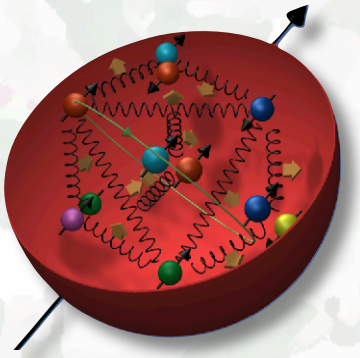
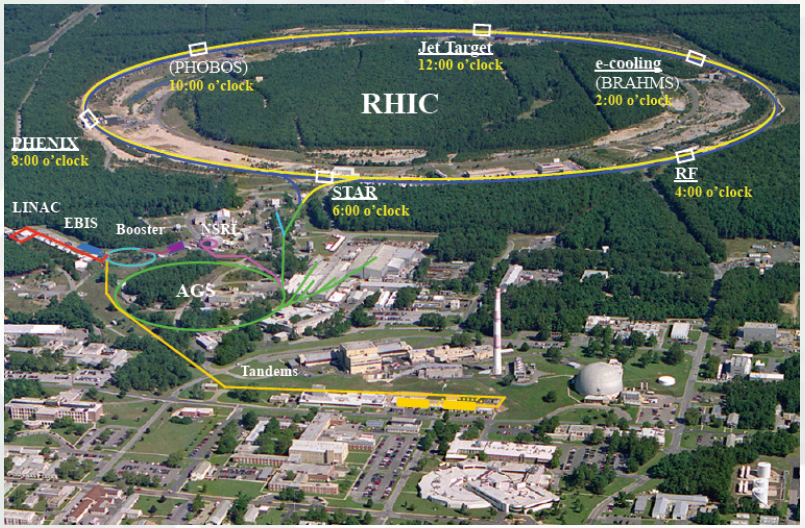
Recent results on hadron/jet and W production of the high-energy polarized p+p program at RHIC at BNL

Bernd Surrow

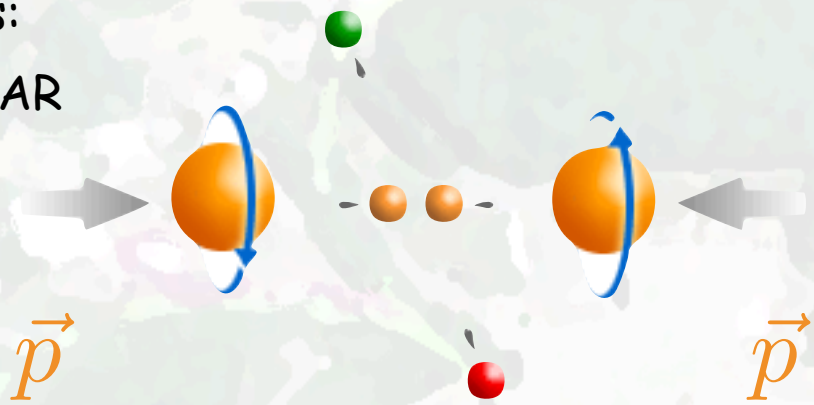
TEMPLE UNIVERSITY



Outline

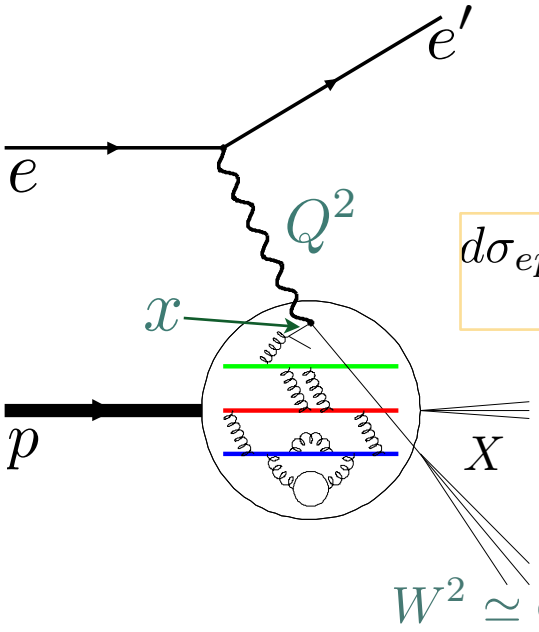


- Selected recent results and future prospects
  - Gluon polarization
  - Quark / Anti-quark polarization
- Experimental aspects: RHIC / PHENIX /STAR
- Theoretical foundation
- Summary and Outlook



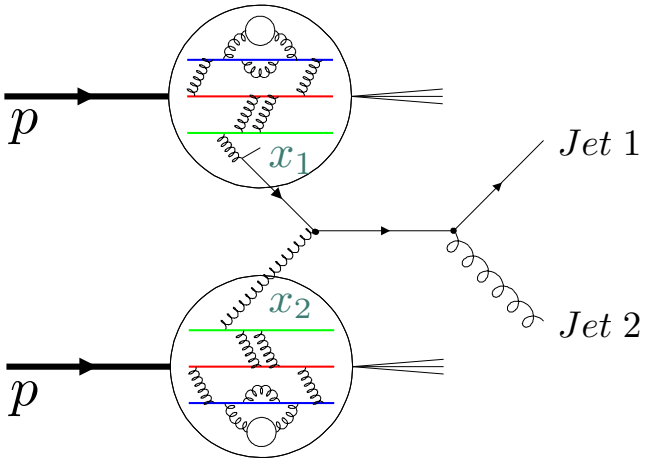
Theoretical foundation

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



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

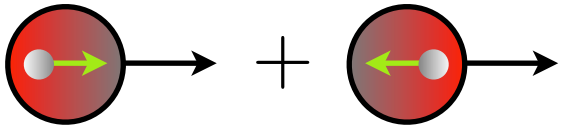
Universality



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

Momentum contribution

$$f(x) =$$



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

$$\Delta f(x) =$$

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

Spin contribution

Theoretical foundation

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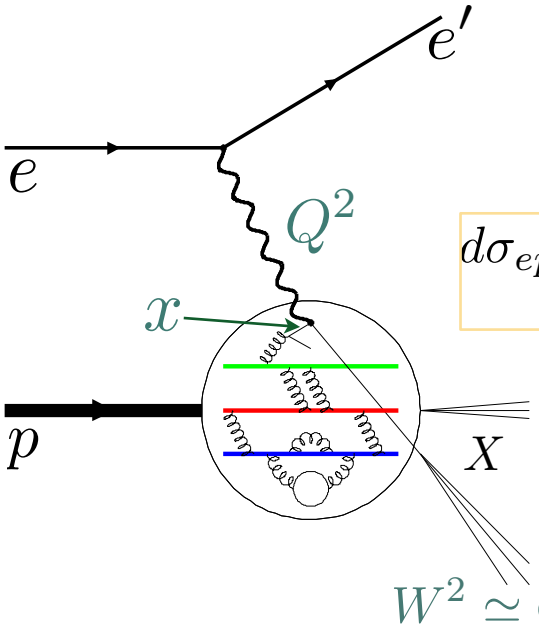

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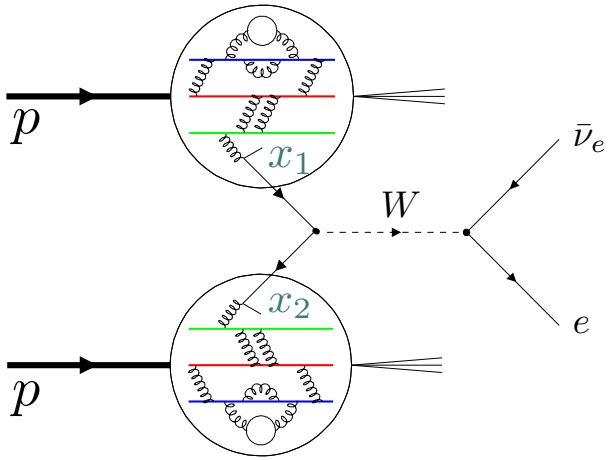

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Factorization

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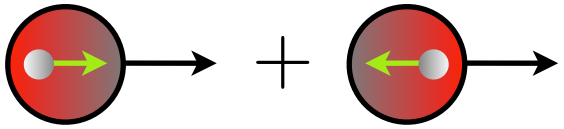

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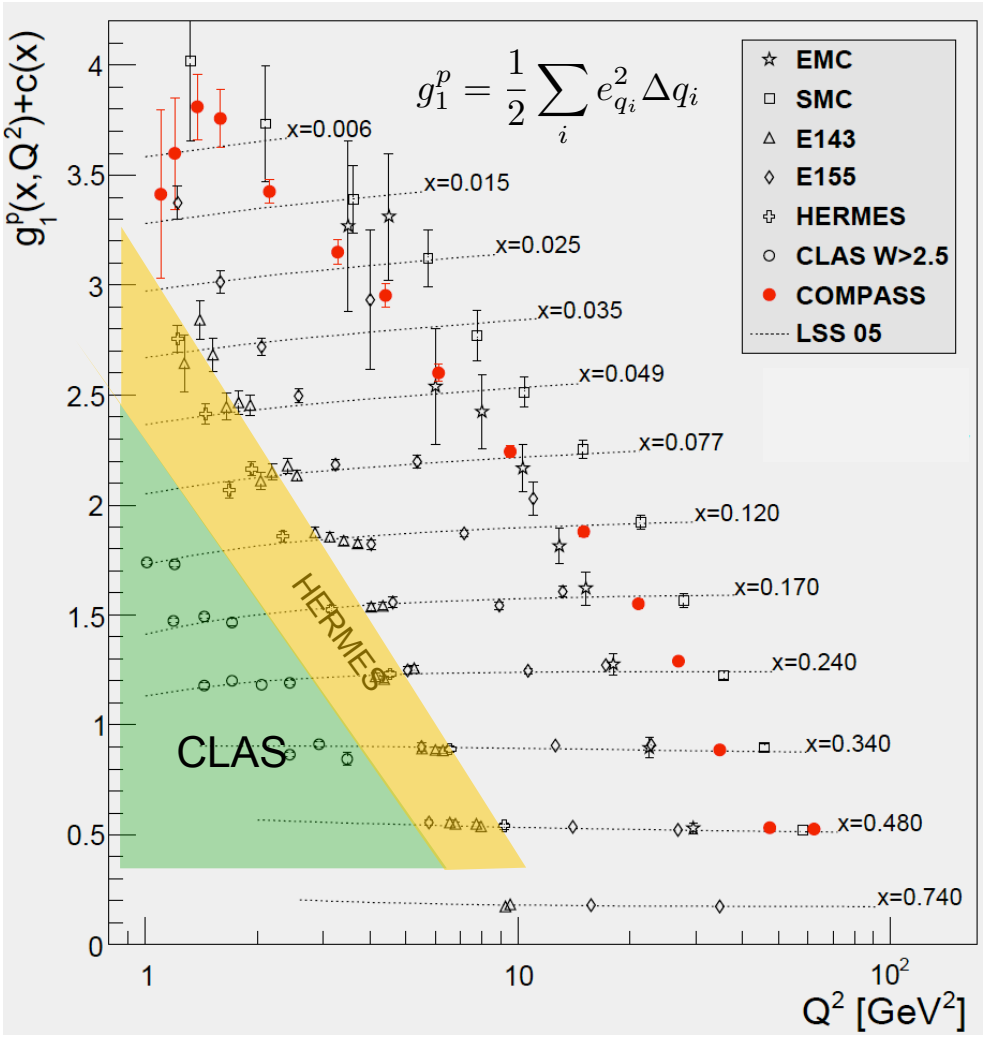
Spin contribution

Theoretical foundation

- Picture of the proton from polarized ep scattering



- Spin sum rule:

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

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

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

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

Theoretical foundation

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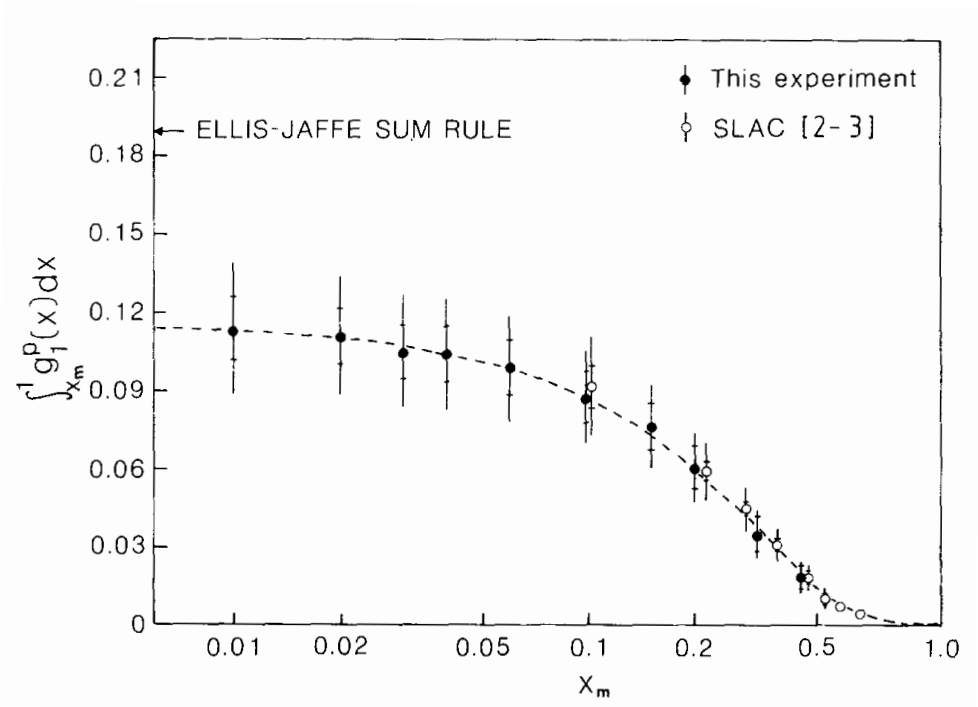

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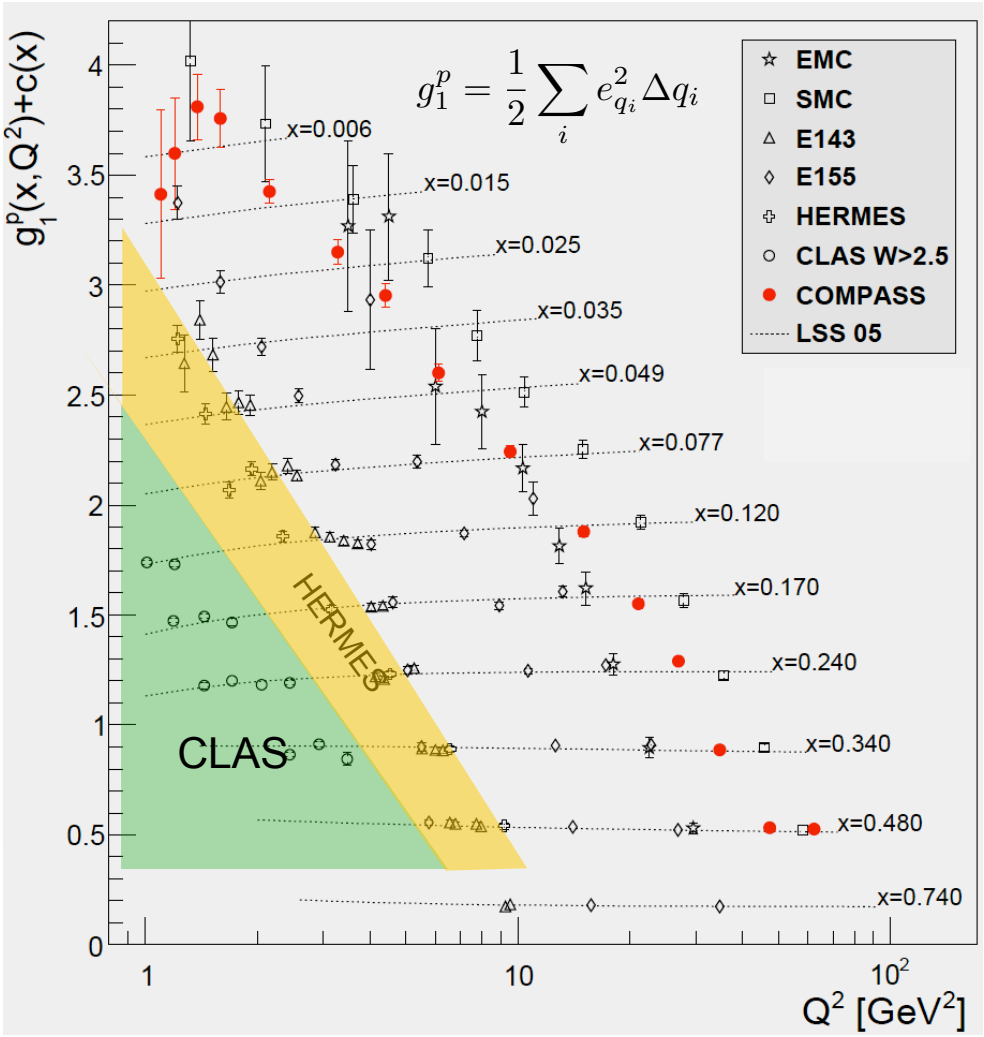

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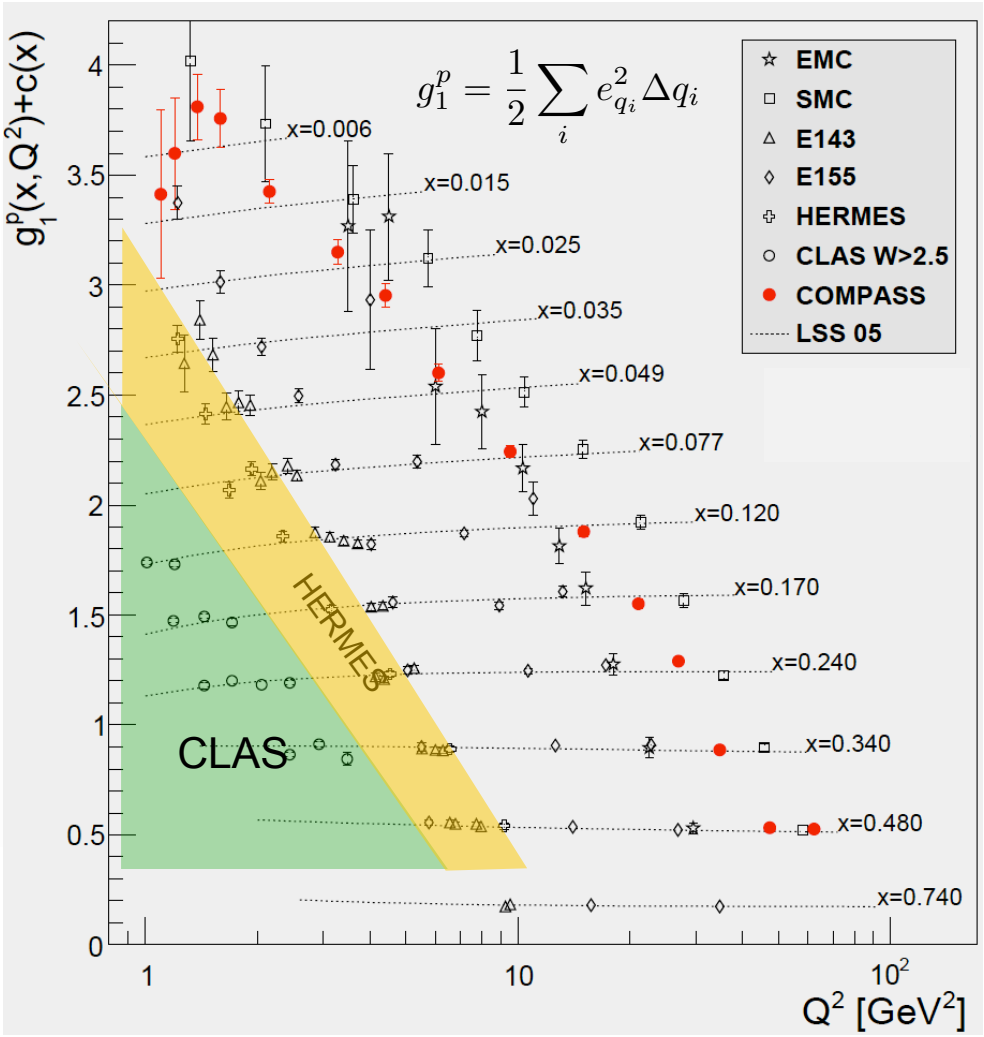

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Theoretical foundation

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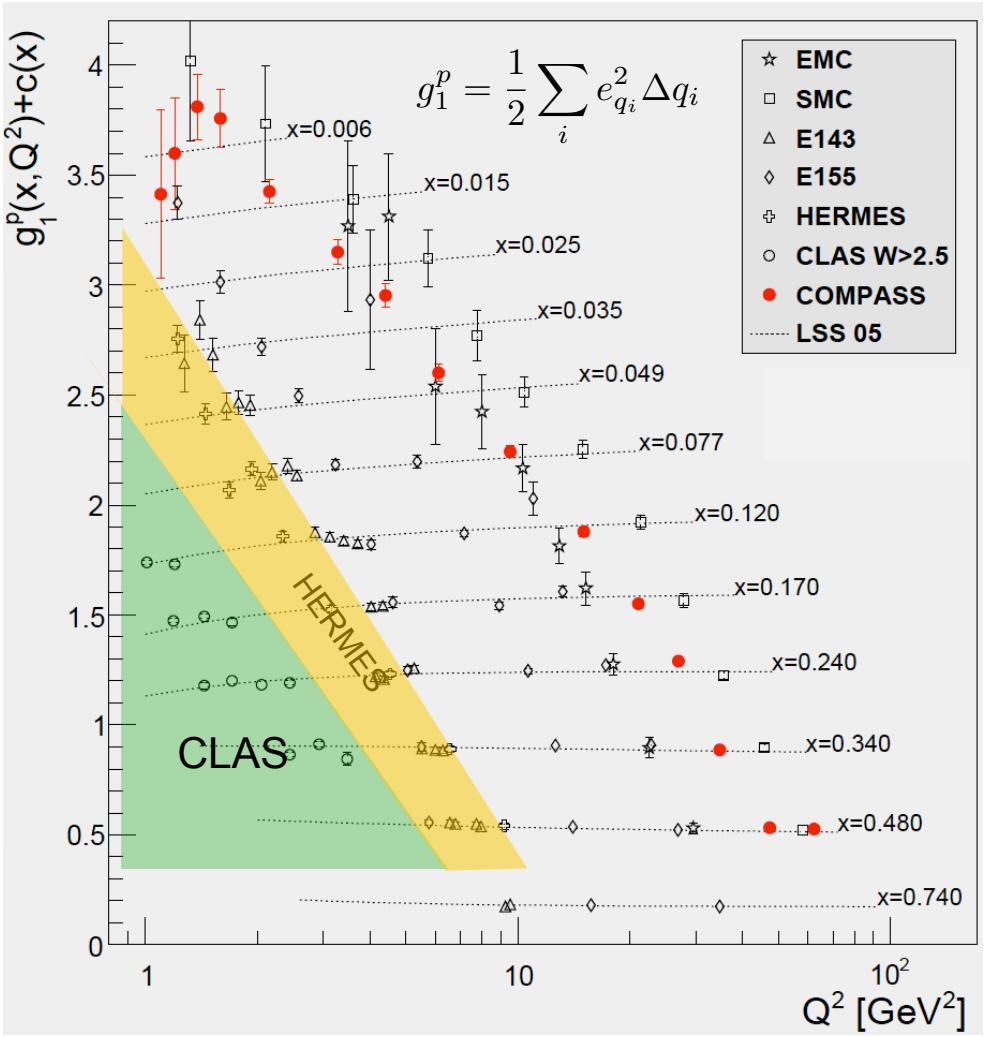

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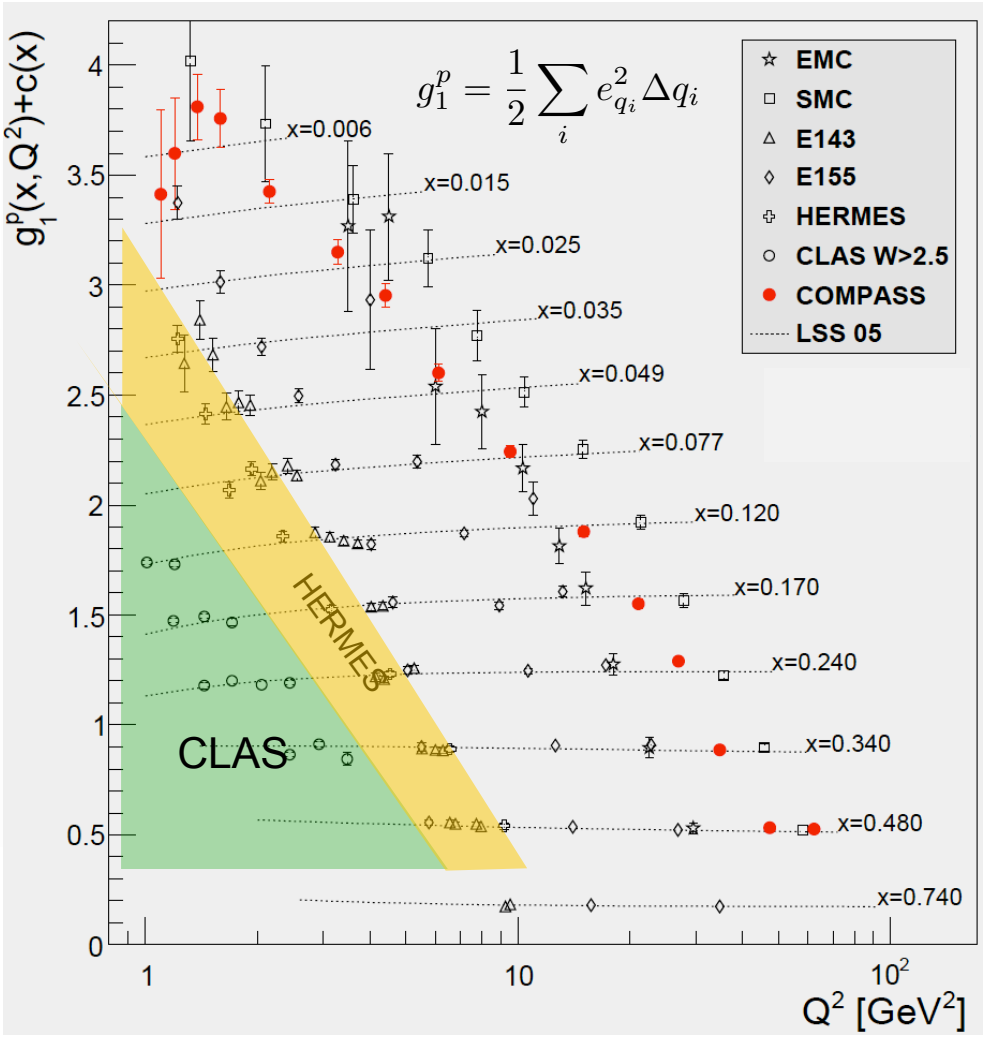

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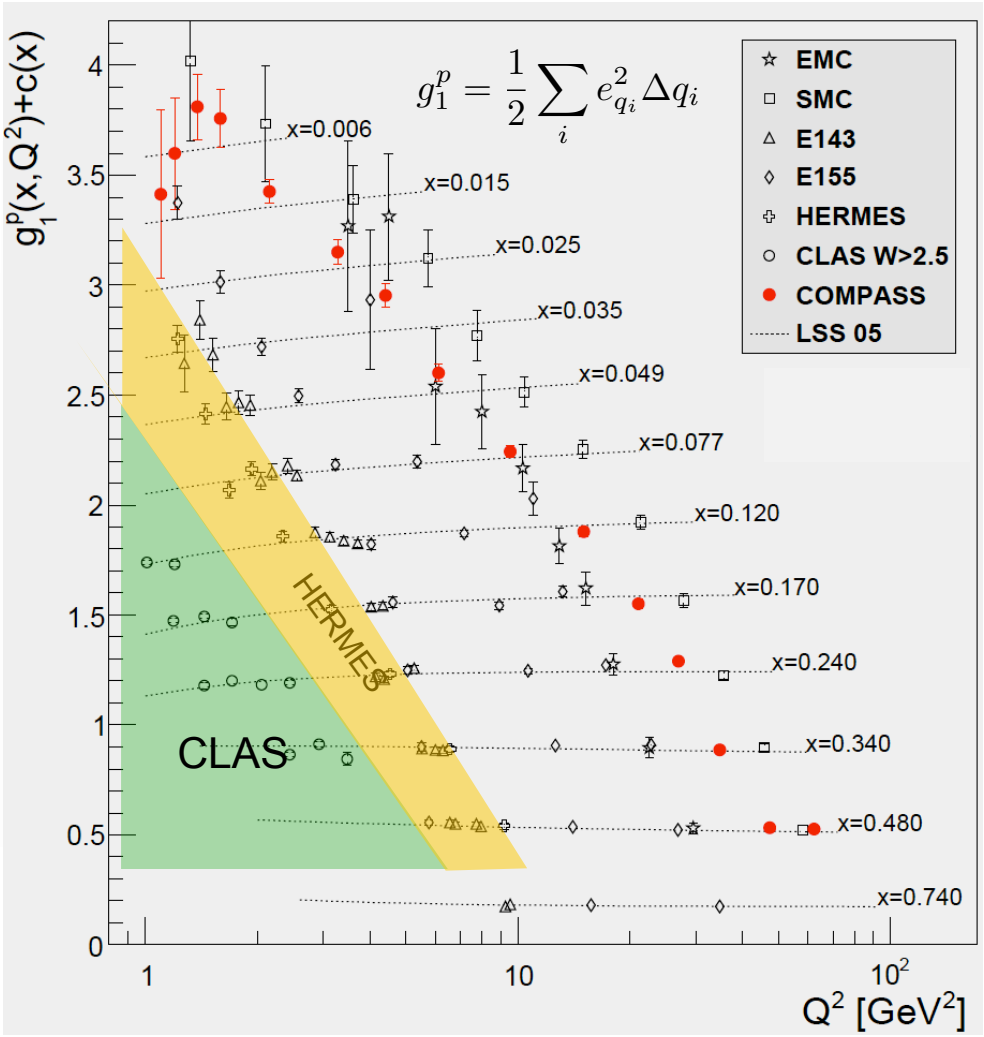

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  - Δg - from scaling violations - unconstrained so far!

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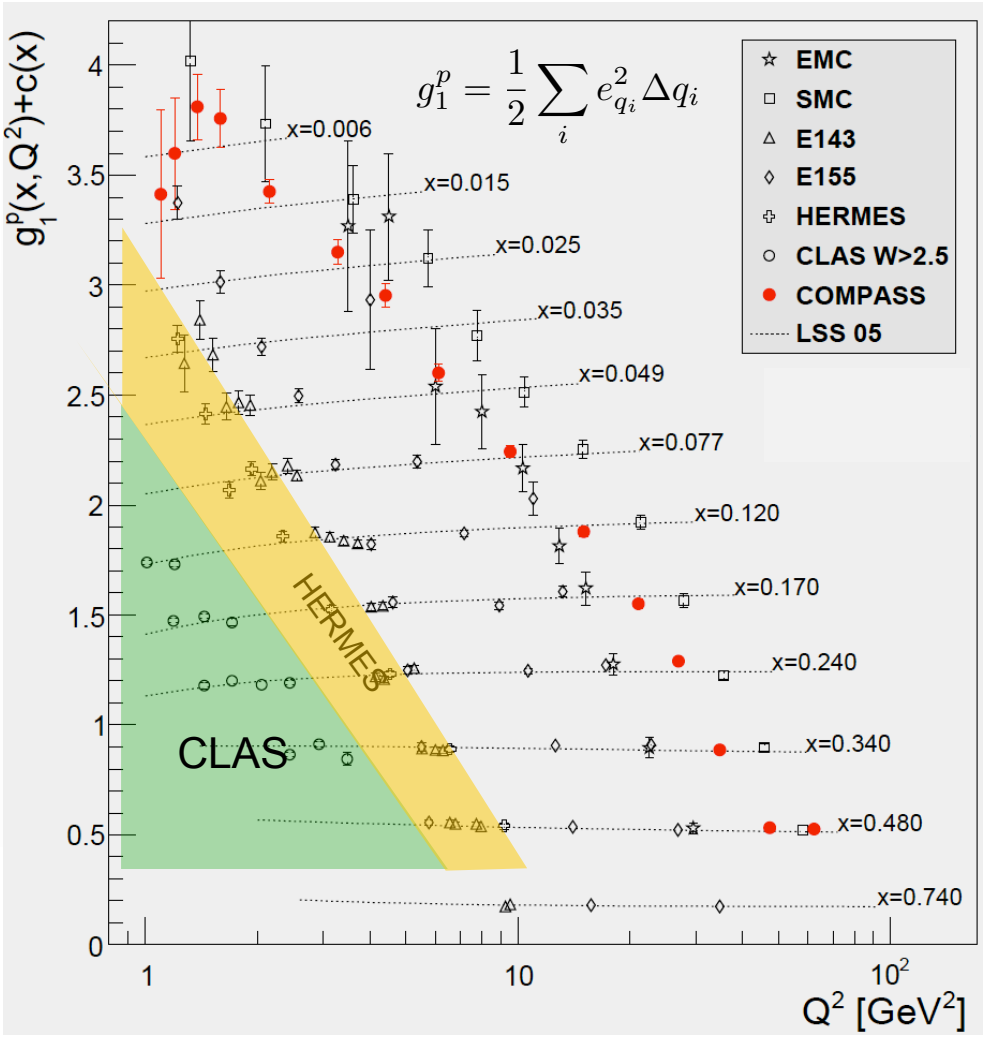

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- Current status:
  - Data only from fixed-target experiments (Limited reach in x and Q^2) mostly at lower energy
  - Quark spin contribution is small (~25%):

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

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

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Theoretical foundation

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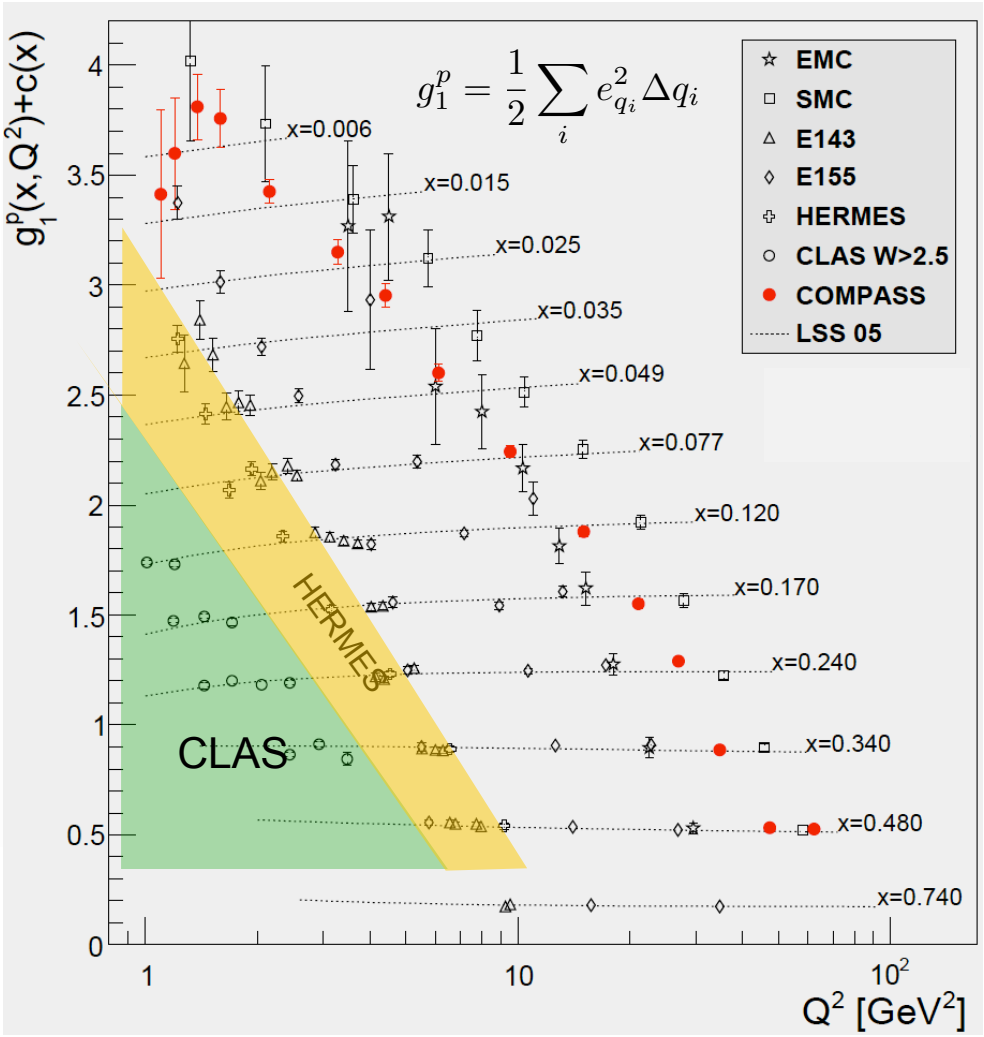

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$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{} + \underbrace{\Delta G}_{} + \langle L_q \rangle + \langle L_g \rangle$$

$\langle S_q \rangle$ $\langle S_g \rangle$

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

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

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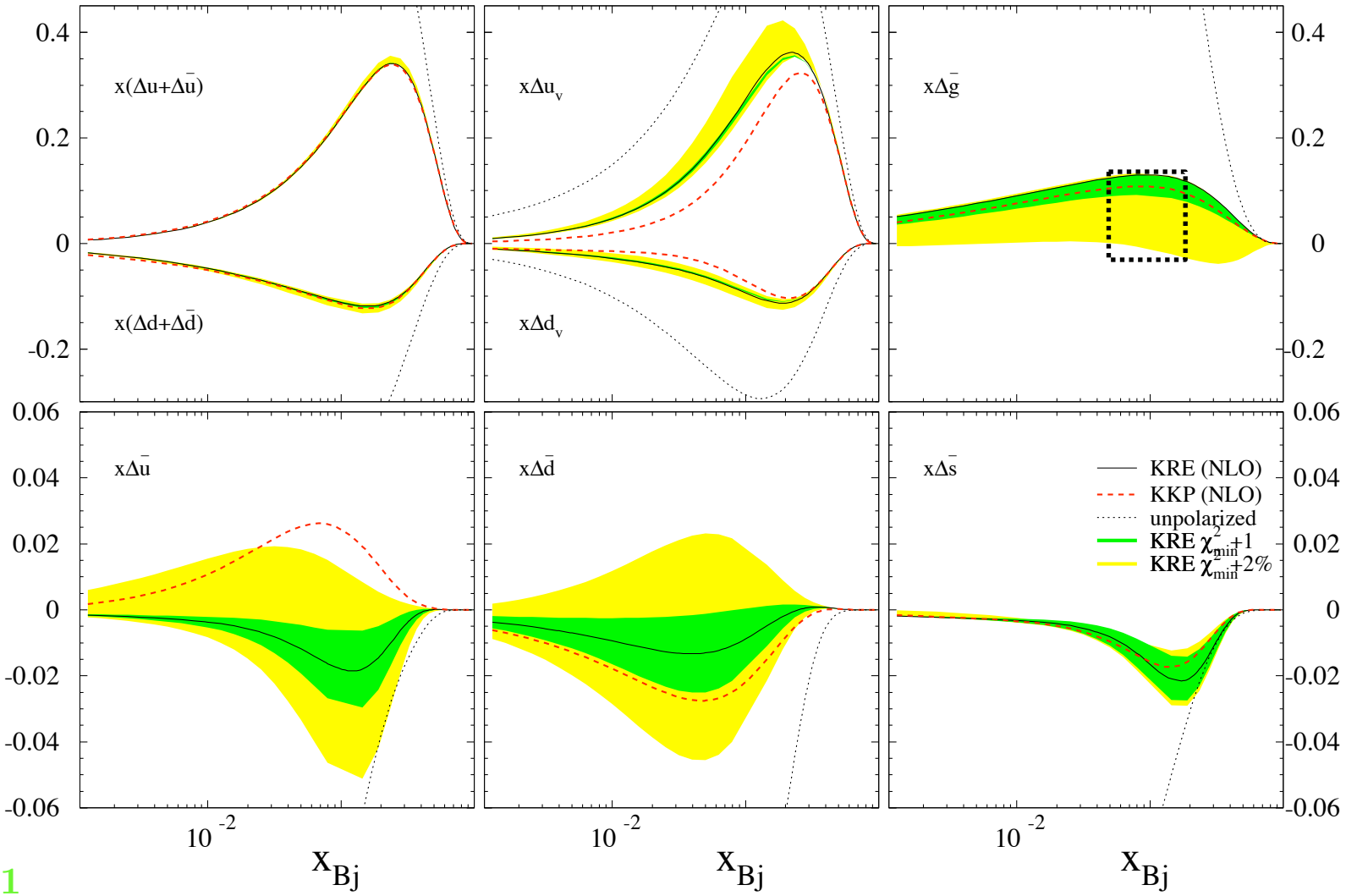
Theoretical foundation

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



$\Delta\chi^2 = 1$

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

Theoretical foundation

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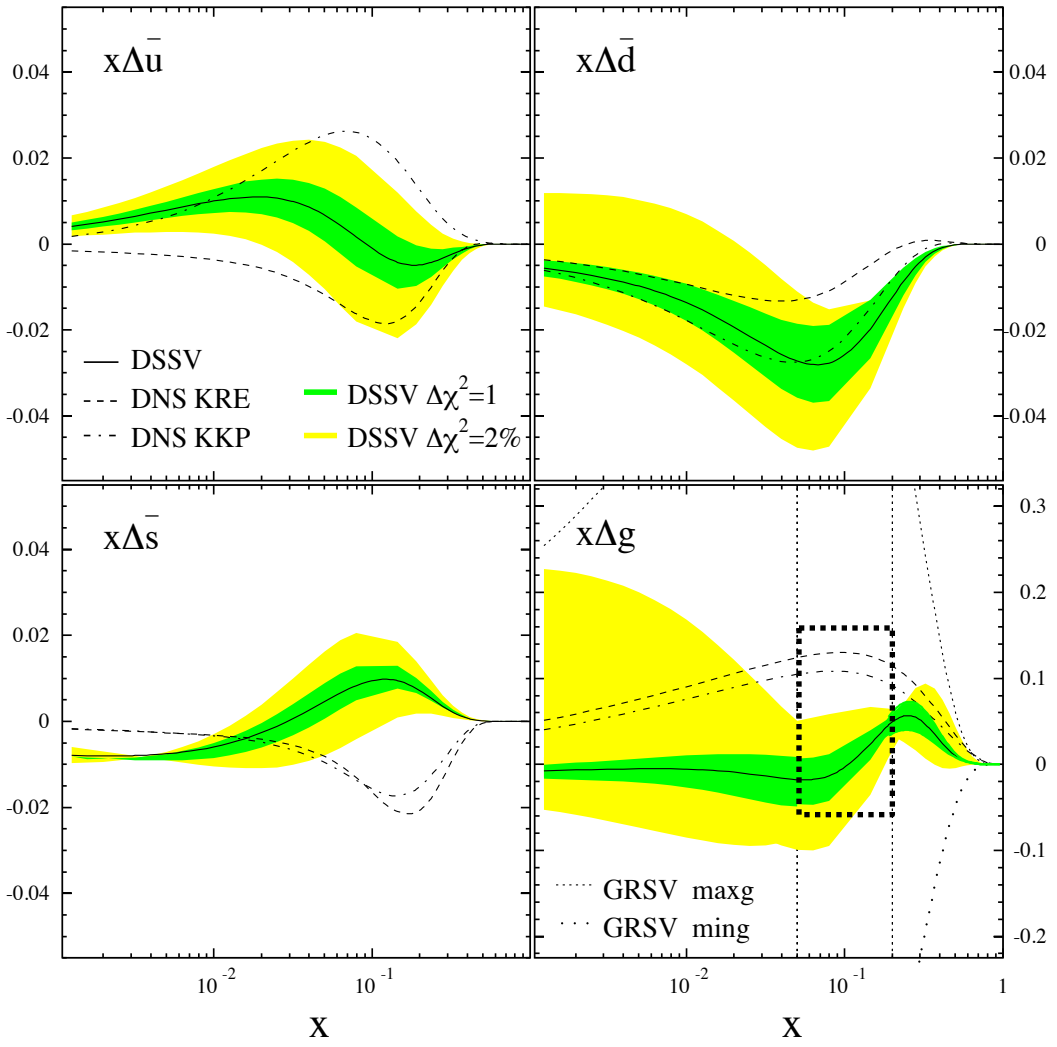


u/d sea-quark polarizations large uncertainties!

Substantial improvement from polarized p+p data data at RHIC

$\Delta\chi^2 = 1$

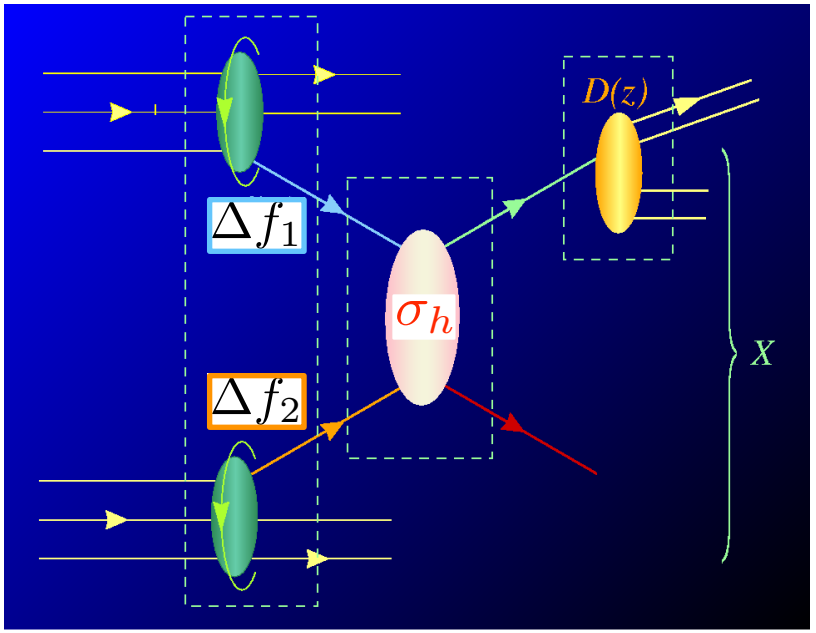
D. de Florian et al., Phys. Rev. Lett. 101 (2008) 072001

Theoretical foundation

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

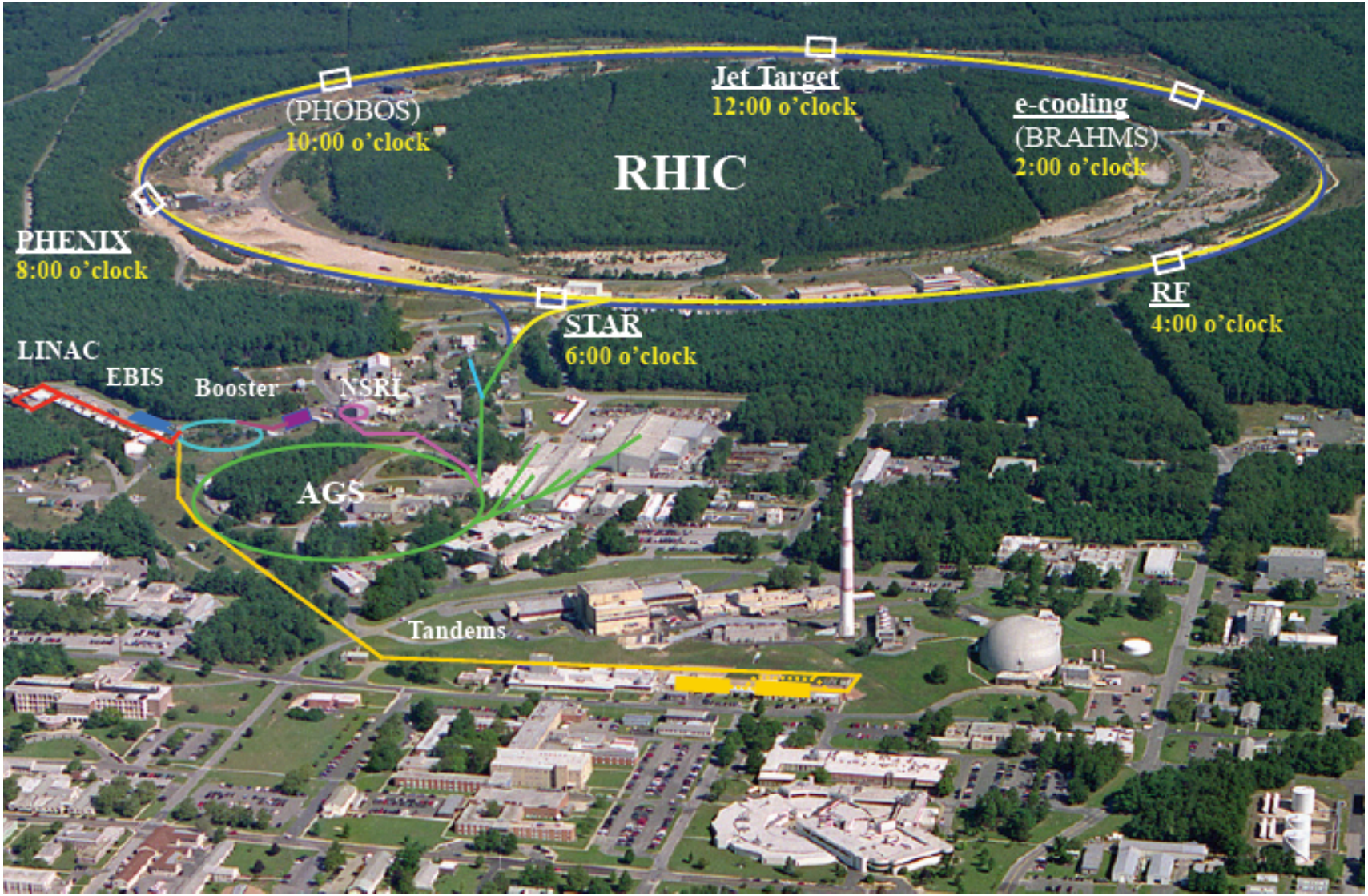
$$a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$$

Input

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

Experimental aspects - RHIC

- The world's first polarized proton-proton collider



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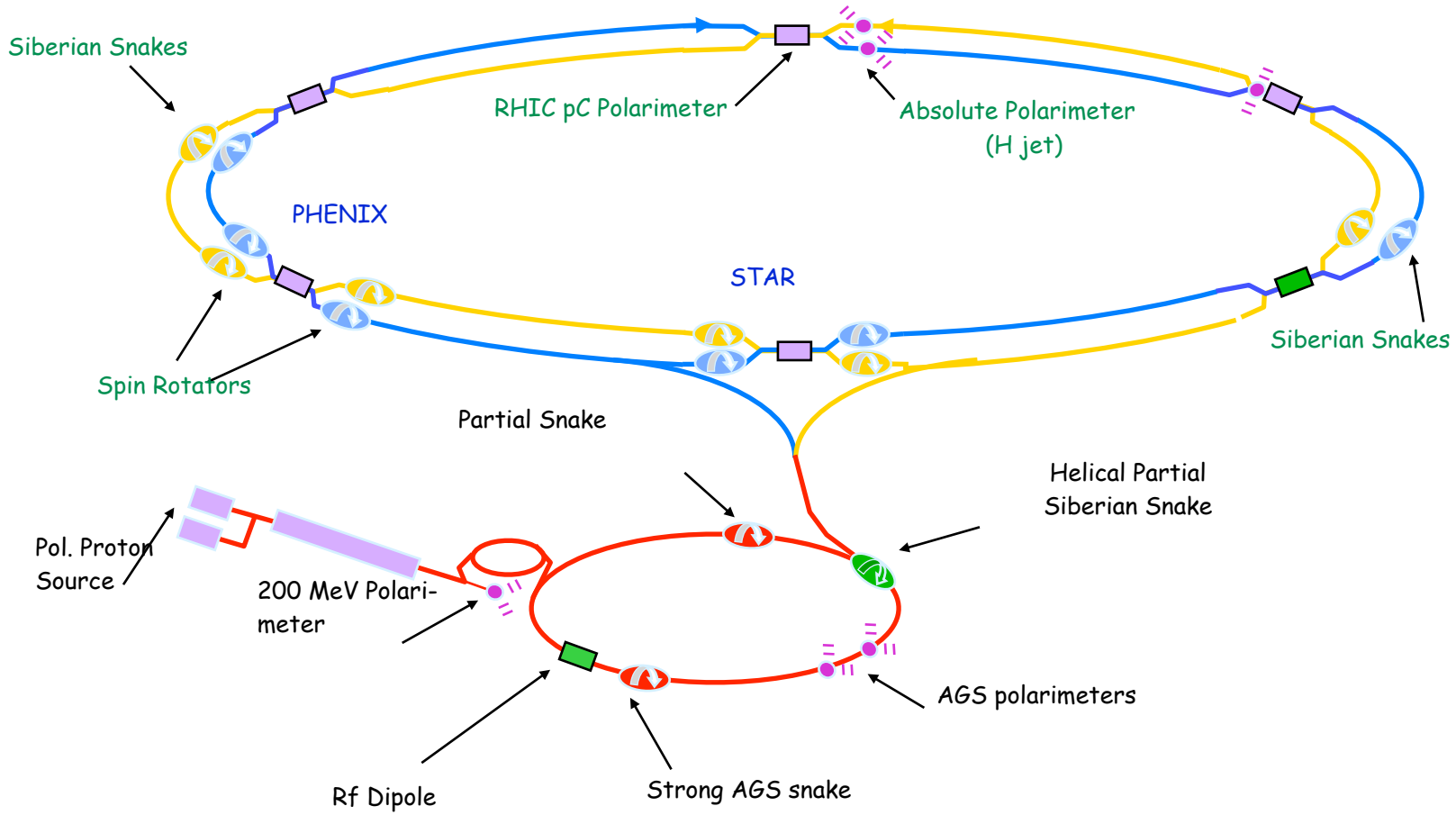

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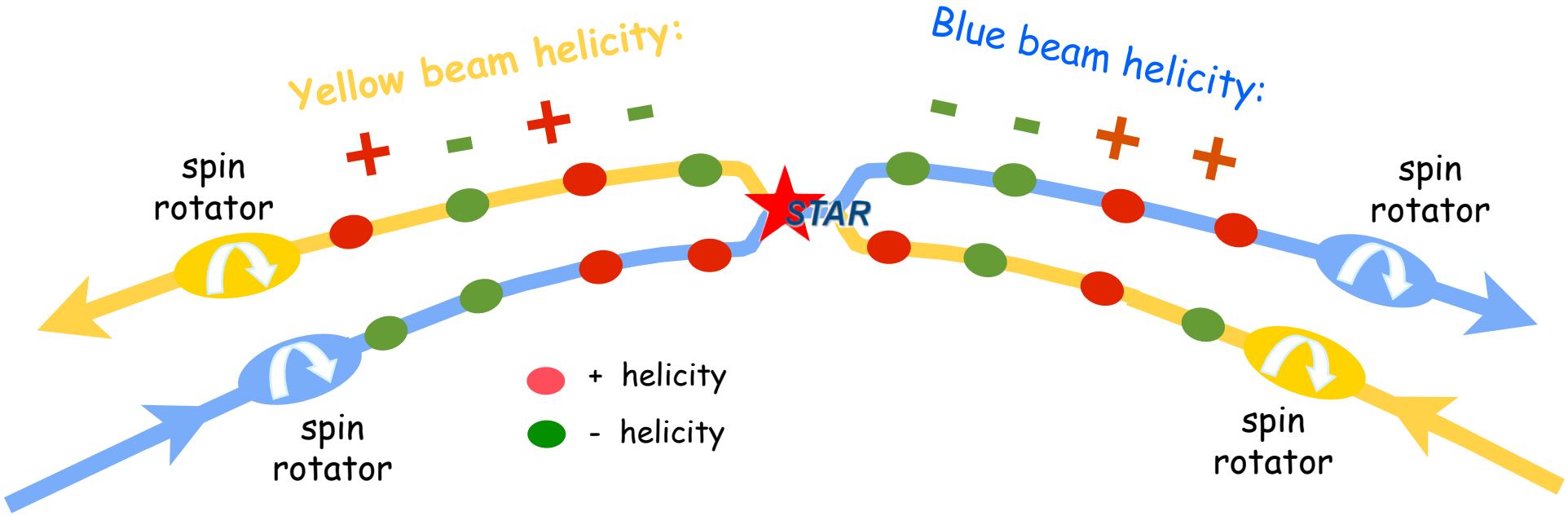
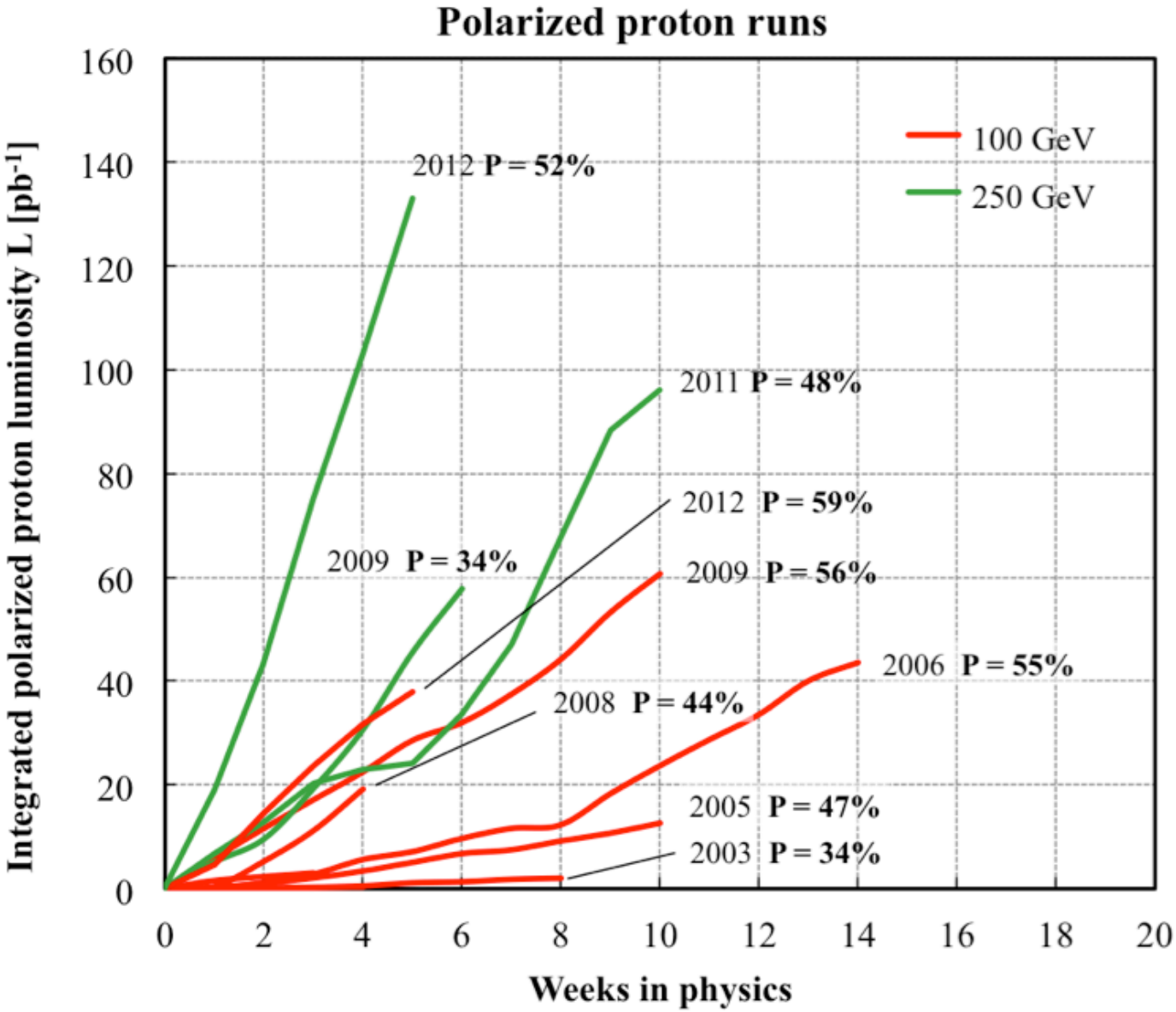


Experimental aspects - RHIC

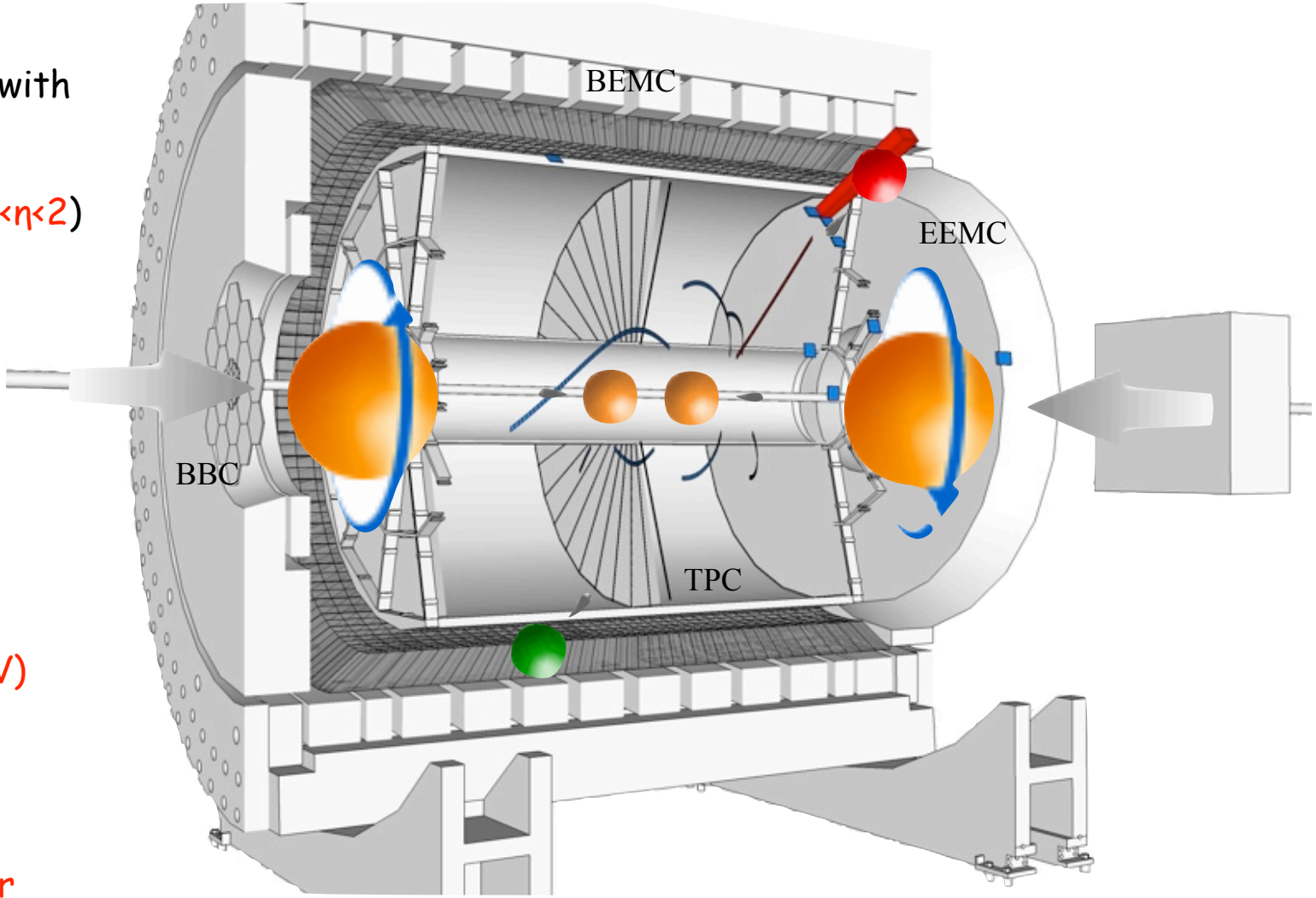
- Polarized p-p collisions
  - Long production runs at $\sqrt{s}$=200GeV (long. polarization) in 2005, 2006, 2009 and 2012: Jet and Hadron production (Gluon polarization)
  - First collisions of polarized proton beams at $\sqrt{s}$=500GeV (long. polarization) in 2009 and 2012: W production (Quark polarization)



Experimental aspects - STAR

Overview

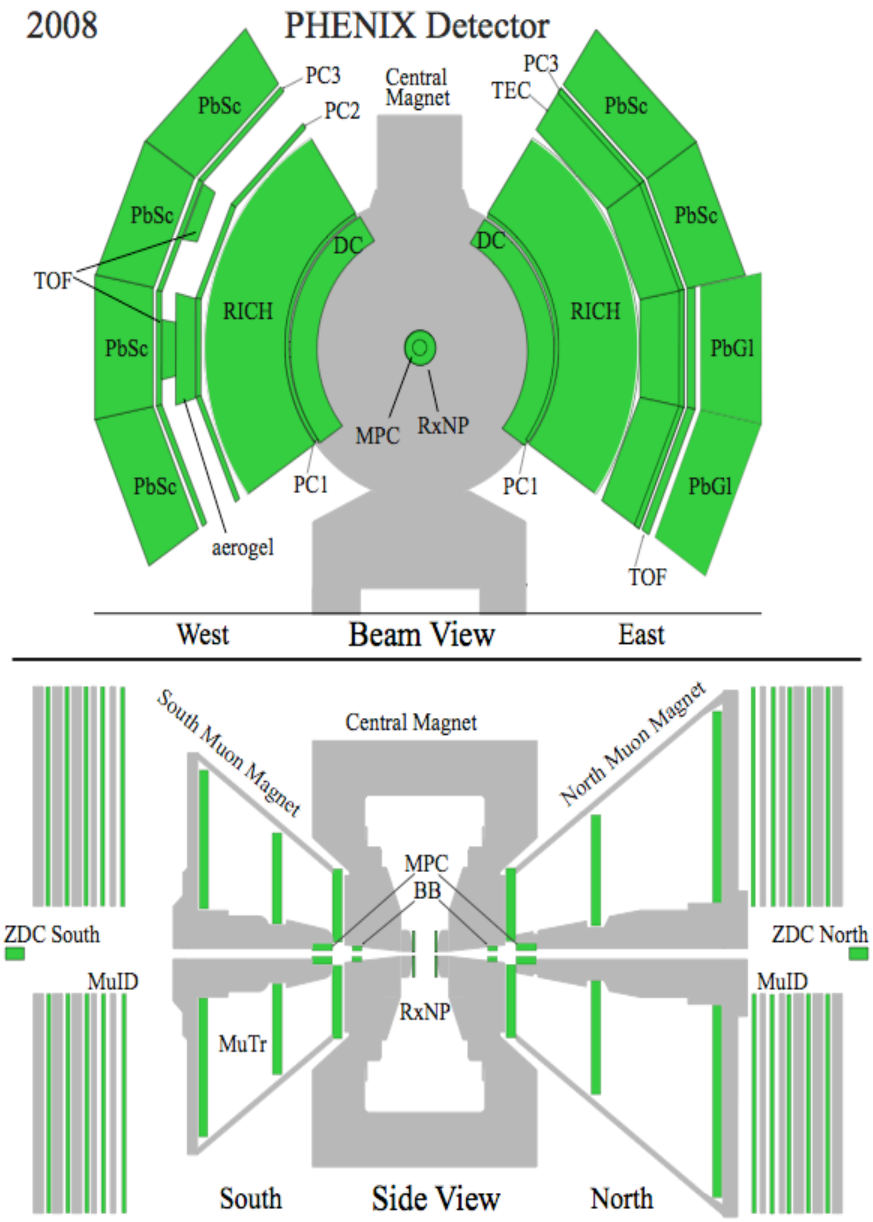
- Calorimetry system with 2π coverage: BEMC ($-1<\eta<1$) and EEMC ($1<\eta<2$)
- TPC: Tracking and particle ID
- ZDC: Relative luminosity and local polarimetry (500GeV)
- BBC: Relative luminosity and Minimum bias trigger



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

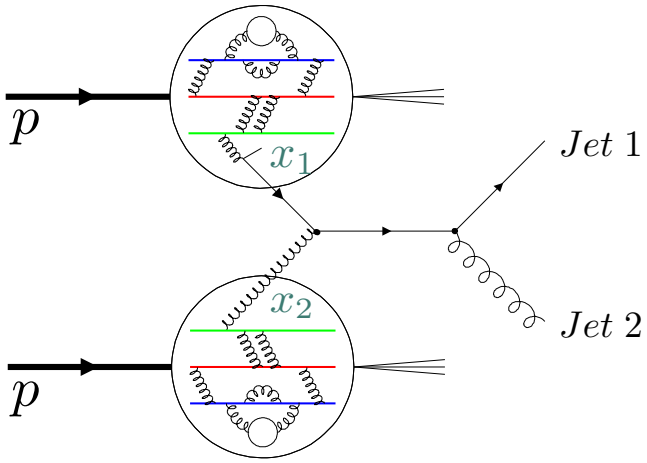
Experimental aspects - PHENIX

- Overview
  - 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)

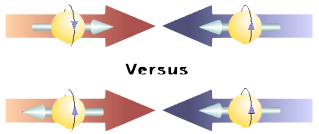


Experimental aspects - Asymmetry measurement

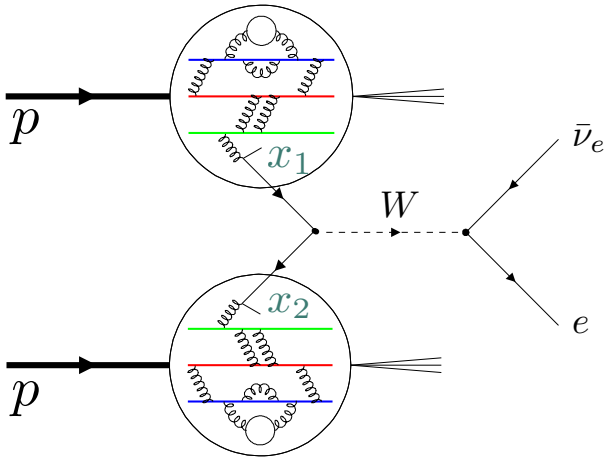
- Double and single longitudinal spin asymmetry measurements



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



- 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



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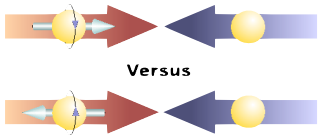
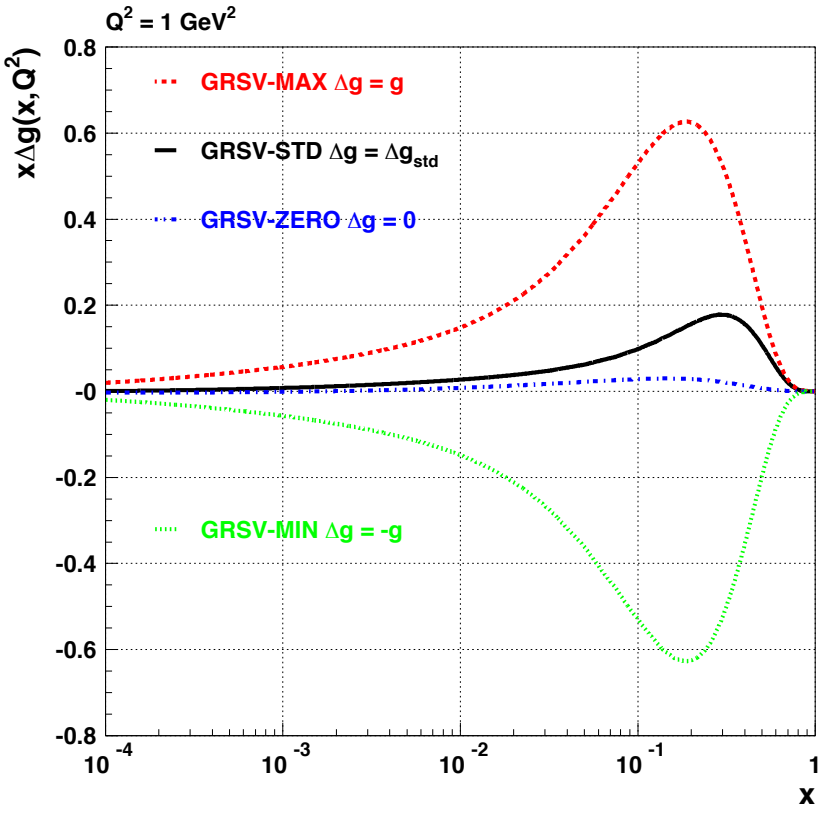


Recent results - Gluon polarization program

Measurement: Connection of Δg and A_{LL}



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

$\Delta G(Q^2 = 1GeV^2) \approx 0.4$

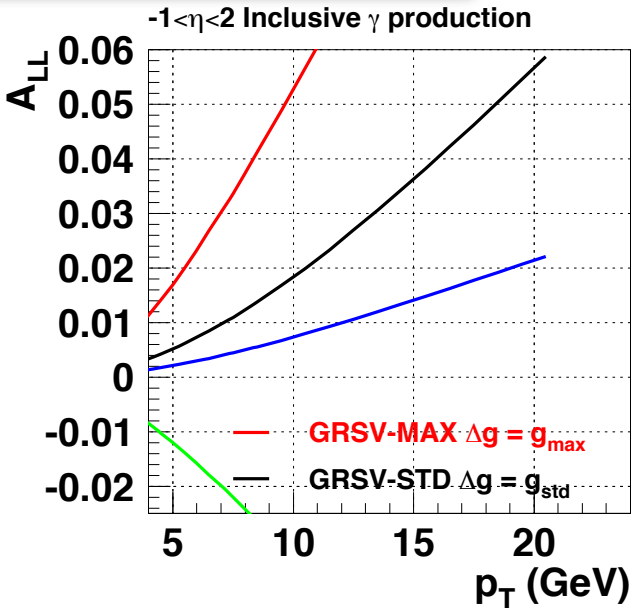
$\Delta G(Q^2 = 1GeV^2) \approx 0.1$

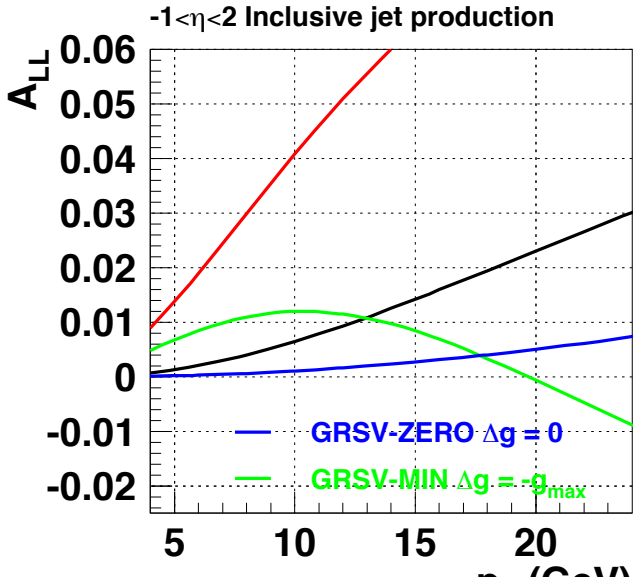
$\Delta G(Q^2 = 1GeV^2) \approx -1.8$

- 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.

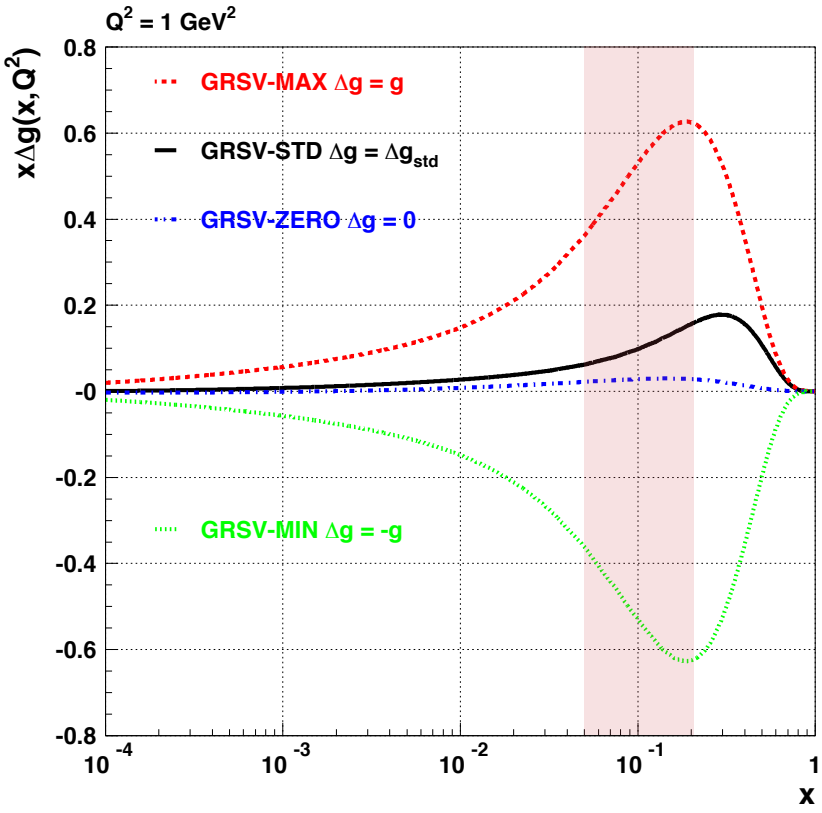
$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$





Recent results - Gluon polarization program

Measurement: Connection of Δg and A_{LL}



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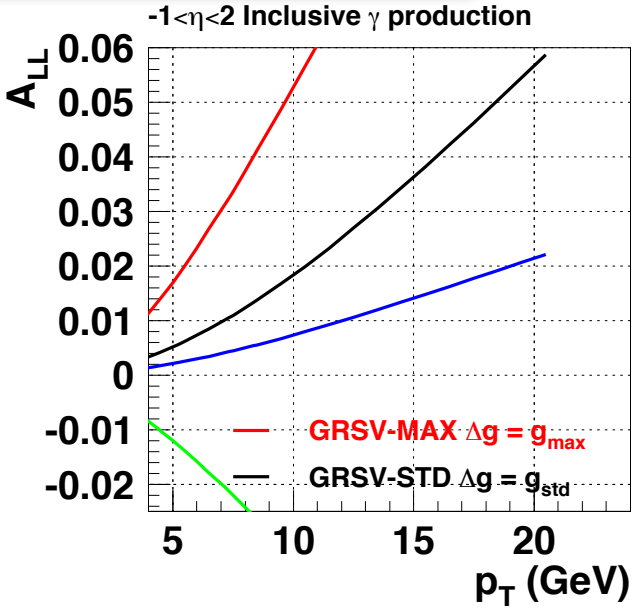

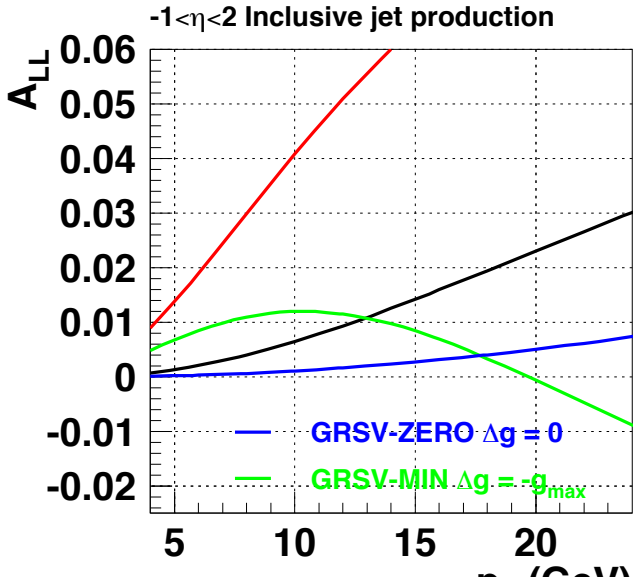

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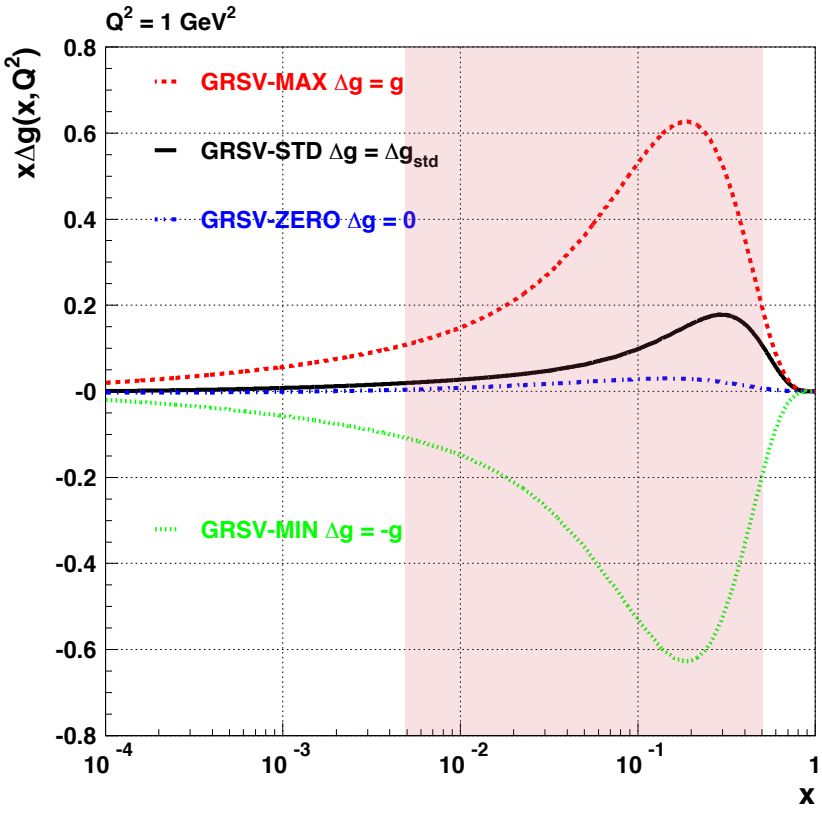

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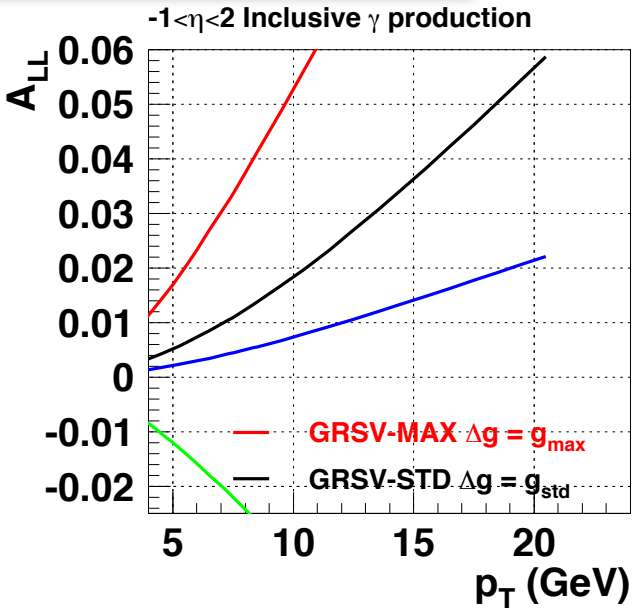

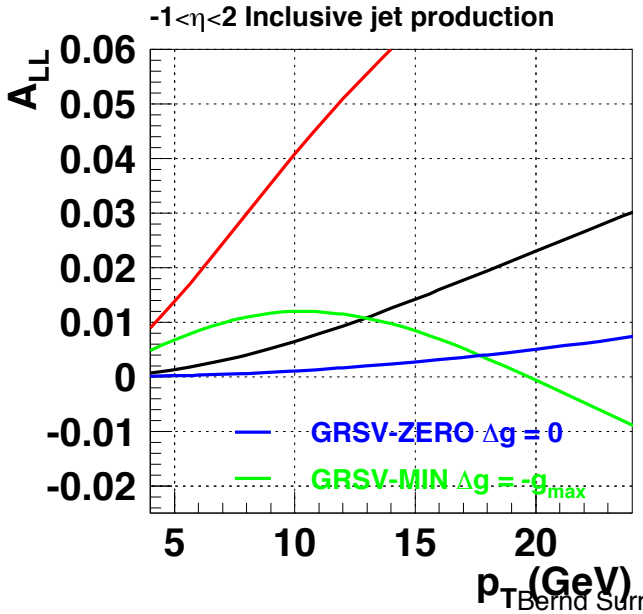

Recent results - Gluon polarization program

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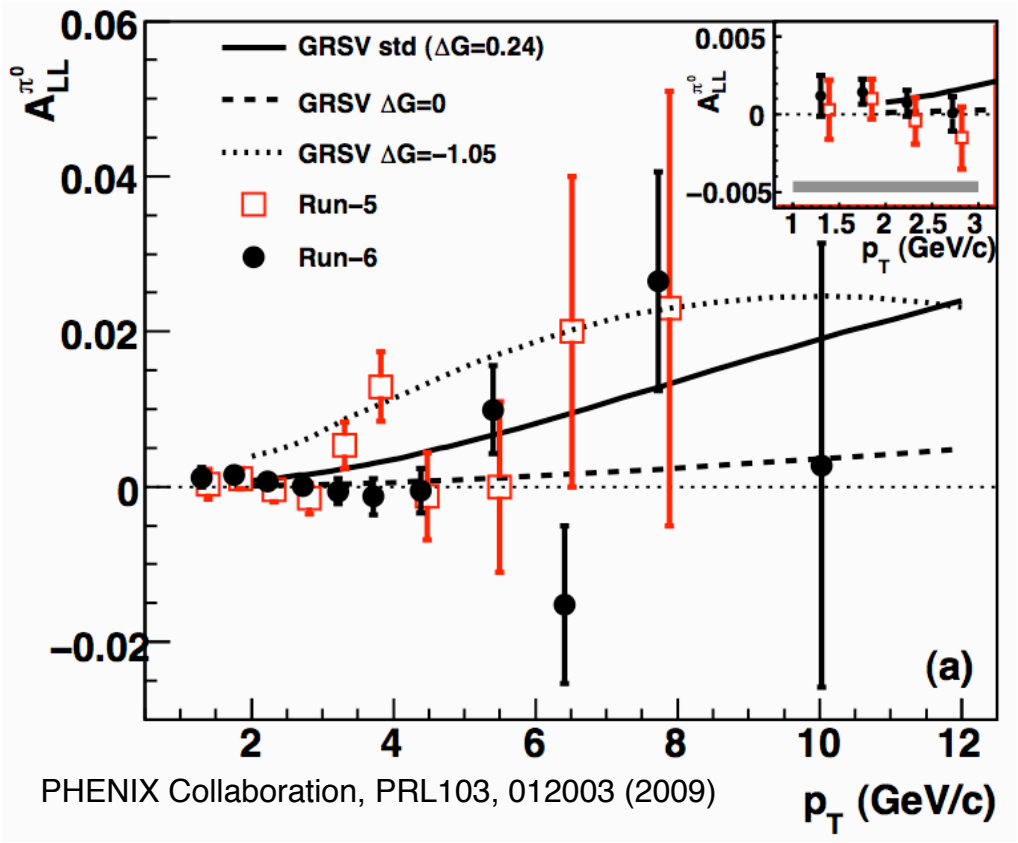
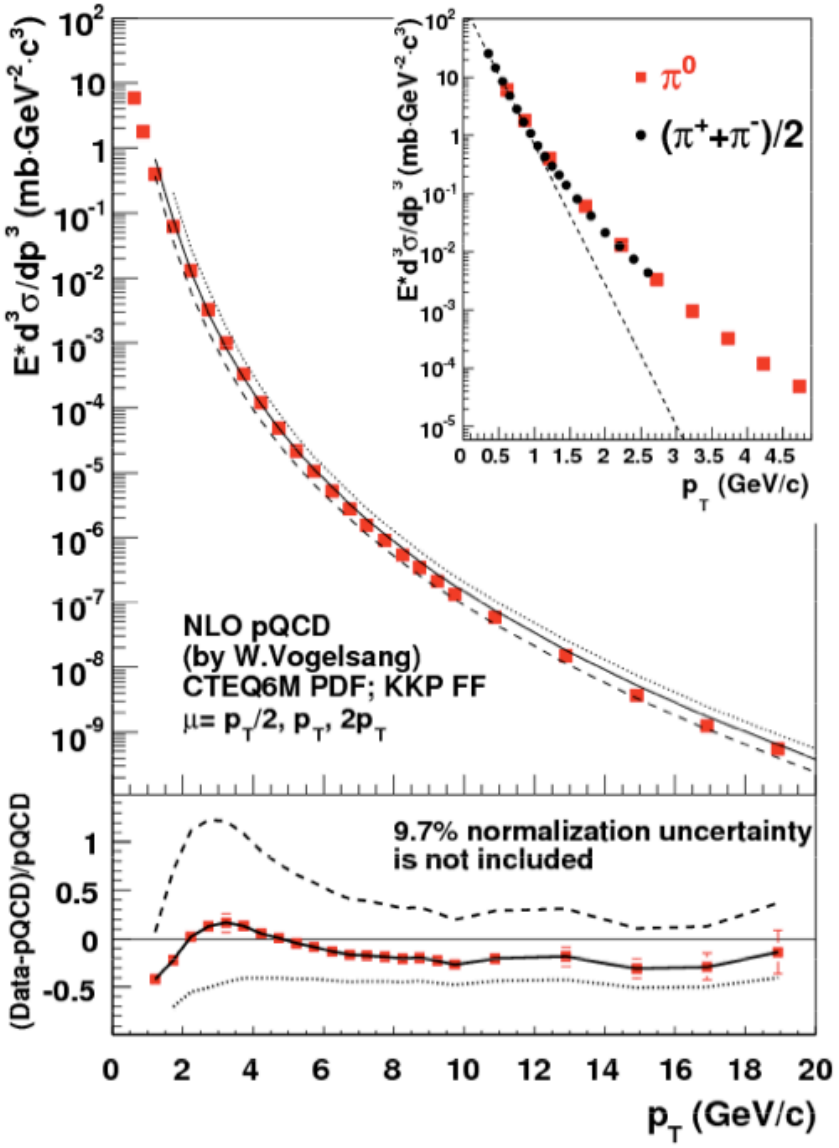


PHENIX Collaboration, PRL103, 012003 (2009)



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Recent results - Gluon polarization program

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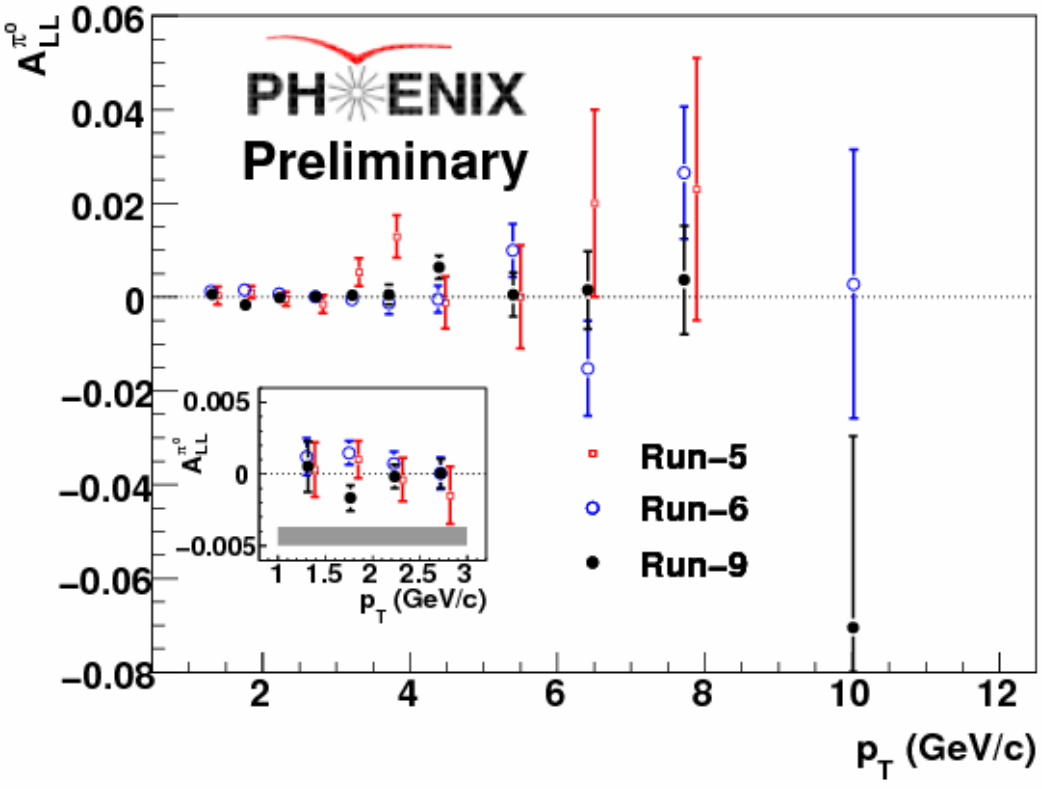

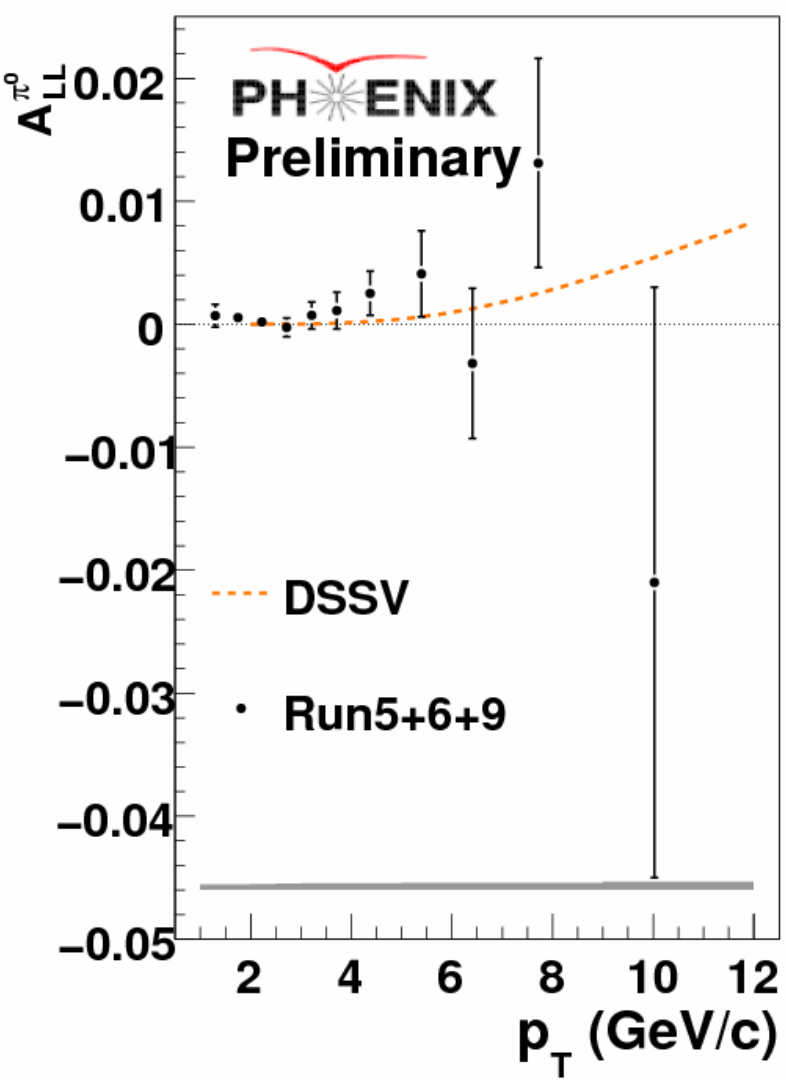

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Recent results - Gluon polarization program

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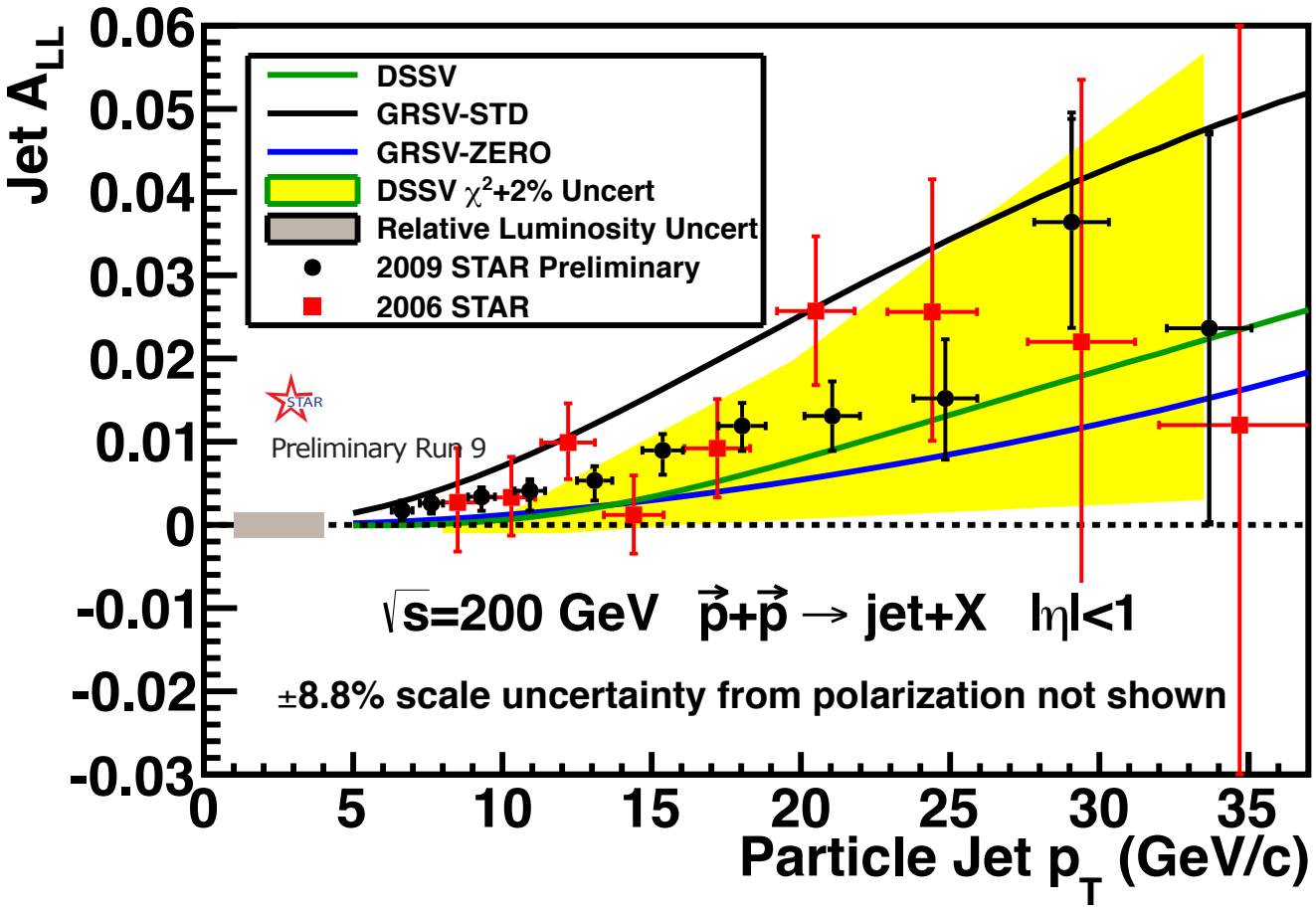

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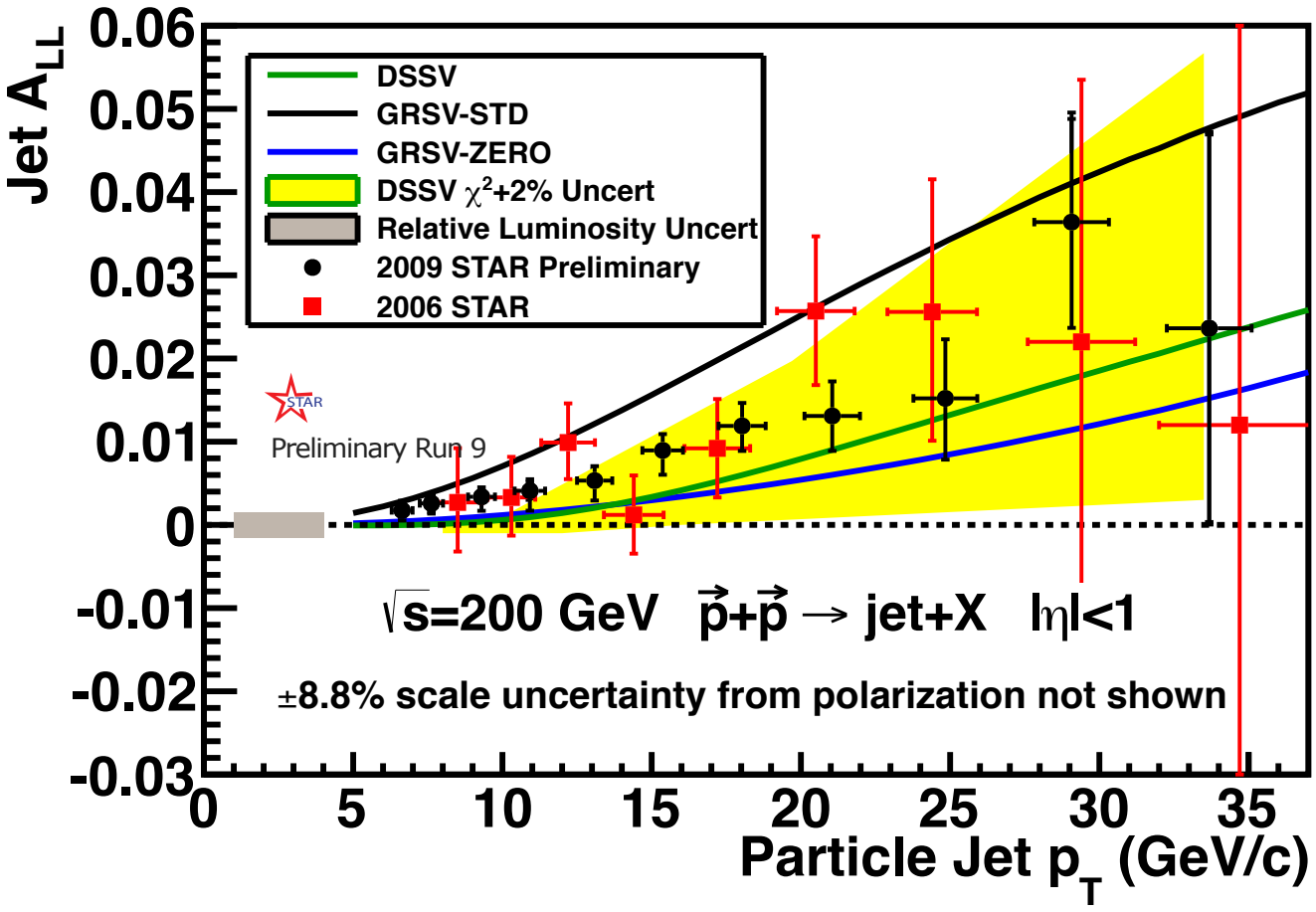

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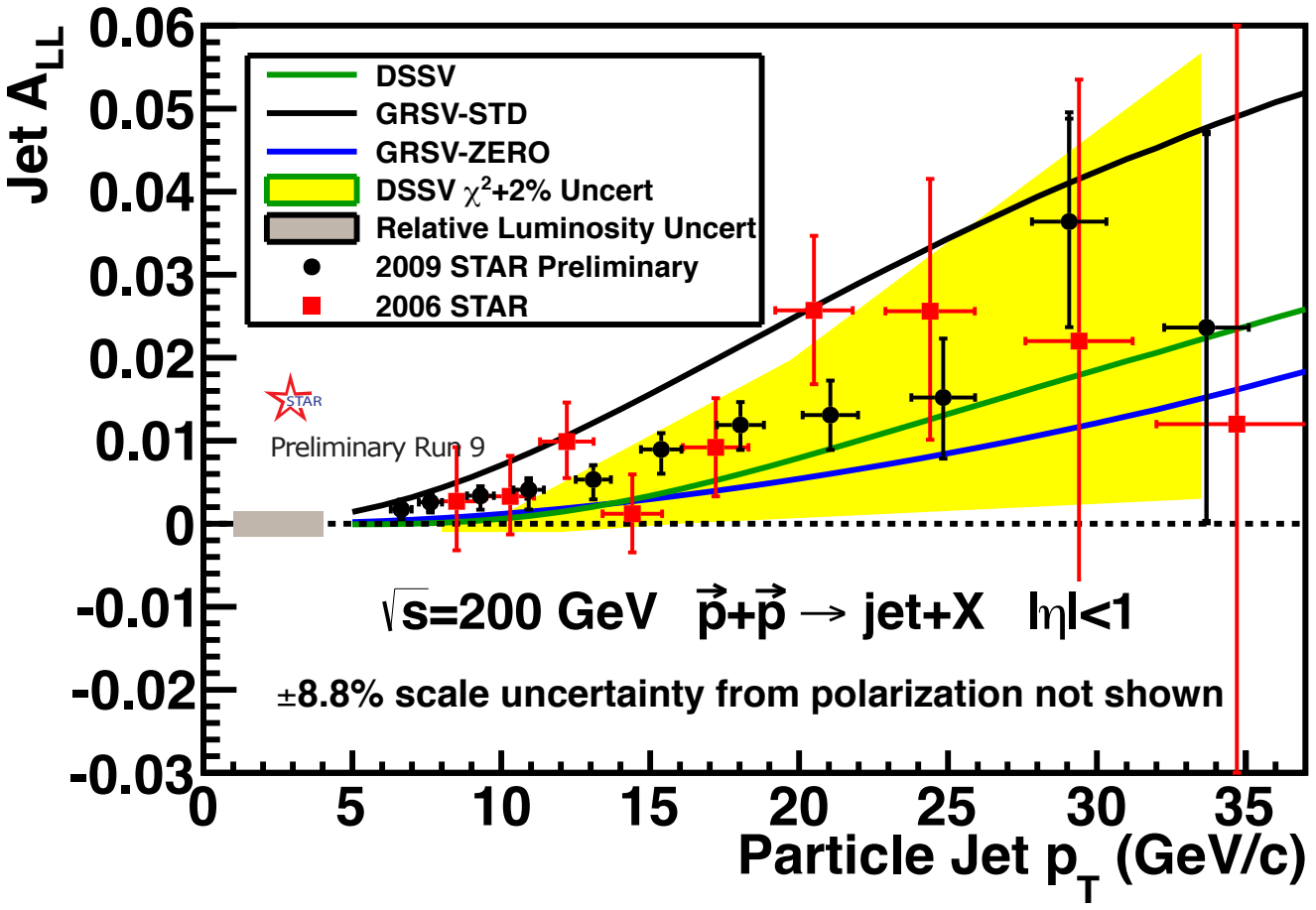

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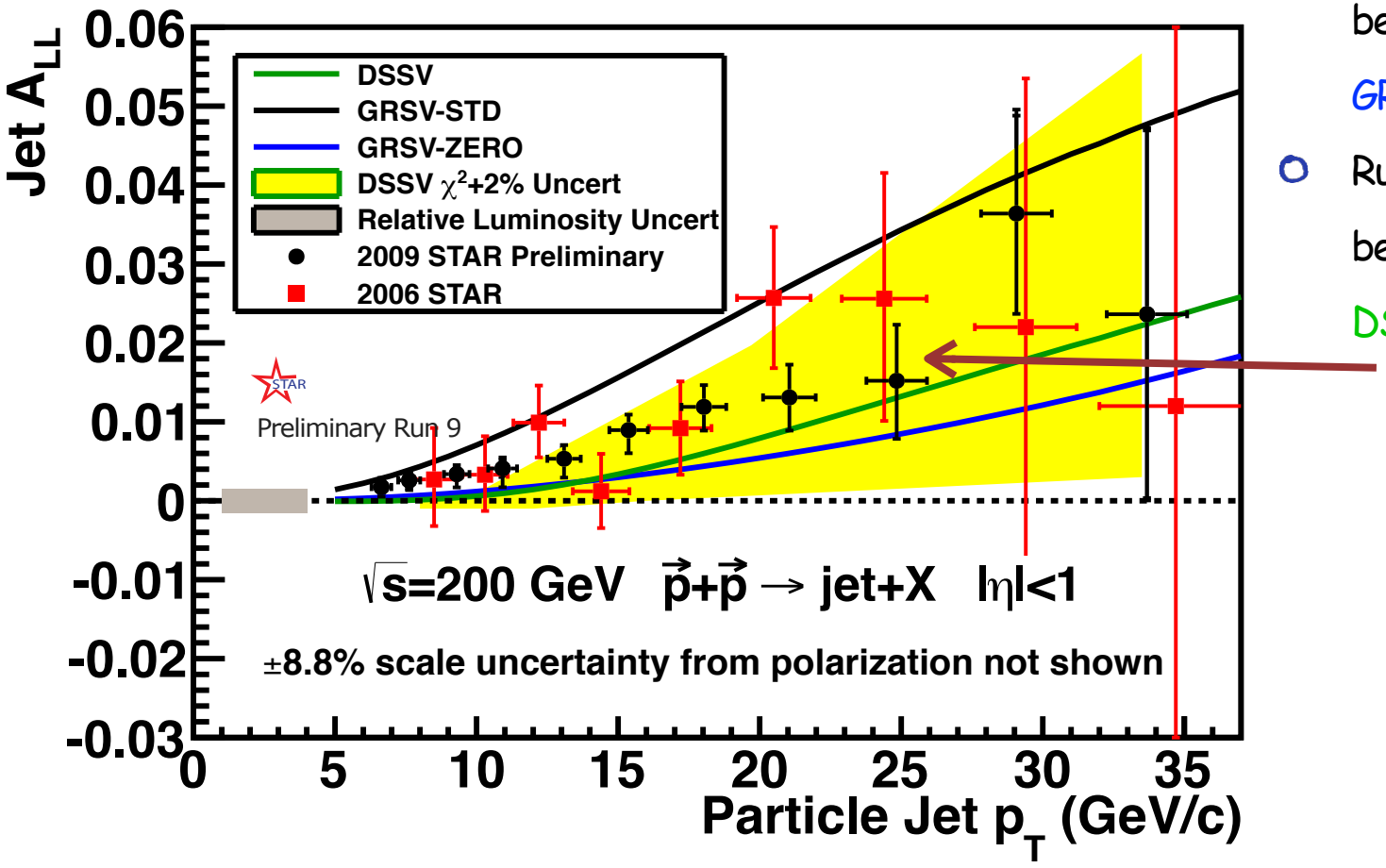

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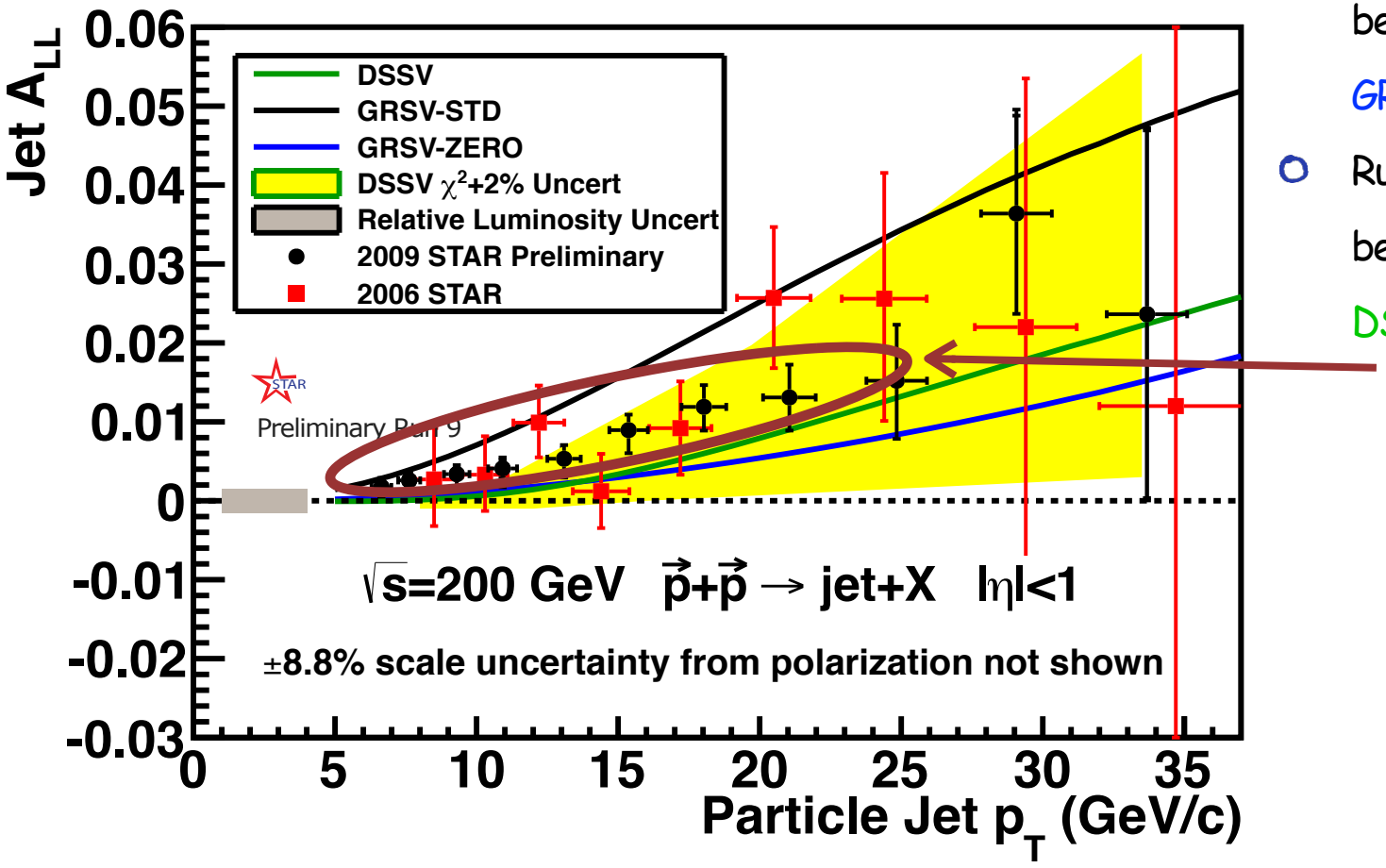

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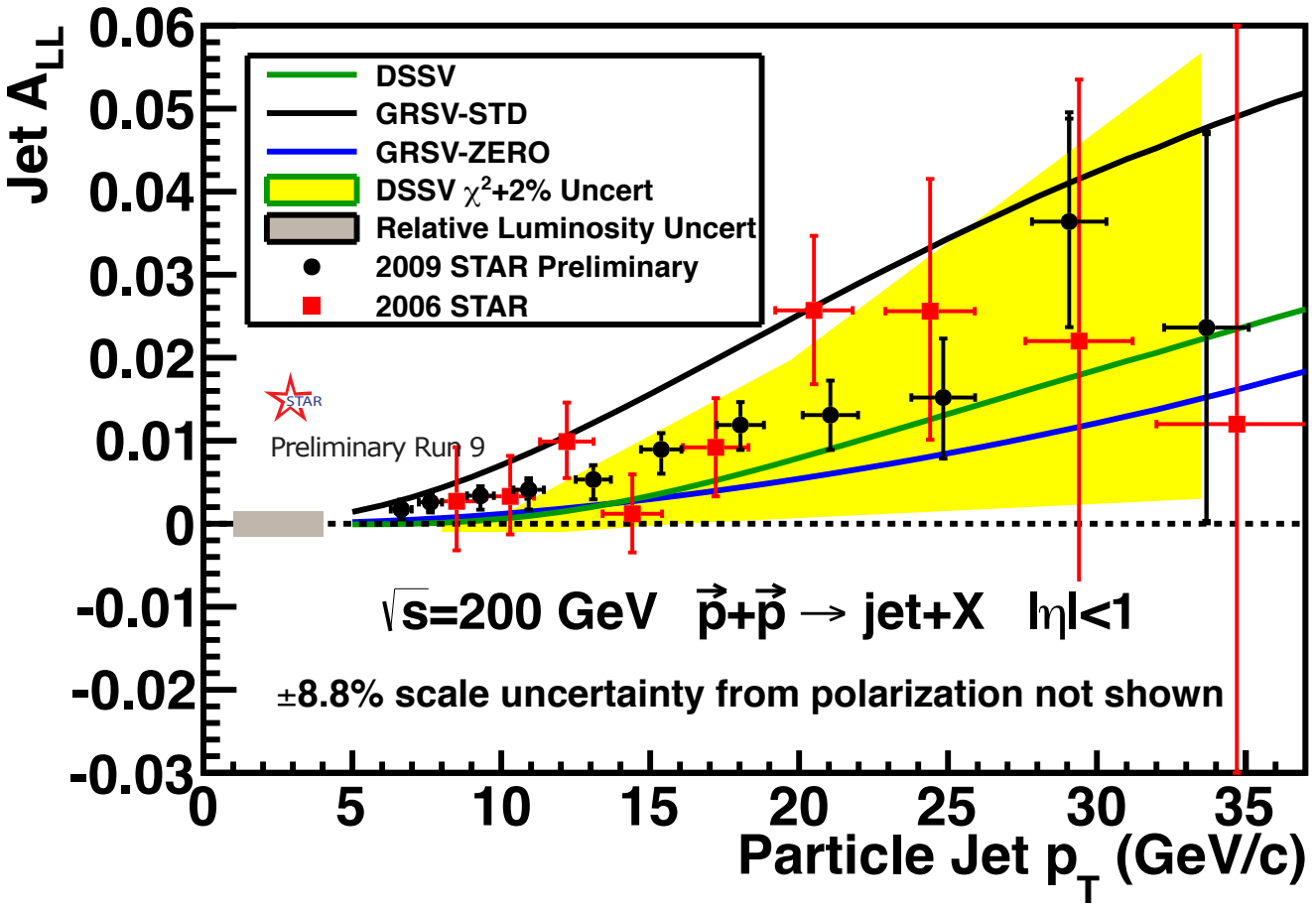

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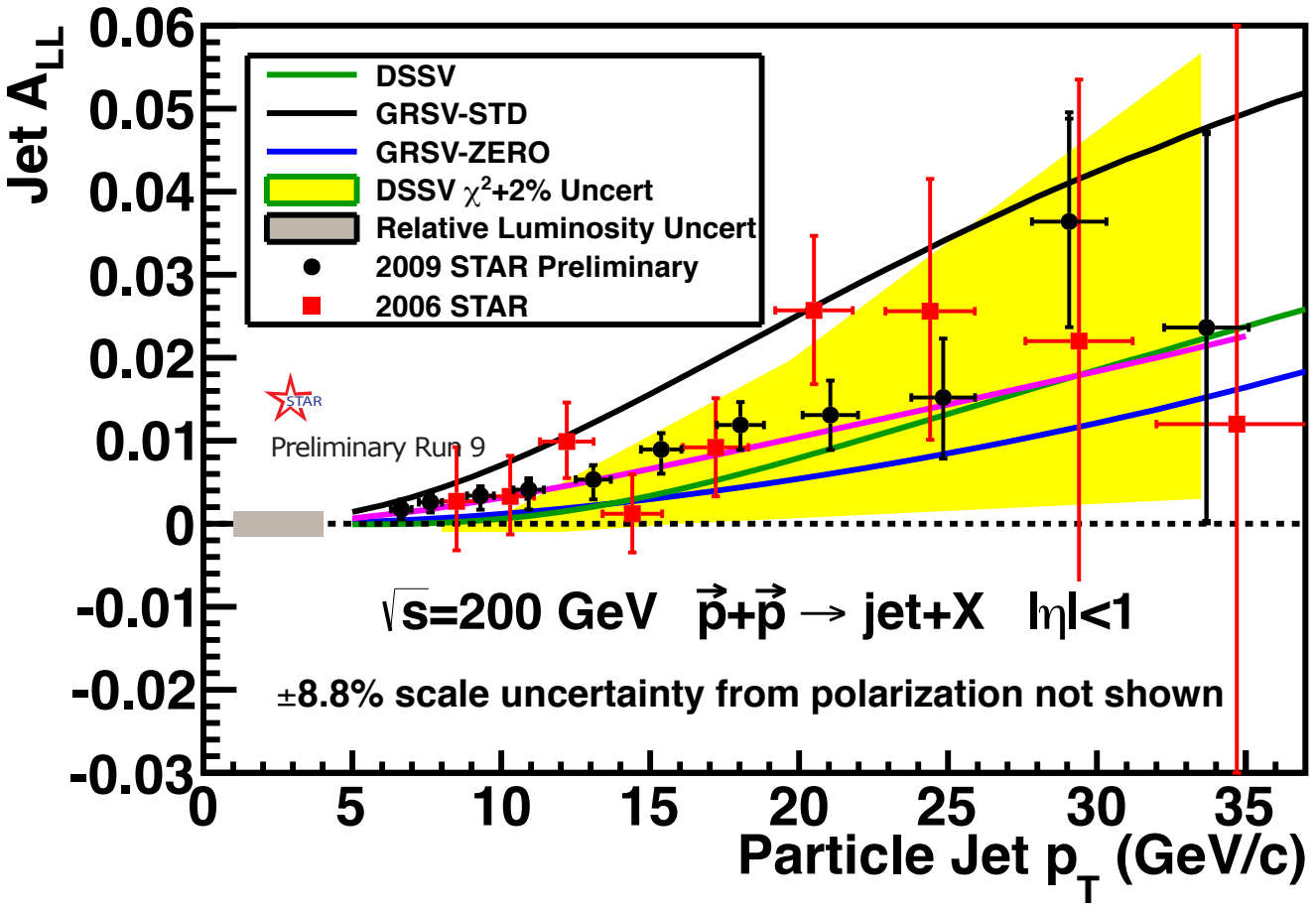

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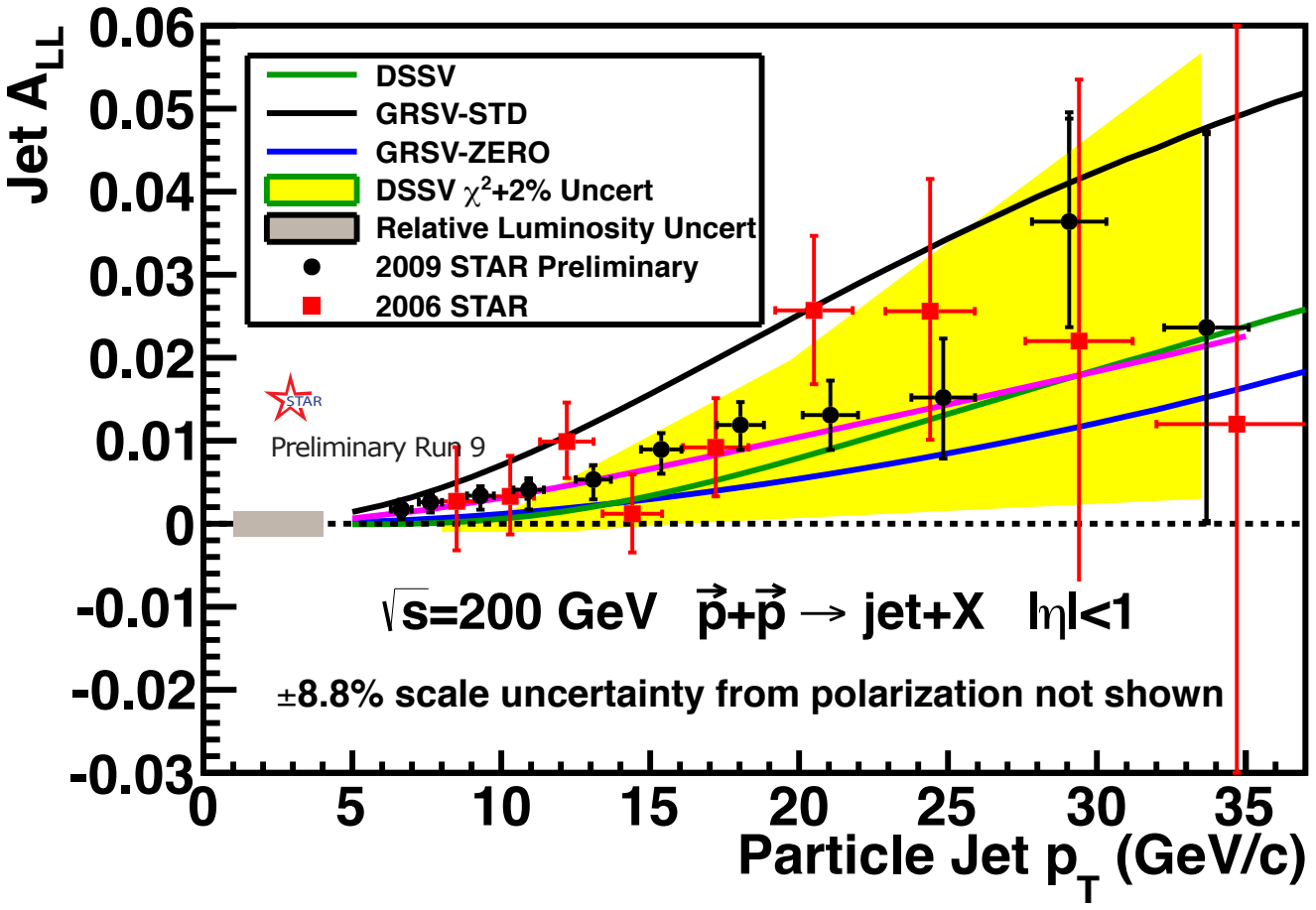

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Recent results - Gluon polarization program

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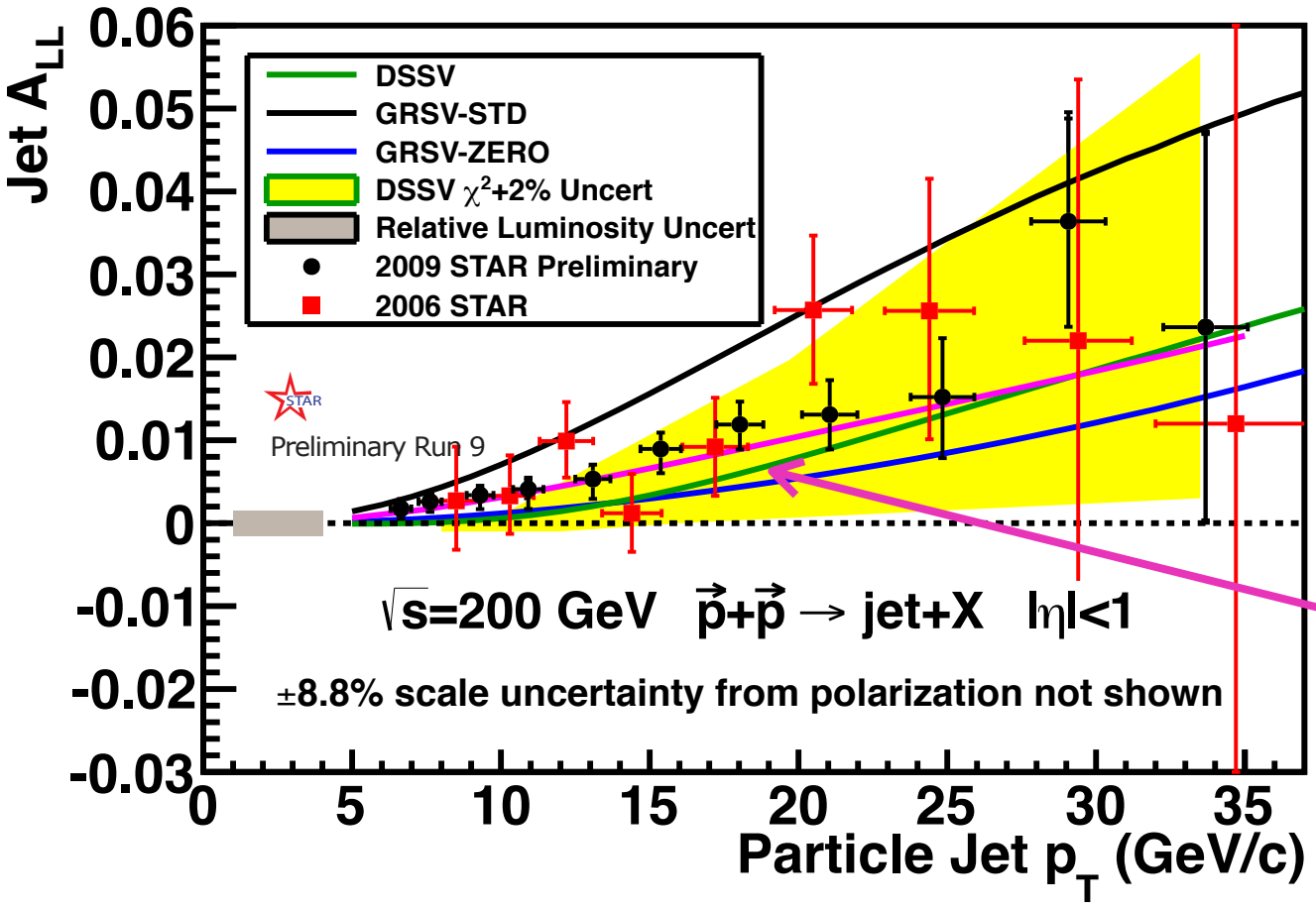

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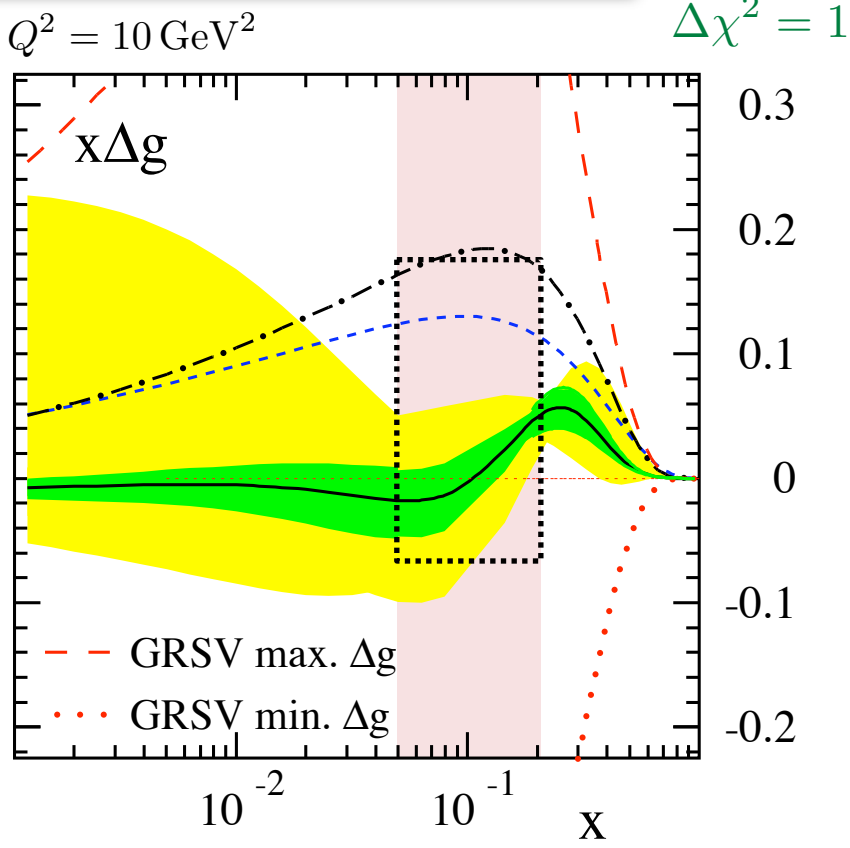
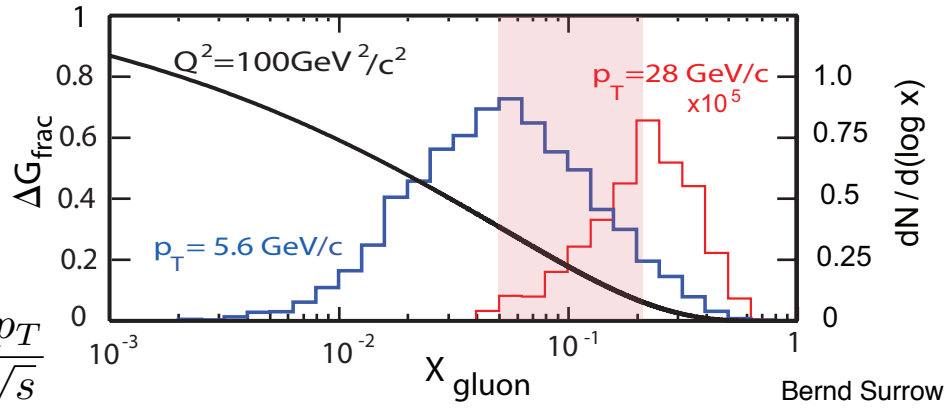
(D. deFlorian et al.,
Prog. Nucl. Part. Phys. 67, 251 (2012))

Recent results - Gluon polarization program

- Impact on Δg from RHIC data

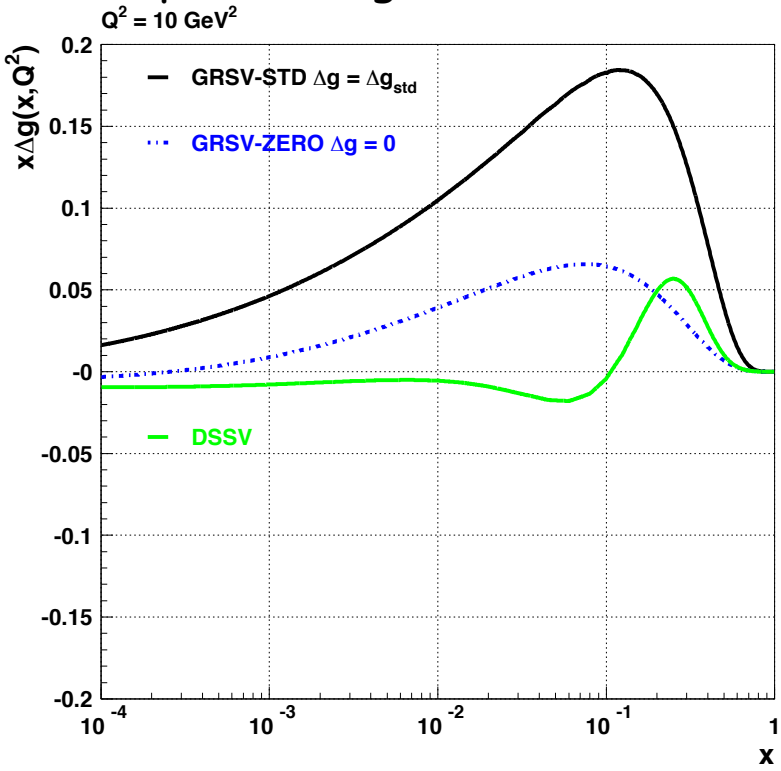


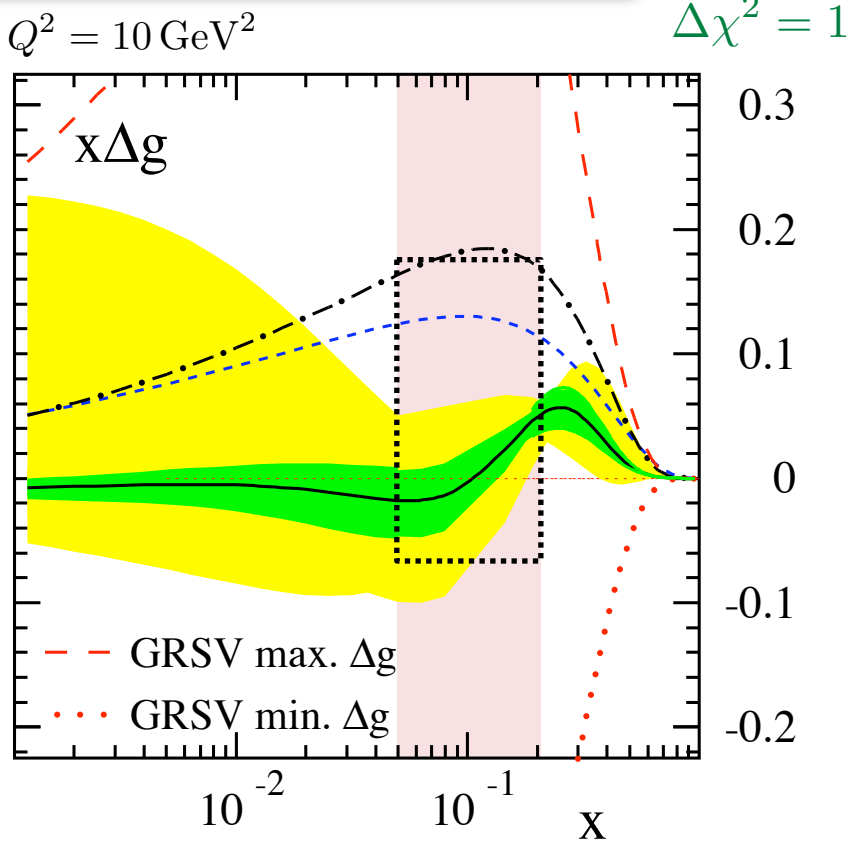


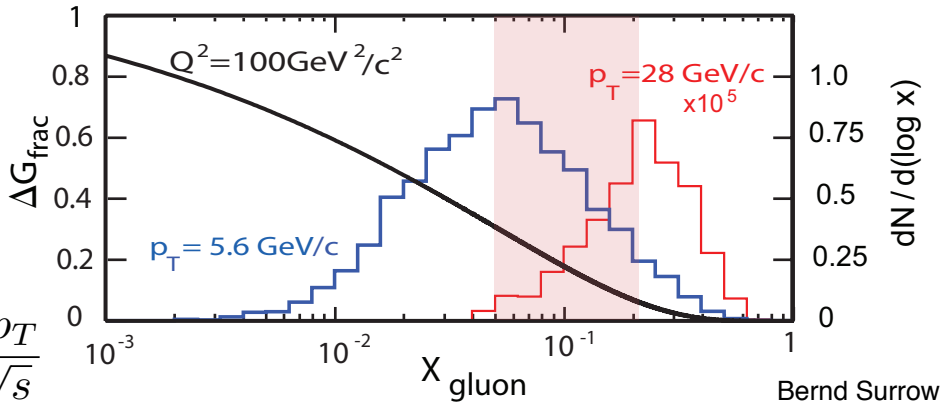
$$x \sim \frac{2p_T}{\sqrt{s}}$$

Recent results - Gluon polarization program

Impact on Δg from RHIC data







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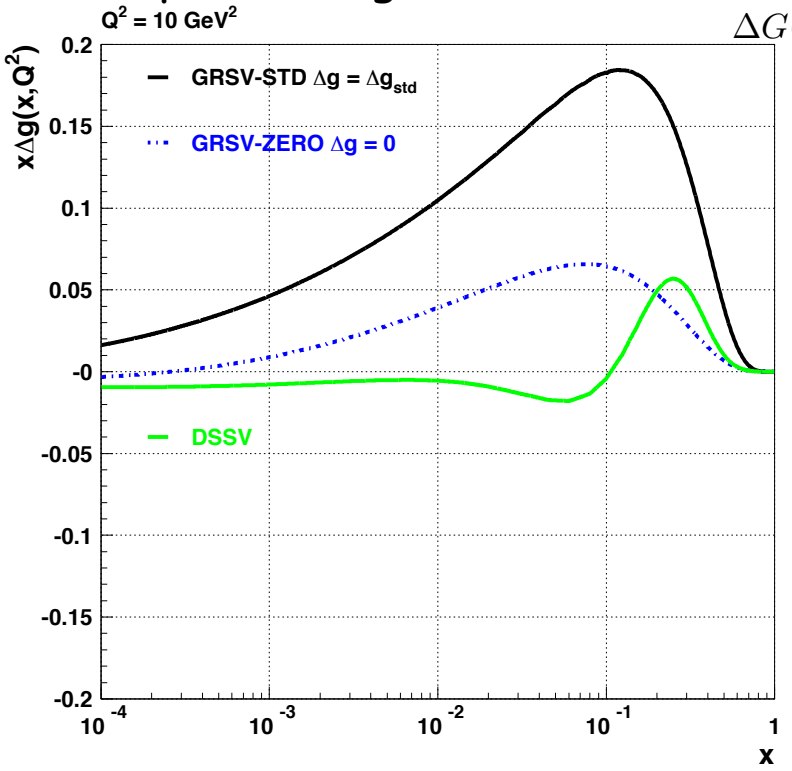

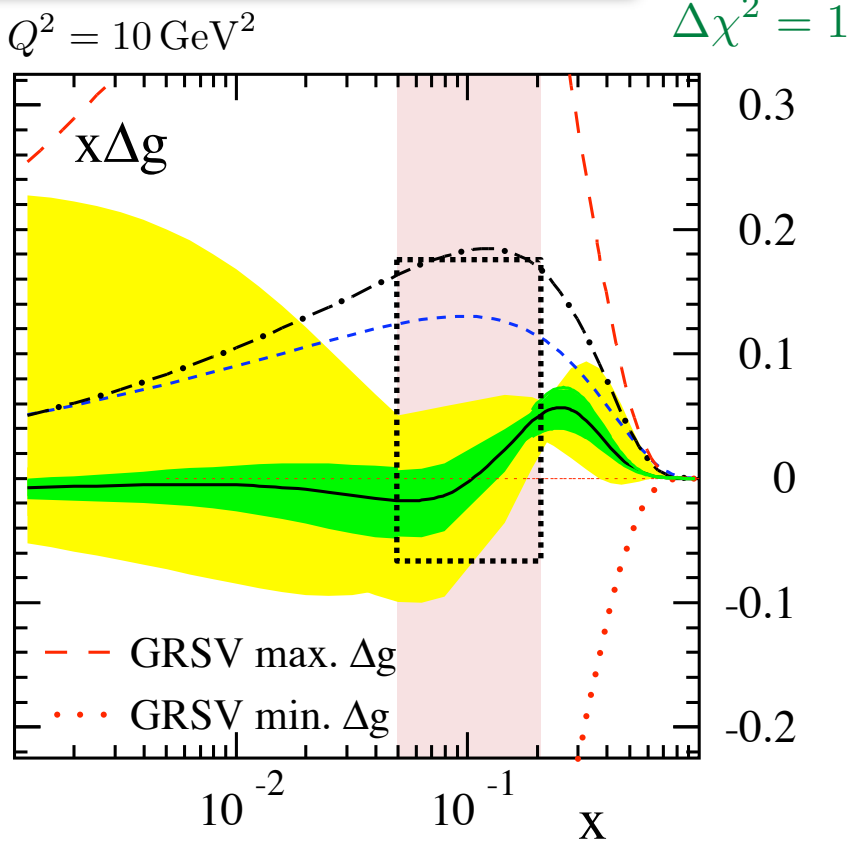

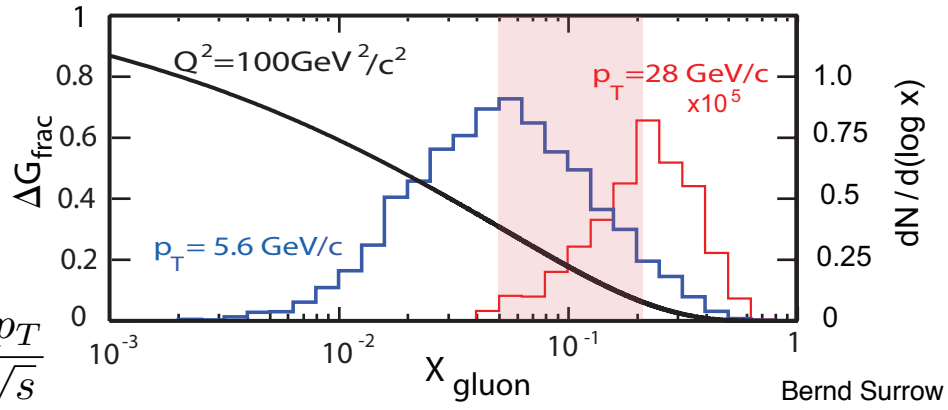

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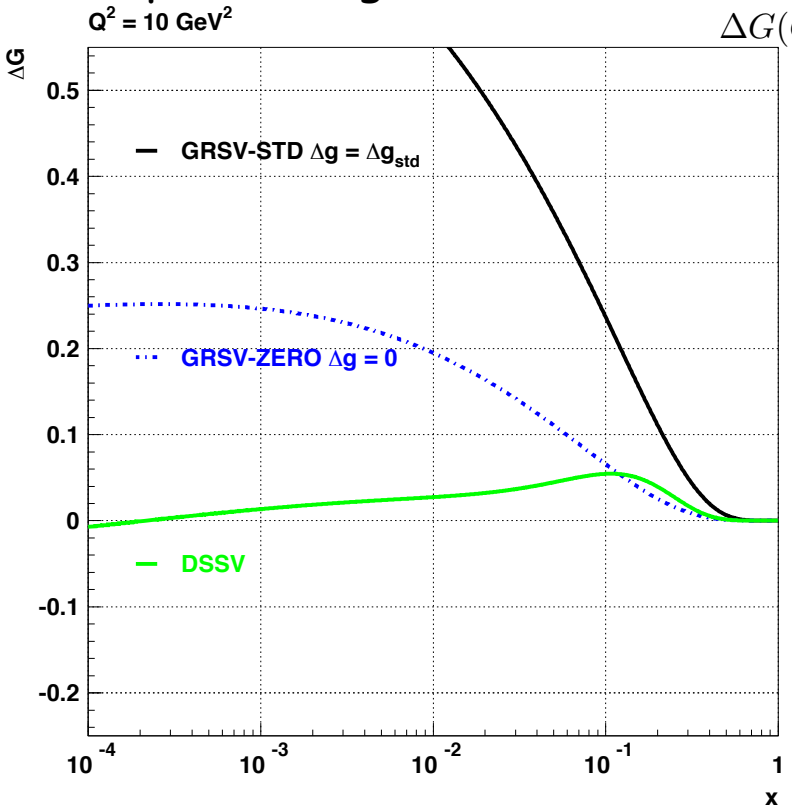

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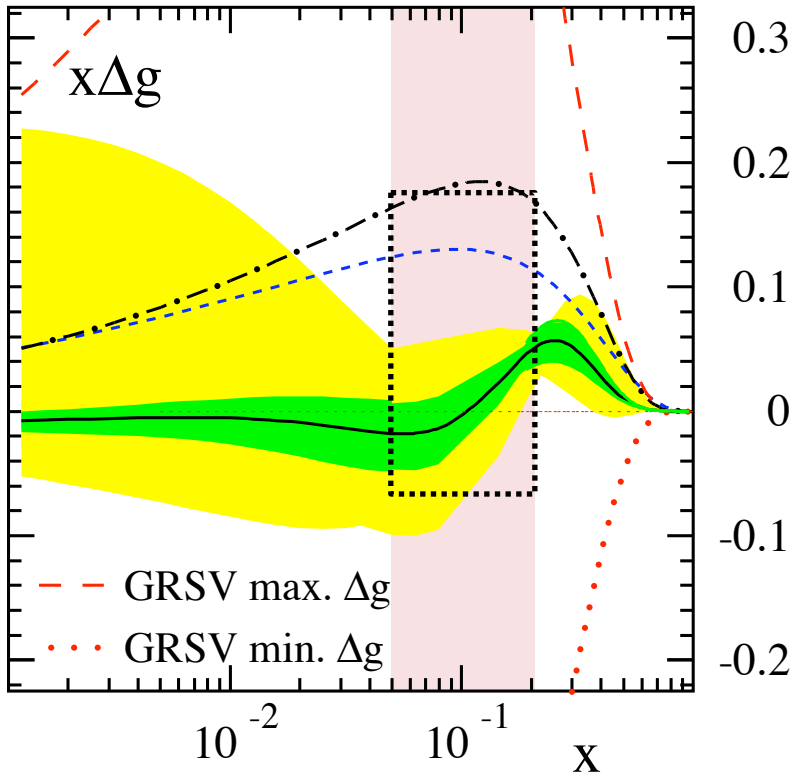

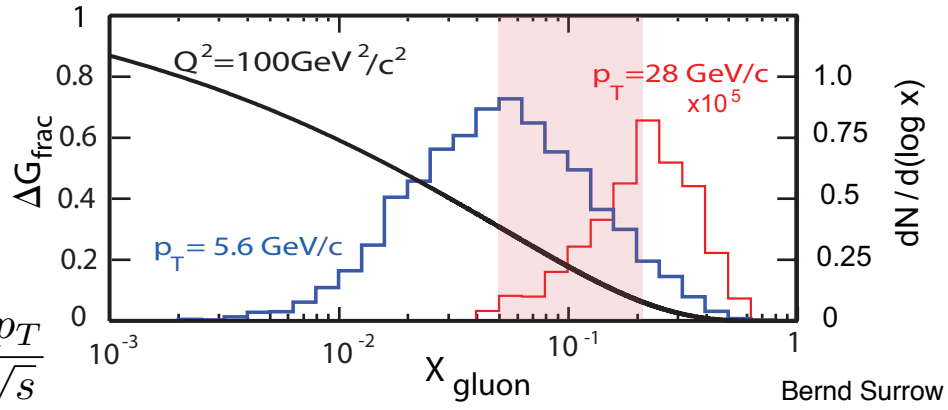

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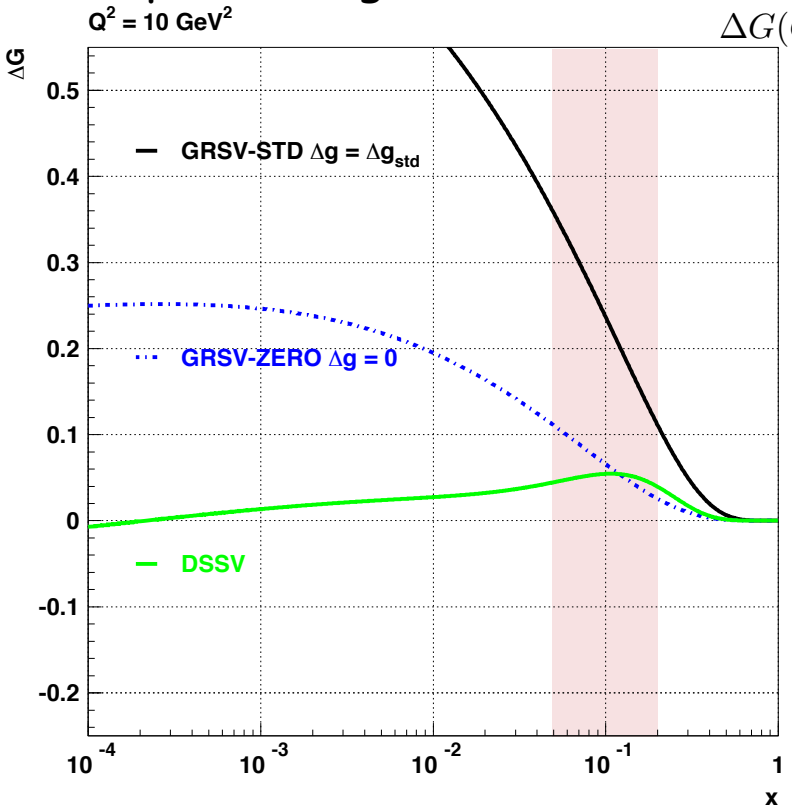

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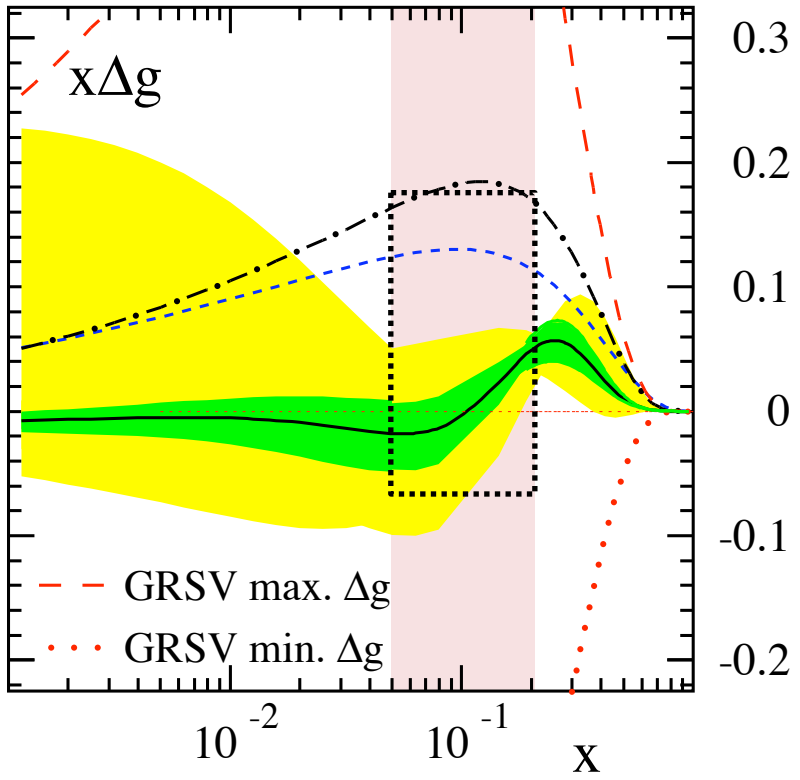

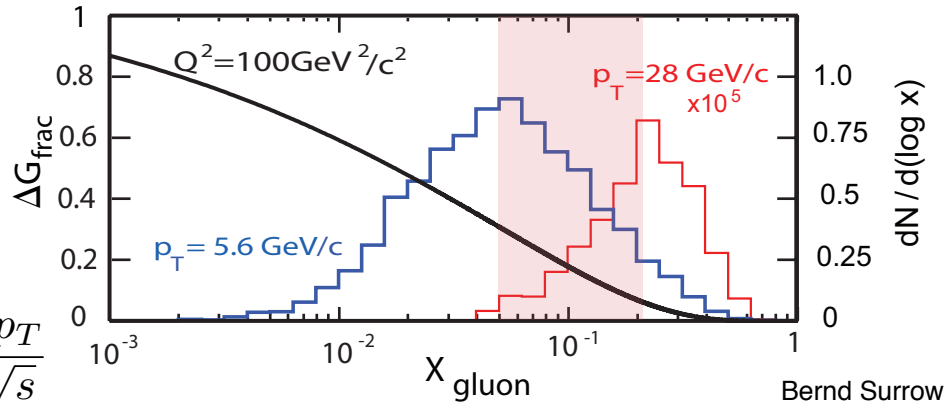

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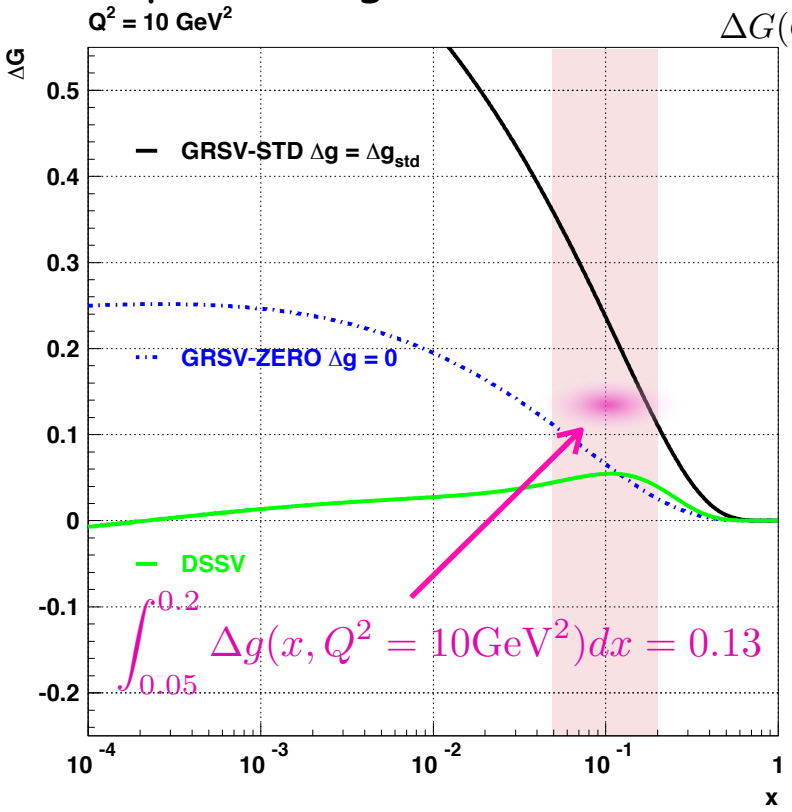

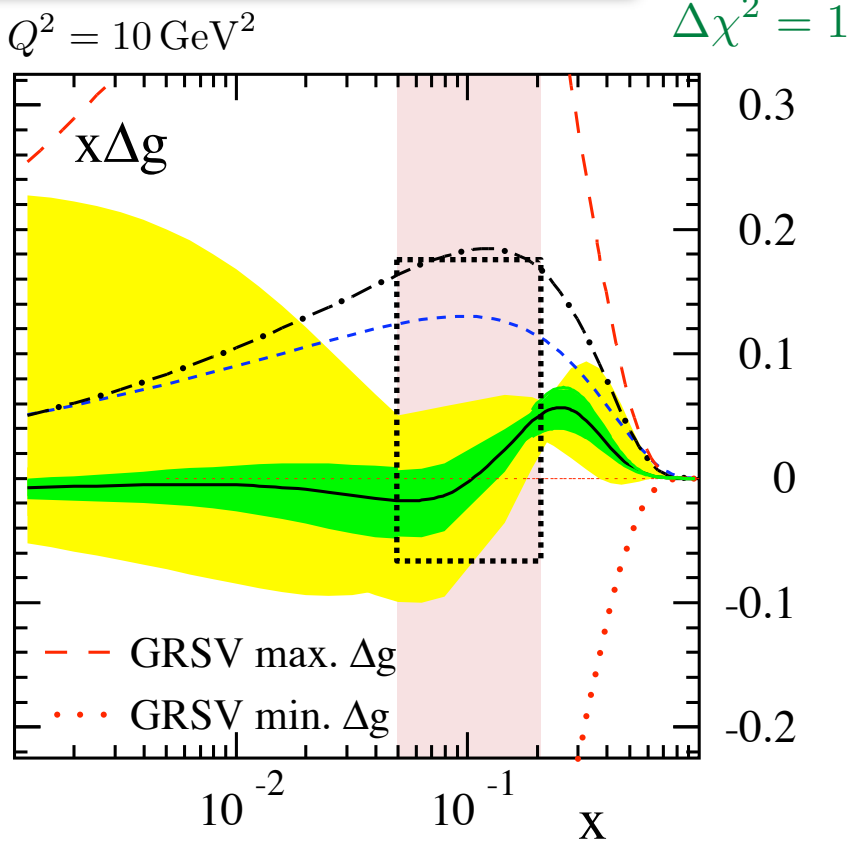

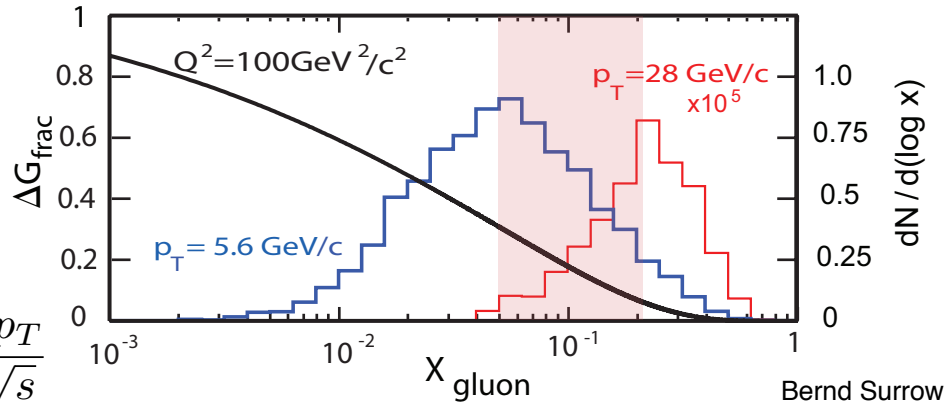

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Recent results - Gluon polarization program

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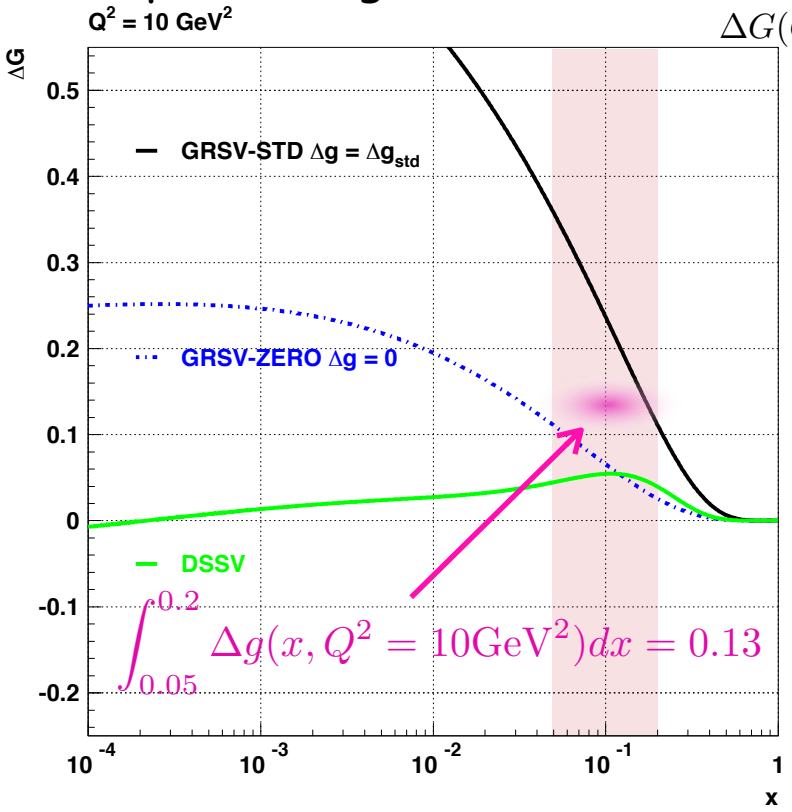
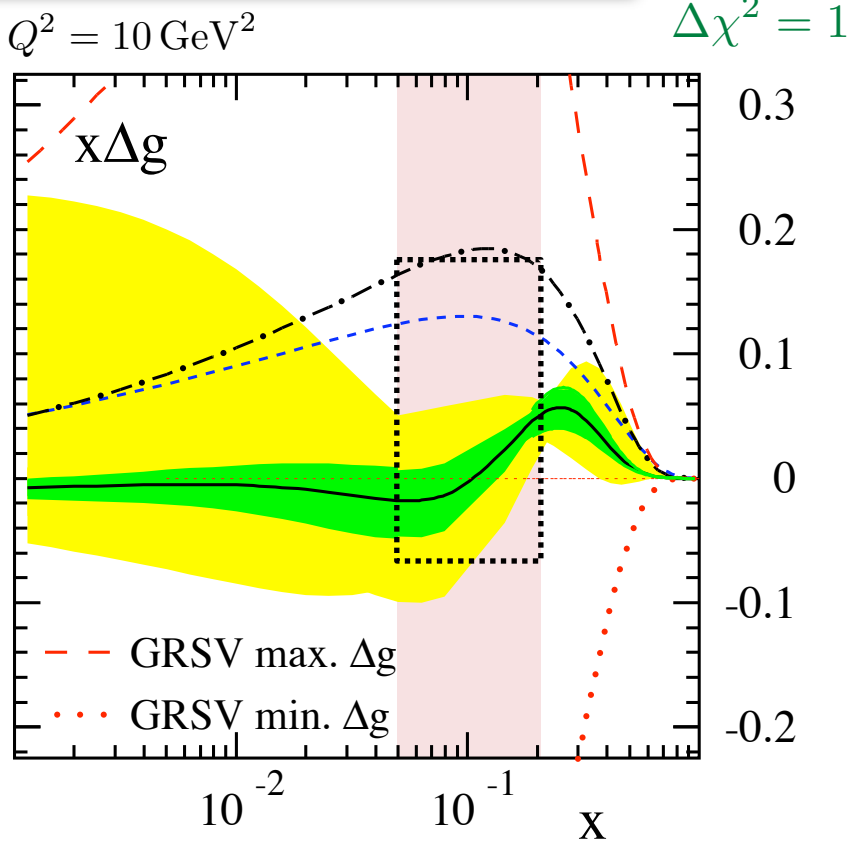
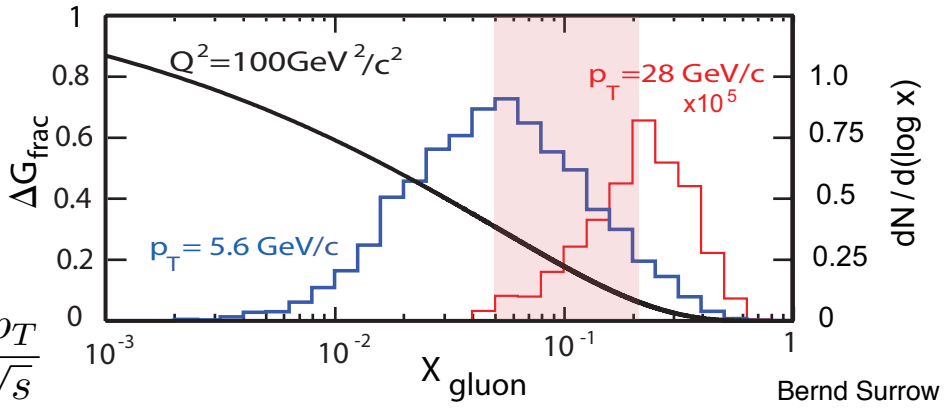


- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)





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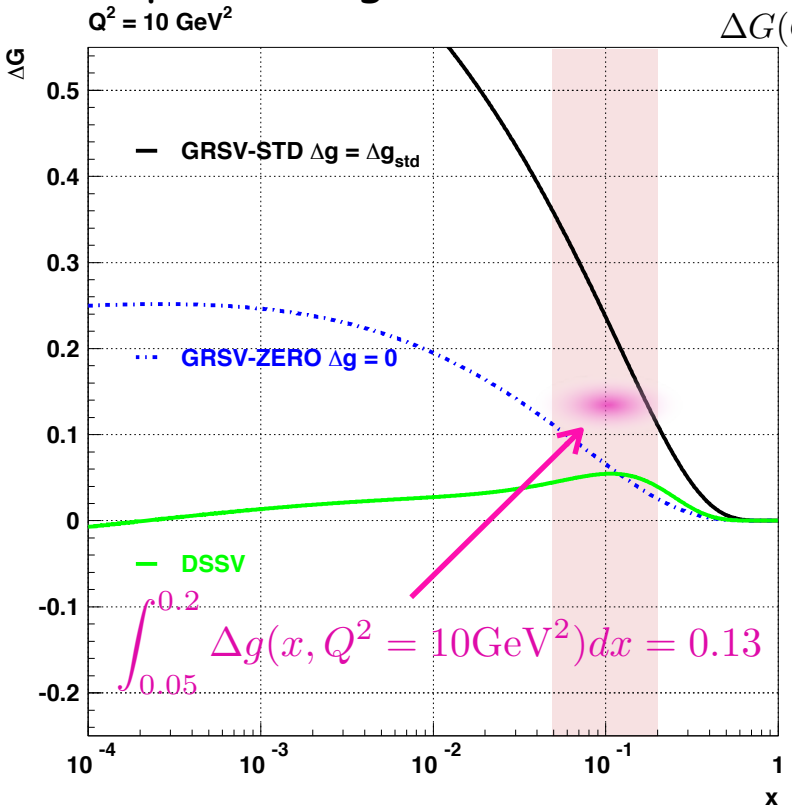
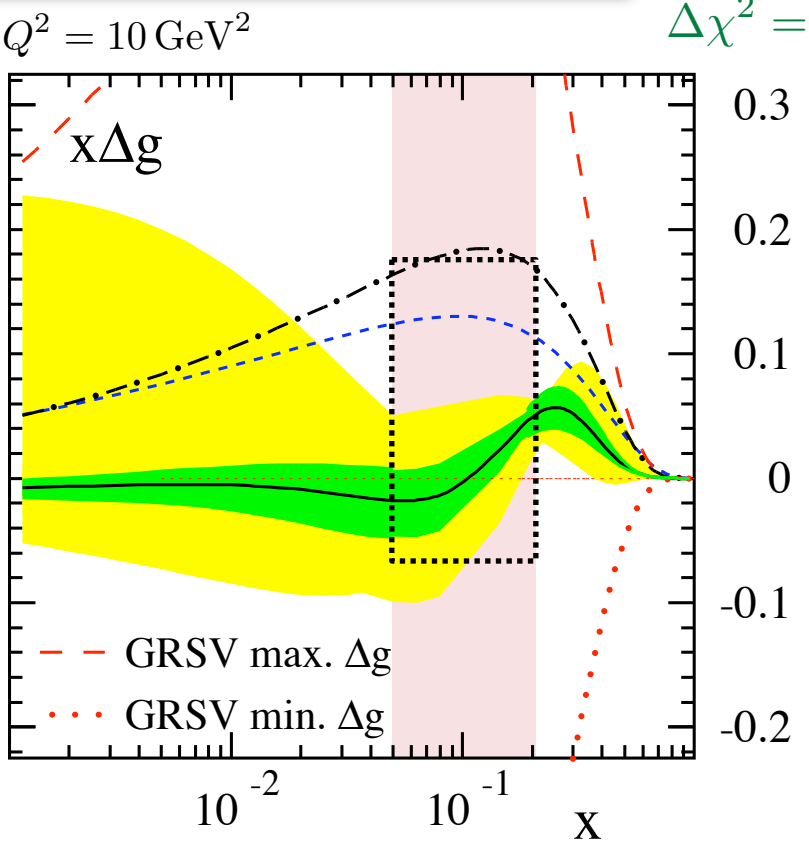
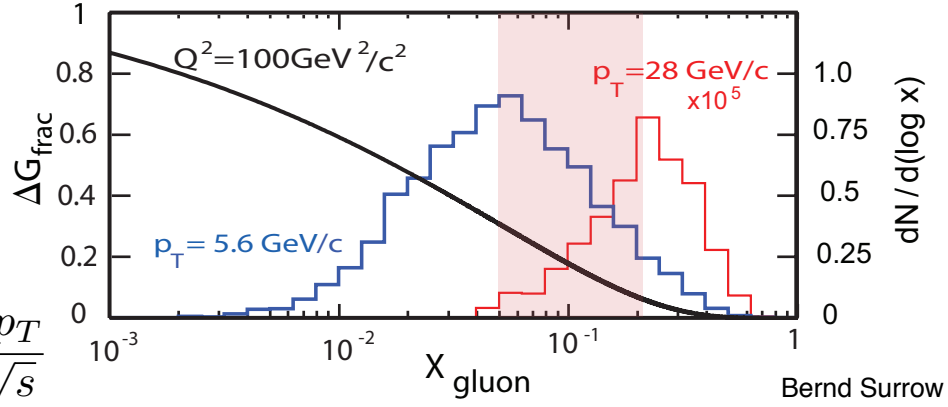




- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)
- Strong indication for a small, non-zero ΔG!



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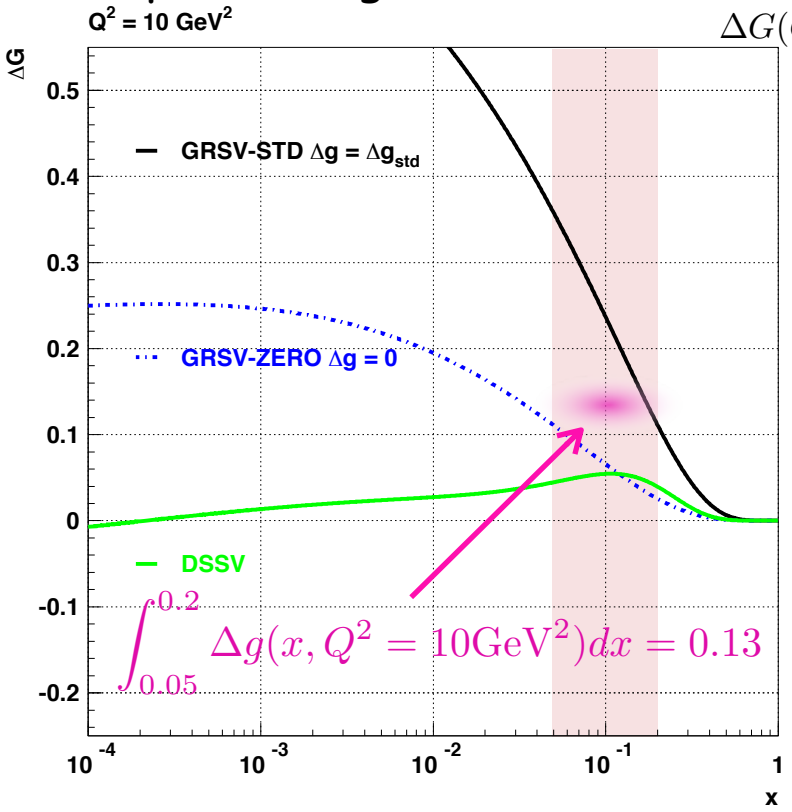

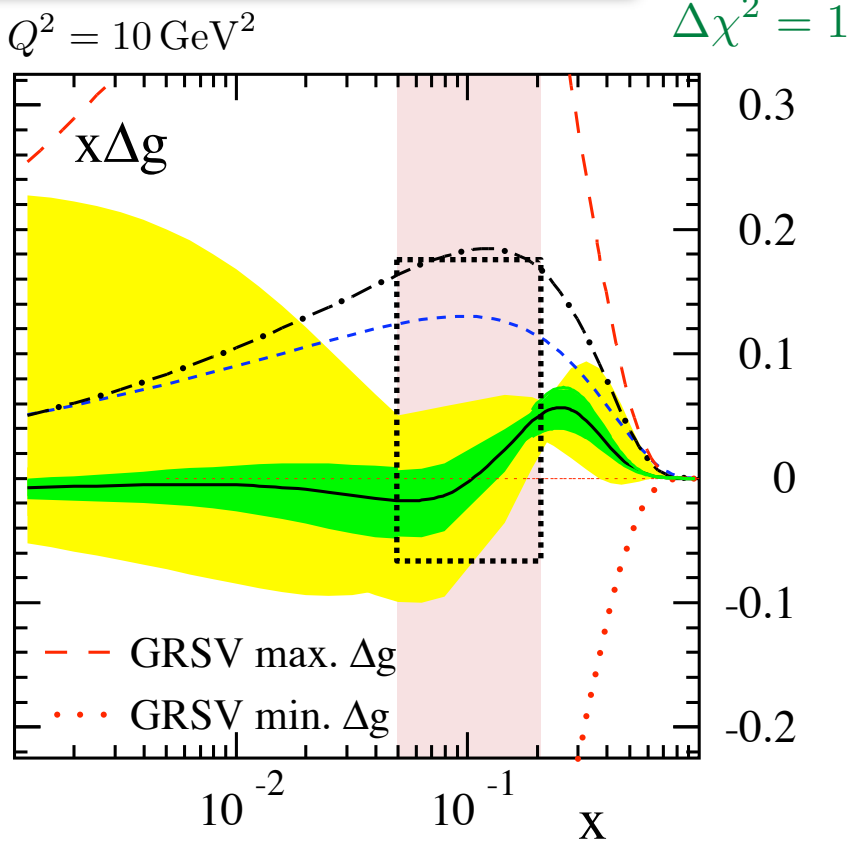

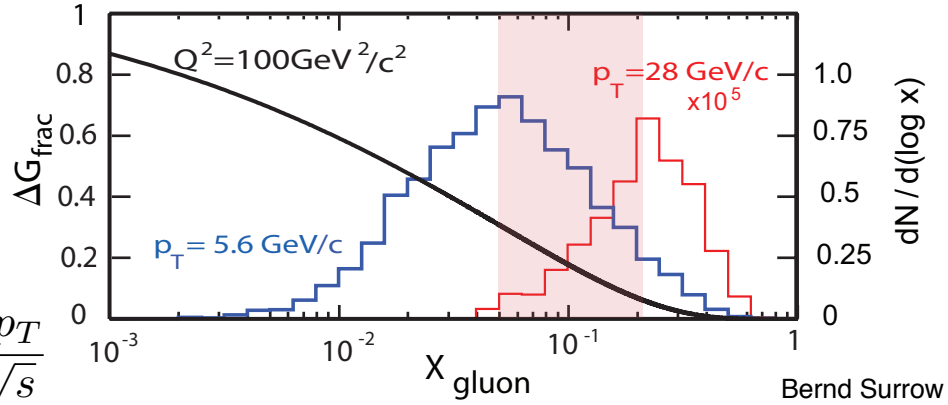

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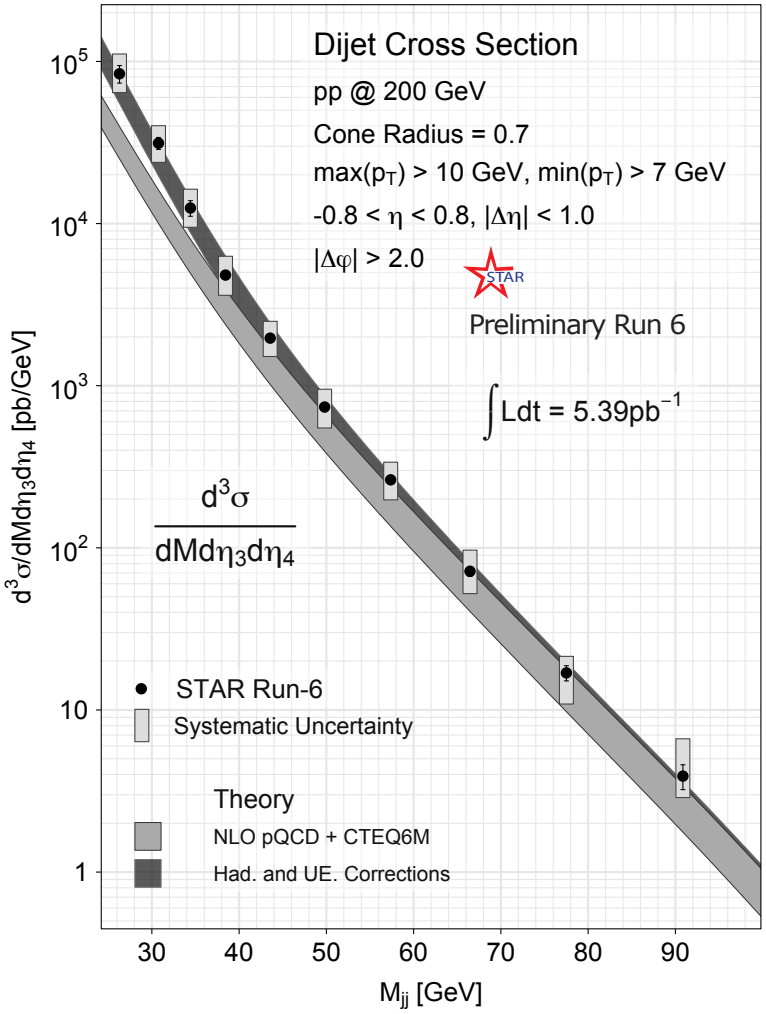
- Strong indication for a small, non-zero ΔG!
- Next steps: Mapping of x-dependence and extension of x-coverage needed (Di-Jet measurements)!

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

Recent results - Gluon polarization program

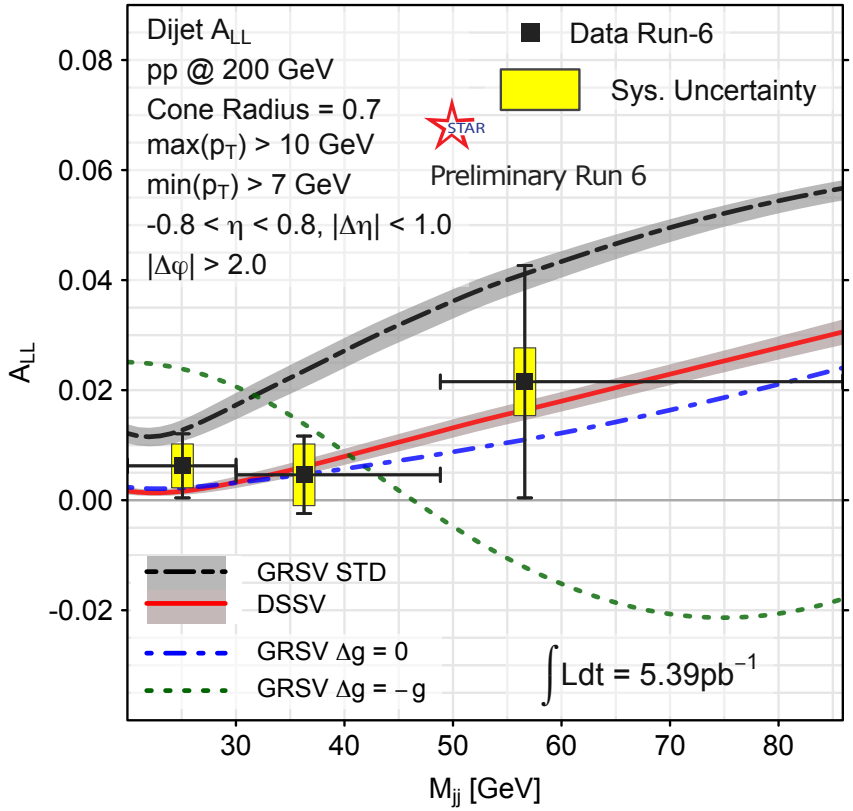
- First STAR Di-Jet A_{LL} measurement



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

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

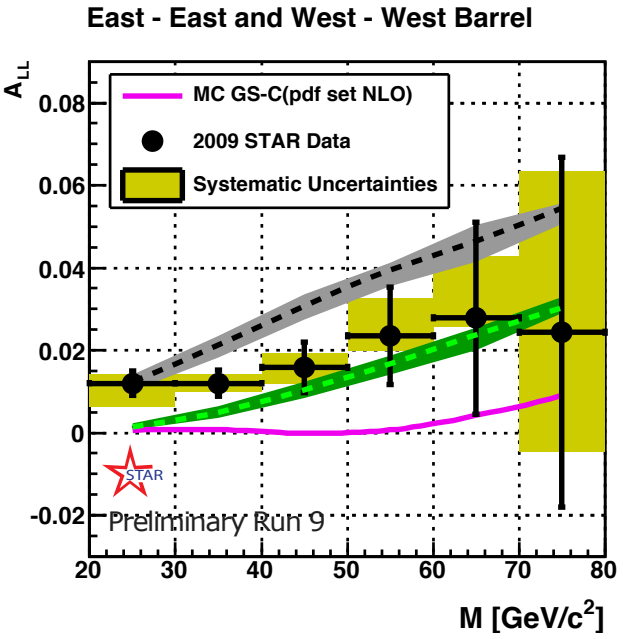
$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

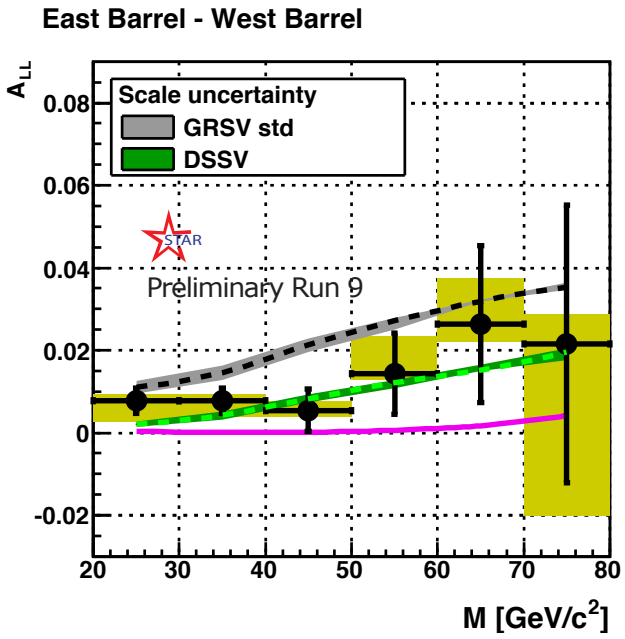


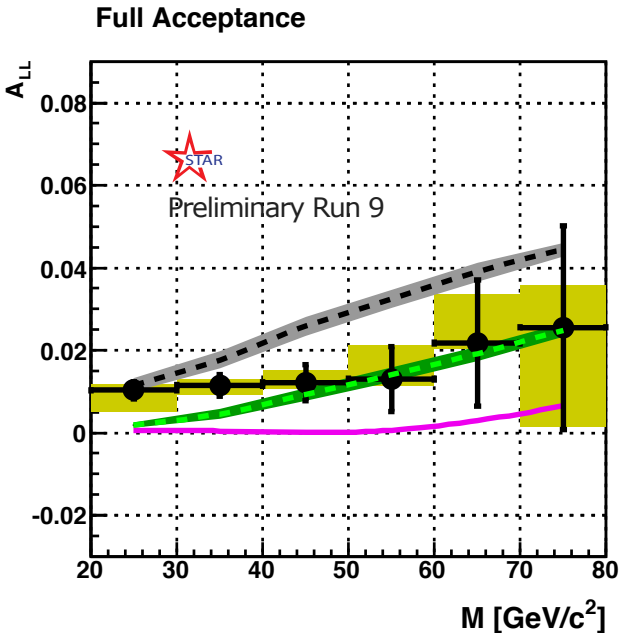
- First Di-Jet A_{LL} measurement in agreement with Δg constrained by previous inclusive jet result, i.e. small gluon polarization preferred!

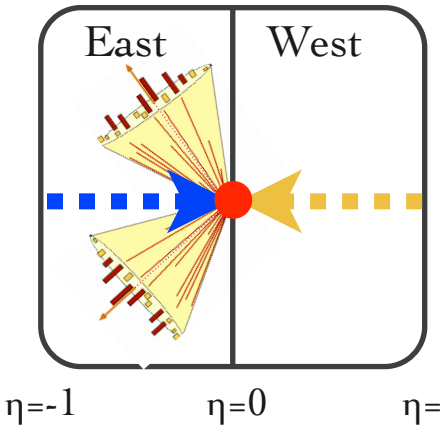
Recent results - Gluon polarization program

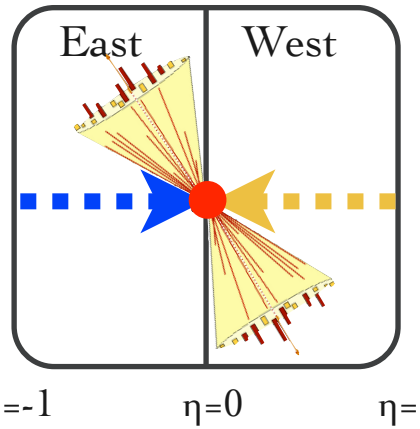
- First STAR Di-Jet A_{LL} measurement in bins of η











- Run 9 data: First rapidity dependent di-jet measurement

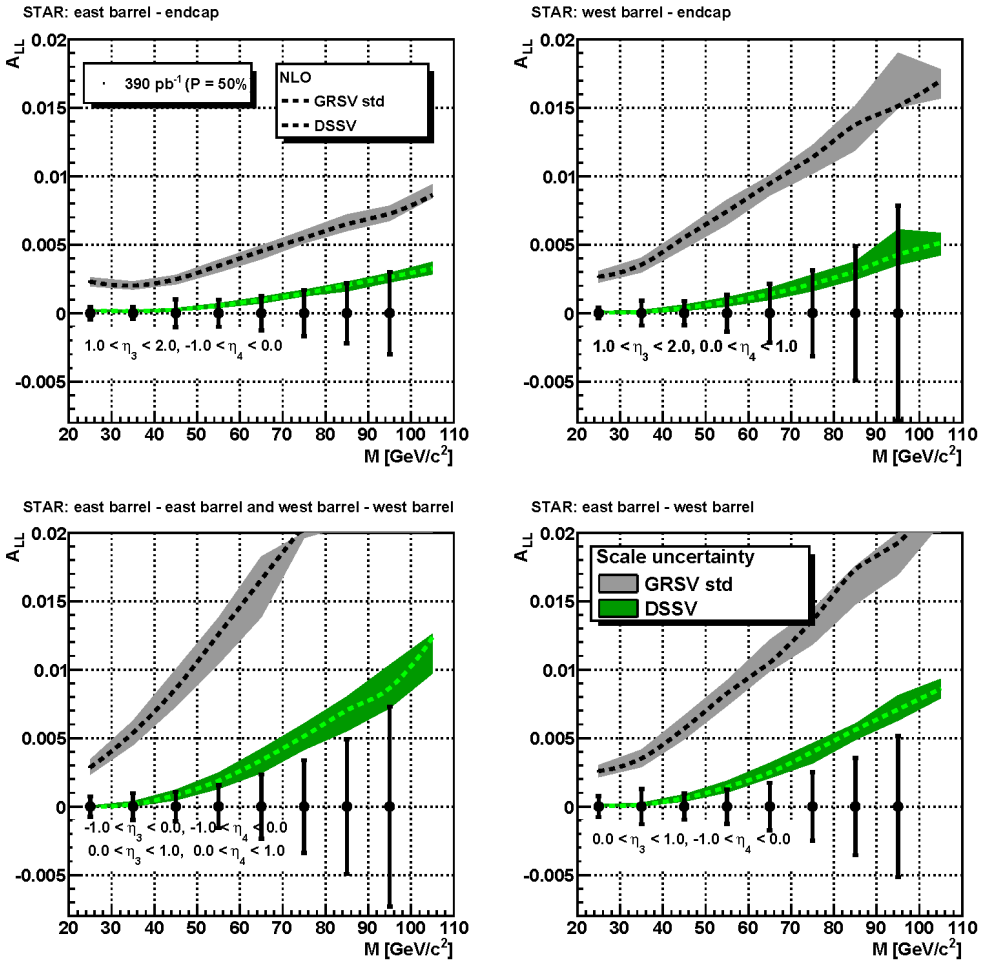
  ⇒ Constrain x dependence!

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

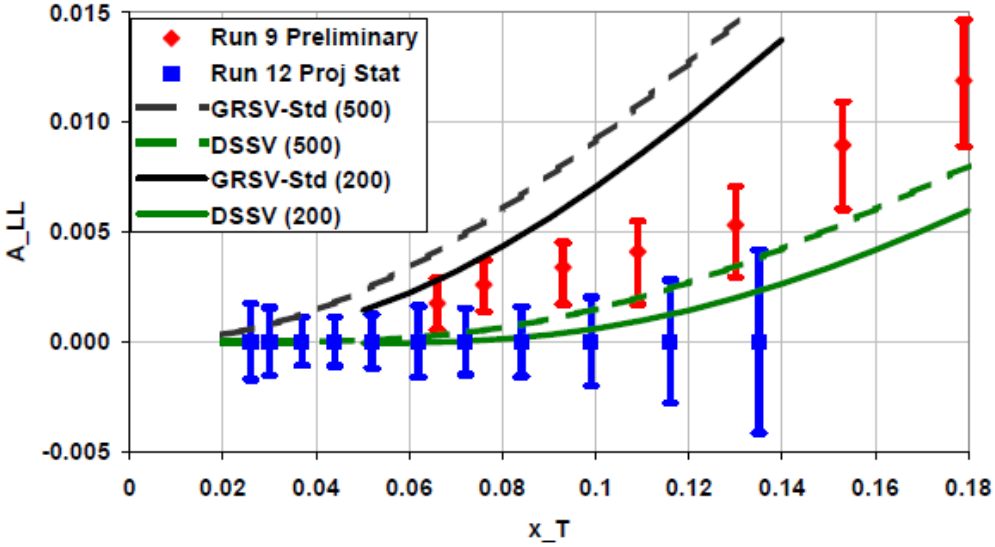
Future prospects - Gluon polarization program

Future Di-Jet / Inclusive Jet measurements

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



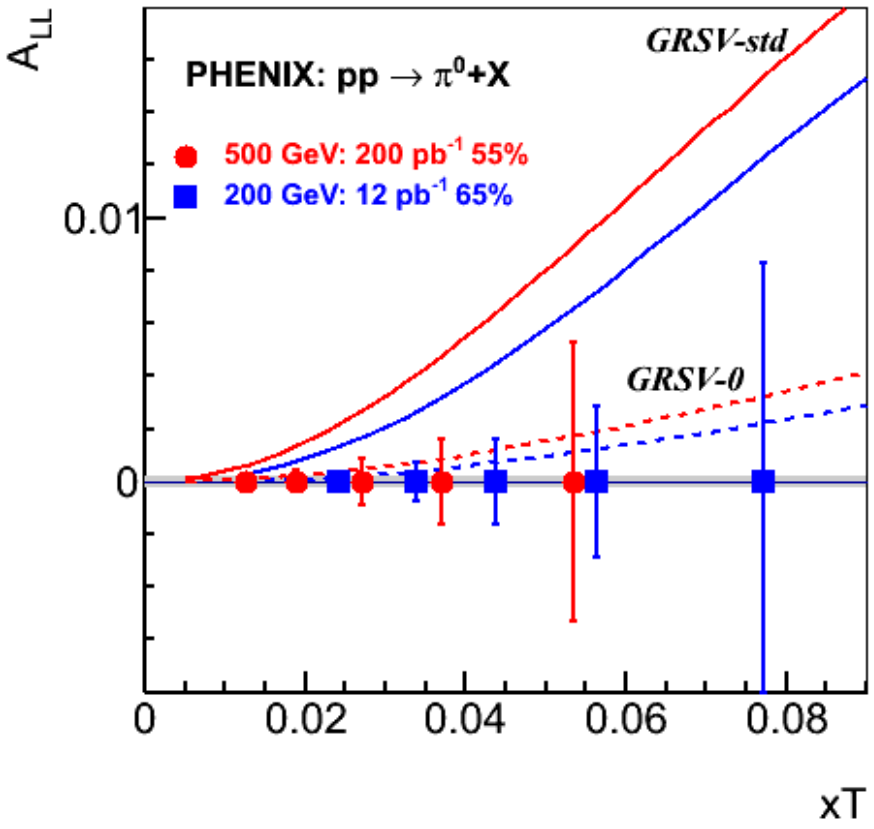
P=0.5 and $L_{recorded}$=85pb^{-1}

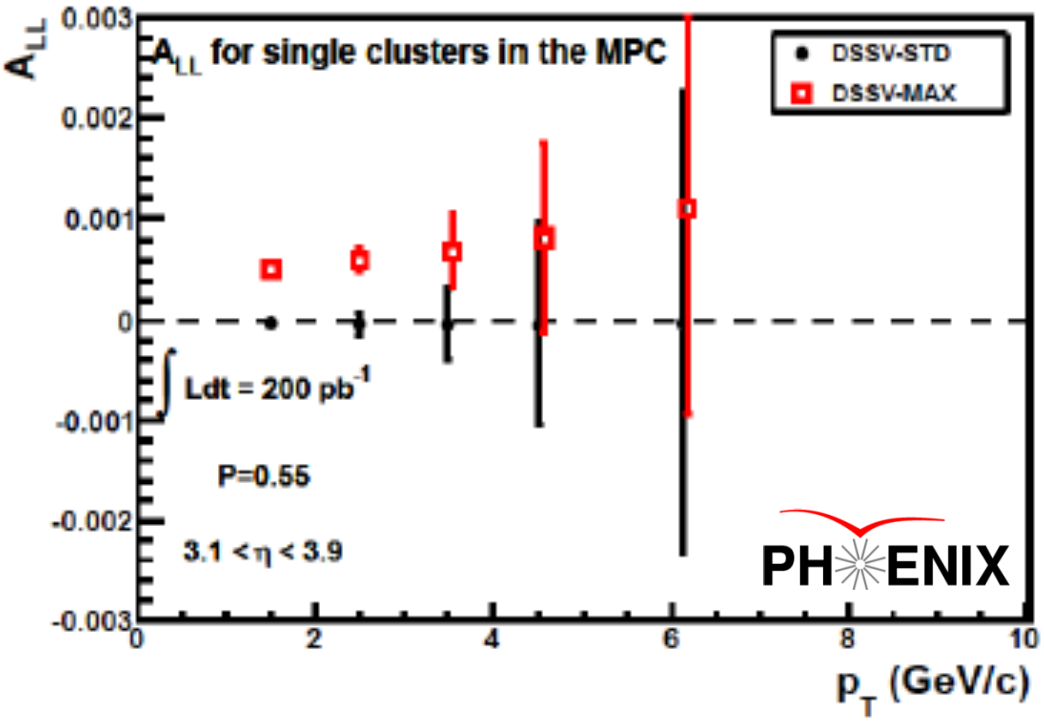


- Access lower Bjorken-x region at 500GeV ⇒ Expect smaller A_{LL}
- Important constrain from future Di-Jet and Inclusive Jet measurements

Future prospects - Gluon polarization program

- PHENIX Future Neutral pion measurements



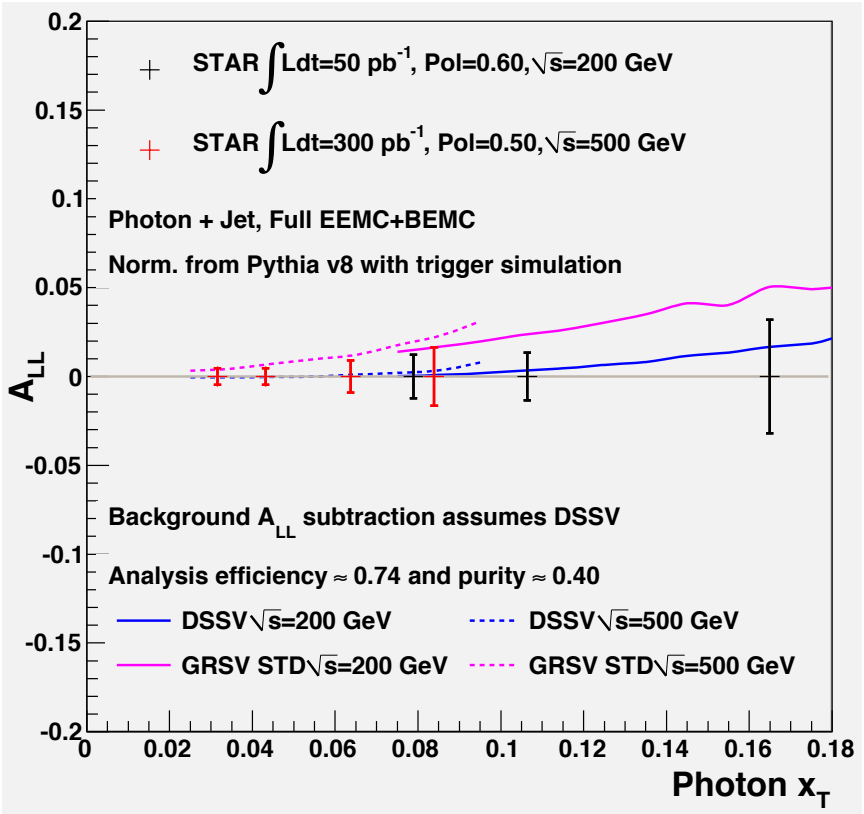


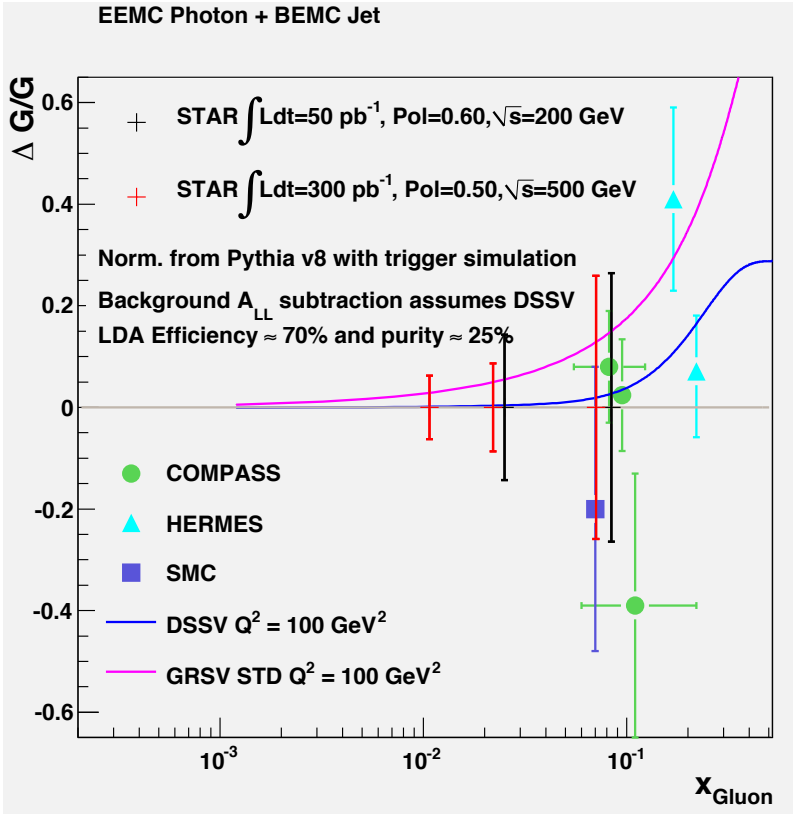
- Access lower Bjorken-x region at 500GeV ⇒ Expect smaller A_{LL}
- Important constrain from future neutral pion measurements

Future prospects - Gluon polarization program

Future Photon-Jet measurements

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

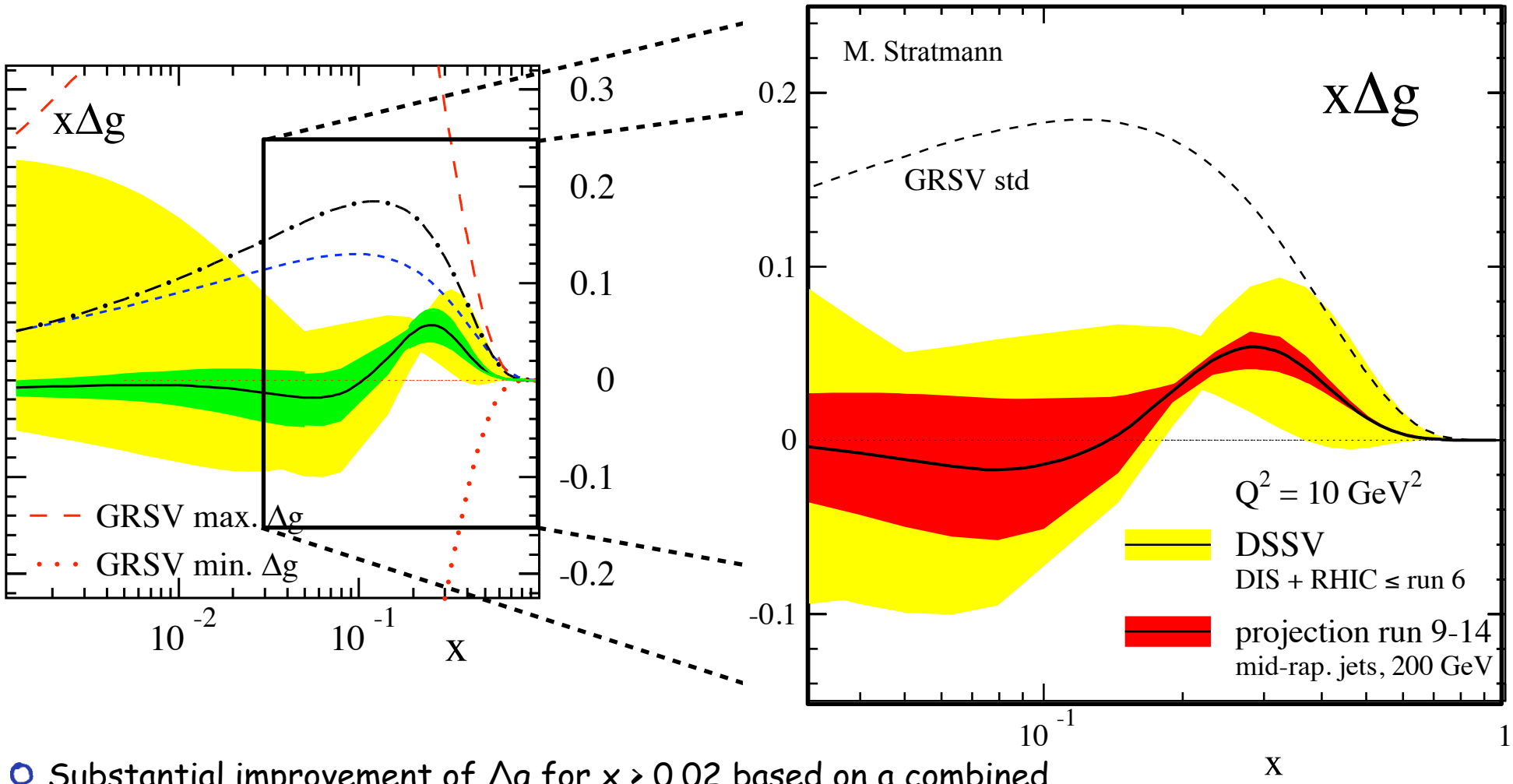




- Direct impact on $\Delta g(x)$
- Projections are for STAR EEMC - STAR FMS will reach lower x region (Few 10^{-3})

Future prospects - Gluon polarization program

- Impact on gluon polarization for future RHIC measurements



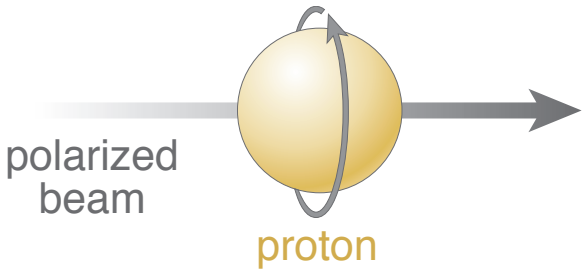
- Substantial improvement of Δg for $x > 0.02$ based on a combined Run 9 + Run 14 data sample of inclusive jet at $\sqrt{s}$=200GeV for $|\eta|<1$

Quark measurement: W production

- Probing the quark flavor structure using W boson production: Unique new probe

Quark measurement: W production

- Probing the quark flavor structure using W boson production: Unique new probe



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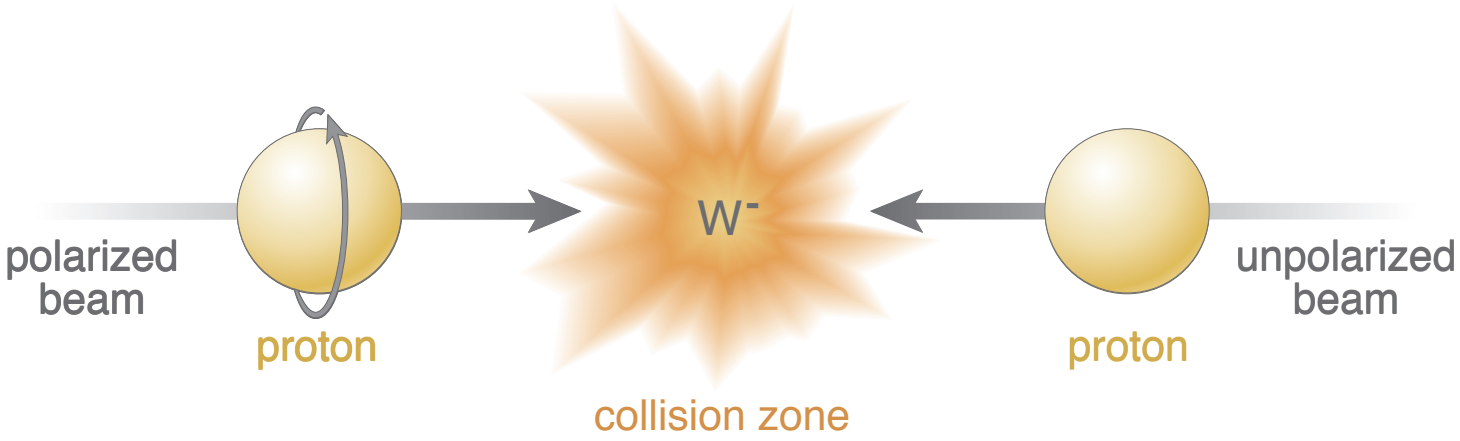

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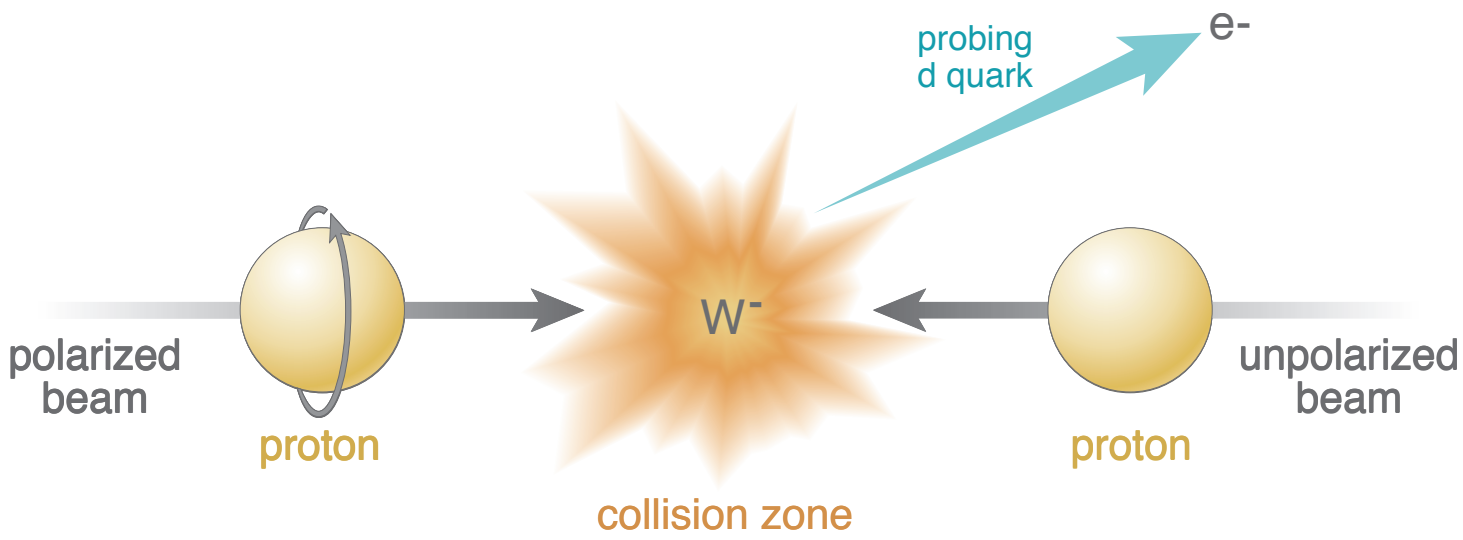

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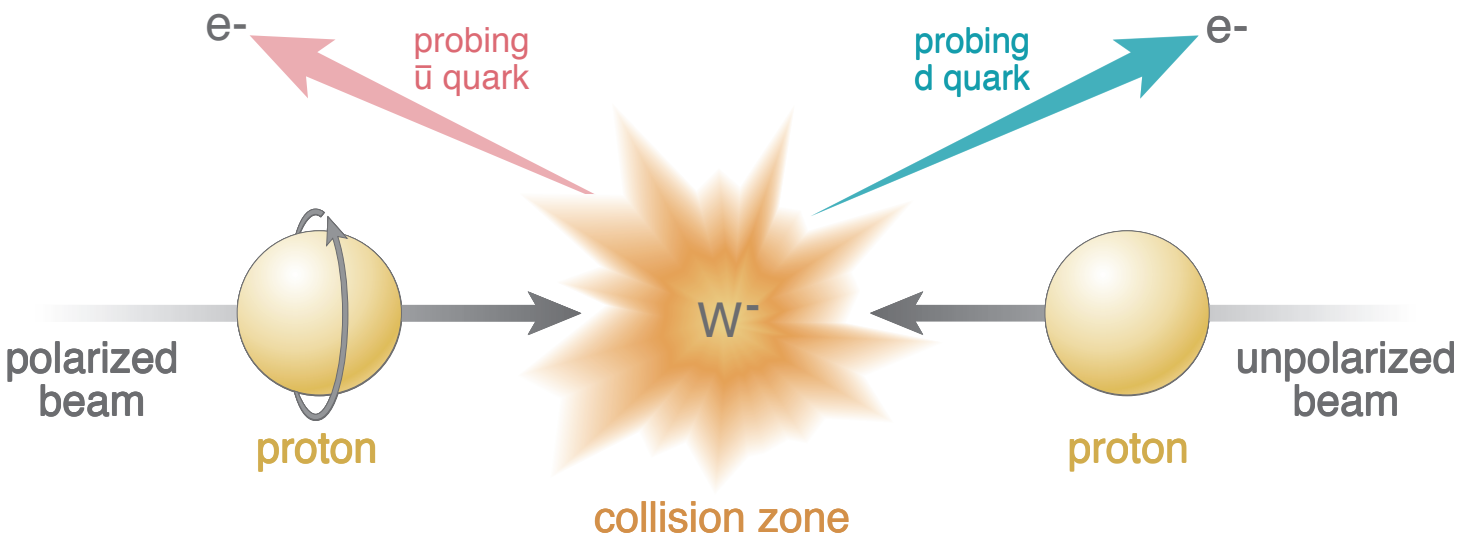

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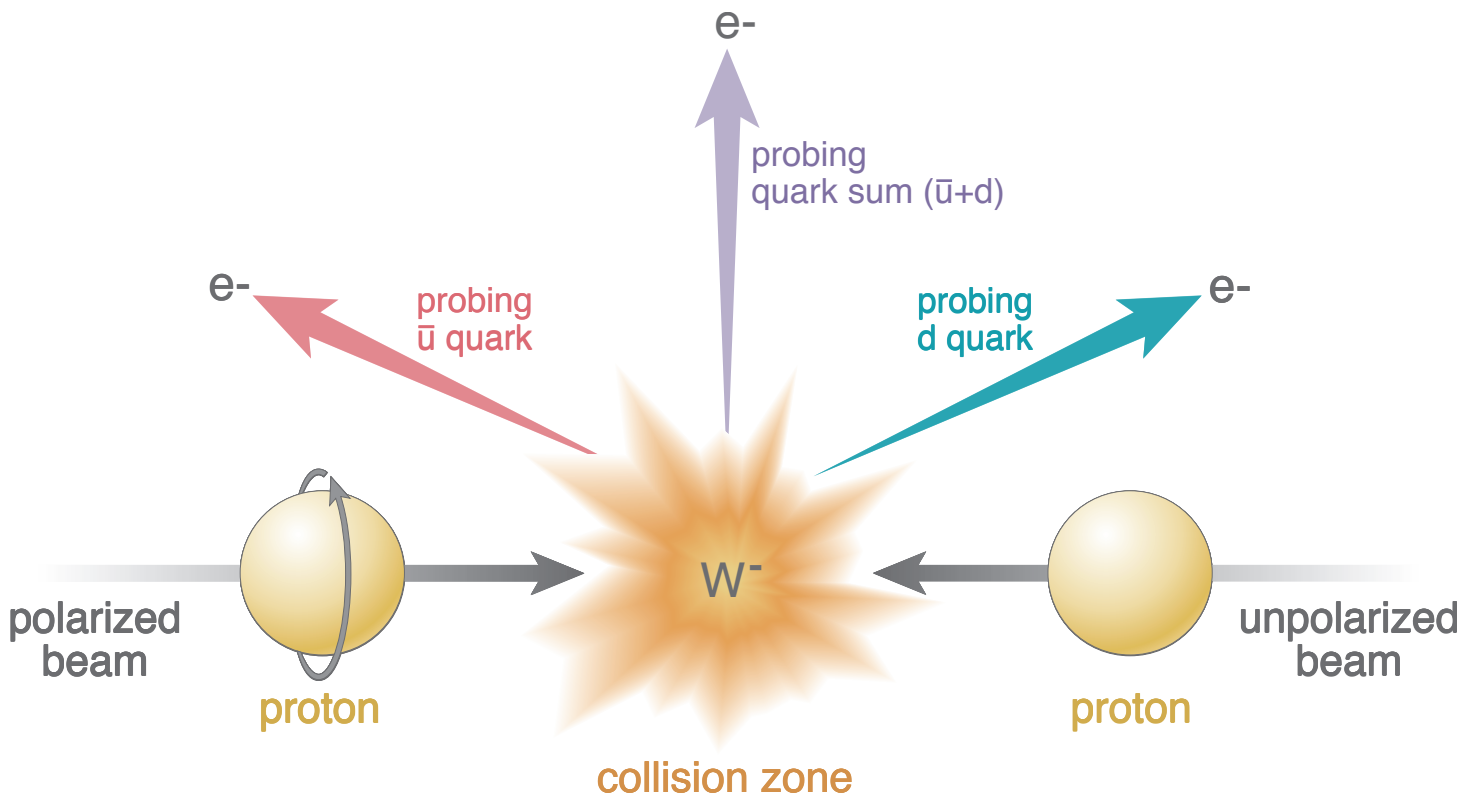


Quark measurement: W production

- Probing the quark flavor structure using W boson production: Unique new probe

Unique New Probe of Proton Spin Structure at RHIC

Direct measurements allow detailed look at how quarks of different flavors contribute to spin

February 15, 2011

UPTON, NY — Scientists hoping to unravel the mystery of proton spin at the Relativistic Heavy Ion Collider (RHIC), a 2.4-mile-circumference particle accelerator at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, have a new tool at their disposal — the first to *directly* explore how quarks of different types, or "flavors," contribute to the overall spin of the proton. The technique, described in papers just published by RHIC's STAR and PHENIX collaborations in *Physical Review Letters*, relies on the measurement of particles called W bosons, the mediators of the weak force responsible for the decay of radioactive nuclei.

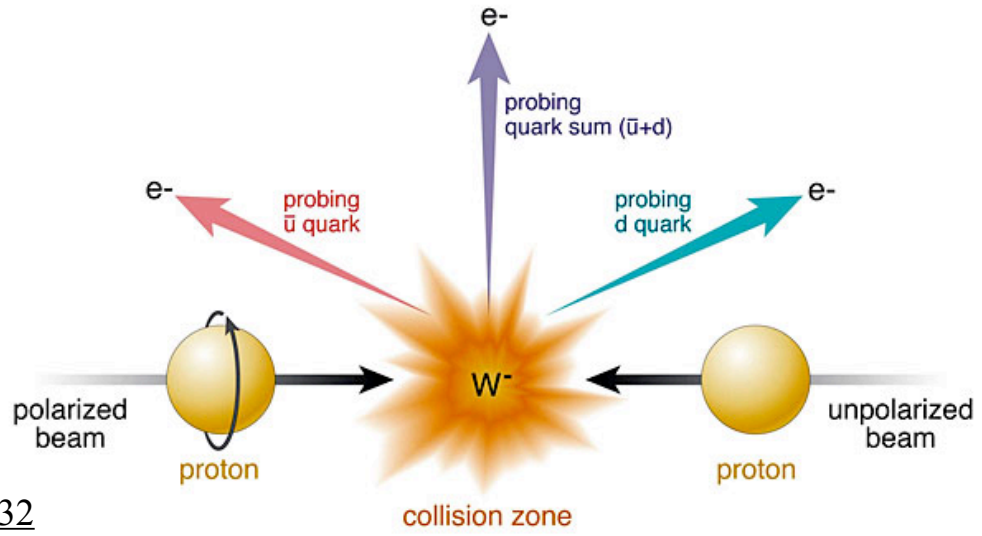


Illustration of a new measurement using W boson production in polarized proton collisions at RHIC. Collisions of polarized protons (beam entering from left) and unpolarized protons (right) result in the production of W bosons (in this case, W-). RHIC's detectors identify the particles emitted as the W bosons decay (in this case, electrons, e-) and the angles at which they emerge. The colored arrows represent different possible directions, which probe how different quark flavors (e.g., "anti-up," ū; and "down," d) contribute to the proton spin. + ENLARGE

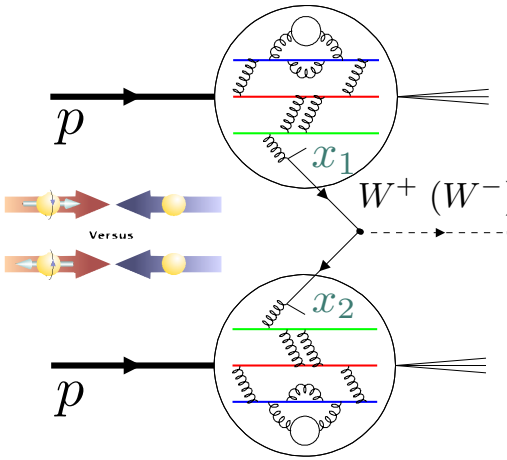
News Release:

http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=1232

Recent results - Quark / Anti-quark pol. program

- Probing the quark flavor structure using W boson production

$\Delta d + \bar{u} \rightarrow W^-$
$\Delta \bar{u} + d \rightarrow W^-$



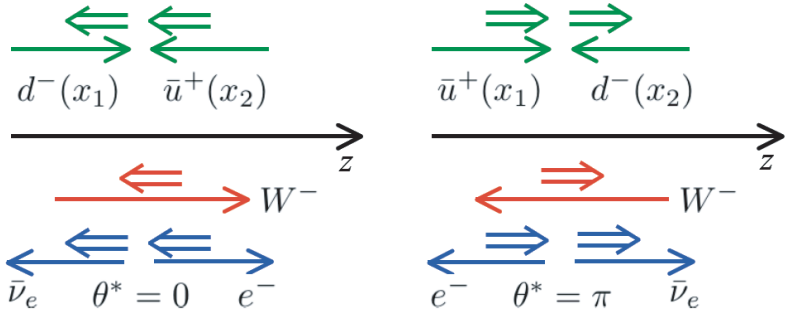
$W^+ \ (W^-)$

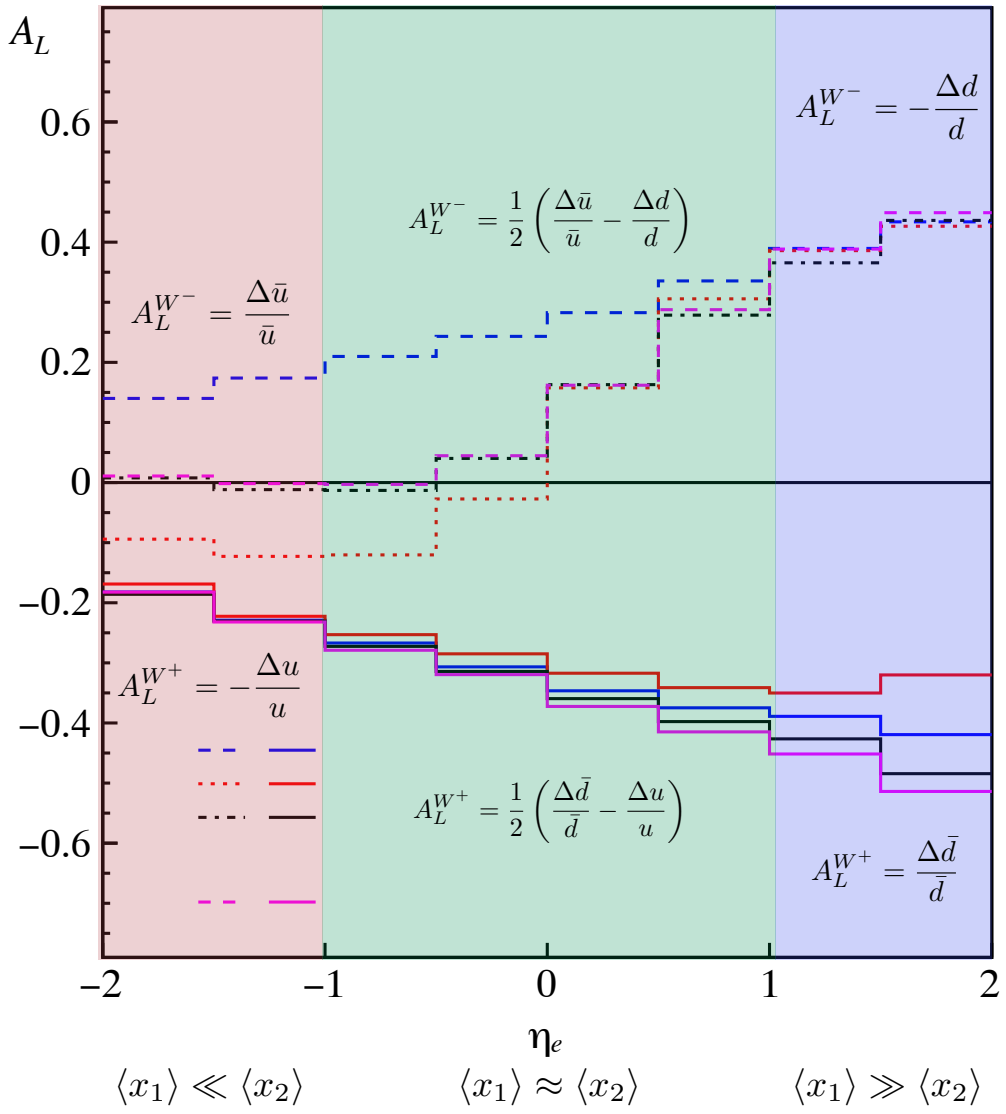
$\nu_e \ (\bar{\nu}_e)$

$e^+ \ (e^-)$

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

$\Delta \bar{d} + u \rightarrow W^+$
$\Delta u + \bar{d} \rightarrow W^+$





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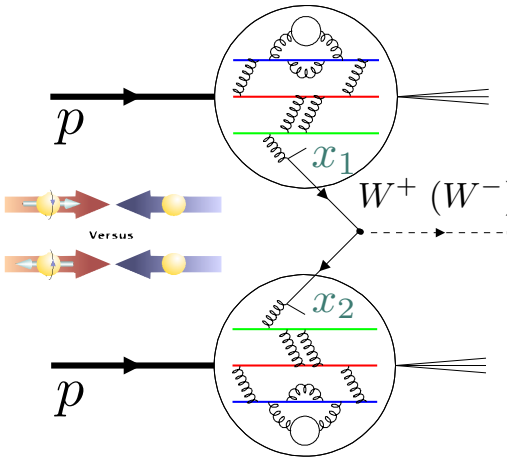

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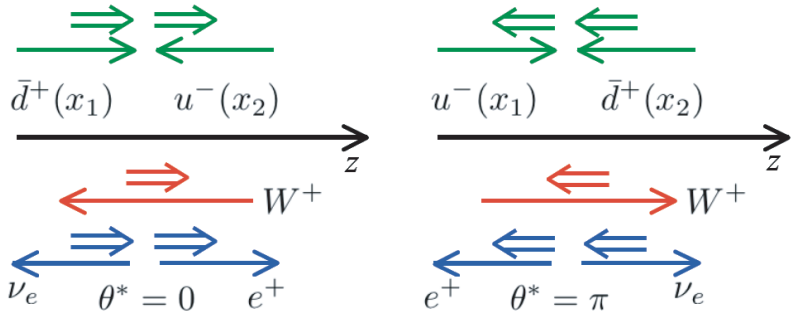
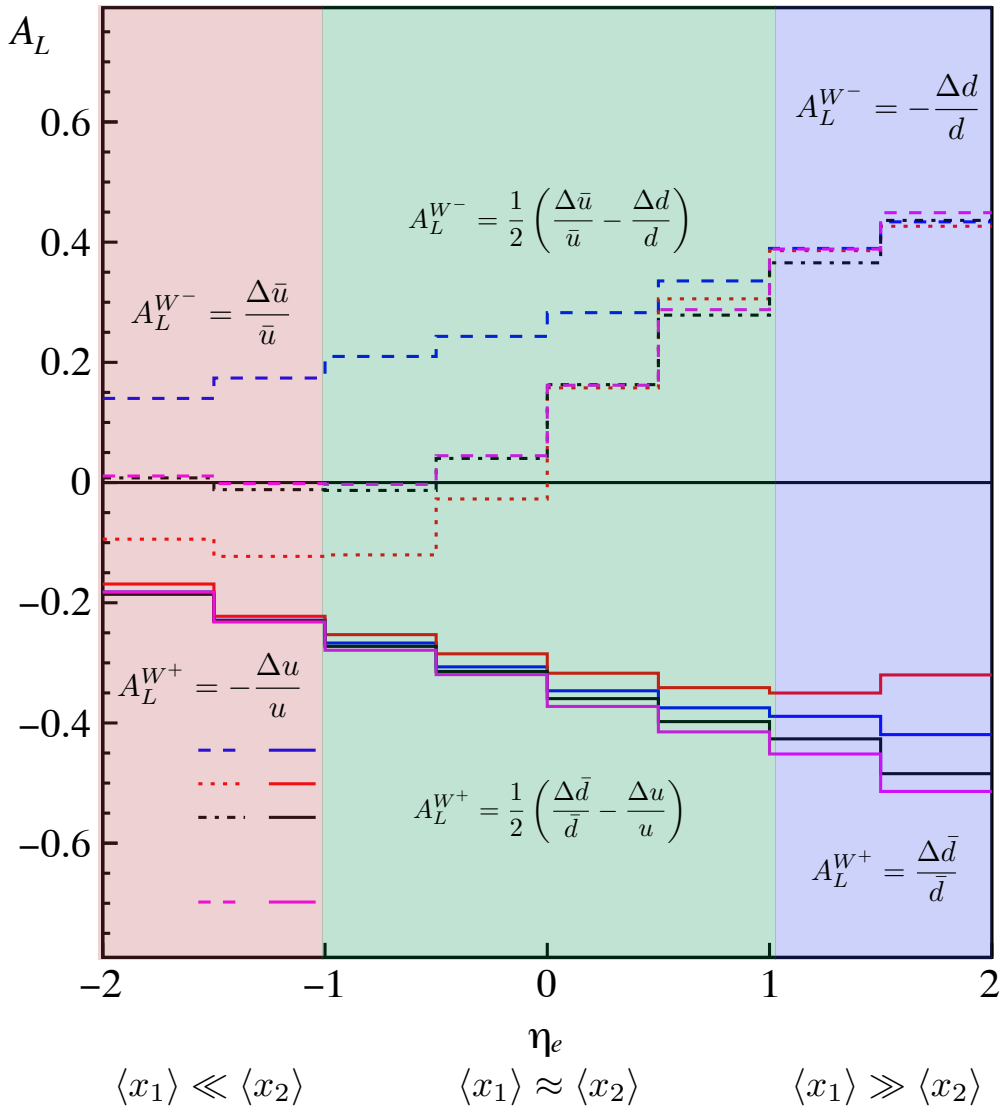
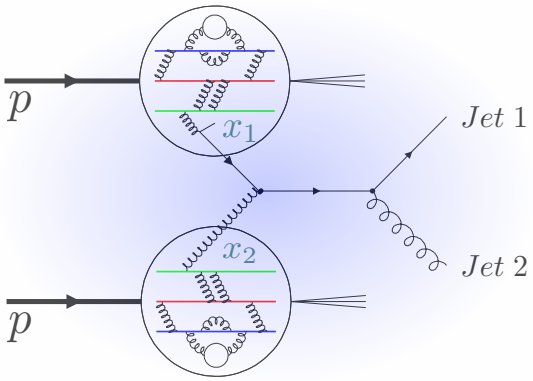




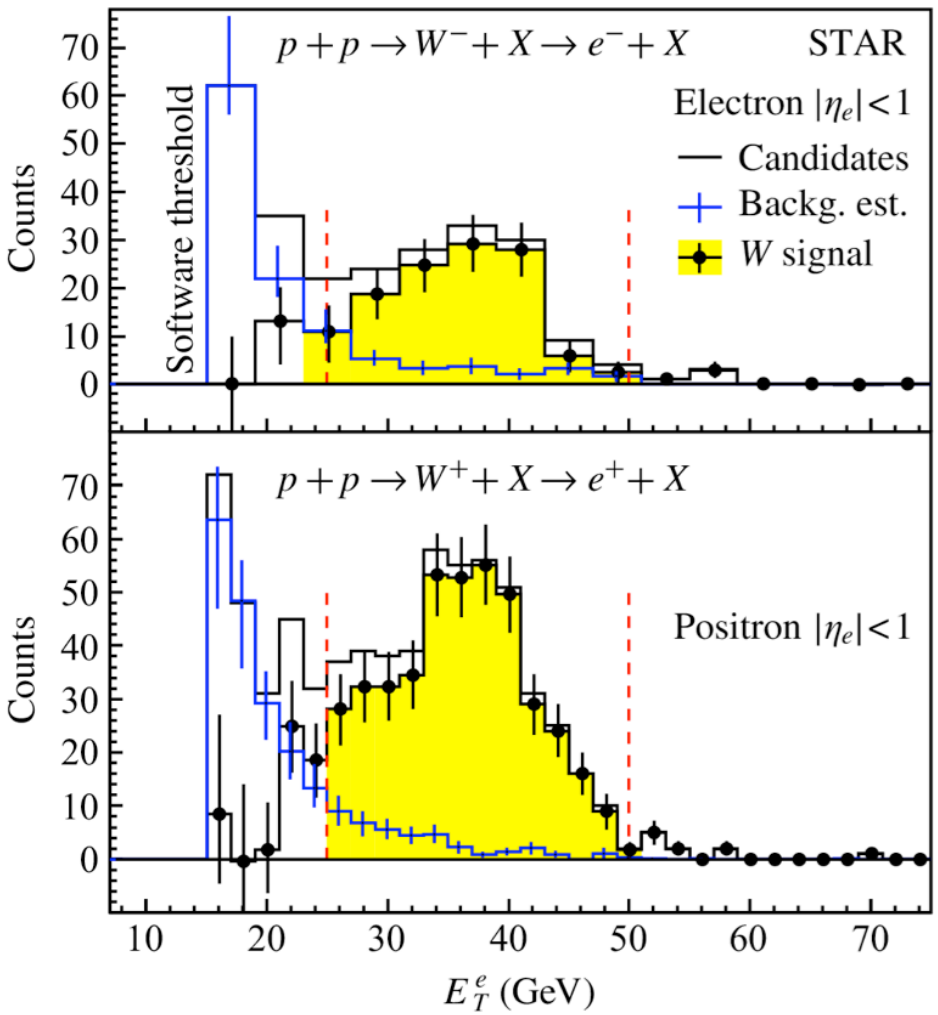
Recent results - Quark / Anti-quark pol. program

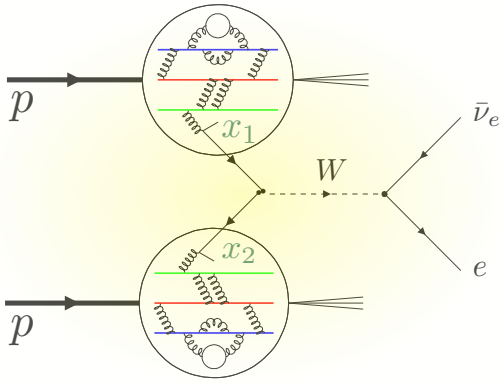
Measurement: Background treatment / Signal distribution



- Background dominated by QCD background (Data driven estimate) with smaller fractions from W boson induced τ decays and Z^0 boson events (MC estimate)

- Total background (B):
  - e^+: 39 ± 9
  - e^-: 23 ± 6



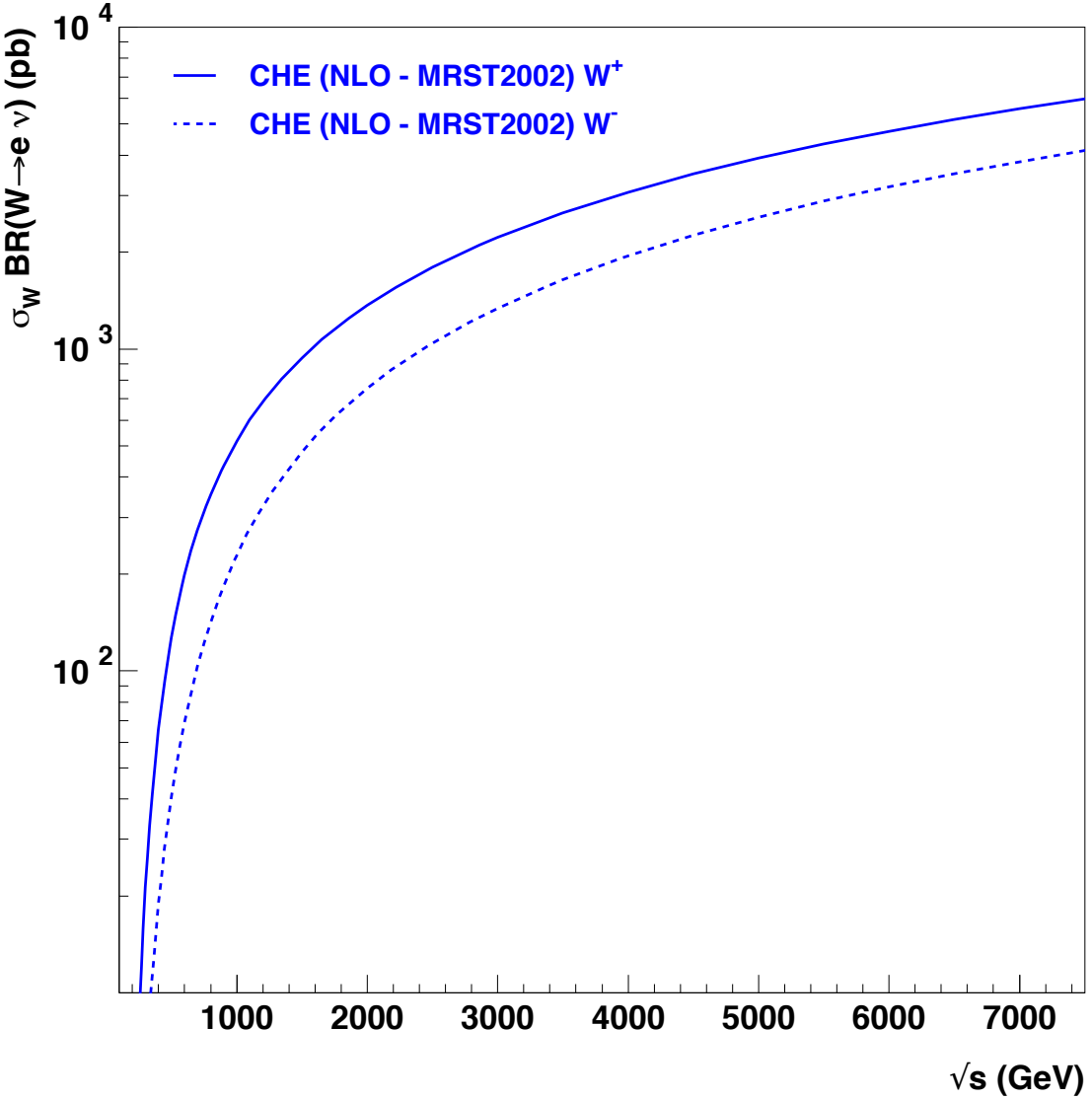


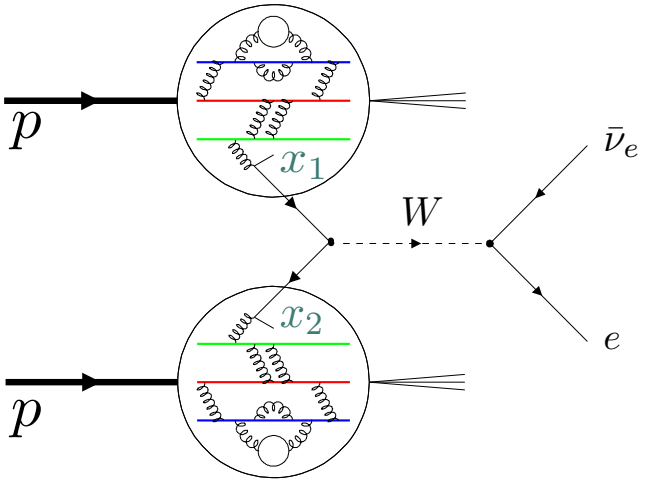
- Total e^+/e^- cand. events (S+B):
  - e^+: 462
  - e^-: 139

STAR Collaboration, PRL 106, 062002 (2011)

Recent results - Quark / Anti-quark pol. program

- PHENIX and STAR W^+ / W^- cross section measurement in pp collisions





- Measured and theory evaluated cross-sections agree within uncertainties
- Theory calculations: Full NLO framework

Recent results - Quark / Anti-quark pol. program

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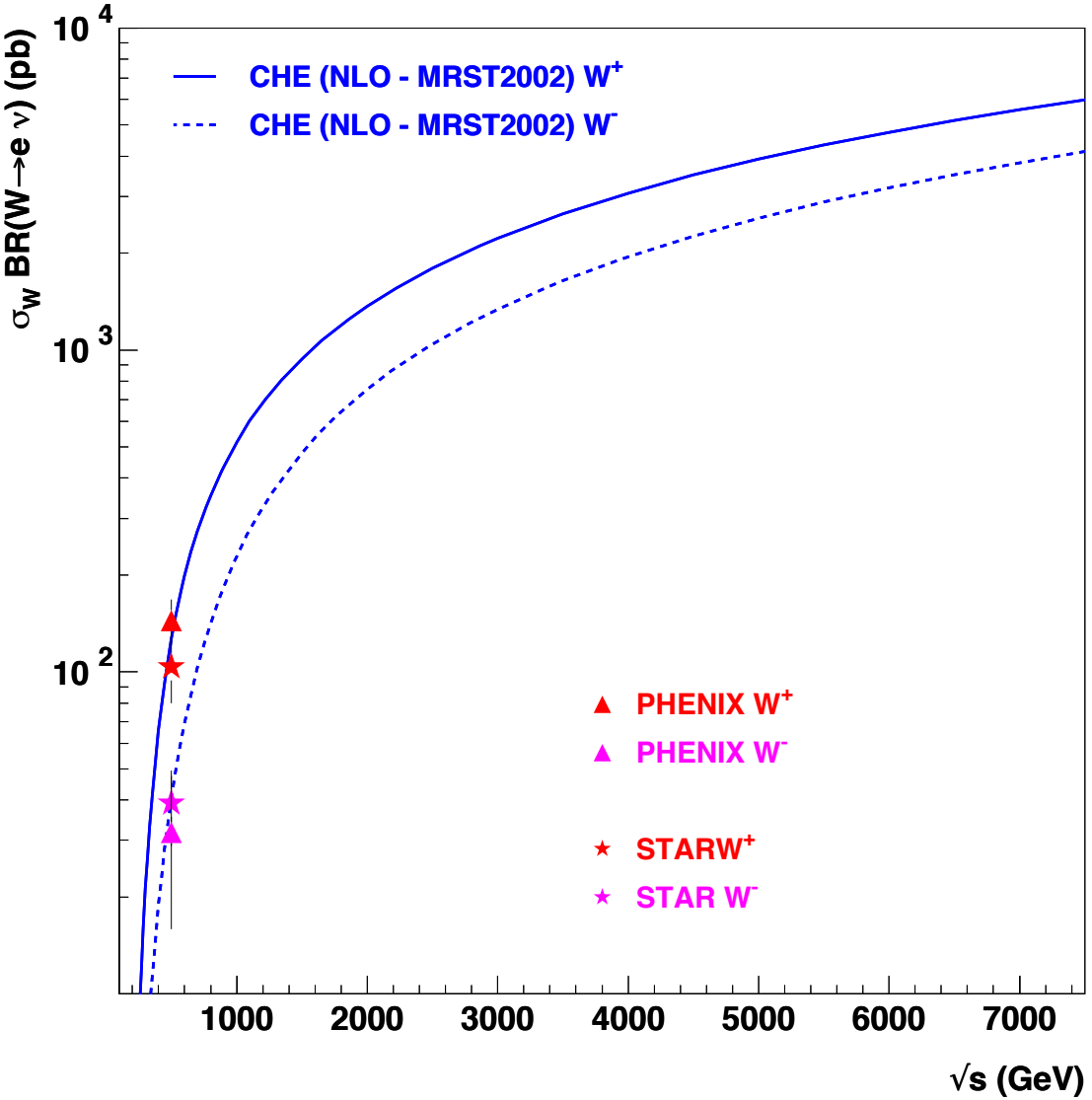

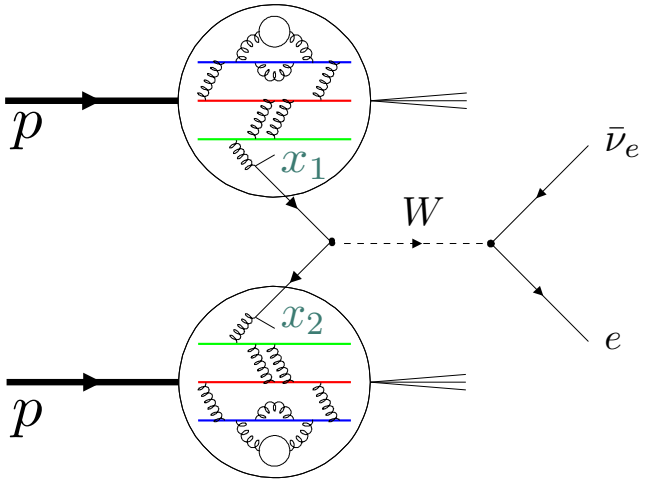

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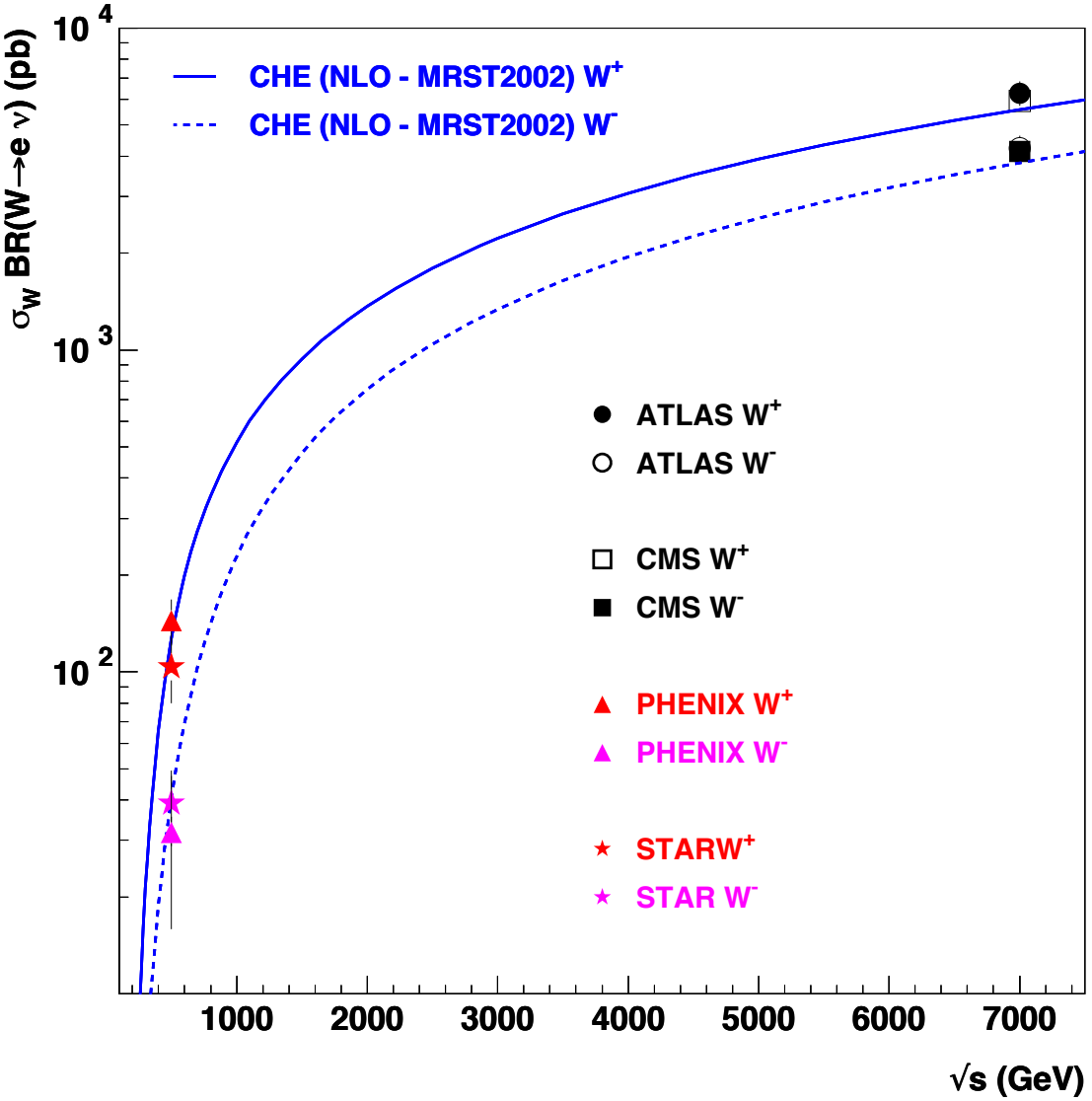

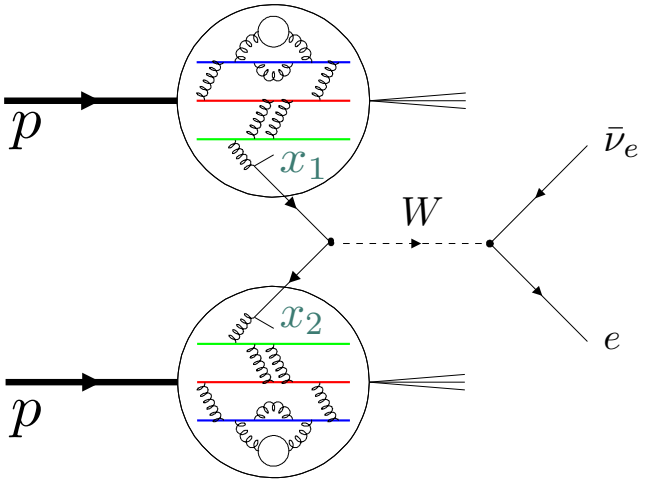

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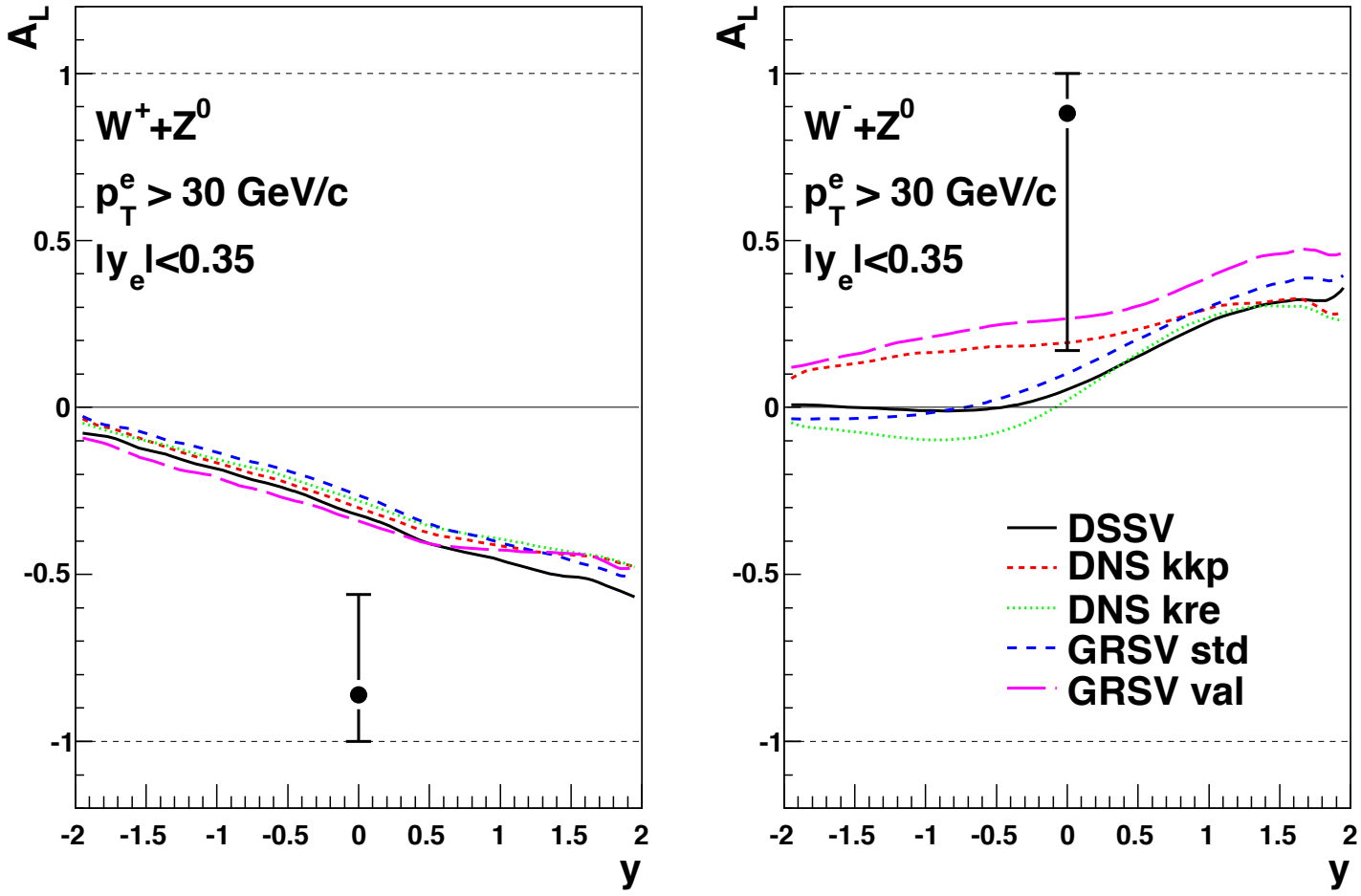
Recent results - Quark / Anti-quark pol. program

- PHENIX: Status and projections A_L



- A_L result consistent with all models
- A non-zero asymmetry (98.4%CL) is observed in the positive candidates

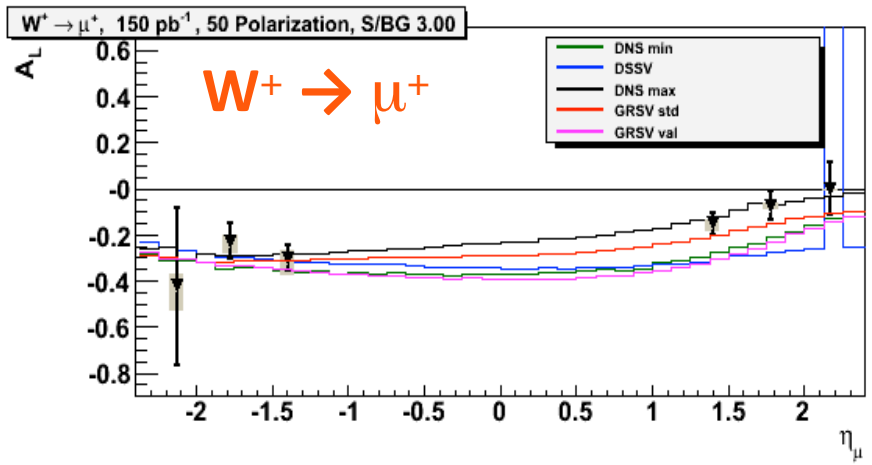
PHENIX Collaboration, PRL 106, 062001 (2011)

Recent results - Quark / Anti-quark pol. program

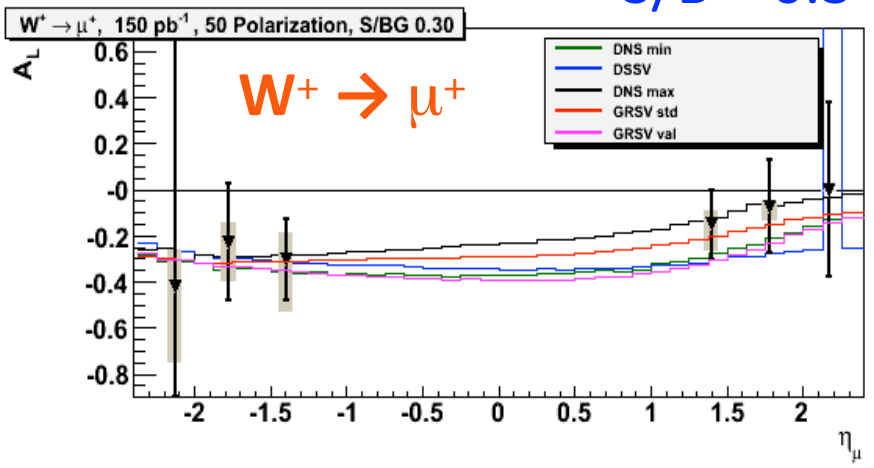
- PHENIX: Status and projections A_L

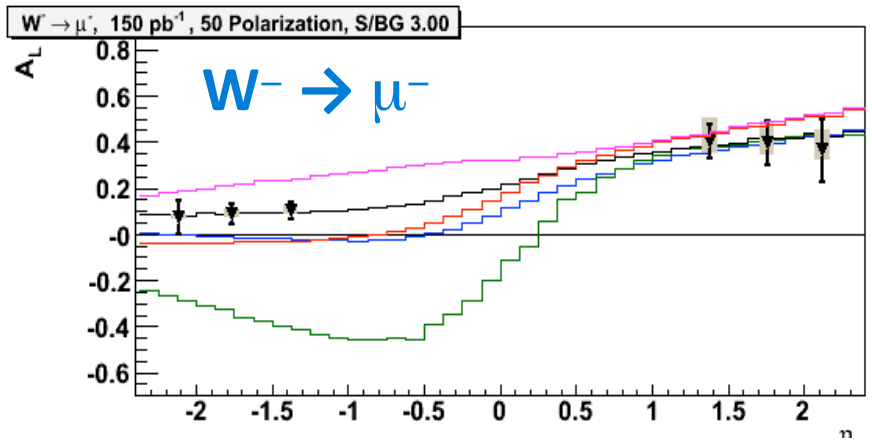
$L=150pb^{-1}$ / $P=50\%$

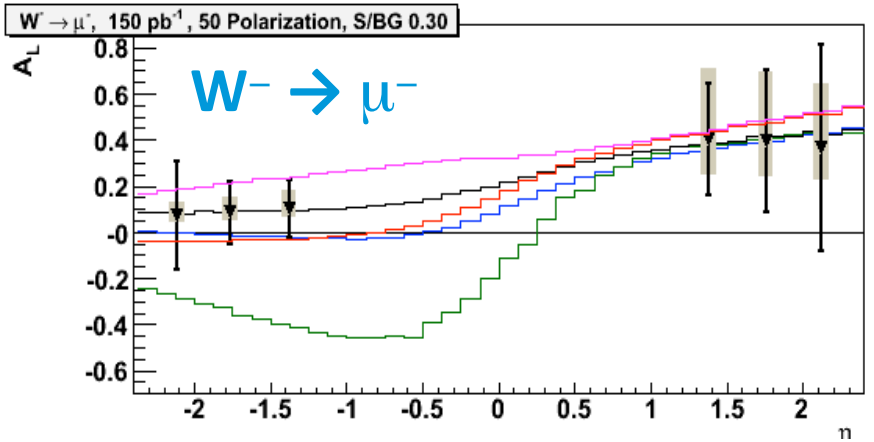
S/B = 3.0



S/B = 0.3







η_μ (muon pseudo-rapidity)

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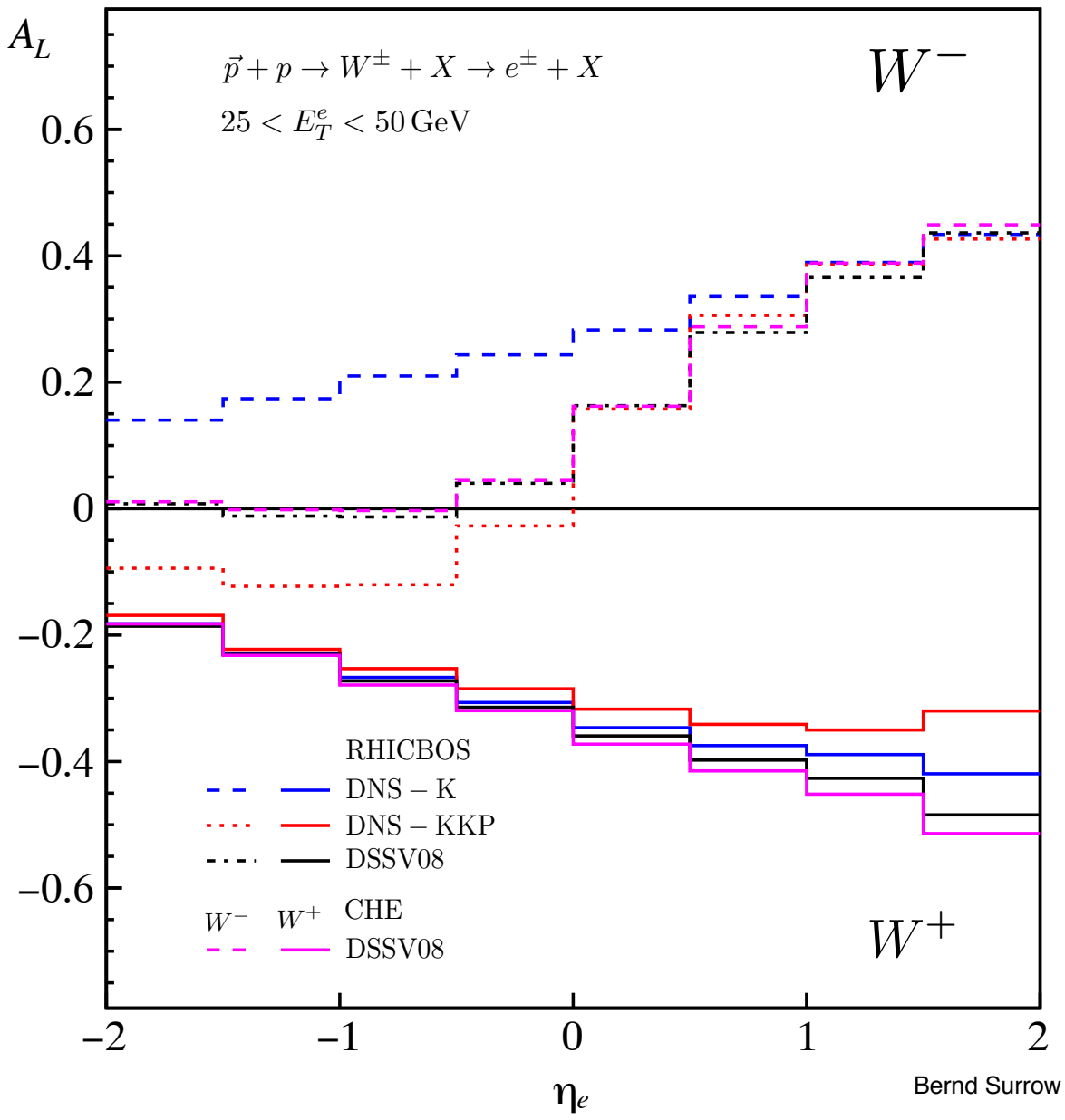
Recent results - Quark / Anti-quark pol. program

- STAR: Status and projections A_L



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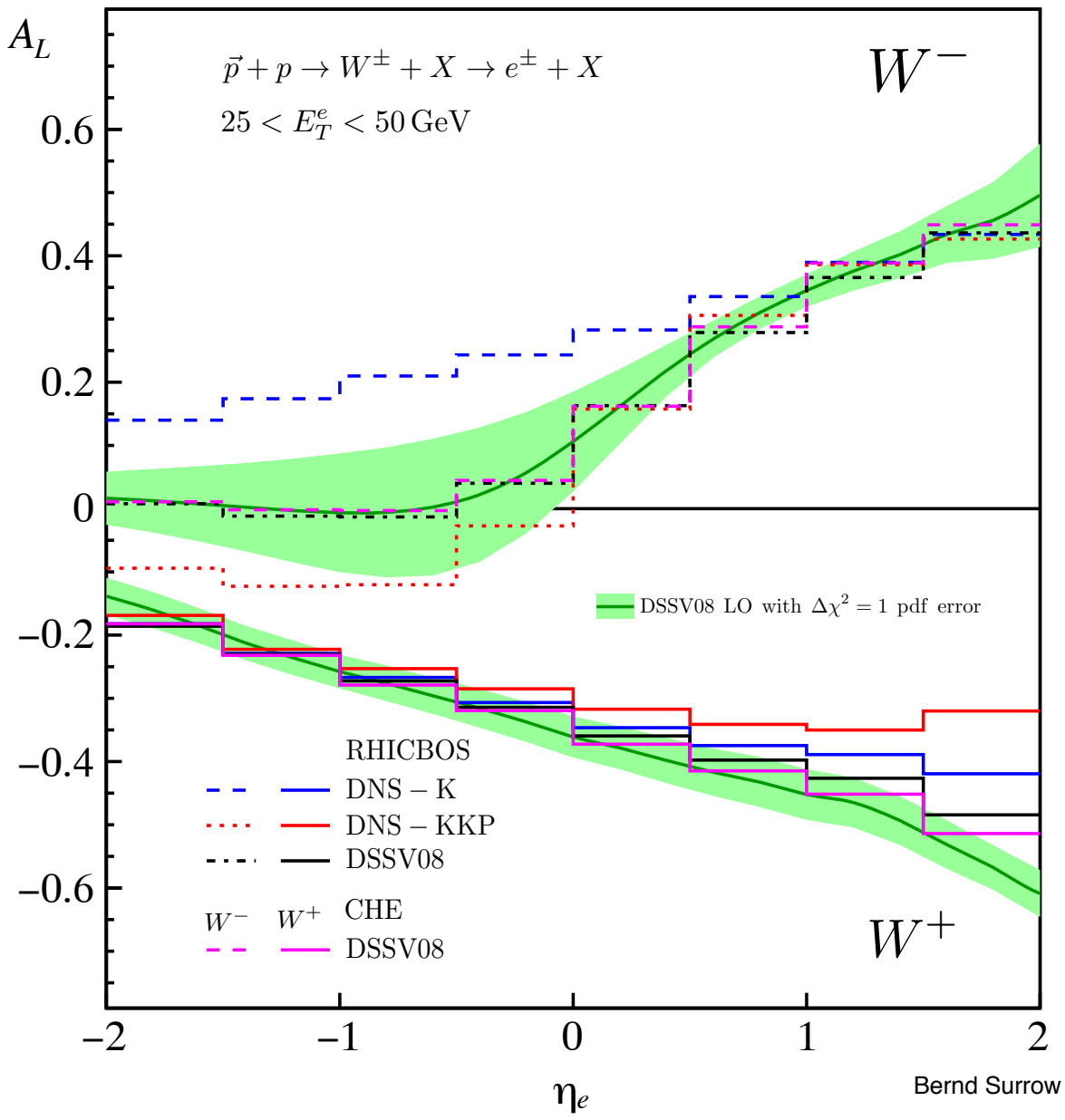


Recent results - Quark / Anti-quark pol. program

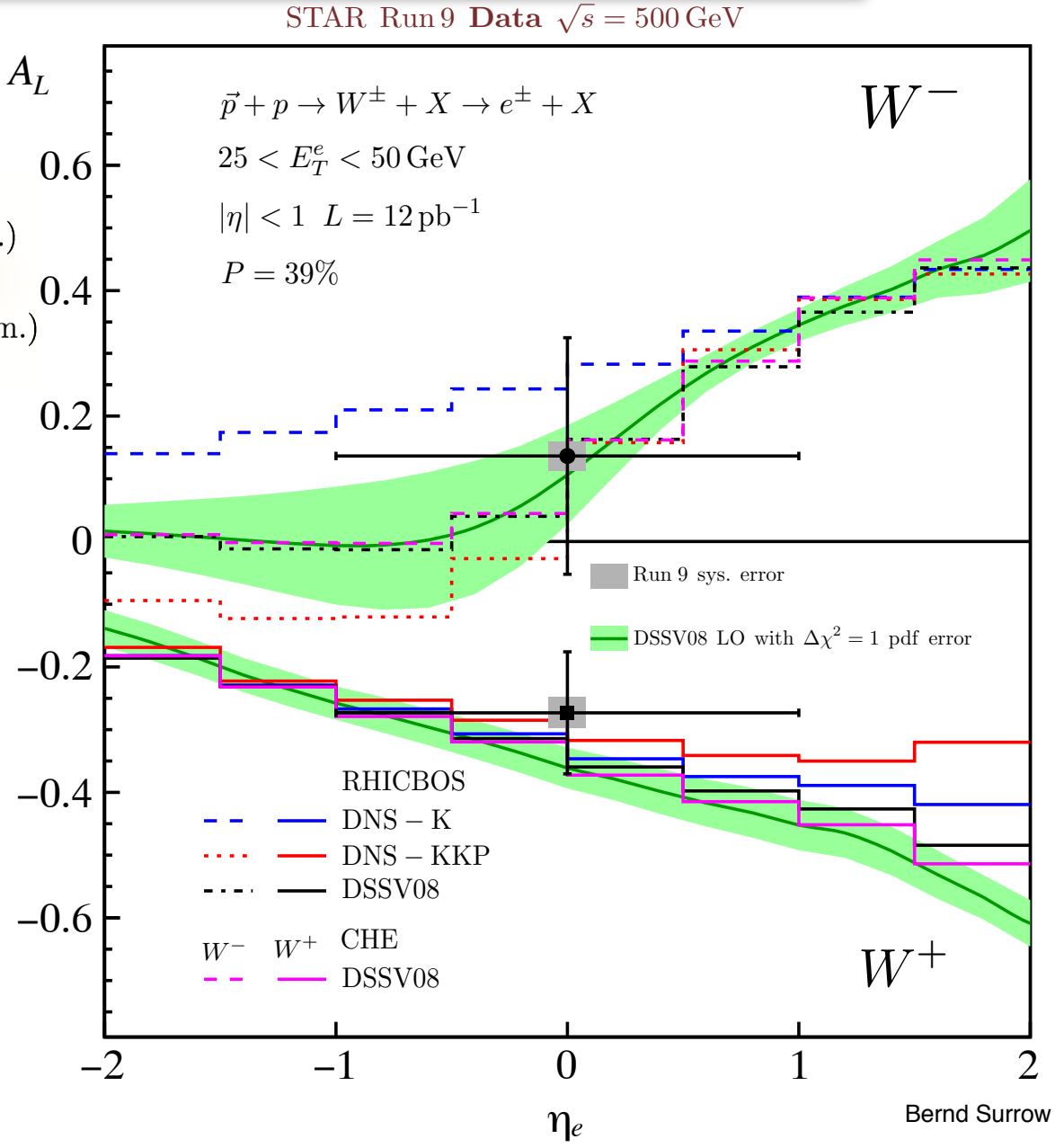
- STAR: Status and projections A_L

$$A_L^{W^-} = 0.14 \pm 0.19\ (\text{stat.}) \pm 0.02\ (\text{syst.}) \pm 0.01\ (\text{norm.})$$

$$A_L^{W^+} = -0.27 \pm 0.10\ (\text{stat.}) \pm 0.02\ (\text{syst.}) \pm 0.03\ (\text{norm.})$$

- $A_L(W^+)$ negative with a significance of ~3σ
- $A_L(W^-)$ central value positive
- Measured asymmetries are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data

  ⇒ Universality of helicity distr. functions!



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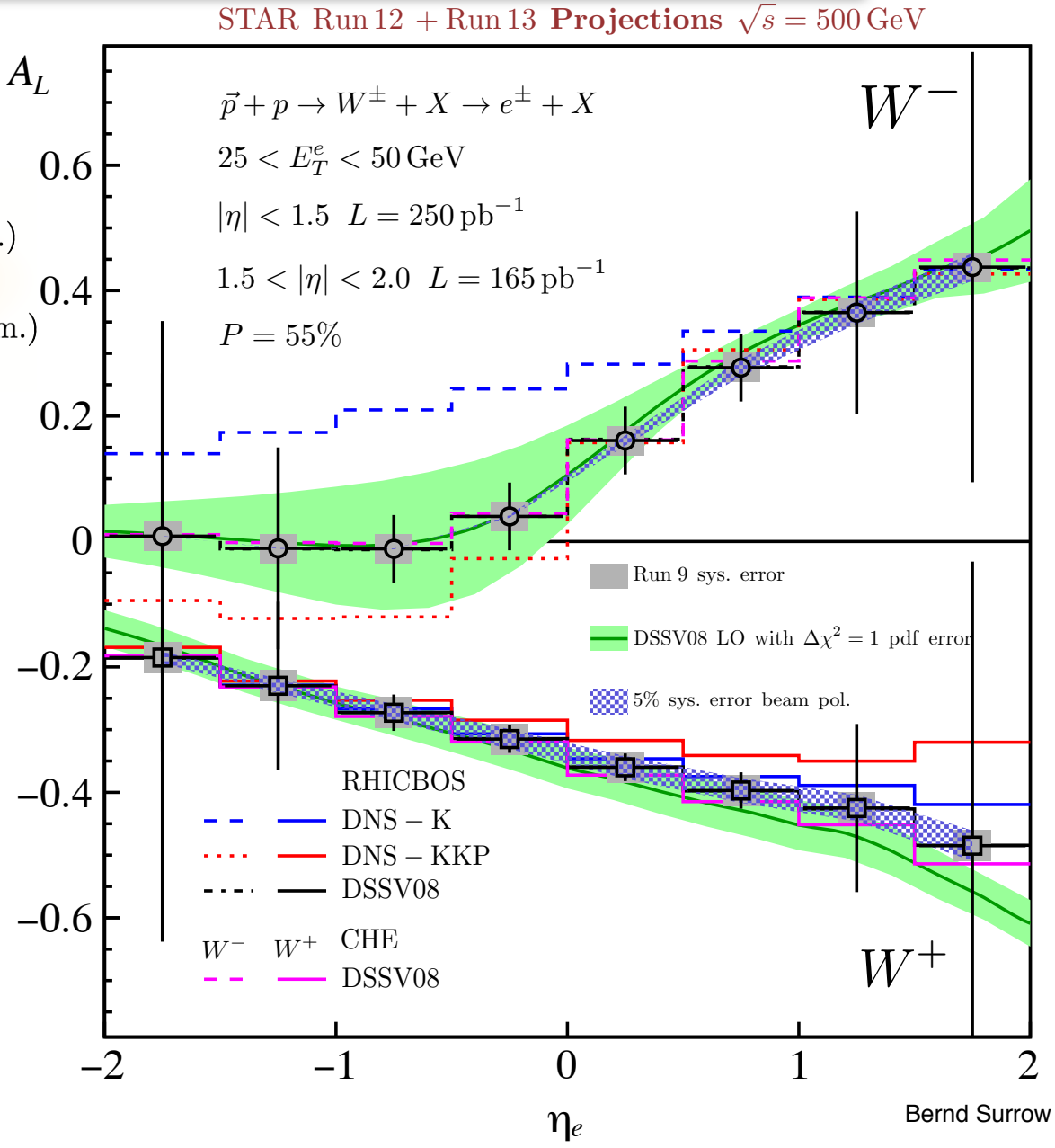
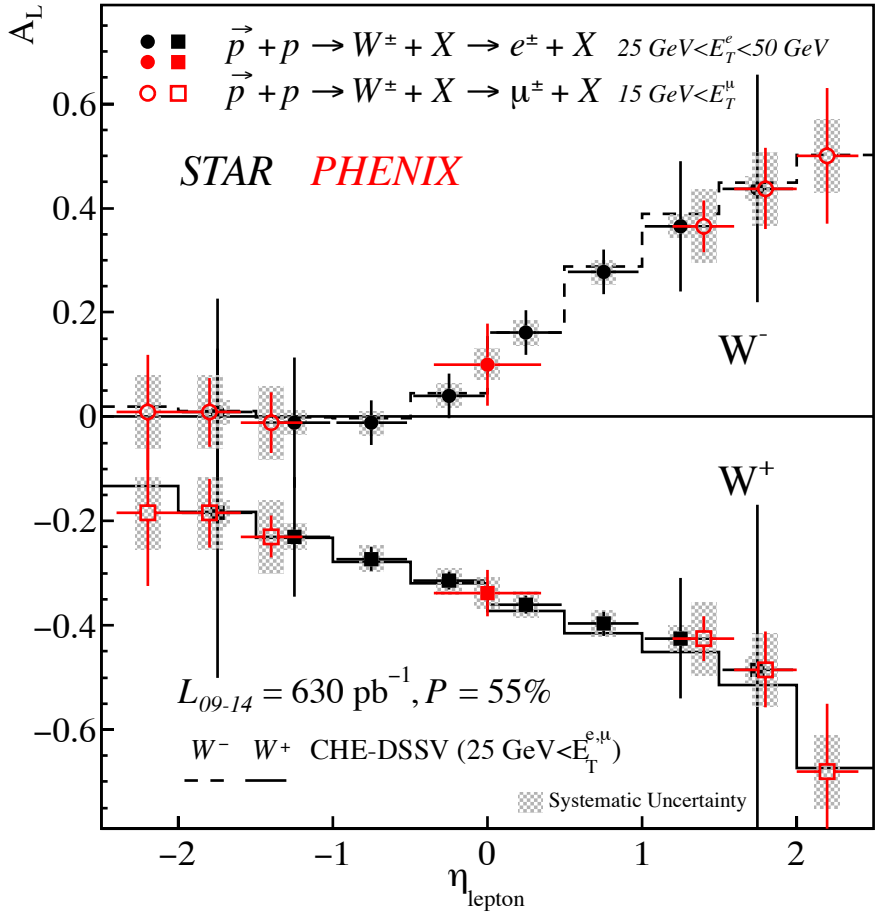
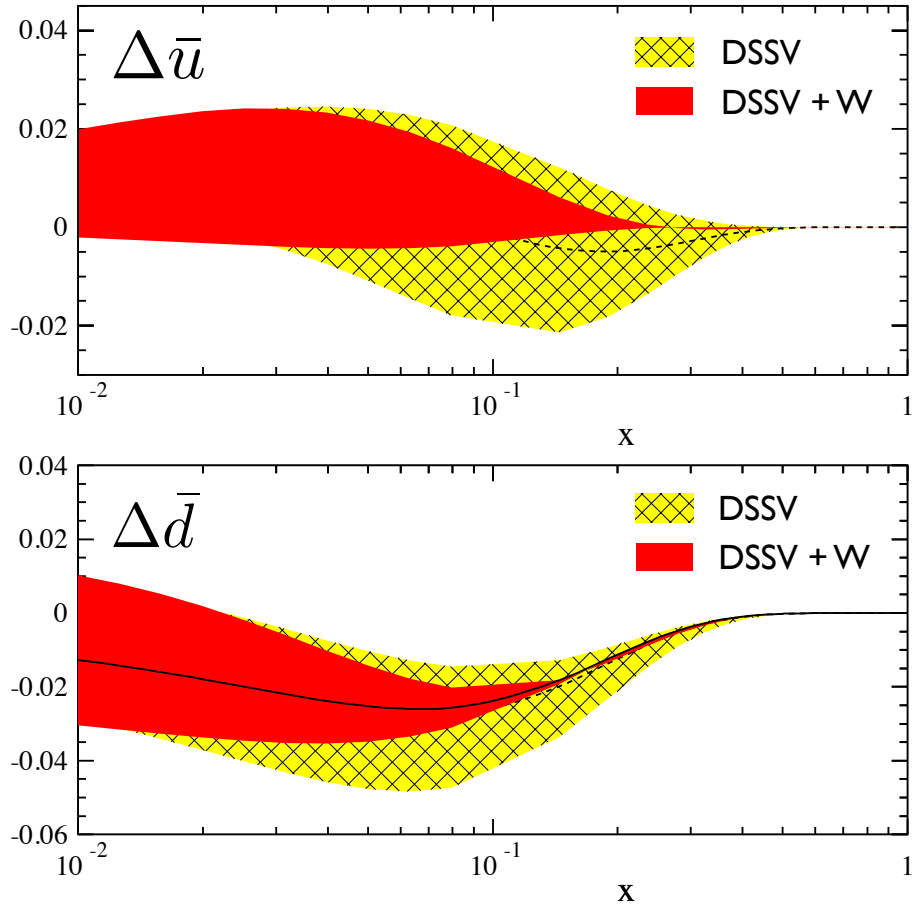


Future - Quark / Anti-quark pol. program

- RHIC W Impact on polarized QCD sea





- Substantial improvement of anti-u/anti-d quark polarization for x ≳ 0.05 based on $L_{\text{delivered}} = 630\text{pb}^{-1}$ and P=55%

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- Run 12 and future
  - Run 12: Successful trans. 200GeV (~20pb^{-1} rec.) and long. 510GeV (~85pb^{-1} rec.) runs
  - Future: Expect and need several long 500GeV production runs beyond Run 12 (e.g. Run 13)

THANKS

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Greetings from Lanzarote!