

Cross-sections and SSAs of π^\pm and K^\pm at High- x_F at RHIC

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for



April 18, DIS2007, Munich

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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

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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}
 - Efremov, Teryaev (final state)
 - Qiu, Serman (initial state)
- Challenge to have a consistent partonic description:
 - Energy dependent SSA vs x_F , p_T ,
 - Flavor dependent SSA
 - Cross-section

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Determination of Single Spin Asymmetry: A_N

- Single Spin Asymmetries are defined as

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

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 $\Delta\mathcal{P}/\mathcal{P} \sim 18\%$

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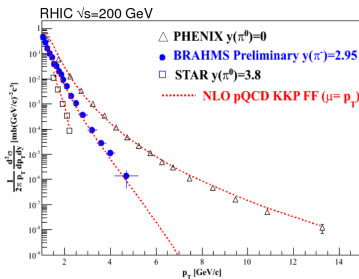
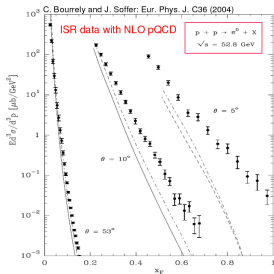
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Calculations compared at the BRAHMS kinematic region

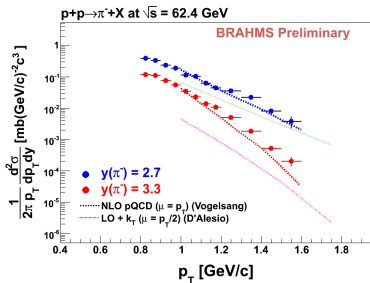
- **Twist-3 parton correlation calculation** provide by F. Yuan
 - Kouvarius, Qiu, Vogelsang, Yuan, Phys. Rev. D74 (2006)
 - Only “soft-gluon” (quark-gluon) correlation function considered with LO calculation (hard scattering, PDF, FF)
 - Parameterizations from “global” fit ($\sqrt{s} = 20 - 200$ GeV)
 - 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

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



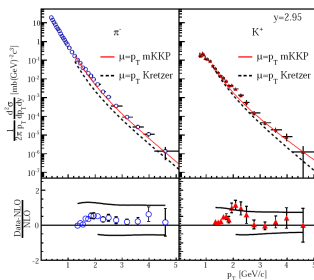
- At $\sqrt{s} = 200$ GeV, NLO pQCD framework is successful at mid- and forward rapidities
- At $\sqrt{s} = 52$ GeV, NLO pQCD significantly deviates, especially at high- x_F , from the ISR measurements

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



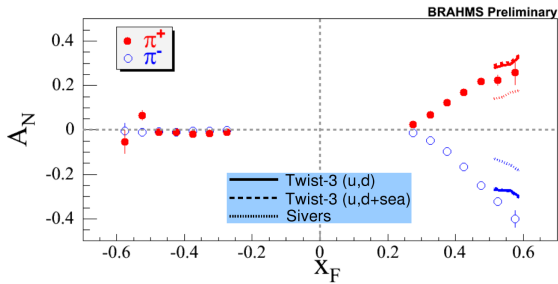
- NLO pQCD calculations in a good agreement with data at forward rapidities at 62.4 GeV
- LO pQCD with k_T describe the spectral shape but significantly under-predict the data

Cross-sections at 200 GeV at $y \sim 3$ (hep-ex:0701041)



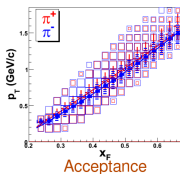
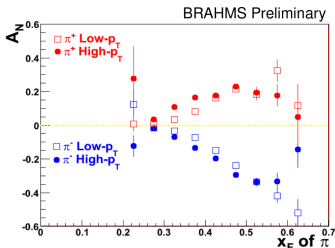
- NLO pQCD describes data at forward rapidity at 200 GeV
- π^- , K^+ are described better by mKKP (Kniehl-Kramer-Potter) than Kretzer FF
- NLO pQCD Calculations done by W. Vogelsang. mKKP: “modified” KKP for charge separations for π and K . Two curves in the bottom panels are for $\mu = 2p_T$ and $\mu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

SSA of π^\pm at $\sqrt{s} = 62.4$ GeV



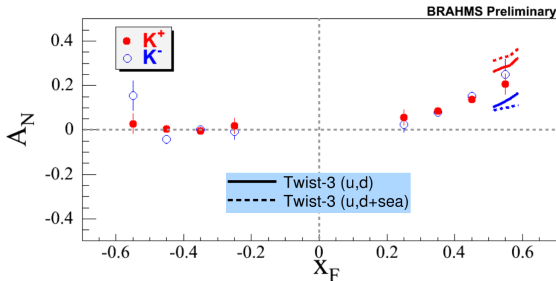
- Large $A_N(\pi^-)$: 40% at $x_F \sim 0.6$, $p_T \sim 1.3$ GeV/c, $A_N(-x_F) \sim 0$.
- Strong x_F -dependence
- $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F
- Sivers and Twist-3 calculations are compared with the data: Twist-3 calculations are in a better agreement with data.

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



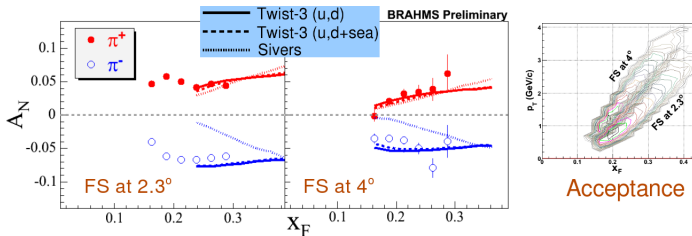
- At low- p_T ($p_T \sim < 1 \text{ GeV}/c$) $A_N(\pi)$ decreases as p_T decreases: (Constraint: $A_N \rightarrow 0$ as $p_T \rightarrow 0$). Non-pQCD effect dominant?
- At $p_T \sim > 1 \text{ GeV}/c$, $A_N(\pi)$ increase with p_T
- Perturbative/Non-perturbative $\sim 1 \text{ GeV}/c$?

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



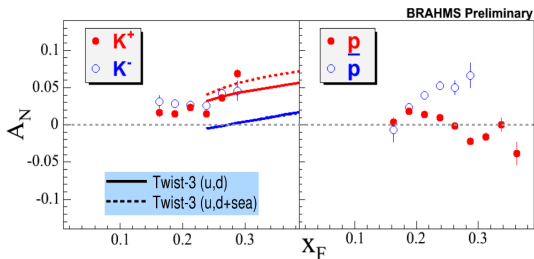
- $A_N(K^+) \sim A_N(K^-)$: positive $\sim 20\%$ at $x_F \sim 0.5-0.6$
- If main contribution to A_N at large x_F is from valence quarks:
 $A_N(K^+) \sim A_N(\pi^+)$, $A_N(K^-) \sim 0$: disagreement with naïve expectations

A_N of π^\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
- Siverts effect significantly underestimates $A_N(\pi)$ at low- x_F, p_T

A_N of K^\pm , p and \bar{p} at 2.3° 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 π^\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 π^\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.