

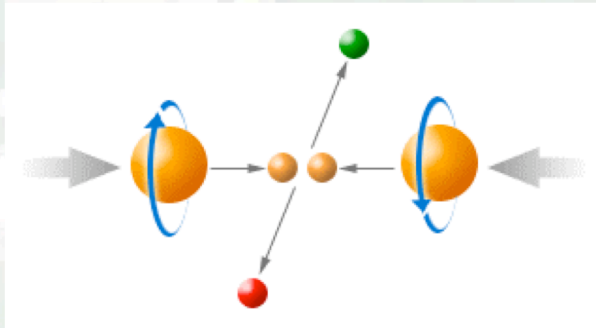


# Recent *STAR* results of the polarized pp program at RHIC

Bernd Surrow



Massachusetts  
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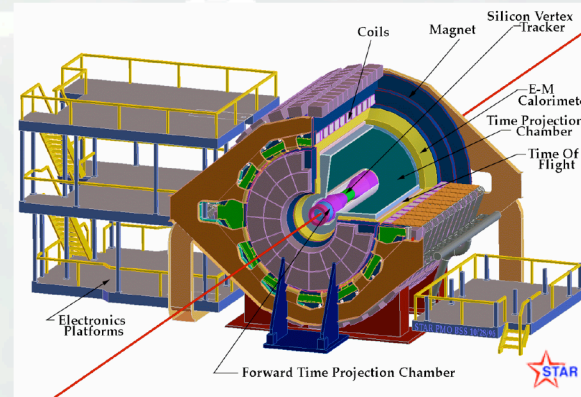


**SPIN**  
2006

The 17th International Spin Physics Symposium



Kyoto, Japan, Oct. 2-7 '06

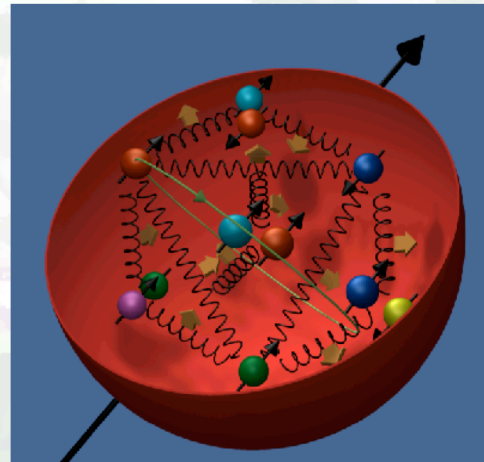


## ■ The STAR detector



## ■ The polarized proton collider RHIC

## ■ Introduction



## ■ STAR transverse spin program - Recent results

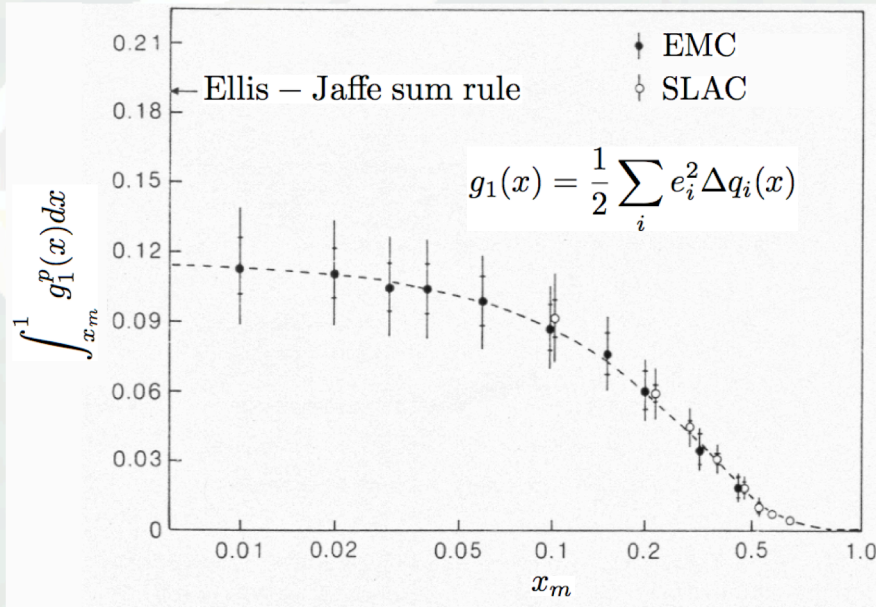
## ■ STAR longitudinal spin program - Recent results

## ■ Summary and Outlook



## RHIC SPIN program

- Polarized DIS: European Muon collaboration (EMC)
- Where is the spin of the proton?



- Need: New generation of experiments to explore the spin structure of the proton: **polarized proton-proton collisions at RHIC**

## RHIC spin program

- Unique multi-year program
- Explore various aspects on the spin structure and dynamics of the proton in a new domain:

- Spin carried by quarks is very small!

$$\frac{1}{2} \Delta \Sigma \quad \Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}$$

$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

$\Delta G$

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

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

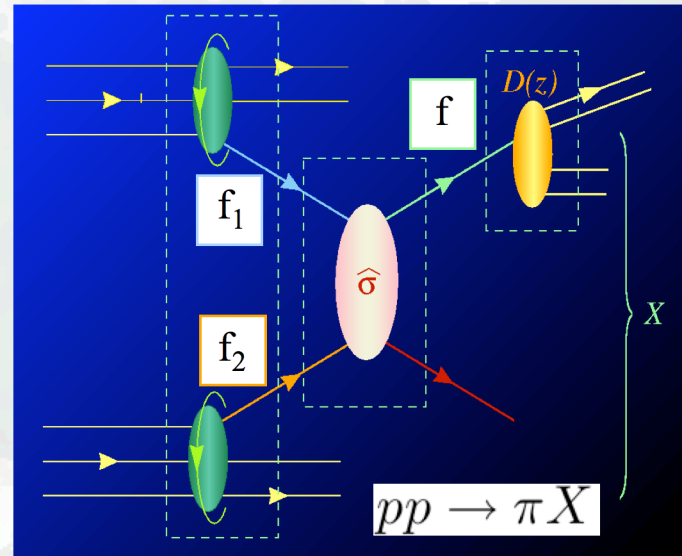
- Transverse spin dynamics and transversity
- Gluon polarization
- Quark/anti-quark polarization of different flavors

## Theoretical aspects: Longitudinal spin physics

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



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



long-range    short-range    long-range

Quark ( $\Delta q$ ) pdf's: Known only at high  $x$ .  
Gluon ( $\Delta g$ ) pdf: Poorly constrained!

How do quarks and gluons make up the proton spin?

$$A_{LL} = \frac{d\Delta\sigma_{pp \rightarrow \pi+X}}{d\sigma_{pp \rightarrow \pi+X}}$$

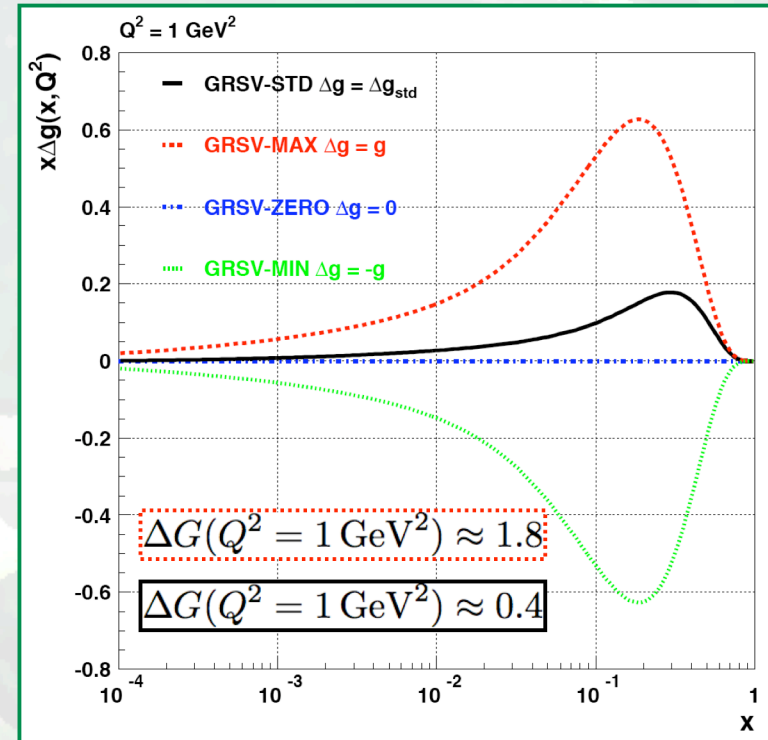
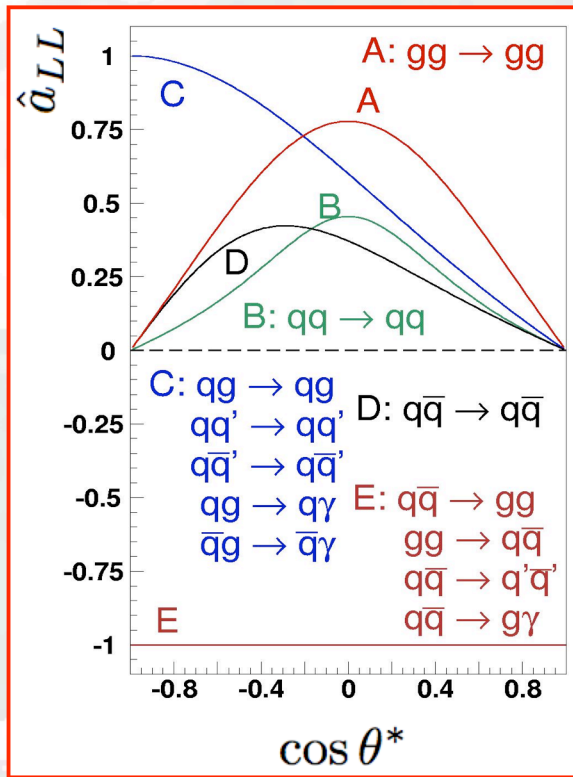
$$= \frac{\sum_{f_1, f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \rightarrow f X} \cdot \hat{a}_{LL}^{f_1 f_2 \rightarrow f X} \otimes D_f^\pi}{\sum_{f_1, f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \rightarrow f X} \otimes D_f^\pi}$$

$$\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}$$

$$D_f^\pi$$

## ■ Theoretical aspects: Longitudinal spin physics

### □ Partonic asymmetries (LO) in polarized pp collisions



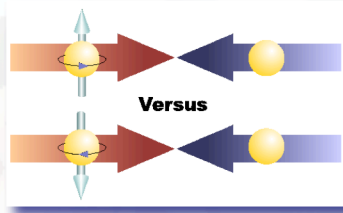
- Sizeable partonic asymmetries
- NLO calculations available!

- Theoretically allowed range in  $\Delta g$ :  $-g < \Delta g < +g$
- GRSV-STD: Global fit (NLO QCD analysis) to polarized DIS experiments!



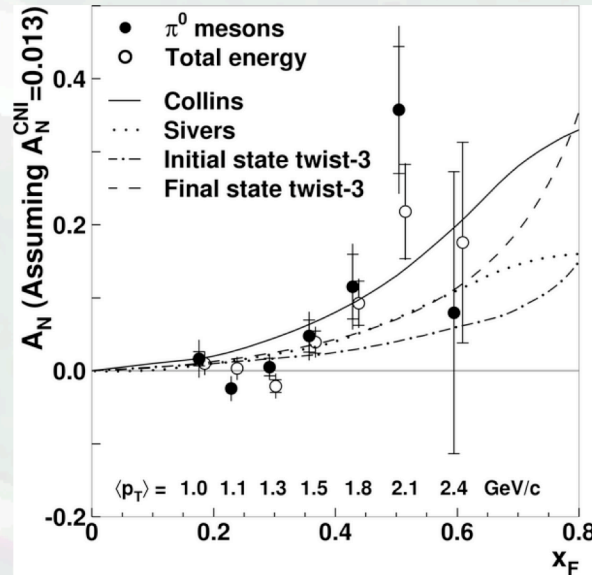
## Theoretical aspects: Transverse spin physics

□ Single transverse-spin asymmetry:



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

□ First measurement of  $A_N$  at  $\sqrt{s} = 200 \text{ GeV}$  at STAR



□ Non-zero values of  $A_N$  at  $\sqrt{s} = 20 \text{ GeV}$  have been observed previously at E704

□ Basic, naive QCD calculations (leading-twist, zero quark masses) predict:  $A_N = 0$  ( $A_N \sim m_q/\sqrt{s}$ )

□ Study transverse spin effects:

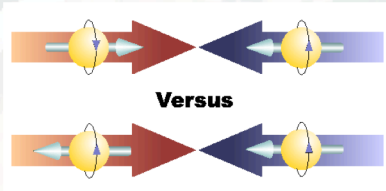
- Qiu and Sterman (Initial-state twist-3)/Koike (final-state twist-3)
- Sivers:  $k_{\perp}$  in initial state (Correlation of quark  $k_{\perp}$  and proton spin):  $\Rightarrow$  Orbital momentum
- Collins:  $k_{\perp}$  in final state (Correlation of quark spin and  $k_{\perp}$  of hadron):  $\Rightarrow$  Transversity

Fundamental trans. spin sum rule:

$$\frac{1}{2} = \frac{1}{2} \sum_{i=q,\bar{q}} \int dx \delta q_a(x, Q^2) + \sum_{i=q,\bar{q},g} \langle L_{ST} \rangle_i(Q^2)$$

## ■ Asymmetry measurements at RHIC

### □ Double longitudinal-spin asymmetry: $A_{LL}$



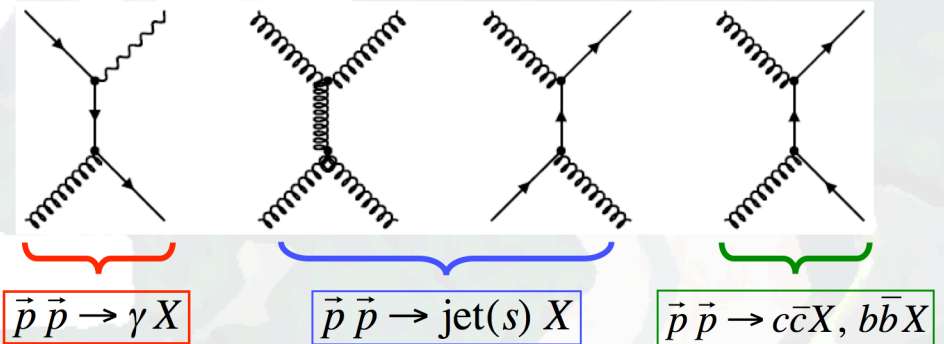
- Study helicity dependent structure functions (*Gluon polarization*)!

### □ Require concurrent measurements:

- Magnitude of **beam polarization**,  $P_{1(2)}$   
RHIC polarimeters
- **Direction of polarization vector** at interaction point
- **Relative luminosity** of bunch crossings with different spin directions:
- **Spin dependent yields** of process of interest  $N_{ij}$

RHIC polarimeters

STAR experiment



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

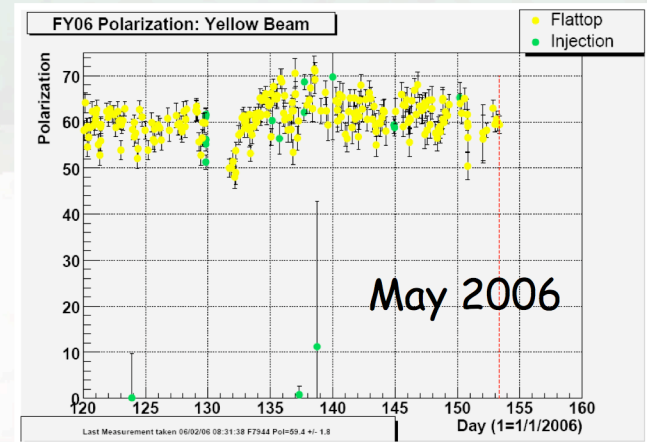
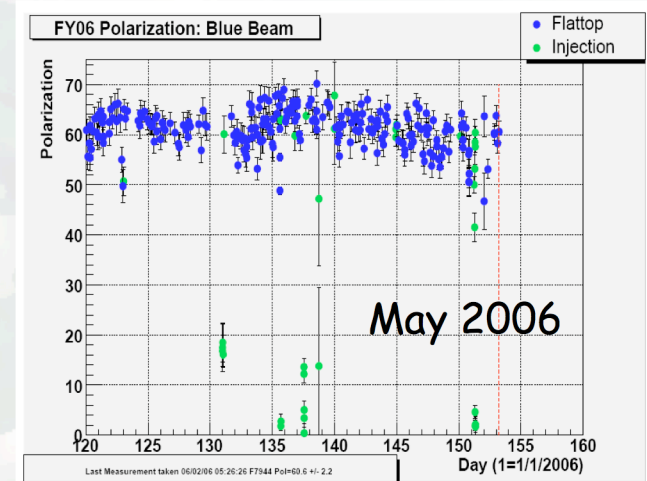


# The polarized proton collider RHIC

## ■ Luminosity and polarization performance

### □ Overview of performance parameters

RHIC RUN	$\sqrt{s}$ [GeV]	$L_{\text{recorded}}$ [pb <sup>-1</sup> ] (Transverse)	$L_{\text{recorded}}$ [pb <sup>-1</sup> ] (Longitudinal)	Polarization [%]
RUN 2	200	0.15	0.3	15
RUN 3	200	0.25	0.3	30
RUN 4	200	0	0.4	40-45
RUN 5	200	0.1	3.1	45-50
RUN 6	200	3.4/6.8	8.5	60

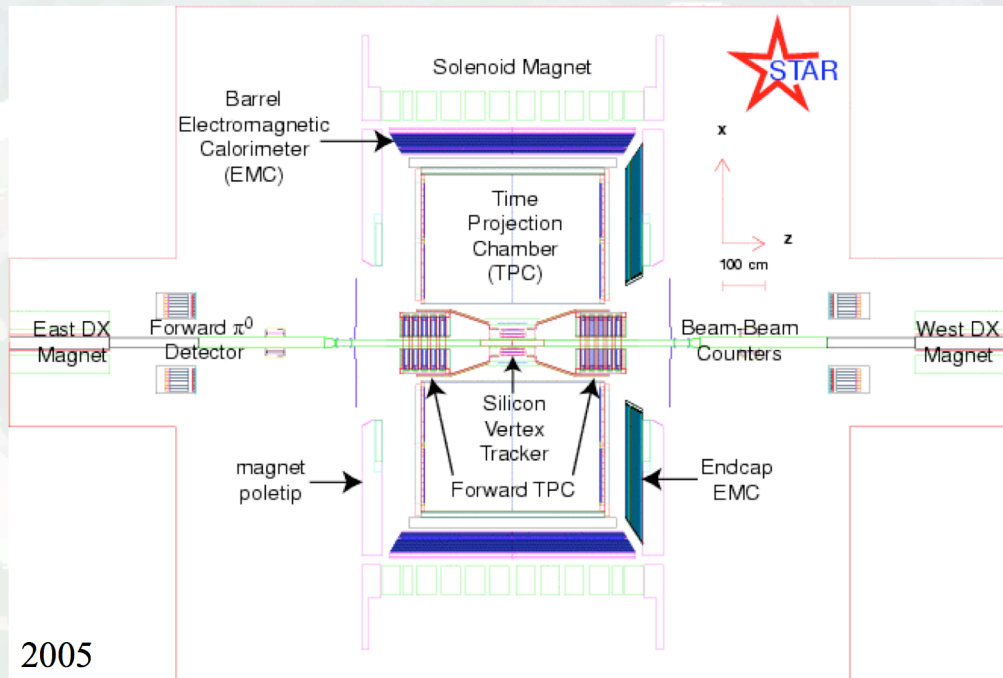


Yellow and Blue Beam polarization

- All RHIC polarized pp accelerator components are in place!
- 2006 performance ( $\sqrt{s}=200\text{GeV}$ ): **~60% polarization** (70% design) and **~1pb<sup>-1</sup>/day** (~3pb<sup>-1</sup>/day design) **delivered luminosity**



## Overview

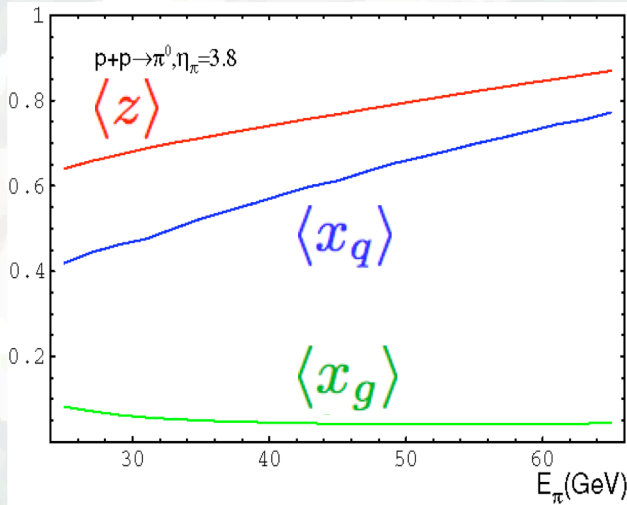
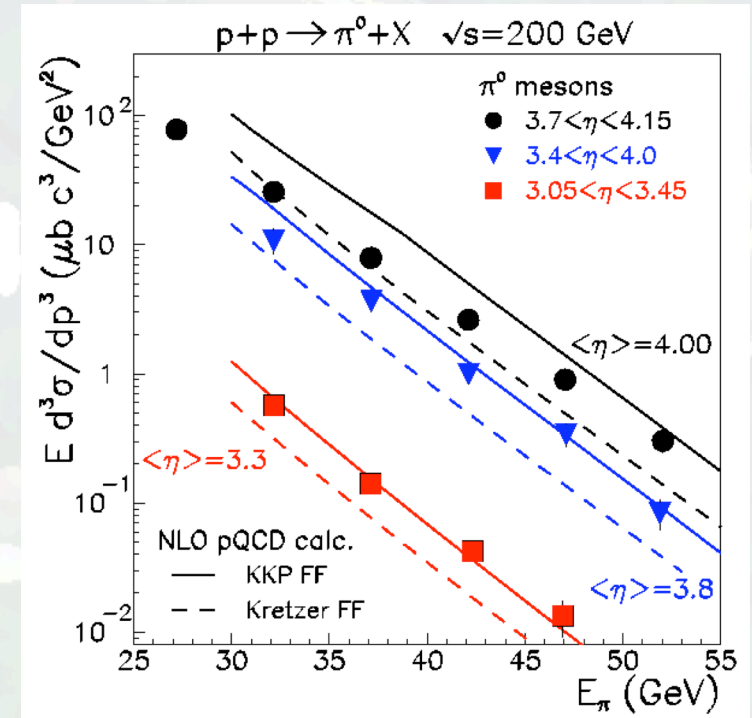
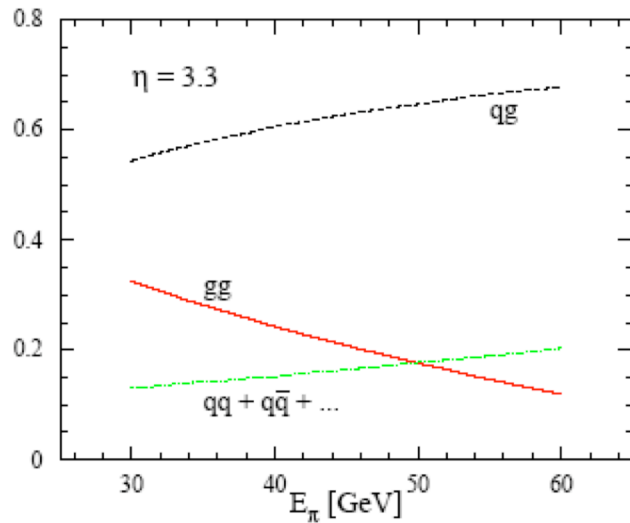


- **Forward-Pion Detector (FPD)** ( $3 < |\eta| < 4$ )
- **FPD++** (Extended coverage for Run 6 with  $3 < \eta < 4$ )
- **FMS** upgrade (Run 7 and beyond with  $2.5 < \eta < 4$ )

- **Beam-Beam Counter (BBC)**: ( $3.4 < |\eta| < 5$ )
  - Relative luminosity measurement
  - Absolute luminosity measurement
  - Local polarimeter ( $A_N$  for charged particles)
- **EM-Calorimeter**: (**Barrel - BEMC**:  $-1 < \eta < 1$  & **Endcap - EEMC**:  $1.09 < \eta < 2$ )
  - Reconstruction of  $\gamma$ ,  $e^\pm$  and  $\pi^0$
  - Jet-reconstruction in combination with TPC

## ■ Cross-section measurement: Forward neutral pion production

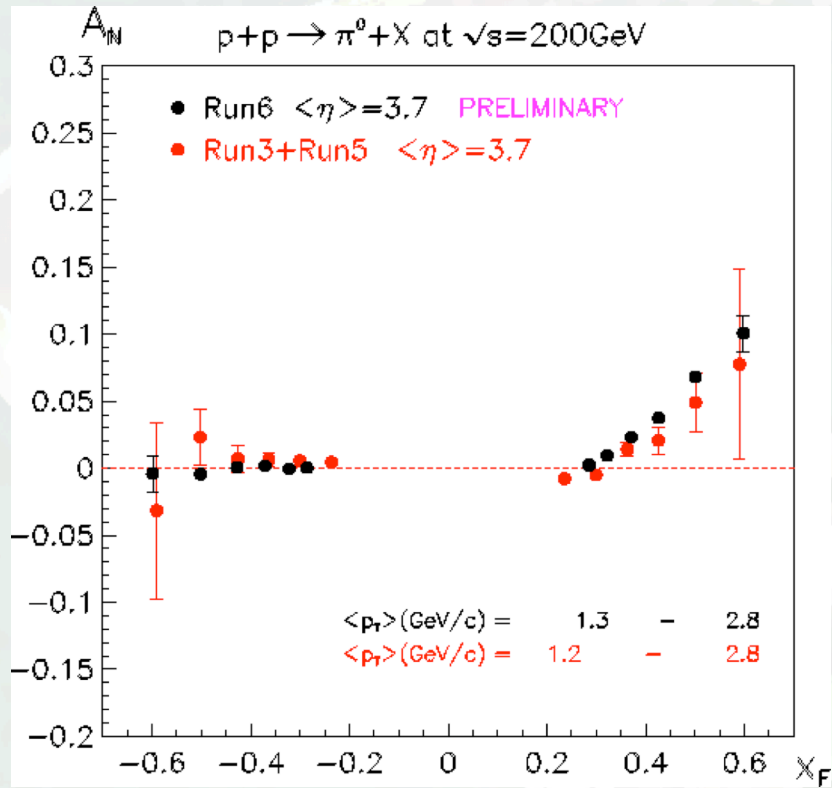
L. Nogach (IHEP-Protvino)

 Jaeger, Stratmann, Vogelsang  
and Kretzer

 V. Guzey, M. Strikman and W. Vogelsang,  
Phys. Lett. B603 (2004) 173.


- Forward  $\pi^0$  production : Dominated by asymmetric  $qg$  collisions
- NLO pQCD calculations for two sets of fragmentation functions
- Data compares favorably to NLO pQCD at  $\sqrt{s} = 200 \text{ GeV}$  in contrast to fixed-target or ISR energies

## ■ $A_N$ measurement as a function of $x_F$ and $p_T$

L. Nogach (IHEP-Protvino)

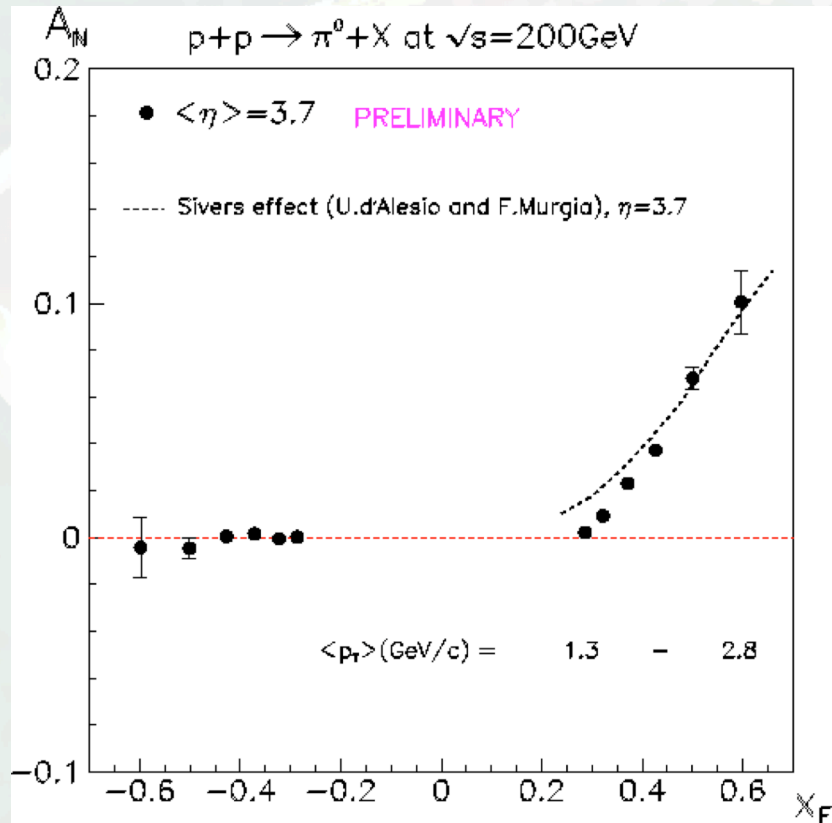


- Run 6 results consistent with previous results



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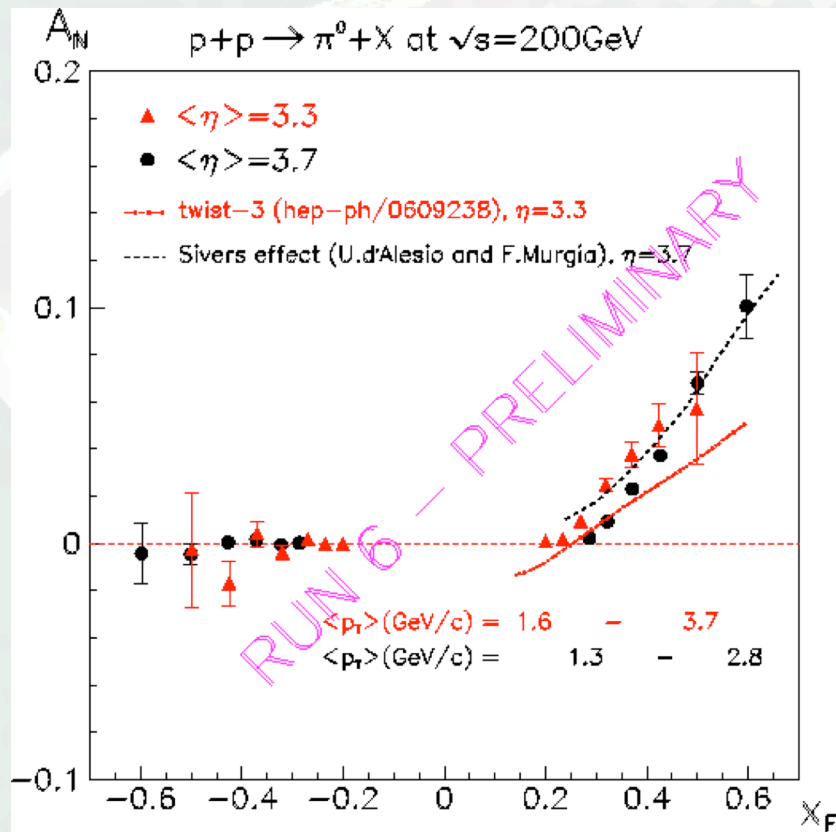
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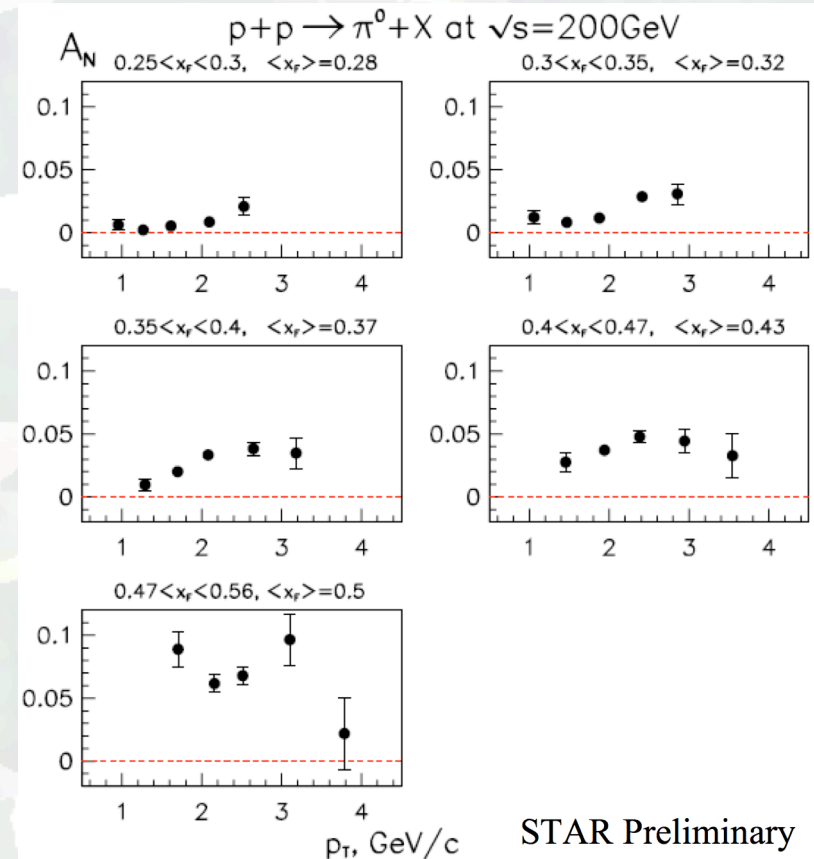
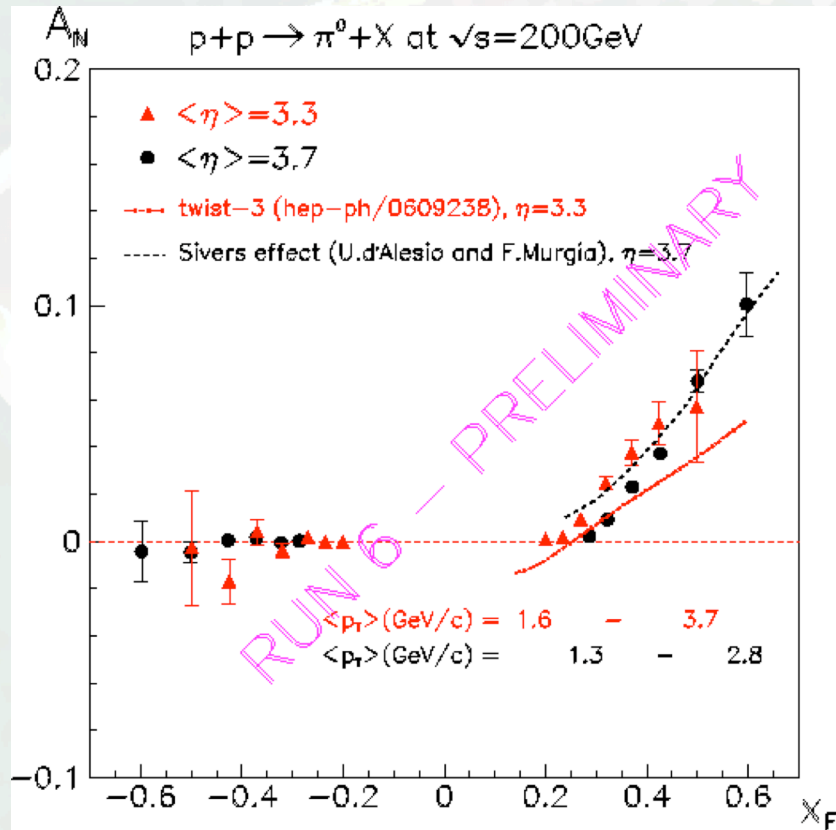
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- Run 6 results consistent with previous results
- $A_N$  calculations (Sivers / Twist-3) inconsistent with precise  $x_F$  dependence of measured  $A_N$

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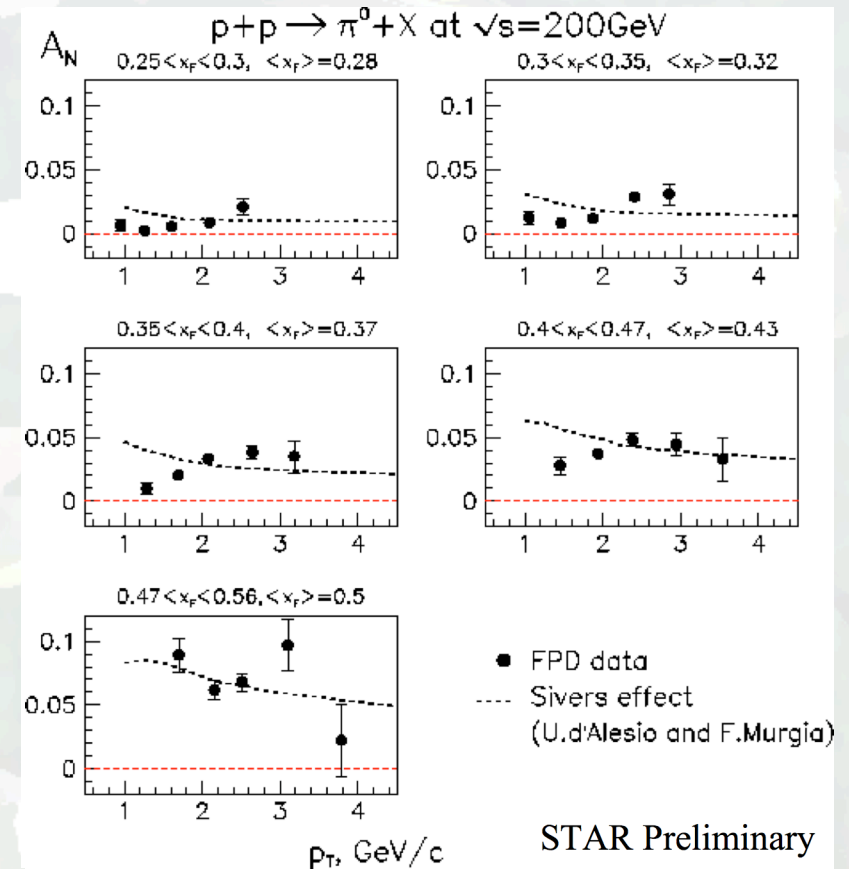
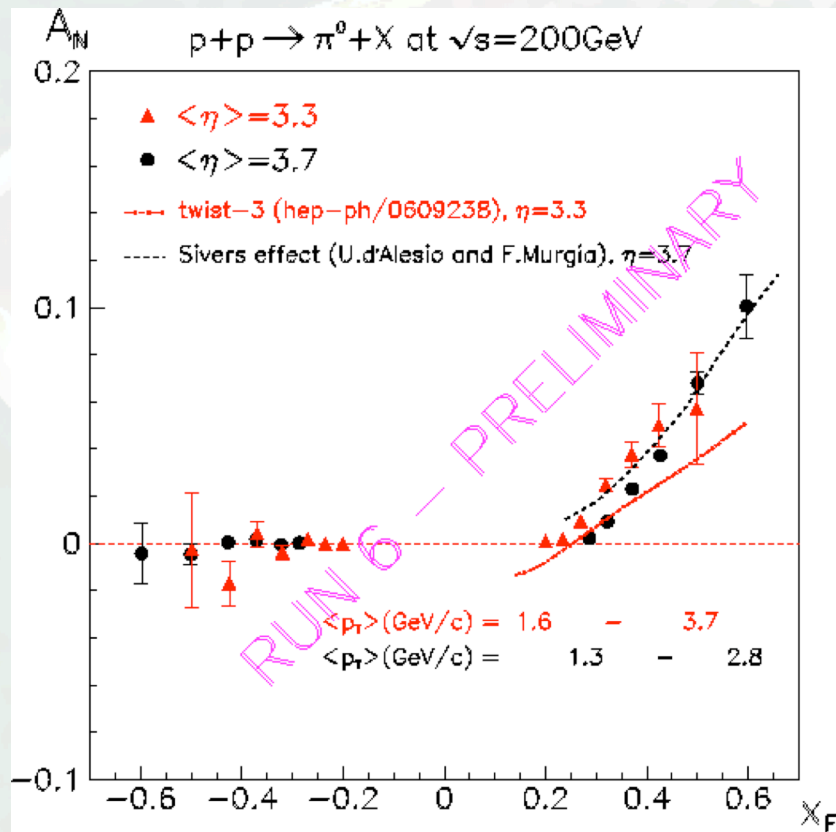


- Run 6 results consistent with previous results
- $A_N$  calculations (Sivers / Twist-3) inconsistent with precise  $x_F$  dependence of measured  $A_N$
- Measured  $A_N$  is not found to decrease in  $p_T$  in all  $x_F$  bins



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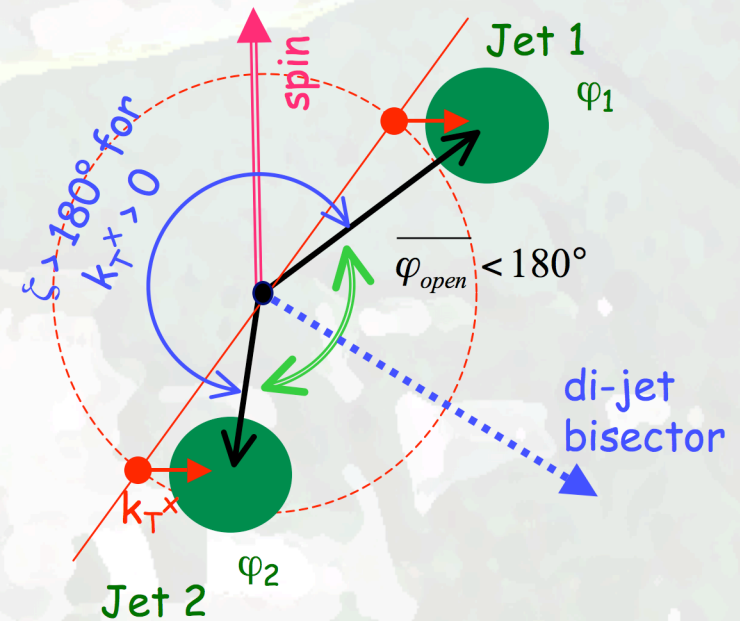
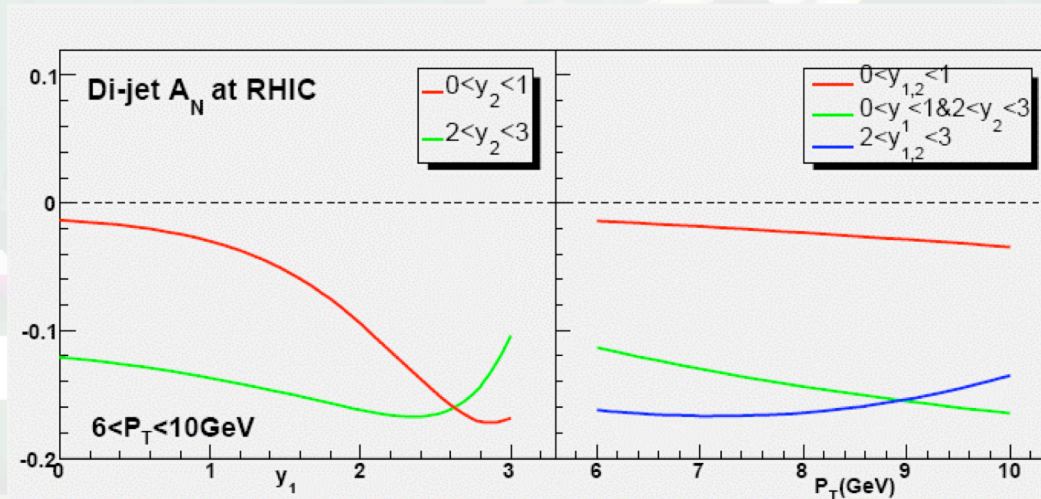
- Run 6 results consistent with previous results
- $A_N$  calculations (Sivers / Twist-3) inconsistent with precise  $x_F$  dependence of measured  $A_N$

- Measured  $A_N$  is not found to decrease in  $p_T$  in all  $x_F$  bins
- In contrast: Theoretical models predict  $A_N$  to decrease with  $p_T$

## Theoretical aspects: Probing Sivers functions - Di-Jet production

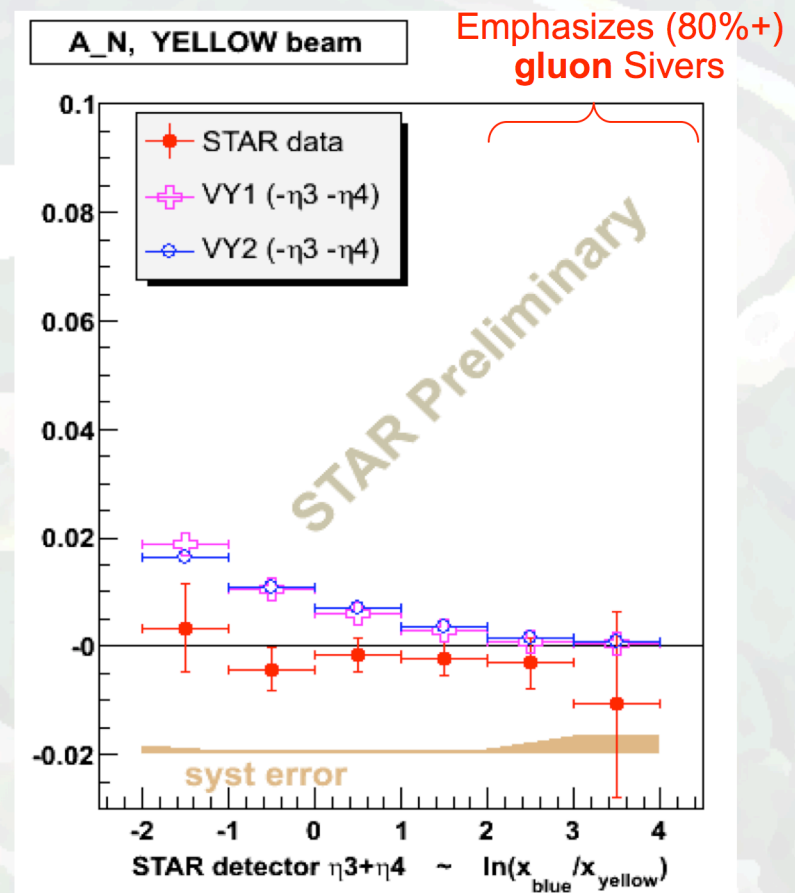
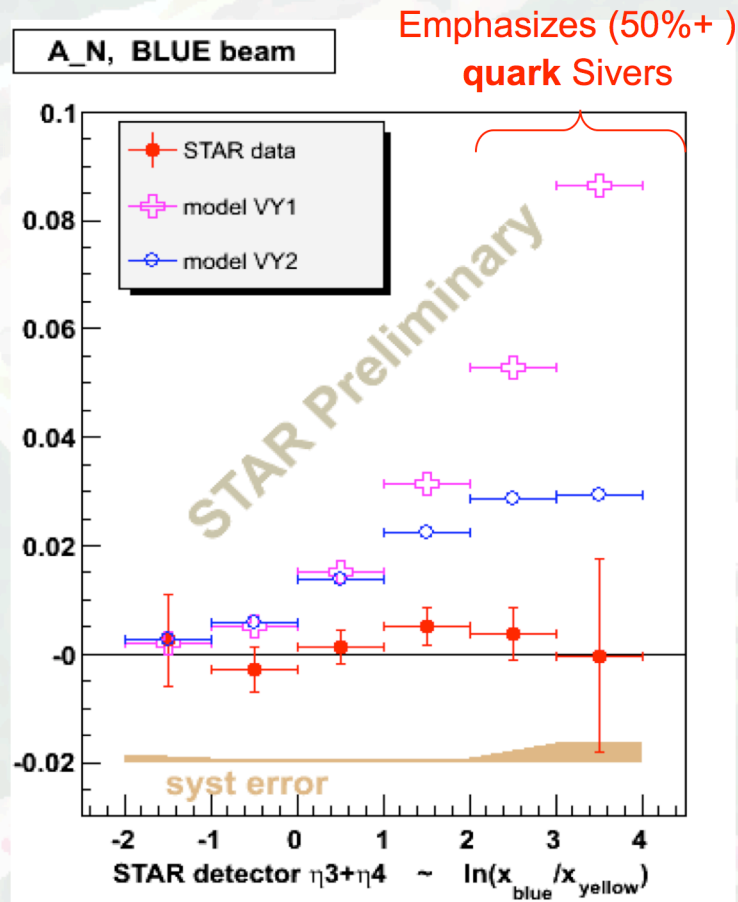
J. Balewski (IUCF)

- Sivers effect:  $\langle k_T^{\text{parton}} \cdot (\vec{s}_{\text{proton}} \times \vec{p}_{\text{proton}}) \rangle \neq 0$
- Sensitivity to **parton orbital angular momentum**
- **HERMES transverse spin SDIS asymmetries: Non-zero u/d quark Sivers functions** of opposite sign and magnitude
- Sivers effect in polarized pp: **Spin-dependent side-ways boost to di-jet opening angle** (D. Boer and W. Vogelsang, PRD 69 (2004) 094025.)
- Prediction based on HERMES results:
- **Measure correlation between spin-direction and di-jet bisector direction**
- Asymmetric collisions probe quark / gluon contribution with two polarized beams



## ■ $A_N$ results: Probing Siverson functions - Di-Jet production

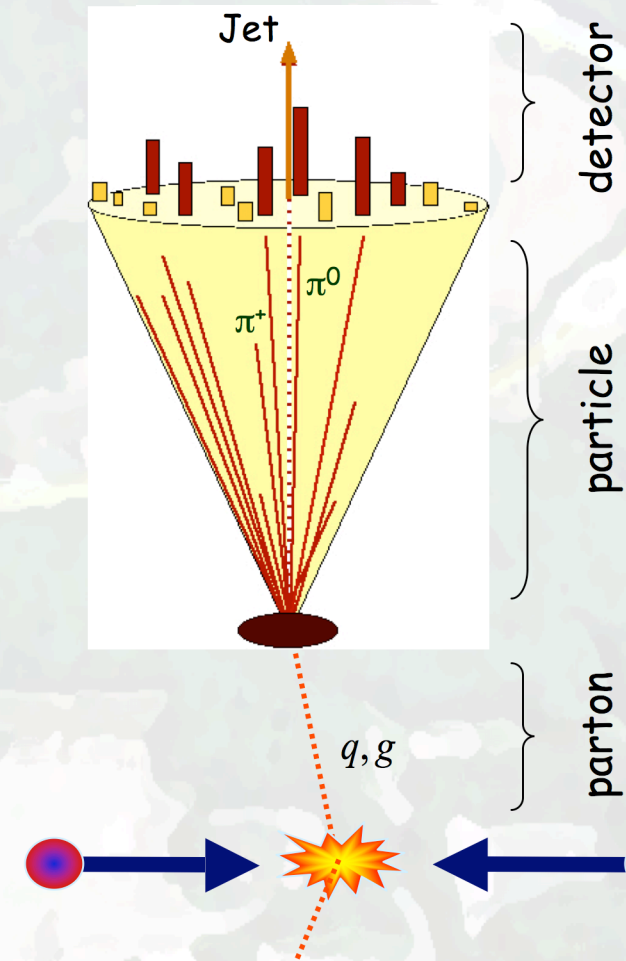
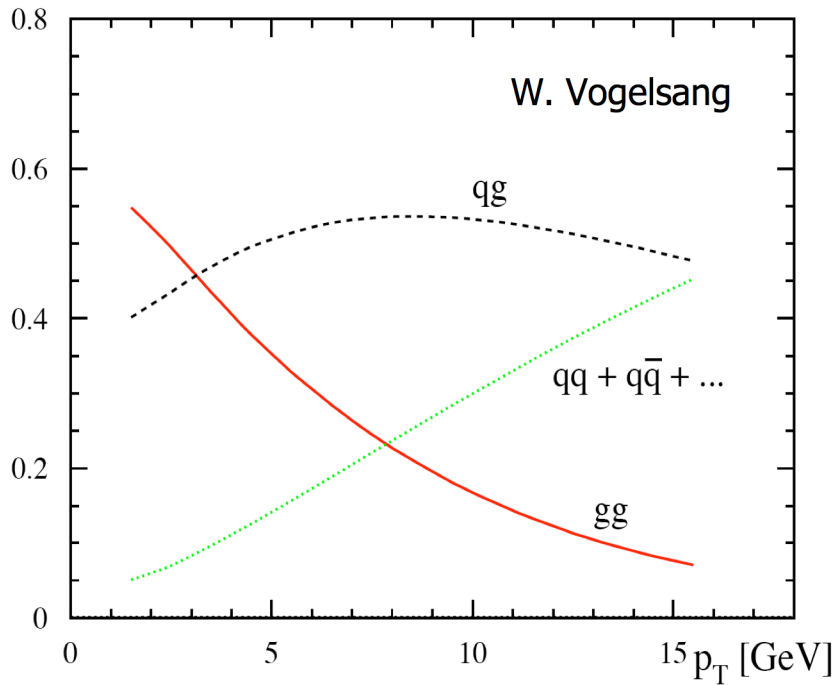
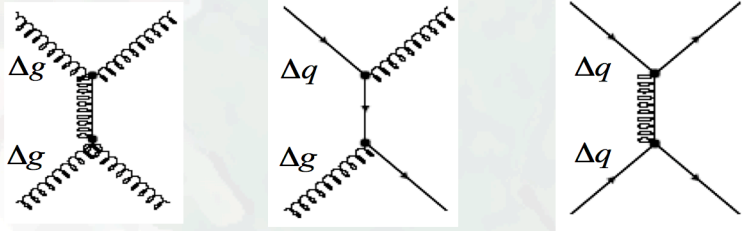
J. Balewski (IUCF)



- Di-jet Siverson calculations (VY1 / VY2) based on HERMES extracted quark Siverson functions
- Measured  $A_N$  di-jet asymmetries are found to be consistent with zero

## ■ Inclusive measurements: Jet and Hadron production

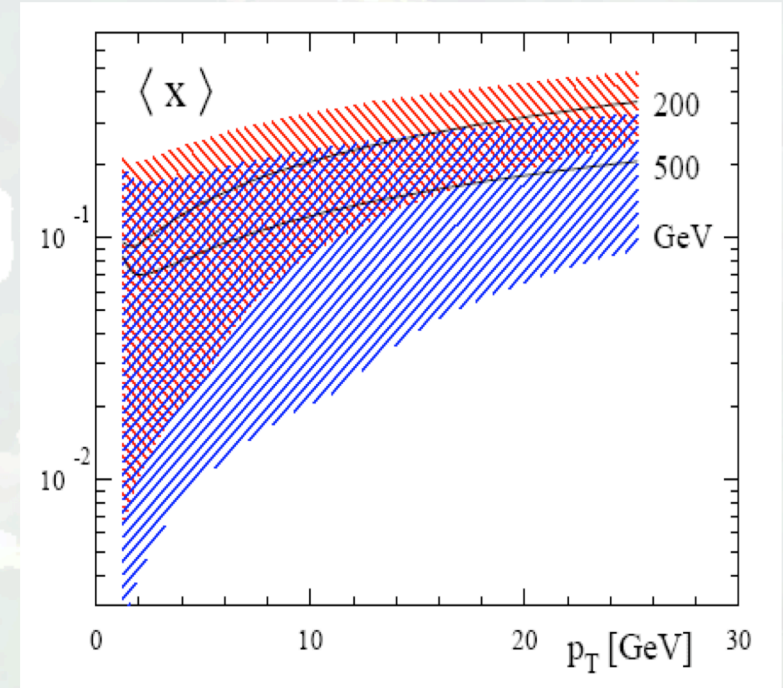
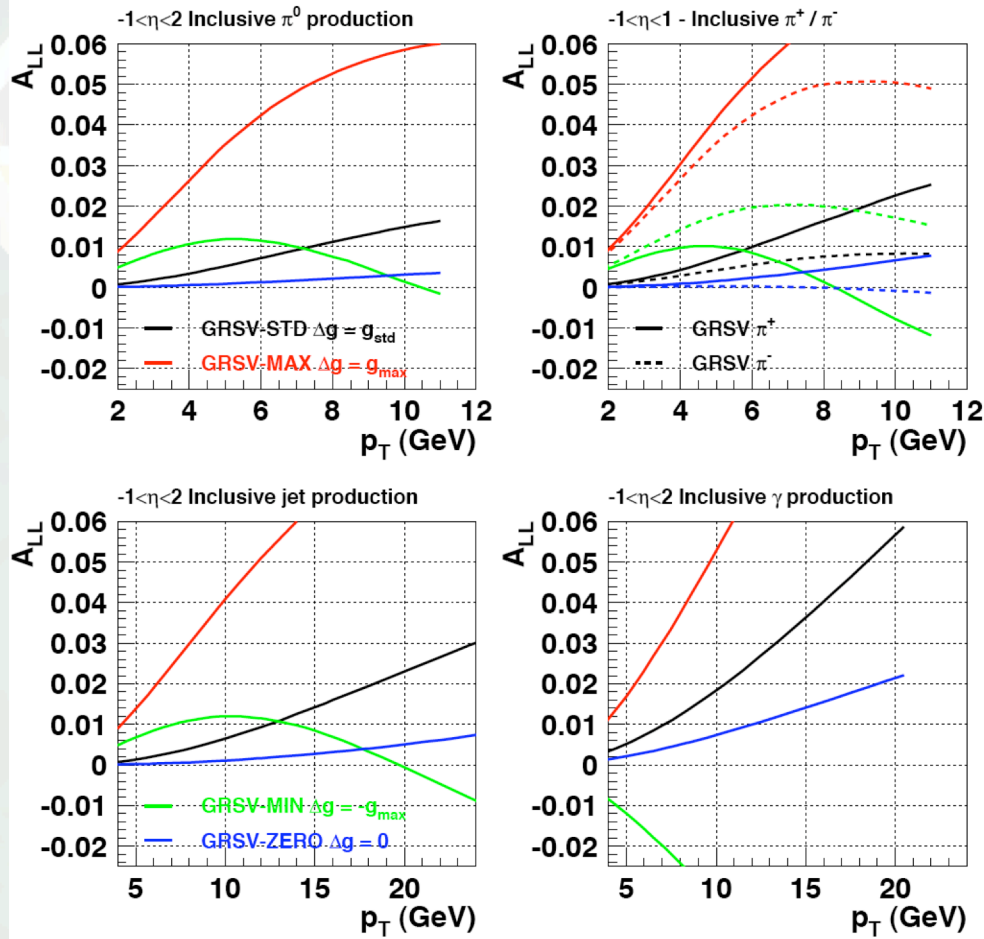
- Underlying processes contributing to inclusive jet production and  $\pi^0 / \pi^\pm$  production:





## ■ Inclusive measurements: Jet / $\pi^0$ / $\pi^\pm$ and $\gamma$ production

### □ $A_{LL}$ sensitivity for different $\Delta G$ scenarios



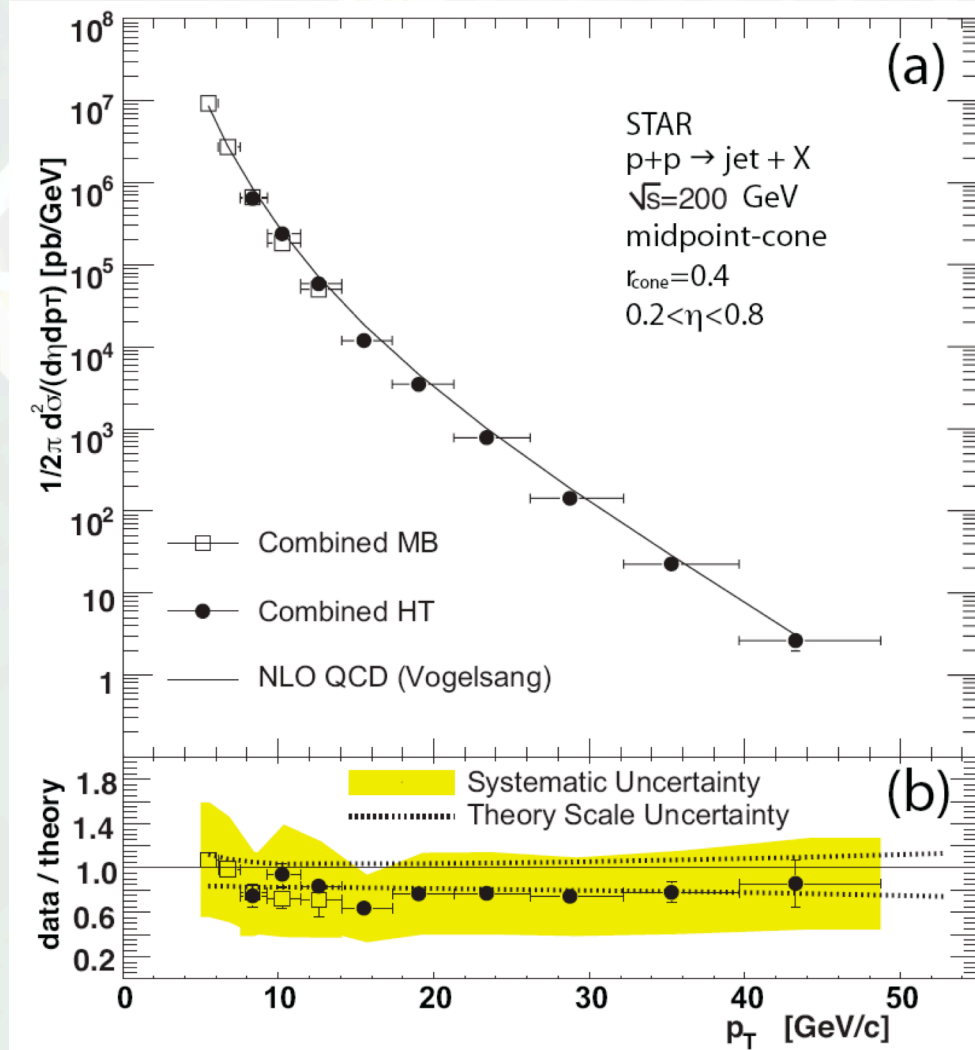
□ Mean Bjorken- $x$  and rms-spread as a function of  $p_T$  for inclusive  $\pi^0$  production

□ Central production ( $\eta \approx 0$ ):

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

## ■ Cross-section measurement: Inclusive jet production

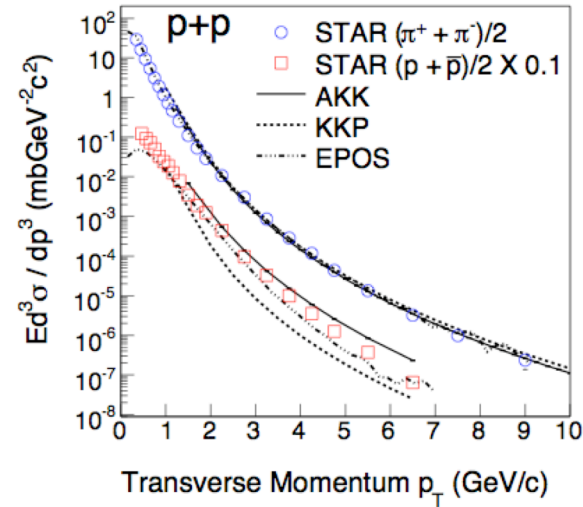
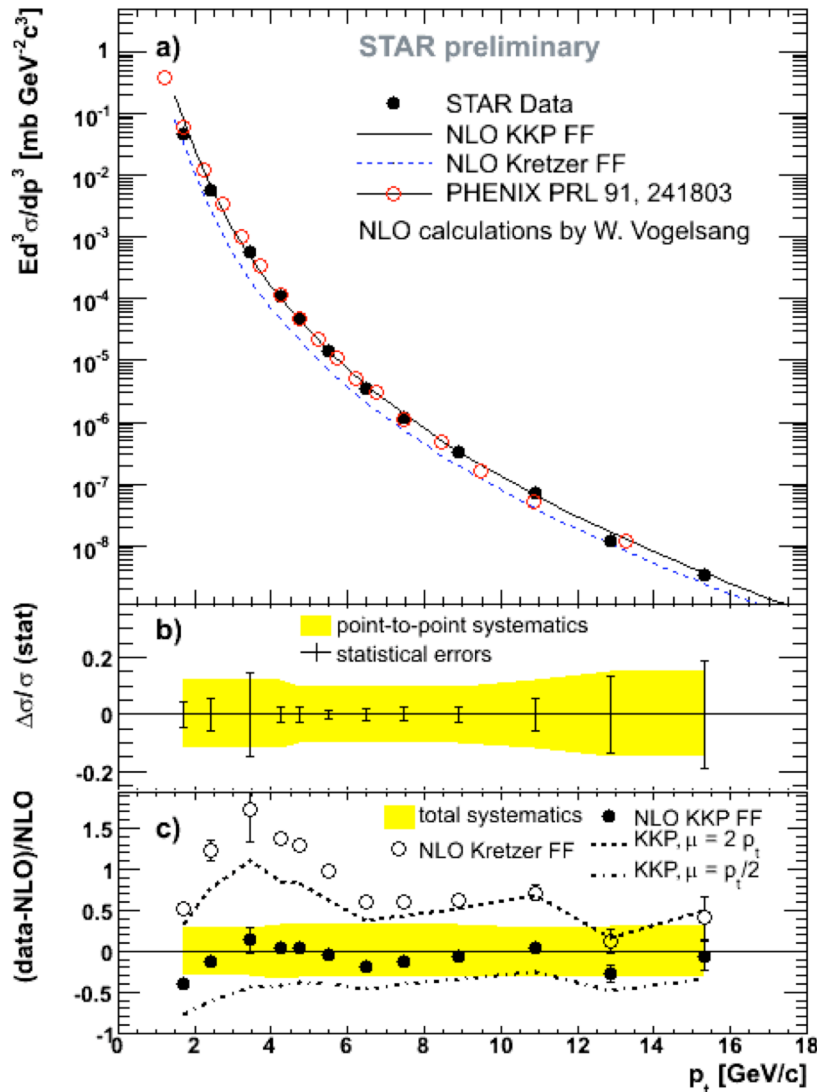
D. Relyea (CalTech)



- First measurement of inclusive jet cross-section at RHIC
- Good agreement of data with NLO pQCD calculations over 7 orders of magnitude within large systematic uncertainties

## ■ Cross-section measurement: Hadron production

F. Simon (MIT)



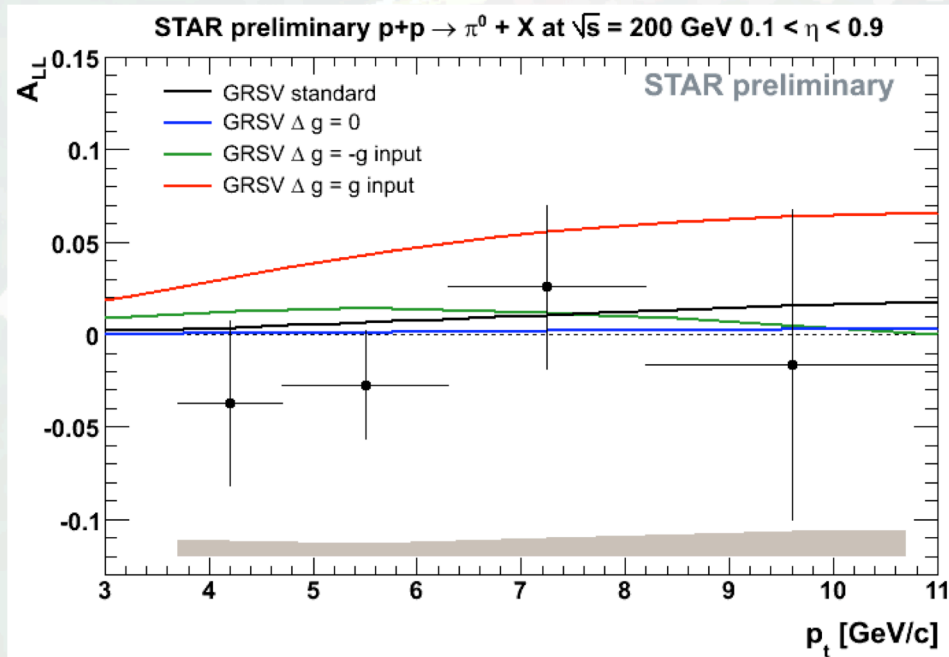
- Good agreement of data with NLO pQCD calculations over several order of magnitude for neutral and charged pion cross-section
- KKP fragmentation preferred
- Scale uncertainties at the level of systematic uncertainties (Shown here for neutral pion cross-section)



# STAR longitudinal spin program - Recent results

## ■ $A_{LL}$ measurement: Neutral pion production (STAR BEMC)

F. Simon (MIT)



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

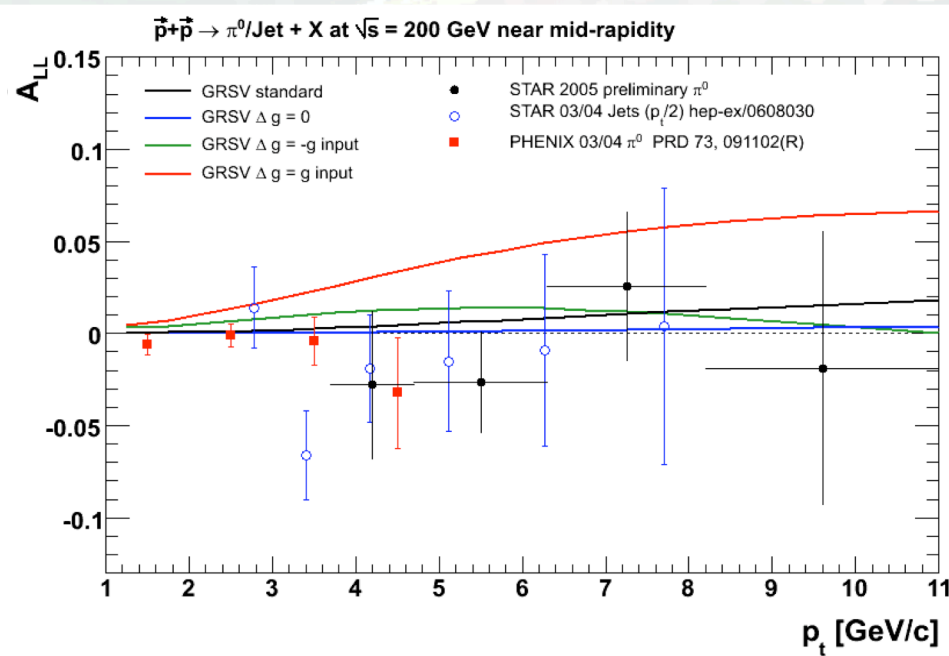
$$\Delta G(Q^2 = 1 \text{ GeV}^2) \approx 1.8$$

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



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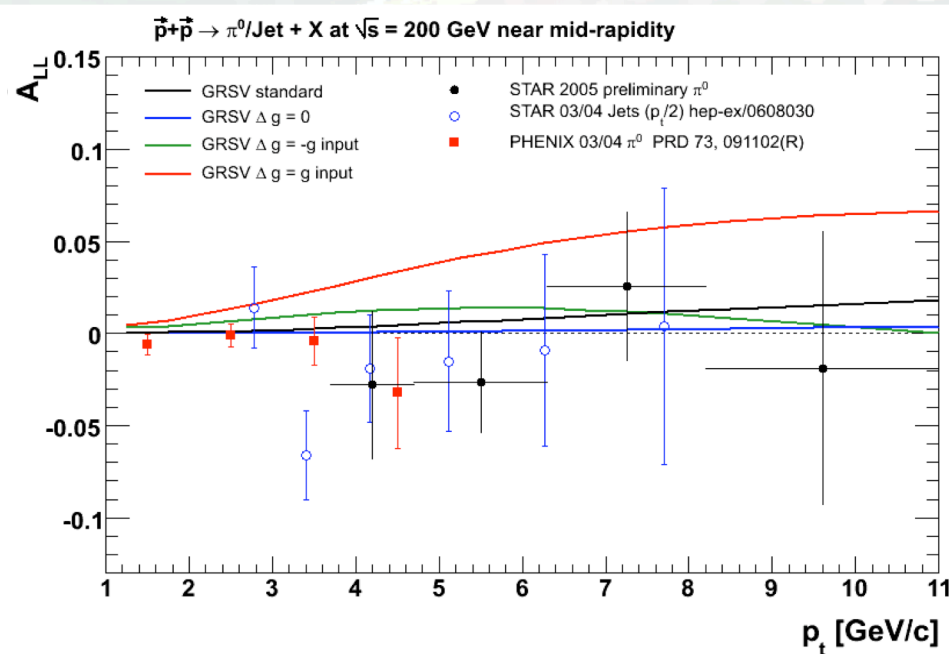
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- $A_{LL} \pi^0$  result (Run 5) with Run 3/4 jet result and PHENIX  $\pi^0$  result

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

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 $\chi^2 / \text{ndf}$  to curves: (no sys. errors included)

GRSV-STD: 0.8

DG = G: 2.4

DG = 0: 0.8

DG = -G: 0.5

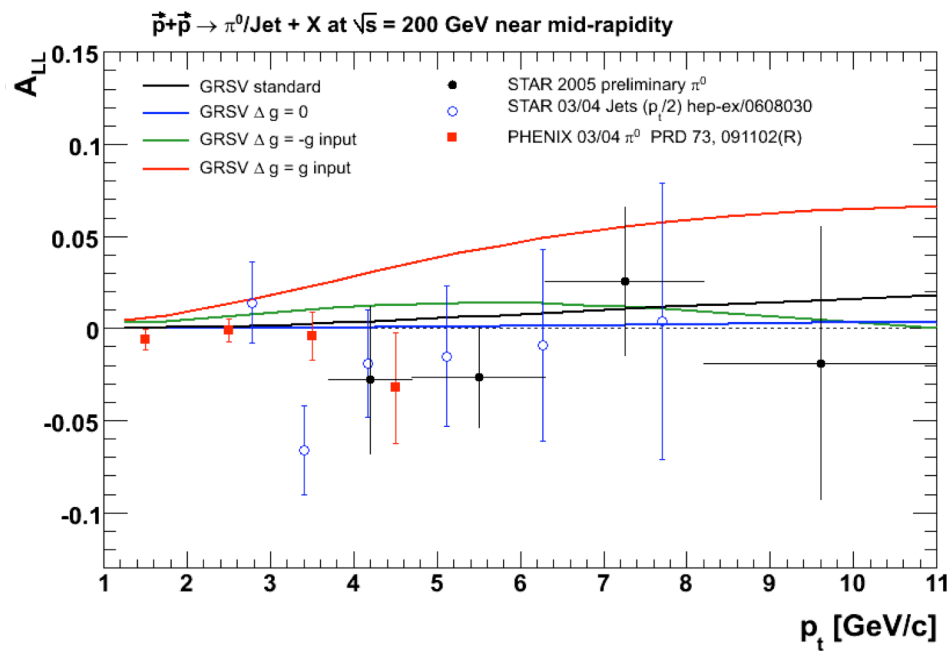
- $A_{LL} \pi^0$  result (Run 5) with Run 3/4 jet result and PHENIX  $\pi^0$  result
- Maximum gluon polarization (GRSV-MAX) scenario ruled out



# STAR longitudinal spin program - Recent results

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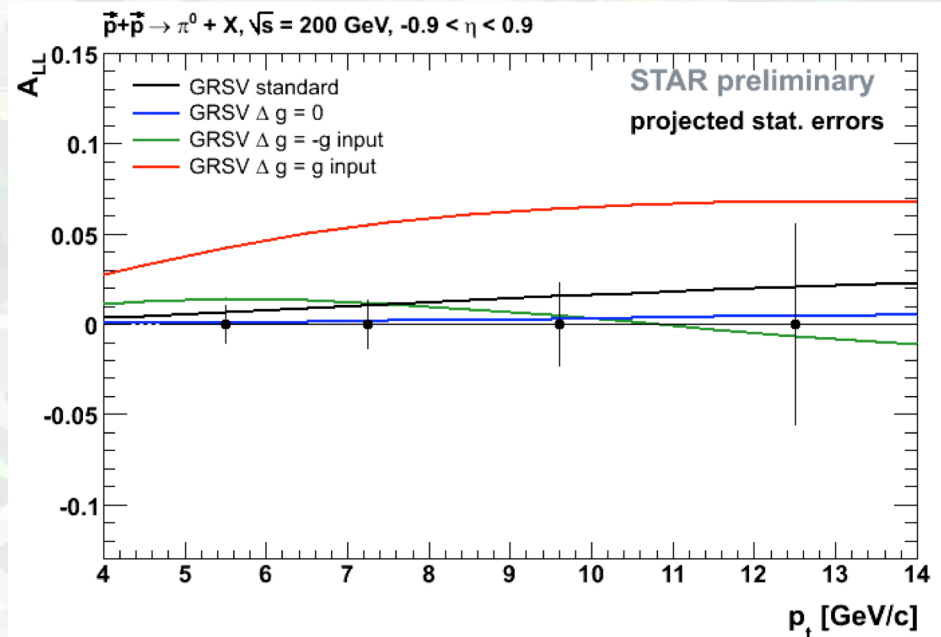
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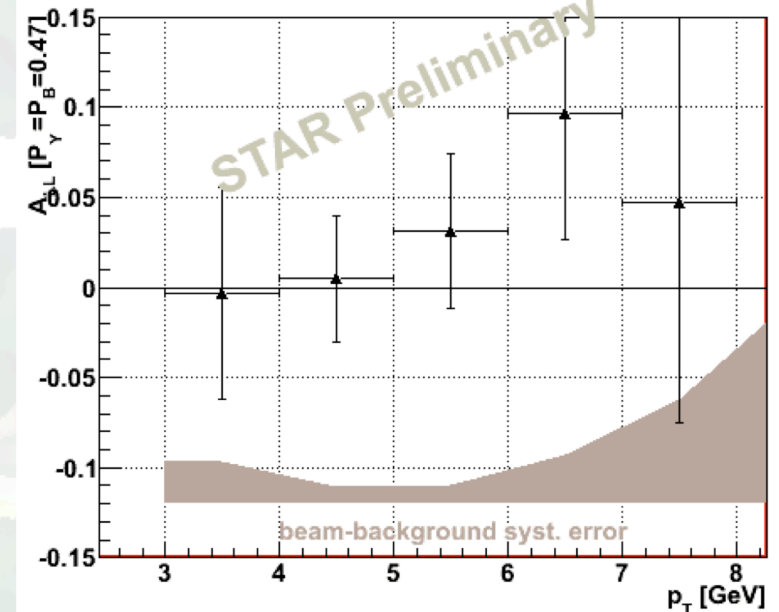
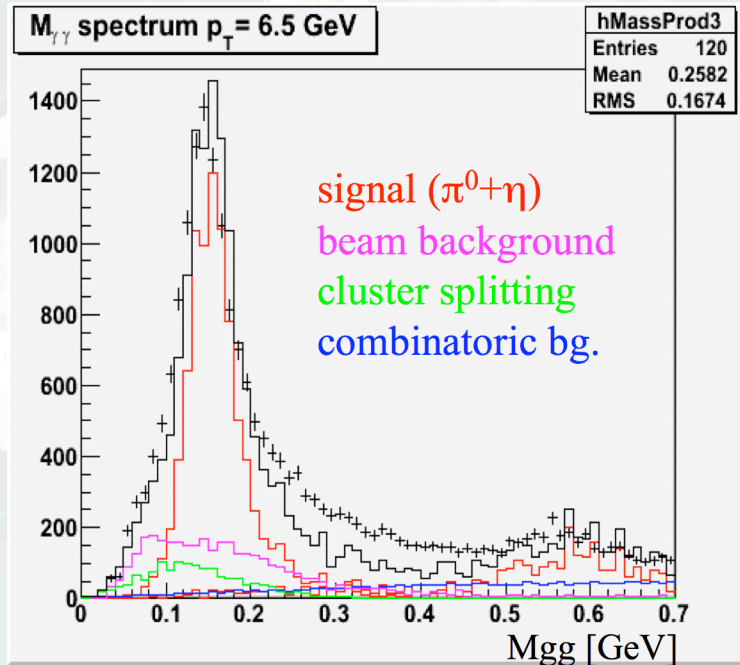
DG = -G: 0.5

- $A_{LL} \pi^0$  result (Run 5) with Run 3/4 jet result and PHENIX  $\pi^0$  result
- Maximum gluon polarization (GRSV-MAX) scenario ruled out
- Improved measurement with Run 6 data



## ■ $A_{LL}$ measurement: Neutral pion production (STAR EEMC)

J. Webb (Valparaiso University)

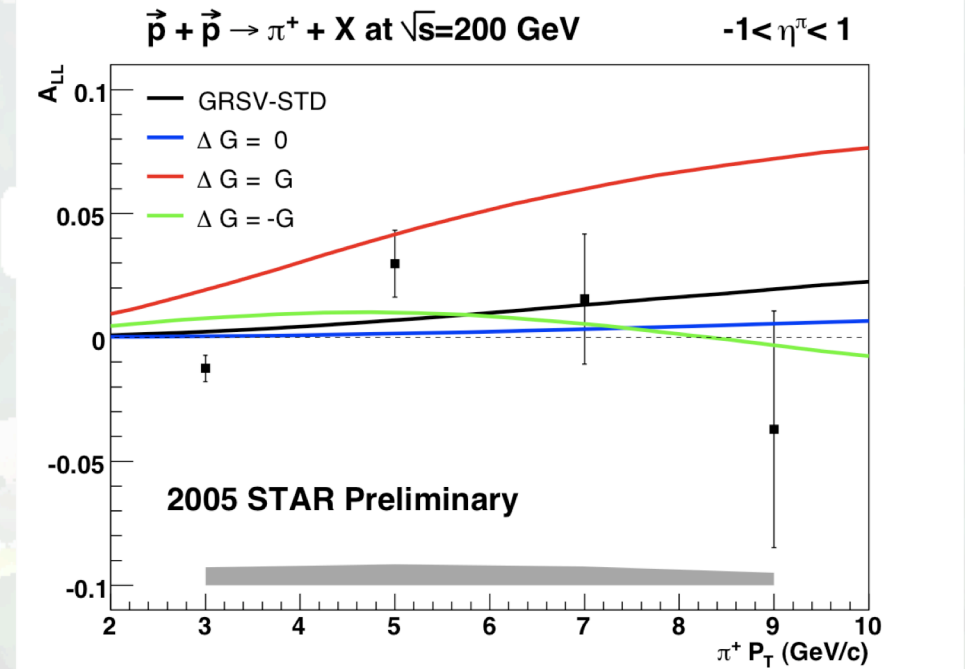
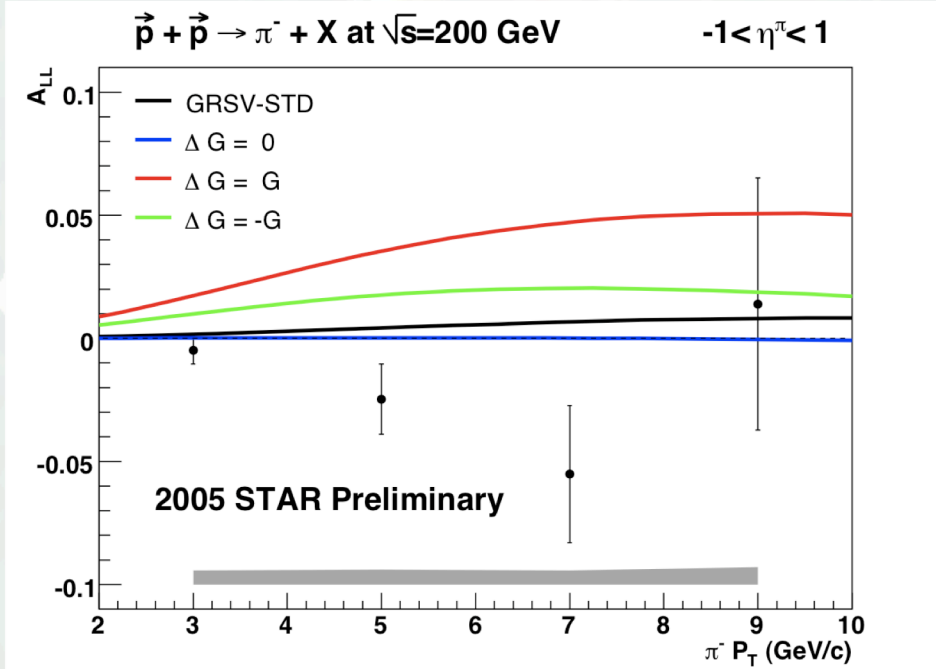


- Forward direction probes different  $q/g$  sub-process mixture
- Current analysis (Run 5) in STAR EEMC region ( $1.09 < \eta < 2$ ) dominated by beam background
- Several improvements in Run 6 such as reduction in beam background
- Important baseline measurement for future prompt photon measurements



## ■ $A_{LL}$ measurement: Charged pion production ( $-1 < \eta < 1$ )

A. Kocoloski (MIT)



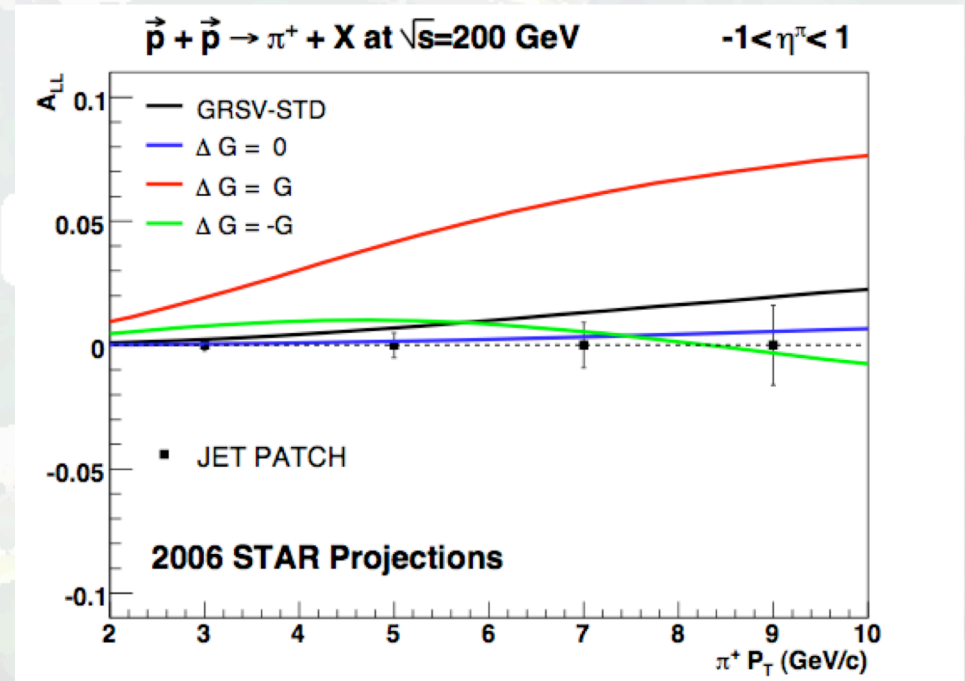
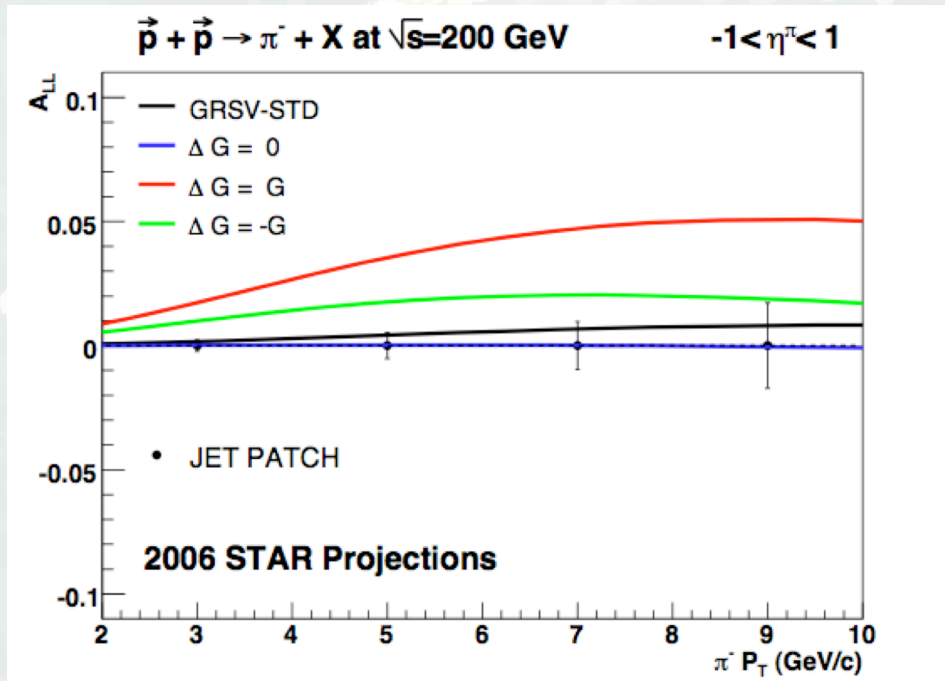
- $A_{LL}(\pi^-) / A_{LL}(\pi^+)$  allows to track **sign of  $\Delta G$**  at high  $p_T$  (**qq process dominates**)
- Maximum gluon polarization (GRSV-MAX) scenario disfavored
- Improved precision with Run 6 data - Study of charged pions based on away-side jet to reduce jet trigger bias (Leading systematic uncertainty in Run 5 analysis)



# STAR longitudinal spin program - Recent results

## ■ $A_{LL}$ measurement: Charged pion production ( $-1 < \eta < 1$ )

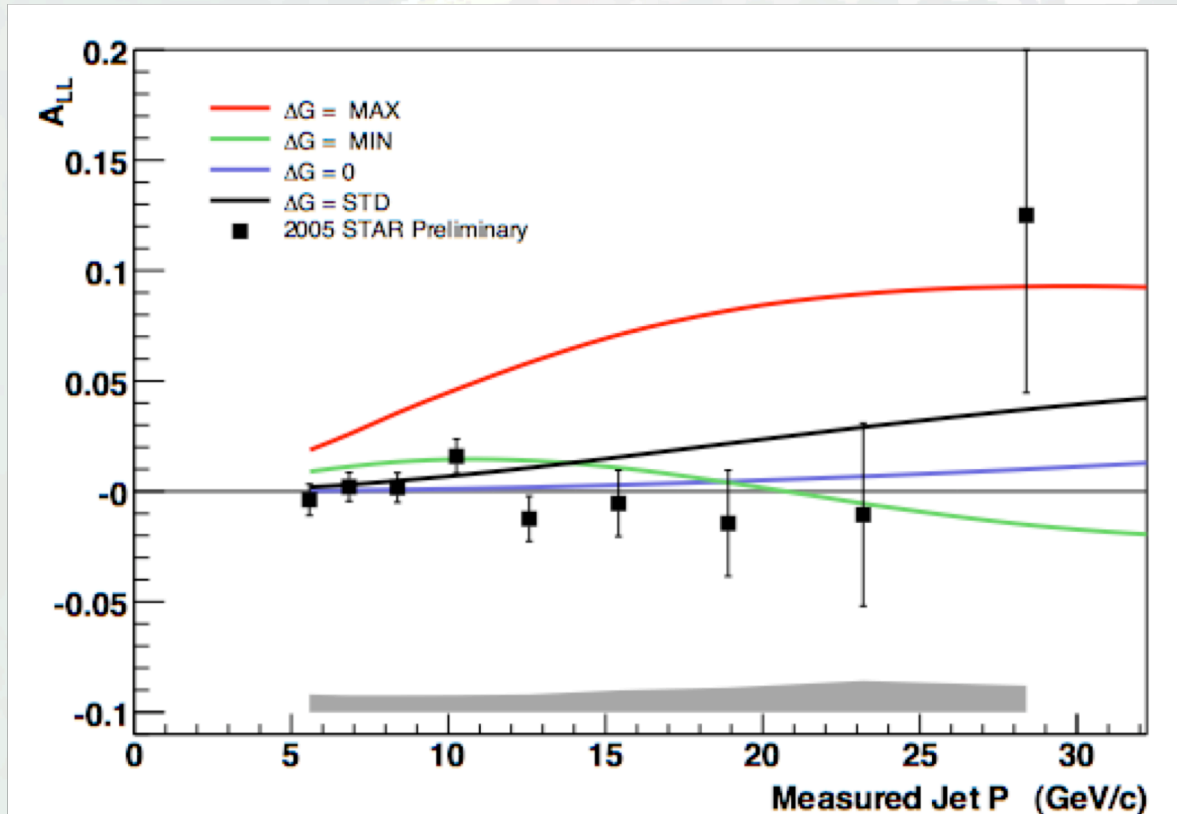
A. Kocoloski (MIT)



- $A_{LL}(\pi^-) / A_{LL}(\pi^+)$  allows to track **sign of  $\Delta G$**  at high  $p_T$  (**qq process dominates**)
- Maximum gluon polarization (GRSV-MAX) scenario disfavored
- Improved precision with Run 6 data - Study of charged pions based on away-side jet to reduce jet trigger bias (Leading systematic uncertainty in Run 5 analysis)

## ■ $A_{LL}$ measurement: Inclusive jet production (STAR BEMC)

D. Relyea (CalTech)



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

$\chi^2 / \text{ndf}$  to curves:  
(stat.+sys. error  
in quadrature)

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

GRSV-STD: 1.1

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

$DG = G$ : 12

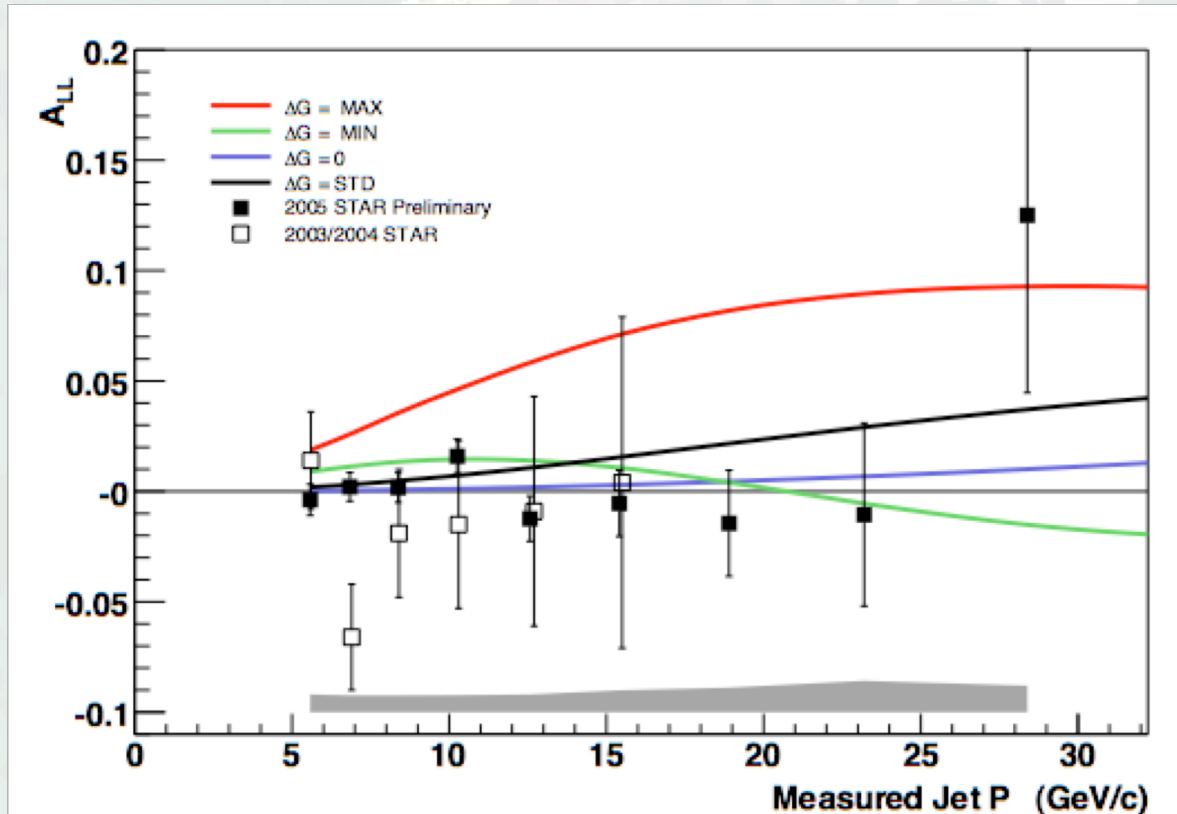
$DG = 0$ : 0.7

$DG = -G$ : 1.4

- Maximum gluon polarization scenario (GRSV-MAX) ruled out

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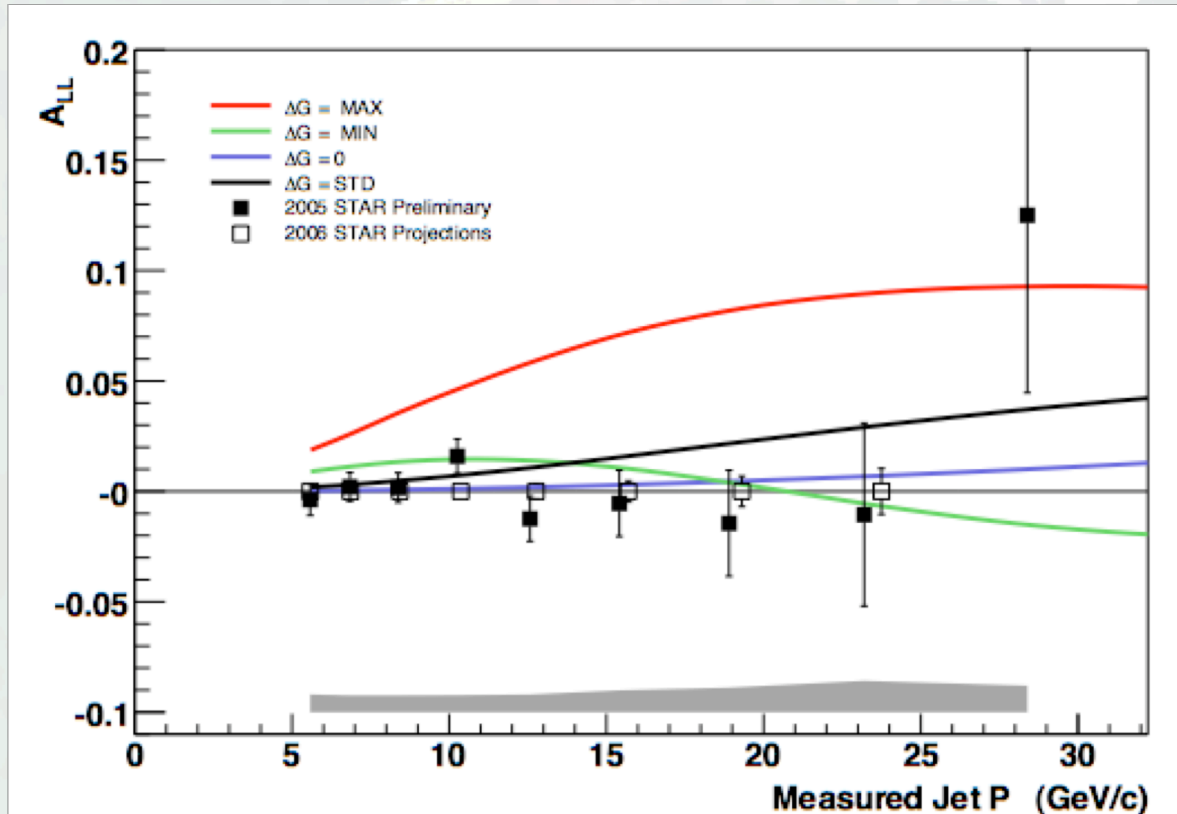
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- $A_{LL}$  inclusive jet result (Run 5) consistent with previous Run 3/4 result



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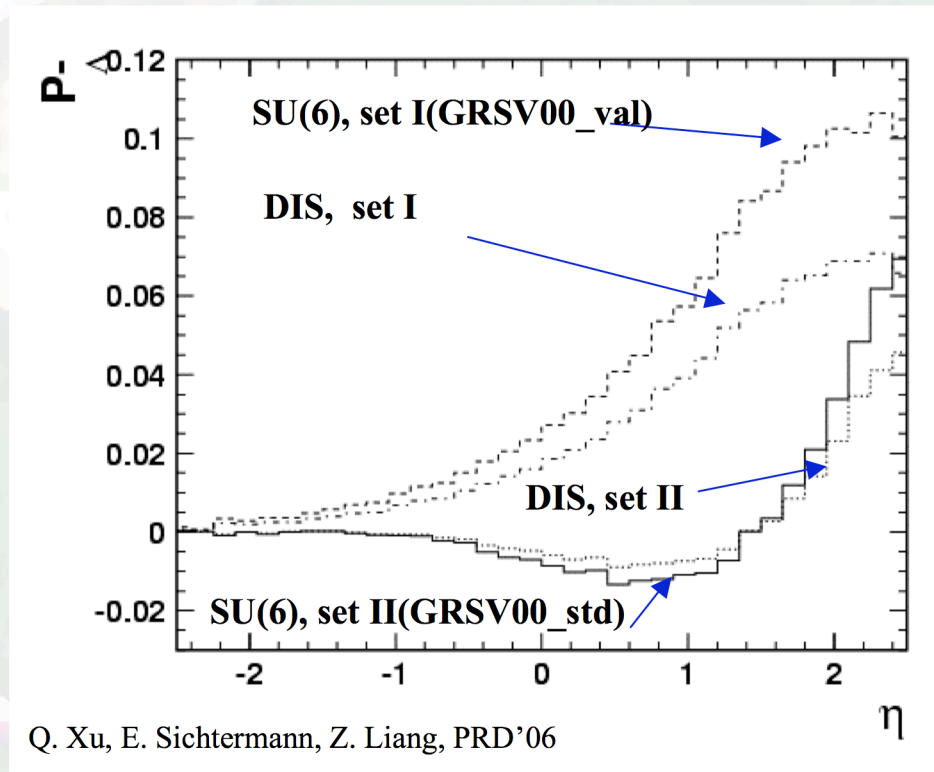
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- Precise measurement of  $A_{LL}$  inclusive jets with Run 6 data

## ■ Lambda production

Q. Xu (LBL)

- The measurement of  $\Lambda$  polarization at RHIC can give insights into polarized fragmentation and parton distribution functions

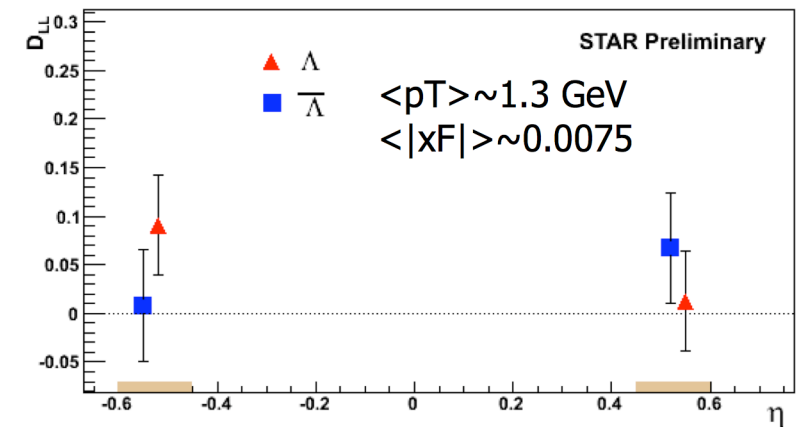


$$\vec{p}p \rightarrow \vec{\Lambda}X$$

$$(\Lambda \rightarrow p + \pi)$$

$$D_{LL} \equiv \frac{\sigma_{p^+p \rightarrow \Lambda^+X} - \sigma_{p^+p \rightarrow \Lambda^-X}}{\sigma_{p^+p \rightarrow \Lambda^+X} + \sigma_{p^+p \rightarrow \Lambda^-X}}$$

- Longitudinal spin transfer  $D_{LL}$



- Lambda-bar polarization is sensitive to  $\Delta\bar{s}(x)$  at large  $p_T$   
( $p_T > 5\text{GeV}/c$ )

- Proof-of-principle measurement from 2005 minimum-bias data

## ■ STAR transverse spin program

- pQCD NLO calculations describe measured cross-sections (Forward  $\pi^0$ )
- Precise  $A_N$  measurement (Run 6) of forward neutral pion production in disagreement with Twist-3 / Sivers calculations
- Measured  $A_N$  is not found to decrease in  $p_T$  in all  $x_F$  bins - In contrast: Theoretical models predict  $A_N$  to decrease with  $p_T$
- Di-jet  $A_N$  measurement (Run 6) are found to be zero in striking disagreement to calculations based on quark Sivers functions constrained by SDIS HERMES data

### ➤ Run 6 data:

- Analysis of  $A_N$  (Forward rapidity  $\pi^0$ ) at  $\sqrt{s} = 62\text{GeV}$
- Analysis of  $A_N$  (Forward rapidity) of jet-like events at  $\sqrt{s} = 200\text{GeV}$  (Sivers/Collins effect)

## ■ STAR longitudinal spin program

- pQCD NLO calculations describe measured cross-sections (Jets, Neutral pions and Charged pions)
- Consistent picture emerging to **disfavor large gluon polarization scenario**
- STAR  $A_{LL}$  measurements: **Important contribution to understanding of  $\Delta G$ !**
- Next step: **Global analysis** incorporating various  $A_{LL}$  measurements
- Run 6 data: **Improved measurements on  $A_{LL}$  inclusive measurements**: Inclusive jets, Neutral pions and Charged pions and new results on correlation measurements: **Di-hadrons** and **Di-jets** (Constrain parton kinematics)

## □ Future:

- **Prompt photons (Medium term)**
- **Flavor decomposition through W production (Long term)**

