2024 RHIC/AGS Annual Users' Meeting
11/June/2024 – 14/June/2024

Prospects with the sPHENIX

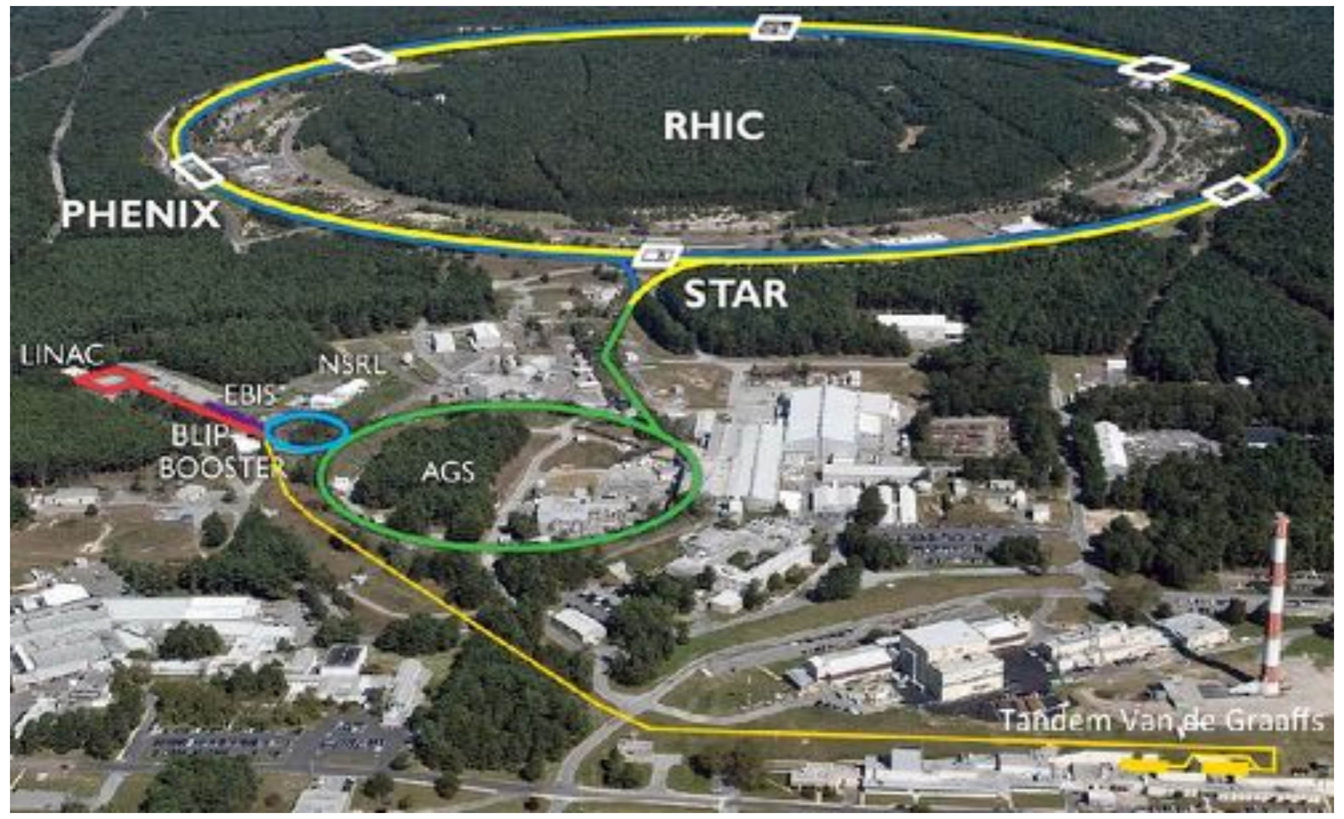
Genki Nukazuka (RIKEN/RBRC)
on behalf of the sPHENIX Collaboration

Table of Contents

sPHENIX Collaboration

Relativistic Heavy Ion Collider (RHIC)

- First collisions in 2000
- p+p, Au+Au, O+O, etc
- $\vec{p}^{(\uparrow)} + \vec{p}^{(\uparrow)}$
- $\sqrt{s_{NN}} \sim 7$ — 500 GeV



NEXT STEP

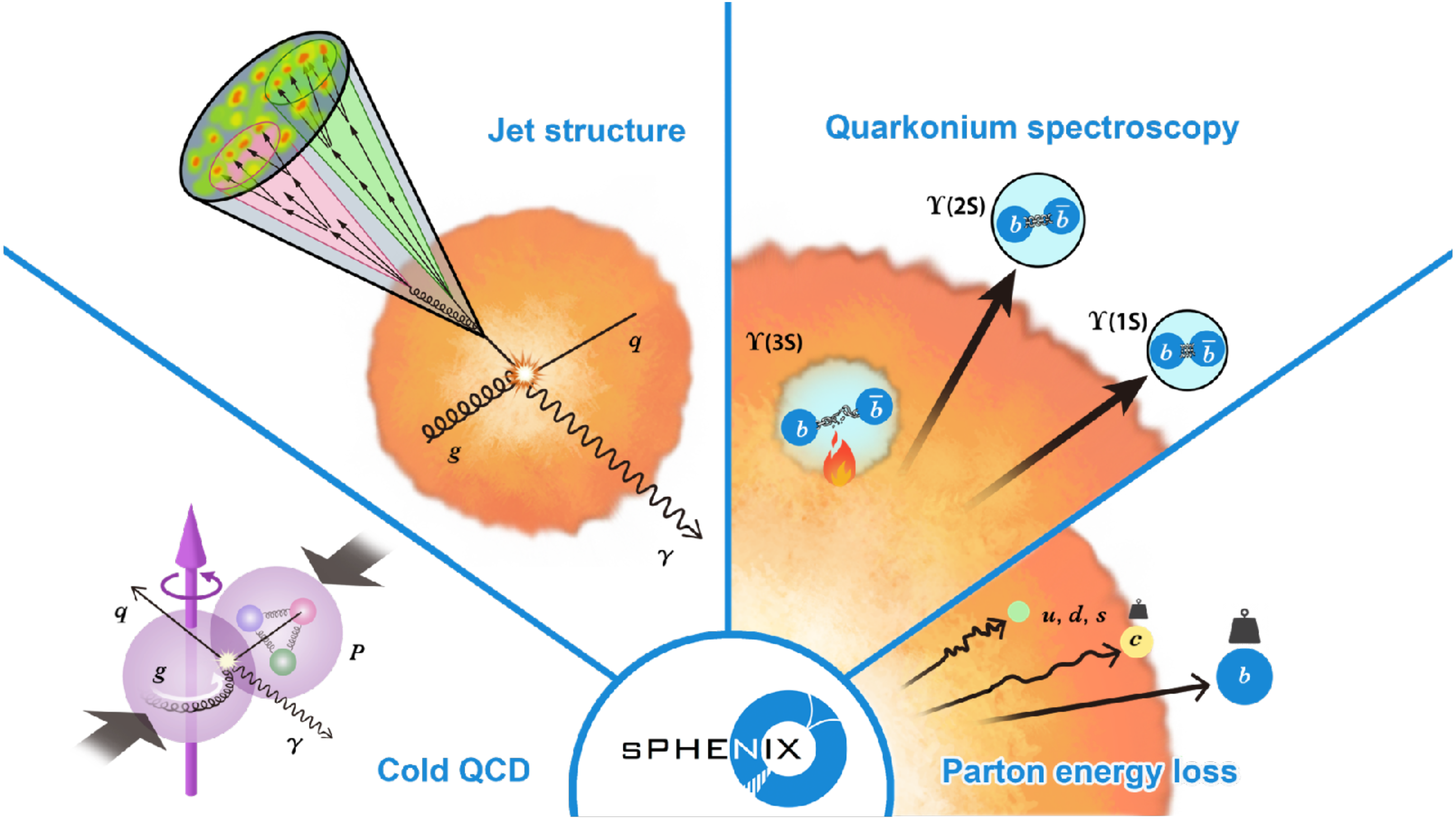
sPHENIX

PHENIX

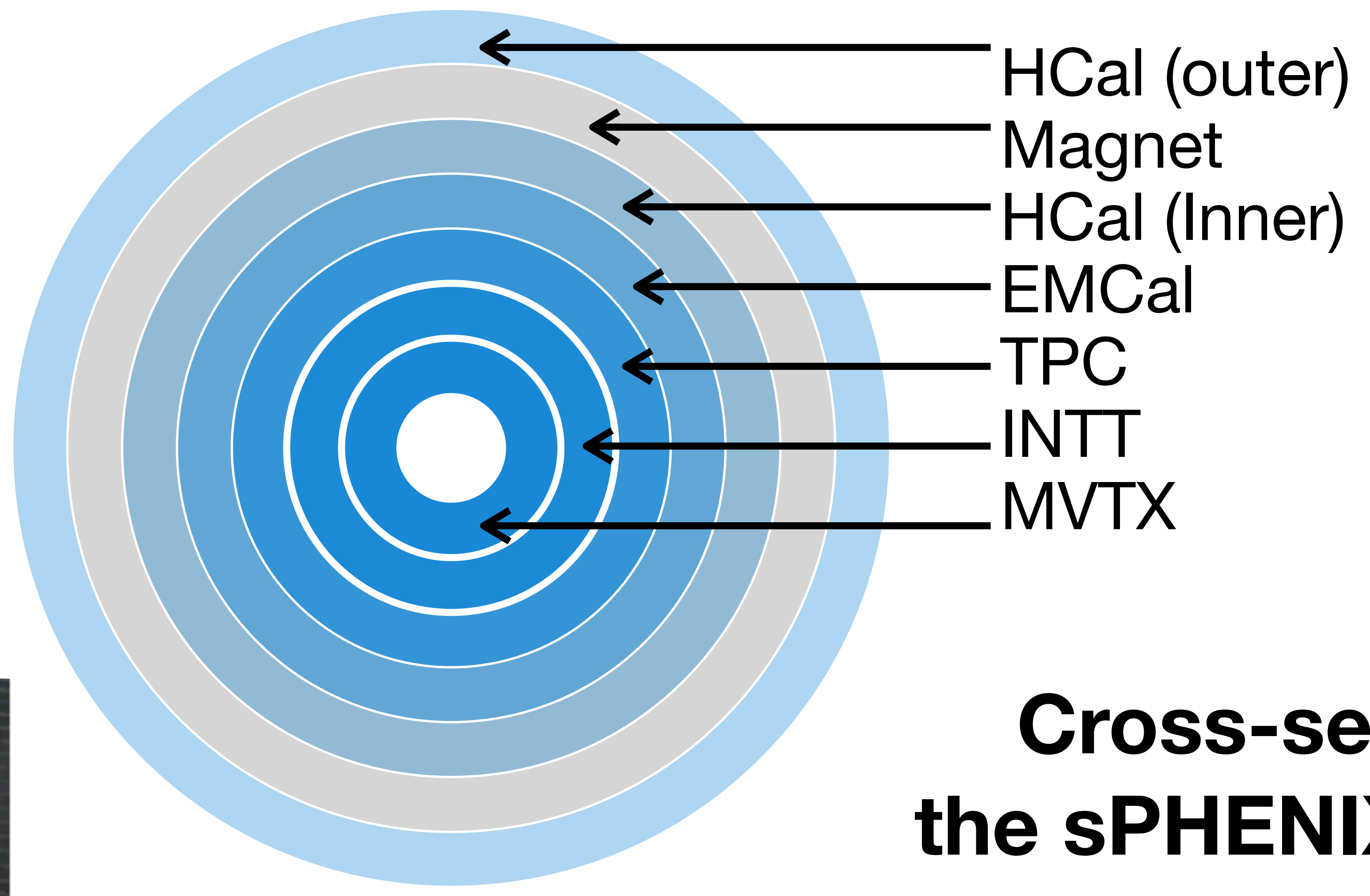
ran at RHIC from 2001 to 2016.
They contributed to the discovery of Quark-Gluon Plasma (QGP) and the study of proton spin structure.
Data analysis is still continuing.

- State-of-the-Art Jet Detector at RHIC
- The collaboration was formed in 2016.
- Quark-Gluon Plasma (QGP) and Cold-QCD
- About 400 members from 81 institutions and 14 countries
- Home Page: https://www.sphenix.bnl.gov/

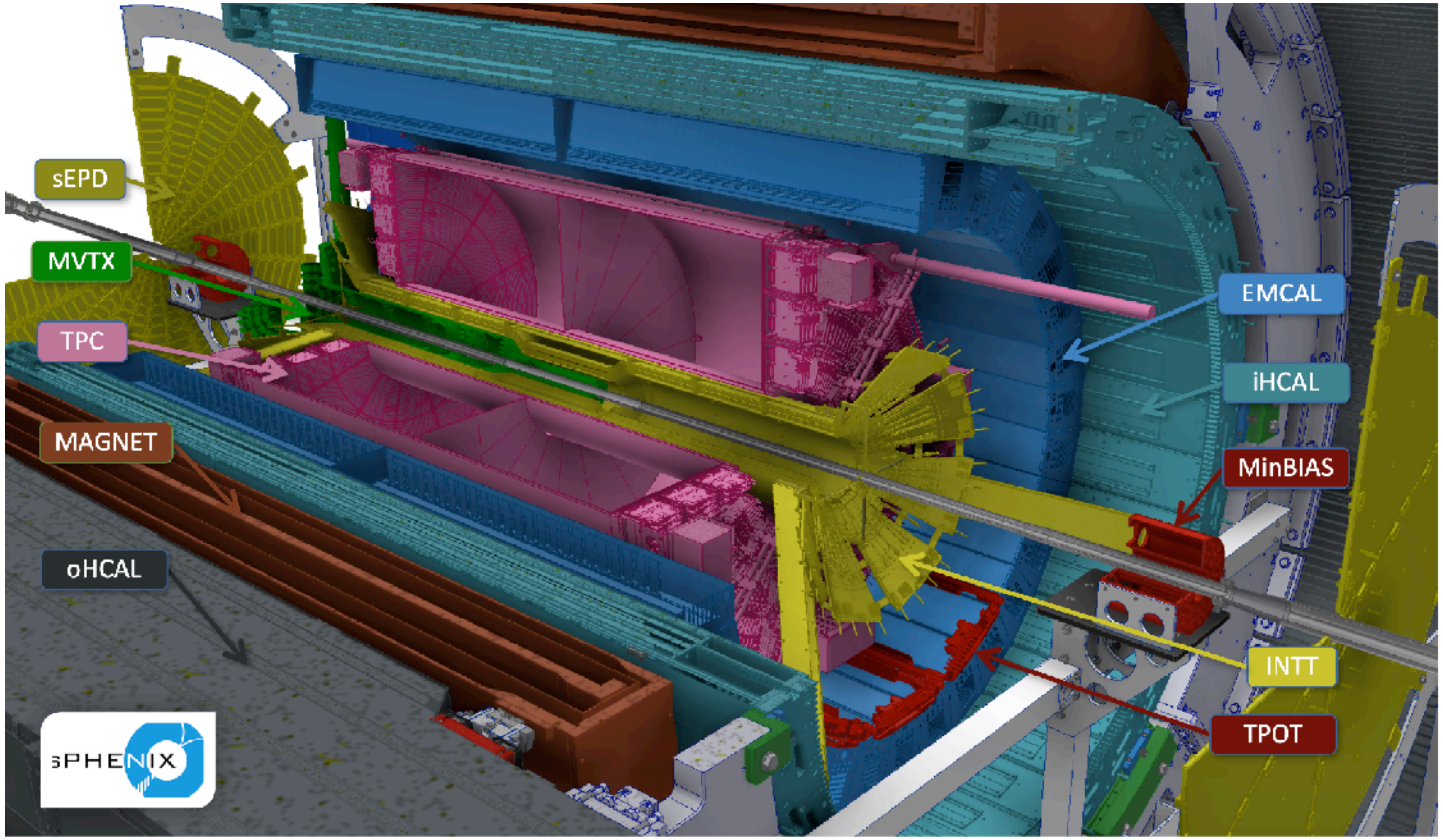
sPHENIX Physics Programs



sPHENIX Detector



Cross-section of the sPHENIX detector



The sPHENIX detector

The sPHENIX detector

- full azimuthal angle 2π and $|\eta| < 1.1$ coverage in $|z_{vtx}| < 10$ cm
- 1.4 T Babar solenoid magnet
- the hadronic & electromagnetic calorimeters (the first HCAL in midrapidity at RHIC)
- 3 tracking detectors in midrapidity (TPC (+TPOT), INTT, and MVTX)
- 3 general detectors in forward region (MBD, sEPD, and ZDC/SMD)

Plan and Status

sPHENIX Beam Use Proposal 2023 (not all shown)

Year	Beam	$\sqrt{s_{NN}}$ (GeV)	Data taking (week)	Luminosity, ($\lvert z \rvert < 10$ cm) Recorded	Luminosity, ($\lvert z \rvert < 10$ cm) Sampled
2023	Au + Au	200	~~9~~	~~3.7 nb^{-1}~~	~~4.5 nb^{-1}~~
2024	$p^{\uparrow} + p^{\uparrow}$	200	17	0.44 pb^{-1} (5 kHz)	31 pb^{-1}
2024	Au + Au	200	3	0.4 nb^{-1}	-
2025	Au + Au	200	24.5	6.3 nb^{-1}	-

2023: Commissioning

- The construction was finished in April/2023.
- The first beam came in May/2023.
- 2023/08/01: Beam was stopped.
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2024: $p^{\uparrow}$+$p^{\uparrow}$, Au + Au

- Transversely polarized proton $p^{\uparrow}$ + $p^{\uparrow}$ (~60% polarization) collision at $\sqrt{s}$ = 200 GeV
- Commissioning with Au + Au for 6 weeks, which was planned for 2023, is carried over.

RHIC preparation starts → $p^{\uparrow}p^{\uparrow}$ → AuAu

↑ 4/15 ... ↑ Planned to be ended at early Oct

sPHENIX Plan and Status

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2025: Au + Au

- Au + Au data taking

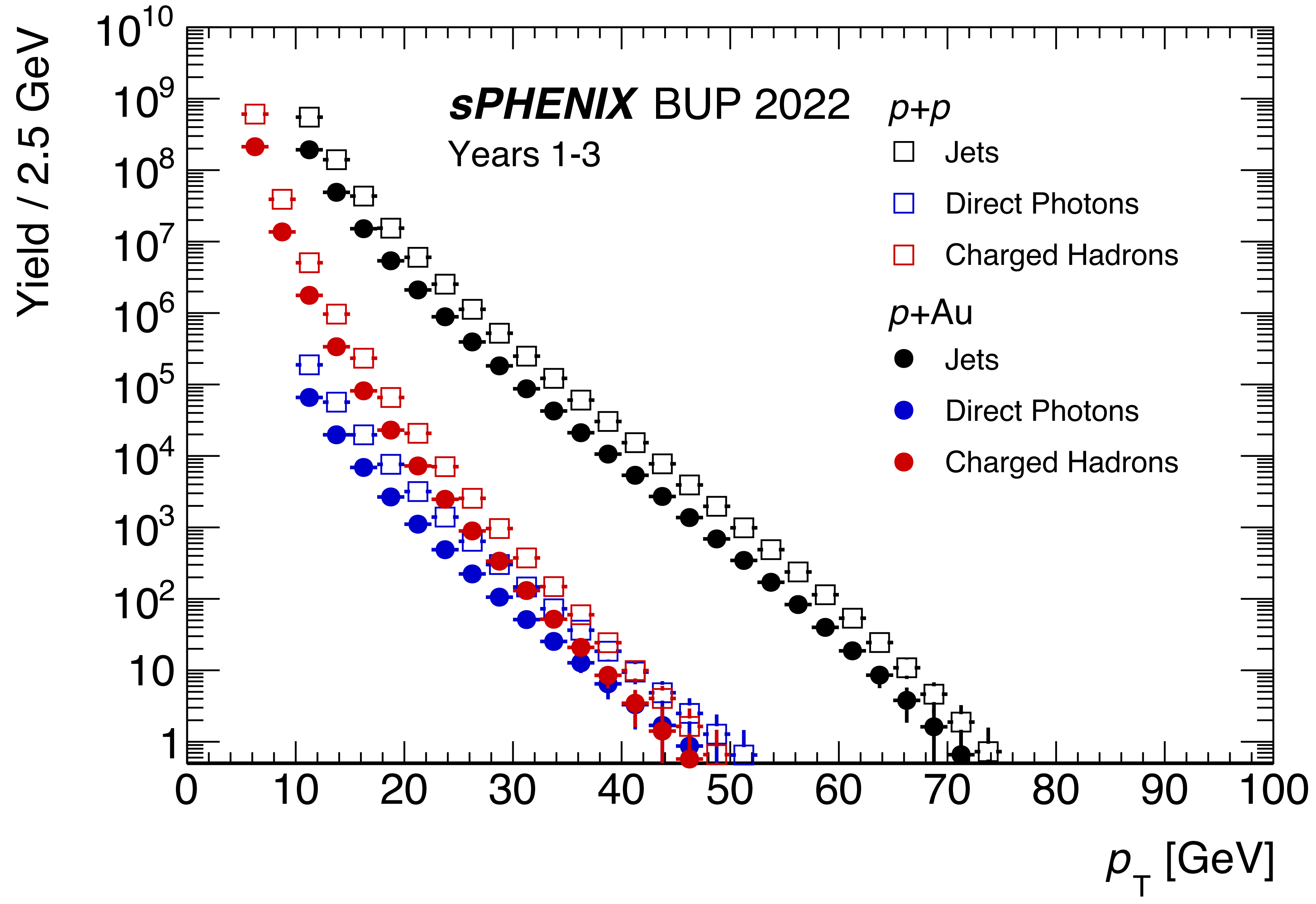
Table of Contents

Spin Physics at sPHENIX

Measurements of transverse single spin asymmetries (TSSA) enable us to study

- Transverse-momentum dependent parton distribution functions (TMDs)
- Correlators in the collinear higher-twist framework
- Fragmentation functions (FF)
- etc.

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



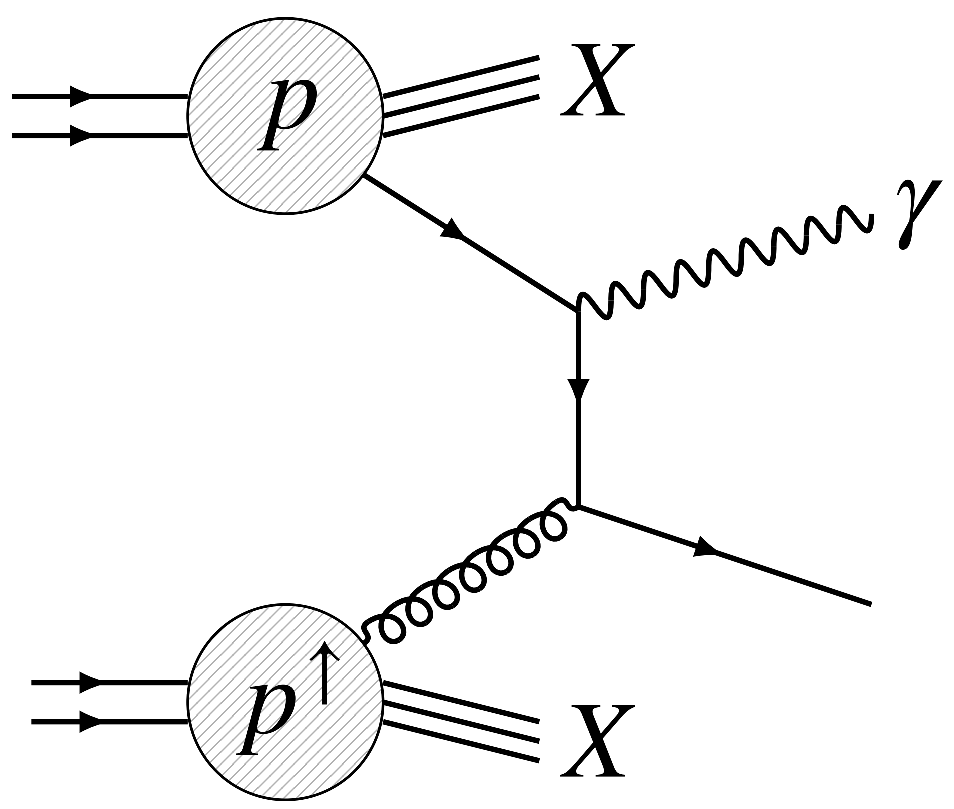
The projected total yield from p + p or p + Au at sPHENIX.

Table of TMDs

Spin state of parton \ Spin state of nucleon	No pol.	Long.	Trans.
No pol.	Number density f_1		Sivers $f_{1T}^{\perp}$
Long.		Helicity g_{1L}	Worm-Gear g_{1T}
Trans.	Boer-Mulders $h_1^{\perp}$	Worm-Gear $h_{1L}^{\perp}$	Transversity h_1 Pretzelosity $h_{1T}^{\perp}$

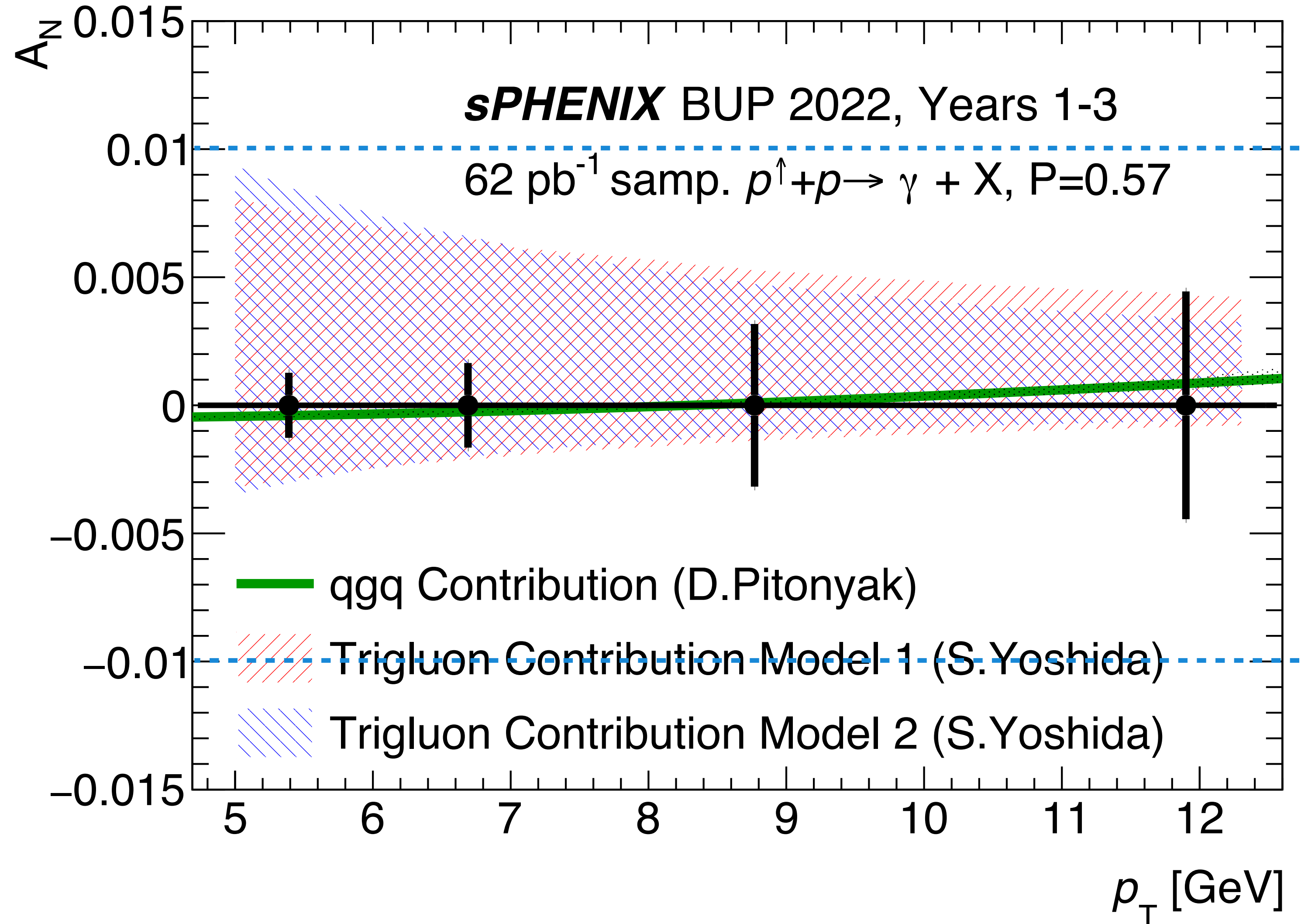
Spin Physics at sPHENIX

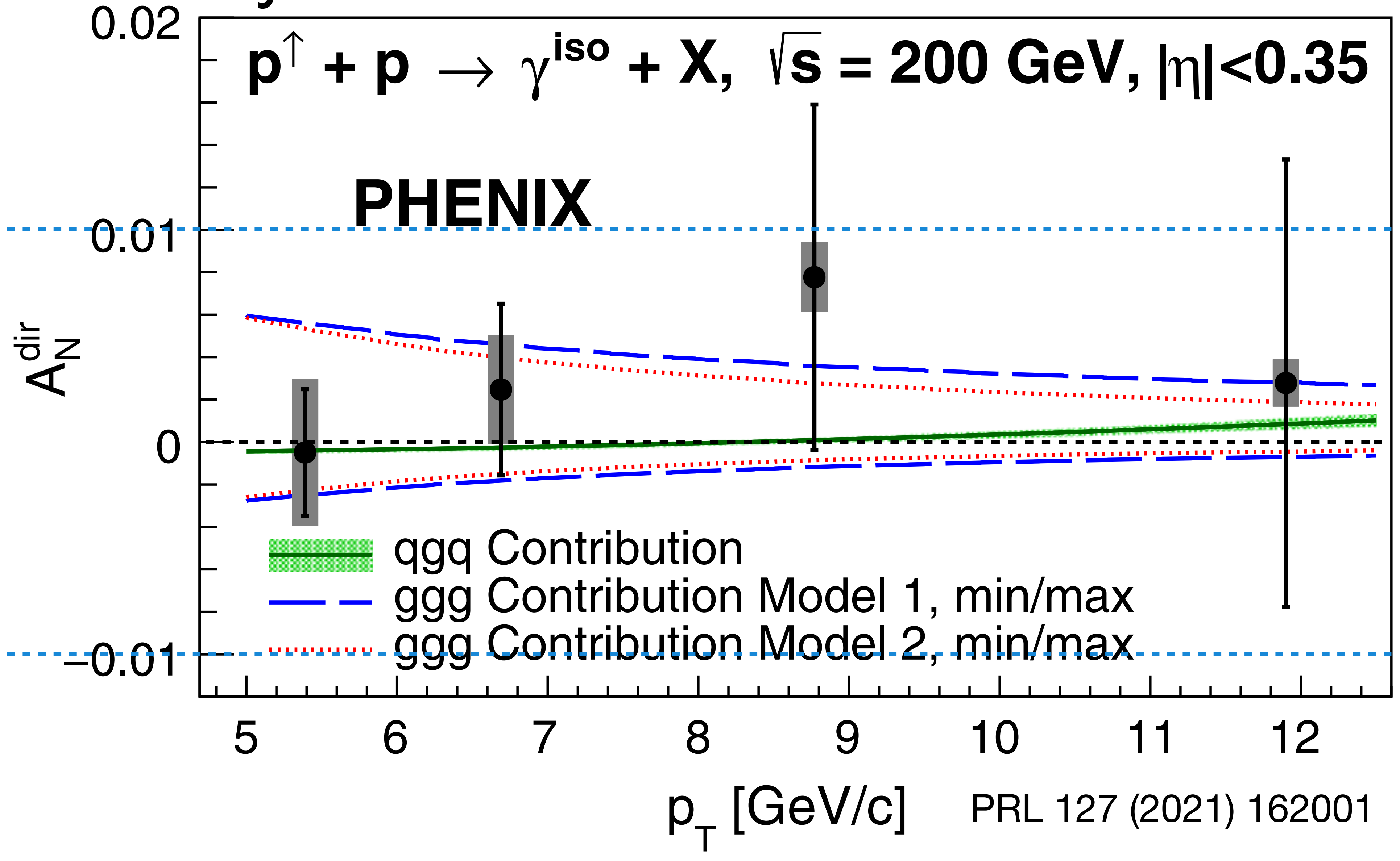
Direct photon $p^{\uparrow} + p \rightarrow \gamma + X$



- **Only the initial state effect** is involved.
- **Tri-gluon correlation function** in the collinear twist-3 framework can be studied.
- It's connected with the gluon Sivers TMD PDF.
- PHENIX reported the first measurement of A_N from the direct photon.
- sPHENIX can improve the statistics of the measurement significantly.

Statistical projection of direct photon measurement at sPHENIX.





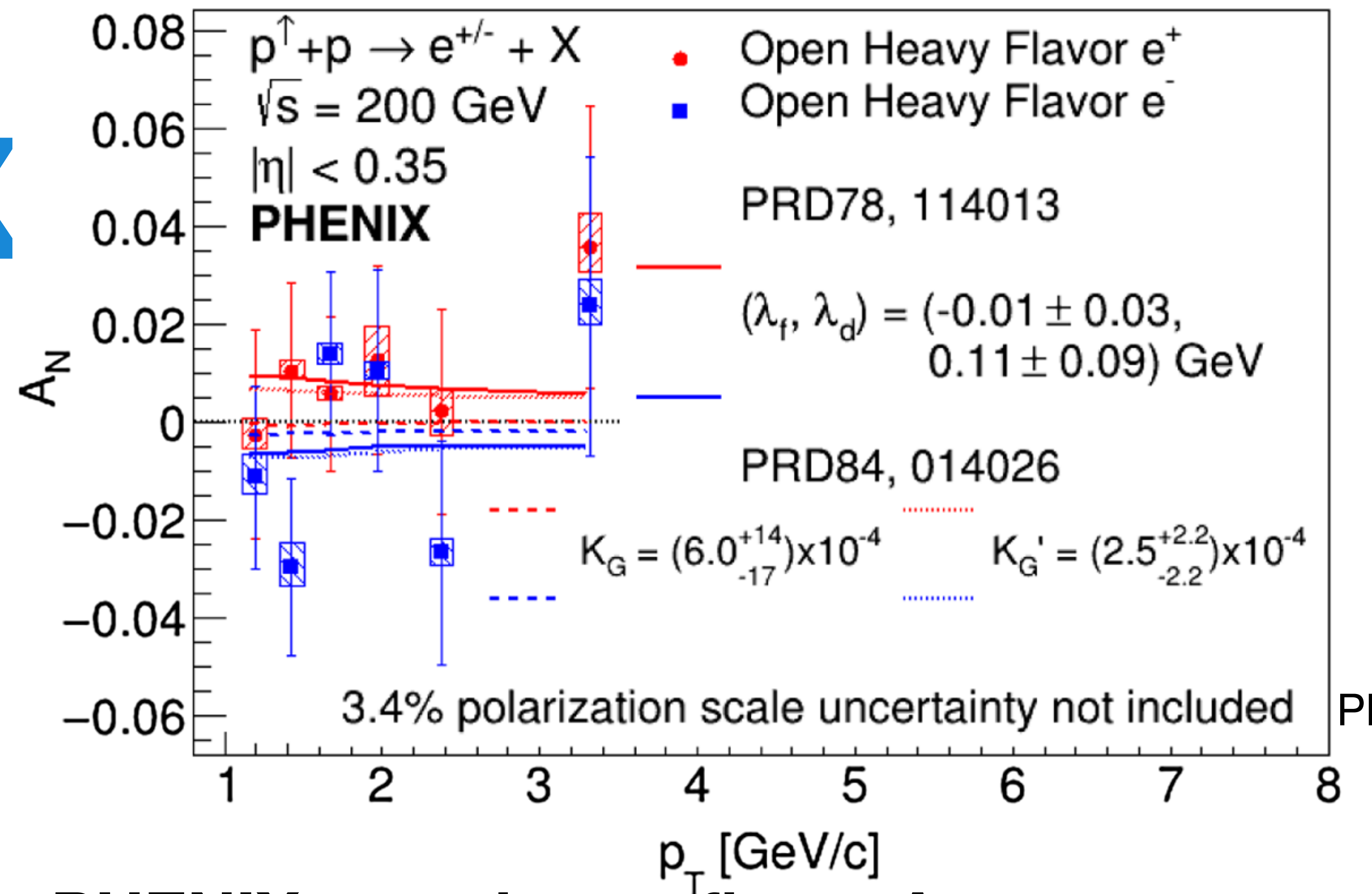
PRL 127 (2021) 162001

Spin Physics at sPHENIX

Open heavy flavor $p^{\uparrow} + p \rightarrow e^{+/-} + X$

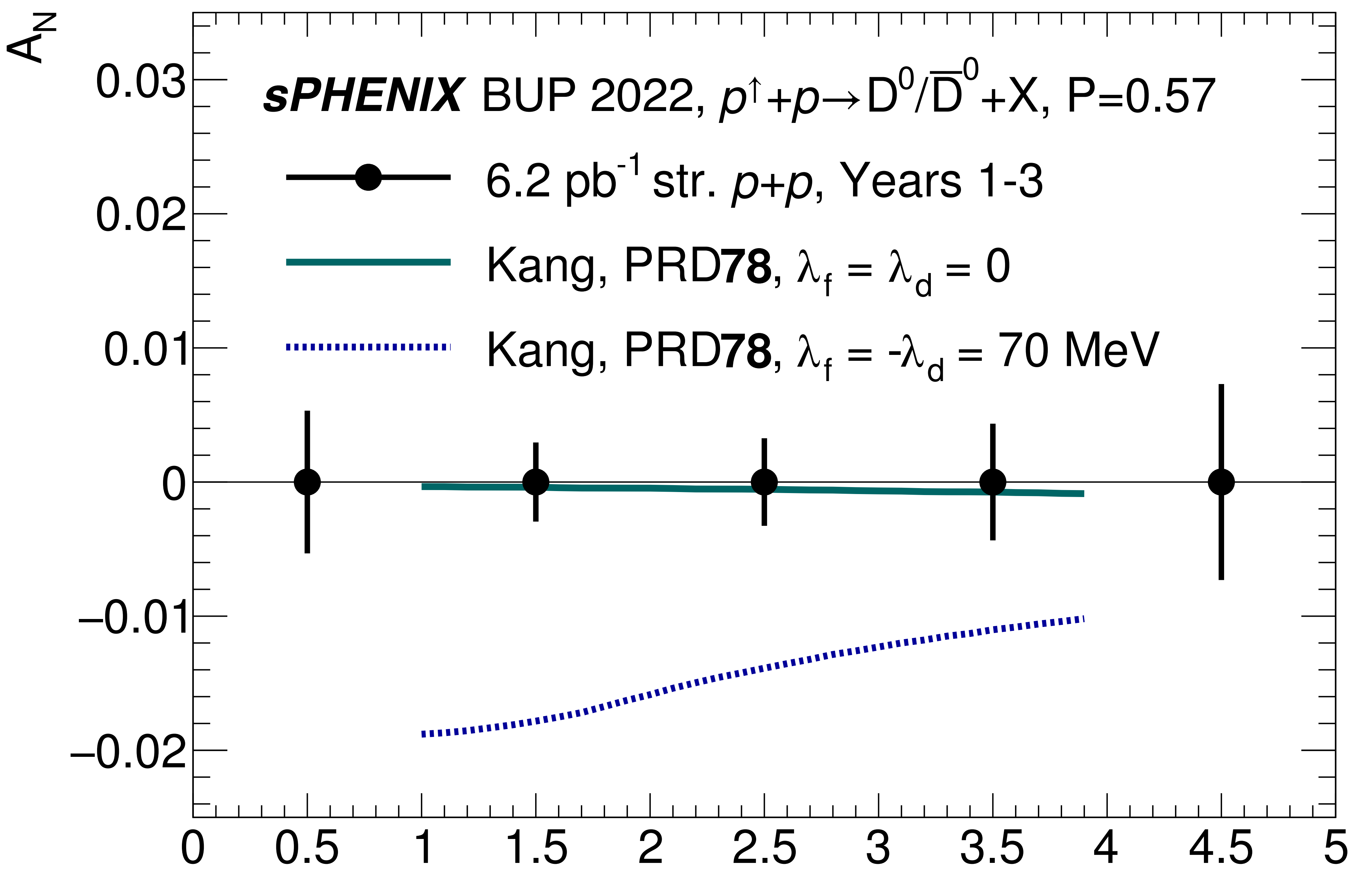
Prompt D⁰ $p^{\uparrow} + p \rightarrow D^0/\bar{D}^0 + X$

- Tri-gluon correlation function in the collinear twist-3 framework can be studied.
- It's connected with the gluon Sivers TMD PDF.
- sPHENIX can measure not only open heavy flavor electrons but D^0.
- The streaming readout for tracking detectors is necessary for D^0 measurements.



PRD 107(2023) 052012

PHENIX open heavy flavor A_N measurement.



Statistical projection of $D^0/\bar{D}^0$ measurement at sPHENIX.

Spin Physics at sPHENIX

Jet measurements: Jet, Dijet, and γ-Jet

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

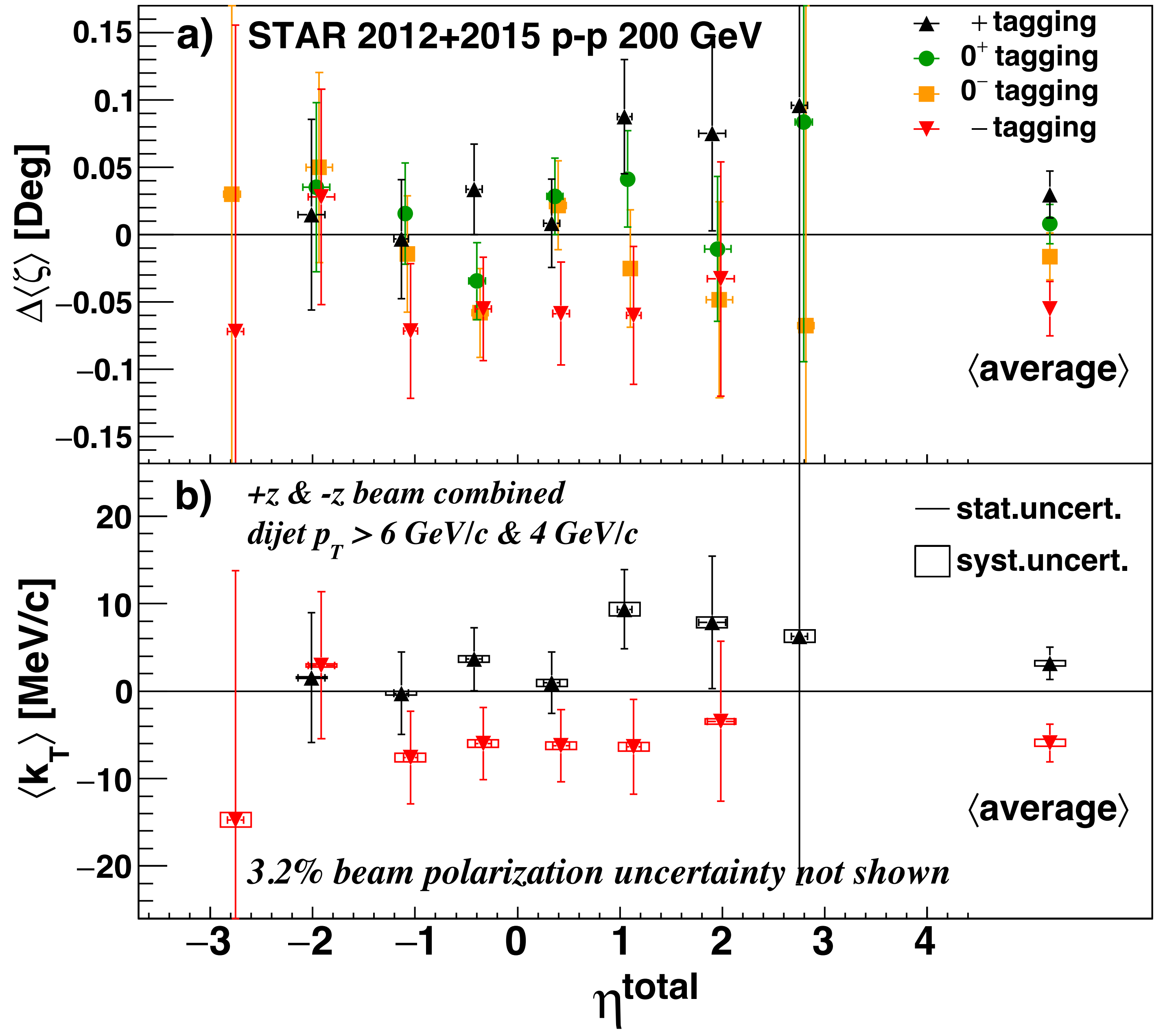
- TSSA has not been measured at central rapidity.
- sPHENIX can provide measurements with uncertainties at the level of 10^{-4}.
- Flavor separation by tagging leading hadron charge.

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

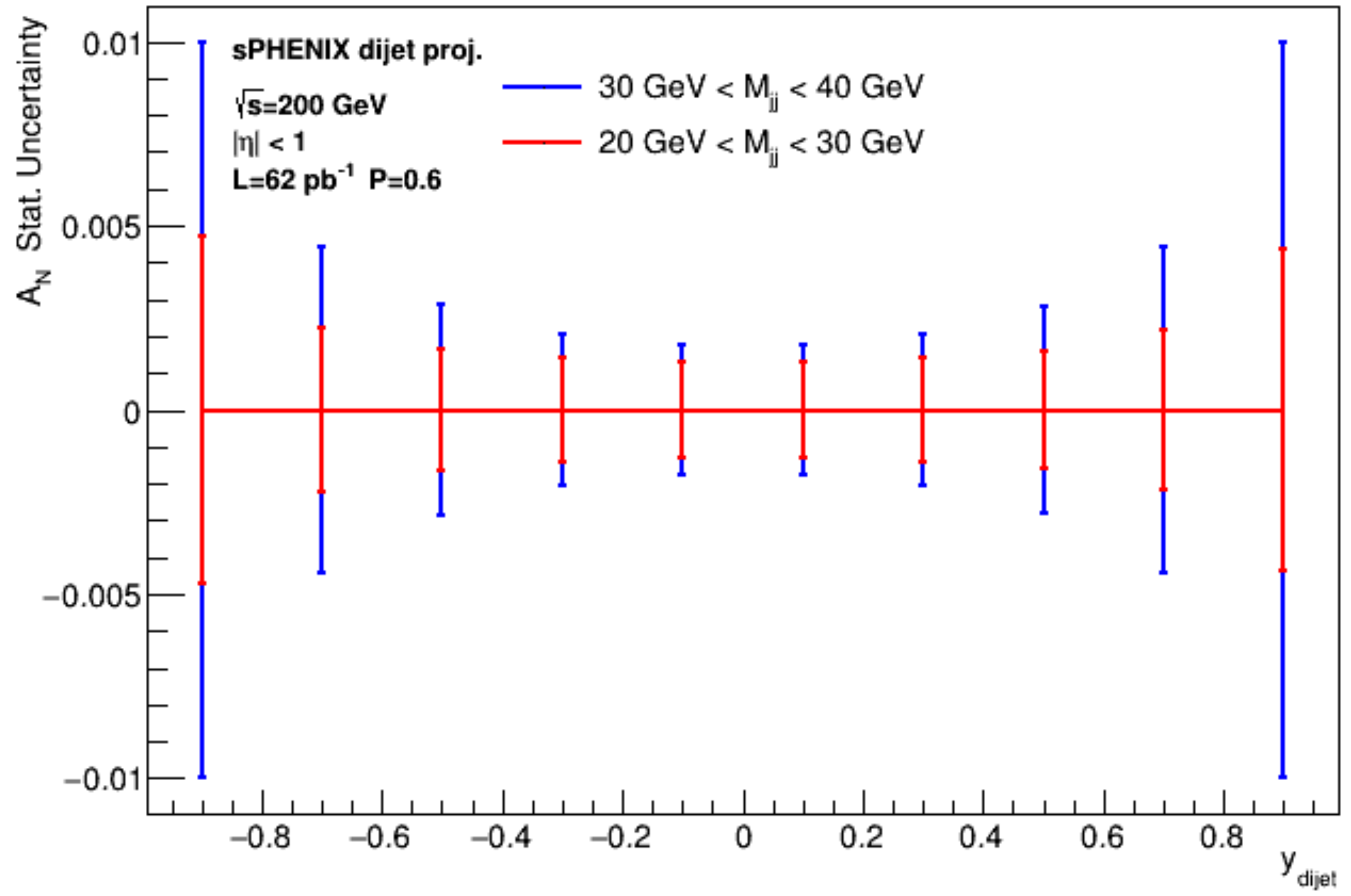
- Direct access to parton intrinsic transverse momentum.
- STAR preliminary results showed a nonzero effect for charge-tagged jets.
- sPHENIX will significantly contribute to dijet measurement.

γ-Jet $p^{\uparrow} + p \rightarrow \gamma + \text{jet} + X$

- discussed later

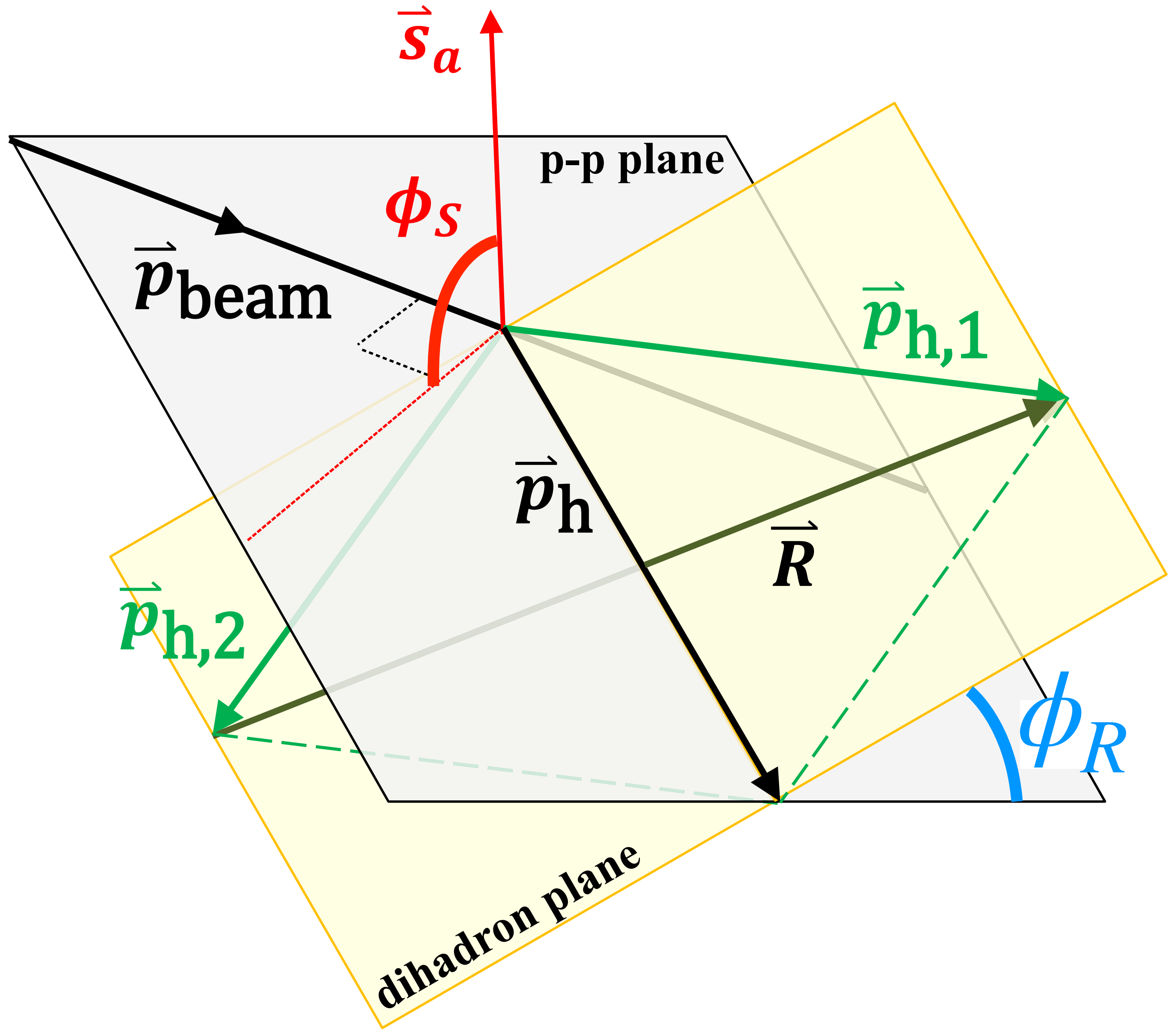


Dijet TSSA by STAR (arXiv:2305.10359)



Statistical projection of dijet measurement at sPHENIX.

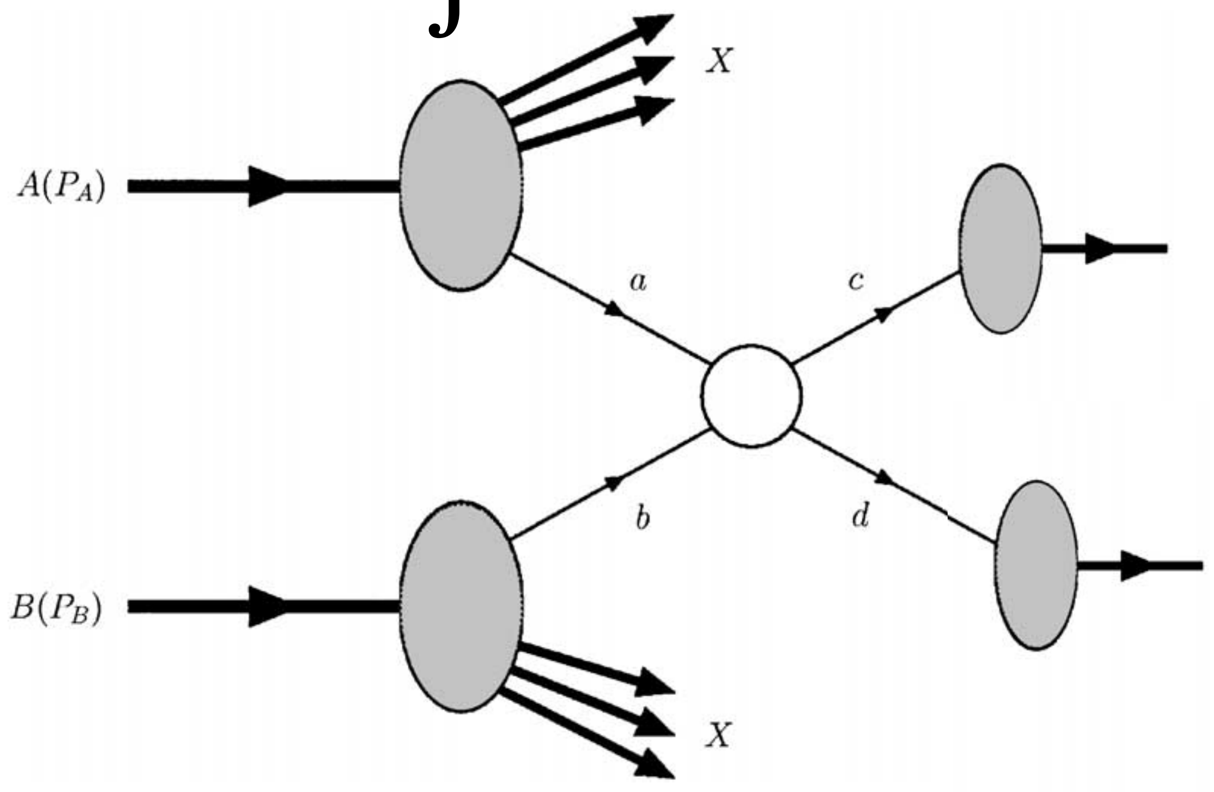
Spin Physics at sPHENIX



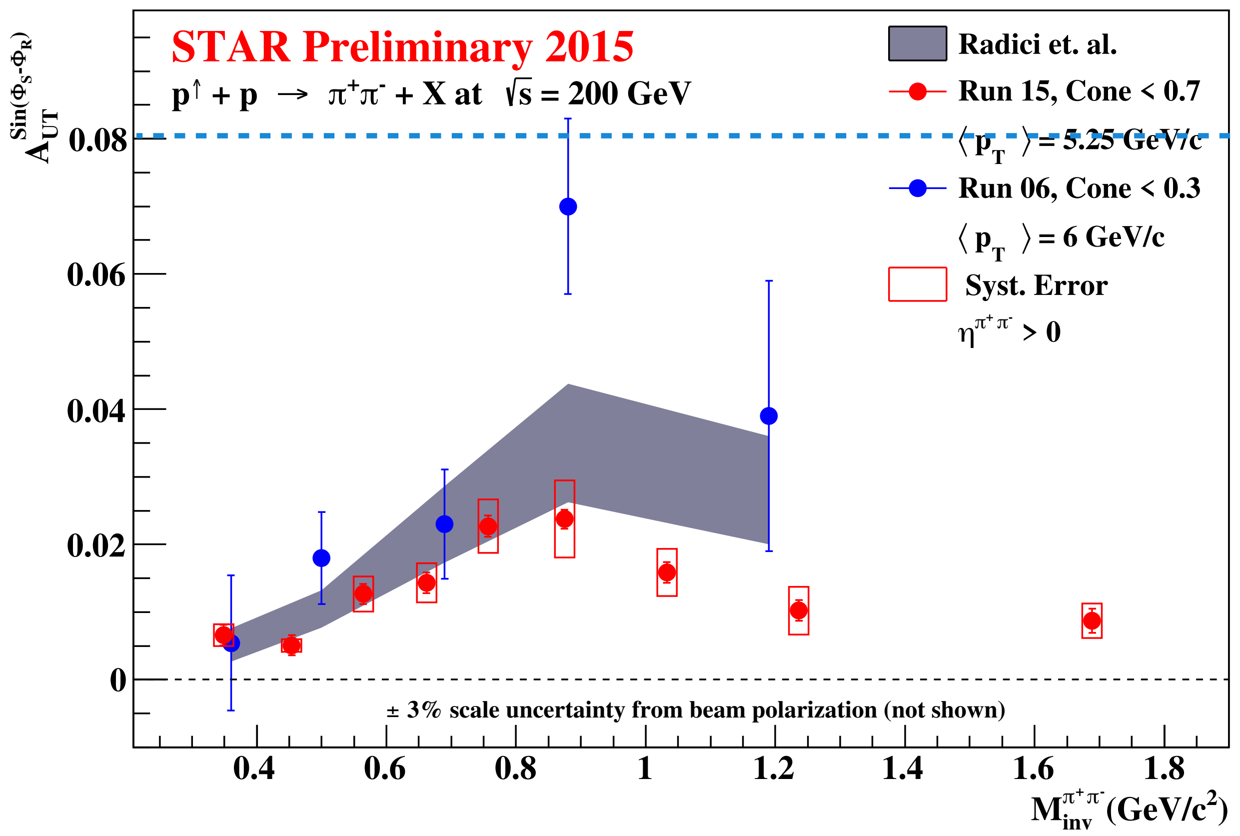
Di-hadron $p^{\uparrow} + p \rightarrow h^{+} + h^{-} + X$

- Di-hadron TSSA A_{UT} gives access to Transversity PDF h_1 and InterferenceFragmentation Function (FF) $H_{1,q}^{\sphericalangle}$:

$$d\sigma_{UT} \propto \sin(\phi_{RS}) \int dx_a dx_b f_1(x_a) h_1(x_b) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_{1,q}^{\sphericalangle}(z, M)$$



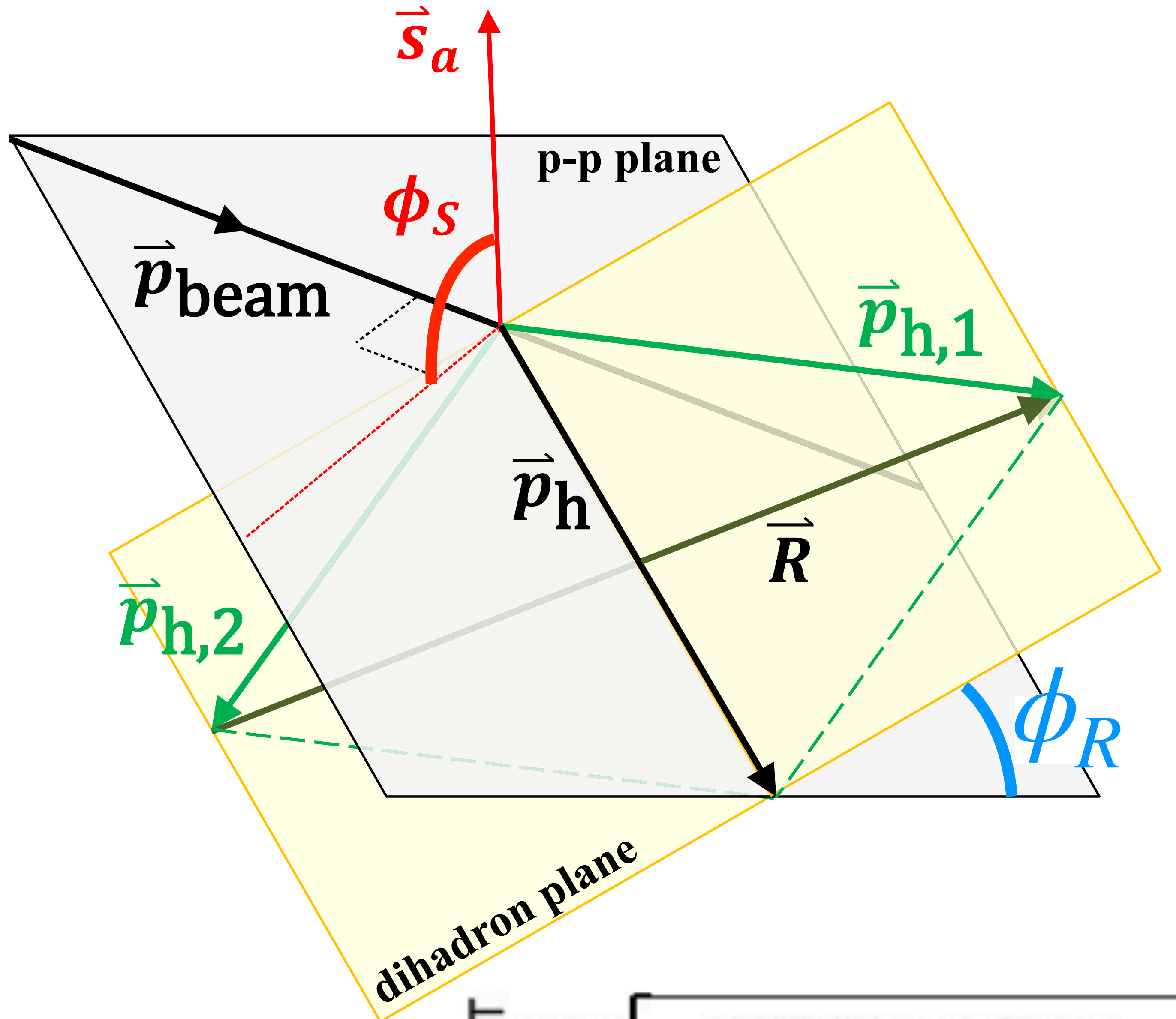
JPS Conf. Proc. 37(2023) 020121



Di-pion TSSA from STAR. $A_{UT}^{\sin(\phi_S-\phi_R)}$

- The results from STAR agree with the theoretical prediction using SIDIS and e^+e^- data within statistical uncertainty.
- sPHENIX can extract it with great statistical uncertainty.

Spin Physics at sPHENIX



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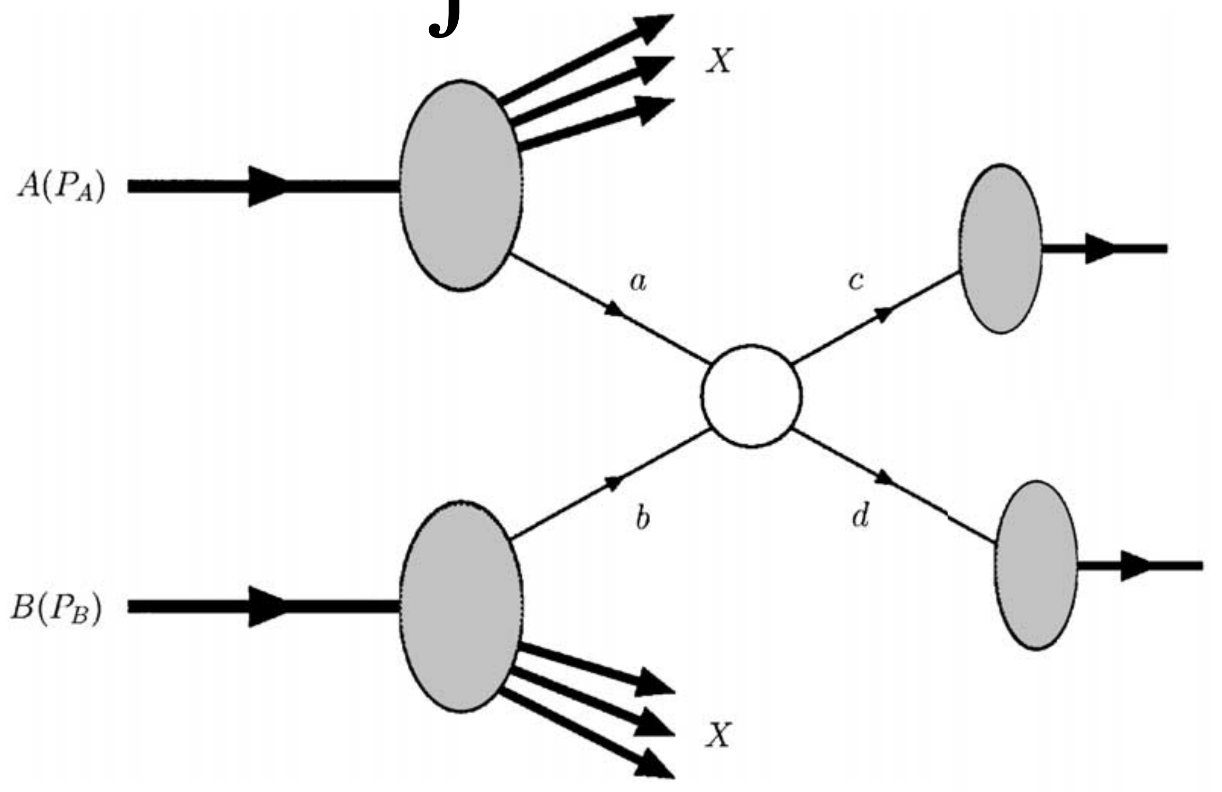

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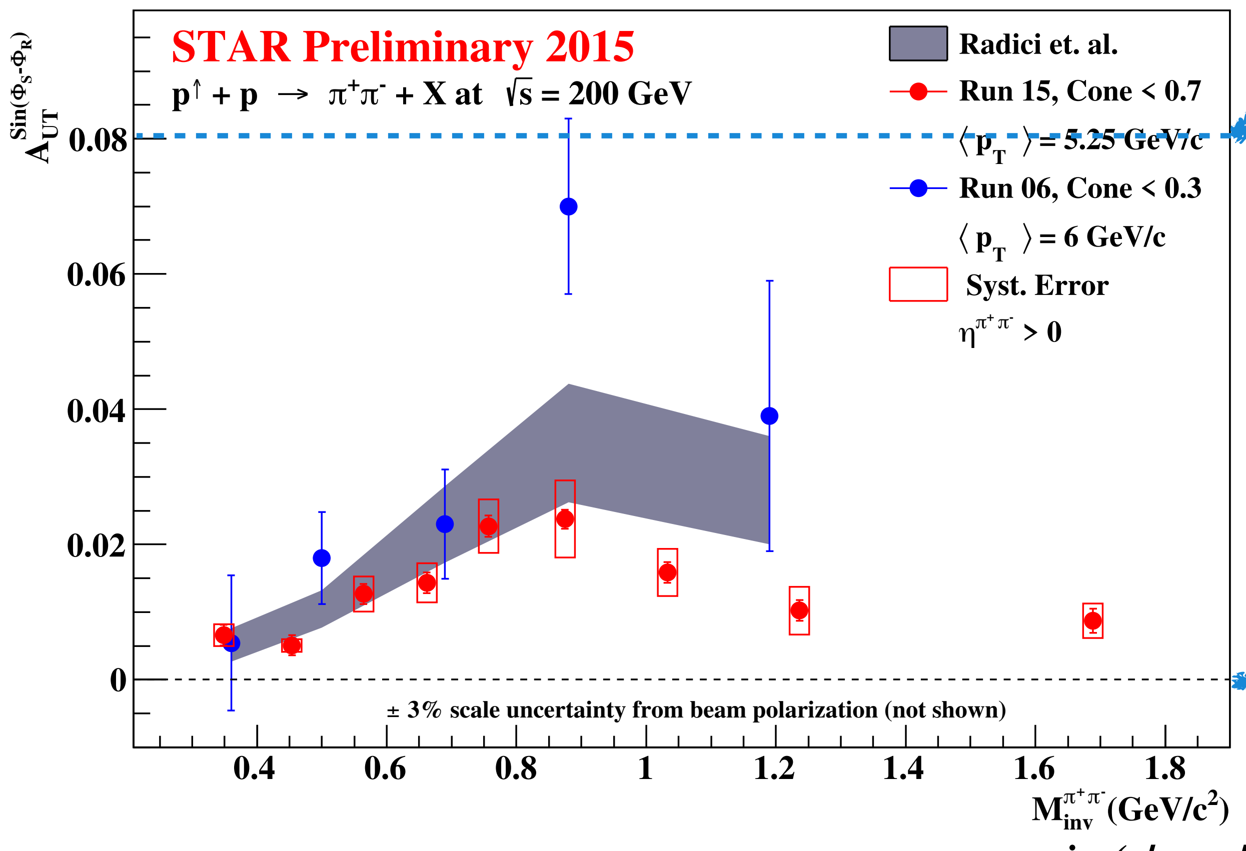

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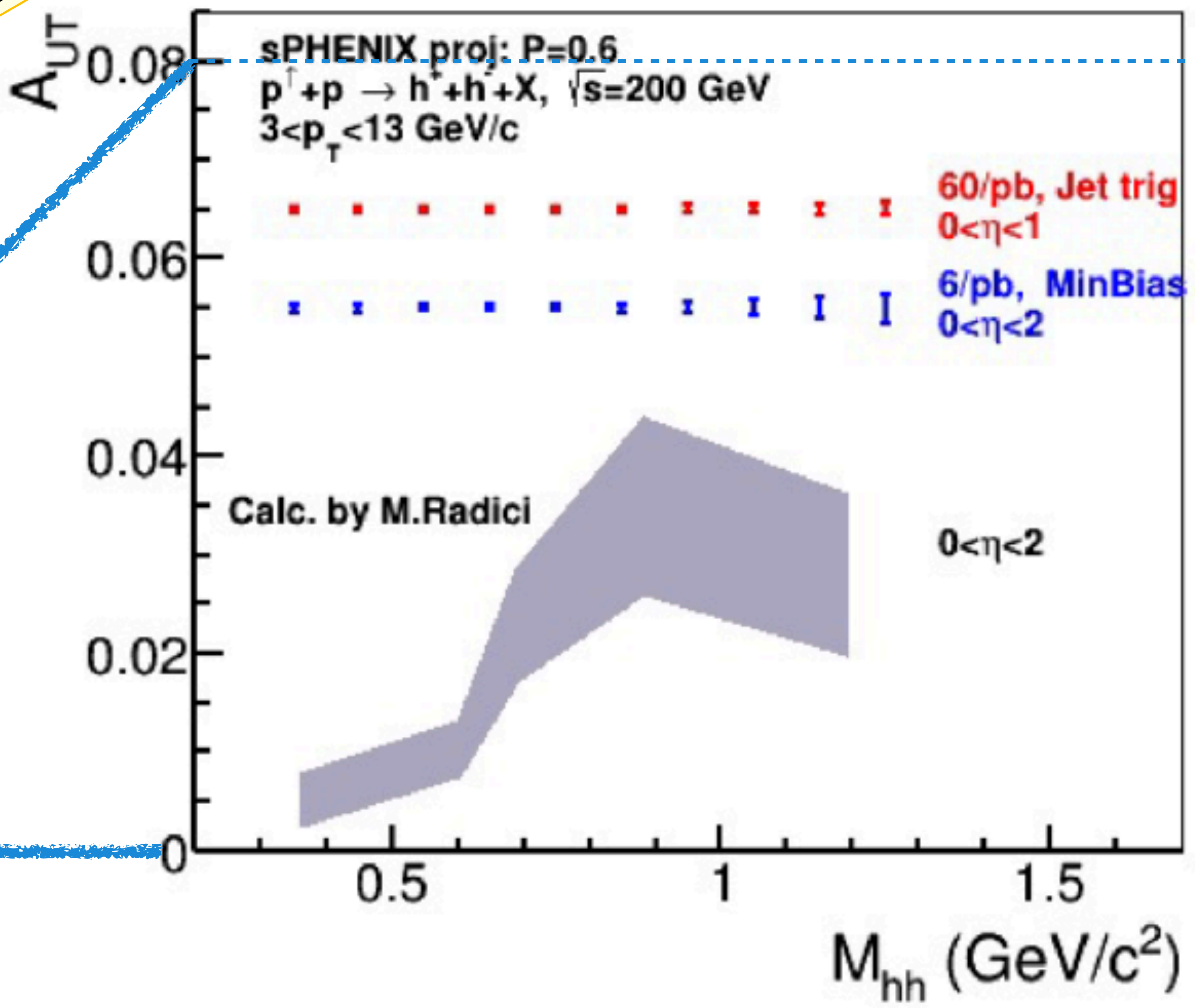

Statistical projection of dihadron A_{UT} measurement at sPHENIX.

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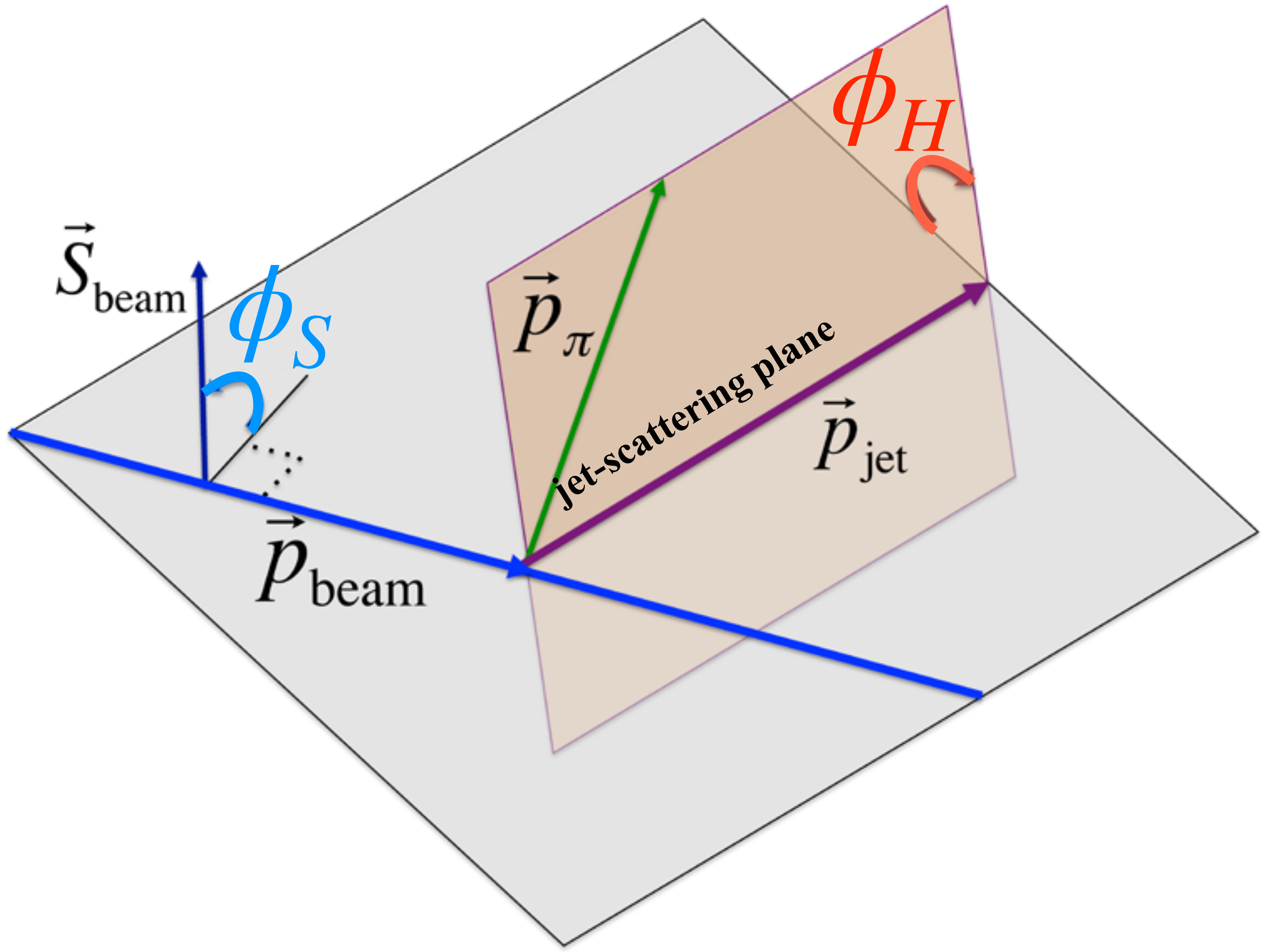
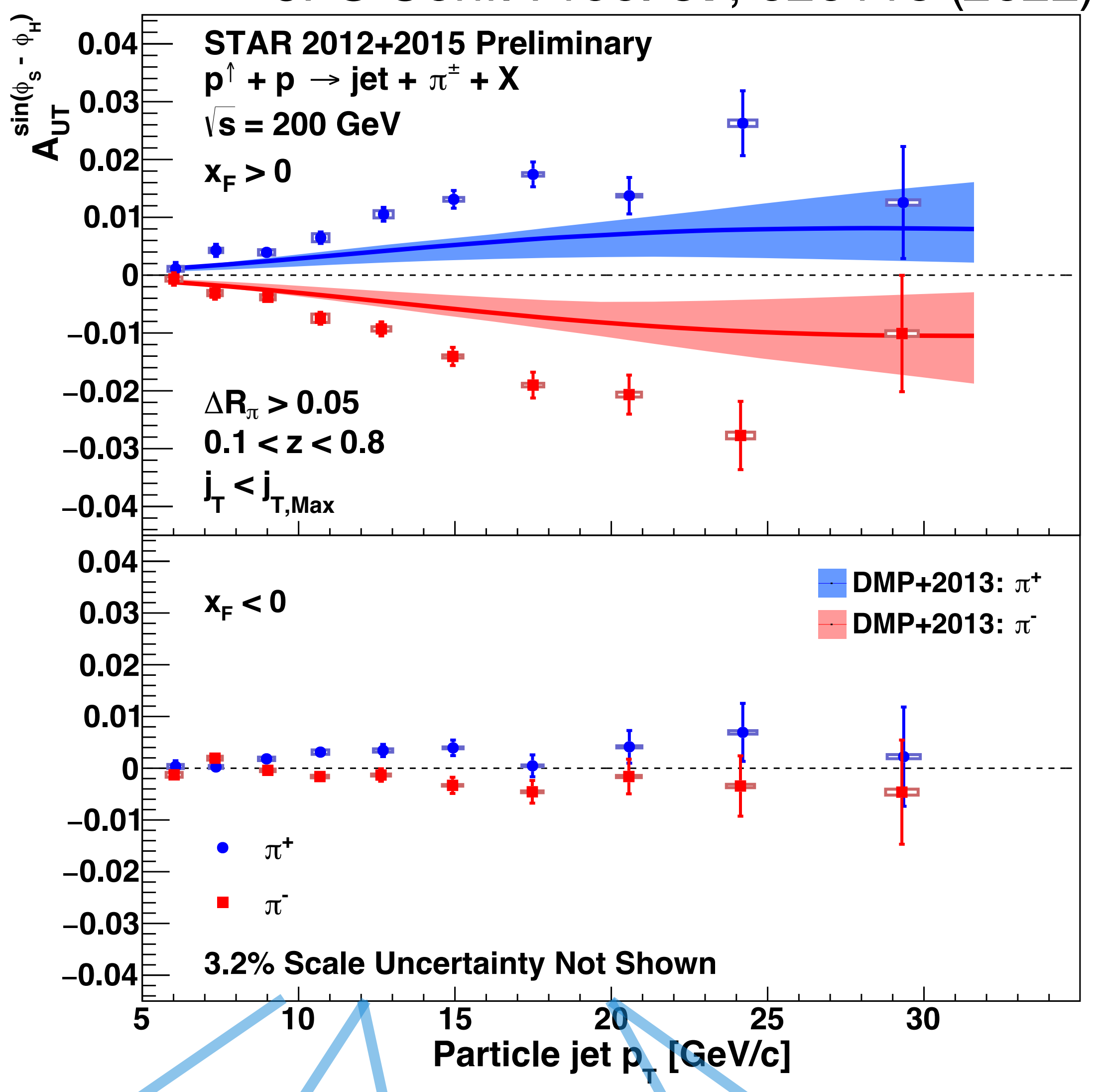
Spin Physics at sPHENIX

Hadron in Jets $p^{\uparrow} + p \rightarrow \mathrm{jet} + \mathrm{h} + X$

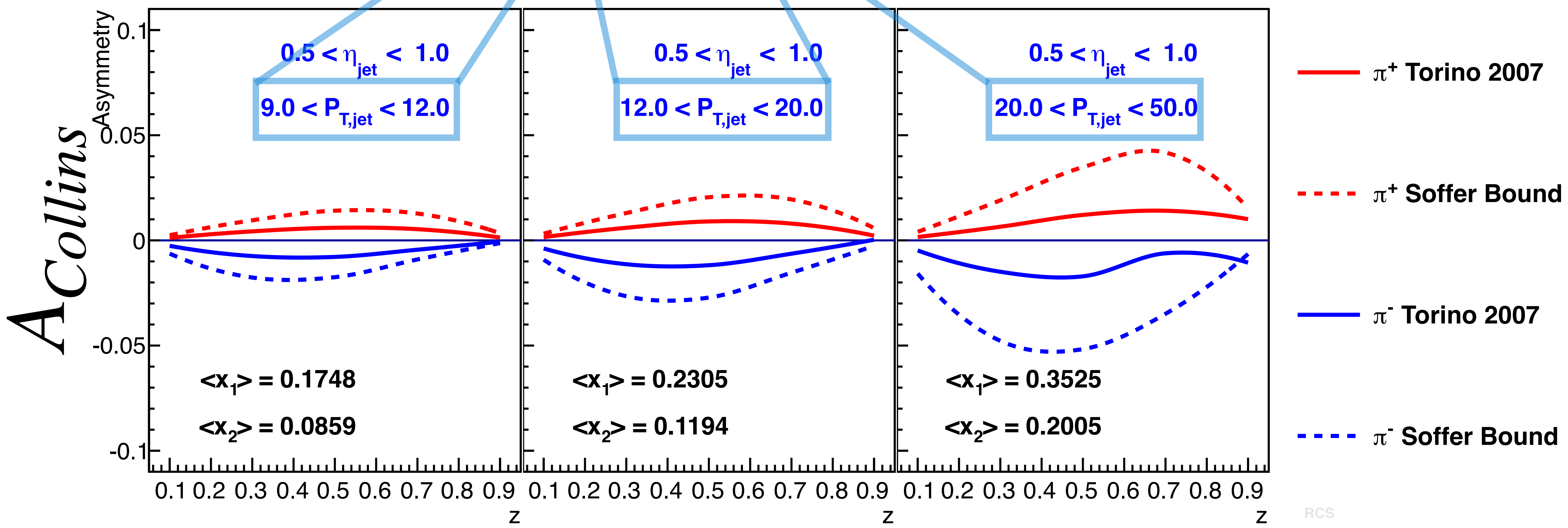
- Collins effect: the correlation of **transverse spin of a quark** and **the momentum of a hadron fragment** transverse to the scattered quark direction
- Collins asymmetry $A_{UT}^{\sin(\phi_S - \phi_H)}$ is related to Transversity PDF and Collins FF.



JPS Conf. Proc. **37**, 020118 (2022)



→ Asymmetries from STAR (jet + π) are larger than theoretical prediction based on SIDIS & e^+e^-



Range of expected Collins asymmetry in sPHENIX kinematics.

Spin Physics at sPHENIX: Speaker's Choice

γ-Jet asymmetry with $p^{\uparrow}$+p: Unique channels for sPHENIX

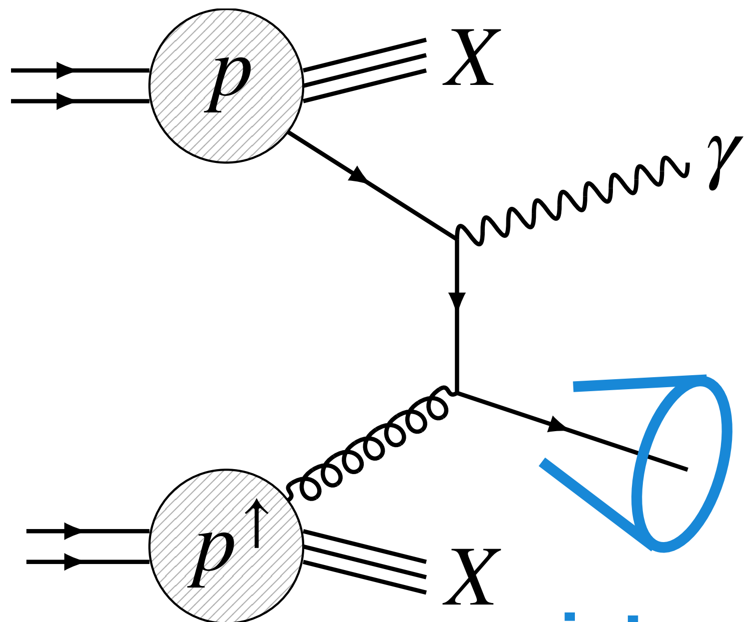
Spin Physics at sPHENIX: Speaker's Choice

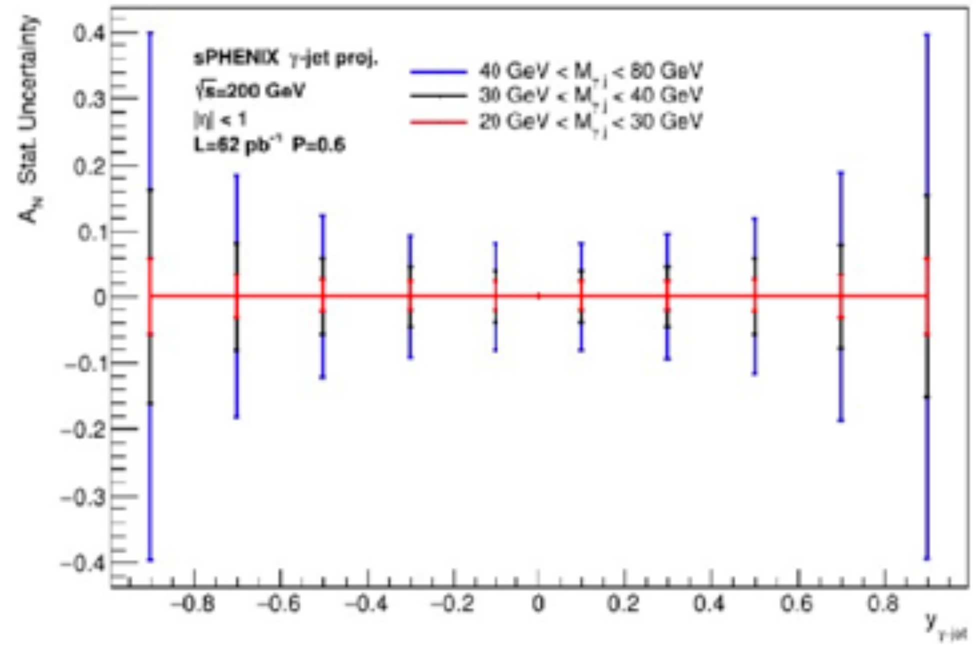
γ-Jet asymmetry with $p^{\uparrow}$+p: Unique channels for sPHENIX

Back-to-back in the transverse plane

γ-Jet $p^{\uparrow} + p \rightarrow \gamma + \text{jet} + X$

- Quark-gluon scattering process isolated at leading order.
- Gluon Sivers effect can be accessed.





Statistical projection of γ-jet measurement at sPHENIX.

The minimum error bar in this figure: ~0.02

Spin Physics at sPHENIX: Speaker's Choice

γ-Jet asymmetry with p↑+p: Unique channels for sPHENIX

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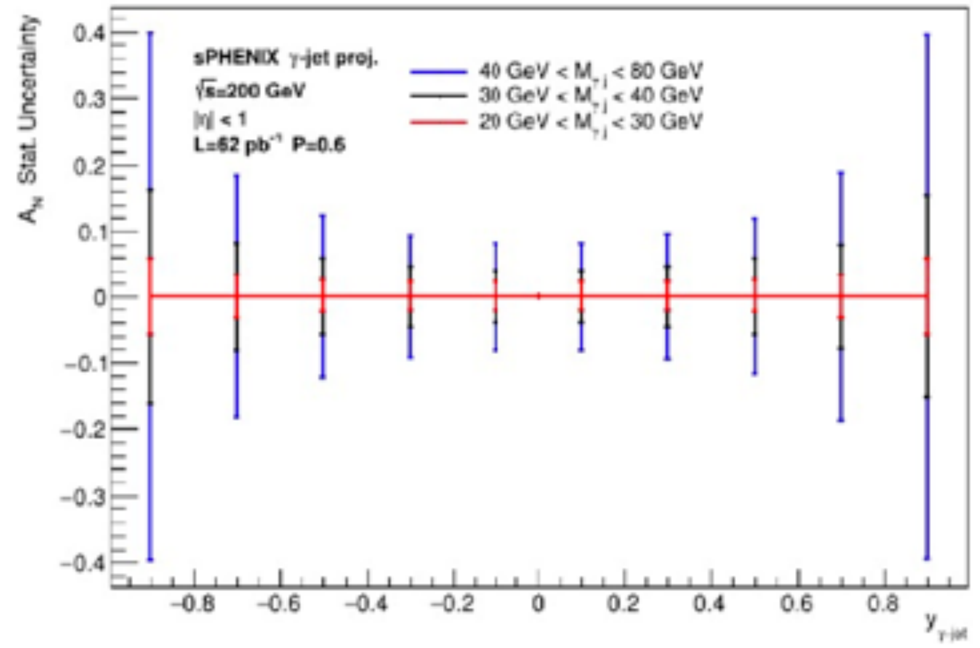

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A_N measurement

PHYSICAL REVIEW D 72, 054028 (2005)

Single-transverse-spin asymmetries: From deep inelastic scattering to hadronic collisions

Werner Vogelsang[1,2,*] and Feng Yuan[2,†]

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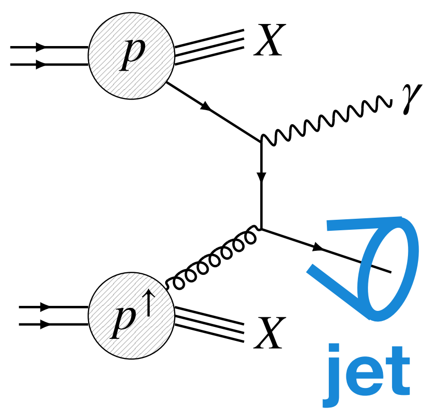
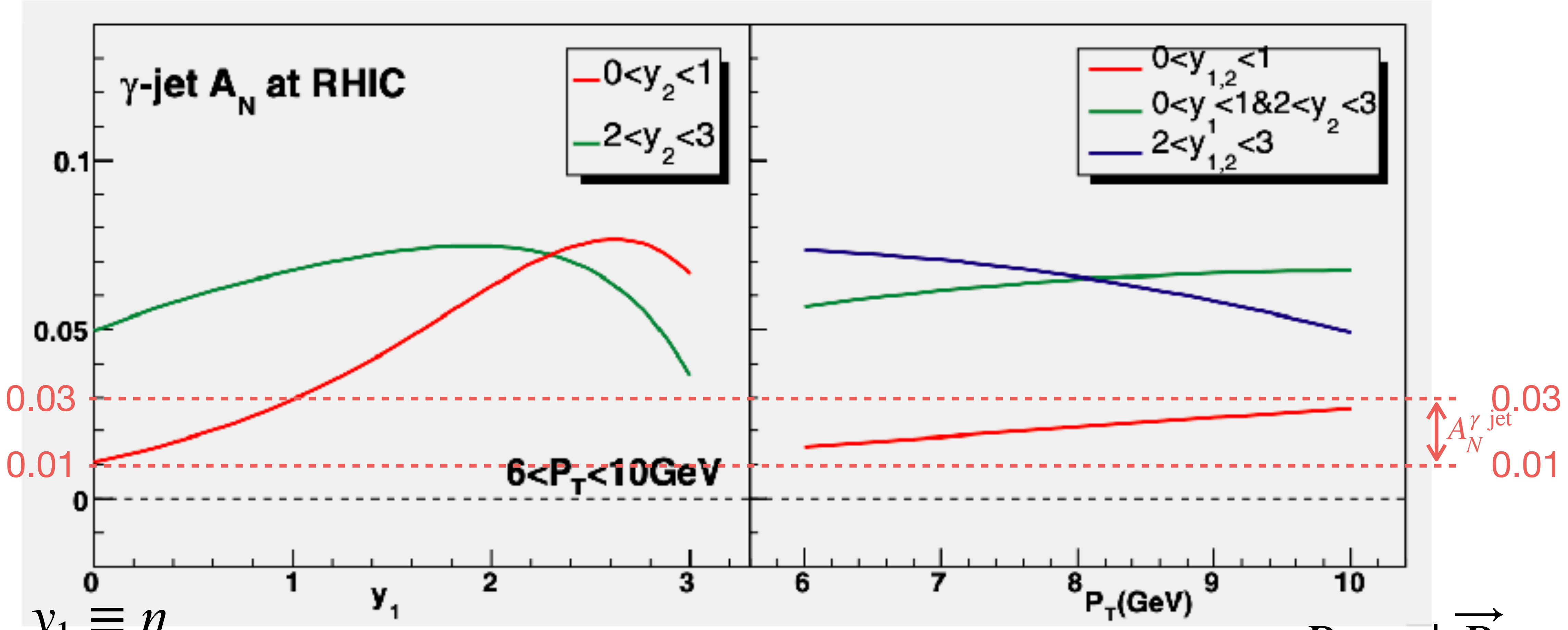
[2]*RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

(Received 27 July 2005; published 30 September 2005)

We study single-spin asymmetries in semi-inclusive deep inelastic scattering with transversely polarized target. Based on the QCD factorization approach, we consider Sivers and Collins contributions to the asymmetries. We fit simple parametrizations for the Sivers and Collins functions to the recent HERMES data, and compare to results from COMPASS. Using the fitted parametrizations for the Sivers functions, we predict the single-transverse-spin asymmetries for various processes in pp collisions at the Relativistic Heavy Ion Collider, including the Drell-Yan process and angular correlations in dijet and jet-plus-photon production. These asymmetries are found to be sizable at forward rapidities.



PRD 72 (2005) 054028



$y_1 \equiv \eta_\gamma$

Theoretical prediction for γ-Jet A_N, PRD 72 (2005) 054028

$P_\perp \equiv |\vec{P}_{\gamma\perp}| = |\vec{P}_{jet\perp}|$

Spin Physics at sPHENIX: Speaker's Choice

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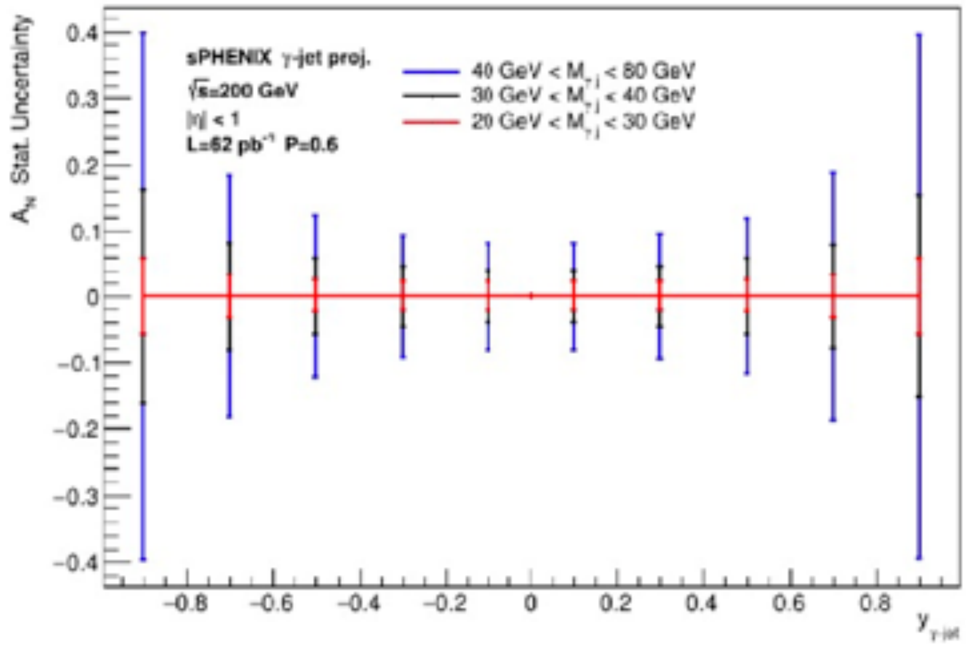

Statistical projection of γ-jet measurement at sPHENIX.

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A_N measurement

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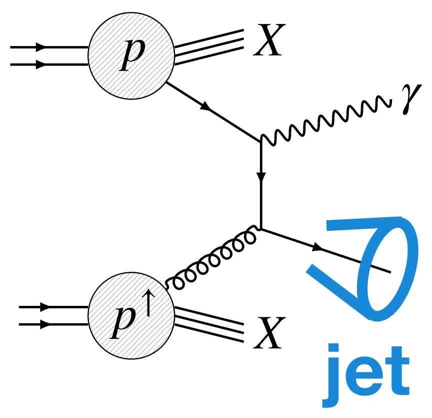
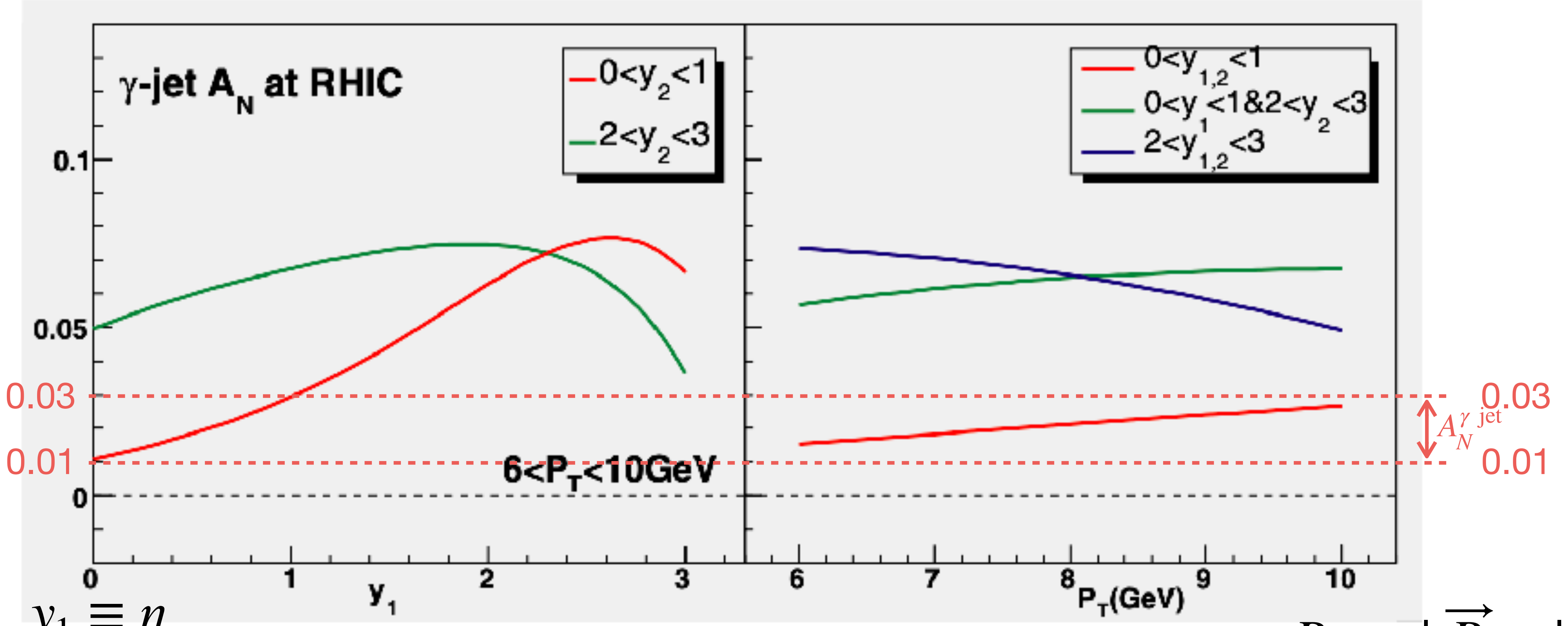


PRD 72 (2005) 054028



$y_1 \equiv \eta_\gamma$

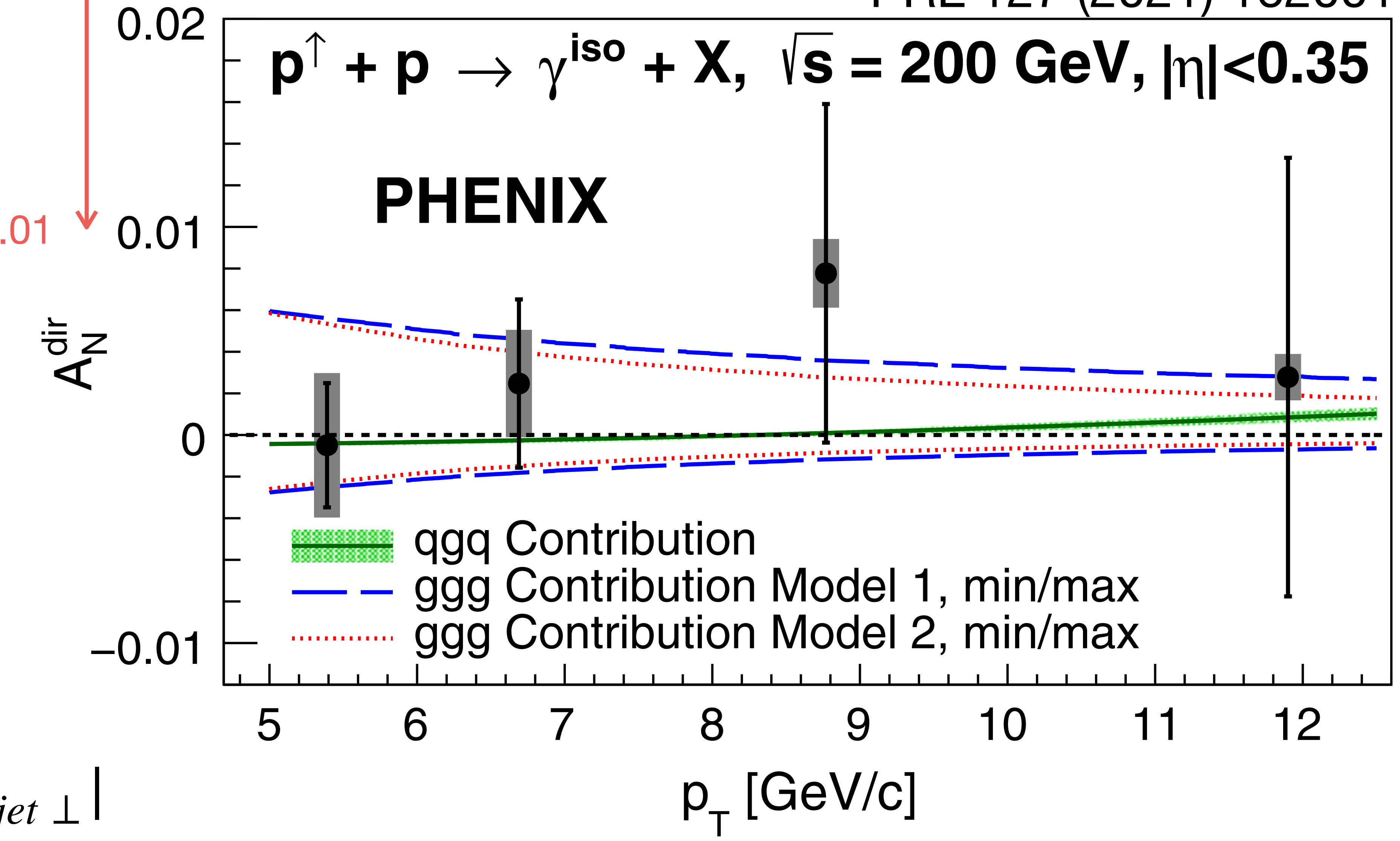
Theoretical prediction for γ-Jet A_N, PRD 72 (2005) 054028

$P_\perp \equiv |\vec{P}_{\gamma\perp}| = |\vec{P}_{jet\perp}|$

0.03

0.01

PRL 127 (2021) 162001



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PRL **99**, 212002 (2007) PHYSICAL REVIEW LETTERS week ending 23 NOVEMBER 2007

Sivers Single-Spin Asymmetry in Photon-Jet Production

Alessandro Bacchetta,[1] Cedran Bomhof,[2] Umberto D'Alesio,[3] Piet J. Mulders,[2] and Francesco Murgia[3]
[1]*Theory Group, Deutsches Elektronen-Synchroton DESY, 22603 Hamburg, Germany*
[2]*Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands*
[3]*INFN, Sezione di Cagliari and Dipartimento di Fisica, Università di Cagliari, 09042 Monserrato, Italy*
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PRL **99**(2007)212002

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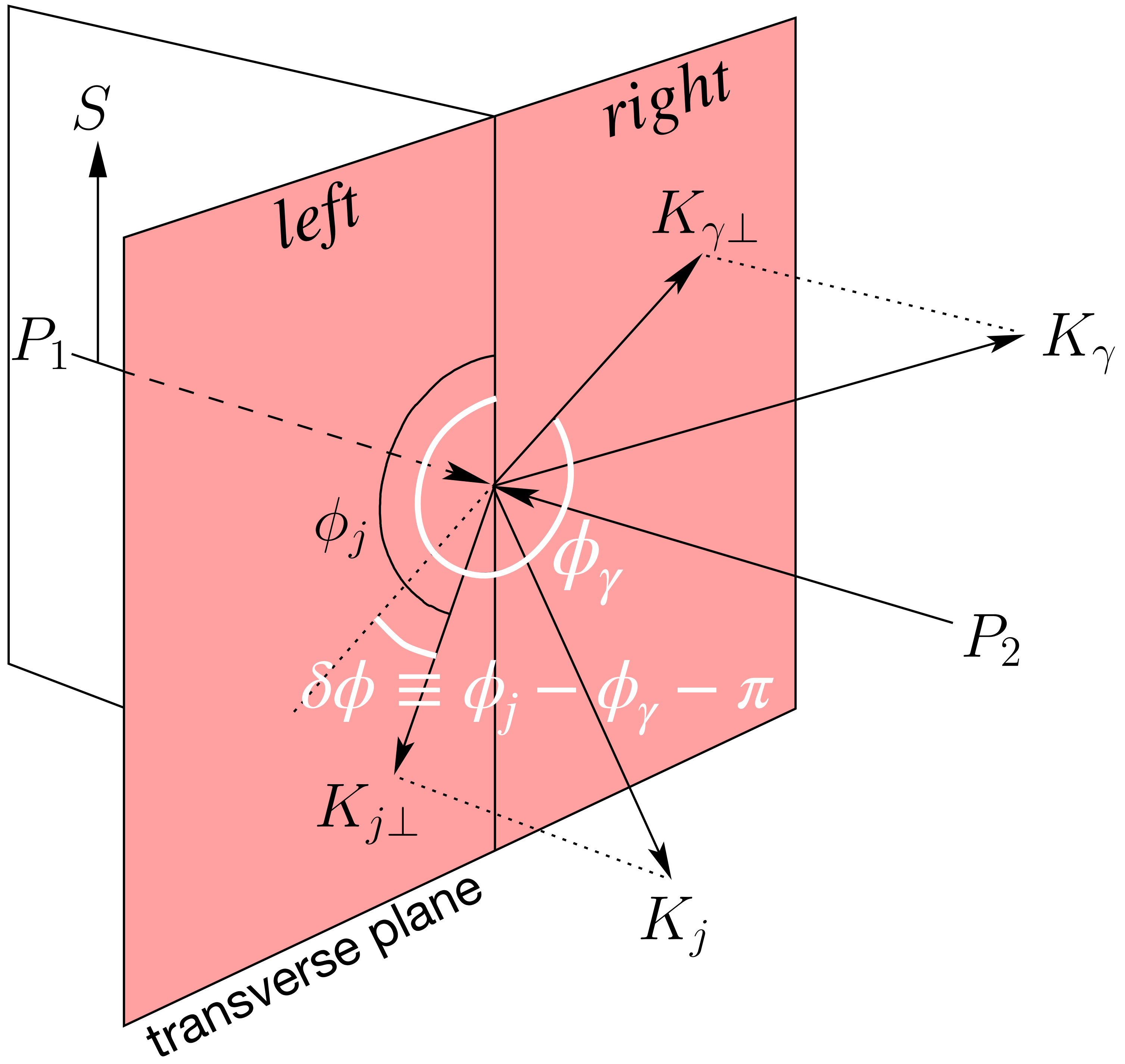

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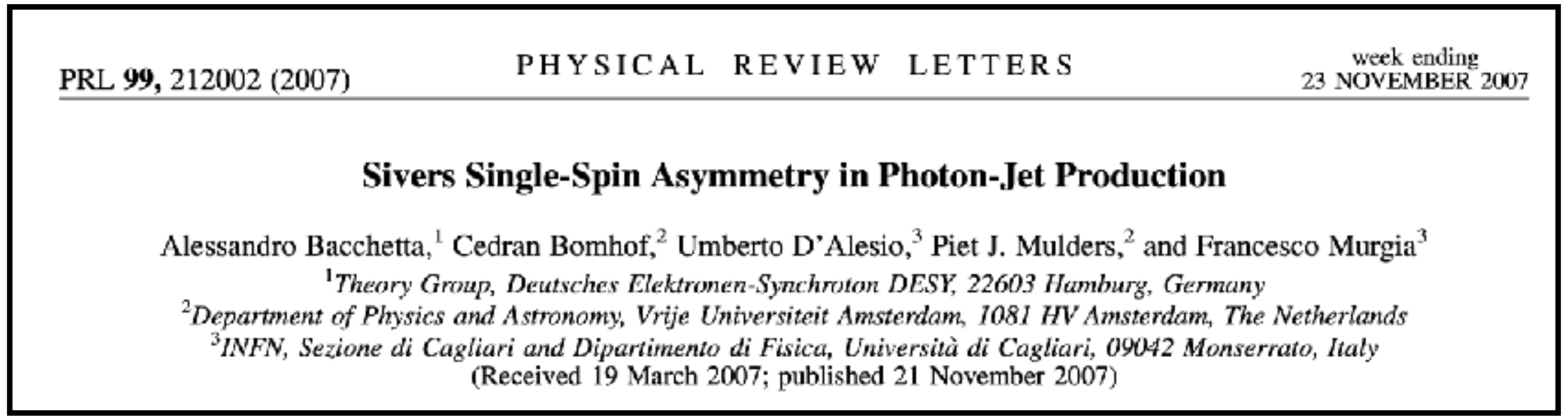
PRL **99**, 212002 (2007) PHYSICAL REVIEW LETTERS week ending 23 NOVEMBER 2007

Sivers Single-Spin Asymmetry in Photon-Jet Production

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Spin Physics at sPHENIX: Speaker's Choice

γ-Jet asymmetry with p↑+p: Unique channels for sPHENIX

Back-to-back in the transverse plane

γ-Jet $p^{\uparrow} + p \rightarrow \gamma + \text{jet} + X$

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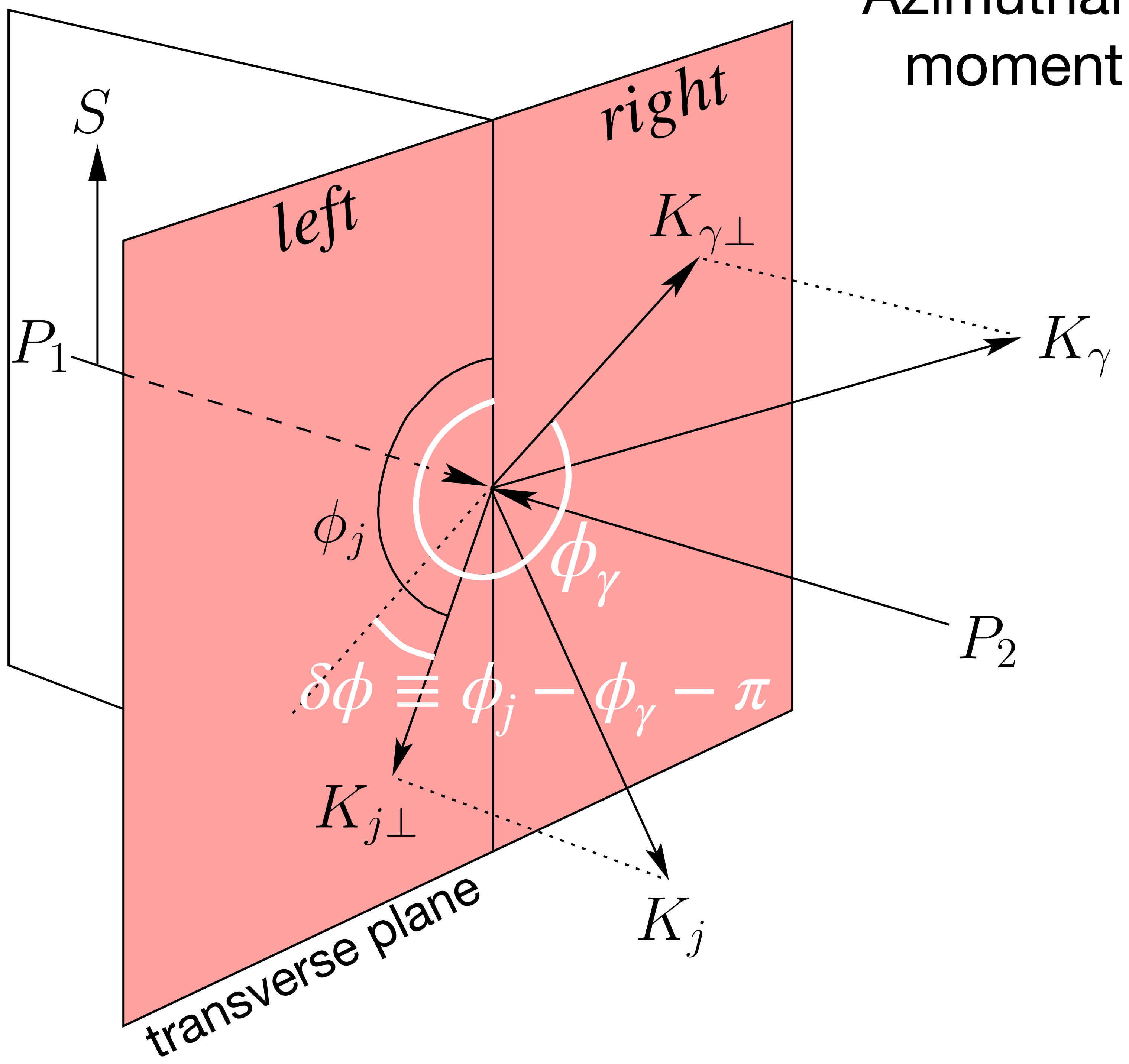

Azimuthal moment

$$M_N^{\gamma j}(\eta_\gamma, \eta_j, x_\perp) = \frac{\int d\phi_j d\phi_\gamma \frac{2|K_{\gamma\perp}|}{M} \sin(\delta\phi)\cos(\phi_\gamma)\frac{d\sigma}{d\phi_j d\phi_\gamma}}{\int d\phi_j d\phi_\gamma \frac{d\sigma}{d\phi_j d\phi_\gamma}} \equiv -\frac{A+B}{C}. \quad (3)$$

$A+B$ ← pol

C ← unpol

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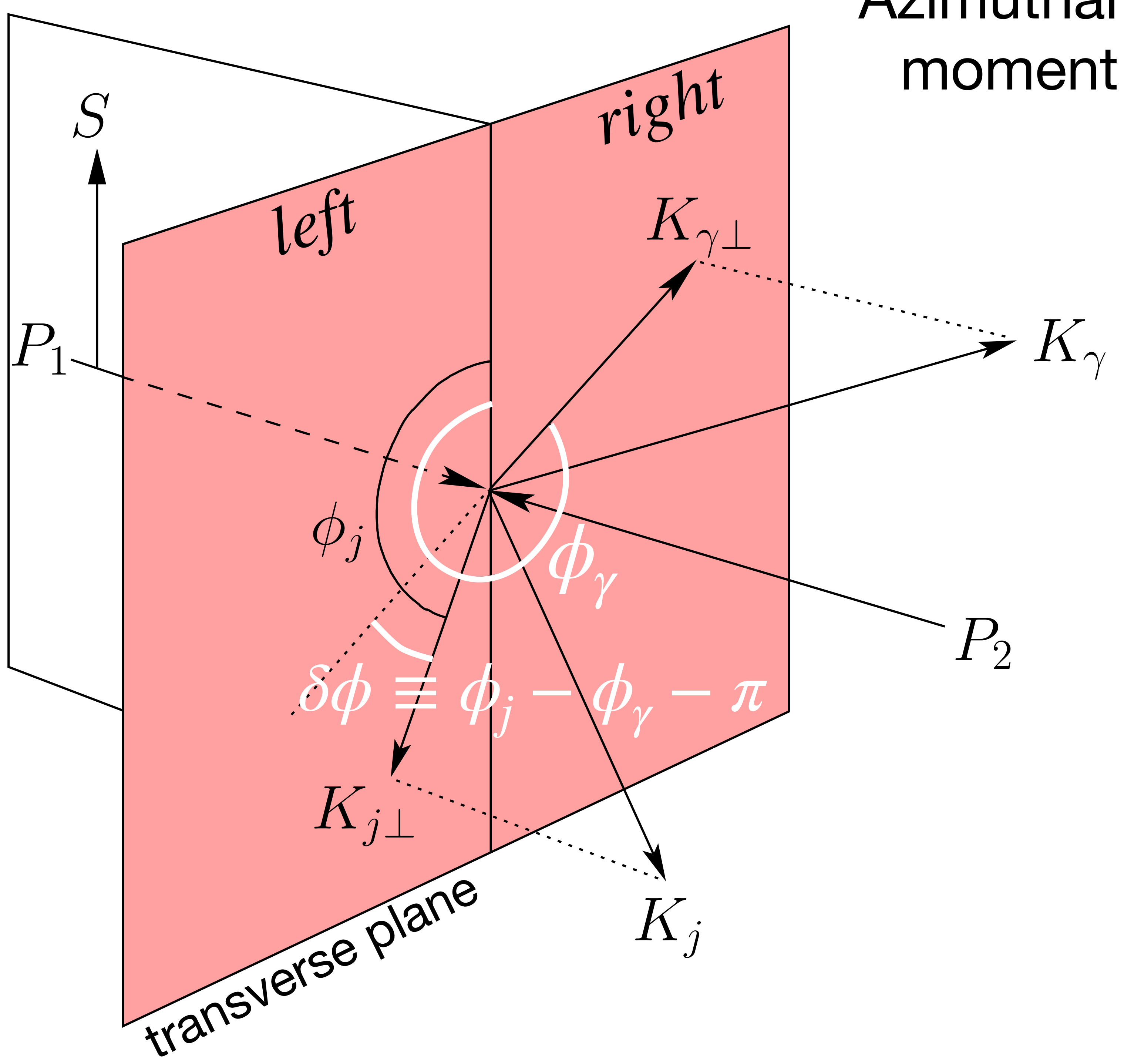

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$$A = x_\perp x_1 x_2 \sum_q [f_{1T}^{\perp(1)g_d}(x_1) f_1^q(x_2) d\hat{\sigma}^{(d)}_{[g]q\to\gamma q} + f_{1T}^{\perp(1)g_f}(x_1) f_1^q(x_2) d\hat{\sigma}^{(f)}_{[g]q\to\gamma q} + f_{1T}^{\perp(1)q}(x_1) \times (f_1^{\bar{q}}(x_2) d\hat{\sigma}_{[q]\bar{q}\to\gamma g} + f_1^g(x_2) d\hat{\sigma}_{[q]g\to\gamma q})],$$

$$B = x_\perp x_1 x_2 \sum_q h_1^q(x_1) h_1^{\perp(1)\bar{q}}(x_2) d\delta\hat{\sigma}_{q^\uparrow[\bar{q}]^\uparrow\to\gamma g},$$

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The first transverse moments of the Sivers function for gluon can be accessed.

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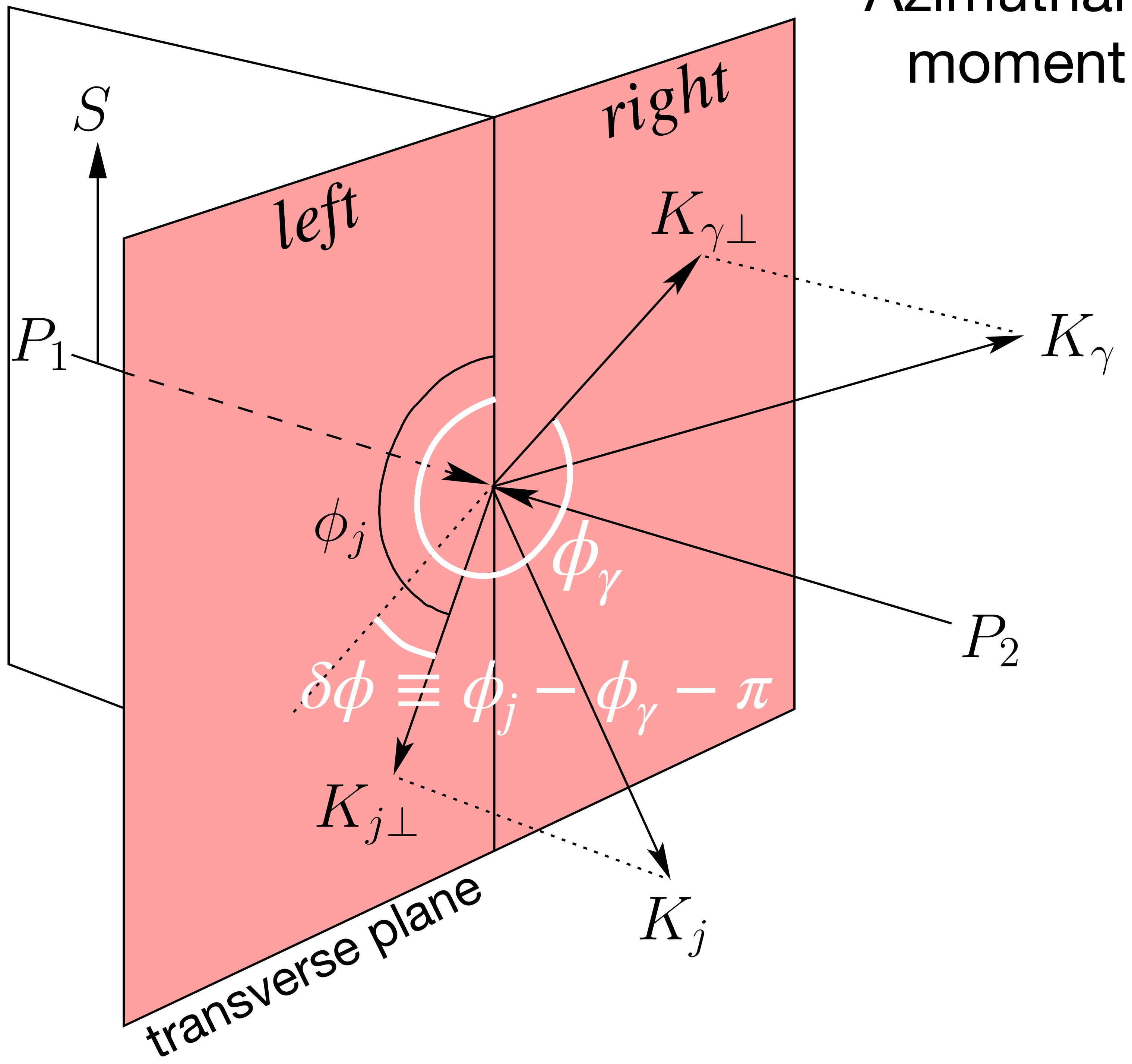

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← pol (numerator $A+B$)

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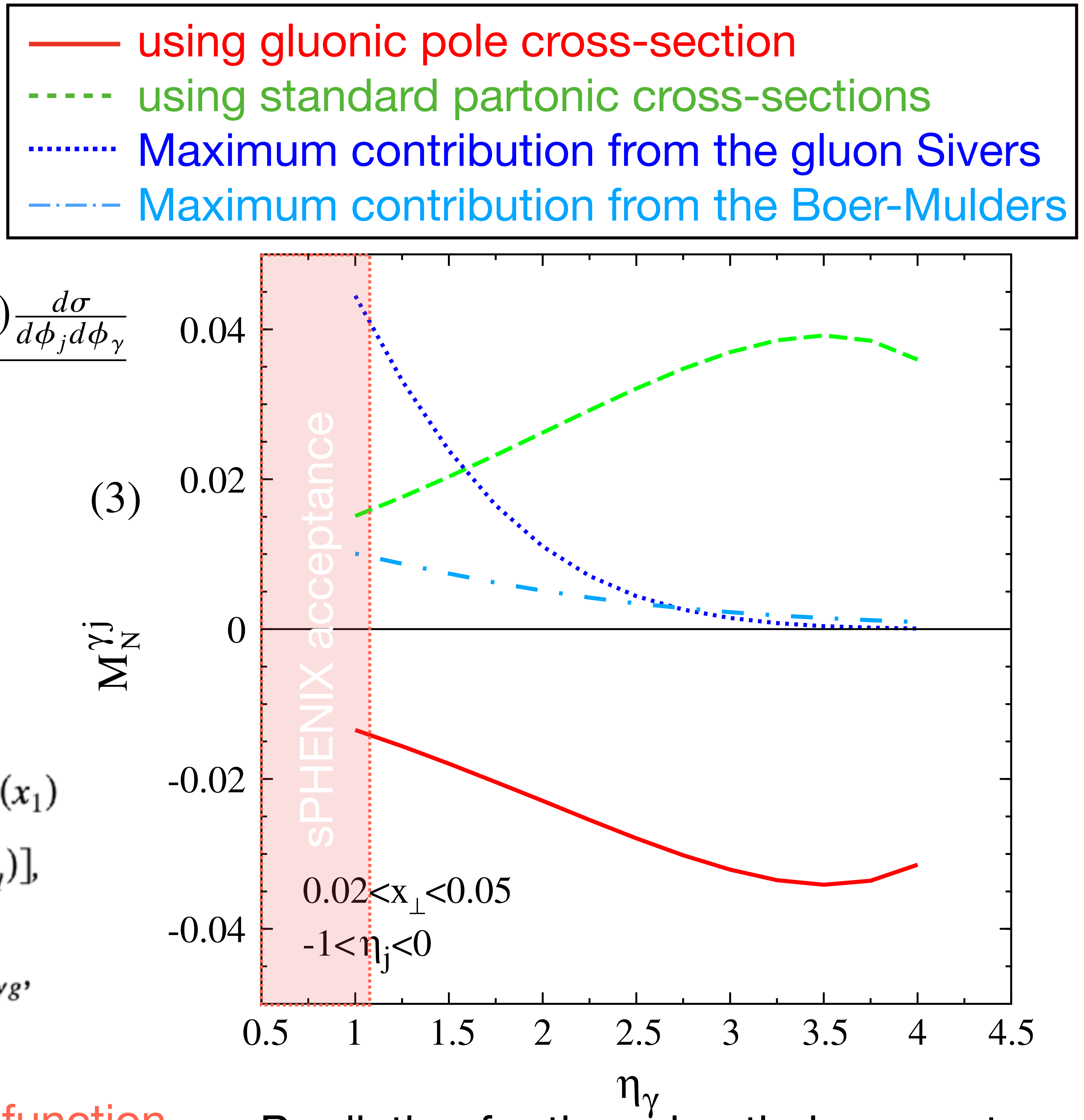


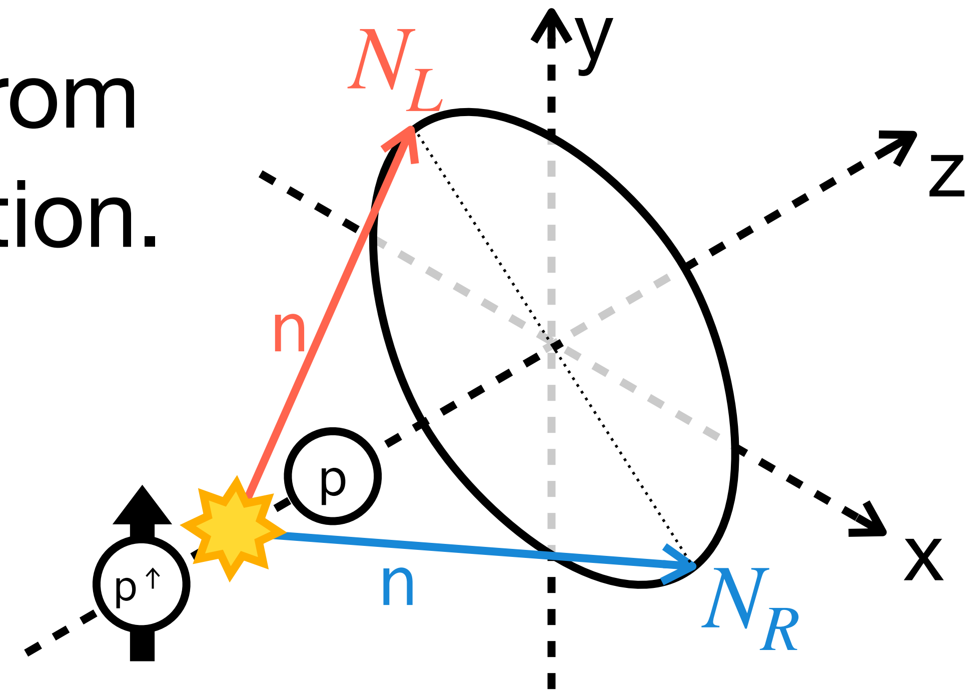
Prediction for the azimuthal moment $M^{\gamma j}_N$ at $\sqrt{s}$ = 200 GeV.

sPHENIX Today: Essential Detectors for Spin Physics

ZDC & SMD

TSSA of very forward neutrons from $p^{\uparrow}$+p collisions ∝ beam polarization.

Few % of TSSA with 50%-60% polarized beam is expected (PRD88(2013)032006).



Square root asym.: $A(\phi) \equiv \dfrac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}$

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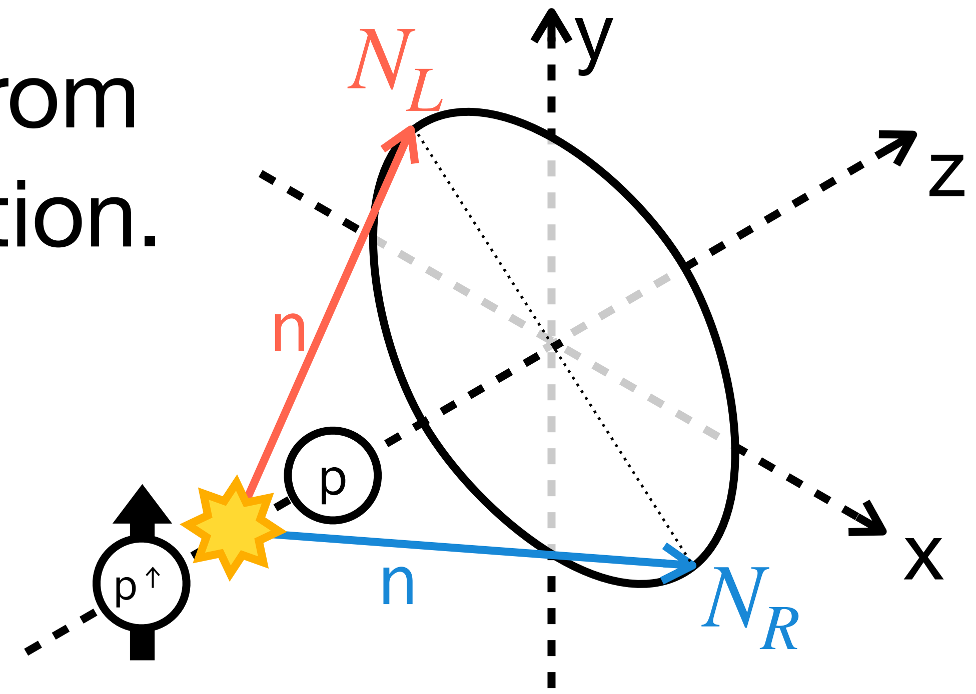

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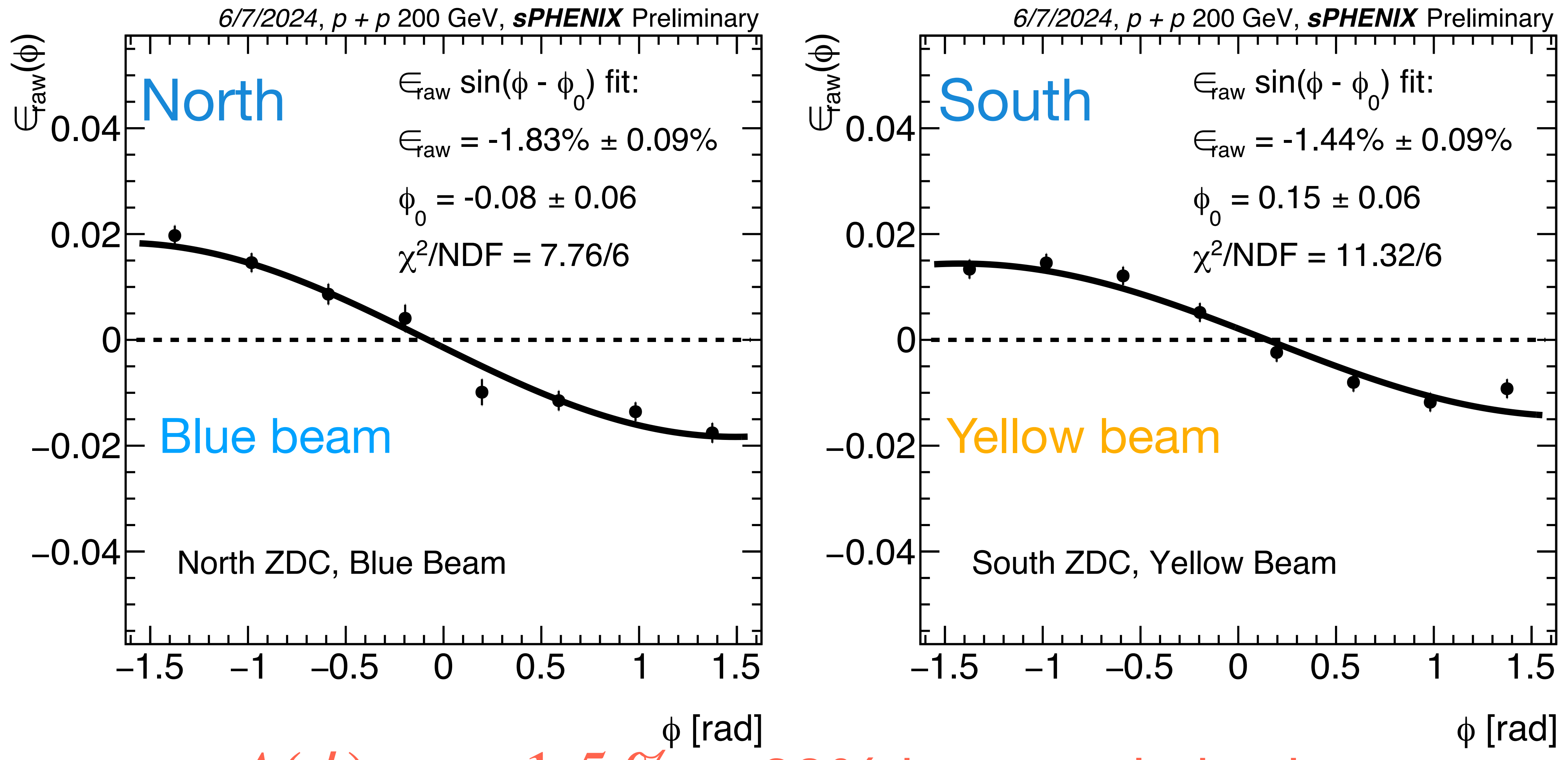

$A(\phi) \sim -1.5\ \%$ → 30% beam polarization

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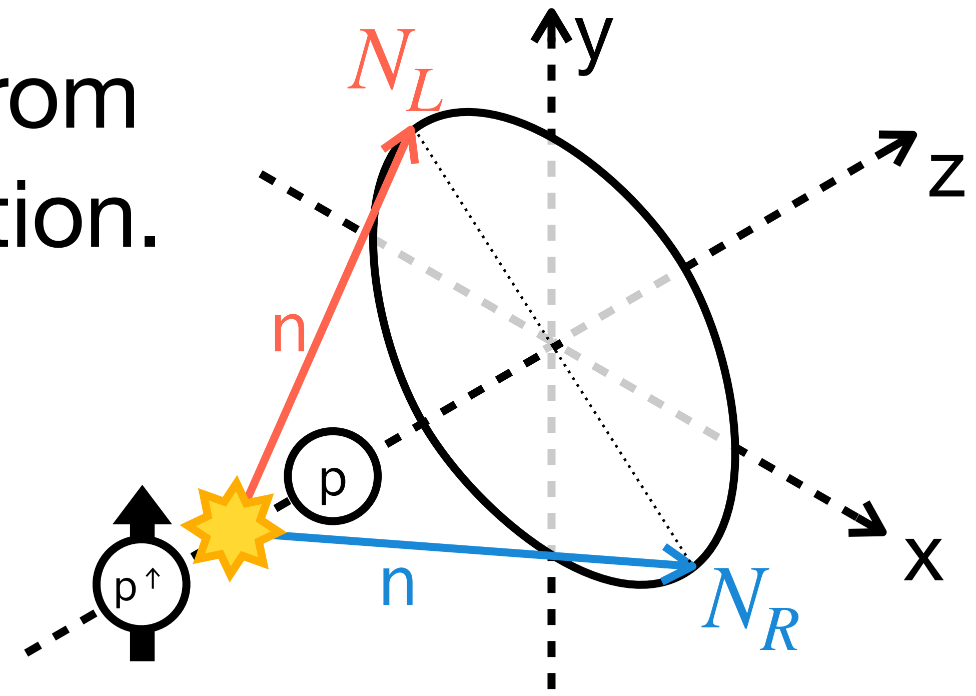

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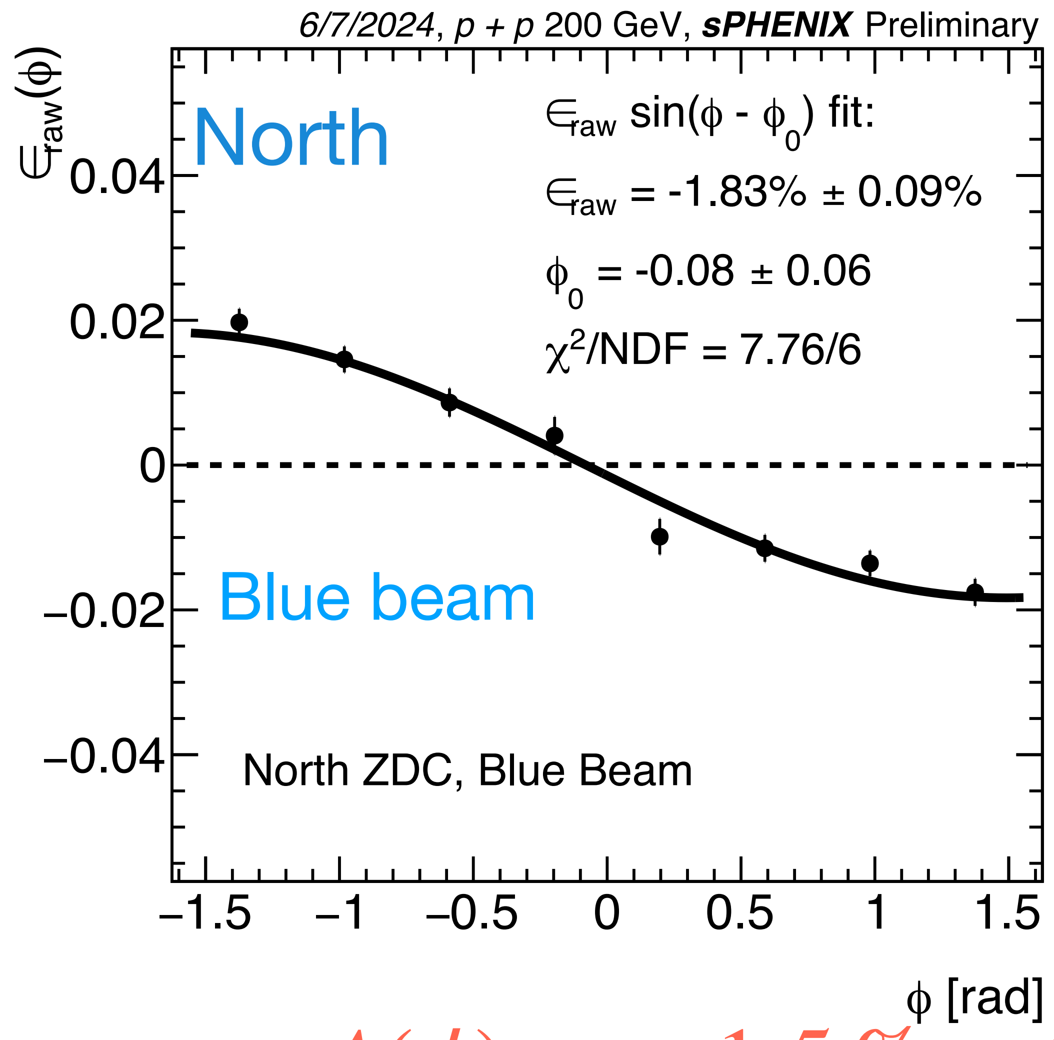

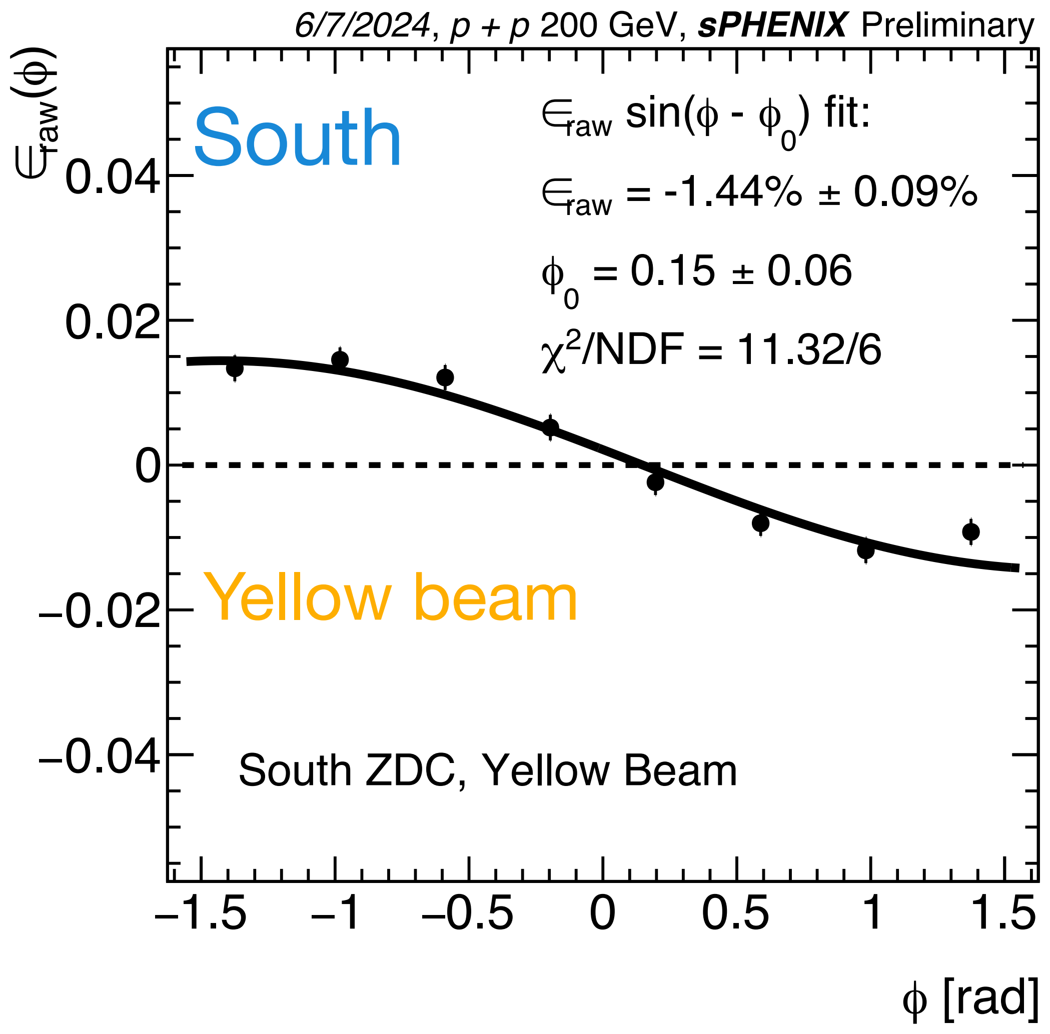

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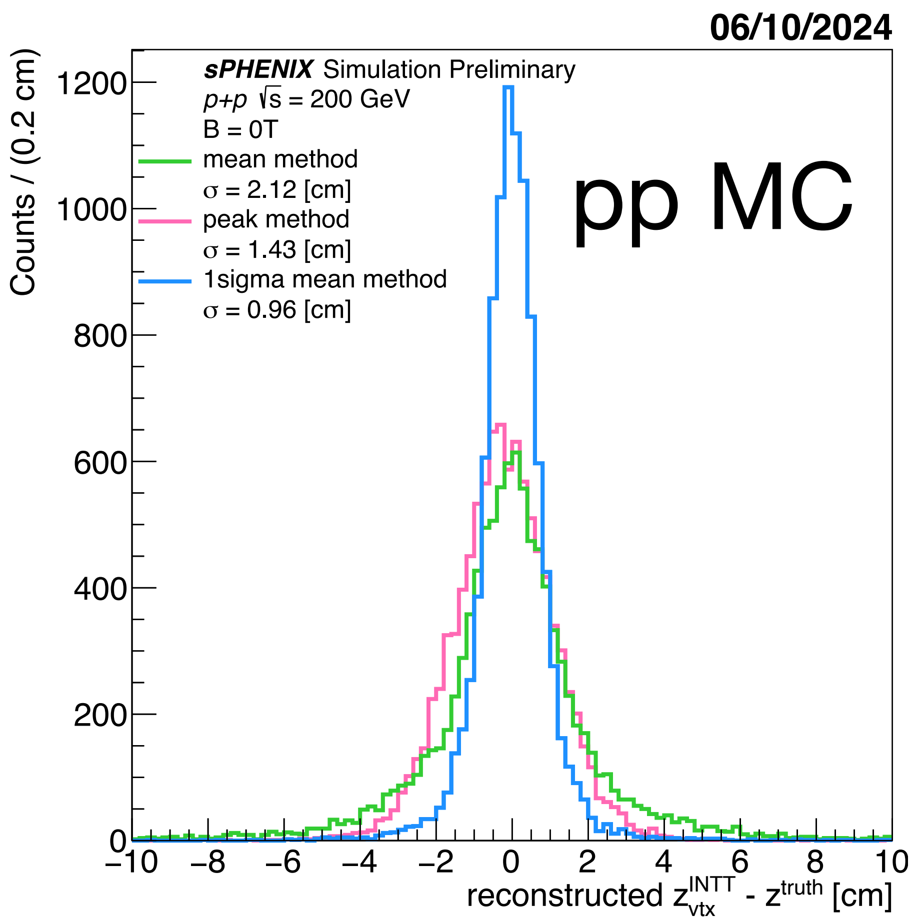
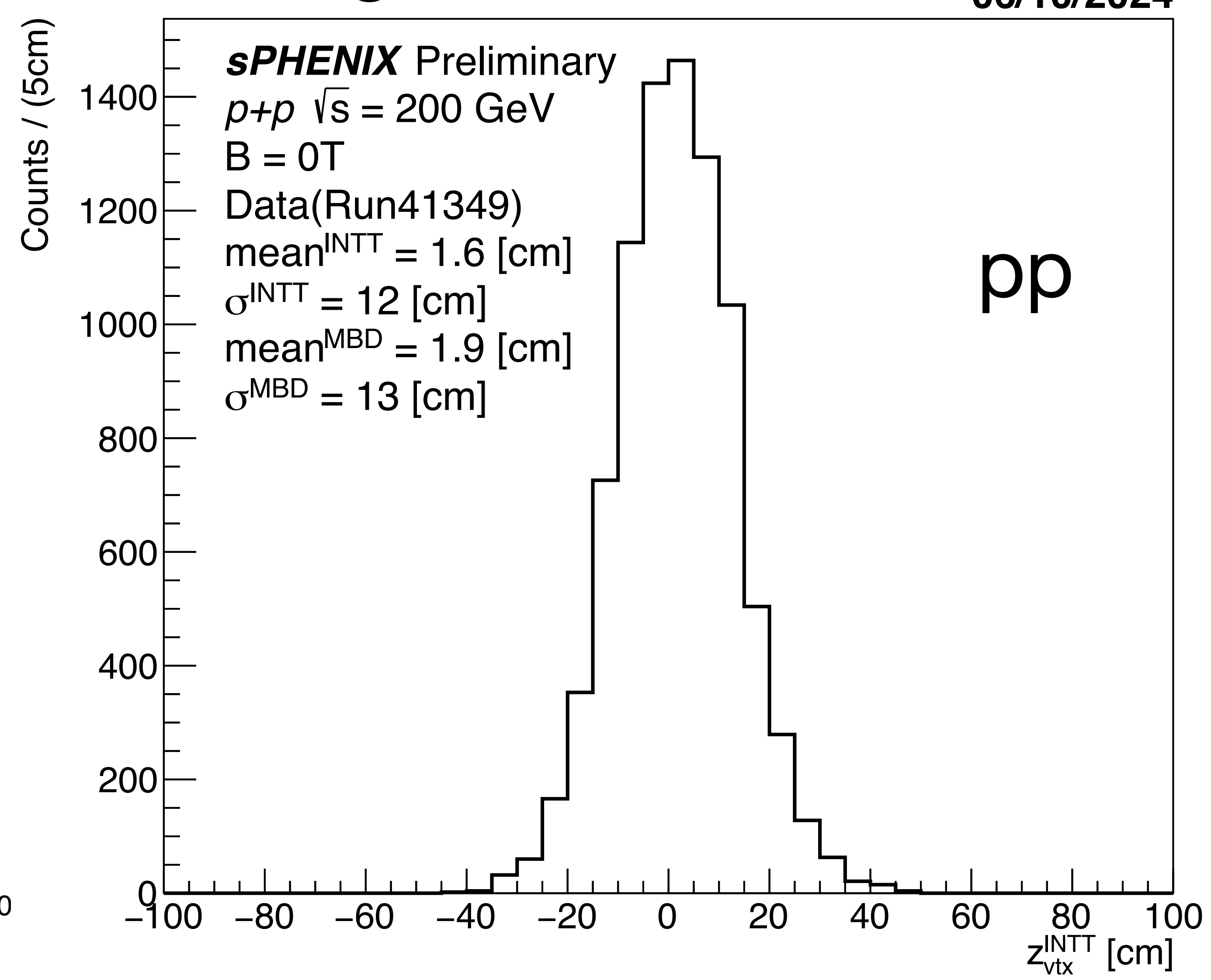
INTT

INTT is the only tracking detector in sPHENIX that has enough timing resolution to identify bunch-crossing. Currently,

- the healthy operation was confirmed by vertexing and tracking using INTT alone.
- INTT was timed in within a single beam clock. We can identify bunch-crossing with INTT.





sPHENIX started taking physics data for spin since June 9th.

Summary

- sPHENIX, a state-of-the-art jet detector at RHIC, studies QGP and Cold-QCD. It consists of
  - Hcal and EMcal
  - Superconducting solenoid magnet
  - Tracking detectors at the central rapidity $|\eta| < 1.1$: TPC, TPOT, INTT, and MVTX
  - Forward detectors: sEPD, MBD, and ZDC
- Measurement with $p^{\uparrow} + p^{\uparrow}$ collisions enables us to study
  - Tri-gluon correlator
  - Sivers TMD PDF, Transversity PDF
  - Collins FF, Interference FF
  - etc.
- The construction was finished last year.
- We are taking $p^{\uparrow} + p^{\uparrow}$ data for spin physics now!

STAY TUNED