Transverse Single Spin Asymmetries for identified charged hadrons in pp collisions at 200 GeV and 62 GeV

F. Videbaek and J.H. Lee
Physics Department
Brookhaven National Laboratory

for BRAHMS Collaboration

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Single transverse Spin Asymmetry (SSA): Introduction

- Large SSAs have been observed at forward rapidities in hadronic reactions: E704/FNAL & @AGS, 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, anda 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 effects
  -Hadron spin-flip through gluons
    -Efremov, Teryaev (final state)
    -Qiu, Sterman (initial state)
• Or combination of above
  -Ji, Qiu, Vogelsang, Yuan...

Challenge to have a consistent partonic description with data from 19, 200 and now 62 GeV:
- Energy dependent SSA vs $x_F$, $p_T$,
- Flavor dependent SSA
- Cross-section
**BRAHMS SSA measurements in** $p^+p \rightarrow \pi/K/p + X$ **at 200/62 GeV**

- Spin Asymmetries are defined as
  \[ A_N = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\varepsilon}{P} \]
  For non-uniform bunch intensities
  \[ e = \frac{N^+ / L^+ - N^- / L^-}{N^+ / L^+ + N^- / L^-} = \frac{N^+ - L^*N^-}{N^+ + L^*N^-} \]
  where $L = \text{relative luminosity} = L^+ / L^-$
  and the yield of \( \pi \) in a given kinematic bin with the beam spin direction is \( N^+ \) (up) and \( N^- \) (down).
- Most of the systematic error in $N^+/N^-$ cancel out
- Uncertainties on relative luminosity $L$ estimated to be $< 0.3\%$

**BRAHMS measures identified hadrons ($\pi,K,p,pbar$)**

in the kinematic ranges of
- $0 < x_F < 0.35$ and $0.2 < p_T < 3.5 \text{ GeV/c}$ at $\sqrt{s}=200 \text{ GeV}$
- $0 < x_F < 0.6$ and $0.2 < p_T < 1.5 \text{ GeV/c}$ at $\sqrt{s}=62 \text{ GeV}$
  - $x_F$, $p_T$, flavor, $\sqrt{s}$ dependent SSA
  - cross-section of un-polarized hadron production
    (constraint for theoretically consistent description)
Does pQCD explain inclusive spectra at 200 GeV at large rapidities?

Yes, for $p_T > 1.5$ GeV/c; NLO pQCD by Vogelsang.
BRAHMS FS Acceptance at 2.3 deg. and 4 deg. 
/Full Field (7.2 Tm) at $\sqrt{s} = 200$ GeV

- Strong $x_F$-$p_T$ correlation due to limited spectrometer solid angle acceptance
$A_N(\pi)$ at 2.3 deg. at $\sqrt{s} = 200$ GeV compared with Twist-3

- **Twist-3 parton correlation** calculation provided by F. Yuan
- Kouvarius, Qiu, Vogelsang, Yuan
- Solid lines: two-flavor ($u$, $d$) fit
- Dashed lines: valence + sea, anti-quark
- Calculations done (valid) only for $<p_T(\pi)> > 1$ GeV/c
Kinematic coverage at $\sqrt{s} = 62.4$ 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
- $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with $x_F$-$p_T$
$A_N(\pi)$ at $\sqrt{s} = 62$ GeV compared with Twist-3 and Sivers

Curves: Twist-3 by F. Yuan
Curves: Sivers effect by U. D’Alesio
$A_N(K)$ at $\sqrt{s} = 62$ GeV compared with Twist-3

Experiments shows that $A_n$ is the same for $K^+$ and $K^-$
Calculations have clear difference between $K^+$ and $K^-$
Spectra of $\pi^-$ at 62 GeV

Is it reasonable to expect pQCD to work at 62 GeV? Earlier work by Soffer et al. NO BRAHMS have preliminary spectra for $\pi^-$ at forward rapidity that can be compared to NLO pQCD.
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
- 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
  Open Questions:
  - 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 is pQCD applicable at 62 GeV
- 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? In particular for 62 GeV.