sPHENIX Highlights:

First Results from sPHENIX

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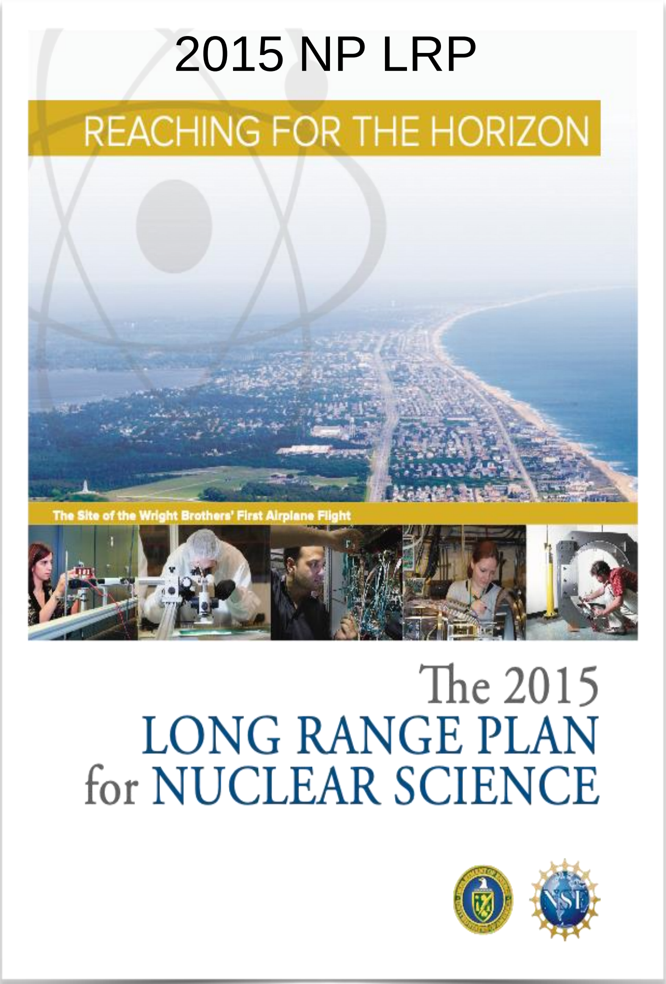
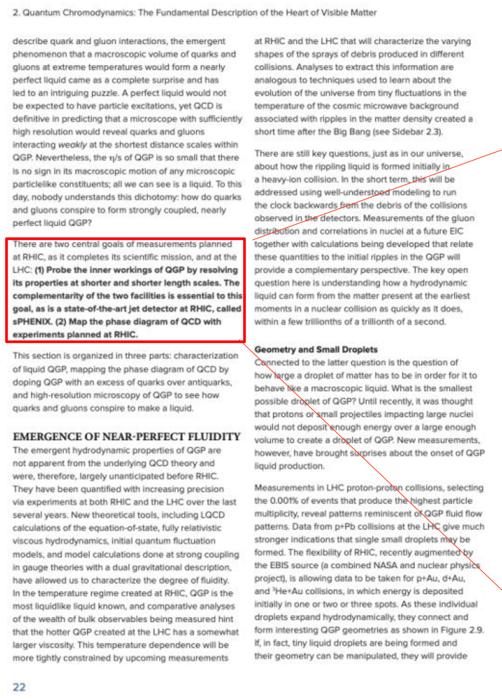
Brookhaven National Laboratory

SQM 2024

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

sPHENIX Science Mission





2. Quantum Chromodynamics: The Fundamental Description of the Heart of Visible Matter

describe quark and gluon interactions, the emergent phenomenon that a macroscopic volume of quarks and gluons at extreme temperatures would form a nearly perfect liquid came as a complete surprise and has led to an intriguing puzzle. A perfect liquid would not be expected to have particle excitations, yet QCD is definitive in predicting that a microscope with sufficiently high resolution would reveal quarks and gluons interacting *weakly* at the shortest distance scales within QGP. Nevertheless, the η/s of QGP is so small that there is no sign in its macroscopic motion of any microscopic particlelike constituents; all we can see is a liquid. To this day, nobody understands this dichotomy: how do quarks and gluons conspire to form strongly coupled, nearly perfect liquid QGP?

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

This section is organized in three parts: characterization of liquid QGP, mapping the phase diagram of QCD by doping QGP with an excess of quarks over antiquarks, and high-resolution microscopy of QGP to see how quarks and gluons conspire to make a liquid.

EMERGENCE OF NEAR-PERFECT FLUIDITY

The emergent hydrodynamic properties of QGP are not apparent from the underlying QCD theory and were, therefore, largely unanticipated before RHIC. They have been quantified with increasing precision via experiments at both RHIC and the LHC over the last several years. New theoretical tools, including LQCD calculations of the equation-of-state, fully relativistic viscous hydrodynamics, initial quantum fluctuation models, and model calculations done at strong coupling in gauge theories with a dual gravitational description, have allowed us to characterize the degree of fluidity. In the temperature regime created at RHIC, QGP is the most liquidlike liquid known, and comparative analyses of the wealth of bulk observables being measured hint that the hotter QGP created at the LHC has a somewhat larger viscosity. This temperature dependence will be more tightly constrained by upcoming measurements at RHIC and the LHC that will characterize the varying shapes of the sprays of debris produced in different collisions. Analyses to extract this information are analogous to techniques used to learn about the evolution of the universe from tiny fluctuations in the temperature of the cosmic microwave background associated with ripples in the matter density created a short time after the Big Bang (see Sidebar 2.3).

There are still key questions, just as in our universe, about how the rippling liquid is formed initially in a heavy-ion collision. In the short term, this will be addressed using well-understood modeling to run the clock backwards from the debris of the collisions observed in the detectors. Measurements of the gluon distribution and correlations in nuclei at a future EIC together with calculations being developed that relate these quantities to the initial ripples in the QGP will provide a complementary perspective. The key open question here is understanding how a hydrodynamic liquid can form from the matter present at the earliest moments in a nuclear collision as quickly as it does, within a few trillionths of a trillionth of a second.

Geometry and Small Droplets

Connected to the latter question is the question of how large a droplet of matter has to be in order for it to behave like a macroscopic liquid. What is the smallest possible droplet of QGP? Until recently, it was thought that protons or small projectiles impacting large nuclei would not deposit enough energy over a large enough volume to create a droplet of QGP. New measurements, however, have brought surprises about the onset of QGP liquid production.

Measurements in LHC proton-proton collisions, selecting the 0.001% of events that produce the highest particle multiplicity, reveal patterns reminiscent of QGP fluid flow patterns. Data from p+Pb collisions at the LHC give much stronger indications that single small droplets may be formed. The flexibility of RHIC, recently augmented by the EBIS source (a combined NASA and nuclear physics project), is allowing data to be taken for p+Au, d+Au, and ^{3}He+Au collisions, in which energy is deposited initially in one or two or three spots. As these individual droplets expand hydrodynamically, they connect and form interesting QGP geometries as shown in Figure 2.9. If, in fact, tiny liquid droplets are being formed and their geometry can be manipulated, they will provide

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https://inspirehep.net/literature/1398831

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2015 US NP LRP

sPHENIX recognized by the U.S. Nuclear Physics community as the *essential* tool for QGP microscopy at RHIC.

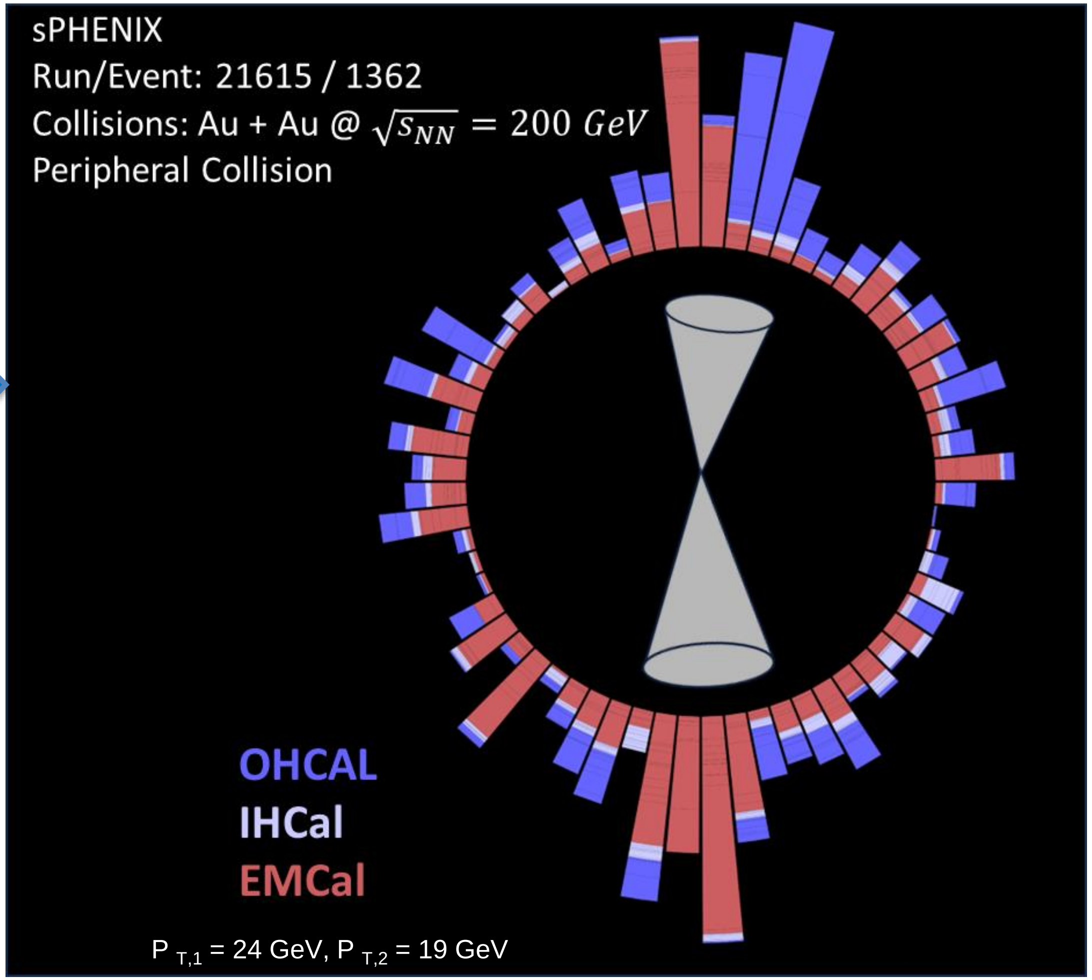
sPHENIX Science Mission

- sPHENIX is a new state-of-the-art detector constructed 2015/2023 at BNL/RHIC.

- It was commissioned and took first Au+Au collisions data in the RHIC Run-2023:
  → First full calorimeter jets observation at RHIC

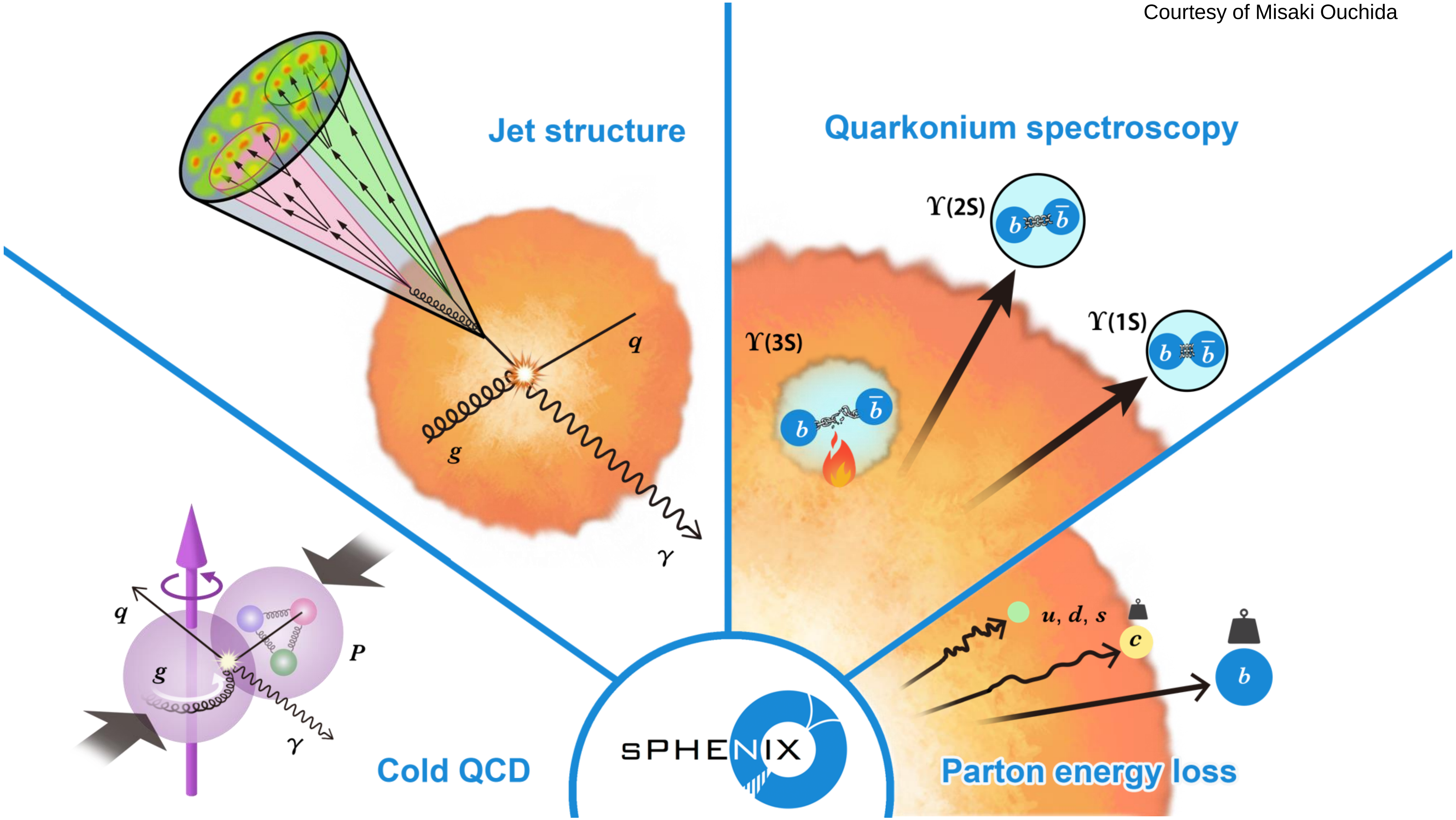
- Fundamental questions on the nature of the QGP, including its coupling strength and temperature dependence, by using precision jet and upsilon measurements probing different length scales of QGP.

- With the increased RHIC's luminosity, sPHENIX will perform high statistics measurements extending the kinematic reach at RHIC to overlap the LHC's.



Pillars of sPHENIX Scientific Program

Courtesy of Misaki Ouchida



Detector design, computing effort and run schedule focused on these physics goals

Run Plan to Achieve Physics Goals

- Run-2024: transversely polarized *p+p* running, with a few options for short Au+Au running:

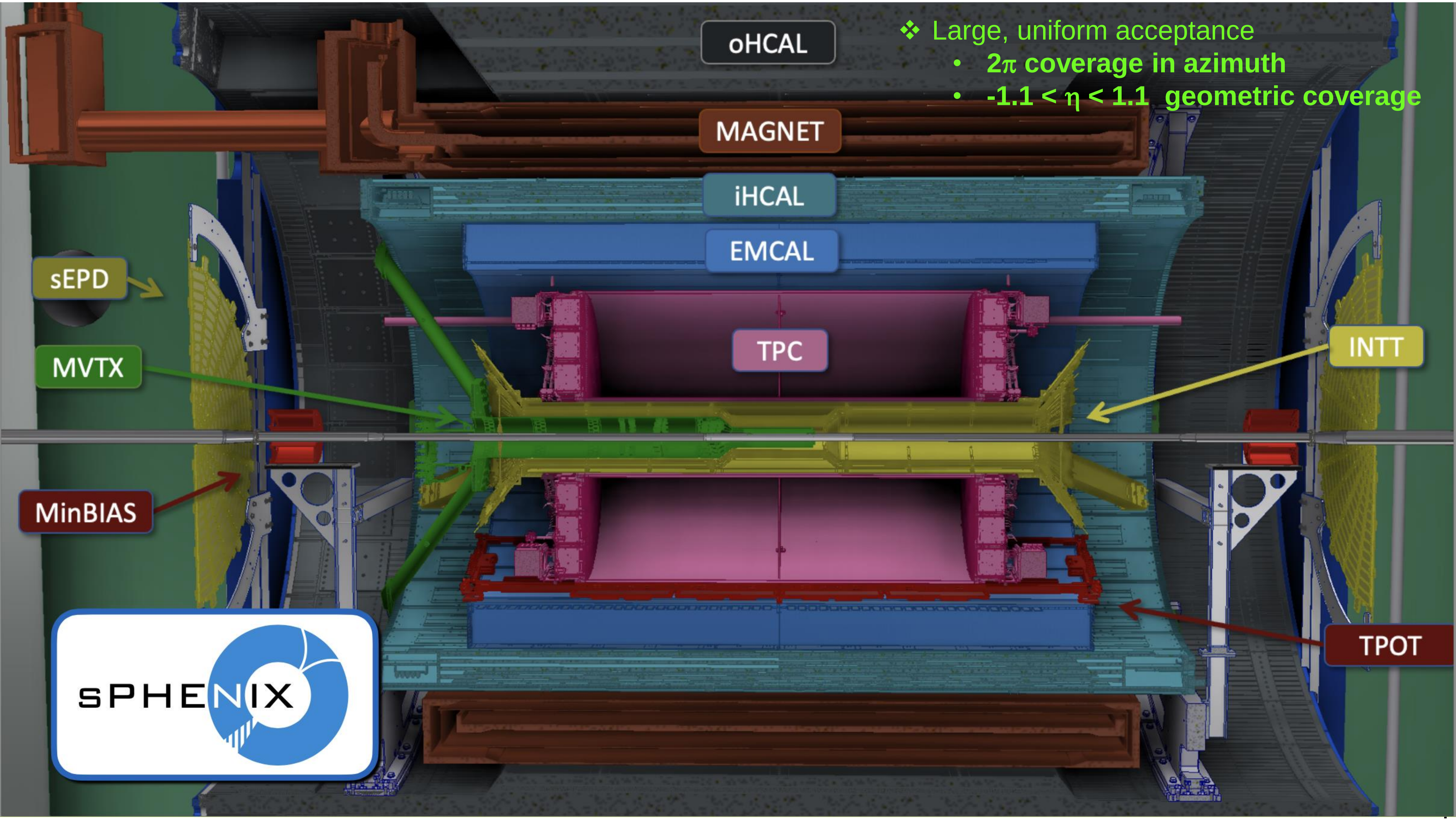
  → finish commissioning, ColdQCD *p+p* program,
  crucial reference data for AA program

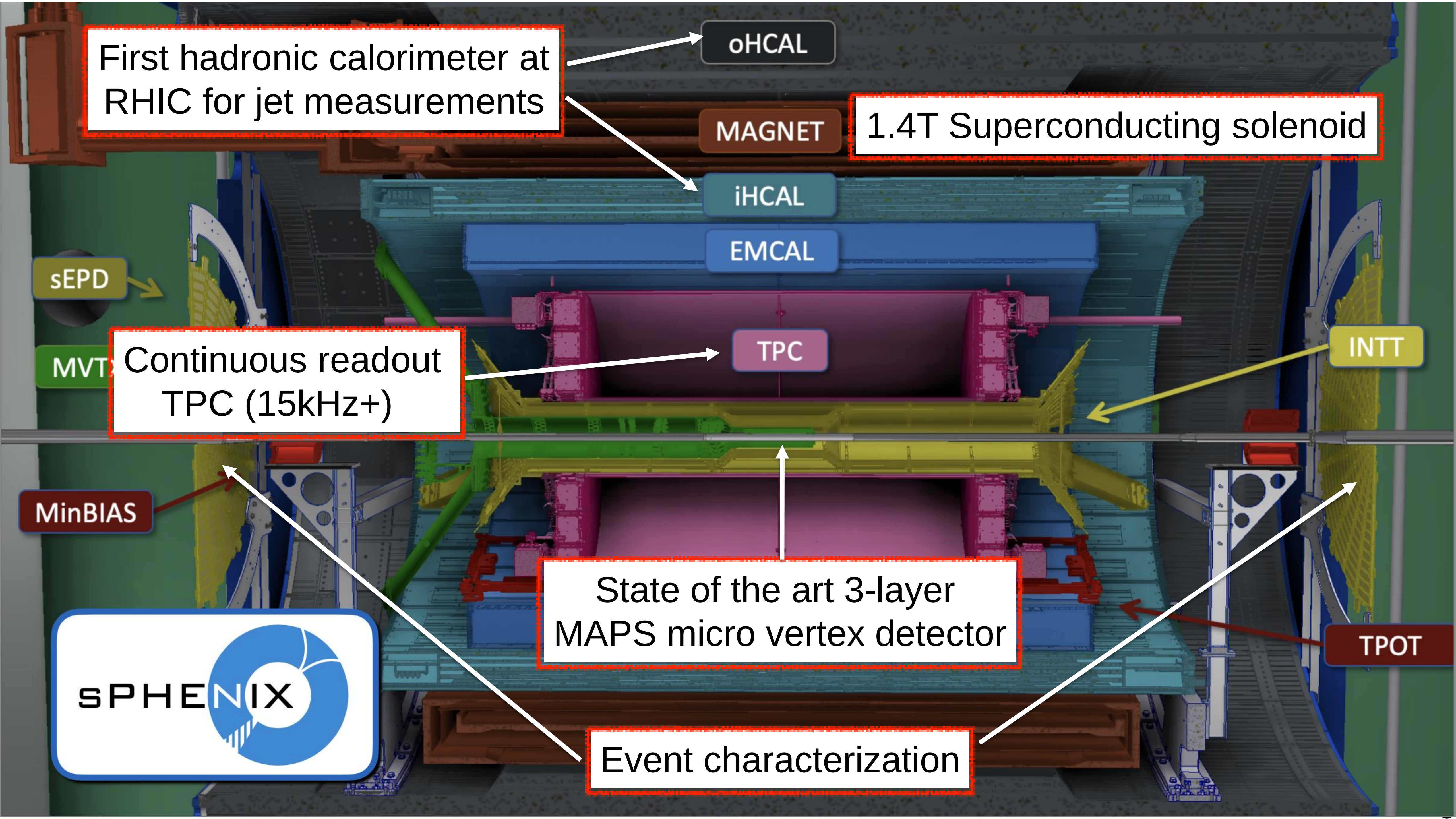
- Run-2025: high-luminosity Au+Au running measurements of jets and heavy flavor observables with unprecedented statistical precision

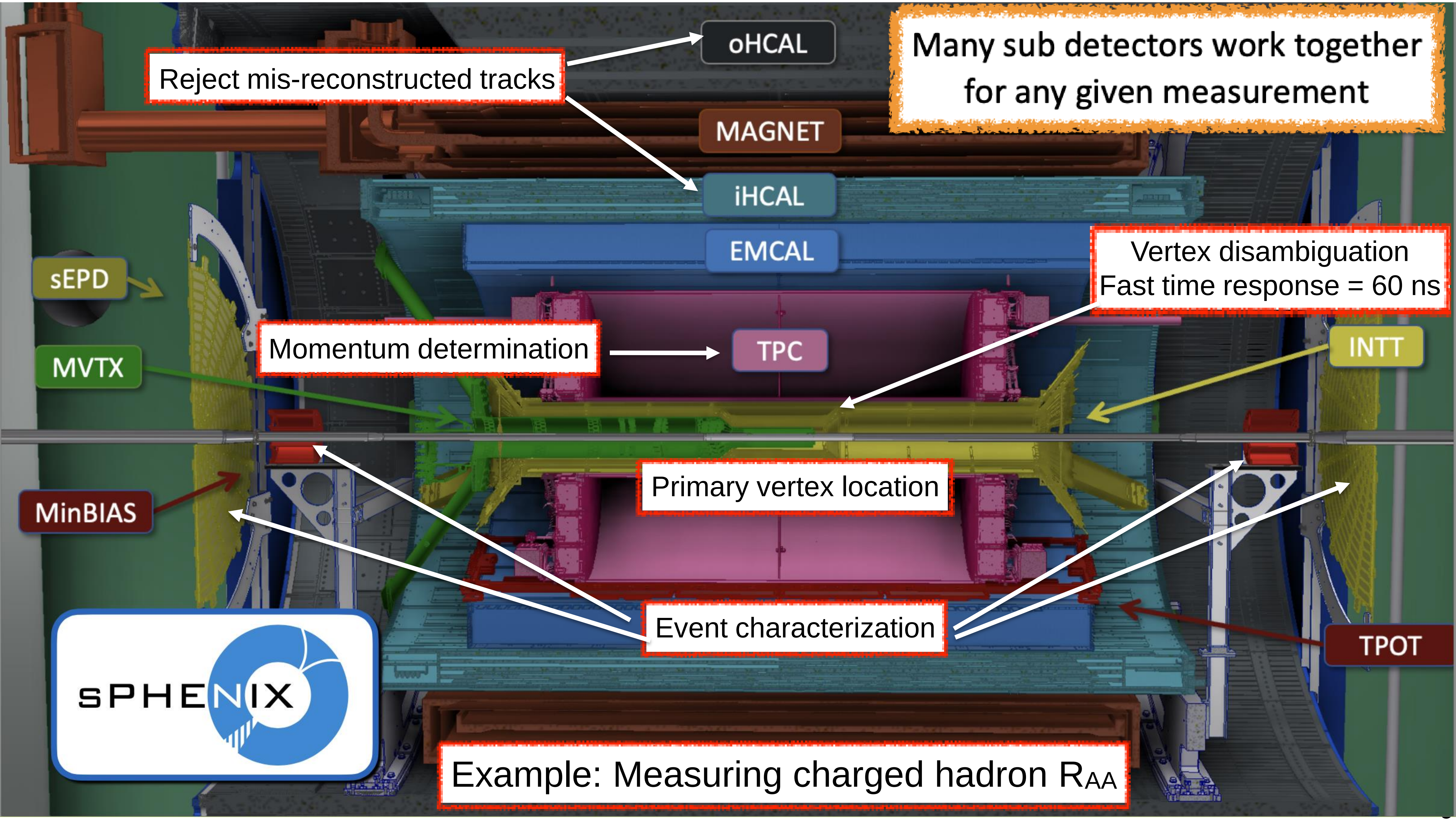
Year	Cryo-weeks	Species	Goal
2023	11.5	Au+Au	Start of commissioning
2024	25	*p+p* (at least 19 weeks) Au+Au	Finish commissioning, reference data & ColdQCD
2025	28	Au+Au	High-statistics jet and heavy-flavor QGP probes
2026	28	*p*+Au, *p+p* O+O, Ar+Ar	Small systems
2027	28	…	Additional unique sPHENIX opportunities!

sPHENIX Detector

sPHENIX has a large-acceptance, high-rate detector optimized to measure jet and heavy quark physics in HI collisions by incorporating **Hadronic** and **EM Calorimetry**, a **Time Projection Chamber**, a **Micromegas detector**, **Silicon Strip** and **Pixel detectors**, **Event Plane** detector, plus **Trigger detectors** with a **high rate DAQ/Trigger** and a **1.4 T solenoidal magnetic field**.

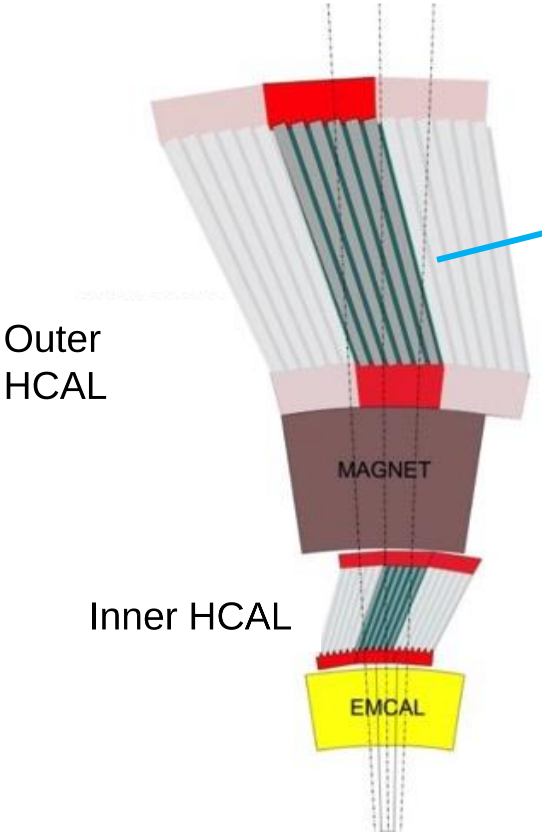

❖ Large, uniform acceptance
• 2π coverage in azimuth
• -1.1 < η < 1.1 geometric coverage
oHCAL
MAGNET
iHCAL
EMCAL
TPC
sEPD
MVTX
INTT
MinBIAS
TPOT
sPHENIX

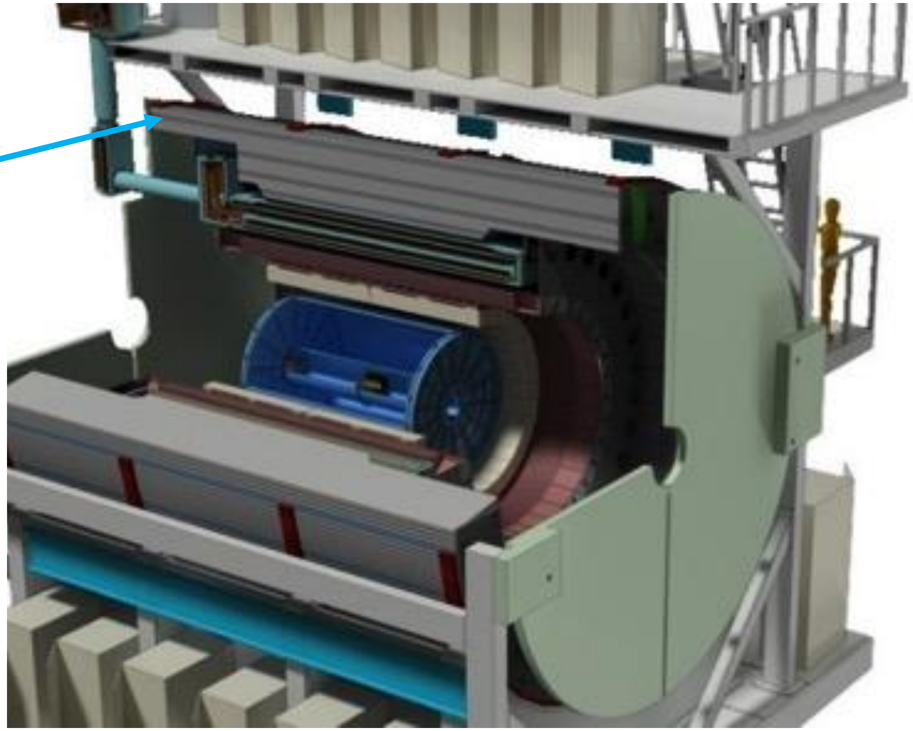

First hadronic calorimeter at RHIC for jet measurements
oHCAL
MAGNET
1.4T Superconducting solenoid
iHCAL
EMCAL
sEPD
TPC
Continuous readout TPC (15kHz+)
INTT
MinBIAS
State of the art 3-layer MAPS micro vertex detector
TPOT
sPHENIX
Event characterization



Many sub detectors work together for any given measurement
oHCAL
Reject mis-reconstructed tracks
MAGNET
iHCAL
EMCAL
Vertex disambiguation
Fast time response = 60 ns
sEPD
Momentum determination
TPC
MVTX
INTT
Primary vertex location
MinBIAS
Event characterization
TPOT
sPHENIX
Example: Measuring charged hadron R_{AA}

Hadronic Calorimeters (HCal = oHCal + iHCal)





Calorimetry has become a well-understood, powerful, and versatile measurement method, and fits perfectly to achieve sPHENIX physics goals.

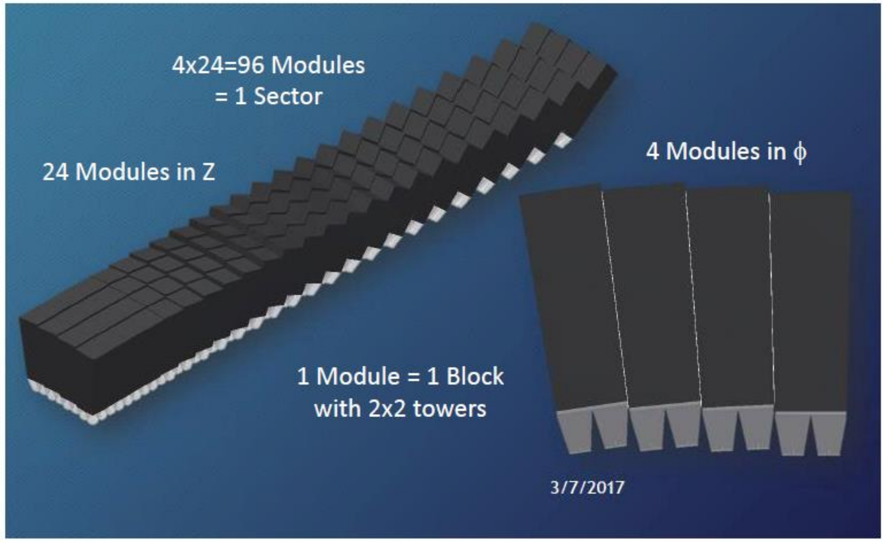
- Outer HCAL $\approx 3.5\lambda_I$
- Magnet $\approx 0.31\lambda_I$
- IHCal $\approx 0.25\lambda_I$
- EMCal $\approx 18X_0 \approx 0.7\lambda_I$

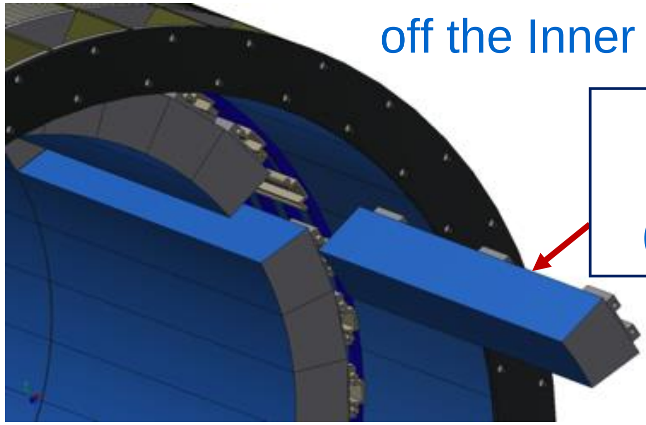
- OHCAL steel (IHCal aluminum) and scintillating tiles with wavelength shifting fiber
  - Outer HCal (outside the solenoid) and Inner HCal (inside the solenoid)
  - $\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$
  - 1,536 readout channels each
- SiPM Readout
- Uniform fiducial acceptance: $-1.1 < \eta < 1.1$ and $0 < \phi < 2\pi$

ElectroMagnetic Calorimeter (EMCal)

- Blocks made of tungsten-powder/epoxy composite encasing ~ 2500 scintillating fibers/block
- Aluminum support mechanics
- Sectors and blocks are approximately projective and tiled in η and ϕ

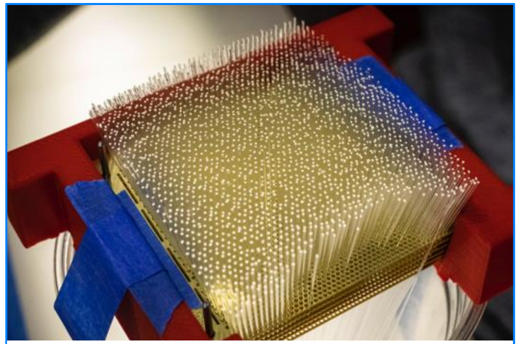
Electromagnetic calorimeter covering ± 1.1 in η and 2π in ϕ





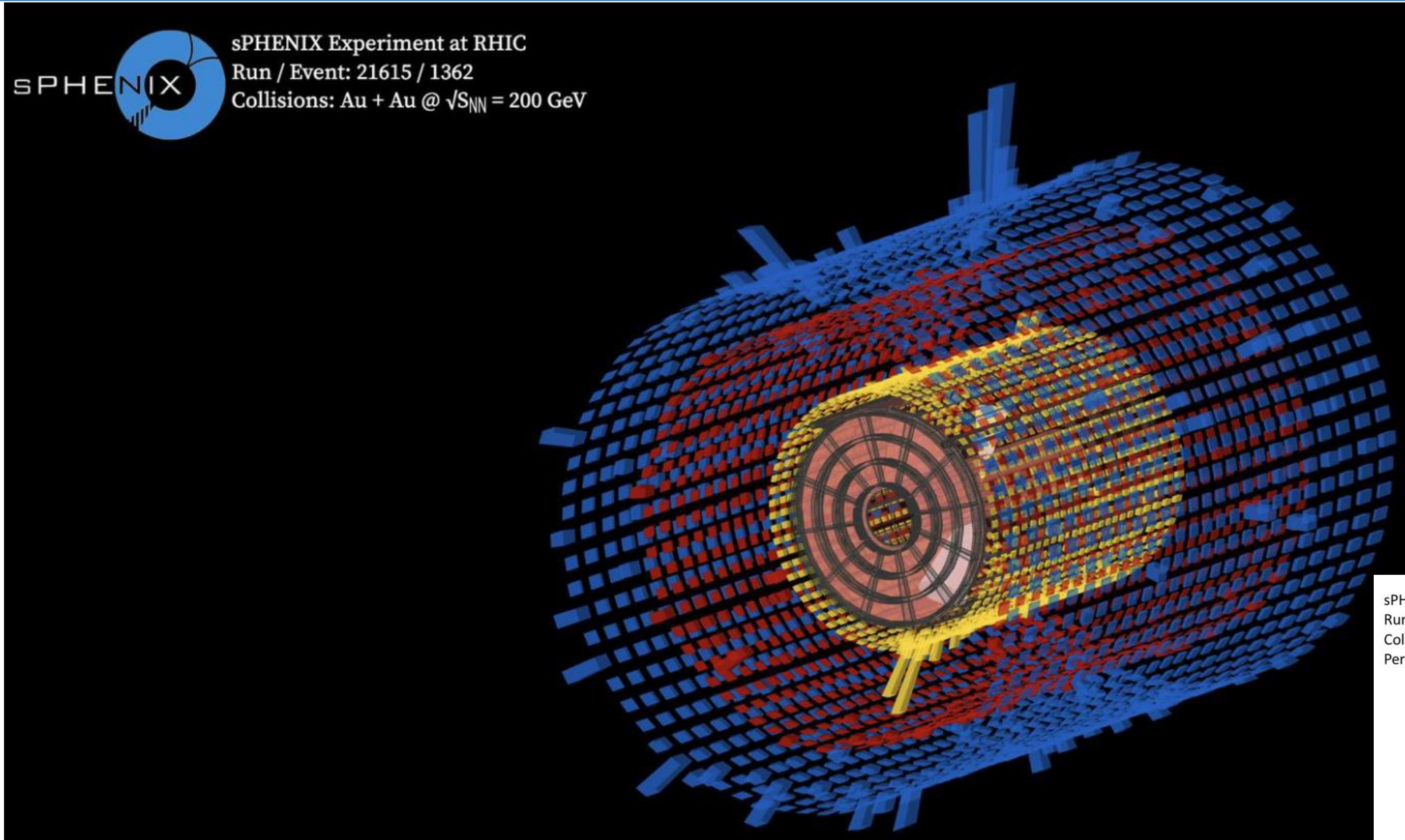
Sector are supported off the Inner HCAL

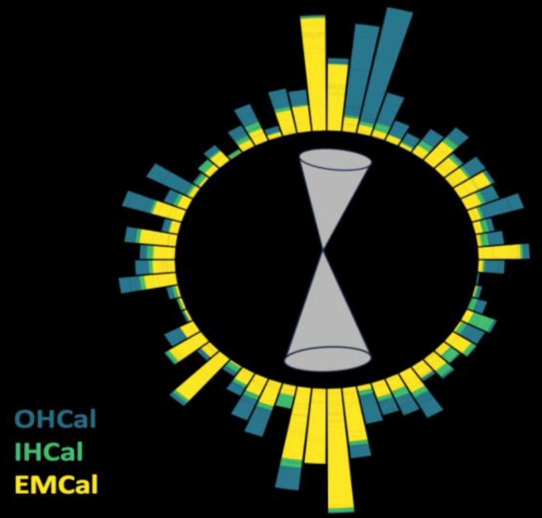
EMCAL Sector (~ 900 lbs)



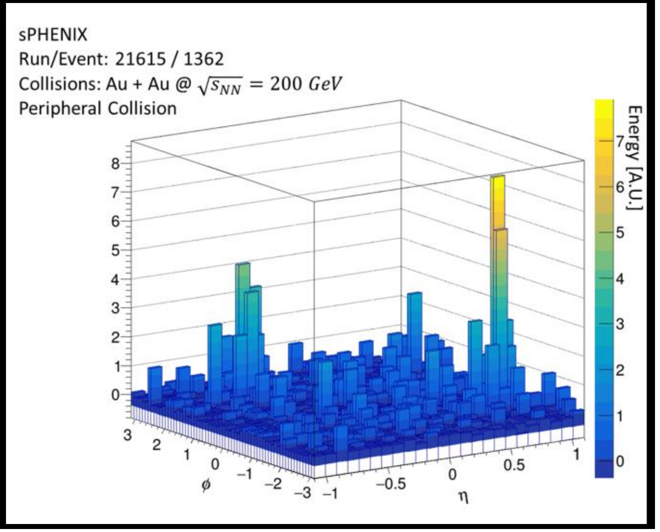
2500 scintillating fibers/block

Calorimeters (HCal+EMCal): Performance Plots



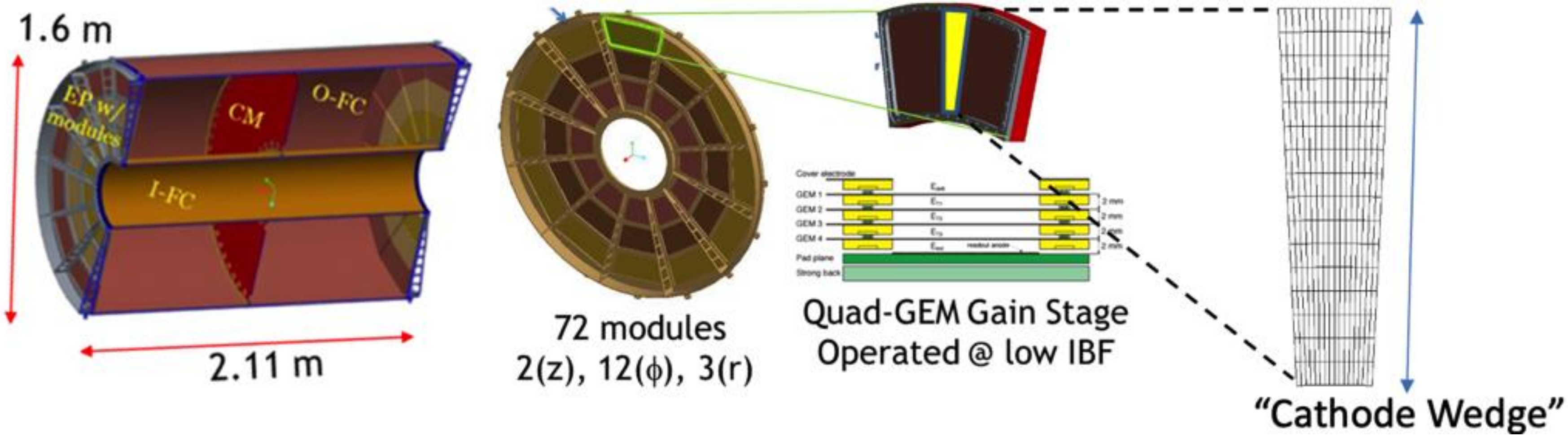


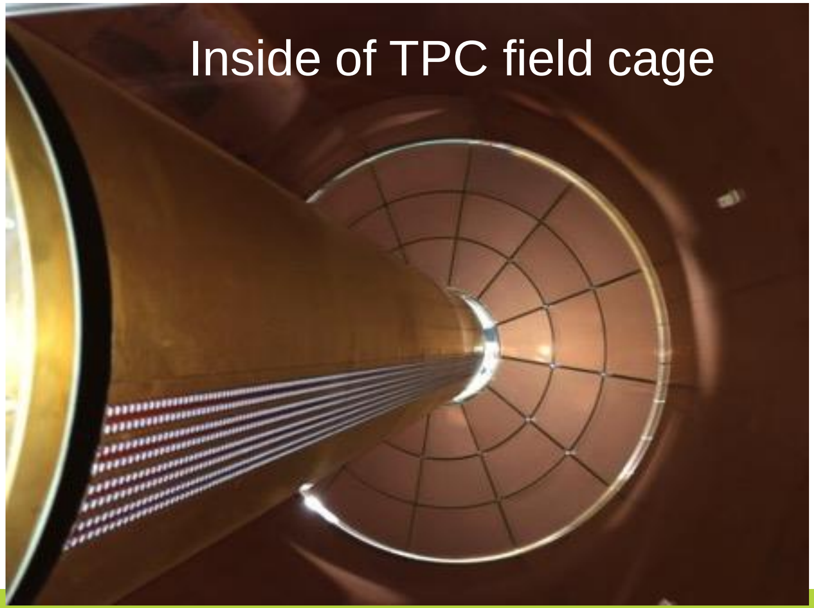
$P_{T,1}$ = 24 GeV, $P_{T,2}$ = 19 GeV



First full calorimeter jets observation at RHIC

TPC Assembly

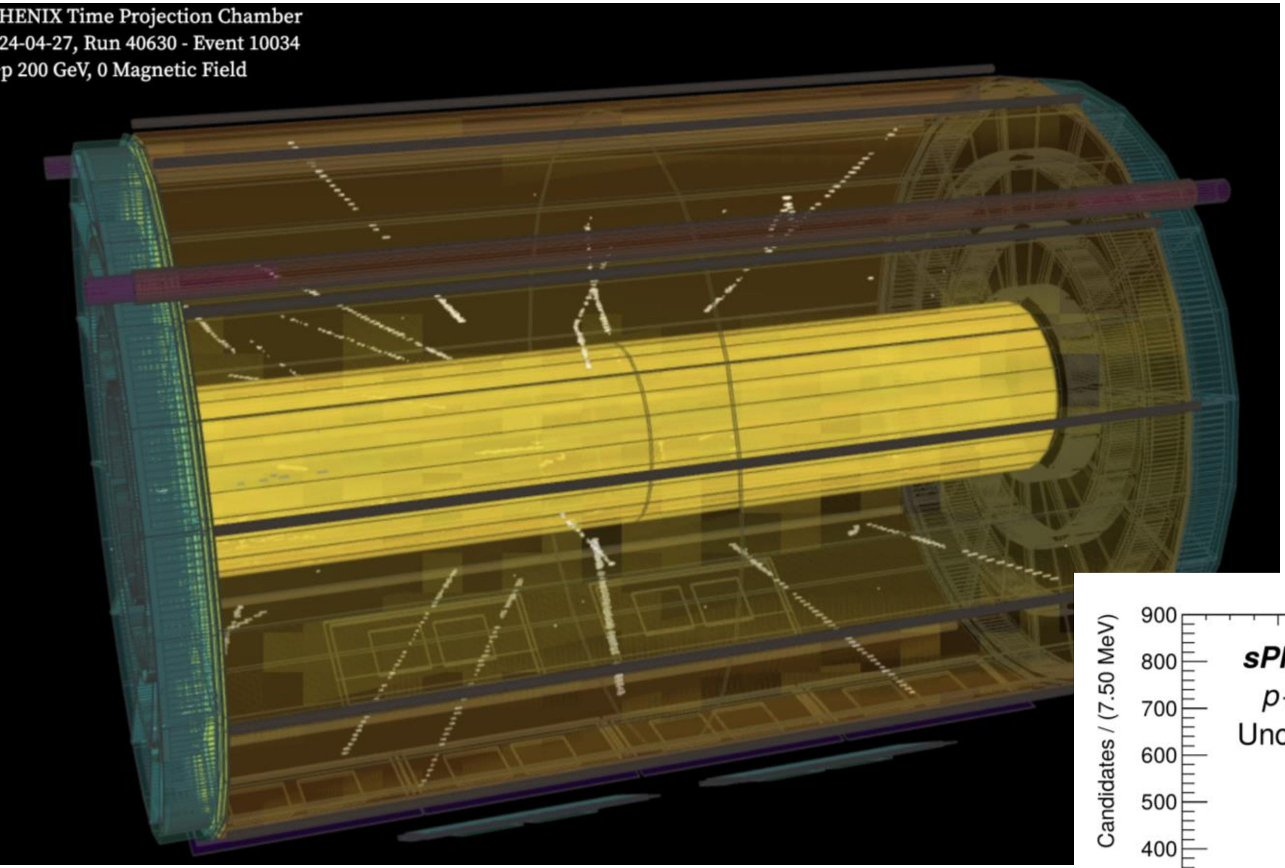




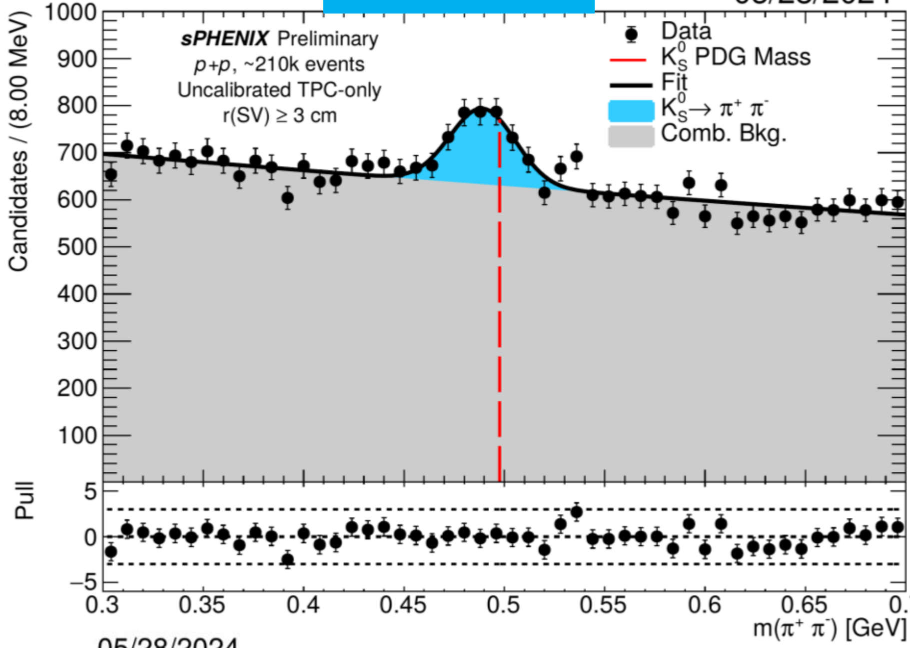
- TPC serves as the main tracking detector of the sPHENIX experiment,
- Determine charged particle momentum
- Operated in continuous readout mode using Gas-Electron Multiplier (GEM) avalanche
- Charge Field cages are Kapton-carbon fiber
- Internal chamber volume is filled with Ar-CF4 60/40 gas (4 m^3 gas volume)
- ASIC modified SAMPA chip from ALICE

Time Projection Chamber (TPC): TPC only

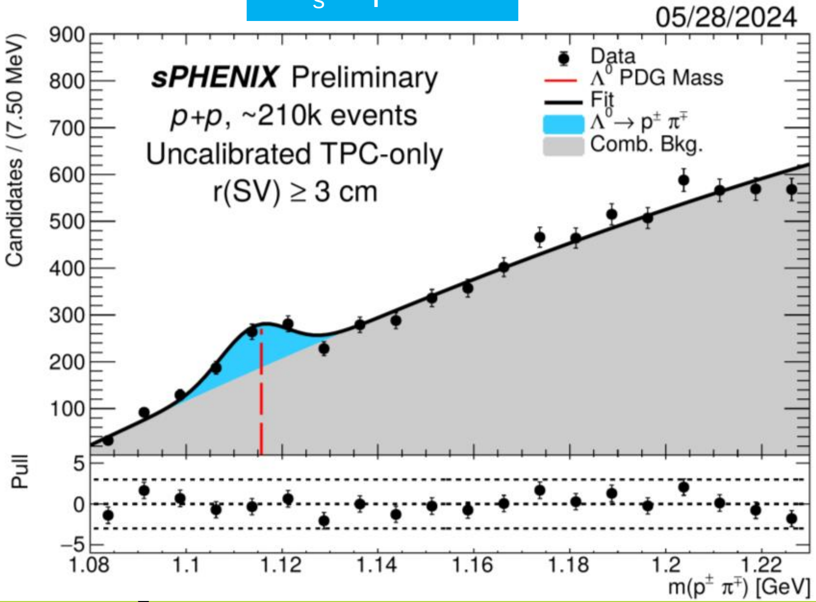
RHIC Run-24: *p+p* at 200 GeV



$K^0_s \rightarrow \pi^+\pi^-$

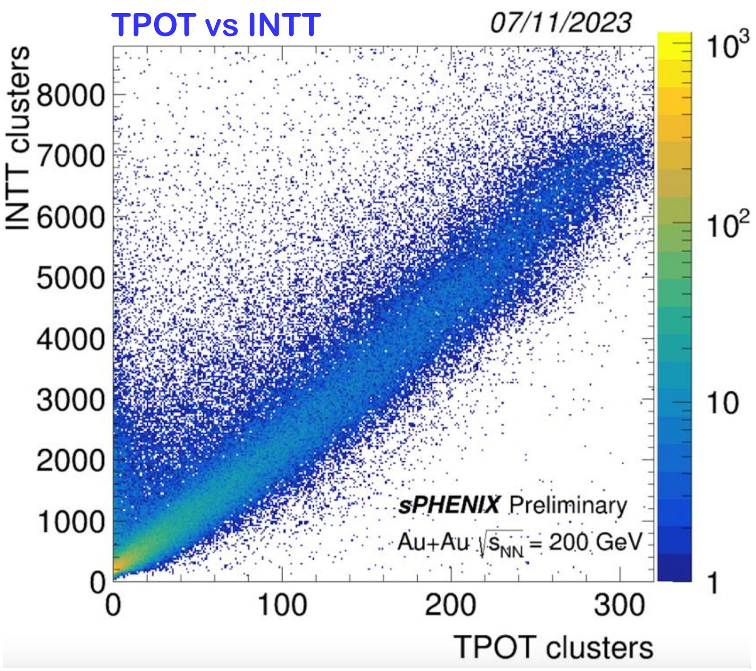


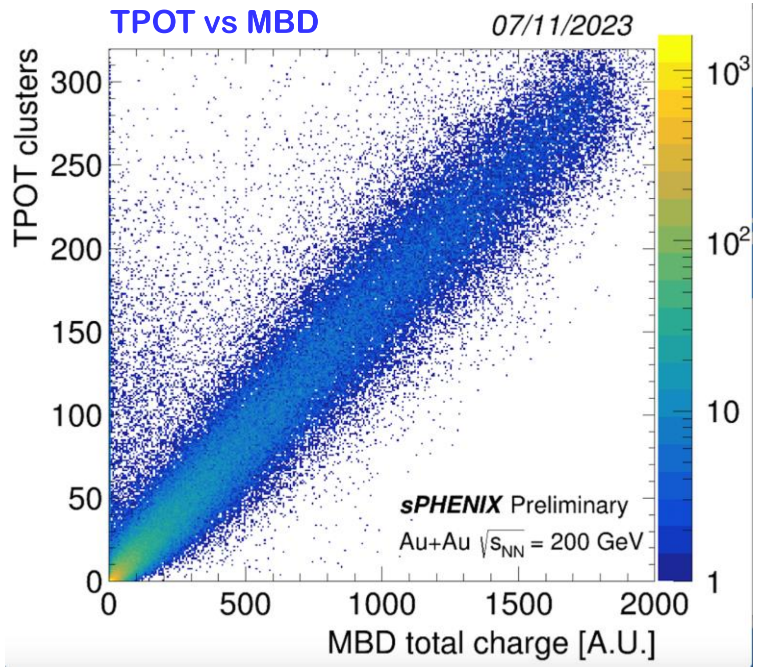
$\Lambda^0_s \rightarrow p^{\pm}\pi^{\pm}$



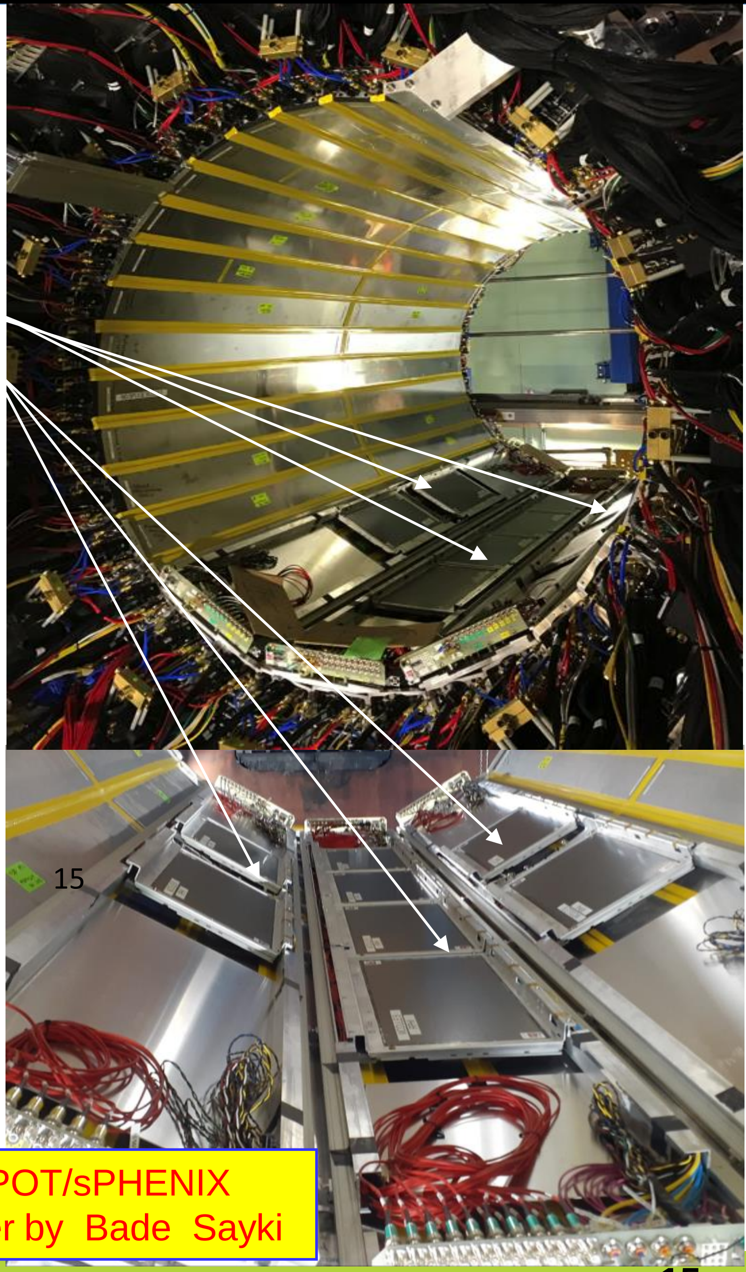
Time Projection Outer Tracker (TPOT)

- TPOT are made from thin gas detectors called Micromegas and its located between the TPC and the EMCal subdetectors. TPOT consists of 8 identical modules.
- TPOT's function is to provide tracking distortion correction information for the TPC
- TPOT has approximately 8% coverage of the TPC acceptance
- TPOT utilizes the same electronics as the TPC: SAMPA chips
- TPOT Gas mixture used is Argon/Isobutane 95/5.





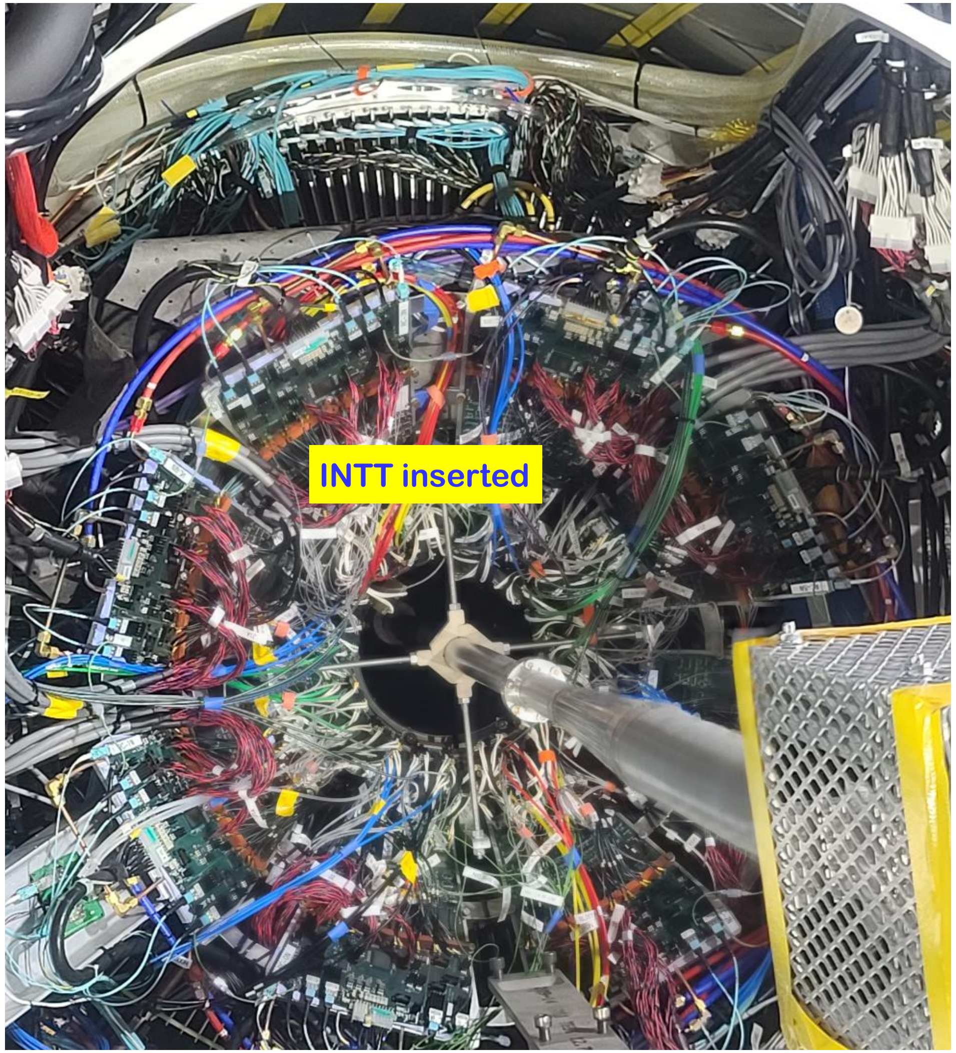
TPOT

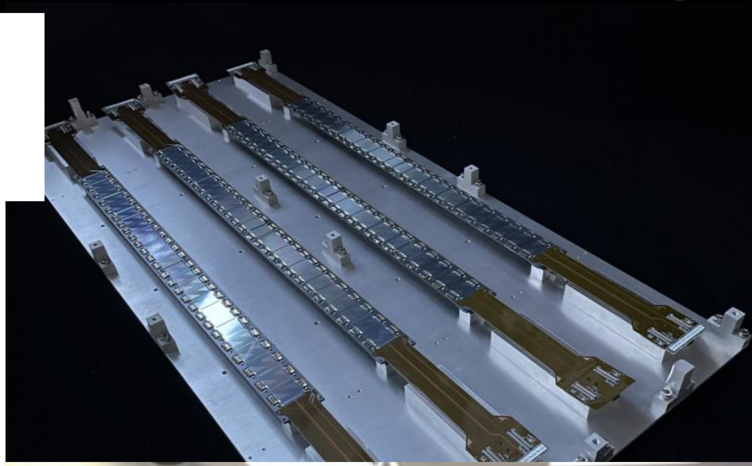


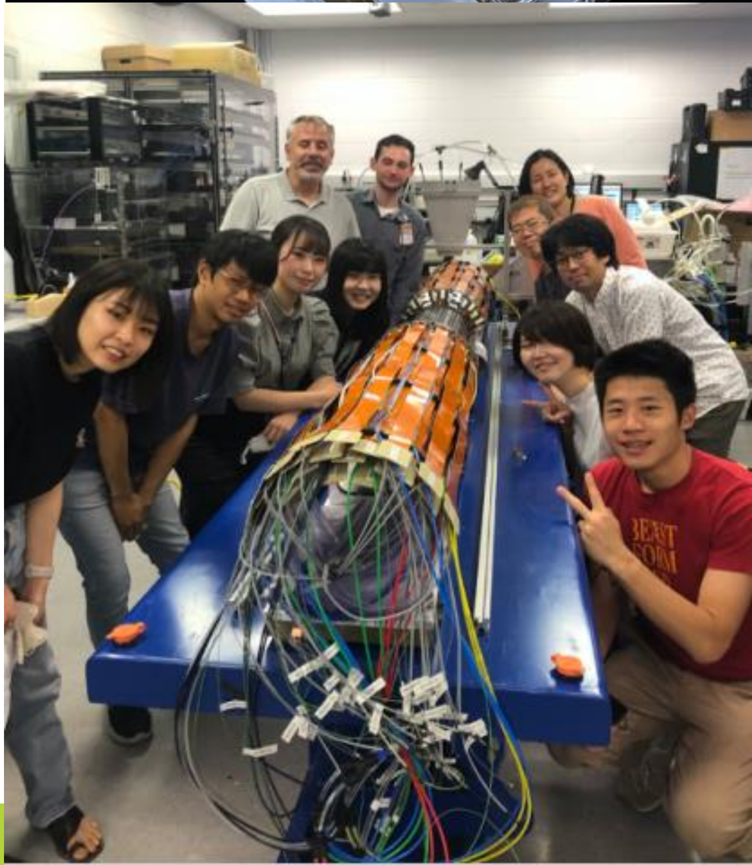
TPOT/sPHENIX poster by Bade Sayki

INTermediate silicon Tracker (INTT)

- Two layers of silicon strip detector with acceptance: $|\eta| < 1.1$ and $\phi = 2\pi$
- Fast time response of 60ns allowing to readout collisions each data from each single RHIC's beam bunch-crossing and suppress event-pileup background.







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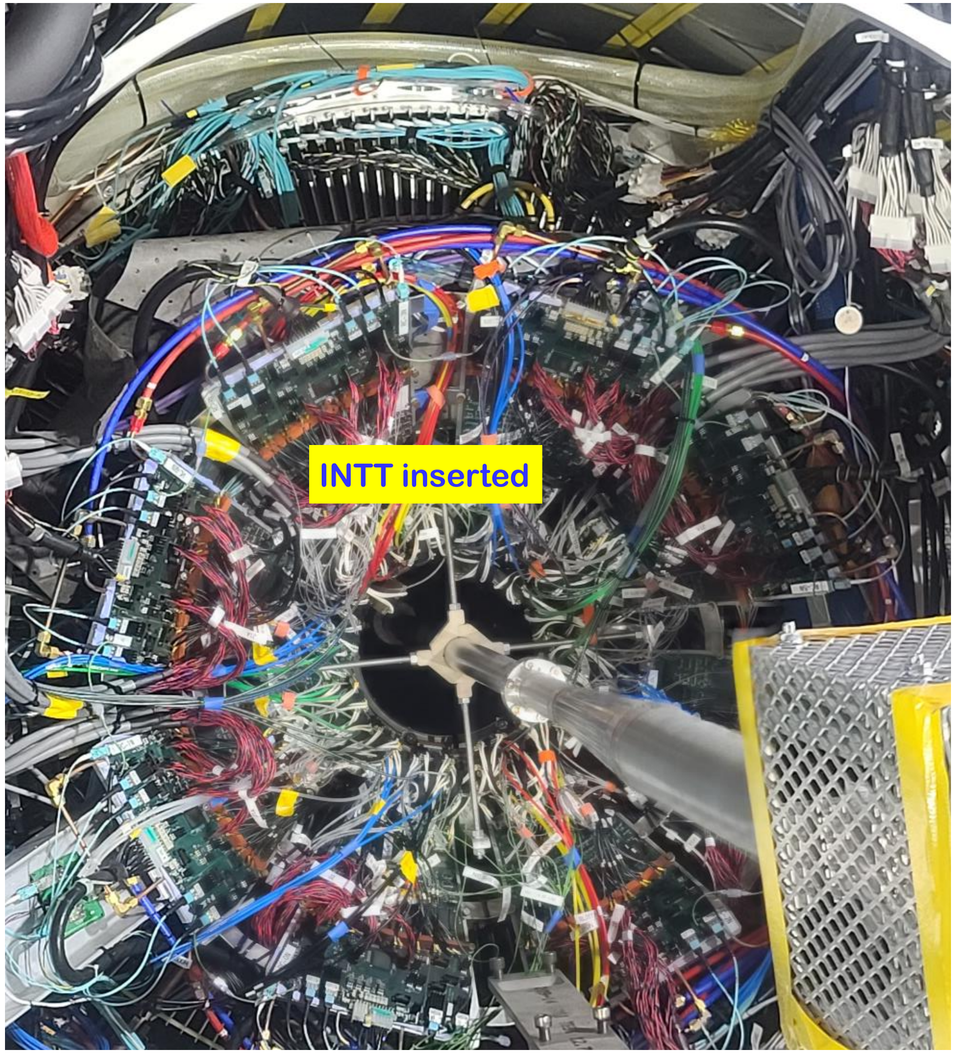
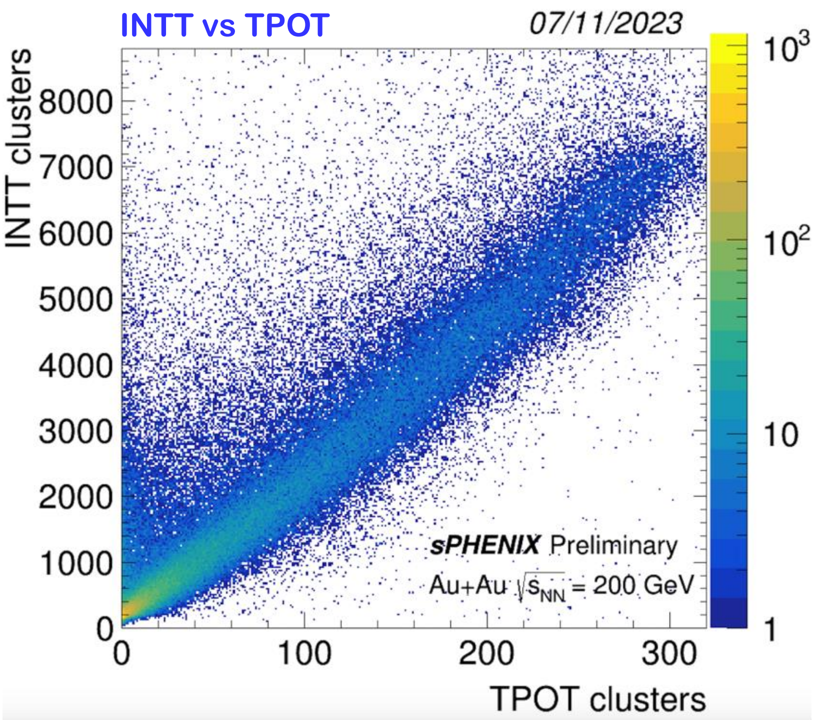
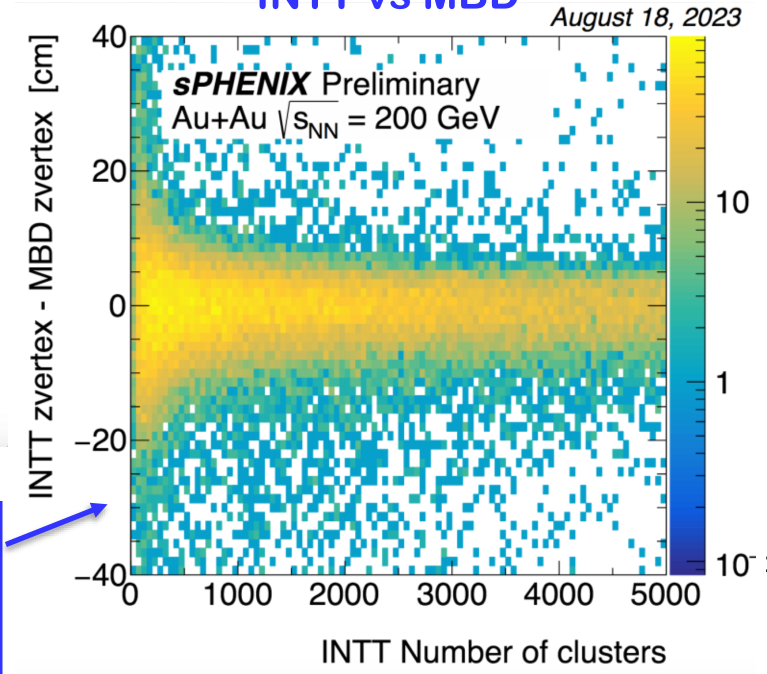
INTT/sPHENIX poster #157 by Jaein HWang





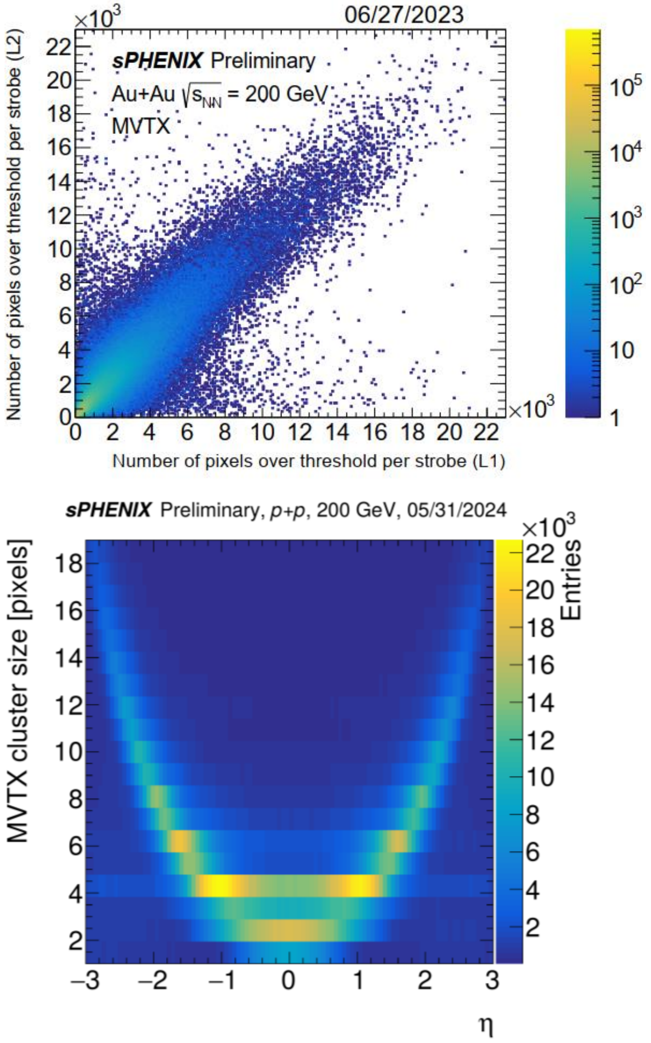
Vertex Correlation:
INTT vs MBD

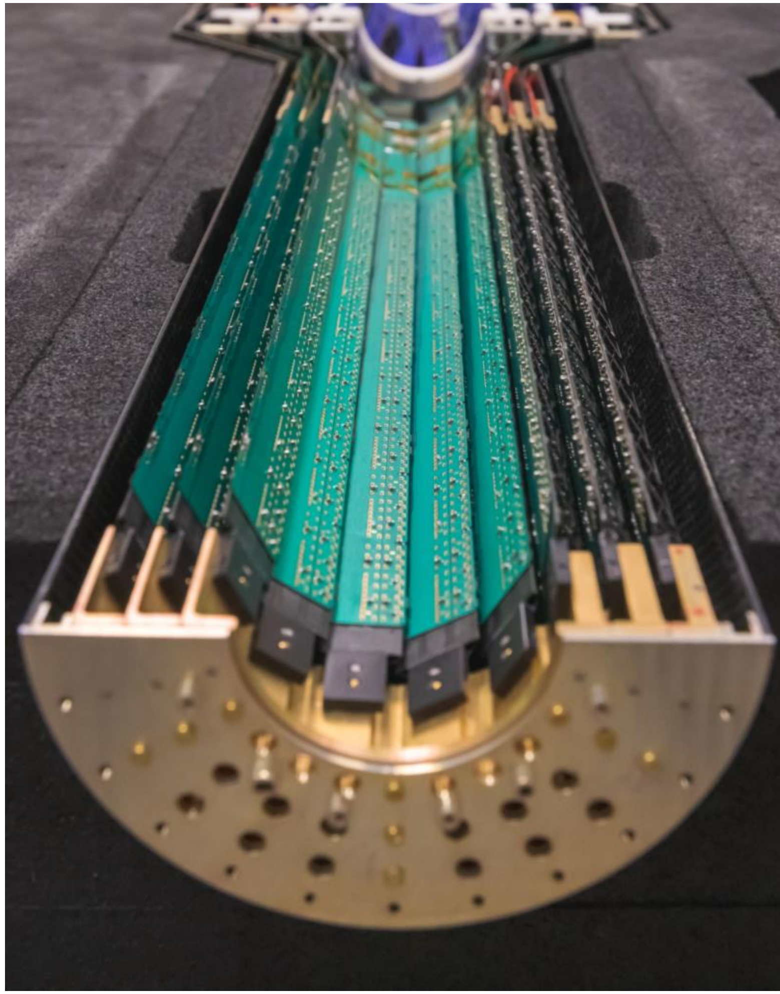


MBD determines vertex position by timing σ = 50 ps, INTT determines vertex by tracklets

Monolithic active pixel VerTeX detector (MVTX)

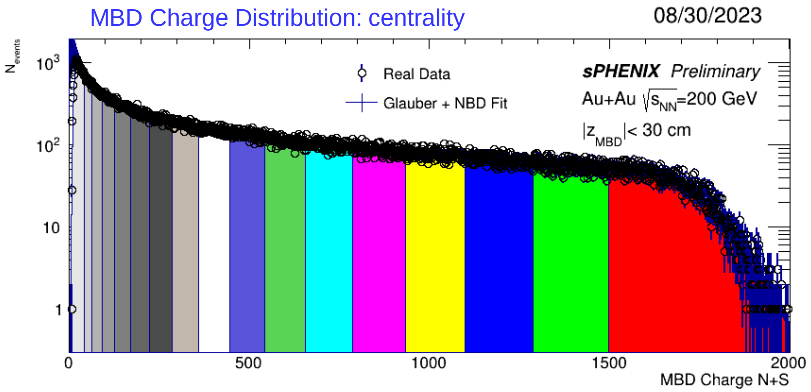
- The MVTX is a 230M channel, 3-layer MAPS-based pixel detector
- The MVTX is a copy of inner 3 layers of the ALICE ITS w/ a custom design of service supports to meet sPHENIX needs
- Staves and Readout Units produced at CERN w/ participation from sPHENIX collaborators

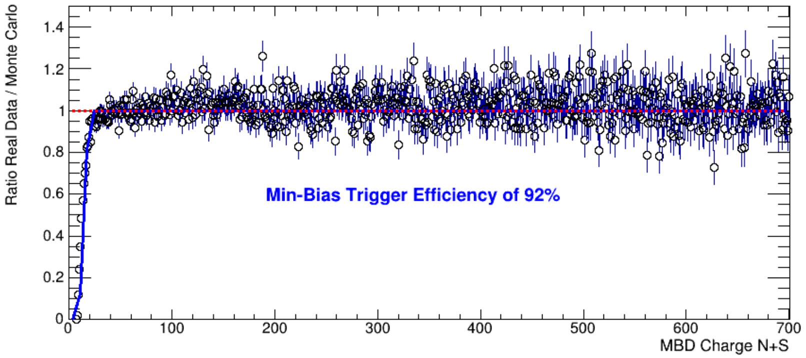


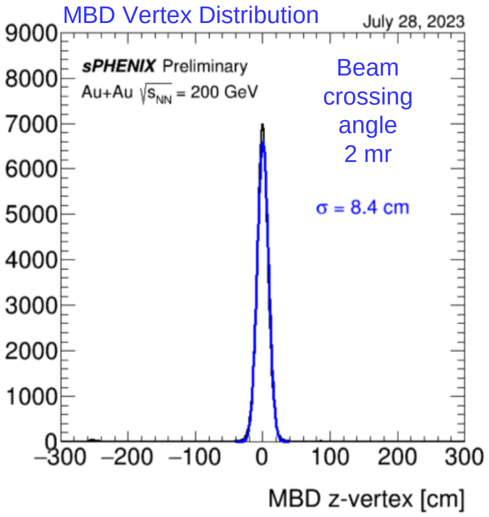


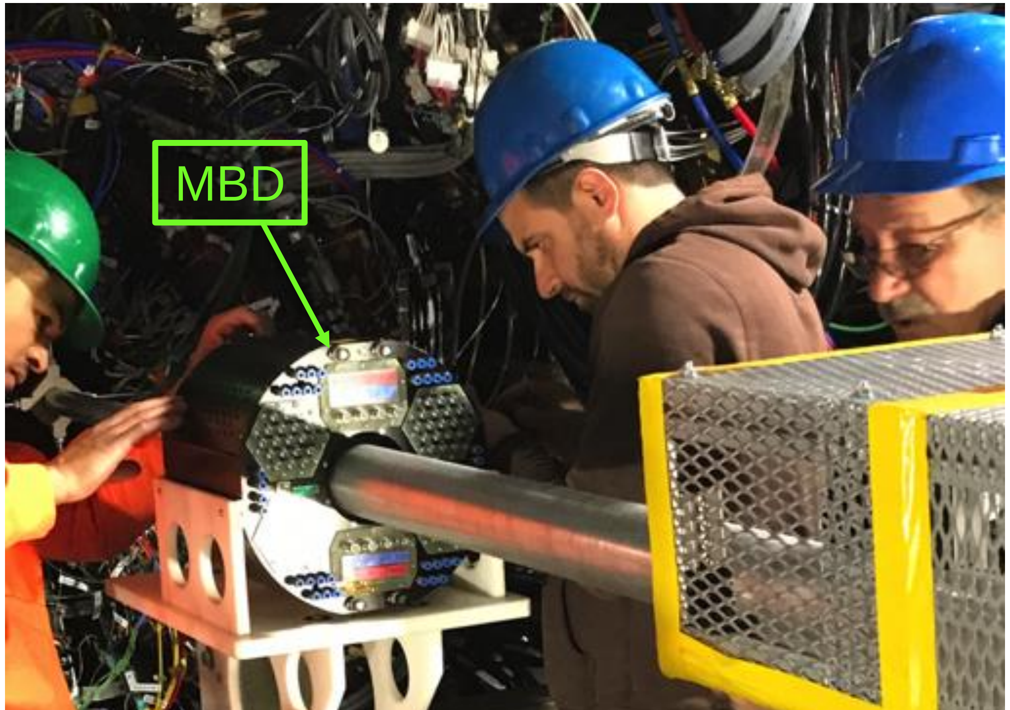
Min Bias Detector (MBD)

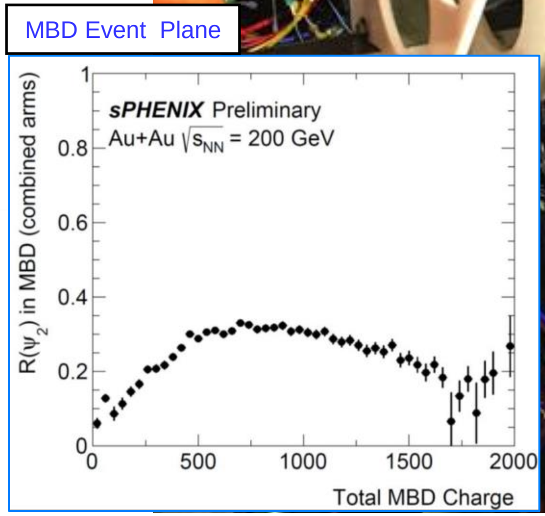
- Consists of two arms with 64 channels each
- 3 cm thick quartz radiator on mesh dynode PMT
- Pseudo-rapidity range of [3.51, 4.61]
- Used as trigger and for z-vertex determination
- used for centrality determination
- used for event plane determination in run 2023





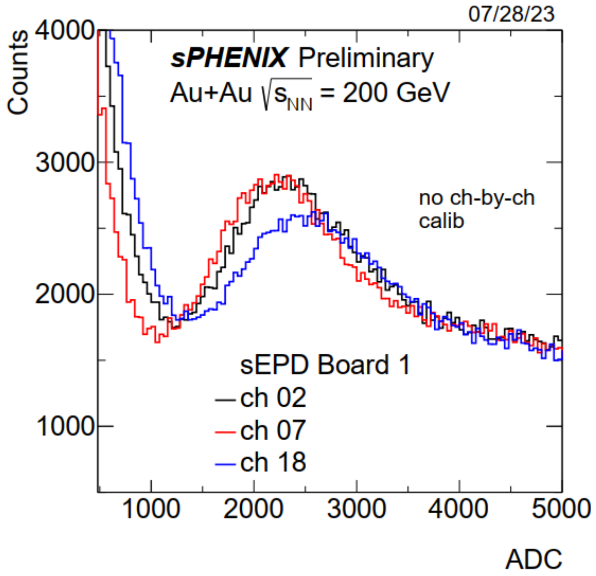


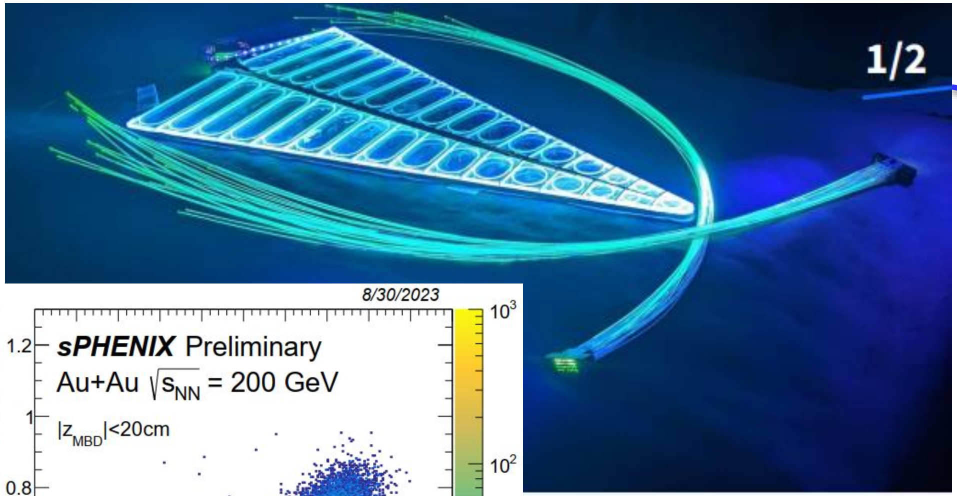


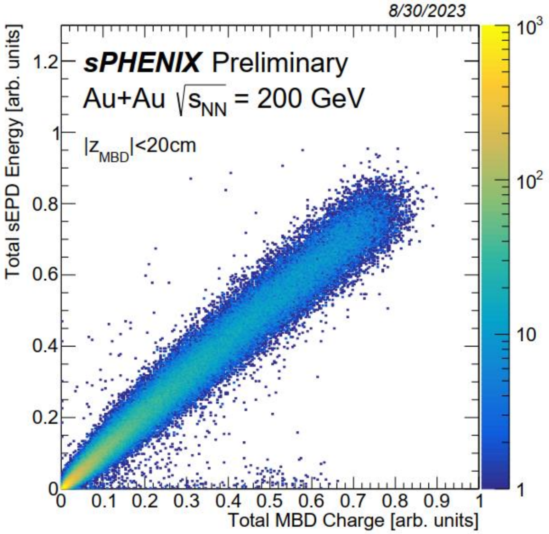


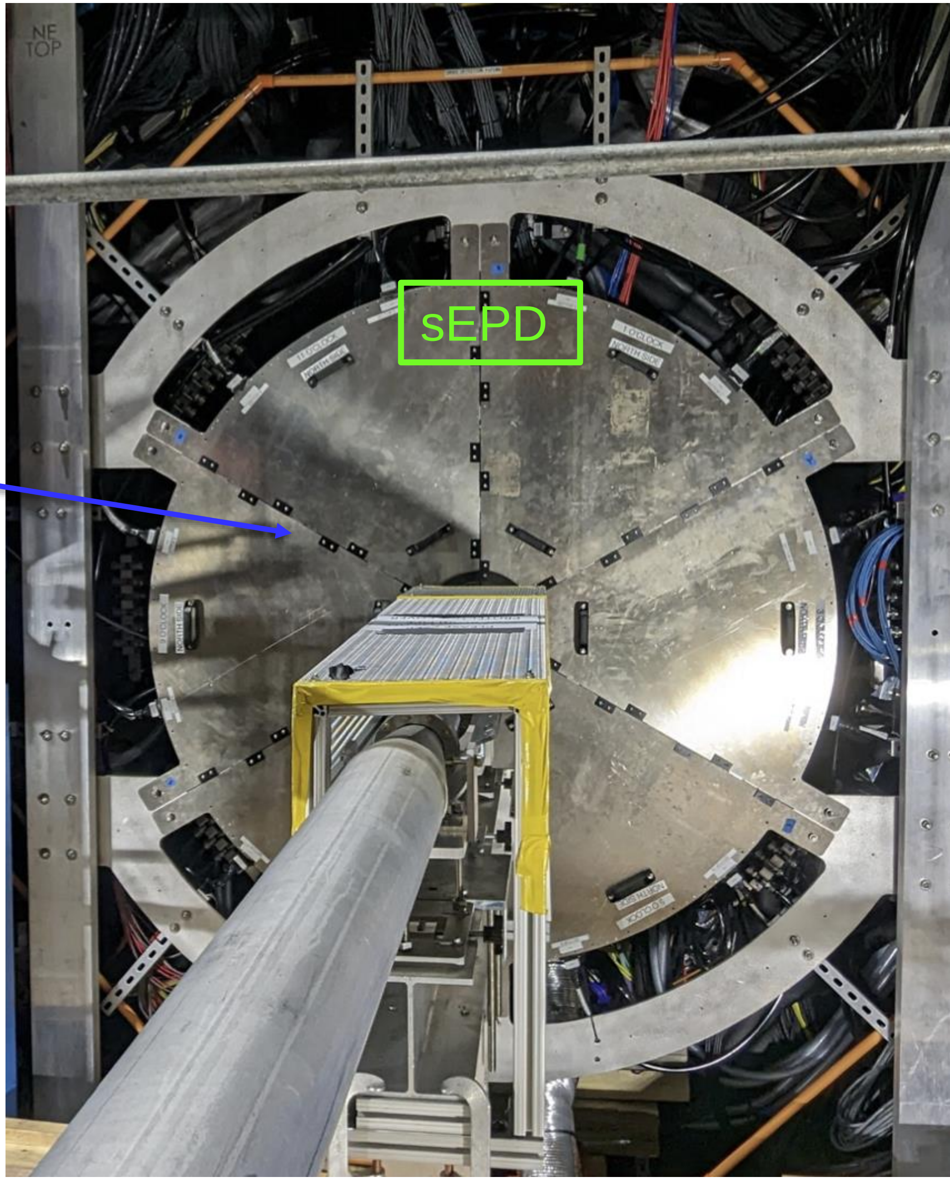
sPHENIX Event Plane Detector (sEPD)

- The sEPD is comprised of two scintillator disks
- 12 sectors/disk each subdivided into 31 tiles
- Covers both forward & backward rapidity region in 2.1<|η|<4.9
- Total 744 channels with 16 segments in η and 24 in ϕ
- Essential role for event plane determination w/ high resolution



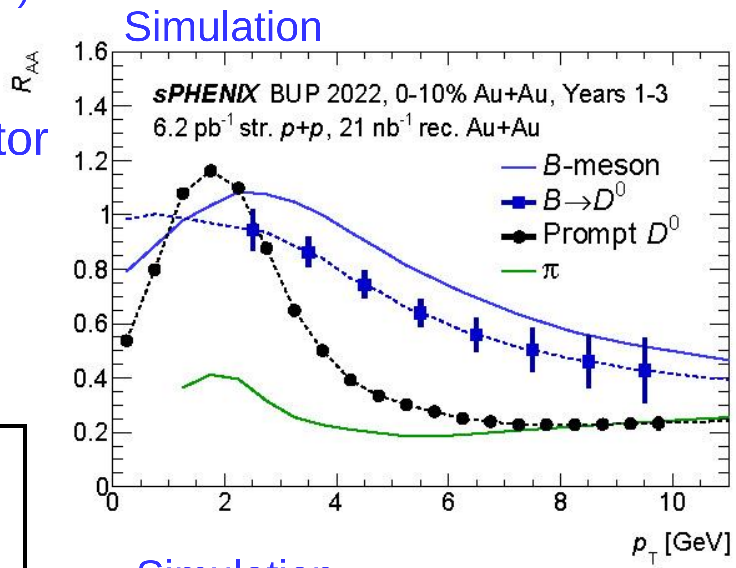


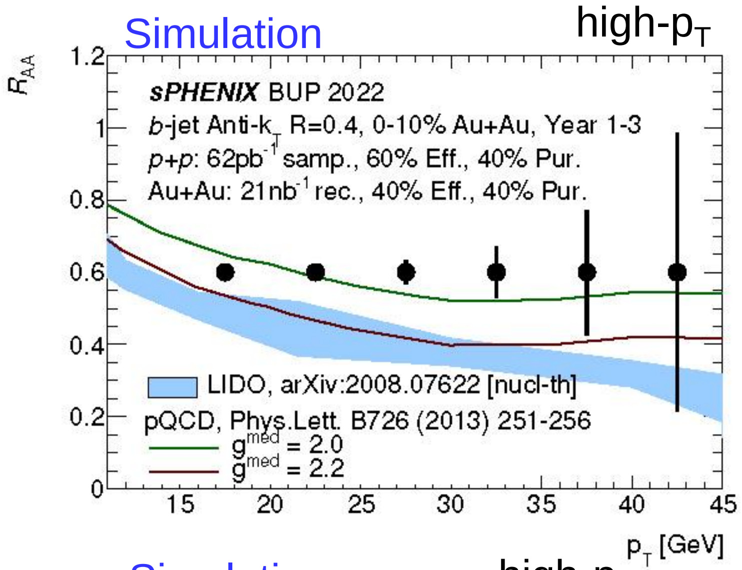




Expectations from sPHENIX Beam Use Request (BUP)

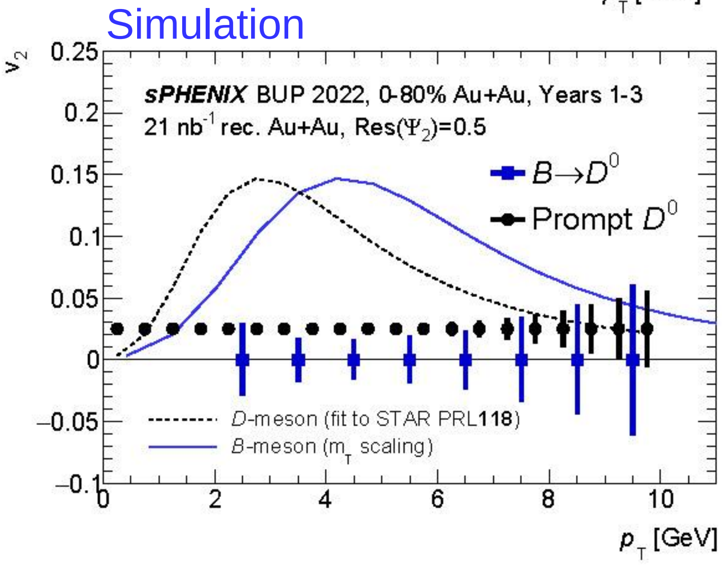
Nuclear modification factor

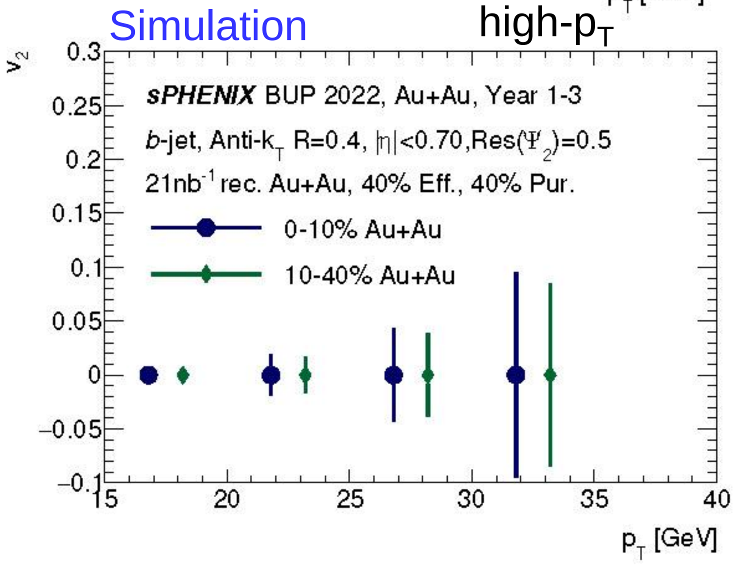




p+p running right now is key for HF program — streaming readout boost HF statistics which is needed for R_{AA}, Λ_C / D0, …

Elliptic Flow





For more details see sPHENIX contributed talk by Huan Huang on 6/5/24 at 11:40 pm

Fast Data Processing: Tagging with machine learning

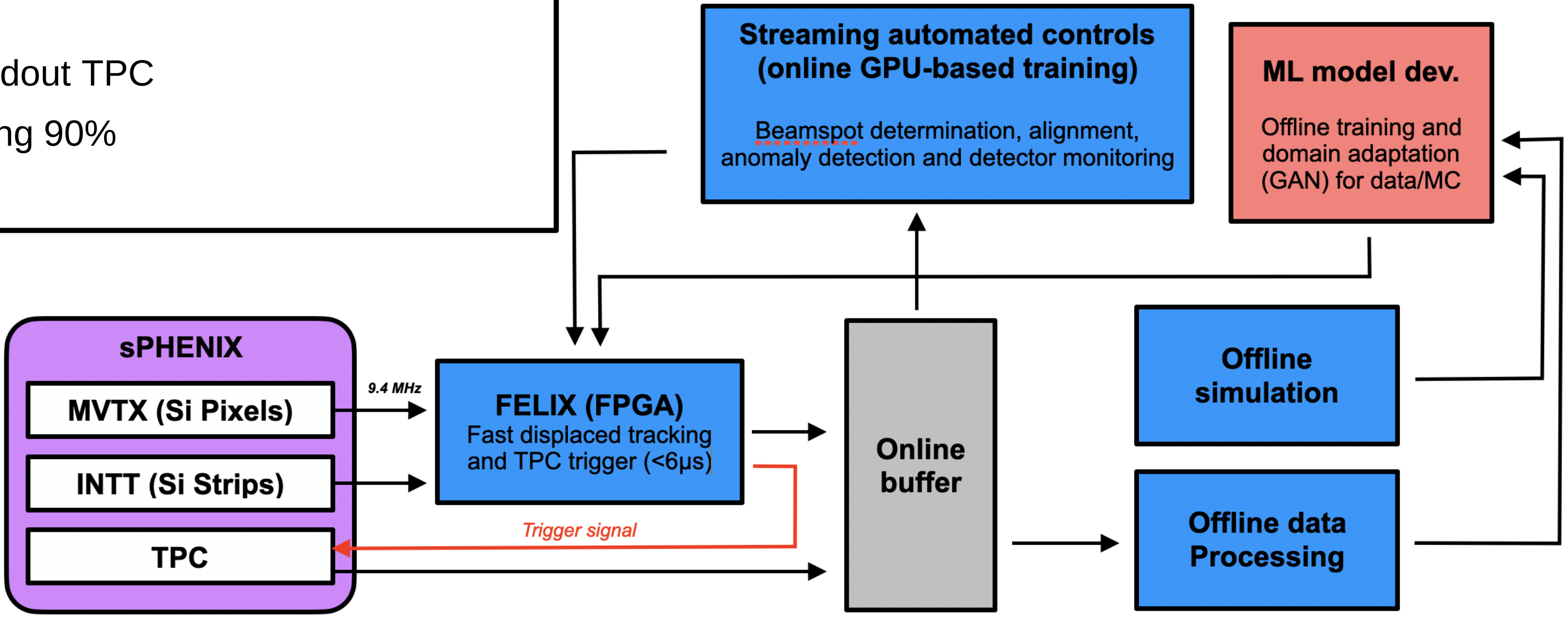
Intelligent experiments through real-time AI: Fast Data Processing and Autonomous Detector Control for sPHENIX and future EIC detectors

A proposal submitted to the DOE Office of Science

- Embed ML algorithms on FPGAs
- Stream MVTX and INTT to FPGAs and determine if HF event is present through topology
- Send tag downstream to readout TPC
- Allows us to sample remaining 90% of collisions

arXiv 2103.05579

FELIX card (712) on server for FW testing



For more details see sPHENIX contributed talk by Huan Huang on 6/4/24 at 4:30 pm

First Physics Results from sPHENIX at RHIC

$\pi^0 v_2$ and $\frac{dE_T}{d\eta}$

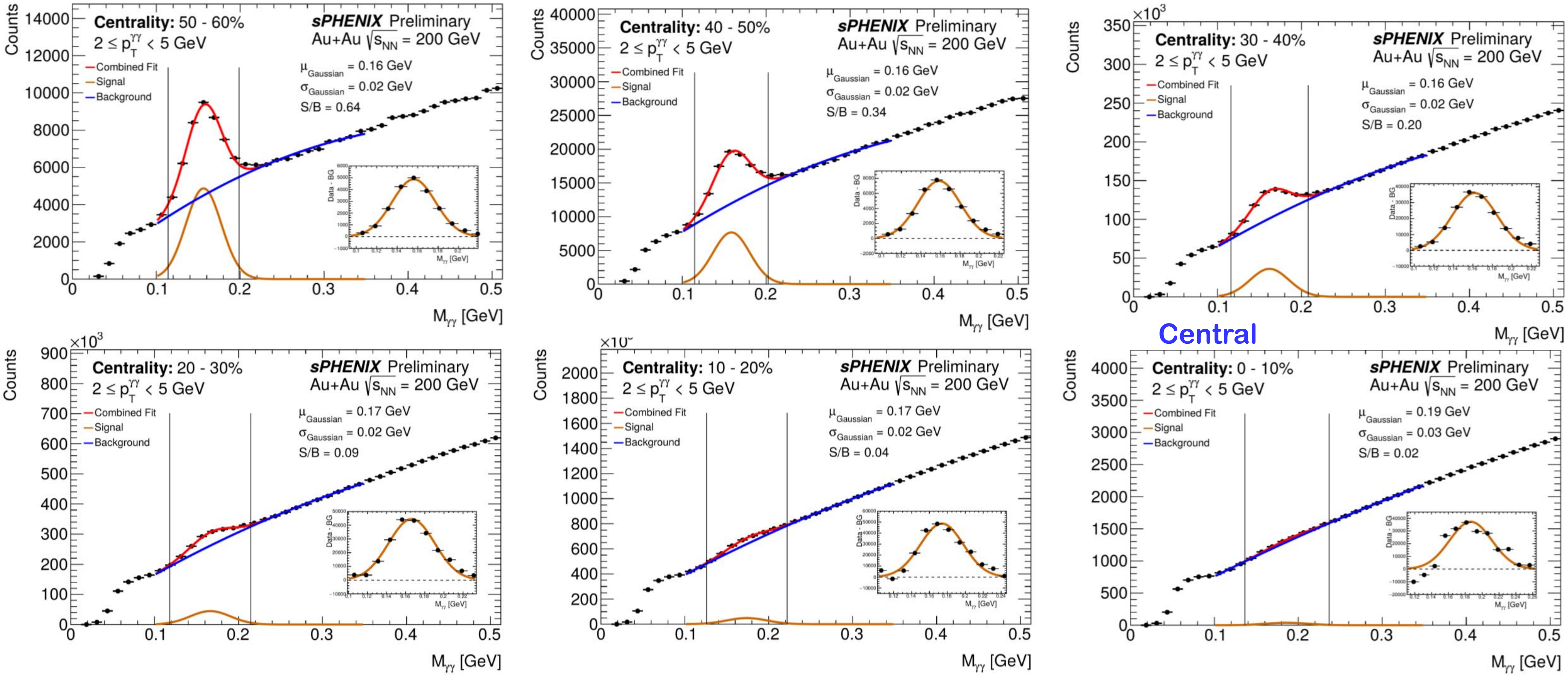
in Au+Au at 200 GeV

First Physics Measurements in Au+Au: $\pi^0 v_2$ versus Centrality

Using commissioning data ~ 5 M events from Run 2023 with EMCal and MBD to measure $\pi^0 v_2$

π^0 mass peaks at different centrality classes

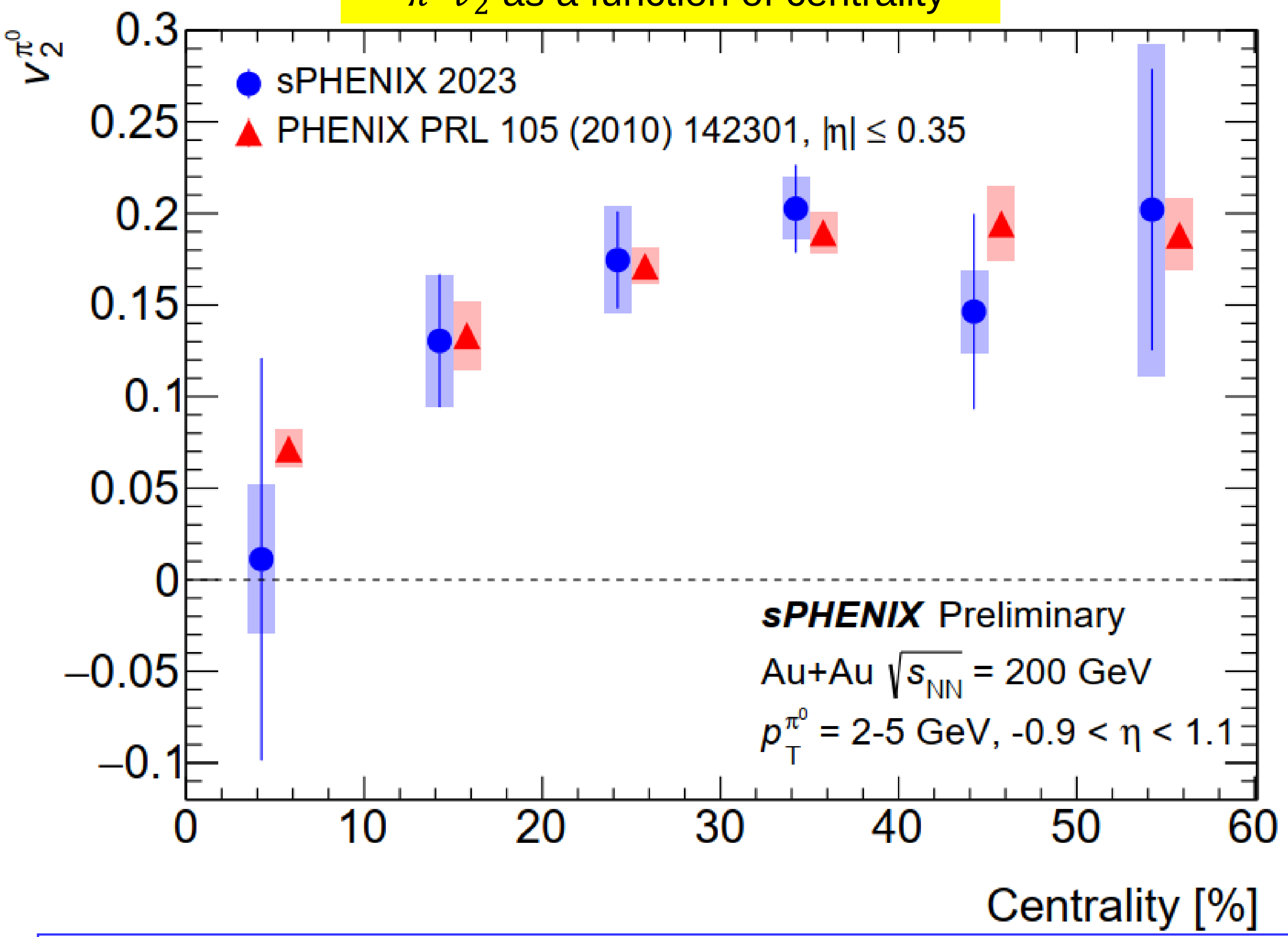
Peripheral



First Physics Measurements in Au+Au: $\pi^0 v_2$ versus Centrality

Using commissioning data ~ 5 M events from Run 2023 with EMCal and MBD to measure $\pi^0 v_2$

$\pi^0 v_2$ as a function of centrality

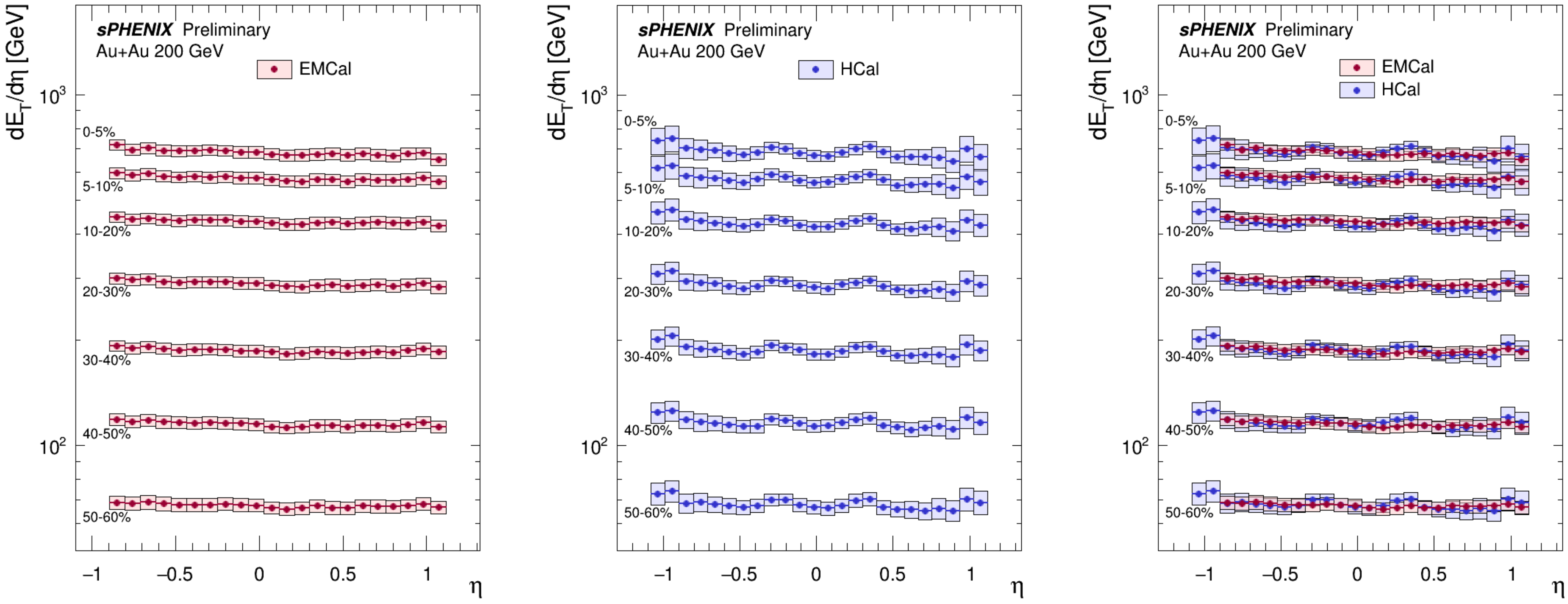


For more details/results see sPHENIX contributed talk by Emma McLaughlin on 6/7/24 at 4:30 pm

First Physics Measurements in Au+Au: $dE_T/d\eta$ versus Centrality

Using commissioning data ~ 249k events from Run 2023 with EMCal+IHCal+OHCal+MBD to measure $\frac{dE_T}{d\eta}$

$\frac{dE_T}{d\eta}$ distribution in each calorimeter subdetector

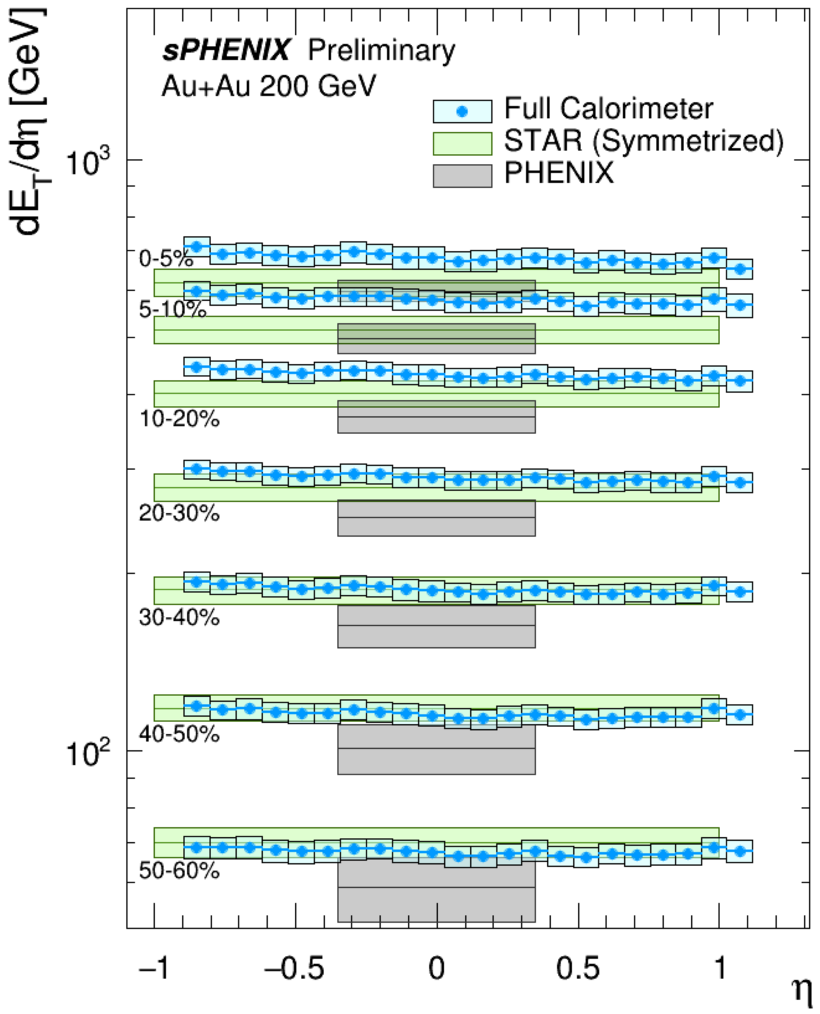


For more details/results see sPHENIX contributed talk by Emma McLaughlin on 6/7/24 at 4:30 pm

First Physics Measurements in Au+Au: $dE_T/d\eta$ Comparison

Using commissioning data ~ 249k events from Run 2023 with EMCal+IHCal+OHCal+MBD to measure $\frac{dE_T}{d\eta}$

$\frac{dE_T}{d\eta}$ distribution, comparison to other experiments STAR and PHENIX



Presented are sPHENIX centrality intervals from preliminary centrality calculations which will be updated before finalizing centrality selections and reporting quantities like <N_{part}>

For more details/results see sPHENIX contributed talk by Emma McLaughlin on 6/7/24 at 4:30 pm

Summary

- sPHENIX presents first physics measurements using commissioning data from RHIC Run-23:
  - Full set of current and future sPHENIX results: https://www.sphenix.bnl.gov/PublicResults
  - Only approved measurements shown today, several papers are in the pipeline for publication
- sPHENIX remains focused on science mission established in 2015 Long Range Plan.
- sPHENIX is taking spectacular p+p data from RHIC Run-24 (ongoing)
- Stay tuned for more results on jet and heavy flavor production coming soon

sPHENIX Collaboration Meeting at BNL: May 28th, 2024