Solving the Proton Spin Crisis at

PHENIX

Christine Aidala
Columbia University

ISSP, Erice
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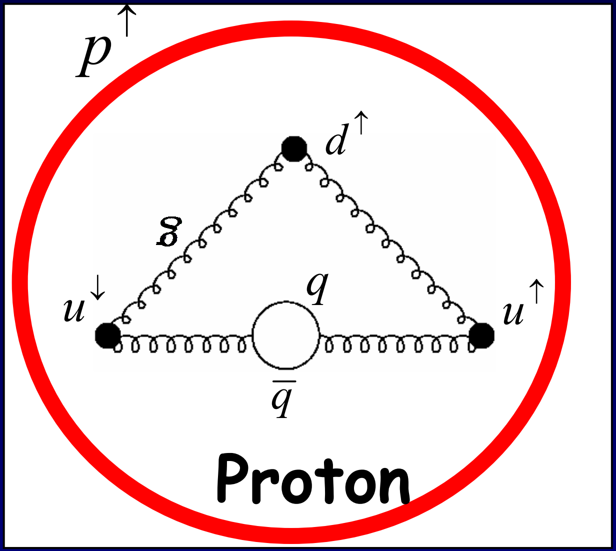
The Proton Spin Crisis



In the naïve parton model, a proton consists of two valence up quarks and one down. With a total proton spin of 1/2, the simplest expectation would be that two valence quarks have spin +1/2 and one -1/2.

Surprising data from polarized muon-nucleon scattering at CERN in the late 1980s! Only 12% +- 16% of proton's spin carried by quark spin!

The proton spin crisis begins!!

Quark Spin

Gluon Spin

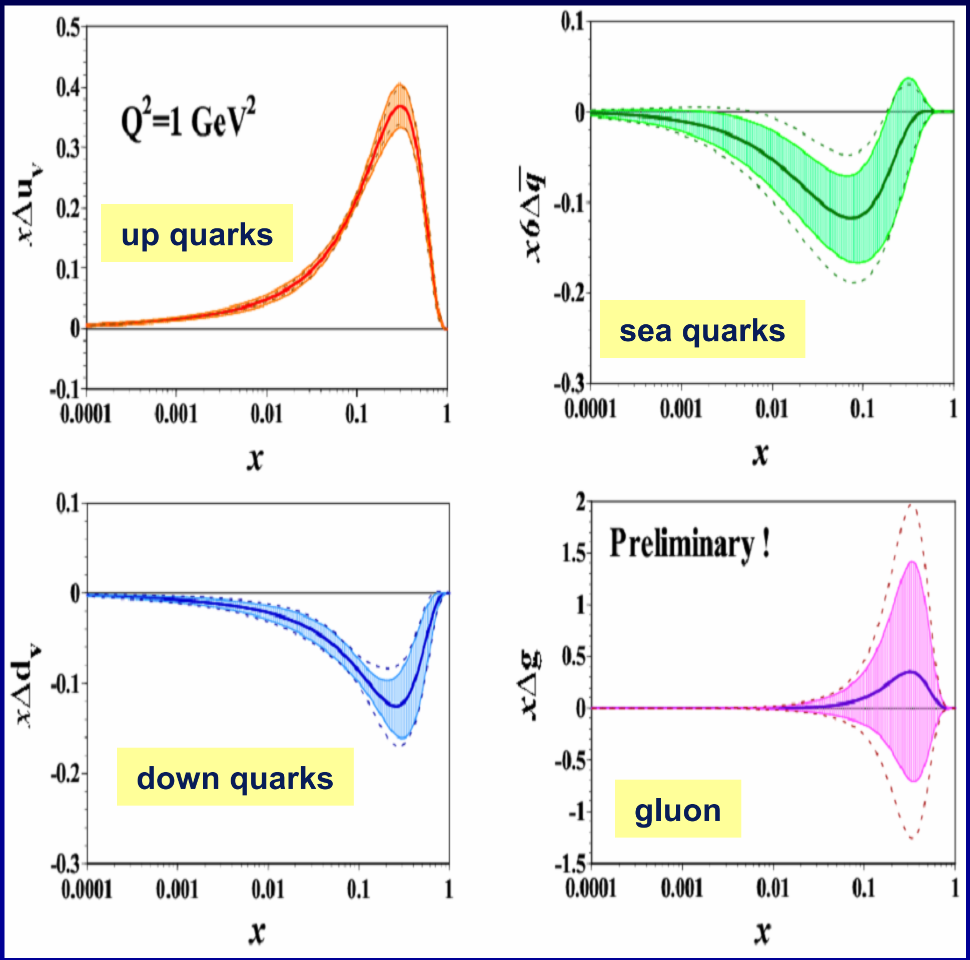
Spin $\quad \dfrac{1}{2} = \dfrac{1}{2}\Delta\Sigma + \Delta G + L_z$

Orbital Angular Momentum

The rest now expected to be from gluon spin and orbital angular momentum of quarks and gluons, but this hasn't been easy to measure!

Polarized quark and gluon distributions

M. Hirai et al (AAC collab)



EMC, SMC at CERN
E142 to E155 at SLAC
HERMES at DESY

$\Delta\Sigma = \int_0^1 \Delta\Sigma(x,Q^2)dx$ **is constrained**

$\Delta G = \int_0^1 \Delta g\left(x,Q^2\right)dx$ **is largely unknown**

Even the sign of the gluon spin contribution remains unconstrained!

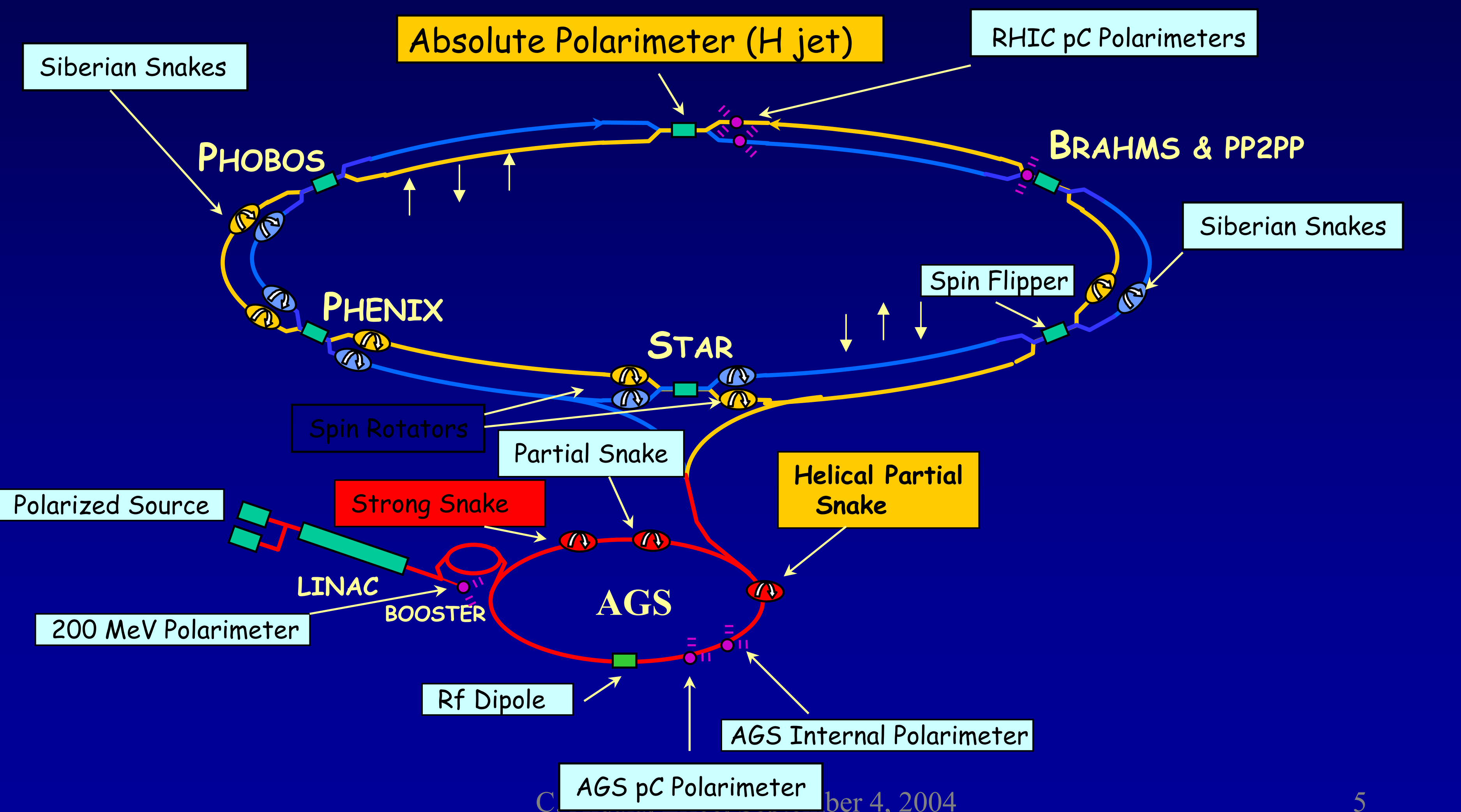
RHIC Physics

Broadest possible study of QCD in A-A, p-A, p-p collisions

- *Heavy ion physics*
    - Investigate nuclear matter under extreme conditions
    - Examine systematic variations with species and energy
- *Nucleon structure in a nuclear environment*
    - Nuclear dependence of pdf's
    - Saturation physics
- ***Explore the spin of the proton***
    - In particular, contributions from
        - Gluon polarization (ΔG)
        - Sea-quark polarization $\left(\Delta\bar{u}, \Delta\bar{d}\right)$
        - Transversity distributions (δq)

RHIC as a Polarized p-p Collider

source: Thomas Roser, BNL

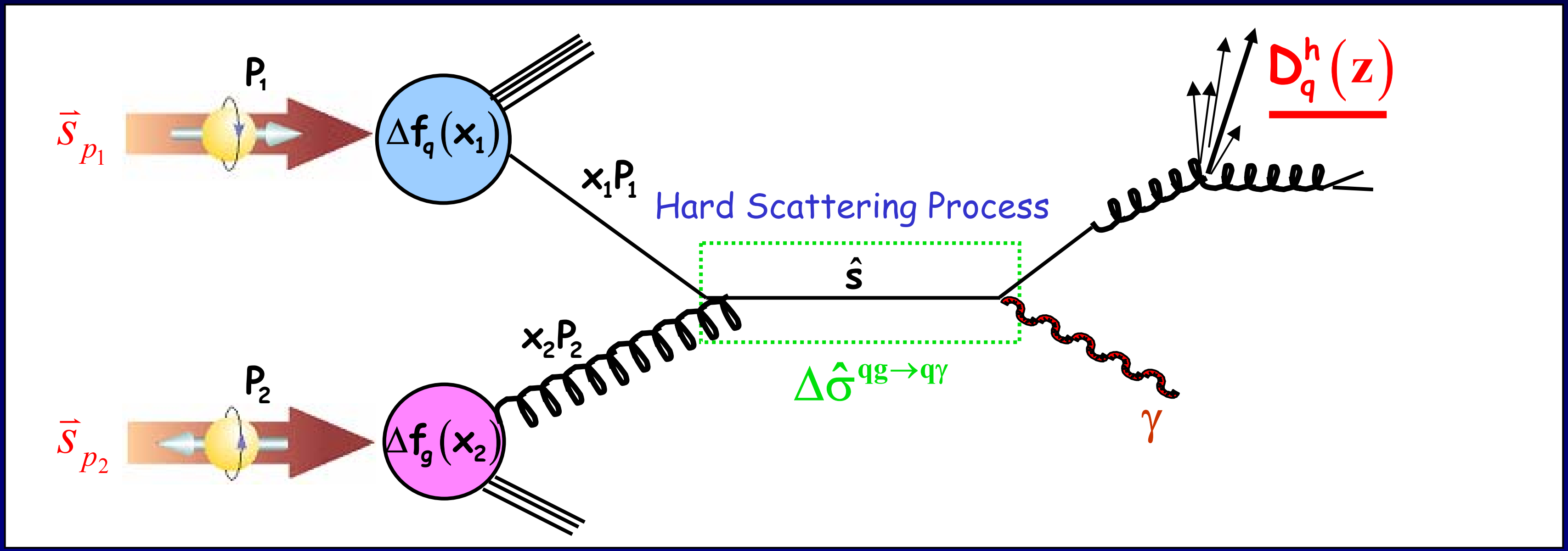


Proton Spin Structure at PHENIX

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π Production $A_{LL}(gg, gq \to \pi + X)$ Prompt Photon $A_{LL}(gq \to \gamma + X)$ Heavy Flavors $A_{LL}(gg \to c\bar{c}, b\bar{b} + X)$	W Production $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	Transversity δq: π^+, π^- Interference fragmentation: $A_T\left(p_\perp p \to (\pi^+, \pi^-) + X\right)$ Drell Yan A_{TT} Single Asymmetries A_N

- Why RHIC?
  - High energy (collider rather than fixed target) ➔ factorization
  - High energy ➔ new probes (W's)
  - Polarized hadrons (rather than DIS) ➔ gq, gg collisions

Hard Scattering in Polarized p+p: Factorization

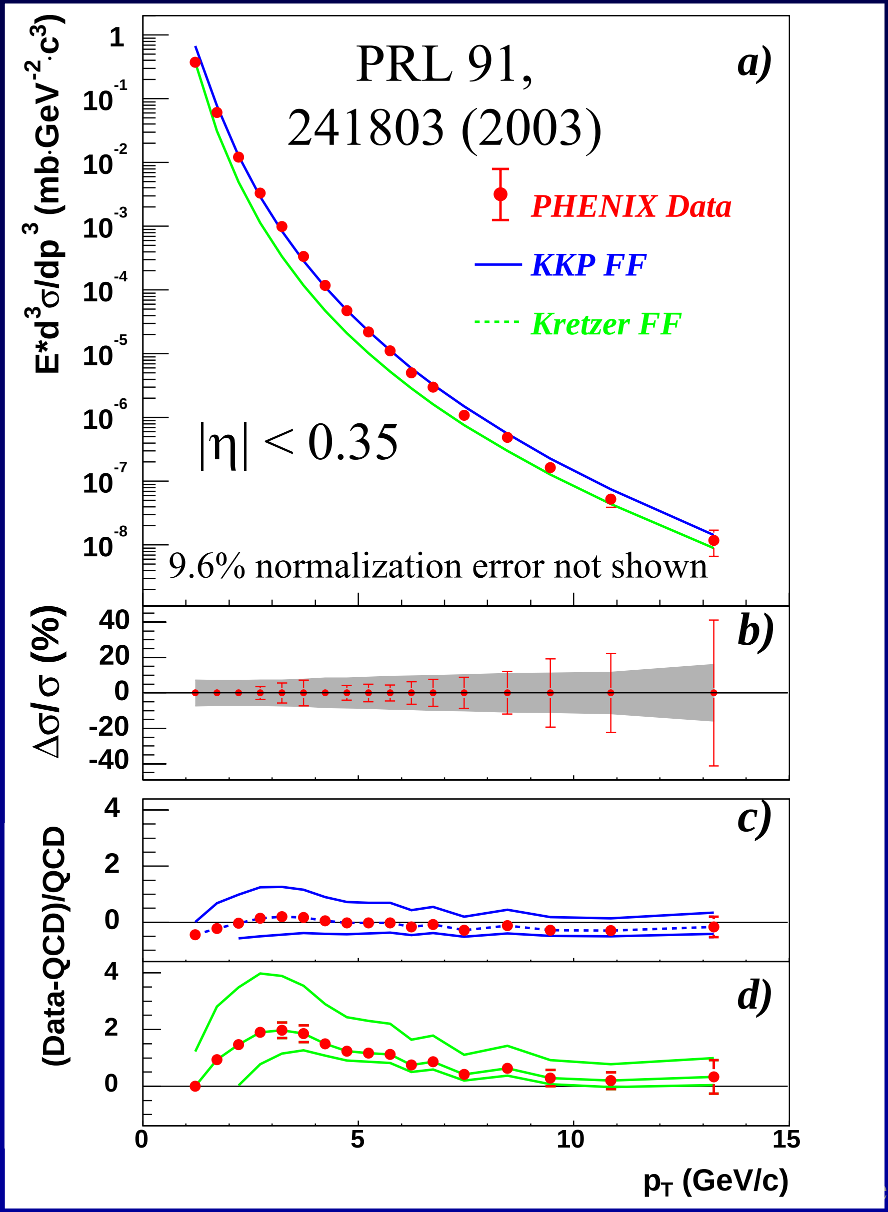


$$\Delta\sigma(pp \to \gamma X) \propto \underline{\Delta f_q(x_1) \otimes \Delta f_g(x_2)} \otimes \underline{\Delta\hat{\sigma}^{qg\to q\gamma}(\hat{s})}$$

"Hard" probes have predictable rates given:

- Parton distribution functions (need experimental **input**)
- **pQCD hard scattering rates (calculable in pQCD)**
- **Fragmentation functions (need experimental input)**

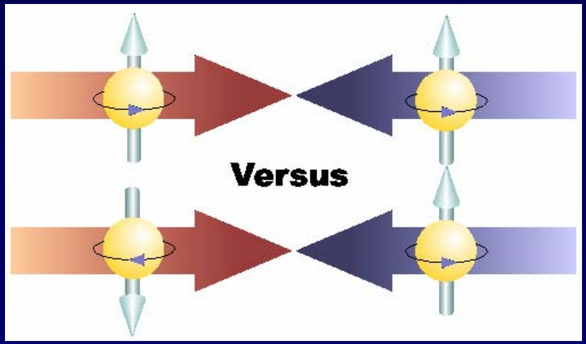
π^0 Cross Section from 2001-2 Run



- NLO pQCD consistent with data within theoretical uncertainties.
  - PDF: CTEQ5M
  - Fragmentation functions:
    - Kniehl-Kramer-Potter (KKP)
    - Kretzer
  - Spectrum constrains D(gluon ➡ π) fragmentation function
- **pQCD and factorization work at RHIC for unpolarized data. Therefore expect to be able to apply it in the interpretation of polarized data.**

How Can We Investigate the Proton's Spin at PHENIX?

$$Asymmetry \propto \frac{B-C}{B+C}$$



- Collide polarized protons in different configurations and see what we observe in our detector
- Most often examining *asymmetries*
  - *e.g.* difference in production rate of a certain particle when the beams have the same vs. opposite polarization
- Knowing what partonic processes led to production of the observed particle gives us a handle on the quarks' and gluons' contribution to the spin.

Recent Neutral Pion Measurements at PHENIX

- π^0 production in currently accessible kinematic region at PHENIX mostly due to gluon-gluon scattering
  - Single-transverse spin measurements, in which one colliding proton beam is polarized transversely with respect to the momentum direction, can probe the instrinsic transverse momentum distribution of (mostly) the gluons
  - Double-longitudinal spin measurements, in which both colliding beams are polarized parallel or antiparallel to the momentum direction, can probe the gluon spin's contribution to the (longitudinal) spin of the proton

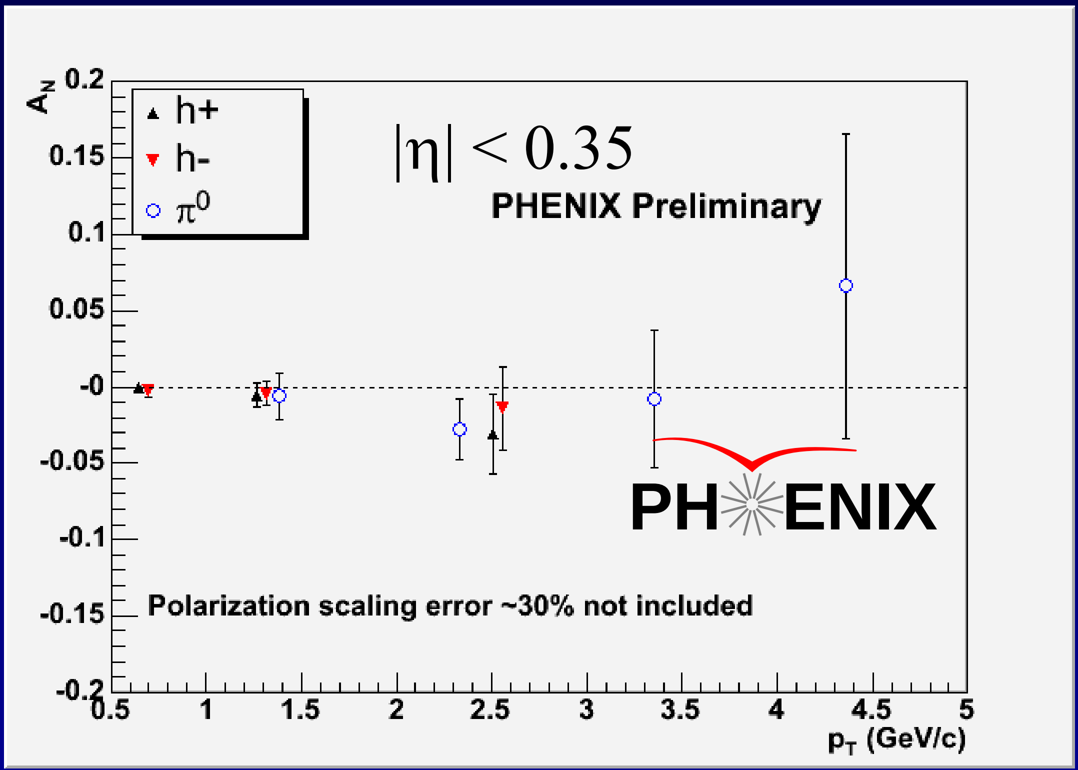
Single-transverse spin asymmetries A_N

$$A_N^{\mathrm{Left}} = \frac{1}{P} \cdot \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Large single-transverse spin asymmetries (~20-40%) seen previously at lower energies, as well as for forward production of neutral pions at the STAR experiment, which various models have tried to explain

- Sivers Effect – Spin-dependent initial partonic transverse momentum
- Collins Effect – Spin-dependent transverse momentum kick in fragmentation
  - Requires *transversity*, the degree to which *quarks* are transversely polarized in a transversely polarized proton, to be non-zero

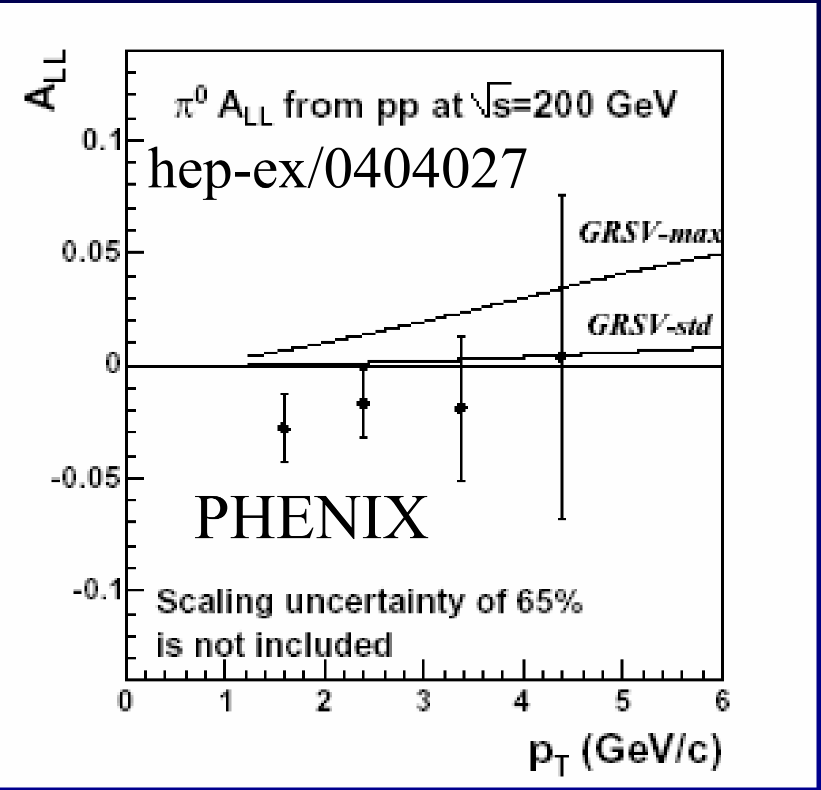
A_N for Neutral Pions and Charged Hadrons



Asymmetry for both neutral pions and charged hadrons consistent with zero.

- Current data primarily sensitive to Sivers effect because particle production in this kinematic region is mostly from gluon scattering
- Future measurements reaching higher transverse momentum will be dominated instead by quark scattering and thus more sensitive to transversity + Collins

A_{LL} Measurements: To Probe the Gluon Polarization's Contribution to the Spin of the Proton



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

++ same helicity $\quad$ N: # pions

+– opposite helicity $\quad$ R: luminosity++/luminosity+-

Comparison with two NLO pQCD calculations:

M. Glueck et al., PRD 63 (2001) 094005

B. Jaeger et al., PRD 67 (2003) 054005

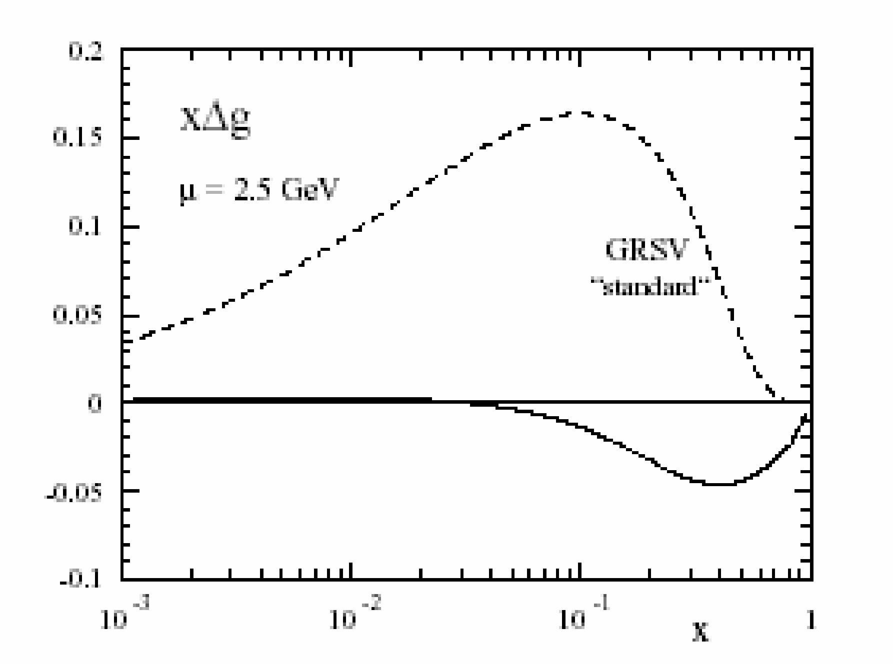
Hints at a negative asymmetry?? But since neutral pion production in this case is dominated by gluon-gluon scattering, Δg should enter the factorized cross section squared, making a negative asymmetry impossible!

One Possibility: A Node in Δg

- Since the gluons aren't necessarily probed at exactly the same *x*, a node in Δg would allow a negative A_{LL}.
- However, analytical calculation of a lower bound on A_{LL} for neutral pions finds

$$A_{LL}^{\pi}\,|_{\min} \cong O(-10^{-3})$$

- Need more data! Smaller error bars, greater p_T range, and *charged* pion asymmetries. Since charged pions have a significant contribution from quark-gluon scattering, they will allow a clearer determination of the sign of Δg. Work in progress!



Jaeger et al., PRL 92 (2004) 121803

Conclusions

- Understanding the details of the proton's spin has been a challenging question for the past 25 years and remains so today.
- RHIC, as the world's first polarized proton collider, has opened up a new regime in which to study proton spin.

The proton spin crisis continues, but the RHIC spin program looks forward to many more years of exciting and elucidating results.