Nucleon spin structure study at RHIC

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聊城，2013.2.17
RHIC - the first polarized pp collider in the world

- Spin pattern changes from bunch to bunch
- Spin rotators provide choice of spin orientation
RHIC performance with pp collisions

- First Collisions at 500 GeV in 2009 and 2012.
The RHIC/STAR spin program

- **Longitudinal spin program**: determination of helicity distributions:
  - Gluon polarization $\Delta g(x)$ in the nucleon
    -- inclusive jet, hadrons
    -- di-jets, $\gamma+$jet
  - Flavor separation: quark & anti-quark polarization
    -- RHIC 500 GeV program ($W^\pm$ production)
    -- Hyperon spin transfer & strange quark polarization

- **Transverse spin program**:
  - Single spin asymmetry $A_N$ (SSA) on $\pi^0$, $\eta$
    -- QCD mechanisms (Sivers, Collins, high-twist)
  - Transversity measurement
Detailed knowledge on $\Delta q(x)$, $\Delta g(x)$- global fit using DIS and pp data

W@ RHIC 500 GeV

RHIC (jet, $\pi^0$, photon) 200 GeV, 500 GeV

Hyperons

D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)
The STAR Detector

Magnet
- 0.5 T Solenoid

Triggering & Luminosity Monitor
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters

Central Tracking
- Large-volume TPC
  - $|\eta| < 1.3$

Calorimetry
- Barrel EMC (Pb/Scintillator)
  - $|\eta| < 1.0$
  - Shower-Maximum Detector
- Endcap EMC (Pb/Scintillator)
  - $1.0 < \eta < 2.0$
$\Delta G$ measurement
Accessing $\Delta g(x)$ in pp collision

- Longitudinal spin asymmetry:

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

$$\Delta f_1 \quad \Delta f_2$$

$$\hat{a}_{LL} = \frac{d\Delta \hat{\sigma}}{d\hat{\sigma}}$$

$D_f^\pi$

**Observables**

- $p\bar{p} \rightarrow {\text{jet(s)} X}$: No FF! Average over partonic kinematics
- $p\bar{p} \rightarrow \gamma X$: Requires $D_f^\pi$ for interpretation
- $p\bar{p} \rightarrow \pi^+ X$, $p\bar{p} \rightarrow \pi^0 X$: Reconstruct partonic kinematics, challenging pion background.

**Processes**

- A: $gg \rightarrow gg$
- B: $qq \rightarrow qq$
- C: $qq' \rightarrow qq'$
- D: $q\bar{q} \rightarrow q\bar{q}$
- E: $q\bar{q} \rightarrow q\bar{q}$
- G: $gg \rightarrow g\gamma$
- $q\bar{q} \rightarrow q'\bar{q}'$
Measurements of longitudinal spin asymmetry

\[ A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \times \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \]

Ingredients:

- Polarization \( P_1, P_2 \): measured by RHIC polarimeters;
- Spin dependent yields \( N_{++}, N_{+-} \): number of detected jets/particles for a given combination of beam polarization directions;
- Relative Luminosity \( R \) measured with the STAR BBC:

\[ R = \frac{L_{++}}{L_{+-}} \]
Experimental cross section agrees with NLO pQCD over 7 orders of magnitude

STAR Results on jet spin asymmetry

PRL 97, 252002 (2006)

STAR
p+p → jet + X
√s=200 GeV
midpoint-cone
r_cone=0.4
0.2<η<0.8

2005

PRL 100, 232003 (2008)

±9.4% scale uncertainty from polarization not shown

2006

PRD86, 32006(2012)

±8.3% scale uncertainty from polarization not shown
Impact of RHIC early results on $\Delta g(x)$

de Florian et al., PRL101(2008)

- Early RHIC data (2005, 2006) included in a global analysis along with DIS and SIDIS data.
- Find a node in gluon distribution near $x \sim 0.1$. 
STAR inclusive jet $A_{LL}$ from run9

$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$

- 2009 STAR data is a factor of 4 more precise than 2006.
- The $A_{LL}$ asymmetry is small, but clearly non-zero!
- Results fall between predictions from DSSV and GRSV-STD
Updated global analysis with new STAR data

Truncated first moment:

\[ \int_{0.05}^{0.2} dx \Delta g(x, Q^2 = 10 \text{ GeV}^2) = 0.13 \]

Access to partonic kinematics through di-jet production

\[ x_1(2) = \frac{1}{\sqrt{s}} \left( p_{T_3}e^{-\eta_3} + p_{T_4}e^{-\eta_4} \right) \]

2006 di-jet cross section

- pp @ 200 GeV
- Cone Radius = 0.7
- max(p_T) > 10 GeV, min(p_T) > 7 GeV
- |\eta| < 0.8
- |\Delta\eta| < 1.0
- |\Delta\phi| > 2.0
- \( \int \text{Ldt} = 5.39 \text{pb}^{-1} \)

\[ \frac{d^2\sigma}{dM d\eta_3 d\eta_4} \]

- STAR Run-6
- Systematic Uncertainty
- NLO pQCD + CTEQ6M
- Had. and UE. Corrections
2009 dijet $A_{LL}$ from STAR

- For fixed $M$, different kinematic regions sample different $x$ ranges
  - East-east and west-west sample higher $x_1$, lower $x_2$, and smaller $|\cos(\theta^*)|$
  - East-west samples lower $x_1$, higher $x_2$, and larger $|\cos(\theta^*)|$
- $A_{LL}$ falls between DSSV and GRSV-STD
Future di-jet / inclusive jet measurement

- Access lower Bjorken-x region at 500GeV ⇒ Expect smaller $A_{LL}$
- Important constrain from future Di-Jet and Inclusive Jet measurements

$P=0.5$ and $L_{recorded}=85\text{pb}^{-1}$
Prospects on prompt photons

- Future Photon-Jet measurements:
Anti-quark pol. with $W$ production
Flavor separation of quark spin via W production in pp
(\(\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}\) through \(W^\pm\) production)

- Quark polarimetry with W-bosons:

- Spin measurements:

\[
A_{L}^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1) \bar{d}(x_2) + \Delta \bar{d}(x_1) u(x_2)}{u(x_1) \bar{d}(x_2) + \bar{d}(x_1) u(x_2)} = \begin{cases} \\
-\frac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\
\frac{\Delta \bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \\
\end{cases}
\]

\[
A_{L}^{W^-} = \begin{cases} \\
-\frac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\
\frac{\Delta \bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \\
\end{cases}
\]

W-detection through high energy lepton
Background dominated by QCD background, estimated with a data driven method. Also smaller fraction from $W \rightarrow \tau \nu$ decay, and Z$^0$ boson decay (MC estimate).
W cross section in pp at RHIC energy

- Data in agreement with NLO calculations:
First STAR $W A_L$ results

\[ A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]


\[ A_L(W^+) = -0.27 \pm 0.10 \text{(stat)} \pm 0.02 \text{(syst)} \]
\[ A_L(W^-) = 0.14 \pm 0.19 \text{(stat)} \pm 0.02 \text{(syst)} \]

- $A_L(W^+)$ negative, as predicted, $\sim 3$ sigma $< 0$
- $A_L(W^-)$ central value positive, as expected
**STAR 2012 W $A_L(\eta)$**

- $A_L(W^+)$ is consistent with theoretical predictions using the DSSV polarized PDFs
- $A_L(W^-)$ is systematically larger than the DSSV predictions
- The enhancement at $\eta_e < 0$, in particular, is sensitive to the $\bar{u}$ antiquark distribution
- The systematic uncertainties for $A_L$ are well under control for $|\eta_e| < 1.4$
- DSSV $\Delta \chi^2 = 1$ band underestimates the theoretical uncertainty and Lagrange multiplier estimates for a $\Delta \chi^2/\chi^2 = 2\%$ error are in progress
In $1 < |\eta| < 2$ we access the antiquark polarizations directly.

Endcap Calorimeter already provides coverage in this region, but we need tracking in order to separate charge signs.

-> FGT upgrade
The Forward GEM Tracker

Triple-GEM disks positioned around the beam pipe within the inner field cage of the TPC to cover $1<\eta<2$.

Partial installation before run 12 and in operation during run 12.
STAR Run 12+13 Projections at 500 GeV

\[ \bar{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X \]

25 < \text{\textit{E}}_T < 50 \text{ GeV}

|\eta| < 1.5 \quad L = 250 \text{ pb}^{-1}

1.5 < |\eta| < 2.0 \quad L = 165 \text{ pb}^{-1}

P = 55%
Strange quark polarization
\( \Delta S \) from polarized inclusive DIS

- Determination of \( \Delta S \), \( \Delta \Sigma \) with polarized inclusive DIS:

\[
\Gamma_1^p = \int_0^1 g_1^p(x) dx = \frac{1}{2} \int \sum_i e_i^2 \Delta q_i(x) = \frac{1}{18} [4\Delta U + \Delta D + \Delta S] 
\]

\[
\Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}
\]

Each flavor’s contribution to nucleon spin:

\[
\Delta q = \int_0^1 \Delta q(x) dx \\
\Delta q(x) = q^+(x) - q^-(x) : \text{helicity distribution function}
\]

- Together with neutron, hyperon \( \beta \) decay data using SU(3)\(_f\) symmetry:

\[
\Rightarrow \Delta \Sigma = 0.33 \pm 0.03 \pm 0.01 \pm 0.03: \quad \begin{cases} 
\Delta U &\sim 0.84, \\
\Delta D &\sim -0.43, \quad (\text{HERMES}, Q^2=5 \text{ GeV}^2) \\
\Delta S &\sim -0.08 \pm 0.01 \pm 0.01 \pm 0.01*
\end{cases}
\]

*COMPASS also obtained similar results.
$\Delta S$ from semi-inclusive DIS

- Recent measurements in semi-inclusive DIS - consistent with zero:

$$\Delta S' = 0.037 \pm 0.019 \pm 0.027$$

0.02 < $x$ < 0.6, at a scale $Q^2 = 2.5$ GeV$^2$.

$$\Delta S' = -0.01 \pm 0.01 \pm 0.02$$

0.004 < $x$ < 0.3, at $Q^2 = 3$ GeV$^2$

Different as inclusive DIS results?

Our knowledge on $\Delta S$ is far from comprehensive.

More measurements are needed.
Detailed knowledge on $\Delta q(x)$, $\Delta g(x)$ - global fit using DIS and pp data

W@ RHIC 500 GeV

RHIC (jet, $\pi^0$, photon) 200 GeV, 500 GeV

D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)
Study $\Delta S$ at RHIC with hyperons?

- $\Lambda$'s contain a strange quark, whose spin is expected to carry most of the $\Lambda$ spin.

- $\Lambda$ polarization can be measured in experiment via weak decay

$$\frac{dN}{d\Omega} \propto 1 + \alpha (\vec{P}_\Lambda \cdot \vec{p}_p^*)$$

- Unit vector along proton momentum in $\Lambda$'s rest frame.
- $\vec{P}_\Lambda \cdot \vec{p}_p^* \propto \cos \theta^*$

- decay parameter 0.642 ±0.013

- $\Lambda$ polarization vector

- Can $\Lambda(\bar{\Lambda})$ polarization measurements provide sensitivity to $\Delta S$ at RHIC?
Hyperon production in pp collisions

- The factorized framework enables perturbative description,

\[ d\sigma \propto \int f_a(x_1) \cdot f_b(x_2) \otimes d\hat{\sigma} \otimes D^\Lambda(z) \]

- Hyperon spin transfer \( D_{LL} \) provides access to \( \Delta f \) and \( \Delta D \):

\[ D_{LL} = \frac{\sigma_{p^+ p \to \Lambda^+ X} - \sigma_{p^+ p \to \Lambda^- X}}{\sigma_{p^+ p \to \Lambda^+ X} + \sigma_{p^+ p \to \Lambda^- X}} = \frac{d\Delta\sigma}{d\sigma} \]
Current knowledge on $\Delta D$ and corresponding predictions in pp

- Pol. frag. function from global parameterization:
  

- Modeling Pol. Frag. Function, related to hyperon spin structure:
  
D_{LL}-Longitudinal spin transfer at RHIC

- Expectations at LO show sensitivity of D_{LL} for anti-Lambda to $\Delta \vec{s}$:

- $\sqrt{s} = 200$ GeV
- $p_T > 8$ GeV

- $\Delta \vec{s}$ models
- Pol. frag. func. models

- $\Lambda$ D_{LL} is less sensitive to $\Delta s$, due to large u,d quark fragmentation.
- Promising measurements---effects potentially large enough to be observed.
D_{LL} Results of STAR with data-2005

At \( <p_T> = 3.7 \text{ GeV} \) and \( <\eta> = 0.5 \):

\[
D_{LL}(\Lambda) = -0.03 \pm 0.13(\text{stat}) \pm 0.04(\text{sys})
\]

\[
D_{LL}(\bar{\Lambda}) = -0.12 \pm 0.08(\text{stat}) \pm 0.04(\text{sys})
\]

• D_{LL} for Lambda and anti-Lambda are consistent with each other
• Uncertainties are similar to the spread in model expectations.
Results of STAR with Data-2009 extended to $p_T \sim 6.0$ GeV with $\sim 4\%$ precision, compared to $8\%$ at 3.7 GeV for 2005 data.

Systematic uncertainties vary from 0.01 to 0.03 for each point which include:

- 4.7% Beam polarization
- 2.0% Decay parameter
- 1.9% Residual trans. pol.
- $5 \times 10^{-3}$ Relative luminosity
- $<6 \times 10^{-3}$ Residual background.
- $\leq 0.03$ Trigger bias, increases with $p_T$.
- $\leq 0.01$ Pile-up, decreases with $p_T$. 
Comparison of $D_{LL}$ with predictions

D. de Florian, M. Stratmann, and W. Vogelsang, PRL. 81. (updated calculation to low $p_T$)

scen. 1: SU(6) picture.
scen. 2: DIS picture.
scen. 3: equal contribution.

• $D_{LL}$ results are still consistent with zero within the uncertainties.
• $D_{LL}$ for Lambda and Anti-Lambda are consistent with each other.
• The statistics are similar to the spread of different models.
Transverse spin transfer and $\delta q(x)$

- **Transverse** spin transfer of hyperons can provide access to transverse spin structure of nucleon:

\[
P_T^H = \frac{d\sigma^{(p_T \rightarrow p \rightarrow \uparrow X)}}{d\sigma^{(p_T \rightarrow p \rightarrow \downarrow X)}} - \frac{d\sigma^{(p_T \rightarrow p \rightarrow \downarrow X)}}{d\sigma^{(p_T \rightarrow p \rightarrow \uparrow X)}} = \frac{d\Delta_T \sigma}{d\sigma}
\]

Transversity distribution:

$\delta f(x) = f_{\uparrow}(x) - f_{\downarrow}(x)$

- Transverse spin transfer can give insights into transversity.
- Such measurements can be made at mid-rapidity with TPC at STAR.

Transversely polarized fragmentation function, may be obtained at BELLE
Induced $\Lambda$ polarization in unpolarized pp

- Large polarization with unpolarized beam $p + p \rightarrow \Lambda^\uparrow + X$, observed in many experiments.
  - G. Bunce et al, PRL36, 1113, (1976)

- LO pQCD calculation gives $\sim 0$ ($\propto m_q$).

\[ \vec{N} : \quad \vec{N} = \vec{p}_b \times \vec{p}_\Lambda / (|\vec{p}_b \times \vec{p}_\Lambda|) \]

- Measurement at higher energy (at RHIC) would be very interesting.

\[ ( = 2p_L/\sqrt{s}) \]
Forward hyperon physics with STAR upgrade

- Addition of Forward Hadron Calorimeter (FHC) at STAR may enable the study of forward $\Lambda$ physics together with FMS through $\Lambda \rightarrow n\pi^0$ (Br=36%).
Transverse spin physics at STAR
Transverse spin program at STAR

- Single transverse-spin asymmetry

\[ A_N = \frac{N_L - N_R}{N_L + N_R} \]

- Basic QCD calculations (leading-twist, zero quark mass) predict \( A_N \sim 0 \)

--- \( A_N \sim 0.4 \) for \( \pi^+ \) in pp at E704 (1991)

- Understanding transverse spin effect:
  - Qiu and Sterman (initial-state) / Koike (final-state) twist-3 pQCD calculations
  - Sivers: spin and \( k_\perp \) correlation in initial state (related to orbital angular momentum)
  - Collins: spin and \( k_\perp \) correlation in fragmentation process (related to transversity)

Twist-3 correlation and the \( k_\perp \) dependent distribution/fragmentation in intermediate \( p_T \) generate the same physics.

Ji-Qiu-Vogelsang-Yuan, PRL97, 2006
Separating Sivers and Collins effect in pp collisions

- **Sivers effect:**
  - spin and $k_\perp$ correlation in initial state (related to orbital angular momentum)
  - Sensitive to orbital angular momentum

- **Collins effect:**
  - spin and $k_\perp$ correlation in fragmentation process (related to transversity)
  - Sensitive to transversity

- For hadron SSA, both Sivers and Collins effects can contribute.
- Sivers and Collins effects can be separated in SIDIS processes.
Recent results on SSA

- X-section reproduced with pQCD
- $A_N$ increase with $x_F$, in agreement with pQCD model calculation.
Recent results on SSA

STAR, PRL97,152302(2006)

- $p+p \rightarrow \pi^0 + X$, $\sqrt{s} = 200$ GeV

- $A_N$ increase with $x_F$, in agreement with pQCD model calculation.

- pQCD based models predicted decreasing $A_N$ with $p_T$, which is not consistent with data.

- X-section reproduced with pQCD

In addition to the $\pi^0$'s, we measured the forward cross-section (slide 4) and $A_N$ for the $\eta$ mesons using the FPD. At high $x_F$ ($x_F > 0.55$), the $A_N$ for the $\eta$ is very large, and may not be consistent (~3%) with that of the $\pi^0$.

Kanazawa & Koike calculates larger $A_N$ for $\eta$ than $\pi^0$, from the strangeness contribution. However, the $x_F$ dependence deviates from the data.
Continuing the previous FPD measurement, the FMS reported the $p_T$ dependence of forward $\pi^0 A_N$ at $\sqrt{s}=500$ GeV, up to $\sim10$ GeV.

Even at $7\sim10$ GeV, we see no sign of $1/p_T$ like fall. While this is counter-intuitive, Kanazawa & Koike obtain an almost flat $p_T$ dependence based on twist-3 formalism combined with DSS fragmentation function, which has a large gluon component.
**STAR** forward instrumentation upgrade

- Forward instrumentation optimized for p+A and transverse spin physics
  - Charged-particle tracking
  - e/h and γ/π⁰ discrimination
  - Baryon/meson separation

Future Drell-Yan Physics at STAR
Transversity study at STAR

- To access proton transversity
  a) Mid-rapidity hadron-jet correlations
  b) Mid-rapidity di-hadron production
Mid-rapidity hadron-jet correlations

- Measure proton transversity through its coupling with Collins fragmentation function

- Spin-correlated azimuthal distribution of hadrons inside jet

\[
\frac{d\sigma}{dPS} = \frac{d\sigma_{UU}}{dPS} + |S_\perp| \frac{|P_{hT}|}{M_h} \sin(\phi_h - \phi_s) \frac{d\sigma_{TU}}{dPS}
\]

observable:

\[
A_{meas}(z, j_T) = \frac{2 \sum N(z, j_T) \sin(\phi_C)}{\phi_C \sum PN(z, j_T)} = A_N(z, j_T)
\]


Mid-rapidity hadron-jet correlations

STAR run6 Collins Asymmetries

Collins Asymmetry $A = 2 \langle \sin(\phi_h - \phi_S) \rangle$ vs. $z$

- $\pi^+$ Asymmetry
- $\pi^-$ Asymmetry

Systematic uncertainties

STAR Preliminary
- $\pi^-$ data horizontally offset for clarity

RHIC 2006 $\sqrt{s} = 200$ GeV
$p^+p \rightarrow \text{jet}(\pi^\pm) + X; \text{jet } p_T > 10$ GeV

Systematic effects contributing to <1% of total uncertainty excluded

only look at forward rapidities of polarized beam

$E_{\text{jet}} > 10$ GeV
Mid-rapidity di-hadron production

*Extract proton transversity through its coupling with chiral-odd Interference Fragmentation Function*

\[
\frac{d\sigma_{UU}}{dP_{C\perp}} = 2|P_{C\perp}| \sum_{a,b,c,d} \int \frac{dx_a dx_b}{4\pi^2 z_C} \frac{d\hat{\sigma}_{ab\rightarrow cd}}{dt} \frac{f_1^a(x_a)f_1^b(x_b)}{S_{BT} \sin(\phi_{SB} - \phi_{RC})} \int \frac{dx_a dx_b}{16\pi z_c} \frac{H_{1,ot}(\bar{z}_C, M_C^2)}{dt}
\]

Unpolarized quark distribution
Known from DIS

Transversity to be extracted

Hard Scattering cross section from pQCD

IFF+Di-hadron FF measured in $e^+e^-$

\[A. \text{ Bacchetta, M. Radici, Phys. Rev. D 70, 094032 (2004)}\]

collinear factorization is preserved
Di-hadron spin asymmetries at STAR

STAR shows significant signal in di-hadron asymmetries

$A_{UT}$ peaks at around $\rho$ mass, inherited from the structure of $H_1^{<}(z,M_{Inv})$

Different cone size $\rightarrow$ different mean $p_T$, $z$
STAR shows significant signal in di-hadron asymmetries

At forward rapidities, transverse polarization of the quark is more effectively transferred to the hard scattered partons
Summary & Outlook

- Probing sea quark polarization via W-boson at RHIC:
  - New results on W-boson single-spin asymmetry measurement in pp
  - Currently probes with jets, are providing important constraints on $\Delta G$. Global analysis indicates small gluon polarization ($0.05 < x < 0.2$).
  - Correlation measurements (di-jet, photon-jet) with access to partonic kinematics will provide better resolution in $x$ and direct probe to $\Delta G$.

- Determination of gluon polarization $\Delta G$ at STAR/RHIC:
  - Currently probes with jets, providing important constraints on $\Delta G$.
    - Global analysis indicates small gluon polarization ($0.05 < x < 0.2$).
  - Correlation measurements (di-jet, photon-jet) with access to partonic kinematics will provide better resolution in $x$ and direct probe to $\Delta G$.

- Hyperon spin transfer in pp collision can provide sensitivity for (anti-)strange quark polarization in nucleon.

- Transverse spin physics at STAR:
  - Single spin asymmetry $A_N$ (SSA) on $\pi^0$, $\eta$
  - Transversity measurement
## Envisioned EIC Timeline

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Probing the quark flavor structure using $W$ boson production

Use lepton rapidity as a surrogate for $W$ rapidity based on $W$ decay kinematics

$e^{- (+)}$ are emitted along (opposite) the $W^{- (+)}$ direction
BELLE: Collins Effect in di-Hadron Correlations in $e^+e^-$ Annihilation into Quarks!

Collins effect in $e^+e^-$ quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

**Experimental requirements:**
- Small asymmetries $\Rightarrow$ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
Interference Fragmentation Function measured in $e^+e^-$ annihilation

Single spin asymmetries in semi-inclusive deep inelastic scattering

\[ A_{UT}(\phi, \phi_S) \approx 2\langle \sin(\phi + \phi_S) \rangle_{UT}^h \sin(\phi + \phi_S) + 2\langle \sin(\phi - \phi_S) \rangle_{UT}^h \sin(\phi - \phi_S) + \cdots \]

Collins moment

\[ \propto h_l(x) \otimes H_{lq}^q(z) \]

Sivers moment

\[ \propto f_{1T}^q(x) \otimes D_{lj}^q(z) \]

Sivers DF

Unpolarized FF

\[ A_{UT}(\phi, \phi_S, \ldots) = \frac{I}{S_{\perp}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \]

\( \phi \) - angle between the lepton scattering and hadron production planes

\( \phi_S \) - angle between the target spin direction and the lepton scattering plane
Large $A_N$ in the forward region of “high energy” hadron-hadron interaction has a long experimental history, dating back to 1976.

Until the RHIC era, these measurements were performed in fixed target environments with polarized targets.

However, it was generally believed that these fixed target results could not be interpreted within the framework of pQCD.
In contrast, at RHIC (200GeV), there are good agreements between forward hadron cross-sections and pQCD predictions, with appropriate fragmentation functions.

Consequently, many believe that the RHIC forward transverse spin results CAN be understood by pQCD.
Spin structure of nucleon

• Spin sum rule (longitudinal case):

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G^+ < L_{q,g} > \]

- Quark spin, (~30%)-DIS
- Gluon spin, RHIC
- Orbital Angular Momenta
  Little known (DVCS)

\[ \Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \quad [\Delta q = \int_0^1 \Delta q(x) \, dx] \]

• Polarized parton densities:

\[ \Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2) \]

\[ q(x,Q^2) = q^+(x,Q^2) + q^-(x,Q^2) \]
PHENIX π0 $A_{LL}$ run 9 results