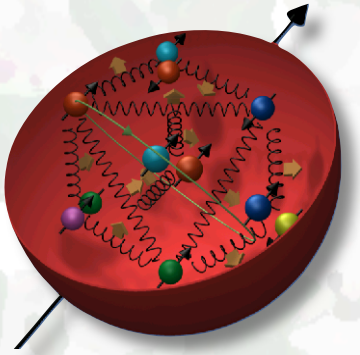
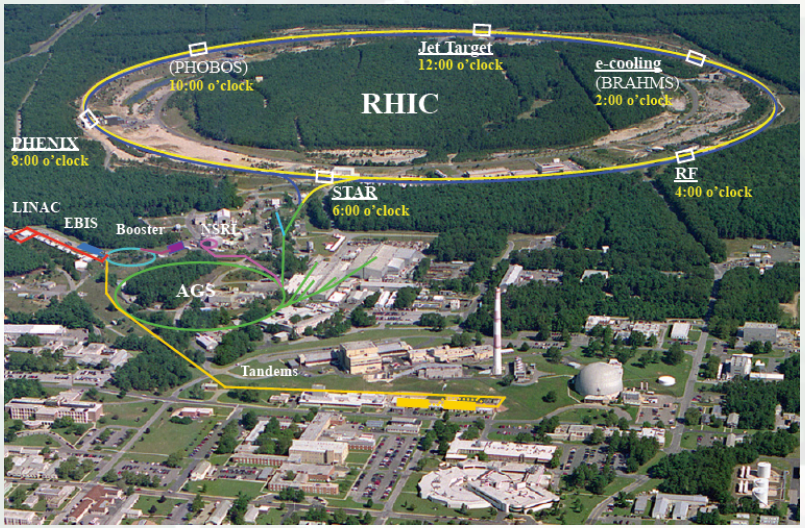
Recent results and future prospects of the high-energy polarized p+p program at RHIC at BNL

Bernd Surrow

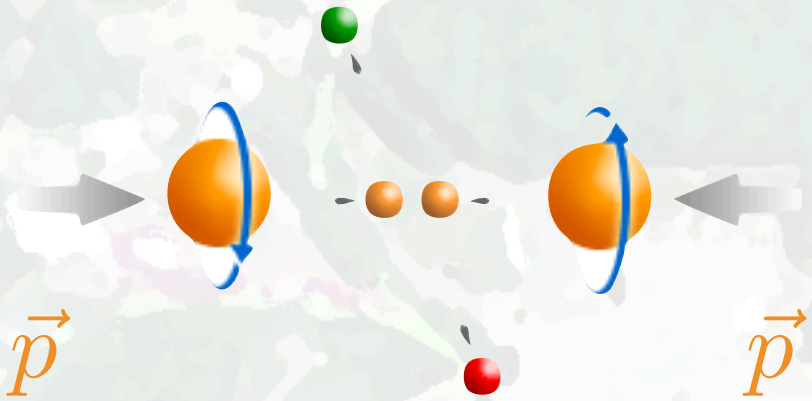
Massachusetts Institute of Technology



Outline

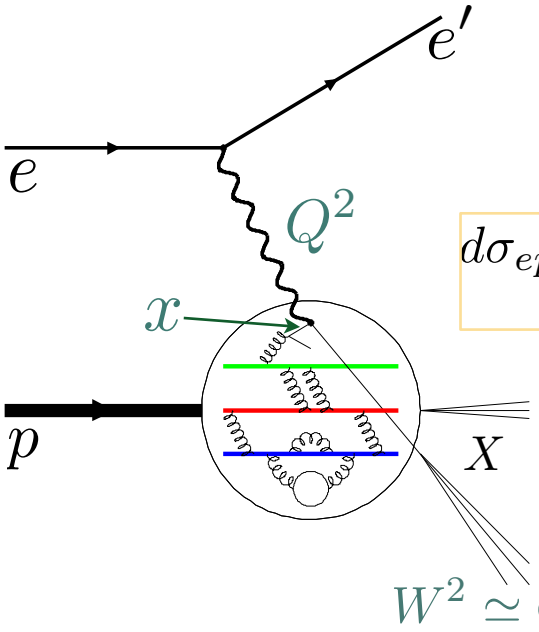


- Selected recent results and future prospects
  - Transverse spin dynamics
  - Gluon polarization
  - Quark / Anti-quark polarization
- Experimental aspects: RHIC / PHENIX / STAR
- Theoretical foundation
- Summary and Outlook



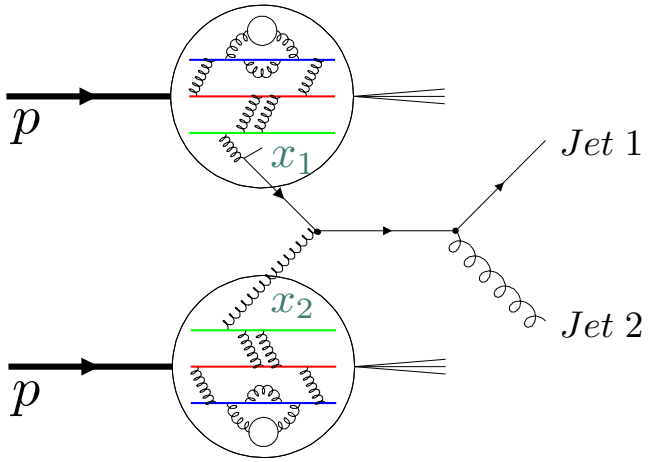
Theoretical foundation

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



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

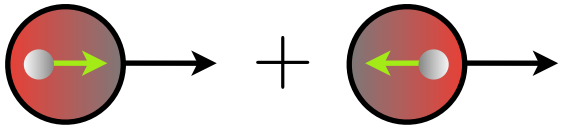
Universality



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

Momentum contribution

$$f(x) =$$



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

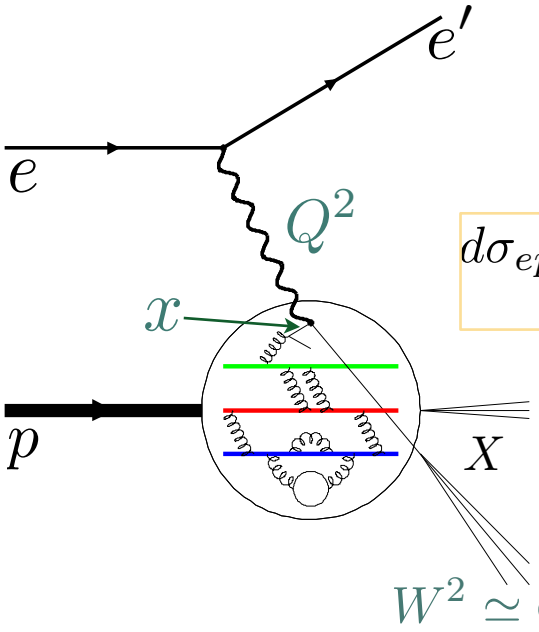
$$\Delta f(x) =$$

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

Spin contribution

Theoretical foundation

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



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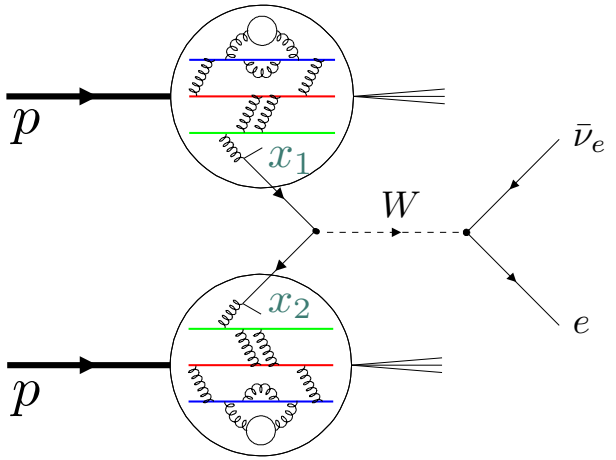

$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

Factorization

Momentum contribution

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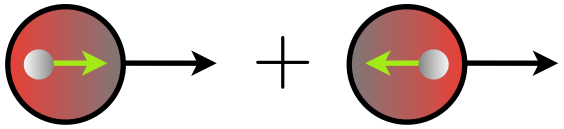

$$f^+(x) + f^-(x)$$

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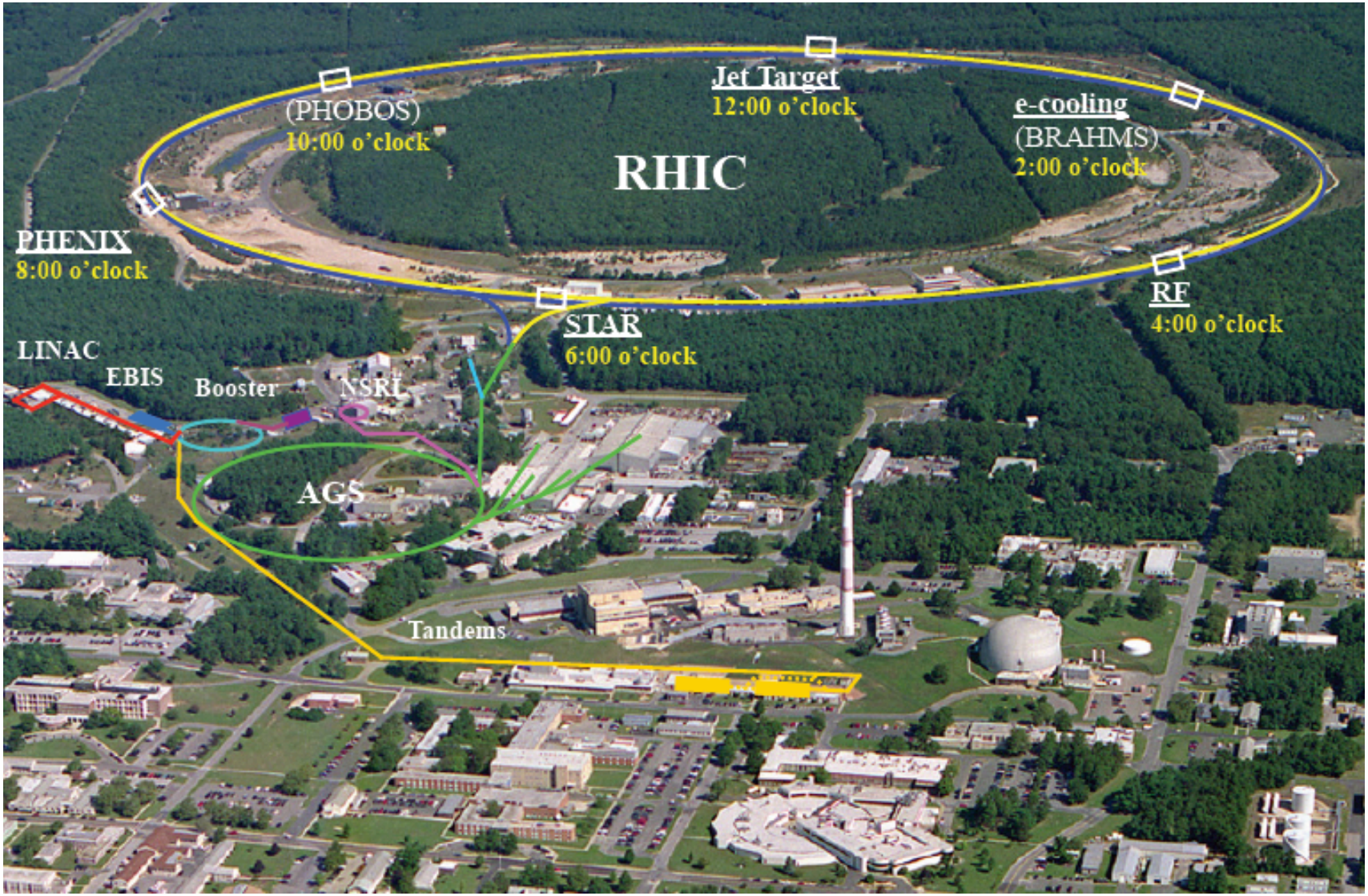
Spin contribution

Experimental aspects - RHIC

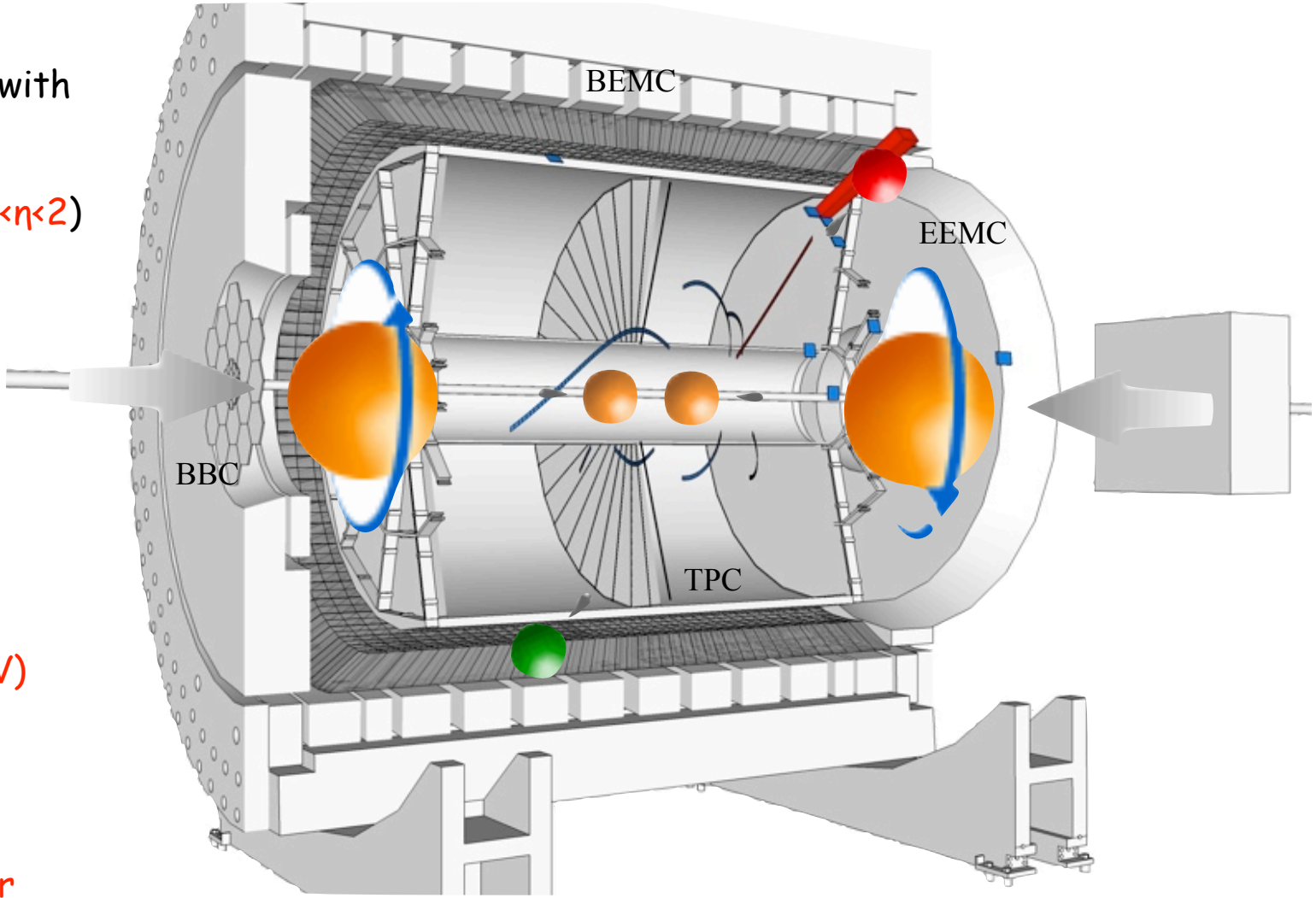
- The world's first polarized proton-proton collider



Experimental aspects - STAR

Overview

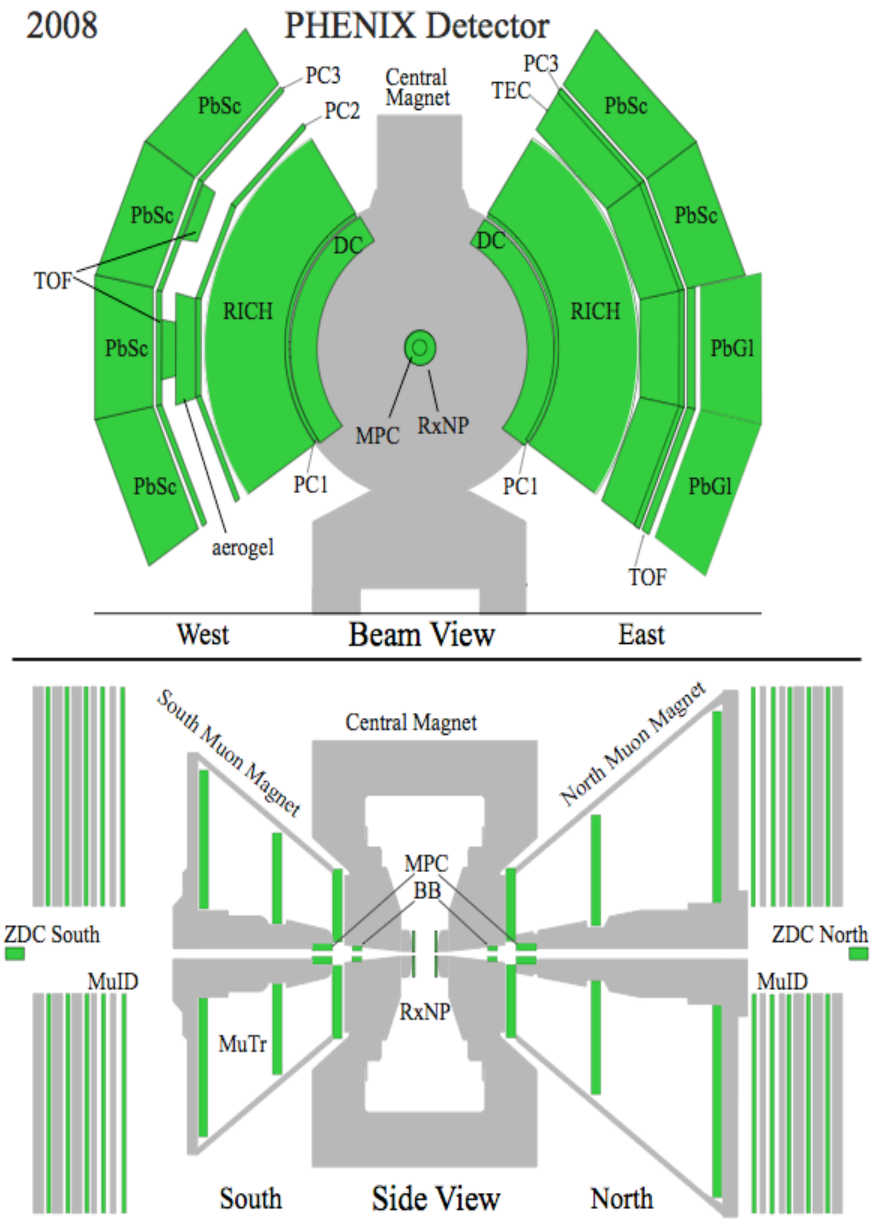
- Calorimetry system with 2π coverage: BEMC ($-1<\eta<1$) and EEMC ($1<\eta<2$)
- TPC: Tracking and particle ID
- ZDC: Relative luminosity and local polarimetry (500GeV)
- BBC: Relative luminosity and Minimum bias trigger



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

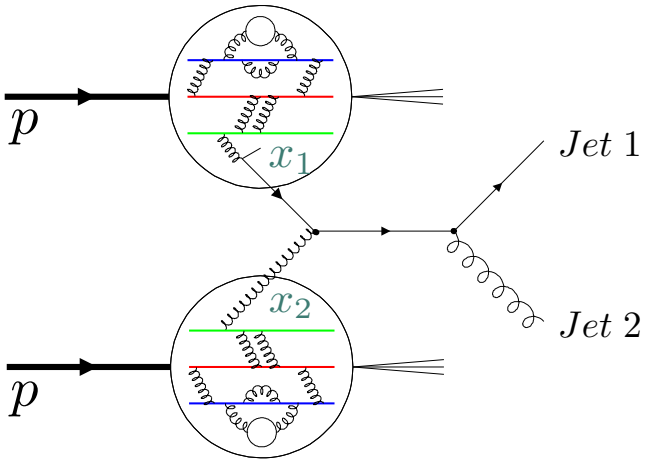
Experimental aspects - PHENIX

- 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)

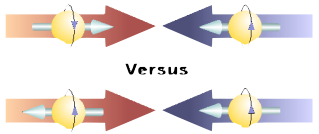


Experimental aspects - Asymmetry measurement

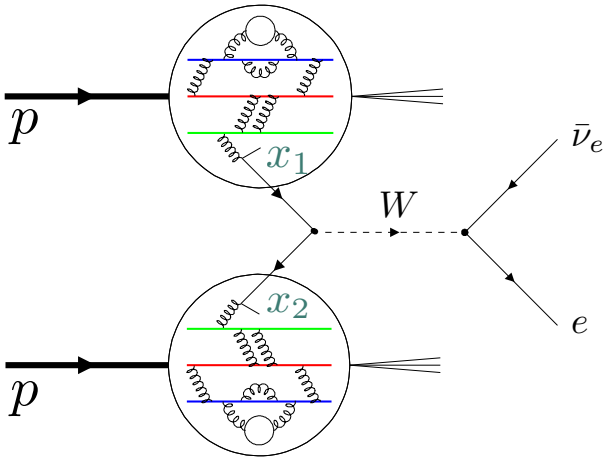
- Double and single longitudinal spin asymmetry measurements



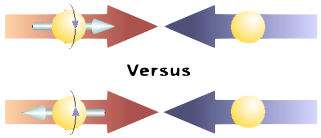
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$



- 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 N_{ij}

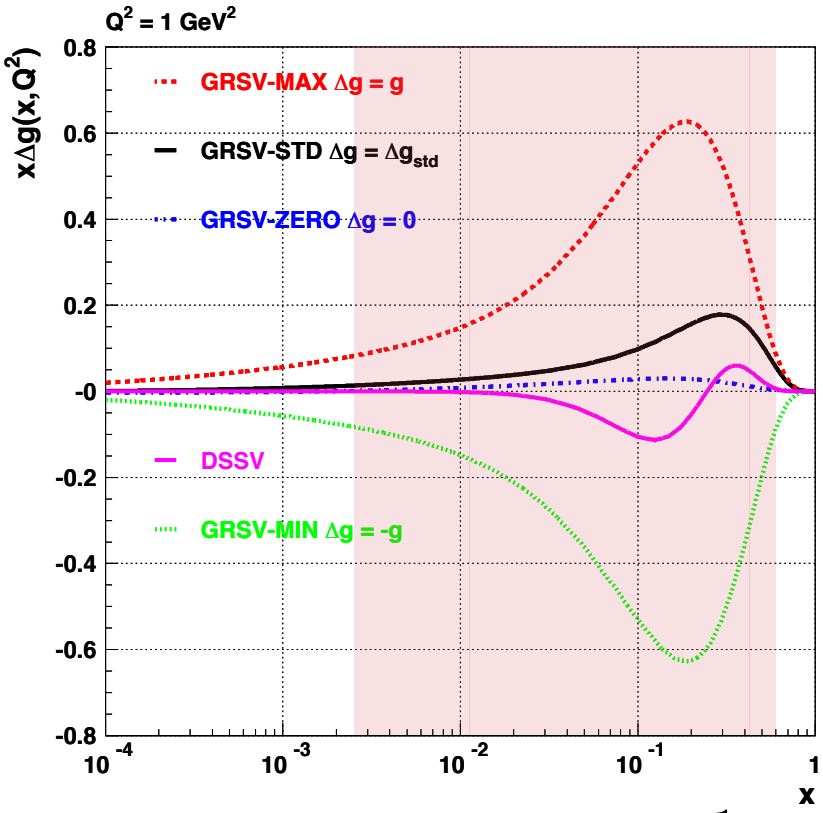


$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P} \frac{N_+ - R N_-}{N_+ + R N_-}$$



Recent results - Gluon polarization program

Measurement: Connection of Δg and A_{LL}



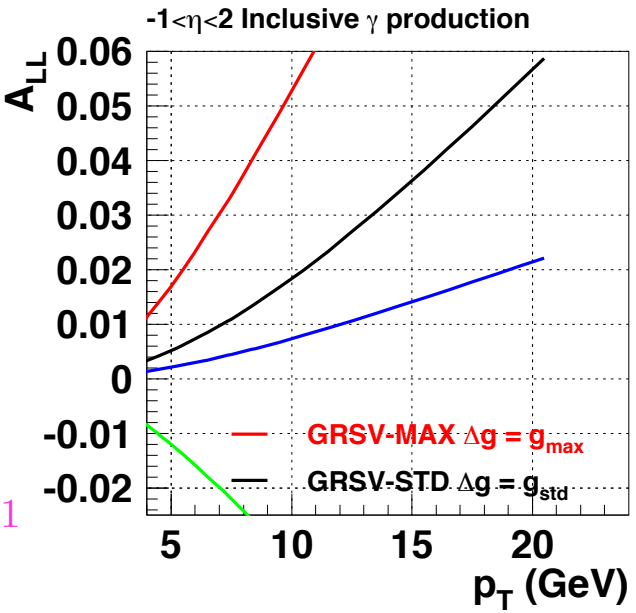
$$\Delta G(Q^2 = 1GeV^2) \approx 1.8$$

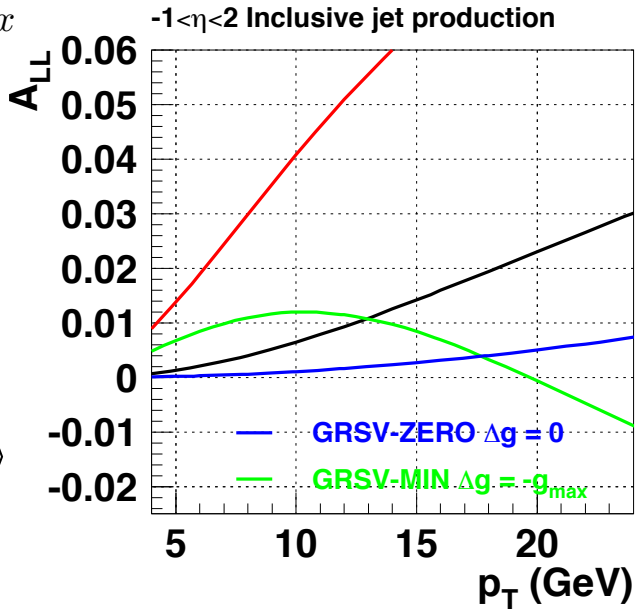
$$\Delta G(Q^2 = 1GeV^2) \approx 0.4$$

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

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

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





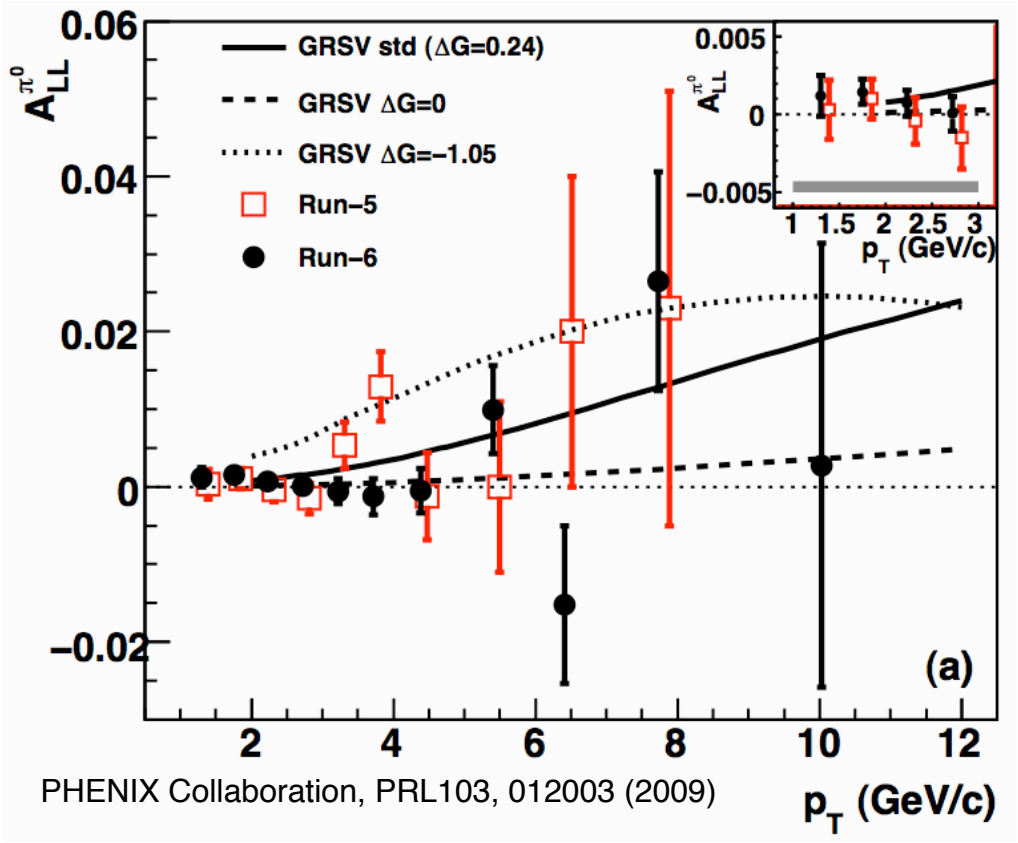
Proton Spin decomposition in infinite momentum frame:

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

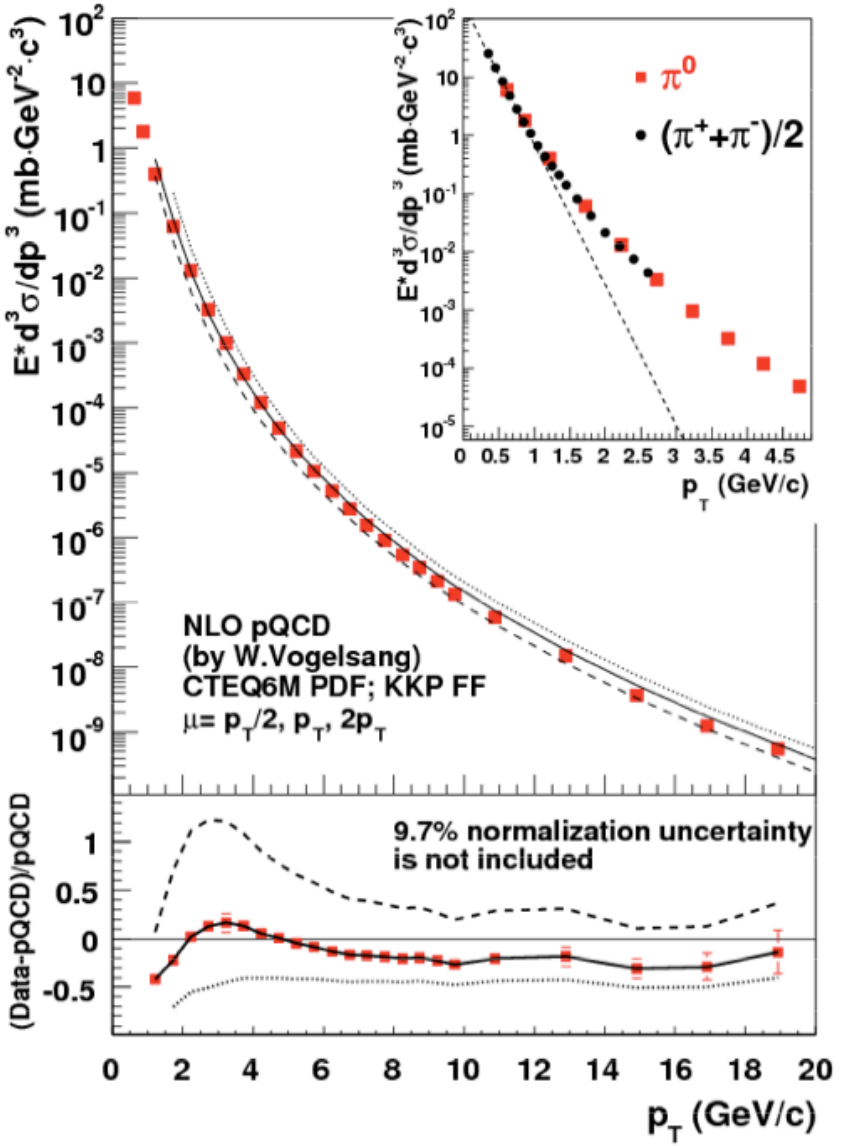
(R.L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990))

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
- Run 9 A_{LL} results slightly above DSSV fit result (Incl. PHENIX and STAR Run 5/6 results)

Recent results - Gluon polarization program

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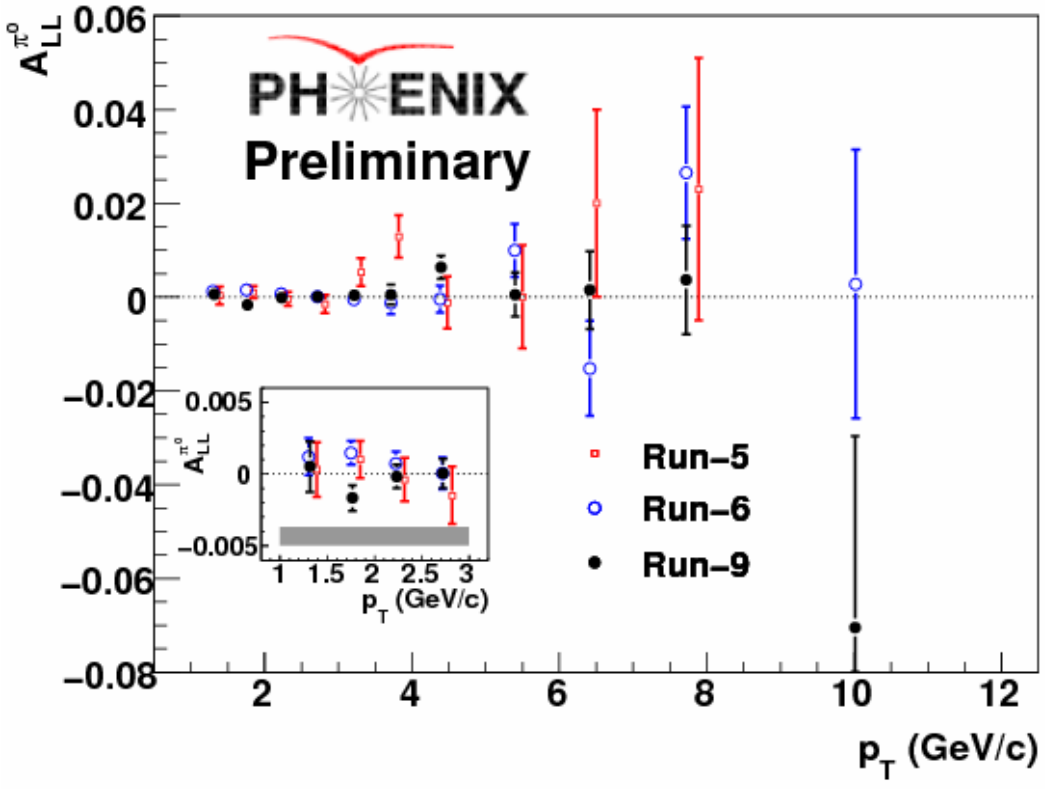
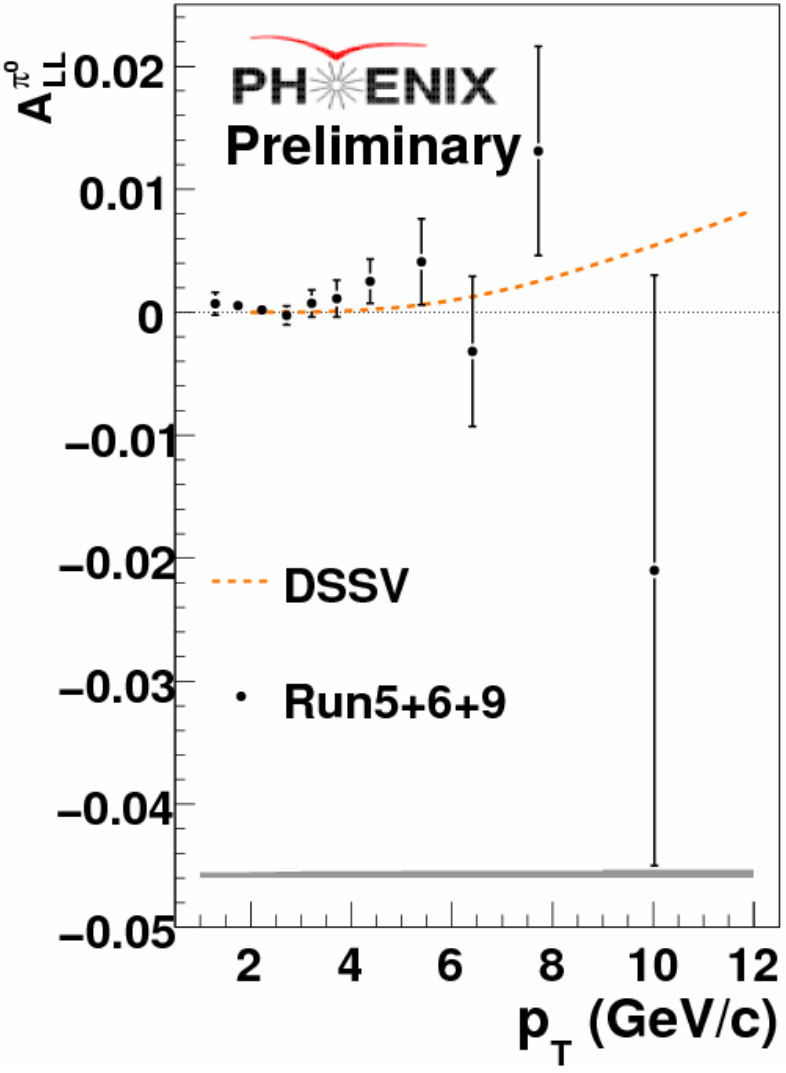
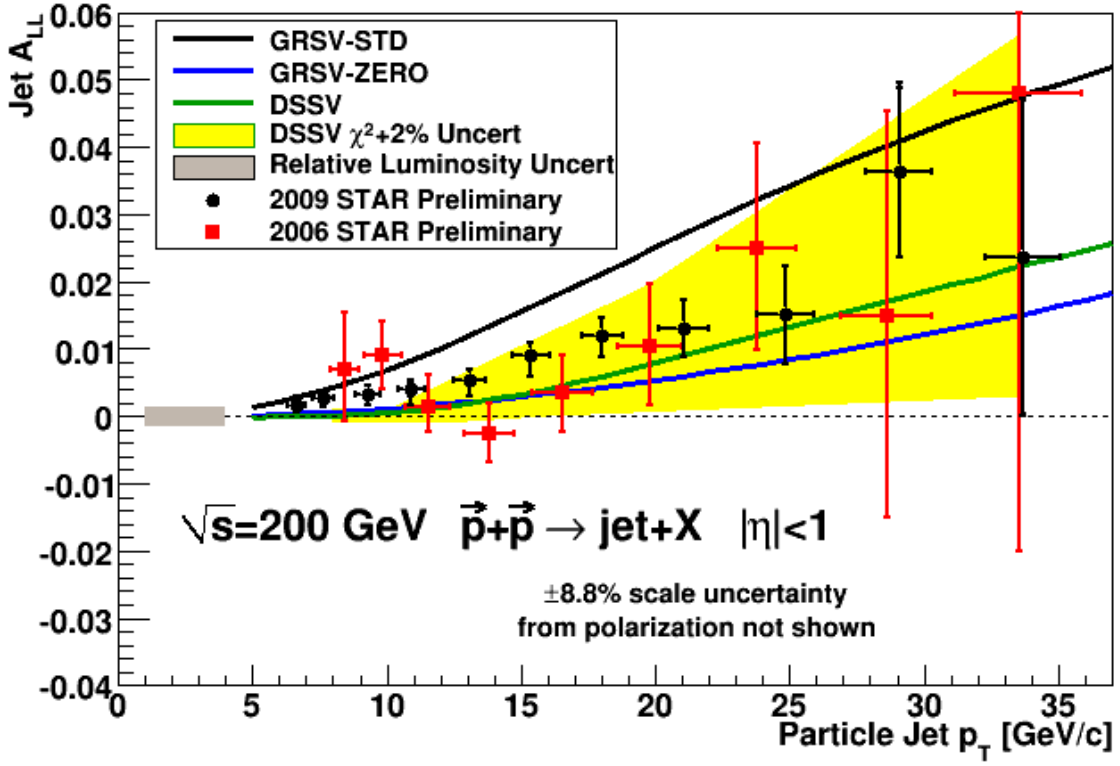


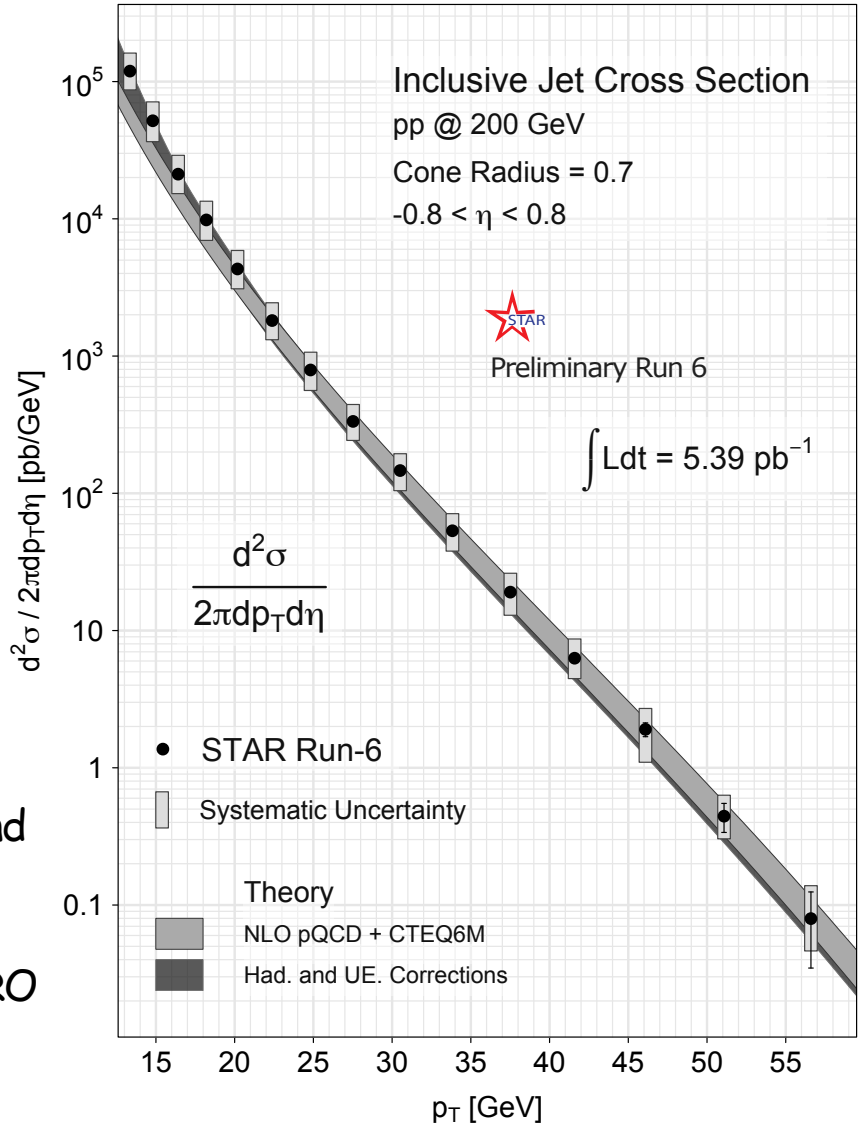


- Data are well described by NLO pQCD calculations
- Run 9 A_{LL} results slightly above DSSV fit result (Incl. PHENIX and STAR Run 5/6 results)

Recent results - Gluon polarization program

- STAR: Mid-rapidity Inclusive Jet A_{LL} measurement

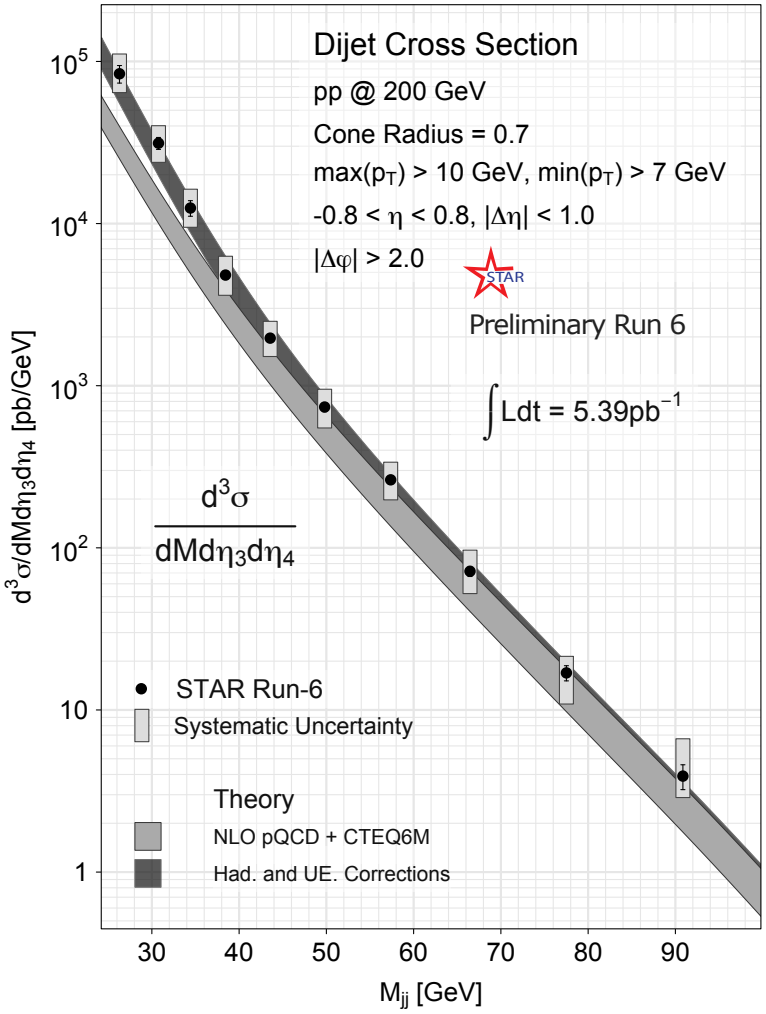




- Data are well described by NLO pQCD plus hadronization and underlying event corrections
- Run 6 A_{LL} measurement between GRSV-STD and GRSV-ZERO
- Run 9 A_{LL} measurement between GRSV-STD and DSSV

Recent results - Gluon polarization program

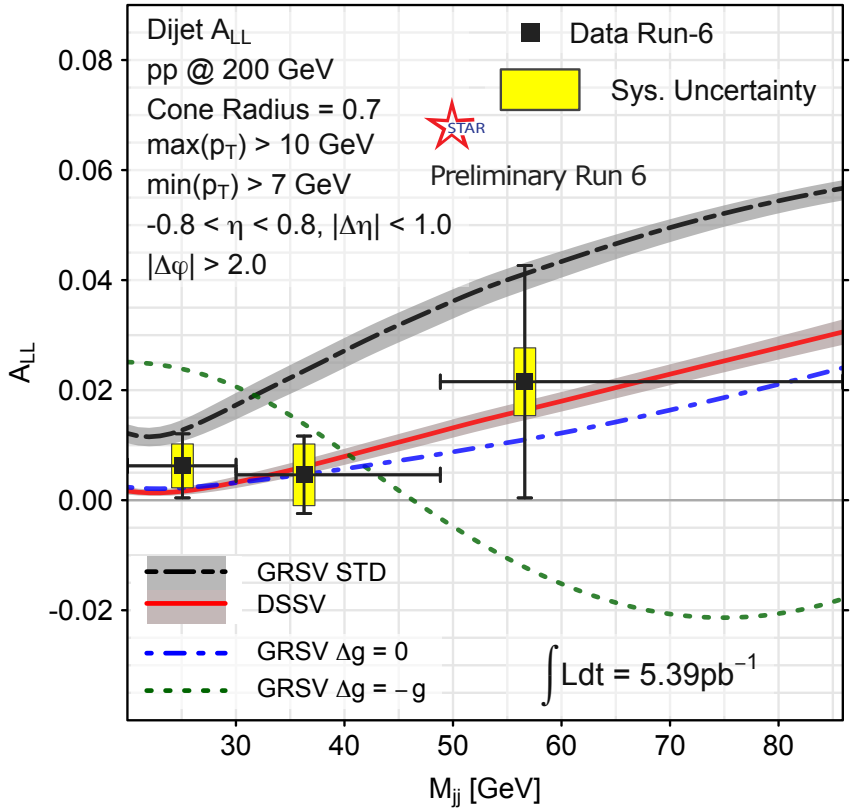
- First STAR Di-Jet A_{LL} measurement



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

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

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

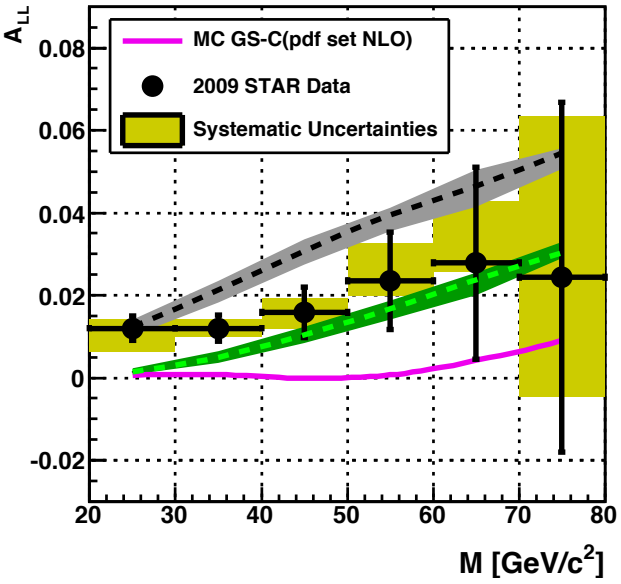


- First Di-Jet A_{LL} measurement in agreement with Δg constrained by previous inclusive jet result, i.e. small gluon polarization preferred!

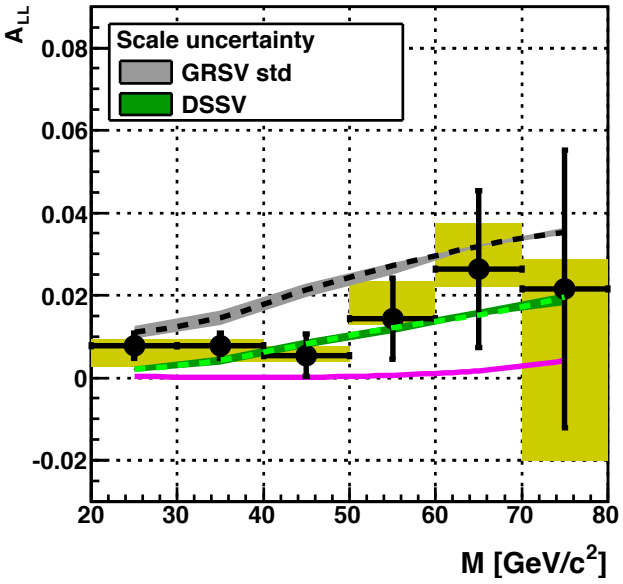
Recent results - Gluon polarization program

First STAR Di-Jet A_{LL} measurement

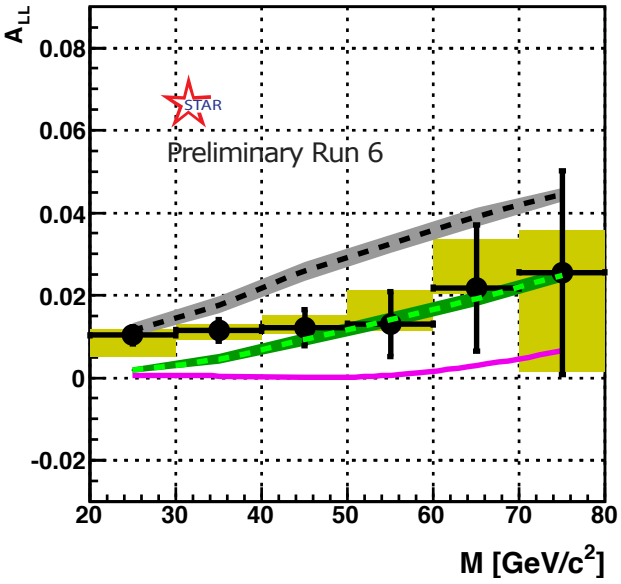
East - East and West - West Barrel

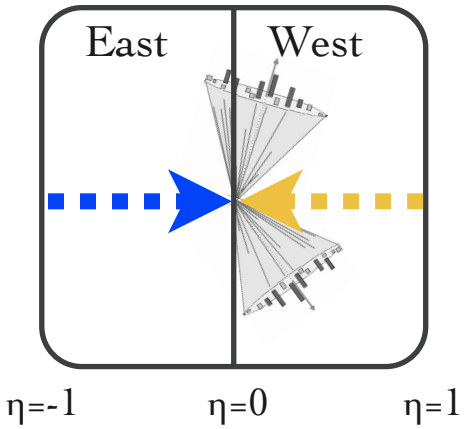


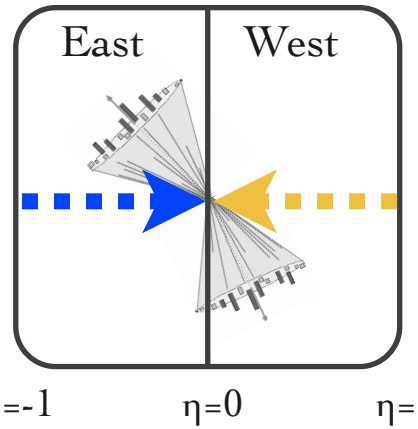
East Barrel - West Barrel



Full Acceptance







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

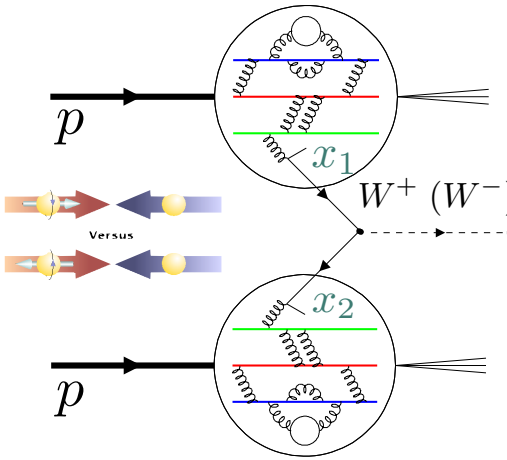
- ALL measurements tend to fall in-between GRSV-STD and DSSV
- Run 9 data: First rapidity dependent di-jet measurement

  ⇒ Constrain x dependence!

Recent results - Quark / Anti-quark pol. program

- Probing the quark flavor structure using W boson production

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



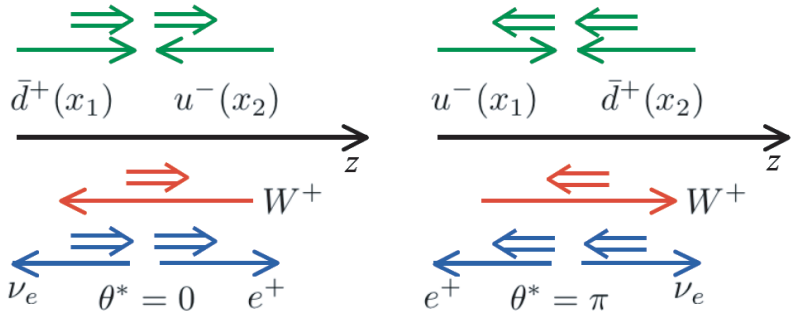
$W^+ \ (W^-)$

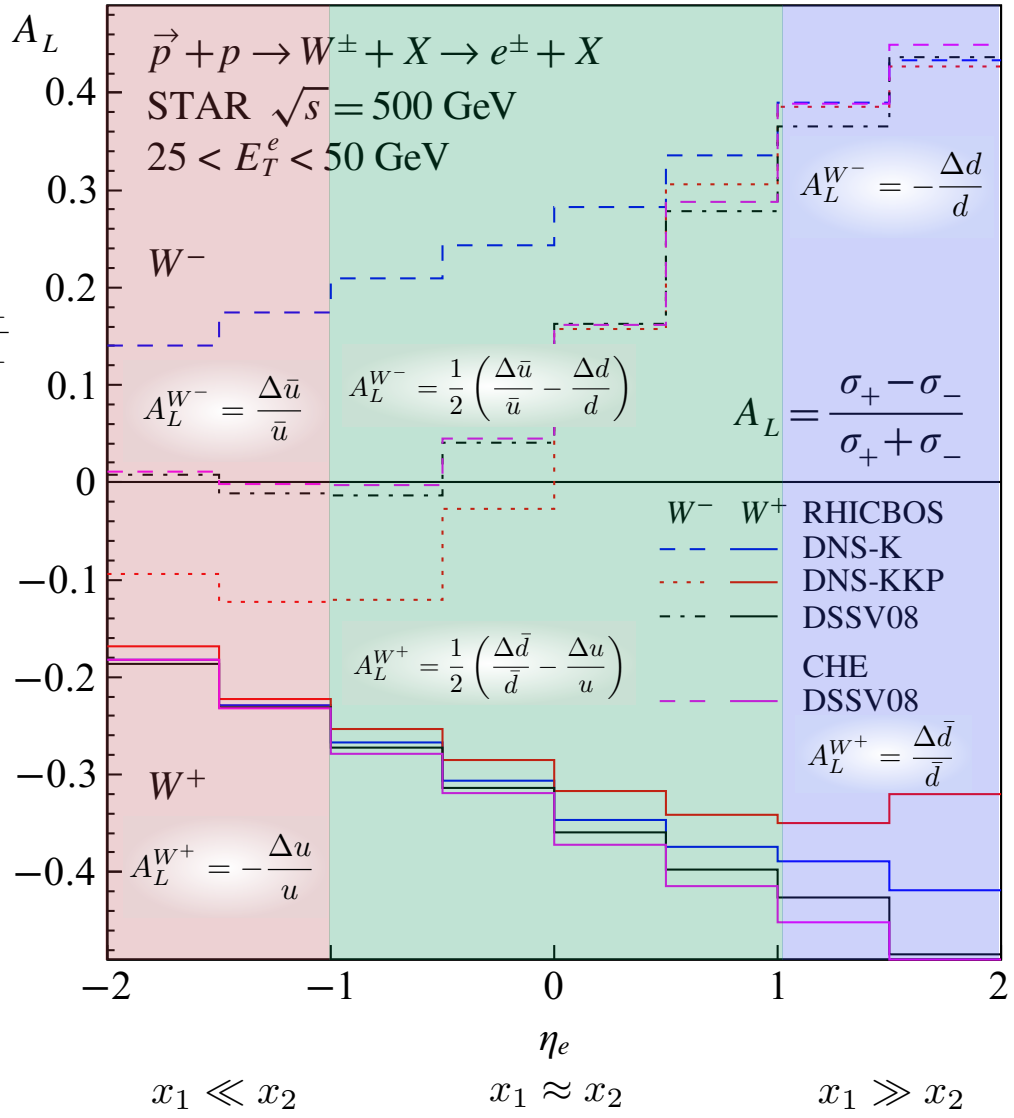
$\nu_e \ (\bar{\nu}_e)$

$e^+ \ (e^-)$

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

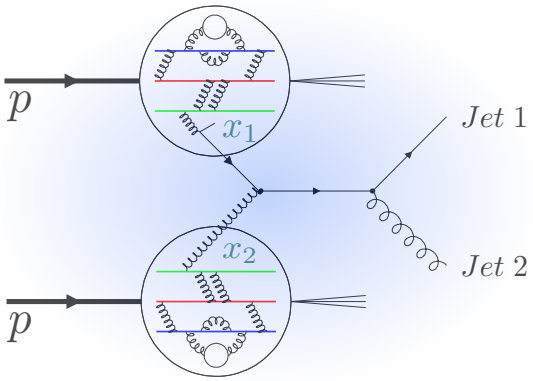
$\Delta \bar{d} + u \rightarrow W^+$
$\Delta u + \bar{d} \rightarrow W^+$





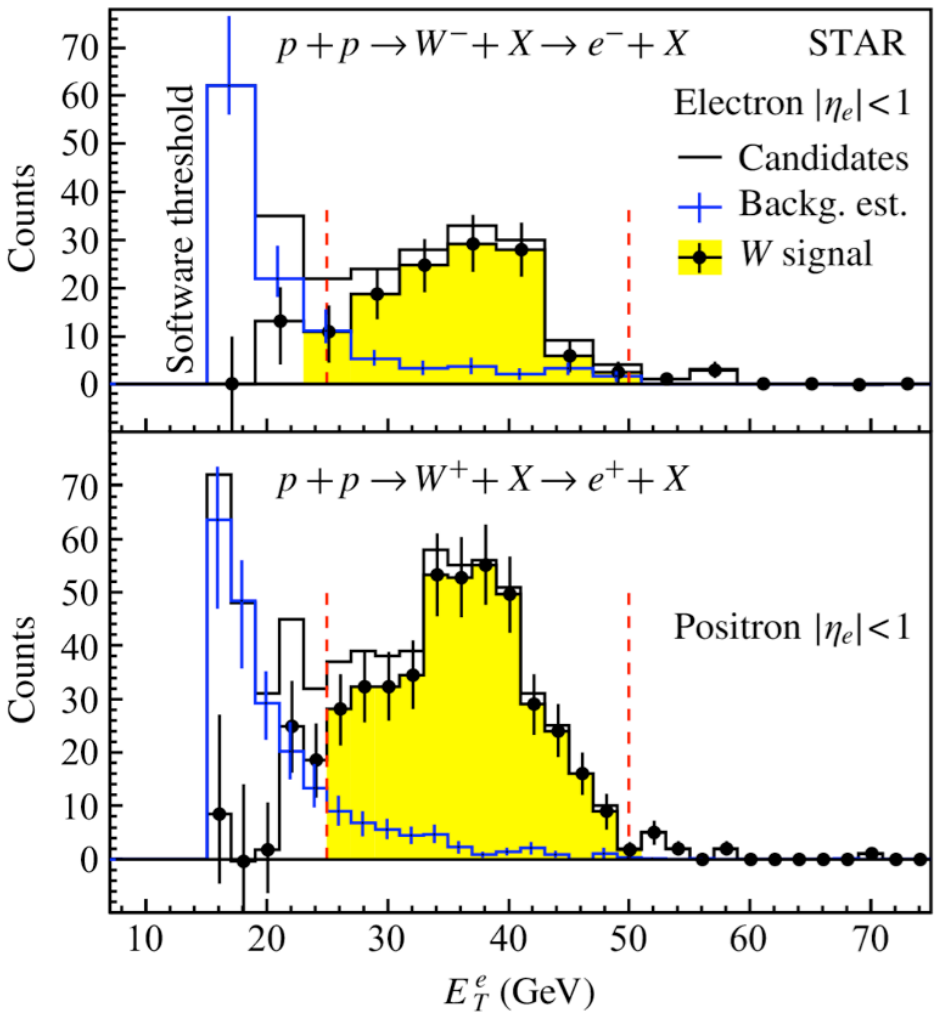
Recent results - Quark / Anti-quark pol. program

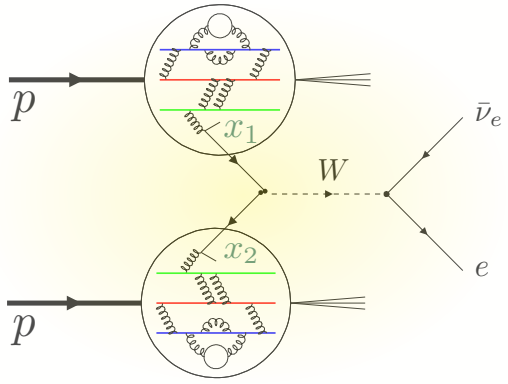
Measurement: Background treatment / Signal distribution



- 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



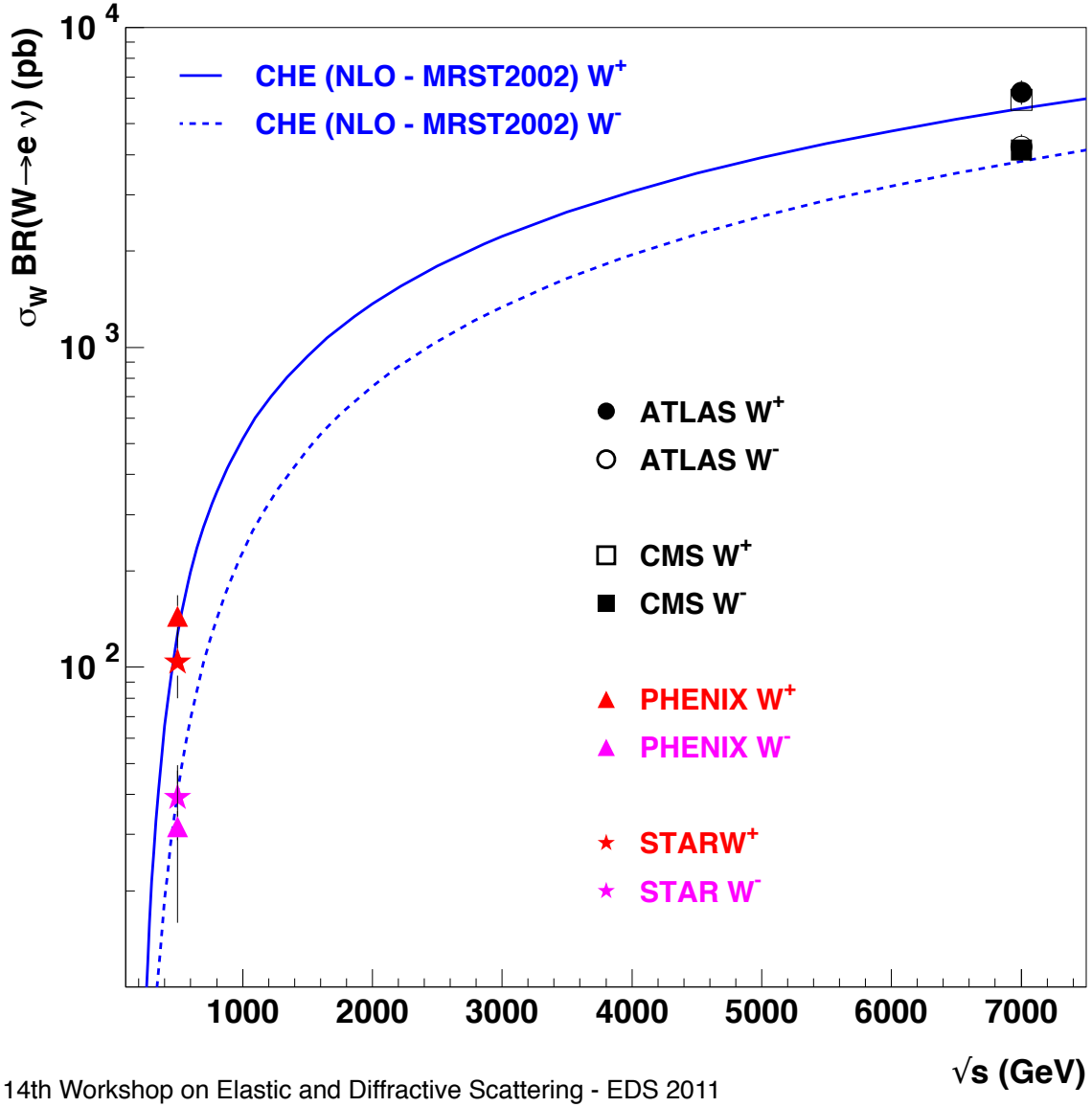


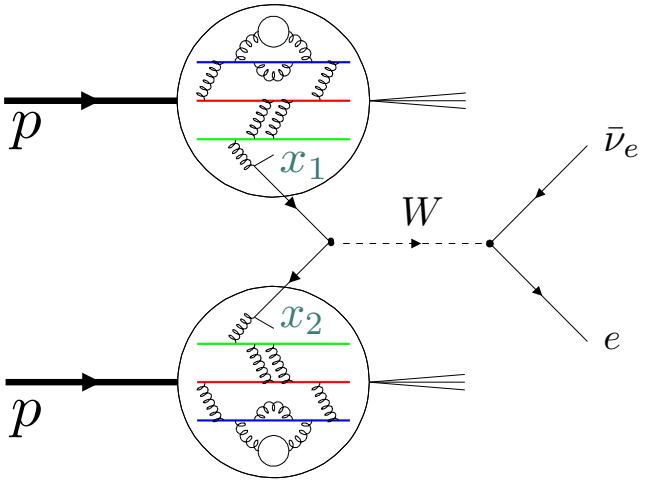
- Total e^+/e^- cand. events (S+B):
  - e^+: 462
  - e^-: 139

STAR Collaboration, PRL 106, 062002 (2011)

Recent results - Quark / Anti-quark pol. program

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

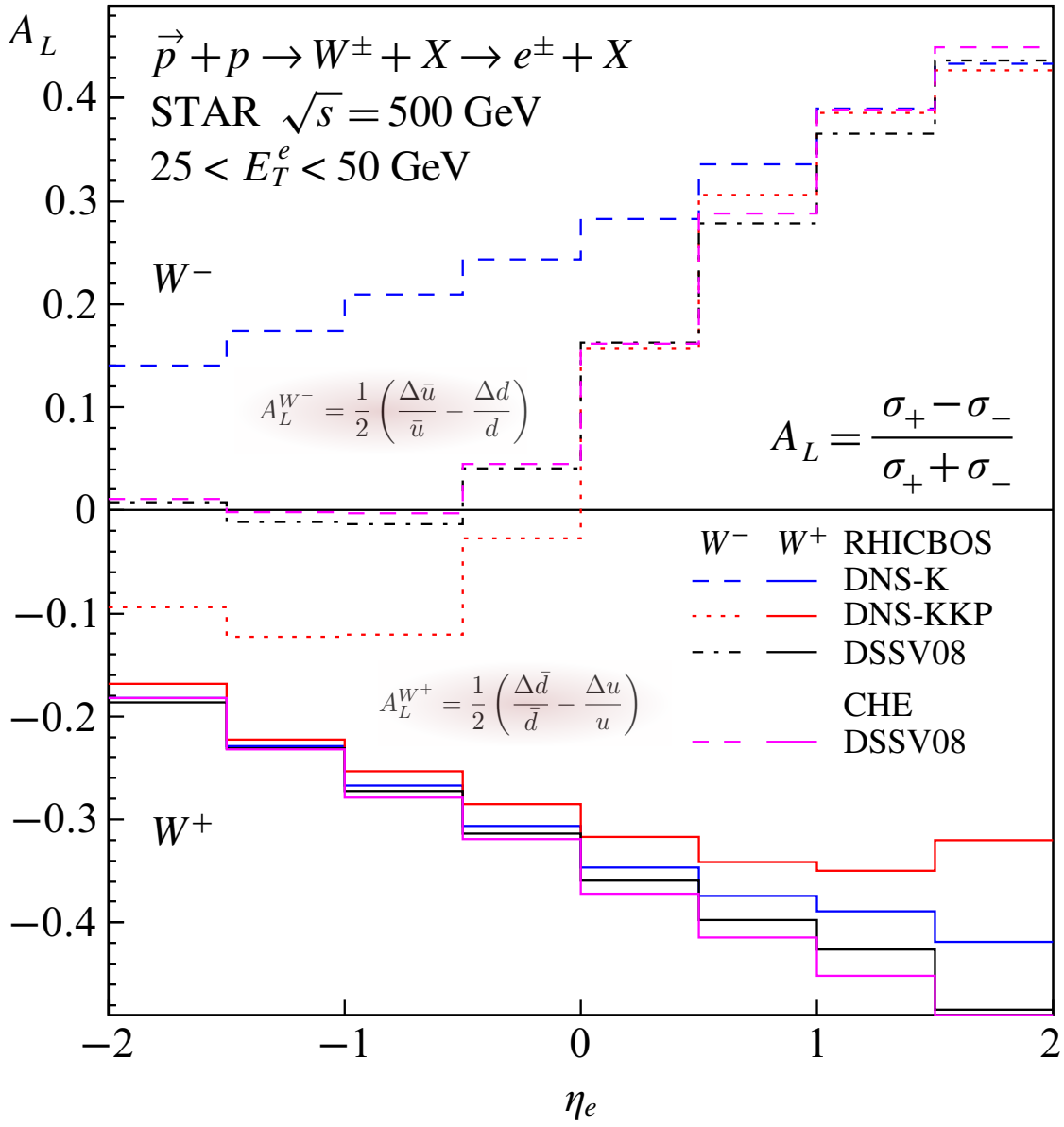




- Measured and theory evaluated cross-sections agree within uncertainties
- Theory calculations: Full NLO framework

Recent results - Quark / Anti-quark pol. program

- First STAR A_L result

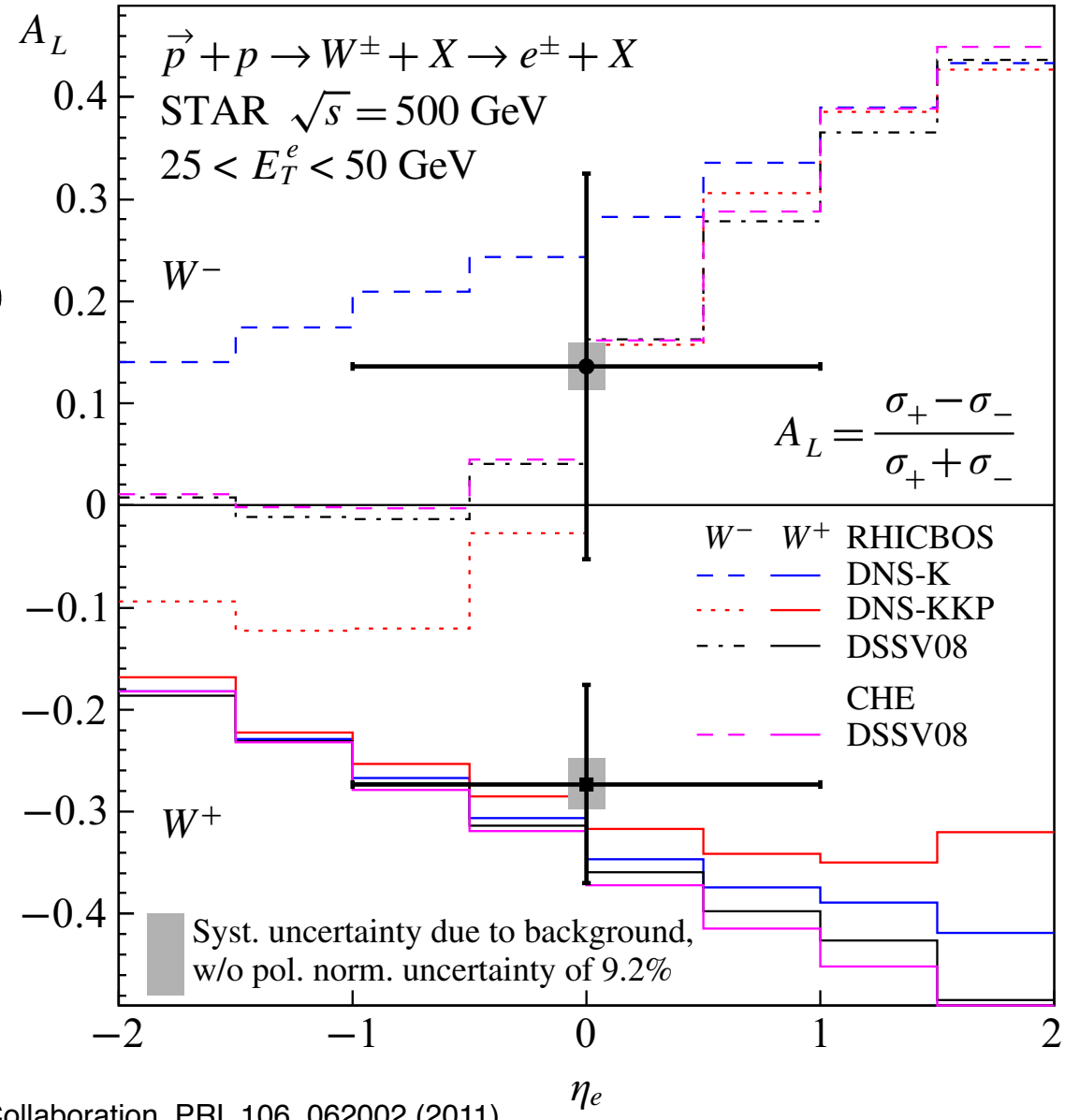


Recent results - Quark / Anti-quark pol. program

- First STAR A_L result

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

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



STAR Collaboration, PRL 106, 062002 (2011)

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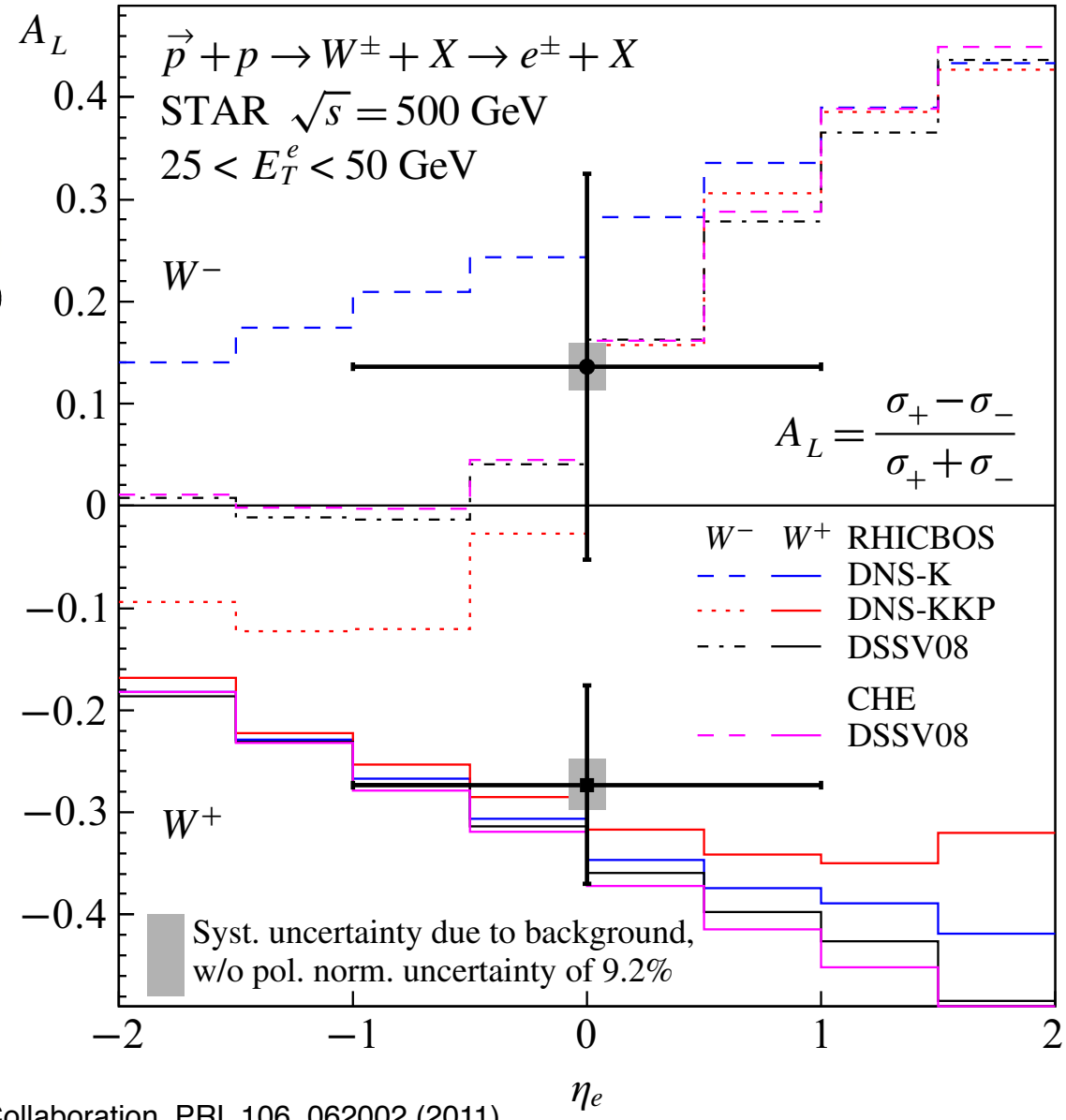
$$A_L^{W^+} = -0.27 \pm 0.10\ (\text{stat.}) \pm 0.02\ (\text{syst.}) \pm 0.03\ (\text{norm.})$$

- $A_L(W^+)$ negative with a significance of ~3σ
- $A_L(W^-)$ central value positive



STAR Collaboration, PRL 106, 062002 (2011)

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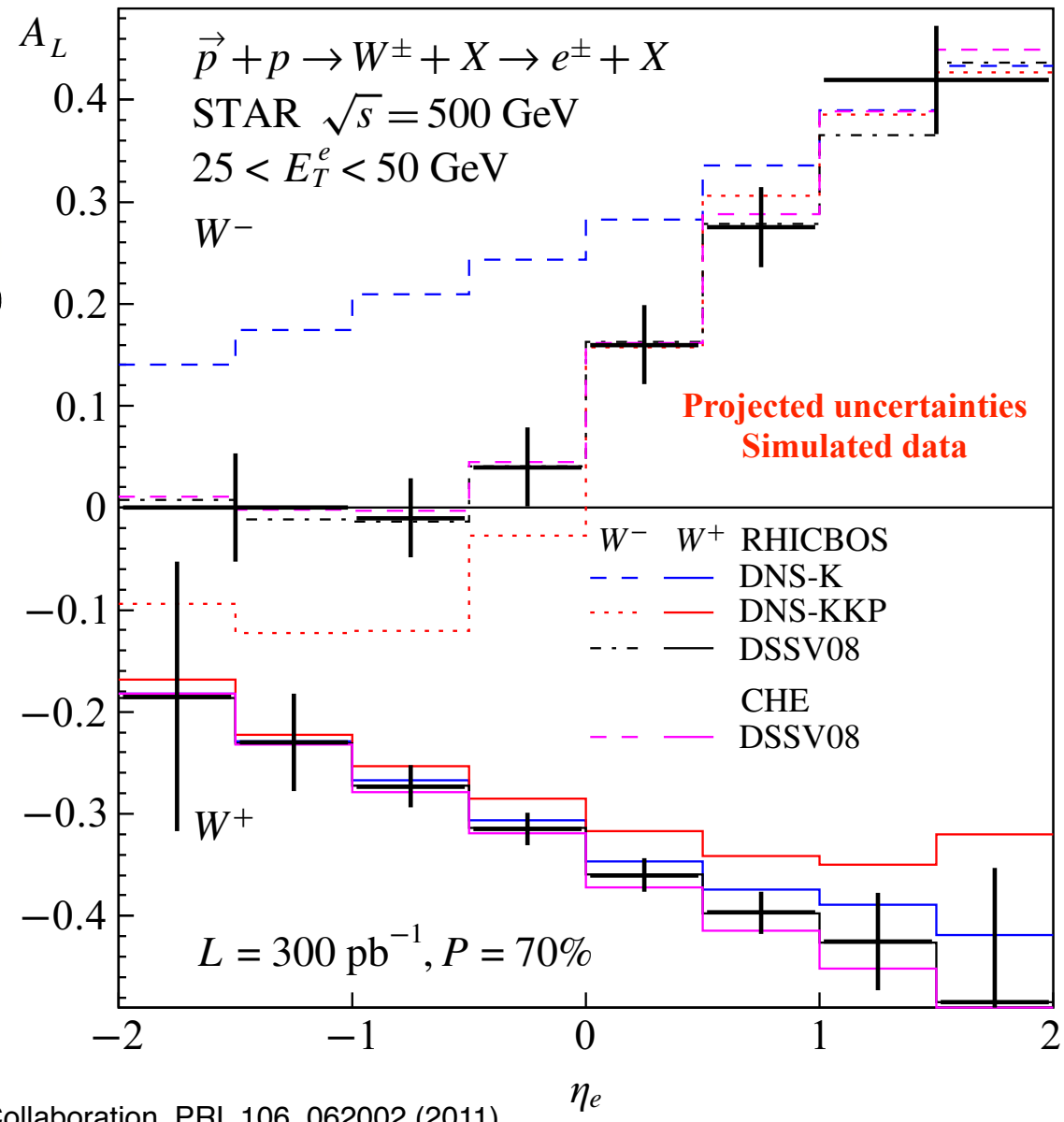
$$A_L^{W^-} = 0.14 \pm 0.19\ (\text{stat.}) \pm 0.02\ (\text{syst.}) \pm 0.01\ (\text{norm.})$$

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



- $A_L(W^+)$ negative with a significance of ~3σ
- $A_L(W^-)$ central value positive

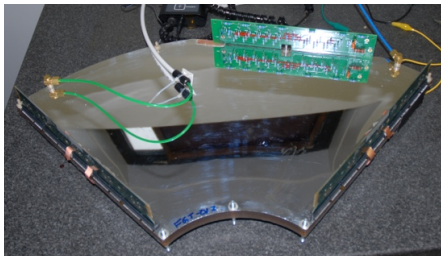
- Measured asymmetries are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data

  ⇒ Universality of helicity distr. functions!

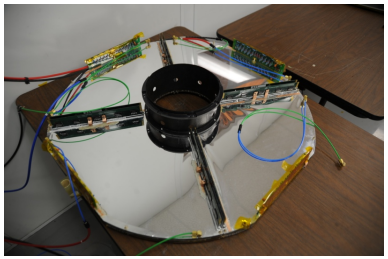
STAR Collaboration, PRL 106, 062002 (2011)

Triple-GEM Forward Tracking System - EIC R&D

- Forward system: STAR Experience

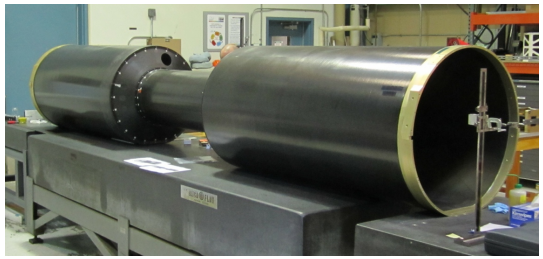


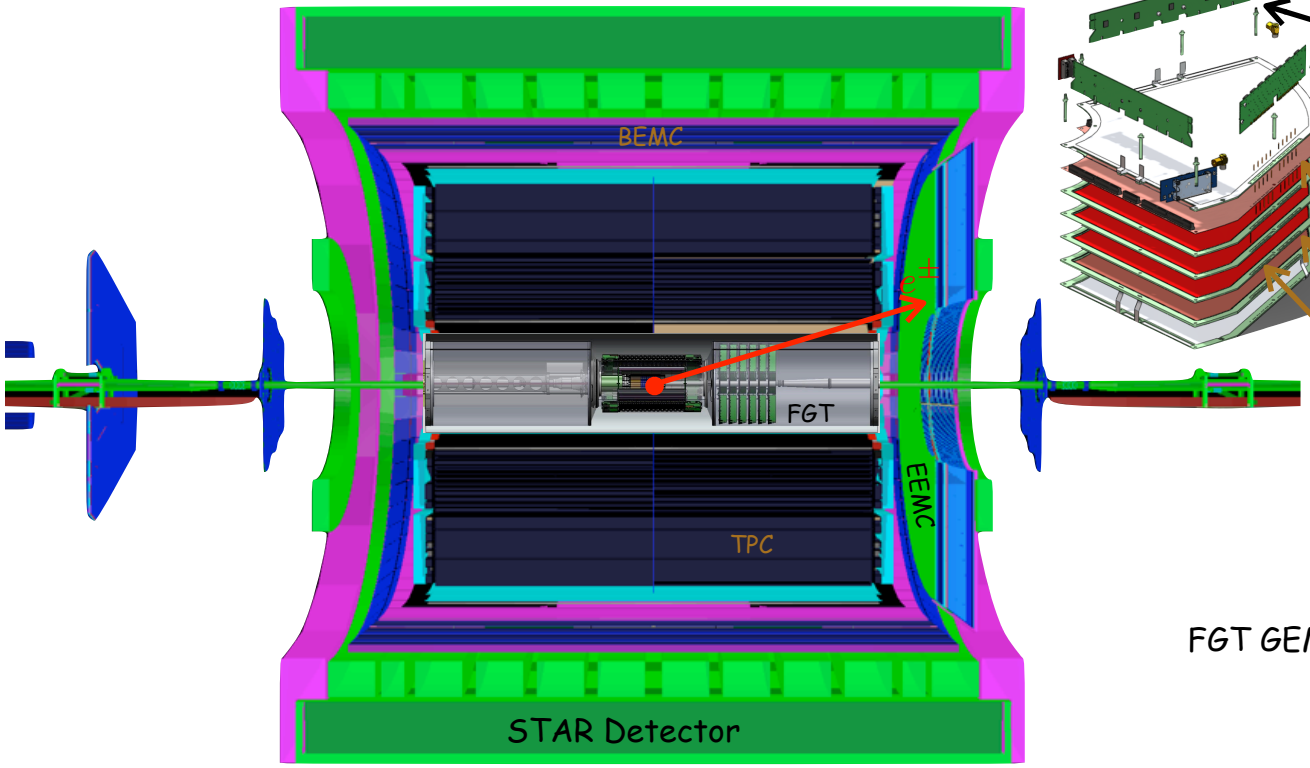
Quarter section

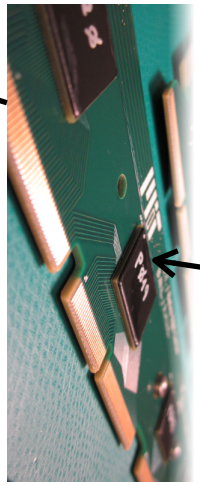


Disk

Quarter section







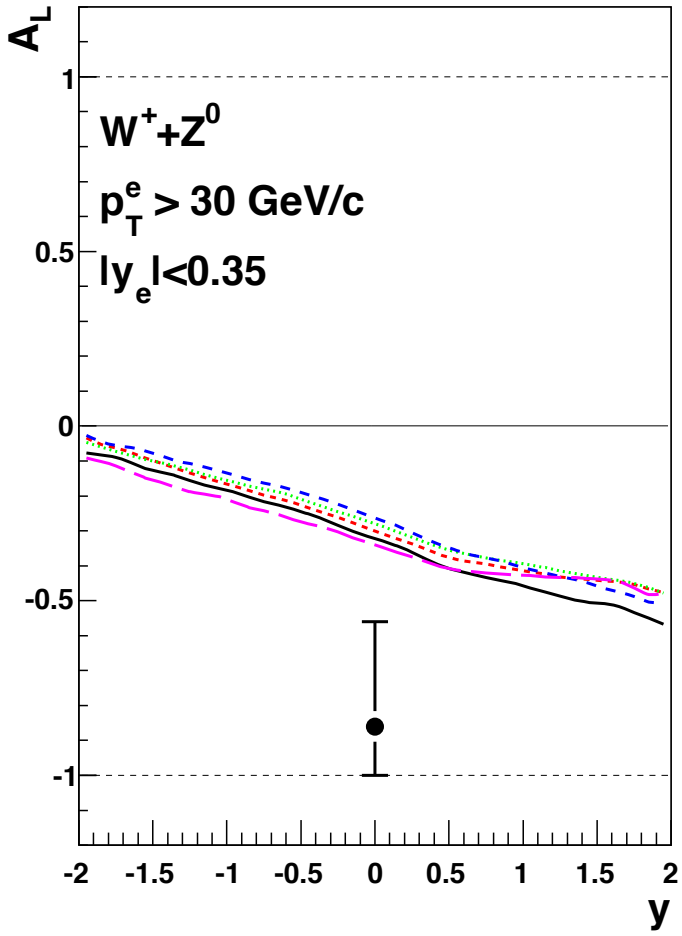
APV module

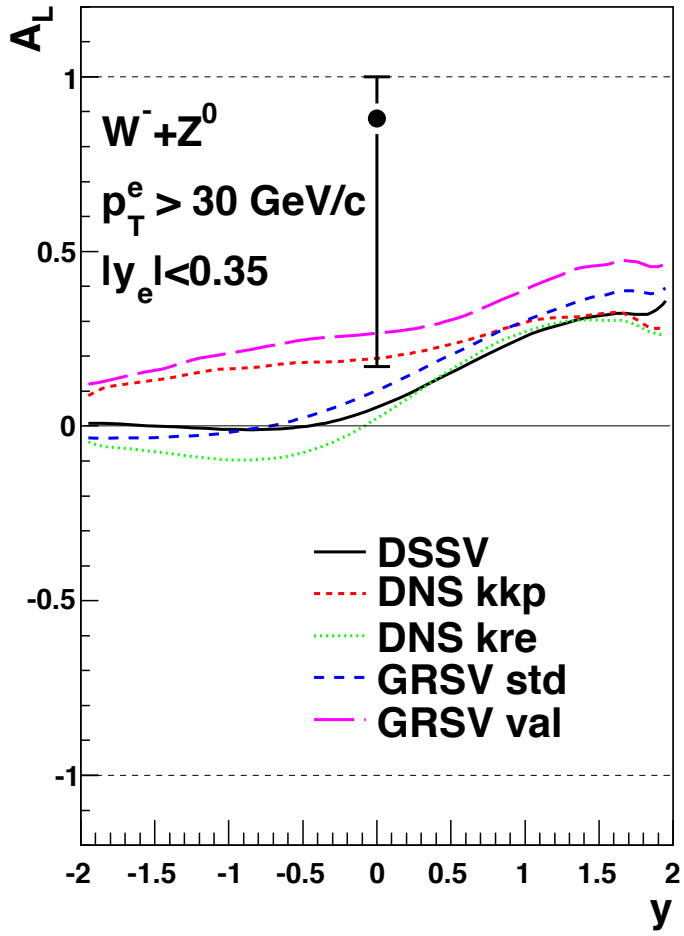
Packaged APV chip

FGT GEM foil

Recent results - Quark / Anti-quark pol. program

- PHENIX: Mid-rapidity A_L





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

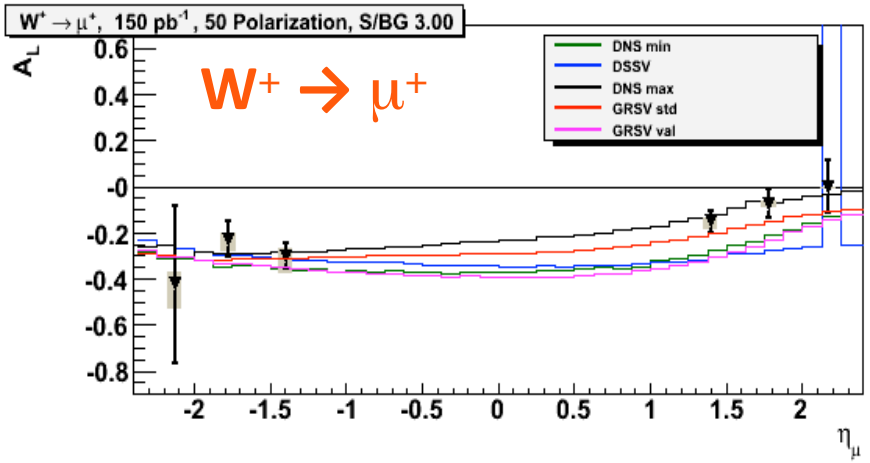
PHENIX Collaboration, PRL 106, 062001 (2011)

Recent results - Quark / Anti-quark pol. program

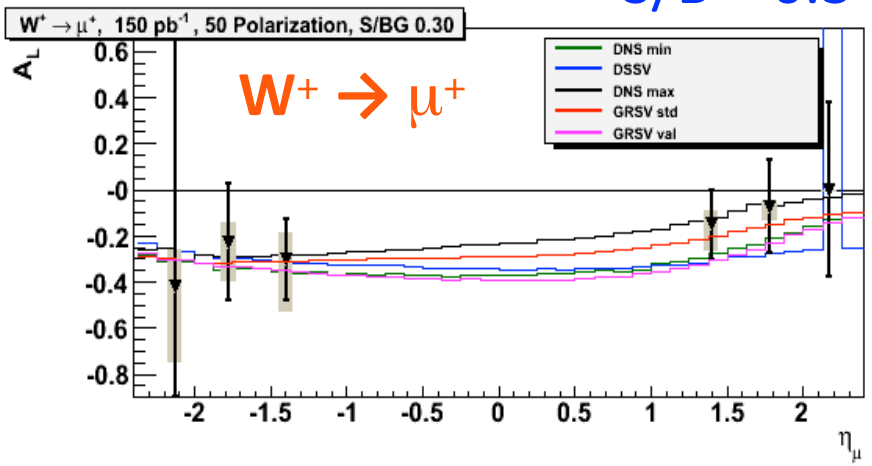
- PHENIX: Mid-rapidity A_L

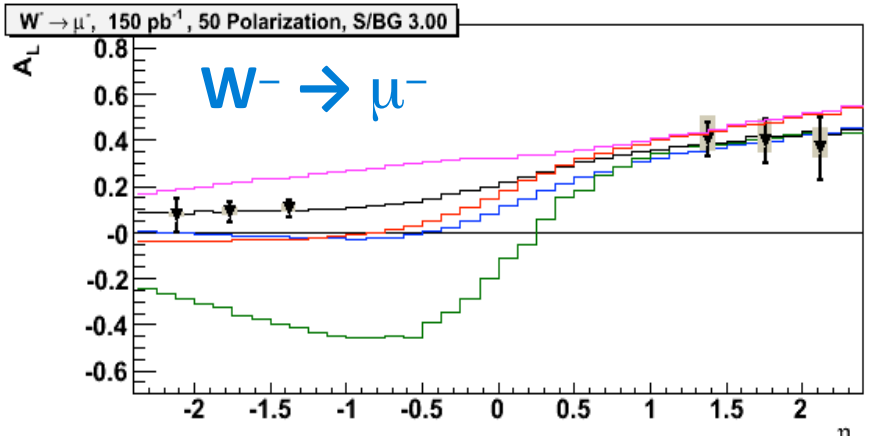
$L=150pb^{-1}$ / P=50%

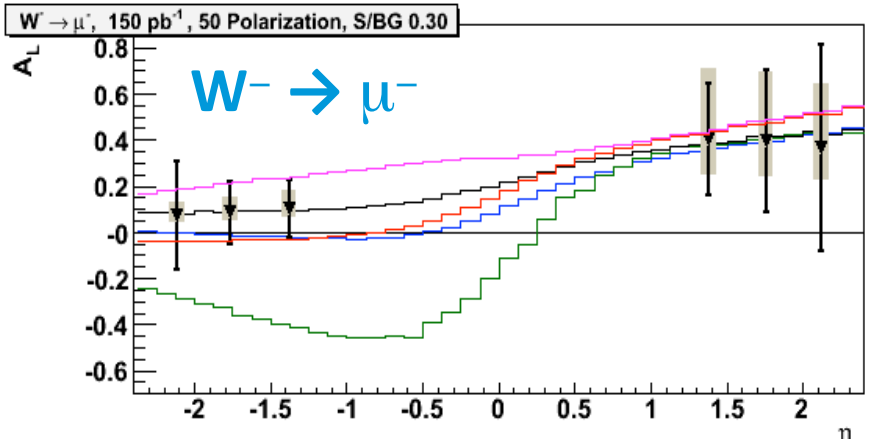
S/B = 3.0



S/B = 0.3





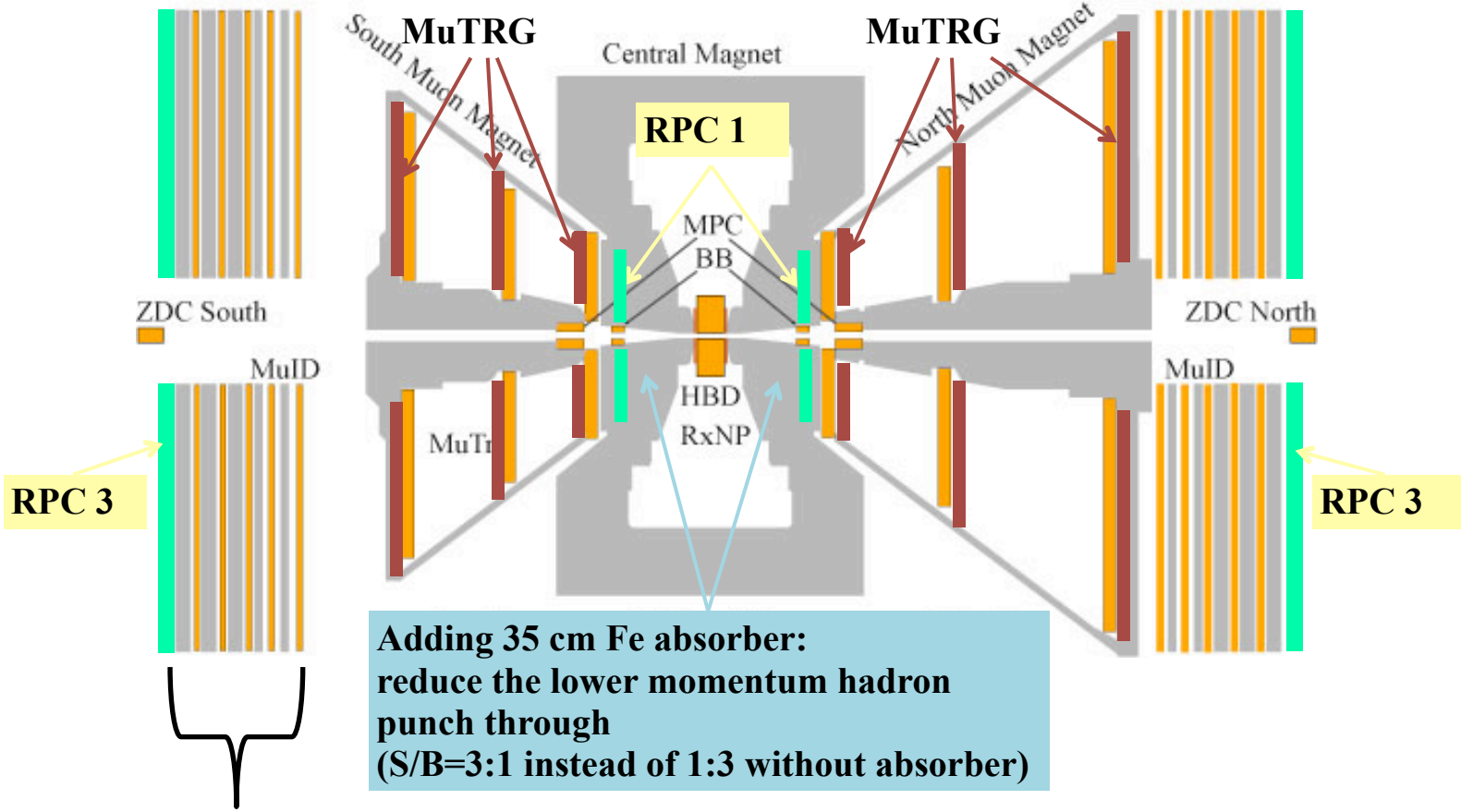


η_μ (muon pseudo-rapidity)

η_μ (muon pseudo-rapidity)

Future - Quark / Anti-quark pol. program

- PHENIX Muon trigger system



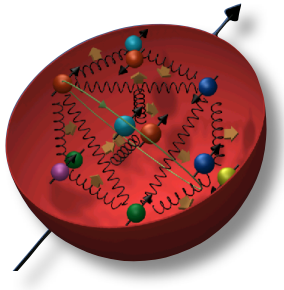
MuID Trigger:
Selecting momentum above 2 Gev/c

MuTRG:
Fast selection of high momentum tracks

RPC:
Provide timing information and rough position information

Summary / Outlook

- Hadron/Jet production: Gluon polarization
  - Several final states (Hadron / Jet) have been measured all pointing to the same conclusion that the gluon polarization is small, much smaller than the proton spin itself, in contrast to earlier theoretical - controversial - speculations
  - First Di-Jet measurement opens the path to constrain the shape of Δg
  - Run 9 results: Precise A_{LL} measurement above DSSV fit suggesting $\Delta G > 0$

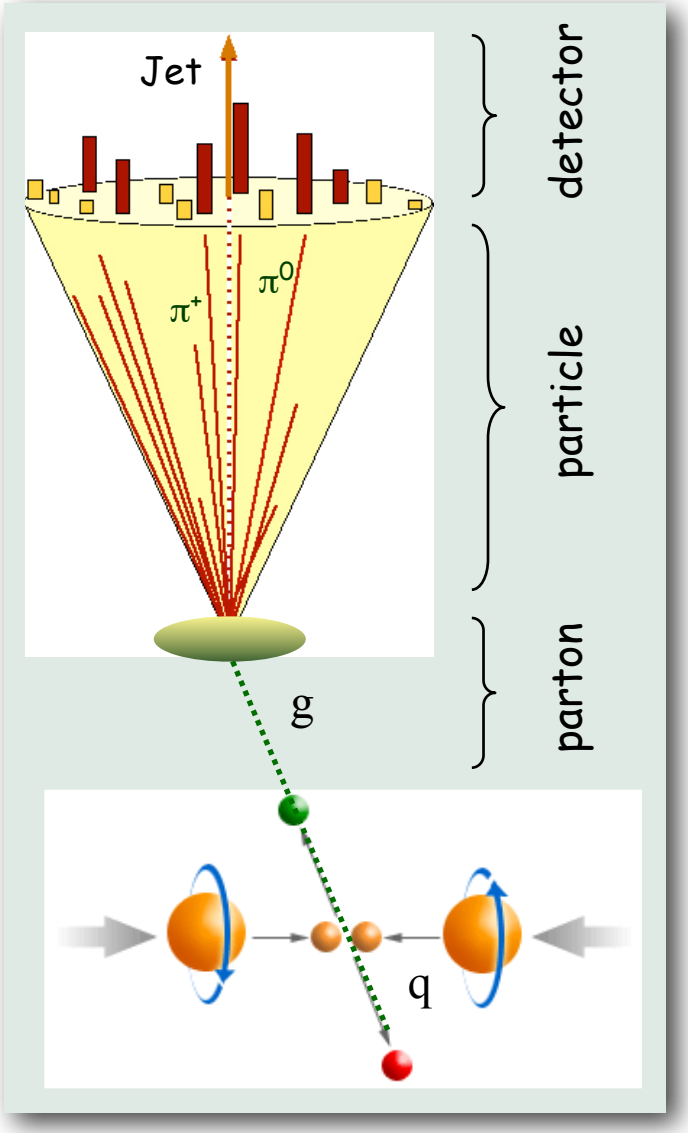


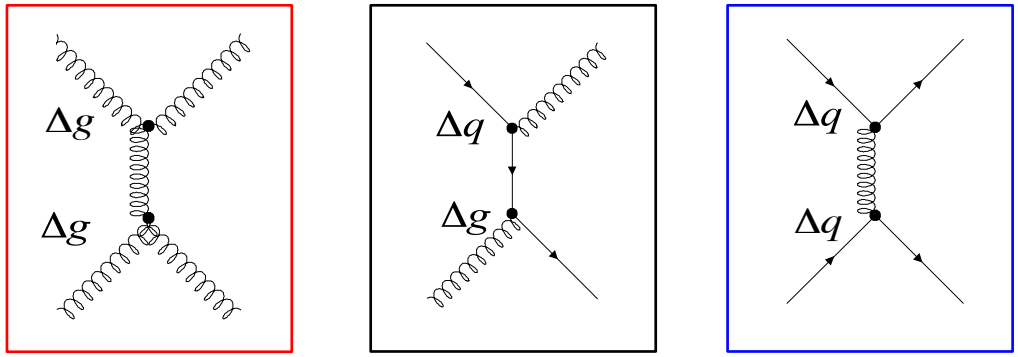
- W boson production: Quark/Antiquark polarization
  - First measurement of W boson production in polarized p+p collisions at RHIC
  - Establish a completely new and direct way to probe quark and anti-quark polarization in a high-energy polarized hadron collider environment

- Long-term: Establish a new collider facility at BNL/JLAB - Electron-Ion Collider!

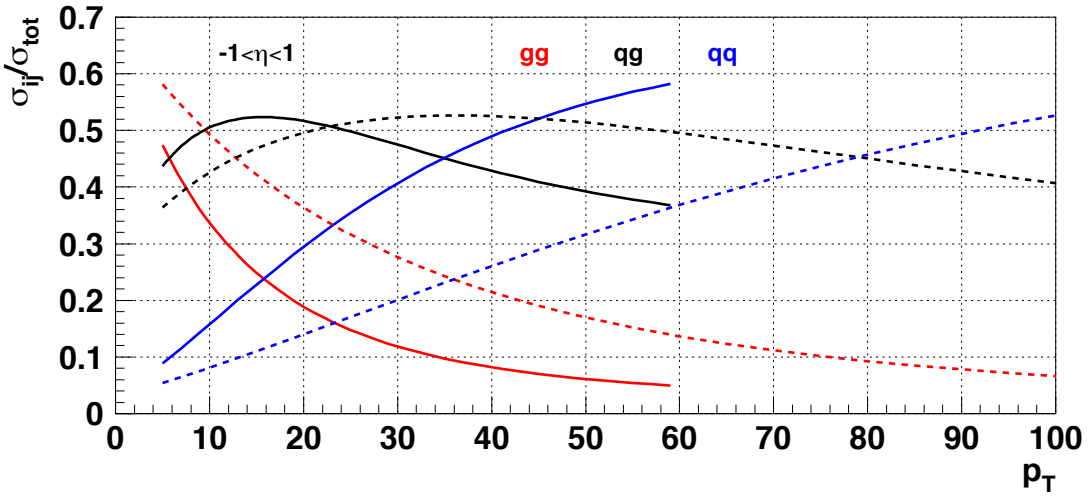
Backup: Jet/Hadron production

- RHIC Gluon polarization: Inclusive measurements





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



Backup: Jet/Hadron production

RHIC Gluon polarization - Correlation Measurements

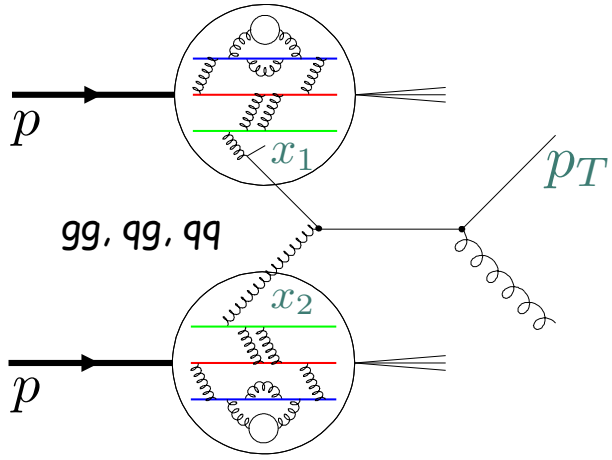
- Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:

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

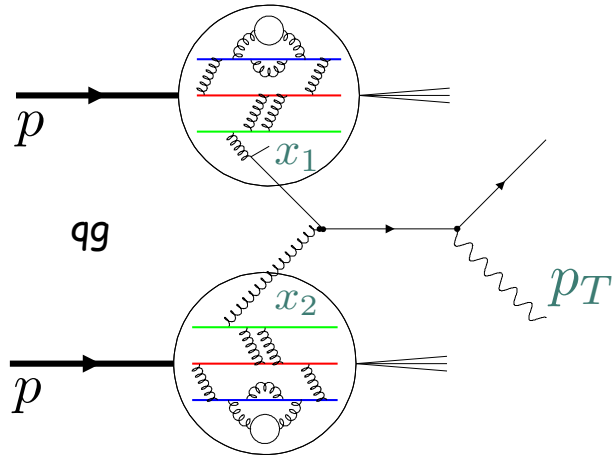
$$M = \sqrt{x_1 x_2 s}$$

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

- Di-Jet production / Photon-Jet production
  - Di-Jets: All three (LO) QCD-type processes contribute: gg, qg and qq
  - 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 QCD analysis



Di-Jet production

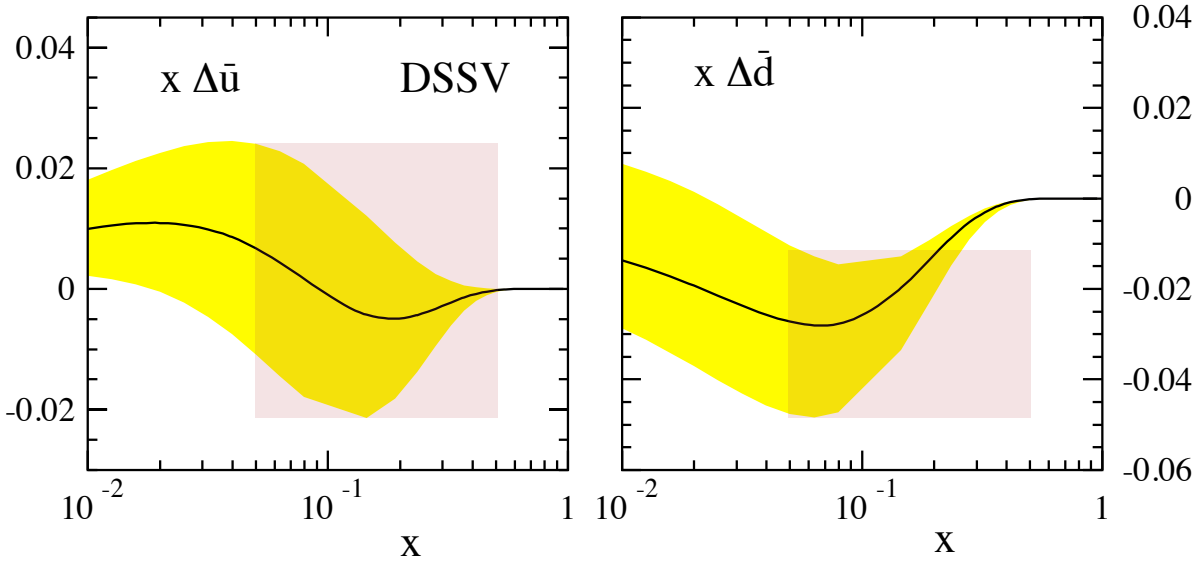


Photon-Jet production

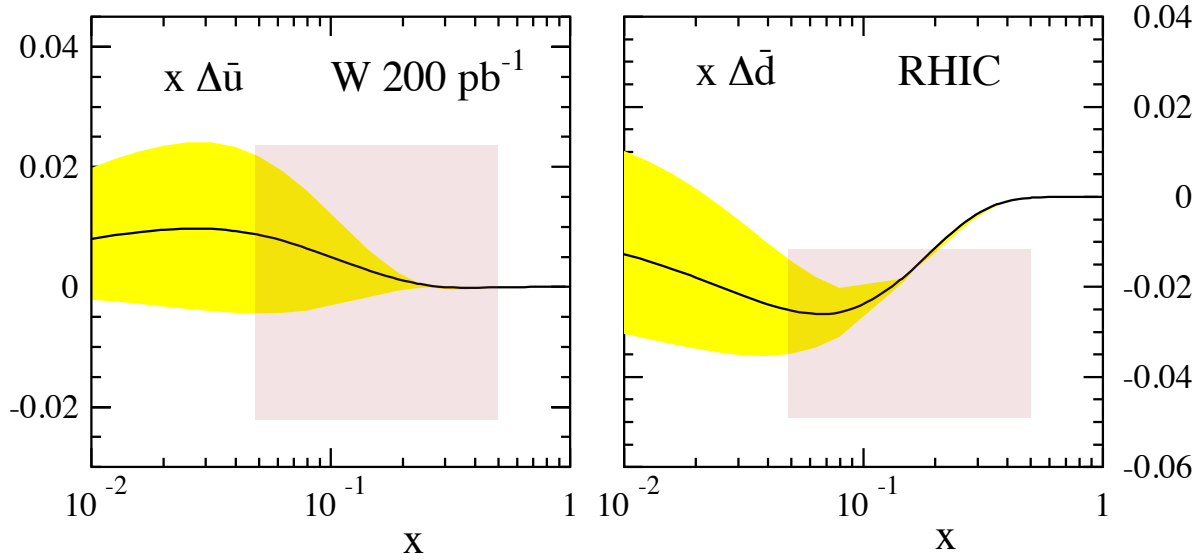
Backup: Quark / Anti-quark pol. program

- RHIC W Impact on polarized QCD sea

D. deFlorian and W. Vogelsang, PRD81, 094020 (2010)



DSSV08 Fit



Include W results at RHIC

(PHENIX and STAR)

assuming $-2 < \eta < 2$

with 200pb-1

Strong constrain for x>0.05