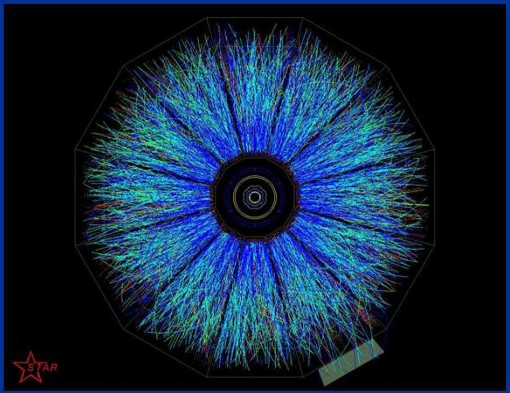
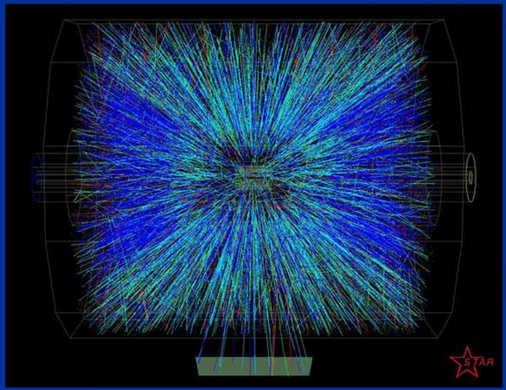
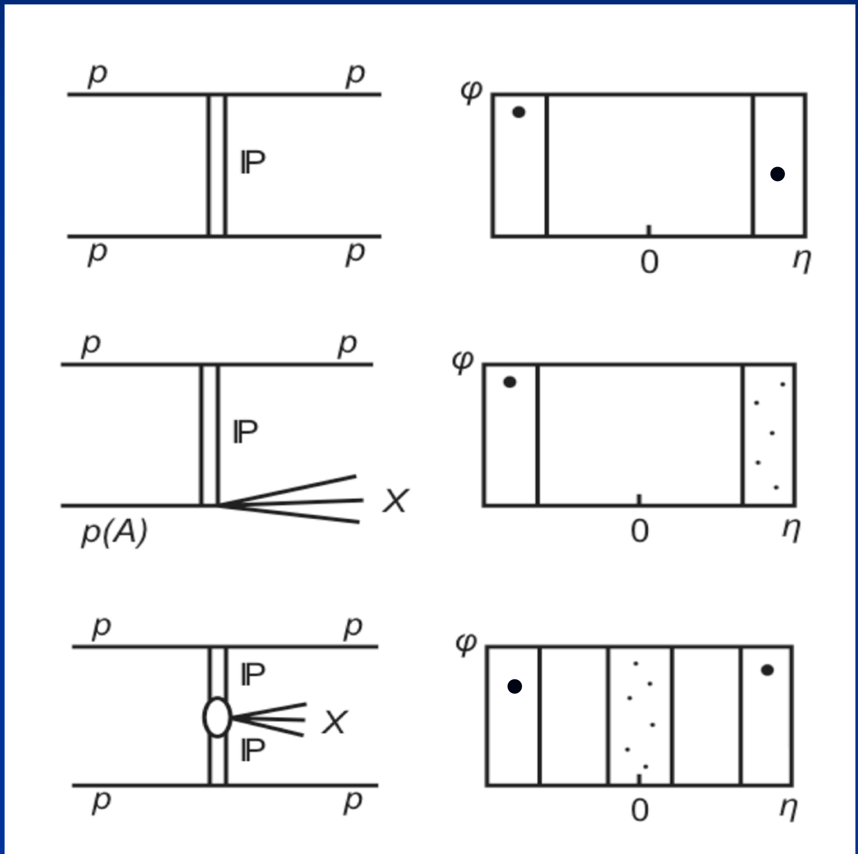
Physics with Tagged Forward Protons using the STAR Detector at RHIC

- The Relativistic Heavy Ion Collider
- The pp2pp Experiment 2002 – 2003
- STAR 2009





Elastic and Diffractive Processes



Elastic scattering

- Detect protons in very forward direction with Roman Pots

Single diffractive dissociation

- Detect one proton with RP and M_X in forward STAR detector

Central production

- Detect both protons in forward direction plus M_X in central STAR detector (SVT, TPC, …)

The RHIC Accelerator

Designed for colliding heavy ion beams

$\rightarrow$ Need two separate beam lines with individual transport magnets except in the interaction regions

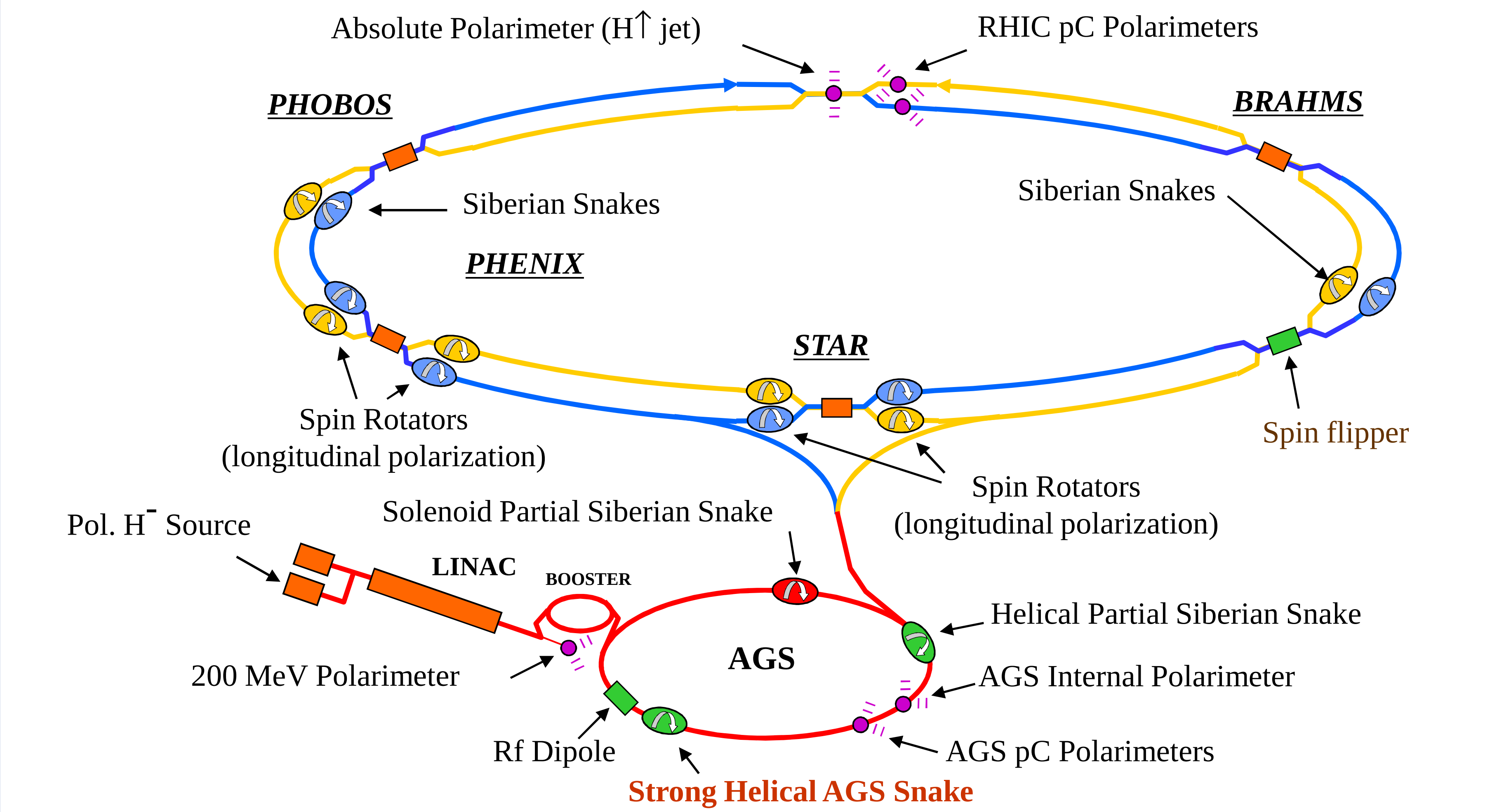
$\rightarrow$ Can also collide identical particles, like polarized protons

For collision of polarized proton beams need

- Polarized proton source
- Magnets to maintain polarization as much as possible (vertically)
- Polarization measurement (to about 5%)
- Magnets to change polarization from transverse to longitudinal

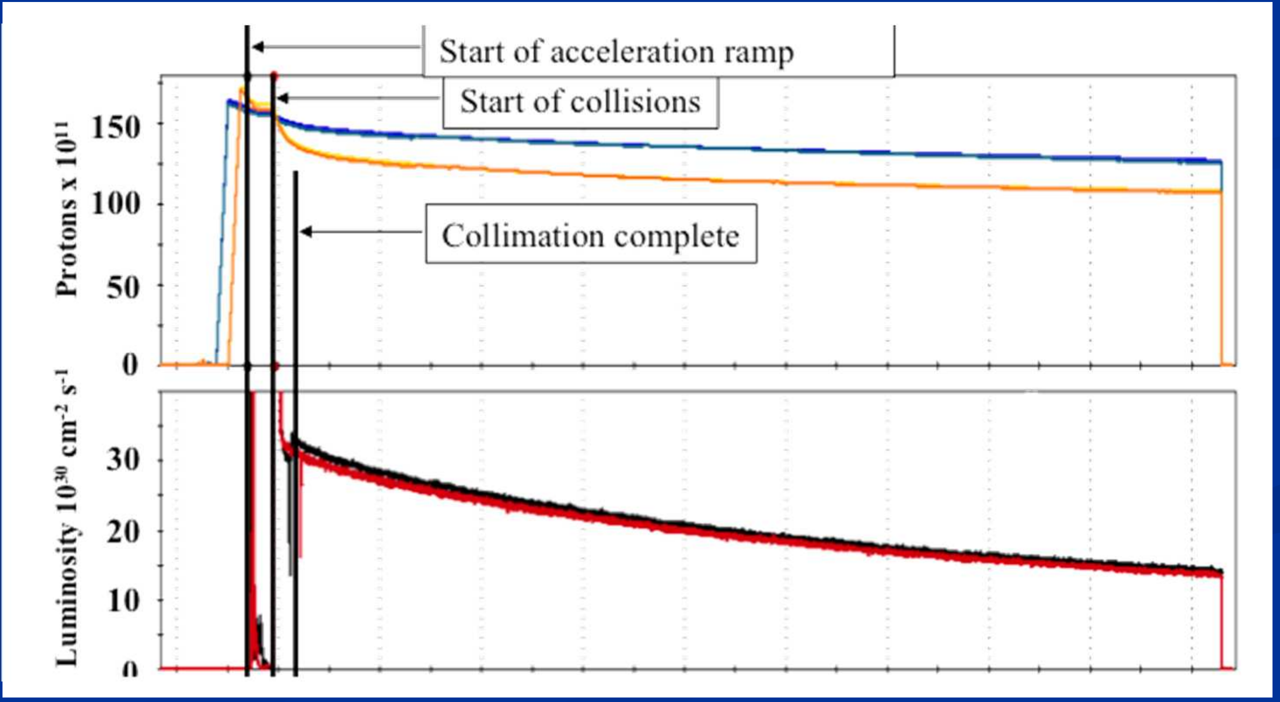
Birds Eye View of RHIC

The RHIC Accelerator



The RHIC *pp* Run 09

- 111 proton bunches per beam (120 bunch structure)
- $1.5 \cdot 10^{11}$ protons per bunch (design $2 \cdot 10^{11}$)
- Beam momentum 100 GeV/*c* (design up to 250 GeV/*c*)
- Fill life time about one shift of eight hours
- Polarization about 0.6 (design 0.7)



Elastic *pp*-Scattering at RHIC

Studies the dynamics and spin dependence of the hadronic interaction through elastic scattering of polarized protons in unexplored cms energy range of $50\ \text{GeV} < \sqrt{s} < 500\ \text{GeV}$, in the range of $4 \cdot 10^{-4}\ \text{GeV}^2 \leq |t| \leq 1.5\ \text{GeV}^2$, covering region of

Coulomb interaction for $|t| < 10^{-3}\ \text{GeV}^2$

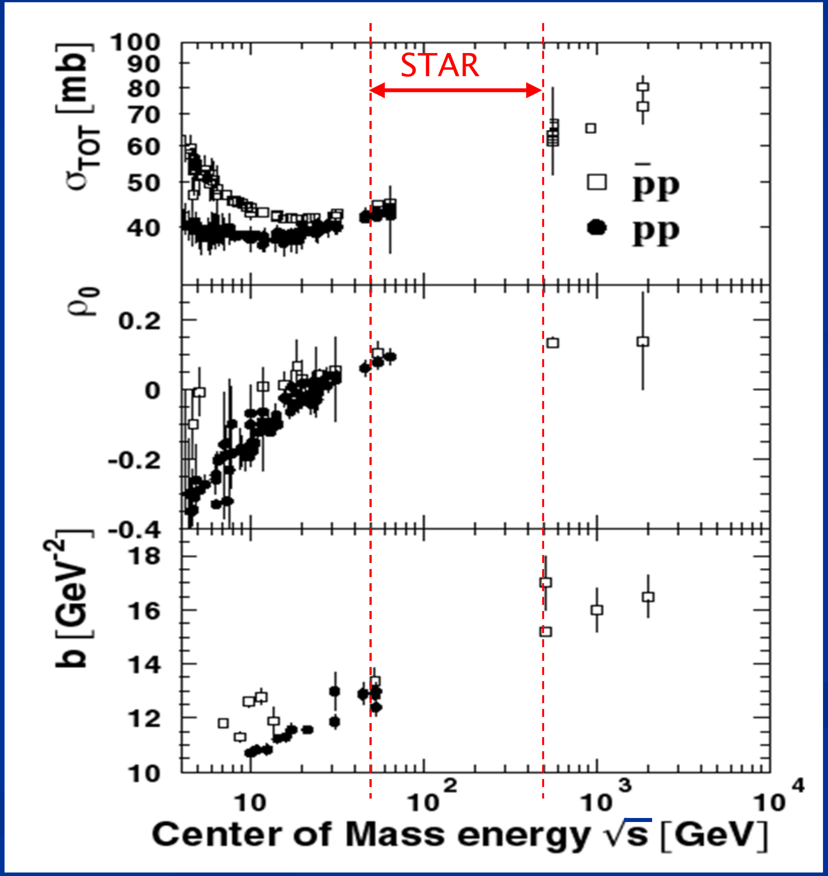
Measure total cross section σ_{tot} and access imaginary part of scattering amplitude via optical theorem

Hadronic interaction for $5 \cdot 10^{-3}\ \text{GeV}^2 \leq |t| \leq 1\ \text{GeV}^2$

Measure forward diffraction cone slope *b*

Interference between Coulomb and hadronic interaction (CNI-region)

Measure ratio of real and imaginary part of forward scattering amplitude ρ_0 and extract its real part using measured σ_{tot}



Differential Elastic Cross Section

For Proton–Proton Scattering

$$\frac{dN}{dt} \approx \frac{4\pi\,(\alpha G_E{}^2)^2}{t^2} + \frac{(1+\rho^2)\,\sigma_{\text{tot}}{}^2\, e^{+bt}}{16\pi} + \frac{(\rho+\Delta\Phi)\,\alpha G_E{}^2\,\sigma_{\text{tot}}\, e^{+\frac{1}{2}bt}}{t}$$

$\Delta\Phi =$ Coulomb Phase

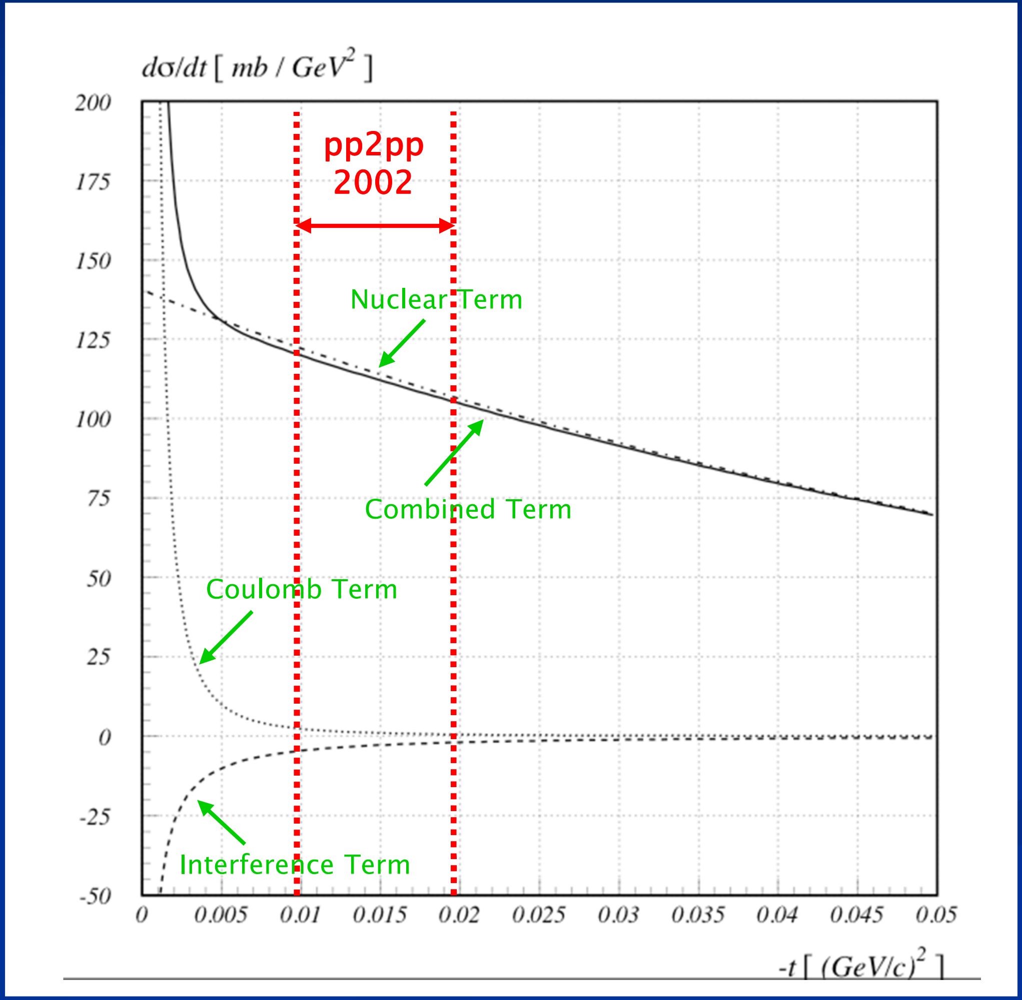
$G_E =$ Proton Electric Form Factor

Input : σ_{tot} = 52 mb

ρ = 0.13

b = 14 GeV^{-2}

Values for $\sqrt{s}$ = 200 GeV



pp Elastic Scattering Amplitudes

The helicity amplitudes describe elastic proton-proton scattering

$\phi_1(s,t) \propto <++|M|++>$

$\phi_2(s,t) \propto <++|M|-->$

$\phi_3(s,t) \propto <+-|M|+->$

$\phi_4(s,t) \propto <+-|M|-+>$

$\phi_5(s,t) \propto <++|M|+->$ $(= \phi_{\text{flip}})$

$\phi_n(s,t) \propto <h_3\, h_4\, |M| h_1\, h_2>$

with $h_x = s$–channel helicity

$p_1 = -p_2$ incoming protons

$p_3 = -p_4$ scattered protons

$$\phi_+(s,t) = \frac{1}{2}\left(\phi_1(s,t) + \phi_3(s,t)\right) = \phi_{\text{no-flip}}$$

Measure

$$\sigma_{tot} = \frac{8\pi}{s}\, Im\, [\phi_+(s,t)]_{t=0}$$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\left(|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2| + 4\, |\phi_5|^2\right)$$

$$\Delta\sigma_T = -\frac{8\pi}{s}\, Im\, [\phi_2(s,t)]_{t=0} = \sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}$$

$$2\pi\, \frac{d^2\sigma}{dt\, d\varphi} = \frac{d\sigma}{dt}\left(1 + (P_B + P_Y)\, A_N \cos\varphi + P_B\, P_Y\, (A_{NN} \cos^2\varphi + A_{SS} \sin^2\varphi)\right)$$

Single Spin Asymmetry

- Single spin asymmetry A_N of transversely polarized protons arises in CNI region from interference of hadronic non-flip with electromagnetic spin-flip amplitude
- Measure dependence of $|t|$ to probe for interference contribution from hadronic spin-flip amplitude with electromagnetic amplitude
- Disentangle Real and Imaginary part of hadronic spin flip contribution by measuring shift or slope change of A_N with possible zero crossing

$$A_N(t) = \frac{1}{P_Y \cdot \cos\varphi} \frac{N_{\uparrow\uparrow}(t) + N_{\uparrow\downarrow}(t) - N_{\downarrow\downarrow}(t) - N_{\downarrow\uparrow}(t)}{N_{\uparrow\uparrow}(t) + N_{\uparrow\downarrow}(t) + N_{\downarrow\downarrow}(t) + N_{\downarrow\uparrow}(t)}$$

for small t

$$\propto \frac{\mathcal{Im}\left(\phi_{\text{flip}}^{\text{em}\,*}\,\phi_{\text{no-flip}}^{\text{had}} + \phi_{\text{flip}}^{\text{had}\,*}\,\phi_{\text{no-flip}}^{\text{em}}\right)}{d\sigma\,/\,dt}$$

$$r_5 = \frac{m_p}{\sqrt{-t}} \frac{\phi_5^{\text{had}}}{\text{Im}(\phi_+^{\text{had}})}$$

With $N(t) = \dfrac{dN}{dt}$

P_Y = beam pol.

φ = azimuth

Double Spin Asymmetries

Measure A_{NN} and A_{SS} with transversely polarized protons to find limit on detectable Odderon, C = -1 partner of the Pomeron, contribution to interference between ϕ_1 and ϕ_2

Pomeron and Odderon out of phase by about 90° at $t = 0$

$$A_{NN}(t) = \frac{1}{P_Y \cdot P_B \cdot \cos^2\varphi} \frac{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) - N_{\uparrow\downarrow}(t) - N_{\downarrow\uparrow}(t)}{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) + N_{\uparrow\downarrow}(t) + N_{\downarrow\uparrow}(t)} \propto \frac{\mathcal{R}e\,(\phi_{\text{no-flip}}\,\phi_2^{*})}{d\sigma / dt}$$

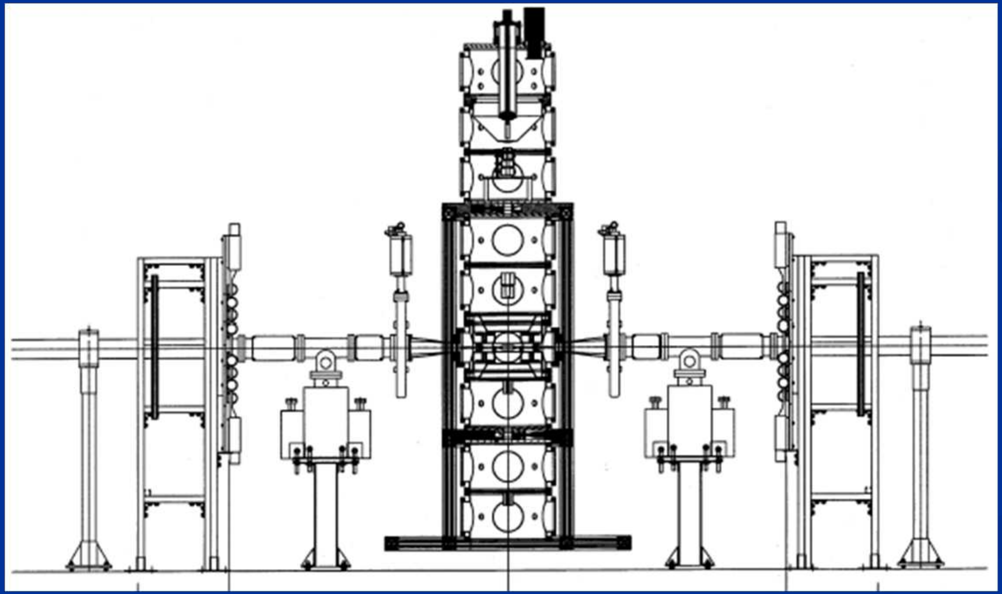
$$A_{SS}(t) = \frac{1}{P_Y \cdot P_B \cdot \sin^2\varphi} \frac{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) - N_{\uparrow\downarrow}(t) - N_{\downarrow\uparrow}(t)}{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) + N_{\uparrow\downarrow}(t) + N_{\downarrow\uparrow}(t)} \propto \frac{\mathcal{R}e\,(\phi^{*}_{\text{no-flip}}\,\phi_2)}{d\sigma / dt}$$

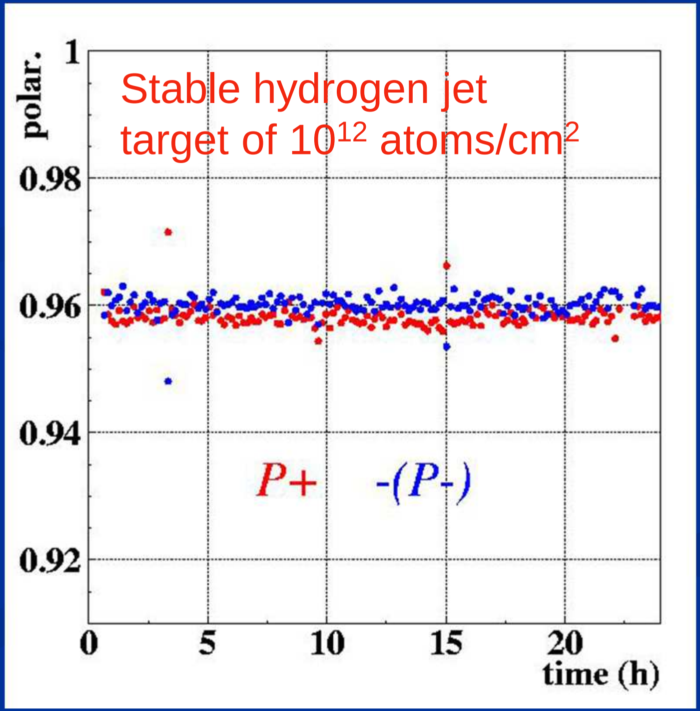
for small t

Beam Polarization Measurement

Measuring the analyzing power A_N by scattering one (polarized) proton beam off a polarized hydrogen jet of known polarization at $\sqrt{s}$ = 13.7 GeV and $\sqrt{s}$ = 6.7 GeV

Used for simultaneous calibration of proton-carbon CNI polarimeter



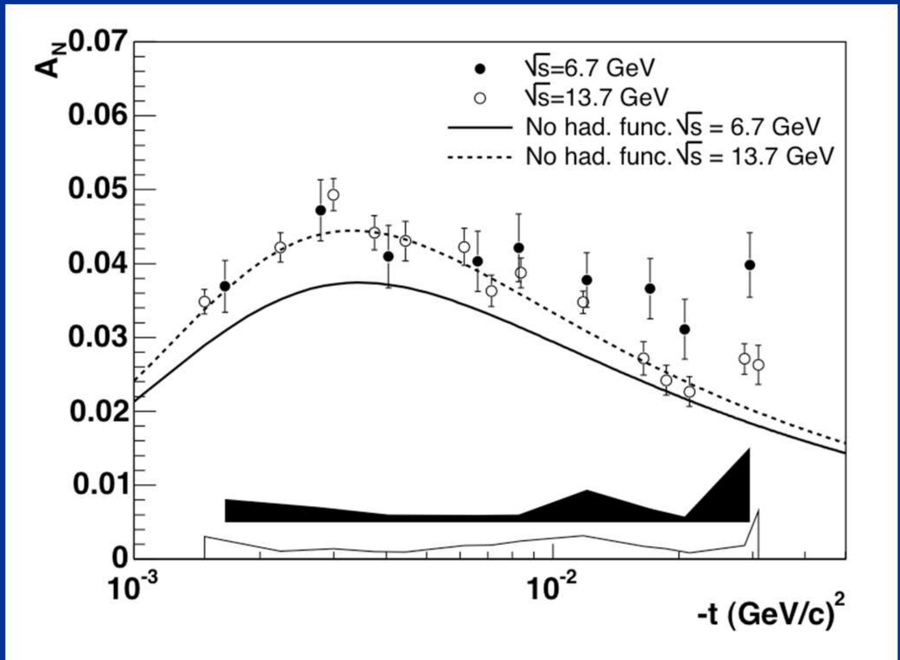


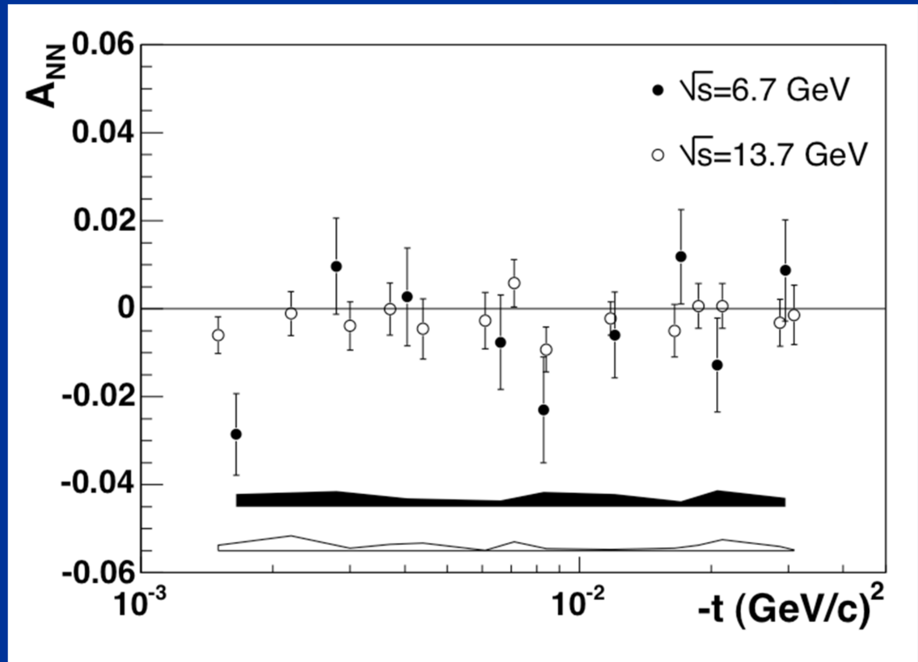
Jet-Target Results for A_N and A_{NN}

Measurement of A_N at $\sqrt{s}$ = 13.7 GeV in agreement with assumption of no hadronic spin-flip contribution to scattering amplitude

Not the case for measurement at $\sqrt{s}$ = 6.7 GeV (statistically limited)

Measurement of A_{NN} consistent with zero

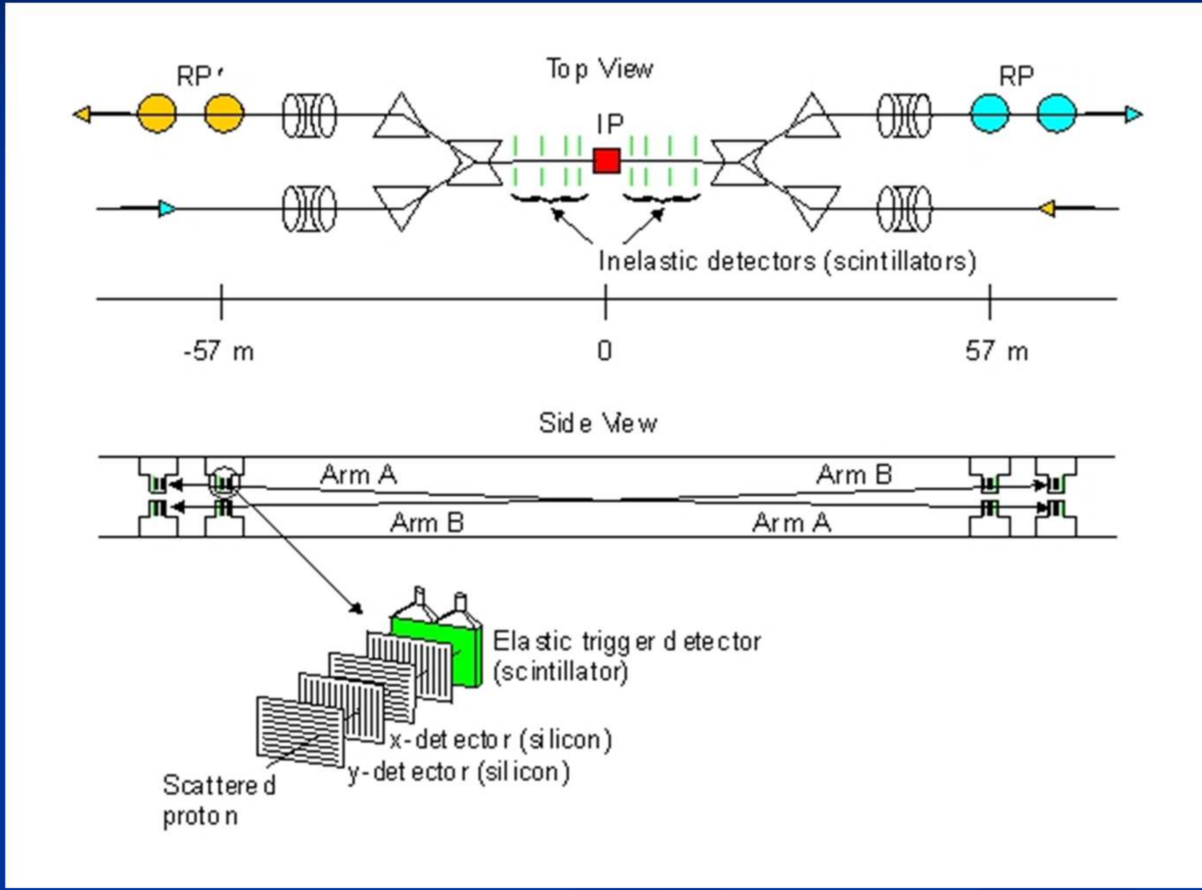




H. Okada et al., AIP Conf.Proc.915:681 (2007)

Experimental Technique

- Elastically scattered protons have very small scattering angle Θ^*, hence beam transport magnets determine trajectory of scattered protons
- The optimal position for the detectors is where scattered protons are well separated from beam protons
- Need Roman Pot to measure scattered protons close to the beam without breaking accelerator vacuum



Principle of Measurement

Elastically forward scattered protons have very small scattering angle θ^*

Beam transport magnets determine trajectory of beam and scattered protons

Scattered protons need to be well separated from the beam protons

Need Roman Pot to measure scattered protons close to beam

Beam transport equations relate measured position at detector to scattering angle

$x = a_{11}\, x_0 + L_{eff}\, \theta^*_x$ $\rightarrow$ Optimize so that a_{11} small and L_{eff} large

$\theta_x = a_{12}\, x_0 + a_{22}\, \theta^*_x$ $\rightarrow$ x_0 can be calculated by measuring θ_x (2nd RP)

Similar equations for y-coordinate

Neglect terms mixing x- and y-coordinate in above equations

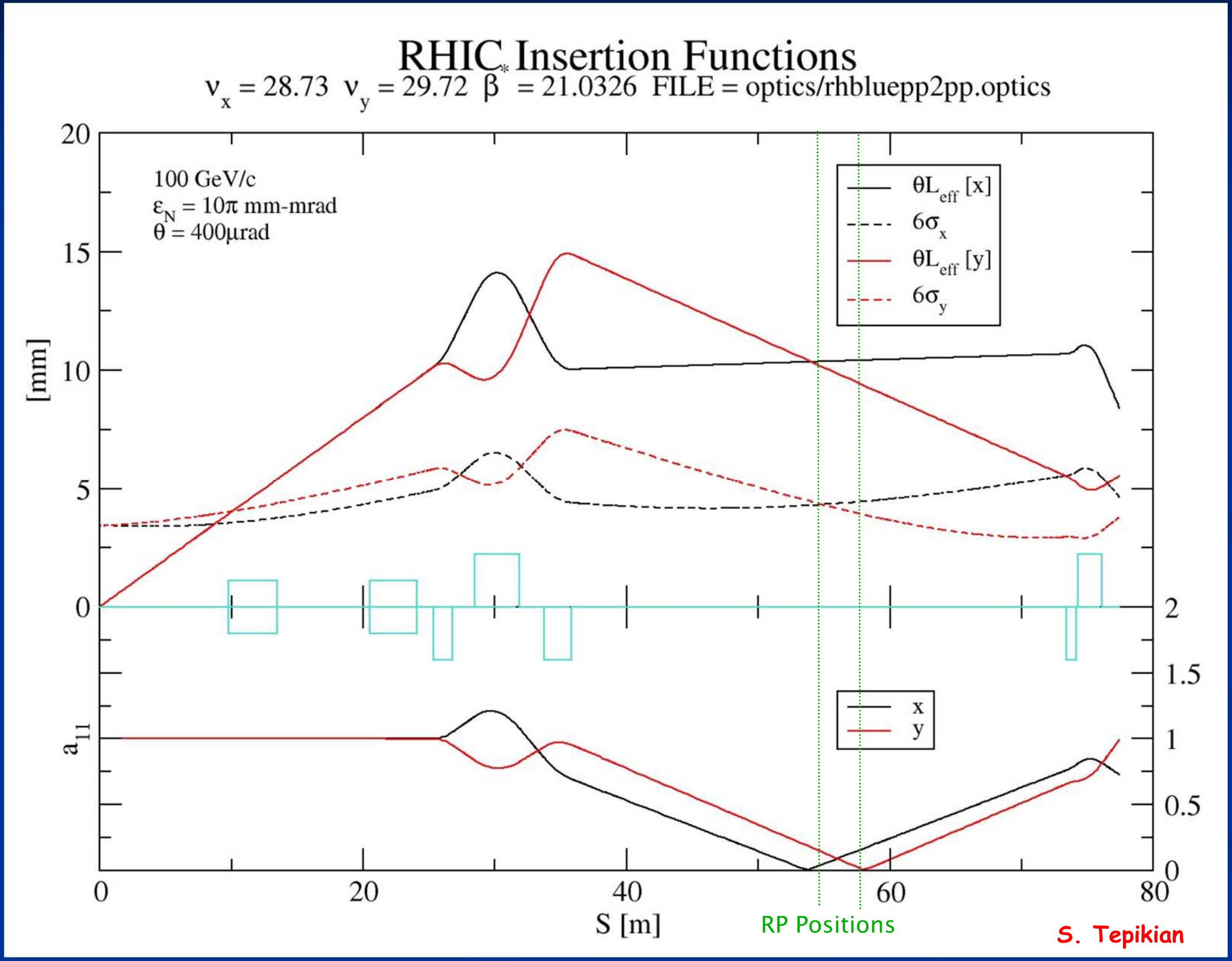
x : Position at Detector

θ_x : Angle at Detector

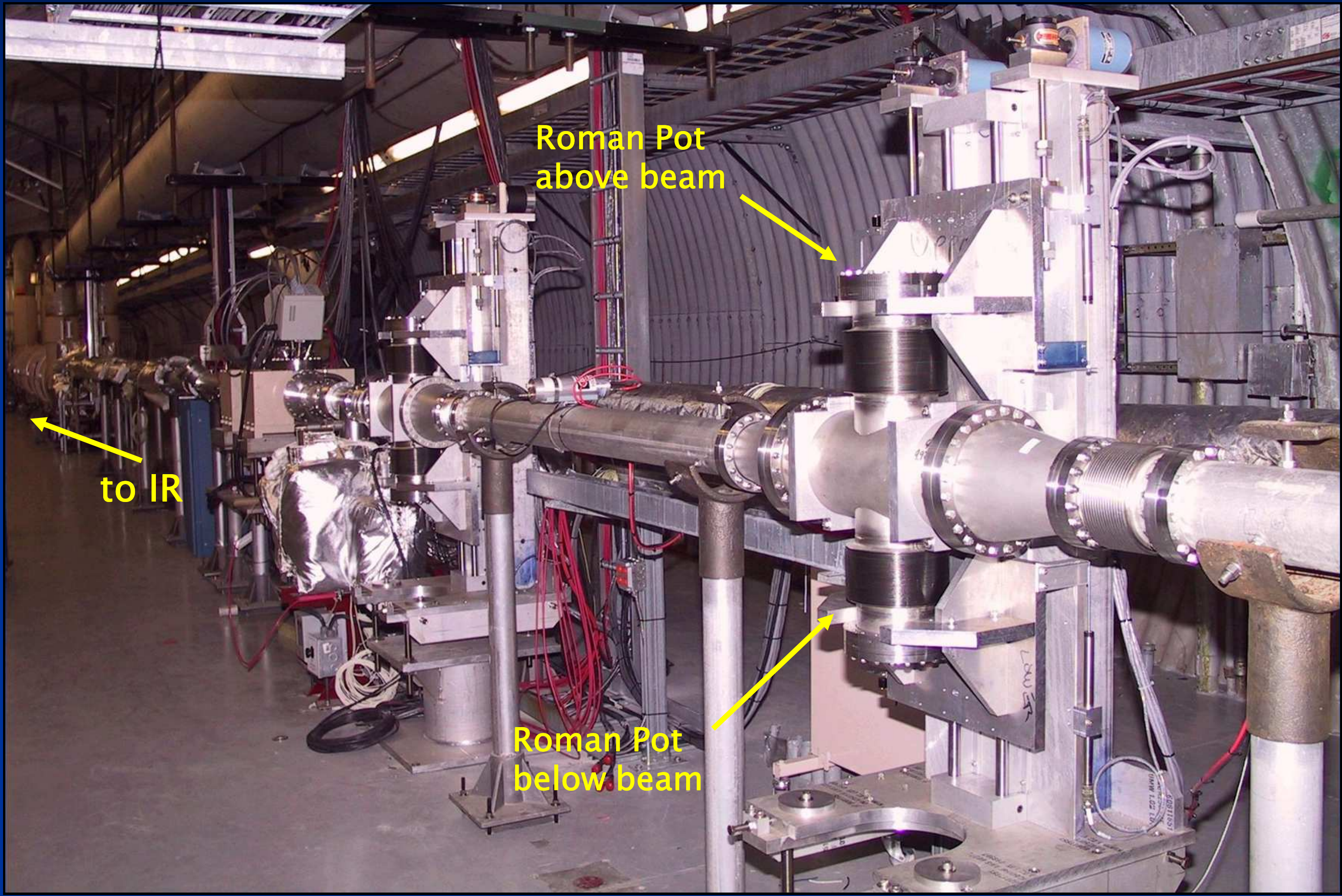
x_0 : Position at Interaction Point

θ^*_x : Scattering Angle at IP

Beam Transport



pp2pp Experimental Setup 2003



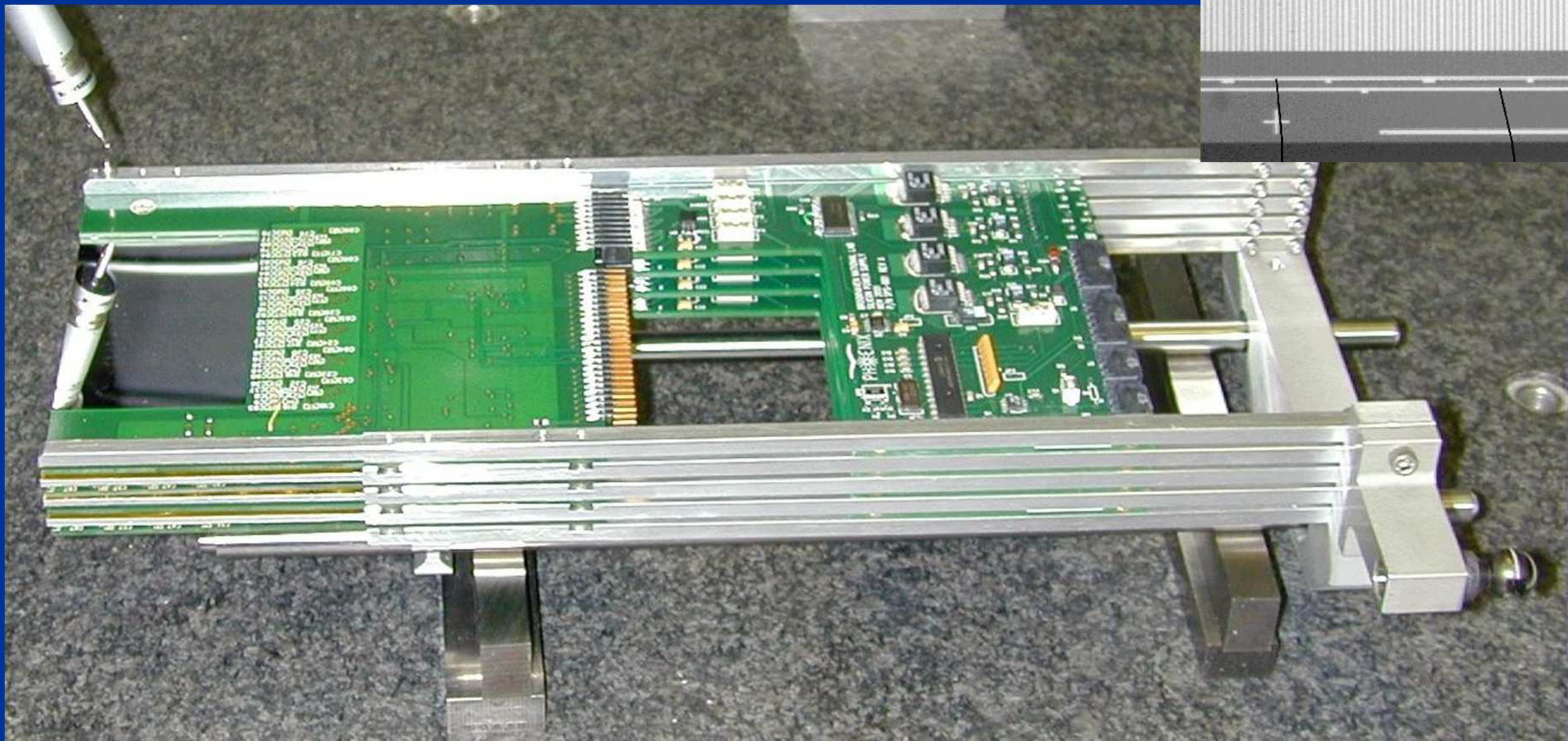
STAR Experimental Setup 2009

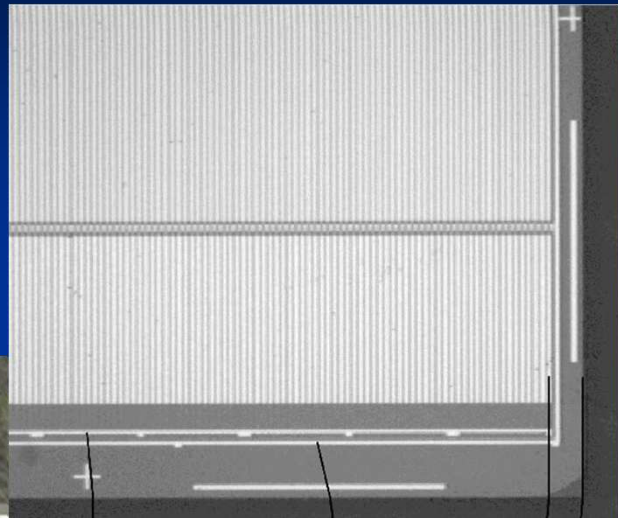
Silicon Detector

400 micron thick Silicon

Good Position Resolution with Strip Pitch ~100 micron

Distance between first strip and edge about 500 micron





2009 Data Taking

Conditions

Five days of data taking with high $\beta^* = 21$ m beam tune

Beam momentum p = 100 GeV/c

111 proton bunches per beam

Beam scraped to emittance $\varepsilon \approx 12\,\pi \cdot 10^{-6}$ m

and luminosity $\leq 2 \cdot 10^{28}$ cm^{-2} sec^{-1}

Beam polarization $P_B + P_Y = 1.224 \pm 0.038 \pm 4.4\%$

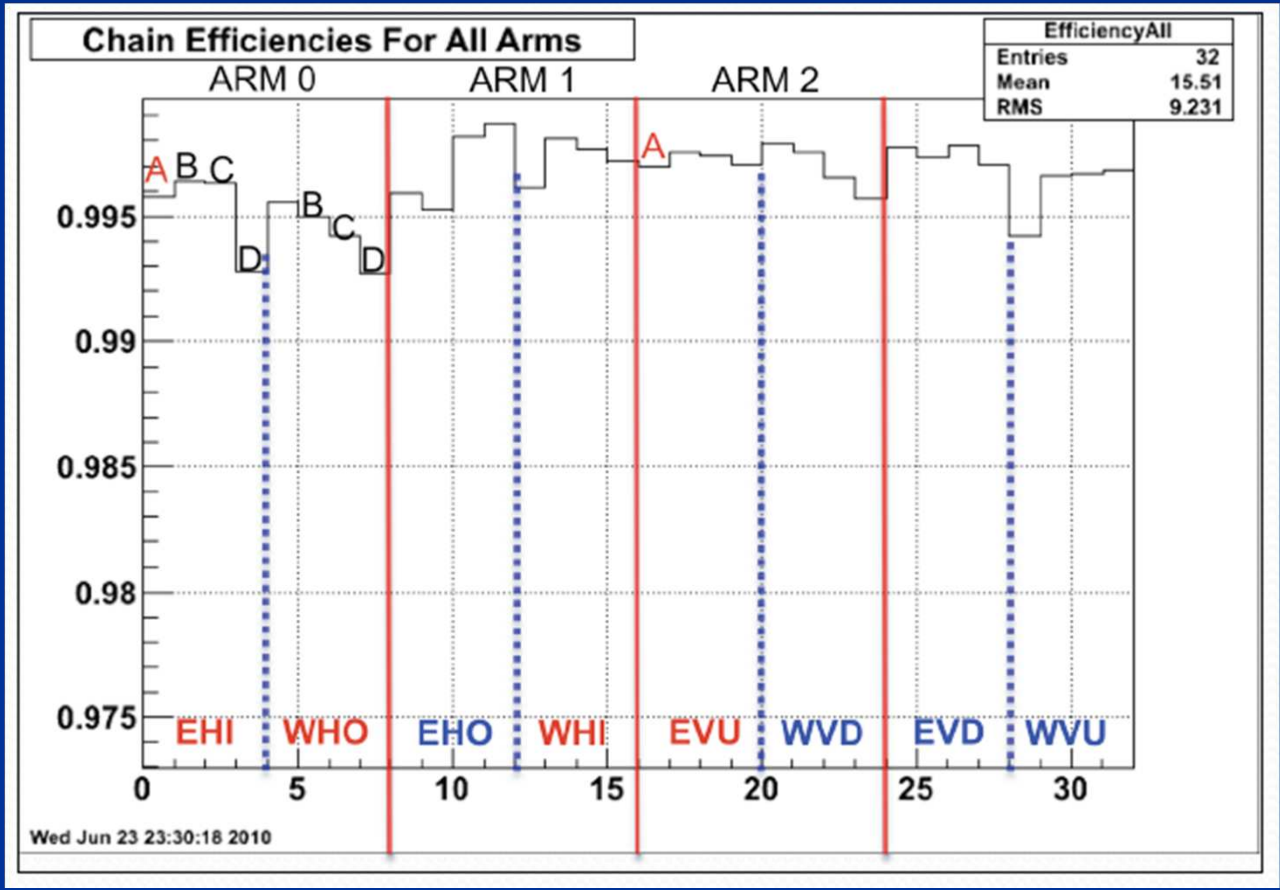
Very high detector efficiency with 5 dead/noisy strips in 14,000 active strips

20 million reconstructed elastic scattering events

Background less than 1%

Silicon Detector Efficiency

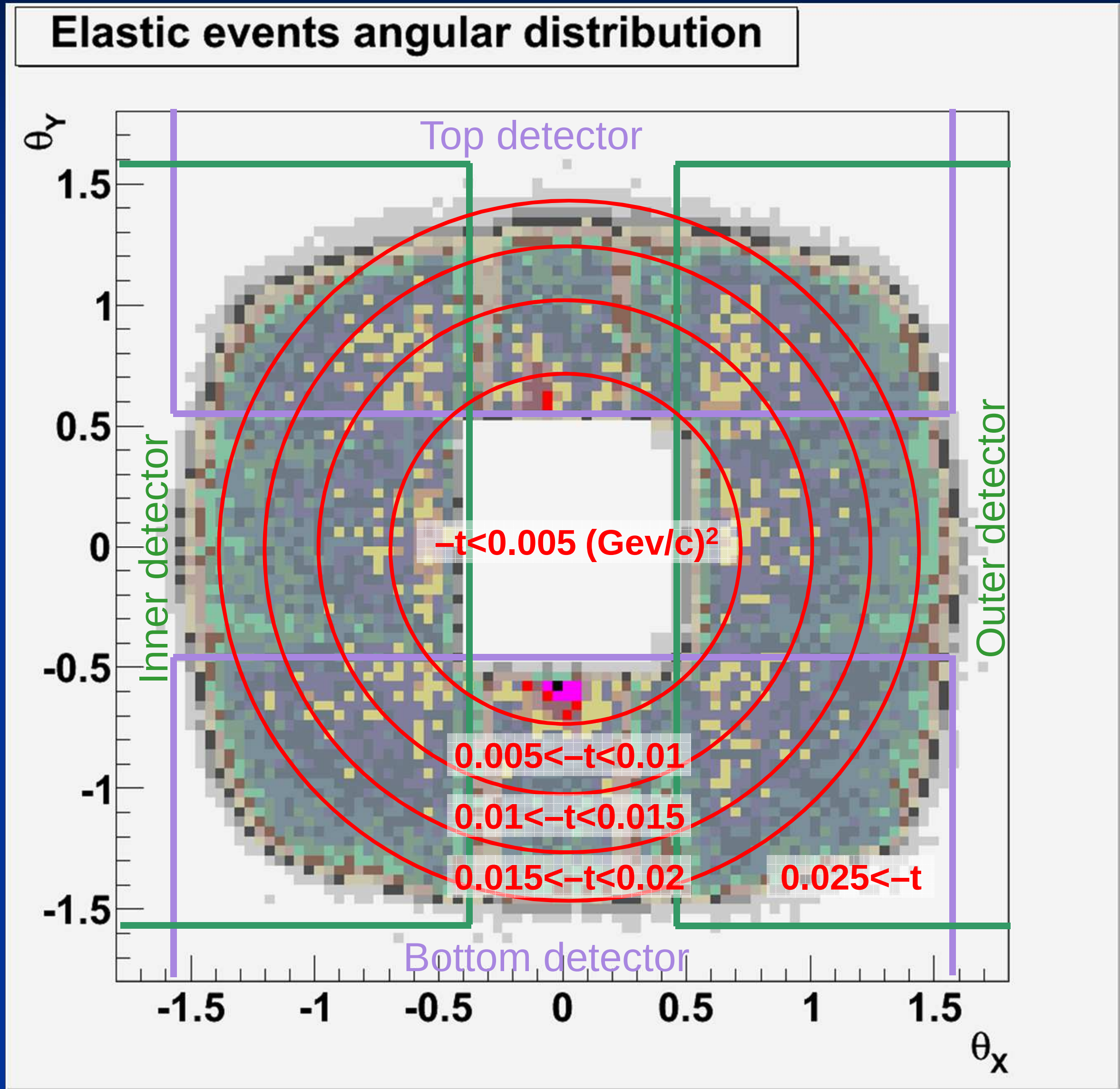
- After excluding hot/noisy strips
- 5 dead strips for ~14,000 strips in active area (acceptance)



Elastic Hit Pattern

Hit distribution of scattered protons within 3σ - correlation cut reconstructed using the nominal beam transport

Agreement between Monte Carlo simulation and data



Experimental Raw Asymmetries

All four possible relative spin orientations available

Can use square-root formula to avoid normalization for A_N

$$\varepsilon_N(\varphi) = \frac{(P_B + P_Y) A_N \cos\varphi}{1+\delta(\varphi)} = \frac{\sqrt{N^{++}(\varphi)N^{--}(\pi+\varphi)} - \sqrt{N^{--}(\varphi)N^{++}(\pi+\varphi)}}{\sqrt{N^{++}(\varphi)N^{--}(\pi+\varphi)} + \sqrt{N^{--}(\varphi)N^{++}(\pi+\varphi)}}$$

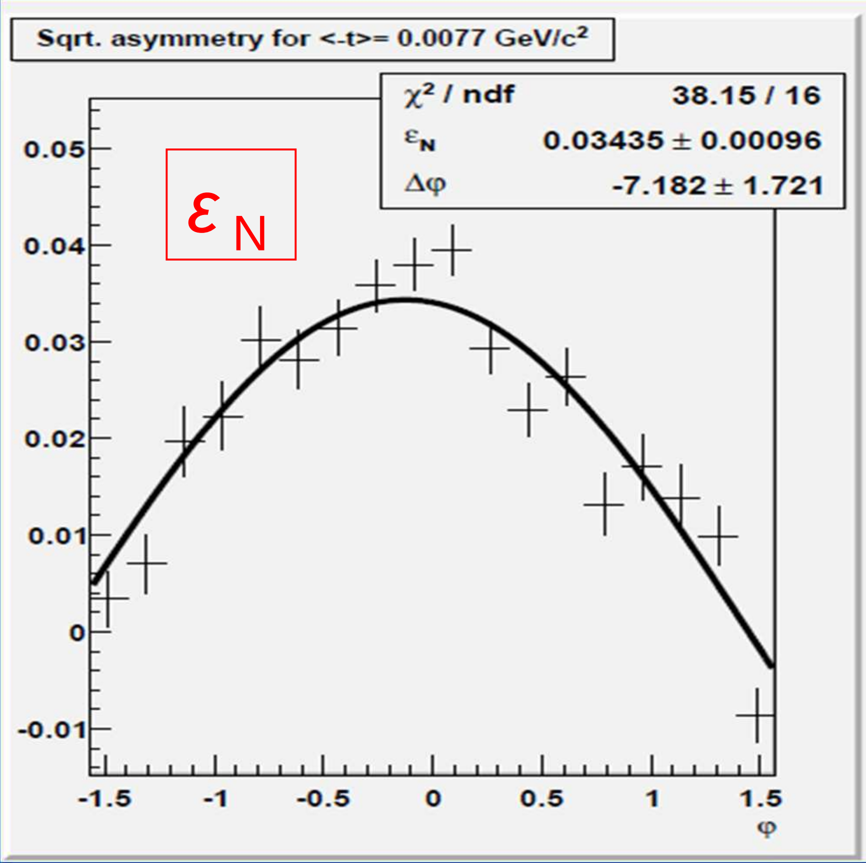
$$\varepsilon_N^B(\varphi) = P_B A_N \cos\varphi = \frac{\sqrt{N_B^+(\varphi)N_B^-(\pi+\varphi)} - \sqrt{N_B^-(\varphi)N_B^+(\pi+\varphi)}}{\sqrt{N_B^+(\varphi)N_B^-(\pi+\varphi)} + \sqrt{N_B^-(\varphi)N_B^+(\pi+\varphi)}}$$

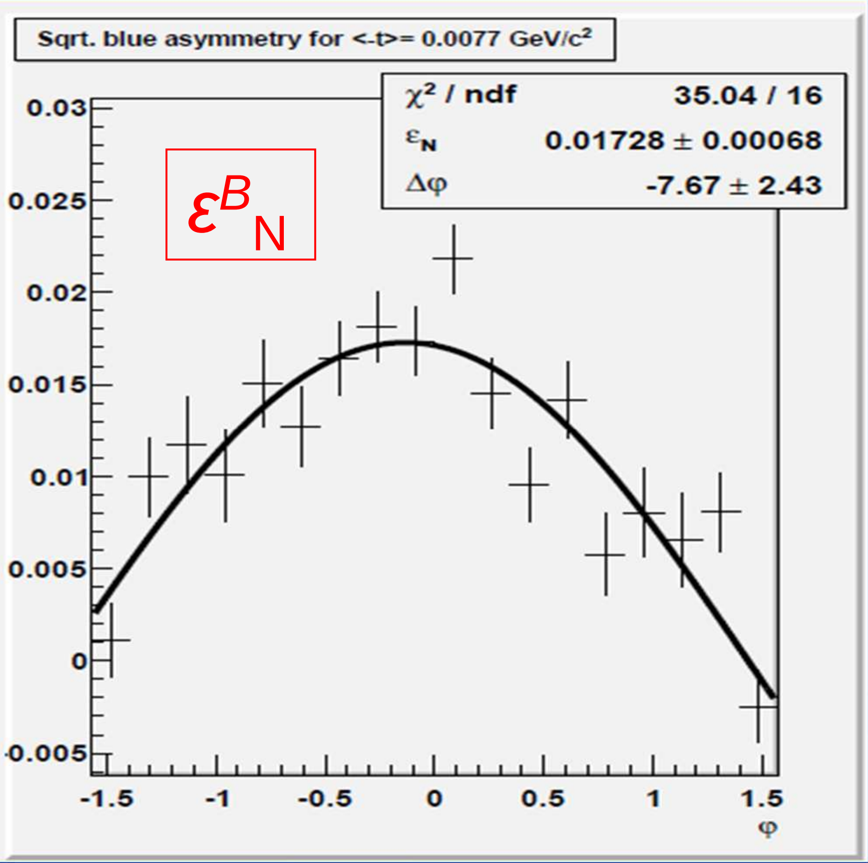
$$\varepsilon_N'(\varphi) = \frac{(P_B - P_Y) A_N \cos\varphi}{1-\delta(\varphi)} = \frac{\sqrt{N^{+-}(\varphi)N^{-+}(\pi+\varphi)} - \sqrt{N^{-+}(\varphi)N^{+-}(\pi+\varphi)}}{\sqrt{N^{+-}(\varphi)N^{-+}(\pi+\varphi)} + \sqrt{N^{-+}(\varphi)N^{+-}(\pi+\varphi)}}$$

$$\delta(\varphi) = P_B P_Y (A_{NN} \cos^2\varphi + A_{SS} \sin^2\varphi) < 0.01 << 1$$

Analyzing Power Measurement 2009

$\varepsilon_N = A_N \cdot P$ for one bin with $< -t > = 0.0077$ GeV/c^2





Analyzing Power Measurement 2009

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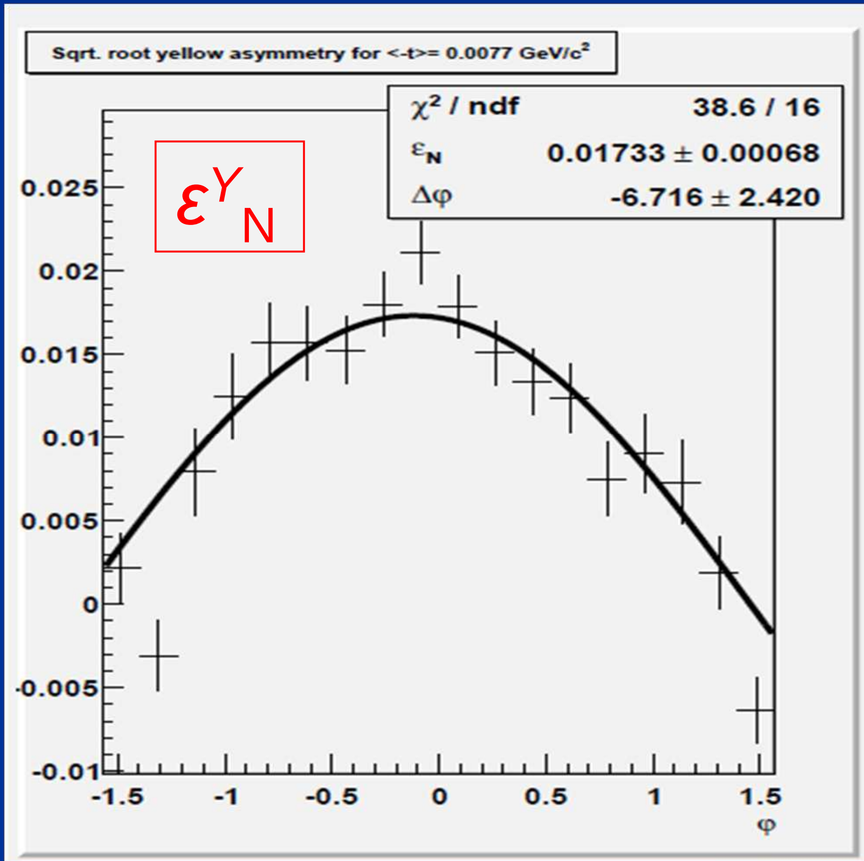
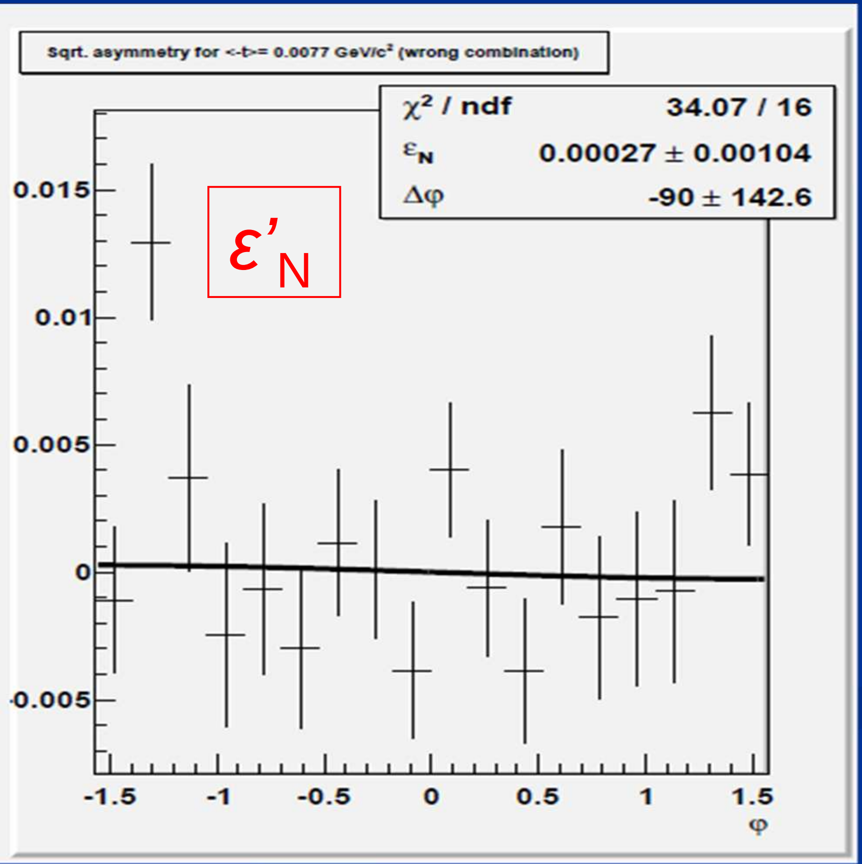
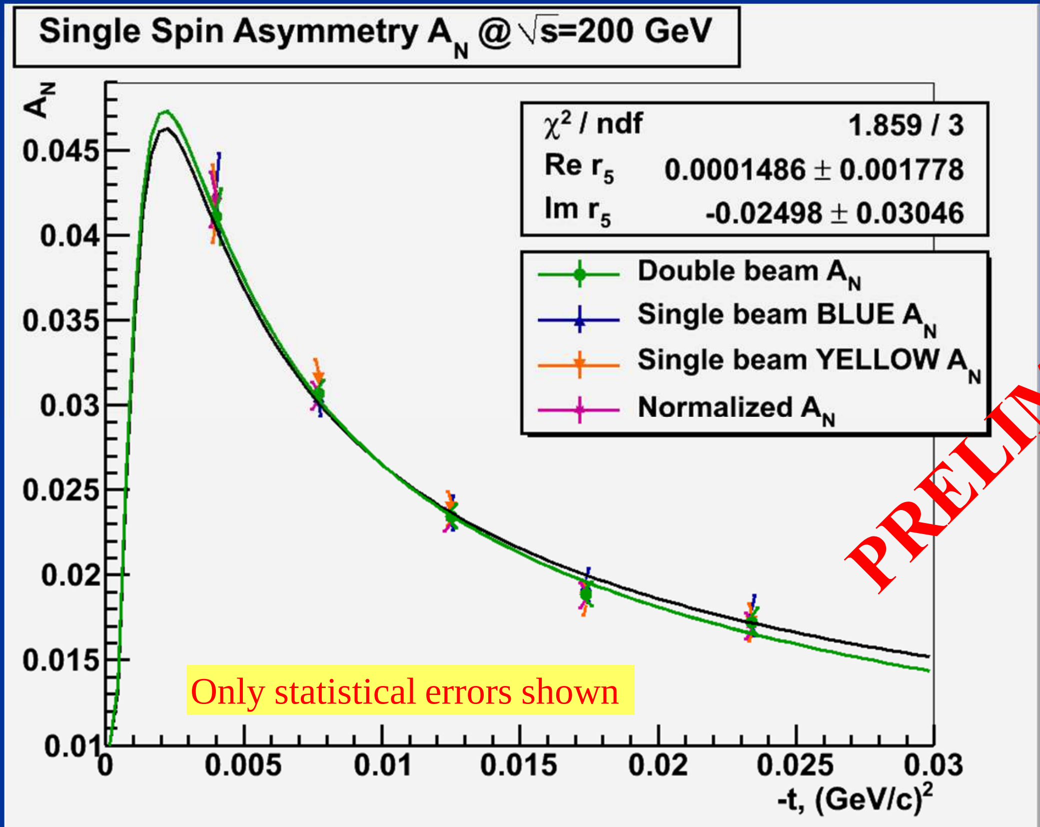
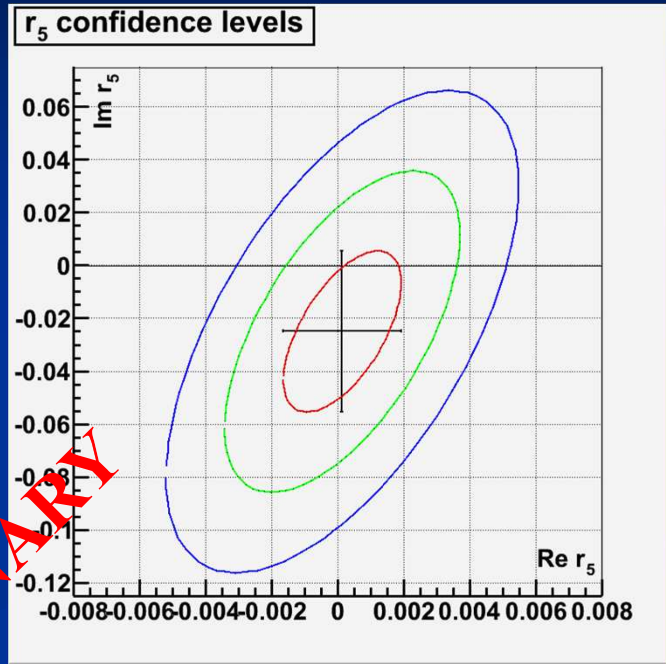




Analyzing Power Measurement 2009

$$A_N(t) = \frac{\sqrt{-t}}{m}\,\frac{[\kappa(1-\rho\,\delta)+2(\delta\,\mathrm{Re}\,r_5-\mathrm{Im}\,r_5)]\frac{t_c}{t}-2(\mathrm{Re}\,r_5-\rho\,\mathrm{Im}\,r_5)}{\left(\frac{t_c}{t}\right)^2-2(\rho+\delta)\frac{t_c}{t}+(1+\rho^2)}$$

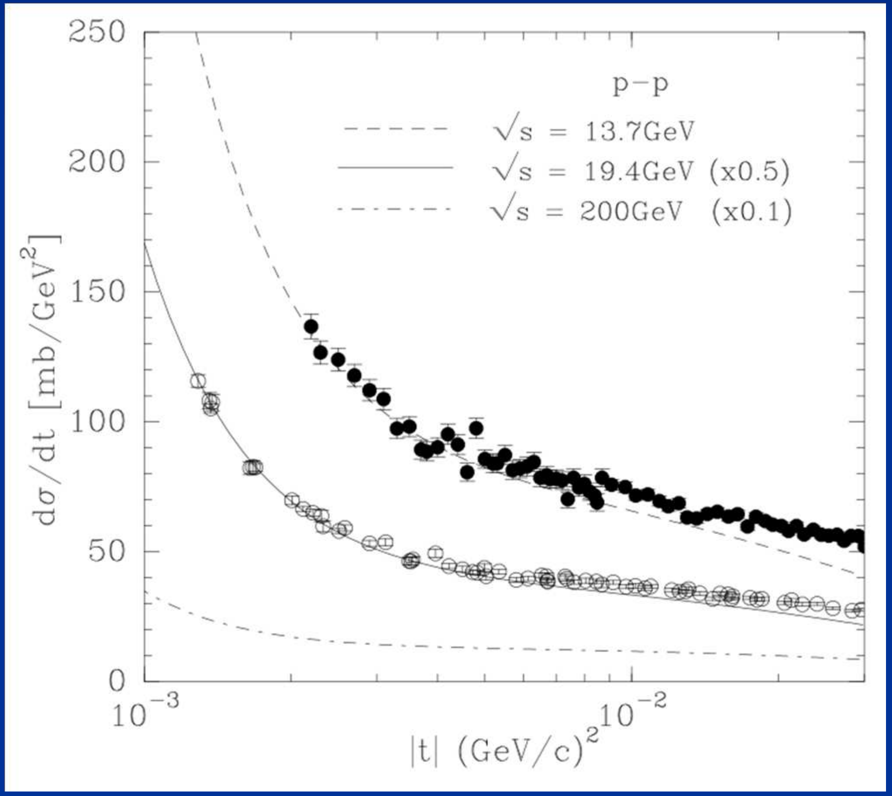




$$r_5 = \frac{m_p}{\sqrt{-t}}\,\frac{\phi_5^{had}}{\mathrm{Im}(\phi_+^{had})}$$

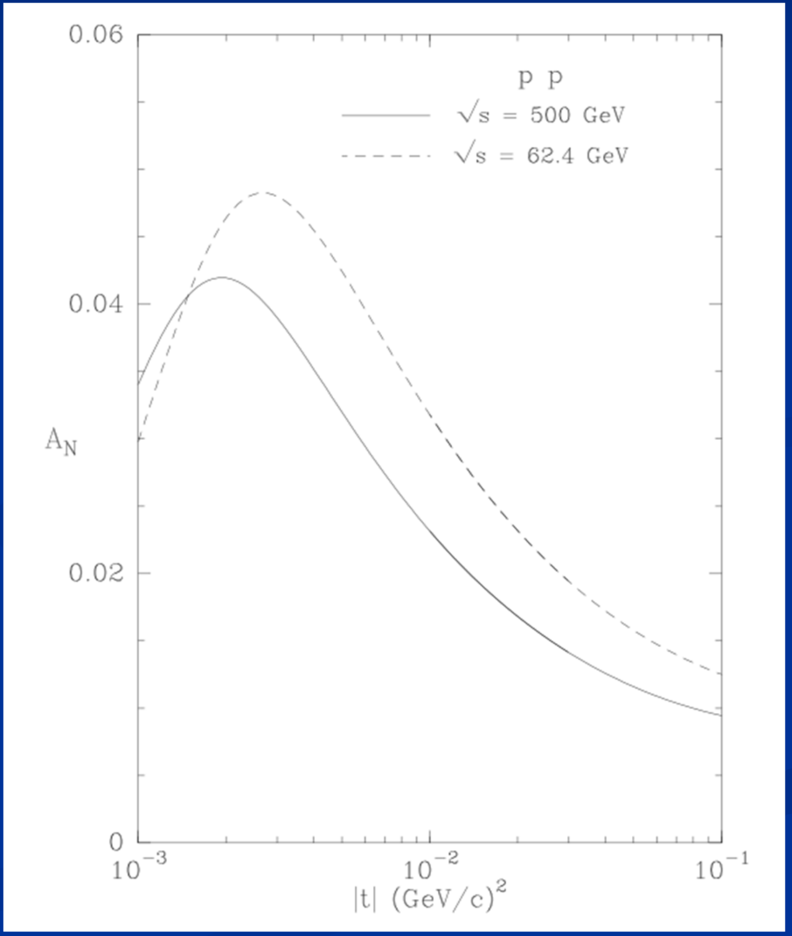
Comparison with Calculations

Impact picture calculation predicts
b = 16.25 GeV^{-2}



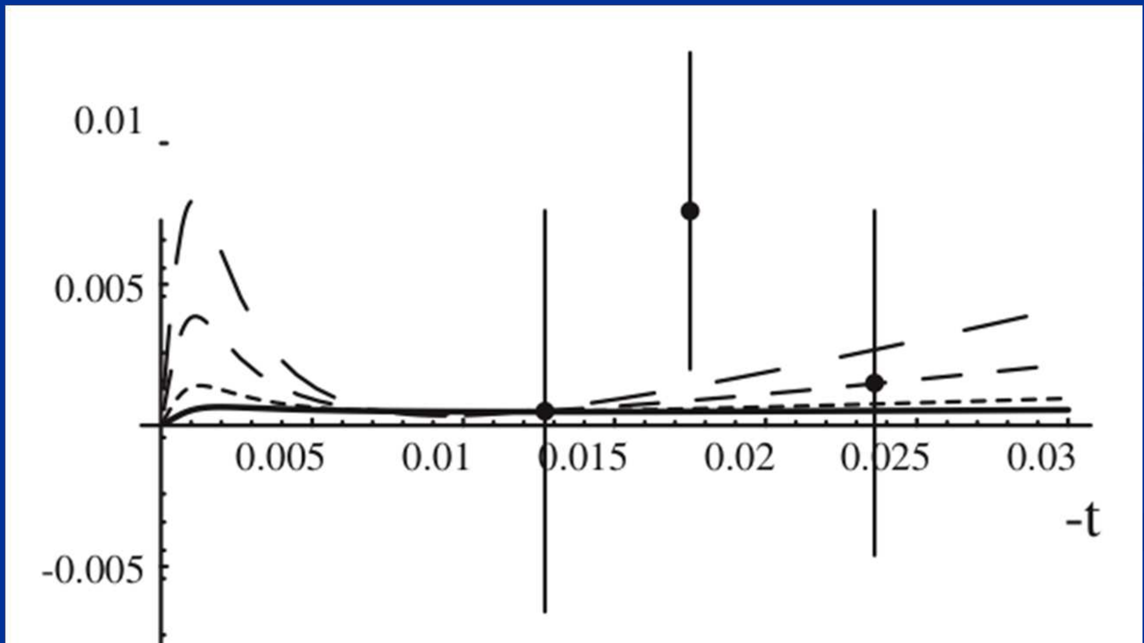
C. Bourrely, J. Soffer, T.T. Wu, arXiv:0707.2222 (2007)

Expectation for A_N at $\sqrt{s}$ = 500 GeV



Double Spin Asymmetry A_{SS}

- Prediction for A_{SS} at cms energy of 200 GeV for different spin-flip coupling constants β and zero nonflip coupling
- Solid line for zero spin-flip coupling
- Data points from pp2pp measurement 2003
- Cannot rule out Odderon with modest spin-flip coupling

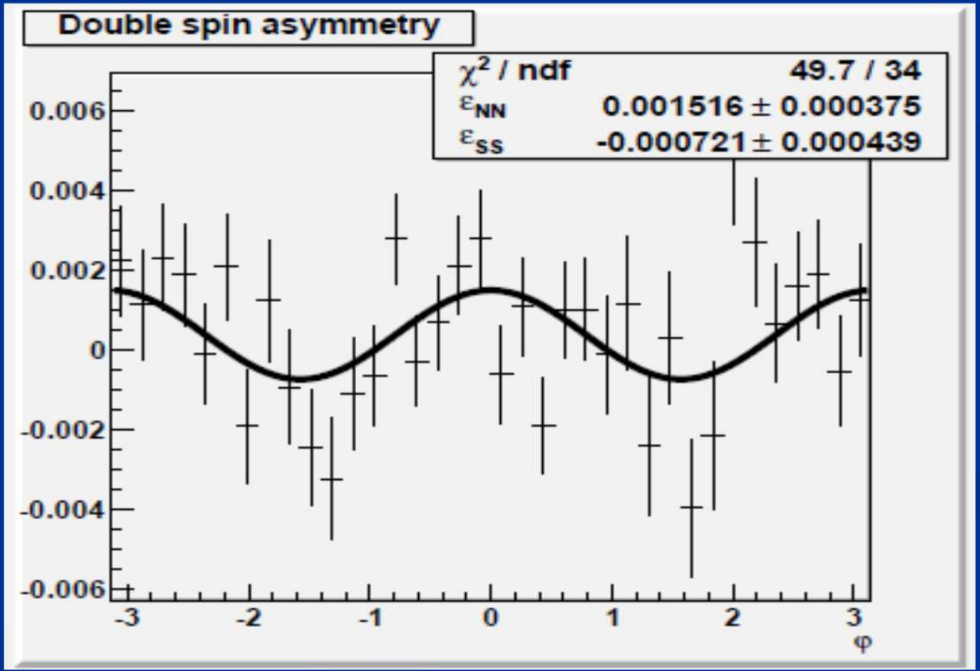


T.L. Trueman,
"Spin asymmetries for elastic proton scattering and the spin-dependent couplings of the Pomeron"
PRD 77, 054005 (2008)

Double Spin Asymmetry ε_{NN}

- Cannot use square-root formula
- Use normalized count rates *K*
  - Use STAR beam-beam counters and vertex position detectors
  - Both covering 2π acceptance
- Good agreement for single-spin asymmetries analyzed both ways

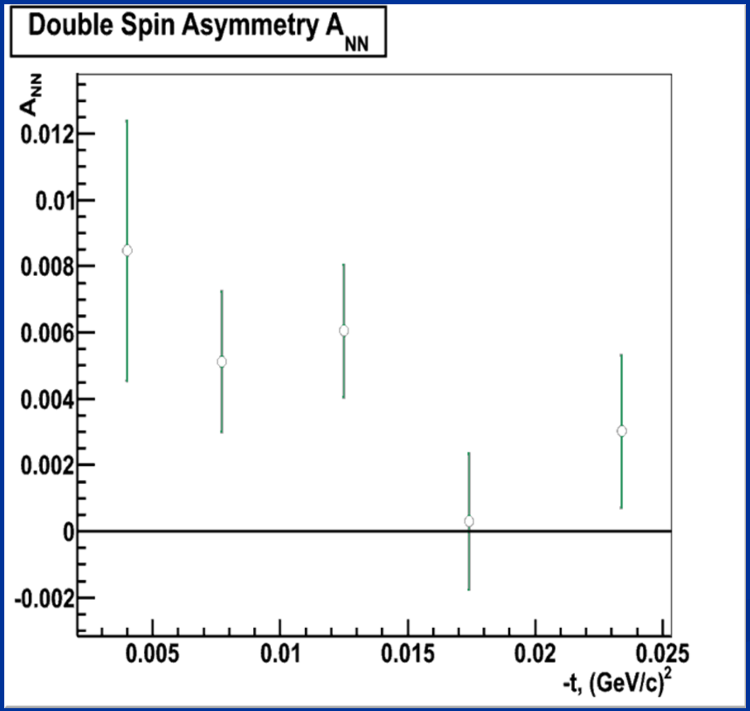
$$\varepsilon_{NN}(\varphi) = P_B P_Y (A_{NN} \cos^2 \varphi + A_{SS} \sin^2 \varphi) =$$
$$= \frac{(K^{++}(\varphi) + K^{--}(\varphi)) - (K^{+-}(\varphi) + K^{-+}(\varphi))}{(K^{++}(\varphi) + K^{--}(\varphi)) + (K^{+-}(\varphi) + K^{-+}(\varphi))}$$

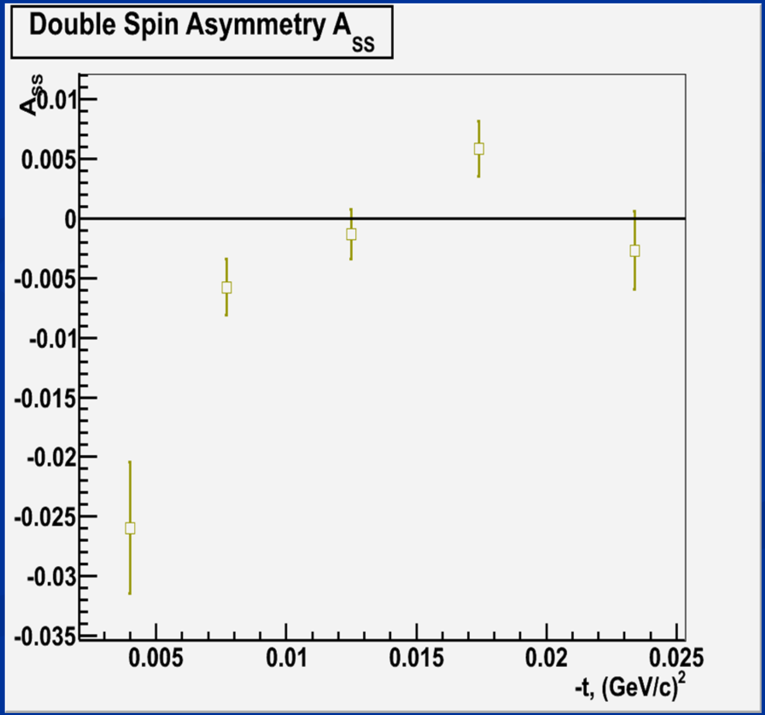


Double Spin Asymmetry ε_{NN}

- Both double spin asymmetries A_{NN} and A_{SS} very small
- Need more systematic studies

$$\varepsilon_{NN}(\varphi) = P_B P_Y (A_{NN}\cos^2\varphi + A_{SS}\sin^2\varphi) = $$
$$= \frac{(K^{++}(\varphi)+K^{--}(\varphi)) - (K^{+-}(\varphi)+K^{-+}(\varphi))}{(K^{++}(\varphi)+K^{--}(\varphi)) + (K^{+-}(\varphi)+K^{-+}(\varphi))}$$





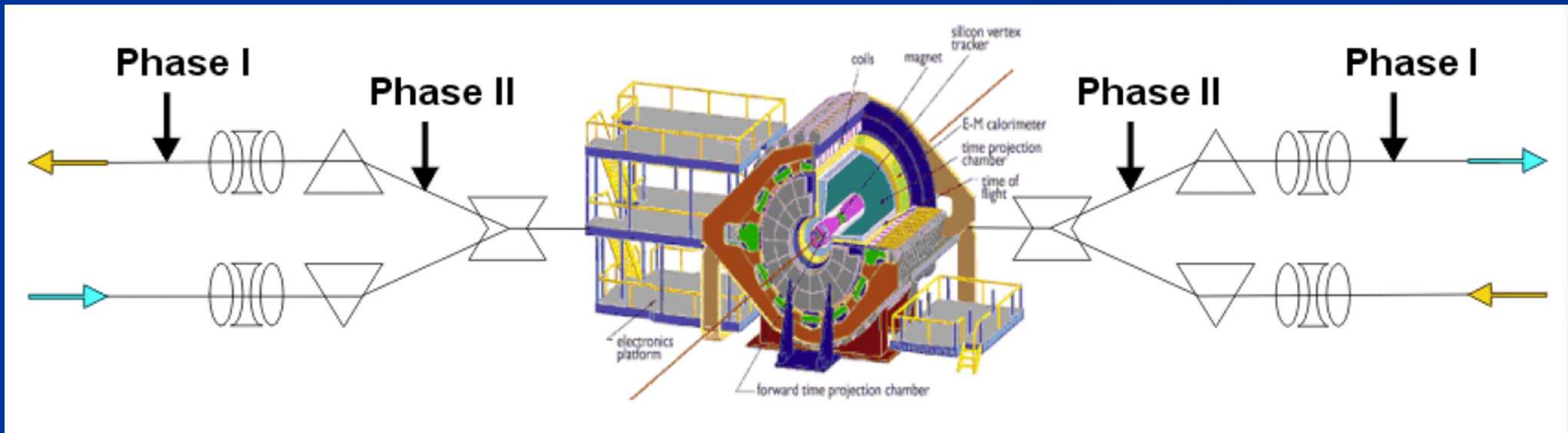
Adding Roman Pots to STAR

Phase I very similar to setup at BRAHMS

- Added STAR central detection capability
  very good central particle ID and p_T resolution
- Study elastic and diffractive scattering

Phase II adding Roman Pots between dipole magnets DX and D0

- Extends kinematic range ($-t$ < 1.5 GeV^2/c^2 for $\sqrt{s}$ = 500 GeV)
- Beam pipe between dipole magnets needs to be rebuild



Central Production at STAR

- Detect both scattered protons in Roman Pots
- Resonance state at mid-rapidity depends on transferred transverse momentum $dp_T = | p_{T1} - p_{T2} |$ (CERN WA 102)
- For large dp_T $q\bar{q}$ meson states are dominant
- For small dp_T resonances may include glueball candidates produced in Double Pomeron Exchange
- Glueballs likely to decay with emission of η mesons

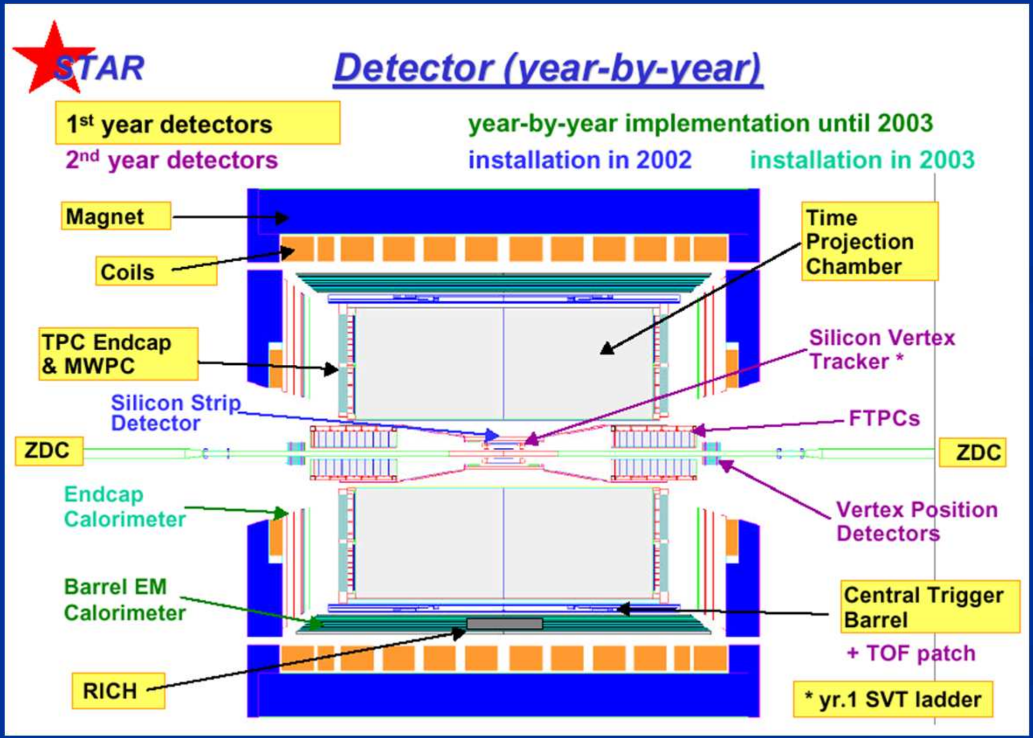
F.E. Close,
Rep. Prog. Phys. 51 (1988) 833.

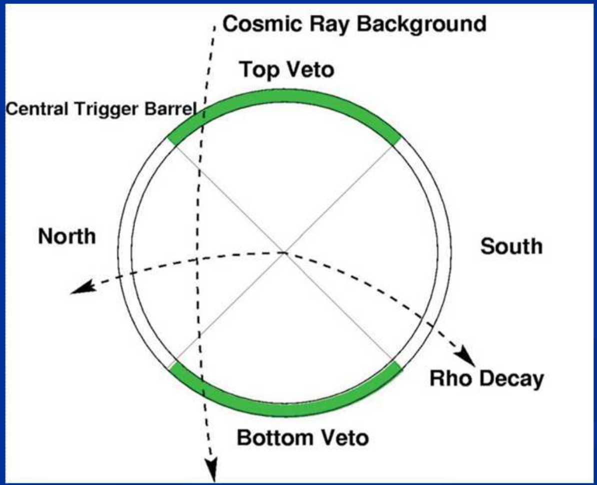
D. Barberis et al. (WA 102),
Phys. Lett. B 479 (2000) 59.

Central Production at STAR

In central region use Central Trigger Barrel to

- veto cosmic events (top and bottom veto)
- select low multiplicity events in north and south quadrants of STAR

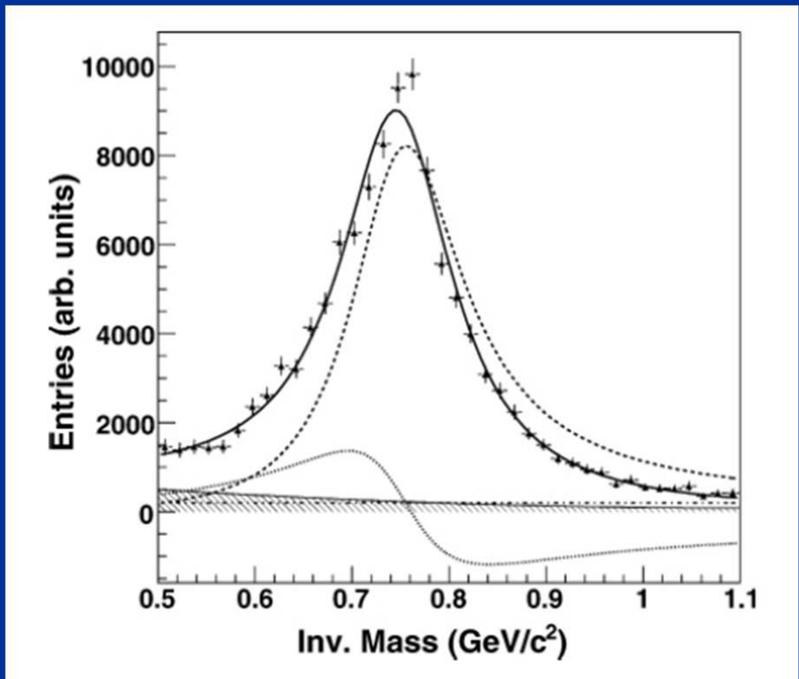


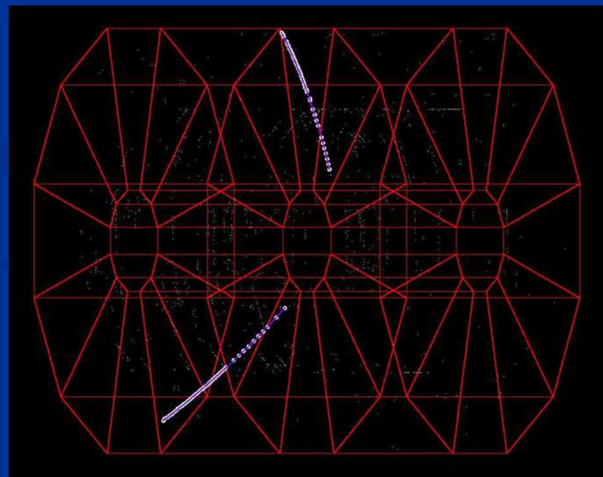


From Y. Gorbunov

Low Multiplicity Events at STAR

- ρ^0 virtual photoproduction in ultra peripheral Au-Au collisions at 200 GeV cms energy
- Select events with two tracks ($\pi^+ \pi^-$) of the same vertex in opposite quadrants of STAR



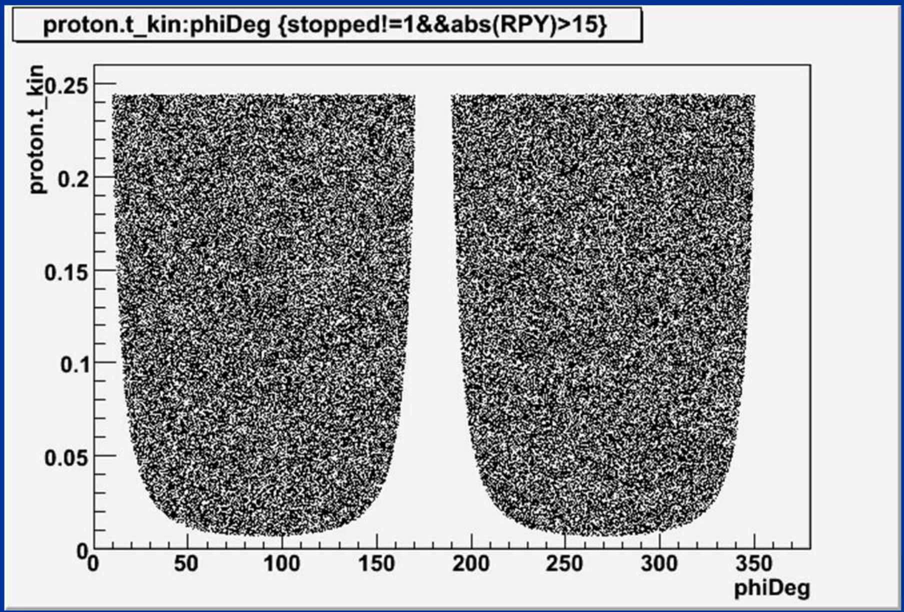


B.I. Abelev, et al. (STAR Collaboration), Phys. Rev. C 77, 034910 (2008).

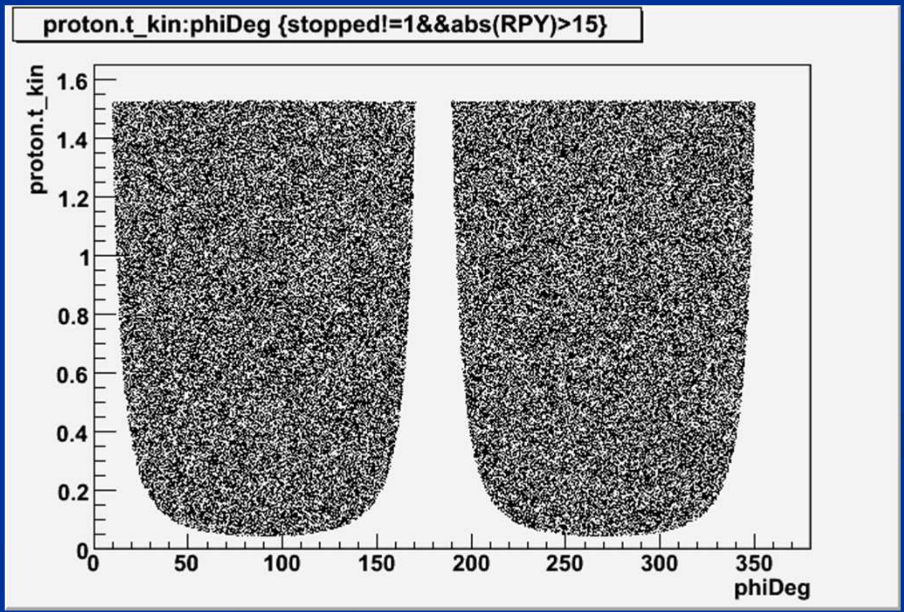
Phase II Simulated Kinematic Range for Elastically Scattered Protons

- Data taking concurrent with standard proton beam tune (using β^* = 1 m)
- Using Hector simulation program *(J. de Favereau, X. Rouby)*
- Detector positioned between DX and D0 (around z = 18 m)
- 200 x 100 mm^2 sensitive silicon detector area (15 mm distance to beam)

100 GeV/*c* proton beam momentum



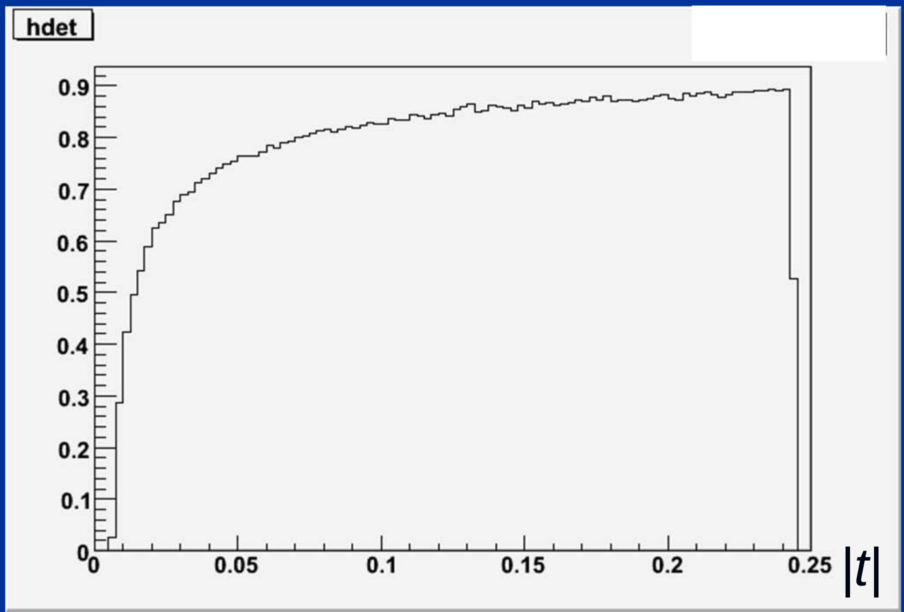
250 GeV/*c* proton beam momentum



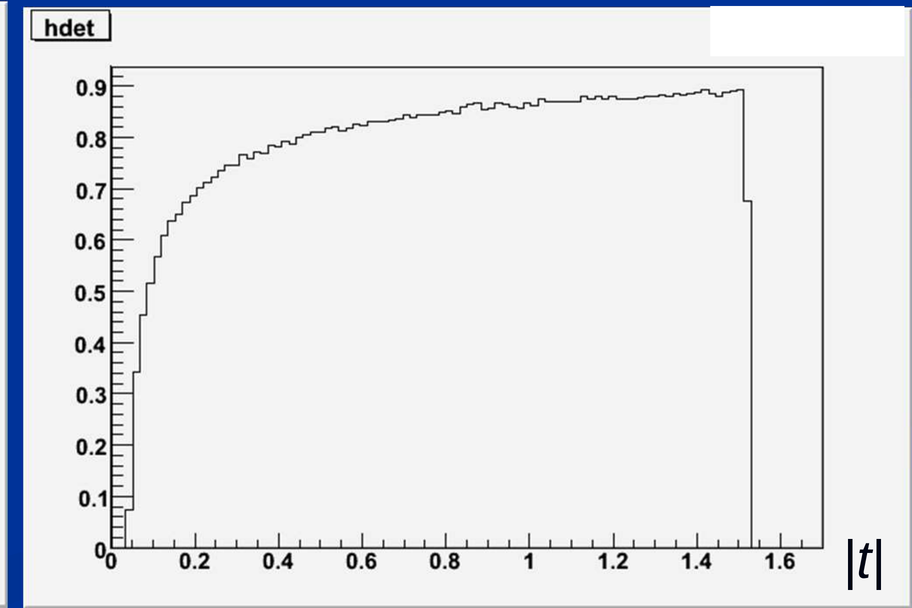
Phase II Simulated Acceptance for Elastically Scattered Protons

- $|t|$-Acceptance integrated over the azimuthal angle ϕ

100 GeV/*c* proton beam momentum



250 GeV/*c* proton beam momentum



Outlook

Phase I

- Measure in Run 09 and future runs elastic and diffractive scattering at cms energy of 200 GeV and $0.003\ (\mathrm{GeV}/c)^2 < -t < 0.038\ (\mathrm{GeV}/c)^2$ and 500 GeV
- Need special data taking run with proton beam tune of $\beta^* \approx 20$ m

Phase II

- Add Roman Pot detectors between DX and D0 magnets at 17 and 18 m positions to increase t - range to a maximum of $-t < 1.5\ (\mathrm{GeV}/c)^2$ for cms energy of 500 GeV
- Data taking for Phase II does not require special beam tune

Additional Slides

Double Spin Asymmetry Result A_{NN}

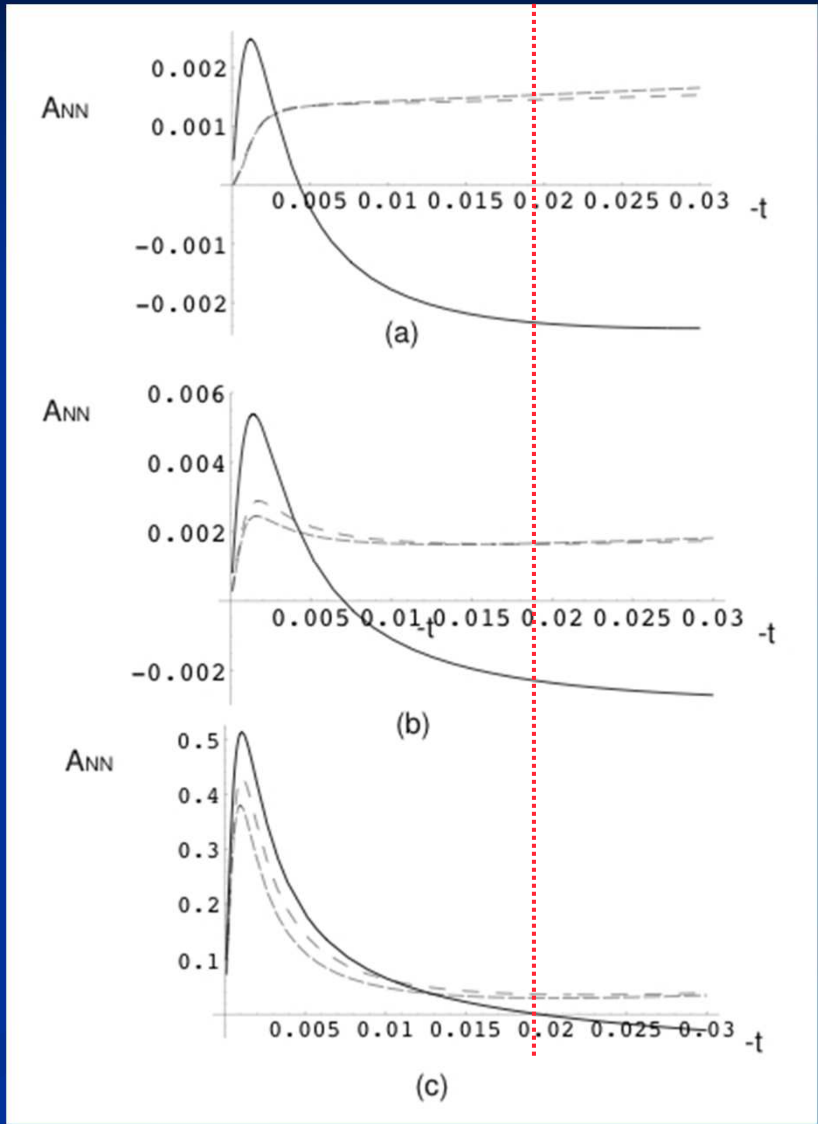
Average < t > = - 0.0185 (GeV/c)^2

A_{NN} = 0.030 ± 0.017 (stat.+nor.)
± 0.005 (sys.)

Large errors do not really allow to discriminate between model predictions

Curves for √s = 14 GeV ———
√s = 200 GeV – – –
√s = 500 GeV – – – –

T. L. Trueman, arXiv:hep-ph/0604153 (2006)
a) No Odderon spin coupling
b) Weak Odderon spin coupling (like Pomeron)
c) Strong Odderon spin coupling



Double Spin Asymmetry Result A_{SS}

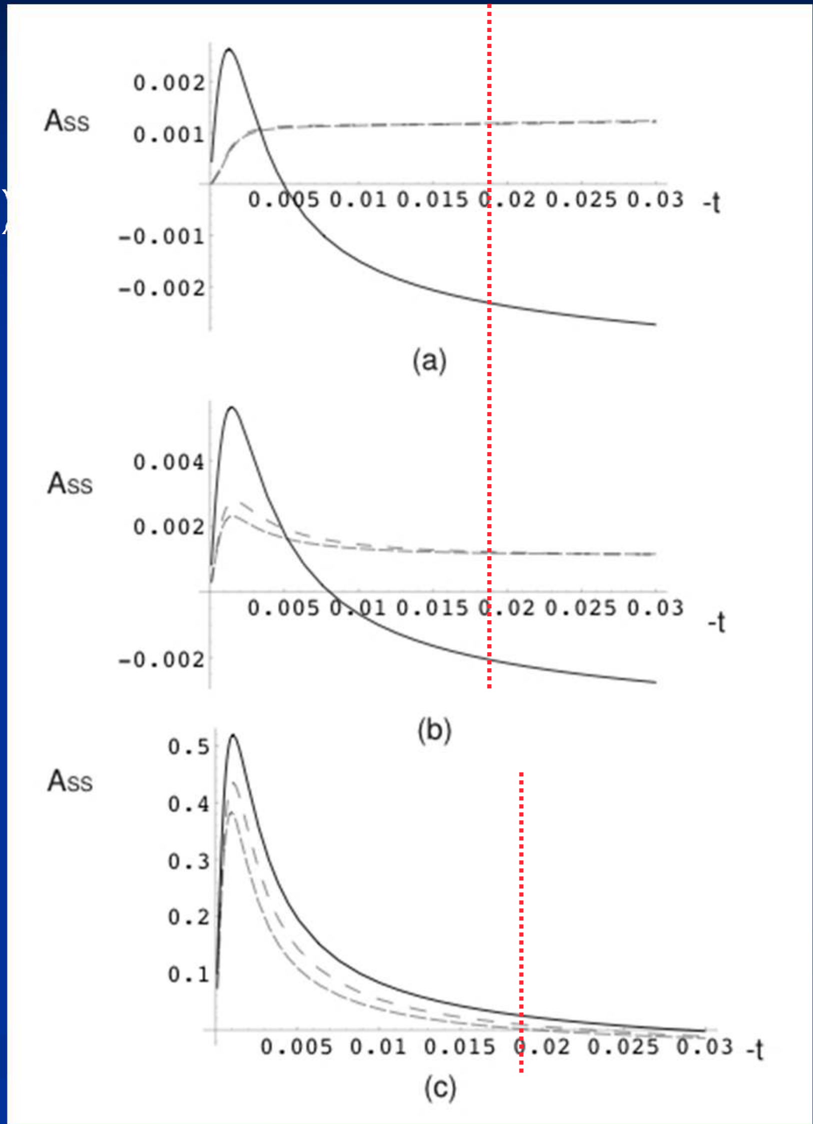
Average < t > = - 0.0185 (GeV/c)^2

A_{SS} = 0.004 ± 0.008 (stat.+nor.) ± 0.003 (sys.)

But

< -t >	0.013	0.018	0.024
A_{SS}	0.001	0.008	0.002
ΔA_{SS} (stat.)	0.007	0.006	0.006

Results maybe weakly favour no or weak Odderon spin coupling



T. L. Trueman, arXiv:hep-ph/0604153 (2006)
a) No Odderon spin coupling
b) Weak Odderon spin coupling (like Pomeron)
c) Strong Odderon spin coupling

Phase I at STAR with 200 GeV

- Special beam tune of $\beta^* = 20$ m
- Luminosity $2 \cdot 10^{29}$ cm^{-2} sec^{-1}
- Four days of data taking
- Two Roman Pot stations at each 58 m position from IP

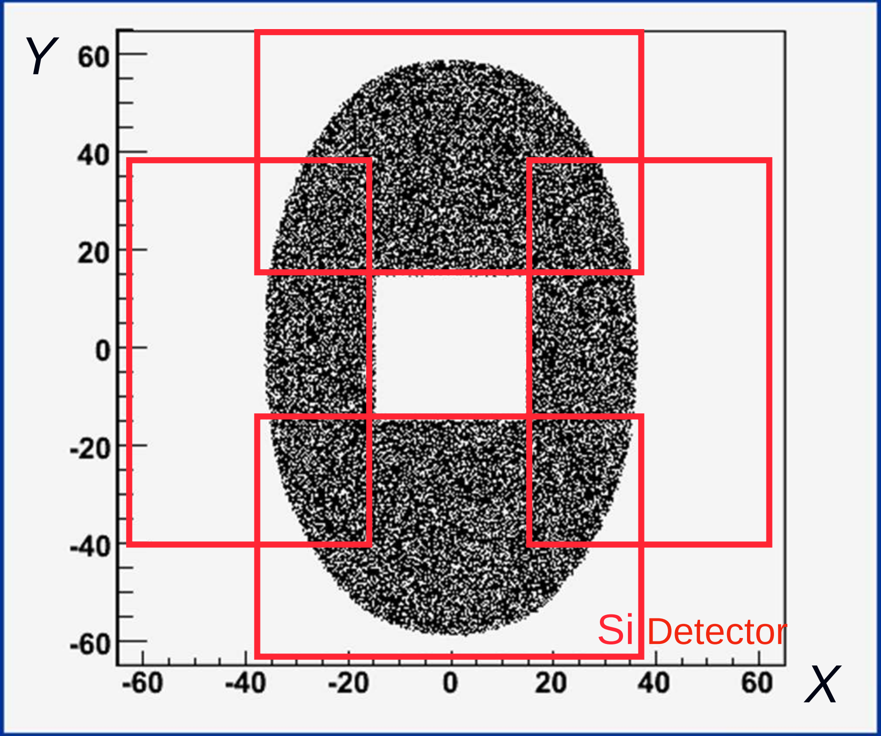
- Elastic rate of 400 Hz ($3.1 \cdot 10^{7}$ events)
- DPE rate of 8 Hz ($6.3 \cdot 10^{5}$ events)

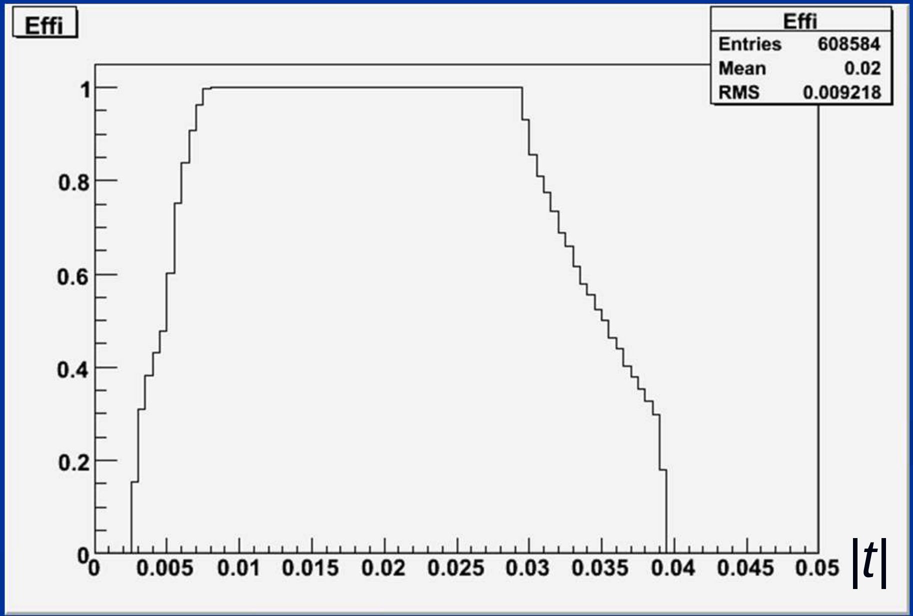
- Elastic trigger using Roman Pot co-linearity
- DPE trigger using Roman Pot trigger in same hemisphere plus STAR detector Central Trigger Barrel (or future ToF)

Phase I Elastic Scattering with STAR at 200 GeV

Expand $-t$ range to 0.003 - 0.038 GeV^2/c^2

- Maximum of A_N for 200 GeV is at $-t$ = 0.002 GeV^2/c^2
- Need to constrain shape of A_N, not only maximum value





Phase I Elastic Scattering with STAR at 200 GeV

Expected uncertainties for elastic scattering

- Nuclear slope parameter Δb = 0.3 (GeV/c) $^{-2}$

  1.6 (GeV/c)$^{-2}$ from 1st measurement
- Total cross section $\Delta\sigma$ = 3 mb — **not measured so far**
- ρ-parameter $\Delta\rho$ = 0.01 — **not measured so far**
- Analyzing power ΔA_N = 0.0017 — **0.0023 from 1st measurement**
- Double spin asymmetries $\Delta A_{NN} = \Delta A_{SS}$ = 0.0053

  0.017 (0.008) from 1st measurement