G. Bunce
Dubna Spin07, September 2007

The RHIC Spin Program

I would like to thank Les Bland, Werner Vogelsang, Abhay Deshpande, Sasha Bazilevsky, Matthias Grosse Perdekamp, for their advice and many plots.

RHIC Spin Outline

The key points for RHIC Spin are:

- Spin structure of proton
- Strongly interacting probes

- P=60%, L=2x10^31, root(s)=200 GeV in 2006
- Polarized atomic H jet: absolute P, pp elastic physics
- Very forward n asymmetry

- Cross sections for pi^0, jet, direct photon described by pQCD—include new result for low p_T region

- Helicity asymmetries: sensitivity to gluon spin contribution to proton
- Photon+jet: gluon pol. vs. x_gluon

- W boson parity violating production: ubar and dbar polarizations in proton

----

- Very large transverse spin asymmetries in pQCD region

- Future: transverse spin Drell-Yan

RHIC Spin Outline

The key points for RHIC Spin are:

- Spin structure of proton
- Strongly interacting probes

- P=60%, L=2x10^31, root(s)=200 GeV in 2006
- Polarized atomic H jet: absolute P, pp elastic physics
- Very forward n asymmetry

- Cross sections for pi^0, jet, direct photon described by pQCD—include new result for low p_T region

- Helicity asymmetries: sensitivity to gluon spin contribution to proton
- Photon+jet: gluon pol. vs. x_gluon

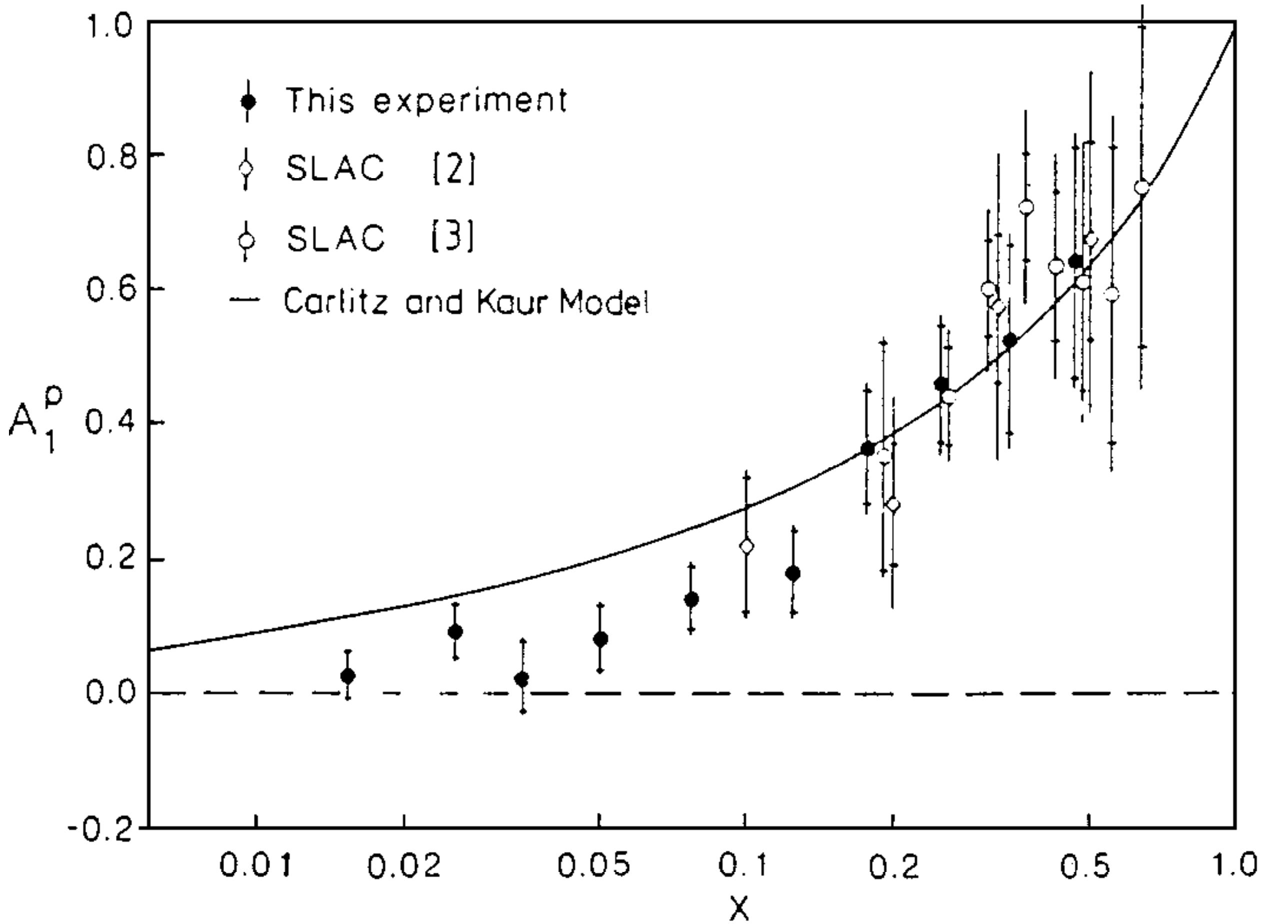
- W boson parity violating production: ubar and dbar polarizations in proton

----

- Very large transverse spin asymmetries in pQCD region

- Future: transverse spin Drell-Yan

EMC at CERN: J. Ashman et al., NPB 328, 1 (1989):
polarized muons probing polarized protons



$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"proton spin crisis"

- **What else carries the proton spin ?**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$\rightarrow$ **How are gluons polarized ?**
$\rightarrow$ **How large are parton orbital angular mom. ?**

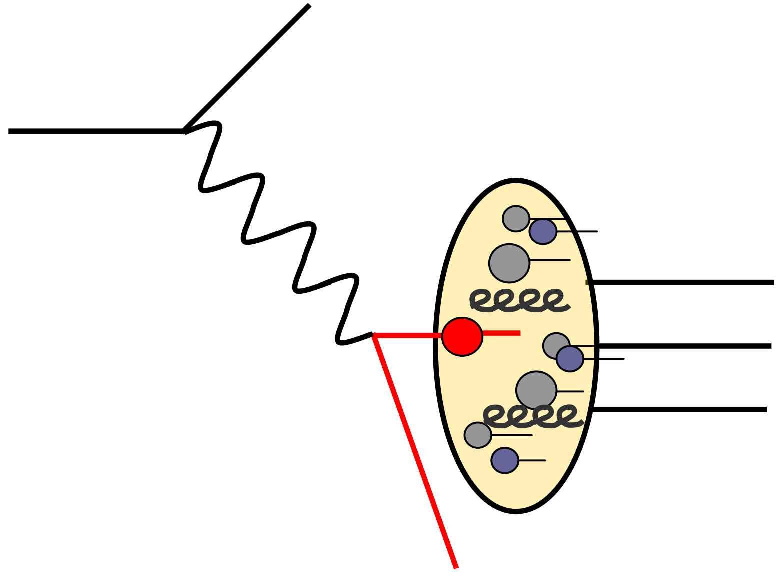
- **What are the detailed patterns of quark & antiquark polarizations ?**

$\rightarrow$ **Flavor asymmetries in sea ? Strangeness ?**

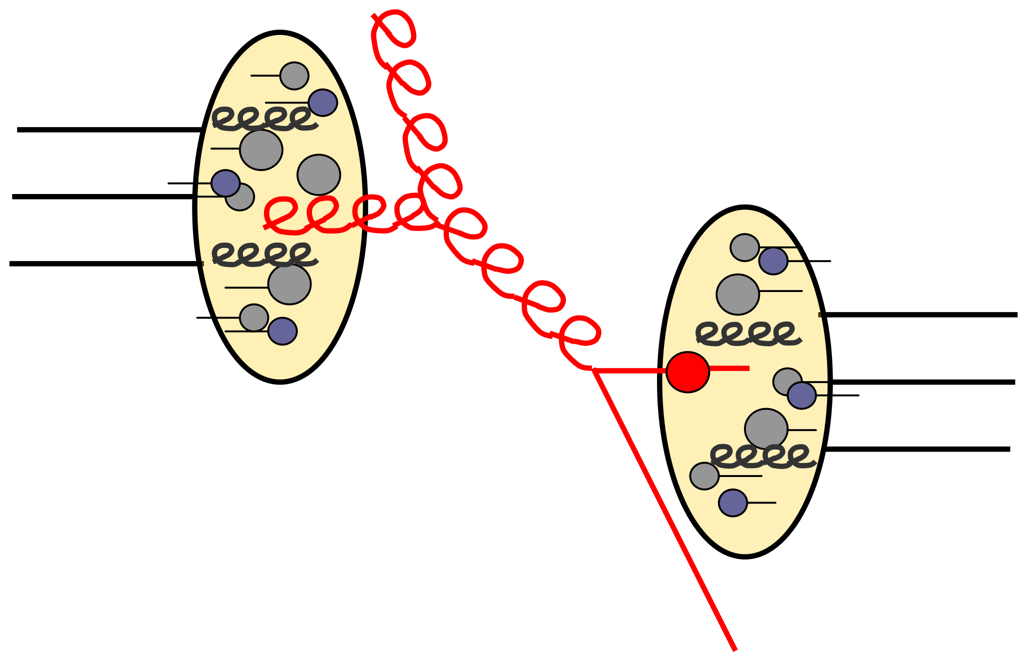
- **What are the origins of large observed single-transverse-spin asymmetries ? What do they tell us about the nucleon ?**

$\rightarrow$ **Transverse quark pol.? Correlations spin / parton k_T ? Orbital angular momentum? Spatial distributions?**

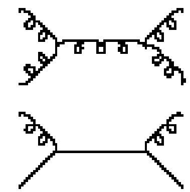
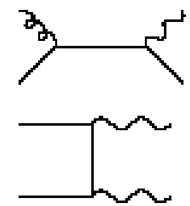
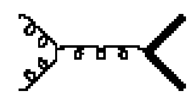
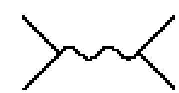
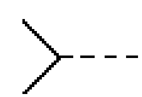
DIS



pp



Probing the spin structure of the nucleon in polarized pp collisions

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm,\ q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

RHIC Spin Outline

The key points for RHIC Spin are:

- **Spin structure of proton**
- **Strongly interacting probes**

- **P=60%, L=2x10^31, root(s)=200 GeV in 2006**
- **Polarized atomic H jet: absolute P, pp elastic physics**
- **Very forward n asymmetry**

- **Cross sections for pi^0, jet, direct photon described by pQCD—include new result for low p_T region**

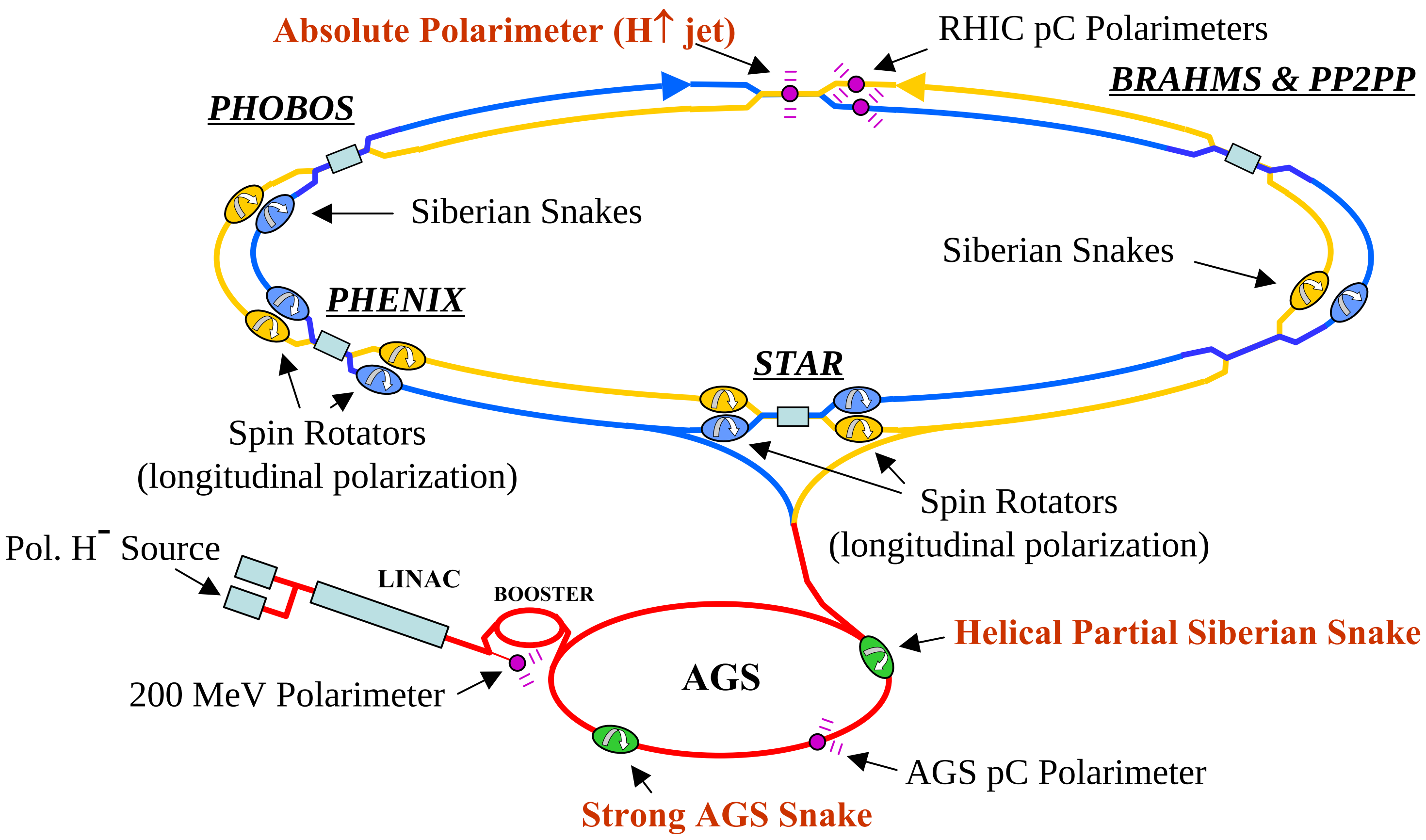
- **Helicity asymmetries: sensitivity to gluon spin contribution to proton**
- **Photon+jet: gluon pol. vs. x_gluon**

- **W boson parity violating production: ubar and dbar polarizations in proton**

- **Very large transverse spin asymmetries in pQCD region**

- **Future: transverse spin Drell-Yan**

RHIC Polarized Collider

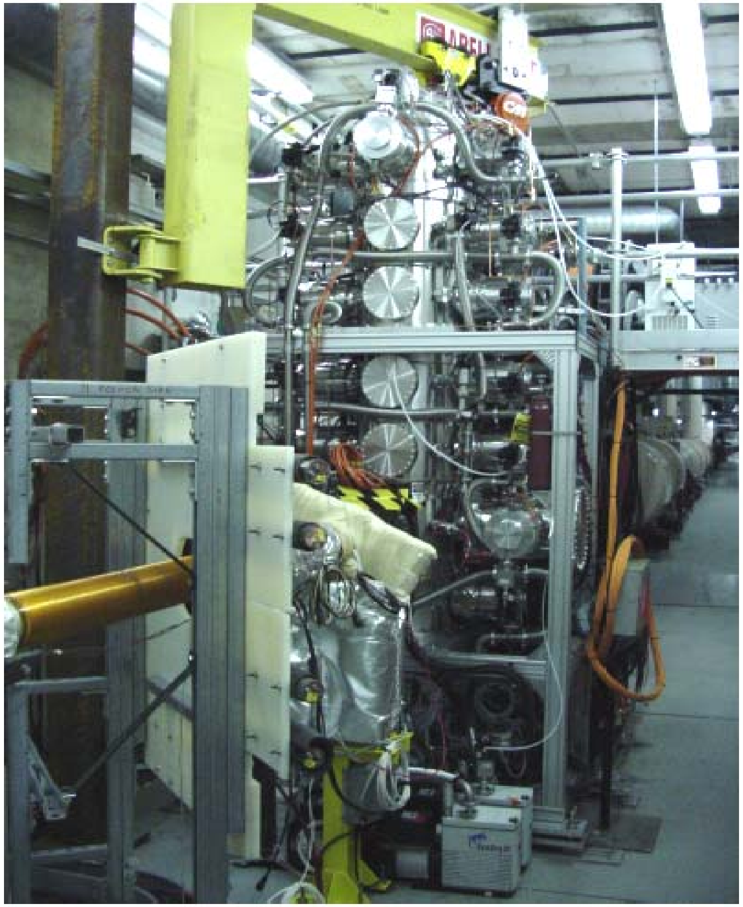
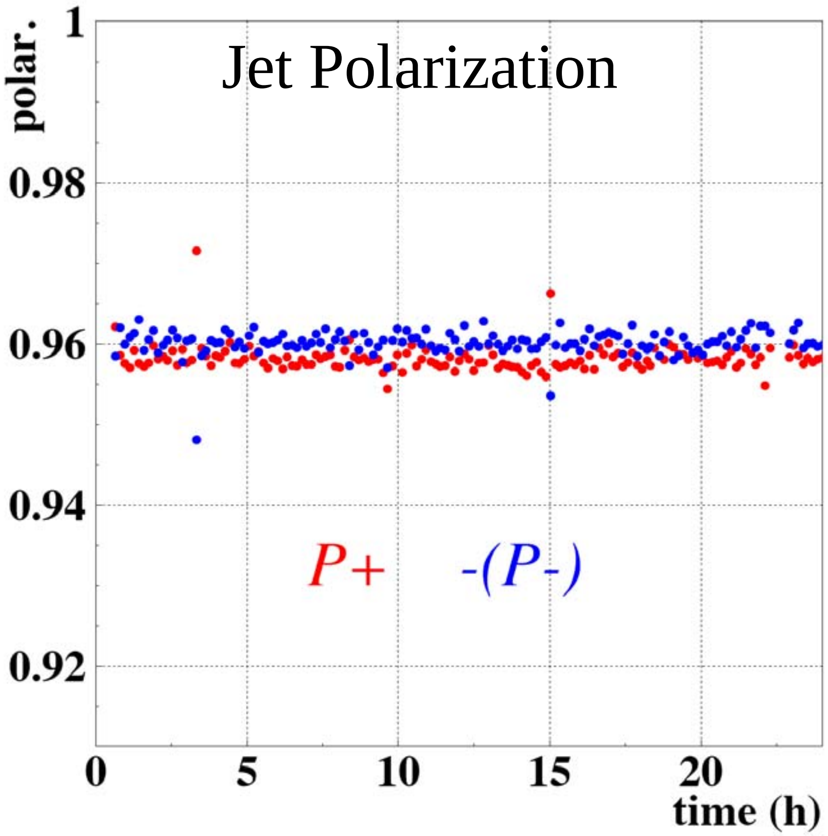


2006: 1 MHz collision rate; P=0.6

RHIC Spin Runs

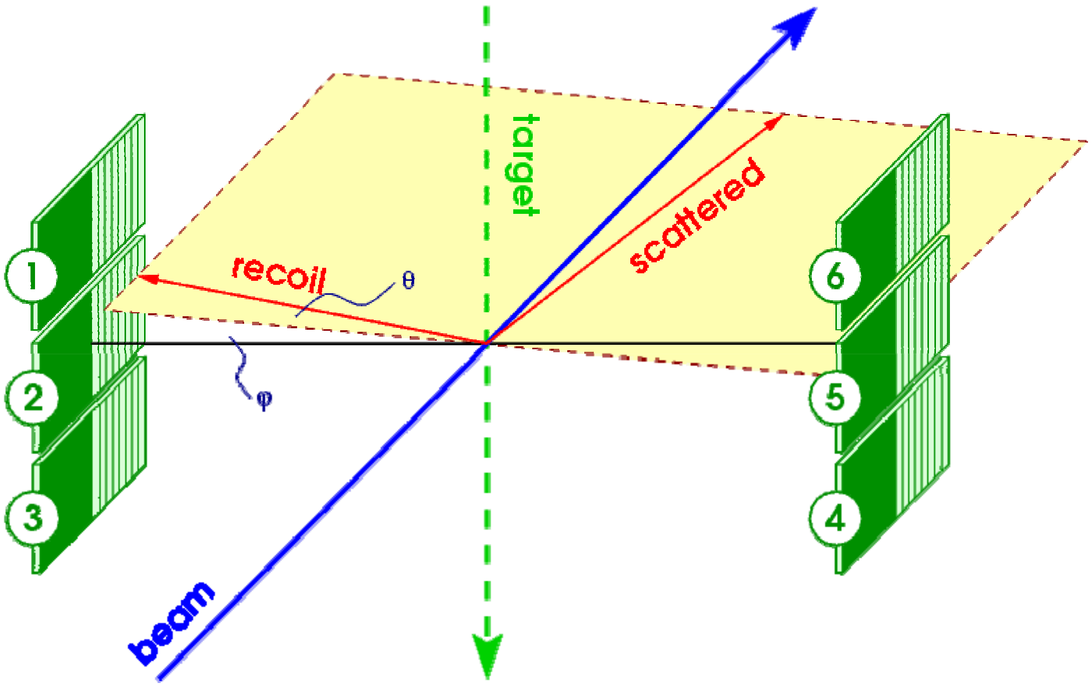
	P	L(pb^-1)	Results
2002	15%	0.15	first pol. pp collisions! disc. large n asymmetry
2003	30%	1.6	pi^0, photon cross section, A_LL(pi^0), 3 PRLs
2004	40%	3.0	polarized hydrogen jet, PLB
2005	50% (P^4 x L = 0.8)	13	warm snake (RIKEN); large gluon pol. ruled out
2006	60% (P^4 x L = 6)	46	cold snake; first long spin run (prelim. to Kyoto)

RHIC Polarimetry

-  

$$P_{Beam} = P_{Jet} \times \frac{\epsilon_{Beam}}{\epsilon_{Jet}} \text{ where } \epsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$$

Recoil Silicon Strip Spectrometer



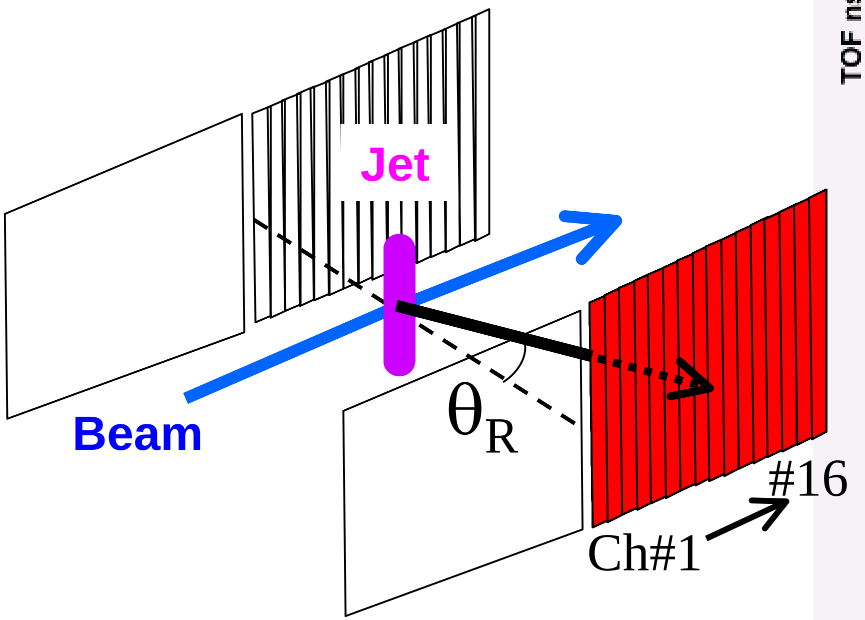
For p-p elastic scattering only:

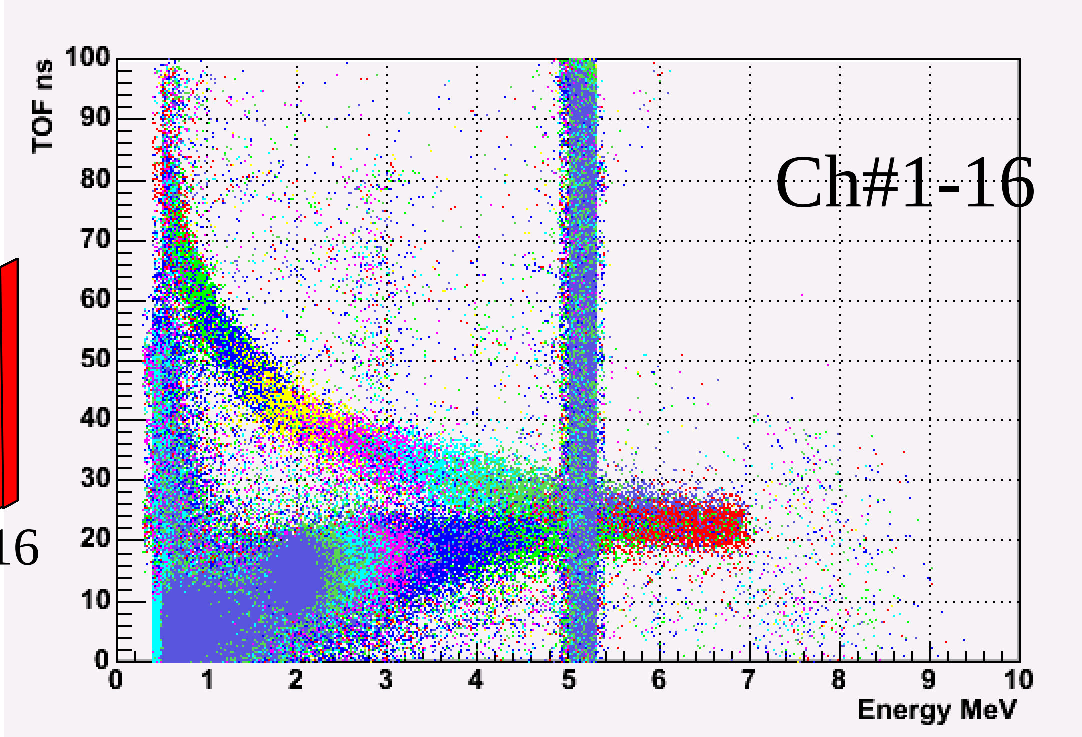
$$\varepsilon = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

$$\varepsilon_{beam} = A_N \cdot P_{beam}$$

$$\varepsilon_{target} = -A_N \cdot P_{target}$$

$$P_{beam} = -\frac{\varepsilon_{beam}}{\varepsilon_{target}} \cdot P_{target}$$

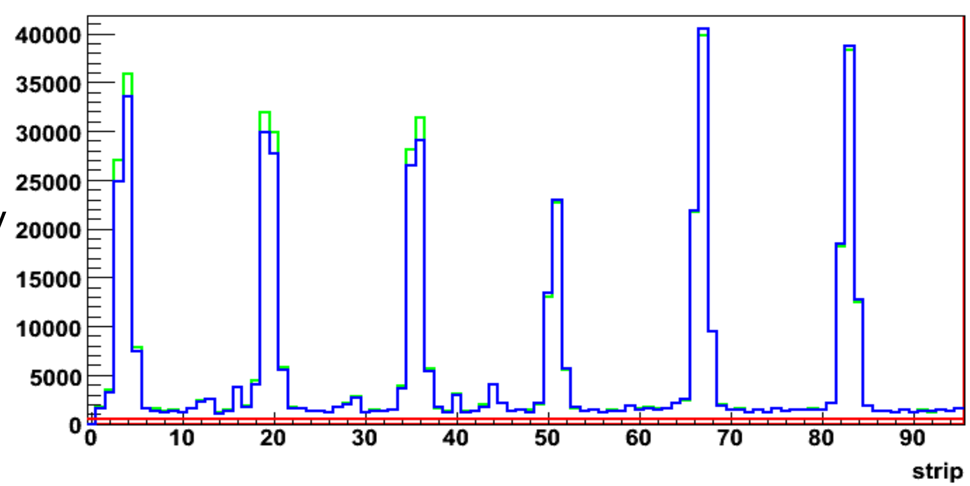




Example of background for one recoil energy slice:

Yield
(**up** / **down**)

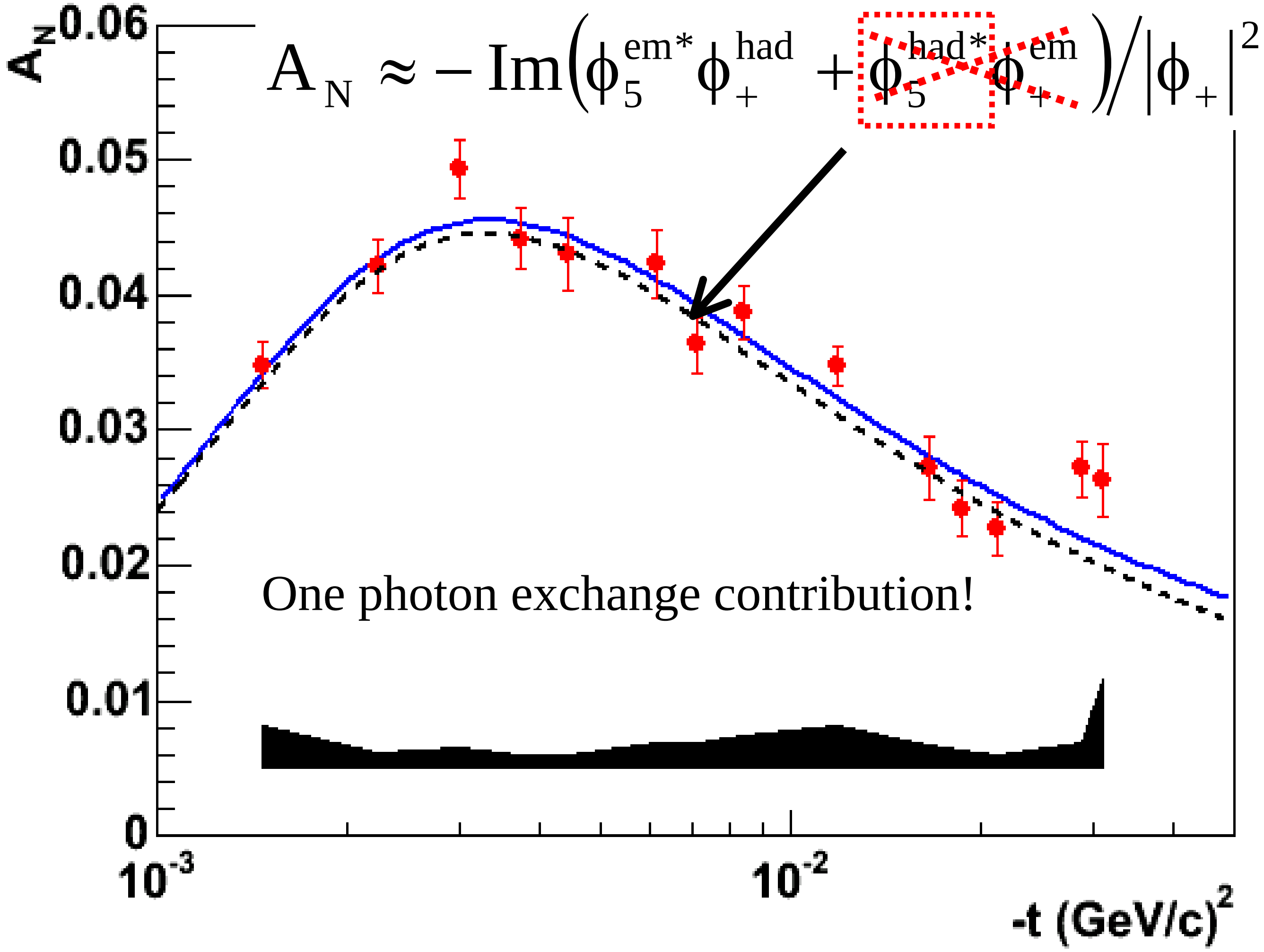
E= 1.0–1.5 MeV



Strip number (6 detectors)

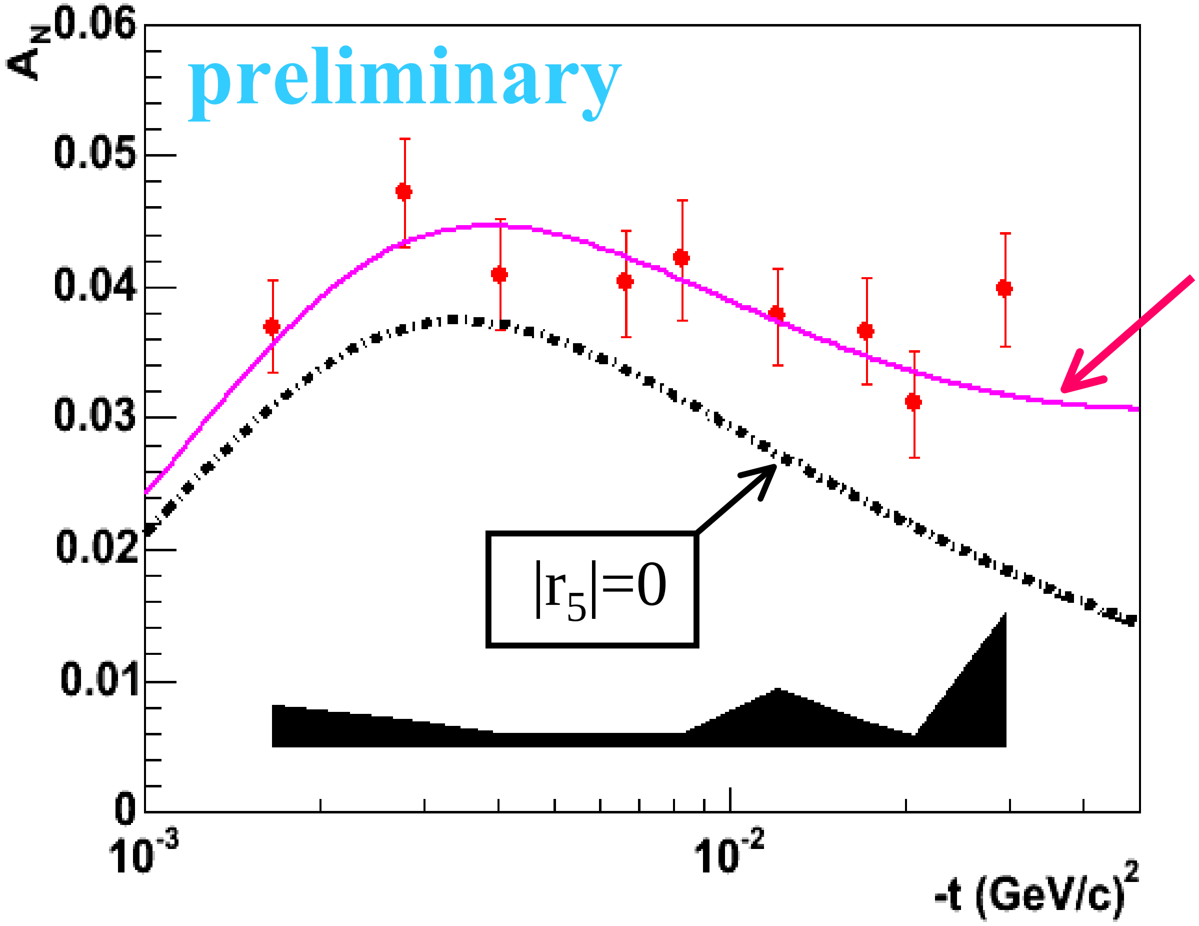
A_N in the CNI region @ $\sqrt{s}$=13.7 GeV

2004 Data



H. Okada et al., PLB 638 (2006), 450-454

A_N and r_5 results at √s= 6.9 GeV

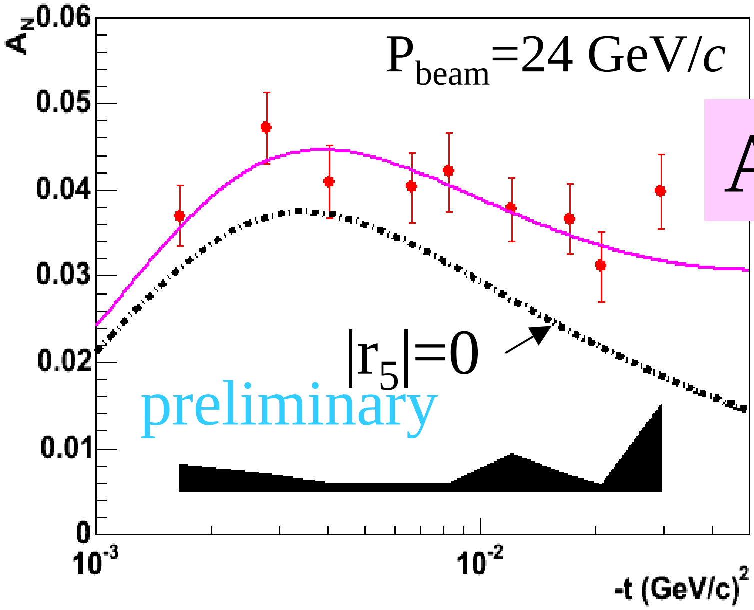


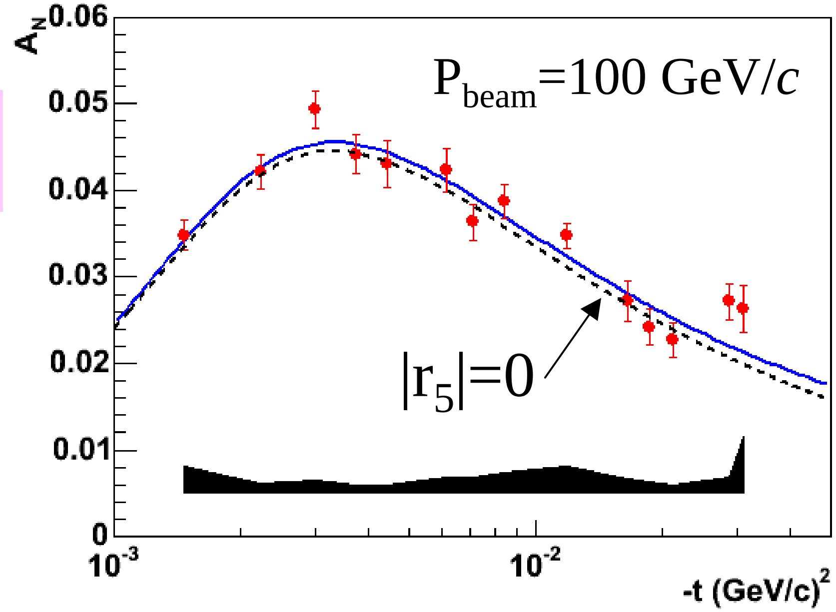
Set r_5 as free parameter
→ Im r5 = –0.152 ± 0.014
→ Re r5 = –0.045 ± 0.038
→ χ^2/ndf = 2.87/7

$$r_5 = \frac{m_p \phi_5^{had}}{\sqrt{-t}\,\mathrm{Im}\,\phi_+^{had}}$$

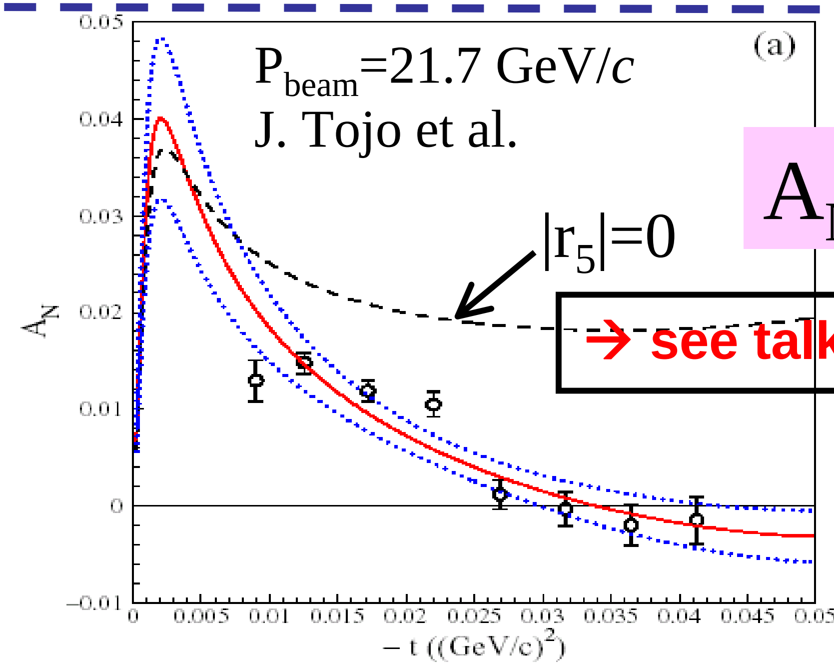
- r_5 is not zero at √s=6.9 GeV ! χ^2/ndf = 35.5/9
- r_5 has √s dependence ? → Not improbable; theoretical prediction using A_N^{pC} @24GeV/*c*, 100GeV/*c* and A_N @100GeV/*c*.

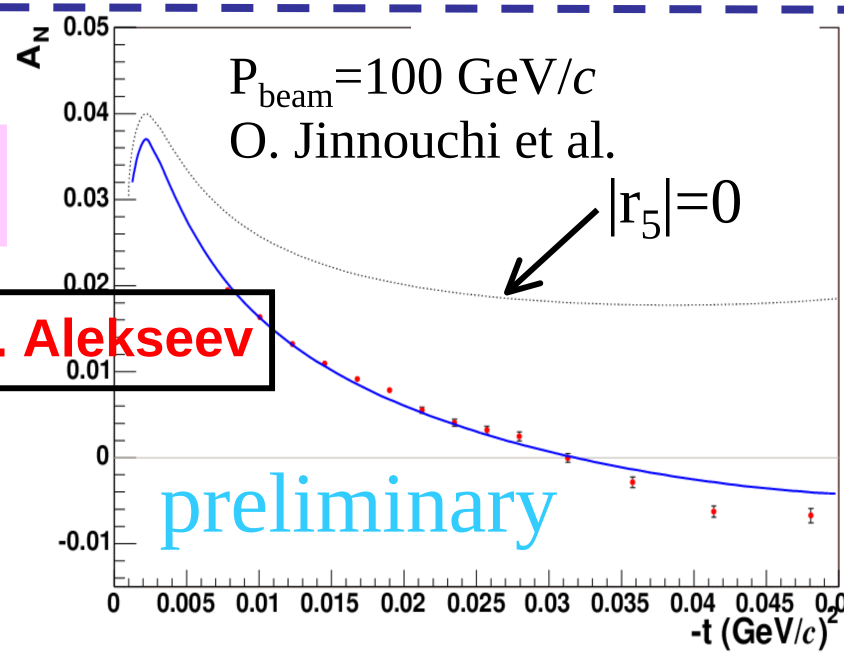
A_N collection in the CNI region





A_N^{pp}

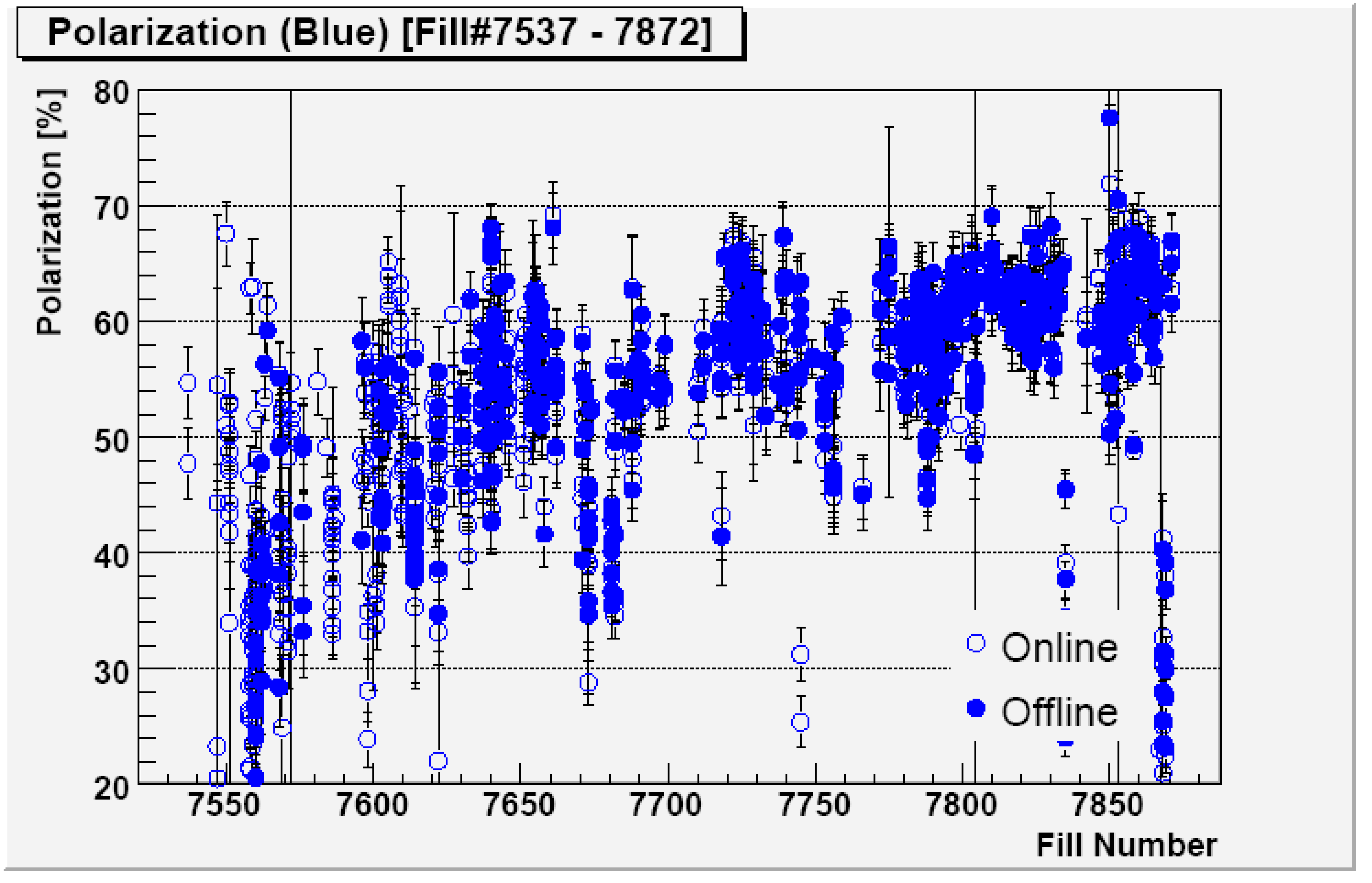




A_N^{pC}

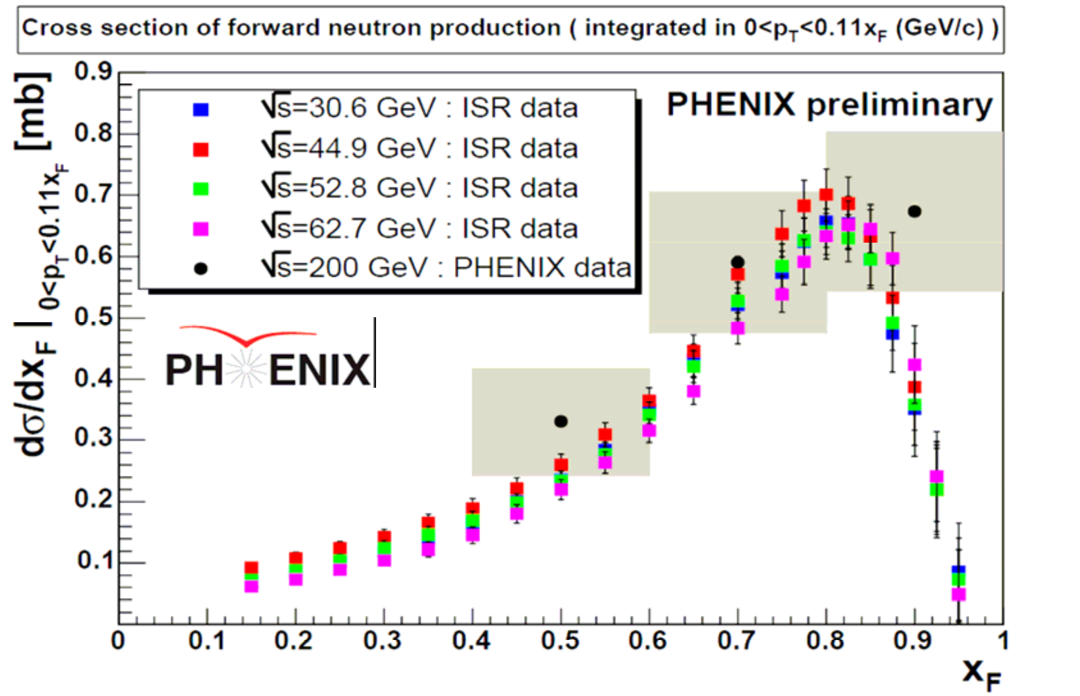
→ see talk by I. Alekseev

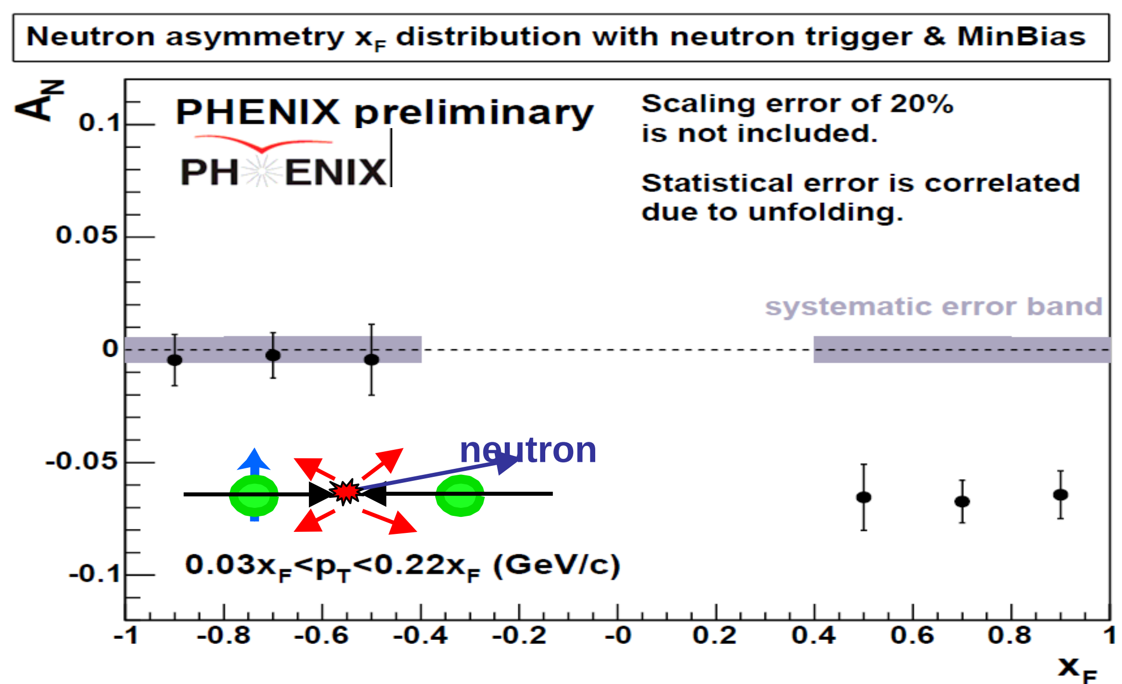
Polarization Measurements
2006 Run



Very forward neutron asymmetry from p-p collisions at RHIC-PHENIX

Manabu Togawa (Kyoto Spin06)





RHIC Spin Outline

The key points for RHIC Spin are:

- **Spin structure of proton**
- **Strongly interacting probes**

- **P=60%, L=2x10^31, root(s)=200 GeV in 2006**
- **Polarized atomic H jet: absolute P, pp elastic physics**
- **Very forward n asymmetry**

- **Cross sections for pi^0, jet, direct photon described by pQCD—include new result for low p_T region**

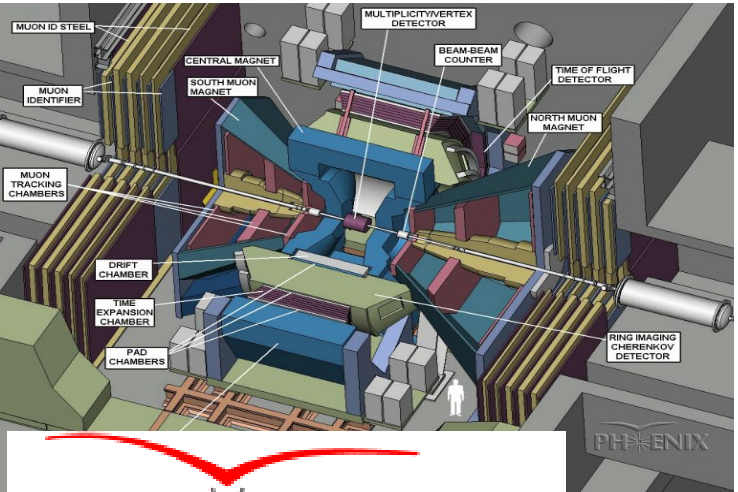
- **Helicity asymmetries: sensitivity to gluon spin contribution to proton**
- **Photon+jet: gluon pol. vs. x_gluon**

- **W boson parity violating production: ubar and dbar polarizations in proton**

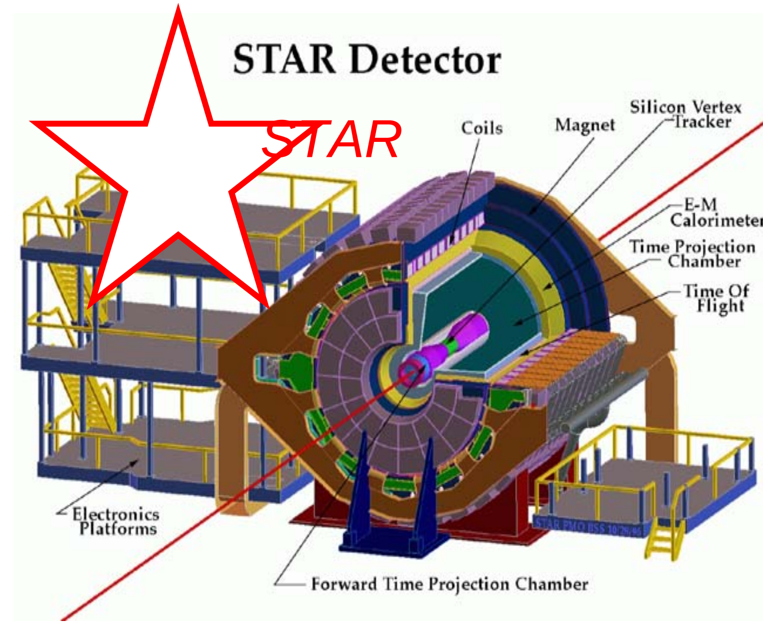
- **Very large transverse spin asymmetries in pQCD region**

- **Future: transverse spin Drell-Yan**

PHENIX and STAR



PHENIX:
High rate capability
High granularity
Good mass resolution and PID
Limited acceptance

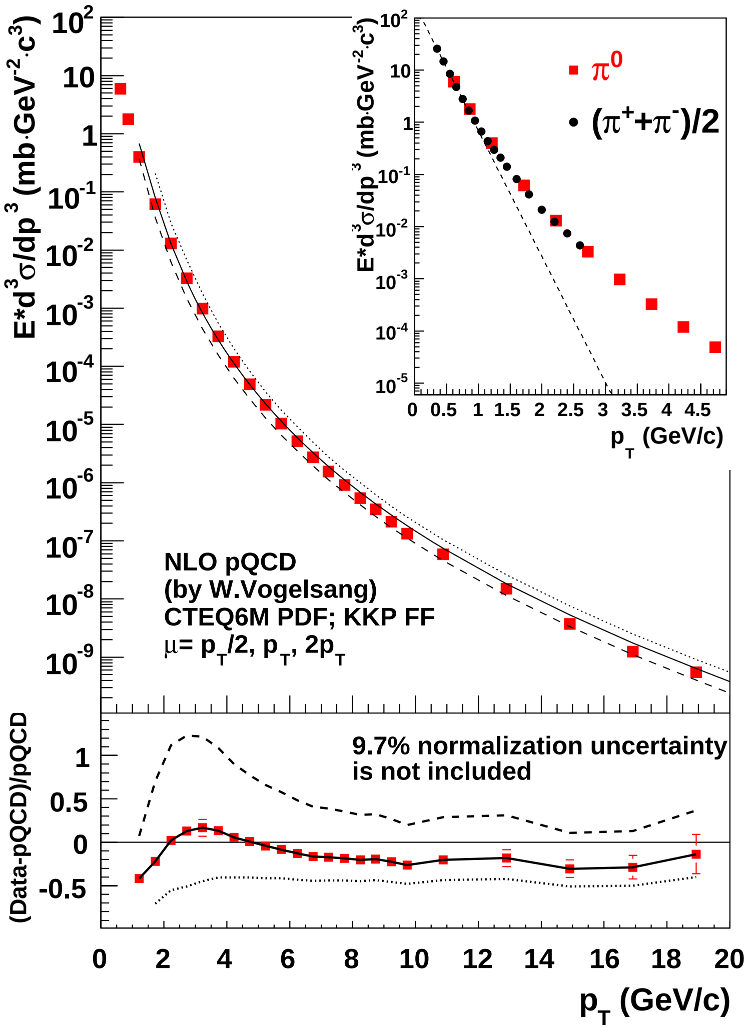


STAR:
Large acceptance with azimuthal symmetry
Good tracking and PID
Central and forward calorimetry

Cornerstones to the RHIC Spin program

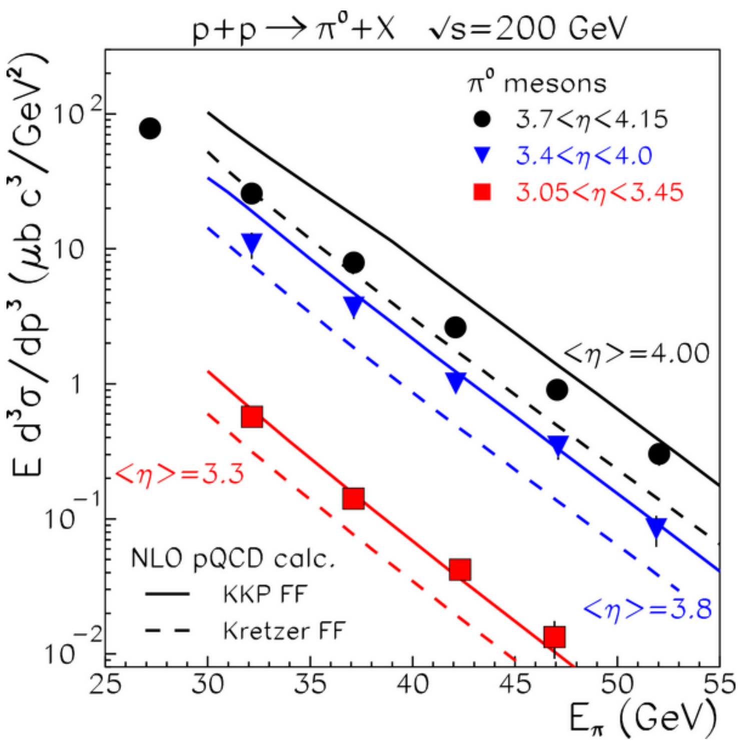
Mid-rapidity: PHENIX

$pp \rightarrow \pi^0 X$



To appear PR**D** Rapid, hep-ex-0704.3599

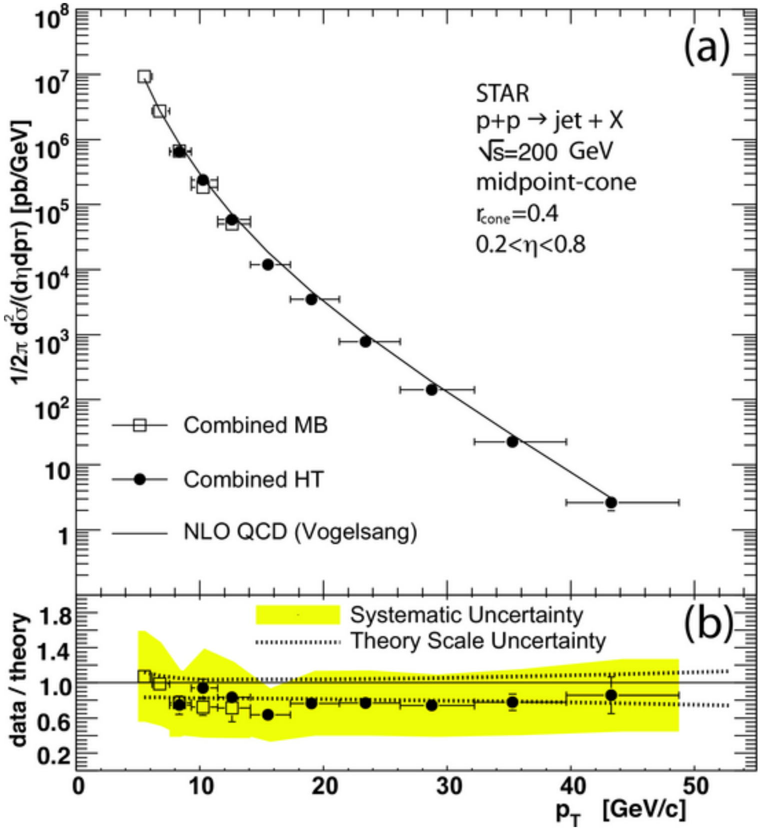
Forward: STAR



PRL **97**, 152302 (2006)

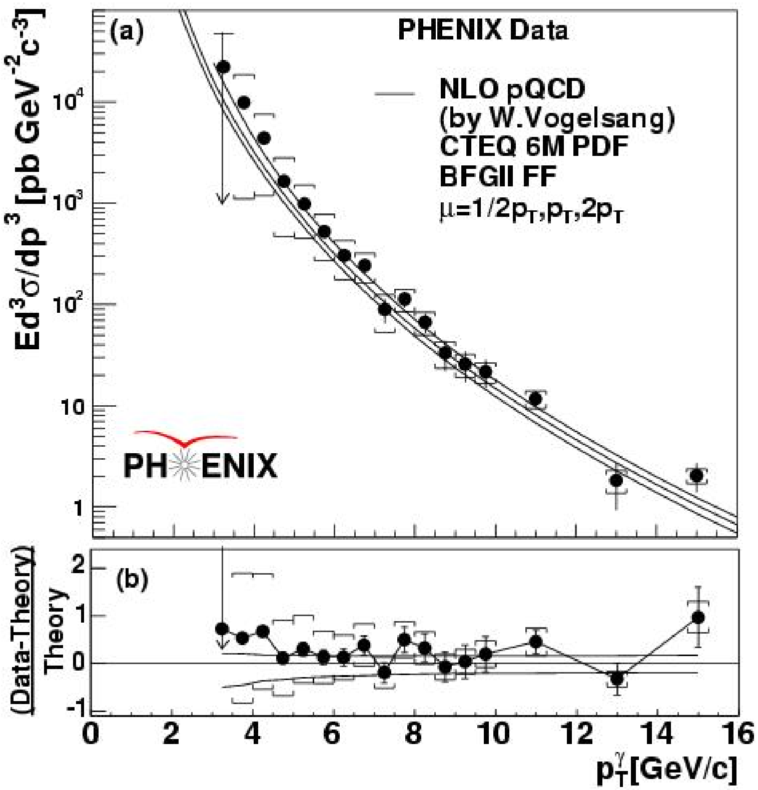
And Jets and Direct γ

pp → jet X : STAR



PRL 97, 252001 (2006)

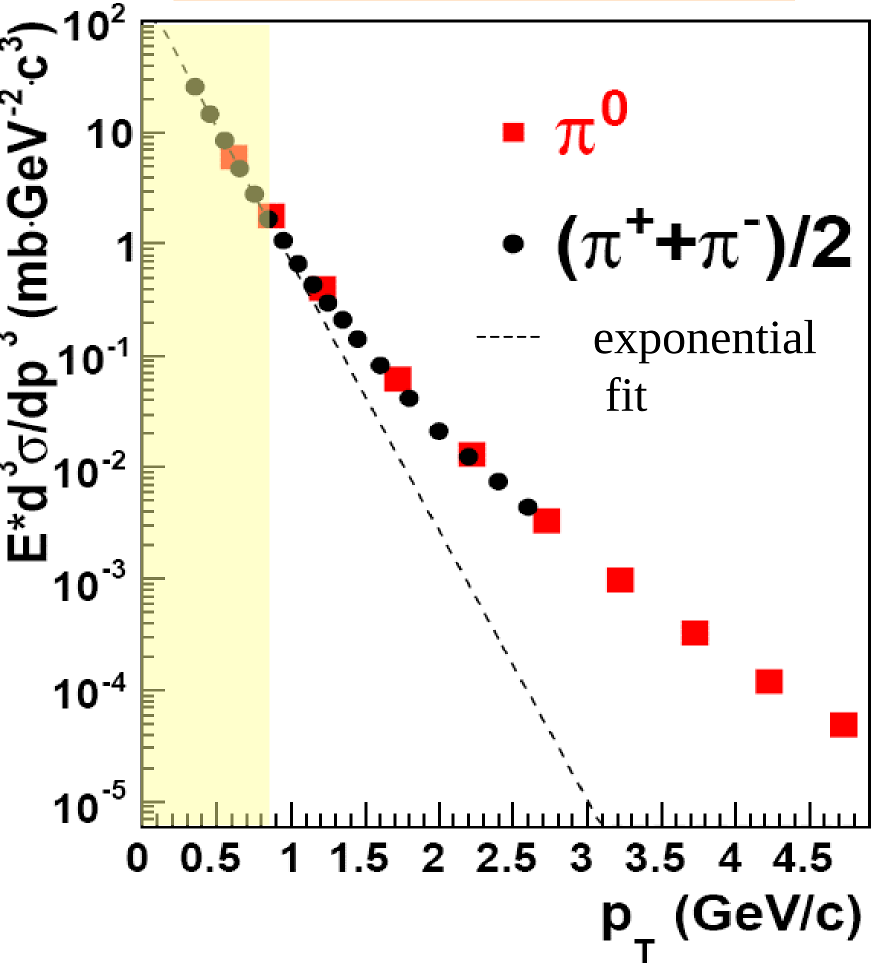
pp → γ X : PHENIX



PRL 98, 012002 (2007)

From soft to hard

PHENIX: hep-ex-0704.3599



Exponent ($e^{-\alpha \cdot pT}$) describes our pion cross section data perfectly well at p_T<~1 GeV/c (dominated by soft physics):

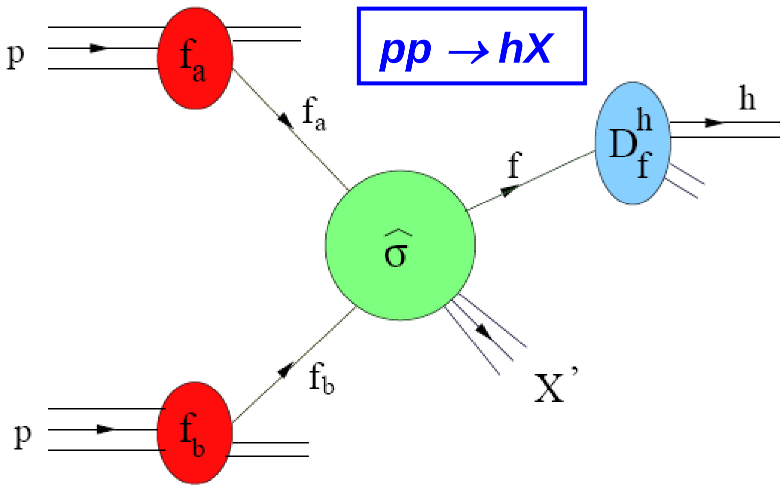
α=5.56±0.02 (GeV/c)$^{-1}$

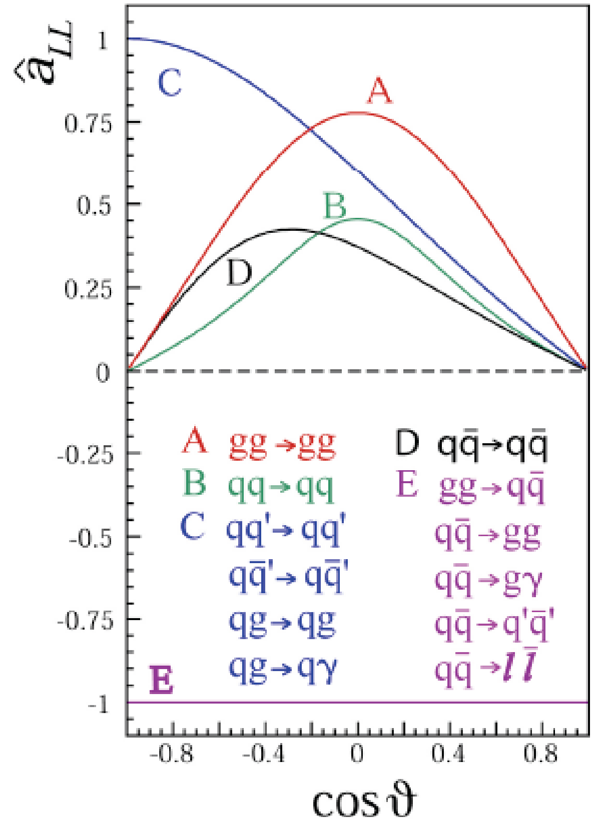
χ^2/NDF=6.2/3

Assume that exponent describes soft physics contribution also at higher pTs ⇒ soft physics contribution at pT>2 GeV/c is <10%

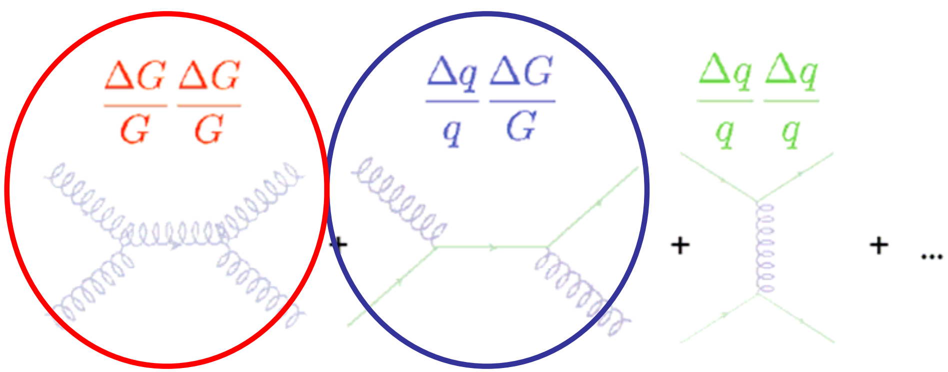
For ΔG constraint use pi0 A_{LL} data at pT>2 GeV/c

Probing ΔG in pp Collisions





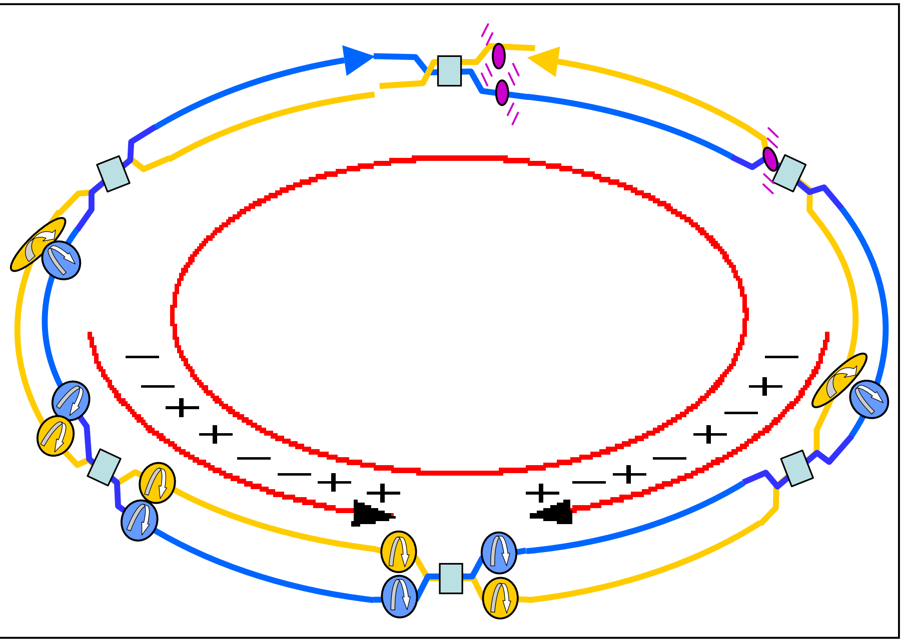
$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$



Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$



(N) Yield

(R) Relative Luminosity

- ✓ BBC vs ZDC

(P) Polarization

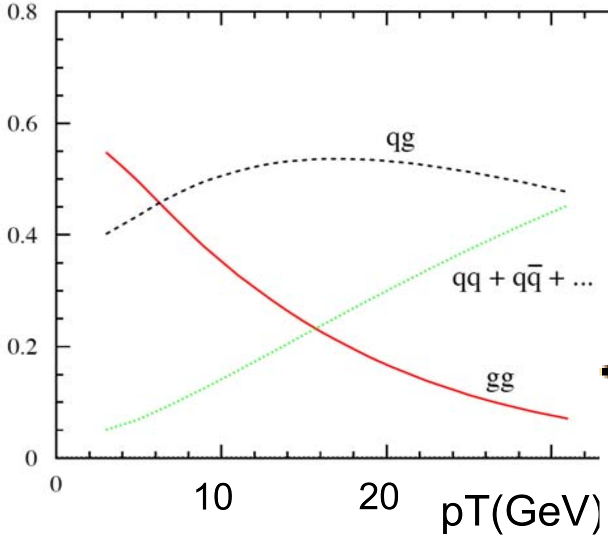
- ✓ RHIC Polarimeter (at 12 o'clock)
- ✓ Local Polarimeters (SMD&ZDC in PHENIX and BBC in STAR)

✓ Bunch spin configuration alternates every 106 ns

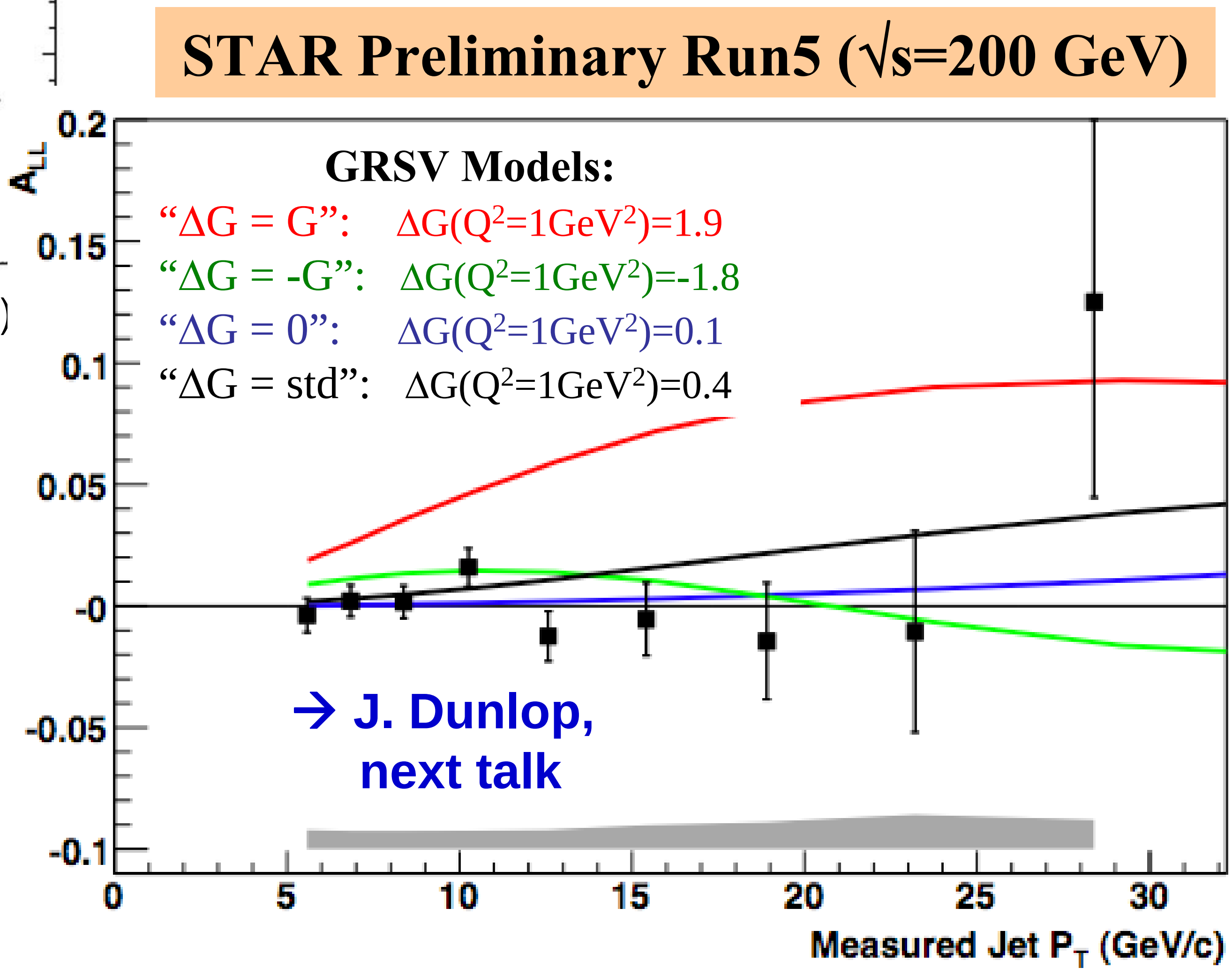
✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries are greatly reduced

A_{LL}: jets

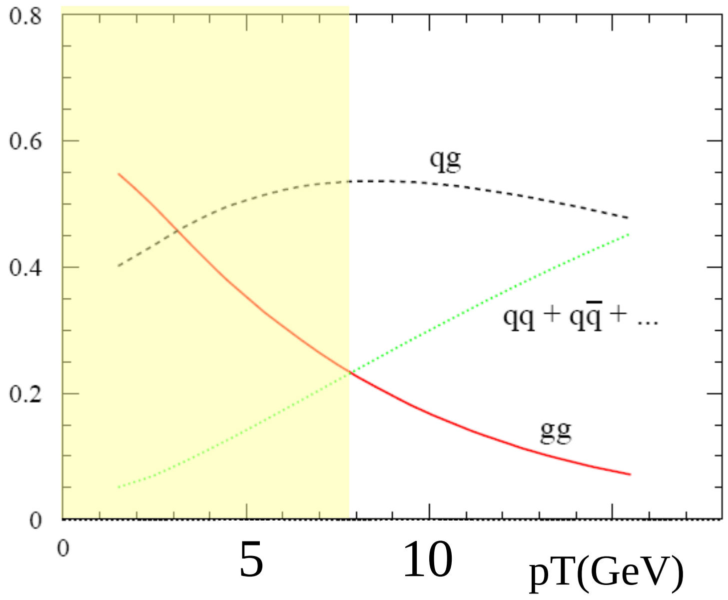


Large gluon polarization scenario is not consistent with data

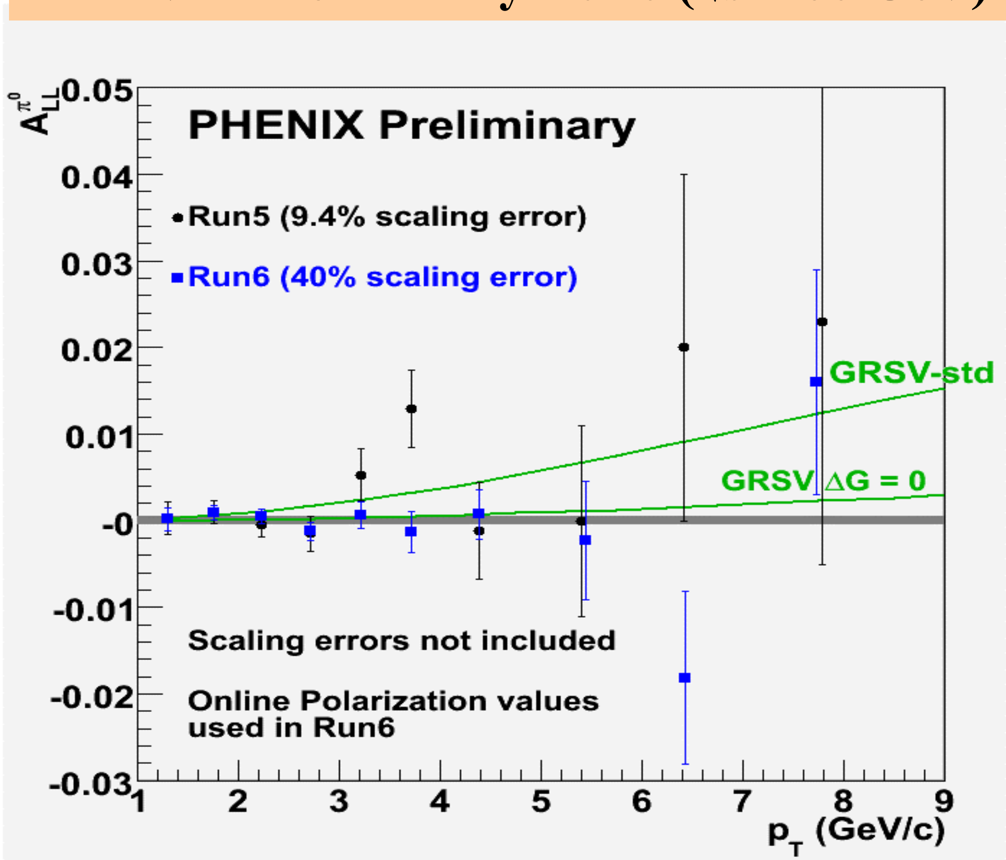


Run3&4: PRL 97, 252001

A_{LL}: π0



PHENIX Preliminary Run6 (√s=200 GeV)



GRSV model:

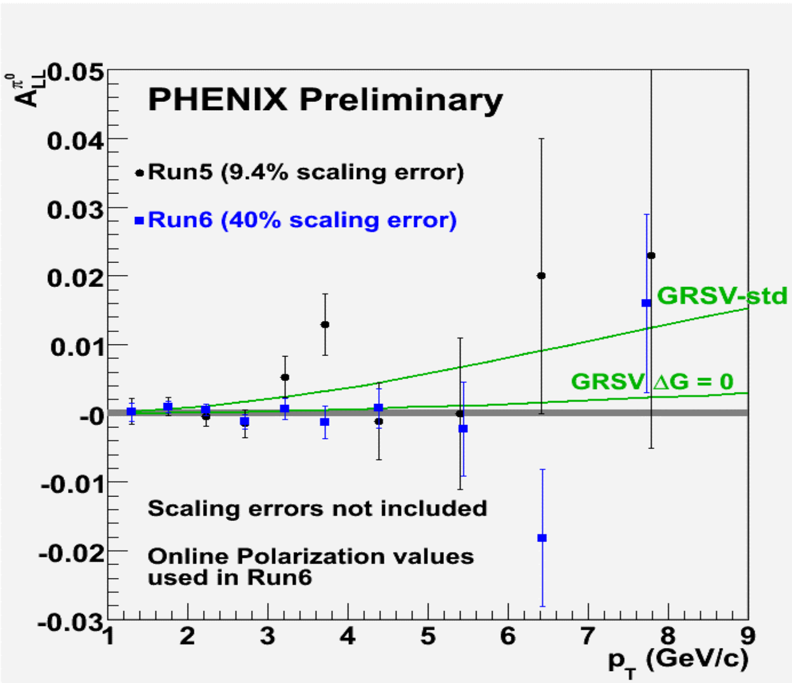
"ΔG = 0": $\Delta G(Q^2=1GeV^2)=0.1$

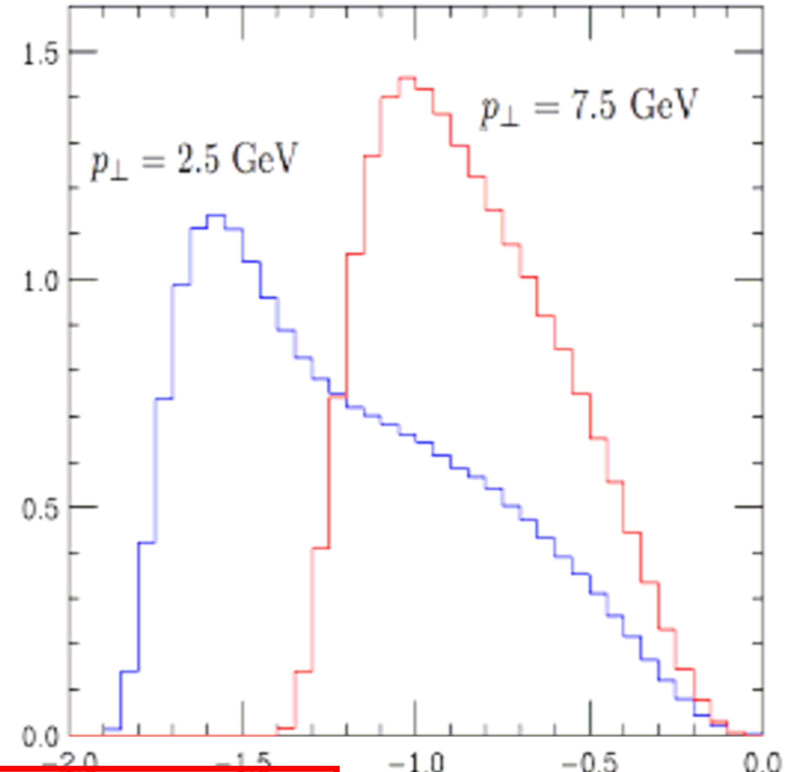
"ΔG = std": $\Delta G(Q^2=1GeV^2)=0.4$

Stat. uncertainties are on level to distinguish "std" and "0" scenarios? …

Run3,4,5: PRL 93, 202002; PRD 73, 091102; hep-ex-0704.3599

From p_T to x_{gluon}





$Log_{10}(x_{gluon})$

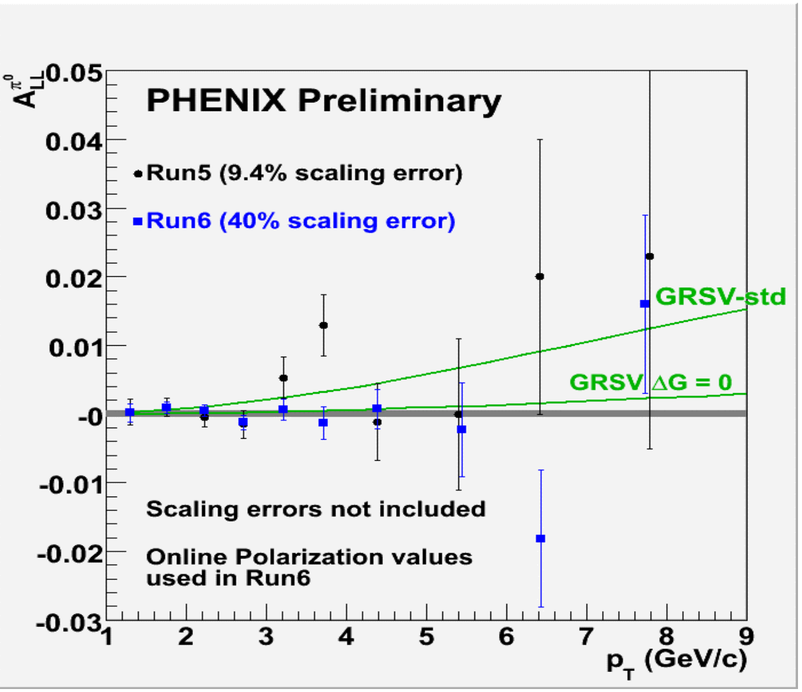
NLO pQCD: π^0 p_T=2–9 GeV/c → x_{gluon}=0.02–0.3

- ✓ GRSV model: $\Delta G(x_{gluon}=0.02\rightarrow0.3) \sim 0.6\cdot\Delta G(x_{gluon}=0\rightarrow1)$

Each p_T bin corresponds to a wide range in x_{gluon}, heavily overlapping with other p_T bins

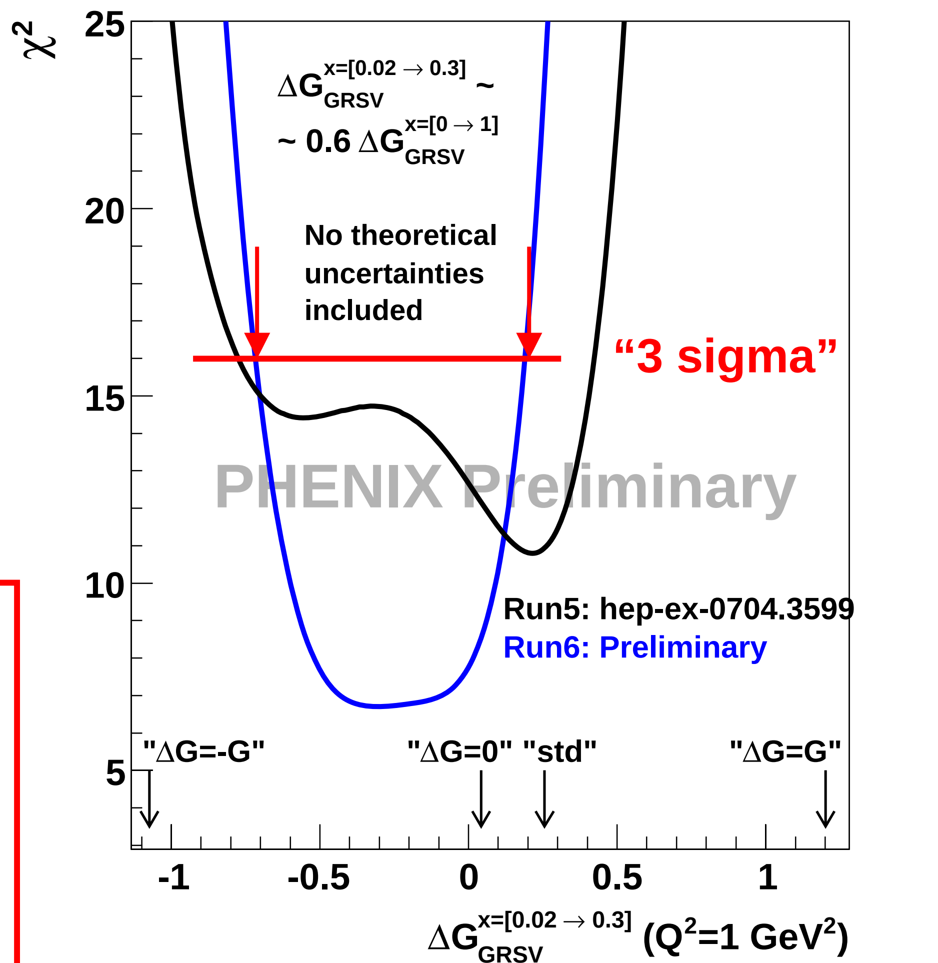
- ✓ These data is not much sensitive to variation of $\Delta G(x_{gluon})$ within our x range
- ✓ Any quantitative analysis should assume some $\Delta G(x_{gluon})$ shape

From A_{LL} to ΔG (with GRSV)



⇒

Calc. by W.Vogelsang and M.Stratmann

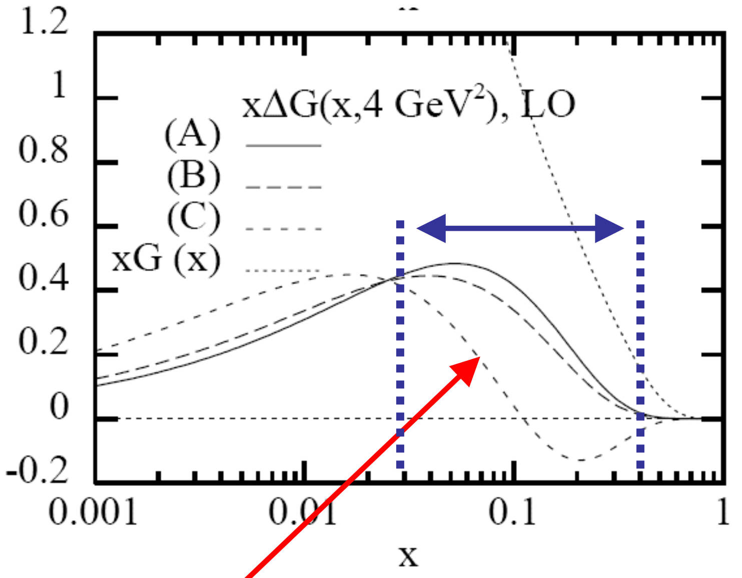


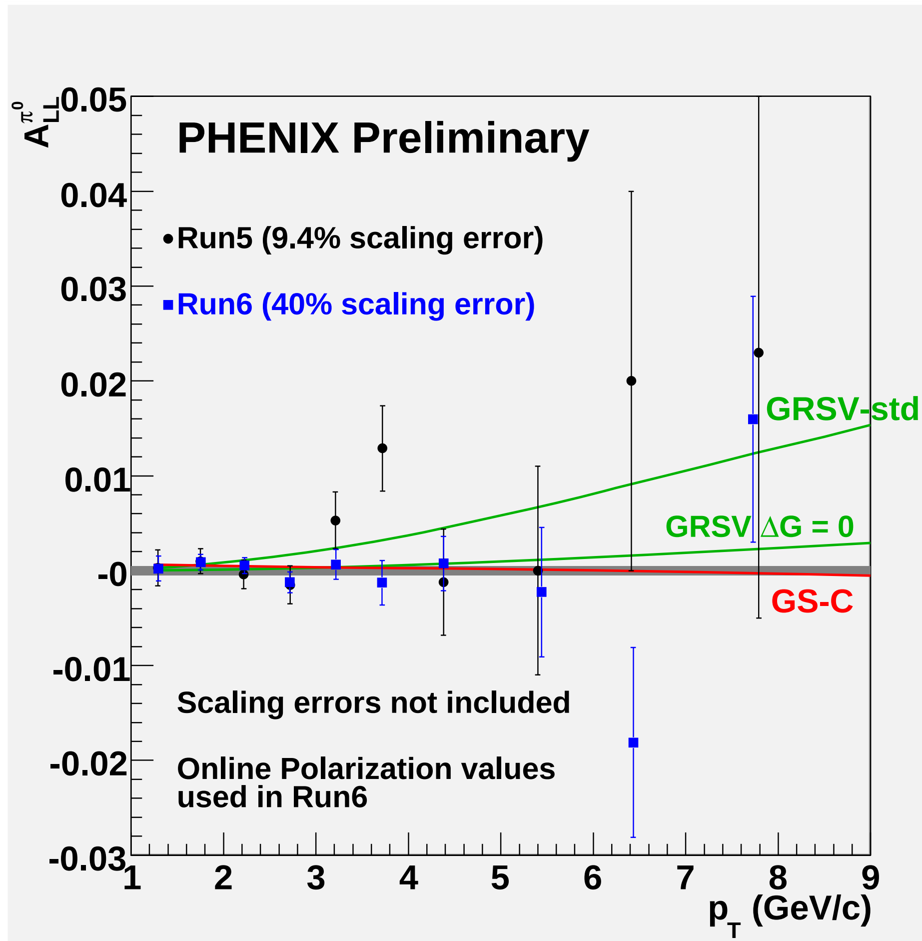
"std" scenario, $\Delta G(Q^2=1GeV^2)=0.4$, is excluded by data on >3 sigma level: $\chi^2(\text{std})-\chi^2_{min}>9$

- ✓ Only exp. stat. uncertainties are included (the effect of syst. uncertainties is expected to be small in the final results)
- ✓ Theoretical uncertainties are not included

Extending x range is crucial!

Gehrmann-Stirling models





GSC: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 1$

$\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0$

GRSV-0: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 0$

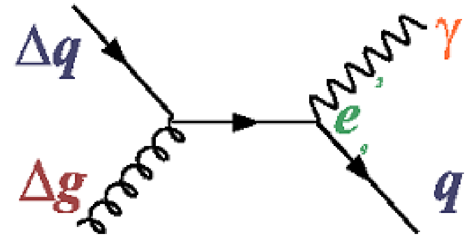
$\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0$

GRSV-std: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 0.4$

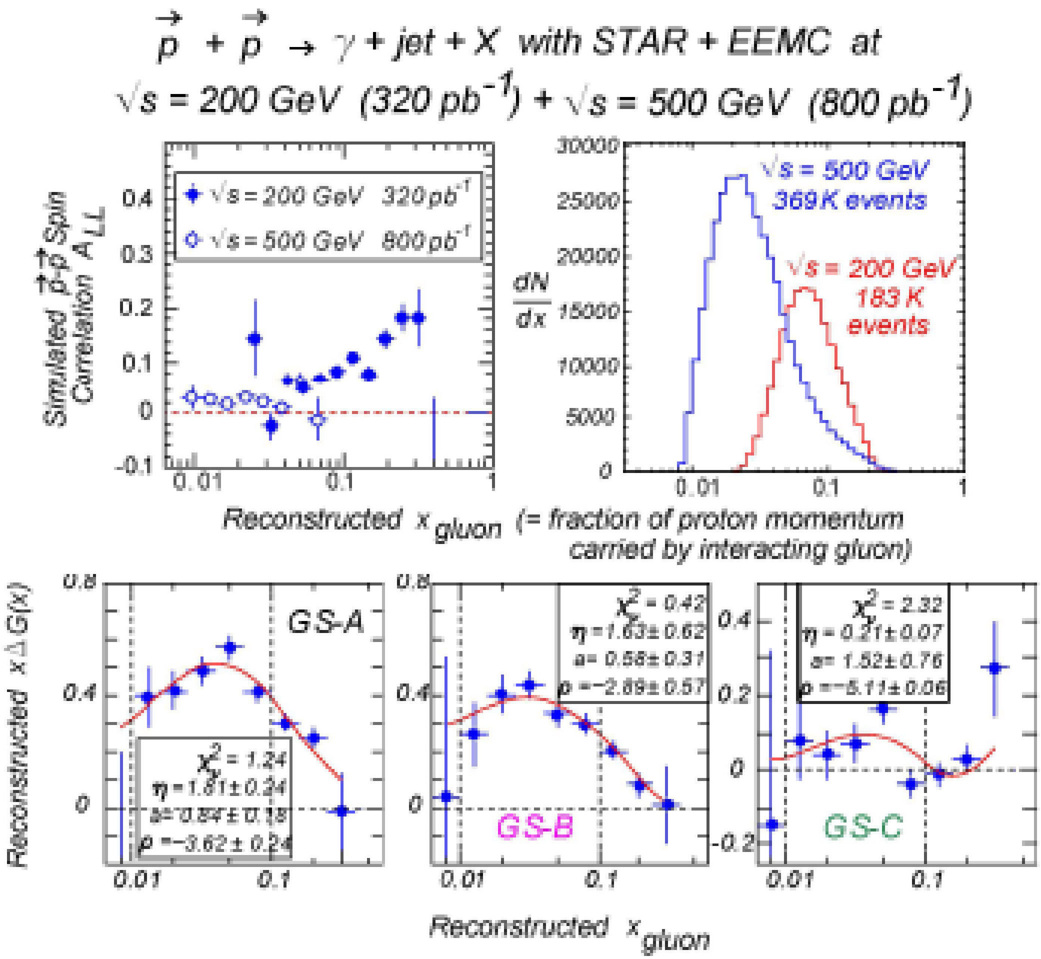
$\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0.25$

Current data is sensitive to ΔG for $x_{gluon} = 0.02 \rightarrow 0.3$

$pp \rightarrow \gamma + \text{jet}$



Simulation for STAR by Les Bland



Parton kinematics is well constrained, event-by-event

Lower x data provided by √s=500 GeV data is essential for reducing extrapolation (to lower x) errors

→ see next talk, J. Dunlop

RHIC Spin Outline

The key points for RHIC Spin are:

- Spin structure of proton
- Strongly interacting probes

- P=60%, L=2x10^31, root(s)=200 GeV in 2006
- Polarized atomic H jet: absolute P, pp elastic physics
- Very forward n asymmetry

- Cross sections for pi^0, jet, direct photon described by pQCD—include new result for low p_T region

- Helicity asymmetries: sensitivity to gluon spin contribution to proton
- Photon+jet: gluon pol. vs. x_gluon

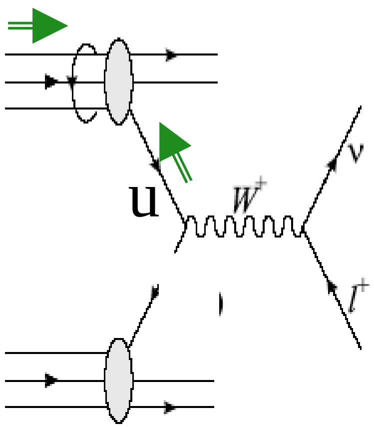
- W boson parity violating production: ubar and dbar polarizations in proton

----

- Very large transverse spin asymmetries in pQCD region

- Future: transverse spin Drell-Yan

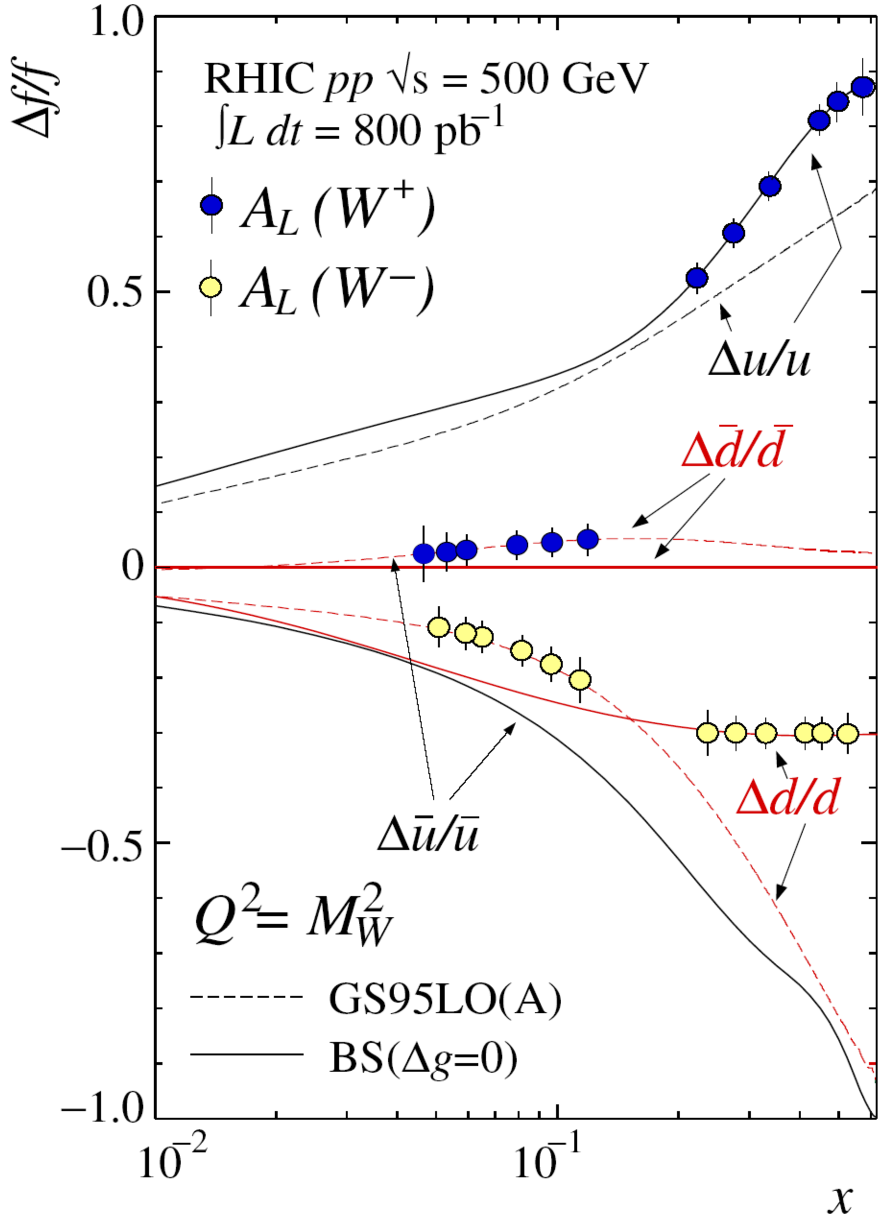
Δq-$\overline{\Delta q}$ at RHIC via W production



unpol.

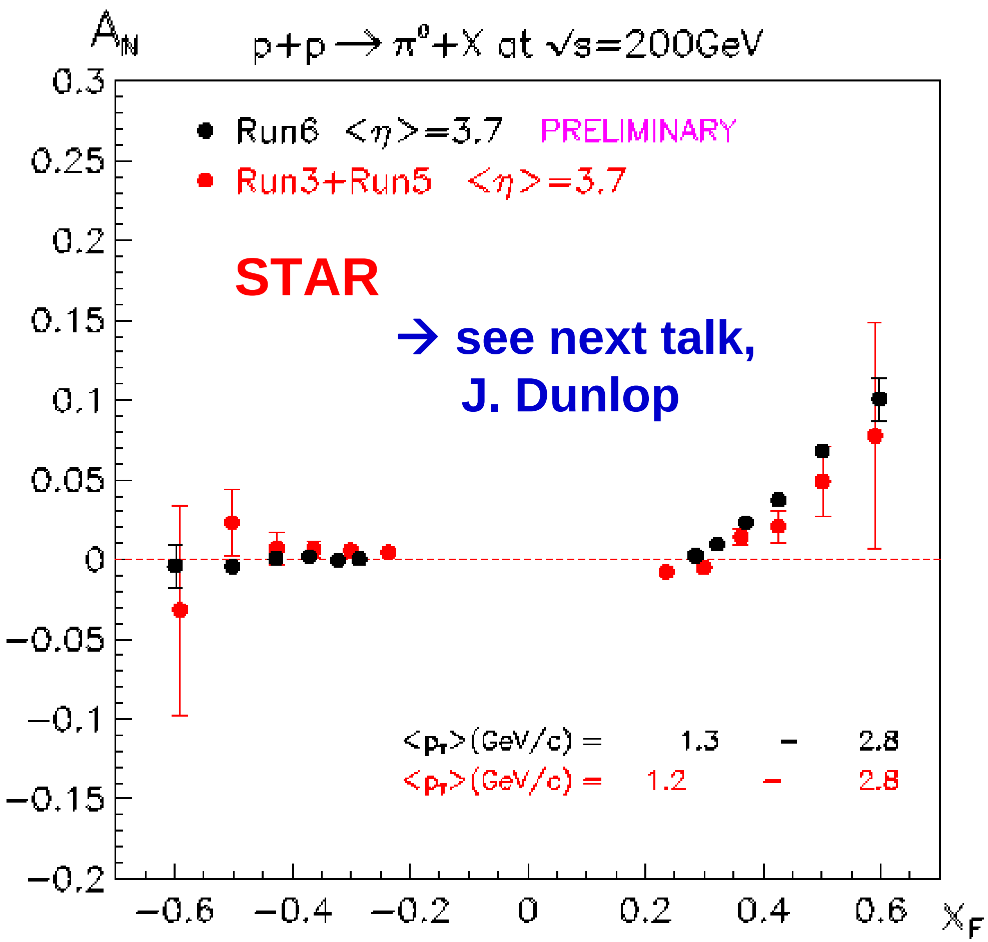
$$\Delta d + \bar{u} \rightarrow W^-$$
$$\Delta\bar{u} + d \rightarrow W^-$$
$$\Delta\bar{d} + u \rightarrow W^+$$
$$\Delta u + \bar{d} \rightarrow W^+$$

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

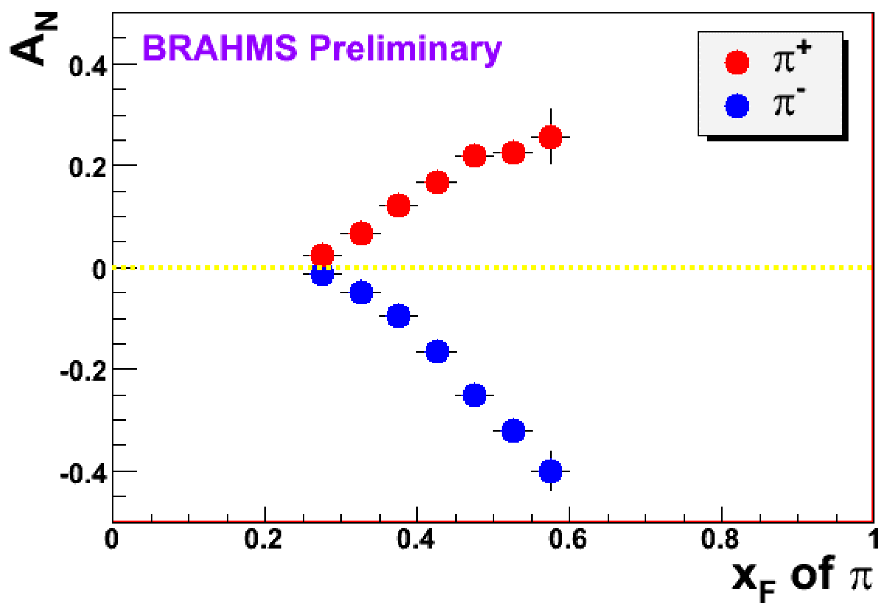


Expected start: 2009

Transverse spin: pion A_N
--very large forward asymmetries



$A_N(\pi)$ at 62 GeV



Kyoto Spin2006

RHIC Spin Outline

The key points for RHIC Spin are:

- **Spin structure of proton**
- **Strongly interacting probes**

- **P=60%, L=2x10^31, root(s)=200 GeV in 2006**
- **Polarized atomic H jet: absolute P, pp elastic physics**
- **Very forward n asymmetry**

- **Cross sections for pi^0, jet, direct photon described by pQCD—include new result for low p_T region**

- **Helicity asymmetries: sensitivity to gluon spin contribution to proton**
- **Photon+jet: gluon pol. vs. x_gluon**

- **W boson parity violating production: ubar and dbar polarizations in proton**

- **Very large transverse spin asymmetries in pQCD region**

- **Future: transverse spin Drell-Yan**

A Fundamental Test of Universality:
Transverse Spin Drell Yan at RHIC vs
Sivers Asymmetry in Deep Inelastic Scattering

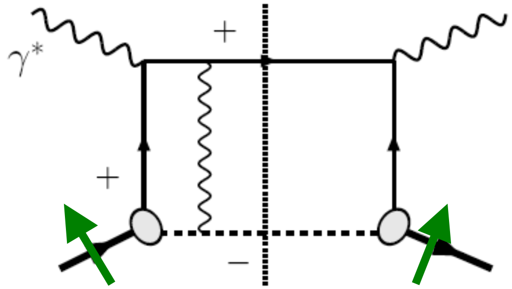
- Important test at RHIC of recent fundamental QCD predictions for the Sivers effect, demonstrating… **attractive vs repulsive color charge forces**

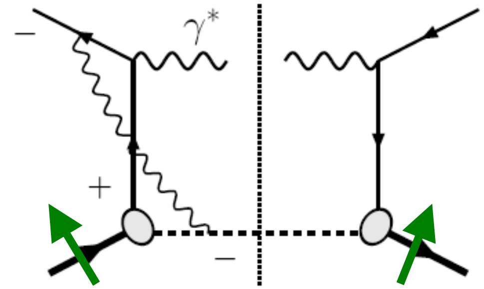
- Possible access to quark **orbital angular momentum**
- Latest development from DIS: first direct evidence of Sivers and Collins effects (recent new results at DIS 2007 in Műnchen, April 2007, HERMES, Diefenthaler et al.)
- Requires very high luminosity (RHIC II)
- Both STAR and PHENIX can make important, exciting, measurements
- Discussion available at http://spin.riken.bnl.gov/rsc/

Attractive vs Repulsive Sivers Effects

Unique Prediction of Gauge Theory !

Simple QED example:

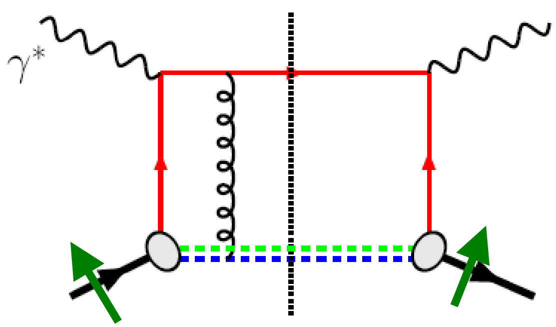


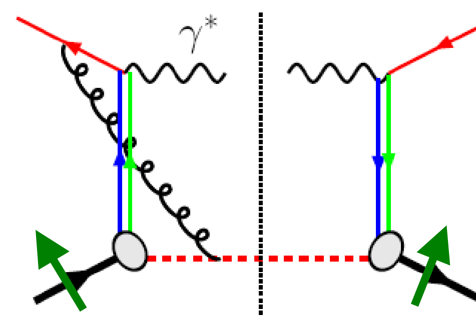


DIS: attractive

Drell-Yan: repulsive

Same in QCD:





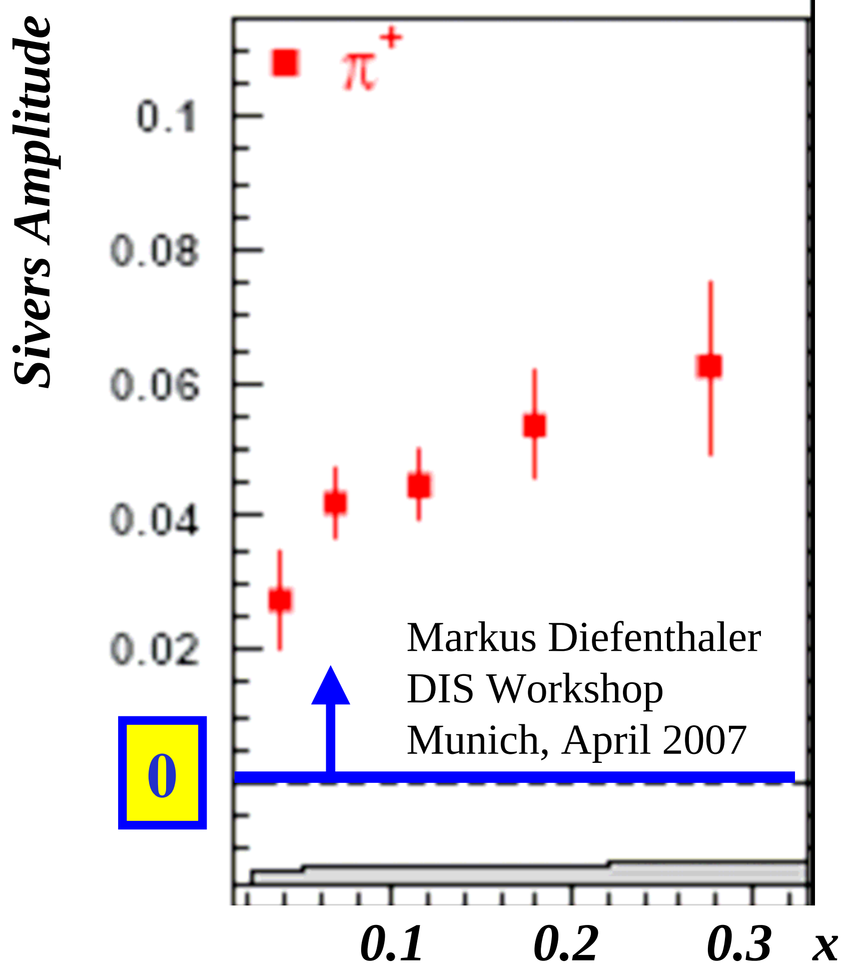
As a result:

$$\mathrm{Sivers}|_{\mathrm{DIS}} = -\mathrm{Sivers}|_{\mathrm{DY}}$$

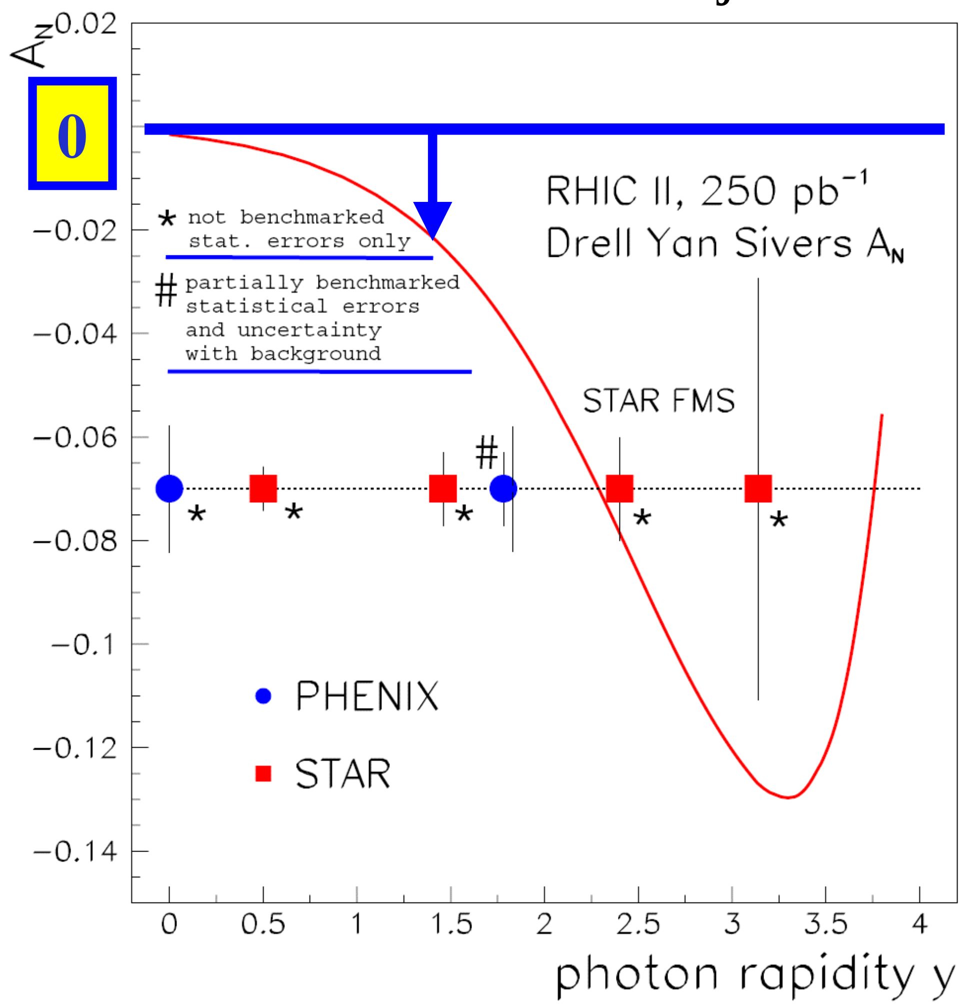
Experiment SIDIS vs Drell Yan: Sivers$|_{DIS}$= − Sivers$|_{DY}$

*** Probes QCD attraction and QCD repulsion ***

HERMES Sivers Results



RHIC II Drell Yan Projections



Concluding Remarks

- **High luminosity and high polarization achieved!**

- **Delta G: direct photon; global fits with RHIC, DIS; new vertex and forward detectors**

- **W boson parity violating production: ubar and dbar**

- **Very strong theoretical support**

- **Transverse spin renaissance!**