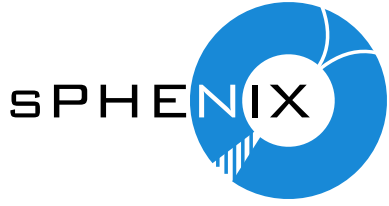
The Cold QCD Program at

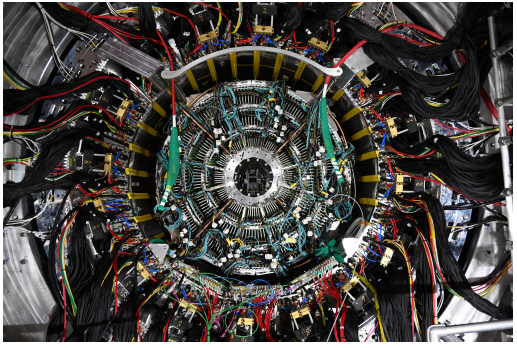


RHIC/AGS Users Meeting 2025

Virgile Mahaut - CEA - Université Paris-Saclay
On behalf of the sPHENIX Collaboration

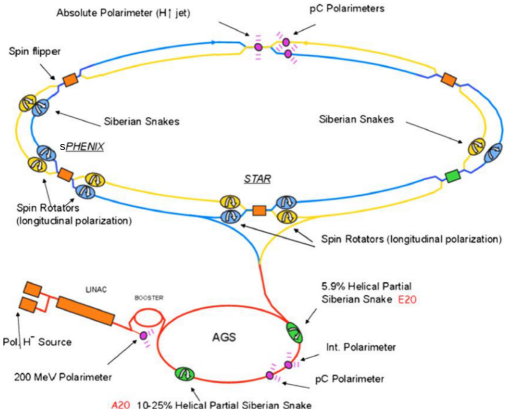
sPHENIX Collaboration at RHIC

sPHENIX



Collaboration started in 2016
$\sim$ 300 members (53 institutions)
Commissioned from 2023 to 2024

RHIC



First collisions in 2000
$p+p,\ p+Au, Au+Au, \cdots,$

Hot QCD: Quark-Gluon plasma

This talk: **Cold QCD** with **polarized** $p^{\uparrow} + p^{\uparrow}$ **at** $\sqrt{s} = 200\,\mathrm{GeV}$ **(Run 2024)**

Towards completing RHIC science mission with sPHENIX

Exciting Cold QCD physics opportunities with sPHENIX with polarized $p^{\uparrow}p^{\uparrow}$, $p^{\uparrow}$ *Au* data in FY25/26. Supported by Program Advisory Committee (PAC)

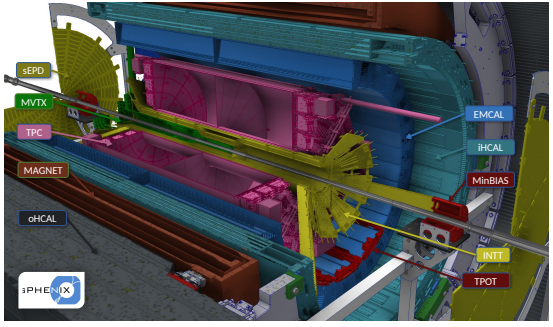
- PAC report: "The PAC recommends a Au+Au run in which sPHENIX collects at least 7 nb^{-1} of data as the highest priority for Run 25."
- PAC24 report: "The PAC has received beam use requests for running p+p, p+Au, and O+O collision systems. The PAC sees all three of these proposed runs as fully aligned with RHIC's core scientific mission, and in fact as key elements of completing that mission."

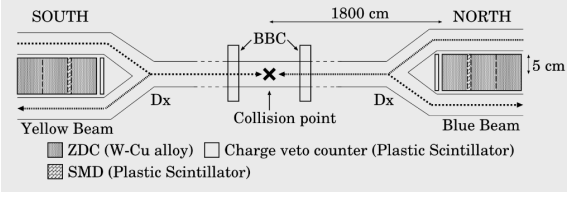
sPHENIX Beam Use Proposal, Presented to PAC24 [link]

Run-25 Projection, sPHENIX Physics Target: **7 nb^{-1} (50B events)**		
Collision Species	Cryoweeks	Projected luminosity, $\|z\| < 10$ cm
Au+Au 200 GeV	20	2.8 – 5.4 nb^{-1} recorded
Au+Au 200 GeV	28	4.2 – 8.1 nb^{-1} recorded
Once Au+Au target is met, ordered priority list for additional running in FY26:		
Collision Species	Physics weeks	Projected luminosity, $\|z\| < 10$ cm
1. p+p 200 GeV	8	13 pb^{-1} sampled + 3.9 pb^{-1} streaming
2. p+Au 200 GeV	5	80 nb^{-1} sampled + 24 nb^{-1} streaming
3. O+O 200 GeV	2	13 nb^{-1} sampled + 3.9 nb^{-1} streaming

sPHENIX detector

sPHENIX optimized for jet reconstruction and heavy-flavor reconstruction





High rate DAQ

Forward MinBias detectors

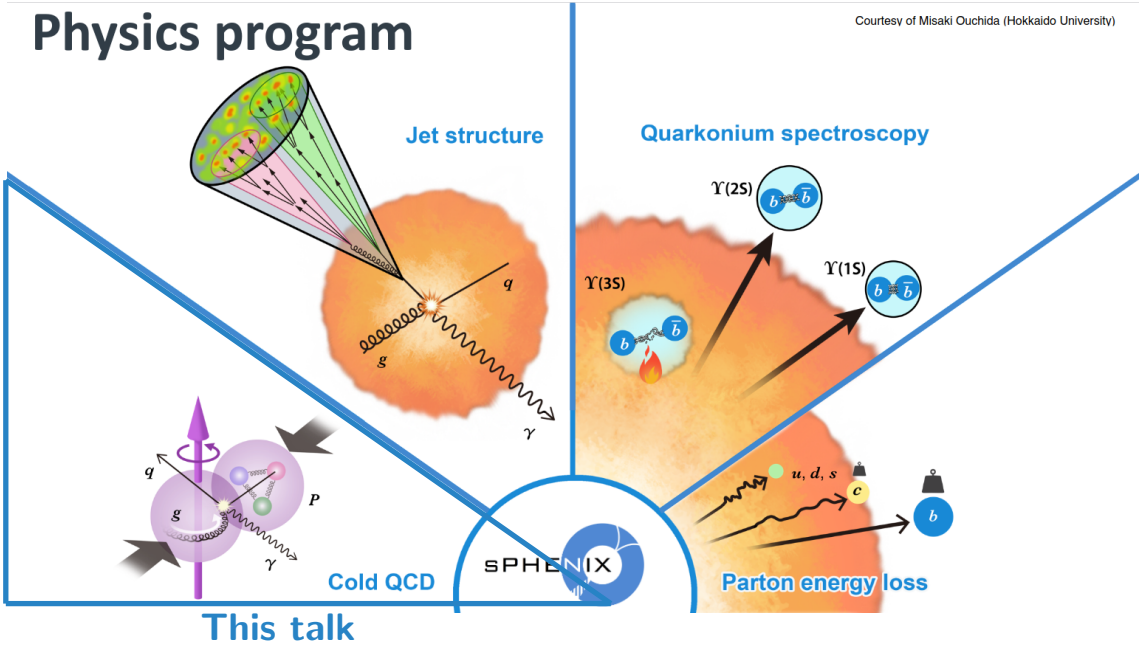
Calorimeters
Hermetic EMCal and HCal coverage
with first RHIC HCal at midrapidity ($|\eta| < 1.1$)

Central Tracking Detectors
MVTX (MAPS-based) ($r < 5\,\mathrm{cm}$),
INTT (Intermediate Tracker) ($r < 10\,\mathrm{cm}$),
TPC ($r < 80\,\mathrm{cm}$), TPOT (TPC Outer Trackers)

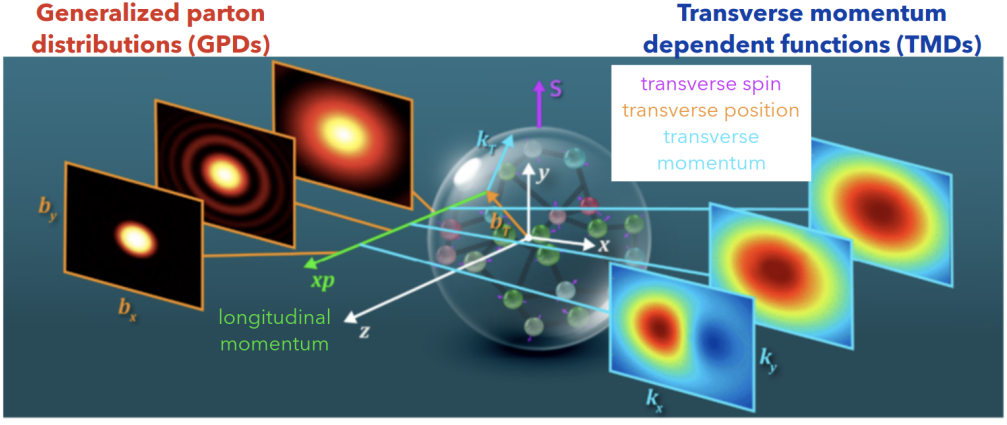
Local polarimetry to monitor vertical polarization
Zero-Degree Calorimeter (ZDC) and Shower Maximum Detector (SMD) to measure well-known transverse single-spin asymmetries of neutrons produced in the far forward region

Physics program

Courtesy of Misaki Ouchida (Hokkaido University)



Goal: Transverse spin effects in nucleon structure



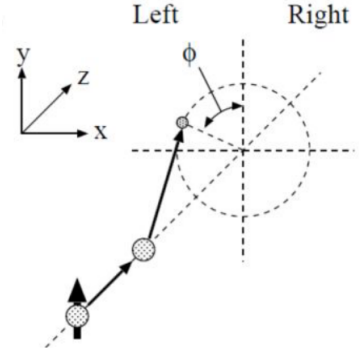
Historical PDFs:
Only functions of the longitudinal momentum fraction as: $q(x)$ and $\Delta q(x)$

Beyond 1D:
GPDs and TMDs dependent of **transverse** spin, momentum k_T, position b_T

Transverse Single Spin Asymmetries (TSSA)

Inclusive hadron production in polarized proton-proton collision:

$$p^{\uparrow} p \to hX$$



Asymmetric distribution to left
and right of polarized proton spin

In terms of QCD parton model,
TSSA expected to vanish

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

Kane, Pumplin, Repko PRL 41, 1689 (1978)
Efremov, Teryaev Nucl. Phys. 36, 140 (1982)

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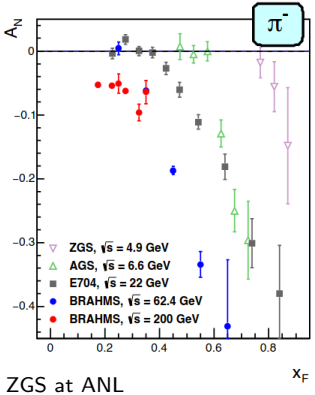
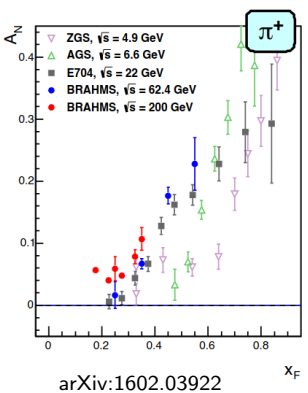
In terms of QCD parton model, TSSA expected to vanish: $A_N \propto m_q/\sqrt{s}$

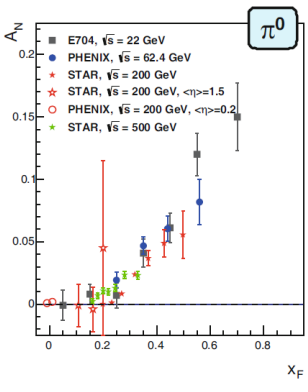
Nonetheless, large TSSA are observed (mostly independent of energy)



ZGS at ANL
AGS, RHIC at BNL
FNL



arXiv:1602.03922



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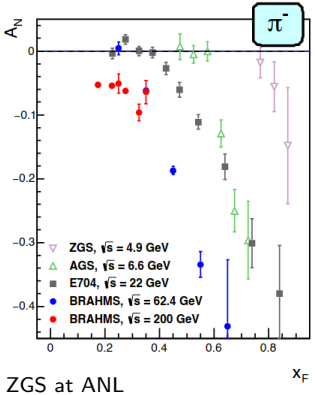
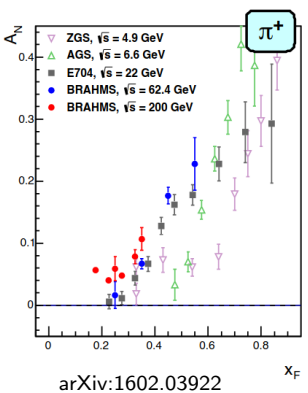
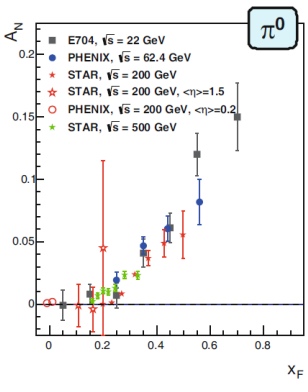






ZGS at ANL
AGS, RHIC at BNL
FNL

arXiv:1602.03922

Hint to more subtle aspects of QCD dynamics

Non-perturbative contributions to TSSA

Multi-parton correlations in Collinear Twist-3 factorization

Qiu, Sterman PRD 59.014004 (1998)

Initial-/Final-state collinear correlators: A, B, C

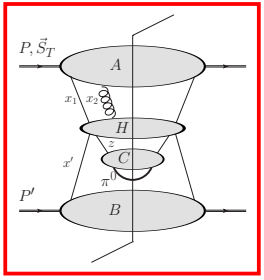
H: Hard perturbative part

$$A_N \propto \sum_{a,b,c} \underbrace{\phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{c\to\pi}(z)}_{\text{“Sivers-like”}}$$

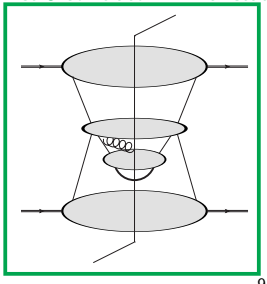
$$+ \sum_{a,b,c} \underbrace{h_{a/A}(x, \vec{s}_T) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}'' \otimes D_{c\to\pi}(z)}_{\text{“Boer-Mulders”-like (small)}}$$

$$+ \sum_{a,b,c} \underbrace{h_{a/A}(x, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}' \otimes D^{(3)}_{c\to\pi}(z_1, z_2)}_{\text{“Collins”-like}}$$

Twist-3 correlator in polarized p



Twist-3 correlator in final state



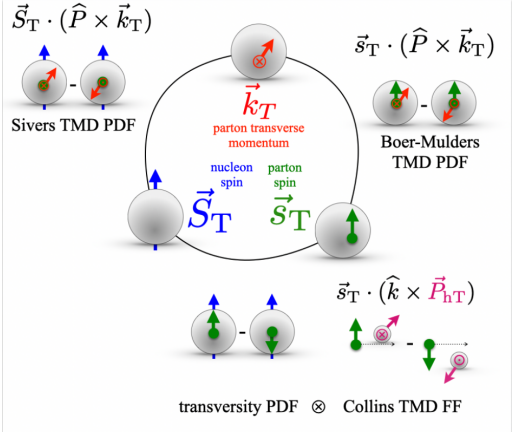
Non-perturbative contributions to TSSA

TMD factorization

Sivers effect: Parton Distribution Functions (PDF) correlating the ingoing proton transverse spin and the parton transverse momentum (initial-state effect)

Collins effect: Chiral-odd Fragmentation Functions (FF) correlating the transverse spin of fragmenting parton and the outgoing hadrons' transverse momentum (final-state effect)

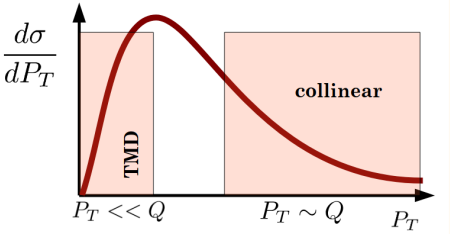
Boer-Mulders effect: Chiral-odd Parton Distribution Functions (PDF) correlating the parton's transverse momentum and the parton transverse polarization $\vec{s}_T$ (initial-state effect)



TSSA probe the spin structure of the nucleon

- Perturbative QCD in the QCD parton model does not explain the TSSA
- Non-perturbative effects are involved:
  - Interference with Collinear twist-3 correlators (qgq and ggg)
    $P_{\mathrm{T}} \sim Q$
  - TMD effects (Sivers and Collins)
    $Q^2 \gg P_{\mathrm{T}} > \Lambda_{\mathrm{QCD}}$
- At RHIC, both schemes equivalent at overlapping kinematics

$$-\int d^2\boldsymbol{k}_\perp \frac{\boldsymbol{k}_\perp{}^2}{M} \underbrace{f_{1T}^{\perp,q}(x,\boldsymbol{k}_\perp{}^2)|_{\mathrm{SIDIS}}}_{\text{Sivers TMD PDF}} = \underbrace{T_{q,F}(x,x)}_{\text{twist-3 ETQS function}}$$

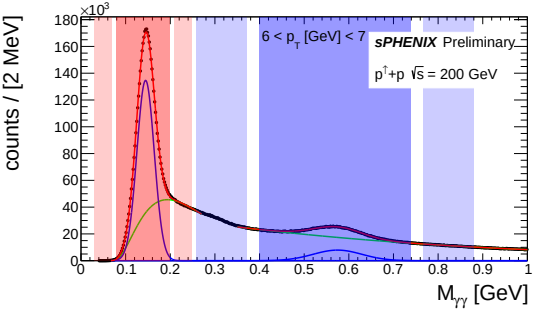


Ji, Qiu, Vogelsang, Yuan
PRL 97, 082002 (2006)

Neutral meson TSSA $p^{\uparrow}p \to \pi^0/\eta X$

$\Rightarrow$ Sensitive to **TMD** (initial-state Sivers and final-state Collins) and **twist-3 effects** (quark-gluon-quark and tri-gluon correlators)

One of the first preliminary results of sPHENIX



$$A_N^{\text{total}} = (1-r)\ A_N + r\, A_N^{\text{bk}}$$

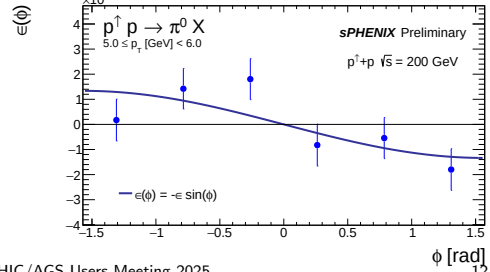
$$\epsilon = A_N \times \text{polarization}$$

$$\epsilon(\phi) = \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$

$\phi \in [-\pi/2, \pi/2]$ (full azimuth)

Fitted with: $\epsilon(\phi) \sim -\epsilon \sin\phi$

Fit performed for each bin in p_T



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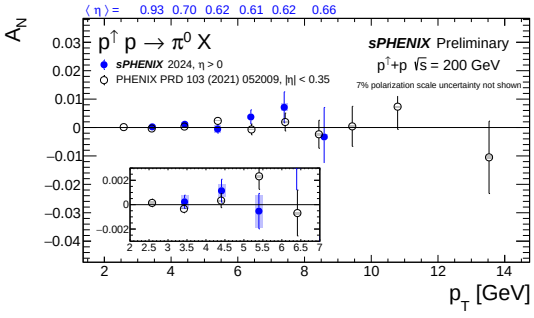
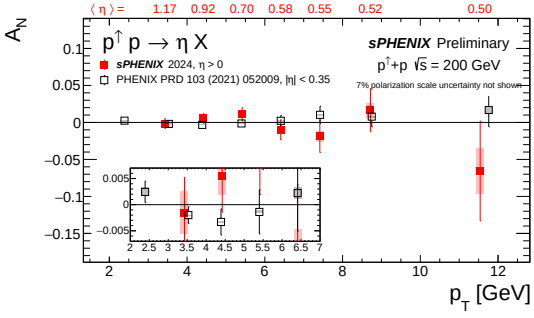




Beam-averaged forward-going p_{T} asymmetries from sPHENIX ($0 < \eta < 2$, small x_{F}) plotted along side published PHENIX data ($|\eta| < 0.35$, small x_{F})

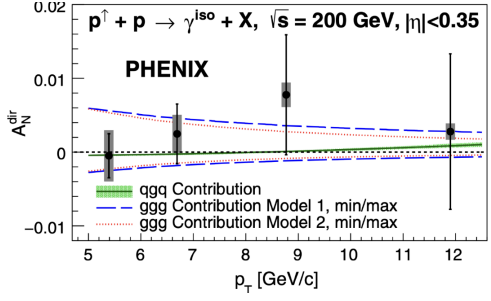
One of the first preliminary results of sPHENIX

Shown at APS 2025, DIS 2025 and QM 2025

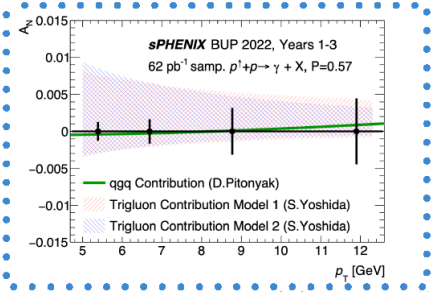
Direct photon TSSA $p^{\uparrow}p \to \gamma X$

- **Cleaner process:** only initial state nonperturbative QCD involved
- Sensitive to the **twist-3 effects** with the **tri-gluon contribution**
- Sensitive to the **gluon Sivers TMD**

PRL 127 (2021) 162001



Statistical projection for sPHENIX



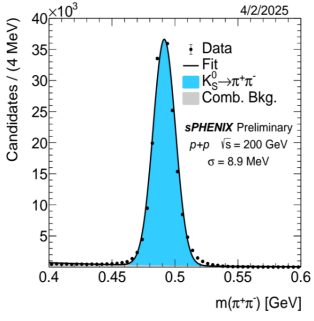
$p^{\uparrow}p \to \gamma\,\text{jet}\,X \to$ Focus on the gluon Sivers TMD

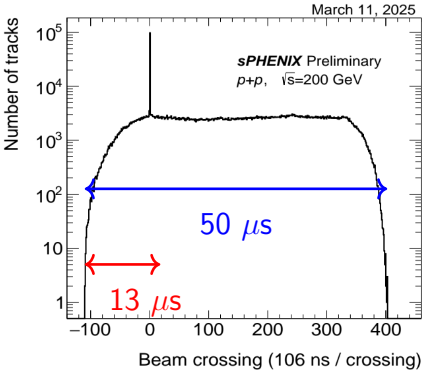
Heavy Flavour TSSA

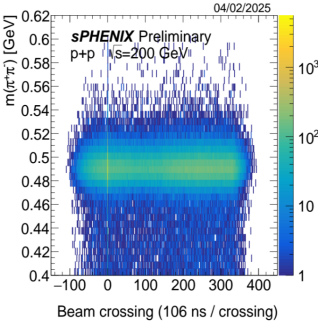
- As for direct photons, sensitive to twist-3 **tri-gluon correlators** and **gluon Sivers TMD**
- PHENIX: Open heavy flavour through leptonic decay: $p^{\uparrow}p \to e^{+/-}X$
- New with sPHENIX: Prompt D^0: $p^{\uparrow}p \to D^0/\bar{D}^0X$

→ New Precision Tracker
New streaming readout for the sPHENIX tracking detectors!

Streaming readout

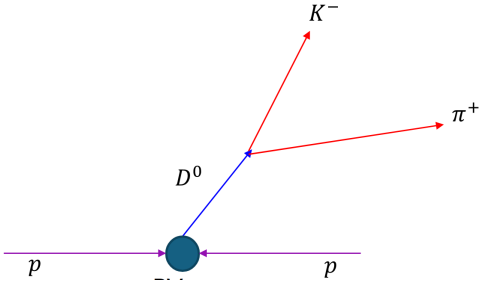




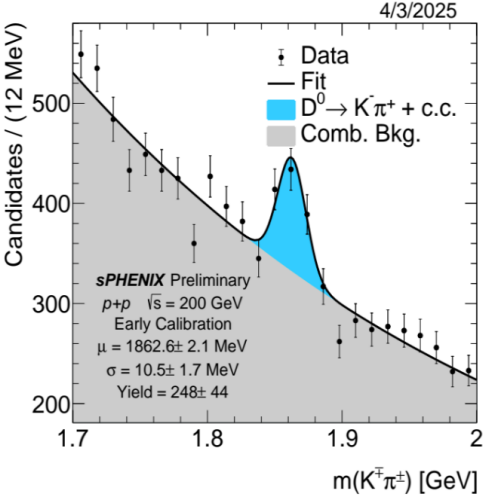


- $\text{Trig. rate} \sim 15\,\text{kHz} < \text{eff. streaming rate} \sim 300\,\text{kHz} < \text{coll. rate} \sim 1\text{MHz}$
- INTT timing resolution: 106 ns (sync with RHIC clock)
- Trigger defines beam crossing 0
- Uniform detection of K^0_s peak at all beam crossings: streaming works!

Streaming readout and improved D^0 statistics



- Clear D^0 peak observed after only one hour of data
- Results with early tracking calibrations



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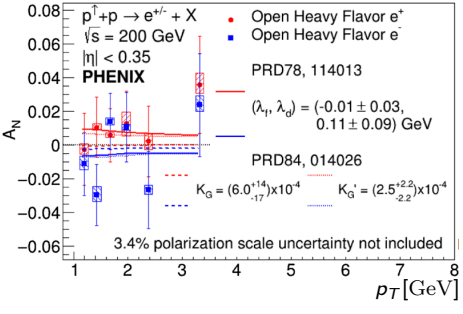
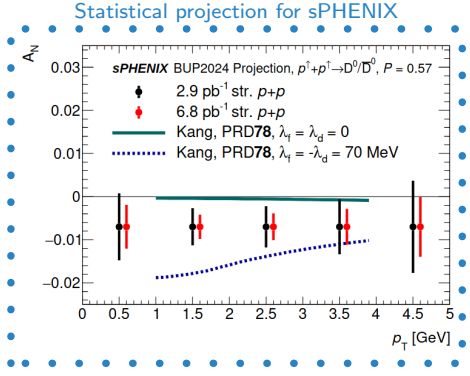
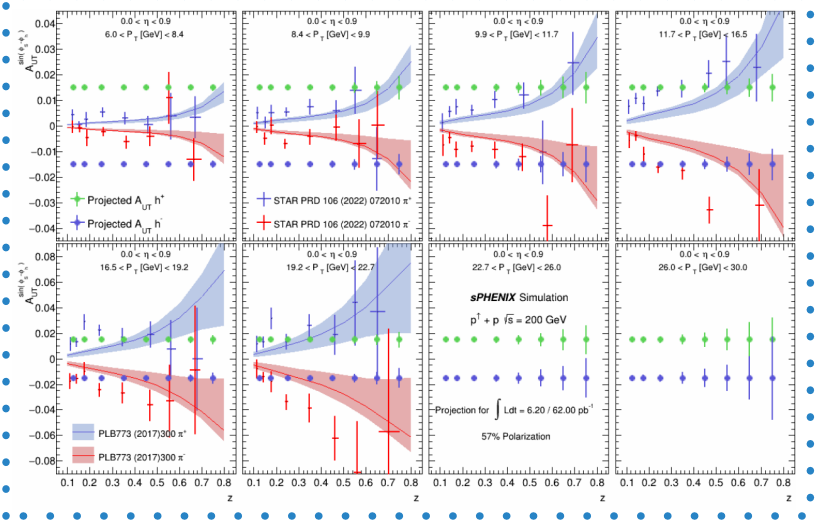




Hadron in jet TSSA $p^{\uparrow}p \rightarrow$ jet hX

Hadron in jets
$p^{\uparrow}p \rightarrow$ jet h X
Access to Collins Fragmentation Function and **transversity PDF**

Statistical projection for sPHENIX



RHIC Cold QCD Plan 2024-2028

Summary

Assets of the sPHENIX design

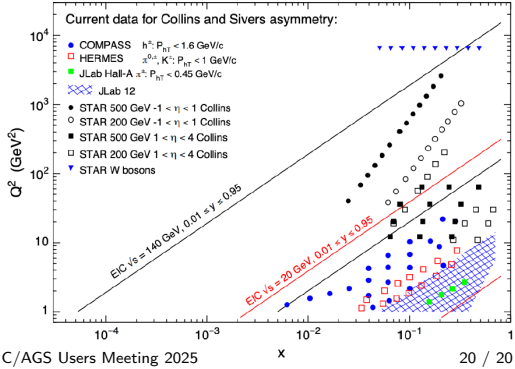
- Fast DAQ rate, tracking streaming readout, precise jet measurements
- Technology transfer to the EIC: HCal barrel, EMCal design, Streaming readout

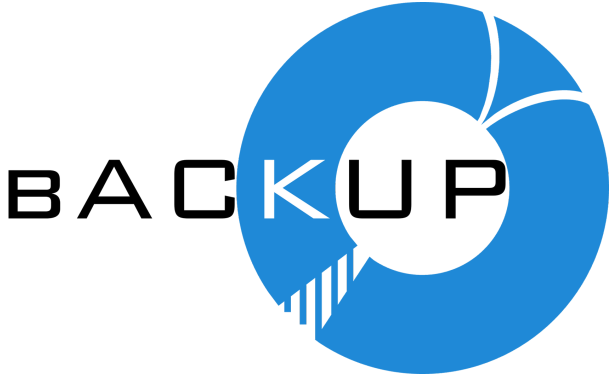
Transverse Single Spin Asymmetries (TSSA)

- First preliminary results for the **neutral meson TSSA**
- Prospects for **Direct** Photon, **Heavy Flavor**, **Hadron in Jet**, **di-hadron**, **di-jets** TSSA

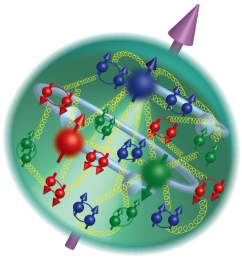
Associated spin physics and EIC

RHIC with PHENIX, STAR, sPHENIX and EIC in the future, will test TMD **factorization** and **universality** by comparing ***lp*** with ***pp*** collisions to bring solid foundation to a deeper understanding of QCD.

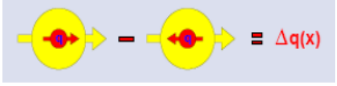



BACKUP

Nucleon spin structure



$$\Delta q(x) = q^{+}(x) - q^{-}(x)$$



$q^{+(-)}(x)$: Probability of finding a quark with momentum fraction x and spin parallel (anti-parallel) to that of the nucleon

$\Delta q = \int_0^1 \Delta q(x) dx$ and $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ (1/4 to 1/3 of proton spin)

$\Delta G = \int_0^1 \Delta g(x) dx$ (found positive)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_q + \mathcal{L}_G$$

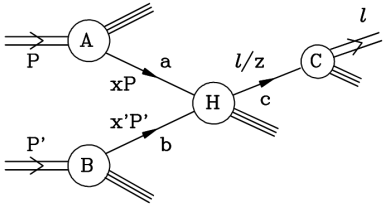
Beyond this simple picture, we can add:

- Multi-parton correlations or interactions of partons with the color field of the hadron
- Or impact of the quark transverse momentum k_T

Non-perturbative contributions to TSSA

Multi-parton correlations in Collinear Twist-3 factorization

Qiu, Sterman PRD 59.014004 (1998)

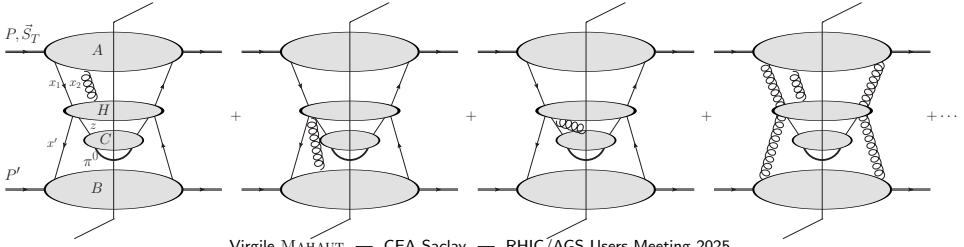


$$A_N \propto \sum_{a,b,c} \underbrace{\phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{c\to\pi}(z)}_{\text{"Sivers-like"}}$$

$$+ \sum_{a,b,c} \underbrace{h_{a/A}(x, \vec{s}_T) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma'} \otimes D_{c\to\pi}(z)}_{\text{"Boer-Mulders"-like (small)}}$$

$$+ \sum_{a,b,c} \underbrace{h_{a/A}(x, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}' \otimes D^{(3)}_{c\to\pi}(z_1, z_2)}_{\text{"Collins"-like}}$$

qgq correlator in polarized p | qgq correlator in unpolarized p | qgq Fragmentation Function | ggg correlator in polarized p



Jet TSSA

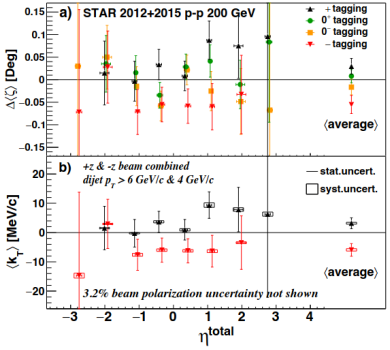
Inclusive jets $p^{\uparrow}p \rightarrow \text{jet } X$

First TSSA Measurement at mid-rapidity

Di-jets

$p^{\uparrow}p \rightarrow \text{jet jet } X$

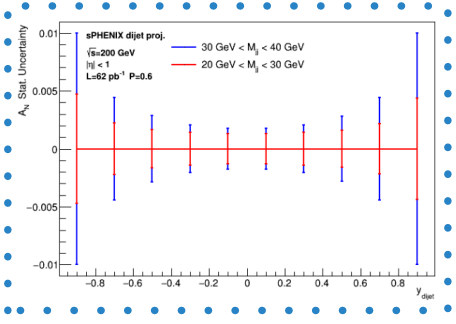
Direct access to **parton intrinsic transverse momentum** and Sivers effect



Di-jets at STAR

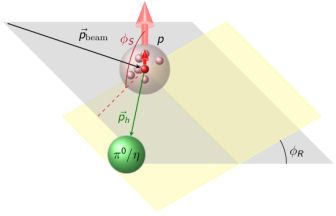
arXiv:2305.10359

Statistical projection for sPHENIX



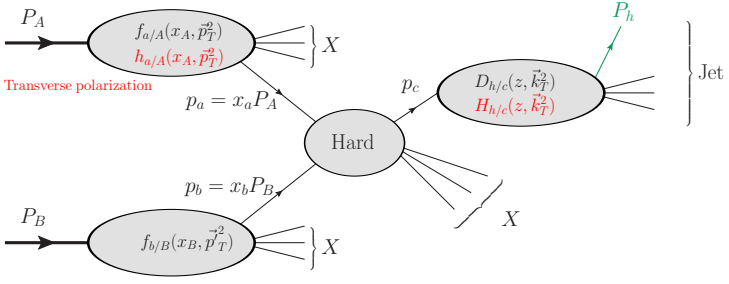
Collins effect: $p^{\uparrow}p \to hX$

Hadron-in-jet TSSA



$\Rightarrow$ Access to chiral-odd **transversity PDF** h and chiral-odd Collins Fragmentation Function $H_q^{\perp}$ in **TMD factorization**

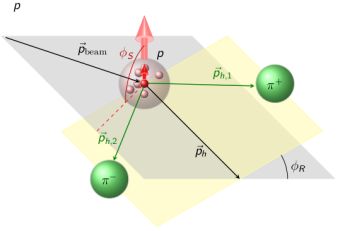
$$A_{UT}^{\sin(\phi_R-\phi_S)} \sim \frac{\frac{d\Delta\hat{\sigma}_{a^{\uparrow}b\to c^{\uparrow}}}{d\hat{t}} \otimes h_{a/A}(x_a,\vec{p}_T^{\,2}) \otimes f_{b/B}(x_b,\vec{p'}_T^{\,2}) \otimes H_{h/c}^{\perp}(z,\vec{k}_T^{\,2})}{\frac{d\hat{\sigma}_{ab\to c}}{d\hat{t}} \otimes f_{a/A}(x_a,\vec{p}_T^{\,2}) \otimes f_{b/B}(x_b,\vec{p'}_T^{\,2}) \otimes D_{h/c}(z,\vec{k}_T^{\,2})}$$

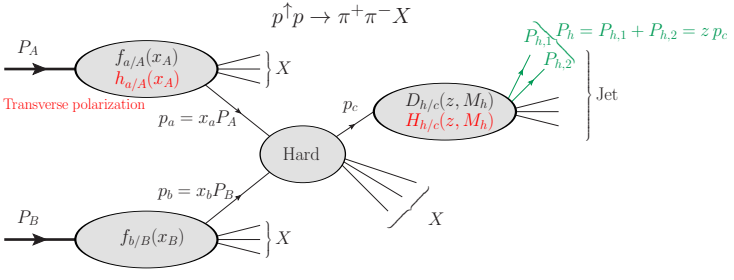


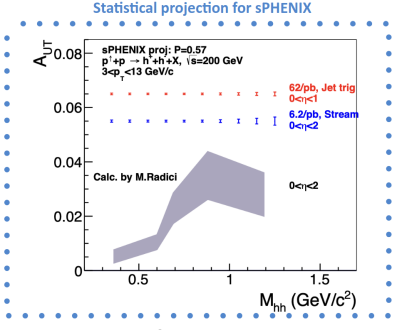
Di-hadron TSSA $p^{\uparrow}p \to \pi^{+}\pi^{-}X$

$\Rightarrow$ Access to chiral-odd **transversity PDF** h and chiral-odd Interference Fragmentation Function (IFF) $H_q^{\sphericalangle}$ in **leading-twist collinear factorization**

$$A_{UT}^{\sin(\phi_R-\phi_S)} \sim \frac{\frac{d\Delta\hat{\sigma}_{a^{\uparrow}b\to c^{\uparrow}}}{d\hat{t}} \otimes h_{a/A}(x_a) \otimes f_{b/B}(x_b) \otimes H_{h/c}^{\sphericalangle}(z, M_H)}{\frac{d\hat{\sigma}_{ab\to c}}{d\hat{t}} \otimes f_{a/A}(x_a) \otimes f_{b/B}(x_b) \otimes D_{h/c}(z, M_h)}$$







RHIC Cold QCD Plan 2024-2028

sPHENIX measurement opportunities

Table 1: Measurement opportunities for transverse single-spin asymmetries A_N at sPHENIX in $p^{\uparrow}p$ collisions at $\sqrt{200}$ GeV including the requirements (x) to reconstructed objects - calorimeter clusters, charged tracks, and jets. "Mesons" also includes heavy flavor and quarkonia.

physics	channel	clusters	tracks	jets
tri-gluon correlator	neutral mesons, direct γ	x		
tri-gluon correlator	mesons	x	x	
transversity PDF, IFF	di-hadrons	x	x	
Collins effect	hadrons-in-jets	x	x	x
Sivers TMD PDF (valence q)	di-jets	x	x	x
Sivers TMD PDF (g)	jet-γ	x	x	x
tri-gluon correlator	inclusive jets	x	x	x