Cross-sections and SSAs of $\pi^{\pm}$ and $K^{\pm}$ at High-x_F in p$^{\uparrow}$+p at $\sqrt{s} = 62.4$ and 200 GeV

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June 19 2007, RHIC & AGS Users' Meeting Workshop

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Partonic description of hadronic dynamics in $p + p$ at RHIC

- Description of partonic dynamics without understanding of spin-dependent cross-section is incomplete
- Large SSAs have been observed at forward rapidities in hadronic reactions in a wide energy range: $\sqrt{s} = 20$ - 200 GeV while they are suppressed in naïve parton models
- SSAs: Probing internal degree of freedom: transverse partonic motion and multi-parton correlations
- Present Energy (62.4, 200 GeV) and Flavor-Dependent (π,K) SSAs and Cross-sections at large-x_F measured by BRAHMS at RHIC

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 parton correlations
  - Hadron spin-flip through gluons and hence the quark mass is replaced by Λ_{QCD}
  - Koike (final state)
  - Qiu, Sterman (initial state)
- Challenge to have a consistent partonic description:
  - Energy dependent SSA vs x_F , p_T ,
  - Flavor dependent SSA
  - Cross-section

Calculations compared at the BRAHMS kinematic region

- **Twist-3** parton correlation calculation provide by F. Yuan
  - Kouvarius, Qiu, Vogelsang, Yuan, Phys. Rev. D74 (2006)
  - Only "soft-gluon" (quark-gluon) correlation function considered with LO calculation (hard scattering, PDF, FF)
  - Parameterizations from "global" fit ($\sqrt{s} = 20 - 200$ GeV)
  - Two flavor (u_v, d_v) fit and valence+sea+antiquarks fit
- **Sivers** function calculation provided by U. D'Alesio
  - D'Alesio, Murgia, Phys. Rev. D70 (2004)
  - "Sivers effect with complete and consistent k_T kinematics plus description of unpolarized cross-section"
- Calculations are done for $p_T > 1$ GeV/c

Cross-Section and SSA mesasuremets in BRAHMS

- Data
  - Run-5: $\sqrt{s} = 200$ GeV 2.5 pb^{-1} recorded (polarization:45-50%)
  - Run-6: $\sqrt{s} = 62.4$ GeV 0.21 pb^{-1} recorded (polarization:45-65%)
  - $\pi^{\pm}$,$K^{\pm}$ data from BRAHMS Forward Spectrometer at 2.3^o - 4^o covering "high"-x_F ($0.15 < x_F < 0.6$) are presented.
- Particle identification using Ring Image Cherenkov (RICH) detector
  - π,K identification $< \sim$30 GeV/c
  - Efficiency $\sim$ 97%
- Min-Bias Selection using "CC" Cherenkov detector
  - Covering ∼70% (∼45%) of pp inelastic cross-section of 41 mb (36 mb) at 200 GeV (62.4 GeV) in $3.25 < |\eta| < 5.25$
  - Main relative luminosity monitor for SSA analysis

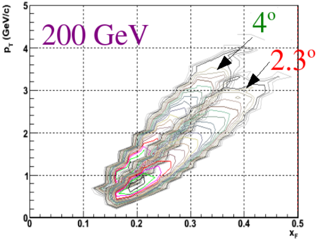
Determination of Single Spin Asymmetry: A_N

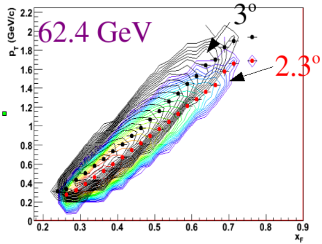
- Single Spin Asymmetries are defined as

$$A_N = \frac{1}{\mathcal{P}} \frac{(N^+ - \mathcal{L}N^-)}{(N^+ + \mathcal{L}N^-)}, \tag{1}$$

  where $\mathcal{P}$ is polarization of the beam, $\mathcal{L}$ is the spin dependent relative luminosity ($\mathcal{L} = \mathcal{L}_+/\mathcal{L}_-$) and $N^{+(-)}$ is the number of detected particles with beam spin vector oriented up (down).
- Most of the systematics in N^+/N^- cancel out (0.5-3%)
- Uncertainties on relative luminosity $\mathcal{L}$ estimated to be < 0.3 %
- Beam polarization $\mathcal{P}$ from on-line measurements: systematic uncertainty of $\Delta\mathcal{P}/\mathcal{P} \sim 18\%$

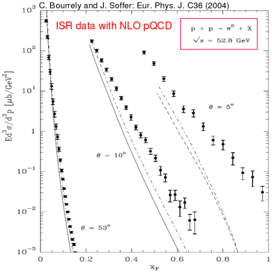
SSA Measurements: Acceptance in p_T vs x_F

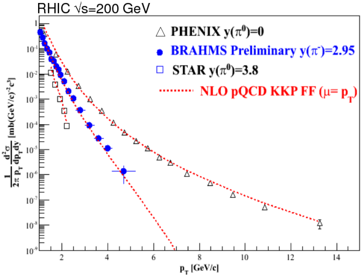




- Strong x_F-p_T correlation in acceptance due to limited spectrometer solid angle acceptance
- FS at 2.3° and 4° with full field (7.2 Tm) at $\sqrt{s} = 200$ GeV
- FS at 2.3° and 3° with half field (3.6 Tm) at $\sqrt{s} = 62.4$ GeV

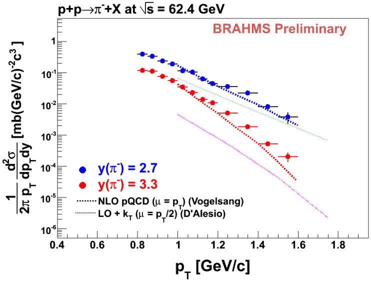
Unpolarized Cross-Sections at $\sqrt{s} = 200$ GeV





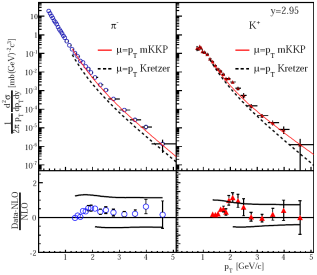
- At $\sqrt{s} = 200$ GeV, NLO pQCD framework is successful at mid- and forward rapidities
- At $\sqrt{s} = 52$ GeV, NLO pQCD significantly deviates, especially at high-x_F, from the ISR measurements

Cross-sections in $p + p = \pi^{-} + X$ at 62.4 GeV at $y \sim$2.7,3.3



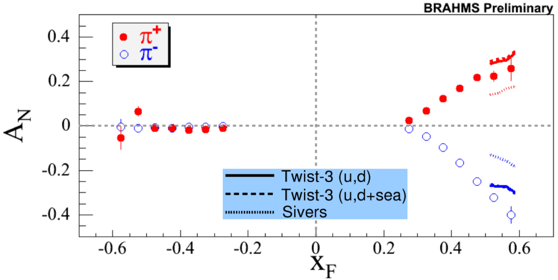
- NLO pQCD calculations in a good agreement with data at forward rapidities at 62.4 GeV
- LO pQCD with k_T describe the spectral shape but significantly under-predict the data

Cross-sections at 200 GeV at $y \sim 3$ (hep-ex:0701041, To be published in PRL)



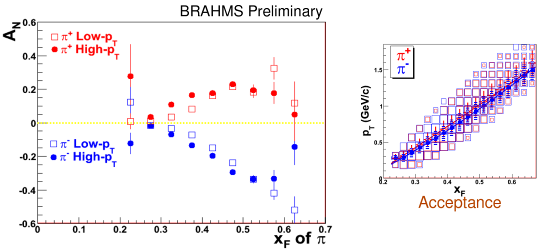
- NLO pQCD describes data at forward rapidity at 200 GeV
- π^- ,K^+ are described better by mKKP (Kniehl-Kramer-Potter) than Kretzer FF
- NLO pQCD Calculations done by W. Vogelsang. mKKP: "modified" KKP for charge separations for π and K. Two curves in the bottom panels are for $\mu = 2p_T$ and $\mu = p_T/2$.

SSA of $\pi^{\pm}$ at $\sqrt{s} = 62.4$ GeV



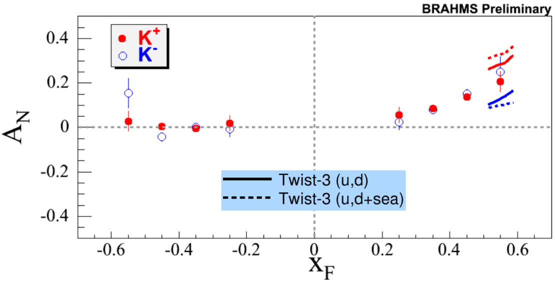
- Large $A_N(\pi^-)$: 40% at $x_F \sim 0.6$, $p_T \sim 1.3$ GeV/c, $A_N(-x_F) \sim 0$.
- Strong x_F-dependence
- $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F
- Sivers and Twist-3 calculations are compared with the data: Twist-3 calculations are in a better agreement with data.

p_T-dependent SSAs of $\pi^{\pm}$ at $\sqrt{s} = 62.4$ GeV



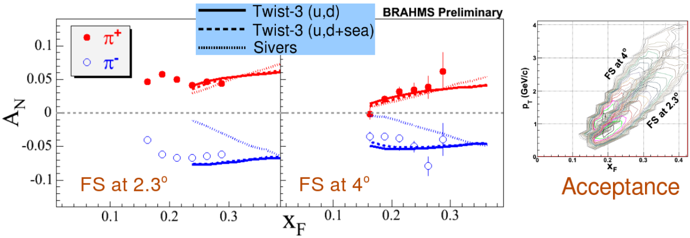
- At low-p_T (p_T $\sim<$ 1GeV/c) $A_N(\pi)$ decreases as p_T decreases: (Constraint: $A_N \rightarrow 0$ as $p_T \rightarrow 0$). Non-pQCD effect dominant?
- At p_T $\sim>$ 1 GeV/c, $A_N(\pi)$ tends to increase with $1/p_T$
- Perturbative/Non-perturbative $\sim$ 1 GeV/c?

SSA of $K^{\pm}$ at $\sqrt{s} = 62.4$ GeV



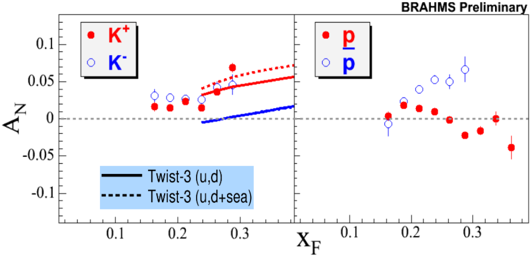
- $A_N(K^+) \sim A_N(K^-)$: positive $\sim 20\%$ at $x_F \sim 0.5$-0.6
- If main contribution to A_N at large x_F is from valence quarks: $A_N(K^+) \sim A_N(\pi^+), A_N(K^-) \sim 0$: disagreement with naïve expectations

A_N of $\pi^{\pm}$ at $\sqrt{s} = 200$ GeV



- $A_N(\pi^+)$: positive $\sim (<)$ $A_N(\pi^-)$: negative: 4-6% in $0.15 < x_F < 0.3$
- $A_N(\pi)$ decreases with p_T
- Sivers effect significantly underestimates $A_N(\pi)$ at low-x_F, p_T

A_N of $K^{\pm}$, p and $\bar{p}$ at 2.3^o at $\sqrt{s} = 200$ 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
- $A_N(\bar{p}) \sim A_N(K^-)$ while $A_N(p) \sim 0$

Summary

BRAHMS measures A_N of $\pi^{\pm}$, $K^{\pm}$ at $\sqrt{s}$=62.4 GeV and 200 GeV π, K cross-sections described by NLO pQCD Large x_F dependent SSAs seen for pions and kaons:

- Collinear factorization and (NLO) pQCD describe unpolarized cross-section at RHIC in wide kinematic region
- TMD PDF (Sivers function) alone cannot describe polarized and unpolarized data
- Gluonic degree of freedom (Twist-3) is significantly responsible for the large A_N
- "Power-suppression" behavior at high-p_T (> 1 GeV/c) (Perturbative/Non-perturbative ~ 1 GeV/c?)
- Sea quark contributions not well understood: $A_N(K^-)$,$A_N(\bar{p})$

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- The BRAHMS spin program has been completed.
- Final results will include cross-sections at $y = 0 - 3.3$ for $\pi^{\pm}, K^{\pm}, p$ and $\bar{p}$ at $\sqrt{s} = 62.4$ and 200 GeV and their SSAs.
- Partonic dynamics at intermediate-high x_F-p_T at RHIC likely driven by interplay among various degree of freedom. The energy and flavor dependent cross-sections and asymmetries in a wide kinematic region serve as ingredients for theoretical understanding of rich partonic dynamics at RHIC.