STAR Upgrades

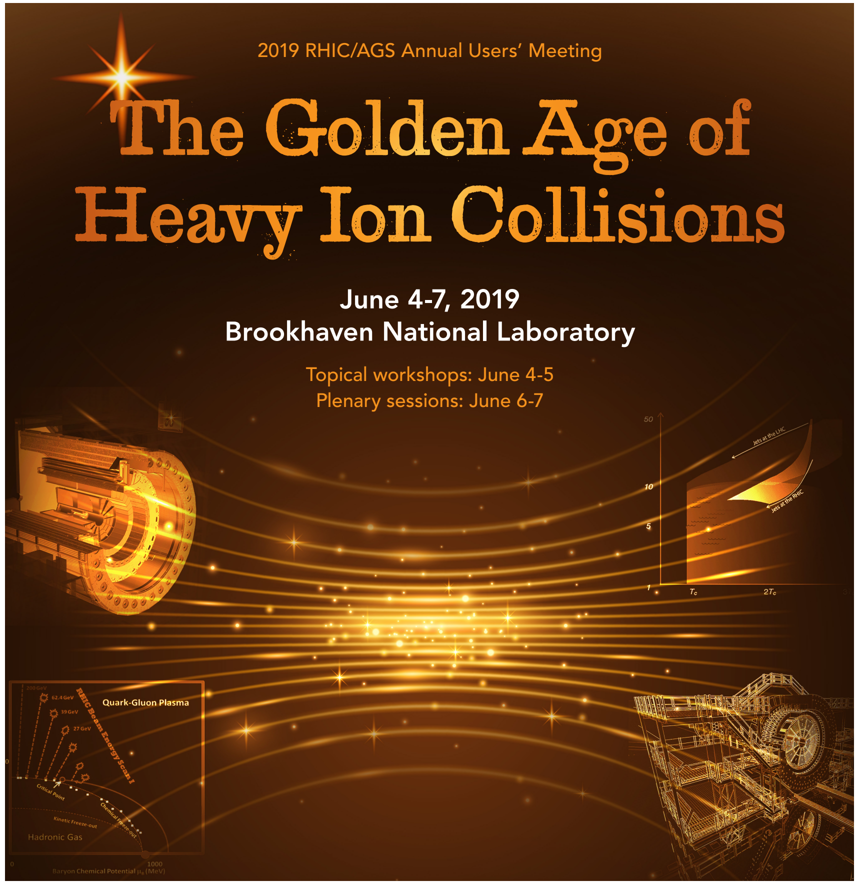
Daniel Brandenburg (Shandong University / BNL)

→ for the **STAR Collaboration**

RHIC & AGS Users Meeting

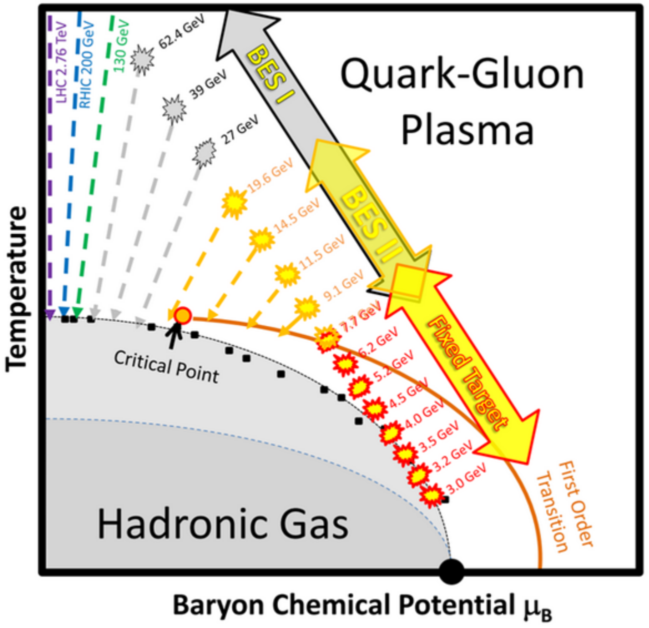
June 4-7, 2019 : Brookhaven National Lab

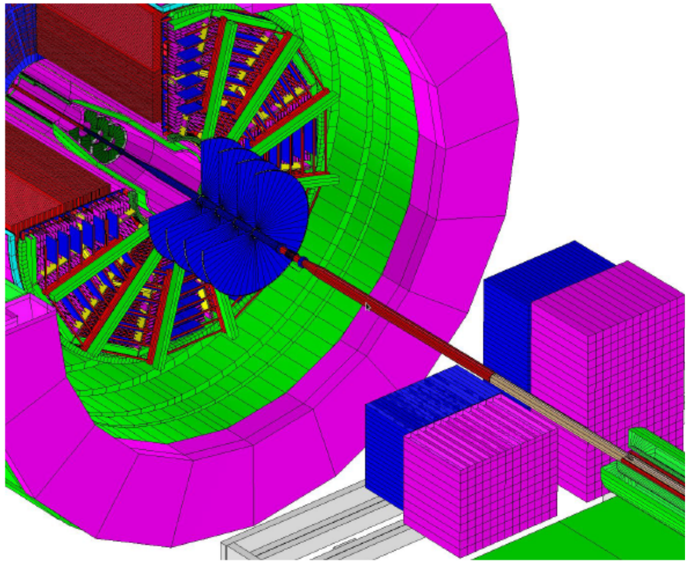
U.S. DEPARTMENT OF ENERGY



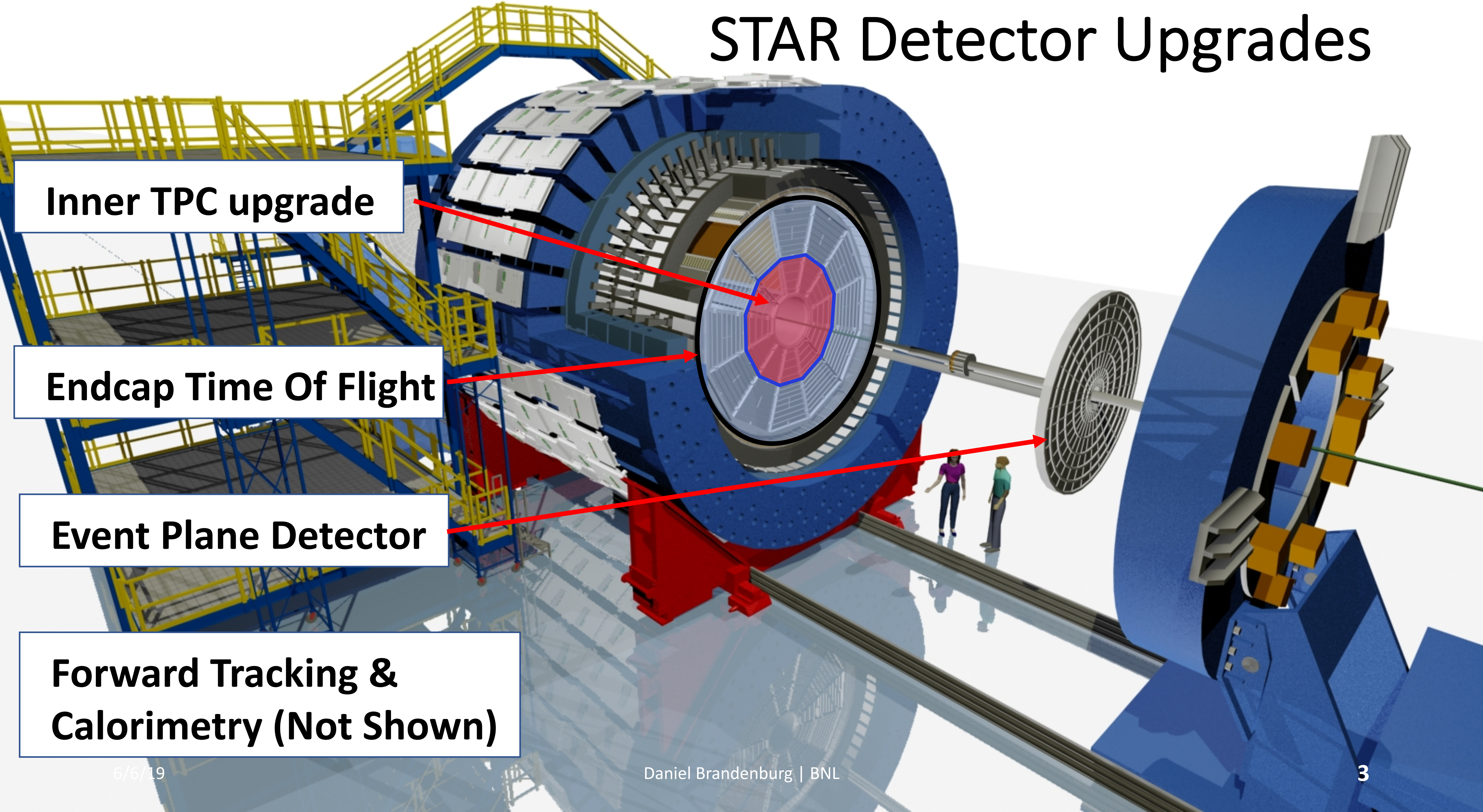
STAR Upgrades : Outline

- 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

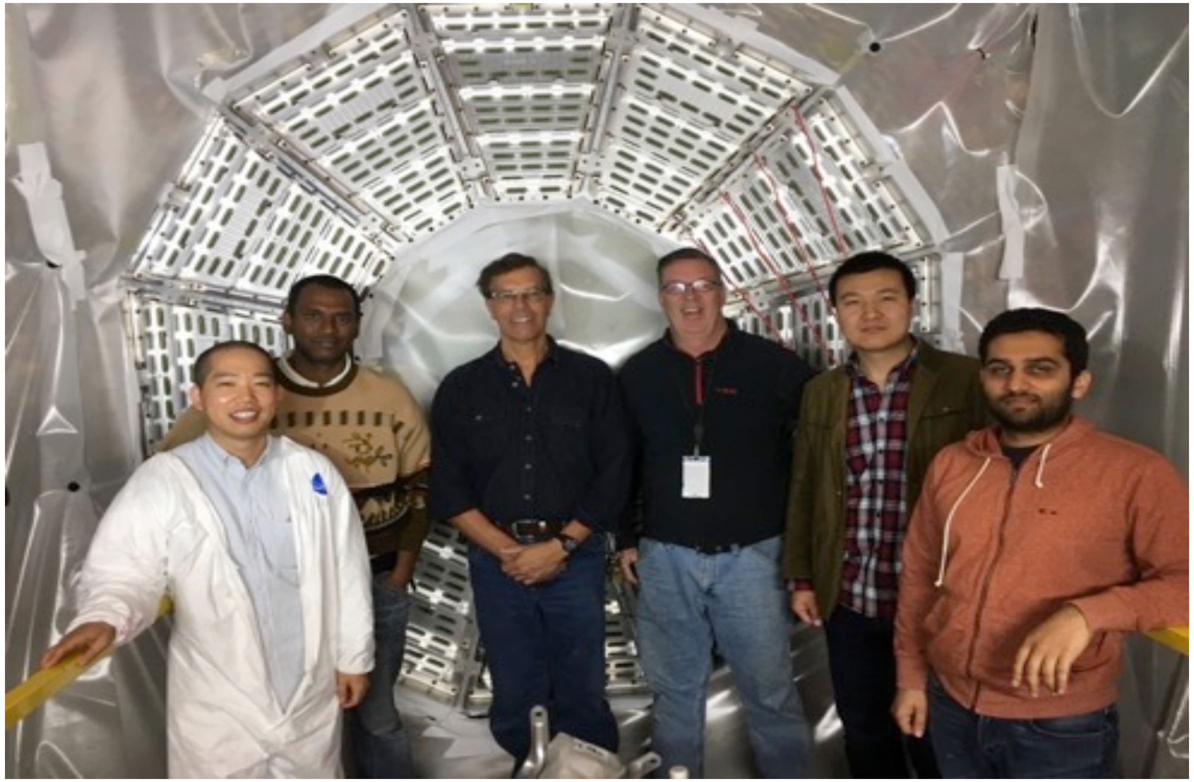




STAR Detector Upgrades



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

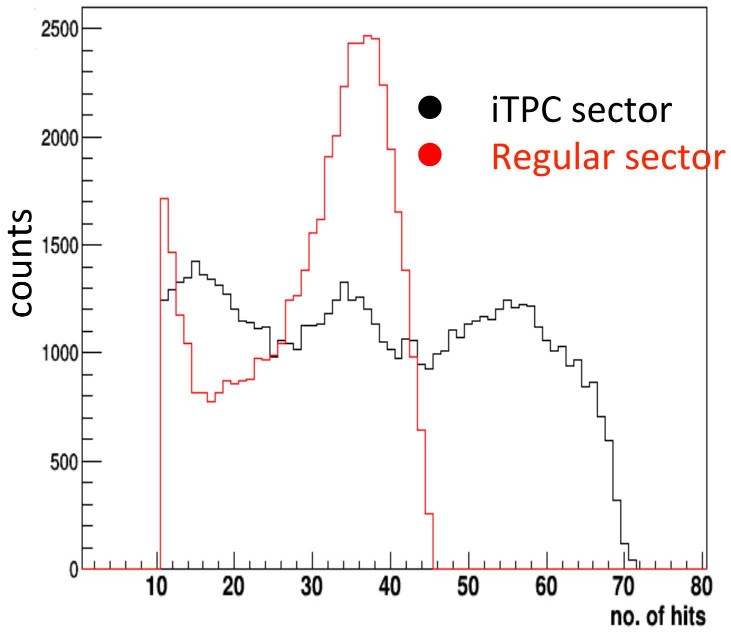
2019 Schedule followed:

- 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**



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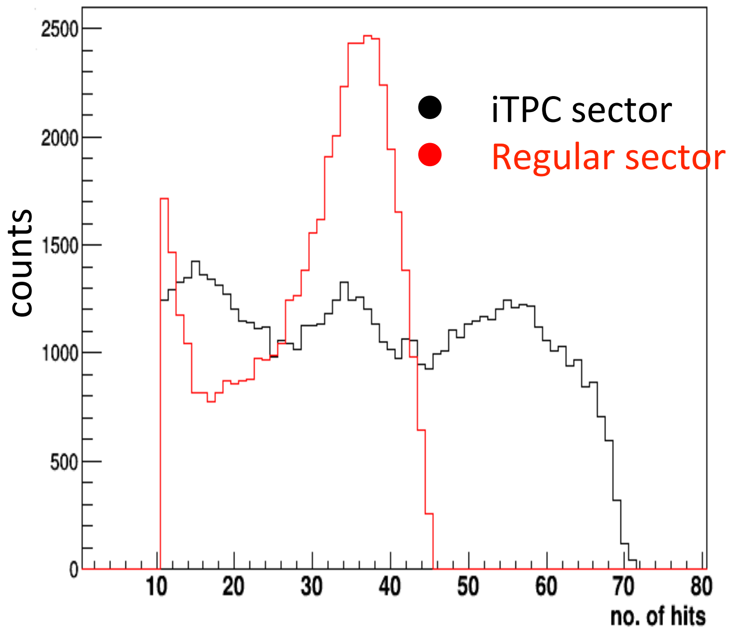

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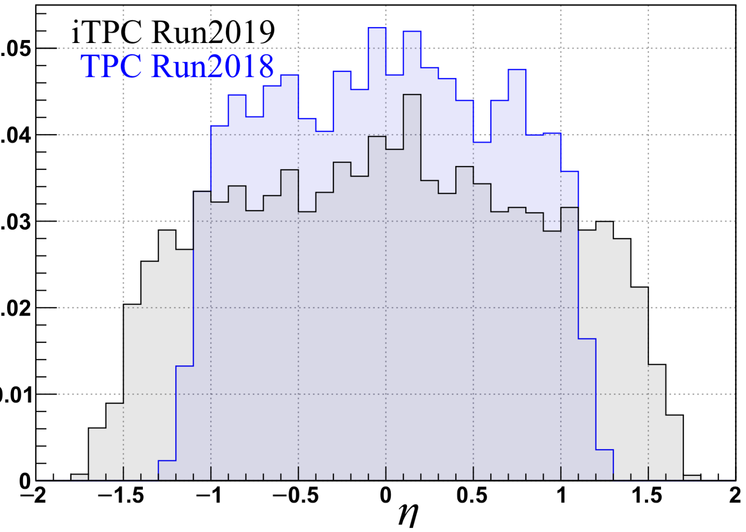
- **Increase mid-rapidity coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$**



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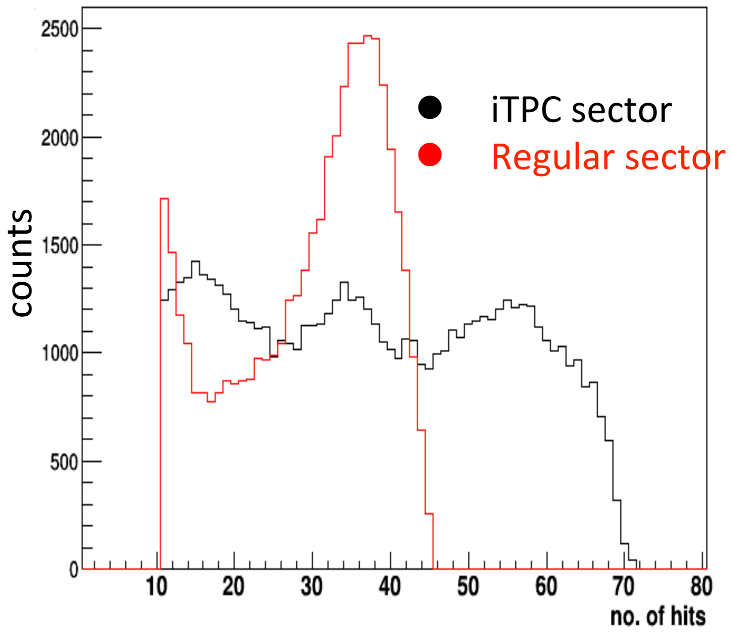

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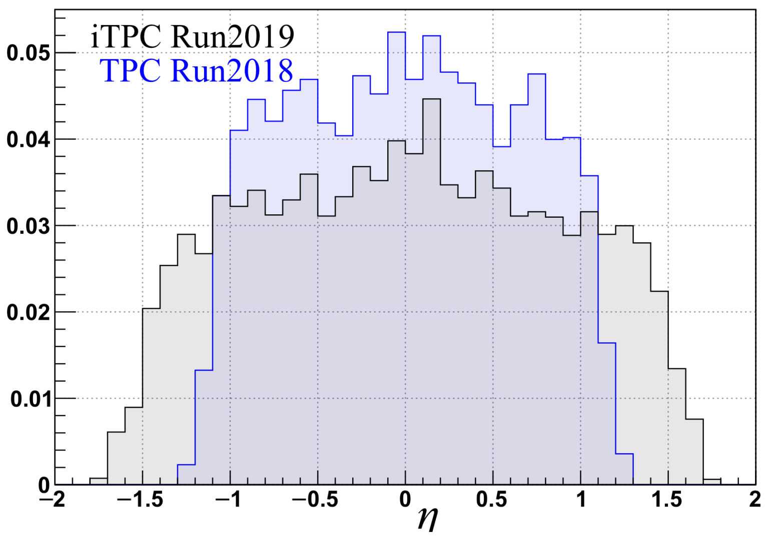
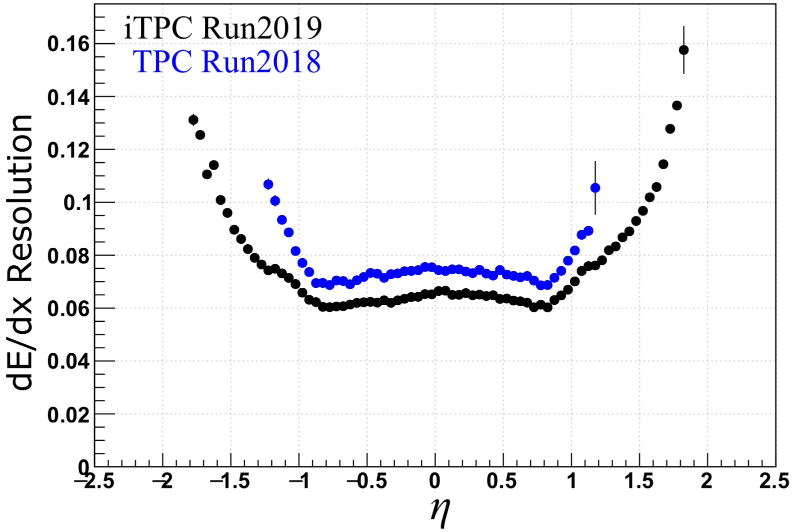


- **Improved dE/dx Resolution (15%-30%)**



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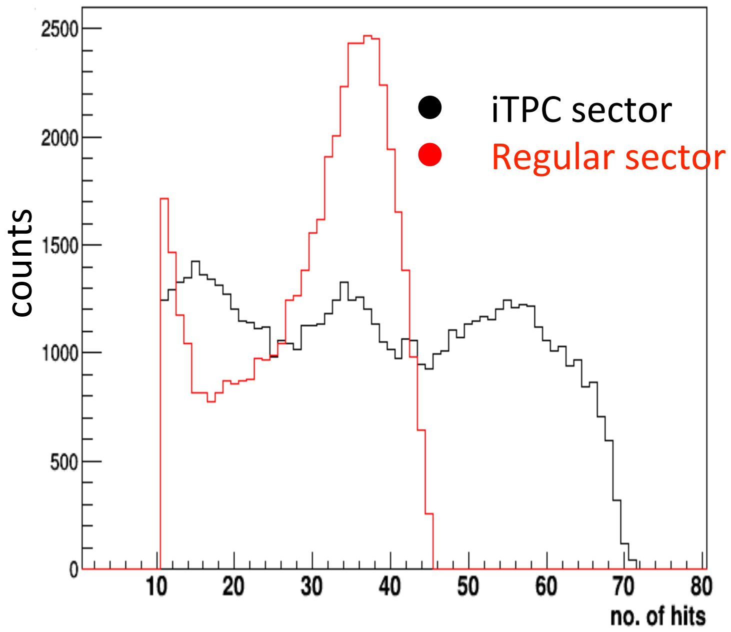

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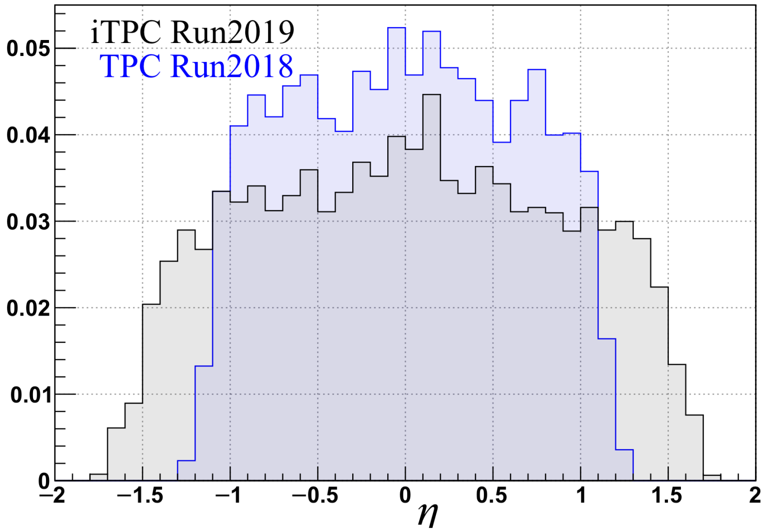
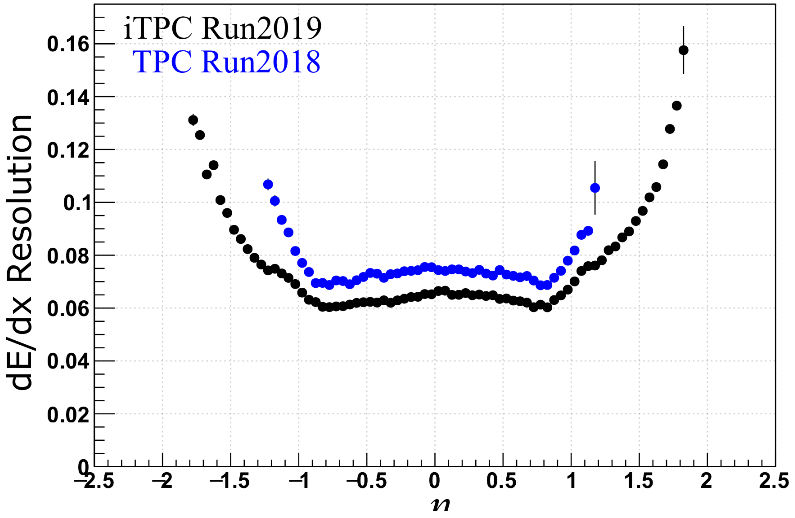
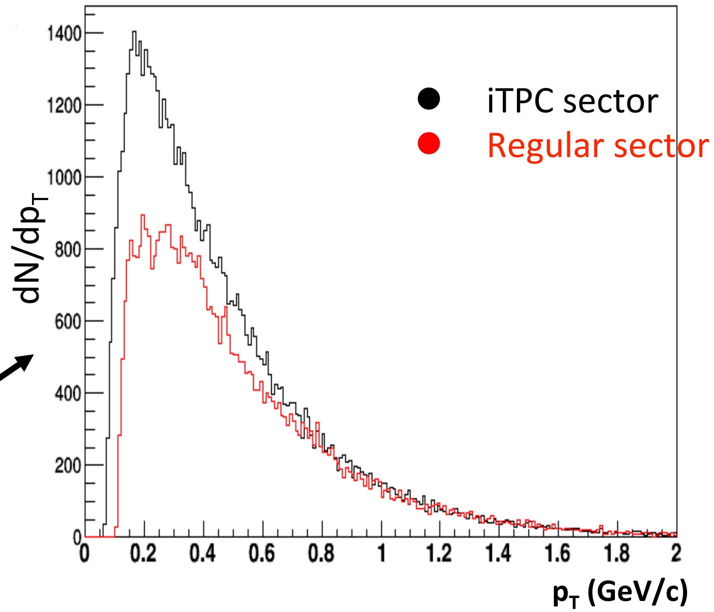


○ Improved Momentum Resolution

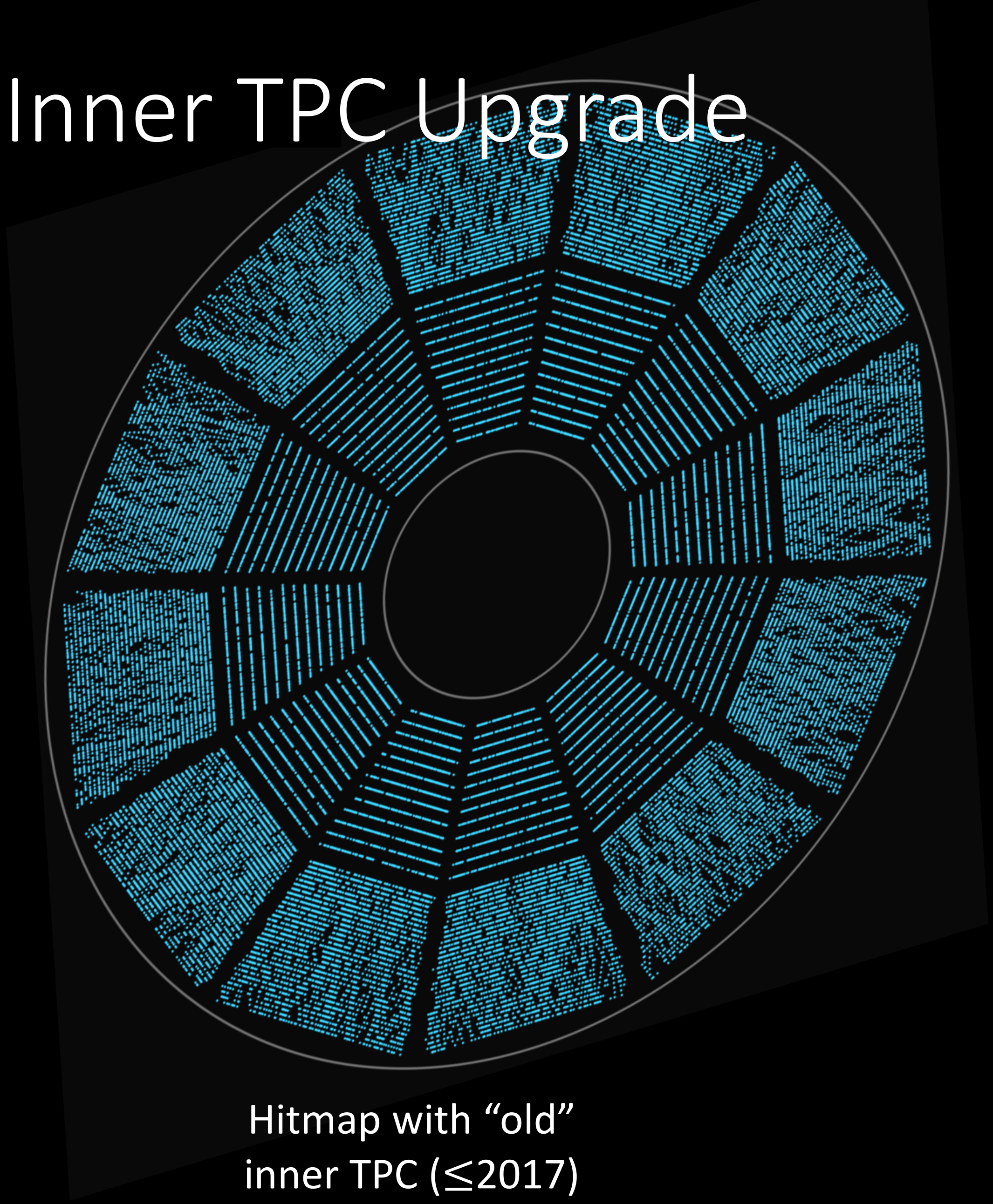
○ Decrease minimum p_T threshold from $p_T > 125\ MeV/c$ **to $p_T > 60\ MeV/c$**

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



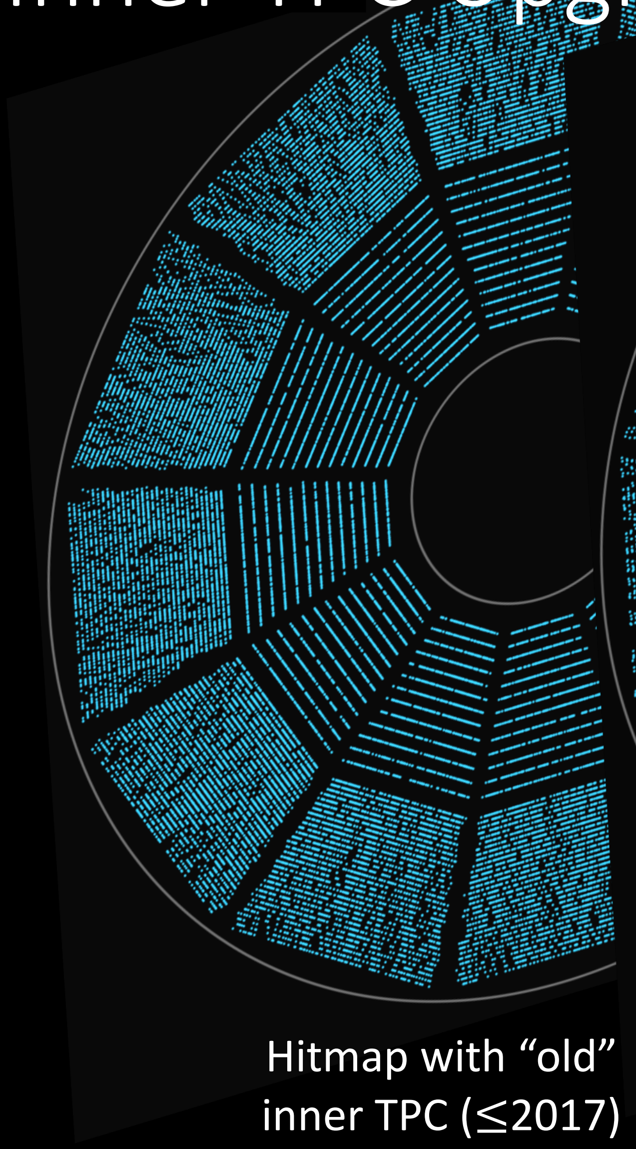


Inner TPC Upgrade



Hitmap with “old”
inner TPC (≤2017)

Inner TPC Upgrade



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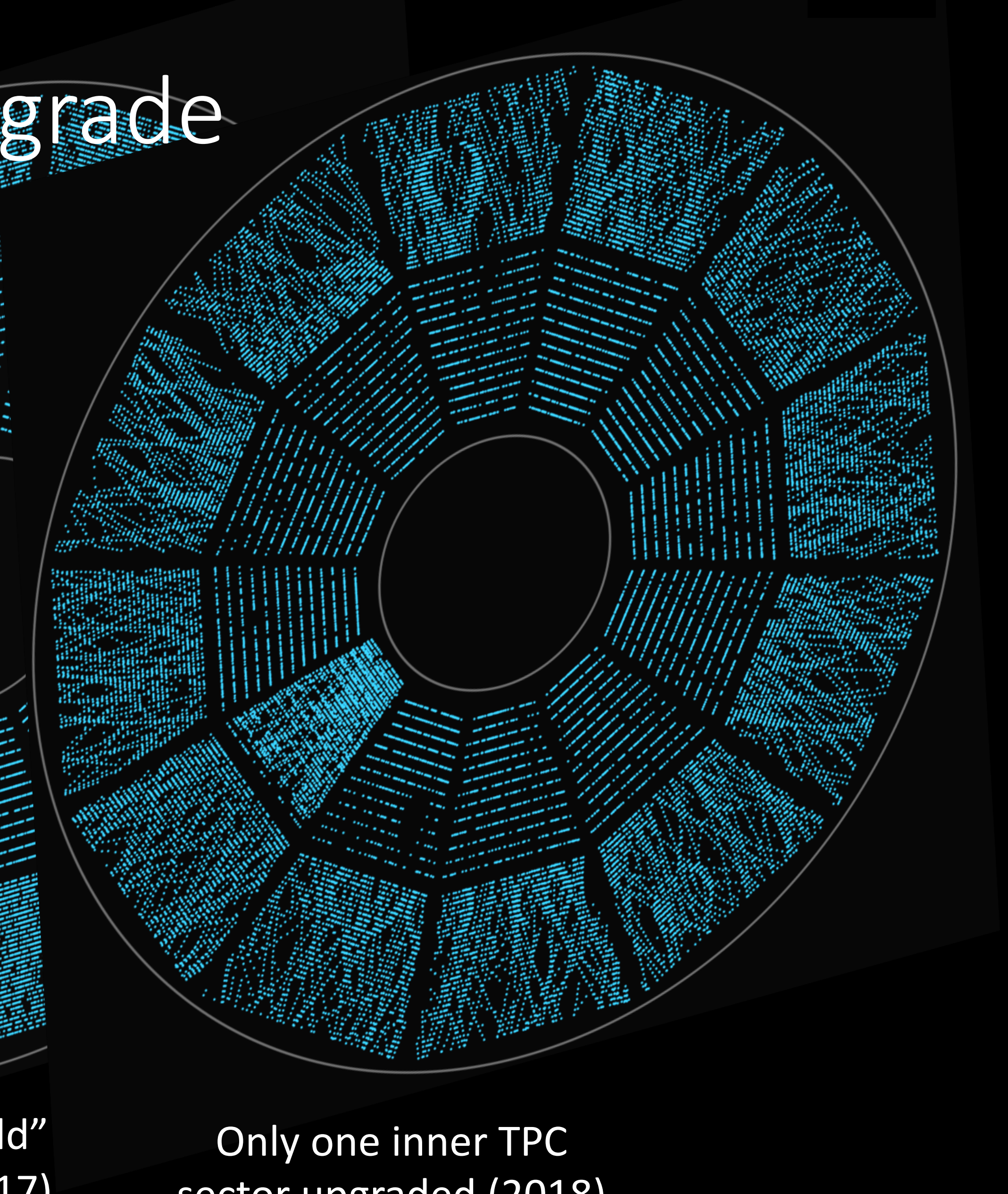
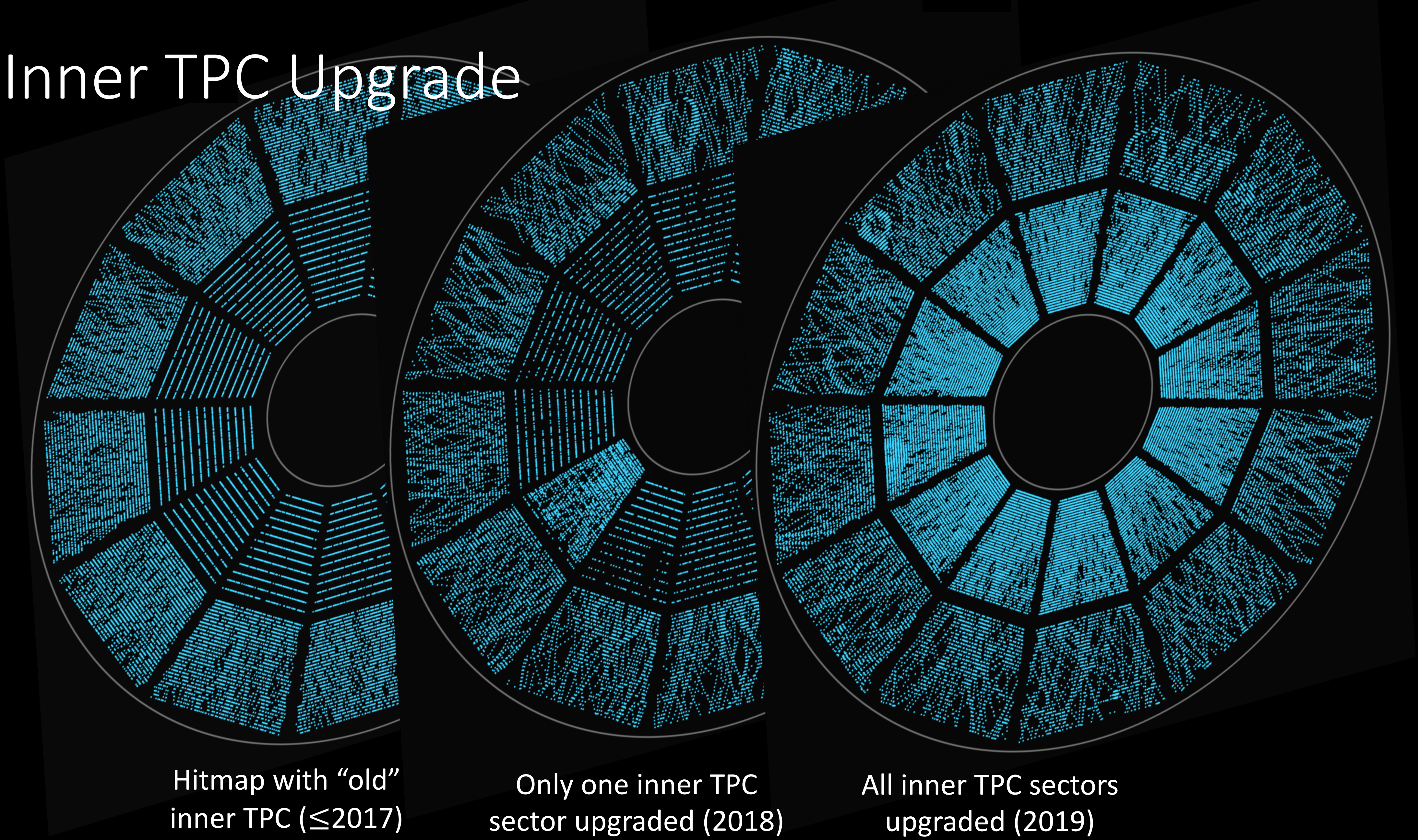


Only one inner TPC sector upgraded (2018)

Inner TPC Upgrade



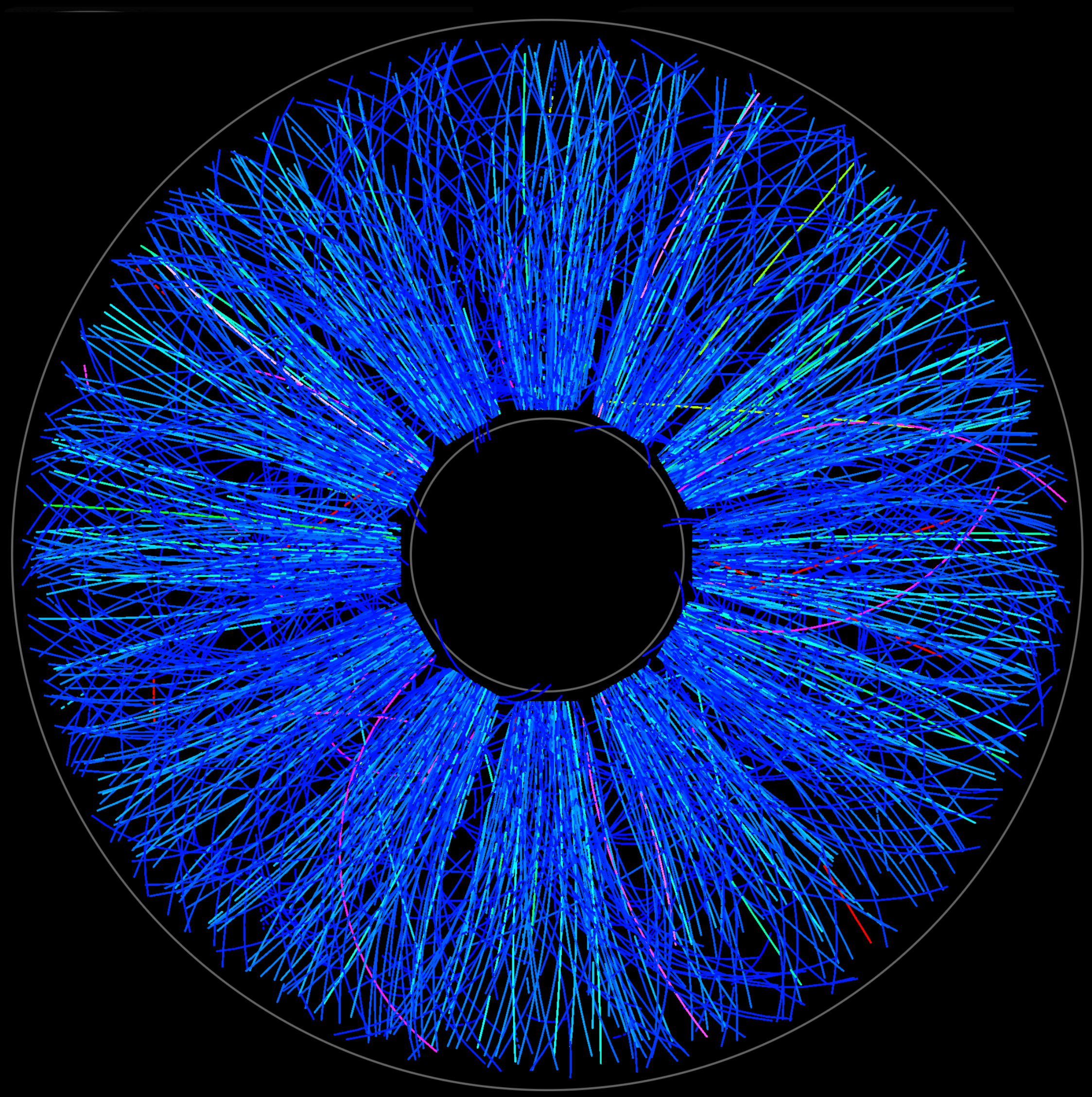
Hitmap with “old” inner TPC (≤2017)

Only one inner TPC sector upgraded (2018)

All inner TPC sectors upgraded (2019)

Inner TPC Upgrade

Successful, <u>on-time & under budget</u> completion of the iTPC upgrade

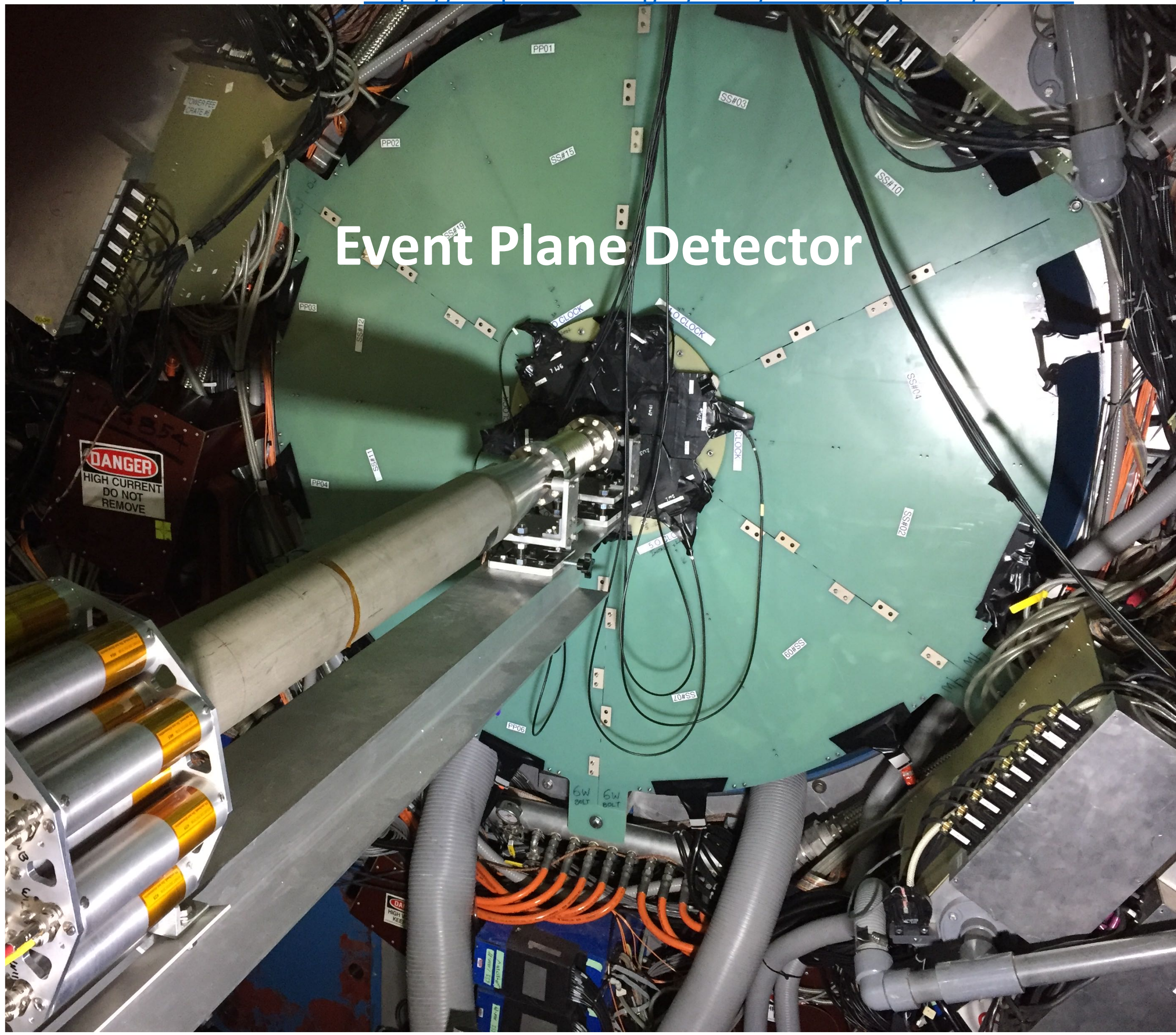


2019 Event Display : Au+Au 19.6 GeV
Full tracking with all iTPC sectors

Event Plane Detector

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

- Replaces Beam-Beam Counter (BBC)
  - Improved triggering capabilities
  - Improves background rejection
- Coverage : $2.1 < |\eta| < 5.1$
- Greatly improves event plane resolution
  - Especially 1st order event plane
  - Crucial for achieving BES II physics goals
- Smooth installation (completed in 2018), commissioning, and operation
- Already used for physics analysis of 2018 data



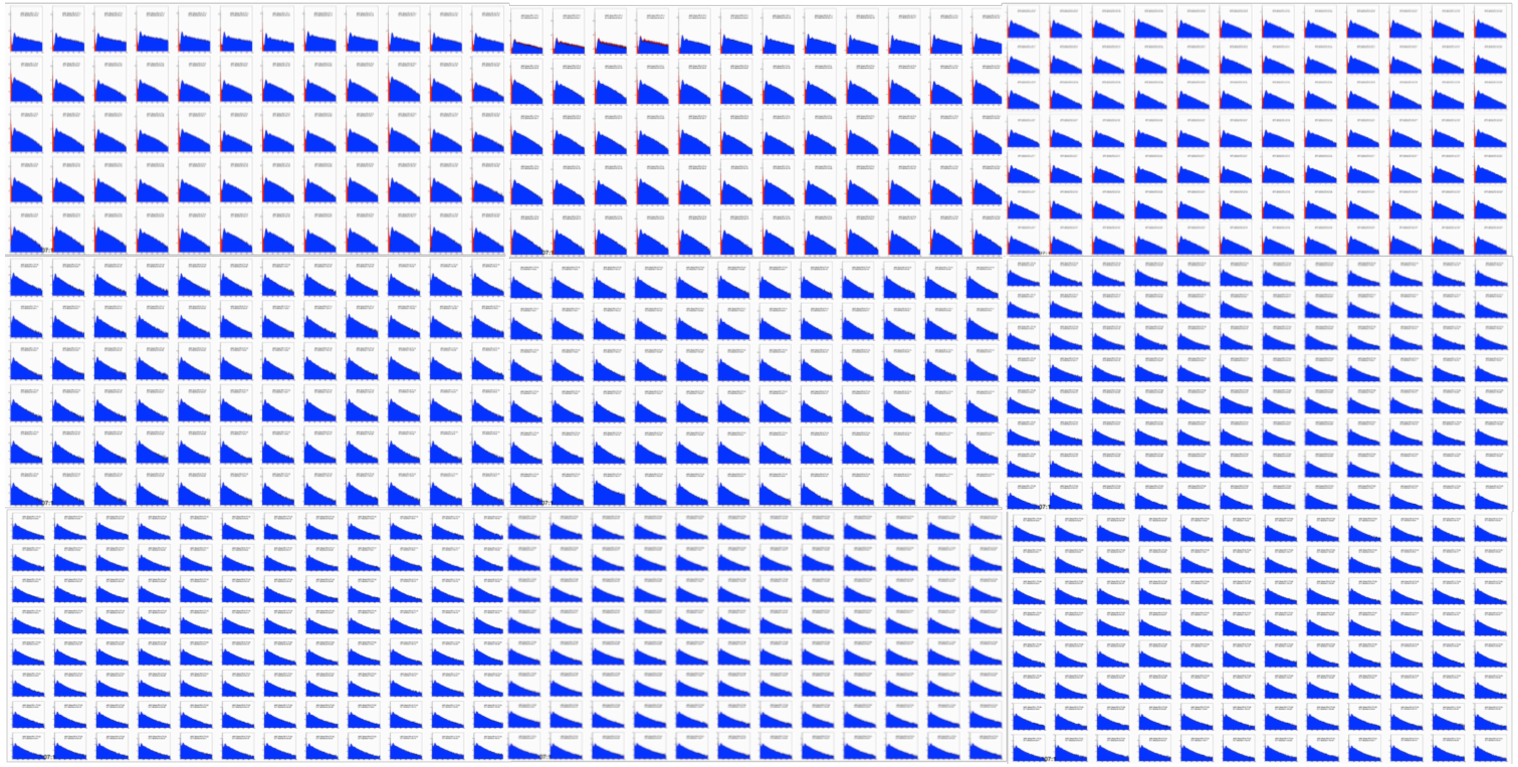
Each (East, West) wheel:

- 16 tile "rows" at given radius
- 24 tiles per row (except 12 for innermost)

➢ 372 tiles x 2 = **744 tiles in total**

Event Plane Detector Performance

<u>Good signal & clear MIP peak</u> from ALL 744 tiles



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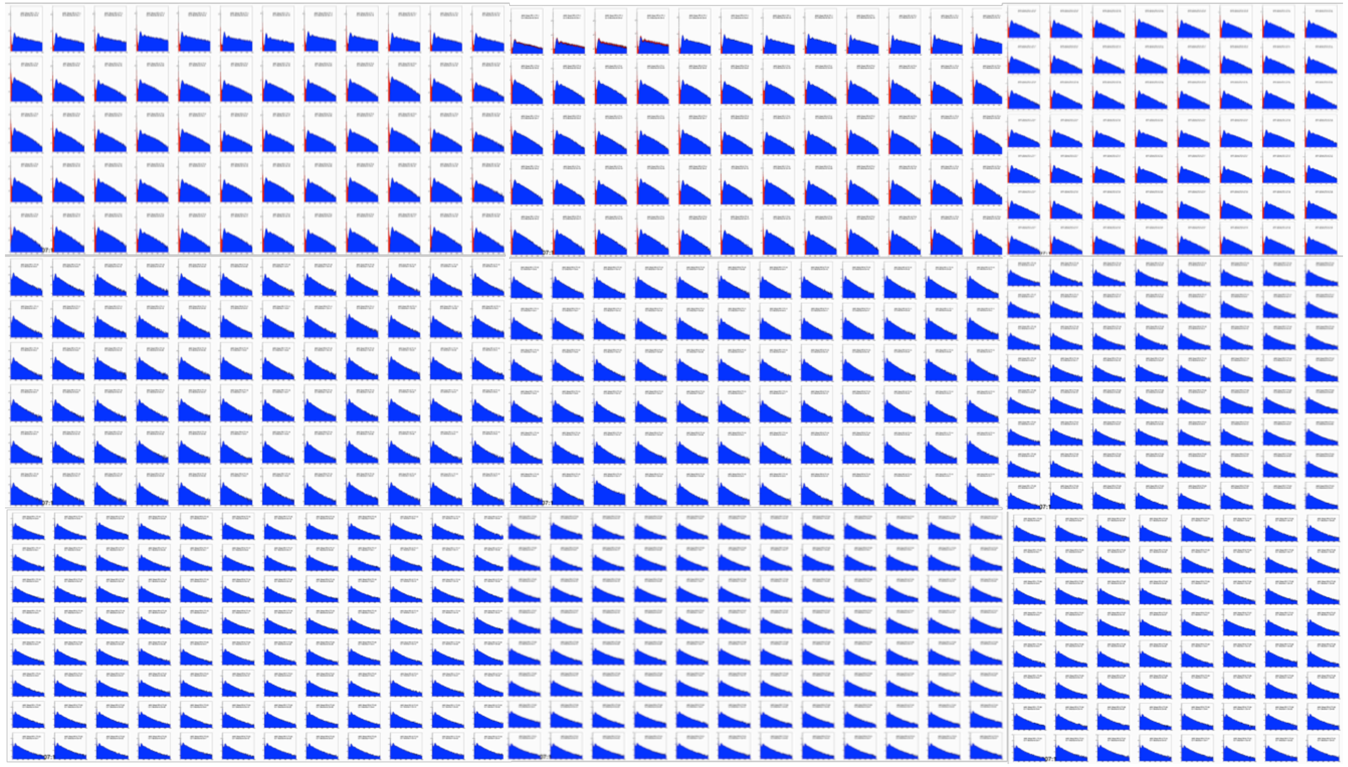
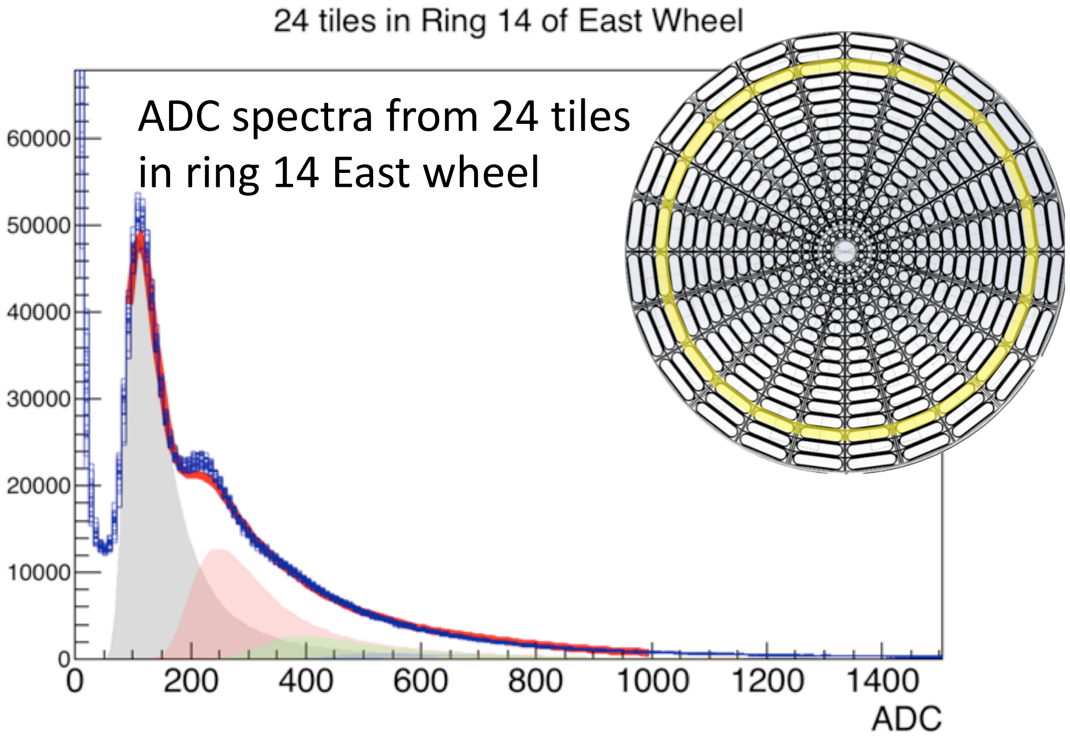


Very good uniformity

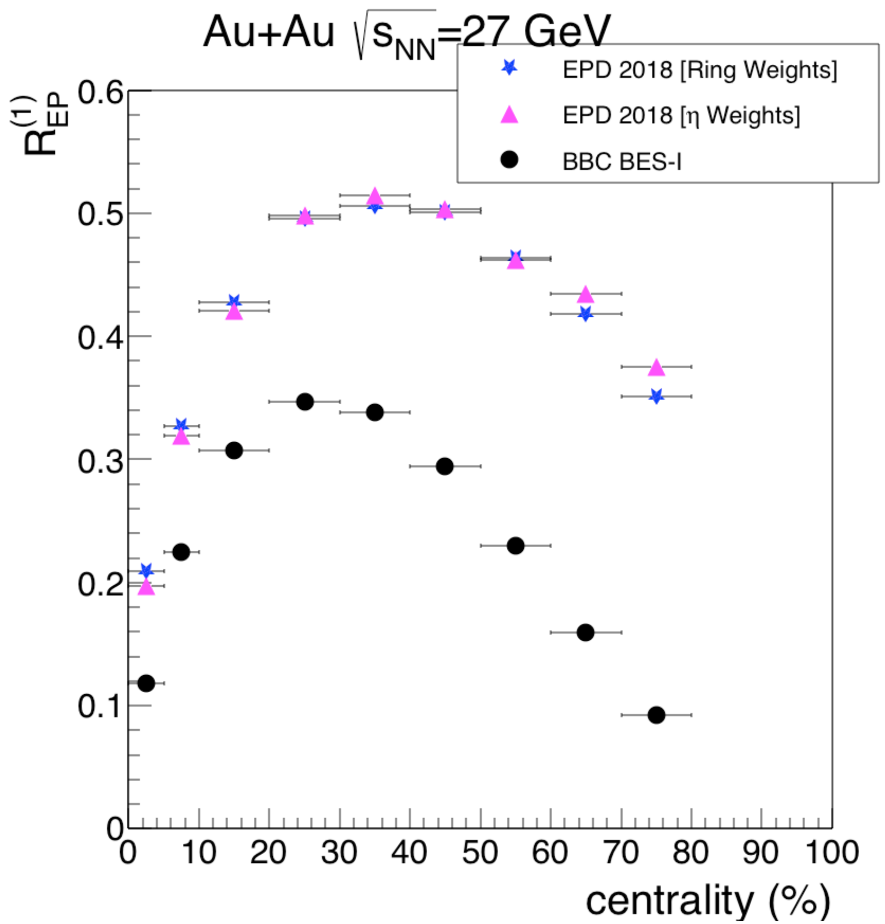
~identical ADC distribution within a ring



Event Plane Performance

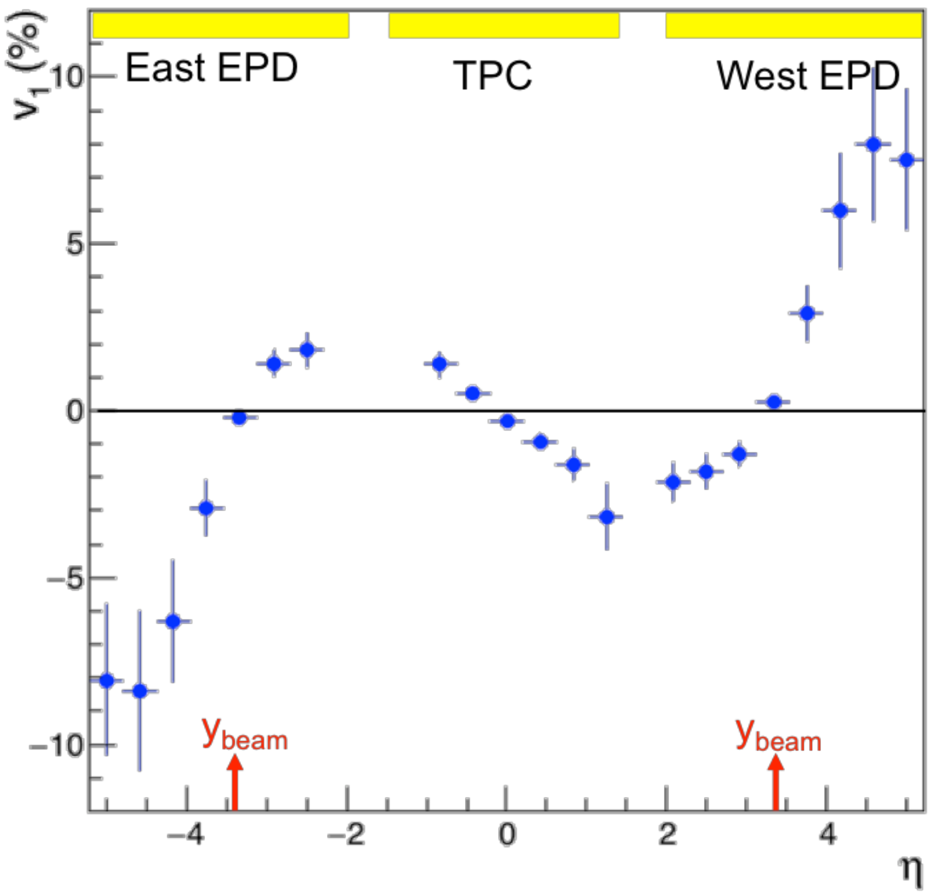
1st order Event Plane Resolution

→ **Significant improvement across all centrality**



Added coverage from EPD

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



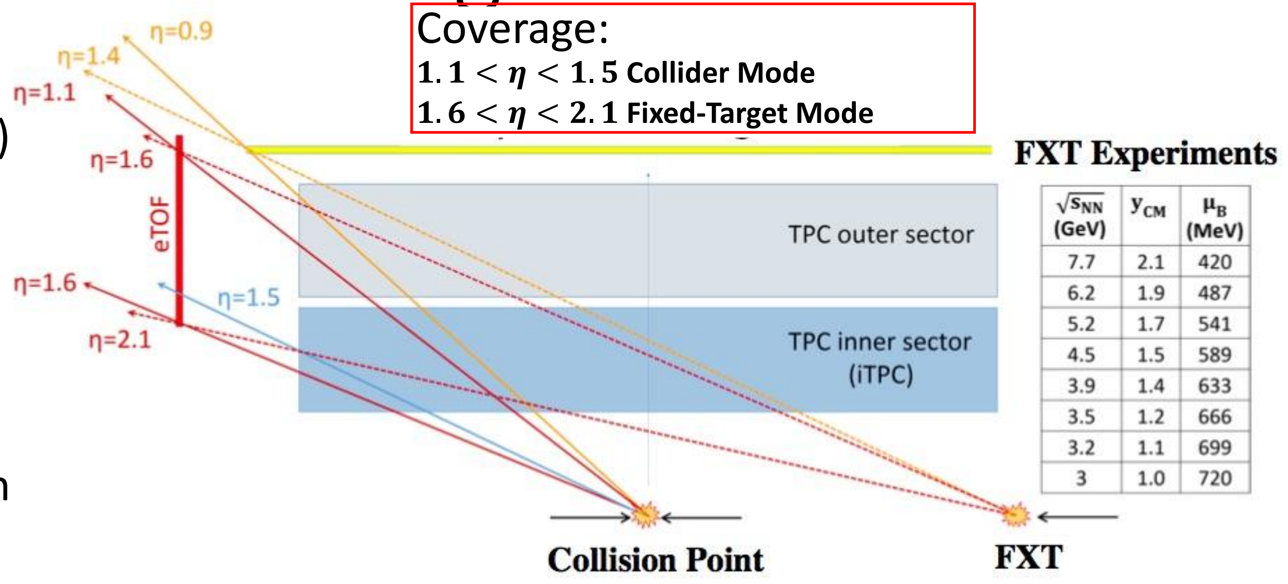
Motivation: Endcap Time-of-Flight Detector

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

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

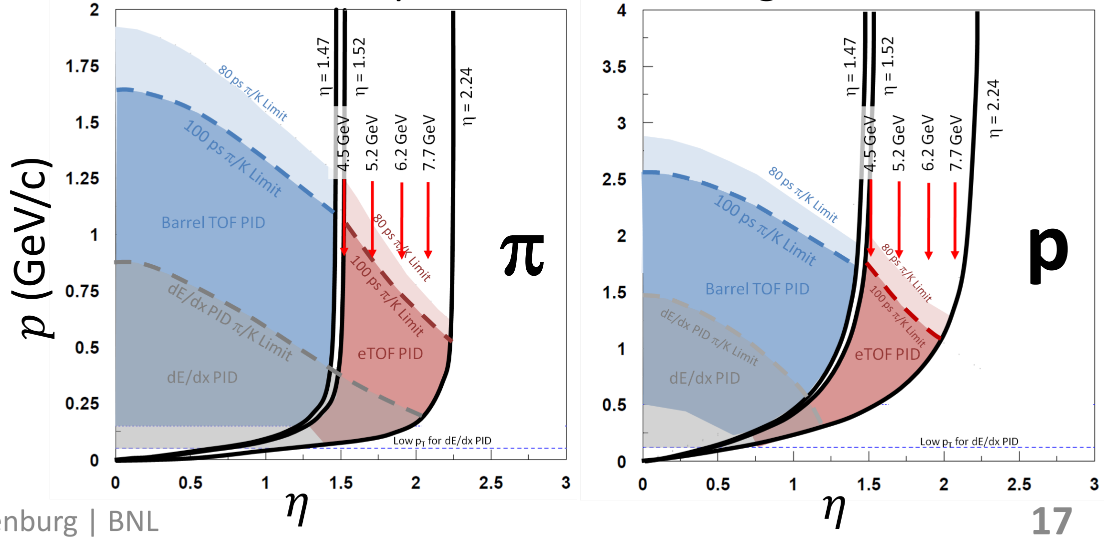
- ➢ First streaming DAQ system at RHIC – important step towards the future

- ➢ Collaboration with CBM Fair phase 0



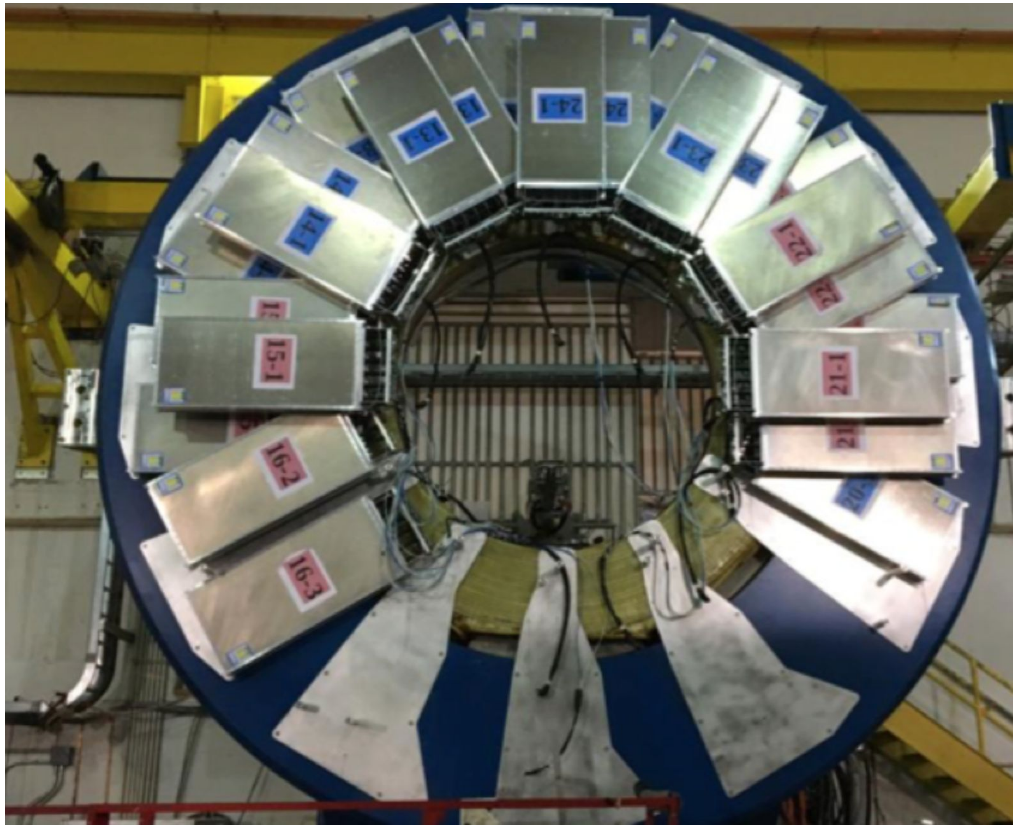
$\sqrt{s_{NN}}$ (GeV)	y_{CM}	μ_B (MeV)
7.7	2.1	420
6.2	1.9	487
5.2	1.7	541
4.5	1.5	589
3.9	1.4	633
3.5	1.2	666
3.2	1.1	699
3	1.0	720

Acceptance in Fixed Target Mode

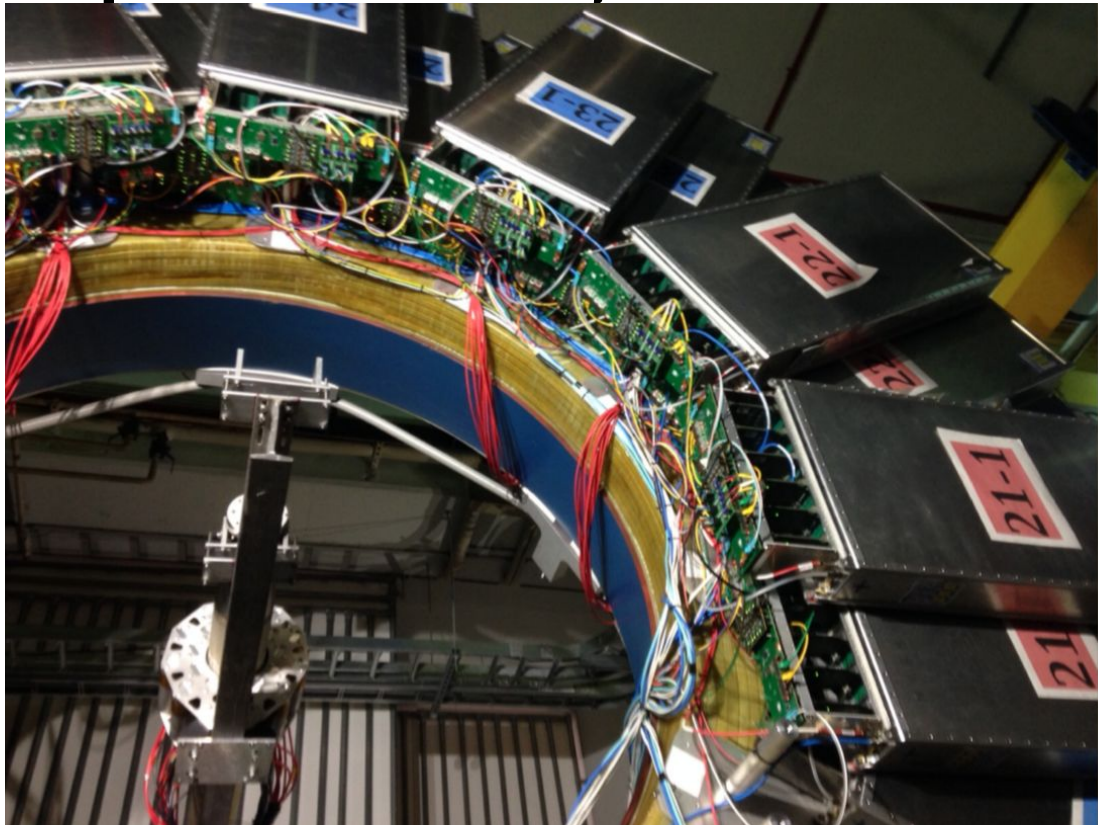


Endcap Time-of-Flight Detector

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

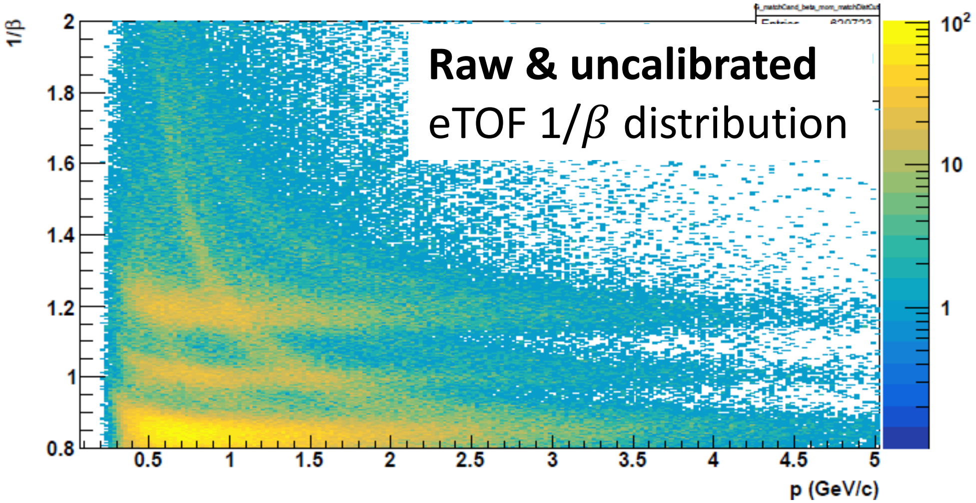


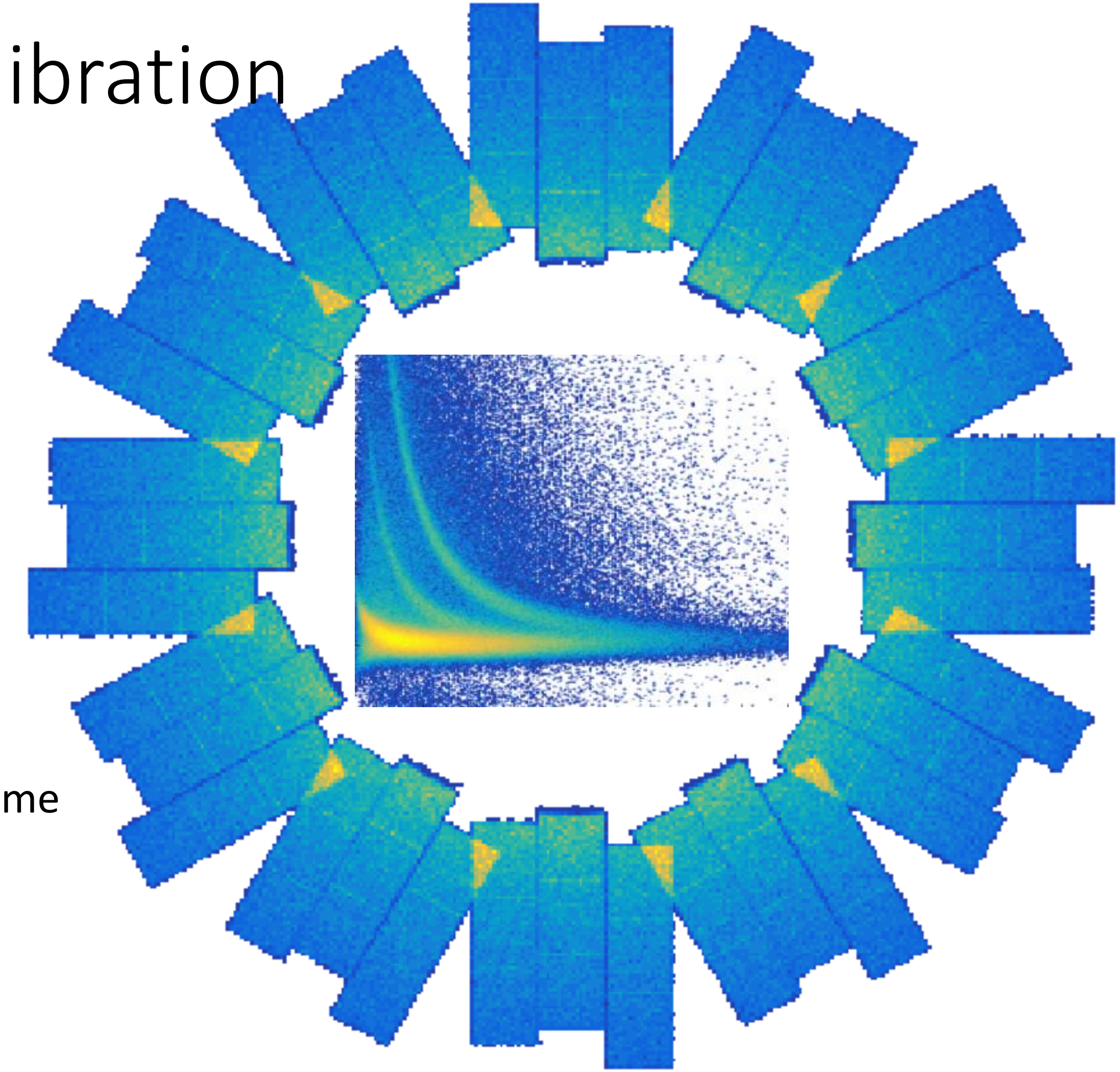
Inside face of east pole-tip, partially installed



Fully installed and cabled

eToF Performance & Calibration



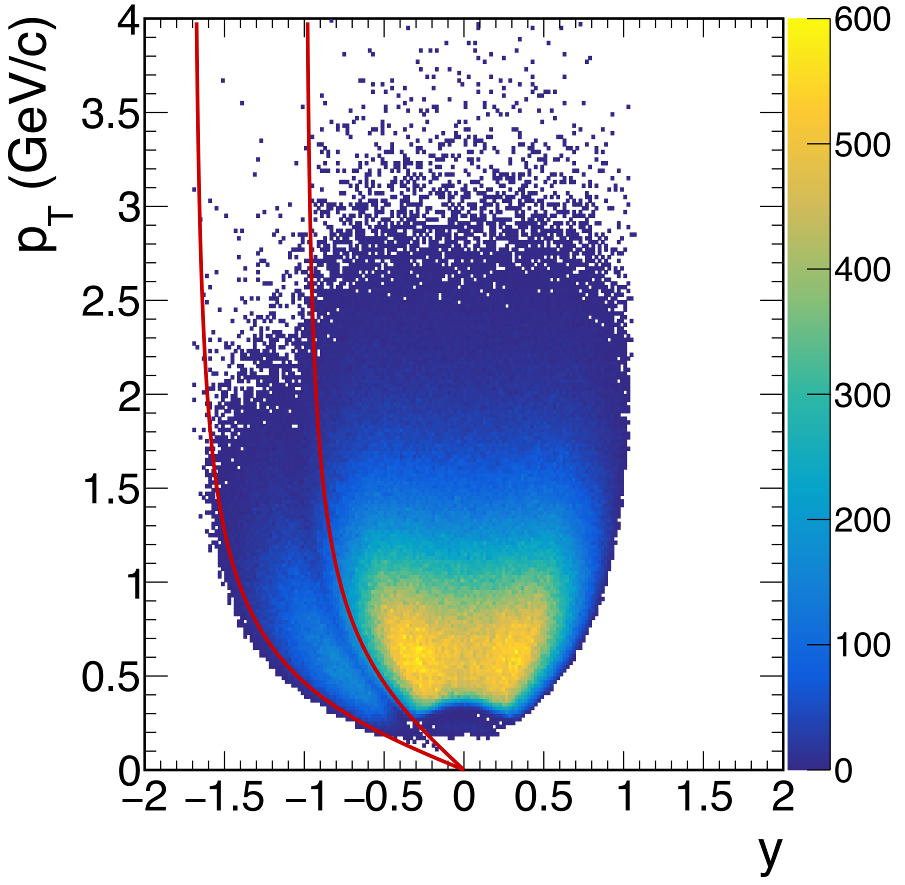


eToF calibration procedure:

- Time delays between channels
  - Local Y position (along strips)
  - T0 offsets (cable length etc.)
- Clock range & sync between eTOF and barrel time of flight
- Gain matching between different preamps
- Global position alignment
- ➢ **After calibration : Time resolution ~85 ps**

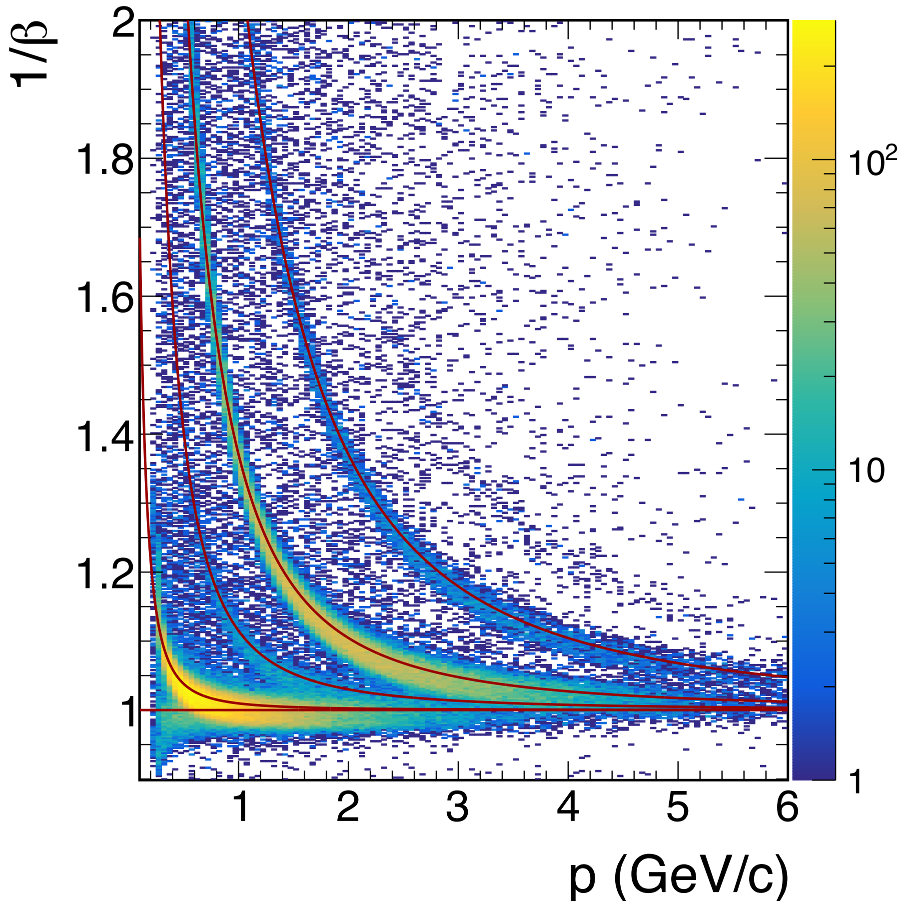
ETOF Performance in 2019 Running

Identified Protons : Au+Au 14.6 GeV



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

Particle Identification : Fixed Target test run



Achieved expected time resolution → particle bands are clearly distinguished over large momentum range

STAR Physics Program after BES II

➢ **STAR Upgrades for BES II → provide unique 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

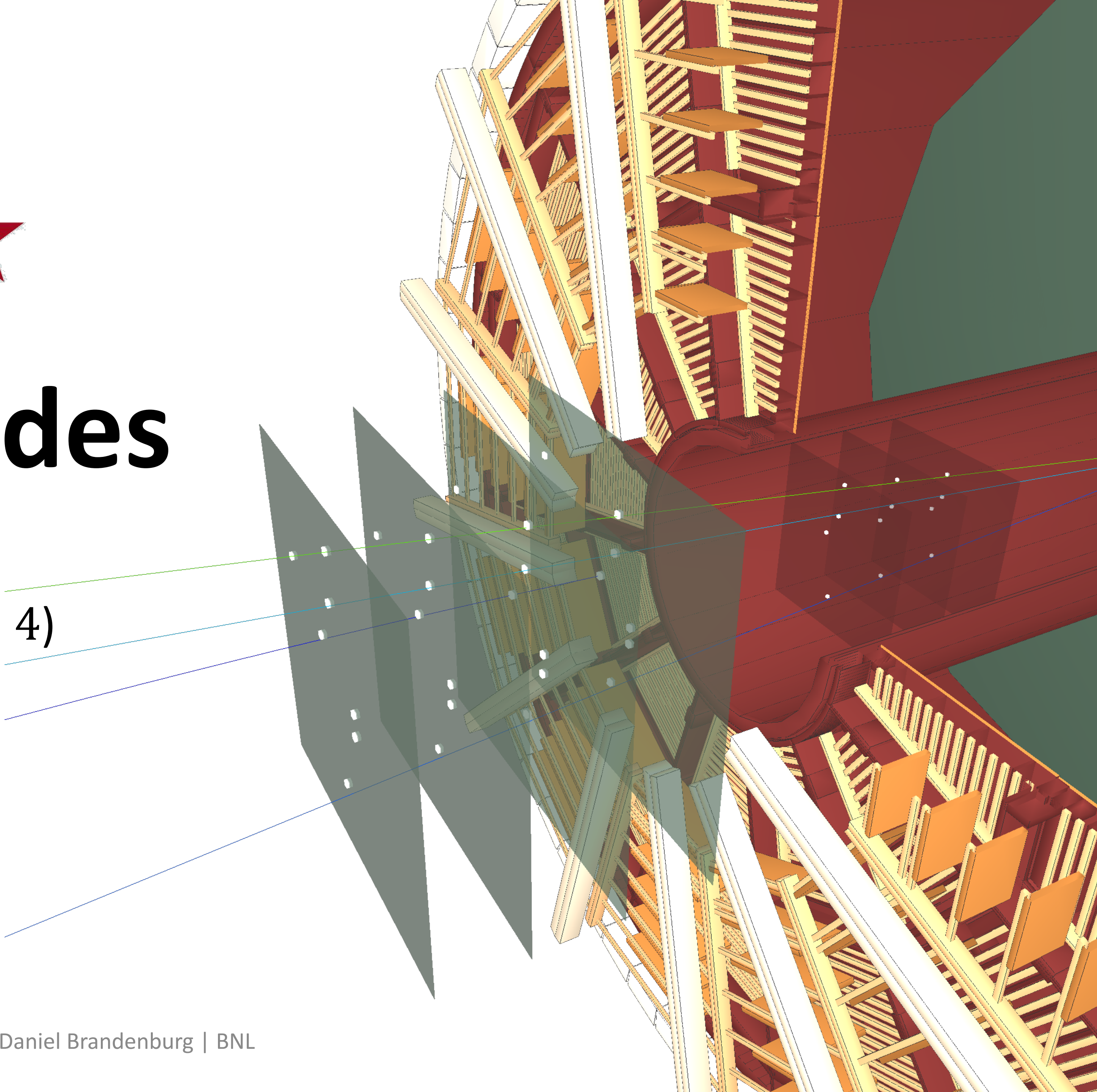
Physics Topics:
Improve statistical precision:

- 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 $\eta\sim4$
- Longitudinal decorrelation up to $\eta\sim4$
- Global Lambda Polarization → Test for strong rapidity dependence

p+A, p+p

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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

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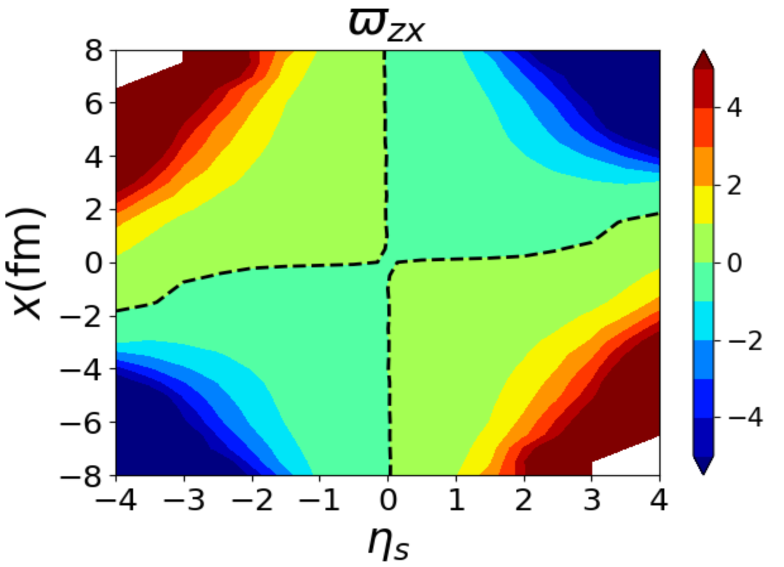
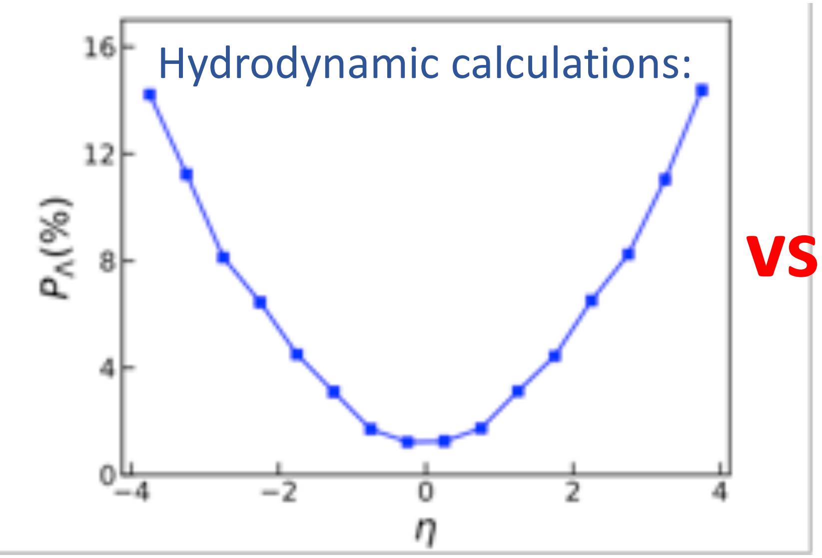
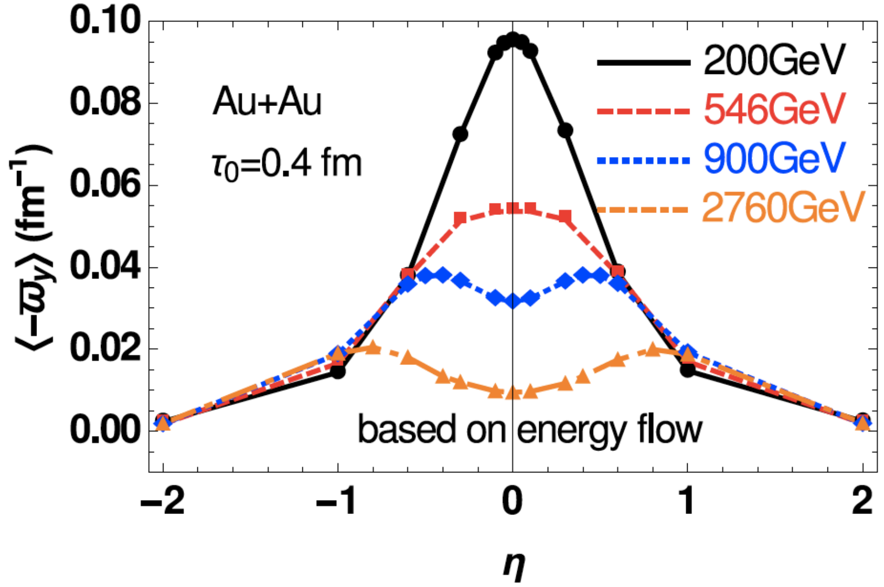
Global Hyperon Polarization

➢ Sensitive to <u>Thermalization</u> and <u>Viscosity</u>





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:

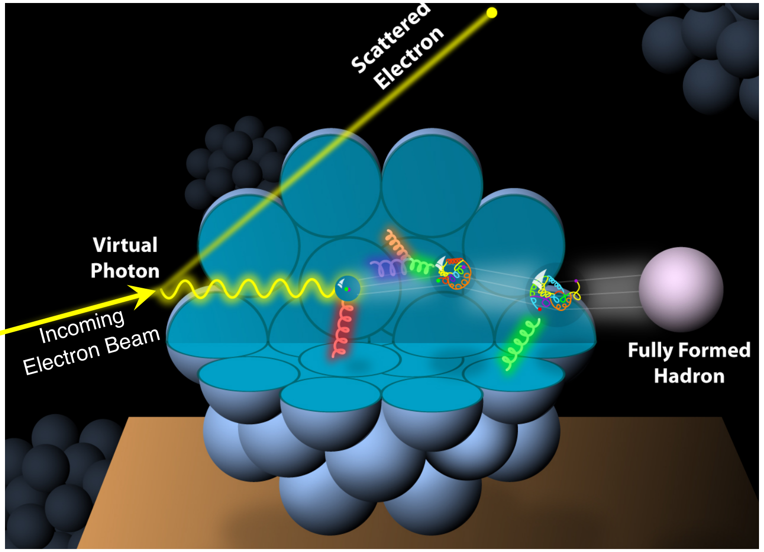
Deng & Huang, PRC 93 (2016) 064907

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

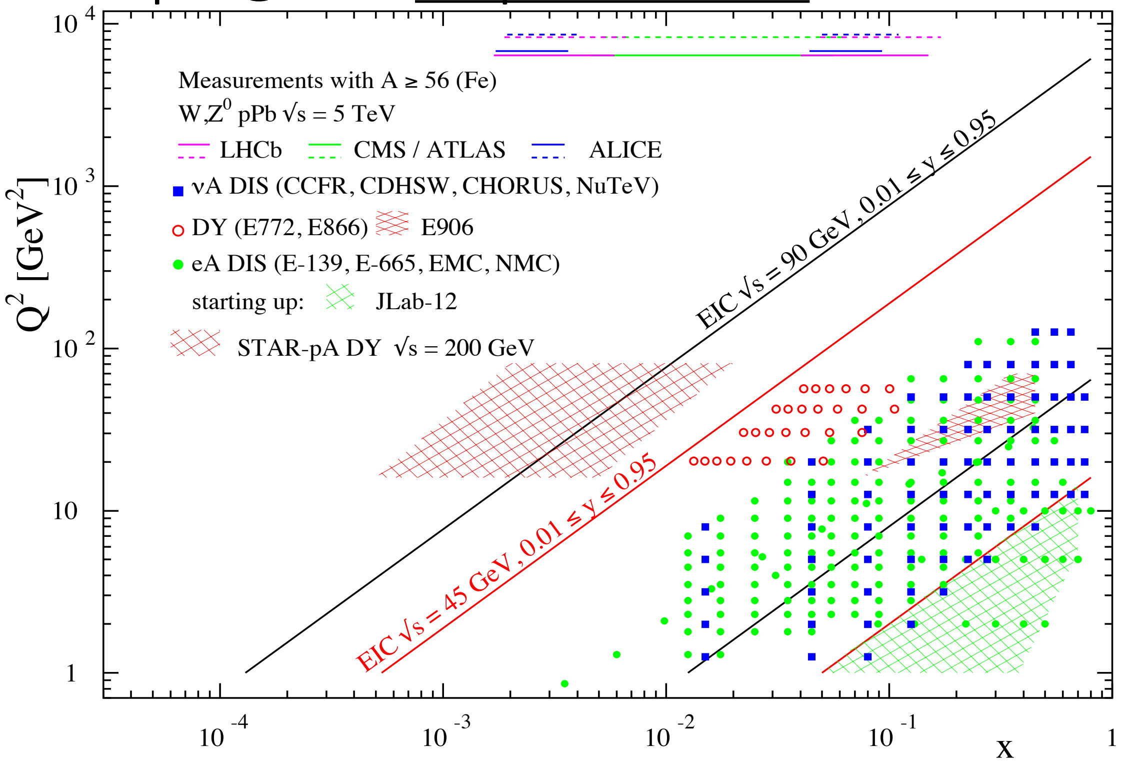
Probing the Initial State in A+A

➢ 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



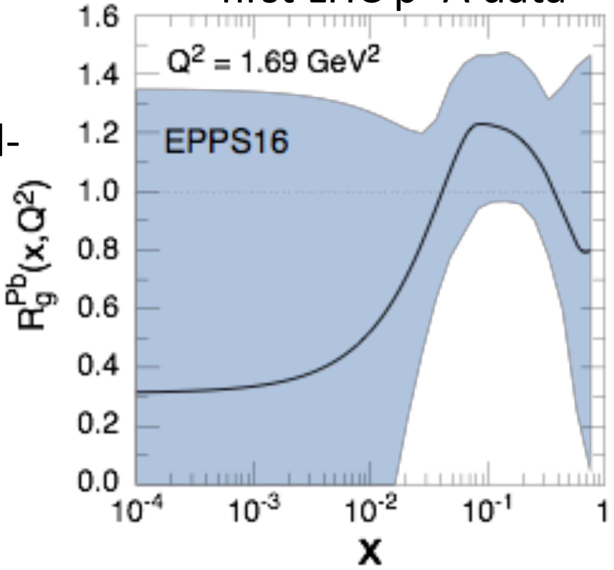
Observables free of final state effects:

- Gluons: R_{pA} for direct photons
- Sea-quarks: R_{pA} for Drell-Yan

➢ Scan A-dependence prediction by saturation models

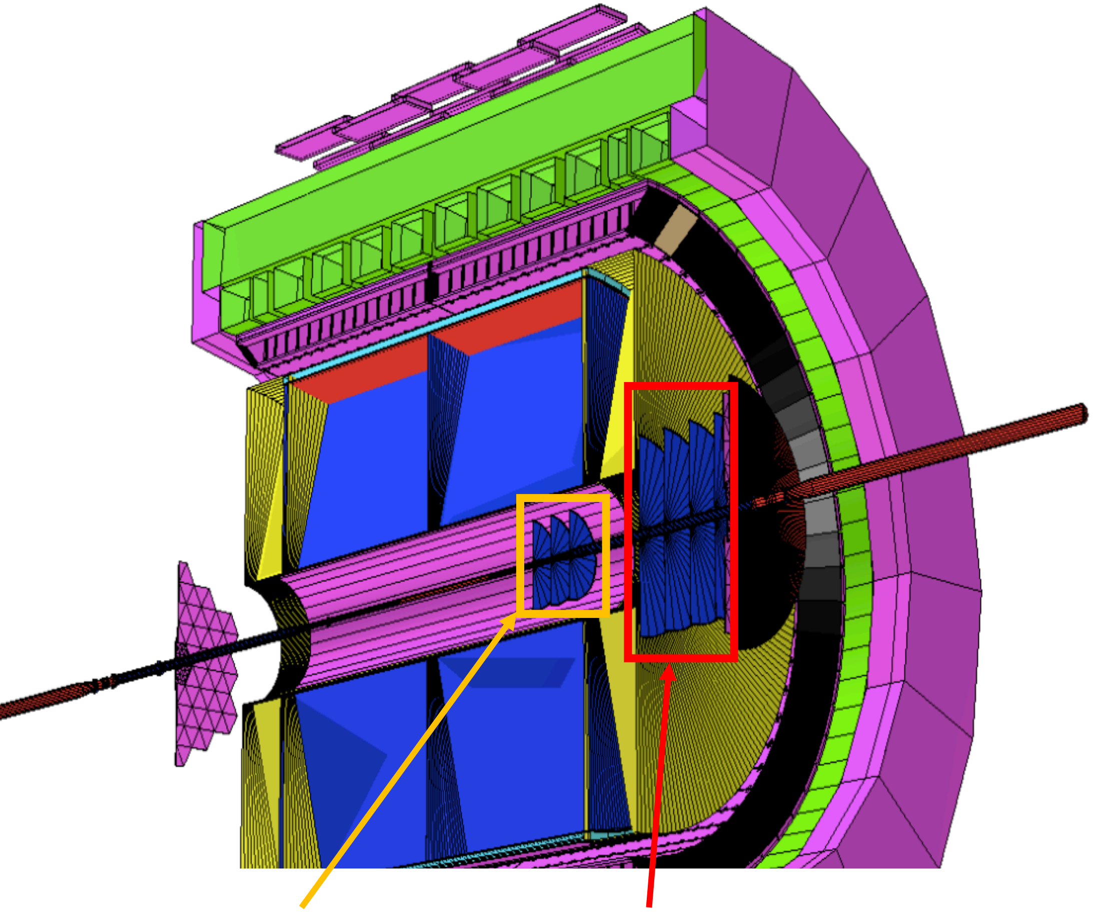
➢ Accessible at forward rapidity

Current knowledge including first LHC p+A data



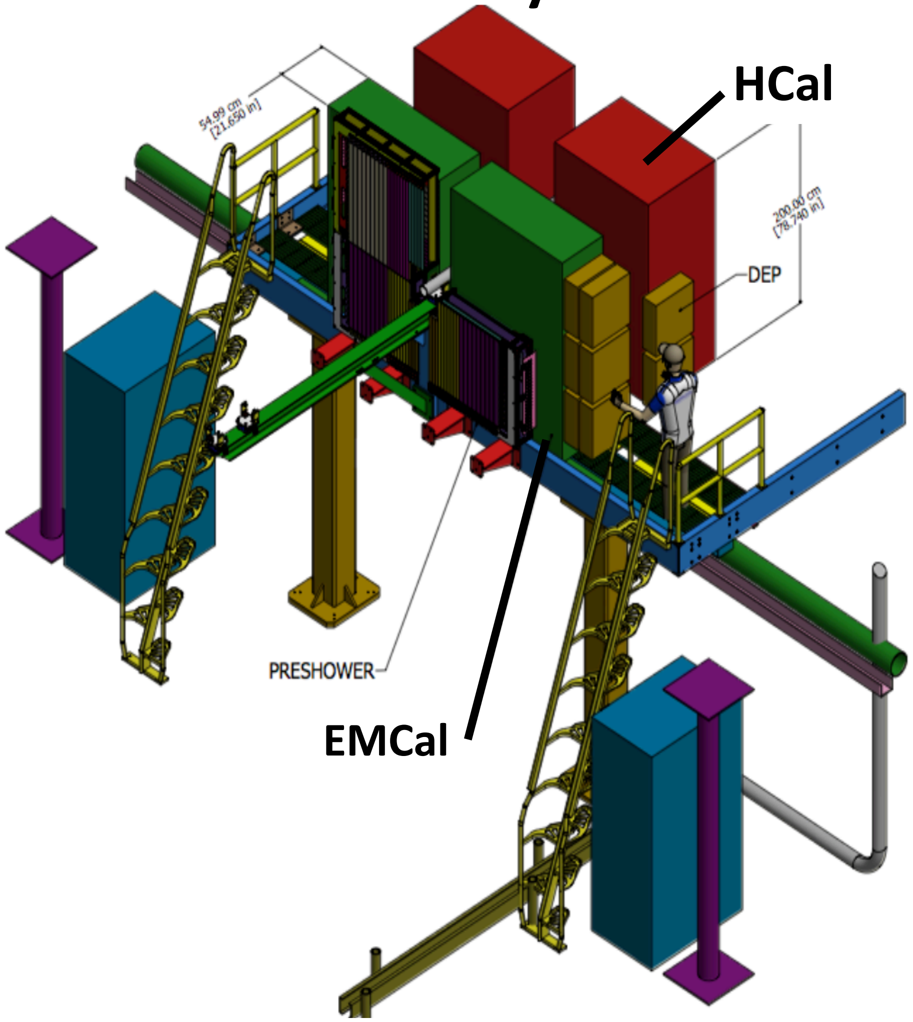
STAR Forward Detectors: FTS + FCS

Forward Tracking System



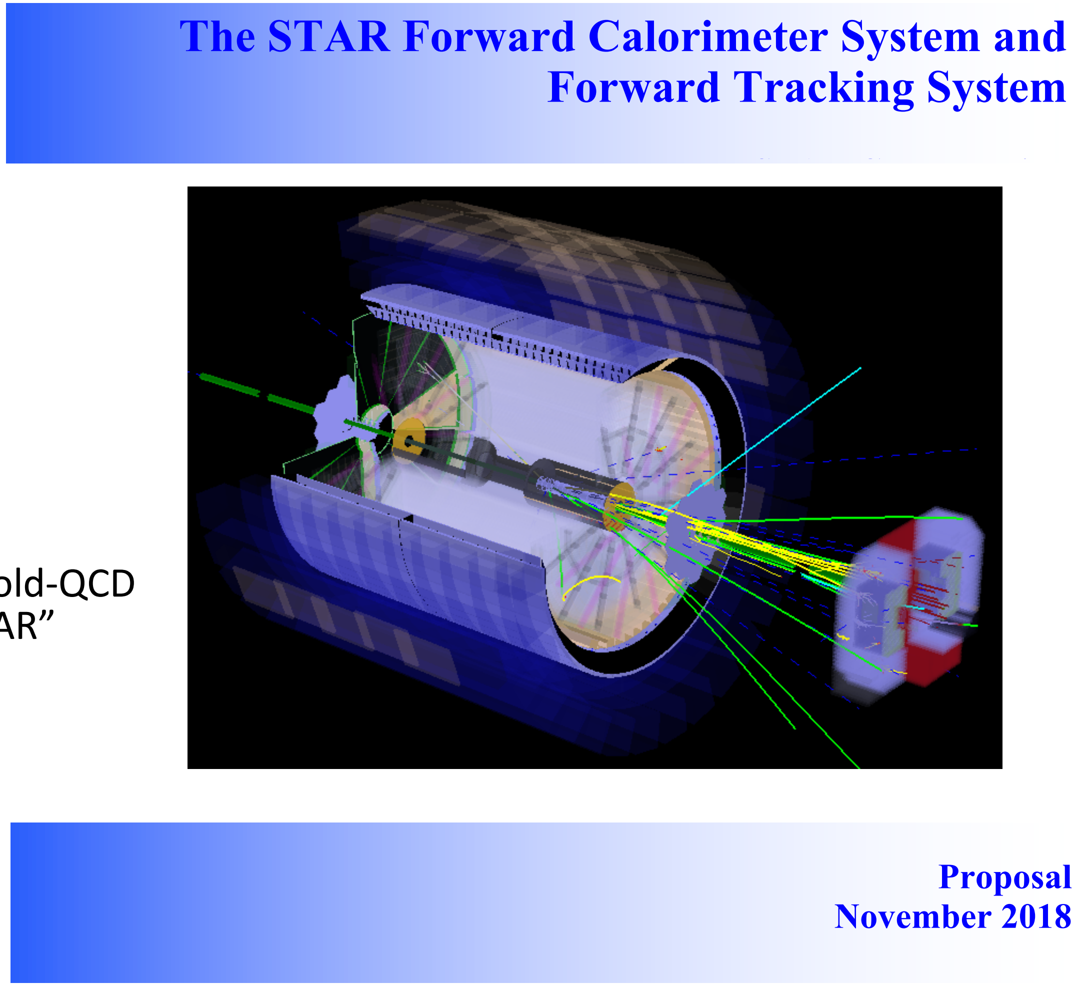
Silicon + small-Strip Thin Gap Chambers (sTGC)

Forward Calorimeter System



STAR Forward Upgrade Status

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



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”

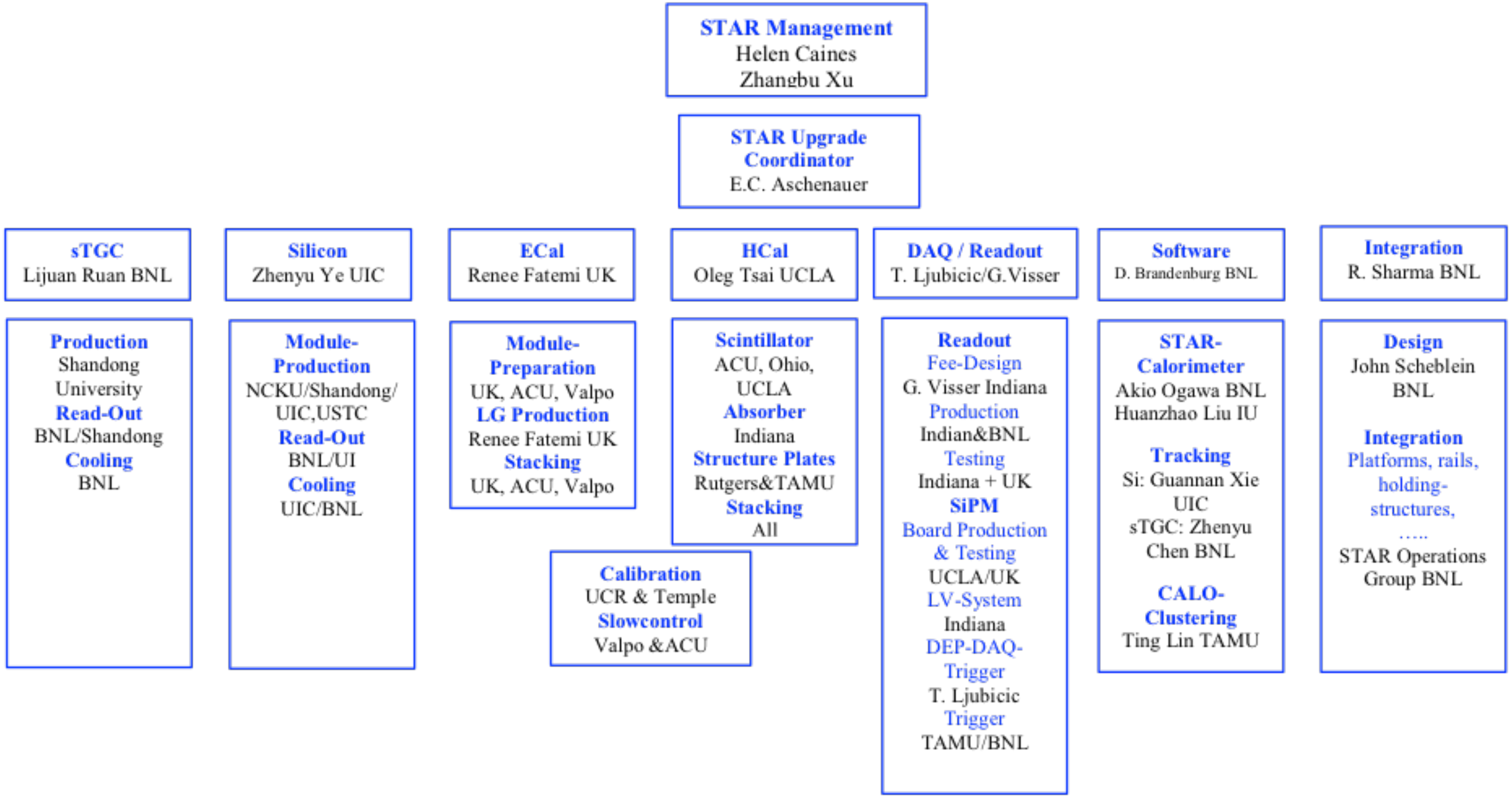
NSF proposal submitted Jan 2019

- Funding for Forward Calorimeter systems
- Received very positive feedback
- Awaiting final response – fully expect funding

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

Organizational Structure STAR Forward Upgrade

- Large project → Dedicated manpower & expertise for each system



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sTGC

- BROOKHAVEN NATIONAL LABORATORY
- 山东大学 SHANDONG UNIVERSITY

Silicon

- UIC UNIVERSITY OF ILLINOIS AT CHICAGO
- University of Science and Technology of China
- INDIANA UNIVERSITY
- BROOKHAVEN NATIONAL LABORATORY
- 山东大学 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 UNIVERSITY

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

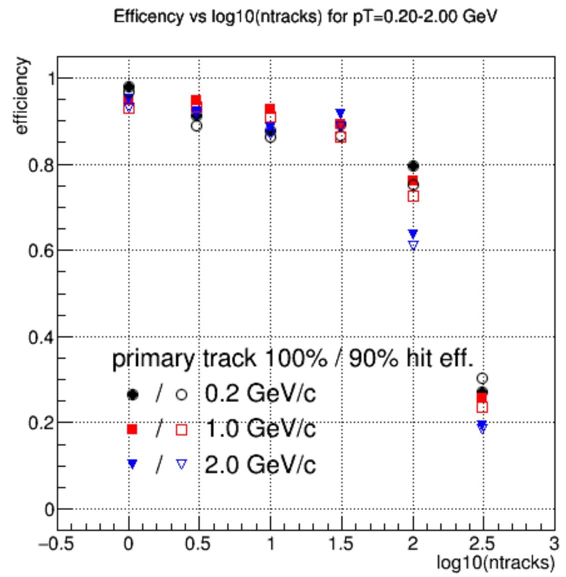
- VALPARAISO UNIVERSITY
- ABILENE CHRISTIAN UNIVERSITY

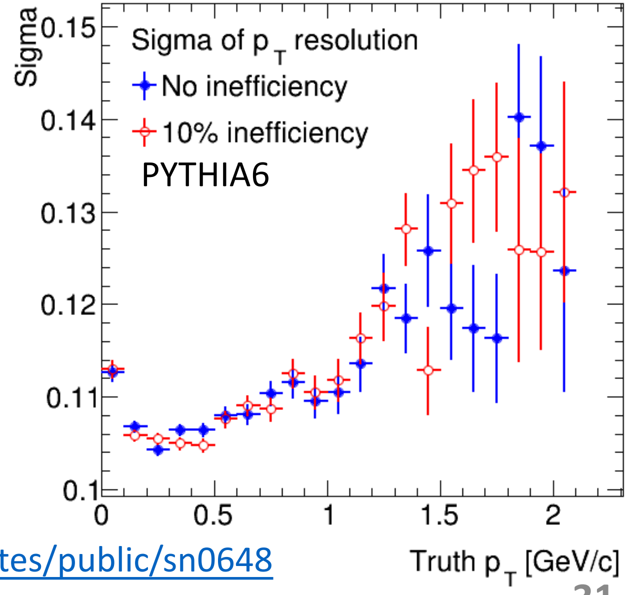
Details : Forward Tracking System

- Forward Tracking Requirements:
  - Momentum resolution: <30% in $0.2 < p_T < 2$ GeV/c (A+A goals)
  - Tracking efficiency: 80% at 100 tracks/event (A+A goals)
  - Charge separation (p+p /p+A)

- Silicon mini-strip disks $\times$3 layers
  - Location from interaction point : z = 90, 140, 187 cm
  - Build on and utilize STAR experience of successful Intermediate Silicon Tracker(IST) detector
- Small-Strip Thin Gap Chamber (sTGC) $\times$4
  - Location from interaction point : z = 270, 300, 330, 360 cm
  - Significant reduction in cost
  - Prototype at BNL, testing in STAR during 2019 run

Simulation Results



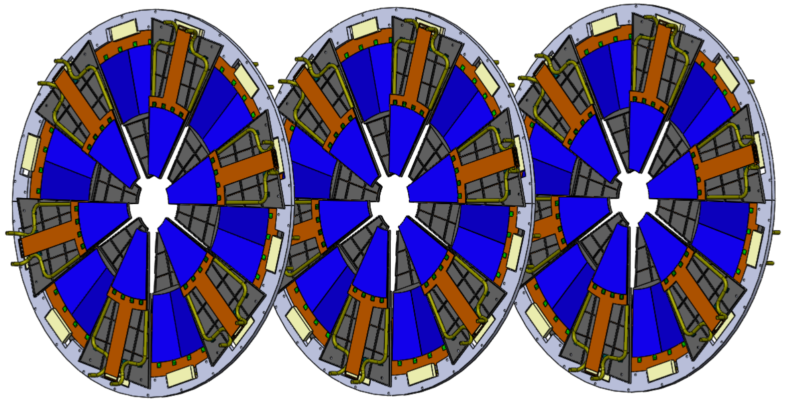


https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

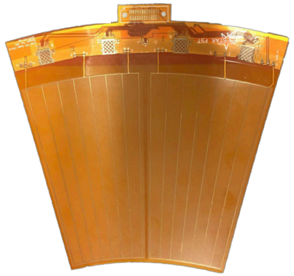
Forward Tracking System Current Status

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



Outer hybrid



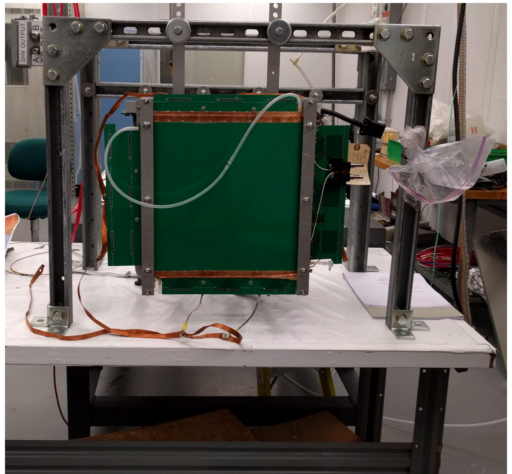
Inner hybrid

sTGC Detector

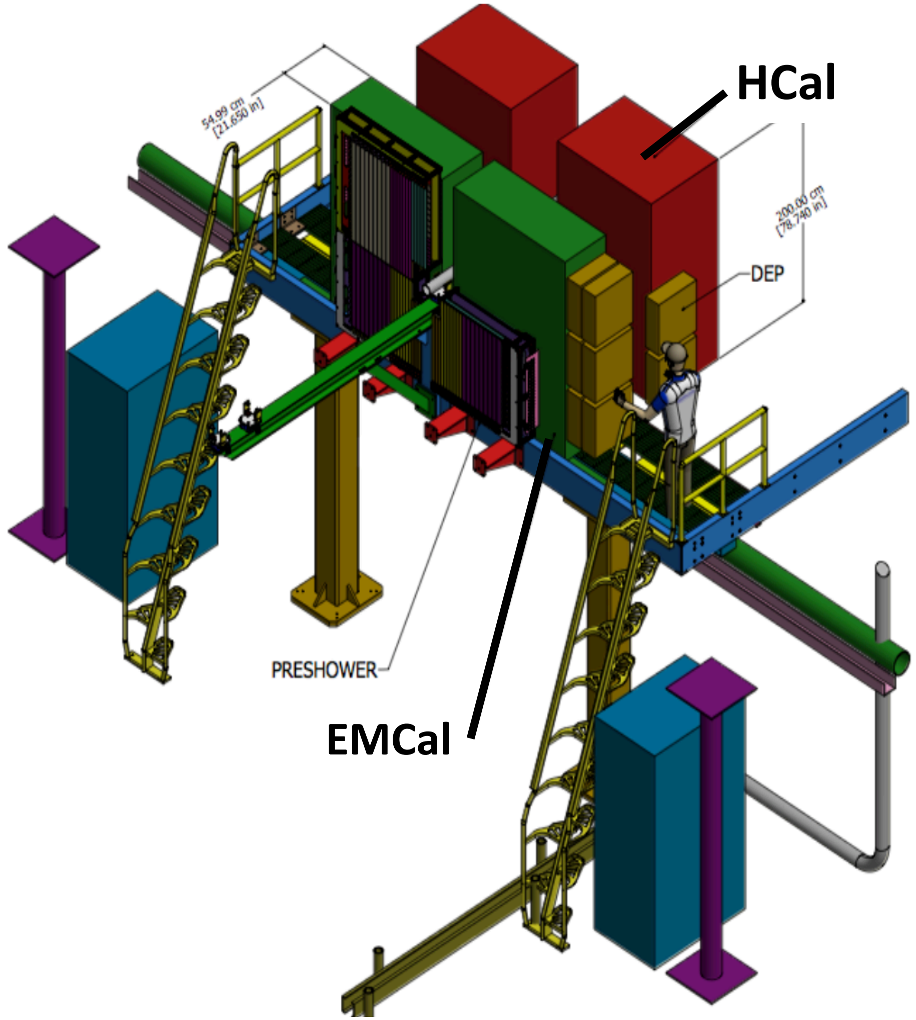
- 30x30 cm prototype delivered to BNL in January 2019
- Module tested in test-stand using cosmic rays + scintillator pads for trigger
- Connected to STAR Data Acquisition system – first test data being analyzed now
- Installed in STAR on June 5, 2019
- Full-size 60x60 cm prototype being produced at Shandong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

Prototype in STAR Clean Room,

On the Mounting Structure



Details : Forward Calorimeter System



FCS Requirements

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

Electromagnetic Calorimeter
- Use PHENIX PbSc
- New readout SiPM/APD

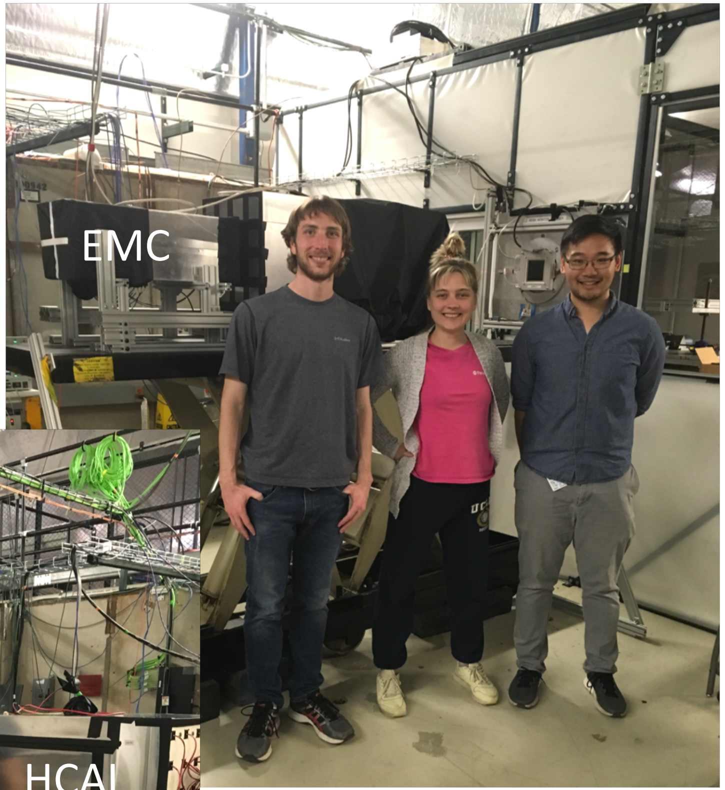
Hadronic Calorimeter
- Sampling iron-scintillator
- Uses same readout as EMC

R&D in support of EIC
→ HCal development
→ All readout electronics
→ Balance Cost & performance

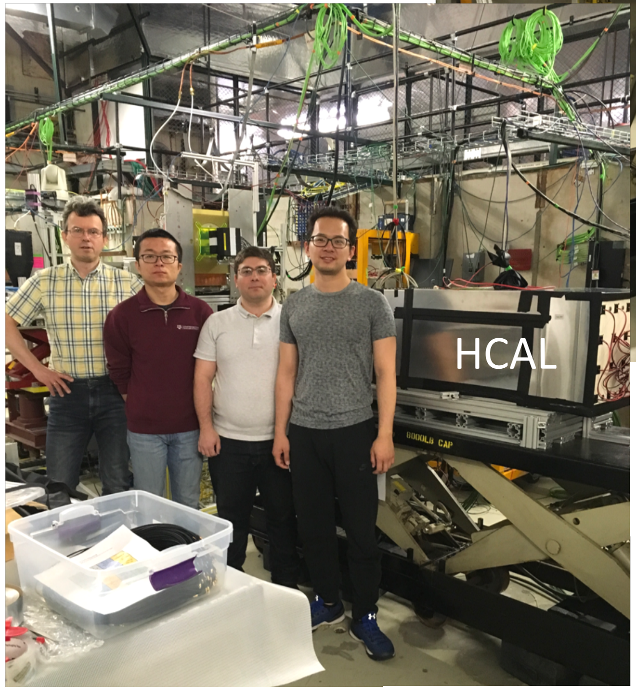
Large scale test run at Fermilab:
- 16 Ch HCAL, 16 Ch EMcal, DAQ etc. delivered to Fermilab in April
- Planned Tests:
  - Test new FEEs
  - Test HCal response to e/h/mips
  - Test HCal calibration using mips (muon beam)
- All test completed as planned

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
  - Pedestal
  - LED
  - Physics runs
- Online + slow controls + offline software being developed



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



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

D. Chen (UCR)
G. Visser (IUCF)
O. Tsai (UCLA)

Looking Forward

Measurements planned for 2021+ with the STAR forward upgrade

$\sqrt{s}$ (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

Addresses important topics in hot and cold QCD:

- 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

Looking Forward

Future A+A Measurements with the STAR forward upgrade

Physics Measurements: Detectors	Physics Measurements: Acceptance	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
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 $\eta\sim4$

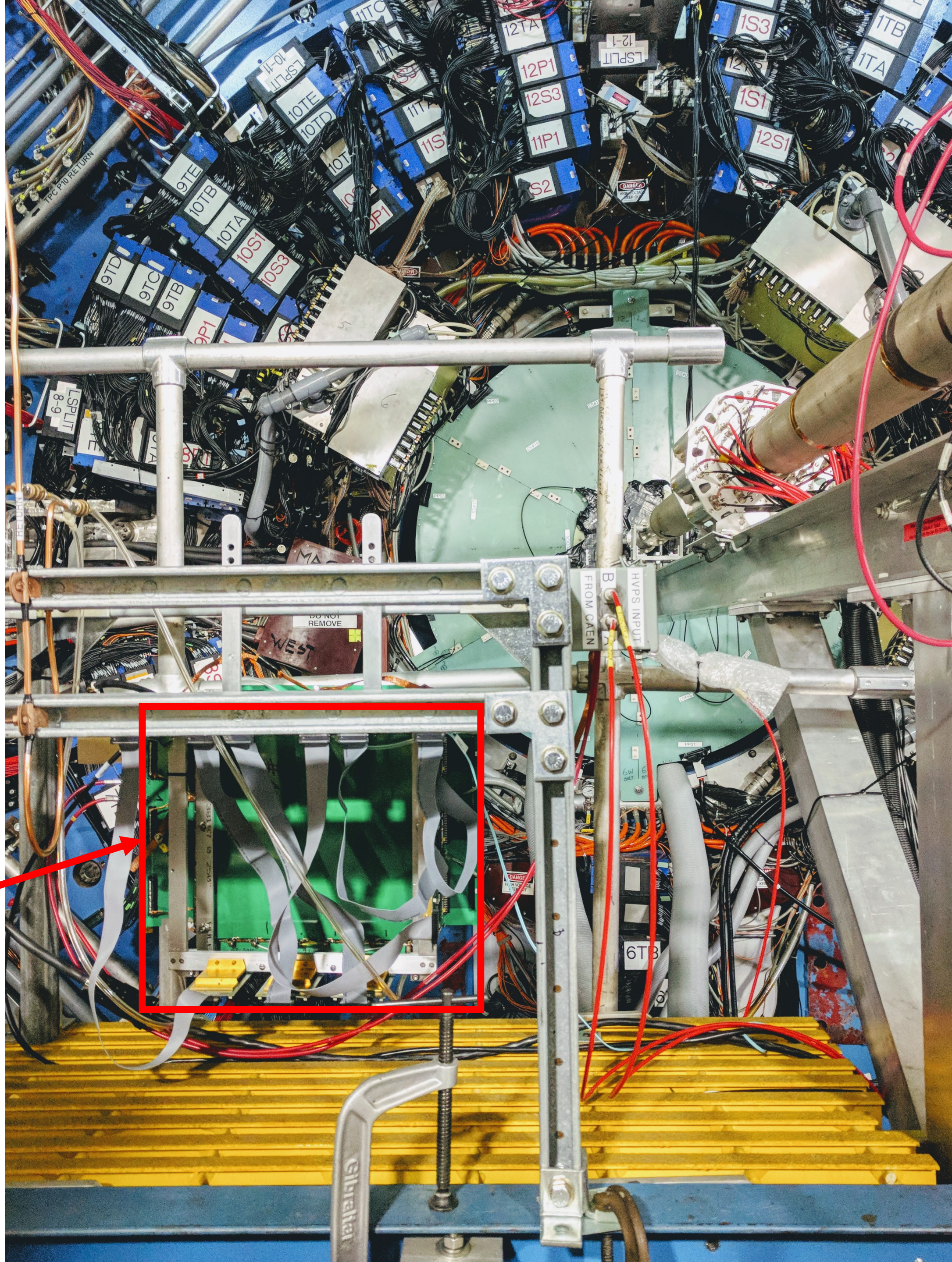
Plan/Goals for Run 19

Forward Calorimeter System

- 10-20 hours of Au+Au 200 GeV collisions (taken during APEX running)
  - Test readout of calorimeters at ~ 10kHz rate
  - Finish commissioning of DEP (digitizer/trigger) boards with this data
  - Look at MIPS – use for calibration etc.

Forward Tracking System

- Silicon Detectors
  - Complete the design of detector module in June 2019
  - Build the first complete prototype module in Summer/Fall 2019
  - Fully test the prototype module in Fall/Winter 2019
- sTGC Detectors
  - 30x30 cm prototype installed in STAR on June 5th, 2019
  - Test in STAR DAQ with C10 (90% argon + 10% CO_2)
  - Test performance with various gas mixtures at Shandong University in full size (60 x 60 cm) prototypes



Summary

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:

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

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

➢ Forward Tracking System : Silicon + small-Strip Thin Gap Chambers
  - ➢ sTGC prototype delivered by SDU and being tested at BNL
  - ➢ Silicon design and R&D at UIC + NCKU

➢ Forward Calorimetry System : EMCal + Hcal
  - ➢ Large scale prototype testing at Fermilab