The STAR Forward Rapidity Upgrade

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for the

STAR Collaboration

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STAR

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

Physics with STAR in 2021+

Opportunity:

- Unique program addressing several fundamental questions in QCD

Motivation: **(**The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC (arXiv:1602.03922)**)**

- Central to the mission of the RHIC physics program in cold and hot QCD
- Fully realize the scientific promise of the EIC
  - → Lay the groundwork for the EIC, both scientifically and by refining the experimental requirements
  - → Test EIC detector technologies under real conditions, i.e SiPMs

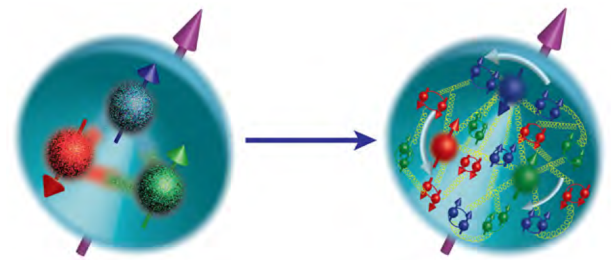
Take full advantage of STAR's unique capability including upgrades for BES-II:

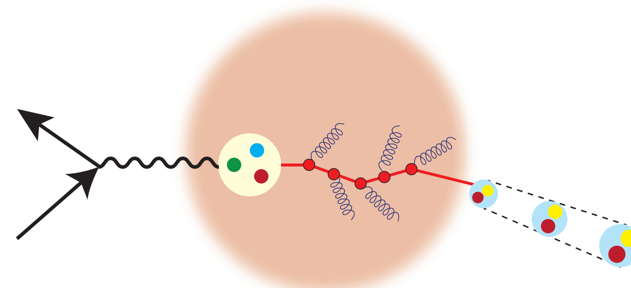
- Midrapidity program based on existing STAR detector utilizing iTPC, eToF and EPD upgrades (https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669)
- **Forward rapidity program based on upgrade consisting of Hcal + Ecal+ Tracking (Si + sTGCs) at 2.5 < η < 4 [Focus of Talk] (https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648)**

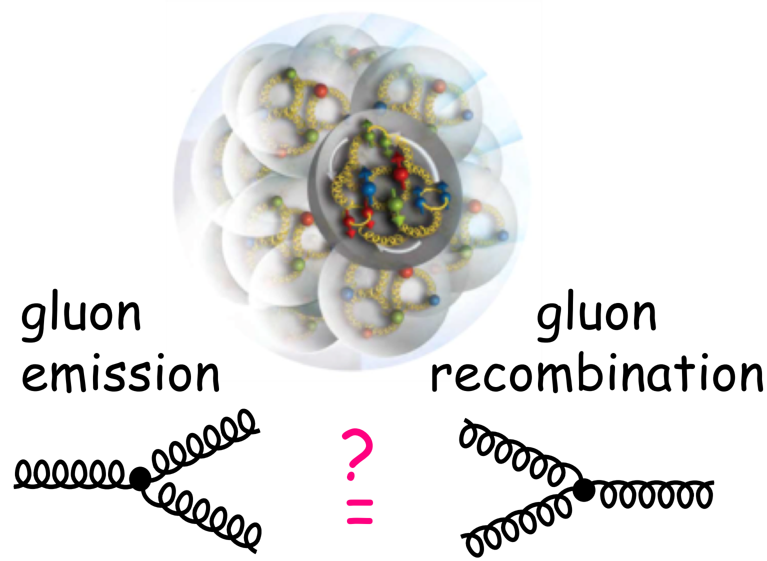
Goal: Complete upgrade for potential polarized pp@500 GeV run in 2021 and the sPHENIX data taking periods

Open Questions in Cold QCD

- How are the sea quarks & gluons and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?
- How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



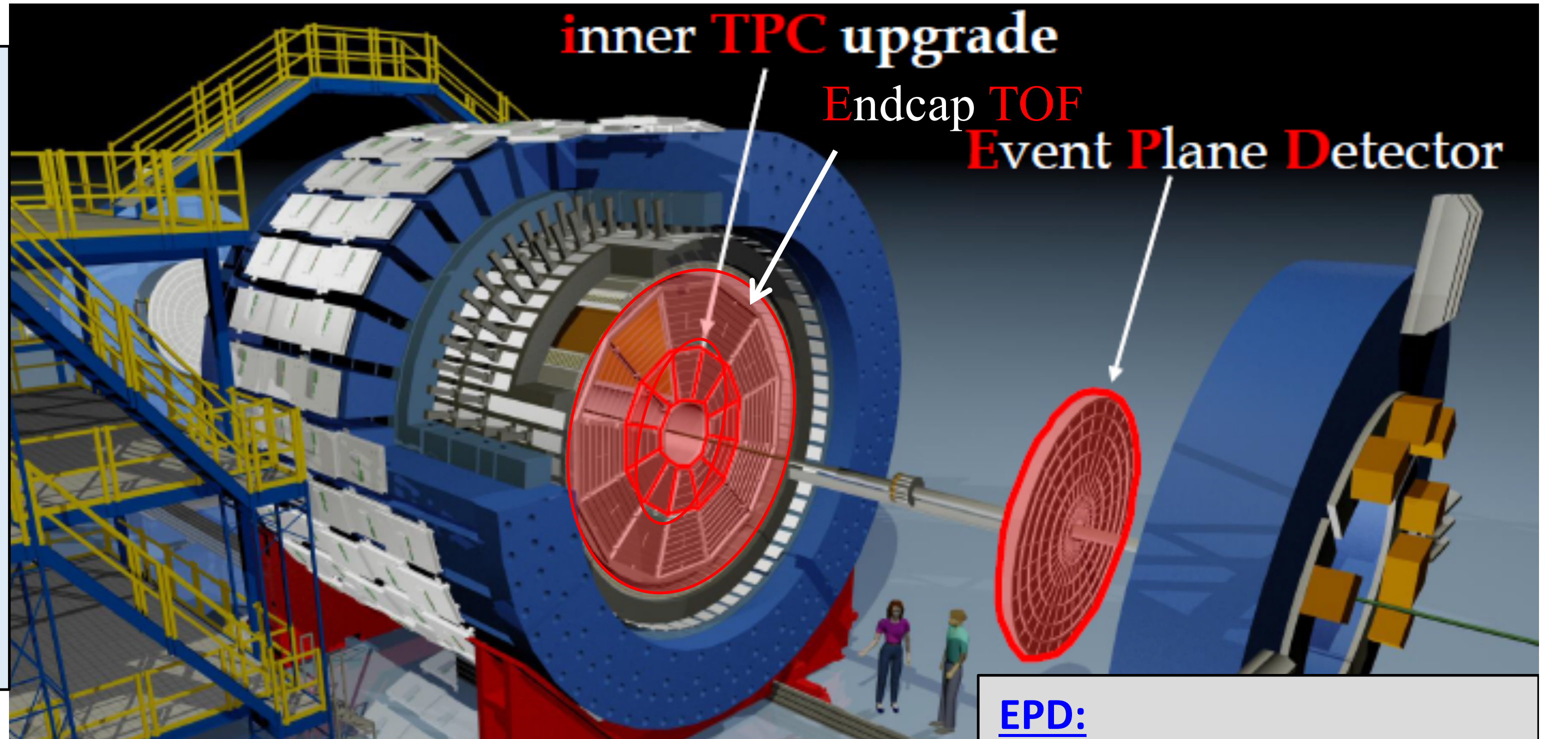




STAR in 2021

iTPC:

- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends h coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c



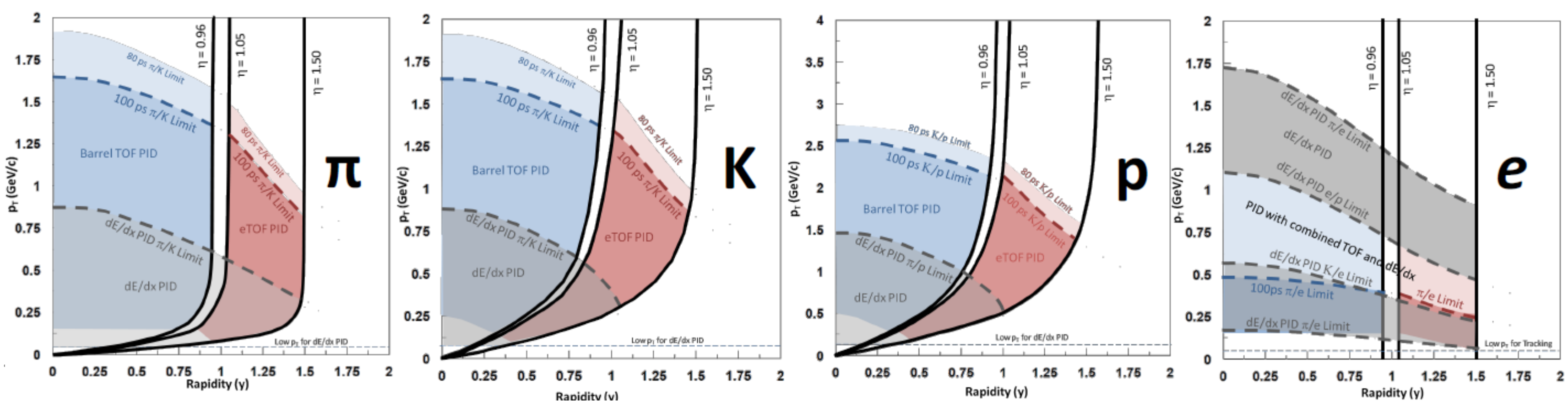
EndCap TOF:

PID at η = 0.9 to 1.5

EPD:

- Improves trigger
- Reduces background
- Allows a better and independent reaction plane

π,K,p,e Acceptance and PID capabilities with the combination of iTPC and eTOF.



Forward Instrumentation for STAR Upgrade (I)

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

Calorimeter System

Intensive R&D work on both ECal and HCal as part of STAR and EIC Detector R&D

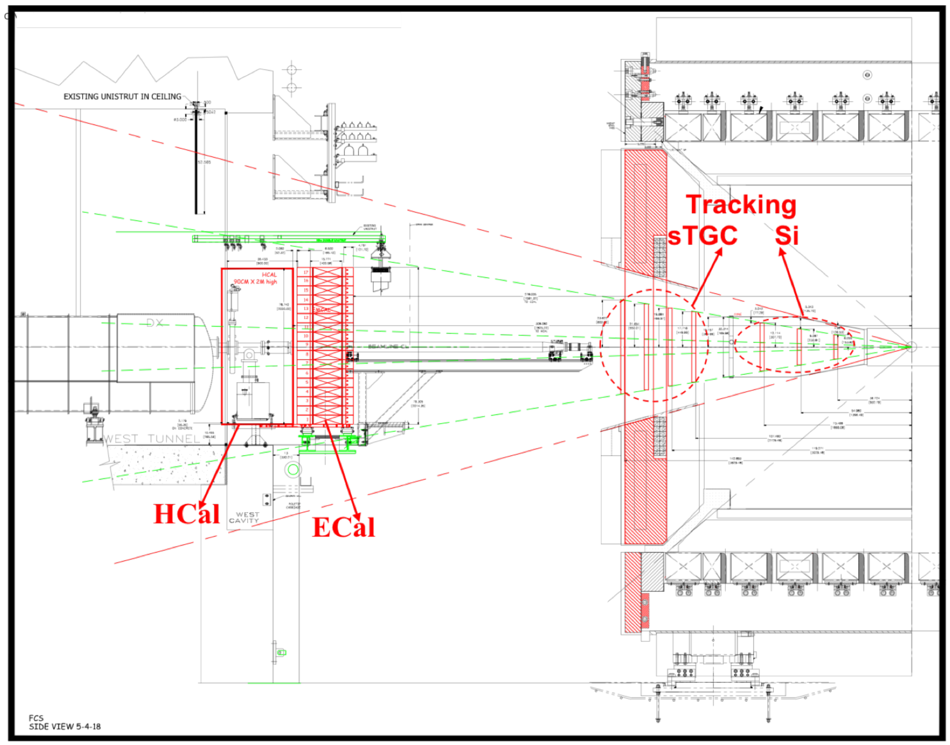
- ➢ Beam tests and STAR in situ tests
- ➢ System optimized for cost and performance
- ➢ Same readout for both calorimeters → cost

ECal Reuse PHENIX PbSC calorimeter with new readout instead of W/ScFi SPACAL

- ➢ Significant cost reduction ☺
- ➢ Non-compensating calorimeter system ☹

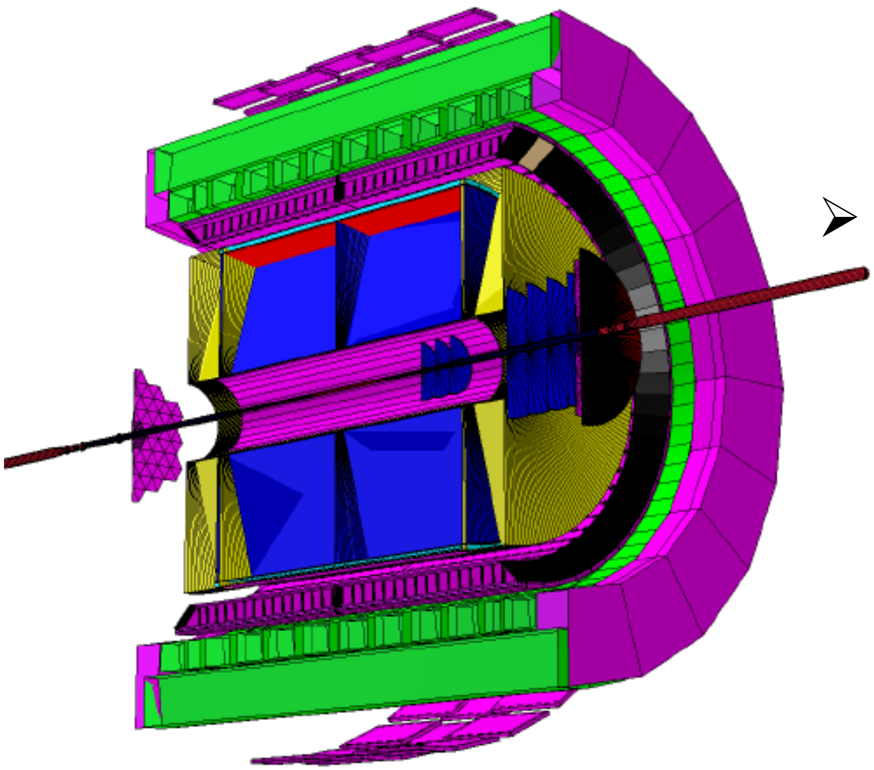
HCal: Sandwich iron-scintillator plate sampling calorimeter.

Side View



Forward Instrumentation for STAR Upgrade (II)

Si + Small-strip Thin Gap Chambers

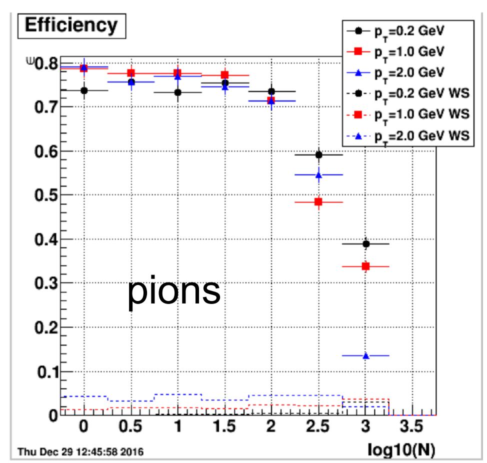


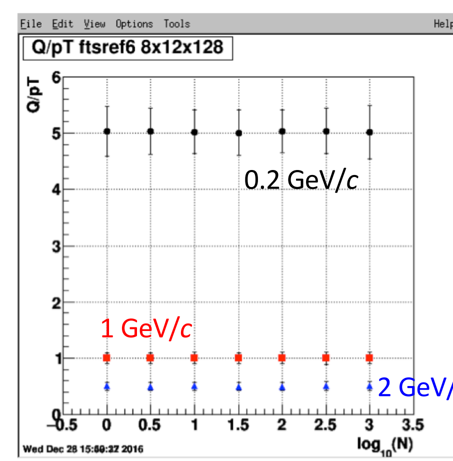
3 Silicon disks + 4 sTGC disks

- Si- disks: 90, 140, 187 cm from IP
  Built on successful experience with STAR IST
  → Single-sided double-metal mini-strip sensors
  → Granularity: fine in ϕ and coarse in R
  → Reuse of the IST cooling system
- sTGC: 270, 300, 330, 360 cm from IP (outside Magnet)
  → Position resolution: ~100 μm
  → Material budget: ~0.5% per layer, 2 layers / disk
  → Readout: reuse current STAR TPC electronics

Momentum resolution:

20-30% for $0.2 < p_T < 2$ GeV/c
track finding efficiency: 80%@100 tr/ev

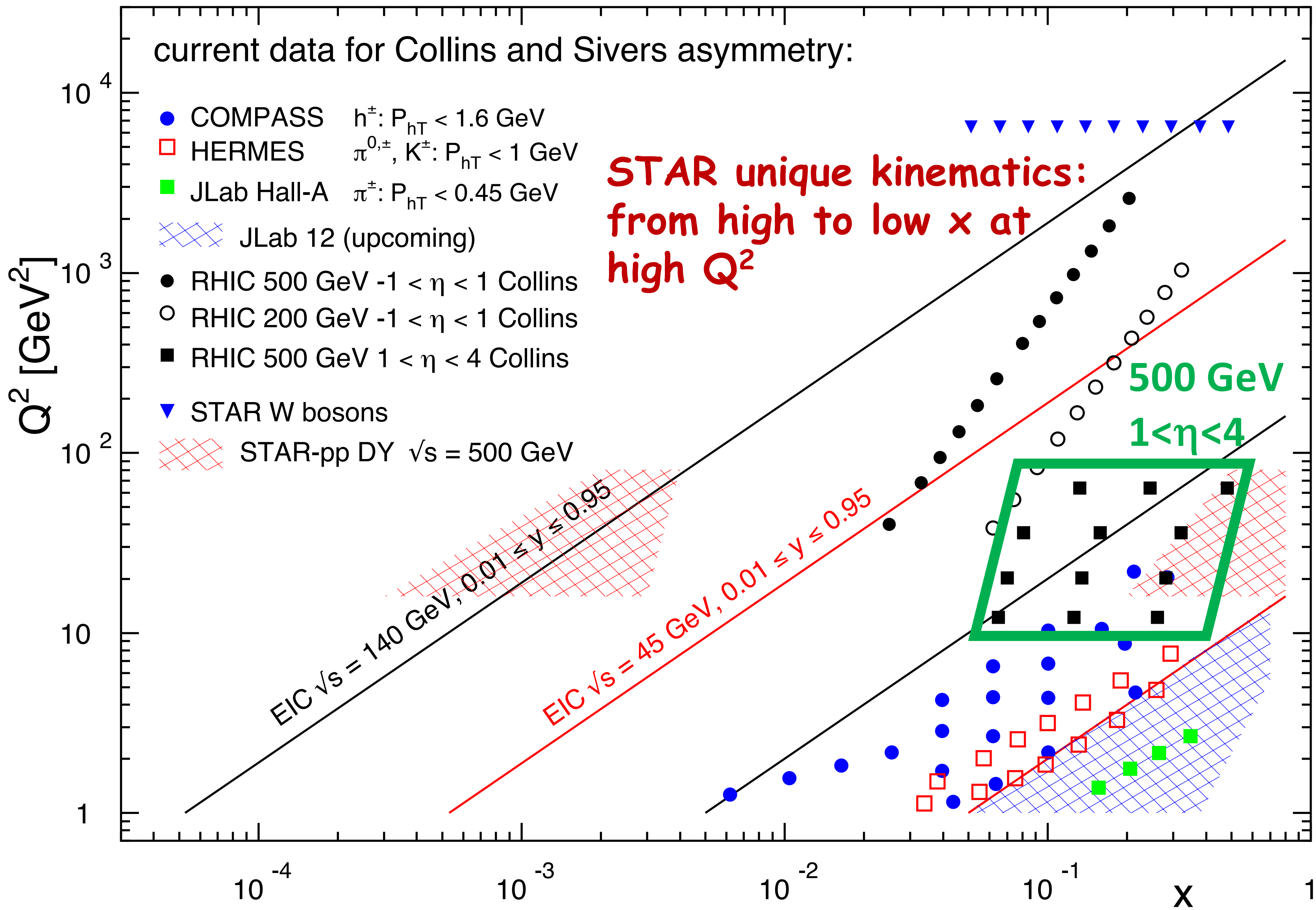




TMDs at STAR (I)

Pushing forward => higher x:

$0.05 \lesssim x \lesssim 0.5,\ 10 \lesssim Q^2 \lesssim 100\ \mathrm{GeV}^2$



TMDs at STAR (II)

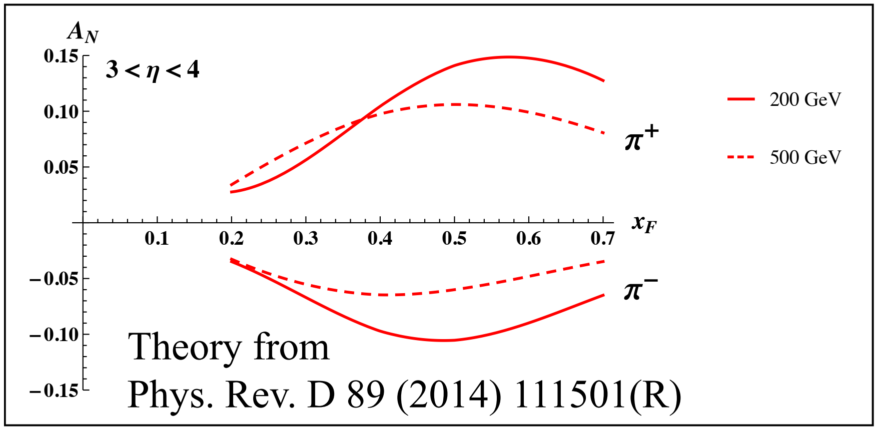
Unique Opportunities:

- constrains TMD evolution
- are TMDs relevant in the gluon and sea-quark dominated regime?
- high precision data sets to test QCD concepts of factorization and universality

→ **answers critical to have a optimal TMD program at EIC**

Goals:

- Increase statistics for A_N DY from 2017
  - → TMD evolution world best constrain
    - ← → $A_N(W^{+/-} Z^0)$
  - → Sivers sign change
- Unravel the mystery what is the underlying process of A_N
  - → measure A_N for $\pi^{+/-}$
  - → clear prediction of importance of special Collins like FF
- flavor tagging of the Twist-3 equivalent of the Sivers fct.
  - → Observable $h^{+/-}$ with z > 0.5 in jet

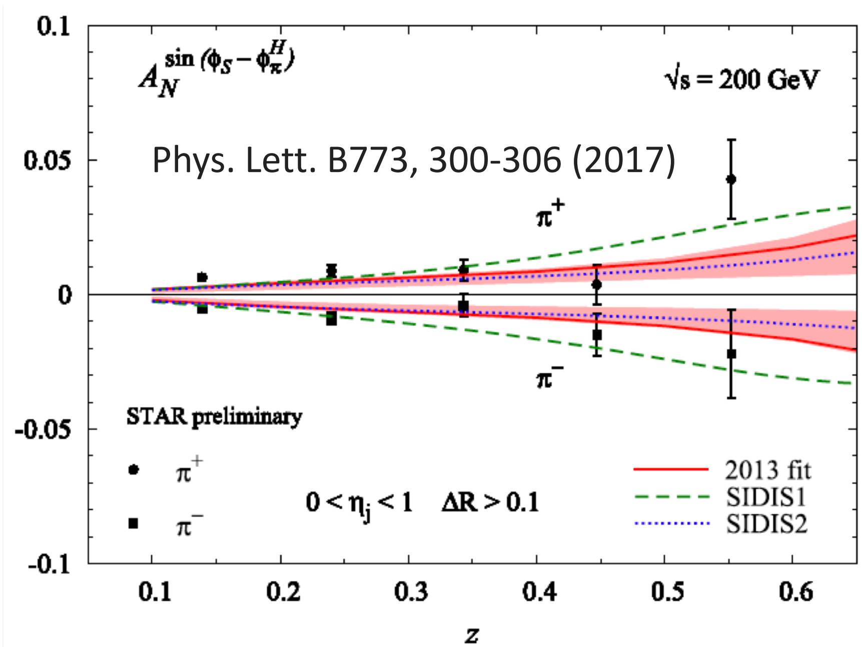


TMDs at STAR (III): Collins

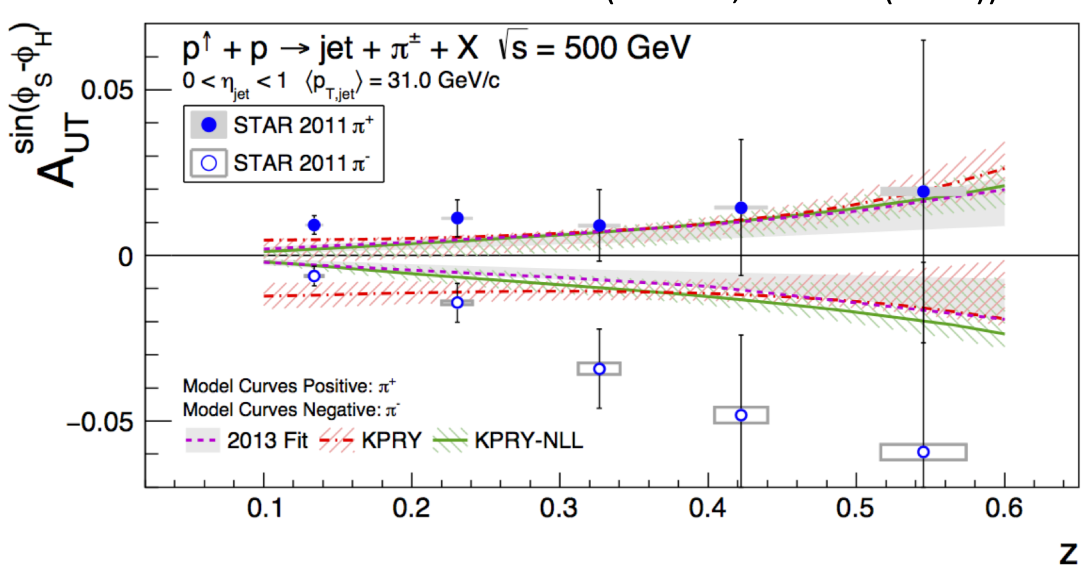
200 vs. 500 GeV Comparison:

- First observation of a TMD at low x and high Q^2
- Evolution: 200 GeV ←→ 500 GeV factor 3 in Q
- Test of factorization & Universality
  - → compare with transversity from IFF
  - → compare with SIDIS and e+e-
- Inspired a lot of theory work
  - → proof of factorization: Kang et al. arXiv:1705.08443
  - → asymmetry calculation: Kang et al. arXiv:1707.00913

$$A_{UT}^{\pi^\pm} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u})\Delta D_{q_1}^{\pi^\pm}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{\sigma}_{UU} D_{q_1}^{\pi^\pm}(z,j_T)}$$

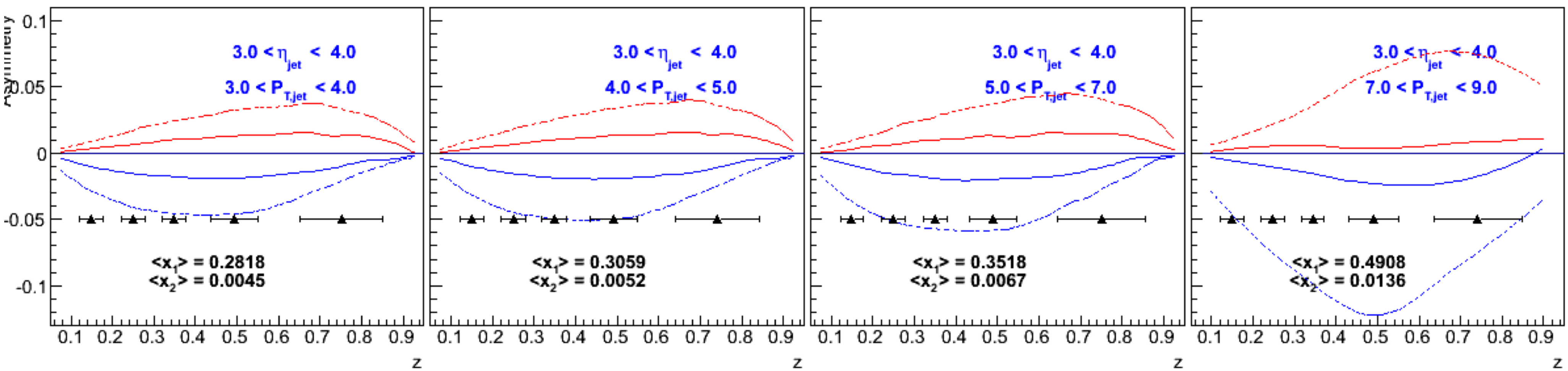


STAR arXiv:1708.07080 (PRD 97, 032004 (2018))



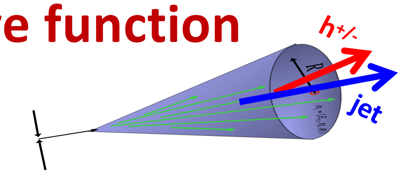
First Sign TMDs survive at low x and high Q^2

TMDs at STAR (III): Transversity



Transversity is the 3rd PDF critical to fully describe the Proton wave function

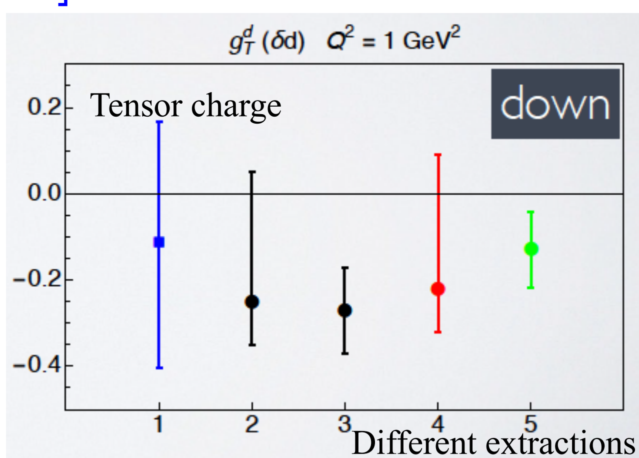
- Measure at high x via hadron in jet: p + p → jet($h^{\pm}$)

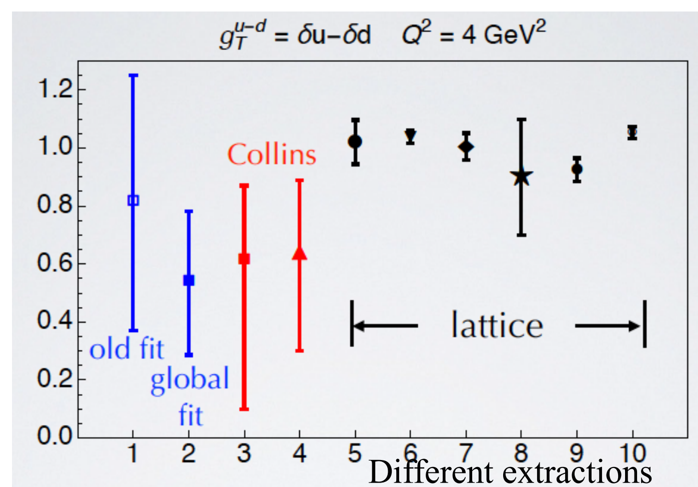


Understating transversity enables constraints of tensor charge

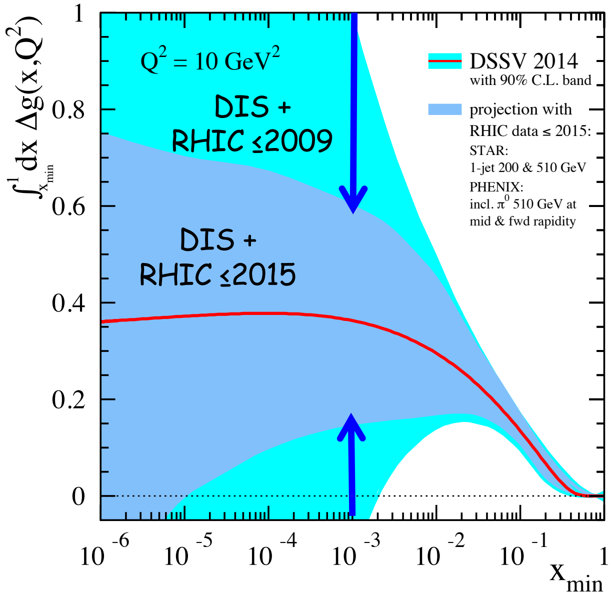
- tensor charge useful for low-energy explorations of BSM, but precision required.

$$\delta q^a = \int_0^1 \left[\delta q^a(x) - \delta \bar{q}^a(x)\right] dx$$





Gluon Polarization



Data till 2009

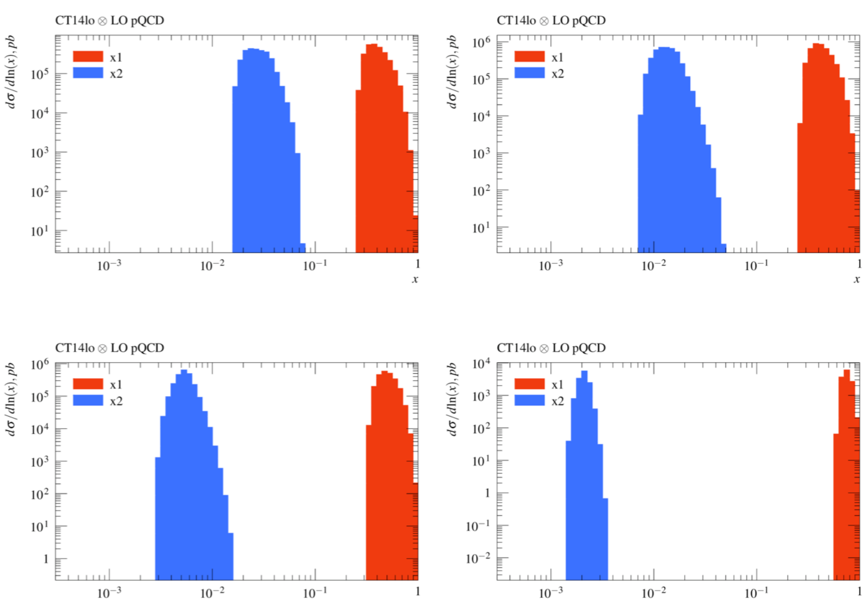
$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} \text{ @ } 10\ \text{GeV}^2$$

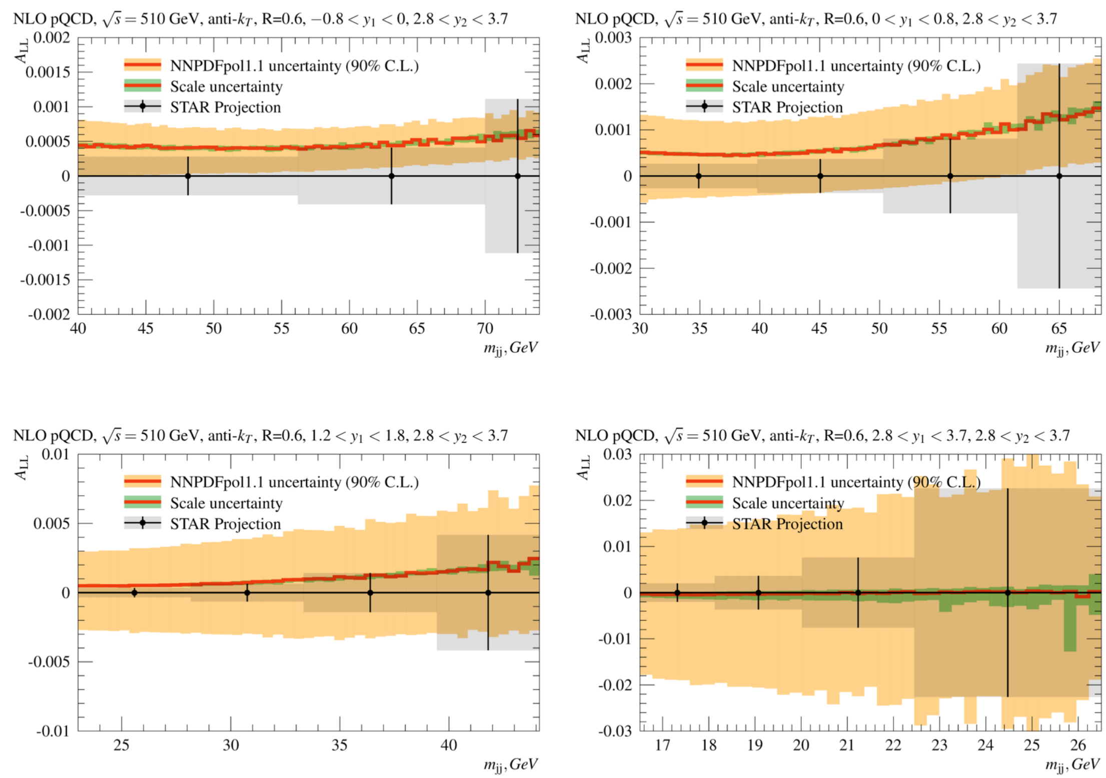
STAR and PHENIX data till 2015 reduce uncertainties at $x \sim 10^{-3}$ by factor 2

Only way to constrain low x further

→ go forward

Di-Jets@2.5 < η < 4.0

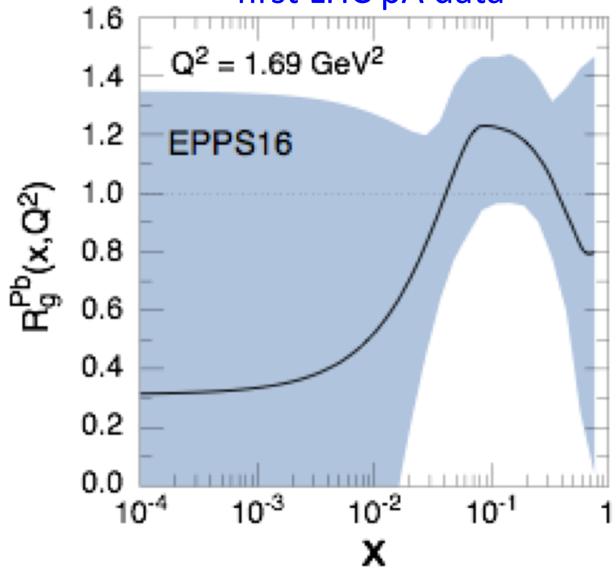




Initial State of Nuclei

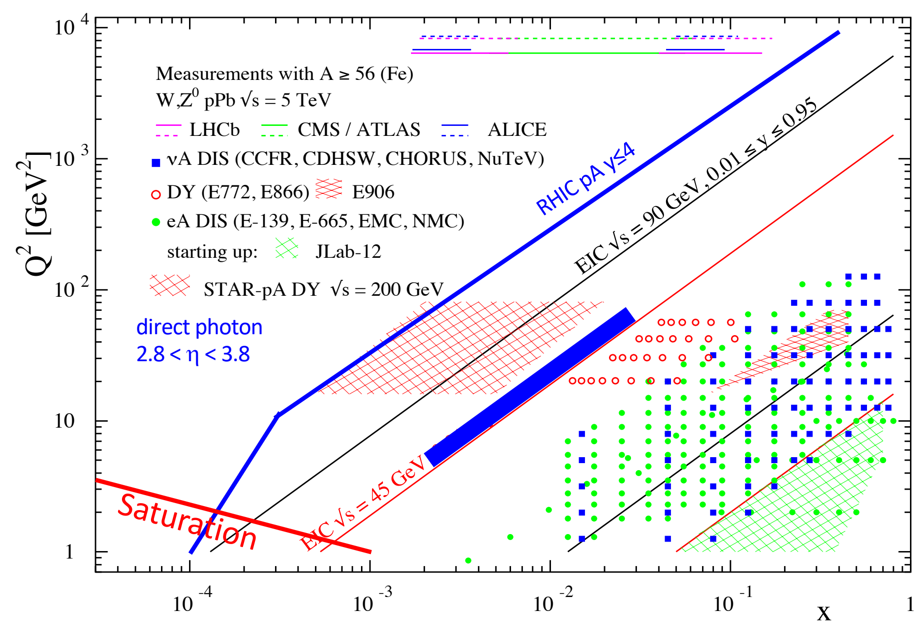
- **Understanding the initial state of heavy nuclei is critical to RHIC and LHC programs**
  - Knowledge currently limited when compared to our knowledge of free protons
- **Opportunities with pA@RHIC:**
  - Can measure nuclear PDFs (nPDFs) in a x-Q^2 region where nuclear effects are large
    - $Q^2 > Q_s^2$ over a wide range in x
  - Access to observables free of final state effects
    - Gluons: R_{pA} for direct photons
    - Sea-quarks: R_{pA} for DY
  - Access to saturation region at forward rapidities
  - Capability to scan A-dependence prediction by saturation models

Current knowledge including first LHC pA data



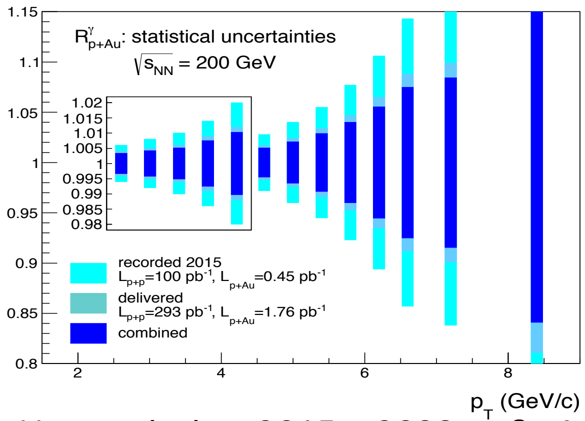
EPJ C77, 163 (2017)

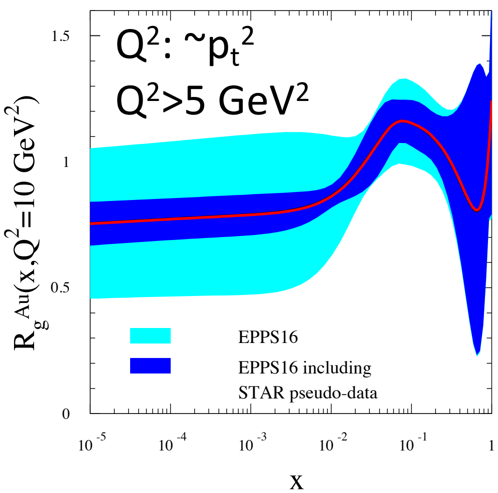
pA@RHIC: unique kinematics



Nuclear PDFs

pA: Direct Photon@2.5 < η < 4.5





Uncertainties: 2015 + 2023 pp&pA

Probe gluon nPDF via forward direct-γ

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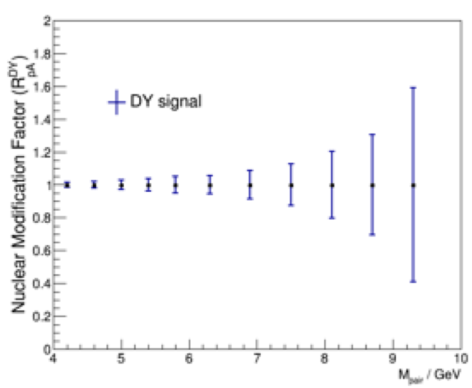
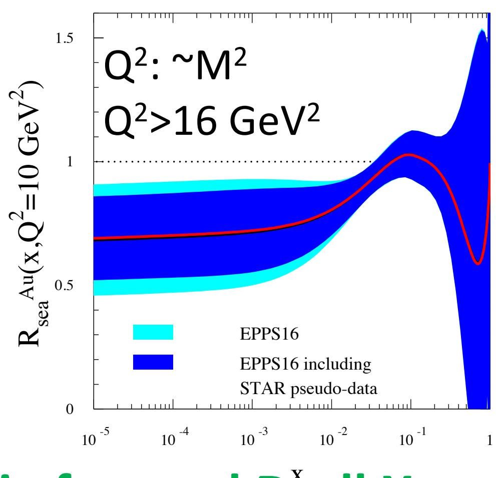
pA: Drell-Yan@2.5 < η < 4.5



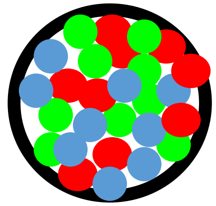


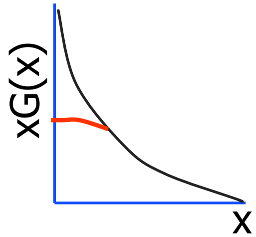
Uncertainties: 2023 pp & pA

Probe sea-quark nPDF via forward Drell-Yan

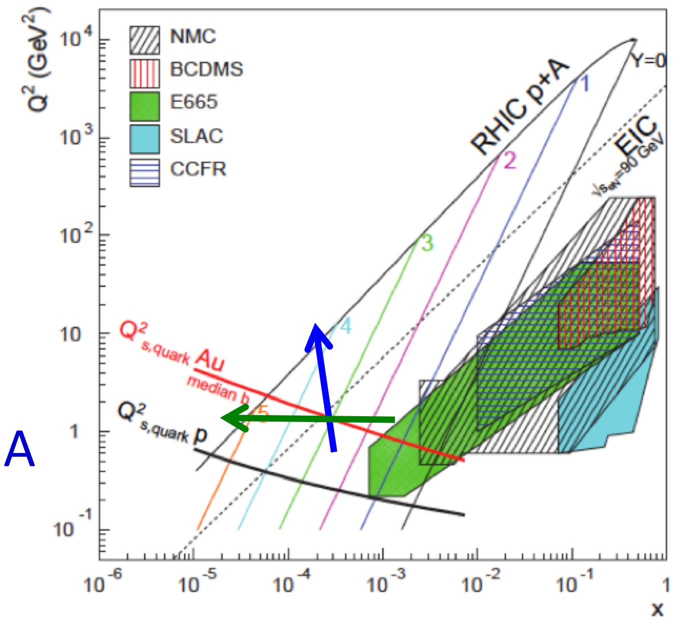
- Pilot measurements from 0.45 pb^{-1} p+Au and 1 pb^{-1} p+Al taken in 2015
- Planned 2023 runs -> significant impact on global analyses
- Sensitive to $10^{-3} \lesssim x \lesssim 10^{-2}$ and $6 \lesssim Q^2 \lesssim 40$ GeV^2 where nuclear modifications should be significant
- Complimentary observables and kinematics with EIC
- Precision of pA data-> enable stringent test of nPDF universality when combined with data from EIC

Saturation

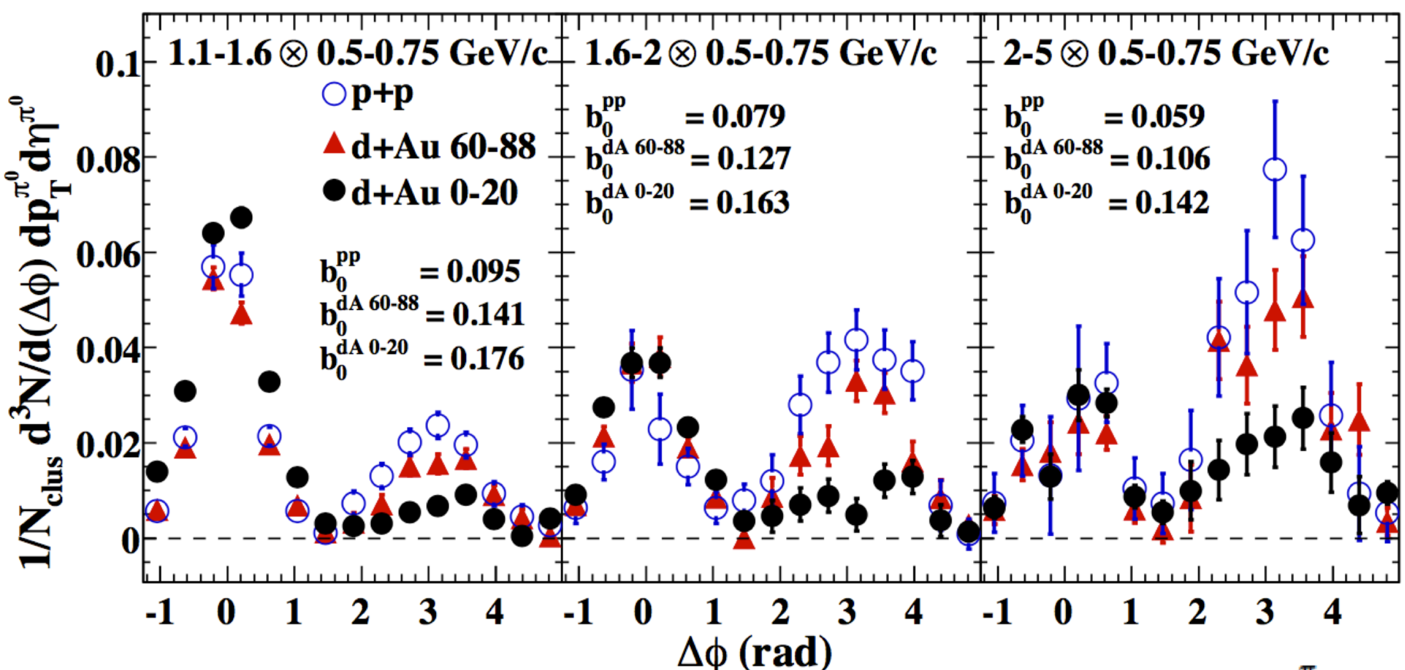


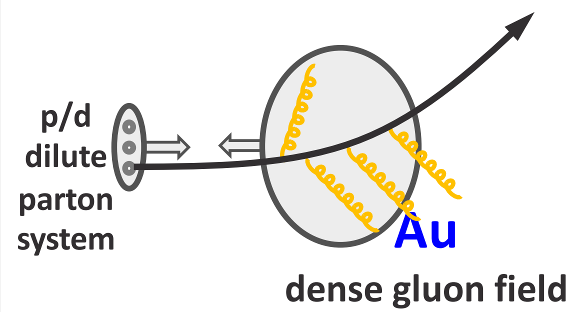


- Evidence seen at HERA, RHIC, and LHC → alternative explanations remain
- Key observable at RHIC: **Di-hadron correlations**
- Scan in x → study the evolution of Q_s^2 in x
- Scan A-dependence → study the evolution of $Q_s^2(x)$ vs. A
- Resolve ambiguity what causes the suppression in dAu



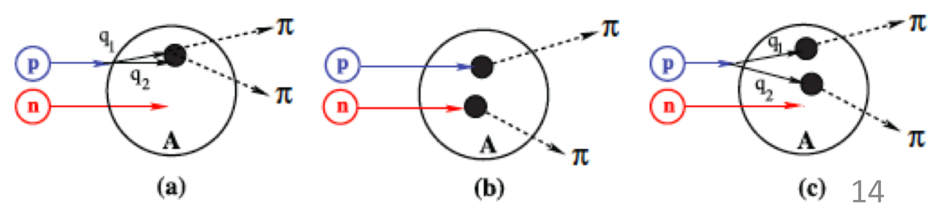
PHENIX Phys. Rev. Lett. 107, 172301 (2011)





CGC predicts suppression of back-to-back correlation

dA: alternative explanation through double interactions



Saturation with Forward Upgrade

Future increased luminosity+upgrades enables additional probes, e.g. forward γ + jet.

- Sensitive only to dipole gluon density
- Sample $0.001 < x < 0.005$ for both γ and jet in range $1.3 < \eta < 4.0$ with $p_T > 3.2$ GeV/c^2
- Complement with probes, e.g. $\gamma + h$ and di-jet

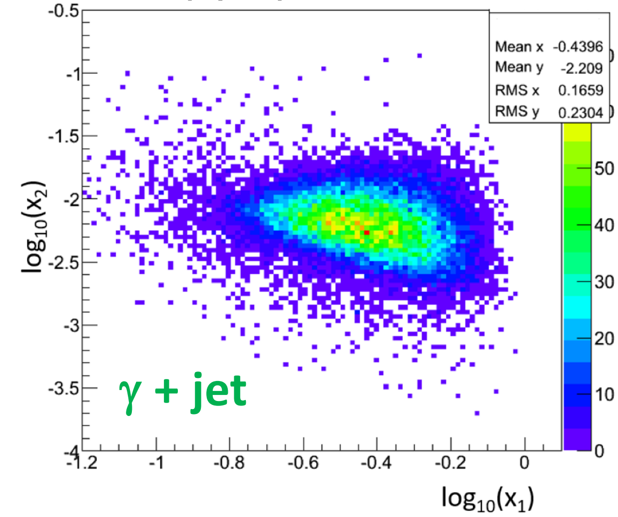
→ **rigorous test of theory predictions**

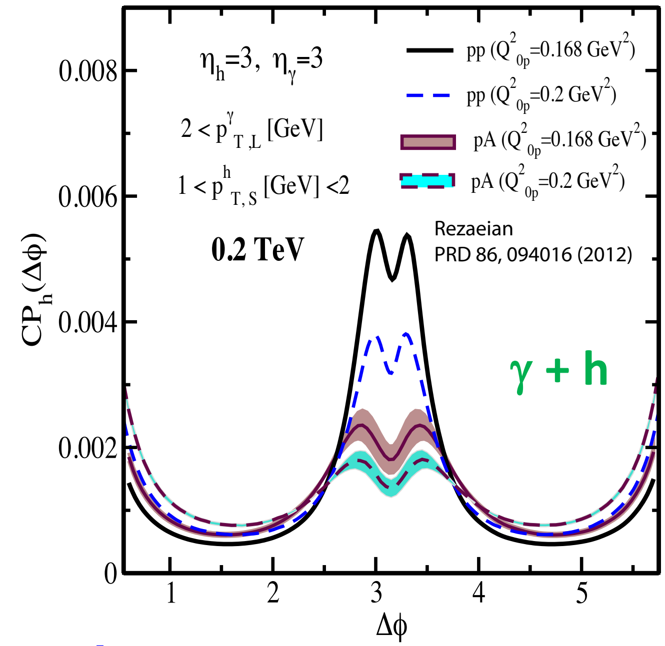
→ **get a handle on the different gluon distributions**

→ **provide variety of high precision data to test universality of CGC ←→ EIC**

→ **study of evolution/universality of Q_s^2 with A and x for different probes**

jet-hadron / jet photon correlations





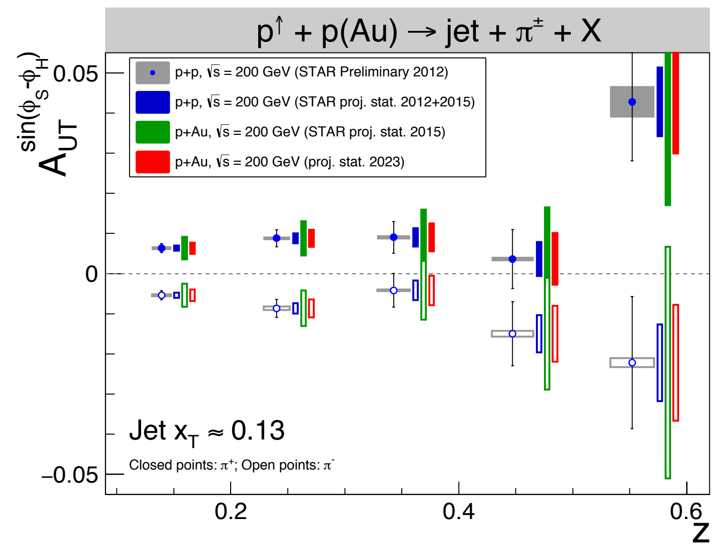
→ 1M events with forward upgrade in 2023 pAu and pAl

Summary of Forward pp & pA Measurements

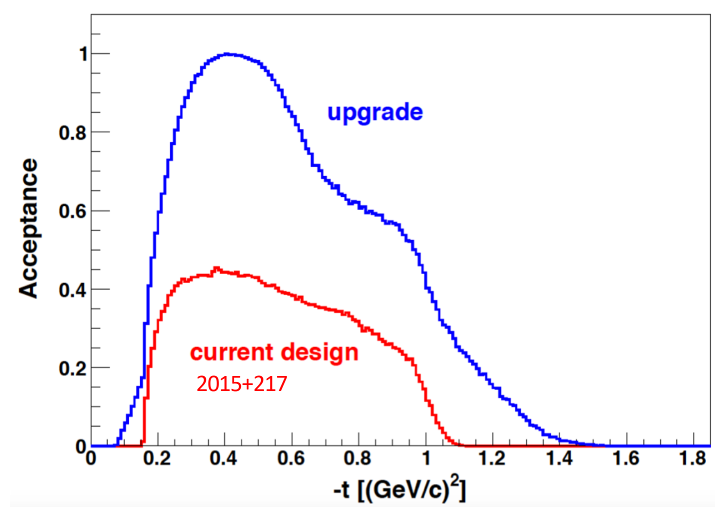
	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
Potential future running	2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal

Opportunities at Midrapidity

- **Related Studies at Midrapidity**
  - ✓ Fragmentation functions in pp and pA, e.g. through hadrons within jets
  - ✓ Nuclear modification of hadronization, e.g. through Collins effect in pA
- **Diffractive Physics**
  - ✓ SSA for UPC J/Ψ production → GPDs
  - ✓ Di-jets in UPC → gluon Wigner function (arXiv:1706.01765)
  - ✓ R_{pA} for diffractive events → saturation

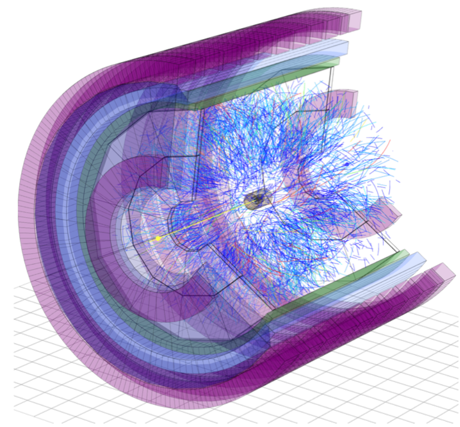


STAR Roman Pot the optimal tool to tag diffractive processes



Much, much more: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669

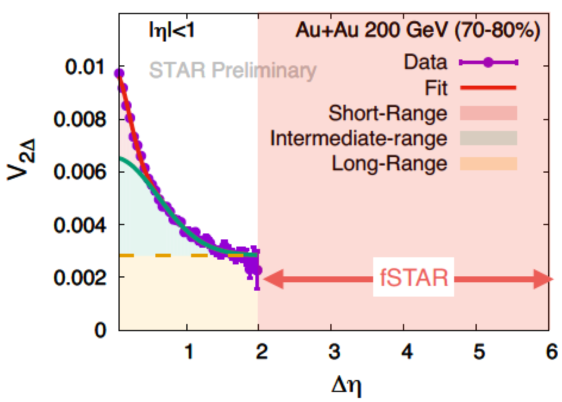
Opportunities in AA Collisions

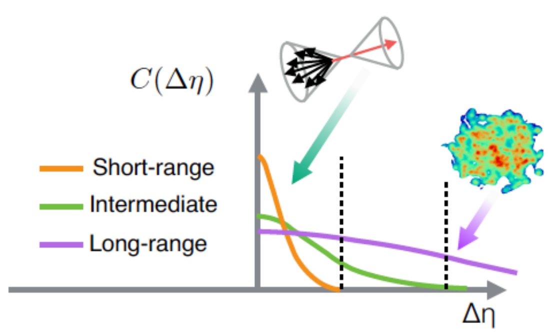


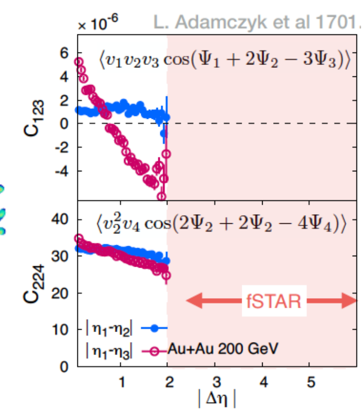
The forward STAR upgrade unique opportunity to:

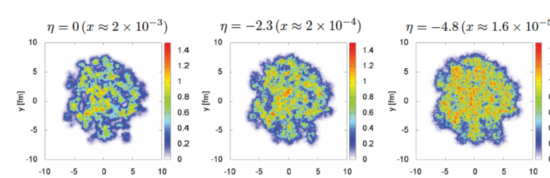
study the structure of the initial state that leads to breaking of boost invariance in heavy ion collisions and to explore of the transport properties of the hot and dense matter formed in heavy ion collisions near the region of perfect fluidity.

Physics Measurements		Longitudinal de-correlation $C_n(\Delta\eta)$ $r_n(\eta_a,\eta_b)$	η/s(T), ζ/s(T)	Mixed flow Harmonics $C_{m,n,m+n}$	Ridge	Event Shape and Jet-studies
Detectors	**Acceptance**					
Forward Calorimeter **(FCS)**	$-2.5 > \eta > -4.2$ E_T (photons, hadrons)	One of these detectors necessary		One of these detectors necessary	Good to have	One of these detectors needed
Forward Tracking System **(FTS)**	$-2.5 > \eta > -4.2$ (charged particles)		Important		Important	









Summary

- STAR results play a central role in expanding the frontier of cold-QCD
- The forward upgrade builds upon the strengths of STAR to establish innovative and precision probes
  - to address critical questions, now
  - to fully realize the scientific promise of the future EIC
- Strongly endorsed by the RHIC PAC:
  - …a rich program for future operation after BES II that addresses many important and innovative topics in p + p, p + A and A + A physics.
  - …would enable studies of novel reaction channels…of interest to hadron structure and QGP physics alike.

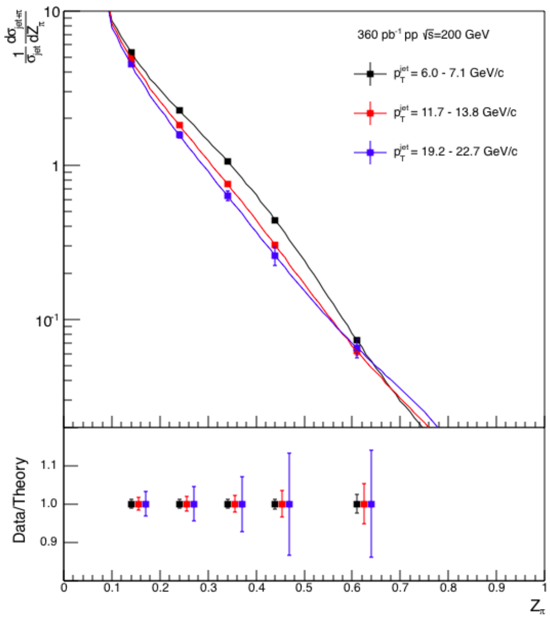
Additional slides …

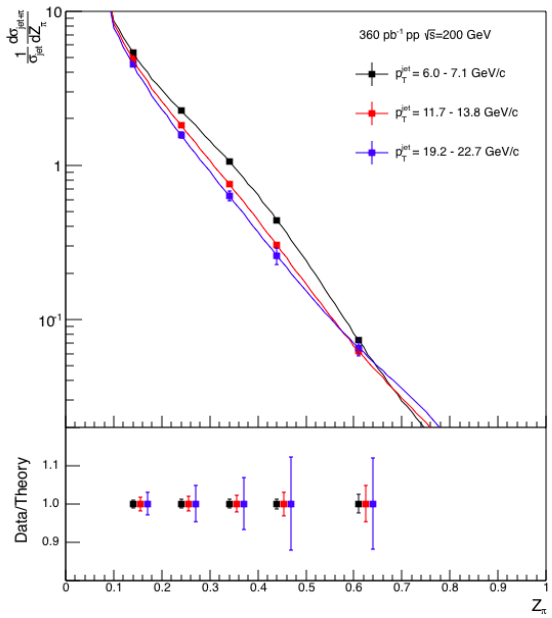
Fragmentation Functions in pp & pA

Observable: hadron in jet

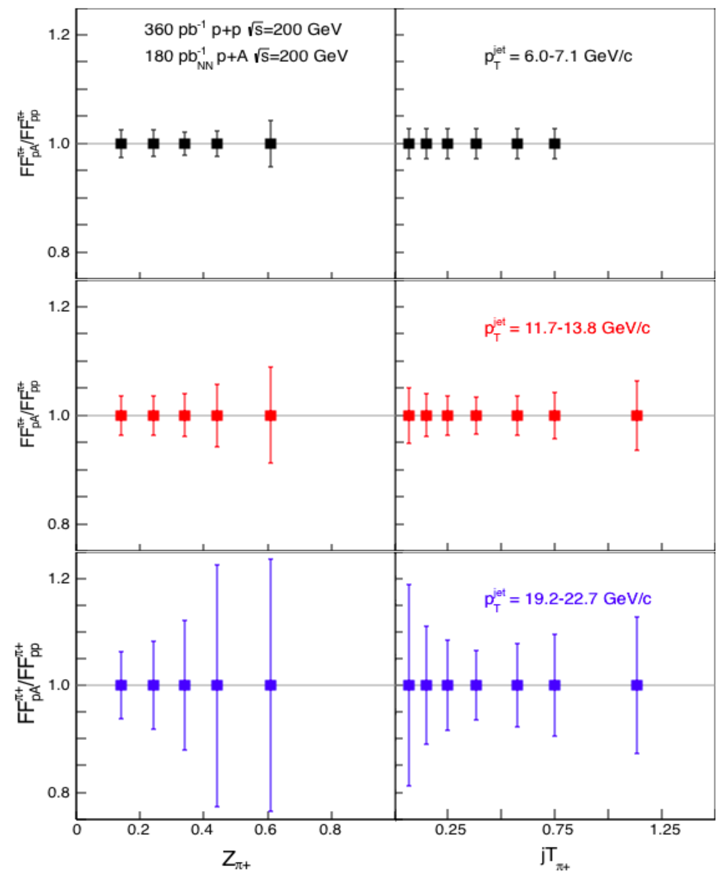
p+p:

$\pi+$ $\pi-$

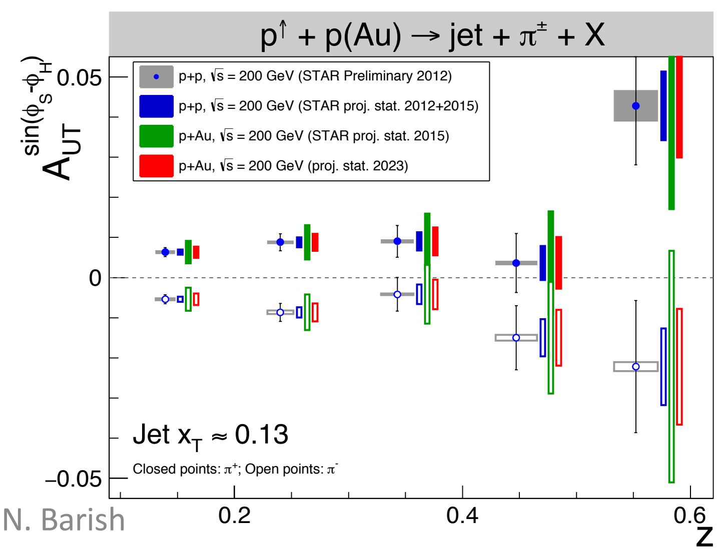




Fragmentation functions in p+A/p+p at $|\eta| < 0.4$



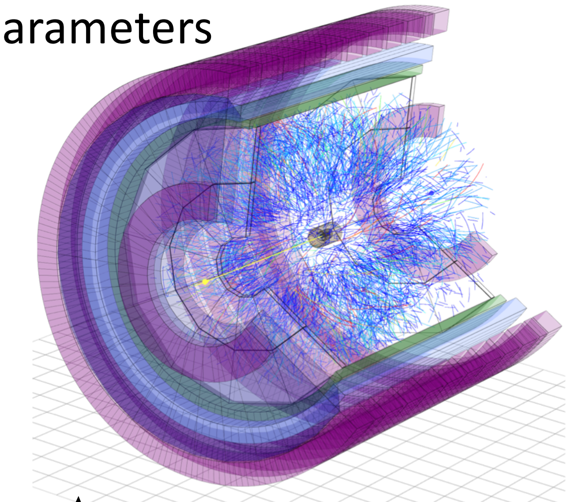
only at RHIC: measure nuclear effects for polarized FF → nCollins



Opportunities in AA Collisions (I)

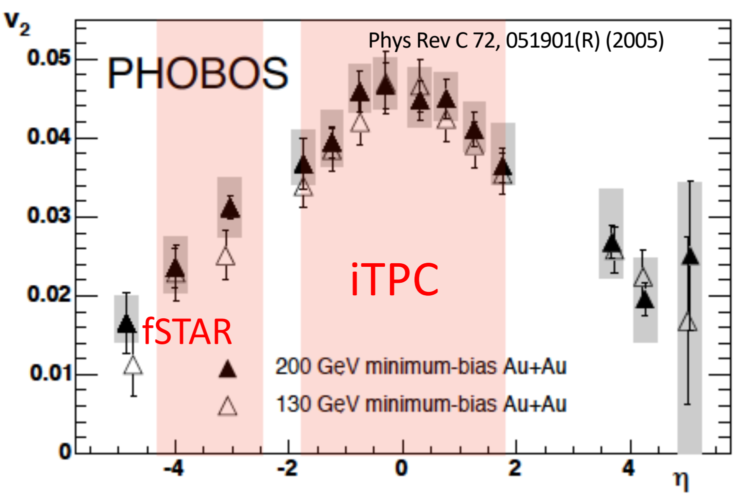
Goal : Measurements of global observables in heavy ion collisions over wide range of rapidity

- ➢ Constraining longitudinal structure of the initial stages of HICs
- ➢ Constraining the temperature dependence profile of transport parameters



Till today:

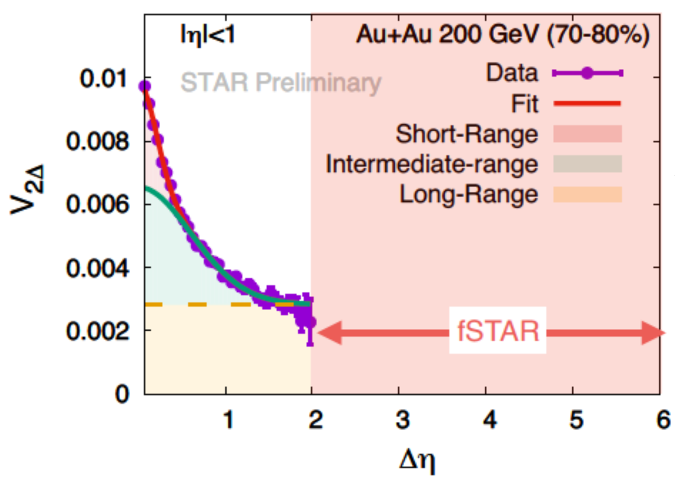
No RHIC data for higher order flow harmonics (v_3, v_4, v_5) & rapidity density correlations/fluctuations $\left\langle \frac{dN}{dY_1}\frac{dN}{dY_2} \right\rangle$



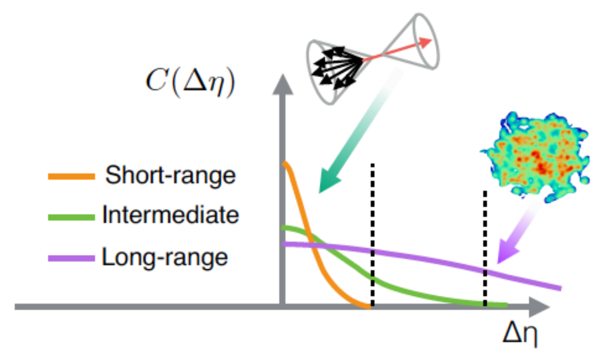
Why do we need wider window in rapidity?

- ➢ Flow like correlations are early time long-range → large Δη
- ➢ Background comes from Jets & non-flow → small Δη

Precise extraction of flow (azimuthal correlations) requires measurements over wide window of rapidity



$$V_{2\Delta} = \left\langle \cos\left(2\left(\phi_1(\eta_1) - \phi_2(\eta_2)\right)\right)\right\rangle$$

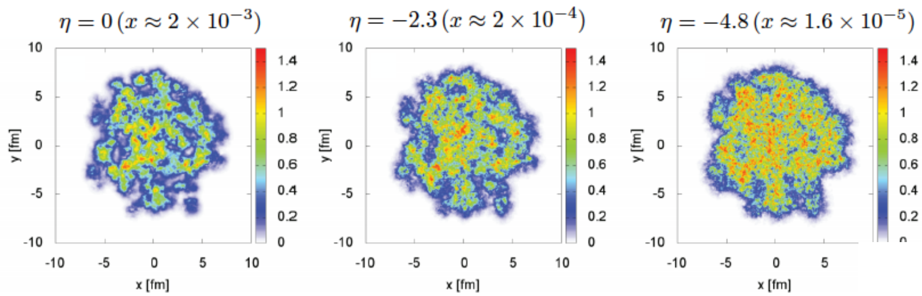


Opportunities in AA Collisions (II)

Long-range two particle correlations are of great interest → ridge in small systems

Rapidity ←→ x

Schenke, Schlichting 1605.07158

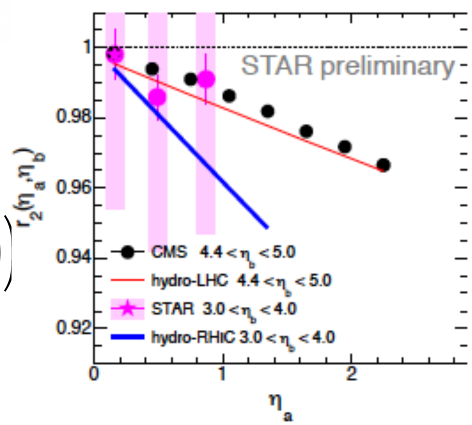


Rapidity evolutions → predictions of non-linear regime of High energy QCD effective theory (CGC)
→ LHC data provide constrains for BK, JIMWLK, RHIC data will provide test

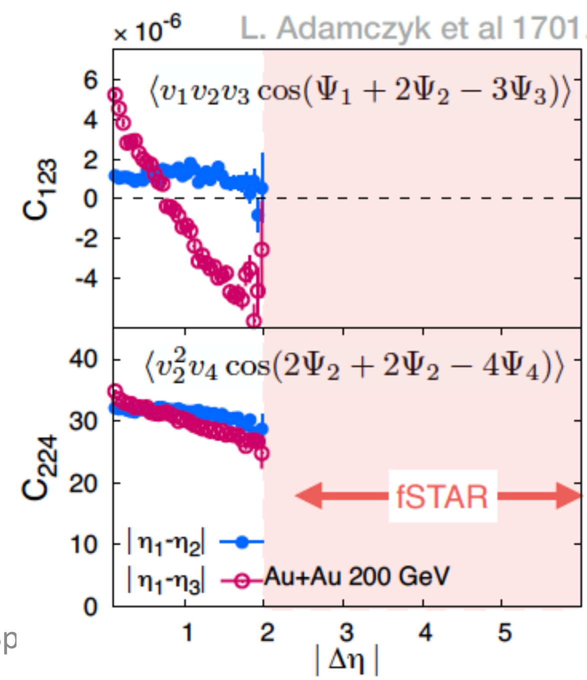
Observables:

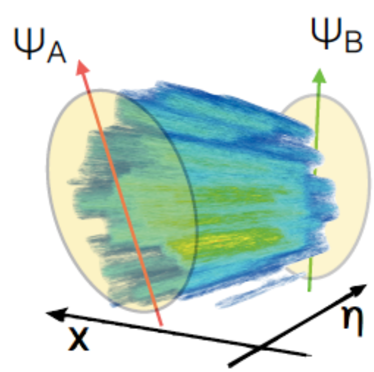
$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$

$$V_{n\Delta} = \langle \cos(n(\phi_1(\eta_1) - \phi_2(\eta_2))) \rangle$$



Stronger De-correlation predicted at RHIC than LHC





Measurement from STAR with existing detectors :

- Hint of longitudinal de-correlations
- Wider Δη can probe this in more details

BNL PAC Recommendations

2017:

- As the physics program that is foreseen for forward physics is substantial, full utilization of future polarized proton beam time must be made to realize the proposed forward physics program.
- RHIC management is encouraged to find a way to enhance and include a forward physics program at RHIC.

2018:

STAR presented a rich program for future operation after BES II that addresses many important and innovative topics in p+p, p+A and A+A physics. The most interesting of these is focused on forward physics that would be made possible by a forward upgrade covering rapidities up to 4.2 with $5.3 M further investment, and would enable studies of novel reaction channels including several specific diffractive reactions and ultra-peripheral collisions of interest to hadron structure and QGP physics alike. Hadron structure measurements, such as diffractive dijet production, are highly relevant for the physics to be investigated at EIC, both for their e+p and e+A components, and may help to further sharpen the EIC physics case. From the heavy-ion perspective, QGP vorticity and Lambda polarization measurements in peripheral collisions would address vorticity generation at the microscopic level. Several international groups have submitted or are ready to submit proposals to finance most of the needed cost-efficient forward hardware upgrades. We commend STAR for developing and sharpening this option, which enriches the range of future opportunities for BNL. However, to realize a significant fraction of this program, multi-year running will be necessary. We urge the directorate to decide within this year whether the realization of these plans is realistic. A timely analysis of the 2017 data with transverse polarization could set the pace for the data analysis of possible STAR running after BES II and should be given high priority.