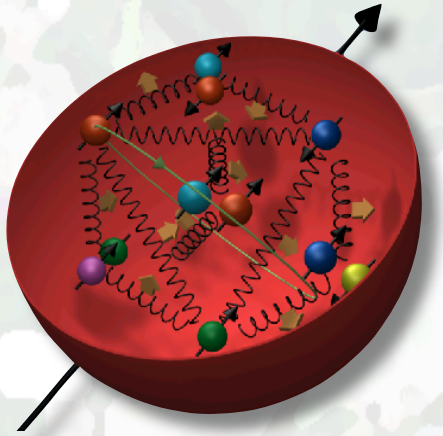
Future perspectives of the high-energy polarized proton-proton program at RHIC

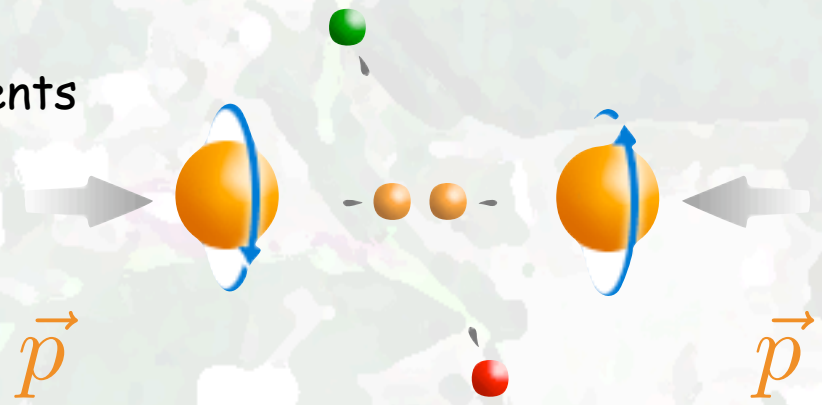
Bernd Surrow

Massachusetts Institute of Technology



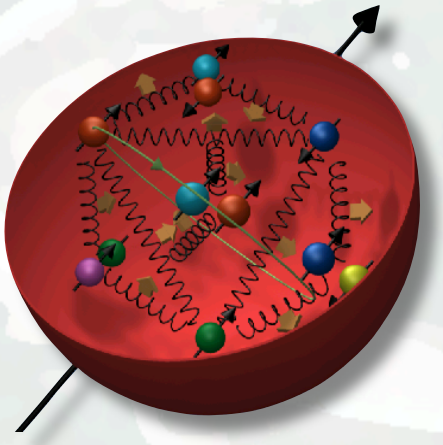
Outline

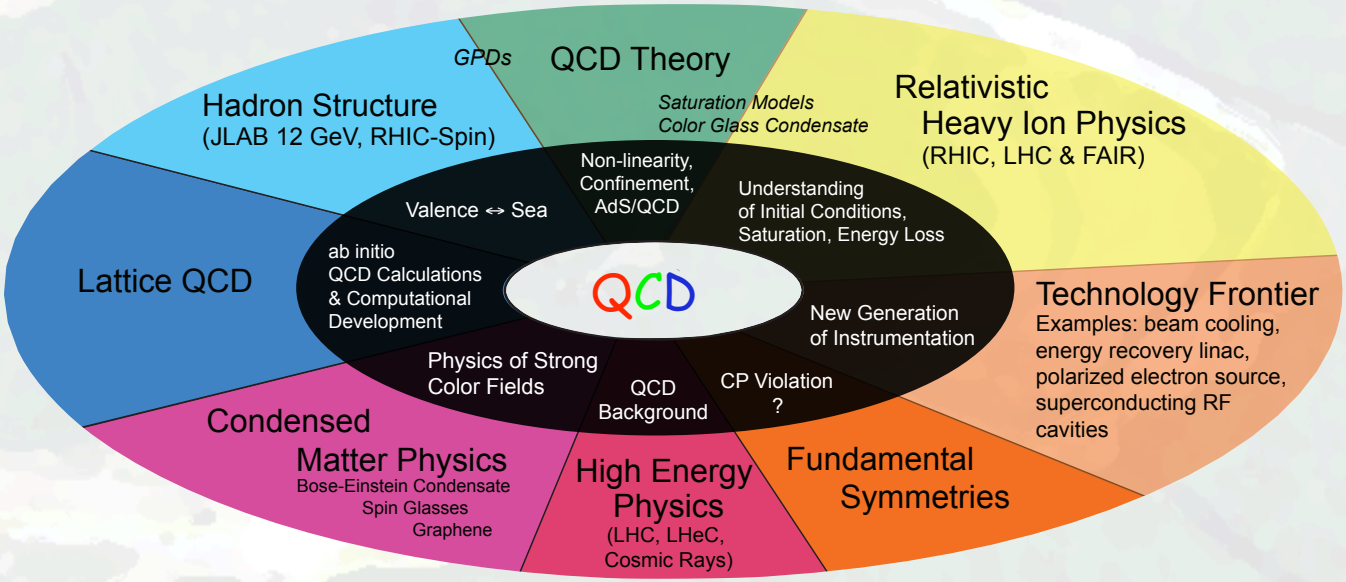
- Future polarized p-p collider performance
- Future polarized p-p physics program
  - Gluon polarization
  - Quark / Anti-Quark Polarization
  - Transverse spin dynamics
- Highlights of recent results and achievements
- Theoretical foundation
- Summary and Outlook



Theoretical foundation

- Exploring the proton spin structure and dynamics





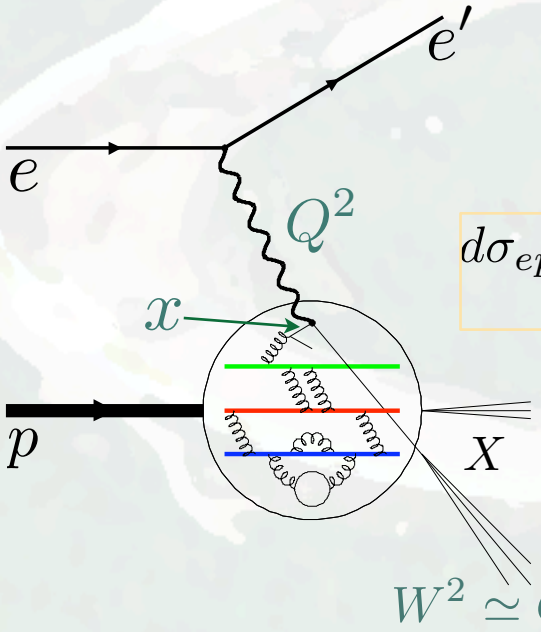
Structure and dynamics of proton (**mass**) (→ visible universe) originates from QCD-interactions!

What about **spin** as another fundamental quantum number?

Synergy of experimental progress and theory (Lattice QCD / Phenomenology incl. phenomenological fits / Modeling) critical!

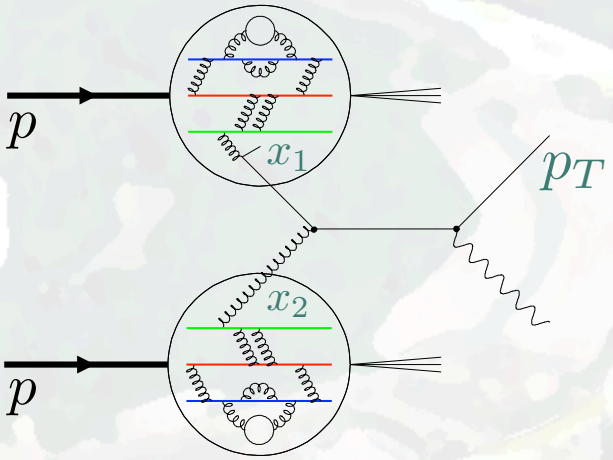
Theoretical foundation

General



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

Universality



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

Momentum contribution

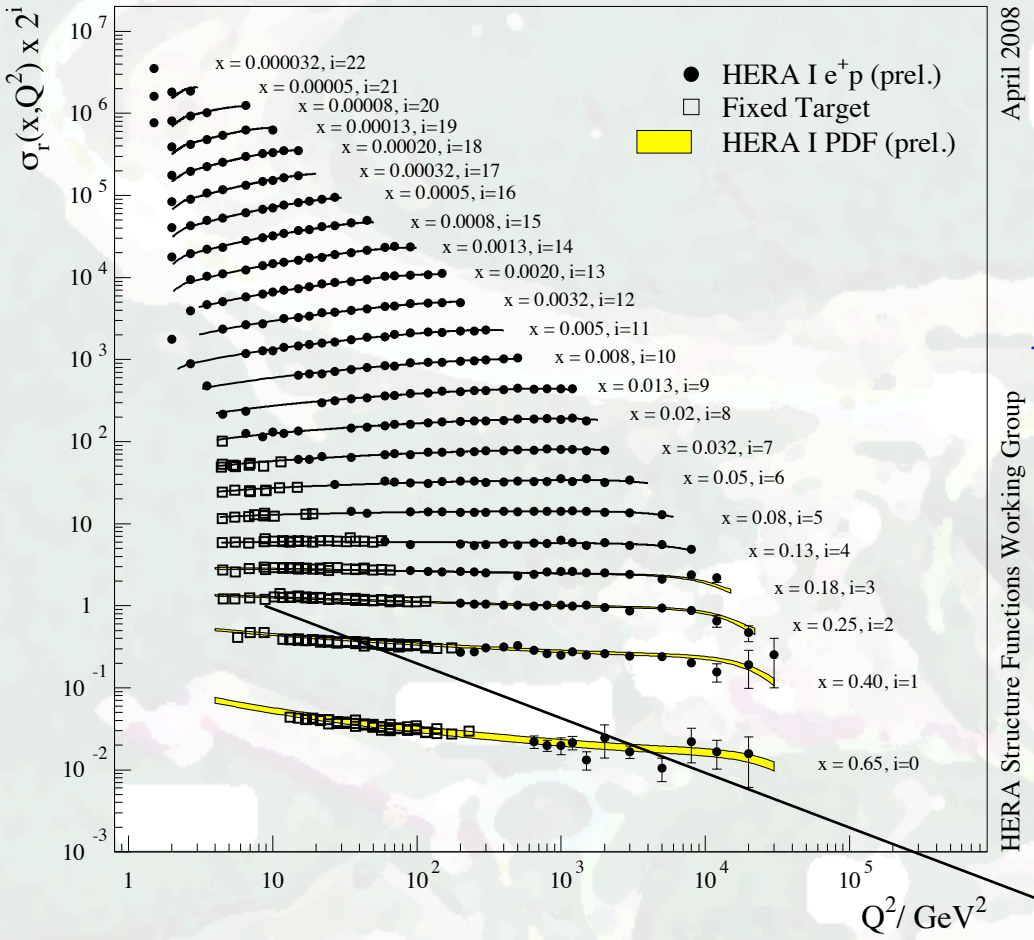
$$f(x) = f^+(x) + f^-(x)$$

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

Spin contribution

Theoretical foundation

- Precision measurements (e.g. F_2) ⇒ Precision on quark/gluon structure

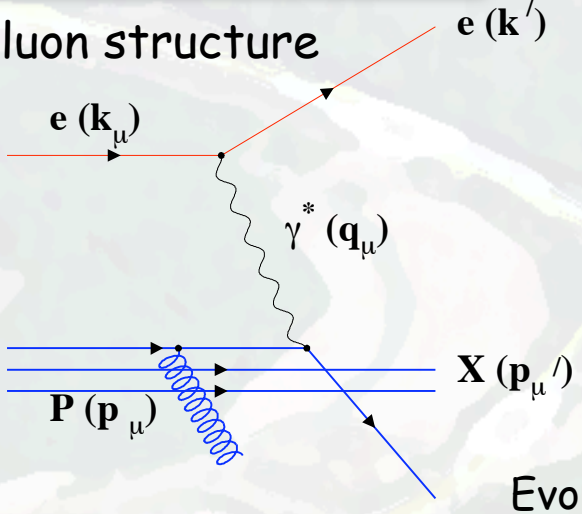


Strong violation of scaling at low x and high Q^2

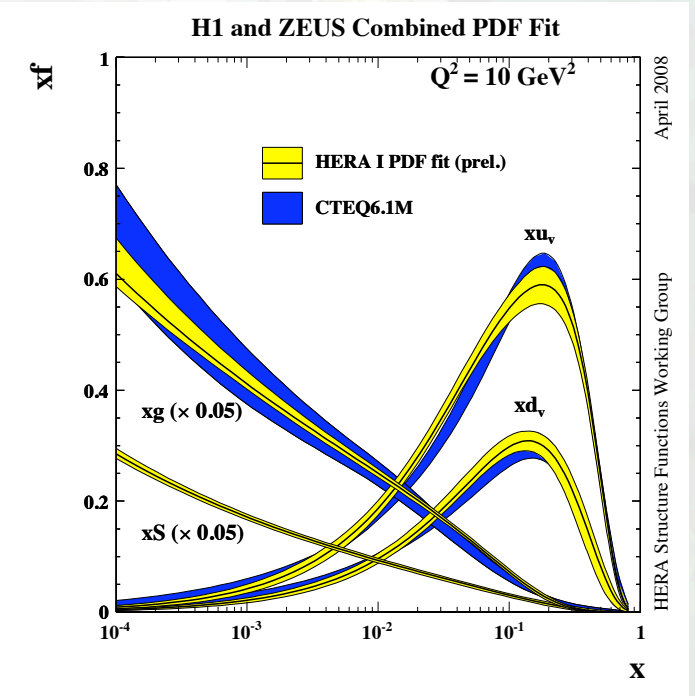
$$xg \propto \left(\frac{dF_2}{d\ln Q^2}\right)$$

In contrast to:

Low Q^2 high x!



Evolution



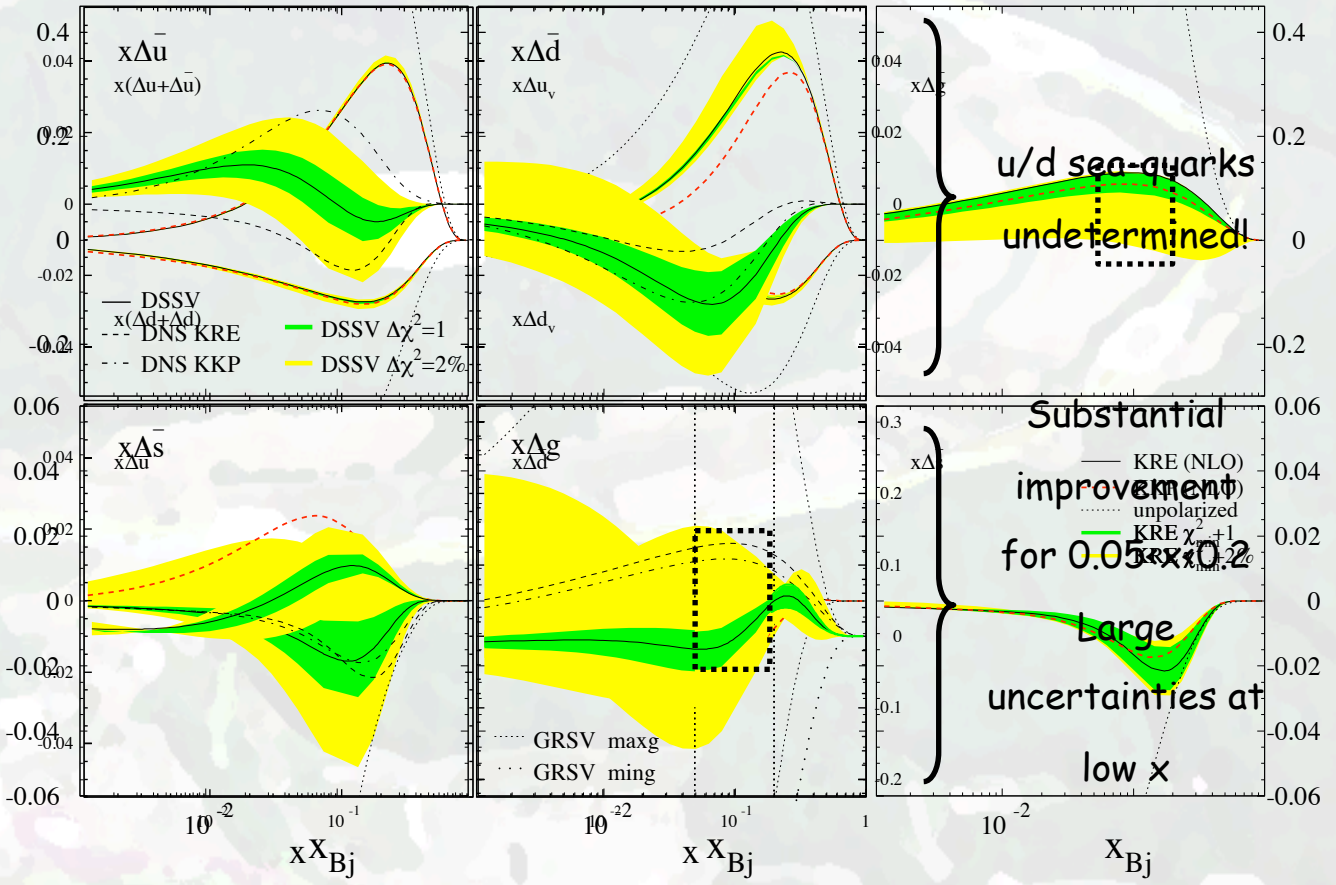
Theoretical foundation

- What do we know about the polarized quark and gluon distributions?
  - Spin carried by quarks is very small ($\Delta\Sigma \sim 0.4$)!

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

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

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



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

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

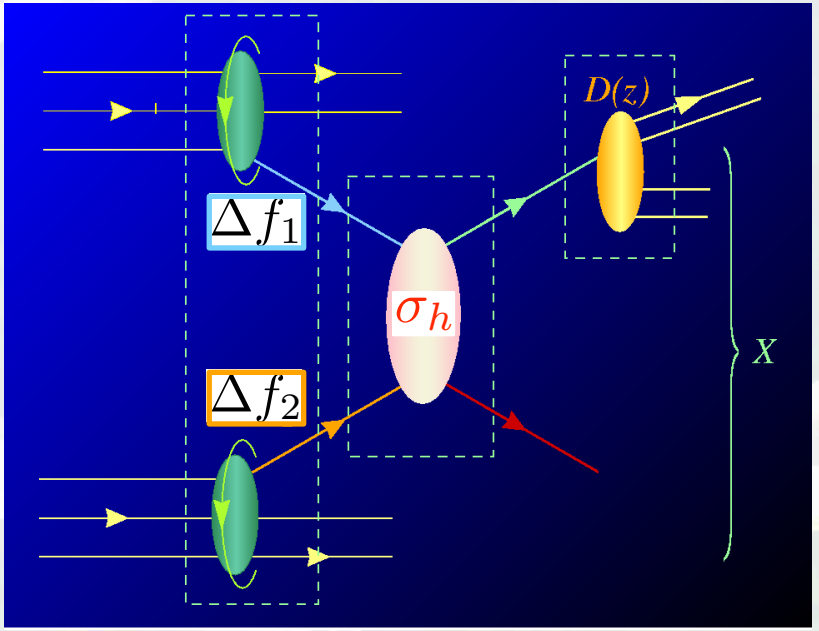
$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)dx$$

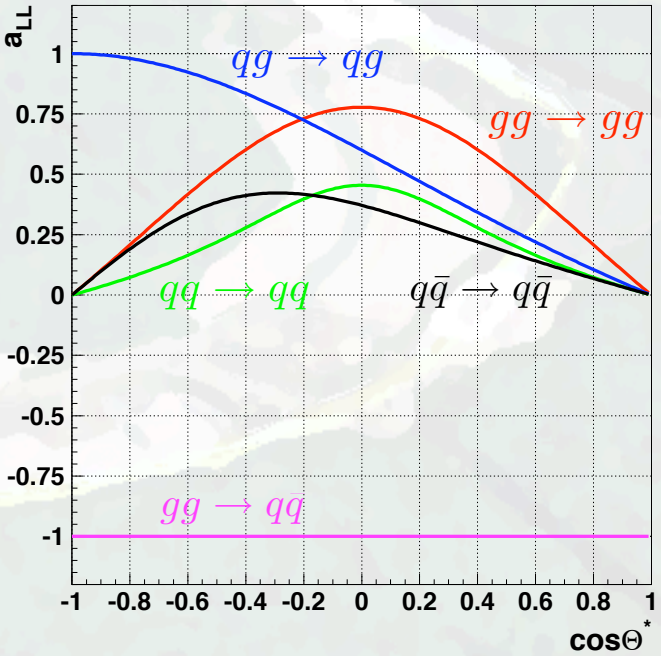
Theoretical foundation

- Gluon polarization - Extraction

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

Extract $\Delta g(x,Q^2)$ through Global Fit (Higher Order QCD analysis)!





$$A_{LL} = \frac{d\Delta\sigma}{d\sigma}$$

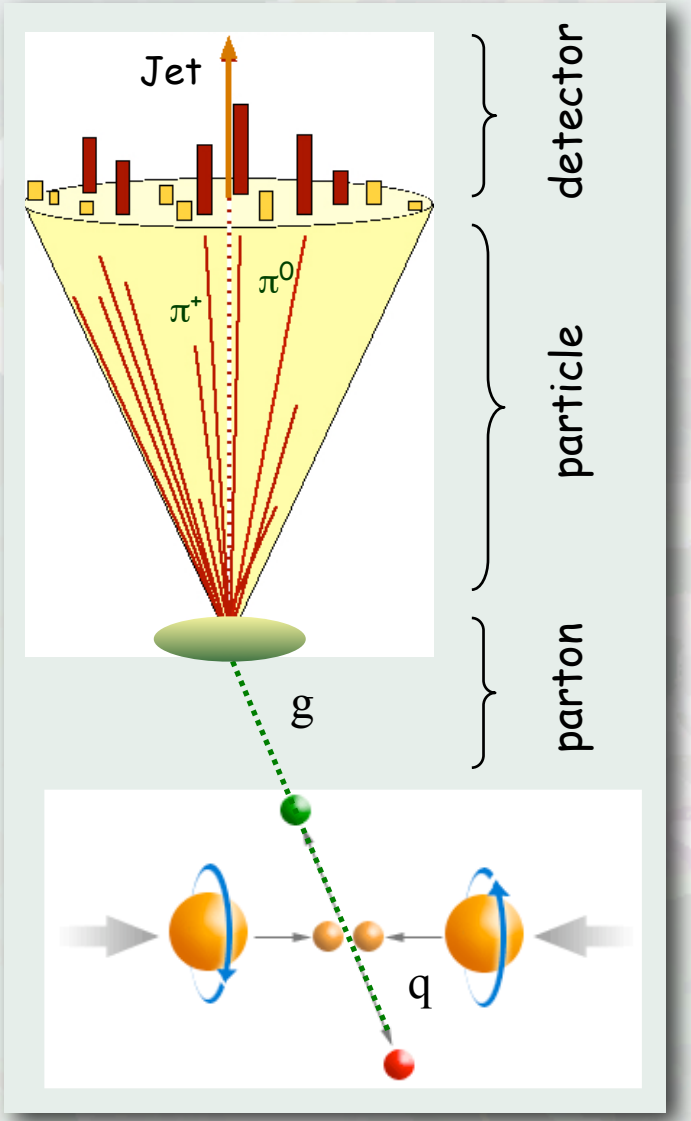
$$\propto \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

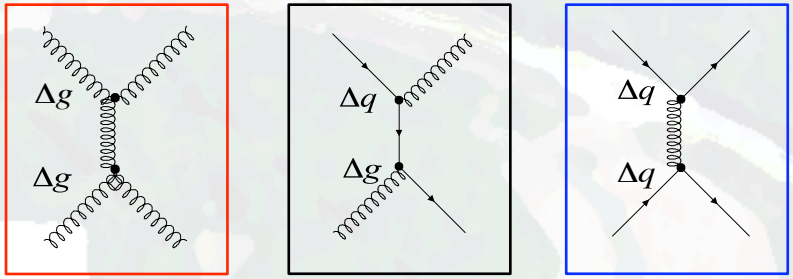
$$a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$$

Input

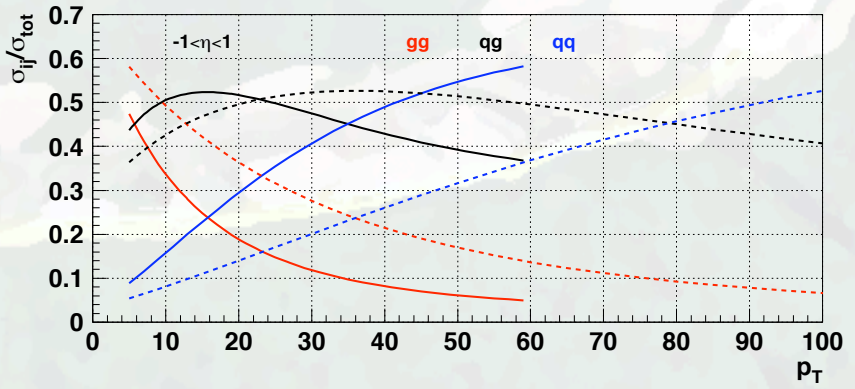
Theoretical foundation

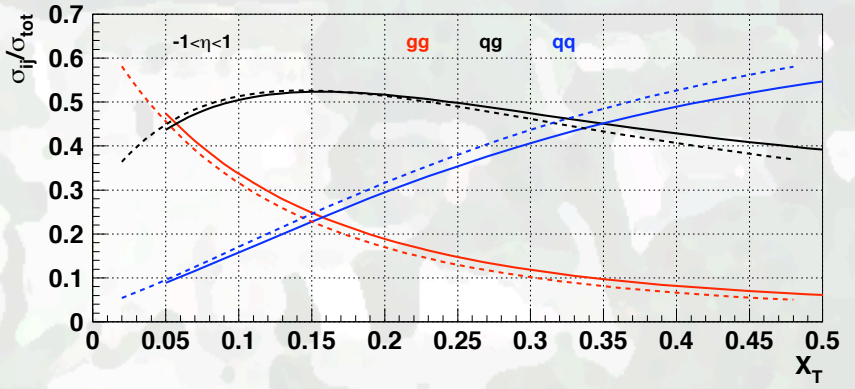
Gluon polarization - Inclusive Measurements





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



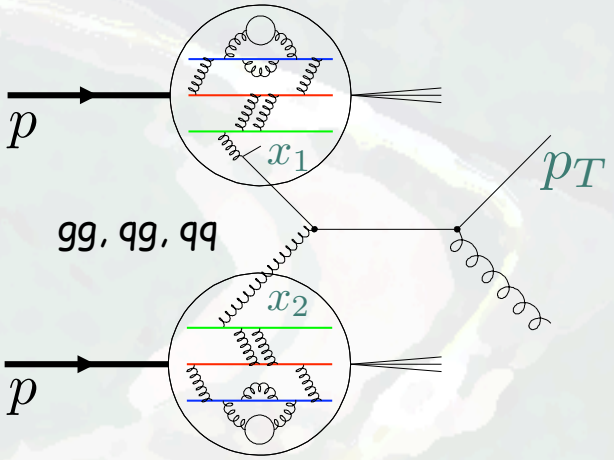


$$x_T = 2p_T/\sqrt{s}$$

Theoretical foundation

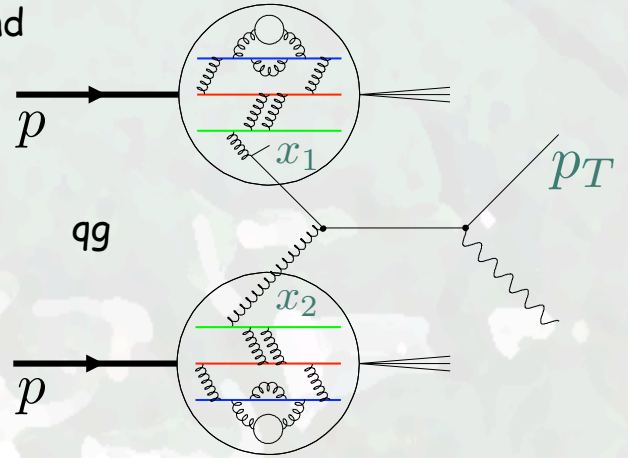
- Gluon polarization - Correlation Measurements
  - Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production

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



Di-Jet production

  - Di-Jet production / Photon-Jet production
    - Di-Jets: All three (LO) QCD-type processes contribute: gg, qg and gg with relative contribution dependent on topological coverage
    - Photon-Jet: One dominant underlying (LO) process
    - Larger cross-section for di-jet production compared to photon related measurements
    - Photon reconstruction more challenging than jet reconstruction
    - Full NLO framework exists ⇒ Input to Global analysis

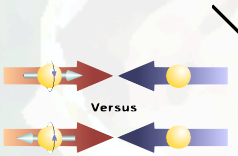


Photon-Jet production

Theoretical foundation

Quark / Anti-Quark Polarization - W production

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



$$W^- \rightarrow e^- + \bar{\nu}_e$$

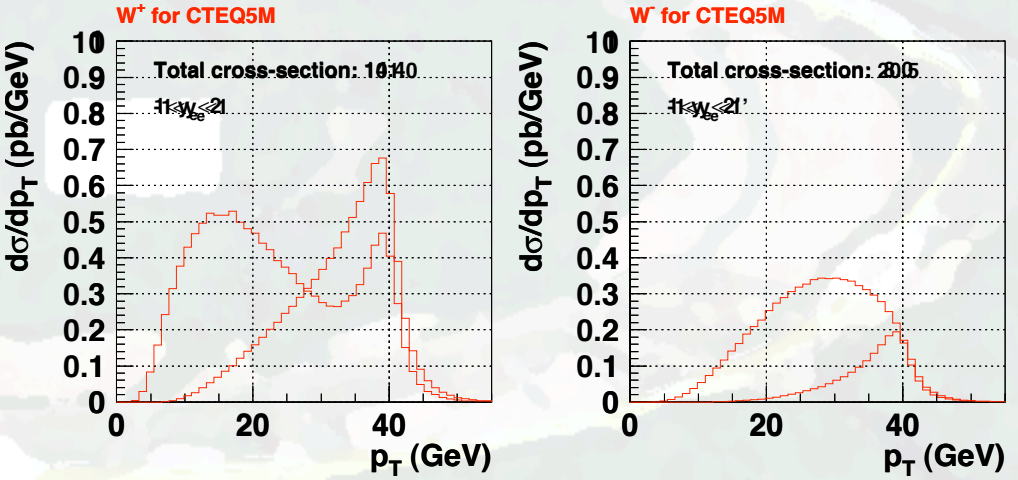
$$W^{\mp}$$

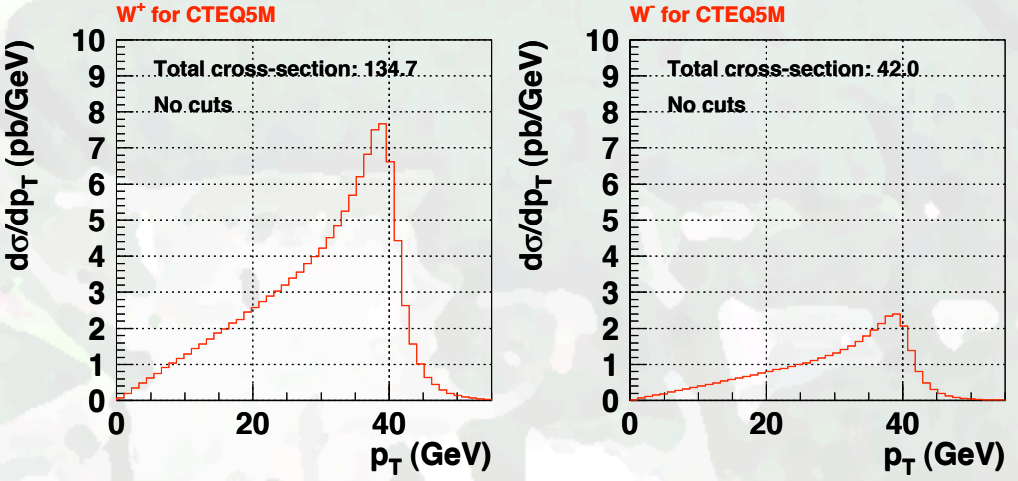
$$A_L^W = \frac{1}{P}\frac{N^+(W) - N^-(W)}{N^+(W) - N^-(W)}$$

$$W^+ \rightarrow e^+ + \nu_e$$

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

RHICBOS W simulation at 500GeV CME

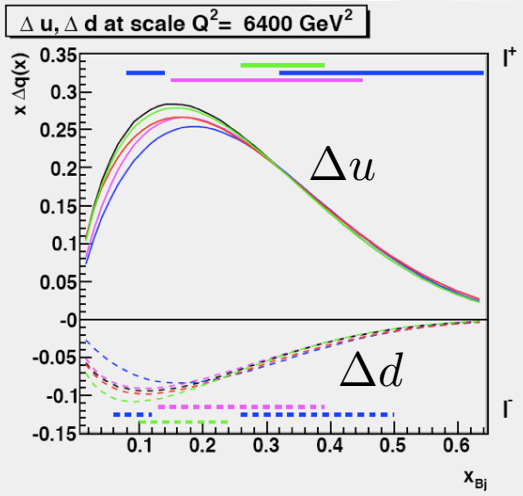


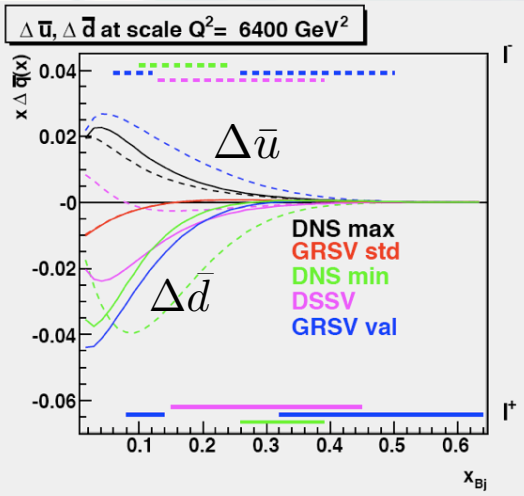


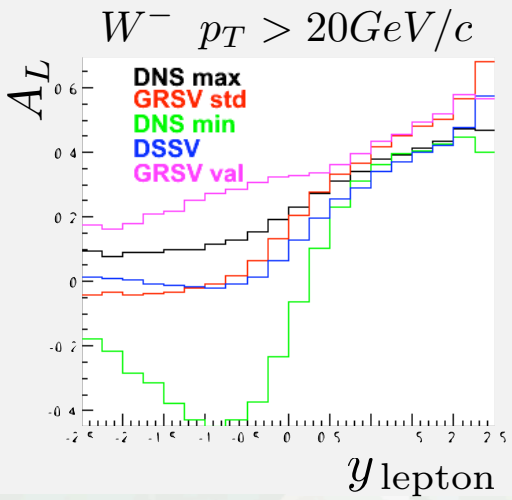
- Key signature: High p_T lepton (e^-/e^+ or μ^-/μ^+) (Max. $M_W/2$) - Selection of W^-/W^+ : Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination

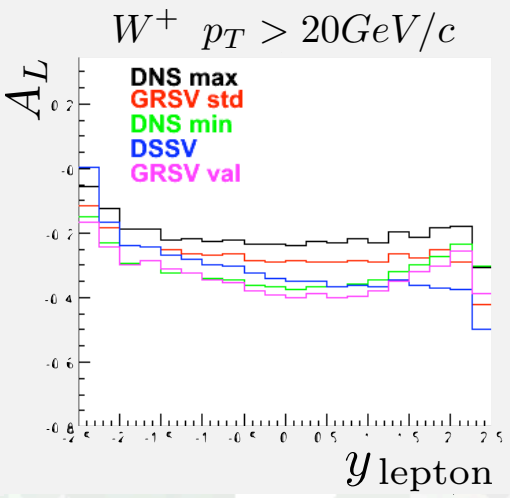
Theoretical foundation

Quark / Anti-Quark Polarization - Sensitivity in W production









- Theoretical framework for leptonic asymmetries exists (RHICBOS) ⇒ Basis for input to global analysis!
- Reconstruction of W-rapidity only possible in approximative way in forward direction
- Important contribution from forward and mid-rapidity region

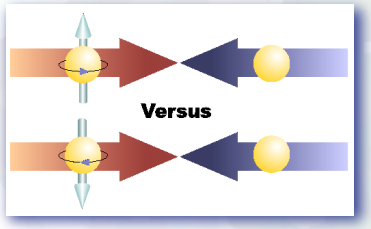
$$A_L^{W^-} = -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}}e^{y_W} \qquad x_2 = \frac{M_W}{\sqrt{s}}e^{-y_W}$$

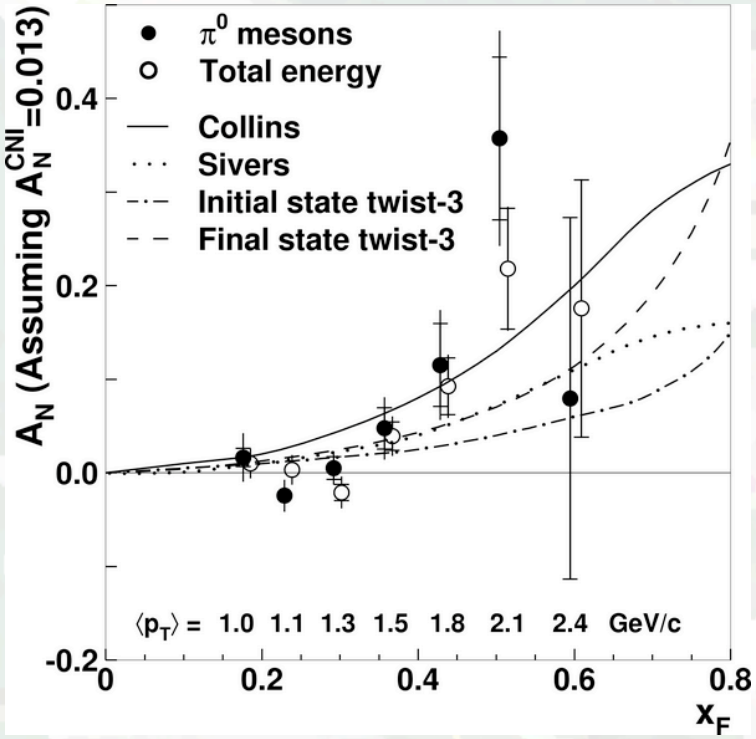
- Large uncertainties for polarized anti-quarks reflected in leptonic asymmetries!

Theoretical foundation

- Transverse spin dynamics
  - Single transverse-spin asymmetry



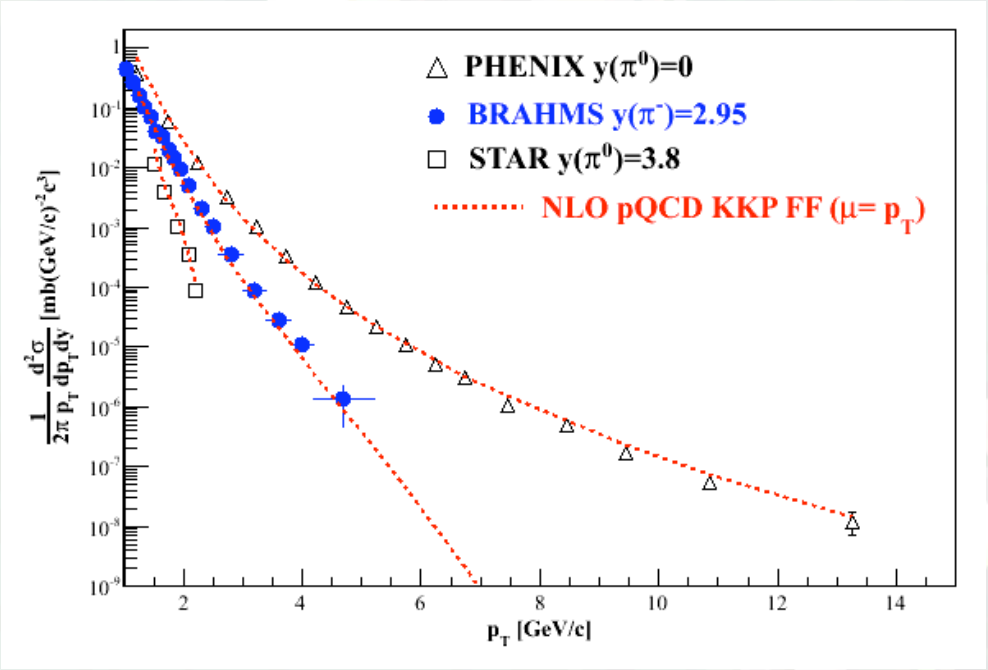
$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

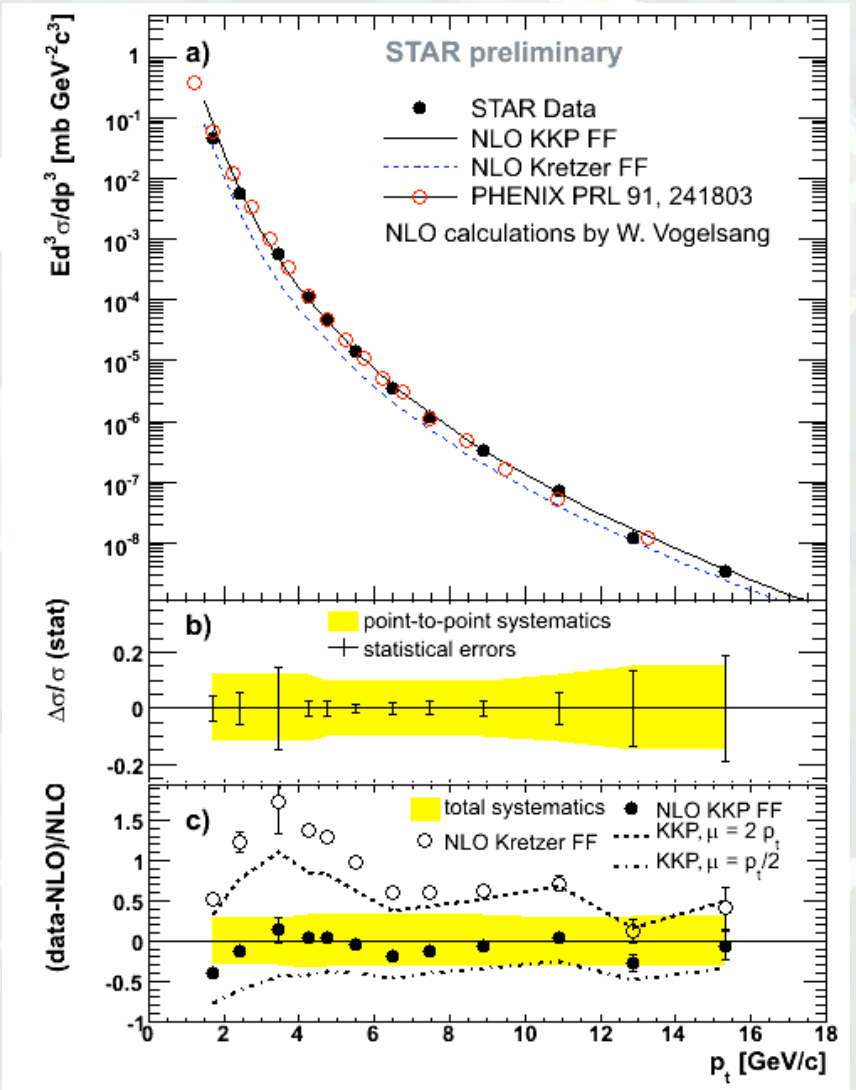


  - Basic, naive QCD calculations (leading-twist, zero quark masses) predict: A_N=0 ($A_N \sim m_q/\sqrt{s}$)
  - Study transverse spin effects:
    - Qiu and Sterman (Initial-state twist-3)/ Koike (final-state twist-3)
    - Sivers: $k_\perp$ in initial state (Correlation of quark $k_\perp$ and transverse proton spin): ⇒ Orbital momentum
    - Collins: $k_\perp$ in final state (Correlation of transverse quark spin and $k_\perp$ of hadron): ⇒ Transversity

Highlights of recent results and achievements

Cross Section Results

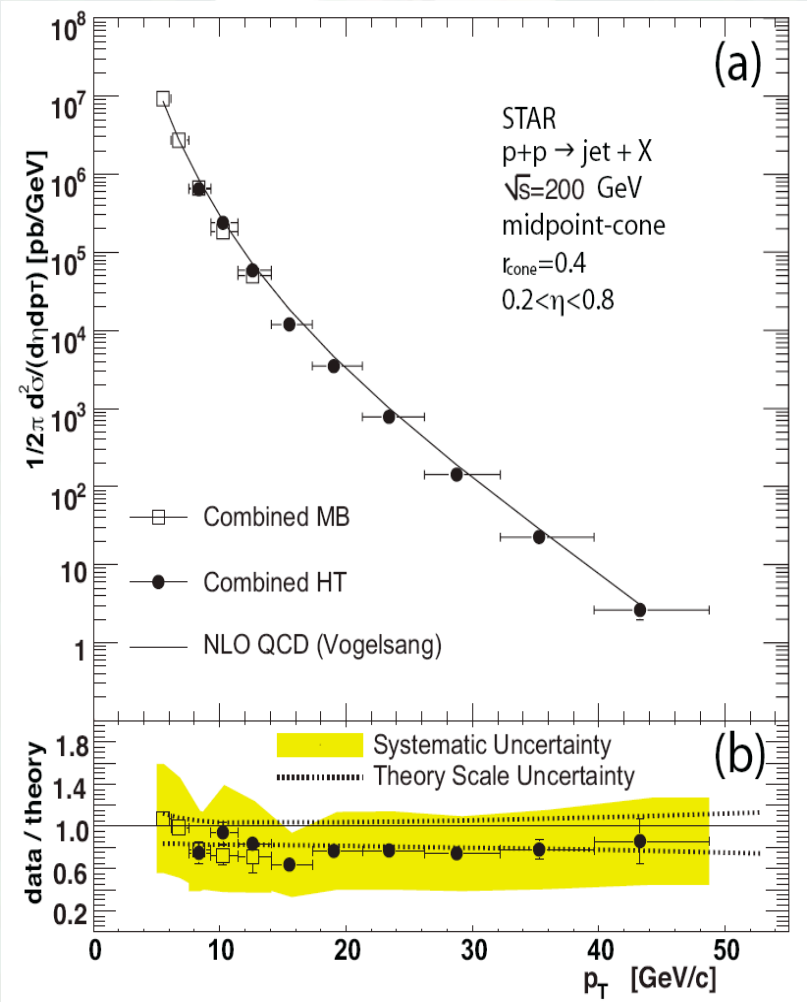


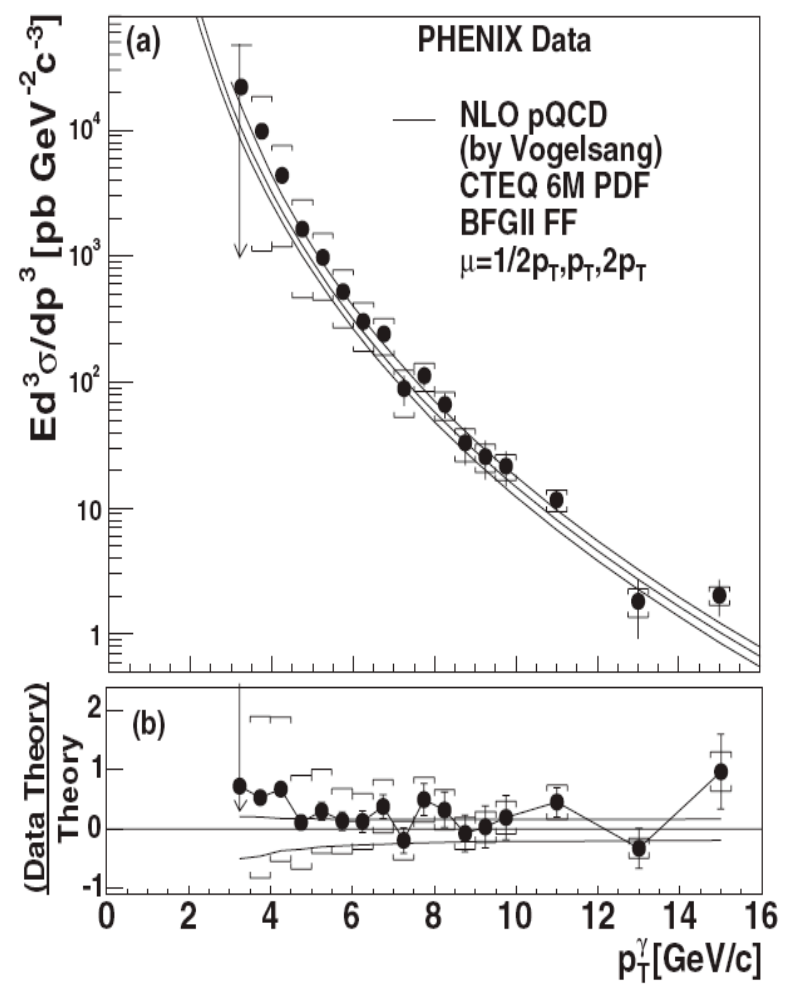


- Good agreement between data and NLO calculations for neutral pion production at forward and central rapidity

Highlights of recent results and achievements

Cross Section Results

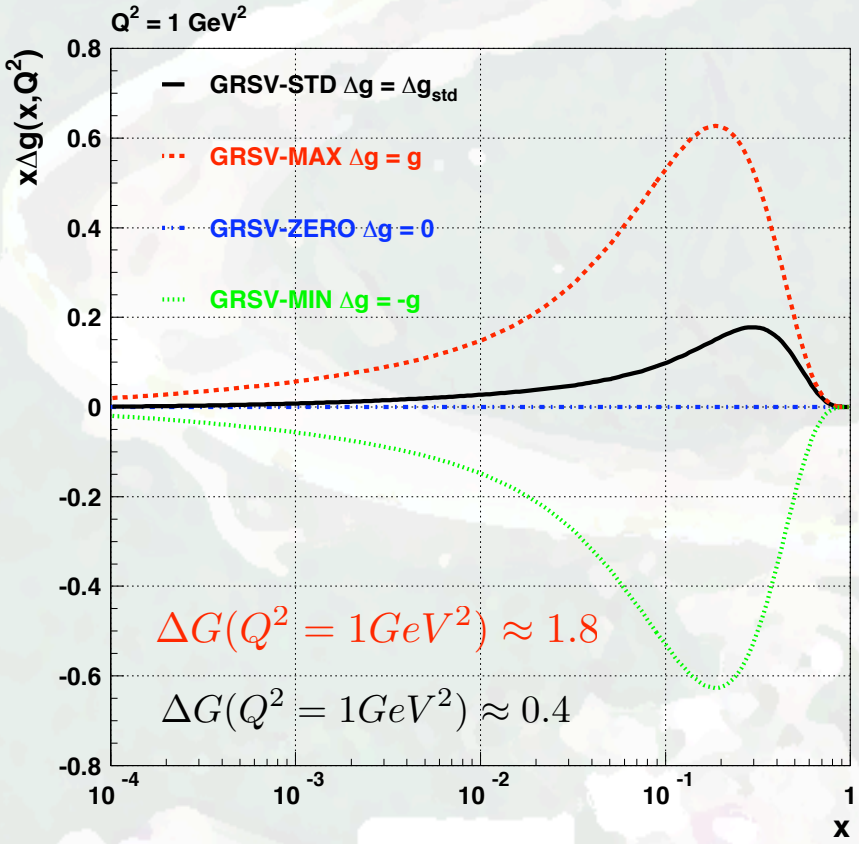


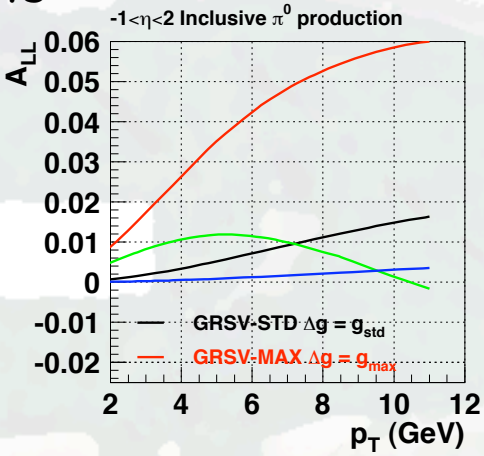


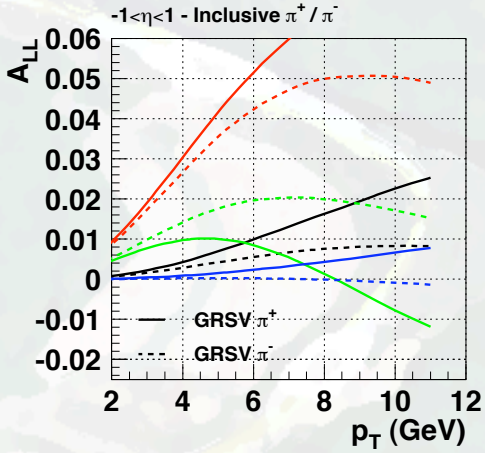
- Good agreement between data and NLO calculations for jet production and prompt photon production at central rapidity

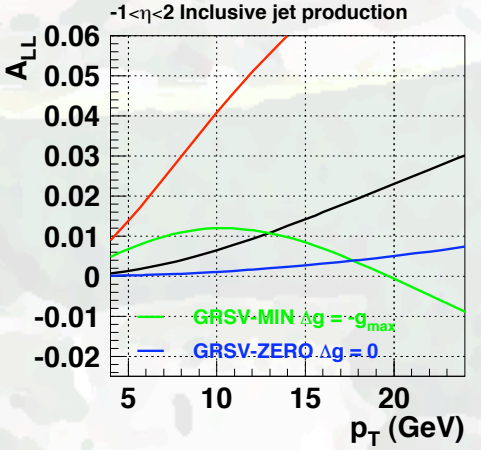
Highlights of recent results and achievements

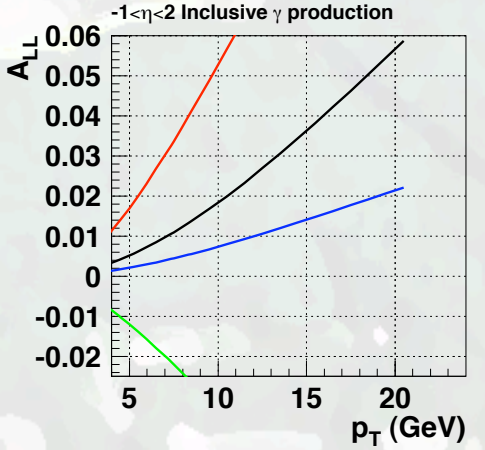
Gluon polarization - Inclusive Measurements











- Examine wide range in Δg: $-g < \Delta g < +g$

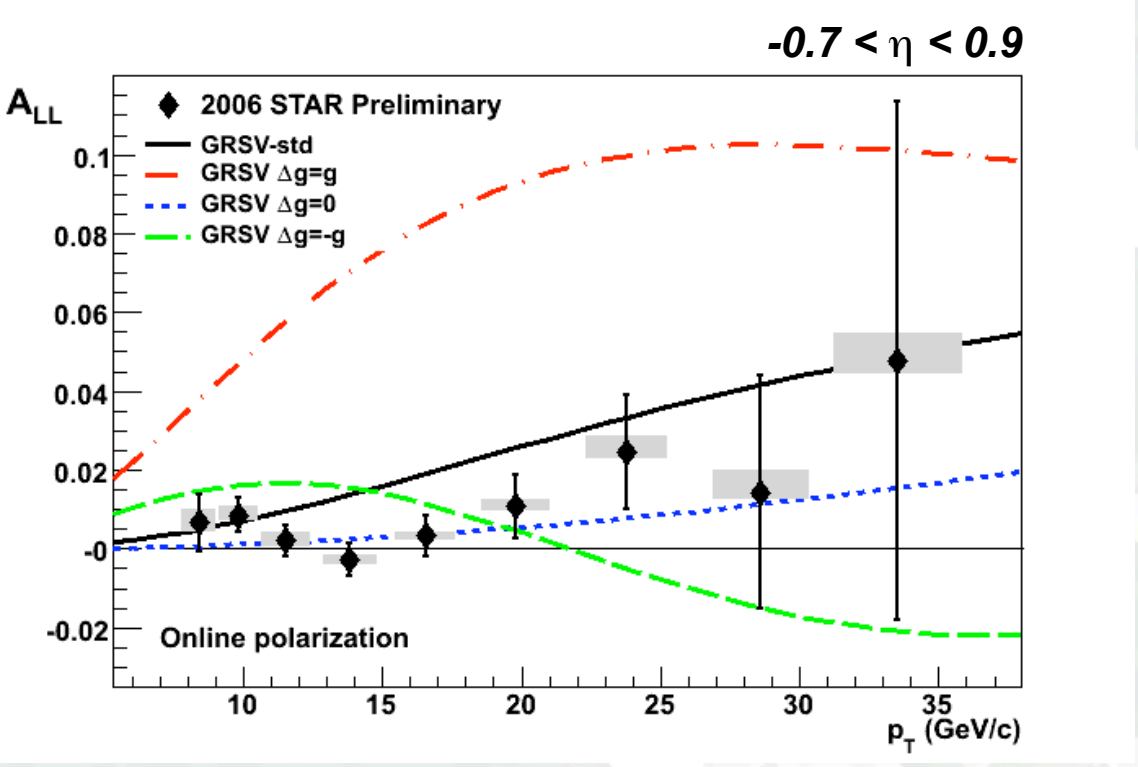
- GRSV-STD: Higher order QCD analysis of polarized DIS experiments!

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

$$x_{\mathrm{parton}} \simeq 2p_T/\sqrt{s}$$

Highlights of recent results and achievements

A_{LL} Results - Inclusive Jet Production

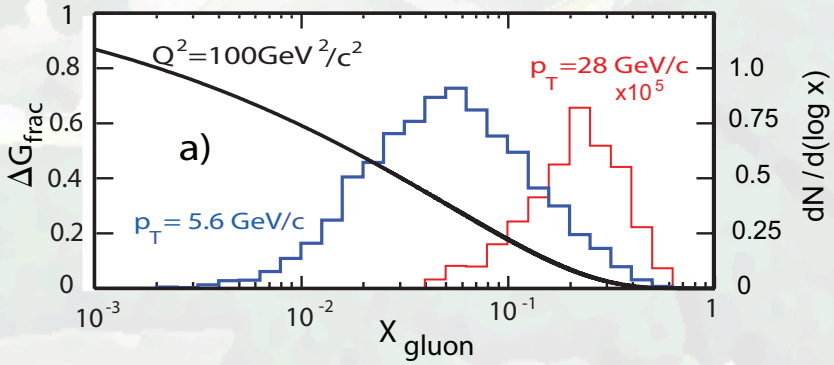


$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

$$\Delta G(Q^2 = 1\,\mathrm{GeV}^2) \approx 1.8$$

$$\Delta G(Q^2 = 1\,\mathrm{GeV}^2) \approx 0.4$$

$$x_{\mathrm{parton}} \simeq 2p_T/\sqrt{s}$$



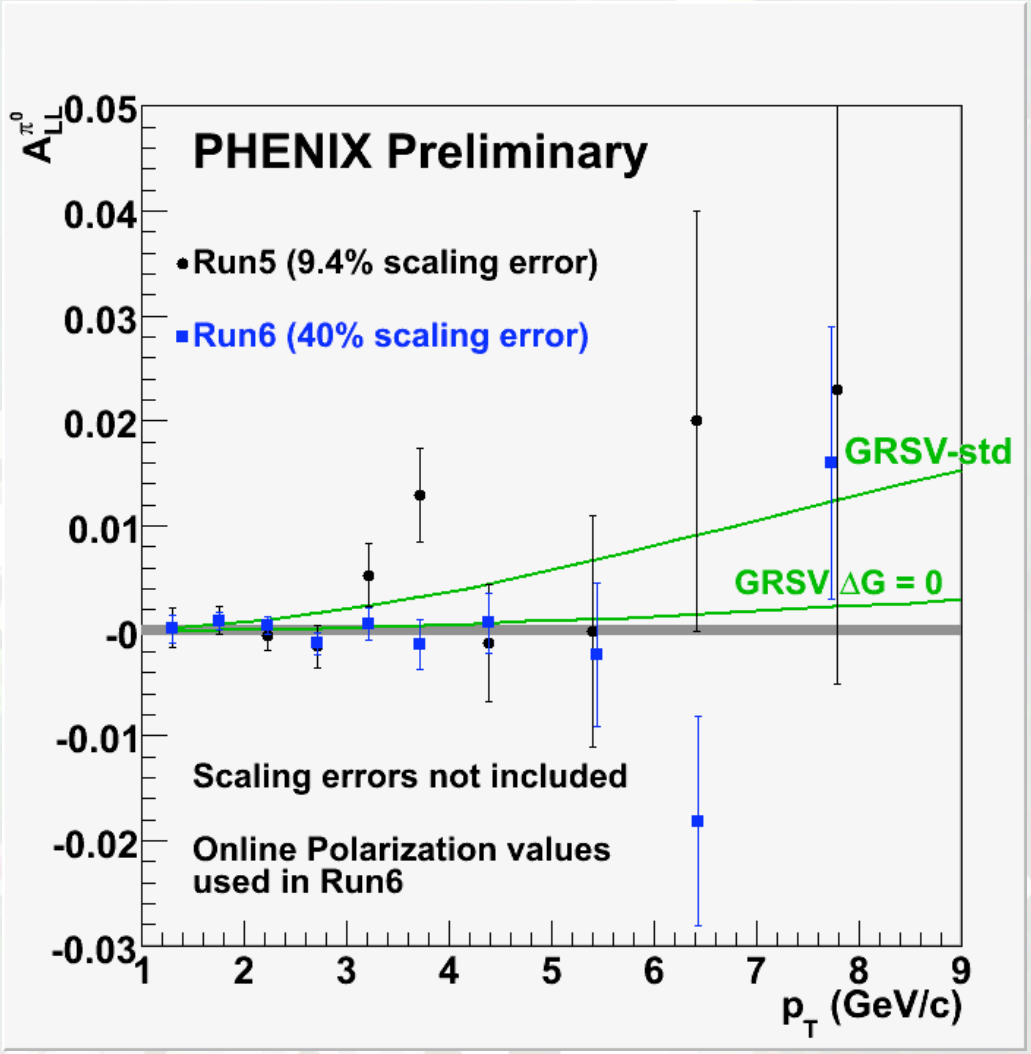
- RUN 6 results: GRSV-MAX / GRSV-MIN ruled out - A_{LL} result favor a gluon polarization in the measured x-region which falls in-between GRSV-STD and GRSV-ZERO
- Consistent with RUN 5 result (Factor 3-4 improved statistical precision for p_T>13GeV/c)

Highlights of recent results and achievements

- A_{LL} Results - Neutral pion production

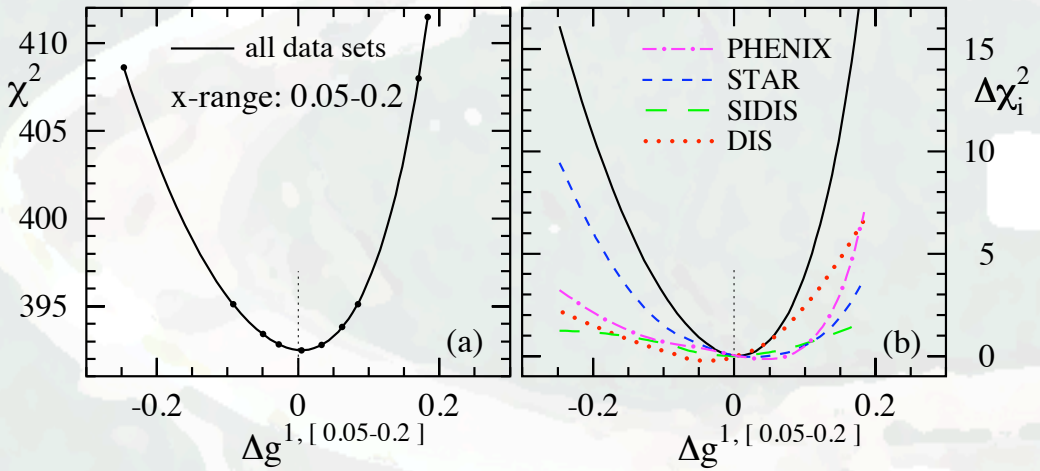
  - Consistent RUN 5/6 results

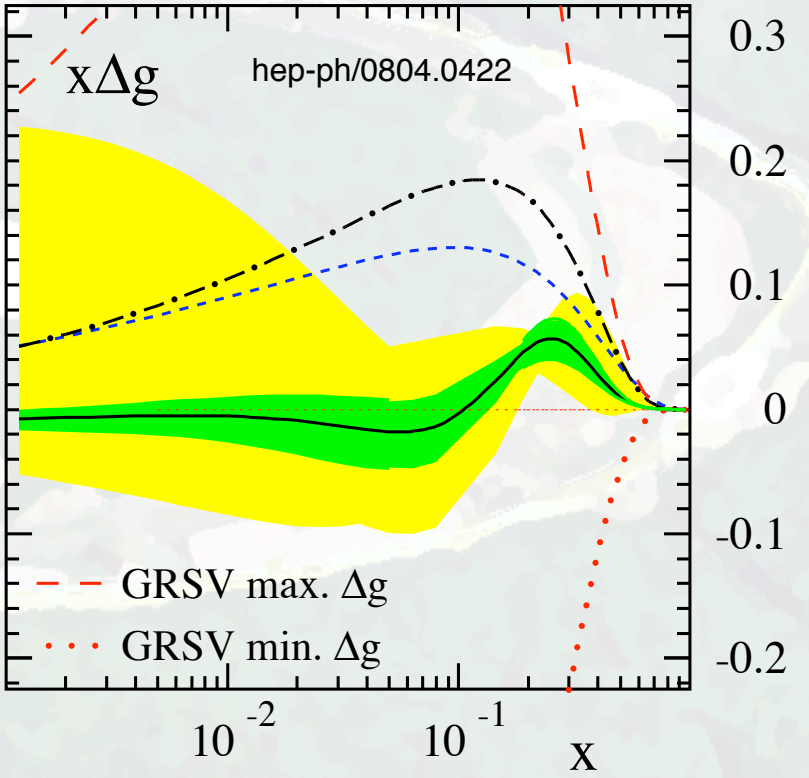
  - RUN 6 results: A_{LL} result favor a gluon polarization in the measured x-region which falls in-between GRSV-STD and GRSV-ZERO



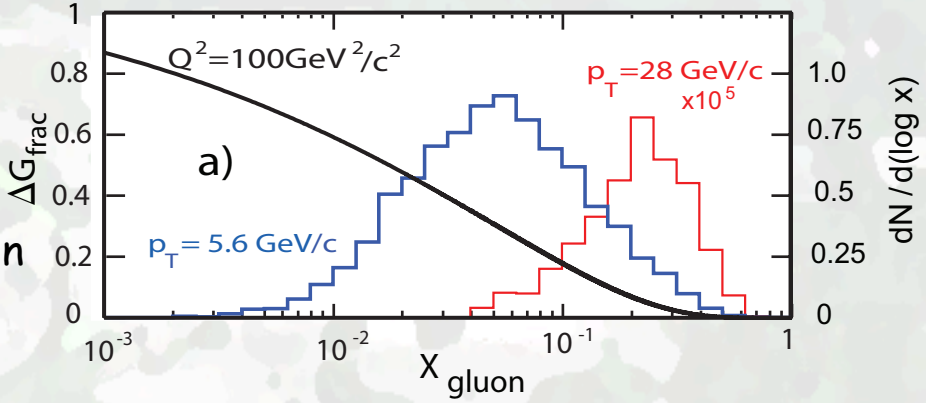
Highlights of recent results and achievements

- Global analysis incl. RHIC pp data



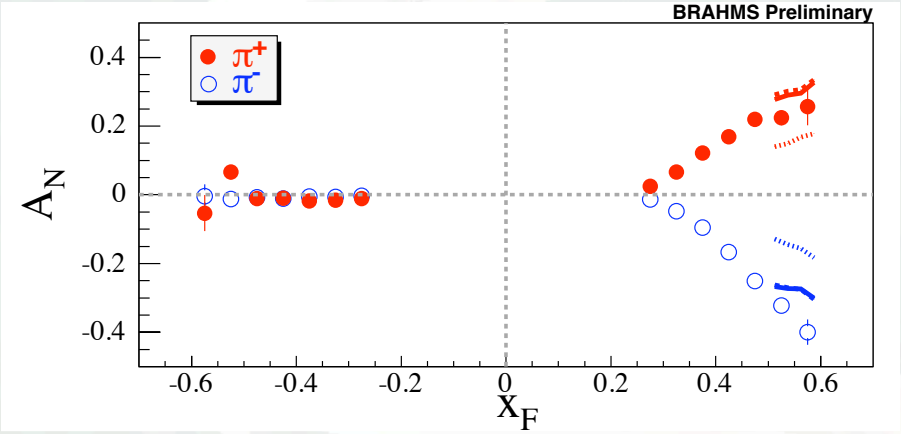


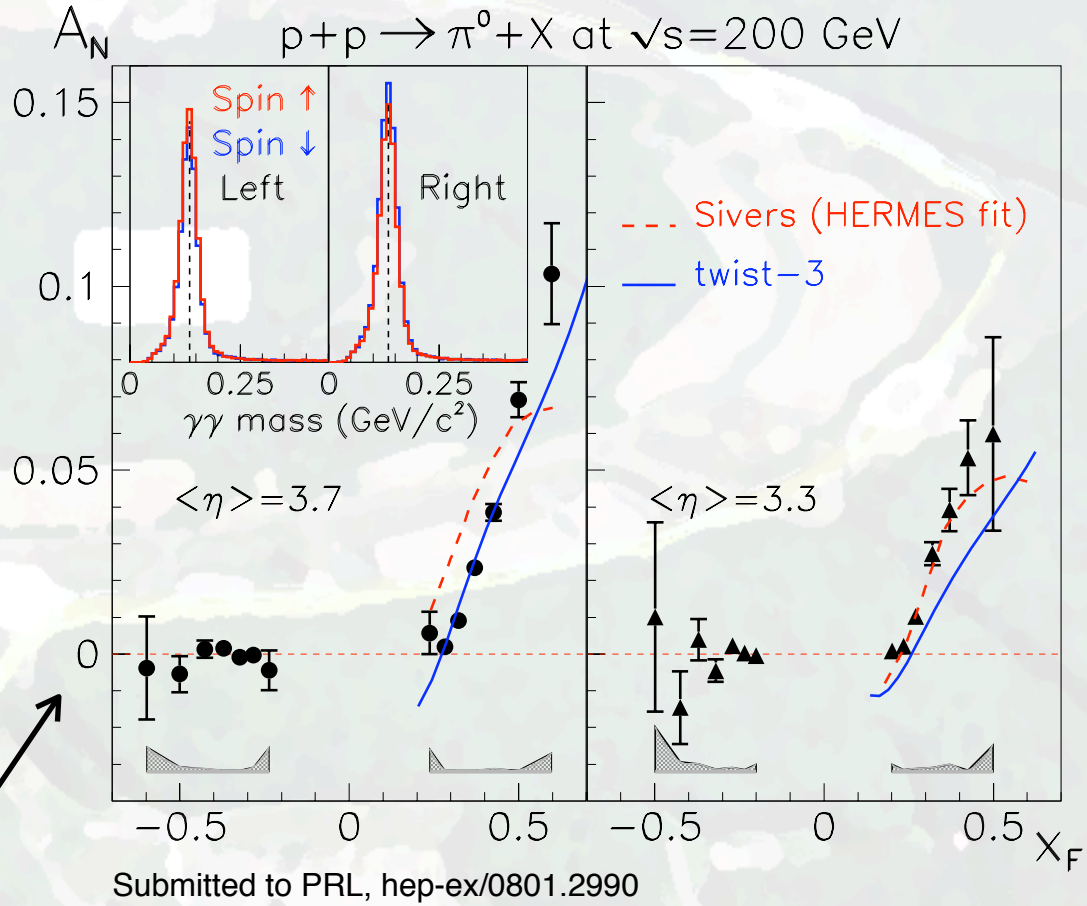
- Strong constraint on the size of Δg from RHIC data for $0.05<x<0.2$
- Evidence for a small gluon polarization over a limited region of momentum fraction
- Important: Mapping x-dependence and extension of x-coverage needed!



Highlights of recent results and achievements

- A_N results



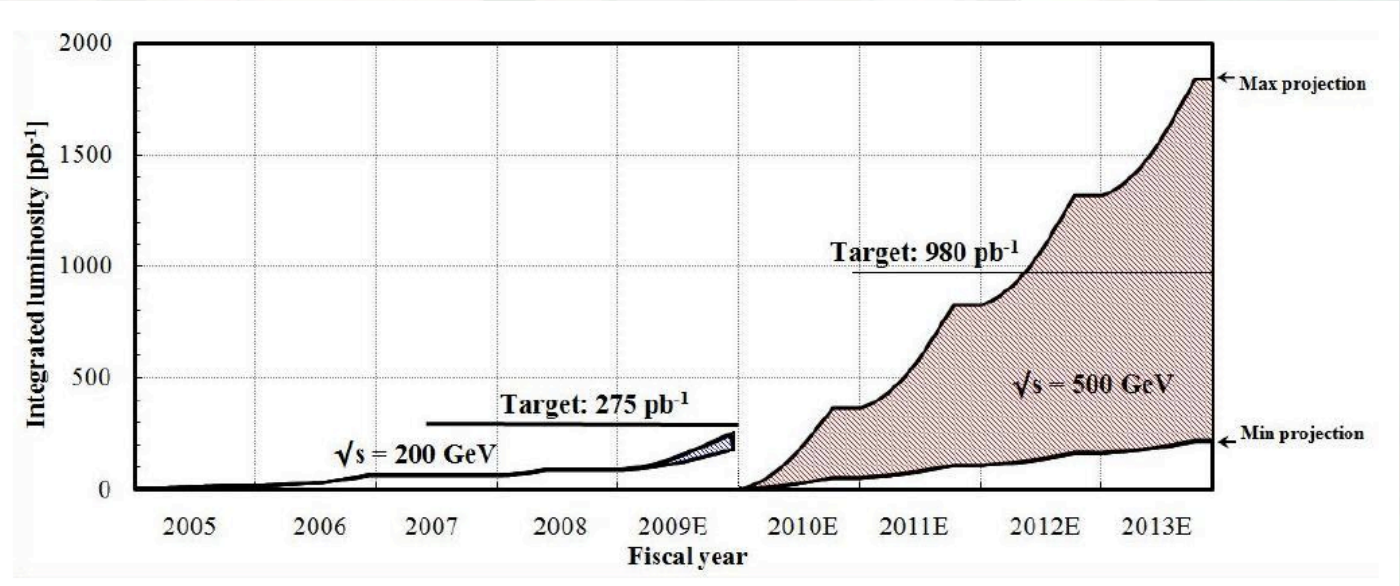


Submitted to PRL, hep-ex/0801.2990

- Precise measurement of A_N as a function of x_F
- A_N calculations (Sivers / Twist-3) in comparison to precise x_F dependence of measured $A_N \Rightarrow$ Constrain models!

Future polarized p-p collider performance

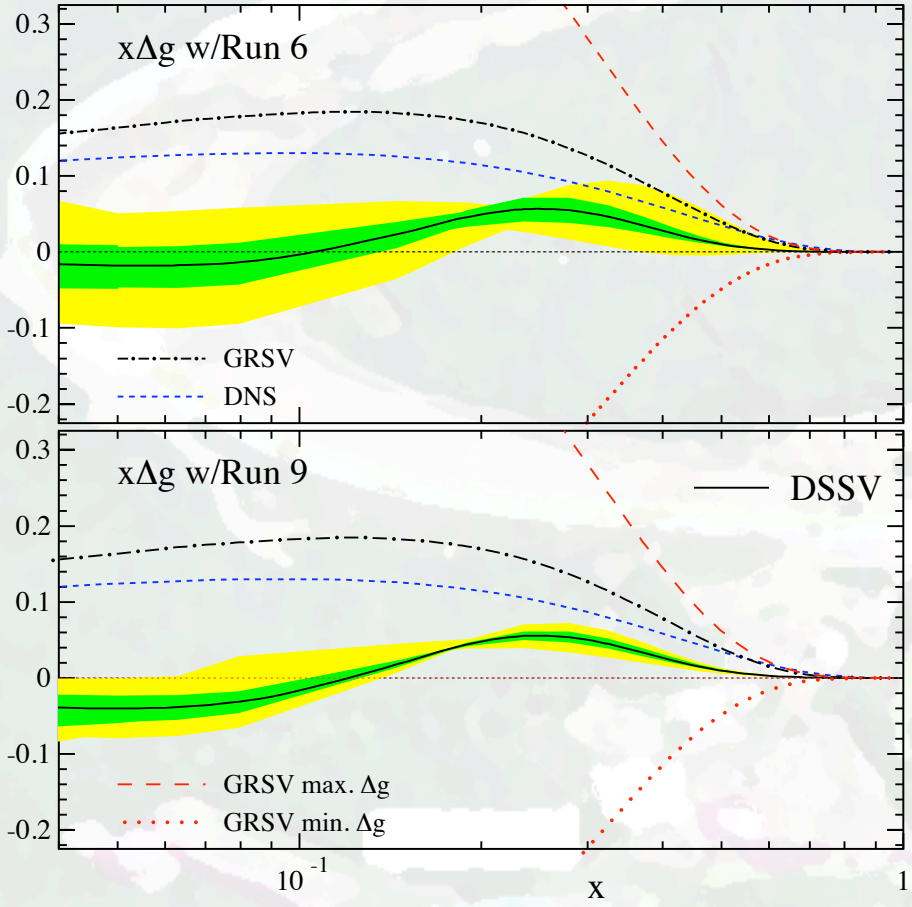
- Polarized proton-proton operation at RHIC at 200 / 500 GeV
  - During last longest polarized proton-proton run (RUN 6):
    - Luminosity: ~1pb^{-1}/day (~3pb^{-1}/day design) delivered luminosity
    - Polarization: ~60% polarization (70% design)
  - 500GeV development: Achieved 45%(*) beam polarization for single beam at 250GeV
  - Goal: At 70% beam polarization
    - 200GeV: $60 \cdot 10^{30} cm^{-2} s^{-1}$
    - 500GeV: $150 \cdot 10^{30} cm^{-2} s^{-1}$

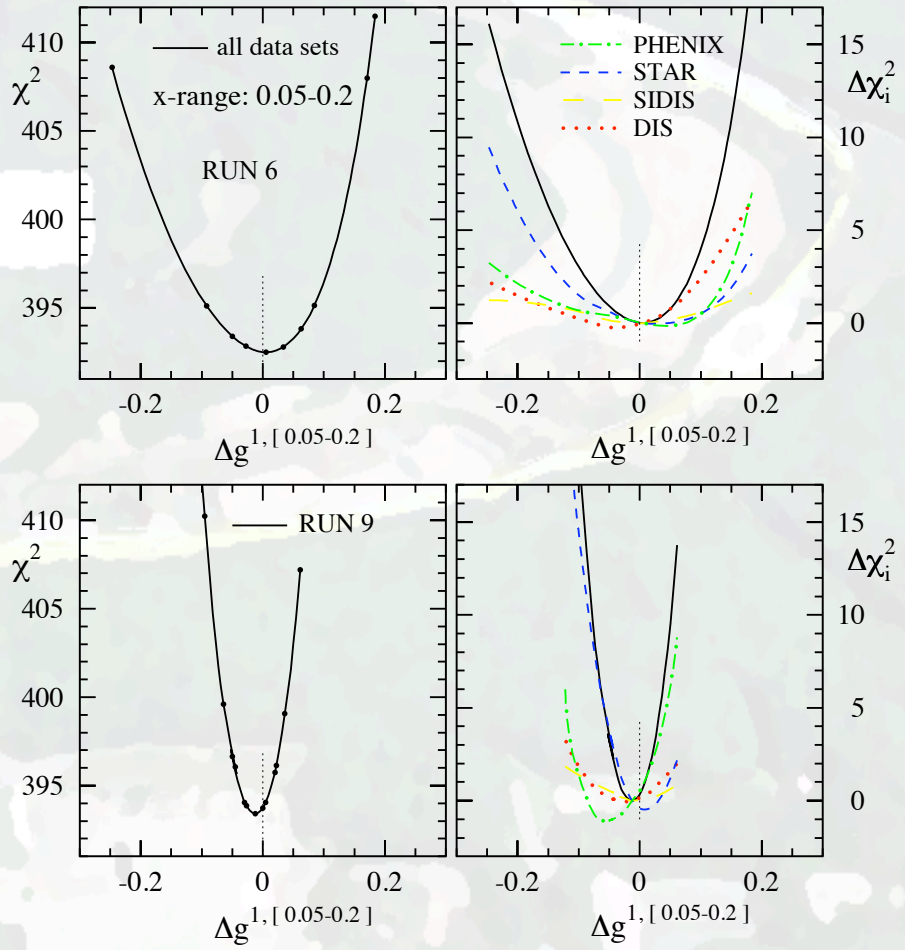


(*) Assumption: Analyzing power at 250GeV same as for 100GeV!

Future polarized p-p physics program

Gluon polarization - Projection Run 9

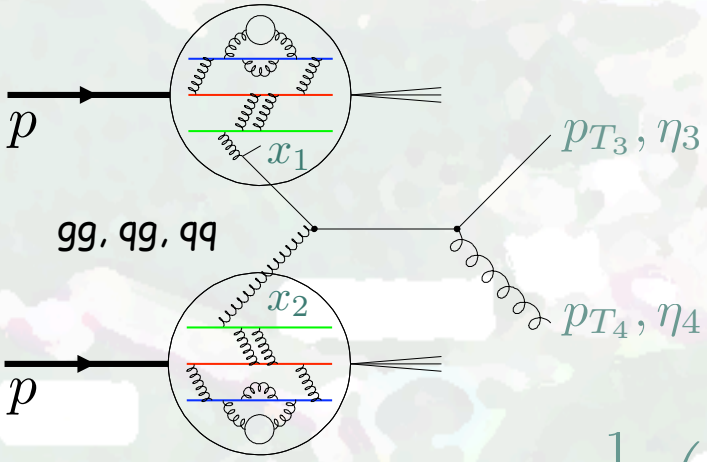


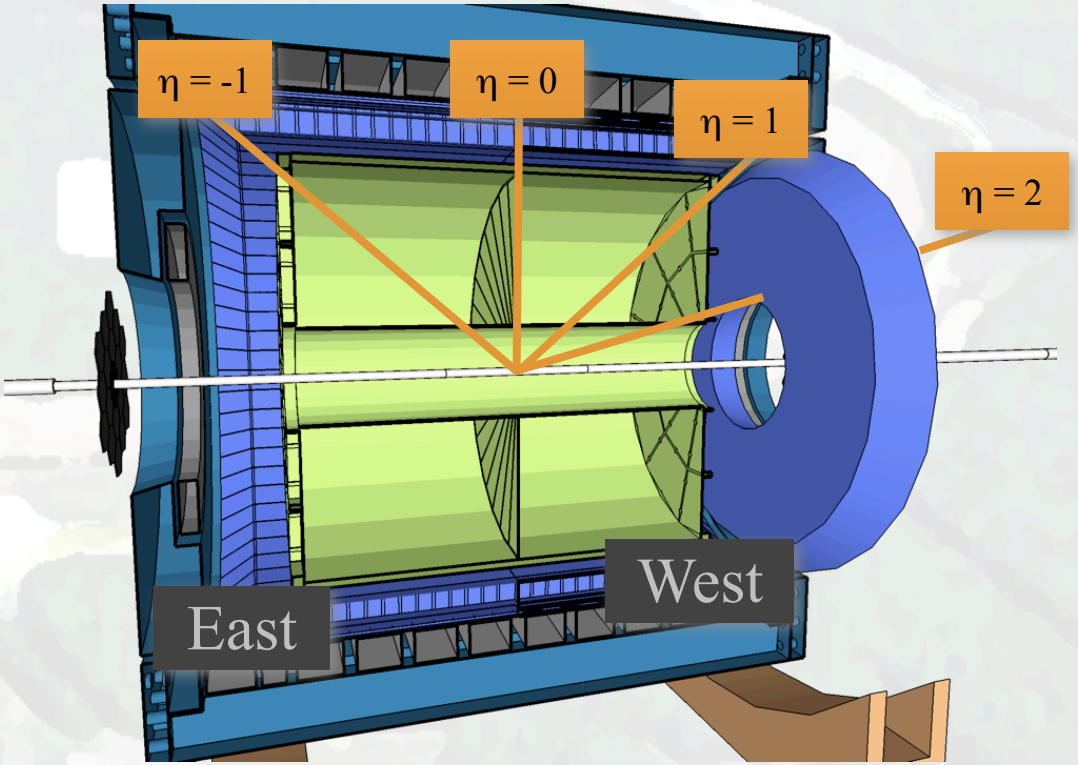


- Substantial improvement on gluon polarization from inclusive measurements
- Complementary information from STAR and PHENIX

Future polarized p-p physics program

- Gluon polarization - Correlation Measurements
  - Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production
  - 2-2 processes:





$$x_{1\,(2)} = \frac{1}{\sqrt{s}}\left(p_{T_3}e^{\eta_3(-\eta_3)} + p_{T_4}e^{\eta_4(-\eta_4)}\right)$$

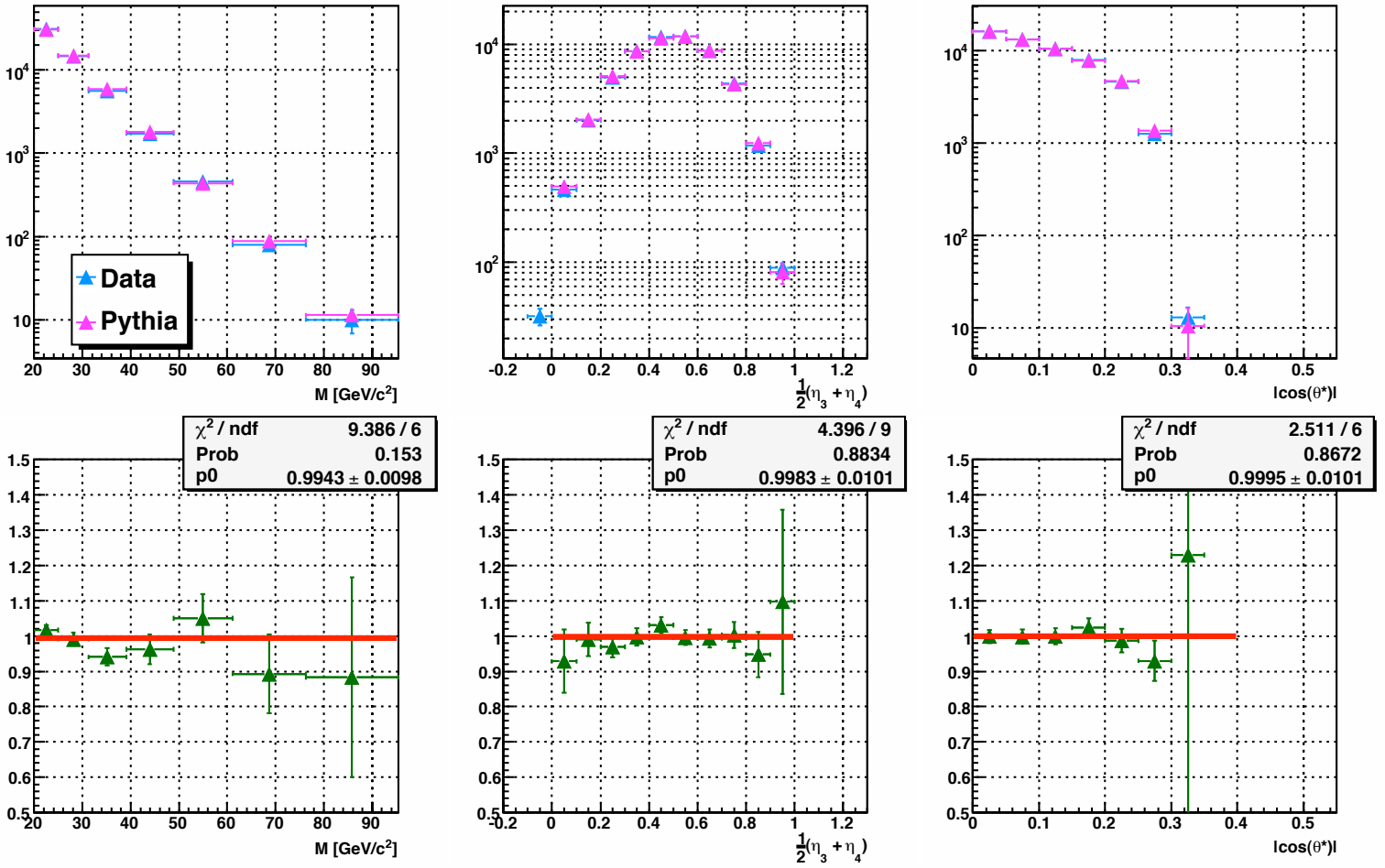
$$M = \sqrt{x_1 x_2 s}$$

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

$$\cos\theta^* = \tanh\left(\frac{\eta_3 - \eta 4}{2}\right)$$

Future polarized p-p physics program

- Correlation measurements: Di-Jet production - Data Understanding



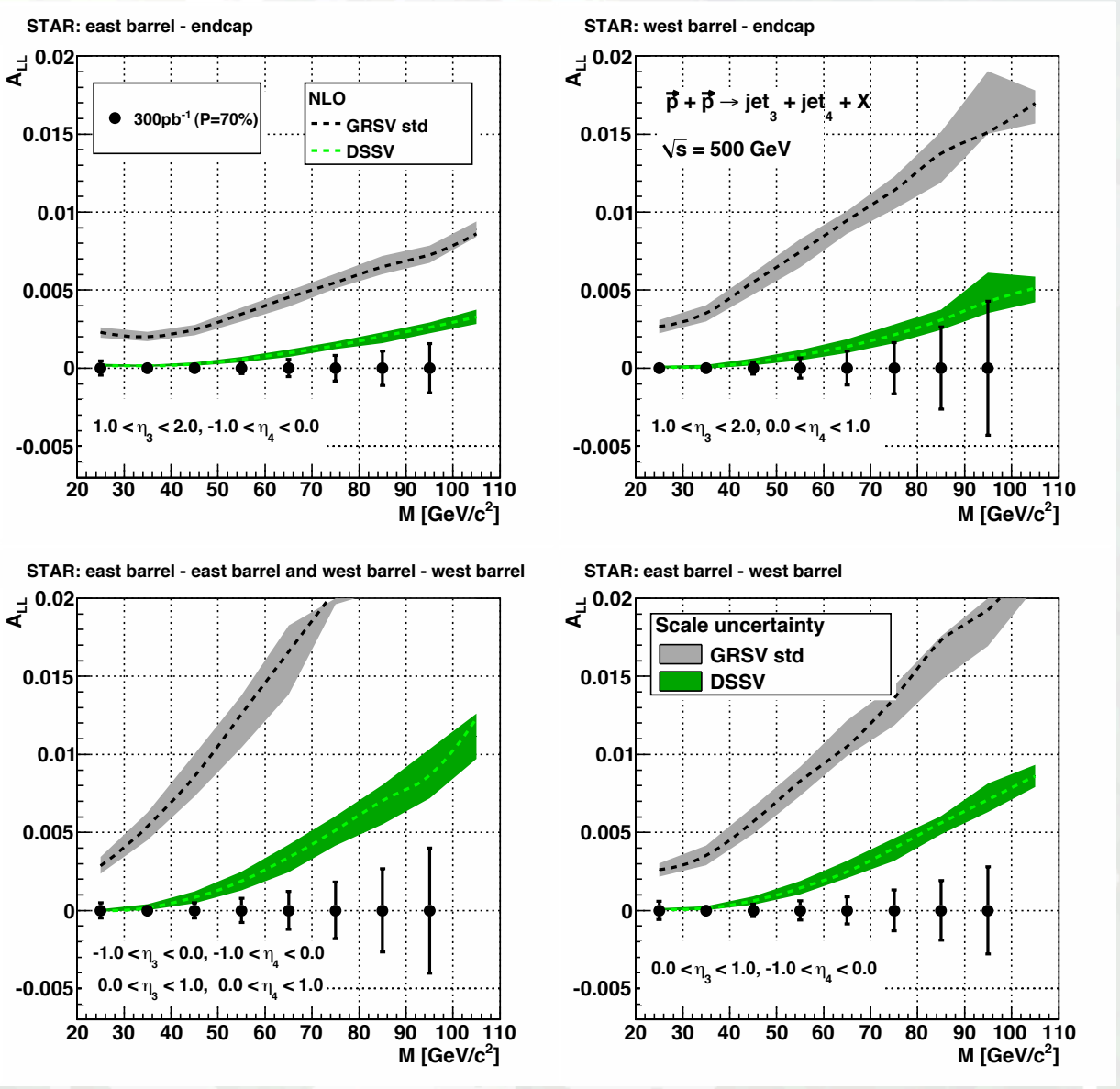
- Data/MC comparison complete - Good agreement in Di-Jet variables
- First cross-section and A_{LL} measurement in progress

$$M = \sqrt{x_1 x_2 s} \qquad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \qquad \cos\theta^* = \tanh\left(\frac{\eta_3 - \eta 4}{2}\right)$$

Future polarized p-p physics program

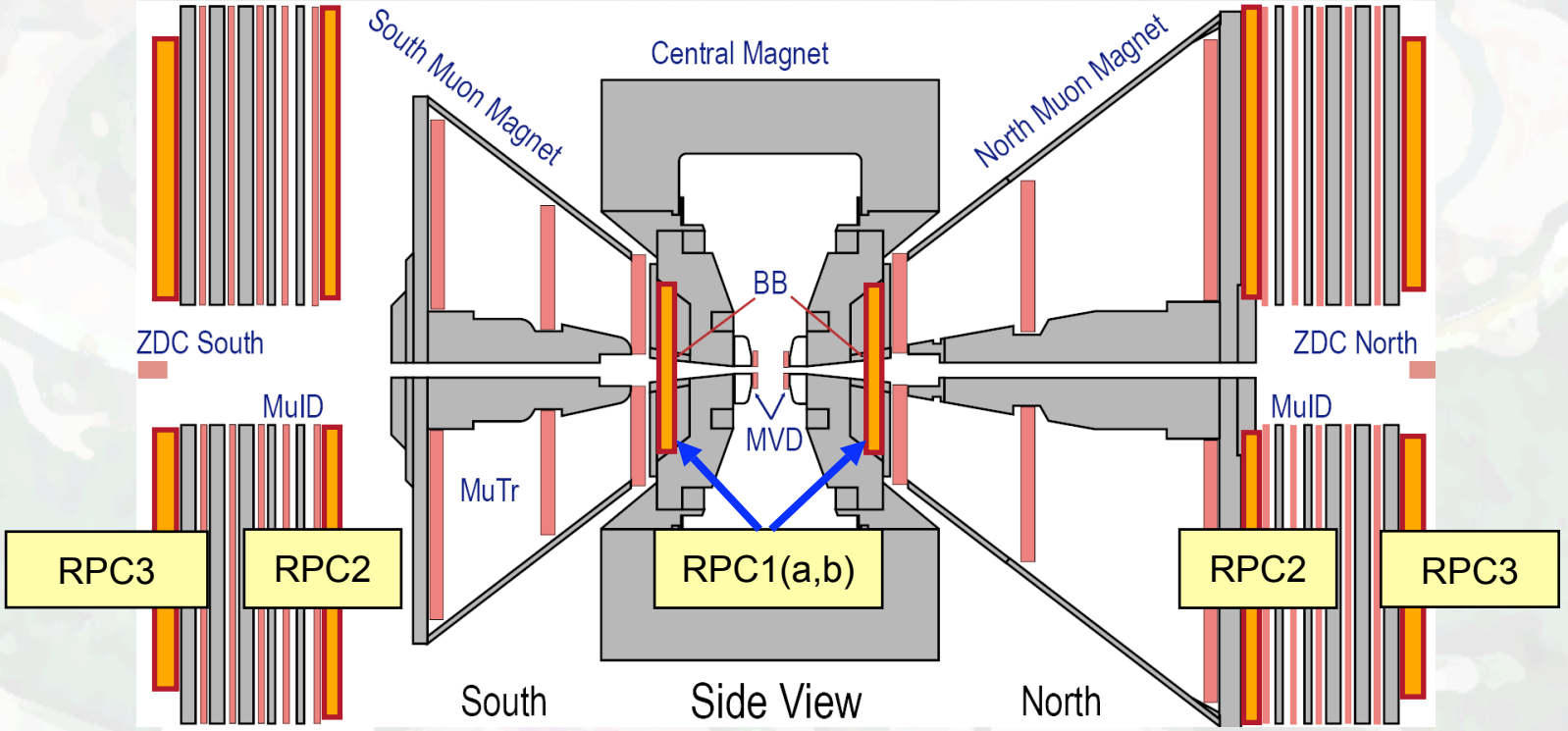
- Gluon polarization - Di-Jets
  - Substantial improvement in Run 9 from Di-Jet production
  - Good agreement between LO MC evaluation and full NLO calculations

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



Future polarized p-p physics program

- Quark / Anti-Quark polarization program at PHENIX
  - Forward Muon Trigger layout

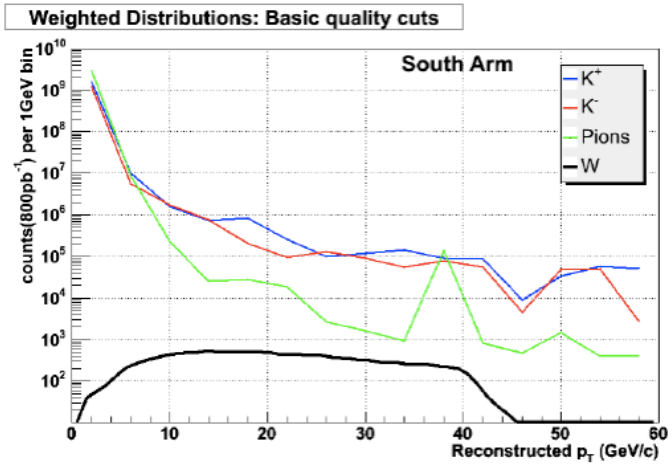


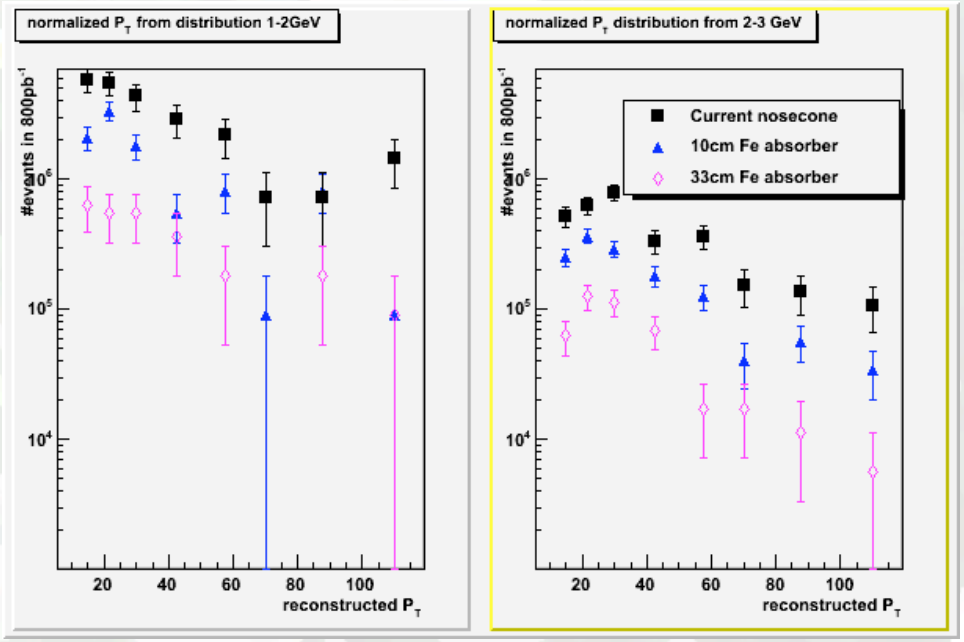
- 3 RPC planes for each muon chamber - Expected installation: Stations 2/3-North in 2009 - 2/3-South in 2010
- FEE upgrade of muon tracking - Expected installation: North in Summer 2008 / South in Summery 2009

Future polarized p-p physics program

- Quark / Anti-Quark polarization program at PHENIX

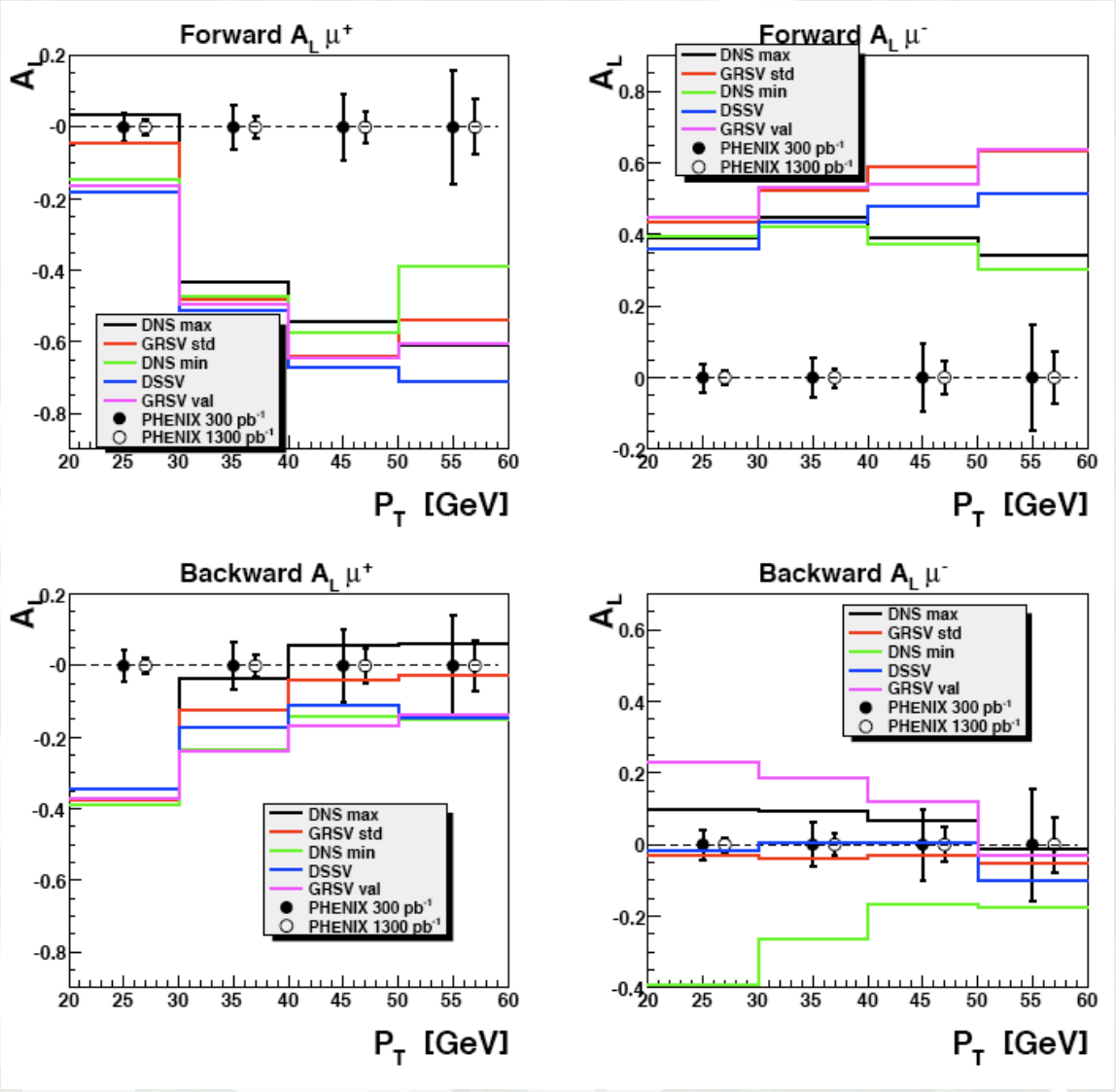
  - Main offline background: Low p_T hadrons decaying within muon tracker volume mimicking a high p_T track
  - Tight cuts reduce S/B ratio to 1/3
  - Hadron absorber after central magnet yoke allows S/B ratio of 3/1





Future polarized p-p physics program

- Quark / Anti-Quark polarization program at PHENIX (Forward rapidity)
  - Large asymmetries dominated by quark polarization - Important consistency check to existing DIS data with 100pb^{-1} (Phase I)
  - Strong impact constraining unknown antiquark polarization requires luminosity sample at the level of 300pb^{-1} for 70% beam polarization (Phase II)



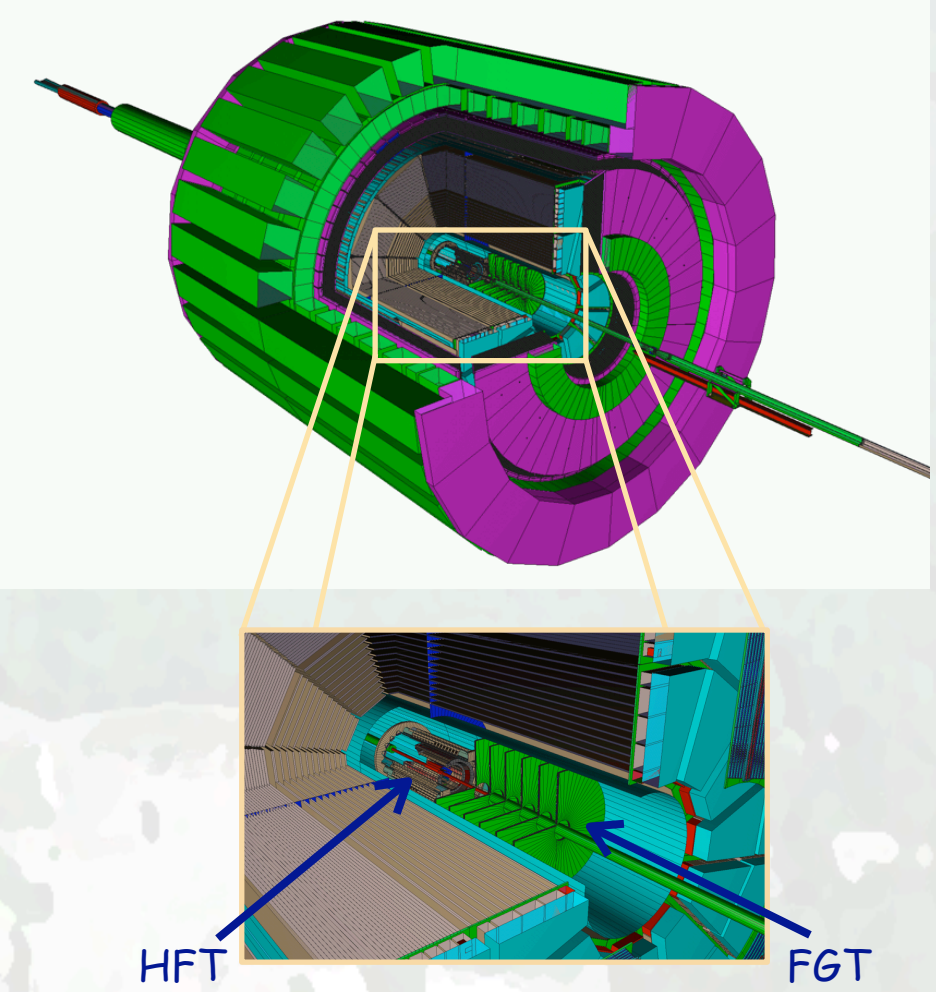
Future polarized p-p physics program

- Quark / Anti-Quark polarization program at STAR

Forward GEM Tracker: FGT

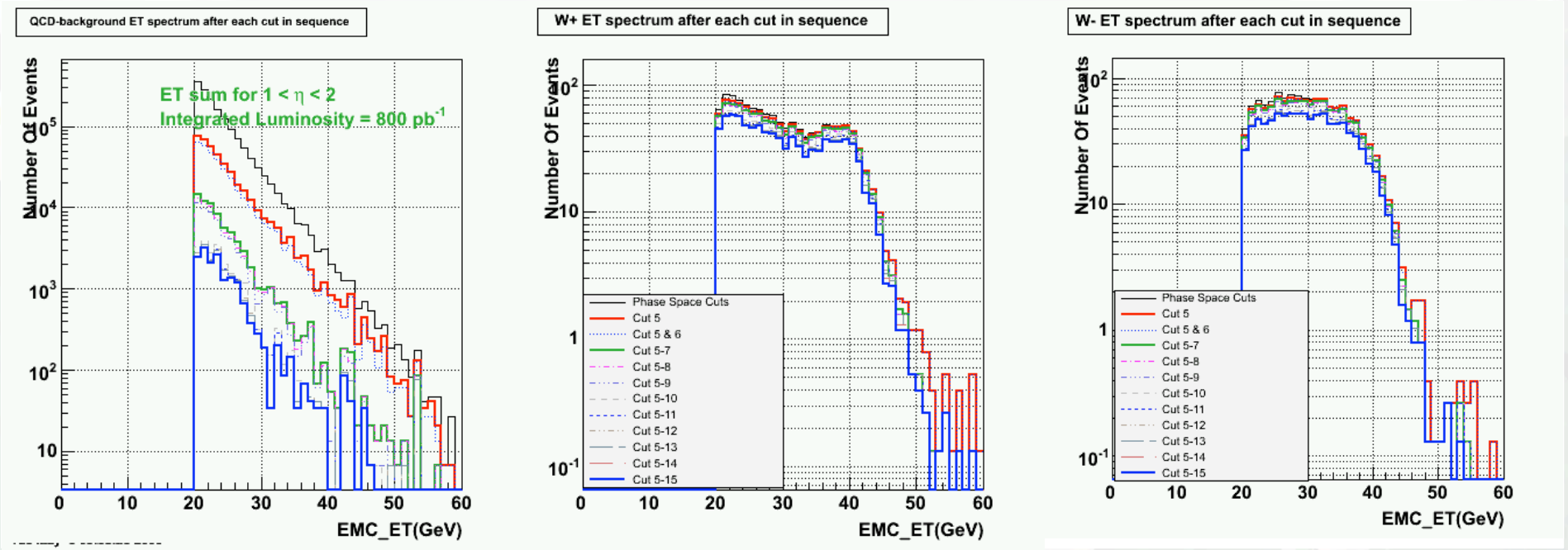
- Charge sign identification for high momentum electrons from $W^{\pm}$ decay (Energy determined with EEMC)
- Triple-GEM technology
- FGT project:

  ANL, IUCF, LBL, MIT, University of Kentucky, Valparaiso University, Yale
- Successful project review (Capital equipment funding): January 2008
- Expected installation: Summer 2010



Future polarized p-p physics program

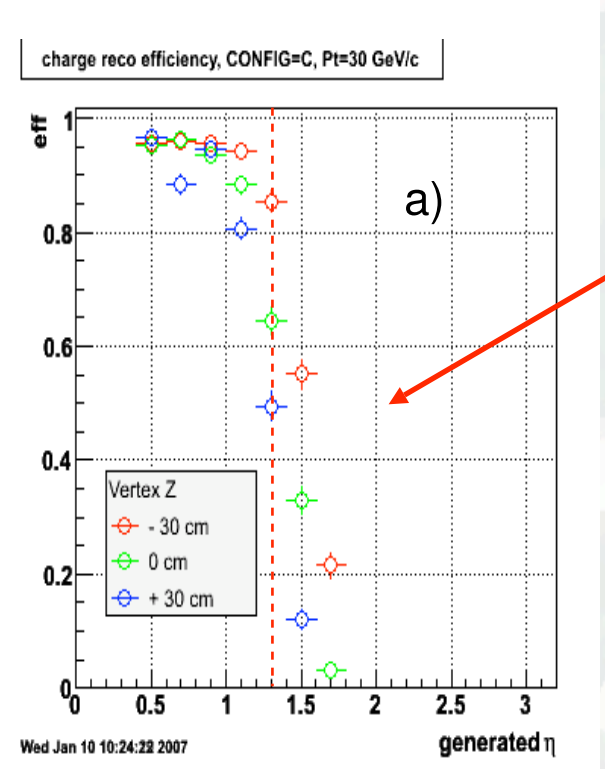
- Quark / Anti-Quark polarization program at STAR
  - e/h separation: Full PYTHIA QCD background and W signal sample including detector effects



- e/h separation based on global cuts (isolation/missing E_T) and EEMC specific cuts as
- With current algorithm: $E_T > 25$GeV yields S/B > 1 (For $E_T < 25$GeV S/B ~ 1/5) used for A_L uncertainty estimates

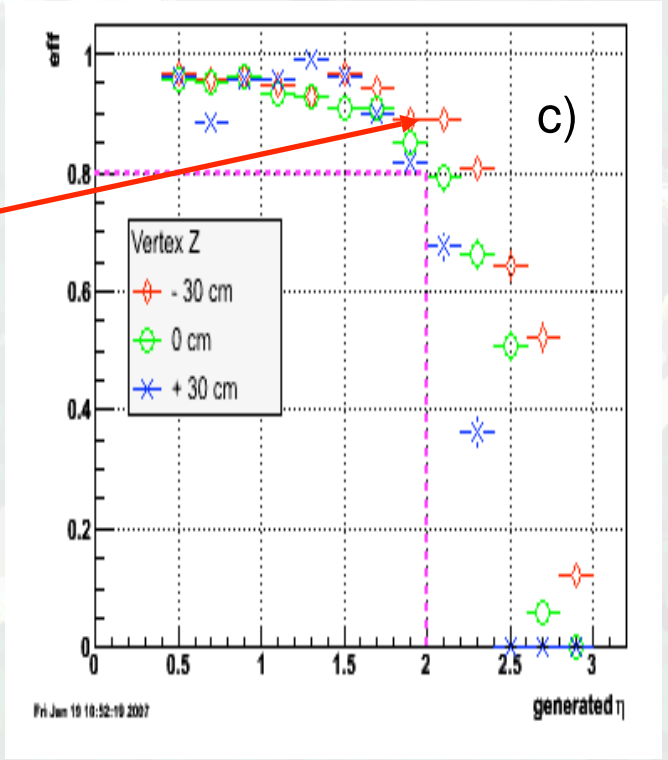
Future polarized p-p physics program

- Quark / Anti-Quark polarization program at STAR



Reach of EEMC Acceptance

TPC + FGT Tracking, p_T = 30 GeV/c



Conclusion:

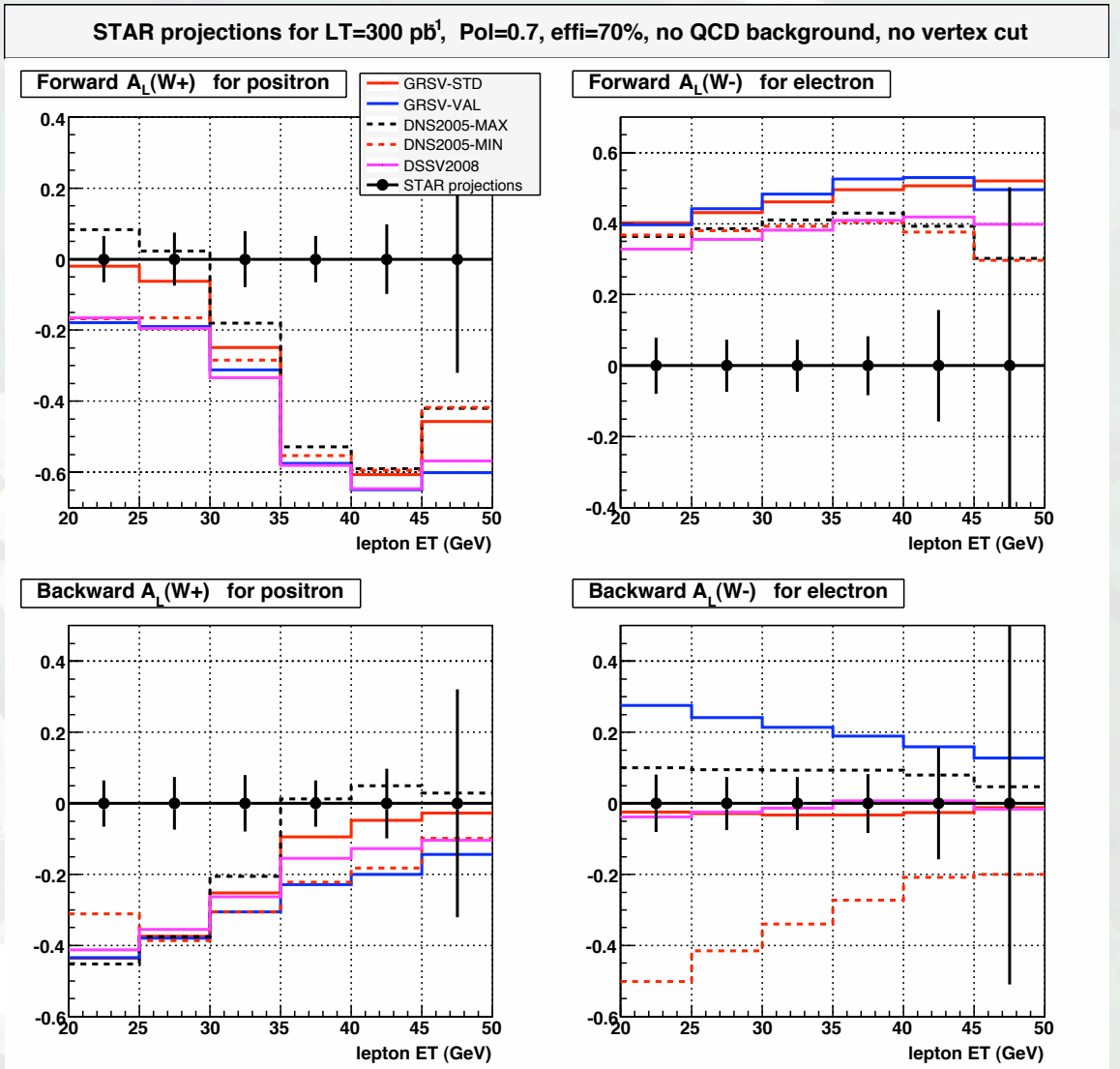
Charge sign reconstruction impossible beyond η = ~1.3

6 triple-GEM disks, assumed spatial resolution 60 μm in x and y (Fairly insensitive for 60-100 μm)

Charge sign reconstruction probability above 90% for 30 GeV p_T over the full acceptance of the EEMC for the full vertex spread

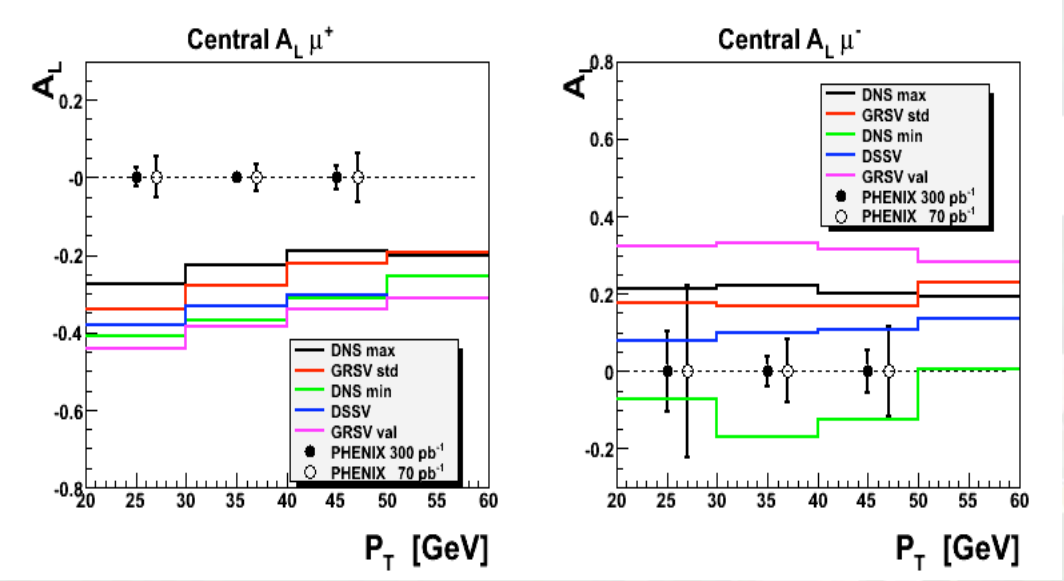
Future polarized p-p physics program

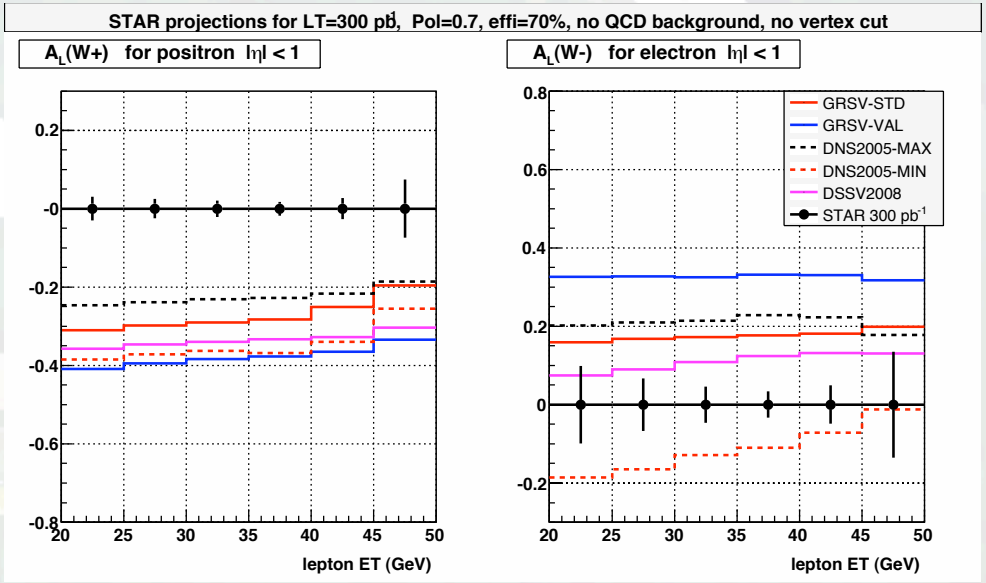
- Quark / Anti-Quark polarization program at STAR (Forward rapidity)
  - Large asymmetries dominated by quark polarization - Important consistency check to existing DIS data with 100pb^{-1} (Phase I)
  - Strong impact constraining unknown antiquark polarization requires luminosity sample at the level of 300pb^{-1} for 70% beam polarization (Phase II)



Future polarized p-p physics program

- Quark / Anti-Quark polarization program at PHENIX / STAR (Mid-rapidity)

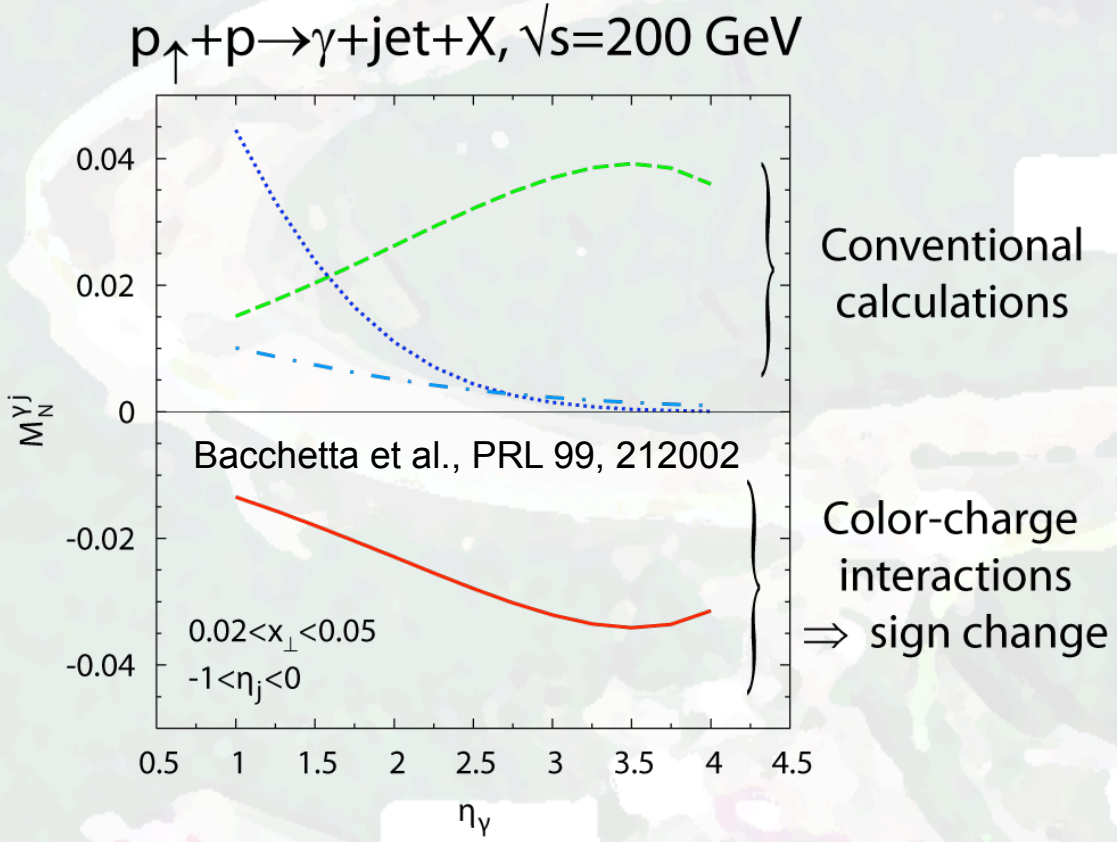


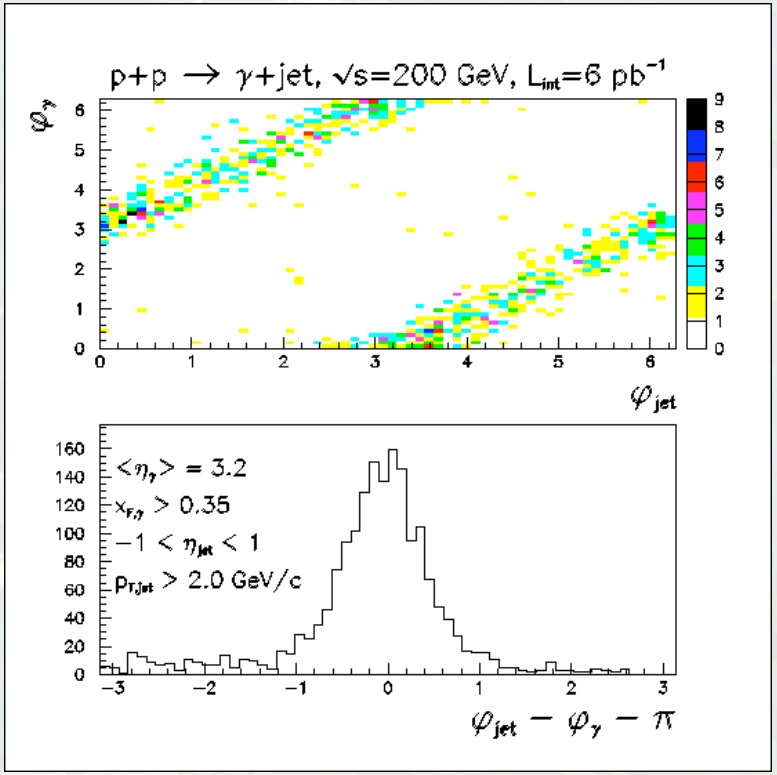


- Preliminary projections at mid-rapidity (No QCD background effects included)
- Important constraint on anti-u and in particular anti-d distribution functions at mid-rapidity!

Future polarized p-p physics program

- Transverse spin dynamics

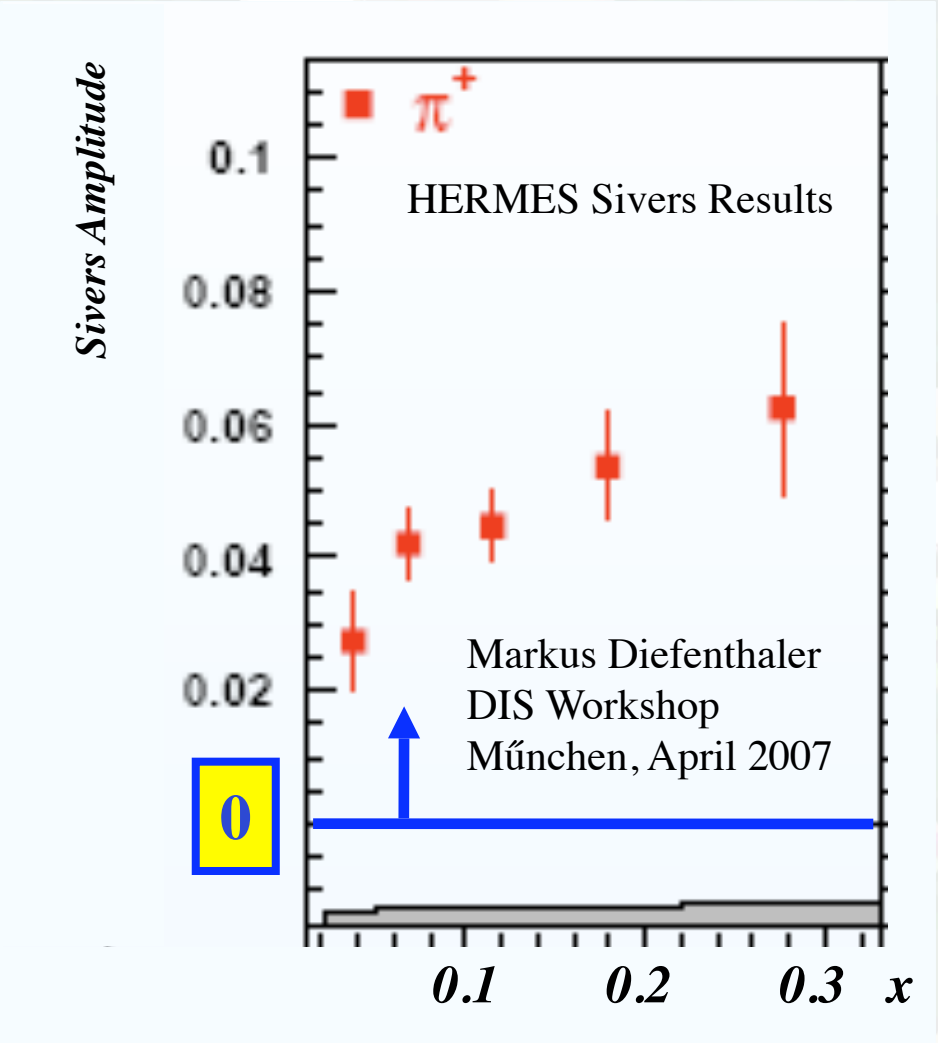




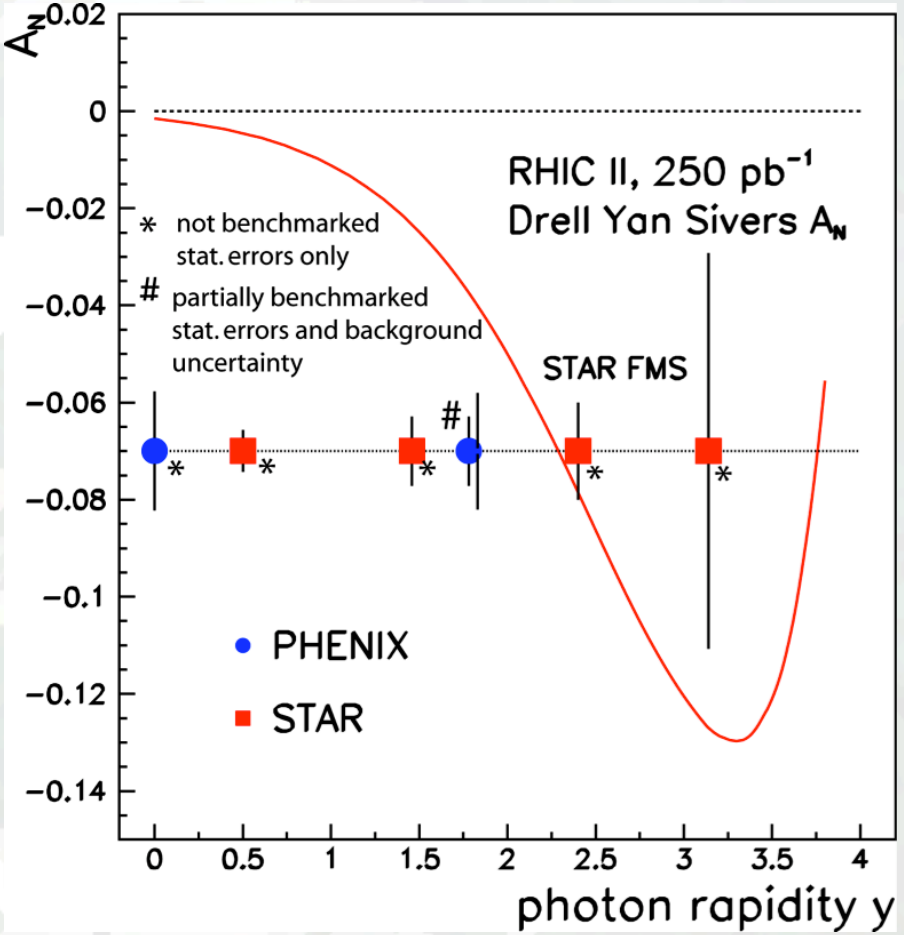
- Conventional calculations predict the asymmetry to have the same sign in SDIS and γ + jet whereas calculations that account for repulsive interactions between like color charges predict opposite sign
- Critical test on Sivers effect

Future polarized p-p physics program

- Transverse spin dynamics



0



- Important test at RHIC of fundamental QCD prediction of non-universality of Sivers effect

Summary and Outlook

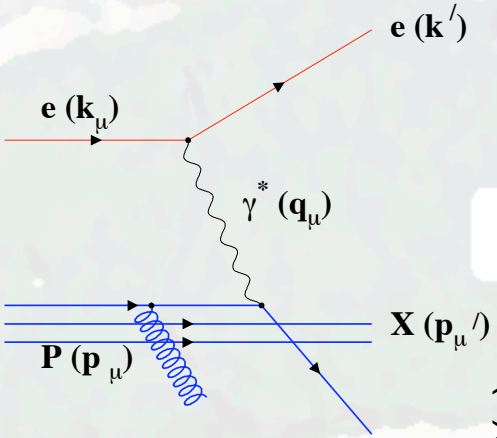
- Summary
  - Three key elements:
    - Gluon polarization
    - Quark / Anti-Quark Polarization
    - Transverse spin dynamics
  - Critical:

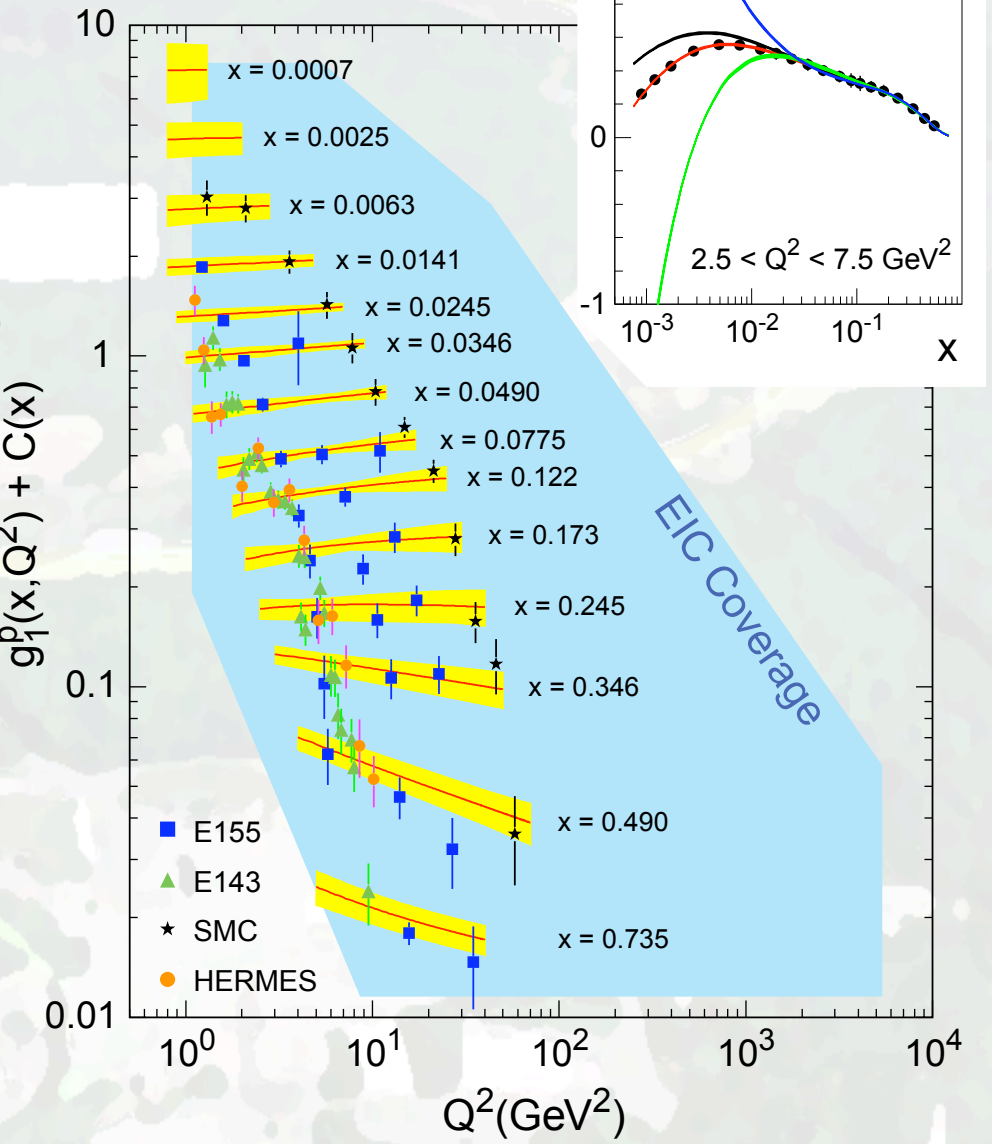
Recorded Luminosity	Main physics Objective	Remarks
~50pb^{-1}	Gluon polarization using di-jets and precision inclusive measurements	200 GeV
~100pb^{-1}	W production (Important consistency check to DIS results - Phase I) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~300pb^{-1}	W production (Constrain antiquark polarization - Phase II) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~30pb^{-1}	Transverse spin gamma-jet	200 GeV
~250pb^{-1}	Transverse spin Drell-Yan (Long term)	200 GeV

- Beam polarization: 70% / Narrow vertex region / Spin flipper for high precision asymmetry measurements
- Critical: Sufficient running time!

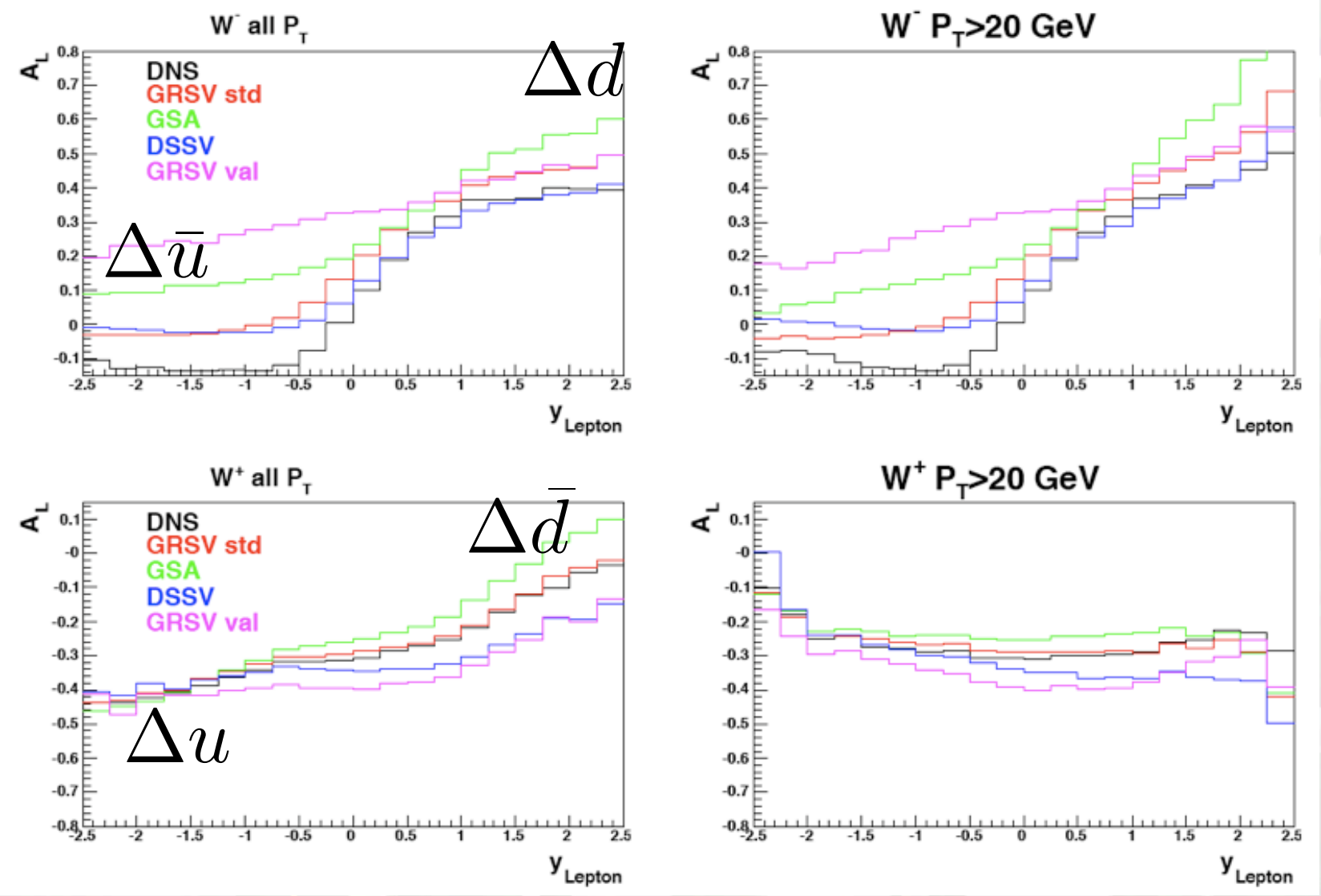
Summary and Outlook

- Outlook
  - New insight into spin structure and dynamics of the proton at a future Electron-Ion Collider facility:





  - Precision inclusive measurements - Scaling violation of g_1^p
    ⇒ Gluon polarization at low x
  - Semi-Inclusive measurements
    ⇒ Quark flavor studies at low x

Backup

- A_L sensitivity