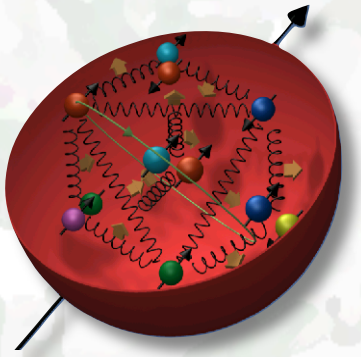
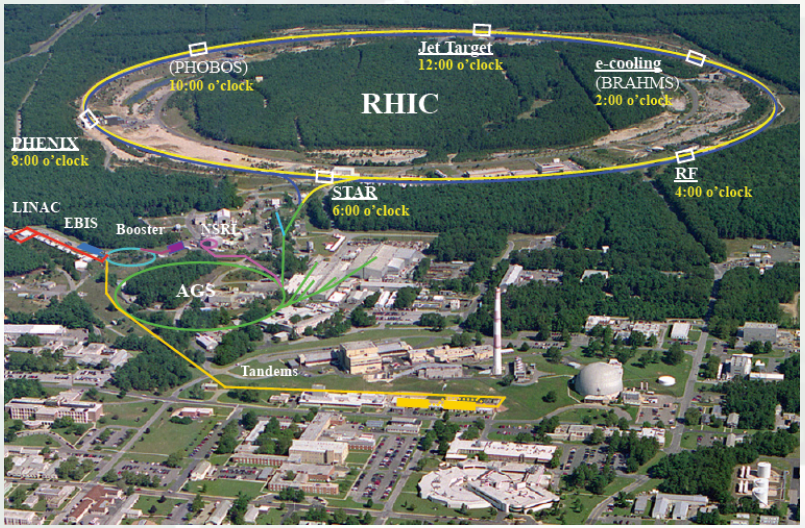
Recent results on hadron / jet and W production of the high-energy polarized p+p program at RHIC at BNL

Bernd Surrow

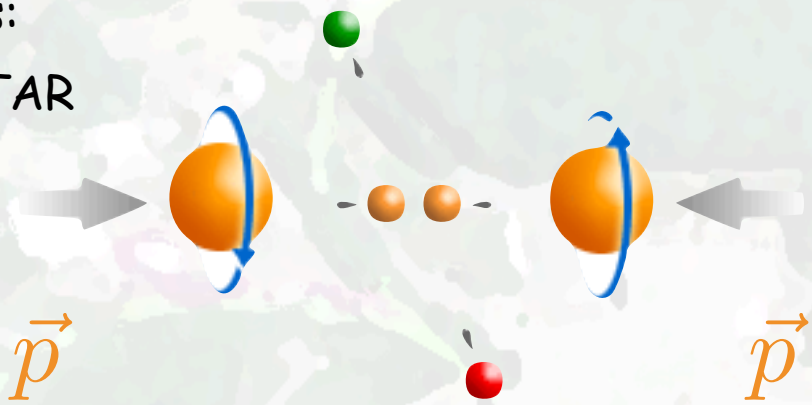
TEMPLE UNIVERSITY



Outline

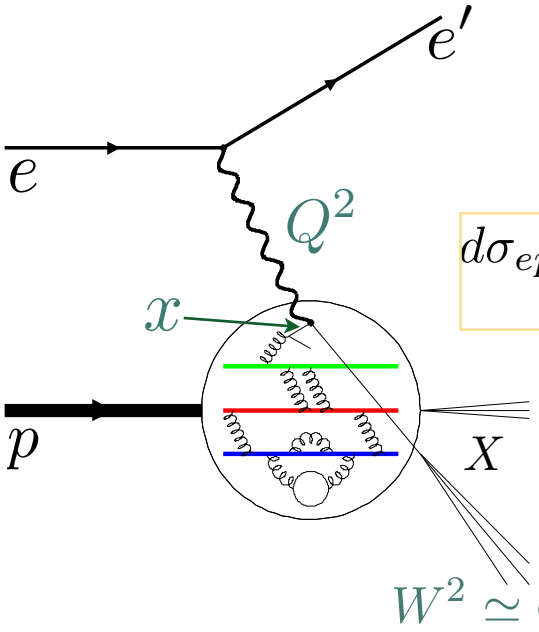


- Selected recent results and future prospects
  - Gluon polarization
  - Quark / Anti-quark polarization
- Experimental aspects: RHIC / PHENIX / STAR
- Theoretical foundation
- Summary and Outlook



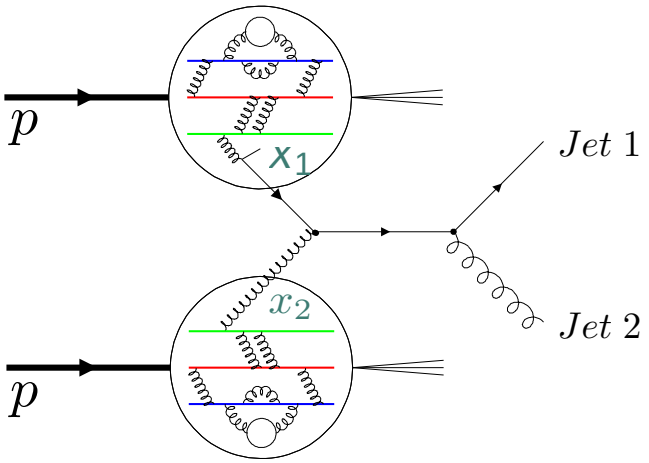
Theoretical foundation

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



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

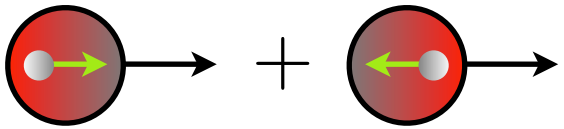
Universality



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

Momentum contribution

$$f(x) =$$



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

$$\Delta f(x) =$$

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

Spin contribution

Theoretical foundation

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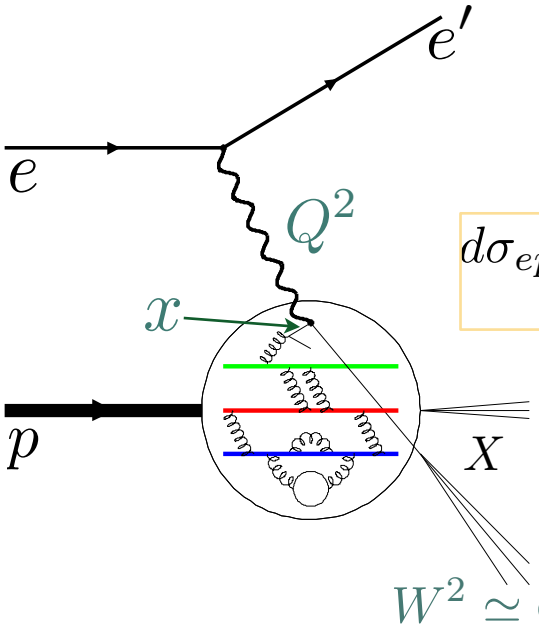

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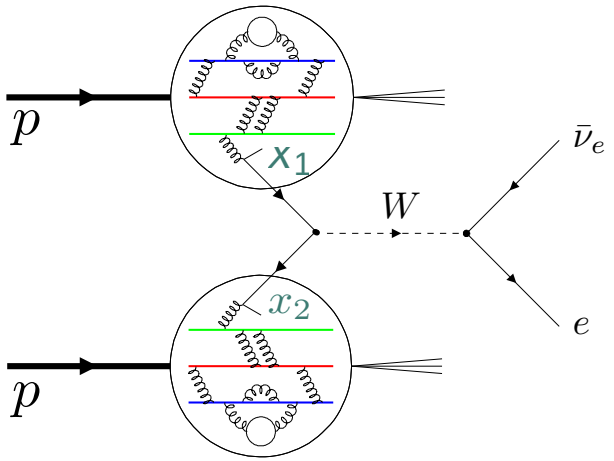

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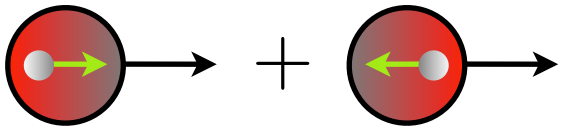

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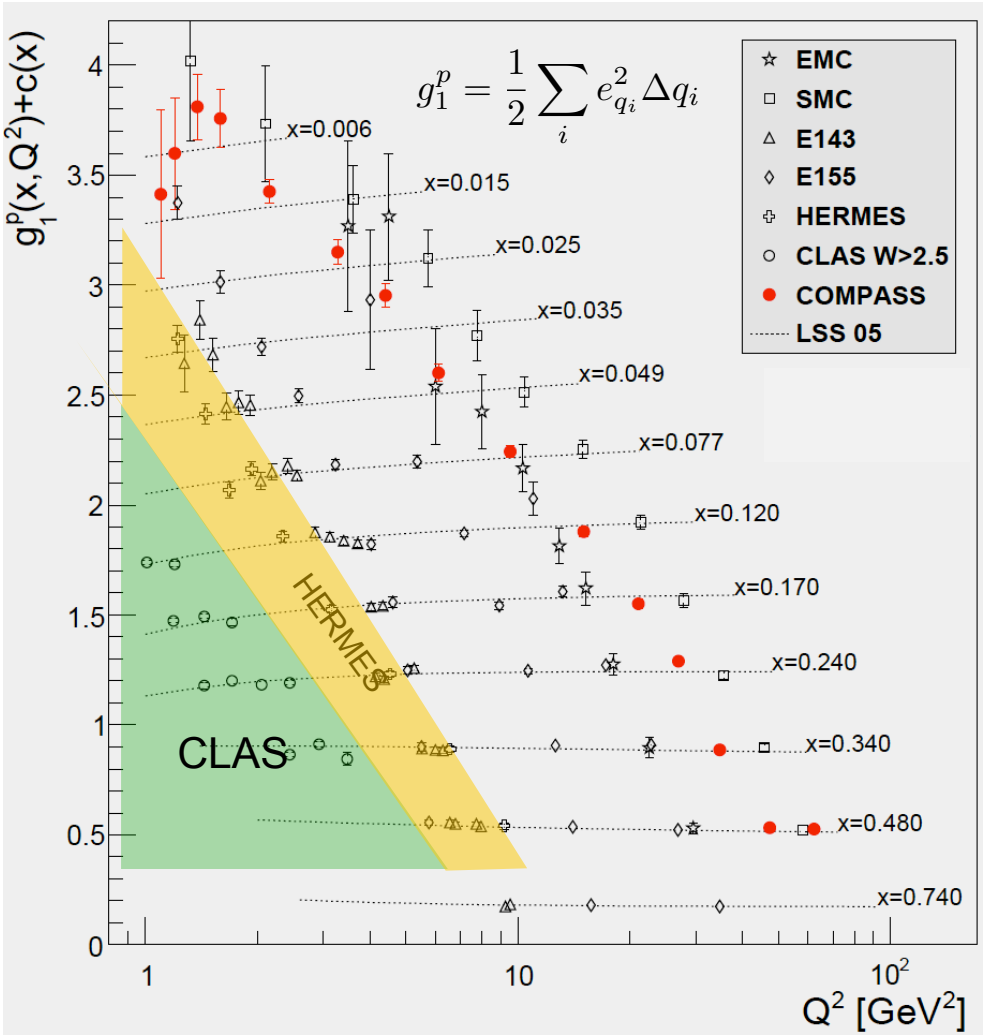
Spin contribution

Theoretical foundation

- Quark / Gluon polarization from incl. DIS data



- Spin sum rule:

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

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

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

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

- 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%):

$$\Delta\Sigma = 0.242 \ (Q^2 = 10\,\mathrm{GeV}^2) \qquad \frac{1}{2}\Delta\Sigma = 0.121$$

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

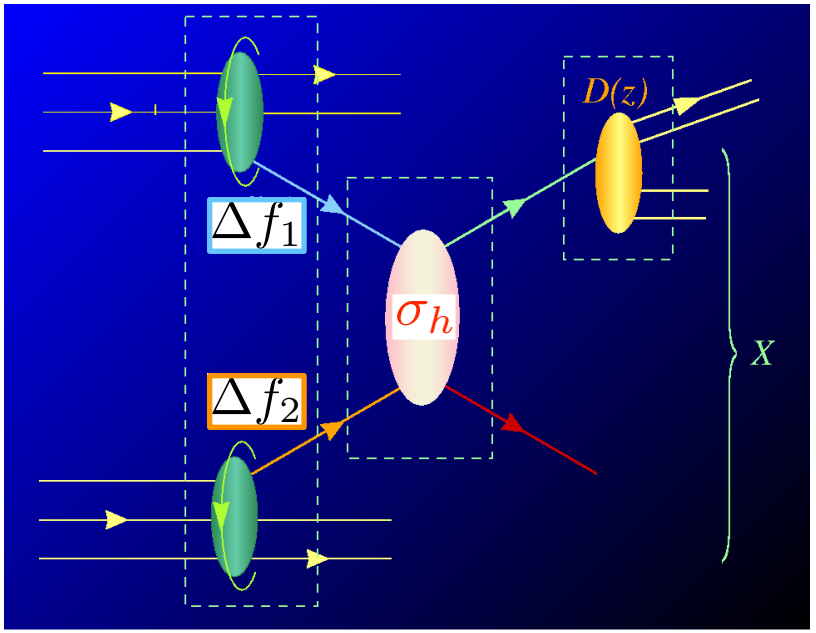
  - Δg - from scaling violations - unconstrained so far!

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

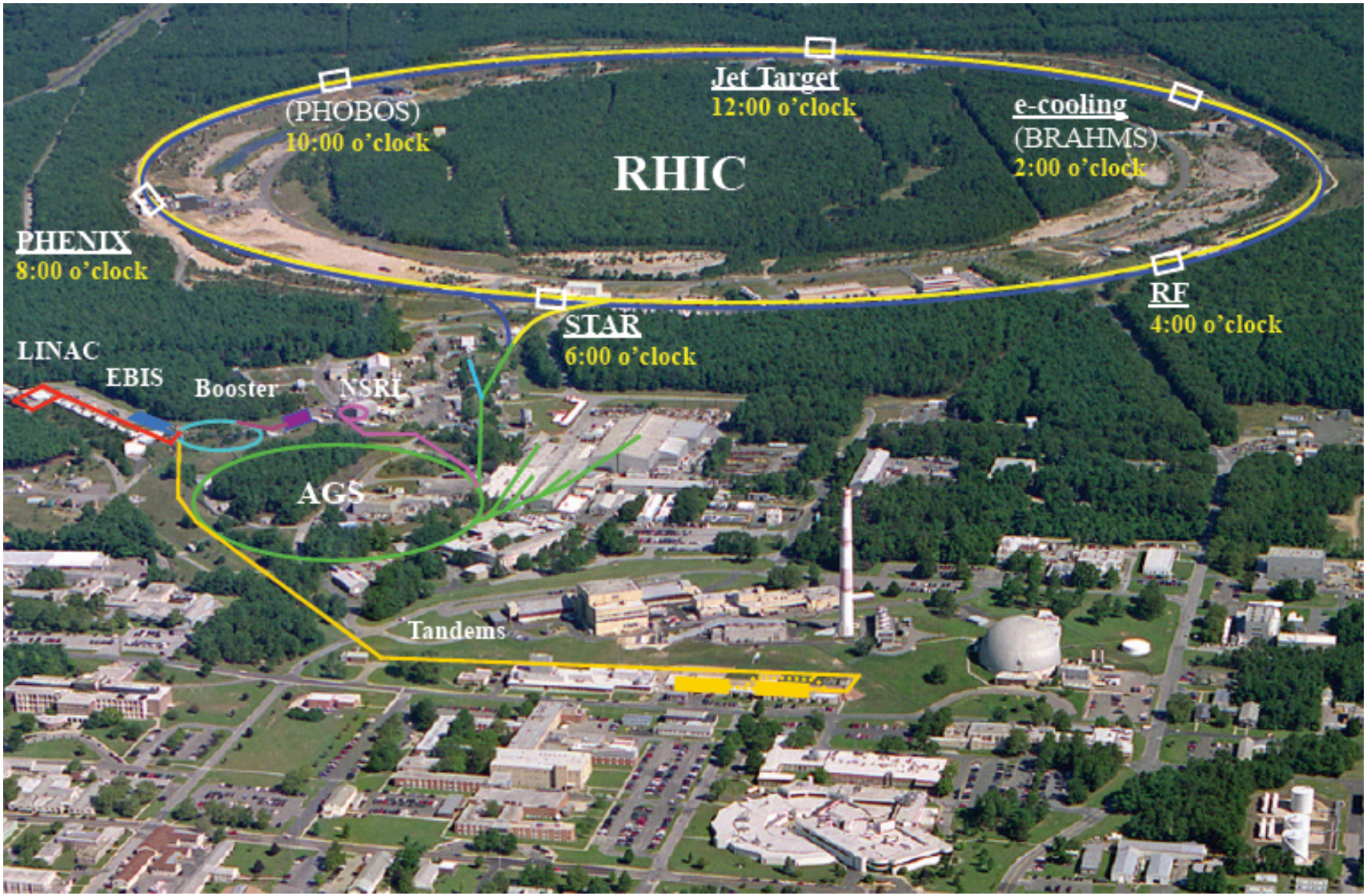
$$a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$$

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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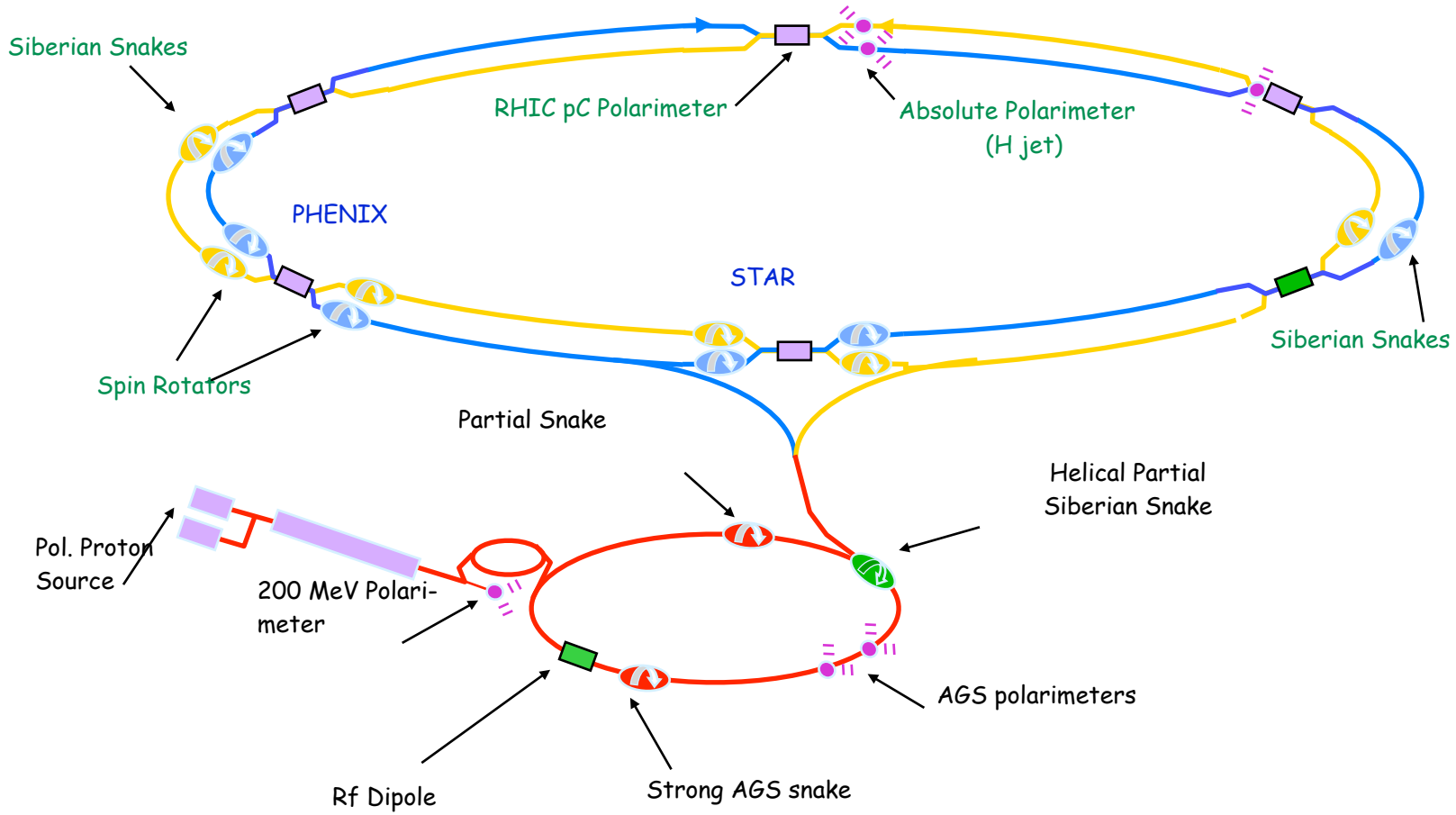

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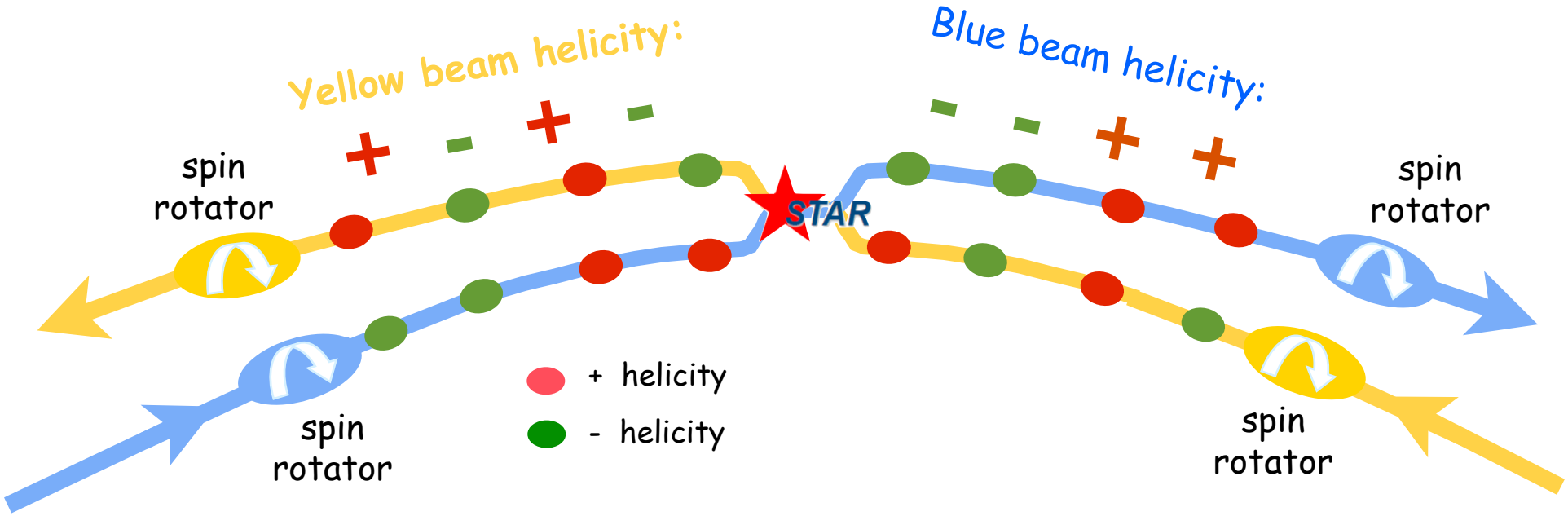
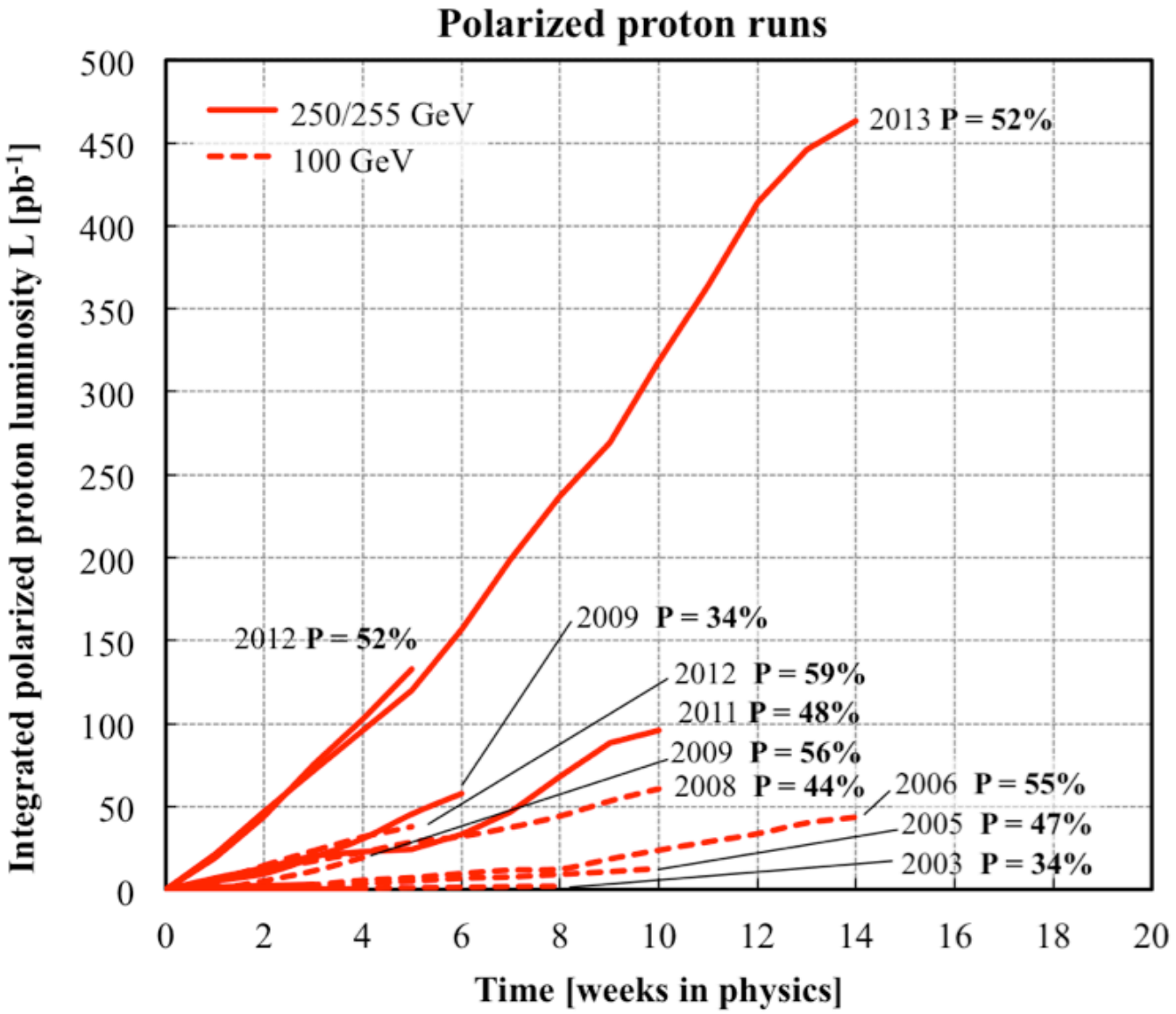


Experimental aspects - RHIC

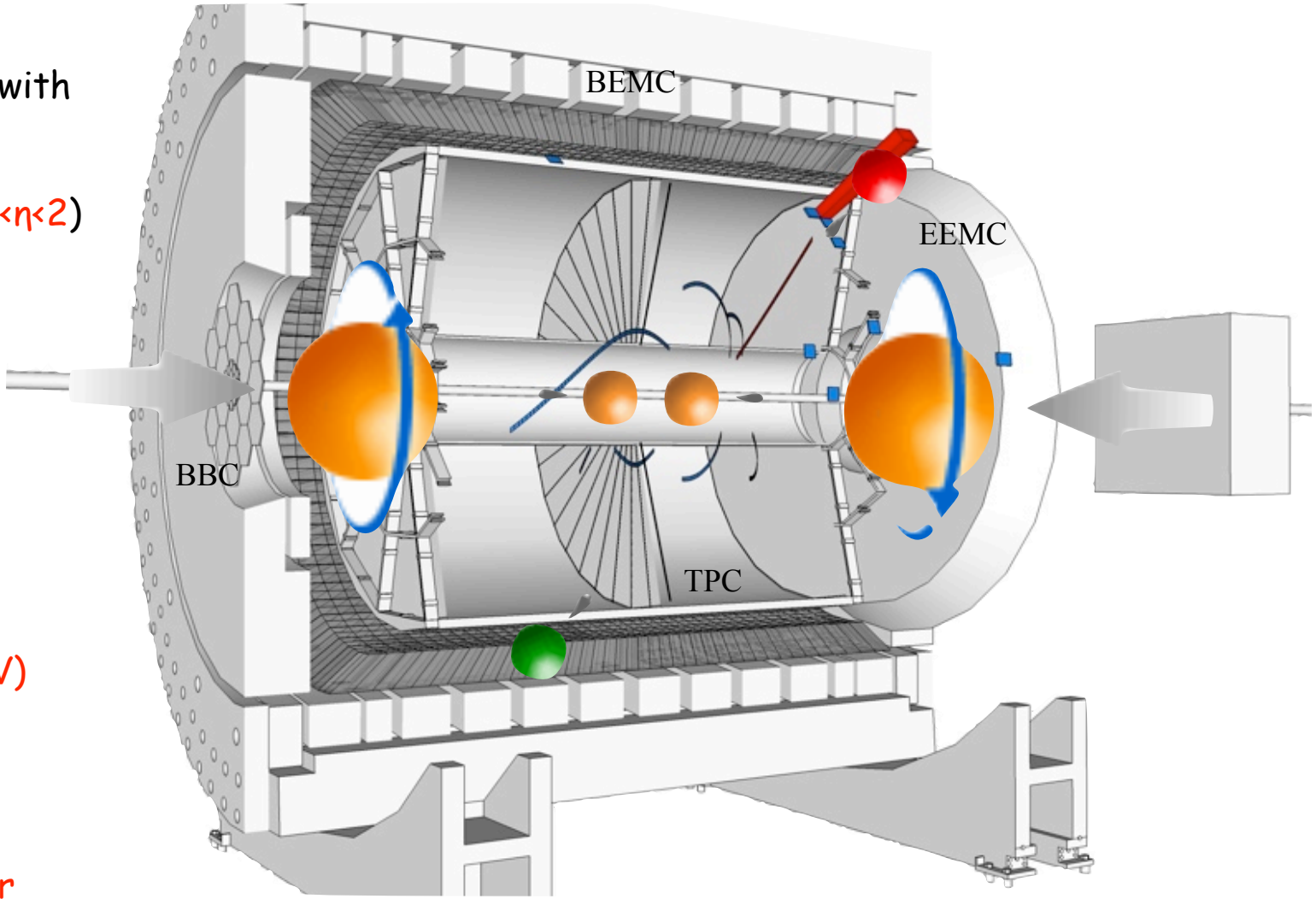
- Polarized p-p collisions
  - Long production runs at $\sqrt{s}$=200GeV (long. polarization) in 2009: Jet and Hadron production (Gluon polarization)
  - Collisions of polarized proton beams at $\sqrt{s}$=500GeV (long. polarization) in 2009, 2012 and 2013: W production (Quark polarization)



Experimental aspects - STAR

Overview

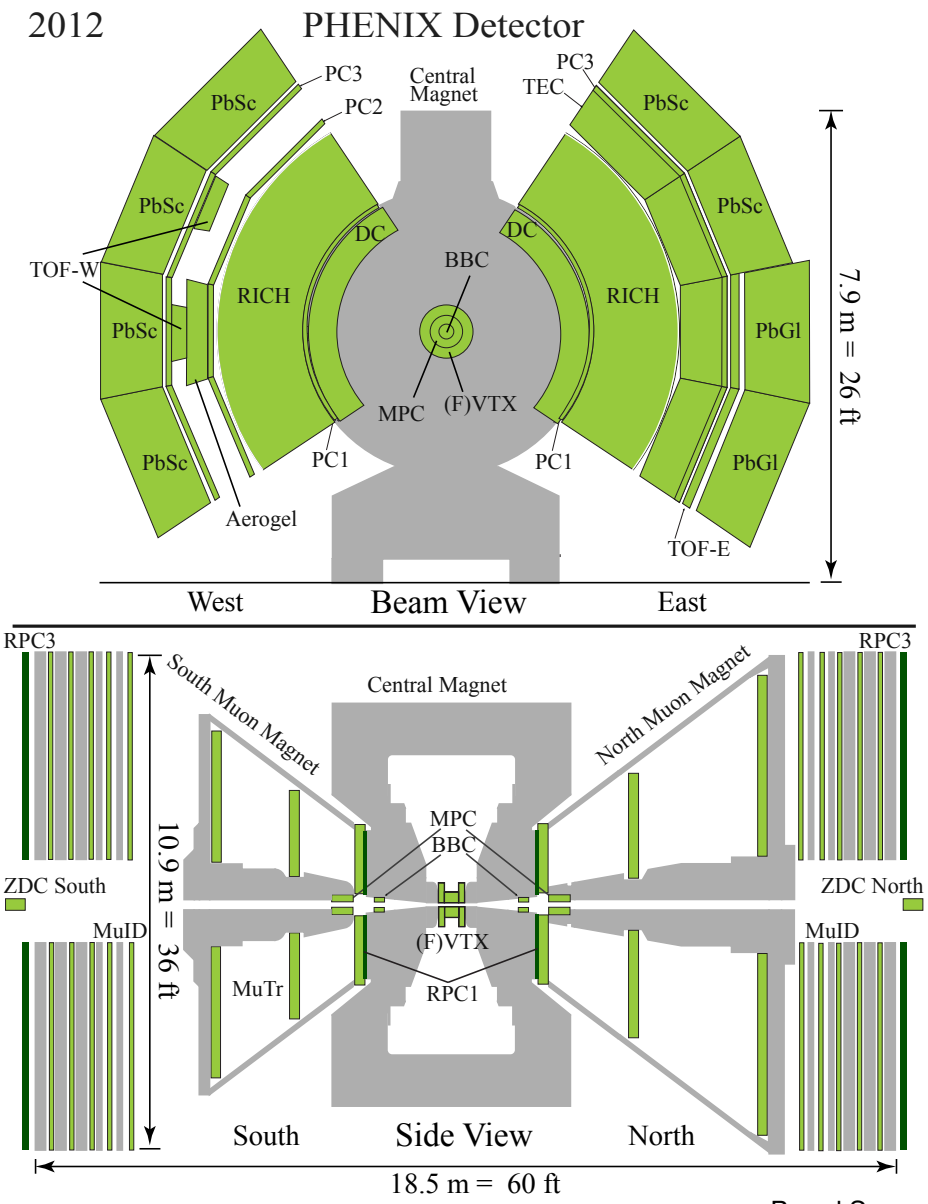
- Calorimetry system with 2π coverage: BEMC (-1<η<1) and EEMC (1<η<2)
- TPC: Tracking and particle ID
- ZDC: Relative luminosity and local polarimetry (500GeV)
- BBC: Relative luminosity and Minimum bias trigger



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

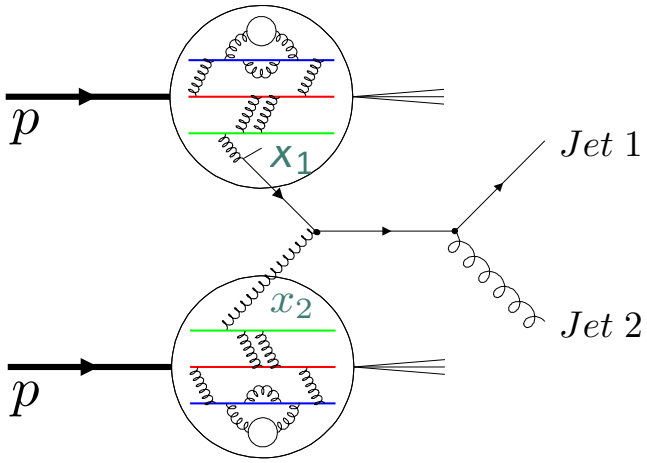
Experimental aspects - PHENIX

- 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)

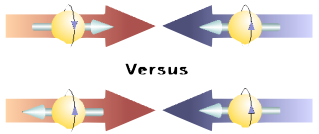


Experimental aspects - Asymmetry measurement

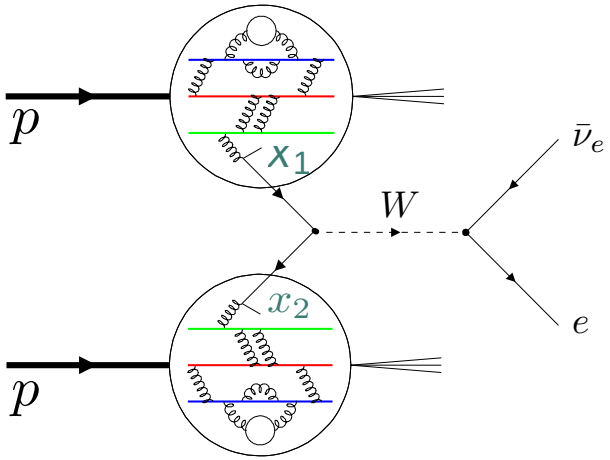
- Double and single longitudinal spin asymmetry measurements



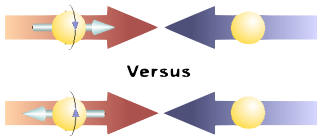
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$



- 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

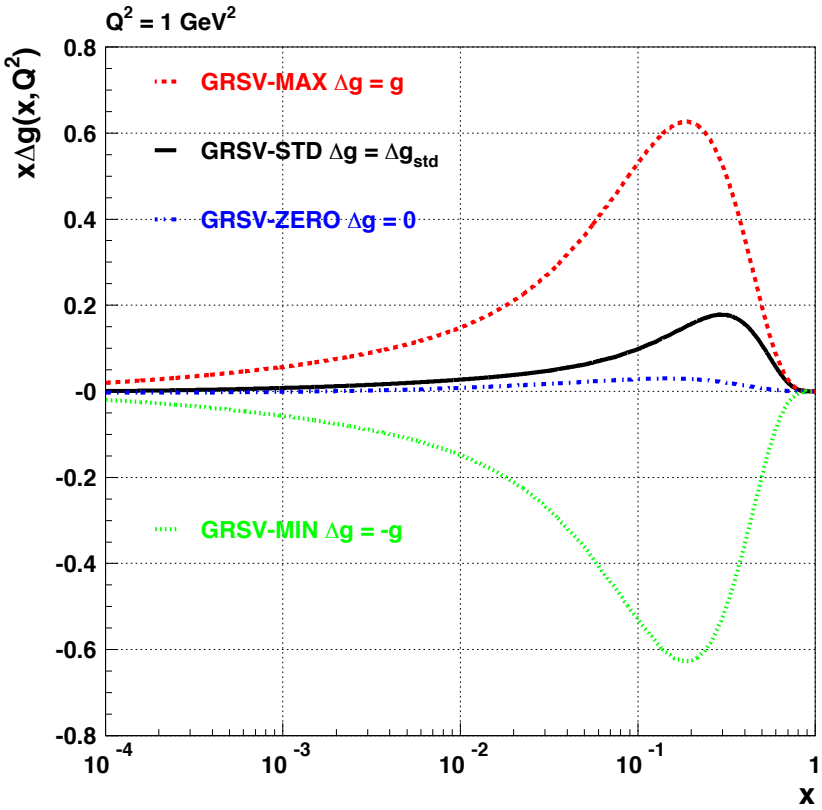


$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P} \frac{N_+ - R N_-}{N_+ + R N_-}$$



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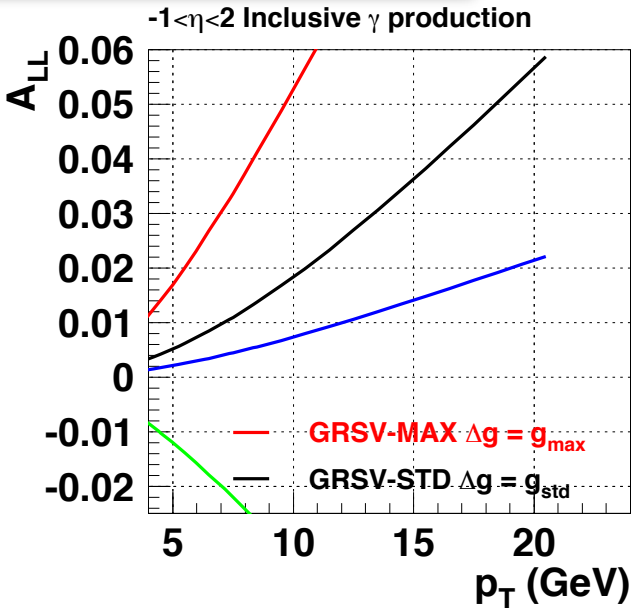
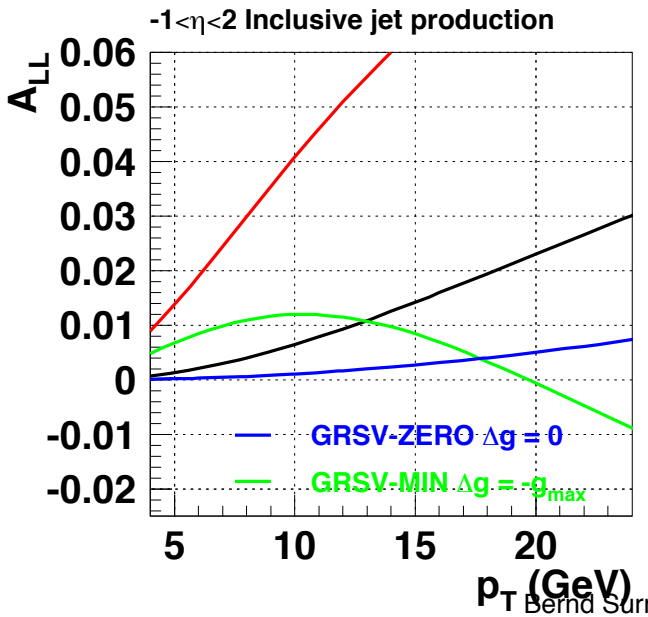
$\Delta G(Q^2 = 1GeV^2) \approx -1.8$

- 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.

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





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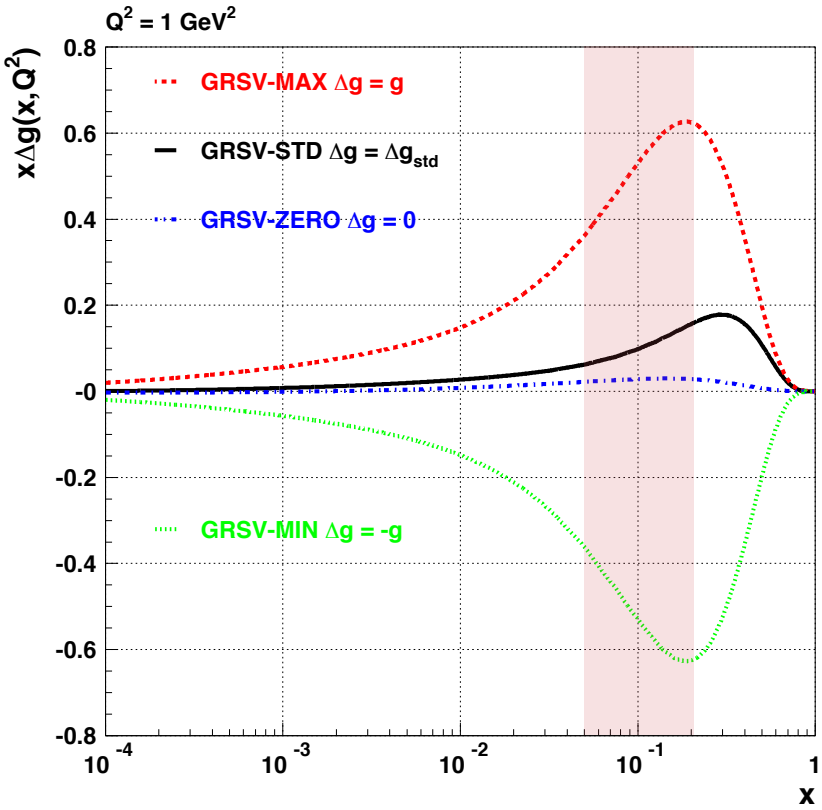

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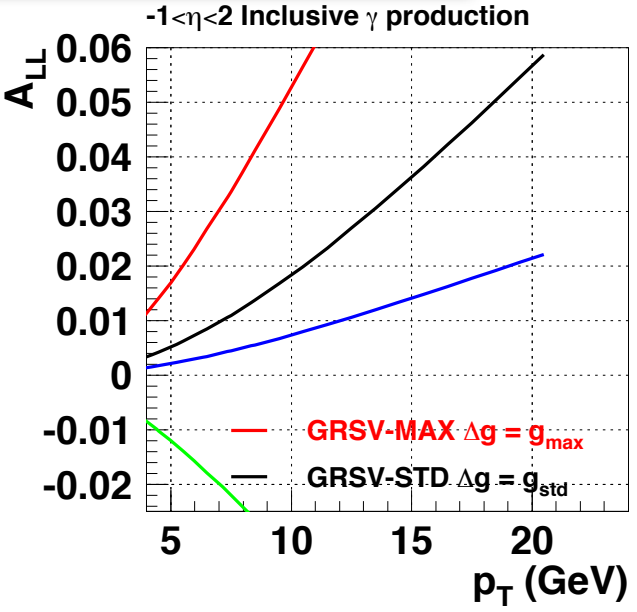

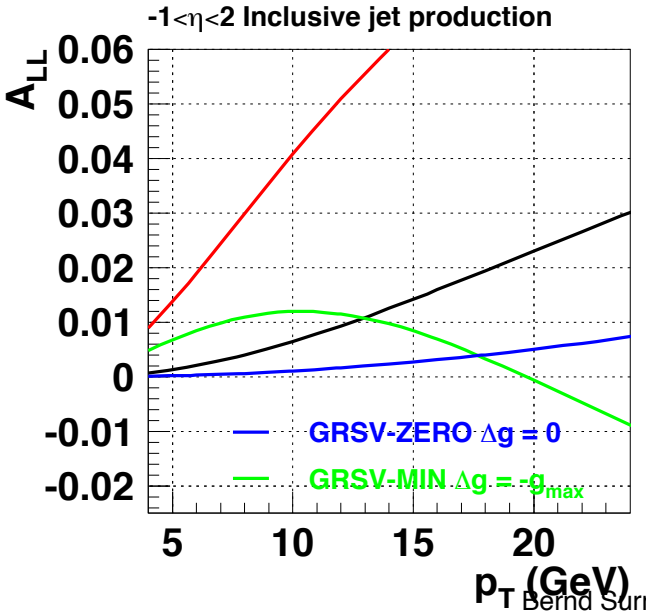

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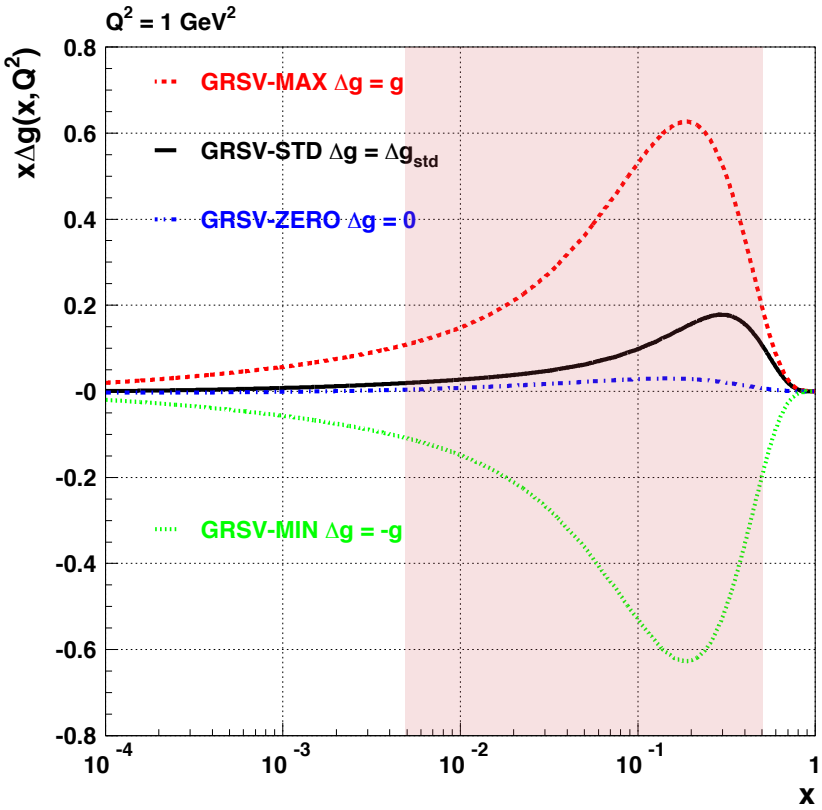

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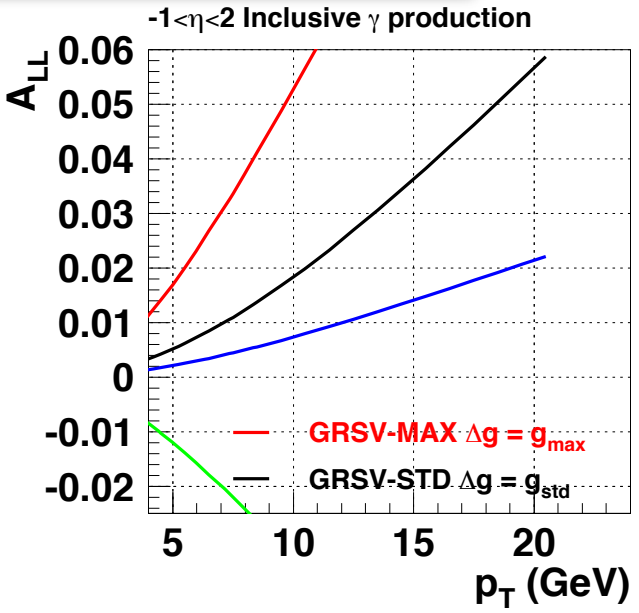
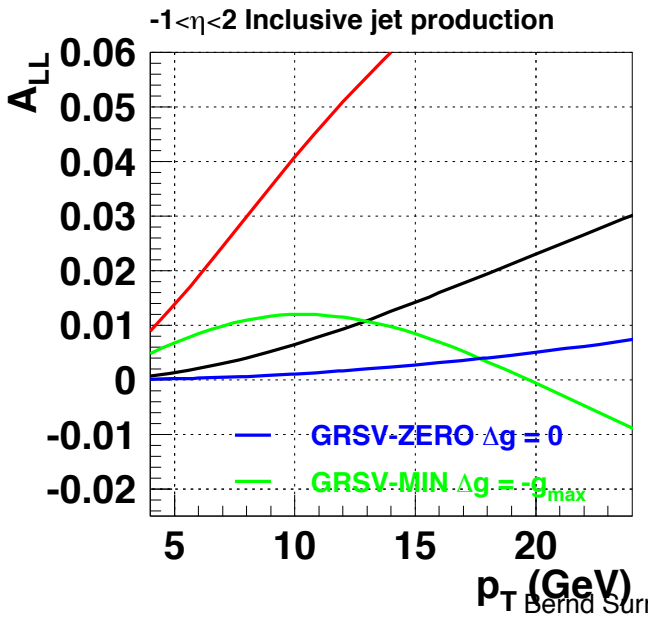
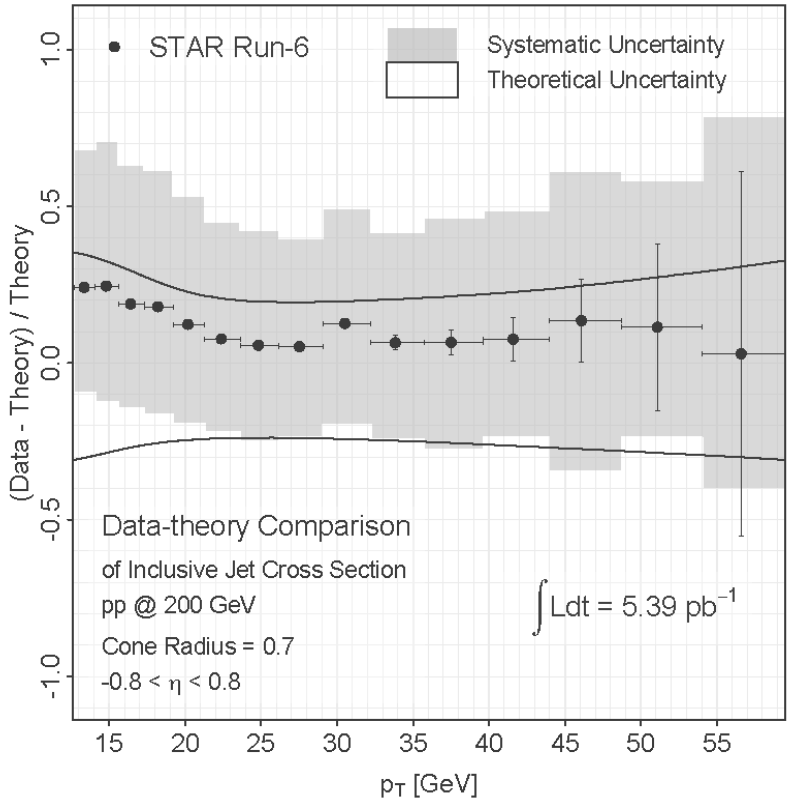
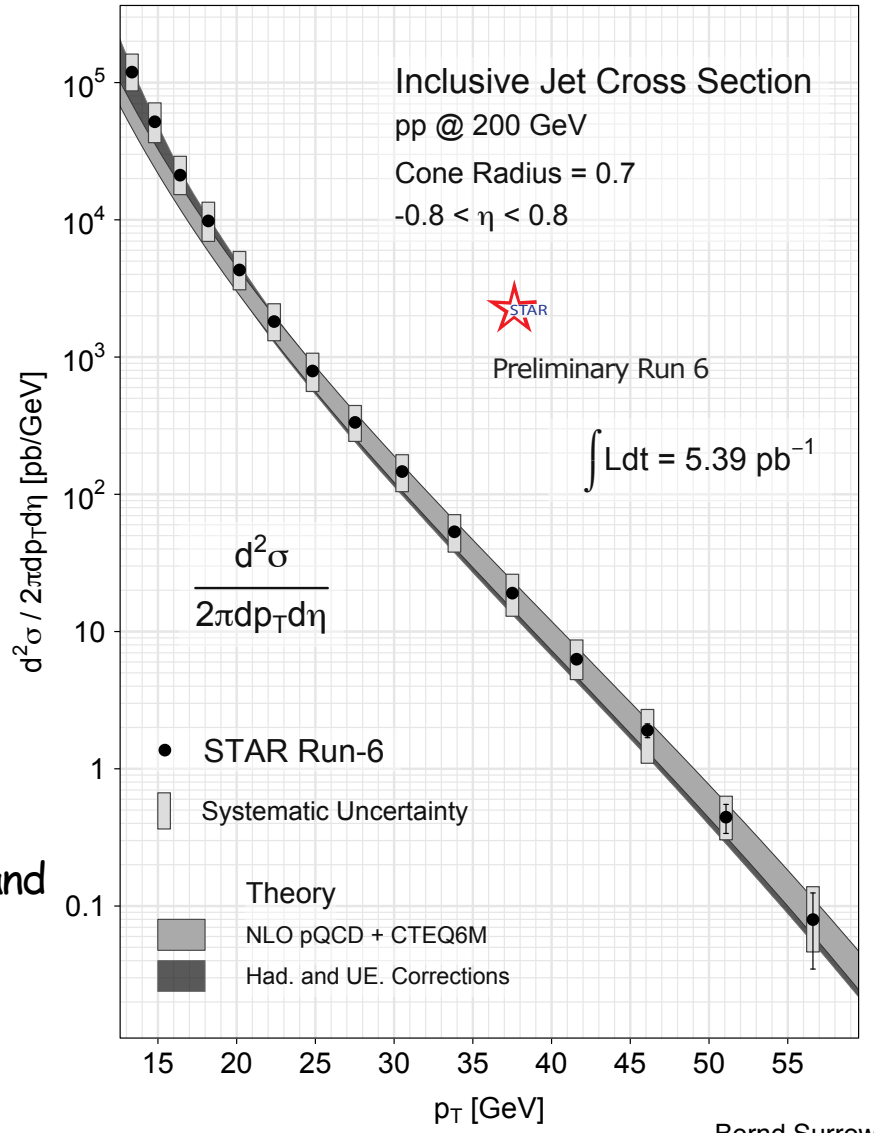




Recent results - Gluon polarization program

- 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 (Run 9)

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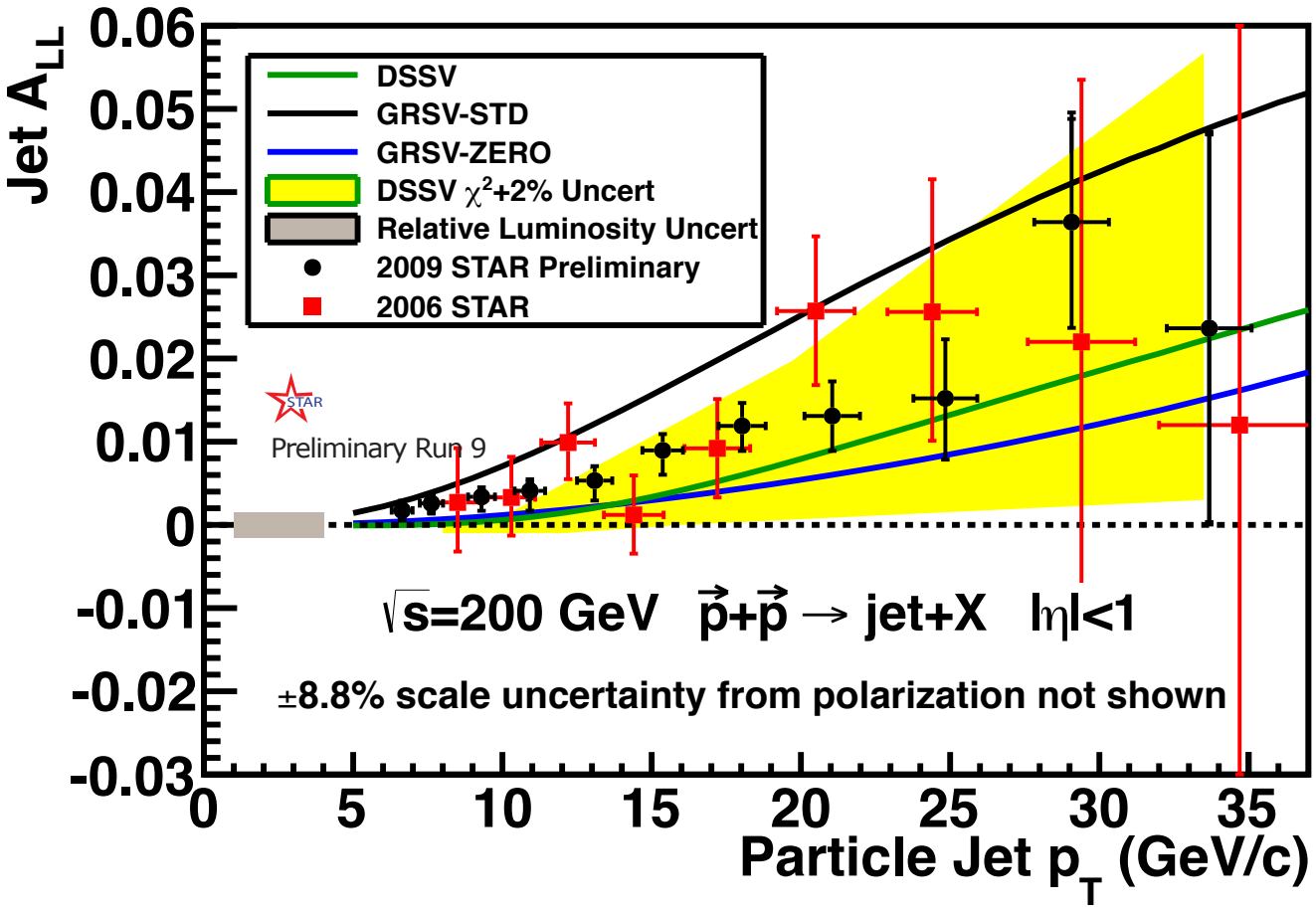

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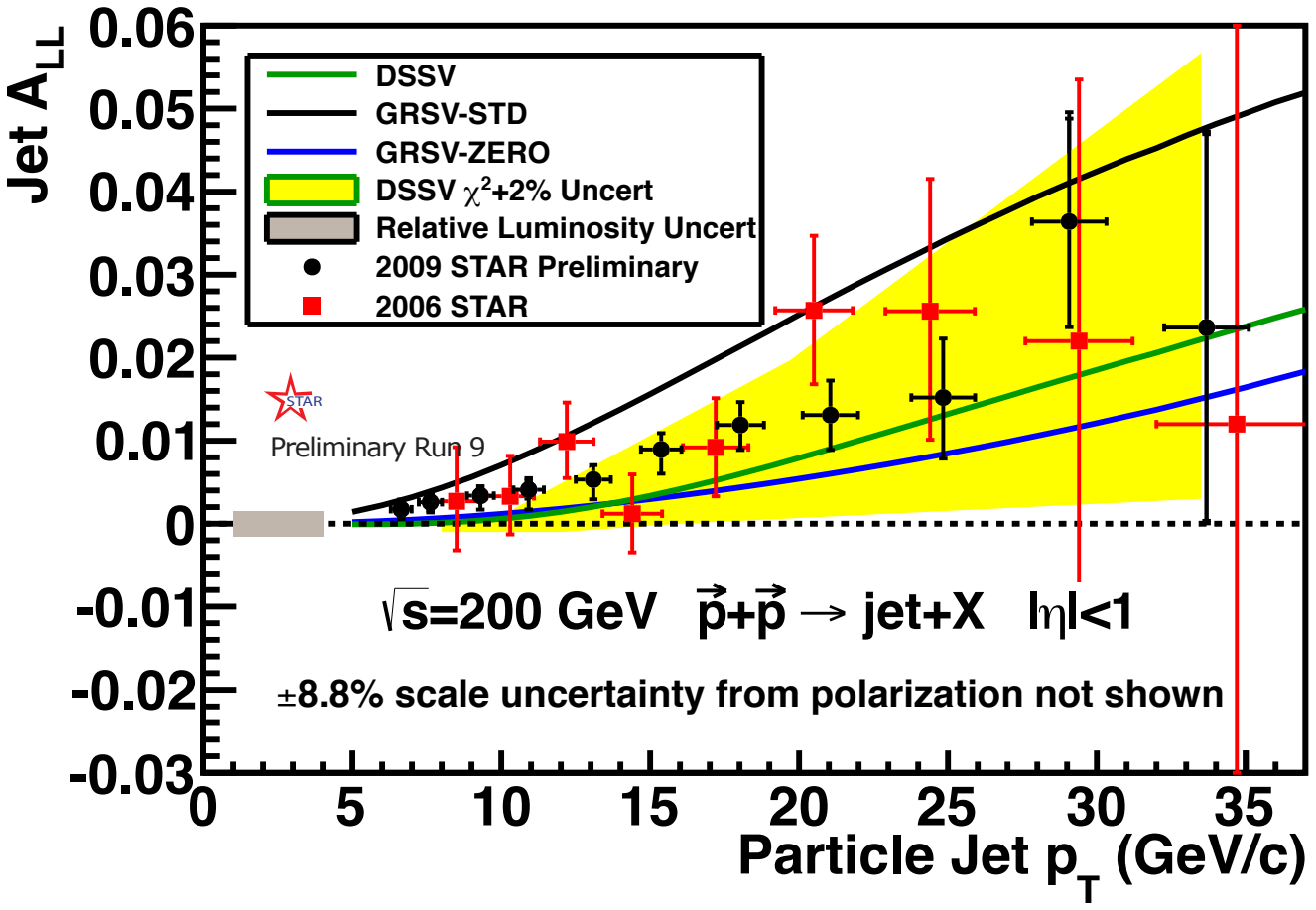

- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO

Recent results - Gluon polarization program

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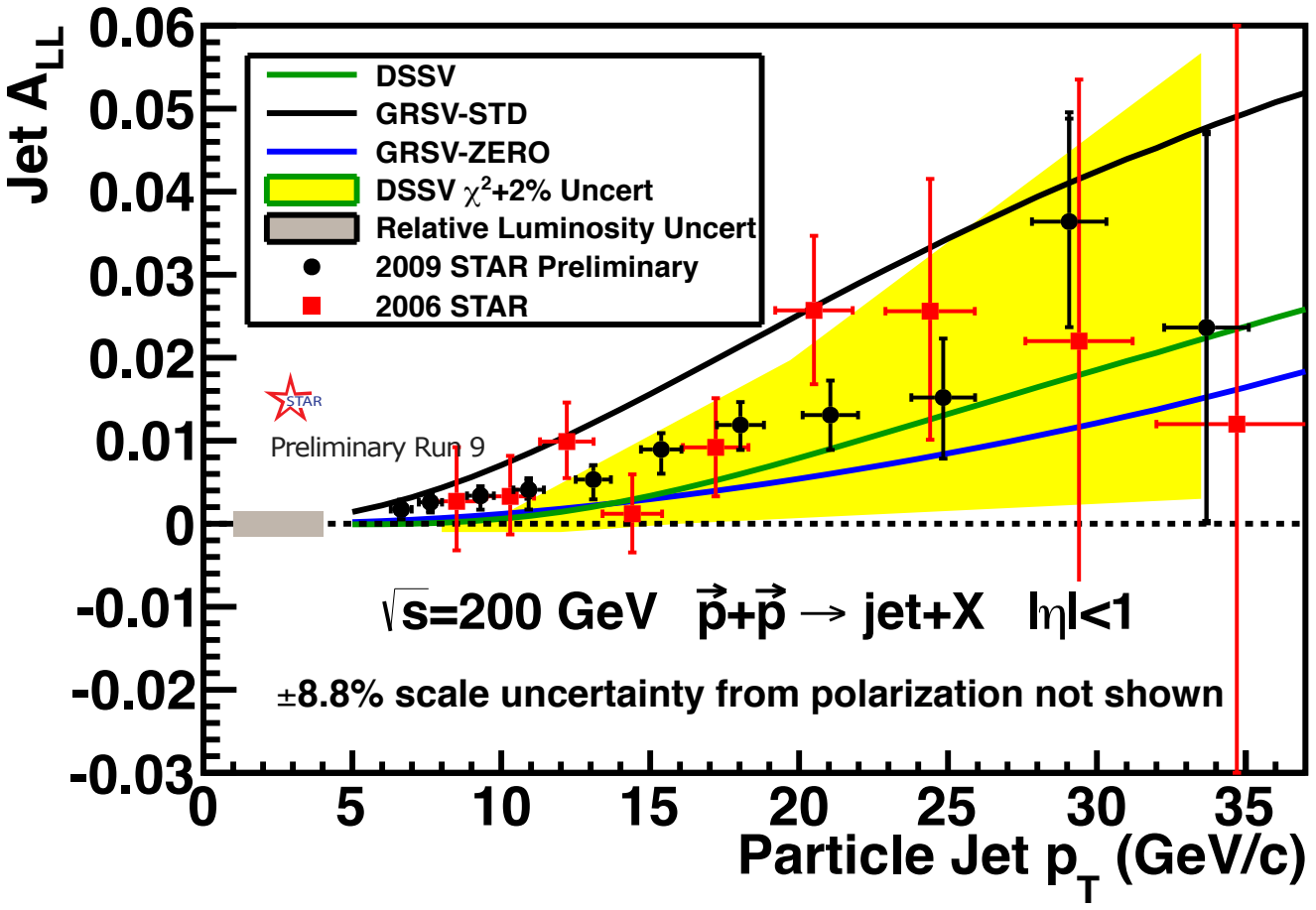

- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO
- Run 9 A_{LL} measurement between GRSV-STD and DSSV / Clearly above at low p_T

Recent results - Gluon polarization program

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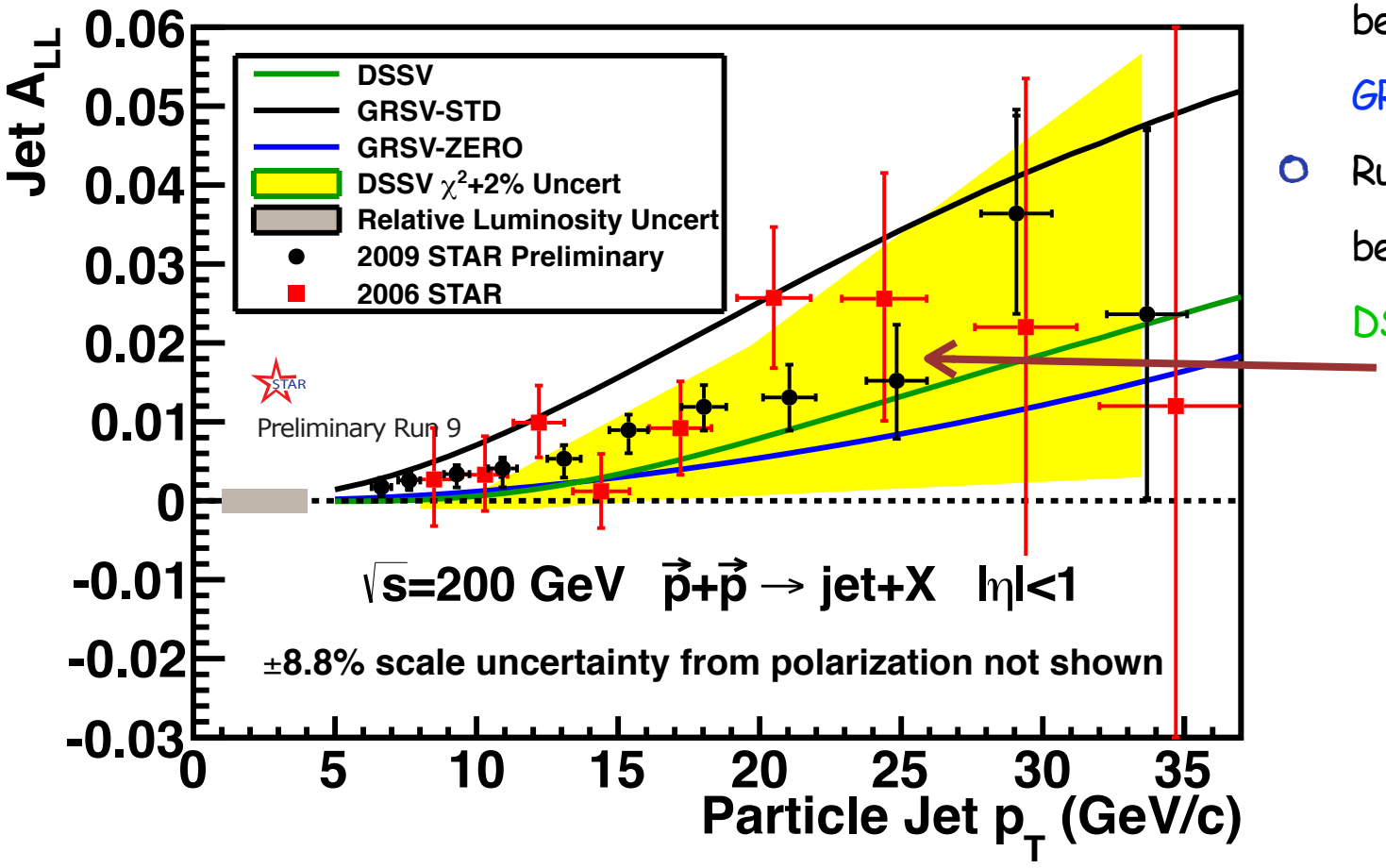

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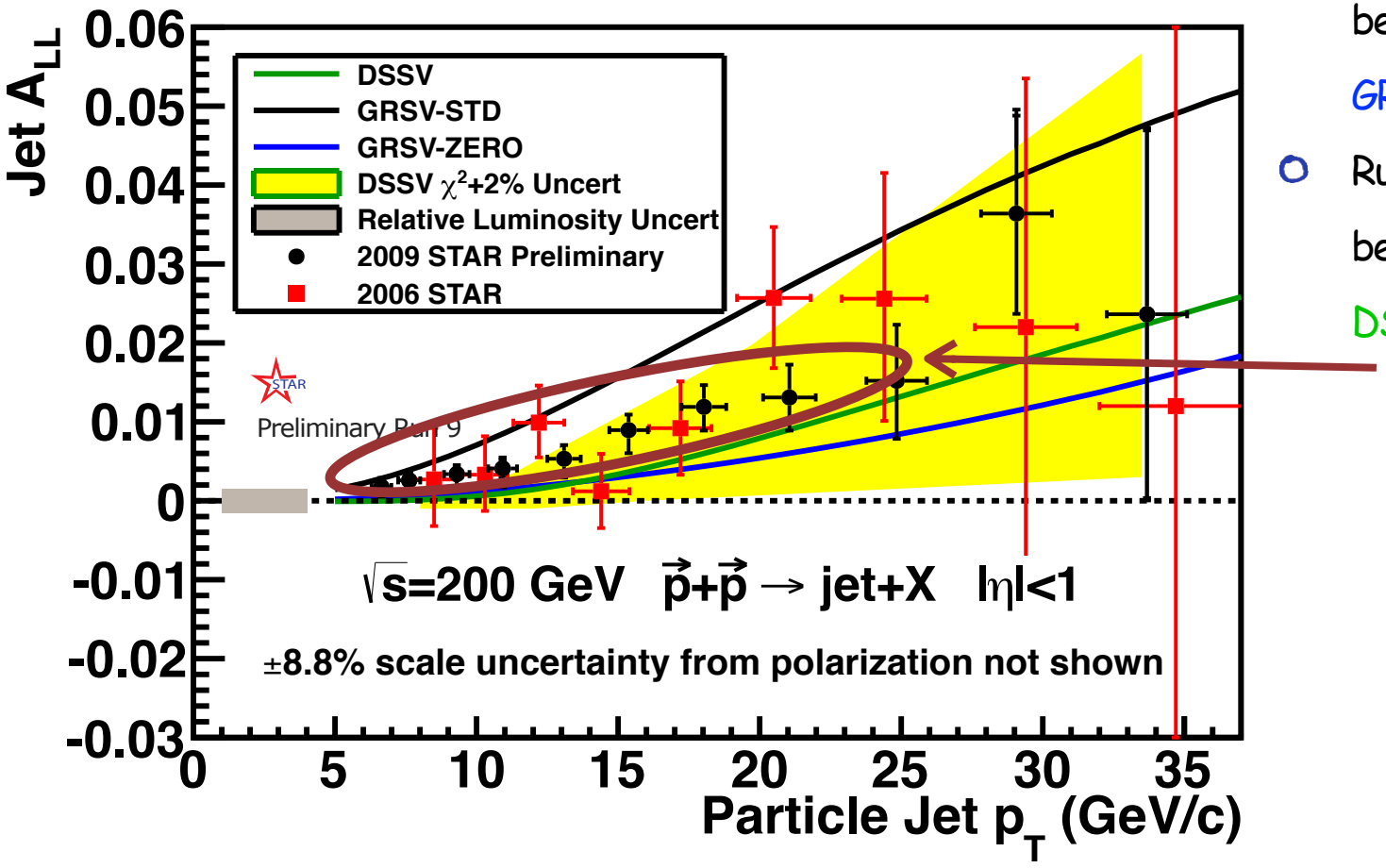

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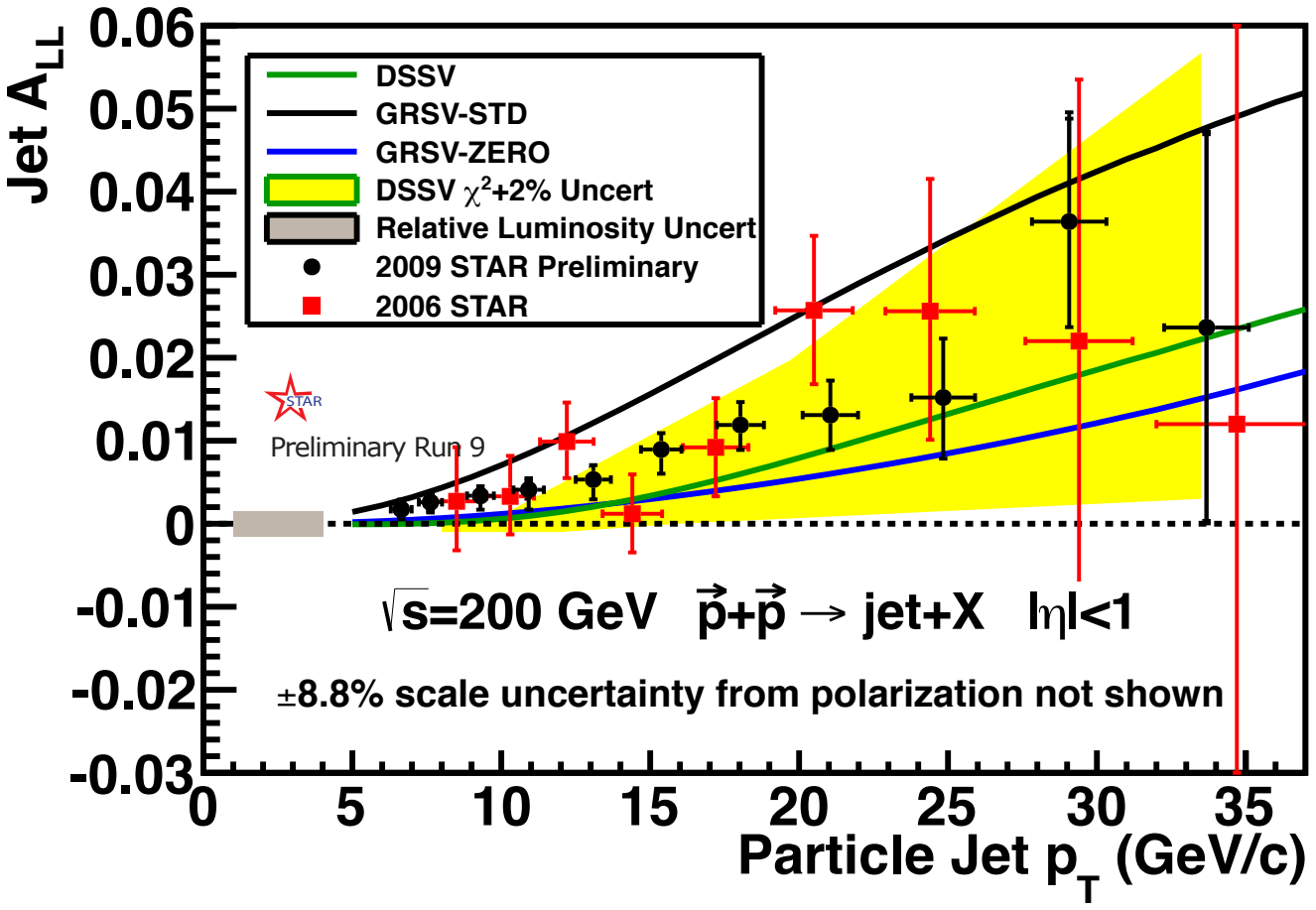

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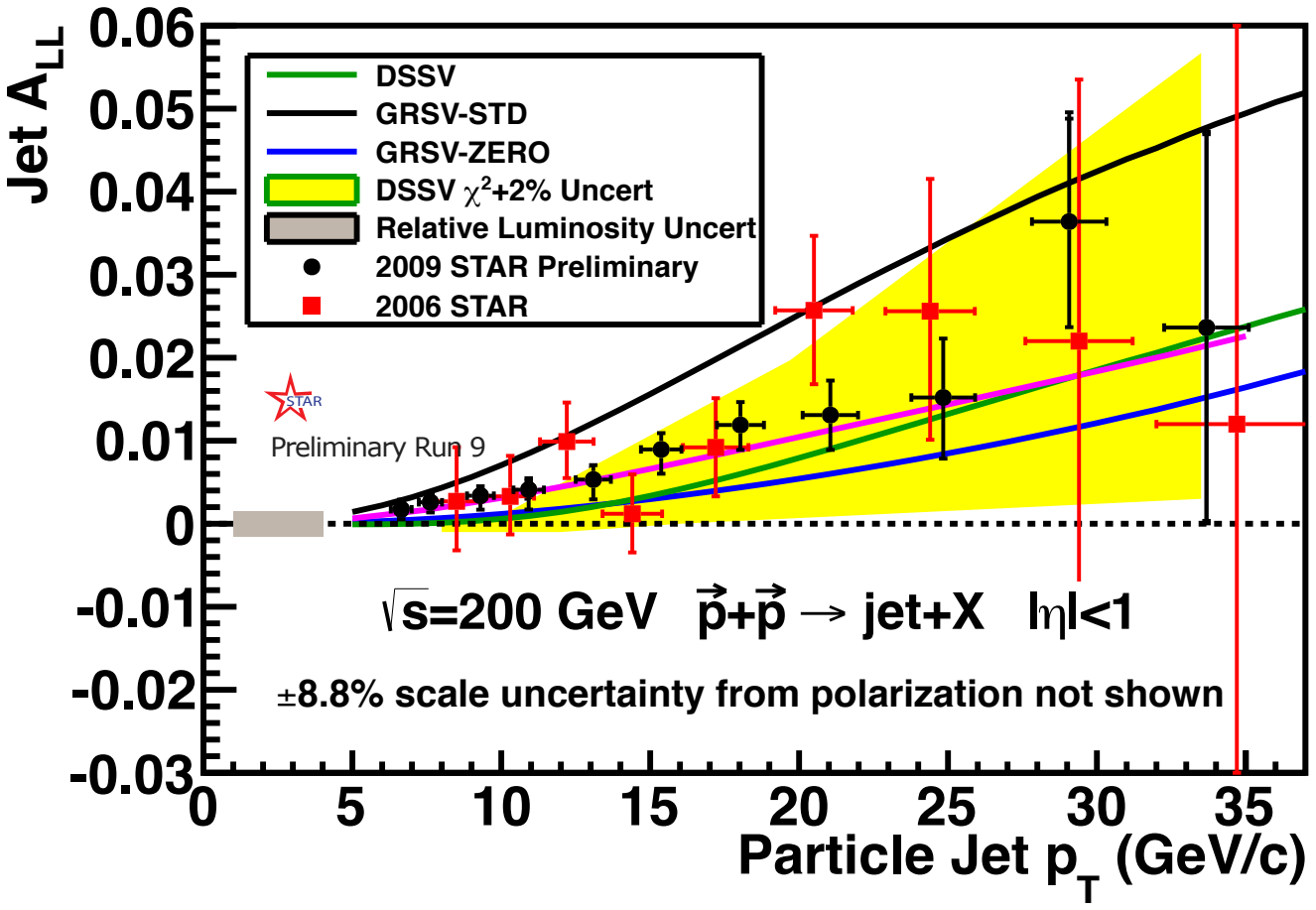

- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO
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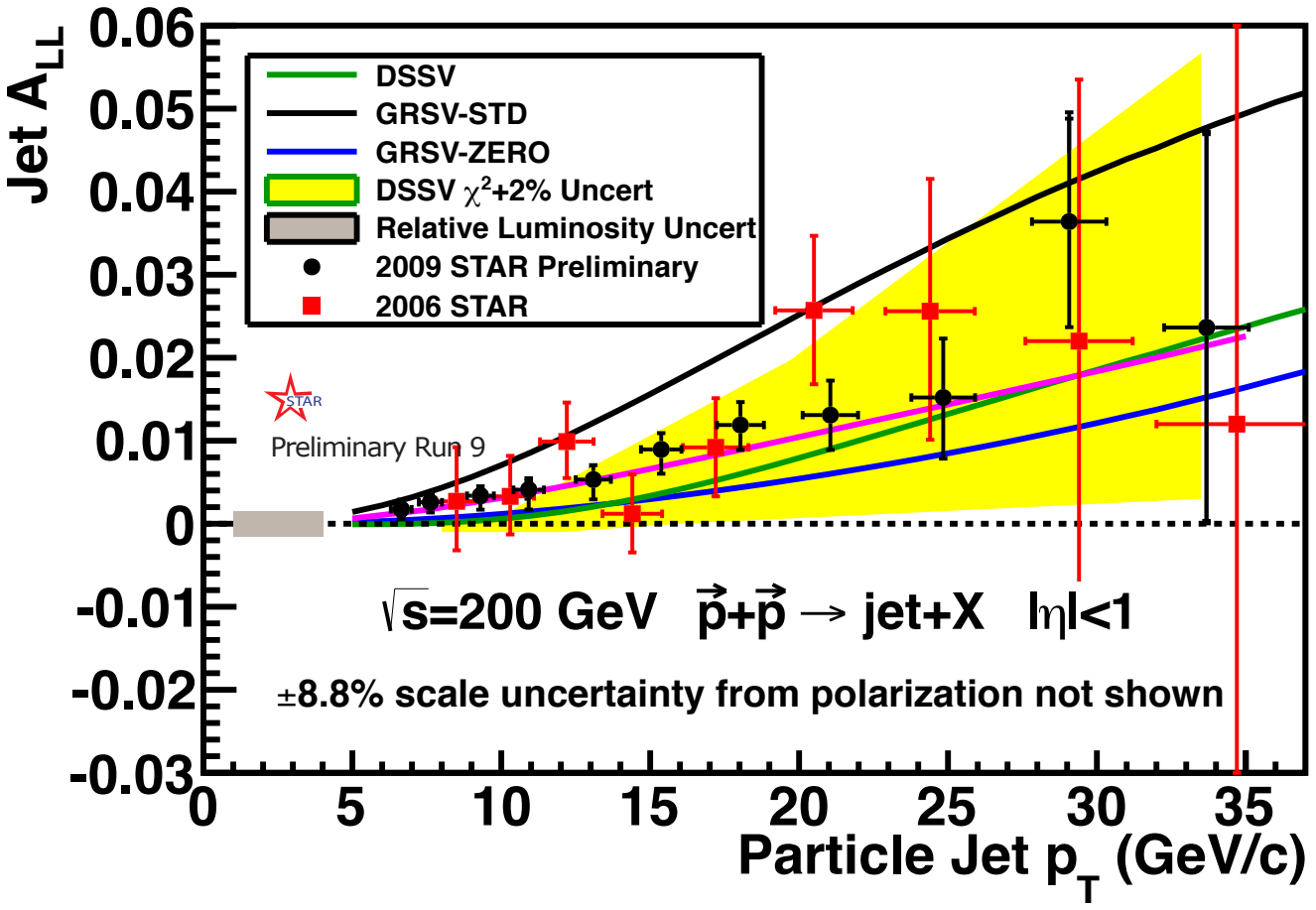
Recent results - Gluon polarization program

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



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Recent results - Gluon polarization program

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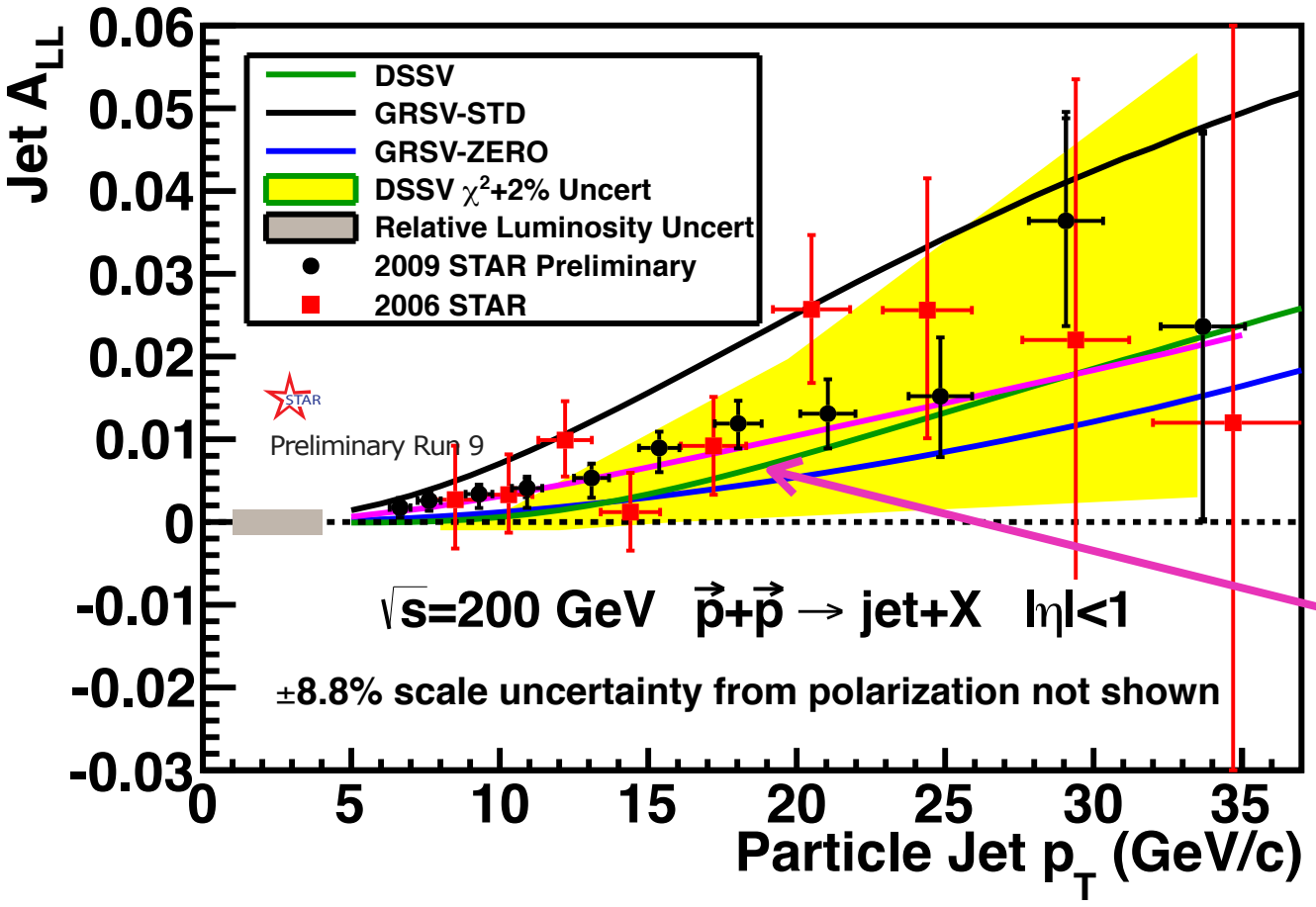

- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO
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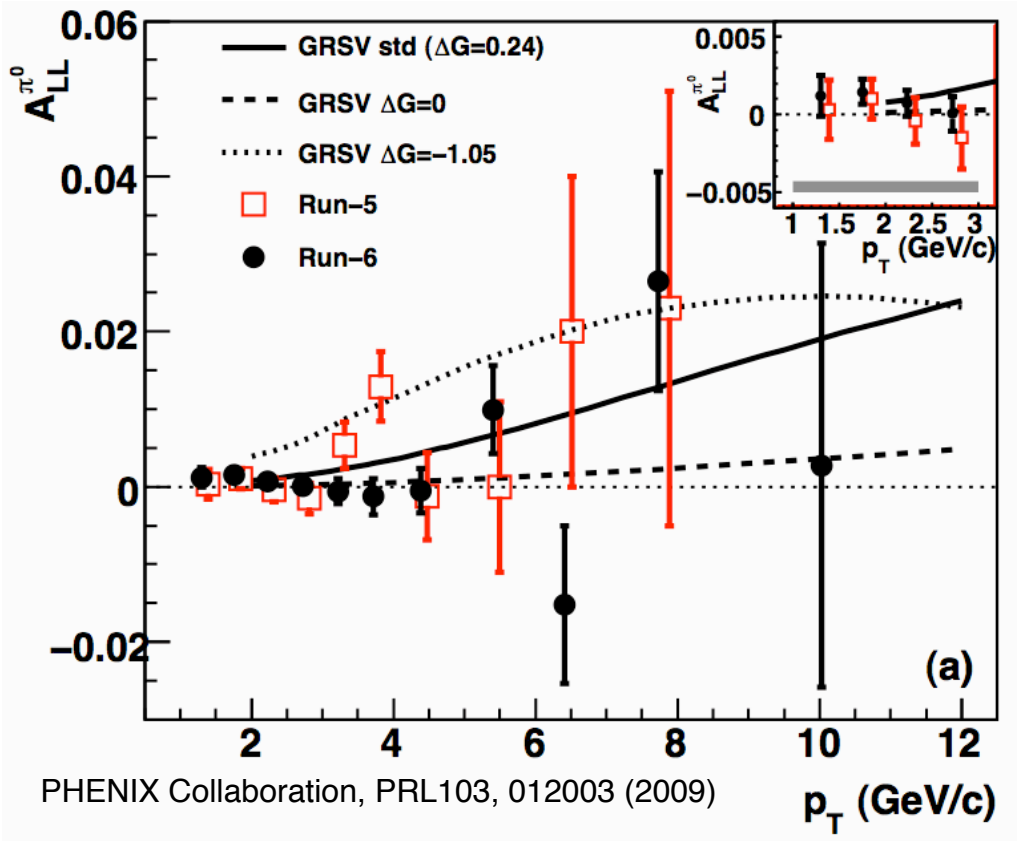
$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\mathrm{GeV}^2) dx = 0.13$$

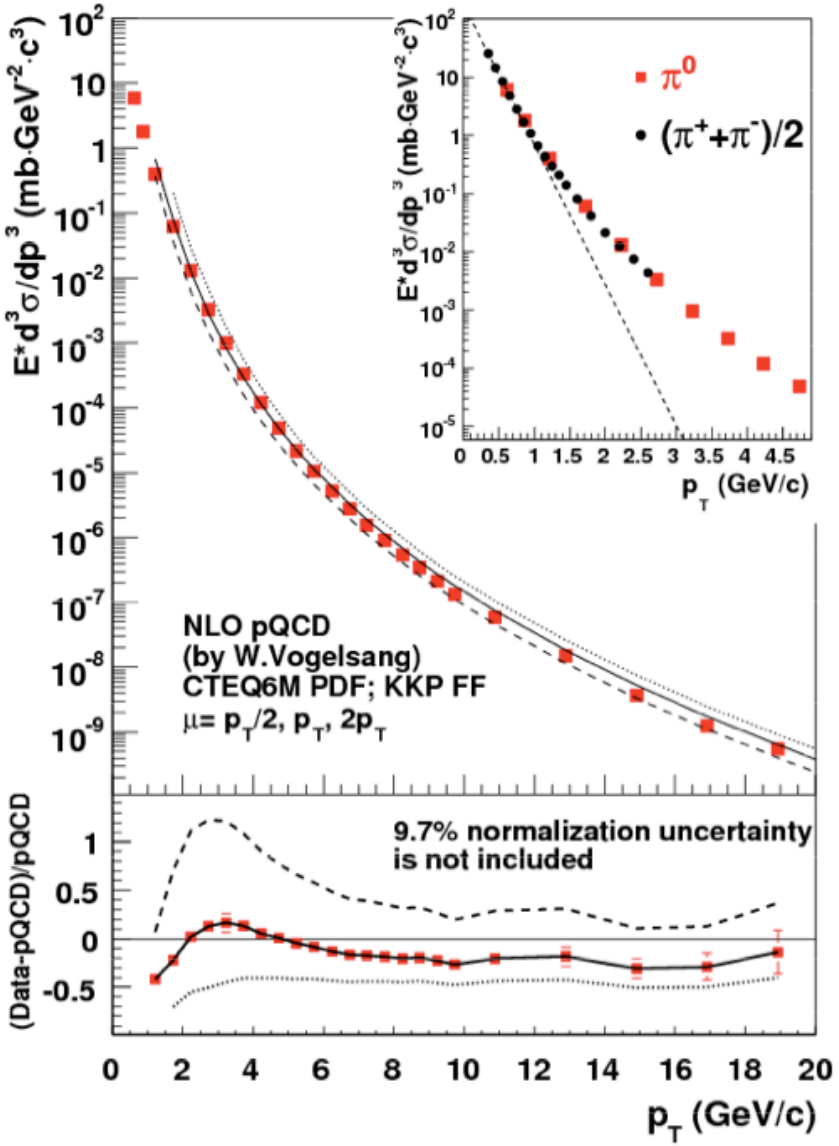
(D. deFlorian et al.,
Prog. Nucl. Part. Phys. 67, 251 (2012))

Recent results - Gluon polarization program

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



PHENIX Collaboration, PRL103, 012003 (2009)



- Data are well described by NLO pQCD calculations
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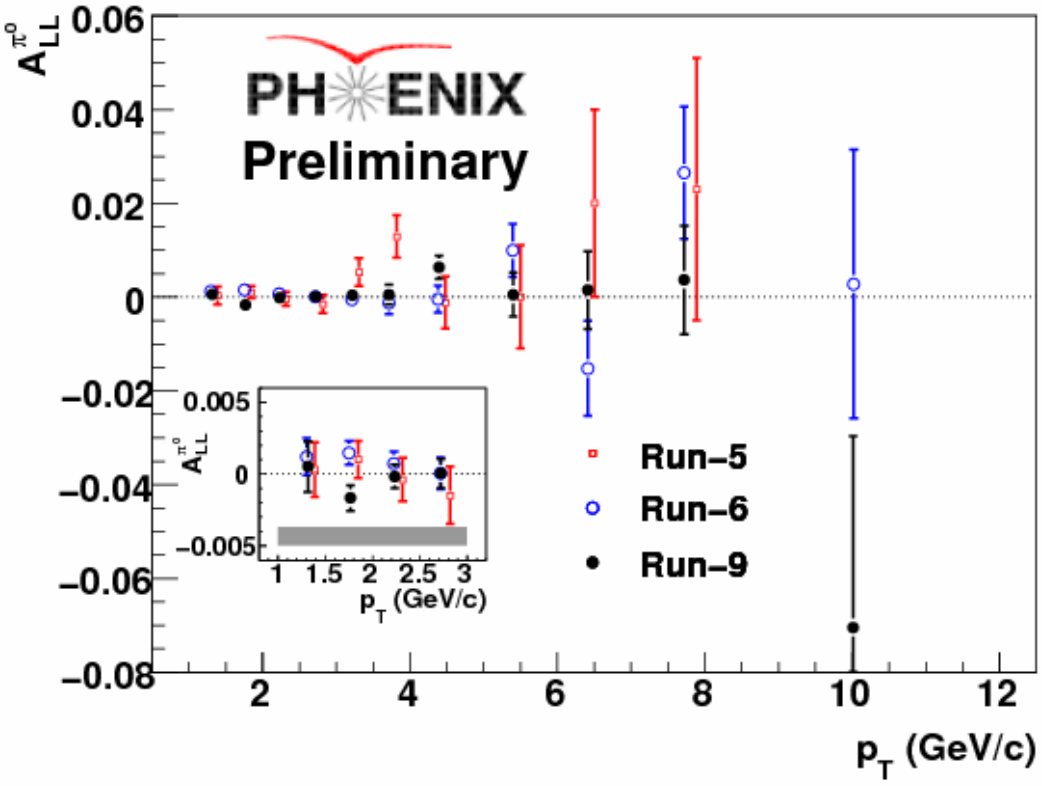
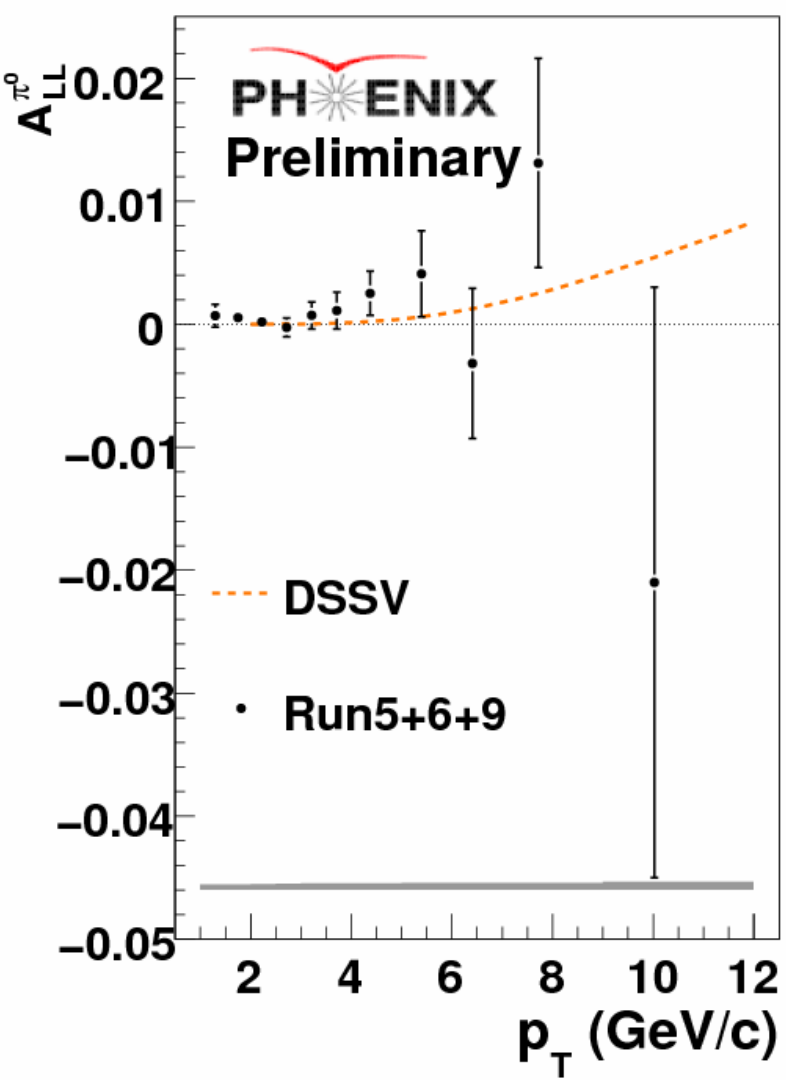
Recent results - Gluon polarization program

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





- Data are well described by NLO pQCD calculations
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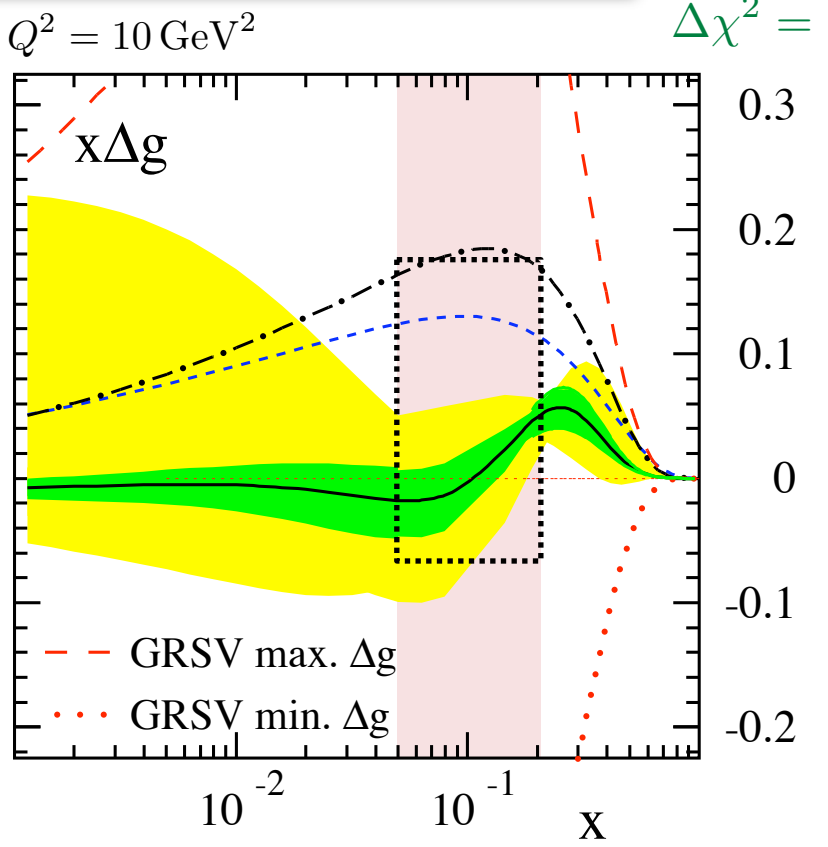
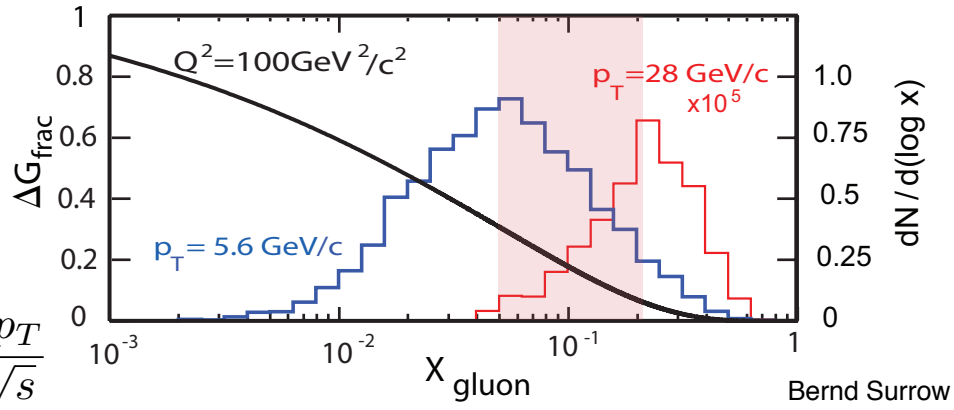
Recent results - Gluon polarization program

- Impact on Δg from RHIC data

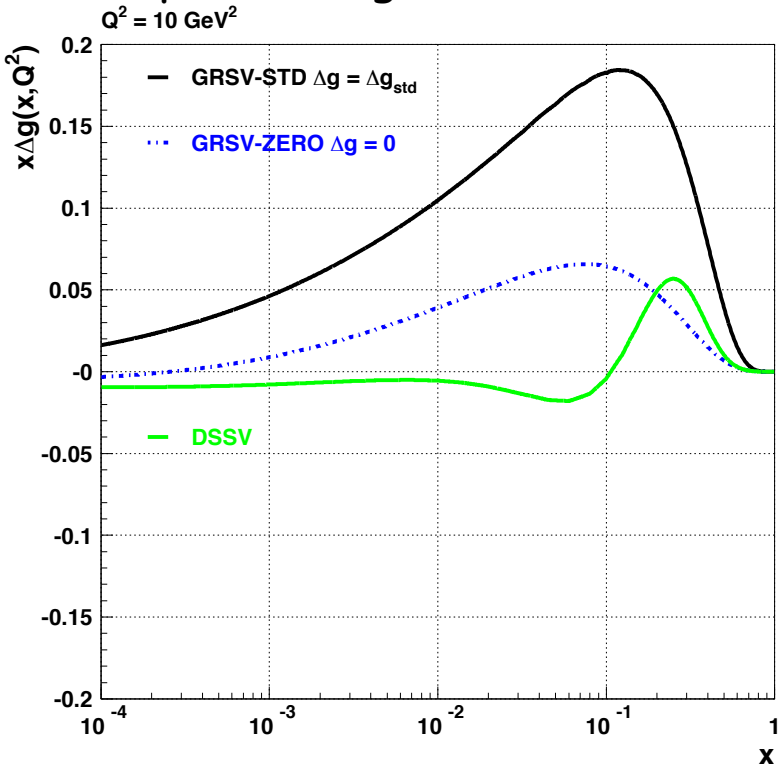


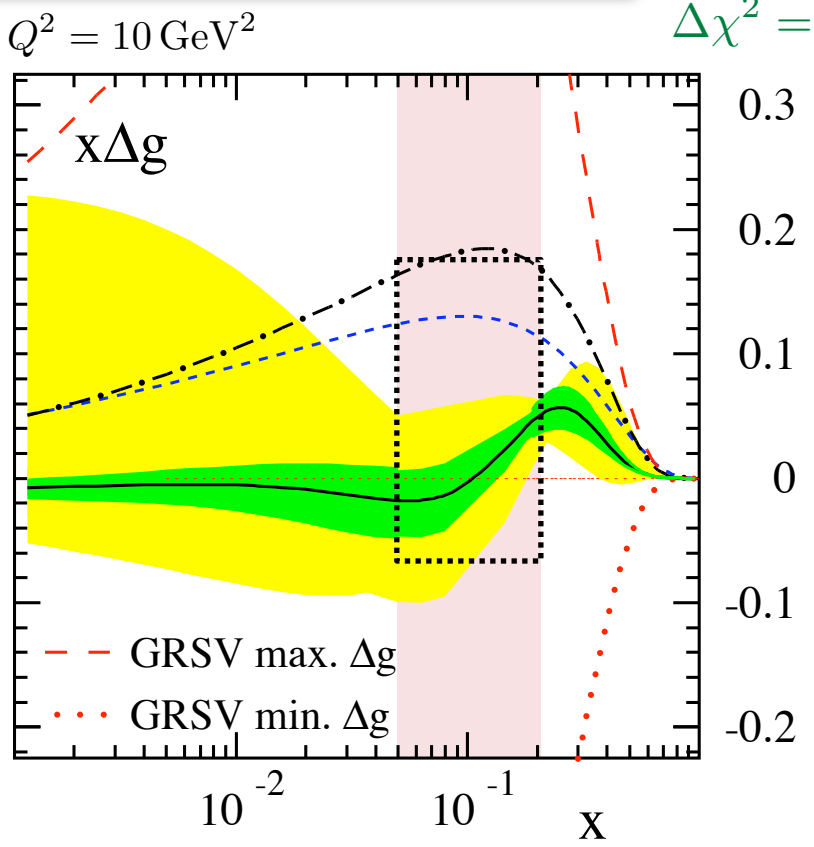


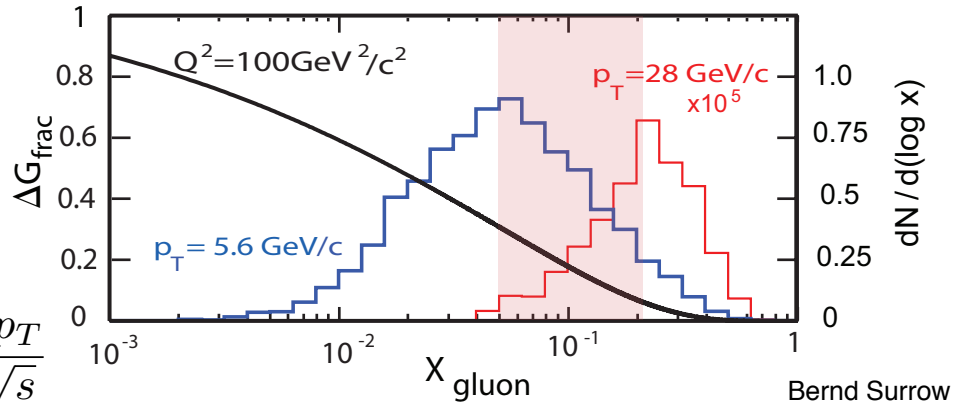
$$x \sim \frac{2p_T}{\sqrt{s}}$$

Recent results - Gluon polarization program

Impact on Δg from RHIC data







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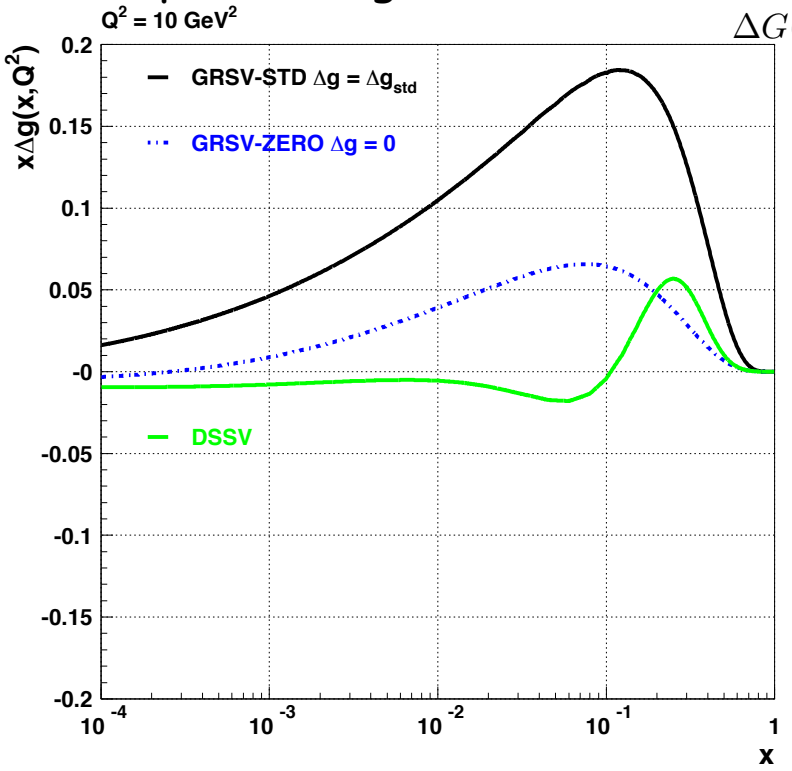
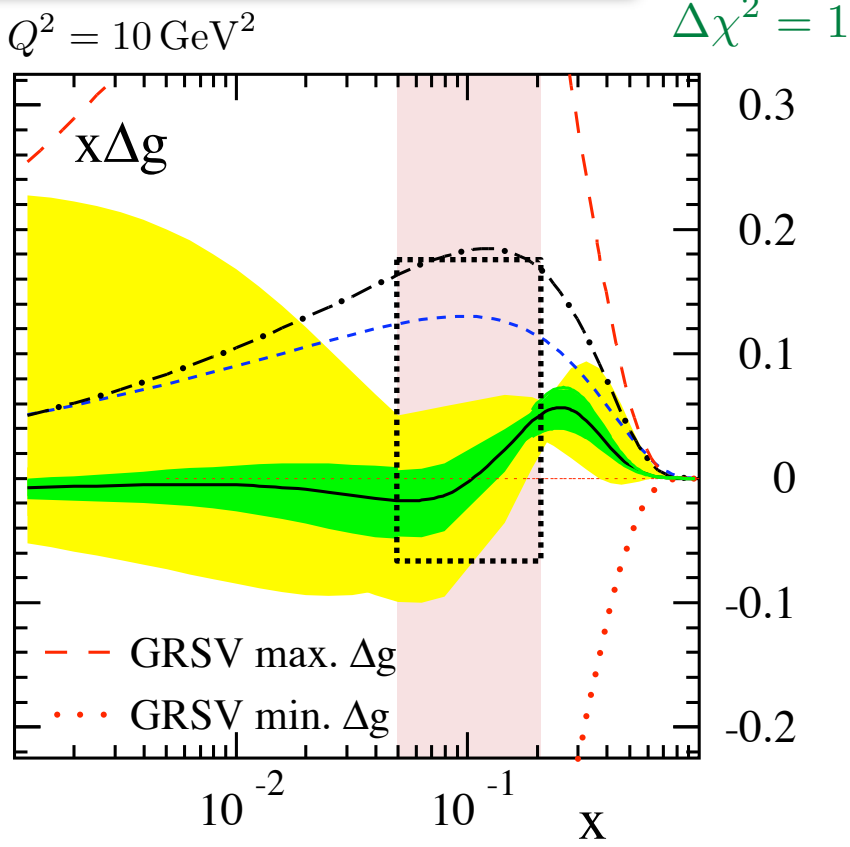
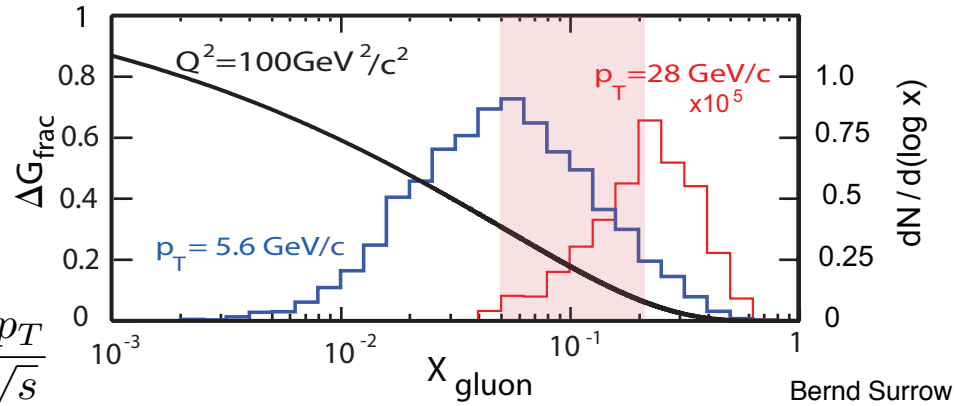
Recent results - Gluon polarization program

Impact on Δg from RHIC data

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







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Recent results - Gluon polarization program

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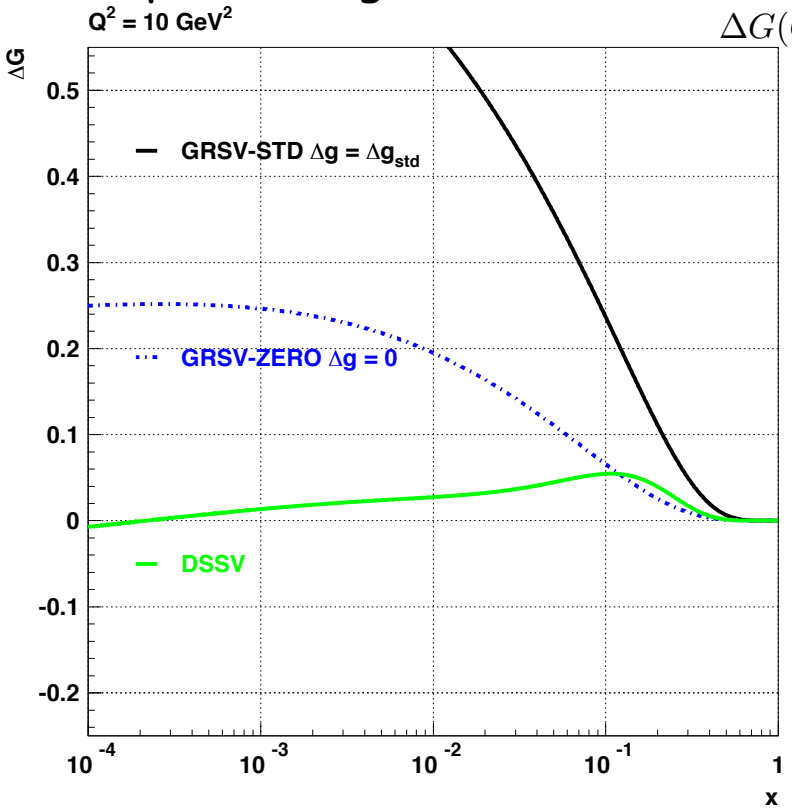
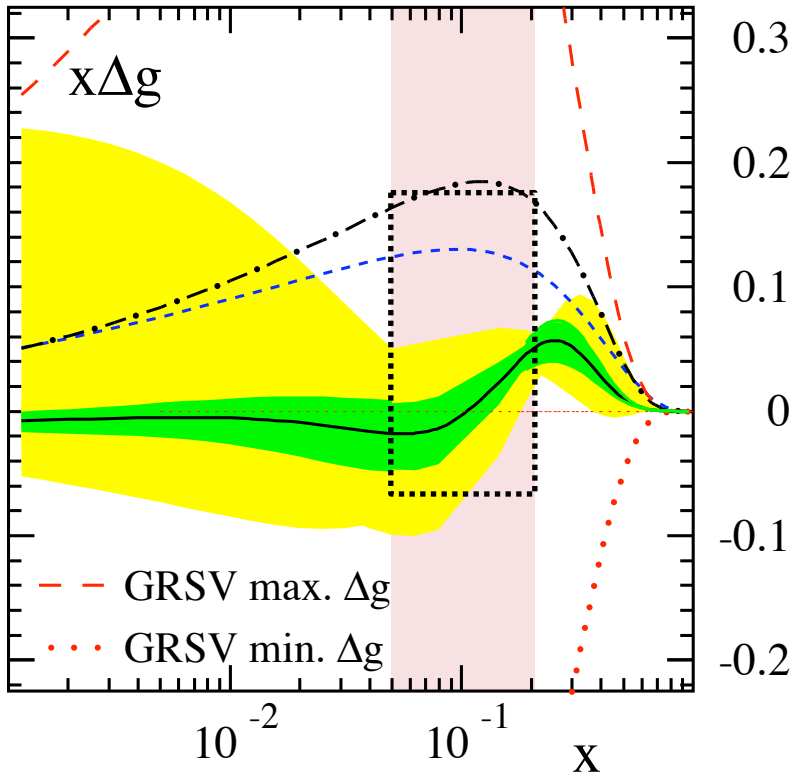
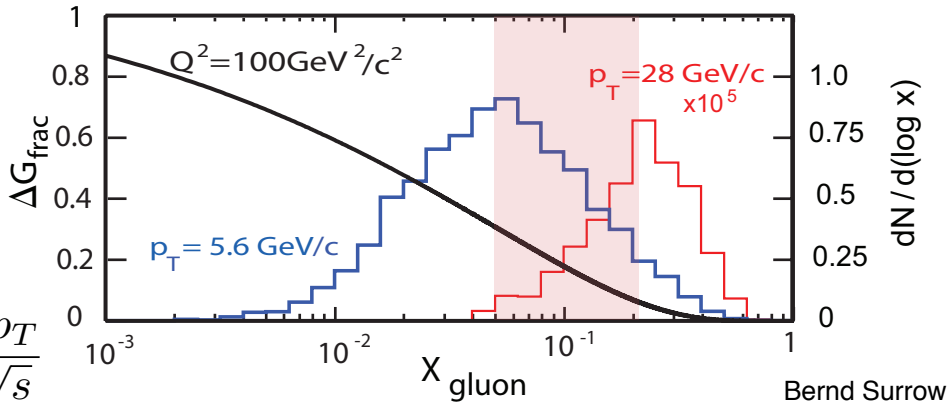


$Q^2 = 10\,\mathrm{GeV}^2$ $\Delta\chi^2 = 1$





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Recent results - Gluon polarization program

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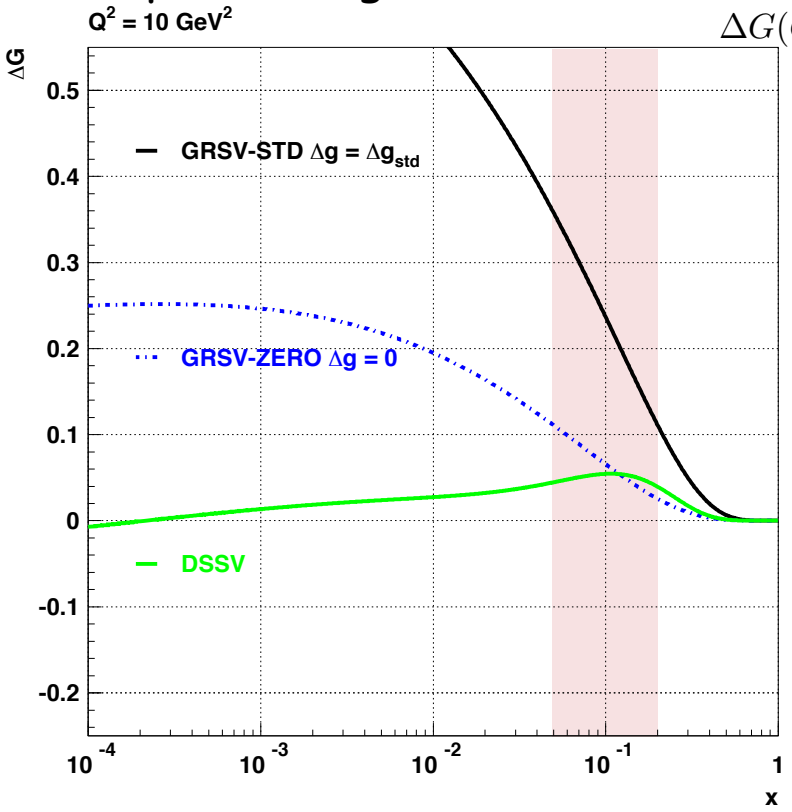

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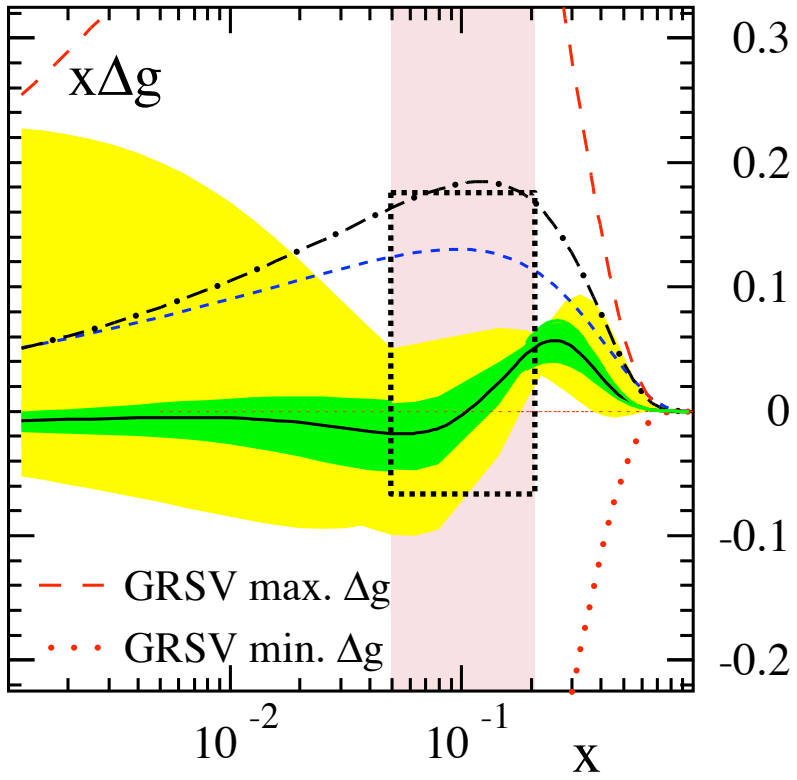

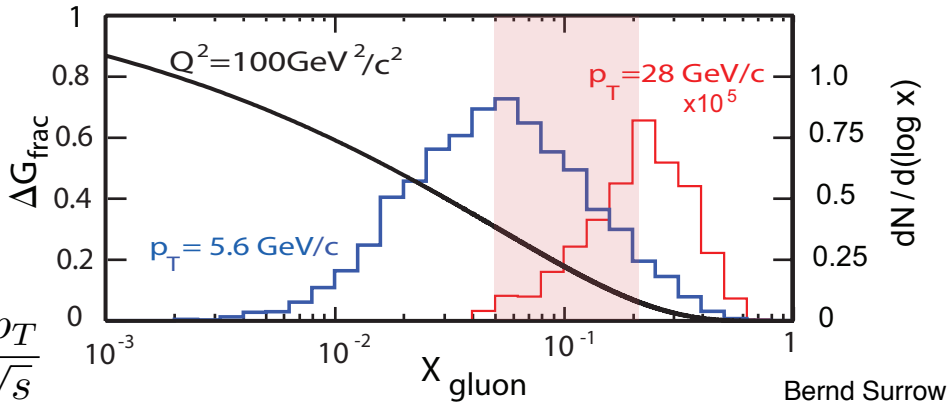

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Recent results - Gluon polarization program

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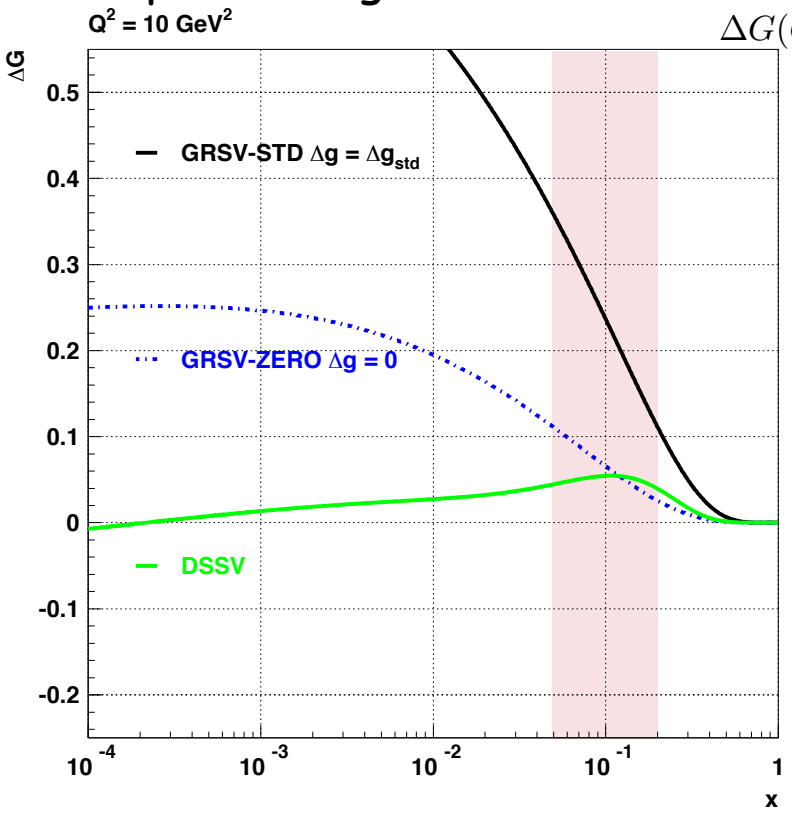

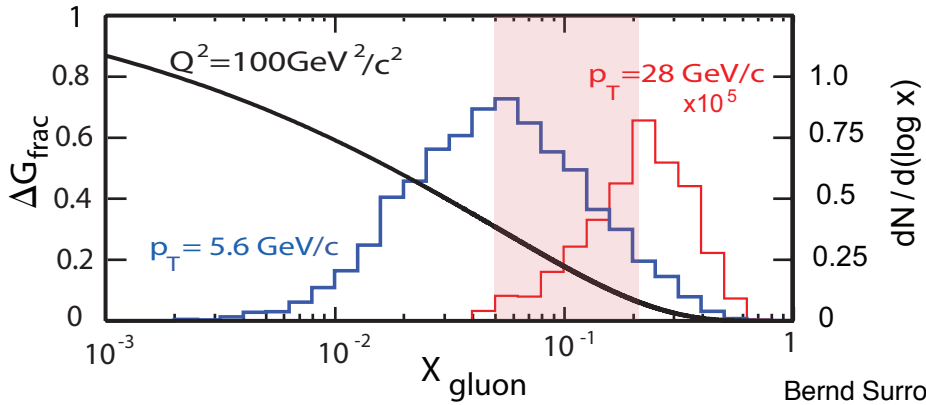

Recent results - Gluon polarization program

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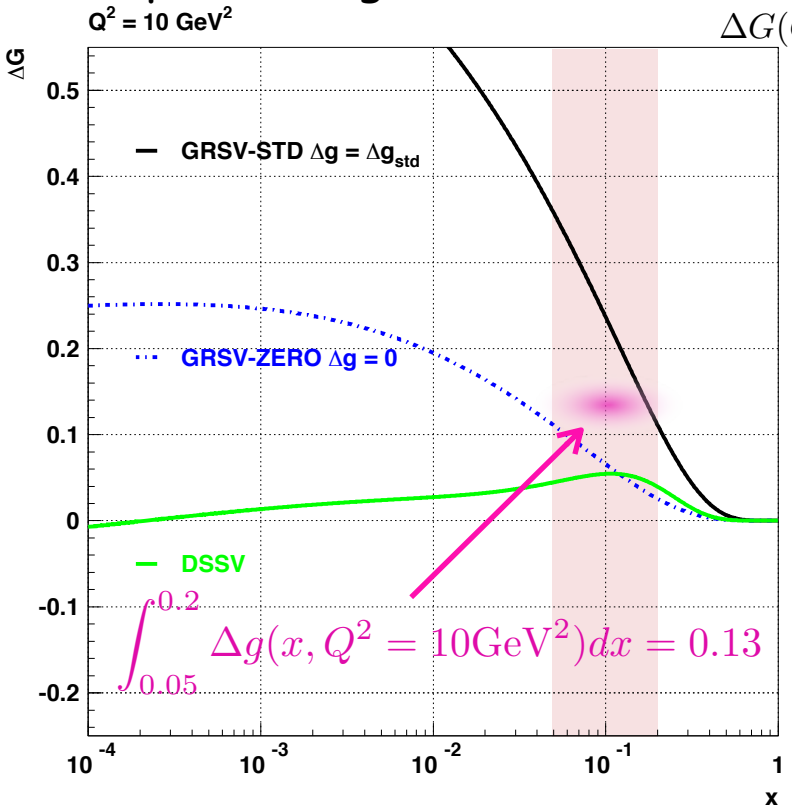
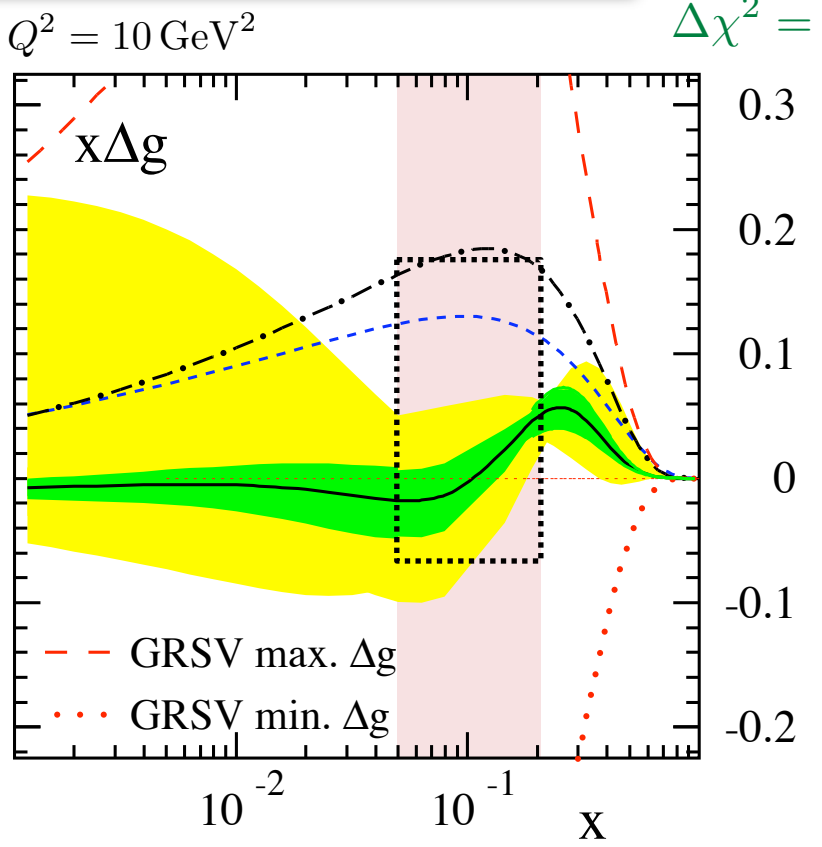
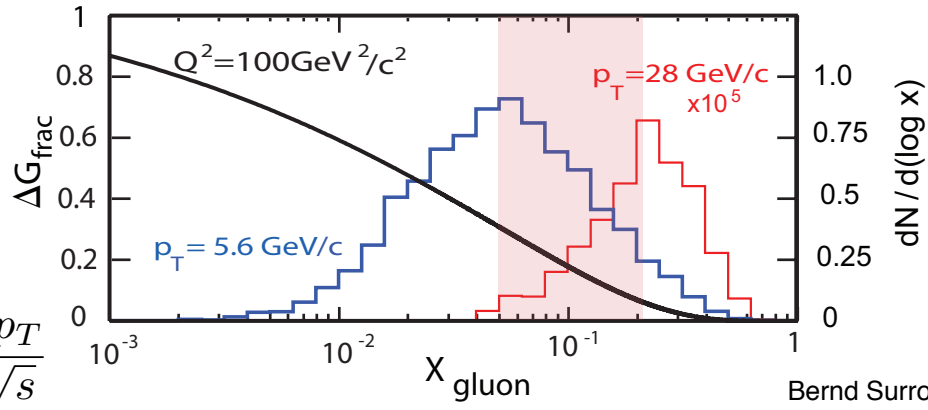


- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)





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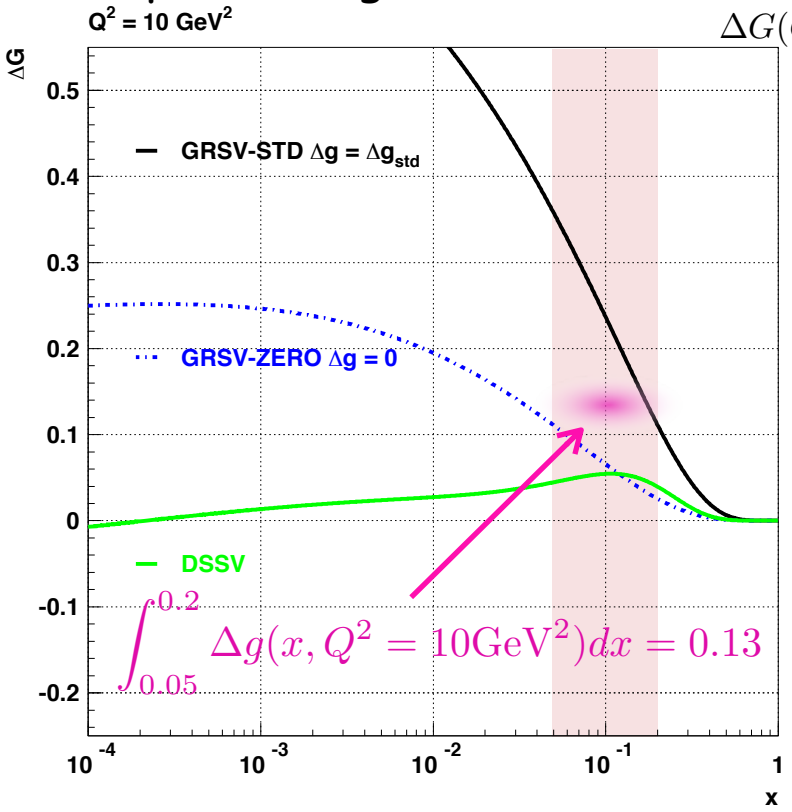
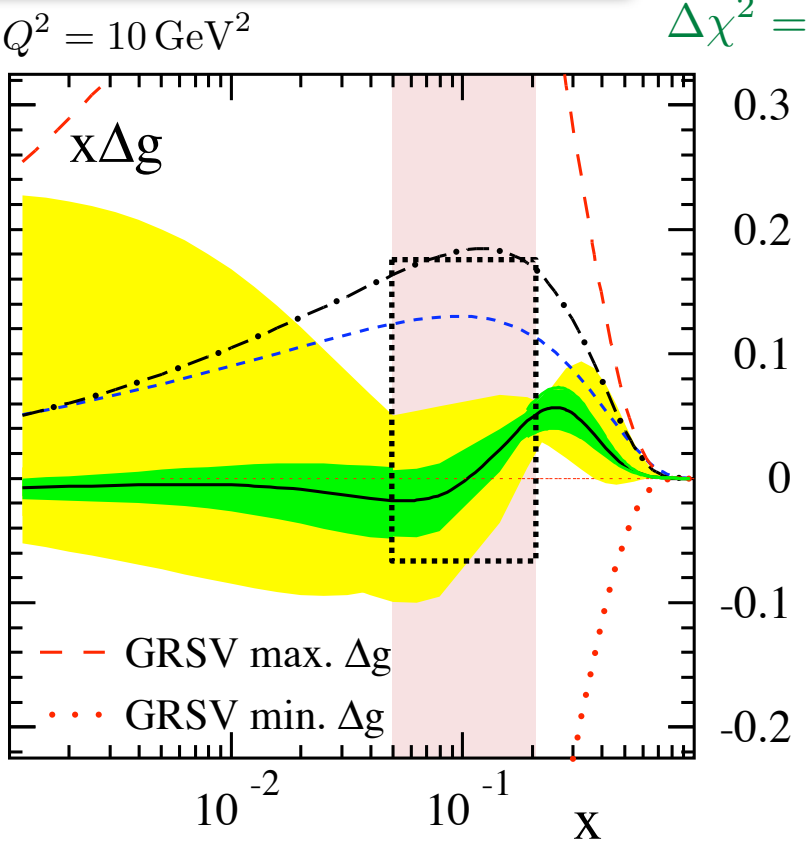
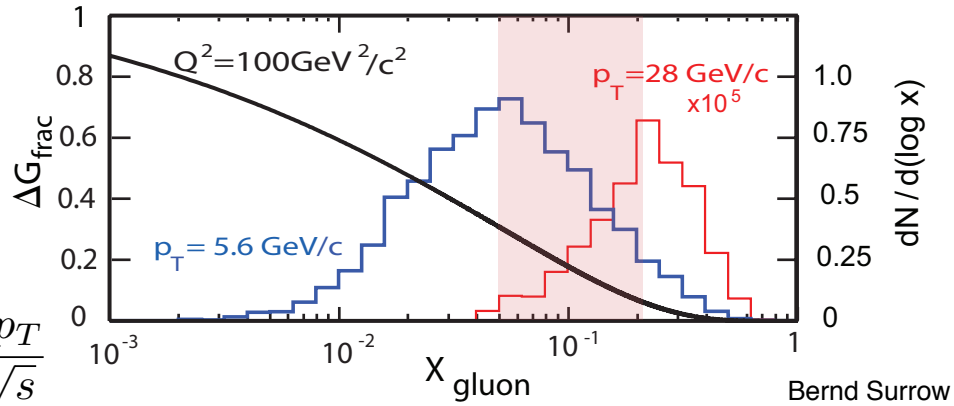


- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)
- Strong indication for a small, non-zero ΔG!





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Recent results - Gluon polarization program

Impact on Δg from RHIC data

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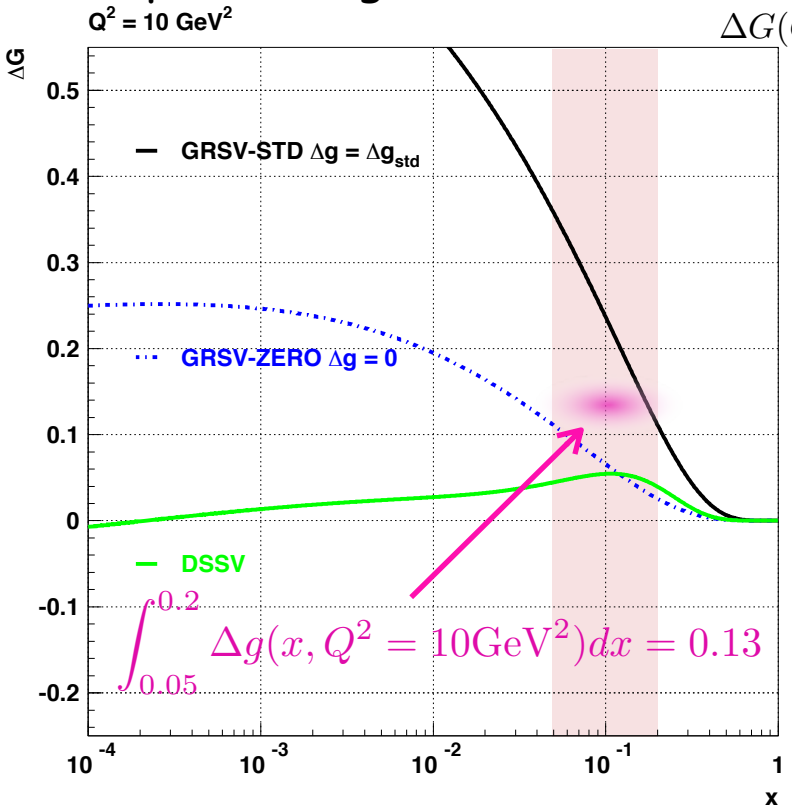
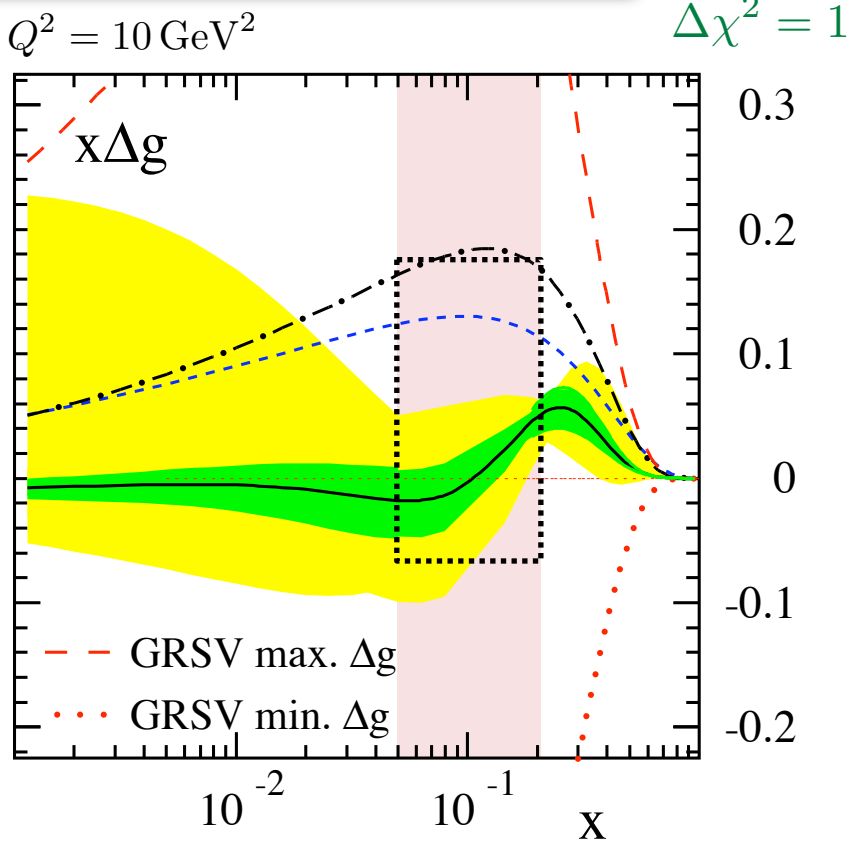
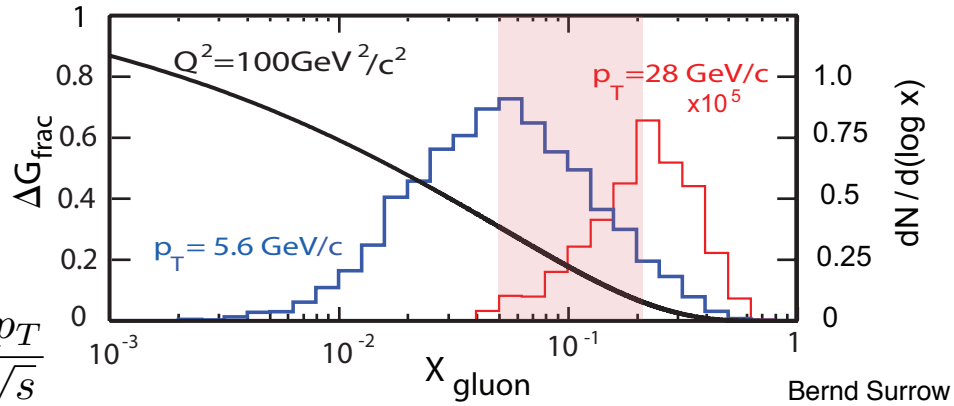




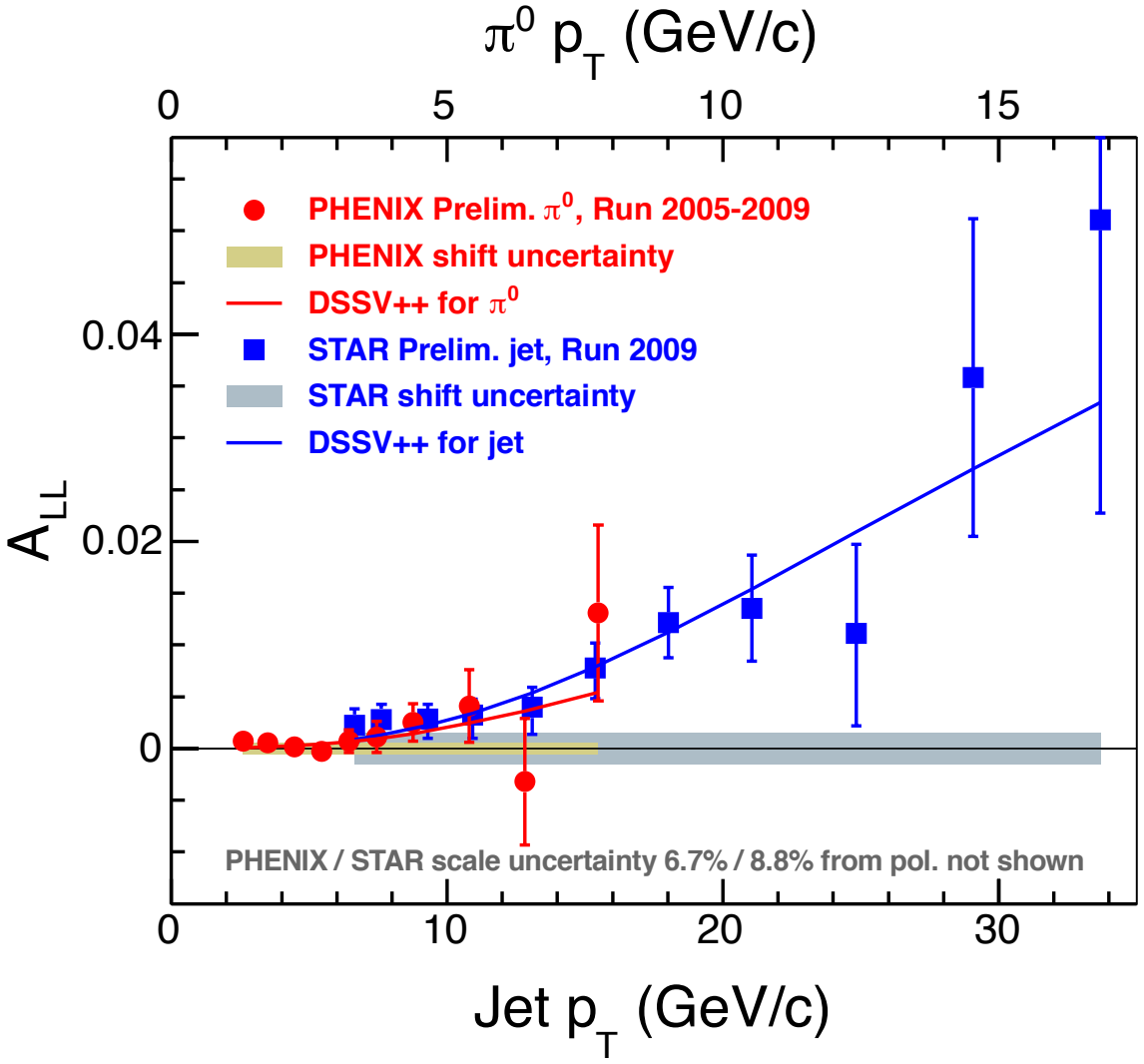


- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)
- Strong indication for a small, non-zero ΔG!
- Next steps: Mapping of x-dependence and extension of x-coverage needed (Di-Jet measurements)!

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

Recent results - Gluon polarization program

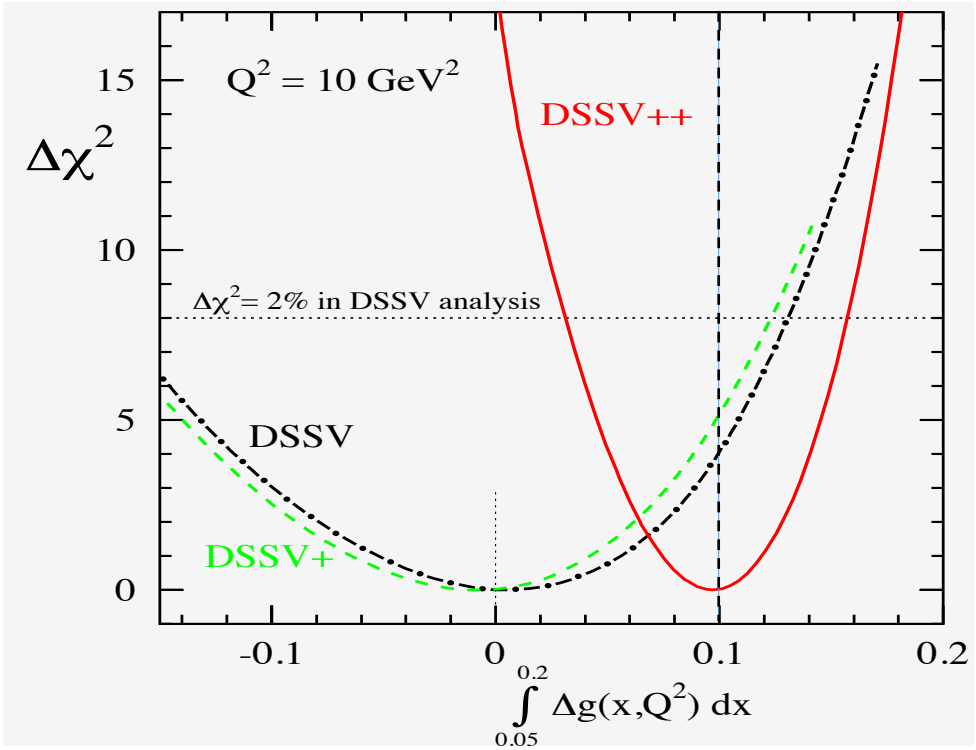
- Data input for new global analysis by DSSV
  - STAR Inclusive Jet and PHENIX Neutral pion result from RHIC Run 9 consistent
  - New global analysis by DSSV contains STAR and PHENIX RHIC Run 9 data
  - DSSV: polarized DIS plus RHIC data (Run 5/6) published: D. de Florian et al. Phys. Rev. Lett. 101 (2008) 072001
  - DSSV+: DSSV & COMPASS
  - DSSV++: DSSV+ and RHIC Run 9 data

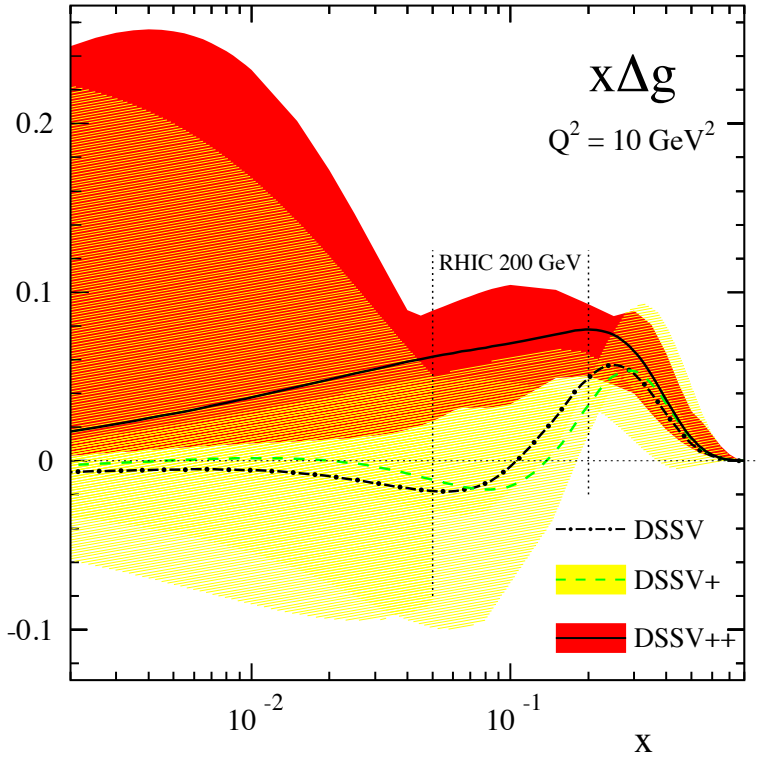


RHIC Spin Collaboration (2012)

Recent results - Gluon polarization program

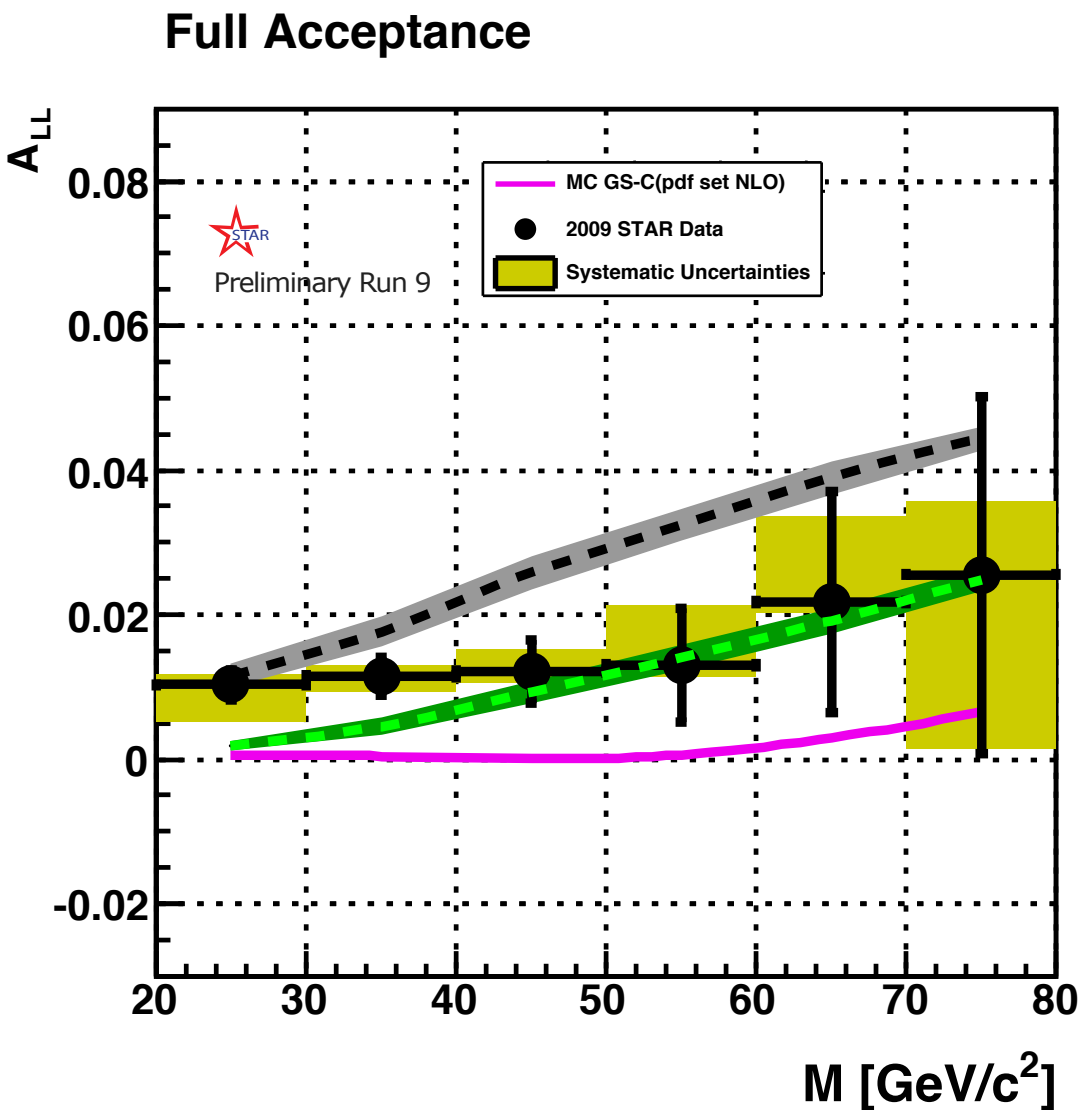
- Evolution of DSSV fit result





- RHIC Run 9 data narrows chi2-profile and shifts central value
- DSSV++ fit gives first non-zero ΔG in RHIC sensitivity region
- DSSV++ stat. consistent with DSSV

Recent results - Gluon polarization program



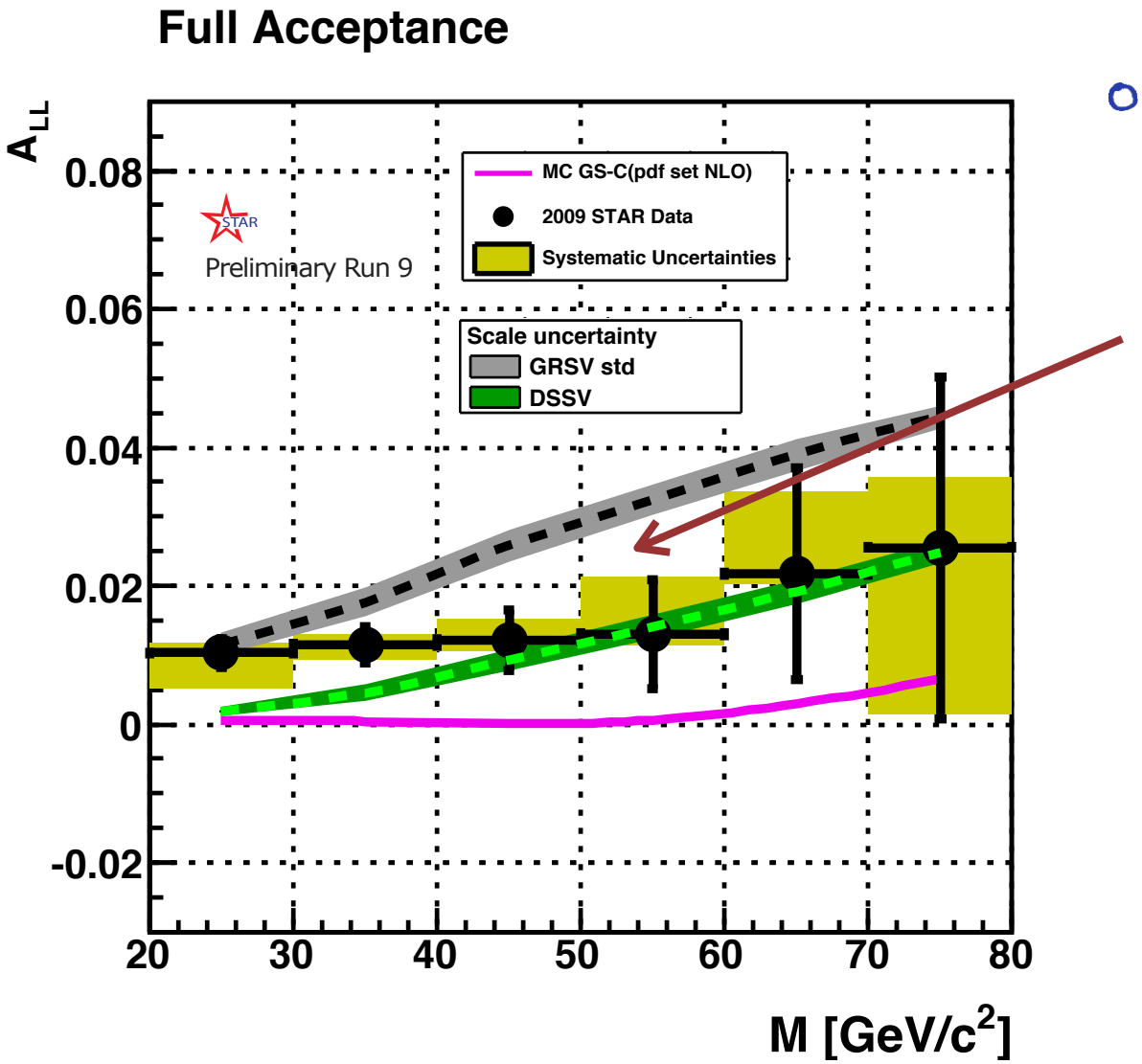
- A_{LL} measurements fall in-between GRSV-STD and DSSV - **Above** DSSV at low M similar to inclusive jet result at low p_T

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

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

Recent results - Gluon polarization program

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



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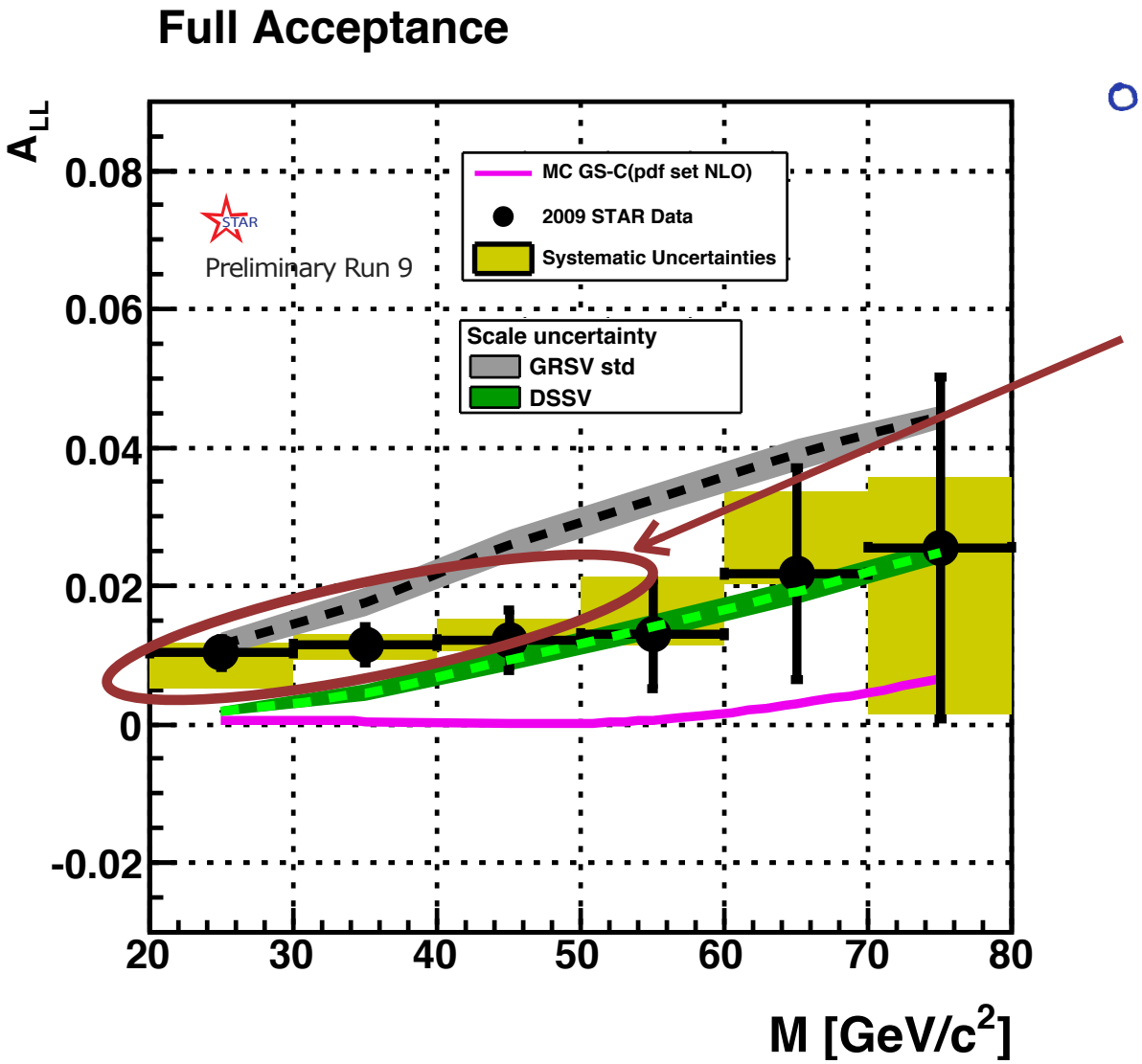

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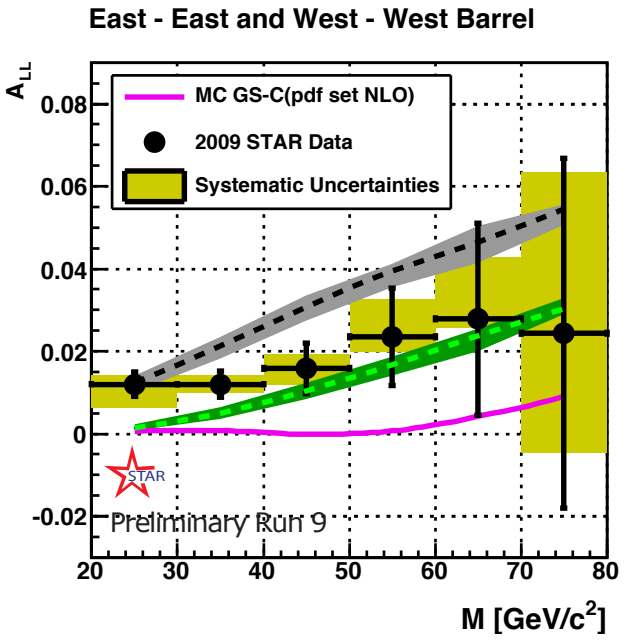
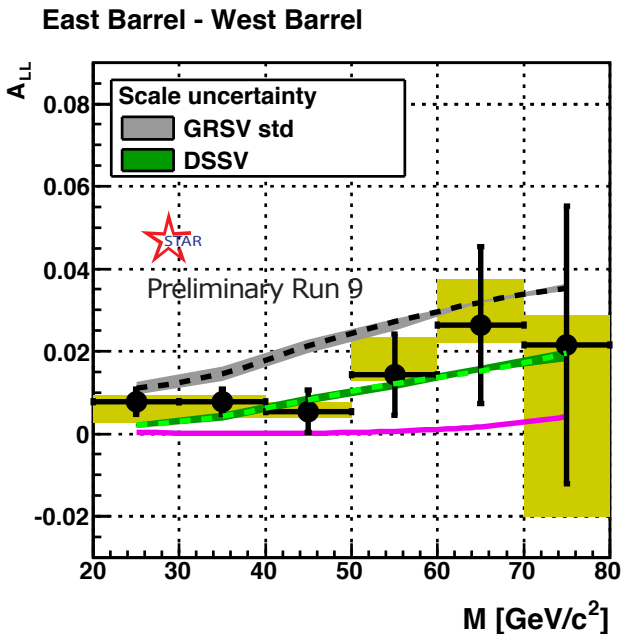
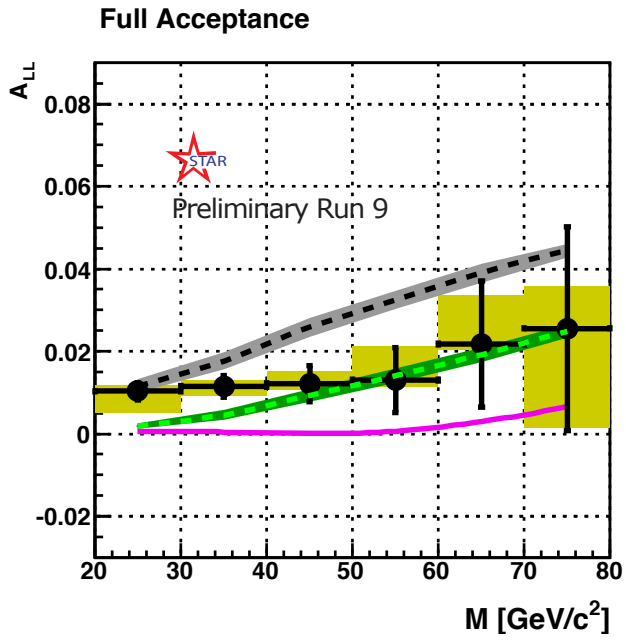
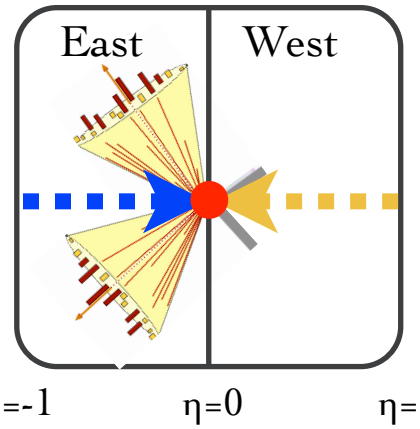
Recent results - Gluon polarization program

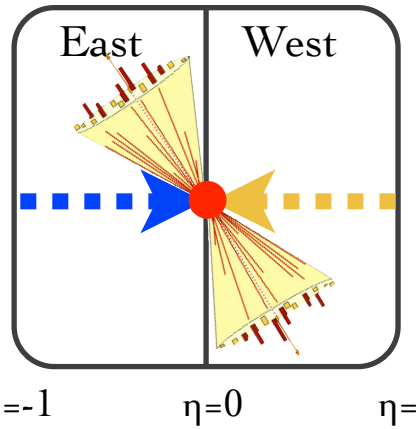
- First STAR Di-Jet A_{LL} measurement in bins of η









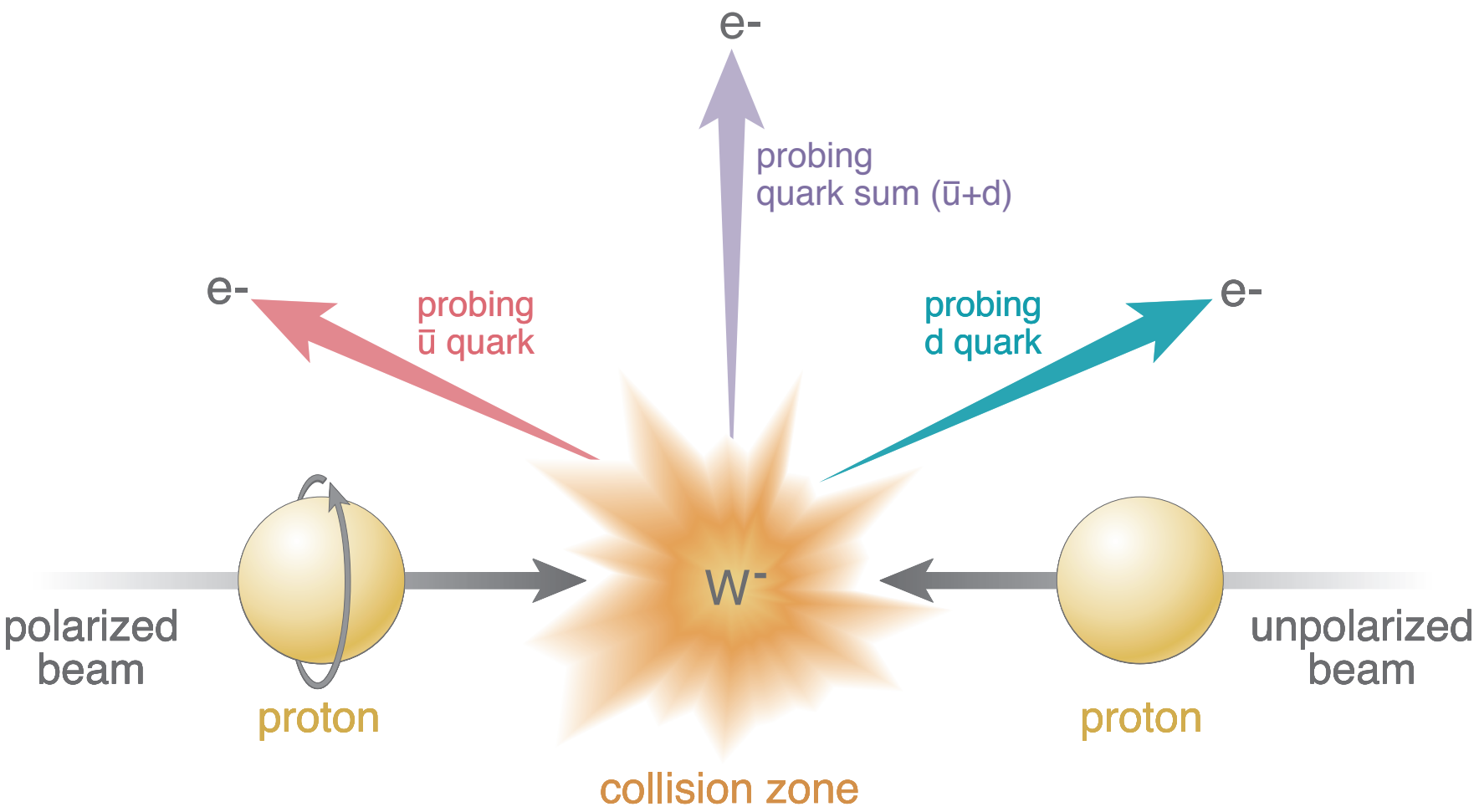


- Run 9 data: First rapidity dependent di-jet measurement
  ⇒ Constrain x dependence!

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

Recent results - W production

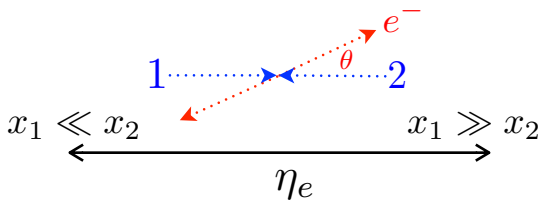
- Probing the quark flavor structure using W boson production: Unique new probe



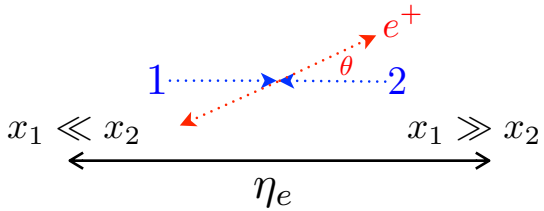
Recent results - W production

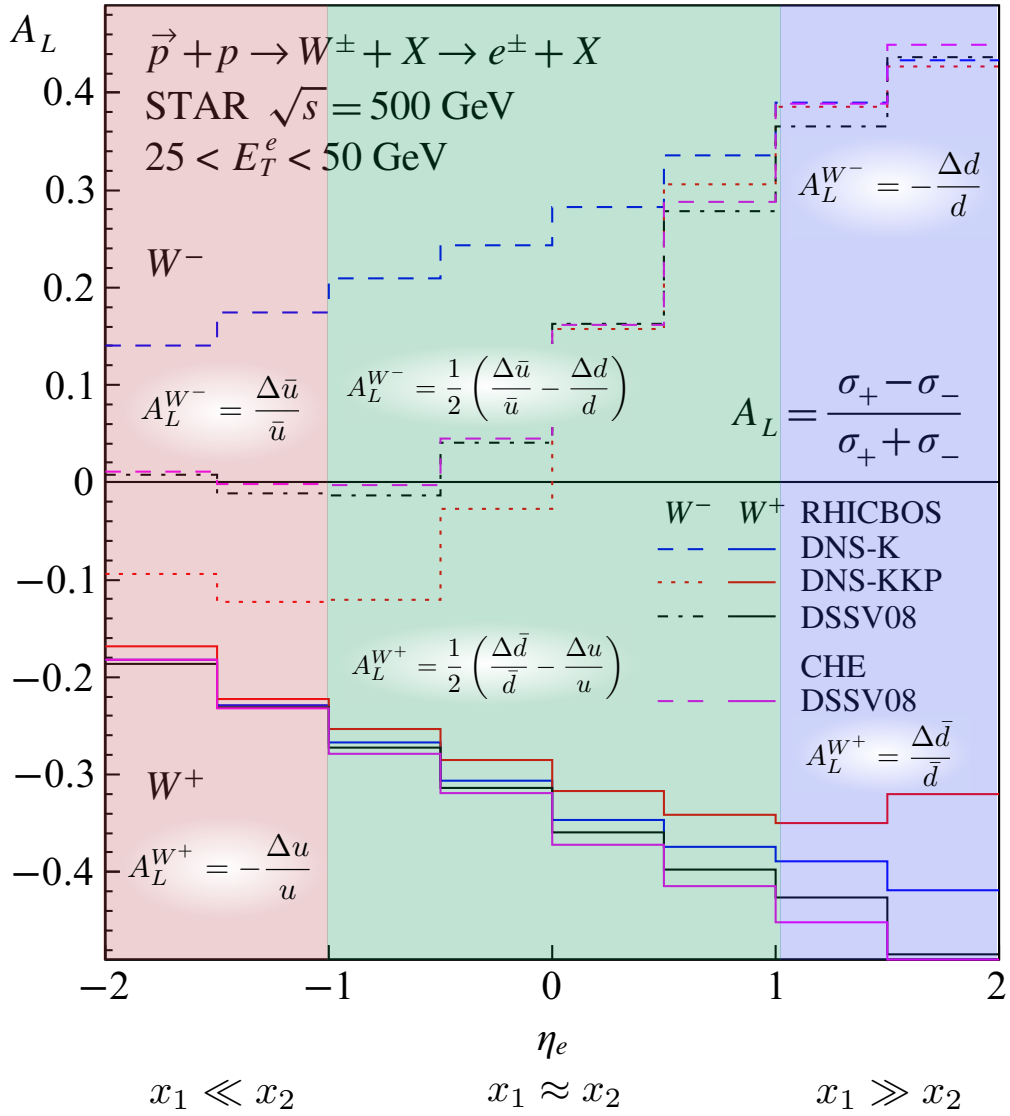
- Probing the quark flavor structure: W boson production

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



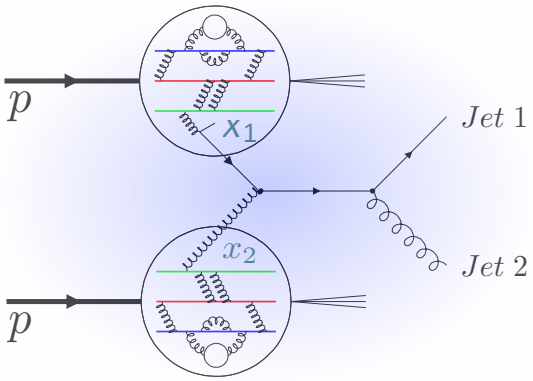
$$A_L^{e^+} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}$$

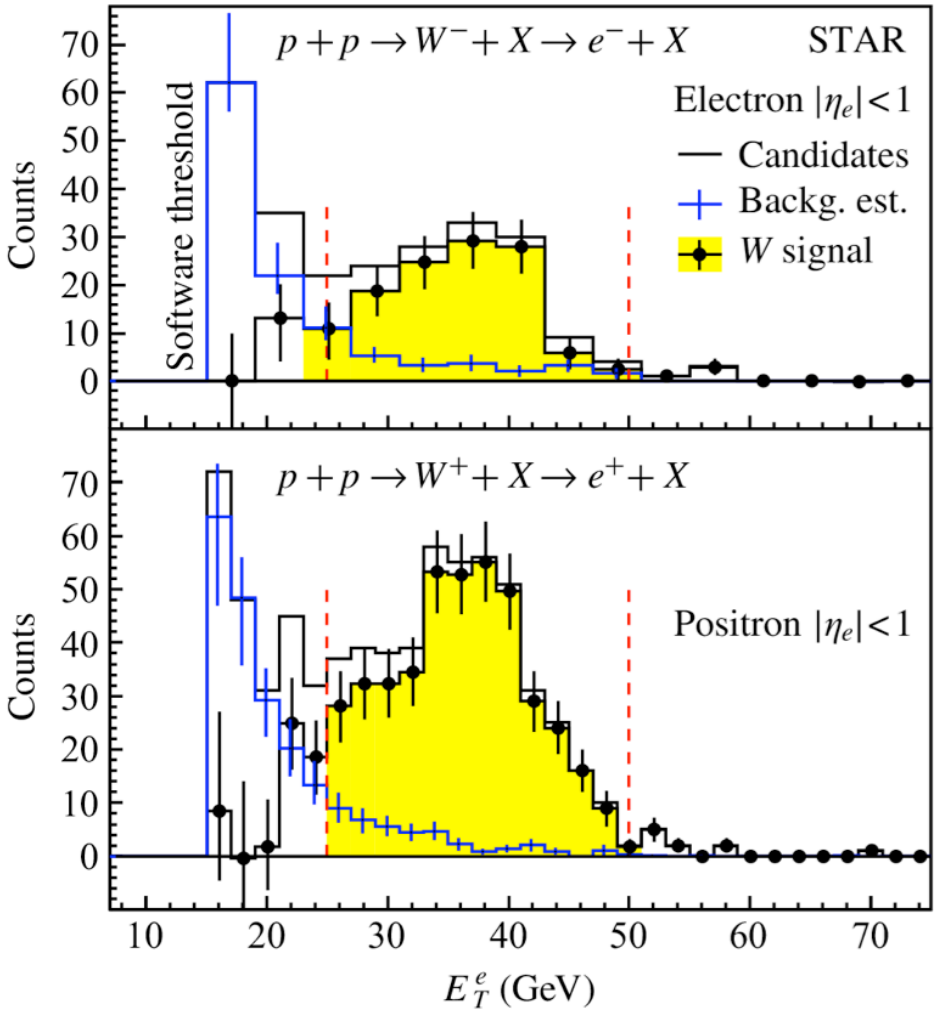


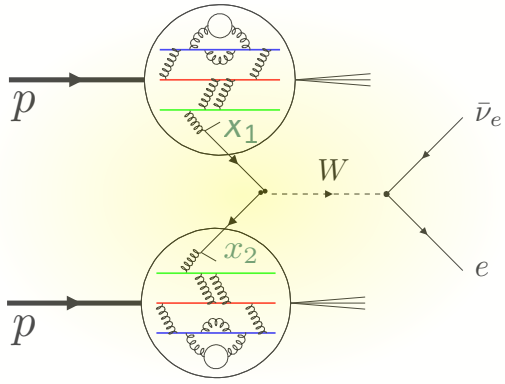


Recent results - W production

- Measurement: STAR Background treatment / Signal distribution (Run 9)







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

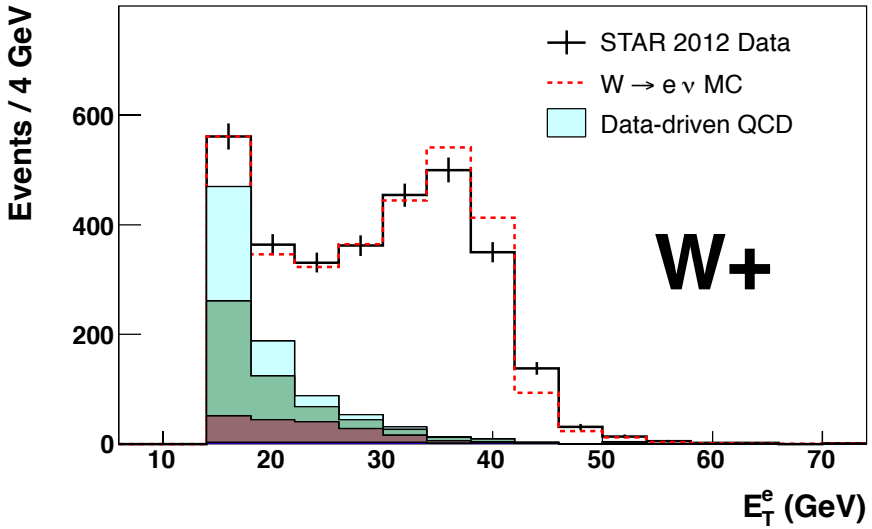
- Total background (B):
  - e^+: 39 ± 9
  - e^-: 23 ± 6

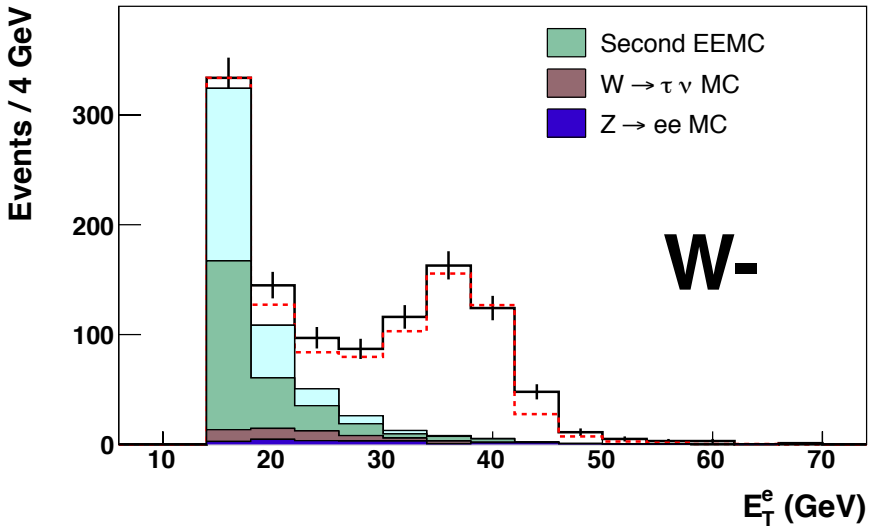
- Total e^+/e^- cand. events (S+B):
  - e^+: 462
  - e^-: 139

STAR Collaboration, PRL 106, 062002 (2011)

Recent results - W production

- Mid-rapidity: STAR Background treatment / Signal distribution (Run 12)

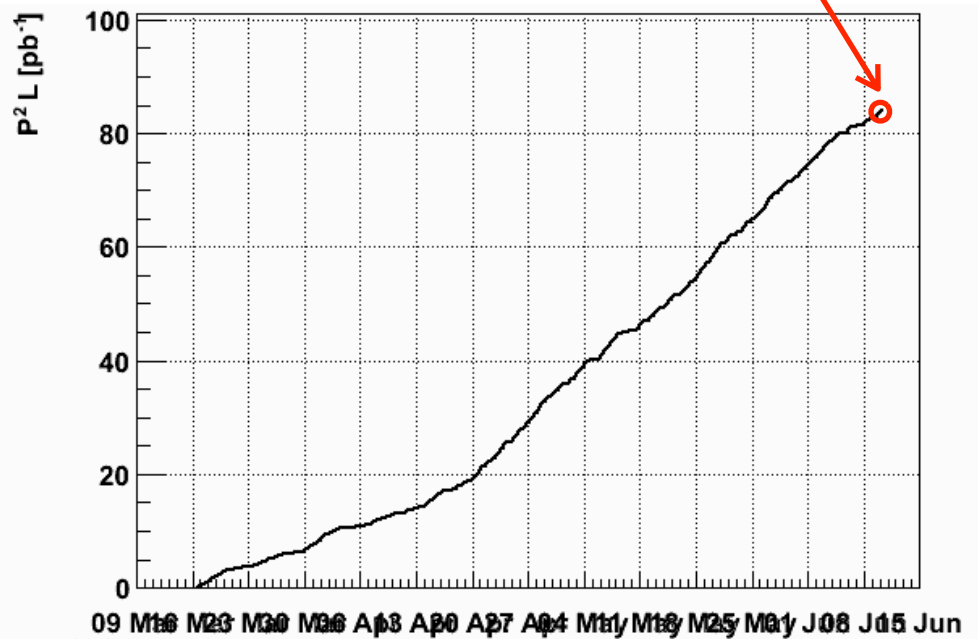




	L (pb^{-1})	P	P^2L (pb^{-1})
Run 9	12	0.40	1.9
Run 12	72	0.56	22.6

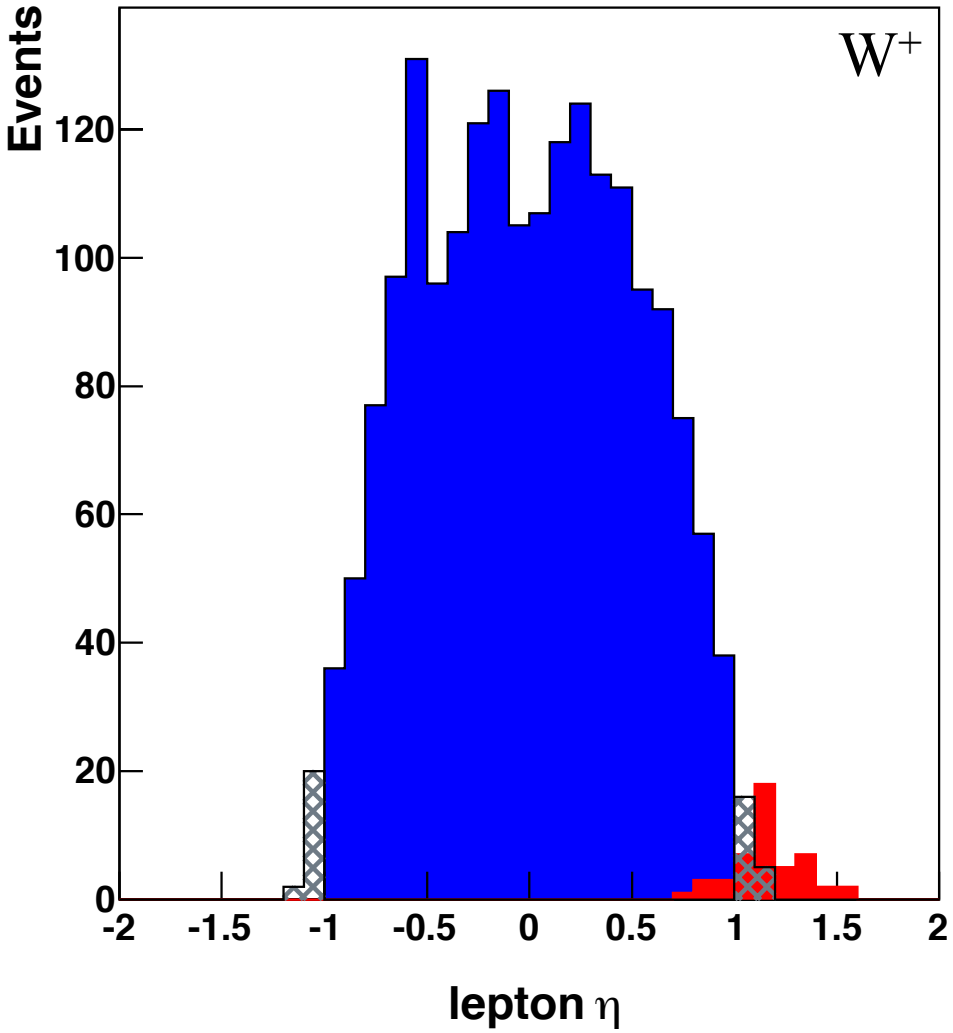
FOM Run 13 (Mid-rapidity W trigger BHT3): ~ 85pb^{-1}

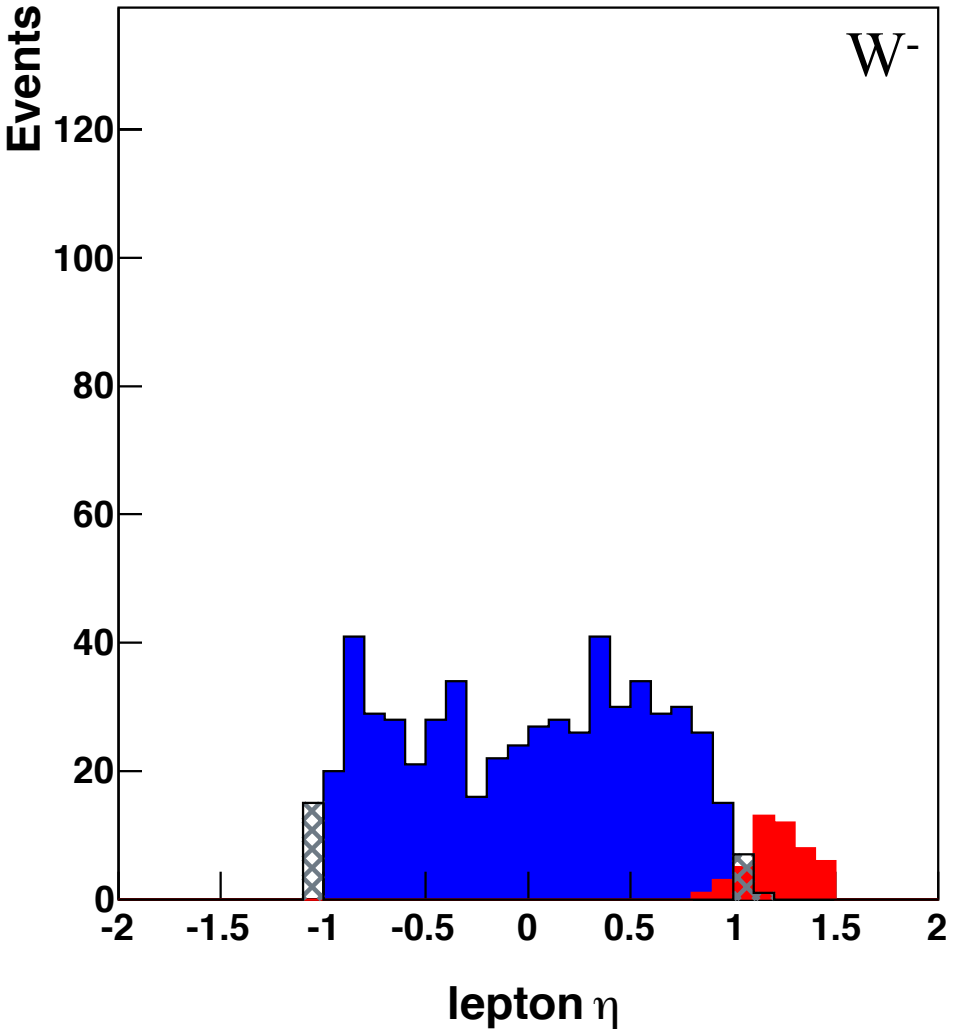
Goal for Run 13: ~50pb^{-1}



Recent results - W production

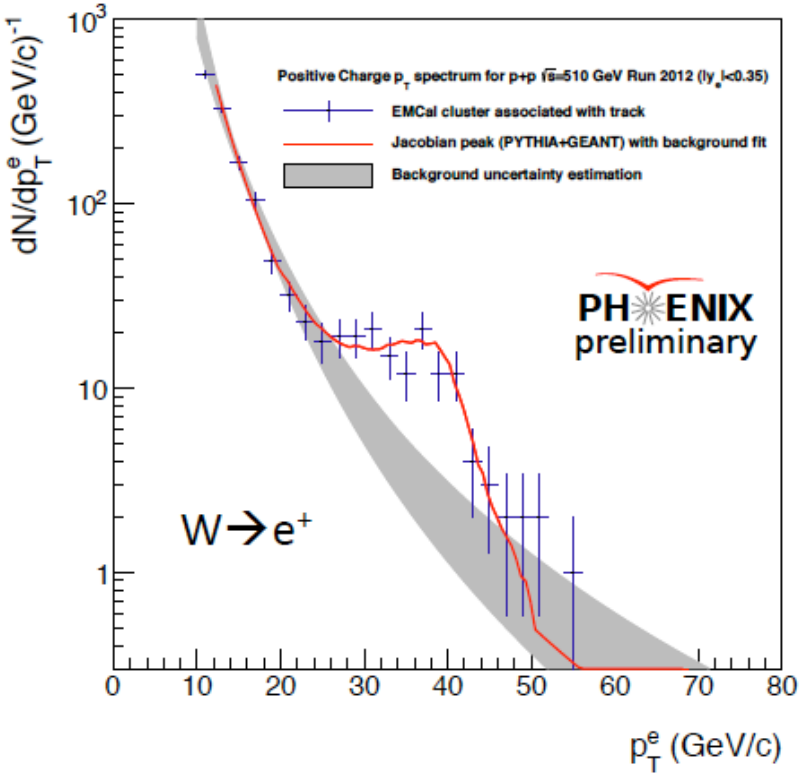
- Mid rapidity / Forward rapidity: W candidate distributions (Run 12)

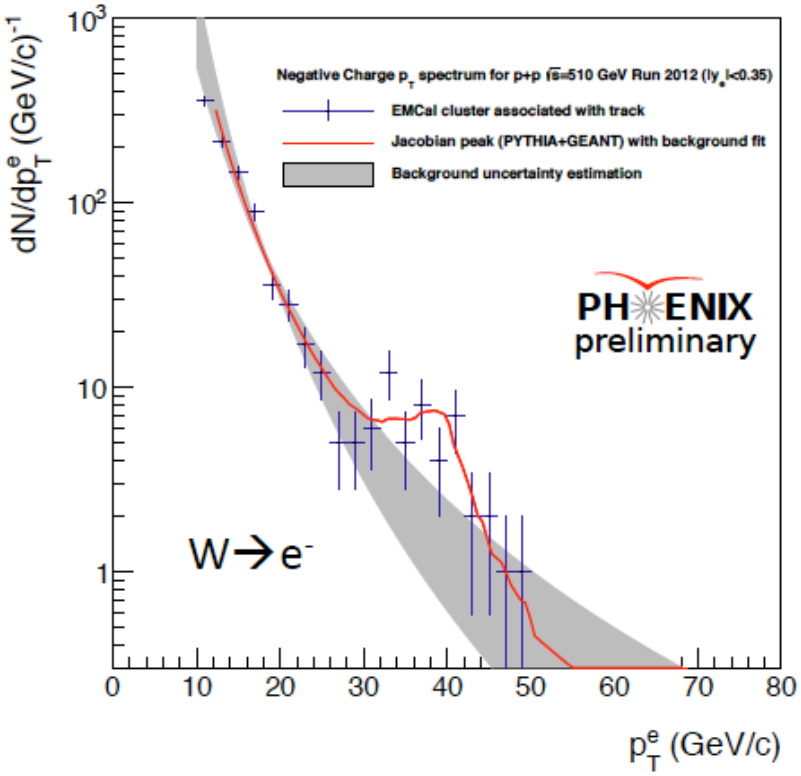




Recent results - W production

- Measurement: PHENIX Background treatment / Signal distribution (Run 12)



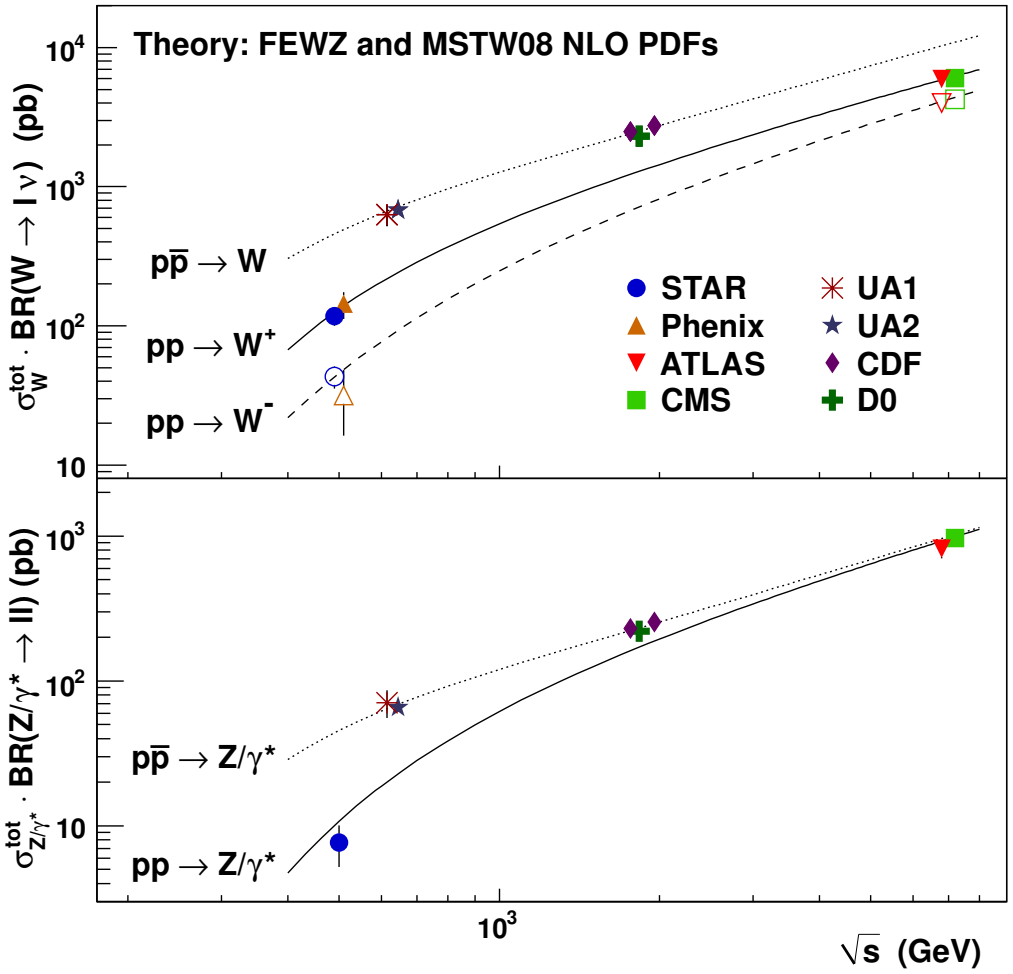


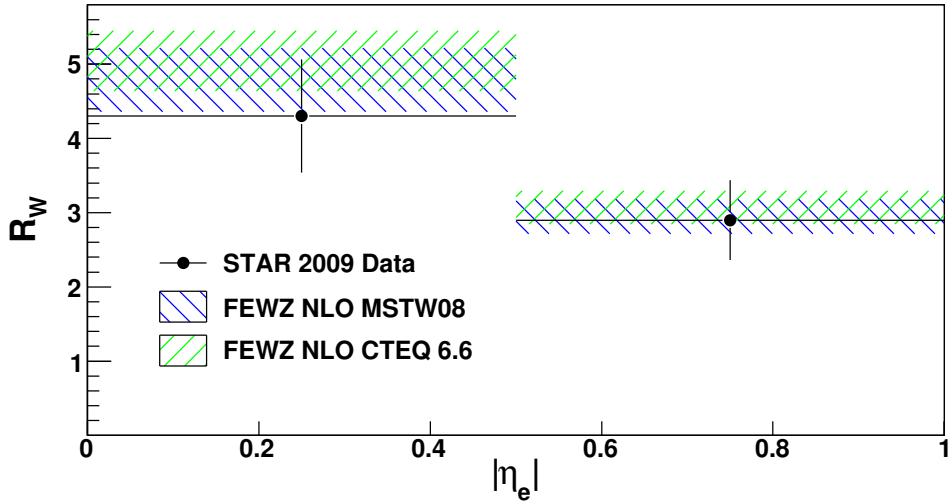
- Background dominated range: p_T=10-30GeV/c
- Signal region: p_T=30-50GeV/c
- Background estimation: Fit 10-69GeV/c range with power-law and 20-50GeV/c with power-law and Jacobian peak (Simulation)

Recent results - W/Z production

- STAR Z / γ* cross-section results

STAR Collaboration, PRL 106, 062002 (2011)



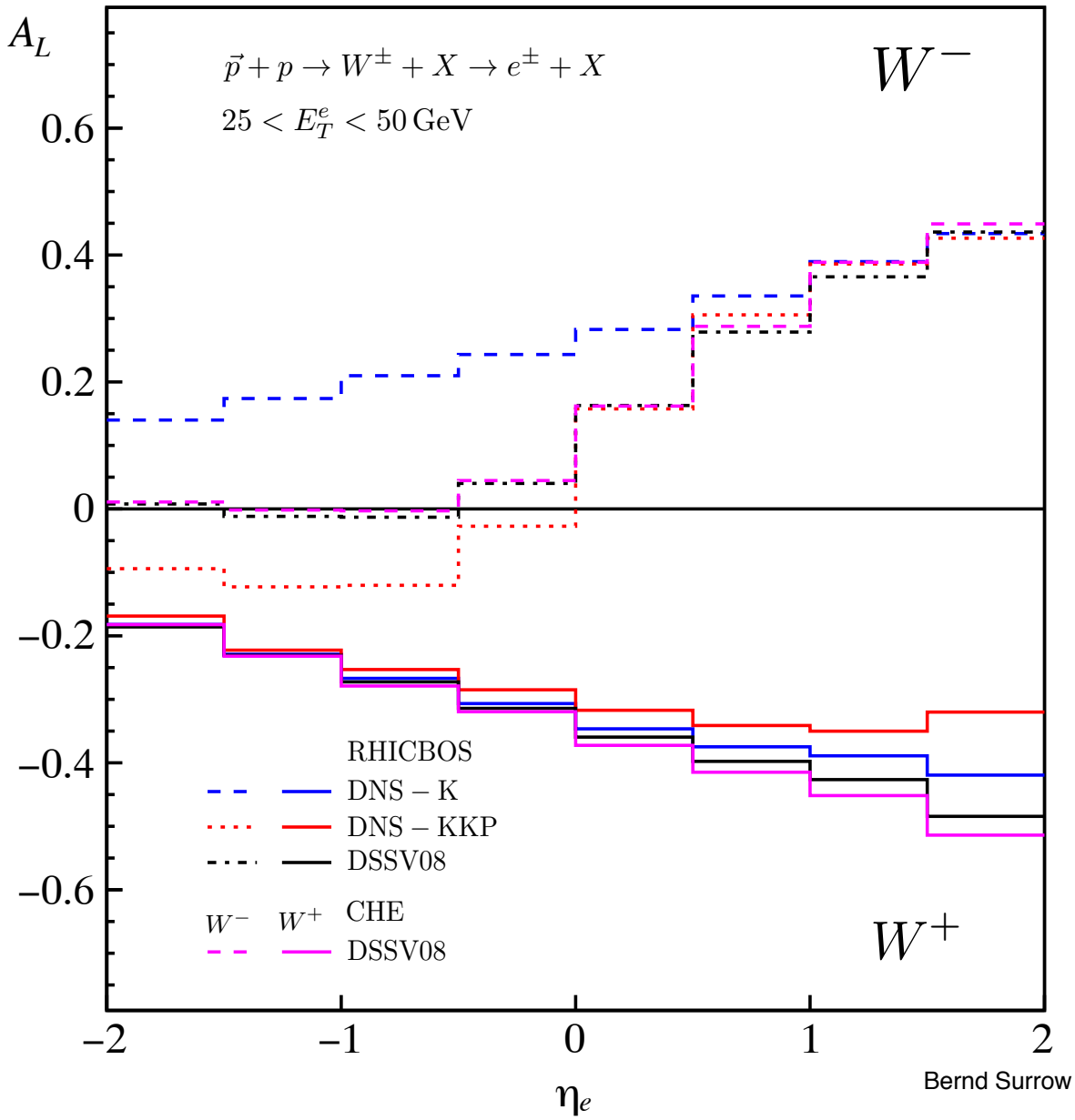


$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^!}} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

LO decomposition of cross-section ratio $R(x_F)$

Recent results - W production

- STAR A_L results / projections



Recent results - W production

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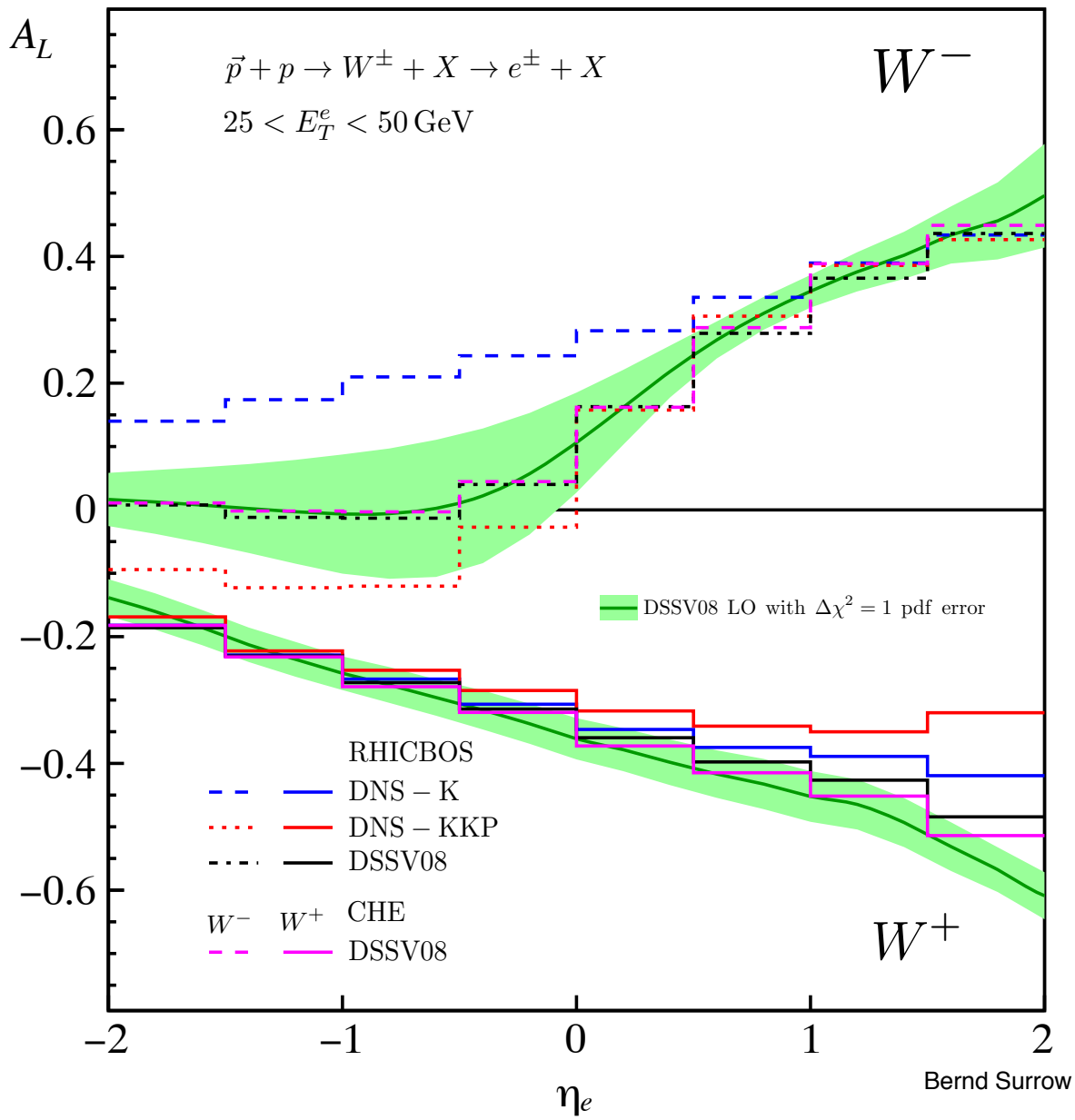
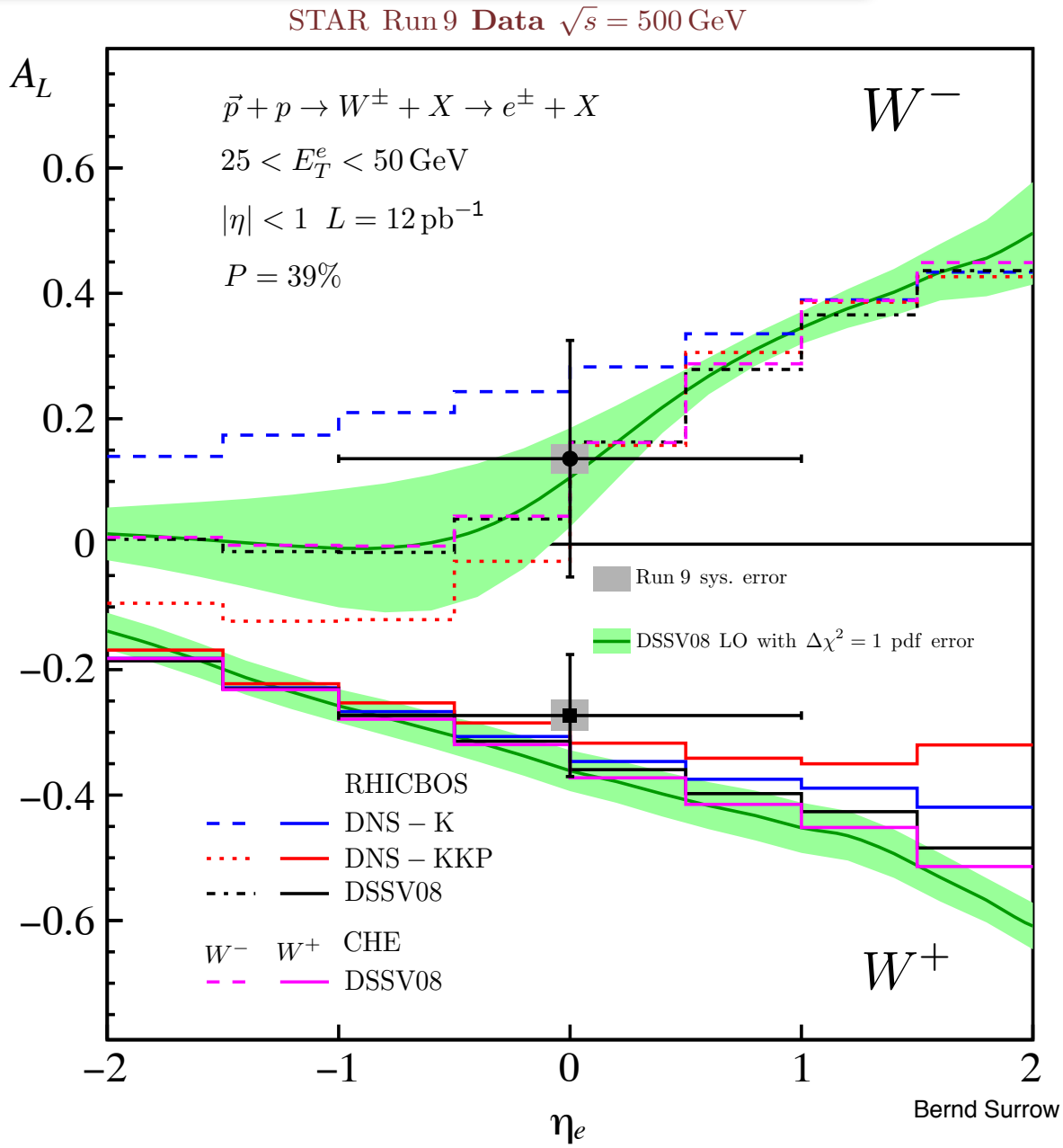


Recent results - W production

- STAR A_L results / projections

Measured asymmetries (Run 9) 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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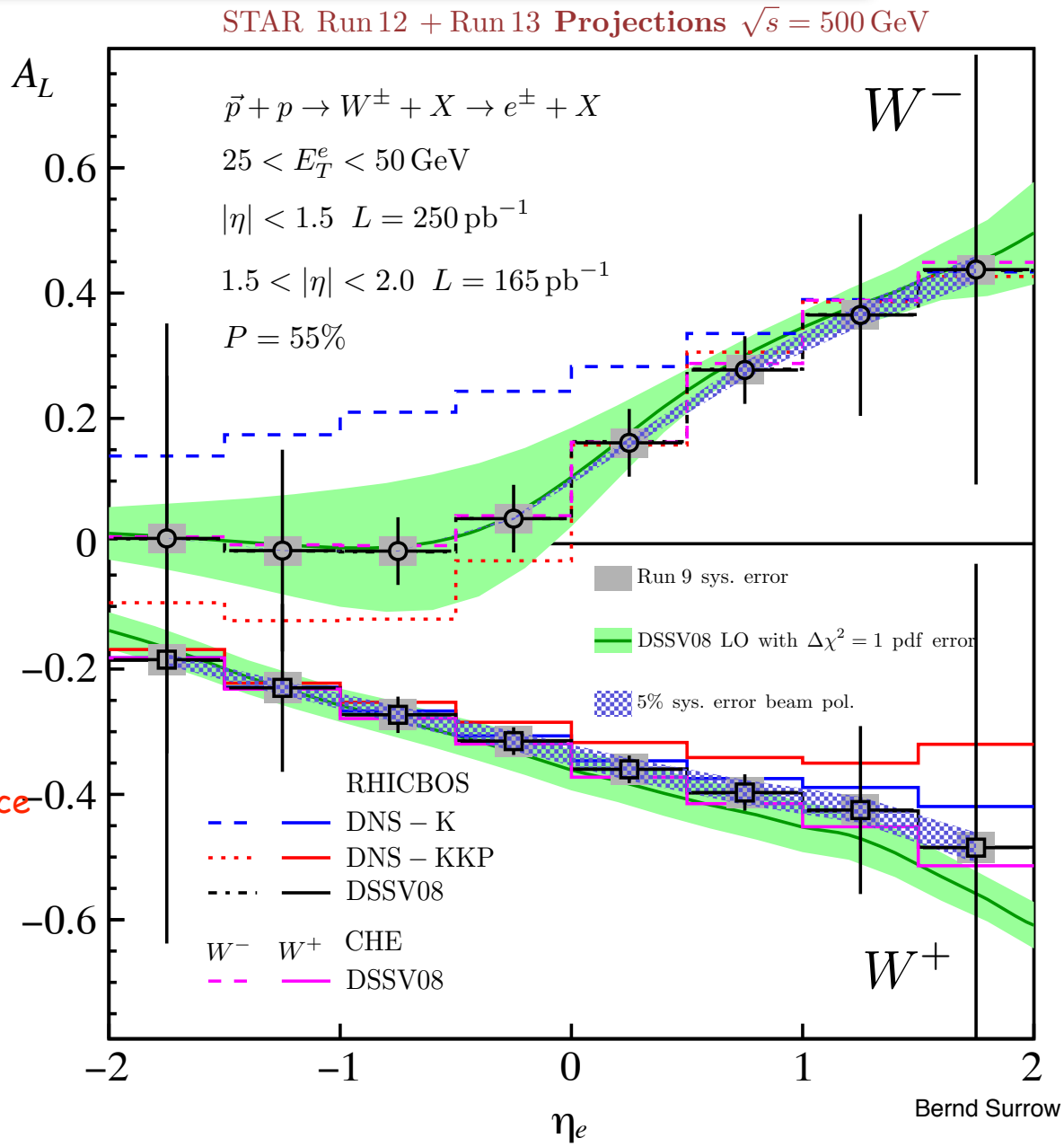
Critical: Measurement of W^+ and W^- asymmetries as a function η_e

Extension of backward / forward η_e acceptance enhances sensitivity to anti-u / anti-d quark polarization

⇒ STAR Forward GEM Tracker ($1<|\eta_e|<2$)



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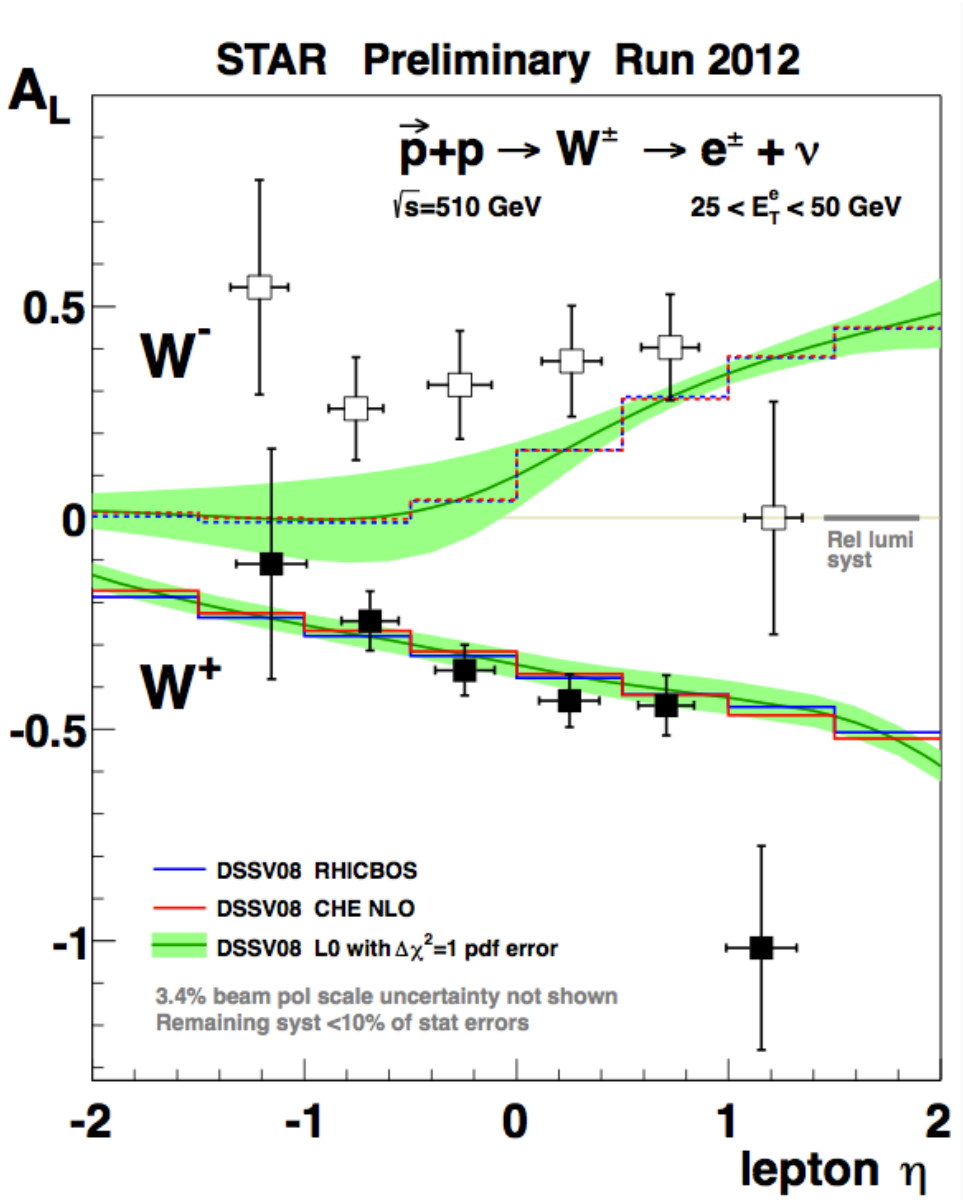
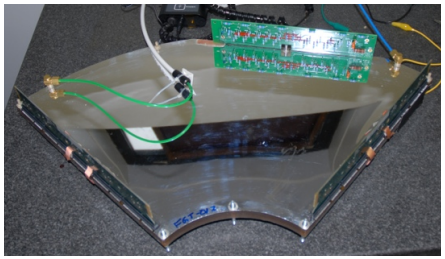
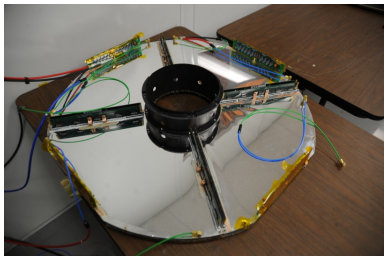


Future prospects - W production / STAR

- STAR Forward GEM Tracker - Layout

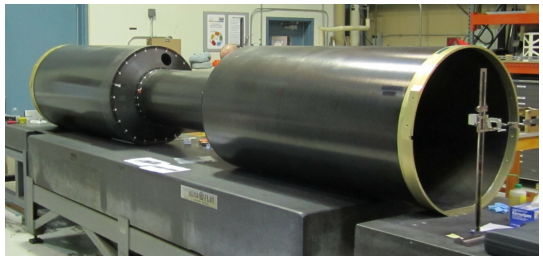


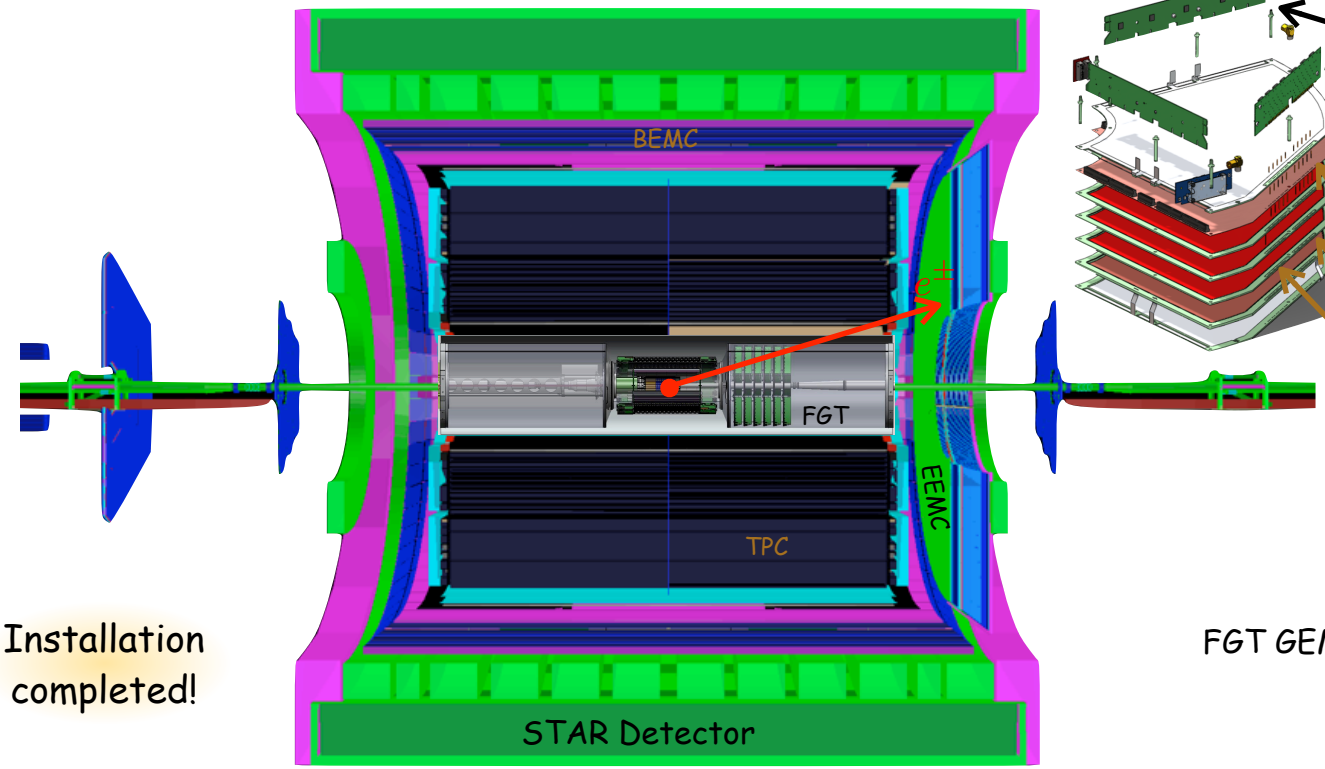
Quarter section



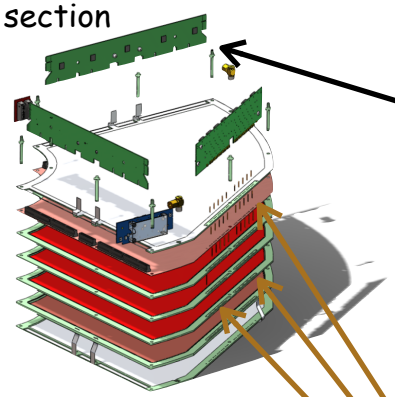
Disk

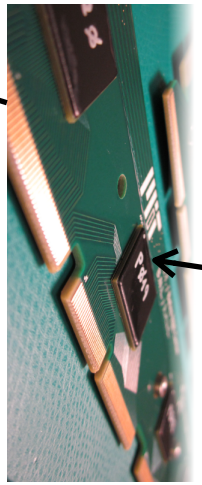
Quarter section





Installation completed!





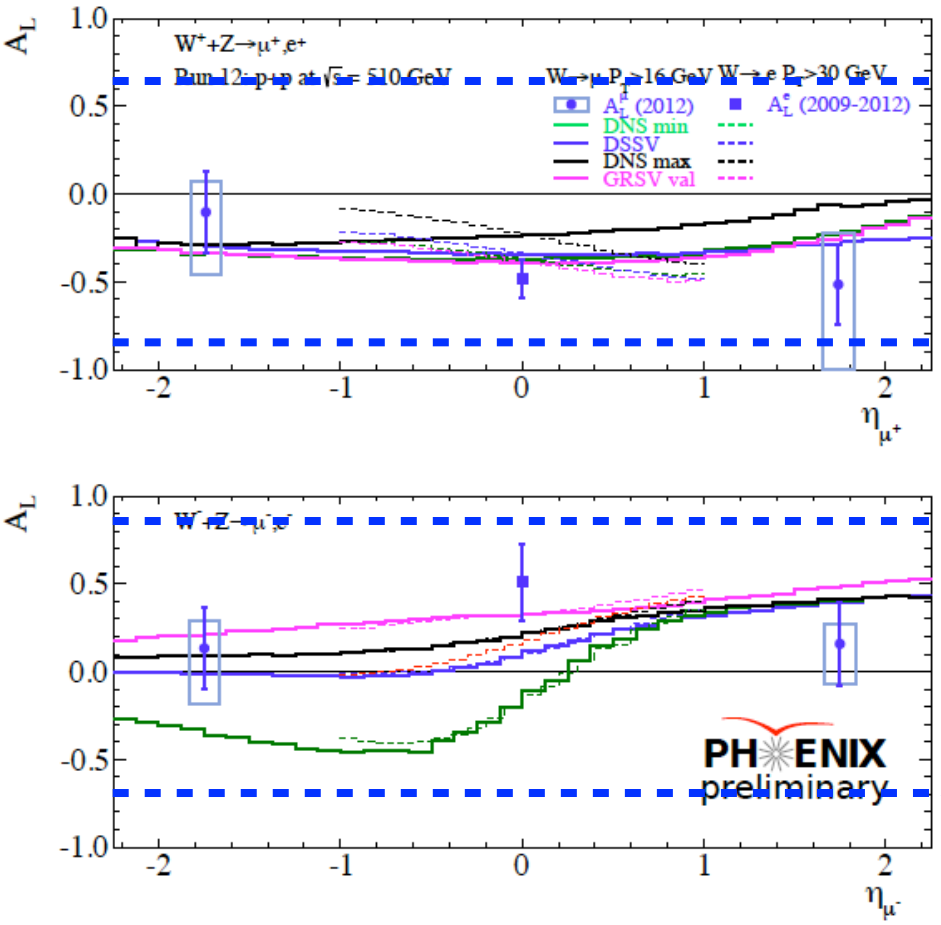
APV module

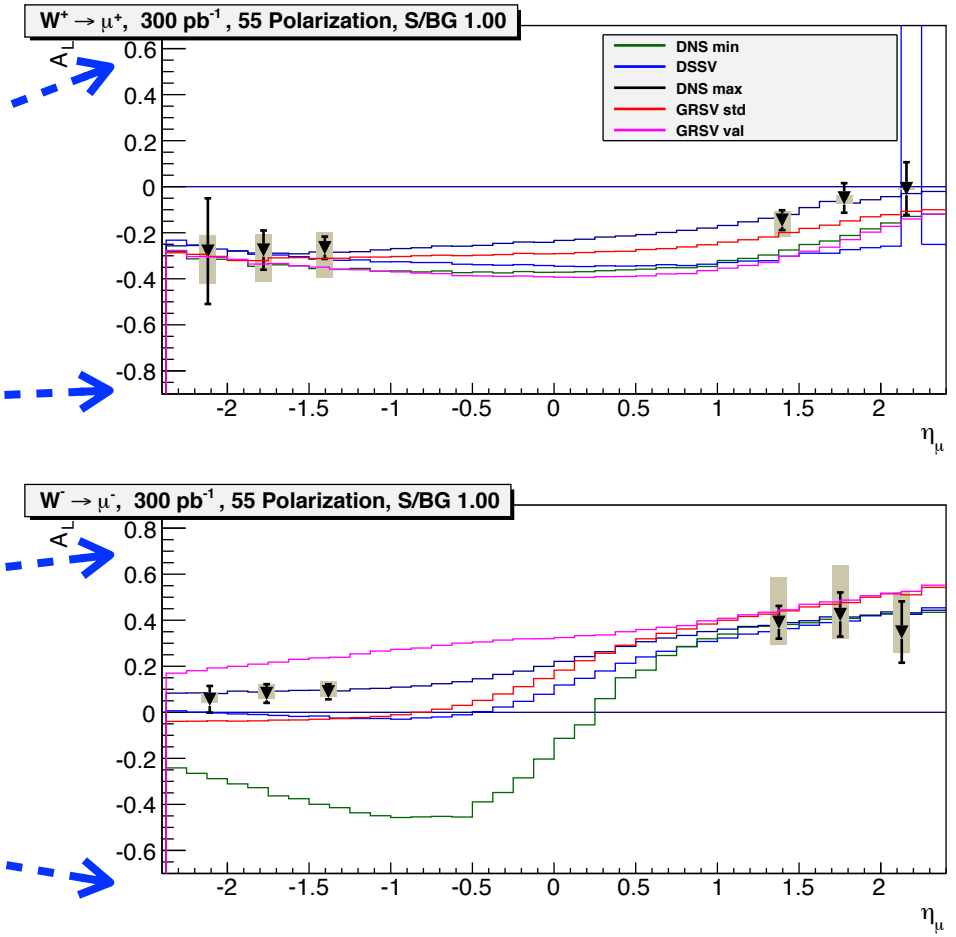
Packaged APV chip

FGT GEM foil

Recent results - W production

- PHENIX A_L mid-rapidity results / projections

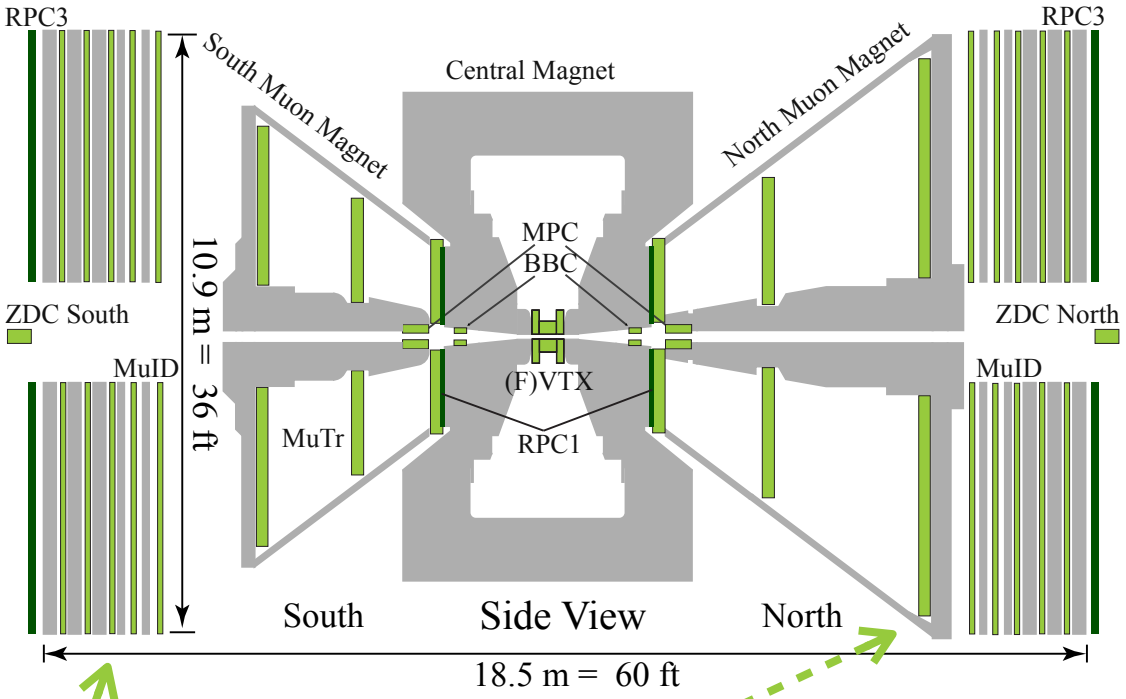




- Run 11/12: First forward rapidity muon results
- Projected uncertainties shown for 300pb^{-1} / 55% and S/B=1

Future prospects - W production / PHENIX

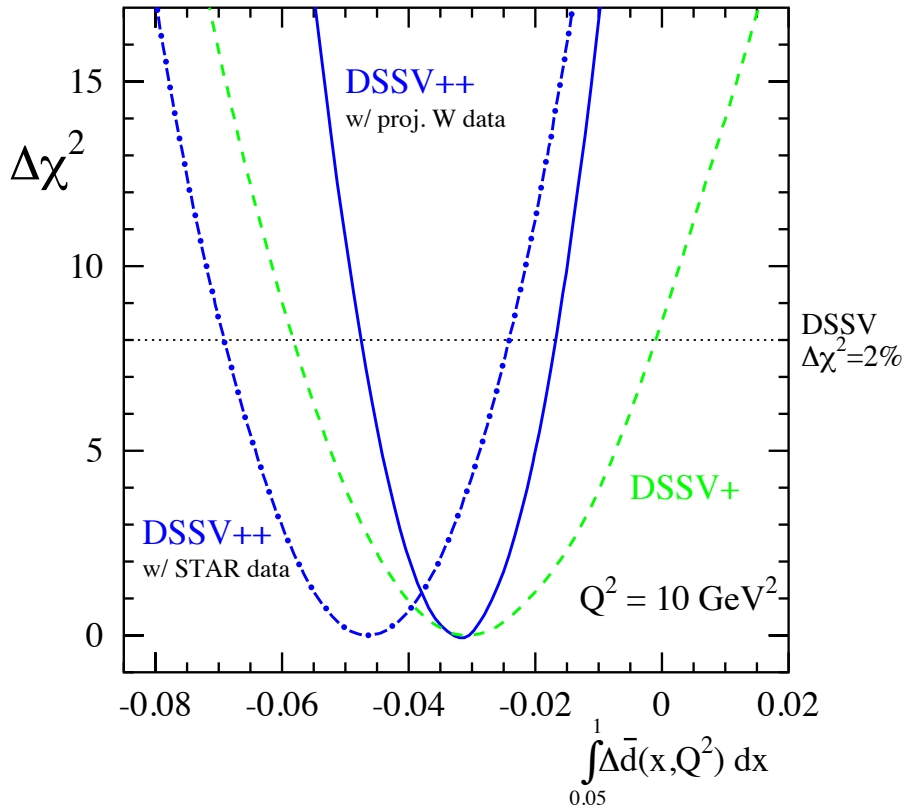
- PHENIX Forward Muon system - Layout

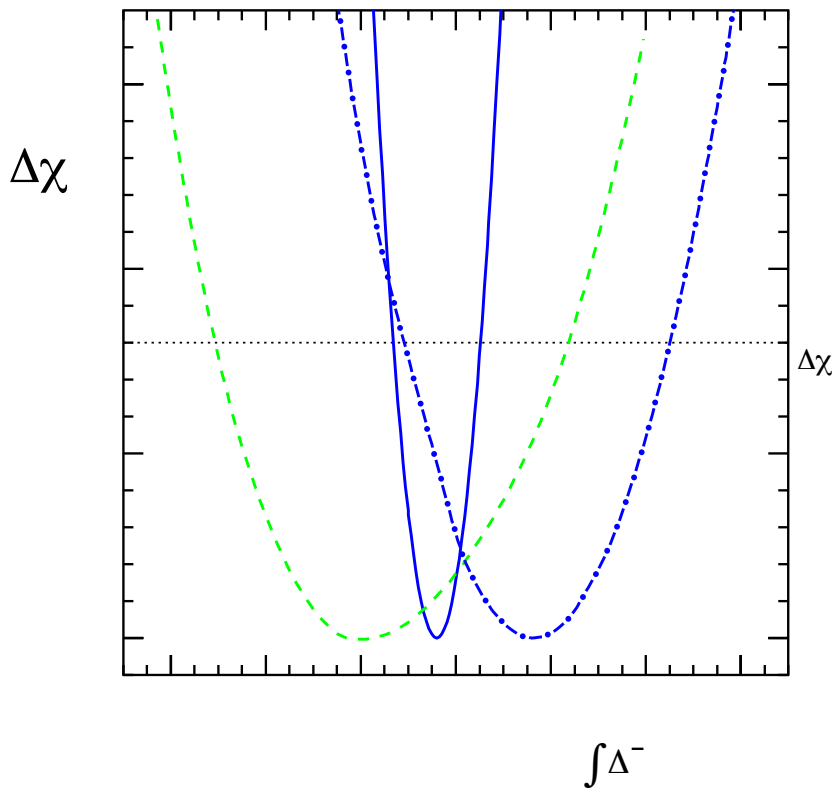


- South Muon Arm and North Muon Arm
- Signal: Isolated high-pT muon, detected with MuTr, MuID, RPC
- Trigger on small Sagitta in magnetic field, MuID and timing cut from BBC
- Reduced collisions background of several MHz to trigger rate of few kHz
- Absorber between vertex, MuTr and interspersed in MuID

Recent results - W production

- Impact of new DSSV result
  - DSSV++ includes 2009 A_{LL} data and 2012 A_L data
  - Significant shift in anti-u quark polarization from W^- Run 12 data





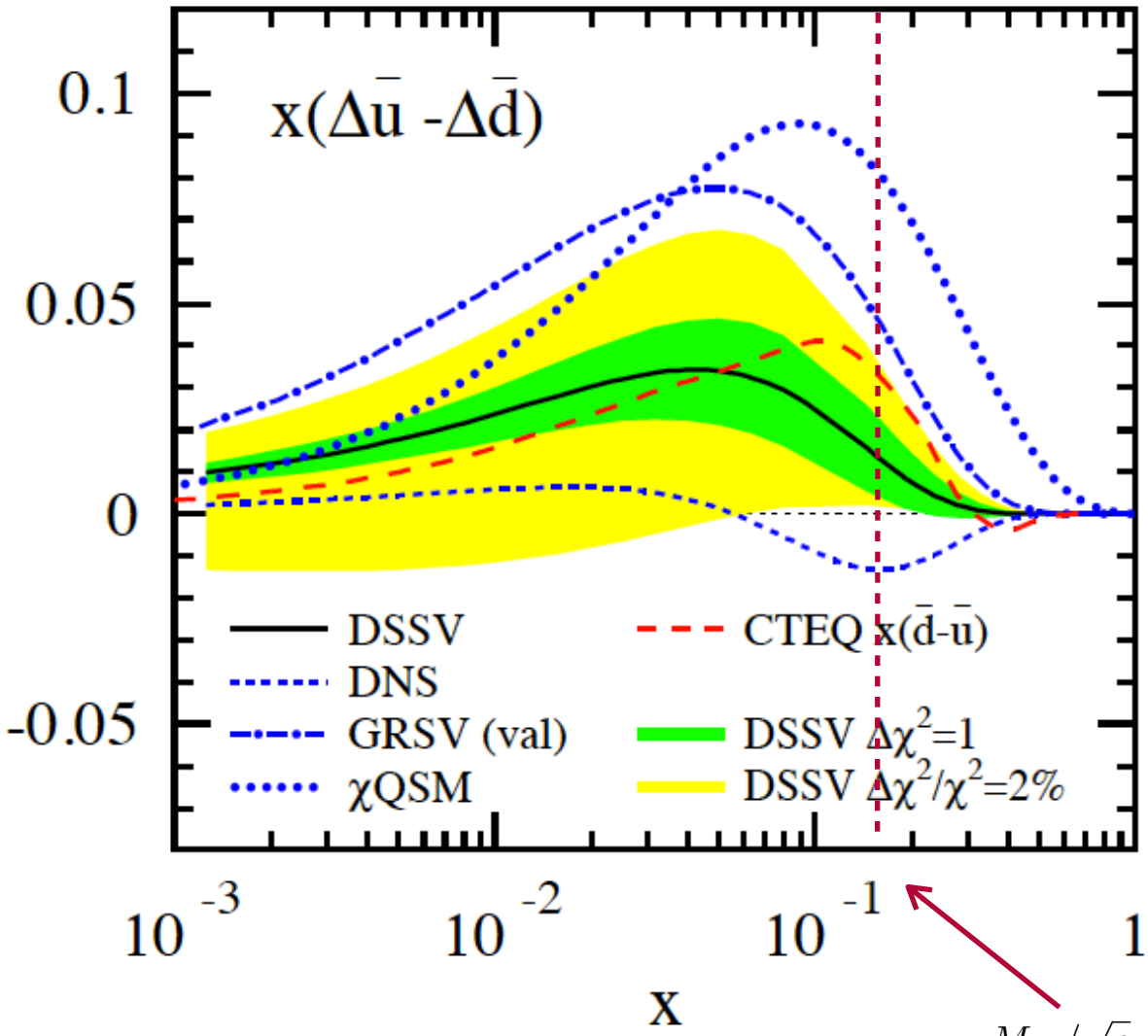
RHIC Spin Collaboration (2012)

Recent results - W production

- Impact of new DSSV result

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

RHIC Spin Collaboration (2012)



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

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

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

Summary / Outlook

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- Gluon polarization program
  - Several final states (Hadron / Jet) have been measured all pointing to the same conclusion that the gluon polarization is small
  - First Di-Jet measurement opens the path to constrain the shape of Δg
  - Run 9 results: Precise A_{LL} measurement suggesting small, non-zero ΔG

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- Run 12 and future
  - Run 12 / Run 13: Long. 510GeV runs in Run 12 (~85pb^{-1} rec.) and Run 13 (~310pb^{-1} rec.)
  - Future: 200GeV production run in Run 15 and likely additional 500GeV running at a later stage