The 19th International Conference on Strangeness in Quark Matter
May 17-21, 2021, sponsored by Brookhaven National Laboratory, Upton, New York
SQM2021

The STAR Detector Upgrades

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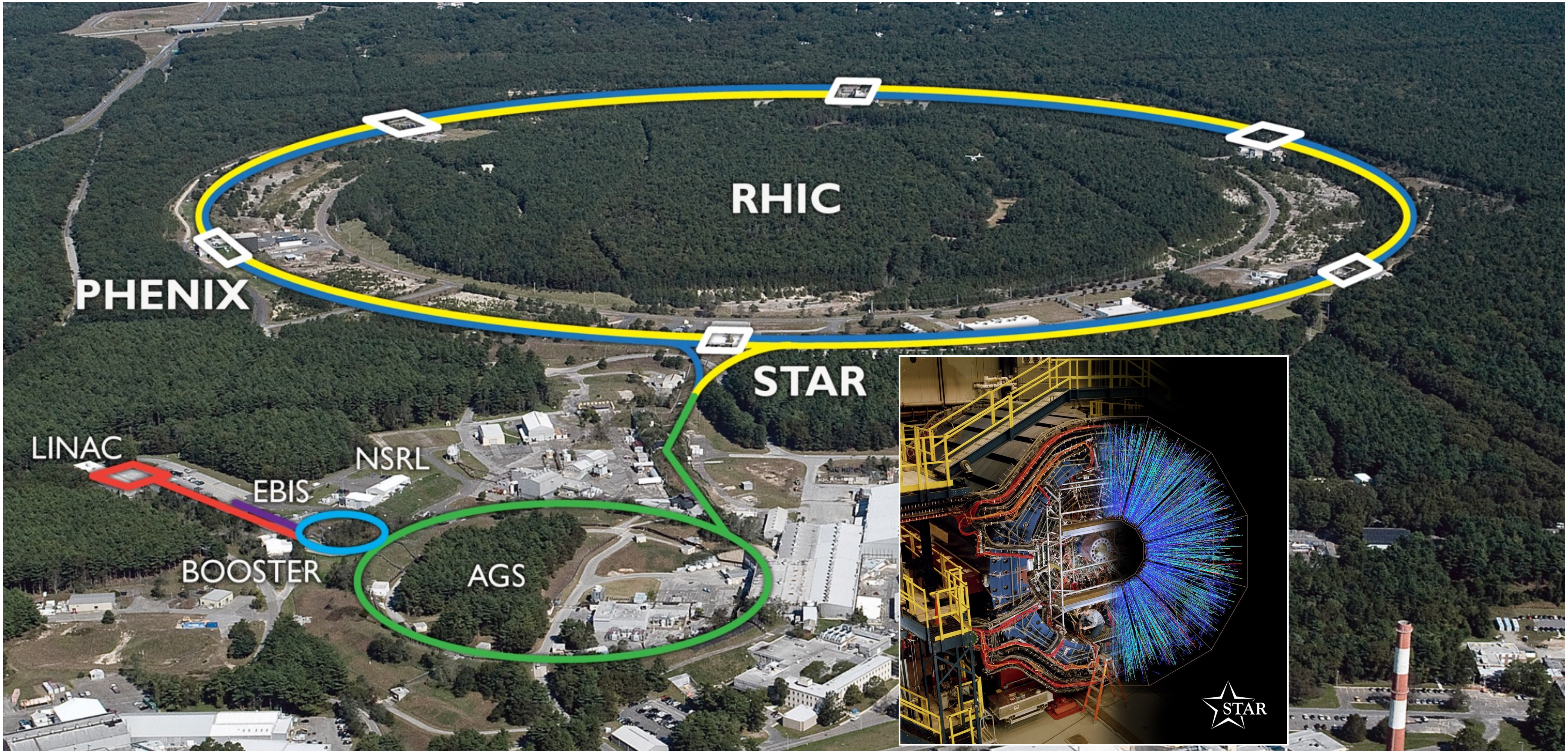
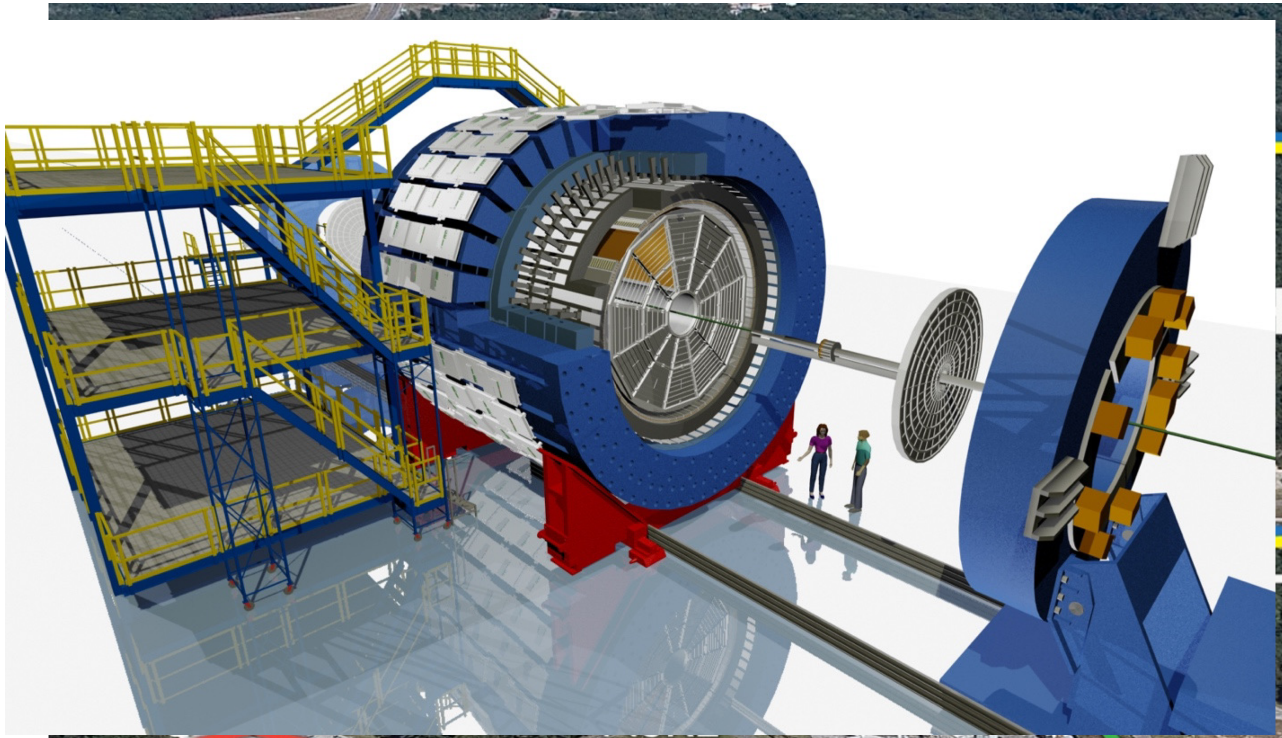
Shandong University

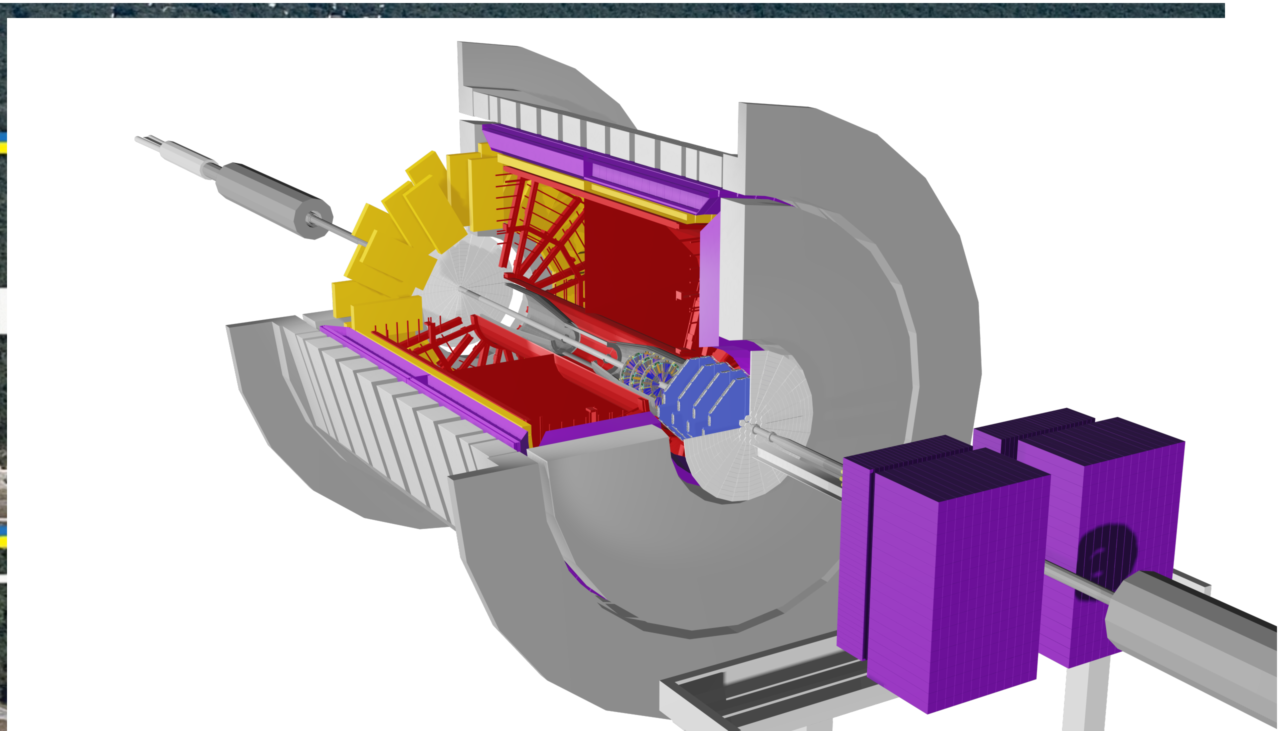
Supported by U.S. DEPARTMENT OF ENERGY Office of Science
NSFC National Natural Science Foundation of China

Recent Physics Programs at RHIC



Recent Physics Programs at RHIC





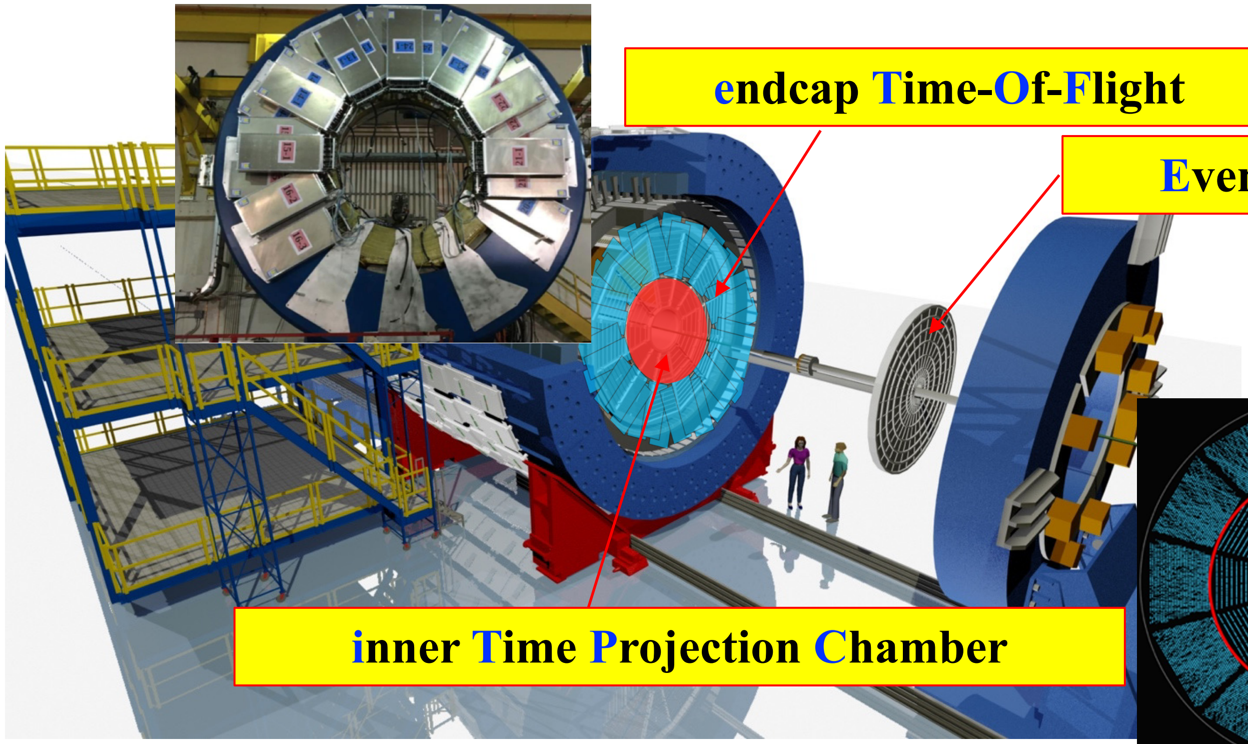
Beam Energy Scan Phase II program:

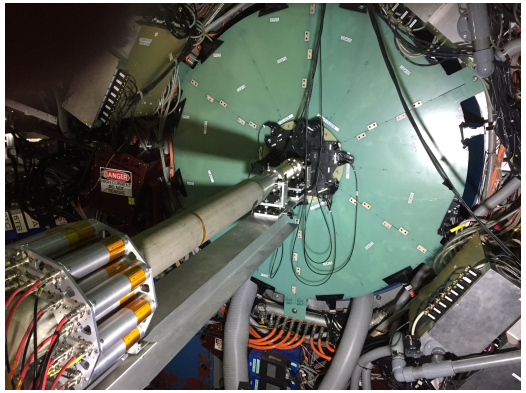
- RHIC run 2019-2021
- QCD phase diagram
- Such as CEP, Chiral phase transition...

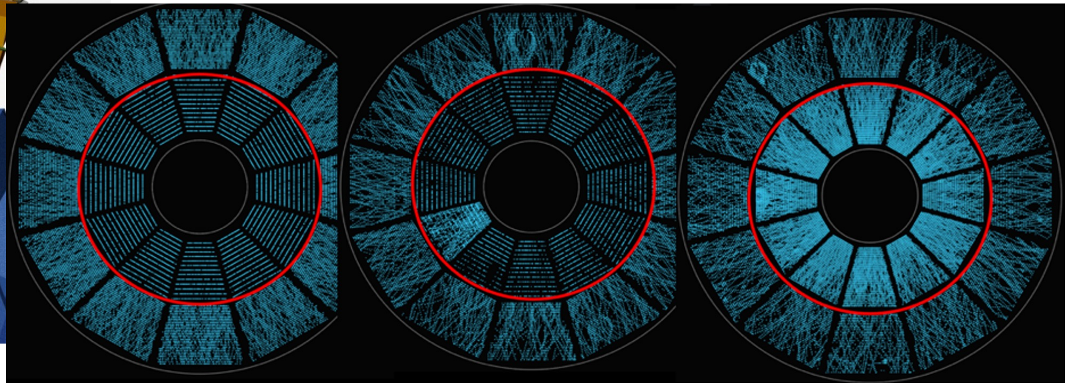
Cold and hot QCD plans:

- RHIC run 2022+
- Properties of QCD matter
- Such as precise imaging of gluons and sea quarks inside protons and nuclei...

Detector Upgrades Commissioned by Run19 at RHIC

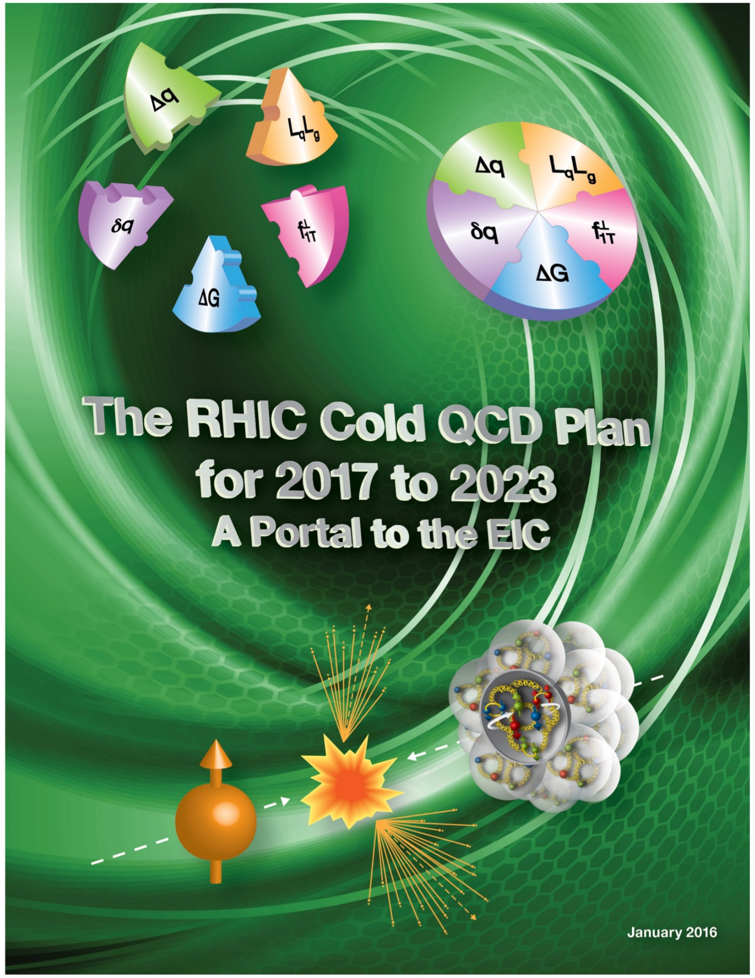




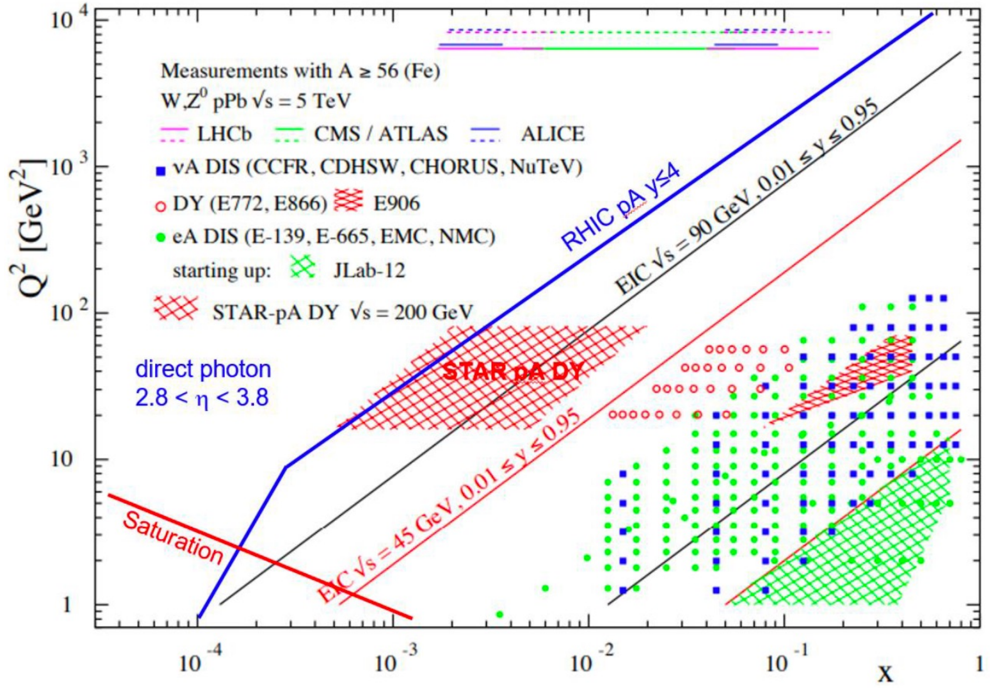


iTPC upgrade	EPD upgrade	eTOF upgrade
|η|<1.5	**2.1<|η|<5.1**	**-1.6<η<-1.1**
p_T >60 MeV/c	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	**Fully operational in 2018**	**Fully operational in 2019**

Cold QCD Plan at RHIC



arXiv:1602.03922



Unique and wide kinematic ranges in x-Q^2

With the detection capabilities at forward rapidity, STAR will provide unique opportunities in the study of fundamental QCD properties from nucleon to nuclei.

- ✓ Observables free of final state effects
  - Gluons: R_{pA} of direct photon
  - Sea-quarks: R_{pA} of DY
- ✓ Access saturation regime at forward rapidity
- ✓ ...

The Physics at RHIC beyond 2021+

Mid-rapidity -1.5<η<1.5 | **Forward-rapidity 2.8< η <4.2**

Mid-rapidity

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 & Ds 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

Forward-rapidity

A+A

Beam:

Full Energy AuAu (2023/25)

Physics Topics:

- Temperature dependence of viscosity through flow harmonics up to η ~4
- Longitudinal decorrelation up to η ~4
- Strong rapidity dependence in Global Lambda Polarization

p+A, p+p

Beam:

500 GeV: p+p

200 GeV: p+p and p+A

Physics Topics:

- TMD measurements at high x
  - o transversity → tensor charge
  - o Sivers through DY, direct **γ** and tagged jets
- Gluon PDFs for nuclei
- ➢ R_{pA} for direct photons & DY, and hadrons
- Test of Saturation predictions through di-hadrons, **γ** -Jets, di-jets

When Looking Forward

Observables:
- ✓ Inclusive and di-jets
- ✓ Hadrons in jets
- ✓ Lambda's
- ✓ Correlations mid-forward & forward-forward rapidity

Requirements from Physics:
- ✓ Good e/h separation
- ✓ Hadrons, photon, π^0 identification

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

FY2022: 500 GeV polarized pp run
All other data taking in parallel to sPHENIX data taking campaign

Forward-rapidity $2.8< \eta <4.2$

A+A

Beam:
Full Energy AuAu (2023/25)
Physics Topics:
- Temperature dependence of viscosity through flow harmonics up to η ~4
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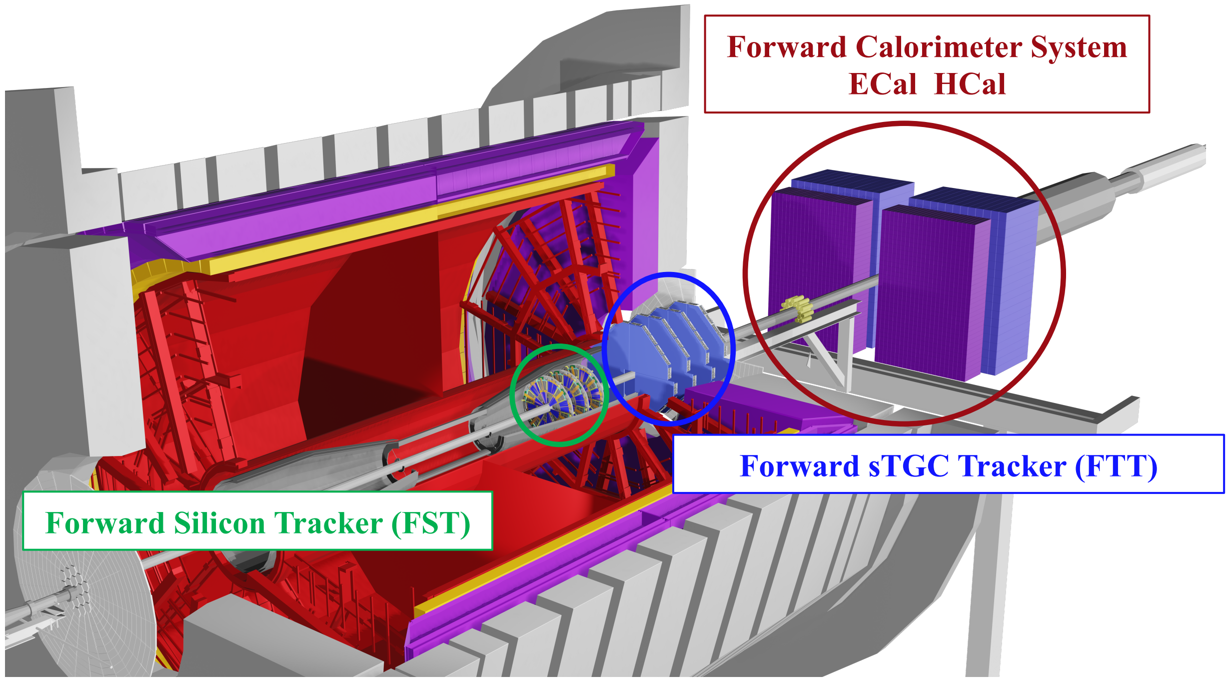
These crucial physics topics called for new detectors at forward rapidity.

New Detectors at STAR Forward Rapidity



FCS: 7 m from the IP

ECal: reuse PHENIX SHASHLYK 1496 Ch.

- Lateral tower Size 5.5 x 5.5 x 33 cm^3 ($18X_0$)

HCal: Fe/Sc (20mm/3 mm) sandwich 520 Ch.

- Lateral tower size 10 x 10 cm^2, ~ 4.5λ
- ✓ in close collaboration with EIC R&D

Preshower:

- Existing EPD, with additional splitter

FST, 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 f and coarse in R
  - ✓ Si from Hamamatsu
- Frontend chips: APV25-S1 → IST all in hand
- Reuse IST DAQ system and cooling system

FTT, 4 sTGC disks: at 307, 325, 343 and 361 cm from IP

- location inside Magnet pole tip opening
  - ✓ inhomogeneous magnetic field
- 4 quadrants double sided sTGC → 1 disk
  - ✓ sTGC technique developed by ATLAS
- Position resolution: ~200 um
- Readout: based on VMM-chips

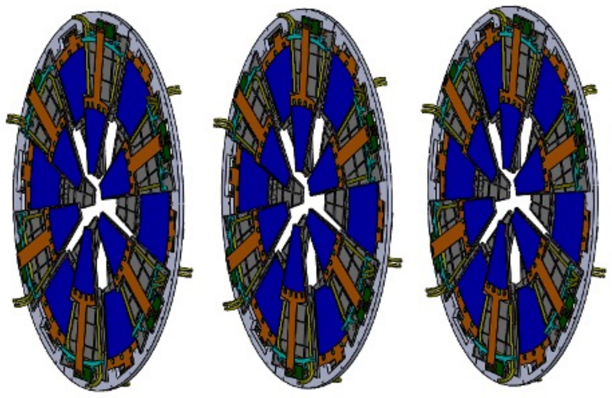
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

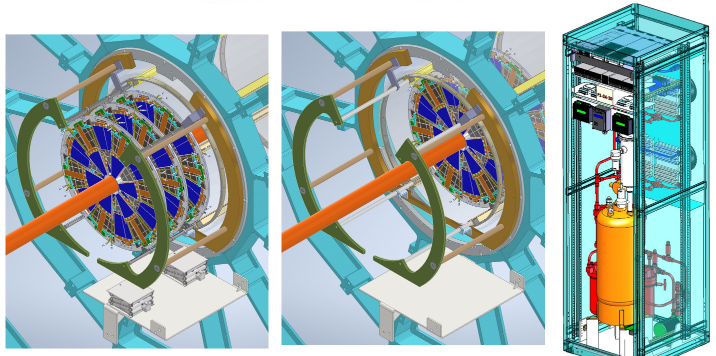
Forward Silicon Tracker, fSTAR

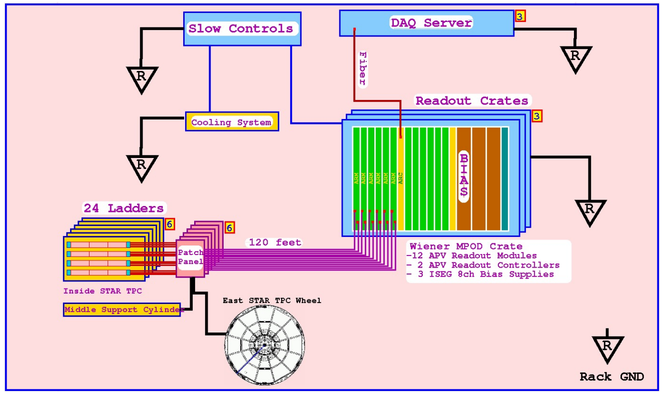
- Three disks, 36(+12) modules (NCKU/UIC)
  - Mechanical structure (NCKU)
  - Flexible hybrid (SDU/IU)
  - Silicon strip sensors (UIC/BNL)
  - APV25 frontend chips* (UIC)

    * in-hand and probe-tested
- Integration (BNL)
  - Mechanical supporting structure
  - Installation tooling
- Cooling system (BNL/NCKU)
  - Cooling lines
  - Cooling manifold
  - Rack (cooler, pumps)
- DAQ system (BNL/IU/SDU)
  - Inner signal cables
  - Outer signal cables, patch panel boards, readout modules, readout controllers, crates

Blue: existing **Red: new**







Forward Silicon Tracker, Module Design

Each module splits into two regions

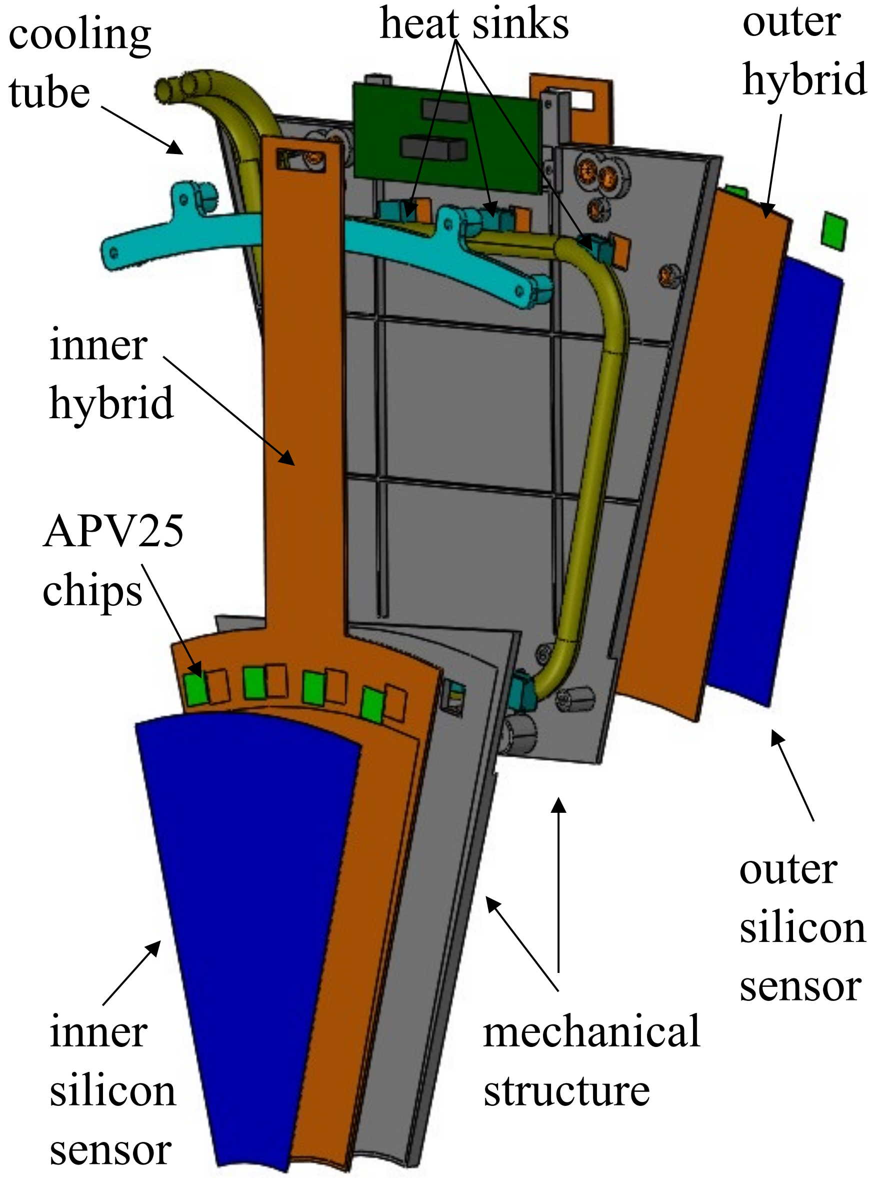
- ✓ Inner-radius region: 5<R<16.5 cm
  - 1 Kapton flexible hybrid
  - 1 Si sensor: 128 × 4 (ϕ×R) strips
  - 4 APV chips
- ✓ Outer-radius region: 16.5<R<28 cm
  - 1 Kapton flexible hybrid
  - 2 Si sensors: 128 × 4 (ϕ×R) strips
  - 4 APV chips
- ✓ material budget: ~1.5% X_0 per disk

Mechanical structure is made of

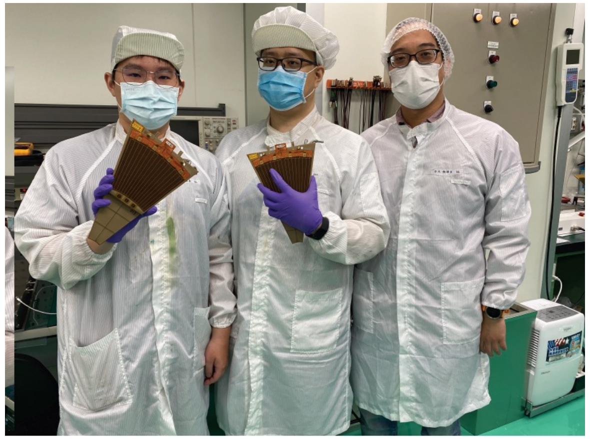
- ✓ PEEK (main structure, tube holder)
- ✓ Stainless steel (cooling tube)
- ✓ Aluminum (heat sinks)

Module assembly is done at two sites

- ✓ TiDC (NCKU): gluing inner/outer hybrids and mechanical structures together
- ✓ FNAL (UIC): mount/wire-bond AVPs and Silicon sensors on hybrids

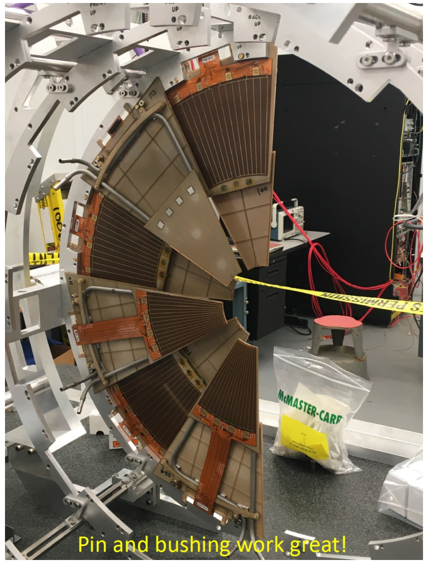


Forward Silicon Tracker – Prototype Module Performance

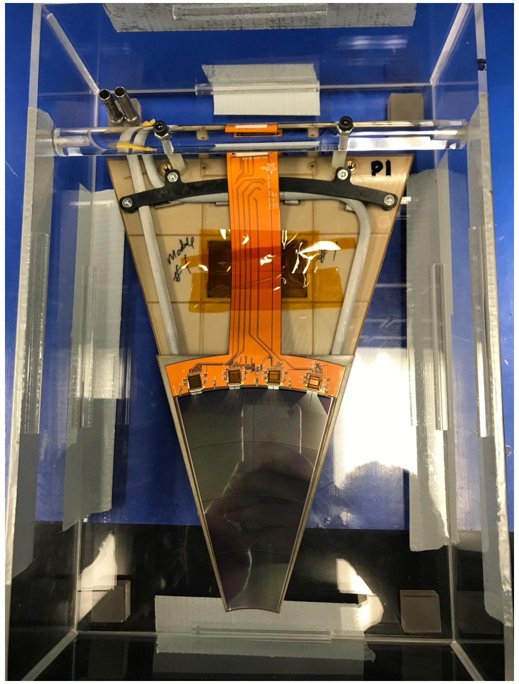


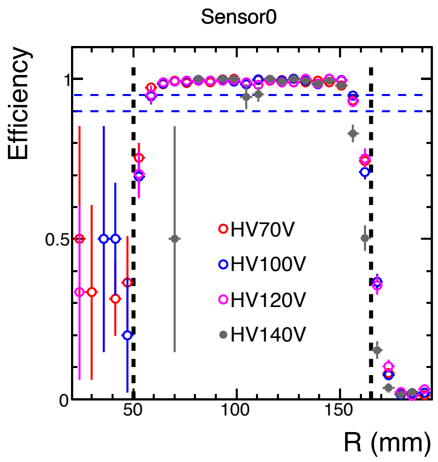
Mechanical structure production at NCKU

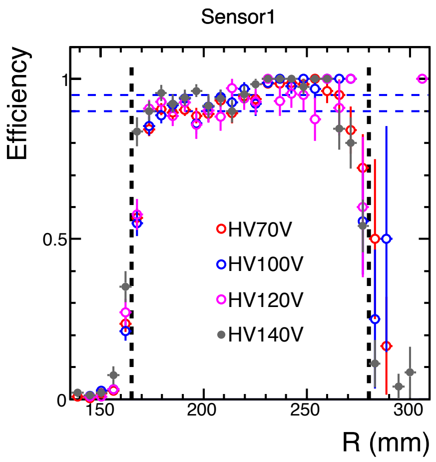
T-Board production at SDU

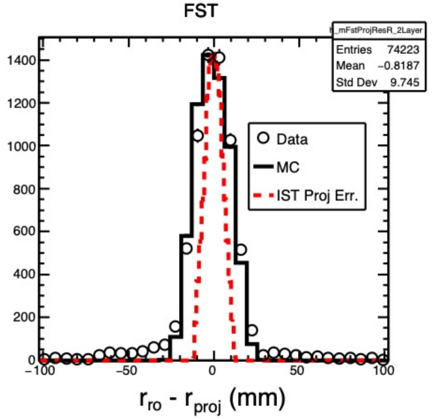


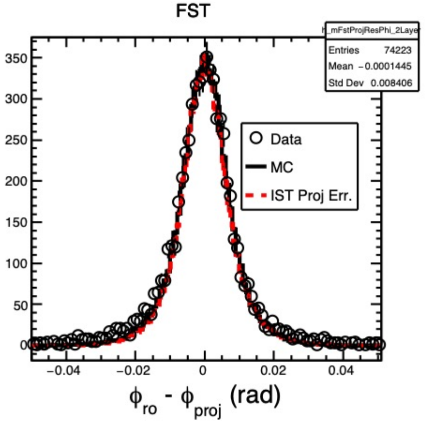
Pre-Installation at BNL











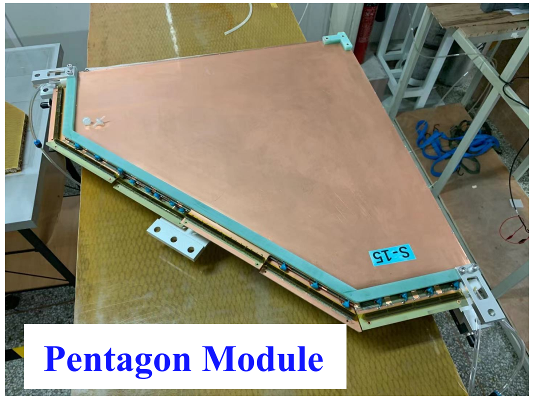
Performance of two fully assembled prototype modules evaluated with cosmic ray:

- ✓ **All channels can be read out (KPP: > 85%)**
- ✓ **Efficiency higher than 90% (KPP: > 90%)**

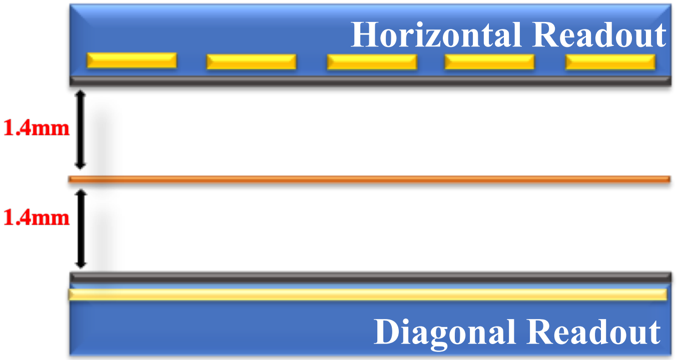
Key Performance Parameter

The estimated completion of module production is end of May 2021.

Forward sTGC Tracker, fSTAR



Pentagon Module



sTGC chamber sideview layout

Anode:

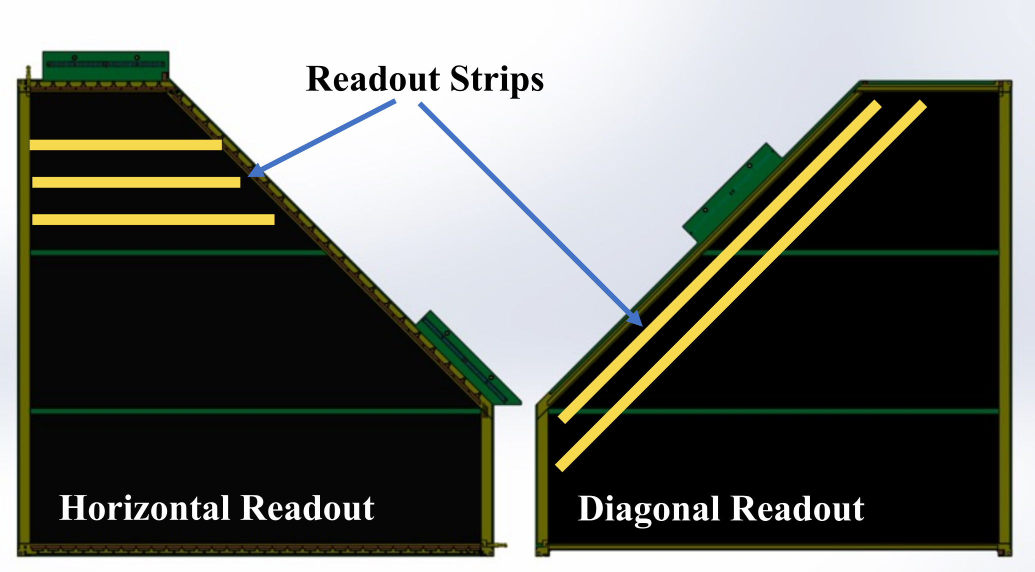
50 um gold-plated tungsten wire

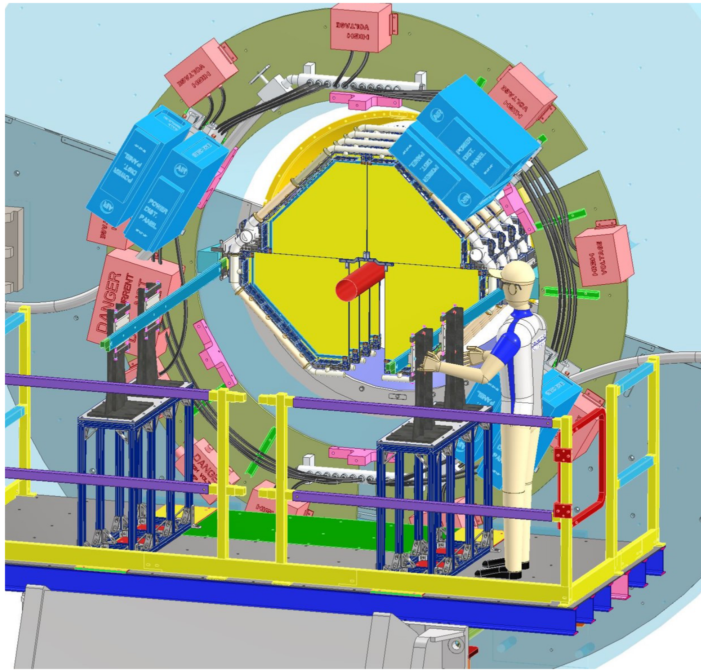
1.8 mm wire pitch

350g wire tension

Cathode: graphite

Joint test of the first pentagon prototype and electronics prototypes at SDU in Sep.2020.





FTT integration layout

Forward sTGC Tracker, fSTAR

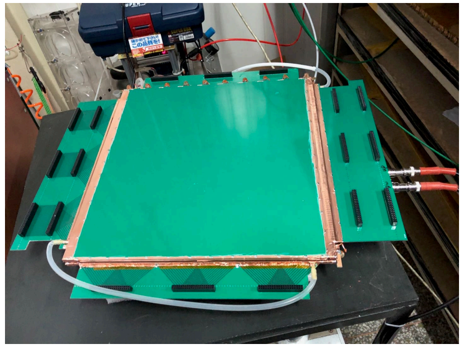
From 2018 till now:
- ✓ Three versions of module prototypes
- ✓ Three versions of electronics prototype

Integrations & DAQ: **BNL**

Commissioning & software: **BNL, SDU**

Detector	Produced	Shipped	Installed
1st prototype	Oct.2018	Jan.2019	Jun.2019
2nd prototype	Jan.2019	Jul.2020	May 2021
3rd prototype	Oct.2020	N/A	N/A
Final modules	*May 2021*	*Jun.2021*	*Sep.2021*

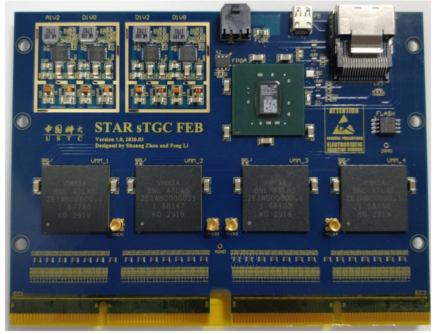
30 x 30 cm^2 prototype

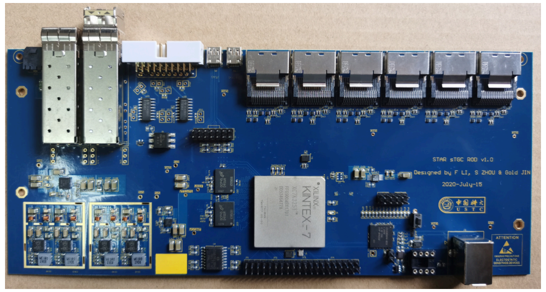


60 x 60 cm^2 prototype

Module Production: **SDU**

55 x 55 cm^2 pentagon

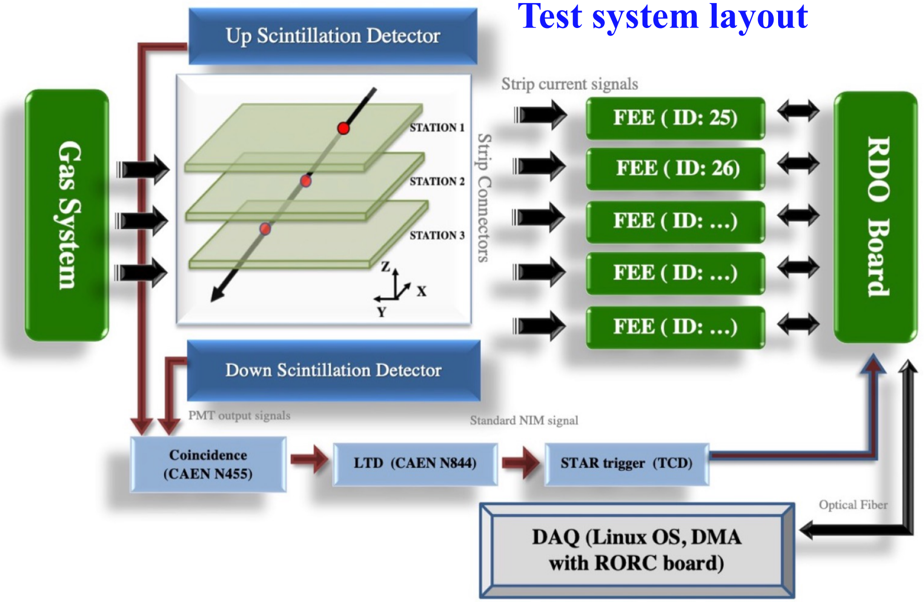


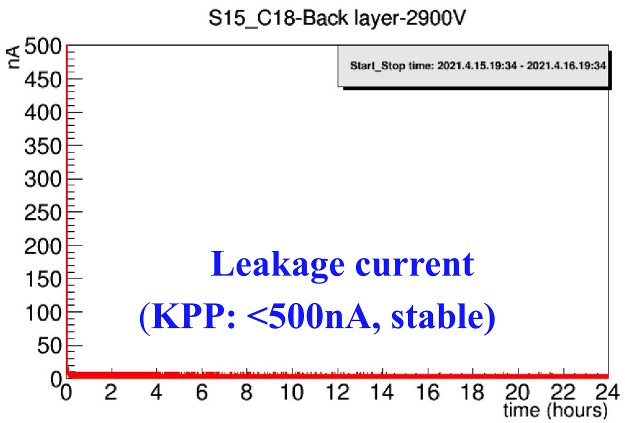


Electronics: **USTC**

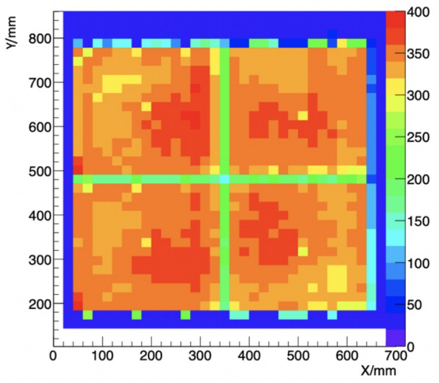
Forward sTGC Tracker – Prototype Module Performance

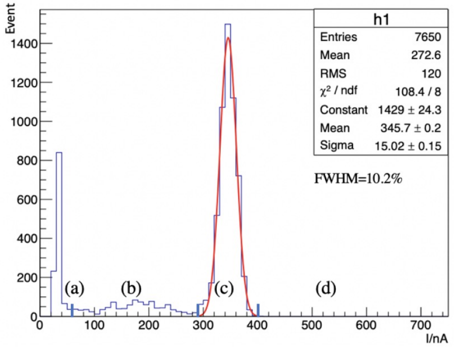
Test system layout



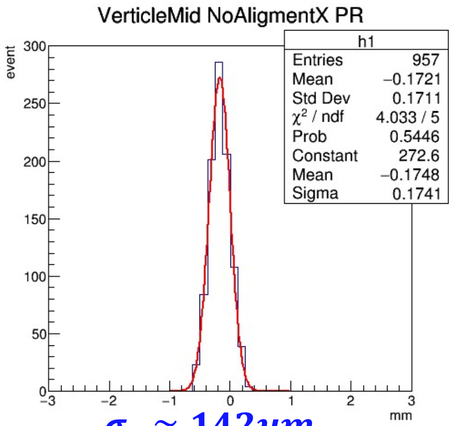


Leakage current
(KPP: <500nA, stable)

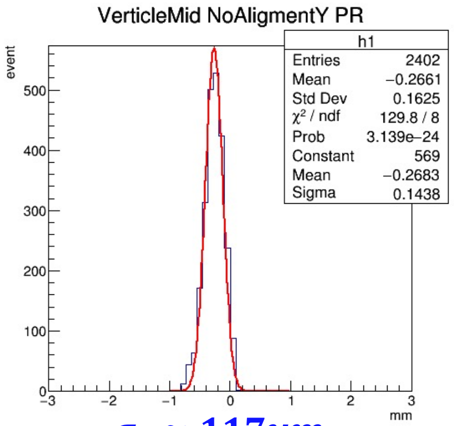




X-ray scan

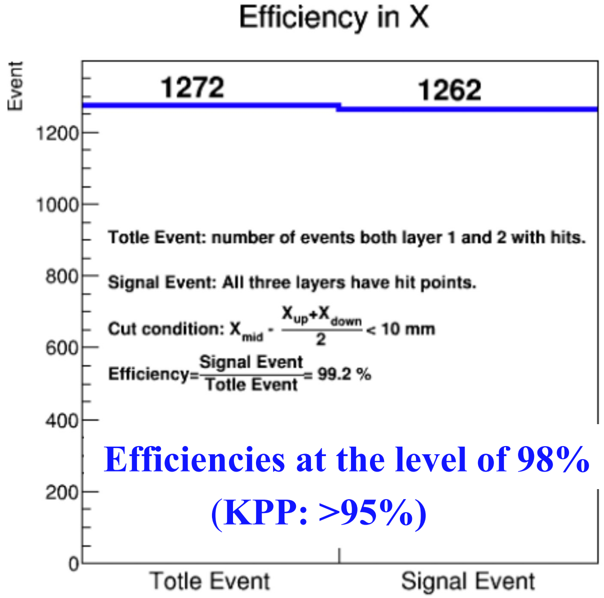


$\sigma_x \approx 142um$

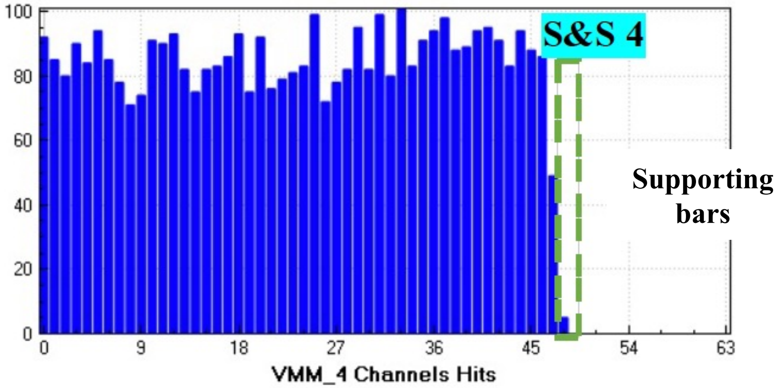


$\sigma_y \approx 117um$

Position resolution
(KPP: <200um)



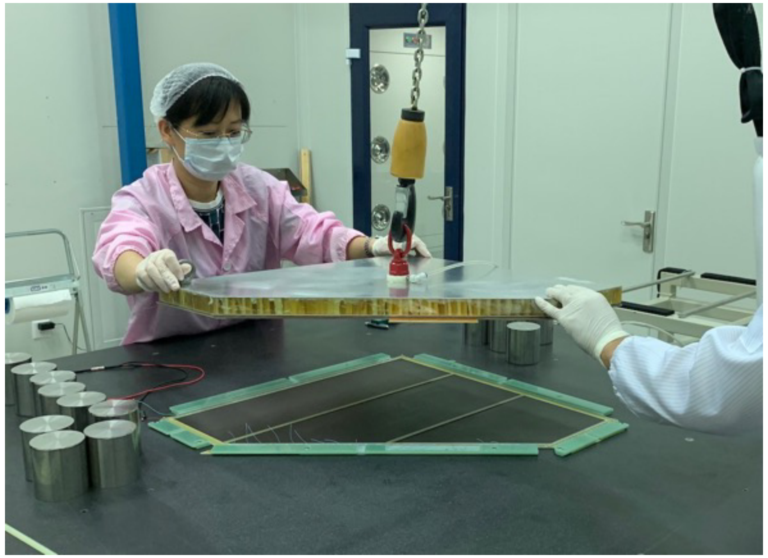
Efficiencies at the level of 98%
(KPP: >95%)



All channel responses
(KPP: >98%)

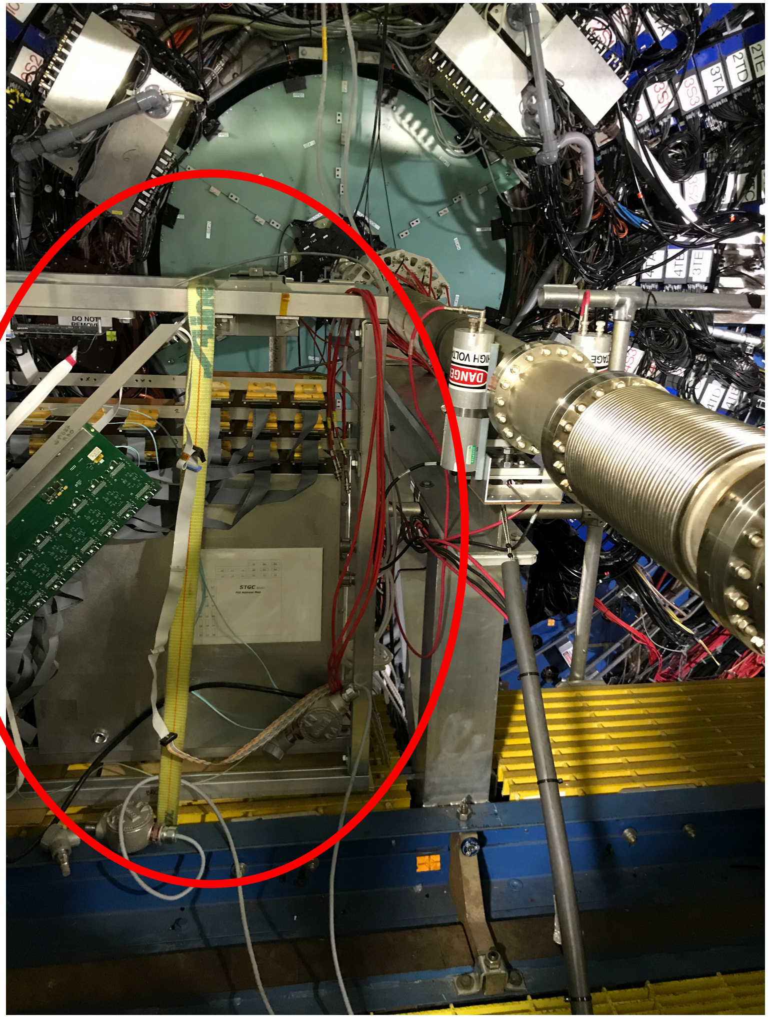
Forward sTGC Tracker Commissioning

20 stations (16+4 spares) needed:
- ✓ 40 chambers (32+8)
- ✓ 120 Front-End Boards (96+24)
- ✓ 40 Read Out Drivers (32+8)



sTGC module production at SDU

sTGC module test at SDU



2nd prototype installed at STAR in Run21

The estimated completion of module production is end of May 2021.

Forward Calorimeter System, fSTAR

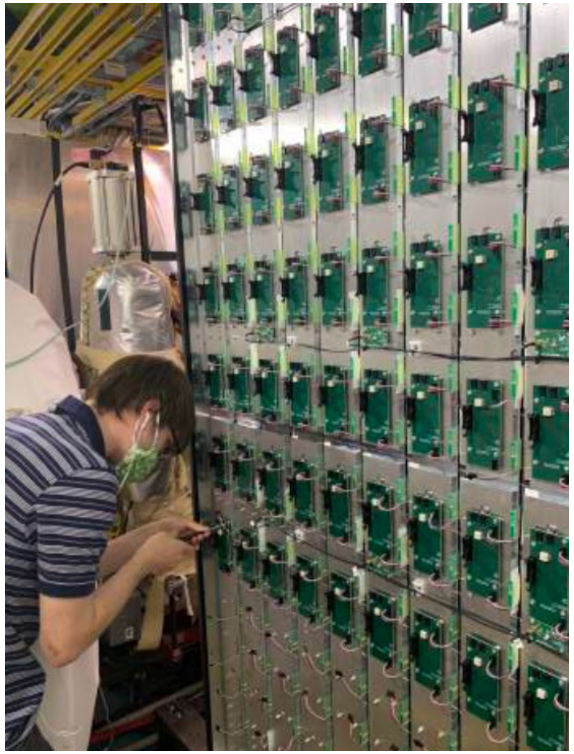
FCS Requirements

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---

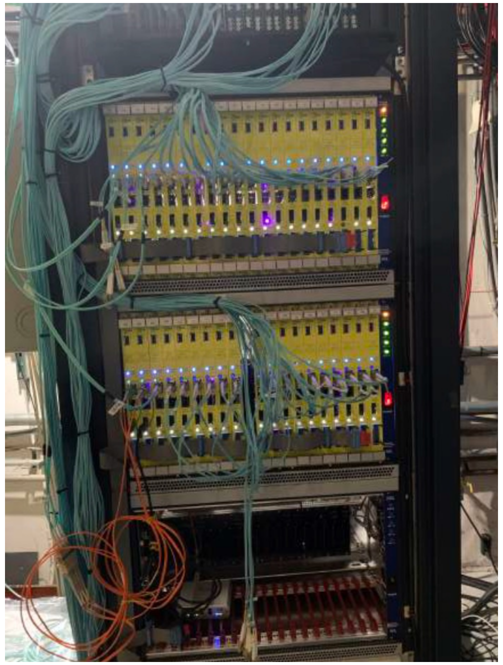
Forward Calorimeter System (FCS)

- ✓ ECal – 1496 channels ~ 8 tons
- ✓ HCal – 520 channels ~ 30 tons
- ✓ SiPM Readout Bias ~ 67V
- ✓ New digitizers + Trigger FPGA = DEP boards
- ✓ Total of 48+18+12 = 78 DEP boards
- ✓ 3 DEP-IO boards for triggering

Module Installation



DEP installation



DAQ

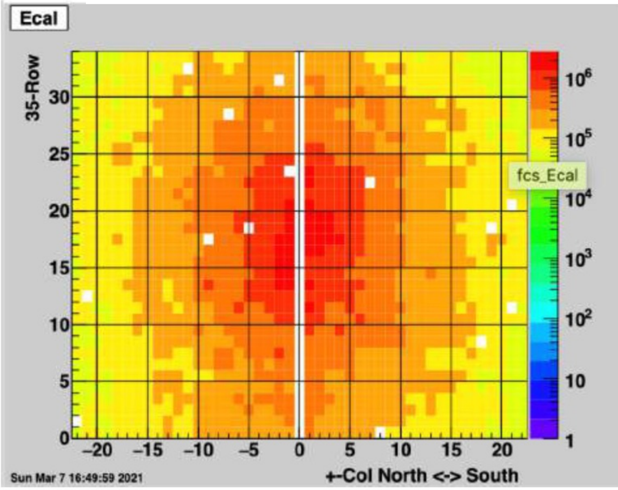
FCS Commissioning, Run21

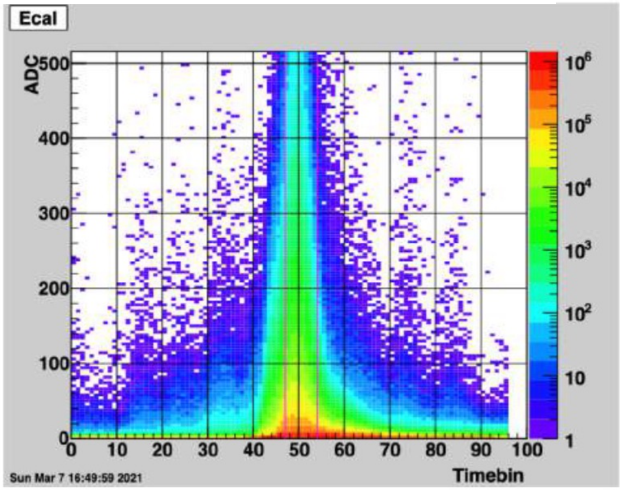
https://www.bnl.gov/newsroom/news.php?a=217681

Assembling FCS in Dec. 2020 at BNL

FCS fully operational in Run21.
Works great out of box!

From Online @ STAR Physics run （Au+Au 7.7 GeV）





Organizational Structure in STAR Forward Upgrade

sTGC
- BROOKHAVEN NATIONAL LABORATORY
- SHANDONG UNIVERSITY 1901
- University of Science and Technology of China 1958

Silicon
- UIC UNIVERSITY OF ILLINOIS AT CHICAGO
- SHANDONG UNIVERSITY 1901
- INDIANA UNIVERSITY
- BROOKHAVEN NATIONAL LABORATORY
- NATIONAL CHENG KUNG UNIVERSITY 1931

ECal
- UK KENTUCKY
- VALPARAISO UNIVERSITY
- ABILENE CHRISTIAN UNIVERSITY

HCal
- THE UNIVERSITY OF CALIFORNIA UCLA
- TEXAS A&M UNIVERSITY
- INDIANA UNIVERSITY
- VALPARAISO UNIVERSITY
- RUTGERS
- ABILENE CHRISTIAN UNIVERSITY
- OHIO STATE

DAQ
- BROOKHAVEN NATIONAL LABORATORY
- INDIANA UNIVERSITY
- UK KENTUCKY
- THE UNIVERSITY OF CALIFORNIA UCLA
- TEXAS A&M UNIVERSITY

Software
- BROOKHAVEN NATIONAL LABORATORY
- UIC UNIVERSITY OF ILLINOIS AT CHICAGO
- INDIANA UNIVERSITY
- TEXAS A&M UNIVERSITY
- SHANDONG UNIVERSITY 1901

Integration
- BROOKHAVEN NATIONAL LABORATORY

Calibration
- UC RIVERSIDE
- TEMPLE UNIVERSITY

Slow Controls
- VALPARAISO UNIVERSITY
- ABILENE CHRISTIAN UNIVERSITY
- Creighton UNIVERSITY

Efficient and professional collaborating within STAR collaboration!

fSTAR at RHIC provides opportunities in:

✓ Detector R&D with techniques potentially used in EIC

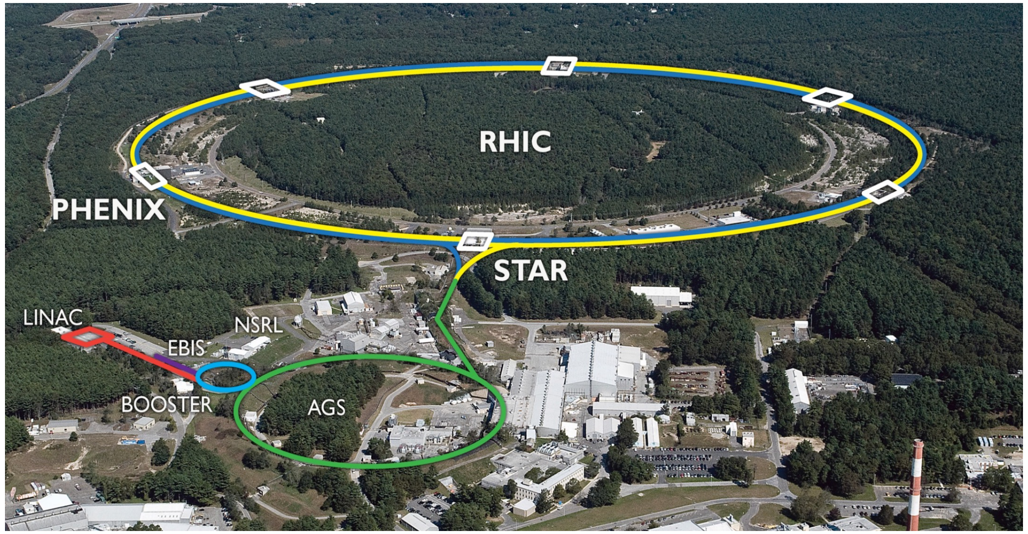
- HCal+SiPM readout same as EIC-fHCal (joint STAR EIC R&D)
- Silicon technique for EIC tracker
- sTGC technique for EIC trigger/tracker

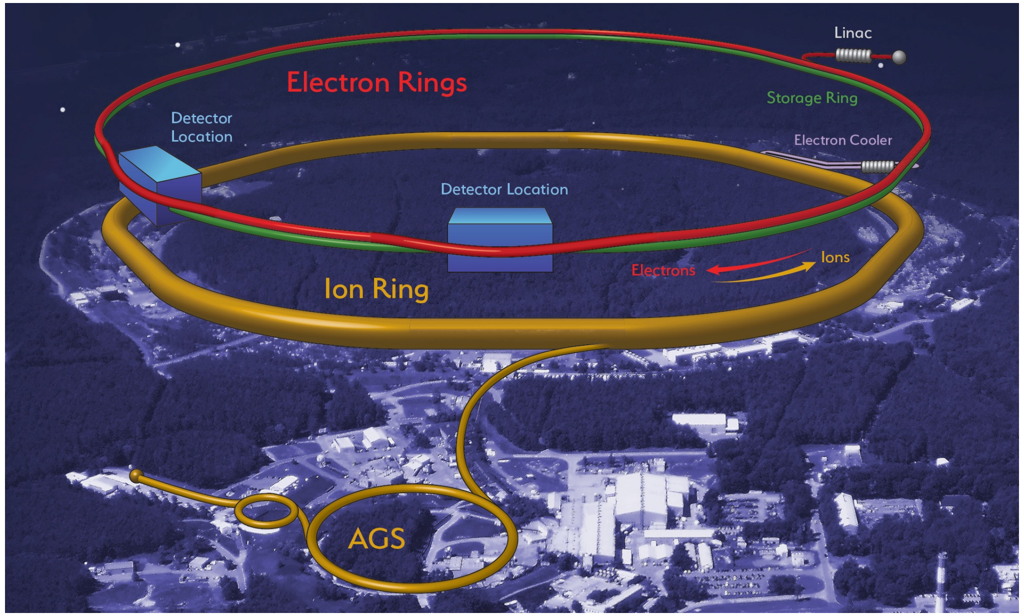
✓ Help to realize the scientific promise of the EIC

- Inform the physics program
- Quantify experimental requirements

✓ Train the young talents especially on detector R&Ds for EIC

- Several tens of the graduate/undergraduate students working on fSTAR



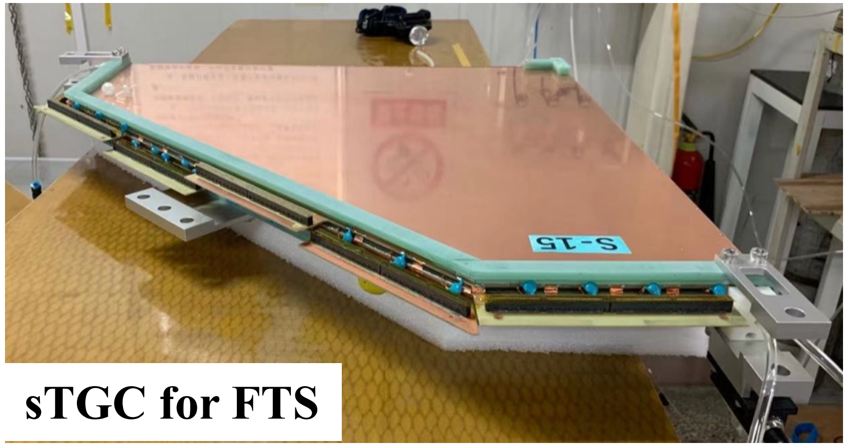


Summary

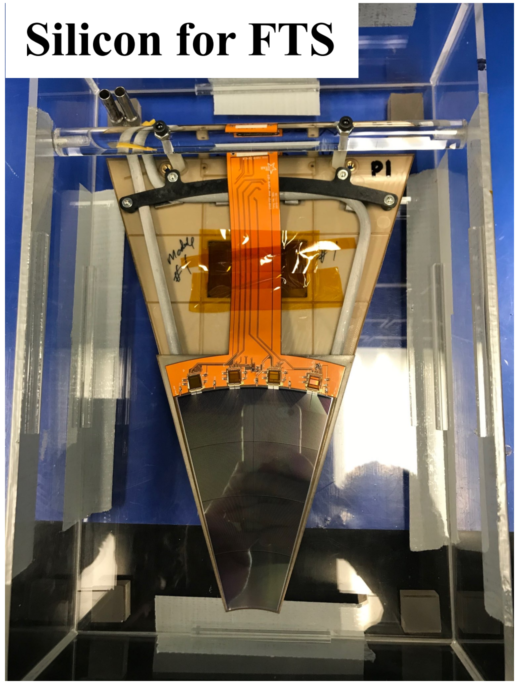
- **Detector upgrades finished for BES-II at STAR significantly increase the detection capabilities at mid-rapidity.**
- **Detector upgrades in forward rapidity at STAR pushes the detection capability to forward.**

✓ FCS fully operational in the current RHIC Run21.

✓ FTS fully operational in the coming RHIC Run22.



sTGC for FTS

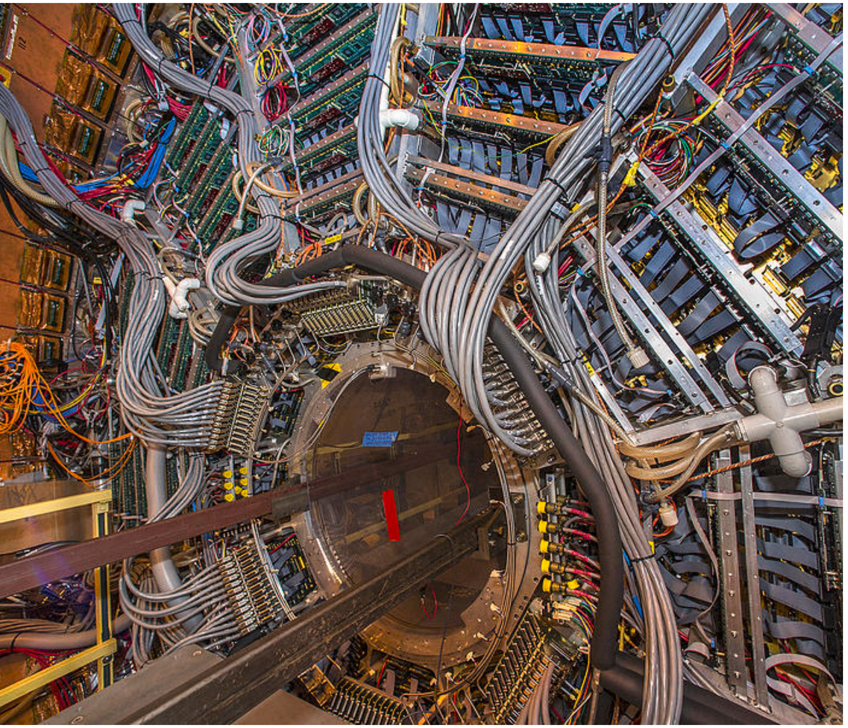


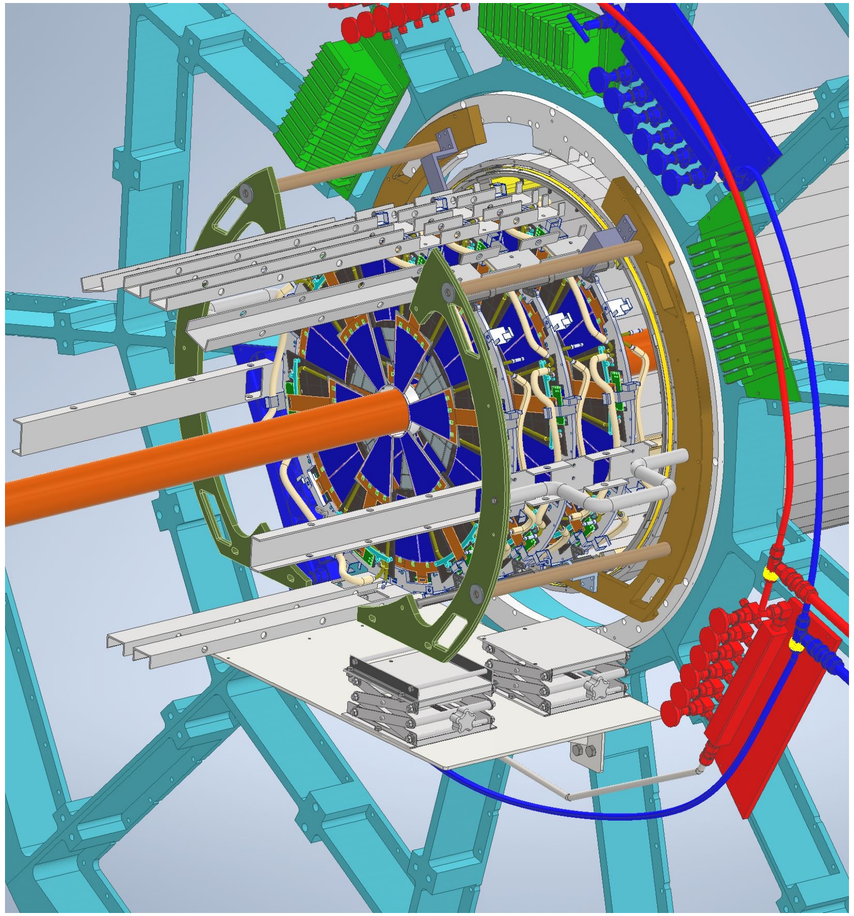
Silicon for FTS

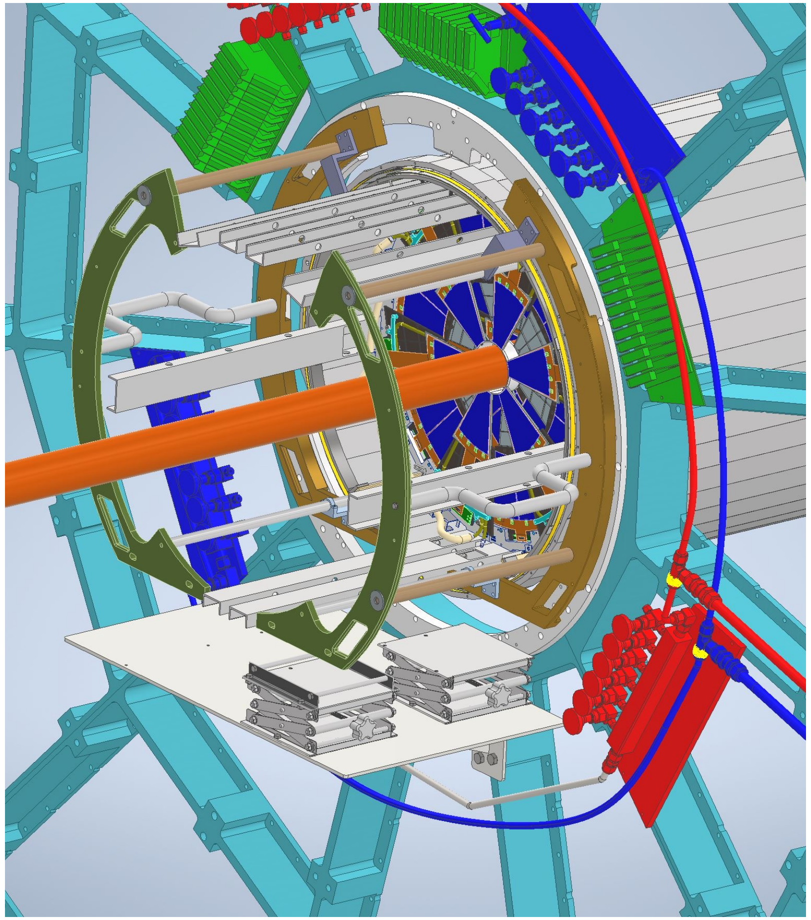
FCS

- **fSTAR will enable crucial measurements in RHIC Cold QCD and Hot QCD plans in the coming years from 2022 to 2025.**
- **fSTAR provides a “bridge” connecting RHIC and EIC.**

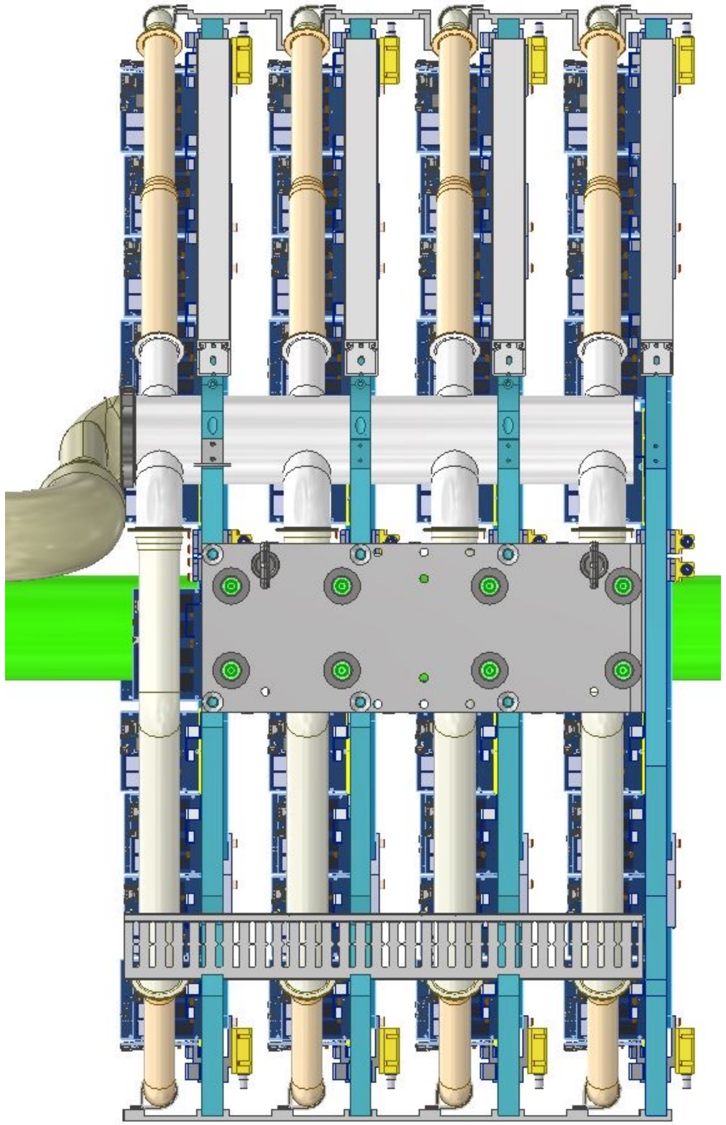
FST Integration -- Backup

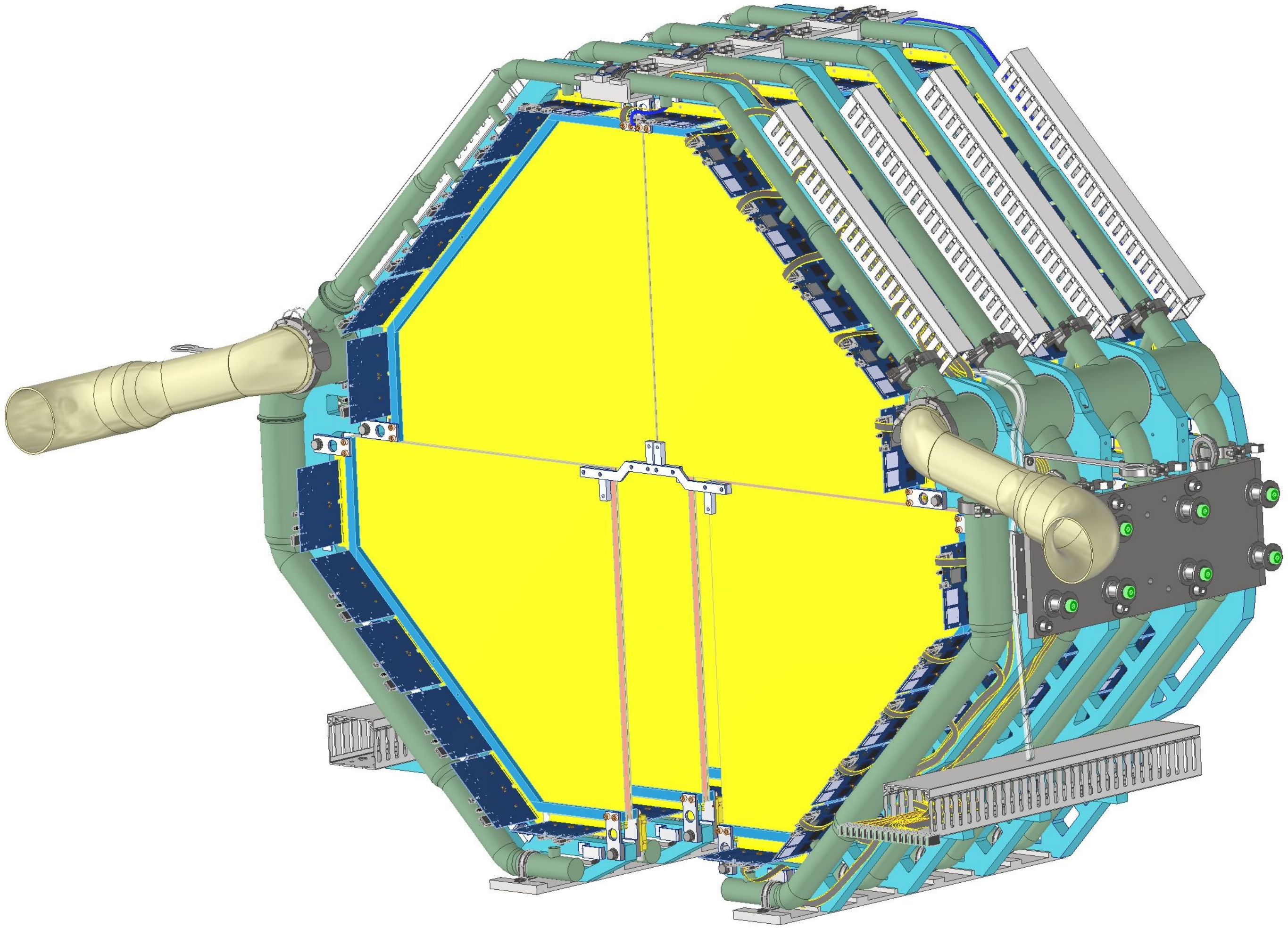






FTT Multiplane Assembly -- Backup





N-Pentane+CO_2 Gas Mixing System -- Backup