What did we learn from 200 and 62 GeV pp collisions at RHIC?

A BRAHMS perspective

Flemming Videbaek
Physics Department, BNL
Outline of the presentation

• Background.
• pp at 200 GeV
  • Bulk properties
  • Results and comparisons to NLO pQCD.
• pp at 62 GeV
  • Preliminary results and comparison to pQCD
• A BRAHMS unexpected benefit:
  • Single Spin Asymmetries at 200 and 62 GeV
Introduction

- Forward rapidity at RHIC collider $\sqrt{s} = 200$ GeV offers insight into pp, p(d)A and AA in
  - Low-x region (for target like p, A)
  - Probing larger $x_F$ region where kinematic constraints may be important.

Today's focus on pp collisions, which also serves as reference for HI data.
pp data and pQCD

- At mid-rapidity NLO pQCD works well for $p_0$. This even down to lower energies.
- Question to ask is how well it works at more forward rapidities in view of previous failures?

*Fig. 4. $E d^3 \sigma / d^3 p$ at $\sqrt{s} = 52.8$ GeV, as a function of $x_F$ for three different scattering angles. The data are from [20] and the curves are the corresponding NLO pQCD calculations with $\mu = p_T$. The dotted-dashed curves are for $\mu = p_T/2$.*

BRAHMS is still at 2 o’clock, but will not run this year.
The long 200 GeV pp run5 have resulted in high quality pp reference spectra at high rapidity.

Together with mid rapididity data look at net-p
Together with mid-rapidity data look at net-protons.

Despite larger systematic uncertainties better agreement with the baryon transport in Hijing/B.
Ratios $p/\pi^+$ at $y=3.0$ and $3.3$

The $\pi^-/\pi^+$ ratio is consistent with dominance of valence quarks at these rapidities at the higher $p_T$.

Small $\overline{p}/p$ ratio eliminates possible strong gluon $\rightarrow p$ or $\overline{p}$ fragmentation ($p/\overline{p}\sim 1$)

The difference between protons and anti-protons indicates another mechanism besides fragmentation that puts so many protons at high $p_T$.

Red: $p/\pi^+$

Blue: $\overline{p}/\pi^-$
NLO pQCD comparisons to BRAHMS data

Calculations done by W. Vogelsang. Only one scale \( \mu = p_T \) and the same fragmentation functions as used for the PHENIX/STAR comparisons.

KKP has only \( \pi^0 \) frag. Modifications were needed to produce charged pions.

KKP FF does a better job compared to Kretzer, Pi and Kaon production still dominated by \( gg \) and \( gq \) at these rapidities apart from the highest \( p_T \).

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Another view of rapidity dependence.

Notice the significant change in shape due to available phase space.
Brahms had the last data taking during the two-week 62.4 GeV in June 2006. The focus was on Reference spectra for AuAu Single Spin asymmetries.

Coverage for \(\pi^-\) at forward rapidities. Note the kinematic limits.
Spectra

Near mid-rapidity
Y~0 and y~1
Spectra for pi, K and p using Time-of-flight.
dn/dy for pi+ at y=0 compared to Alper et.al. ISR
Particle Ratios

Proton, pion spectra and particle ratio $p/\pi$ at $y\sim0$. As known in $pp$ the $p/\pi$ saturates at $\sim0.4$.

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Pions at high rapidity

pp -> $\pi^-$
62.4 GeV

Brahms preliminary

y=2.65

y=3.25

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Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS pi- data. Calculation is for pi0, but $\pi^+/\pi^0 \sim 1$ with 5% in range of $p_T$ - measured.
Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS $\pi^-$ data at high rapidity. The calculations are for KKP and a scale factor of $\mu=pt$. The agreement is surprisingly good. The kinematic cutoffs as moving to higher $y$ is reproduced.
Summary pp spectra

• At RHIC we now have identified charged particle production at high rapidity to large $p_T$
• NLO pQCD calculations describe the pion and kaon production with fragmentation functions known as mKKP. This agreement imply a dominance of $gq$ and $gg$ processes at these high rapidities as was the case for the measurements of neutral pions at mid-rapidity.
• The behavior of protons around $y=3$ cannot be explained with NLO calculation and the abundance of protons (with respect to positive pions) at high $p_T$ is an open question clear related to baryon transport; Protons have larger mass-scale and larger number of constituents
• Even at 62.4 GeV the NLO pQCD describes the data at high rapidity. This is surprising in view of the previous studies (Soffer). It may be related to the kinematic range studied in our data.
Single transverse Spin Asymmetry (SSA): Introduction

- Large SSAs have been observed at forward rapidities in hadronic reactions: E704/FNAL and STAR/RHIC
- SSA is suppressed in naïve parton models ($\sim \alpha_s m_q/Q$)
- Non-zero SSA at partonic level requires
  - Spin Flip Amplitude, and
  - Relative phase
- SSA: Unravelling the spin-orbital motion of partons?
Beyond Naïve Parton Models to accommodate large SSA

• Spin and Transverse-Momentum-Dependent parton distributions
  - “Final state” in Fragmentation (Collins effect),
  - “Initial state” in PDF (Sivers effect)
• Twist-3 matrix effects
  - Hadron spin-flip through gluons and hence the quark mass is replaced by $\Lambda_{QCD}$
  - Efremov, Teryaev (final state)
  - Qiu, Sterman (initial state)
• Or combination of above
  - Ji, Qiu, Vogelsang, Yuan…

Challenge to have a consistent partonic description:
- Energy dependent SSA vs. $x_F$, $p_T$,
- Flavor dependent SSA
- Cross-section
BRAHMS measures identified hadrons ($\pi, K, p, \bar{p}$) in the kinematic ranges of:
- $0 < x_F < 0.35$ and $0.2 < p_T < 3.5$ GeV/c at $\sqrt{s}=200$ GeV
- $0 < x_F < 0.6$ and $0.2 < p_T < 1.5$ GeV/c at $\sqrt{s}=62$ GeV for
  - $x_F$, $p_T$, flavor, $\sqrt{s}$ dependent SSA
  - cross-section of un-polarized hadron production
    (constraint for theoretically consistent description)

Data:
- Run-5: $\sqrt{s} = 200$ GeV 2.5 pb$^{-1}$ recorded (45-50% of polarization)
- Run-6: $\sqrt{s} = 62$ GeV 0.21 pb$^{-1}$ recorded (45-65%)

Data from Forward Spectrometer at 2.3-4 deg. covering “high”-$x_F$ ($0.15 < x_F < 0.6$) are presented.
Determination of Single Spin Asymmetry: $A_N$

- Asymmetries are defined as
  
  \[ A_N = \frac{(\sigma^+ - \sigma^-)}{(\sigma^+ + \sigma^-)} = \frac{\varepsilon}{P} \]

- For non-uniform bunch intensities
  
  \[ \varepsilon = \frac{N^+ / \mathcal{L}^+ - N^- / \mathcal{L}^-}{(N^+ / \mathcal{L}^+ + N^- / \mathcal{L}^-)} \]
  
  \[ = \frac{(N^+ - \mathcal{L}^*N^-)}{(N^+ + \mathcal{L}^*N^-)} \]

  where $\mathcal{L}$ = relative luminosity = $\mathcal{L}^+ / \mathcal{L}^-$

  and the yield of in a given kinematic bin with the beam spin direction is $N^+$ (up) and $N^-$ (down).

- Most of the systematics in $N^+/N^-$ cancel out

- Uncertainties on relative luminosity $\mathcal{L}$ estimated to be $< 0.3\%$

- Beam polarization $P$ from on-line measurements:
  
  systematic uncertainty of $\sim 18\%$

- Overall systematic error on $A_N$: $\sim 25\%-30\%$
• Strong $x_F$-$p_T$ correlation due to limited spectrometer solid angle acceptance
Calculations compared at the BRAHMS kinematic region

- **Twist-3 parton correlation** calculation provide by F. Yuan
  - Kouvarius, Qiu, Vogelsang, Yuan
  - “Extended” with non-derivative terms
    - (“moderate” effects at BRAHMS kinematics)
  - Two flavor \((u,d)\) and valence+sea+antiquarks Fits
- **Sivers effect** calculation provided by U. D’Alesio
  - Anselmino, Boglione, Leader, Melis, Murgia
  - “Sivers effect with complete and consistent \(k_T\) kinematics plus description of unpolarized cross-section”

These models describe the low energy data reasonably well.
$A_N(\pi)$ at 2.3 deg. at $\sqrt{s} = 200$ GeV

- $A_N(\pi^+)$: positive $\sim(<)$
- $A_N(\pi^-)$: negative: 4-6% in $0.15 < x_F < 0.3$

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$A_N(\pi)$ at 2.3 deg. at $\sqrt{s} = 200$ GeV compared with Twist-3

Solid lines: two-flavor ($u, d$) fit
Dashed lines: valence + sea, anti-quark
Calculations done only for $<p_T(\pi)> > 1$ GeV/c
$A_N(\pi)$ at 2.3 deg. at $\sqrt{s} = 200$ GeV compared with Sivers effect

Curves: Sivers effect by U. D’Alesio
**A_N(K) at 2.3 deg at \( \sqrt{s} = 200 \text{ GeV} \)**

- \( A_N(K^+) \sim A_N(K^-) \): positive 2-5% for \( 0.15 < x_F < 0.3 \)
- If main contribution to \( A_N \) at large \( x_F \) is from valence quarks: \( A_N(K^+) \sim A_N(\pi^+) \), \( A_N(K^-) \sim 0 \): disagreement with naïve expectations
$A_N(K)$ at 2.3 deg at $\sqrt{s} = 200$ GeV compared with Twist-3

Curves: Twist-3 by F. Yuan

Solid lines: two-flavor ($u, d$) fit
Dashed lines: valence + sea, anti-quark
Calculations done only for $<p_T(\pi)> > 1$ GeV/c
Kinematic coverage at $\sqrt{s} = 62$ GeV (FS at 2.3 and 3 deg)
$A_N(\pi)$ at $\sqrt{s} = 62$ GeV

- Large $A_N(\pi)$: 40% at $x_F \sim 0.6$ $p_T \sim 1.3$ GeV
- Strong $x_F$ -$p_T$ dependence ("Alligator")
- $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with $x_F$-$p_T$
$$A_N(K) \text{ at } \sqrt{s} = 62 \text{ GeV}$$
$A_N(K)$ at $\sqrt{s} = 62$ GeV compared with Twist-3

Curves: Twist-3 by F. Yuan
Summary

BRAHMS measures $A_N$ of identified hadrons at 62 GeV and 200 GeV

- P, K cross-section at 200 GeV described by NLO pQCD. At 62 GeV intriguing results showing that pQCD may actually still be valid at large $y$.

- Large SSAs seen for pions and kaons

  Suggesting:
  - Sivers mechanism plays an important role.
  - Described (qualitatively) by Twist-3
  - Main contributions are from leading (favored) quarks
  - Power-suppression $1/p_T$ set the scale

Questioning:

- Where the large positive $A_N(K^-)$ come from then?
- Sea quark contributions not well understood: $A_N(K^-)$ and $A_N(p\bar{p})$
- How well pQCD applicable at 62 GeV
  (cross-sections at 62 GeV will be delivered)
- What can (not) be learned from $A_N$ at $p_T < 1$ GeV/c
- $A_N(-x_F) \sim 0$ set limits on Sivers-gluon contribution?
- Can $A_N(p, p\bar{p})$ be described in the consistent framework?
- What are the theoretical uncertainties, $p_T \sim 1$ GeV valid for QCD description?
BRAHMS Collaboration

I. C. Arsene\textsuperscript{12}, I. G. Bearden\textsuperscript{7}, D. Beavis\textsuperscript{1}, S. Bekele\textsuperscript{12}, C. Besliu\textsuperscript{10}, B. Budick\textsuperscript{6}, H. Bøggild\textsuperscript{7}, C. Chasman\textsuperscript{1}, C. H. Christensen\textsuperscript{7}, P. Christiansen\textsuperscript{7}, H. Dahlsgaard\textsuperscript{7}, R. Debbe\textsuperscript{1}, J. J. Gaardhøje\textsuperscript{7}, K. Hagel\textsuperscript{8}, H. Ito\textsuperscript{1}, A. Jipa\textsuperscript{10}, E. B. Johnson\textsuperscript{11}, J. I. Jørdre\textsuperscript{9}, C. E. Jørgensen\textsuperscript{7}, R. Karabowicz\textsuperscript{5}, N. Katrynska\textsuperscript{5}, E. J. Kim\textsuperscript{11}, T. M. Larsen\textsuperscript{7}, J. H. Lee\textsuperscript{1}, Y. K. Lee\textsuperscript{4}, S. Lindahl\textsuperscript{12}, G. Løvhøiden\textsuperscript{12}, Z. Majka\textsuperscript{5}, M. J. Murray\textsuperscript{11}, J. Natowitz\textsuperscript{8}, C. Nygaard\textsuperscript{7}, B. S. Nielsen\textsuperscript{8}, D. Ouerdane\textsuperscript{8}, D. Pal\textsuperscript{12}, F. Ramí\textsuperscript{3}, C. Riste\textsuperscript{8}, O. Riste\textsuperscript{a11}, D. Röhrich\textsuperscript{9}, B. H. Samset\textsuperscript{12}, S. J. Sanders\textsuperscript{11}, R. A. Scheetz\textsuperscript{1}, P. Stasz\textsuperscript{5}, T. S. Tvet\textsuperscript{er12}, F. Videbæk\textsuperscript{1}, R. Wada\textsuperscript{8}, H. Yang\textsuperscript{9}, Z. Yin\textsuperscript{9}, I. S. Zgura\textsuperscript{2}

1. Brookhaven National Laboratory, Upton, New York, USA
2. Institute of Space Science, Bucharest - Magurele, Romania
3. Institut Pluridisciplinaire Hubert Curien et Université Louis Pasteur, Strasbourg, France
4. Johns Hopkins University, Baltimore, USA
5. M. Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
6. New York University, New York, USA
7. Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
8. Texas A&M University, College Station, Texas, USA
9. University of Bergen, Department of Physics and Technology, Bergen, Norway
10. University of Bucharest, Romania
11. University of Kansas, Lawrence, Kansas, USA
12. University of Oslo, Department of Physics, Oslo, Norway