Measurements of Transverse Spin Dependent $\pi^{+} \pi^{-}$ Azimuthal Correlation Asymmetry and Unpolarized $\pi^{+} \pi^{-}$ Cross Section in $p p$ Collisions at $V_{s}=200 \mathrm{GeV}$ at STAR


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Science


- Proton structure studied in terms of parton distribution functions (PDFs).
- Leading order PDFs:

$\vec{P}=$ Nucleon polarization
$\vec{p}=$ Nucleon momentum
$\vec{s}=$ Quark polarization
$z=$ Proton's momentum axis

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H1 and ZEUS


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- Well constrained by the SIDIS data.

Motivation
Proton Structure


- Proton structure studied in terms of parton distribution functions (PDFs). - Leading order PDFs:

- Evidence of non-zero gluon polarization from the STAR data.

$$
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$$

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NNPDF, Nucl. Phys. B887(2014)276-308

$0.4=\mathrm{x} \Delta \mathrm{u}\left(\mathrm{x}, \mathrm{Q}^{2}=10 \mathrm{GeV}^{2}\right.$





- Proton structure studied in terms of parton distribution functions (PDFs). - Leading order PDFs:

- $h_{1}(x)$ is least known, as it is not easily accessible in the physical process.
- $h_{1}(x)$ has gained a lot of attention lately, as it provides access to the nucleon tensor charge - an important nucleon property.
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$z=$ Proton's momentum axis
- Helicity flipped amplitude.
- Chiral-odd; conservation of chirality requires another chiral-odd counterpart to be appeared in the physical process.

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- Measurement is not possible in inclusive DIS.

Proton-proton (pp) collisions provide multiple opportunities for the $h_{1}^{q}(x)$ measurement.

- Identified hadron inside jet (Collins Channel)
$p^{\uparrow}+p \rightarrow$ jet $+h+X \sim h_{1}^{q}(x) H_{1}^{\perp}\left(z, j_{T}\right)$
- $h_{1}^{q}(x)$ coupled with the Collins FF, $H_{1}^{\perp}$.
- $j_{T}=$ pion momentum transverse to the jet axis.
- $z=p_{\pi} / p_{j e t}$
- Identified hadron-in-jet
- TMD formalism



## - Exclusively produced dihadron (Dihadron Channel)

$p^{\uparrow}+p \rightarrow h^{+} h^{-}+X \sim h_{1}^{q}(x) H_{1}^{\Varangle}(z, M)$
$-h_{1}^{q}(x)$ coupled with the interference FF (IFF), $H_{1}^{\downarrow}$. $-z=\mathrm{E}^{\mathrm{h}^{+} \mathrm{h}^{-}} / \mathrm{E}^{\text {quark }}, \mathrm{M}=h^{+} h^{-}$invariant mass

Observed azimuthal asymmetry due to the quark transverse polarization:
$A_{U T}^{\sin \left(\phi_{s}-\phi_{H}\right)} \sim h_{1}^{q}(x) H_{1}^{\perp}\left(z, j_{T}\right)$
$A_{U T}^{\sin \left(\phi_{s}-\phi_{R}\right)} \sim h_{1}^{q}(x) H_{1}^{\Varangle}(z, M)$


- No jet reconstruction required
- Collinear approach

Observables for $h_{1}^{q}(x)$ via Dihadron Channel in $p p$
Reaction Channel: $\quad p^{\uparrow}+p \rightarrow \pi^{+} \pi^{-}+X$
$\vec{p}_{h}=\vec{p}_{h, 1}+\vec{p}_{h, 2}, \vec{R}=\frac{1}{2}\left(\vec{p}_{h, 1}-\vec{p}_{h, 2}\right)$, Spin transfer via $\sim \vec{s}_{a} \cdot\left(\vec{R} \times \vec{p}_{h}\right)$
Quark polarization favors $\pi^{+} \pi^{-}$production to one direction in azimuth $\left(\phi_{R S}\right)$ resulting in azimuthal correlation asymmetry, $A_{U T}^{\sin \left(\phi_{R S}\right)}$.


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## $\pi^{+} \pi^{-}$Correlation Asymmetry:

$$
A_{U T}^{\sin \left(\phi_{R S}\right)}=\frac{d \sigma^{\uparrow}-d \sigma^{\downarrow}}{d \sigma^{\uparrow}+d \sigma^{\downarrow}} \propto \frac{\sum_{i, j, k} h_{1}^{i / p_{a}}\left(x_{a}\right) f_{1}^{j / p_{b}}\left(x_{b}\right) H_{1}^{\triangleleft h_{1} h_{2} / k}\left(z, M_{h}\right)}{\sum_{i, j, k} f_{1}^{i / p_{a}}\left(x_{a}\right) f_{1}^{j / p_{b}}\left(x_{b}\right) D_{1}^{h_{1} h_{2} / k}\left(z, M_{h}\right)}
$$

- $A_{U T}^{\sin \left(\phi_{R S}\right)}$ is sensitive to the product $h_{1}(x) H_{1}^{\Varangle}(z, M)$.
- STAR observed significant $A_{U T}^{\sin \left(\phi_{R S}\right)}$ signal, enhanced around the $\rho$-mass ( $\mathrm{M}_{\mathrm{inv}} \sim 0.8 \mathrm{GeV} / \mathrm{c}^{2}$ ) - expected due to the interference of hadrons produced via different channel.

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A_{U T}^{s i n\left(\phi_{R S}\right)}=\frac{d \sigma^{\uparrow}-d \sigma^{\downarrow}}{d \sigma^{\uparrow}+d \sigma^{\downarrow}} \propto \frac{\sum_{i, j, k} h_{1}^{i / p_{a}}\left(x_{a}\right) f_{1}^{j / p_{b}}\left(x_{b}\right) H_{1}^{\Varangle h_{1} h_{2} / k}\left(z, M_{h}\right)}{\sum_{i, j, k} f_{1}^{i L_{a}}\left(x_{a}\right) f_{1}^{j / p_{b}}\left(x_{b}\right) D_{1}^{h_{1} l_{2} / k}\left(z, M_{h}\right)} \quad \begin{aligned}
& \text {-spin averaged FF, } D_{1} . \\
& \text { - dominant uncertainty in } h_{1}^{q}(x) \text {, specifically from } D_{1} \text { for gluon. } \\
& \text { Unpolarized } \pi^{+} \pi^{-} \text {cross section, } \sigma^{\pi^{+} \pi^{-}} \text {, give access to } D_{1}^{\pi^{+} \pi^{-}} \text {in } \boldsymbol{p} .
\end{aligned}
$$

$$
\begin{aligned}
& \frac{5}{4} \\
& \square
\end{aligned} \begin{aligned}
& \text { Radicl, et al. } \sqrt{s}=500 \mathrm{GeV} \\
& \text { STAR } \sqrt{s}=500 \mathrm{GeV}
\end{aligned}
$$



- $A_{U T}^{\sin \left(\phi_{R S}\right)}$ is sensitive to the product $h_{1}(x) H_{1}^{\Varangle}(z, M)$.
- STAR observed significant $A_{U T}^{\sin \left(\phi_{R S}\right)}$ signal, enhanced around the $\rho$-mass ( $\mathrm{M}_{\mathrm{inv}} \sim 0.8 \mathrm{GeV} / \mathrm{c}^{2}$ ) - expected due to the interference of hadrons produced via different channel.
- Significant impact on the $h_{1}(x)$ from STAR data at 200 GeV in the valence region $(0.1<x<0.3)$.


Relativistic Heavy Ion Collider (RHIC)


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$5 \cdot 11.2$

## STAR Run 2015 Precision $\mathrm{A}_{\mathrm{UT}}^{\sin \left(\phi_{\mathrm{RS}}\right)}$ Measurement

## - Event Selection

- This dataset provides the most precise $A_{U T}$ at $\sqrt{s}=200 \mathrm{GeV}$ to date.
- Triggers : JP1, JP2
- Pion selection: $|\eta|<1,1.5<\mathrm{p}_{\mathrm{T}}<15 \mathrm{GeV} / \mathrm{c},-1<\mathrm{n} \sigma_{\pi}<2$
- All possible pion pairs of opposite charge.
- Fix charge ordering in a pair: $\overrightarrow{\mathrm{p}}_{\mathrm{h}, 1}=\pi^{+}, \overrightarrow{\mathrm{p}}_{\mathrm{h}, 2}=\pi^{-}$
$-\pi^{+} \pi^{-}$selection cuts:
cone $<0.7,\left|\eta^{\pi^{+} \pi^{-}}\right|<1,2.5<\mathrm{p}_{\mathrm{T}}^{\pi^{+} \pi^{-}}<15 \mathrm{GeV} / \mathrm{c}, 0.2<\mathrm{M}_{\mathrm{inv}}<4 \mathrm{GeV} / \mathrm{c}^{2}$
scattering
plane
di-hadron
plane

$$
\phi_{R S}=\phi_{s}-\phi_{R}
$$

## - Cross-Ratio Method:

$$
A_{U T} \sin \left(\phi_{R S}\right)=\frac{1}{P} \frac{\sqrt{N^{\uparrow}\left(\phi_{R S}\right) N^{\downarrow}\left(\phi_{R S}+\pi\right)}-\sqrt{N^{\downarrow}\left(\phi_{R S}\right) N^{\uparrow}\left(\phi_{R S}+\pi\right)}}{\sqrt{N^{\uparrow}\left(\phi_{R S}\right) N^{\downarrow}\left(\phi_{R S}+\pi\right)}+\sqrt{N^{\downarrow}\left(\phi_{R S}\right) N^{\uparrow}\left(\phi_{R S}+\pi\right)}}
$$

- Free from detector effects and associated uncertainties.

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N
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N
polarization is Up( \) (Down (\downarrow)).
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P is average beam polarization.

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## STAR Run 2015 Precision $\mathrm{A}_{\mathrm{UT}}^{\sin \left(\phi_{\mathrm{RS}}\right)}$ Measurement



Aut vs $\mathbf{M}_{\text {inv }}$ : Aut is enhanced around $M_{i n v}^{\pi^{+} \pi^{-}} \sim$ 0.8 , consistent with the previous measurement.


Aut vs $\eta^{\pi^{+} \pi^{-}}$:

- Mean $x$ and $z$ as a function of $\eta^{\pi^{+} \pi^{-}}$from simulation.
- $\left|\eta^{\pi^{+} \pi^{-}}\right|<1$.
- $0.1<x<0.22, z \sim 0.46$
- Significant AUT in the forward region, where $h_{1}(x)$ is expected to be sizeable.
- Significant improvement in the statistical precision than previous STAR measurements.

STAR Run 2015 Precision $A_{U T}^{\sin \left(\phi_{\mathrm{RS}}\right)}$ Measurement


Aut vs $\mathrm{M}_{\text {inv }}$ in $\mathrm{p}_{\mathrm{T}}^{\pi^{+} \pi^{-}}$bins:

- 2D binning, Aut as a function of $\mathrm{M}_{\mathrm{inv}}$ in $5 \mathrm{p}_{\mathrm{T}}$ bins.
- Higher AUt in the higher $\mathrm{p}_{\mathrm{T}}$ bin, where higher $x$ is probed.
- Growing prominence of the resonance peak around $\mathrm{M}_{\mathrm{inv}} \sim 0.8 \mathrm{GeV} / \mathrm{c}^{2}$ with increasing $\mathrm{p}_{\text {т }}$.
- Small backward asymmetry, where lower $x$ is probed.
- Significant AUT in the forward region, where $h_{1}(x)$ is expected to be sizeable.
- Significant improvement in the statistical precision than previous STAR measurements.

STAR Run 2015 Precision $A_{\mathrm{UT}}^{\sin \left(\phi_{\mathrm{RS}}\right)}$ Measurement


Aut vs $\mathrm{p}_{\mathrm{T}}^{\pi^{+} \pi^{-}}$in $\mathrm{M}_{\text {inv }}$ bins:

- 2 D binning, AUt as a function of $\mathrm{p}_{\mathrm{T}}^{\pi^{+} \pi^{-}}$in $5 \mathrm{M}_{\mathrm{inv}}$ bins.
- Aut increases with the $\mathrm{p}_{\mathrm{T}}$ in the forward region, where higher $x$ is probed.
- Aut signal is larger when $\mathrm{M}_{\mathrm{inv}} \sim 0.8 \mathrm{GeV} / \mathrm{c}^{2}$ which is due to the resonance effect.
- Small backward asymmetry.

Aut vs $\mathrm{M}_{\text {inv }}$ in $\mathrm{p}_{\mathrm{T}}^{\pi^{+} \pi^{-}}$bins:

- 2 D binning, $\mathrm{A}_{\mathrm{Ut}}$ as a function of $\mathrm{M}_{\mathrm{inv}}$ in $5 \mathrm{p}_{\mathrm{T}}$ bins.
- Higher AUt in the higher $\mathrm{p}_{\mathrm{T}}$ bin, where higher $x$ is probed.
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$$
p+p \rightarrow \pi^{+} \pi^{-}+X \text { at } \sqrt{s}=200 \mathrm{GeV} \text { from run } 2012
$$



Polarization integrated $\approx$ Unpolarized

- Lower trigger threshold than 2015 dataset, and thus better for crosssection measurement.
- Inclusive $\pi^{+} \pi^{-}$differential cross section:
- As a function of invariant mass, $M_{i n v}^{\pi^{+} \pi^{-}}$, in $|\eta|<1$.
- Much needed for the $D_{1}^{h_{1} h_{2}}$ extraction.
- Access to $D_{1}^{h_{1} h_{2} / g}$.
- We will release preliminary result very soon, STAY TUNED.



## Summary

- Azimuthal correlation asymmetries, which are sensitive to transversity, have been measured at STAR.
-The statistical precision of the new 2015 results is significantly improved compared to previous STAR measurements.
- We expect to significantly reduce the systematic uncertainty from the PID by using the Time-of-Flight detector in the final result.
- Preliminary result on the unpolarized dipion cross-section will be released VERY SOON using the STAR Run 12 data.
- Differential cross section as a function of $M_{i n v}^{\pi^{+} \pi^{-}}$in $|\eta|<1$.
-Constrain unpolarized FF, $D_{1}$.
-These measurements will provide a basis for the transversity extraction with better precision.
- These results can be used to test the universality between SIDIS, $e^{+} e^{-}$, and $\boldsymbol{p} \boldsymbol{p}$, and further constrain global fits of transversity, especially in the high $\boldsymbol{x}(0.1<\boldsymbol{x}<0.3)$ region.

