IWHSS 2023
25/June/2023 — 28/June/2023

sPHENIX Cold-QCD Program

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

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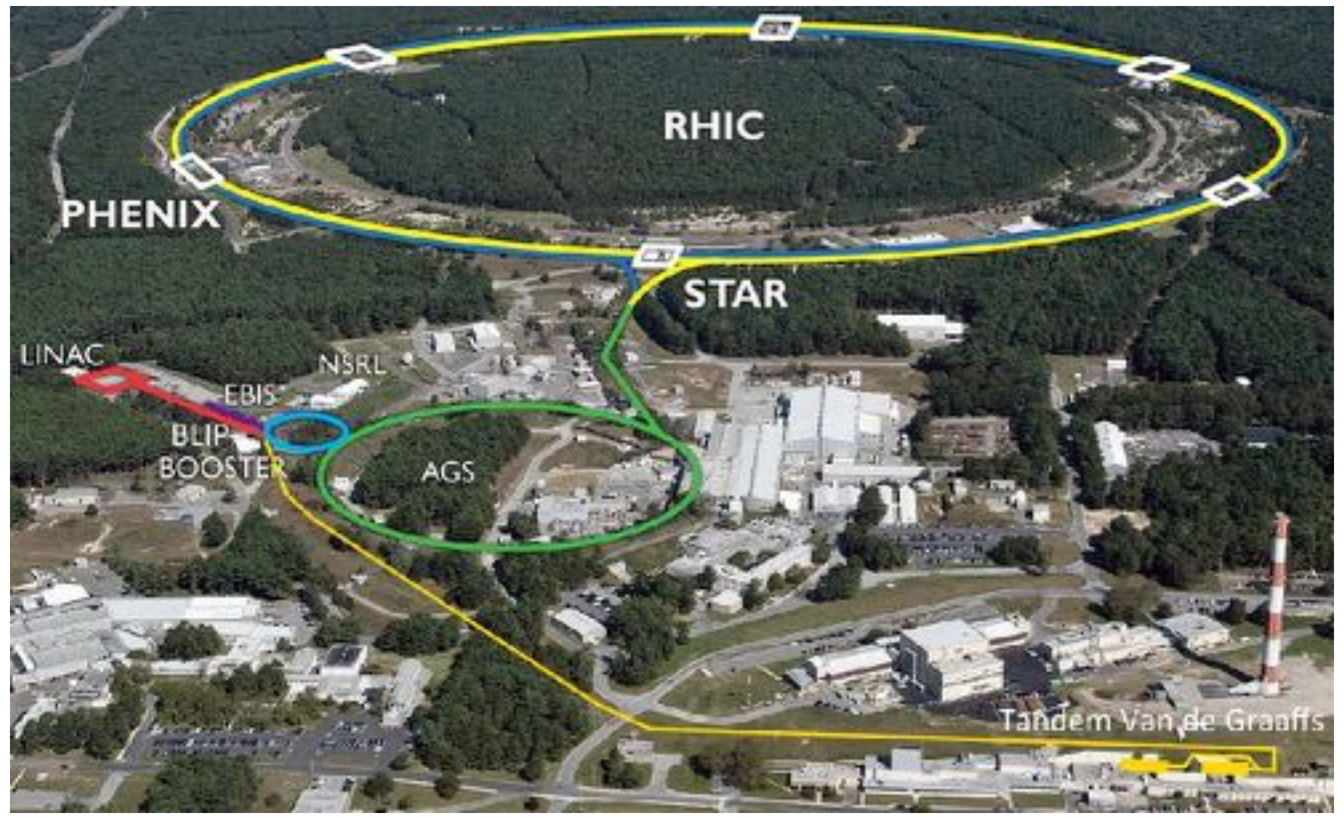
sPHENIX Collaboration

Relativistic Heavy Ion Collider (RHIC)

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



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.

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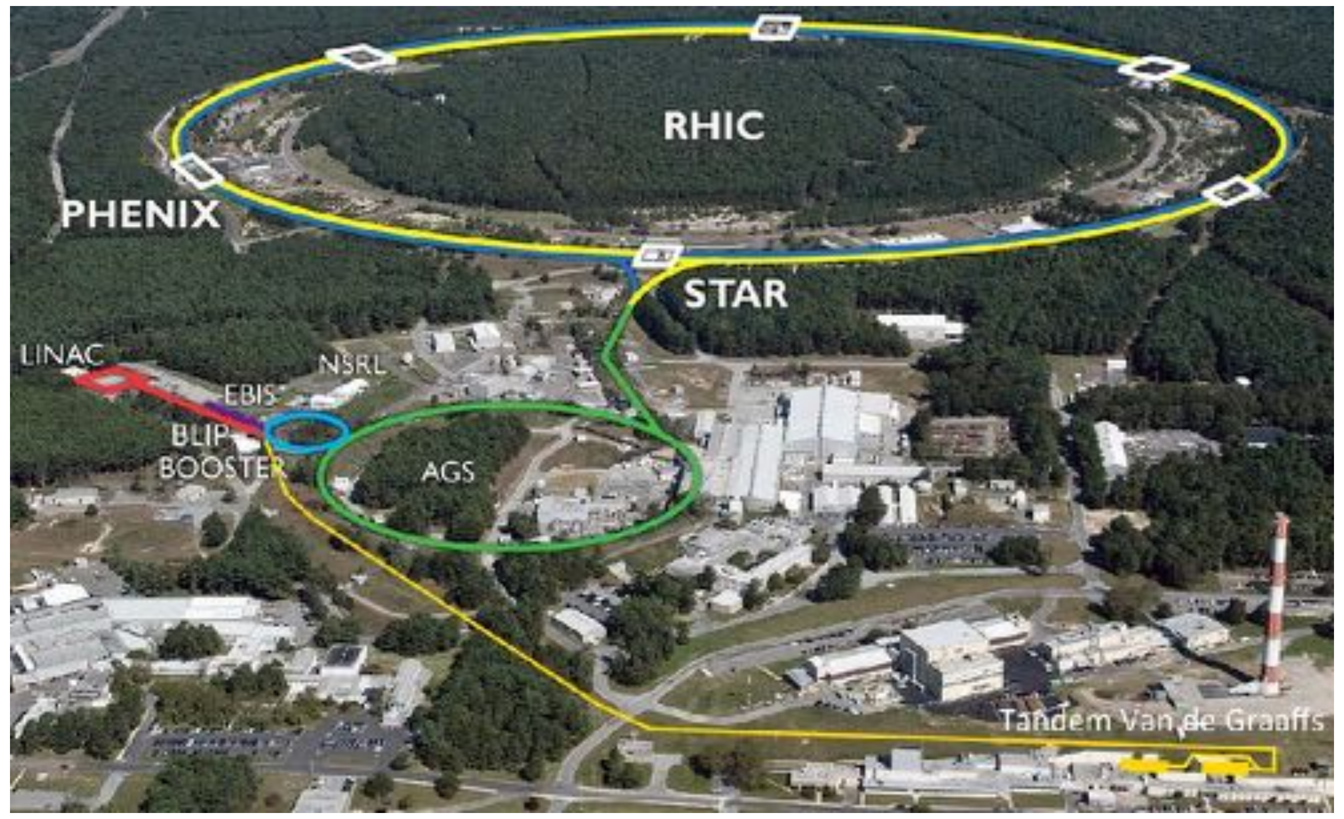

NEXT STEP

- 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/

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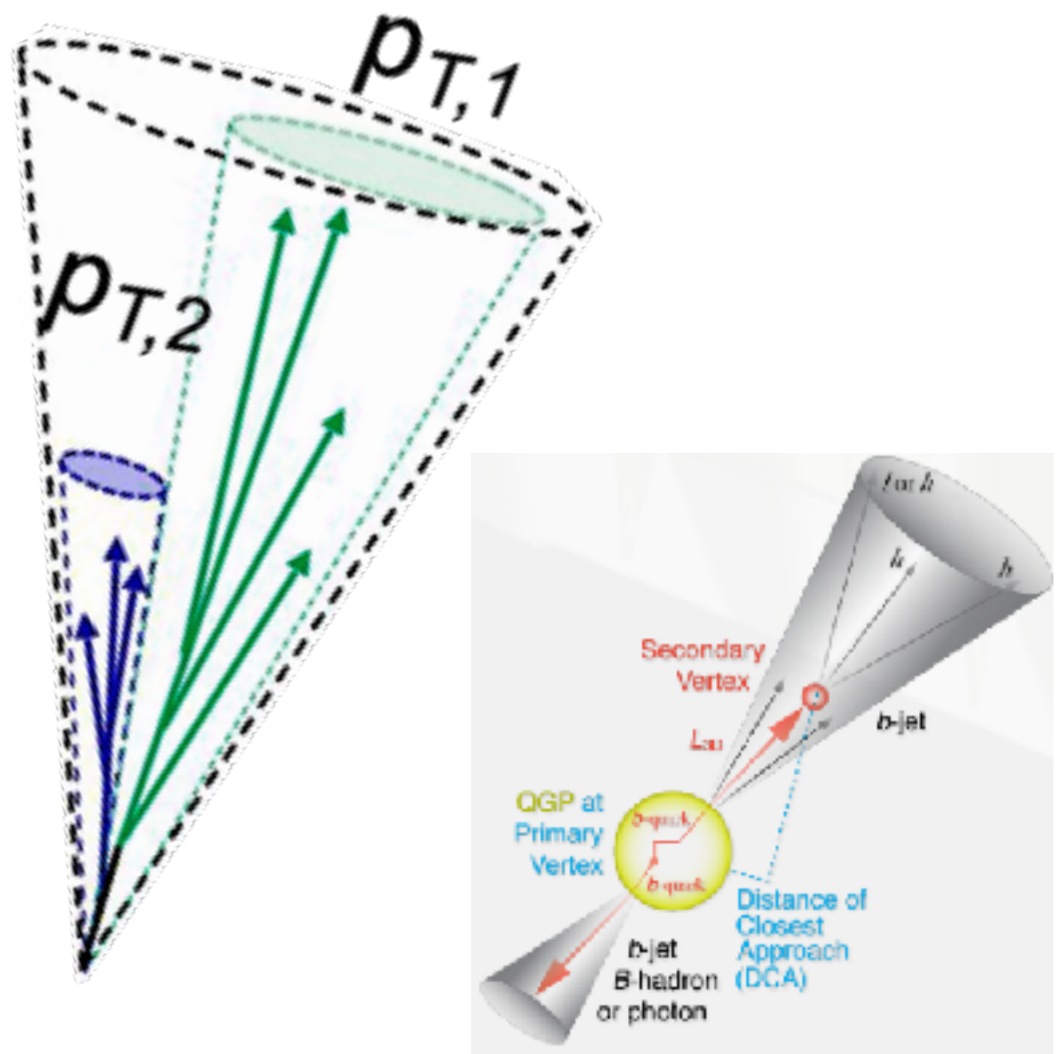
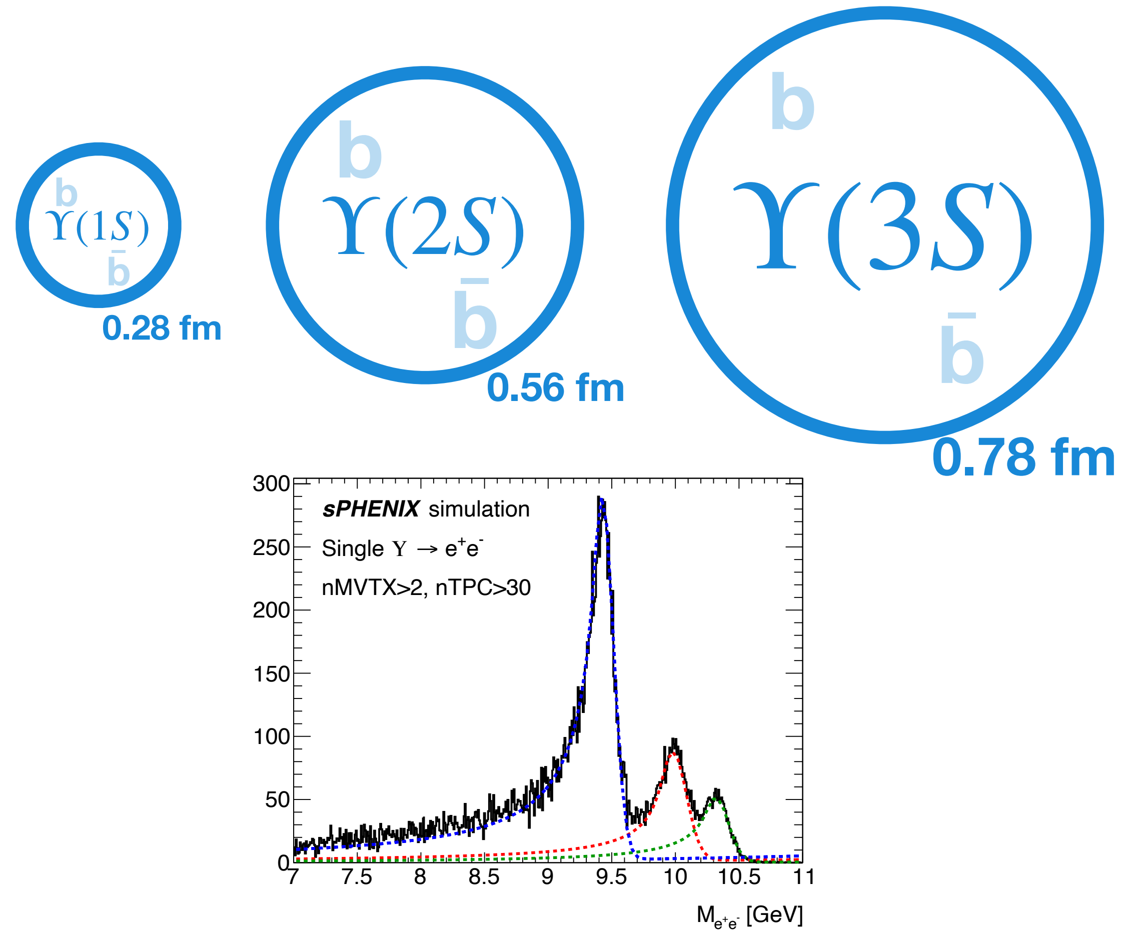
sPHENIX Physics Programs

Jet Physics



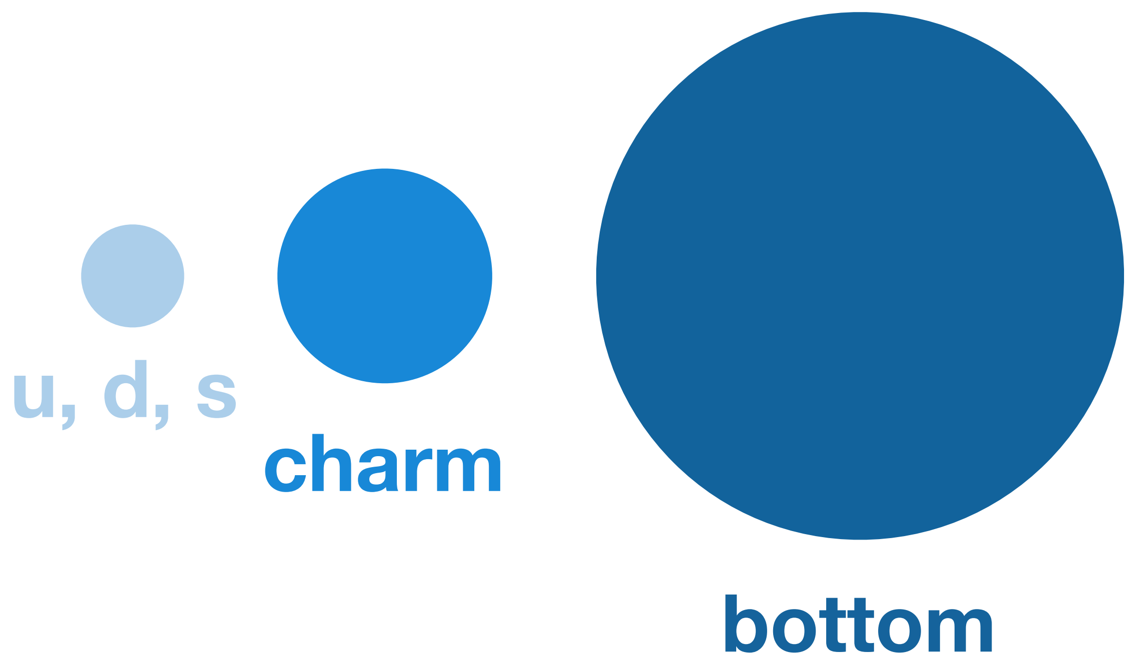
- Jet correlations
- Nuclear Modification Factor
- Jet structure
- Jet flavor dependencies

Quarkonium Spectroscopy



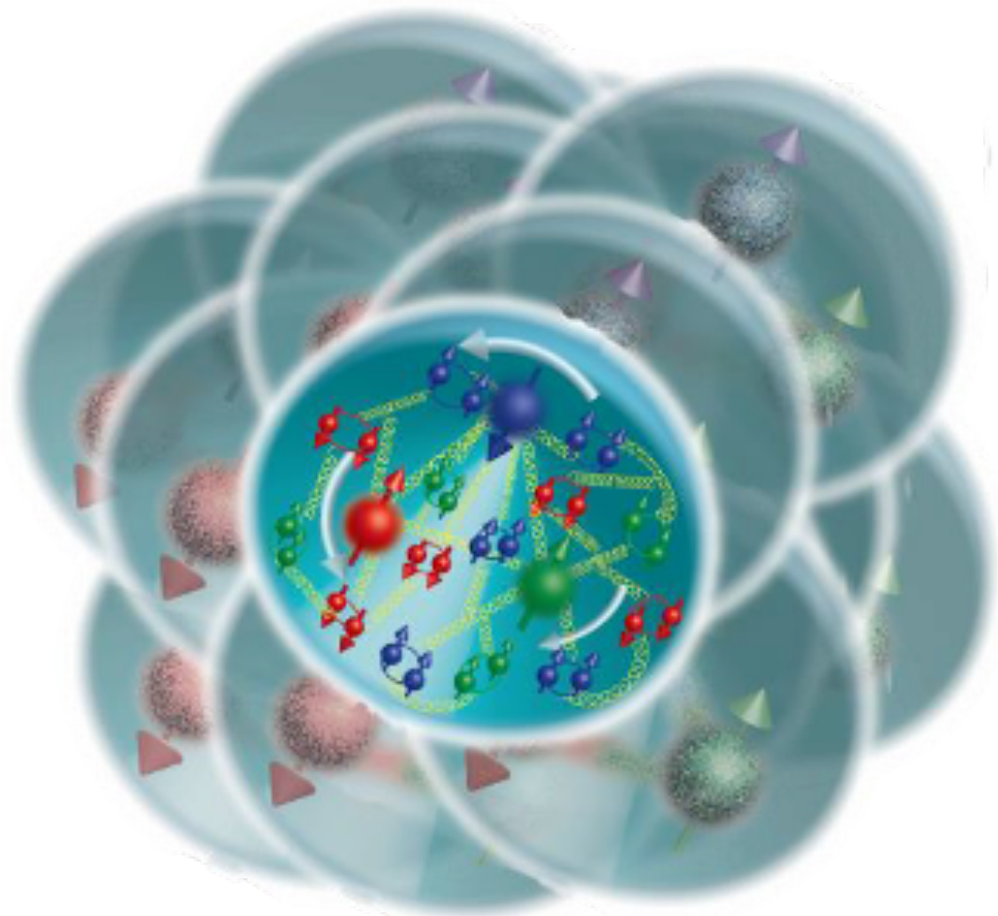
- Sequential quarkonia melting: Suppression of quarkonium depending on the state

Energy Loss in QGP



- Flavor (mass) dependence of parton energy loss in QGP

Cold-QCD



- Origin of the transverse single spin asymmetries
- Nucleon structure
- Fragmentation functions
- Nuclear effects

sPHENIX Detector

sPHENIX has a hadron calorimeter in midrapidity at RHIC first time for jet reconstruction.

It covers full azimuthal angle 2π and $|\eta| < 1.1$ in $|z_{vtx}| < 10$ cm.

Magnet

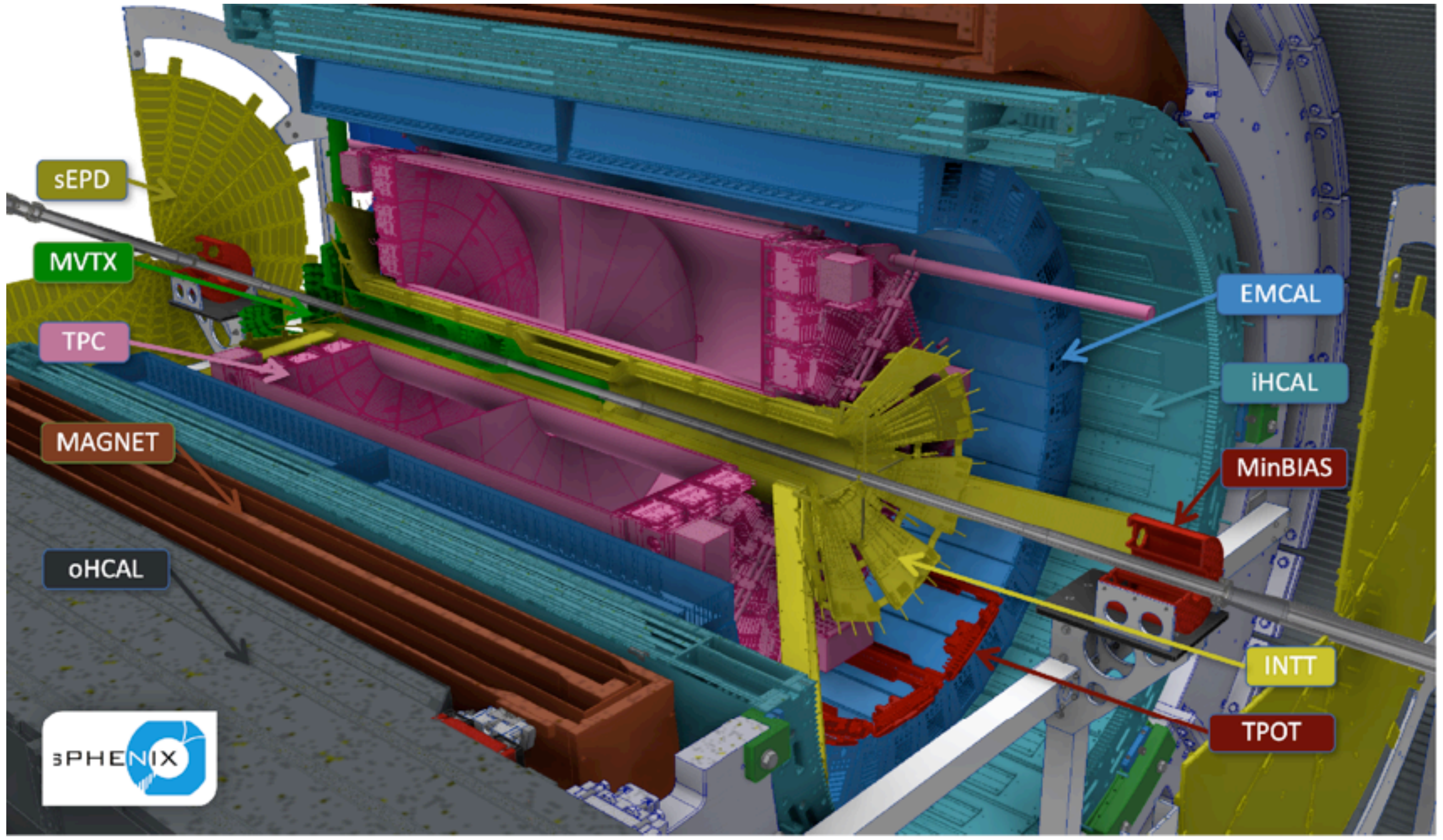
Superconducting solenoid magnet from Babar at SLAC provides 1.5 T

Outer and Inner Hcal (Hadronic Calorimeter)

- Inner part: non-magnetic metal and scintillator
- Outer part: Iron and scintillator
- Measurements can be done before multiple scattering of hadron shower by the cryostat for the magnet

EMcal (Electromagnetic Calorimeter)

- consists of tungsten and scintillating fibers
- compact, small segmentation ($\Delta\eta \times \Delta\phi = 0.024 \times 0.024$)



sPHENIX Detector

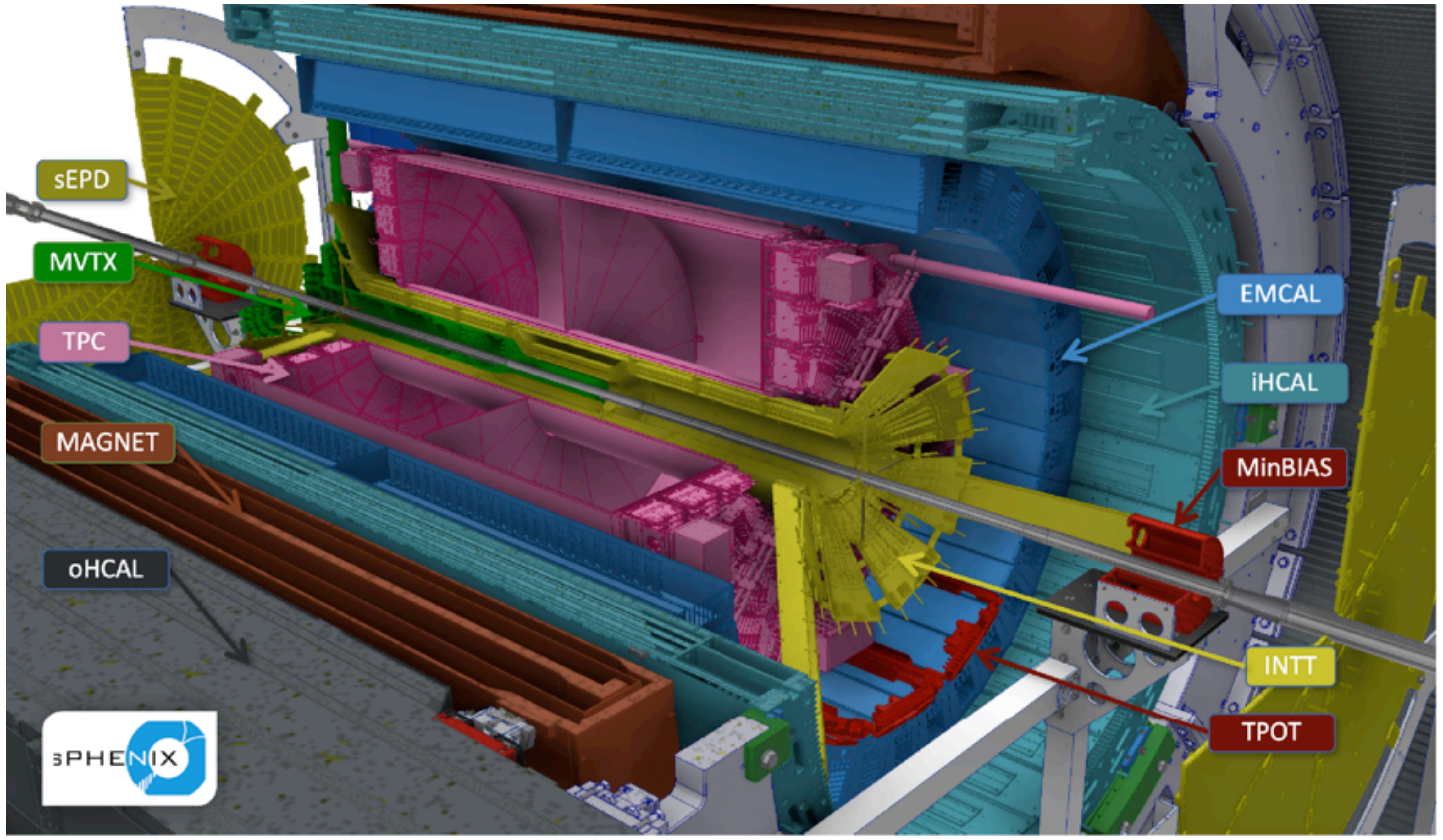
sPHENIX Detector

Tracking detectors

- **TPC** (Time Projection Chamber)
  - r < 80 cm
  - contributes good momentum resolution
- **TPOT** (TPC Outer Tracker)
  - Micromegas
  - for calibration of beam-induced space charge distortions
- **INTT** (Intermediate Tracker)
  - r < 10 cm
  - tracking between TPC and MVTX with great timing resolution
- **MVTX** (MAPS-based Vertex Detector)
  - r < 4 cm
  - Monolithic active pixel detector with 30 μm pitch for vertexing

Forward Detectors

- **MBD** (Minimum Bias Detector)
  - 3.51 < | η | < 4.61
  - provides minimum bias trigger, reuse of the PHENIX BBC
- **sEPD** (sPHENIX Event Plane Detector)
  - 2.0 < |η| < 4.9,
  - contributes to the great event place resolution
- **ZDC** (Zero Degree Calorimeter)
  - z =± 18.5 m
  - works for centrality and luminosity measurements and trigger



sPHENIX Detector

Run Plan

Year	Beam	$\sqrt{s_{NN}}$ (GeV)	Data Taking (Weeks)	Luminosity, (|z| < 10 cm) Recorded	Sampled
2023	Au + Au	200	9	3.7 nb^{-1}	4.5 nb^{-1}
2024	$p^{\uparrow} + p^{\uparrow}$	200	12	0.3 pb^{-1} (5 kHz)	45 pb^{-1}
2024	$p^{\uparrow}$ + Au	200	5	0.003 pb^{-1}	11 pb^{-1}
2025	Au + Au	200	20.5	13 nb^{-1}	21 nb^{-1}

2023: Commissioning&Calibration

- The construction was finished in April/2023.
- The first beam came in May/2023.
- Commissioning and calibration are ongoing NOW.
- We will start Physics data taking soon.

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2024: $p^{\uparrow}+p^{\uparrow}$ and $p^{\uparrow}$ + Au

- A large amount of data with
  - $p^{\uparrow}+p^{\uparrow}$ @$\sqrt{s_{NN}}$ = 200 GeV (~60% polarization)
  - $p^{\uparrow}$ + Au @$\sqrt{s_{NN}}$ = 200 GeV (~60% polarization)
- Trackers' readout will be updated to streaming readout for a part of the run.

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2025: Au + Au

- Very large Au + Au dataset (140B events)

Table of Contents

- sPHENIX Collaboration
  - Physics Programs
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  - Runs
- sPHENIX Cold-QCD program
- sPHENIX Today

sPHENIX Cold-QCD Program

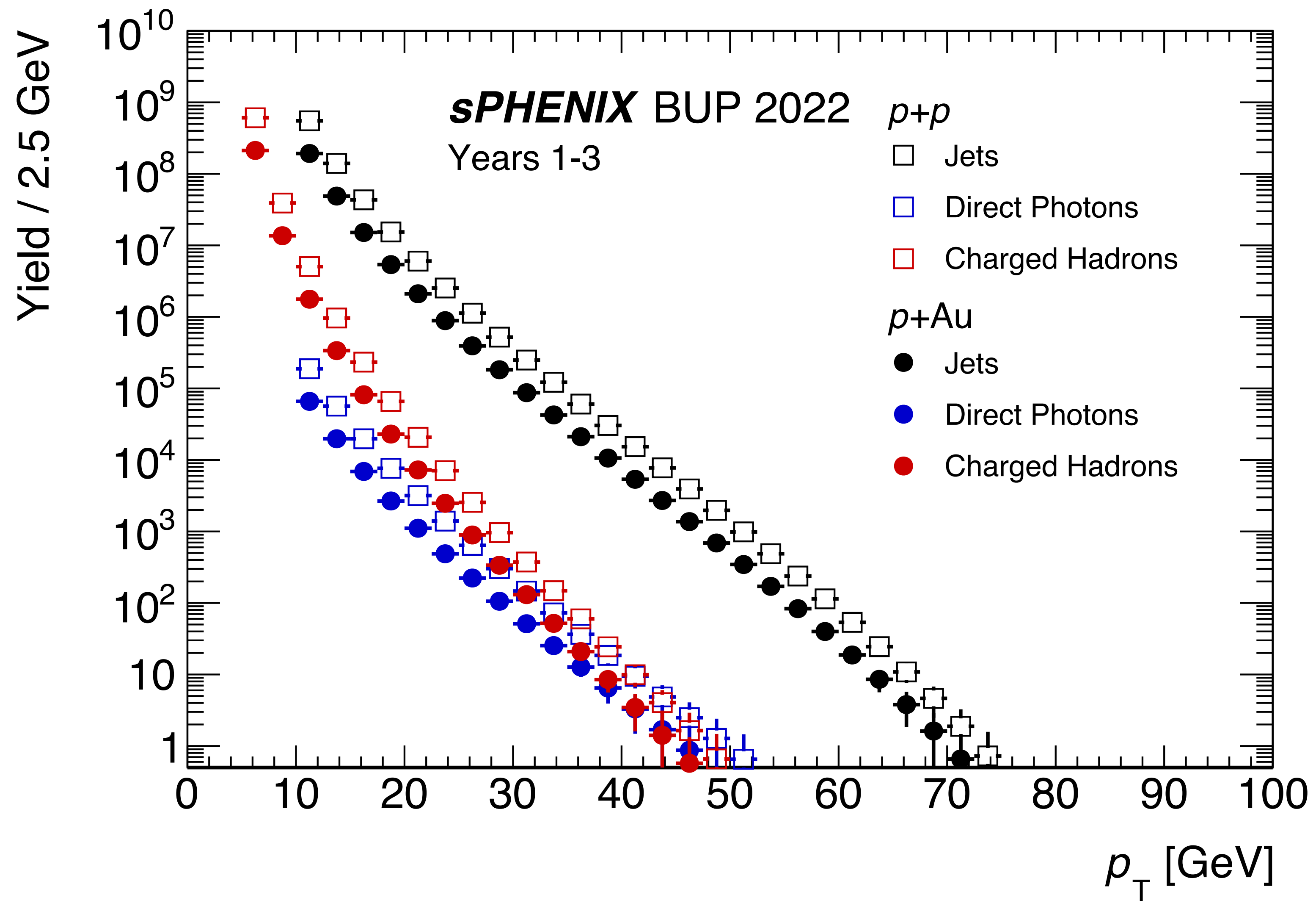
Measurements of transverse single spin asymmetries (TSSA) enable us to study

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

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

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 $h_{1T}^{\perp}$

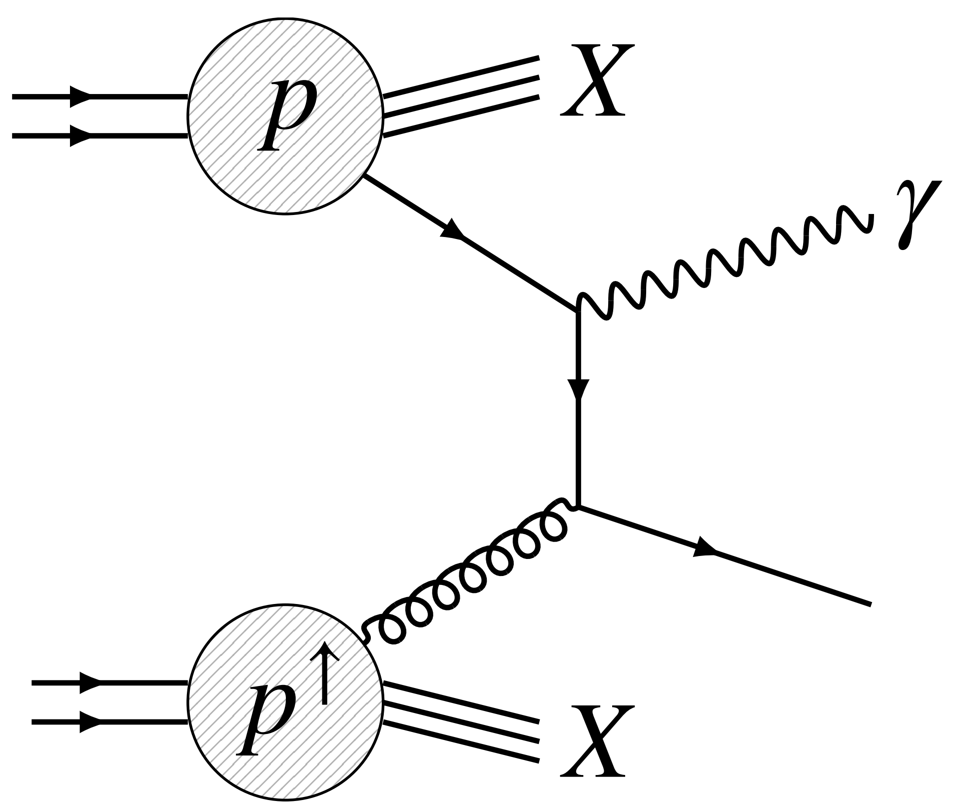


The projected total yield from p + p or p + Au at sPHENIX.

See J. Zhang's (STAR) and B. Ujvári's (PHENIX) talk for details of referred studies.

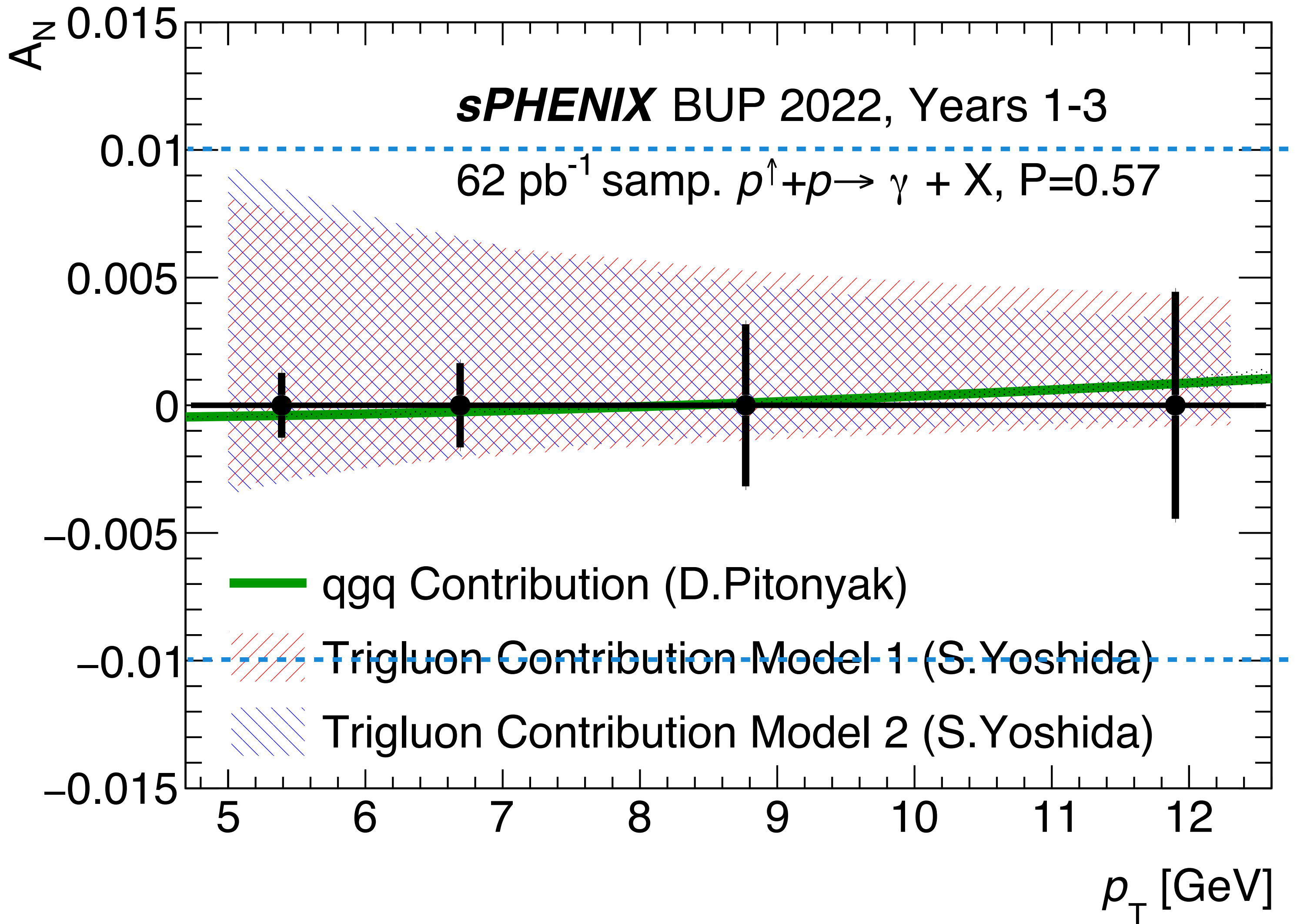
sPHENIX Cold-QCD Program

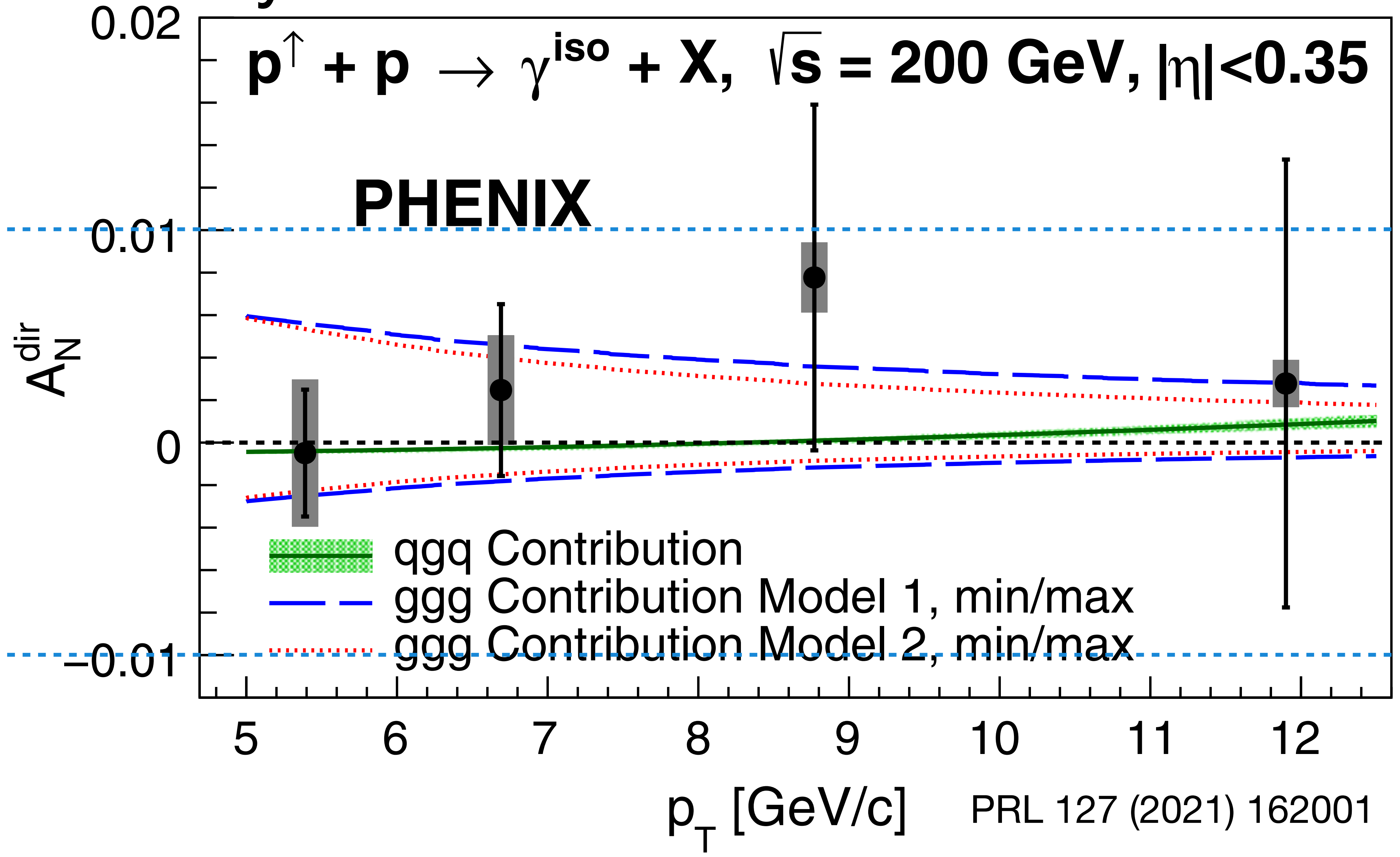
Direct photon $p^{\uparrow} + p \rightarrow \gamma + X$



- **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.





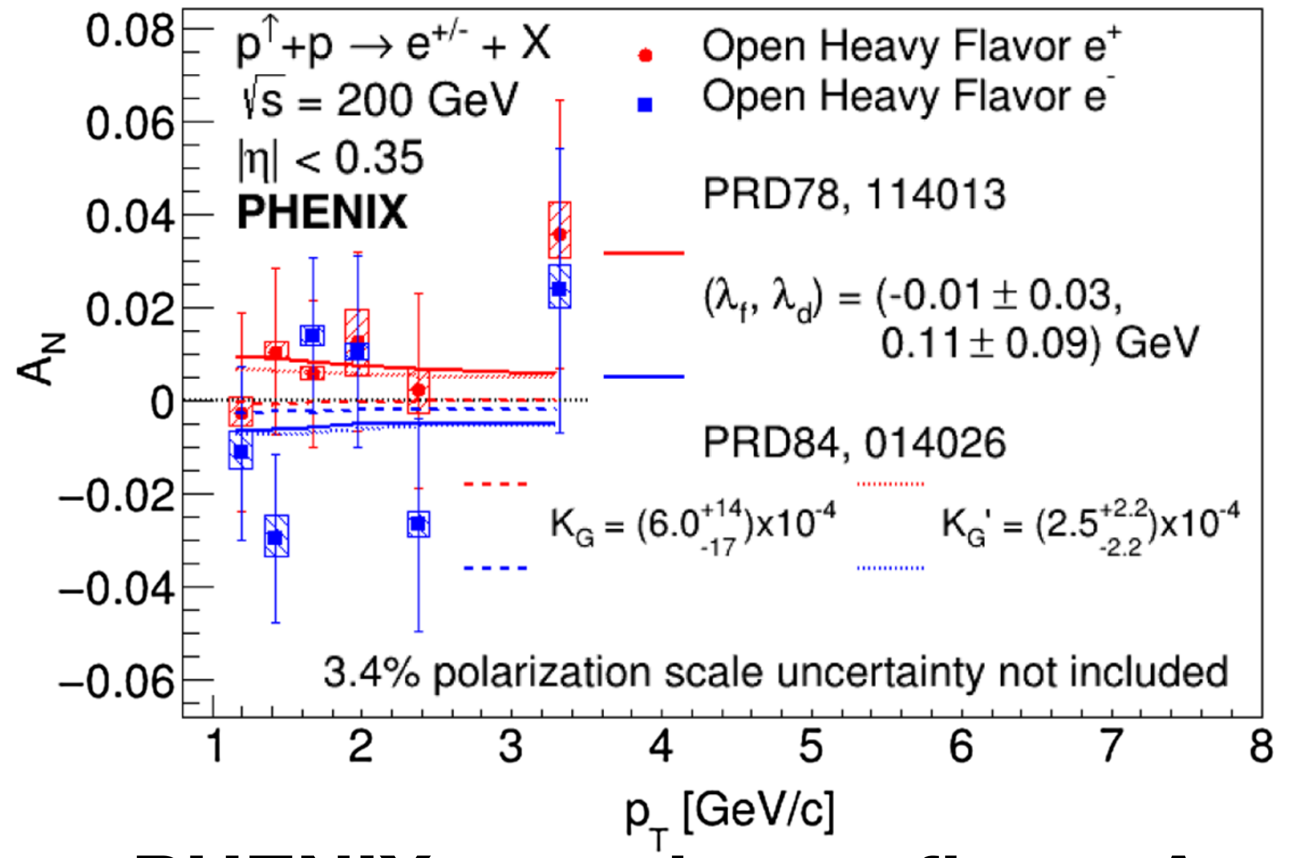
PRL 127 (2021) 162001

sPHENIX Cold-QCD Program

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

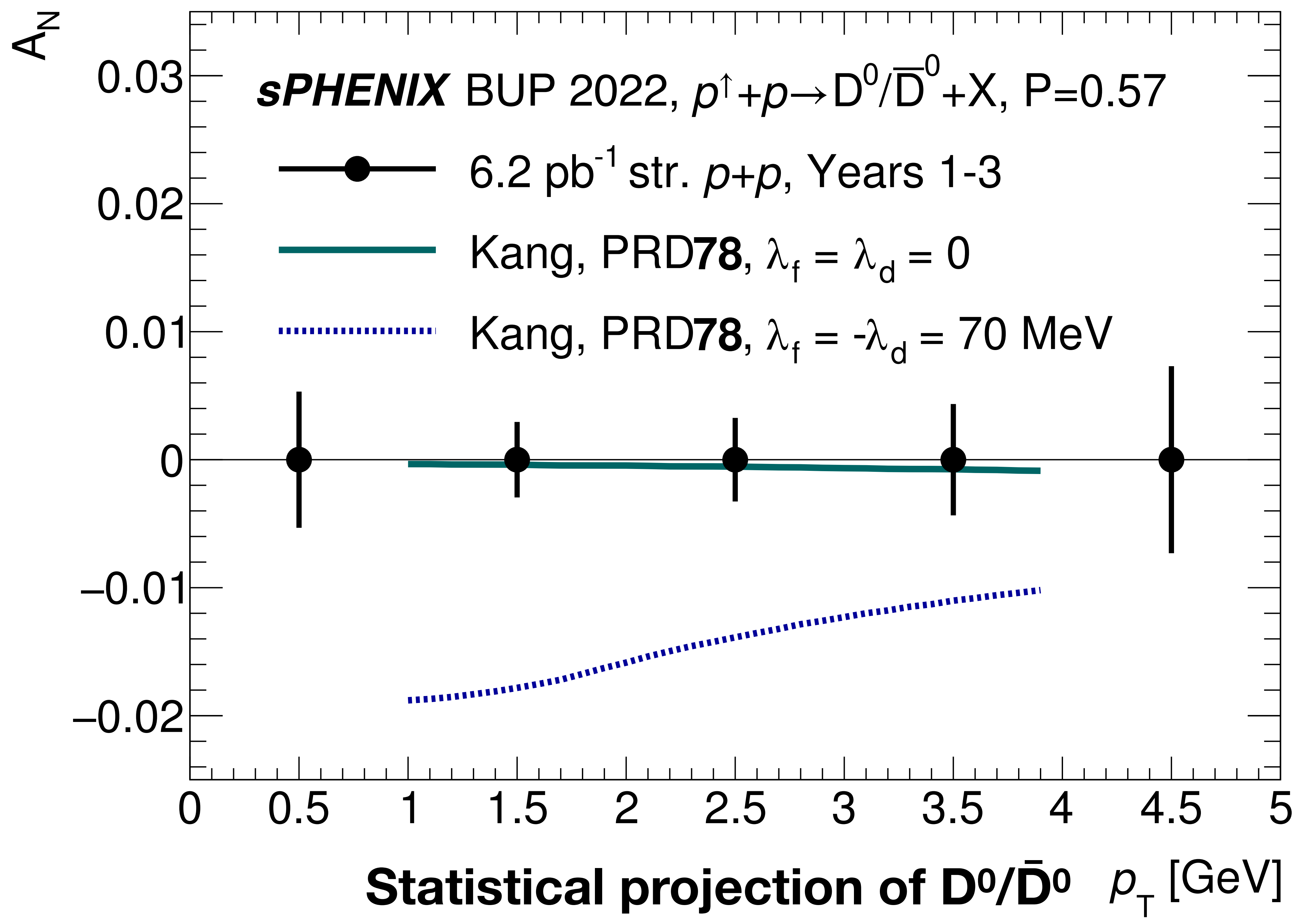
Prompt D⁰ $p^{\uparrow} + p \rightarrow D^0/\bar{D}^0 + X$

PRD 107(2023) 052012



PHENIX open heavy flavor A_N measurement.

- 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 D⁰.
- The sPHENIX streaming readout necessary for D⁰ measurements.



Statistical projection of D⁰/D̄⁰ measurement at sPHENIX.

sPHENIX Cold-QCD Program

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.

sPHENIX Cold-QCD Program

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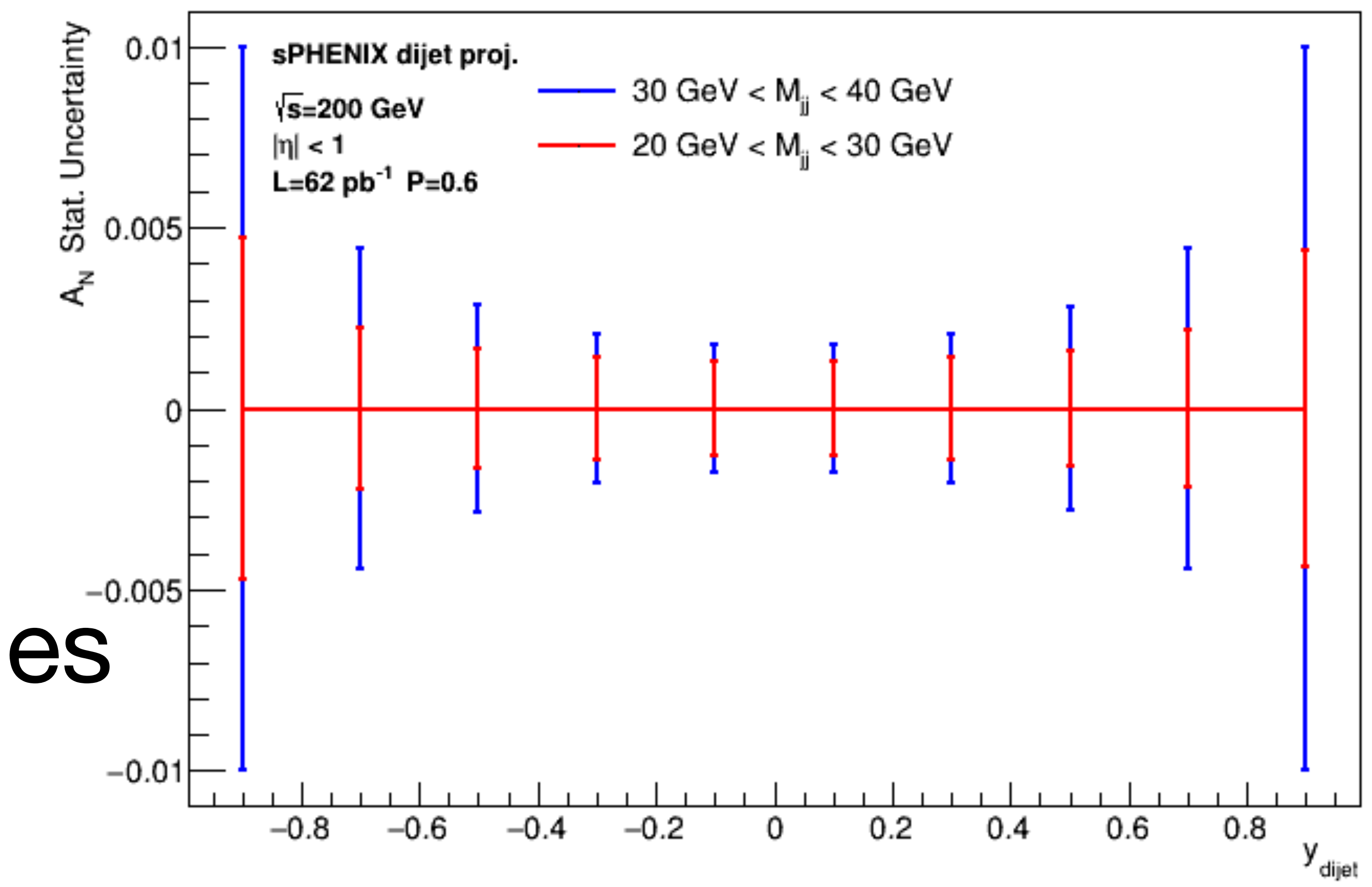
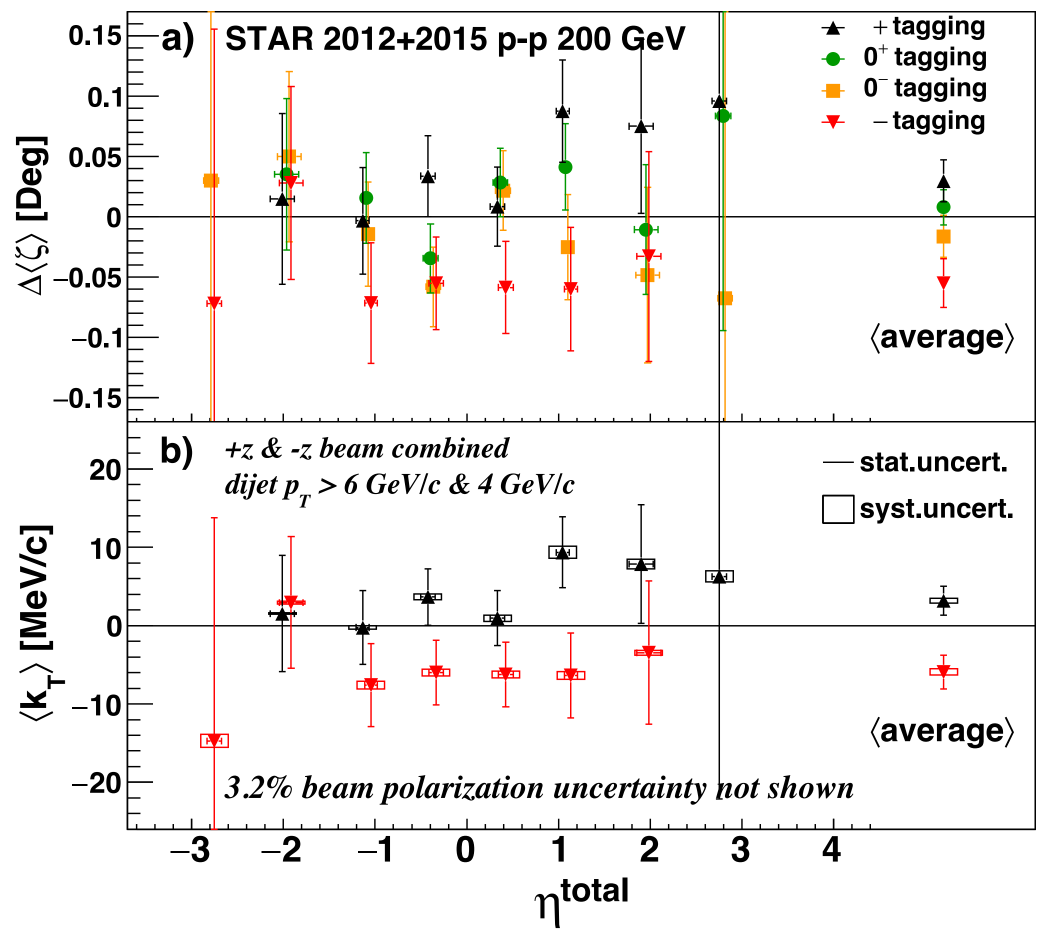
Dijet $p^{\uparrow} + p \rightarrow \text{jet} + \text{jet} + X$

- 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.



Statistical projection of dijet measurement at sPHENIX.



Dijet TSSA by STAR (arXiv:2305.10359)

sPHENIX Cold-QCD Program

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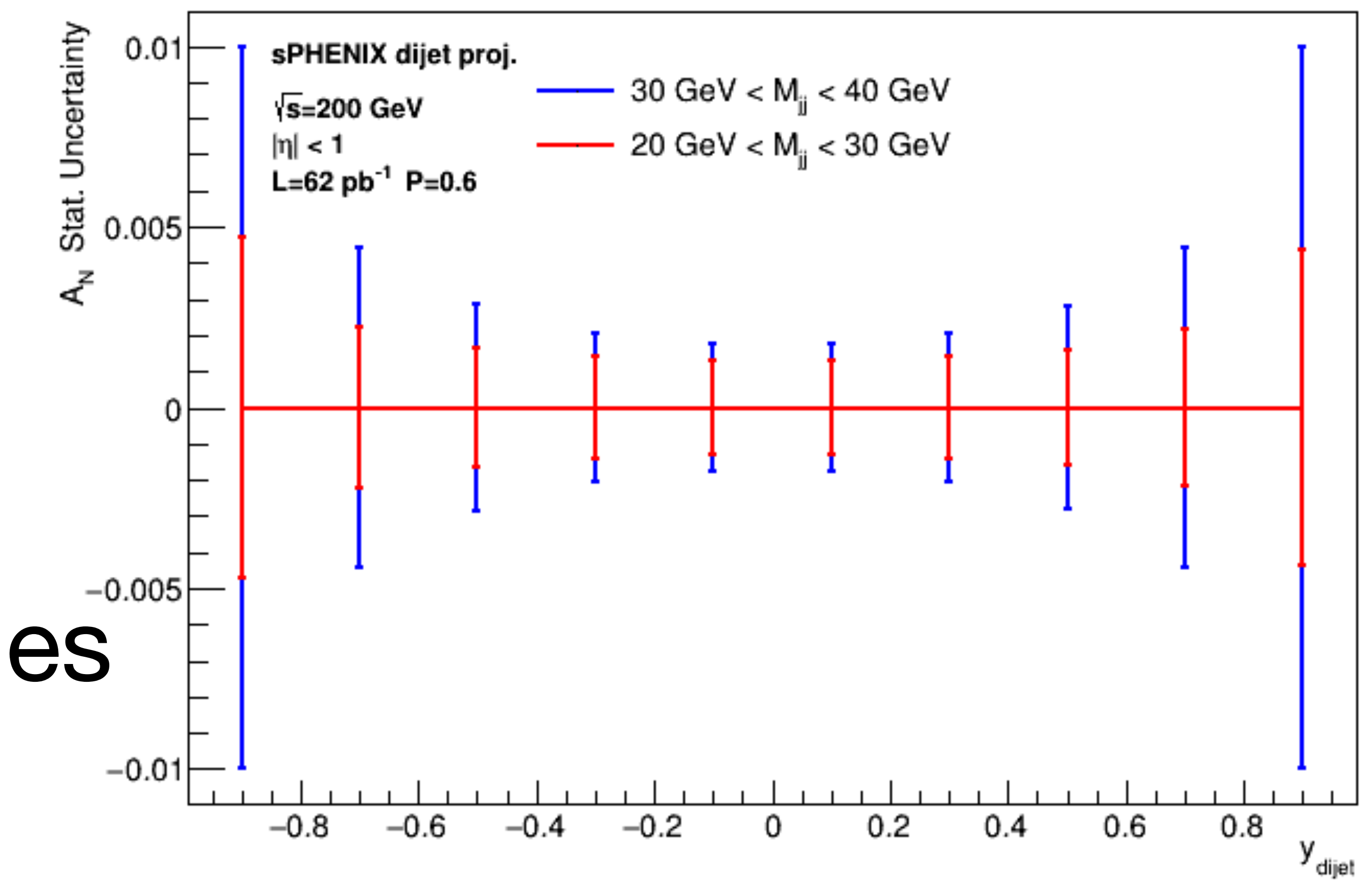
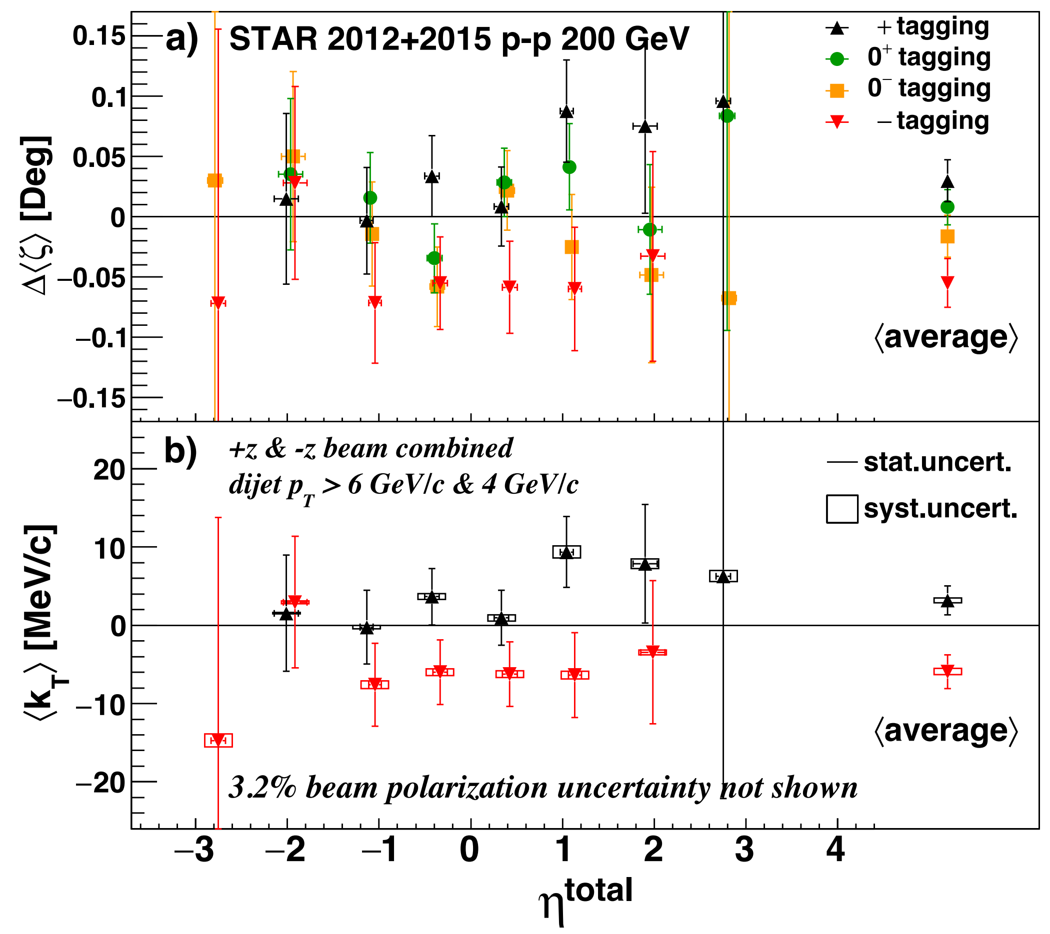
γ-Jet $p^{\uparrow} + p \rightarrow \gamma + \mathrm{jet} + X$

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

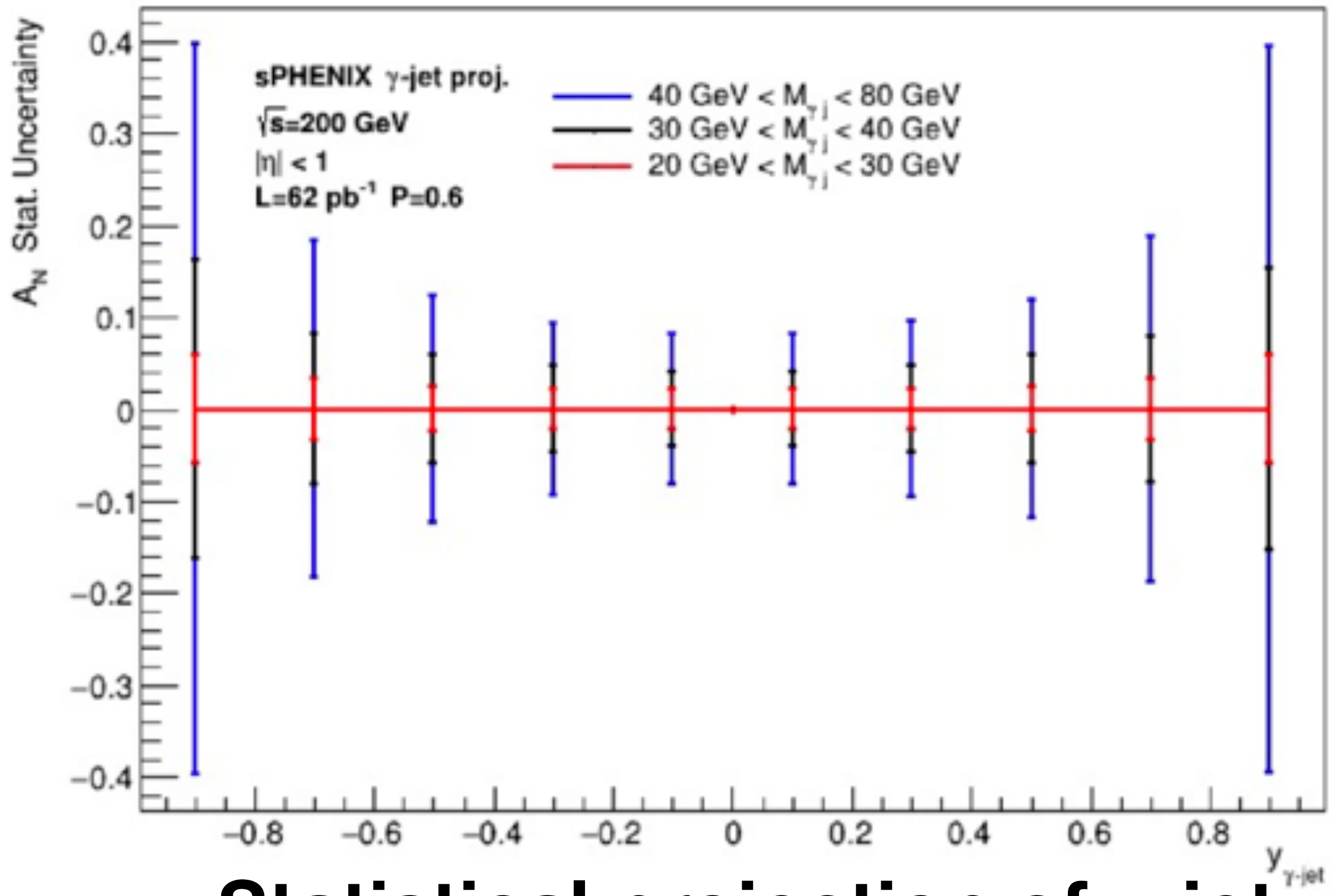


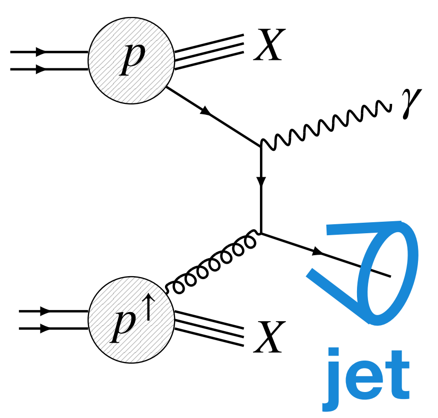
Statistical projection of dijet measurement at sPHENIX.



Dijet TSSA by STAR

(arXiv:2305.10359)





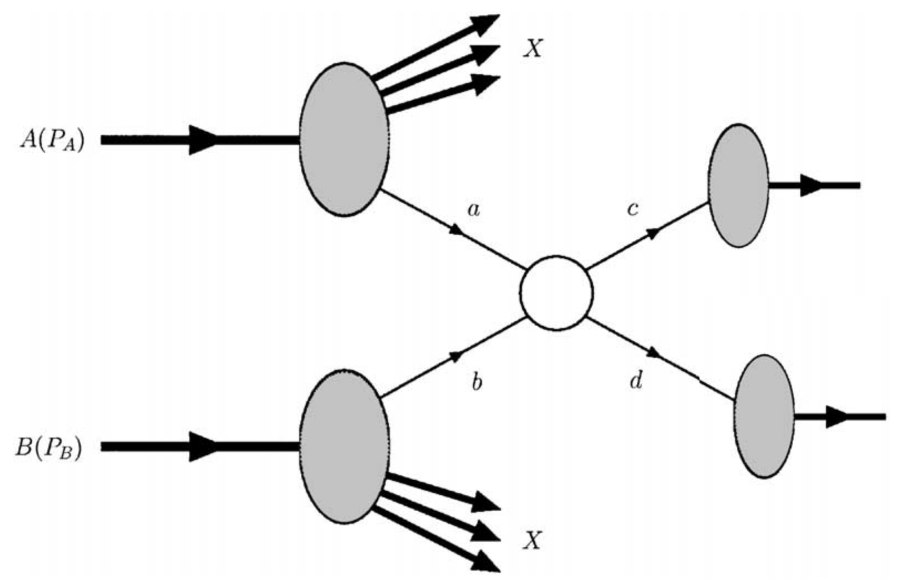
Statistical projection of γ-jet measurement at sPHENIX.

sPHENIX Cold-QCD Program

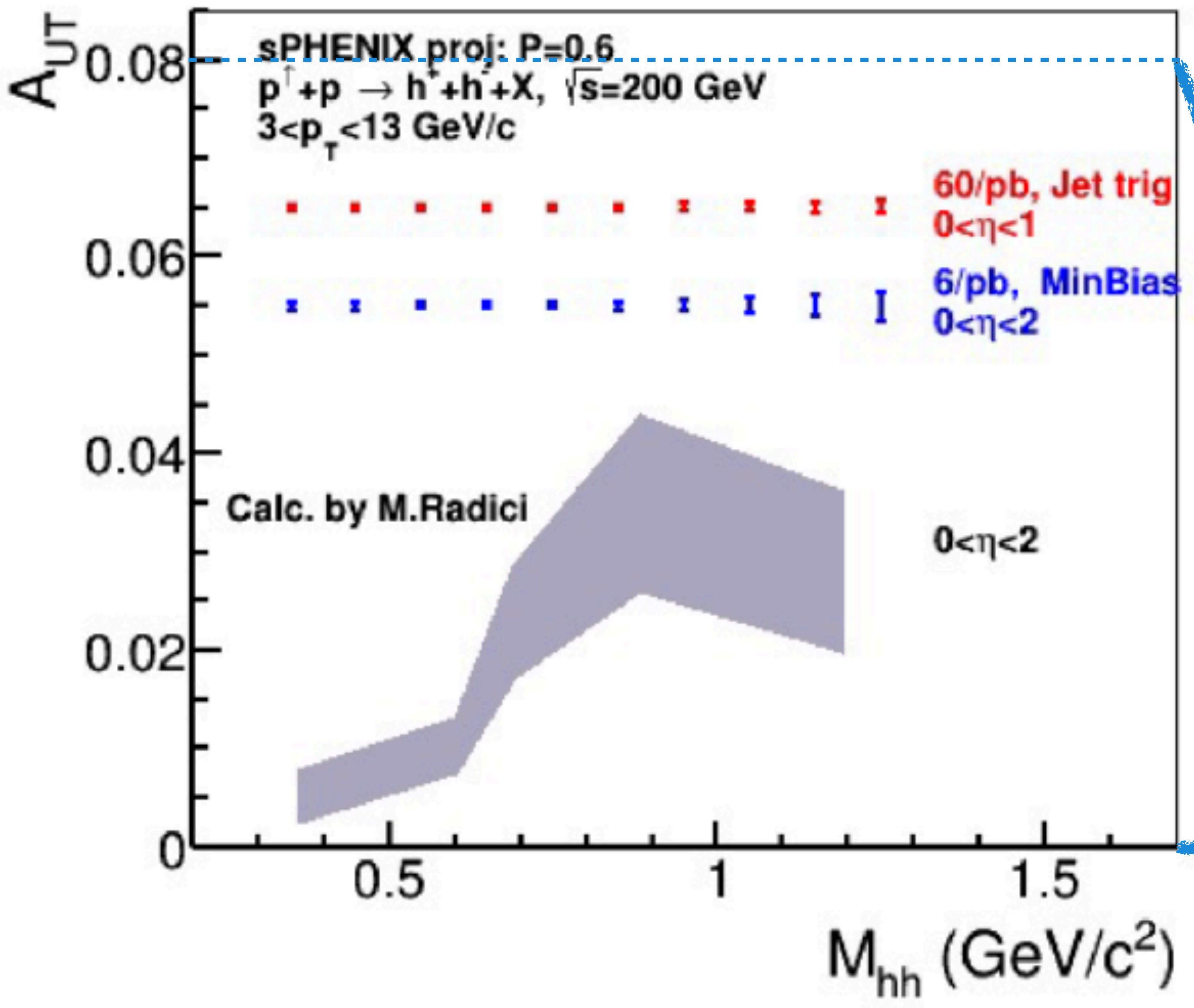
Di-hadron $p^{\uparrow} + p \rightarrow \mathrm{h}^{+} + \mathrm{h}^{-} + X$

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

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

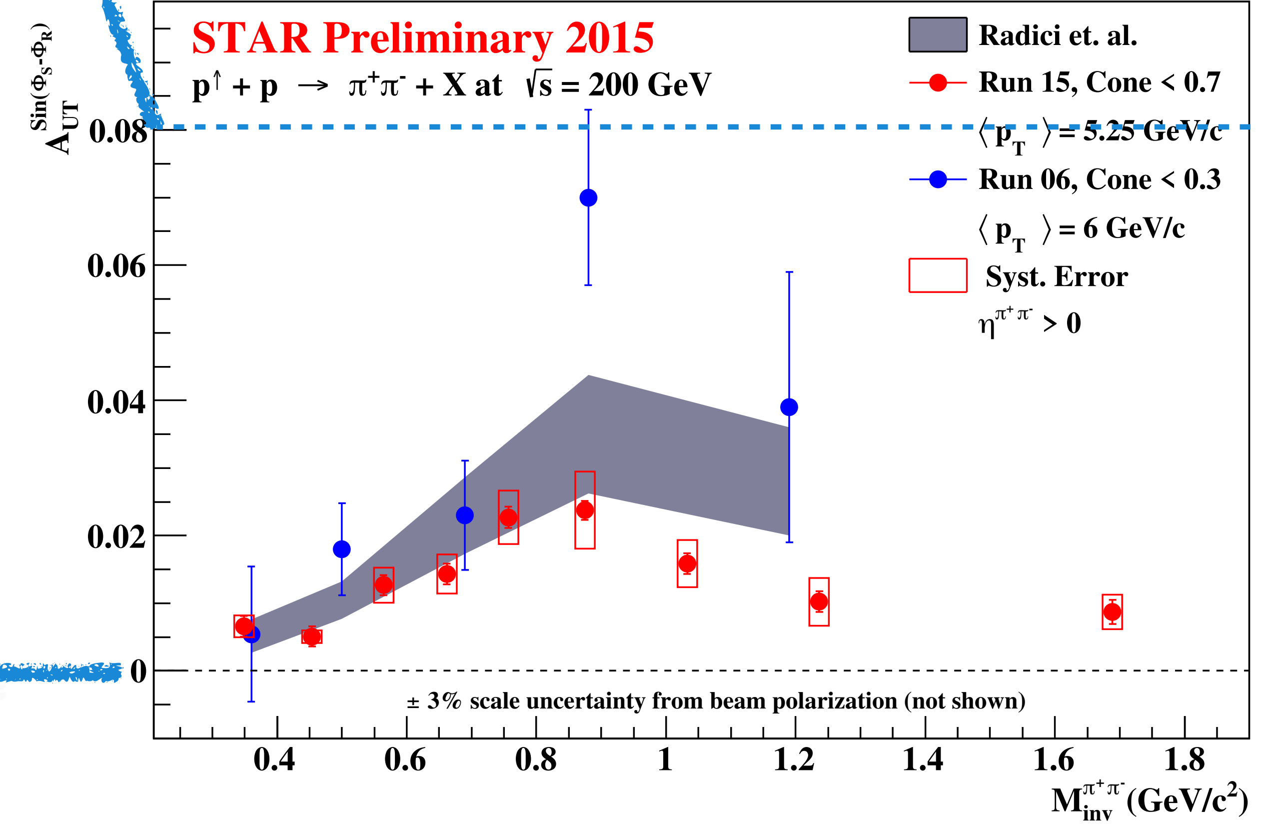


- The results from STAR agree with the theoretical prediction using SIDIS and e^+e^- data within statistical uncertainty.



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

JPS Conf. Proc. 37(2033) 020121



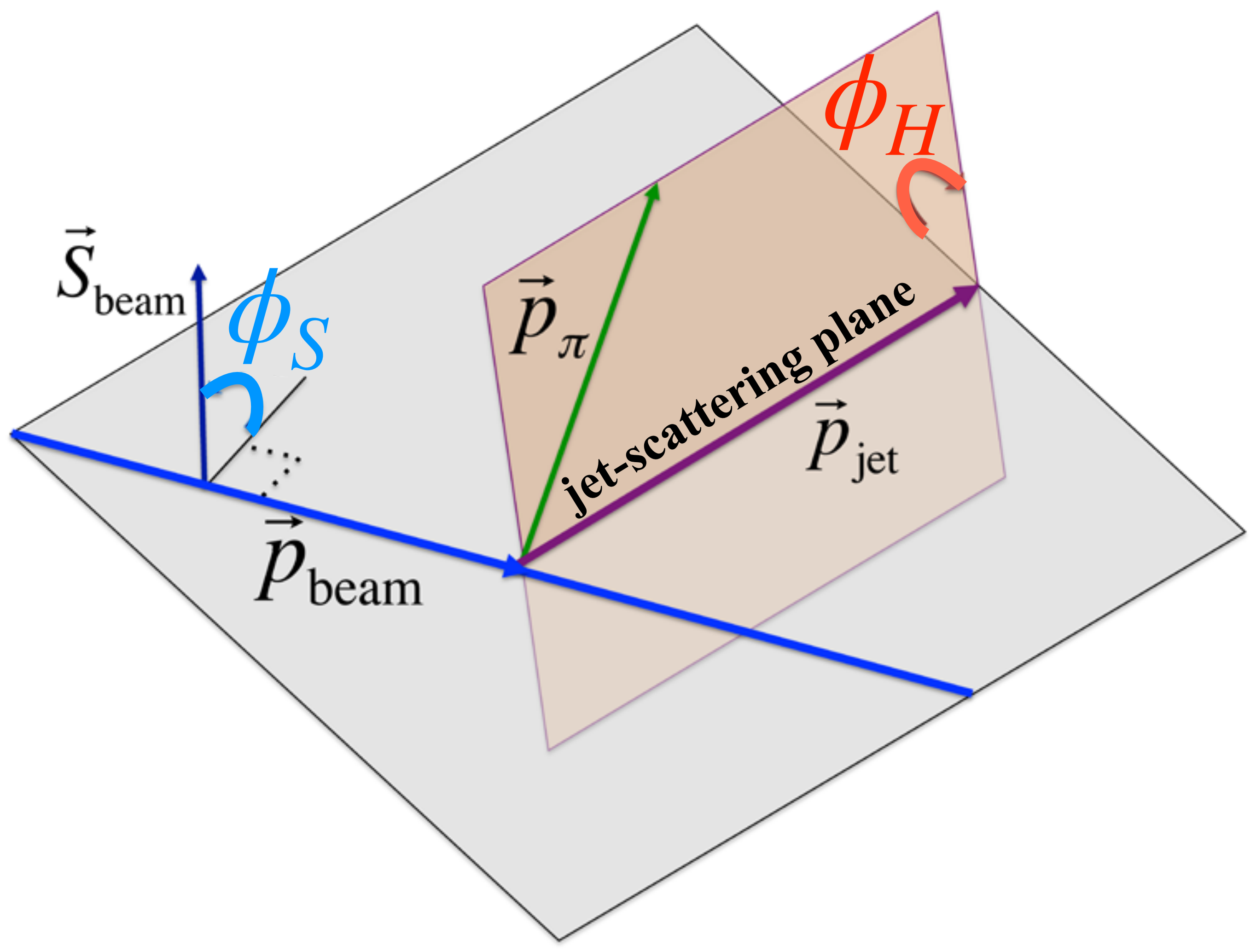
Di-pion TSSA from STAR. $A_{UT}^{\sin(\phi_S-\phi_R)}$

- sPHENIX can extract it with great statistical uncertainty.

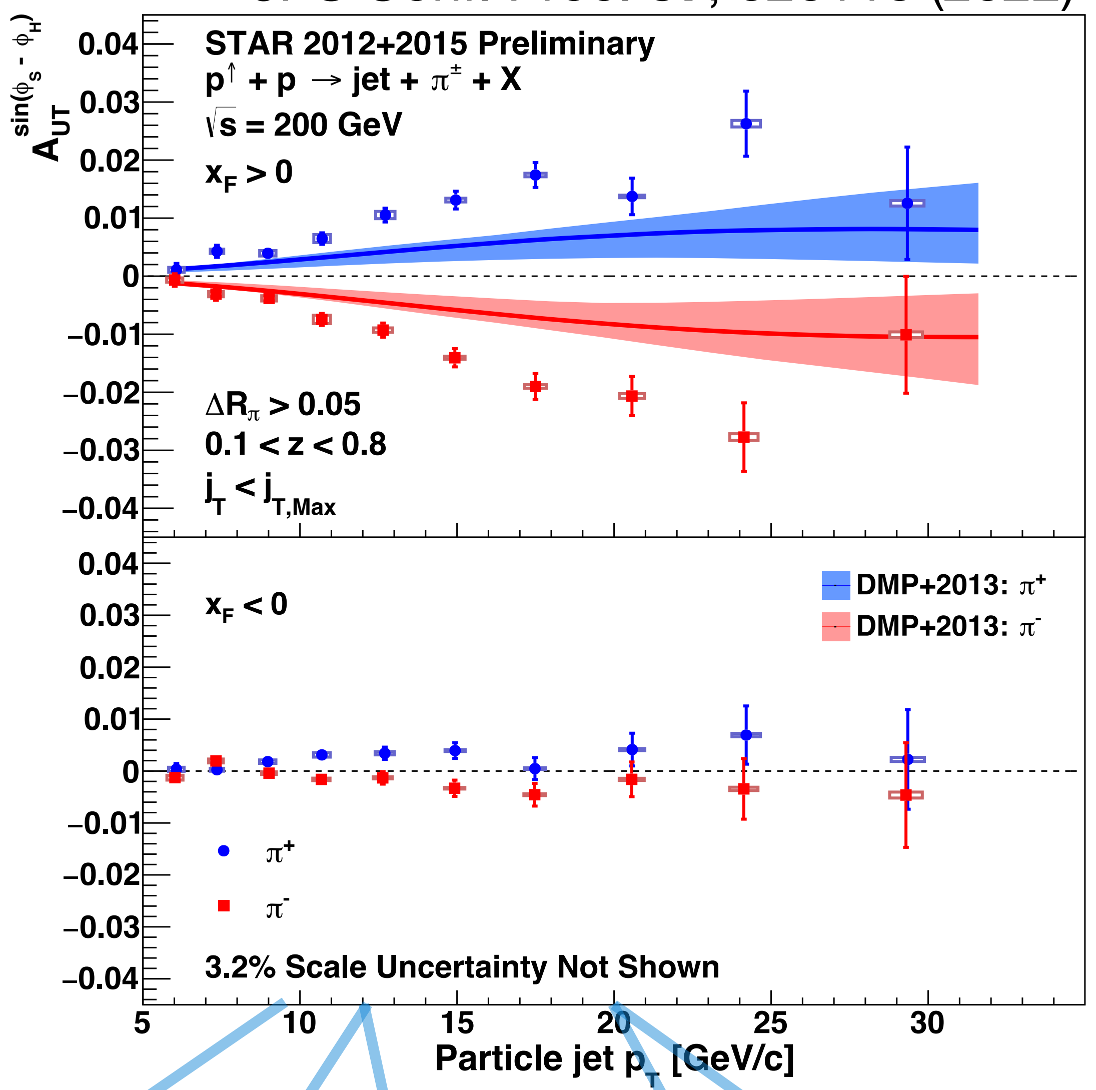
sPHENIX Cold-QCD Program

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

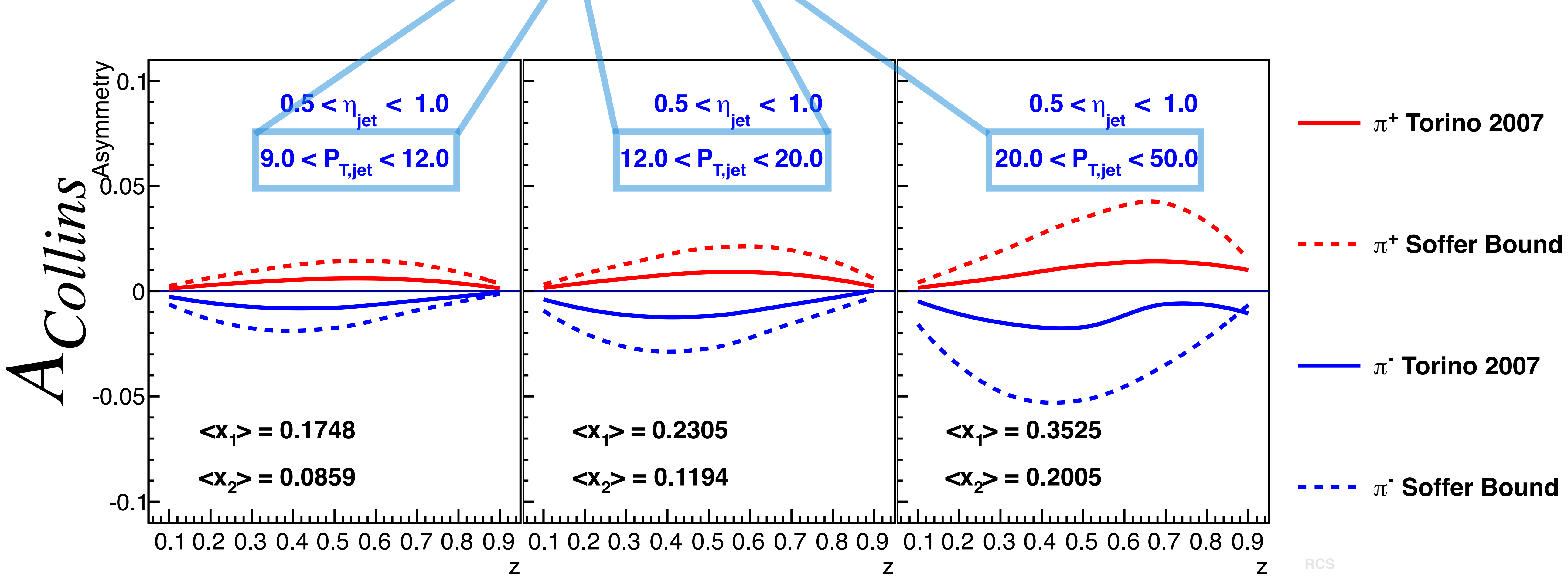
- Collins effect: the correlation of **transverse spin of a quark** and **the momentum of a hadron fragment** transverse to the scattered quark direction
- Collins asymmetry $A_{UT}^{\sin(\phi_S - \phi_H)}$ is related to Transversity PDF and Collins FF.



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



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

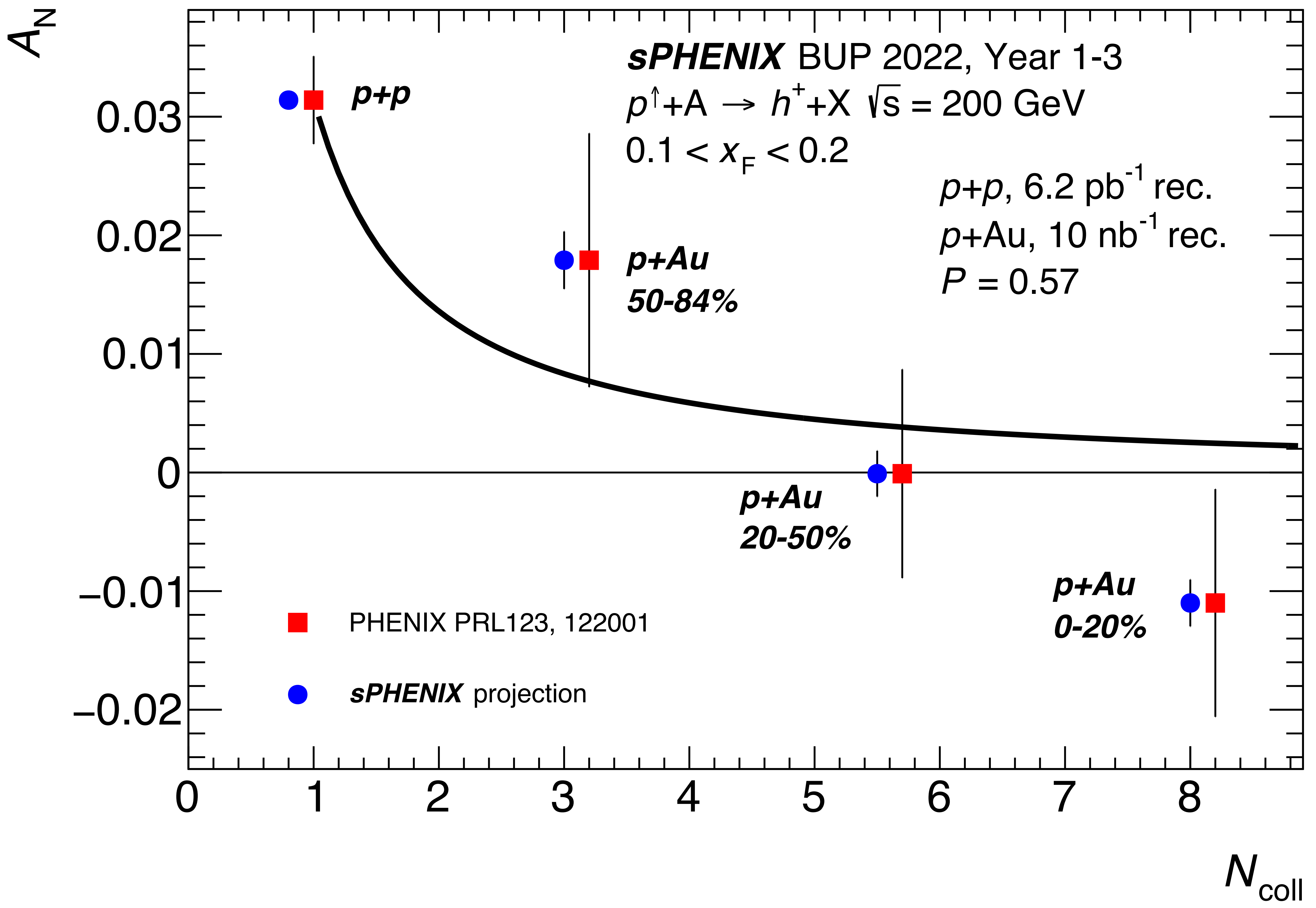


Range of expected Collins asymmetry in sPHENIX kinematics.

sPHENIX Cold-QCD Program

Nuclear Dependence

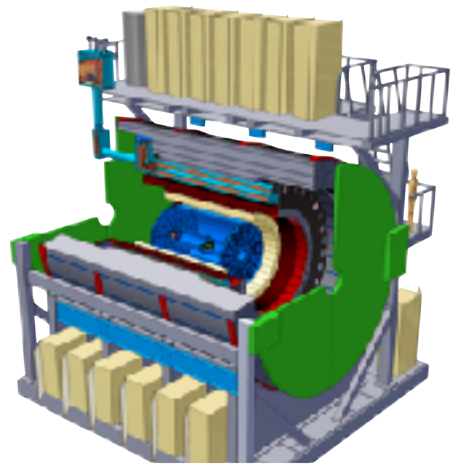
- A_N from $p^{\uparrow}$ + p, $p^{\uparrow}$ + Al, and $p^{\uparrow}$ + Au from RHIC:
  - PHENIX: **Strong nuclear dependency in A_N** for h^+ in the intermediate rapidity range (with $0.1 < x_F < 0.2$).
  - STAR: no significant nuclear dependence in A_N for π^0 in forward rapidity (with $0.2 < x_F < 0.7$).
- No clear explanation at the moment.
- sPHENIX is able to collect much more data in this channel with fine binning.



Statistical projection of A_N from p + p or p + Au at sPHENIX.

Those are a just part of the topics!!

Construction of sPHENIX

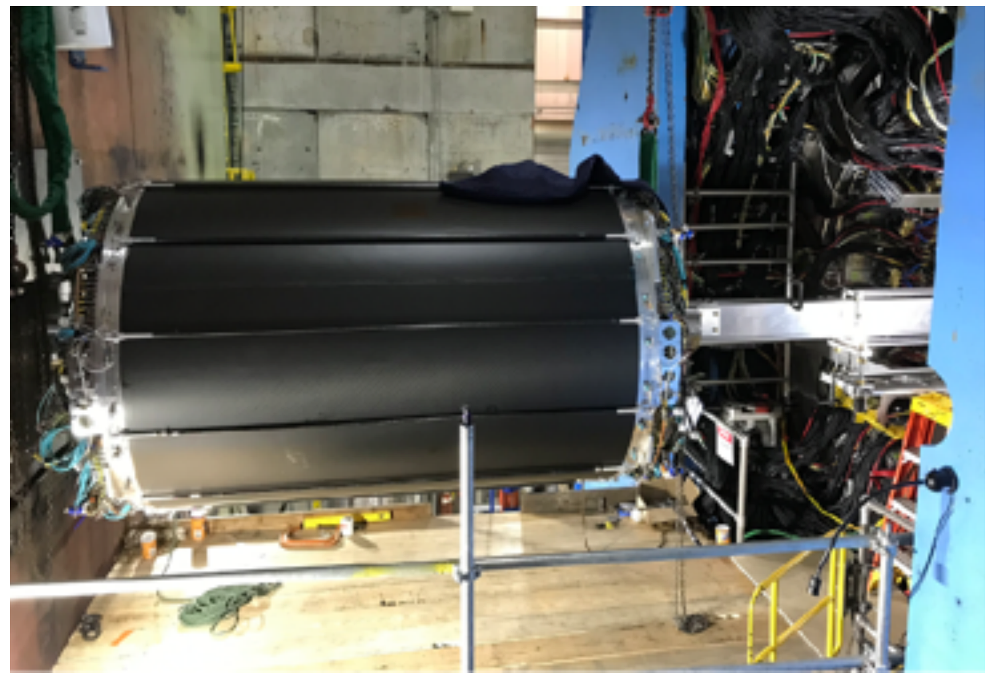


2021/10 Magnet

2022/05 Outer HCAL

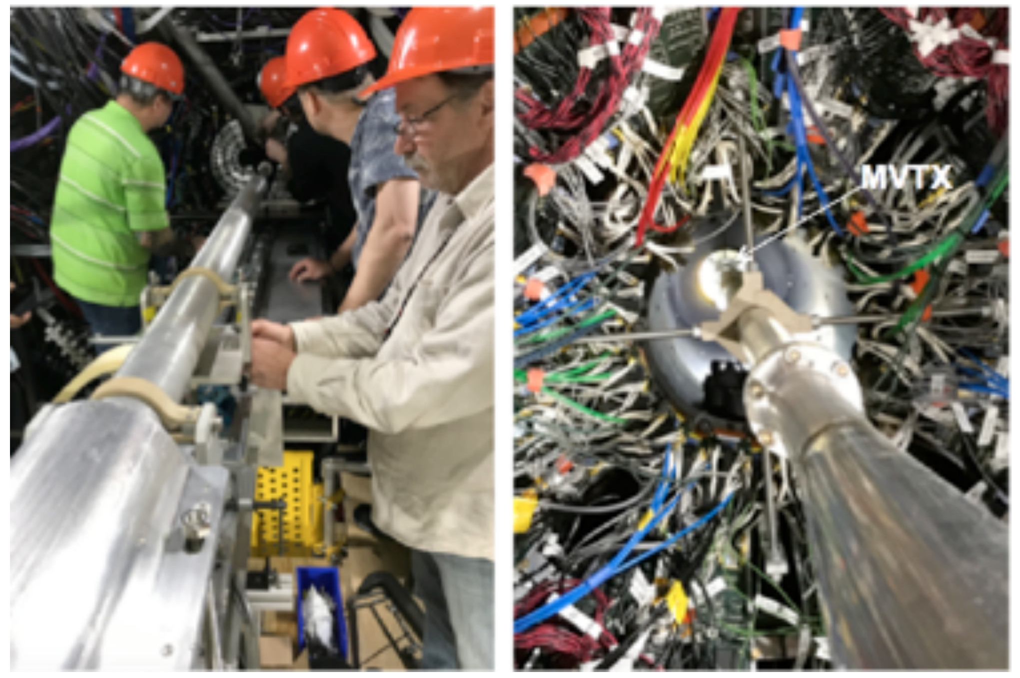
2022/06 Inner HCAL

2022/11 EMCAL

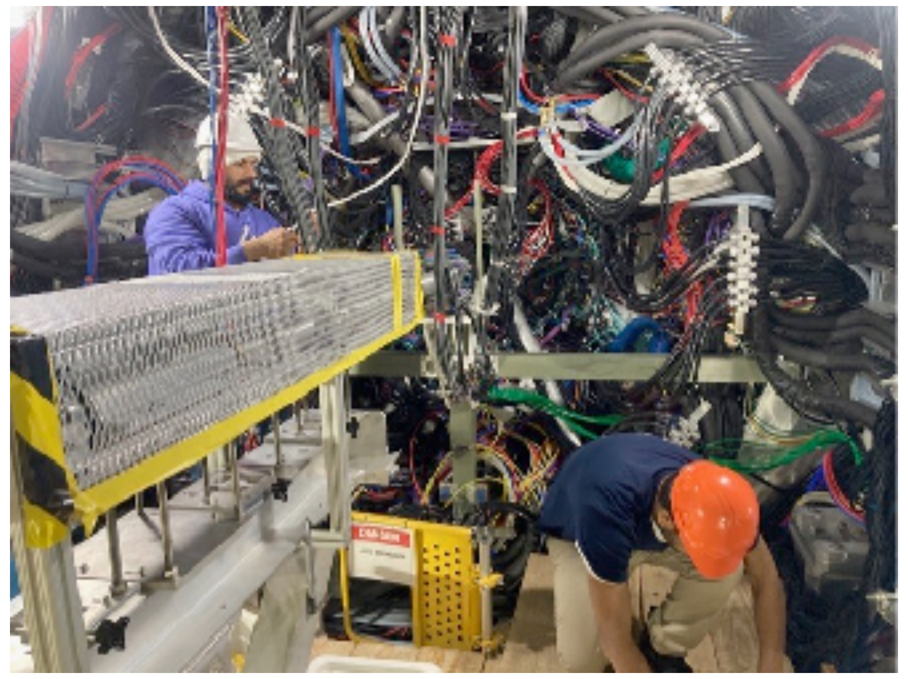


2023/01 TPC

2023/03 INTT



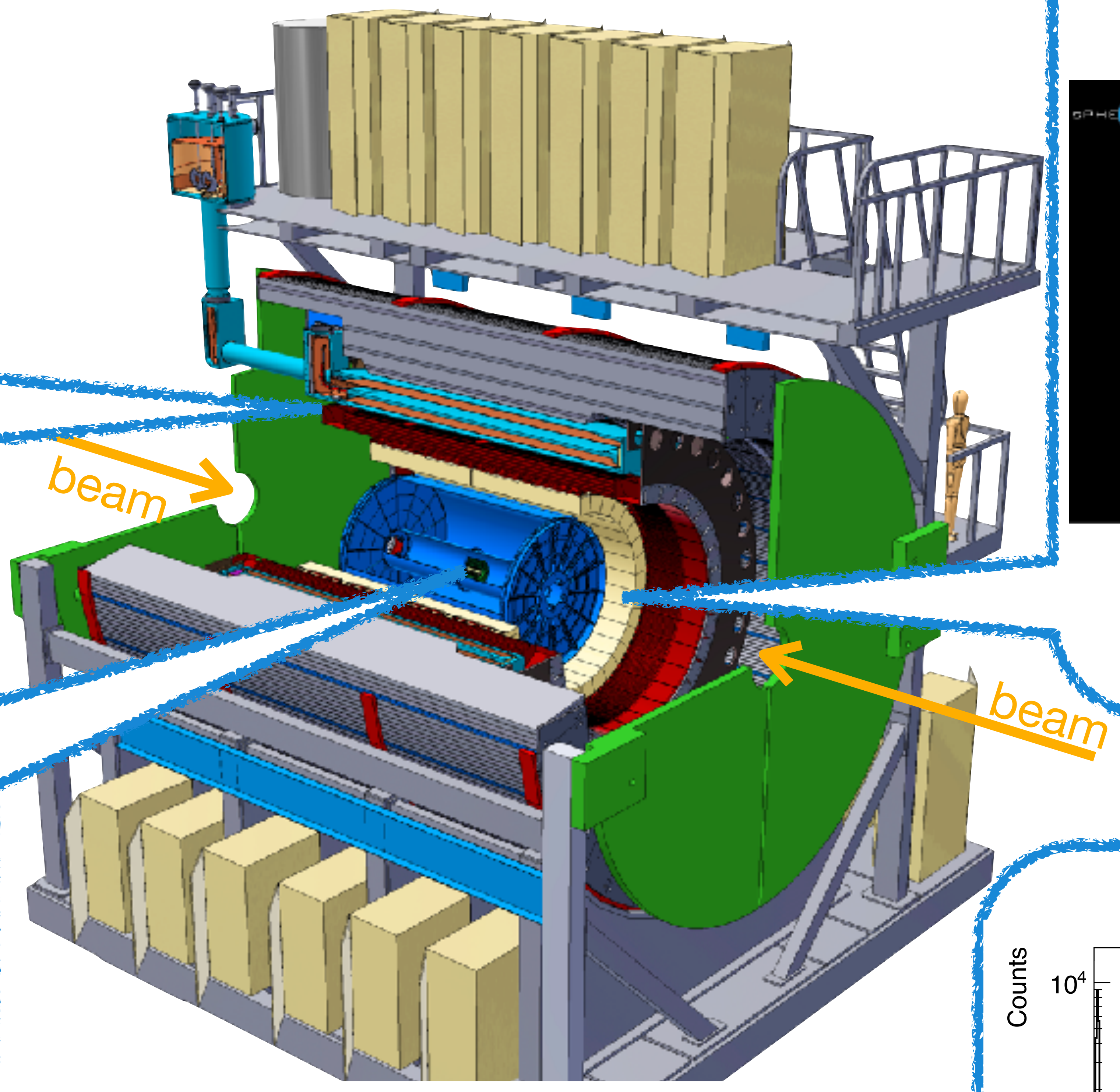
2023/03 MVTX



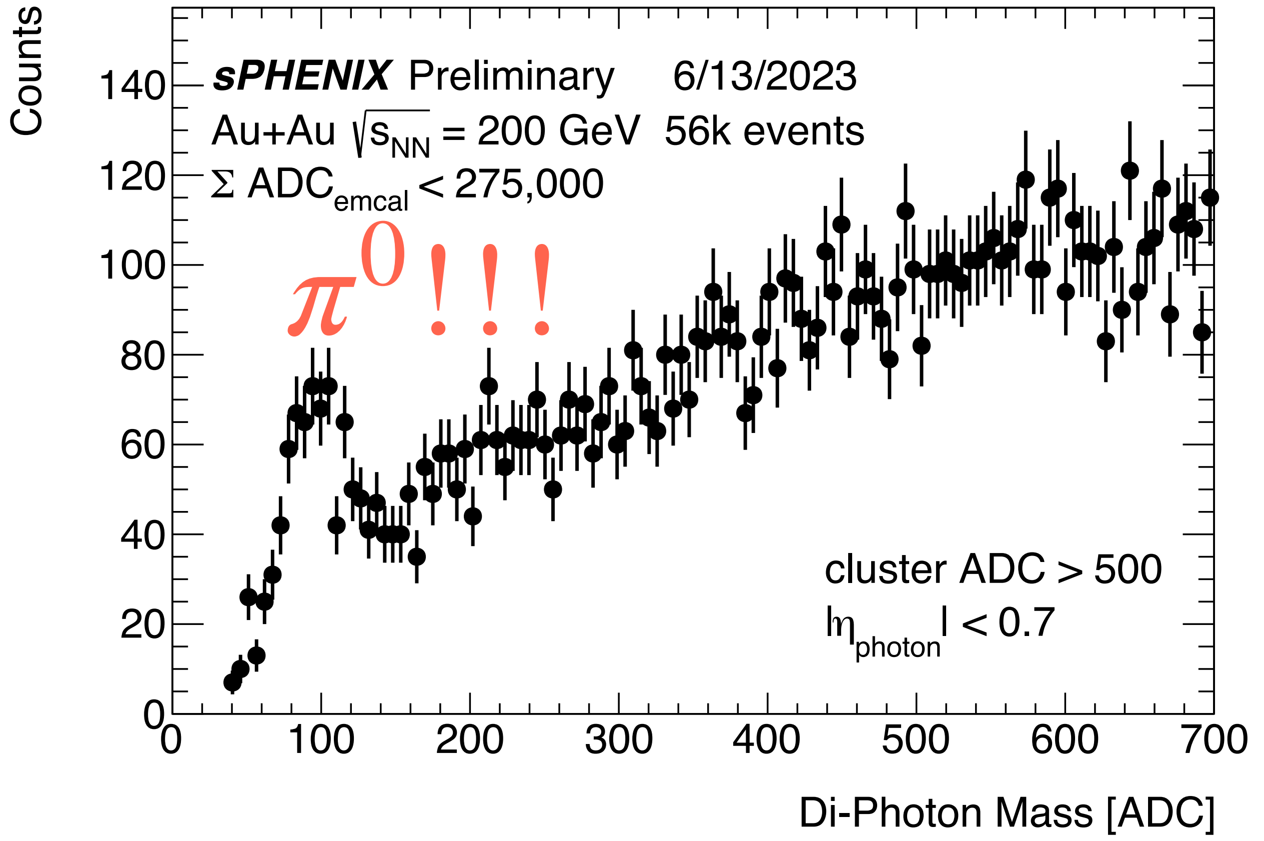
2023/04 MBD

The first beam came in 2023/May!!!

sPHENIX Today

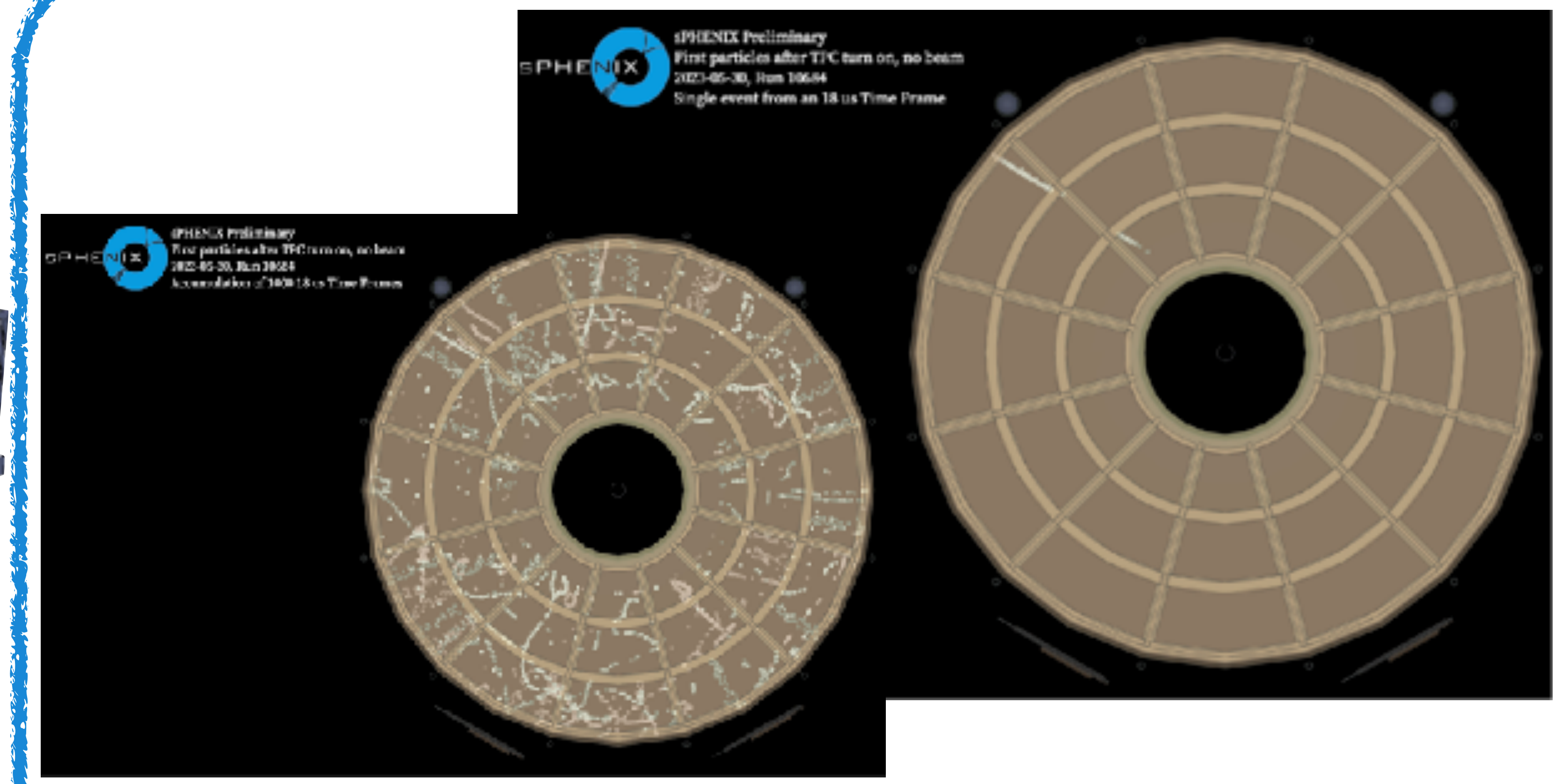


EMcal



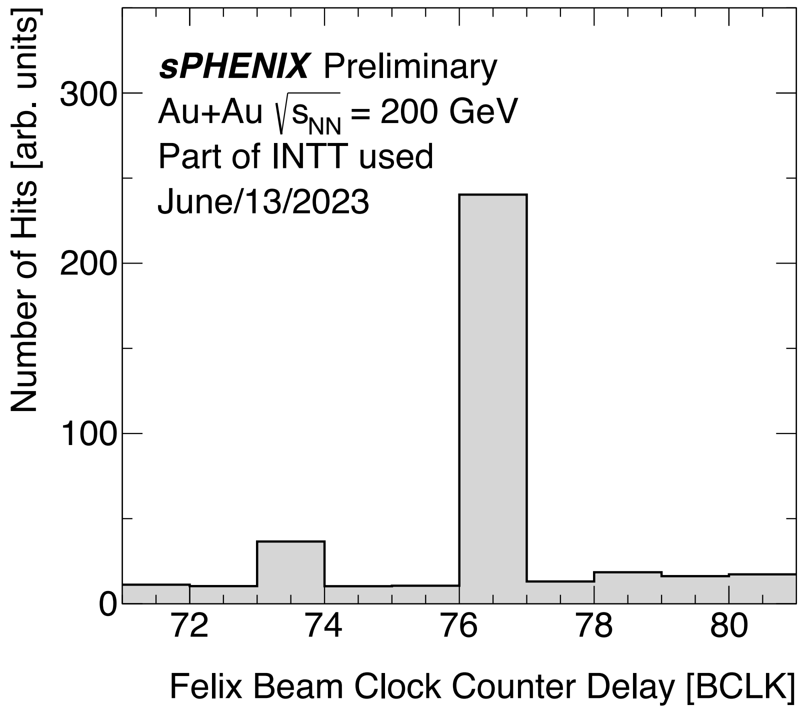
Peak by π0 decay
in di-photon mass distribution!

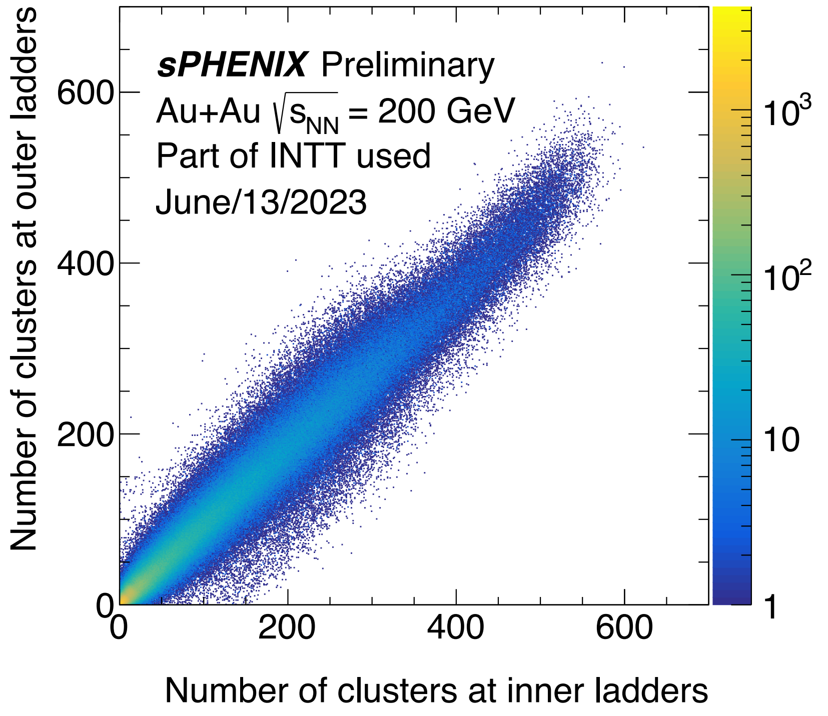
TPC



Event displays of accumulated events (left) and a single track (right).

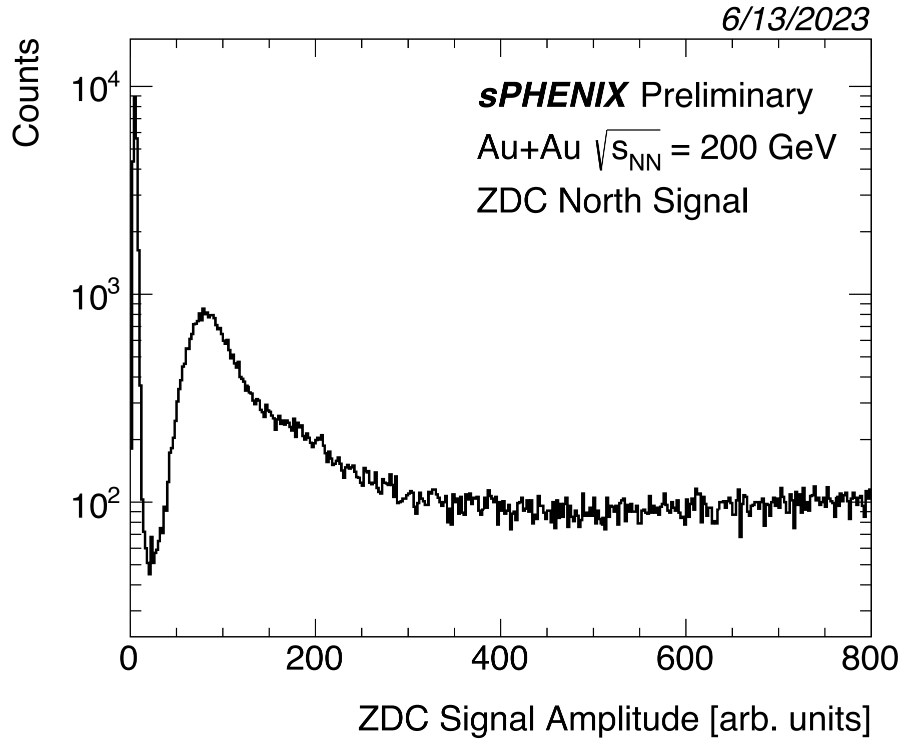
INTT

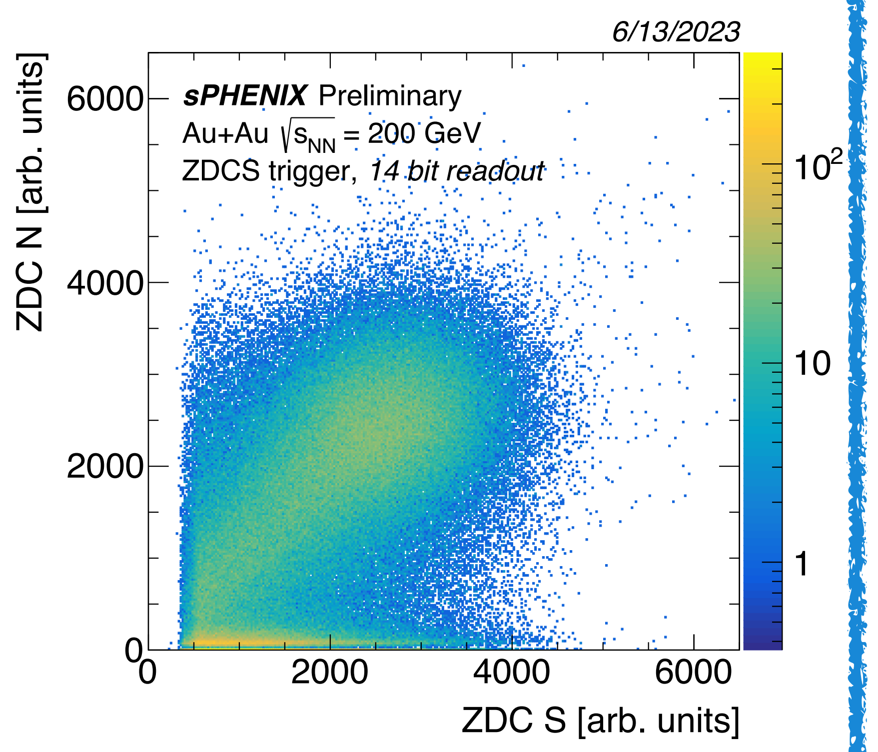




Left: High hit rate by beam-beam collisions
means successful tuning of timing.
Right: Hit rate correlation in the barrels.

ZDC





Neutron peaks in ADC distribution.
Correlation b/w the North and the South parts.

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 $p^{\uparrow} + p^{\uparrow}$ and $p^{\uparrow}$ + Au collisions in 2024 enables us to study
  - Tri-gluon correlator
  - Sivers TMD PDF, Transversity PDF
  - Collins FF, Interference FF
  - Nuclear modification , nuclear PDF,
  - etc.
- The construction was finished. Beam came from 2023/May.
- We are now in the commissioning phase.

STAY TUNED

BACKUP SLIDES

sPHENIX Runs

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z \rvert < 10$ cm	Samp. Lum. $\lvert z \rvert < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-str]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-str]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

sPHENIX Runs

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| < 10$ cm	Samp. Lum. $\|z\| < 10$ cm
2026	$p^{\uparrow}p^{\uparrow}$	200	28	15.5	1.0 pb^{-1} [10 kHz] 80 pb^{-1} [100%-*str*]	80 pb^{-1}
–	O+O	200	–	2	18 nb^{-1} 37 nb^{-1} [100%-*str*]	37 nb^{-1}
–	Ar+Ar	200	–	2	6 nb^{-1} 12 nb^{-1} [100%-*str*]	12 nb^{-1}
2027	Au+Au	200	28	24.5	30 nb^{-1} [100%-*str*/DeMux]	30 nb^{-1}