Nucleon spin structure and hyperon spin transfer study at STAR

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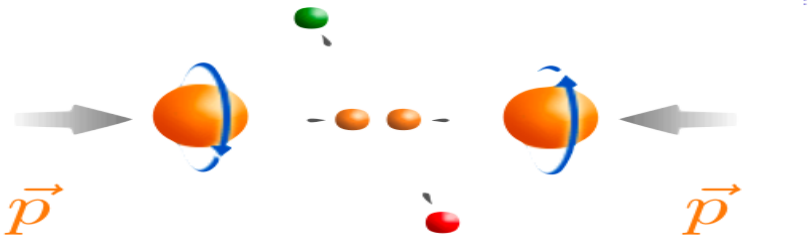
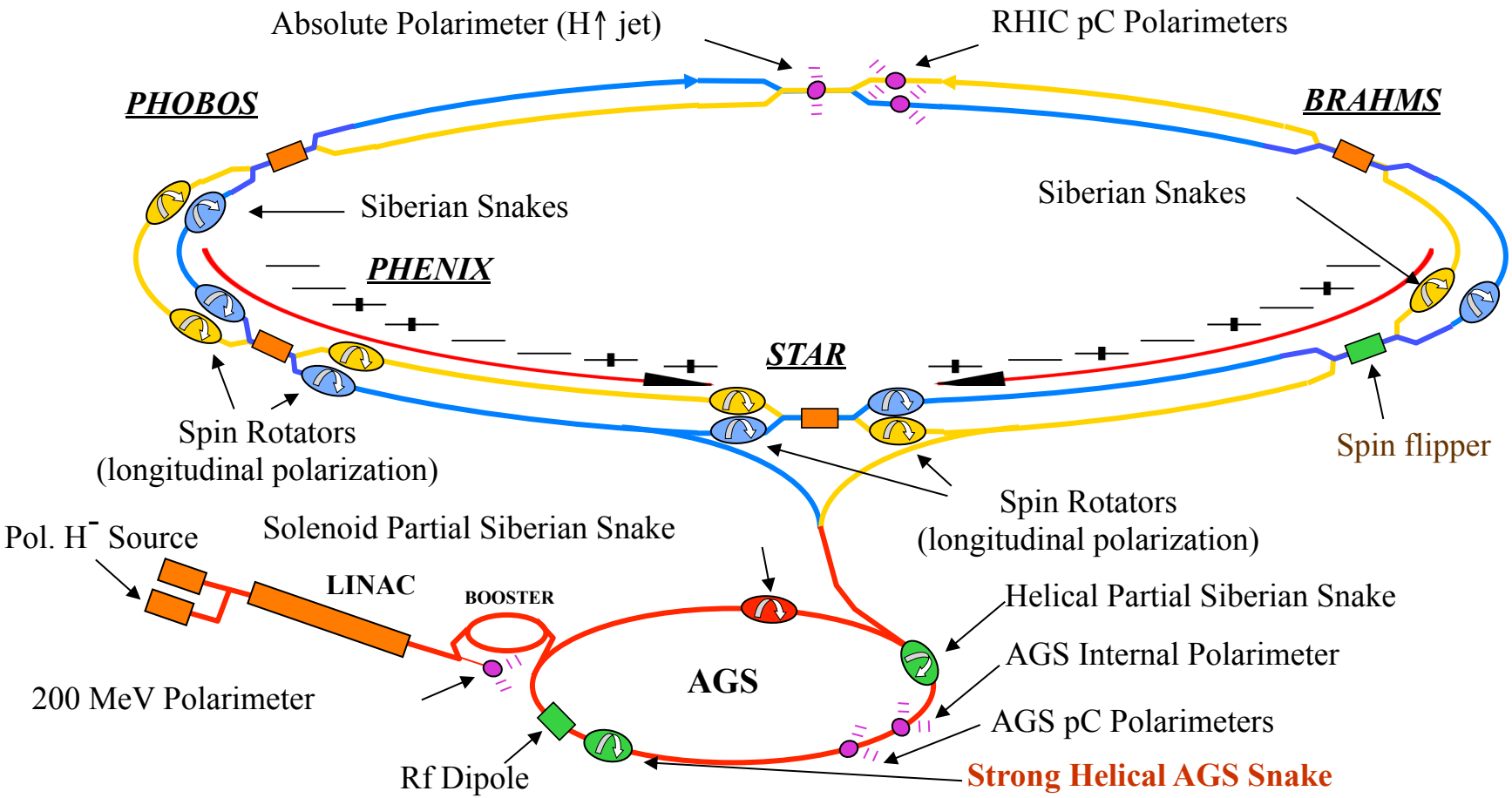
"Hadron 2012", July 20, 2012



Content:

- Introduction to RHIC spin program
- ΔG measurement at STAR/RHIC
- Quark / Anti-quark polarization via W production
- Hyperon spin transfer and strange quark pol.
- Summary

RHIC- the first polarized pp collider in the world



- Spin pattern changes from bunch to bunch
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little if any depolarization

The RHIC spin program

- Longitudinal spin program: determination of helicity distributions:
  - Gluon polarization $\Delta g(x)$ in the nucleon

    -- inclusive jet, hadrons

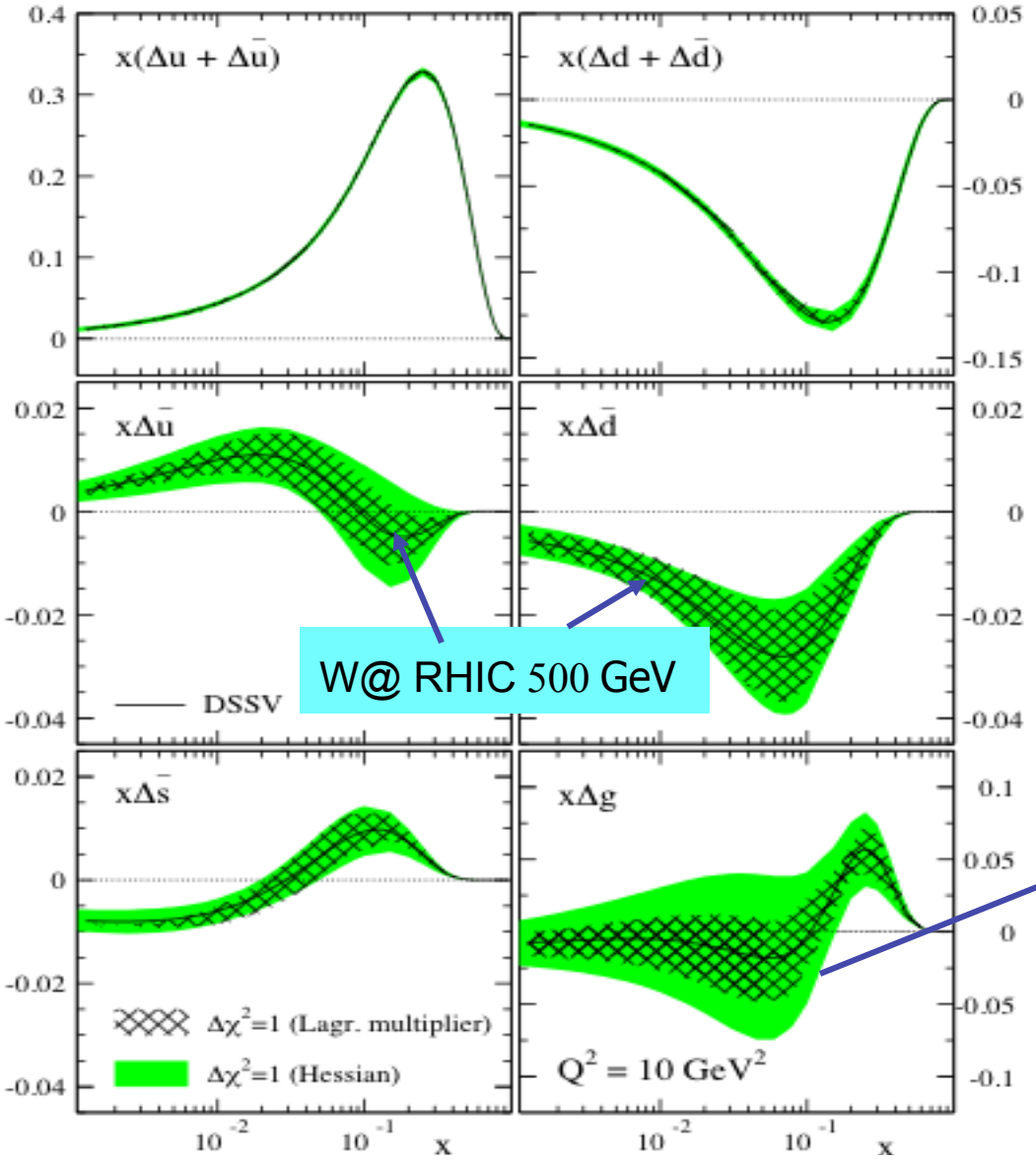
    -- di-jets, γ+jet
  - Flavor separation: quark & anti-quark polarization

    -- RHIC 500 GeV program ($W^{\pm}$ production)

    -- Hyperon spin transfer & strange quark polarization

- Transverse spin program:
  - Single spin asymmetry A_N (SSA) on π^0, η
  - QCD mechanisms (Sivers, Collins, high-twist)

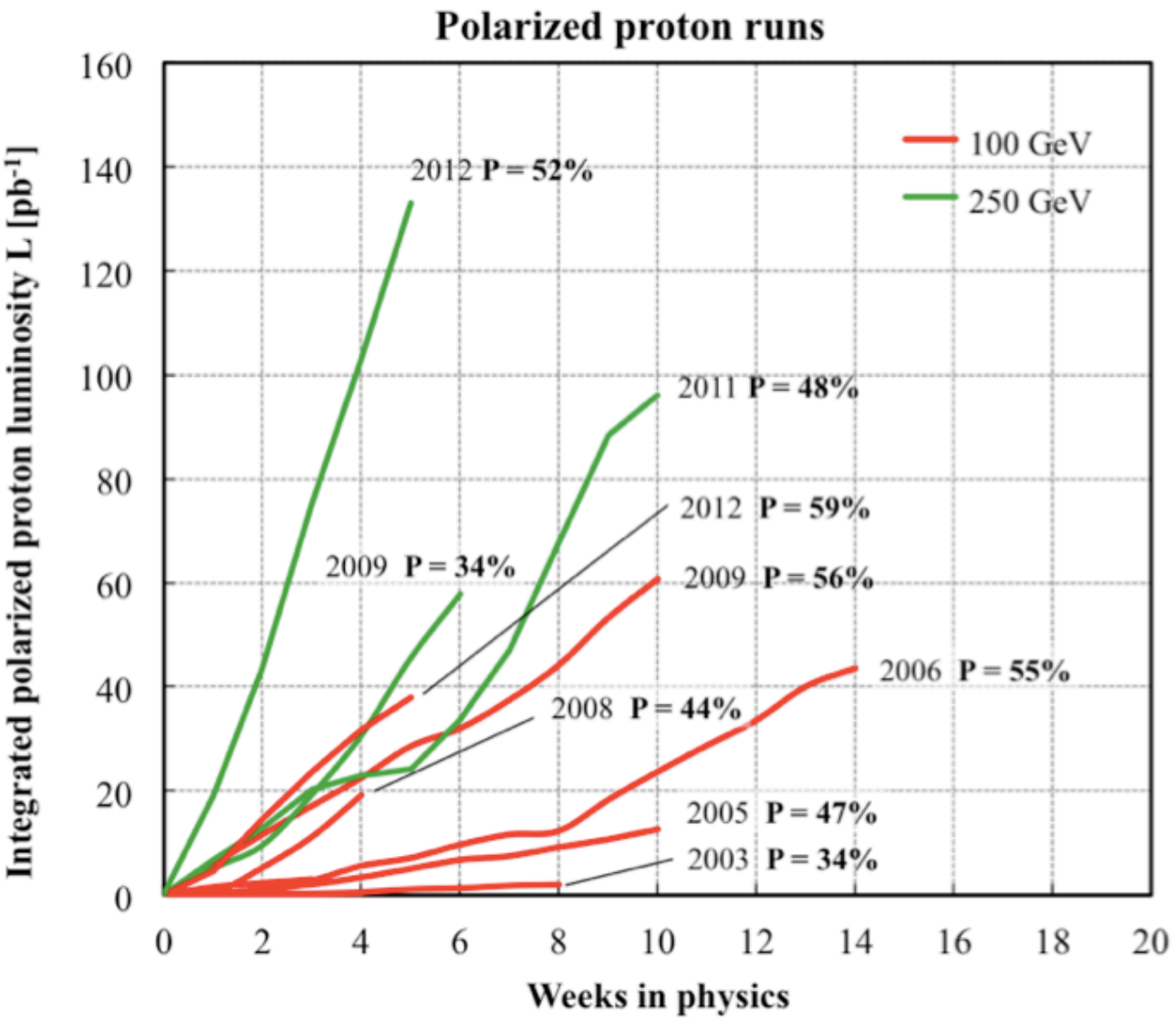
Detailed knowledge on $\Delta q(x)$, $\Delta g(x)$ - global fit using DIS and pp data



D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)

Experimental aspects - RHIC

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



The STAR Detector

Magnet

- 0.5 T Solenoid

Triggering & Luminosity Monitor

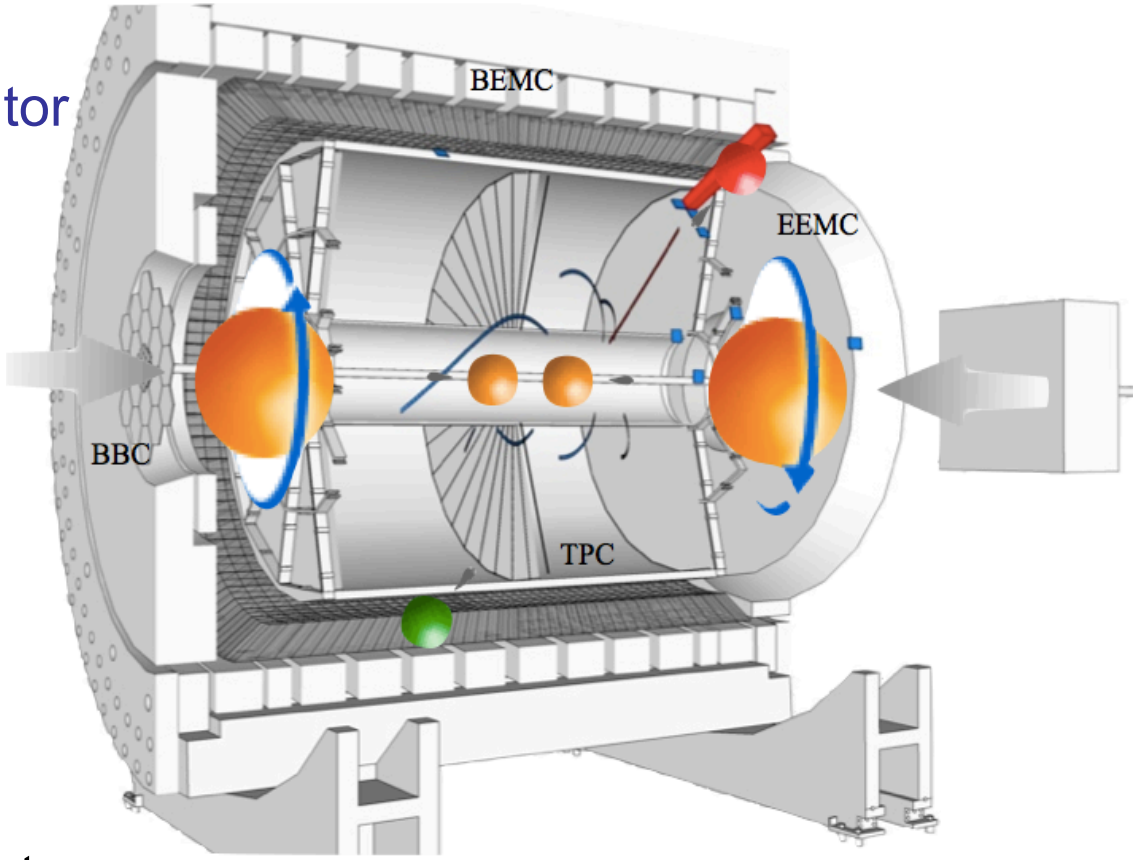
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters

Central Tracking

- Large-volume TPC
  - $|\eta| < 1.3$

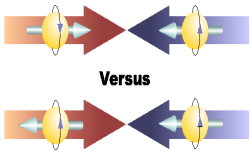
Calorimetry

- Barrel EMC (Pb/Scintilator)
  - $|\eta| < 1.0$
  - Shower-Maximum Detector
- Endcap EMC (Pb/Scintillator)
  - $1.0 < \eta < 2.0$



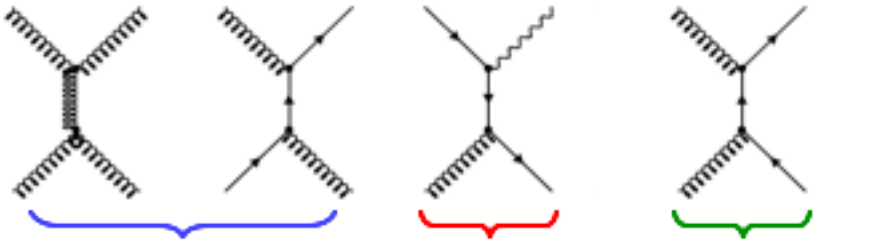
Accessing Δg(x) in pp collision

- Longitudinal spin asymmetry:



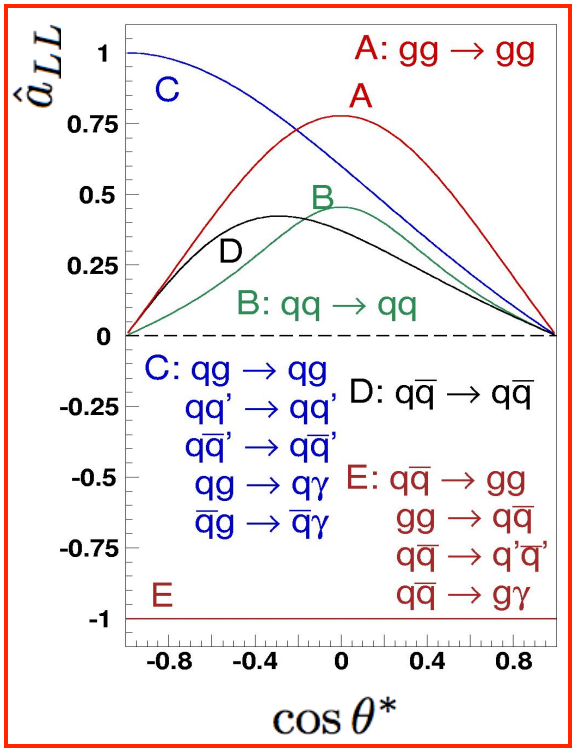
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

Δf_1 Δf_2 $\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}$ D_f^{π}

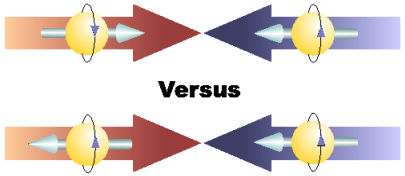


$\vec{p}\,\vec{p} \to \text{jet}(s)\, X$ $\vec{p}\,\vec{p} \to \gamma X$ $\vec{p}\,\vec{p} \to c\bar{c}X,\ b\bar{b}X$

$\vec{p}\vec{p} \to jet + X$	No FF! Average over partonic kinematics
$\vec{p}\vec{p} \to \pi^{+/-} + X$ $\vec{p}\vec{p} \to \pi^{0} + X$	Requires D_f^{π} for interpretation
$\vec{p}\vec{p} \to \gamma + jet$	No FF! Reconstruct partonic kinematics. challenging pion background



Measurements of longitudinal spin asymmetry



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

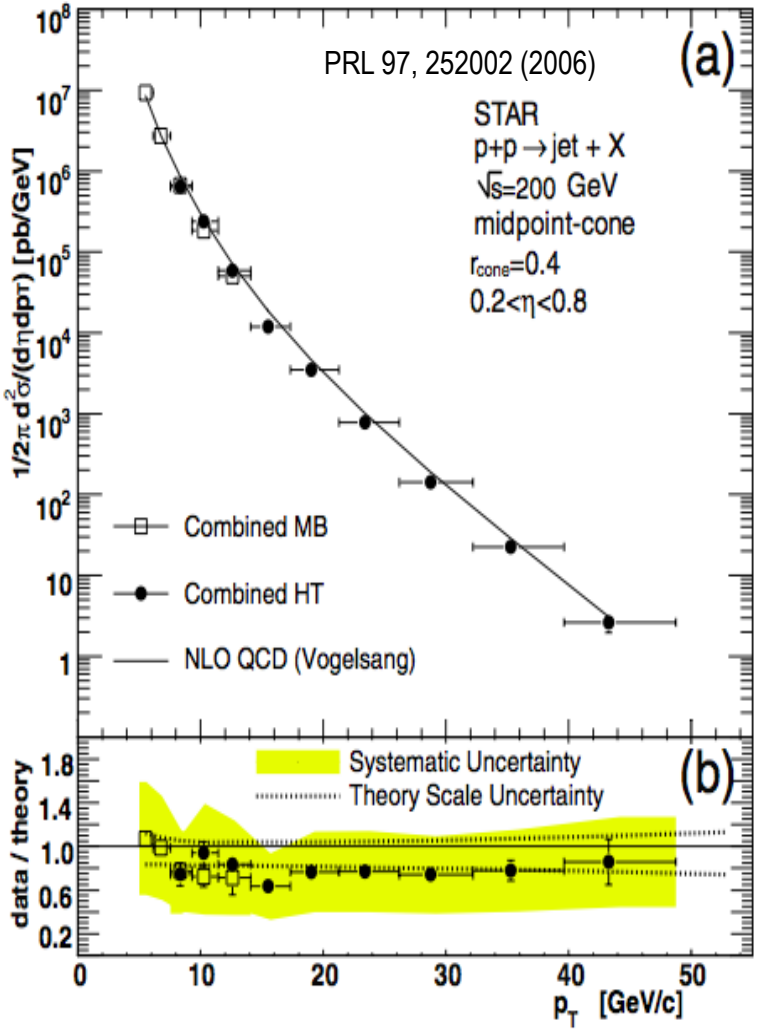
Ingredients:

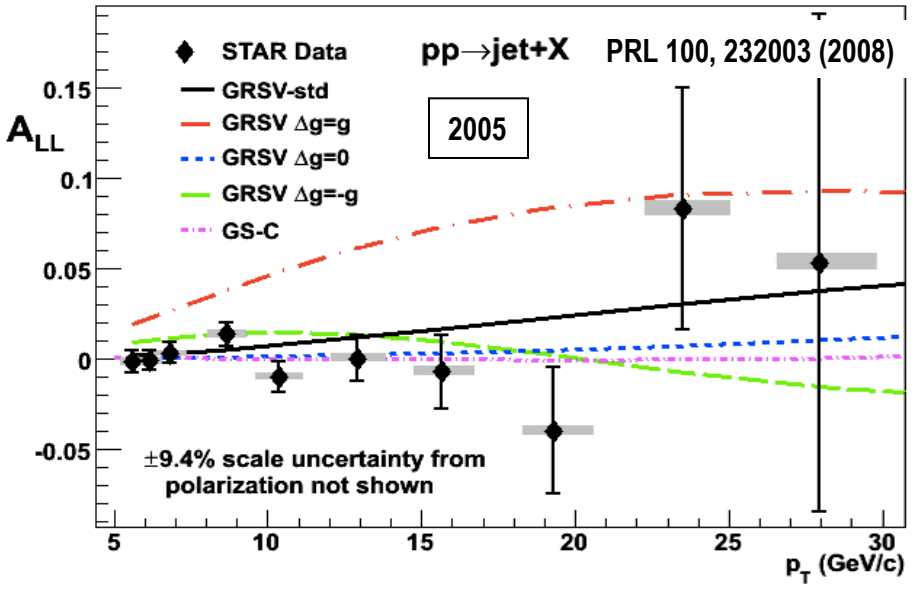
- Polarization P_1,P_2: measured by RHIC polarimeters;
- Spin dependent yields N_{++}, N_{+-} : number of detected jets/particles for a given combination of beam polarization directions;
- Relative Luminosity R measured with the STAR BBC:

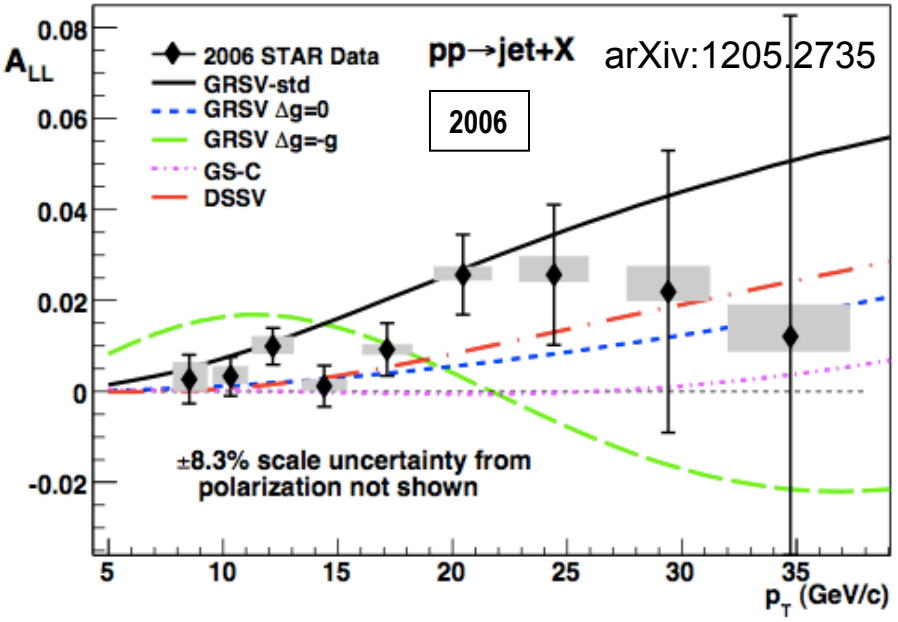
$$\boldsymbol{R = \frac{L_{++}}{L_{+-}}}$$

STAR Results on jet spin asymmetry

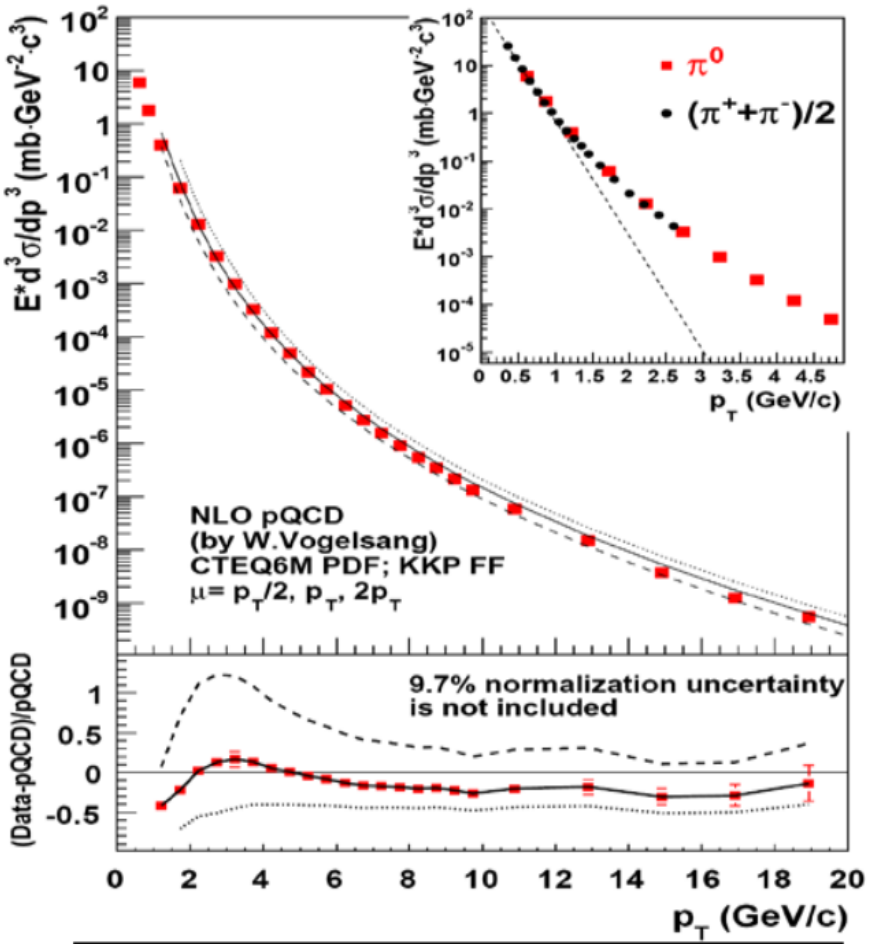
Experimental cross section agrees with NLO pQCD *over 7 orders of magnitude*

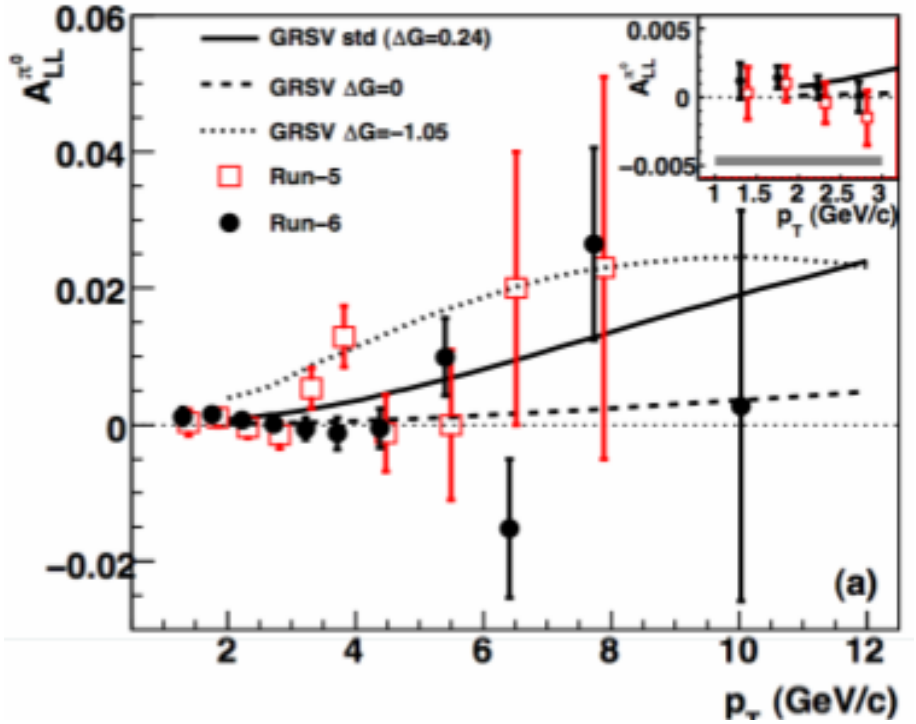






PHENIX results on pi0 spin asymmetry

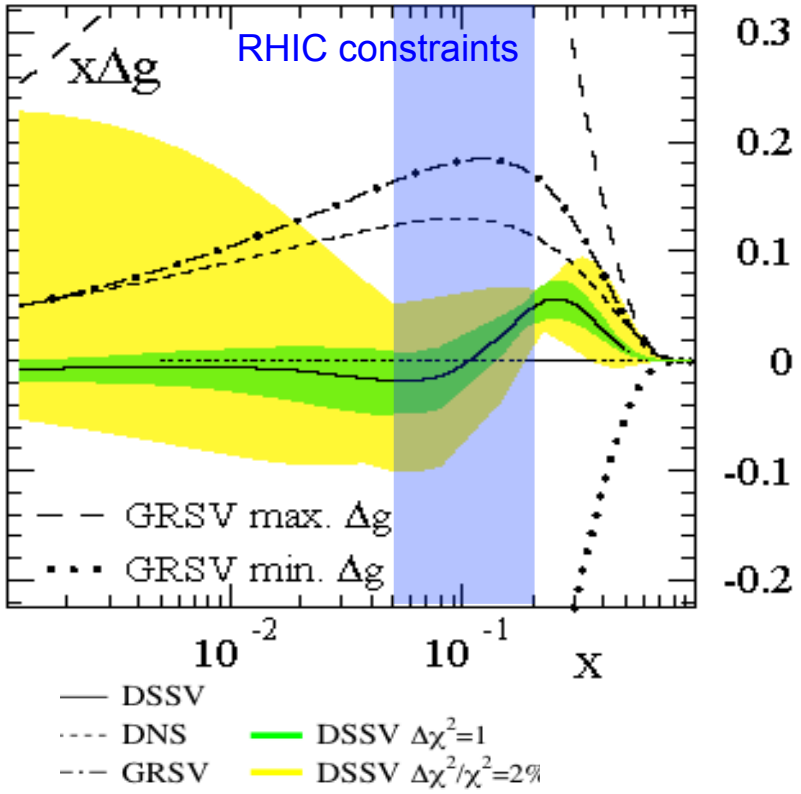


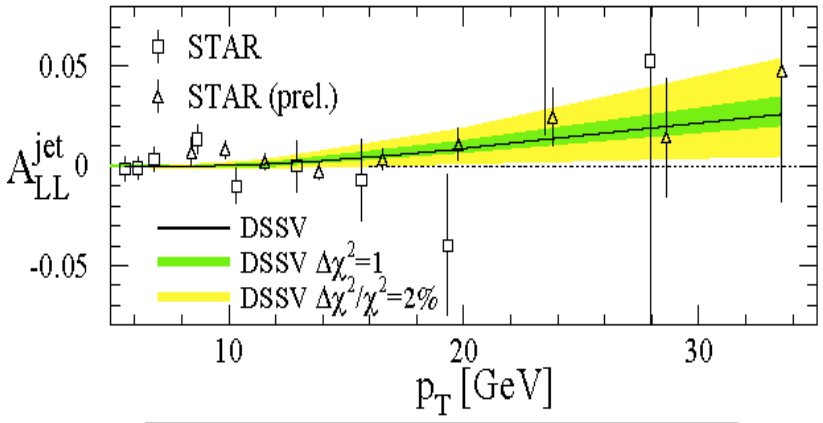


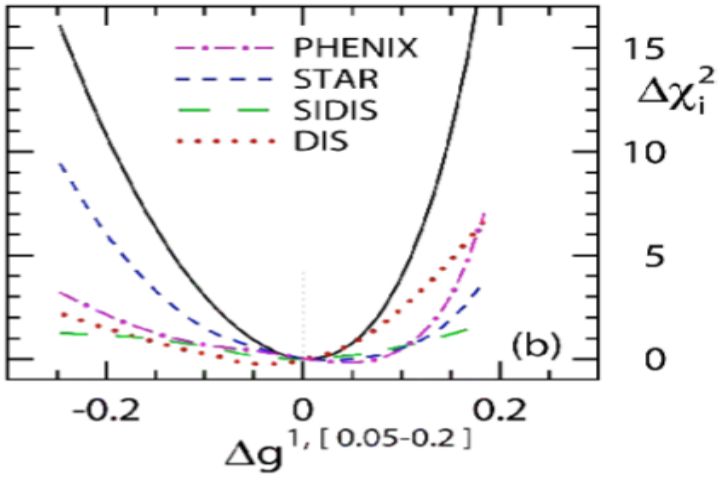
PRD76,051106 ;
PRL 103, 012003 (2009)

Impact of RHIC early results on Δg(x)

de Florian et al., PRL101(2008)



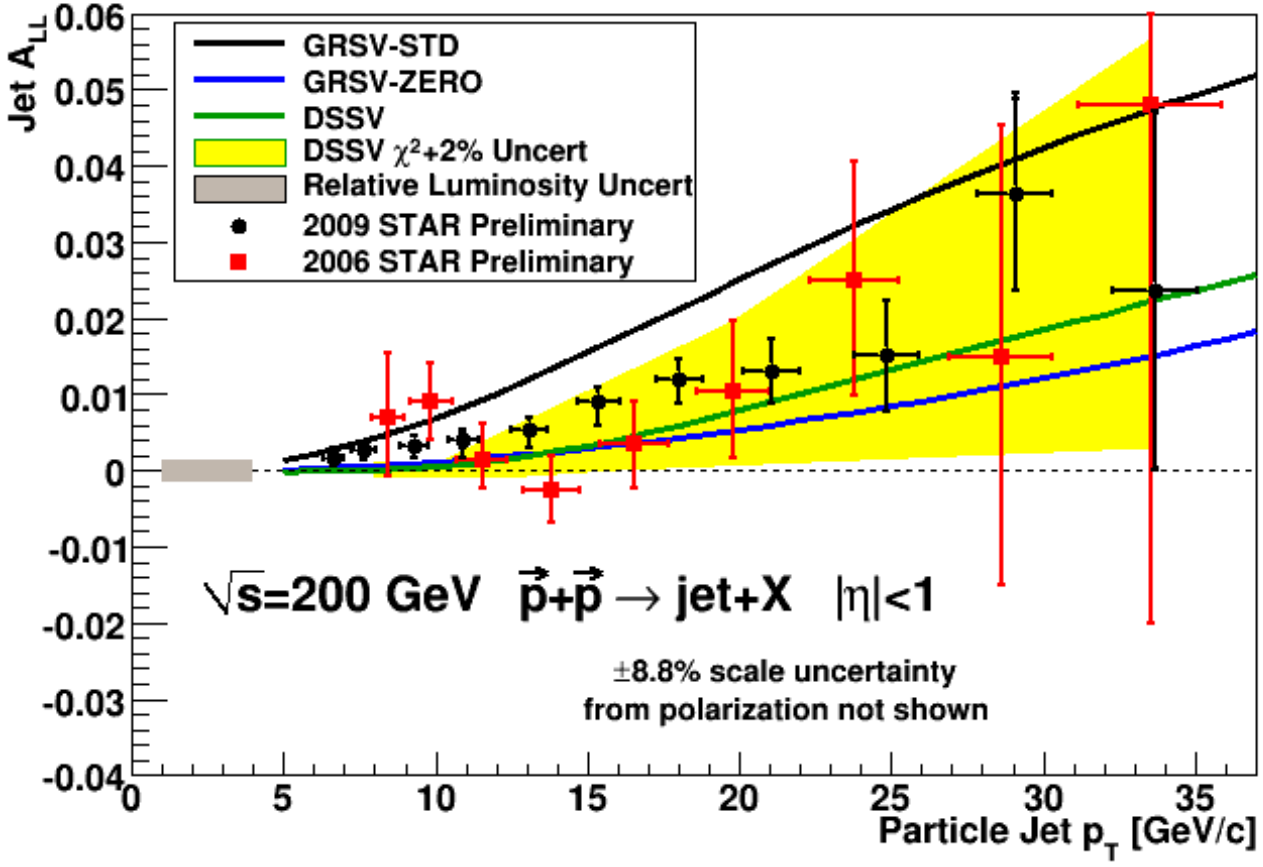




- Early RHIC data (2005, 2006) included in a global analysis along with DIS and SIDIS data.
- Evidence for a small gluon polarization over a limited region of momentum fraction (0.05<x<0.2).

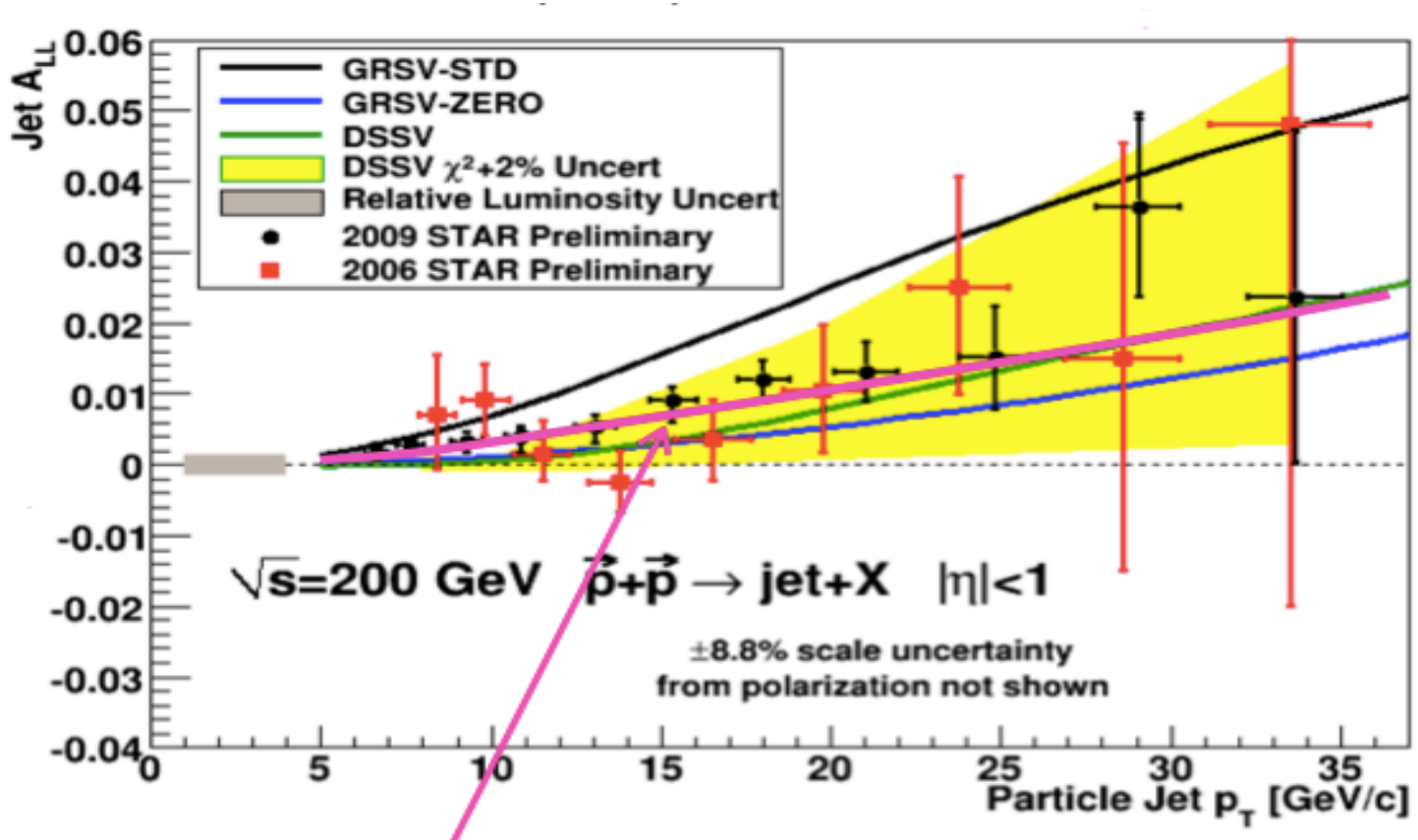
STAR inclusive jet A_{LL} from run9

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$



- 2009 STAR data is a factor of 4 more precise than 2006.
- The A_{LL} asymmetry is small, but clearly non-zero !
- Results fall between predictions from **DSSV** and **GRSV-STD**

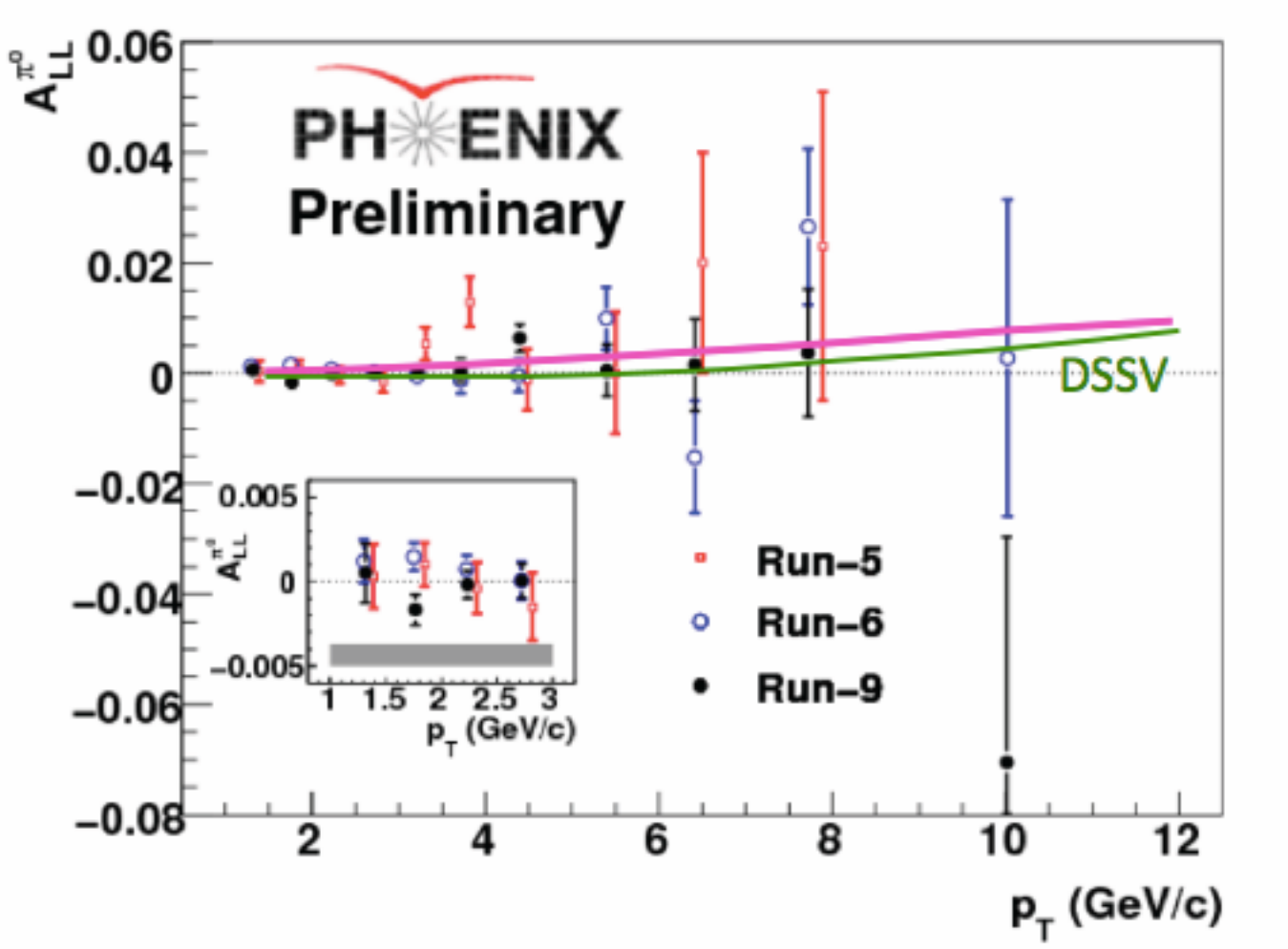
Updated global analysis with new STAR data



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

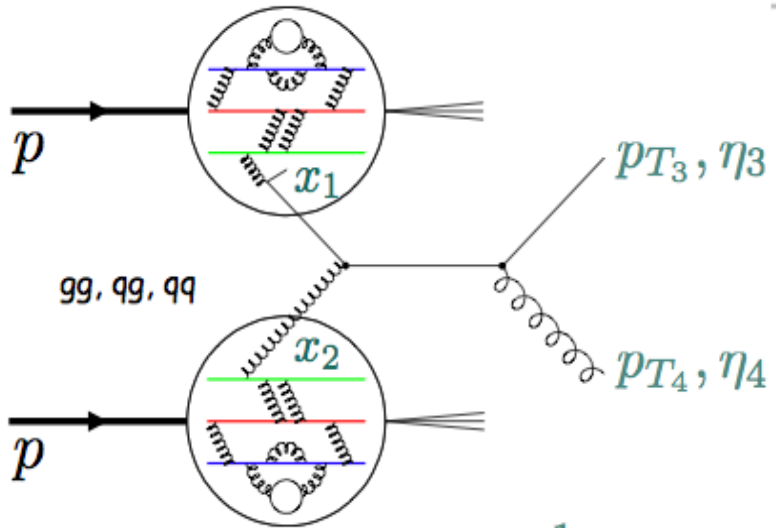
D. de Florian et al., arXiv/1112.0904.

PHENIX pi0 A_{LL} run 9 results



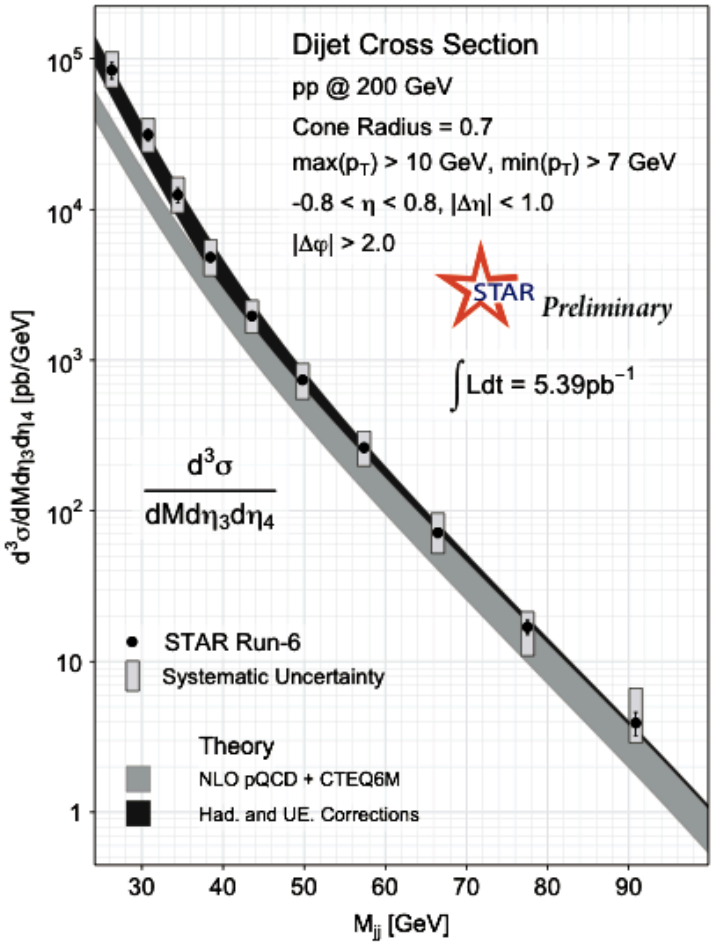
Correlation measurements with partonic kinematics

- Access to partonic kinematics through di-jet production

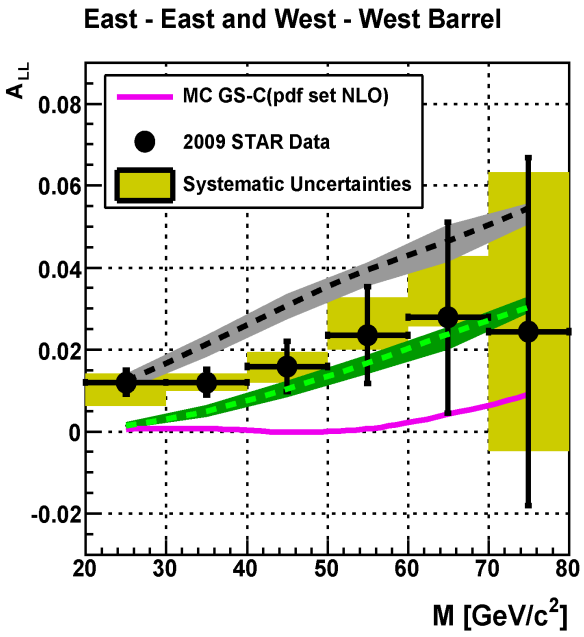


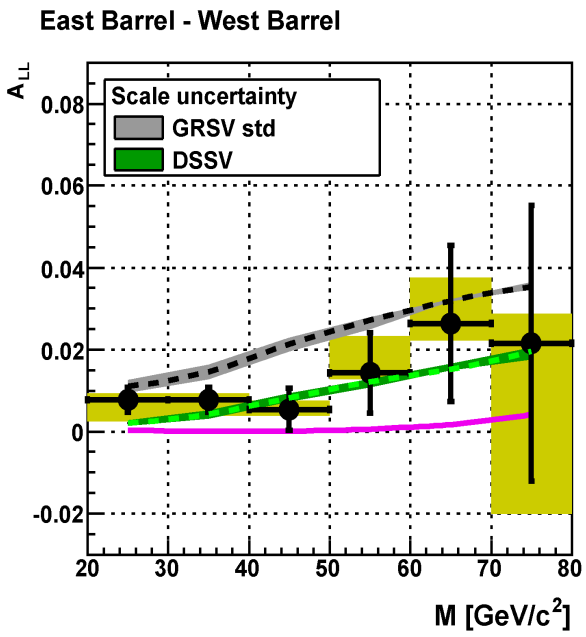
$$x_{1(2)} = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3(-\eta_3)} + p_{T4}e^{\eta_4(-\eta_4)}\right)$$

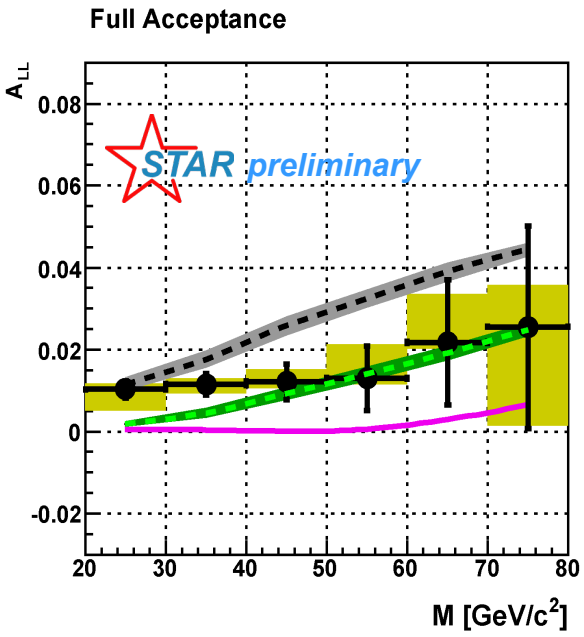
2006 di-jet cross section



2009 dijet A_{LL} from STAR

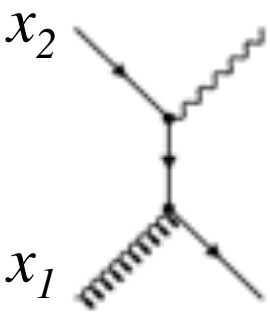


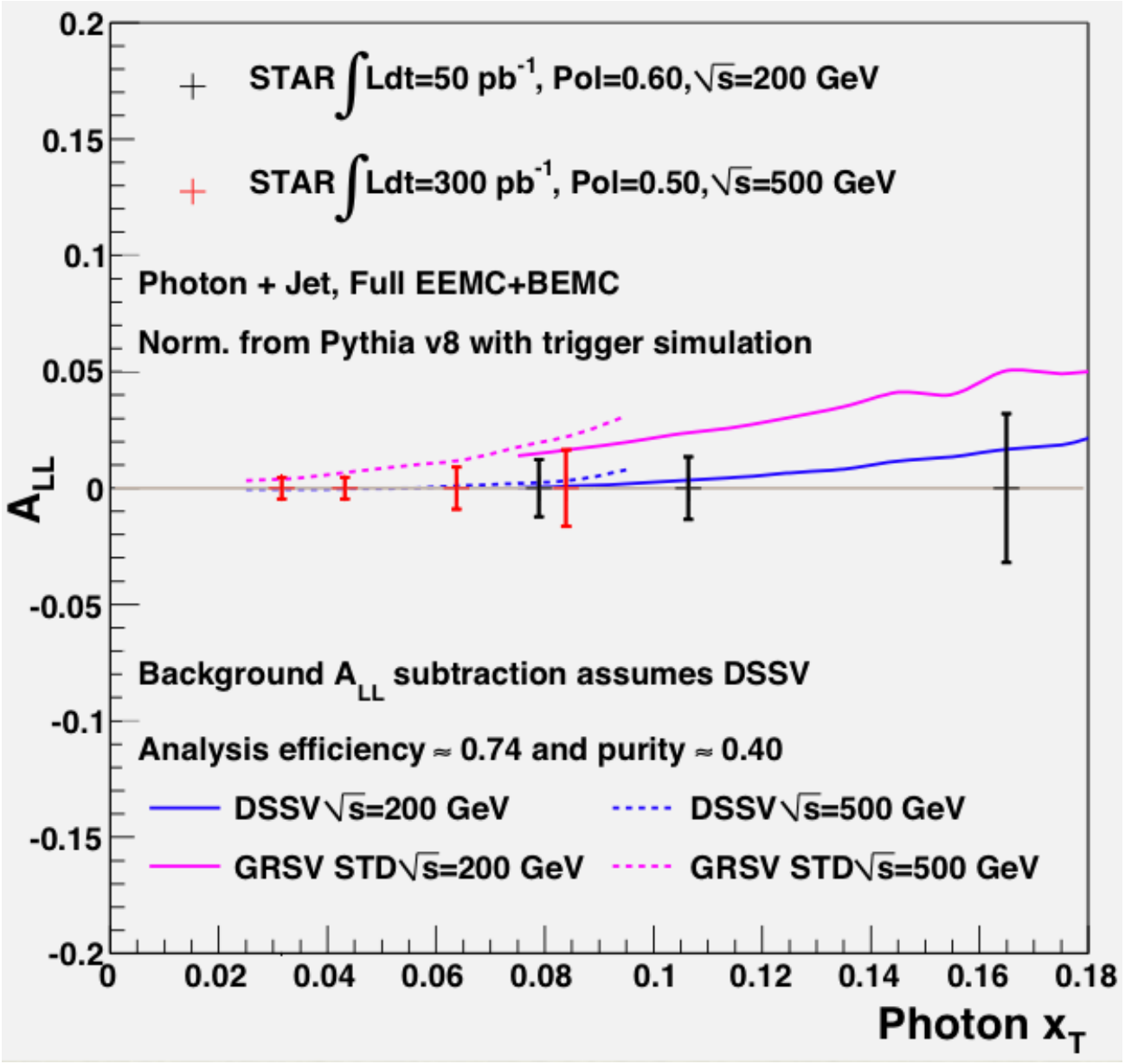




- For fixed M, different kinematic regions sample different *x* ranges
  - East-east and west-west sample higher x_1, lower x_2, and smaller |cos(θ*)|
  - East-west samples lower x_1, higher x_2, and larger |cos(θ*)|
- **A_{LL} falls between DSSV and GRSV-STD**

Prospects on prompt photons

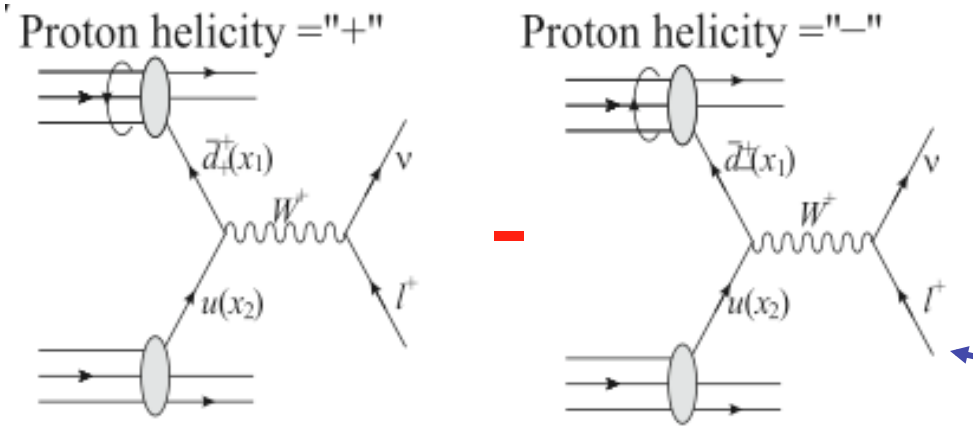




Flavor separation of quark spin via W production in pp

($\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}$ through $W^{\pm}$ production)

- Quark polarimetry with W-bosons:



$$\propto \Delta\bar{d}(x)u(x)$$

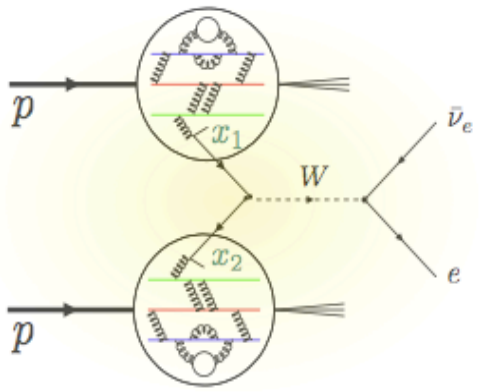
W-detection through high energy lepton

- Spin measurements:

$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} = \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

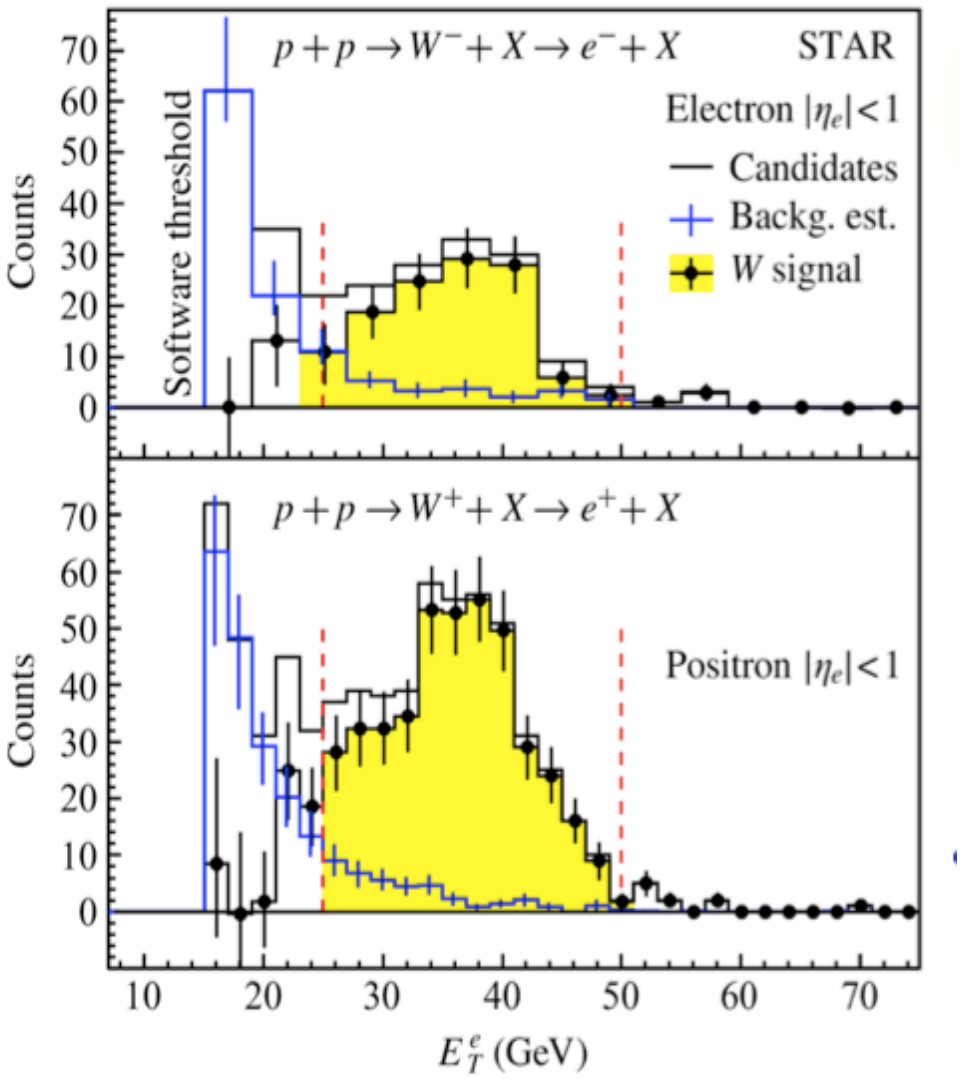
$$A_L^{W^-} = \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \end{cases}$$

W production : Jacobian peak



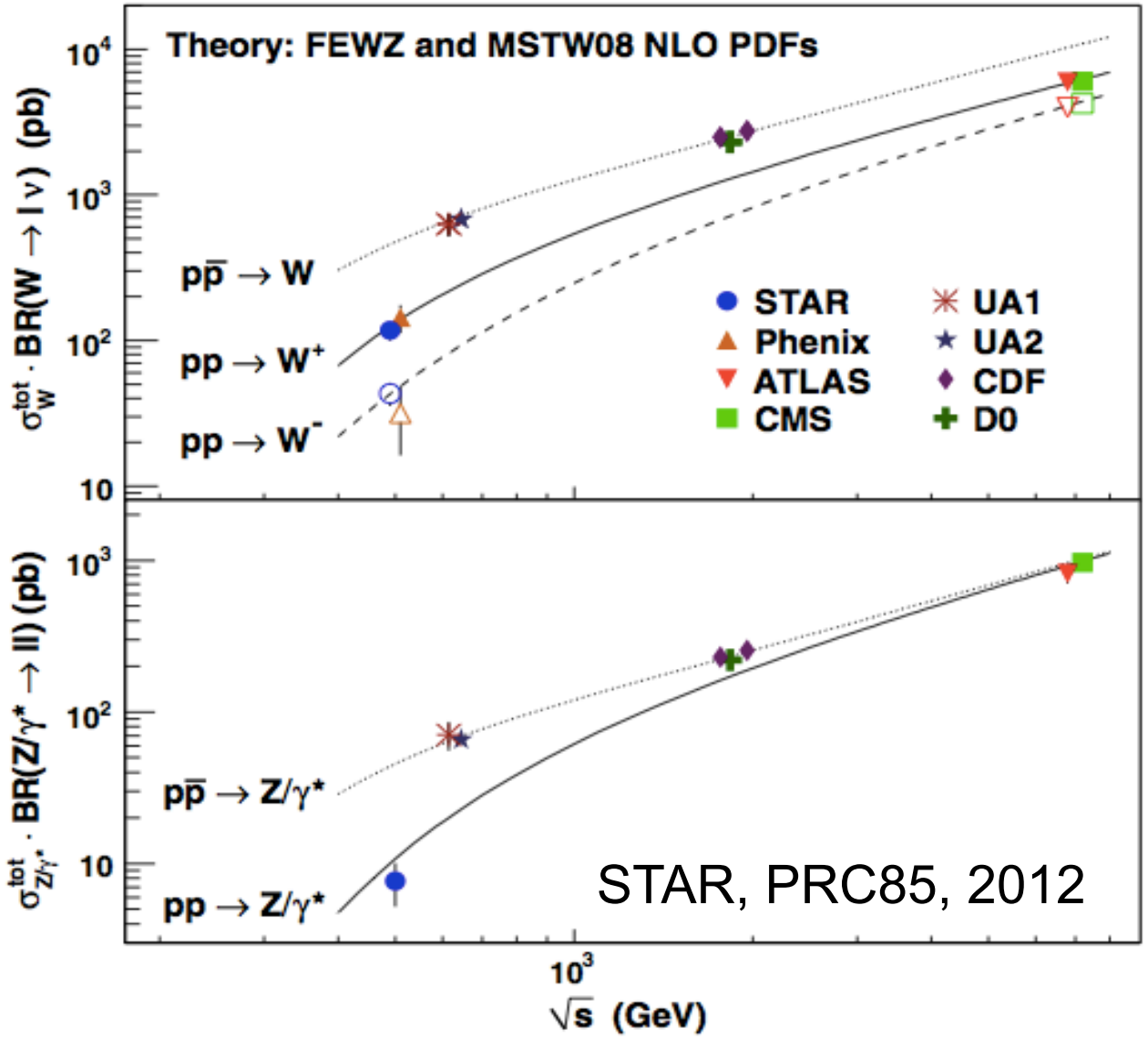
- Background dominated by QCD background, estimated with a data driven method. Also smaller fraction from $W \rightarrow \tau\upsilon$ decay, and Z^0 boson decay (MC estimate).

STAR: Phys. Rev. Lett. 106, 062002(2011)

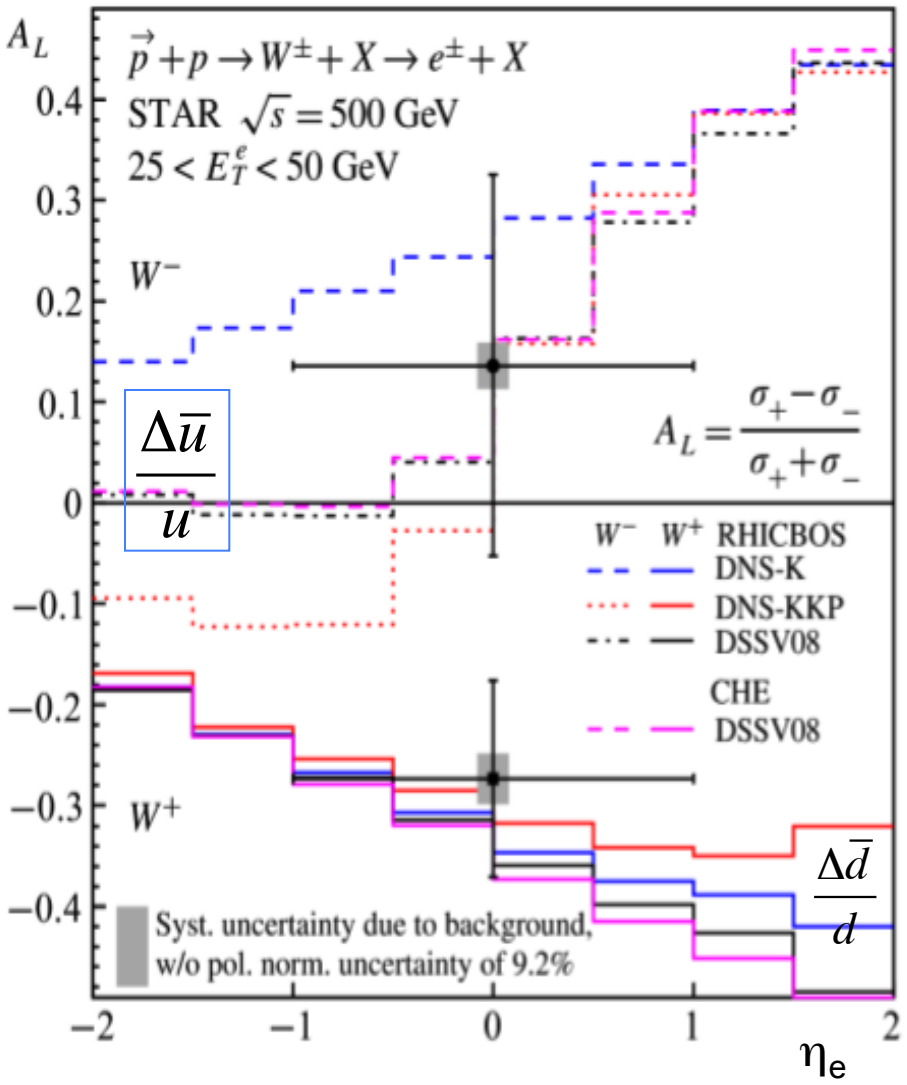


W cross section in pp at RHIC energy

- Data in agreement with NLO calculations:



First STAR W A_L results



STAR: Phys. Rev. Lett. 106, 062002(2011)

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

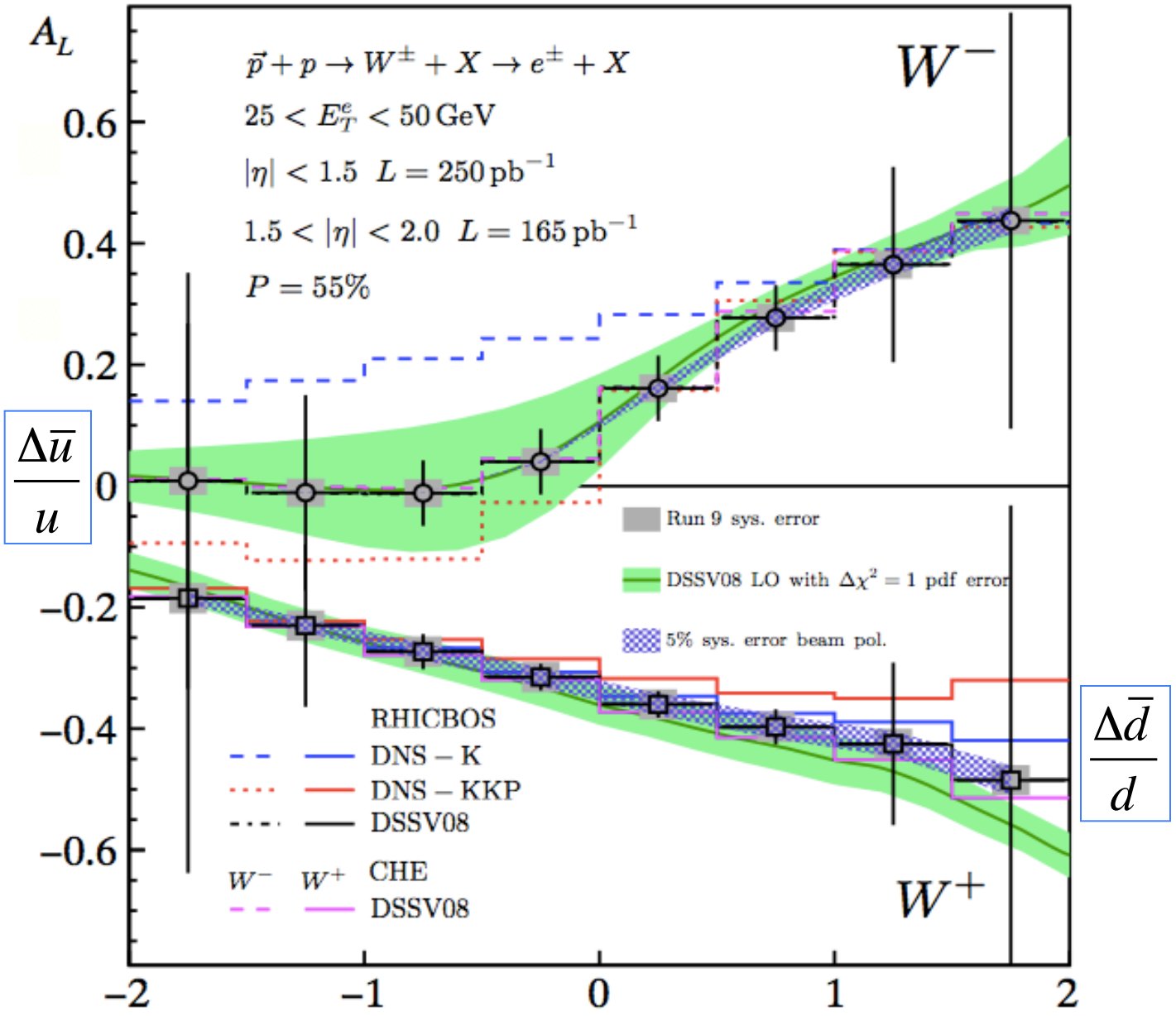
STAR Run 9 Result

$$A_L(W^+) = -0.27 \pm 0.10(stat) \pm 0.02(syst)$$

$$A_L(W^-) = 0.14 \pm 0.19(stat) \pm 0.02(syst)$$

- $A_L(W^+)$ negative, as predicted, **~3 sigma <0**
- $A_L(W^-)$ central value positive, as expected

STAR Run 12+13 Projections at 500 GeV

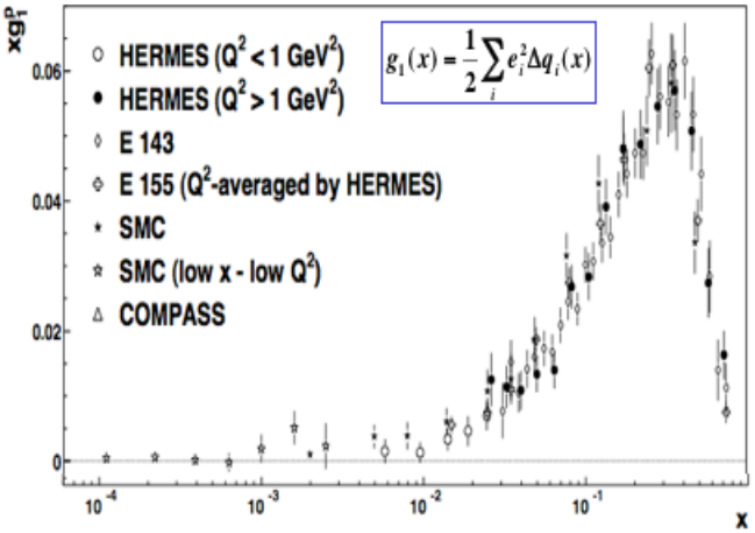


ΔS from polarized inclusive DIS

- Determination of ΔS , ΔΣ with polarized inclusive DIS:

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{1}{2}\int \sum_i e_i^2 \Delta q_i(x) = \frac{1}{18}[4\Delta U + \Delta D + \Delta S]$$

$$\Delta\Sigma = \underbrace{\Delta u + \Delta\bar{u}}_{\Delta U} + \underbrace{\Delta d + \Delta\bar{d}}_{\Delta D} + \underbrace{\Delta s + \Delta\bar{s}}_{\Delta S}$$



Each flavor's contribution to nucleon spin:

$$\Delta q = \int_0^1 \Delta q(x)dx$$

$\Delta q(x) = q^+(x) - q^-(x)$: helicity distribution function

- Together with neutron, hyperon β decay data using SU(3)_f symmetry:

$\Rightarrow \Delta\Sigma = 0.33 \pm 0.03 \pm 0.01 \pm 0.03$:

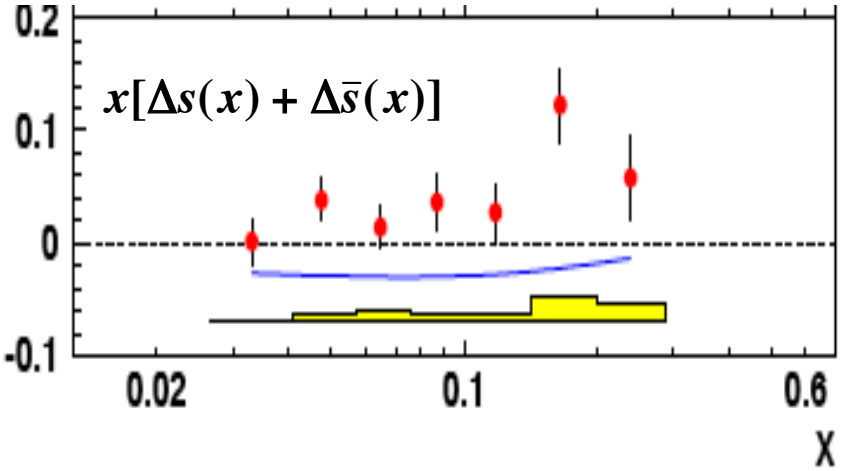
$\Delta U \sim 0.84$,
$\Delta D \sim -0.43$, (HERMES, $Q^2 = 5$ GeV^2)
$\Delta S \sim -0.08 \pm 0.01 \pm 0.01 \pm 0.01$*

*COMPASS also obtained similar results.

ΔS from semi-inclusive DIS

- Recent measurements in semi-inclusive DIS - consistent with zero:

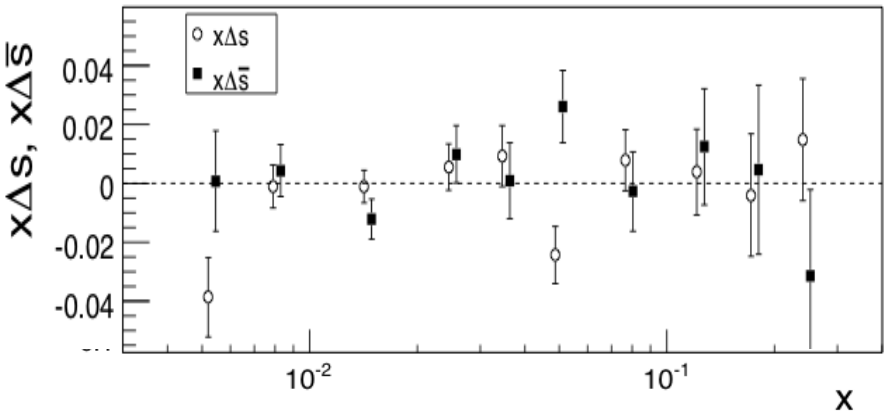
HERMES, PLB666,446(2008)



$$\Delta S' = 0.037 \pm 0.019 \pm 0.027$$

0.02<x<0.6, at a scale Q^2=2.5 GeV^2.

COMPASS, PLB680, 217(2009);1007.4061



$\Delta S' = -0.01 \pm 0.01 \pm 0.02$

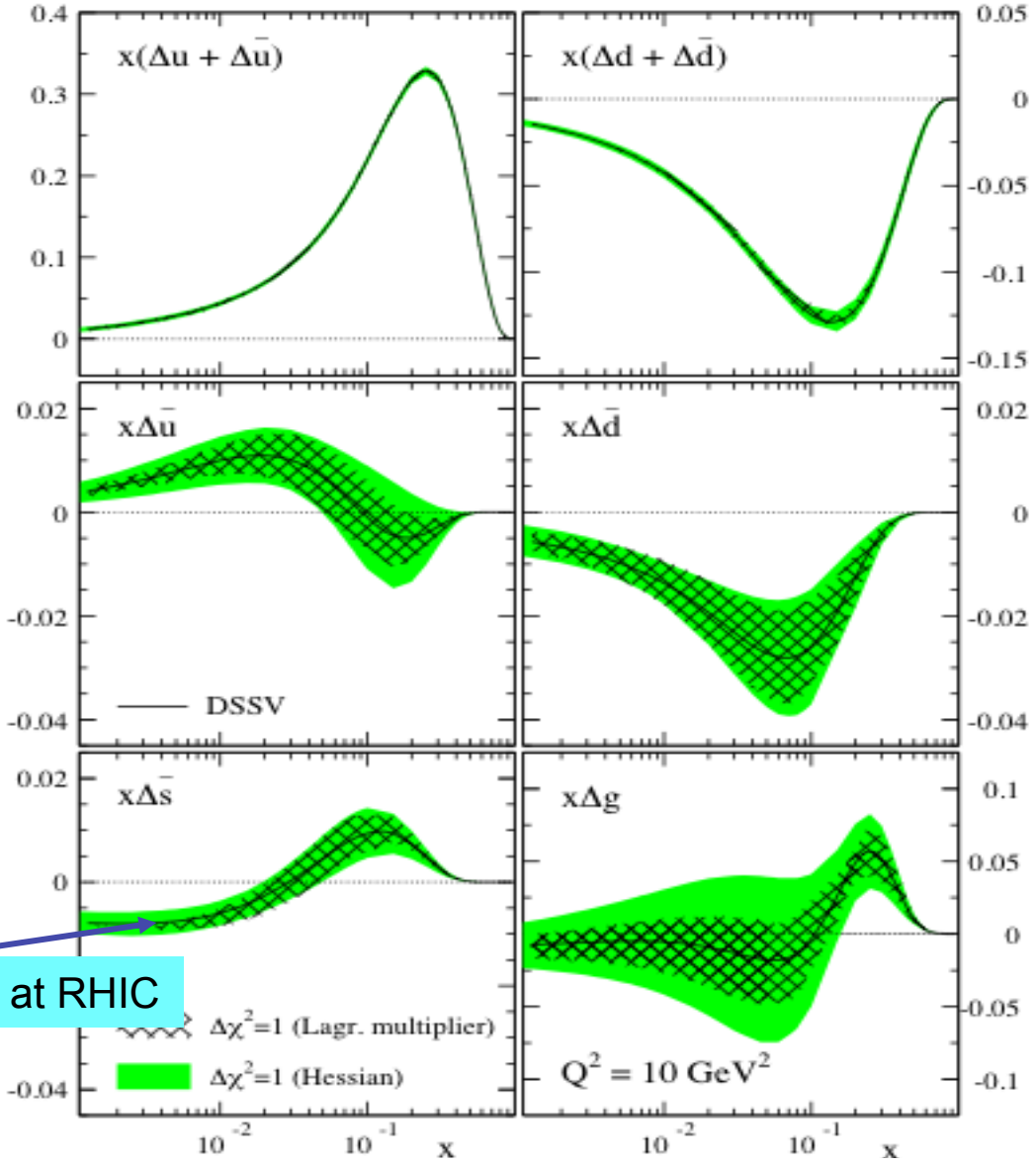
0.004<x<0.3, at Q^2=3 GeV^2

⇒ Different as inclusive DIS results?

Our knowledge on ΔS is far from comprehensive.

More measurements are needed.

Detailed knowledge on $\Delta q(x)$, $\Delta g(x)$ - global fit using DIS and pp data



Hyperons at RHIC

D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)

Study ΔS at RHIC with hyperons?

- Λ's contain a strange quark, whose spin is expected to carry most of the Λ spin.
- Λ polarization can be measured in experiment via weak decay

$$\frac{dN}{d\Omega} \propto 1 + \alpha (\vec{P}_\Lambda \cdot \vec{p}_p^{\,*})$$

Unit vector along proton momentum in Λ's rest frame.

$\vec{P}_\Lambda \cdot \vec{p}_p^{\,*} \propto \cos\theta^*$

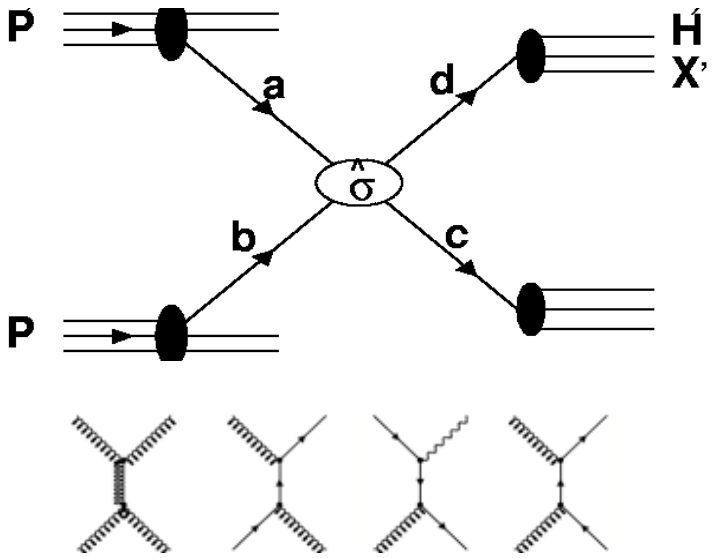
decay parameter 0.642 ±0.013

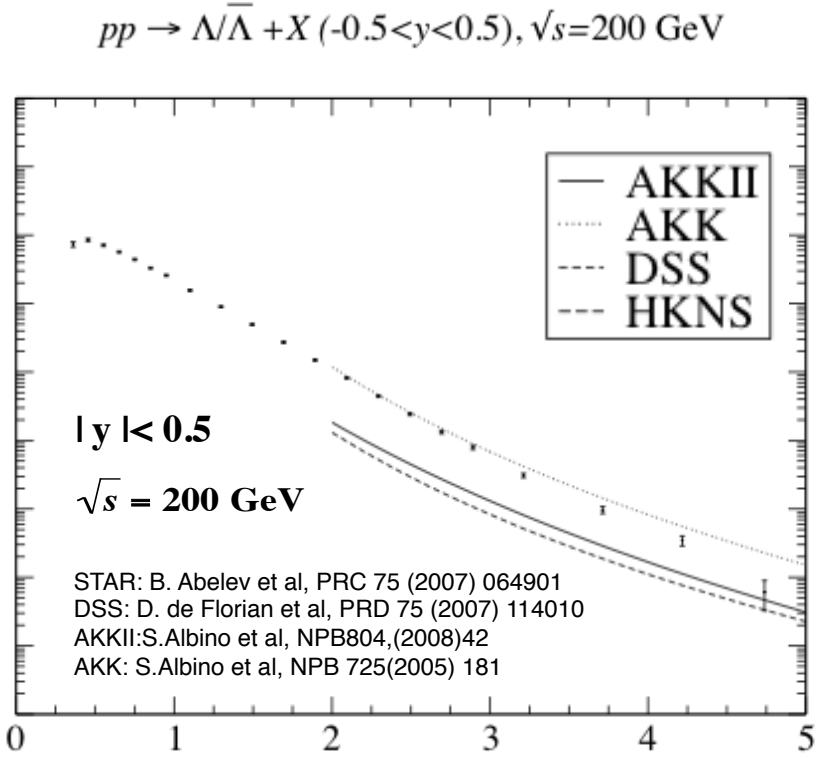
Λ polarization vector

- Can $\Lambda(\bar{\Lambda})$ polarization measurements provide sensitivity to ΔS at RHIC?

Hyperon production in pp collisions

- The factorized framework enables perturbative description,





$$d\sigma \propto \int f_a(x_1)\cdot f_b(x_2) \otimes d\hat{\sigma} \otimes D^{\Lambda}(z)$$

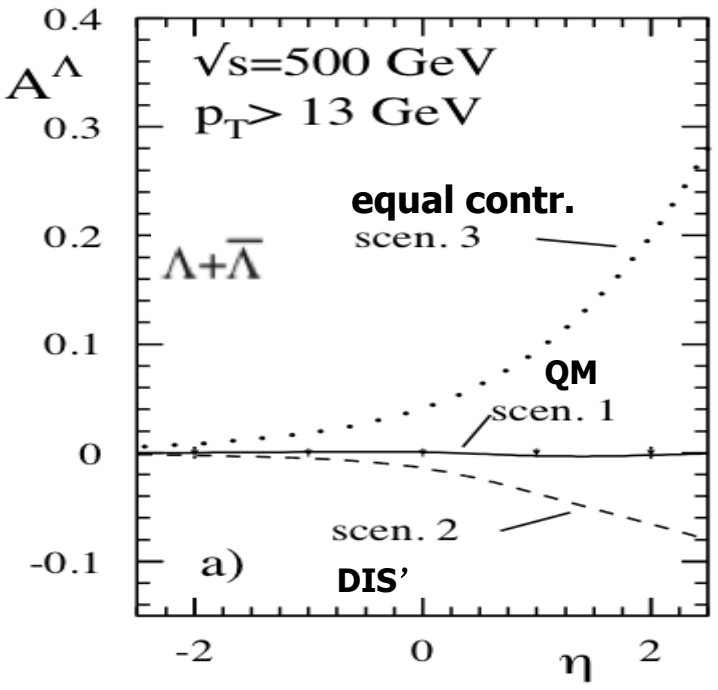
- Hyperon spin transfer D_{LL} provides access to Δf and ΔD :

$$D_{LL} \equiv \frac{\sigma_{p^+p\to\bar{\Lambda}^+X} - \sigma_{p^+p\to\bar{\Lambda}^-X}}{\sigma_{p^+p\to\bar{\Lambda}^+X} + \sigma_{p^+p\to\bar{\Lambda}^-X}} = \frac{d\Delta\sigma}{d\sigma}$$

Current knowledge on ΔD and corresponding predictions in pp

- Pol. frag. function from global parameterization:

  D.de Florian, M.Stratmann, And W.Vogelsang, PRL81 (1998)530



- Modeling Pol. Frag. Function, related to hyperon spin structure:

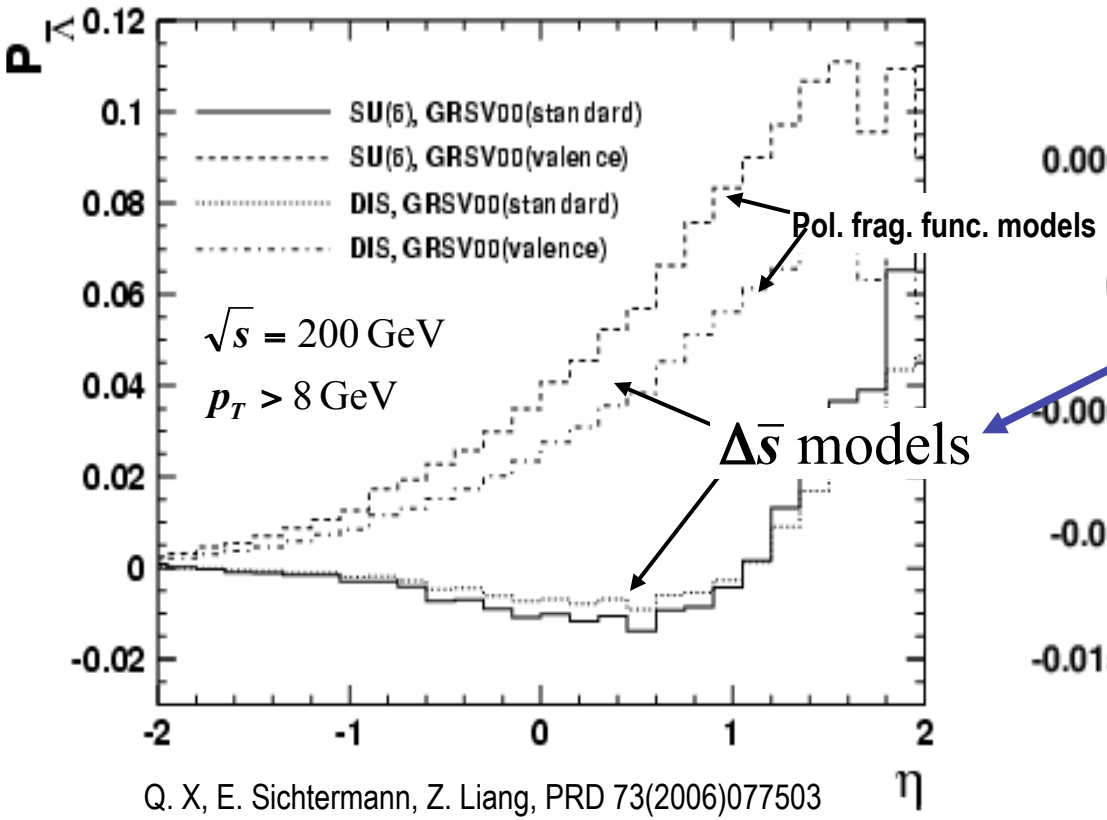
  C. Boros, J.T.Londergan, A.W.Thomas, Phys. Rev. D62 (2000)

  B.Q. Ma, I.Schmidt, J.Soffer, J.J.Yang, Nucl. Phys. A703 (2002)

  Q.H. Xu, C.X. Liu, Z.T. Liang, Phys. Rev. D65, 114008 (2002).

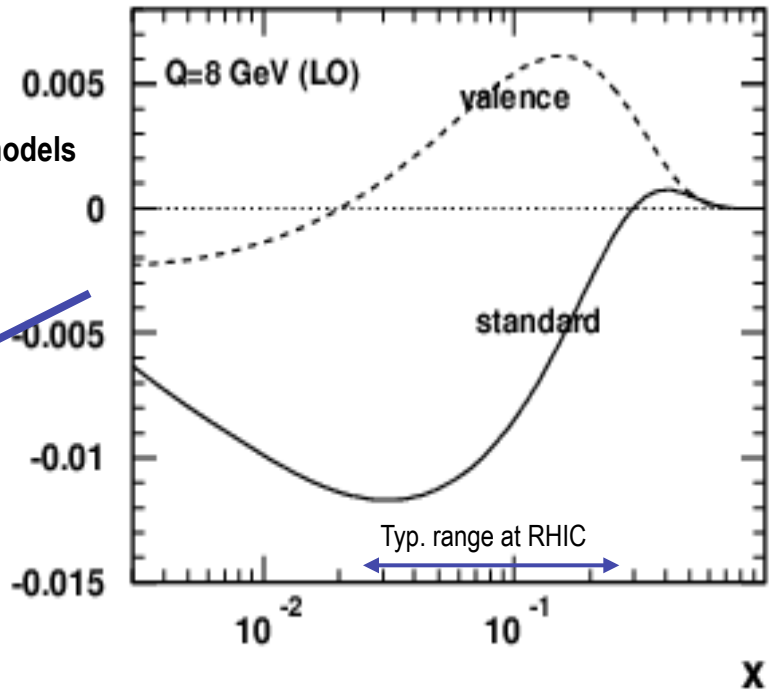
D_{LL}-Longitudinal spin transfer at RHIC

- Expectations at LO show sensitivity of D_{LL} for anti-Lambda to $\Delta\bar{s}$:



Q. X, E. Sichtermann, Z. Liang, PRD 73(2006)077503

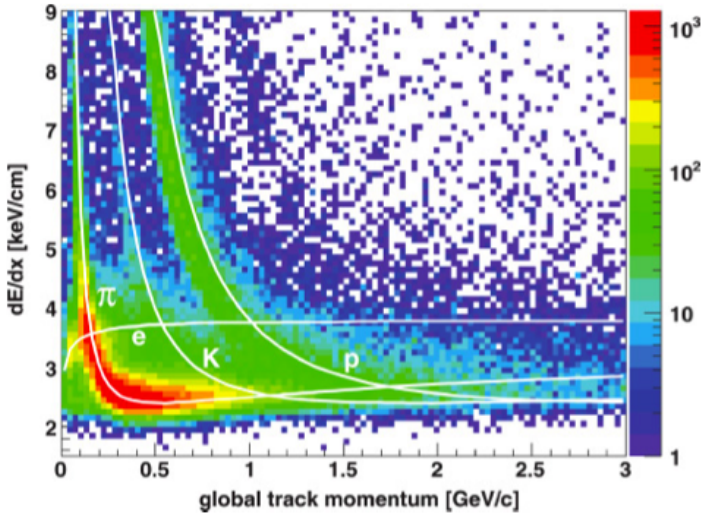
GRSV00-M.Gluck et al, Phys.Rev.D63(2001)094005

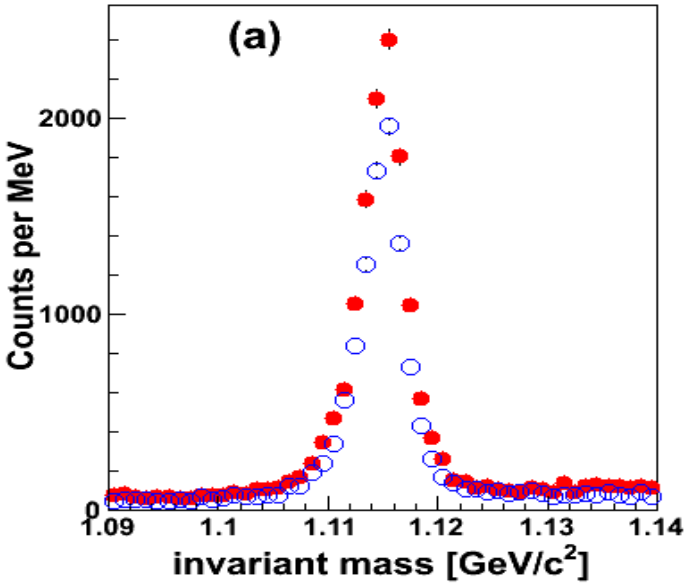


- Λ D_{LL} is less sensitive to Δs, due to large u,d quark fragmentation.
- Promising measurements---effects potentially large enough to be observed.

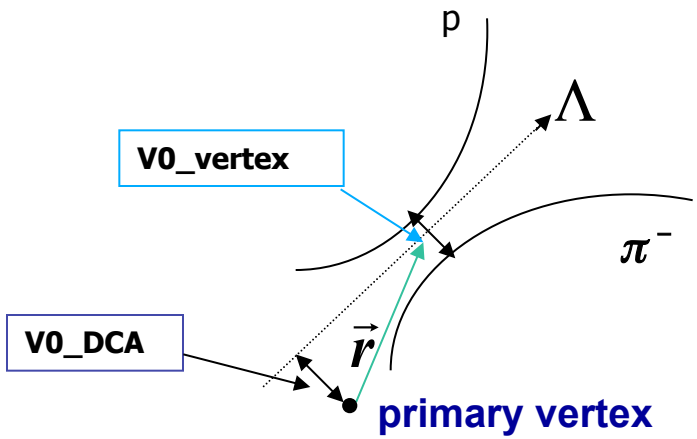
Hyperon reconstruction at STAR

Time Projection Chamber enables PID

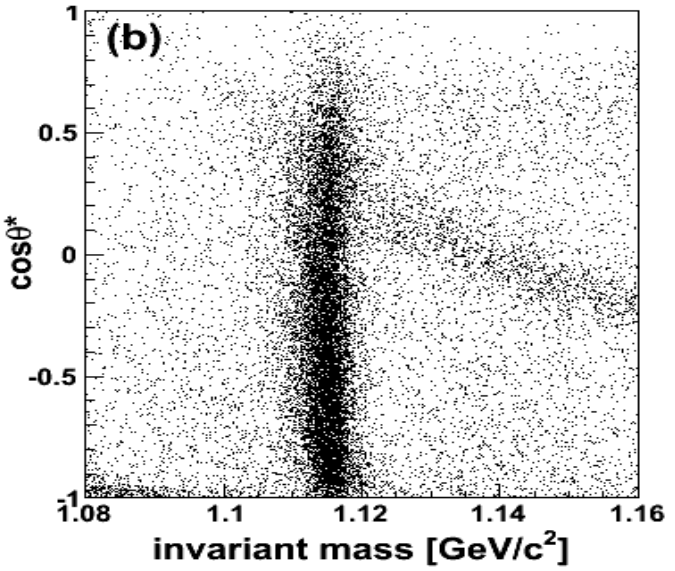




Plus topological reconstruction:



for |η|<~1.3



Extraction of spin transfer D_{LL}

- Λ polarization is usually extracted from the momentum distribution of its weak decay ($\Lambda \rightarrow p\pi^-$):

$$dN = \frac{N_{tot}}{2} A(\cos\theta^*)(1 + \alpha P_\Lambda \cos\theta^*) \qquad \cos\theta^* \propto \vec{P}_\Lambda \cdot \vec{p}_p^{\,*}$$

α: decay parameter: 0.642
A(cosθ*): detector acceptance

- D_{LL} has been extracted from Λ counts with opposite beam polarization within a small interval of cosθ*:

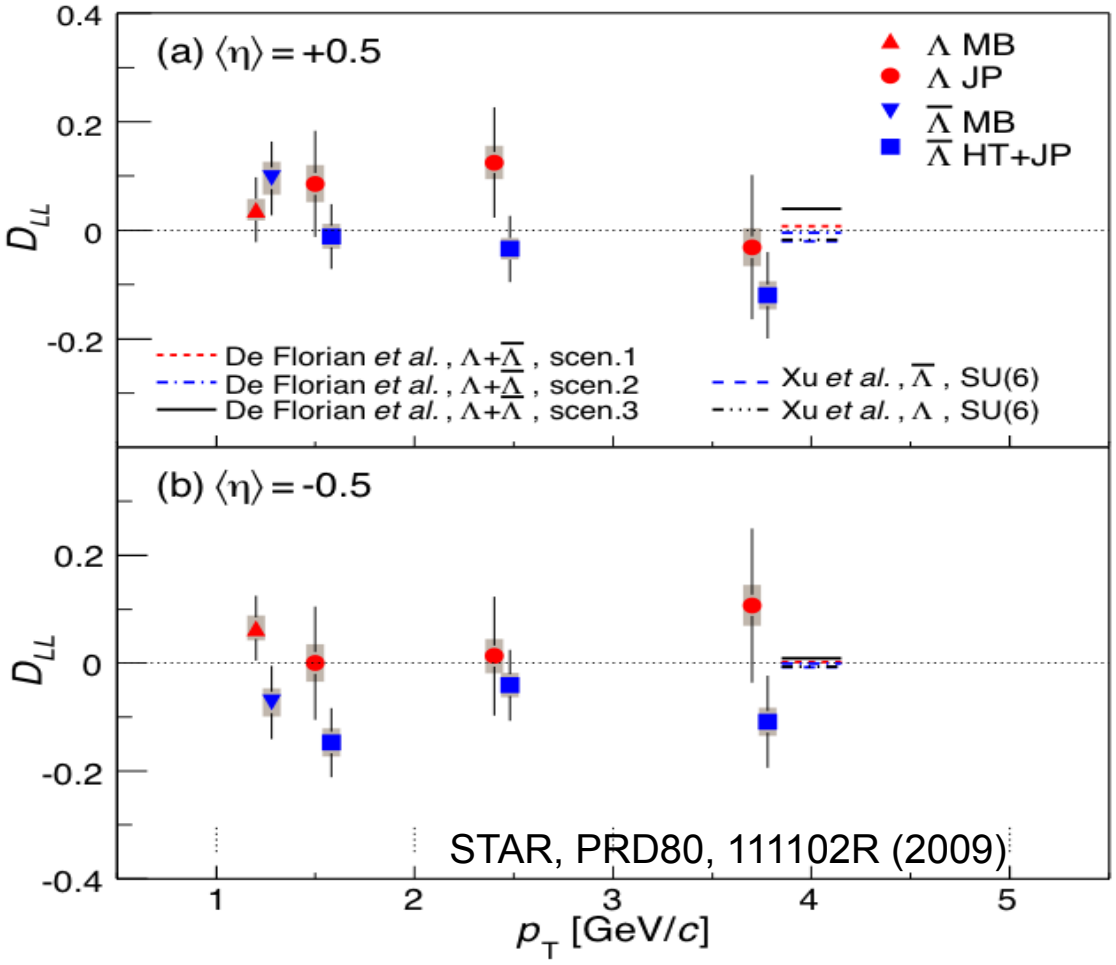
$$D_{LL} = \frac{1}{\alpha \cdot P_{beam} < \cos\theta^* >} \cdot \frac{N^+ - N^-}{N^+ + N^-}$$, where the acceptance cancels.

$$N_\Lambda^+ = N^{++} \frac{L_{--}}{L_{++}} + N^{+-} \frac{L_{--}}{L_{+-}}$$

$$N_\Lambda^- = N^{-+} \frac{L_{--}}{L_{-+}} + N^{--}$$

Relative luminosity ratio measured with BBC, and P_b in RHIC.

D_{LL} Results of STAR (2005)



At $< p_T >$ = 3.7 GeV and $< \eta >$ = 0.5 :

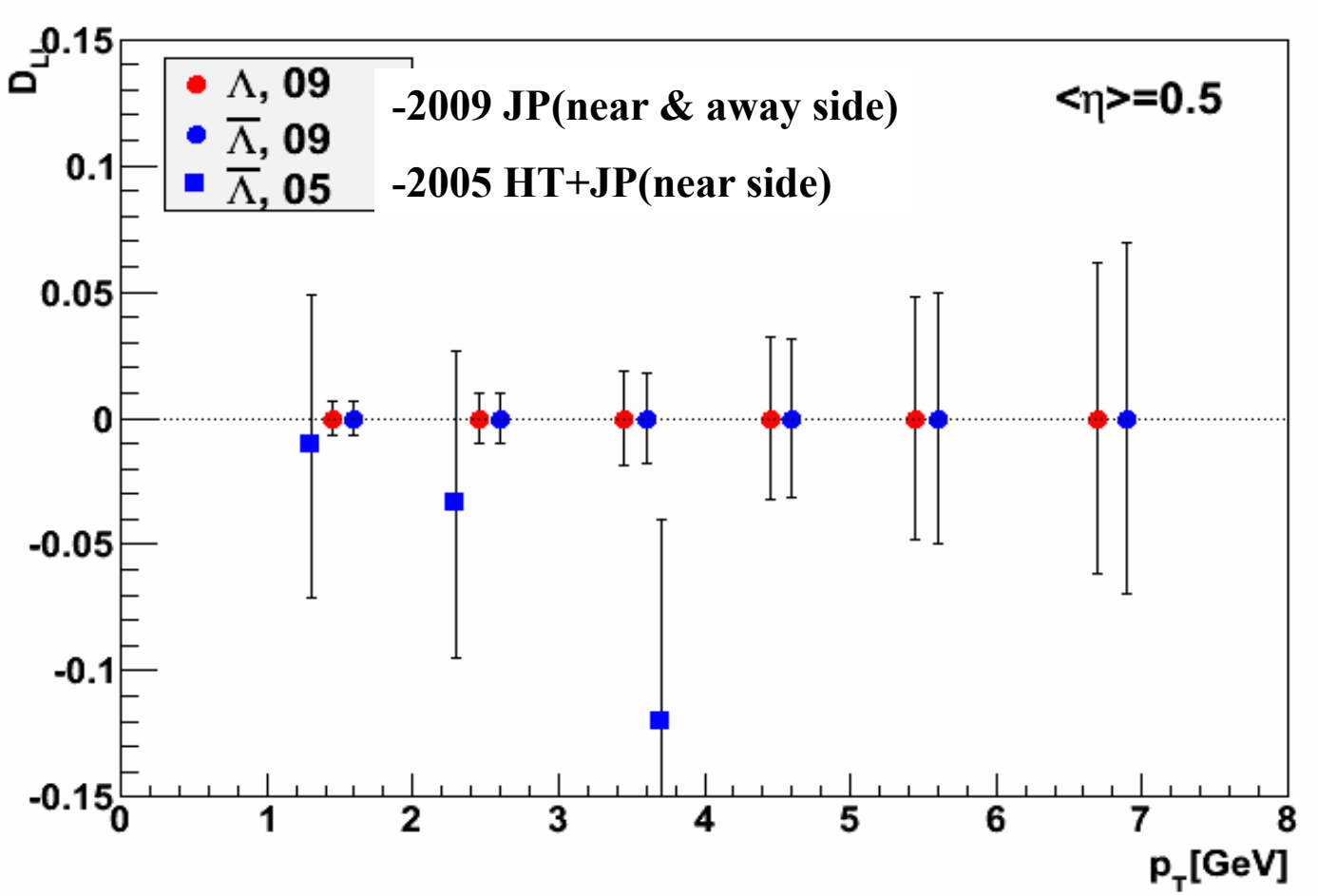
$$D_{LL}(\Lambda) = -0.03 \pm 0.13(stat) \pm 0.04(sys)$$

$$D_{LL}(\overline{\Lambda}) = -0.12 \pm 0.08(stat) \pm 0.04(sys)$$

- D_{LL} for Lambda and anti-Lambda are consistent with each other
- Uncertainties are similar to the spread in model expectations.

Prospects from STAR 2009 data

• Achieved (2005) and projected (2009) uncertainties on D_{LL}:



- p_T coverage will be extended significantly with 2009 data.

Transverse spin transfer and δq(x)

- Transverse spin transfer of hyperons can provide access to transverse spin structure of nucleon:

$$P_T^H = \frac{d\sigma^{(p_\uparrow p \to H_\uparrow X)} - d\sigma^{(p_\uparrow p \to H_\downarrow X)}}{d\sigma^{(p_\uparrow p \to H_\uparrow X)} + d\sigma^{(p_\uparrow p \to H_\downarrow X)}} = \frac{d\Delta_T\sigma}{d\sigma}$$

$$d\Delta_T\sigma^{(\vec{p}_\perp p \to \vec{H}_\perp X)} \propto \sum_{abcd} \int dx_a dx_b dz \delta f_a(x_a) f_b(x_b) \Delta_T D_c^H(z) d\Delta_T\hat{\sigma}^{(\vec{a}_\perp b \to \vec{c}_\perp d)}$$

transversity distribution :
$\delta f(x) = f_\uparrow(x) - f_\downarrow(x)$

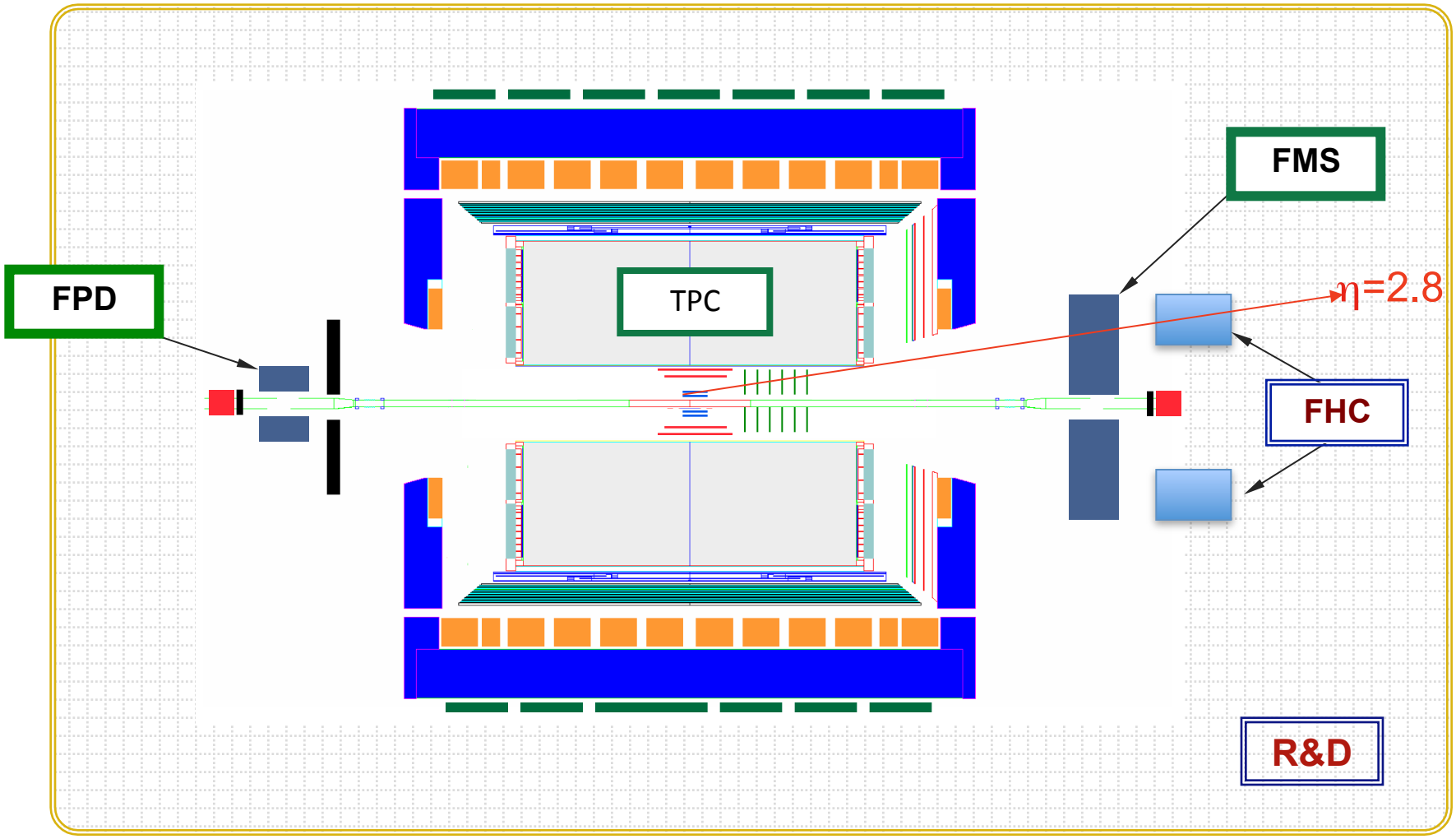
Transversely polarized fragmentation function, may be obtained at BELLE

pQCD

- Transverse spin transfer can give insights into transversity.
- Such measurements can be made at mid-rapidity with TPC at STAR.

Forward hyperon physics with STAR upgrade

- Addition of Forward Hadron Calorimeter (FHC) at STAR may enable the study of forward Λ physics together with FMS through $\Lambda \rightarrow n\pi^0$ (Br=36%).



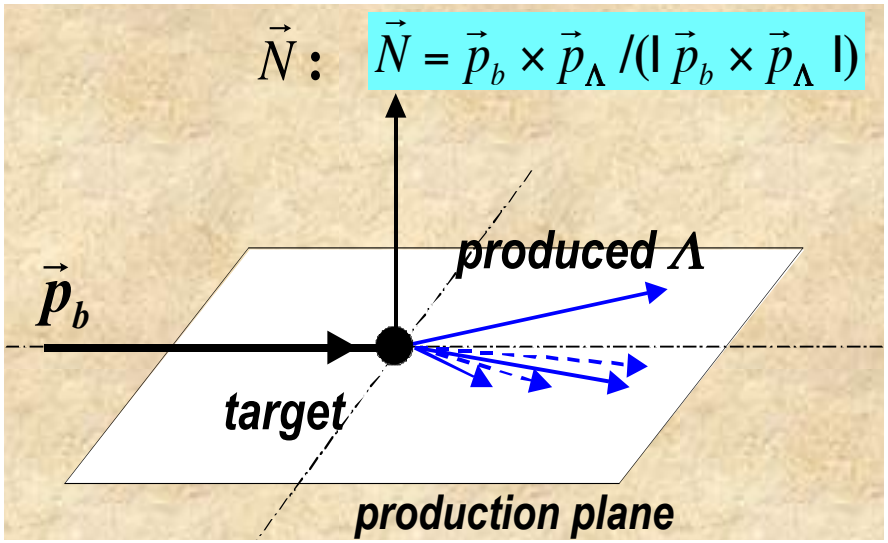
Induced Λ polarization in unpolarized pp

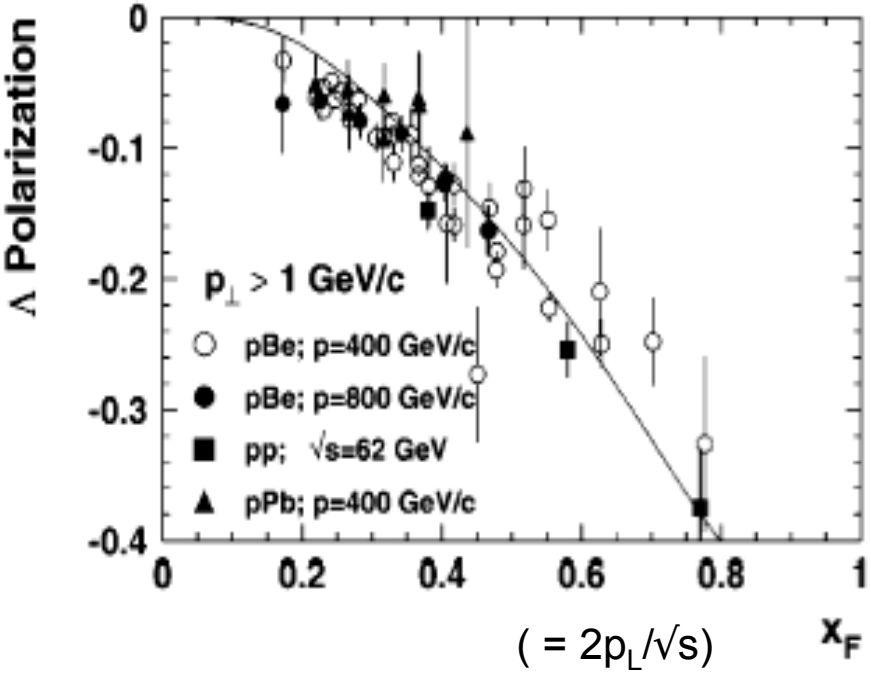
- Large polarization with unpolarized beam p + p → $\Lambda_{\uparrow}$ + X , observed in many experiments.

  -G.Bunce *et al,* PRL36,1113,(1976)

- LO pQCD calculation gives ~0 ($\propto m_q$).

  Kane, Pumplin & Repko, PRL41,1689(1978).





➢ Measurement at higher energy (at RHIC) would be very interesting.

Summary & Outlook

- Determination of gluon polarization ΔG at STAR/RHIC:

  - Currently probes with jets, are providing important constraints on ΔG. Global analysis indicates small gluon polarization ($0.05<x<0.2$).

  - Correlation measurements (di-jet, photon-jet) with access to partonic kinematics will provide better resolution in x and direct probe to ΔG.

- Probing sea quark polarization via W-boson at RHIC:

  - First results on W-boson single-spin asymmetry measurement in pp

- Hyperon spin transfer in pp collision can provide sensitivity for (anti-)strange quark polarization in nucleon.

- Run 12 and future:

  - Run 12: Successful trans. 200GeV (~20pb^{-1}) and long. 510GeV (~85pb^{-1}) runs

  - Future: Expect and need several long 510GeV runs beyond Run 12.