RHIC Spin Program
Recent results

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for

“Hadron Structure and Nonperturbative QCD”

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Proton Spin Structure

Quark Spin

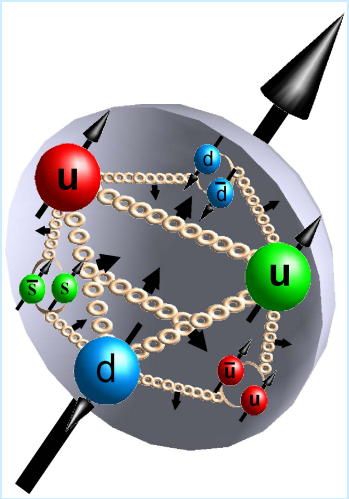
Gluon Spin

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

Orbital Angular Momentum

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}$$

$p^{\uparrow}$



- Polarized DIS: contribution of quarks to proton spin is amazingly small $\Delta\Sigma \approx 0.25$
- Main candidate to carry proton spin - Gluons

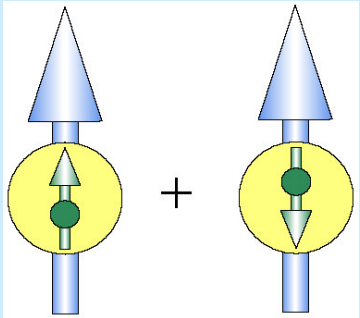
Gluon polarization (ΔG) remains poorly constrained $\rightarrow$ ΔG measurements – main RHIC-Spin goal

Parton Distribution Functions

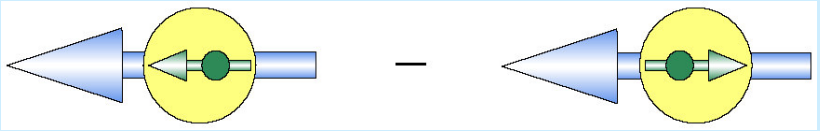
- Quark Distribution

unpolarised distribution

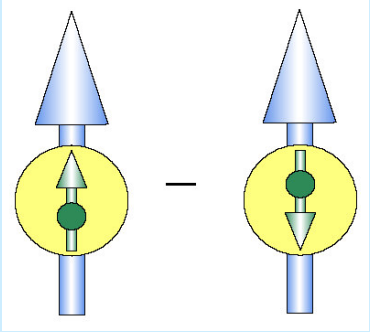
$q(x,Q^2)=$

$=$ 

helicity distribution

$\Delta q(x,Q^2)=$ 

transversity distribution

$\delta q(x,Q^2)=$ 

- Gluon Distributions

$g(x,Q^2)=$

$\Delta g(x,Q^2)=$

No Transverse Gluon Distribution in 1/2

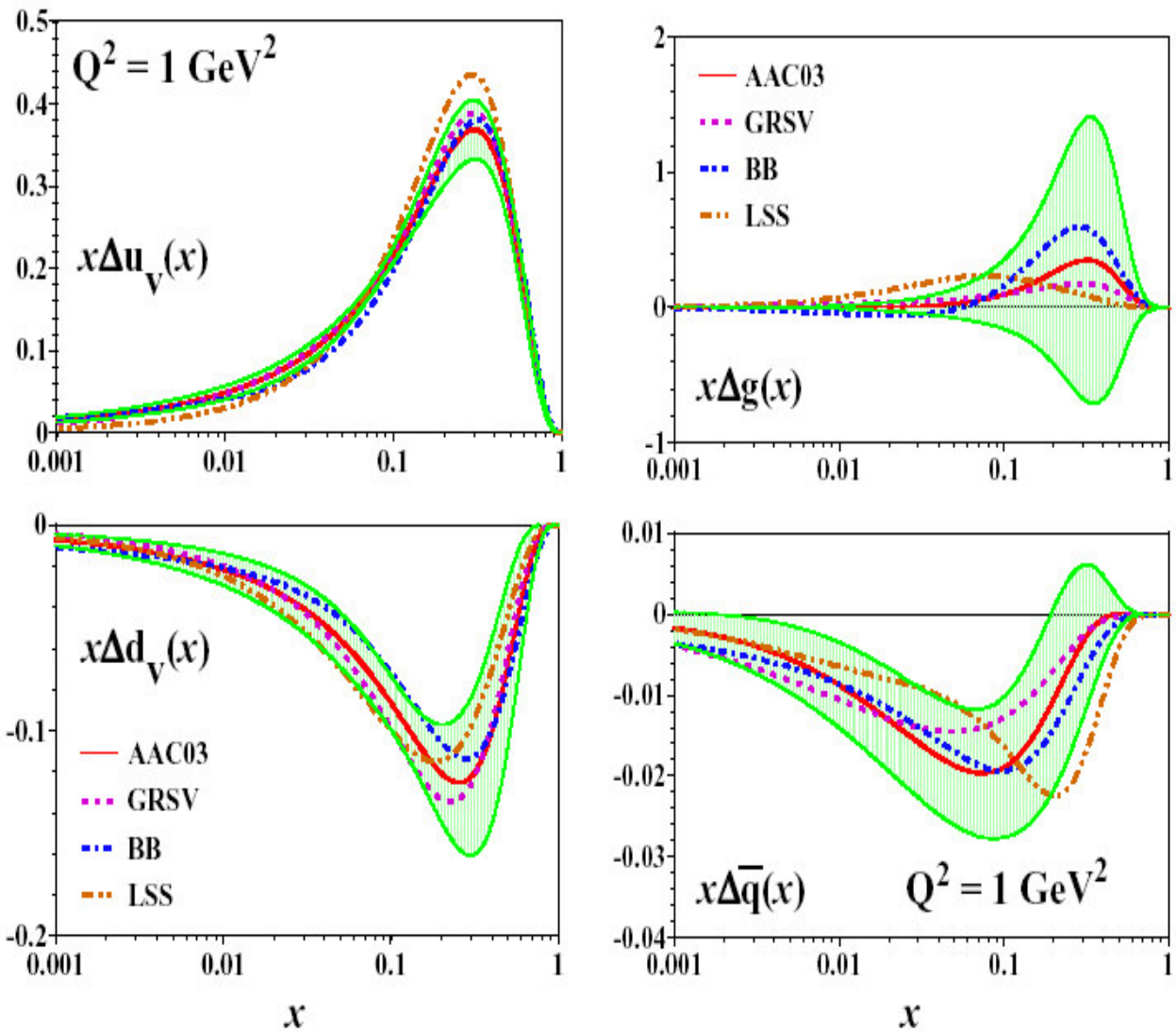
Polarised PDF

Asymmetry Analysis Collaboration

M. Hirai, S. Kumano and N. Saito, PRD (2004)

From polarized DIS:

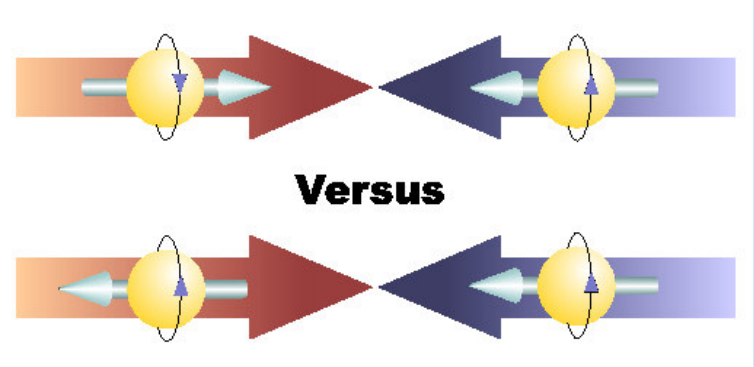
- Valence Dist's are determined well
- Sea Dist' is poorly constrained
- Gluon can be either >0, =0, <0



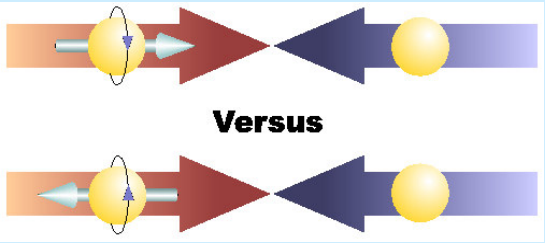
What Do We Measure at RHIC?

- We measure spin asymmetries for cross sections
- A_{LL}: double helicity asymmetry
  - Useful in extracting $\Delta g(x)$

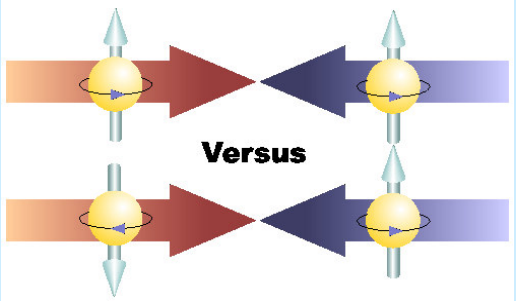
$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$



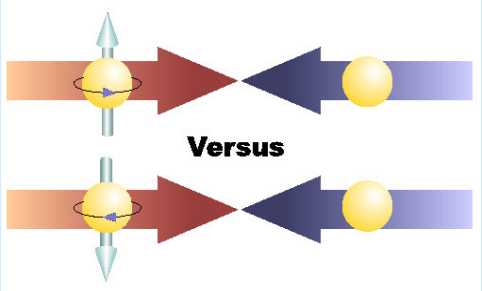
A_L:Parity Violation



A_{TT}: Transversity

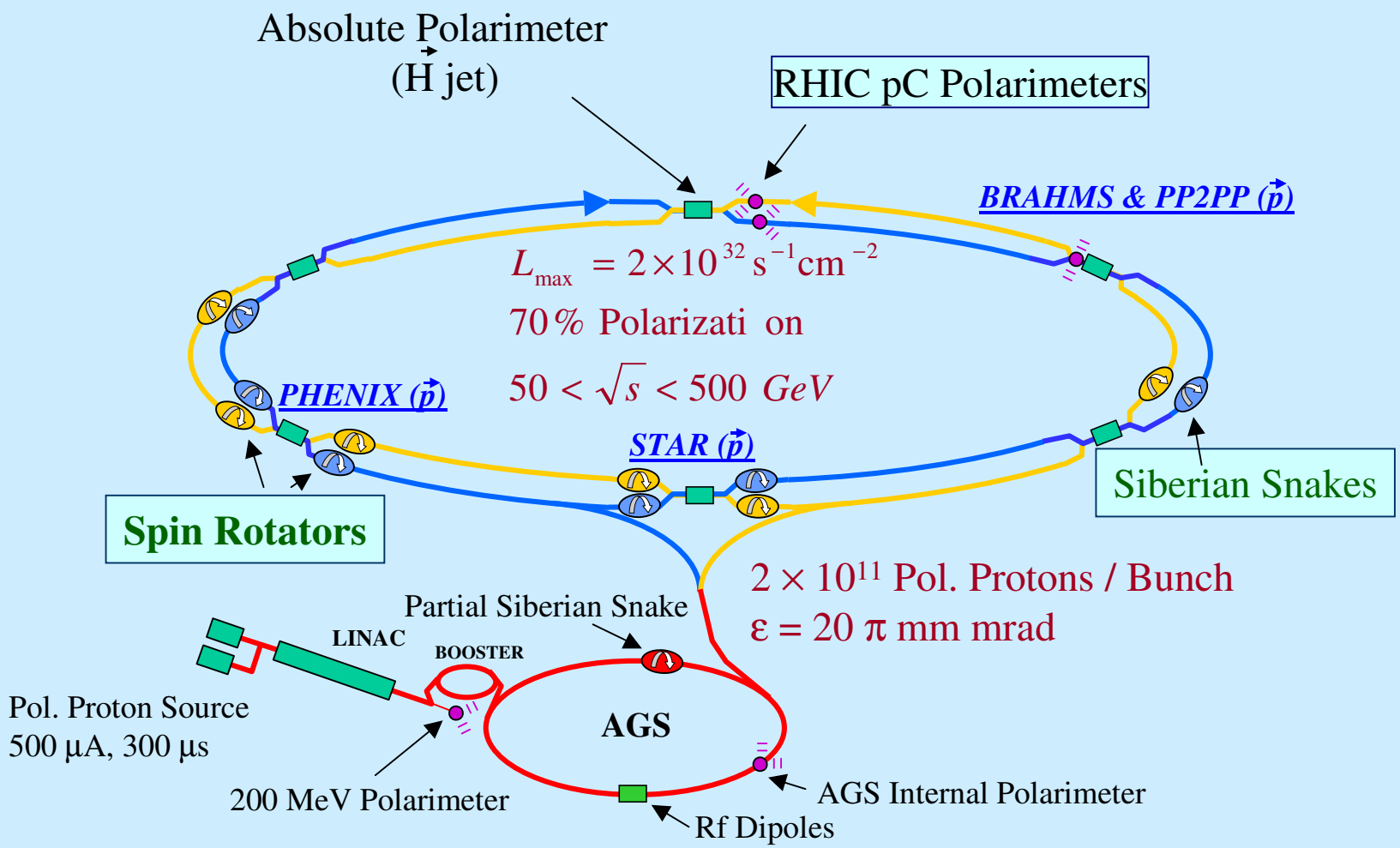


A_N:Twist-3 etc



And various Spin Transfer Asymmetries: D_{NN}, D_{LL}, etc

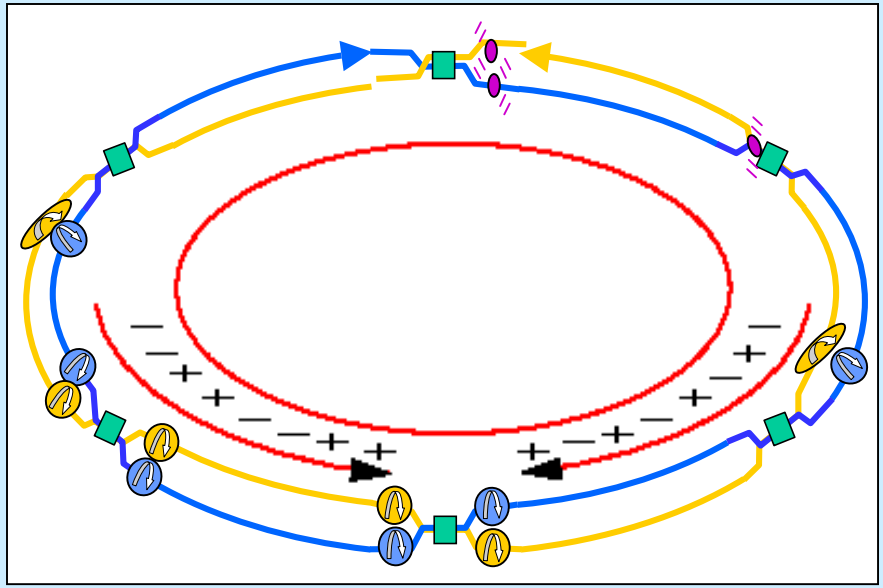
RHIC: the first polarized *pp* collider



Spin Running at RHIC

Data is collected simultaneously for all spin configurations (alternating every ~100 ns) ⇒

Many systematical uncertainties in spin asymmetry measurements are eliminated



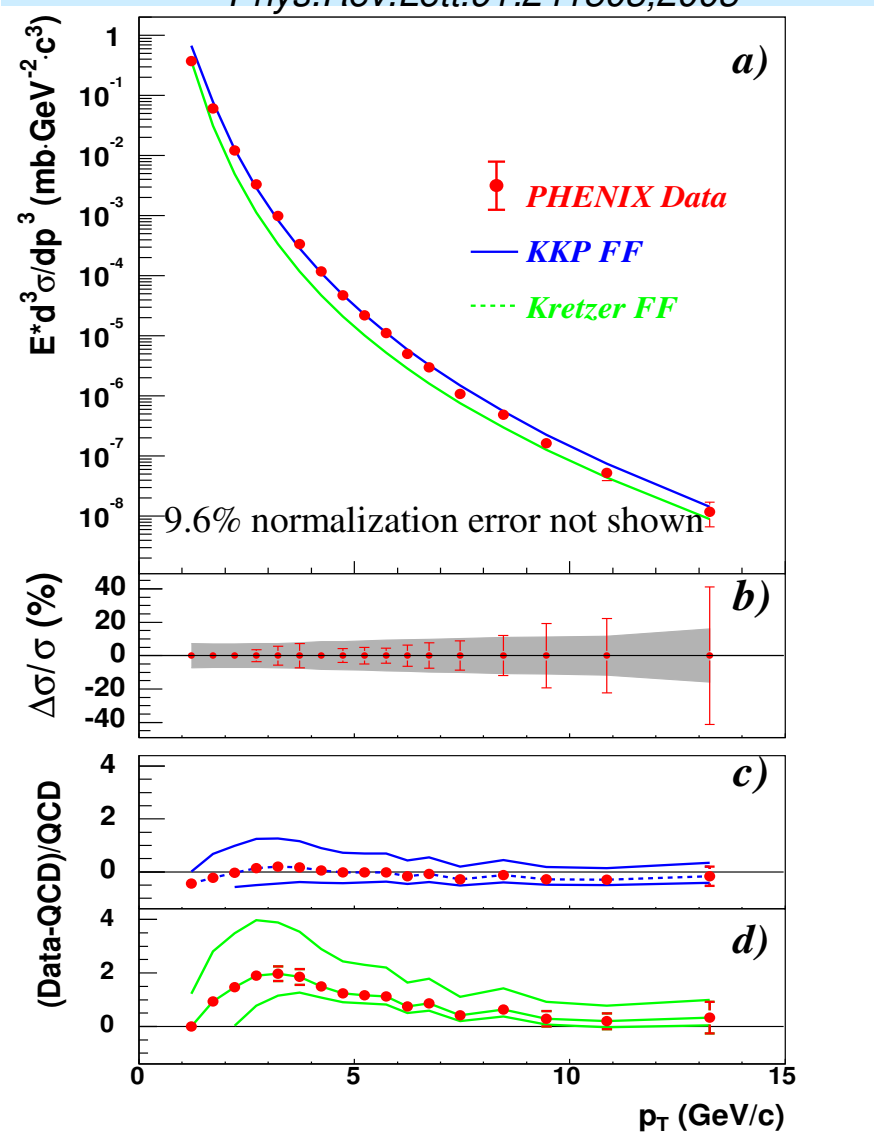
PHENIX Spin Data

	Run2 (2002)	**Run3 (2003)**	**Run4 (2004)**	**Run5 (2005)**
Spin orient.	Trans.	Long.	Long.	**Long.**
<Pol.>	15%	30-35%	40-45%	**45-50%**
Lum.	0.15 pb^{-1}	0.35 pb^{-1}	0.15 pb^{-1}	**3.8 pb^{-1}**

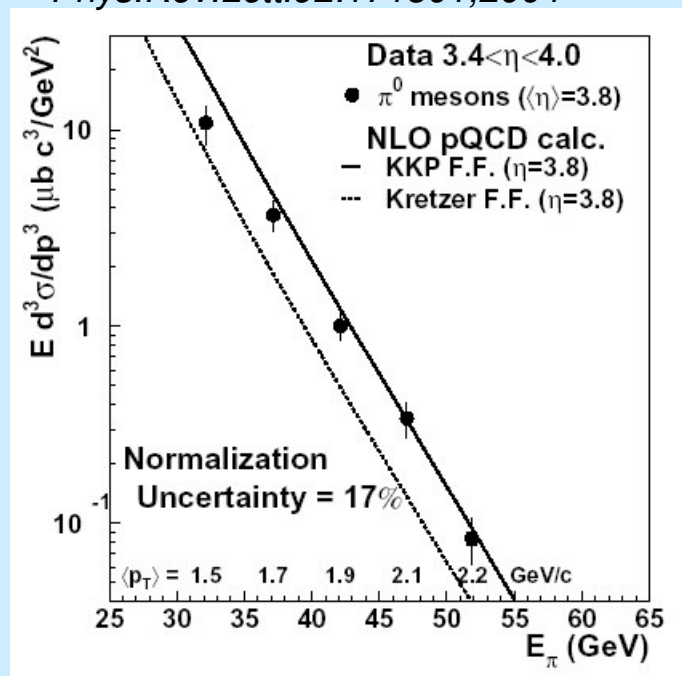
PHENIX and STAR collected both transverse and longitudinal data
BRAHMS collected only transverse data

π^0 Unpol. Cross Section in *pp*

PHENIX π^0 cross section a $|\eta|<0.35$
Phys.Rev.Lett.91:241803,2003



STAR π^0 cross section a $3.4<\eta<4.0$
Phys.Rev.Lett.92:171801,2004

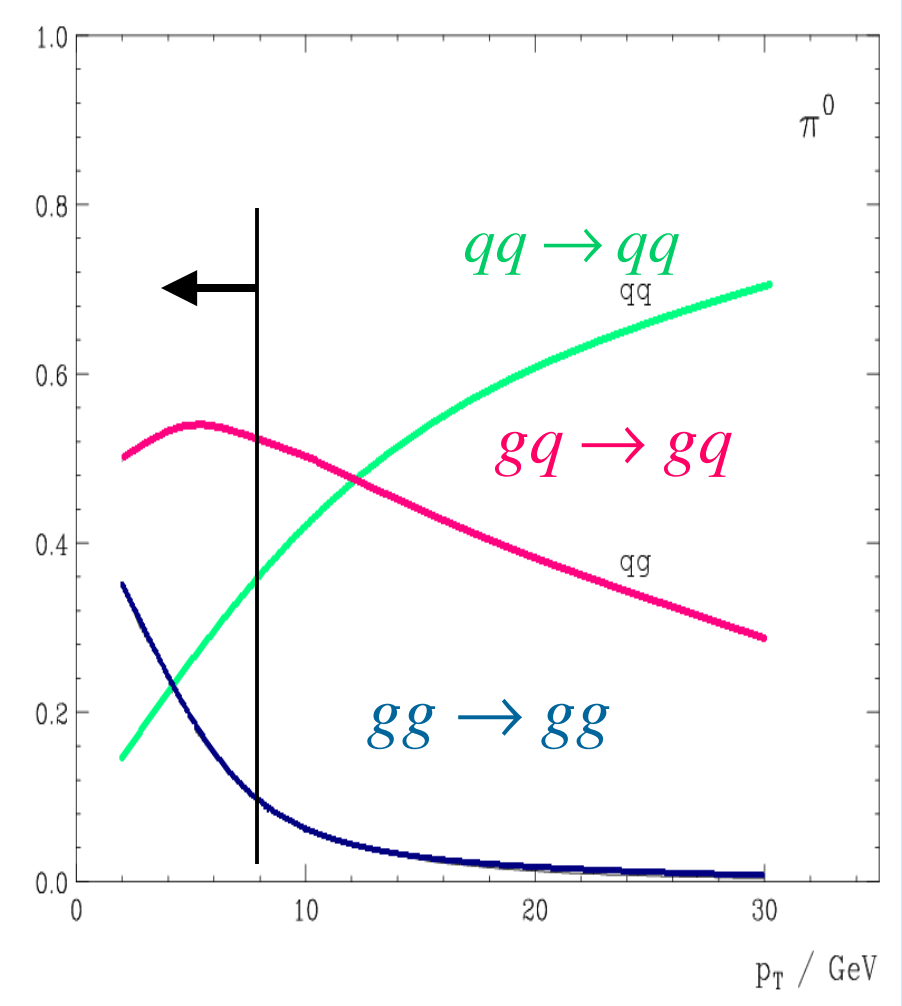


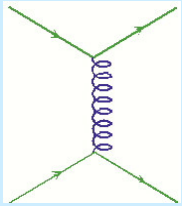
Good agreement between NLO pQCD calculations and data ⇒ confirmation that pQCD can be used to extract spin dependent pdf's from RHIC data.

- Same comparison fails at lower energies

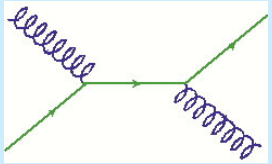
$\pi 0$ A_{LL}: ΔG constrain

Fractional contribution to $pp \rightarrow \pi^0 X$ at $\sqrt{s}$=200 GeV at η~0

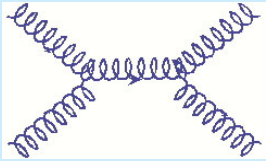




$$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$$



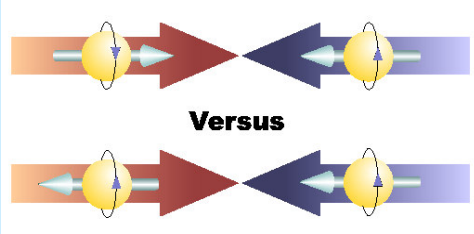
$$\propto \frac{\Delta q}{q}\frac{\Delta G}{G}$$



$$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$$

$\pi 0$ production is sensitive to gluon distribution

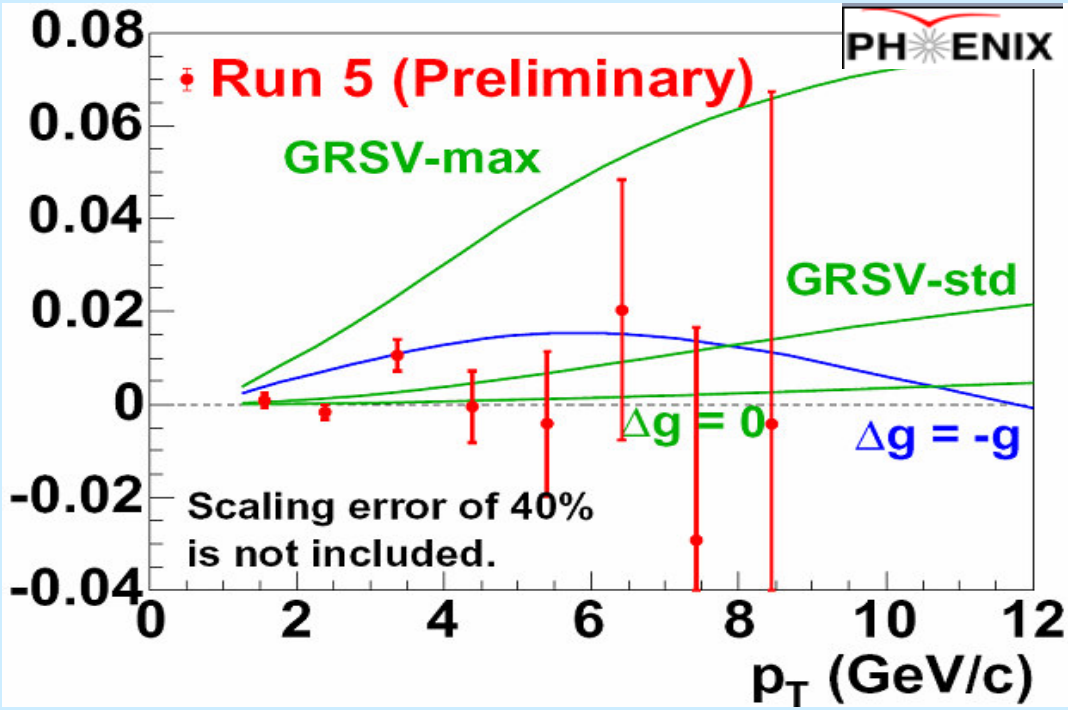
π0 A_{LL}



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

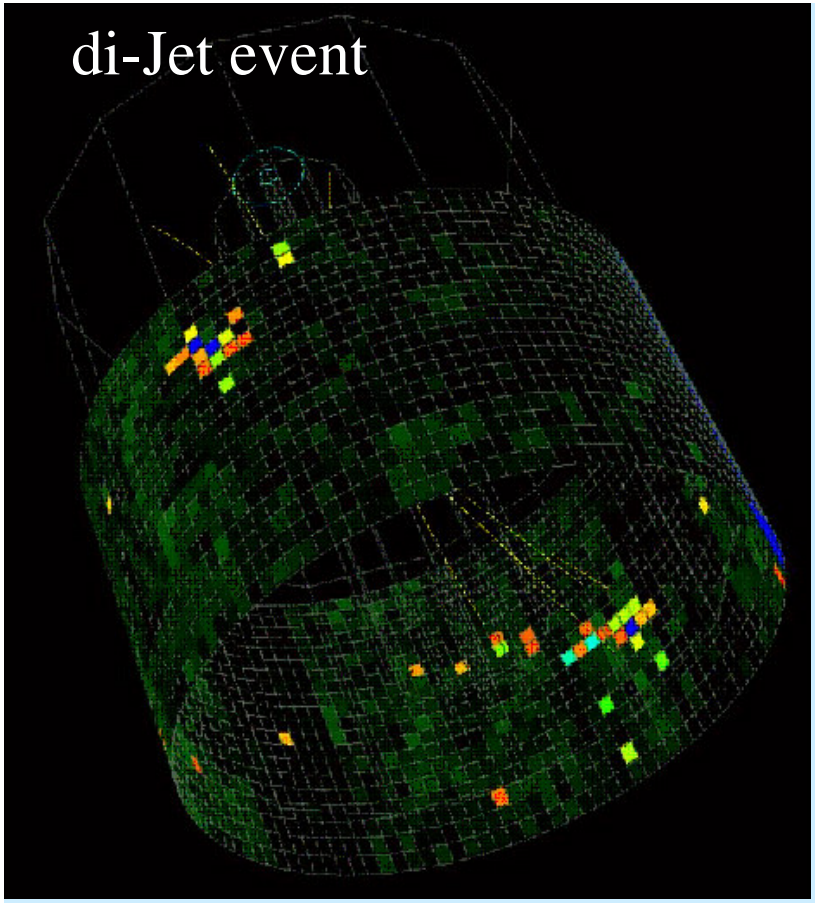
Theory: B.Jager et al., PRD67, 054005 (2003)

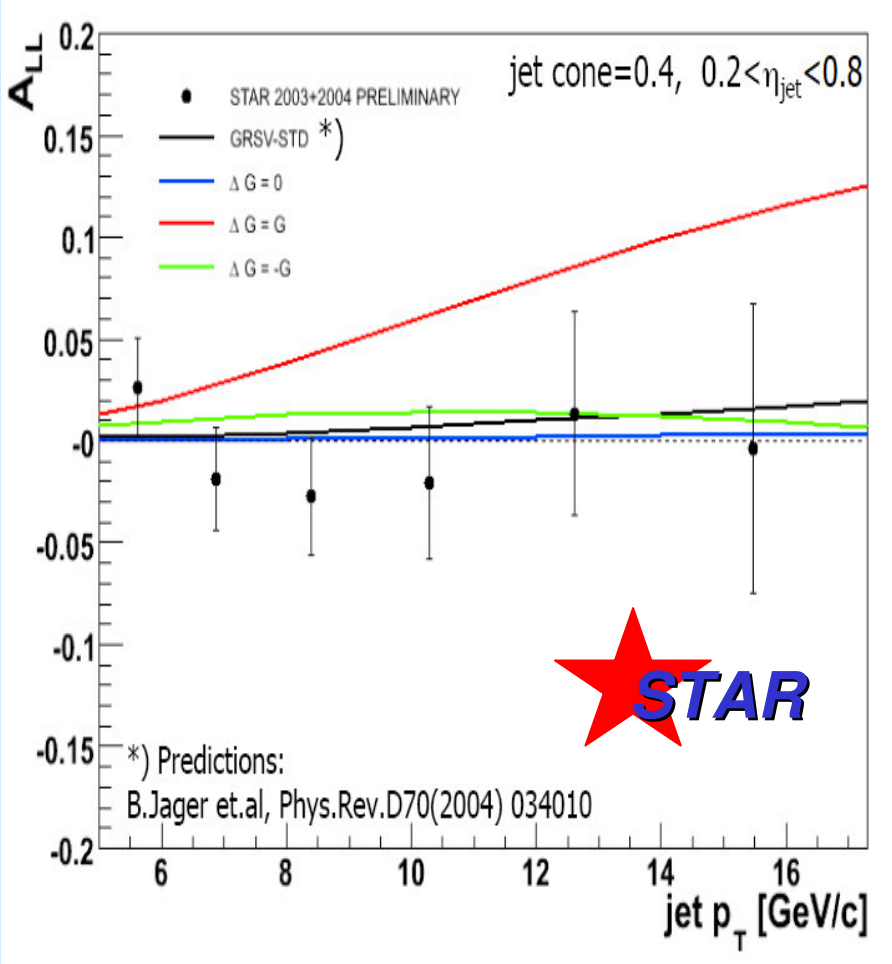
Theory model	C.L. (%)
GRSV-std	21.7-17.1
*GRSV-max (Δg=g)	0.0-0.0
*GRSV Δg=0	16.7-18.4
*GRSV Δg=−g	0.7-0.0



PHENIX π0 A_{LL} data started constraining gluon polarization in the proton in the perturbative QCD regime using strongly interacting probes with sensitivity higher than existing pol-DIS data

Jet A_{LL}

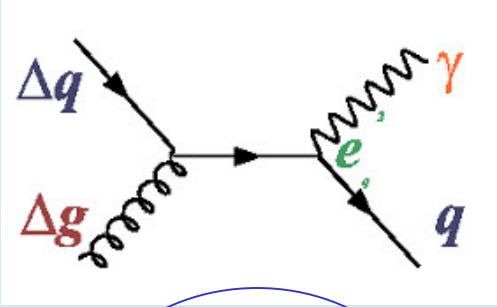




- High rate ! (as high as π^0)
- More direct access to partonic level kinematics!
- Large ΔG rejected
- Not yet all data analyzed (only Run3+4)

Prompt photons and ΔG

- **Gluon Compton Dominates**
  - **At LO no fragmentation contribution**
  - **Small (~15%) contamination from annihilation**

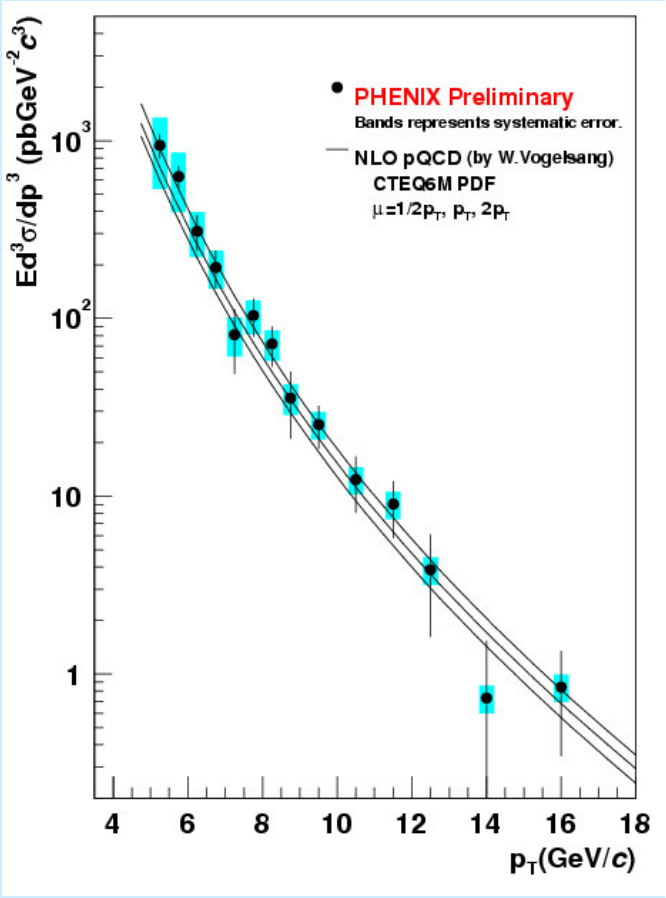


$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum_{i=u,d,s} e_i^2 \Delta f_i(x_2)}{\sum_{i=u,d,s} e_i^2 f_i(x_2)} \otimes \hat{a}_{LL}(gq \to q\gamma)$$

pol-DIS

theory

Unpol. cross section

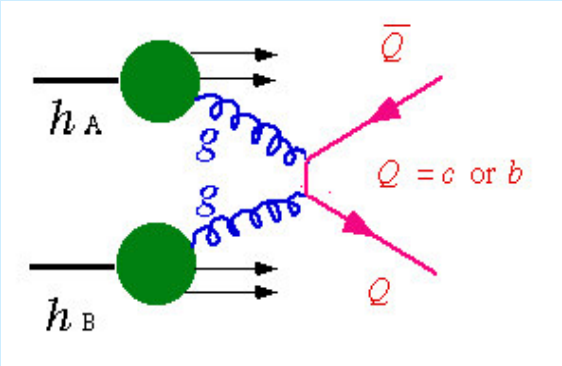


✓NLO pQCD describes data well → can be used to interpret $A_{LL}(\gamma)$

✓$A_{LL}(\gamma)$ needs large luminosity: results expected in 2007-08

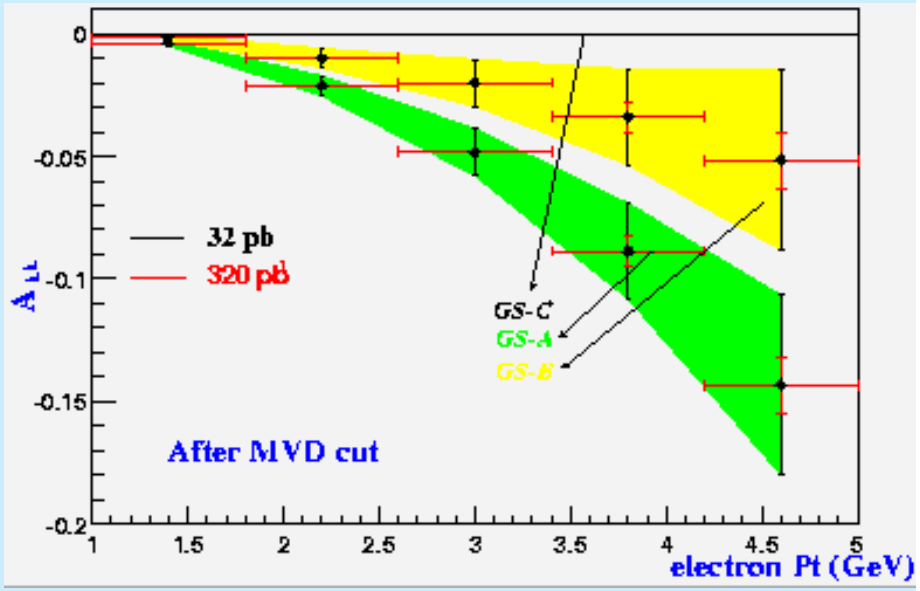
ΔG: Heavy Flavor

Open heavy flavor production



$$A_{LL} \propto \frac{\Delta G(x_A)}{G(x_A)} \otimes \frac{\Delta G(x_B)}{G(x_B)} \otimes \hat{a}_{LL}^{gg \to Q\bar{Q}}$$

A_{LL} for single electrons in PHENIX



Decay channels:

» e^+e^-, $\mu^+\mu^-$, $e\mu$, e, μ, eD, μD

Provides more independent ΔG measurements in PHENIX

» Helps control experimental and theoretical systematic errors

» Different channels cover different kinematic regions

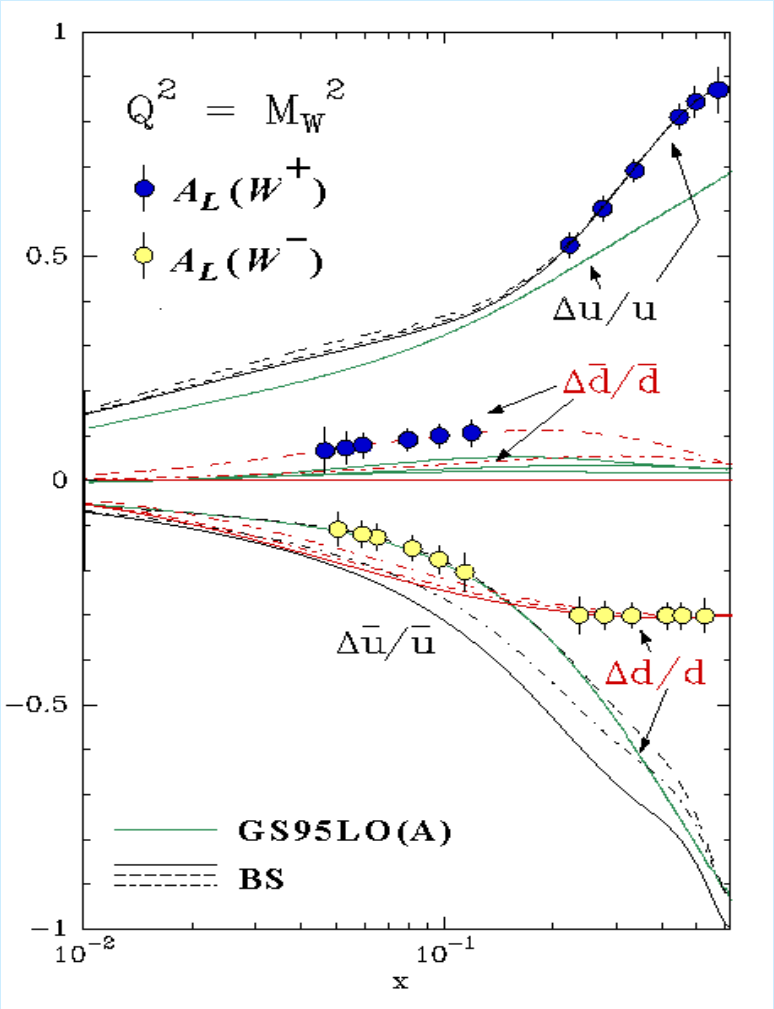
» Needs high luminosity: results expected in 2008-2009

Flavor Decomposition

$\sqrt{s}$=500 GeV L=800 pb^{-1}

W production

- » **Produced in parity violating *V-A* process**
  - — Chirality / helicity of quarks defined
- » **Couples to weak charge**
  - — Flavor almost fixed



$$A_L^{W^+\to\mu^+\nu_\mu} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

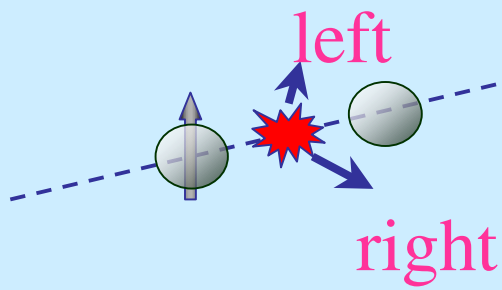
$x_a >> x_b$: $A_L(W^+) \rightarrow \Delta u/u(x)$

$x_b >> x_a$: $A_L(W^+) \rightarrow \Delta\bar{d}/\bar{d}(x)$

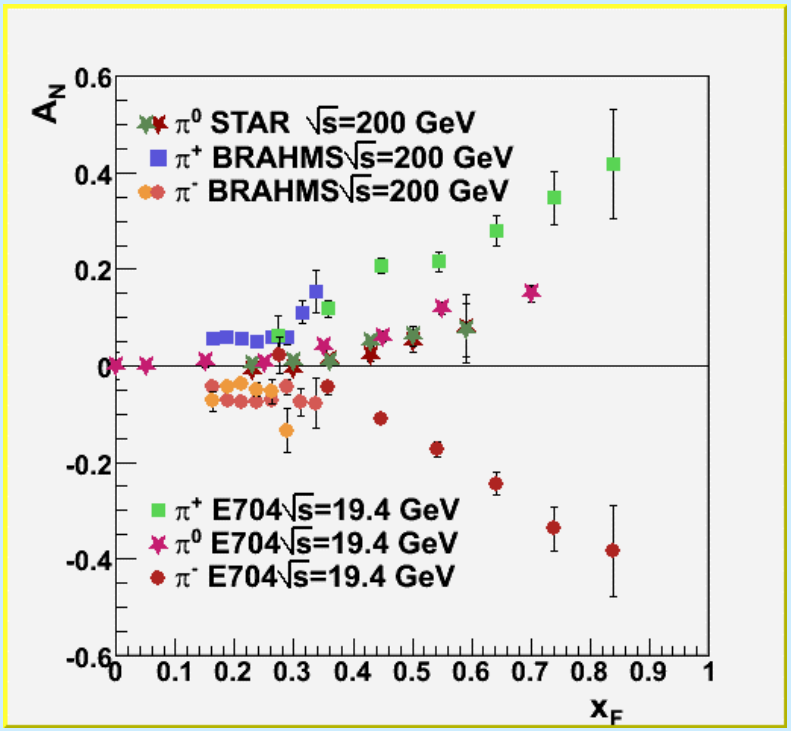
First data on sea quark polarization from $W^{\pm}$ is expected in 2009-2010

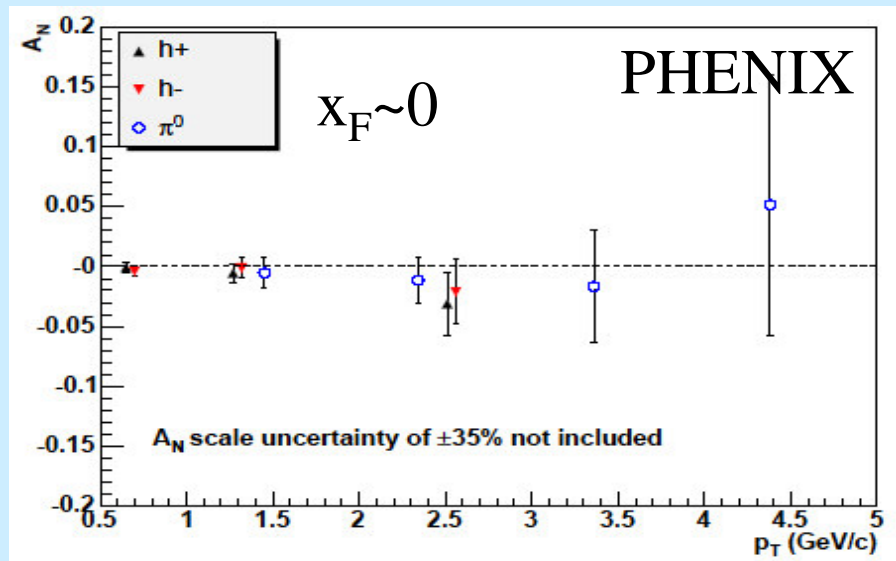
Transverse Single-Spin Asymmetries

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



- Origin of A_N
  - Transversity × Spin-dep fragmentation (Collins effect)
  - Intrinsic-k_T imbalance (Sivers effect)
  - Higher-twist effects
  - Or combination of above





A_N increasing with x_F: positive for π^0 and π^+ and negative for π^-

A_N~0 at x_F~0 for both charged hadrons and neutral pions

Summary

- RHIC has been successful as the world's first polarized proton collider, opening up new kinematic regions for investigating the spin of the proton
- The first spin results from RHIC are out and stimulating discussion within the theoretical community
  - A_N of neutral pions and charged hadrons, for different rapidity
  - A_{LL} of neutral pions and jets

Many more years of exciting data and results to look forward to!

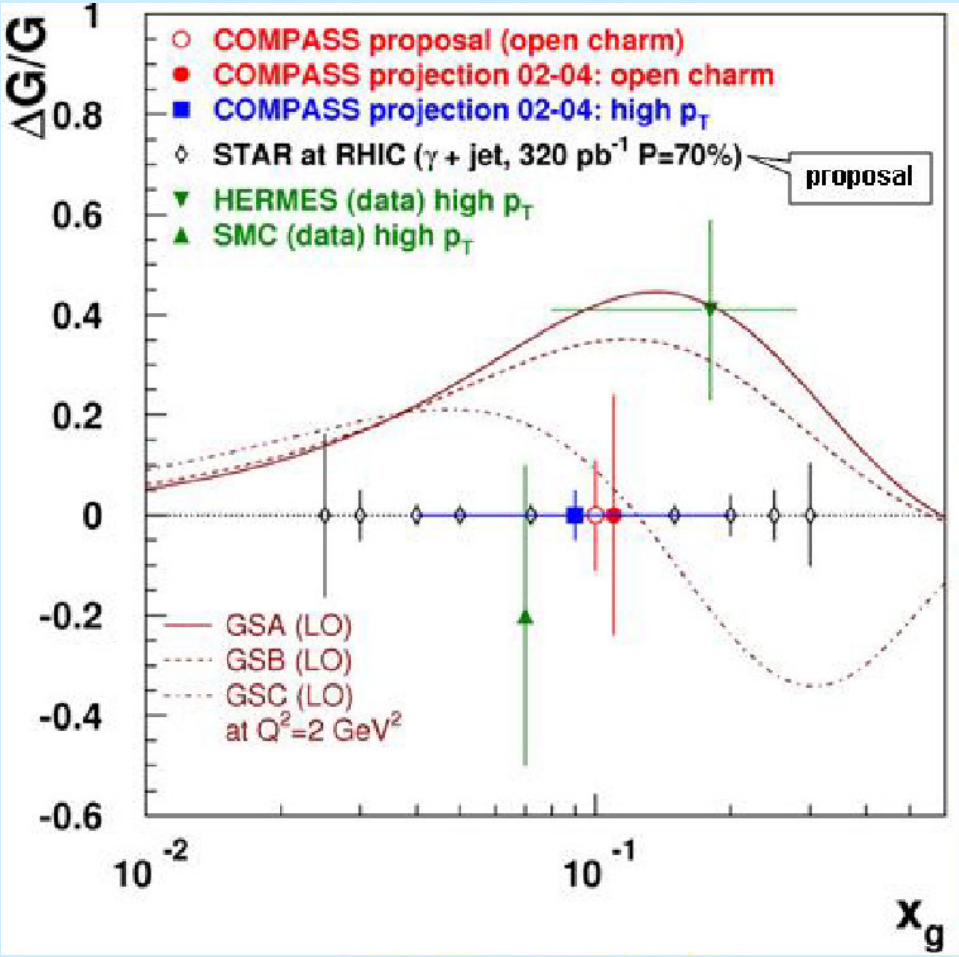
- Spin physics at RHIC planned for 2006 and beyond
  - Measure gluon polarization via direct photon double longitudinal spin asymmetry
  - Probe gluon polarization from heavy flavor production (gg fusion) via electrons
  - Probe polarization of sea quarks via W boson longitudinal single spin asymmetry
  - Transverse spin structure

Summary 2

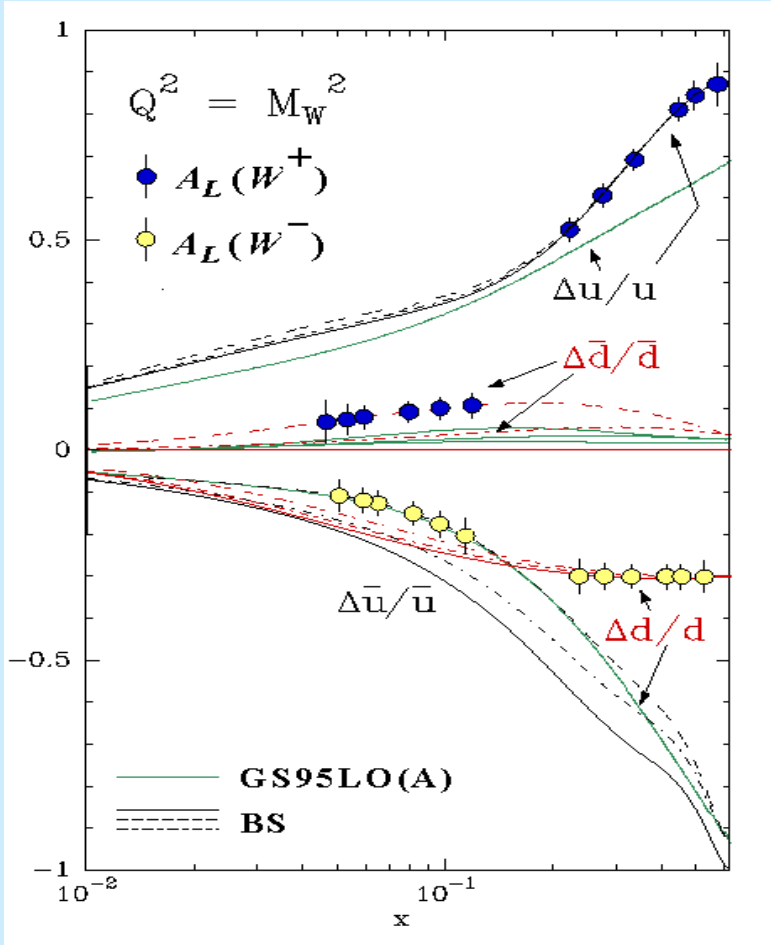
Proton spin structure:

Quark contribution well known

Gluon contribution from *γ+jet*



Sea quark contribution from *W*



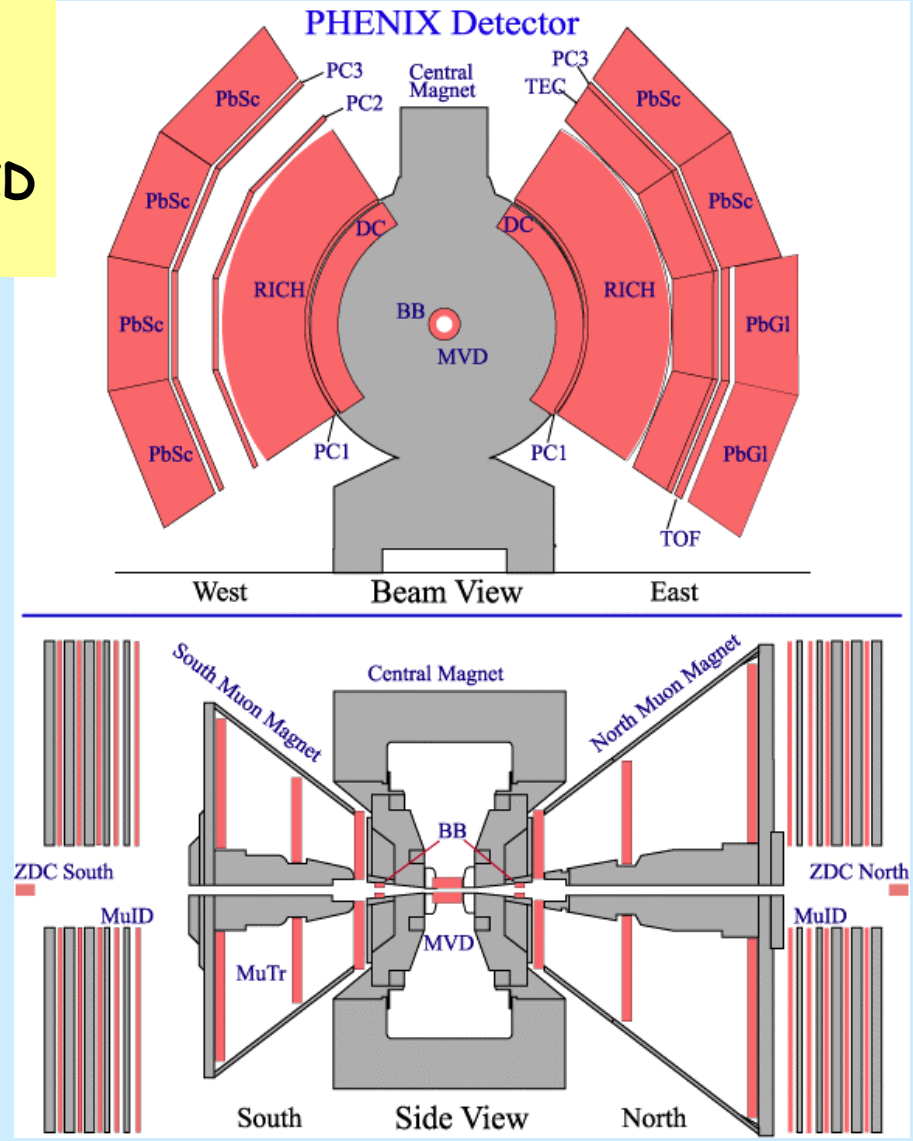
Backup slides

PHENIX Detector

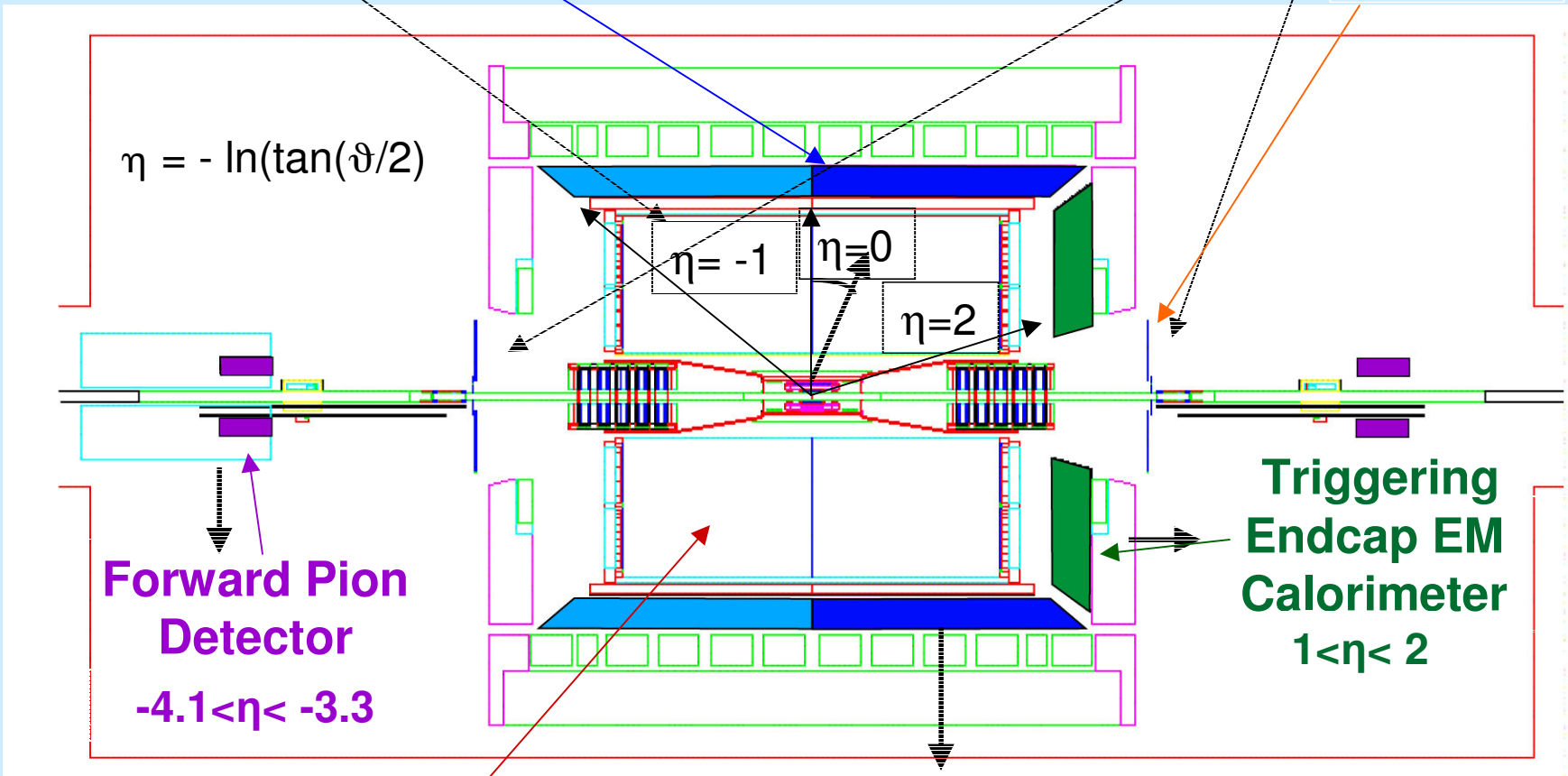
Philosophy:

- ✓ High rate capability & granularity
- ✓ Good mass resolution and particle ID
- ➢ Sacrifice acceptance

- **Central Arms:**
  $|\eta|<0.35$, $\Delta\varphi=2\times90^0$
  Charged particle ID and tracking;
  photon ID
- **Muon Arm:**
  $1.2<|\eta|<2.4$
  Muon ID and tracking
- **Global Detectors**
  Collision trigger
  Collision vertex characterization
  Relative luminosity
  Local Polarimetry

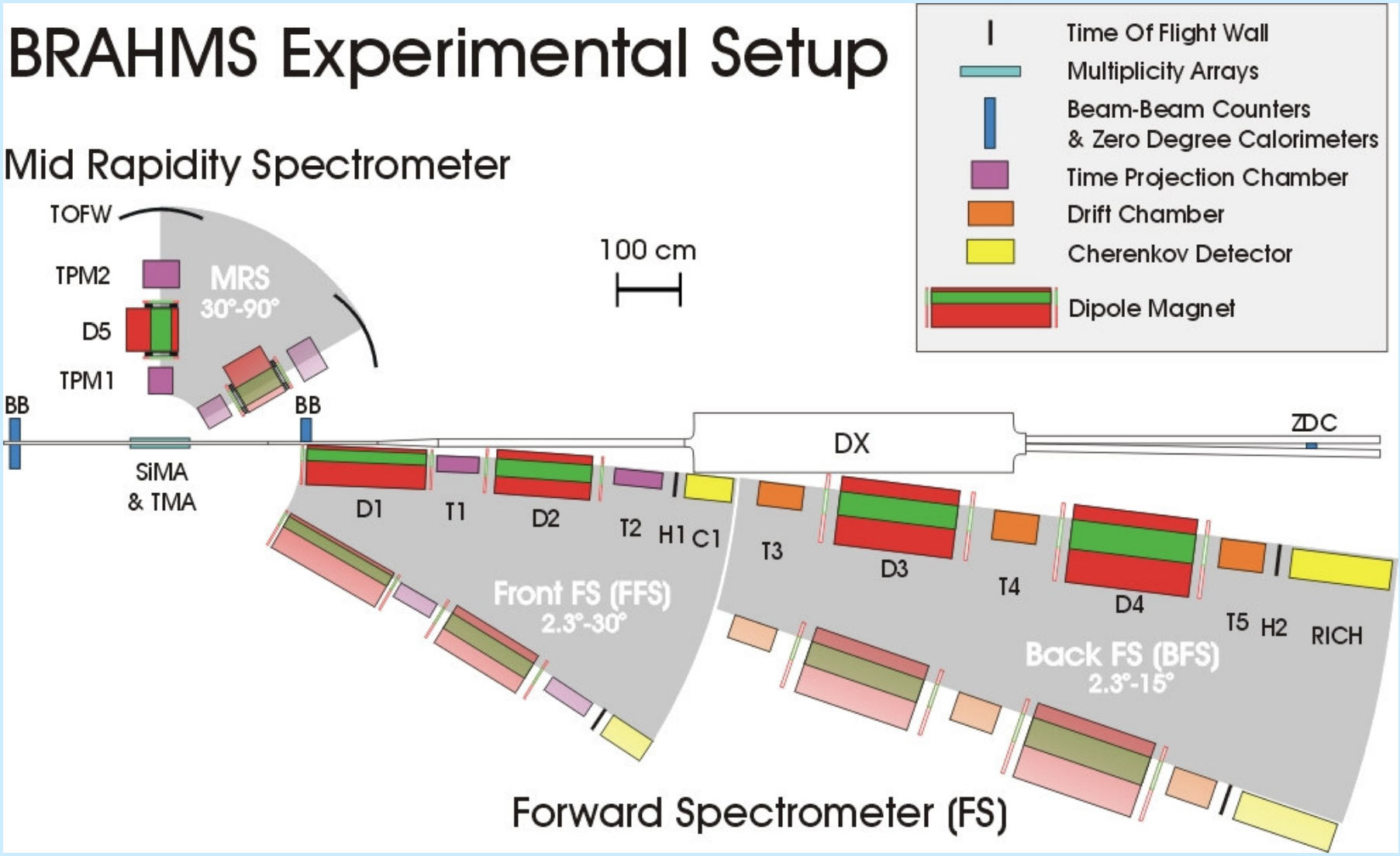


STAR Detector

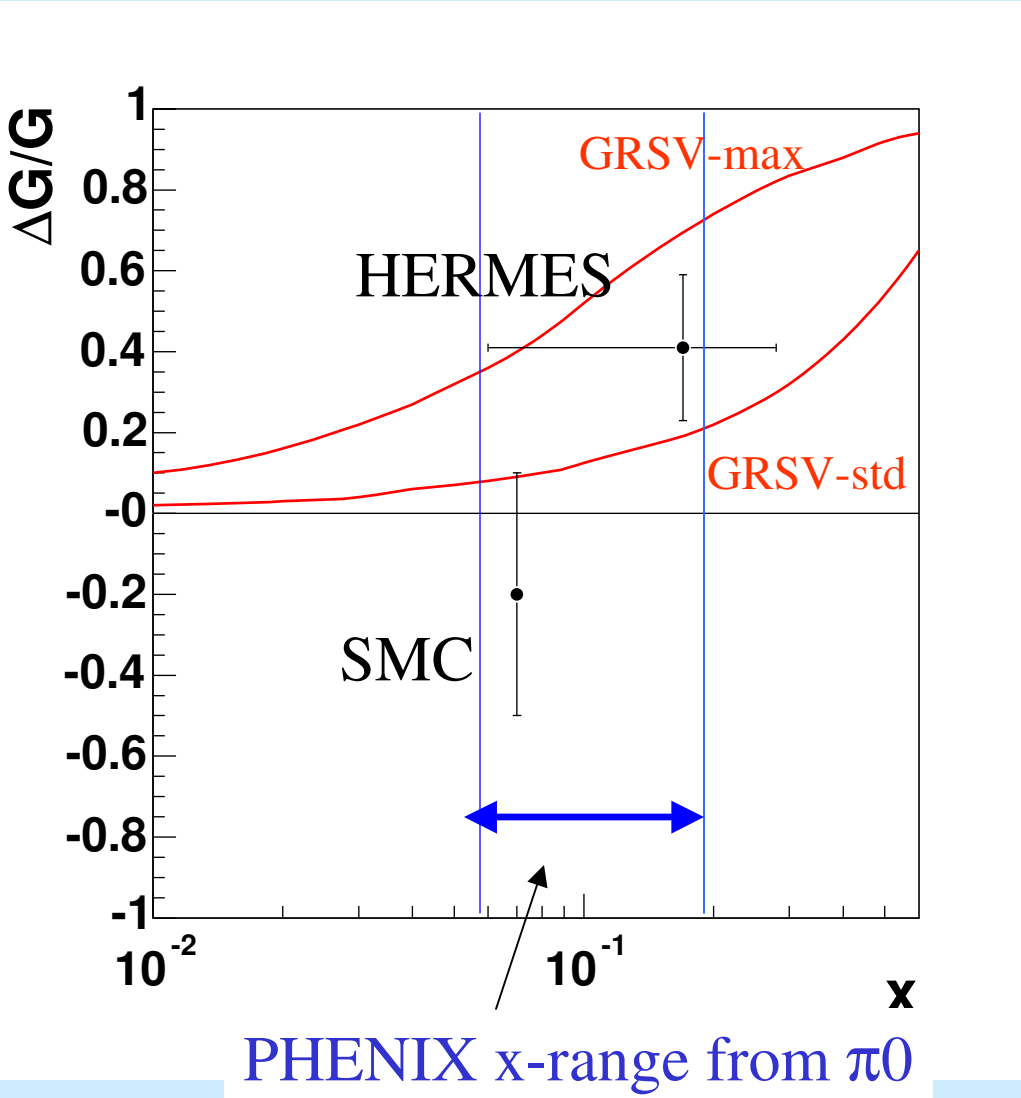


2005

BRAHMS Detector



ΔG: other experiments



- Theory curves from W.Vogelsang
- HERMES: high pt hadron pairs (PRL84, 2584, 2000)
  - Consistent with both GRSV-max and GRSV-std
- SMC: high pt hadron pairs (hep-ex/0402010)
  - Consistent with GRSV-std
- PHENIX: π^0 A_{LL}
  - Consistent with GRSV-std

So far all results are consistent with GRSV-std