Workshop Summary:
Cold QCD, Spin Physics, & UPCs from RHIC to the EIC

June 11, 2024
2024 RHIC-AGS Users Meeting

Organizers:
Jae Nam (Temple University),
SookHyun Lee (UTK),
Daniel Brandenburg (OSU)

In part supported by
U.S. DEPARTMENT OF ENERGY

STAR Foward Systems and Related Topics

Xilin Liang, for the STAR Collaboration

University of California, Riverside

2024 RHIC/AGS ANNUAL USERS' MEETING
Brookhaven National Lab
June 11, 2024

Supported in part by

UC RIVERSIDE STAR U.S. DEPARTMENT OF ENERGY

Dihadron helicity correlatio

Shu-Yi Wei (Shandong University)
shuyi@sdu.edu.cn

H.C. Zhang, S.Y. Wei; PLB 839, 137821 (2023)
X.W. Li, Z.X. Chen, S. Cao, S.Y. Wei, PRD 109, 014035 (2024)
Z.X. Chen, H. Dong, S.Y. Wei, arXiv:2404.19202 (2024)

STAR Brookhaven National Laboratory U.S. DEPARTMENT OF ENERGY Office of Science

Measurement of Λ hyperon polarization and spin-spin correlations in p+p collisions by the STAR experiment

Jan Vanek, for the STAR Collaboration
Brookhaven National Laboratory
AGS/RHIC Annual Users' Meeting
06/11/2024

Highlights from PHENIX Spin

Devon Loomis on behalf of the PHEN

UNIVERSITY OF MICHIGAN

PHENIX

Jet substructure and transverse energy-energy correlator

Yiyu Zhou
South China Normal University
University of California, Los Angeles

UCLA

Entanglement Enabled Intensity Interferometry (E^2I^2): A New Perspective on Vector Meson Production in UPC

Haowu Duan

University of Connecticut
Work in preparation, with Daniel Brandenburg, Zhoudunming Tu, Raju Venugopalan, Zhangbu Xu

2024 RHIC/AGS Annual Users' Meeting, June 11-14, 2024

Ultraperipheral collisions: new isights on collectivity & baryons

In part supported by U.S. DEPARTMENT OF ENERGY

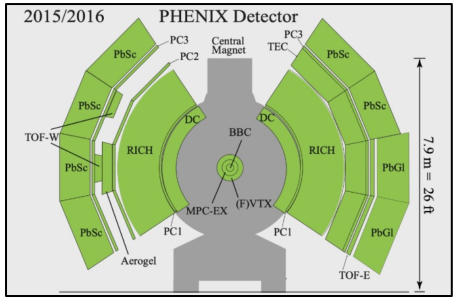
Prithwish Tribedy
(Brookhaven National Laboratory)

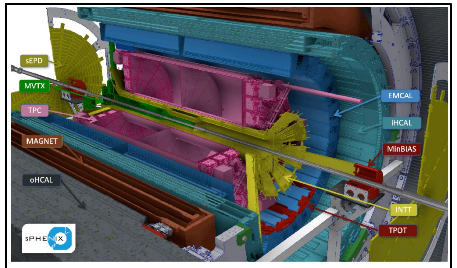
2024 RHIC/AGS Annual Users' Meeting
11/June/2024 – 14/June/2024

Prospects with the sPHENIX

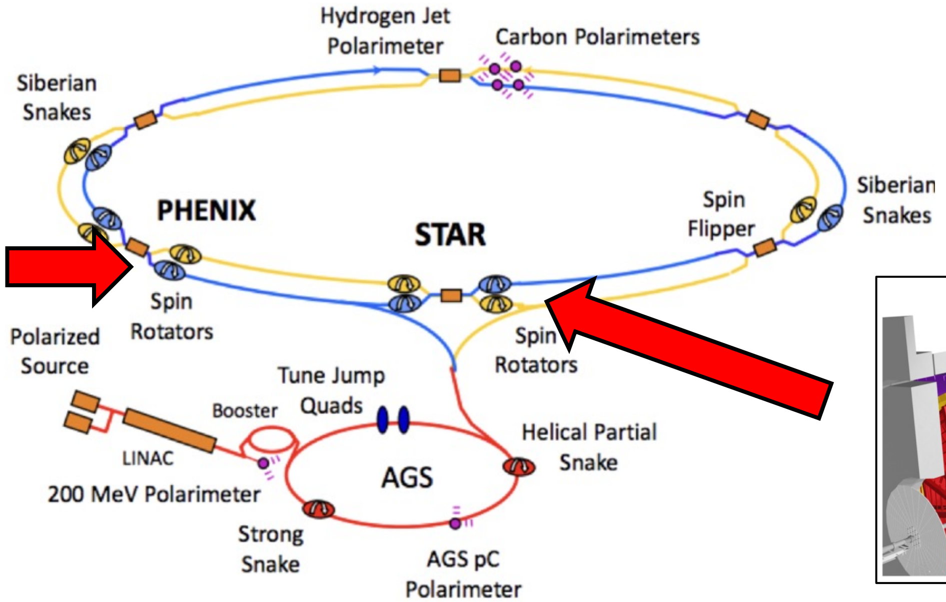
Genki Nukazuka (RIKEN/RBRC)
on behalf of the sPHENIX Collaboration

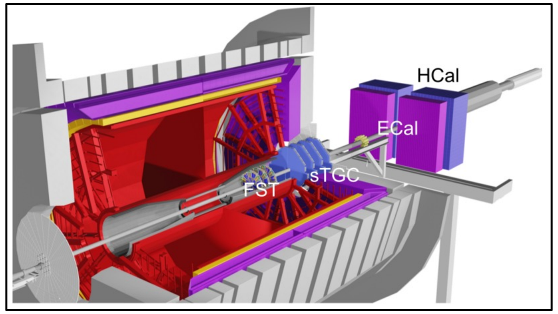
Cold QCD & Spin Physics at RHIC





The sPHENIX detector

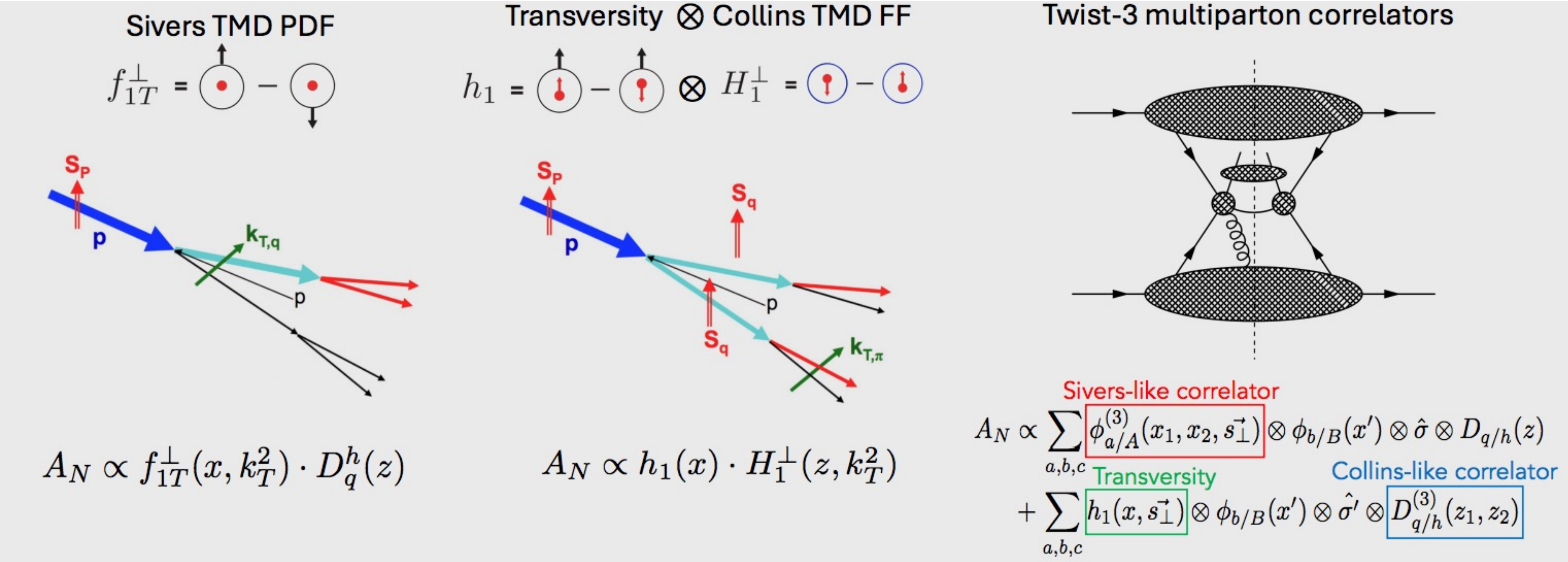




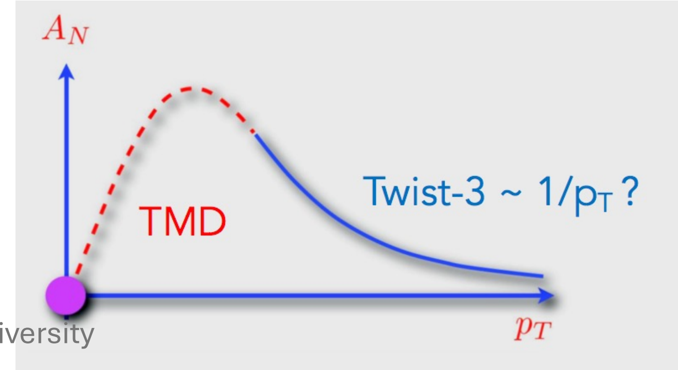
- RHIC provides an ideal testing ground for a wide range of topics in spin physics due to its unique capability of colliding polarized hadrons.
- The workshop discussions include:
  - PHENIX overview
  - sPHENIX prospects
  - STAR forward systems
  - Λ-hyperon theory and experiments

(Transverse) Spin Physics at RHIC

Devon Loomis (Uof Michigan)

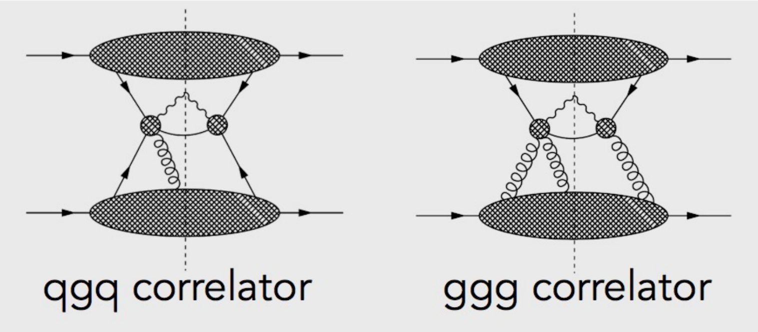


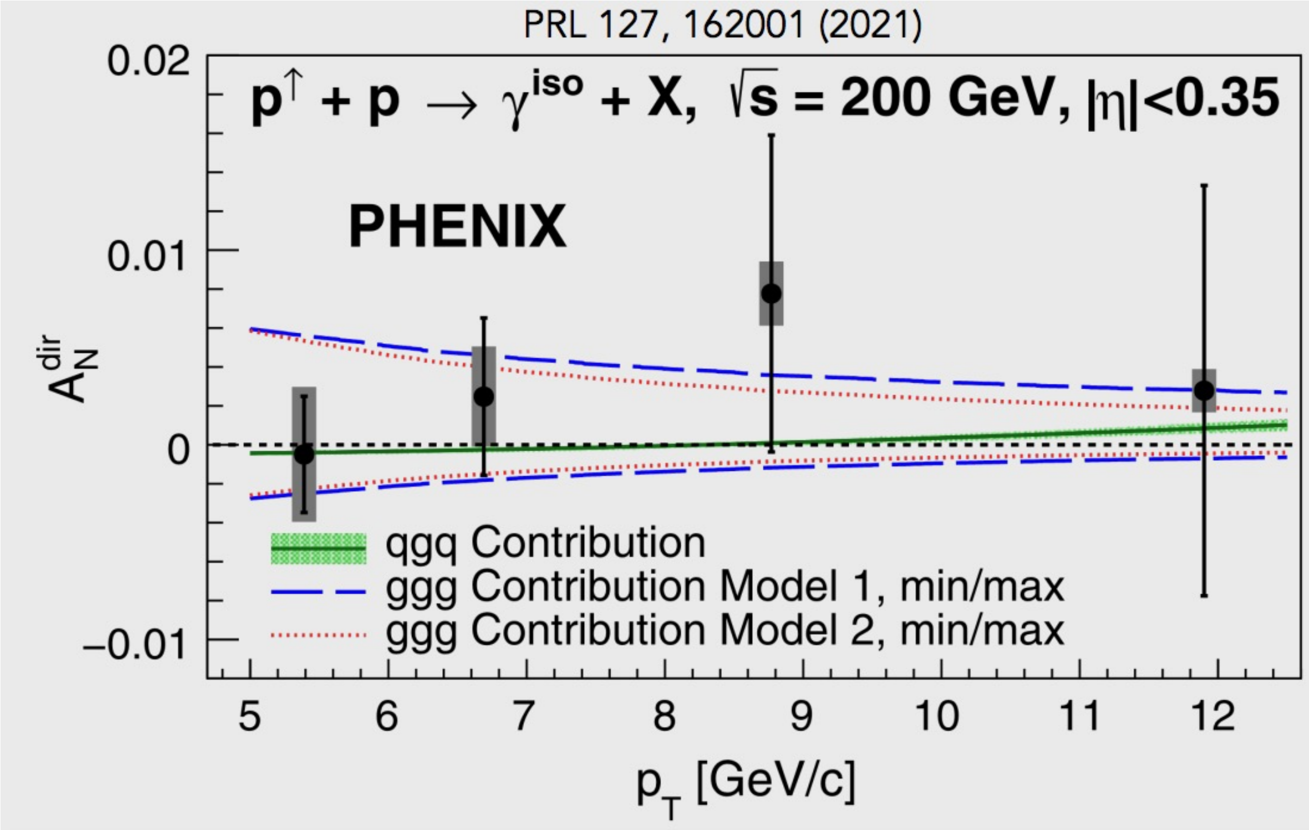
- Leading-twist collinear pQCD predicts $A_N \sim 0$
- Origin of A_N: Non-perturbative spin-momentum correlation
  - Fundamental TMD functions
  - Twist-3 correlators



Direct Photon A_N at PHENIX

Devon Loomis (UofM)



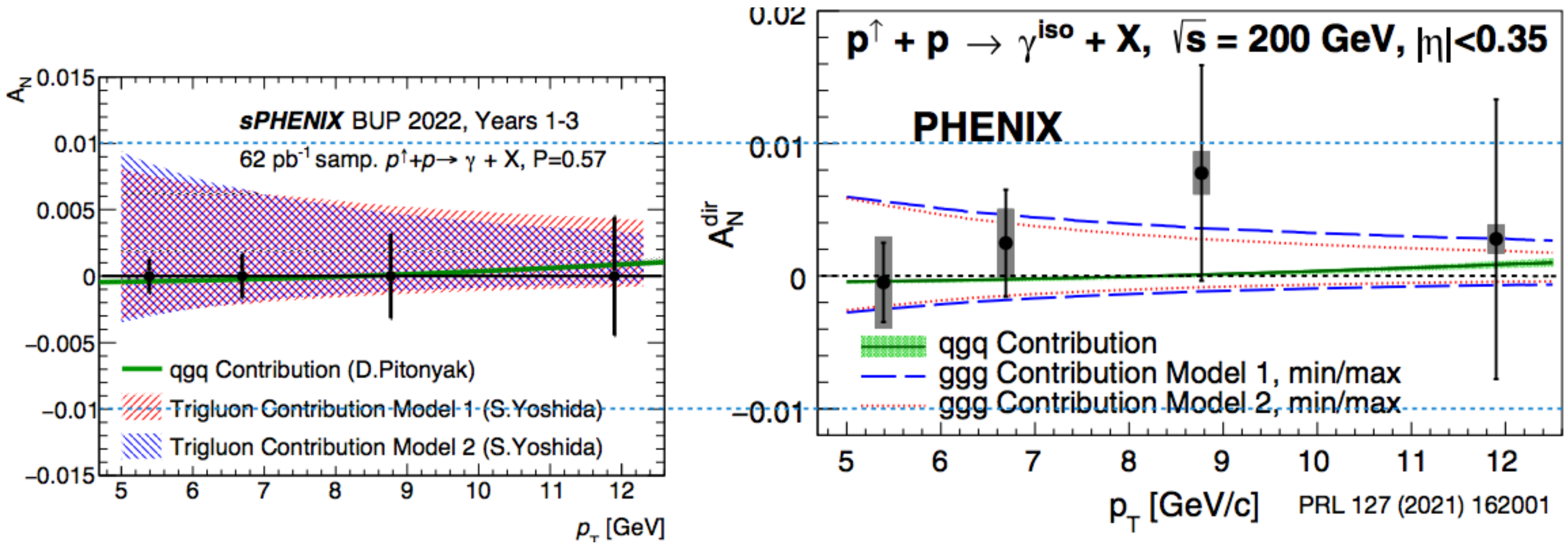


- Photons in final state
  → No final-state effects
- Clean probe of gluon spin-momentum correlations

- **First direct photon A_N from RHIC (PHENIX)**
  → 50 times reduced uncertainty from E704 Fermilab

Direct Photon A_N at sPHENIX

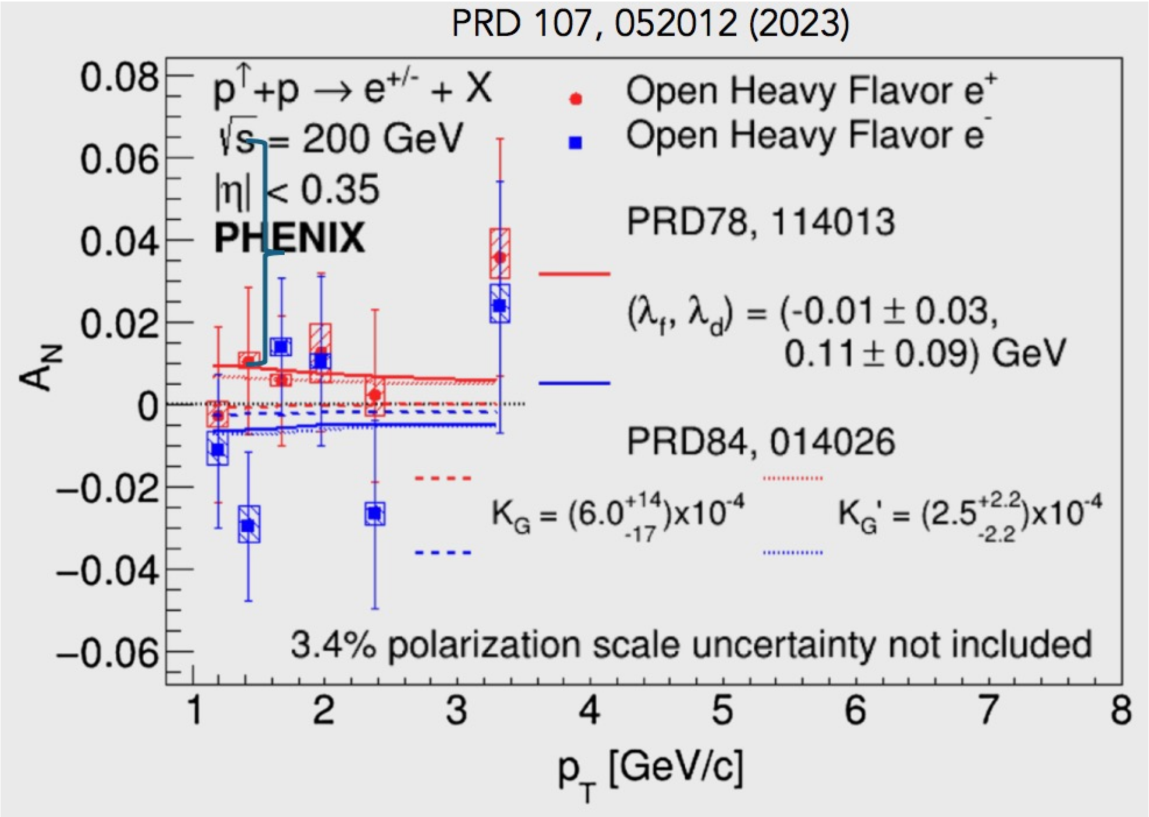
Genki Nukazuka (RIKEN/RBRC)



- First direct photon A_N from RHIC (PHENIX)
  → 50 times reduced uncertainty from E704 Fermilab
- Significant improvements in statistics expected from sPHENIX

Open Heavy Flavors at PHENIX

Devon Loomis (UofM)



- Dominated by gluon-gluon fusion
- Gluon transversity ~ 0

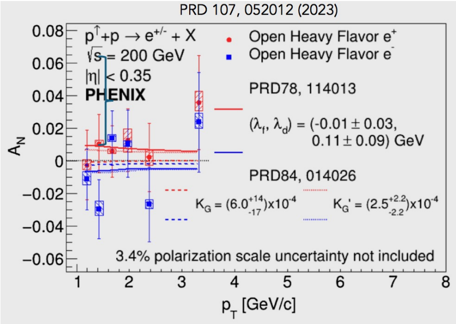
→ Probe of trigluon correlations

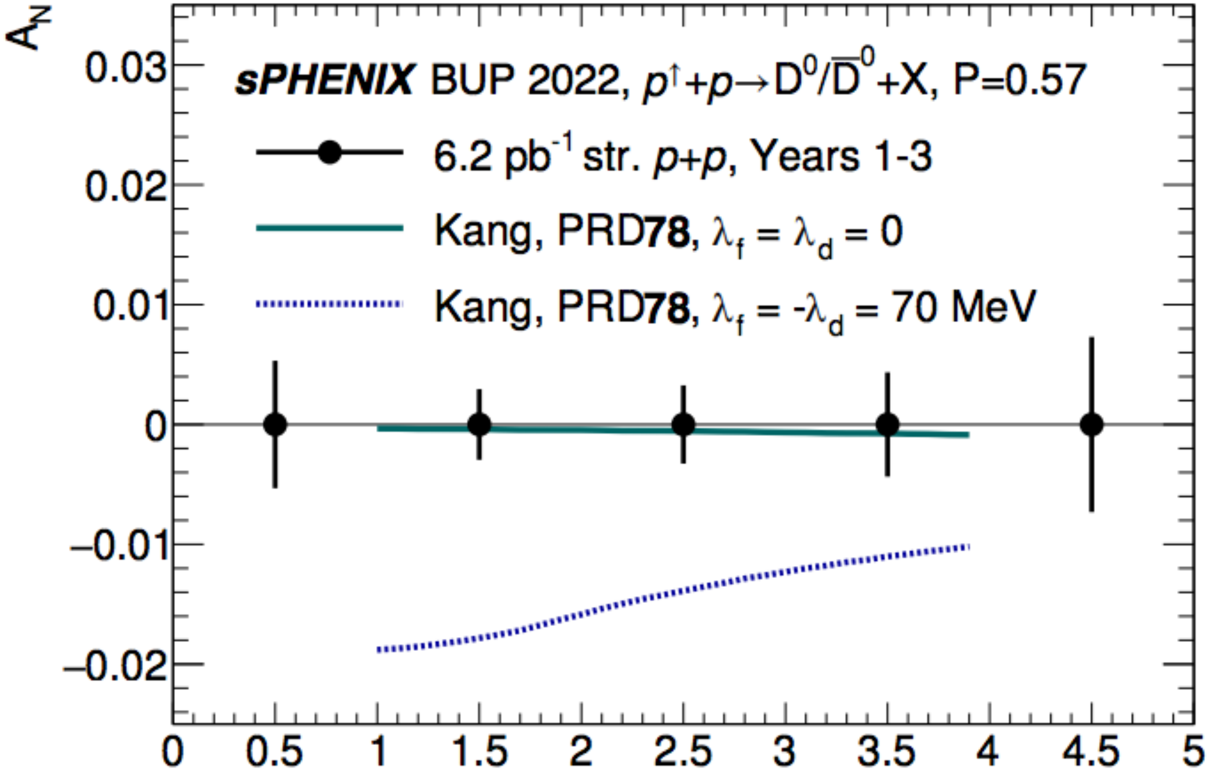
→ Also provides access to gluon Sivers PDF

- PHENIX provides first constraints on phenomenological parameters λ and K_G

Open Heavy Flavors at sPHENIX

Genki Nukazuka
(RIKEN/RBRC)





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

- Dominated by gluon-gluon fusion
- Gluon transversity ~ 0

→ Probe of trigluon correlations

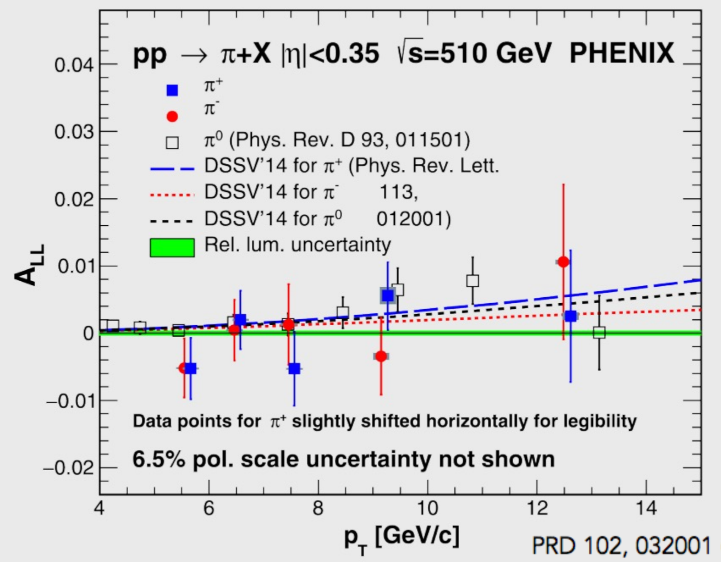
→ Also provides access to gluon Sivers PDF

- PHENIX provides first constraints on phenomenological parameters λ and K_G

- At sPHENIX, open charm A_N can also be measured via prompt D^0 reconstruction.

Helicity at PHENIX

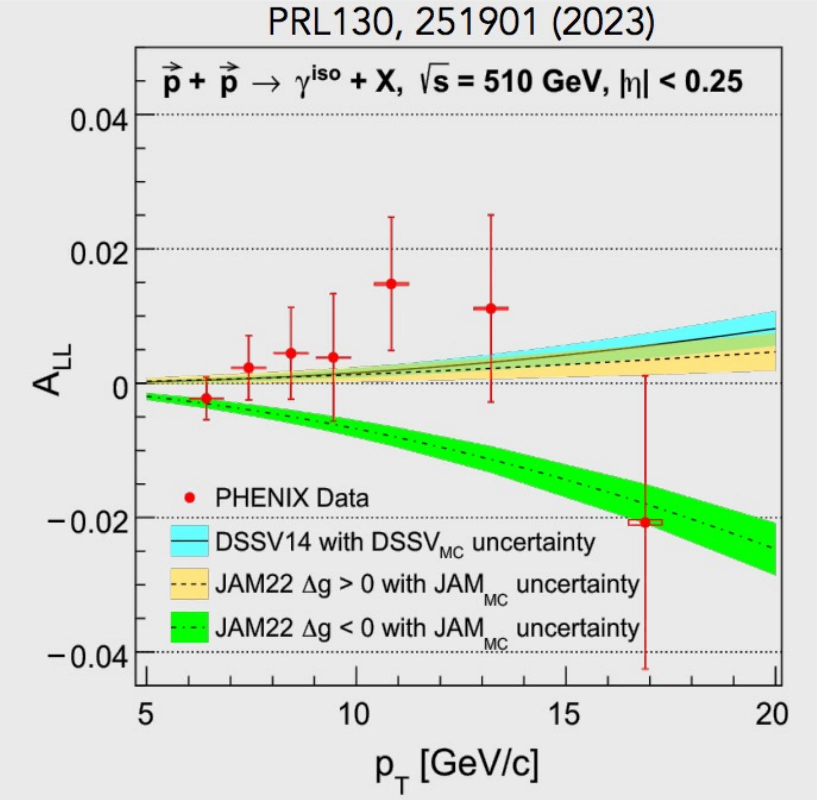
Devon Loomis (UofM)



PRD 102, 032001 (2020)

$$\frac{1}{2} = \frac{1}{2}\sum\Delta q + \Delta g + L_q + L_g$$

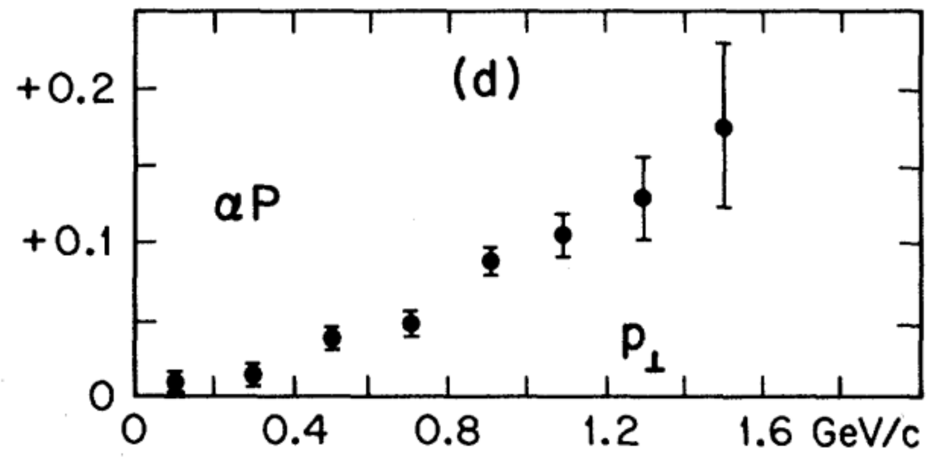
proton spin = quark helicity + gluon helicity + orbital angular



- Gluon helicity accessed via direct photon and charged-π A_{LL}
  - Provide constraints for largely unknown Δg in $x < 0.05$
- Measurements of A_L with $W^{\pm}/Z$
  - Leptonic decay channel $W/Z \to e, \mu$
  - Access to sea quark helicity distribution in the valence region $0.1 < x < 0.4$

Λ −Polarization PUZZLE

p+Be



Phys. Rev. Lett. 36, 1113-1116 (1976)

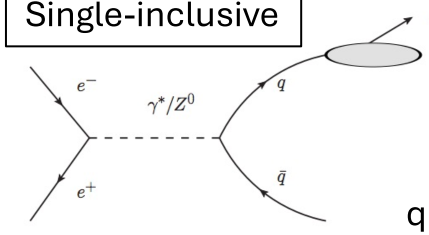
What is the origin of the Λ^0 polarization?

- Does polarization of Λ^0 depend on spin of the target/projectile?
- Is there a contribution of an **initial-state** effect?
- Will parton spin correlation and entanglement manifest in Λ^0 polarization? [*W. Gong, et al.: Phys. Rev. D 106 (2022) 3, L031501*]

Theory of di-Λ correlations

Shu-yi Wei (SDU)

Single-inclusive

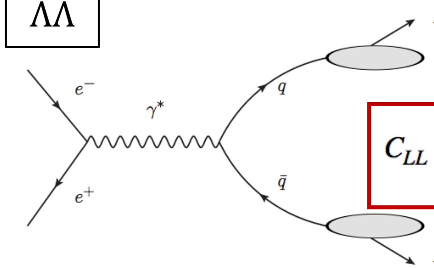


spin transfer

$$P_L^\Lambda = \lambda \frac{G_{1L}}{D_1}$$

quark polarization

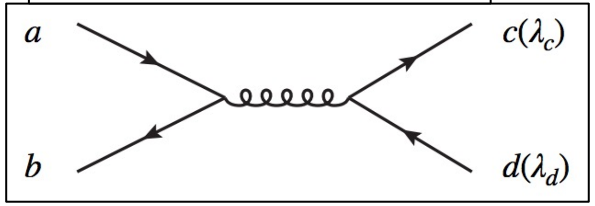
$\Lambda\bar{\Lambda}$



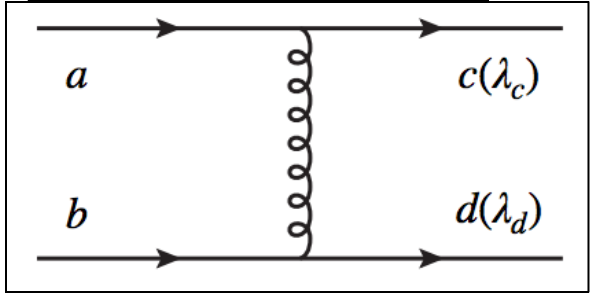
$$C_{LL} = \frac{\sum_q \sigma_0 G_{1Lq}^{\Lambda}(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2)}{\sum_q \sigma_0 D_{1q}^{\Lambda}(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2)}$$

In pp

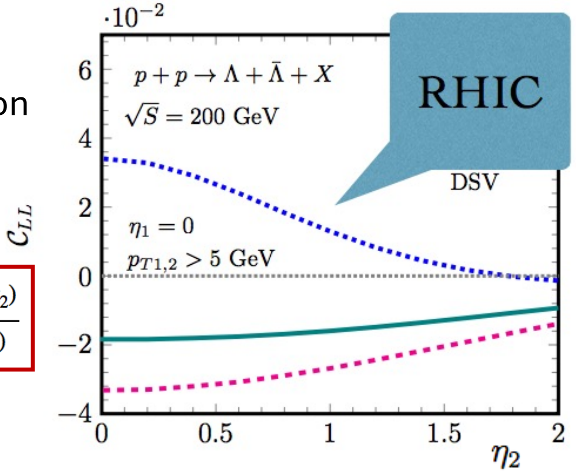
s-channel: $\sigma_{+-} > \sigma_{++} = 0$



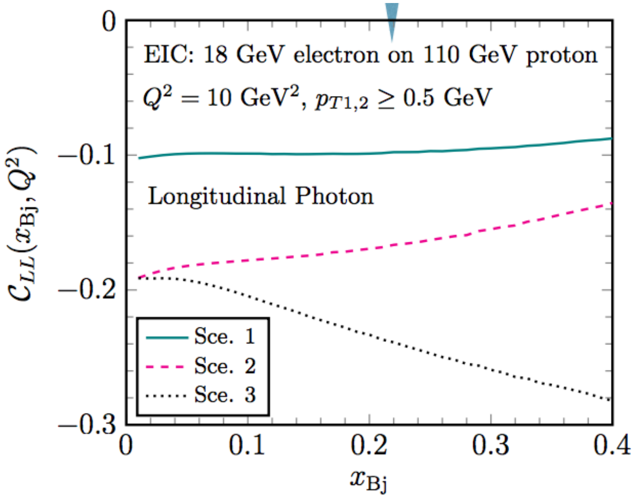
t-channel: $\sigma_{++} > \sigma_{+-} > 0$



Helicity correlations in unpolarized pp

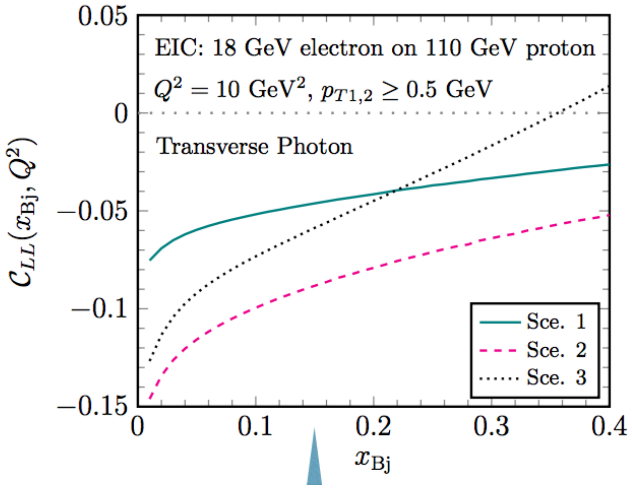


EIC: Longitudinal polarization



- Non-zero spin effects in unpolarized collisions
- Novel platform to investigate flavor-dependent G_{1L} FF
- Predictions for e^+e^-, ep, pp, and UPC/Central AA

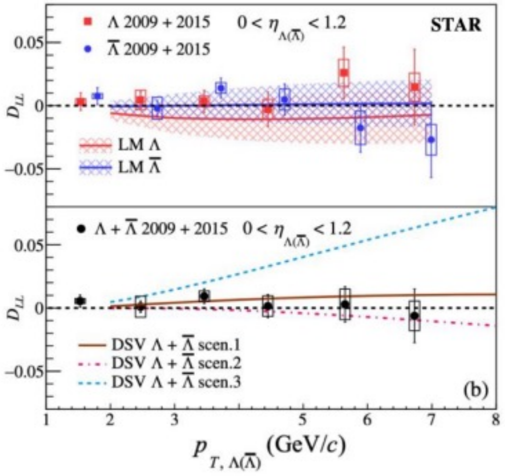
EIC: Transverse polarization

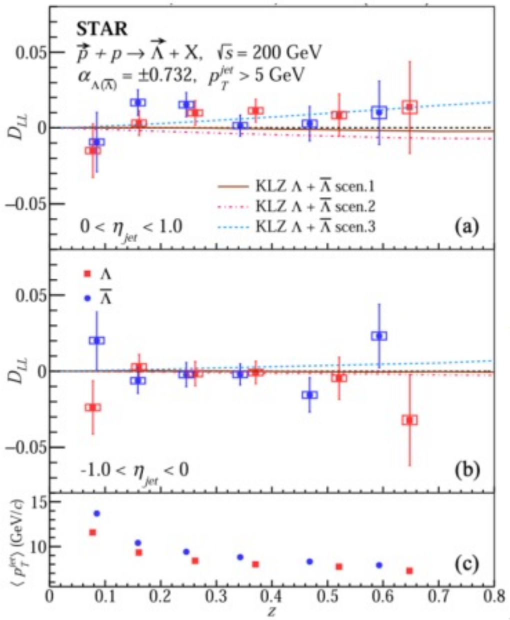


Λ-hyperons at STAR

Jan Vanek (BNL)

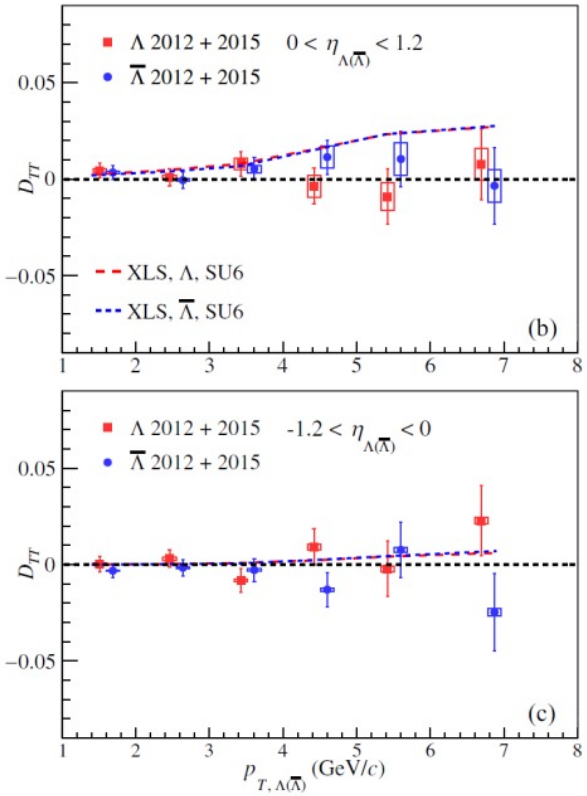
Longitudinal Spin Transfer D_{LL}



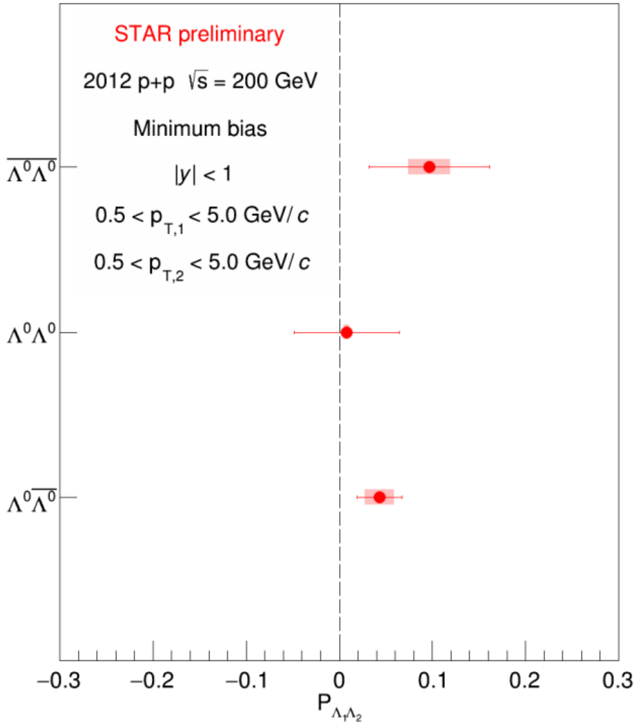


STAR, PRD 109, 12004 (2024)

Transverse Spin Transfer D_{LL}



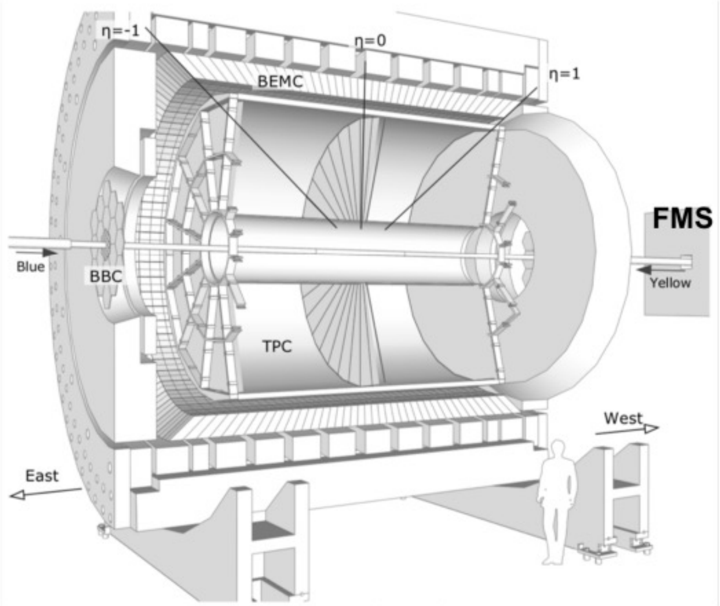
Spin-Spin Correlator $P_{\Lambda_1\Lambda_2}$



- Improved measurements of D_{LL} and D_{TT}
  - Tests of polarized FFs
- First experimental search for Λ^0 spin-spin correlations → New approach to access intial-state parton spin effects

STAR Forward Systems

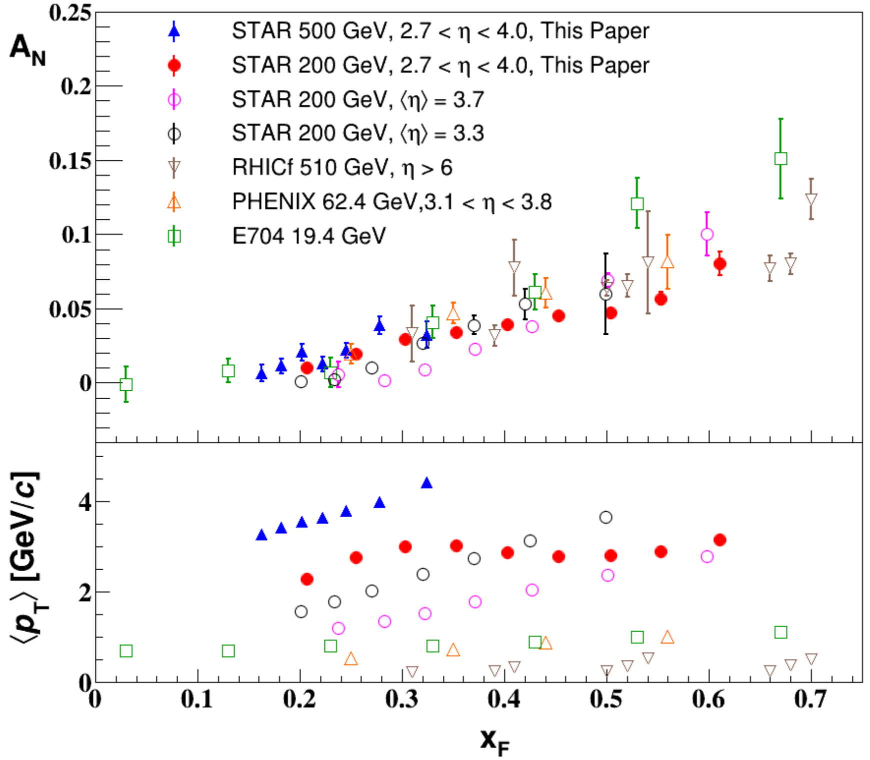
Xilin Liang (UC Riverside)



RP (not shown)

STAR, PRD 103, 092009 (2021)

$p + p \rightarrow \pi^0 + X$



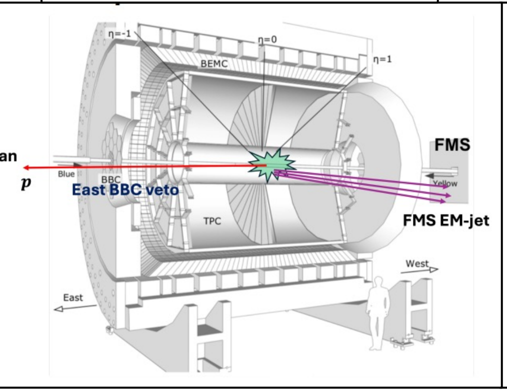
- Forward Meson Spectrometer (FMS) and Roman Pot (RP) detectors provided coverage in the forward ($\eta > 2.5$) regime from 2011 to 2017.

- One of the most intriguing findings is the surprisingly large A_N in the forward region.
- Possible contributions include twist-3 correlators associated with the Sivers, Collins, Diffractive processes.

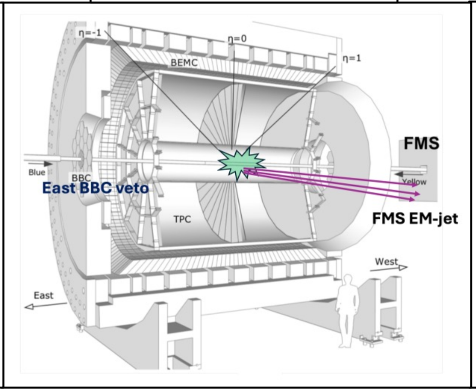
STAR Highlights: Diffractive-AN

Xilin Liang (UC Riverside)

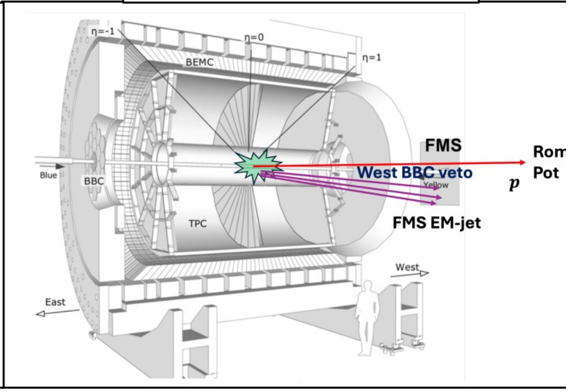
Single-Diffractive



Rapidity Gap

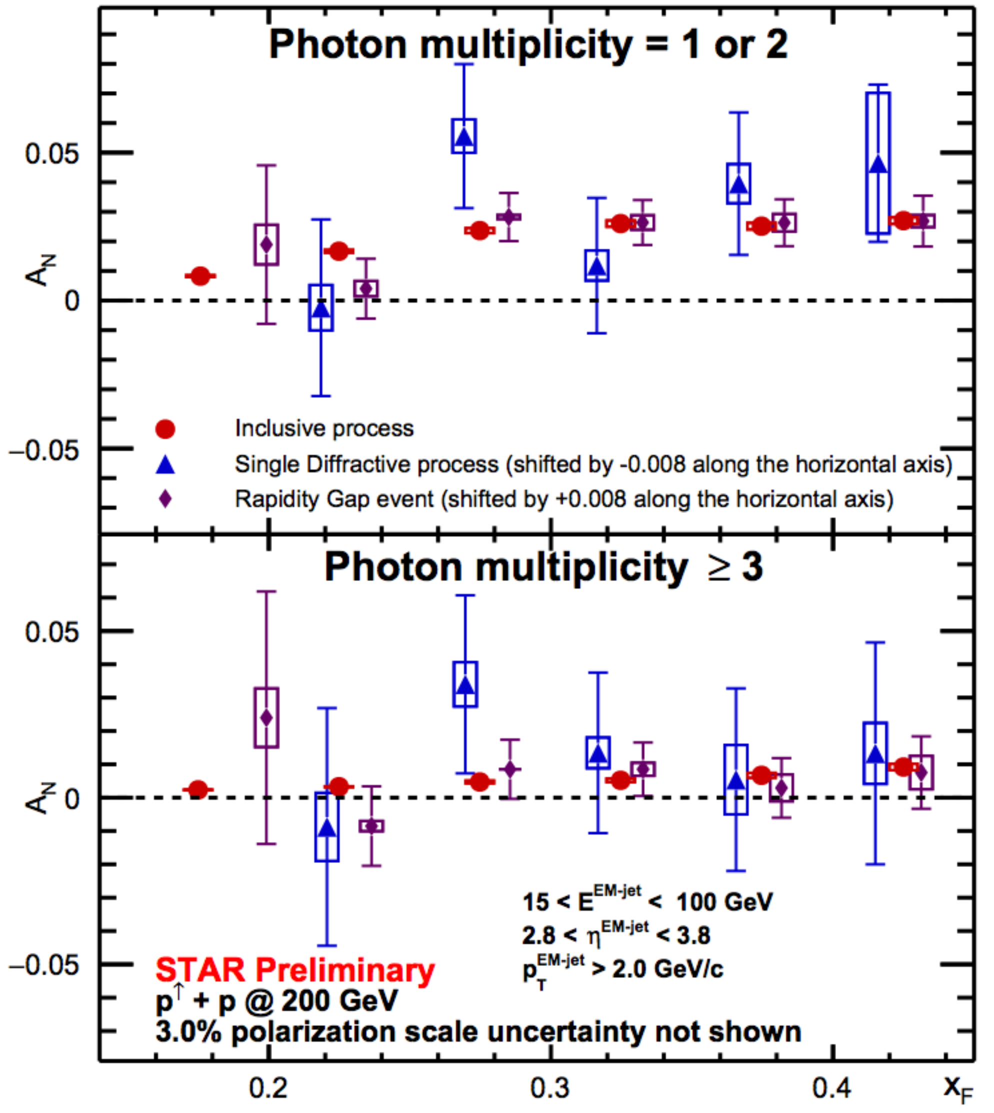


Semi-Exclusive



- A_N measured from Single-Diffractive, Rapidity Gap and Semi-Exclusive events, each consisting differing fraction of diffractive processes.

- The size of A_N from these processes is similar to that of the inclusive process, ruling out diffractive processes as the potential driver of the large A_N.



STAR Forward Upgrade

Xilin Liang (UC Riverside)

STAR Forward Upgrade data taking works well:

Completed:

- Run-22: $p+p$ $\sqrt{s}=508$ GeV
- Run-23: $Au+Au$ $\sqrt{s}=200$ GeV

Plans:

- Run-24: $p+p$ $\sqrt{s}=200$ GeV & $Au+Au$ $\sqrt{s}=200$ GeV
- Run-25: $Au+Au$ $\sqrt{s}=200$ GeV & possible $p+Au$ $\sqrt{s}=200$ GeV

STAR Forward Upgrade

Coverage: $2.5 < \eta < 4.0$

- Located on STAR west side
- Rapidity coverage is the same as the EIC hadron arm

Requirement:

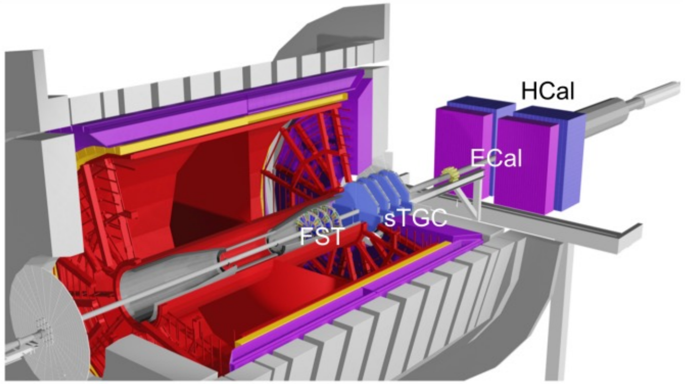
Detector	pp and pA	AA
ECal	$\sim$10 % / $\sqrt{E}$	$\sim$20 % / $\sqrt{E}$
HCal	$\sim$50 % / $\sqrt{E}$ + 10%	-
Tracking	Charge separation photon suppression	$\delta p_T/p_T$ $\sim$20 - 30% for $0.2 < p_T < 2$ GeV/c

Combines:

1. Forward Tracking System (FTS)
   - Forward Silicon Tracker (FST)
   - small-strip Thin Gap Chambers (sTGC)
2. Forward Colorimeter System (FCS)
   - Electromagnetic Calorimeter (ECal)
   - Hadronic Calorimeter (HCal)

Measures:

- $h^{+/-}$, $e^{+/-}$ (with good e/h separation)
- Photon, π^0, jets



Xilin Liang | STAR Forward Physics | RHIC/AGS 2024 | 13 / 19

- STAR forward upgrade has been installed and running **on time** and **on budget**!
- Current efforts focus on software and detector calibration works of Run 22
- Stay Tuned for new results!

Ultra-Peripheral Collisions

Diffractive Processes

Entanglement Enabled Spin Interference

Investigating Baryon Number Transport (Baryon Junction)

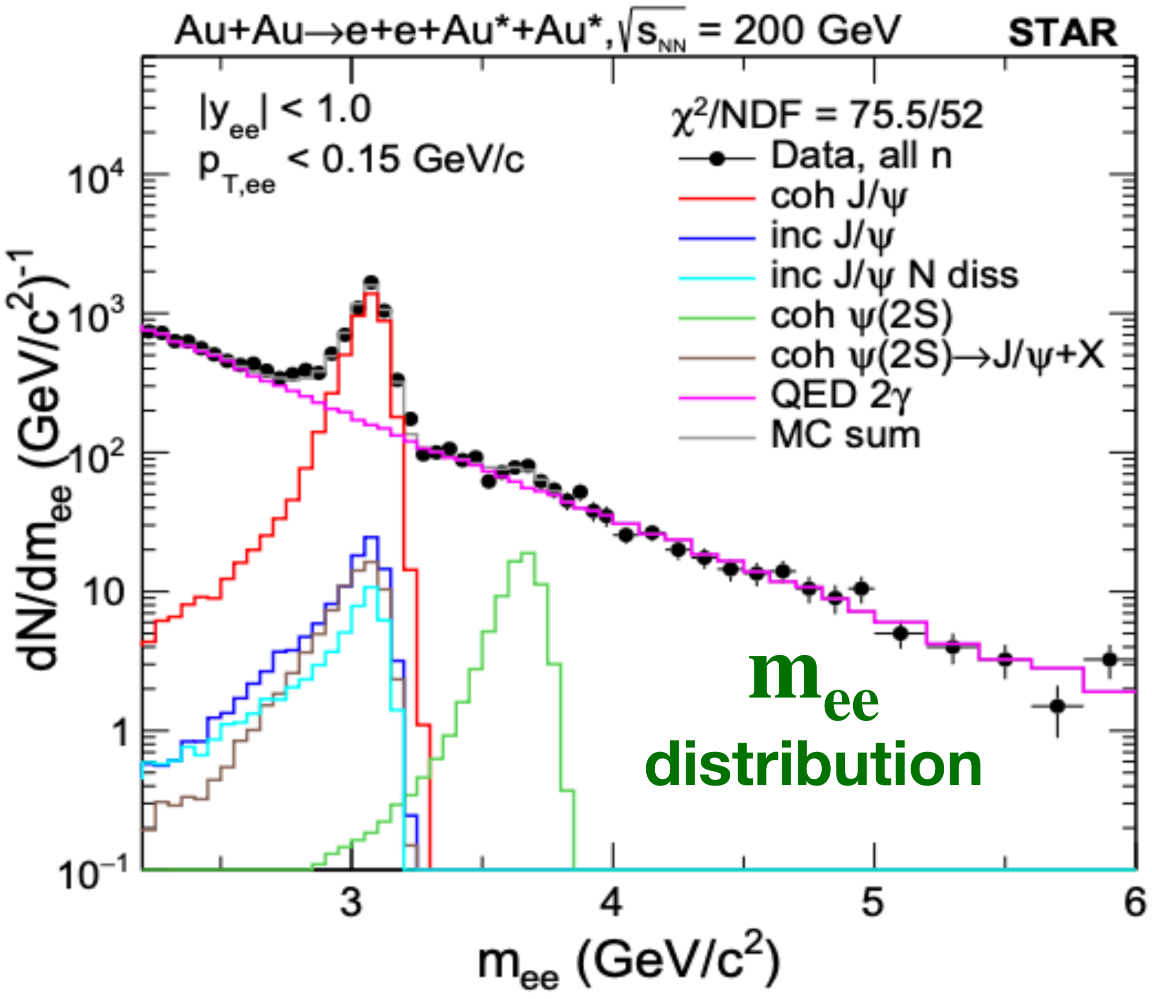
Diffractive J/ψ Production @ 200 GeV

- Measured for **coherent** and **incoherent** contributions for different neutron emission in ZDCs
- Systematic unc. in incoherent to coherent cross-section ratio are largely cancelled
- Sensitive to the nuclear structure and deformation

- Important to constrain theoretical models

Ashik Ikbal (Kent State)

STAR, arXiv:2311.13637



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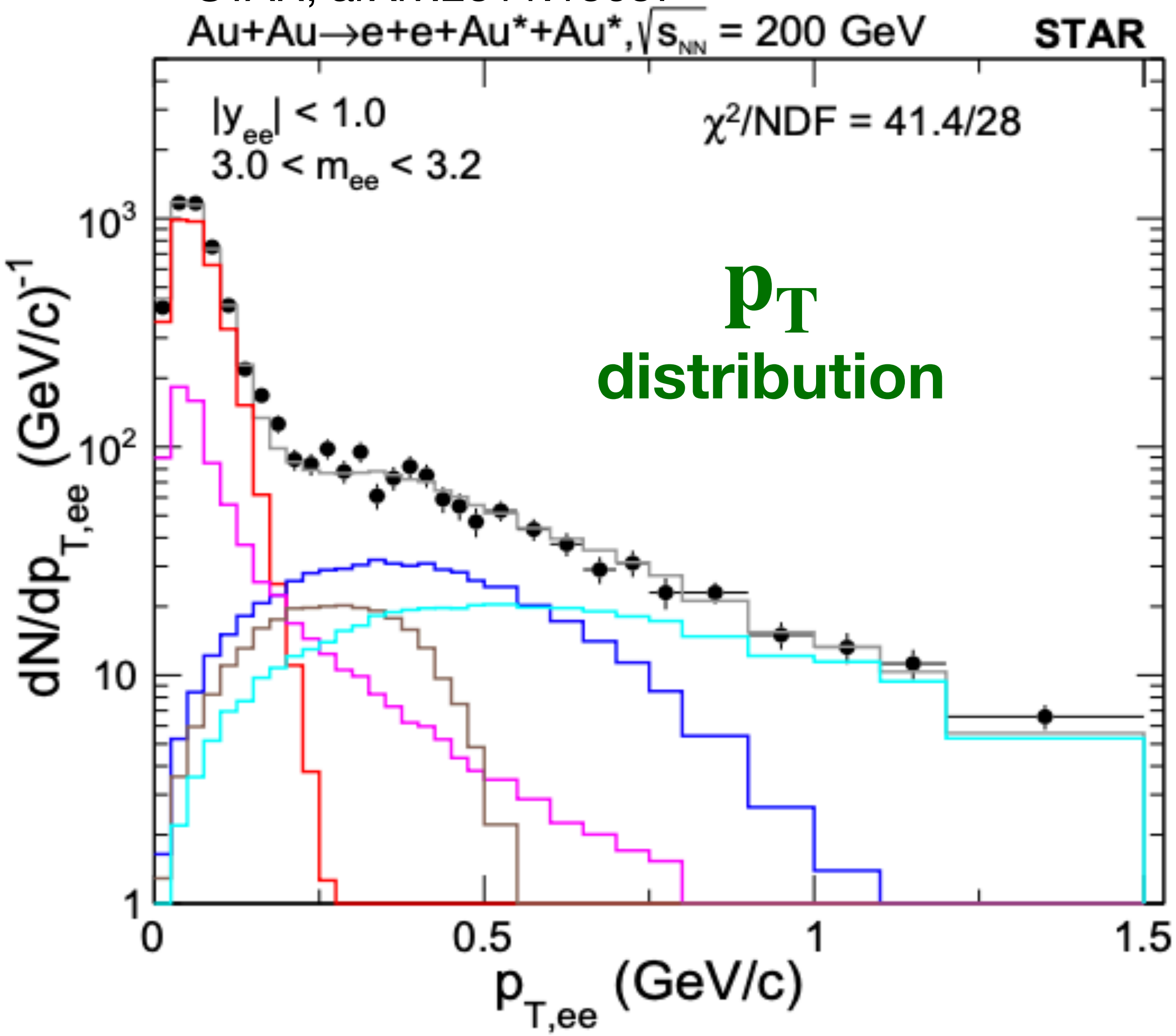

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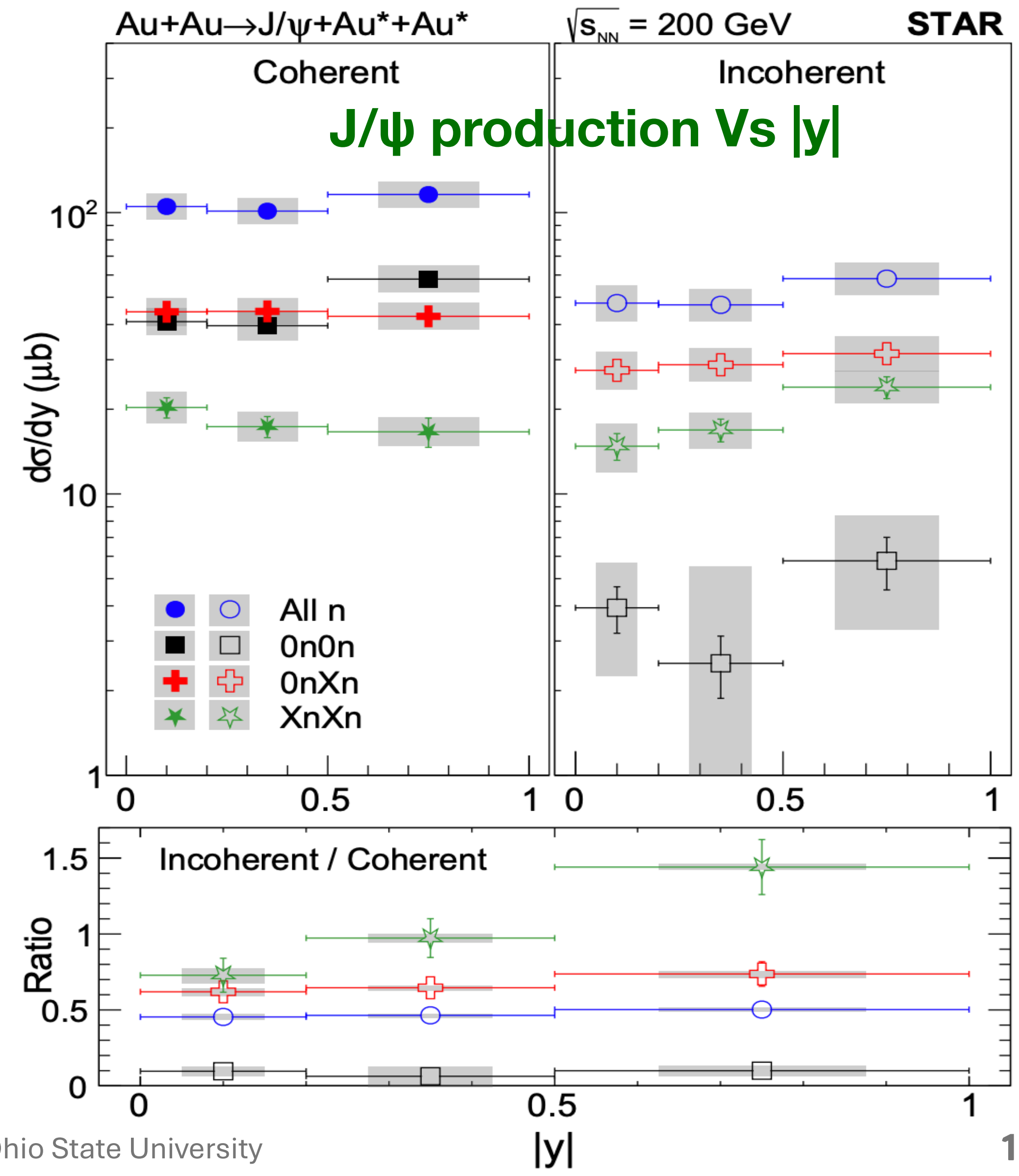
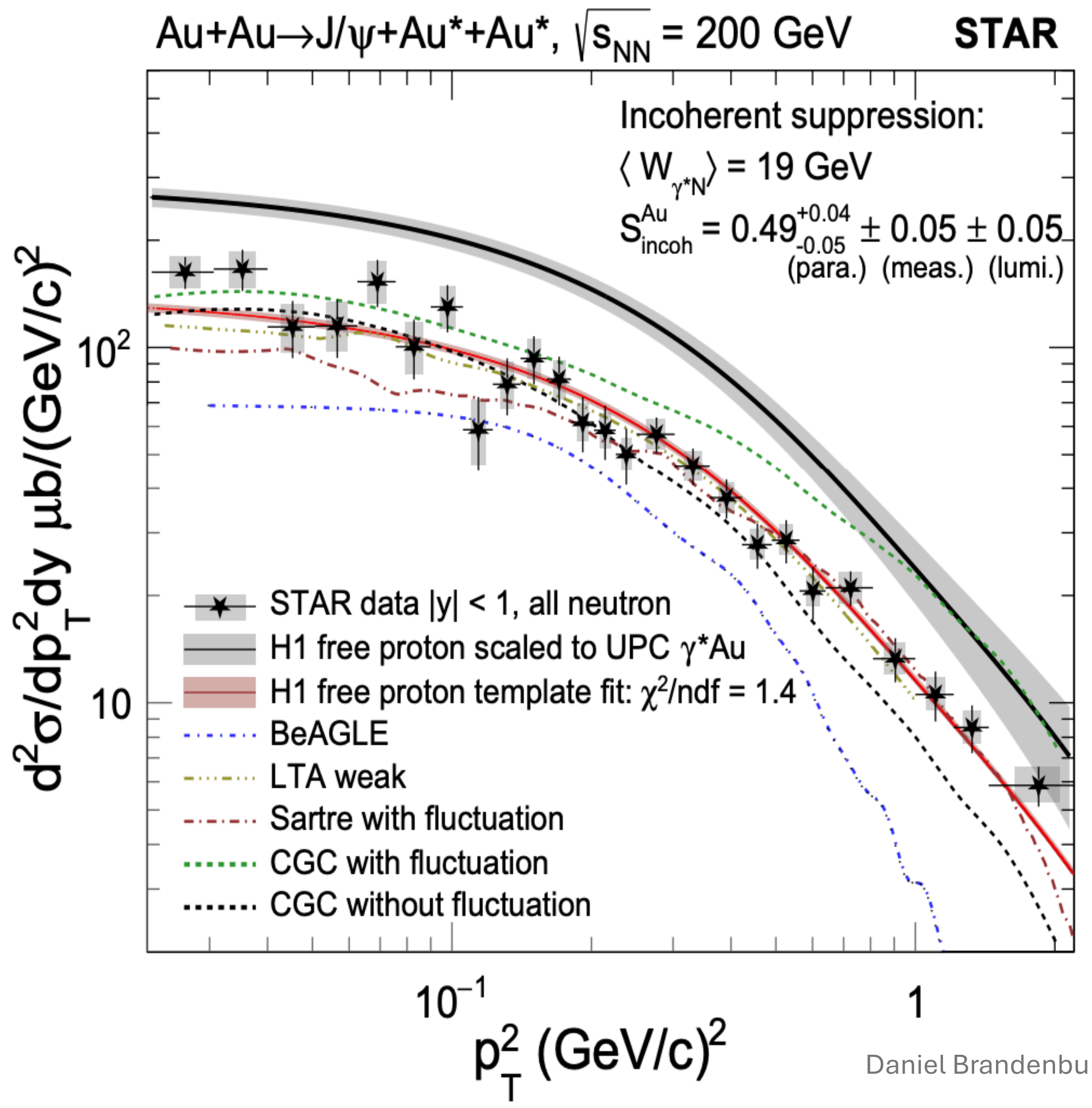


Incoherent J/ψ production cross-section vs p_T^2



- Incoherent production compared with H1 data with free proton
- Strong nuclear suppression (~49%) seen
  (Mäntysaari et. al, Phys. Rev. Lett. **117** (2016) 5, 052301)
- Models found H1 data supports sub-nucleonic fluctuations
  (Mäntysaari et. al, Phys. Rev. D **106** (2022) 7, 074019)
- STAR data shows the bound nucleon has similar shape as the free proton — similar sub-nucleonic fluctuations in heavy nuclei

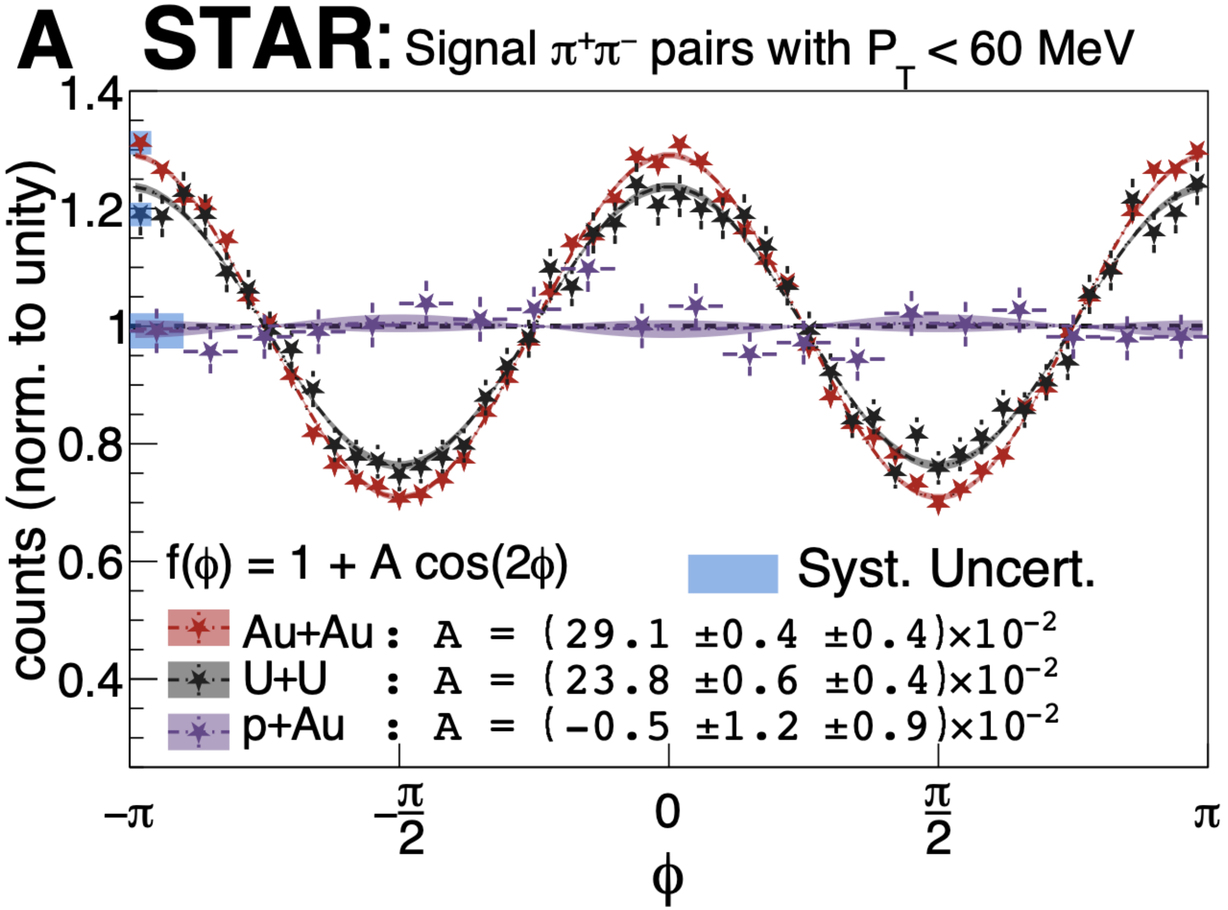
=> Strong nuclear suppression and sub-nucleonic fluctuations in Au nucleus

Ashik Ikbal (Kent State)

Entanglement Enabled Spin Interference

- STAR observed spin interference in diffractive $\pi^+\pi^-$ production (recently confirmed by ALICE)
- Precise measurement of strong-interaction radius at high-energy

Haowu Duan (UCONN)

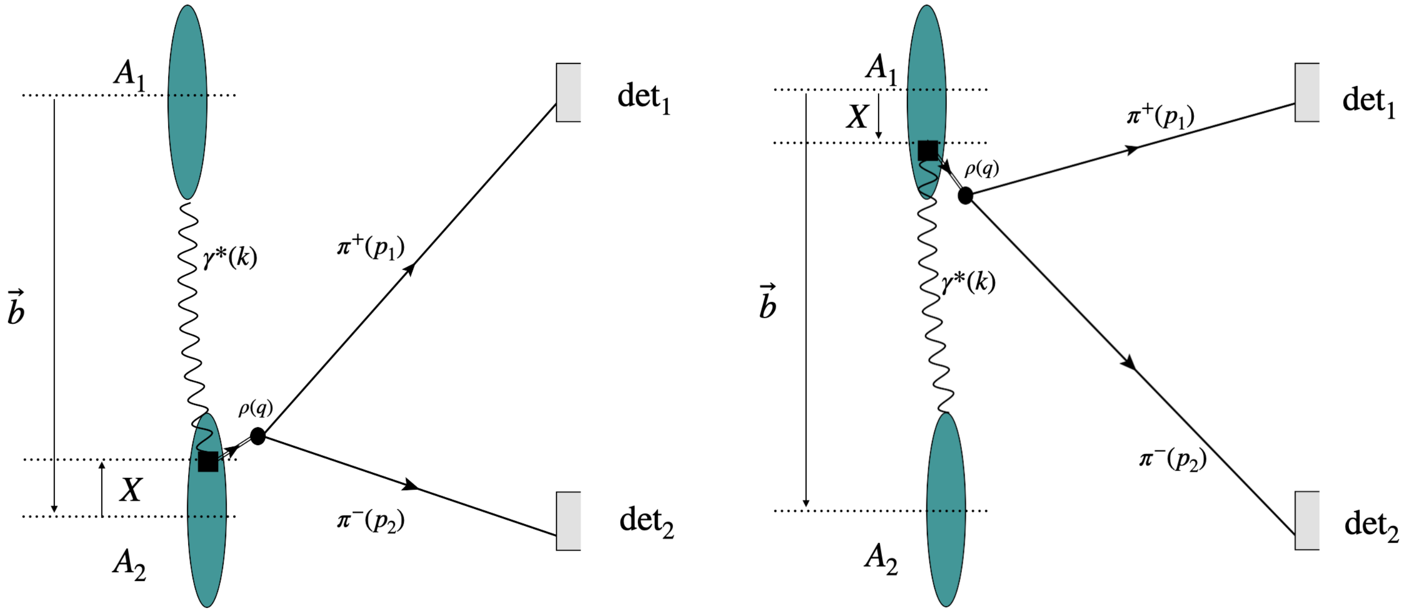


Sci.Adv. 9 (2023) 1, eabq3903
arxiv.2204.01625

Entanglement Enabled Spin Interference

- Goal: understood interference effect in a model-independent way
- Quantum mechanical description – intensity interferometry via entanglement

Haowu Duan (UCONN)



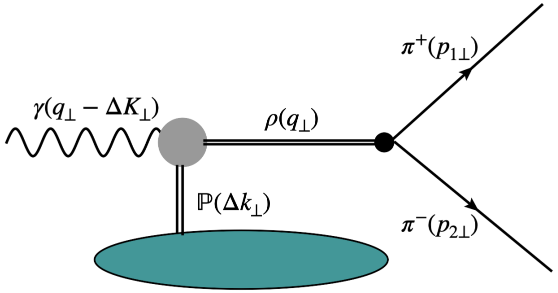
WW(Weizsacker-Williams) photon + nuclear target $\rightarrow$ ρ in mid-rapidity

$$\rho(\boldsymbol{q} = \boldsymbol{p}_1 + \boldsymbol{p}_2) \rightarrow \pi^+(\boldsymbol{p}_1)\pi^-(\boldsymbol{p}_2) + \pi^+(\boldsymbol{p}_2)\pi^-(\boldsymbol{p}_1)$$

- $\langle \pi^+(\boldsymbol{p}_1)\pi^-(\boldsymbol{p}_2) | \pi^+(\boldsymbol{p}_2)\pi^-(\boldsymbol{p}_1) \rangle = 0$
- Similar to a Bell state: $\frac{1}{\sqrt{2}}(|10\rangle + |01\rangle)$

S. Klein and J. Nystrand Phys. Rev. Lett. 84, 2330 (2000)

Entanglement Enabled Spin Interference



Haowu Duan (UCONN)

Figure: $\Delta K_\perp$ net momentum transfer from the target/ momentum of the Pomeron.
$(\boldsymbol{k} \equiv \vec{k}_\perp, \; |\vec{k}_\perp| \equiv k_\perp)$

$$M^{\rho}_{A_1 A_2 \to \pi^+ \pi^-}(\boldsymbol{p}_1, \boldsymbol{p}_2) = M_{A_1 A_2 \to \rho}(\boldsymbol{q}) \otimes M_{\rho \to \pi^+ \pi^-}(\boldsymbol{q}; \boldsymbol{p}_1, \boldsymbol{p}_2)$$

The ρ production amplitude can be decomposed into three general factors,

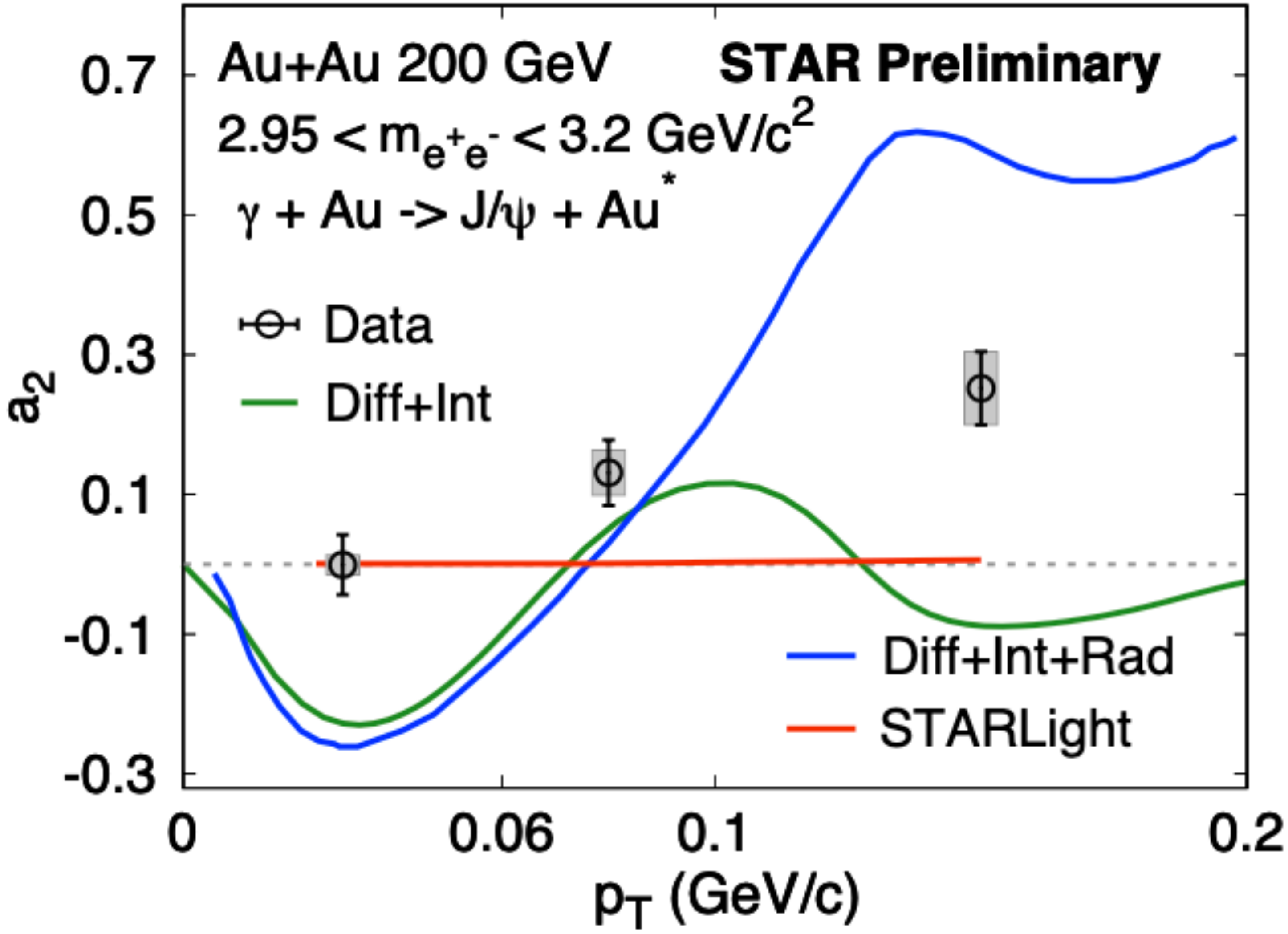
$$M_{A_1 A_2 \to \rho}(\boldsymbol{q}) = F_{\text{Photon}}(\boldsymbol{q} - \Delta \boldsymbol{K}) \otimes P_{\text{Pomeron}}(\Delta \boldsymbol{K}) \otimes M_{\gamma \mathbb{P} \to \rho}(\boldsymbol{q} - \boldsymbol{\Delta} K, \Delta K; \boldsymbol{q})$$

- Model independent formalism – manuscript in preparation, coming soon!
- Observable allows direct access to spin states : Potential for observation of Tensor Pomeron, Odderon etc. depending on channel

EESI Measurement in J/ψ production

Ashik Ikbal (Kent State)

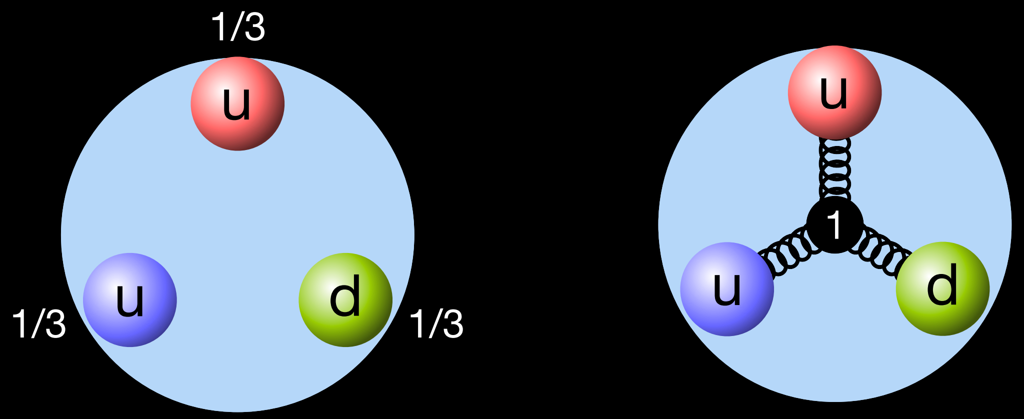
- Interference signal shows strong *pT* dependence and rises toward positive
- Diffractive+interference with additional soft γ radiation predicts
- Negative at low *pT* and rises towards positive value at higher *pT*



Understanding Baryon Transport at High-Energies

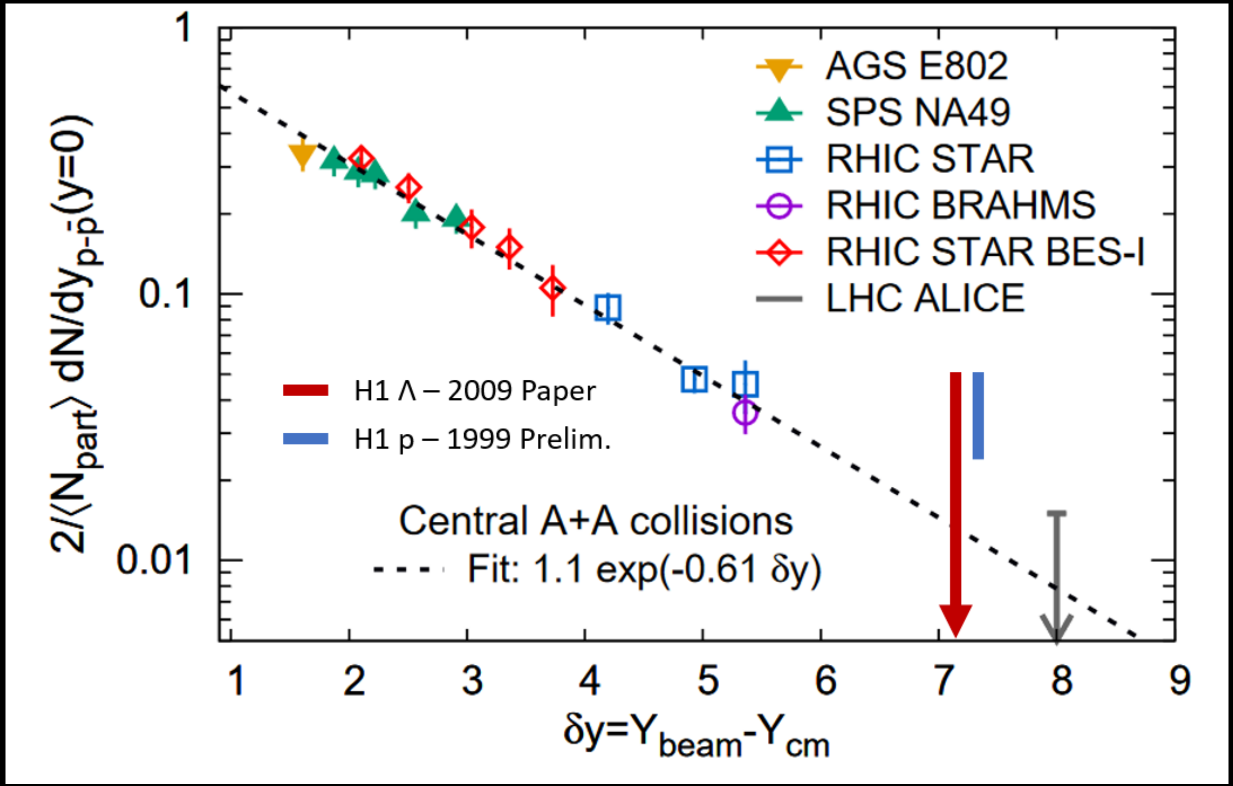
Prithwish Tribedy (BNL)

- 50 Years of investigating baryon transport
- Puzzlingly large baryon number observed in central rapidity (high energy)

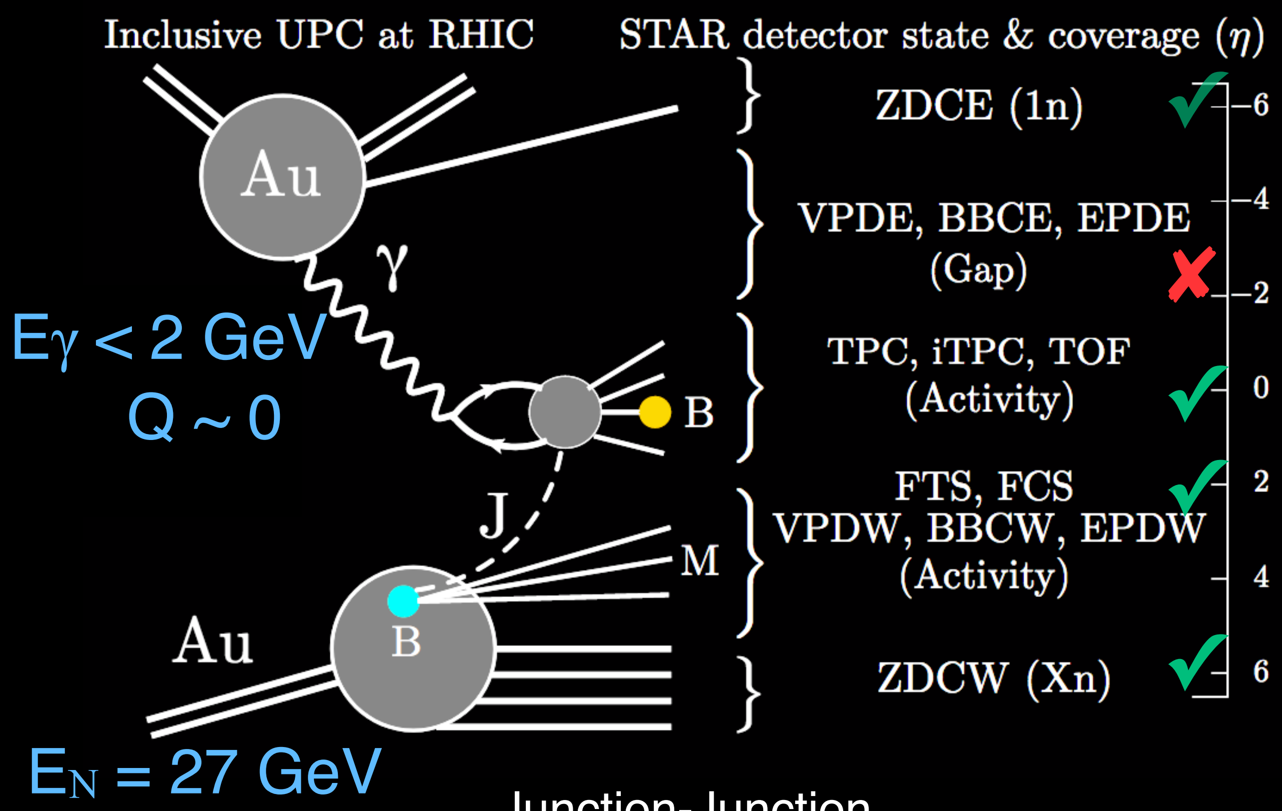


Goldberg and Y. Ne'eman, Nuovo Cimento 27 (1963) 1
Gell-Mann, Zweig, 1964, SLAC 1970
Review: hep-ph/9301246

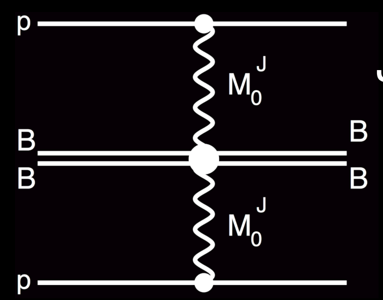
X. Artru, Nucl. Phys. B 85, 442–460 (1975), G.C. Rossi and G. Veneziano, Nucl. Phys.B123(1977) 507; Phys. Rep.63(1980) 149
Kharzeev, Phys. Lett. B, 378 (1996) 238-246



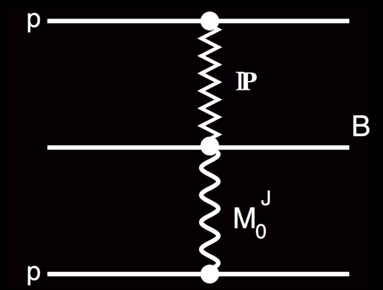
Baryon Transport in Ultra-Peripheral Collisions



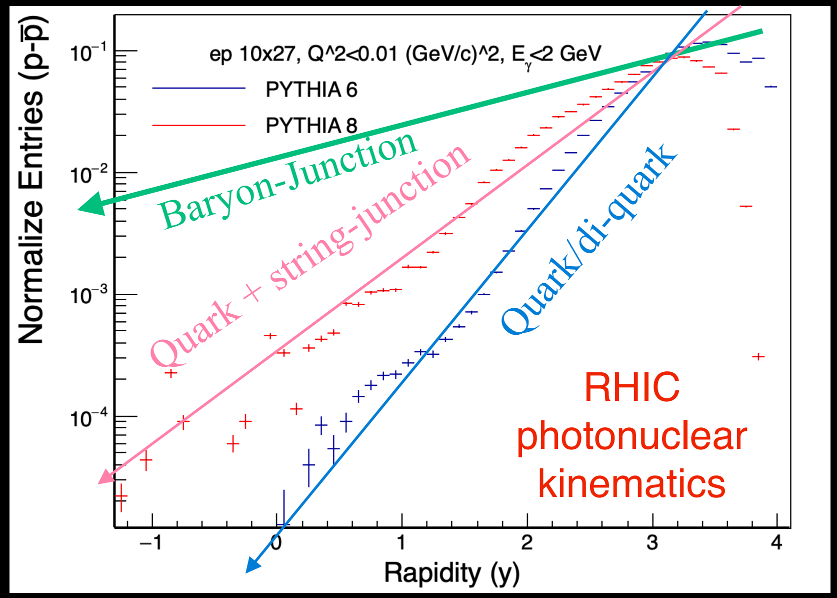
Junction-Junction



Junction-Pomeron



PYTHIA 6: Quark carries baryon
PYTHIA 8: Quark + mimic string-junction

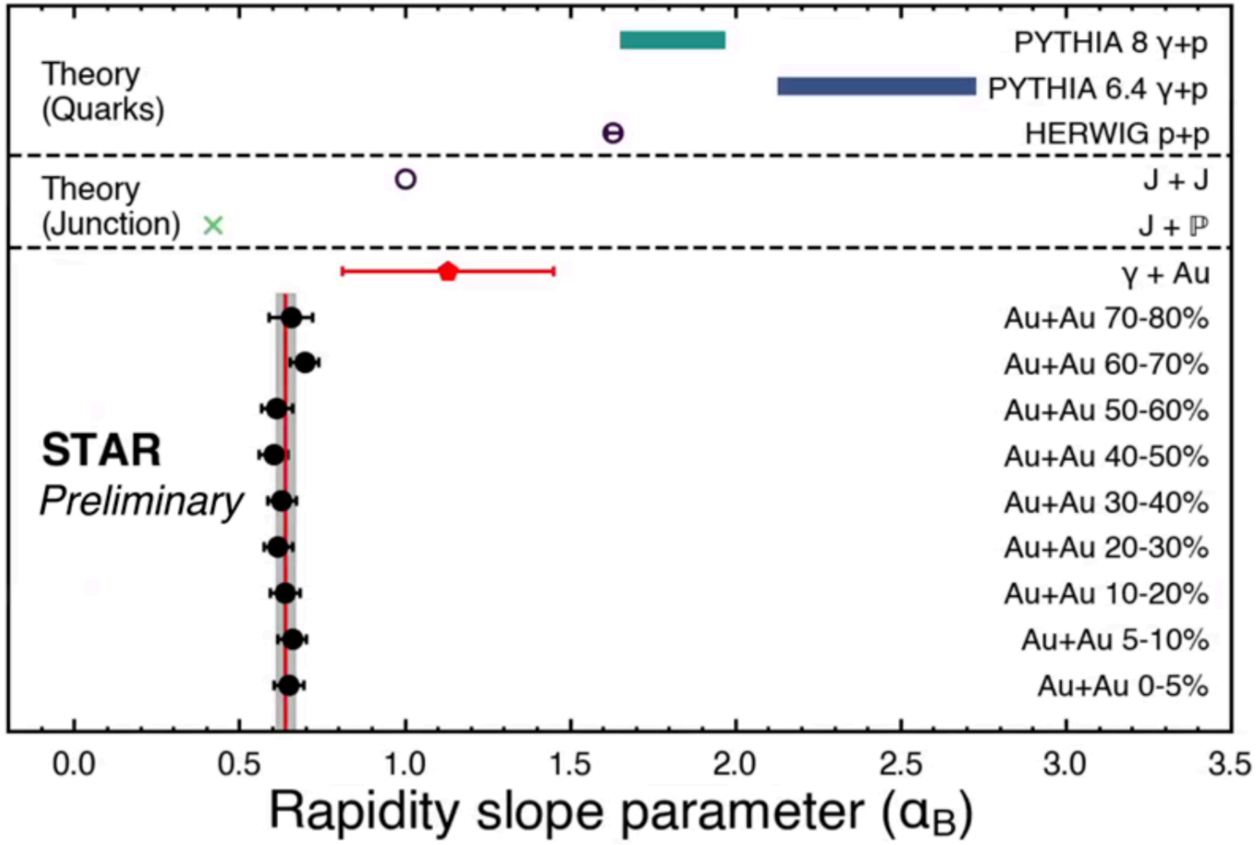


Models with various different carriers predict different rapidity dependence of net-proton yield

Prithwish Tribedy (BNL)

Baryon Production at mid-rapidity

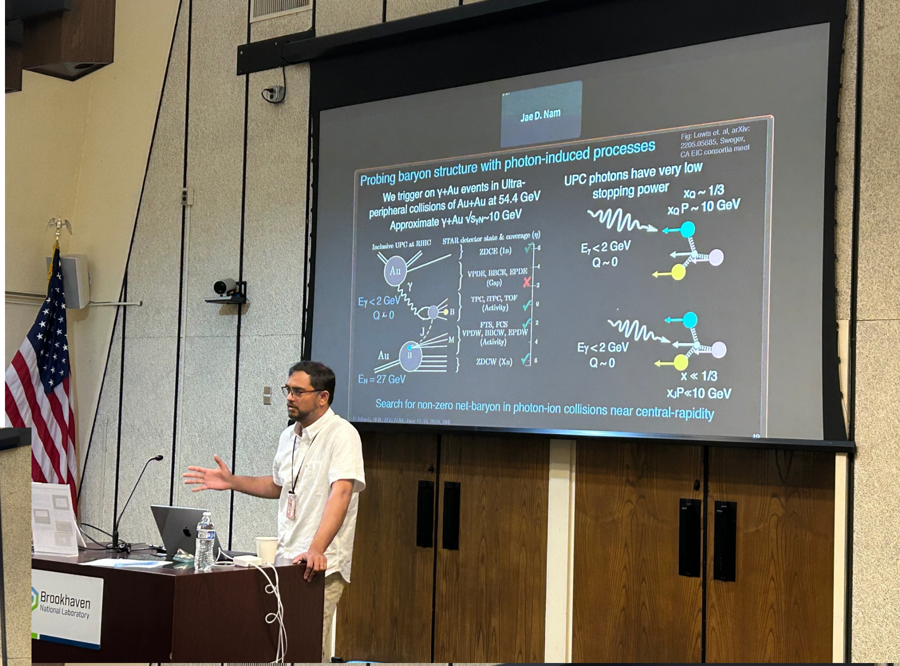
Prithwish Tribedy (BNL)

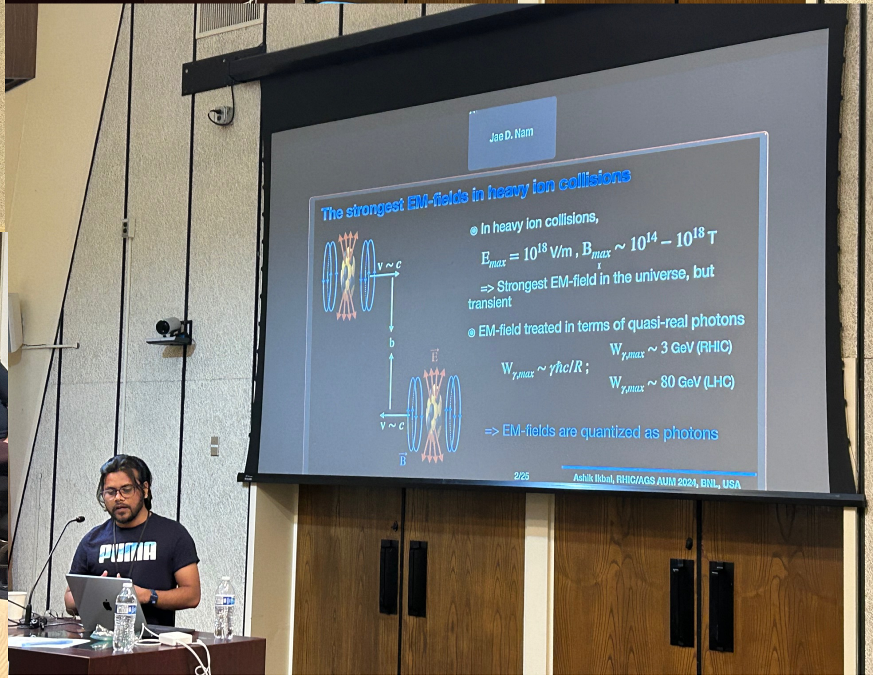


- Rapidity slope (α_B) of net-protons ~ constant for all centralities in Au+Au collisions
- Larger slope observed in UPC - Consistent with Regge theory baryon-junction prediction but smaller than PYTHIA/HERWIG

Summary

- Productive workshop ~ 35 attendees!
- Exciting opportunities ahead with sPHENIX and STAR forward Upgrade

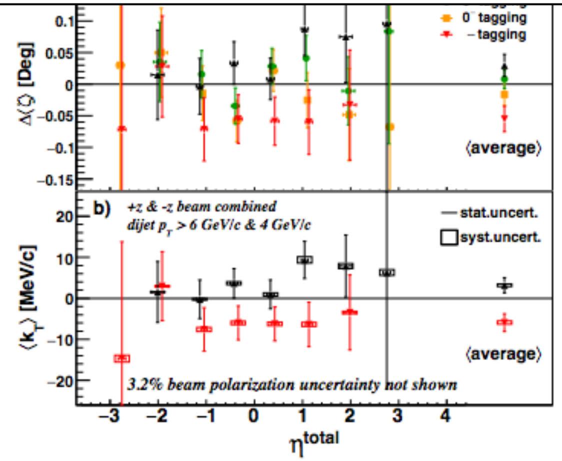




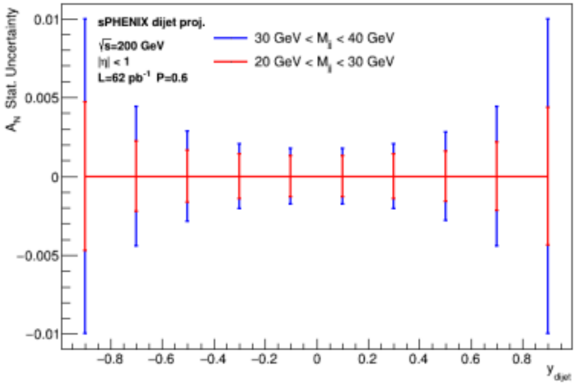
Further Opportunities at sPHENIX

Genki's talk

Sivers Effects at STAR/sPHENIX

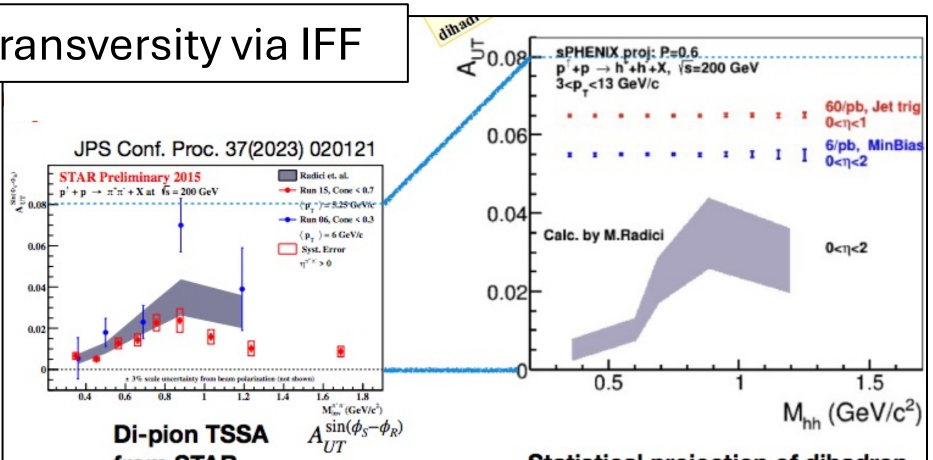


Dijet TSSA by STAR (arXiv:2305.10359)



Statistical projection of dijet measurement at sPHENIX.

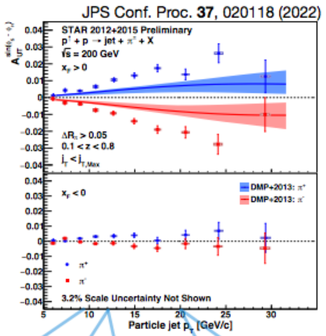
Transversity via IFF



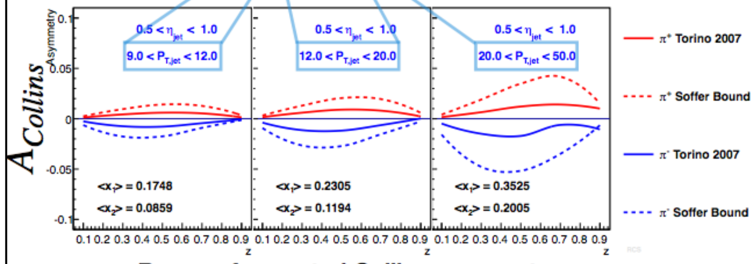
Di-pion TSSA from STAR. $A_{UT}^{\sin(\phi_S-\phi_R)}$

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

Transversity & Collins Effects



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



Range of expected Collins asymmetry in sPHENIX kinematics.