QM 2001

Quark Matter 2001

RHIC

RHIC SPIN Program

The 15th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions

January 15-20, 2001, SUNY at Stony Brook, NY

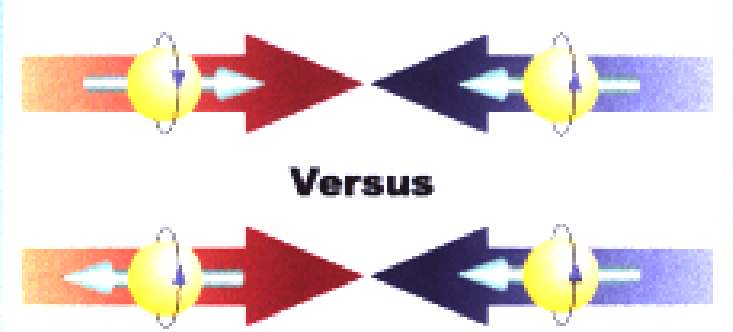
Naohito Saito

RIKEN / RIKEN BNL Research Center

RIKEN

Spin Physics at RHIC

- Measure Spin Asymmetries in *pp* collision to pin down
  - Spin Structure of the Nucleon
    - Proton Spin Sum Rule
    - Transversity Distributions

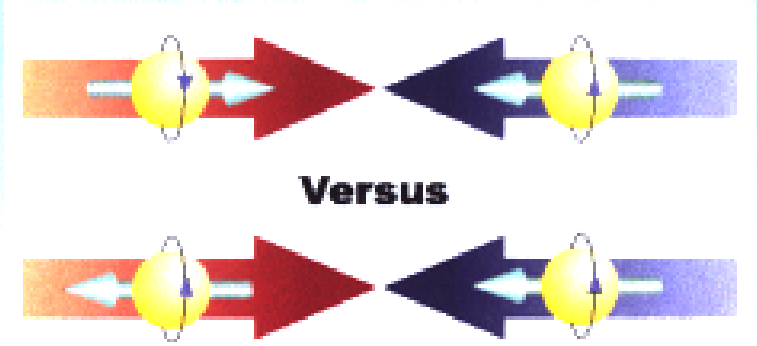


  - Spin Dependence of Fundamental Interactions
    - Parity Violating Interaction
    - CP Violation in Quark Sector and Higgs Sector
  - Spin Dependence of Fragmentation
    - E.g. Lambda fragmentation function
  - Spin Dependence in *pp* elastic scattering

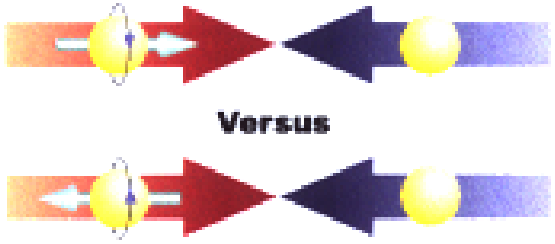
Asymmetries

- A_{LL}: Double Longitudinal Spin Asymmetry
  - Useful in extracting quark/gluon helicity distributions

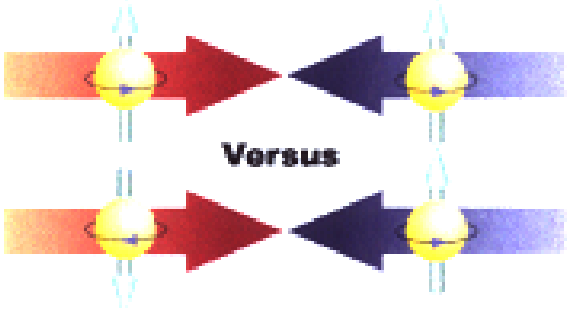
$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$



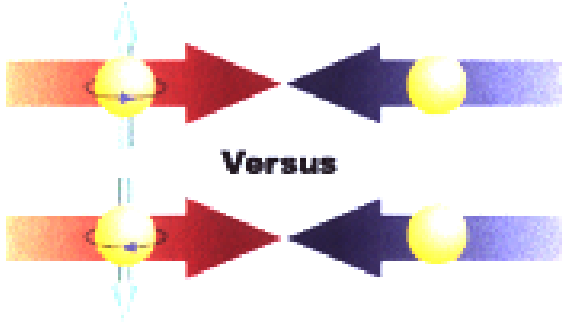
A_L:Parity Violation



A_{TT}: Transversity

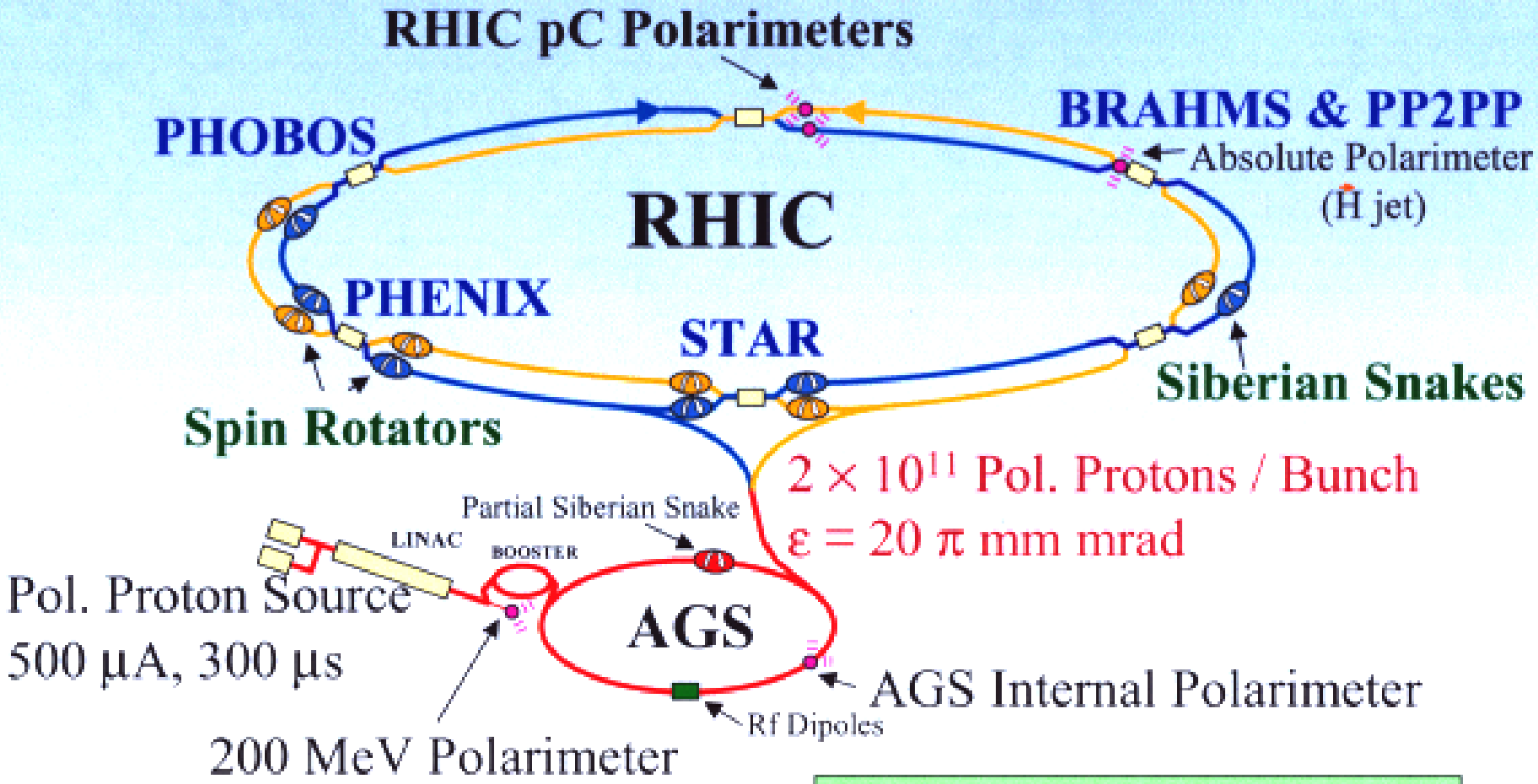


A_N:Twist-3 or $\not{T}$



Polarized Collider : RHIC

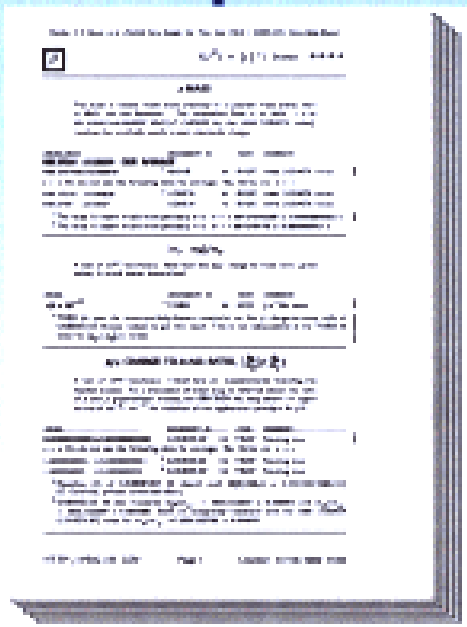
70% Polarization $L_{max} = 2\times10^{32} s^{-1} cm^{-2}$ $50 < \sqrt{s} < 500\, GeV$



Illustrated by Thomas Roser

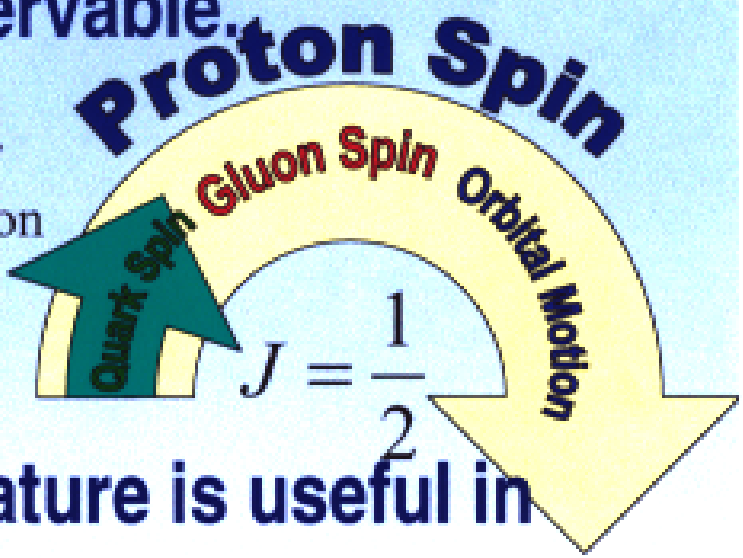
Why Spin Physics?

- "Spin" is a fundamental observable.

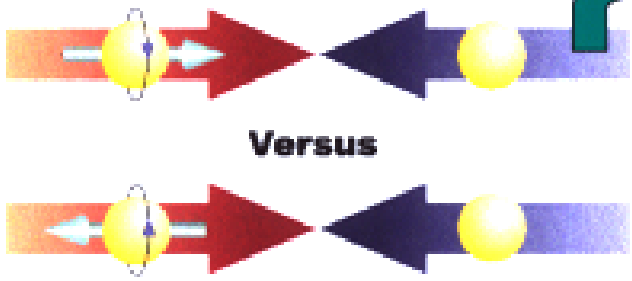


$$\Delta\Sigma = 0.1 \sim 0.2$$

Total fraction of the proton spin carried by the quark spin; Scheme dependent.



- *Axial vector* nature is useful in symmetry tests
  - Parity
  - Time Reversal



		$\mathcal{P}$	$\mathcal{T}$
position	x	$-x$	x
momentum	p	$-p$	$-p$
spin	σ	σ	$-\sigma$

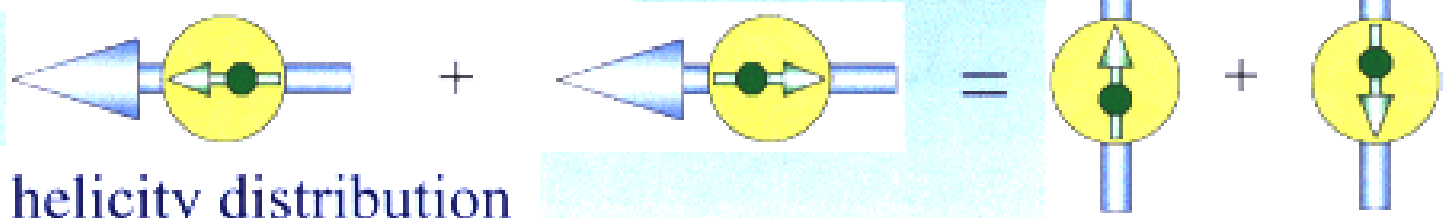
Parton Distribution Functions

RHIC

Quark Distributions

unpolarized distribution

$q(x,Q^2)=$

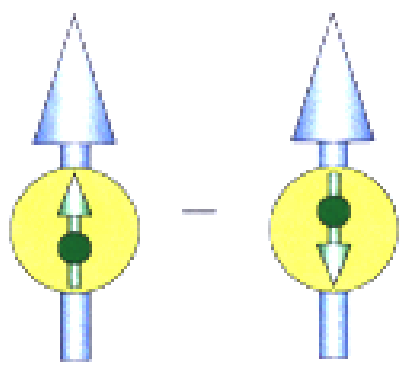


helicity distribution

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

transversity distribution

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



Gluon Distributions

$g(x,Q^2)=$

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

No Transverse Gluon Distribution

RIKEN

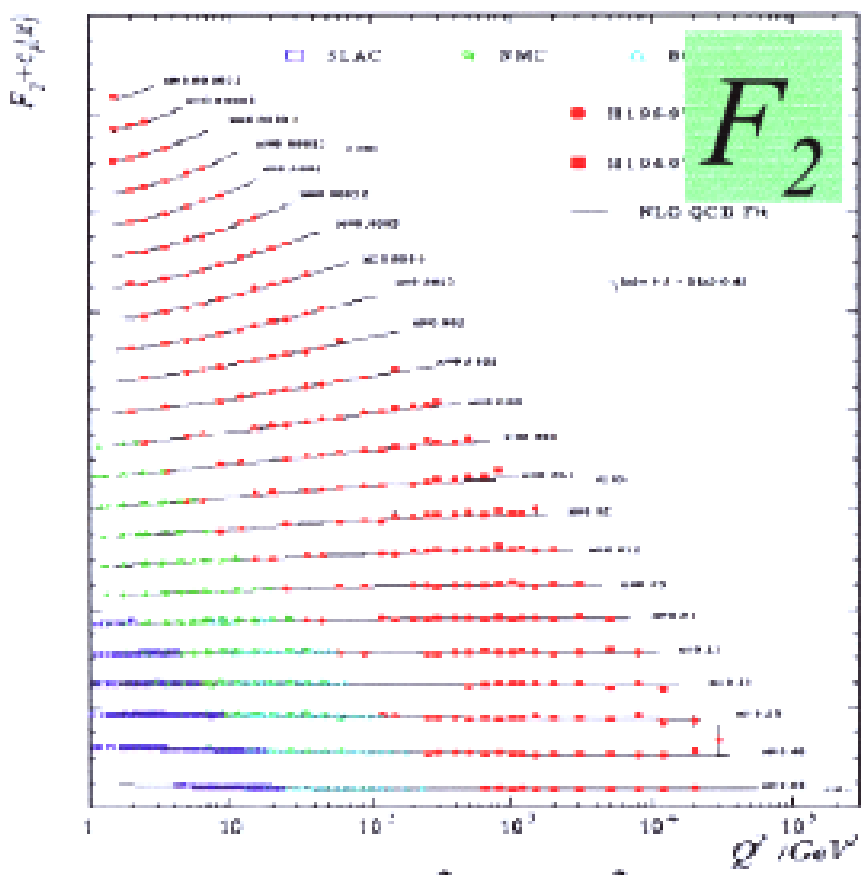
PDFs and their First Moments

- PDFs of interest
  - $\Delta q(x,Q^2)$, $\delta q(x,Q^2)$, and $q(x,Q^2)$ $(q=u,d,s,\bar{u},\bar{d},\bar{s},\ldots)$
  - $\Delta g(x,Q^2)$ and $g(x,Q^2)$
  - Even measurements in limited range of x would HELP!
    - If you know $g(x,Q^2)$ around $x=0.1$, you can calculate $gq \rightarrow \gamma X$ at pT=10 GeV/c in vs=200 GeV collisions at RHIC
- First Moments (and other moments)
  - Integrated over $0<x<1$ to be compared with quantum number carried by the proton
    - First Moments of $q(x)$: $\int_0^1 [u(x)-\bar{u}(x)]dx = 2;\ \int_0^1 [d(x)-\bar{d}(x)]dx = 1$
    - Second Moments $g(x)$: $\int_0^1 xg(x)dx \approx 0.5$
    - First Moment of $\Delta g(x)$: $\int_0^1 \Delta g(x)dx = \Delta g$

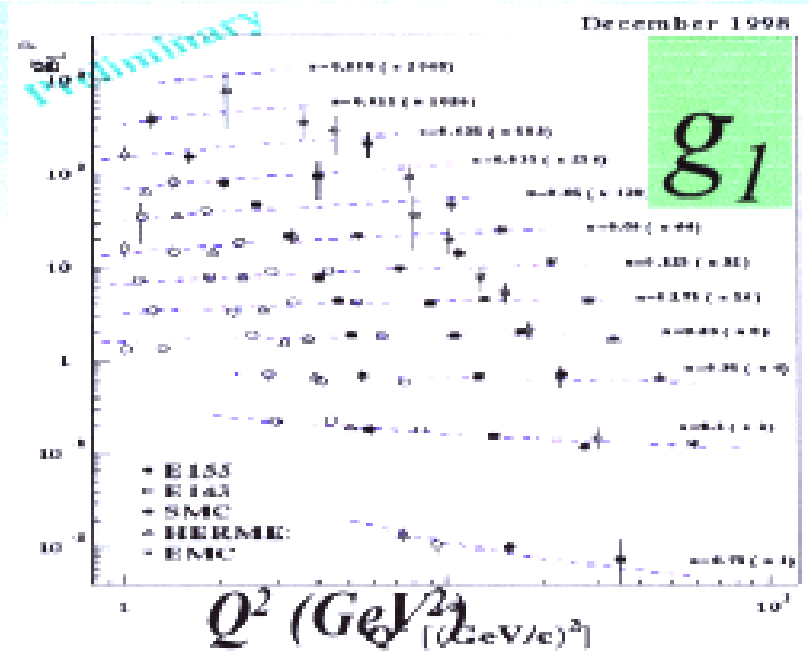
Experimental Inputs for PDFs

- **DIS $(lp \rightarrow lX)$ is a major source**

$$g_1^p(x,Q^2)=\frac{1}{2}\left\{\frac{4}{9}\Delta U(x,Q^2)+\frac{1}{9}\Delta D(x,Q^2)+\frac{1}{9}\Delta S(x,Q^2)\right\};\Delta Q(x)=\Delta q(x)+\Delta\bar{q}(x)$$



Q^2 (GeV^2)

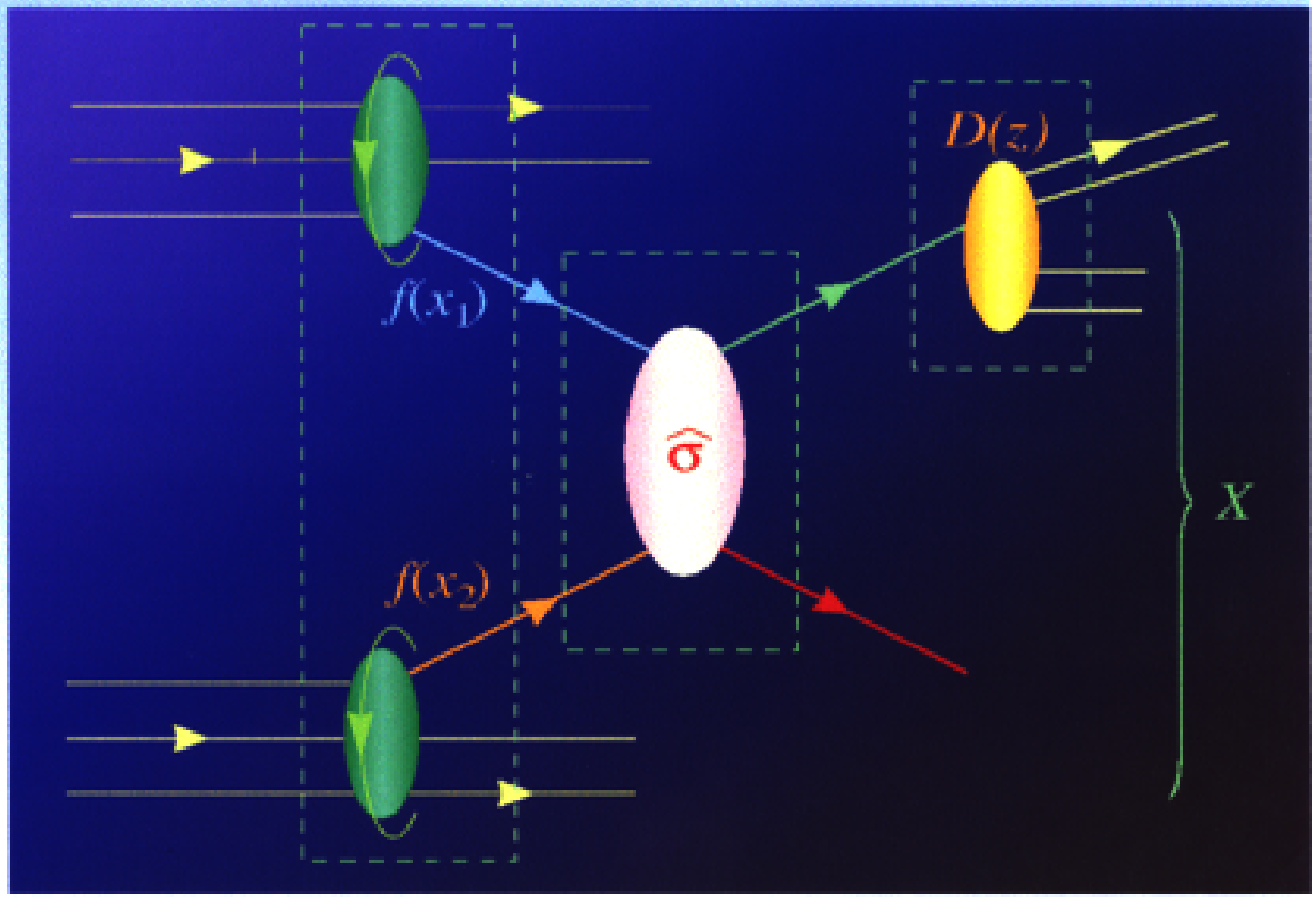


Major Source of Uncertainties:

1. **No Gluon Measurement**
2. **No Separation of Anti-Quark**

Hadron-Hadron Collision
(holds for both unpolarized and polarized cases)

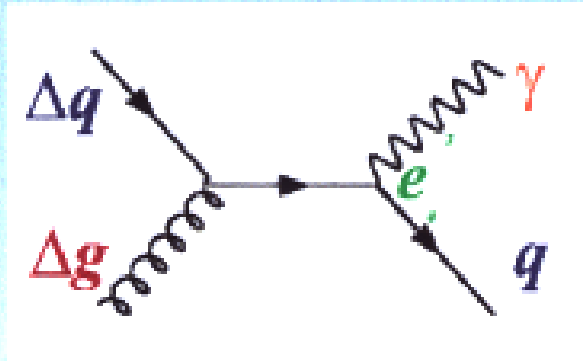
- Emitting Partons : $f(x)$
- Hard interaction of partons : σ
- Parton fragments into hadron : $D(z)$
- Universality of $f(x)$, σ , $D(z)$

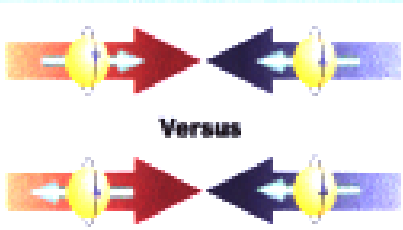


$$E\frac{d^3\sigma}{dp^3} = \sum_{i,j}\int f_i(x_1) f_j(x_2)\frac{d\hat{\sigma}}{dt}D(z)dP$$

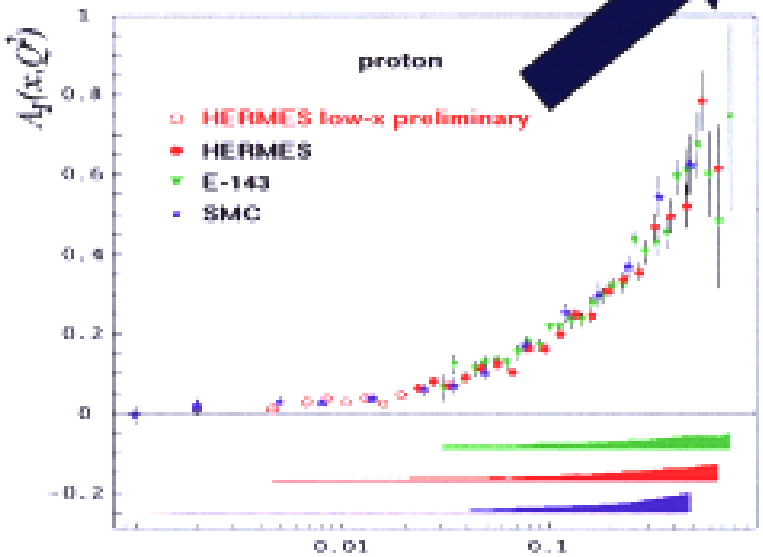
Ex-1: Prompt Photon Production

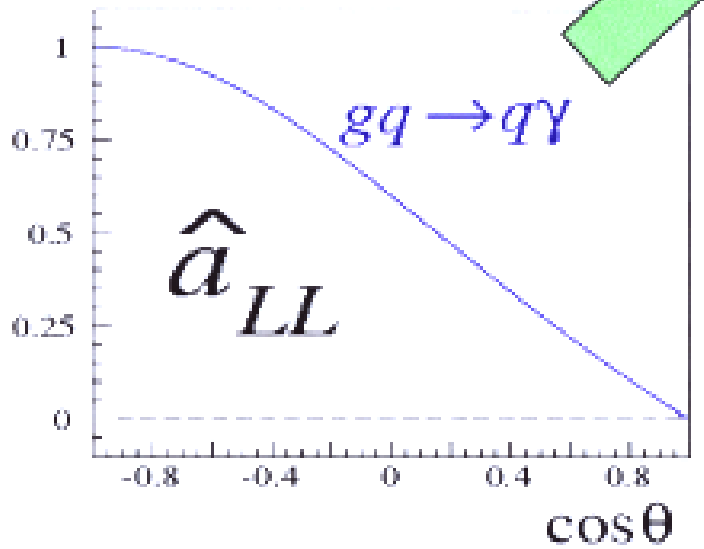
- **Gluon Compton Dominates**
  - Small Contamination from Annihilation
  - No fragmentation contribution in LO





$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum_i e_i^2 \Delta q_i(x_2)}{\sum_i e_i^2 q_i(x_2)} \otimes a_{LL}(gq \to q\gamma)$$





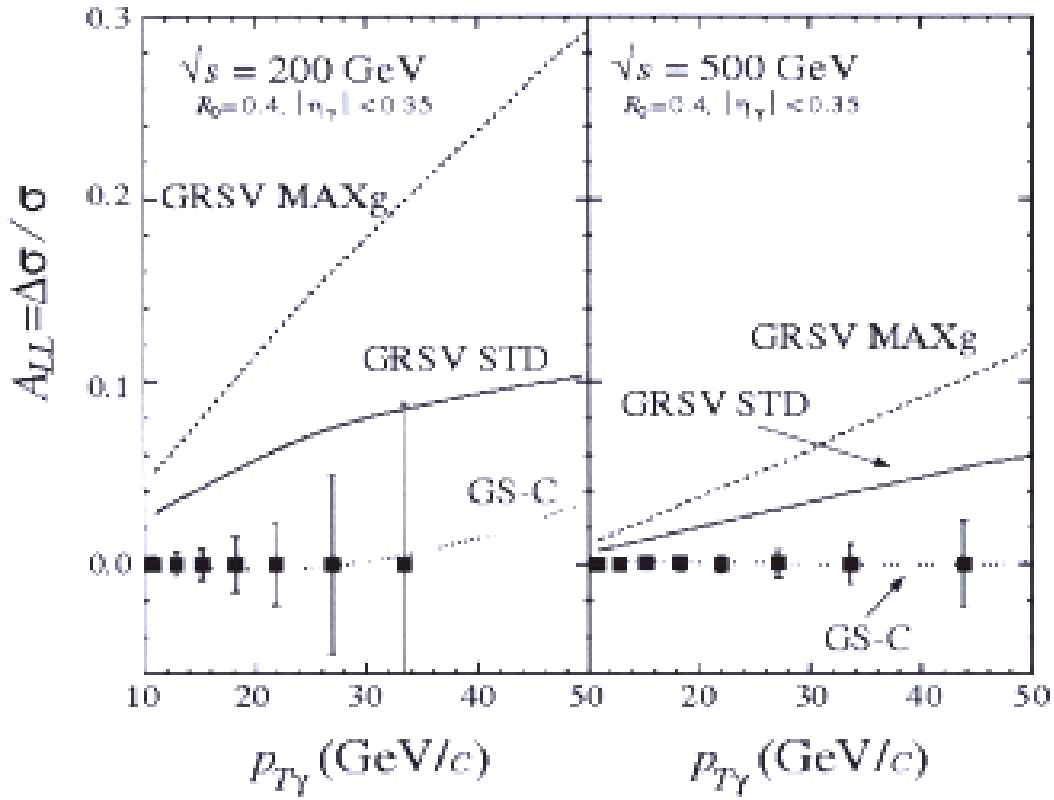
Prompt Photon Production

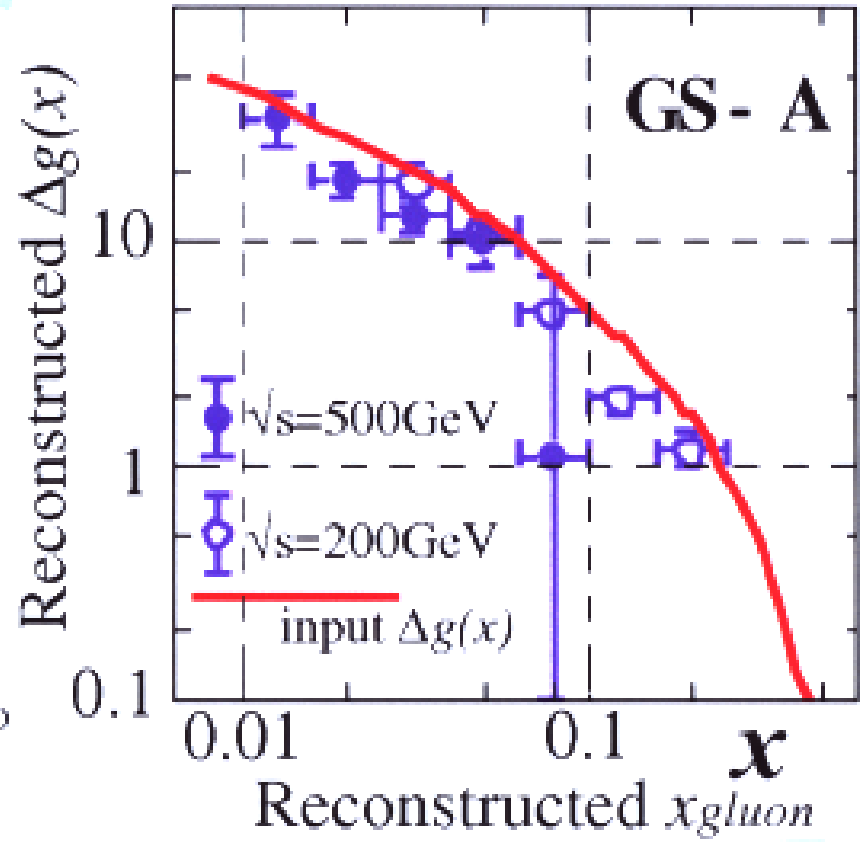
- **Gold Plated mode for both PHENIX & STAR**

Comparison at cross section level

= direct observable

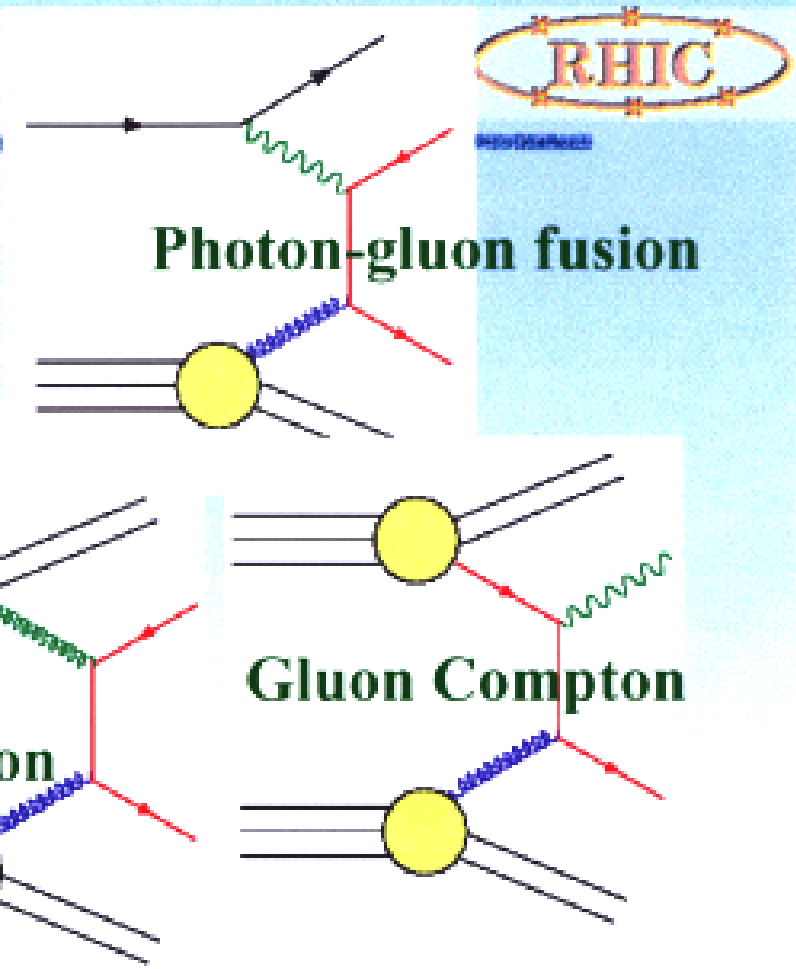
x-reconstructed using jet





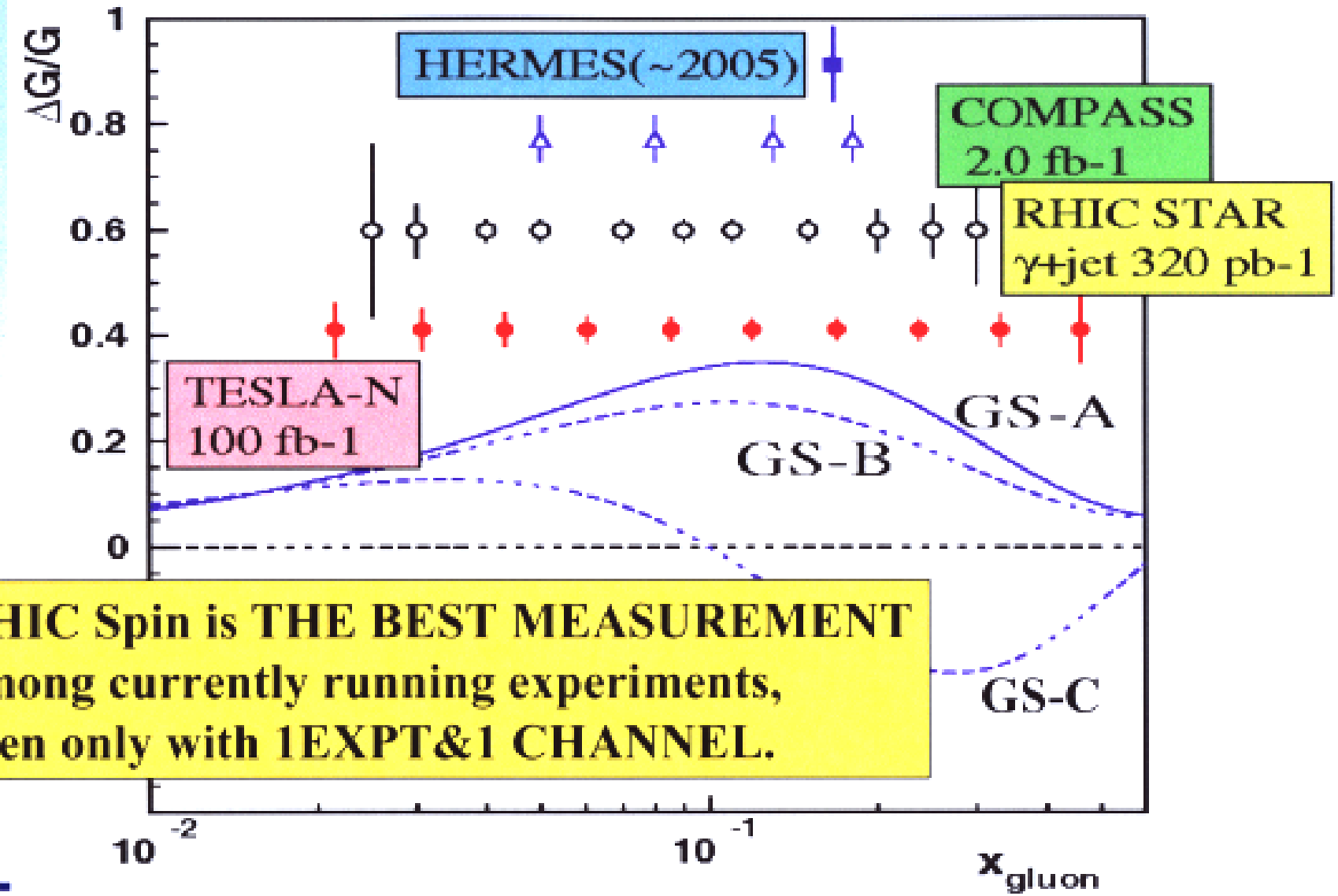
Dig out $\Delta g(x)$ & Δg !

- **Current Experiments**
  - HERMES High-p_T hadron pair
  - RHIC Spin
    - Prompt Photon (+ jet)
    - Jet
    - Inclusive hadron
    - Heavy flavor (charm, bottom, J/ψ ...)
  - COMPASS
    - Open charm
    - High-pT hadron pair



- **Future Possibilities**
  - eRHIC / EPIC
  - Polarized HERA
  - TESLA-N

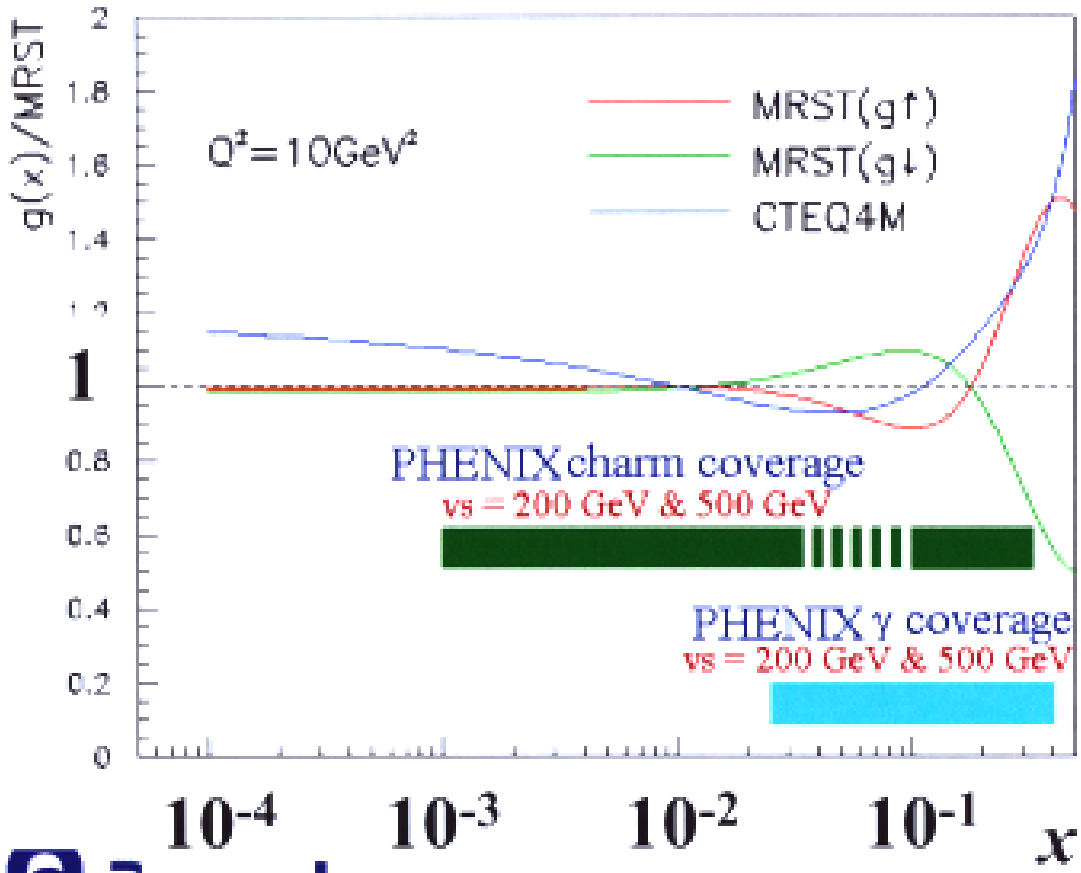
World Competition of Δg/g(x)

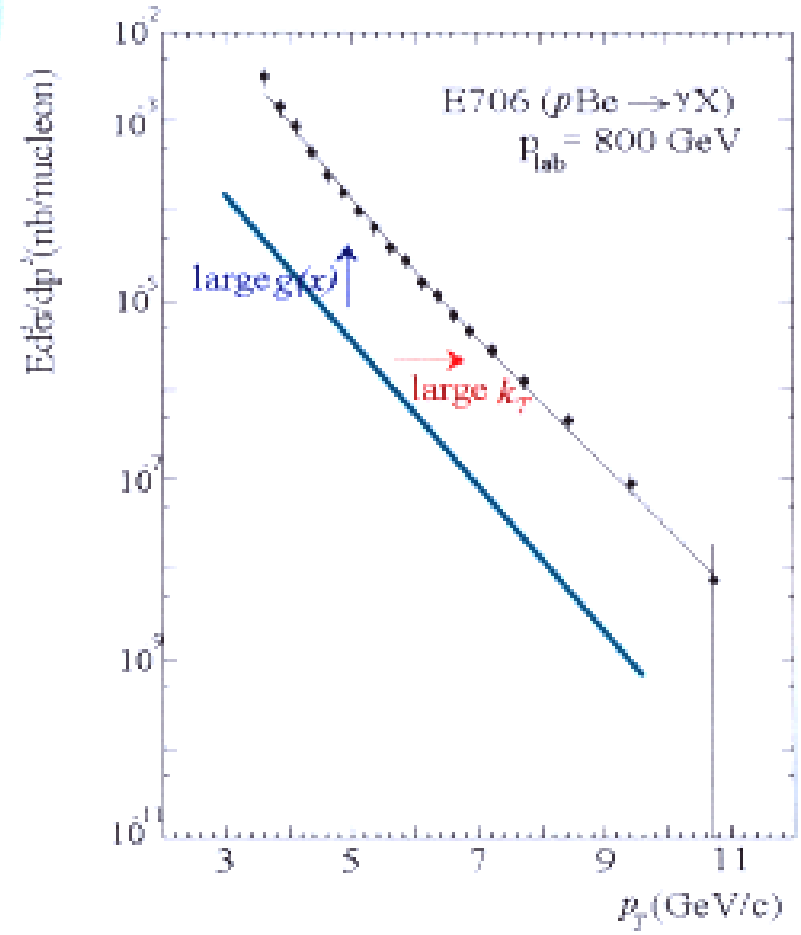


RHIC Spin is THE BEST MEASUREMENT among currently running experiments, even only with 1EXPT&1 CHANNEL.

Unpolarized $g(x)$

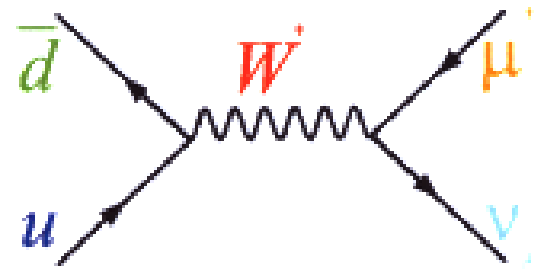
- Large Uncertainties due to assumed intrinsic k_T
- RHIC pp Measurements will fix it !

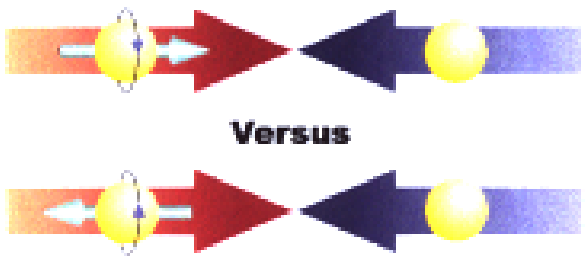




W Production in pp Collisions

- W is produced through pure V-A
  - Chirality is fixed → ideal for spin structure studies
- W couples to weak charge ~ flavor
  - Flavor is (almost) fixed → ideal for flavor structure studies
- Parity Violating Asymmetry A_L :

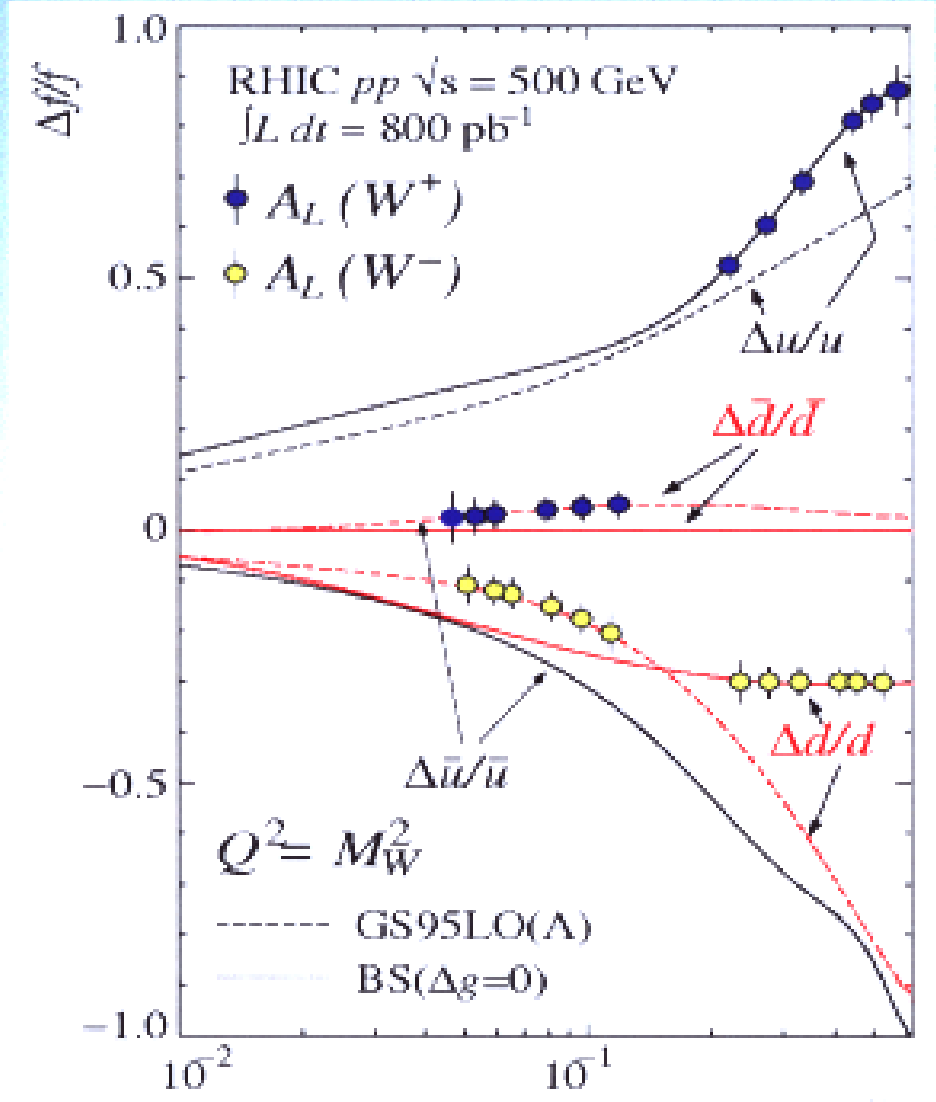




$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

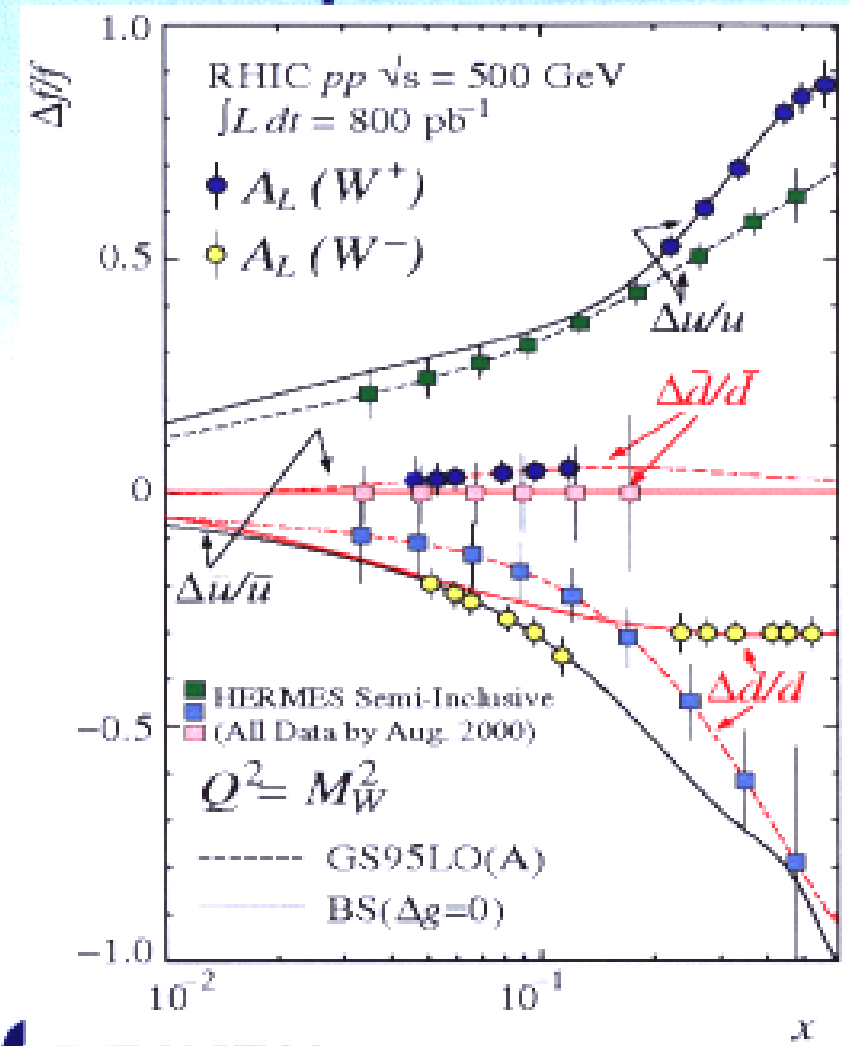
Sensitivity Goal

- Studies with PHENIX Muon Arms
  - STAR Endcap Calorimeter provides similar sensitivity
  - $A_L \sim \Delta u/u(x) \sim 0.7\text{-}0.9$ (!) at large-x
- Charm associated W production will probe Δs ($gs \rightarrow Wc$)
- Studies for upgraded Energy and Luminosity are underway…

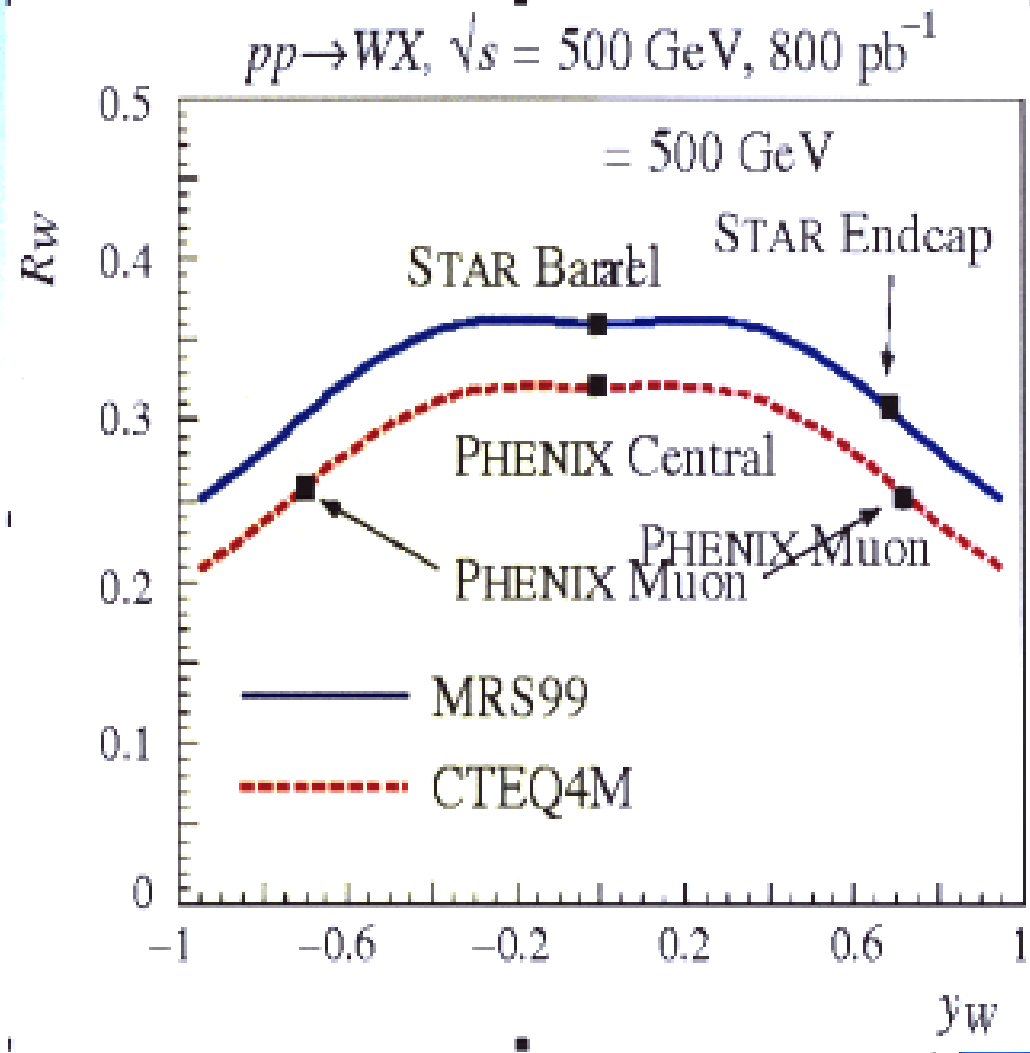


More on W

RHIC Spin vs HERMES

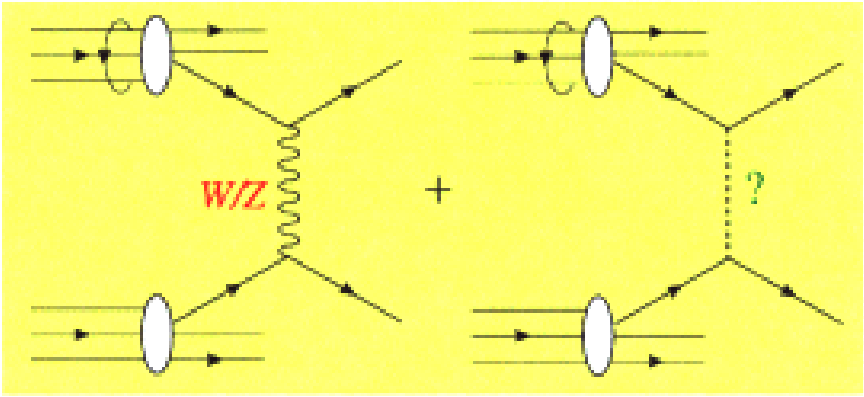


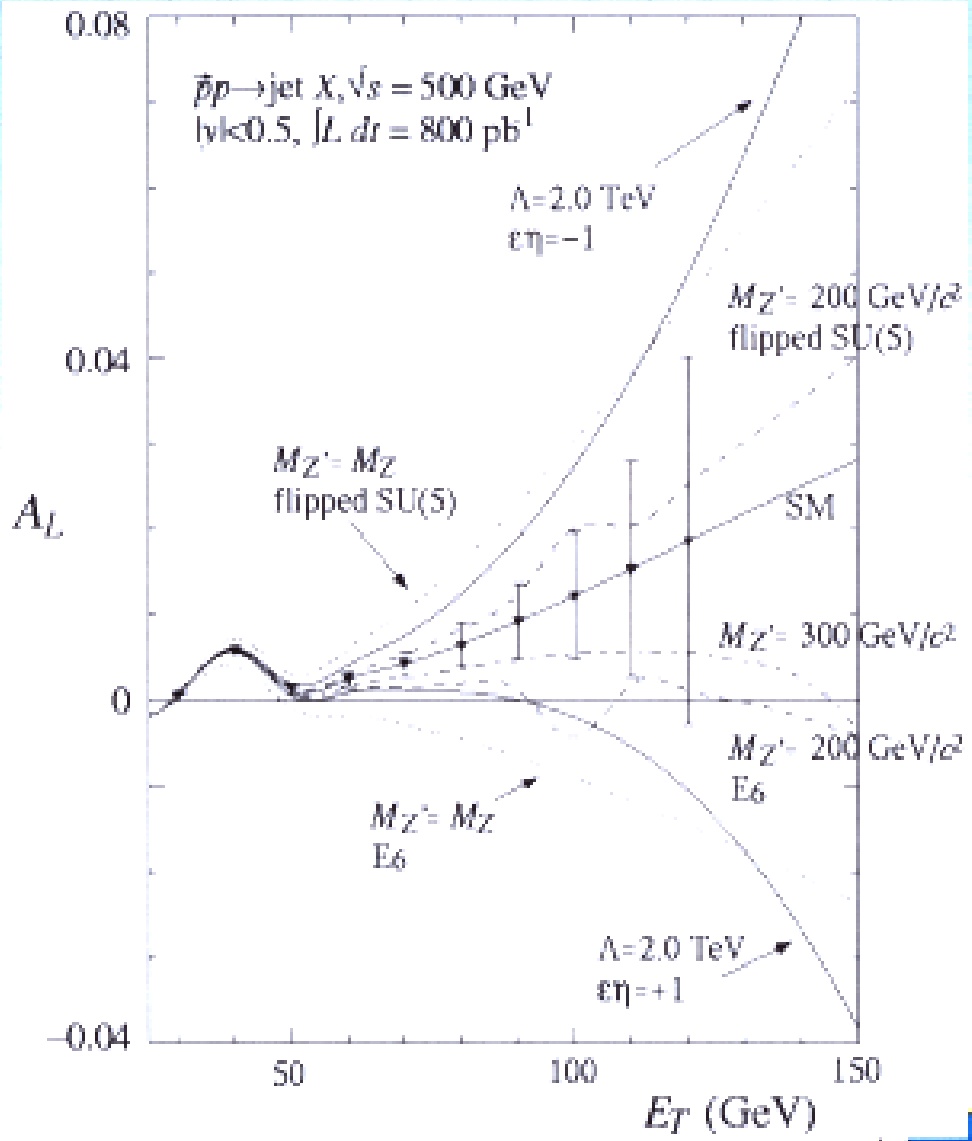
Unpolarized Case



Searches for New Physics

- Anomalous Parity Violation in Jet Production
  - Contact Interaction (Scale Λ)
    - CDF Λ>1.8 TeV
    - D0 Λ>2.4 TeV
    - RHIC Spin Reach Λ~3.3 TeV
  - New Gauge Boson Z′





PDFs and their First Moments

- **PDFs of interest**
  - $\Delta q(x,Q^2)$, $\delta q(x,Q^2)$, and $q(x,Q^2)$ $(q=u,d,s,\bar{u},\bar{d},\bar{s},\ldots)$
  - $\Delta g(x,Q^2)$ and $g(x,Q^2)$
  - Even measurements in limited range of x would HELP!
    - If you know $g(x,Q^2)$ around x=0.1, you can calculate $gq \rightarrow \gamma X$ at pT=10 GeV/c in vs=200 GeV collisions at RHIC
- **First Moments (and other moments)**
  - Integrated over $0<x<1$ to be compared with quantum number carried by the proton
    - First Moments of $q(x)$: $\int_0^1 [u(x)-\bar{u}(x)]dx = 2;\ \int_0^1 [d(x)-\bar{d}(x)]dx = 1$
    - Second Moments $g(x)$: $\int_0^1 xg(x)dx \approx 0.5$
    - First Moment of $\Delta g(x)$: $\int_0^1 \Delta g(x)dx = \Delta g$

Variety of Measurements!

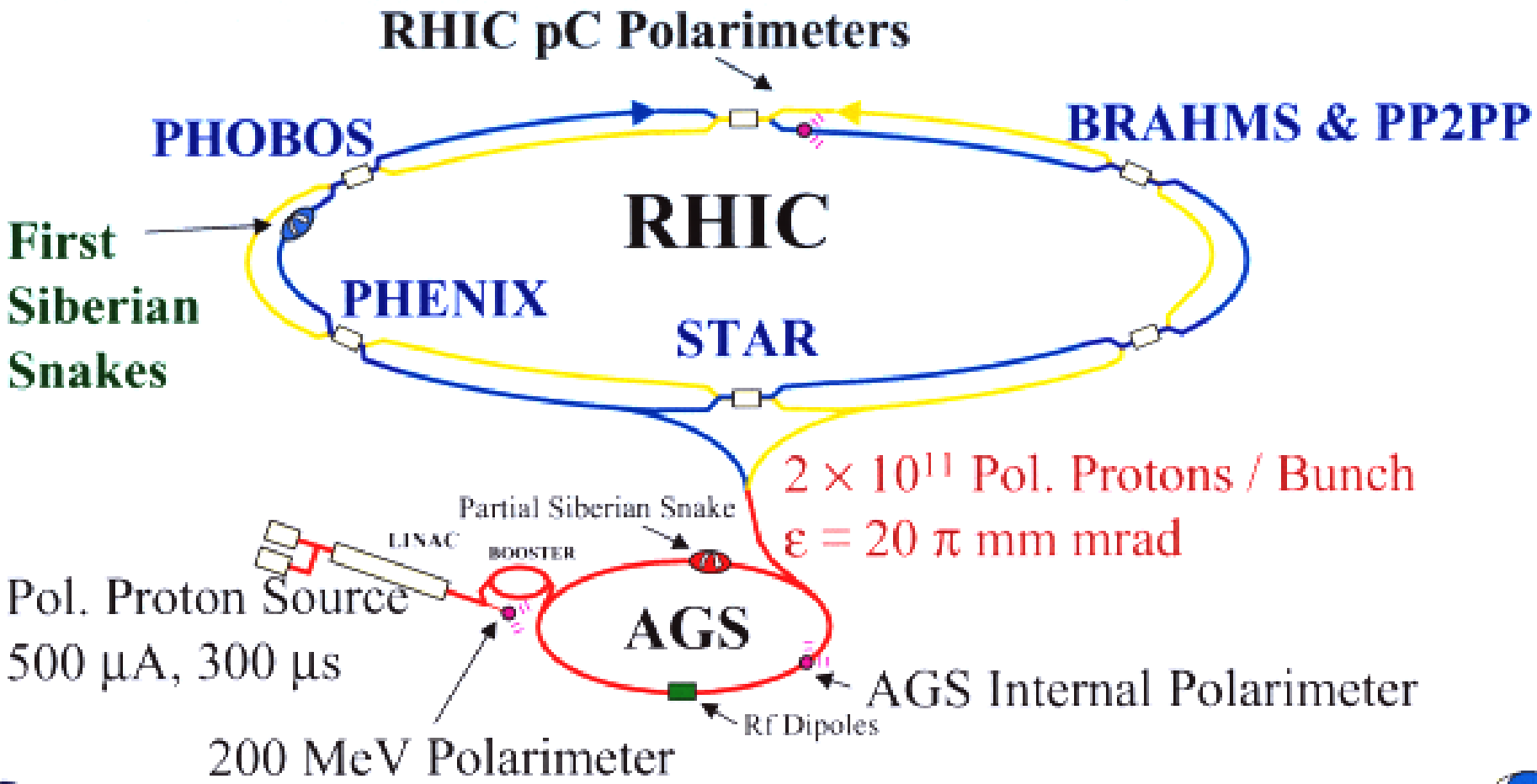
- Cannot be covered in 25 mins talk!
  - Please refer to our review article:

    "Prospects for Spin Physics at RHIC" by Bunce/Saito/Soffer/Vogelsang hep-ph/0007218 and Ann. Rev. of Nucl. And Part. Science 2000

process	$\mathcal{A}_{LL}$	$\mathcal{A}_L$	$\mathcal{A}_{TT}$	$\mathcal{A}_N$
$pp \to \gamma\ (jet)\ X$	$\Delta g \otimes \mathcal{A}_1^p$ [16]	–	~ 0 [17]	twist-3 [18]
$pp \to jet\ X$	$\Delta g \otimes (\Delta g + \Delta\Sigma)$ [19]	W/Z/contact interaction [20]	~ 0 [17]	–
$pp \to Q\bar{Q}X$	$\Delta g \otimes \Delta g$ [21]	Z/MSSM Higgs [22]	–	–
$pp \to J/\psi X$	$\Delta g \otimes \Delta g$ [23]	–	–	–
$pp \to \chi_2 X$	$\Delta g \otimes \Delta g$ [24]	–	–	–
$pp \to W^+ X$	$\Delta u \otimes \Delta\bar{d}$ [25]	$\Delta u, \Delta\bar{d}$ [25]	~ 0 [26]	–
$pp \to W^- X$	$\Delta d \otimes \Delta\bar{u}$ [25]	$\Delta d, \Delta\bar{u}$ [25]	~ 0 [26]	–
$pp \to \gamma^* X$	$\Delta q \otimes \Delta\bar{q}$ [27,15]	γ^*/Z mixing [28]	$\delta q \otimes \delta\bar{q}$ [29]	twist-3 [30]

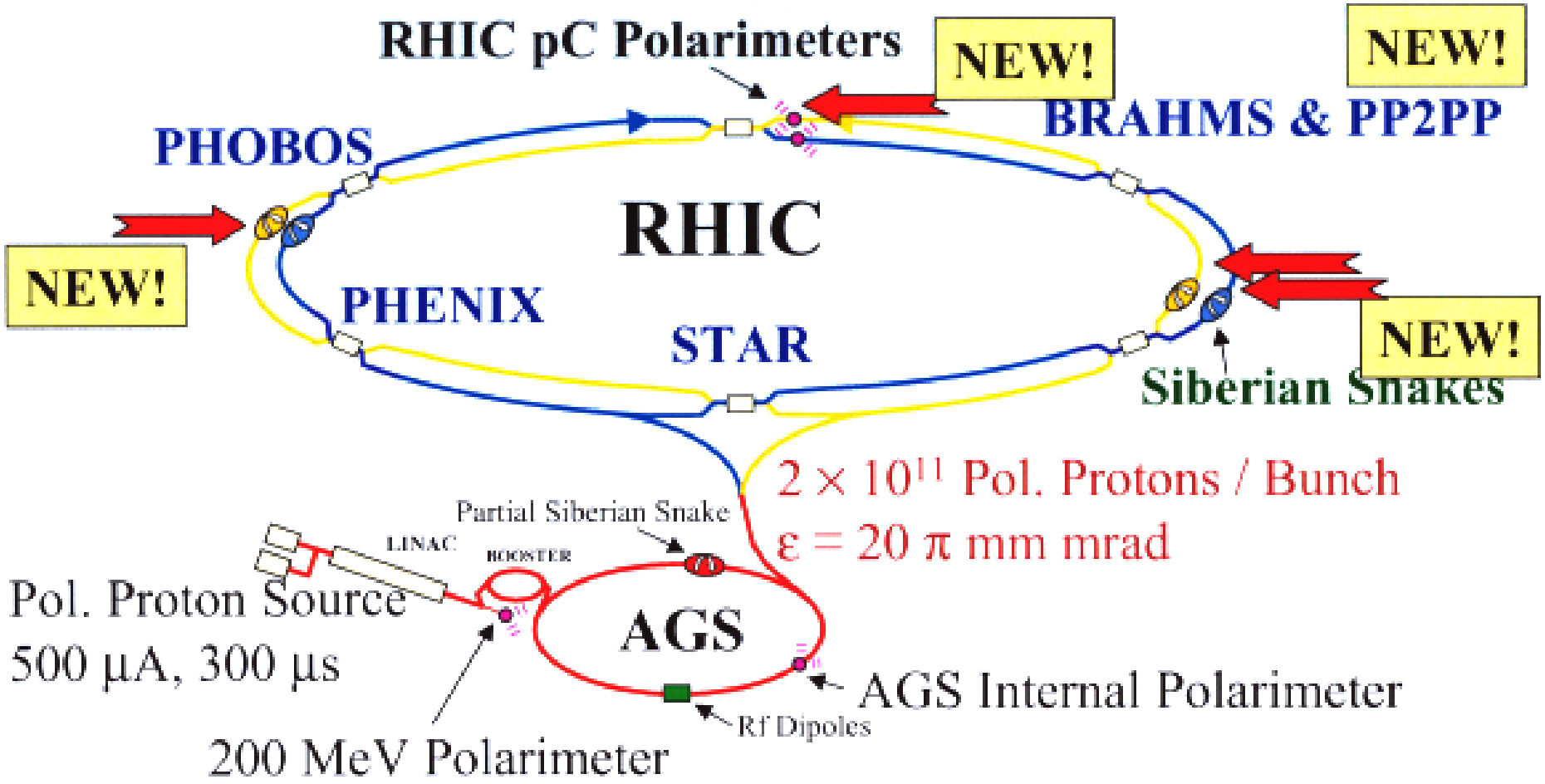
RHIC Year-1: (~ 9/22/2000)

- Spin Commissioning
  - One Snake & One Polarimeter



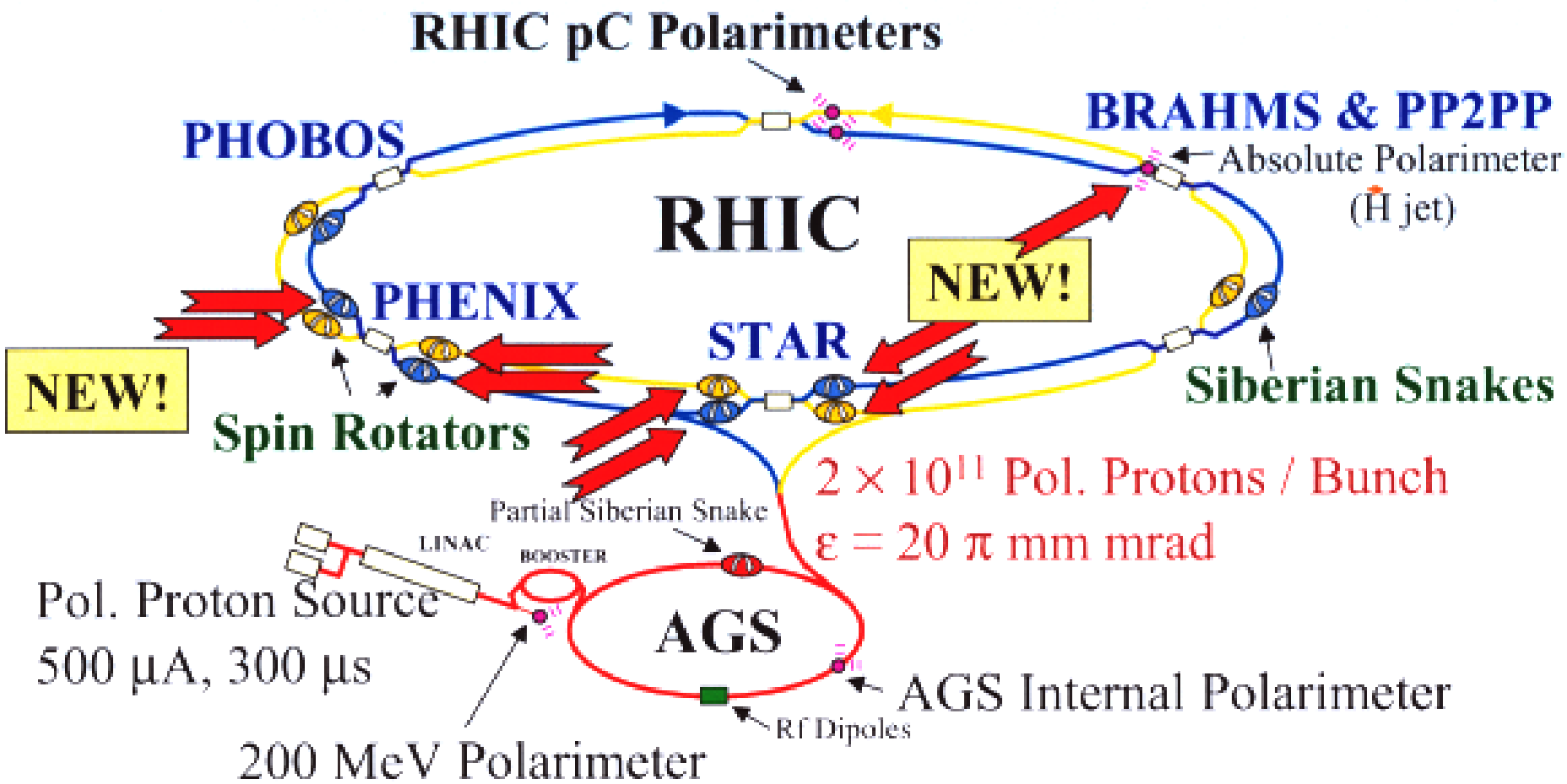
RHIC Year-2: (pp in Summer 2001)

- Fully equipped Snake and Polarimeter



RHIC Year-3+

Complete Polarized Collider



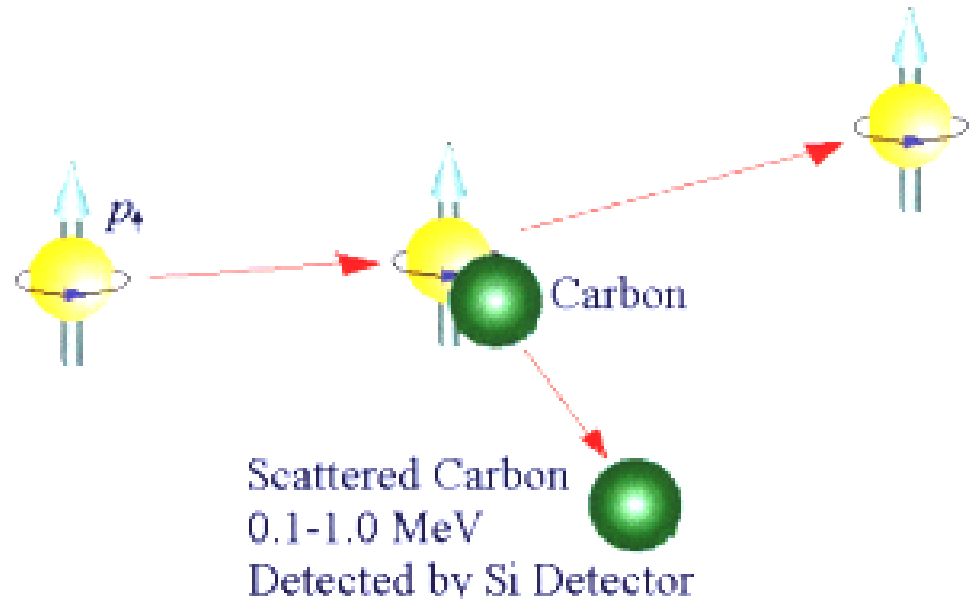
RHIC Spin Plan (PHENIX and STAR)

Year	CM Energy	Weeks	Int. Lum.	Remarks
FY2001	200 GeV	5	7 pb^{-1}	Gluon pol. with pions
FY2002	200 GeV	8	160 pb^{-1}	Gluon pol. with direct γ , jets
	500 GeV	2	90 pb^{-1}	PV W production, u-quark pol.
FY2003	200 GeV	8	160 pb^{-1}	Gluon pol. with γ + jet
	500 GeV	2	120 pb^{-1}	First ubar,dbar pol. meas..
FY2004	500 GeV	8	480 pb^{-1}	Gluon pol. with γ+jet, γ,jet+jet, heavy flavor, ubar, dbar pol.
	200 GeV	2	48 pb^{-1}	Gluon pol. with γ, γ+jet, heavy flavor
FY2005	500 GeV	5	300 pb^{-1}	More statistics
	200 GeV	5	120 pb^{-1}	
FY2006	200 GeV	10	210 pb^{-1}	Transversity measurements

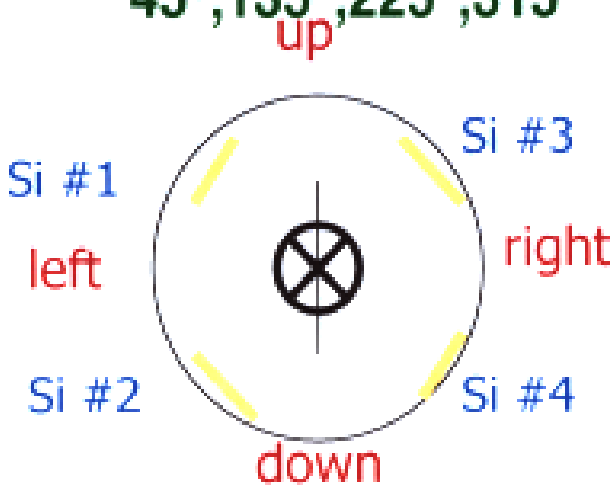
pC CNI Polarimeter

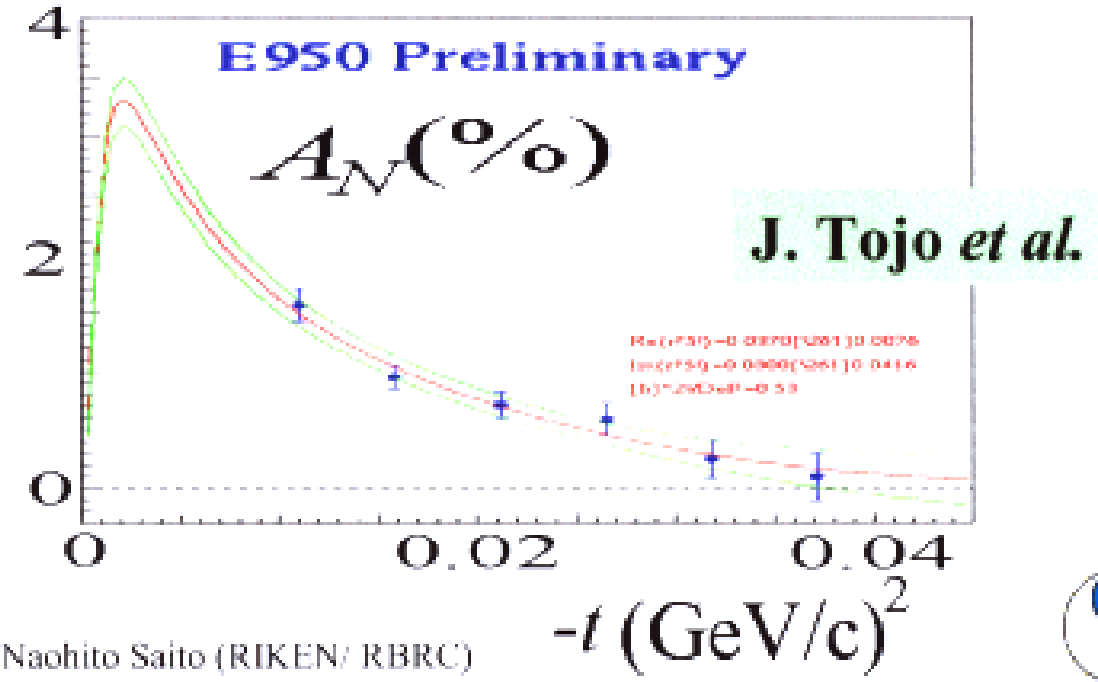
proton Carbon Elastic Scattering

- Designed Basing on Successful AGS-E950 Measurement



- Installed in Blue Ring
  - 4 detectors: 45°,135°,225°,315°

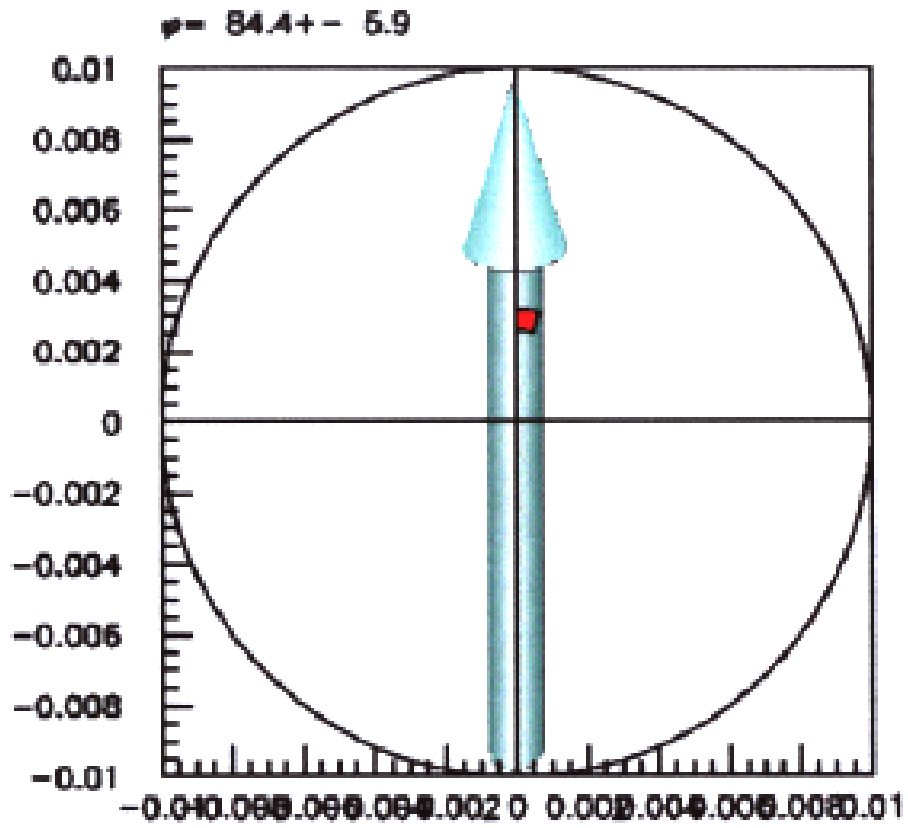




Naohito Saito (RIKEN/ RBRC)

Successful Spin Commissioning

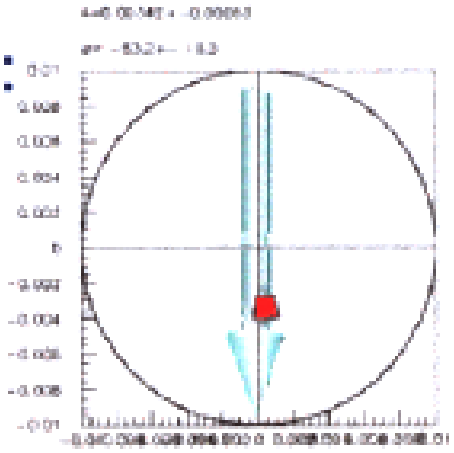
- September 13, 2000 : The Exciting Day
- The First Polarized Proton Beam Stored at RHIC
  - Gγ=46.5 (24.3 GeV/c)
- Then Accelerated up to ~30GeV/c with Snake on
  - Spin Orientation Rotated as Expected



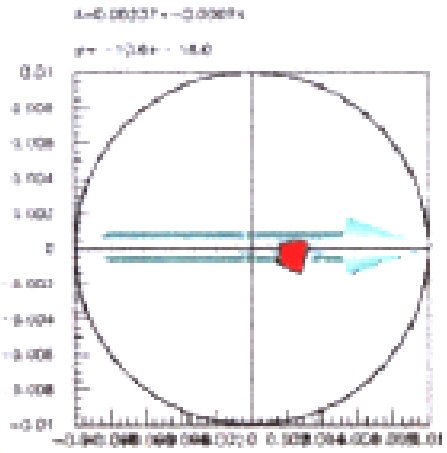
Participating Groups:
BNL
RIKEN, Japan
RBRC
ANL
Indiana
Kyoto
ITEP Moscow

Snake Magnet : Proof of Principle

- Injection with Spin Flipped : Asymmetry Flipped
- Adiabatically Snake on: horizontal polarization
- Accelerate equivalent to 180° rotation: 180° rotated

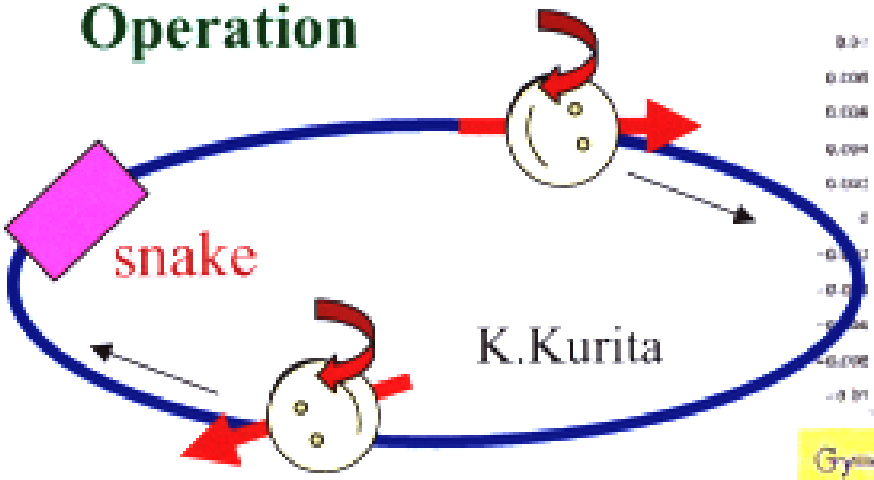


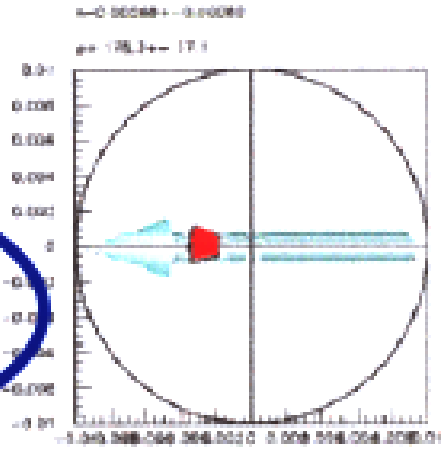
Gγ=46.5 Injection energy
Snake OFF Vertical polarization



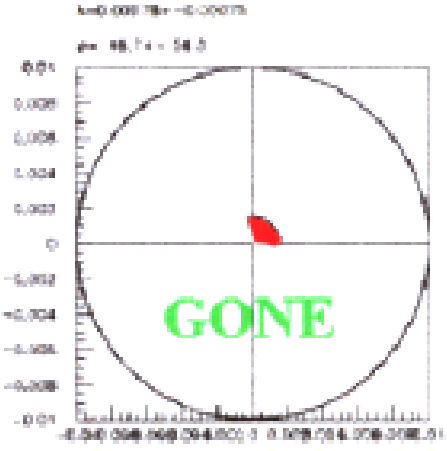
Gγ=46.5 Injection energy
Snake ON Horizontal polarization

Single Snake Operation





Gγ=48 Acceleration with Snake ON
Horizontal polarization



Gγ=48 Acceleration with Snake OF
Polarization lost

RHIC Spin Project

BNL RIKEN Collaboration (1995~)

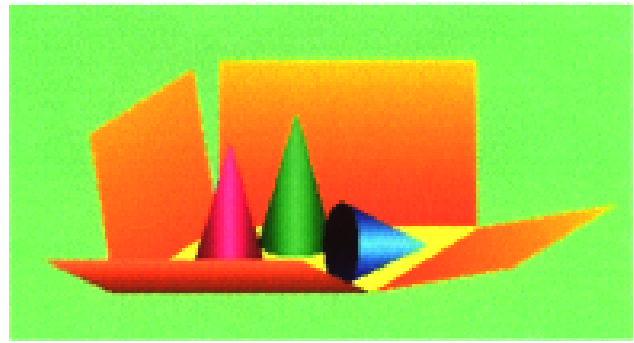
- 1990 Polarized Collider Workshop in Penn State U.
- 1991 RHIC Spin Collaboration Formed
- 1993 Both STAR and PHENIX consider Spin Physics as a major part of program
- 1995 BNL RIKEN Collaboration on RHIC Spin Physics started
  - Muon Arm for PHENIX
  - Siberian Snake and Spin Rotators for PHENIX and STAR
- 1997 RIKEN BNL Research Center established

DOE Funds for STAR Barrel Calorimeter

NSF Funds for STAR Endcap Calorimeter

KEK Contribution for OPPIS

DOE General Supports for Spin Physics



Summary

- RHIC Spin Physics is UNIQUE!
  - "Prospects for Spin Physics at RHIC" by Bunce/Saito/Soffer/Vogelsang hep-ph/0007218 and Ann. Rev. of Nucl. And Part. Science 2000
  - Spin Discussion Home Page:

    http://rikweb.rhic.bnl.gov/rsc/
- Spin Commissioning was VERY SUCCESSFUL!
- RHIC Spin is Coming Soon at the Theater Near You! … rated Excellent!