4 August 2003
Pacific Spin, Seattle
G. Bunce

Spin Physics from PHENIX

1. The goals of the PHENIX spin program
2. RHIC spin: colliding polarized protons at root(s)=200 GeV
3. Spin physics at PHENIX: gluon polarization using π^0

    ---longitudinal polarization
    ---measuring A_{LL}
    ---2003 run
    ---2004/5

4. Gluon polarization using direct γ
5. Anti-quark polarization by flavor using W^+, W^-
6. Micro-vertex detector upgrade

    ---identify jet axis for gluon polarization measurements
    ---heavy quark trigger: gluon pol. using c,b

7. Summary/remarks

See also at this conference:

Gluon session this afternoon:
---RHIC-PHENIX, by Kenske Okada

Low energy hadron physics session Thursday morning:
---pC Polarimetry at AGS, by Sandro Bravar (STAR)
---pC Polarimetry at RHIC, by Osamu Jinnouchi (PHENIX)

Goals of the PHENIX Spin Program

Ref.: "Prospects for Spin Physics at RHIC",
Ann. Rev. Nuclear Part. Sci. 2000, 50:525-75
G. Bunce, N. Saito, J. Soffer, W. Vogelsang

Proton spin sum rule:

$\frac{1}{2} = \frac{1}{2}\Sigma(\Delta q + \Delta\bar{q}) + \Delta G + L$: 1980s-present: $\Sigma(\Delta q + \Delta\bar{q}) \approx \frac{1}{4}$

$\Delta q = q_+ - q_-$, $q = u, d, s, \ldots$; $\Delta G = g_+ - g_-$; $\int_0^1 dx$ assumed

Probe the spin structure of the proton using pQCD

---using polarized quarks (and gluons ?)

===> gluon polarization (γ, jets, c, b)

===> transversity/orbital ang. momentum/ quark-gluon correlations in proton

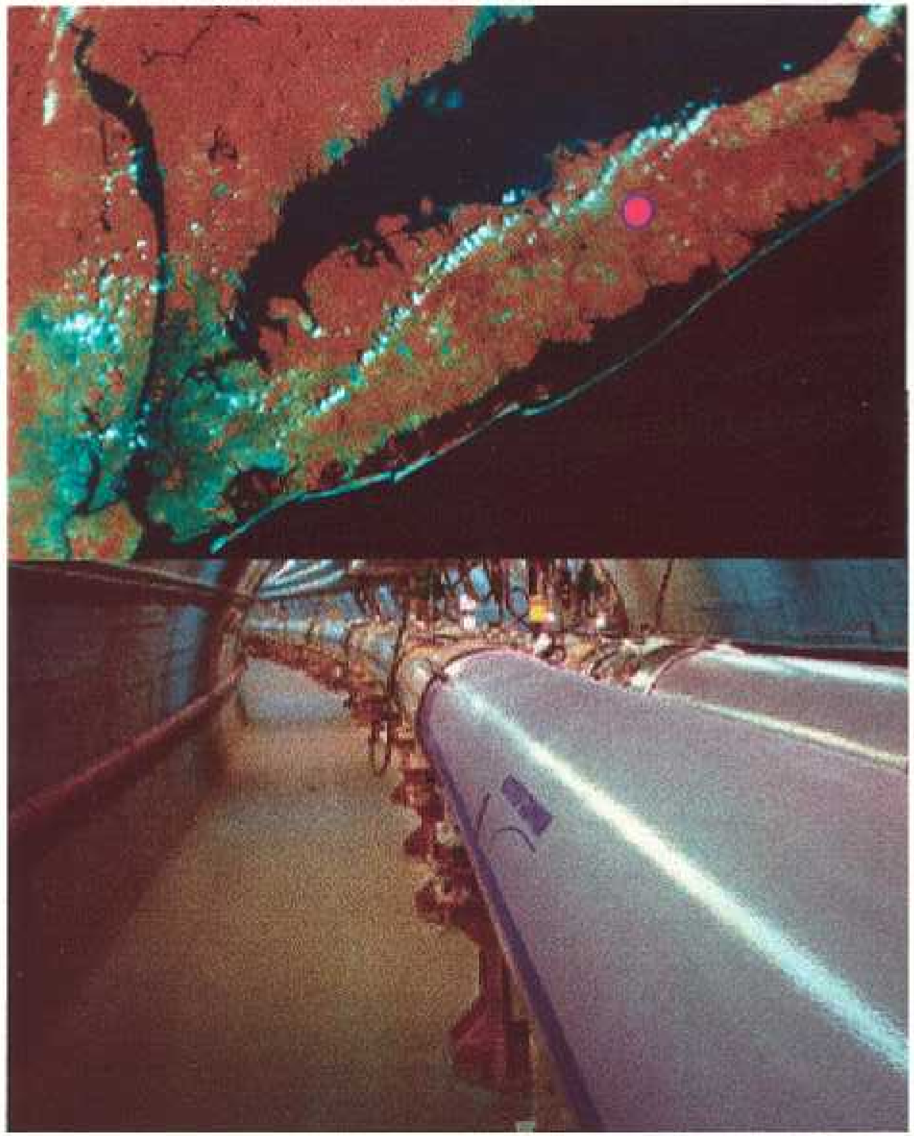
---using parity-violating $W^{+/-}$ production

===> u, dbar, d, ubar polarization in proton

Searches for surprises using parity violation

---sensitivity to right-handed Zs; quark substructure; ...

Relativistic Heavy Ion Collider



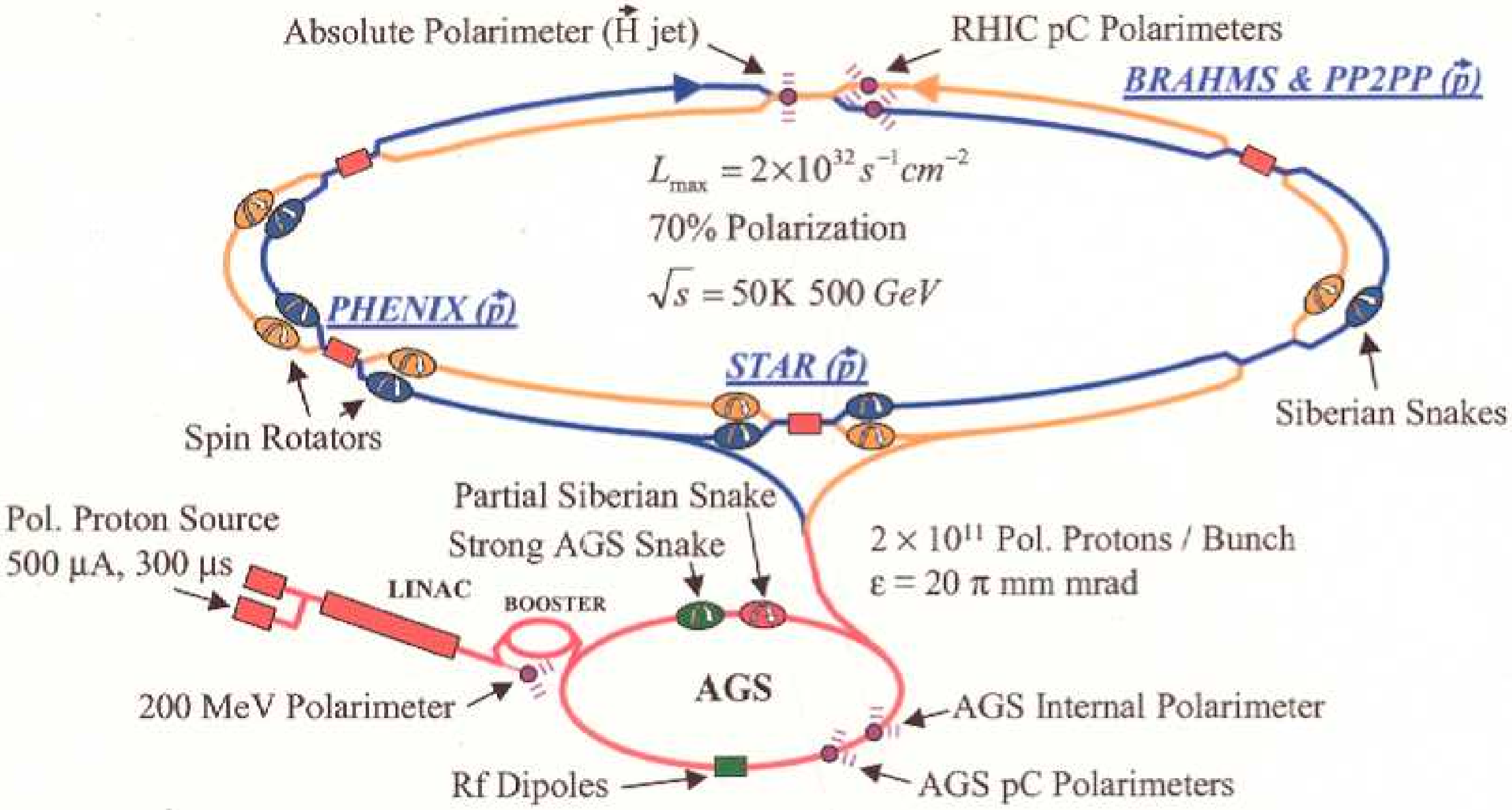
Design Parameters:

Performance	Au + Au	p+p
$\sqrt{s_{nn}}$	200 GeV	500 GeV
L [cm^{-2} s^{-1}]	2 x 10^{26}	2 x 10^{32}
Cross-section	7 barns	60 mbarn
Interaction rates	14 kHz	12 MHz

RHIC Capabilities

- ✓ Au + Au collisions at **200** GeV/u
- ✓ p + p collisions up to 500 GeV
- ✓ spin polarized protons (70%)
- ✓ lots of combinations in species and energy in between

Polarized Proton Collisions in RHIC



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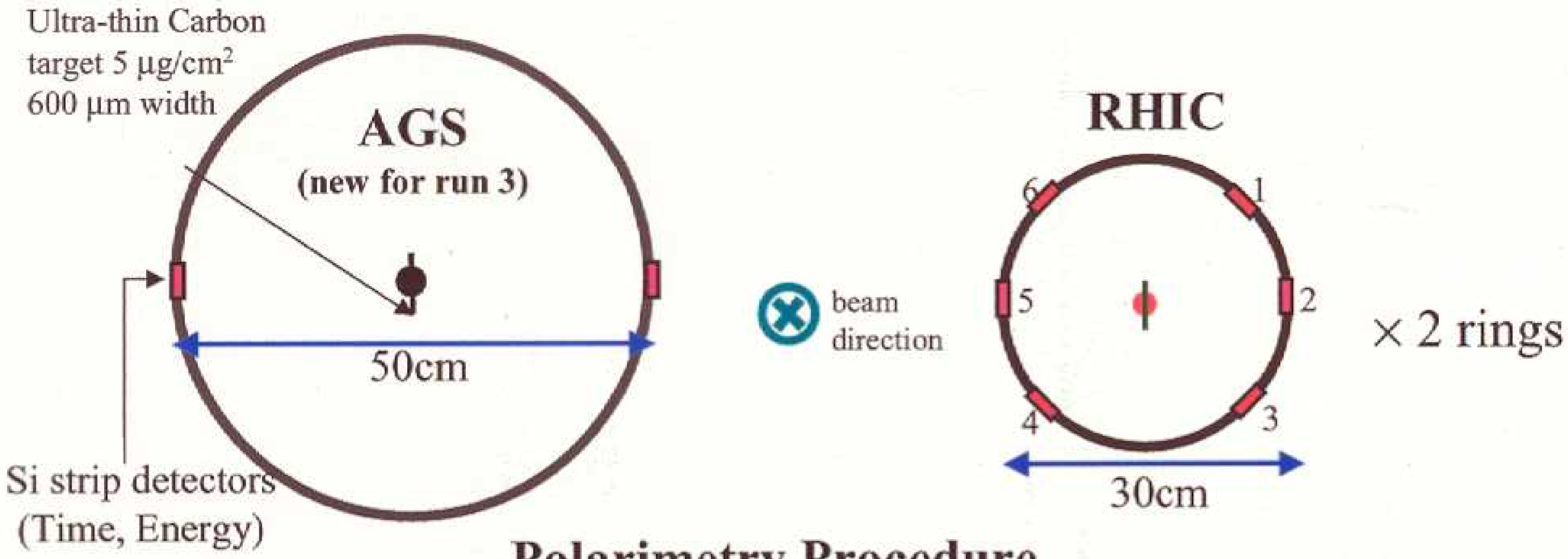
CNI Polarimeters



Polarimetry Procedure

- Measure recoil carbons from $p^{\uparrow}C \rightarrow p^{\uparrow}C$ elastic scattering

- Exploit analyzing power, $A_N \approx 0.01$, originating from anomalous magnetic moment of proton. Calibration of A_N required.

- Measure left/right (more generally, azimuthal variation) spin-dependent asymmetry

$$\varepsilon_{LR} = \frac{\sqrt{N_{L\uparrow}N_{R\downarrow}} - \sqrt{N_{L\downarrow}N_{R\uparrow}}}{\sqrt{N_{L\uparrow}N_{R\downarrow}} + \sqrt{N_{L\downarrow}N_{R\uparrow}}}, \quad P_{beam} = \frac{\varepsilon_{LR}}{A_N}$$

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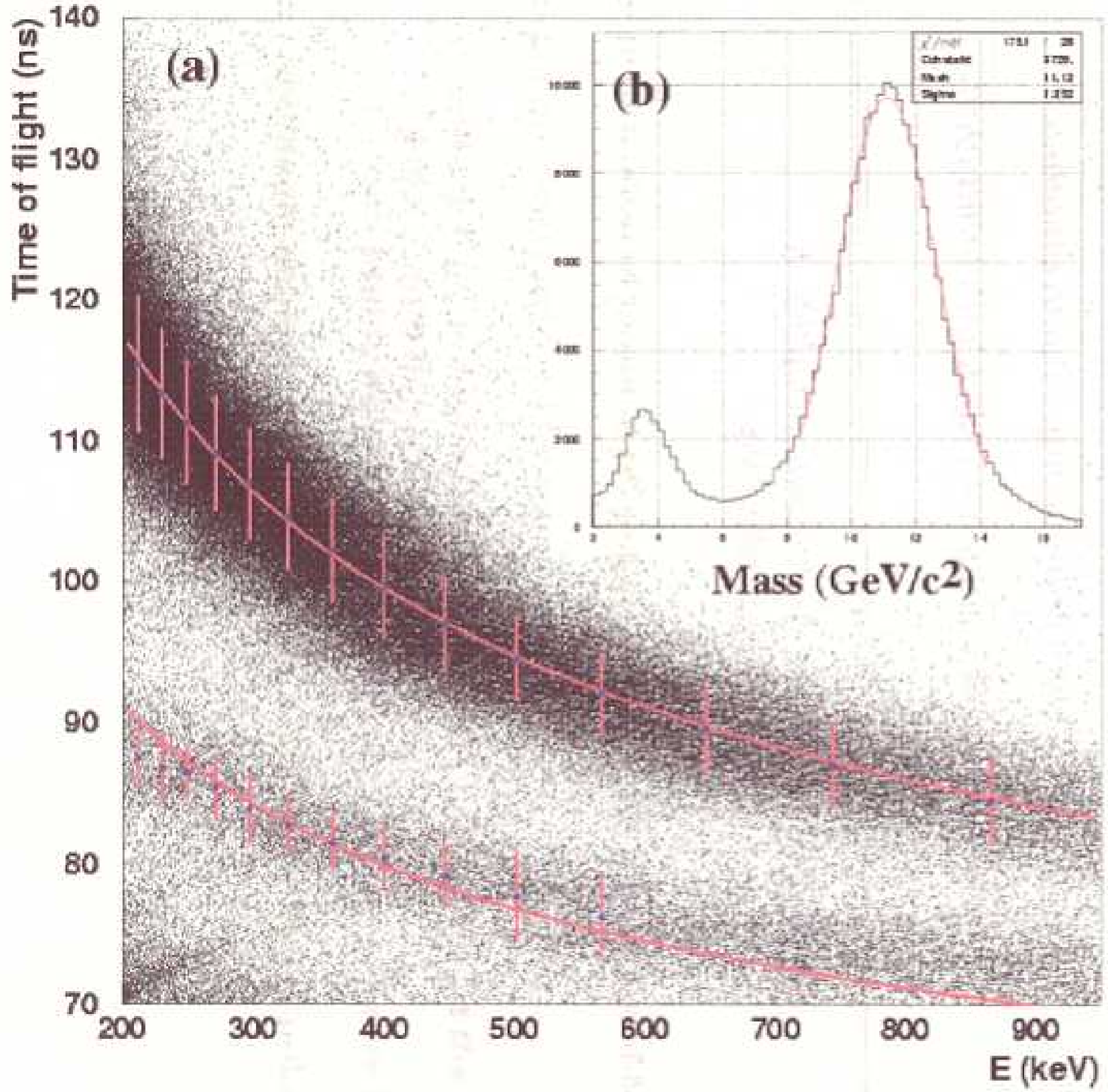
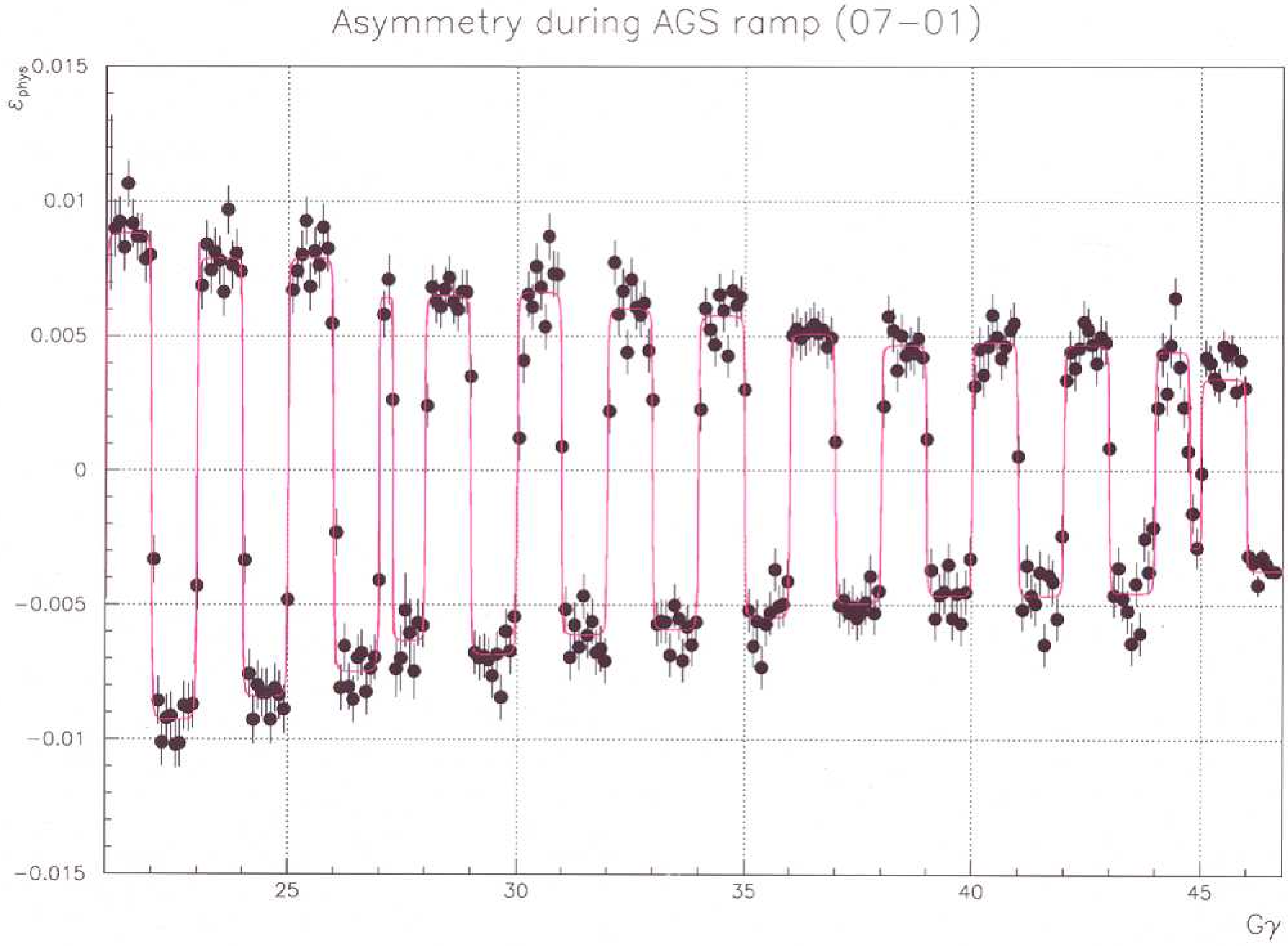
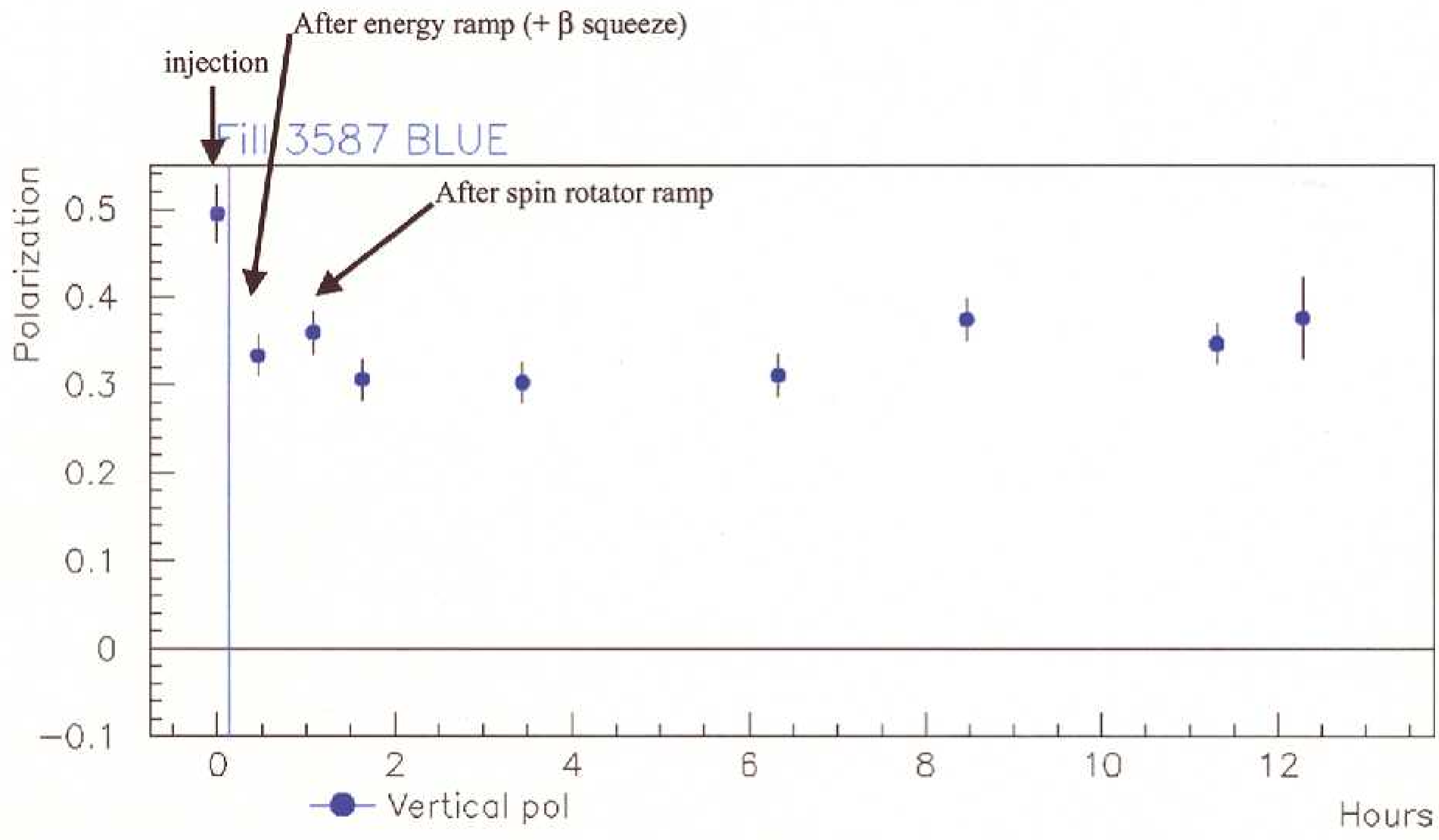
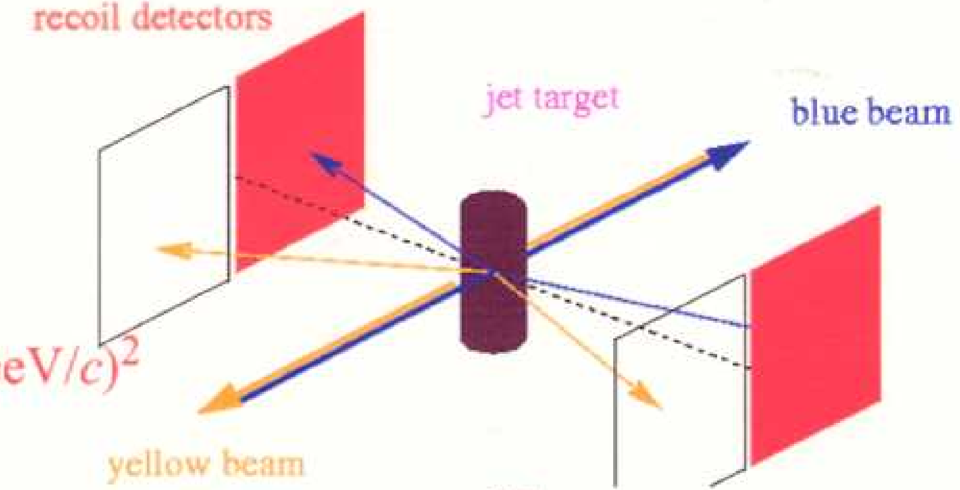

(a)
(b)
Time of flight (ns)
140
130
120
110
100
90
80
70
200
300
400
500
600
700
800
900
E (keV)
Mass (GeV/c2)



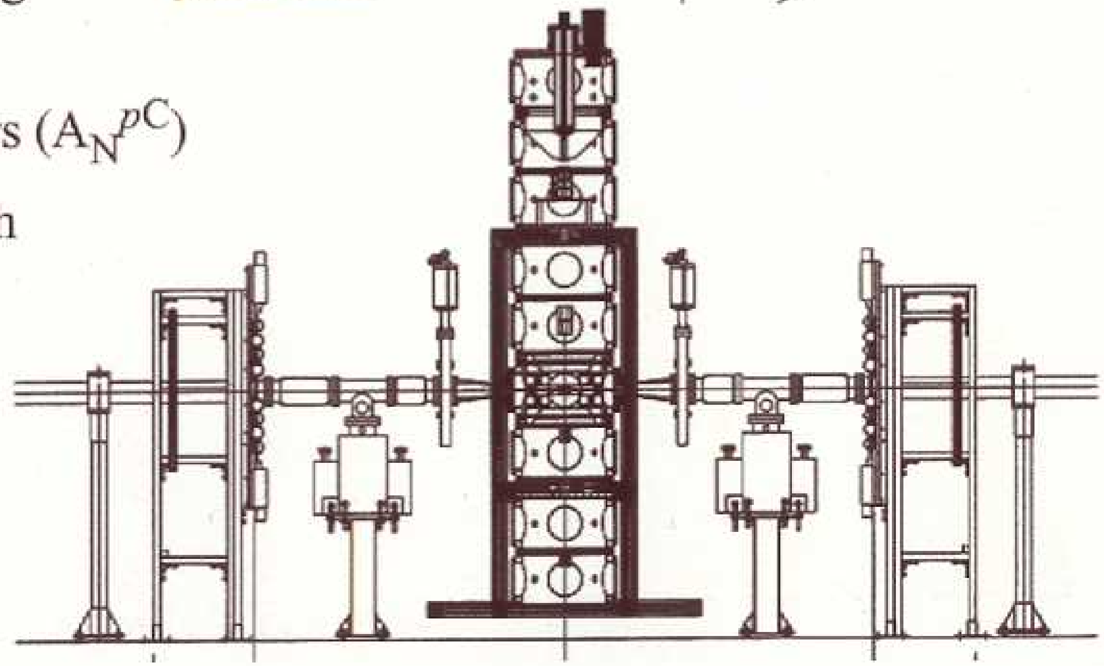
Asymmetry during AGS ramp (07–01)
ε_{phys}
0.015
0.01
0.005
0
−0.005
−0.01
−0.015
25
30
35
40
45
$G\gamma$


injection
After energy ramp (+ β squeeze)
Fill 3587 BLUE
After spin rotator ramp
Polarization
0.5
0.4
0.3
0.2
0.1
0
−0.1
0
2
4
6
8
10
12
Vertical pol
Hours

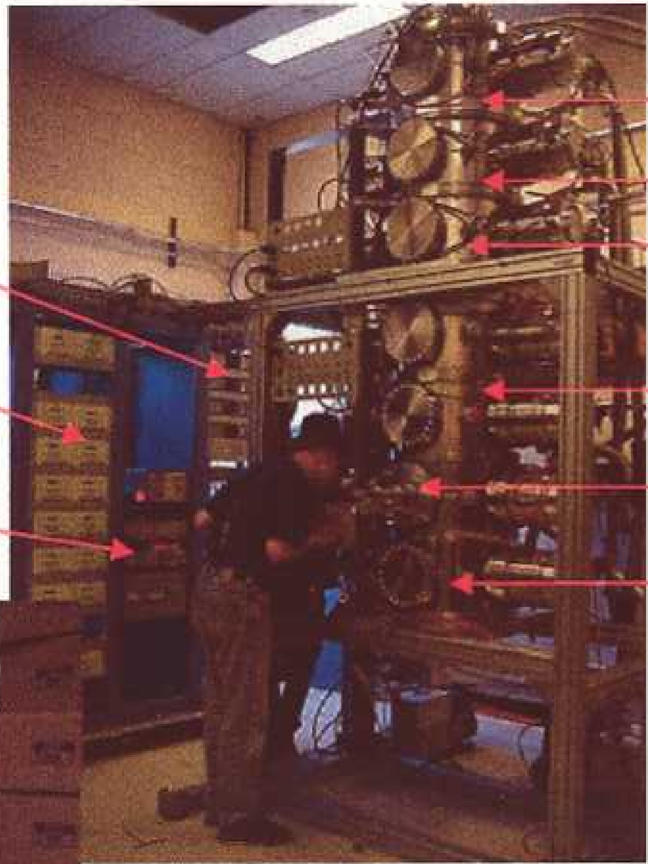
$p_{\uparrow}p$, $pp_{\uparrow}$ and $p_{\uparrow}p_{\uparrow}$ with a Polarized Gas Jet Target

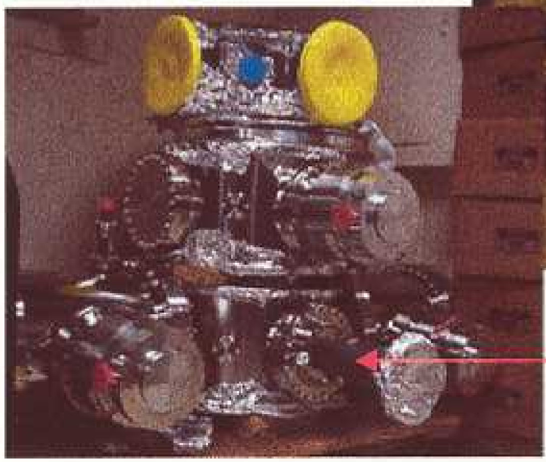


- Polarized Hydrogen Gas Jet Target
  thickness of 5×10^{11} p/cm^2
  polarization > 90%
- Silicon recoil detectors
- Rate: 125 Hz for $0.001 < |t| < 0.02$ (GeV/c)^2
- Measure A_N^{pp} in pp elastic scattering in the CNI region to a 3% accuracy
- Transfer A_N^{pp} to the pC polarimeters (A_N^{pC})
- Expected accuracy on P_B of 6% with "calibrated" pC CNI polarimeters
- Install for the '04 run
- Initially measure P_{beam} to 10%



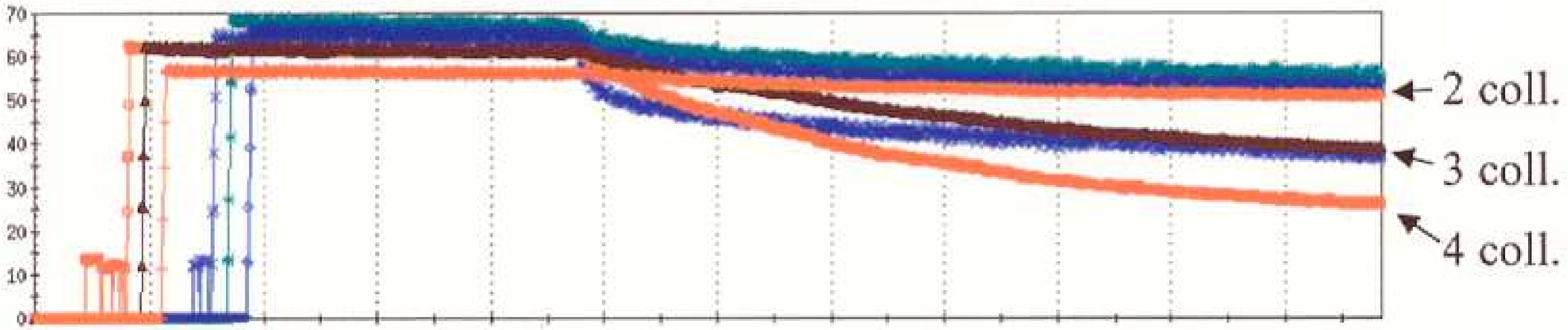
The Polarized Jet Target





Luminosity Limitations (2)

- Electron multipacting (electron cloud)
  - Total charge per ring < 10^{13} e
    - Solenoids, scrubbing, NEG coating
- Beam-beam tune shift and spread
  - First strong-strong hadron collider (after ISR)
  - Limits high luminosity pp operation to two IRs
    - Non-linear corrections, better working point

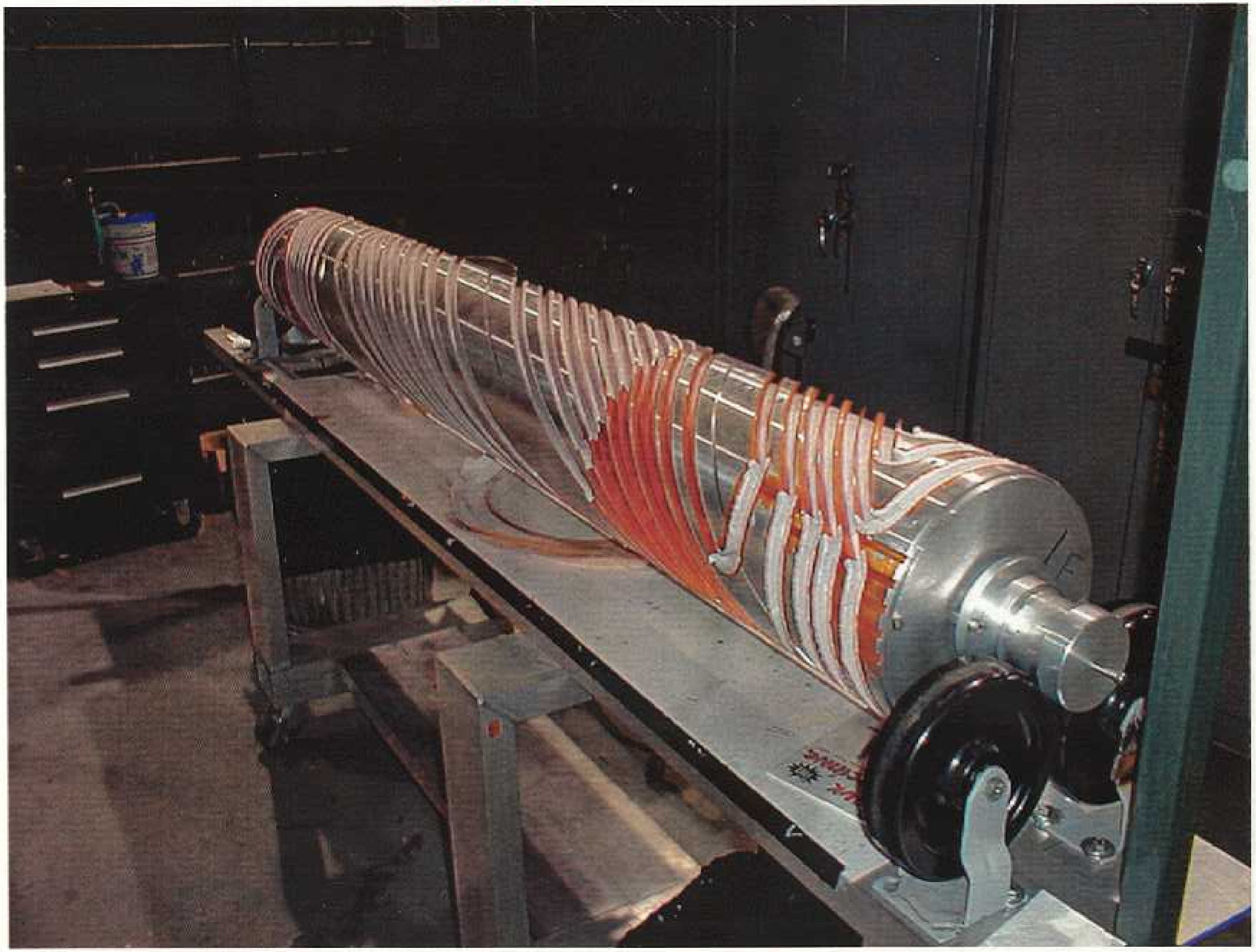


- Intra-Beam Scattering (IBS)
  - Transverse and longitudinal emittance growth
  - Eventually will need electron cooling (see below)

Siberian Snake for AGS: 5% × 180°
-2004

Siberian Snake for AGS: 20% × 180°

-2005



Requirements for the spin program

Ref.: "Polarized proton collider at RHIC",
NIM A499 (2003) 392-414
I. Alekseev et al. (W.W. MacKay Corresp. Author)
Design Report (T. Roser, Spokesman)

Accelerator

Polarized proton (H^-) source ---P=75%, 200 μA

Maintain polarization in AGS to 24 GeV ---P=40% in 2003

Transfer polarized protons to RHIC ---$P_{RHIC,\ 24\ GeV} = P_{AGS}$

Polarimetry in RHIC ---proton-carbon scattering in Coulomb-Nuclear interference region

Accelerate polarized protons to 100 GeV ---Siberian Snakes

Longitudinal polarization at STAR, PHENIX ---Spin rotators and local polarimeters

Maintain polarization over store ---14 hours

---but $P_{store} = .7\ P_{24\ GeV}$ in 2003

Know |P| to +/- 5% ---polarized atomic hydrogen jet target ready for 2004

$L = 8 \times 10^{31}\ cm^{-2}\ s^{-1}$ ---$L = 4 \times 10^{30}$ in 2003

LT = 20 pb^{-1} /week ---L = .5 pb^{-1} /week in 2003

P = .7 at 100 GeV ---P = .3 in 2003

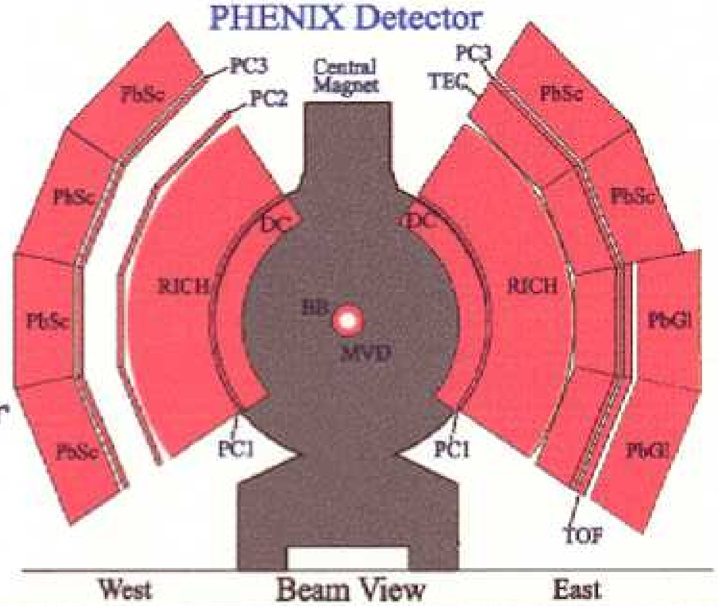
P = .7 at 250 GeV ---not tried yet

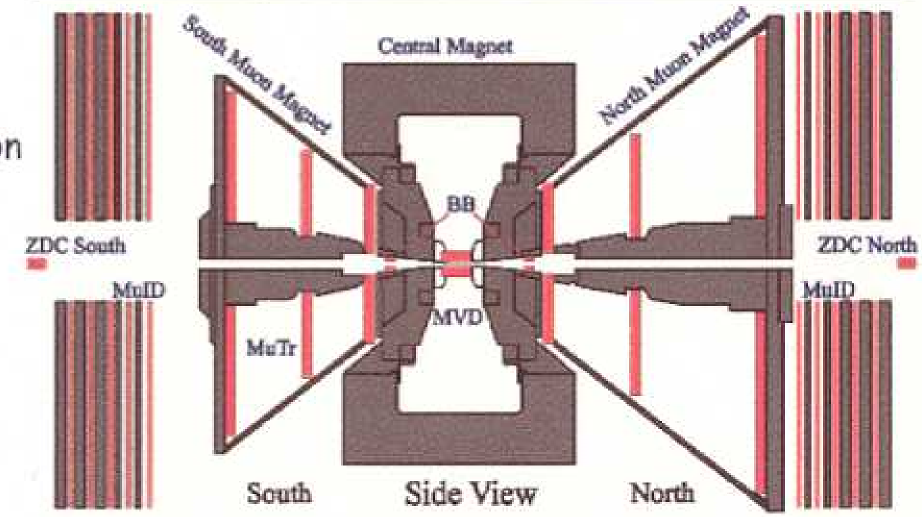
The PHENIX Detector

Philosophy:

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

Central Arm Tracking
Drift Chamber, Pad Chambers, Time Expansion Chamber
Muon Arm Tracking
Muon Tracker
Calorimetry
PbGl and PbSc
Particle Id
Muon Identifier, RICH, TOF, TEC
Luminosity Counters/Vertex Detectors
BBC, ZDC/SMD, Local Polarimeter, forward hadron calorimeters, NTC, MVD
DAQ
High bandwidth
Trigger
Level 2
Level 1 (GL1P, muId, EMC/RICH)
Online
Calibration and production





PHENIX

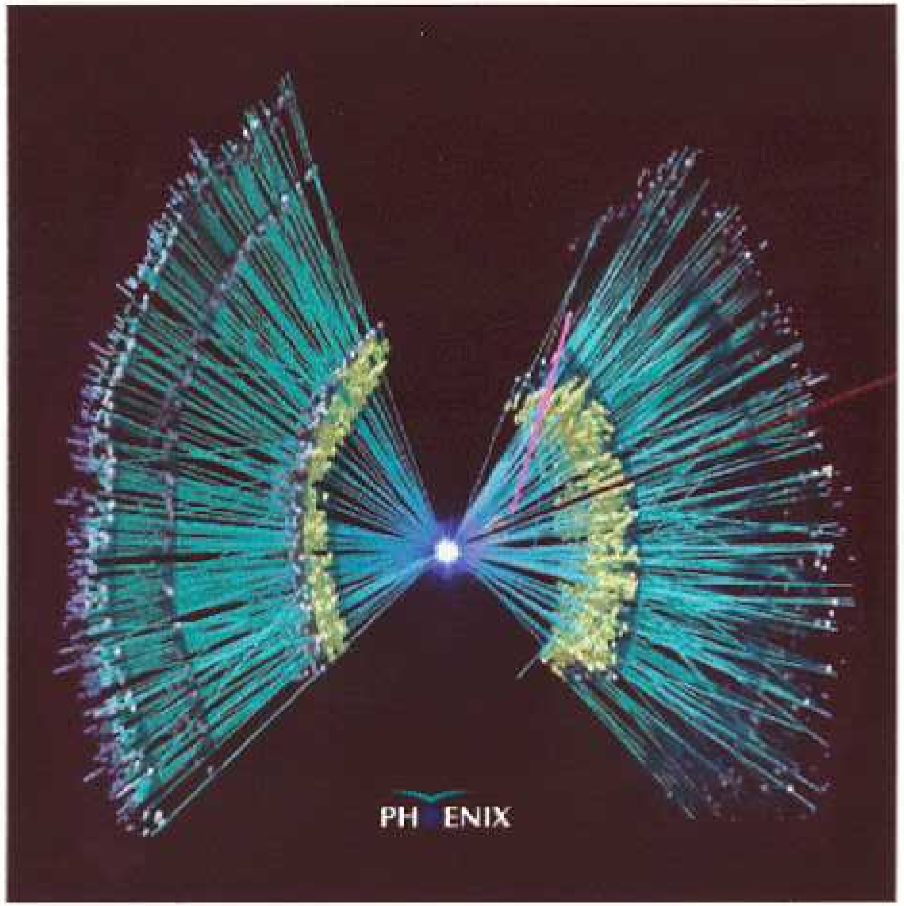
12 Countries; 57 Institutions; 460 Participants

Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	University of Tokyo, Bunkyo-ku, Tokyo
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund
USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

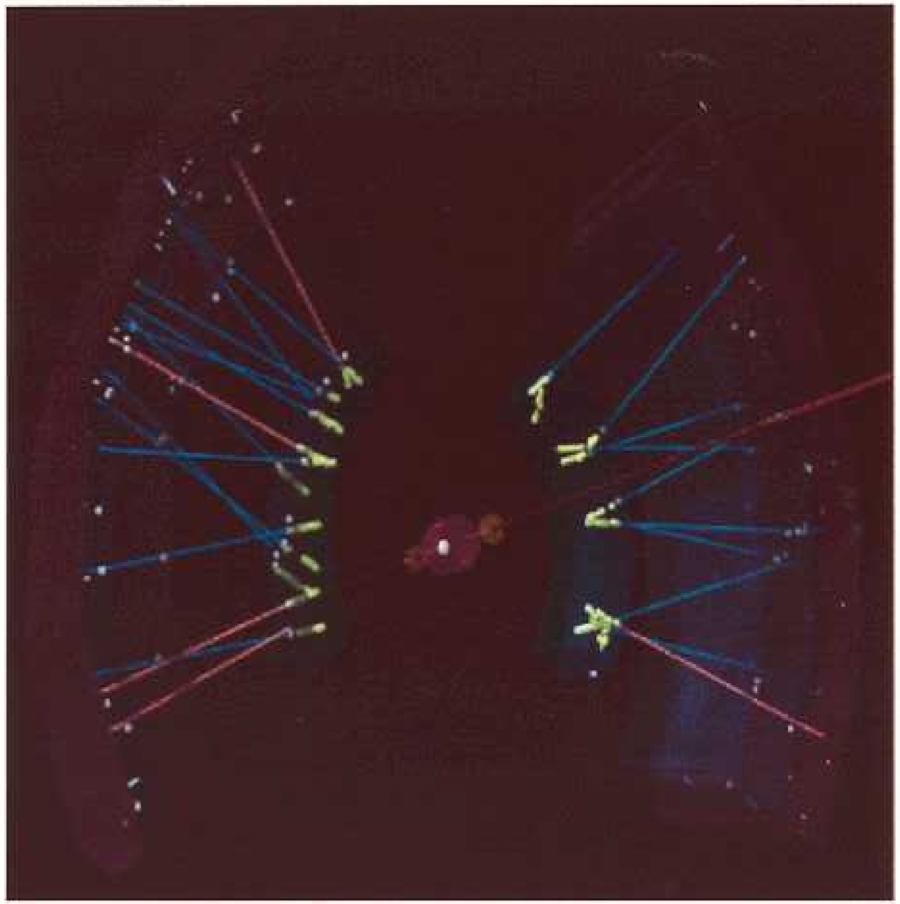
The PHENIX detector: central arms

Two collisions in the central arms

2001/2002 Au-Au

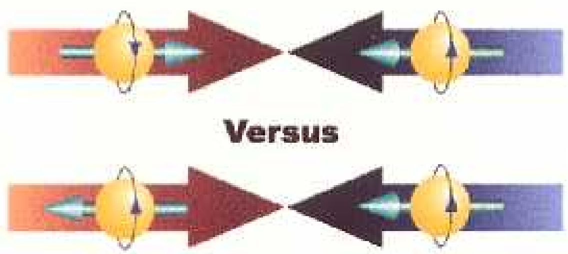


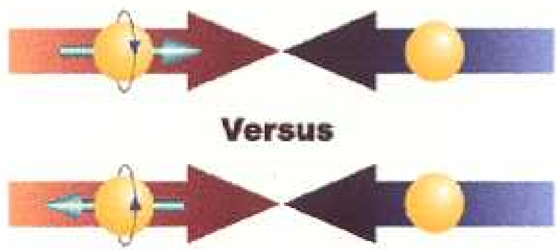
2002/2003 d-Au

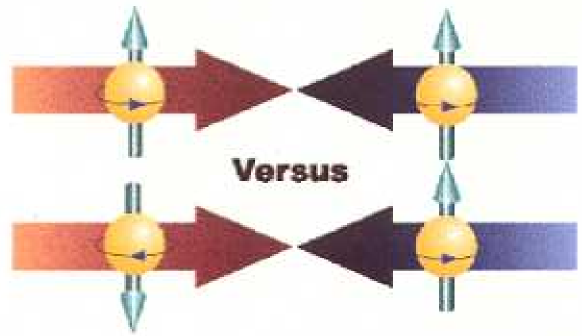


Proton Spin Structure at PHENIX

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 $A_{LL}(gg, gq \rightarrow \pi + X)$ Prompt Photon $A_{LL}(gq \rightarrow \gamma + X)$ Heavy Flavors $A_{LL}(gg \rightarrow c\bar{c}, b\bar{b} + X)$	W Production $A_L(u + \bar{d} \rightarrow W^+ \rightarrow l^+ + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^- \rightarrow l^- + \bar{\nu}_l)$	Transversity δq: π^+, π^- Interference fragmentation: $A_T(p_\perp p \rightarrow (\pi^+, \pi^-) + X)$ Drell Yan A_{TT} Single Asymmetries A_N



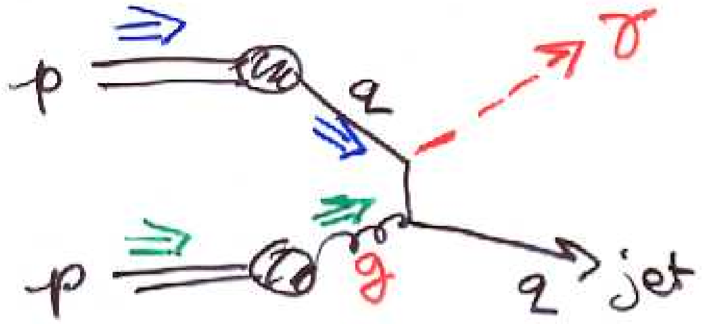




RHIC Spin Probes

Gluon polarization:

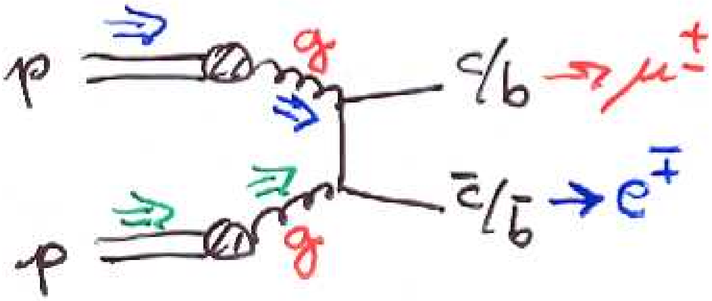
$$A_{LL} = \frac{1}{P^2}\frac{N_{++}(\gamma) - N_{+-}(\gamma)}{N_{++} + N_{+-}}$$



$$A_{LL} = \frac{\Delta G}{G}(x_g)\, A_1^p(x_q)\, \hat{a}_{LL}$$

$$(.3) \quad (.6)$$

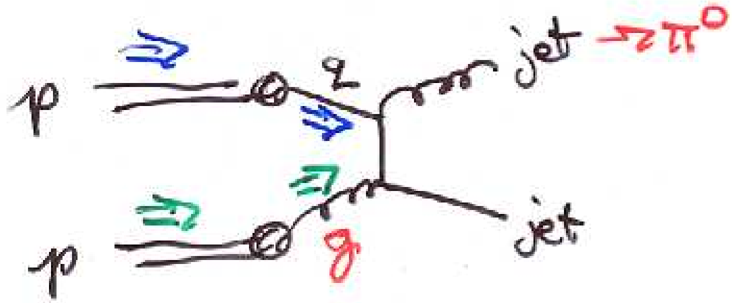
$$\simeq \frac{1}{5}\frac{\Delta G}{G}(x_g)$$



$$A_{LL} = \frac{\Delta G}{G}(x_1)\frac{\Delta G}{G}(x_2)\,\hat{a}_{LL}$$

$$(.5?) \quad (.15)$$

$$\overset{?}{\simeq} \frac{1}{12}\frac{\Delta G}{G}(x_1)$$



$$A_{LL} = \frac{\Delta G}{G}(x_1)\frac{\Delta u}{u}(x_2)\,\hat{a}_{LL}$$

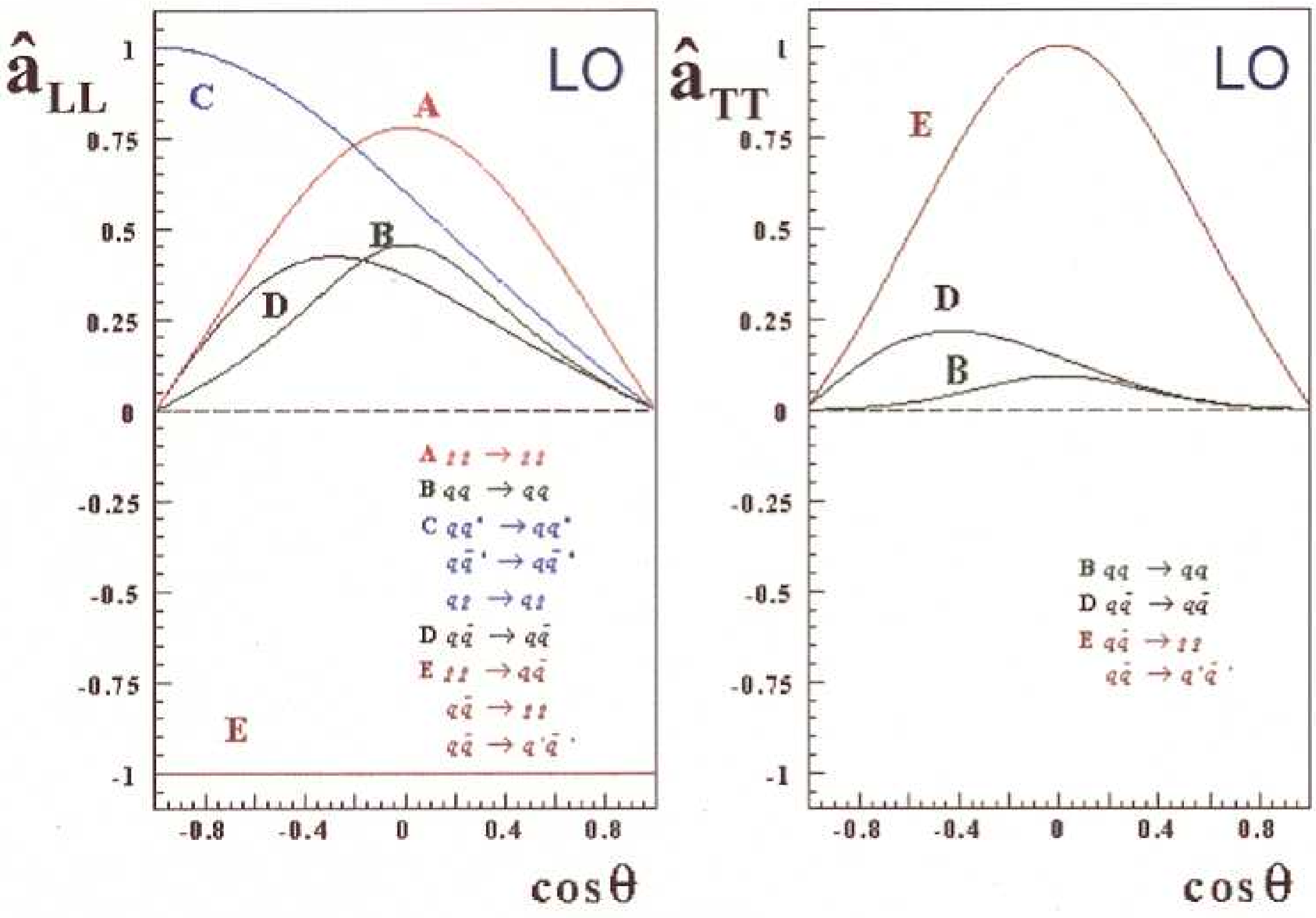
$$(.4) \quad (.6)$$

$$\simeq \frac{1}{4}\frac{\Delta G}{G}(x_1)$$

$+ gg \to gg/q\bar{q}$

also J/Ψ (but production mechanism)

LO pQCD partonic level asymmetries

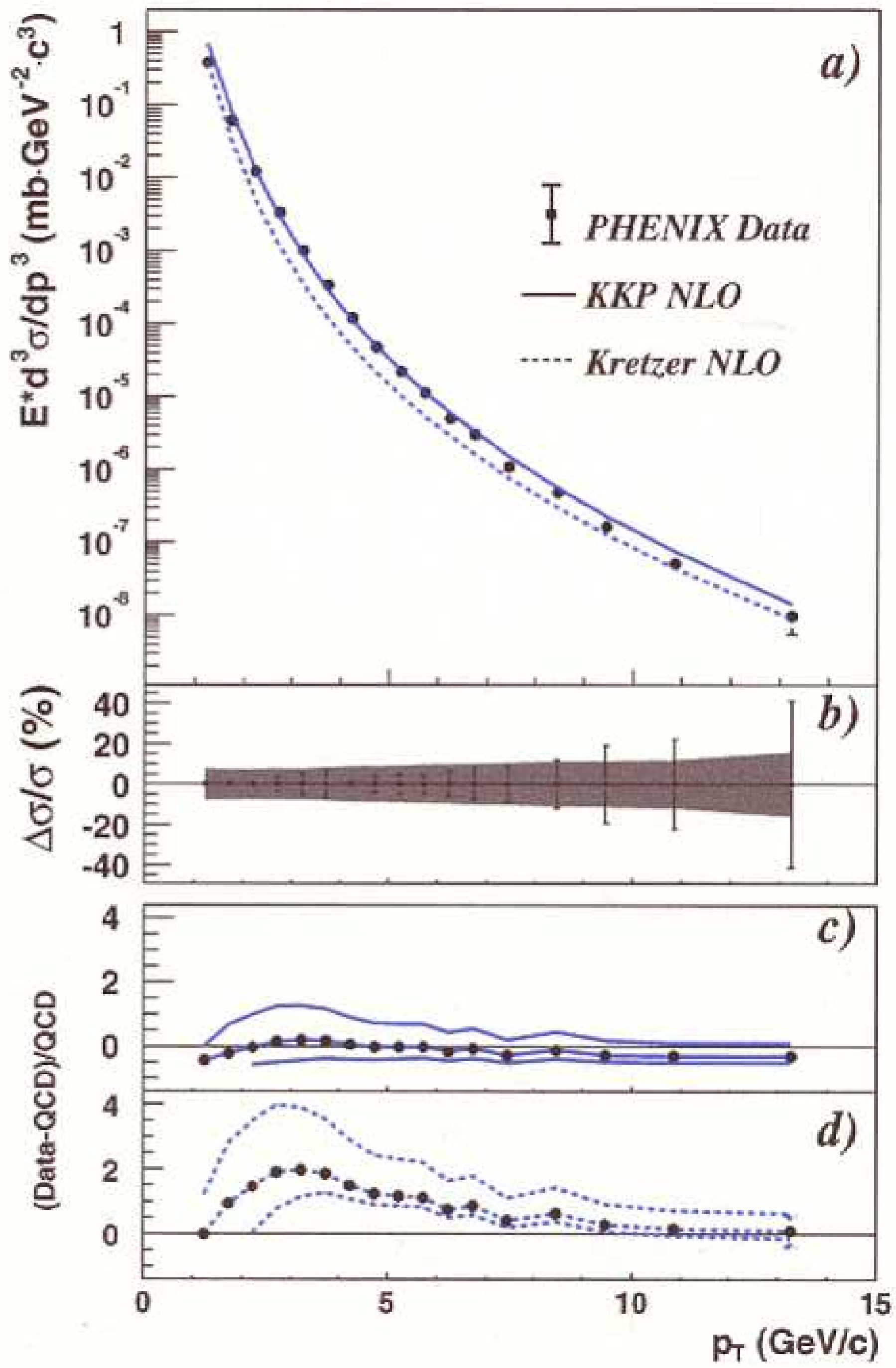


NLO corrections are now known for all relevant reactions

PHENIX

π^0 Cross Section

- The data covers over 8 order of magnitude
  - by combining minimum bias trigger and EMCal trigger data
- NLO pQCD calculation is consistent with data
  - CTEQ5M PDF + KKP FF

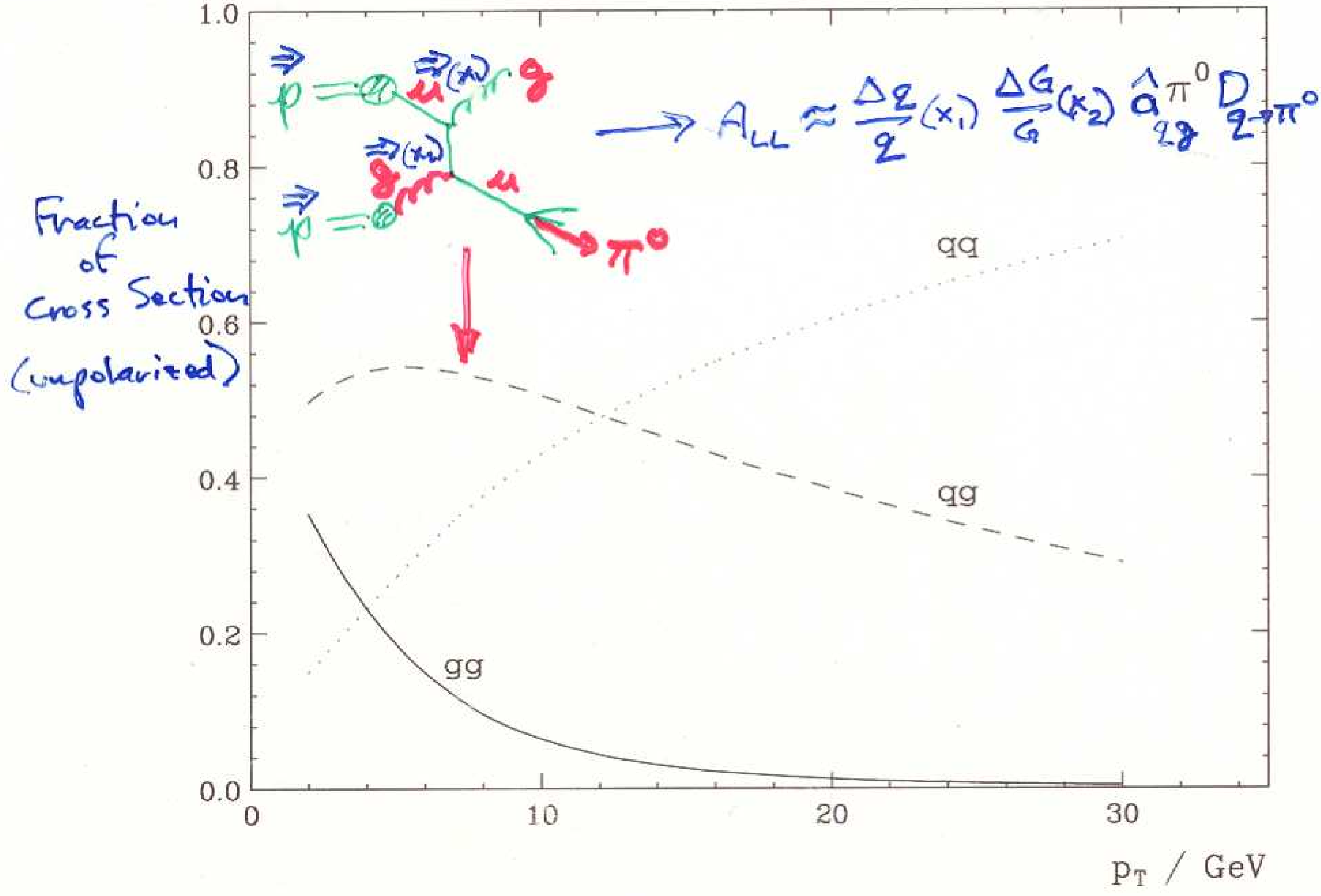


H. Torii, Kyoto University
B. Fox (BNL), SPIN 2002

submitted to PRL, hep-ex/0304038

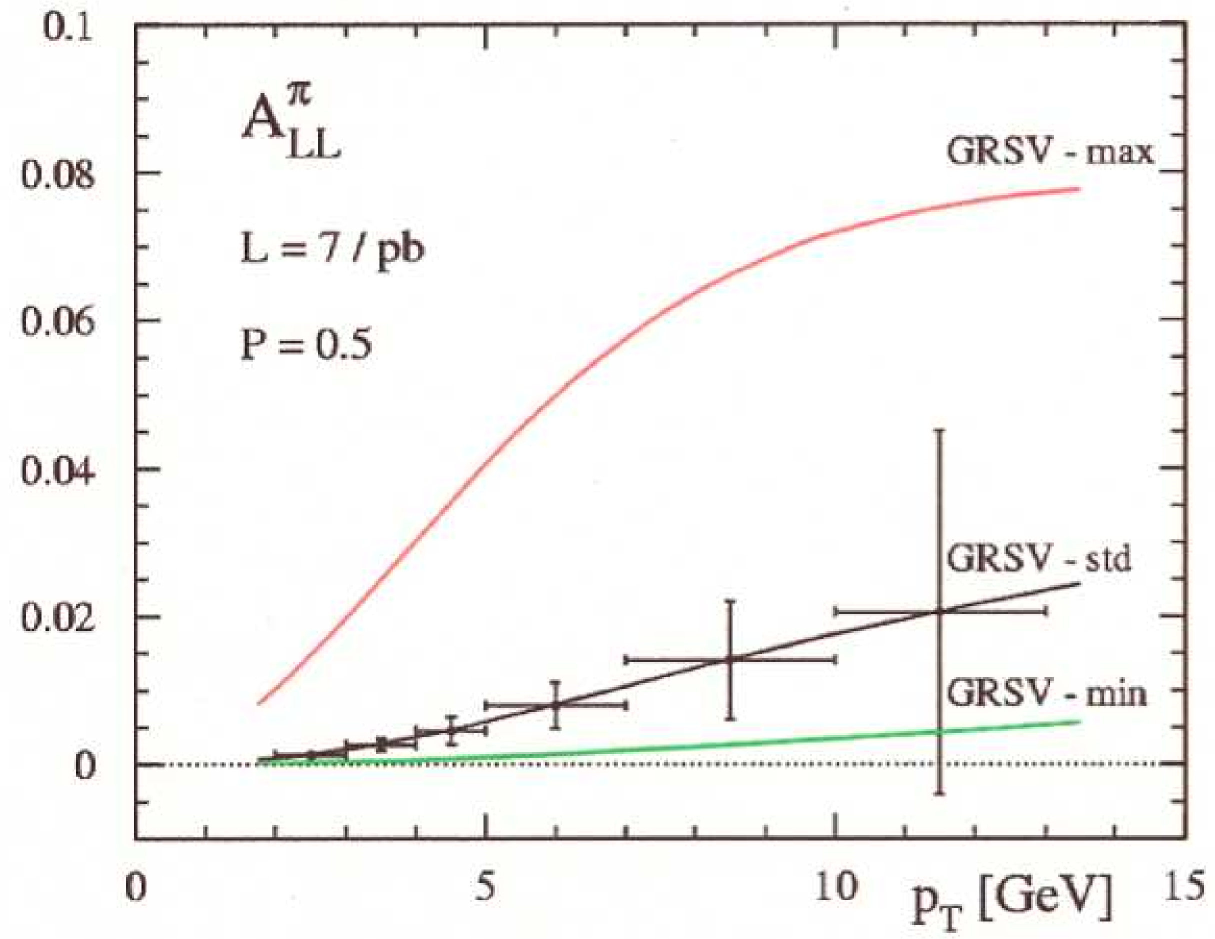
2003: π^0 as a jet surrogate to observe/measure/constrain gluon polarization.

$\sqrt{s} = 200$



π^0 Production and ΔG

π^0 can be used to determine ΔG with limited L & P



Jager, Schafer, Stratmann, Vogelsang

Measuring A_{LL} with π^0 at PHENIX

1. Longitudinal polarization $\rightarrow$ spin rotators

   ---need to find reaction sensitive to spin direction at collision

   ---2001/2 run: very forward neutrons!

   ---calibrated spin rotators in 2003

2. The problem of measuring relative luminosity to 10^{-4}

$A_{LL} = (\sigma_{++} - \sigma_{+-}) / (\sigma_{++} + \sigma_{+-})$, with $\sigma_{--} = \sigma_{++}$ and $\sigma_{-+} = \sigma_{+}$

$= (1/P^2) (N_{++}/ L_{++} - N_{+-}/ L_{+-}) / (N_{++}/ L_{++} + N_{+-}/ L_{+-})$

where L_{+-} = integrated luminosity for (blue beam + helicity, yellow −)

$= (1/P^2) (N_{++} - R\, N_{+-}) / (N_{++} + R\, N_{+-})$

where $R = L_{++}/ L_{+-}$, the ratio of relative luminosities for (+,+) to (+,−)

We use two (primary) luminosity monitors at PHENIX:

---scattered-beam counters along the beam lines (BBC)

---neutron detectors at 0° in crotch of both beams (ZDC)

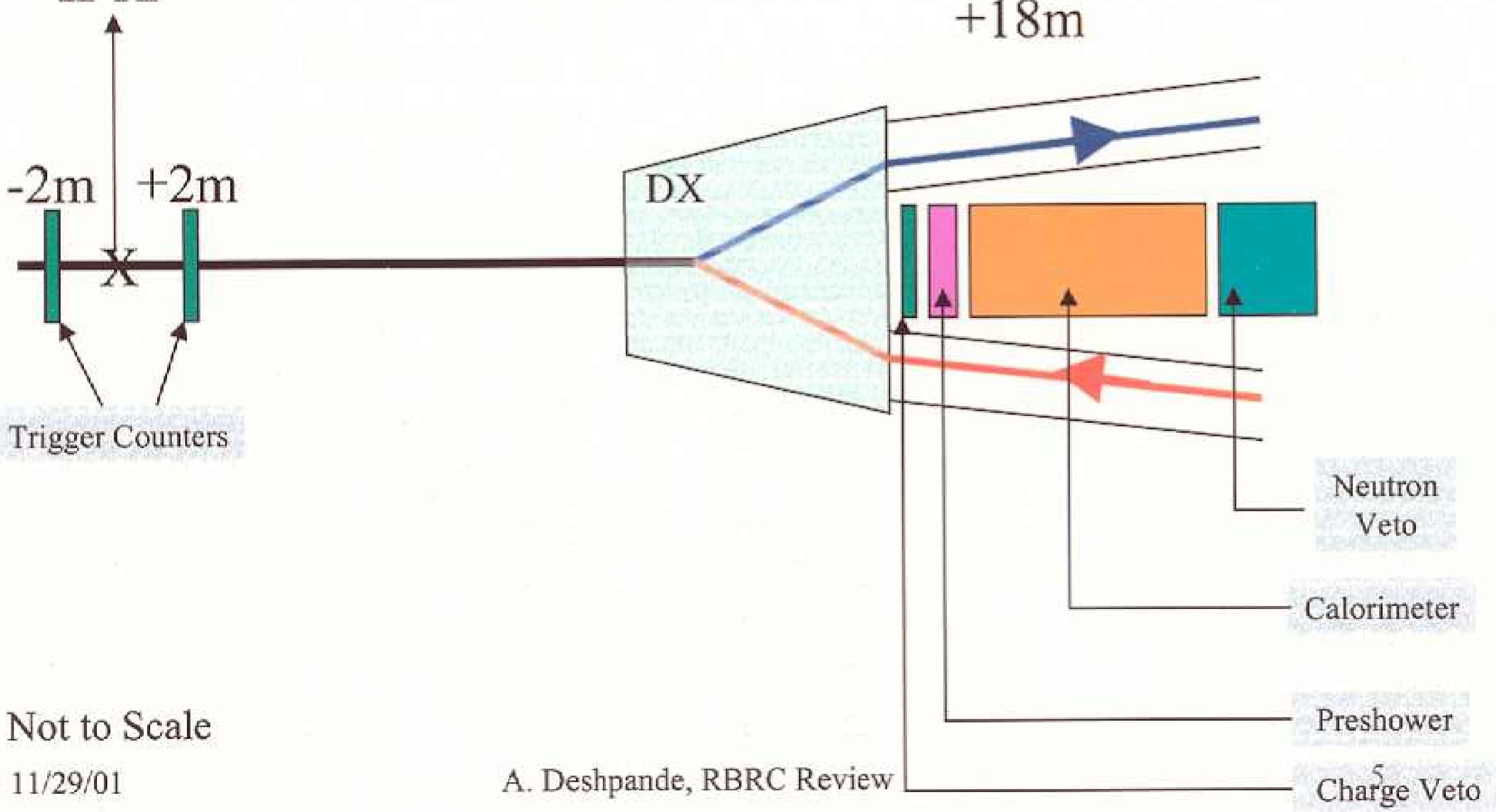
We need to show that these monitors

a. can measure relative luminosity to 10^{-4}

b. are free of polarization effects

12 o'clock: very forward γ, n, π^0

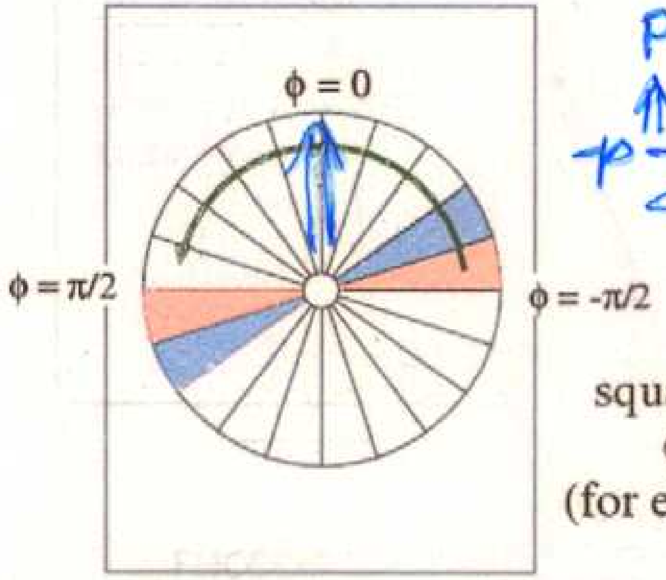
Schematic of the Experiment

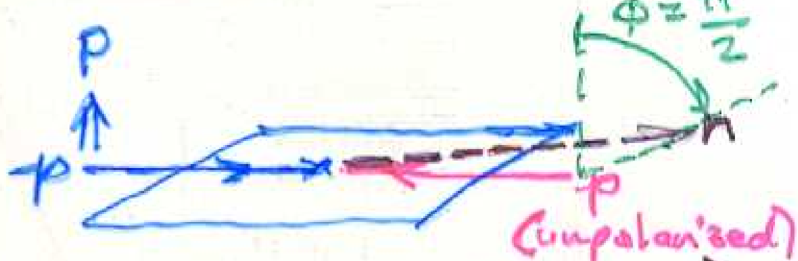


Not to Scale

Local Polarimeter Collaboration/ RHIC Spin

Neutron Asymmetry
ϕ distribution

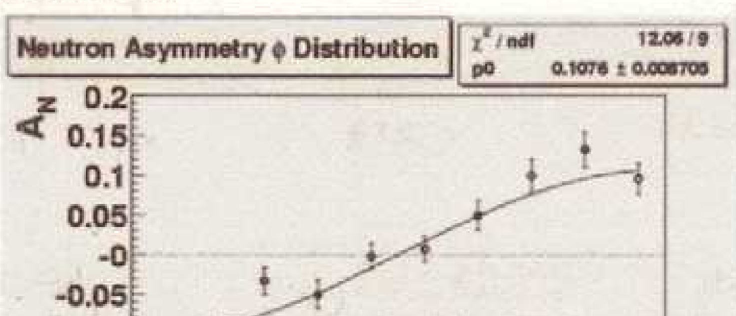




$$N(\phi) = N_0 (1 + P A_N \sin\phi)$$

square root formula is used for
ϕ dependent asymmetry
(for example red area, blue area)

EM Calorimeter



$\langle A_N \rangle = -0.108 \pm 0.0087$
additional scale-error

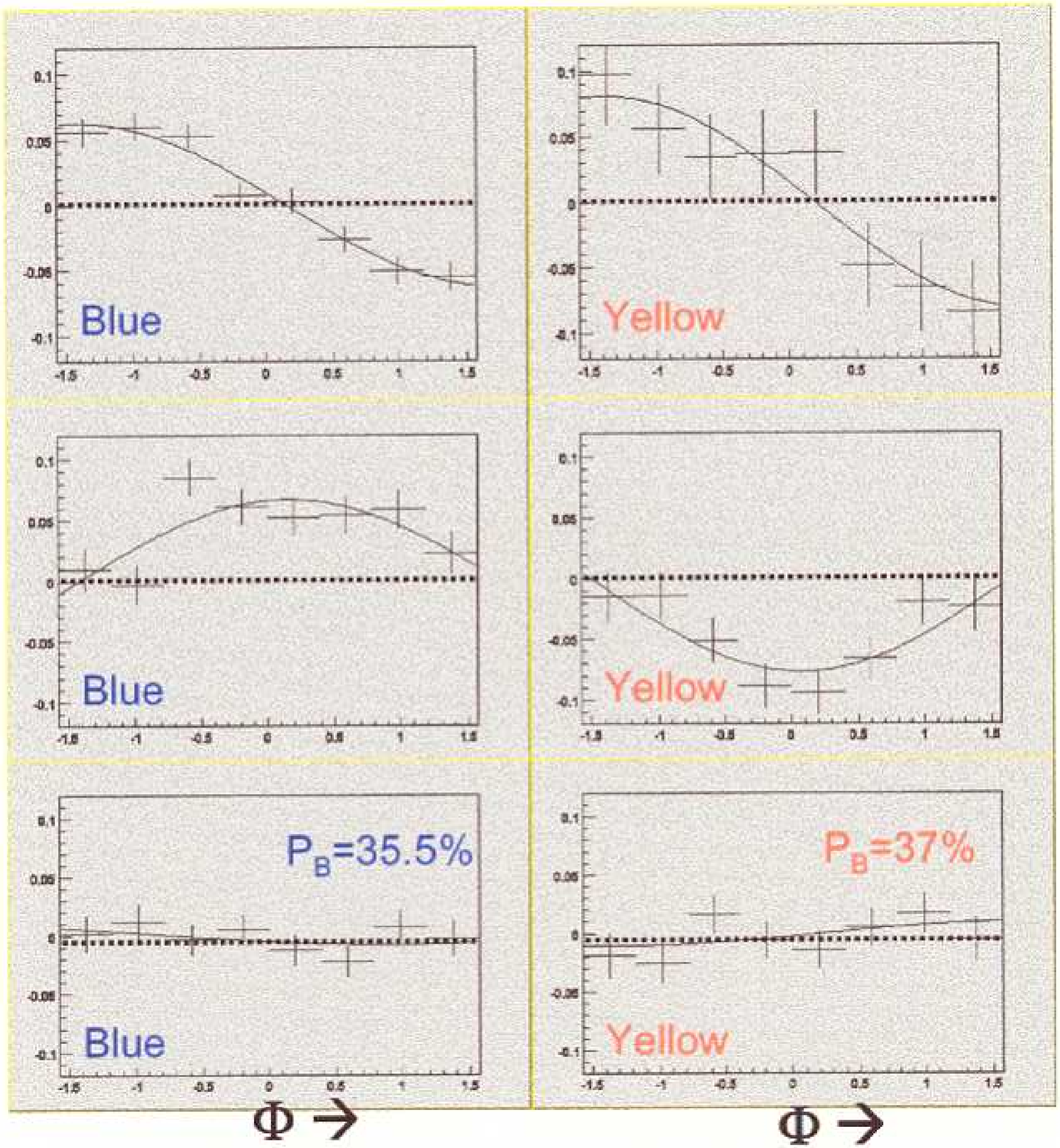
ϕ-dependence is consistent with $\sin\phi$

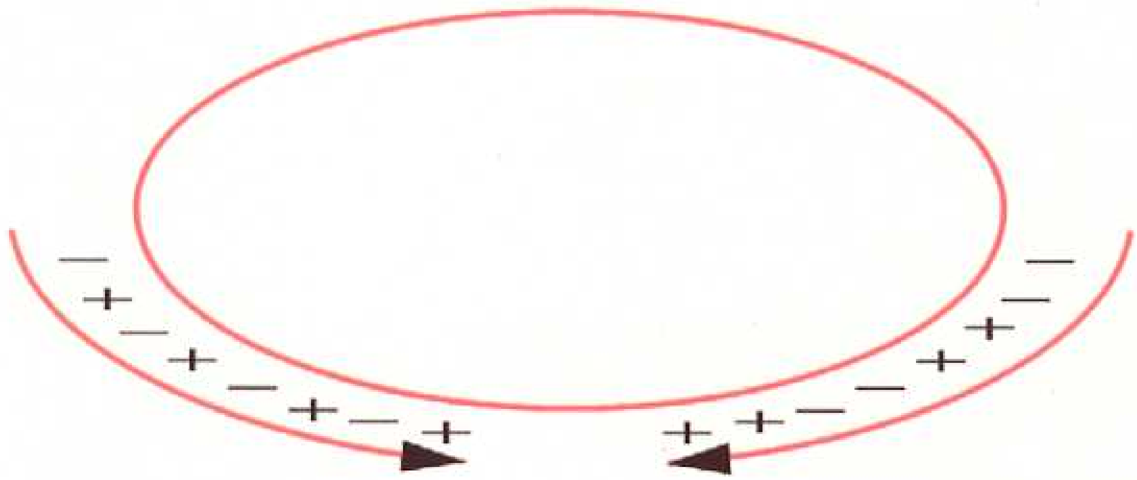
PHENIX Spin Rotator Commissioning using neutron asymemtries vs. ϕ

Spin Rotators OFF

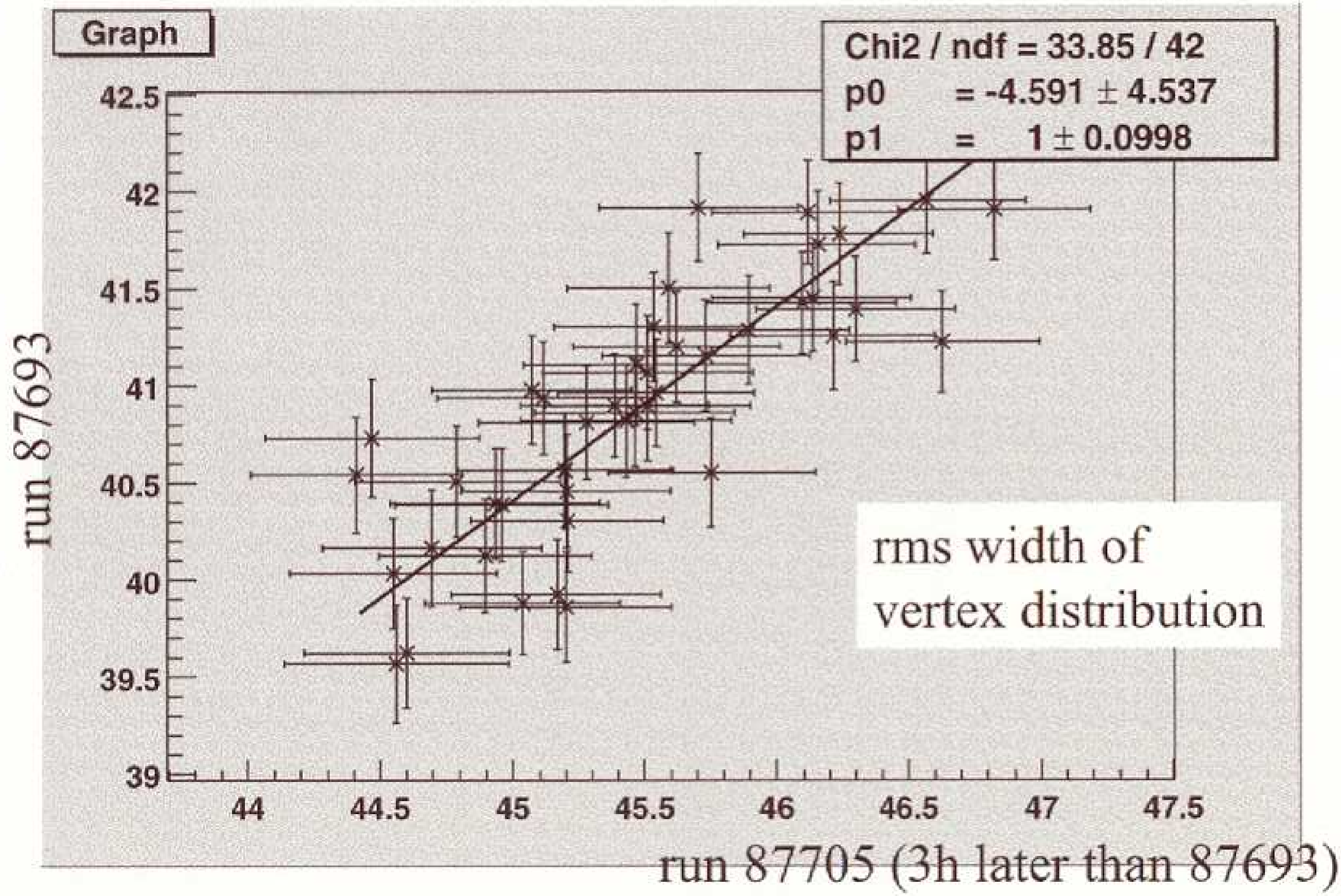
Spin Rotators ON
Current Reversed

Spin Rotators ON
Correct Current !



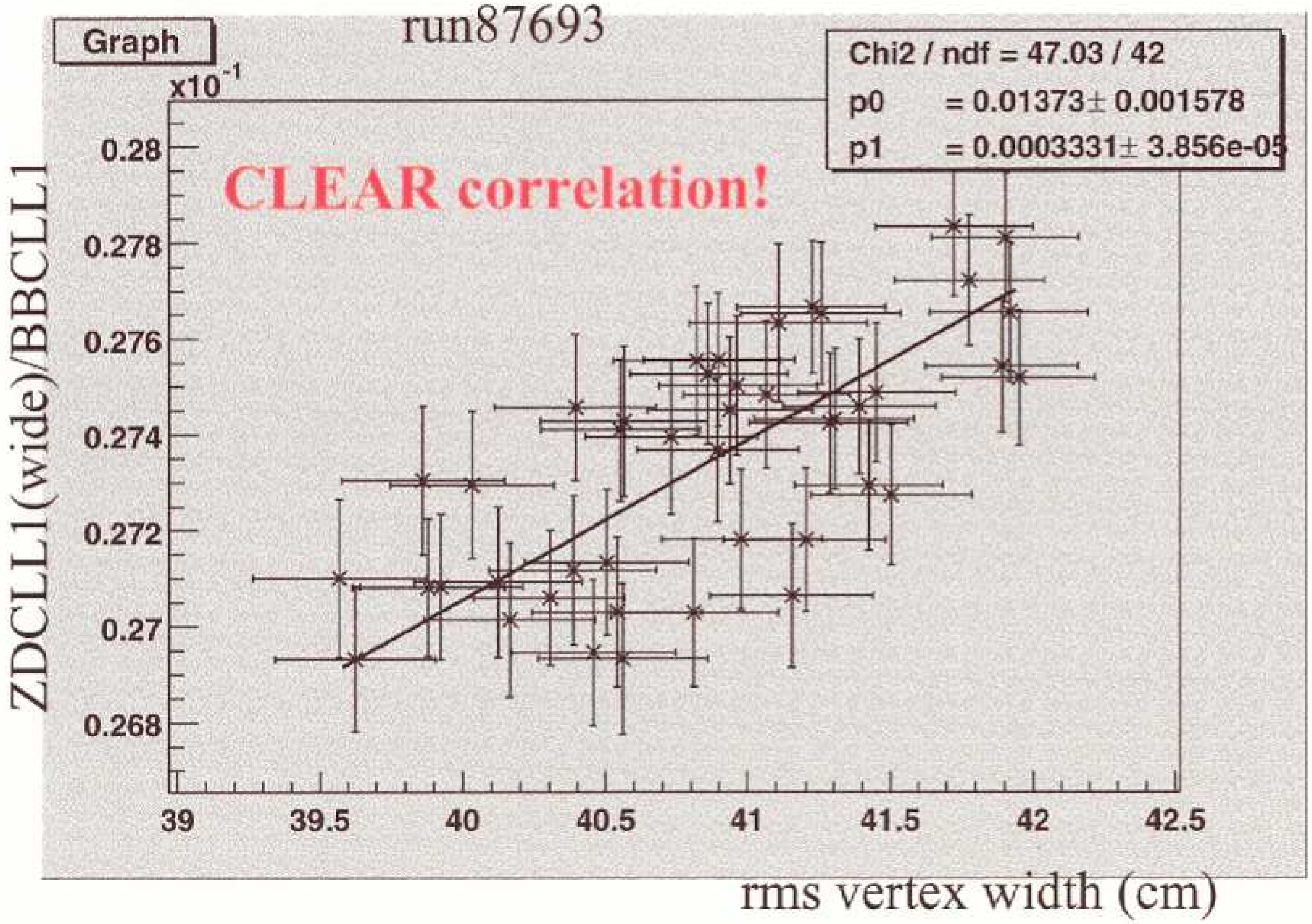


comparison of vertex width in the same fill



→ OK, we can add all data from the same fill

Correlation with bunch width



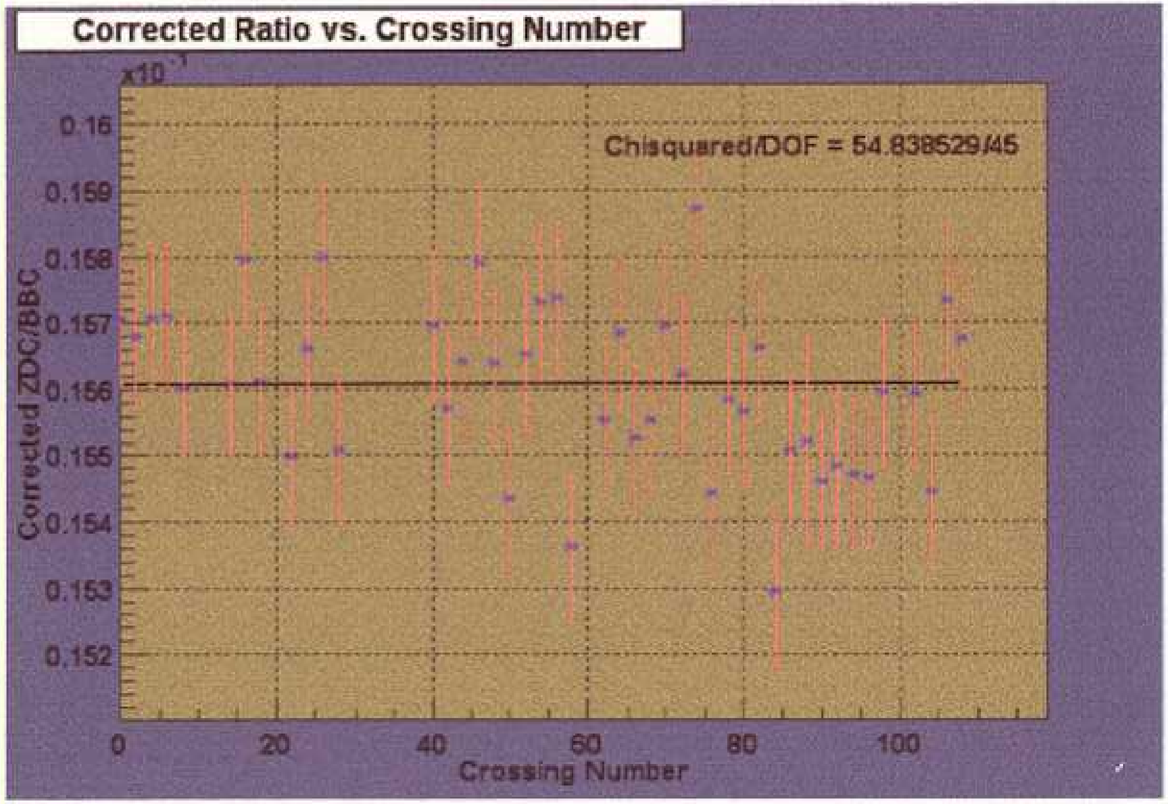
Limit on Relative Luminosity Measurement

(Run 3 Result)

- After correction for (measured) vertex width, the ratio of counts in the ZDC and BBC is consistent with a constant up to our level of statistics
- This means that if we apply correction for vertex width the precision on R goes from:

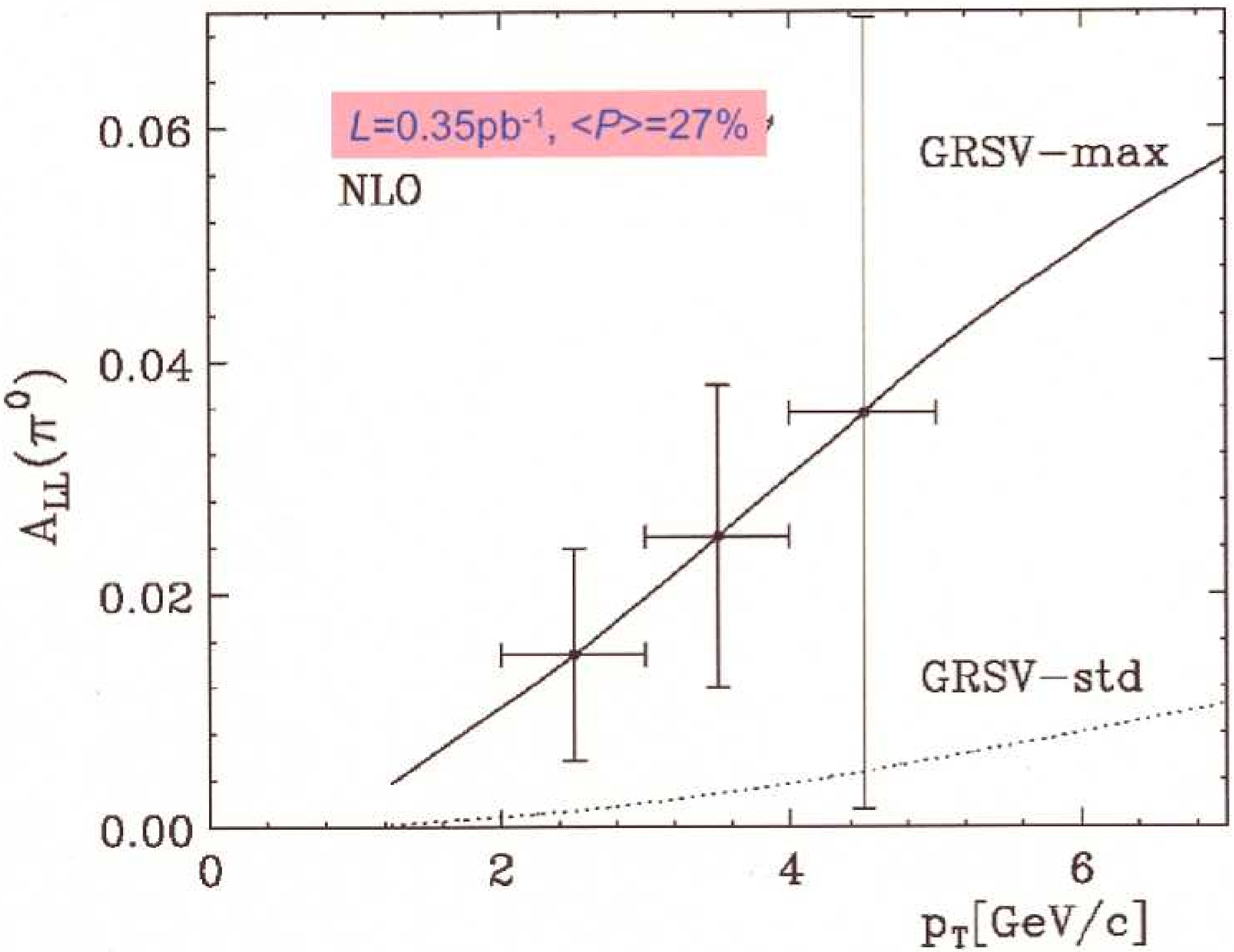
  0.11% → 0.06%

  (syst. limited) (stat. limited)



Projected A_{LL} sensitivity (2002-2003)

π^0 A_{LL} expectation

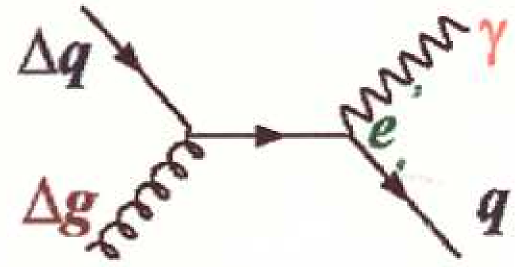


Prompt photon production

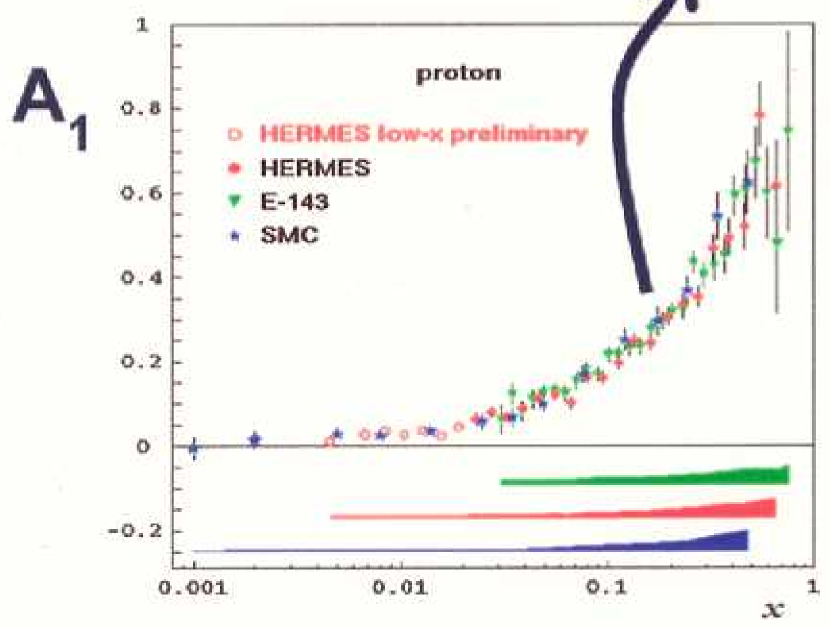
Gluon Compton Dominates

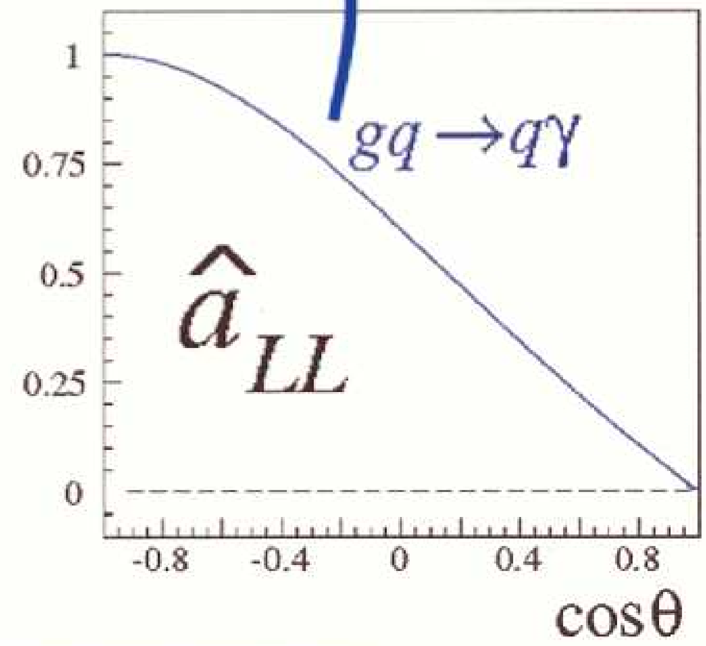
» At LO no fragmentation function

» Small contamination from annihilation



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



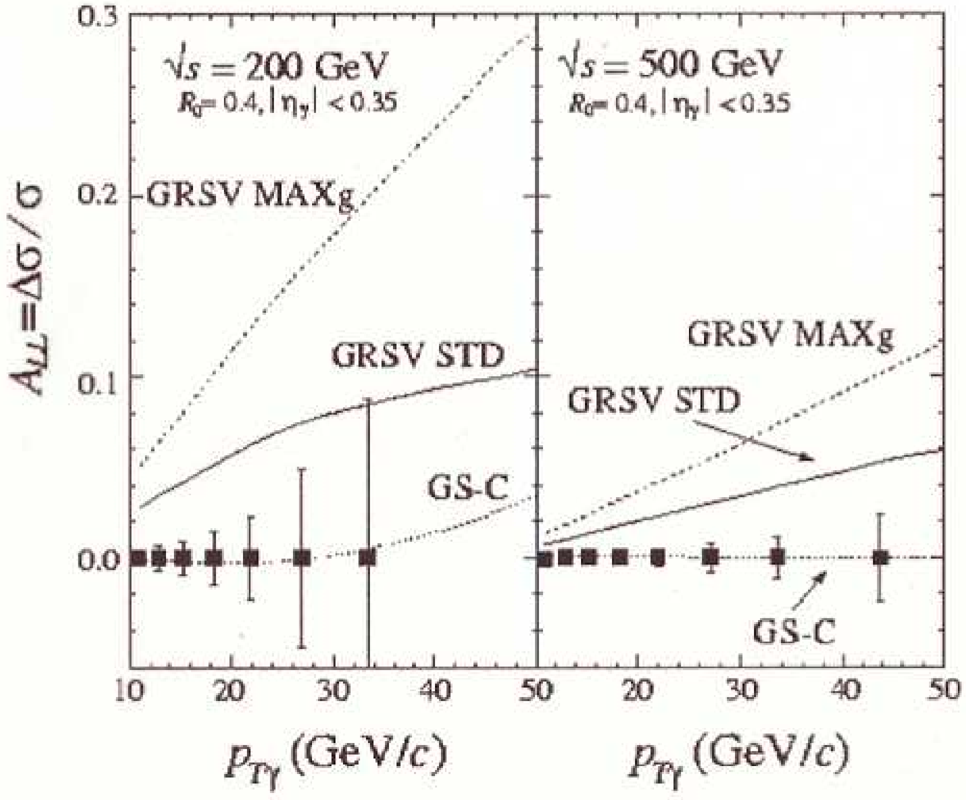


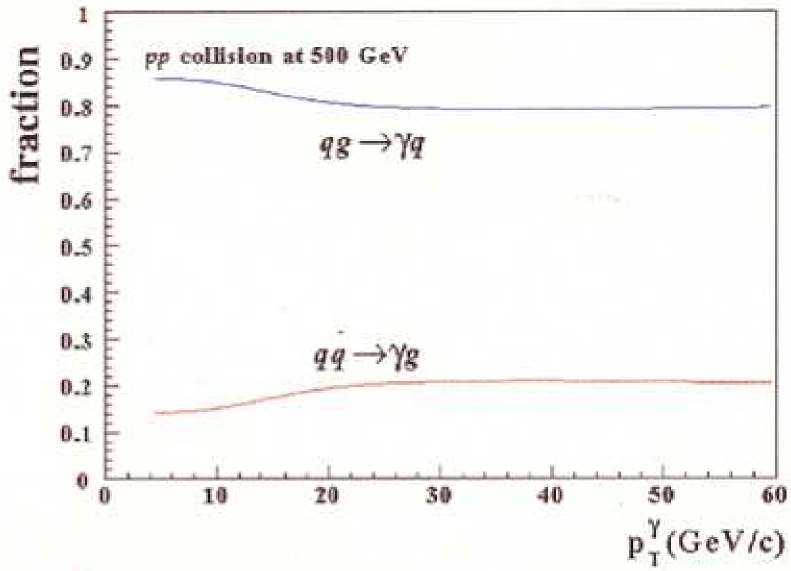
Prompt photon measurement

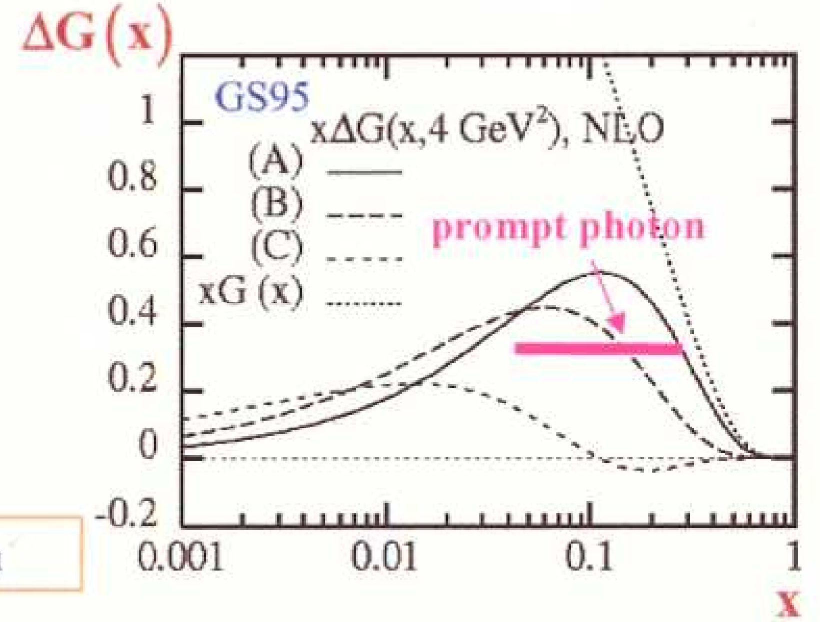
Prompt photon

» clear interpretation

- gluon Compton process dominant



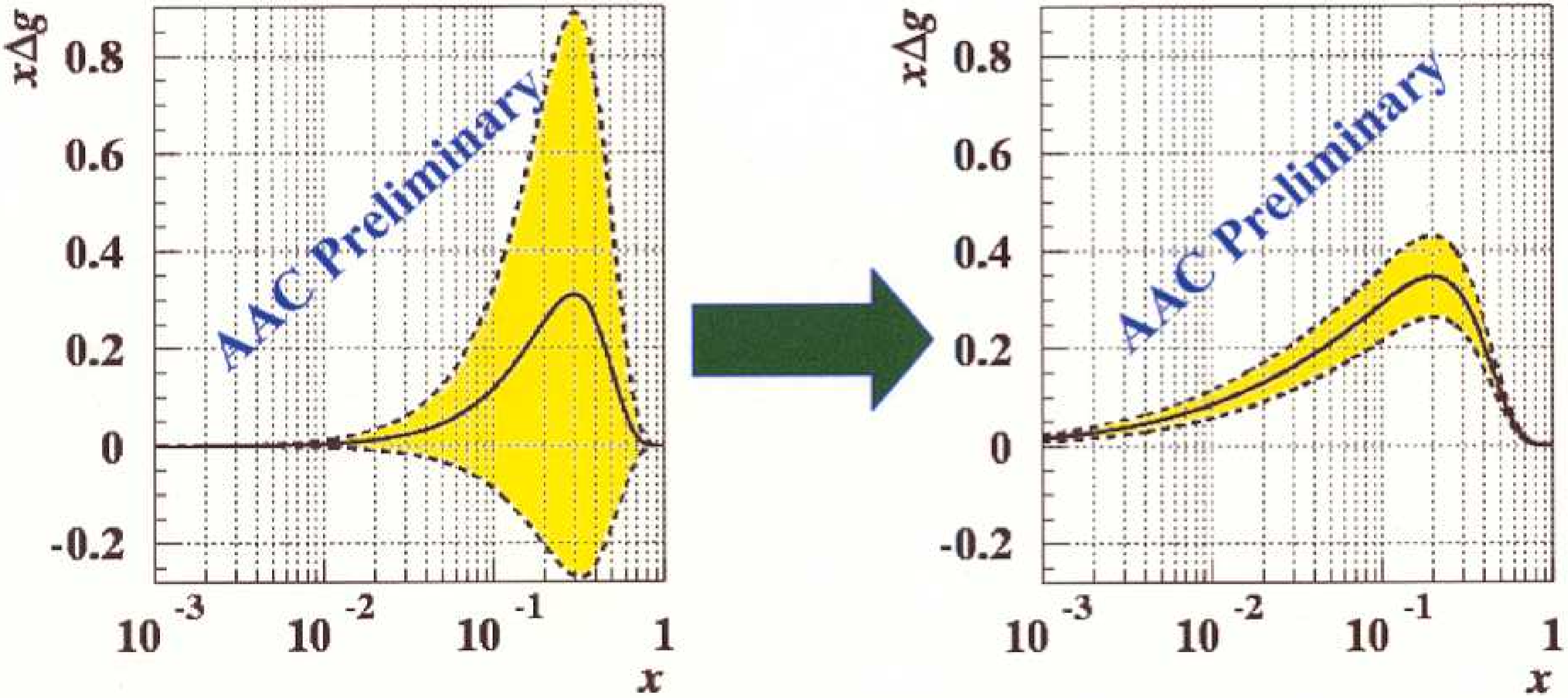




statistics with full design luminosity and polarization

Prompt γ measurement: impact on ΔG

If the projected PHENIX Prompt Photon Data are included in a Global QCD Analysis:



M. Hirai, H.Kobayashi, M. Miyama *et al.*

Parity Violation in W^+ Production

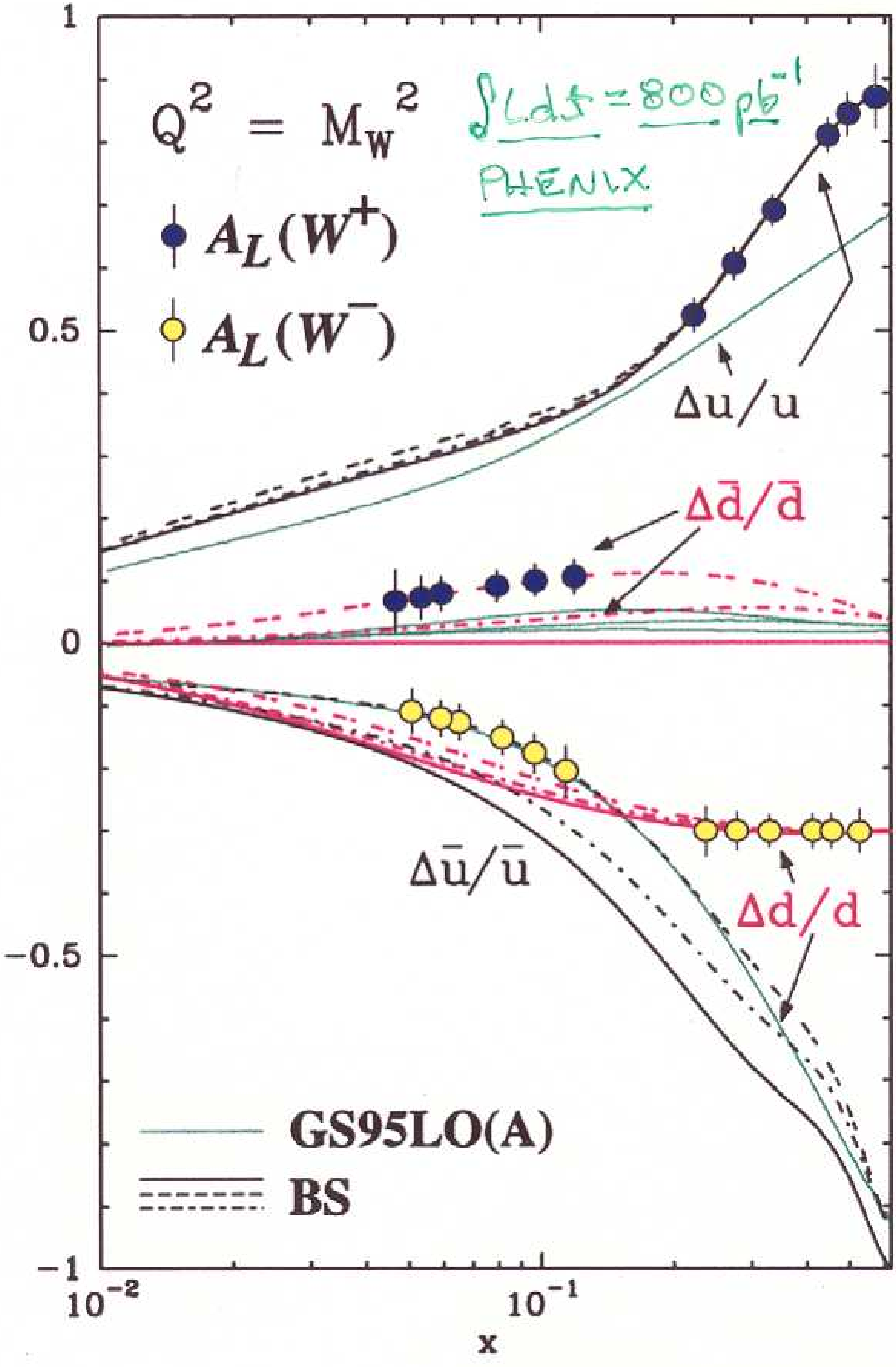
One beam is longitudinally polarized : $A_L = \frac{1}{Pol.} \frac{N_+ - N_-}{N_+ + N_-}$

- if W^+ is produced to $+y \Rightarrow$ large x_1, small x_2
  u $\bar{d}$

- but proton 1 is polarized $\Rightarrow$
  u quark is polarized and
  $$A_L(+y) = \frac{\Delta u}{u}$$

- if W^+ is produced to $-y \Rightarrow$ small x_1, large x_2
  $\bar{d}$ u

- proton 1 is polarized $\Rightarrow$
  $\bar{d}$ is polarized and
  $$A_L(-y) = \frac{\Delta \bar{d}}{\bar{d}}$$



courtesy of Jacques Soffer & Claude Bourrely

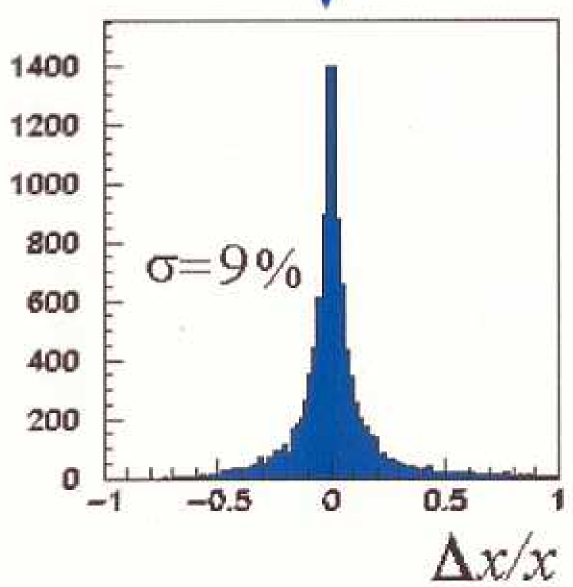
W kinematics and background

x can be determined directly if

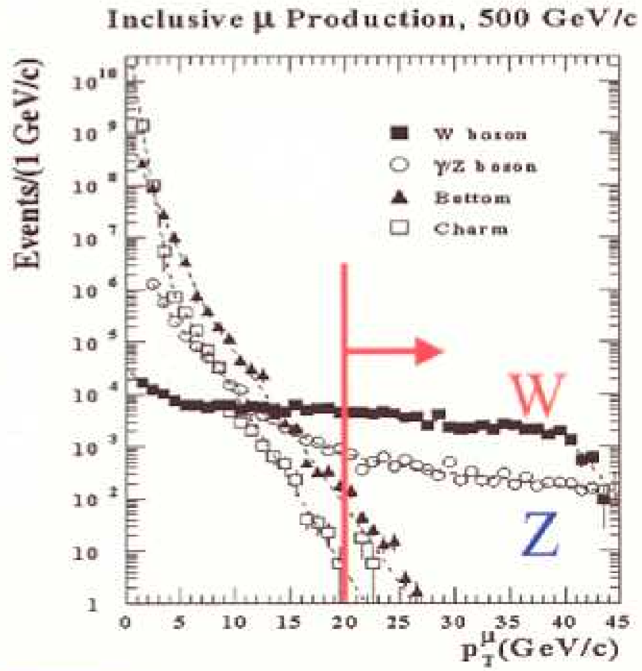
- W has no p_T
- W mass is δ-function

$$\left[\begin{array}{l} x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}; x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W} \\ y_\mu = y_\mu^* + y_w; y_\mu^* = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) \\ \cos\theta = \pm\sqrt{1 - 4p_{T\mu}^2 / M_W^2} \end{array}\right]$$

With realistic p_T and M_W the resolution is $\Delta x/x = 9\%$

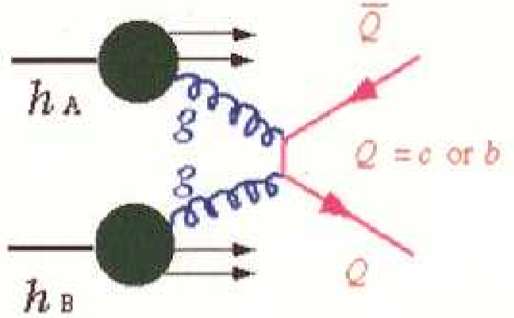


For $p_T > 20$ GeV W dominates with a smaller contribution from Z^0

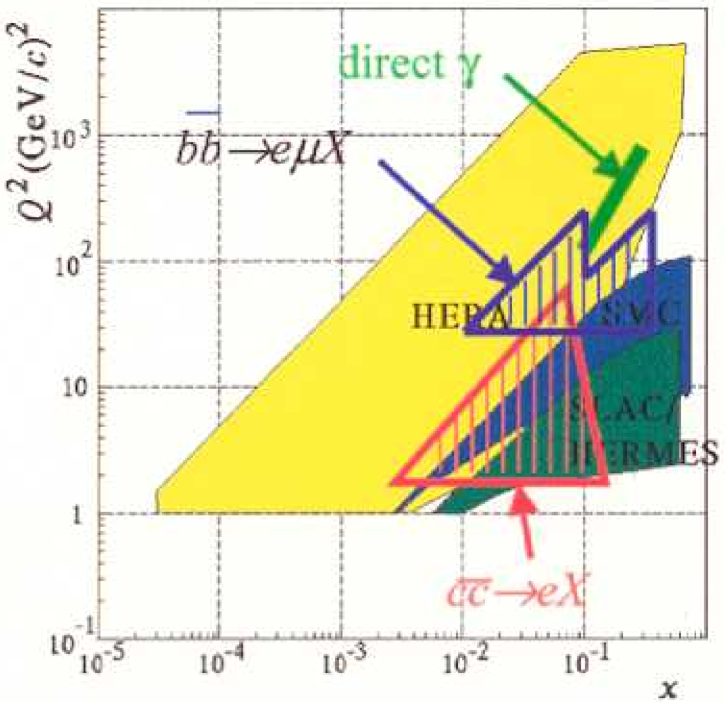


Open heavy flavors in PHENIX

Open heavy flavor production



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



H. Sato

Decay channels:

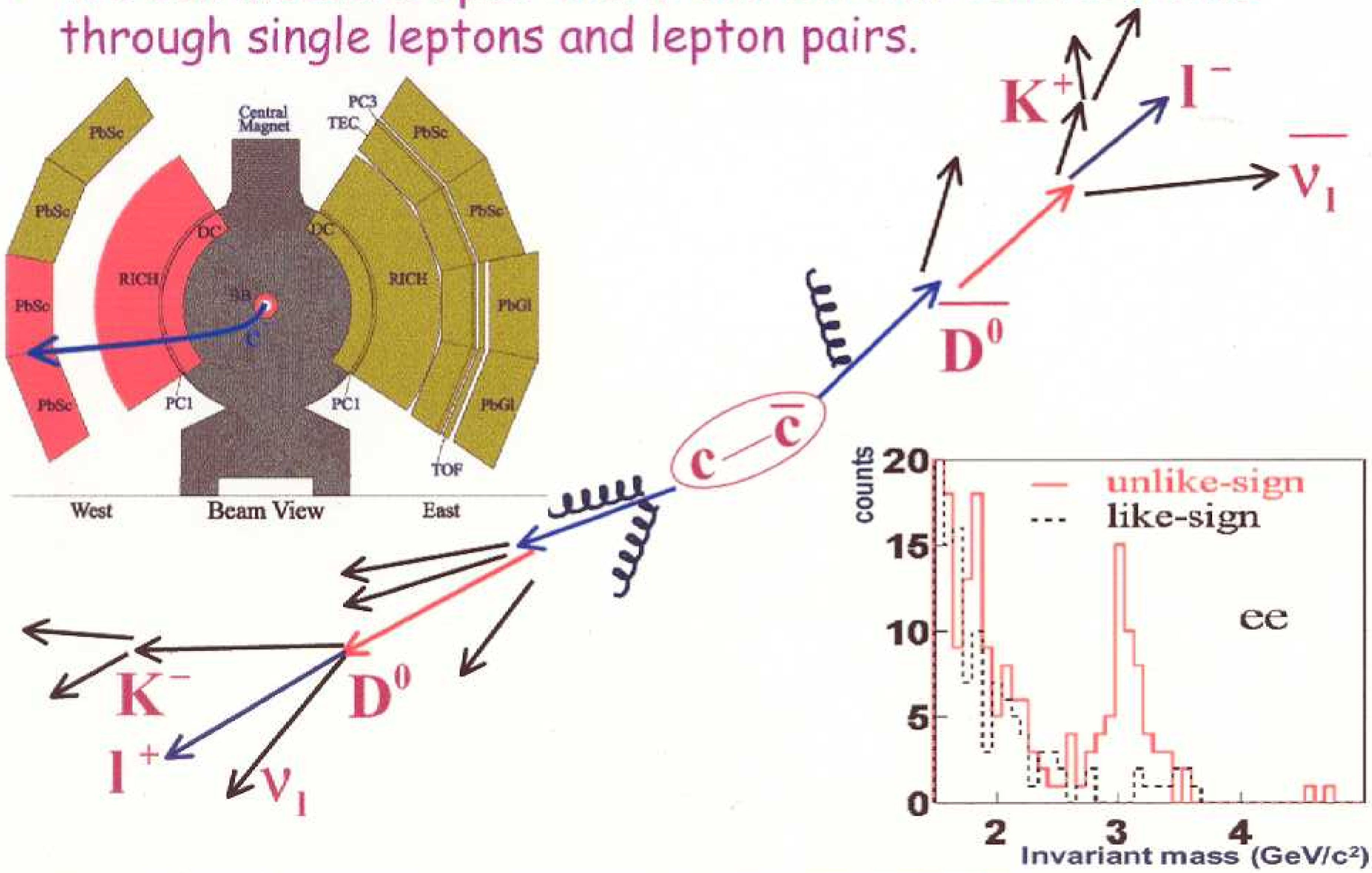
- » e^+e^-, $\mu^+\mu^-$, $e\mu$, e, μ, eD, μD

Provides more independent ΔG measurements in PHENIX

- » Helps control experimental and theoretical systematic errors
- » Different channels cover different kinematic regions

Electrons in PHENIX

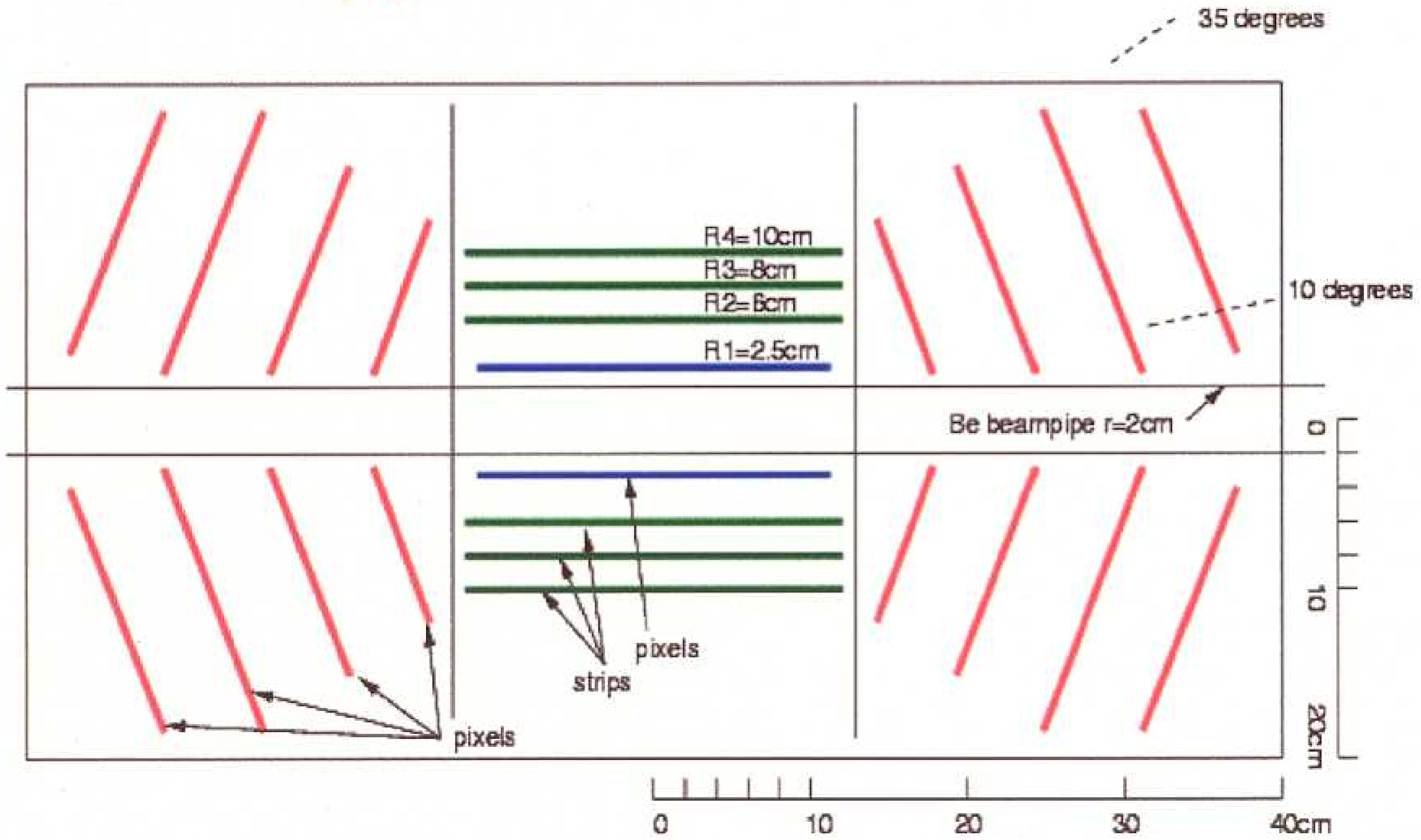
✓ We can measure open charm and bottom contributions through single leptons and lepton pairs.



Plans for PHENIX upgrade

Detection of heavy flavors (charm,bottom)

→ Silicon strip/pixel detectors

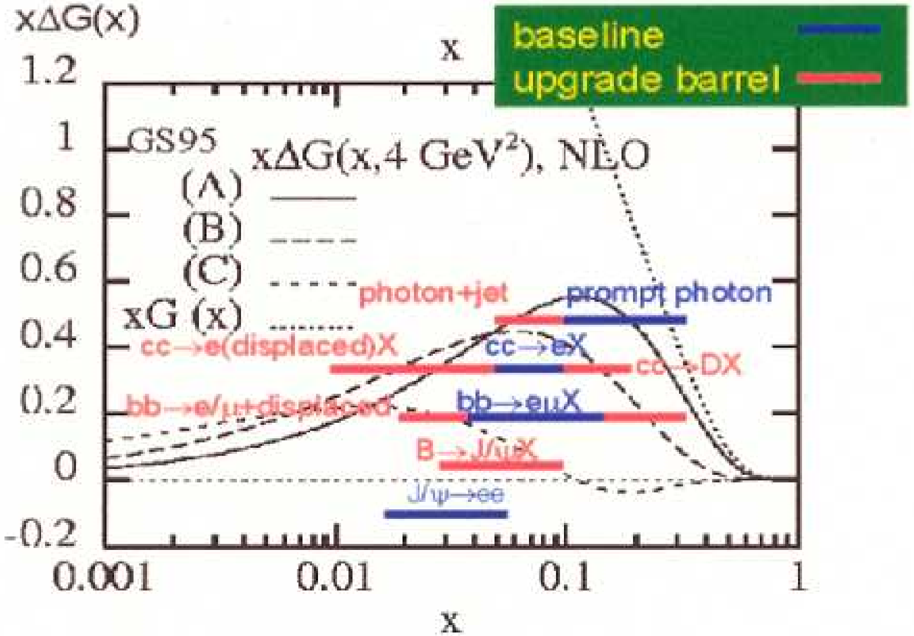


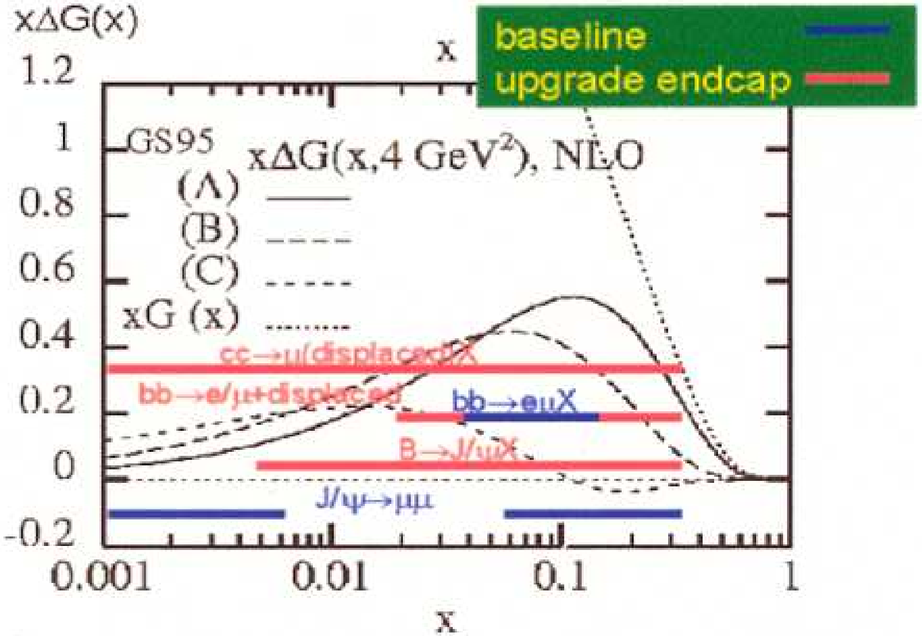
Spin Physics with Vertex Upgrade

Jet-axis for photon+jet-axis ➔ constraint on x

c→e, μ displaced vertex low-x S/B, D→Kπ high-x

b→displaced J/ψ low/high-x, b→e, displaced vertex high -x





Our Progress toward physics goals

1. proton-carbon polarimeter works: large hadronic spin-flip!
2. π^0 cross section at mid-rapidity (PHENIX): ---pQCD with NLO describes cross section well p_T = 2-14 GeV/c
3. beam-beam counters at STAR: ---observe transverse asymmetry, used for local polarimeter (and min-bias for pp spin and heavy-ion comparison data)
4. large n asymmetry for p_T < .5 GeV/c (PHENIX spin) ---used in 2003 as local polarimeter
5. large transverse asymmetry for forward π^0 at STAR ---physics interpretation transversity/orbital ang. momentum/ quark-gluon correlations
6. relative luminosity by crossing measured to .05% (PHENIX) (also expect STAR, BRAHMS)
7. first measurements of A_{LL} ---PHENIX, STAR in 2003 (.35 pb^{-1})
8. measurements of A_N and slope parameter (pp2pp)
9. need 5 pb^{-1}, P=.4 for jet/π measurement: very sensitive to $\Delta G(x)$
10. need 300 pb^{-1}, P=.7 for direct γ probe of $\Delta G(x)$
11. need root(s) = 500 GeV, 800 pb^{-1}, P=.7 for W parity violation

Scenario for Evolution of RHIC Spin Program

RHIC Run	$\sqrt{s}$ (GeV)	$\langle L_{peak} \rangle$ ($\mu b^{-1} s^{-1}$)	$\langle P_{beam} \rangle$	$\int L\,dt$ (pb^{-1})	Commission
2	200	0.5	0.15 (vertical)	0.35	Snakes/polarimeters/experiments
3	200	2	0.25 (vert.+long.)	1	Rotators/AGS+local polarimeters
4+5	200	10	>0.30 (long.)	5	Pol. Jet target/spin flipper/P_{beam}/L
>5	200	80	0.70 (long.)	320	Production
	500	200	0.70 (long.)	800	Production