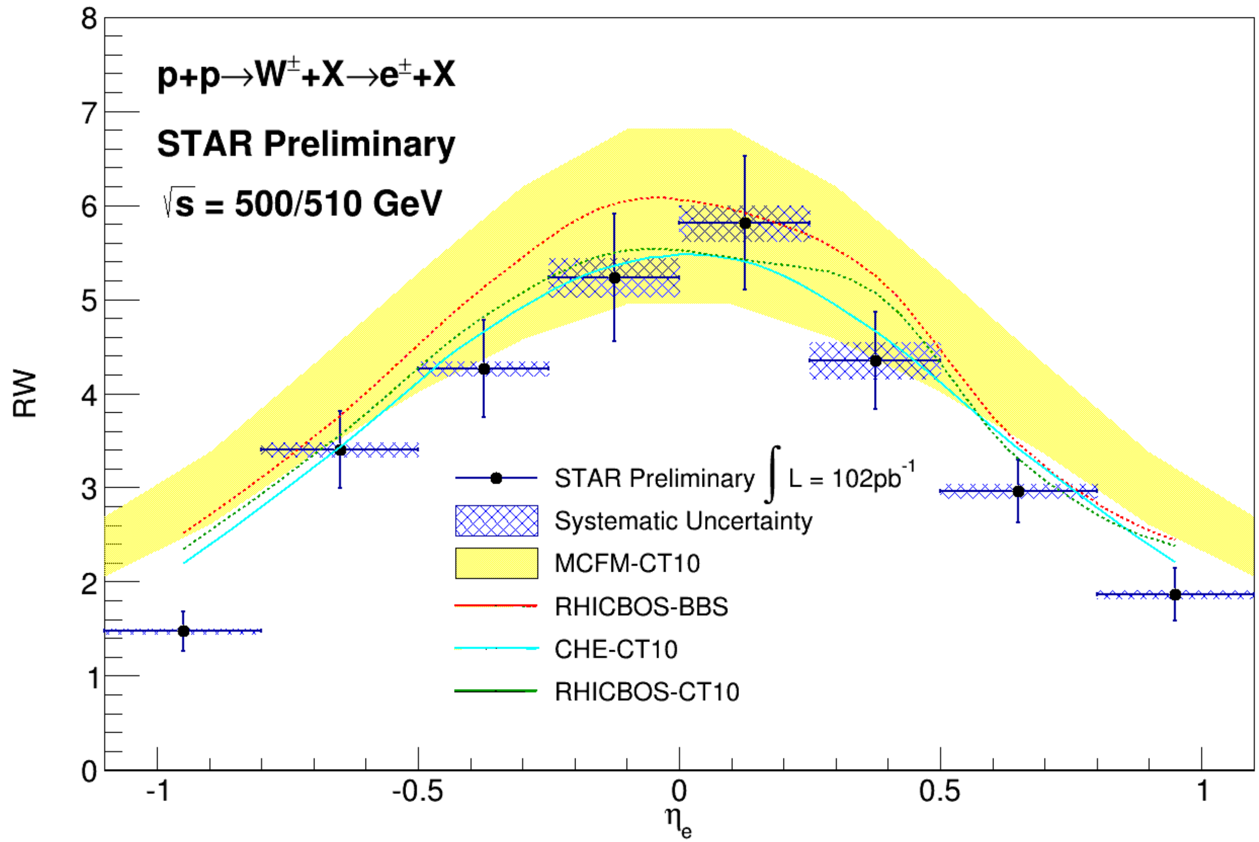
$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$



- 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

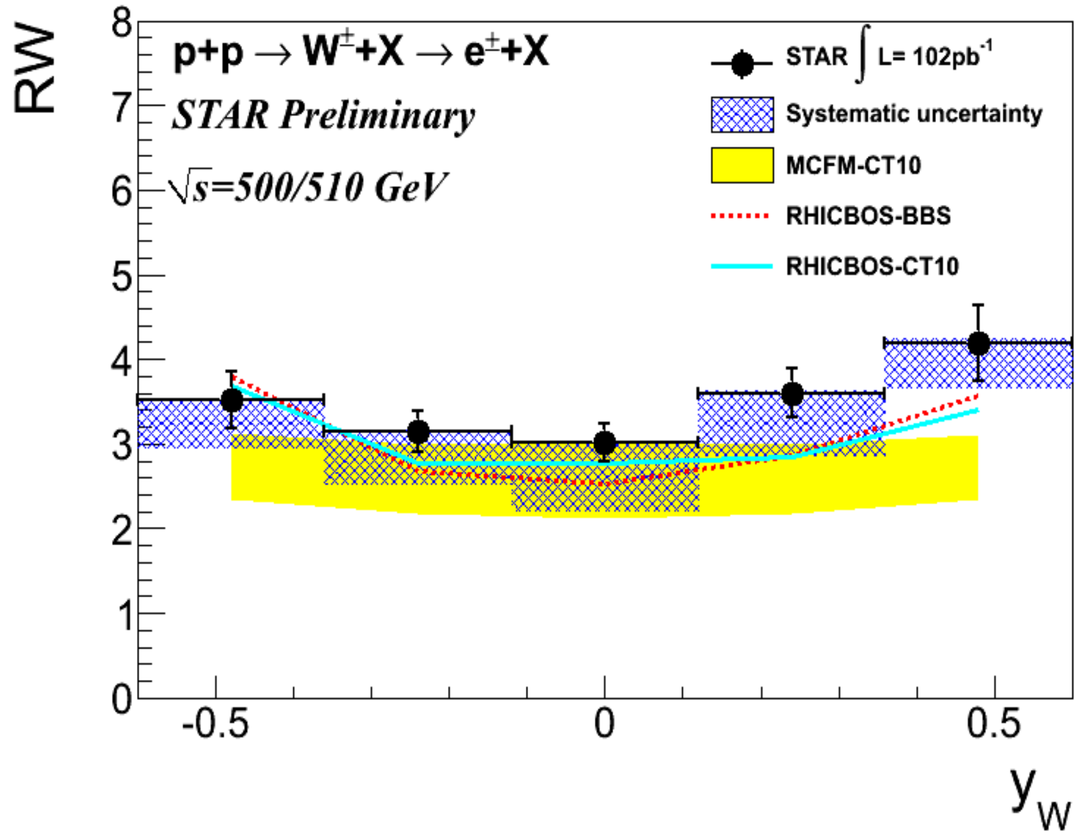
- W cross-section ratio measurements



- 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}

Results / Status - q / qbar related studies

- W cross-section ratio measurements

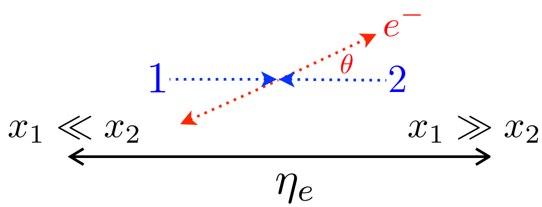


- W boson kinematics can be determined by reconstructing the W kinematics via its recoil
- Combination of data/MC simulations allows W boson rapidity reconstruction
- Critical for transverse single-spin asymmetry result of W production probing Sivers sign change

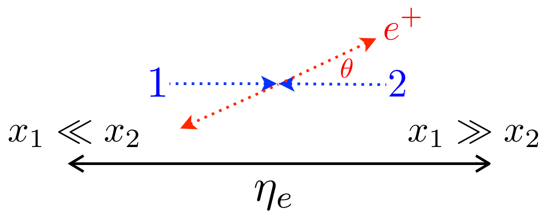
Results / Status - q / qbar related studies

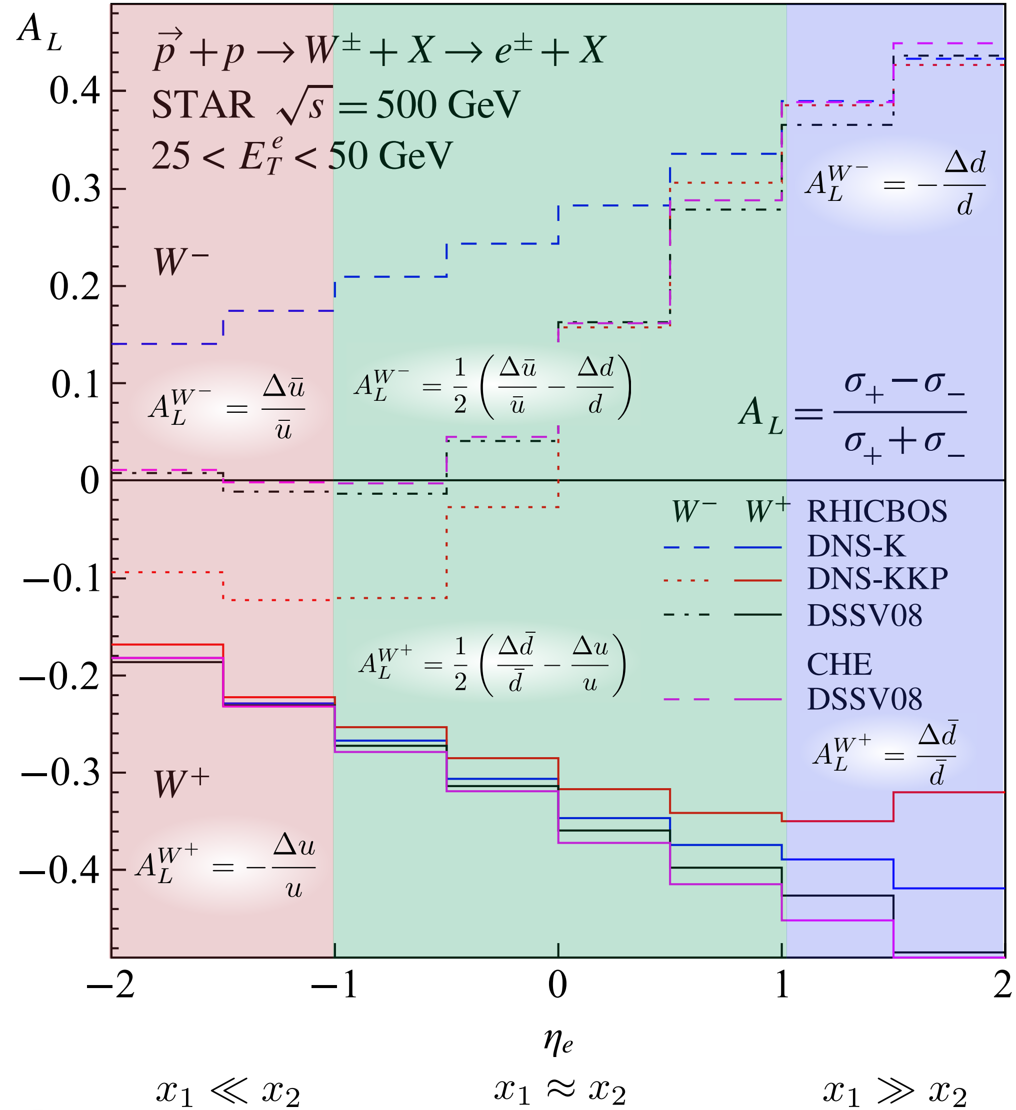
- Probing the quark flavor structure: W boson production

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



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

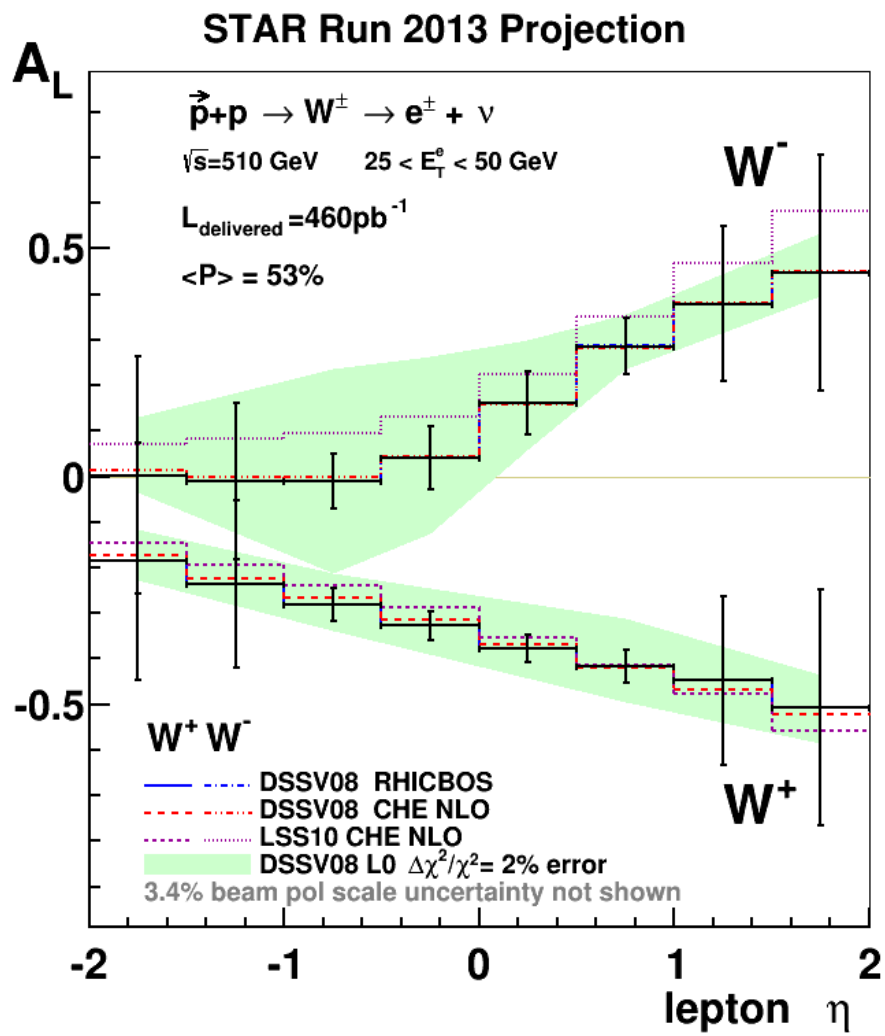




$\sqrt{s} = 500\,GeV$

Results / Status - q / qbar related studies

- STAR W A_L results / projections
  - 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
  - $\Rightarrow$ STAR Forward GEM Tracker ($1<|\eta_e|<2$)



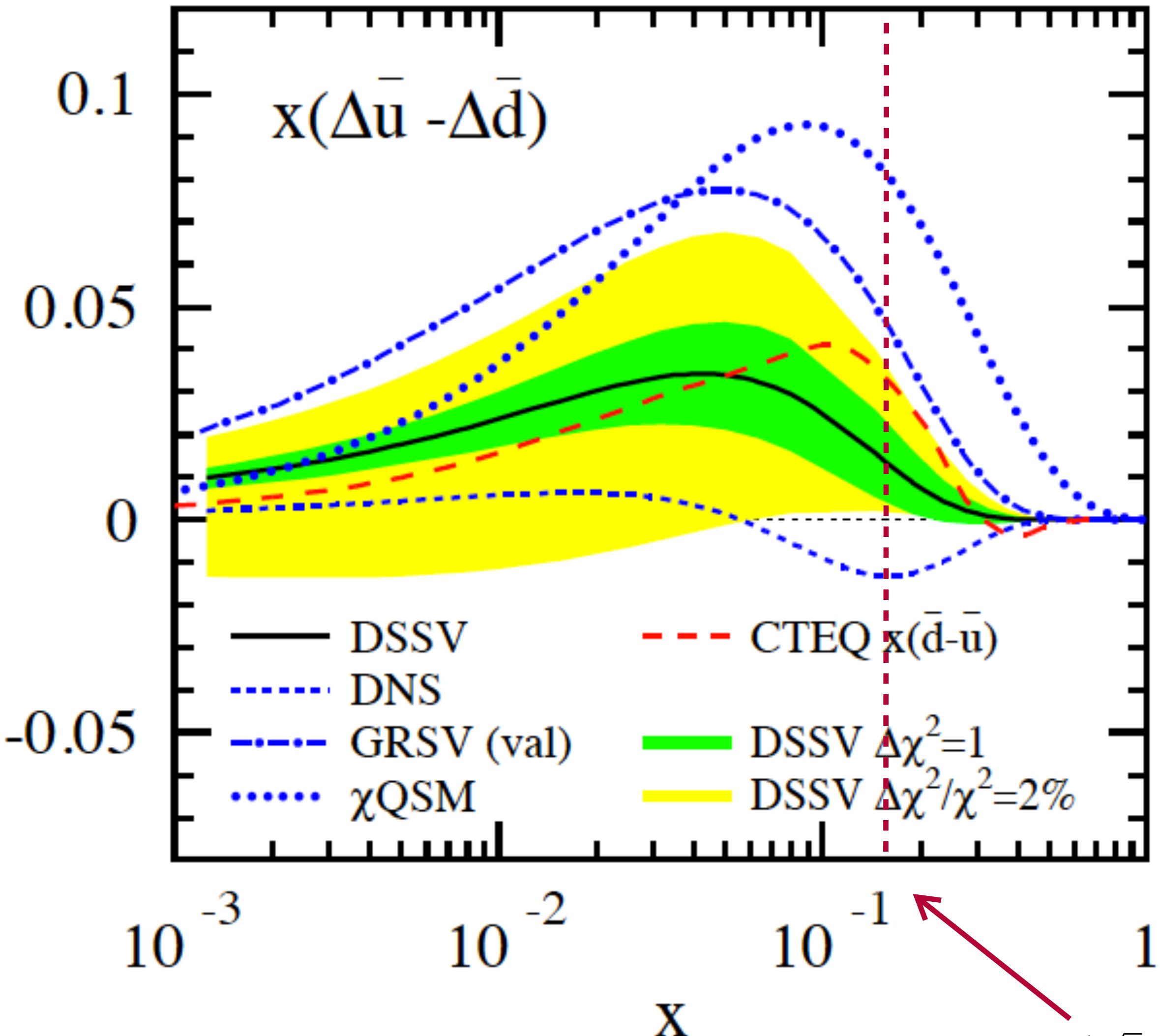
L. Adamczyk et al. (STAR Collaboration), arXiv:1404.6880

Results / Status - q / qbar related studies

- Impact of new DSSV global fit result

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

RHIC Spin Collaboration (2012)



$M_W/\sqrt{s} = 0.16$

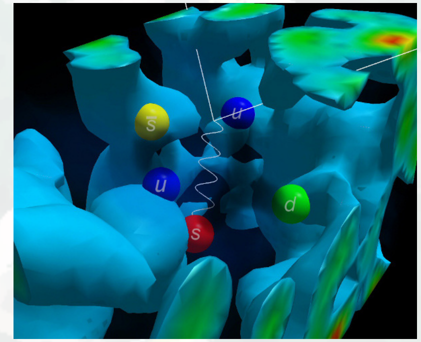
- From recent DSSV++ result incl. STAR A_L data:

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

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

Summary / Outlook

- Gluon polarization program
  - Several final states (Hadron / Jet) have been measured all pointing to the same conclusion that the gluon polarization is small consistent with COMPASS findings
  - 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 constrain for unpol. gluon at high x



- W boson program
  - Mid-rapidity: New W^- results suggest large anti-u quark polarization along with broken QCD sea
  - Strong physics case of unpolarized dbar/ubar probe using W production
  - Backward/Forward rapidity: Upgrade of PHENIX forward muon detector (Muon Trigger) and STAR FGT (Forward GEM Tracker)
- Run 13 / 15 and future
  - Run 13: Long. 510GeV Run 13 (~300pb^{-1} rec.): W (Anti-quarks) and Jet production (Gluons)
  - Run 15: 200GeV (Run 15) with long. / trans. pol. p-p running and for the first time polarized p-A running
  - Future (Run 17 and beyond): Additional long 500GeV prod. runs Drell-Yan (Run 17) and Forward Di-Jets