Challenging Nucleon Spin
– A Report from the PHENIX Experiment

@ XIX International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics & Quantum Chromodynamics"
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What are we aiming at?

- To answer the question: "Where the proton spin comes from?"
- Background: Lepton DIS
  - Quark spin carries only 20-30% of proton spin
    $\rightarrow$spin puzzle
- What carries the rest?
  - Gluon?
  - Orbital angular momentum?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \underbrace{\Delta G}_{\text{RHIC spin}} + L$$

What we can’t know from DIS

- Photon mediated → sensitive to charge^2
  - u : d : s : g = 4 : 1 : 1 : 0
  - Gluon is invisible!
    (c.f., indirect methods: Q^2 evolution, photon-gluon fusion)

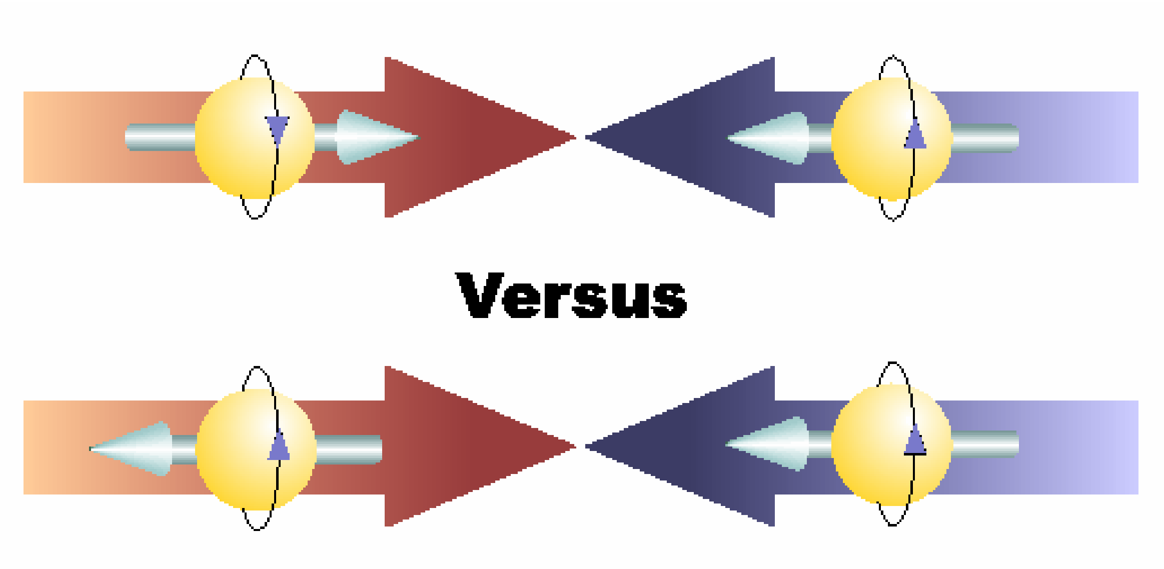
- Can we see gluons directly?
  → Yes, what we need is a

Proton-Proton collider

What we measure?

$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$

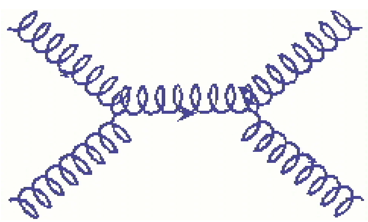
~ (parton pol.)^2 × (a_{LL} in parton reaction)



How can we access gluons?

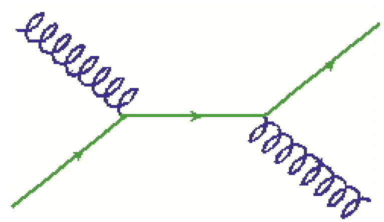
- Typical parton level diagrams LO

$$gg \to gg$$



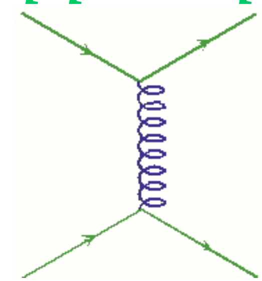
$$\propto \frac{\Delta g}{g}\frac{\Delta g}{g}$$

$$gq \to gq$$



$$\propto \frac{\Delta q}{q}\frac{\Delta g}{g}$$

$$qq \to qq$$



$$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$$

- What we actually measure are not partons, but fragmented hadrons
  - Come from different mix of partons
  - Parton information e.g., Bjorken x is obscured

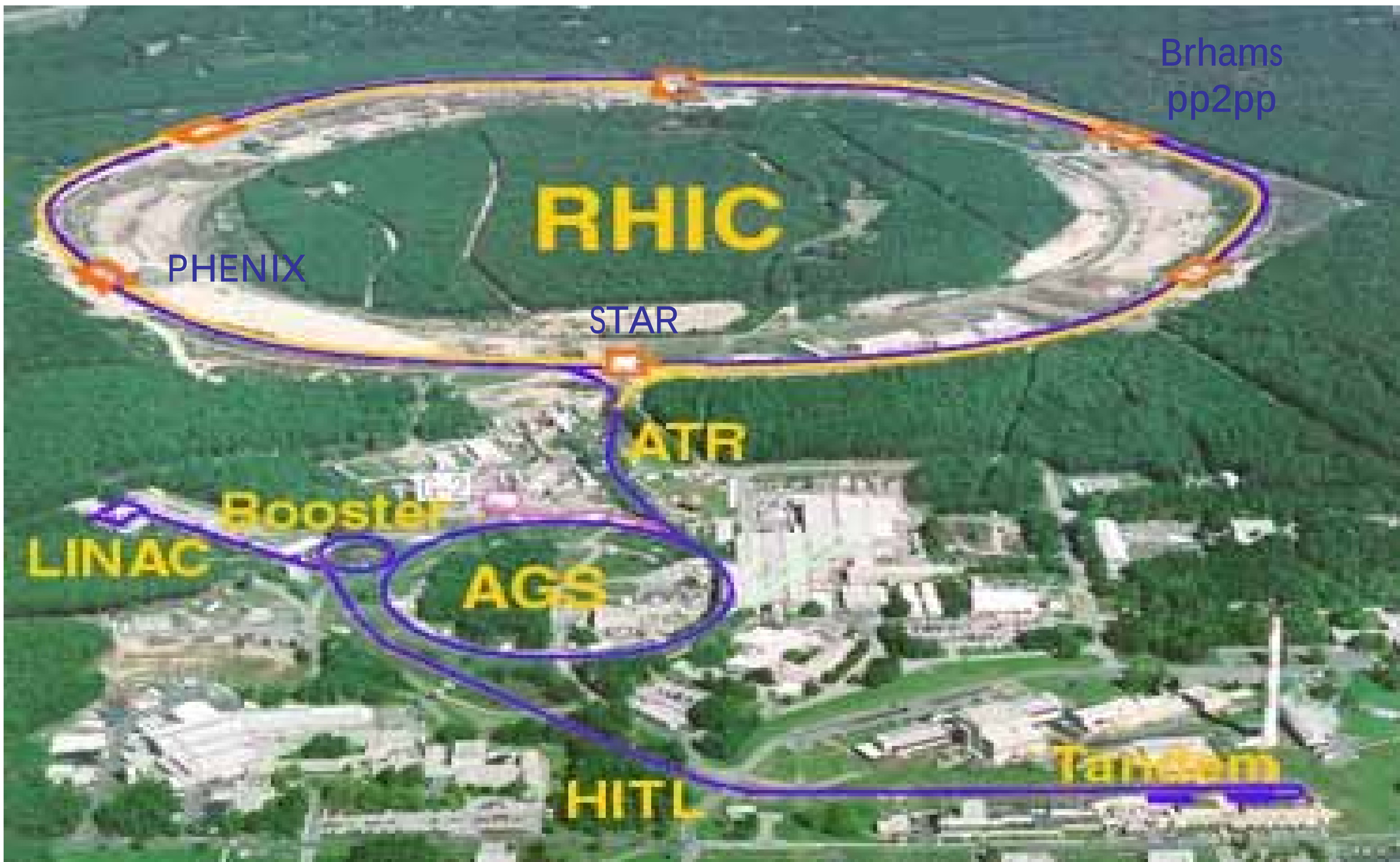
Some examples

- Direct photon: $g + q \rightarrow \gamma + q$
  - No fragmentation
  - Small contamination (e.g. $\bar{q}q \rightarrow \gamma\gamma$)

  → golden channel
- Jet, high-p_T hadron production
  - Mix of all subprocesses
  - LO → highest statistics

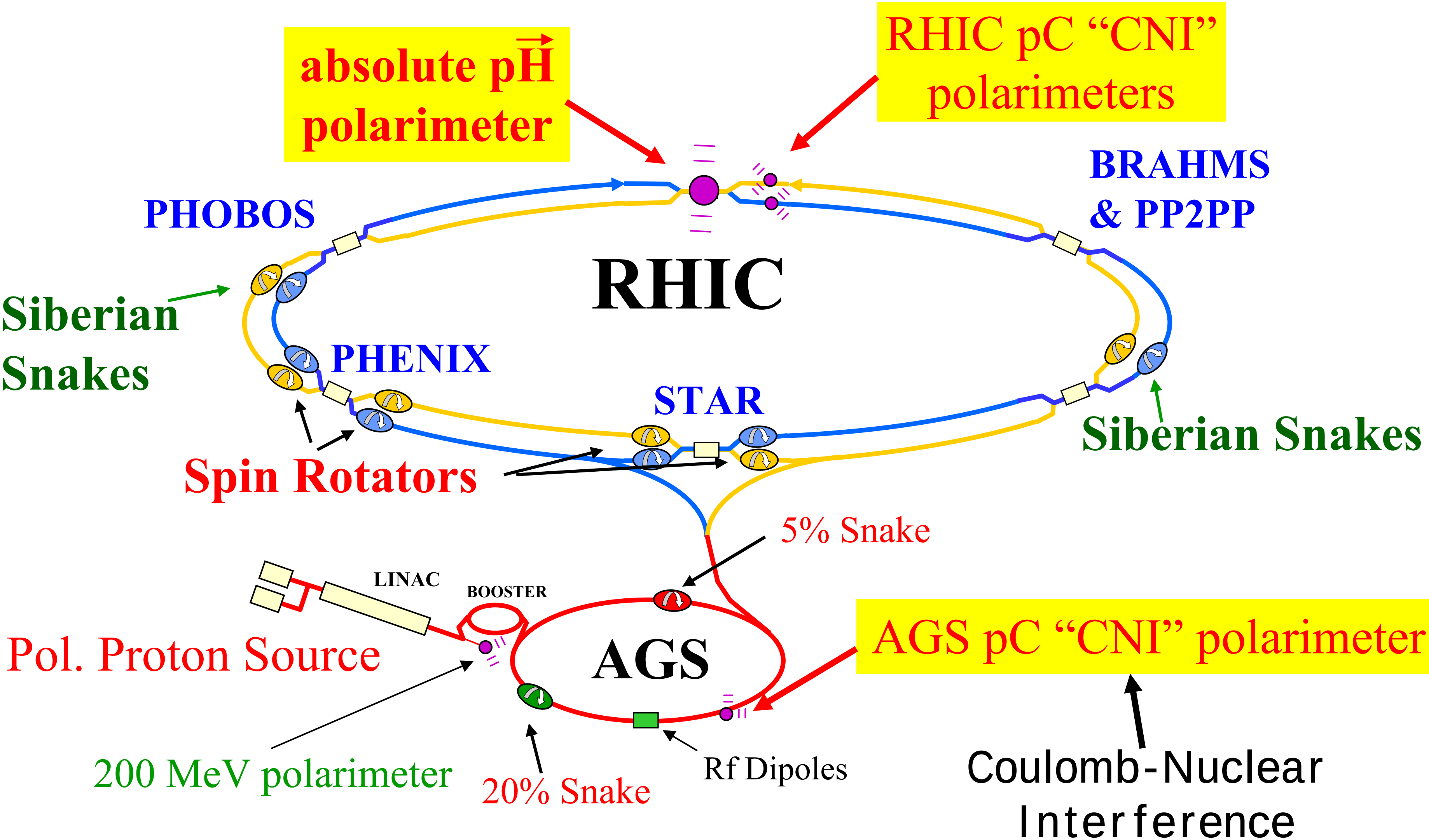
  →Good measurement with lower luminosity
- Heavy quarks (charm, bottom)
  - $gg \rightarrow \bar{q}q$ is the main process at RHIC
- W sensitive to quark flavors
  - e.g., W^+ comes from $\bar{d}u$

The Relativistic Heavy Ion Collider accelerator complex at Brookhaven National Laboratory



RHIC *p+p* accelerator complex

The polarimeters are experimental devices



PHENIX Experiment

Pioneering High Energy Nuclear Interaction EXperiment

PHENIX

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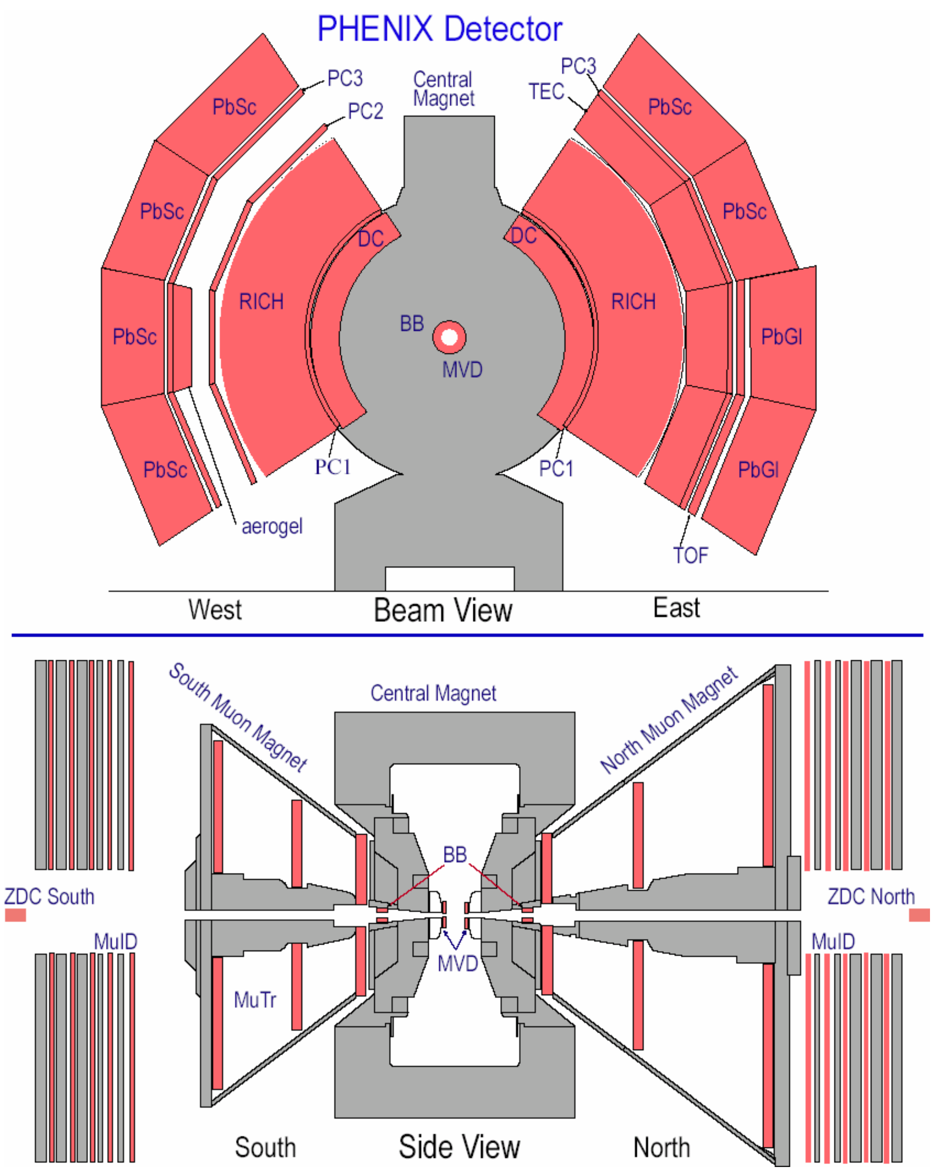
***as of March 2005**

The PHENIX Detector



- Philosophy
  - high resolution & high-rate at the cost of acceptance
  - trigger for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi \sim \pi$
  - γ, π^0, e, π^{+-}, ... – Identified
  - Momentum, Energy
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum (MuTr)

Accumulated data

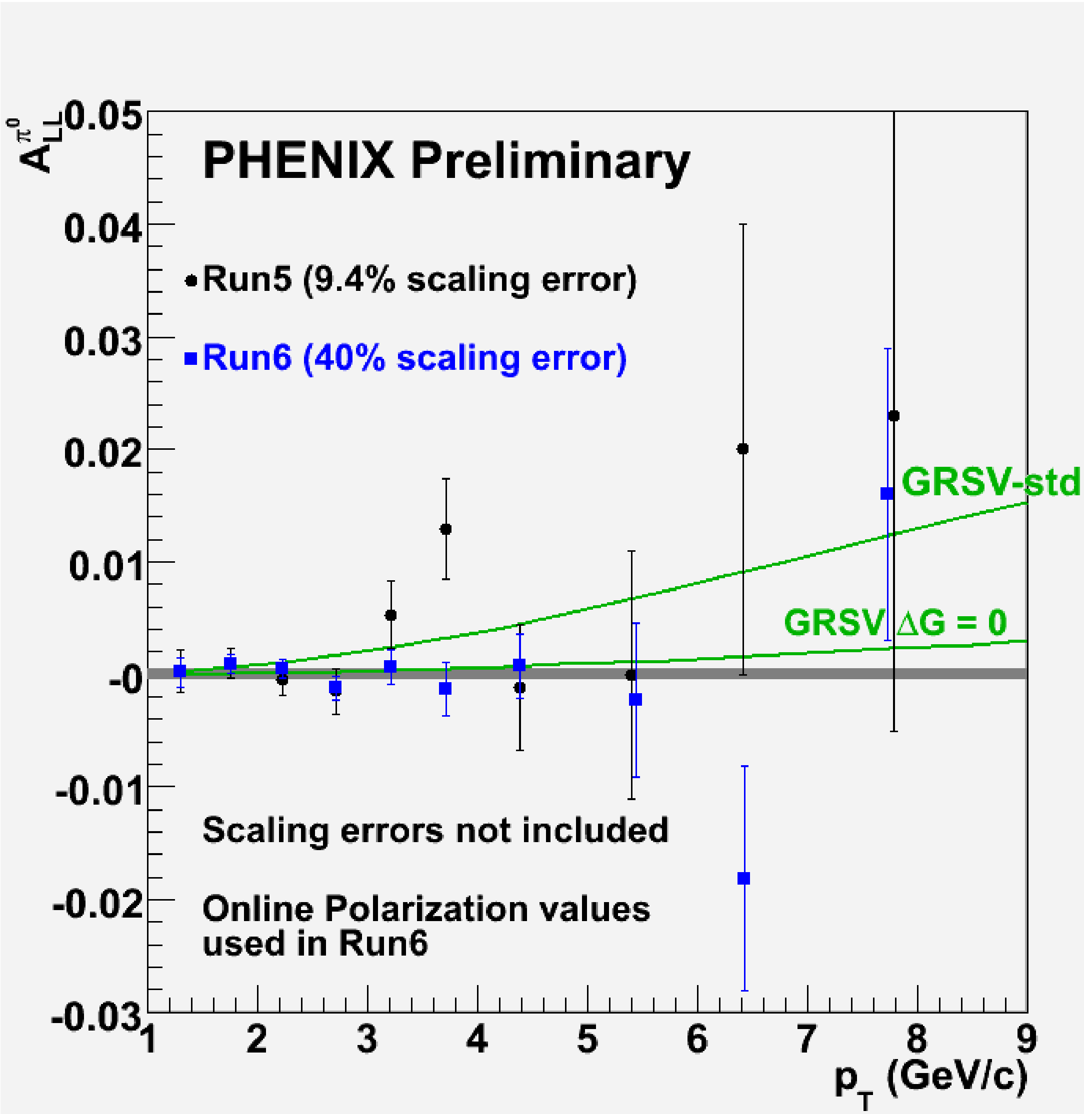
Longitudinal polarization

Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^4L)
2003 (Run 3)	200	.35 pb^{-1}	27	1.5 nb^{-1}
2004 (Run 4)	200	.12 pb^{-1}	40	3.3 nb^{-1}
2005 (Run 5)	200	3.4 pb^{-1}	49	200 nb^{-1}
2006 (Run 6)	200	7.5 pb^{-1}	57	690 nb^{-1}
2006 (Run 6)	62.4	.10 pb^{-1}	48	5.3 nb^{-1}

Transverse polarization

Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2001 (Run 2)	200	.15 pb^{-1}	15	3.4 nb^{-1}
2005 (Run 5)	200	.16 pb^{-1}	47	38 nb^{-1}
2006 (Run 6)	200	2.7 pb^{-1}	51	700 nb^{-1}
2006 (Run 6)	62.4	.02 pb^{-1}	48	4.6 nb^{-1}
2008 (Run 8)	200	5.2 pb^{-1}	46	1100 nb^{-1}

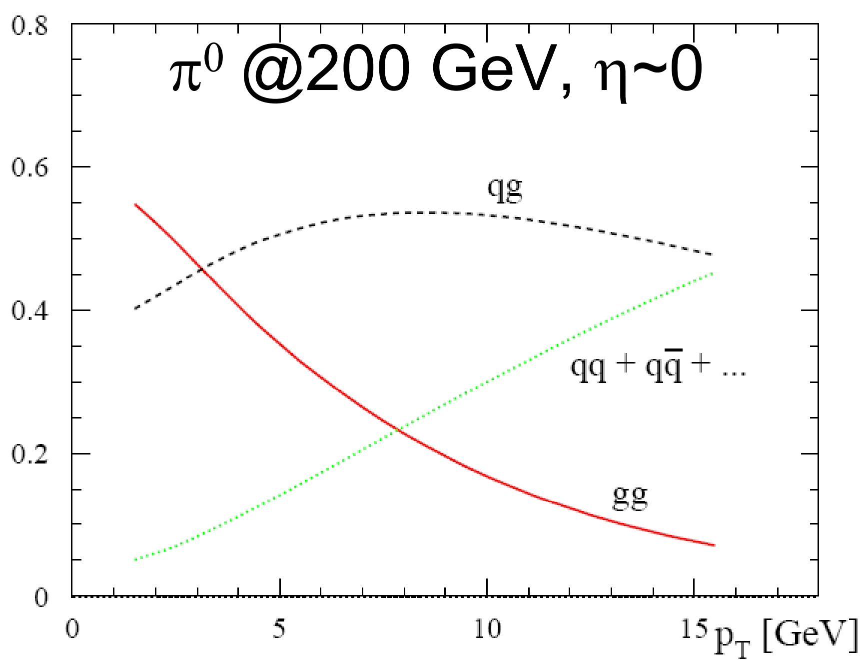
Result: π^0 A_{LL}

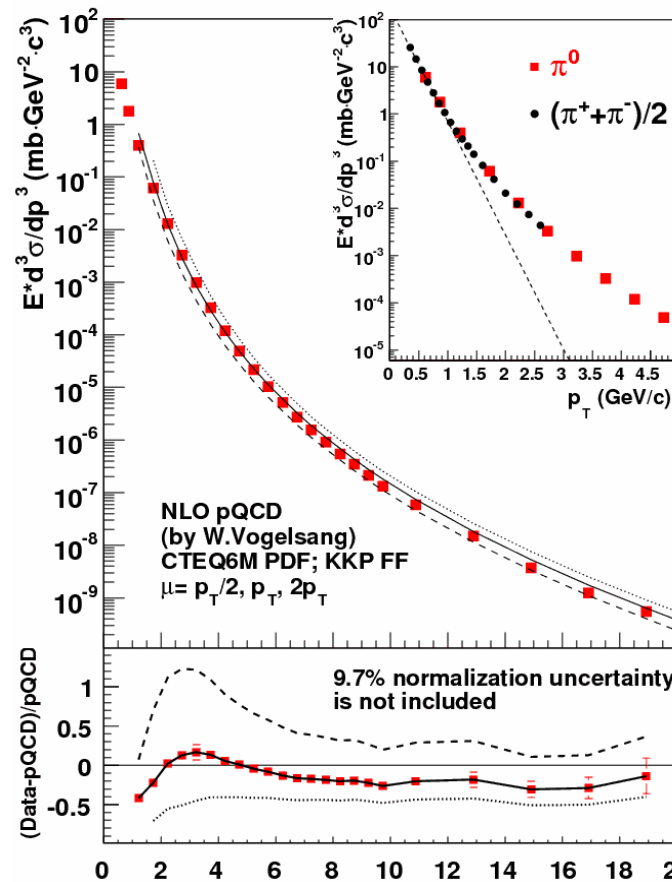


- Run6 scaling error based on online polarization values. Final scaling error expected to be ~10%
- Grey band is systematic uncertainty due to Relative Luminosity, and is pT independent.
- New paper will be submitted next week!

How to extract $\Delta g(x)$? (1)

- π^0s come from quarks and gluons of various x
  → Deconvolution necessary
- Are we sure that we understand contribution of partons? YES!
  - NLO-pQCD calculation reproduces σ well





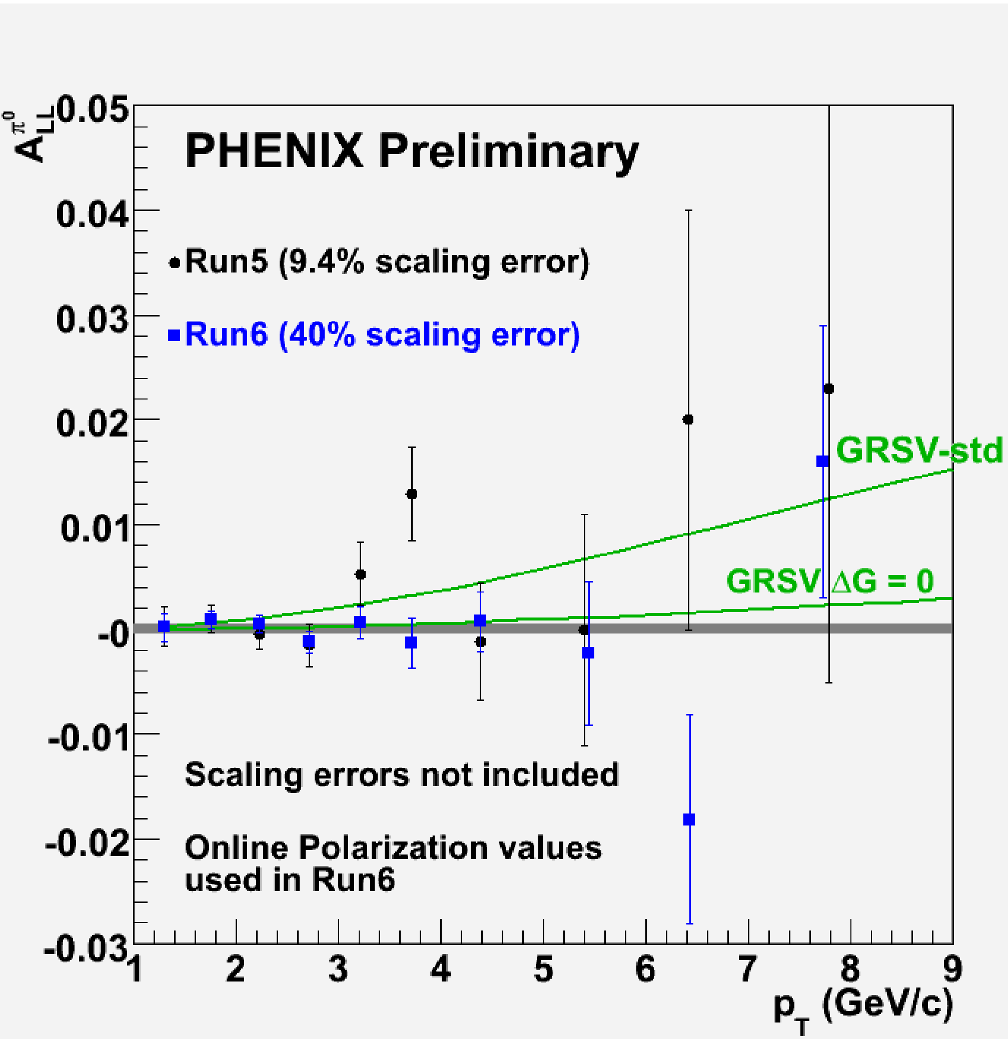
PRD76:051106,2007

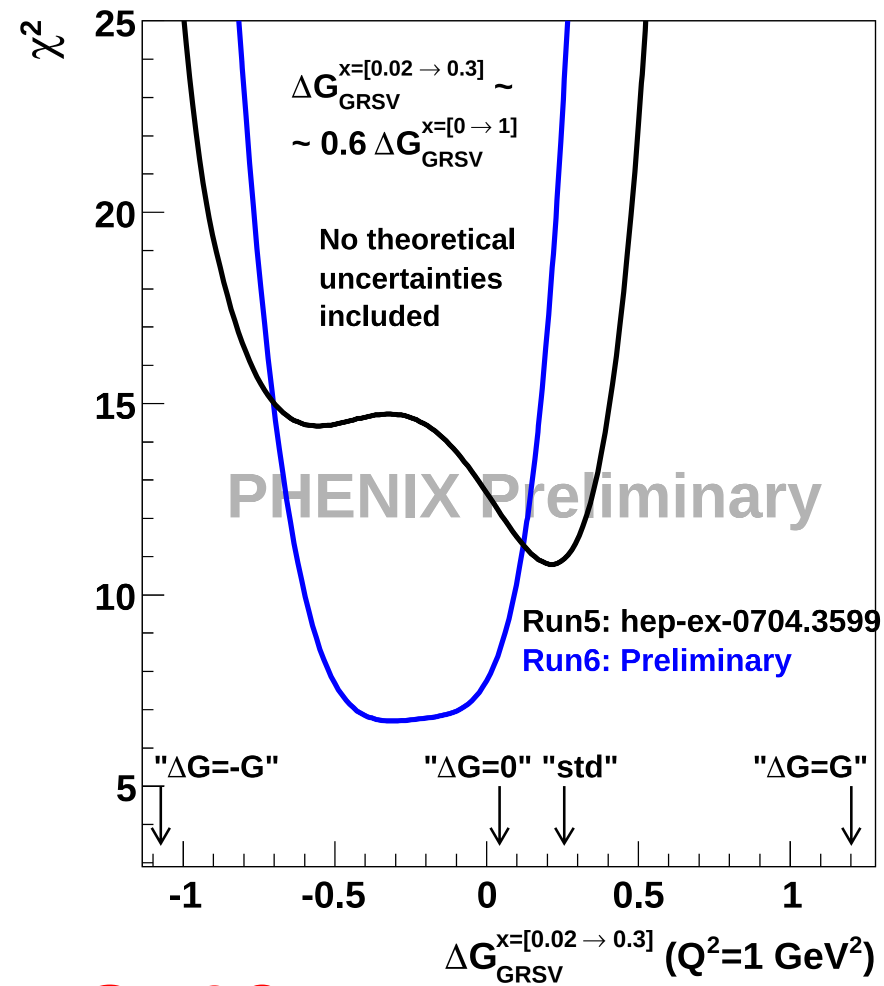
How to extract $\Delta g(x)$? (2)

- Practical analysis
  - Assume functional form: e.g., $\Delta g(x)=Cg(x)x^{\alpha}(1-x)^{\beta}$
  - Search optimum parameters using data, including DIS.
- Ex GRSV M. Gluck et al., PRD 63 (2001) 094005.
  - Assume ΔG, other parameters are determined from DIS.
  - Several versions for various ΔG GRSV-std, max, min, ...
- Several other analyses
  - For the same integral, ΔG, $\Delta g(x)$ could be very different
  - Our measurement mostly constrains $\Delta G_{[0.02,0.3]}$

- Details are available in our new paper (to be submitted next week)

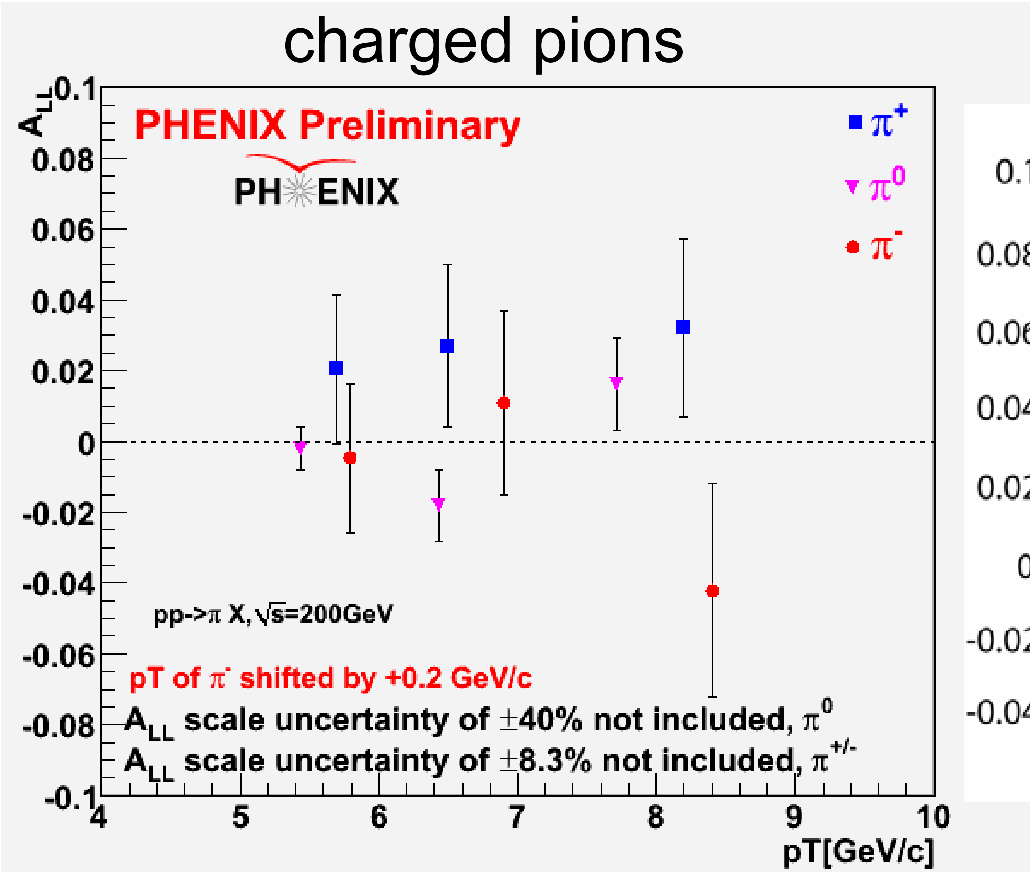
ΔG from π^0 A_{LL}

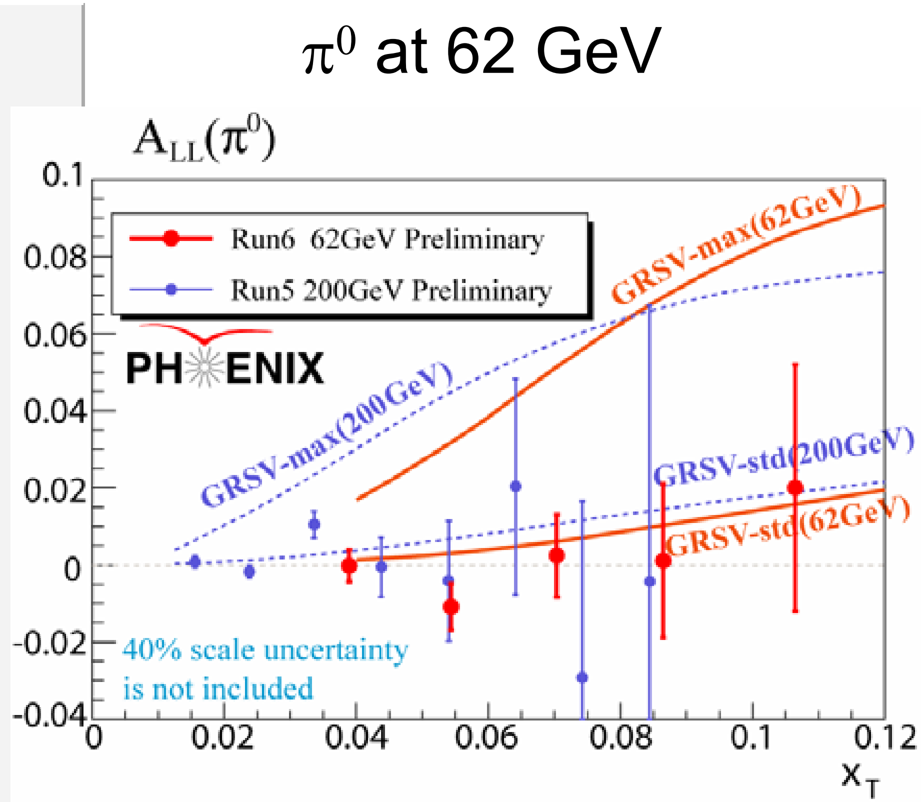




$\Delta G \sim 0$?

More results





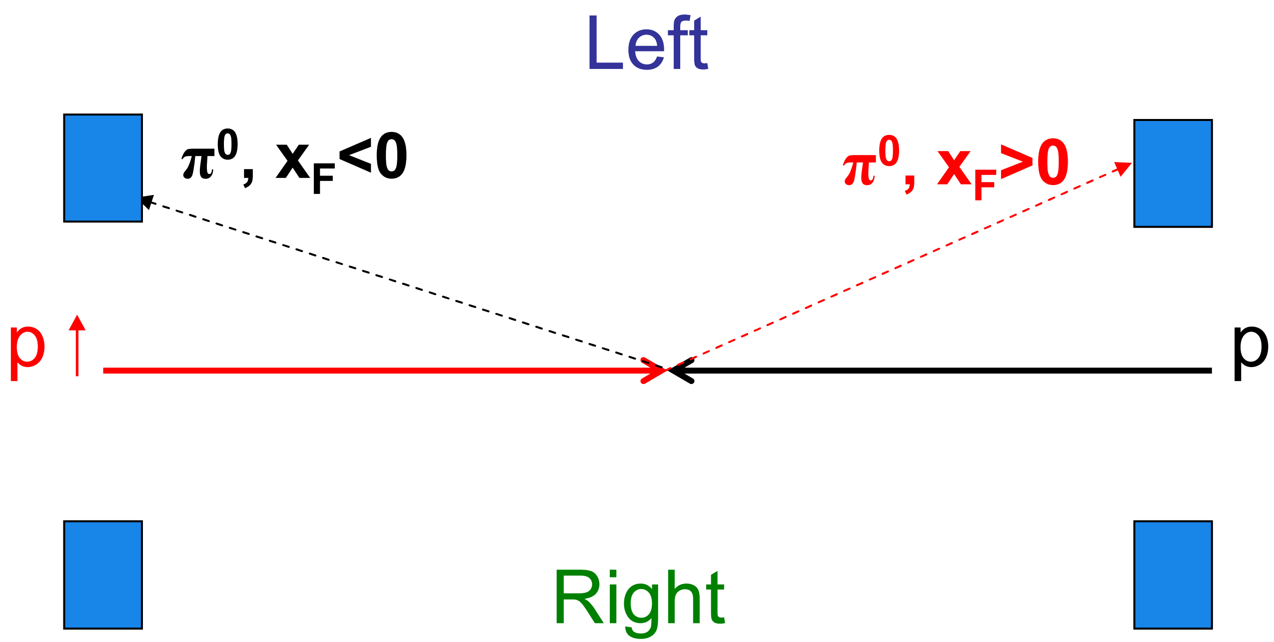
higher sensitivity for larger x

Same gg contribution in π^+ & π^-
→ sign of Δg

Also: direct γ, η, jet, J/ψ, e, μ, ... no time to show them all

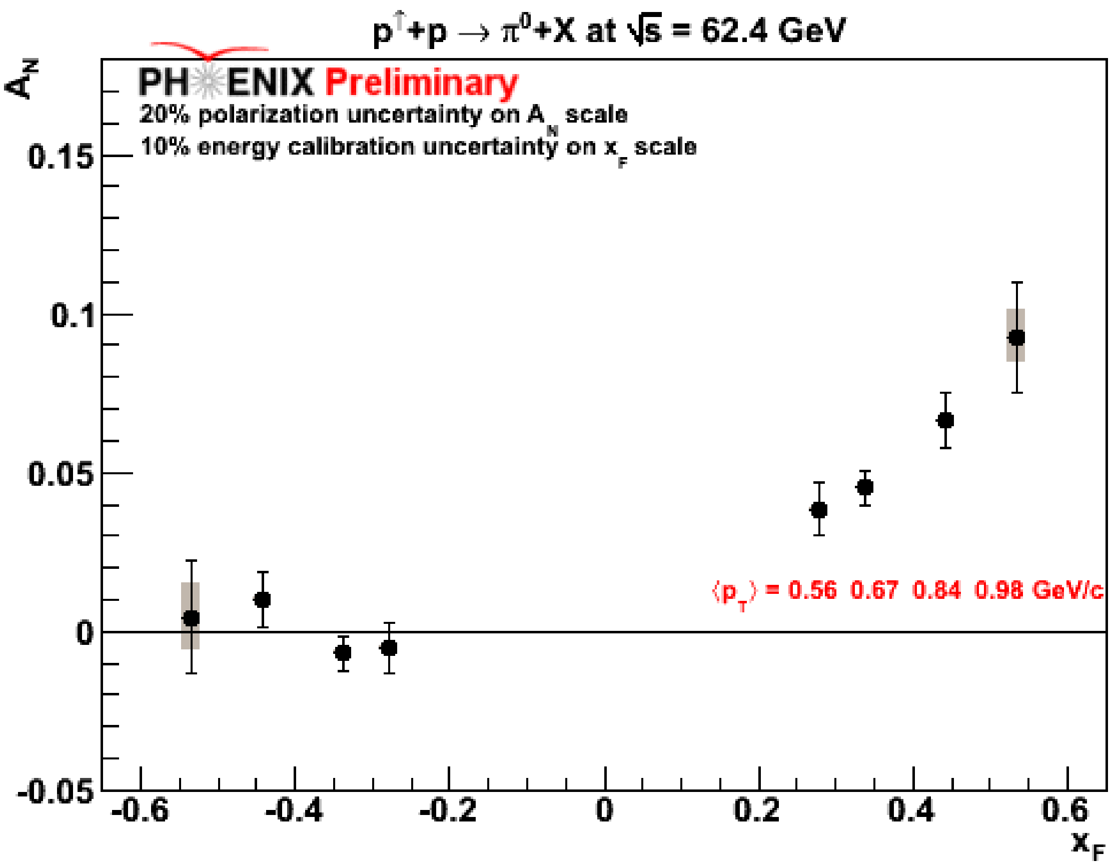
Transverse spin physics

- Transversity δq: Due to Einstein's relativity, not the same as Δq
  - Unexplored leading twist PDF
  - Seen as A_N (via Collins effect) and A_{TT}
- A_N left-right asymmetry wrt transverse polarization



Forward pions

- Naive pQCD predicts $A_N \sim m_q/\mathrm{sqrt}(s) \sim 0$



However, large A_N observed in forward pions. **WHY??**

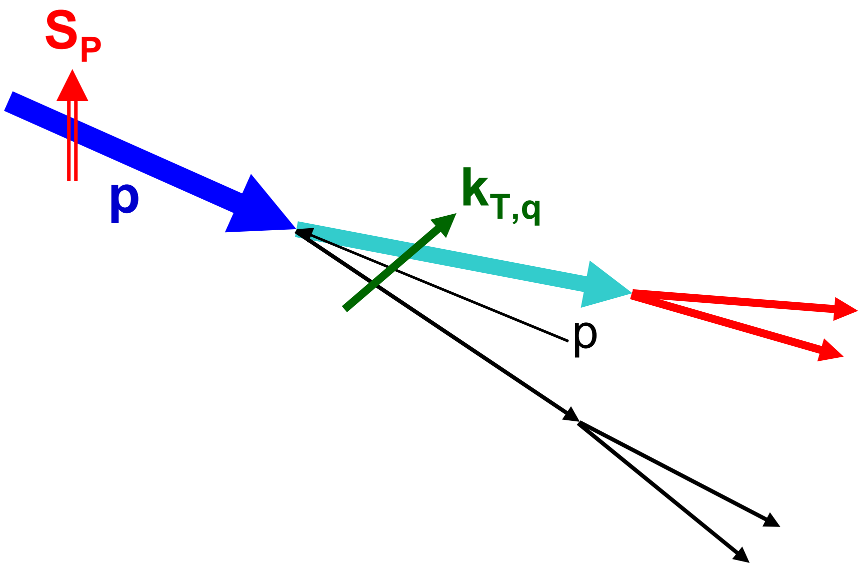
Proposed mechanisms
- -Sivers
- -Collins
- -Twist 3
- -...

Very hot recently

Possible mechanisms (ex.)

Sivers mechanism:

correlation between proton spin & parton k_T

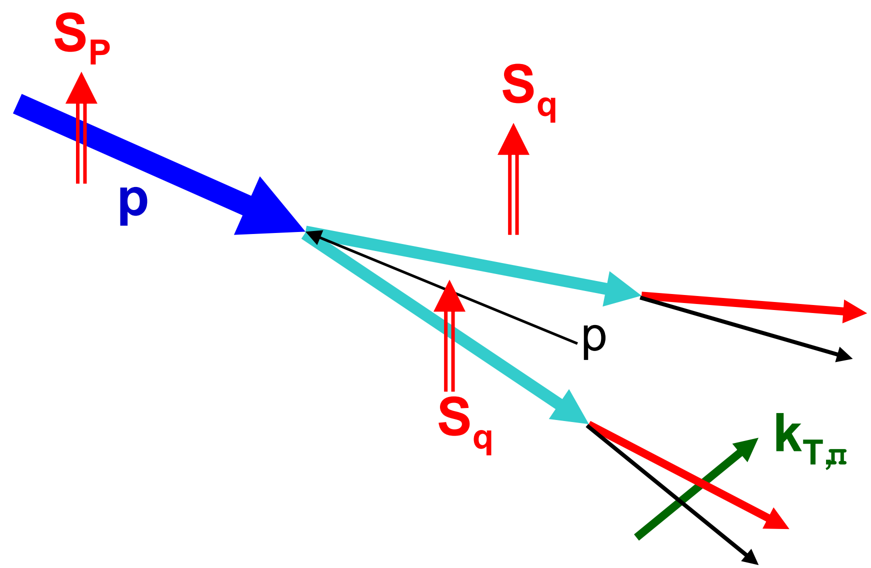


Phys Rev D41 (1990) 83; 43 (1991) 261

gluon effect? yes

Collins mechanism:

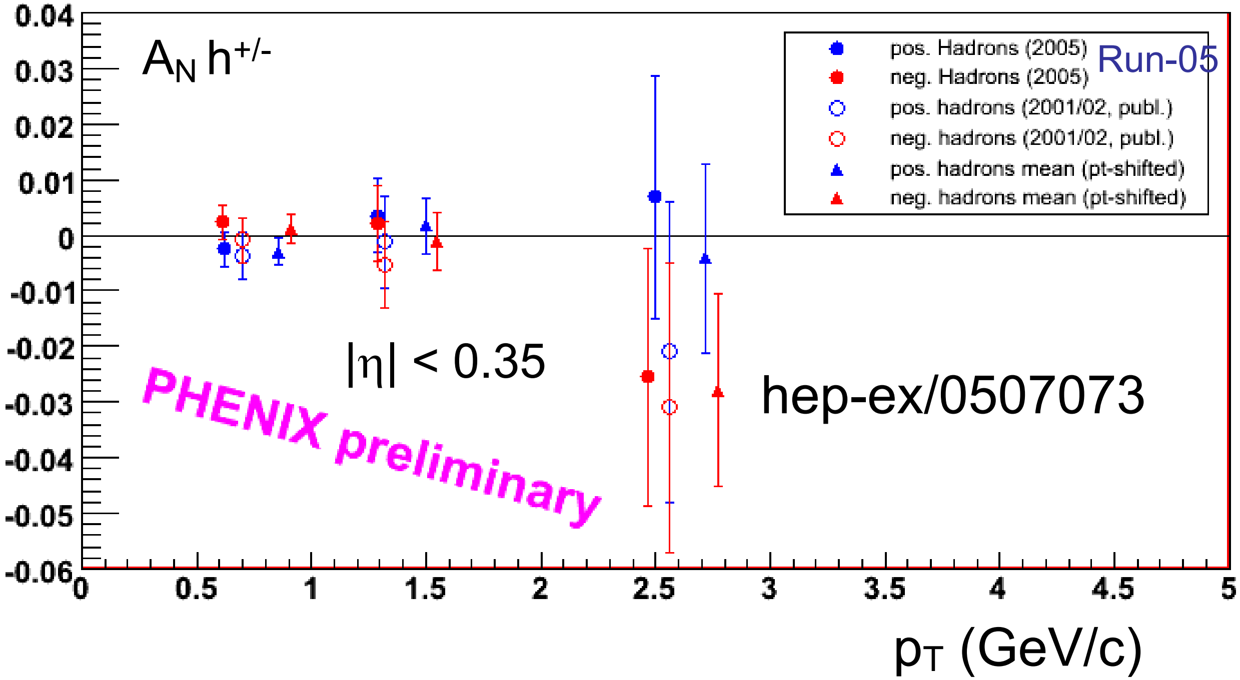
Transversity (quark polarization) ×jet fragmentation asymmetry

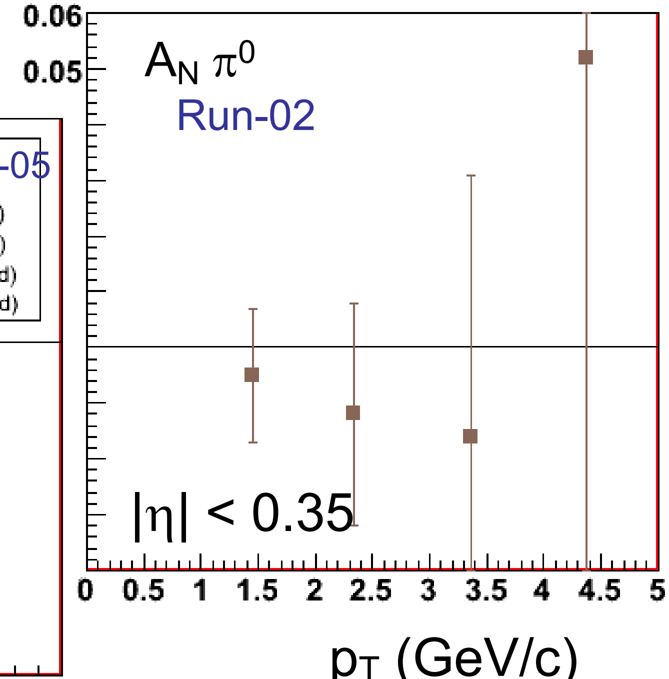


Nucl Phys B396 (1993) 161

no gluon effect

Midrapidity hadron A_N





PRL 95, 202001 (2005)

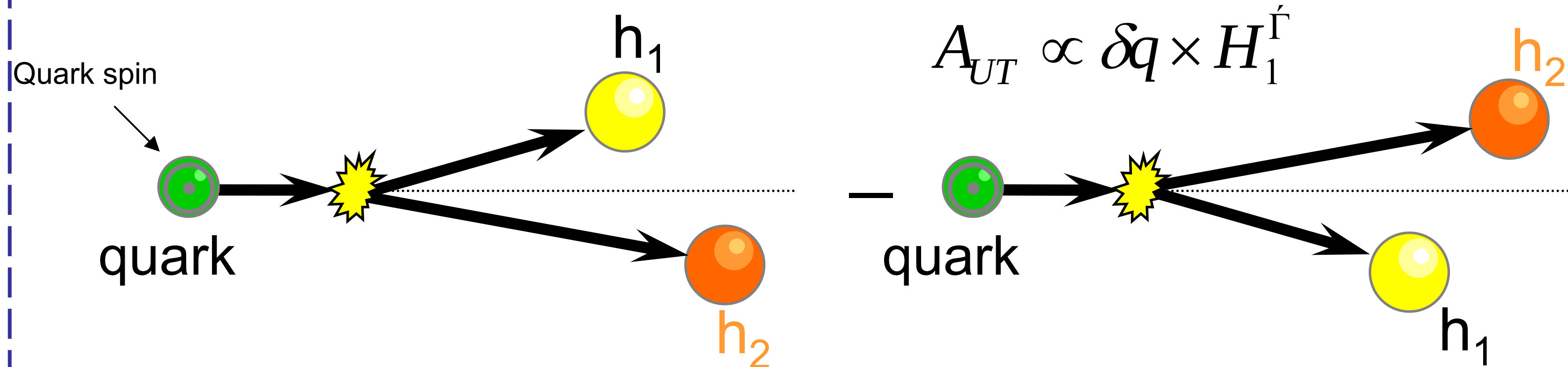
- A_N is zero within 1% → contrast with forward pions
- Constrains Sivers distribution function for gluons

  (Anselmino et al., PRD74, 094011 (2006))
- Updated π^0 analysis with >10x smaller stat. error underway.

IFF and Collins FF

Interference fragmentation function $H_1^{\sphericalangle}(z, M_{\pi\pi}^2)$

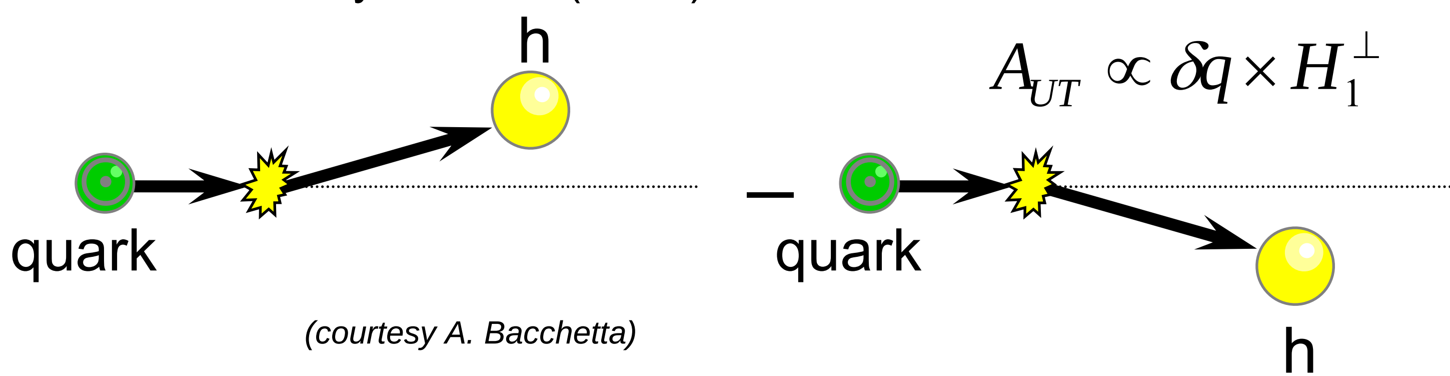
J. Collins, S.Heppelmann, G. Ladinsky, Nuclear Physics B, 420 (1994) 565



$$A_{UT} \propto \delta q \times H_1^{\sphericalangle}$$

Collins fragmentation function $H_1^{\perp}$

J. C. Collins, Nucl. Phys. B396, (1993) 161

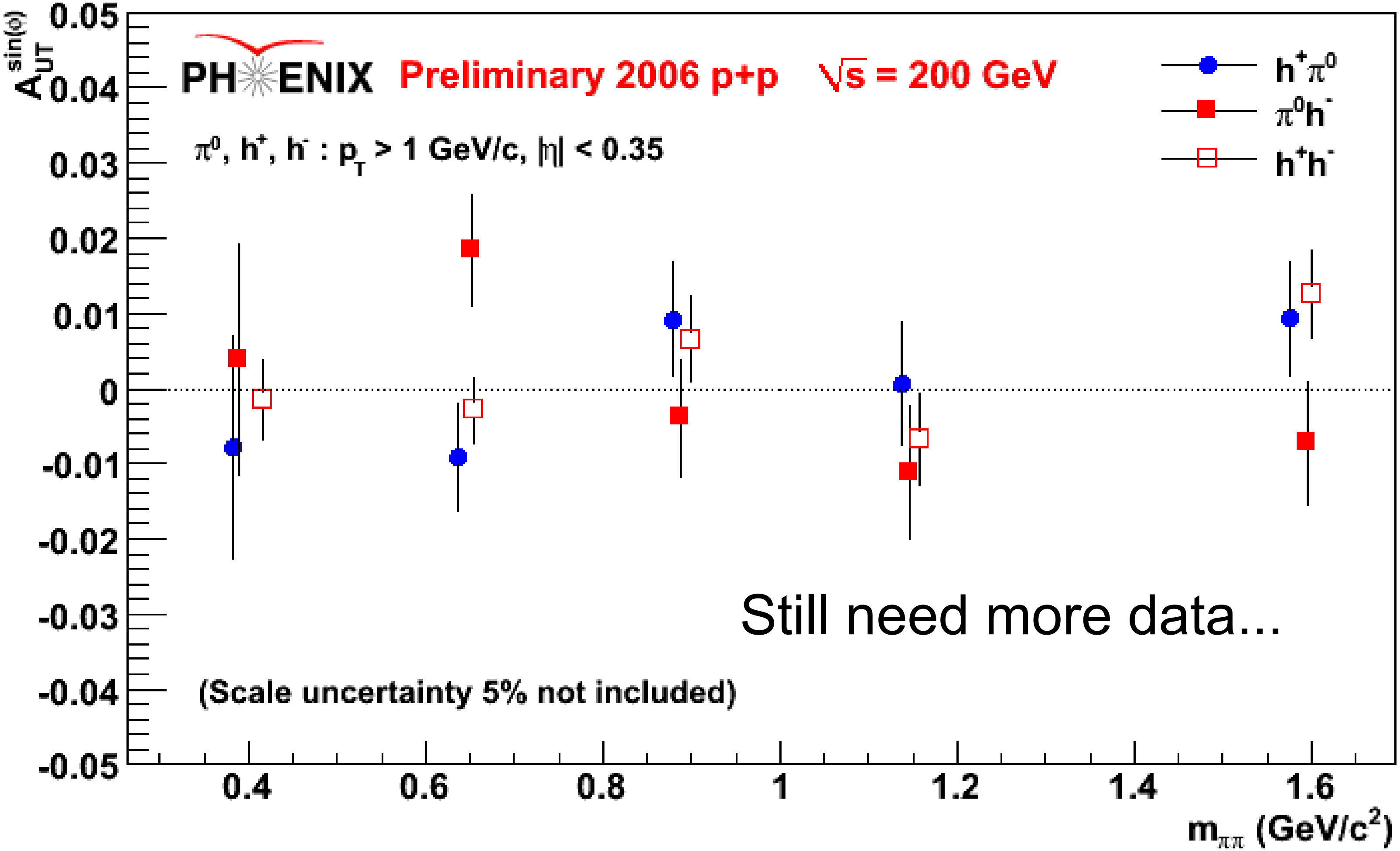


$$A_{UT} \propto \delta q \times H_1^{\perp}$$

(courtesy A. Bacchetta)

FF measurements are ongoing at KEK-BELLE

Asymmetry result



- More results ... again, no time to show them all

Looking forward – More data!

- More data
  - More than 65 pb^{-1} with 70% polarization at 200 GeV
  - 500 GeV data taking starts from 2009 → small x region
  - More channels
- More detectors
  - Central arm: VTX
  - Forward region: MPC, NCC, FVTX, Muon trigger
- More physics
  - W – flavor decomposition of quark polarization
  - A_N – a quest for mechanism
    Analysis of data from Run6 & 8 are underway

Summary

- Gluon polarization
  - Current π^0 data suggests $\Delta g(x)$ is small for $0.02<x<0.3$
  - Extension toward lower x is important
    → detector upgrades, higher energy
  - sign problem → forward upgrades, direct photon
- Transverse spin physics
  - Trying to find the mechanism to produce large A_N in forward region
  - Access transversity
- More data are still to come