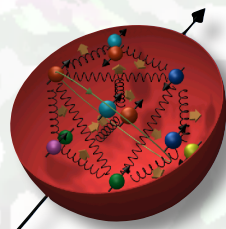


Recent STAR Jet results of the high-energy spin physics program at RHIC at BNL

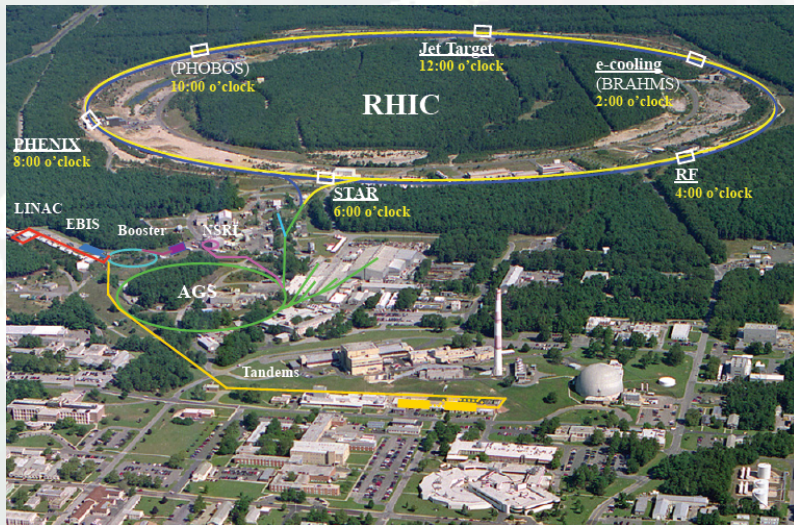
Daniel Olivitt & Bernd Surrow



(On behalf of the STAR Collaboration)



Outline

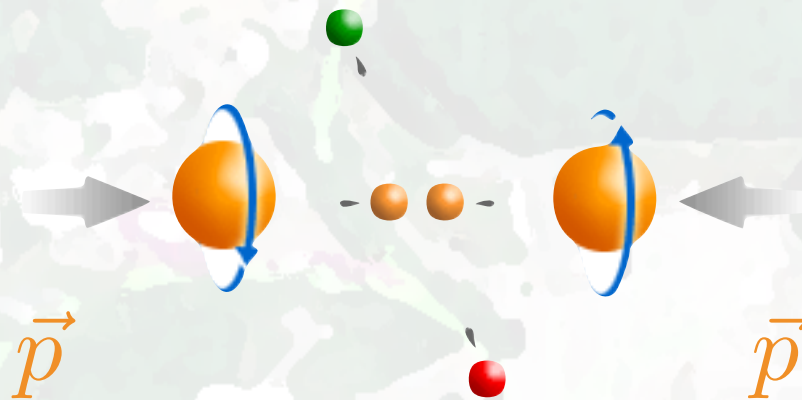


Results / Status: Jet production

Gluon related studies

- Cross-section measurements: g
- Asymmetry measurements: Δg

Experimental aspects: RHIC / STAR

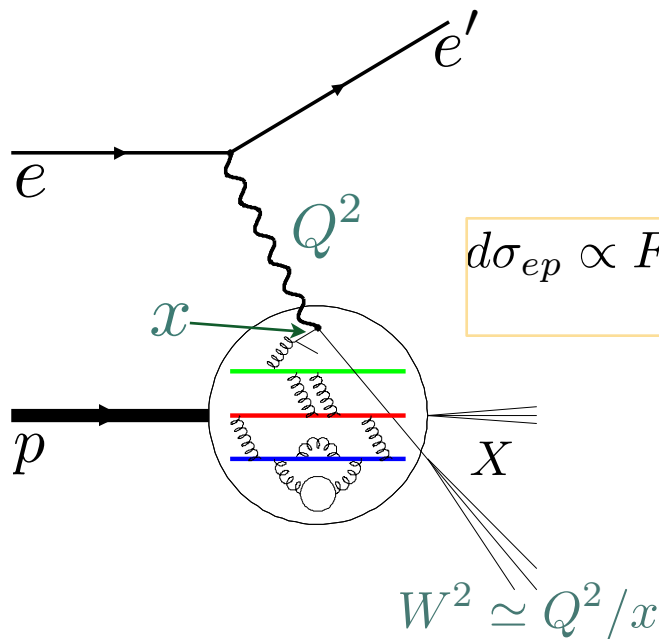


Theoretical foundation

Summary and Outlook

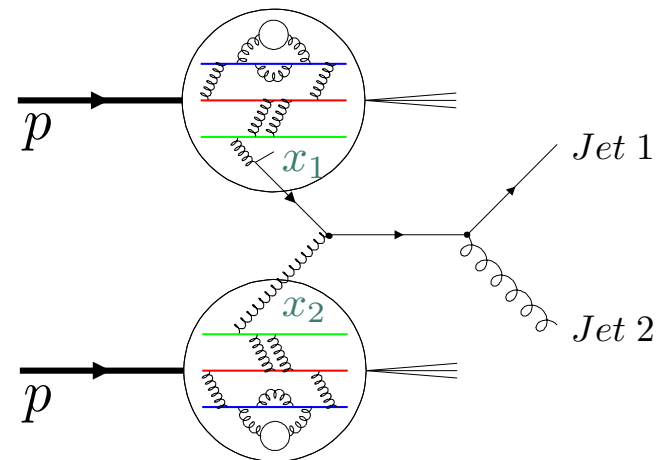
Theoretical foundation

□ Probing gluons 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

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

Spin contribution

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

Theoretical foundation

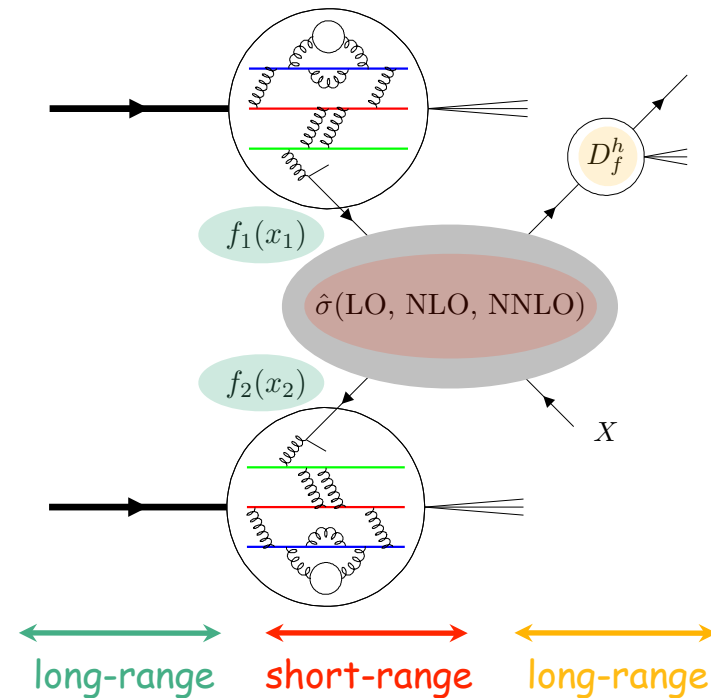
□ Proton spin structure using high-energy polarized p+p collisions: Helicity

- Observable: **Gluon polarization (Jet/Hadron production)**

- Double longitudinal single-spin asymmetry A_{LL}

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

Colliding beam helicities!

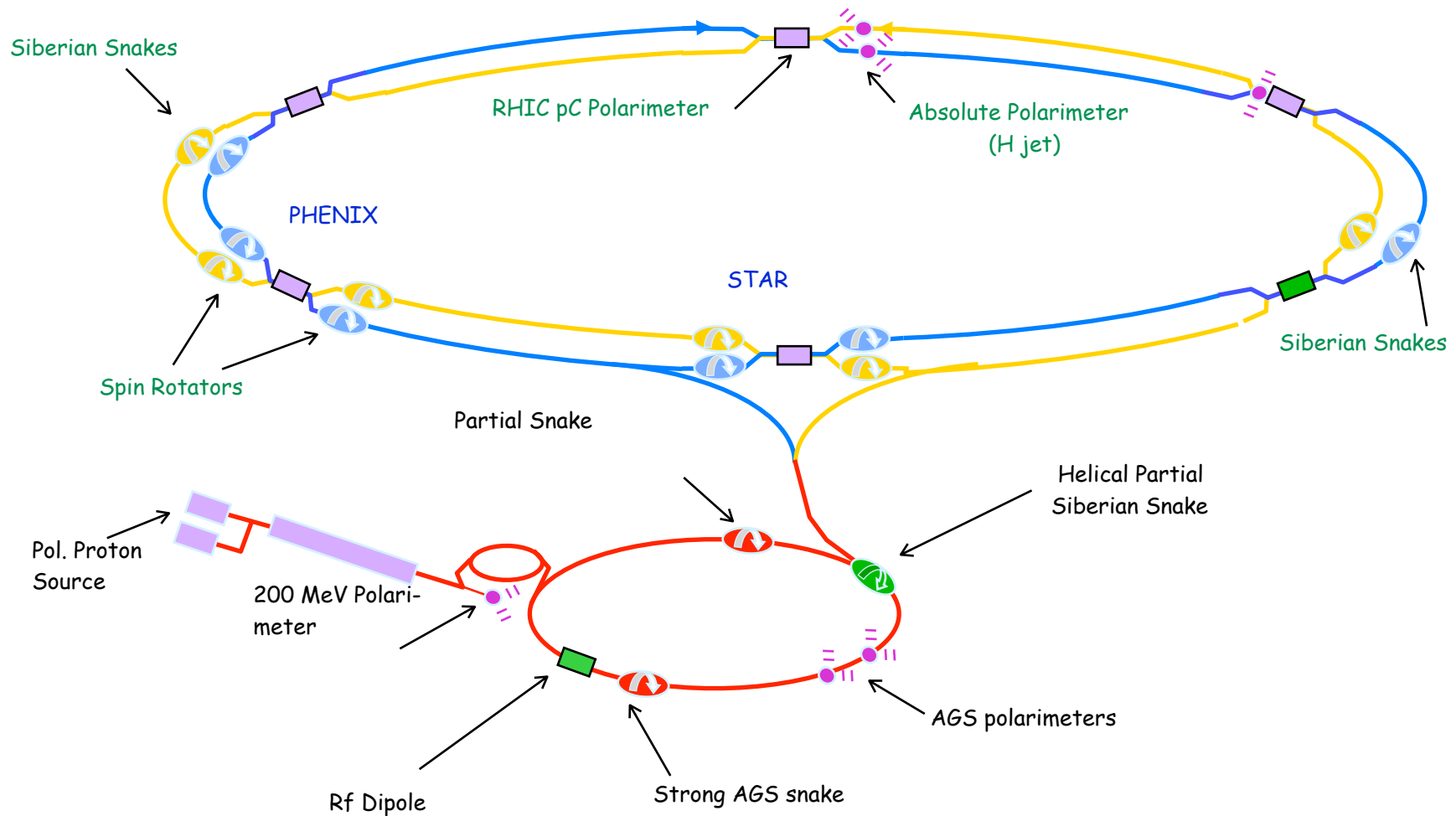


$$= \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

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

Experimental aspects - RHIC

- The world's first polarized proton+proton collider



Experimental aspects - RHIC

□ Polarized p+p collisions

- Production runs at

$\sqrt{s}=200 / 500 / 510 \text{ GeV}$

(long. polarization) in

2009, 2012, 2013 and

2015: **Jet and Hadron**

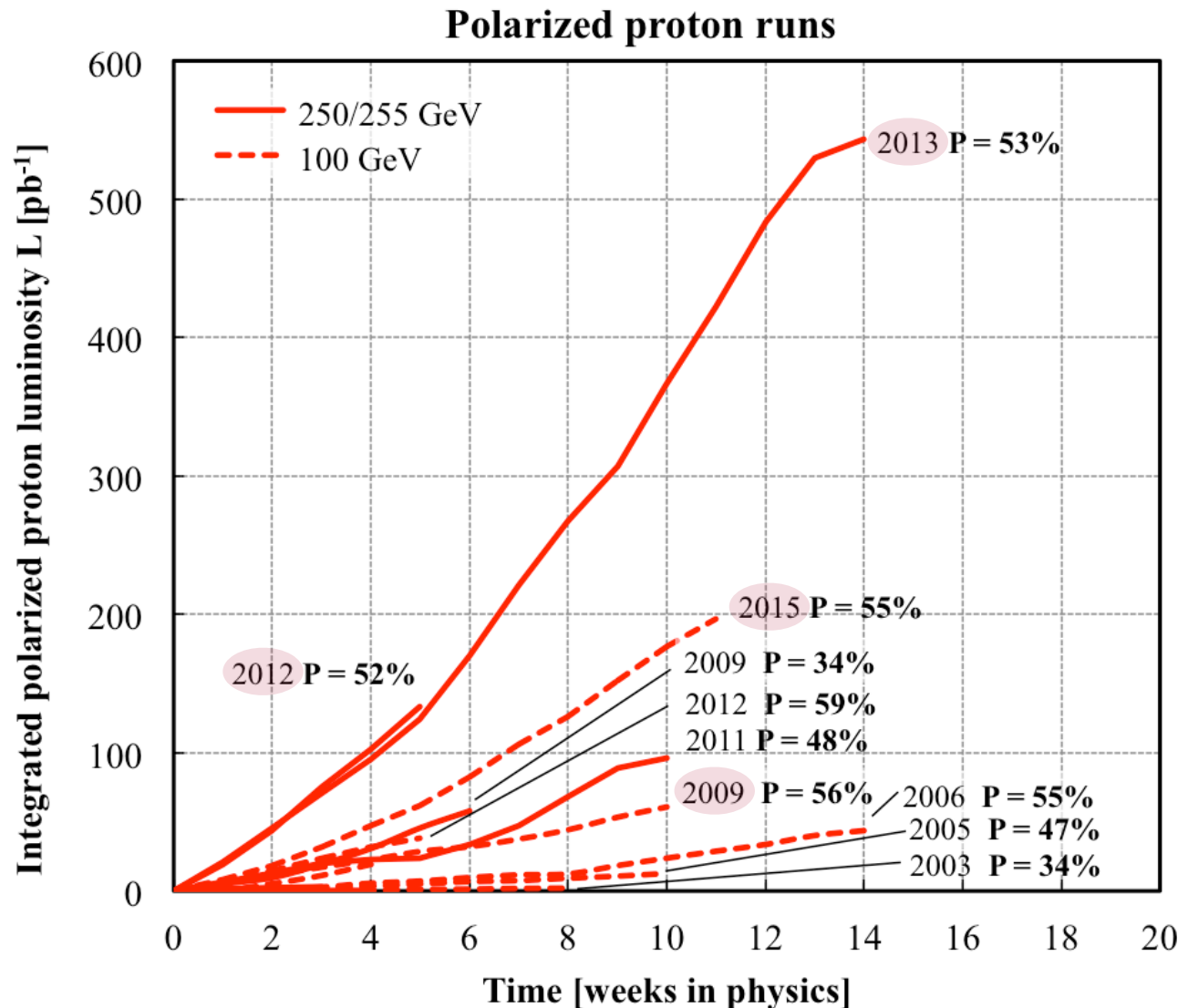
production (Gluon

related studies!)

- Jet results will be

shown from Run 9 and

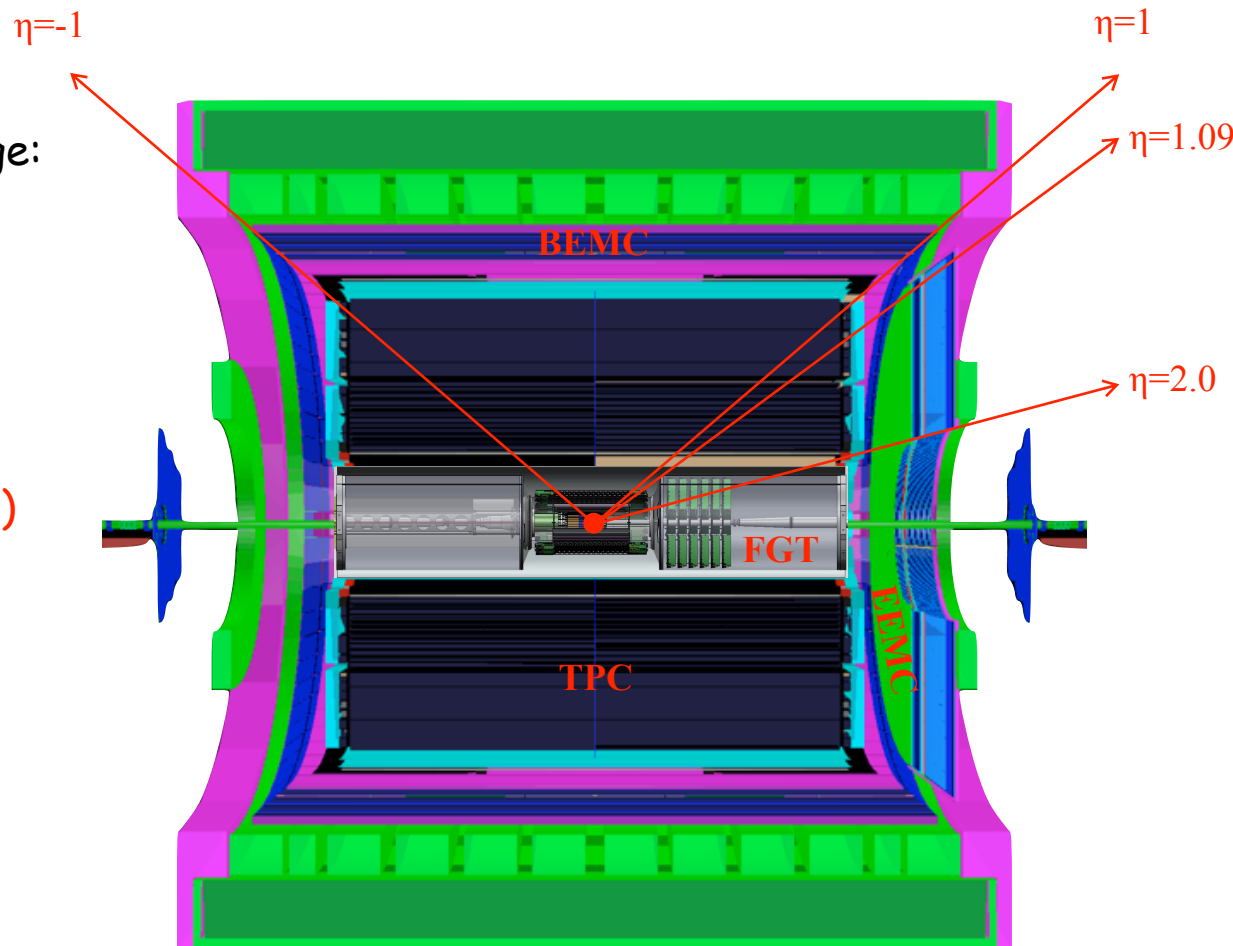
Run 12



Experimental aspects - STAR

□ Overview

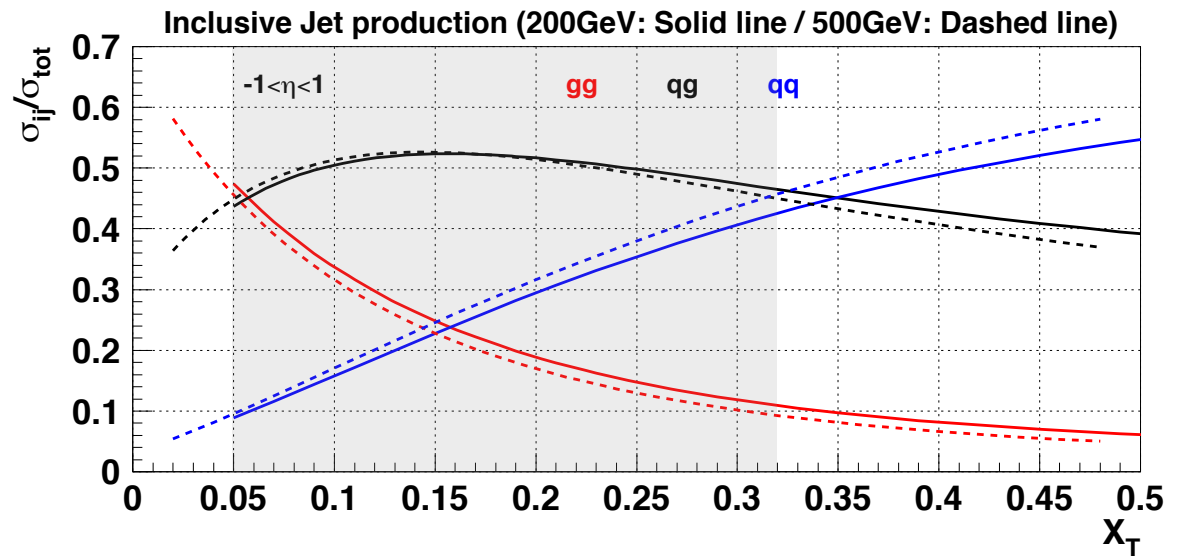
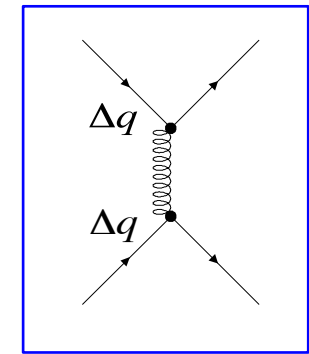
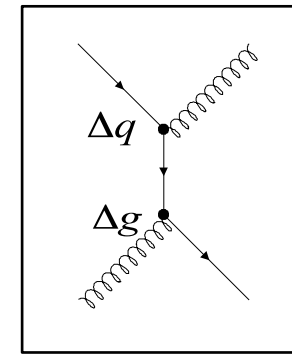
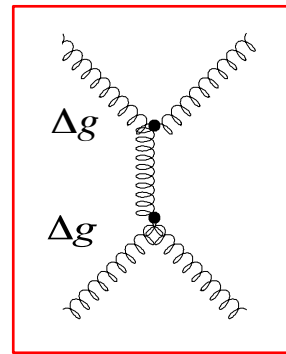
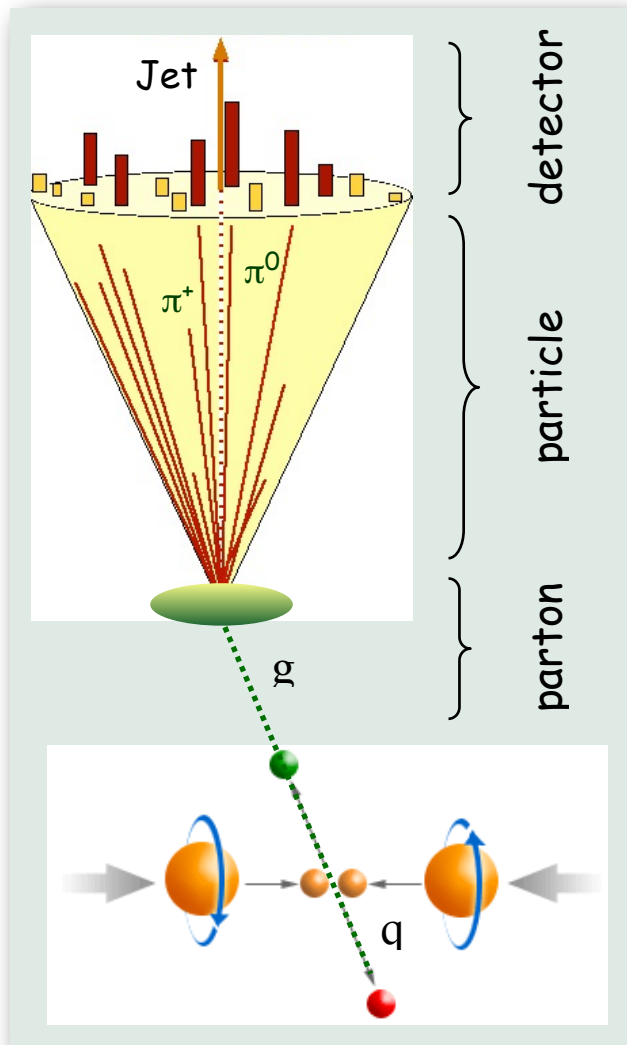
- Calorimetry system with 2π coverage:
BEMC ($-1 < \eta < 1$) and EEMC ($1 < \eta < 2$)
- TPC: Tracking and particle ID
($|\eta| < 1.3$)
- FGT: Forward GEM Tracker (Run 13)
($1 < \eta < 2$)
- ZDC: Relative
luminosity and local
polarimetry
- BBC: Relative
luminosity and
Minimum bias trigger



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

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

□ RHIC Gluon studies: Jet-type measurements



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

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

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

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

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

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

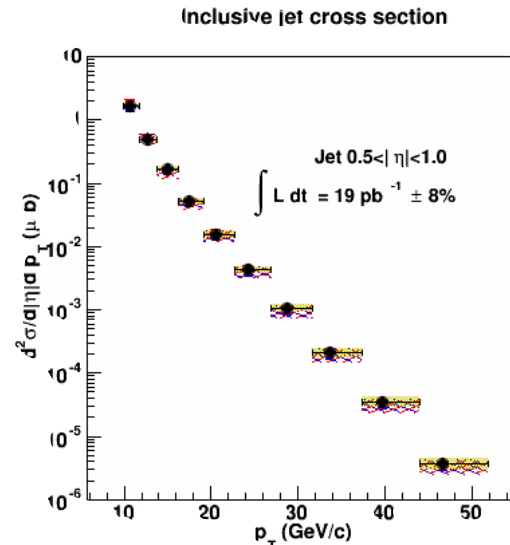
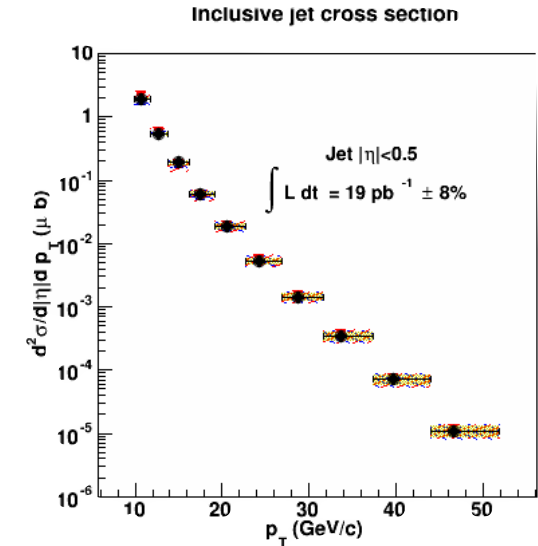
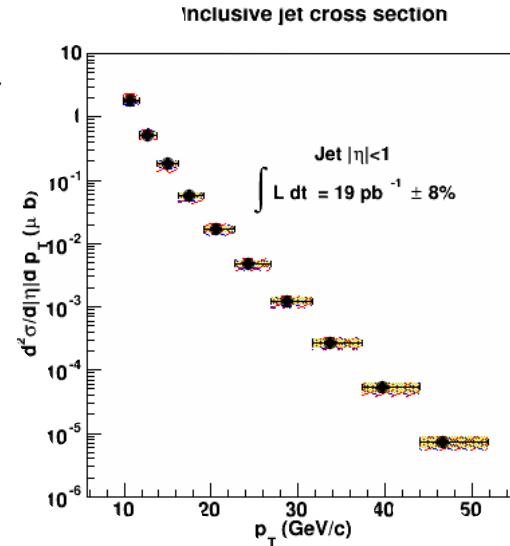
$$d = \min(\{D_{ij}, D_i\})$$

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

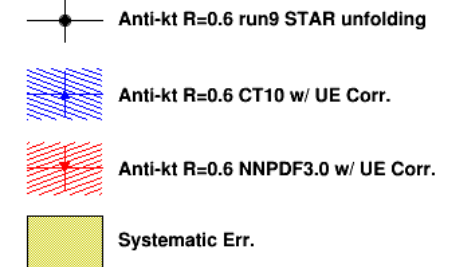
If $d = D_i$: Define jet i as final jet

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
 $\sqrt{s} = 200 \text{ GeV}$



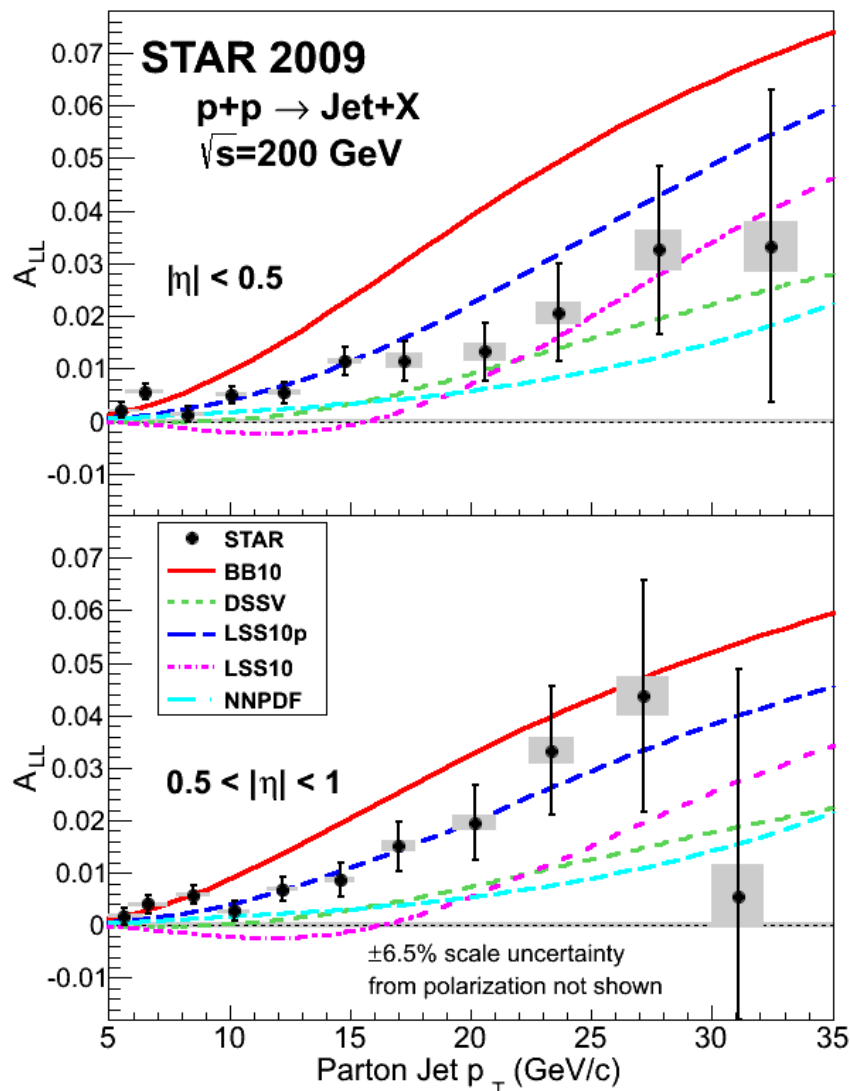
X. Li et al. (STAR Collaboration), DIS 2015.

Bernd Surrow

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

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

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

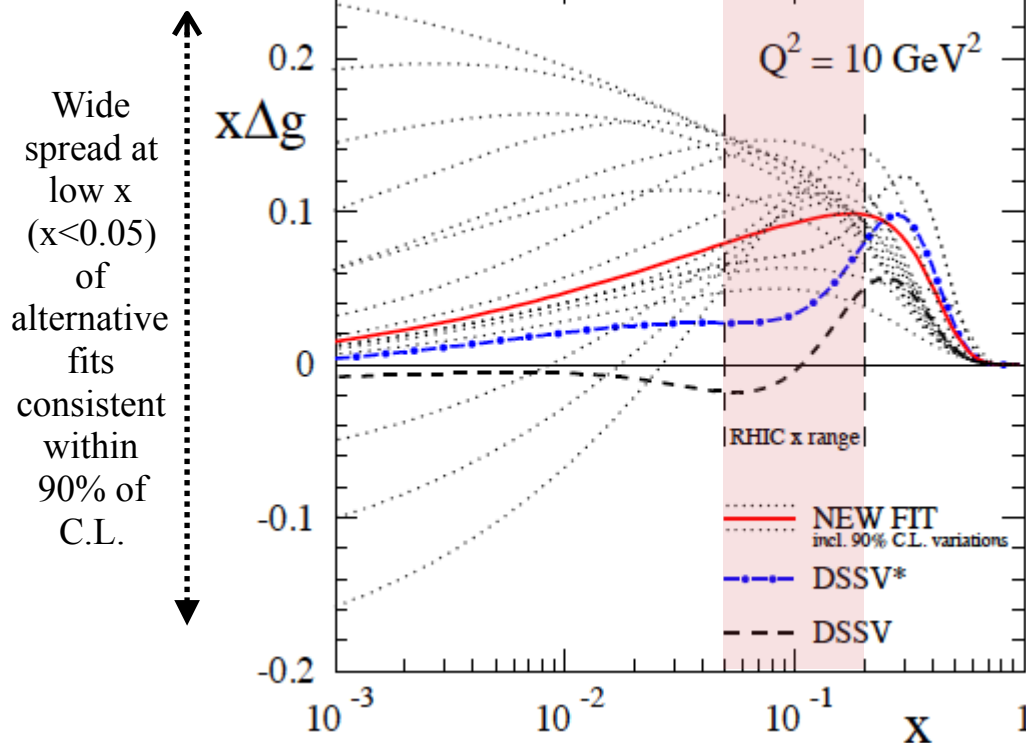


- Run 9 A_{LL} measurement between **BB10** and **DSSV** / Clearly **above** zero at low p_T
- Larger asymmetry at low p_T suggests larger gluon polarization compared to **DSSV**
- With global analysis, A_{LL} jet result provides evidence for positive gluon polarization for $x > 0.05$

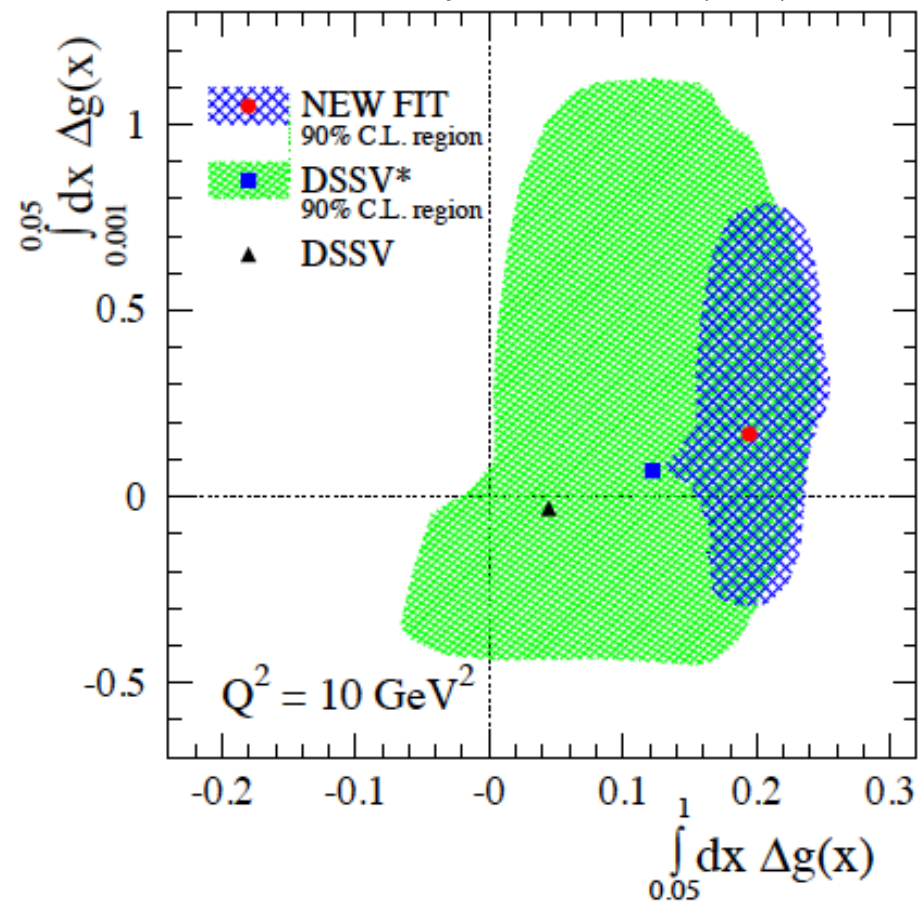
Results / Status - $g / \Delta g(x)$ related studies

Impact on Δg from RHIC data (RHIC Run 9)

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



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



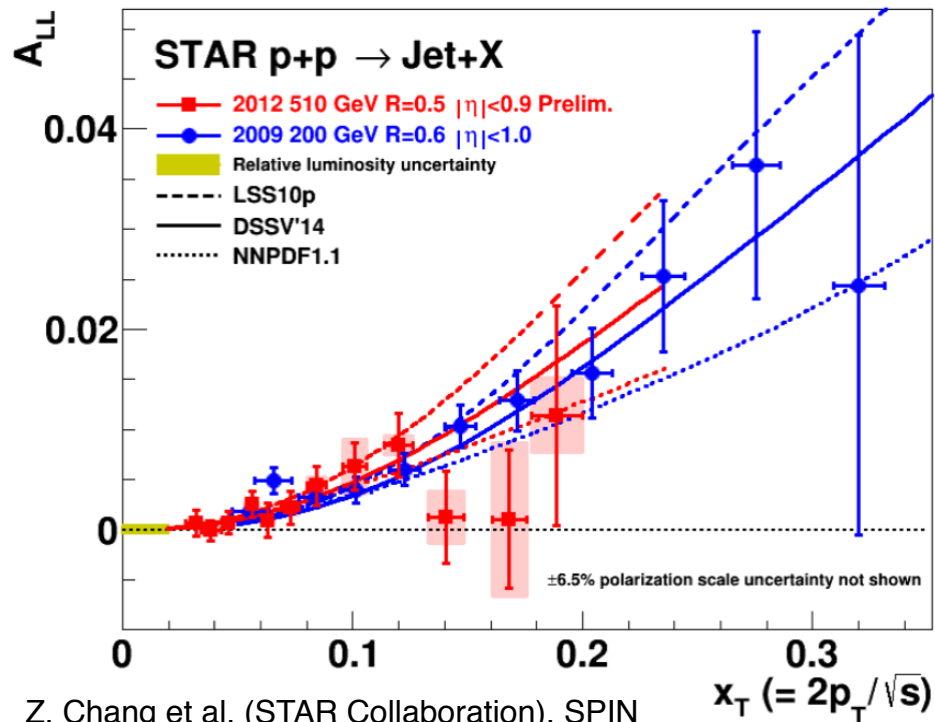
- DSSV: Original global analysis incl. first RHIC results (Run 5/6)
- DSSV*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates
- DSSV - NEW FIT: Strong impact on $\Delta g(x)$ with RHIC run 9 results: $0.20^{+0.06}_{-0.07}$ 90% C.L. for $0.05 < x$
- Similar conclusion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

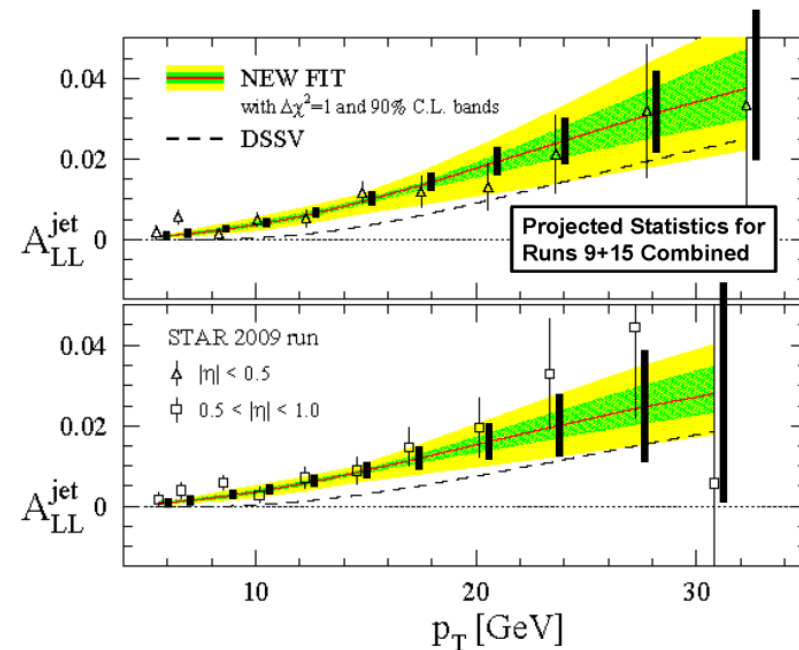
Results / Status - $g / \Delta g(x)$ related studies

□ STAR: Mid-rapidity Inclusive Jet A_{LL} measurement (Run 12) at 510GeV



Z. Chang et al. (STAR Collaboration), SPIN 2014. (Run 12 / 510GeV)

- Probing smaller x -values going from 200GeV to 510GeV in Run 12 and Run 13
- Preliminary results of A_{LL} at 510GeV (Run 12) well described by global fit results including Run 9 constraint
- Additional large data sample in Run 13 at 510GeV will reduce A_{LL} uncertainties further



- Additional data set at 200GeV taken in Run 15
- Projected statistical uncertainties of Run 9 and Run 15 combined at 200GeV in comparison to Run 9 uncertainties

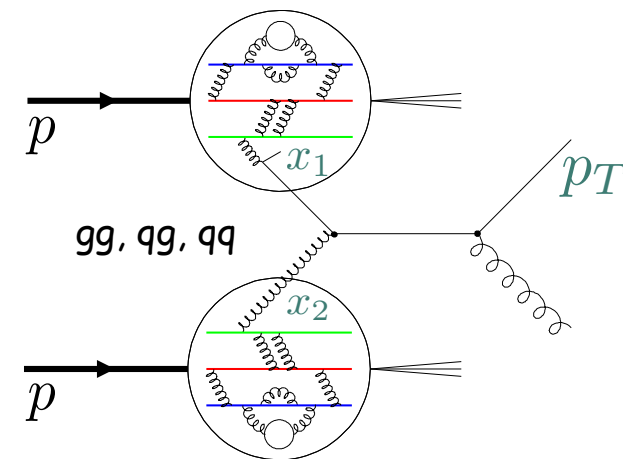
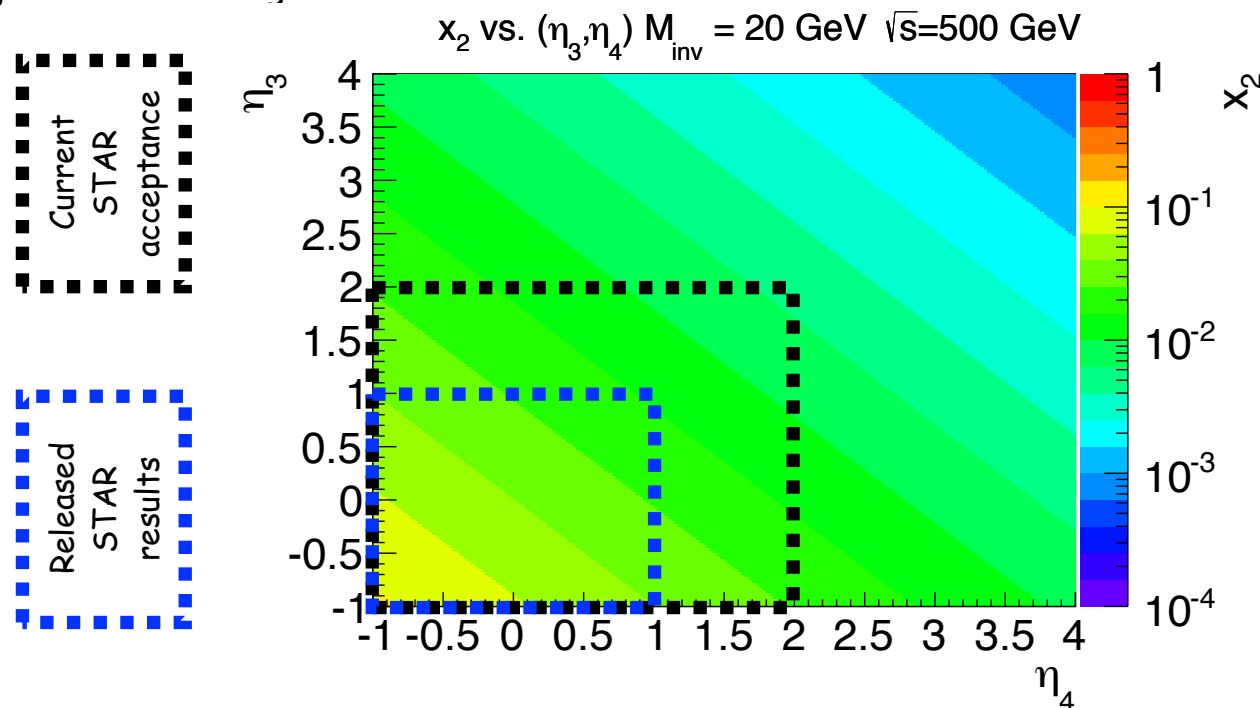
Results / Status - $g / \Delta g(x)$ related studies

□ RHIC Gluon polarization - Correlation Measurements

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

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

- Bjorken x-coverage:

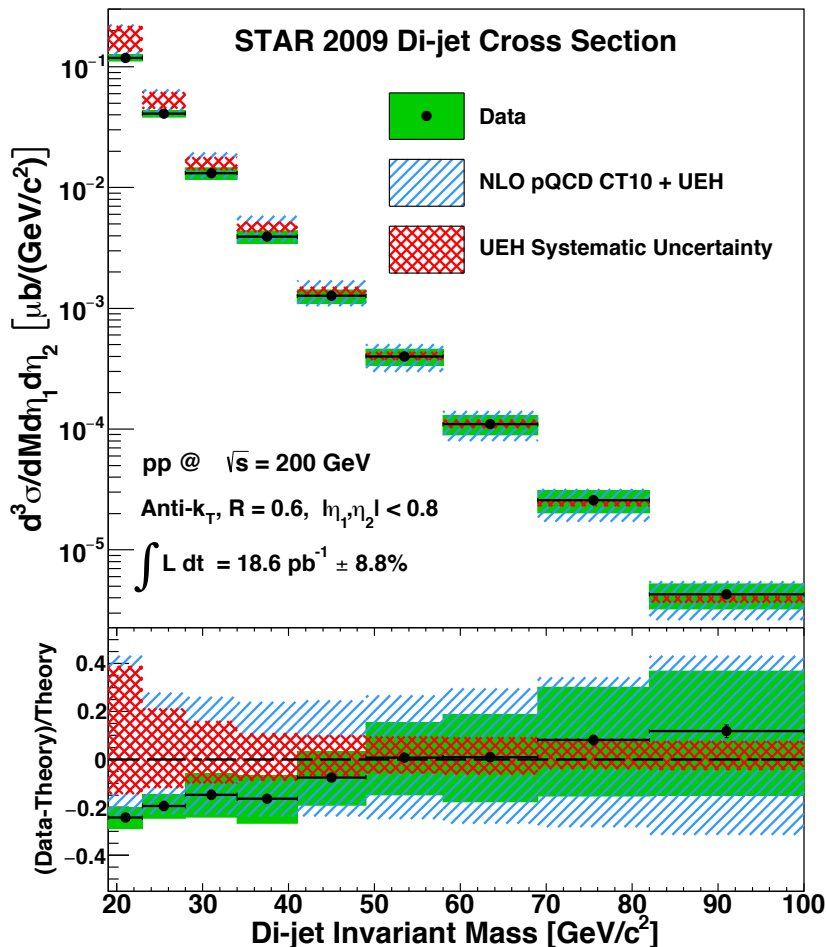


$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

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

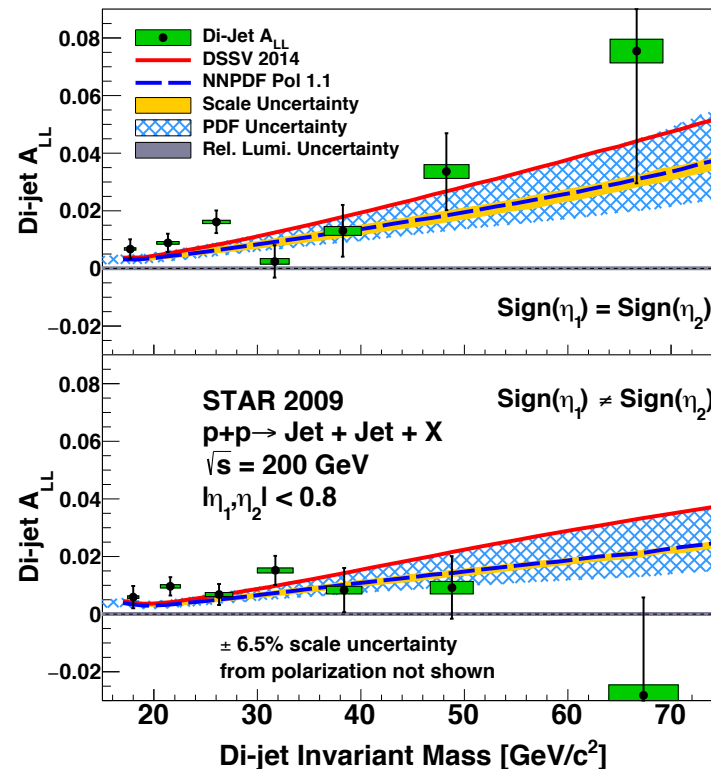
Results / Status - $g / \Delta g(x)$ related studies

- STAR: Mid-rapidity Di-Jet cross-section and A_{LL} measurement (Run 9) at 200GeV



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

L. Adamczyk et al. (STAR Collaboration), arXiv:1610.06616.
(Submitted for publication, PRD)



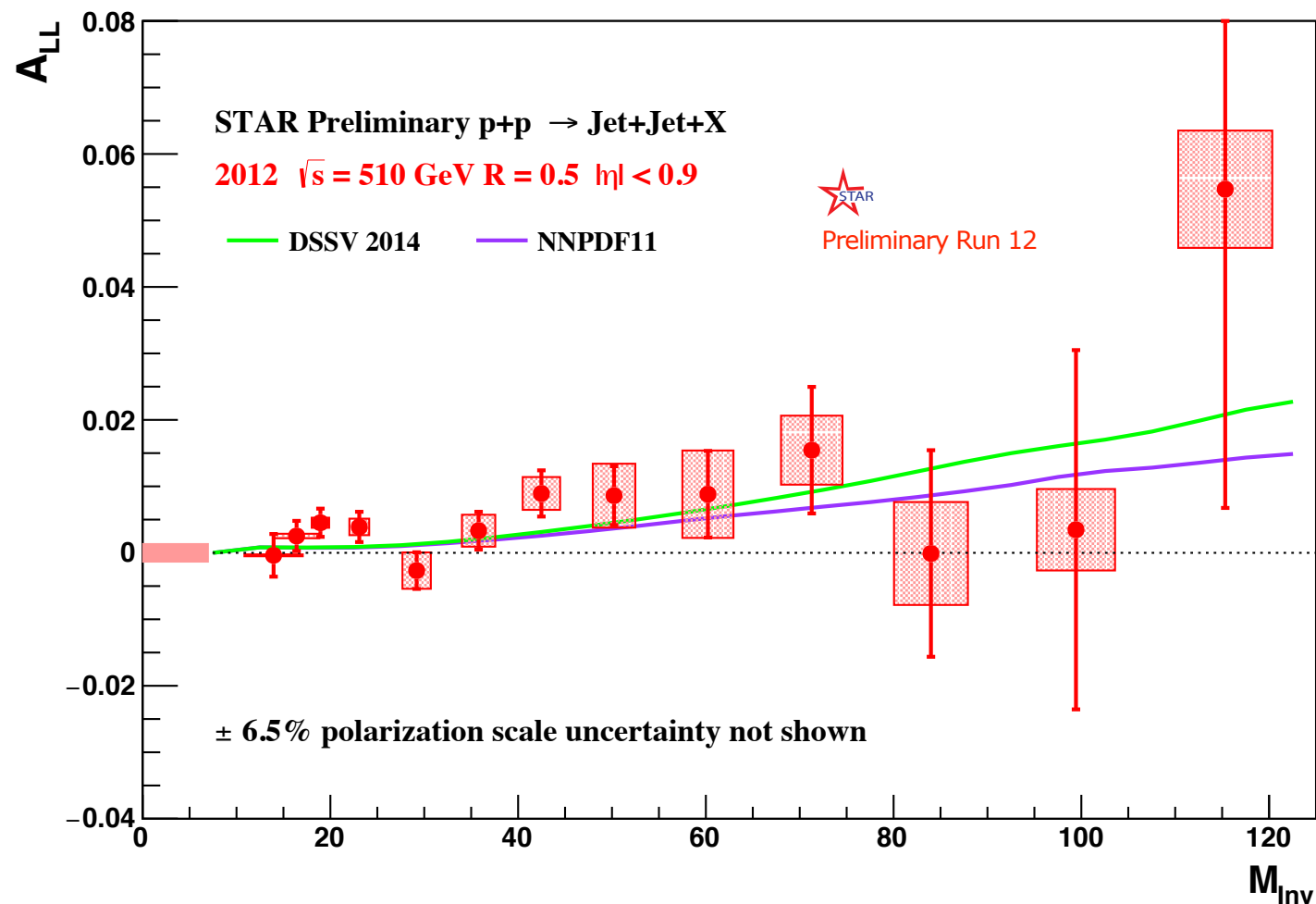
- A_{LL} measurements consistent with DSSV2014 and NNPDF1.1 constrained by Run 9 data

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

Bernd Surrow

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

□ STAR: Mid-rapidity Di-Jet A_{LL} measurement (Run 12) at 510GeV



○ A_{LL} measurements

consistent with

DSSV2014 and

NNPDF1.1

constrained by

Run 9 data and

consistent with

Run 9 di-jet

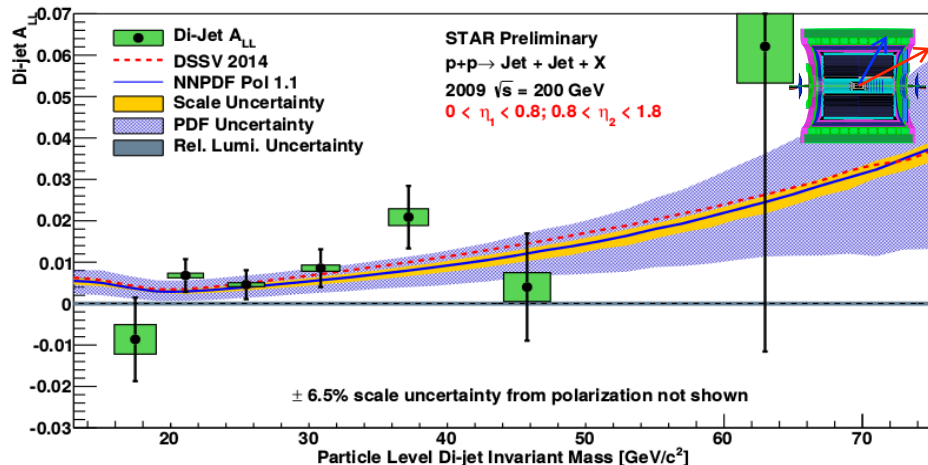
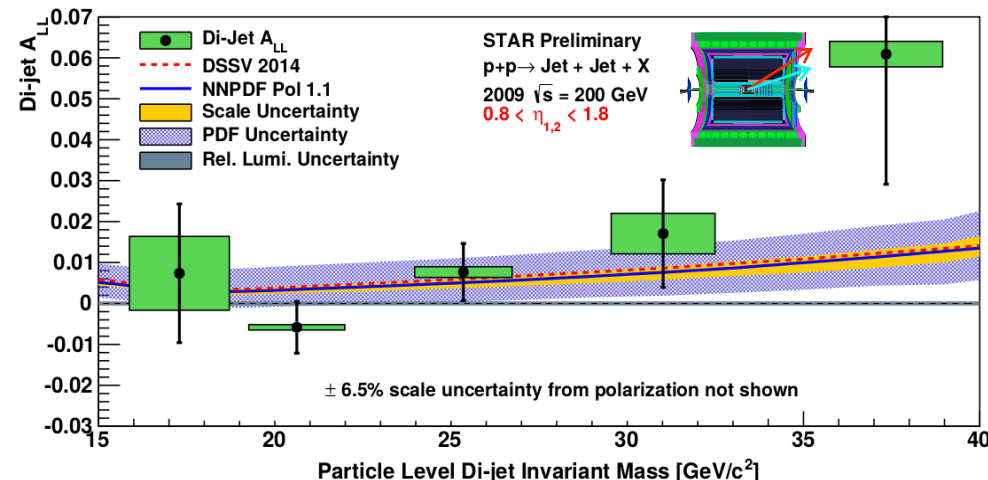
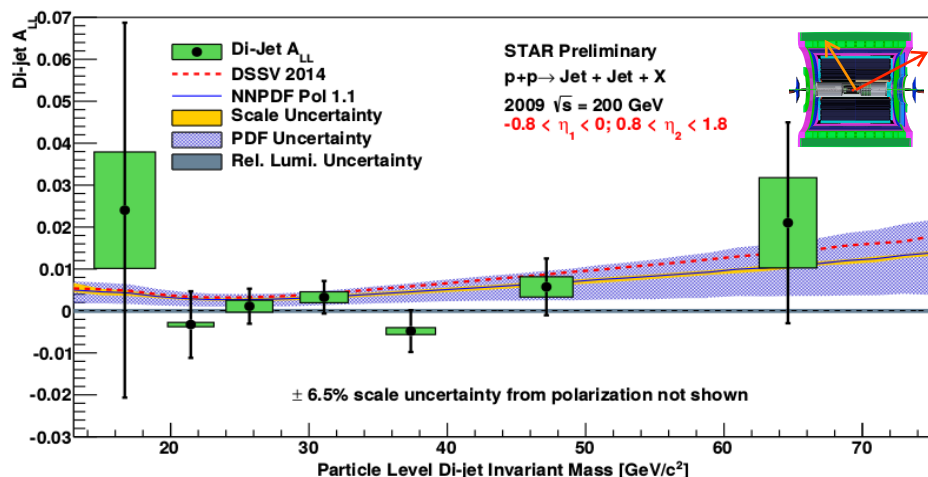
results

S. Ramachandran et al. (STAR Collaboration), DIS 2016. (Run 12 / 510GeV)

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

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

T. Lin et al. (STAR Collaboration), DNP 2016.



Forward rapidity STAR Di-Jet A_{LL} measurement based on three topological combinations in η :

Barrel East ($-0.8 < \eta < 0$) - EEMC ($-0.8 < \eta < 0$)

Barrel West ($0 < \eta < 0.8$) - EEMC ($-0.8 < \eta < 0$)

EEMC ($-0.8 < \eta < 0$) - EEMC ($-0.8 < \eta < 0$)

2009 forward A_{LL} measurement consistent with global fit results constrained by Run 9 A_{LL} data



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

- Status of Run 13 jet analysis: Inclusive Jet and Di-Jet A_{LL} analysis at 510GeV
 - Run 13 data sample: $\sim 250\text{pb}^{-1}$ (Run 12: $\sim 80\text{pb}^{-1}$)
 - Run 13 average beam polarization: $\sim 55\%$ (Run 12: $\sim 55\%$)
 - Run 13 FOM relevant for double-spin asymmetry A_{LL} : $P^4L = 23\text{pb}^{-1}$ (Run 12: 7.3pb^{-1})
→ FOM Factor ~ 3 improvement compared to Run 12!
 - STAR TPC and BEMC calibration (W Run 13 analyses released!): Completed
 - Extensive test of both tracking software and jet triggers: Completed
 - QA of jet analyses: Finalizing
 - MC / Embedding samples Run 13: Initial testing

Future - $g / \Delta g(x)$ related studies

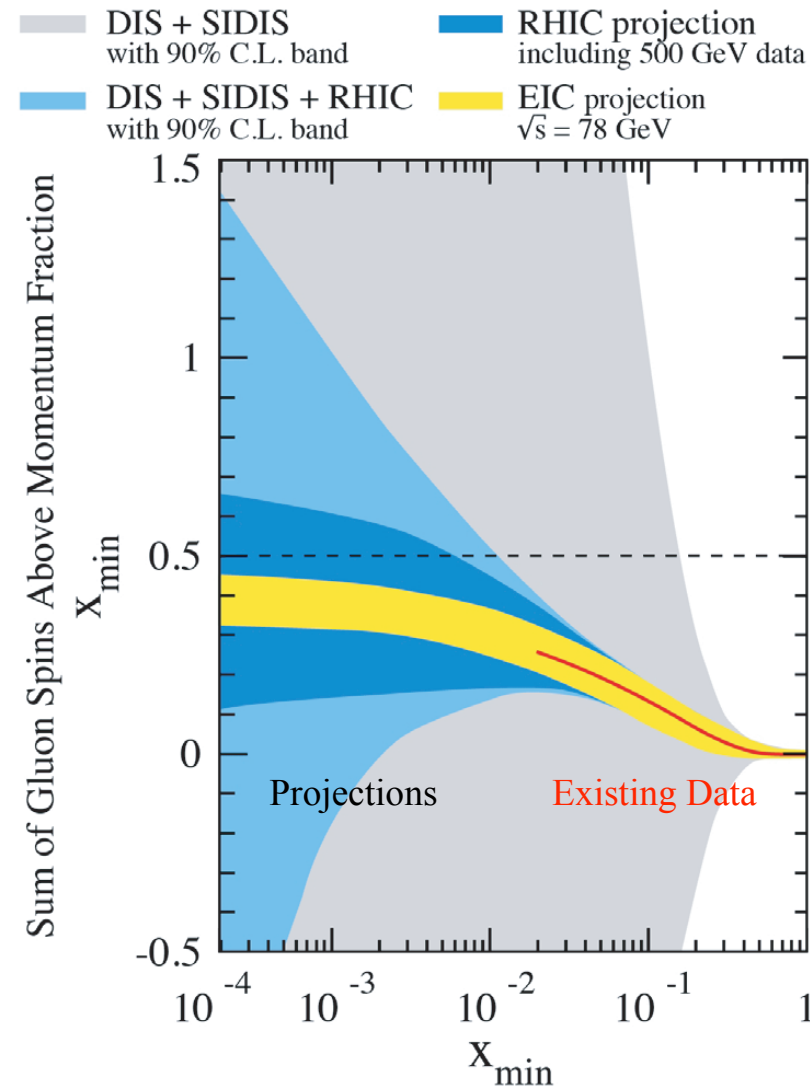
□ Impact of new RHIC data and future EIC facility

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

to 1 as a function of x_{\min}

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

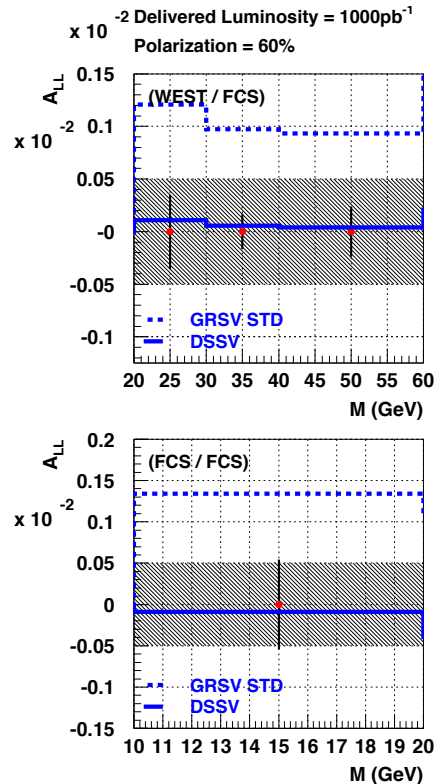
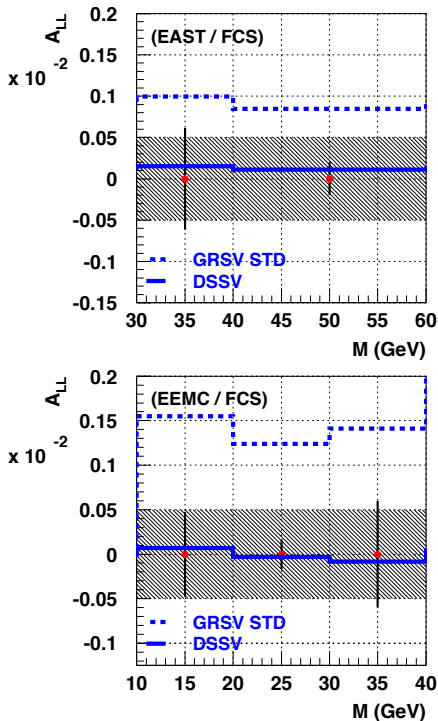
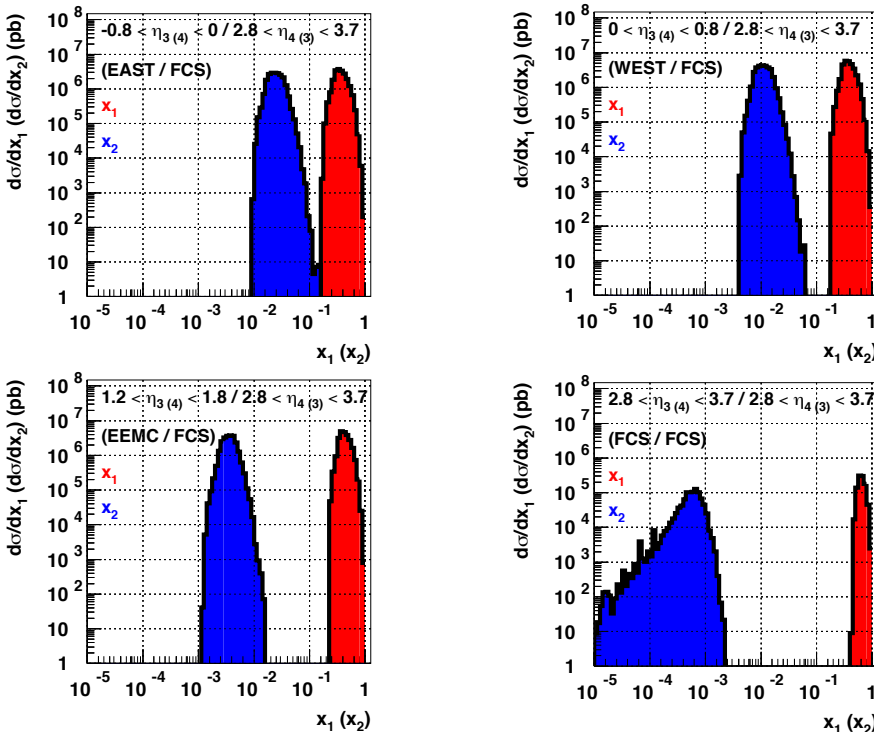
- Uncertainties shown on running integral!
- Important constraint from high-statistics 200GeV data (Run 9 / Published and Run 15) together with 500GeV data (Run 12 and Run 13) and forward rapidity measurements at RHIC prior to EIC - critical for low- x coverage (Di-Jet results not included!)



Future - $g / \Delta g(x)$ related studies

- Forward di-jet production at RHIC

B. Surrow et al. (STAR Collaboration), DIS 2014.

$$\delta R = 5 \cdot 10^{-4}$$


Cone alg. ($R=0.7$) / $E_{T3} > 5\text{GeV}$ $E_{T4} > 8\text{GeV}$

- Probing smaller x-values 'badly needed' (DSSV 2014) - Extend di-jet measurements at forward rapidity
- Forward di-jet measurements allow to probe Δg at very low x values $\sim 10^{-3}$
- Forward hadronic calorimeter upgrade required - Upgrade plans at STAR and sPHENIX

Summary / Outlook

□ Recently published / preliminary results: $g / \Delta g$

- Precise **Run 9 A_{LL} inclusive jet** measurement: Non-zero Δg of similar magnitude as quark polarization (Published!)
- **Run 9 A_{LL} Di-jet** measurements open path to constrain the shape of Δg
- **Run 12 Inclusive jet and di-jet Run 12 preliminary A_{LL}** measurement at 510GeV probe Δg at lower x
- **Run 9 Inclusive jet cross-section** measurement: Important constraint for unpol. gluon distribution at high x

□ Upcoming results: $g / \Delta g$

- **Large Run 13 data sample**: Measurement of **Inclusive jet and di-jet A_{LL} at 510GeV** probing Δg lower x
- **Additional data sample at 200GeV** from **Run 15** combined with Run 9

□ Future

- **Long 510GeV run in 2017 (Run 17) at transverse spin polarization** of about 400pb^{-1} : $W A_N$ / Unpol. QCD sea
- **Exciting long-term prospects beyond 2020** requiring **forward detector upgrade** (Cold QCD plan) / Potential of **probing gluons at low- $x \sim 10^{-3}$ using forward di-jet measurements!**