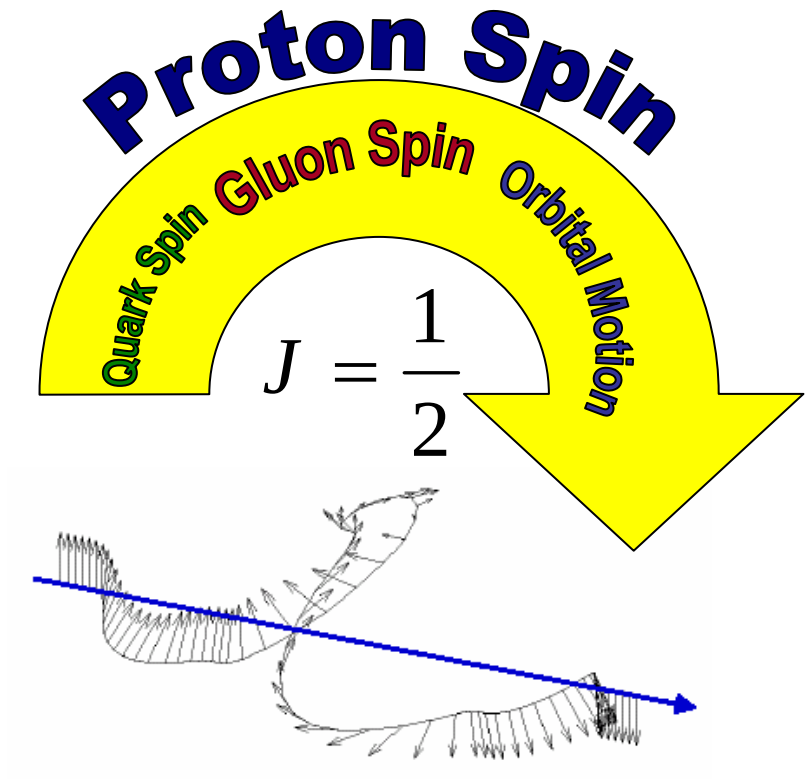
RHIC SPIN: un update



Alessandro Bravar

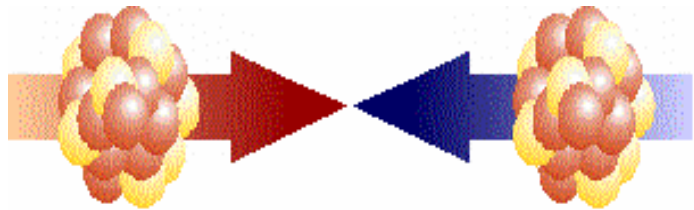
BROOKHAVEN
NATIONAL LABORATORY

COMPASS
June 12, ‘03

Physics @ RHIC

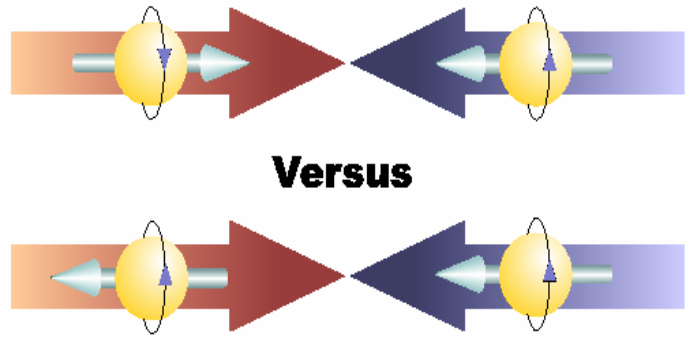
Study of QCD in extreme conditions

- heavy ion physics - hot and dense limit
- spin physics - high Q^2 with spin d.o.f.



Heavy Ion Physics

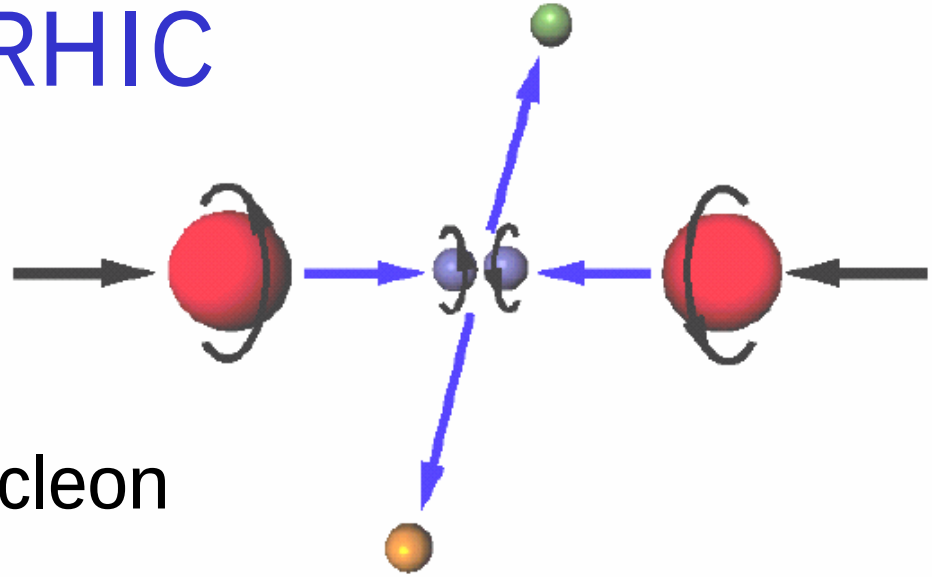
- search for a new state of matter – the Quark Gluon Plasma
- characterize its properties



Spin Physics

- elucidate the spin structure of the nucleon
- search for physics beyond standard model

Spin Physics @ RHIC

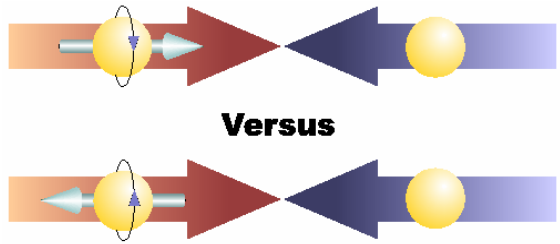


Collide Polarized Protons to study

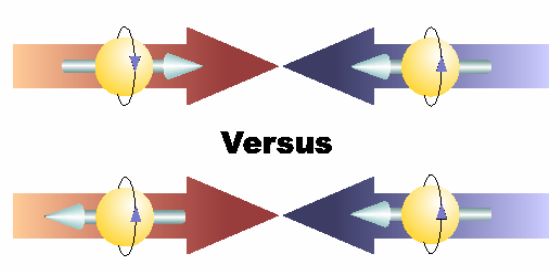
- Spin Structure of the Nucleon
  - Gluon polarization ΔG
  - Quark polarizations $\Delta\bar{u}$ and $\Delta\bar{d}$
  - Transversity Distributions δq
- Spin Dependence of Fundamental Interactions
  - Parity Violating Interactions
  - Physics Beyond Standard Model
- Elastic *pp* Scattering

Spin Asymmetries

A_L:Parity Violation



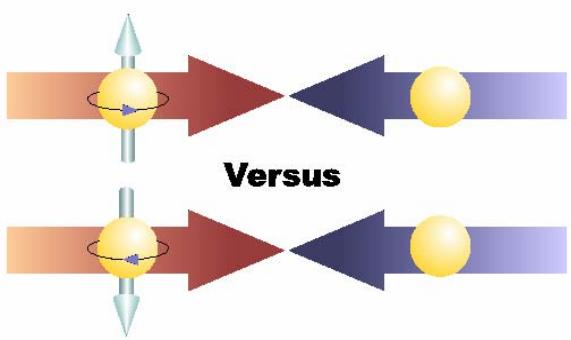
A_{LL}: Double Longitudinal Spin asymmetry



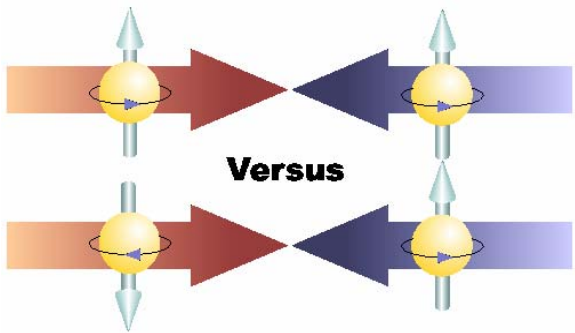
$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$

gives access to quark and gluon helicity distributions

A_N:Twist-3



A_{TT}: Transversity



Hadron - Hadron Collisions

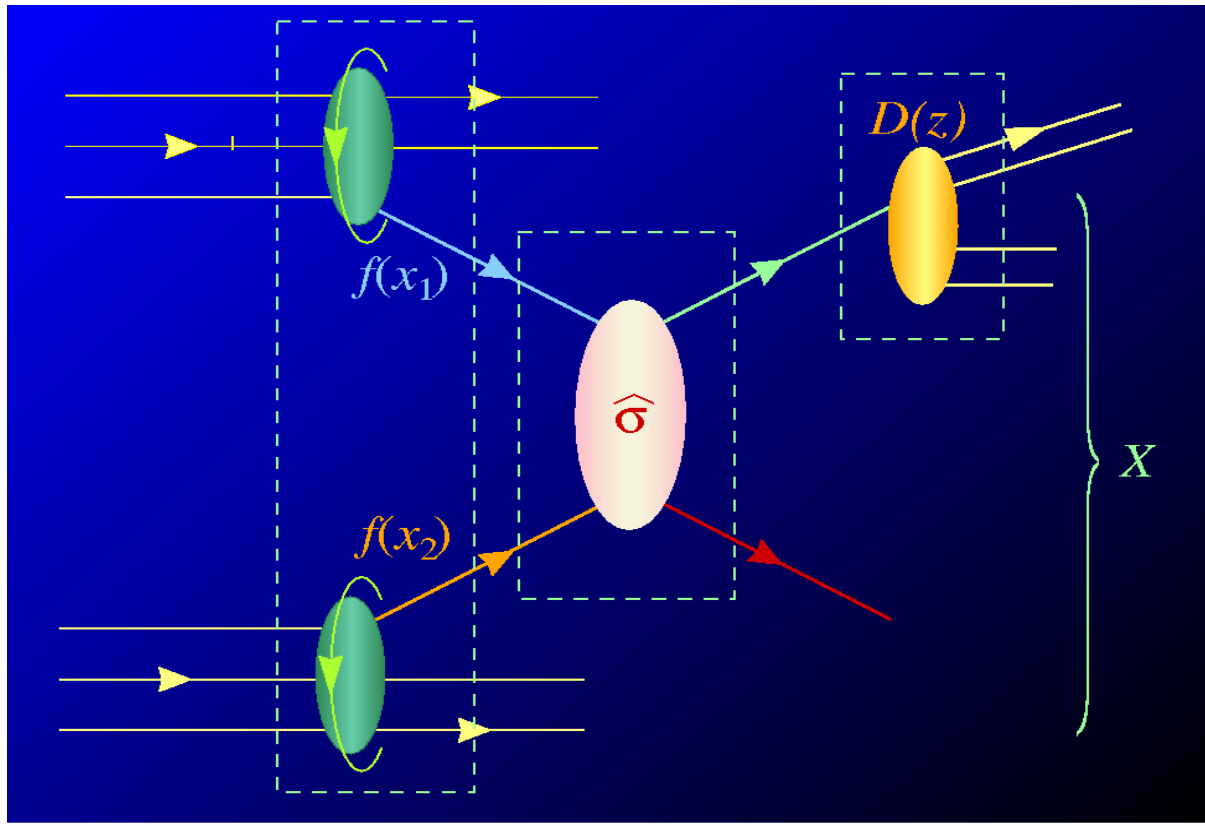
factorization

Emitting Partons: ***f(x)***

Hard interaction of partons : σ

Parton fragment into hadron : ***D(z)***

Universality of ***f(x)***, σ , ***D(z)***

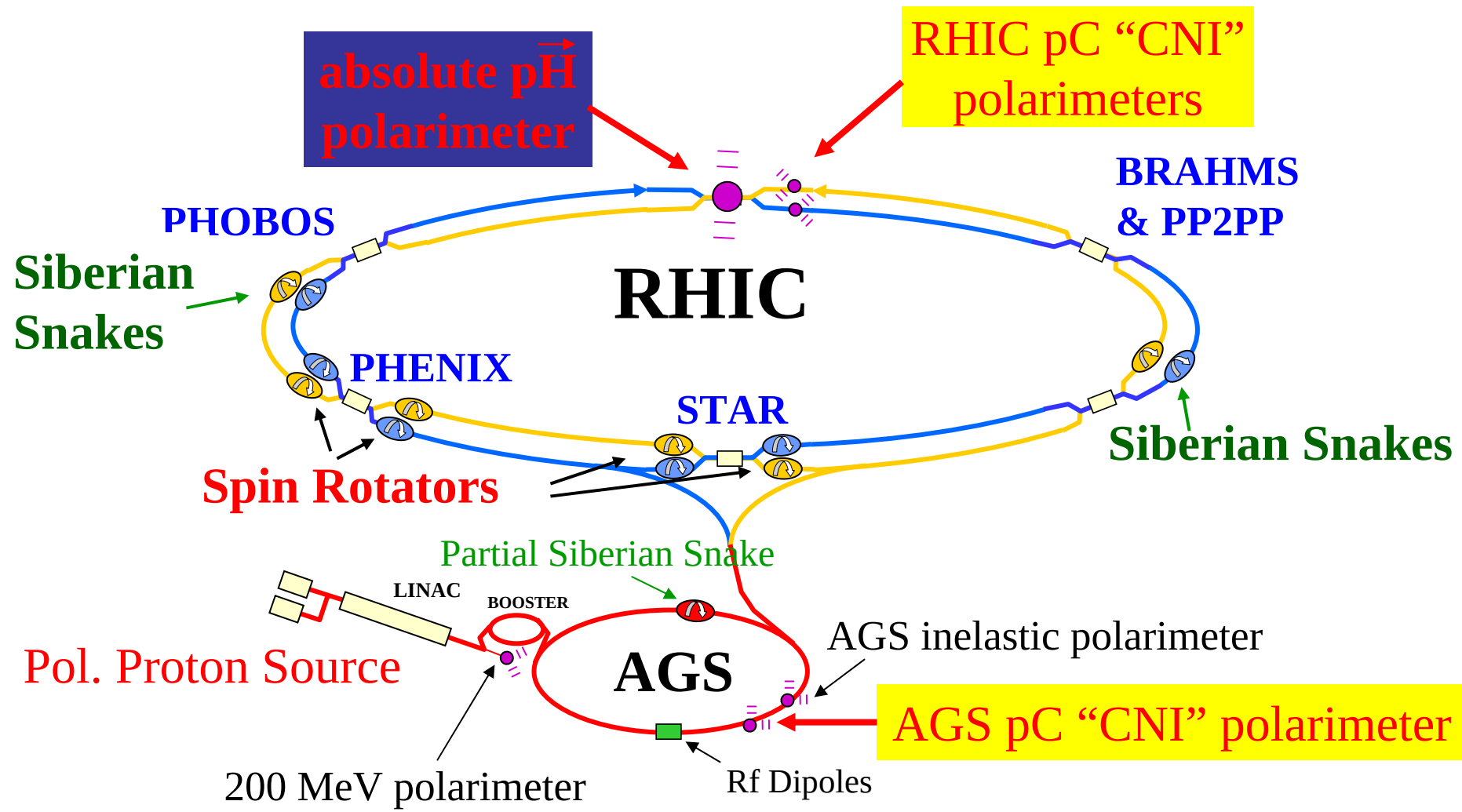


$$E\frac{d^3\sigma}{dp^3} = \sum_{i,j}\int f_i(x_1)\, f_j(x_2)\frac{d\hat{\sigma}}{dt}D(z)dP$$


PHOBOS
pp2pp
BRAHMS
polarimeters
RHIC
STAR
Magnet
Silicon Vertex Tracker
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber
PHENIX
BOOSTER
G-2
LINAC
AGS
TANDEMS
N
W
E
S

RHIC: The "Polarized Collider"

70% Polarization $L_{max} = 2 \times 10^{32}\ s^{-1}cm^{-2}$ $50 < \sqrt{s} < 500$ GeV



Spin Dynamics

Precession Equation in Laboratory Frame:
(Thomas [1927], Bargmann, Michel, Telegdi [1959])

$$d\mathbf{S}/dt = -(e/\gamma m)\,[(G\gamma+1)\mathbf{B}_\perp + (1+G)\,\mathbf{B}_o] \times \mathbf{S} \qquad G\gamma = \mathbf{1.91\ E}$$

Lorentz Force equation:

$$d\mathbf{v}/dt = -(e/\gamma m)\,[\quad \mathbf{B}_\perp \quad] \times \mathbf{v}$$

- For pure vertical field:
  Spin rotates $G\gamma$ times faster than motion, $\nu_{sp} = G\gamma$
- For spin manipulation:
  At low energy, use longitudinal fields
  At high energy, use transverse fields

Depolarizing Spin Resonances

Spin tune: Number of 360 degree spin rotations per turn

Depolarizing resonance condition:

Number of spin rotations per turn = Number of spin kicks per turn

Imperfection resonance (magnet errors and misalignments, closed orbit errors):

$$\mathbf{G\gamma = \nu_{sp} = n}$$

Intrinsic resonance (vertical focusing fields, finite beam emittance):

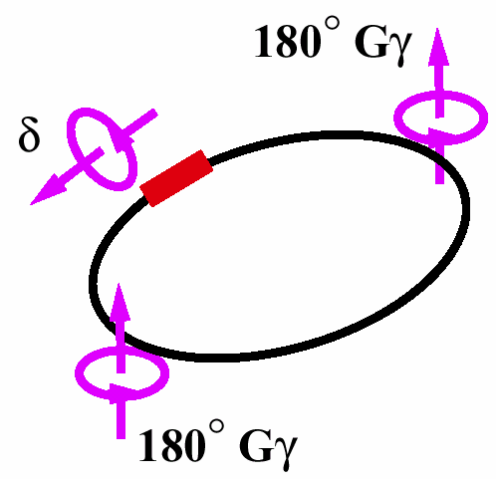
$$\mathbf{G\gamma = \nu_{sp} = Pn \pm \nu_y}$$

P: Superperiodicity [AGS: 12]

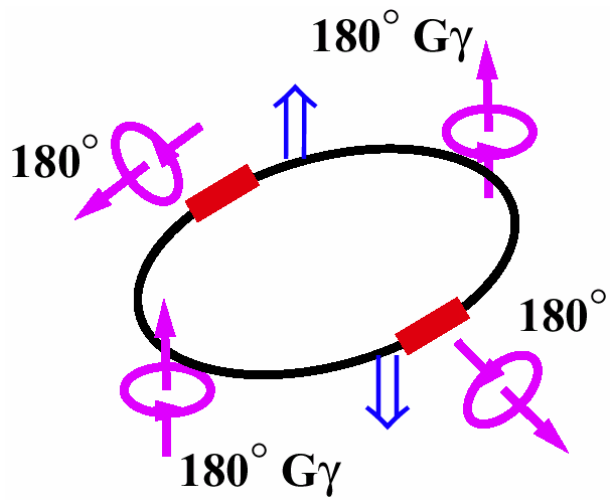
ν_y: Betatron tune [AGS: 8.75]

Siberian Snake Operation

- Partial Snake
  - rotate around beam direction (by 5 degrees)
  - compensate for imperfections



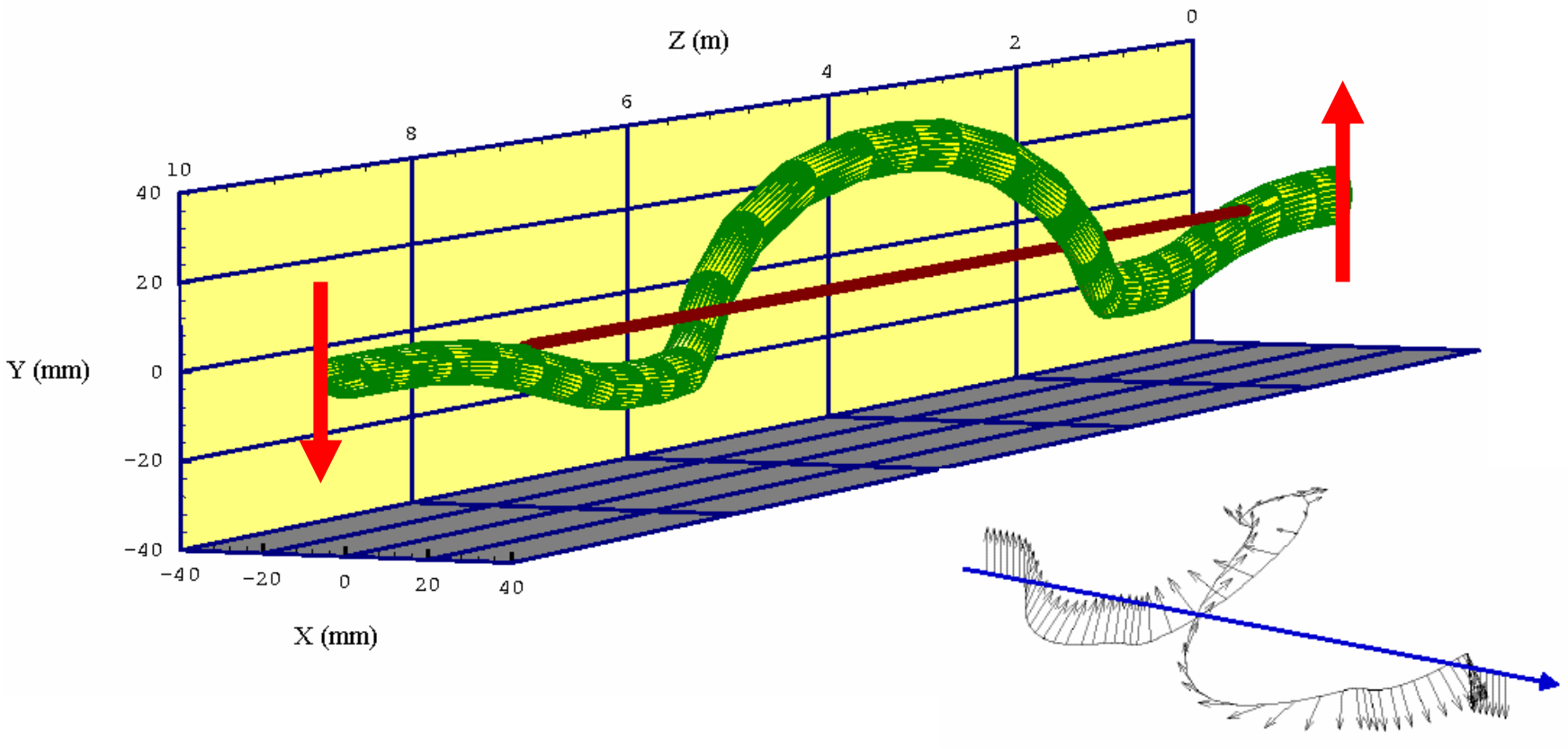
- Full Snake (with 2 rotators)
  - Rotate around two orthogonal axes in the accelerator plane (i.e. x and y comp. separately)
  - compensate for imperfections and intrinsic resonances



Siberian “ Snake ”

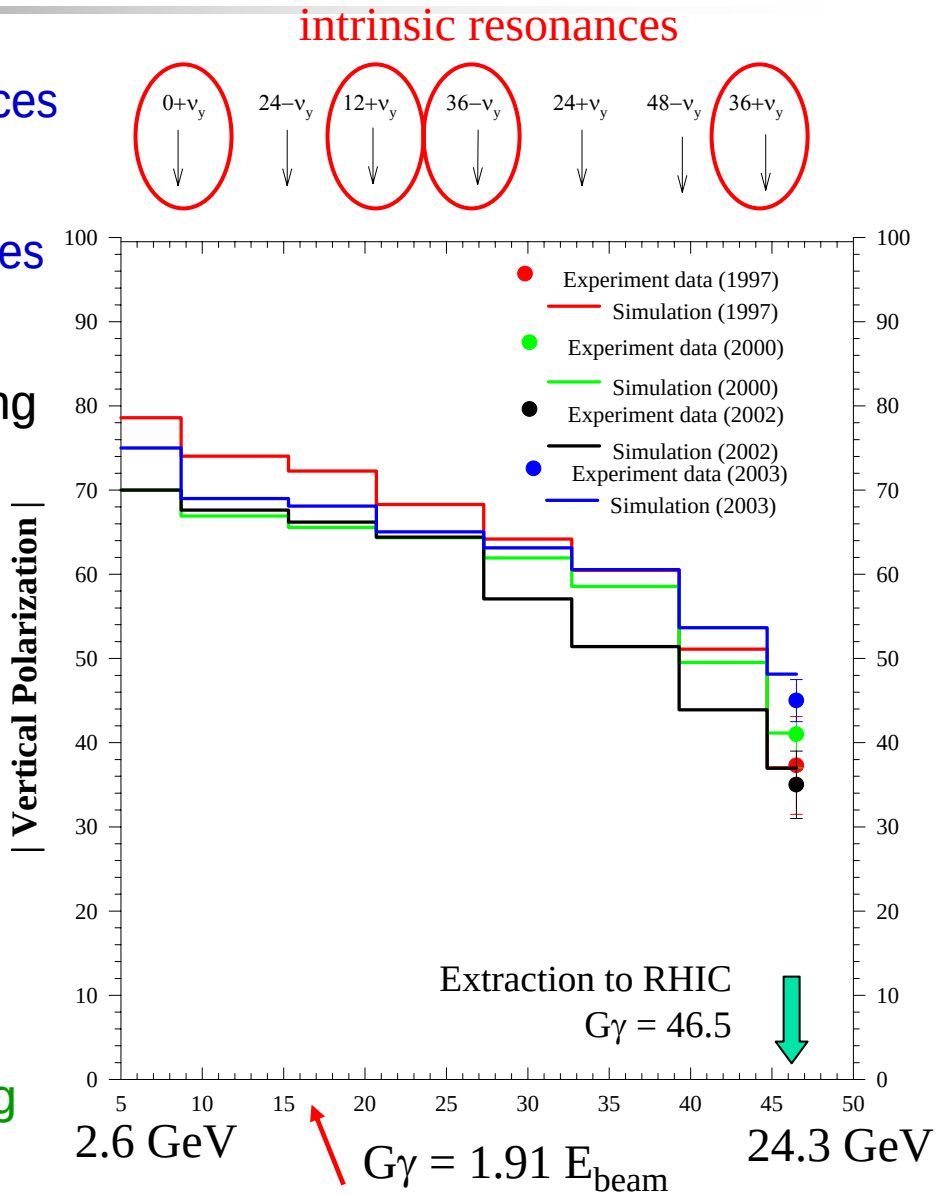
Beam Trajectory while rotating Spin Direction

~ 3D image of “snake”

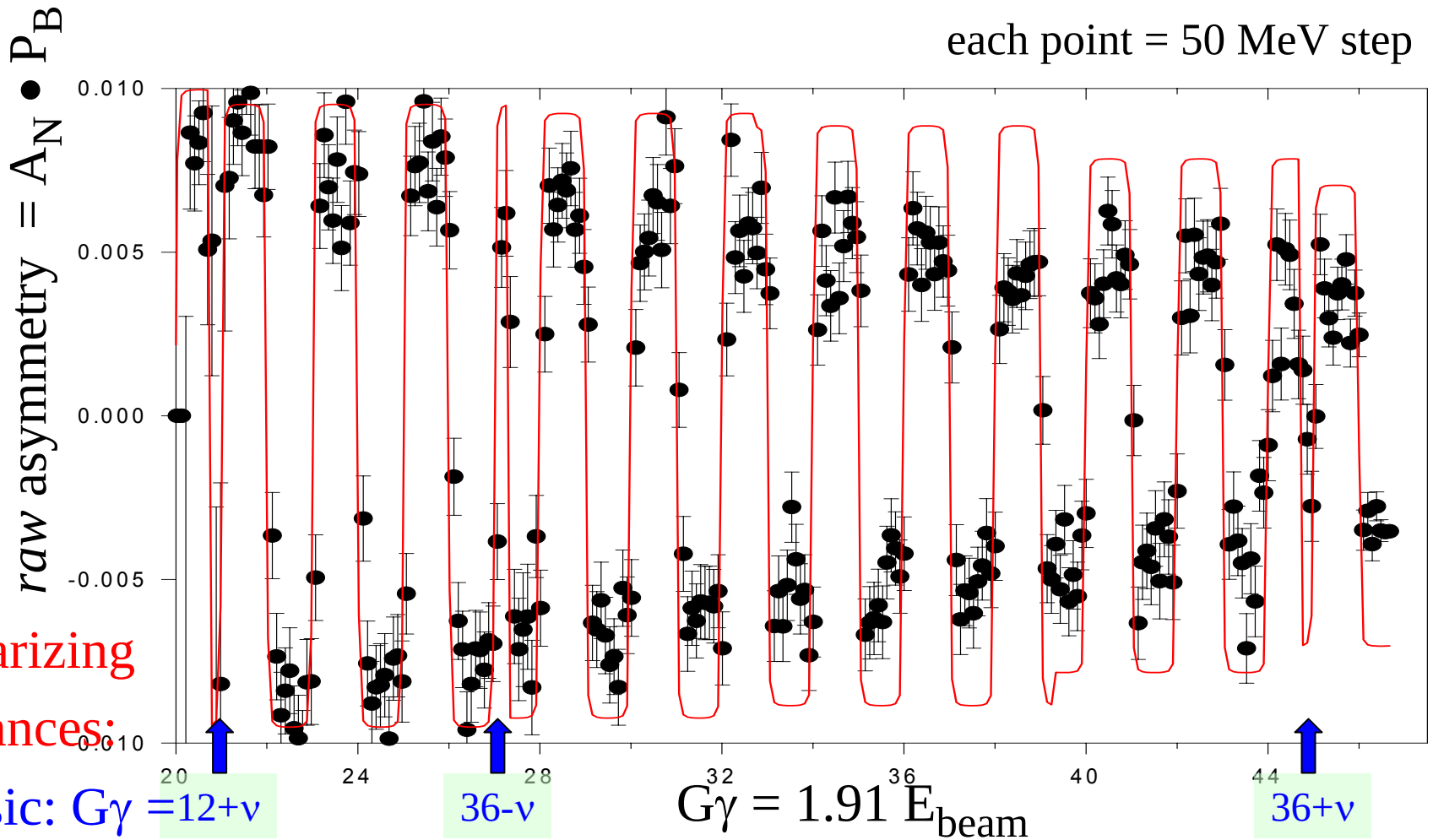


AGS Polarization vs Energy (2003)

- Full spin flip at all imperfection resonances using partial Siberian solenoidal snake
- Full spin flip at strong intrinsic resonances using rf AC dipole
- Remaining polarization loss from coupling and weak intrinsic resonances
- Almost 2 × improvement (on avarage) compared to 2002 run
- Consistently measured polarization of 45%; also reached 50% on occasions
- Small emittance beam of 10 π with scraping: intensity ~ 6 x 10^{10} p / bunch
- Add a warm helical snake (run '04)
- To avoid all depolarization build a strong superconductinb helical Siberian snake snake (2005-2006)



AGS Polarization during acceleration



depolarizing resonances:

intrinsic: $G\gamma = 12+\nu$, $36-\nu$, $36+\nu$

imperfection: $G\gamma = n$

RHIC Polarization from Run '03

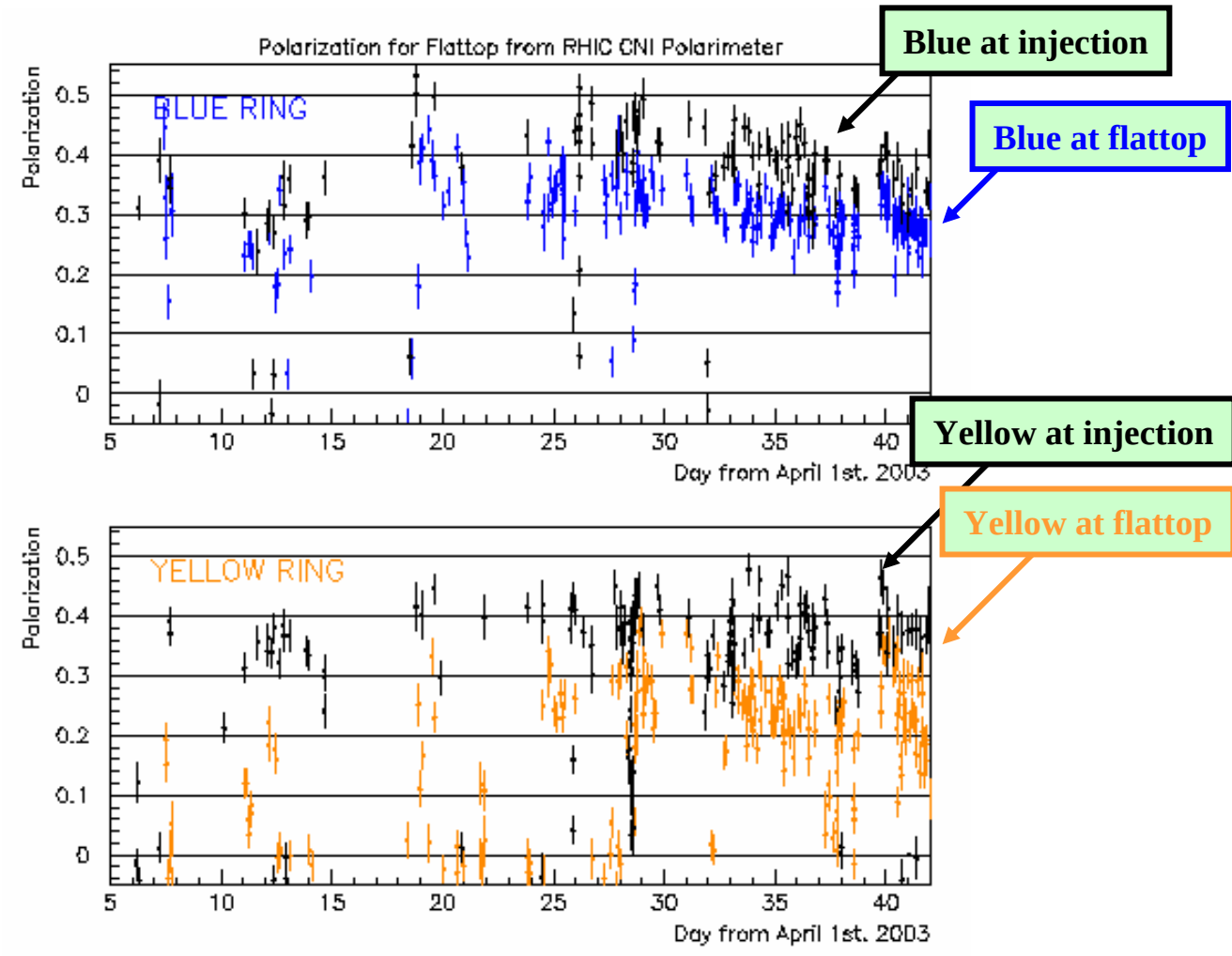
$$P_{beam} = \frac{1}{A_N} \cdot \varepsilon_N$$

not well known
(for now)

polarization on average

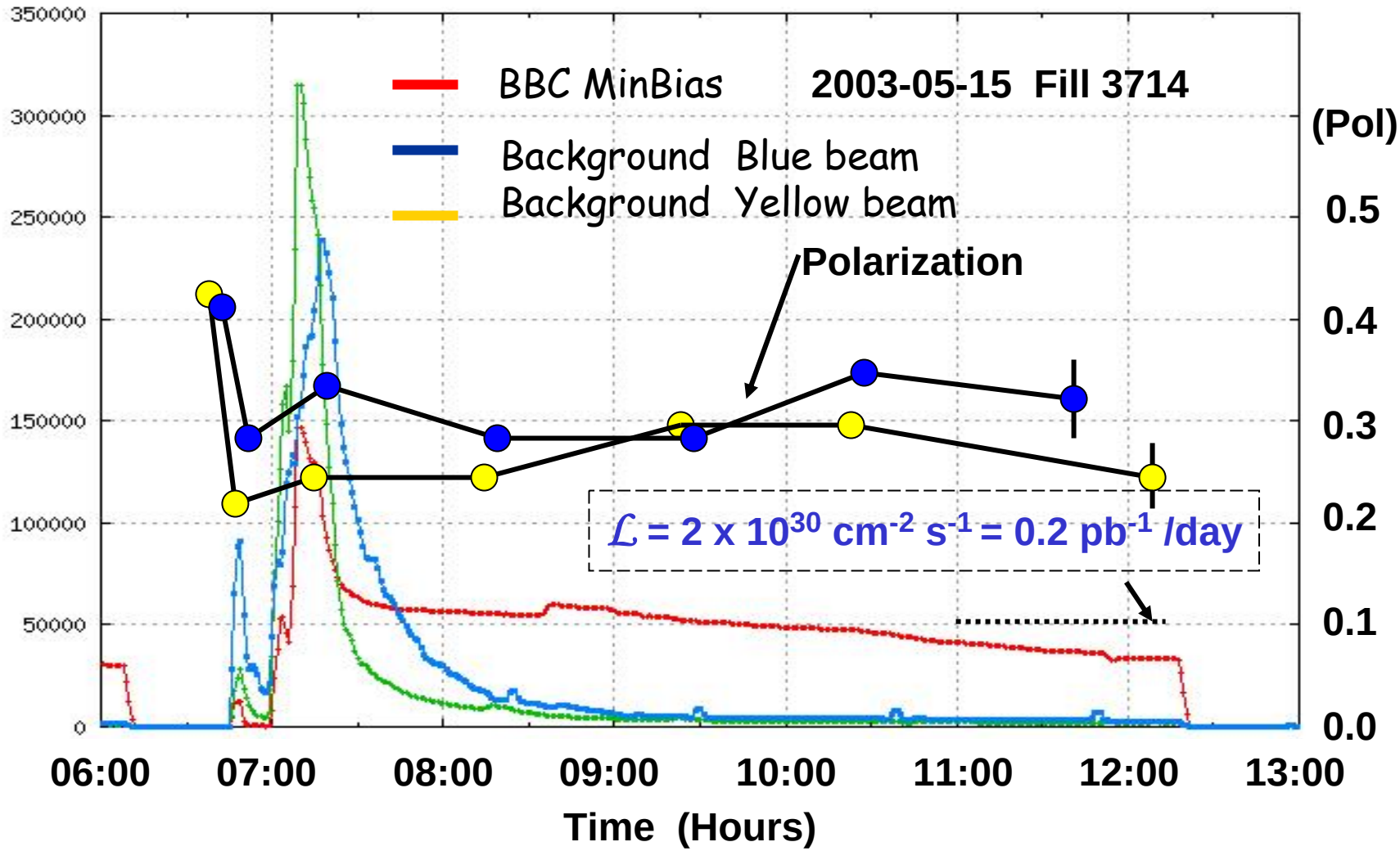
- at injection
  - **Blue ~40%**
  - **Yellow ~40%**
- at flattop
  - **Blue ~ 25-35%**
  - **Yellow ~ 20-30%**

being analyzed right now



A Polarized Proton Store in RHIC

from STAR Luminosity Monitors



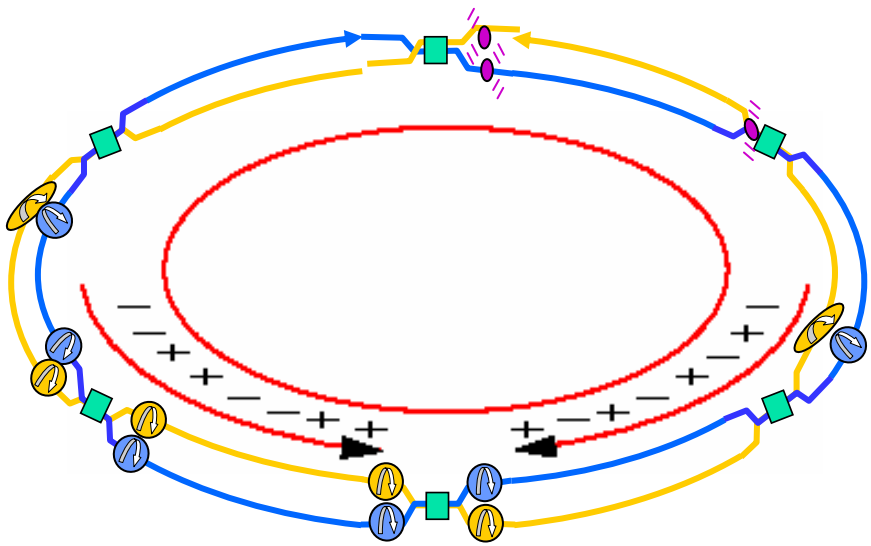
Systematics in RHIC

different spin combination every bunch crossing

55 bunches (planned 110)

Blue: + + – – + +
Yellow: + – + – + –

Spin flip and recogging



OPPIS High Intensity H^- Source

KEK OPPIS
upgraded at Triumph

70 – 80 %
polarization

15×10^{11}
protons / pulse
at the source
(500 μA, 300 μs)

6×10^{11}
protons/pulse
at end of LINAC

The RHIC Magnets

Blue and Yellow Rings

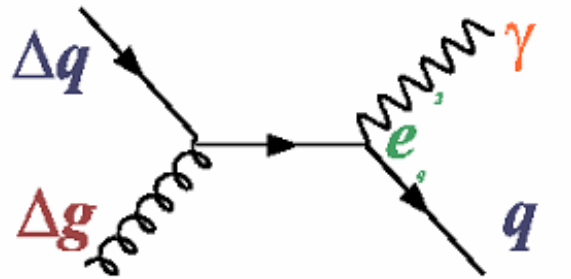
Siberian Snake

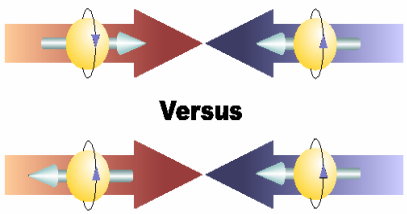
4 super conducting helical dipoles:
4 Tesla, 2.4 m long

Prompt Photon Production

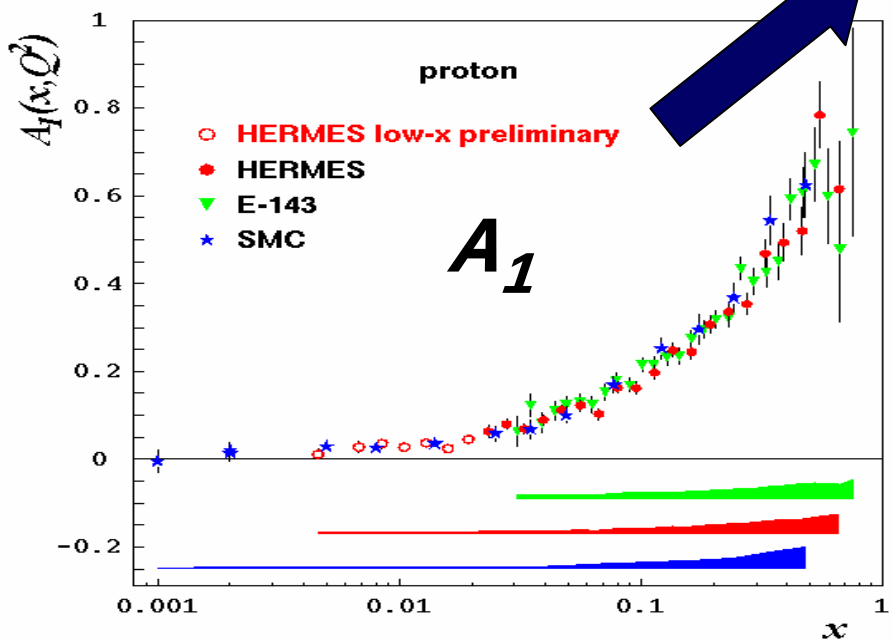
Gluon Compton dominates

- Small Background from Annihilation
- No fragmentation contribution at LO

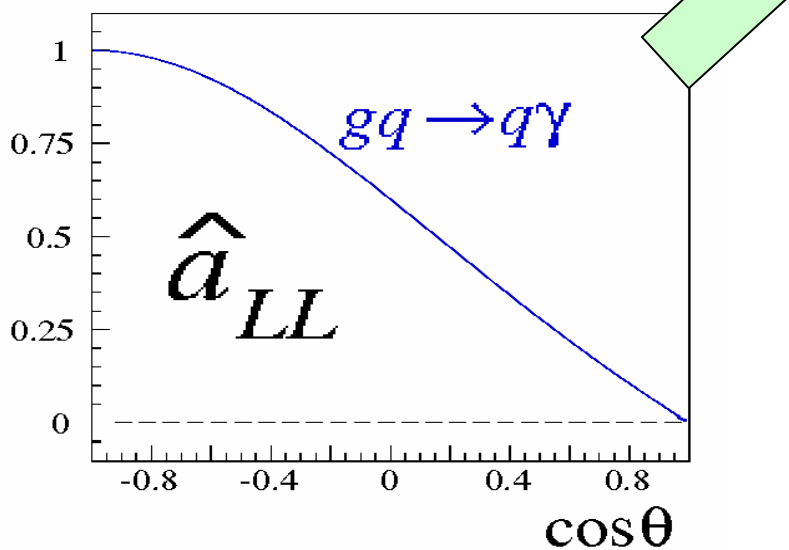




$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum_i e_i^2 \Delta q_i(x_2)}{\sum_i e_i^2 q_i(x_2)} \otimes a_{LL}(gq \to q\gamma)$$



large quark polarization for x > 0.2

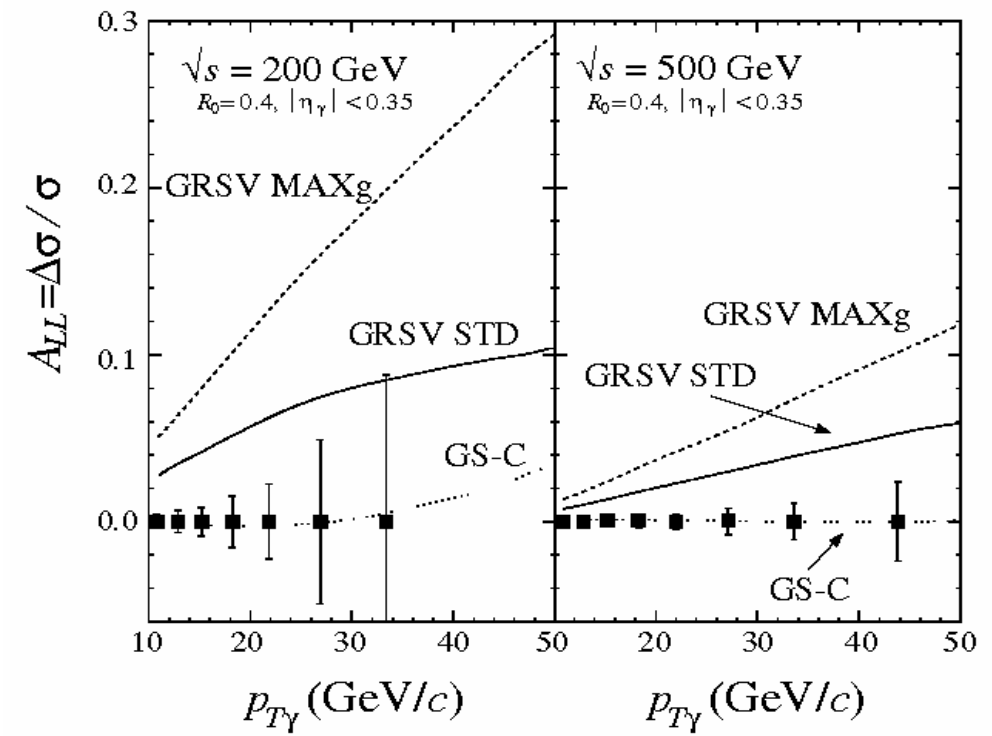


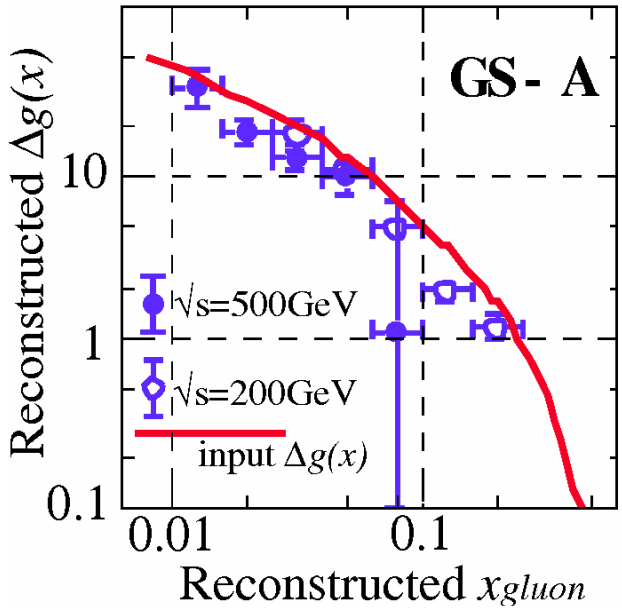
large analyzing power

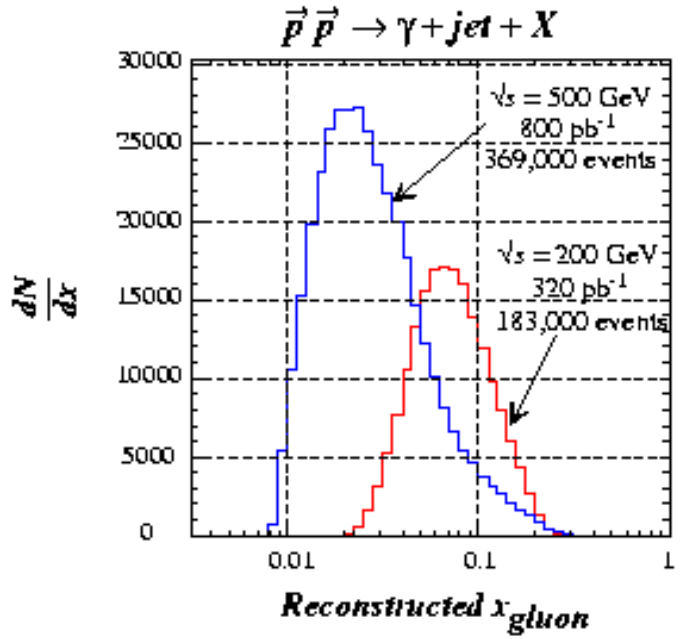
Prompt Photon Production 2

Golden Channel @ RHIC

Comparison at cross section level
= direct observable





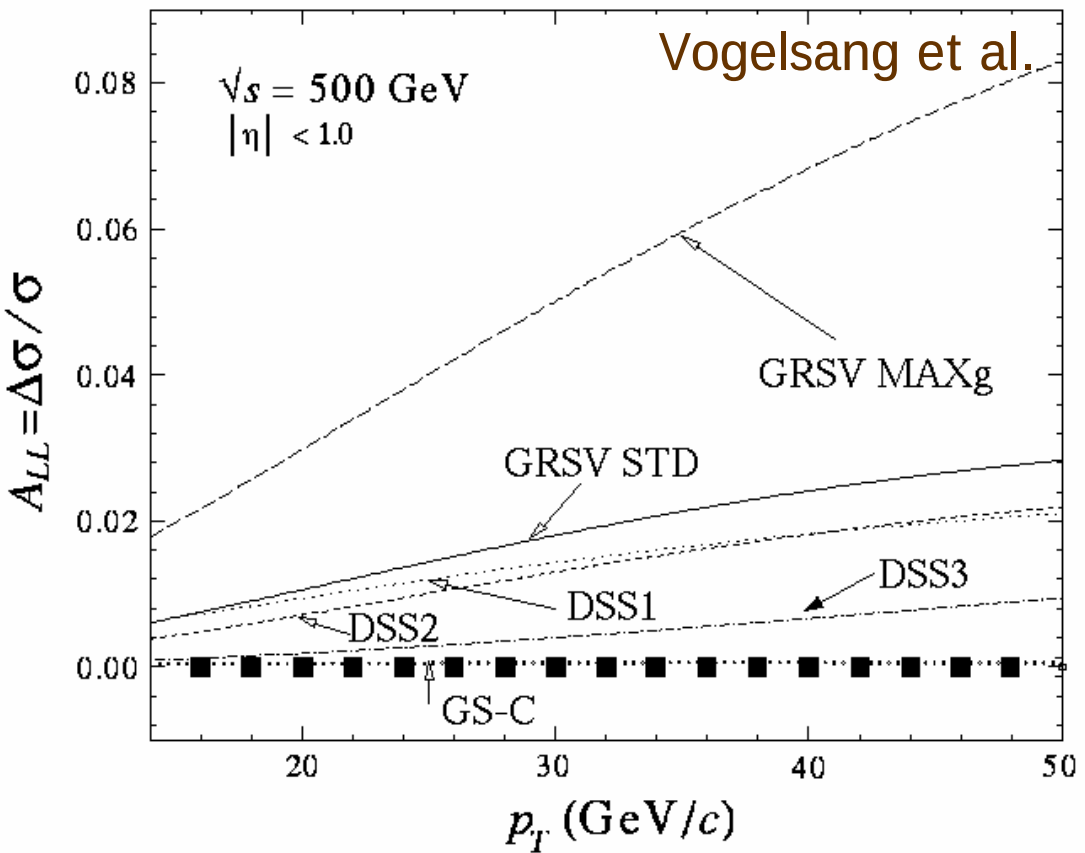


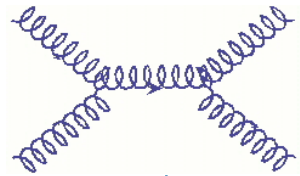
x_{gluon} reconstructed using away side jet

inclusive: integrate over x_{gluon}

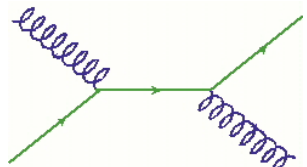
Jet Production

- Mixture of gg / gq / qq scatterings
  - sensitive to gluon polarization
  - very high statistics

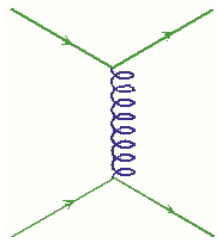




$gg \to gg$ $\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$



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



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

same diagrams for
inclusive hadron production

ΔG Expectations from '03 Run

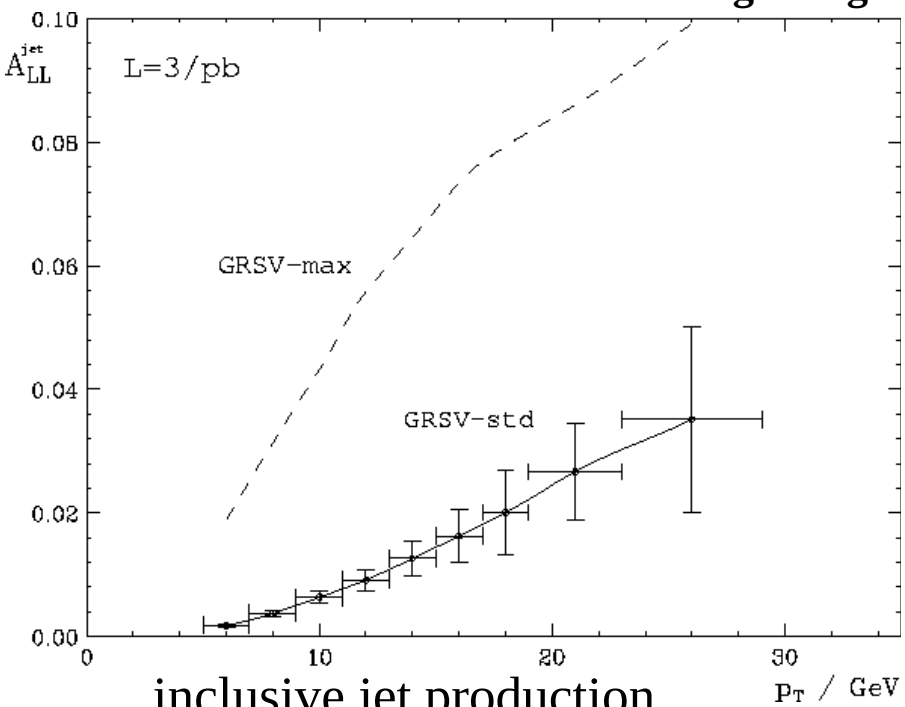
First attempt at Gluon Polarization measurement:

STAR – inclusive jet PHOENIX – inclusive hadron

Projections for L = 3 pb^{-1} and P_B = 50%

STAR

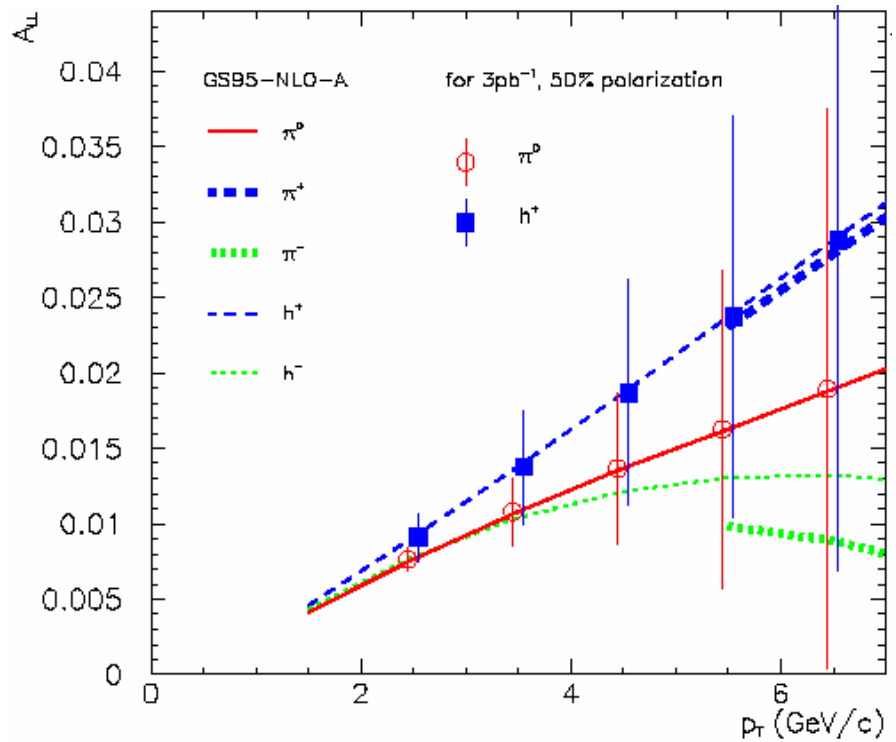
W. Vogelsang



inclusive jet production

PHENIX

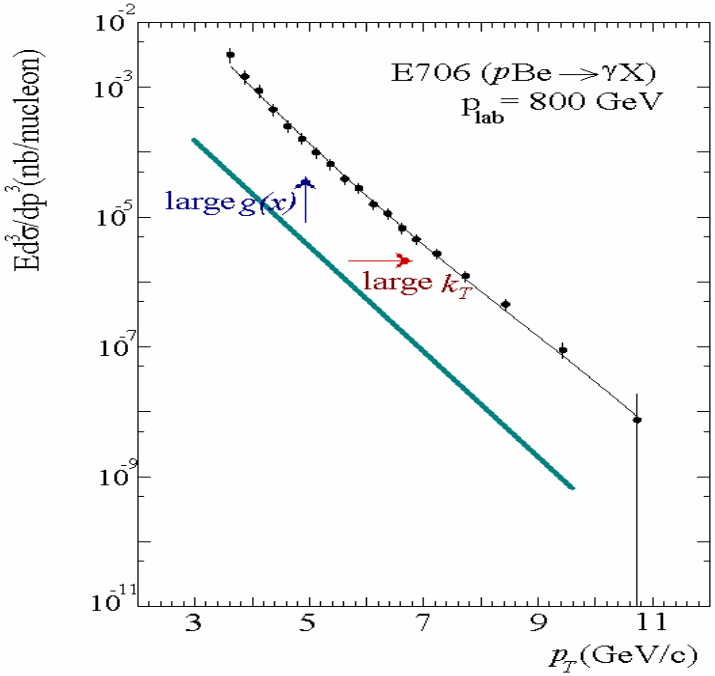
Y. Goto

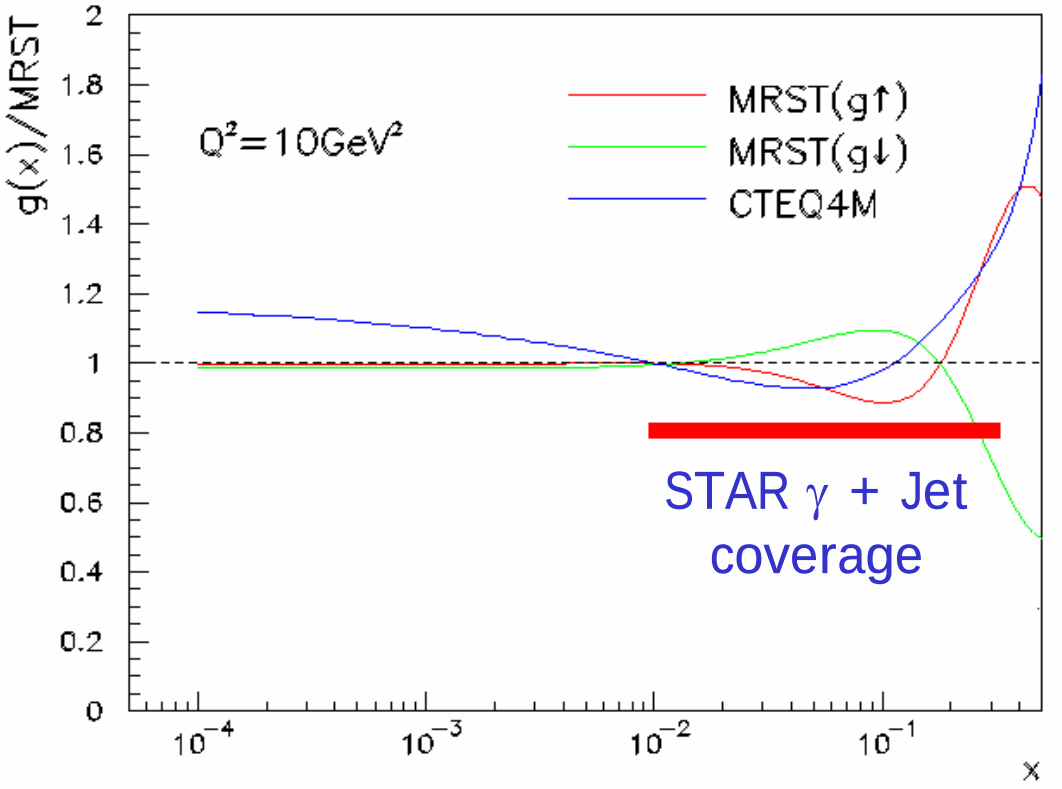


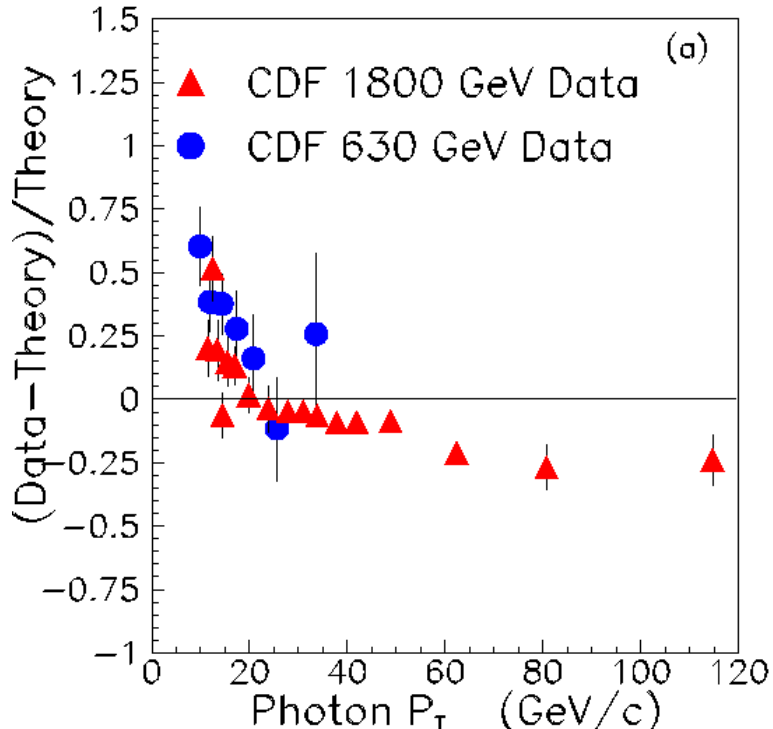
inclusive hadron production

Unpolarized $g(x)$

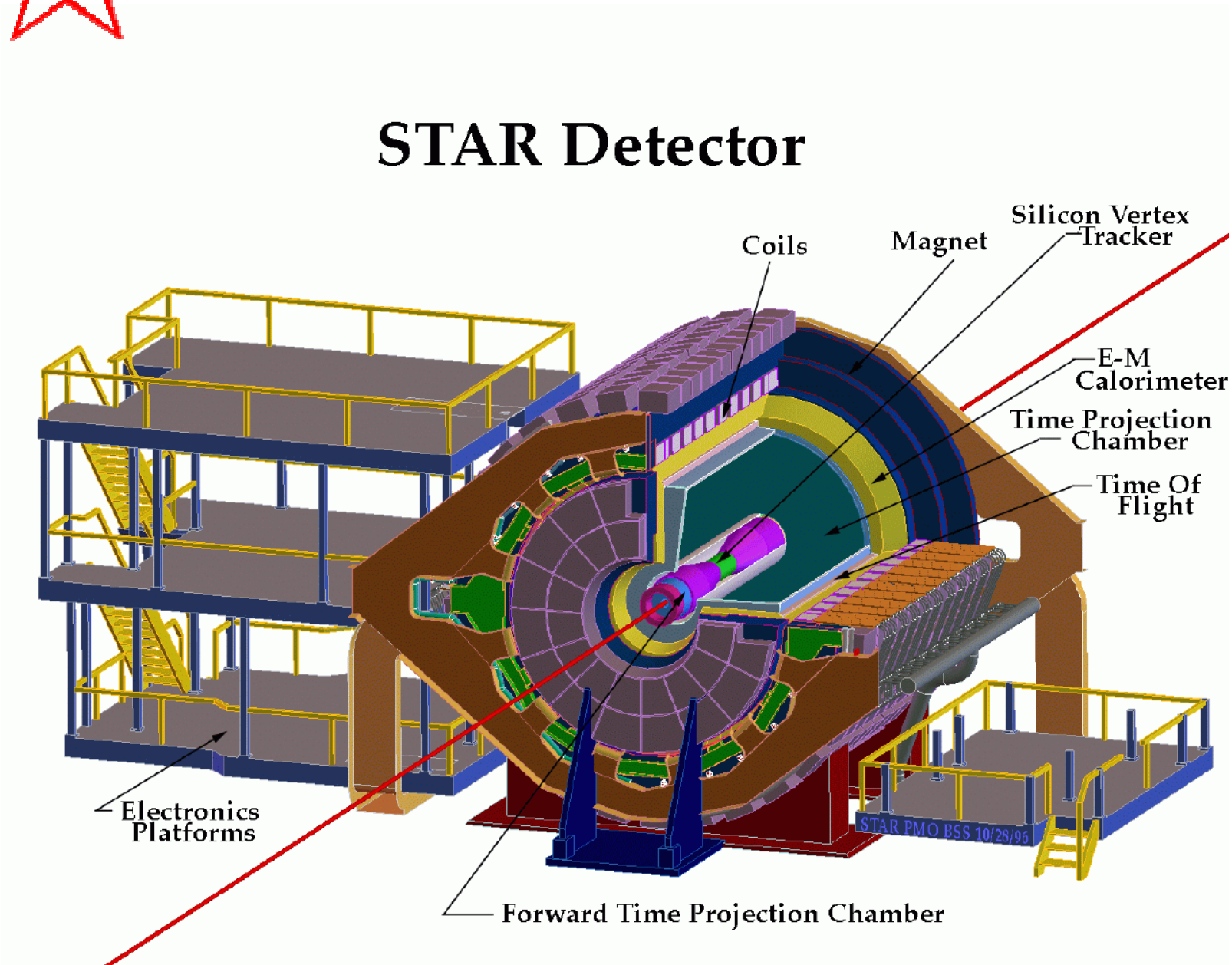
- Large uncertainties due to intrinsic k_T
- RHIC pp can fix it !



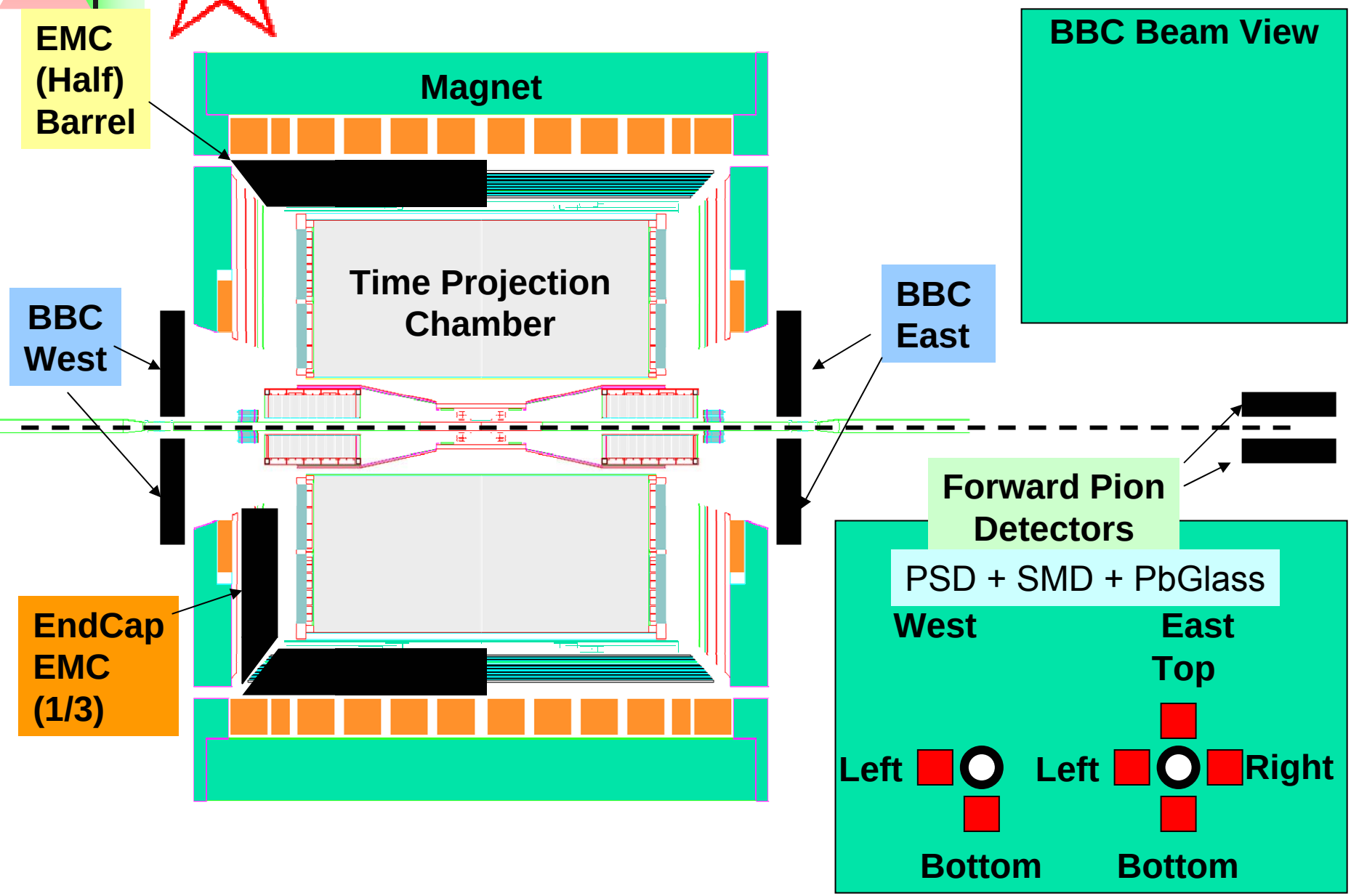




STAR Detector

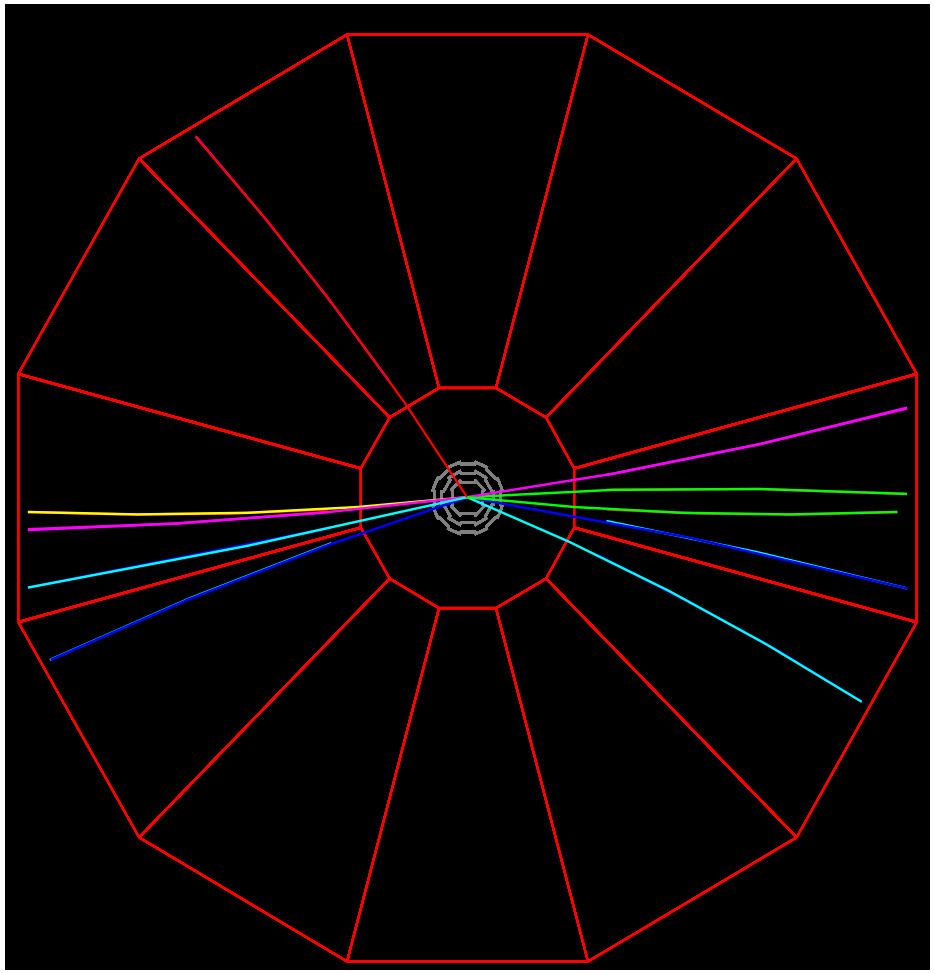


Detector: New Elements

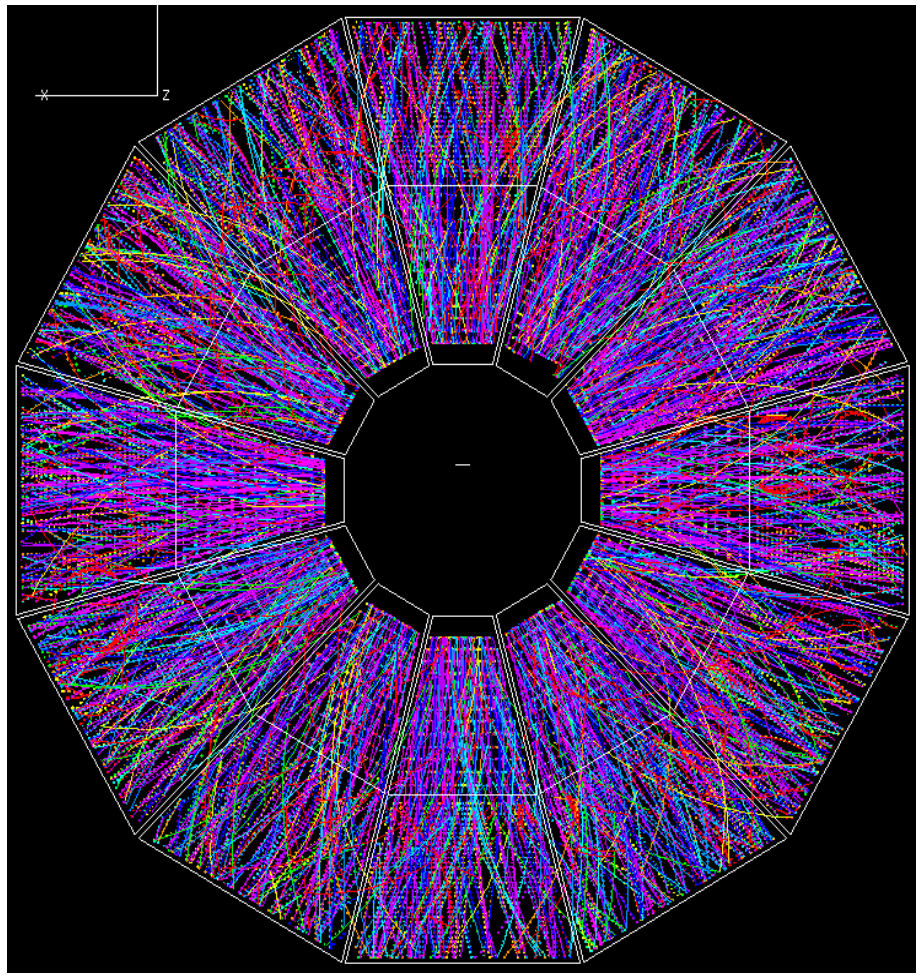


TPC Event

STAR p+p, $\sqrt{s}$ = 200 GeV



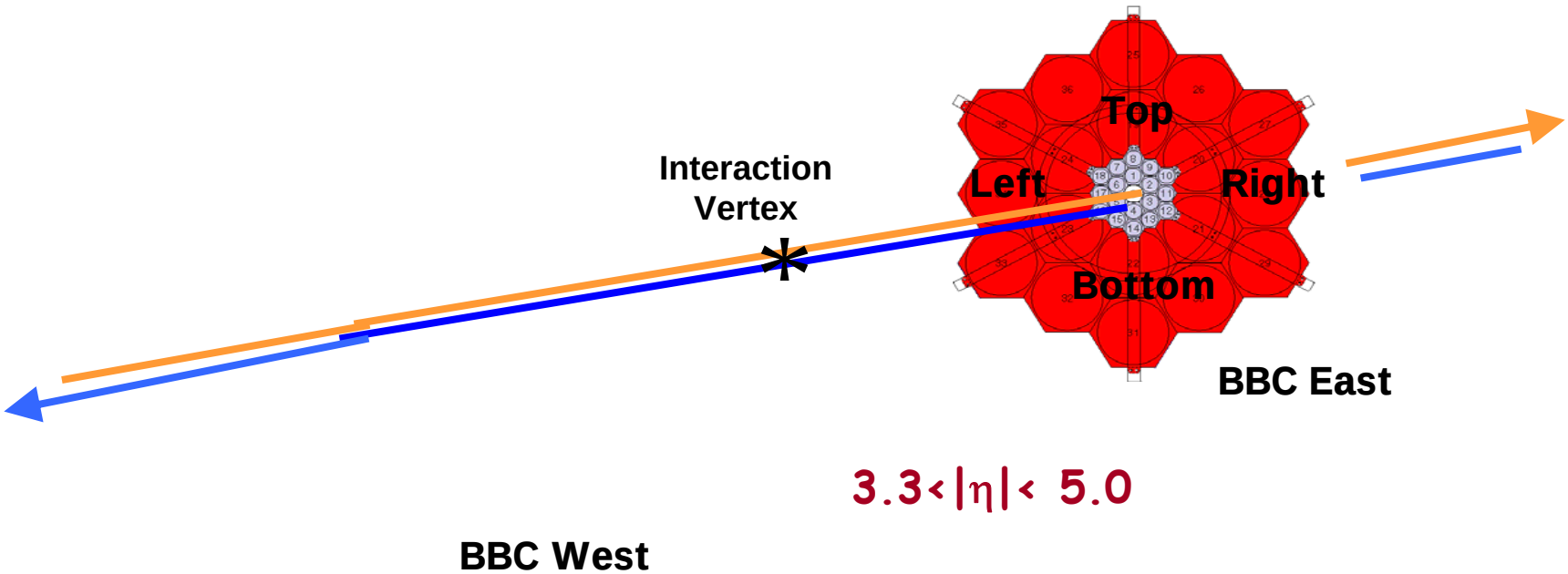
STAR Au+Au, $\sqrt{s_{NN}}$ = 200 GeV



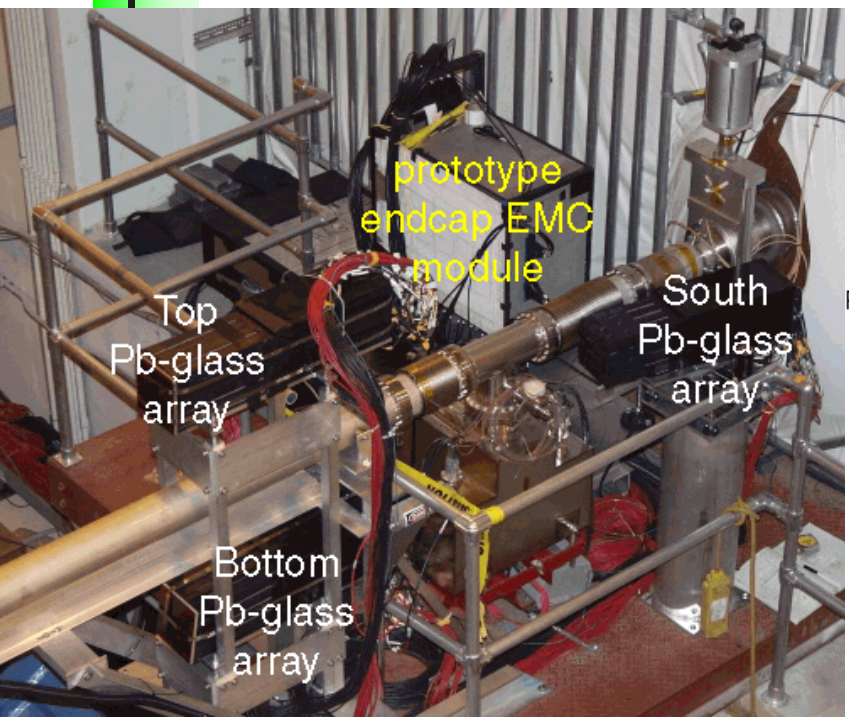
STAR Beam-Beam Counters

Fast, highly-segmented scintillation counters (small tiles only) serve many purposes in STAR:

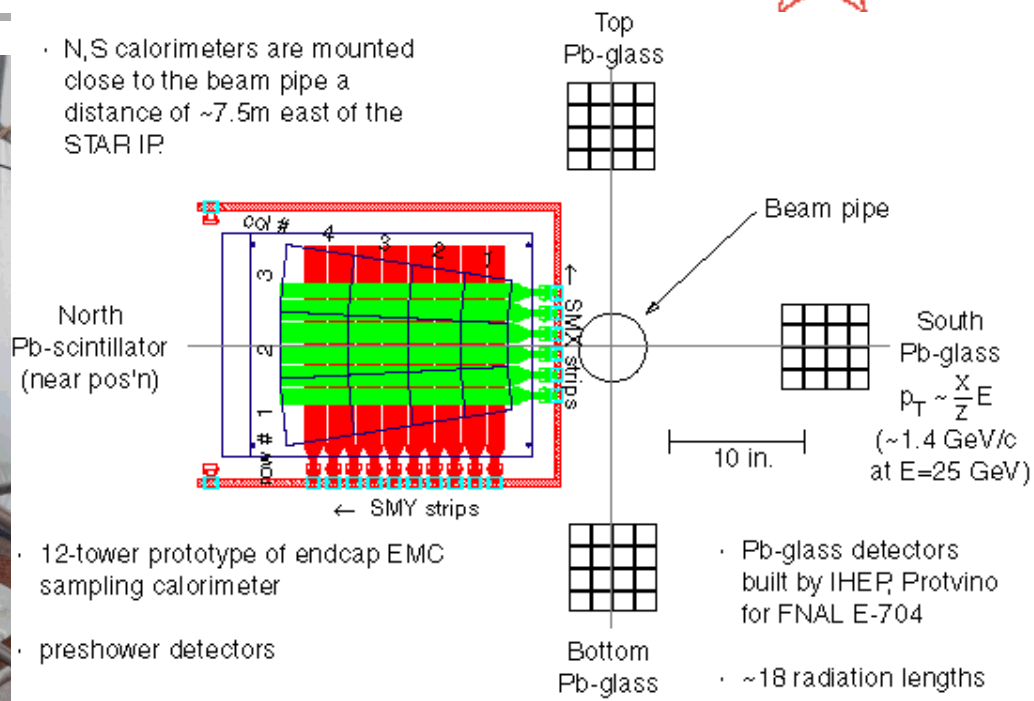
- **Minimum Bias Trigger:** **Sensitive to ~50% of total cross section**
- **Absolute Luminosity:** **Van der Meer scan**
- **Relative Luminosity:** **Fast scalers, updated every beam crossing**
- **Measurement of Transverse Asymmetries** **e.g., for BBC East, sort data by Yellow beam polarization, sum Blue beam polarizations**



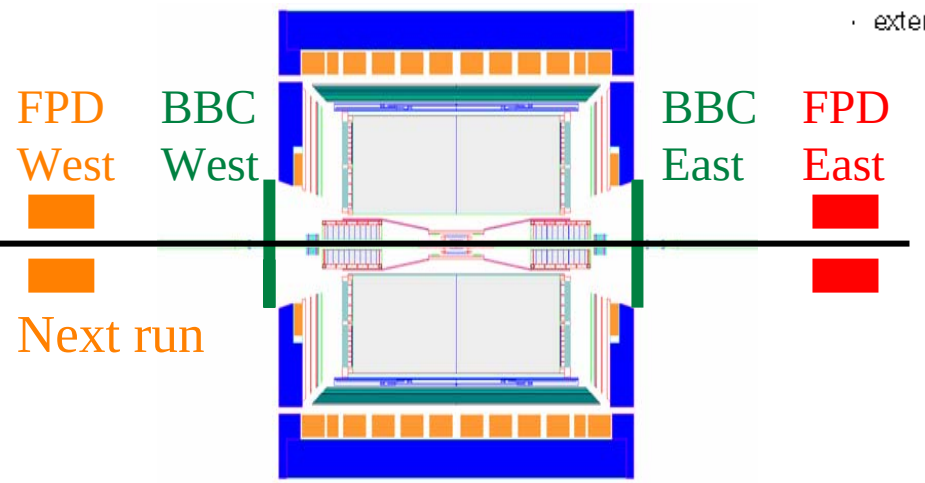
Forward π^0 Detector (FPD) at STAR spin



- N,S calorimeters are mounted close to the beam pipe a distance of ~7.5m east of the STAR IP.



- 12-tower prototype of endcap EMC sampling calorimeter
- preshower detectors
- shower-maximum detector to measure transverse profile
- extensively tested at SLAC
- Pb-glass detectors built by IHEP, Protvino for FNAL E-704
- ~18 radiation lengths
- Cerenkov detector



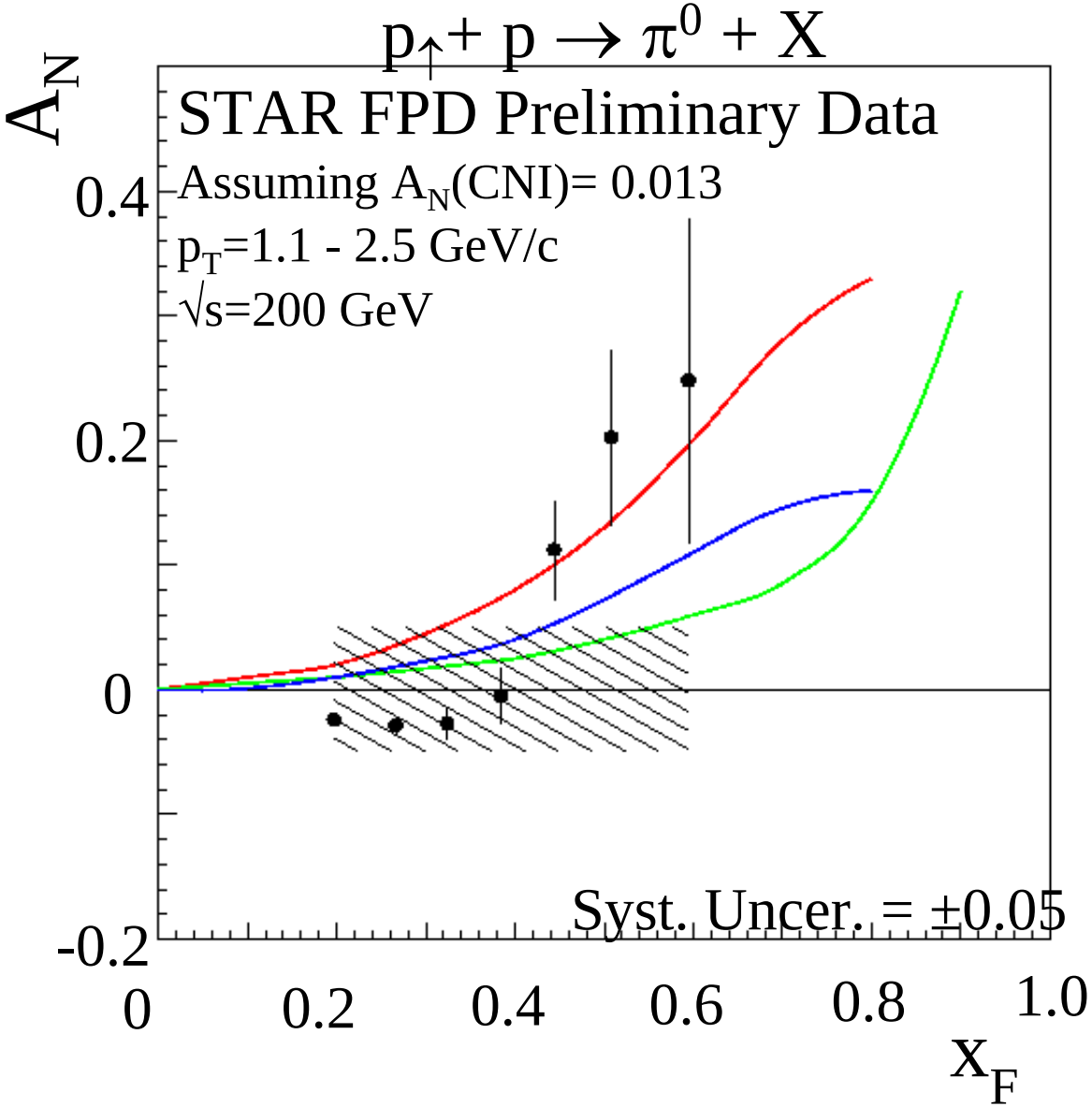
Tunnel Ext. Platform Floor

$x_F \sim E_\pi/100 = 0.2\text{-}0.6$

$p_T \sim E_\pi/\cosh(\eta) = 1\text{-}4$ GeV/c

$\eta = 3.0\text{-}4.0$ $\sqrt{s} = 200$ GeV

Analyzing Power:

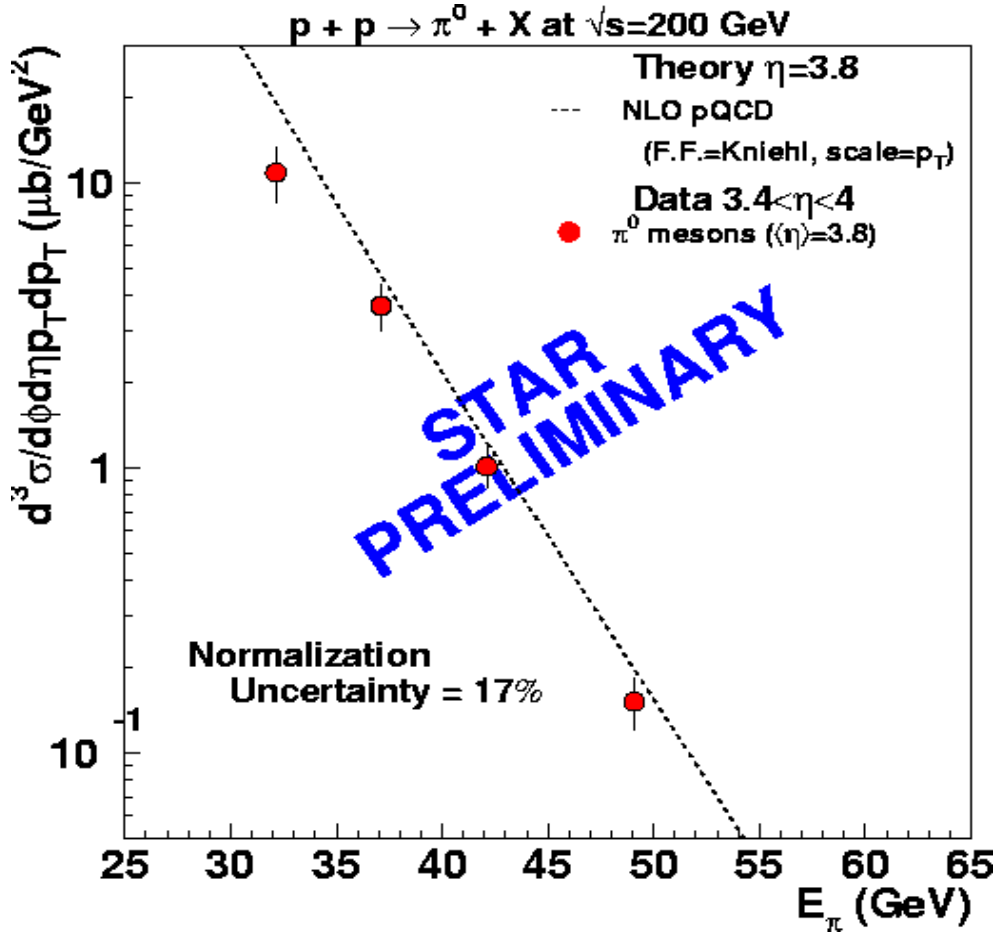


Theory predictions at p_T=1.5 GeV/c:

- Collins effect
  Anselmino, et al., private communication
- Sivers effect
  Anselmino, et al., private communication
- Twist 3 effect
  Qiu and Sterman, private communication

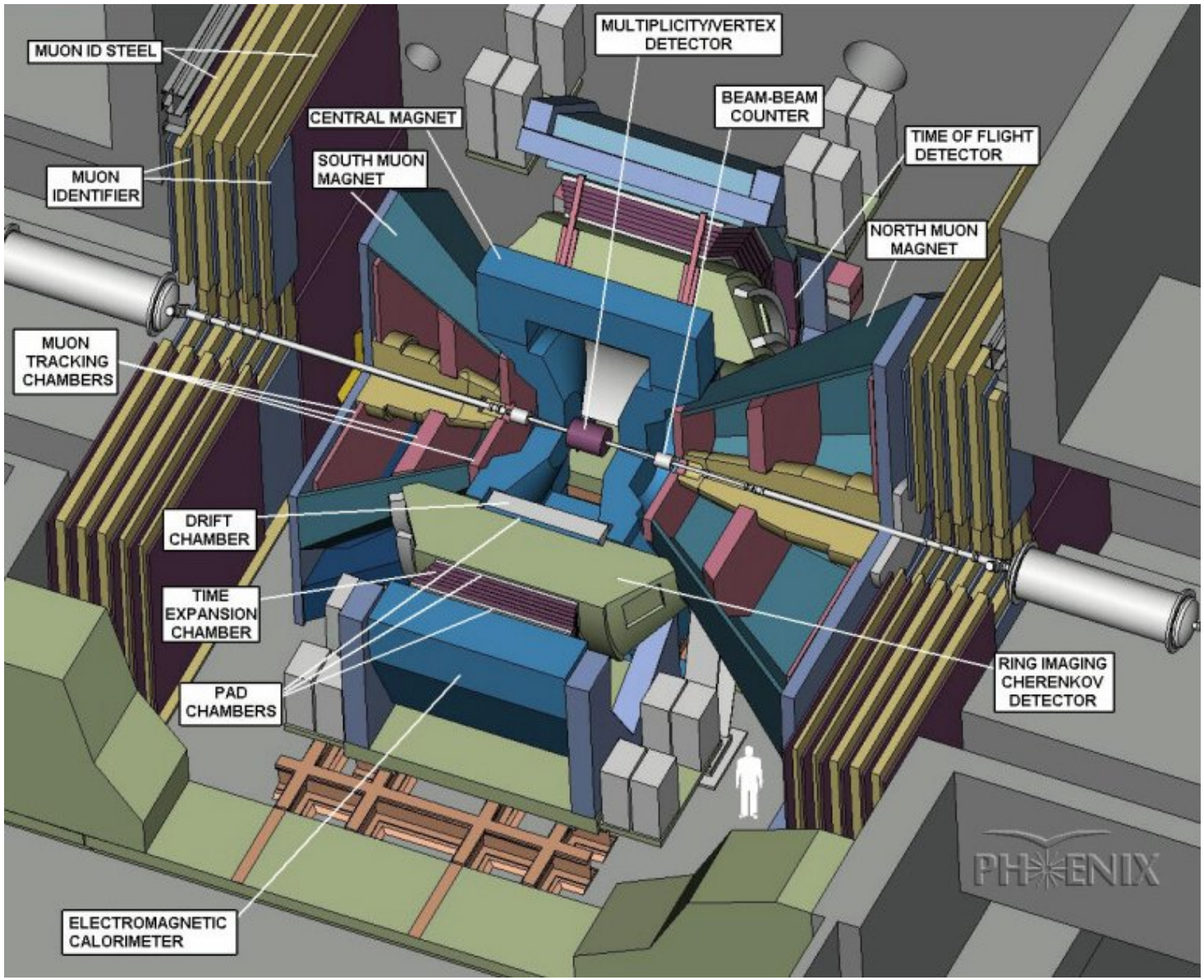
STAR spin

Differential Cross Section

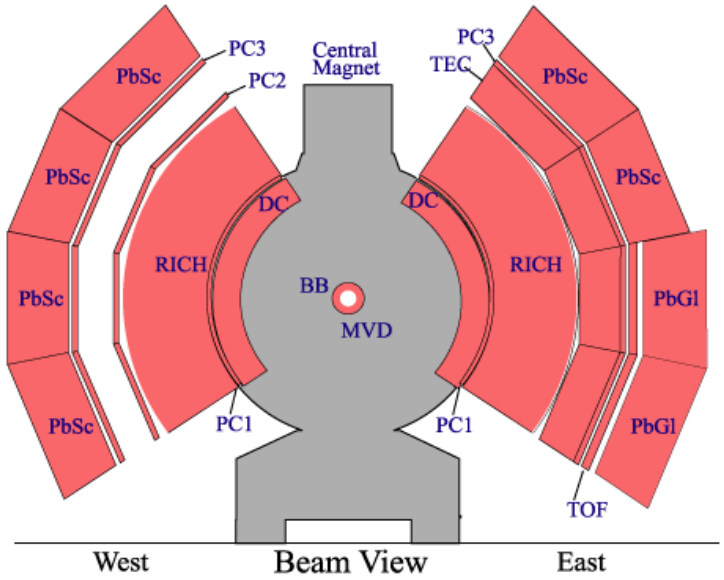


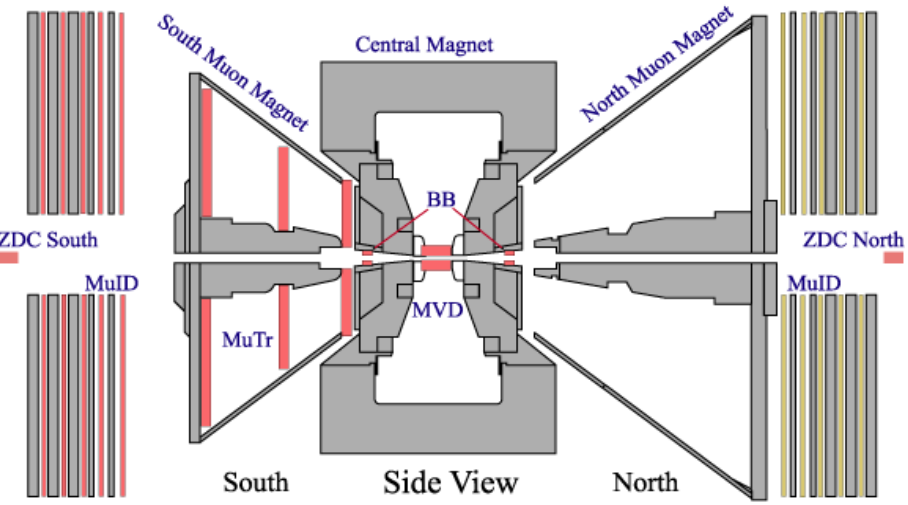
The data are in fair agreement with NLO pQCD calculation...

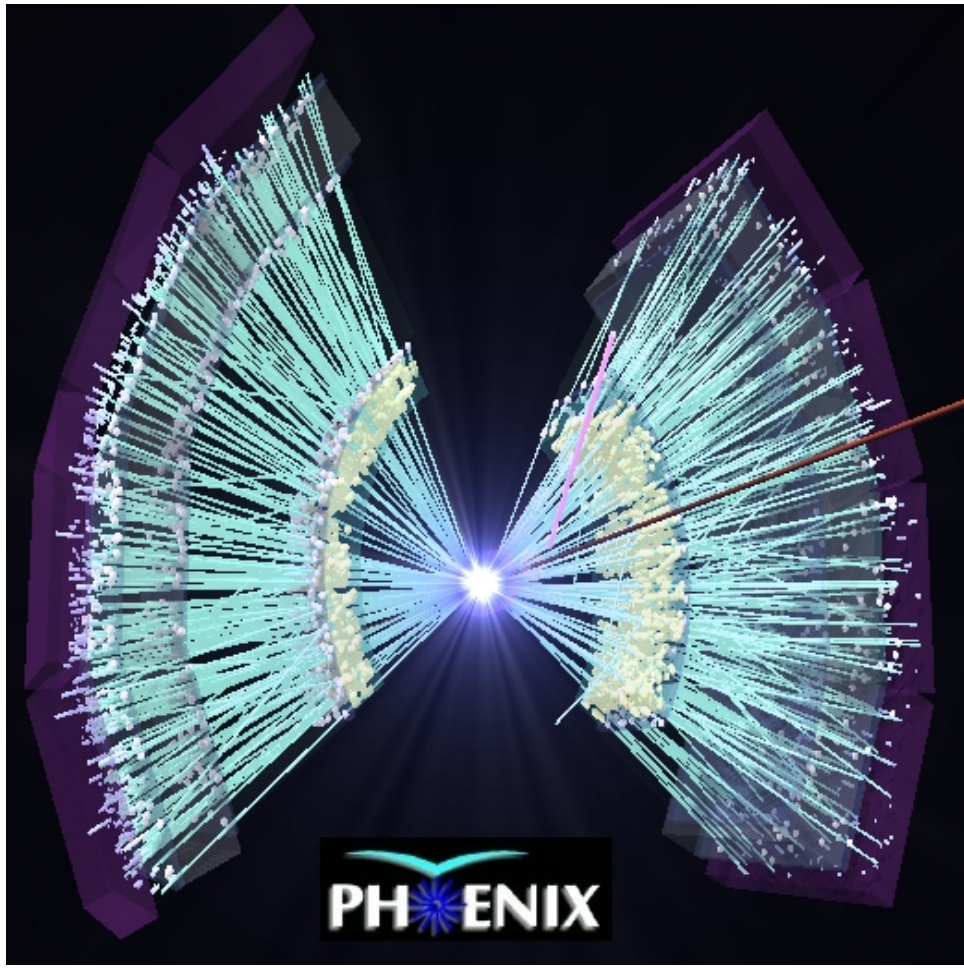
PHENIX Detector System



PHENIX event

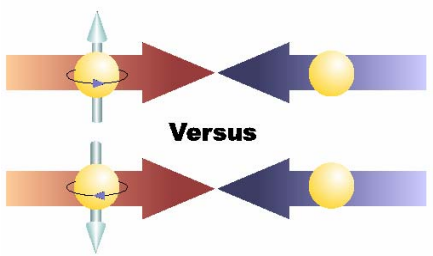




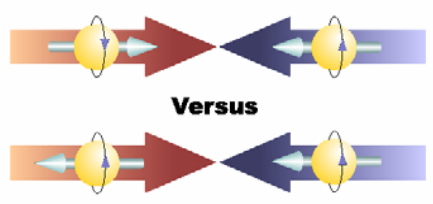


Polarimetry : Impact on Spin Physics

Single Spin Asymmetries



Double Spin Asymmetries



Physics Asymmetries

$$A_N = \frac{1}{P_B}\left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right)$$

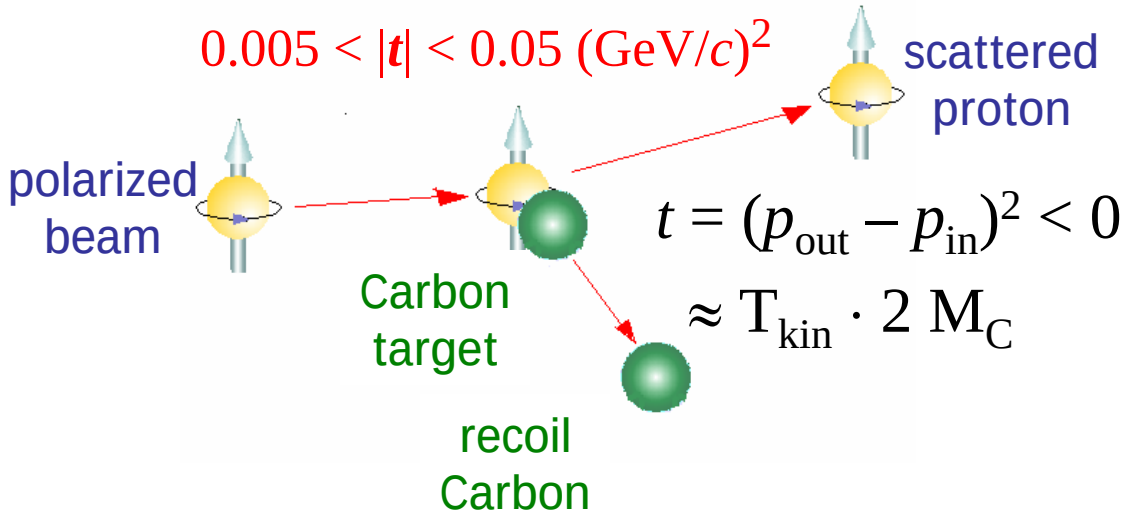
$$A_{LL} = \frac{1}{P_B^2}\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}\right)$$

- In any Spin asymmetry measurement, the raw asymmetries have to be normalized by the beam(s) polarization to obtain the Physics Spin Observables (A_N, A_{LL}, etc.)
- Elastic *p*C Scattering in CNI (Coulomb Nuclear Interference) region adopted as polarimeter for its fast and reliable measurement performance
- Need of absoulte calibration via Elastic *pp* Scattering in CNI region using a polarized gas jet target (planned for run `04)

Elastic pC $\rightarrow$ pC scattering at low t

$$A_N = -\frac{1}{P_B} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

recoil



1. A_N from interference of spin non-flip and spin flip amplitudes
   $\Rightarrow$ spin dependence of interaction
   $\Rightarrow$ hadronic spin flip (spin-coupling of Pomeron)

2. RHIC Polarimetry
   – almost “calculable”
   – sizeable $A_N \sim 1$ % (requires large statistics > 10^7)
   – large cross section
   – weak beam momentum dependence (p > 20 GeV/c)

A_N: from where does it come?

$$\sigma = |A_{hadronic} + A_{Coulomb}|^2 \qquad (|\mathbb{P} + \gamma|^2)$$

around $t \sim -10^{-3}$ (GeV/c)^2 $A_{hadronic} \approx A_{Coulomb} \Rightarrow$ INTERFERENCE

CNI = Coulomb – Nuclear Interference

unpolarized $\Rightarrow$ clearly visible in the cross section $d\sigma/dt$ (charge)

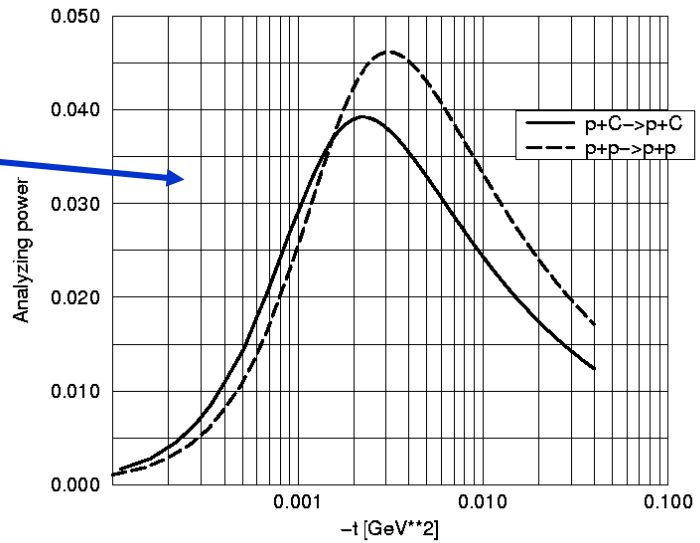
polarized $\Rightarrow$ left – right asymmetry A_N (magnetic moment)

$$A_N = C_1 \Phi^{*\,flip}_{em} \Phi^{non-flip}_{had} + C_2 \Phi^{non-flip}_{em} \Phi^{flip}_{had}$$

$\propto (\mu - 1)_p$ $\qquad$ $\propto \sqrt{\sigma^{pp}_{had}}$

QED $\Rightarrow$ "calculable", expect $A_N \neq 0$ up to 4.5%

$$A_N = \sqrt{\frac{8\pi Z\alpha}{m_p^2 \sigma_{tot}^{pA}}} \frac{y^{3/2}}{1+y^2}(\mu - 1); \qquad y = \frac{\sigma_{tot}^{pA}\, t}{8\pi Z\alpha}$$



QCD $\Rightarrow$ "unpredictable", need direct measurement

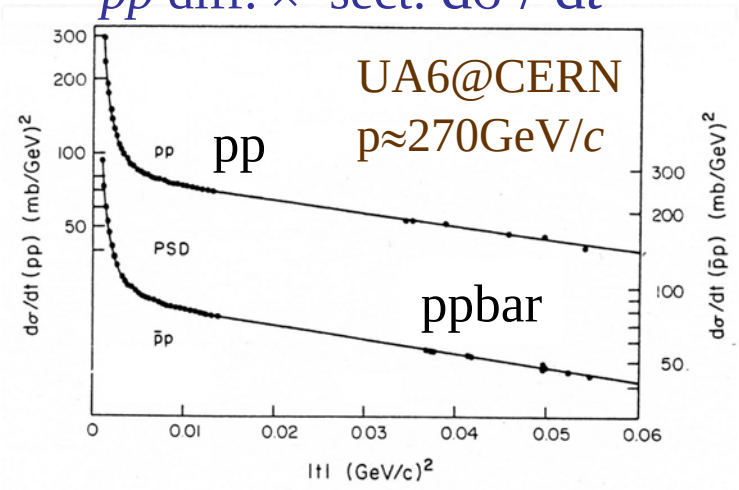
$$g_5(s,t) = \tau(s) \cdot \sqrt{|t|}/m_p \cdot g_0(s,t) \qquad g_0(P, f, \omega)$$

$$r_5^{pC}(s,t) = \tau(s)\left(i + \rho_{pC}(s,t)\right) = m_p / \sqrt{|t|} \cdot F_s^{had} / \Im F_0^{had}$$

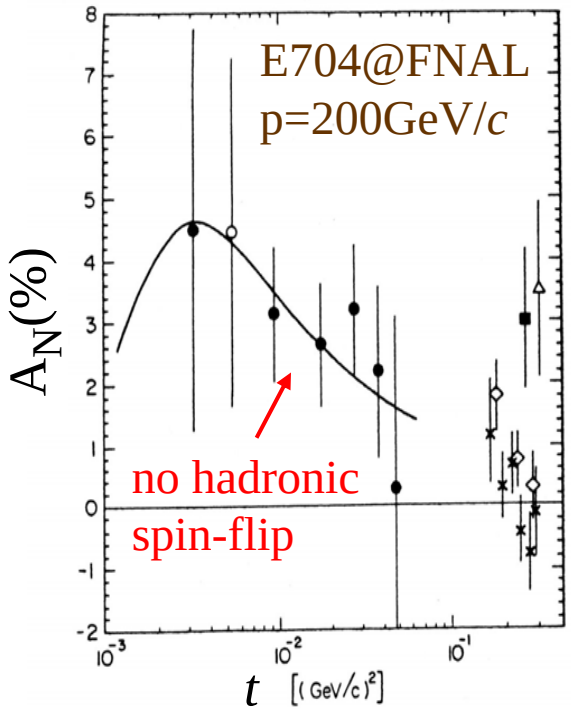
B. Kopeliovich & L.Trueman

Elastic *pp* & *p*C: dσ / d*t* & A_N

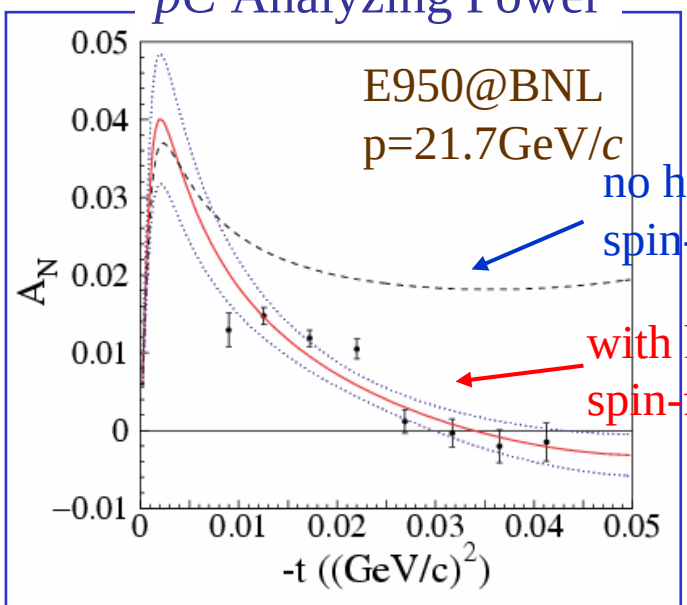
pp diff. ×–sect: dσ / d*t*



pp Analyzing Power A_N

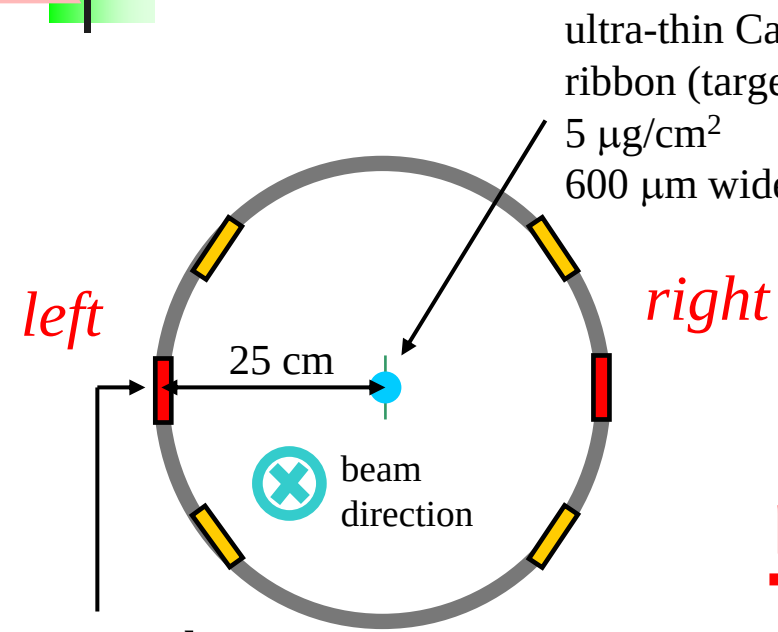


pC Analyzing Power

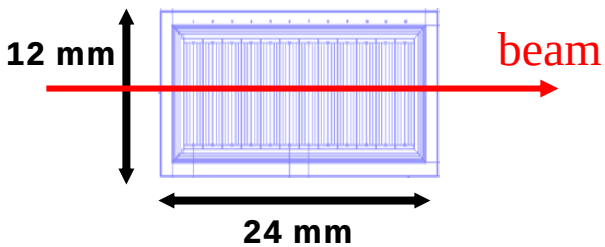


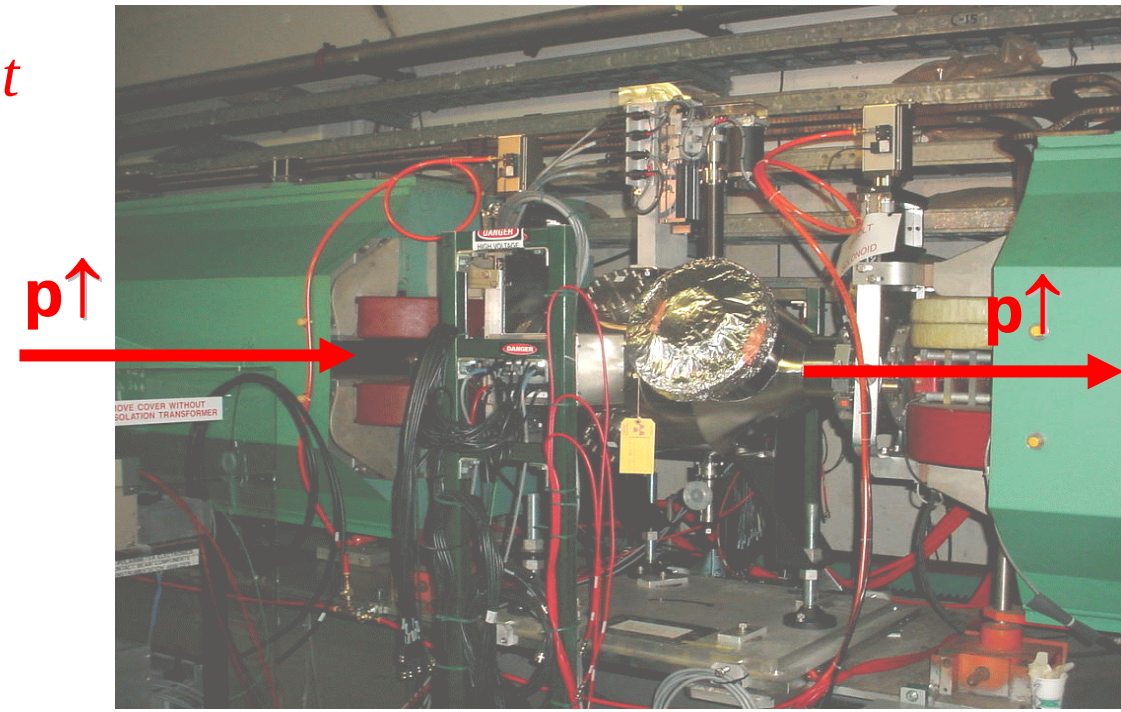
$$r_5^{pC} = 0.088 \pm 0.058 - i\,0.161 \pm 0.226 \propto F_s^{had} / Im\, F_0^{had}$$

Polarimeter Setup in the AGS Ring



Si strip detectors
12 vertical strips





read-out with
waveform digitizers
= CFD and ADC

similar setups in RHIC for each beam

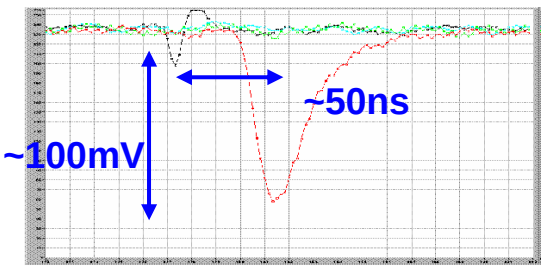
Event Selection

- recoil carbons detected with Si detectors
- "identified" via ToF vs Enery correlation

  position vs energy correlation spoiled by multiple scattering in target

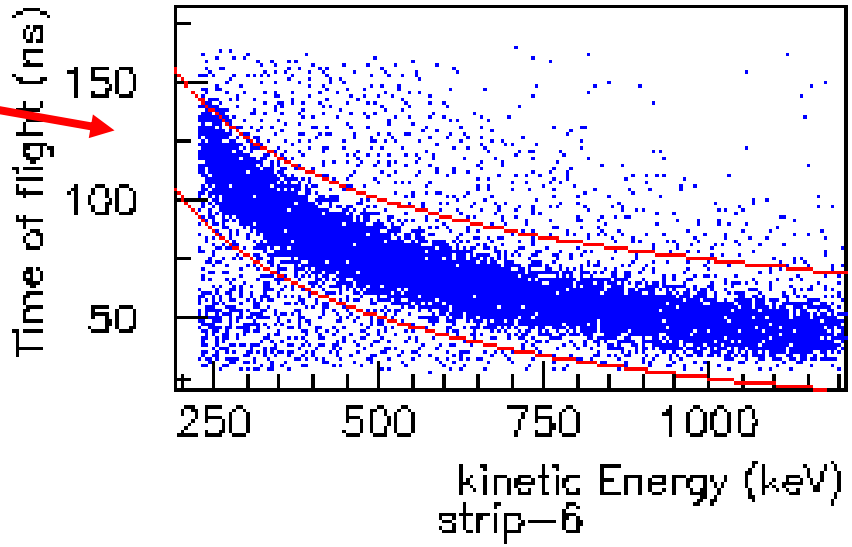
- very high event rate

  events acquired with deadtime free wave-form digitizers



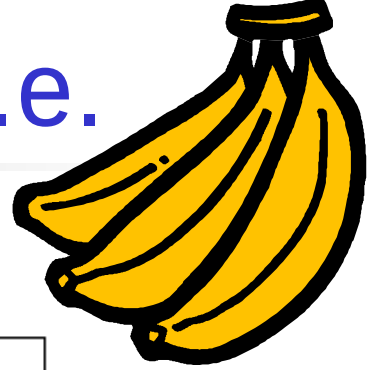
$T_{kin} = \frac{1}{2} M_C (dist / ToF)^2$

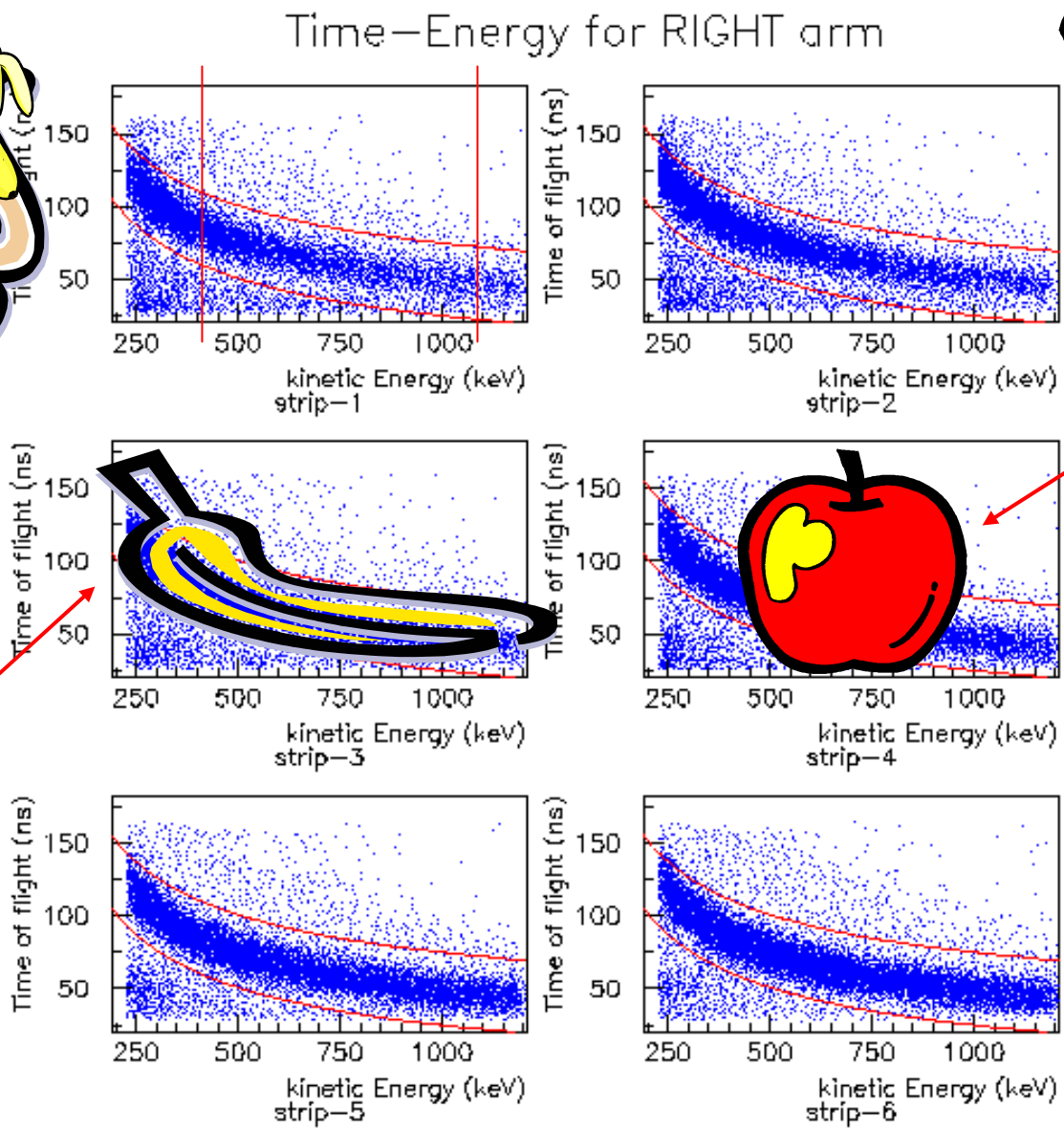
non-realativistic kinematics



- carbon "events" found / selected in ToF vs. T_{kin} correlation band
- background events below 1% within the "banana" cut

Time of Flight vs. Energy i.e.



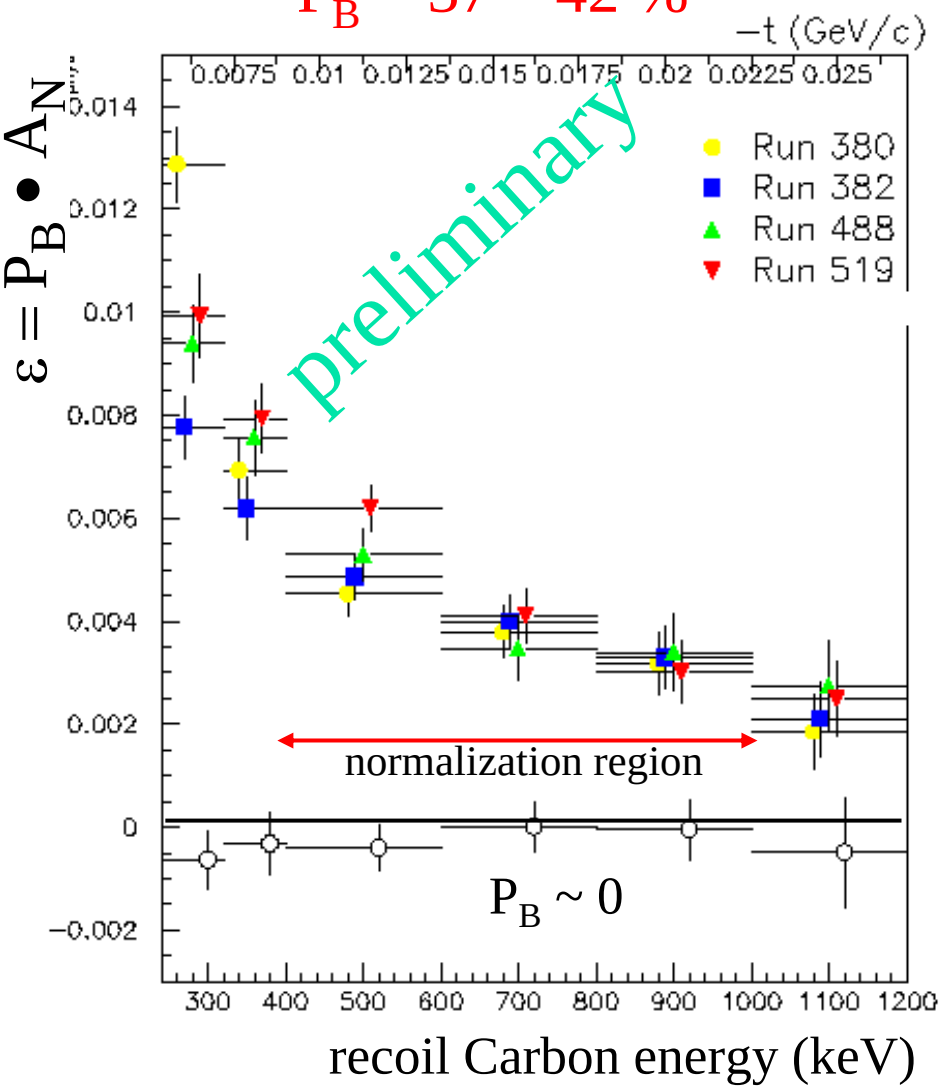


does not pass the cuts

event selection

$p\uparrow$C *raw* asymmetry at 24.7 GeV/*c*

$P_B \sim 37 - 42\ \%$



$$P_{beam} = \frac{1}{\langle A_N \rangle} \cdot \varepsilon_N$$

$$\langle A_N \rangle = \frac{\sum N(t_i) A_N^{th}(t_i)}{\sum N(t_i)}$$

calculated over several *t* bins

A_N^{th} from a fit to E950 data at similar energy and ***t*** range

L. Trueman hep-ph/0305085

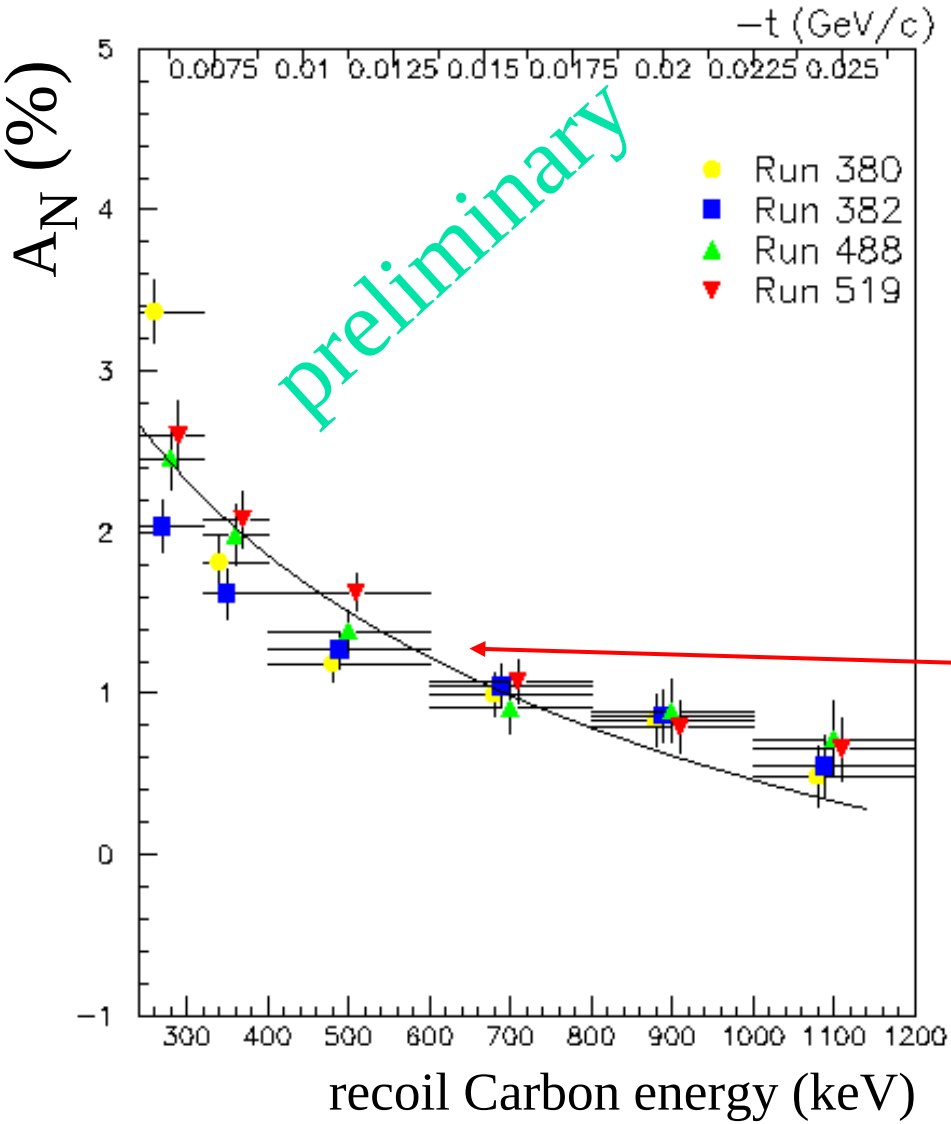
$\langle A_N \rangle \approx 1.12$

$0.009 < |t| < 0.022\ (\mathrm{GeV}/c)^2$

each measurement ~ 5 min

for next run ~ 1 min

A_N: $p\uparrow C \rightarrow pC$ at 24.7 GeV/c

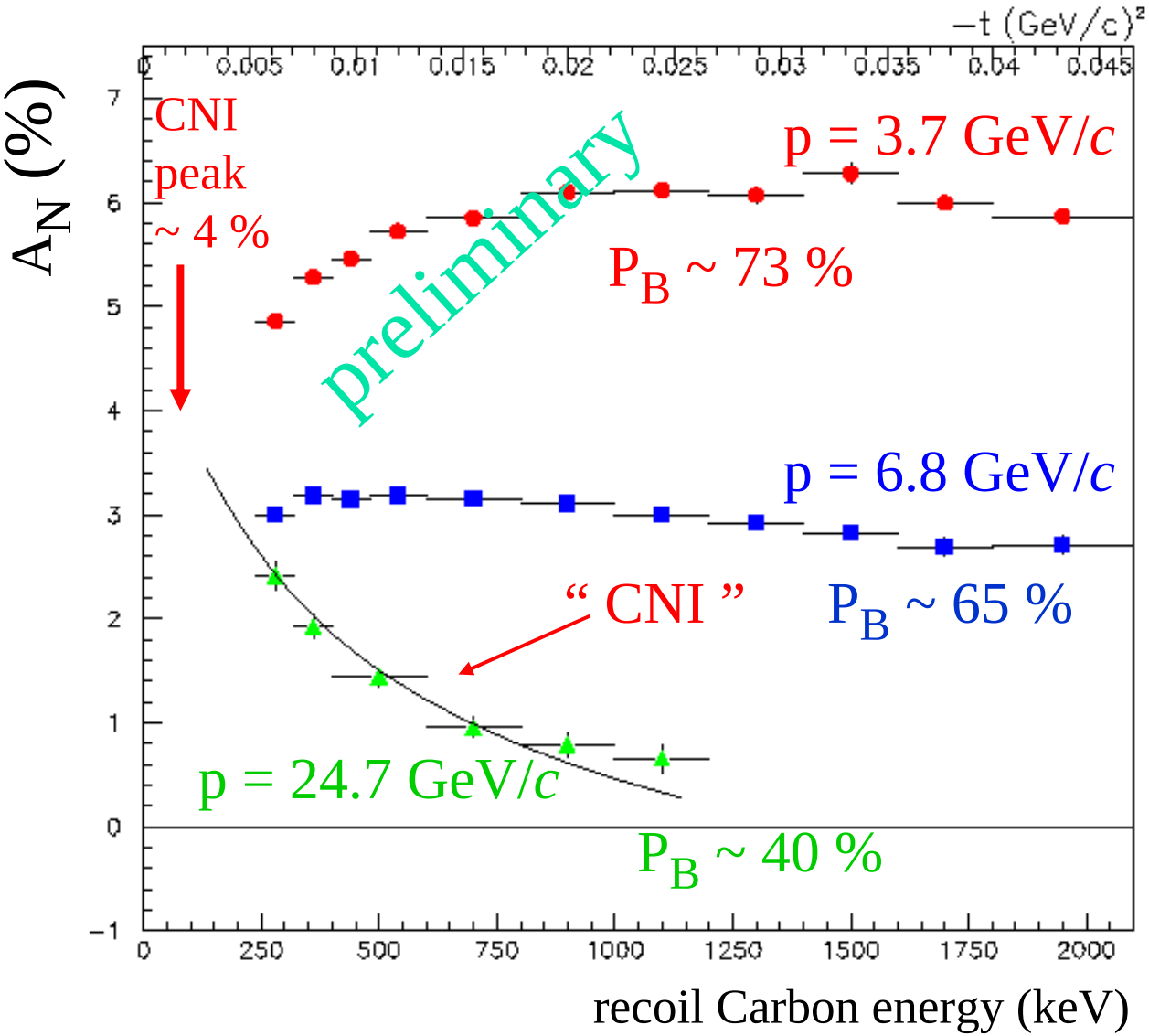


- only statistical errors shown
- normalization error (i.e. P_B) ~ 25% (relative)
- systematic error (background, pileup, etc.) < 20% (relative)

fit to E950 data
L. Trueman hep-ph/0305085

similar behavior E950 ⇒ substantial hadronic spin-flip confirmed
(no time yet to fit these data)

A_N: $p\uparrow C \rightarrow pC$ at 3.7 & 6.8 GeV/c



only statistical errors are shown

normalization errors:

~ 10 % (at 3.7)

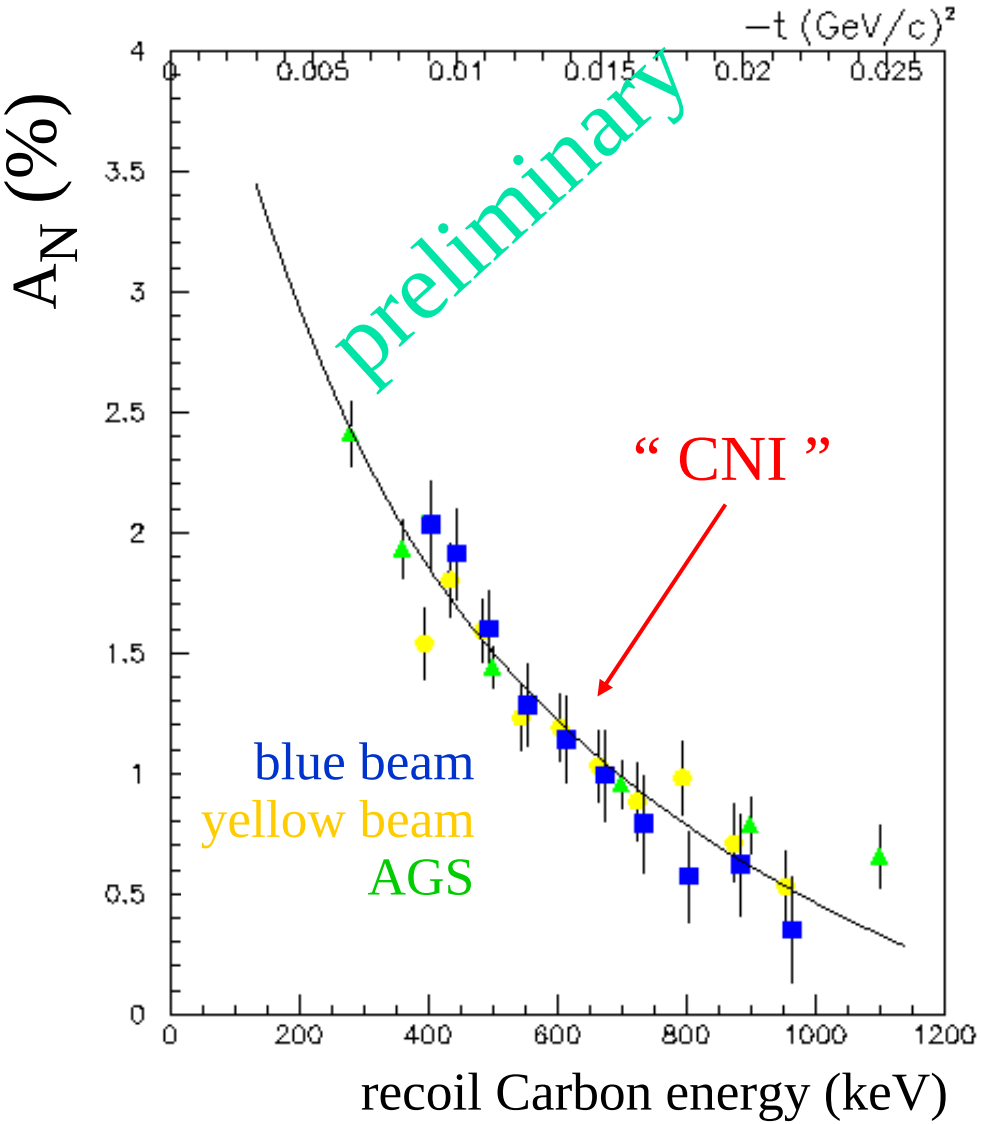
~ 15 % (at 6.8)

~ 25 % (at 24.7)

systematic error:

< 20 %

A_N: $p\uparrow C \rightarrow pC$ at 100 GeV/c (RHIC)



for normalization assume
A_N (24 GeV/c) = A_N (100 GeV/c)
i.e. no energy dependence
[$0.009 < |t| < 0.022$ (GeV/c)^2]

very similar shape of the t dependence at 24 and 100 GeV/c

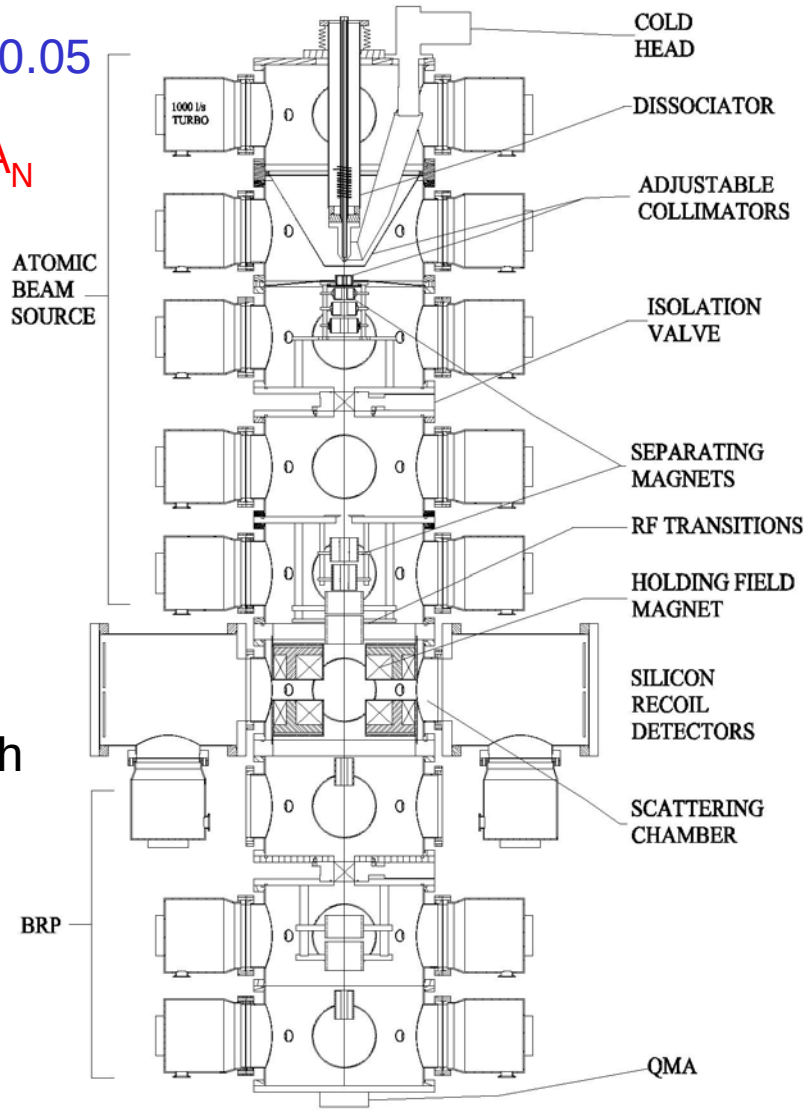
$\Rightarrow$ suggestive of very small energy dependence for A_N between 24 and 100 GeV/c

systematic error for RHIC data < 15%

The RHIC Absolute Polarimeter

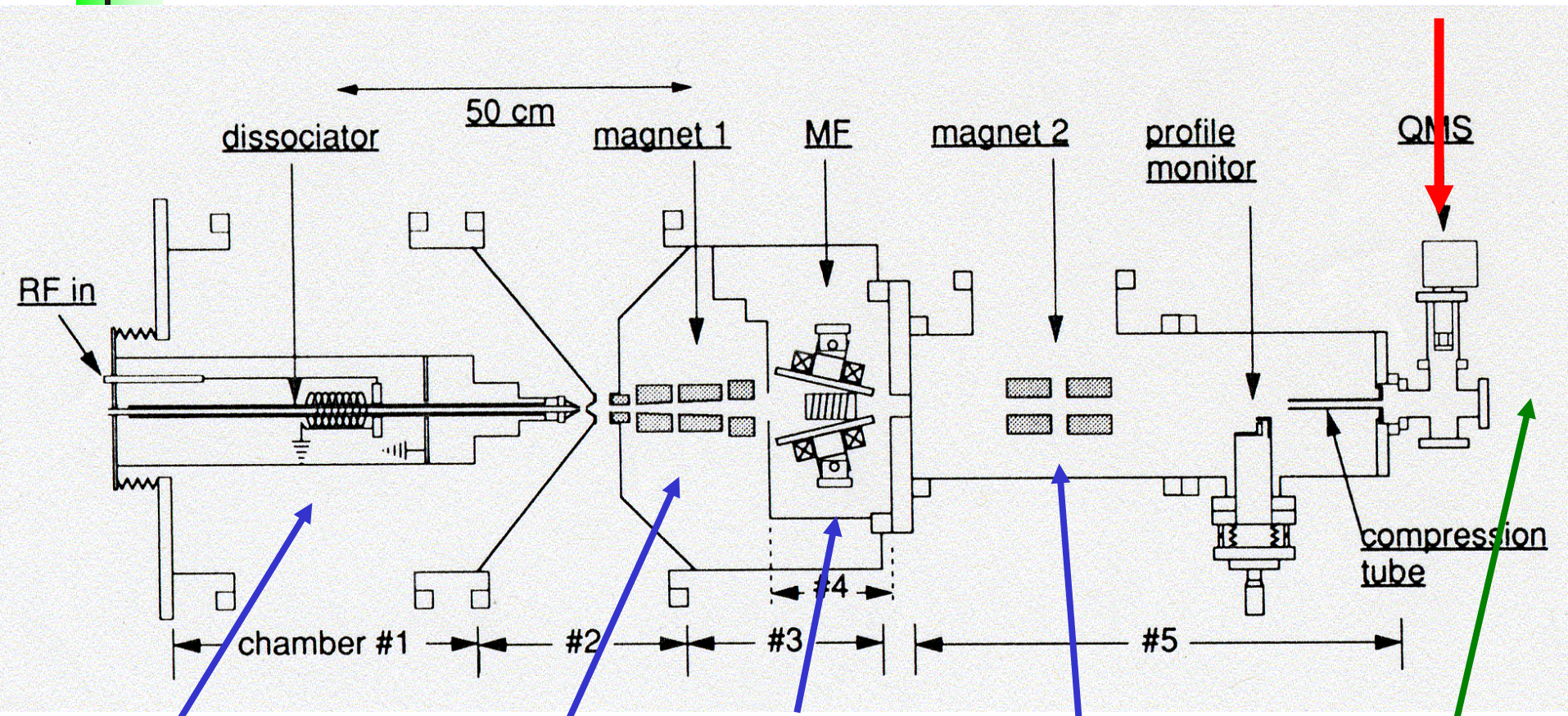
- RHIC Spin Program requires $\Delta P_{beam} / P_{beam} < 0.05$
- Polarimetric process with large σ and known A_N
  - *pp* elastic scattering in CNI region
  - Current knowledge on A_N to poor
- Measure A_N to required accuracy $\Delta A_N < 10^{-3}$ with unpolarized beam and polarized target

  then measure P_{beam} using this A_N with polarized beam and unpolarized target
- or Transfer target pol. to beam polarization: i.e. measure the ratio of spin asymmetries with beam and target polarized
- Target: polarized gas jet
  - low density and almost pointlike very high polarization (>90%)



The Polarized Gas-Jet Target

beam



atomic beam source

separation magnets (sextupoles)

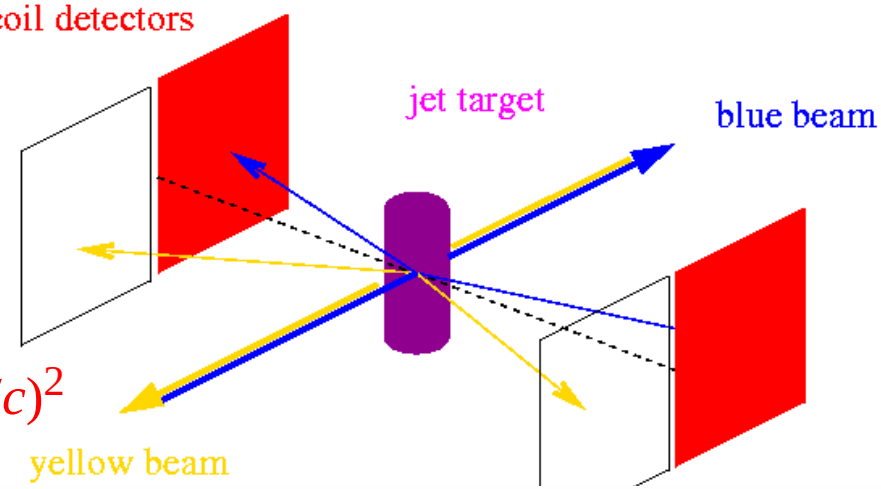
RF transitions

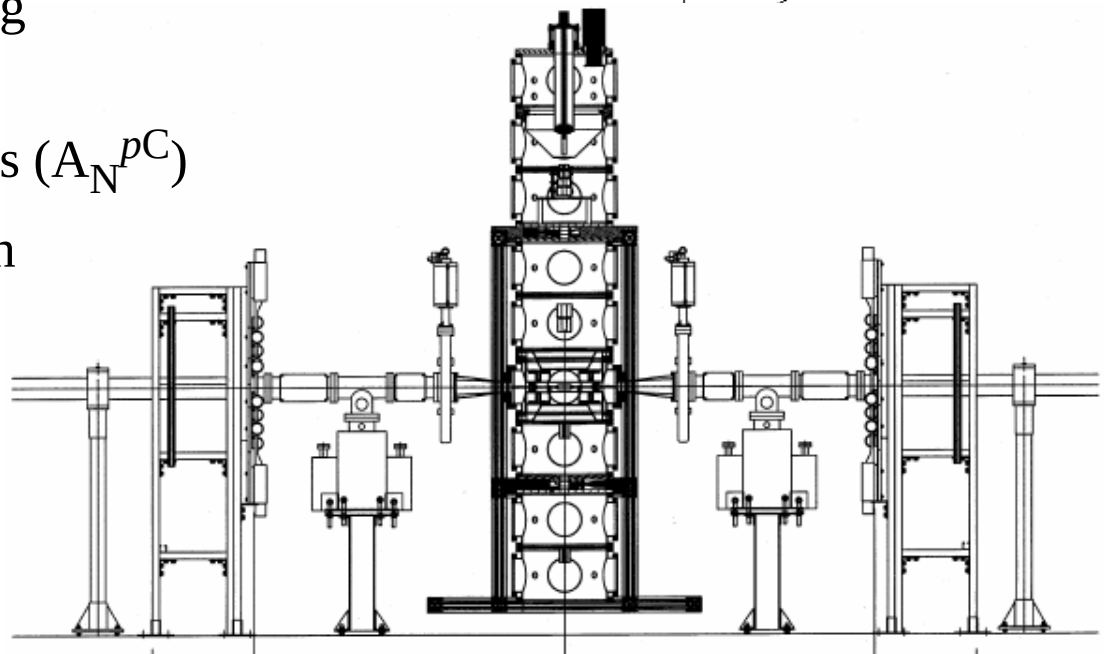
focusing magnets (sextupoles)

Breit-Rabi Polarimeter (not shown)

Next: $p\uparrow p$, $pp\uparrow$ 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_B to 10%
- In 2005 measure P_B to 6(5)%





Conclusions

- Successfully demonstrated acceleration, storage, and collisions of polarized protons up to 100 GeV; no fundamental problems anticipated going to 250 GeV
- All spin experiments work beautifully
- New spin physics results already extracted from the first p + p collisions in 2002
- Commissioning STAR and PHENIX spin rotators has permitted first longitudinal double spin measurements in just completed 2003 run
- Substantial progress has been made in improving beam polarization: on average P_B ~25 – 35 %
- Luminosity: ~ 1 pb^{-1} / week, total several pb^{-1}
- Polarimetry fast and reliable, need absolute calibration