IS2021

The VI[th] International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR COLLISIONS

STAR Heavy Ion and Cold QCD program for 2021+ runs

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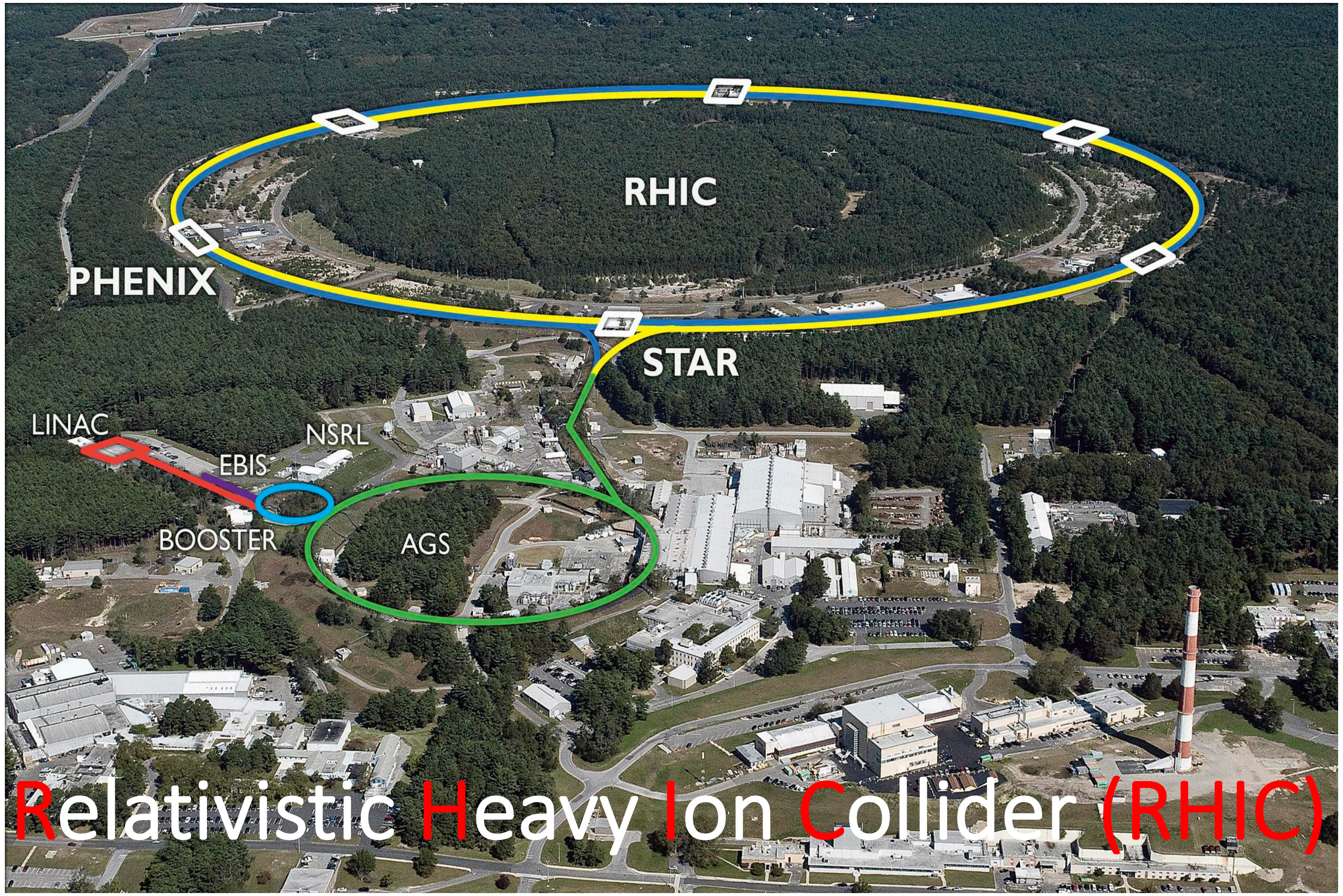
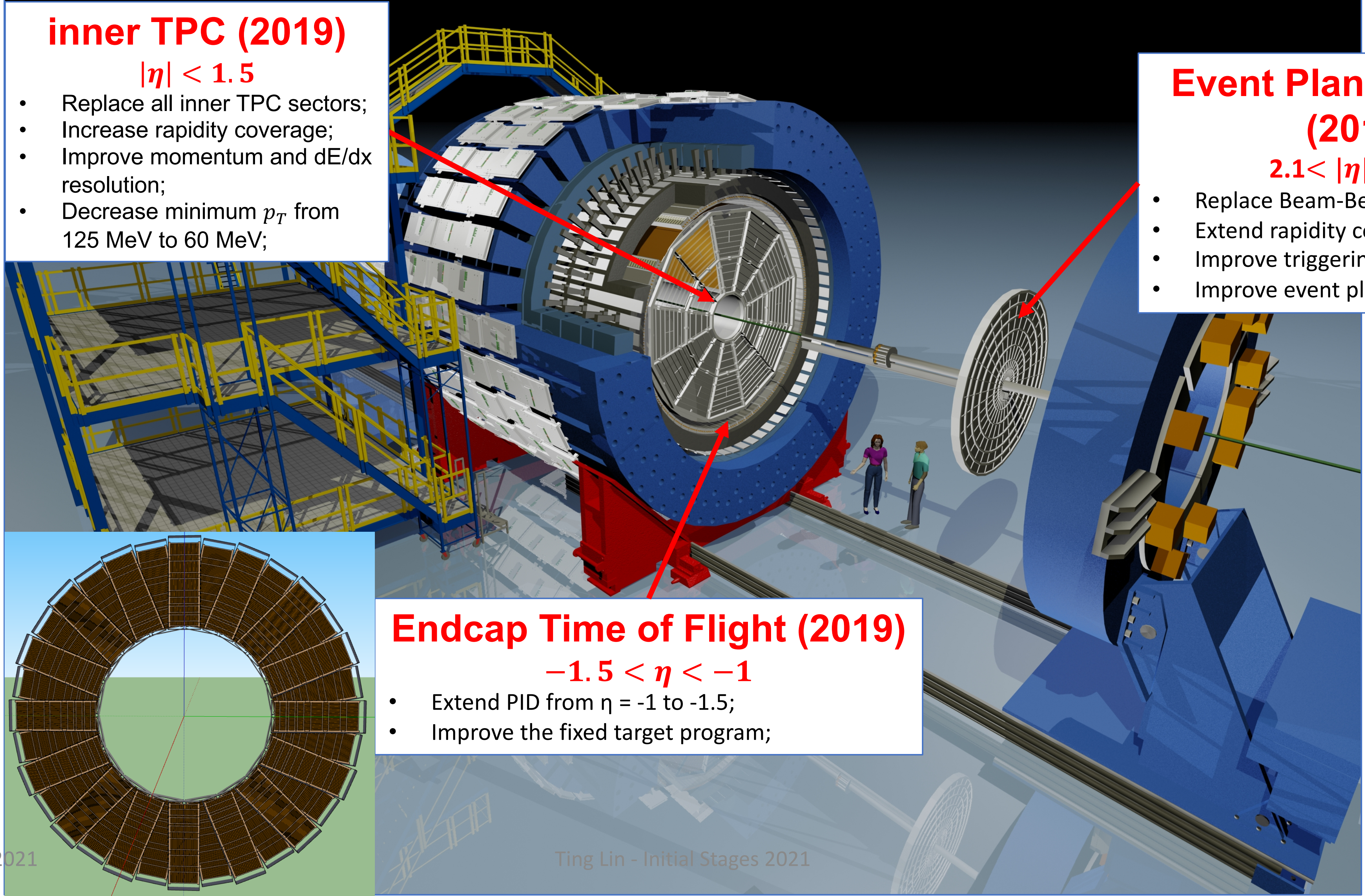
Outline:

- STAR Upgrades
  - Upgrades for BES-II
  - Forward Upgrades
- Heavy Ion Physics for 2021+
- Cold QCD Physics for 2021+
- Summary



STAR Detector Upgrades for BES-II



inner TPC (2019)

$|\eta| < 1.5$

- Replace all inner TPC sectors;
- Increase rapidity coverage;
- Improve momentum and dE/dx resolution;
- Decrease minimum p_T from 125 MeV to 60 MeV;

Event Plane Detector (2018)

$2.1 < |\eta| < 5.1$

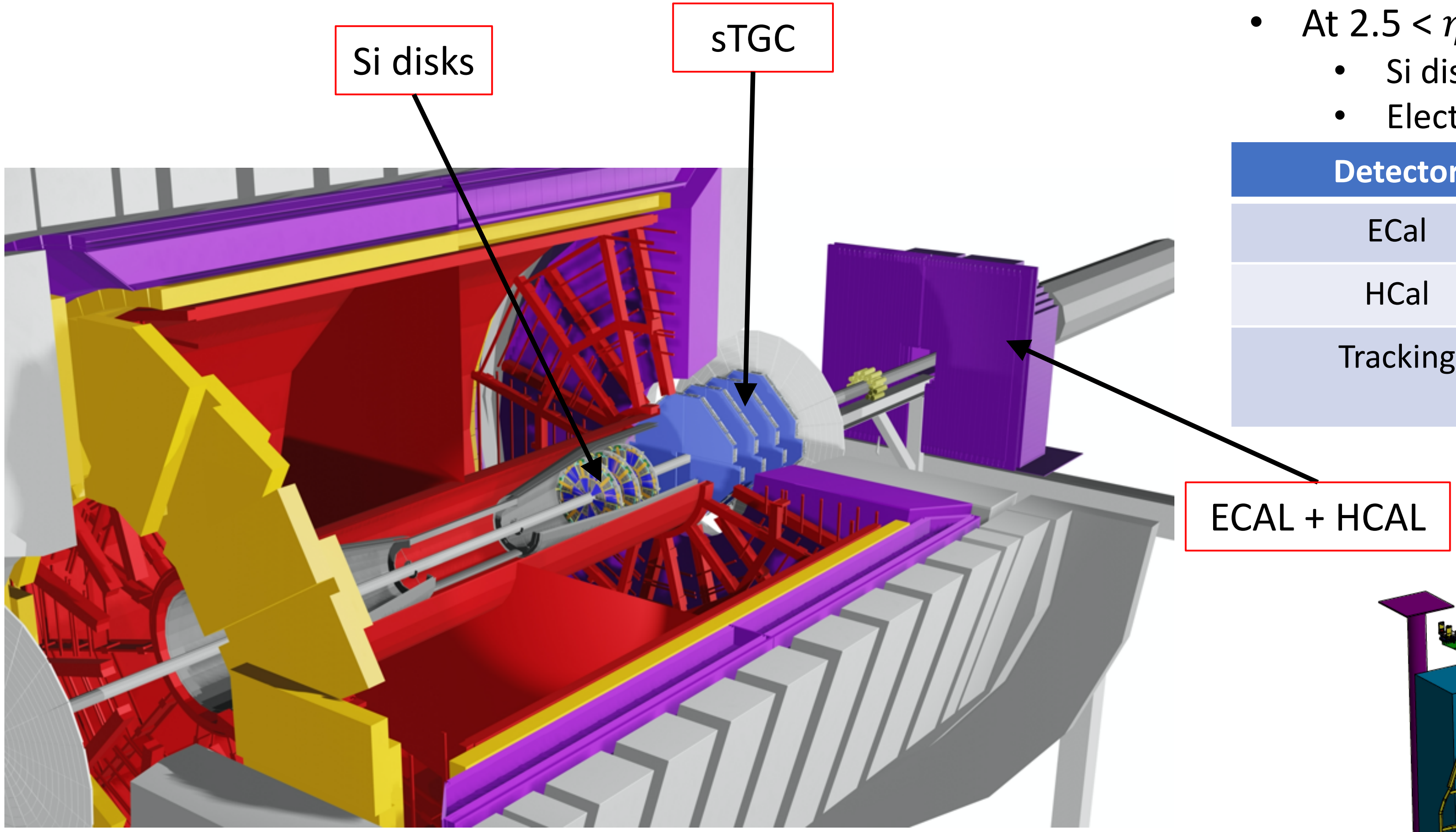
- Replace Beam-Beam Counter (BBC);
- Extend rapidity coverage;
- Improve triggering capabilities;
- Improve event plane resolution;

Endcap Time of Flight (2019)

$-1.5 < \eta < -1$

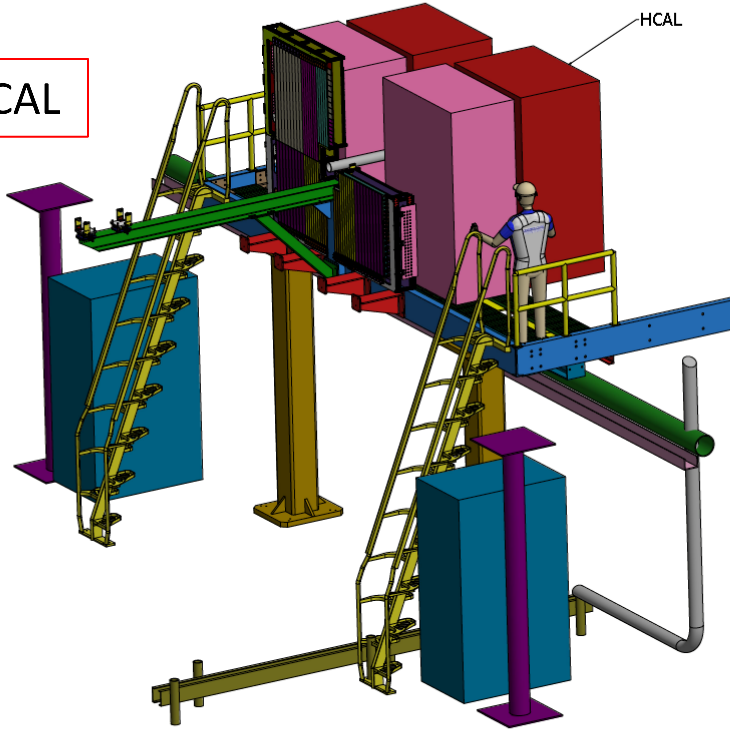
- Extend PID from η = -1 to -1.5;
- Improve the fixed target program;

STAR Forward Upgrade Ongoing:

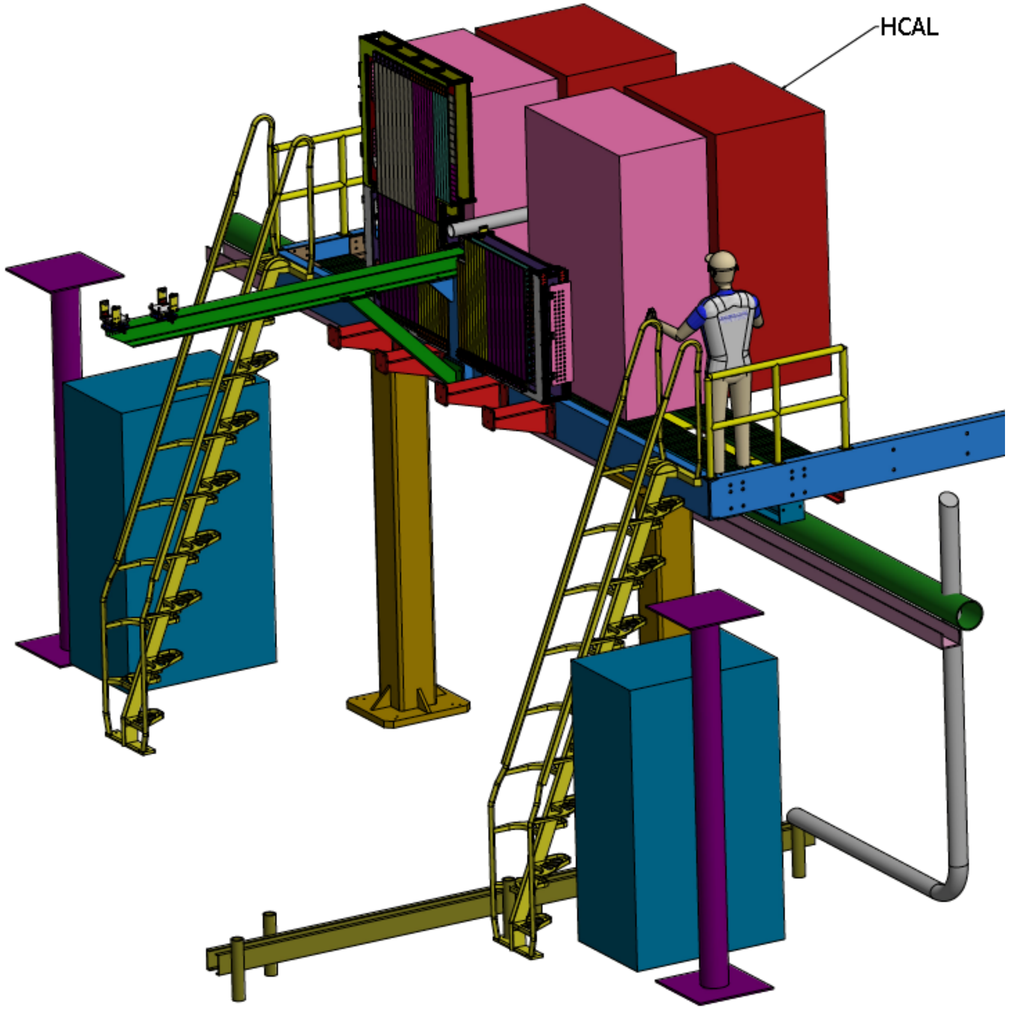


- At $2.5 < \eta < 4$
  - Si disks + Small Thin Gap Chambers (STGC) for tracking;
  - Electromagnetic and hadronic calorimeters;

Detector	p+p and p+A	A+A
ECal	~10%/$\sqrt{E}$	~20%/$\sqrt{E}$
HCal	~50%/$\sqrt{E}$ + 10%	---
Tracking	Charge separation Photon suppression	0.2< p_T < 2 GeV/c, with 20-30% $1/p_T$



STAR Forward Upgrade: ECal & HCal



Location: 7 m from the IP, at $2.5 < \eta < 4$
Readout: SiPMs

- Used in Trigger
- Split in 2 movable halves inside and outside of ring
- Slightly projective

ECal:

- Reuse PHENIX PbSc calorimeter with new readout;
- On front face → 1496 channel;
  - Tower size: $5.52 \times 5.52 \times 33$ cm^3
  - 66 sampling cells with 1.5 mm Pb
  - 4 mm Sc & Wavelength shifting fibers

HCal:

- Fe/Sc (20mm/3mm) sandwich;
- 520 channels in total;
- Tower size $10 \times 10 \times 84$ cm^3
  - In close collaboration with EIC R&D

Preshower

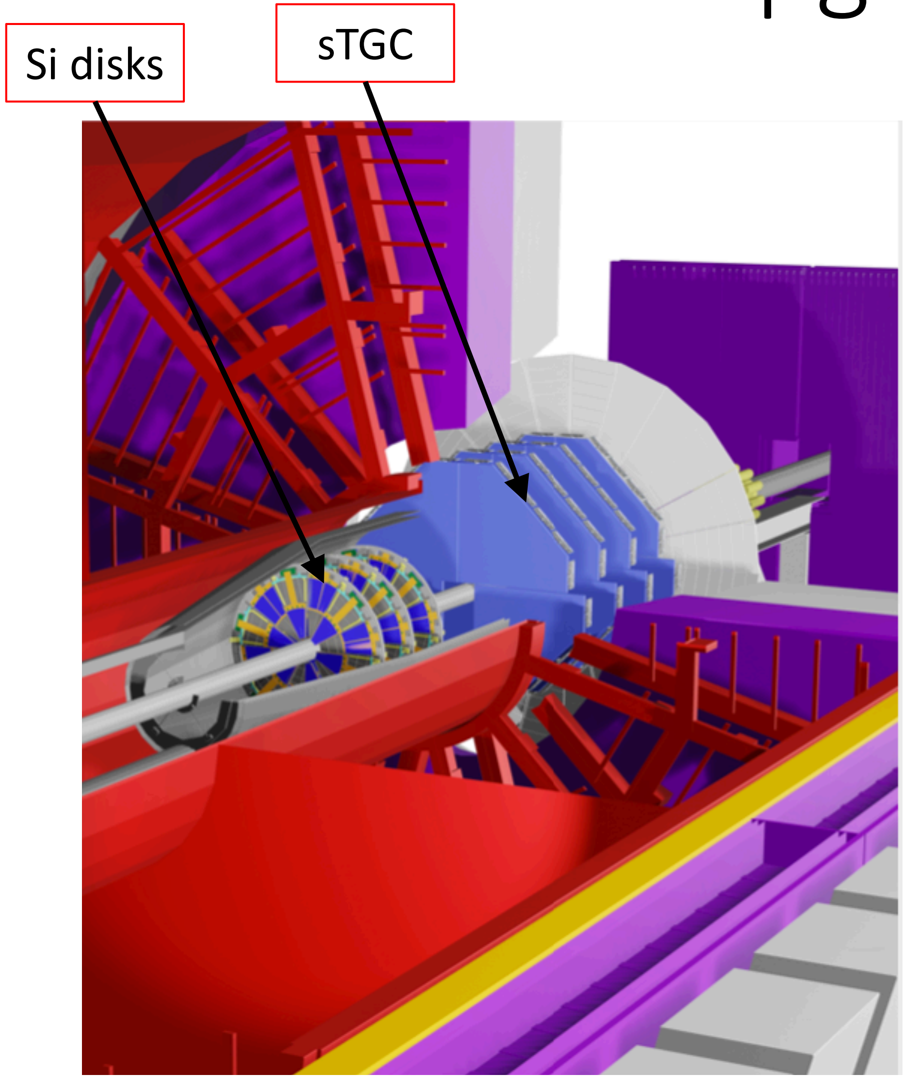
- Use EPD as preshower;

Installation of entire system (HCal + ECal + Electronics) finished last week
~ 10 month to commission systems before Run-22 500 GeV pp

STAR Forward Upgrade: ECal & HCal

Construction completed last week

STAR Forward Upgrade: Silicon and sTGC



3 Silicon disks: at 146, 160, and 173 cm from IP
Built on successful experience with STAR IST

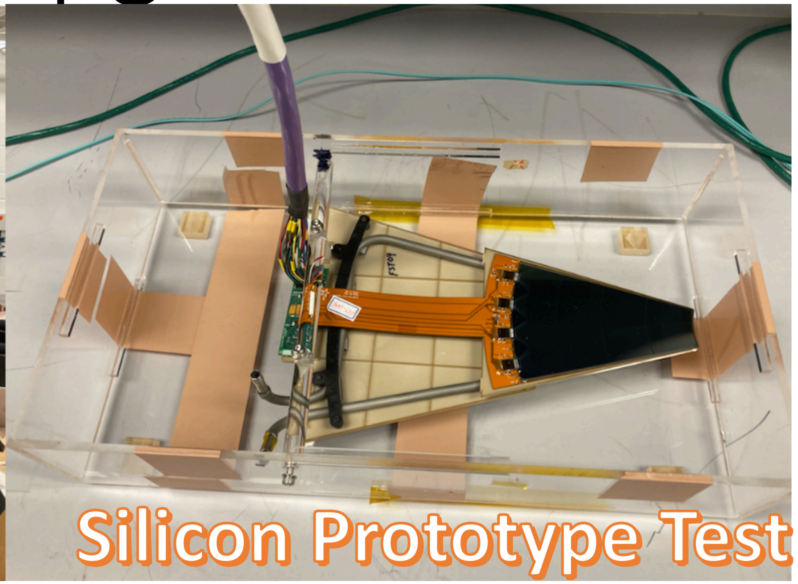
- Single-sided double-metal mini-strip sensors
  - Granularity: fine in ϕ and coarse in R
  - Si from Hamamatsu
- Frontend chips: APV25-S1 → IST all in hand
- Material budget: ~1.5% per disk
- Reuse
  - IST DAQ system for FTS
  - IST cooling system

4 sTGC disks: at 307, 325, 343 and 361 cm from IP
Inside Magnet pole tip opening:

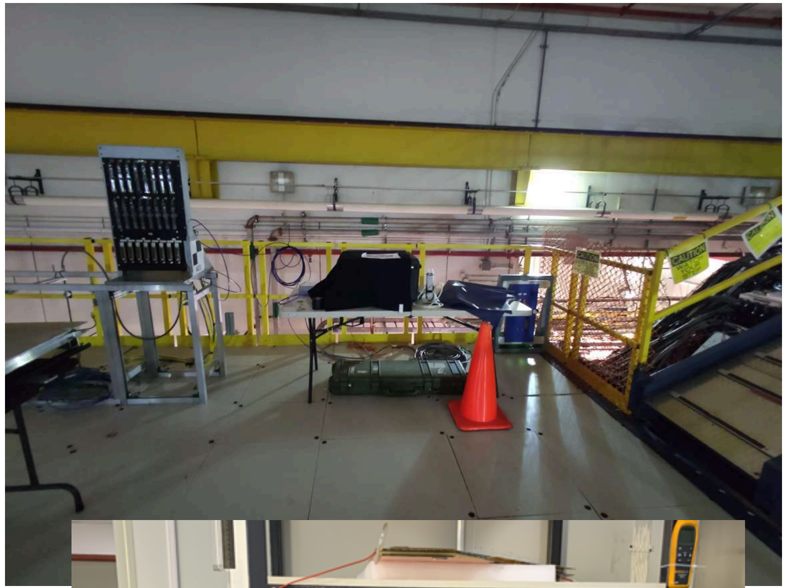
- Inhomogeneous magnetic field
- 4 quadrants double sided sTGC → 1 layer
  - Diagonal strips to break ambiguities in the sTGC
- Position resolution: ~200 μm
- Material budget: ~0.5% per layer,
- Readout: based on VMM-chips
  - following ATLAS design

Installation of entire Si and sTGC finalized by Mid of September 2021
~2-4 month to commission systems before Run-22 500 GeV pp

STAR Forward Upgrade: Silicon and sTGC



Silicon Prototype Test



sTGC Production and Test

The 2021+ Physics program

Mid-rapidity $-1.5 < \eta < 1.5$ → **Forward-rapidity $2.5 < \eta < 4$**

A+A (Mid-rapidity)

Beam:
FXT & 7.7 GeV: Au+Au (2021)
200 GeV: Au+Au (2023/25)
200 GeV: O+O (2021)

Physics Topics:

- Complete BES-II program:
  - Elliptic flow;
  - Chiral magnetic effect;
  - Azimuthal femtoscopy;
  - Net proton kurtosis;
  - Dilepton
  - …
- Origin of small system collectivity via O+O;
- Exploring the Nuclear Equation-of-State (EoS)
- Exploring the Microstructure of the QGP

$p^{\uparrow}+p^{\uparrow}$ & $p^{\uparrow}+A$ (Mid-rapidity)

Beam:
500 GeV: p+p (2022)
200 GeV: p+p and p+A (2024)

Physics Topics:

Improve statistical precision:

- Sivers effect in dijet and W/Z production;
- Collins effect for hadrons in jets;
- Transversity and IFF
- Diffractive studies for spatial imaging of nucleon
- Measurement of GPD E_g through UPC J/Ψ
- Nuclear PDF and fragmentation function;

A+A (Forward-rapidity)

Beam:
200 GeV: Au+Au (2023/25)

Physics Topics:

- Temperature dependence of viscosity through flow harmonics up to η~4;
- Constrain longitudinal structure of initial state;
- Global vorticity transfer:
  - Rapidity dependence of Λ, Ξ, Ω polarization at STAR

$p^{\uparrow}+p^{\uparrow}$ & $p^{\uparrow}+A$ (Forward-rapidity)

Beam:
500 GeV: p+p (2022)
200 GeV: p+p and p+A (2024)

Physics Topics:

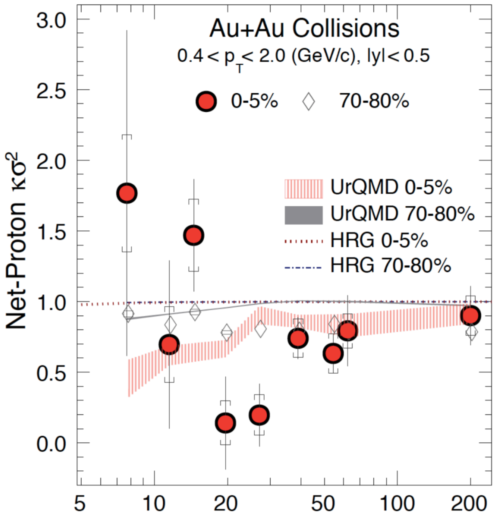
- TMD measurements at high x
  - Transversity, Collins;
  - Sivers through DY and jets
- UPC J/Ψ GPD at forward rapidity;
- Nuclear PDFs and FF:
  - R_{pA} for direct photons & DY, and hadrons
- Gluon Saturation through di-hadrons, γ-Jets, di-jets

All of these measurements are critical to the scientific success of EIC to test universality and factorization

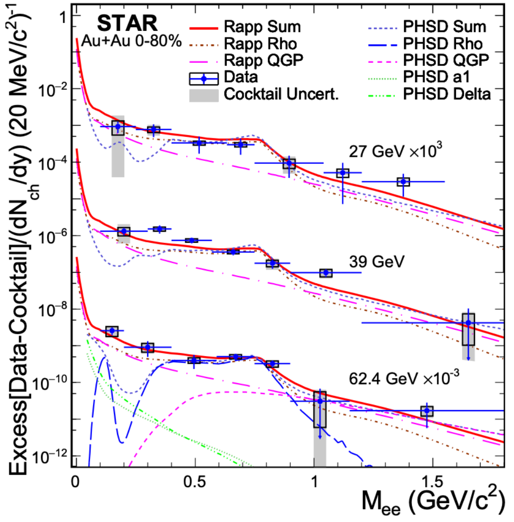
BES-II Progress:

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
13.5	27	156	24 days	(560 M)	Run-18
9.8	19.6	206	36 days	400 M (582 M)	Run-19
7.3	14.6	262	60 days	300 M (324 M)	Run-19
5.75	11.5	316	54 days	230 M (235 M)	Run-20
4.59	9.2	373	102 days	160 M (162 M)[1]	Run-20+20b
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18
3.85	7.7	420	11-20 weeks	100 M	Run-21[2]

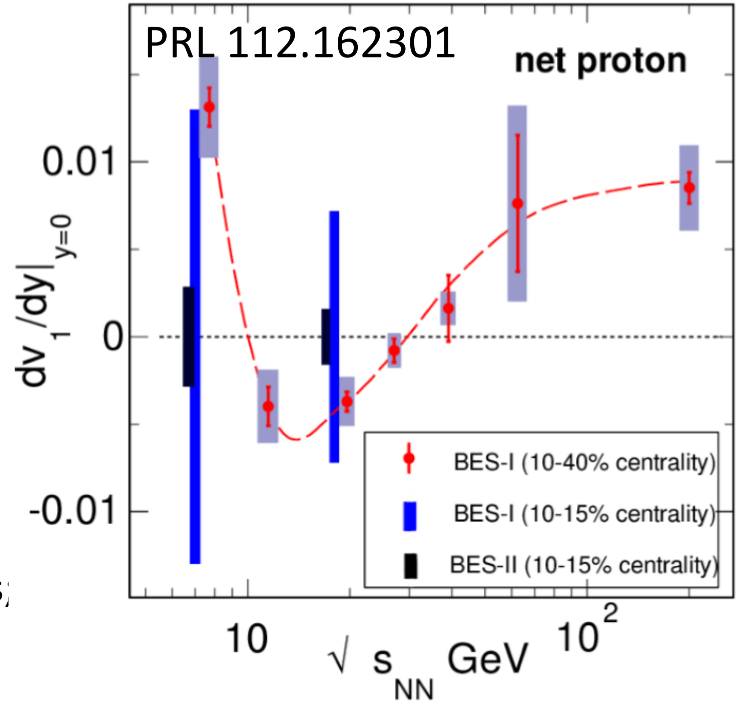
arXiv:2001.02852



arXiv:1810.10159



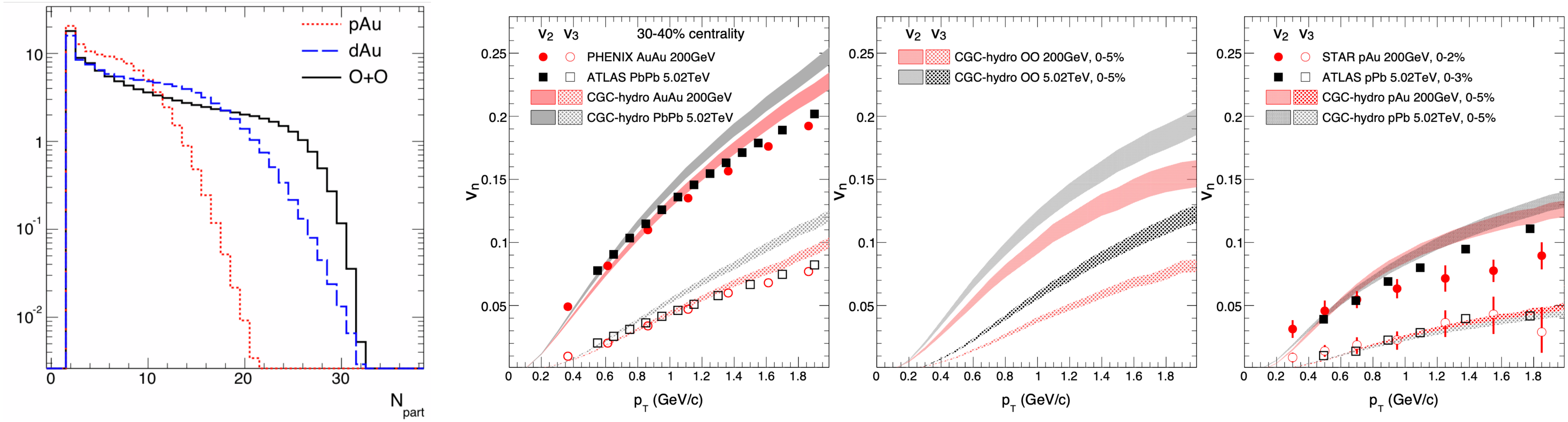
PRL 112.162301



- Collecting 7.7 GeV data in 2021 to finish the BES-II program;
- 7.7 GeV is the essential bridge between Collider and FXT data;
- Hints of features at 7.7 GeV in several studies from BES-I;
- The planned Run-21 FXT measurements at $\sqrt{s_{NN}}$ = 3 GeV with the iTPC and eTOF give access to protons higher moment, precision ϕ, hyper-nuclei, and dilepton measurements;
- FXT data combined with collider data probes nuclear stopping.

See Shengli Huang's talk for details.

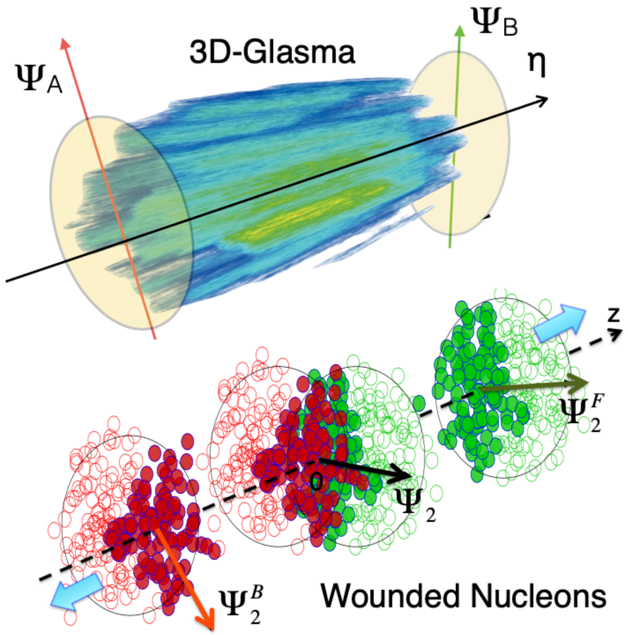
Small System Run: O+O at $\sqrt{s_{NN}}$ = 200 GeV



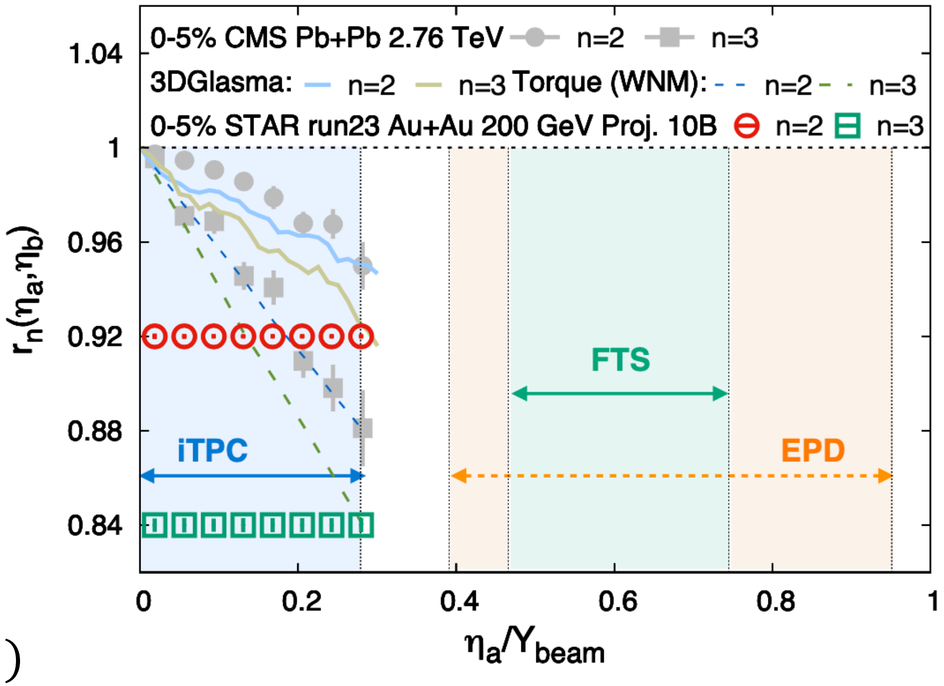
- Prediction of different energy dependence for symmetric and asymmetric systems;
- Small symmetric system with similar N_{part} to p/d+Au, but different nucleon/sub-nucleon fluctuations;
- Analyzing power for 2k-particle cumulants $v_n\{2k\}$ scales with $N_{events} \times N_{part}^{2k}$; much less running time needed than for smaller nuclei;

See Maria Stefaniak's talk for details.

Constrain Longitudinal Structure of Initial State



Extended η coverage by iTPC and Forward detectors

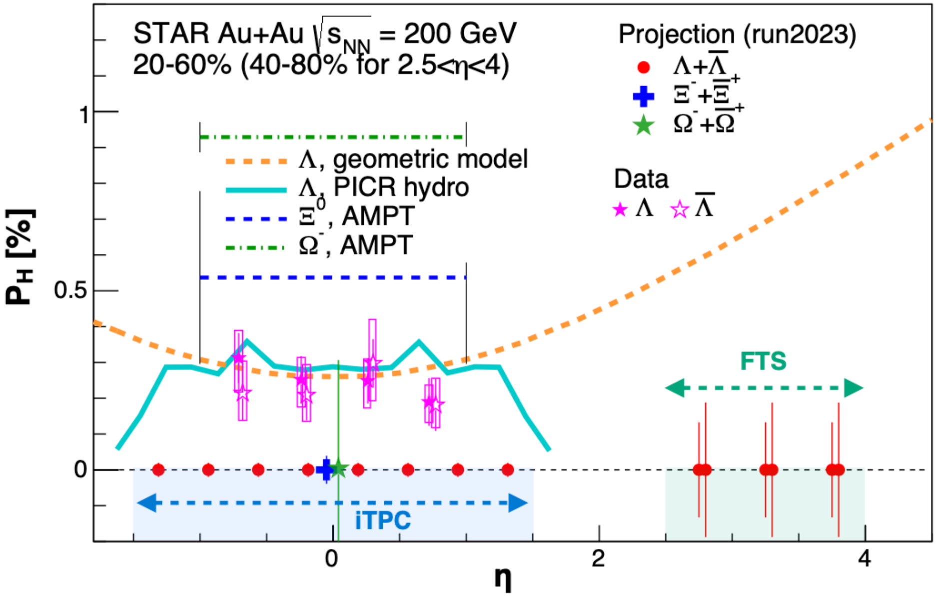


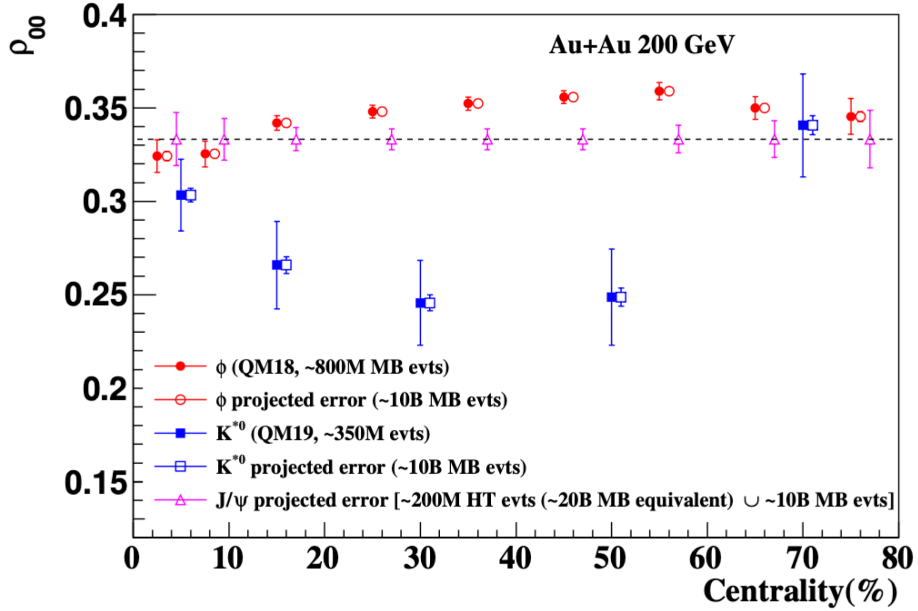
$$r_n(\eta_a, \eta_b) = V_{n\Delta}(-\eta_a, \eta_b)/V_{n\Delta}(\eta_a, \eta_b)$$

- $V_{n\Delta}(\eta_a, \eta_b)$ is the Fourier coefficient calculated with pairs of particles in different η regions;
- $r_n(\eta_a, \eta_b)$ sensitive to different initial state inputs:
  - 3D-Glasma model: weaker decorrelation, describes CMS r_2 but not r_3
  - Wounded nucleon model: stronger decorrelation than data
- Precise measurement of r_n over a wide rapidity window will provide a stringent constraint:
  - Pin down the nature of the 3-dimensional initial state of heavy ion collisions;
  - Constrain different models of QCD from colliding nuclei;

Global Vorticity Transfer

Improved PID, extended η coverage by iTPC and Forward detectors

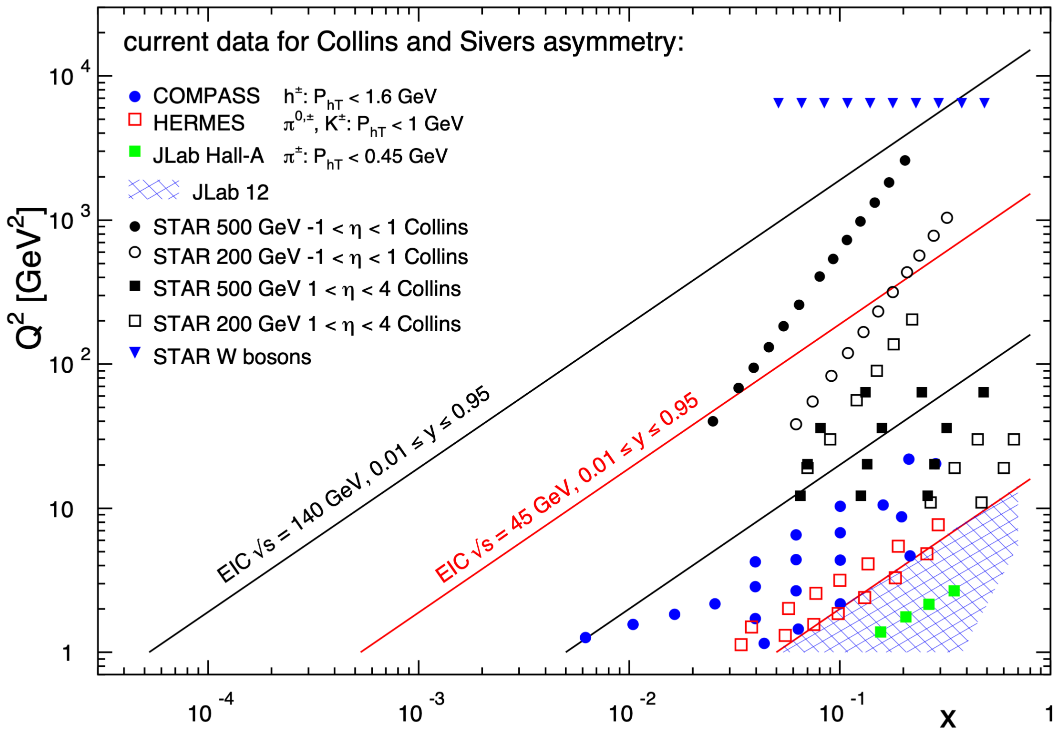




- How exactly is the global vorticity dynamically transferred to the fluid?
- How is the local thermal vorticity of the fluid transferred to the spin angular momentum of the produced particles during the process of hadronization and decay?
    - Rapidity dependence of Λ, Ξ, Ω P_H at STAR, probe the nature of global vorticity transfer: Initial geometry and local thermal vorticity + hydro predict opposite trends.
- Can we reconcile P_H with vector meson spin alignment ρ_{00}? Strong force field effect?
    - Precise measurements of ρ_{00} of K*, ϕ, J/ψ.

Also see David Kapukchyan's poster.

Cold QCD Program:

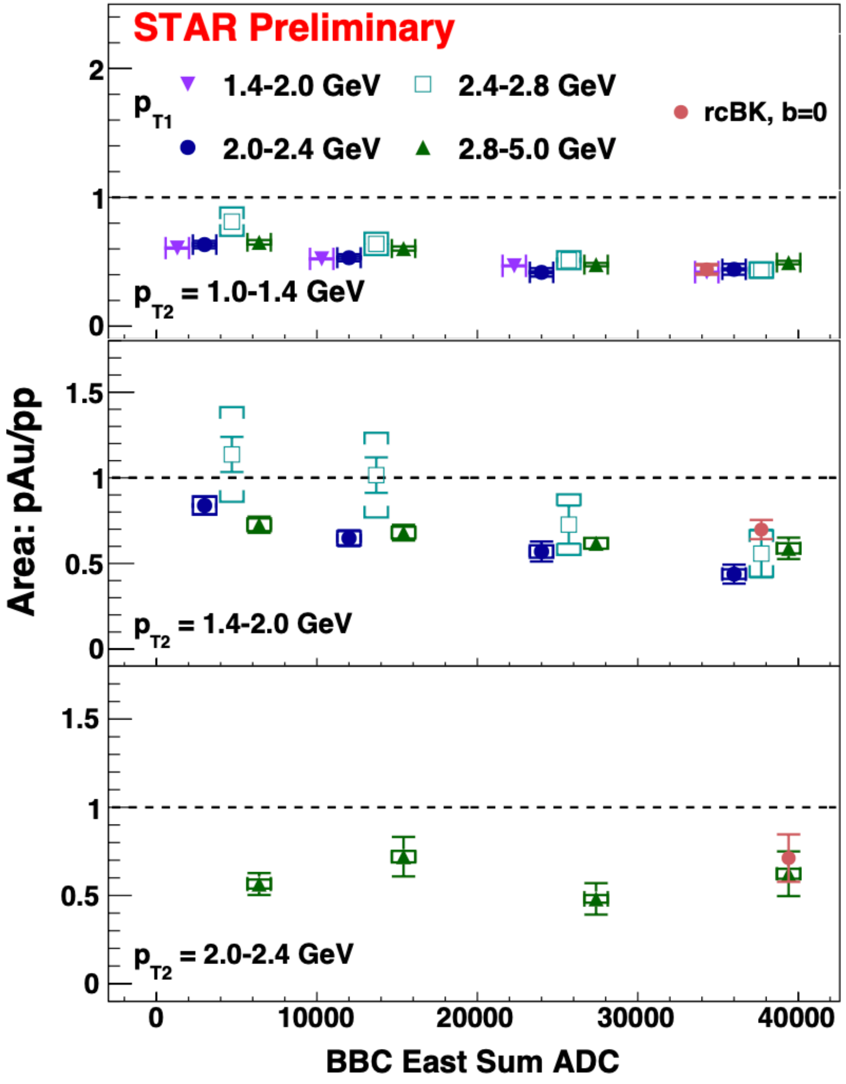


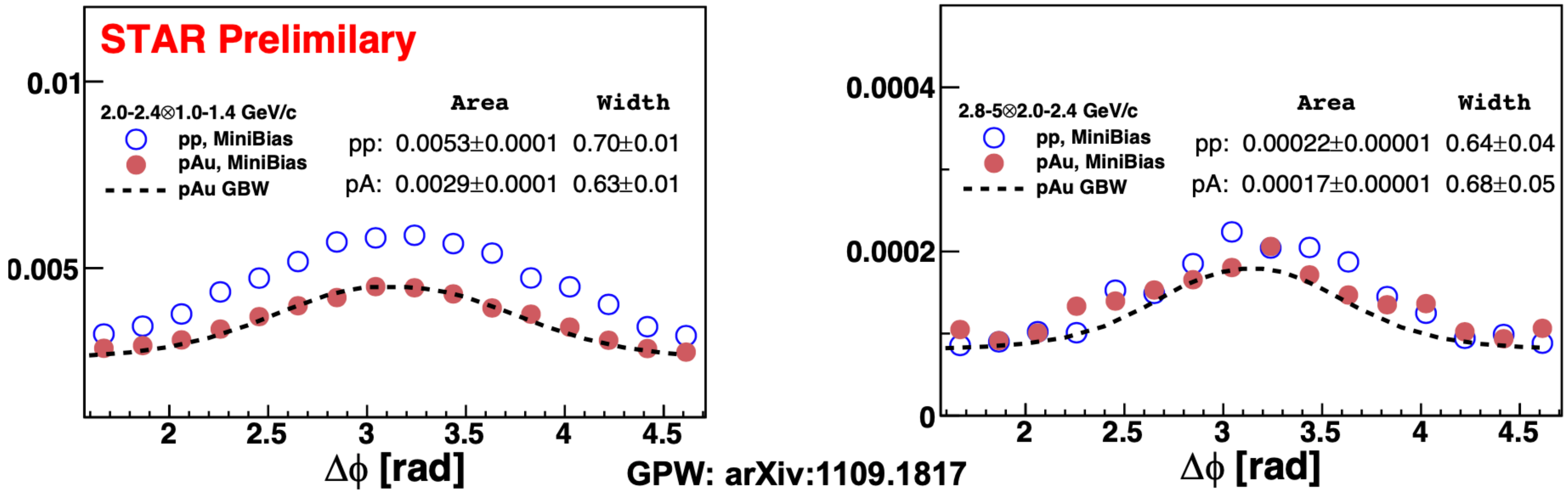
$\sqrt{s}$ (GeV)	Species	Luminosity	Year
500	$p^{\uparrow}+p^{\uparrow}$	400 pb^{-1}	2022
200	$p^{\uparrow}+p^{\uparrow}$	235 pb^{-1}	2024
200	$p^{\uparrow}+Au$	1.3 pb^{-1}	2024

- Kinematic coverage for 200 and 500 GeV p+p at STAR is 0.005<x<0.5;
- Provides best overlap with the x-Q^2 coverage of EIC;
- Precise factorization and universality tests;
- Overlapping x coverage enables detailed evolution studies;

See Xiaoxuan Chu's talk for details.

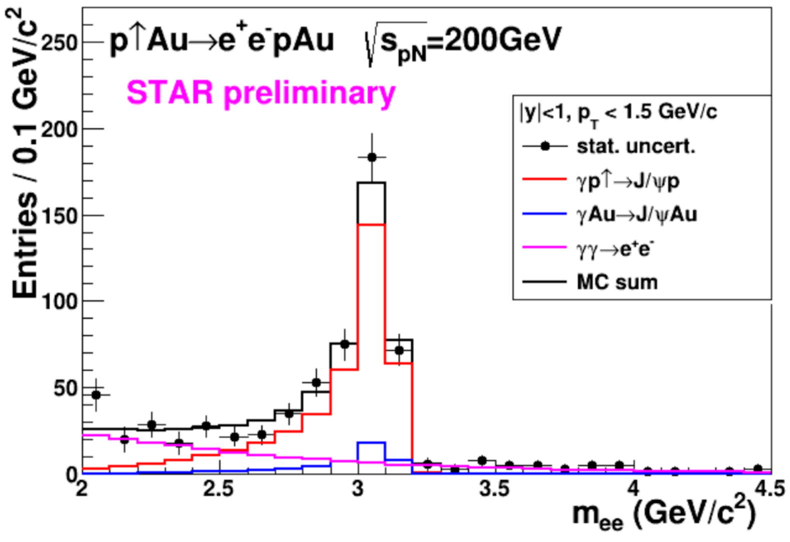
Gluon Saturation

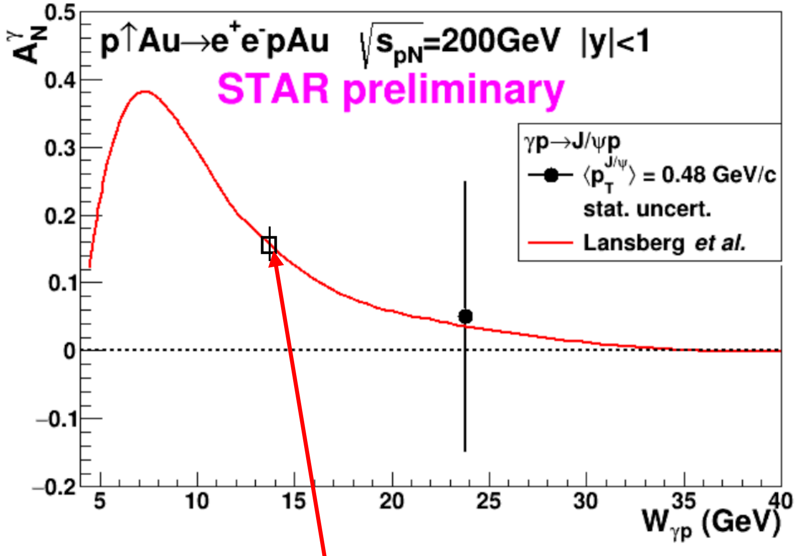


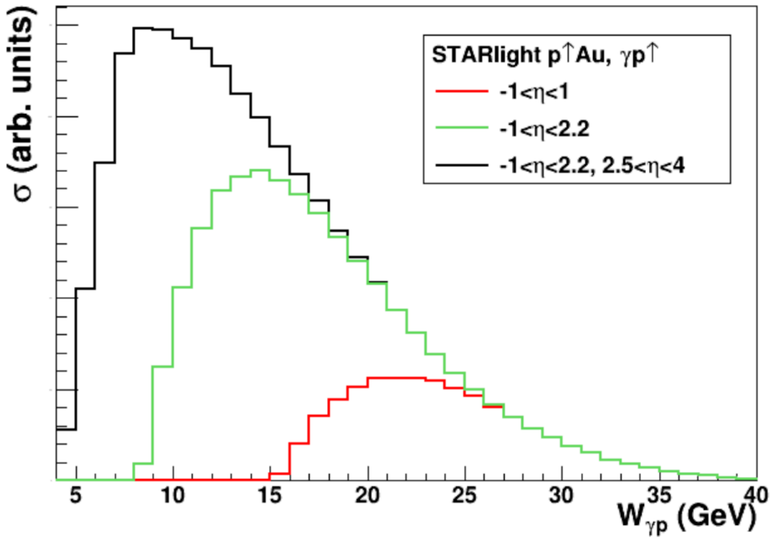


- Forward rapidity at STAR provides an unique opportunity to probe high gluon densities in p+Au collisions;
- STAR Forward upgrades characterize non-linear gluon effects through charged di-hadrons, γ-jet, di-jets;

Generalized Parton Distribution Function

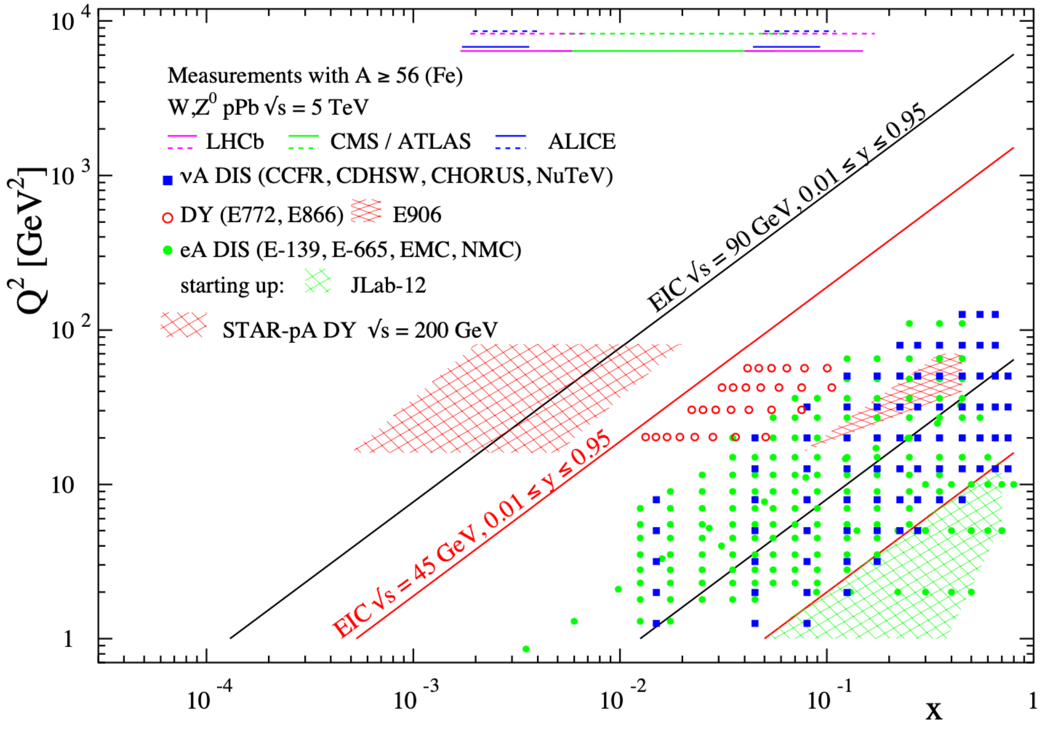


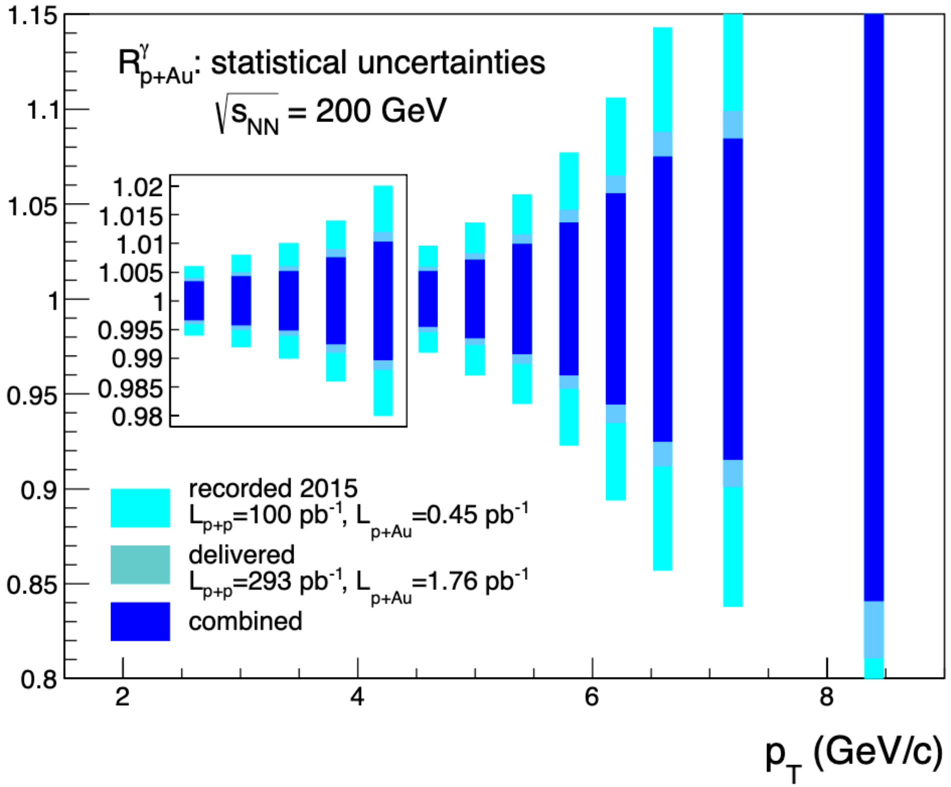




- Exclusive J/ψ TSSA measurement in UPC;
- Access GPD E_g for gluons, sensitive to spin-orbit correlation;
- iTPC and forward detectors will enable a high-impact measurement
  - A factor of 9-10 more data combining iTPC and forward upgrades, expected statistical error 0.02 for $\langle W_{\gamma p} \rangle$ = 14 GeV;

Nuclear PDF





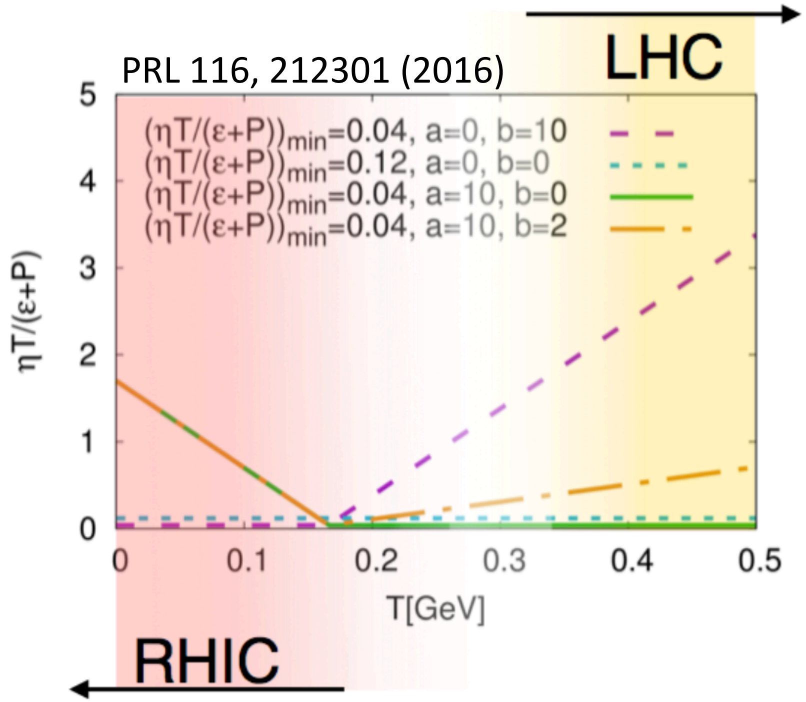
- Direct photon measurement: constrain nuclear gluon distribution in a broad x range;
- Drell-Yan : constrain nuclear sea quark distribution in a broad x range;
- Contribute to a stringent test of the universality of nuclear PDFs when combined with data from EIC;

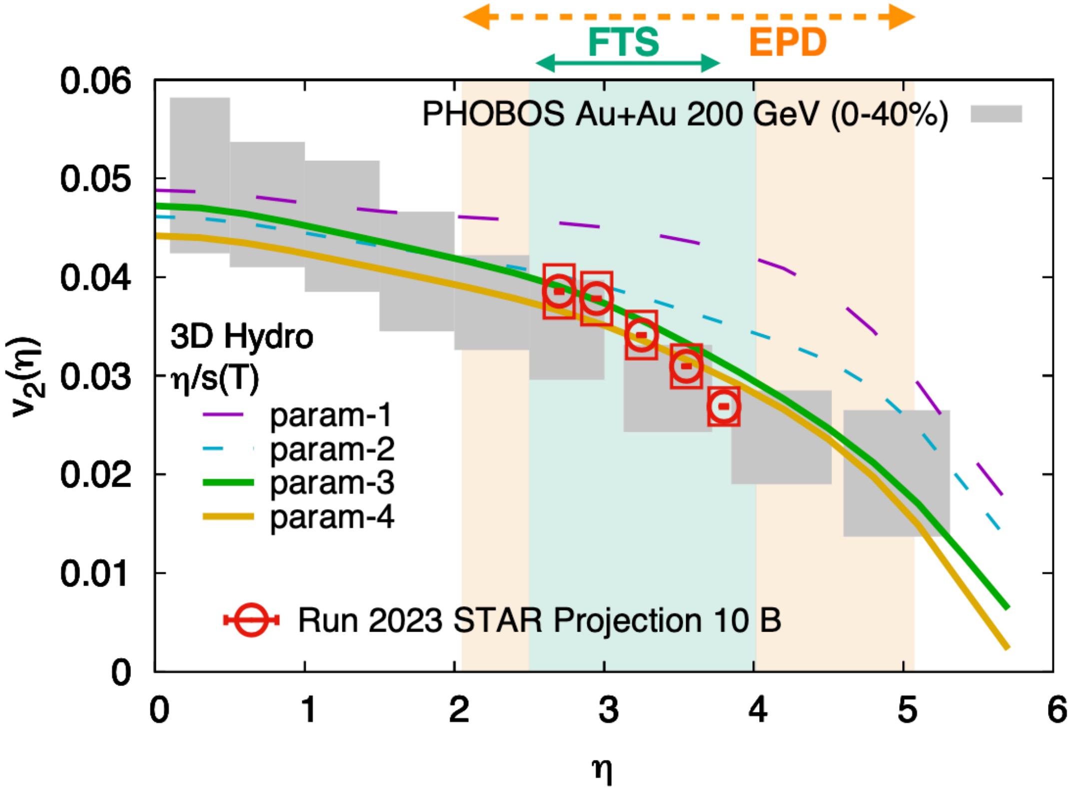
Summary

- The STAR BES-II upgrades have been running very well since 2019;
- The Forward Upgrade is progressing very well, will be fully ready in 2022;
- These upgrades will substantially extend STAR's kinematic reach and further enhance its particle identification capabilities;
- The combination of the existing and ongoing detector upgrades enables a rich and compelling scientific program in the next few years.

Back Up

Constrain Temperature Dependence of Viscosity

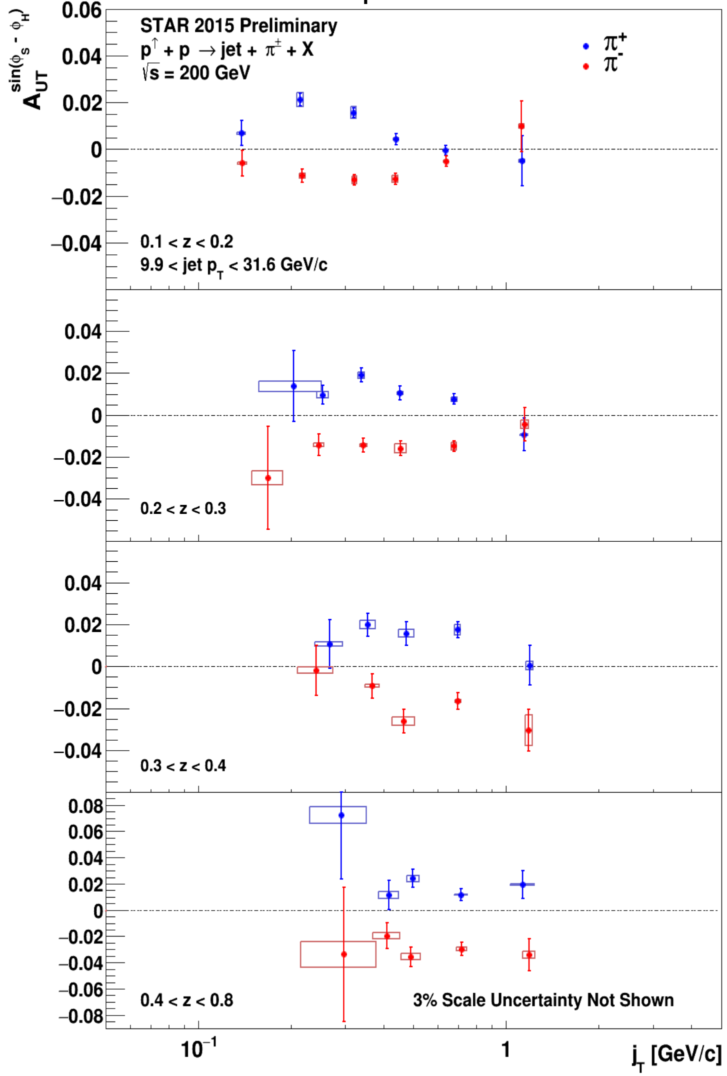




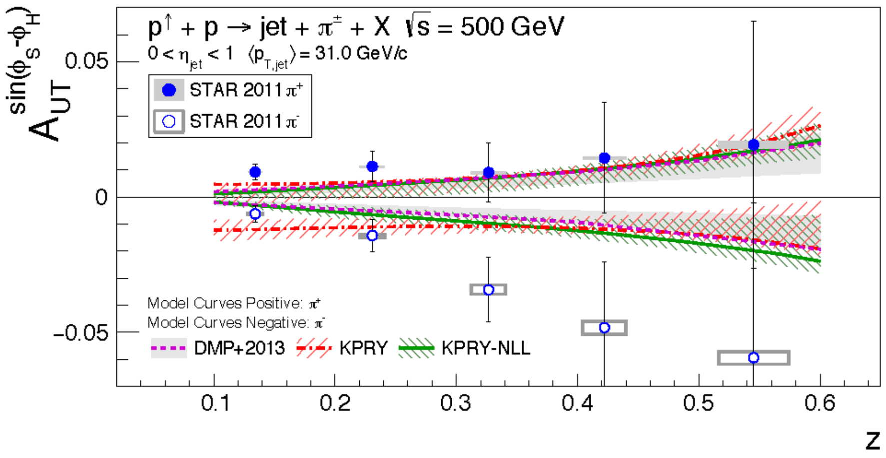
- The rapidity dependence of the flow measurement is sensitive to $\eta/s(T)$;
- Lower beam energy at RHIC provides stronger variations of the temperature with rapidity;
- The BES-II and the forward upgrade of STAR will provide precise estimations of different azimuthal correlation observables;

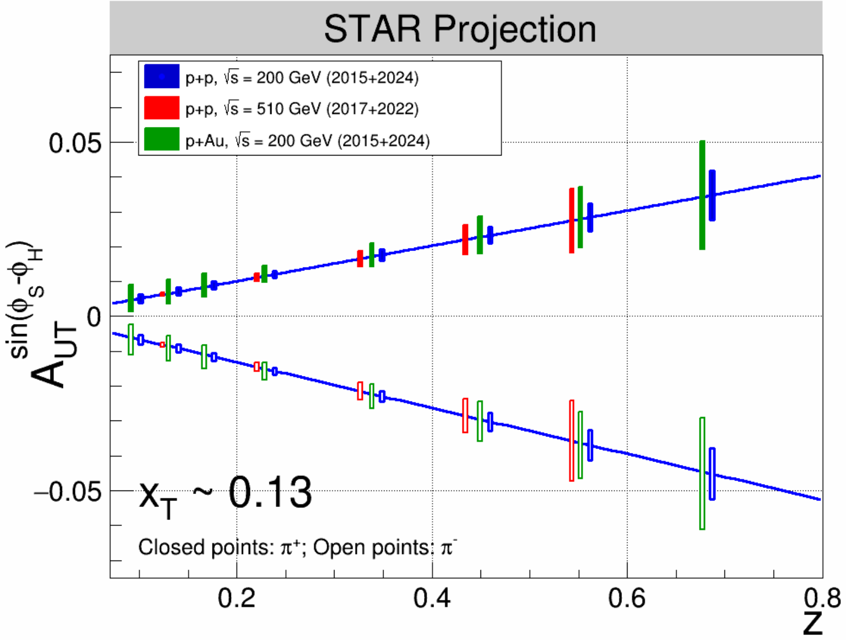
Collins Effect

JetEIC Workshop 2020



pp500GeV: Phys. Rev. D 97, 032004 (2018)





- Collins effect combines the collinear quark transversity in the proton with the TMD dependent Collins fragmentation function;
- Precision measurements at both energies probe TMD evolution and provide important cross-checks and essential x-Q^2 overlap with EIC;
- Collins effect in p+Au will provide an alternative universality test and a unique probe of the spin dependence of hadronization in cold nuclear matter;