The STAR BES-II and Forward Rapidity Physics and Upgrades

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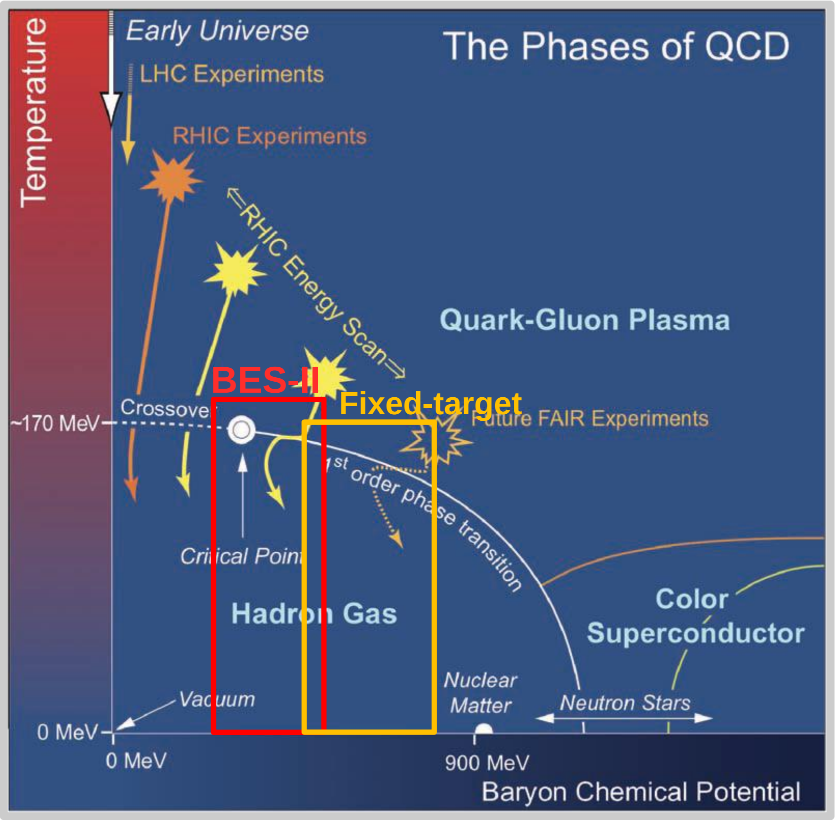
Outline

- **STAR Beam Energy Scan II Program** (start at **2019**)
  - Motivation and projections
  - The inner Time Projection Chamber
  - The endcap Time-Of-Flight
  - The Event Plane Detector
- **Forward Physics Opportunities at STAR** (**2021+**)
  - Motivation
  - The Forward Tracking System
  - The Forward Calorimeter System
- **Summary**

Beam Energy Scan Phase II (BES-II)



$\sqrt{s_{NN}}$ (GeV)	Proposed Event Goals (M)	BES-I Event (M)
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36
3.0 - 7.7	~100 per energy	N/A

Collider mode

Fixed-target mode

- ✓ RHIC BES-II: 10-25 times more statistics and **detector upgrades**

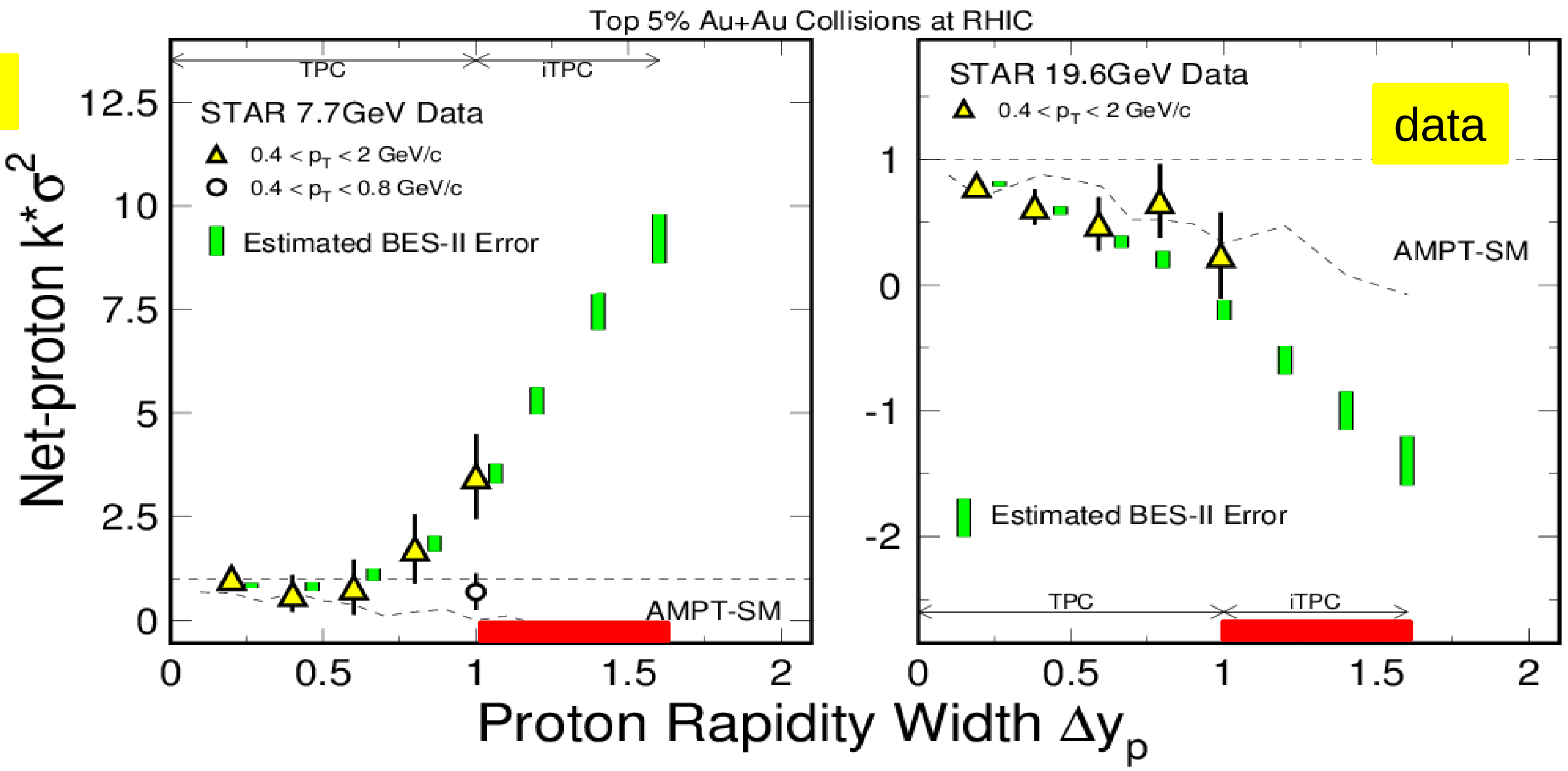
  → Dramatically reduce the uncertainties!

- ✓ Map the QCD phase diagram **$200 < \mu_B \leq 720$ MeV**

  → Signs of 1st-order phase transition, QCD critical point, signature of QGP turn-off.

Searching for Critical Point

Net-proton cumulants



✓ Non-trivial energy dependence from BES-I

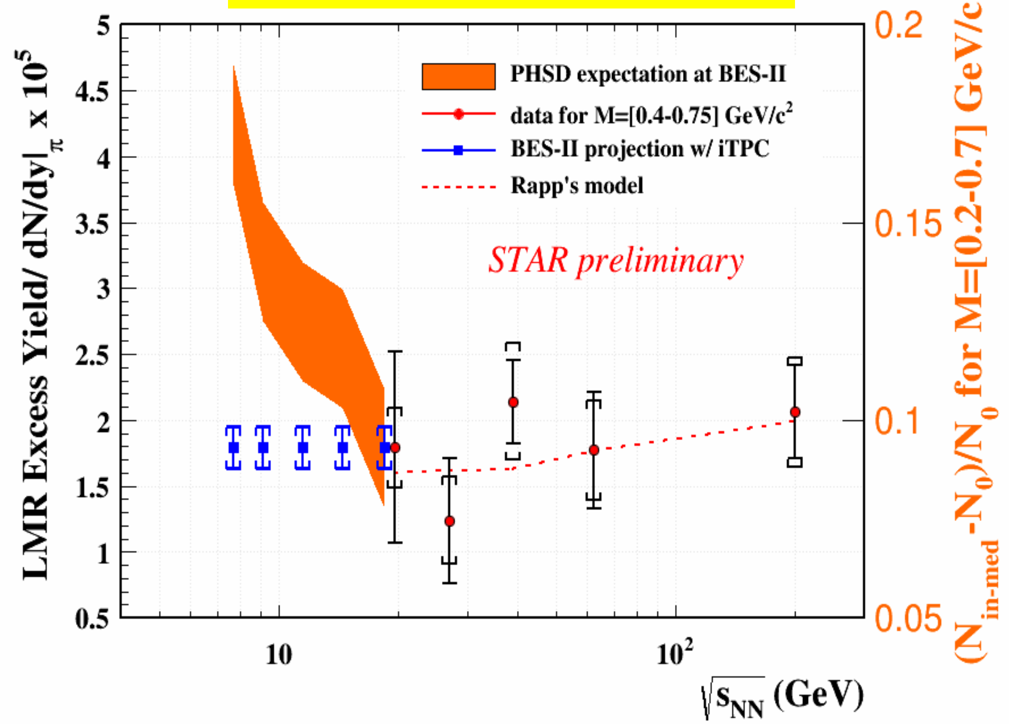
✓ Rapidity length of correlation is important

✓ Measure as fct. of Δy_p in wide range is needed to establish nature of correlation

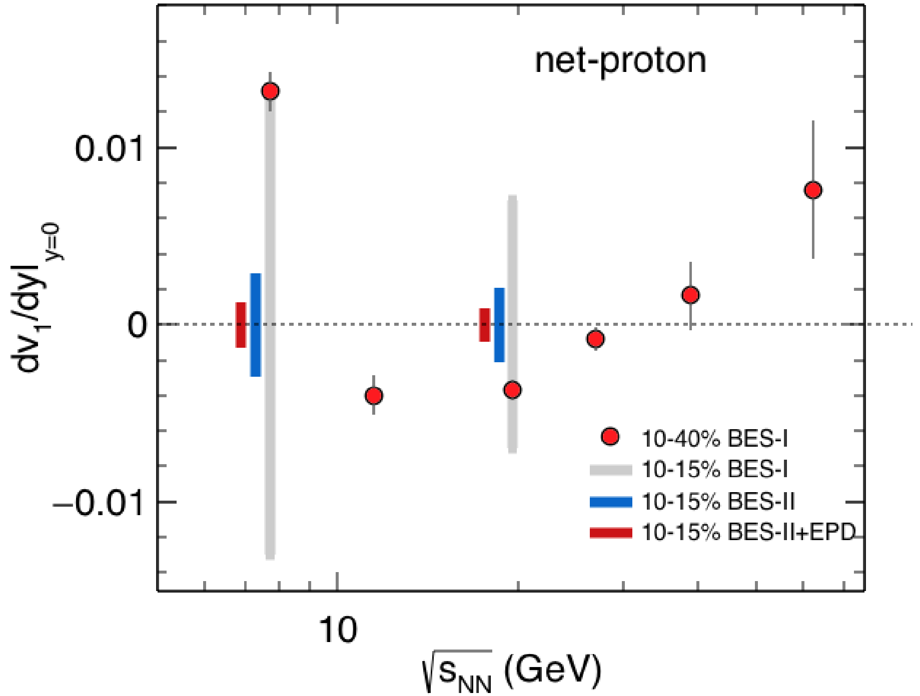
[***STAR Note 644:*** https://drupal.star.bnl.gov/STAR/starnotes/public/sn0644]

Physics Motivation

Dielectron measurement

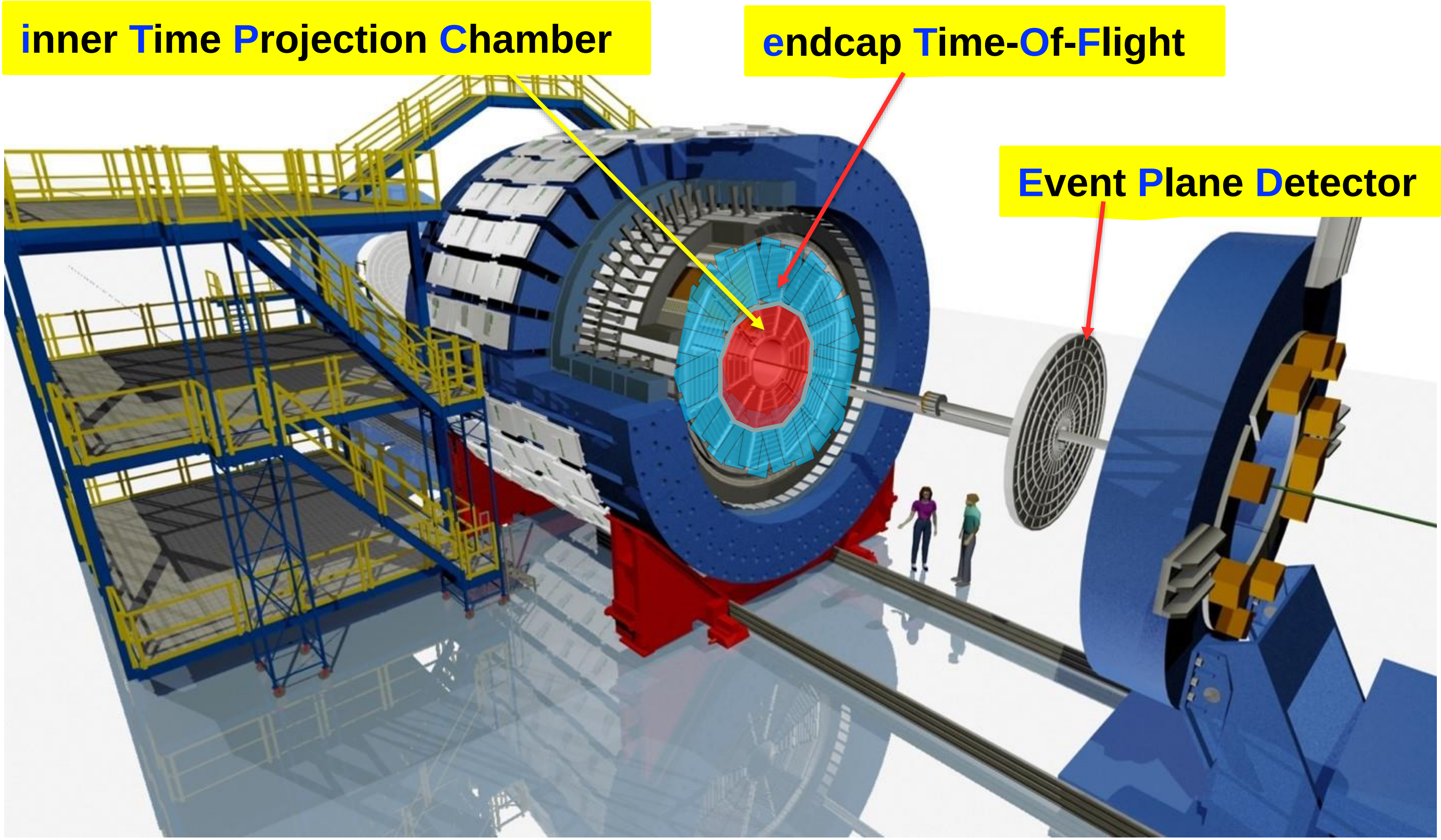


Directed flow

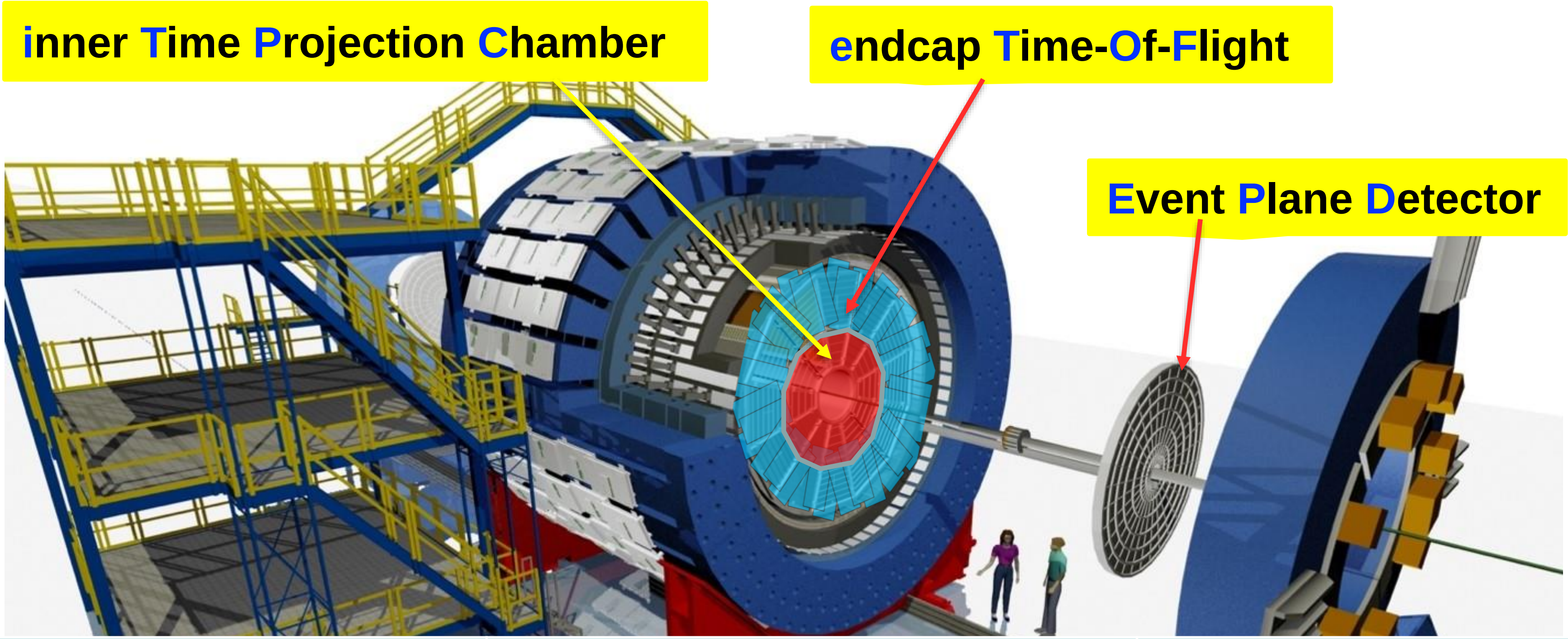


- ✓ Systematically study continuum from 7.7-19.6 GeV and the effect of total baryon density on Low invariant Mass Range (LMR) excess → chiral symmetry restoration
  - ✓ ~10 times more statistics, ~1/2 decrease of systematic uncertainties (improved *dE/dx*)
- ✓ Analysis of v_1 with fine centrality binning will lead a better understanding of baryon stopping at low beam energy
  - ✓ More statistics and a better first-order event plane resolution

Upgrades for BES-II

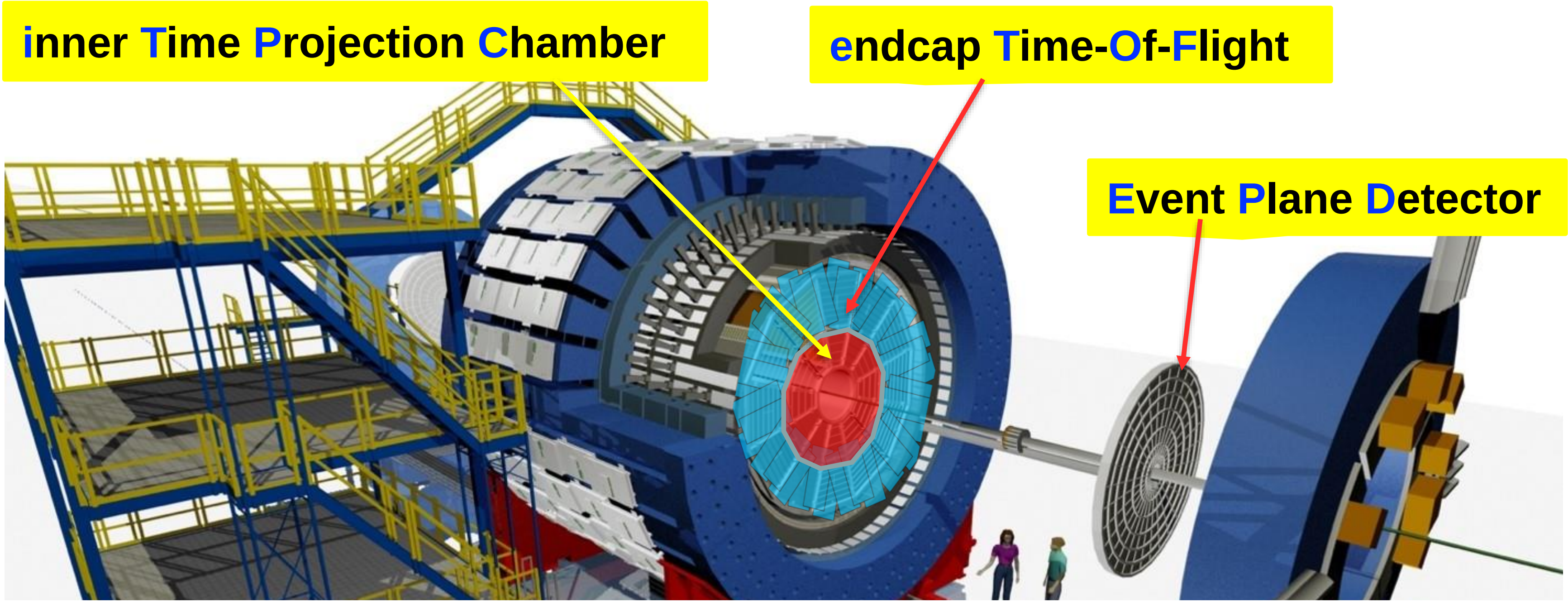


Upgrades for BES-II



iTPC upgrade	eTOF upgrade	EPD upgrade
Continuous pad rows **Replace all inner TPC sectors**	**Add CBM TOF modules and electronics (FAIR Phase 0)**	**Replace Beam-Beam Counter**
$\|\eta\| < 1.5$	**$-1.6 < \eta < -1.1$**	**$2.1 < \|\eta\| < 5.1$**
$p_T > 60$ MeV/c	Extend forward PID capability	Better trigger & b/g reduction
Better dE/dx resolution Better momentum resolution	Allows higher energy range of Fixed-Target program	Greatly improved Event Plane info (esp. 1^{st}-order EP)

Upgrades for BES-II



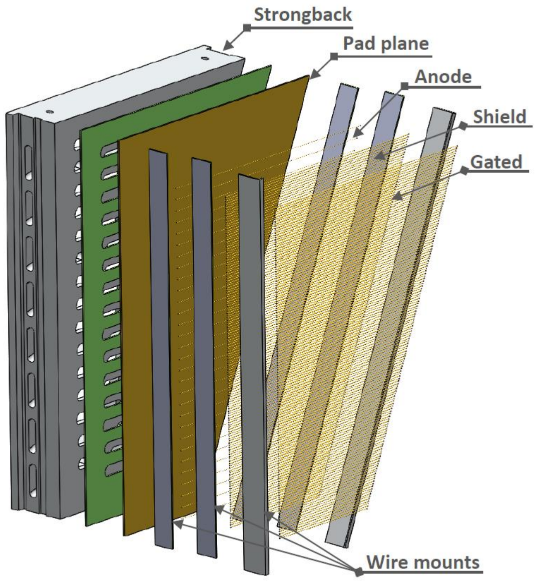
One iTPC sector has been installed

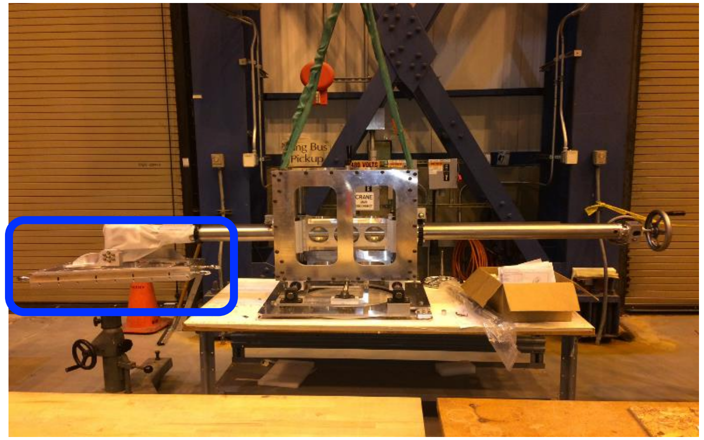
3 eTOF modules have been installed

Full EPD has been installed

The inner TPC upgrade

- ✓ Inner Sectors
  - ✓ New designed strongback
  - ✓ New wire frames
  - ✓ Increase readout pad rows (13 to 40)
    - *Coverage increased from 20% to ~100%*
- ✓ New electronics for inner sectors
  - *Doubled the readout channels. Using ALICE SAMPA chip*
- ✓ New designed insertion tooling
  - *Removal and insertion of inner sectors*
- ✓ **Replace all 24 inner sectors**
  - ***2018: One sector has been installed at STAR***
  - ***70% of the MWPCs have been produced***
  - ***Full installation in autumn 2018***

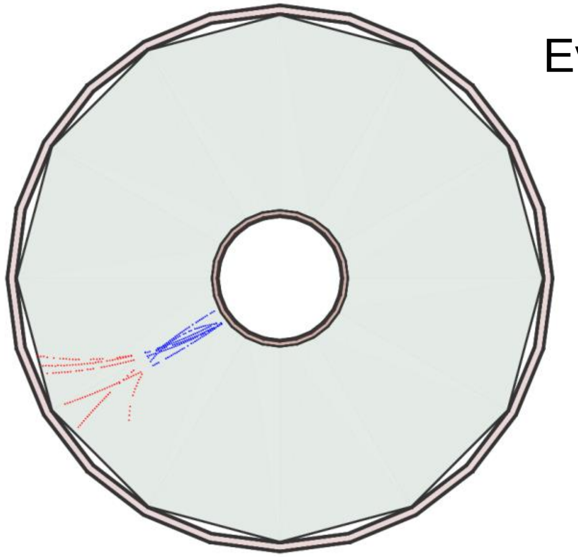


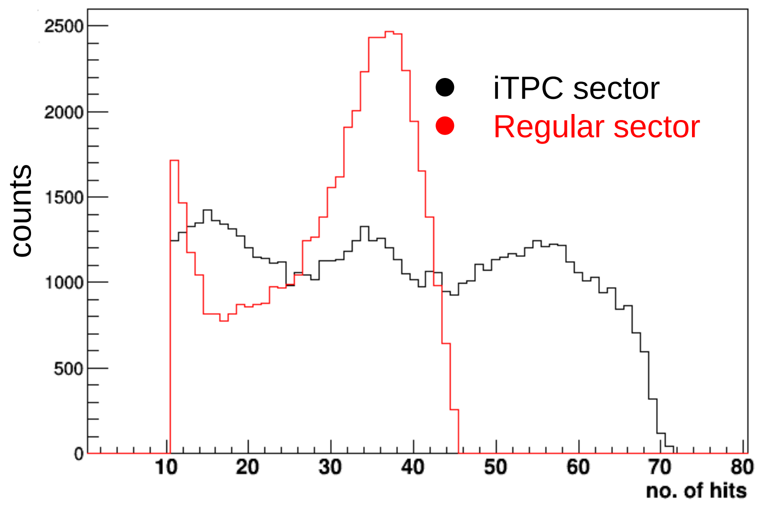


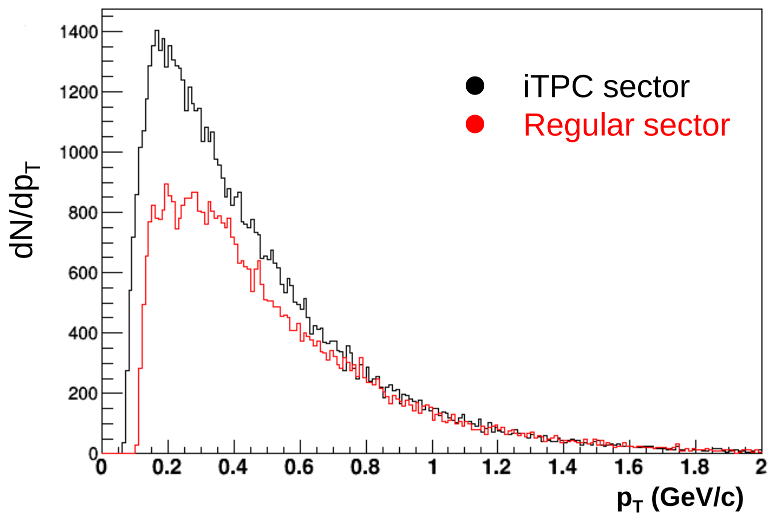
iTPC Performance

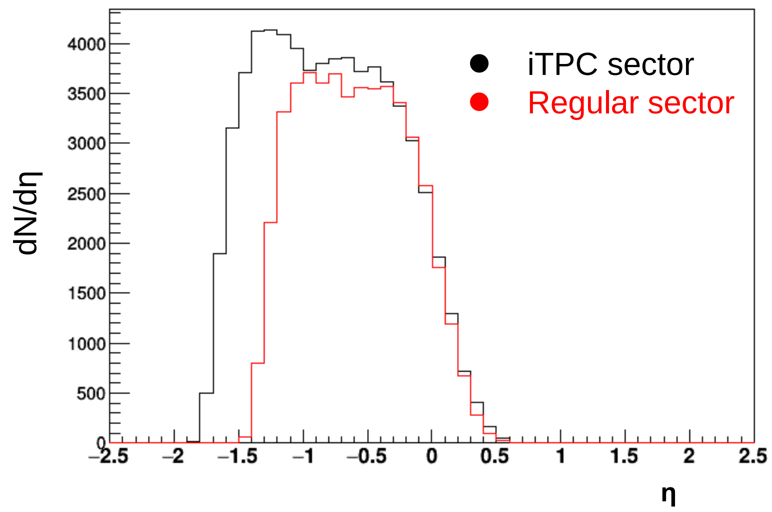
- ✓ Excellent performance in bench test for MWPC: [NIM A 896 (2018) 90]
  - ✓ Gas gain uniformity < 1.5% (RMS) & Energy resolution is < 20% (FWMH)
  - ✓ Reasonable stability under X-ray irradiation test
    - → *500* nA leakage current without trip or any sparks
- ✓ **iTPC (one sector) performance in current isobar collisions :**
  - ✓ Maximum hits per track: 45 → 72
  - ✓ Lower transverse momentum threshold of 60 MeV/c
  - ✓ η coverage extended by 0.4 units.

Event display



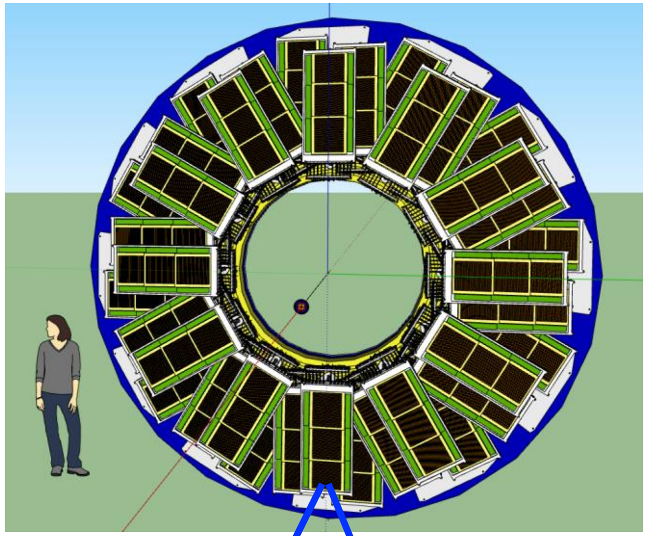


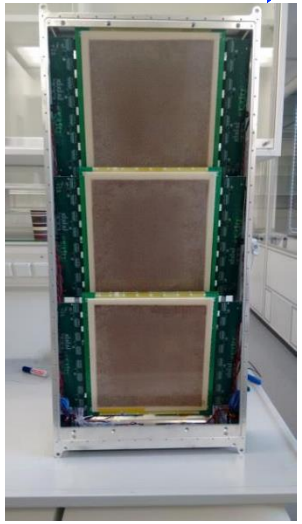




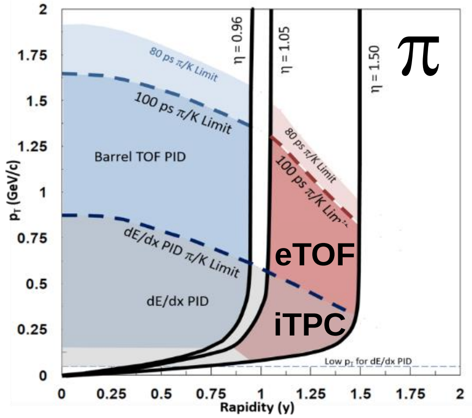
The endcap Time-Of-Flight

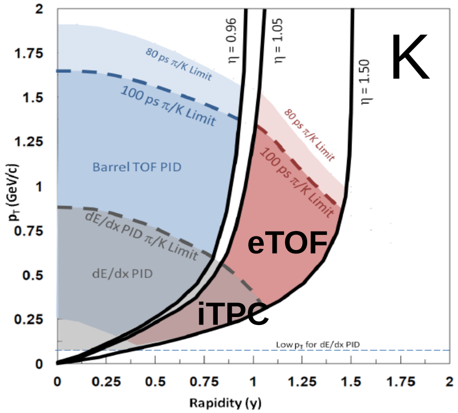
- ✓ Install, commission and use 10% of the CBM TOF modules at STAR
- ✓ Design concept
  - ✓ 3 layers, 12 sectors, 36 modules, 108 MRPCs
- ✓ Provides PID in the forward direction
  - ✓ Extended rapidity and yields
- ✓ **One sector with three modules has been installed for runs in 2018**
- ✓ **Full installation in November 2018**

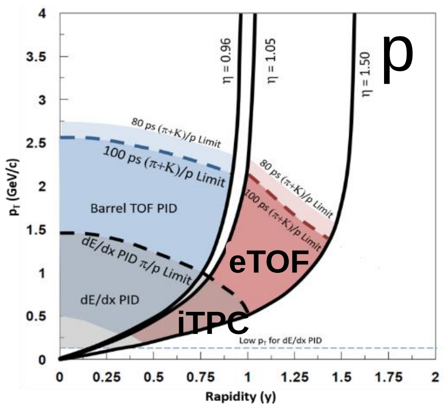




Collider mode

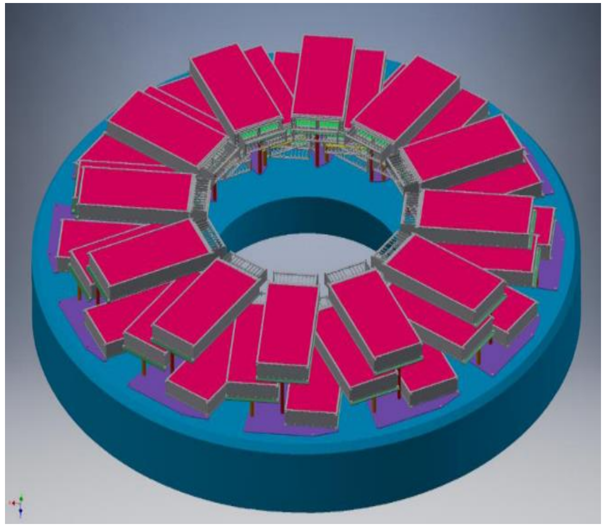


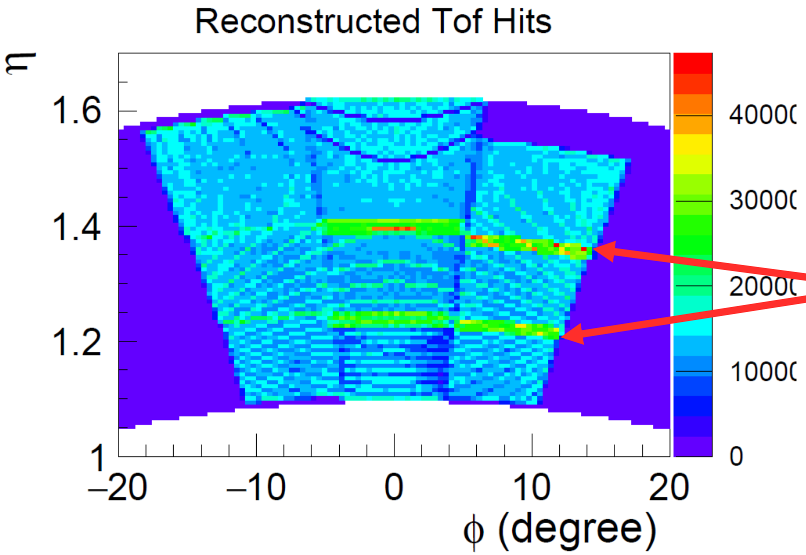




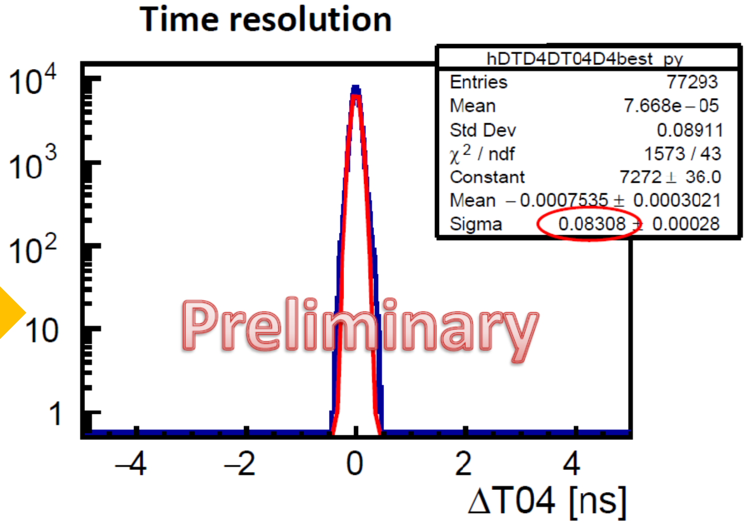
The endcap Time-Of-Flight

- ✓ Successfully commissioned in 2017 (one module)
  - ✓ Interface to STAR event builder & barrel TOF
- ✓ Engineering design for STAR module completed
  - ✓ Mounting scheme, HV distribution, gas system layout, etc.
- ✓ System integration successful → participating in data taking in 2018
  - ✓ Reasonable η-ϕ hit distribution → eTOF working properly
  - ✓ Time resolution 59 ps





Overlap range of two MRPCs



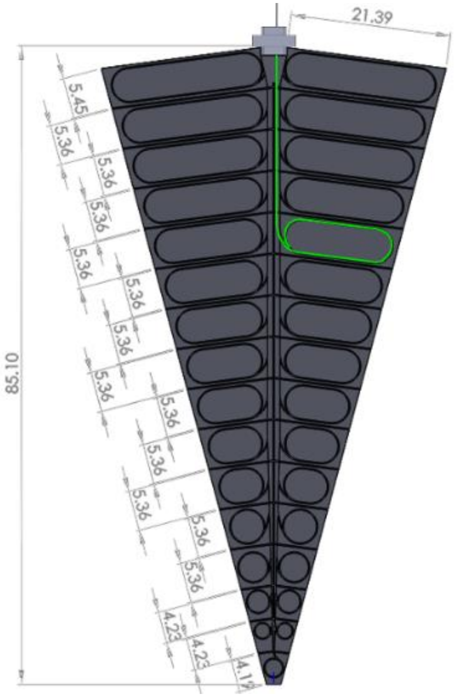
- ✓ System time resolution: 83 ps
- ✓ Counter time resolution: 59 ps

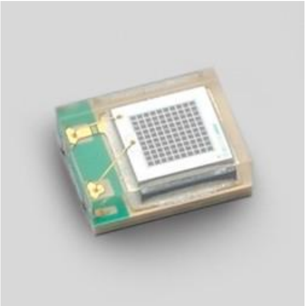
Event Plane Detector

Event Plane Detector

See Joseph Adams's Poster INS-01

- ✓ 2 Wheels
  - East and West EPD (2.1 < |η| < 5.1)
- ✓ 12 super sectors
  - Scintillator wedges, milled to form 31 tiles
  - Optically separated by epoxy
- ✓ Fiber Optics
  - Wavelength-shifting fibers
  - Grouped in 3D-printed connectors
- ✓ Sensors
  - Silicon Photon Multiplier (SiPM)



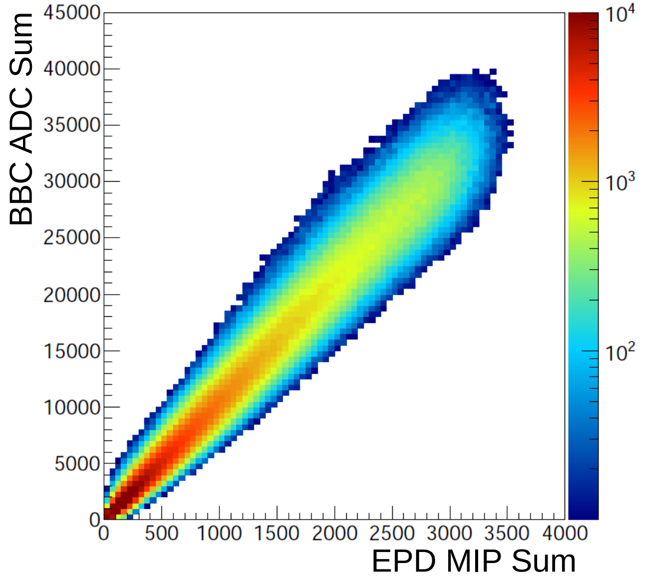


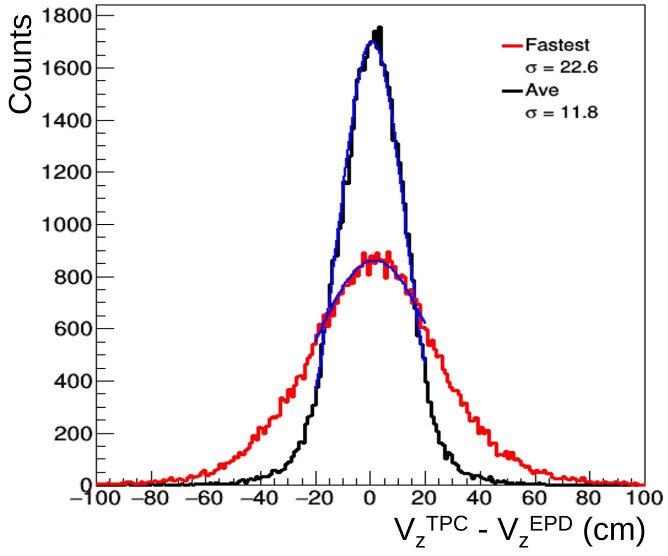
Scintillator + Wave Length Shifting fibers + Silicon Photon Multiplier

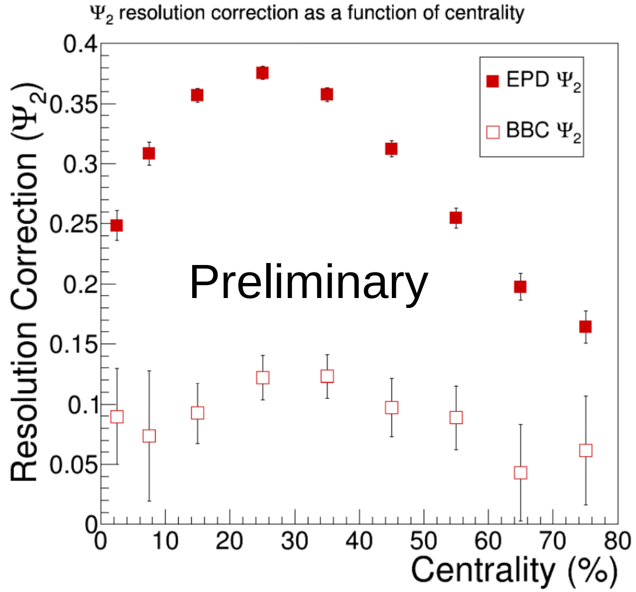
Event Plane Detector Performance

- ✓ Measure current in SiPM using Strontium source
  - ✓ Tile uniformity within 2%, cross-talk less than 1%
- ✓ All 744 tiles are good
- ✓ Good correlation between BBC and EPD → correct timing
- ✓ Timing resolution is about 0.75 ns with fastest TAC method
  - ✓ 0.35 ns with average TAC method, Raw slewing correction
- ✓ The second-order event plane resolution is 0.37 in 20-30% centrality events at top energy isobar collisions

See Justin Ewigleben's Poster INS-11 and Issac Upsal's poster COL-32

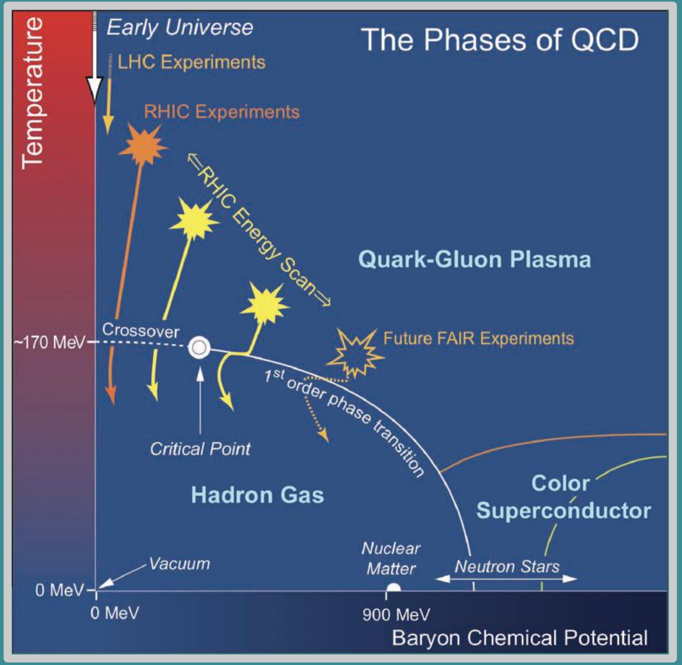






Looking Forward

Beam Energy Scan II Program



QCD phase diagram

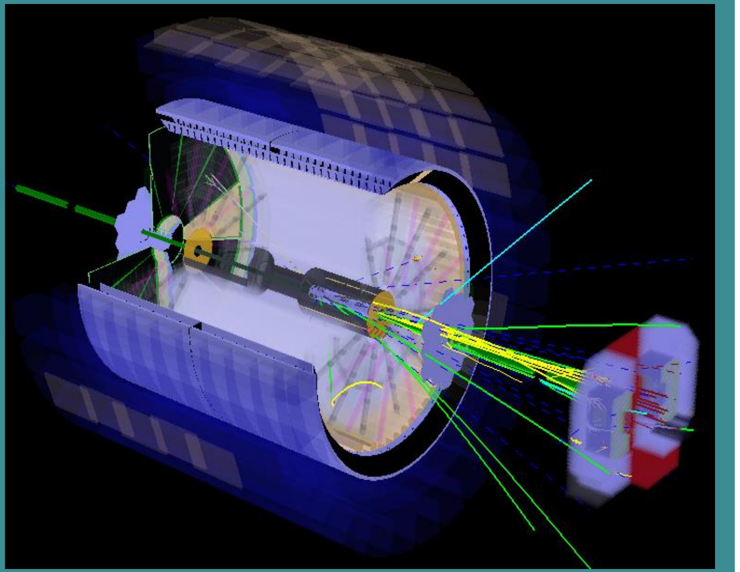
Mid-Rapidity Physics after BES-II

See Qian Yang's Poster PHA-22

2021+ Forward Physics

See Li Yi's Poster INS-38

- ✓ Forward Tracking System
- ✓ Forward Calorimeter System



A Tale of Initial State: Nucleon to Nuclei

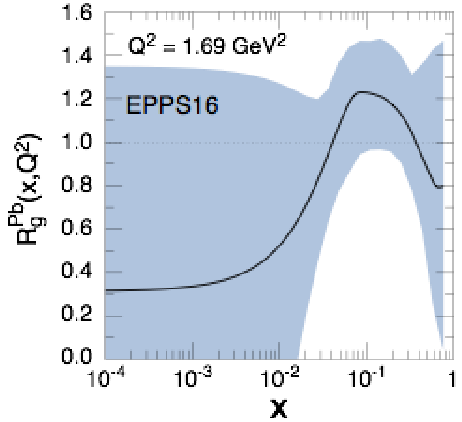
[***STAR Note 598*** : *https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598*]

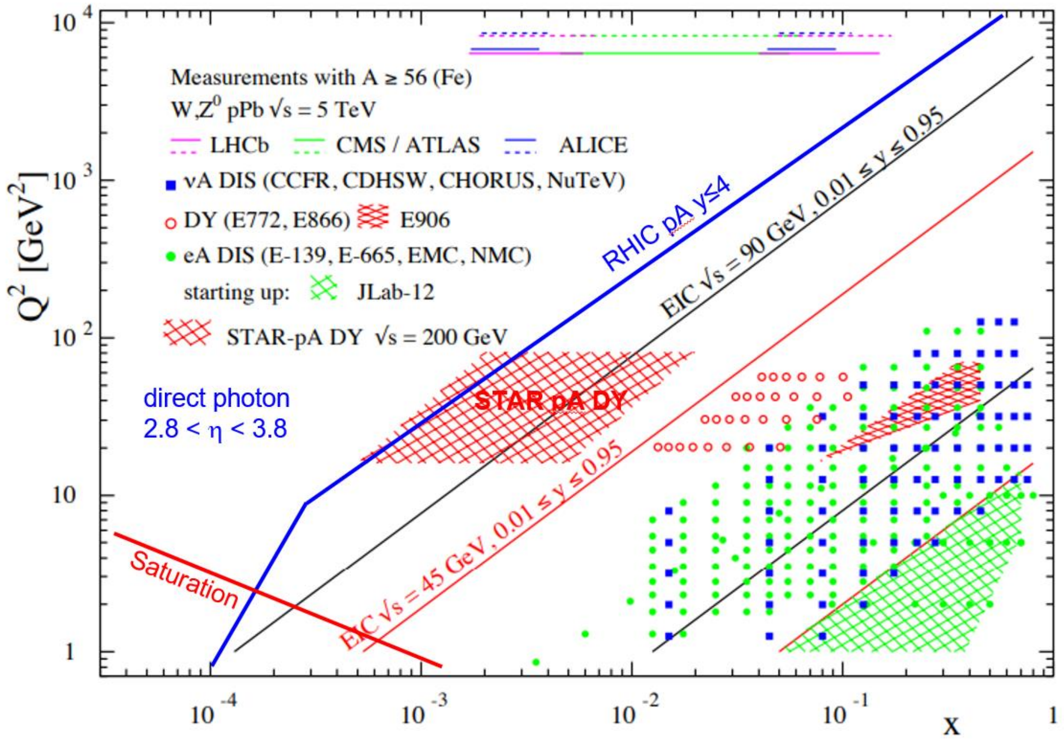
[***STAR Note 669:*** *https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669*]

Unique Kinematic Coverage in p+A Collisions at RHIC

- ✓ What are the nPDFs at low-x?
- ✓ How saturated is the initial state of the nucleus?
- ✓ What is the spatial transverse distribution of nucleons and gluons?
  - ✓ How much does the spatial distribution?
  - ✓ Fluctuate ? Lumpiness, hot-spots etc.

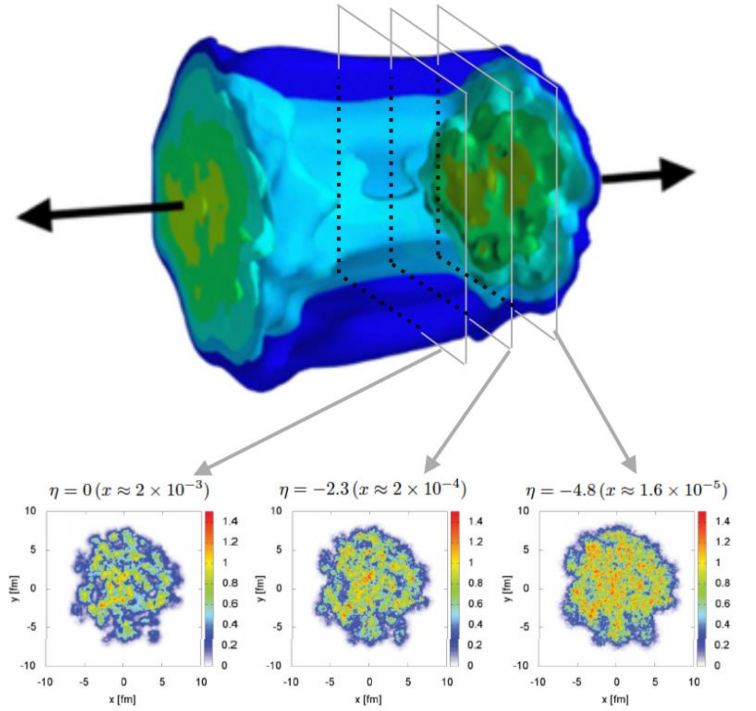
Current knowledge



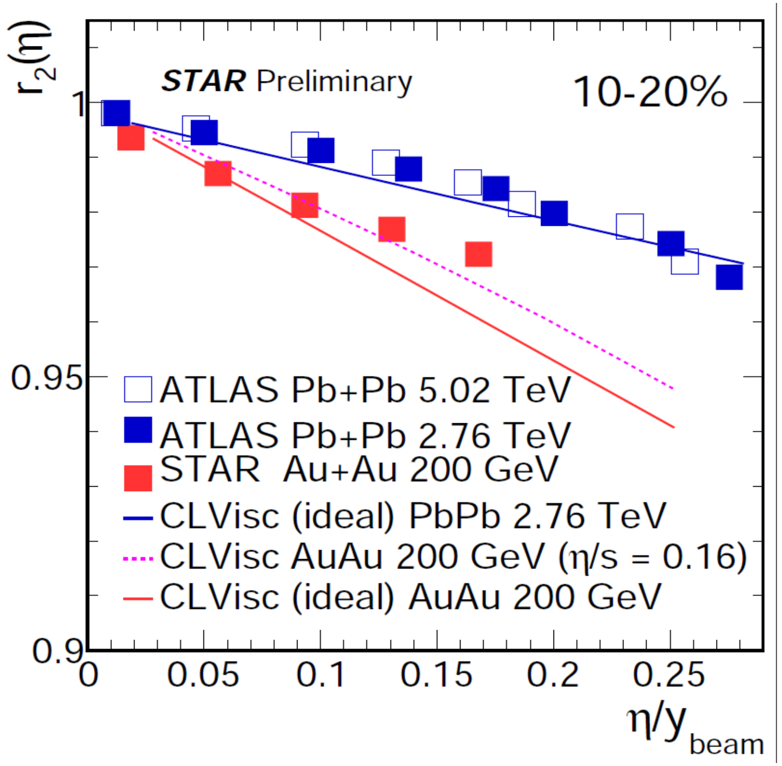


- ✓ Can measure nPDF in a x-Q^2 region where nuclear effects are large
  - $Q^2 > Q_s^2$ over a wide range in x
- ✓ Observables free of final state effects
  - Gluons: R_{pA} for direct photons
  - Sea-quarks: R_{pA} for DY
- ✓ Scan A-dependence prediction by saturation models
- ✓ Access saturation regime at forward rapidity
- ✓ **FTS and FCS are required for these physics**

Physics Opportunities in A+A



credit: B. Schenke



- ✓ Studying the correlation at forward rapidity will constrain the longitudinal structure of initial conditions
- ✓ Discern different scenarios of vorticity by Lambda global polarization vs rapidity
- ✓ Probe small x PDF with forward jets and forward-backward jet correlations
- ✓ Forward jet quenching and QGP tomography

See Maowu Nie's talk #332, May 15 19:10

Forward Tracking System

The Forward Tracking System (2.5 < η < 4.0**):**

✓ 3 layers of silicon mini-strip disk

→ granularity: fine in ϕ and coarse in r direction

→ successful experience of STAR Intermediate Silicon Tracker (IST) detector.

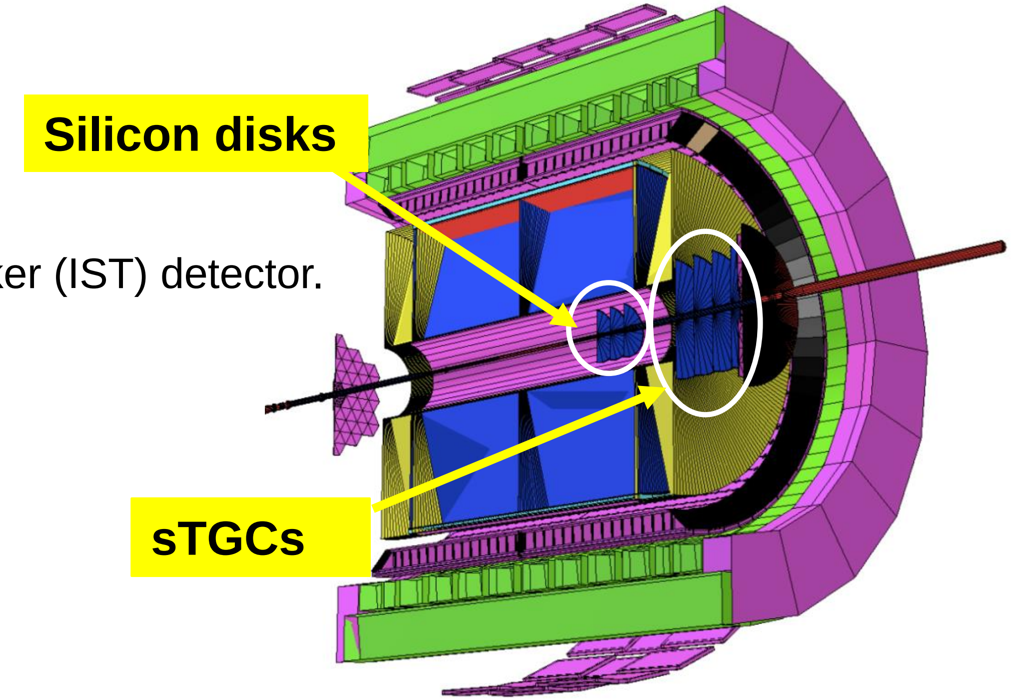
✓ 4 layers of Small-Strip Thin Gap Chamber (sTGC) wheel

→ significant reduction of the project cost

→ maintaining the good momentum resolution

→ possible reuse of STAR TPC electronics for readout

✓ Low material budget in detector acceptance



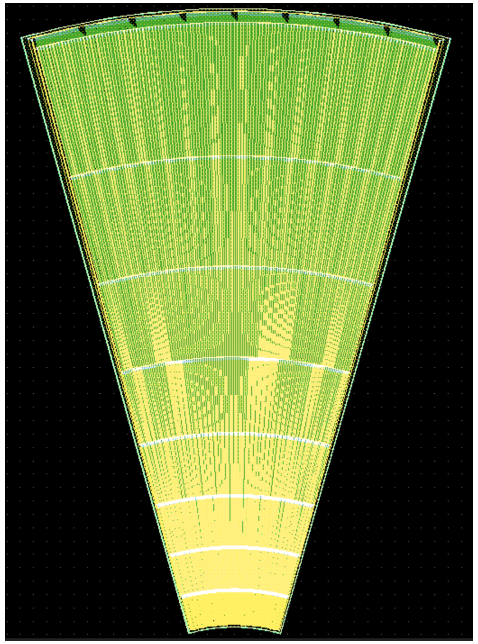
The minimum detector requirements

Detector	p+p and p+A	A+A
FTS	Charge separation	0.2 <p_T <2 GeV/c with 20-30% p_T resolution

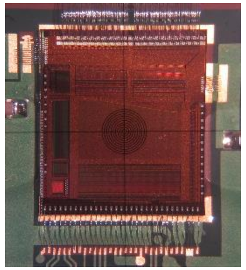
Forward Tracking System

Silicon disks:

- ✓ Single-sided double-metal Silicon Mini-strip sensors
  - → under development
- ✓ Several different frontend chips, APV25-S1 chip → IST
- ✓ IST DAQ system for FTS if using APV25-S1
- ✓ Replicating the STAR IST cooling system to cool the FTS

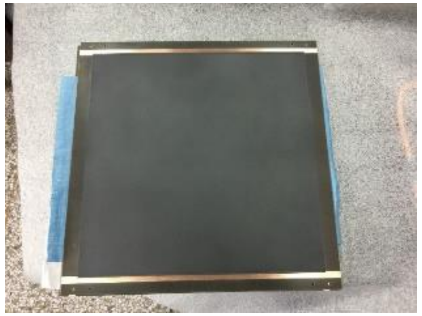


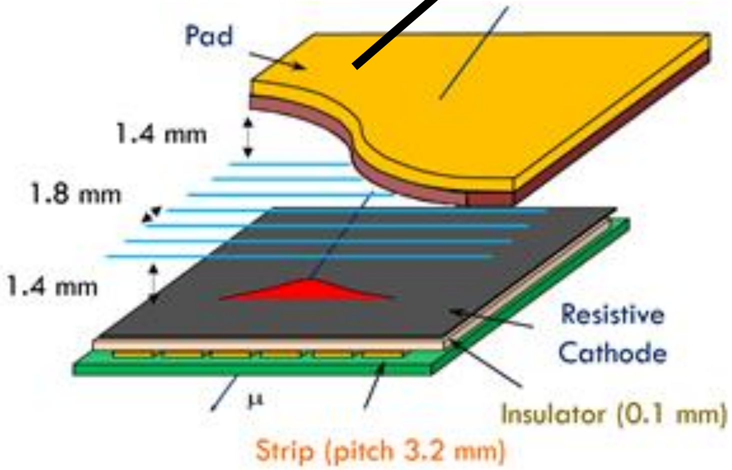
APV25-S1



sTGC:

- ✓ Position resolution ~ 100 μm
- ✓ Material budget: ~ 0.5% per layer, two layers each disk.
- ✓ 1st sTGC prototype for STAR to be made at SDU in 2018
  - ¼ size of ATLAS sTGC
  - 60 cm x 60 cm module with 2 layers
  - Strip of 30 cm each





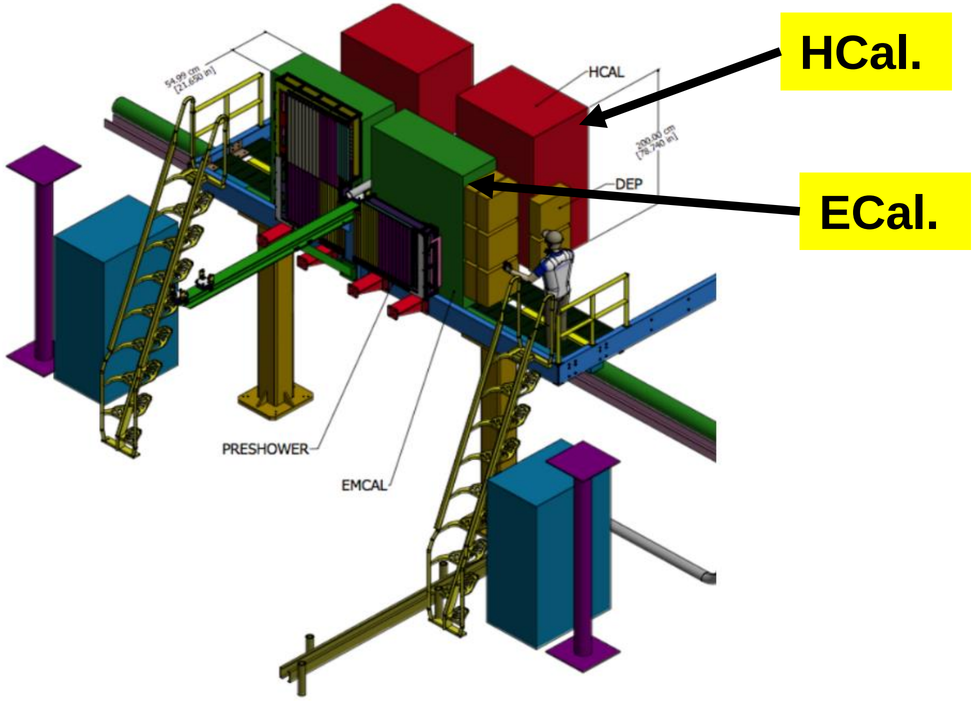
Forward Calorimeter System

The Forward Calorimeter System (2.5 < η < 4.0):

Intensive R&D work on both ElectroMagnetic Calorimeter (ECal) and Hadron Calorimeter (HCal) as part of STAR and EIC Detector R&D

→ several beam test and STAR in situ tests

→ system optimized for cost and performance



Ecal：

- Reuse PHENIX PbSC calorimeter
- With new readout on front instead of W/ScFi SPACAL
- Significant cost reduction
- Uncompensated calorimeter system

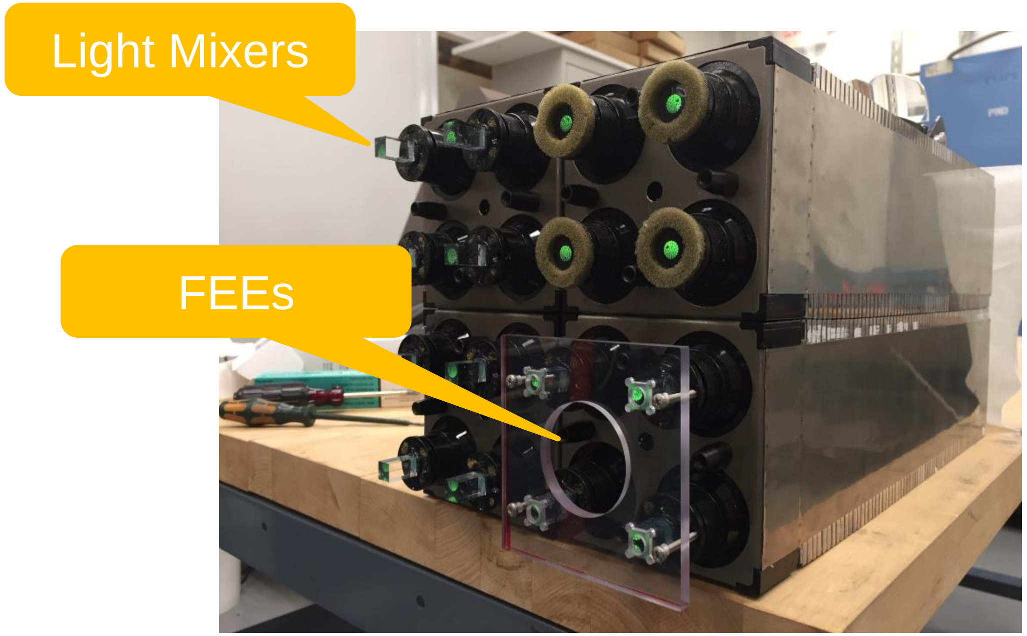
Hcal:

- Sandwich iron-scintillator plate sampling calorimeter.

The minimum detector requirements

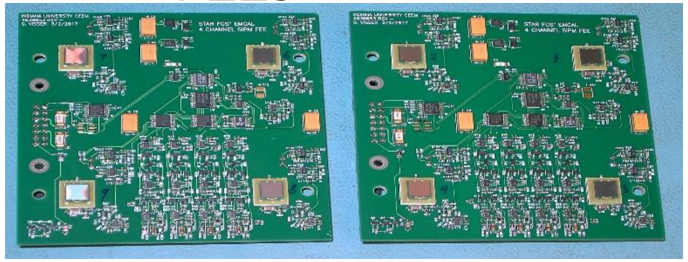
Detecotor	p+p and p+A	A+A
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---

- ✓ Test FCS' ECal in STAR at 2017
  - ✓ Sampling Calorimeter
  - ✓ FEEs
  - ✓ Sensors with help from EIC R&D
    - ✓ SiPMs, Hammamastsu 6x6 mm^2
  - ✓ Digitizers

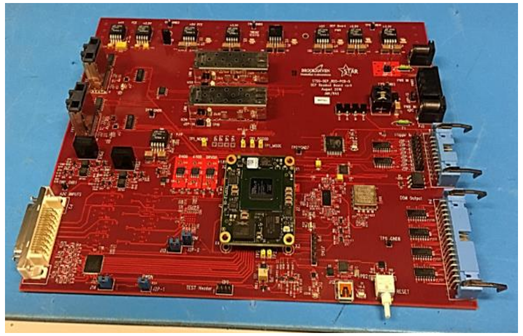


- ✓ FEEs and Detector Electronics Platform has fully integrated to STAR
- ✓ In 2018
  - ✓ Large scale ECal prototype
  - ✓ 2^{nd} iteration of FEEs and DEP
  - ✓ HCal towers

FEEs



Detector Electronics Platform (DEP)



Summary

- BES-II related detector upgrades show excellent progress
  - ✓ iTPC - one sector installed. 70% MWPCs produced, good performance (number of maximum hits, lower p_T threshold and extended in η)
  - ✓ EPD - fully installed. The second order event plane resolution is 0.37 in isobar collisions in 20-30% centrality events, timing resolution is 0.75 ns
  - ✓ eTOF - one sector installed. Engineering design completed, timing resolution is 59 ps
  - ✓ Full installation of iTPC and eTOF in autumn 2018 for the BES-II program

- STAR forward upgrade enables studying the initial state of nuclei (nPDF, saturation and a 3D map of the initial state of AA collisions)
  - ✓ sTGC prototype produced at Shandong University planned to be installed in 2019
  - ✓ Intensive R&D of Silicon sensors is ongoing at UIC&NCKU.
  - ✓ Large scale prototype calorimeter beam test planned for spring 2019 at Fermilab

Thank you !

Summary of forward pp & pA measurements

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023 -2025	$p^{\uparrow}p$ @ 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
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 $C_n(\Delta\eta)$ $r_n(\eta_a,\eta_b)$	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	