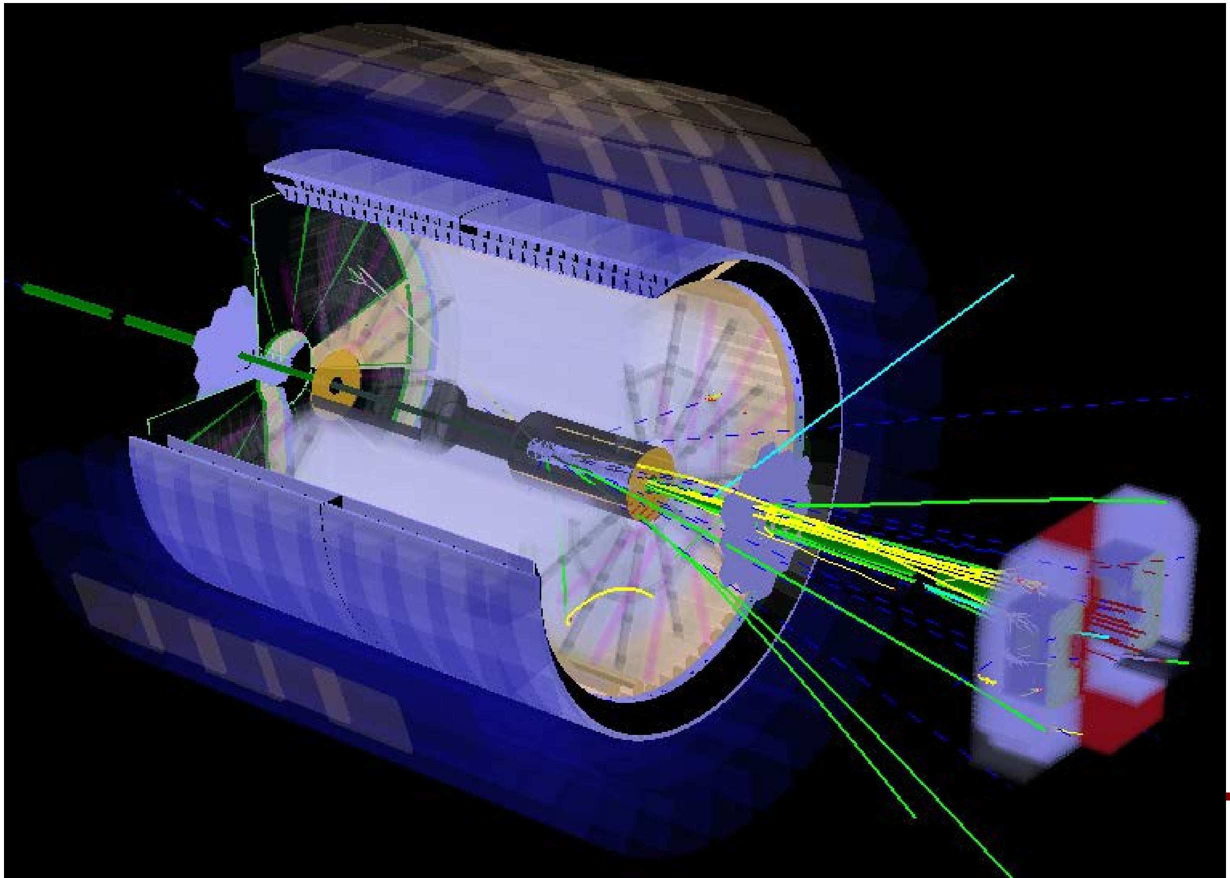
PP, PA & AA PHYSICS WITH THE STAR FORWARD UPGRADE

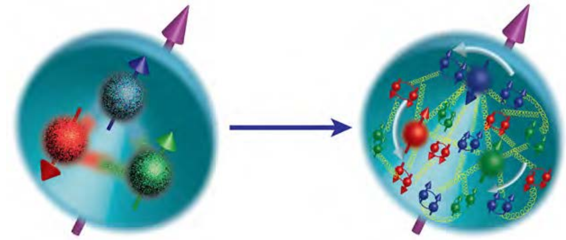
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648



Zhangbu Xu
& Elke Aschenauer

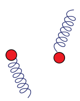
The objectives of the STAR Forward upgrade (I)

- unique measurements to answer the hot questions in cold QCD



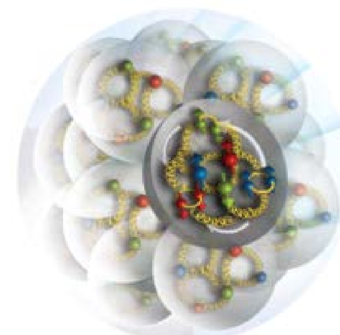
sea quarks and gluons and spins distributed in space and momentum inside the nucleon?

What is the properties of nucleons/nuclei emerge from those interactions?



How energetic color-charged quarks and gluons interact with a nuclear medium (formation time of colorless jet)?

How do the confined hadronic states emerge from these quarks and gluons?



What is the gluon density in nuclei?
How partons interact at high density?
Does it saturate at low-x?

Saturated gluonic matter with universal properties in all nuclei, even the proton?

gluon emission ? = gluon recombination

The objectives of the STAR Forward upgrade

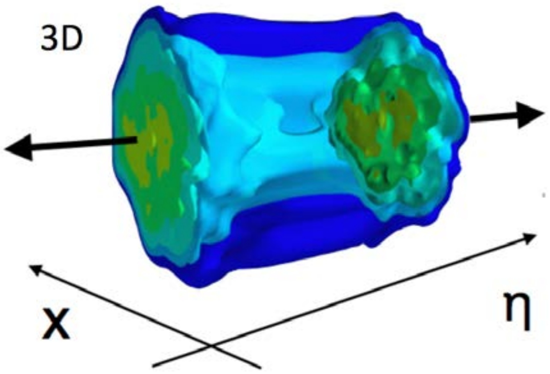
- pp and pA:

  unique measurements to answer the hot questions in cold QCD

- AA:

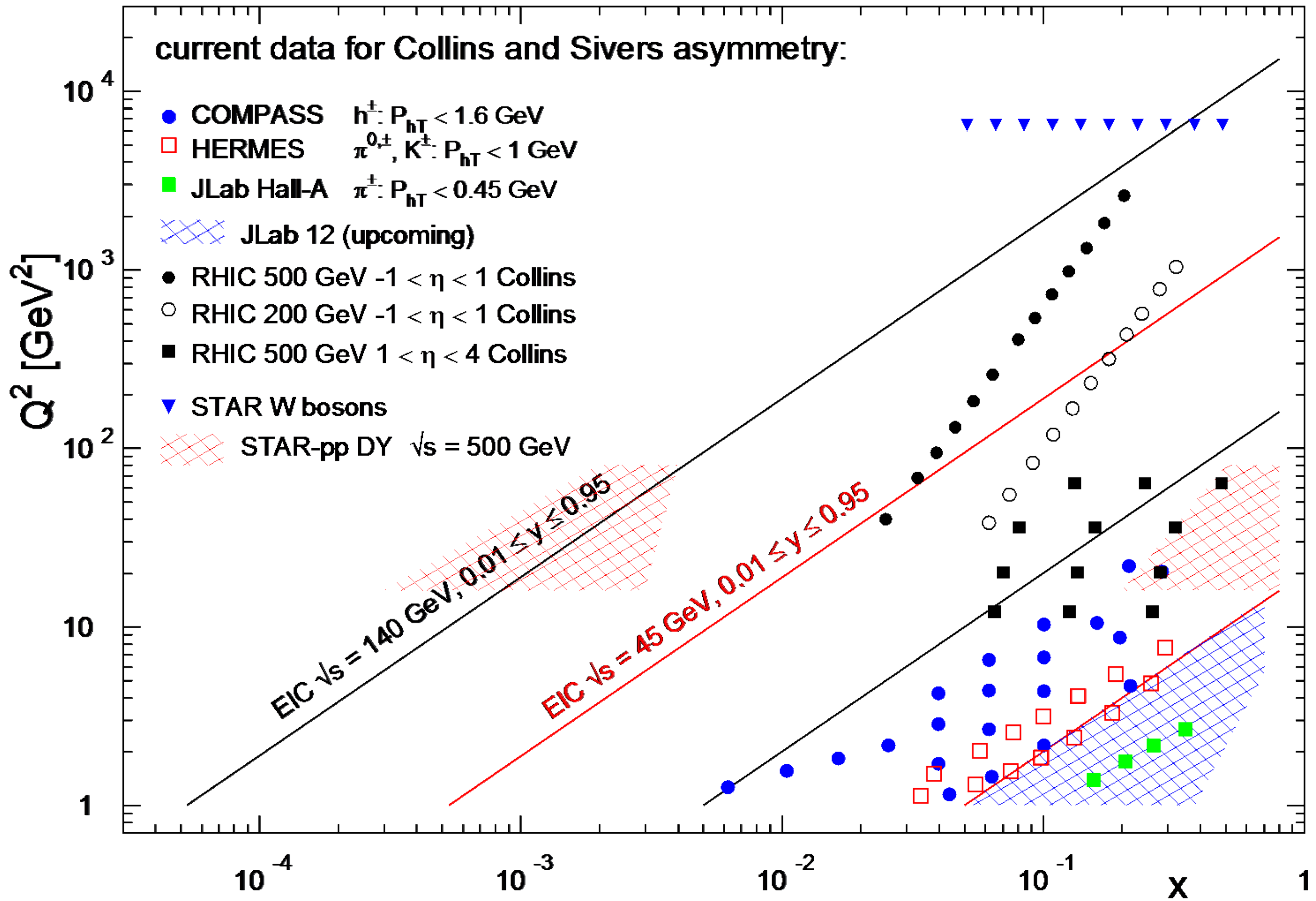
unique measurements to answer the cool questions in hot QCD

What is the longitudinal structure of initial condition?



- Strengthen and Enhance the EIC physics program
  - lay the groundwork for the EIC, both scientifically and by refining the experimental requirements
  - Test EIC detector technologies under real conditions, i.e SiPMs

Transverse Momentum Distributions



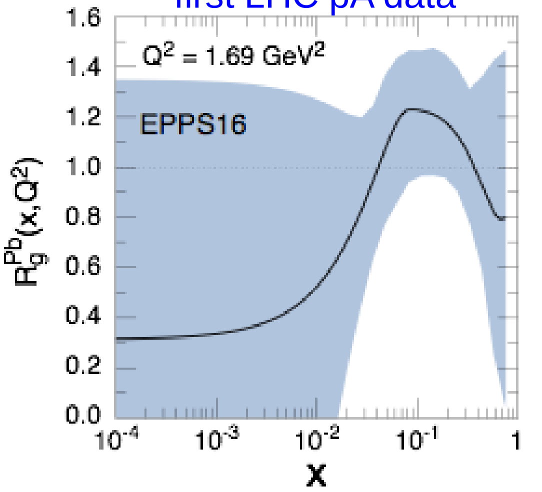
Till today TMDs come only from fixed target data → high x @ low Q^2
need to establish concept at high Q^2 and wide range in x

STAR unique kinematics with polarized pp at RHIC: from high to low x at high Q^2

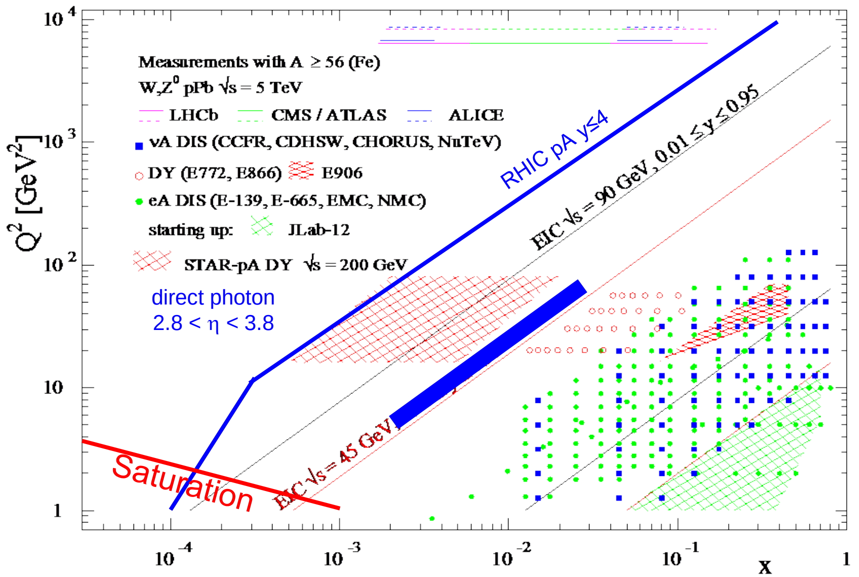
Initial State in Heavy-Ion Collisions

- What are the nPDFs at low-x?
- How saturated is the initial state of the nucleus?
- What is the spatial transverse distributions of nucleons and gluons?

Current knowledge including first LHC pA data



pA@RHIC: unique kinematics



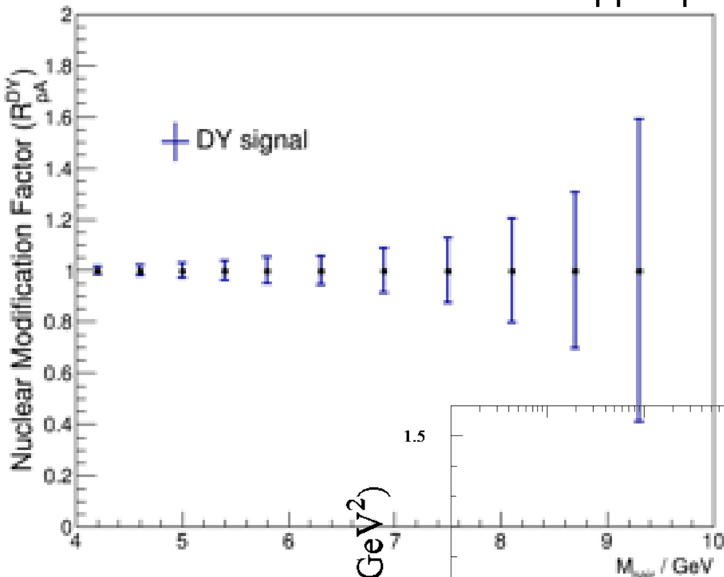
- can measure nPDF in a x-Q^2 region where nuclear effects are large
- Observables free of final state effects
- Scan A-dependence prediction by saturation models
- can access saturation regime at forward rapidities

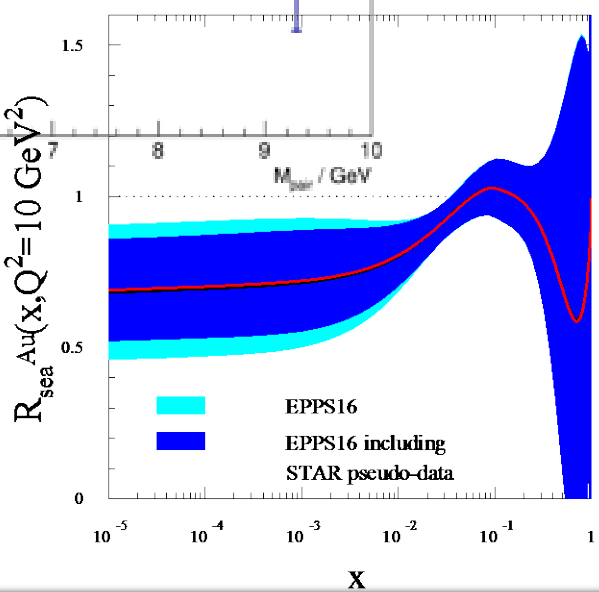
How Does The initial state IN AA Look?

pA: DY@2.5 < η < 4.5

DY: Q^2: ~M^2; Q^2>16 GeV^2

Uncertainties: 2023 pp & pA



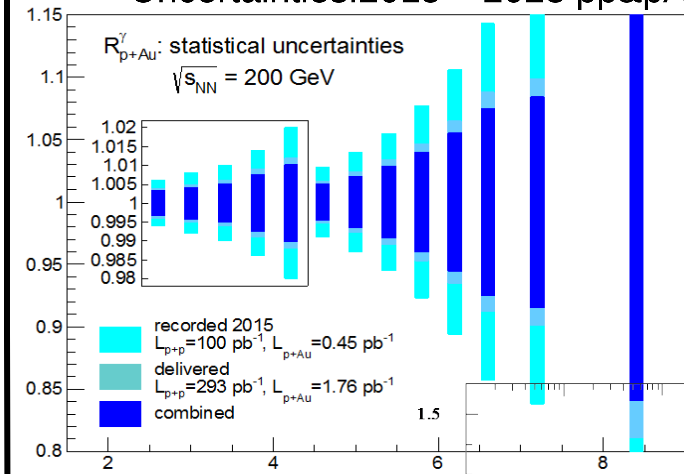


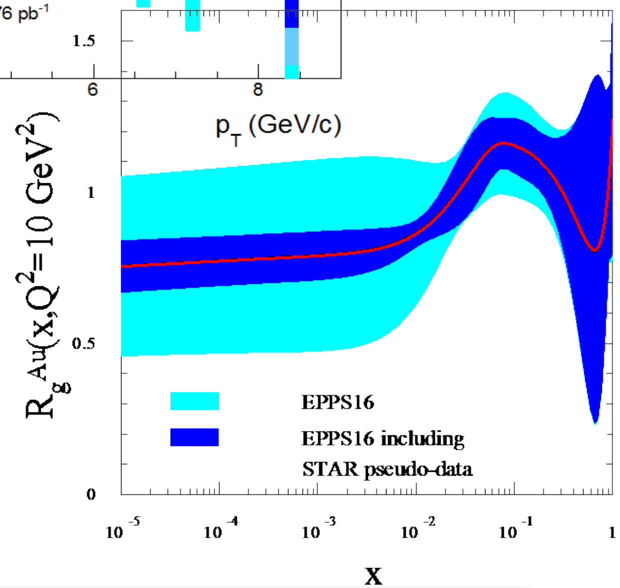
Impact on nPDFs:
→ sea quarks

pA: Direct Photon@2.5 < η < 4.5

direct photon: Q^2: ~p_t^2;Q^2>5 GeV^2

Uncertainties:2015 + 2023 pp&pA

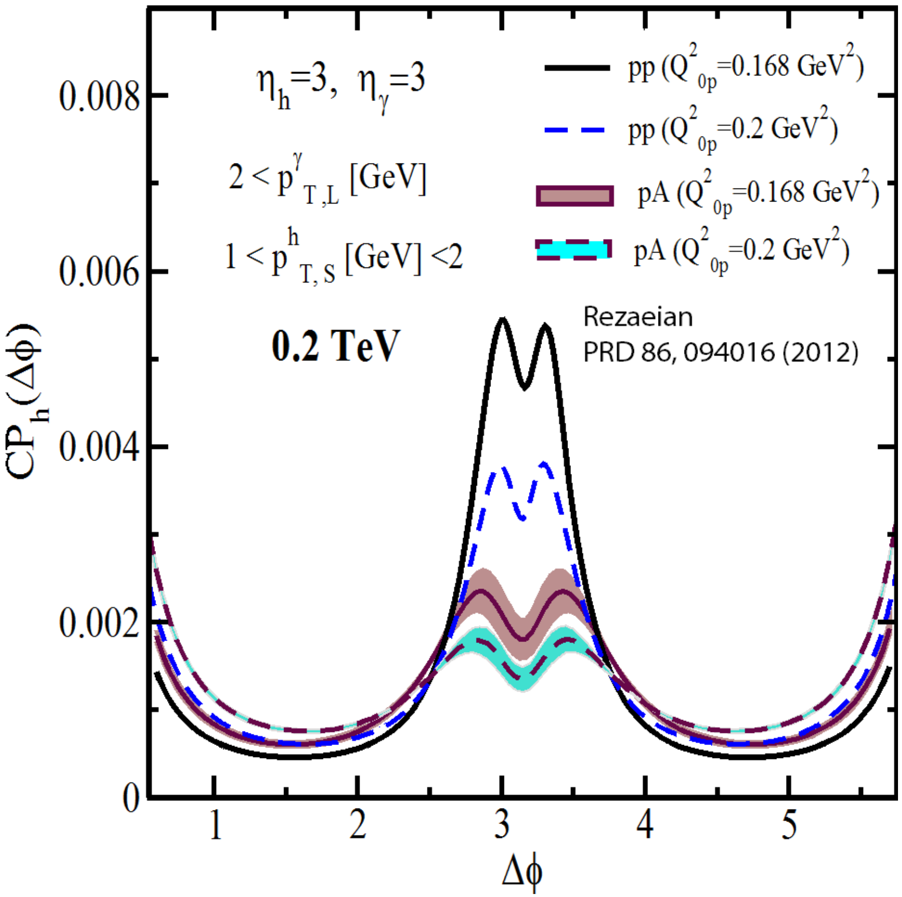


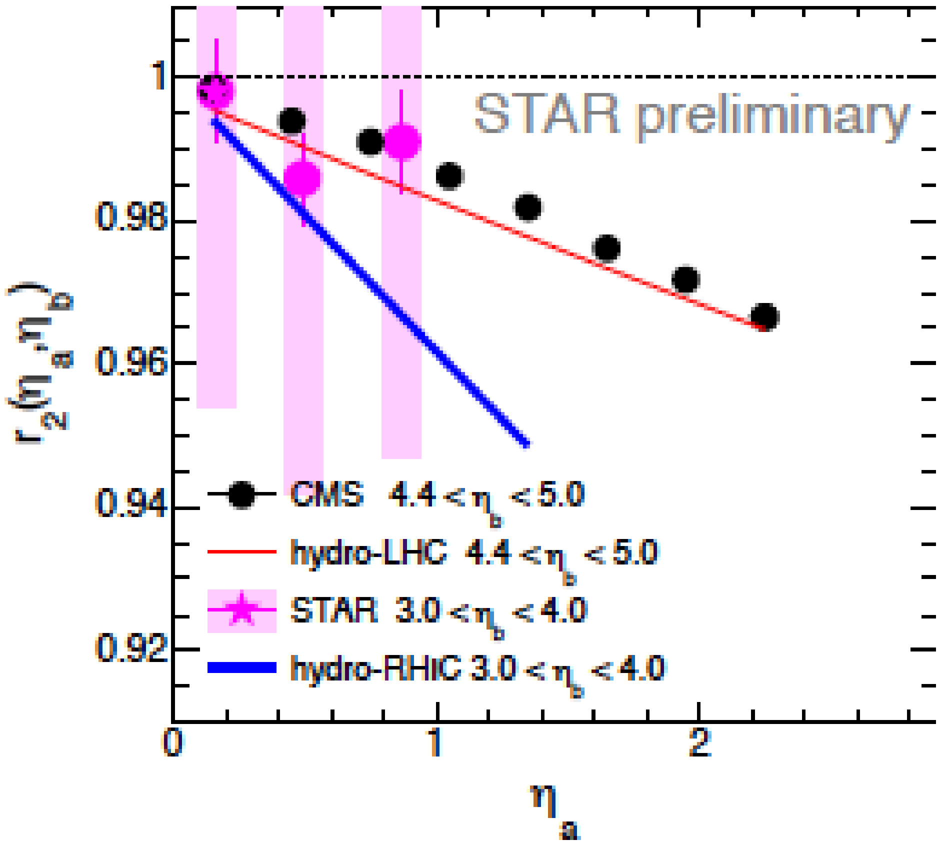


Impact on nPDFs:
→ gluons

Both DY and direct photon R_{pA} give significant constraints on nPDF alternative observables and kinematics to EIC

Rapidity (de)correlations

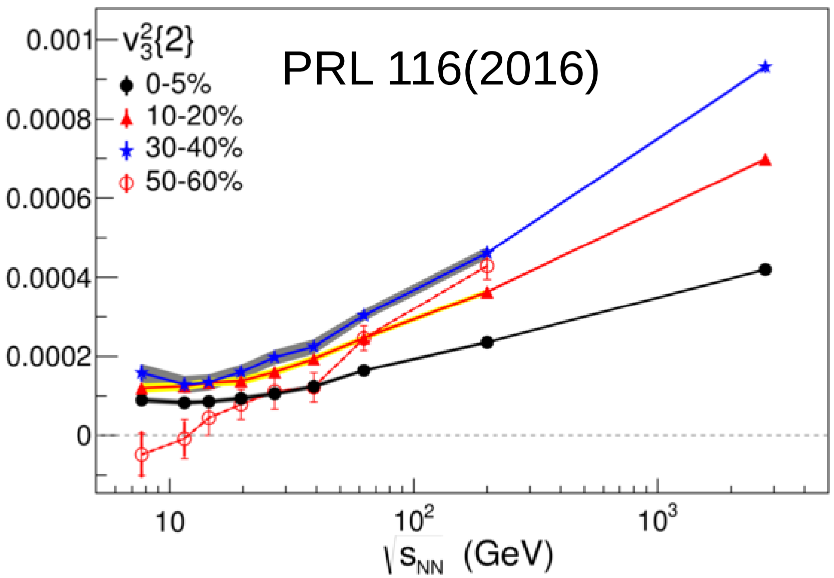


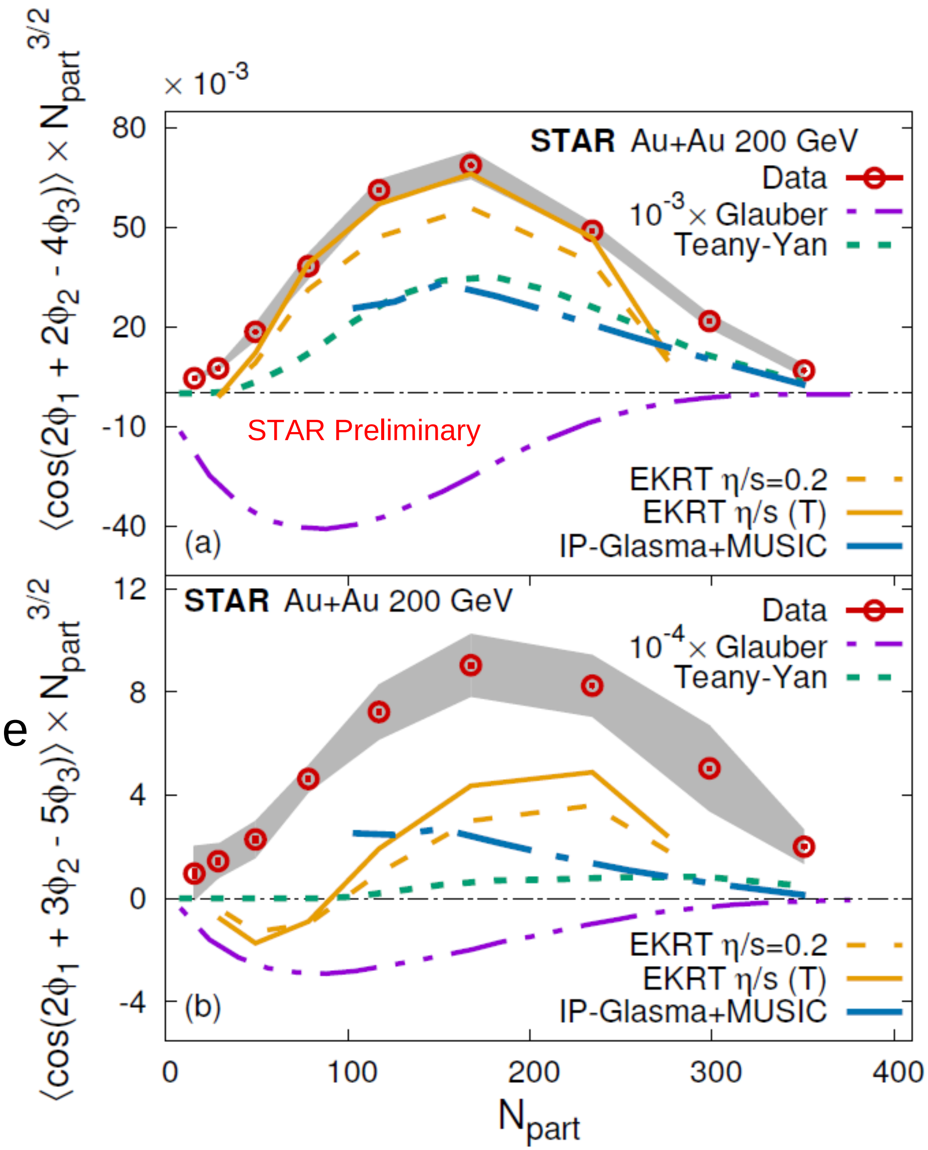


Cold QCD γ-h correlation => saturation effect

Hot QCD study ***η***/s and dynamic evolution

n^{th} order Flows in rapidity





Higher harmonics sensitive to earlier stage
Study BES and small system size:
Turn OFF QGP?

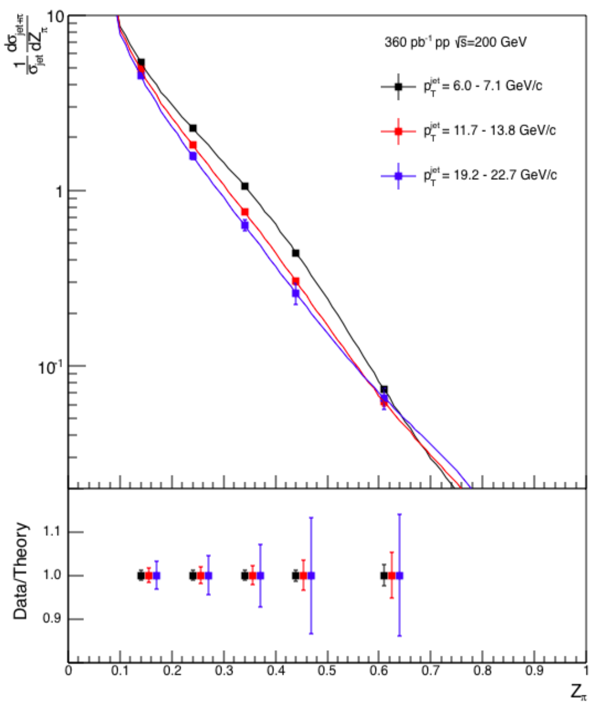
Multiple-Harmonics sensitive to η/s

pp, pA, AA Physics At Midrapidity

- Rich unique program building on the strength and high rate of STAR detector
- measurements complement the forward physics program
  - extending kinematics
  - addressing complement physics topics
  - diffractive & UPC program with Roman Pots, i.e. Wigner functions

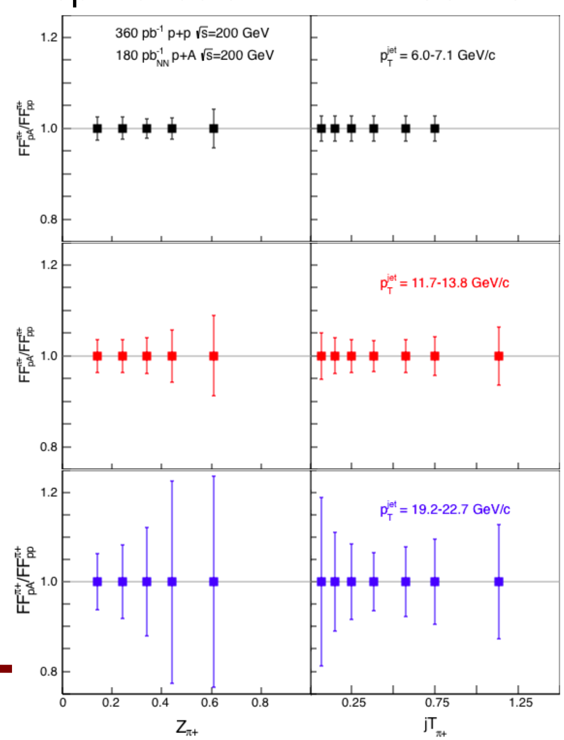
pp:

Fragmentation functions
High precision TMD measurements
→ Universality test → EIC



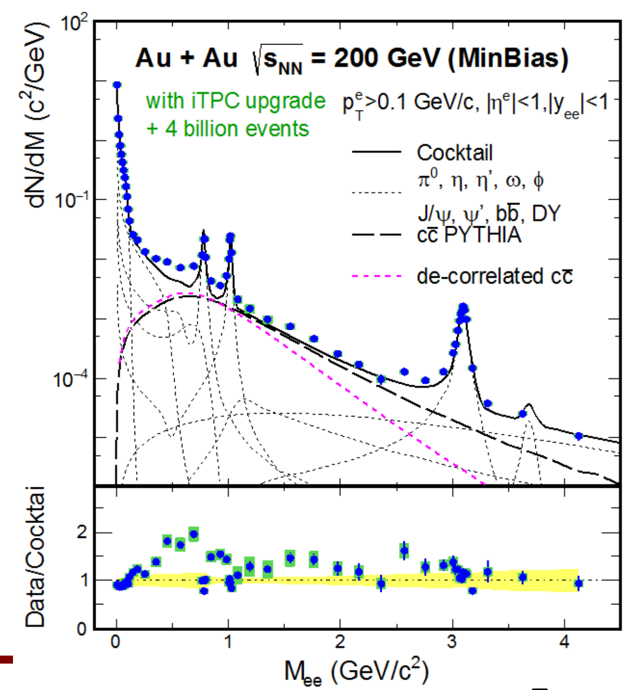
pA:

nuclear Fragmentation functions
complement to nPDFs
only at RHIC p↑A:
→ spin effects in nFF → Collins FF



AA:

a deep look into the properties of the QGP: γ & e+e- pairs
→ chiral symmetry restoration
→ thermal radiation of QGP



Physics Opportunities beyond BES-II (2020+)

Physics Goal	Measurements		Requirements						
			Base	fCal	fTS	RP	HFT+	BSMD	Streaming
Nuclear PDFs	DY, Direct photons +J/Psi R_{pA}	★■	✓	✓	Enh				
Nuclear FF	Hadron + Jet	★■	✓						Enh
Polarized Nuclear FF	Hadron + Jet	★	✓						
Odderon & Polarized Diffraction	A_{UT} of pion + forward proton	★		✓		✓			
Low-x ΔG	Di-jets	★	Enh	✓	✓				
High-x Transversity	Hadron+jet	★■		✓	✓				
Mapping the Initial State in 3-D: QGP Transport Properties	R. Plane Rapidity de-correlations	★	Needs iTPC						
	Ridge |Δη|<3	★	Needs iTPC						
	Ridge |Δη|<6	★	Needs iTPC		✓				
	Forward Energy Flow	★	Needs iTPC	✓					
Effects of Chiral Symmetry at μ_B=0	Di-lepton spectra at μ_B=0	★■	Needs iTPC				HFT out		Enh
	Extended LPV observables	★■	Needs iTPC						Enh
Internal Structure of the QGP and Color Response	ϒ(1S,2S,3S)	○	✓						
	B R_{AA}	★■	✓				✓		
	B v_2	★■	✓				✓	✓	✓
	B-tagged Jets	○	✓				✓		
	Jets	○	✓						Enh
	γ –Jets	○	✓					✓	
Phase Diagram and Freeze-out	BES-II Observables at μ_B=0	★	Needs iTPC						
	C6/C2, C4/C2	★	Needs iTPC						
The Strong Force	Exotics and Bound States (di-Baryons)	★	Needs iTPC						✓

1. Define QCD Phase Structure
2. Study Chiral Properties
3. Map T dependence of η/s
4. Test K_T factorization and Universality

SN0648-
proposal for Forward upgrade Submitted to BNL in May 2017

Extended coverage and targeted upgrades open up many opportunities for a diverse scientific program in 2020+

✓ Measurement needs upgrade   Enh : Enhances measurement, but is not required

★ Unique to STAR   ○ Complementary to sPHENIX   ■ Complemented by LHC and/or JLab

Green highlighted rows require only continued running with STAR as instrumented for the BES-II

Base : STAR as instrumented for the BES-II
iTPC : Inner sector TPC upgrade extending coverage from |η|<1 to |η|<1.5
fTS : Forward Tracking System
fCal : Forward Electromagnetic and Hadronic Calorimeters
HFT+ : An extended faster heavy flavor tracker
Streaming : An electronics and DAQ upgrade allowing significant increase in minbias data rate
BSMD : Replacing the BSMD readout
HFT out: Di-lepton spectra at μ_B=0 improved by running with less material

BNL Program Advisory Committee Report

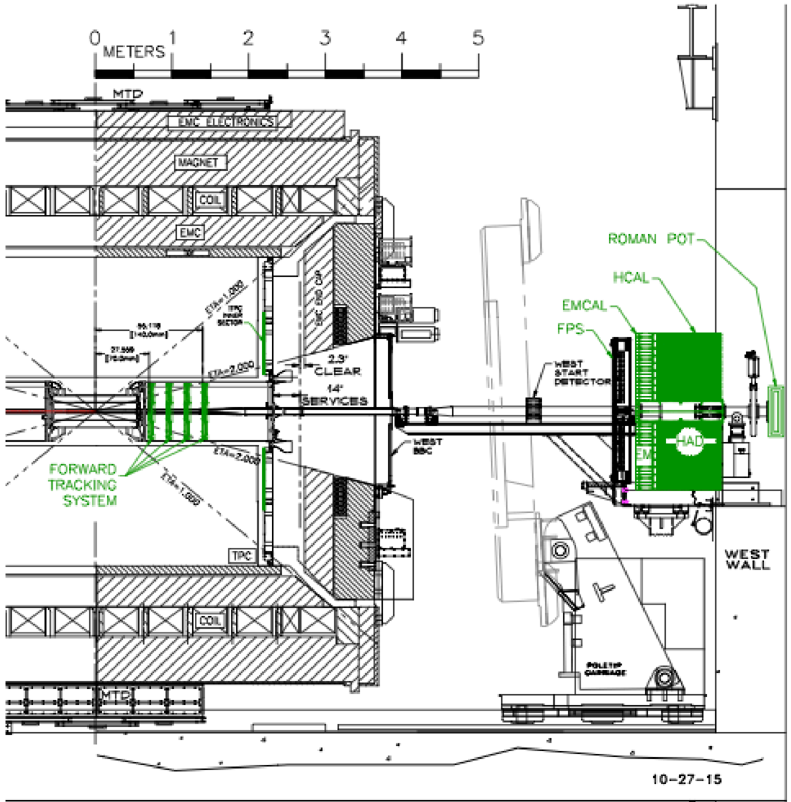
6. **Modest Forward Upgrades**

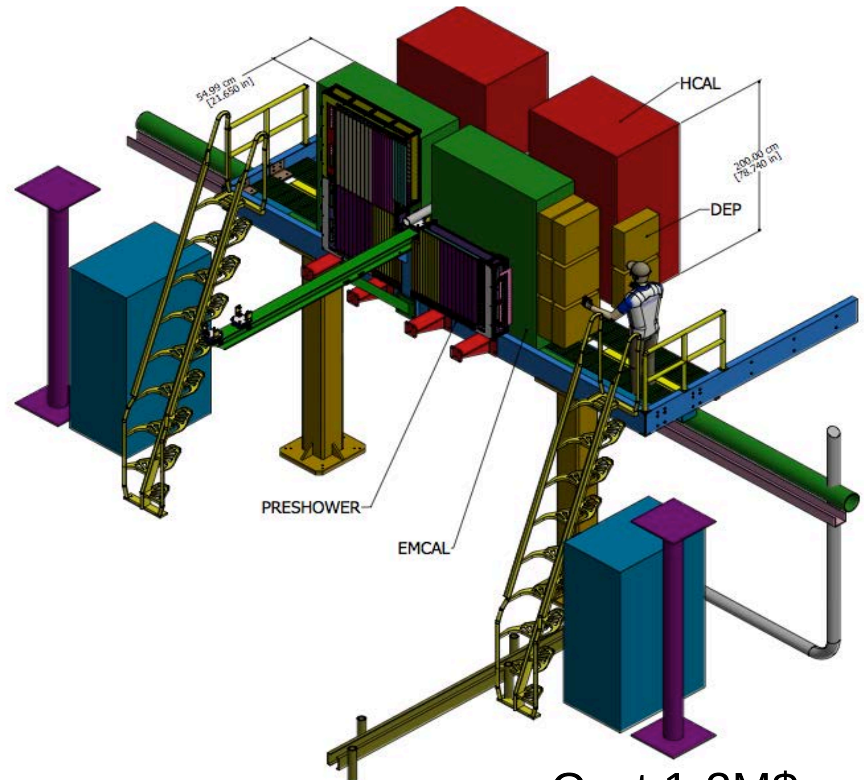
The PAC commends both the sPHENIX and STAR collaborations for their considerable effort in preparation of detailed Letters of Intent that describe their forward detector upgrade plans. The PAC finds that the physics case for a forward upgrade at RHIC remains compelling. The importance of the proposed measurements for the future EIC is clear. The PAC is also impressed by the added benefit to the heavy-ion program of the increased rapidity range provided by the forward detector upgrades.

Recommendations:

- In view of the importance of DY reactions for the forward detector program, high priority should be given to the analysis of the 2017 STAR DY data to demonstrate the feasibility of such a measurement.
- As TMD physics is the major motivation for the forward detector upgrade program, it is of crucial importance that the 2017 RHIC Spin run be analyzed quickly and as completely as possible. This calls for an increase in the RHIC Spin effort rather than the reduction that is being considered.
- 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.

Possible Implementation





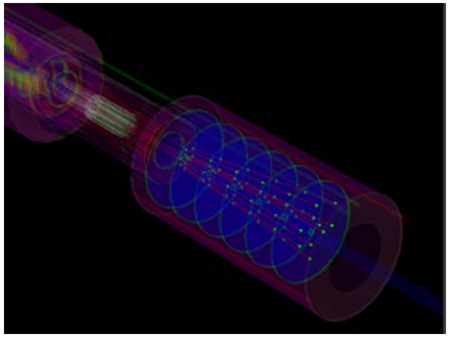
Cost 1-2M$

Forward Electromagnetic calorimeter and hadronic calorimeter
Complete energy measurement with high granularity.

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648
And
The RHIC Cold QCD Plan from 2017 to 2023: A portal to the EIC - Jan. 2016

The STAR Forward Upgrade

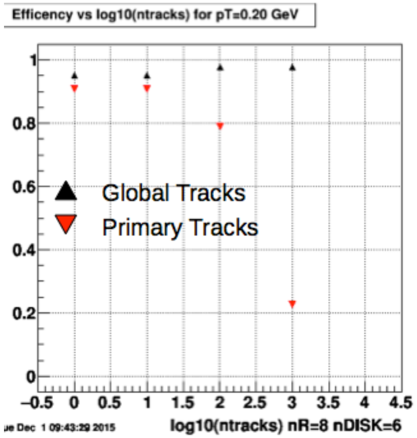
Silicon mini-Strip Detectors only

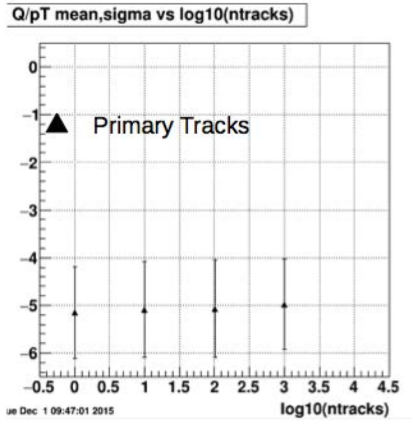


6 disks
12 wedges, each with 128 strips in ϕ at fixed radius and 8 strips in the radial direction at a fixed ϕ
60 – 180 cm from IP

Momentum resolution: 20-30%
for $0.2 < p_T < 2$ GeV/c
track finding efficiency: 95%@100 tr/ev

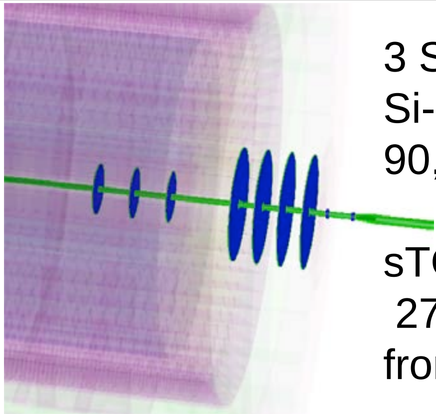
6 disk 8 R 128*12 PHI





Cost: 4.1 M$

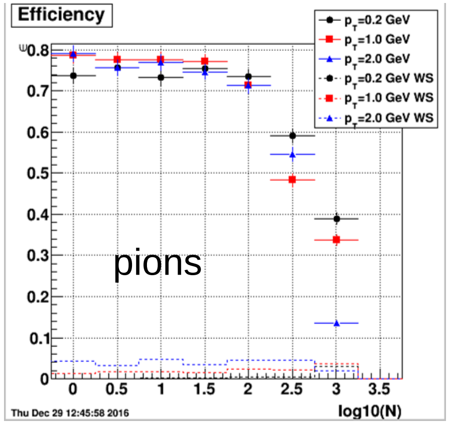
Si + Small-strip Thin Gap Chambers

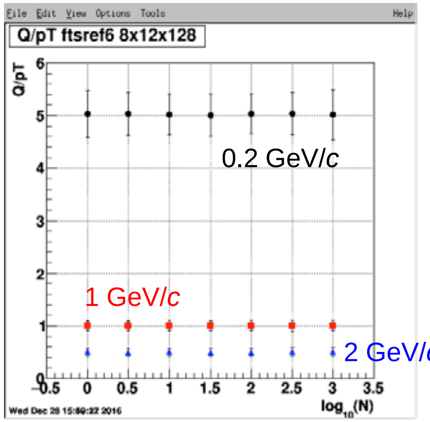


3 Si disks + 4 sTGC
Si- disks:
90, 140, 187 cm from IP

sTGC:
270, 300, 330, 360 cm from IP (outside Magnet)

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





Cost: 3.3 M$

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

Summary of forward AA measurements

Physics Measurements		Longitudinal de-correlation $C_n(\Delta\eta)$ $r_n(\eta_a,\eta_b)$	$\eta/s(T)$, $\zeta/s(T)$	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	

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.

RHIC has been adaptable to science needs

2010-2013	2014	2015	2016	2017	2018	2019	2020		2022+
Au+Au p+p	Au+Au	p+p p+A	Au+Au d+Au	p+p Au+Au	Isobar Au+Au	Au+Au	Au+Au		Au+Au pp,pA
ΔG, QGP property	Charm flow	Ref. A_N	D_c, Λ_c Υ, Jets	Fc sign	CME, $\Lambda\uparrow$	Critical Point, Phase Transition			Jets, Υ forwardA_N
BES-I	200, 14.5	200	200- 19.6	500, 54.4	200, 27	BES-II 11-20	BES-II 7-11		200

BES-I

BES-II

Beam Energy Scan (BES)
Expand to include several programs:
p+A in run 15,
pp500 and 54.4GeV Au+Au in run17,
Isobar (Zr, Ru-96) and 27GeV Au+Au in run 18
BES-II more compelling, detector and machine upgrades in 2018
Future high-luminosity jets and Upsilon in 2020+
3+1D hydrodynamics and Unique Cold QCD (DY) portal to EIC

RHIC Energy nucleus low-x physics & QGP rapidity correlation

- TMD and gluon saturation at Low-x using forward DY and γ-h correlations
- Rapidity decorrelation and global polarization probing QGP properties
- Exotic particle and jet production over large rapidity range
- Adopting new detector concepts toward EIC (Electron-Ion Collider)