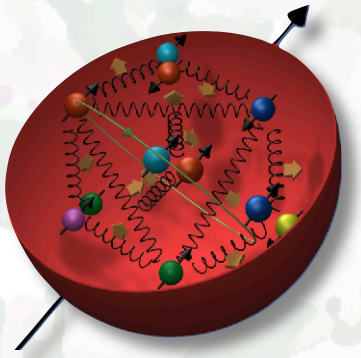
Recent STAR results on the gluon polarization program in high-energy polarized p+p collisions at RHIC

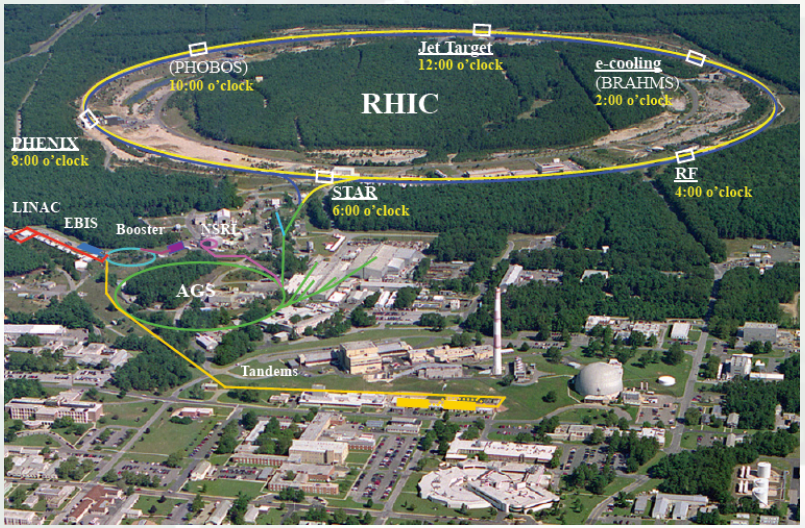
Bernd Surrow

TEMPLE UNIVERSITY

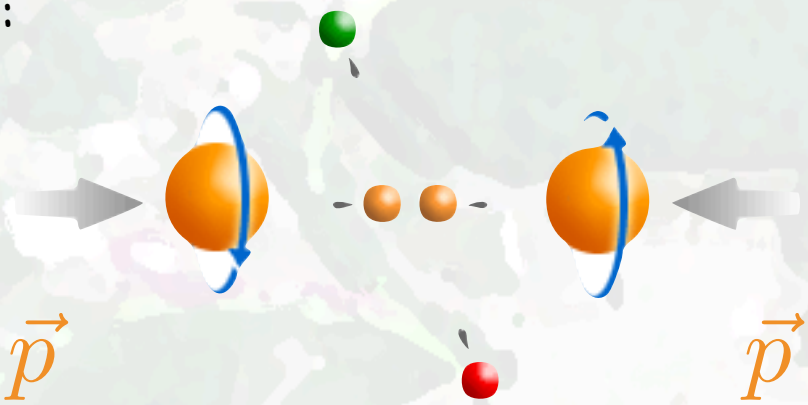


Spin 2012 / 20th International Spin Physics Symposium
Dubna, Russia, September 16-22, 2012

Outline



- Selected recent results and future prospects: Gluon polarization
- Experimental aspects: RHIC /STAR
- Theoretical foundation
- Summary and Outlook



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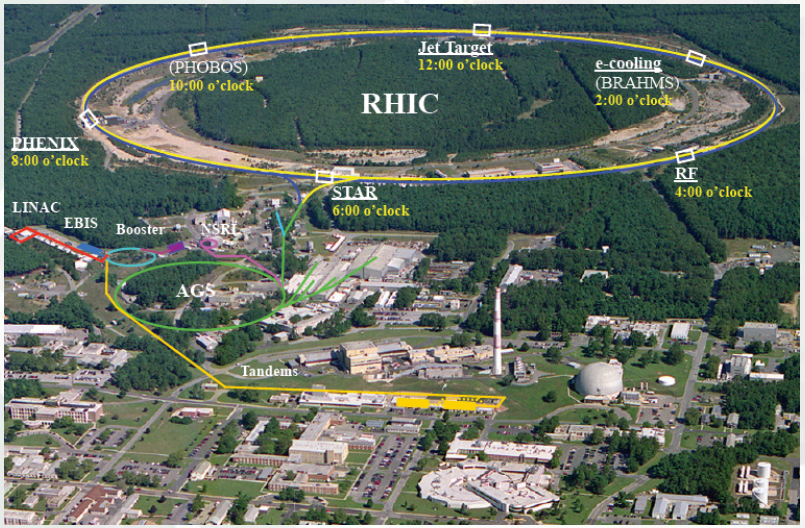

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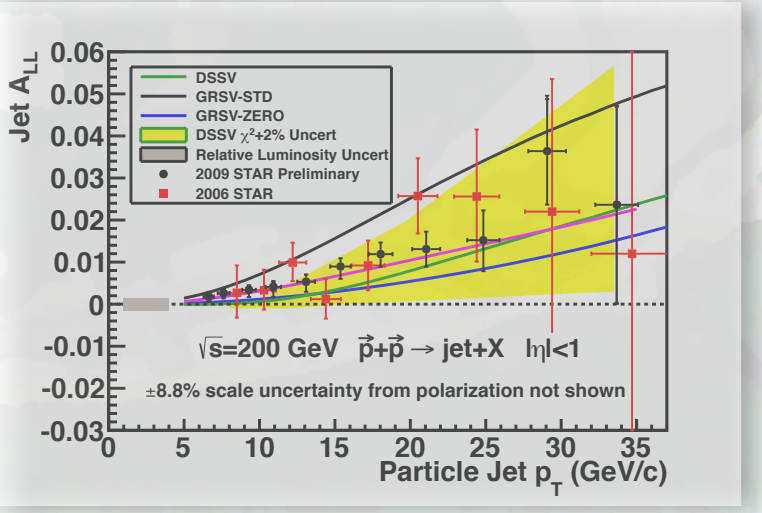

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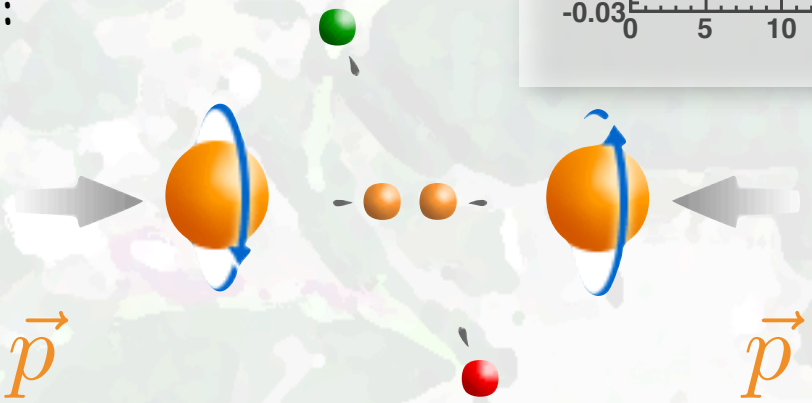

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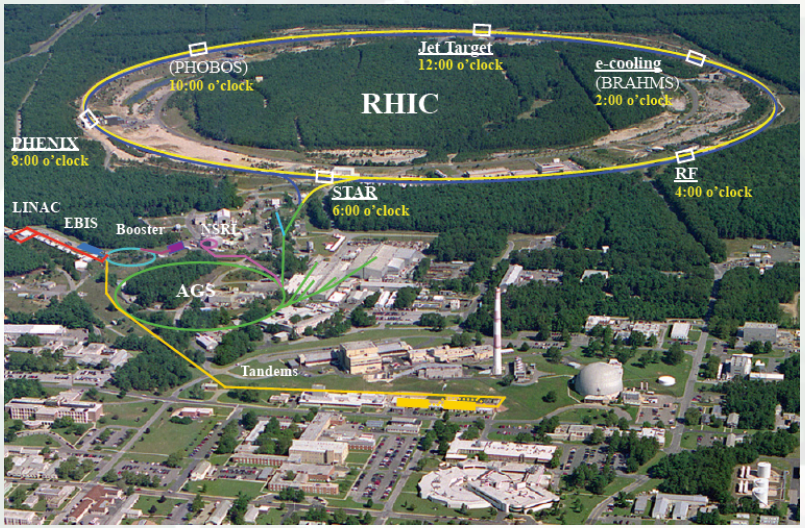

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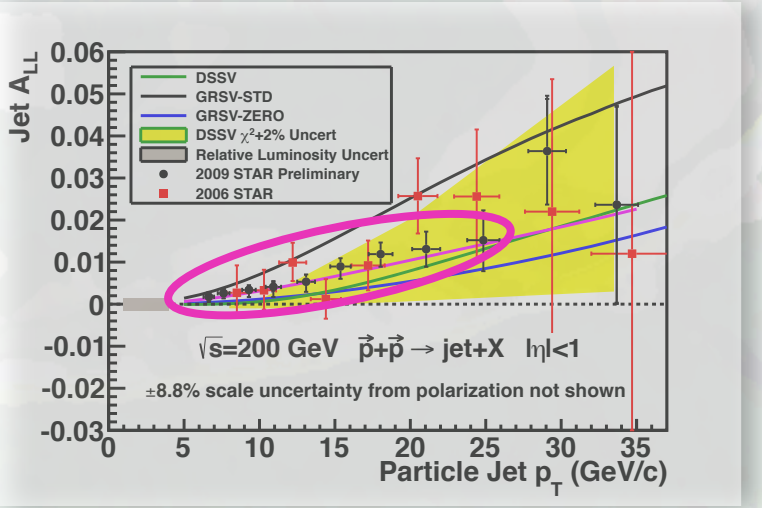

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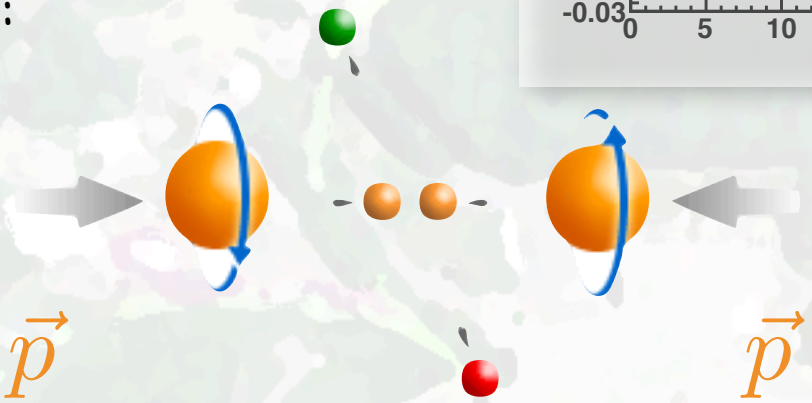
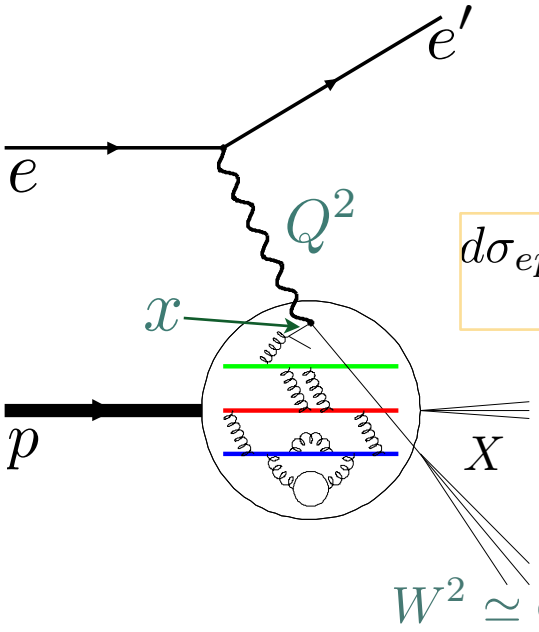


- Theoretical foundation

- Summary and Outlook

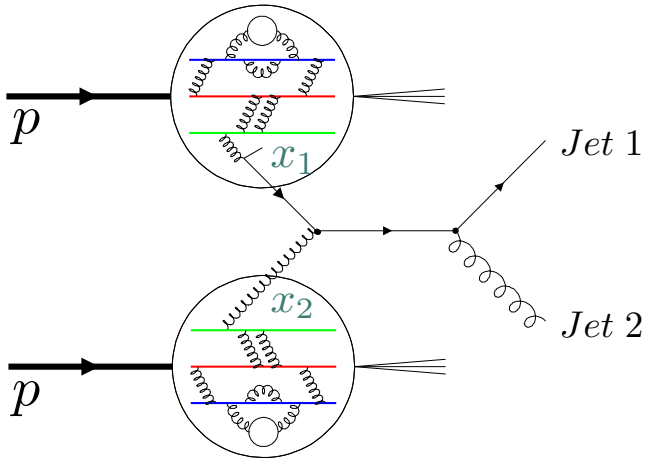
Theoretical foundation

- 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

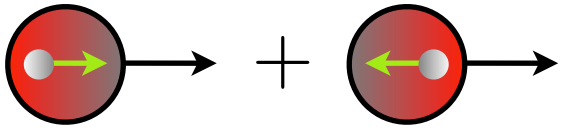


$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

Factorization

Momentum contribution

$$f(x) =$$



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

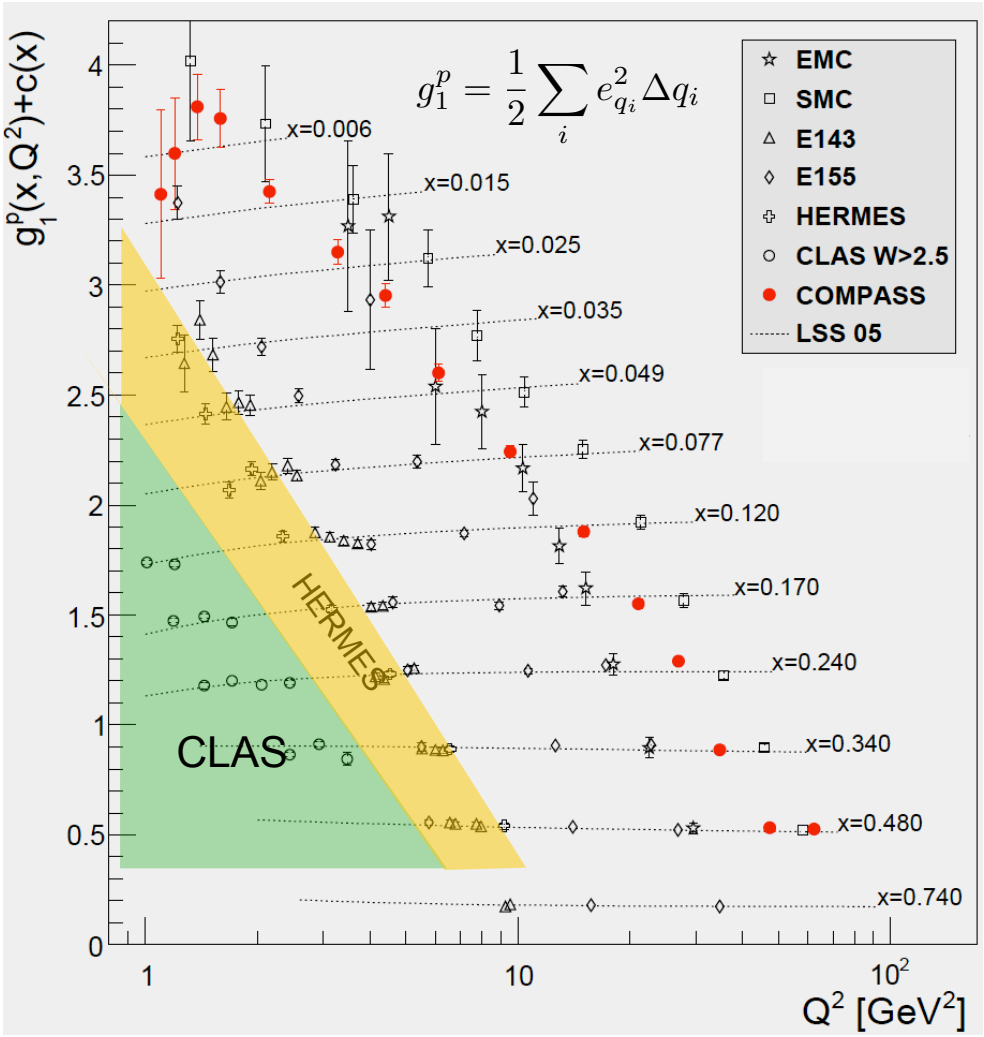
$$\Delta f(x) =$$

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

Spin contribution

Theoretical foundation

- Picture of the proton from polarized ep scattering



- Spin sum rule:

$$\underbrace{\frac{1}{2}\Delta\Sigma}$$

$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \underbrace{\langle L_g \rangle}_{\Delta G}$$

(R.L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990))

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x,Q^2)dx \qquad \Delta G(Q^2) = \int_0^1 \Delta g(x,Q^2)dx$$

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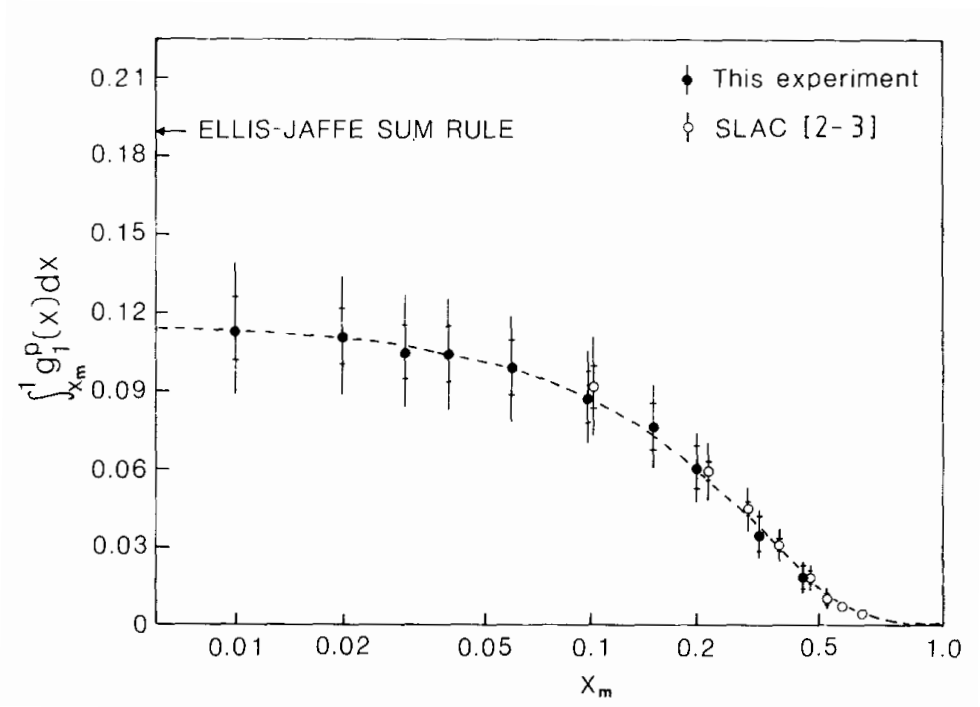

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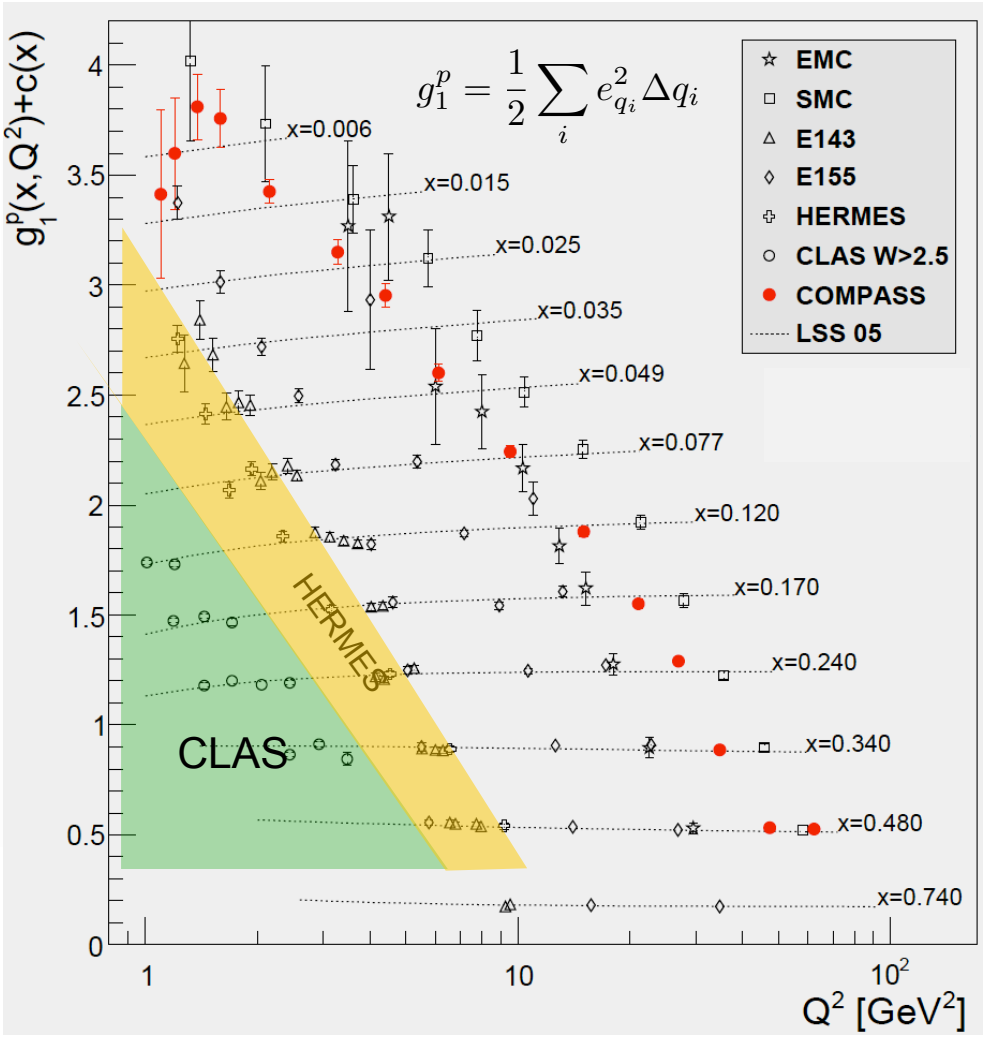

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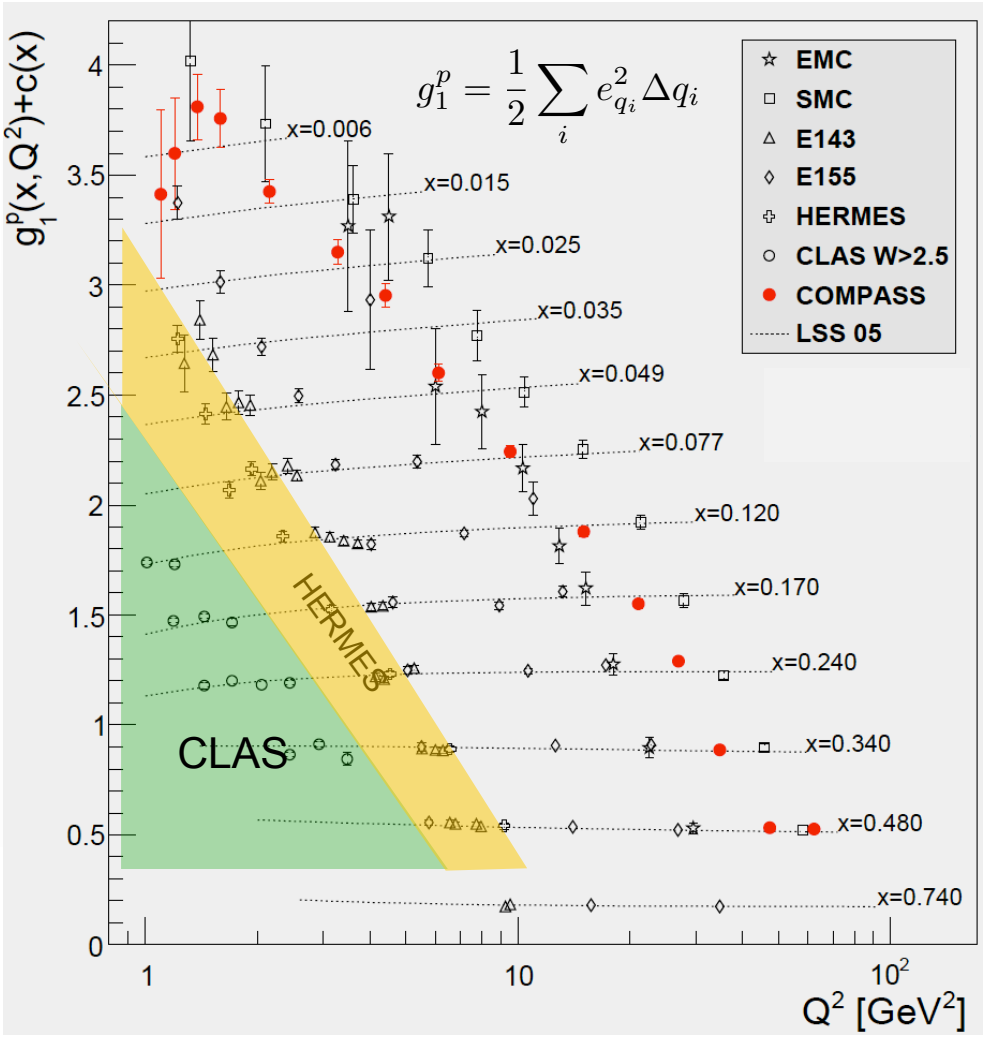

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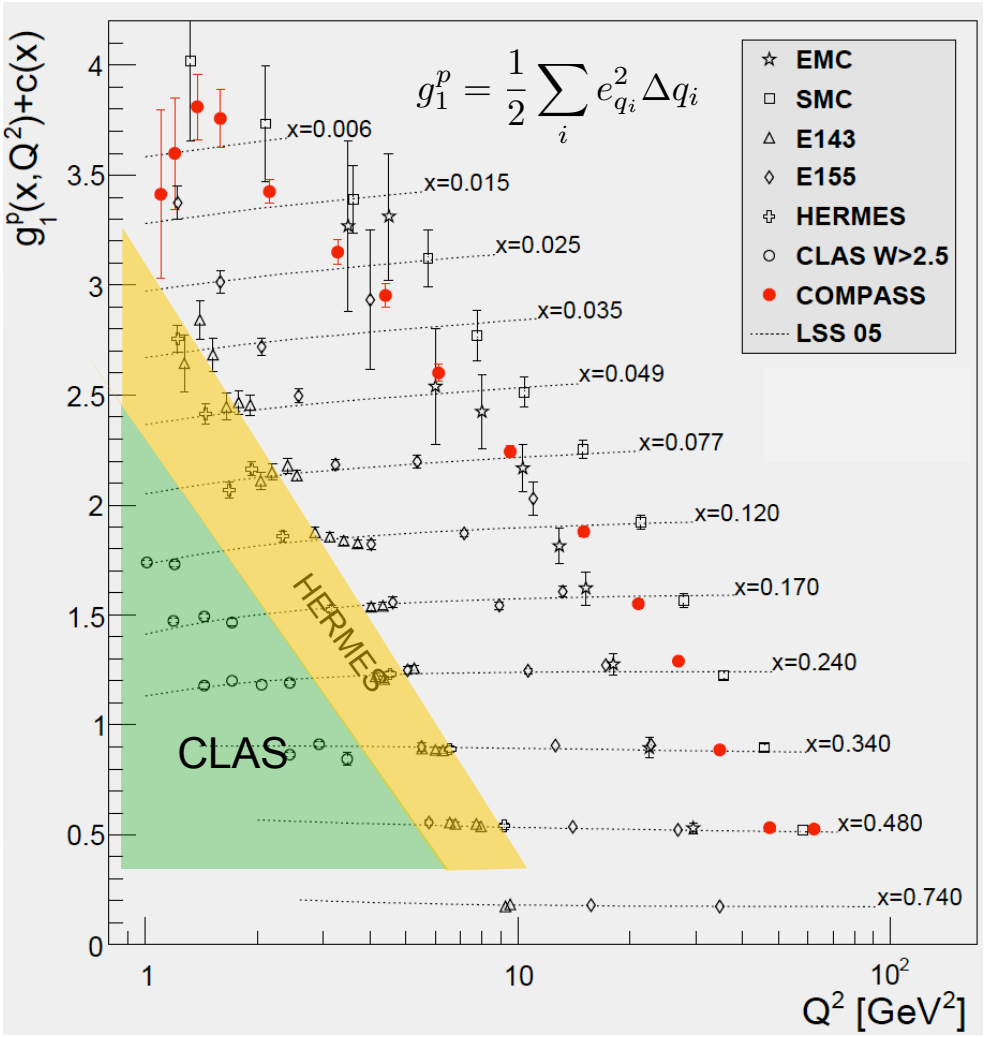

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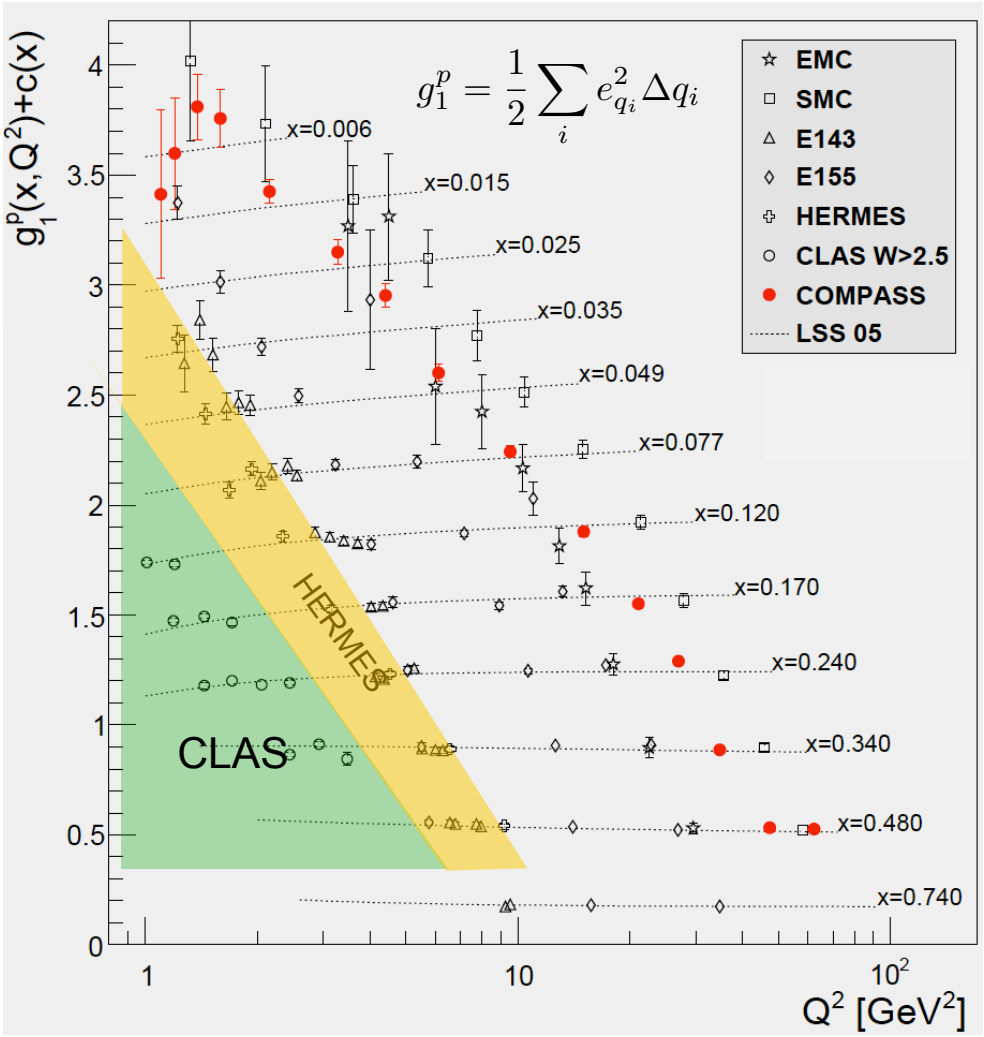

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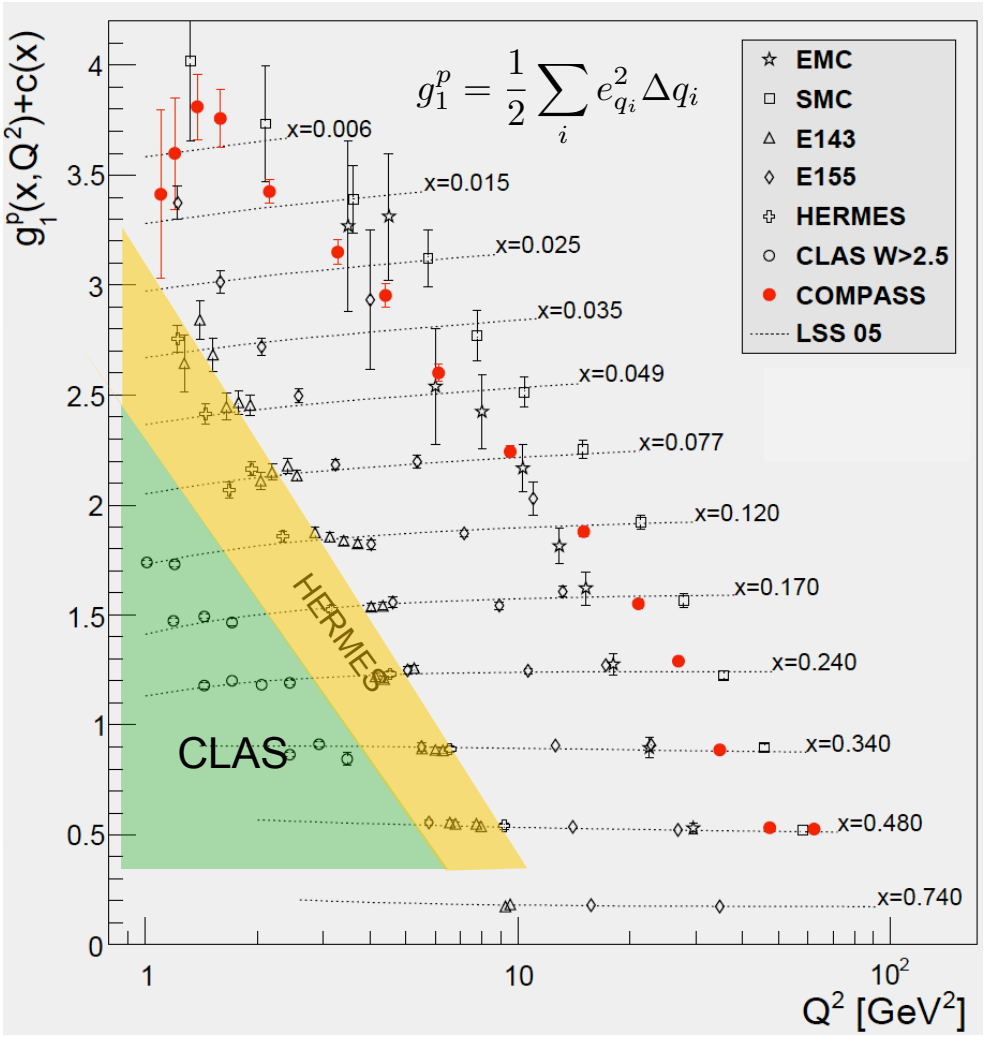

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(D. deFlorian et al., Phys. Rev. D80, 034030 (2009))

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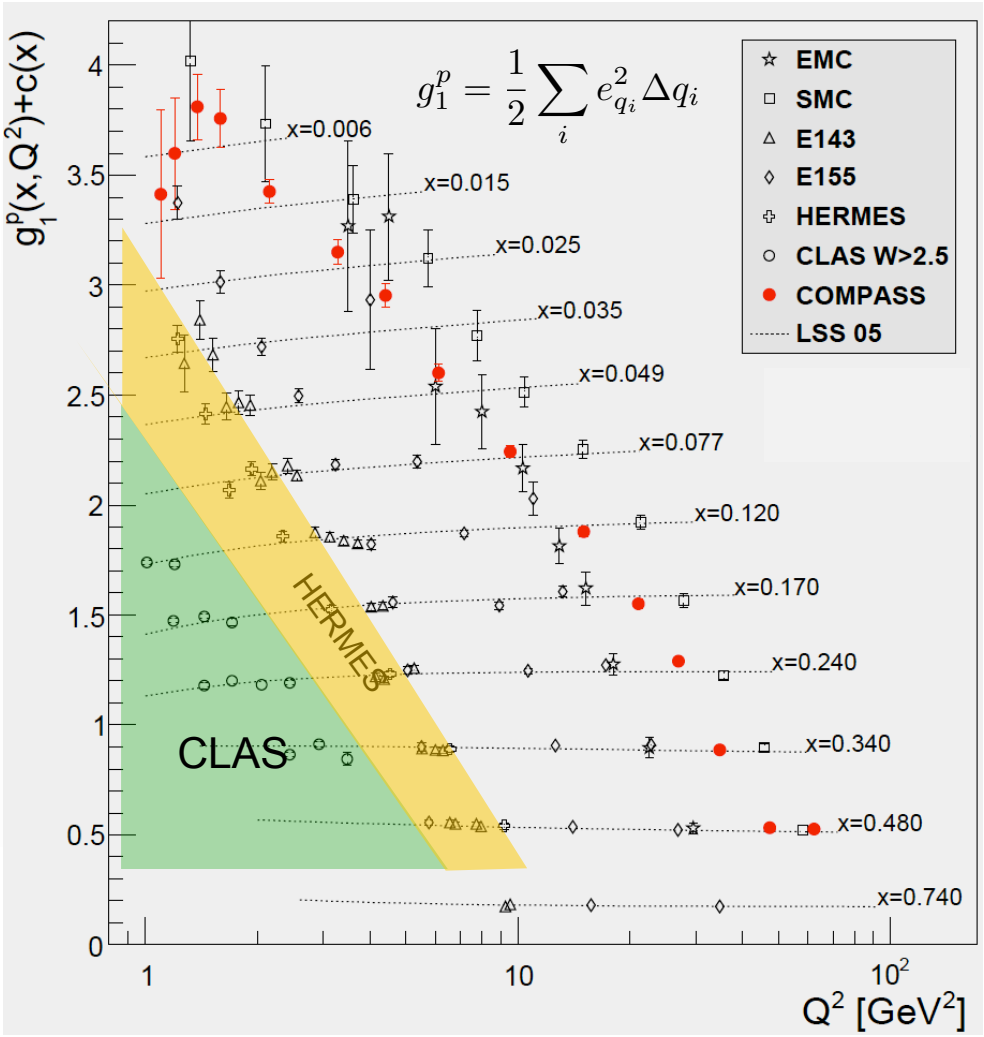

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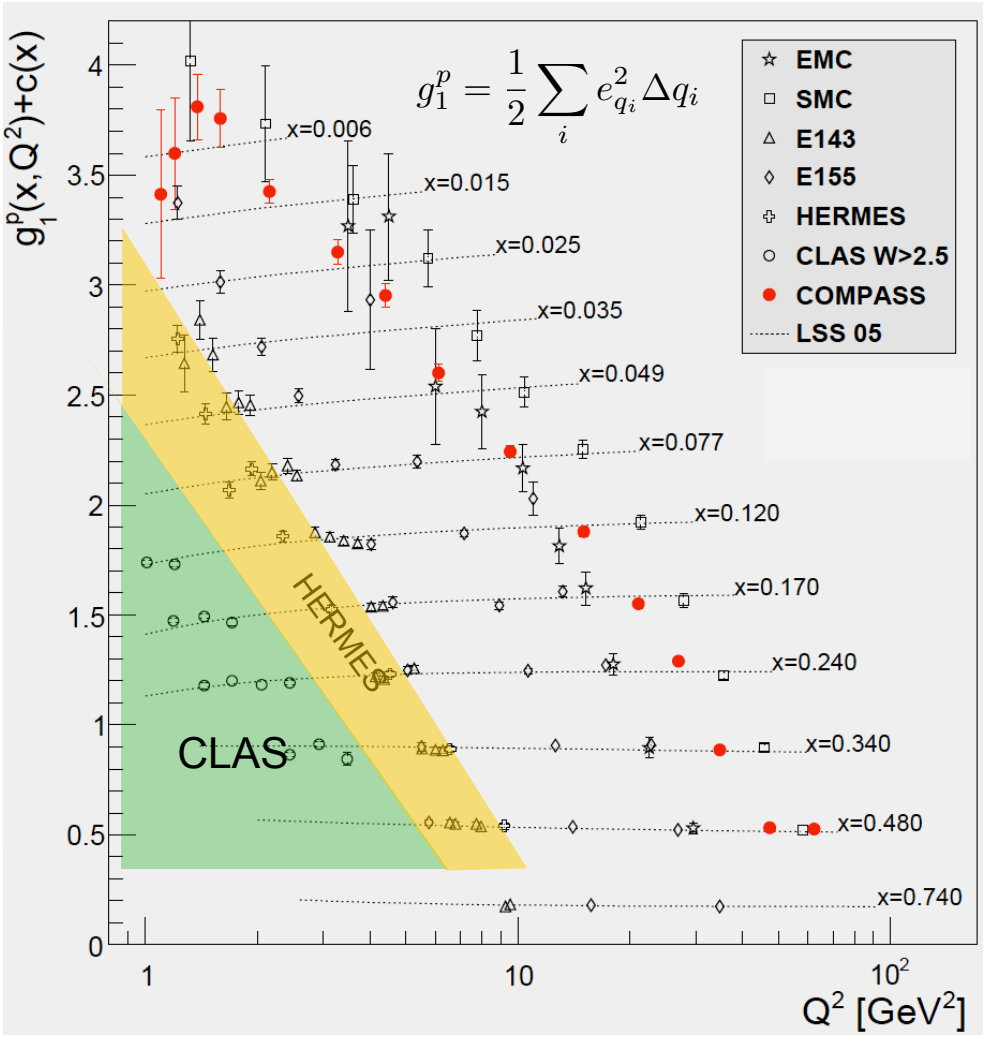

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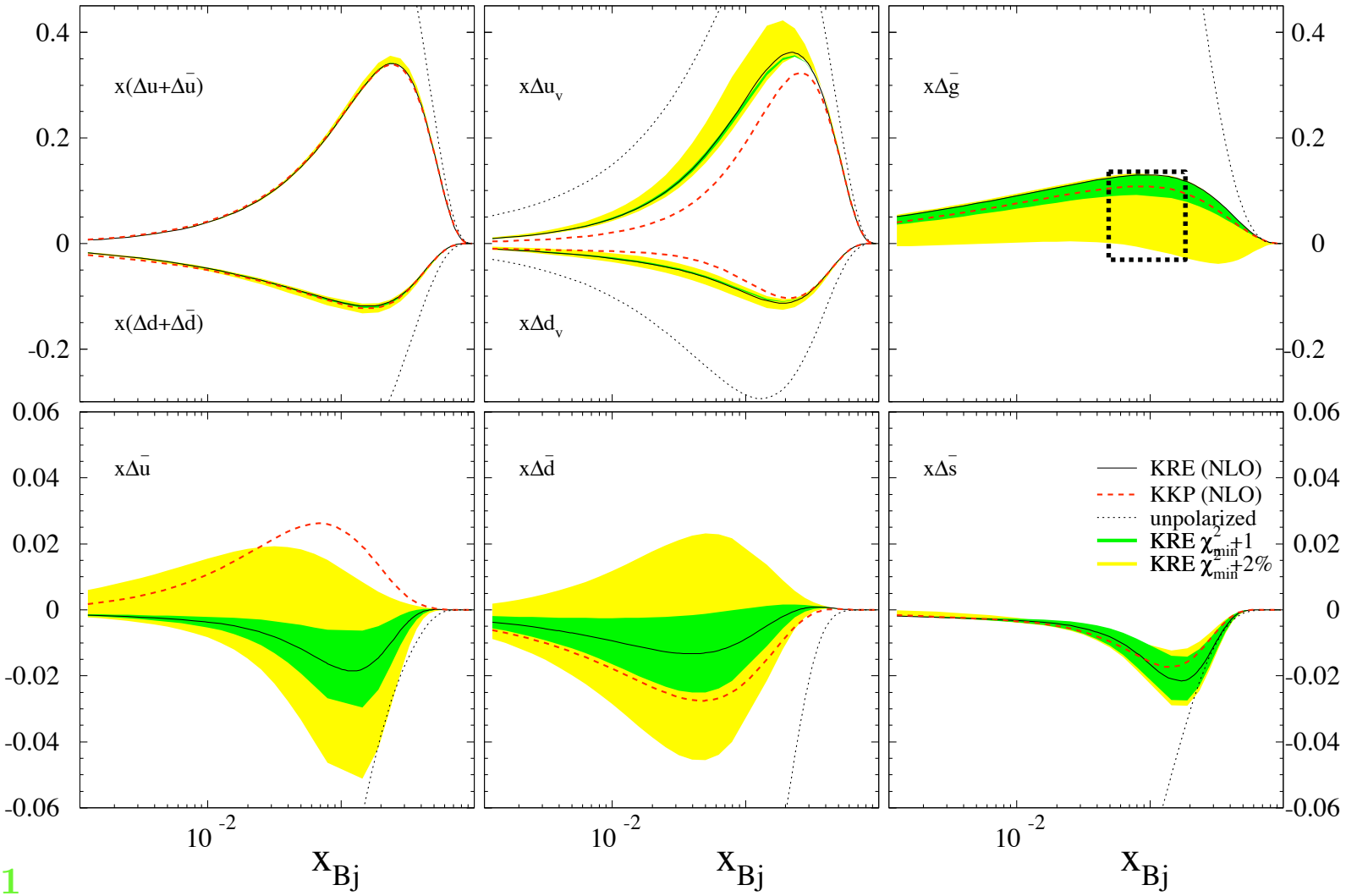
  - Δg - from scaling violations - unconstrained so far!

Theoretical foundation

- Status: Polarization of quarks and gluons from a global QCD analysis (DSSV)



$\Delta\chi^2 = 1$

D. de Florian et al., Phys. Rev. D71, 094018 (2005).

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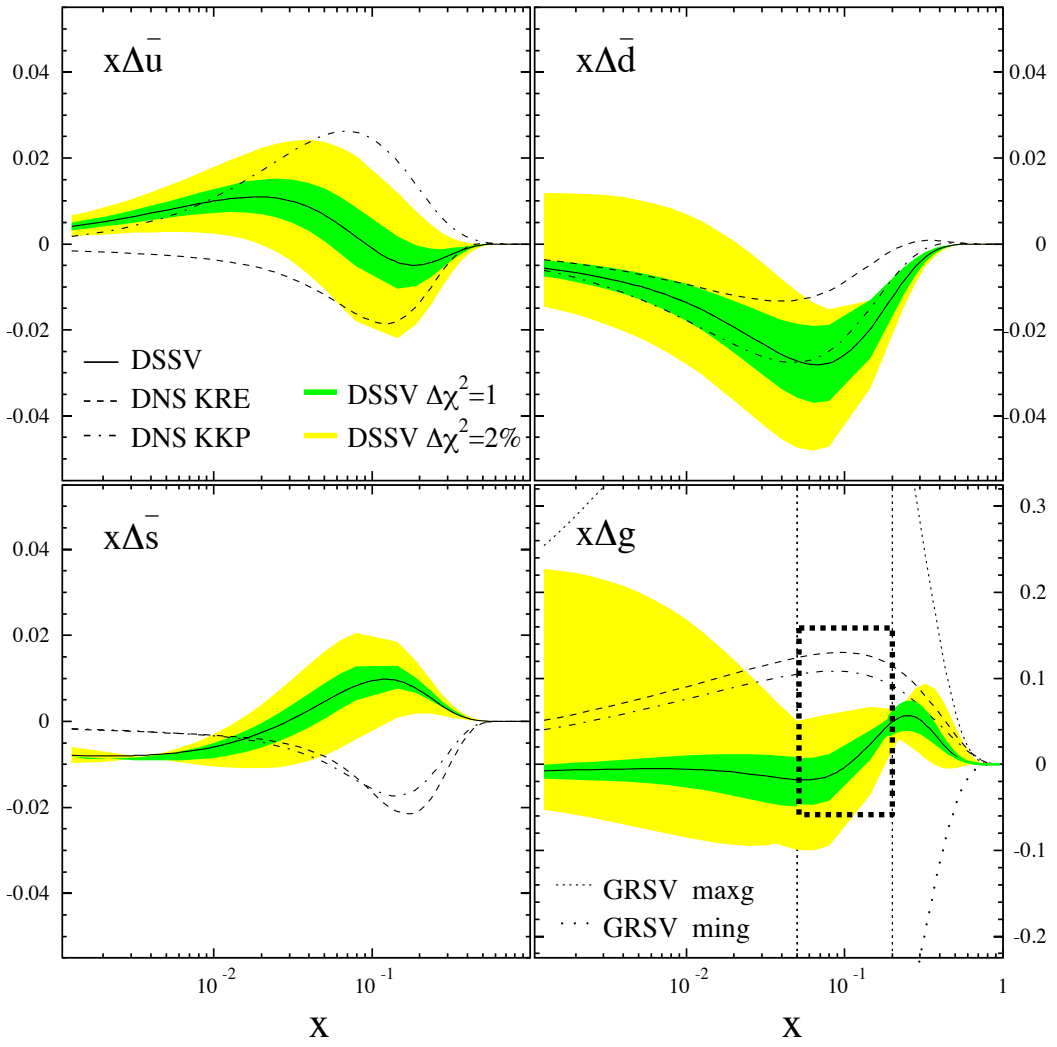


$\Delta\chi^2 = 1$

u/d sea-quark polarizations large uncertainties!

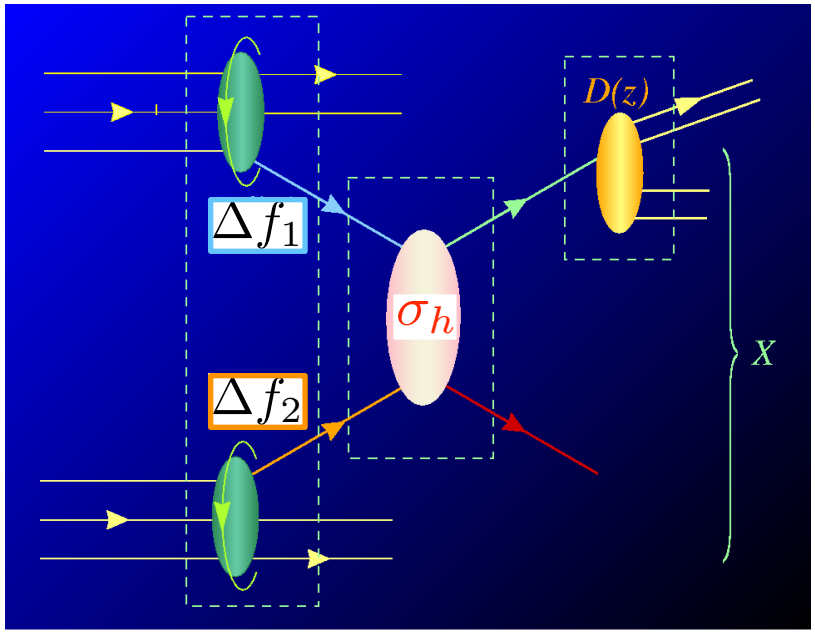
Substantial improvement from polarized p+p data data at RHIC

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

Theoretical foundation

- Explore proton spin structure using high-energy polarized p+p collisions

  - Observable: Gluon polarization (Jet/Hadron production)



  - Longitudinal double-spin asymmetry A_{LL}

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

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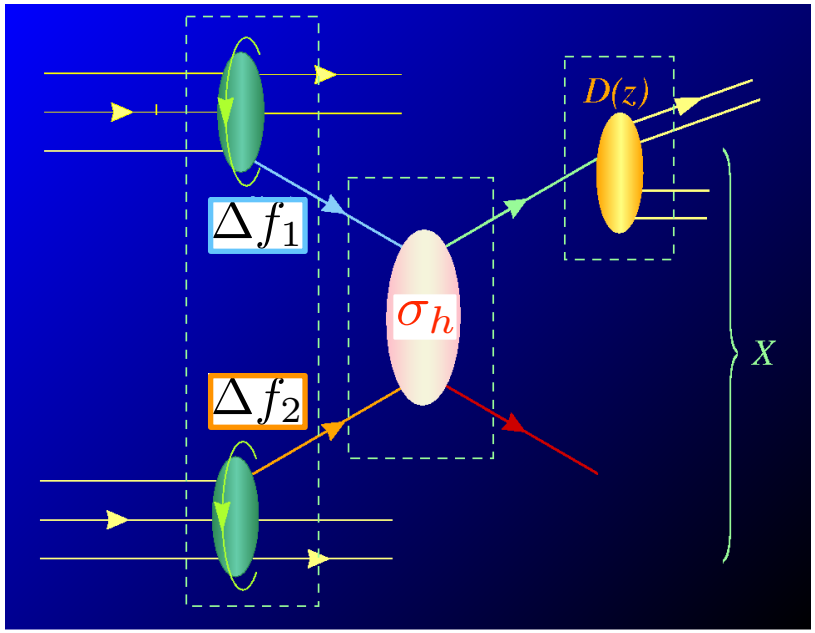

- Longitudinal double-spin asymmetry A_{LL}

long-range | short-range | long-range

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

Input

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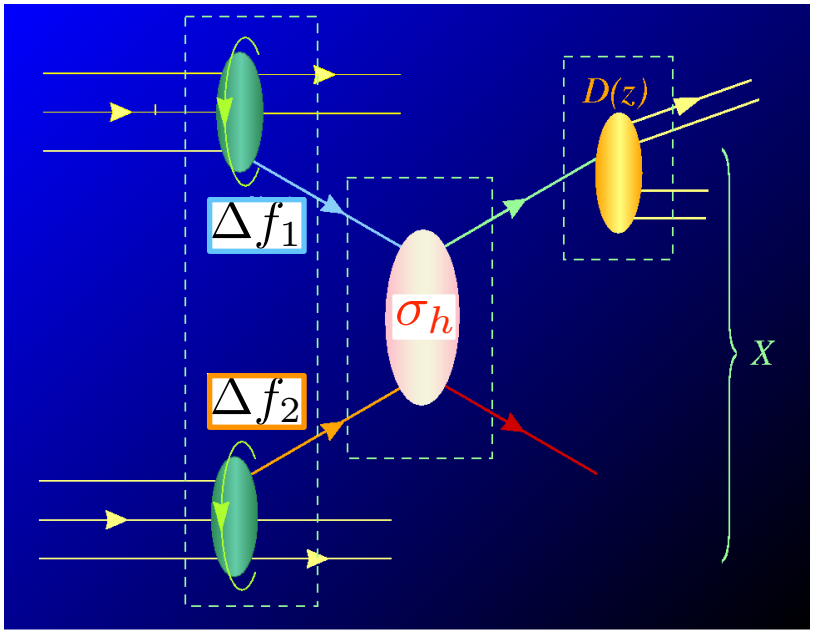

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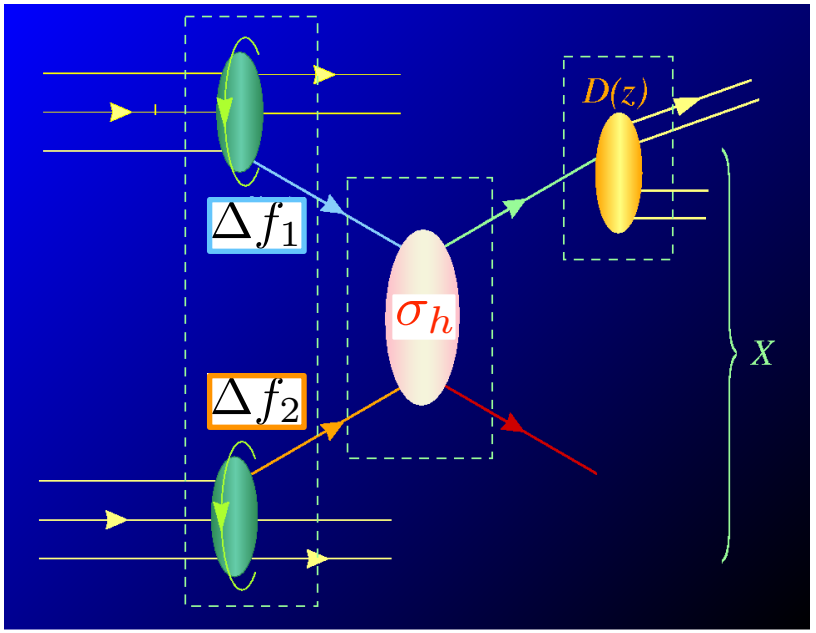

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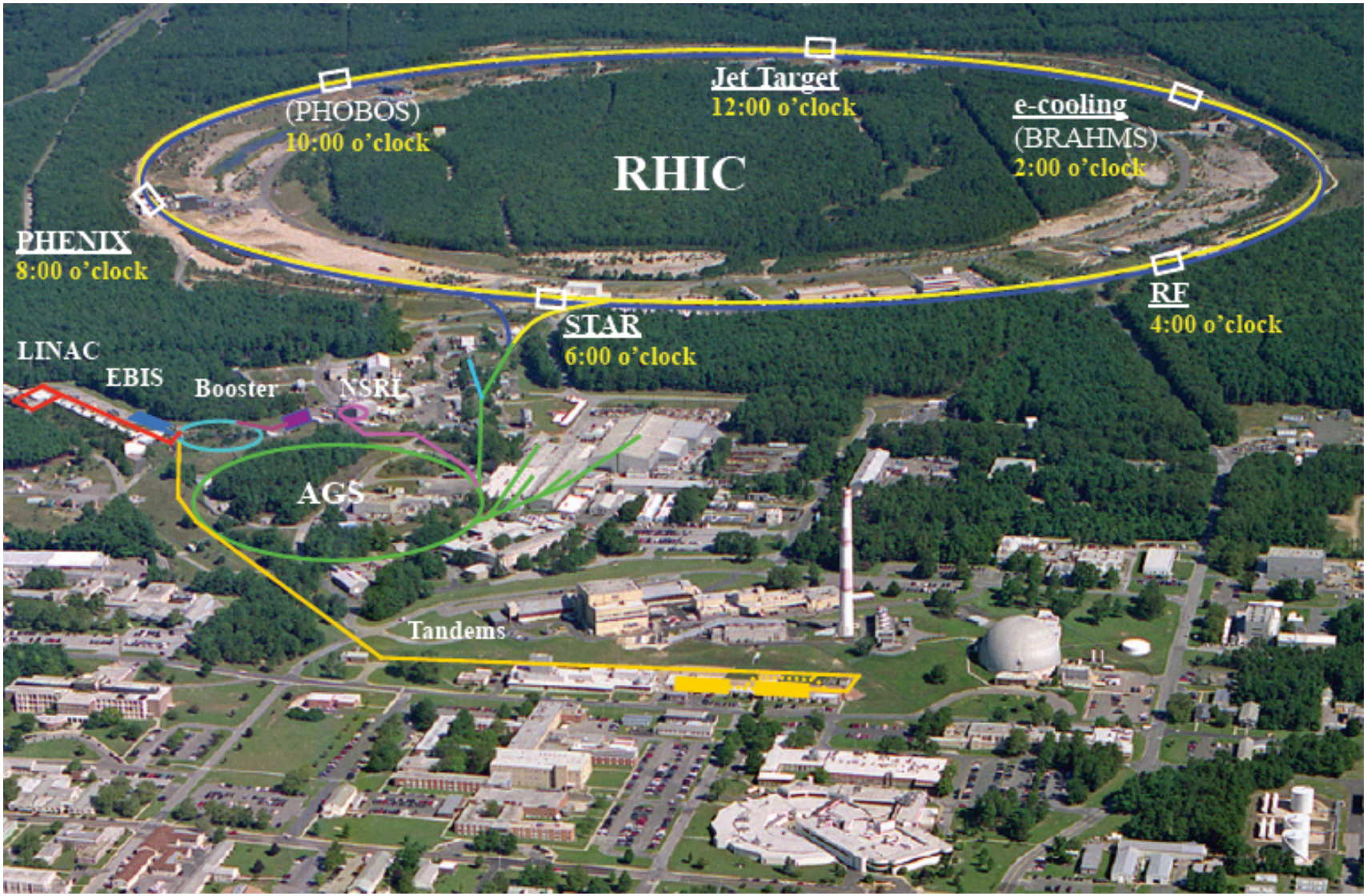
Experimental aspects - RHIC

- The world's first polarized proton-proton collider



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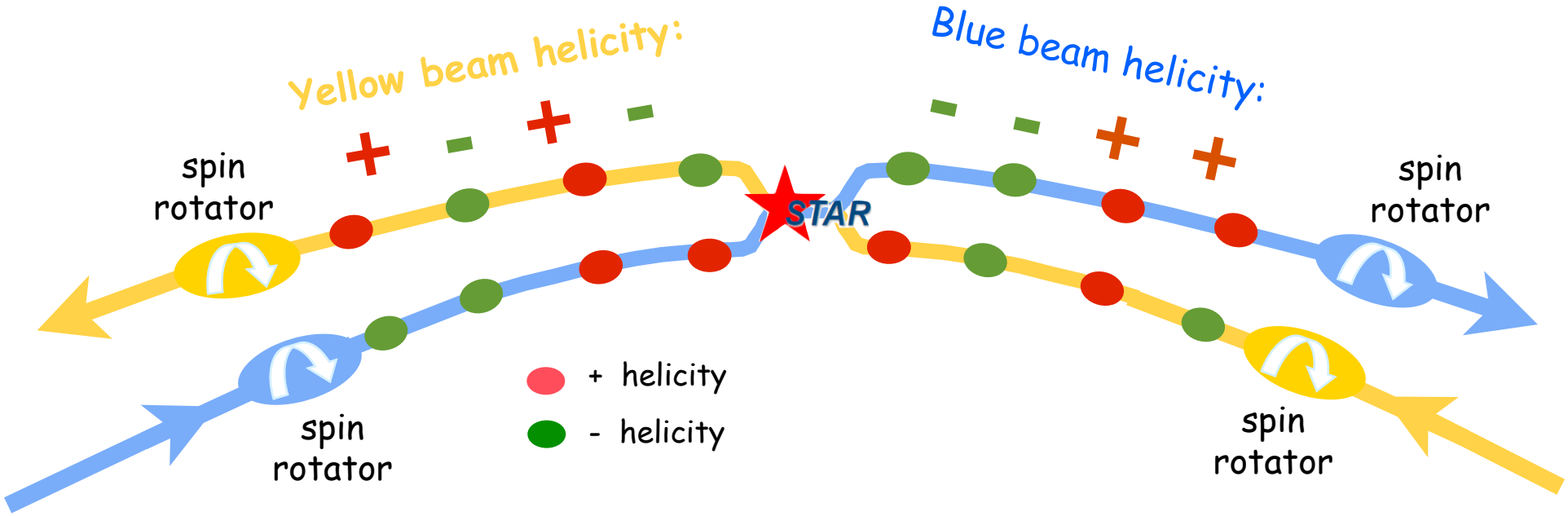
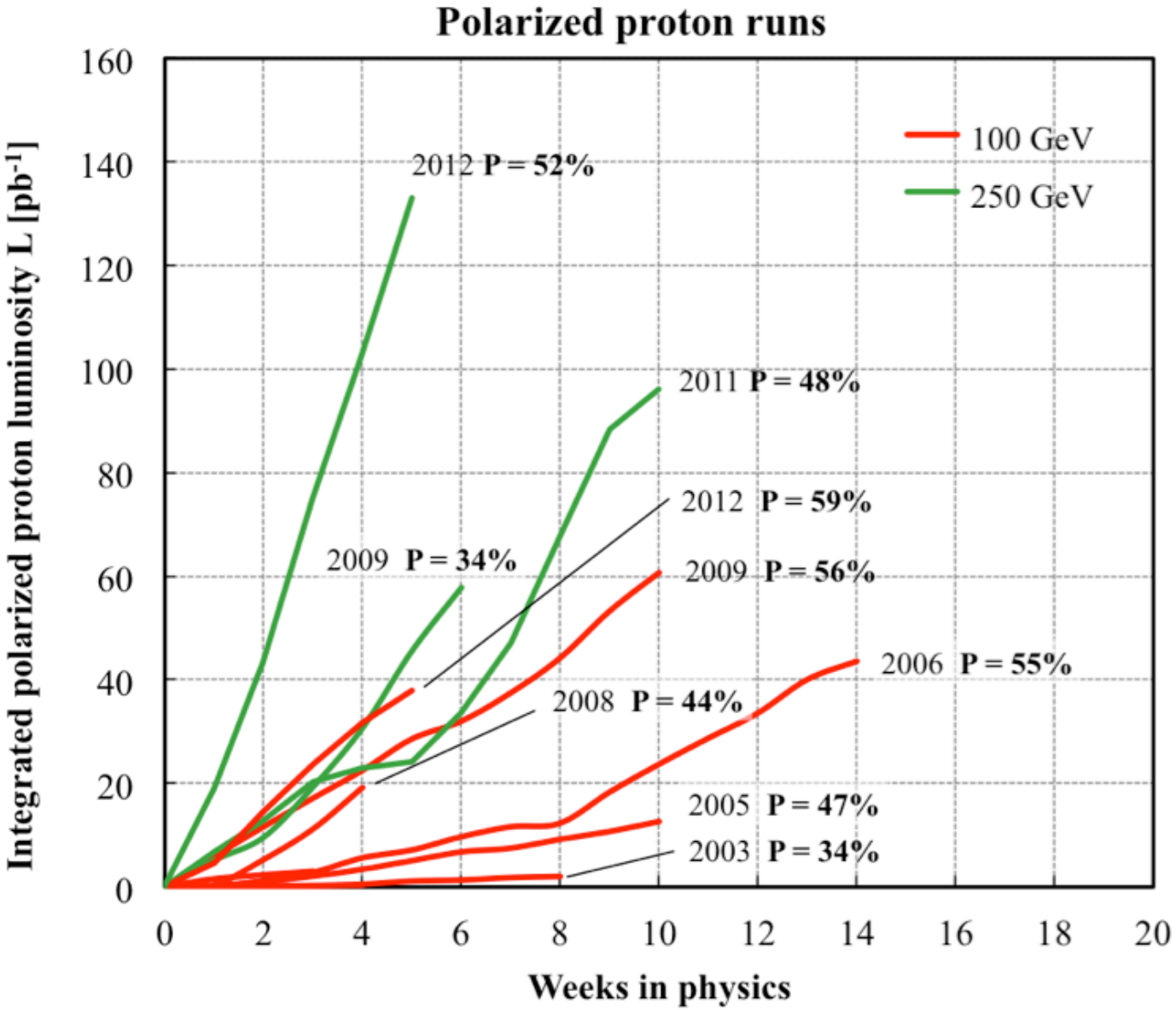


Experimental aspects - RHIC

- RHIC p+p performance
  - Long production runs at $\sqrt{s}$=200GeV (long. polarization) in 2005, 2006, 2009 and 2012: Jet and Hadron production (Gluon polarization)
  - Collisions of polarized proton beams at $\sqrt{s}$=500GeV (long. polarization) in 2009 and 2012: W production (Quark polarization)

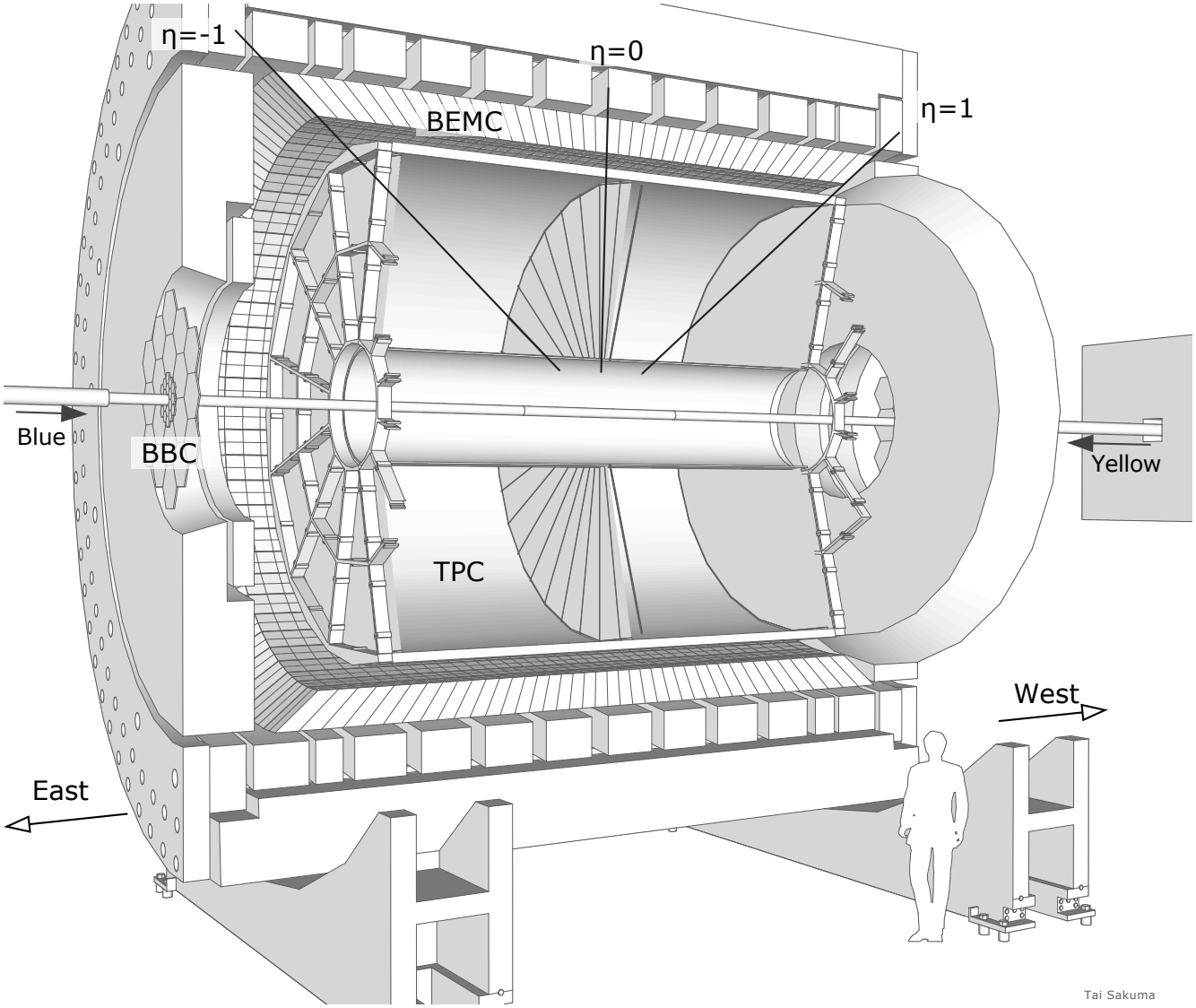


Experimental aspects - STAR

Overview

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

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



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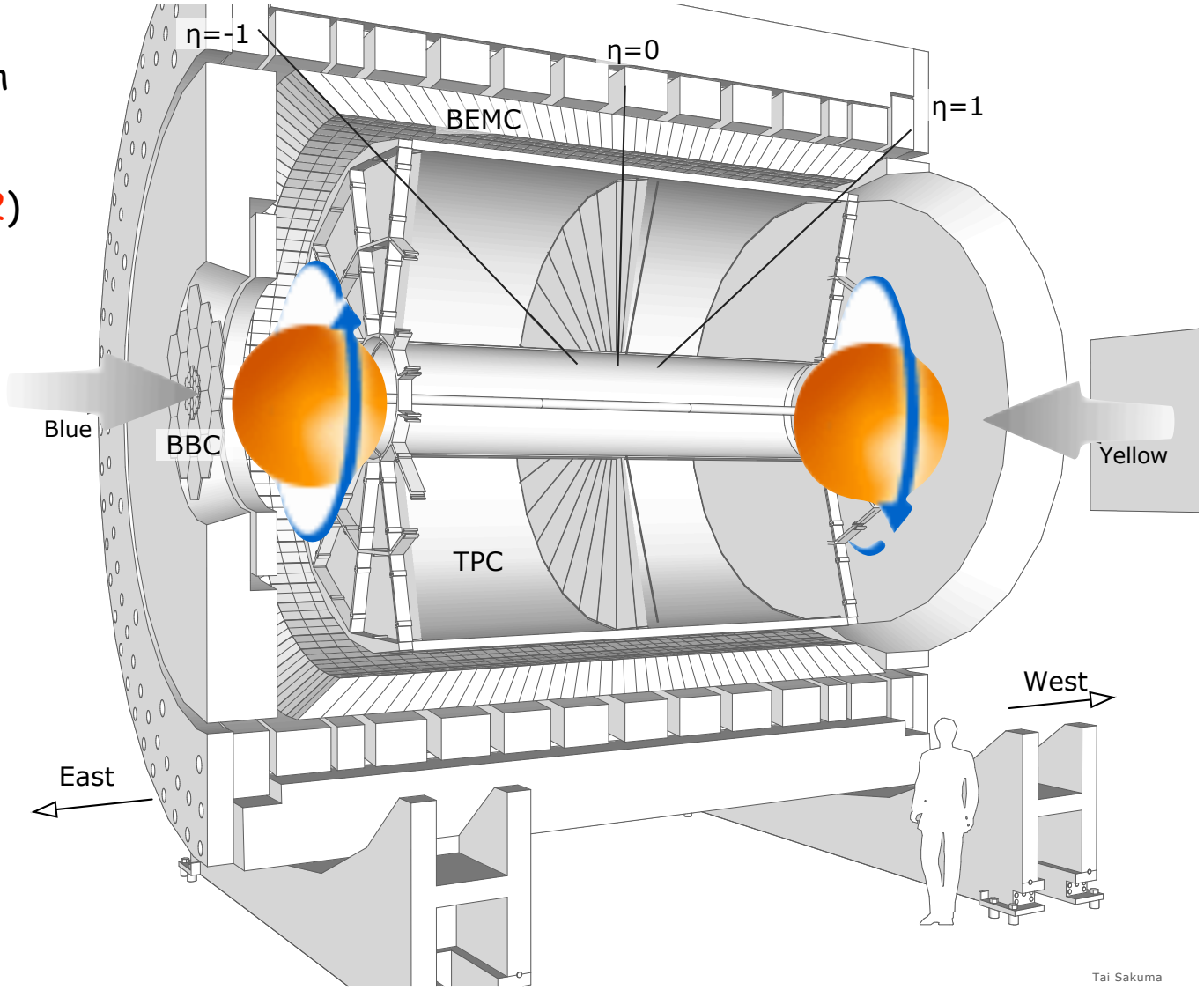

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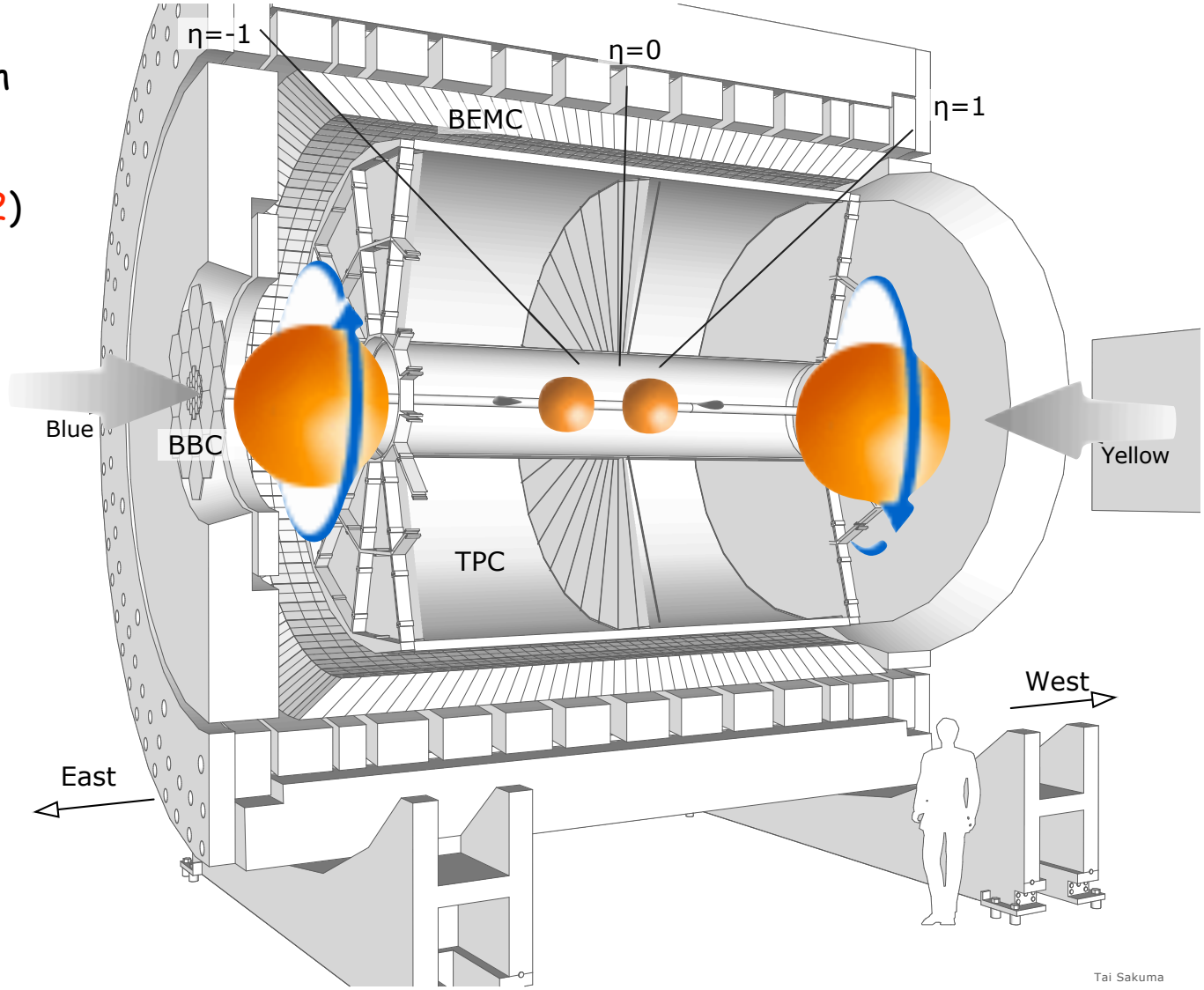

Experimental aspects - STAR

Overview

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

- Calorimetry system with 2π coverage: BEMC ($-1<\eta<1$) and EEMC ($1<\eta<2$)
- TPC: Tracking and particle ID
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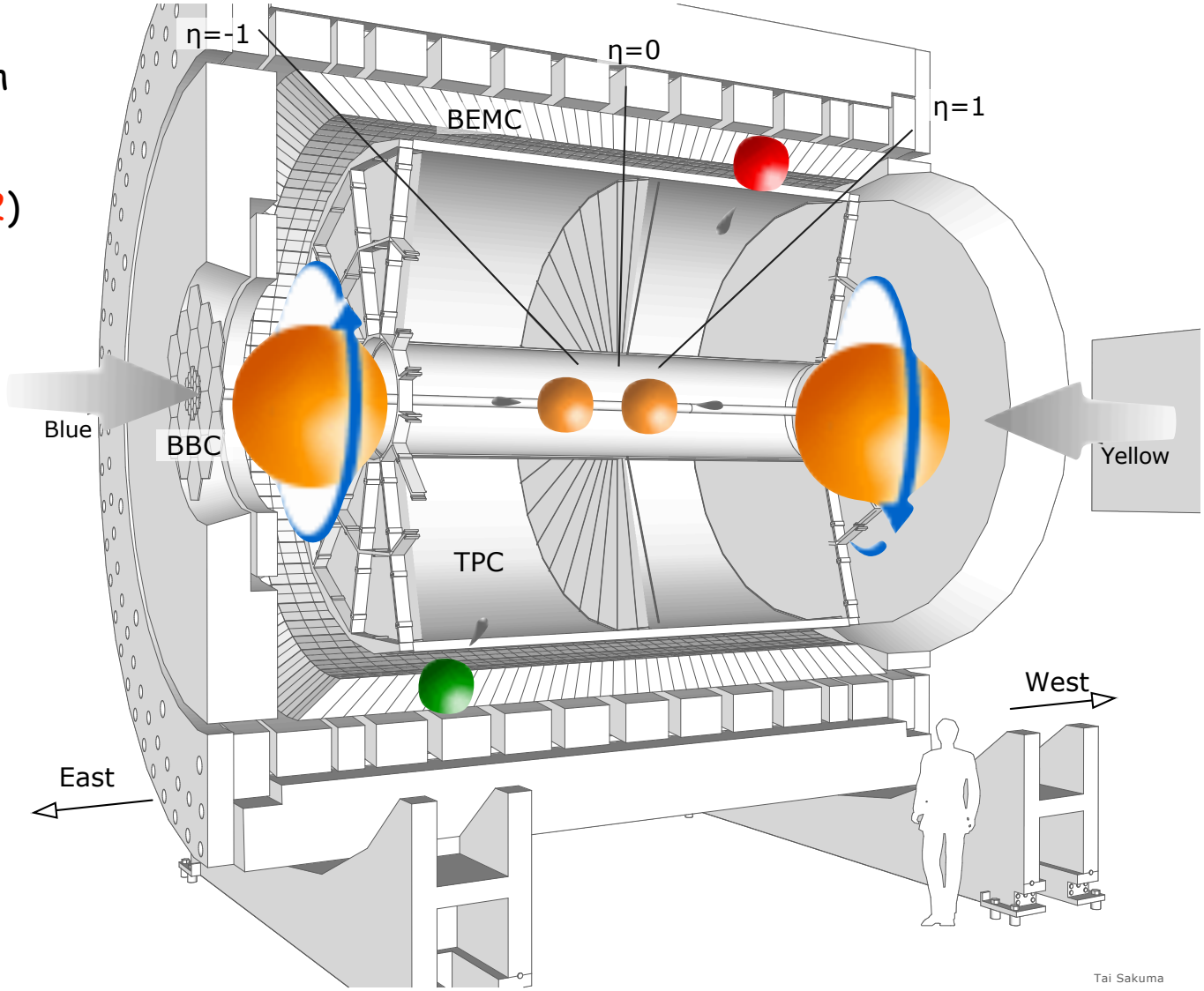

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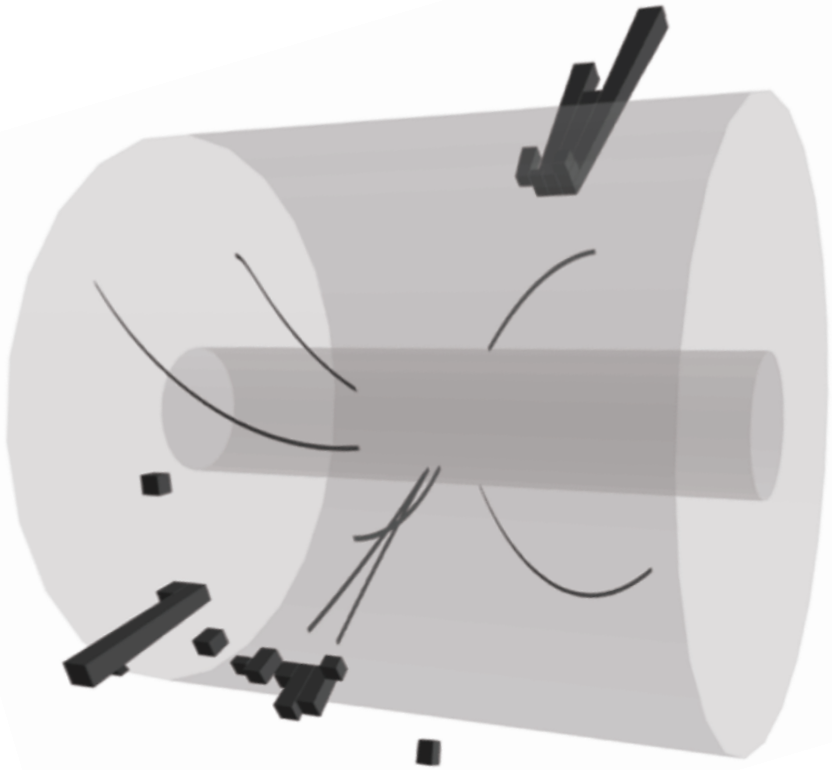
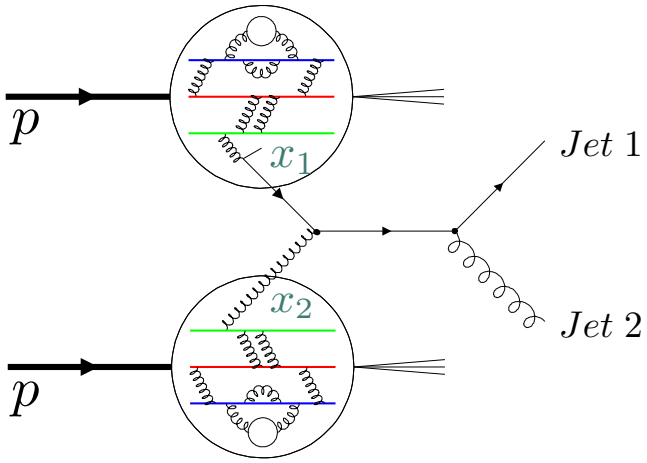
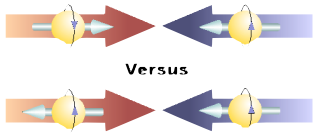


Experimental aspects - Asymmetry measurement

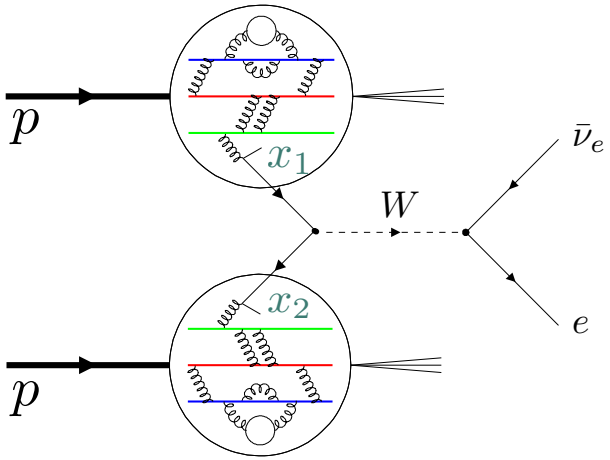
- Double and single longitudinal spin asymmetry measurements



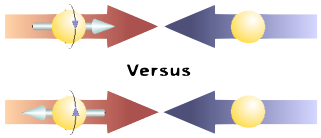
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$



- Require concurrent measurements:
  - Longitudinal beam polarization $P_{1(2)}$ at STAR IR
  - Direction of polarization vector
  - Relative luminosity R of bunch crossings with different spin directions
  - Spin dependent yields of process of interest Nij

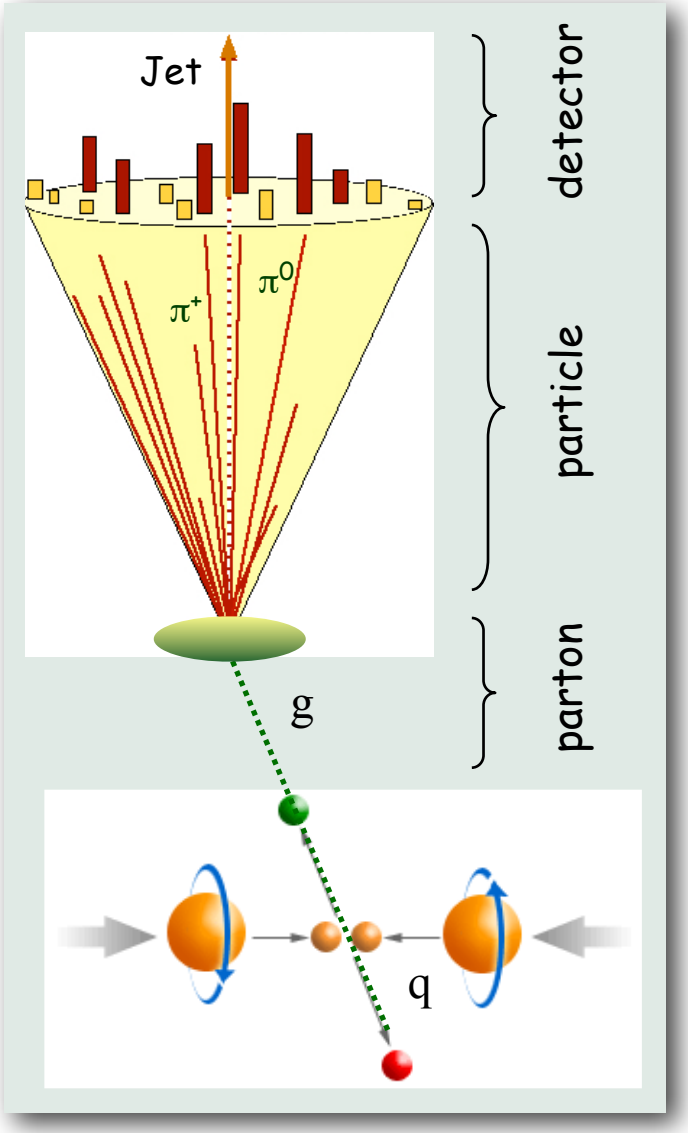


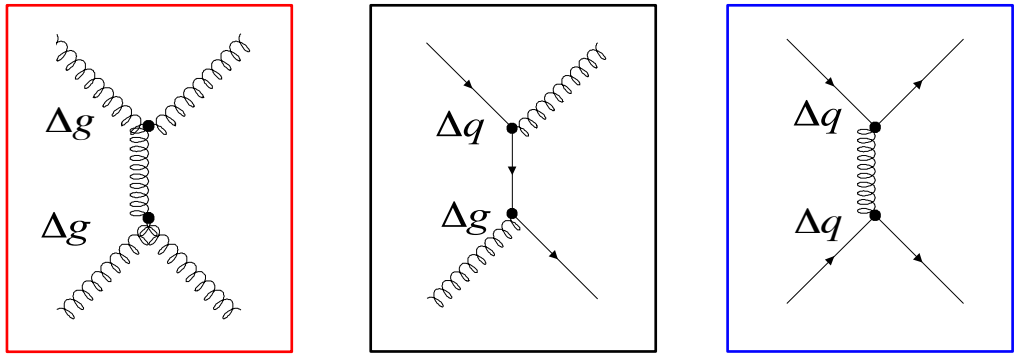
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P} \frac{N_+ - R N_-}{N_+ + R N_-}$$



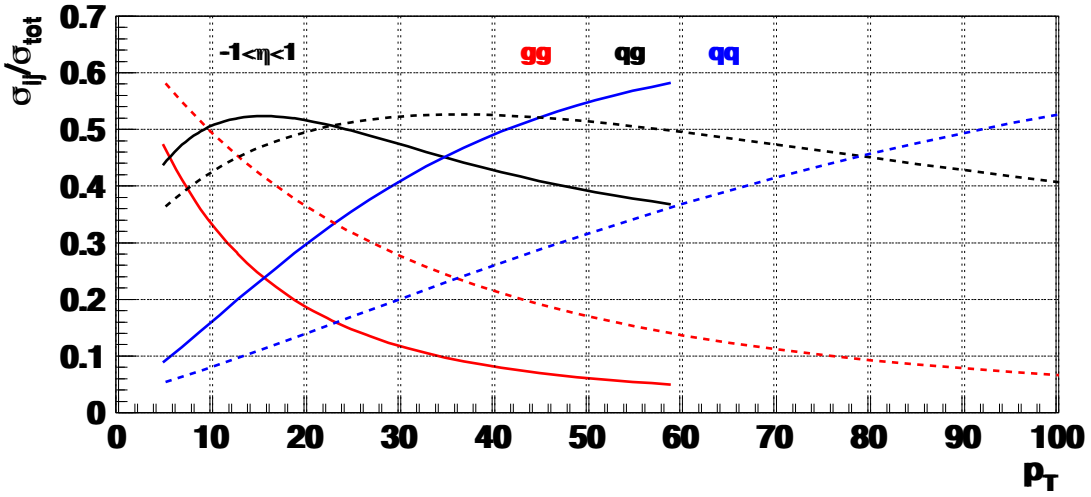
Gluon measurements: Jet/Hadron production

- RHIC gluon polarization: Inclusive measurements





Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)



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Gluon measurements: Jet/Hadron production

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

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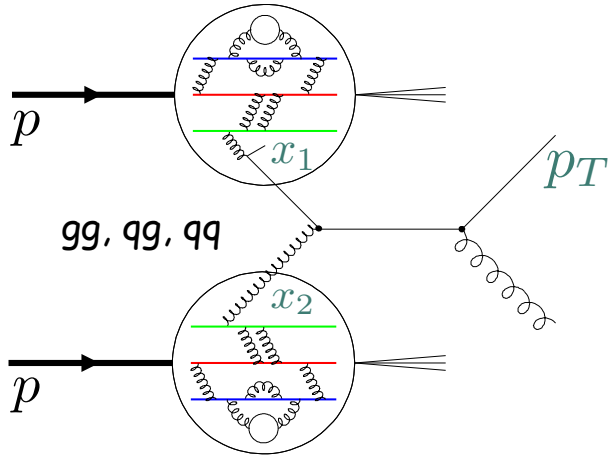

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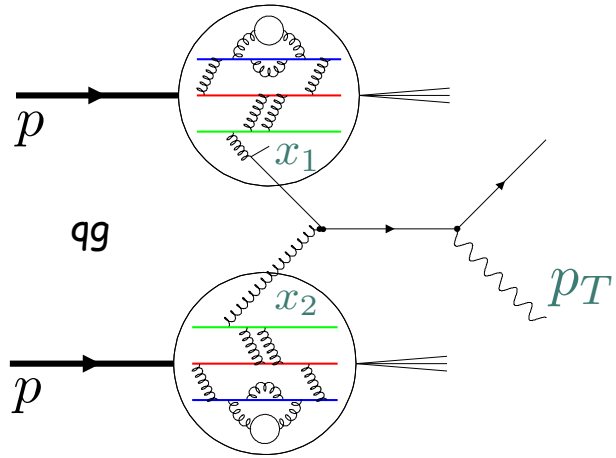

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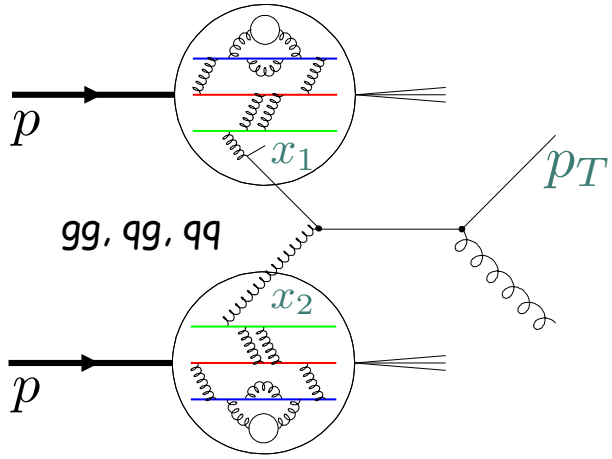

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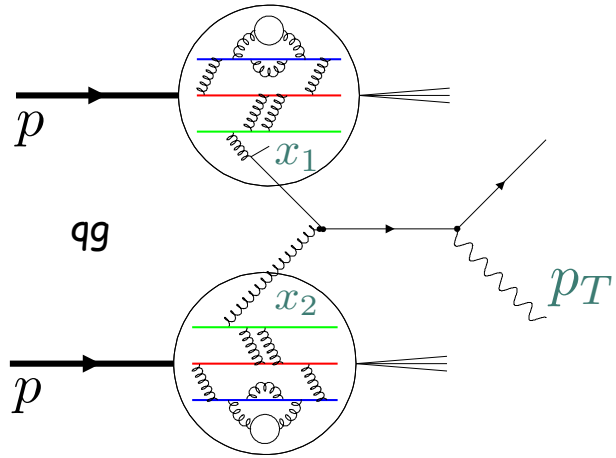

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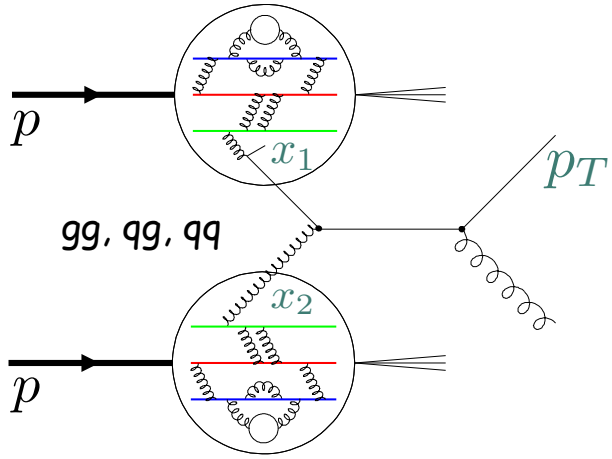

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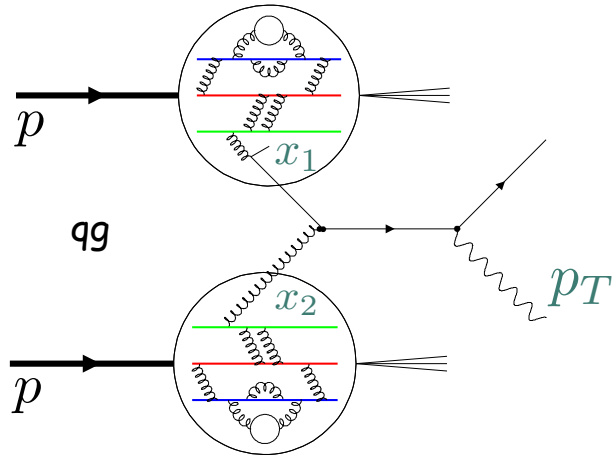

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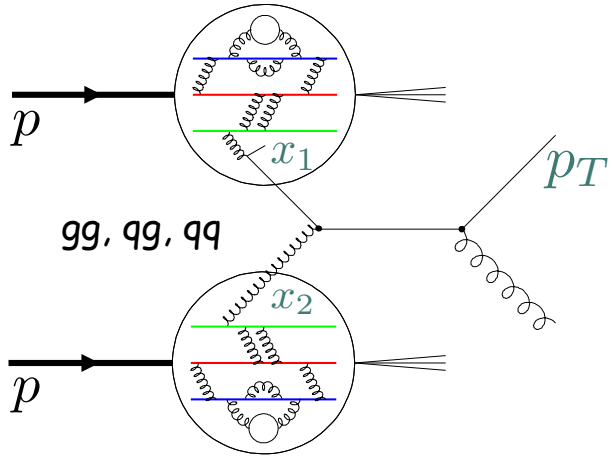

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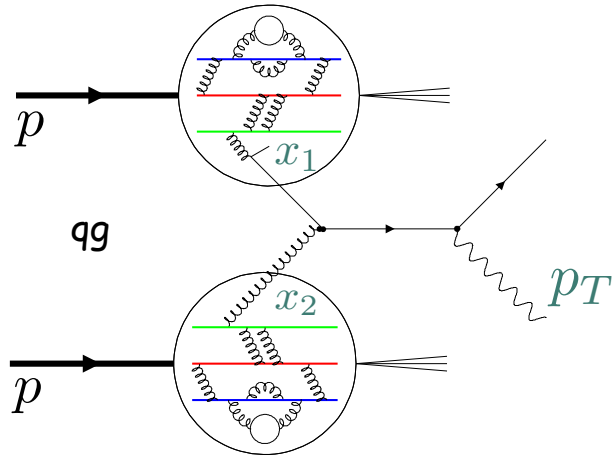

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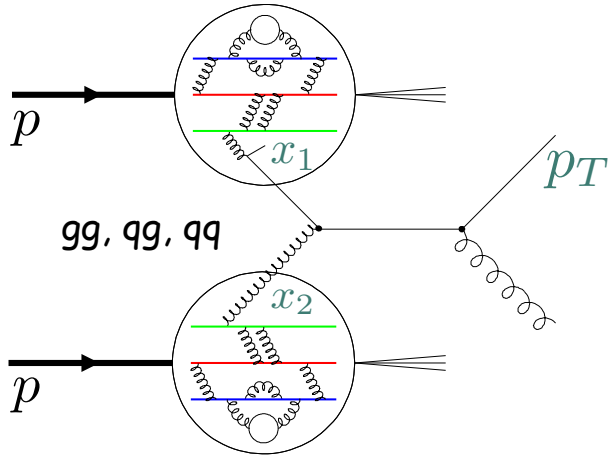

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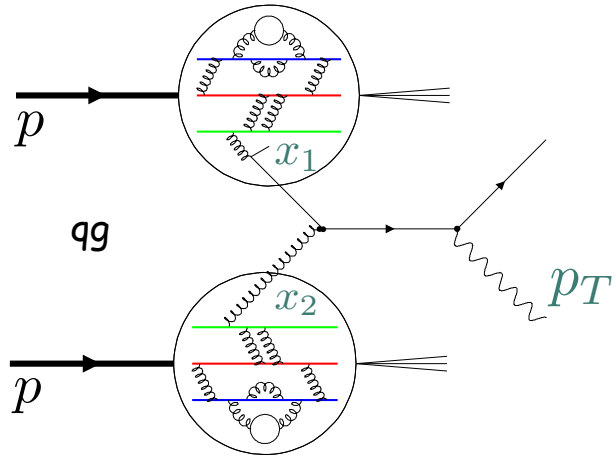

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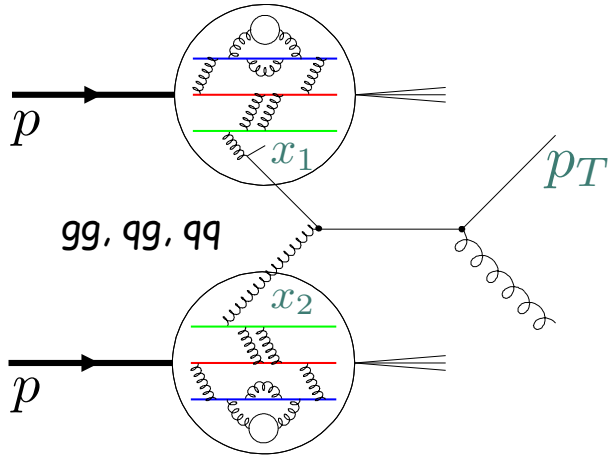

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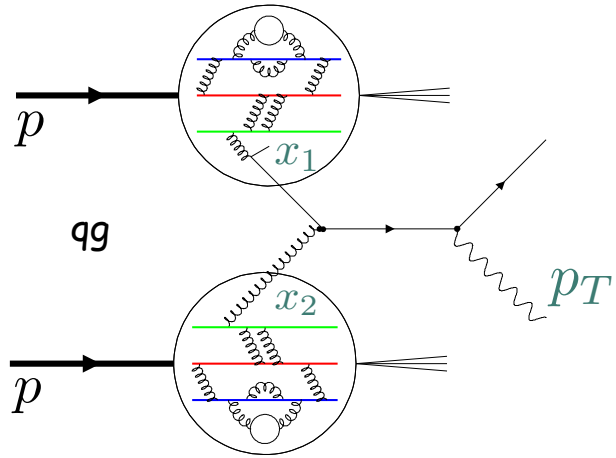

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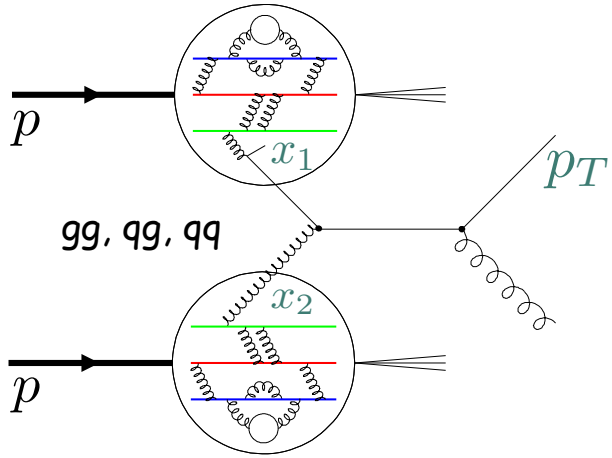
    - Full NLO framework exists ⇒ Input to Global QCD analysis



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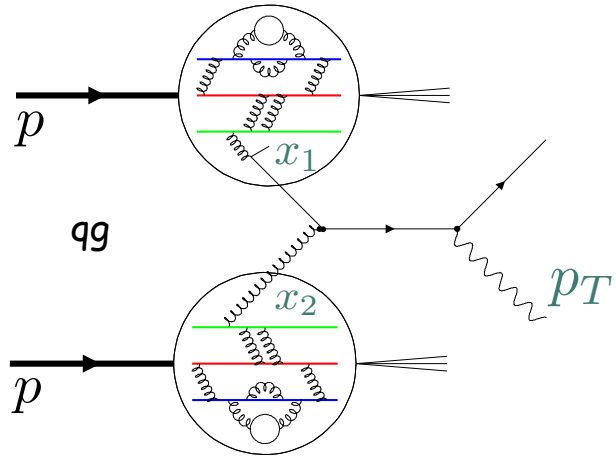
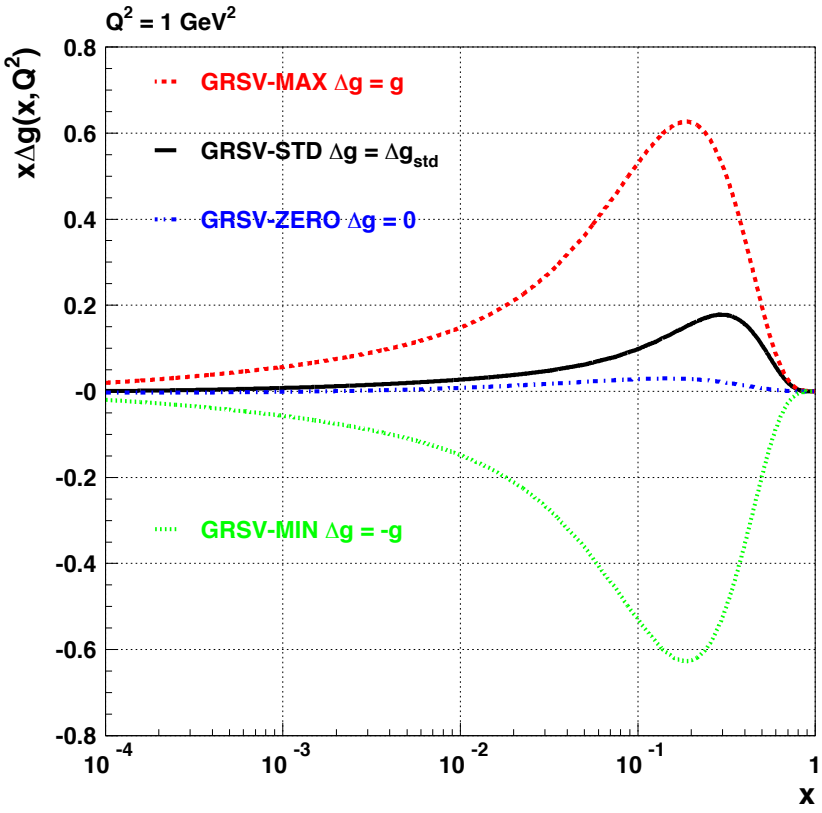


Photon-Jet production

Recent results - Gluon polarization program

Measurement: Connection of Δg and A_{LL}



$\Delta G(Q^2 = 1GeV^2) \approx 1.8$

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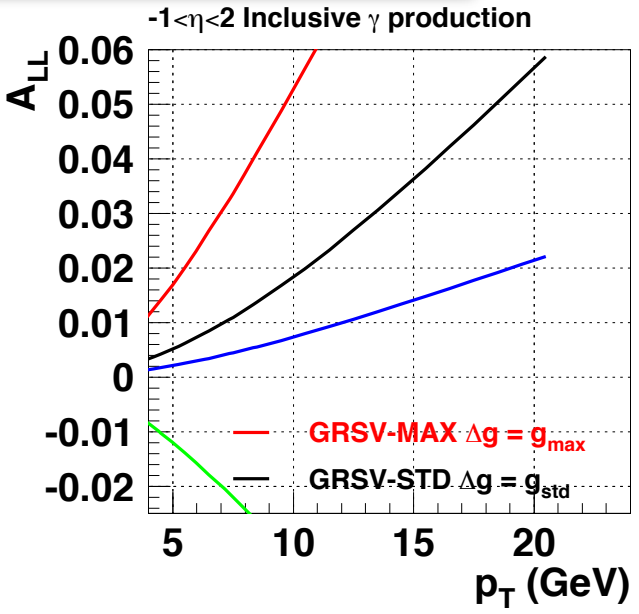
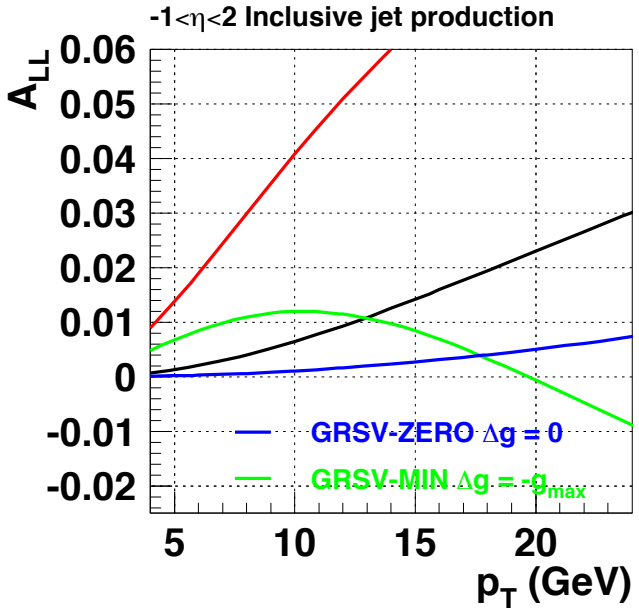
- Examine wide range in Δg: $-g < \Delta g < +g$
- GRSV-STD: Global QCD analysis of polarized DIS experiments only!

M. Gluck et al. PRD 63 (2001) 094005.

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$





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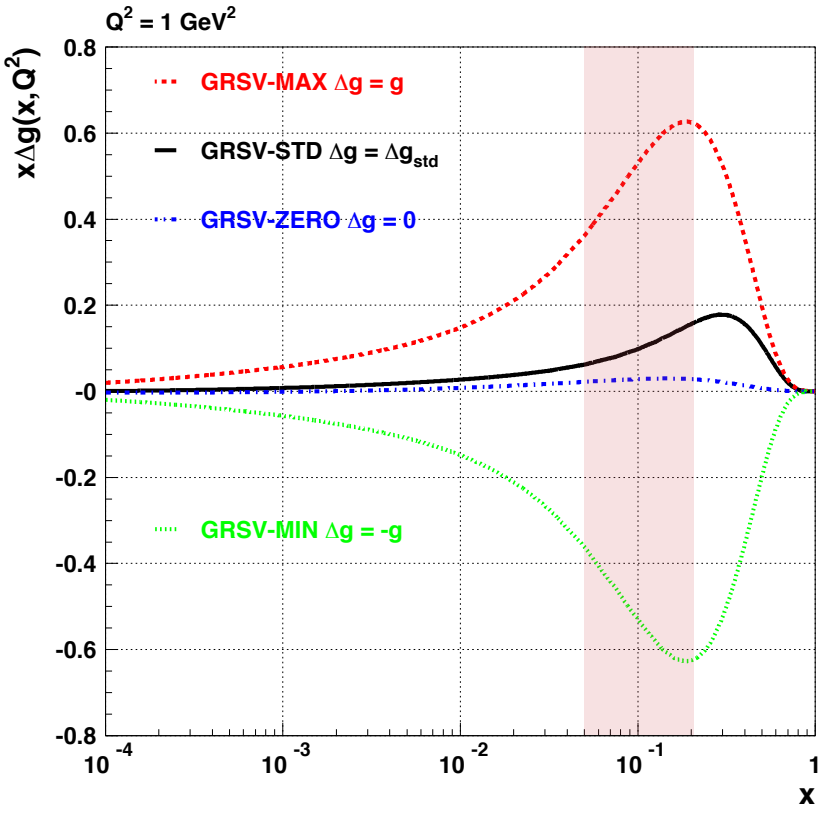

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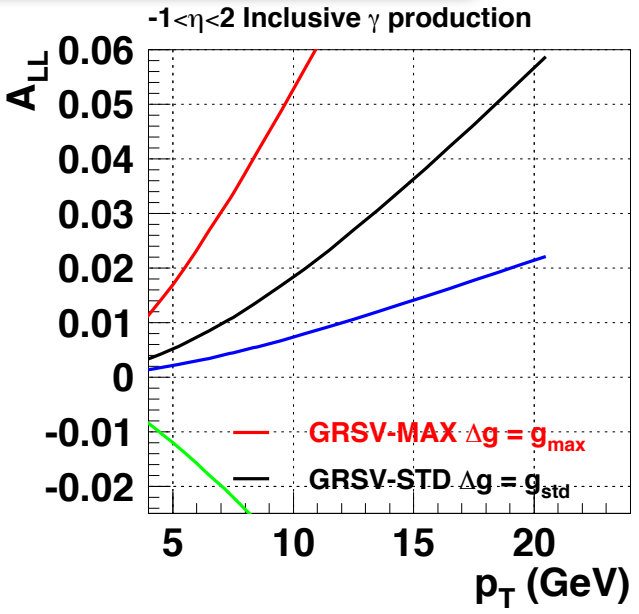

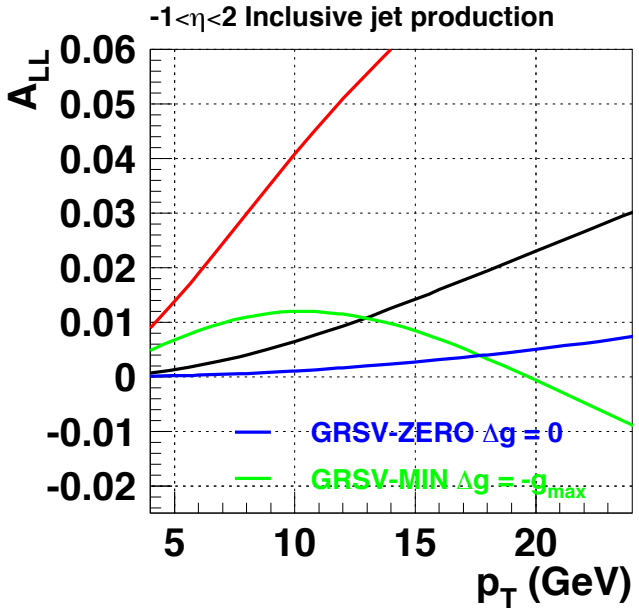

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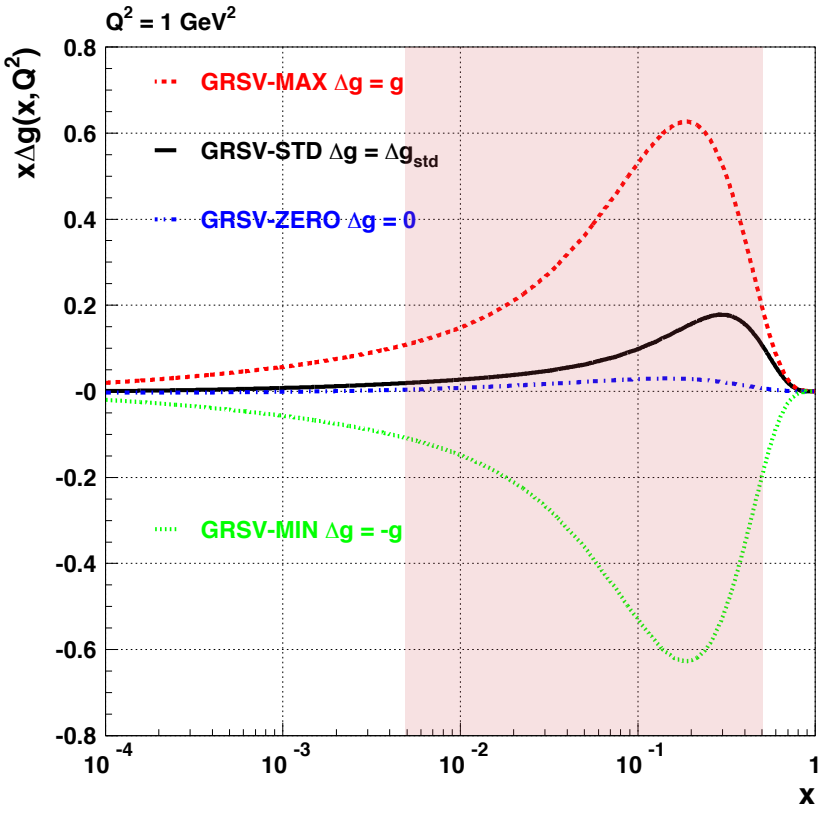

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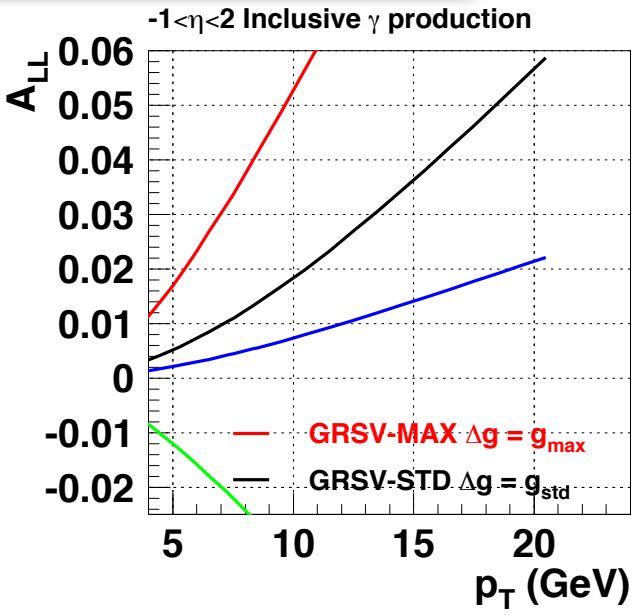
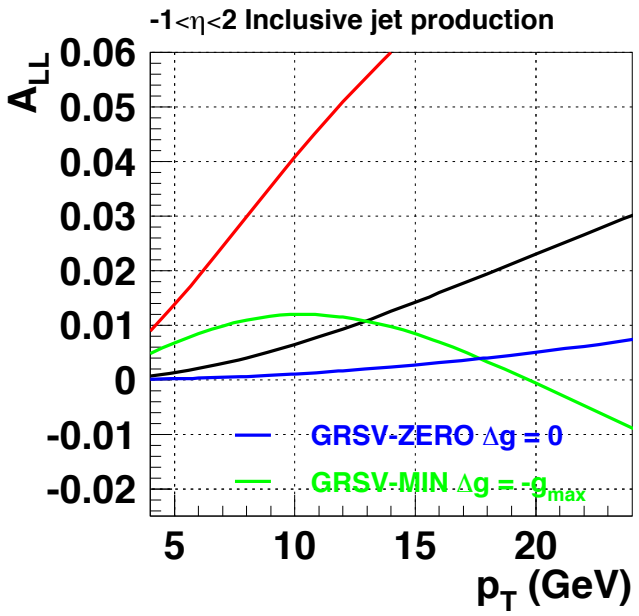
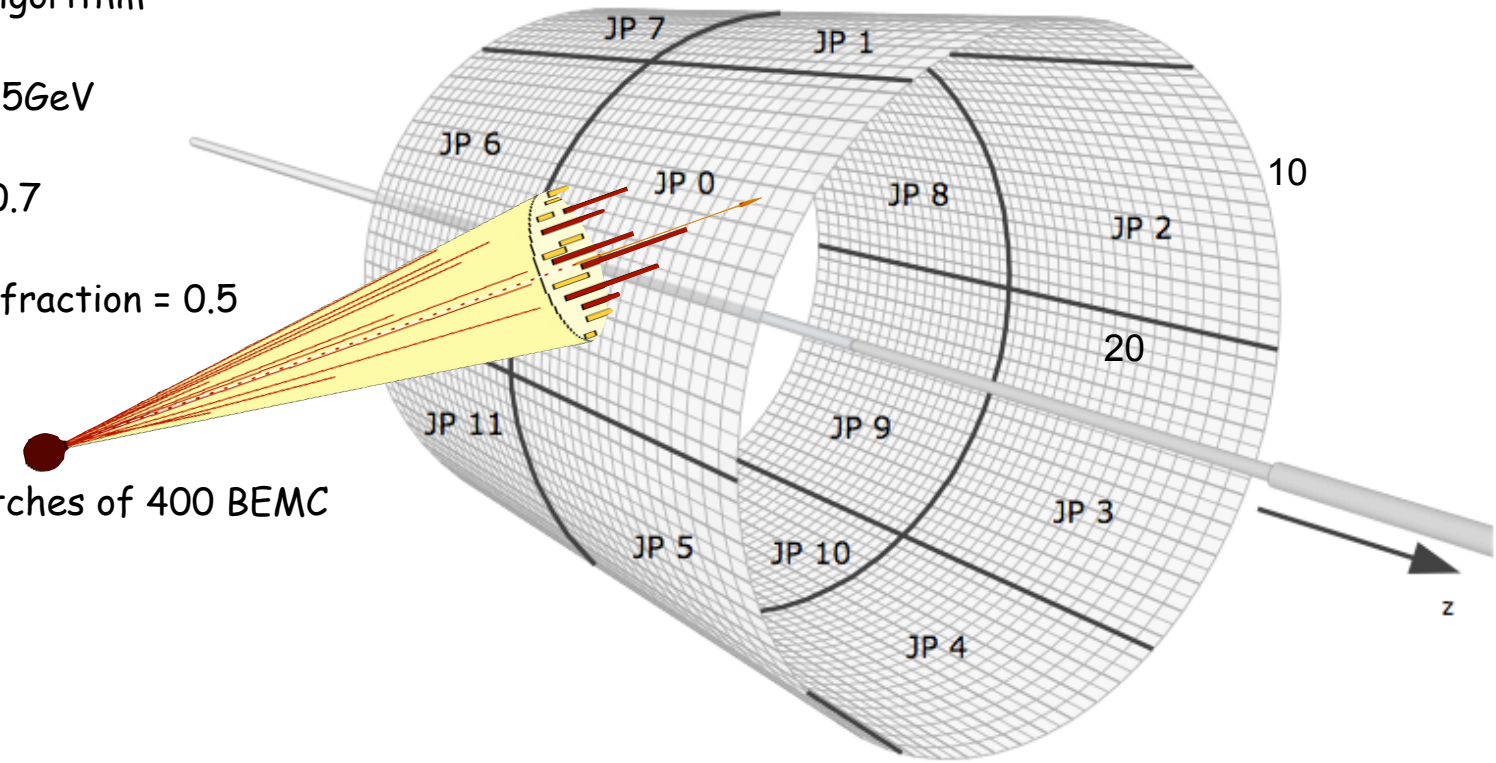




Recent results - Gluon polarization program

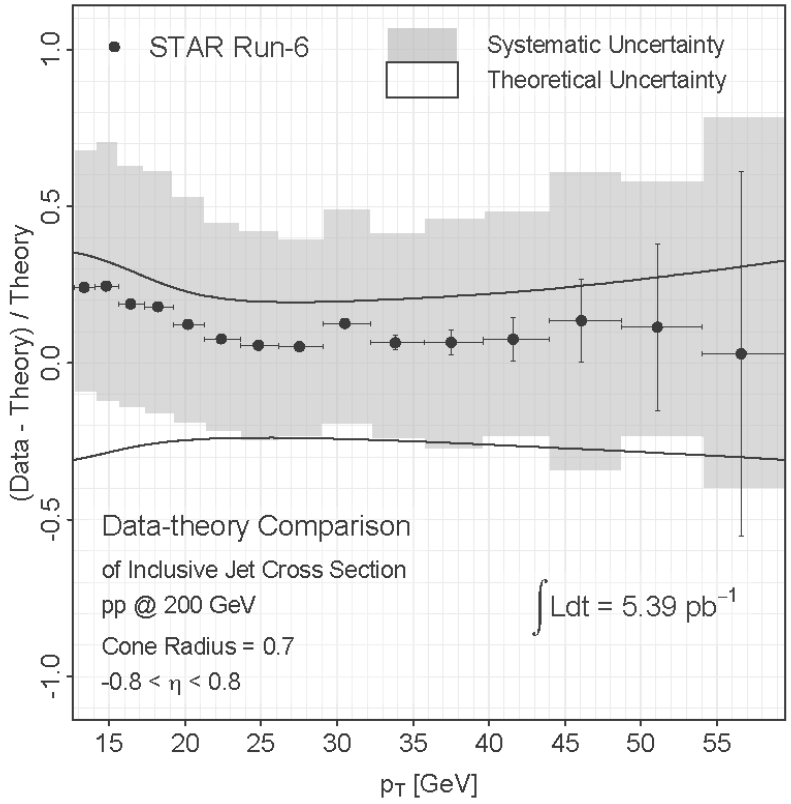
- Jet reconstruction / Inclusive Jet data sample
  - Jet algorithm:
    - Mid-point cone algorithm
    - Seed energy = 0.5GeV
    - Cone radius R = 0.7
    - Splitting/merge fraction = 0.5
  - Jet trigger:
    - 1 X 1 in Φ X η patches of 400 BEMC towers
  - Data sample:
    - 2009 A_{LL} analysis: L=20pb^{-1} / P=58%
    - 2006 cross-section: 5.39pb^{-1}

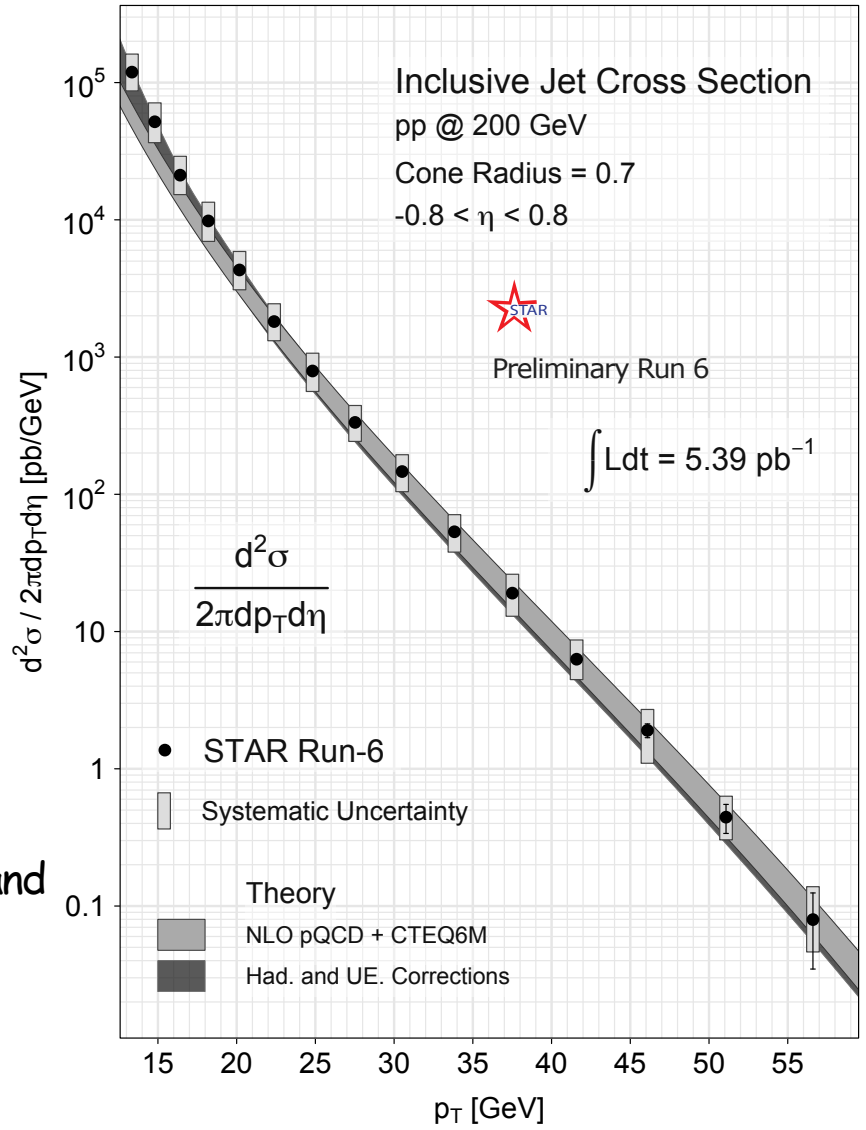
$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Recent results - Gluon polarization program

- Mid-rapidity Inclusive Jet cross-section measurement (Run 6)





- Data are well described by NLO pQCD plus hadronization and underlying event corrections
- Corrections are significant at low jet p_T

Recent results - Gluon polarization program

- Mid-rapidity Inclusive Jet A_{LL} measurement - Improved precision (Run 3/4, 5 and 6)

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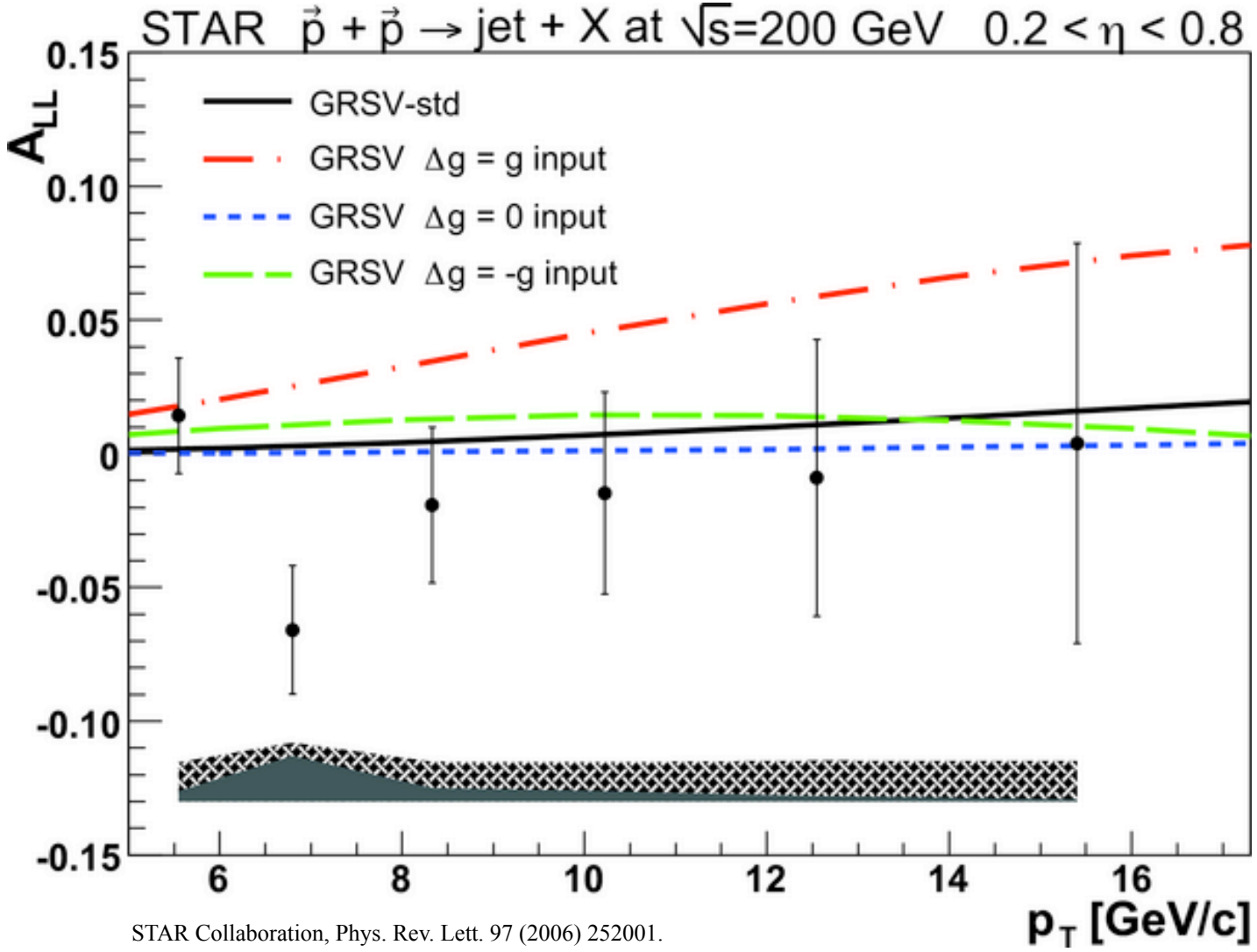

STAR Collaboration, Phys. Rev. Lett. 97 (2006) 252001.

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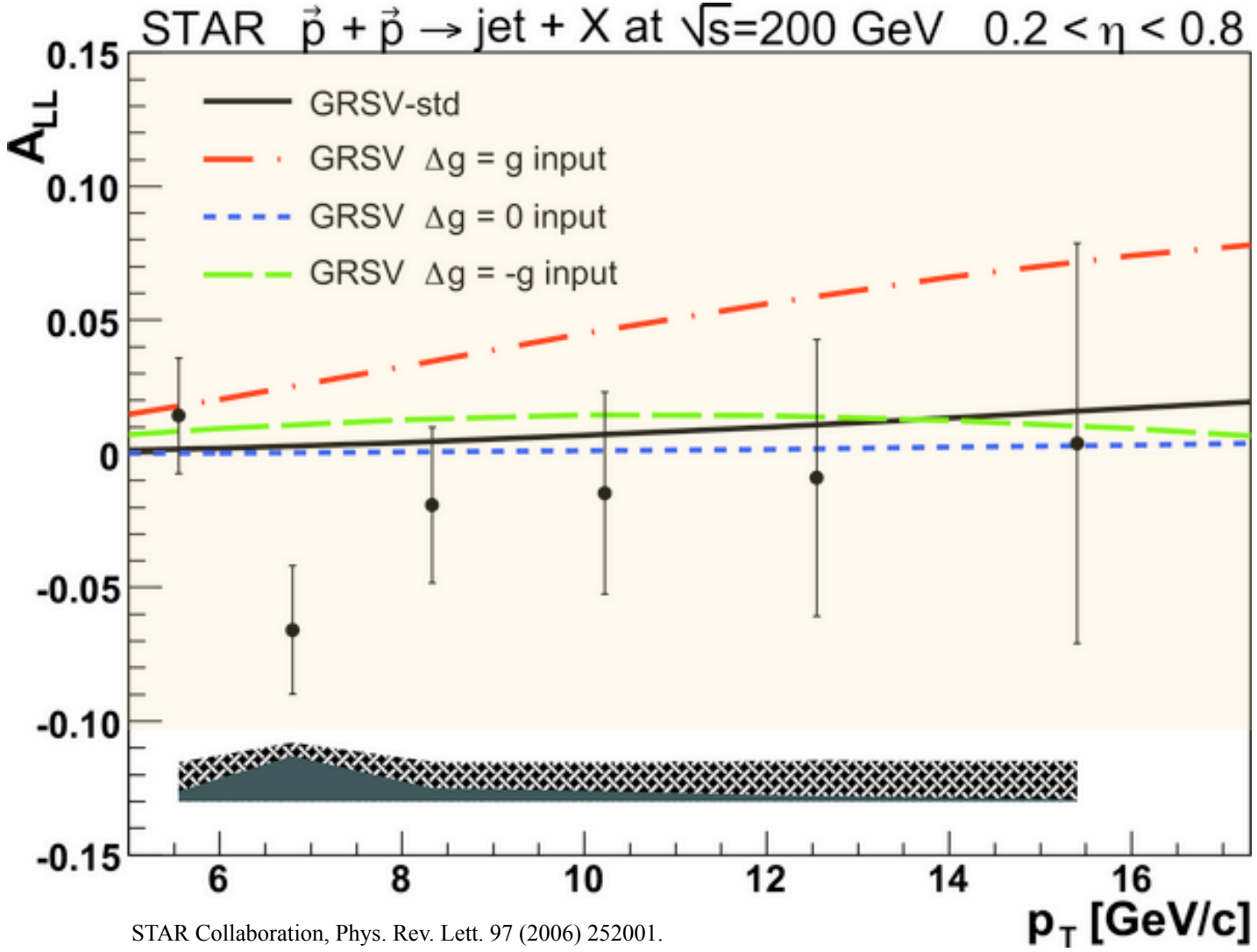

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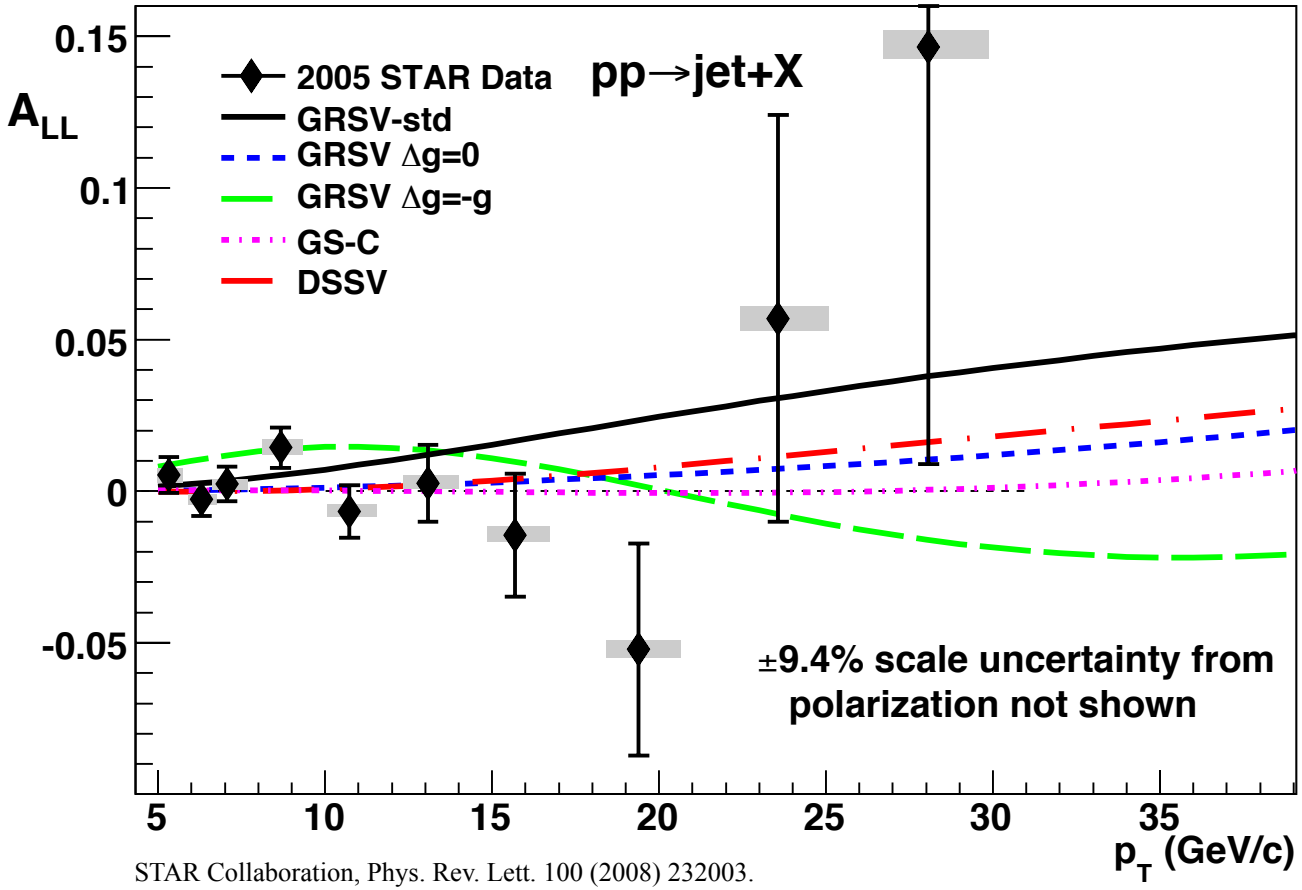

STAR Collaboration, Phys. Rev. Lett. 100 (2008) 232003.

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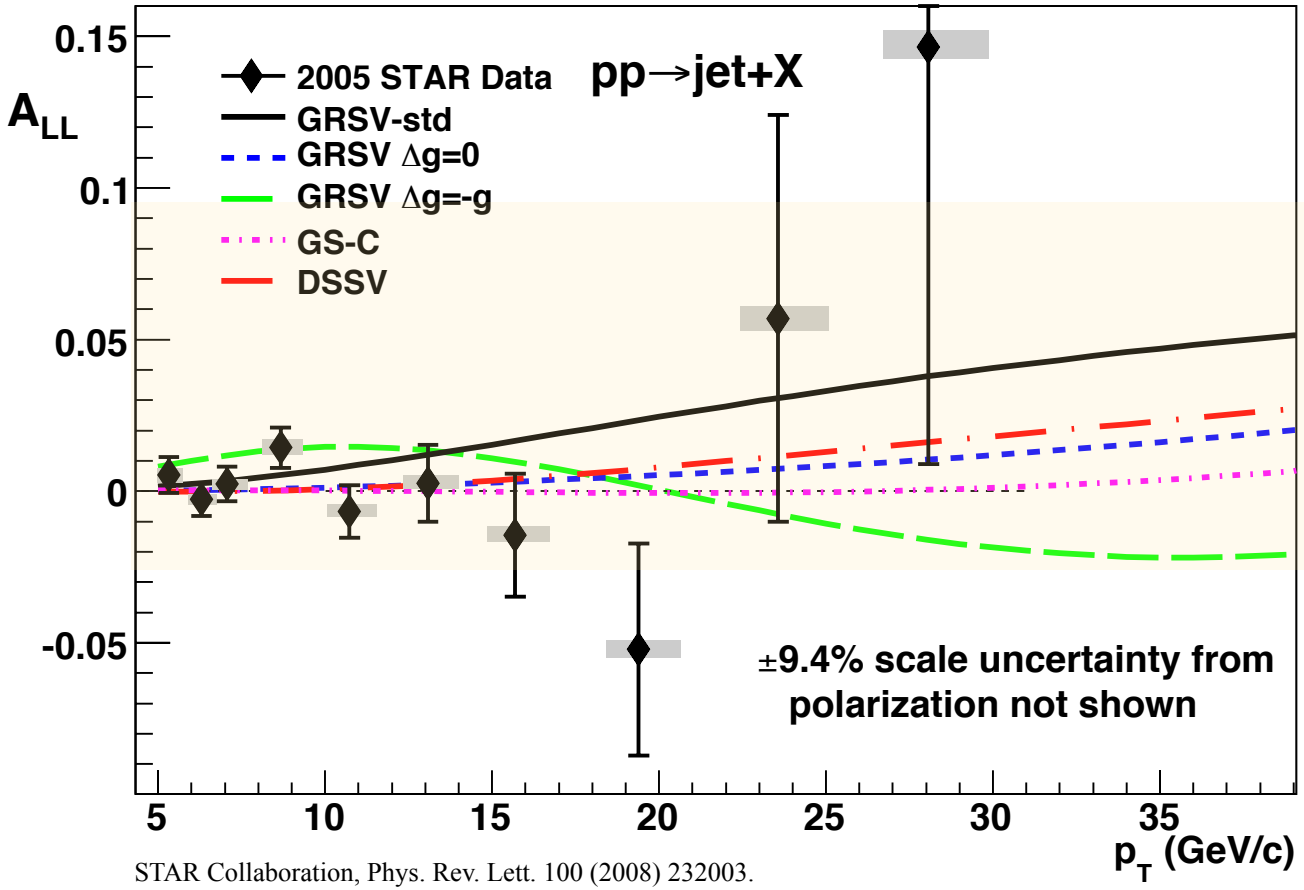

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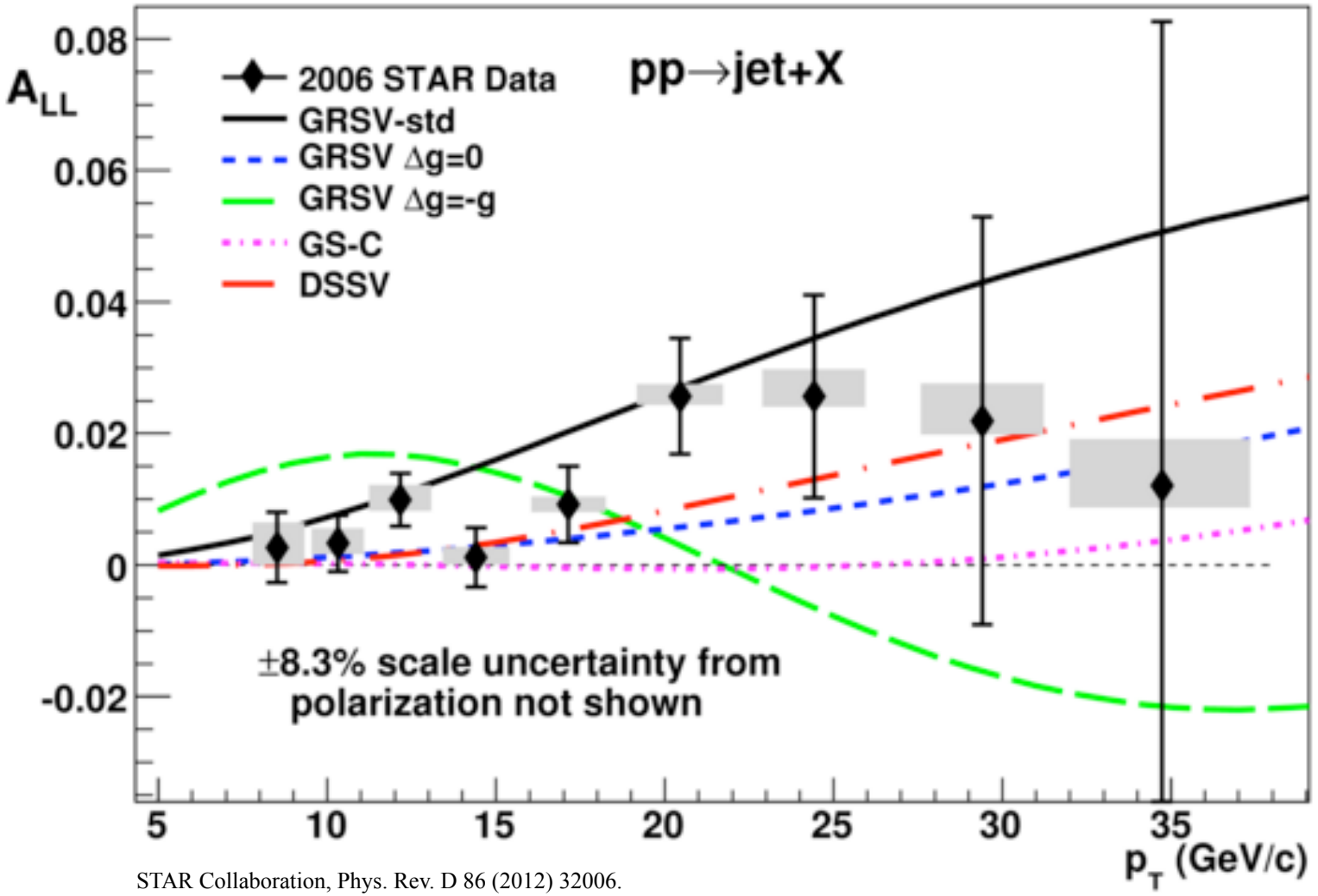

STAR Collaboration, Phys. Rev. D 86 (2012) 32006.

Recent results - Gluon polarization program

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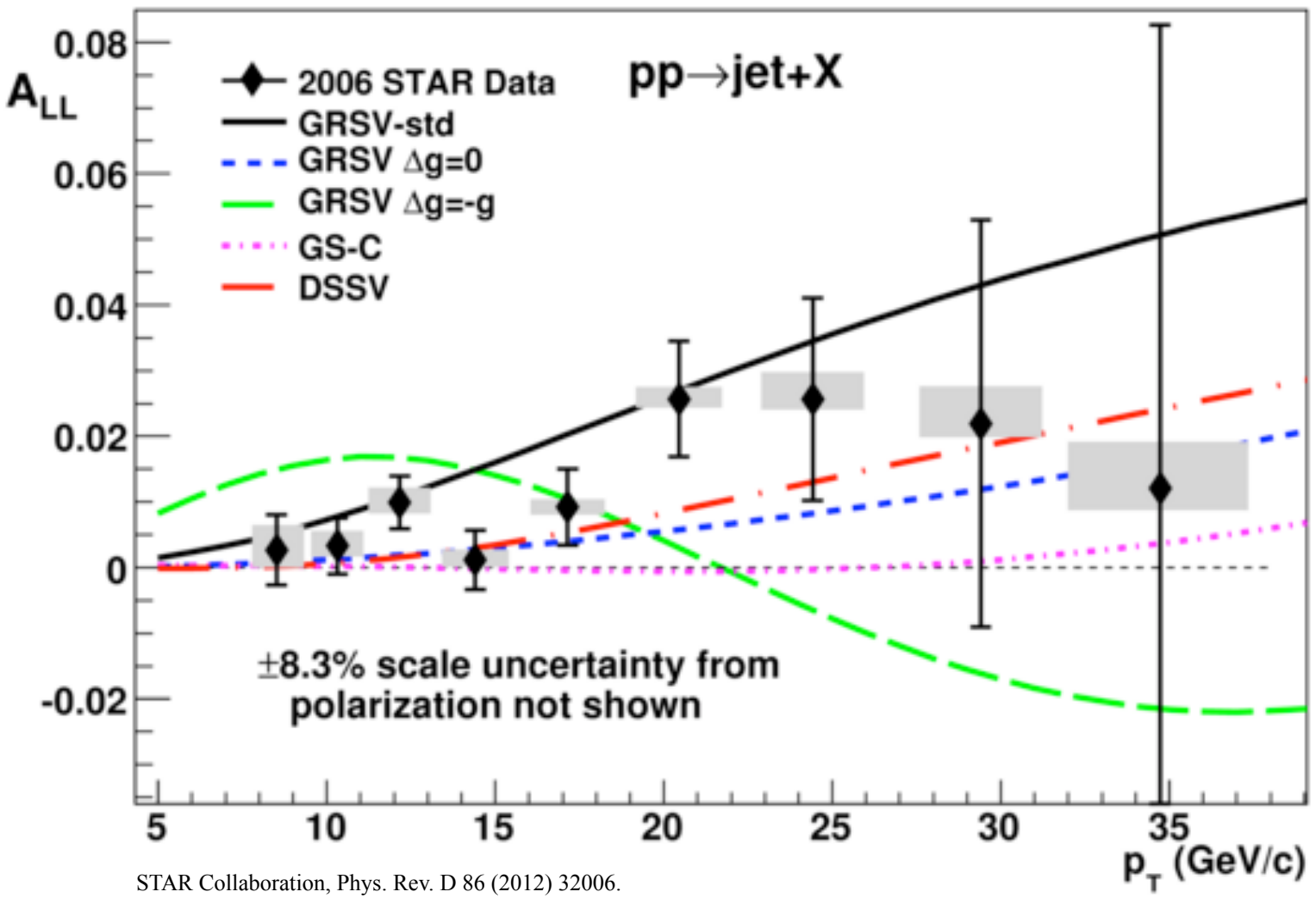

STAR Collaboration, Phys. Rev. D 86 (2012) 32006.

- Improved precision in A_{LL} from first Run 3/4 result to Run 5 and Run 6 results

Recent results - Gluon polarization program

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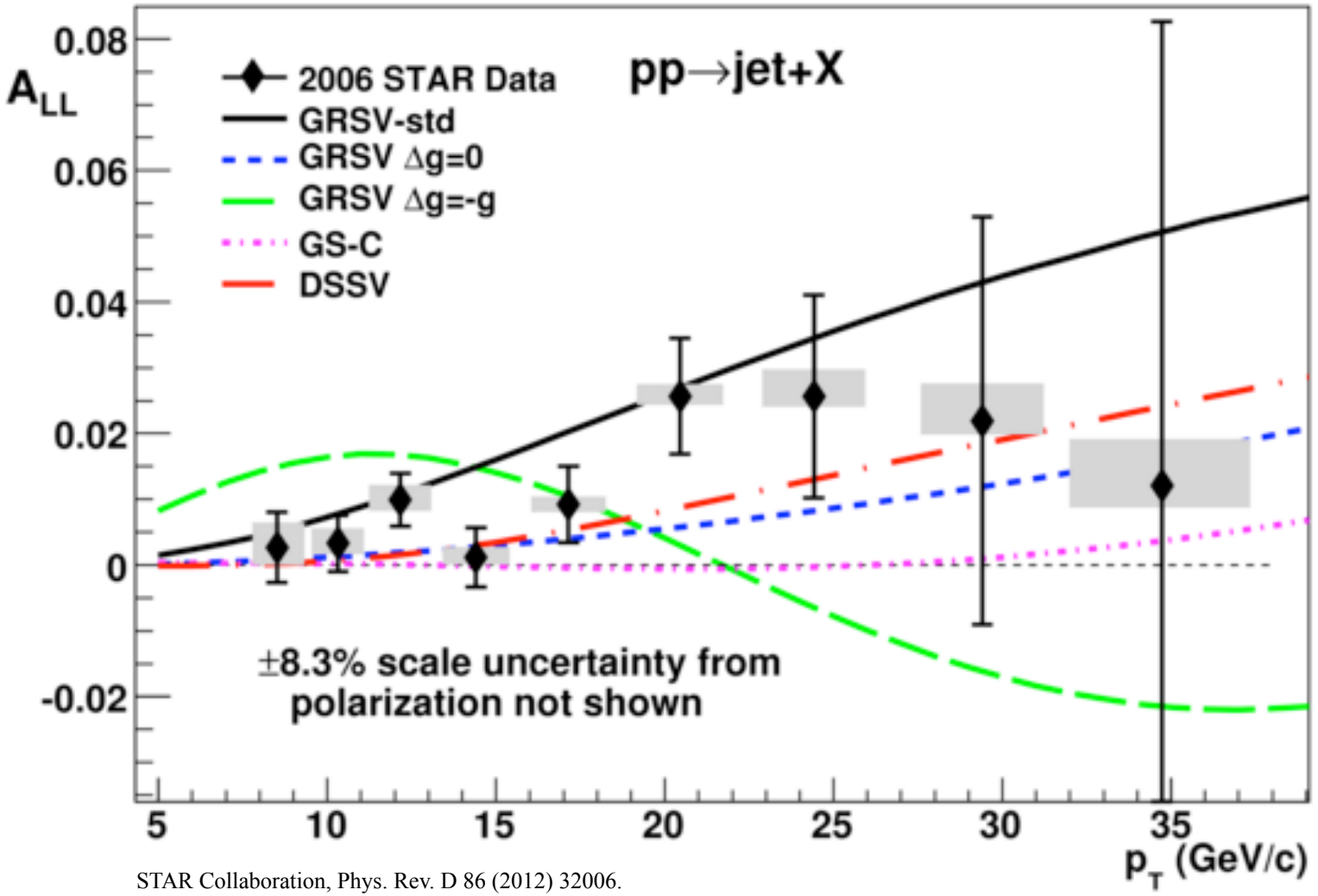

STAR Collaboration, Phys. Rev. D 86 (2012) 32006.

- Improved precision in A_{LL} from first Run 3/4 result to Run 5 and Run 6 results
- Run 5/6 results lead to significant constrain on Δg in global analysis (DSSV)

Recent results - Gluon polarization program

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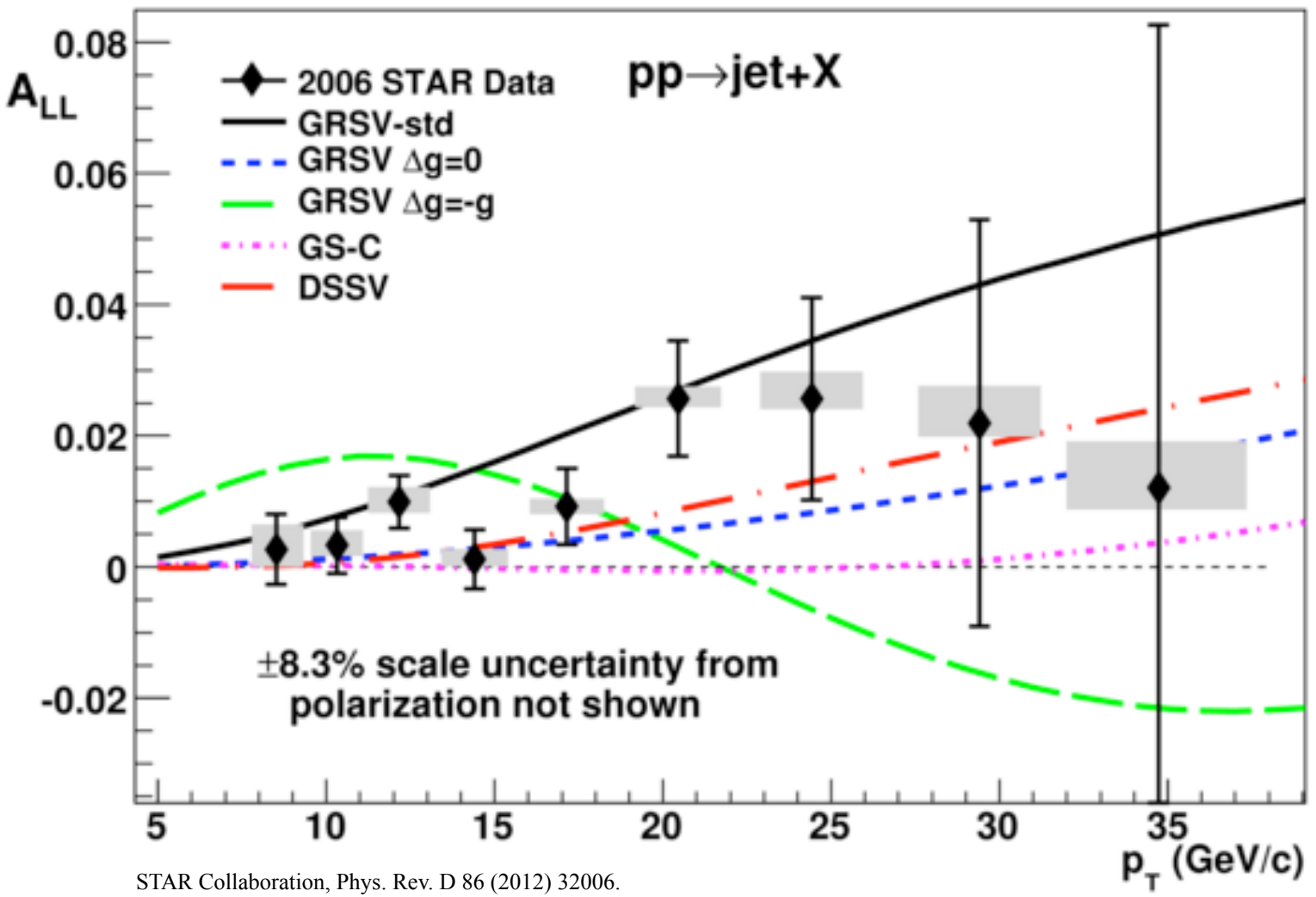
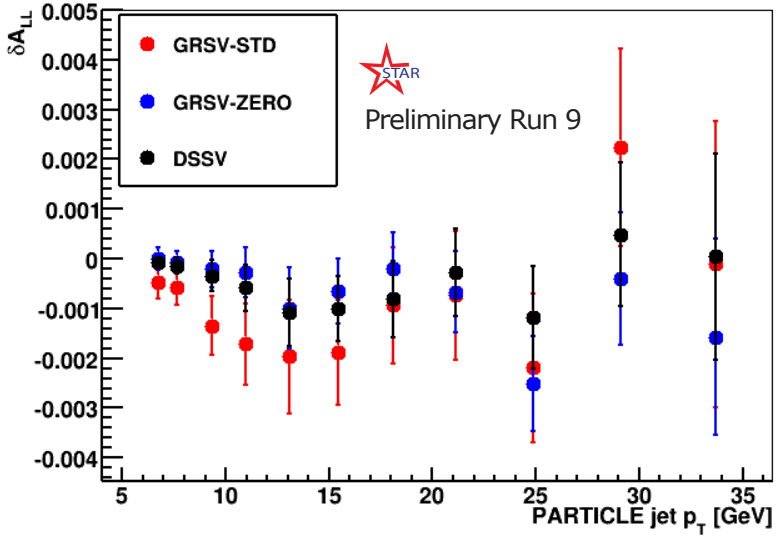


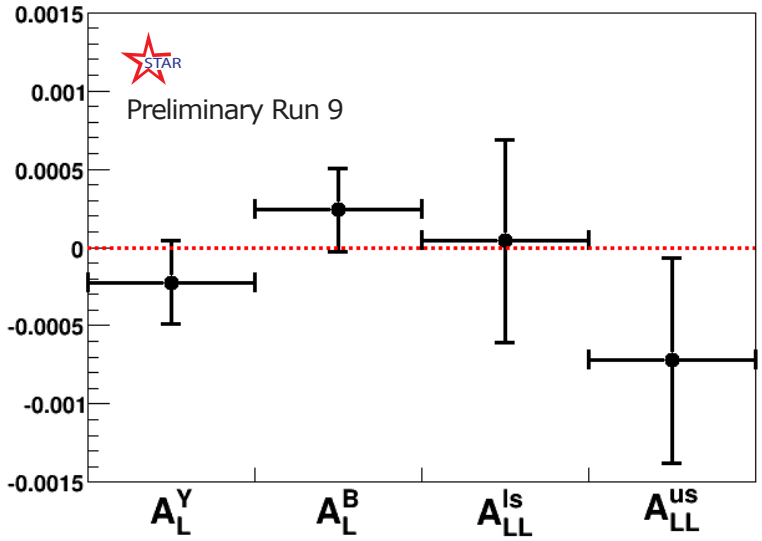
STAR Collaboration, Phys. Rev. D 86 (2012) 32006.

- Improved precision in A_{LL} from first Run 3/4 result to Run 5 and Run 6 results
- Run 5/6 results lead to significant constrain on Δg in global analysis (DSSV)
- Next: Run 9

Recent results - Gluon polarization program

- Mid-rapidity Inclusive Jet A_{LL} systematics (Run 9)
  - Point-to-point systematics:
    - Non-collision background: $1.9 \cdot 10^{-4}$
    - Residual transverse polarization: $6.4 \cdot 10^{-4}$
    - Trigger and reconstruction bias: $15 \cdot 10^{-4}$
  - Correlated systematics:
    - Relative luminosity: $15 \cdot 10^{-4}$
    - Scale uncertainty from beam polarization: 8.8%
    - p_T (horizontal) uncertainties: 4.6%
  - False asymmetry consistent with zero!





Recent results - Gluon polarization program

- Mid-rapidity Inclusive Jet A_{LL} measurement (Run 9)

Recent results - Gluon polarization program

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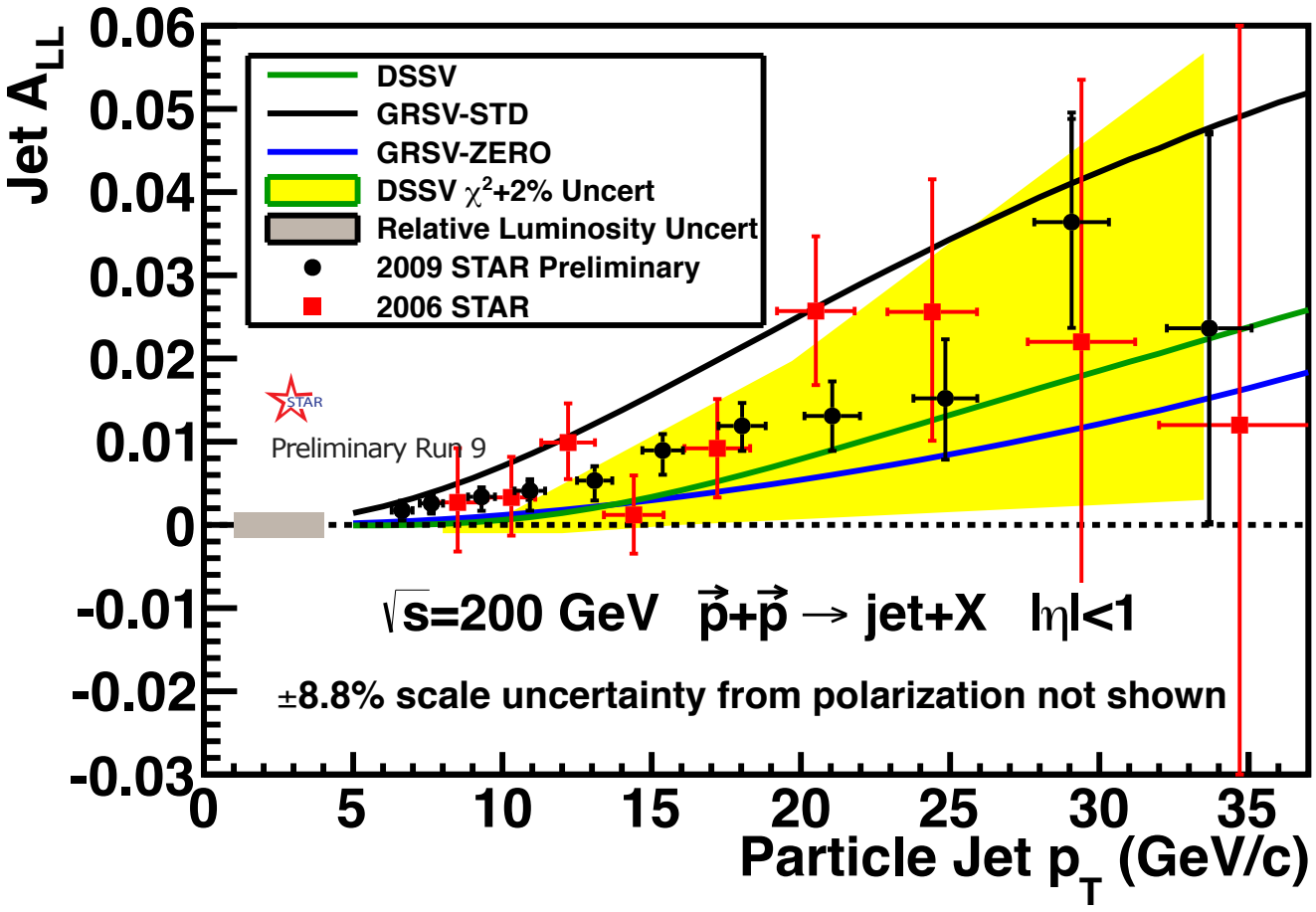

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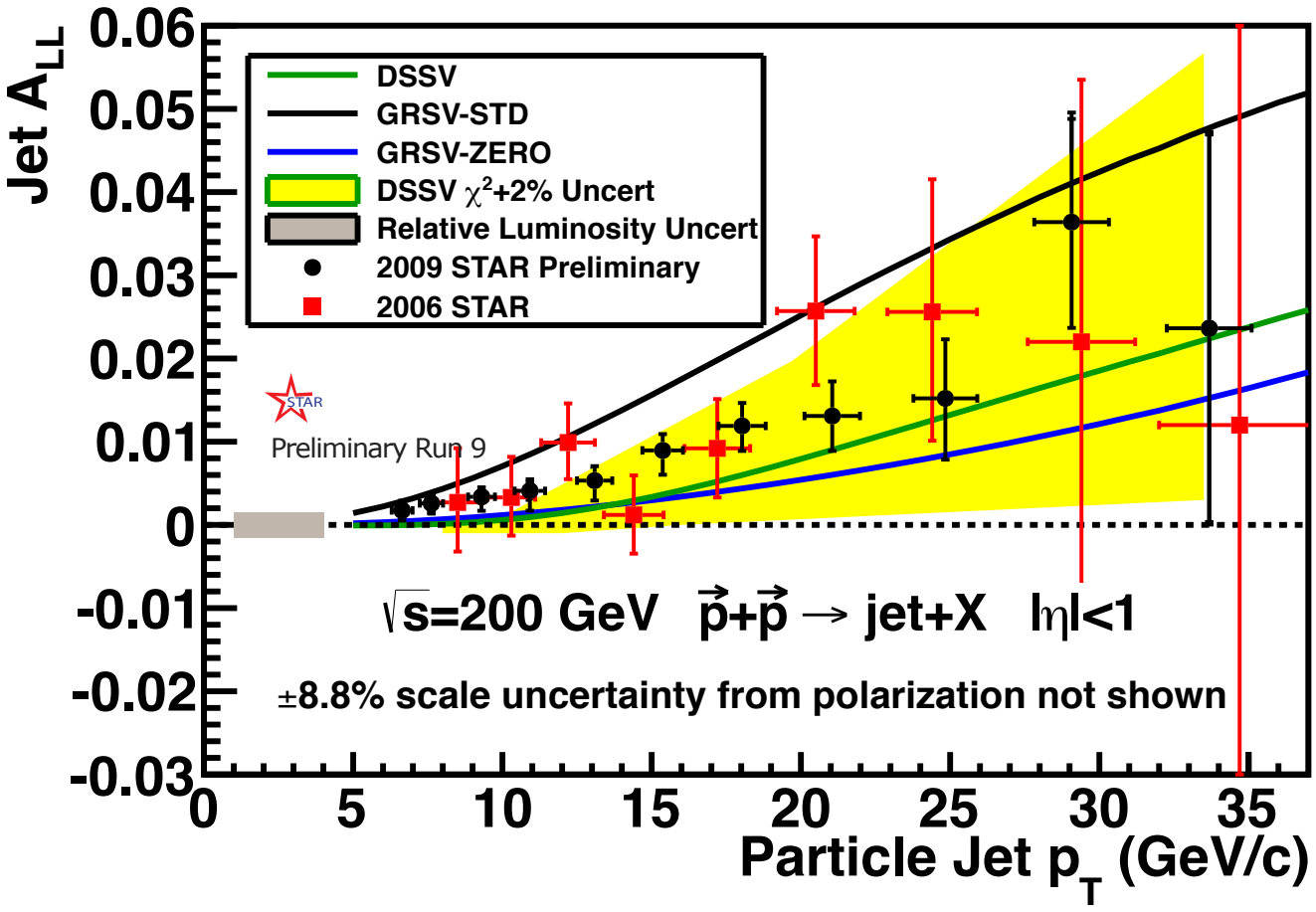

- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO

Recent results - Gluon polarization program

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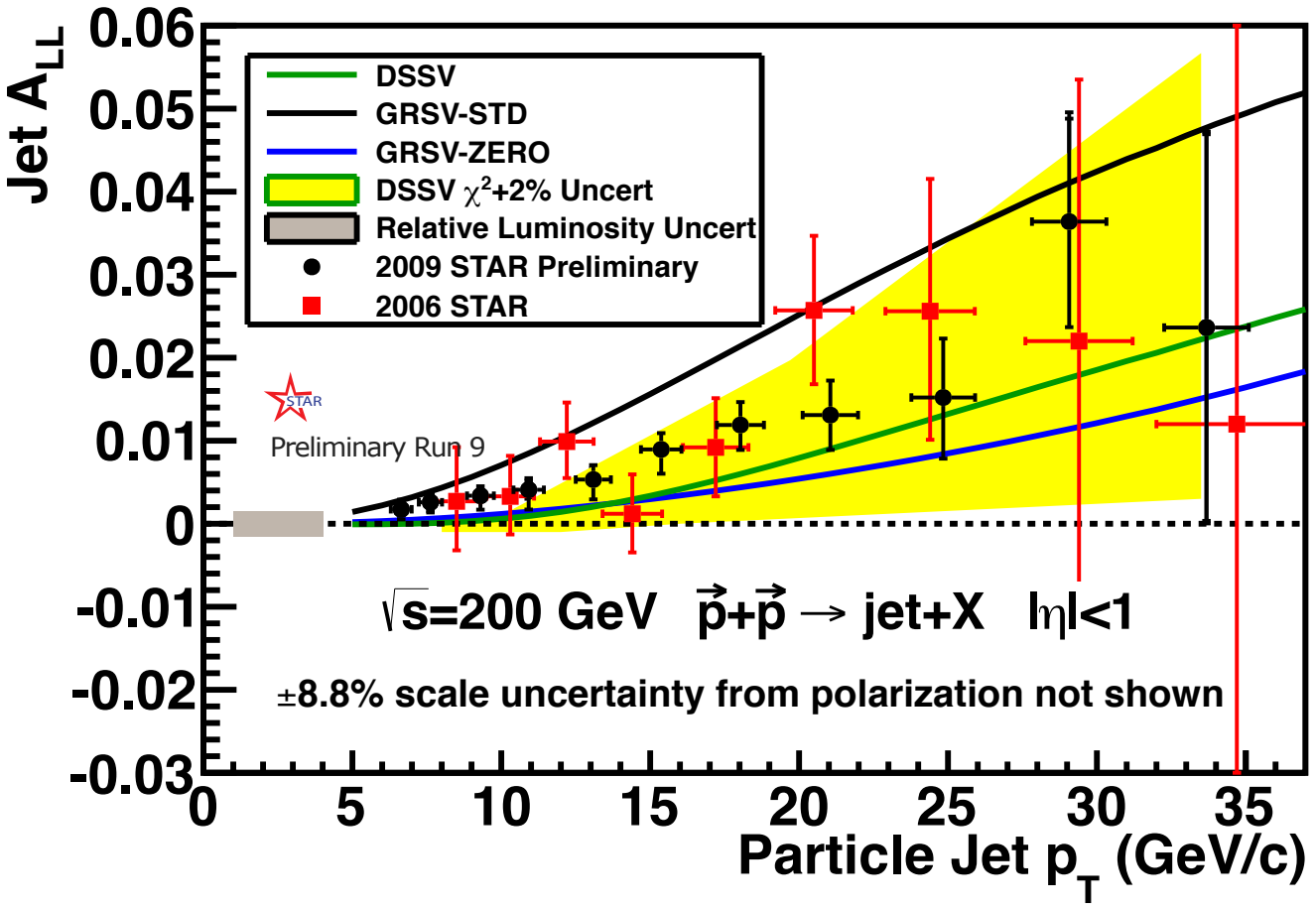

- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO
- Run 9 A_{LL} measurement between GRSV-STD and DSSV / Clearly above at low p_T

Recent results - Gluon polarization program

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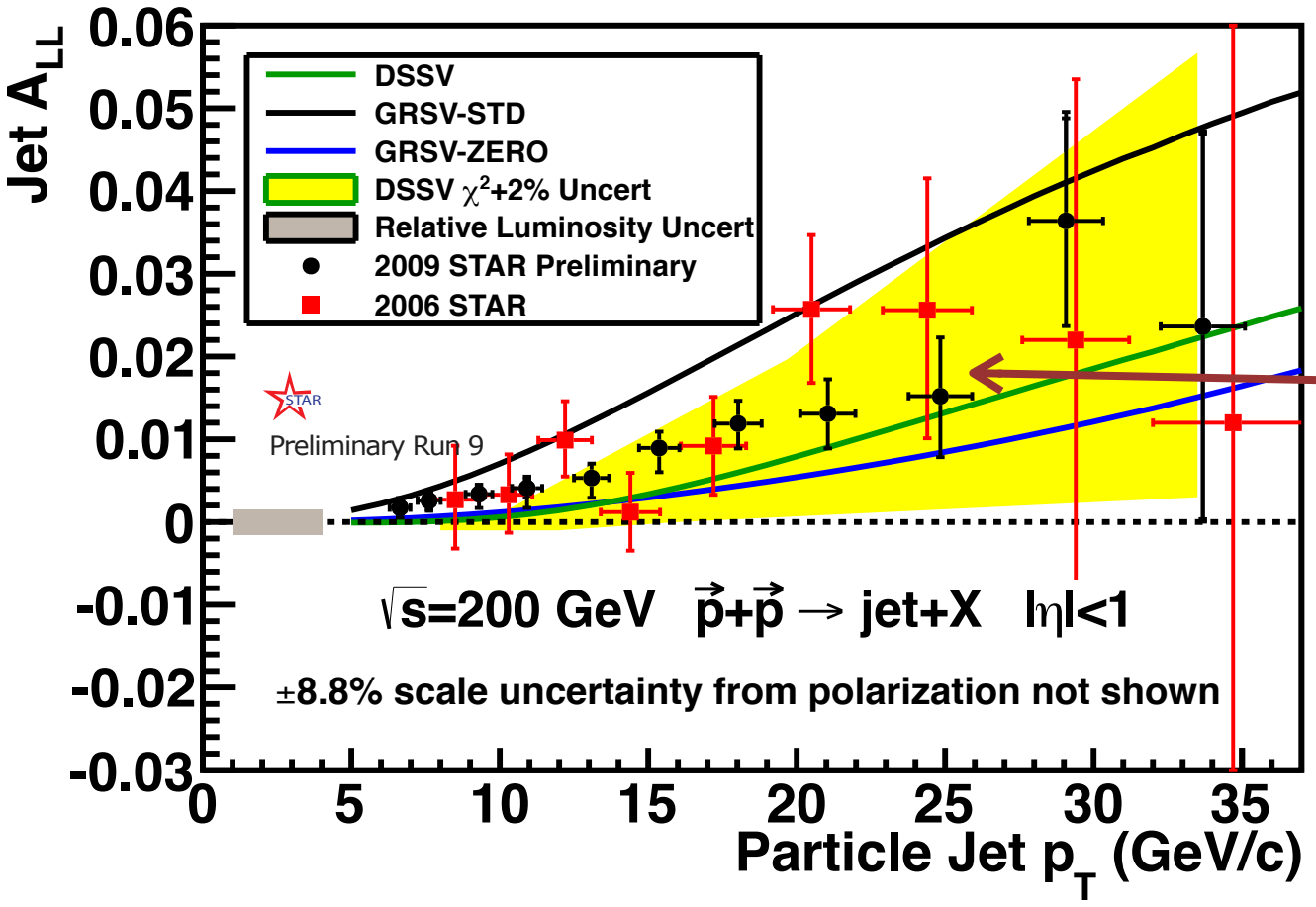

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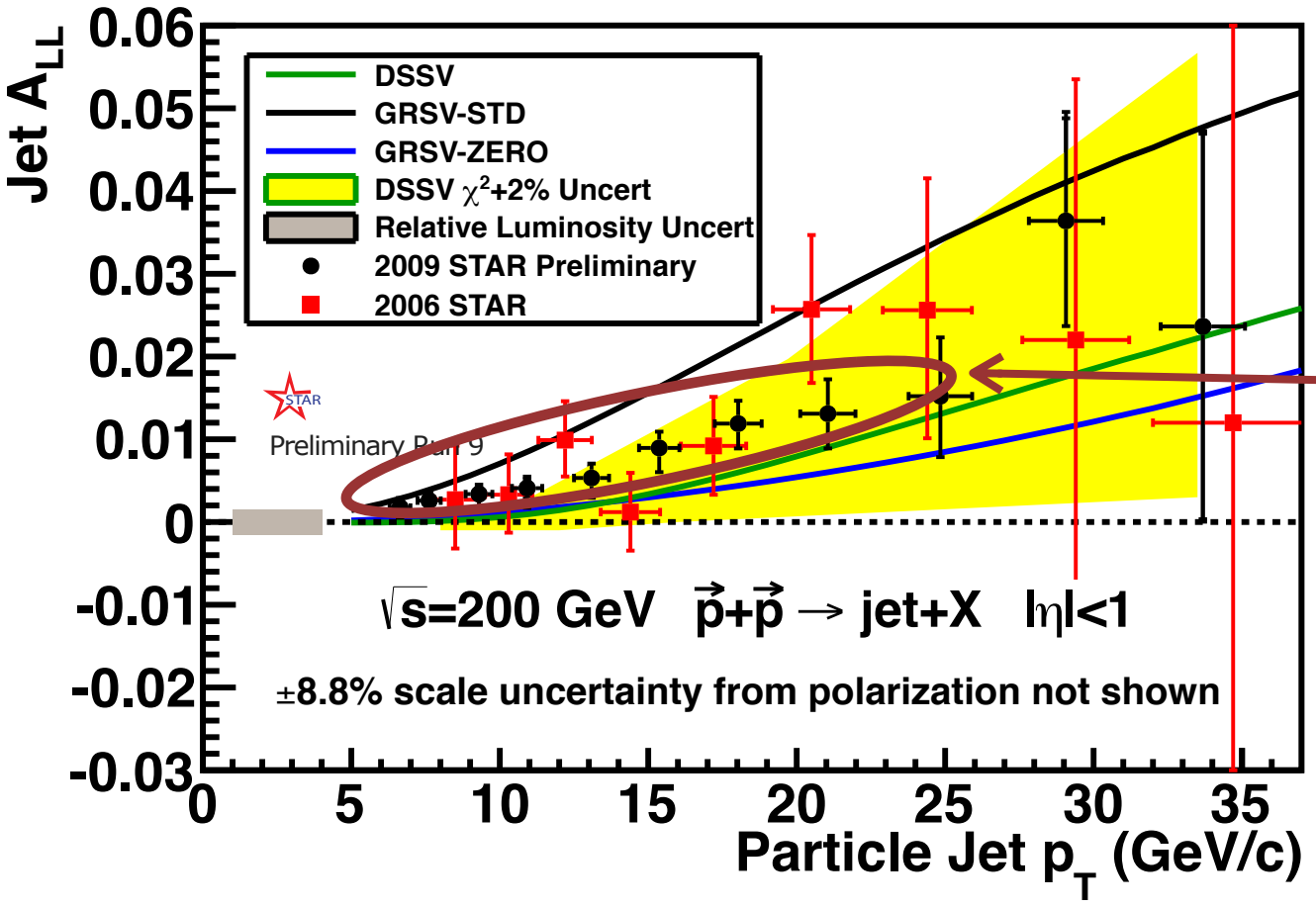

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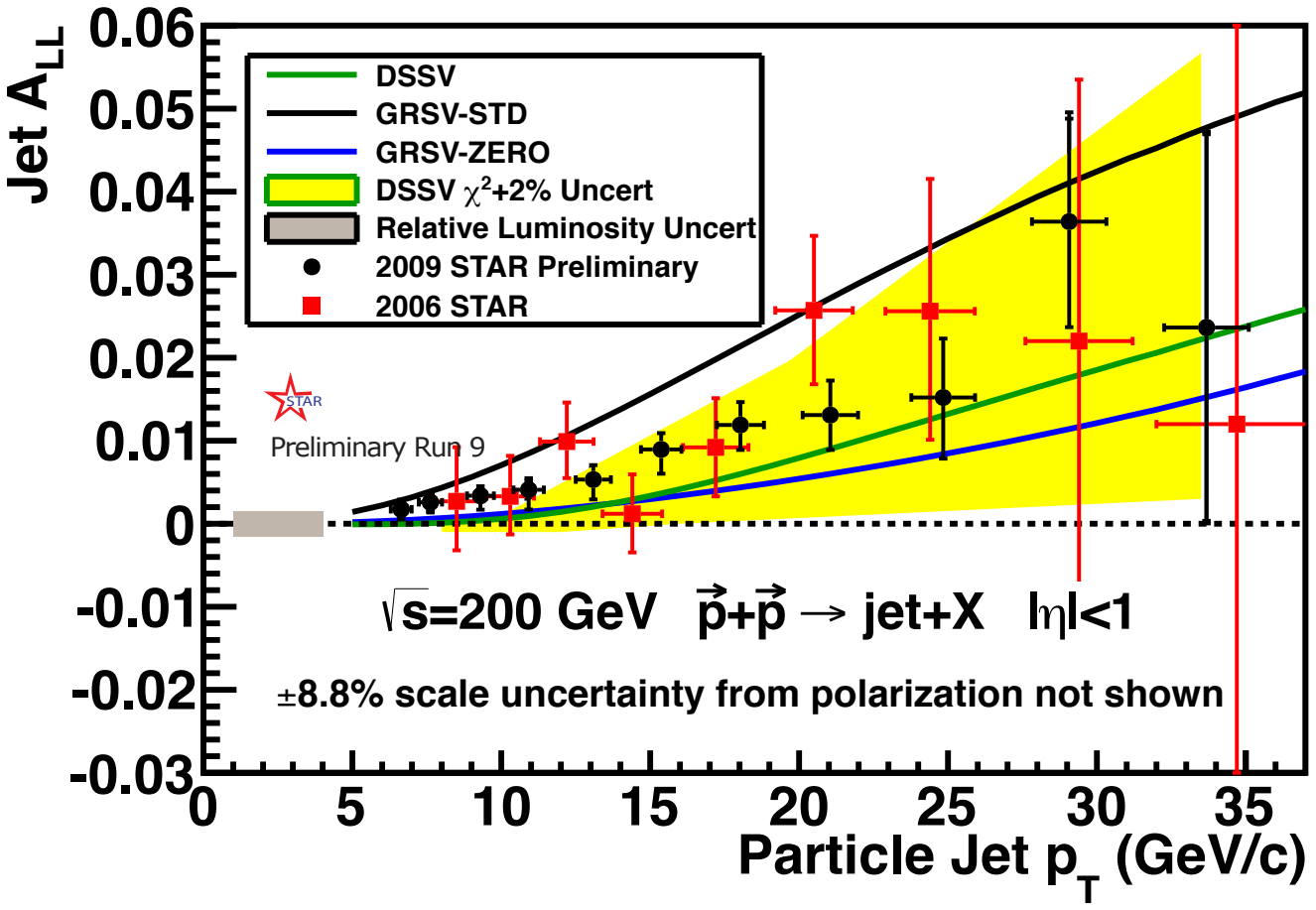

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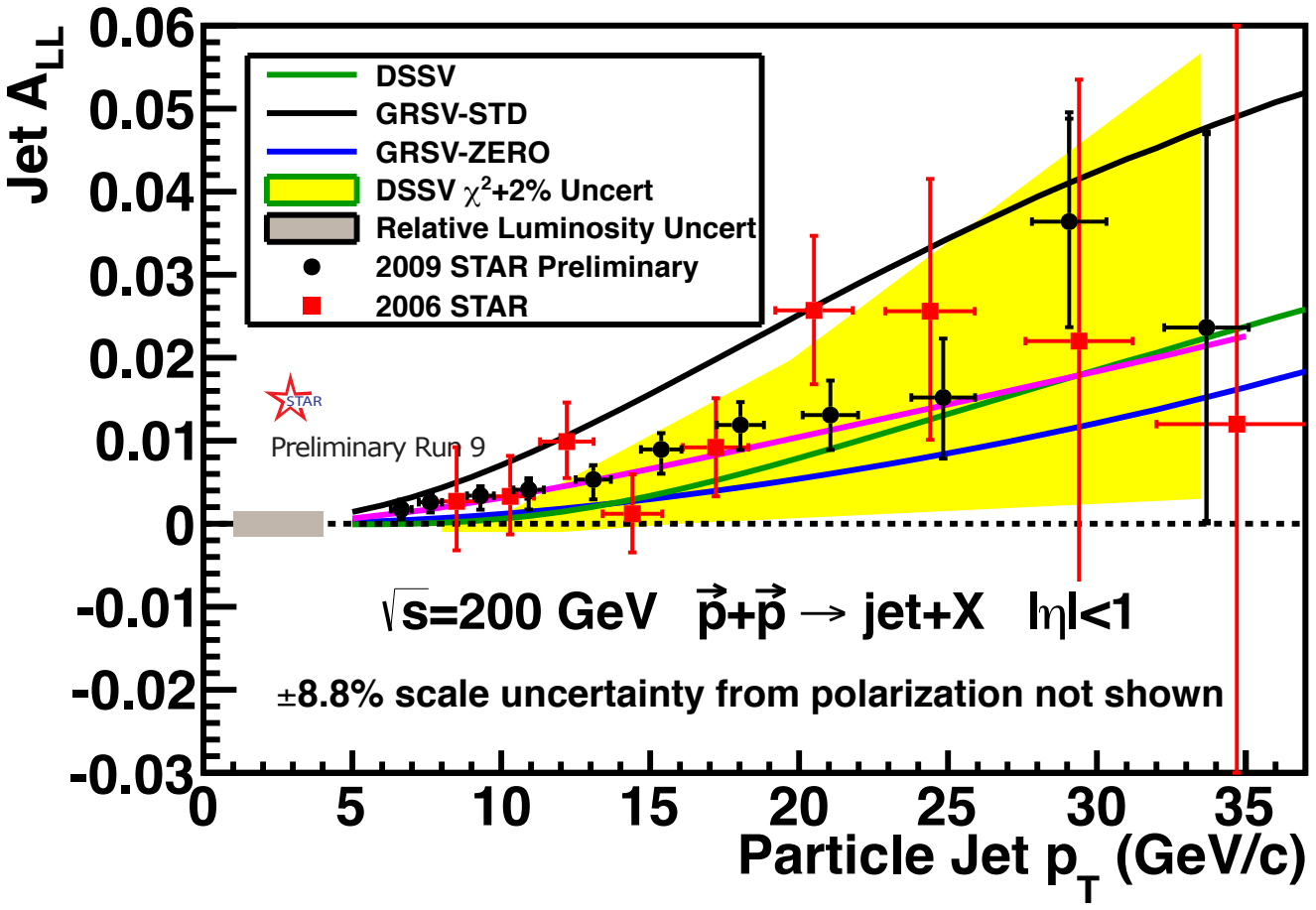

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Recent results - Gluon polarization program

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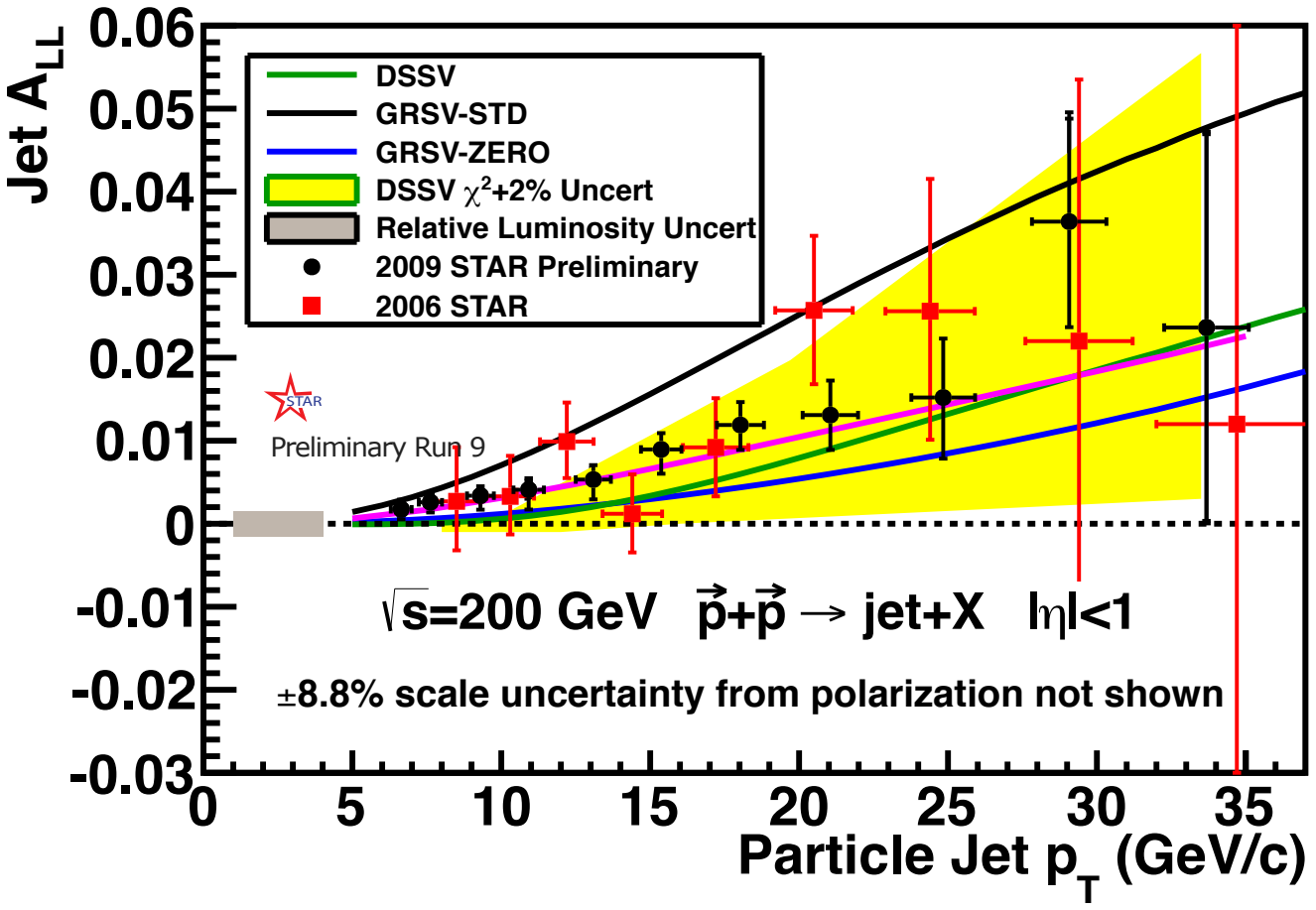
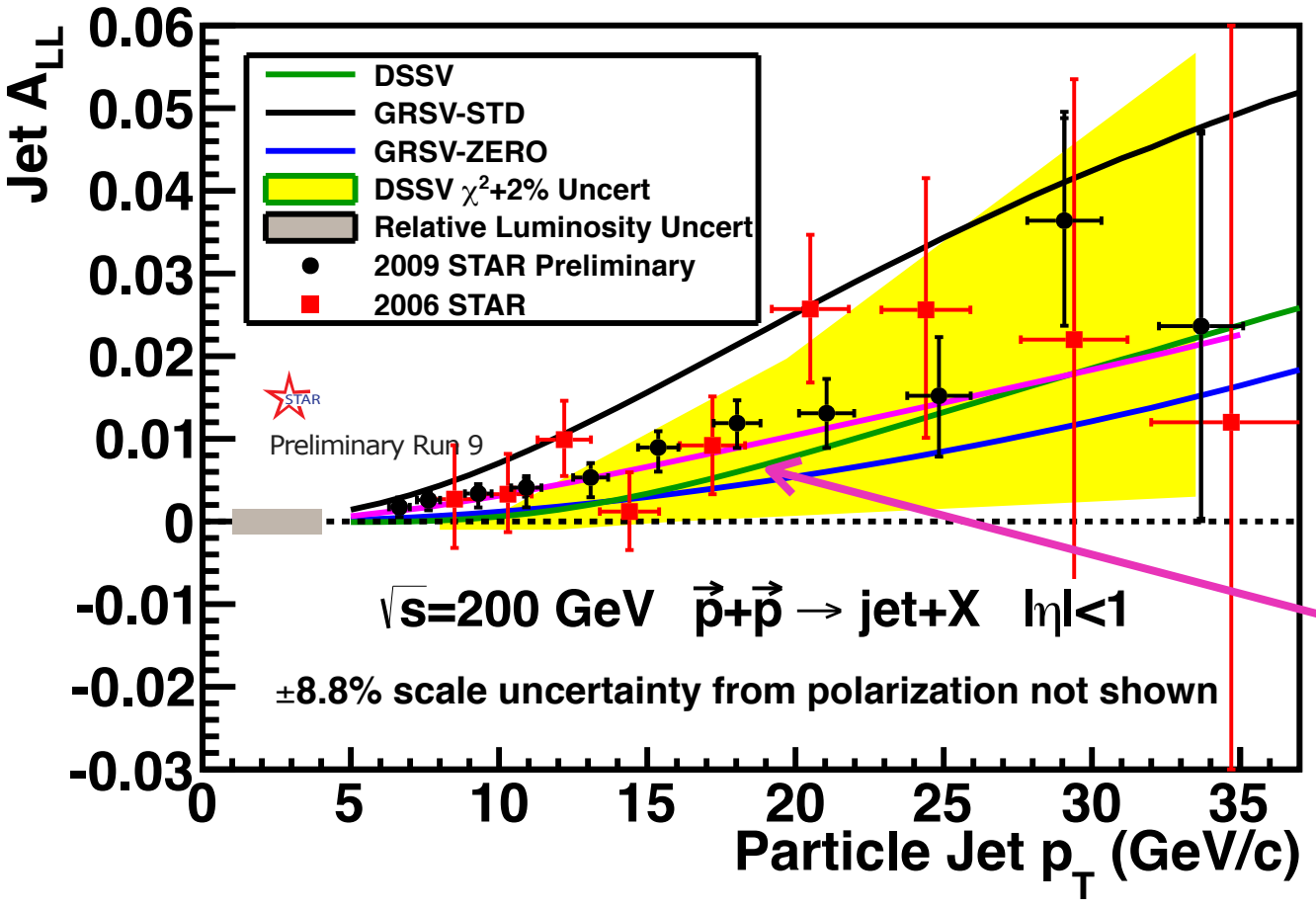


- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO
- Run 9 A_{LL} measurement between GRSV-STD and DSSV / Clearly above at low p_T
- Truncated first moment constrained by Run 9 A_{LL} data:

Recent results - Gluon polarization program

- Mid-rapidity Inclusive Jet A_{LL} measurement (Run 9)



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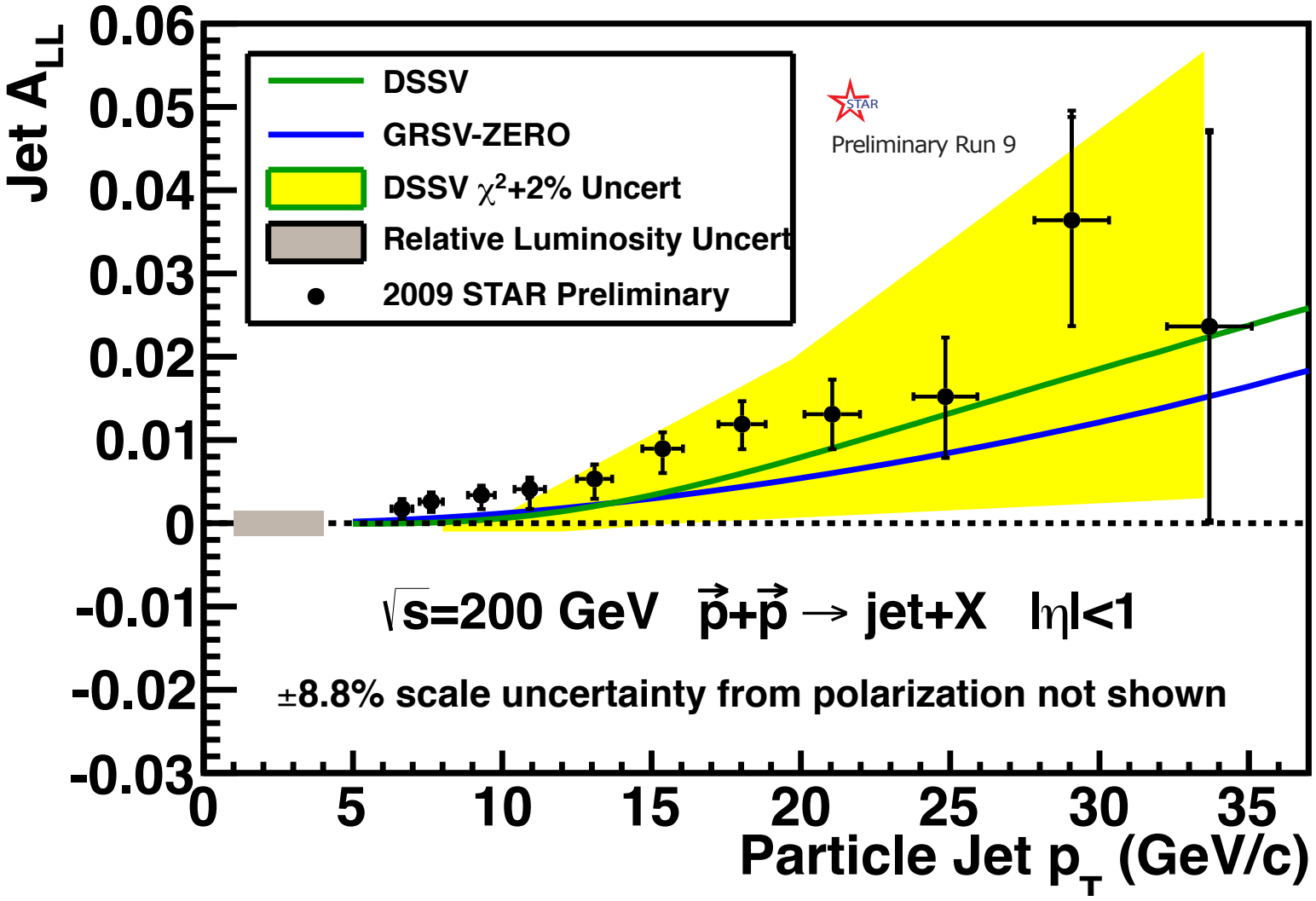
- Run 9 A_{LL} measurement between GRSV-STD and DSSV / Clearly above at low p_T
- Truncated first moment constrained by Run 9 A_{LL} data:

$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\mathrm{GeV}^2) dx = 0.13$$

(D. deFlorian et al.,
Prog. Nucl. Part. Phys. 67, 251 (2012))

Recent results - Gluon polarization program

- Mid-rapidity Inclusive Jet A_{LL} measurement (Run 9)



Recent results - Gluon polarization program

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Recent results - Gluon polarization program

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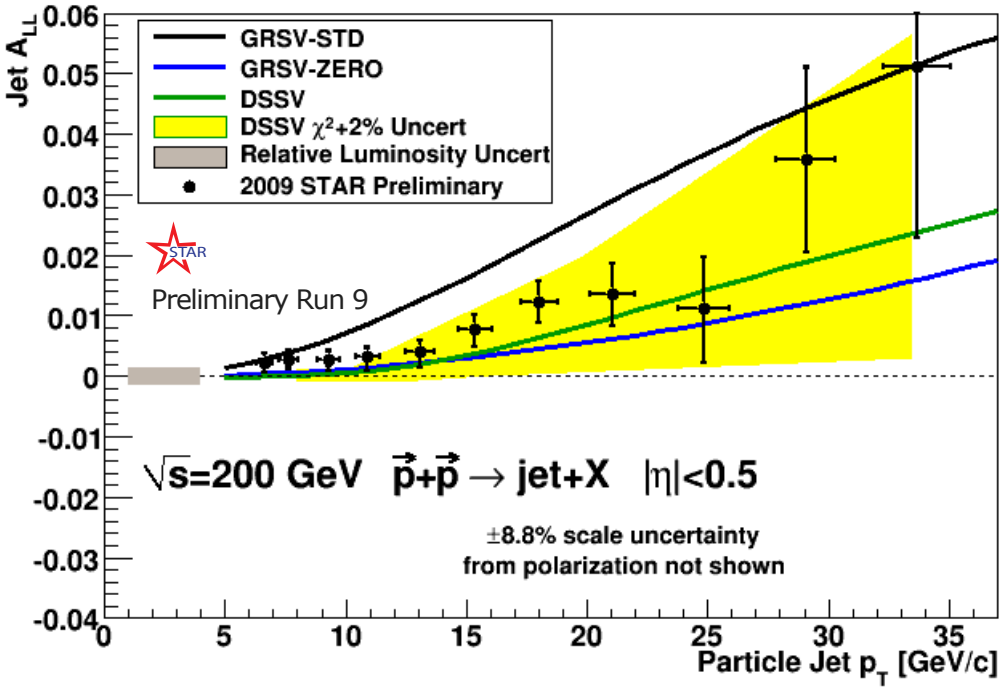
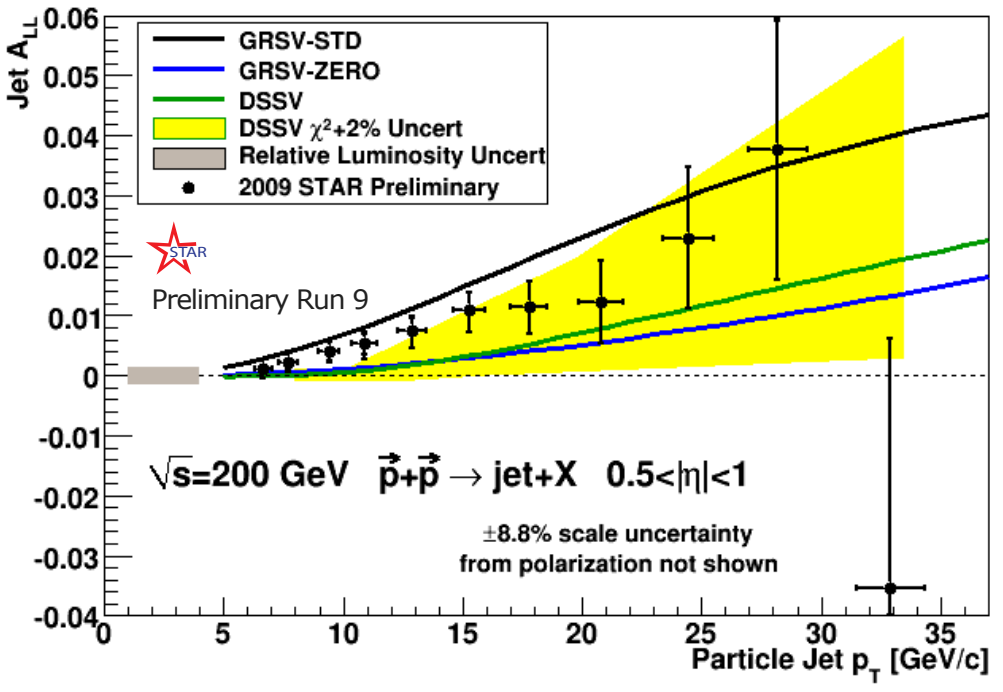
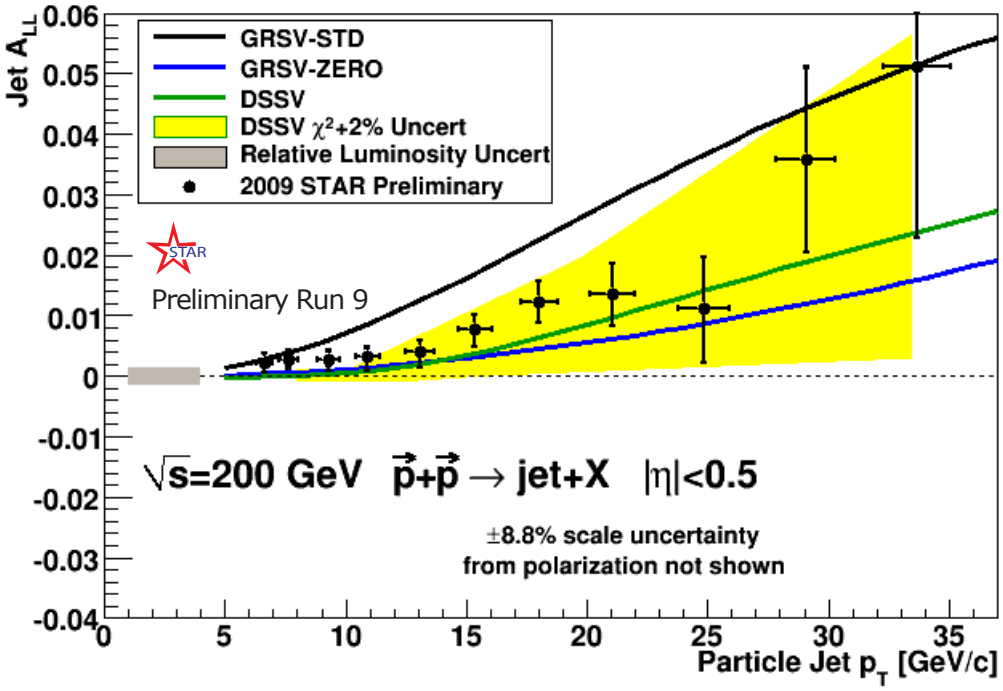


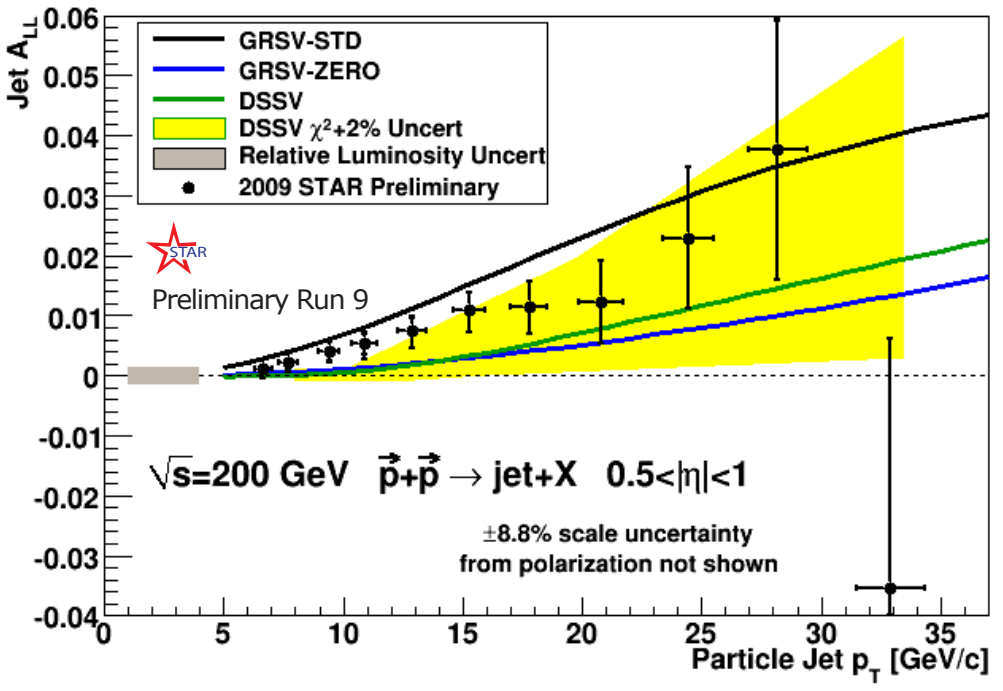


- A_{LL} separated into two η bins ($|\eta|<0.5$ and $0.5<|\eta|<1.0$)

Recent results - Gluon polarization program

- Mid-rapidity Inclusive Jet A_{LL} measurement (Run 9)

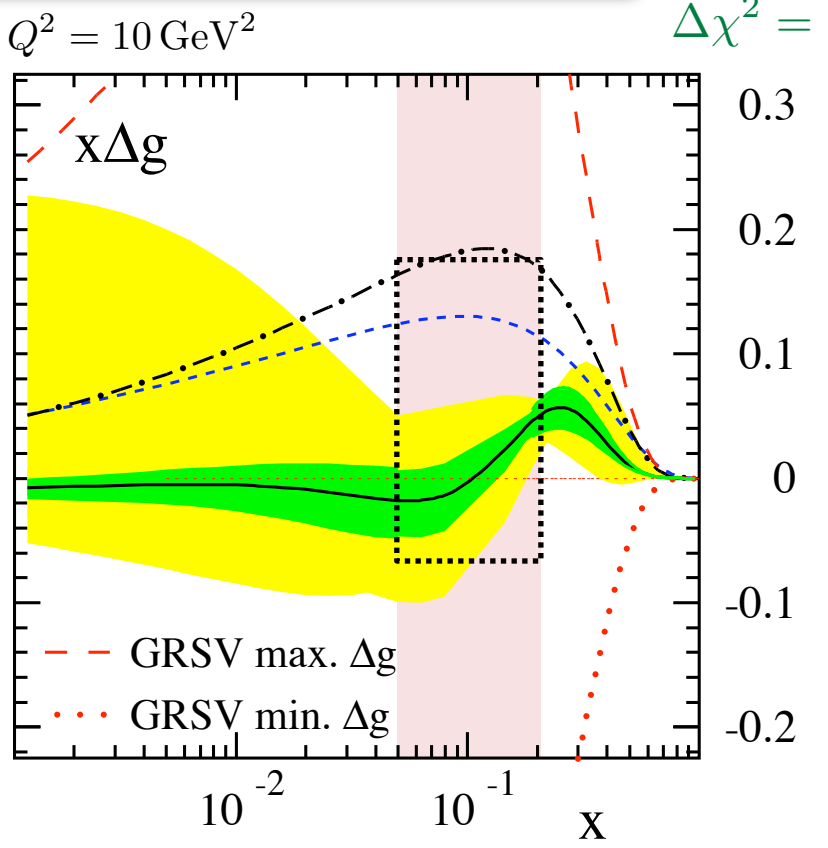


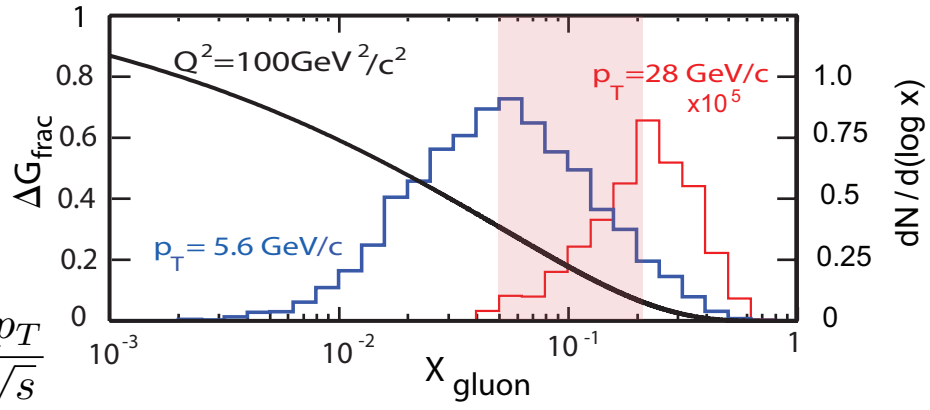


- A_{LL} separated into two η bins ($|\eta|<0.5$ and $0.5<|\eta|<1.0$)
- DSSV smaller at forward η bin ($0.5<|\eta|<1.0$) compared to central bin ($|\eta|<0.5$)

Recent results - Gluon polarization program

- Impact on Δg from RHIC data

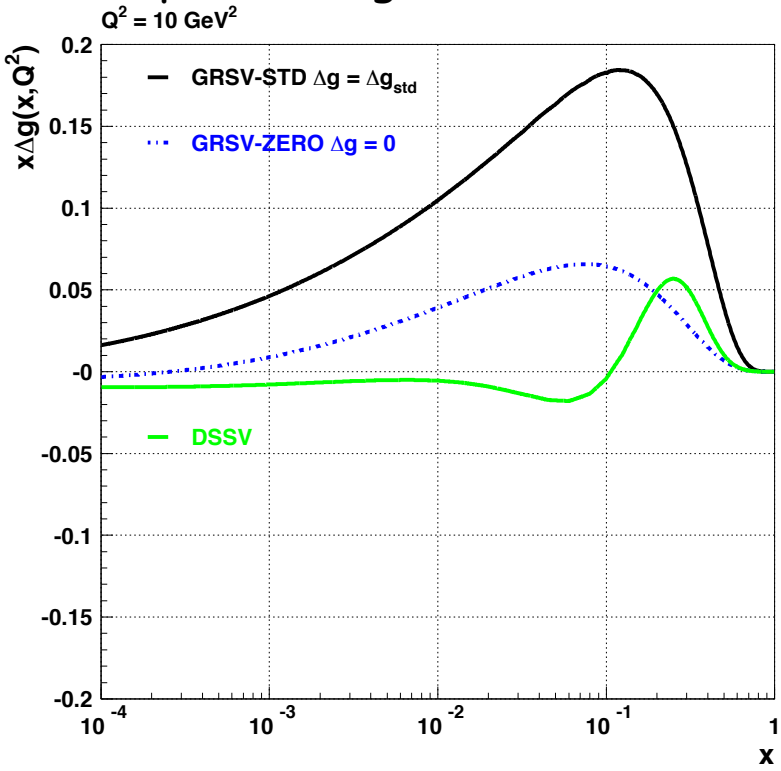


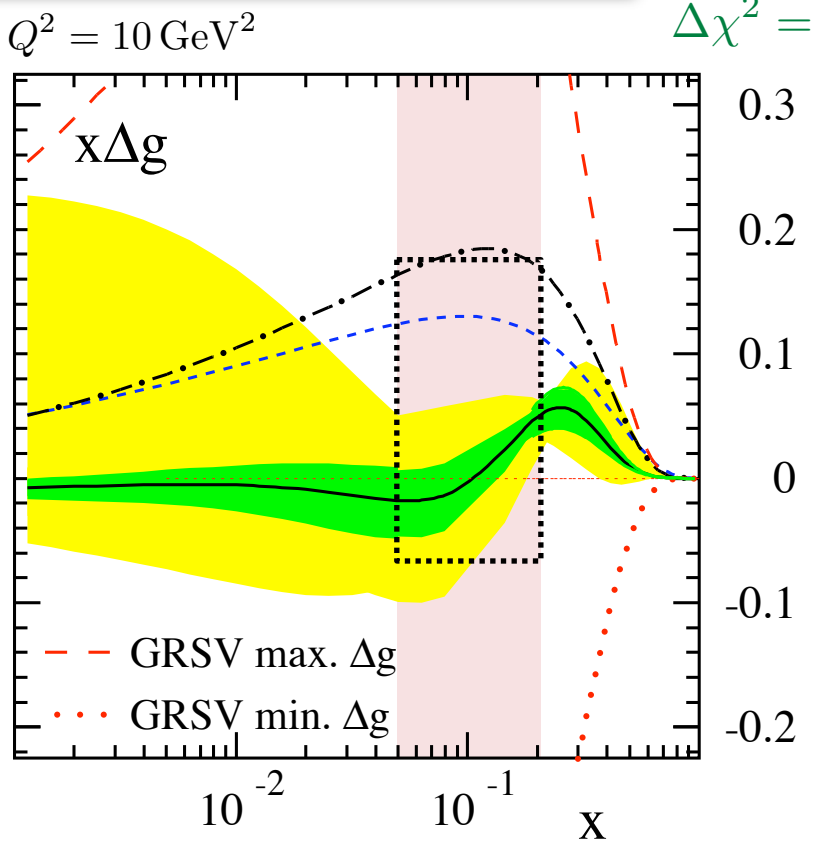


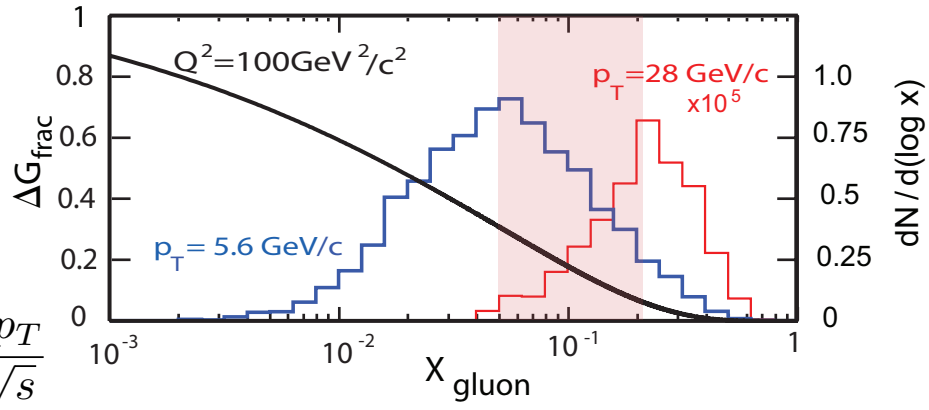
$$x \sim \frac{2p_T}{\sqrt{s}}$$

Recent results - Gluon polarization program

Impact on Δg from RHIC data





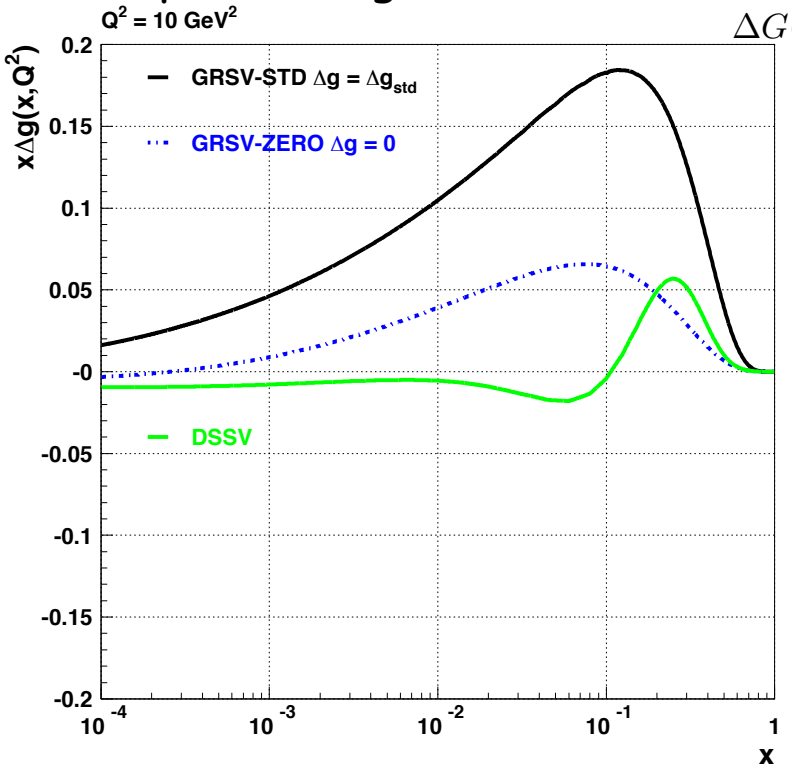


$$x \sim \frac{2p_T}{\sqrt{s}}$$

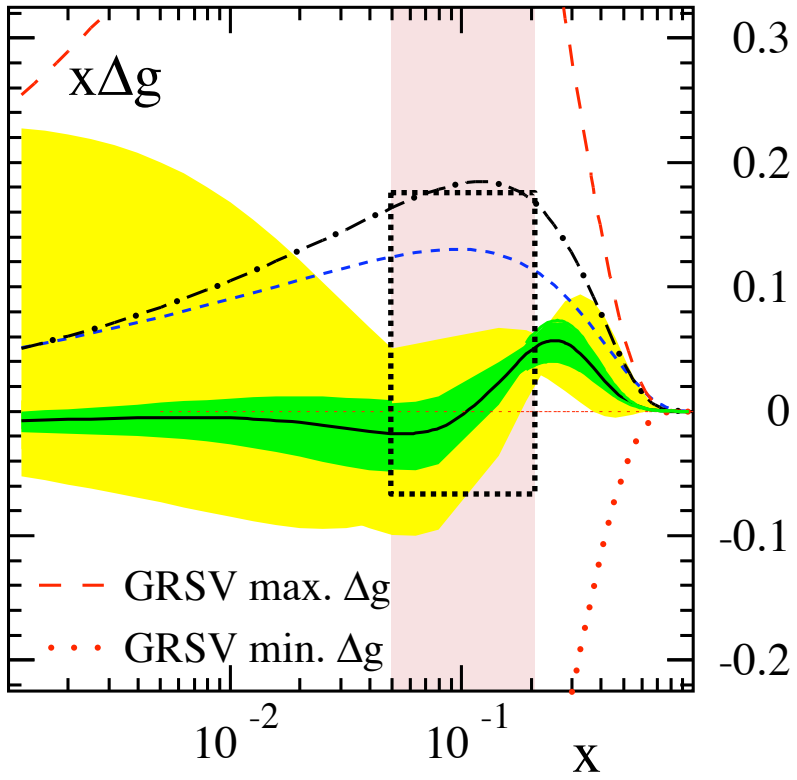
Recent results - Gluon polarization program

Impact on Δg from RHIC data

$$\Delta G(Q^2) = \int_x^1 \Delta g(x, Q^2) dx$$



$Q^2 = 10\,\mathrm{GeV}^2$ $\Delta\chi^2 = 1$



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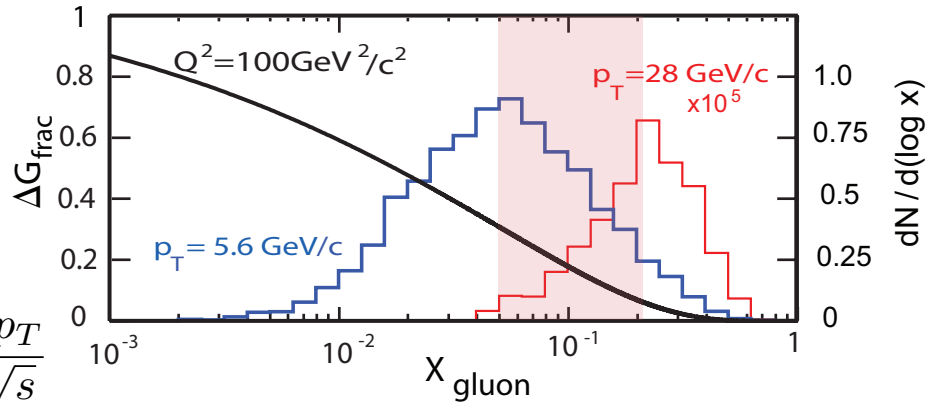

Recent results - Gluon polarization program

Impact on Δg from RHIC data

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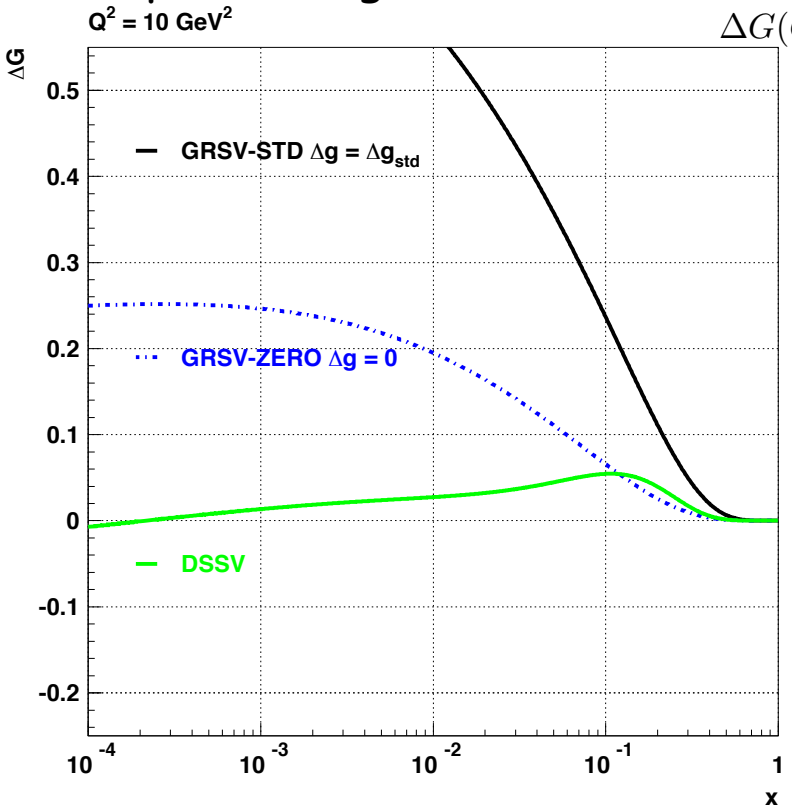

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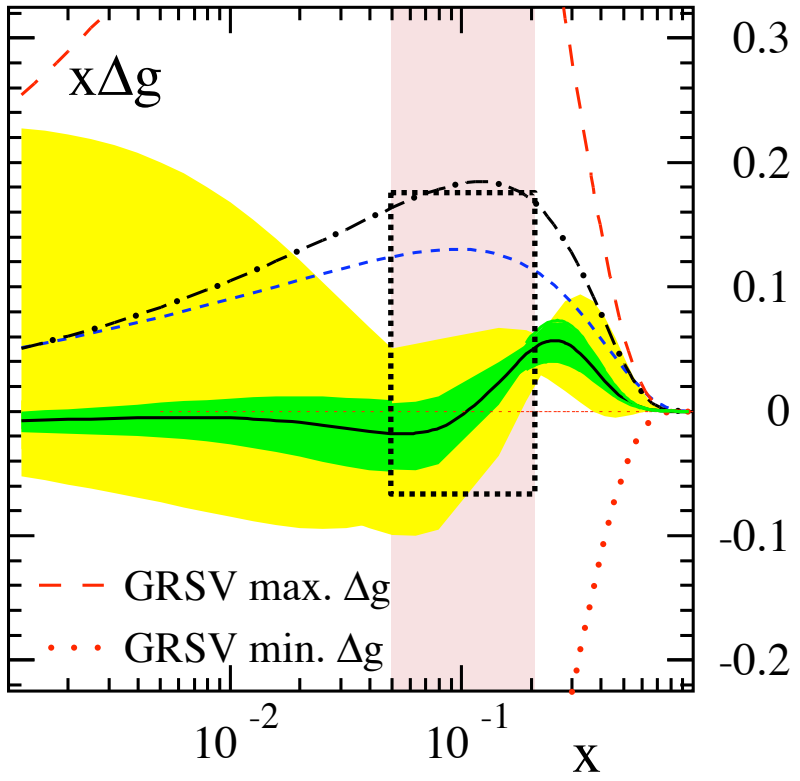

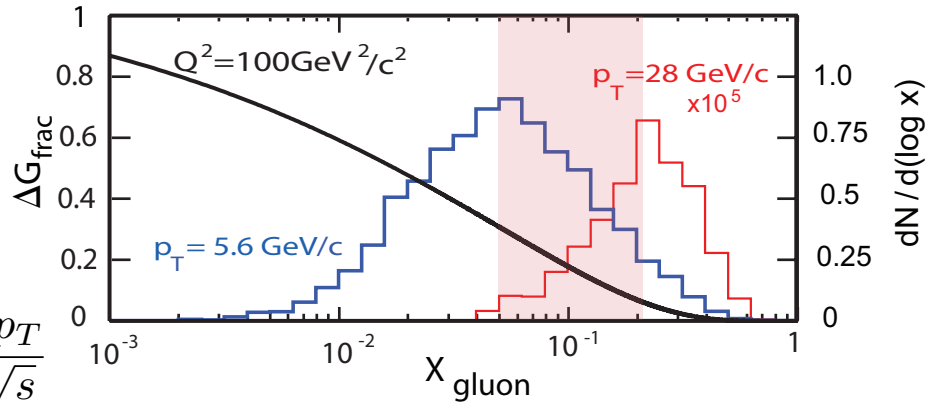

$$x \sim \frac{2p_T}{\sqrt{s}}$$

Recent results - Gluon polarization program

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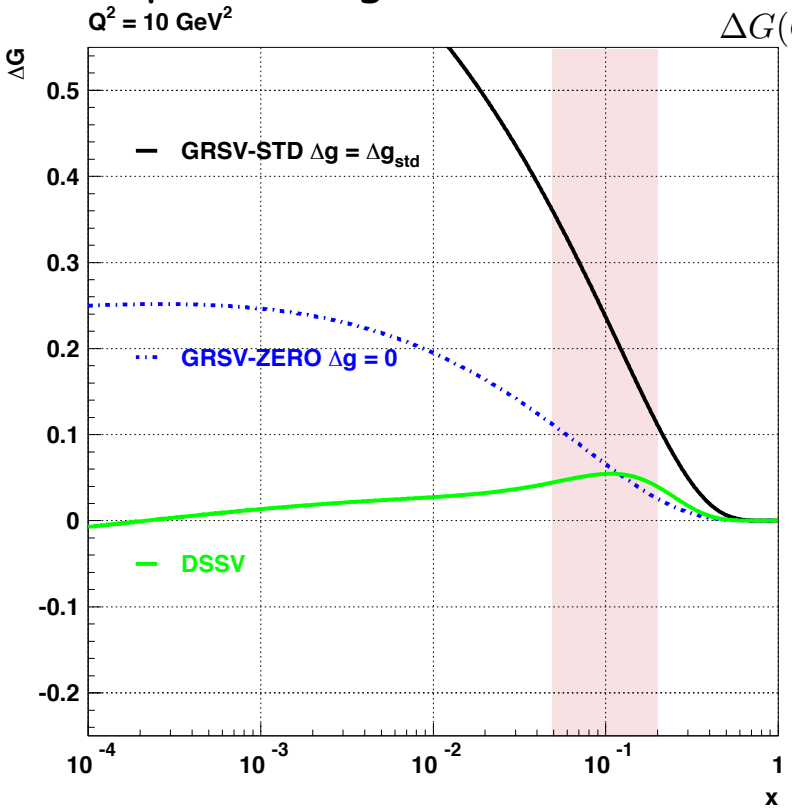

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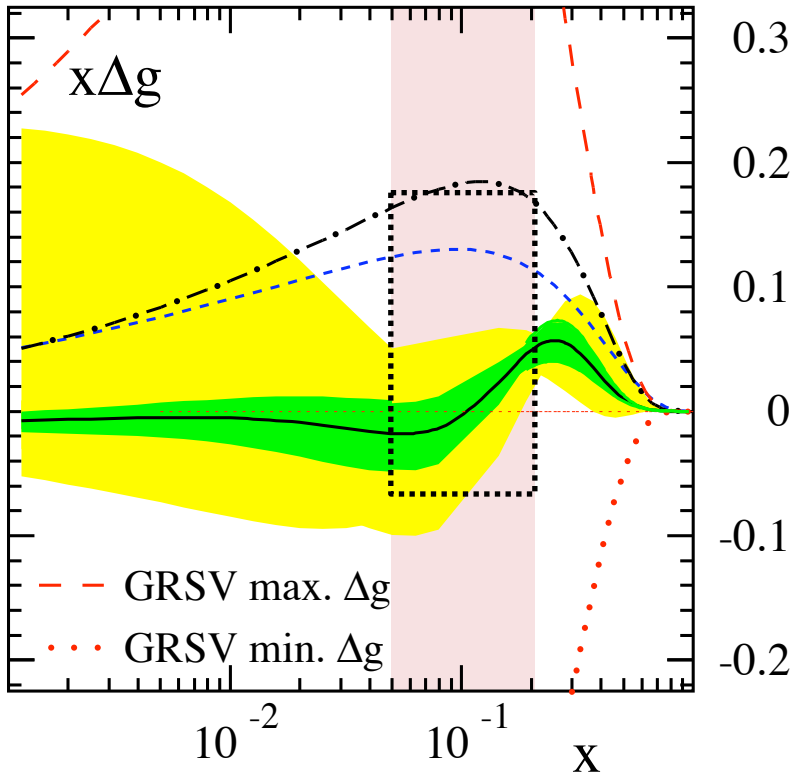
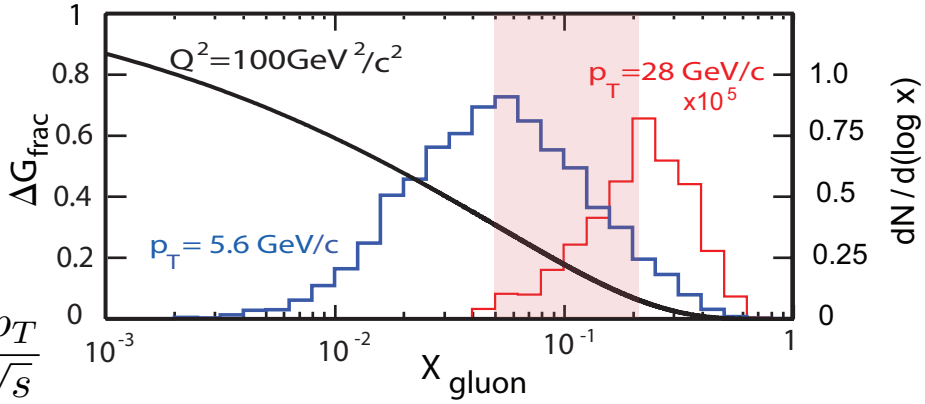


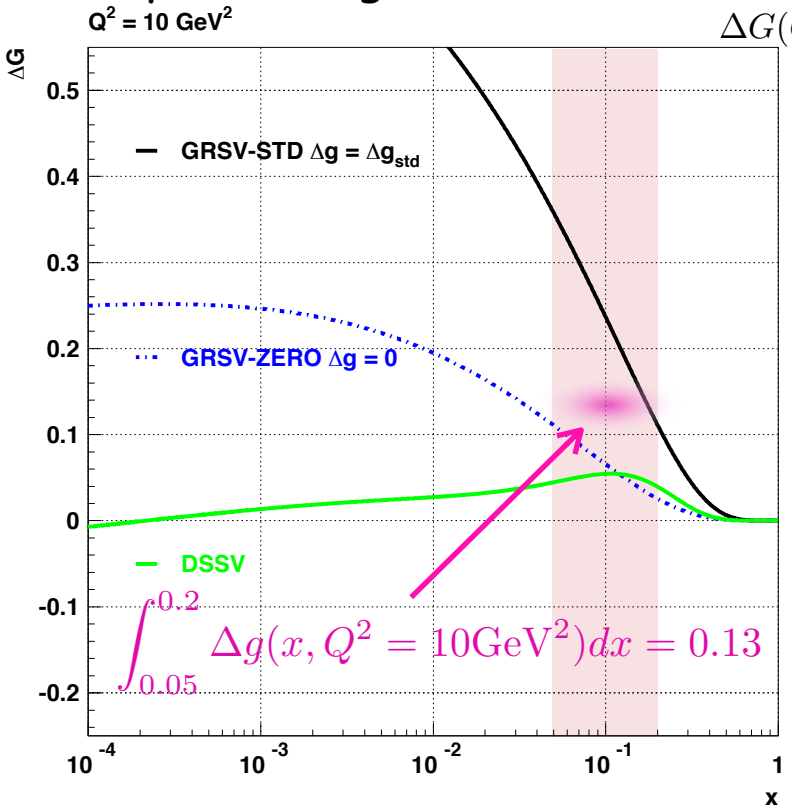


$$x \sim \frac{2p_T}{\sqrt{s}}$$

Recent results - Gluon polarization program

Impact on Δg from RHIC data

$$\Delta G(Q^2) = \int_x^1 \Delta g(x, Q^2) dx$$



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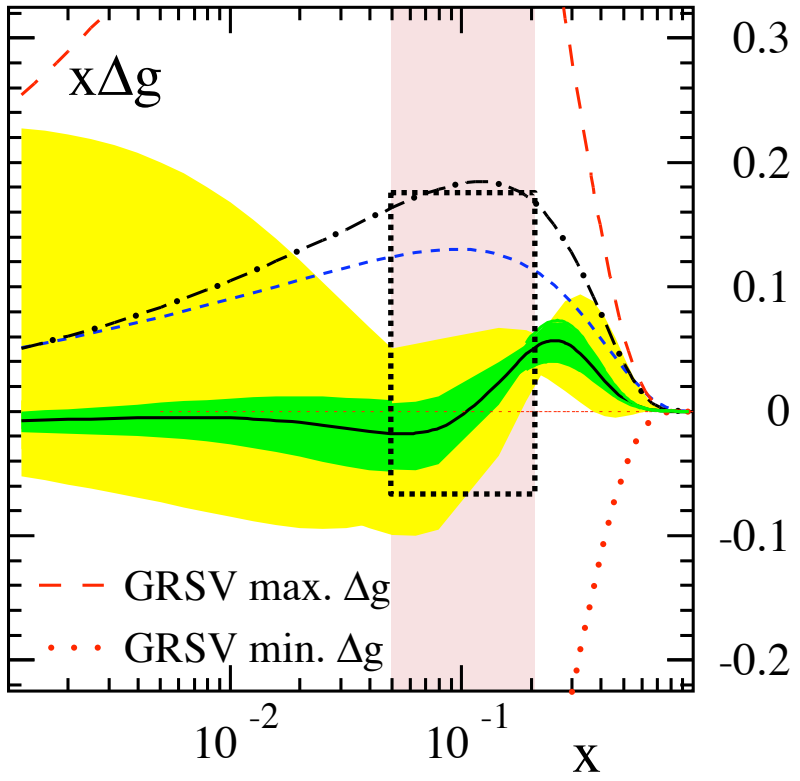

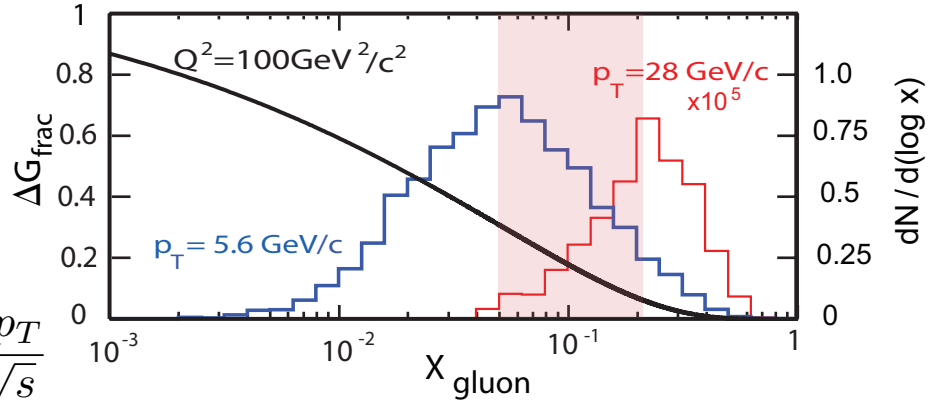

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Recent results - Gluon polarization program

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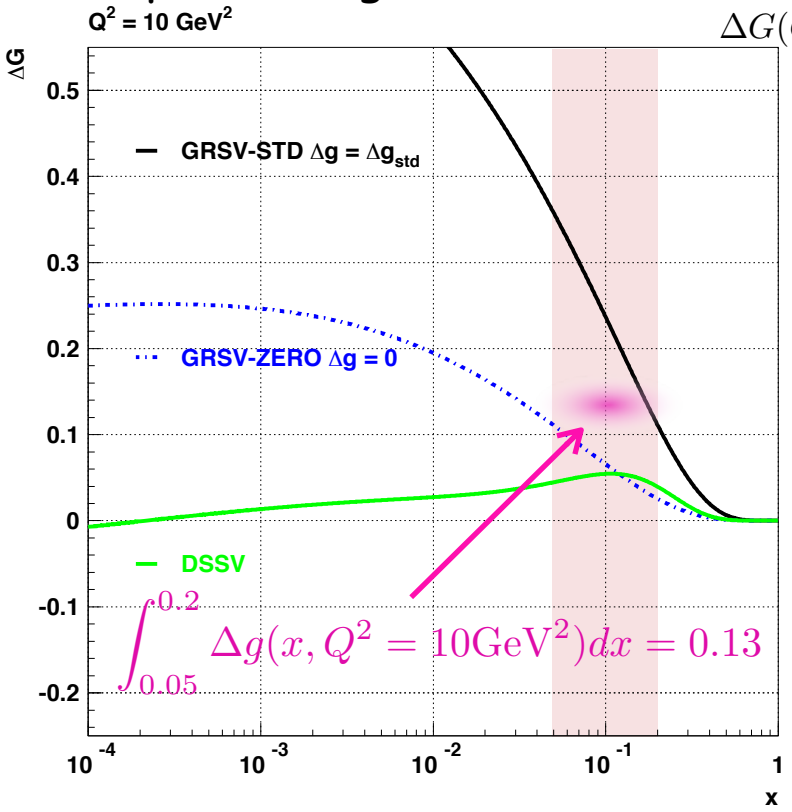

- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)

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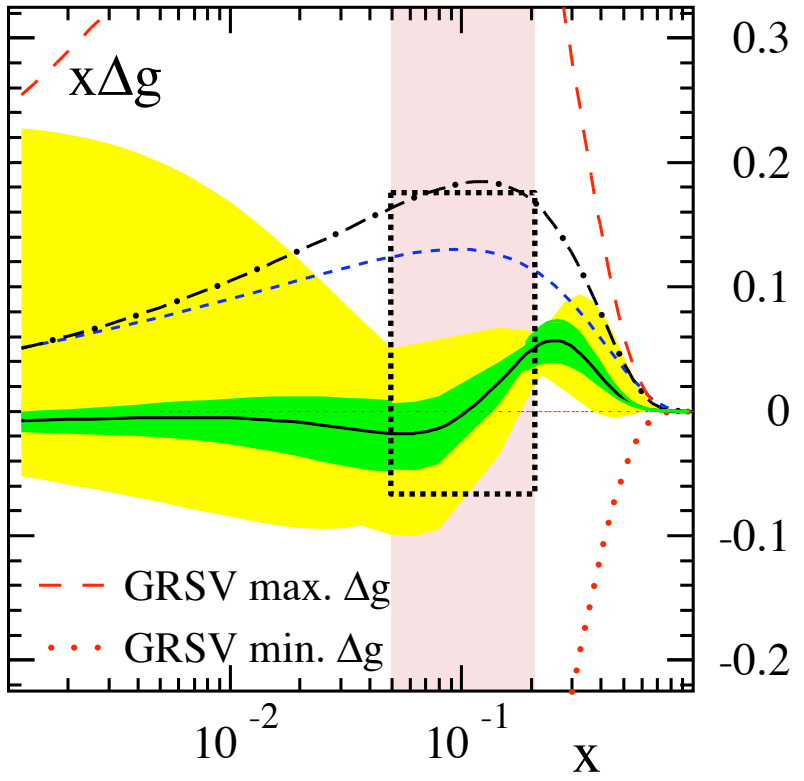

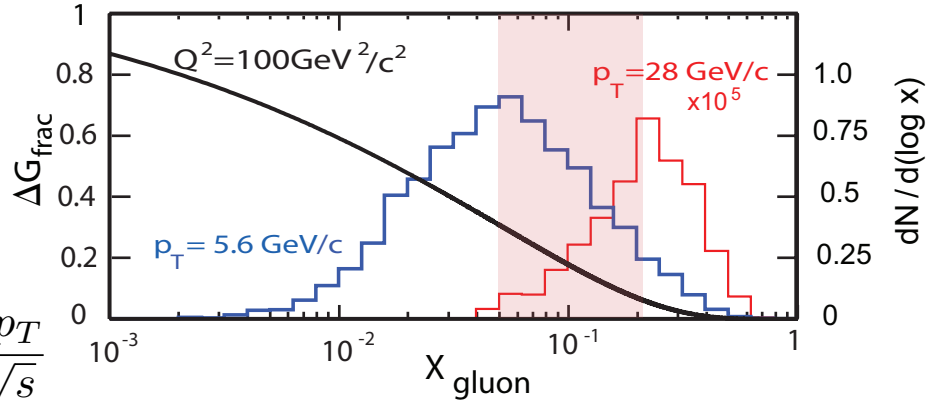

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Recent results - Gluon polarization program

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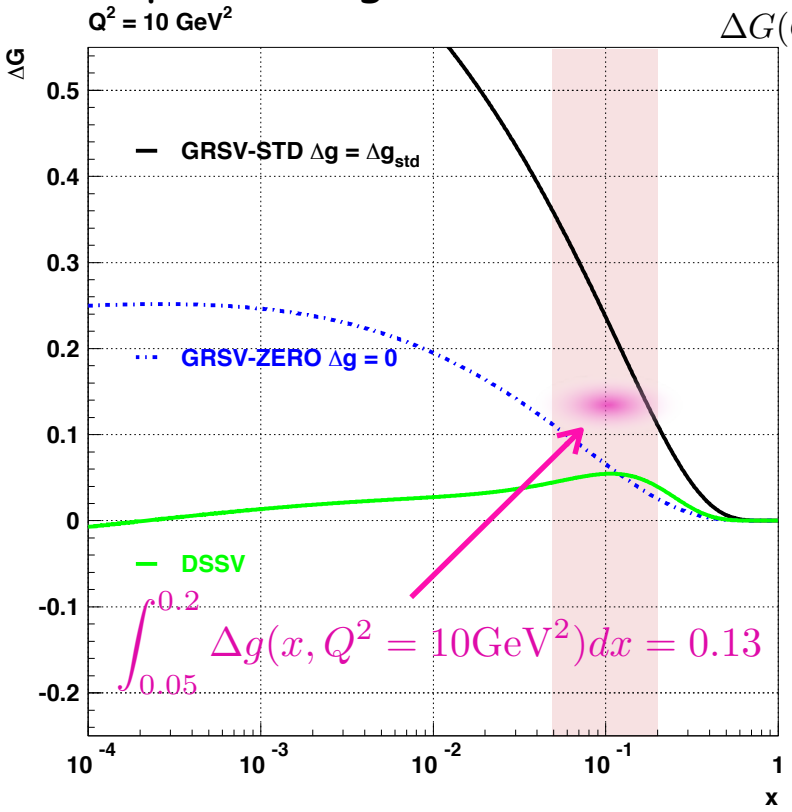
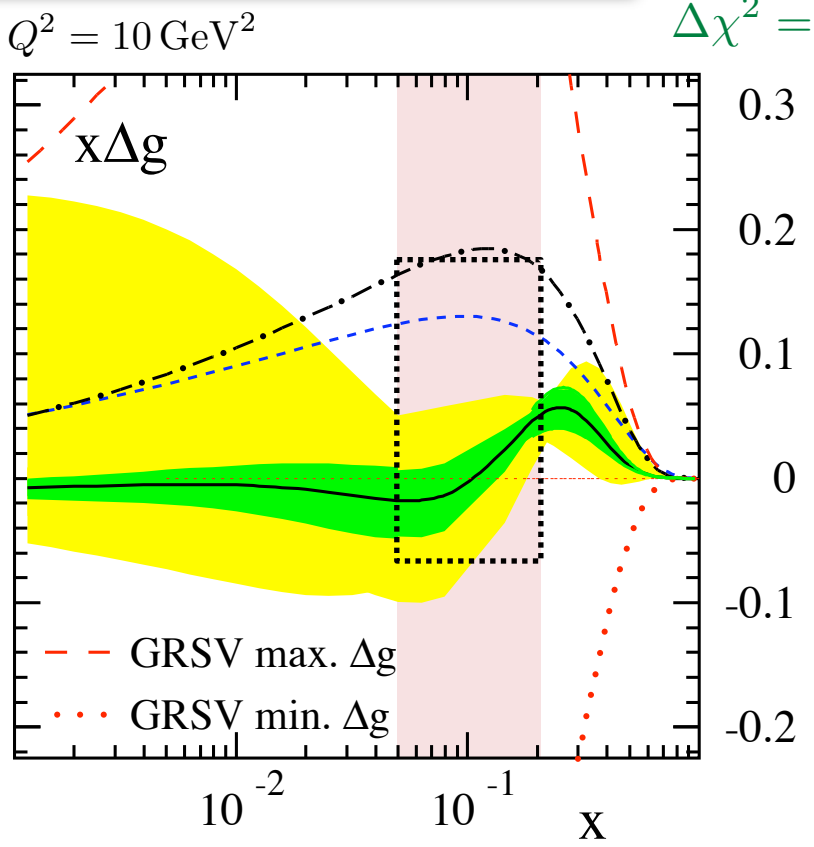
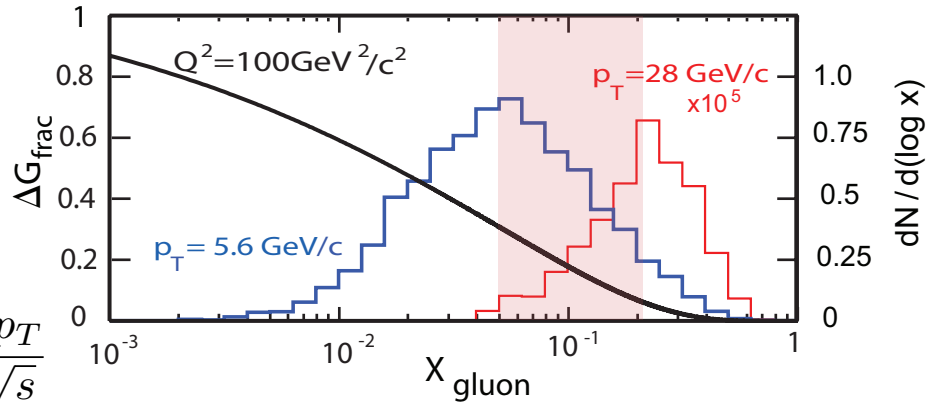






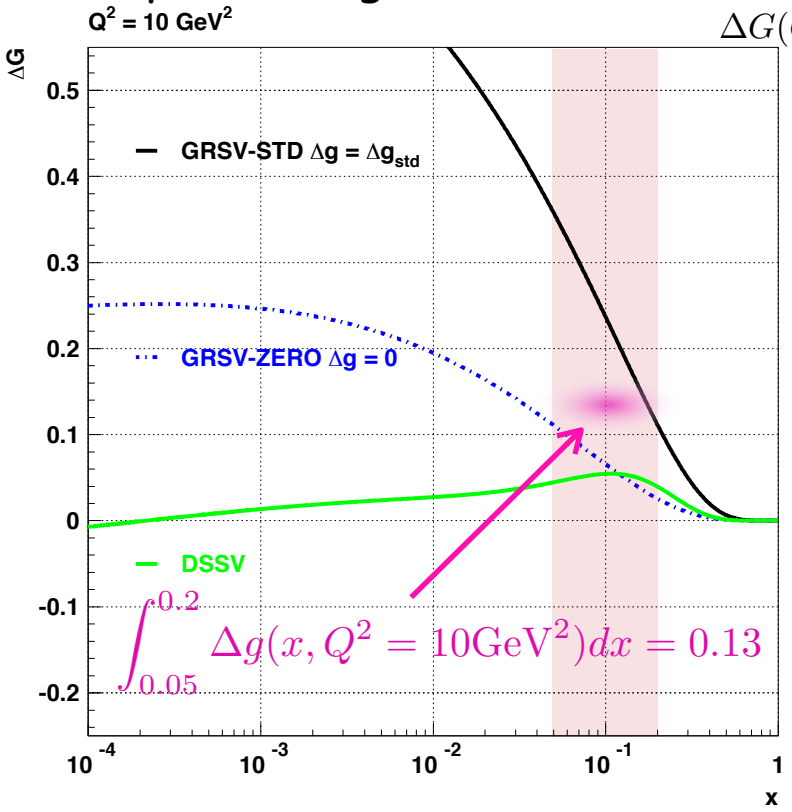
$$x \sim \frac{2p_T}{\sqrt{s}}$$

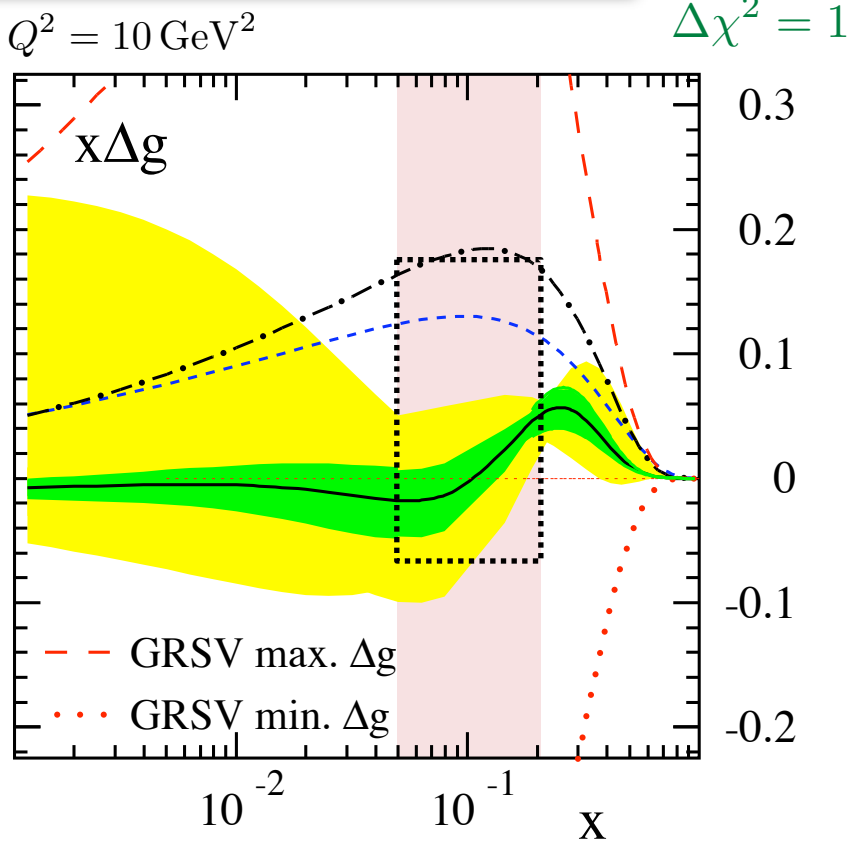
- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)
- Strong indication for a small, non-zero ΔG!

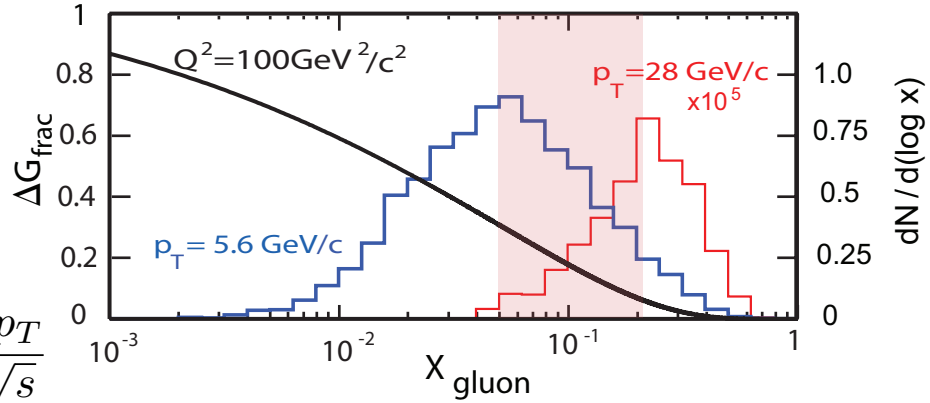
Recent results - Gluon polarization program

Impact on Δg from RHIC data

$$\Delta G(Q^2) = \int_x^1 \Delta g(x, Q^2) dx$$





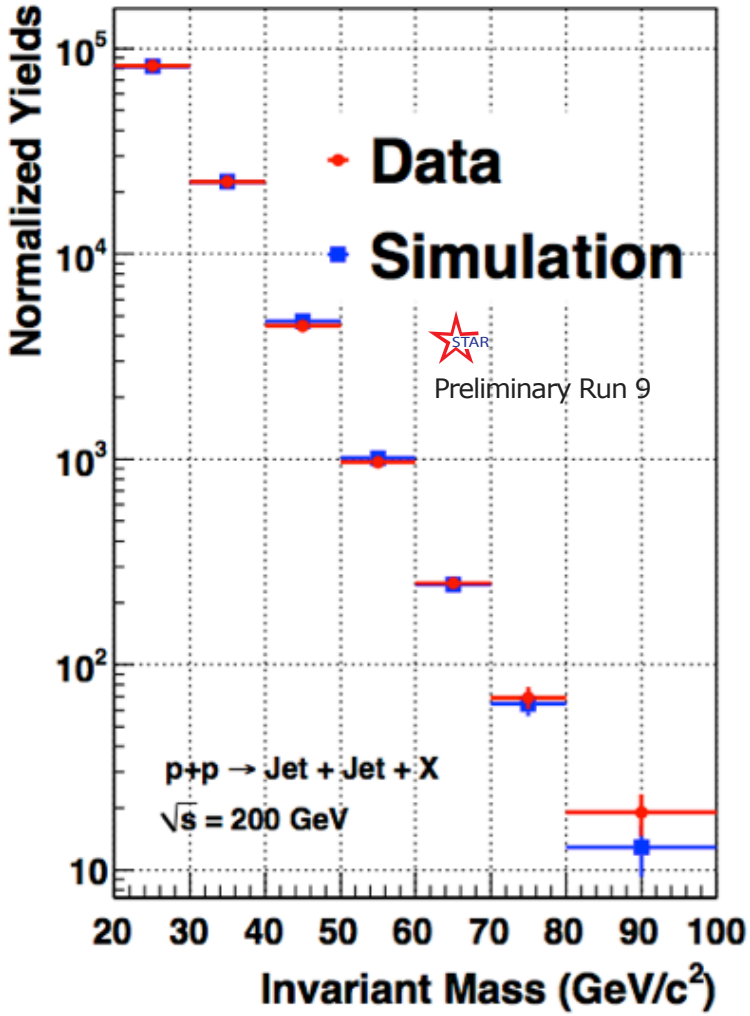


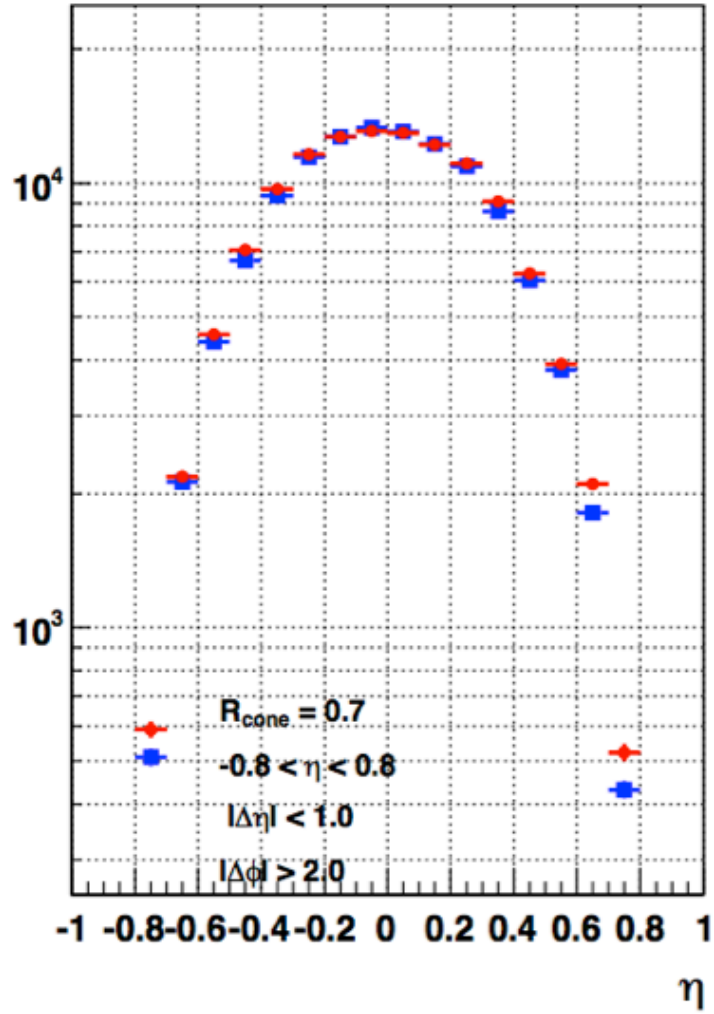
- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)
- Strong indication for a small, non-zero ΔG!
- Next steps: Mapping of x-dependence and extension of x-coverage needed (Di-Jet measurements)!

$$x \sim \frac{2p_T}{\sqrt{s}}$$

Recent results - Gluon polarization program

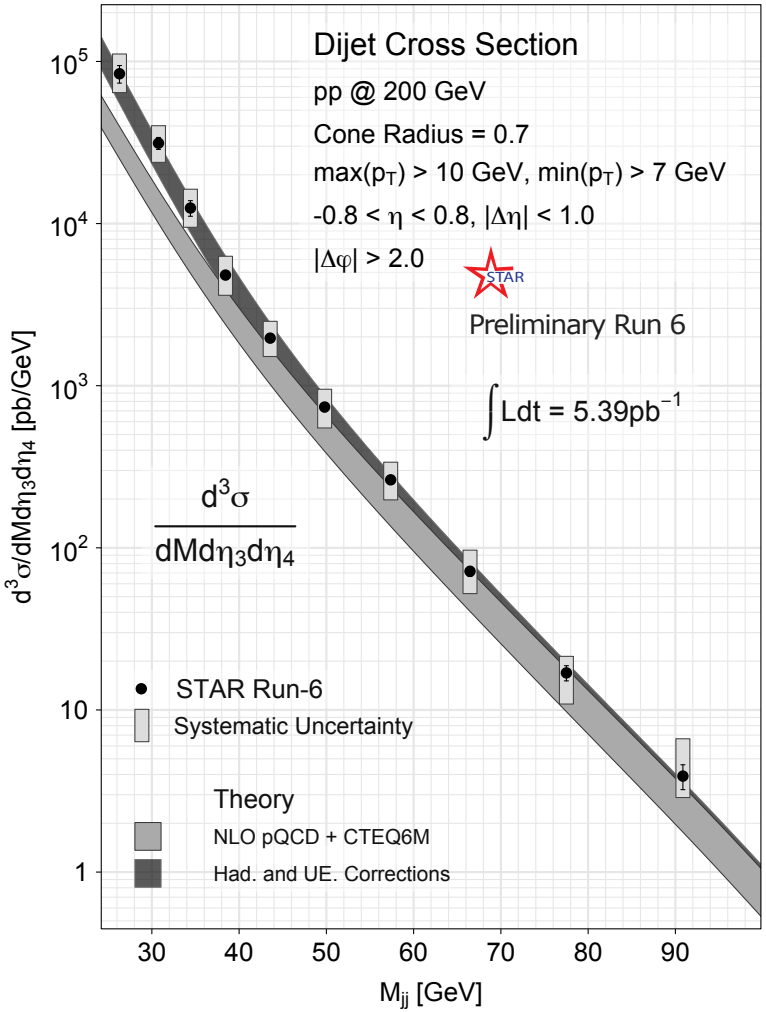
- Di-Jet reconstruction / Di-Jet data sample
  - Data/MC comparison:
    - Good agreement in M_{inv} and η
  - Data sample:
    - Run 9 A_{LL} analysis: L=10pb^{-1} / P=58%
    - Run 6 cross-section: 5.39pb^{-1}





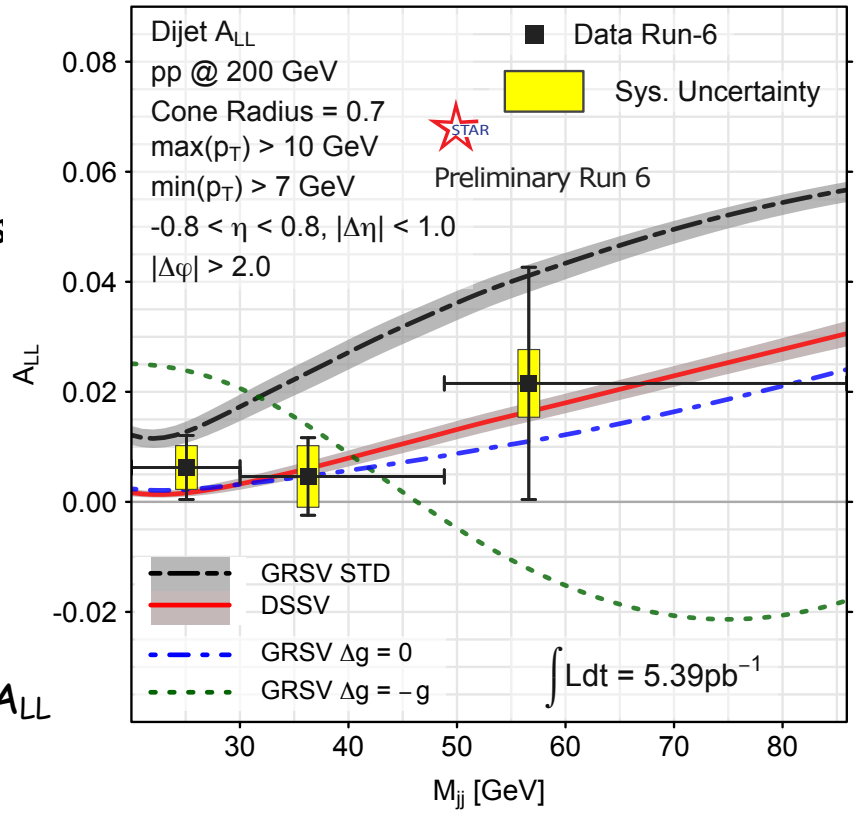
Recent results - Gluon polarization program

- Mid-rapidity Di-Jet cross-section and A_{LL} measurement (Run 6)



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

- First Di-Jet A_{LL} measurement (Run 6) in agreement with Δg (DSSV)!



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

Recent results - Gluon polarization program

- Mid-rapidity Di-Jet kinematics (Run 9)

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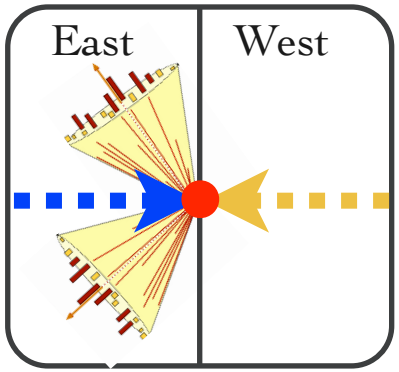
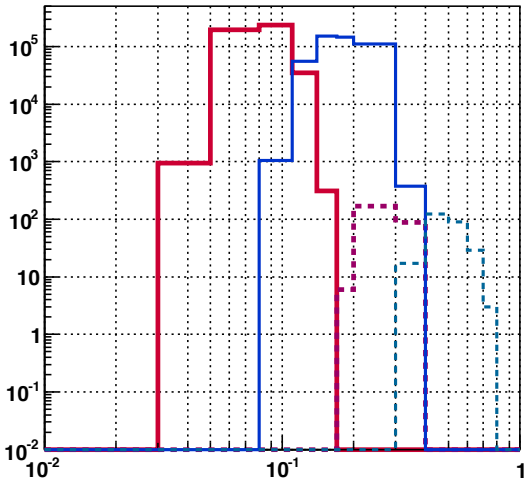
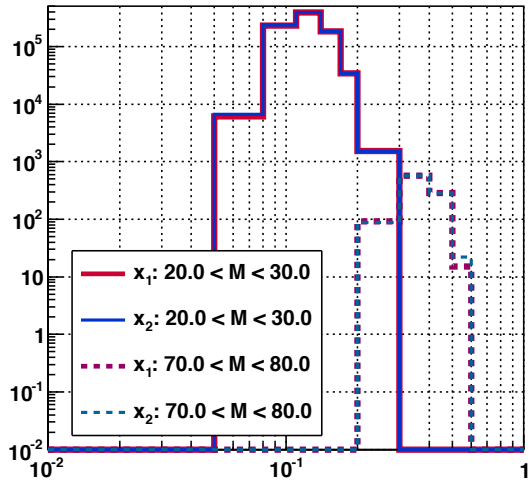


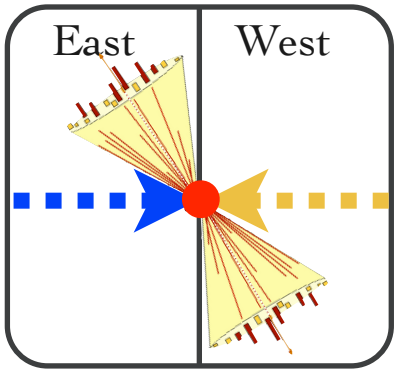
η=-1 η=0 η=1

East Barrel - East Barrel



East Barrel - West Barrel





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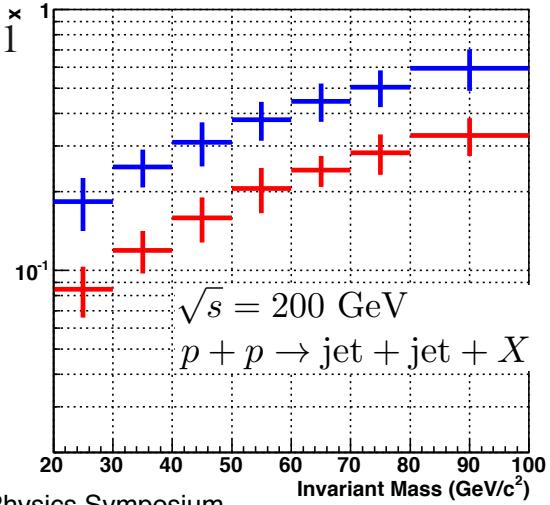

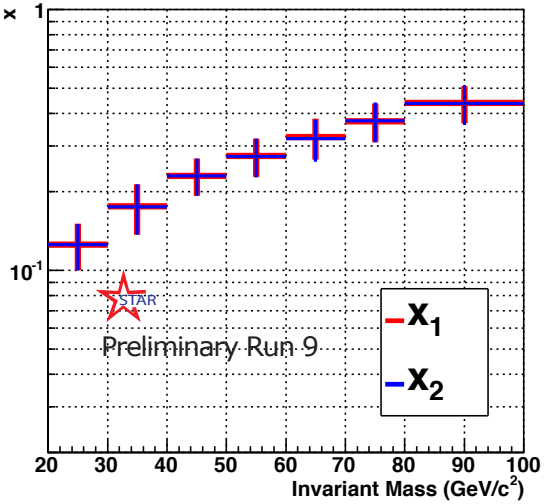

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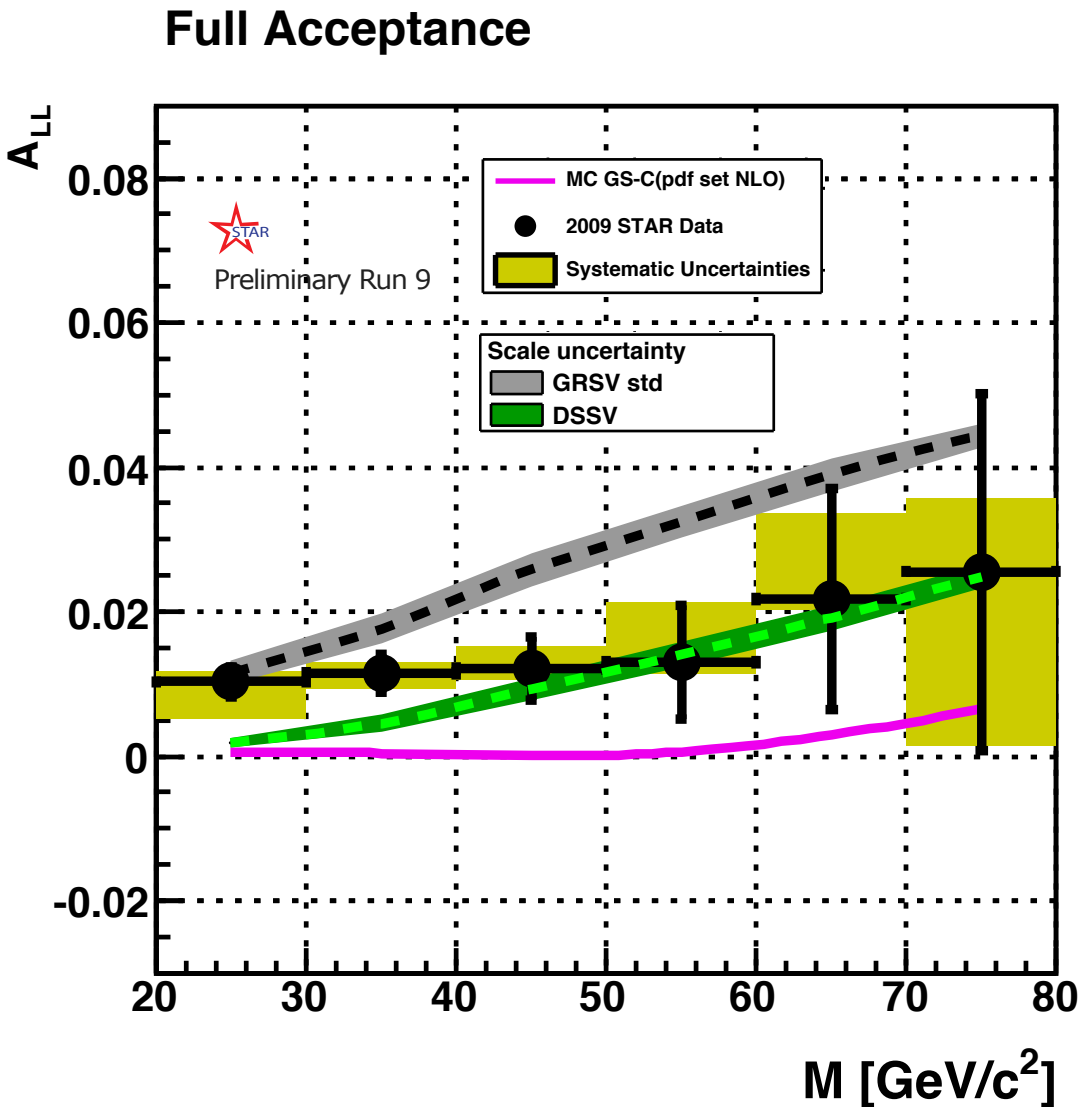

- A_{LL} measurements fall in-between GRSV-STD and DSSV - **Above** DSSV at low M similar to inclusive jet result at low p_T

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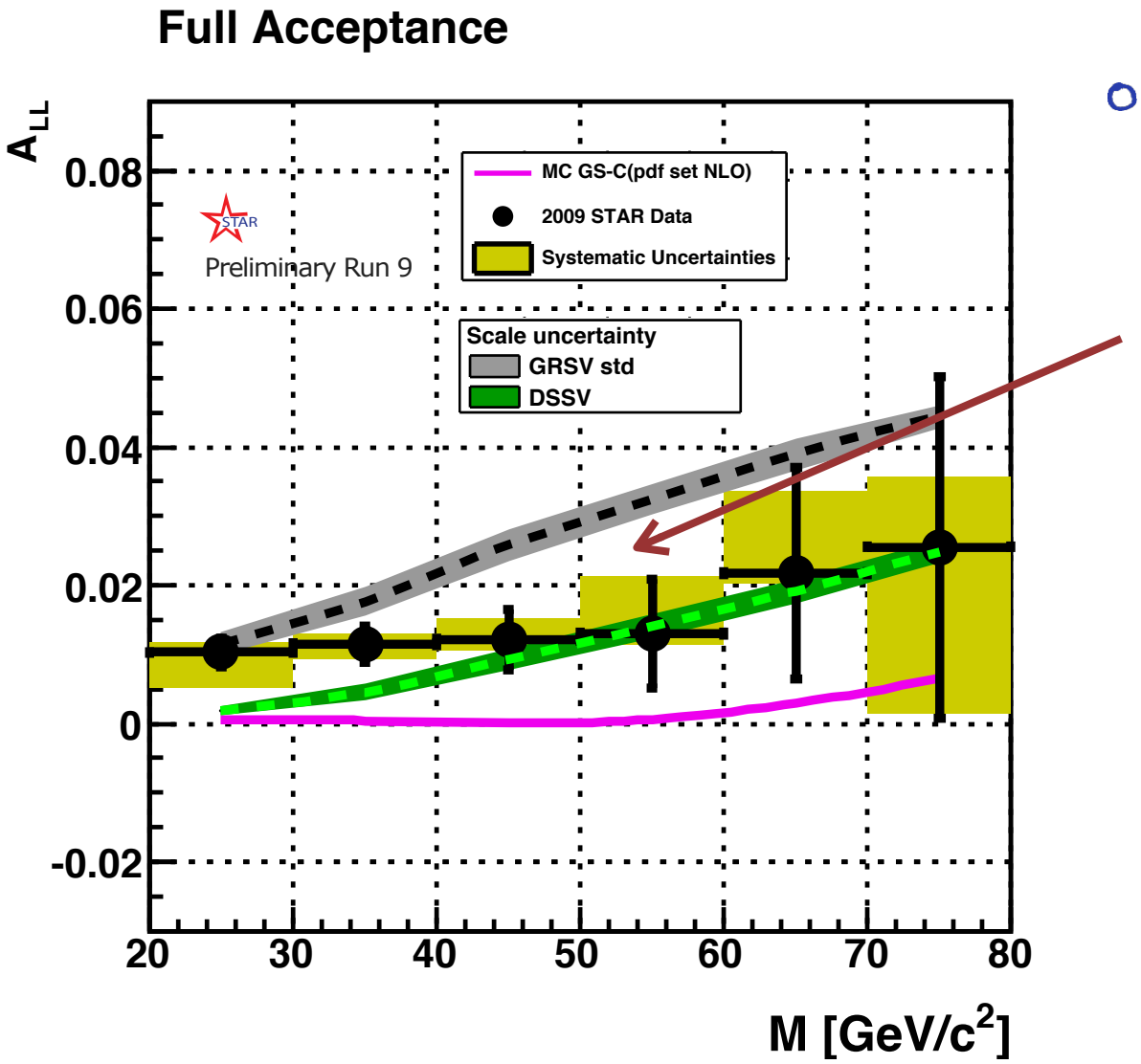

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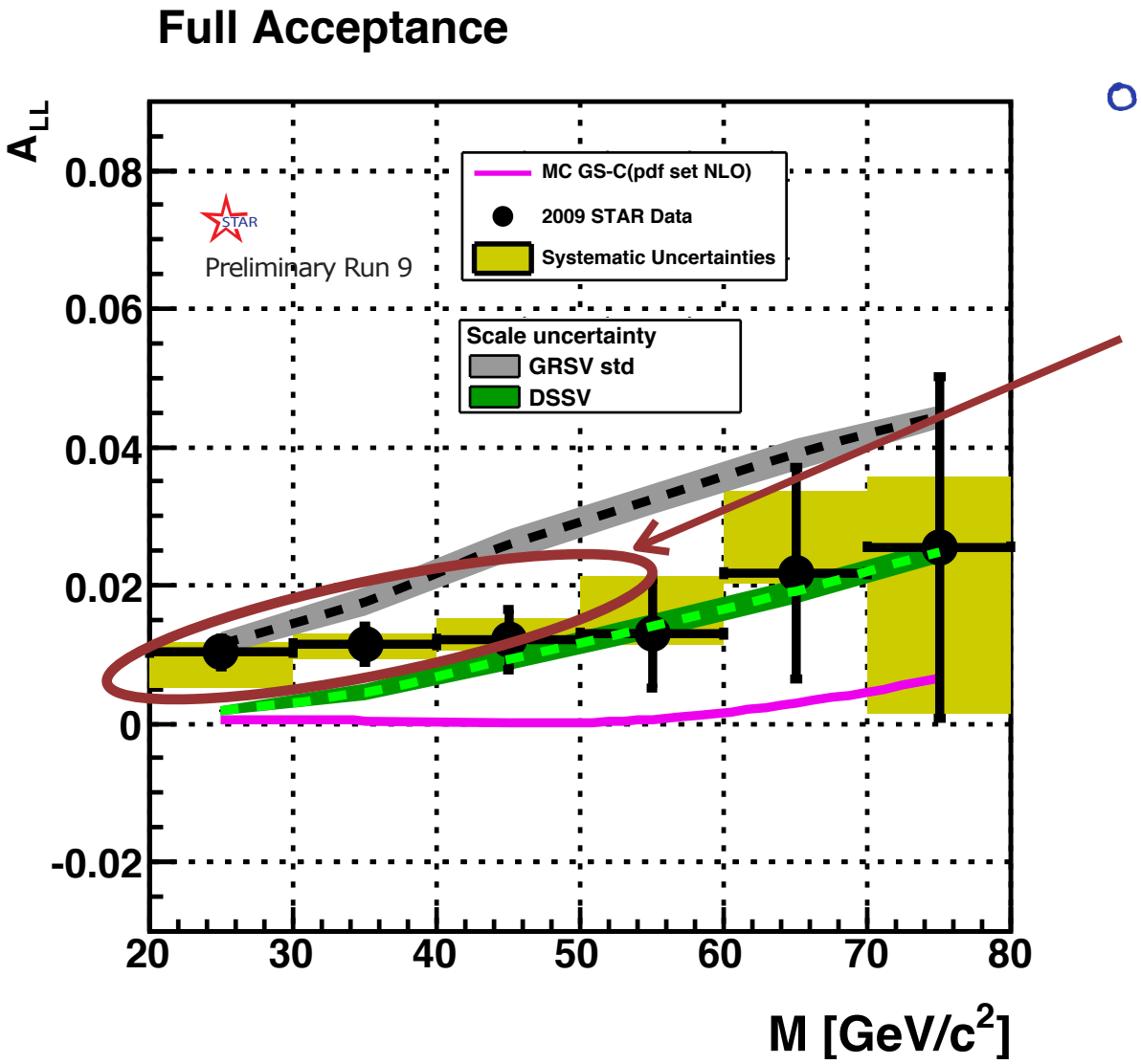

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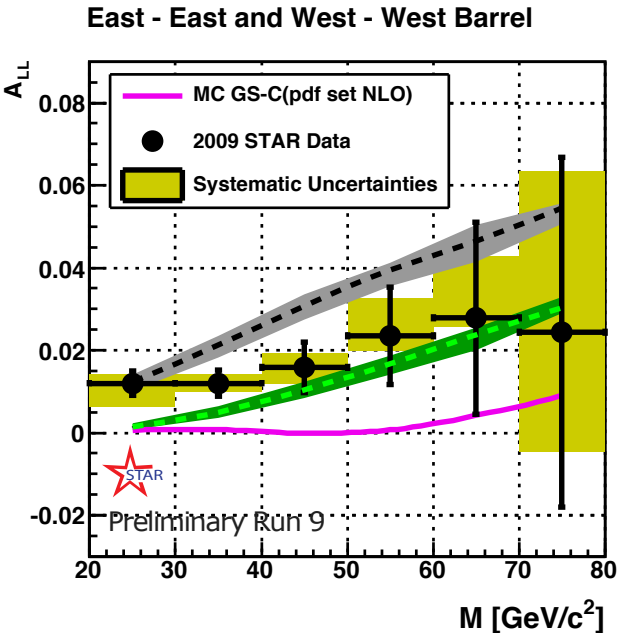
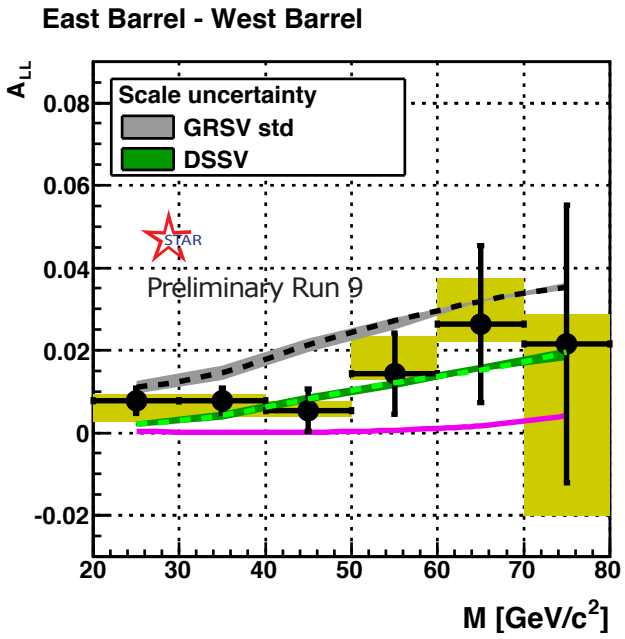
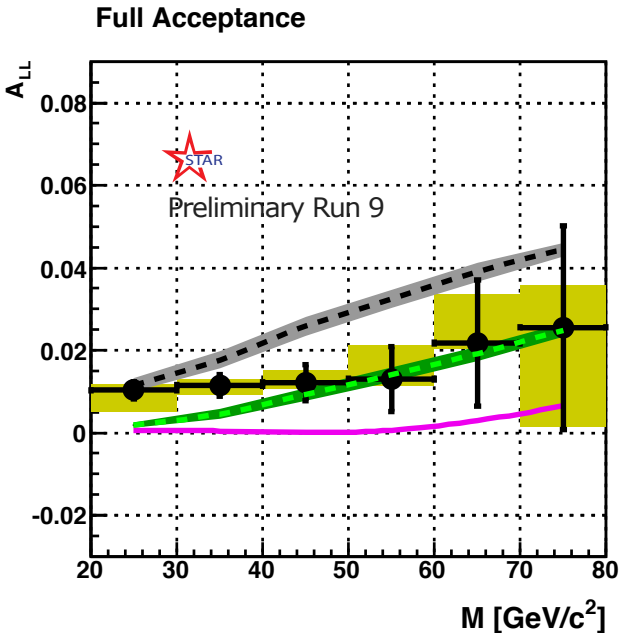
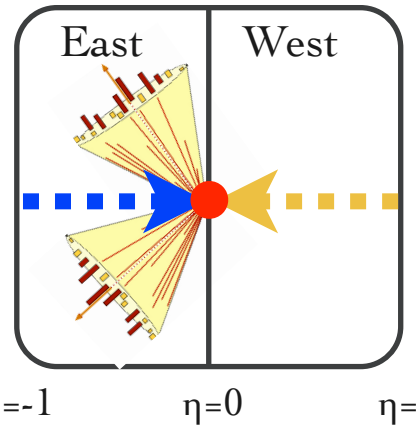
Recent results - Gluon polarization program

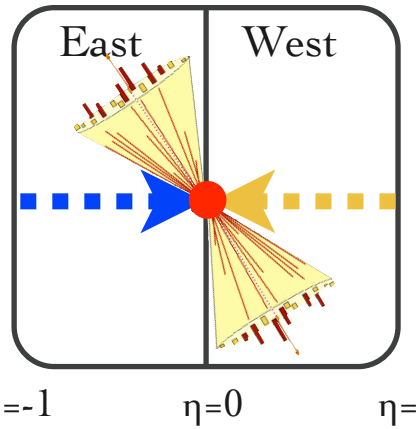
- First STAR Di-Jet A_{LL} measurement in bins of η











- Run 9 data: First rapidity dependent di-jet measurement
  ⇒ Constrain x dependence!

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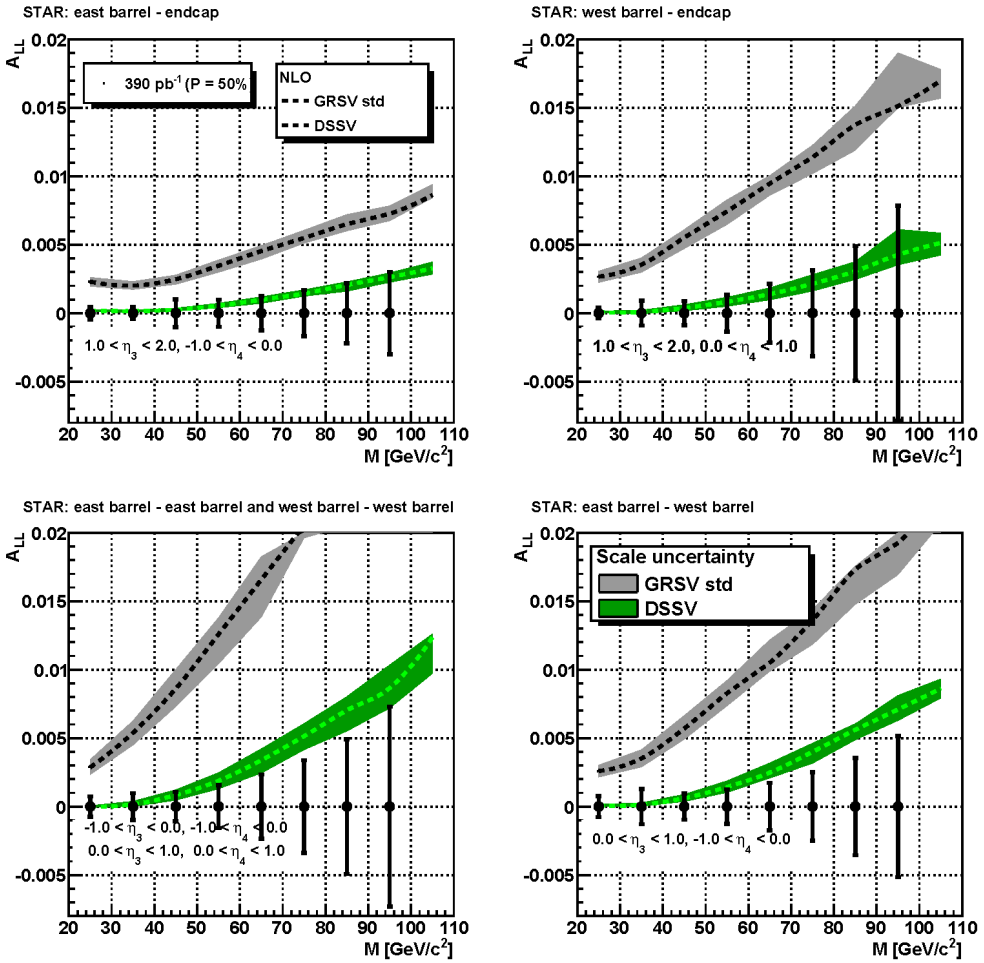
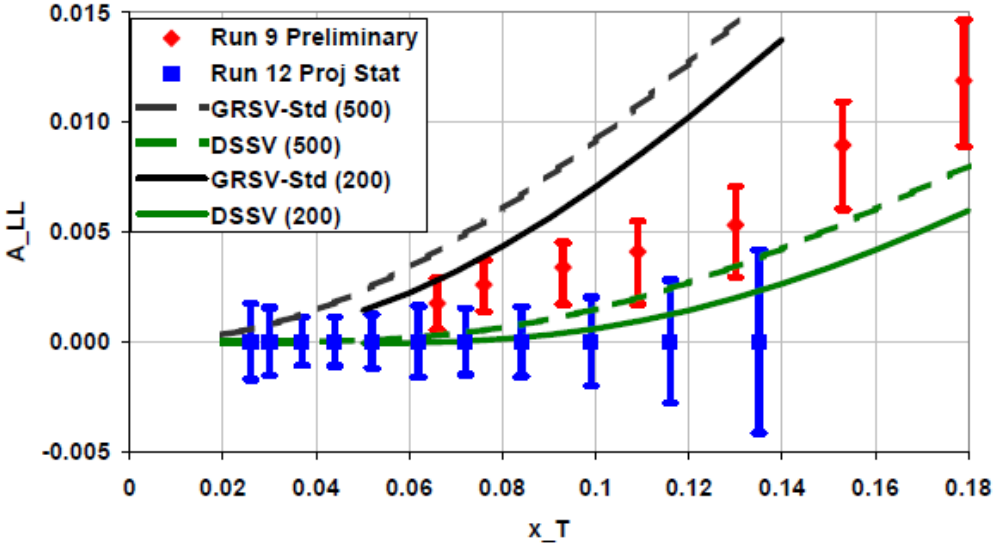
Future prospects - Gluon polarization program

Future Di-Jet / Inclusive Jet measurements

P=0.5 and $L_{recorded}$=390pb^{-1}



P=0.5 and $L_{recorded}$=85pb^{-1}

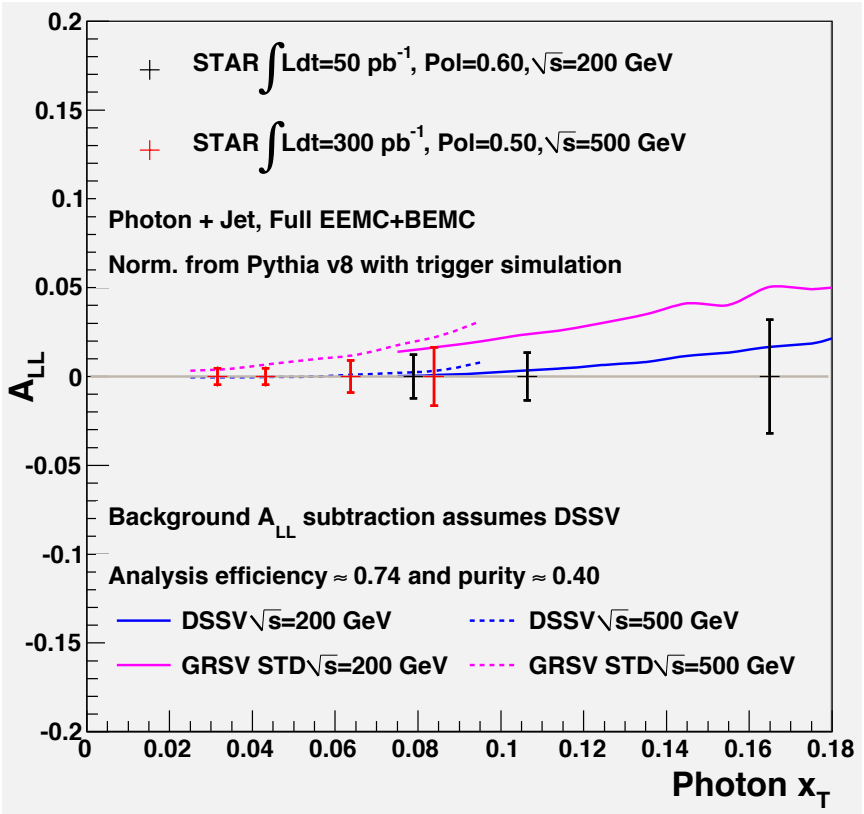


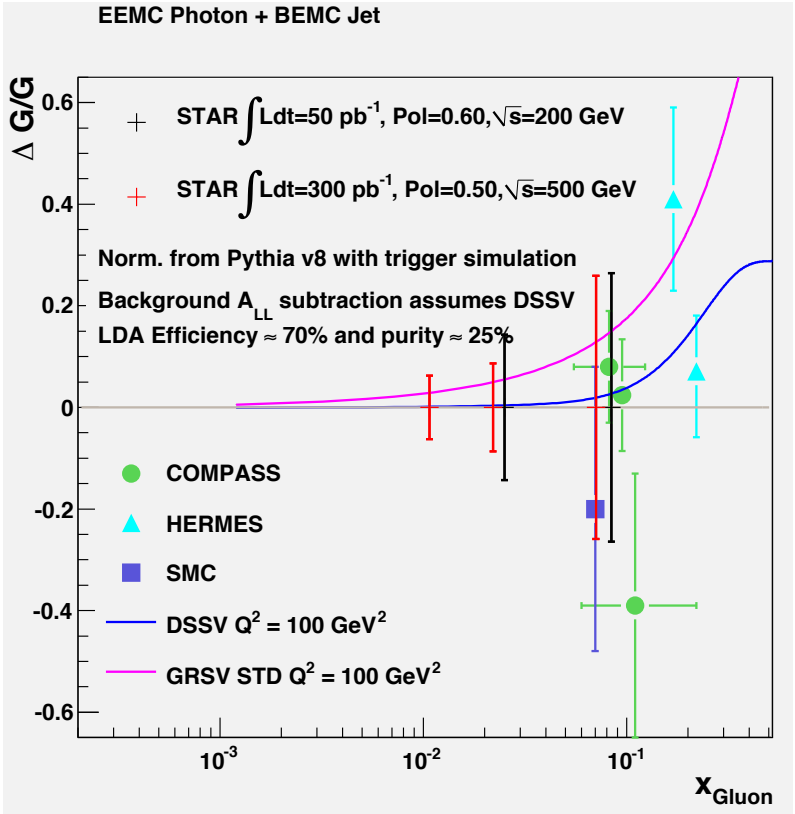
- Access lower Bjorken-x region at 500GeV ⇒ Expect smaller A_{LL}
- Important constrain from future Di-Jet and Inclusive Jet measurements

Future prospects - Gluon polarization program

Future Photon-Jet measurements

200GeV: P=0.6 and $L_{recorded}$=50pb^{-1} 500GeV: P=0.5 and $L_{recorded}$=300pb^{-1}

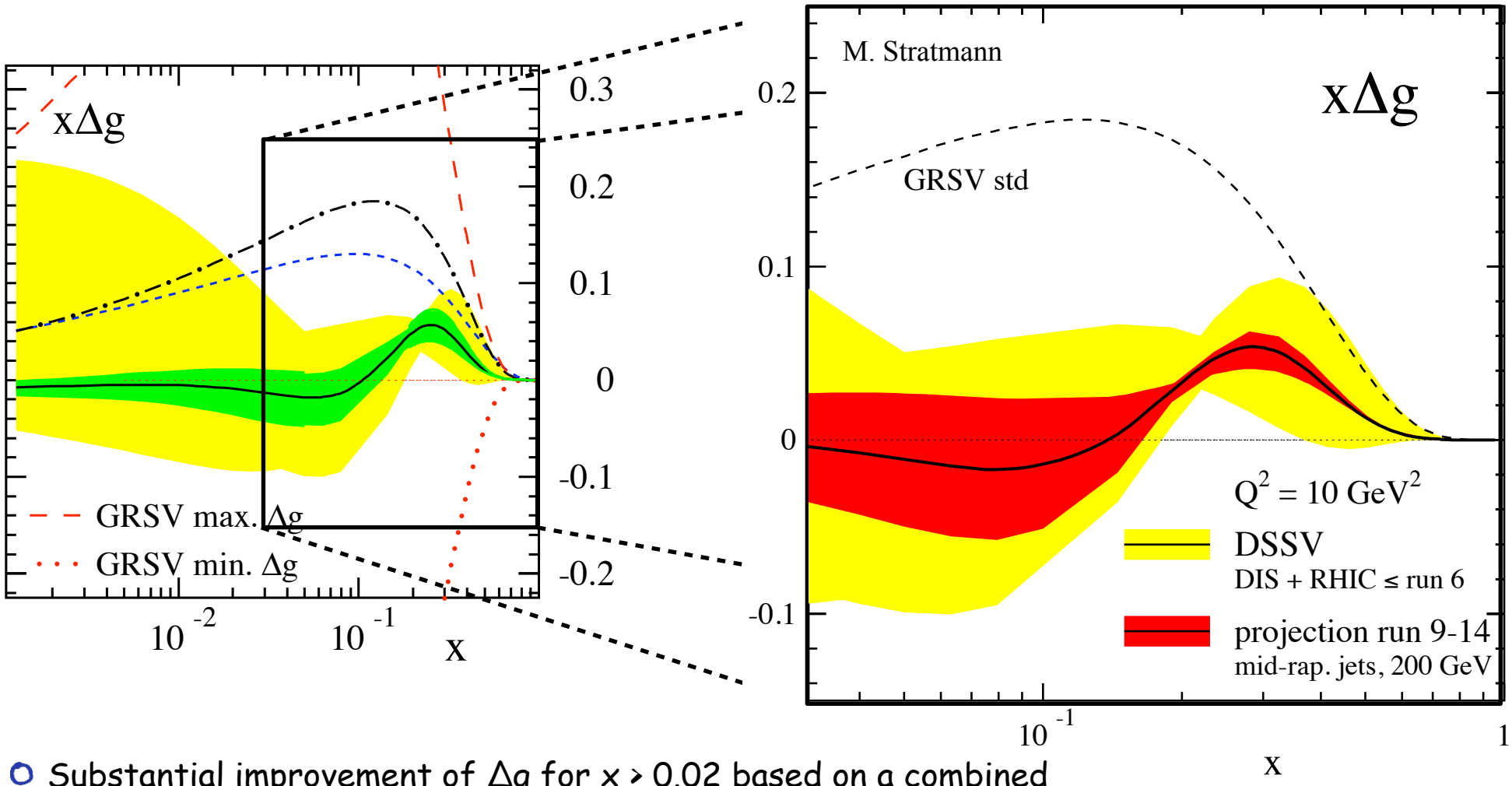




- Direct impact on $\Delta g(x)$
- Projections are for STAR EEMC - STAR FMS will reach lower x region (Few 10^{-3})

Future prospects - Gluon polarization program

- Impact on gluon polarization from STAR inclusive jet measurements



- Substantial improvement of Δg for $x > 0.02$ based on a combined Run 9 + Run 14 data sample of inclusive jet at $\sqrt{s}$=200GeV for $|\eta|<1$

Summary / Outlook

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$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

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$$\Delta\Sigma = 0.242 \; (Q^2 = 10\,\mathrm{GeV}^2)$$

(D. deFlorian et al., Phys. Rev. D80, 034030 (2009))

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  - Δg: Improved precision at 200GeV / 500GeV and forward jet measurements (low-x)

THANKS

I would like to thank my Spin Collaborators for useful discussions, in particular E. Aschenauer (BNL), P. Djawotho (Texas A&M), Maro Stratmann (BNL), W. Vogelsang (University of Tübingen) and M. Walker (Rutgers University)

Greetings from Dubna!