Studying Evolution with Jets at STAR

Renee Fatemi
University of Kentucky
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The Relativistic Heavy Ion Collider is the world's first and only polarized proton collider. It can provide both longitudinal and transversely polarized proton beams.
STAR’s large acceptance allows for jet reconstruction and charged hadron particle identification.

\[ \eta = -\ln[\tan(\Theta/2)] \]
Parton distribution functions in the Proton

\[ f(x) \] 
Number density of partons with flavor \( f \) and momentum fraction \( x \) inside a nucleon

\[ \Delta f(x) \] 
Number density of longitudinally polarized partons inside longitudinally polarized nucleons (Helicity)

\[ \Delta_T f(x) \] 
Number density of transversely polarized partons inside a transversely polarized nucleon (Transversity)
CT10 NNLO Momentum Distributions

\[ x f(x, Q) \text{ versus } x \]

- \( Q = 2 \text{ GeV} \)
- \( Q = 3.16 \text{ GeV} \)
- \( Q = 8 \text{ GeV} \)
- \( Q = 85 \text{ GeV} \)
Inclusive Jet Cross-sections

STAR inclusive jet cross-section data accesses lowest $Q^2$ scales to date.

Currently Tevatron Run-I inclusive jet data are excluded from CT10 NNLO.

STAR data is not included. What impact could we provide?
At large $x$, $g(x, Q)$ is reduced in CT10 NNLO compared to CT10W due to removal of Run-I Tevatron data.

At $\sqrt{s} = 200$ GeV high $p_T$ jets from pp collisions at RHIC push into the high $x$ region where PDF uncertainties start to quickly rise.
Jet Reconstruction at STAR

- Before 2009 STAR used **Mid-point cone algorithm**
  Adapted from Tevatron II – hep-ex/0005012
  - Seed $E = 0.5$ GeV
  - Cone Radius $R = 0.7$ in $\eta$-$\phi$ space
  - Split/merge fraction $f = 0.5$

- Starting in 2009 STAR moves to **Anti-$k_T$ algorithm**
  Cacciari, Salam, and Soyez, JHEP 0804, 063
  - Recombination radius $R = 0.6$ for 200 GeV
  - Recombination radius $R = 0.5$ for 500 GeV
STAR 2009 inclusive jet cross section $|\eta|<1.0$

Inclusive jet cross section

$$\frac{d^2\sigma}{d|\eta|d p_T}(\mu_b)$$

$\int L dt = 19 \text{ pb}^{-1} \pm 8\%$

STAR Run9 Preliminary
Inclusive jet cross section
$\sqrt{s} = 200 \text{ GeV}$

Anti-kt $R=0.6$ run9 STAR unfolding

Anti-kt $R=0.6$ CT10 w/ UE Corr.

Anti-kt $R=0.6$ NNPDF2.3 w/ UE Corr.

Systematic Err.
STAR 2009 inclusive jet cross section \(|\eta|<0.5\)
STAR 2009 inclusive jet cross section

$0.5 < |\eta| < 1.0$

STAR Run9 Preliminary
Inclusive jet cross section
\( \sqrt{s} = 200 \text{ GeV} \)

- Anti-kt R=0.6 run9 STAR unfolding
- Anti-kt R=0.6 CT10 w/ UE Corr.
- Anti-kt R=0.6 NNPDF2.3 w/ UE Corr.
- Systematic Err.
Comparisons of STAR data to C10 NLO
Gluon Helicity Distributions

DSSV

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ x\Delta g \]

\[ x \]

**NEW FIT**
- incl. 90\% C.L. variations

- DSSV*

- DSSV

**NNPDF 1.1**

\[ x\Delta g(x, Q^2=10 \text{ GeV}^2) \]

Phys. Rev. Lett. 113 (2014) 012001

Recent $\sqrt{s} = 200$ GeV jet $A_{LL}$

- 2009 STAR inclusive jet $A_{LL}$ measurements are a factor of 3 – 4 more precise than the 2006 results.

- $A_{LL}$ falls in the middle among several recent polarized PDF fit predictions.

- $A_{LL}$ is somewhat larger than predictions from the 2008 DSSV and NNPDF1.0 indicating a positive $\Delta g$ in the accessible $x$ region.
First $\sqrt{s} = 500$ GeV jet $A_{LL}$!

*Provides first access to lower $x$*

Results are in excellent agreement with newest DSSV and NNPDF NLO predictions!
First $\sqrt{s} = 500$ GeV jet $A_{LL}$! Provides first access to lower $x$.

Results are in excellent agreement with newest DSSV and NNPDF NLO predictions!
Neutral pion $A_{LL}$ at $\sqrt{s} = 500$ GeV in the STAR Forward Meson Spectrometer ($2.5 < \eta < 4$)
$\Delta G (x > 0.05) = 0.2 (+0.06/-0.07)$

**DSSV**


**NPDF**


$\Delta G (0.2 > x > 0.05) = 0.17 (+/- 0.06)$
Transversity Distributions

COLLINS: Simultaneous fit of HERMES p, COMPASS p & d and Belle data

IFF: Simultaneous fit of HERMES p, COMPASS p & d and Belle data
What about pp Collisions?

Since $\Delta_T f(x)$ is CHIRAL ODD must access it by coupling to a second chiral odd function.

- Ralston and Soper proposed Drell-Yan but ...
  - low rates compared to other hadronic processes
  - anti-quark transversity is likely very small

- Could also look at inclusive jet $A_{TT}$ in pp collisions, however ...
  - Gluons are abundant and have ZERO transversity
  - $A_{TT} < A_{LL}$ due to Soffer bound

STAR Inclusive Jet $A_{TT}$

- In 2006 STAR collected $2 \text{ pb}^{-1}$ of transversly polarized $\sqrt{s}= 200 \text{ GeV}$ data
- Data integrates over $7.5 < \text{jet } p_T < 40 \text{ GeV}$
- Data Precision $\sim 0.005$
- Maximized signal for jet $p_T = 10 \text{ GeV}$ is $\sim 0.001$
- Requires at LEAST $x25$ more data to make a significant measurement. Possibly 2015 RHIC run?

Look Instead to the Final State!

_Couple a chiral odd fragmentation function with quark \( \Delta_f(x) \)

**Collins Fragmentation Functions**
Correlation between spin of transversely polarized quark and transverse momentum kick given to fragmentation hadron.

**Interference Fragmentation Functions**
Correlation between spin of transversely polarized quark and momentum cross-product of dihadron pair.

\[
S_Q \cdot (P_Q \times P_H)
\]

\[
S_Q \cdot (P_{H-} \times P_{H+})
\]
Look Instead to the Final State!

Couple a chiral odd fragmentation function with quark $\Delta_f(x)$

**Collins Fragmentation Functions**
Does not survive integration over transverse momentum of hadron $j_T$ with respect to the jet axis. Needs Transverse Momentum Dependent framework!

**Interference Fragmentation Functions**
The center of mass of the hadron pair is traveling collinear with the jet axis. IFF survives integration over $j_T$ of hadrons and therefore works in collinear framework.

\[ S_Q \cdot (P_Q \times P_H) \]
\[ S_Q \cdot (P_{H-} + P_{H+}) \times R \]
\[ R = \frac{1}{2}(P_{H+} - P_{H-}) \]
Unique contributions from pp?

- How do Collins and Interference FF evolve with $Q^2$?
- Are the Collins and Interference FF universal?
- What are the size of factorization breaking effects for Collins in pp?
Full Disclosure

GLUONS dominate at low jet transverse momentum - need to place cut to minimize dilution to asymmetries.
SSA in pp sensitive to Transversity:
Azimuthal distributions of pions in Jets

- $\varphi_S$ is defined as the angle between proton spin and reaction plane
- $j_T$ defines particle transverse momentum in jet
- $\varphi_H$ defines angle between jet particle transverse momentum and reaction plane
- $\varphi_C = \varphi_S - \varphi_H$ (Collins Angle)

$$\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}(\varphi_C) = A_{UT}^{\sin \varphi_C} \sin(\varphi_C) \propto \Delta_T q \otimes H_1^\perp$$
2006 $A_{UT}^{COLLINS}$ of Leading Charged Pions in Mid-Rapidity Jets at STAR in 200 GeV

Average $\pi^+$ asymmetry = $0.02082 \pm 0.0064 \pm 0.02306$

Average $\pi^-$ asymmetry = $-0.0040 \pm 0.0068 \pm 0.02306$
Mid-rapidity Predictions from D’Alesio, Murgia and Pisano

Presented at Transversity 2014 and based on work from PRD 83 034021 (2011)
2012 $A_{UT}^{\text{COLLINS}}$ vs. $j_T$ at 200 GeV ($xF>0$)

$\pi^+ + \pi^- \rightarrow X$ at $\sqrt{s} = 200$ GeV

5.6% Scale Uncertainty Not Shown

$\sin(\phi_s - \phi_H)$ vs. $j_T [\text{GeV/c}]$
2012 $A_{UT}^{\text{COLLINS}}$ vs. $j_T$ at 200 GeV ($x_F<0$)

$p^+ + p \rightarrow \text{jet} + \pi^\pm + X$ at $\sqrt{s} = 200$ GeV

5.6% Scale Uncertainty Not Shown
$200 \text{ GeV} \ A_{UT}^{\text{COLLINS}} \ \text{vs.} \ Z$

STAR Preliminary

$p^+ + p \rightarrow \text{jet} + \pi^+ + X \ \text{at} \ \sqrt{s} = 200 \text{ GeV}$

5.6% Scale Uncertainty Not Shown

Jet $p_T$

- $10 < \text{Jet } p_T < 31.6 \text{ GeV/c}$
- $0.125 < \hat{t} < 4.5 \text{ GeV/c}$
200 GeV $A_{UT}^{\text{COLLINS}}$ vs. $Z$

$p^\uparrow + p \rightarrow \text{jet} + \pi^\pm + X$ at $\sqrt{s} = 200$ GeV

5.6% Scale Uncertainty Not Shown
Higher $Q^2$ and same $x_T$? $\sqrt{s} = 200$ vs 500 GeV

Once scaled to same $x_T$ and average $j_T$, the 200 and 500 GeV asymmetries are similar.

Is this evidence for small evolution effects?
Reduced uncertainties with additional data $\sqrt{s}=200$ GeV in 2015 and $\sqrt{s}=500$ GeV in 2017.
Collecting first data set of $p+Au$ at $\sqrt{s}=200$ !
Additional moments can be and have been measured!

Linearly polarized gluons

Sensitive to Sivers
SSA in pp sensitive to Transversity: Di-hadron pairs

\[ R = \frac{1}{2} (P_{H1} - P_{H2}) \]

\( \varphi_S \): Angle between scattering plane and spin

\( \varphi_R \): Angle between scattering plane and R vector

\( \varphi_{SR} = \varphi_S - \varphi_R \)

\[ \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} (\varphi_{SR}) = A_{UT}^{\sin \varphi_{SR}} \sin(\varphi_{SR}) \propto \Delta_T q \otimes H_q^\perp \]
2006 $A_{UT}^{IFF}$ vs. $M_{inv}$ $\sqrt{s} = 200$ GeV
$200 \text{ GeV } A_{UT}^{\text{IFF}} \text{ vs. } M_{\text{inv}}$

**PHENIX Preliminary**

$p+p \ 2006+2008 \ \sqrt{s}=200 \text{ GeV}$

$\langle \eta \rangle = +0.5$  
$\langle \eta \rangle = -0.5$

$(\langle z \rangle, \langle x \rangle)$

$A_{UT}^{\sin\theta}$

$A_{UT}^{\cos\theta}$

$\pi^0, h^+, h^-$

$M_{\pi\pi} (\text{GeV}/c^2)$

(Scale uncertainty 10% not included)

$p_T > 1 \text{ GeV}/c, |\eta| < 0.35$
200 GeV $A_{UT}^{\text{IFF}}$ vs. $M_{\text{inv}}$
2012 $A_{UT}^{\text{IFF}}$ vs. $M_{\text{inv}} \ \sqrt{s} = 200$ GeV

... x10 more data than before!

$P_T^{\pi^+\pi^-}$, $M_{\text{inv}}^{\pi^+\pi^-}$

$P^+ p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

STAR preliminary

$\langle P_T \rangle = 10.49$

$\langle P_T \rangle = 7.16$

$\langle P_T \rangle = 5.66$

$\langle P_T \rangle = 4.47$

$\langle P_T \rangle = 3.57$

$\eta > 0$
2012 $A_{UT}^{IFF}$ vs. $M_{inv} \sqrt{s} = 200$ GeV

... $x10$ more data than before!
2012 $A_{UT}^{\text{IFF}}$ vs. $M_{inv}$ $\sqrt{s} = 200$ GeV

... x10 more data than before!

$P^+P \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} =$

STAR preliminary

$\langle P_T^{\pi^+} \rangle = 10.49$
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$P^+P \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

STAR preliminary

QCD Evolution Workshop 2015
2011 $\pi^+\pi^-$ IFF at $\sqrt{s} = 500$ GeV

Increasing asymmetry with increasing $p_T$ - similar to 200 GeV but overall suppression in magnitude
2012 $\pi^+\pi^-$ IFF at $\sqrt{s} = 500$ GeV

Trend is same as 200 GeV but asymmetries are smaller. Again due to higher gluon dilution and effective lower x values.
Conclusions

- INCLUSIVE JET CROSS-SECTION at $\sqrt{s} = 200$ GeV
  - Good agreement with CT10 NLO calculations
  - First STAR inclusive jet cross-section with anti-kT algorithm
  - Investigation into constraints placed on gluon momentum distribution ongoing.
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- STAR’s measurements of IFF and Collins SSA over a range of $\sqrt{s}$ provide insight $Q^2$ evolution of the transversity PDF, Collins FF & IFF.

- STAR’s simultaneous measurement of the IFF and Collins SSA provides a test of the TMD factorization framework and facilitates study of factorization breaking effects in pp.
Thank you
RHIC provides a wide range of center of mass collision energies allowing for the study of transversity and fragmentation FF evolution.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>√s [GeV]</th>
<th>STAR</th>
<th>Pol [%]</th>
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</thead>
<tbody>
<tr>
<td>2001 (Run 1)</td>
<td>200</td>
<td>0.15 pb⁻¹</td>
<td>15</td>
</tr>
<tr>
<td>2003 (Run 3)</td>
<td>200</td>
<td>0.25 pb⁻¹</td>
<td>30</td>
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<td>2005 (Run 5)</td>
<td>200</td>
<td>0.1 pb⁻¹</td>
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<td>2006 (Run 6)</td>
<td>200</td>
<td>8.5 pb⁻¹</td>
<td>57</td>
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<tr>
<td>2006 (Run 6)</td>
<td>62.4</td>
<td>/</td>
<td>53</td>
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<tr>
<td>2008 (Run8)</td>
<td>200</td>
<td>7.8 pb⁻¹</td>
<td>45</td>
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<tr>
<td>2011 (Run11)</td>
<td>500</td>
<td>25 pb⁻¹</td>
<td>48</td>
</tr>
<tr>
<td>2012 (Run12)</td>
<td>200</td>
<td>22 pb⁻¹</td>
<td>59</td>
</tr>
<tr>
<td>2015 (Run15)</td>
<td>200</td>
<td>53 pb⁻¹</td>
<td>55</td>
</tr>
</tbody>
</table>
\[ \Delta G (x > 0.05) = 0.2 (+0.06/-0.07) \]

\[ \Delta G (0.2 > x > 0.05) = 0.17 (+/- 0.06) \]

Special thanks to DSSV for this plot!
Charged pion identification

- Pions identified from TPC track $dE/dx$
- Use $-1 < n_\sigma(\pi) < 2.5$ cut to identify pions

$$n_\sigma(\pi) = \frac{1}{\sigma_{exp}} \ln \left( \frac{dE/dx_{obs}}{dE/dx_{\pi,calc}} \right)$$

- Kaons, protons, and electrons contaminate the pion sample
- This contamination is $p_T$ independent for Collins (3% of systematic err) and ranges from 3 – 17% for IFF.

$2012$ $200$ GeV $A_{UT}^{\text{COLLINS}}$ vs. $p_T (x_F > 0)$

$\pi^+$

$\pi^-$

$x_F > 0$

$p^+ + p \rightarrow \text{jet} + \pi^+ + X$ at $\sqrt{s} = 200$ GeV

$5.6\%$ Scale Uncertainty Not Shown
2012 200 GeV $A_{UT}^{\text{COLLINS}}$ vs. $p_T \ (x_F < 0)$

$\pi^+$

$\pi^-$ $x_F < 0$

STAR Preliminary

$p^+ + p \rightarrow \text{jet} + \pi^+ + X \text{ at } \sqrt{s} = 200 \text{ GeV}$

5.6% Scale Uncertainty Not Shown
Asymmetries consistent with zero across the board - BUT gluon dilution larger and average x is smaller for given jet pT! Need more statistics for definitive answer!

Projections for 500 GeV predict nothing larger than 1% at high z
Partial Wave Expansion

\[
\sin \theta H_{1}^{\perp}(z, \cos \theta, M_{inv}^{\pi^+\pi^-}) \approx H_{1,ot}(z, M_{inv}^{\pi^+\pi^-}) \sin \theta
\]

\[
-H_{1,lt}(z, M_{inv}^{\pi^+\pi^-}) \sin \theta \cos \theta
\]

**P/P wave interference**
Interference of L=1 unpolarized pair and L=1 transversely polarized pair

**S/P wave interference**
Interference of L=0 unpolarized pair and L=1 transversely polarized pair

P wave contributions come from a spin-1 resonance \( \rho(770 \text{ MeV}) \)

expect higher asymmetry around .8 GeV
Asymmetry as function of $M_{inv}^\pi\pi^\pm$, $\eta$.
Asymmetry as function of $P_T$, $\eta$.
Particle $p_T > 1.5$ GeV/$c$

Pair $p_T > 3.75$ GeV/$c$

For a given $M_{\text{inv}}$, $p_T$ bin the asymmetry is calculated for 8 $\phi_{RS}$ bins

The asymmetry is the amplitude extracted from a single-parameter fit

Example shown here is one $M_{\text{inv}}, p_T$ bin
2011 π+π- IFF at √s = 500 GeV

Increasing asymmetry with increasing pT - similar to 200 GeV but overall suppression in magnitude