Recent PHENIX Spin Results

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On behalf of the PHENIX collaboration

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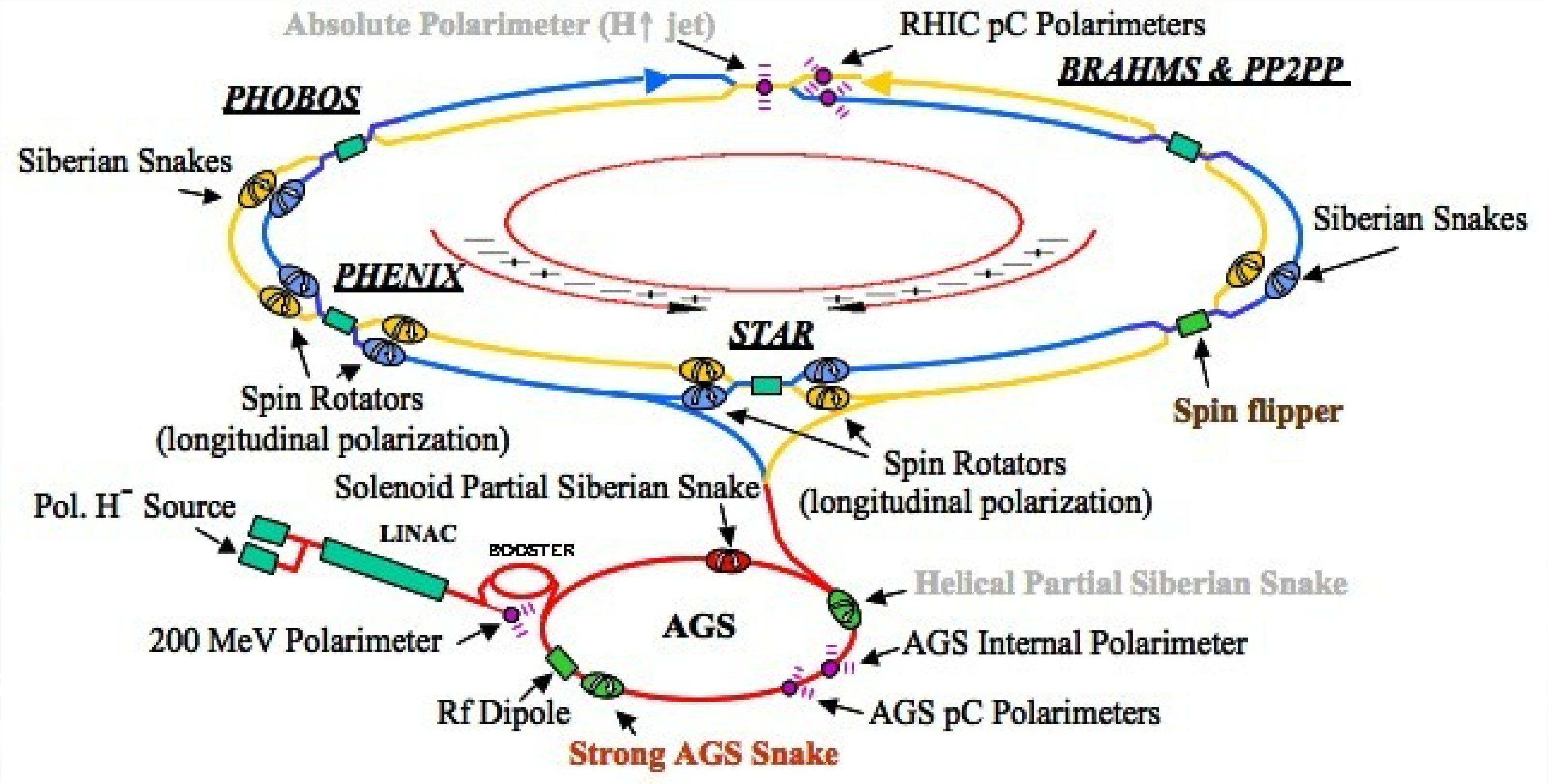
Outline

Illustration by Sebastian Parmentier & Astrid Morreale

- About polarized RHIC, PHENIX
- The Proton Spin Structure via Asymmetries
- Recent PHENIX results from polarized proton running
- Summary

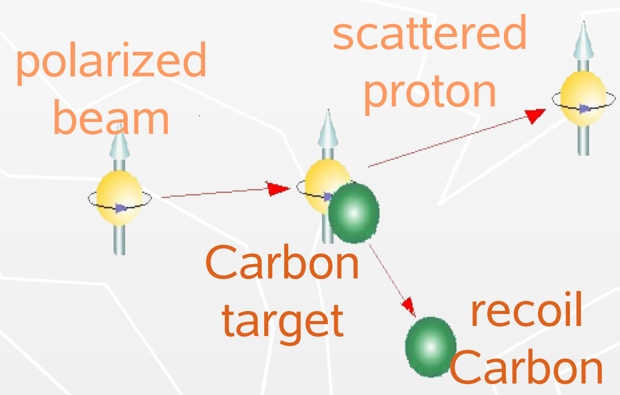
RHIC



- Acceleration of polarized protons between 25 and 250 GeV
- Up to 120 Bunches with $2*10^{11}$ protons (100ns apart)
- Polarization up to 70%
- http://www-nh.scphys.kyoto-u.ac.jp/SPIN2006/SciPro/pres/plenary/MeiBai.ppt

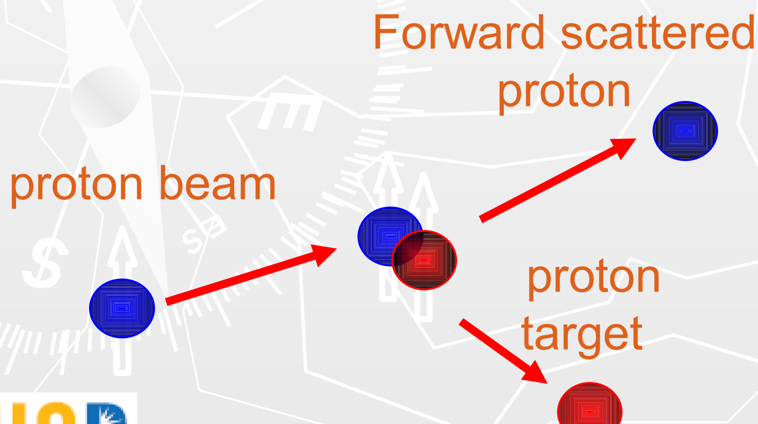
Polarimetry

- “CNI”-Polarimeter measures left-right asymmetries in elastic pC collisions
  - Provides fast relative polarization measurement
  - Scan polarization over x and y range of the beam



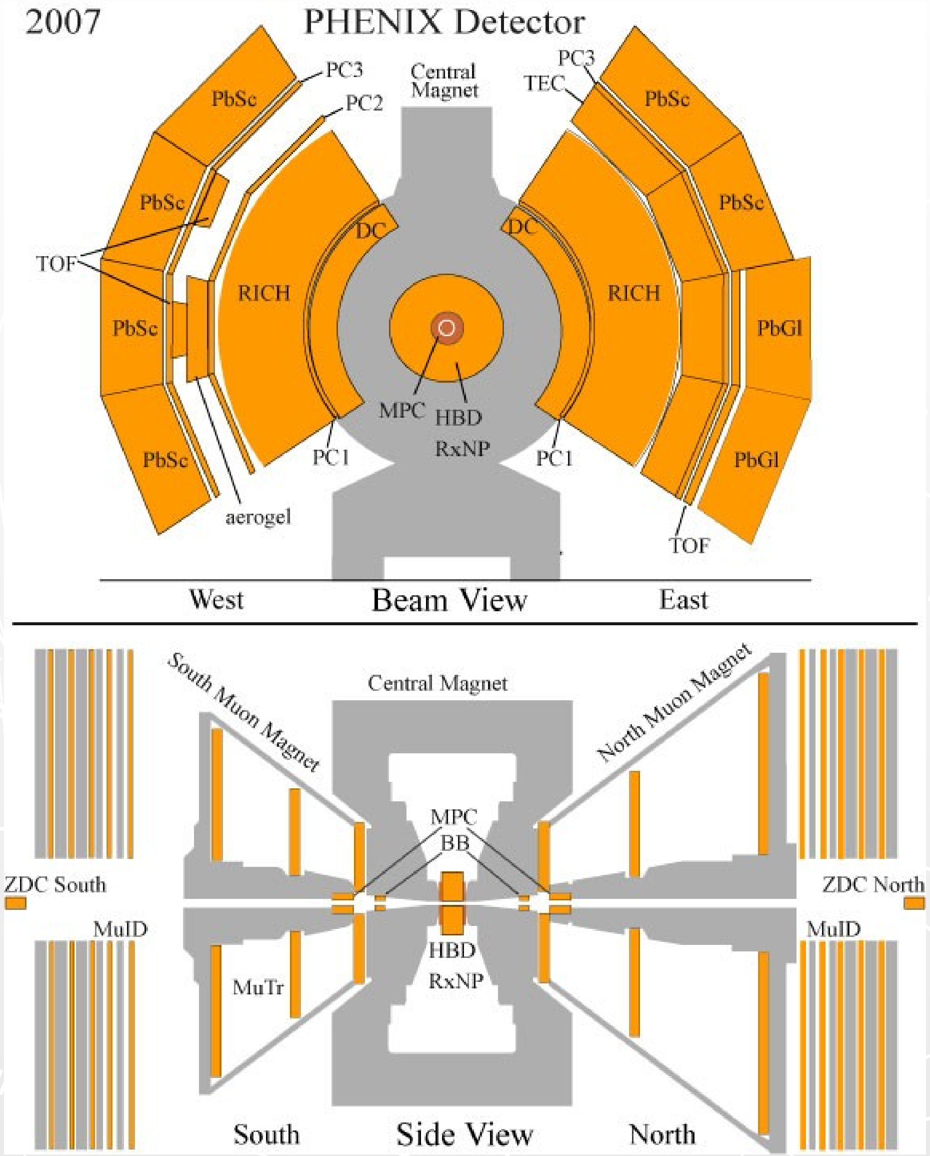
Polarimetry

- "CNI"-Polarimeter measures left-right asymmetries in elastic pC collisions
  - Provides fast relative polarization measurement
  - Scan polarization over x and y range of the beam
- "Jet" Polarimeter measures left-right asymmetries in elastic pp collisions
  - Uses the known polarization of H atoms from Atomic Beam Source
  - Absolute measurement
  - Integrating over beam profile
  - Run 6: total syst. polarization uncertainty $\Delta P_B P_Y/(P_B P_Y)$=8.4%



Year	[GeV]	Luminosity [pb^{-1}] (recorded)	Polarization [%]
2003 *	200	0.35	27
2004 *	200	0.12	40
2005 *	200	3.4	49
2006 *	200	7.5	55
2006 *	62.4	0.08	48

The PHENIX Detector for Spin Physics



Central Detector ***Acceptance: (|η|<0.35, ϕ = 2 x π/2)***:

- $\gamma/\pi^0/\eta$ detection
  - Electromagnetic Calorimeter:
    PbSc + PbGl, $\eta < |0.35|$, $\phi = 2 \times 90°$
- π^+/π^-
  - Drift Chamber
  - Ring Imaging Cherenkov Detector

Muon Arms (forward kinematics (~1.1<| η |<2.4):

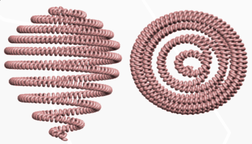
- J/ψ
  - Muon ID/Muon Tracker ($\mu+\mu-$)
- π^0
  - Electromagnetic Calorimeter (MPC)

Global Detectors:

- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)
- Local Polarimetry - ZDC

Intrinsic Spin Violates our intuition:

How can an elementary particle such as the e^- be point like and have perpetual angular momentum.?



The Proton also violates our intuition.
The Proton is composed of quarks, gluons and anti quarks.

We should expect the proton's spin to be predominately carried by its 3 valence quarks

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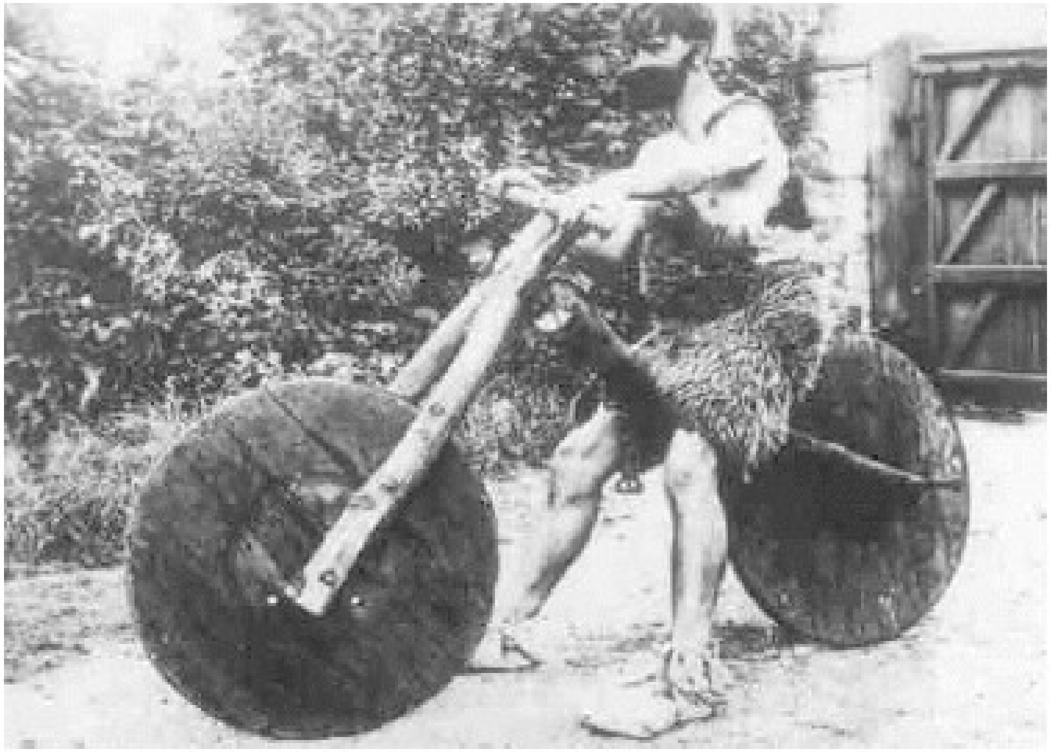
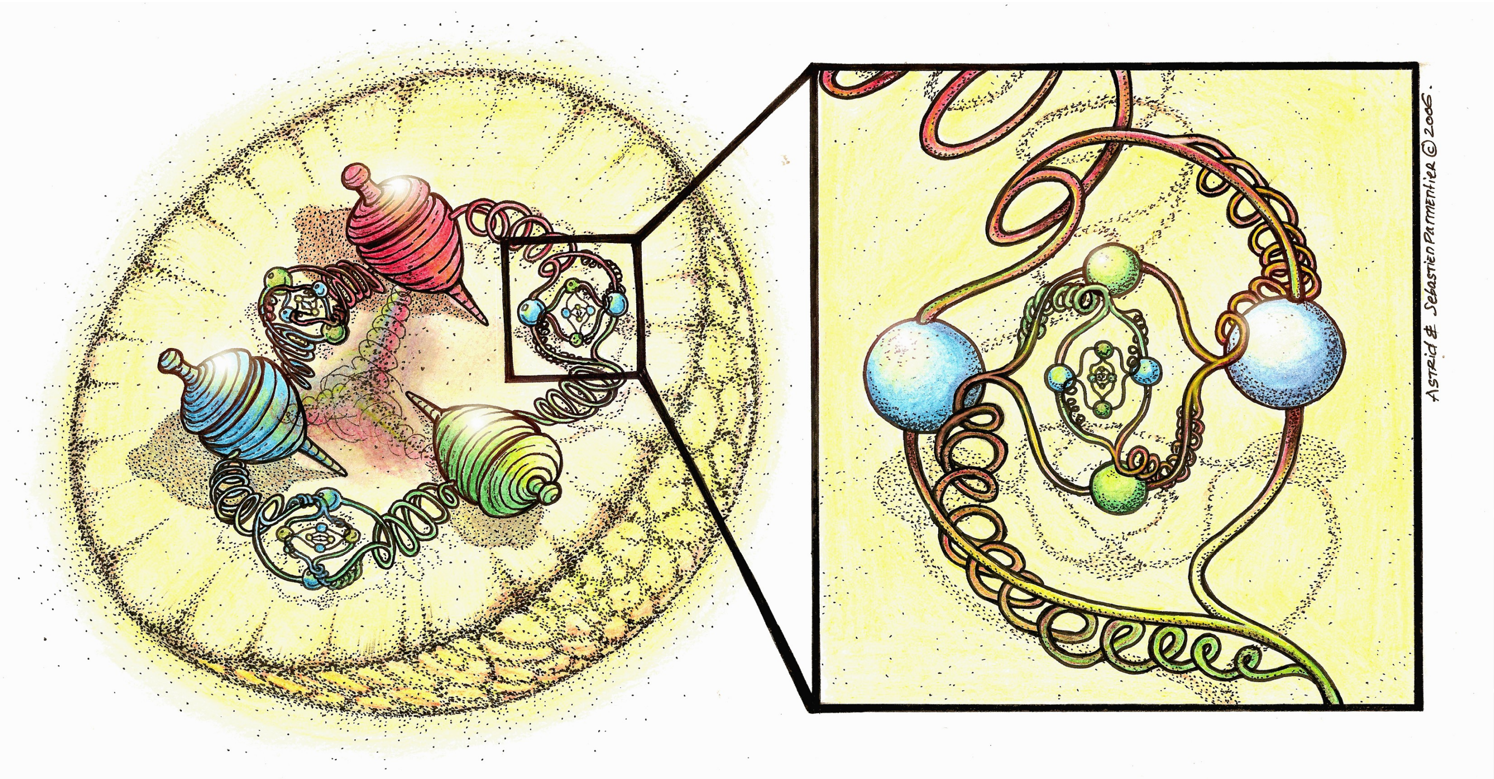
We Think That We Understand the Concept of “Rotational Motion“



...but how does it workout at scales of about one fermi? (Marco Stratman. Lectures on the Longitudinal Spin Structure of the Nucleon, Wako, Japan)



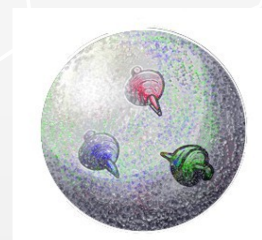
That nucleon has a large anomalous magnetic moment proves that this is not a ***fundamental*** spin1/2 Dirac particle.

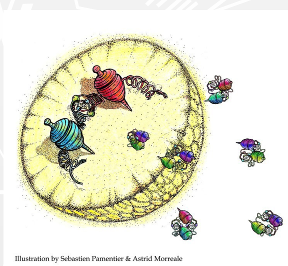
Within the nucleon:
Quarks, gluons and their angular momentum caused by their high speed motion within the nucleon are contributors to the Nucleon's spin.

Contributions to the Proton's Spin

- Quarks and Gluons carry about 50%(each) of the longitudinal momentum
- **What about Spin?**

Valence Quarks (QPM) ~30%





(QCD) Gluons, Sea Quarks: ~>, =, <0?

Orbital Angular Momentum ~?

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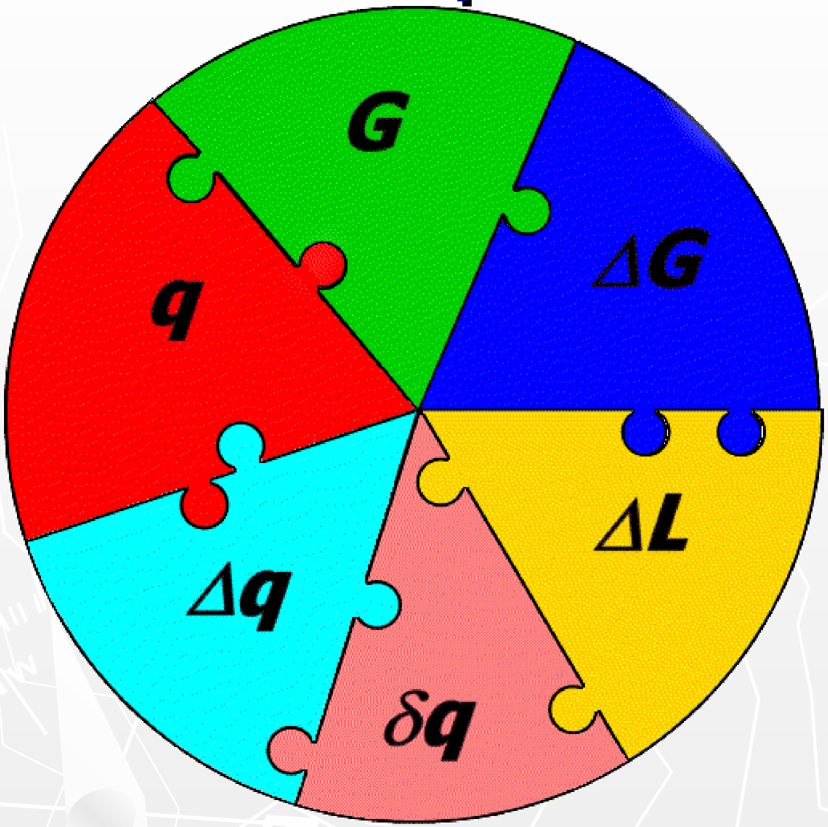
The Spin Structure of the Proton



ΔG, ΔΣ=are the probabilities of
finding a parton with
spin parallel or anti parallel to the
spin of the nucleon.

Longitudinal Spin Sum Rule:

$$\frac{1}{2} = S_z = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

W-production
(pp)

Double Spin
Asymmetries
(pp,SIDIS)

Exclusive
processes
(DVCS,etc)

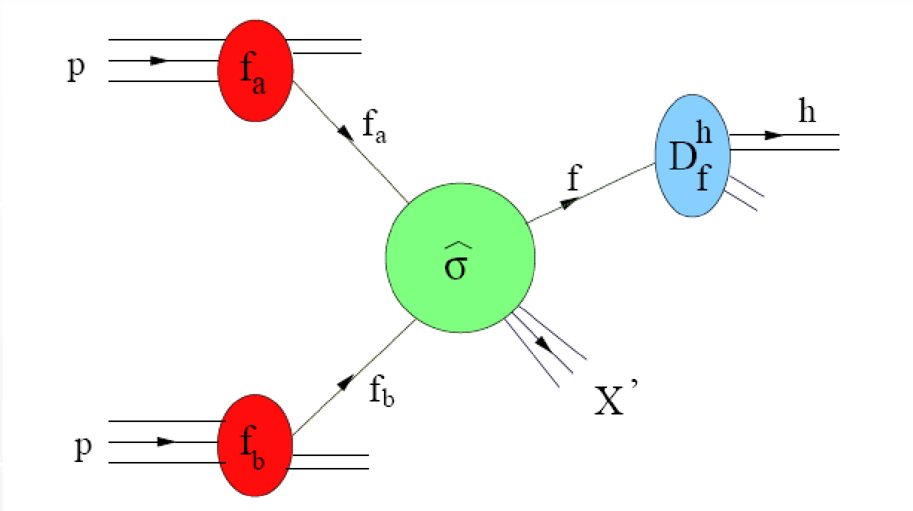
Transverse Spin Sum Rule?

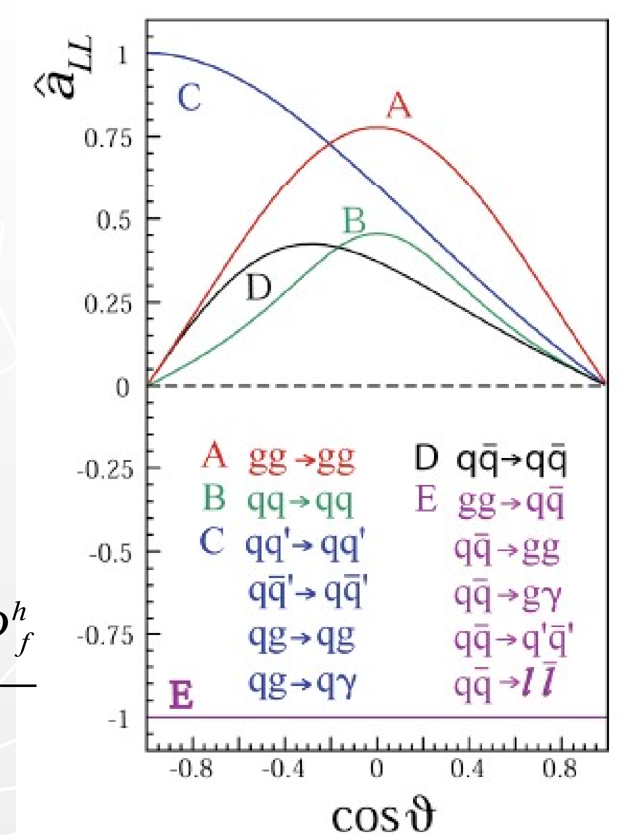
$$\frac{1}{2} = S_x = \frac{1}{2}\delta\Sigma + L_x$$

Chiral-odd Fragmentation
functions (Collins,IFF,L)

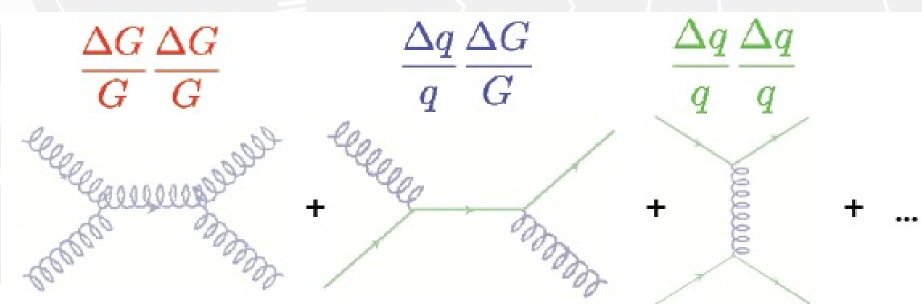
Sivers effect??

Accessing Δg with Asymmetries





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



Increasing x, p_T

Hard subprocess asymmetries (LO)

Asymmetries

- For our Δg program the tools are measurements of helicity cross section asymmetries A_{LL}

$$A_{LL}=\frac{d\sigma_{++}-d\sigma_{+-}}{d\sigma_{++}+d\sigma_{+-}}=\frac{1}{|P_1P_2|}\frac{N_{++}-RN_{+-}}{N_{++}-RN_{+-}}\ ;\ R=\frac{L_{++}}{L_{+-}}$$

(N) Yield

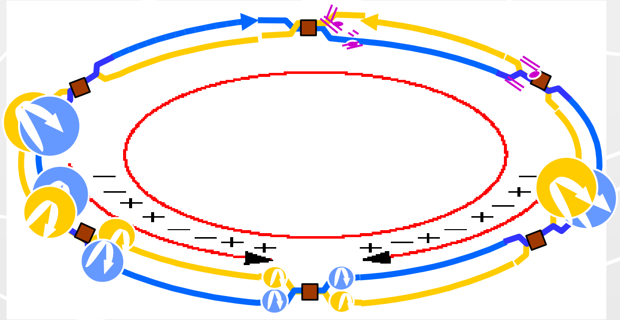
(R) Relative Luminosity

- ✓ BBC vs ZDC

(P) Polarization

- ✓ RHIC Polarimeter (at 12 o'clock)
- ✓ Local Polarimeters (SMD&ZDC)

Bunch spin configuration alternates every 106 ns
Data for all bunch spin configurations are collected at the same time
$\Rightarrow$ Possibility for false asymmetries are greatly reduced



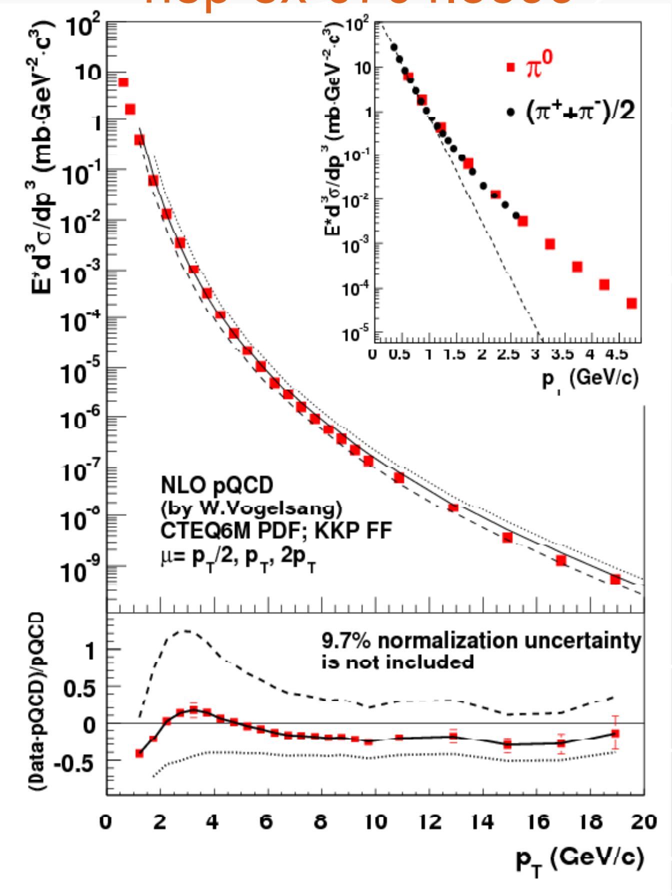
Asymmetries

- **Accessing Δg:** Inclusive channels $A_{LL}(pp \rightarrow AX)$ measurable at Phenix
  - π^0: wide p_T range, mixture with $gg \rightarrow X$ dominant at low p_T
  - η, similar to π^0, different FF's.
  - $\pi^{\pm}$, mixture sensitive to $qg \rightarrow qX$ at high p_T
  - Multiparticle clusters (parts of jets), correlated with $\pi^{0,\pm}$
  - Direct photons: p_T range 6-20+ GeV/c, dominated by $qg \rightarrow q\gamma$
  - J/ψ, $\mu^{\pm}$, $e^{\pm}$ ($gg \rightarrow cc$)

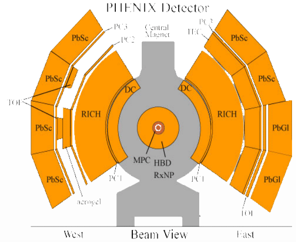
- **$\Delta\Sigma$, $\delta\Sigma$, L_z** : Current k_T, D_L, $A_{N,UT,T}$ measurements at Phenix
  - A_N $\pi^0/\pi^{\pm}/h^{\pm}$, J/ψ, forward neutrons
  - D_{LL} Anti-Λ Spin Transfer
  - k_T azimuthal di-$h^{\pm}$ correlations

π^0 cross section measurement

PHENIX: π^0 mid-rapidity, 200GeV
hep-ex-0704.3599



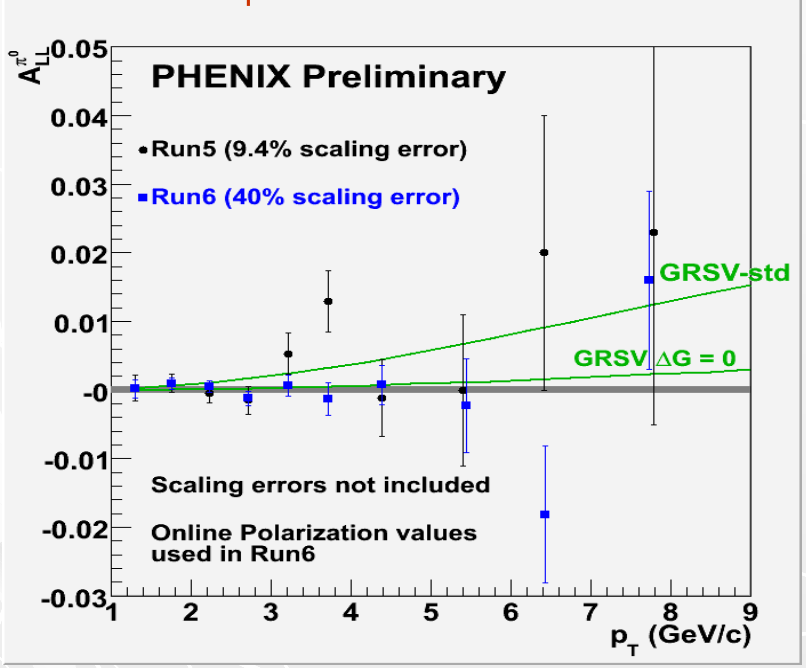
- Agreement between data and pQCD theory
- Shows that pQCD and unpolarized PDFs determined in DIS can describe pp data
- Choice of fragmentation function crucial (dominated by gluon fragmentation)
- Scale uncertainty still large at lower p_T<5 GeV



π^0 Asymmetries

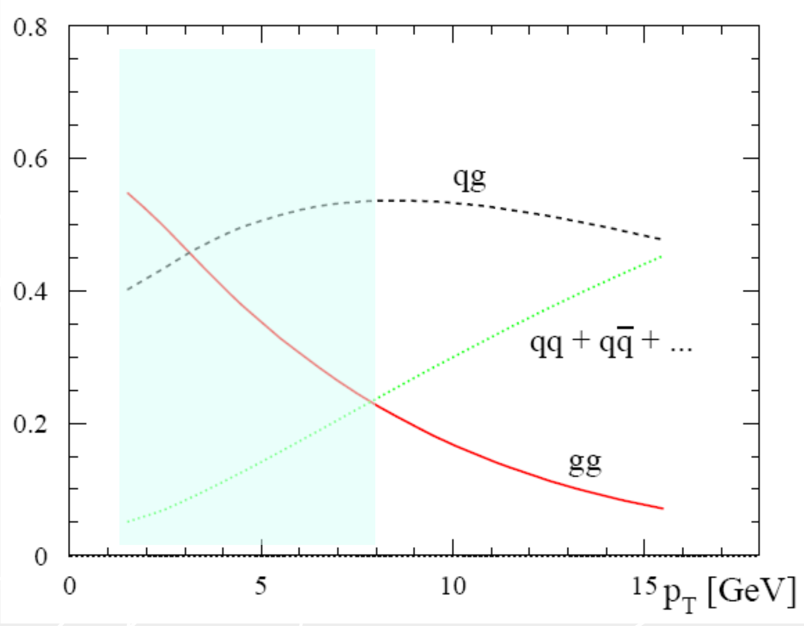
Measured asymmetries for $pp \to \pi^0 X$ from Run 5 ,Run 6

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



- Asymmetry of combinatorial background estimated from sidebands and subtracted

Initial state parton configurations contributing to unpolarized cross section (Fractions)

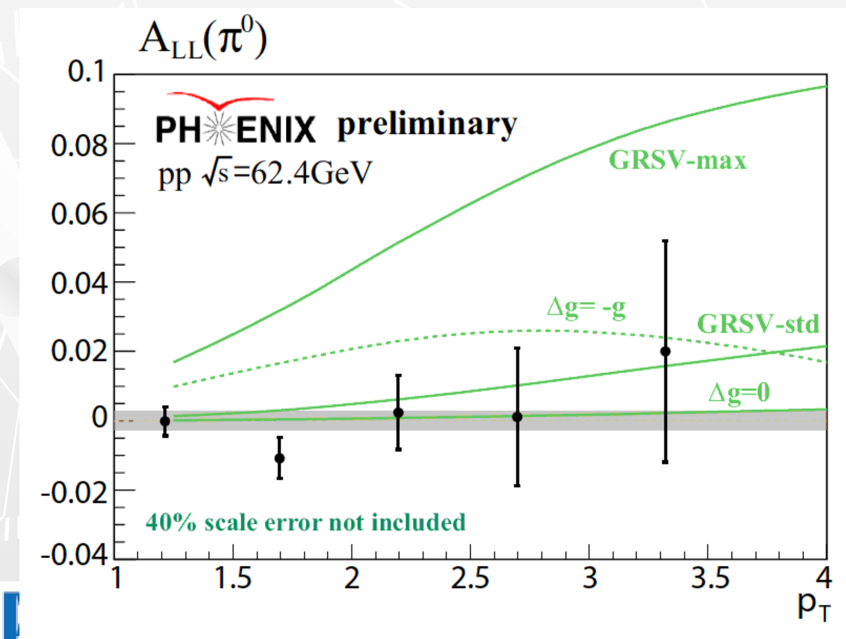


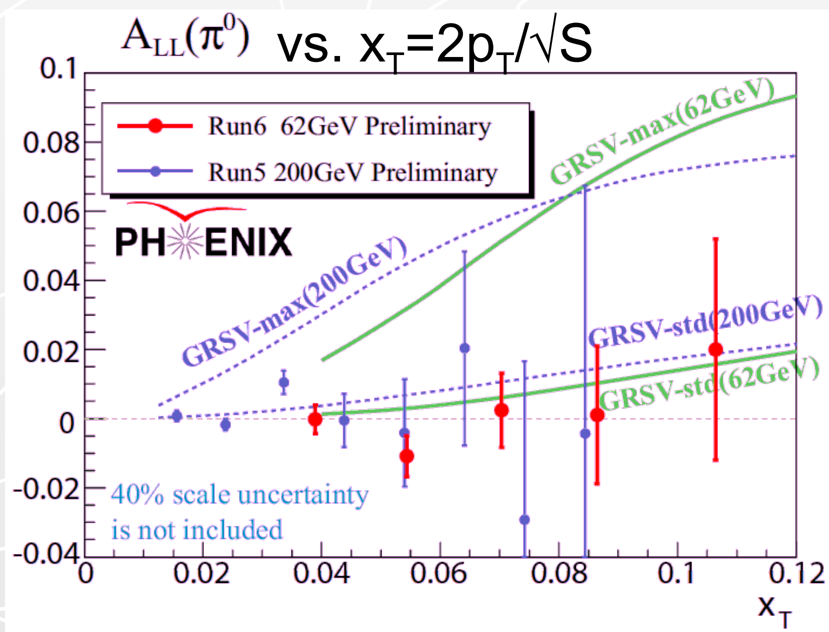
W. Vogelsang et al.

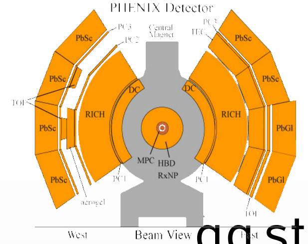
- Dominated by gg for p_T<3, qg for 3<p_T<10 GeV

Information from π^0 Asymmetries

- Inclusive π^0 A_{LL} cannot access $\Delta g(x)$ directly
  - Only sensitive to an average over a wide x range
  - No conclusions about moment of $\Delta g(x)$ possible without a model for its shape
- More (indirect) information from varying cms energies
  - Higher (500 GeV) $\rightarrow$ lower x
  - Smaller (62 GeV) $\rightarrow$ higher x (and larger scale uncertainty)

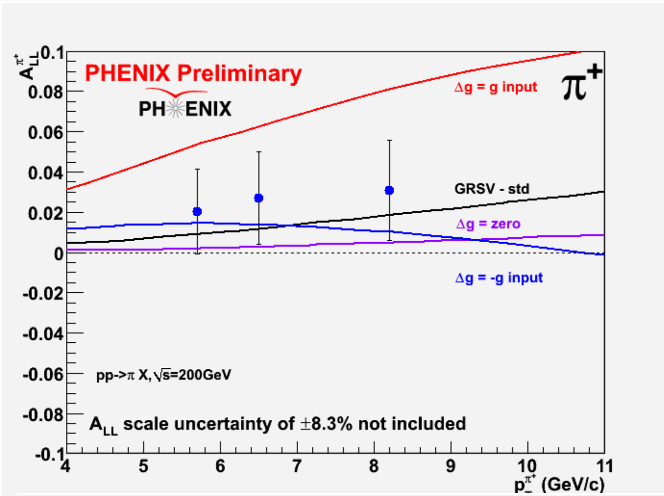


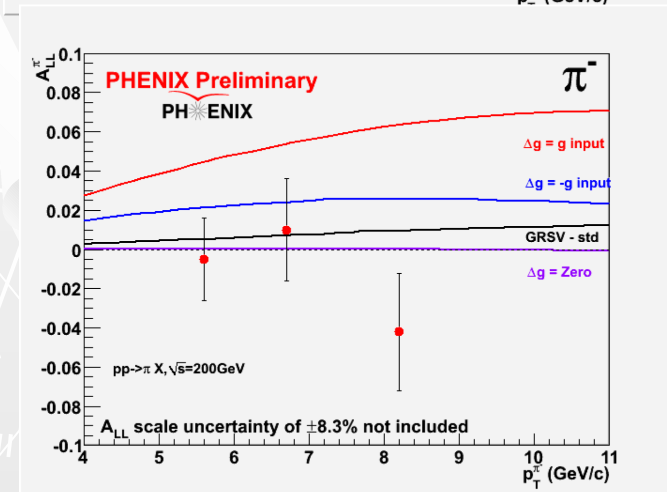


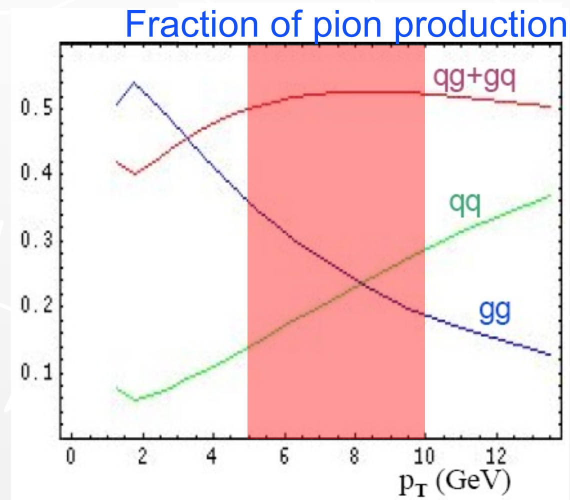


$\pi^{+,-}$ Asymmetries

qg starts to dominate for p_T >~ 5GeV and $D_u^{\pi^+} > D_u^{\pi^0} > D_u^{\pi^-}$
Expect sensitivity to sign of ΔG, e.g., positive $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$







Charged pions above 4.7 GeV identified with RICH.

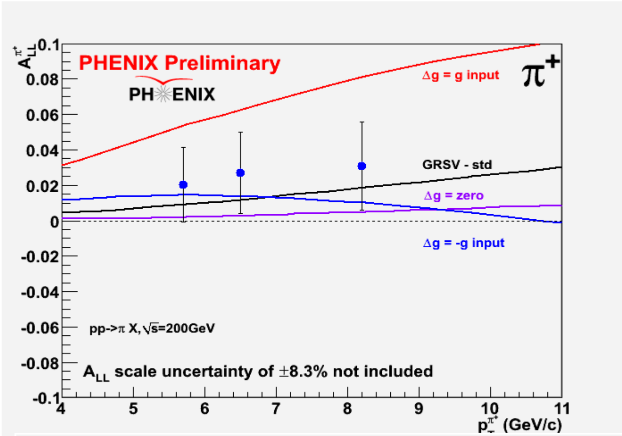
At higher p_T, qg interactions become dominant: $\Delta q \Delta g$ term.

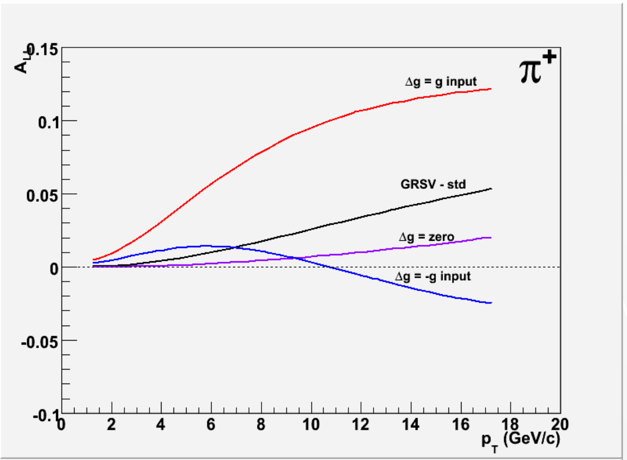
A_{LL} becomes significant allowing access to the sign of ΔG

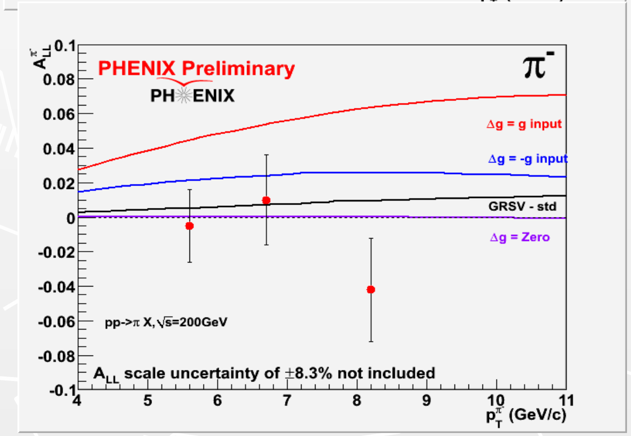
❖ **New set from M. Stratmann et al. is the first to use charged separated π data from SIDIS for fragmentation functions**

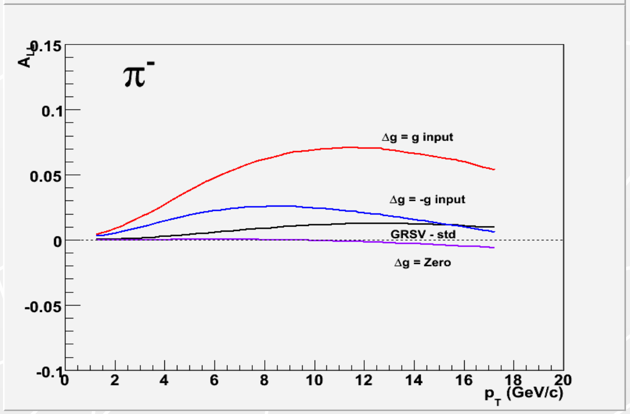
PHENIX

Information from $\pi^{+,-}$ Asymmetries

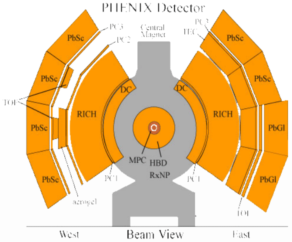




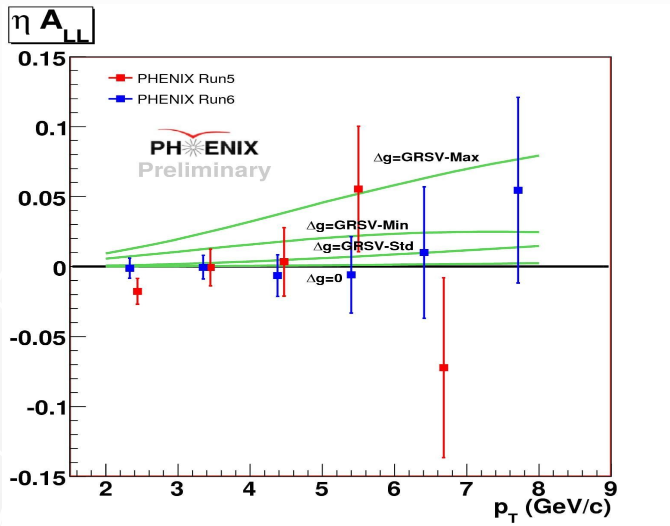


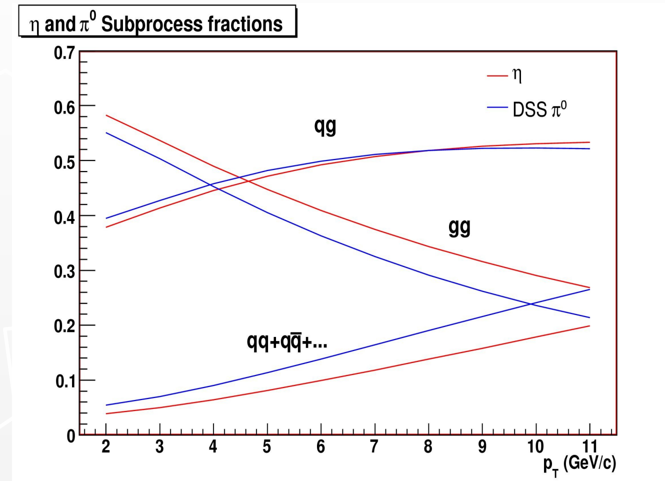


- Inclusive $\pi^{+,-,0}$ A_{LL} has access to sign $\Delta g(x)$ directly
- "Model independent" conclusion possible once enough data is available.

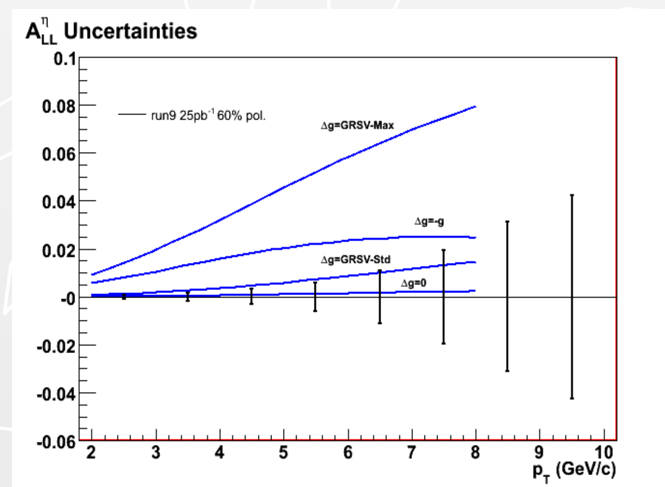


η

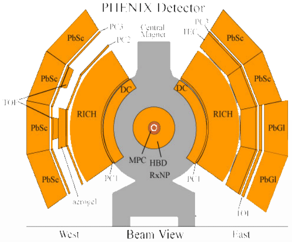


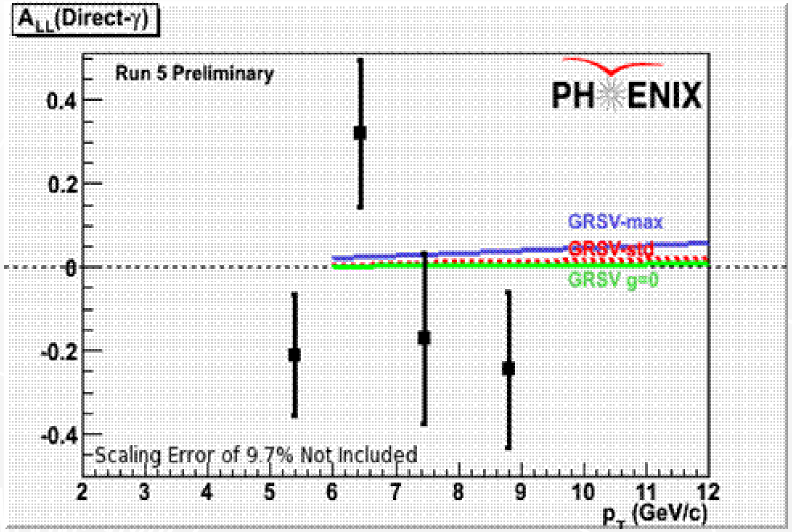


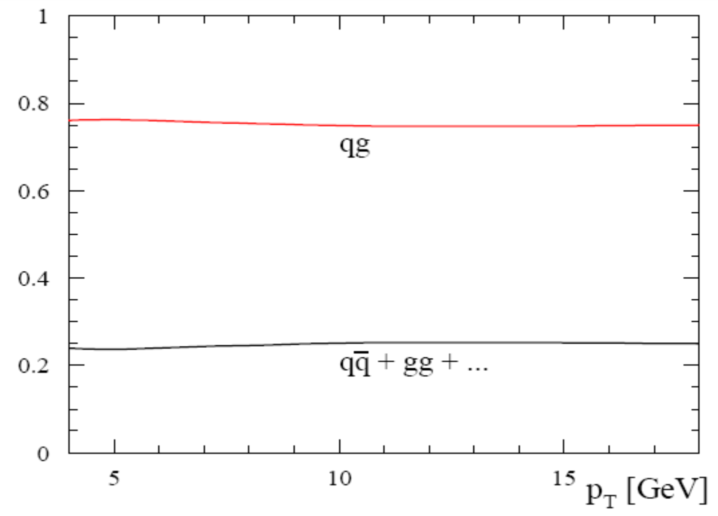
- Recent preliminary extraction of fragmentation functions, ⇒
- Eta has (slightly) enhanced sensitivity to gg (when compared to the π^0) Observation of difference in asymmetries could help disentangle the contributions from the different quarks and the gluons.

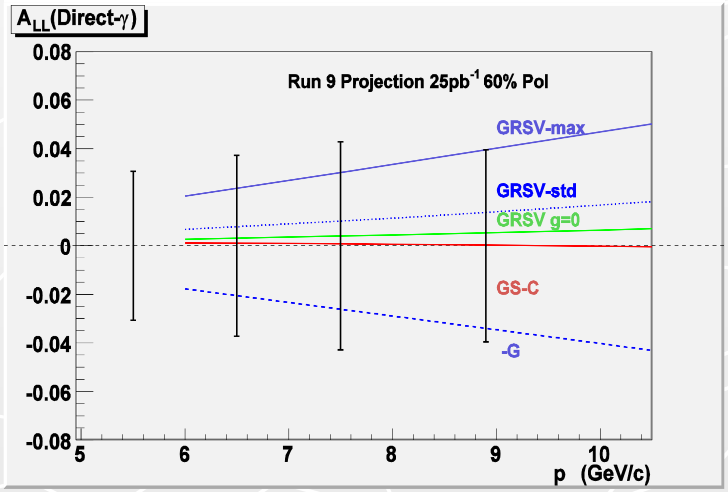


γ Asymmetries





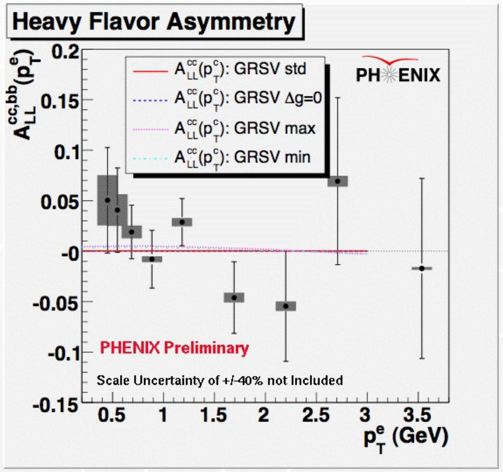


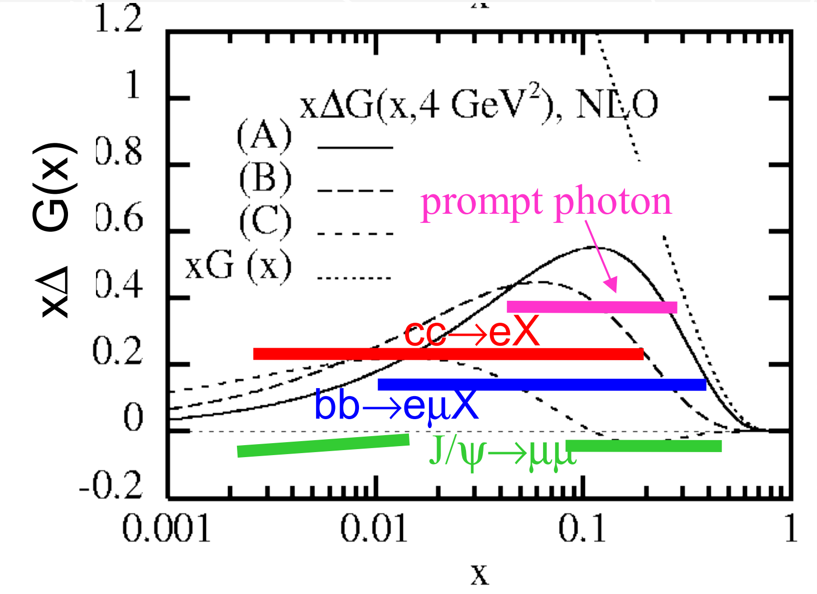


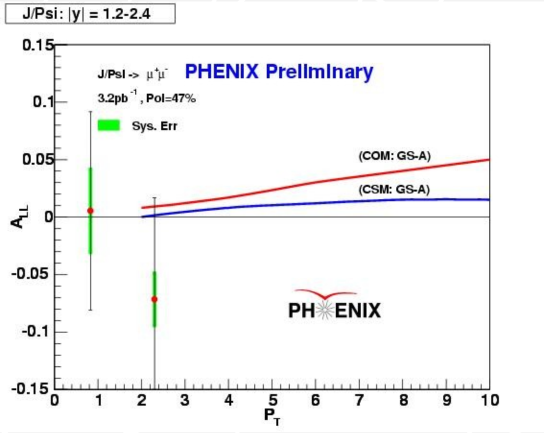
Dominated by qg Compton:
- Small uncertainty from FFs
- Better access to sign of ΔG (ΔqΔG)
-Clean "Golden Channel" :-)
-Luminosity Hungry :-(

Information from γ, μ, $e^{+,-}$ Asymmetries

- Provide access different x range
  - Thresholds
  - $J/\psi \rightarrow \mu\mu$ η range (forward arms)
  - Prompt γ: no fragmentation z=1
  - Rare channels with large background
  - Need more luminosity







$\Delta G(x)$ Global Analysis

- Results from various channels combined into single results for $\Delta G(x)$
- Correlations with other PDFs for each channel properly accounted
- Every single channel result is usually smeared over x $\Rightarrow$ global analysis can do deconvolution (map of ΔG vs x) based on various channel results
- NLO pQCD framework can be used
- Global analysis framework already exist for pol. DIS data and being developed to include RHIC pp data, by different groups

One of the attempts of global analysis by AAC Collaboration using PHENIX π^0 -Preliminary data

Now Run5-Final and Run6-Preliminary $\pi 0$ data are available

$\Delta G(x)$ Global Analysis Latest Results

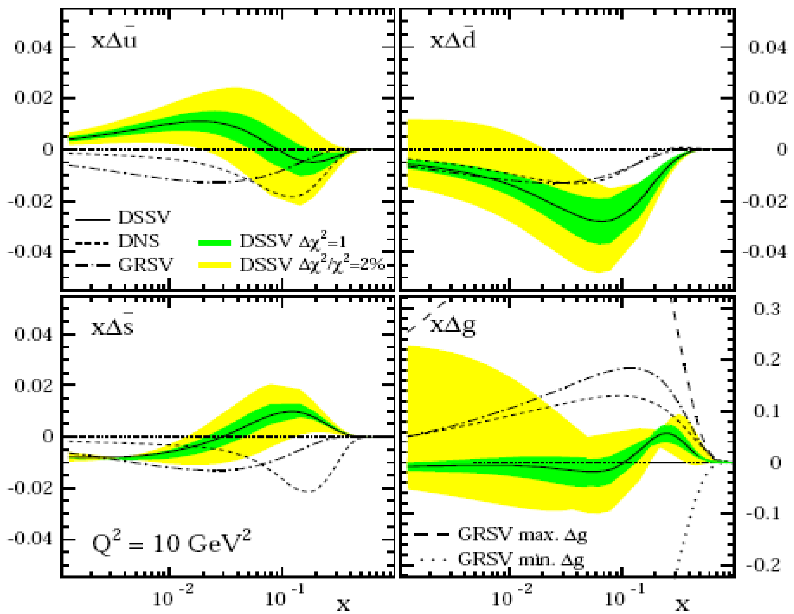


FIG. 2: Our polarized sea and gluon densities compared to previous fits [6, 8]. The shaded bands correspond to alternative fits with $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$ (see text).

-Flavor dependence of the sea

-SU3 symmetry breaking.

"We also find that the SIDIS data give rise to a Robust pattern for the sea polarizations, clearly deviating from SU(3) symmetry, **which awaits further clarification from the upcoming W boson Program at RHIC"**

Global Analysis of Helicity Parton Densities and Their Uncertainties

(de Florian, Sassot, Stratmann and Wogelsang) ArXiv:0804.0422 (April 2008)

ΔG(x) Global Analysis
Latest Results

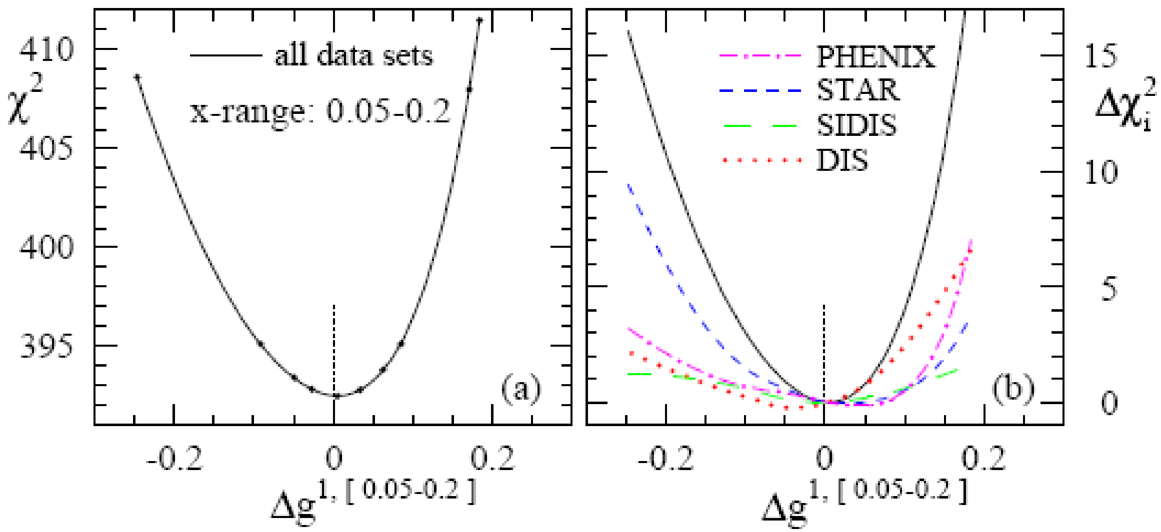


FIG. 3: The χ^2 profile (a) and partial contributions $\Delta\chi_i^2$ (b) of the data sets for variations of $\Delta g^{1,[0.05-0.2]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

-A first demonstration that p-p data can be included in a consistent way in a NLO pQCD calculation.

-RHIC data set significantly constraints on the gluon helicity distribution

-"Inclusion of theoretical uncertainties and the treatment of experimental ones should and will be improved"

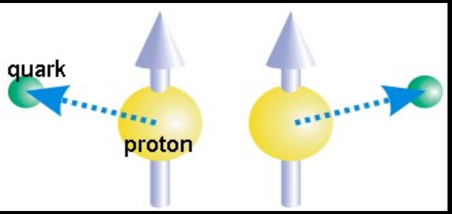
ArXiv:0804.0422 (April 2008)

Transverse Spin

(Sivers effect)

transversely asymmetric

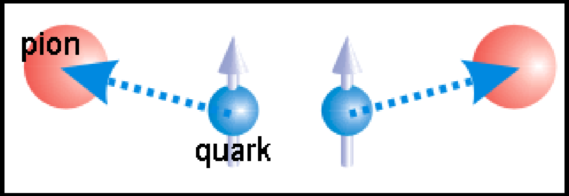
k_t quark distributions



(Collins effect)

spin-dependent

fragmentation functions



(Twist-3)

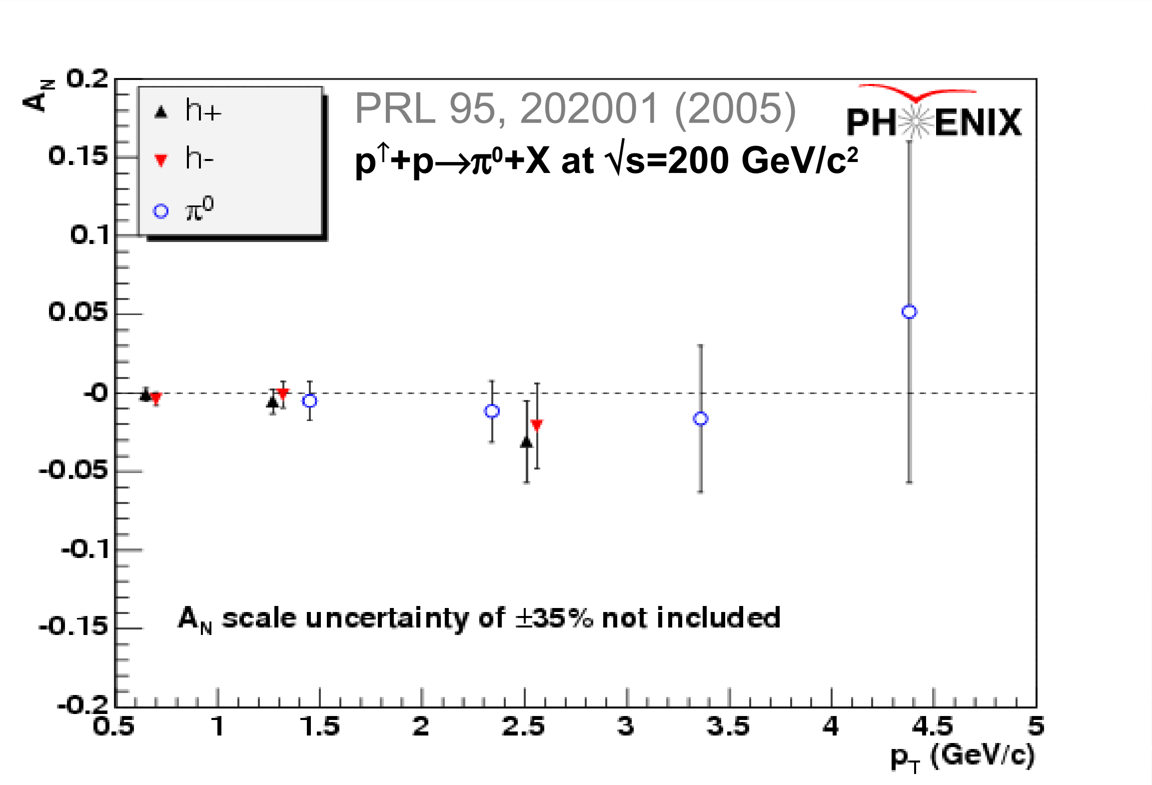
quark gluon field

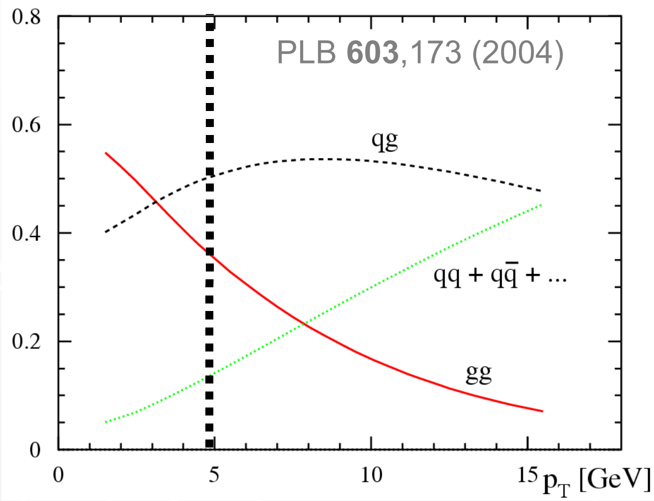
Interference

$$\delta q, f_{1T}^{\perp q}, L$$

Transverse Spin

Mid-rapidity A_N of π^0 and $h^{\pm}$ for y~0 at $\sqrt{s}$=200GeV





process contribution to π^0, η=0, $\sqrt{s}$=200 GeV

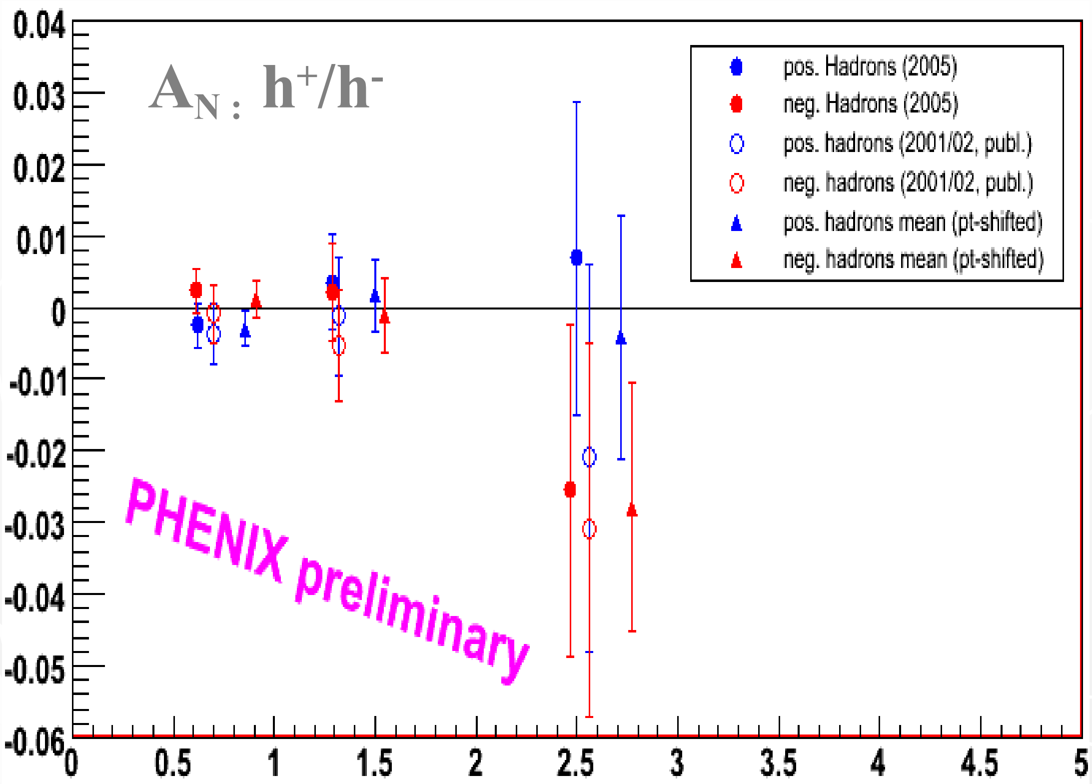
- A_N is 0 within 1% → interesting contrast with forward π

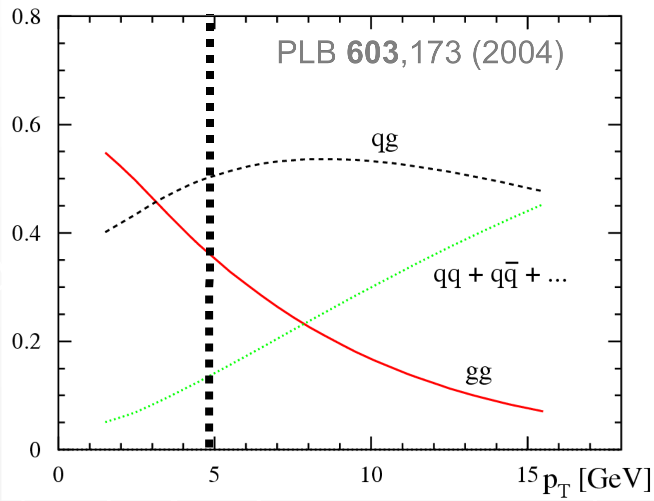
• Mid-rapidity data at small p_T sensitive to gluons, constrains magnitude of gluon Sivers function (Anselmino et al., PRD 74, 2006)

•What happens if qq sets in (valence quarks) at high pT?

Transverse Spin

Mid-rapidity A_N of π^0 and $h^{\pm}$ for y~0 at $\sqrt{s}$=200GeV





process contribution to π^0, η=0, $\sqrt{s}$=200 GeV

- A_N is 0 within 1% → interesting contrast with forward π

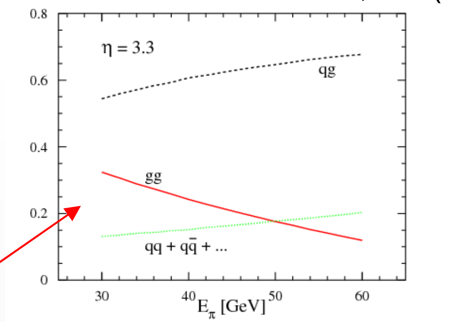
• Mid-rapidity data at small p_T sensitive to gluons, constrains magnitude of gluon Sivers function (Anselmino et al., PRD 74, 2006)

•What happens if qq sets in (valence quarks) at high pT?

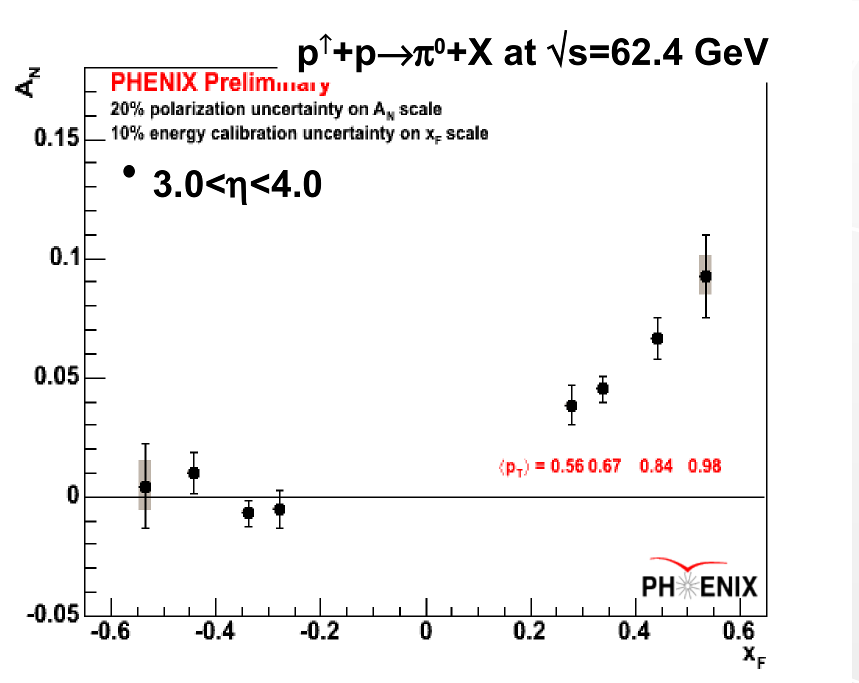
PLB **603**,173 (2004)

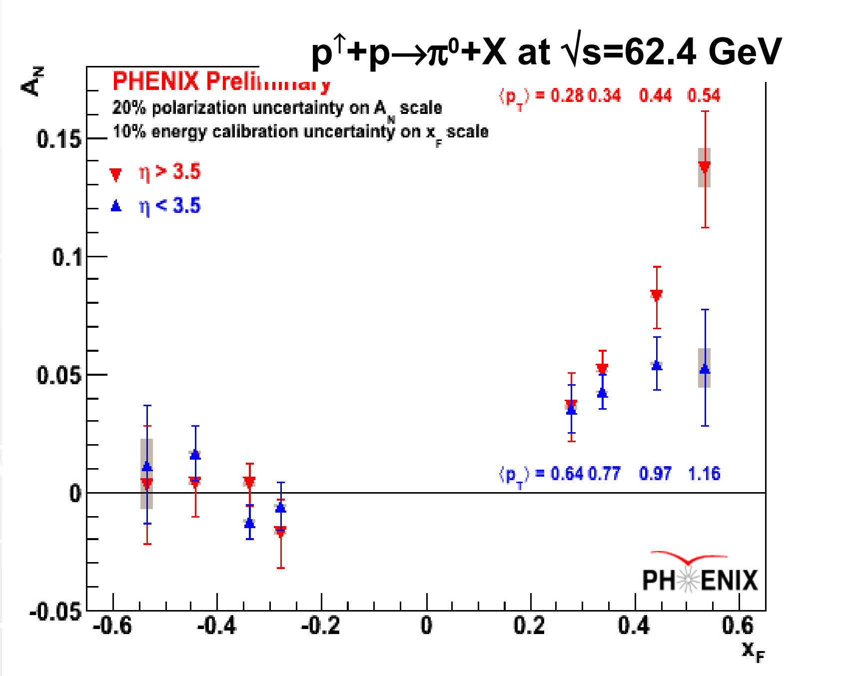
Transverse Spin

π^0 A_N at large x_F



process contribution to π^0, η=3.3, $\sqrt{s}$=200 GeV



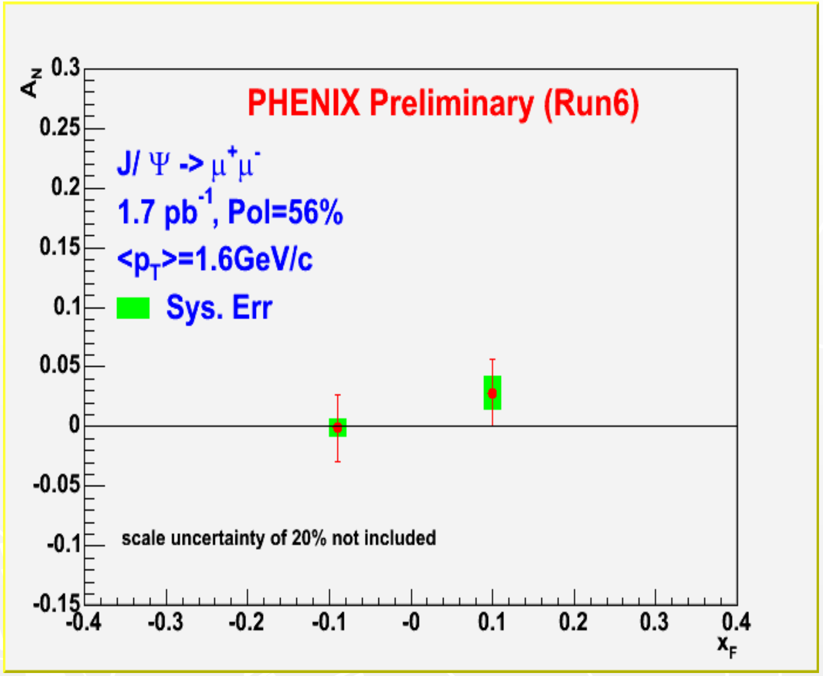


Asymmetry seen in yellow beam (positive x_F), but not in blue (negative x_F)

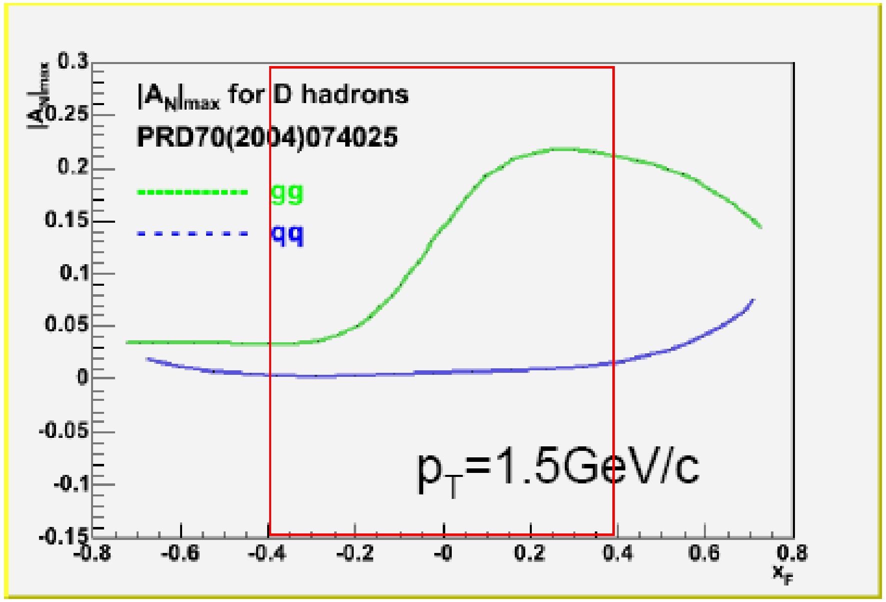
Large asymmetries at forward x_F → Valence quark effect?

x_F, p_T, $\sqrt{s}$, and η dependence provide quantitative tests for theories

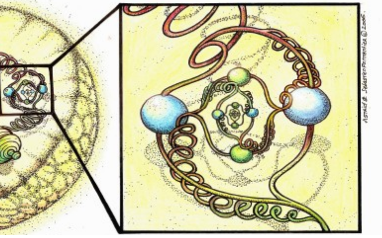
Transverse Spin
A_N of J/ψ at $\sqrt{s}$=200GeV



Theoretical prediction:
For open charm production
--quark Sivers function set to its maximum
gluon Sivers function set to 0
--gluon Sivers function set to its maximum
quark Sivers function set to 0

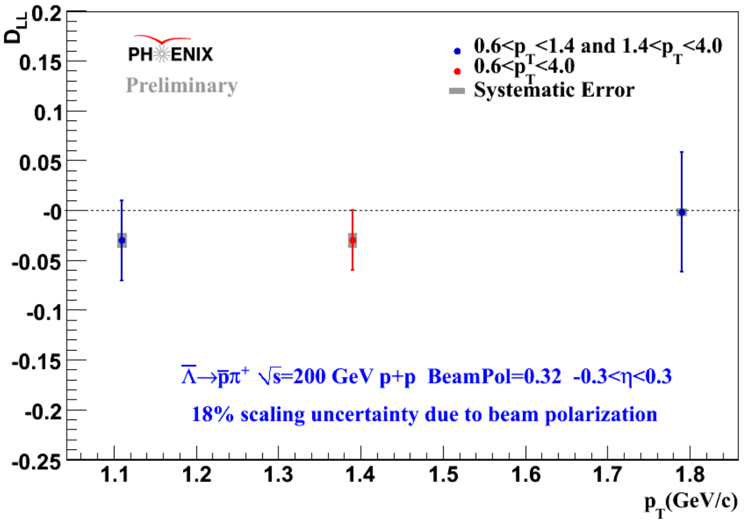


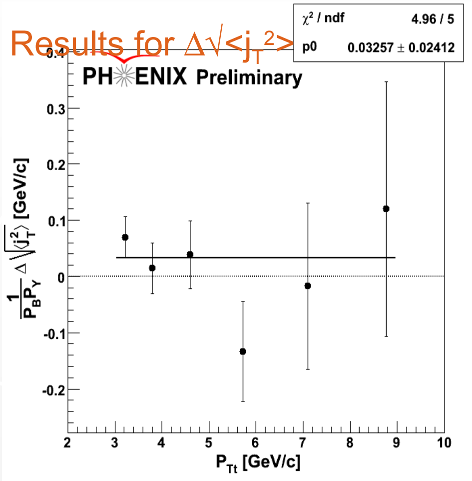
- Sensitive to gluon Sivers as produced through g-g fusion
- Charm theory prediction is available
  - How does J/ψ production affect prediction?

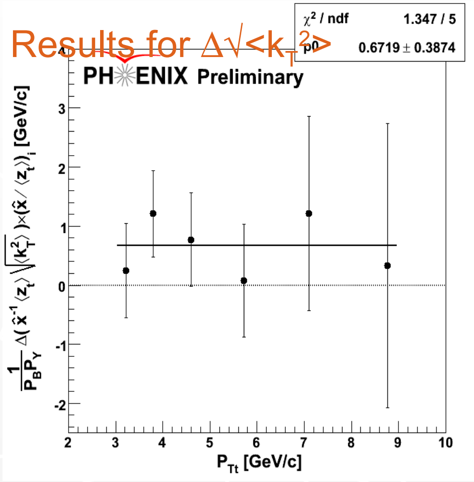


Transverse Spin

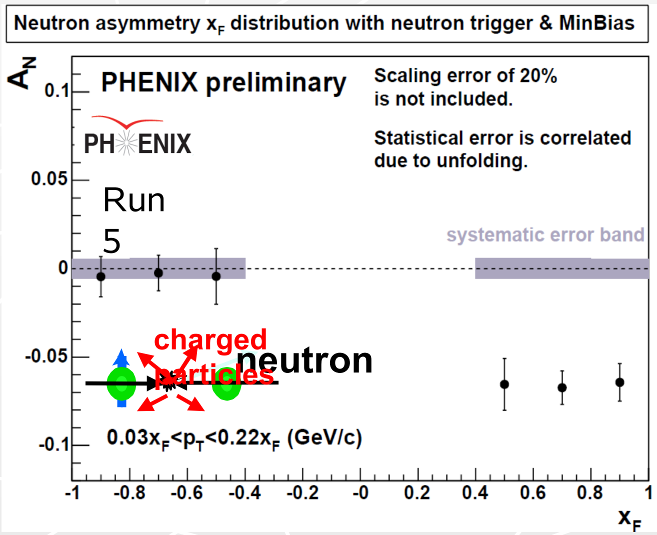
Other asymmetries at √s=200GeV







- **Strange quark Components via Spin Transfer**
  - **In PHENIX the Self-analyzing decay channel (anti-Λ) has been** found to be sensitive to the **polarization of the anti-strange sea** of the nucleon (See: hep-ph/0511061)
- **Probing Orbital angular Momentum with k_T Asymmetries** (See: Phys. Rev. D **74**, 072002 (2006)
- **Neutron asymmetries.** (See:AIP Conf.Proc.915:689-692,2007)



Summary

- PHENIX is well suited to the study of spin physics with a wide variety of probes.
  - Inclusive π^0 data for A_{LL} has reached statistical significance to constrain ΔG in a limited x-range (~0.02-0.3).
- Need more statistics (RHIC running time) to explore different (rare) channels for
  - Different gluon kinematics
  - Different mixtures of subprocesses
- Global Analysis of many channels together with DIS, SIDIS data will give us a more accurate picture of $\Delta g(x)$
- Upcoming W program will give more information about quarks
- PHENIX has an upgrade program that will give us the triggers and vertex information that we need for precise future measurements of ΔG, Δq and new physics at higher luminosity and energy

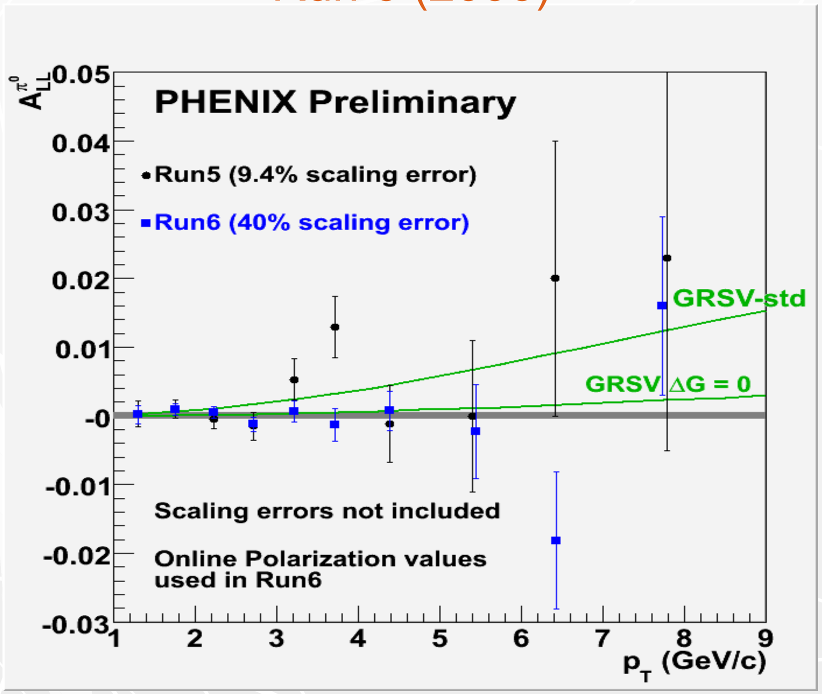
Extras

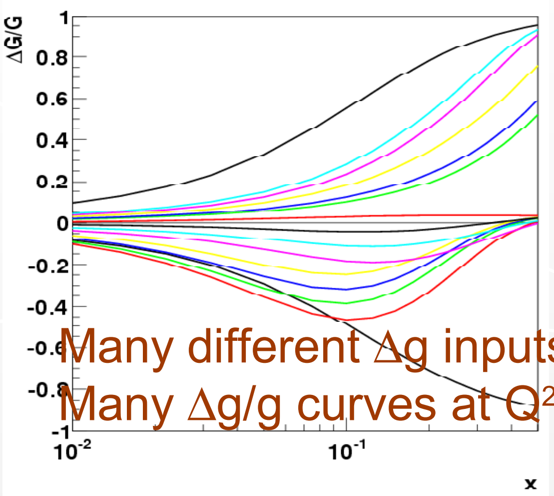
Physics Impact of PHENIX Upgrades

	Physics Goals	**Present vs with upgrades**
$\Delta G(x)$	determine first moment of the spin dependent gluon distribution, $\int_0^1 \Delta G(x)dx$.	Inclusive hadrons + photons forward heavy flavor + photons ➔ low x not pos. without upgrades ➔ parton kinematics
δq	measurement of trans-versity quark distributions.	A_N for inclusive hadrons A_T in Interference-Fragmentation A_T Collins FF in jets
Sivers Effect	Measurement of the Sivers distributions, L_z	A_N for back-to-back hadrons $A_{N,T}$ Ds, DY
$\Delta q(x)$ $\Delta \bar{q}(x)$	flavor separation of quark and anti-quark spin distri-butions	not possible without upgrades (muon trigger, FVTX + NCC helpful)

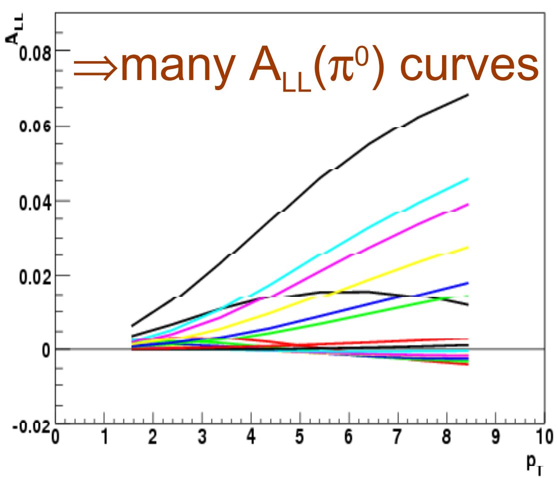
π^0 Asymmetries

Measured asymmetries for $pp \to \pi^0 X$ from Run 5 (2005, published) and Run 6 (2006)





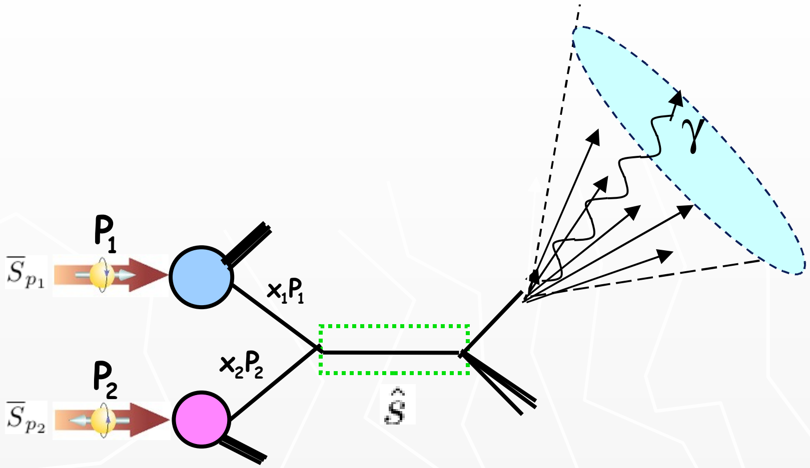
Many different Δg inputs$\Rightarrow$
Many $\Delta g/g$ curves at $Q^2=1$

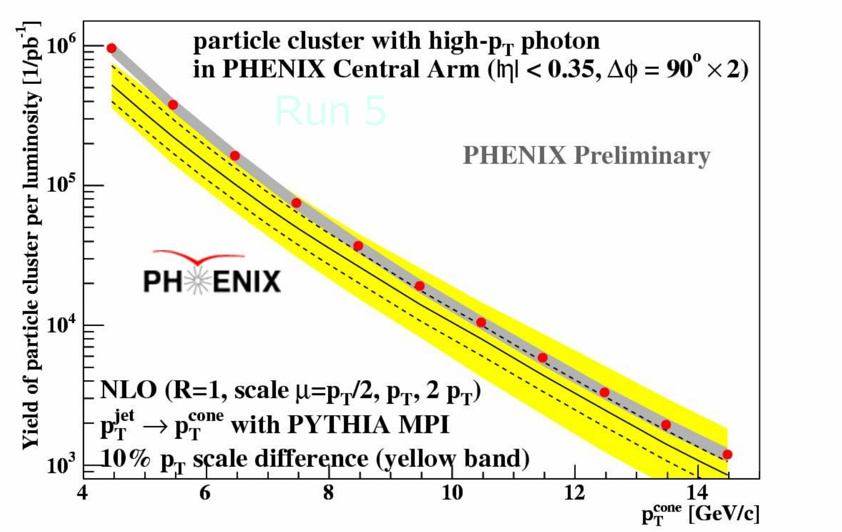


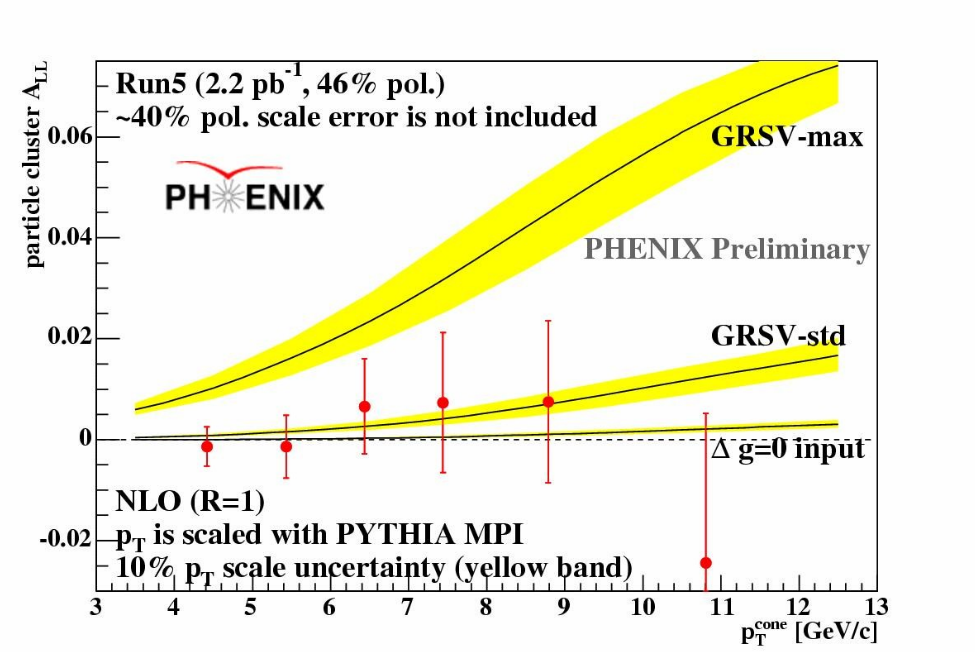
$\Rightarrow$many $A_{LL}(\pi^0)$ curves

A_{LL} of jet-like cluster at $\sqrt{s}$=200GeV

- "Jet" detection: tag one high energy photon and sum energy of nearby photons and charged particles
- Definition of p_T cone: sum of p_T measured by EMCal and tracker with R = $\sqrt{(|\phi|^2+|\eta|^2)}$
- Real p_T of jet is evaluated by tuned PYTHIA



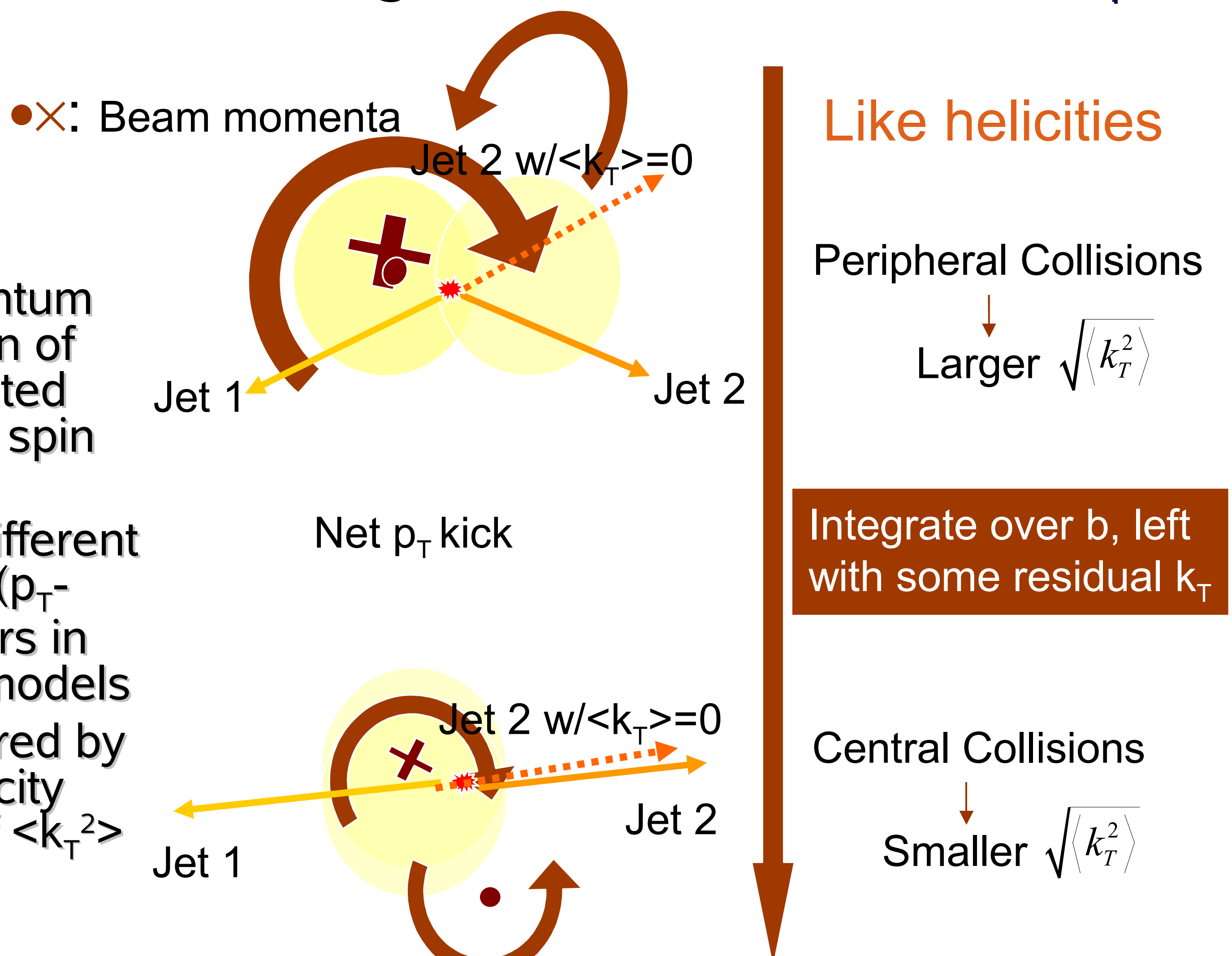




OAM

Probing Quark Orbital Angular Momentum with $<k_T>$

- Partonic orbital angular momentum leads to rotation of partons correlated with the proton spin vector
- This leads to different p_T imbalances (p_T-kicks) of jet pairs in semiclassical models
- Can be measured by measuring helicity dependence of $<k_T^2>$



For details see: Phys. Rev. D 74, 072002 (2006)

Relative Luminosity

- Use BBCs at ±1.5 m from the interaction point to measure bunch-by-bunch luminosity
  - $L_i = N_i/(\sigma \bullet \text{Efficiency})$, $\sigma \bullet$Eff.=const.=22.9mb±9.7%
- Use independent measurement from ZDCs (±18m) to check for intrinsic luminosity asymmetry

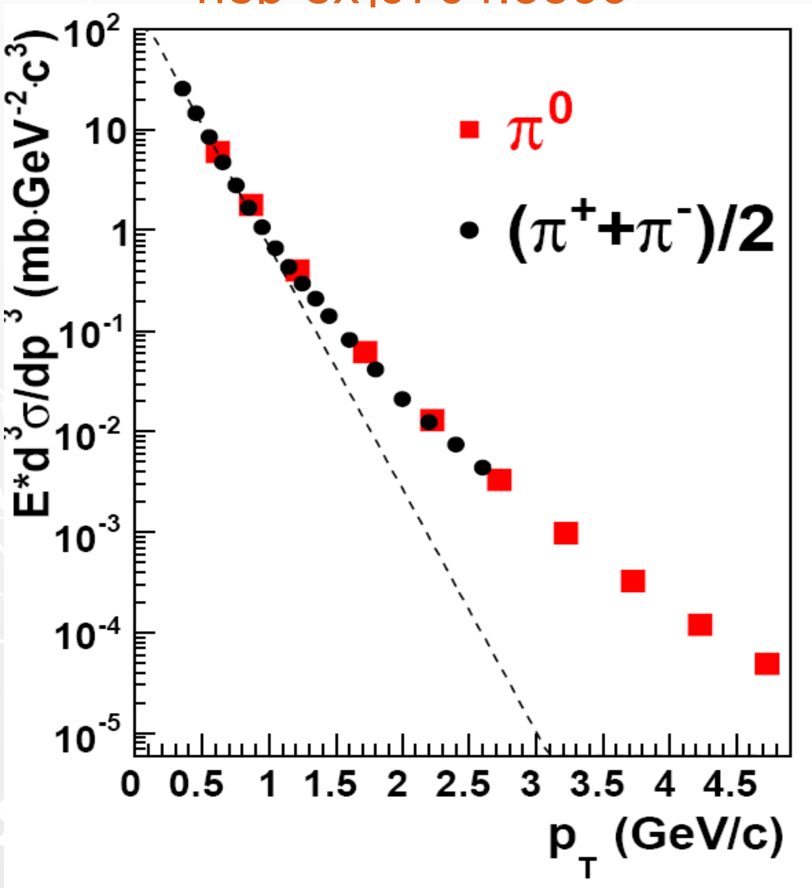
$$\frac{N^{BBC}}{N^{ZDC}} \approx c\left(1 + P_B P_Y (A_{LL}^{BBC} - A_{LL}^{ZDC})\right)$$

- For Run 6 (200 GeV):
  - δA_{LL}(BBC-ZDC)=3.8±1.6*10^{-4} (>2 standard deviations) ⇒ δA_{LL}=5.4*10^{-4}
  - Sizeable asymmetry compared to stat. error of low p_T data
  - Can be instrumental or physics effect → need to find out

π^0 cross section and soft Physics

PHENIX: π^0 mid-rapidity, 200GeV
PHENIX: hep-ex/0704.3599

hep-ex/0704.3599



- Exponent ($e^{-\alpha \cdot pT}$) describes pion cross section 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 p_T $\Rightarrow$ soft physics contribution at p_T>2 GeV/c is <10%

How to measure <k_T>

- Azimuthal di-hadron correlations
  - Width of near side peak $\leftrightarrow$ width of "fragmentation p_T" $\rightarrow \langle j_T \rangle$
  - Width of away side peak $\leftrightarrow$ width of p_T kick from soft/hard QCD radiation and intrinsic k_T $\rightarrow \langle j_T \rangle \oplus \langle k_T \rangle$
  - Expect difference of σ_{far} for like and unlike helicities, if partons carry OAM
- For details see: Phys. Rev. D **74**, 072002 (2006)