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, …)

Stephen Bültmann - ODU
Nuclear Seminar, UVa, October 2011
The RHIC Accelerator

Designed for colliding heavy ion beams

→ Need two separate beam lines with individual transport magnets except in the interaction regions

→ 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

Stephen Bültmann - ODU
Nuclear Seminar, UVa, October 2011
Birds Eye View of RHIC

PHOBOS
10:00 o'clock

PHENIX (π)
8:00 o'clock

BRAHMS & PP2PP (→)
2:00 o'clock

12:00 o'clock

STAR (p)
6:00 o'clock

RHIC

NASA - BAF

μ g-2

HEP/NS(p)

LINAC

BOOSTER

AGS

TANDEMS

Stephen Bültmann - ODU

Nuclear Seminar, UVa, October 2011
The RHIC Accelerator

**RHIC Accelerator Components**

- **RHIC Booster**
- **BRAHMS**
- **PHENIX**
- **PHOBOS**
- **AGS**
- **Siberian Snakes**
- **Spin Rotators**
  - (longitudinal polarization)
- **Solenoid Partial Siberian Snake**
- **RHIC pC Polarimeters**
- **AGS pC Polarimeters**
- **Strong Helical AGS Snake**
- **Spin flipper**
- **200 MeV Polarimeter**
- **Rf Dipole**
- **AGS Internal Polarimeter**
- **LINAC**
- **Pol. H^+ Source**
- **Absolute Polarimeter (H^+ jet)**

**Nuclear Seminar, UVa, October 2011**

**Stephen Bültmann - ODU**
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 $\sigma_{\text{tot}}$ 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 $\rho_0$ and extract its real part using measured $\sigma_{\text{tot}}$
Differential Elastic Cross Section

For Proton–Proton Scattering

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

\(\Delta \Phi\) = Coulomb Phase
\(G_E\) = Proton Electric Form Factor

Input : \(\sigma_{tot} = 52\) mb
\(\rho = 0.13\)
\(b = 14\) GeV\(^2\)

Values for \(\sqrt{s} = 200\) GeV

Stephen Bültmann - ODU

Nuclear Seminar, UVa, October 2011
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

Measure

\[ \sigma_{\text{tot}} = \frac{8 \pi}{s} \quad \text{Im} \left[ \phi_+(s,t) \right]_{t=0} \]
\[ \frac{d\sigma}{dt} = \frac{2 \pi}{s^2} \left( |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4 |\phi_5|^2 \right) \]
\[ \Delta\sigma_T = -\frac{8 \pi}{s} \quad \text{Im} \left[ \phi_2(s,t) \right]_{t=0} = \sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow} \]

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

\[
A_N(t) = \frac{1}{P_Y \cdot \cos \phi} \left( \frac{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) - N_{\downarrow\uparrow}(t) - N_{\uparrow\downarrow}(t)}{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) + N_{\downarrow\uparrow}(t) + N_{\uparrow\downarrow}(t)} \right)
\]

\[
\propto \frac{\text{Im} \left( \phi_{\text{flip}}^{\text{em}} \cdot \phi_{\text{no-flip}}^{\text{had}} + \phi_{\text{flip}}^{\text{had}} \cdot \phi_{\text{no-flip}}^{\text{em}} \right)}{d\sigma / dt}
\]

\[
r_5 = \frac{m_p}{\sqrt{-t}} \cdot \frac{\phi_{\text{had}}^{5\text{had}}}{\text{Im} \left( \phi_{\text{had}}^{5\text{had}} \right)}
\]

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

\[P_Y = \text{beam pol.}\]

\[\varphi = \text{azimuth}\]

*Stephen Bültmann - ODU*  
*Nuclear Seminar, UVa, October 2011*
Double Spin Asymmetries

Measure $A_{\text{NN}}$ and $A_{\text{SS}}$ with transversely polarized protons to find limit on detectable Odderon, $C = -1$ partner of the Pomeron, contribution to interference between $\phi_1$ and $\phi_2$

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

$$A_{\text{NN}}(t) = \frac{1}{P_Y \cdot P_B \cdot \cos^2 \varphi}$$

$$A_{\text{SS}}(t) = \frac{1}{P_Y \cdot P_B \cdot \sin^2 \varphi}$$

For small $t$

$$\frac{\text{Re} \left( \phi_{\text{no-flip}} \phi_2^* \right)}{d\sigma/dt} \propto \frac{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) - N_{\uparrow\downarrow}(t) - N_{\downarrow\uparrow}(t)}{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) + N_{\uparrow\downarrow}(t) + N_{\downarrow\uparrow}(t)}$$
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

Stable hydrogen jet target of $10^{12}$ atoms/cm$^2$
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.


Stephen Bültmann - ODU

Nuclear Seminar, UVa, October 2011
Experimental Technique

• Elastically scattered protons have very small scattering angle $\Theta^*$, 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 $\theta^*$

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

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

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

Similar equations for $y$-coordinate

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

$x$ : Position at Detector

$\theta_x$ : Angle at Detector

$x_0$ : Position at Interaction Point

$\theta_x^*$ : Scattering Angle at IP

Stephen Bültmann - ODU  Nuclear Seminar, UVa, October 2011
Beam Transport

RHIC Insertion Functions

$v_x = 28.73$  $v_y = 29.72$  $\beta = 21.0326$  FILE = optics/rhbluepp2pp.optics

100 GeV/c
$\epsilon_N = 10\pi$ mm-mrad
$\theta = 400\mu$rad

$\theta L_{eff} [x]$  $\theta L_{eff} [y]$  $6\sigma_x$  $6\sigma_y$

Beam Transport

Stephen Bültmann - ODU
Nuclear Seminar, UVa, October 2011
pp2pp Experimental Setup 2003

Roman Pot above beam
Roman Pot below beam

to IR

Stephen Bültmann - ODU
Nuclear Seminar, UVa, October 2011
STAR Experimental Setup 2009

Stephen Bültmann - ODU

Nuclear Seminar, UVa, October 2011
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)
Hit distribution of scattered protons within $3\sigma$ - 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 $A_N$

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

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

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

\[
\delta(\varphi) = P_B P_Y (A_{NN} \cos^2 \varphi + A_{SS} \sin^2 \varphi) < 0.01 << 1
\]
\[ \varepsilon_N = A_N \cdot P \] for one bin with \( \langle -t \rangle = 0.0077 \text{ GeV}/c^2 \)
\[ \varepsilon_N = A_N \cdot P \] for one bin with \( < -t > = 0.0077 \text{ GeV}/c^2 \)
Analyzing Power Measurement 2009

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

- Single Spin Asymmetry \( A_N @ \sqrt{s}=200 \text{ GeV} \)
  - \( \chi^2 / \text{ndf} = 1.859 / 3 \)
  - \( \text{Re} r_5 = 0.0001486 \pm 0.001778 \)
  - \( \text{Im} r_5 = -0.02498 \pm 0.03046 \)

- Only statistical errors shown

\[ r_5 = \frac{m_p}{\sqrt{-t}} \frac{\phi_5^{\text{had}}}{\text{Im} (\phi_+^{\text{had}})} \]
Comparison with Calculations

Impact picture calculation predicts $b = 16.25$ GeV$^2$

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 $\beta$ 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

Double Spin Asymmetry $\varepsilon_{NN}$

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

$$\varepsilon_{NN}(\phi) = P_B P_T (A_{NN} \cos^2 \phi + A_{SS} \sin^2 \phi) =$$

$$= \frac{(K^{++}(\phi) + K^{--}(\phi)) - (K^{-+}(\phi) + K^{++}(\phi))}{(K^{++}(\phi) + K^{--}(\phi)) + (K^{-+}(\phi) + K^{++}(\phi))}$$
Both double spin asymmetries $A_{NN}$ and $A_{SS}$ very small

Need more systematic studies

$$\epsilon_{NN}(\varphi) = P_{h}P_{\gamma}(A_{NN}\cos^2\varphi + A_{SS}\sin^2\varphi) = \frac{(K^{++}(\varphi) + K^{-}(\varphi)) - (K^{+}(\varphi) + K^{-}(\varphi))}{(K^{++}(\varphi) + K^{-}(\varphi)) + (K^{+}(\varphi) + K^{-}(\varphi))}$$
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 ($-t < 1.5 \text{ GeV}^2/c^2$ for $\sqrt{s} = 500 \text{ GeV}$)
  • 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 $d\rho_T = |\rho_{T1} - \rho_{T2}|$ (CERN WA 102)
- For large $d\rho_T$ $q\bar{q}$ meson states are dominant
- For small $d\rho_T$ resonances may include glueball candidates produced in Double Pomeron Exchange
- Glueballs likely to decay with emission of $\eta$ mesons

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

Stephen Bültmann - ODU
Nuclear Seminar, UVa, October 2011
Low Multiplicity Events at STAR

- $\rho^0$ 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
Phase II Simulated Kinematic Range for Elastically Scattered Protons

- Data taking concurrent with standard proton beam tune (using $\beta^* = 1$ 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 $\phi$

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 $0.003 \text{ (GeV/c)}^2 < -t < 0.038 \text{ (GeV/c)}^2$ and 500 GeV
• Need special data taking run with proton beam tune of $\beta^* \approx 20 \text{ m}$

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 $-t < 1.5 \text{ (GeV/c)}^2$ 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 $< t > = -0.0185 \text{ (GeV/c)}^2$

$A_{NN} = 0.030 \pm 0.017 \text{ (stat.+nor.)}$
$\pm 0.005 \text{ (sys.)}$

Large errors do not really allow to discriminate between model predictions

Curves for $\sqrt{s} = 14 \text{ GeV}$ ———
$\sqrt{s} = 200 \text{ GeV}$ – – –
$\sqrt{s} = 500 \text{ GeV}$ – – – –

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)$^2$

$A_{SS} = 0.004 \pm 0.008$ (stat.+nor.) $\pm 0.003$ (sys.)

But

<table>
<thead>
<tr>
<th>$&lt; -t &gt;$</th>
<th>0.013</th>
<th>0.018</th>
<th>0.024</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{SS}$</td>
<td>0.001</td>
<td>0.008</td>
<td>0.002</td>
</tr>
<tr>
<td>$\Delta A_{SS}$ (stat.)</td>
<td>0.007</td>
<td>0.006</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Results maybe weakly favour no or weak Odderon spin coupling

- 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

Stephen Bültmann - ODU

Nuclear Seminar, UVa, October 2011
Phase I Elastic Scattering with STAR at 200 GeV

Expected uncertainties for elastic scattering

- Nuclear slope parameter $\Delta b = 0.3 \text{ (GeV/c)}^{-2}$
  - 1.6 (GeV/c)$^{-2}$ from 1st measurement
- Total cross section $\Delta \sigma = 3 \text{ mb}$
  - not measured so far
- $\rho$-parameter $\Delta \rho = 0.01$
  - not measured so far
- Analyzing power $\Delta A_N = 0.0017$
  - 0.0023 from 1st measurement
- Double spin asymmetries $\Delta A_{NN} = \Delta A_{SS} = 0.0053$
  - 0.017 (0.008) from 1st measurement