STAR Upgrades

Daniel Brandenburg (Shandong University / BNL-CFNS)

→ for the **STAR Collaboration**

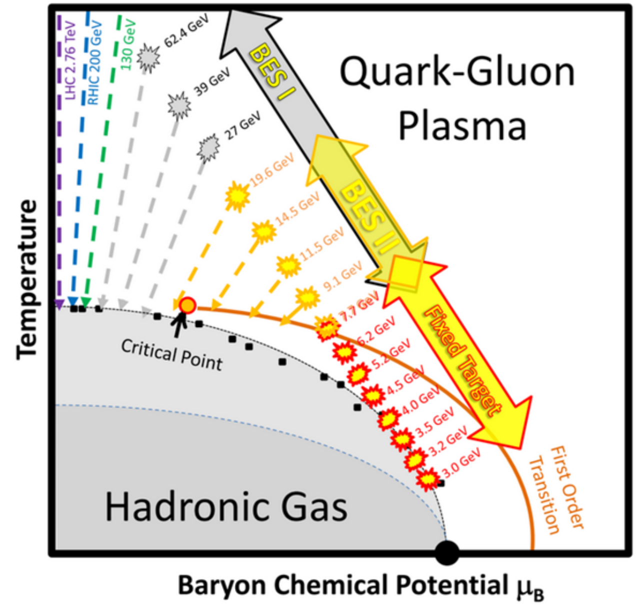
Initial Stages 2019

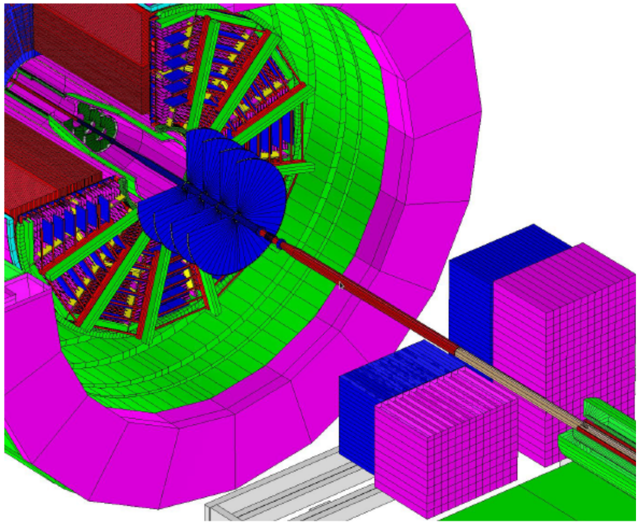
June 24-28, 2019

Columbia University, NY

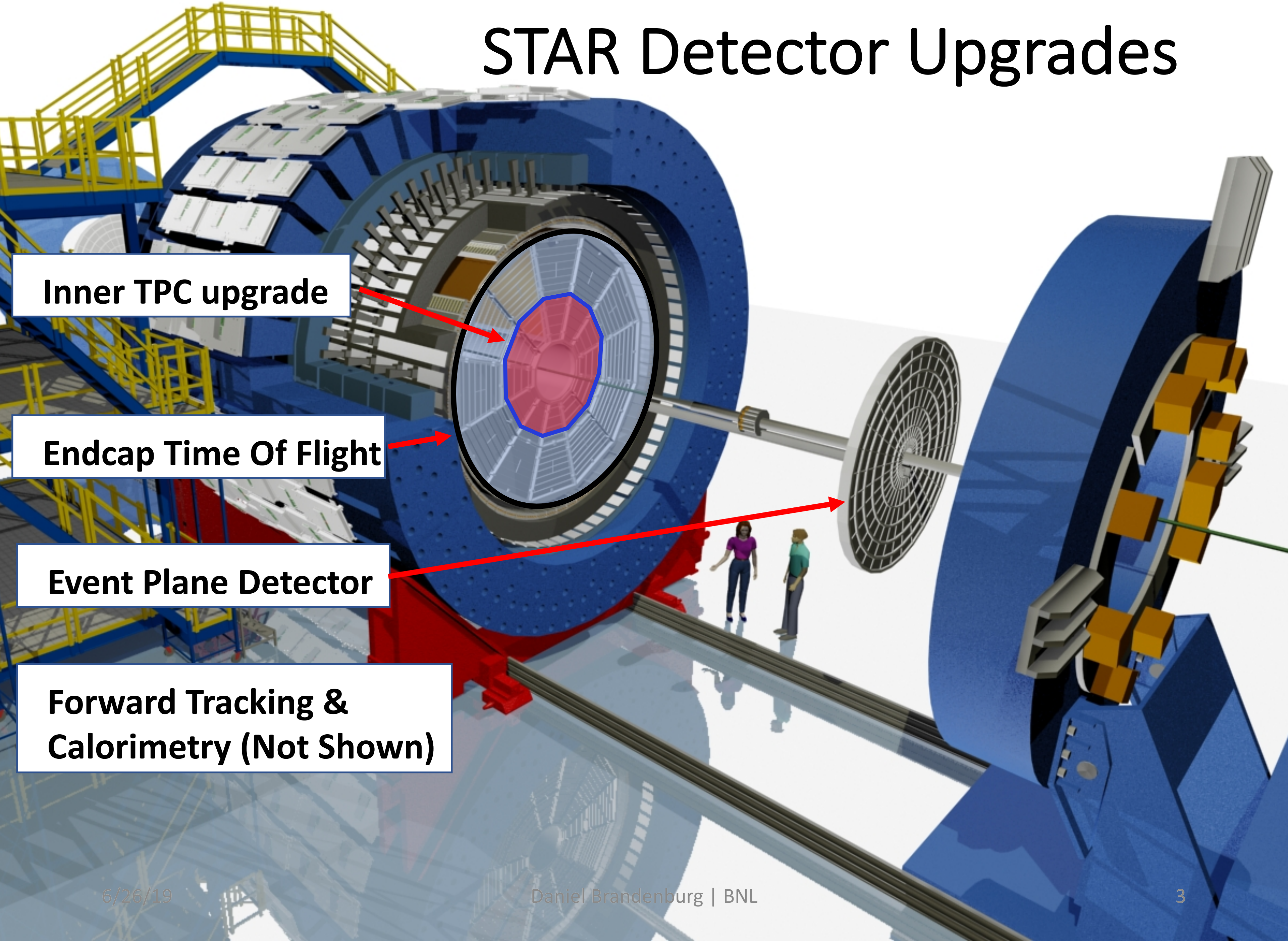
STAR Upgrades : Outline

- STAR Upgrades for BES II
  - Upgrade of the Inner TPC
  - Event Plane Detector
  - Endcap Time-of-Flight
- Forward Rapidity Physics
- The STAR Forward Upgrade
  - Tracking
  - Calorimetry
- Looking Forward
- Summary





STAR Detector Upgrades



Inner TPC Installation

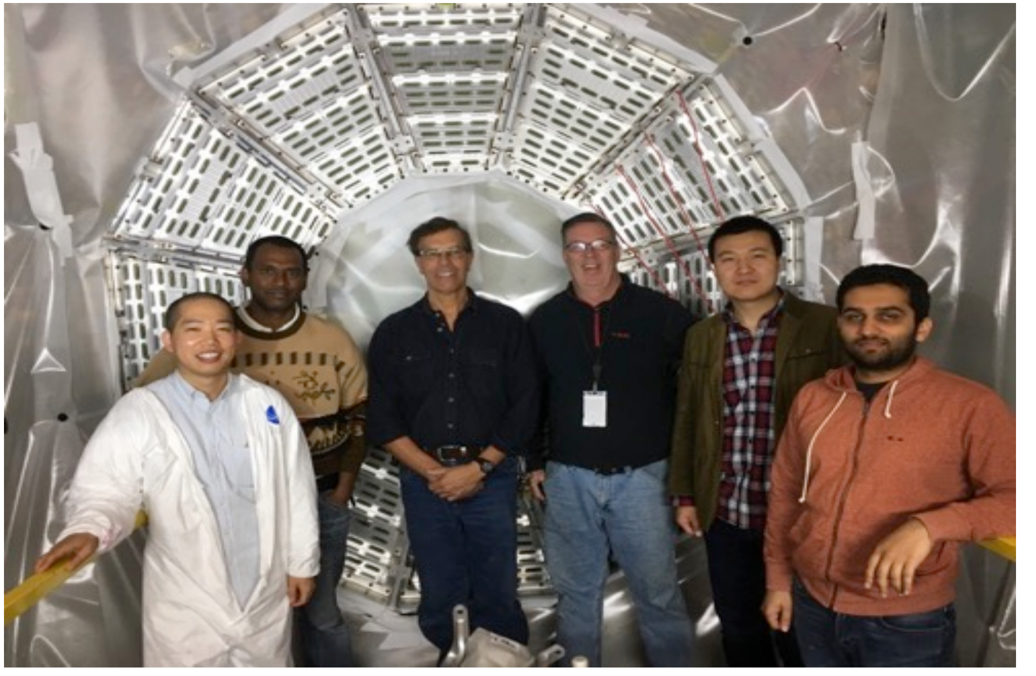
Installation

- East Side Sectors Complete 09/26/18
- West Side Sectors Complete 10/25/18

The testing and commissioning plan was developed~ 2 years ago, and updated following the fall DOE NP review - Includes hardware testing

Important components were:

✓Tests at SDU
✓Test at BNL pre-installation
✓Final inspection at installation time
✓Post Installation checkout
✓Cosmic data taking



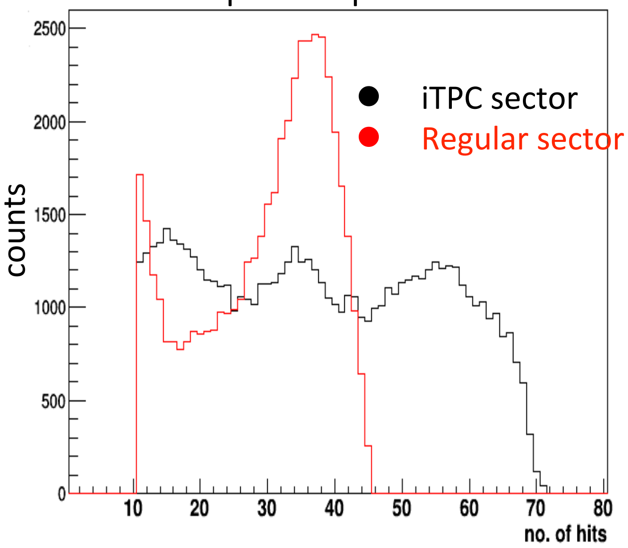
2019 Schedule followed:

- Jan 18 - Feb 4: Cosmic data with forward Full Field
- Feb 4: Change Magnet polarity
- Feb 4 - ~Feb 18 Cosmic data with reverse full field
- Feb. 11: cool down of 2nd half of blue ring begins
- Feb. 14: beam in blue ring starting with the day shift
- Feb. 19: cool down of 2nd half of yellow ring begins
- Feb. 20: beam in yellow ring starting with the day shift
- Feb. 20: 1st collisions in STAR overnight at injection energy
- Feb. 21-27: Physics setup

Inner TPC Upgrade

[NIM A 896 (2018) 90]

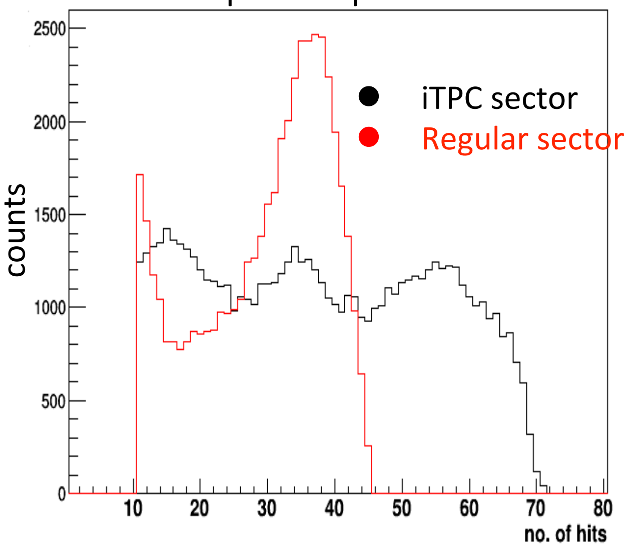
- **Replace all inner TPC sectors → continuous pad rows**
  - Doubled the readout channels. Using SAMPA chip developed for ALICE



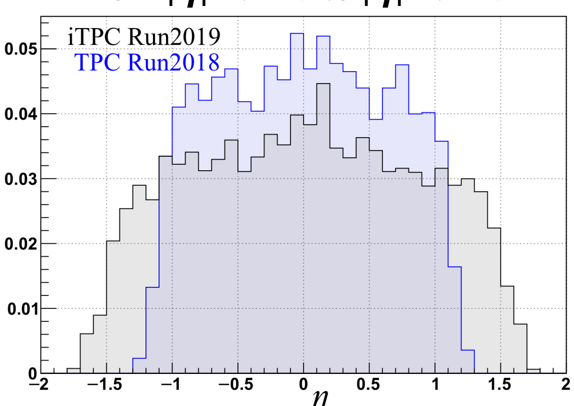
Inner TPC Upgrade

[NIM A 896 (2018) 90]

- **Replace all inner TPC sectors → continuous pad rows**
  - Doubled the readout channels. Using SAMPA chip developed for ALICE



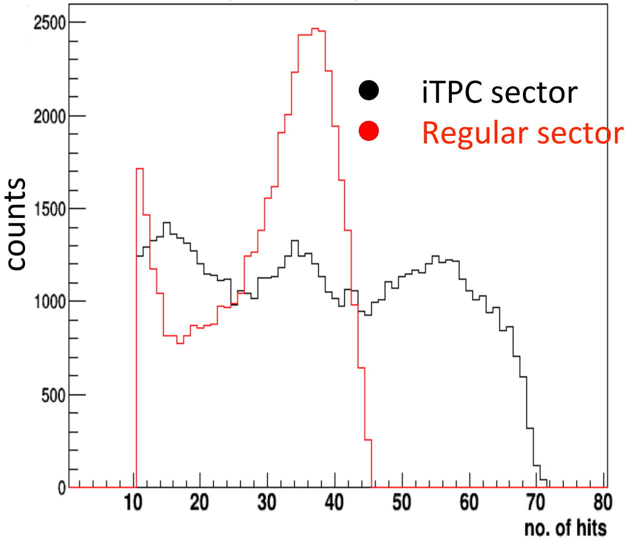
  - **Increase mid-rapidity coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$**



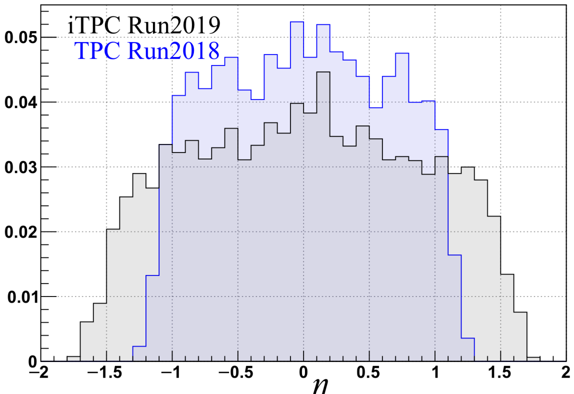
[NIM A 896 (2018) 90]

Inner TPC Upgrade

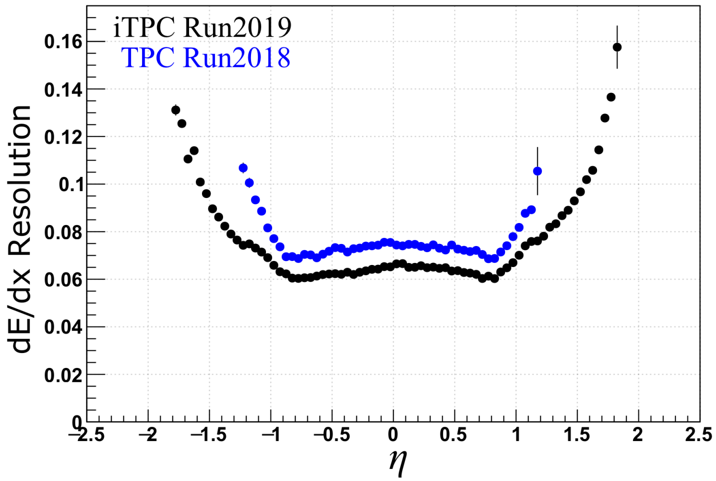
- ➢ **Replace all inner TPC sectors → continuous pad rows**
  - ○ Doubled the readout channels. Using SAMPA chip developed for ALICE



  - ○ **Increase mid-rapidity coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$**



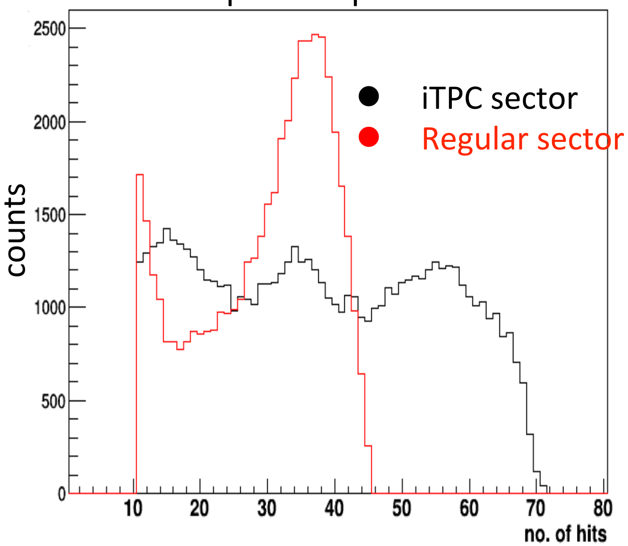
  - ○ **Improved dE/dx Resolution (15%-30%)**



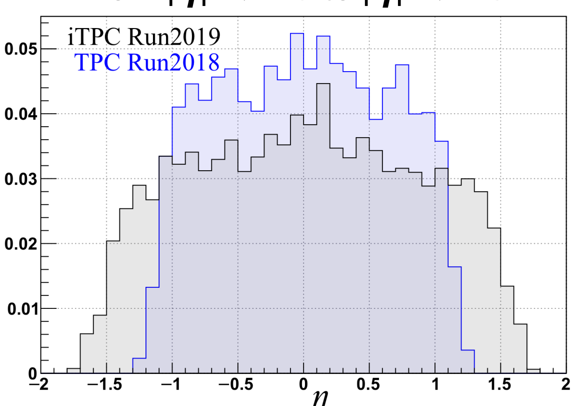
Inner TPC Upgrade

[NIM A 896 (2018) 90]

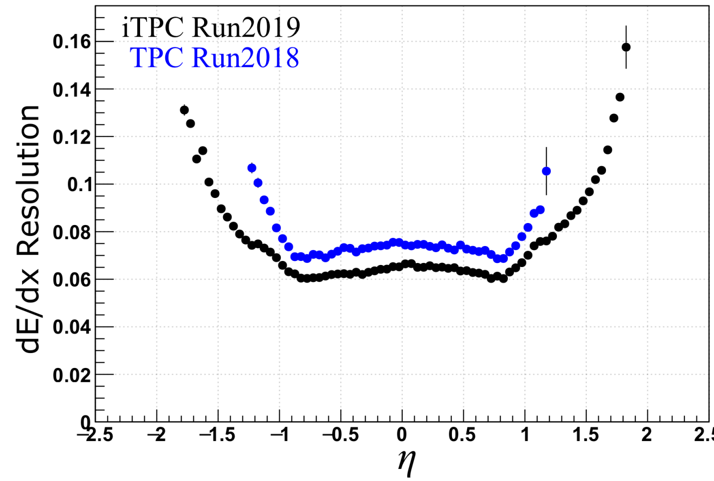
- ➢ **Replace all inner TPC sectors → continuous pad rows**
  - ○ Doubled the readout channels. Using SAMPA chip developed for ALICE



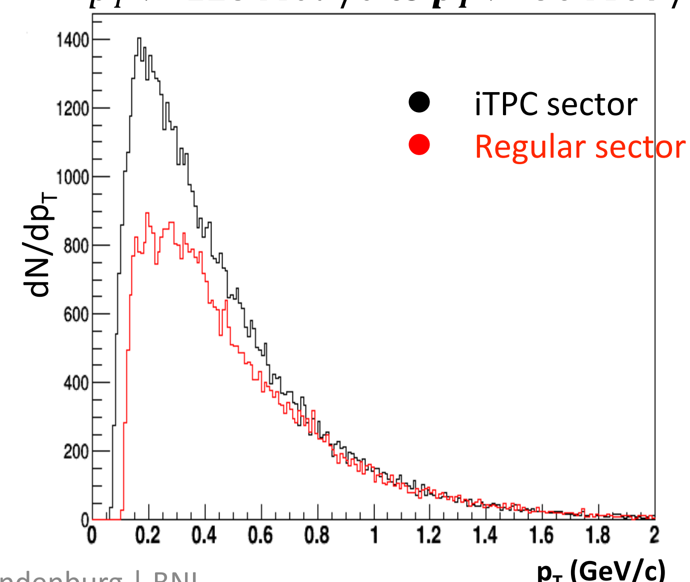
- ○ **Increase mid-rapidity coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$**



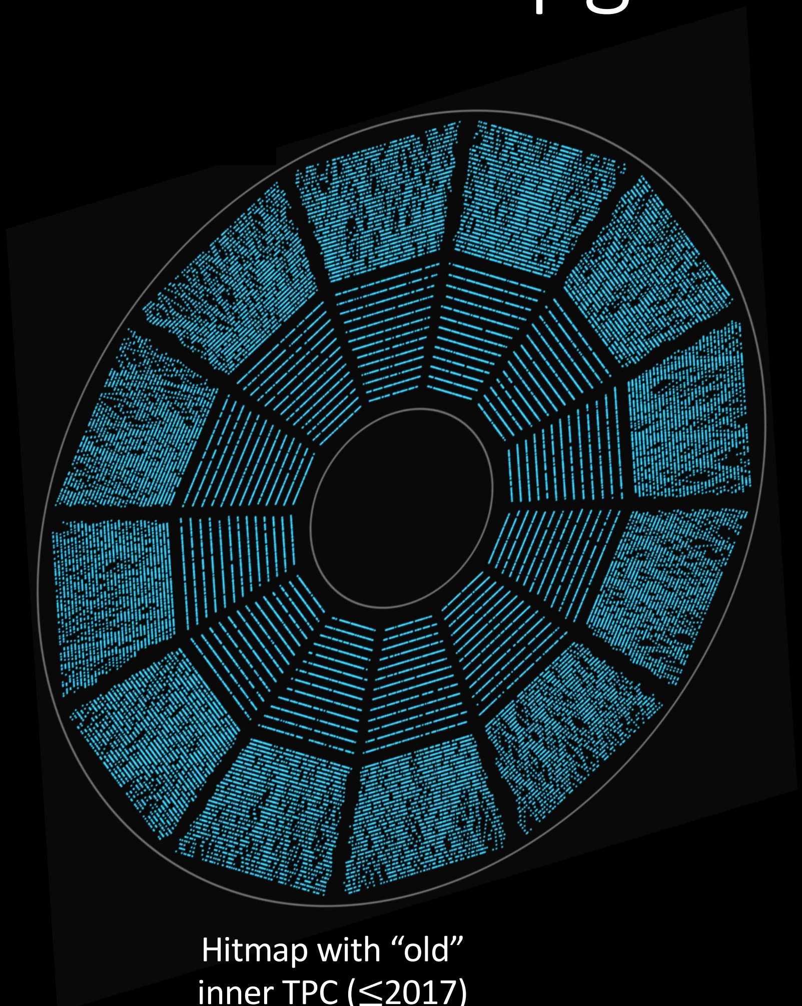
- ○ **Improved dE/dx Resolution (15%-30%)**



- ○ Improved Momentum Resolution
- ○ Decrease minimum p_T threshold from $p_T > 125\ MeV/c$ **to $p_T > 60\ MeV/c$**

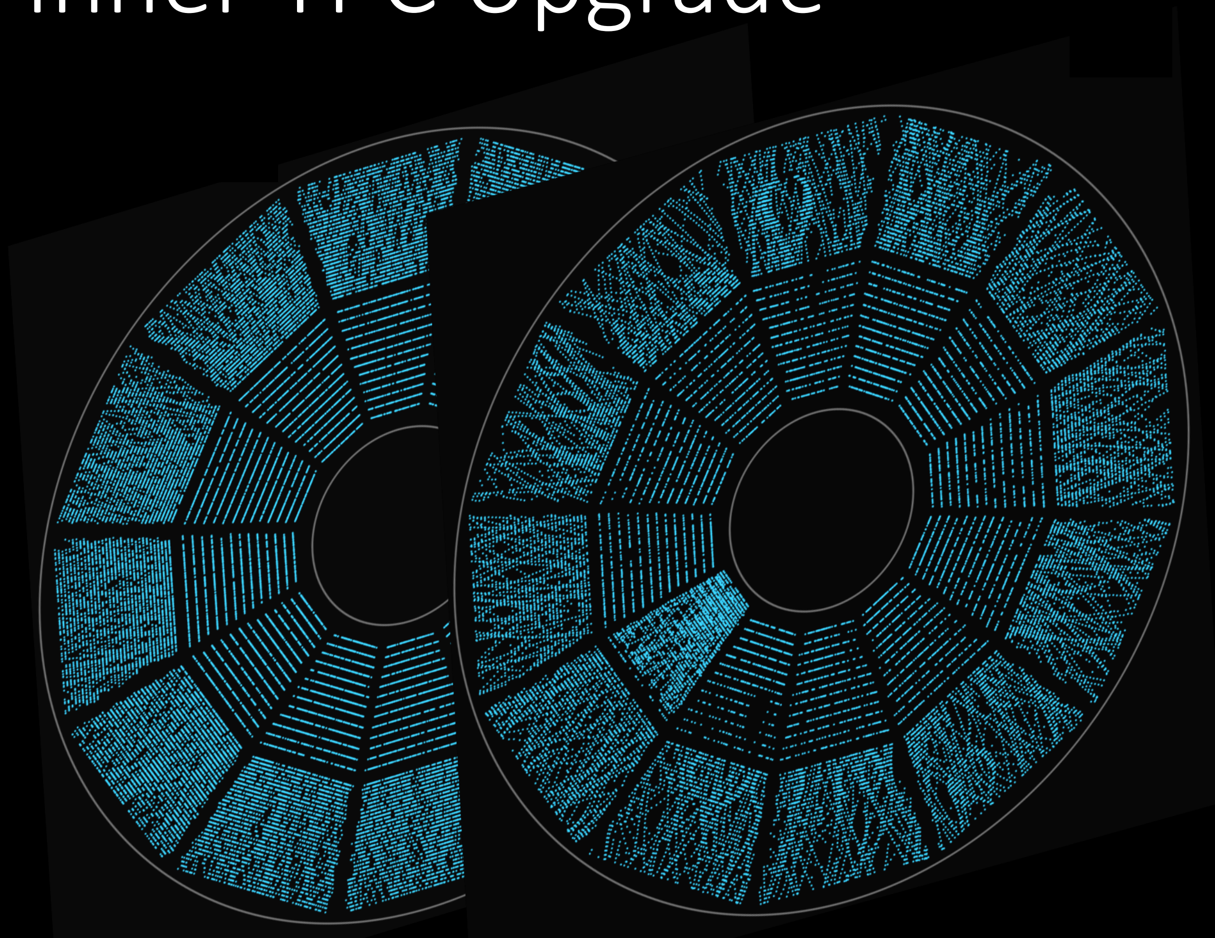


Inner TPC Upgrade



Hitmap with “old” inner TPC (≤2017)

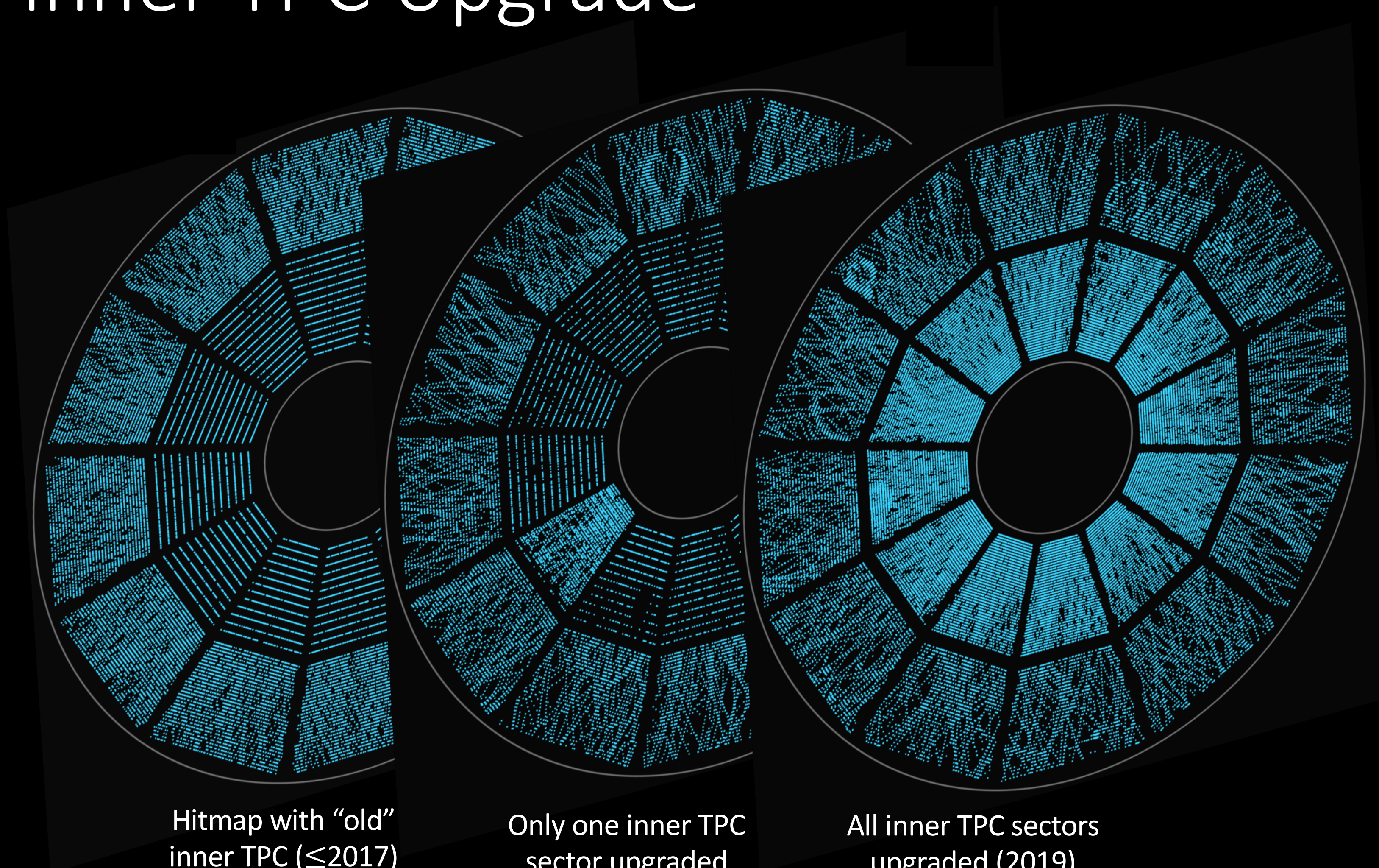
Inner TPC Upgrade



Hitmap with “old” inner TPC (≤2017)

Only one inner TPC sector upgraded (2018)

Inner TPC Upgrade



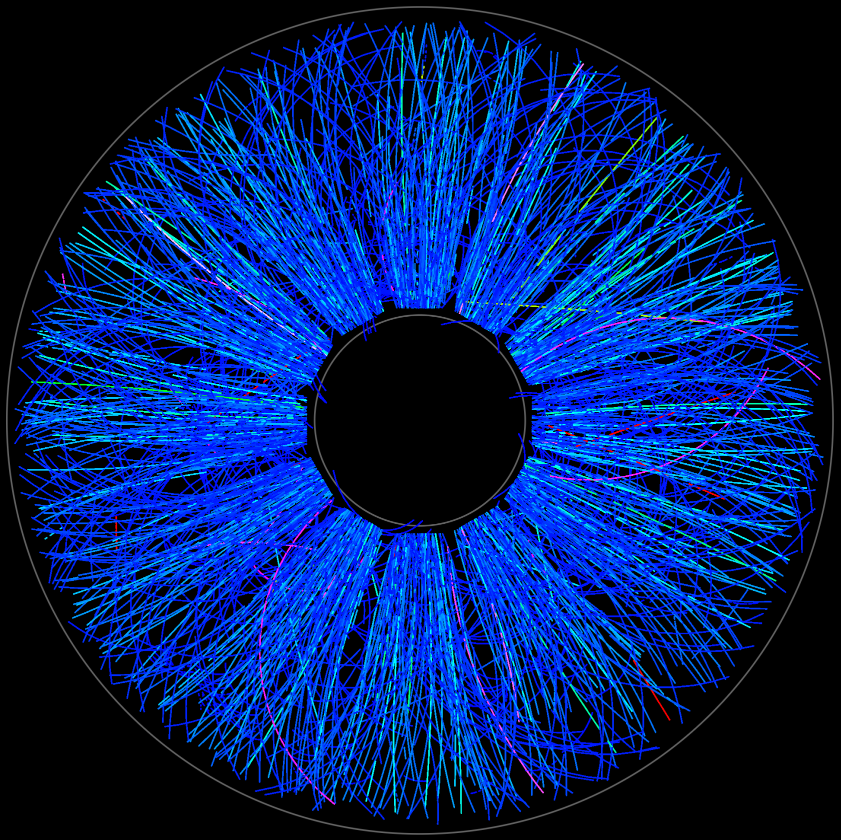
Hitmap with "old" inner TPC (≤2017)

Only one inner TPC sector upgraded (2018)

All inner TPC sectors upgraded (2019)

Inner TPC Upgrade

Successful, on-time & under budget completion of the iTPC upgrade



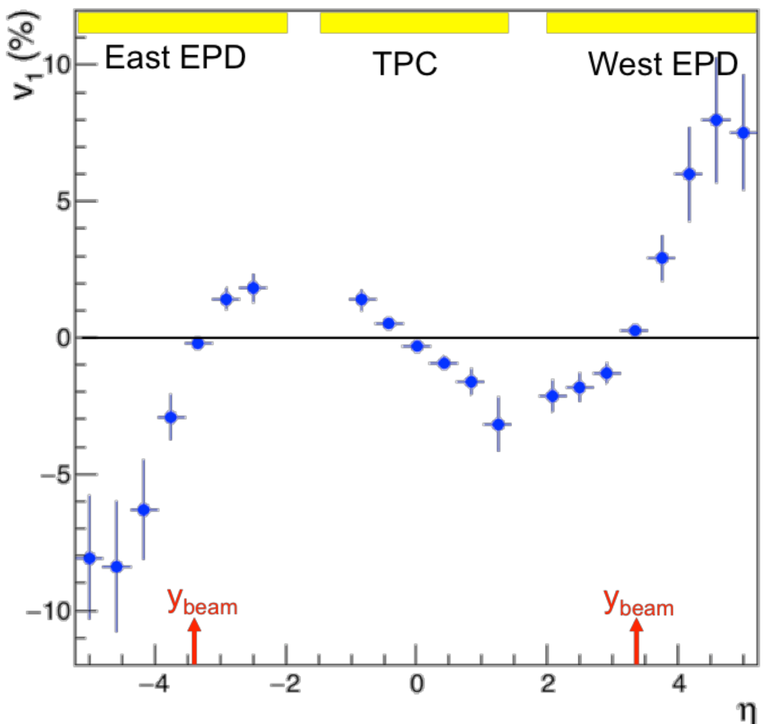
2019 Event Display : Au+Au 19.6 GeV
Full tracking with all iTPC sectors

Event Plane Detector

STARNote 666 https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666

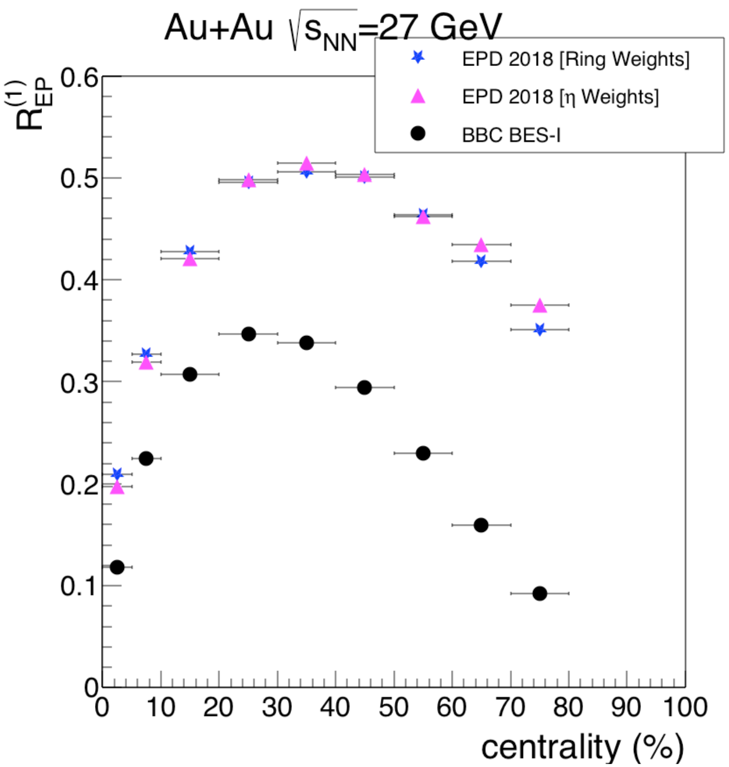
- Replaces Beam-Beam Counter (BBC)
  - Improved triggering capabilities
  - Extend η coverage
  - Improve event plane resolution

- Smooth installation
  - ✓ **Completed in 2018**
  - ✓ Already used in analysis of 2018 data



Added coverage from EPD

→ Allows measurement of v_1 over ~10 units of η!

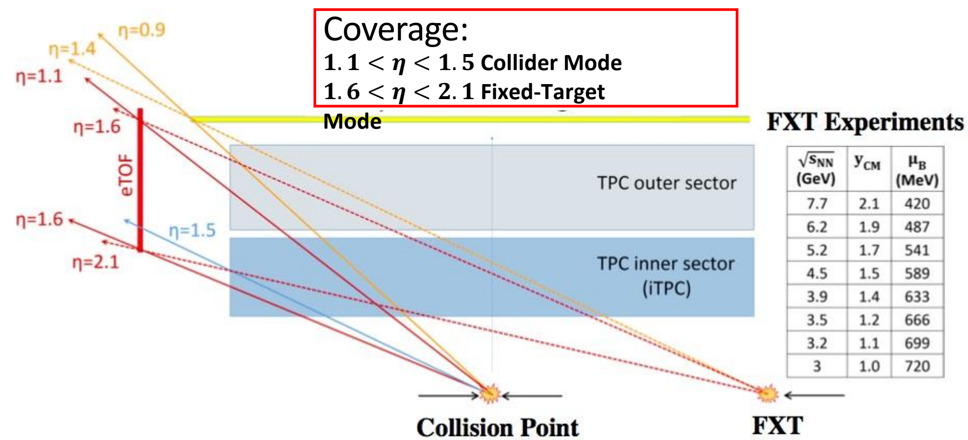


1st order Event Plane Resolution

→ Significant improvement across all centrality

Motivation: Endcap Time-of-Flight Detector

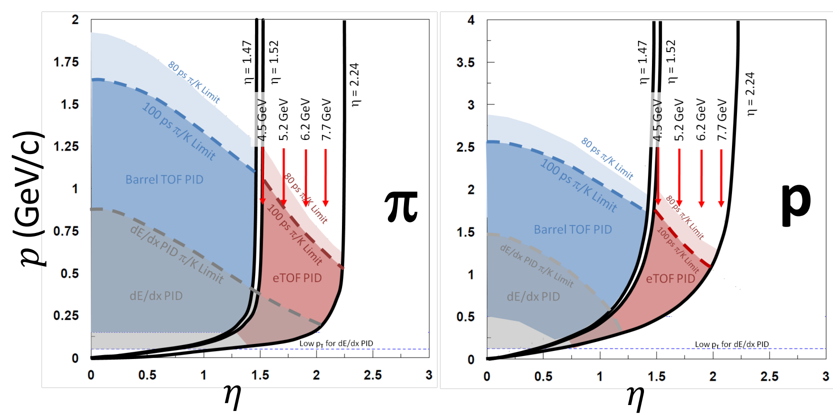
➢ Extend STAR's particle ID capabilities (π, K, p)
- **Complements the increased iTPC coverage $|\eta| < 1.5$**
- **Essential for <u>mid-rapidity</u> particle ID in Fixed Target Program**



$\sqrt{s_{NN}}$ (GeV)	y_{CM}	μ_B (MeV)
7.7	2.1	420
6.2	1.9	487
5.2	1.7	541
4.5	1.5	589
3.9	1.4	633
3.5	1.2	666
3.2	1.1	699
3	1.0	720

➢ Allows "gap-less" scan of phase diagram with collider + Fixed Target Energies
- <u>Rapidity dependence</u> of key bulk observables
- Particle ID – needed for fluctuation measurements in the Fixed Target Program

Acceptance in Fixed Target Mode

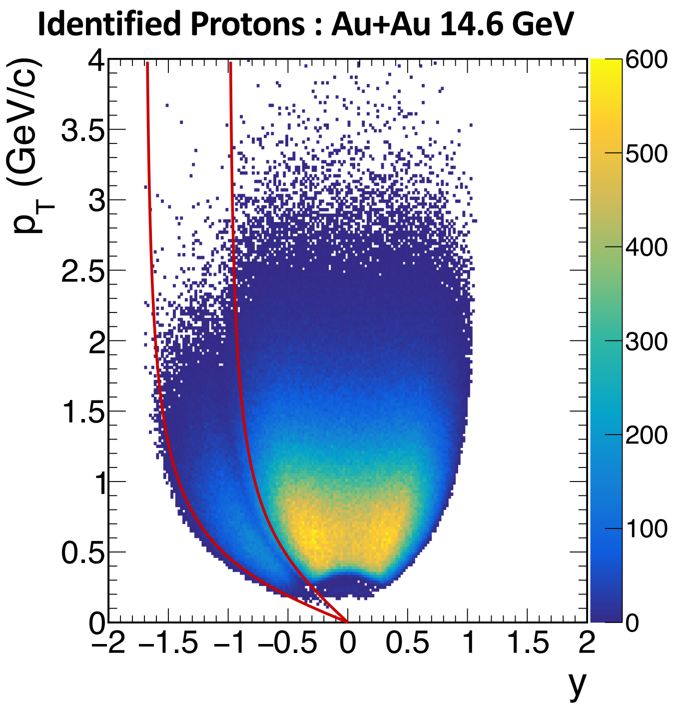


➢ <u>First streaming DAQ system at RHIC</u> – important step towards the future

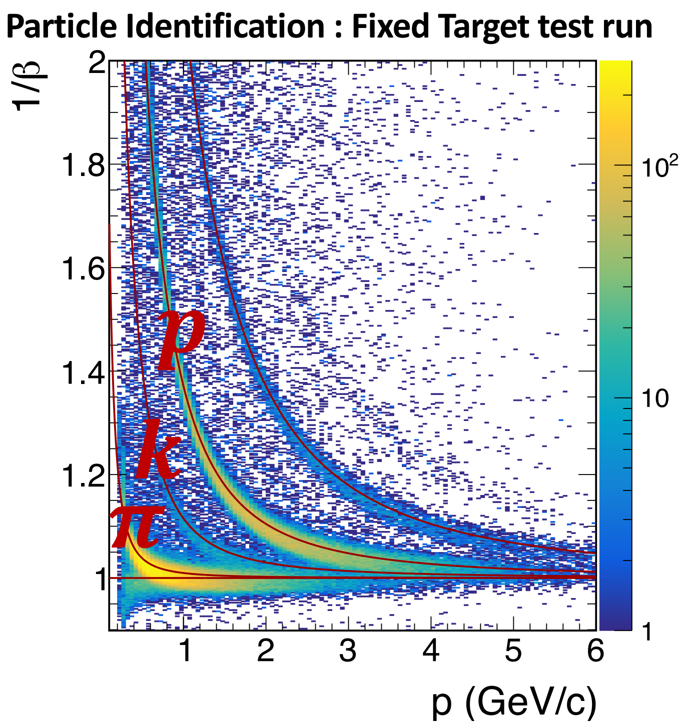
➢ Collaboration with CBM Fair phase 0

➢ Full eToF installation : **completed Nov 22, 2018**

ETOF Performance in 2019 Running



Region in red lines :
extended coverage added by eTOF
for identified protons



Particle bands are clearly distinguished over large momentum range.
Achieved target time resolution →
Calibrated time resolution ~85 ps

STAR Physics Program after BES II

➢ **STAR Upgrades for BES II → provide <u>unique</u> opportunities at mid-rapidity in high energy A+A, p+A, and p+p**

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

A+A

Beam:
Full Energy (200 GeV) Au+Au

Physics Topics:
a deep look into the properties of the QGP:

- ➢ γ & e+e- pairs
- ○ Chiral symmetry restoration
- ○ Temperature and lifetime of hot, dense medium
- ➢ Lower momentum π, K, p spectra
- ➢ Hypertriton Lifetime Measurement
- ➢ Precision measurements of direct photon yields and v_n

p+A, p+p

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

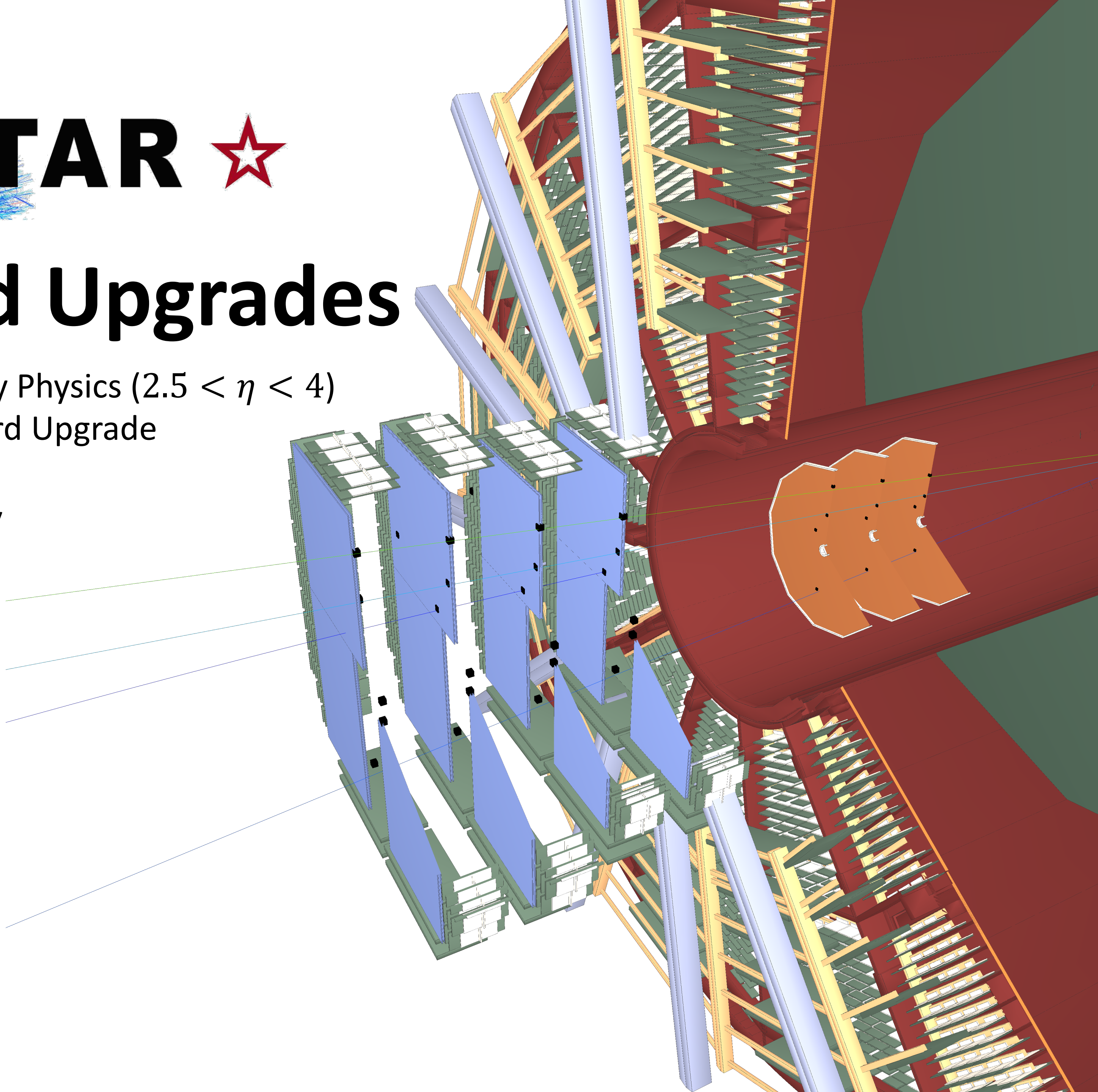
Physics Topics:
Improve statistical precision:

- ➢ TMD measurements, i.e. Collins, Sivers, …
- ➢ Access s & Δs through Kaons in jets
- ▪ Measurement of GPD E_g through UPC J/Ψ
- ▪ First access to Wigner functions through di-jets in UPC
- ▪ Gluon and quark vacuum fragmentation
- ▪ Gluon and quark fragmentation in nuclear medium
- ▪ Nuclear dependence of Collins FF

The STAR midrapidity pp, pA, AA physics program beyond BES-II : https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669

Forward Upgrades

- Forward Rapidity Physics ($2.5 < \eta < 4$)
- The STAR Forward Upgrade
  - Tracking
  - Calorimetry
- A Look Forward



Forward Rapidity Physics at STAR

- ➢ **Unique program addressing several fundamental questions in QCD**
- ➢ Essential to RHIC cold & hot QCD physics mission + fully realize scientific promise of future Electron Ion Collider

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

Au+Au

Beam:
Full Energy (200 GeV) Au+Au

Physics Topics:
- Temperature dependence of viscosity through flow harmonics up to η~4
- Longitudinal decorrelation up to η~4
- Global Lambda Polarization → Test for strong rapidity dependence

p+A, p+p

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- TMD measurements at high x transversity → tensor charge
- Improve statistical precision for Sivers through Drell-Yan
- $\Delta g(x,Q2)$ at low x through Di-jets
- Gluon PDFs for nuclei
- ➢ R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

Forward Rapidity Physics at STAR

- **Unique program addressing several fundamental questions in QCD**
- Essential to RHIC cold & hot QCD physics mission + fully realize scientific promise of future Electron Ion Collider

Mid-rapidity $-1.5<\eta<1.5$ | Forward-rapidity $2.5<\eta<4$

Au+Au

Beam:
Full Energy (200 GeV) Au+Au

Physics Topics:
- Temperature dependence of viscosity through flow harmonics up to $\eta\sim4$
- Longitudinal decorrelation up to $\eta\sim4$
- Global Lambda Polarization → Test for strong rapidity dependence

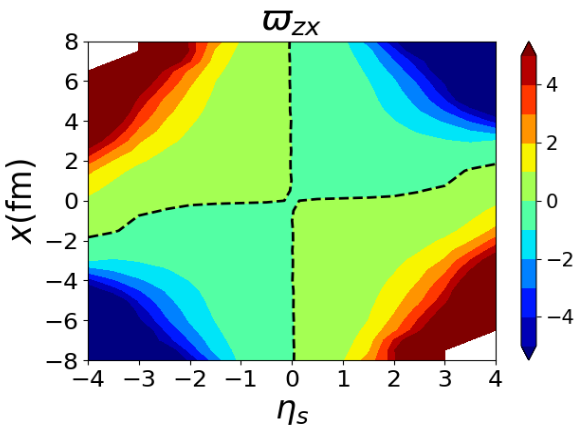
p+A, p+p

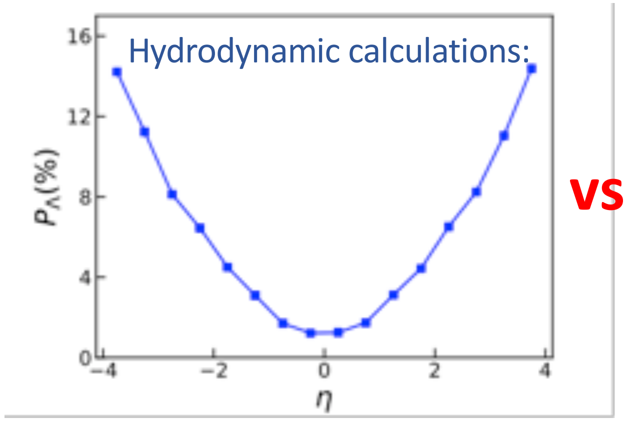
Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- TMD measurements at high x transversity → tensor charge
- Improve statistical precision for Sivers through Drell-Yan
- $\Delta g(x,Q2)$ at low x through Di-jets
- Gluon PDFs for nuclei
  - R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

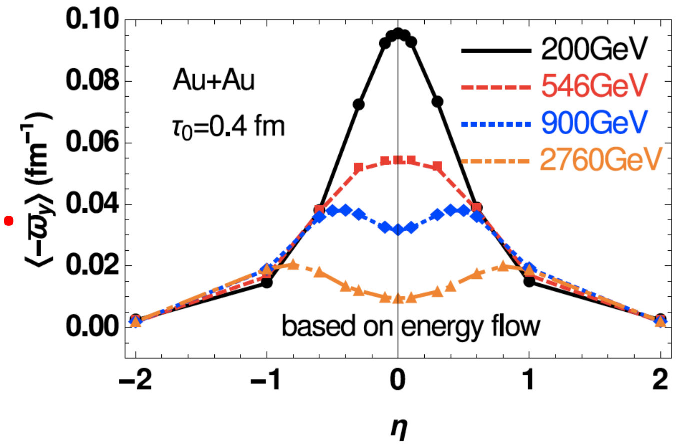
Global Hyperon Polarization

- ➢Sensitive to thermalization and viscosity





vs.



- ➢Polarization increases with viscosity

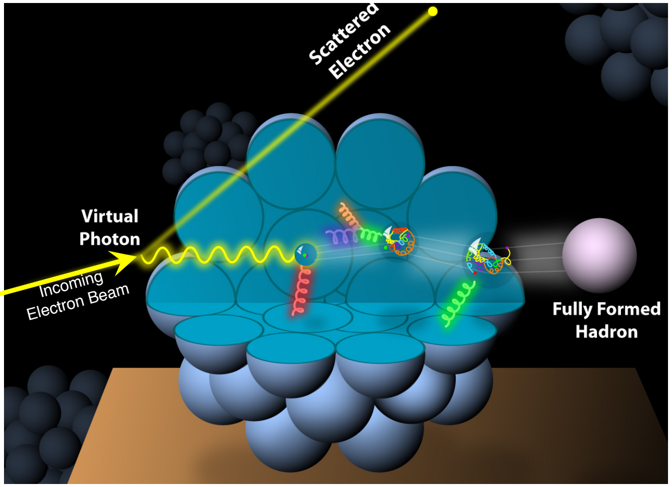
Hydrodynamic calculations:
Li,Pang,Wang & Xia, PRC 96 (2017) 054908; (private comm.)
F. Beccattini et al. EPJC 75(2015)406; arXiv:1501.04468

HIJING with energy flow:
Deng & Huang, PRC 93 (2016) 064907

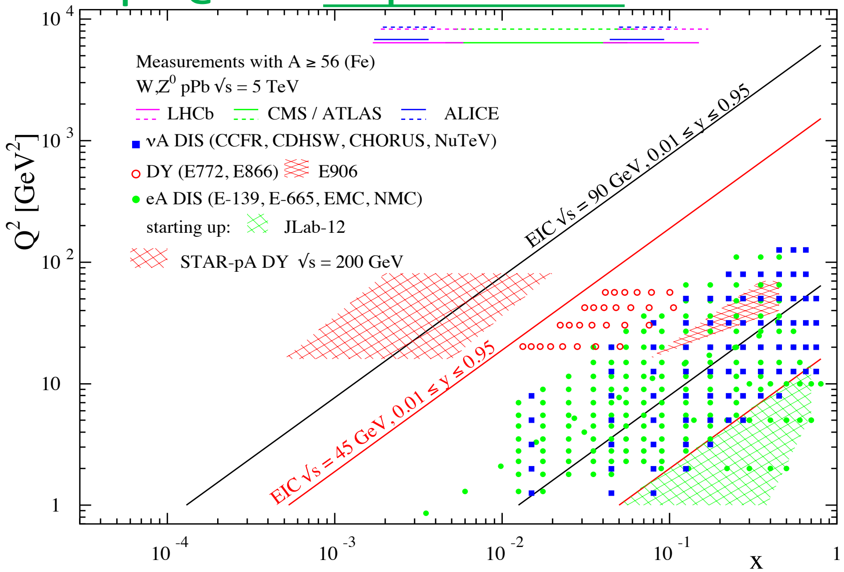
Model's predict opposite Polarization trend with rapidity
→ Measurements at forward rapidity are key

Probing the Initial State in A+A

➢ 3 important questions:
- 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?



p+A@RHIC: unique kinematics

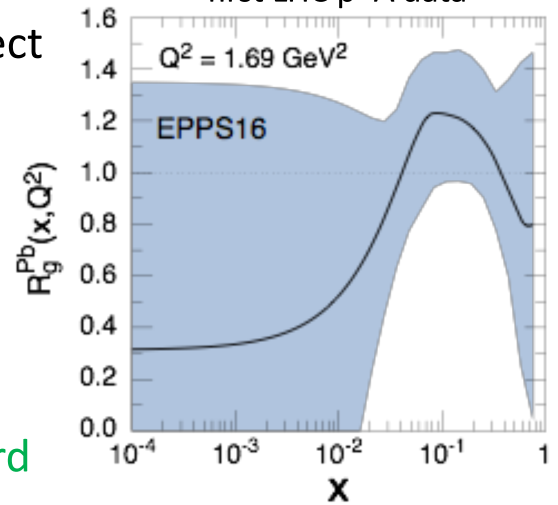


Observables free of final state effects:
- Gluons: R_{pA} for direct photons
- Sea-quarks: R_{pA} for Drell-Yan

➢ Scan A-dependence prediction by saturation models

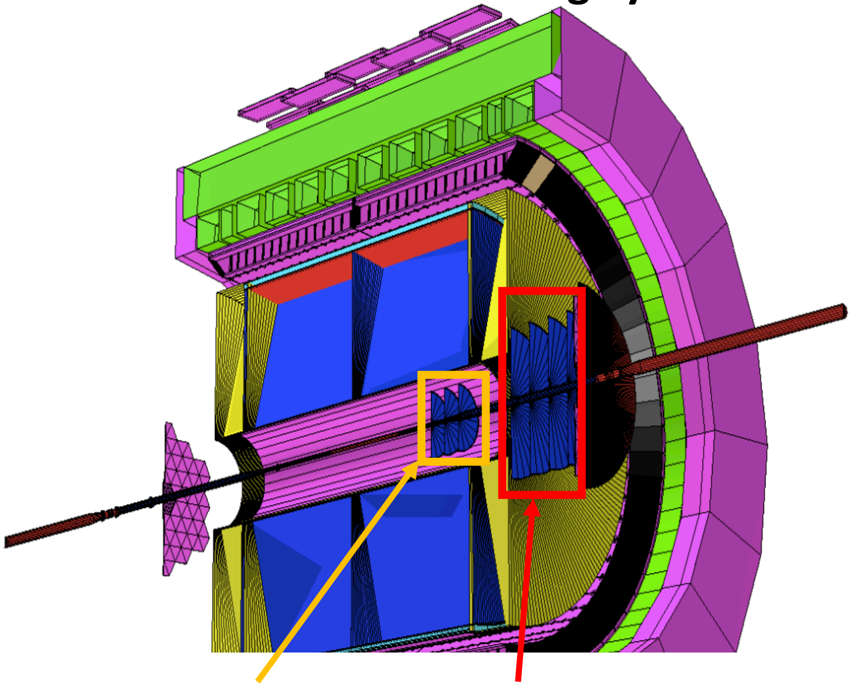
➢ Accessible at forward rapidity

Current knowledge including first LHC p+A data



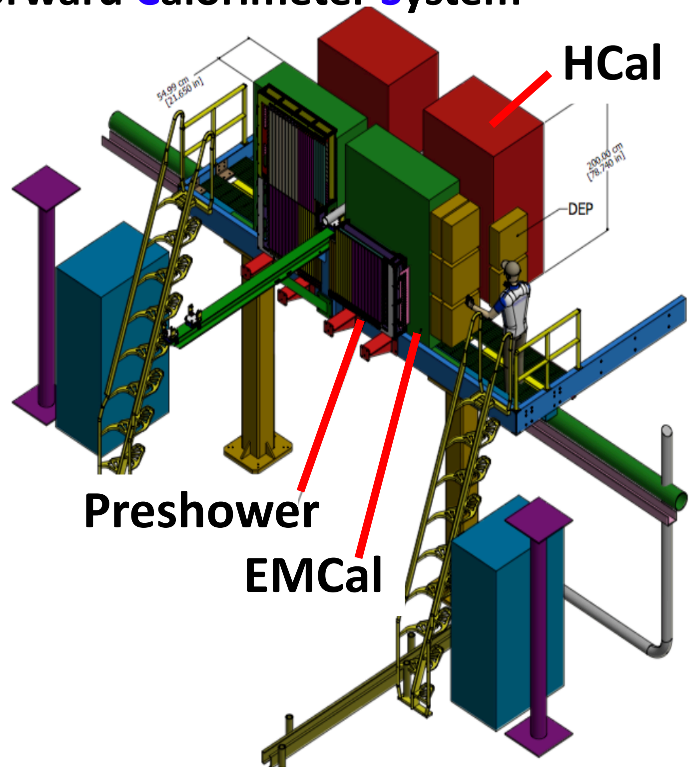
STAR Forward Detectors: FTS + FCS

Forward Tracking System



Silicon + small-Strip Thin Gap Chambers (sTGC)

Forward Calorimeter System

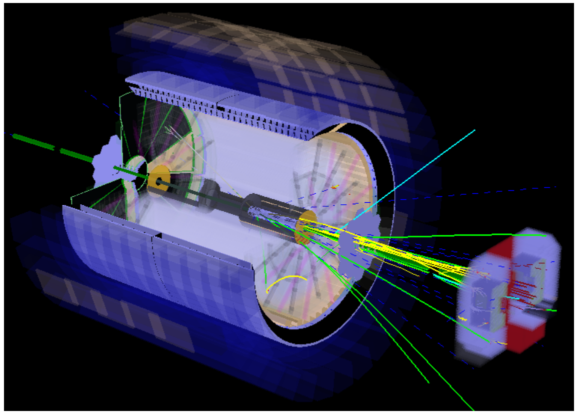


STAR Forward Upgrade Status

Associate Laboratory Director's Review

- Reviewed on 19th, November 2018 :
  - ✓ Physics requirements
  - ✓ Cost & Schedule for each subsystem
  - ✓ Readout & Triggering
  - ✓ Plan for integration and in-situ testing
- **Positive Feedback & Recommendations**
  - "Good progress has been made on an intriguing concept for a cold-QCD program to run in the near future in the forward direction at STAR"

The STAR Forward Calorimeter System and Forward Tracking System



NSF proposal submitted Jan 2019

➢ Funding for Forward Calorimeter systems

✓ **Received very positive feedback**

✓ **Awaiting final response from NSF Division of Grants and Agreements - expect to be funded**

Proposal November 2018

https://drupal.star.bnl.gov/STAR/system/files/ForwardUpgrade.Nov_.2018.Review_0.docx

Final Report ALD's review : https://drupal.star.bnl.gov/STAR/system/files/STAR%20forward%20upgrade%20review%20Final%20Report.pdf

STAR Forward Upgrade Institutions

Large project → **Dedicated manpower & expertise for each system**

sTGC
- BROOKHAVEN NATIONAL LABORATORY
- SHANDONG UNIVERSITY

Silicon
- UIC UNIVERSITY OF ILLINOIS AT CHICAGO
- University of Science and Technology of China
- INDIANA UNIVERSITY
- BROOKHAVEN NATIONAL LABORATORY
- SHANDONG UNIVERSITY
- NATIONAL CHENG KUNG UNIVERSITY

ECal
- KENTUCKY
- VALPARAISO UNIVERSITY
- ABILENE CHRISTIAN UNIVERSITY

HCal
- UCLA
- TEXAS A&M UNIVERSITY
- INDIANA UNIVERSITY
- RUTGERS
- ABILENE CHRISTIAN UNIVERSITY
- OHIO STATE

DAQ / Readout
- BROOKHAVEN NATIONAL LABORATORY
- INDIANA UNIVERSITY
- KENTUCKY
- UCLA
- TEXAS A&M UNIVERSITY

Software
- BROOKHAVEN NATIONAL LABORATORY
- UIC UNIVERSITY OF ILLINOIS AT CHICAGO
- INDIANA UNIVERSITY
- TEXAS A&M UNIVERSITY

Integration
- BROOKHAVEN NATIONAL LABORATORY

Calibration
- UC RIVERSIDE
- TEMPLE UNIVERSITY

Slow Controls
- VALPARAISO UNIVERSITY
- ABILENE CHRISTIAN UNIVERSITY

Forward Tracking System

	Requirement	Motivation
Momentum Resolution	< 30%	A+A goals
Tracking Efficiency	> 80% @ 100 tracks / event	A+A goals
Charge Separation	—	p+p / p+A goals

<u>Silicon mini-strip disks ×3</u>

- Location : z = 90, 140, 187 cm from interaction point
- **Build on and utilize STAR experience of successful Intermediate Silicon Tracker(IST) detector**
- minimal material (≤1% X0/layer) in the acceptance

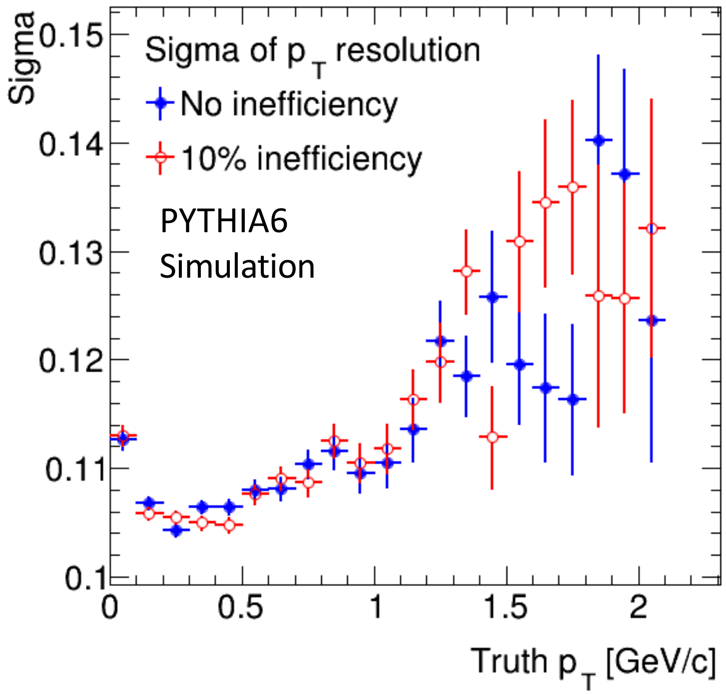
Small-Strip Thin Gap Chamber (sTGC) ×4

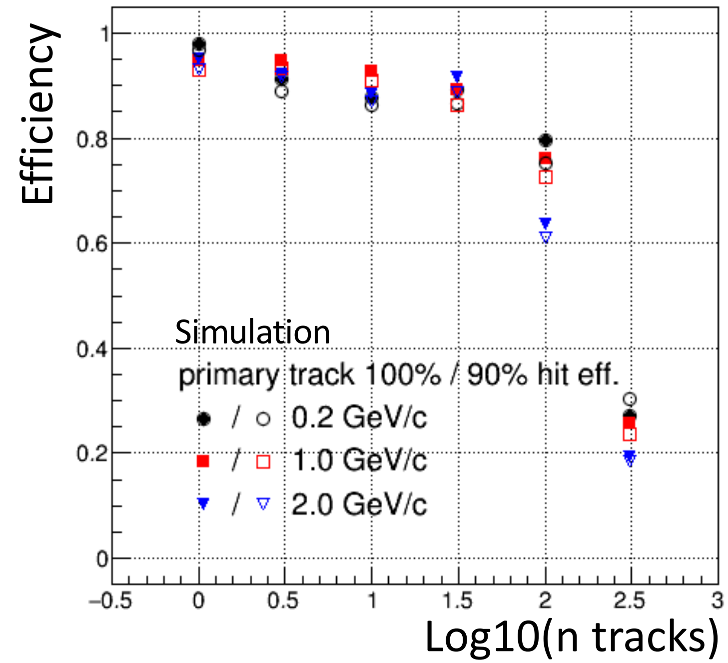
- Location : z = 270, 300, 330, 360 cm from interaction point
- **Significant reduction in cost (compared to all silicon)**
- Prototype at BNL, testing in STAR during 2019 run

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

Forward Tracking System

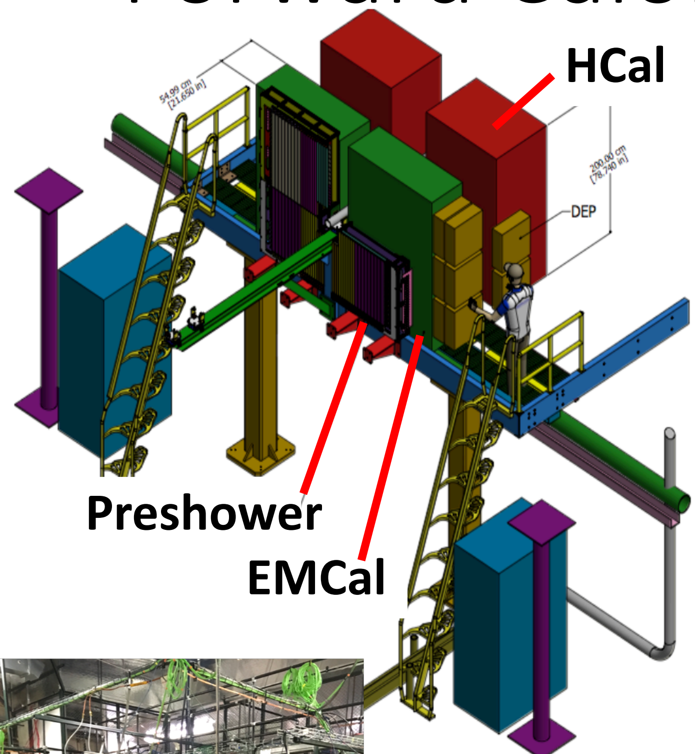
	Requirement	Motivation
Momentum Resolution	< 30%	A+A goals
Tracking Efficiency	> 80% @ 100 tracks / event	A+A goals
Charge Separation	–	p+p / p+A goals





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

Forward Calorimeter System



Detector	Resolution p+p and p+A	Resolution A+A
ECal	$\sim 10\%/\sqrt{E}$	$\sim 20\%/\sqrt{E}$
HCal	$\sim 50\%/\sqrt{E} + 10\%$	–

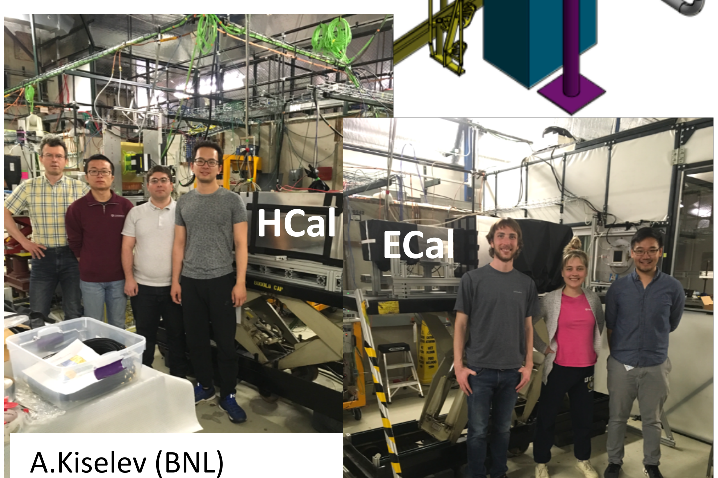
Electromagnetic Calorimeter
- Reuse PHENIX PbSc
- New readout: SiPM

Hadronic Calorimeter
- Sampling iron-scintillator
- Uses same readout as ECal

R&D in support of EIC

→ HCal development
→ All readout electronics
→ Balance Cost & performance

NSF grant expected to provide majority of funds



A.Kiselev (BNL)
T. Lin (TAMU)
D. Kapukchyan (UCR)

D. Neff (UCLA)
M.Sergeeva (UCLA)
B. Chan (UCLA)

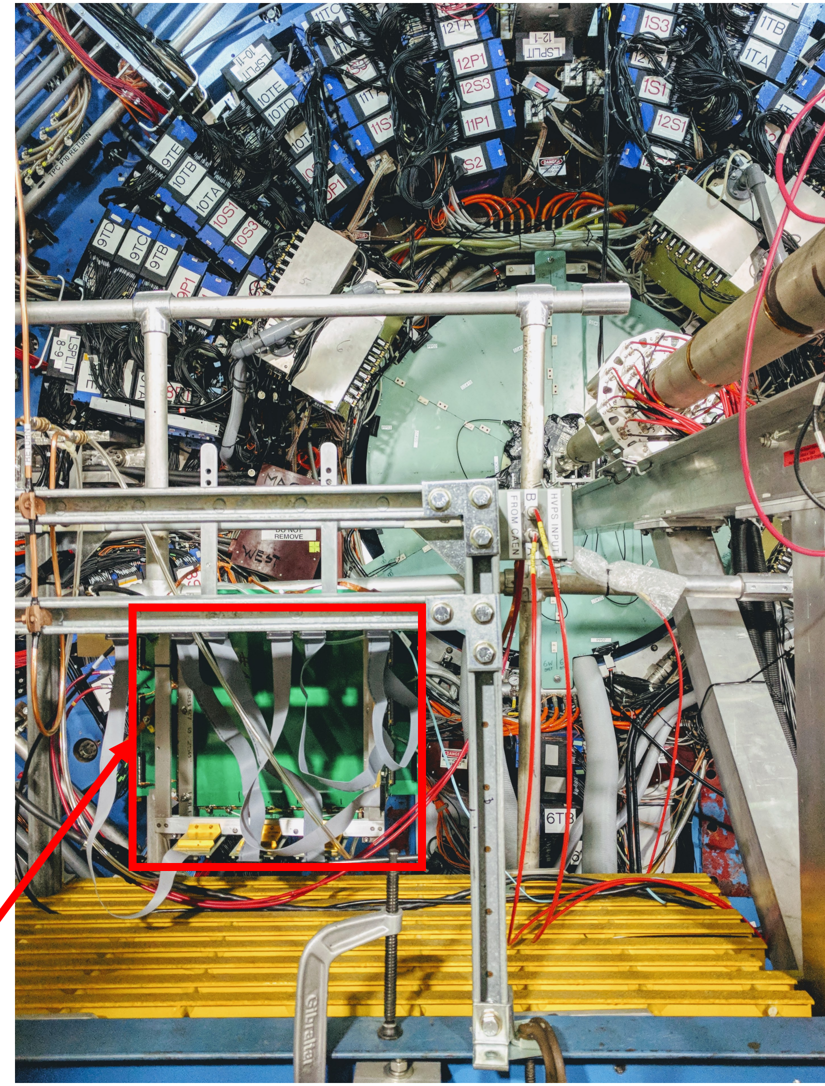
Plan/Goals for Run 19

Forward Calorimeter System

- ✓ Fermilab test beam results completed
- ✓ Measured ECAL energy resolution ~ 10% / $\sqrt{E}$
- o HCAL energy resolution measured ~ 75% / $\sqrt{E}$ + 7%
  - ➢ Work on modified light collection to improve resolution
- ➢ 10-20 hours of Au+Au 200 GeV collisions
  - o Test readout of calorimeters at ~ 10kHz rate
  - o Finish commissioning of DEP (digitizer/trigger) boards with this data
  - o Look at MIPS – use for calibration etc.

Forward Tracking System

- ➢ Silicon Detectors
  - o Complete the design of detector module in June 2019
  - o Build the first complete prototype module in Summer/Fall 2019
  - o Fully test the prototype module in Fall/Winter 2019
- ➢ sTGC Detectors
  - ✓ $\boxed{\text{30x30 cm prototype installed in STAR on June 5}^{\text{th}}\text{, 2019}}$
  - ✓ Test in STAR DAQ with C10 (90% argon + 10% CO2)
  - o Test performance with various gas mixtures at Shandong University in full size (60 x 60 cm) prototypes



Looking Forward

Measurements planned for 2021+ with the STAR forward upgrade

→Address important topics in hot & cold QCD

p+p and p+A

- Transverse polarization effects in the proton : Twist-3 and TMDs
- Transversity, Collins, and Interference fragmentation functions
- Access ΔG through dijets with p+p at $\sqrt{s}$ = 500 GeV
- Probe initial state with p+A collisions

A+A

- Correlation measurements in hot and dense nuclear matter
- Precision measurements of long range correlations
- Temperature dependence of the viscosity through flow measurements at $\eta \sim 4$

$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
$p^{\uparrow}p$ @ 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
$p^{\uparrow}Au$ @ 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
$p^{\uparrow}Al$ @ 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
$p^{\uparrow}p$ @ 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
$\vec{p}\vec{p}$@ 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

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

Summary of STAR Upgrades

Crucial Upgrades for Beam Energy Scan II:

- Inner TPC : Successful, on-time & under budget completion, excellent performance
- Event Plane Detector : Excellent uniformity + delivered expected improvement in the event-plane resolution
- Endcap Time of Flight : Fully installed, commissioning and data taking are ongoing 2019

➢ **Upgrades provide unique opportunities at mid-rapidity in high energy A+A, p+A, and p+p**

STAR Forward Rapidity Upgrade:

➢ Essential to RHIC cold & hot QCD physics mission & to realize scientific promise of future Electron Ion Collider

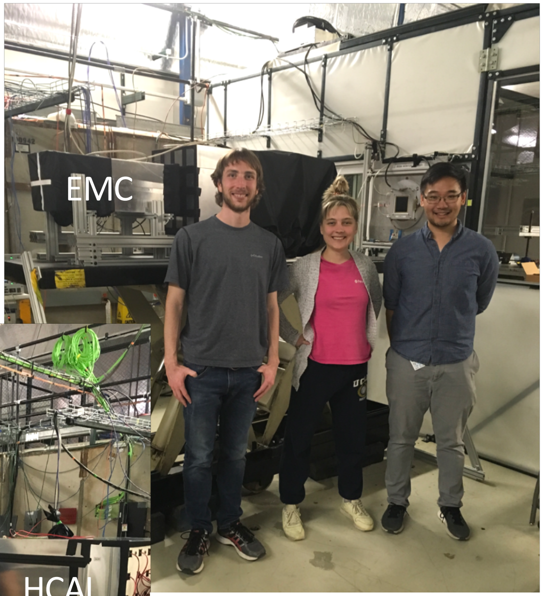
➢ Forward Tracking System
  - ➢ Silicon mini-strip detectors : build on STAR expertise from previous IST detector
  - ➢ Small strip thin gap chambers : reduced cost, already testing prototypes in STAR now

➢ Forward Calorimetry System : Preshower + ECal + Hcal
  - ➢ In-situ testing at STAR now, received positive funding feedback from the NSF

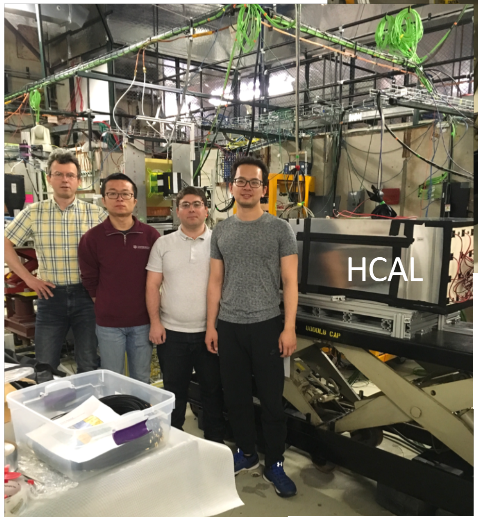
➢ **Unique program addressing several fundamental questions in QCD**

Calorimeter Current Status

- Fermilab test beam results
  - HCAL 16 channels, ECAL 16 channels
  - ECAL energy resolution measured ~ 10% / $\sqrt{E}$ - meets requirement
  - HCAL energy resolution measured ~ 75% / $\sqrt{E}$ + 7%
  - Work on modified light collection to improve resolution
    - Promising results - ongoing development, but does not effect design)
- Installation and in-situ testing at STAR
  - 64 (8x8) EMCAL installed
  - 16 (4x4) HCAL installed
  - 1 layer (9 slats) Pre-shower (former FMS Post-Shower detector)
  - New generation of digitizer/trigger boards for ECAL/HCAL/Preshower readout
- Currently commissioning in STAR with beam
  - Operating pedestal, LED, and physics runs
- Online + slow controls + offline software being developed



D. Neff (UCLA)
M.Sergeeva (UCLA)
B. Chan (UCLA)



A.Kiselev (BNL) D. Chen (UCR)
T. Lin (TAMU) G. Visser (IUCF)
D. Kapukchyan (UCR) O. Tsai (UCLA)

Looking Forward

Future A+A Measurements with the STAR forward upgrade

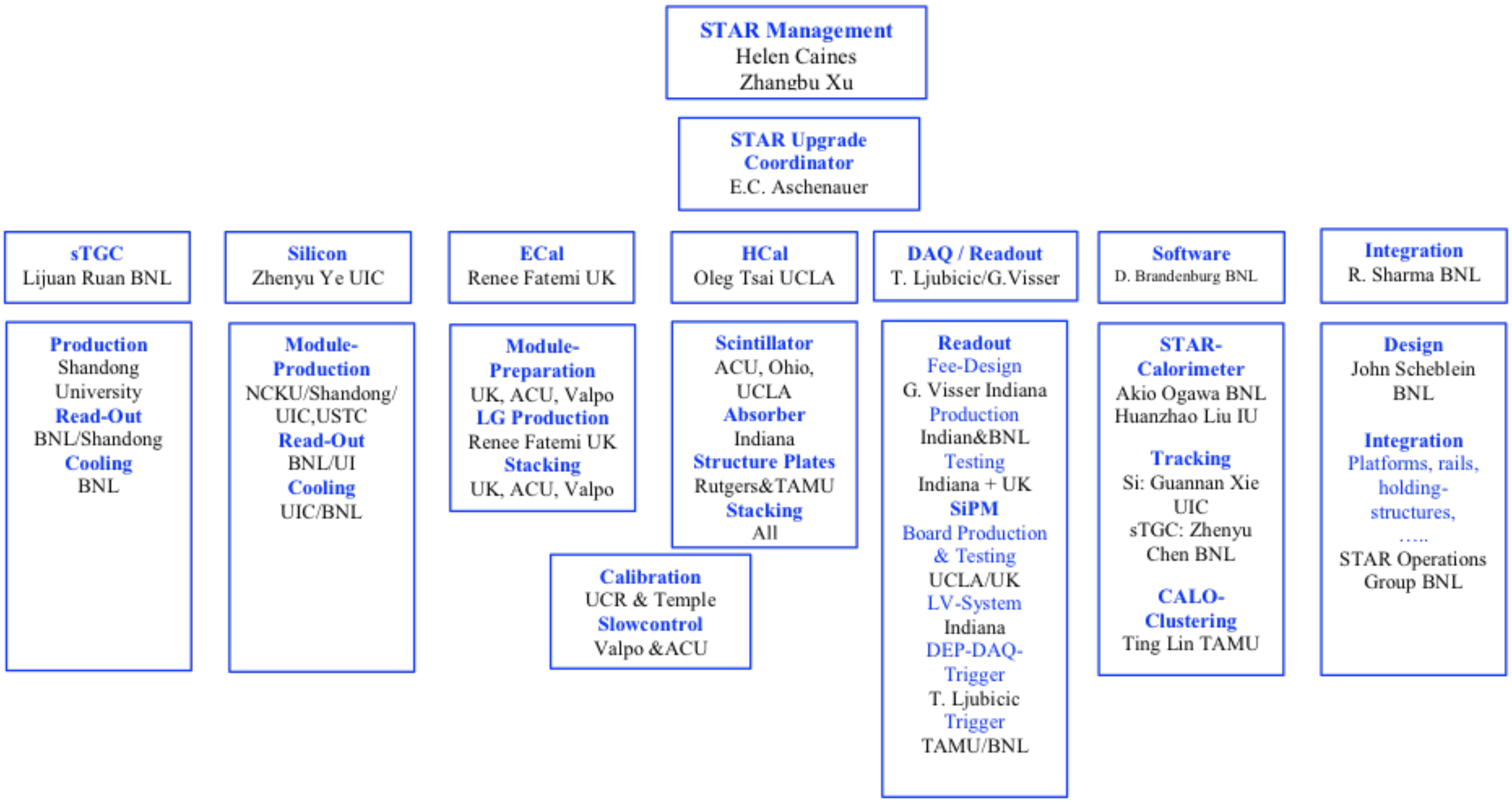
Physics Measurements		Longitudinal de-correlation $C_n(\Delta\eta)$ $r_n(\eta_a,\eta_b)$	$\eta/s(T)$, $\zeta/s(T)$	Mixed flow Harmonics $C_{m,n,m+n}$	Ridge	Event Shape and Jet-studies
Detectors	**Acceptance**					
Forward Calorimeter **(FCS)**	$2.5 < \eta < 4$ (photons, hadrons)	One of these detectors necessary		One of these detectors necessary	Good to have	One of these detectors needed
Forward Tracking System **(FTS)**	$2.5 < \eta < 4$ (charged particles)		Important		Important	

Addresses important topics in hot QCD:

- Ridge in p+p, p+A, and A+A
- Correlation measurements in hot and dense nuclear matter
- Precision measurements of long range correlations
- Temperature dependence of the viscosity through flow measurements at $\eta \sim 4$

Organizational Structure STAR Forward Upgrade

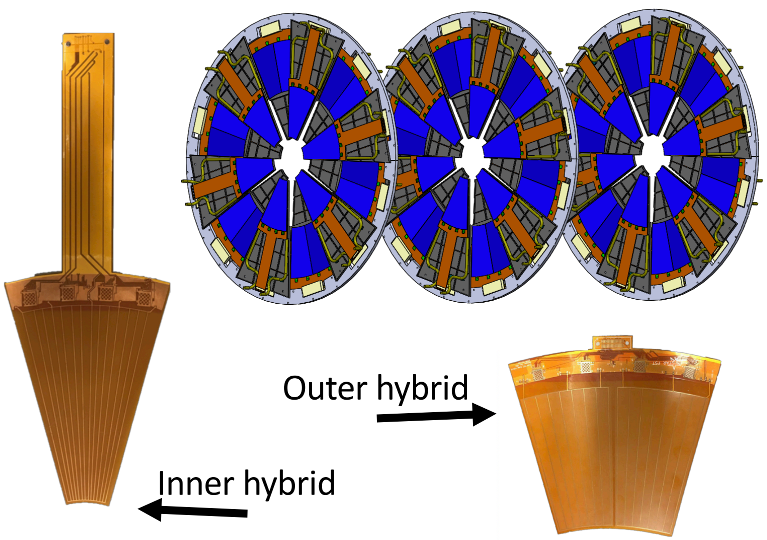
- ➢ Large project → Dedicated manpower & expertise for each system



Forward Tracking System Current Status

Silicon Detector

- Silicon strip sensors ordered from Hamamatsu
- Detector module design and prototyping in progress
- First complete prototype module for test in Fall/Winter 2019



sTGC Detector

- 30x30 cm prototype delivered to BNL in January 2019
- Module tested in test-stand using cosmic rays + scintillator pads for trigger
- Connected to STAR Data Acquisition system – first test data being analyzed now
- Installed in STAR on June 5, 2019
- Full-size 60x60 cm prototype being produced at Shandong University

Prototype in STAR Clean Room,

On the Mounting Structure