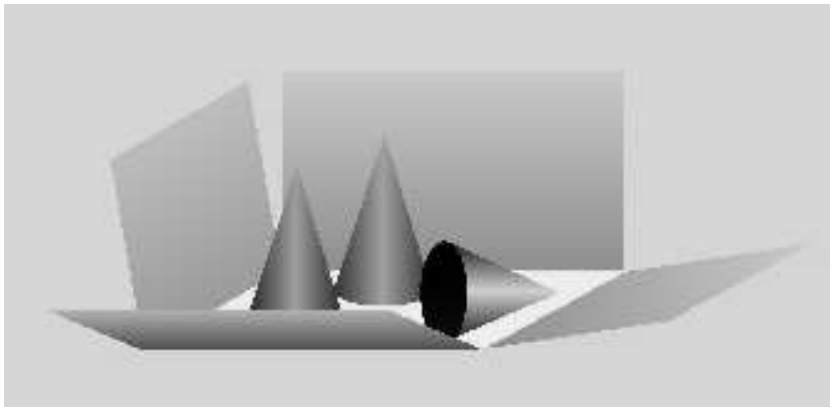
Spin Structure of the Nucleon and Further Perspective of

Spin Physics at RHIC



Naohito Saito
RIKEN

Spin Physics at RHIC

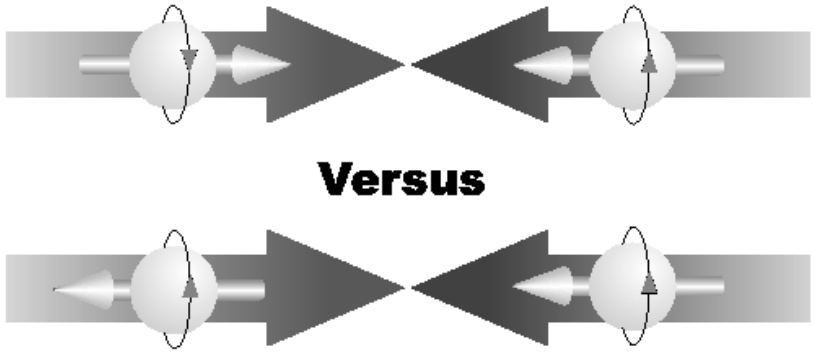
- Spin Structure of the Nucleon
  - $\Delta g(x)$: Gluon polarization via γ,π^0,heavy quark productions

    $\Delta\bar{q}(x)$: Anti-quark polarization via Drell-Yan (W,Z,γ^*)
  - $\Delta_T q(x), \Delta_T \bar{q}(x)$: Quark transversity
- Symmetry Tests
  - parity violating effects, e.g. compositeness
- QCD Selection Rule
  - switch off gluon; $a_{TT}/a_{LL}<<1$
- Single Transverse Spin Asymmetry A_N
  - large at low Energy; higher-twist? ; k_T asymmetry?

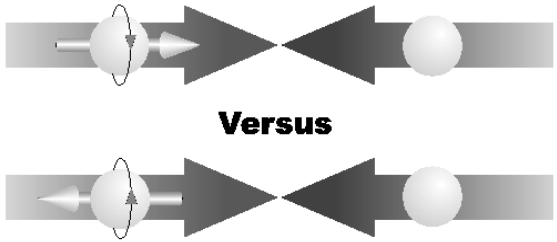
Asymmetries

- A_{LL}: Double Longitudinal Spin Asymmetry
  - cross section asymmetry

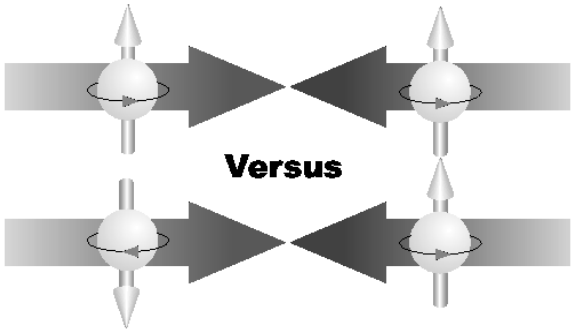
$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$



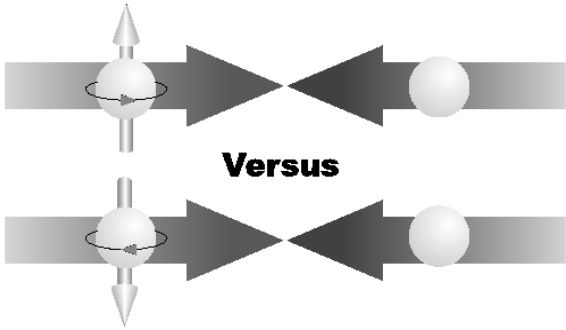
A_L:cross section asymmetry



A_{TT}:cross section asymmetry



A_N:azimuthal asymmetry



RHIC Spin Project

RIKEN-BNL Collaboration

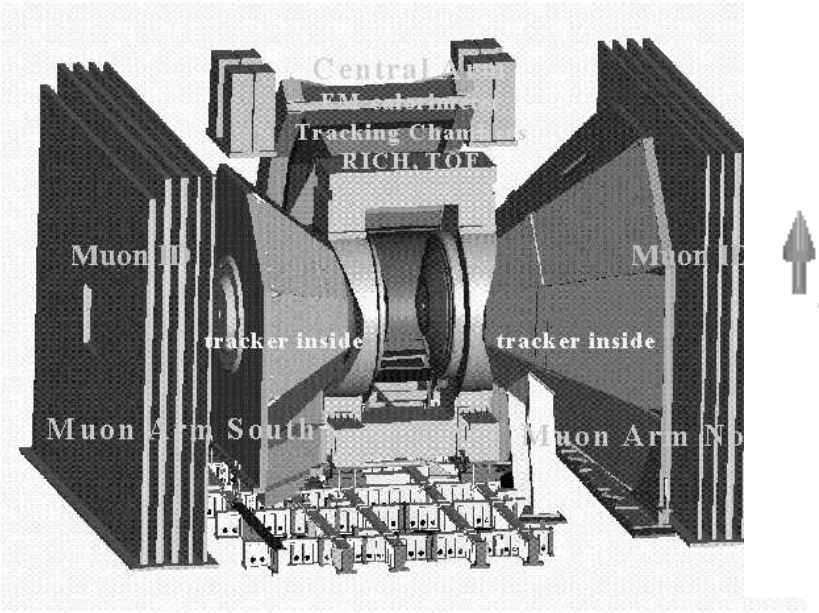
- $\vec{p}$ acceleration and PHENIX Muon Arm for Spin

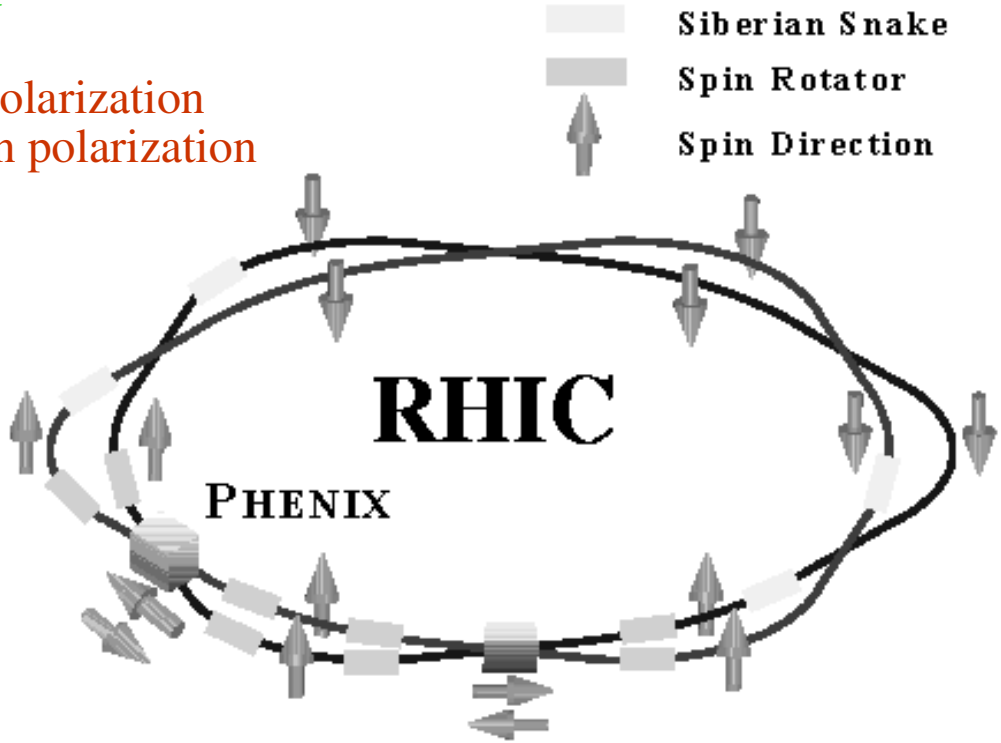
$50 \le \sqrt{s} \le 500\text{GeV}; P_B \approx 70\%$

$L \approx 2.0 \times 10^{32}\,\text{cm}^{-2}\,\text{sec}^{-1}$ @500GeV

Siberian snake to maintain polarization

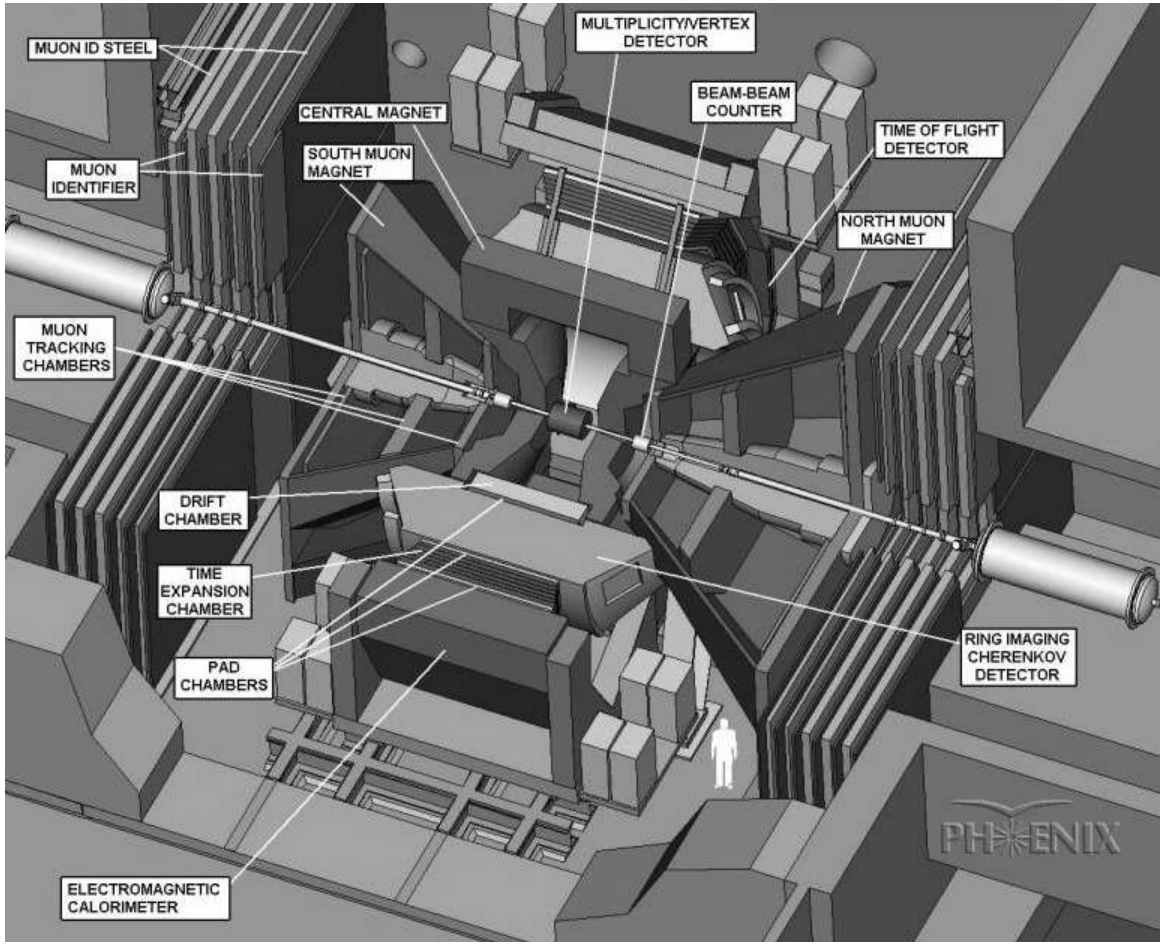
Spin Rotators to obtain given polarization





PHENIX Detector System

- 2 Muon Arms
  - 3 stations of tracking chambers
  - 5 layers of μ-identifier
- Central Arm
  - EMcal
  - Tracking
  - RICH, TOF
  - MVD
  - BB



Recent picture of PHENIX

Naohito Saito, RIKEN

PHENIX Muon Arms

- Magnet+Cathode Strip Chamber+MuID

Magnet

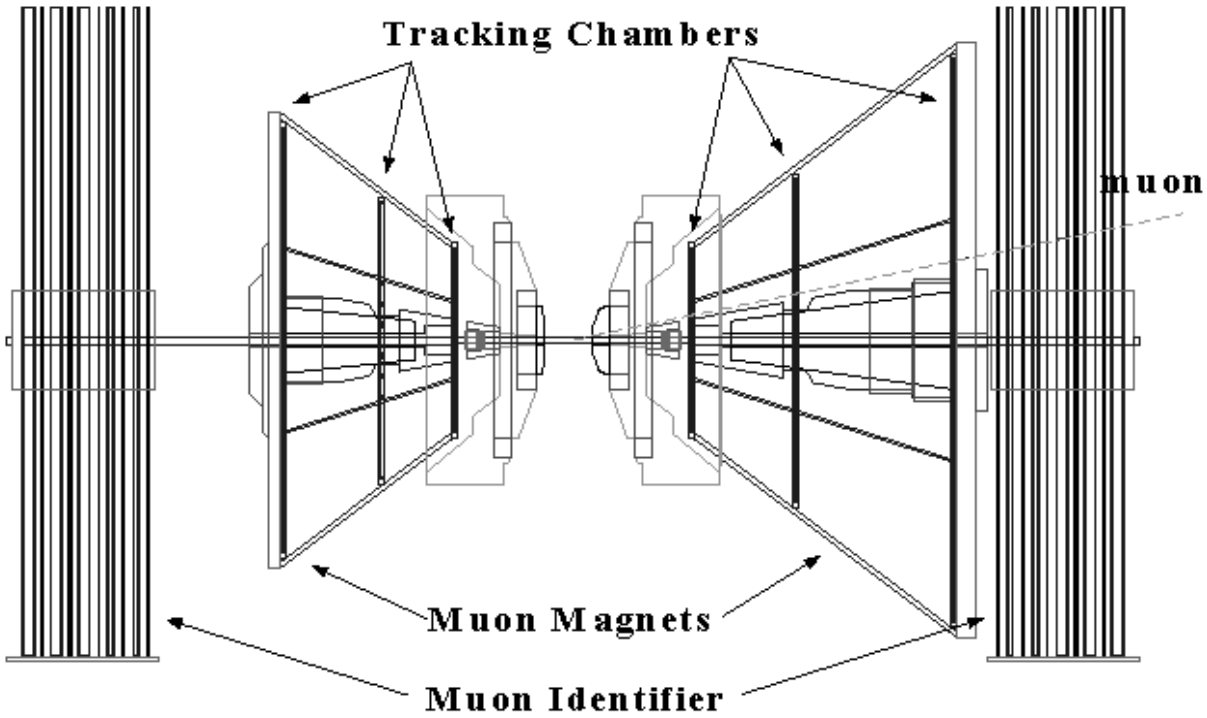
$\int BdL = 2{,}500 - 7{,}700 \text{gauss} - \text{m}$

CSC -100μm

3stations
3 gaps
3 planes

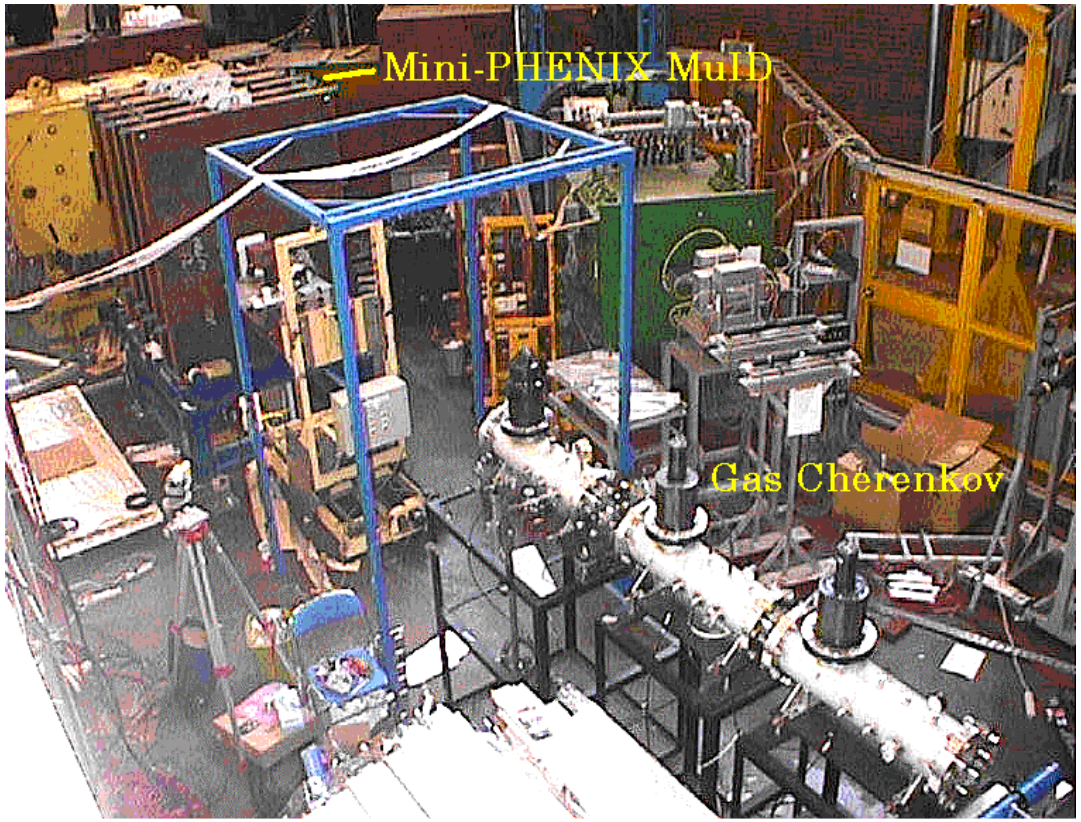
MuID

5 layers
absorber:
North:30+10+10+20+20 cm
South:20+10+10+20+20 cm

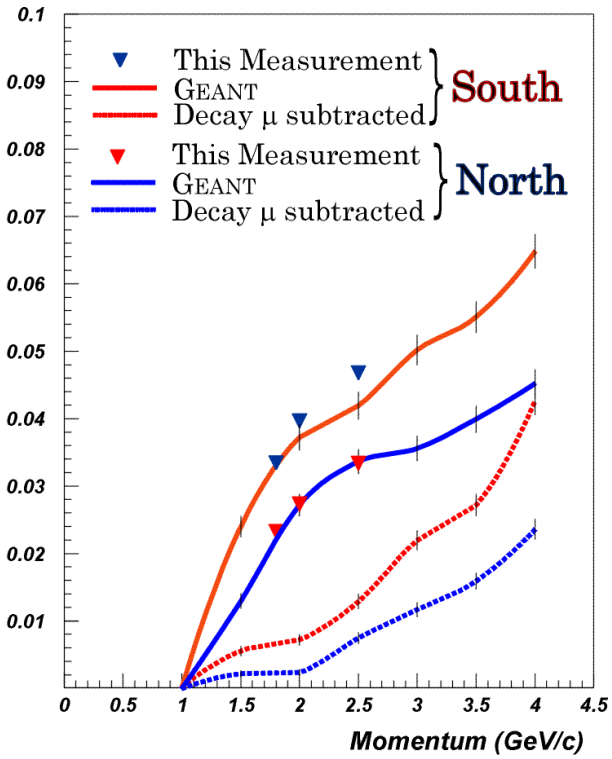


PHENIX MuID Beam Test@KEK

π rejection measured with 1.8-2.5 GeV beam



Fraction of remaining π



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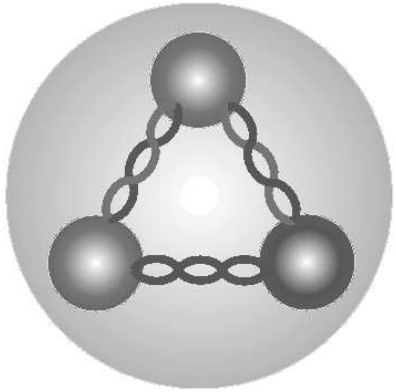
Spin Sum Rule for the Proton

- Proton spin=1/2



Quark Spin: $\Delta\Sigma$

valence quark: $\Delta u_v, \Delta d_v$

sea quark: $\Delta\bar{u}, \Delta\bar{d}, \Delta\bar{s}$

Quark Orbital Motion: L_q

Gluon Spin: ΔG

Gluon Orbital Motion: L_g

$$\Delta f(x) = f_{\uparrow}(x) - f_{\downarrow}(x); \int_0^1 \Delta f(x)dx \equiv \Delta f$$

Spin Sum Rule

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

"Proton Spin Crisis"

- Successful Description of Baryon μ_M by Quark Model

  $\longrightarrow$ *"quark carries all proton spin"*

- Puzzling Data from polarized lepton-Nucleon scattering

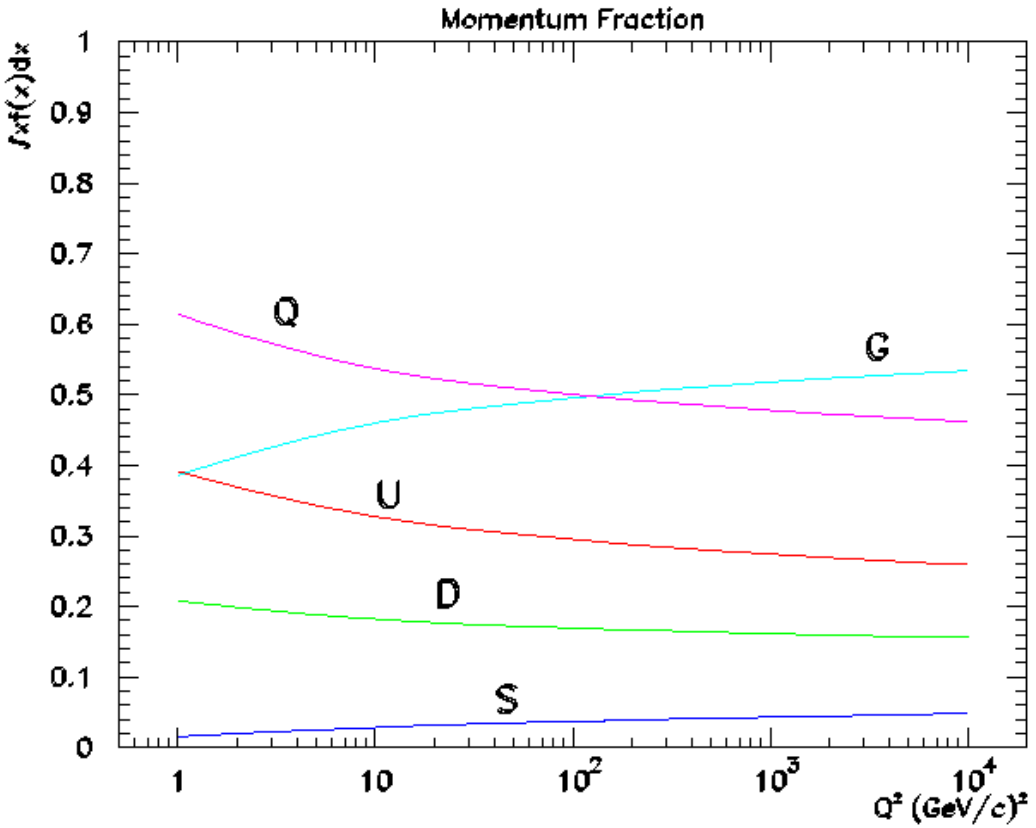
  $$\Delta\Sigma \approx 0.3; \Delta s \approx -0.1$$

- Fixes for *"Spin Crisis"*
  - Gluon is polarized : $\Delta G > 0$
  - Anti-quark is polarized: indirect decomposition suggests $\Delta s < 0$
  - Steeper small-x

Parton as a Carrier of Mom.

- About Half is Carried by Gluon!

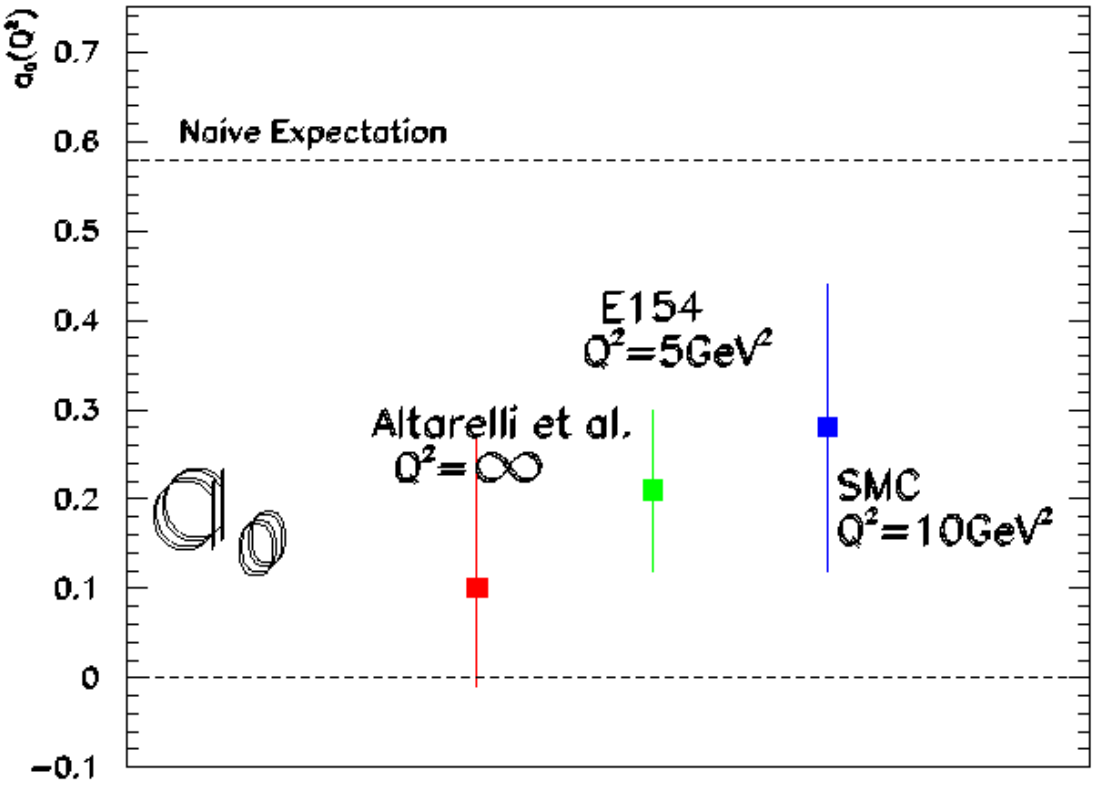
- GRV94LO:
  M.Glueck,
  E. Reya,
  A. Vogt
  ZPC67 (95) 433



Updates on "Spin Crisis" $\Delta\Sigma(Q^2)$

- Most Recent 3 global analysis results
  - Altarelli *et al.*:
    NP B496 (97) 337
    0.10+0.17-0.10
  - E154: K. Abe *et al.*
    PL B405 (97) 180
    0.21+-0.09
  - SMC: D. Adams *et al.*
    PL B412 (97) 414
    0.34+-0.17
    0.22+-0.17

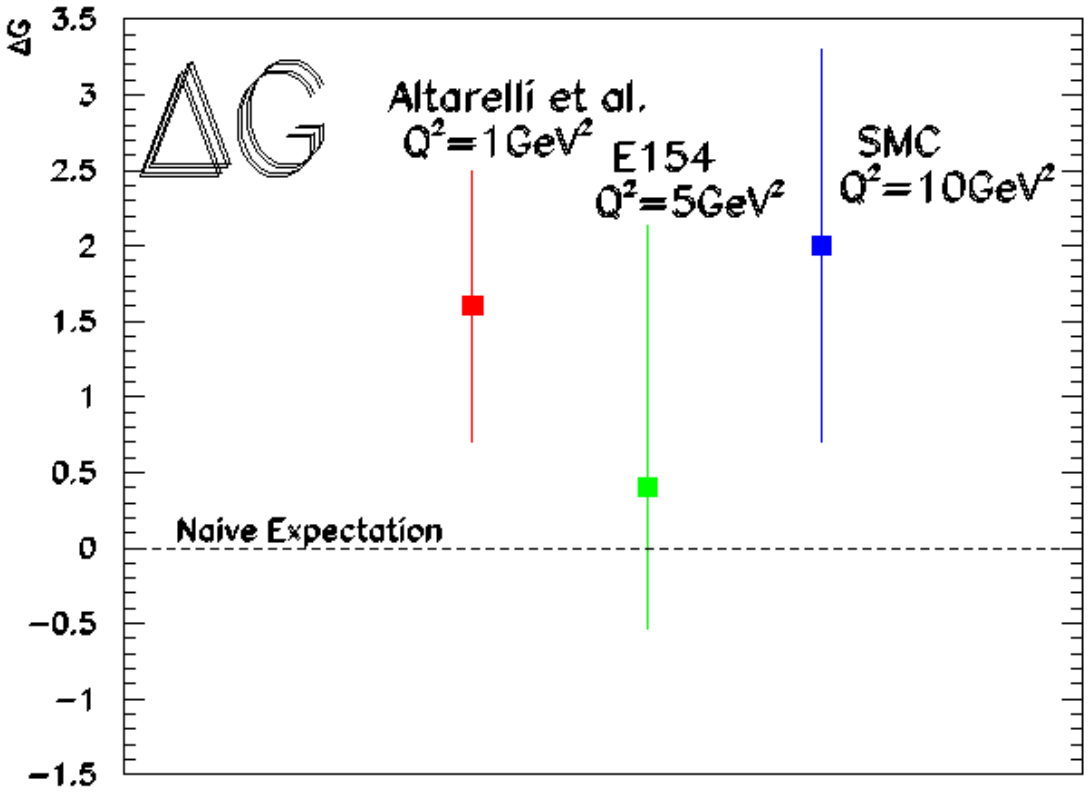
all available data are included



Updates on "Spin Crisis" ΔG

ΔG extracted thru NLO analysis of pol-DIS data

- Altarelli *et al.*:
  NP B496 (97) 337
  1.6+-0.9
- E154: K. Abe *et al.*
  PL B405 (97) 180
  0.4+1.74-0.93
- SMC: D. Adams *et al.*
  PL B412 (97) 414
  0.9+-0.3(exp)+-1.0(tho)

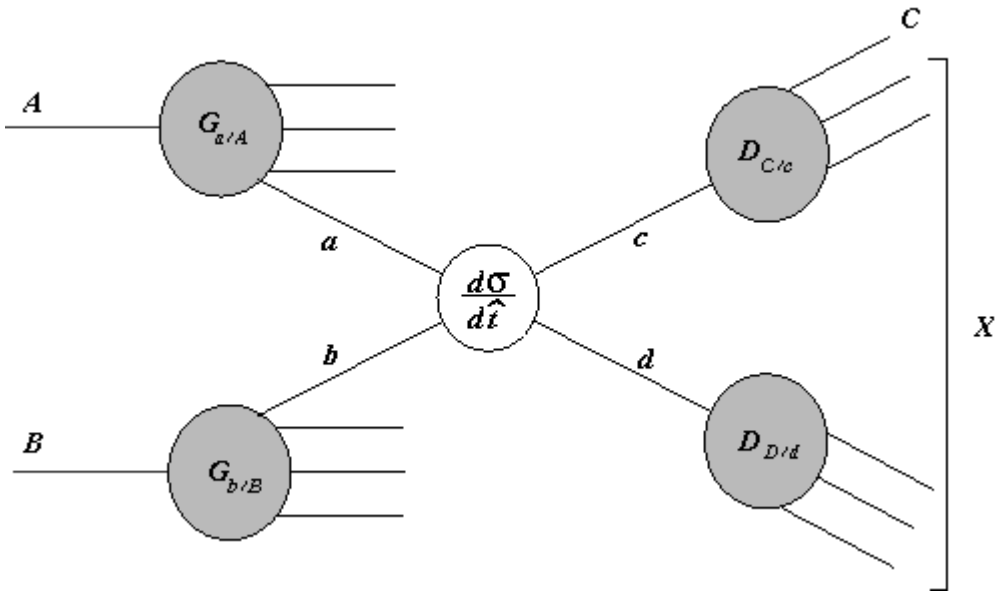


Gluon Helicity Distribution

- Inclusive Prompt Photon Production
  - theoretically reasonably well-understood process
    LO and NLO; spin averaged and difference
  - Experimental difficulty can be overcome
- Inclusive π^0 Production
  - Experimentally rather easy; hi-stat measurement
  - Penalty of fragmentation uncertainty
- Open Heavy Flavor Production
  - Hi-stat measurement; negatively large a_{LL}
  - Possible cancellation at NLO is pointed out
- Quarkonium Production
  - Identification easy; hi-stat
  - Uncertainty in Production Mechanism

σ for Hadron Reaction $AB \to CX$

- Three stages of hadron-hadron interaction
  - pick up partons with x_a, x_b : $G_{a/A}(x)$
  - Parton reaction: $\frac{d\sigma_{cd}^{ab}}{dt}$
  - Hadronization: $D_{C/c}(z)$



$$E\frac{d^3\sigma}{dp^3} \sim \sum_{abcd} G_{a/A}(x_a) \otimes G_{b/B}(x_b) \otimes \frac{d\sigma_{cd}^{ab}}{dt} \otimes D_{C/c}(z)$$

Asymmetry for $AB \to CX$

- Similarly to σ

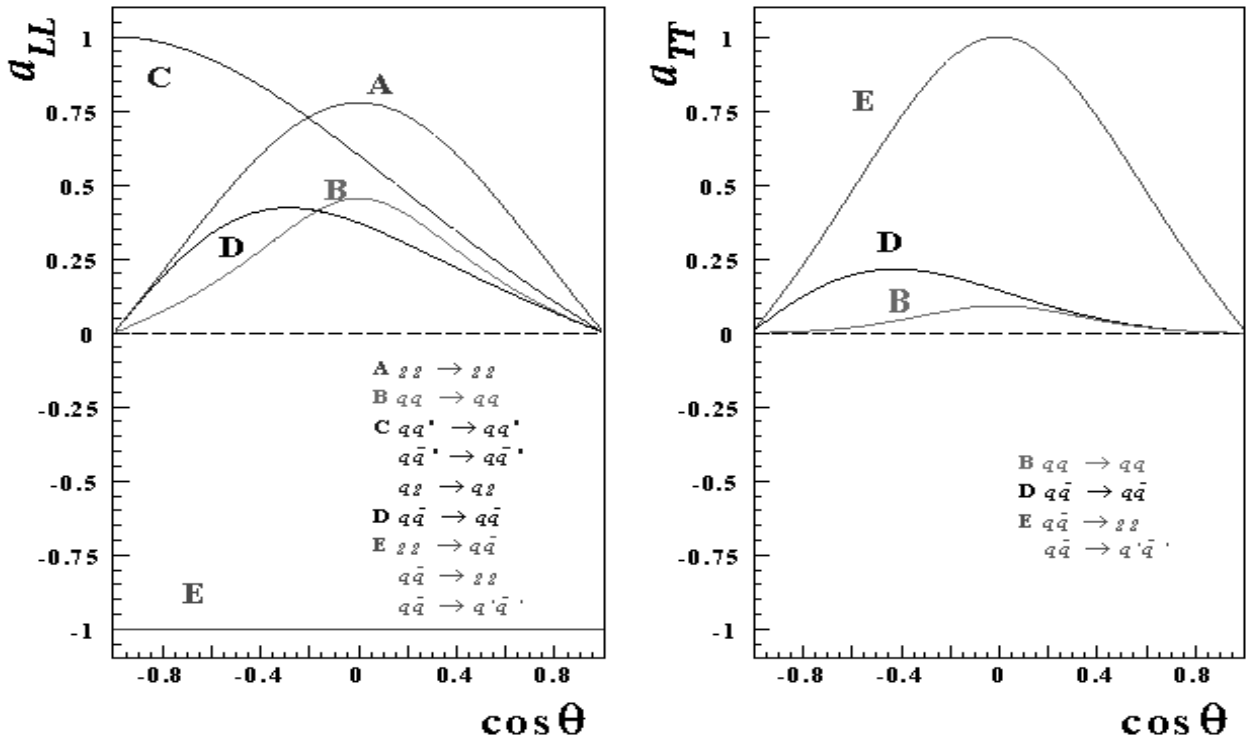
$$A = \frac{Ed^3\Delta\sigma}{dp^3} \Big/ \frac{Ed^3\sigma}{dp^3} \approx \frac{\Delta G_{a/A}(x_a)}{G_{a/A}(x_a)} \otimes \frac{\Delta G_{b/B}(x_b)}{G_{b/B}(x_b)} \otimes a_{LL}(ab \to cd)$$

A	Experimentally Measured
$a_{LL}(ab \to cd)$	Calculated in pQCD

If one of structure function known, we can extract the other directly

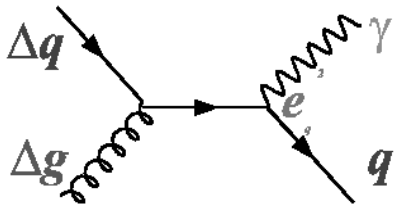
Parton Level Asymmetries

- Calculated in pQCD at Leading Order as functions of scattering angle (θ) in partonic CMS

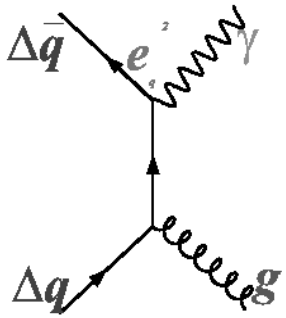


Prompt Photon Production

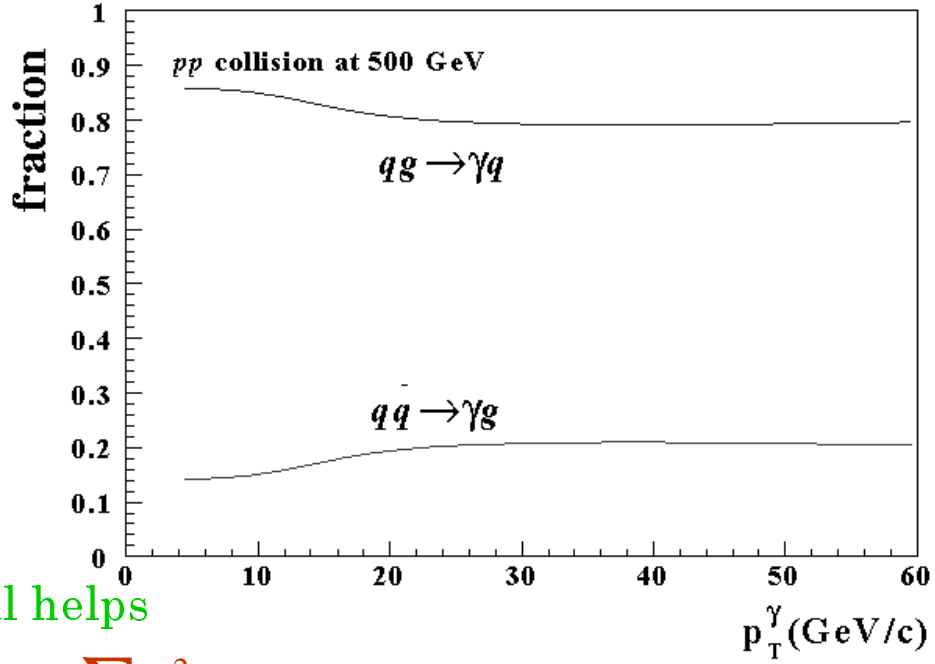
- Gluon Compton Dominates σ



gluon Compton



annihilation

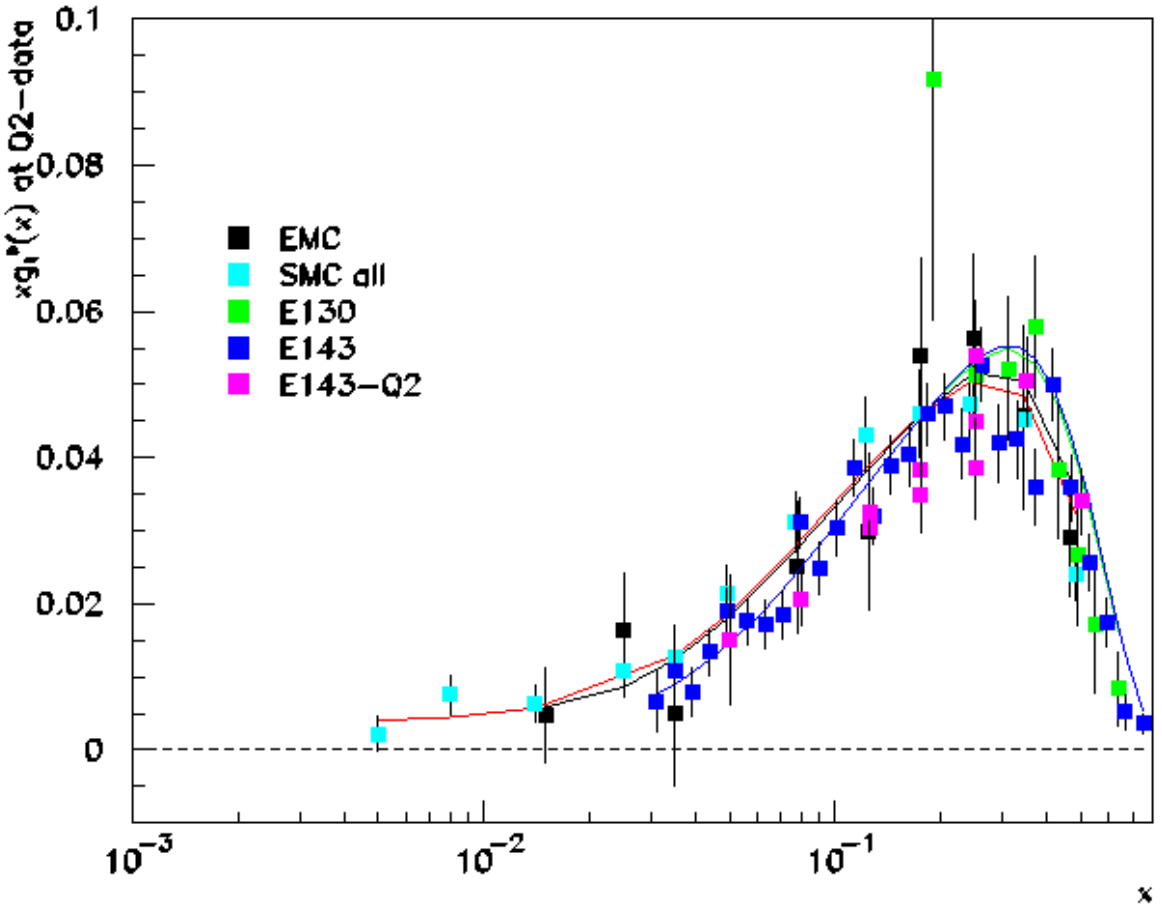


Theoretically clean
Experimentally Hard Object
Fine granuality of PHENIX EMcal helps

$$A_{LL}(p_T) = a_{LL}(qg \to \gamma q) \cdot \frac{\Delta g(x)}{g(x)} \cdot \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)}; i = u, \bar{u}, d, \bar{d}, s, \bar{s} \ldots$$

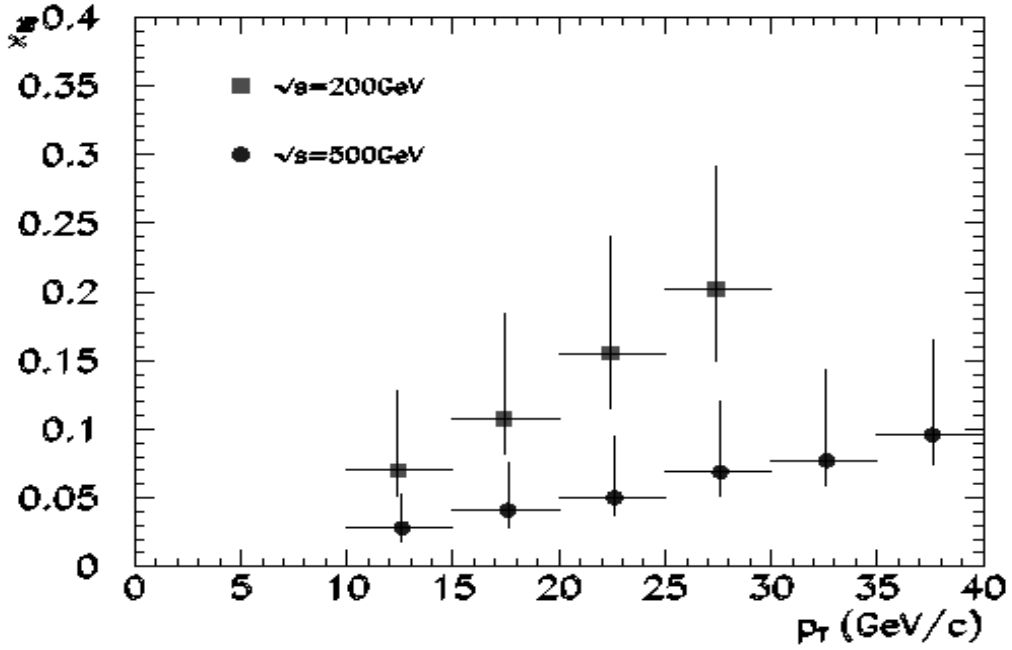
$$A_1^p(x) = \frac{g_1^p(x)}{f_1^p(x)} = \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)}$$

Pol-DIS Data Proton



Partonic Level Kinematics

- Hard to reconstruct : need Monte Carlo Study
- PYTHIA study shows good correlation between p_T^{γ} and x_{gluon}



Sensitivity to $\Delta G(x)/G(x)$

- 370 pb^{-1}@200 GeV and 800 pb^{-1}@500 GeV

	$\sqrt{s}$ = 200GeV			$\sqrt{s}$ = 500GeV		
Photon p_T	Yield	Errors on		Yield	Errors on	
		A_{LL}	$\Delta G/G$		A_{LL}	$\Delta G/G$
10 – 15 GeV/c	100000	0.0062	0.046	900000	0.0022	0.045
15 – 20 GeV/c	13000	0.0168	0.089	180000	0.0048	0.059
20 – 25 GeV/c	2700	0.0376	0.171	53000	0.0089	0.081
25 – 30 GeV/c	590	0.0799	0.309	19000	0.0150	0.115
30 – 35 GeV/c				7700	0.0234	0.141
35 – 40 GeV/c				3300	0.0355	0.198

5-30%@200 GeV and 5-20%@500 GeV Yuji GOTO (RIKEN)

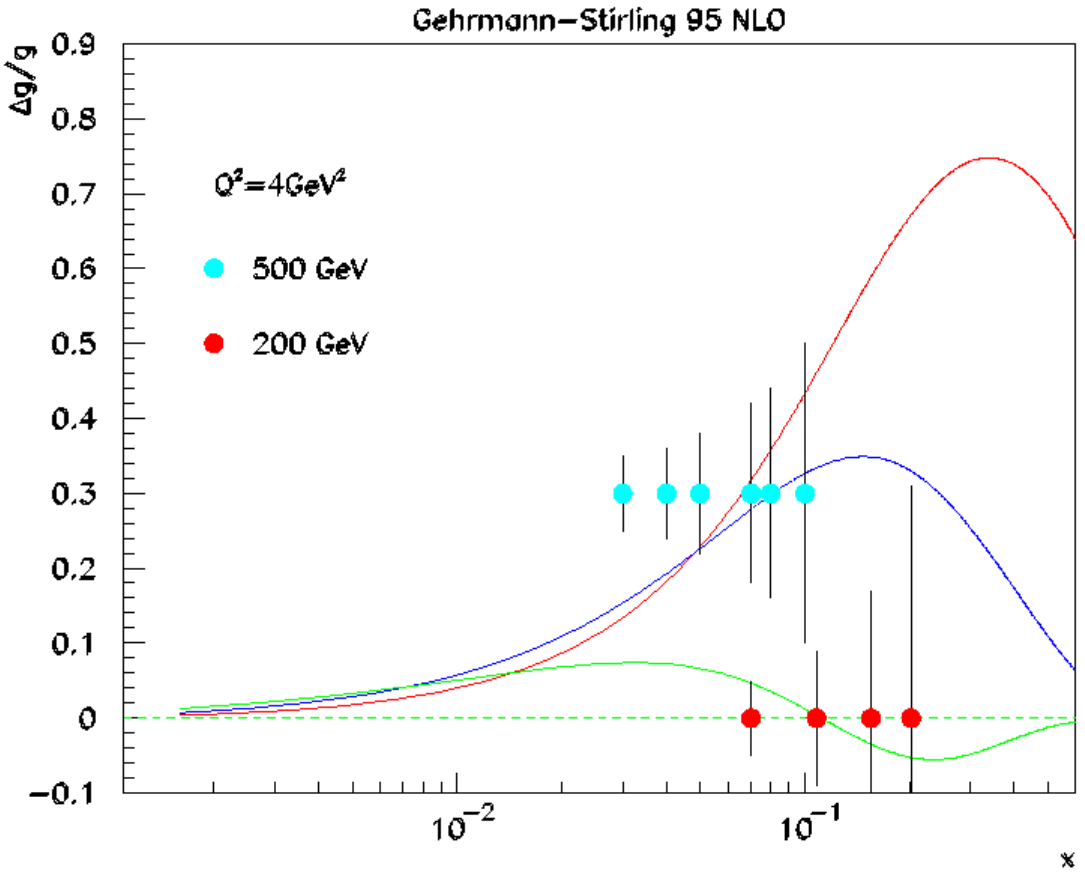
Statistical error only. Other sources are; beam polarization, experimental error on A_l^p, and scale uncertainty etc.

Naohito Saito, RIKEN

Models and Sensitivity Goal

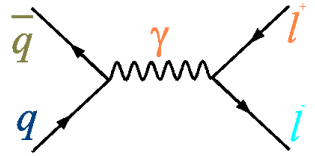
- $\int Ldt$ 10 weeks
  70% efficiency
  - 340 pb^{-1}@200 GeV
  - 800 pb^{-1}@500 GeV

- GSA ΔG=1.71
- GSB ΔG=1.63
- GSC ΔG=1.02



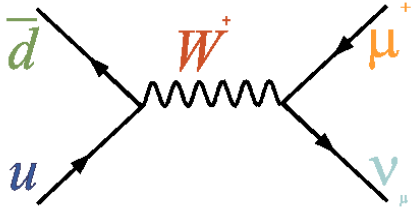
Anti-quark Helicity Distribution

- Drell-Yan Production of lepton pairs
  - maximal parton level asymmetry: a_{LL}= -1
  - possible severe background from semi-leptonic decays of open charm productions



$$A_{LL} = -\frac{\sum_i e_i^2\left[\Delta q_i(x_a)\Delta\bar{q}_i(x_b) + (x_a \leftrightarrow x_b)\right]}{\sum_i e_i^2\left[q_i(x_a)\bar{q}_i(x_b) + (x_a \leftrightarrow x_b)\right]}$$

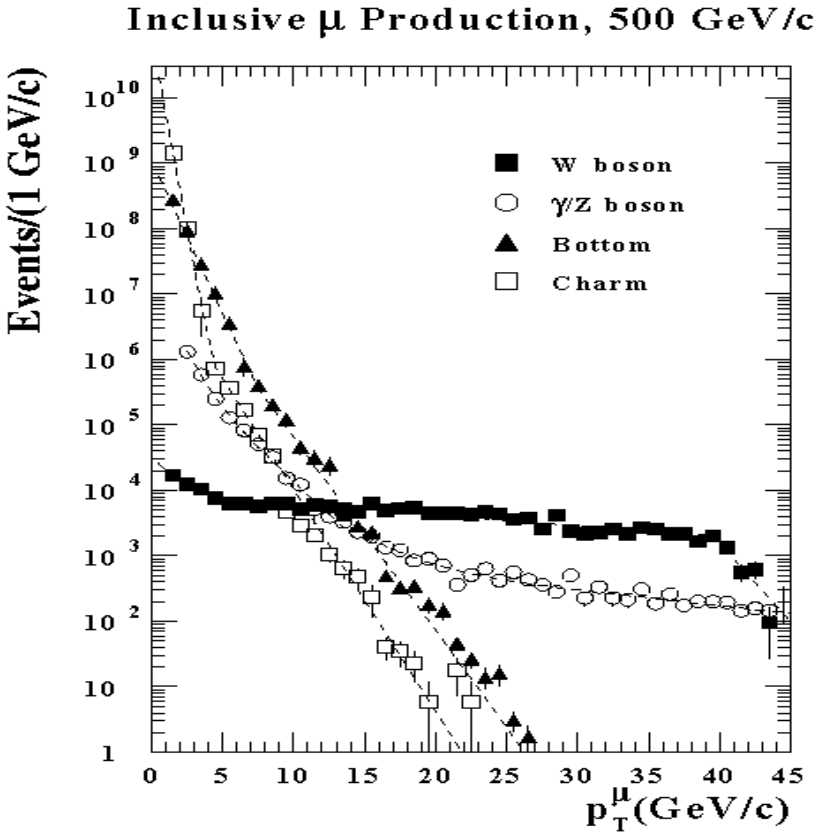
- *W* production
  - helicity of quarks definitely defined via *V-A* nature
  - flavor almost fixed: flavor analysis possible
  - PHENIX-Muon Arms, EMcal important

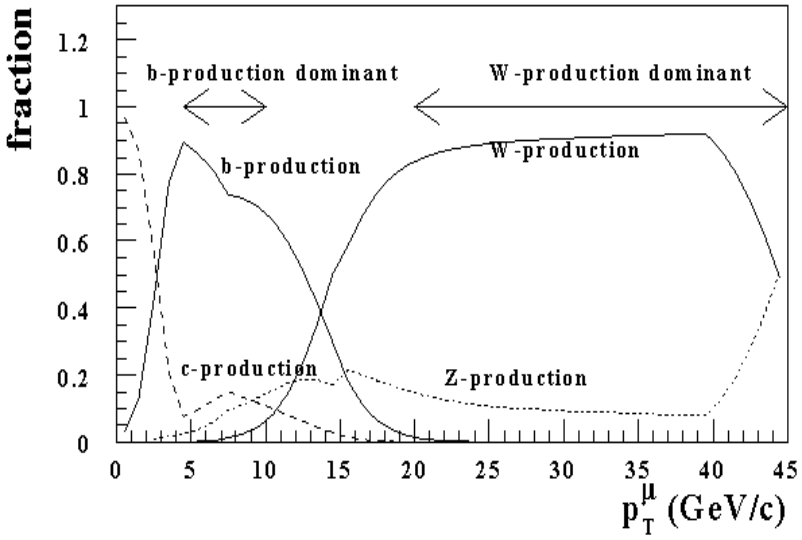


$$A_L^{W^+} = \frac{\Delta u(x_a, M_W^2)\bar{d}(x_b, M_W^2) - \Delta\bar{d}(x_a, M_W^2)u(x_b, M_W^2)}{u(x_a, M_W^2)\bar{d}(x_b, M_W^2) + \bar{d}(x_a, M_W^2)u(x_b, M_W^2)}$$

W detection with hi-p_T lepton

- Inclusive muon p_T spectra





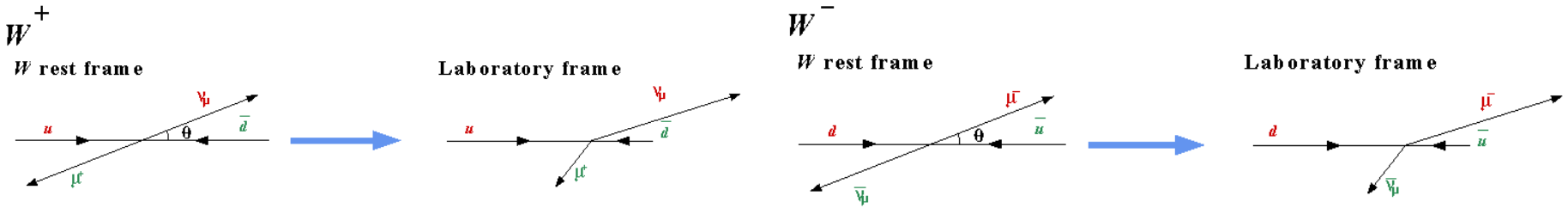
W contribution dominates
@p_T>20 GeV/c

W yield with 800 pb^{-1}

PYTHIA w/ GRV94LO checked against CDF data

	W^-	W^+
acceptance for muon w/ $p_T > 20$ GeV/c	14%	4%
yield (both muon arms)	5100	5600
ΔA_L (statistical only)	2%	2%
rapidity average	0.78±0.34	0.71±0.41
background from Z-decay	1095(21.5%)	984(17.6%)

Acceptance difference between W^- and W^+

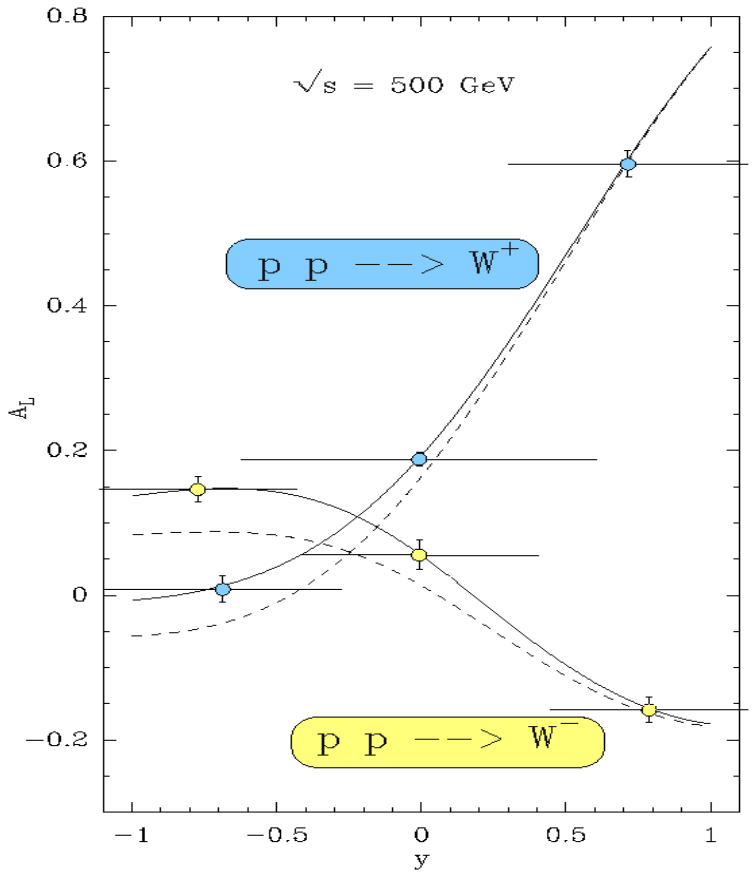


Prediction and Projected Error

- C. Bourrely, J. Soffer Published in Nucl.Phys.B445:341-379,1995

Prediction for the parity violating asymmetry A_L as a function of y^W

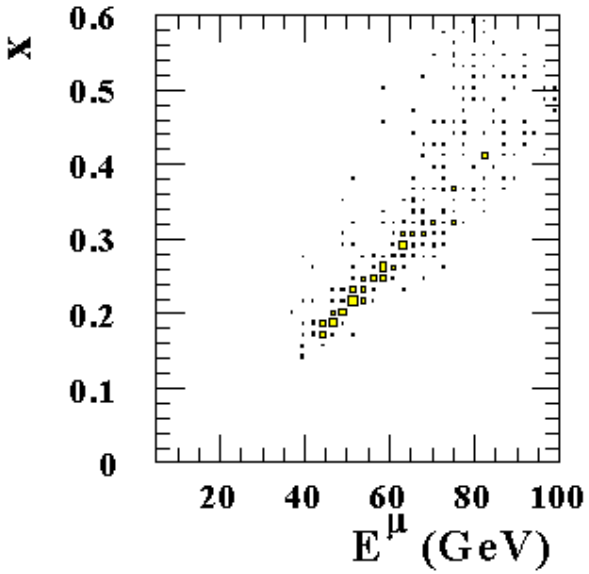
solid line: soft gluon
dashed line: hard gluon



Parton Level Kinematics

- Decay ν cannot be detected: x-determination hard
- but good correlation x vs E^{μ} : V-A requires $(1+\cos\theta)^2$

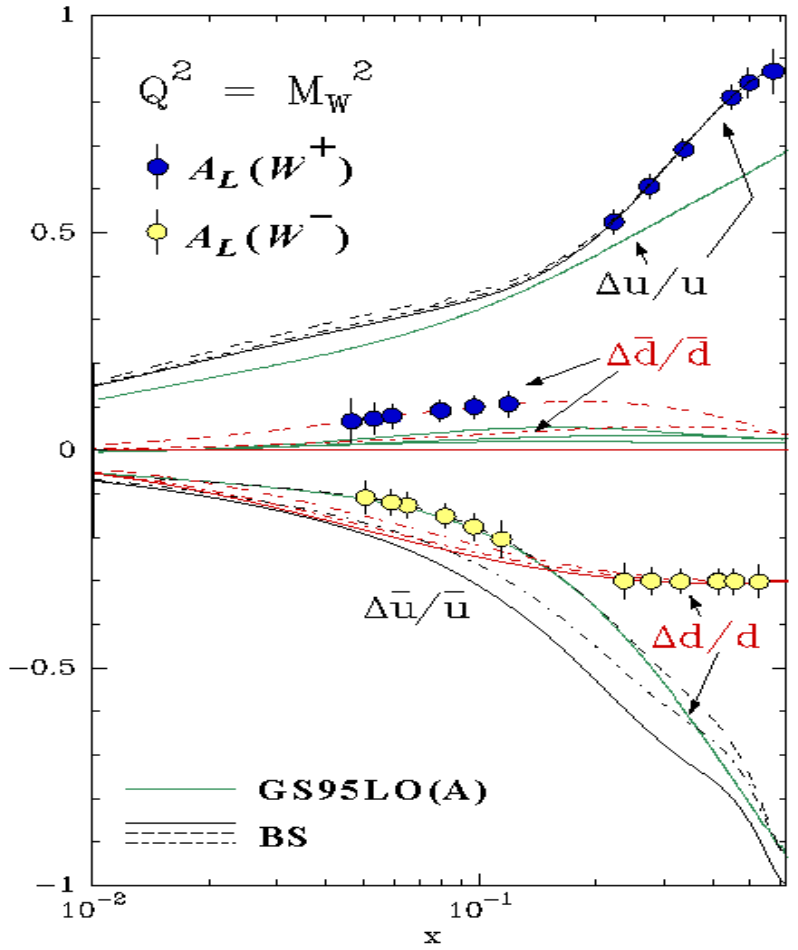
$$p_{\mu} = \frac{\sqrt{s}}{4}\left[(1+\cos\theta)x_u + (1-\cos\theta)x_{\bar{d}}\right]; M_W = \sqrt{x_u x_{\bar{d}} s}$$



p^{μ} region	x-average W^+
$34 < p^{\mu} < 50$ GeV/c	0.22±0.08
$50 < p^{\mu} < 60$ GeV/c	0.27±0.08
$60 < p^{\mu} < 70$ GeV/c	0.33±0.09
$70 < p^{\mu} < 80$ GeV/c	0.44±0.11
$80 < p^{\mu} < 95$ GeV/c	0.49±0.10
$95 < p^{\mu} < 120$ GeV/c	0.56±0.11

Sensitivity Goal - statistical limit

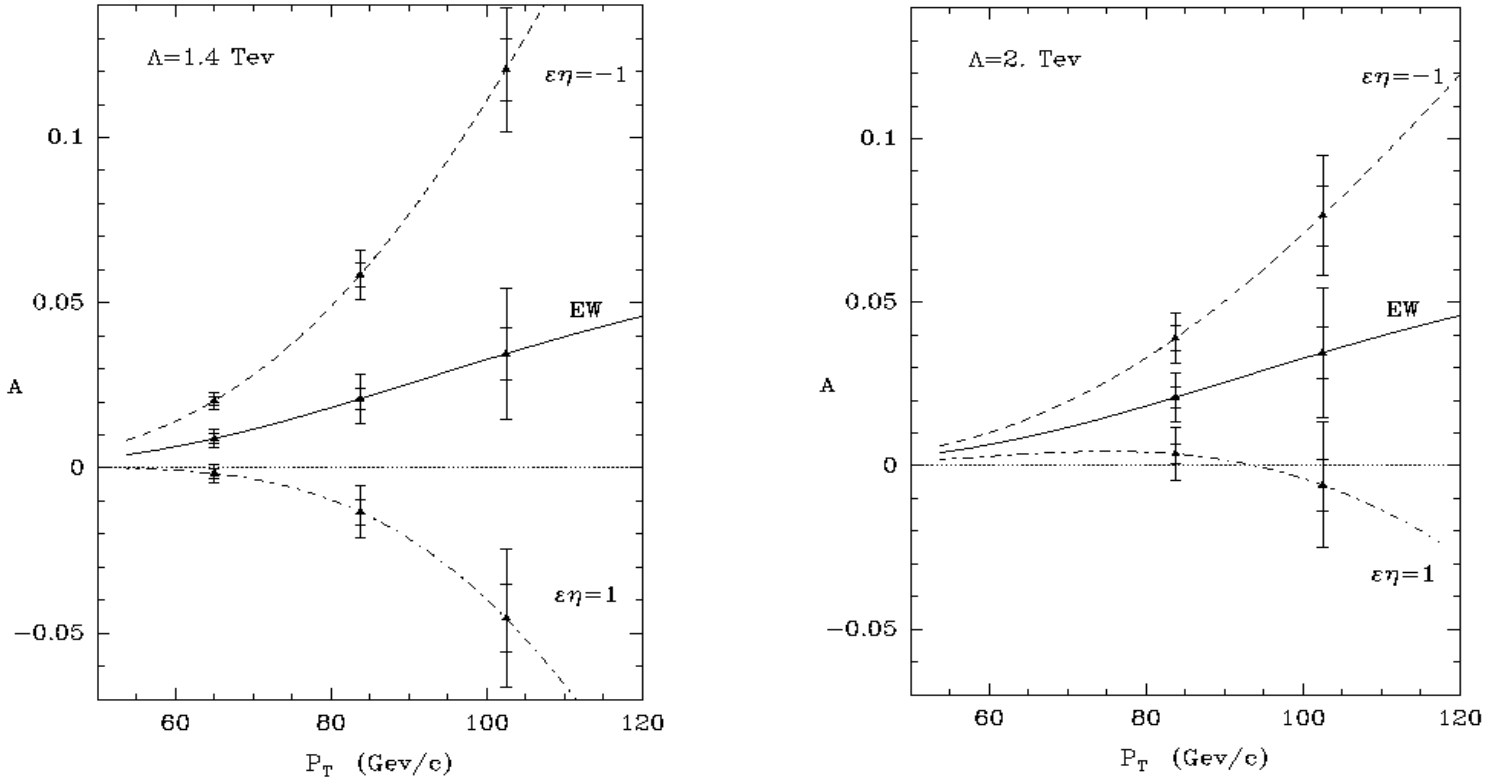
- Anti-quark polarization measured with A_L^W
- More systematic studies are underway
  - background from π/K decays
  - background from Z^0 decays



Parity Violation Beyond SM

P. Taxil, J.M. Virey PLB 364(1995)181-187

PV in Jet Production due to quark Compositeness (scale:Λ)

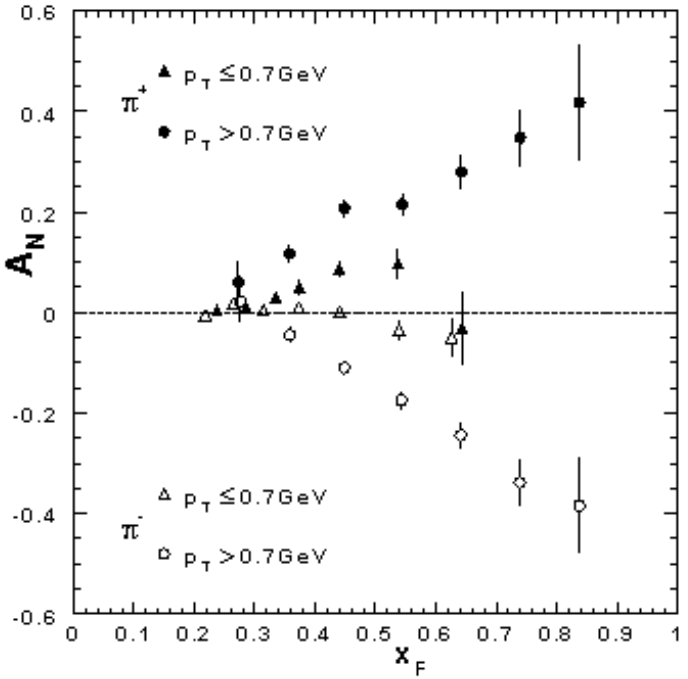


Single Transverse Spin Asymmetry

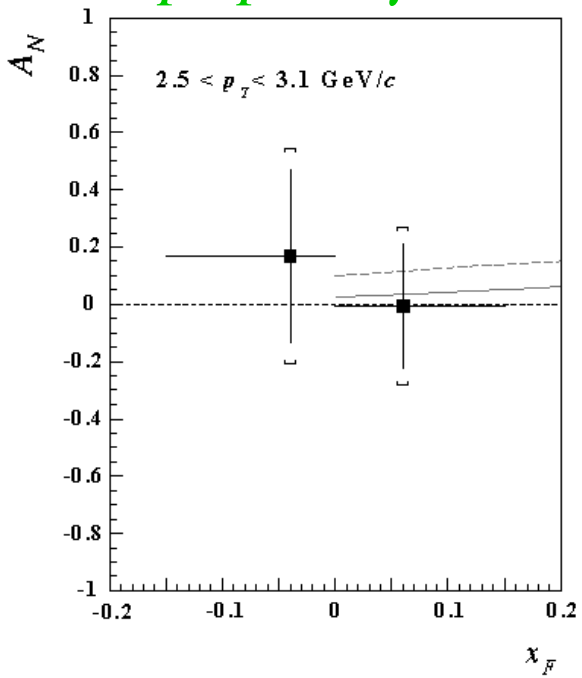
A_N - *higher twist effect*

- FNAL-E704 *pp* collision at $\sqrt{s} \approx 20\text{GeV}$

$p^{\uparrow} p \to \pi X$



$p^{\uparrow} p \to \gamma X$



Summary

- RHIC Spin project provides unique opportunity to perform Spin Physics Study
- Spin Sturucture Studies
  - $\Delta G(x)$ measurement: 5-30%@200 GeV, 5-20%@500 GeV
  - $\Delta q(x)$ measurement: 2% error for A_L^W
  - flavor decomposition is possible thru A_L^W
  - further systemtic studies are underway…
- RHIC Physics Run will start October, 1999!