Status of the sPHENIX experiment

Cheng-Wei Shih

for the sPHENIX Collaboration

National Central University/RIKEN

2025 Annual Meeting of Physical Society of Taiwan
@ National Sun Yat-sen University
January 15th, 2025

The sPHENIX detector

國立中央大學 National Central University

RIKEN

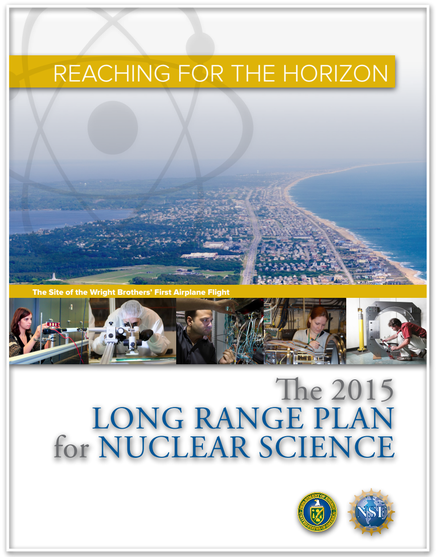
CHiP CENTER FOR HiGH ENERGY AND HiGH FIELD PHYSICS

TIDC Taiwan Instrumentation and Detector Consortium 台灣偵測器聯合實驗室

sPHENIX

The sPHENIX experiment at RHIC*

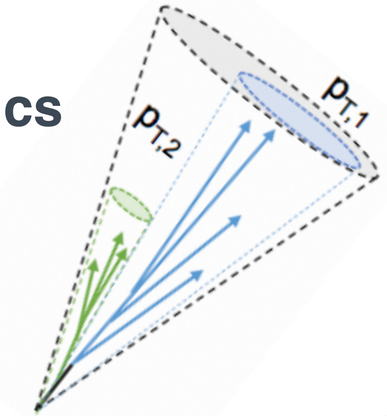
Long Range Plan 2015, page 22



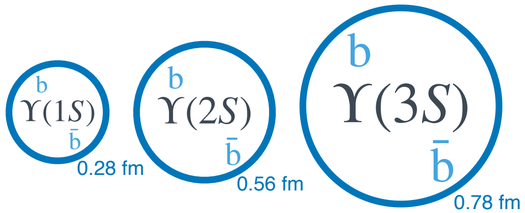
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art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

The main physics at sPHENIX

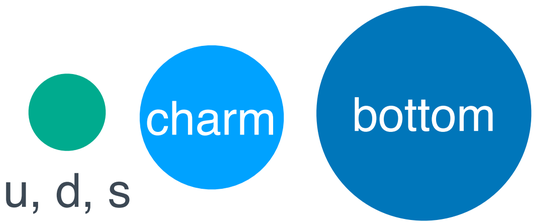
Jet Physics



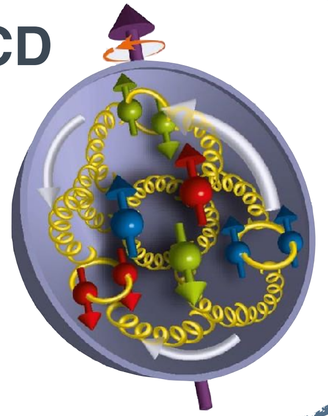
Quarkonium Spectroscopy



Parton Energy Loss in QGP



Cold QCD



*RHIC: Relativistic Heavy Ion Collider in BNL, USA

The sPHENIX detector

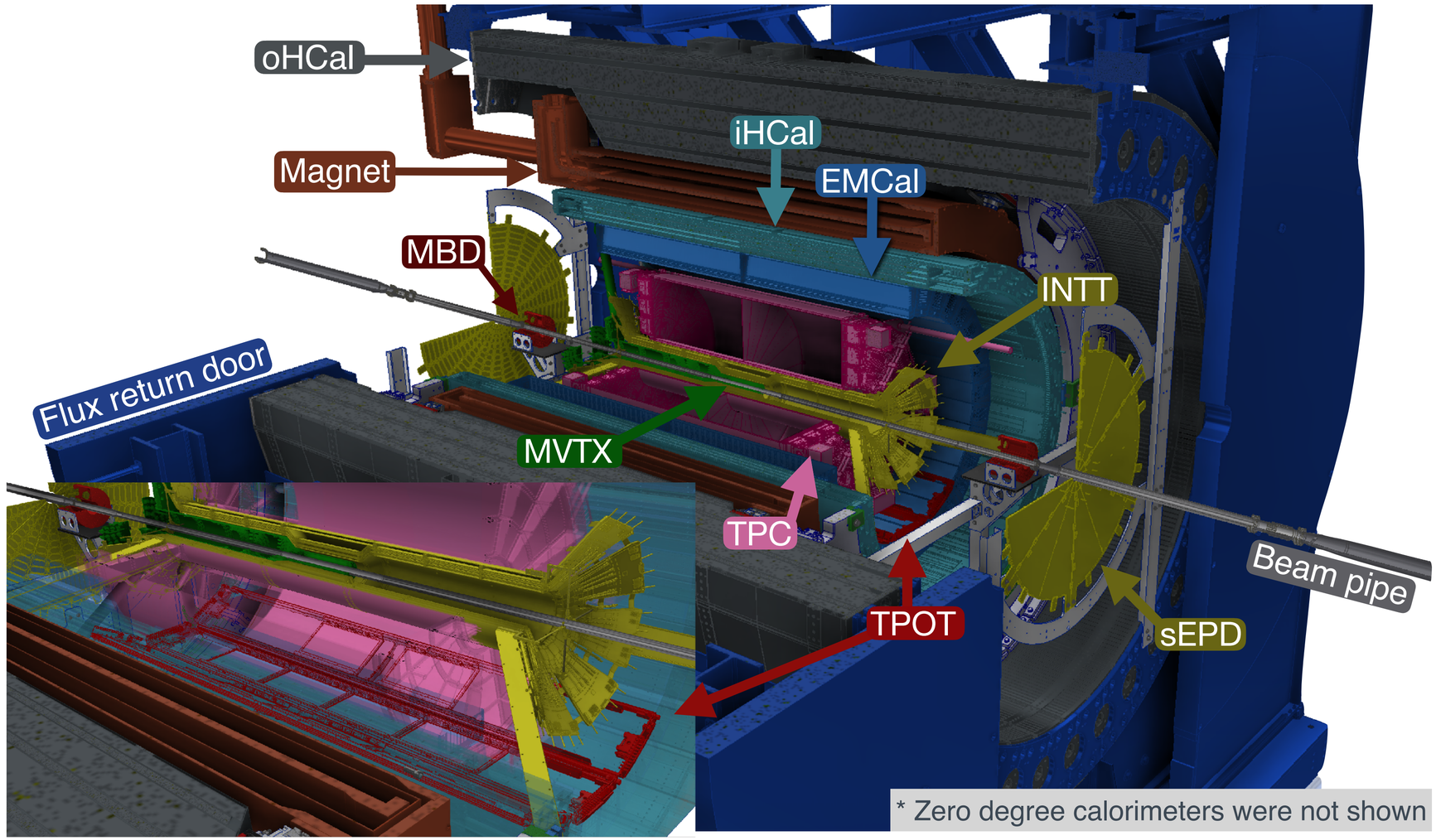
sPHENIX, Super Pioneering High Energy Nuclear Interaction eXperiment, at RHIC 1008, USA

Full barrel calorimeters

Magnet system

Tracking system

Forward detectors

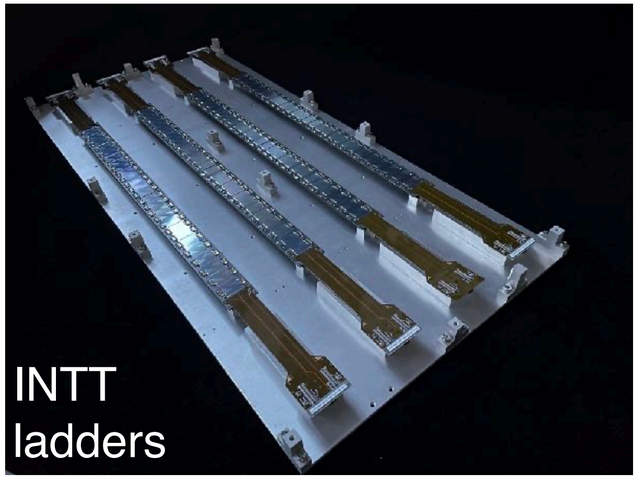


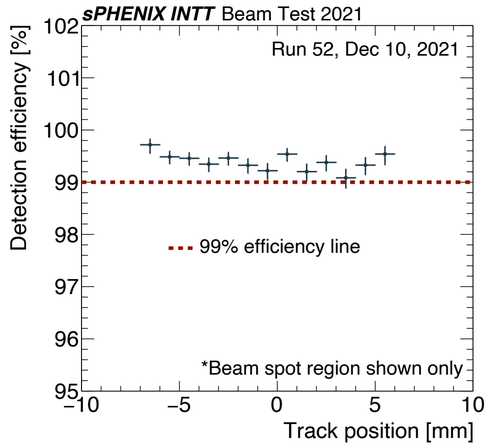
sPHENIX: composed of 11 systems

The journey of sPHENIX

TPS 2023

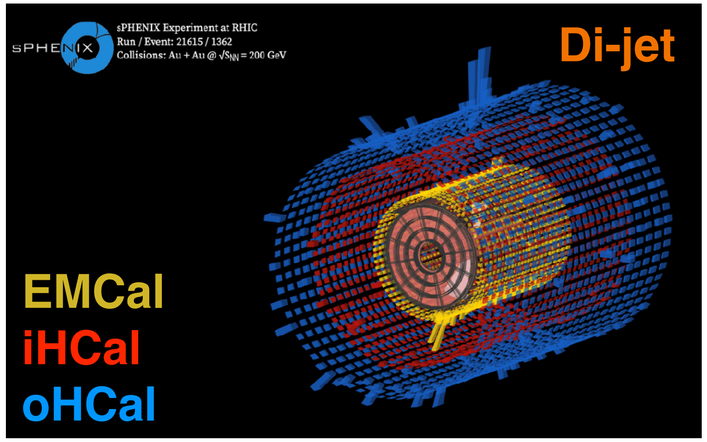
The INTT ladder production and ladder reliability

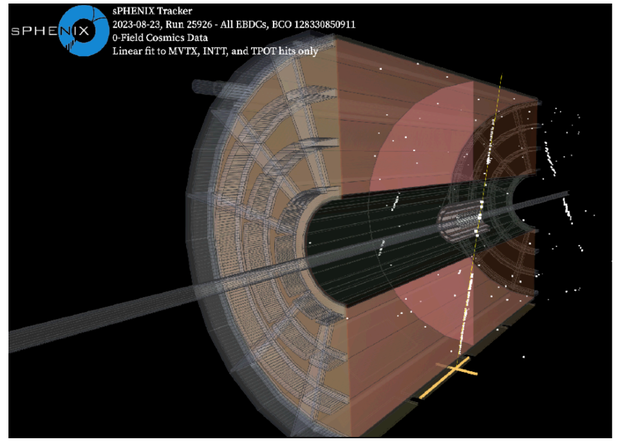




TPS 2024

The success of the first year commissioning





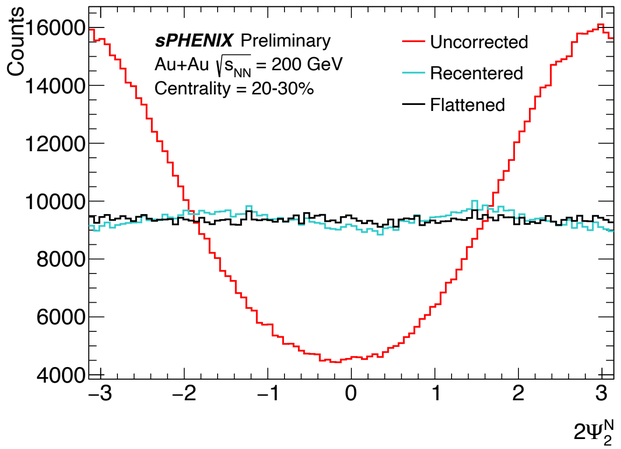
Standard Candle: Neutral Pion v_2

Run 2023 Au+Au commissioning dataset

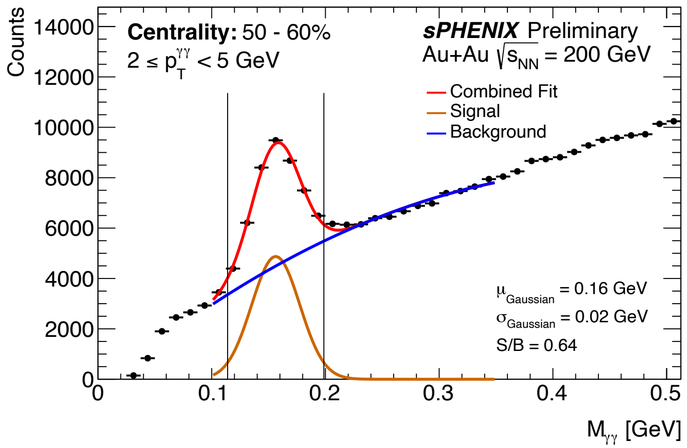
v_2 of π^0: measured via scale product method:

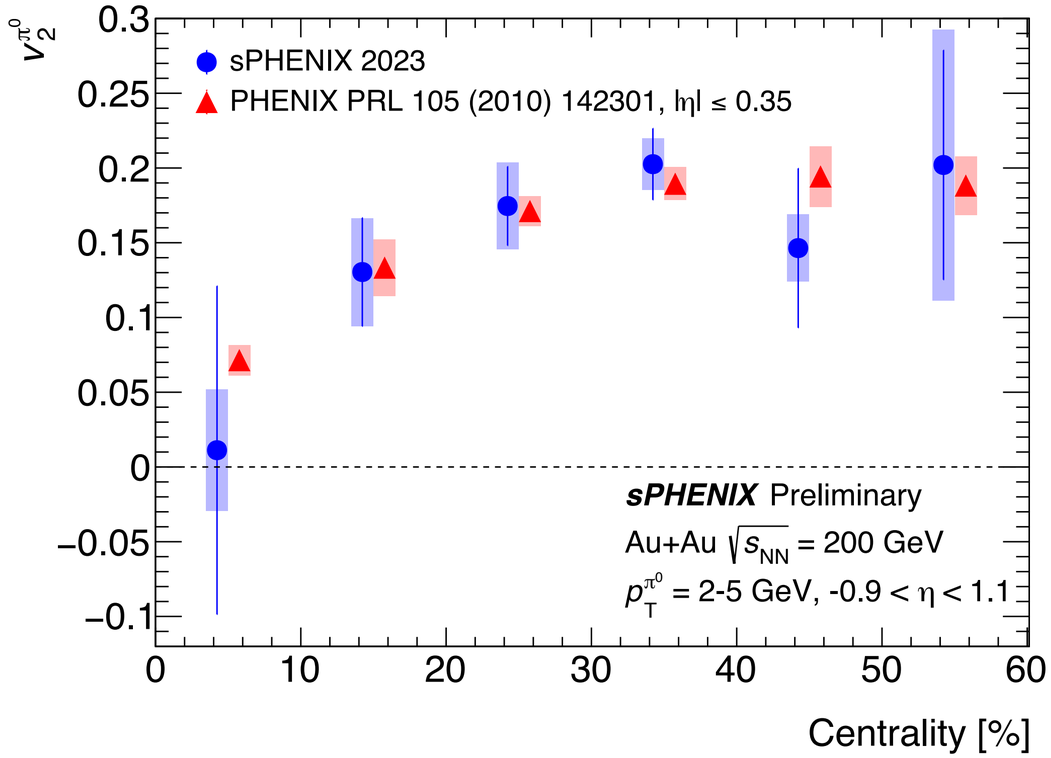
$$v_n\{SP\} \equiv Re\frac{\langle \vec{q}_{n,j}\vec{Q}_n^{S|N*}\rangle}{\sqrt{\langle \vec{Q}_n^S \vec{Q}_n^{N*}\rangle}}, \quad v_2^{\pi^0} = v_2^M + \frac{v_2^M - v_2^{BG}}{S/B}$$

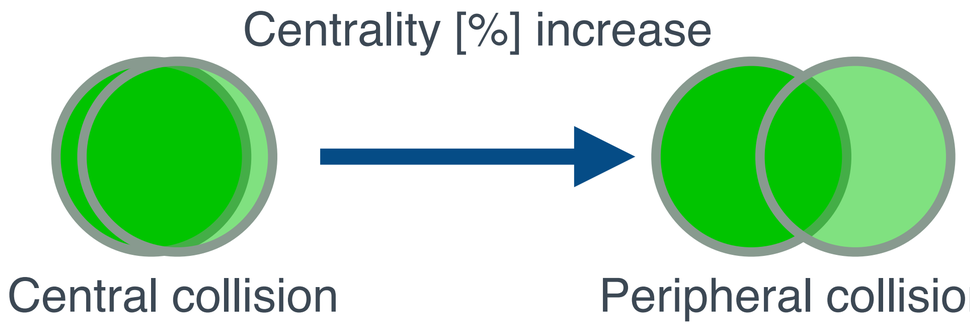
$\vec{Q}$ → MBD information



$\vec{q}$ → π^0 information







See the conference note: sPH-CONF-BULK-2024-01!

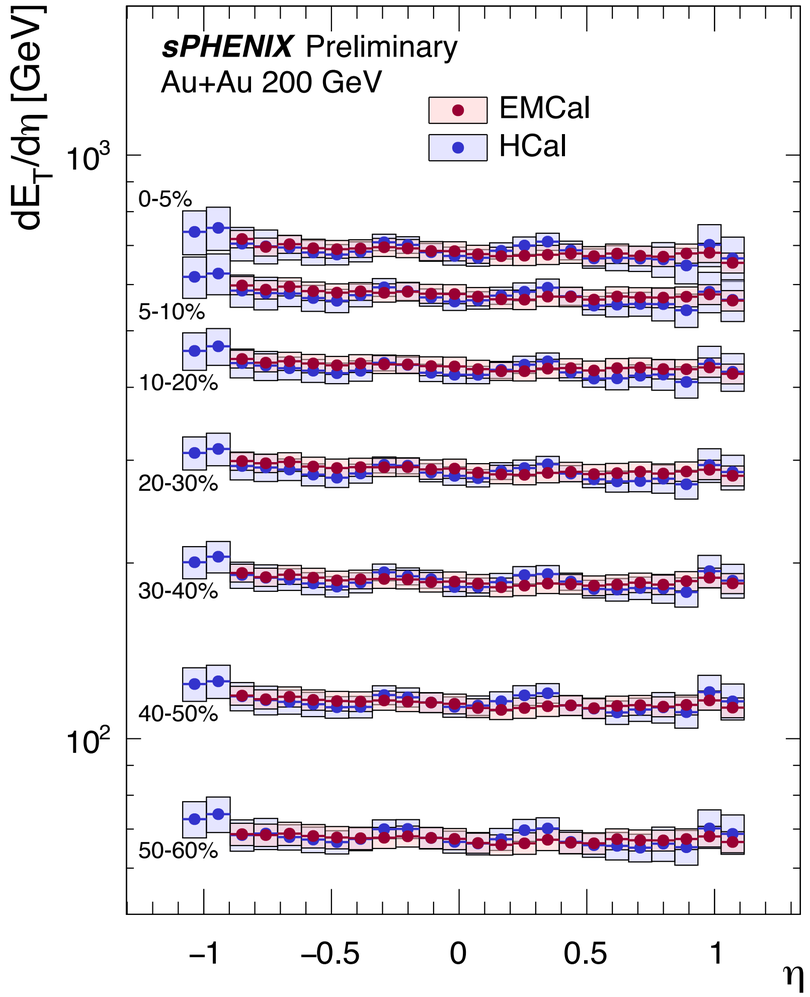
Standard Candle: Calorimeter $dE_T/d\eta$

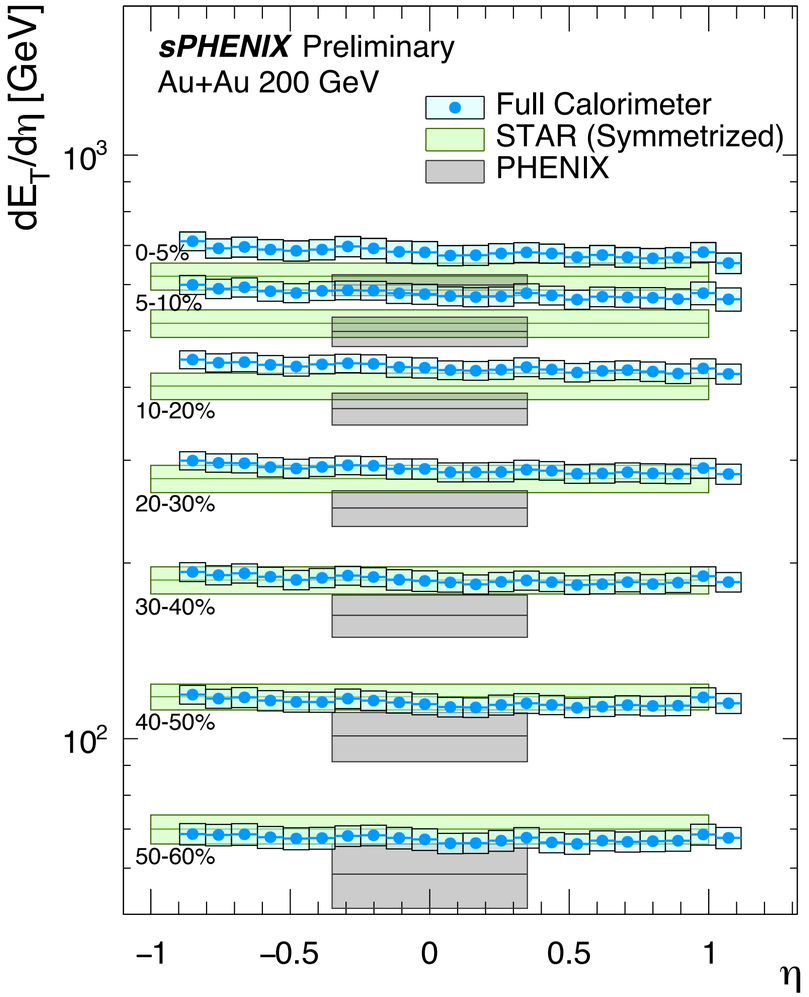
Run 2023 Au+Au commissioning dataset

Fully calibrated transverse energy across EMCal and HCal

Excellent agreement b/w EMCal and HCal

Good agreement with previous measurements at RHIC





See the conference note: sPH-CONF-BULK-2024-02!

Data taking timeline

The Run 2024 ended on Oct 21, 2024

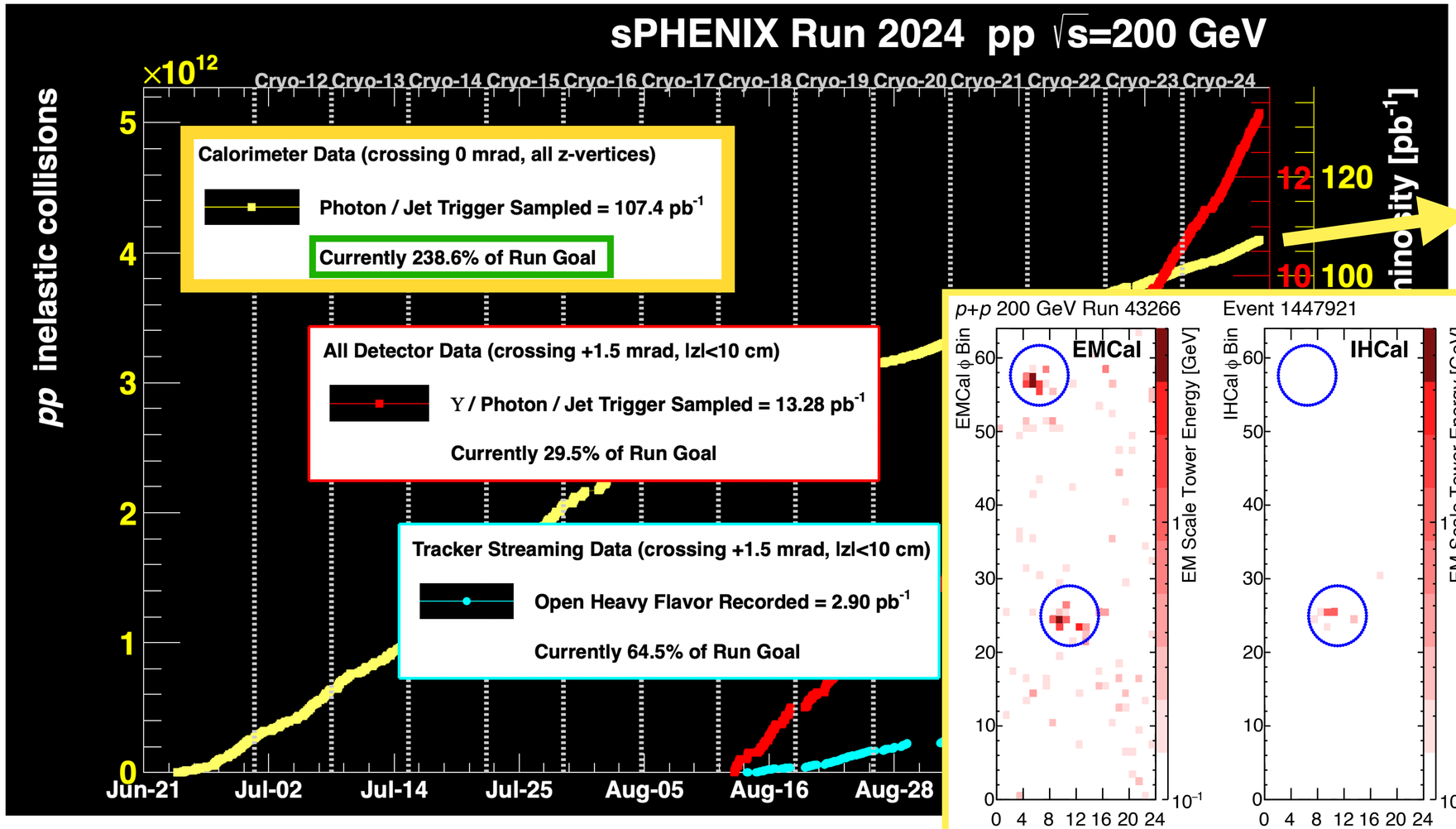
Year	Request (BUP2022)	Run plan	Reality (Species)	Reality (weeks)	Goal
2023	28 weeks	Au + Au	Au + Au	10.5*	Commissioning and RHIC standard candles
2024	28 weeks	$p^{\uparrow} + p^{\uparrow}$ $p^{\uparrow} + Au$	$p^{\uparrow}+p^{\uparrow}$	24	Au+Au baseline and spin, cold-QCD measurments
			Au + Au	3	Commissioning of TPC and MVTX

Run 2024: 6 weeks (FY23 carried over) + 19 weeks (FY24) + 2 weeks (FY25 borrowed)

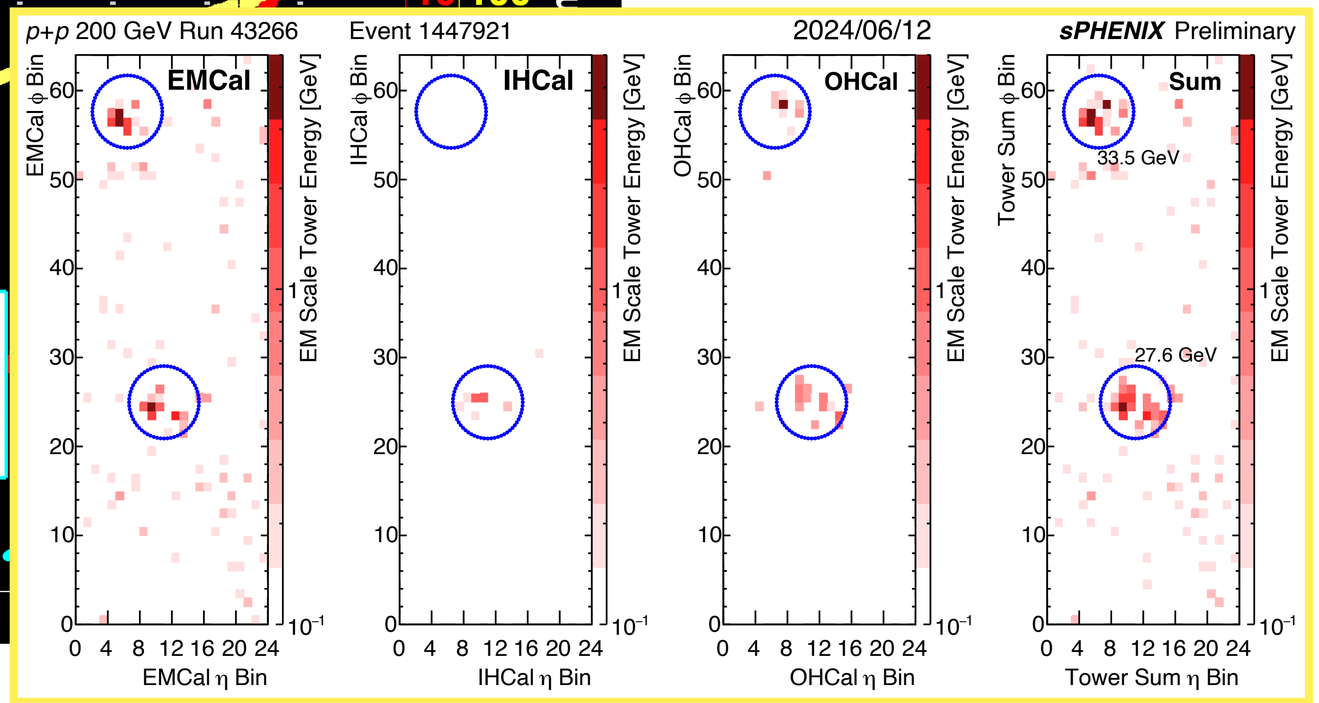
*Due to the accelerator failure

Run 2024 data taking ($p^{\uparrow}+p^{\uparrow}$)

Program 1: Calorimeter photon & jet program with zero beam crossing angle



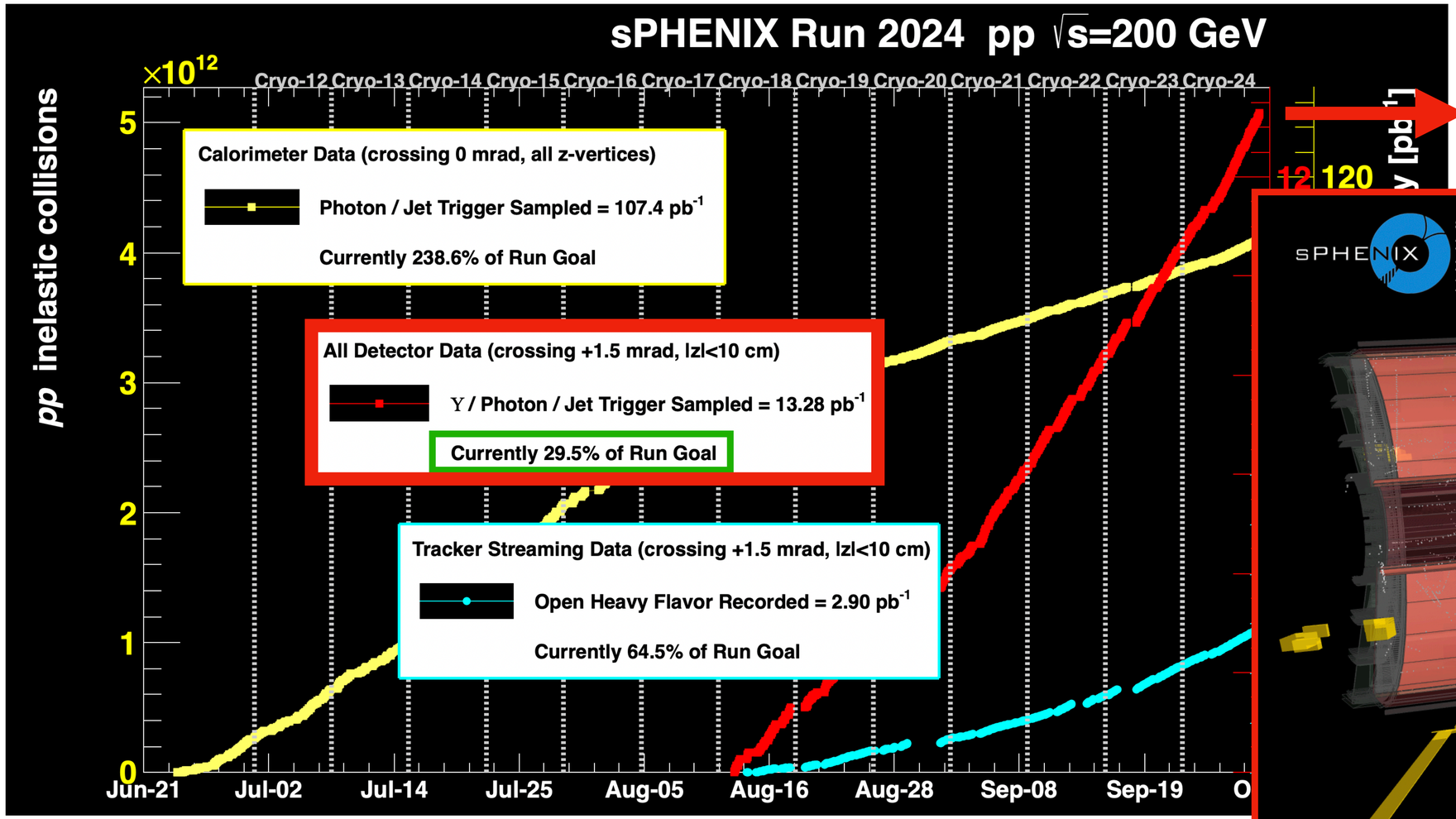
All sPHENIX subsystems taking data (except TPC)
Exceed 200% of goal!



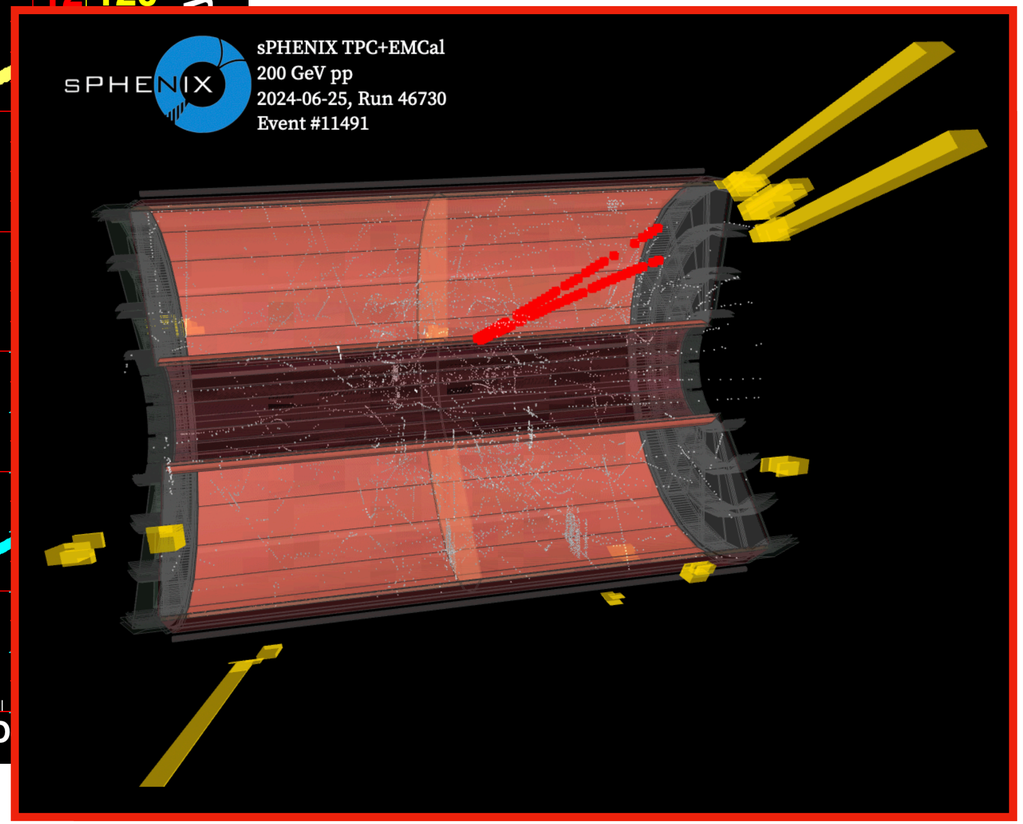
Physics of interest: photon-jet, di-jet, etc

Run 2024 data taking ($p^{\uparrow}+p^{\uparrow}$)

Program 2: All sPHENIX subsystems taking data in triggered mode w/ 1.5 mrad crossing angle



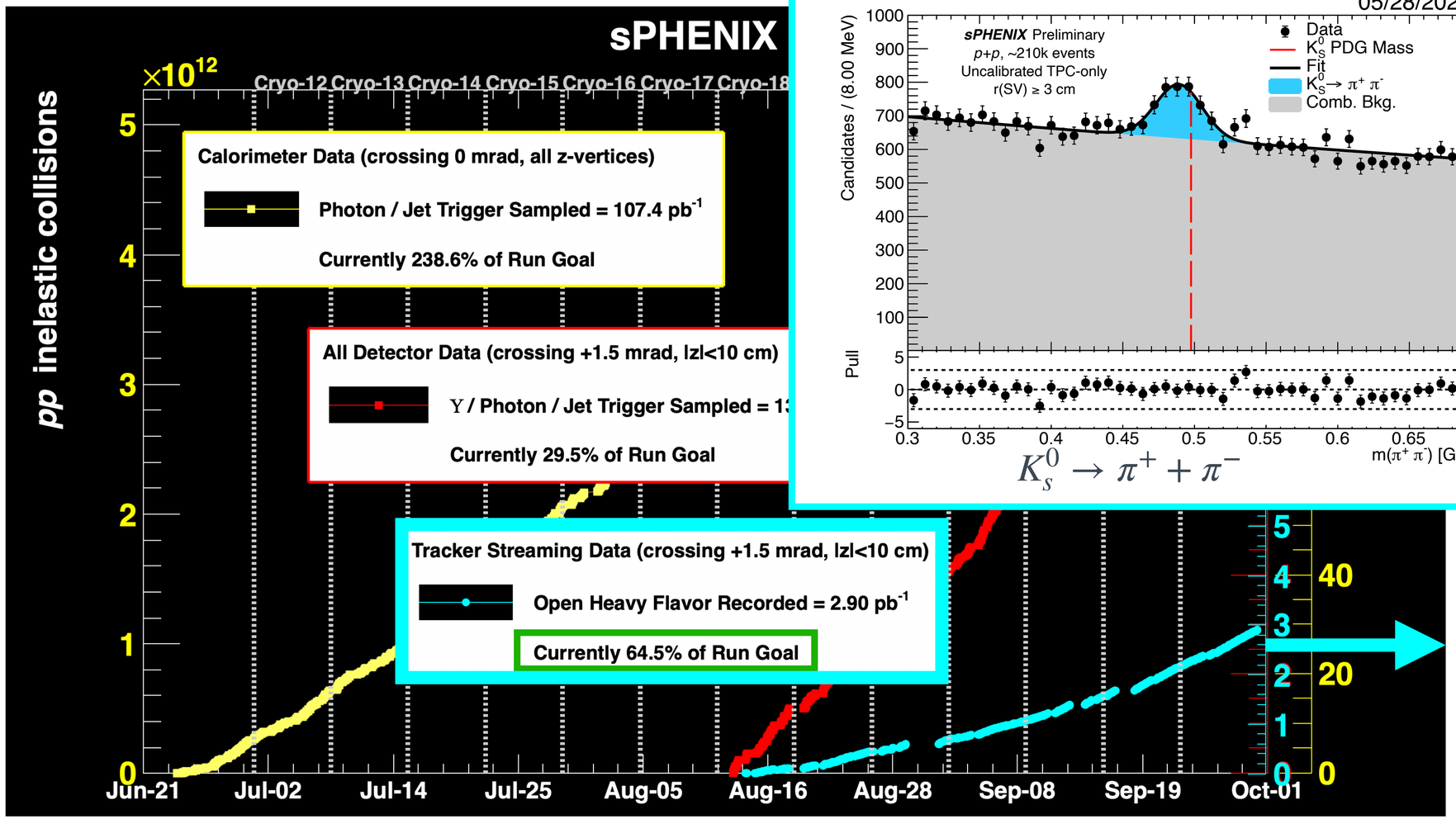
TPC stable data taking after introduction of the 5% isobutane

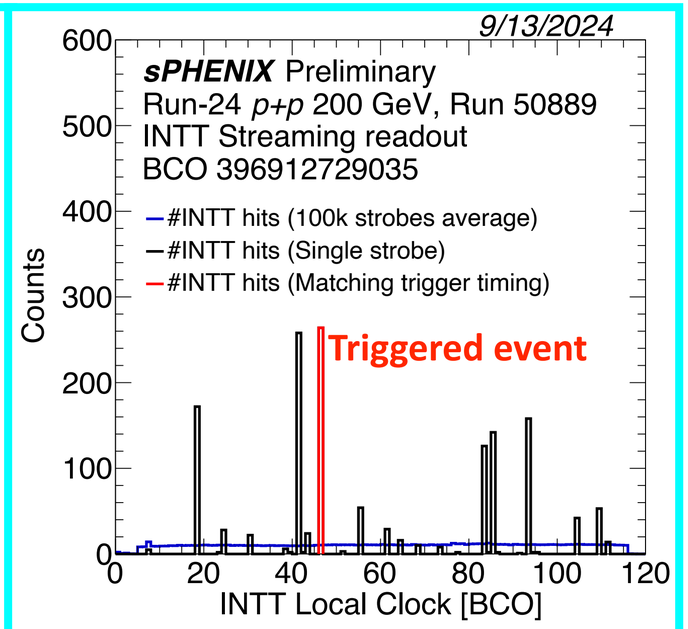


Physics of interest: Upsilon family, jet structure, etc.

Run 2024 data taking ($p^{\uparrow}+p^{\uparrow}$)

Program 3: Open heavy flavor physics program w/ 1.5 mrad crossing angle and streaming readout*





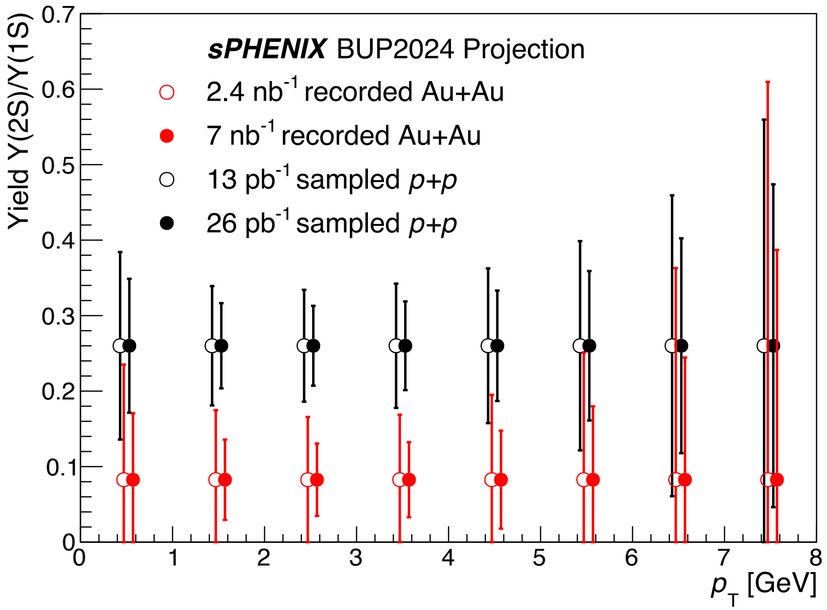
Fully streaming readout for the first time at RHIC > 10%

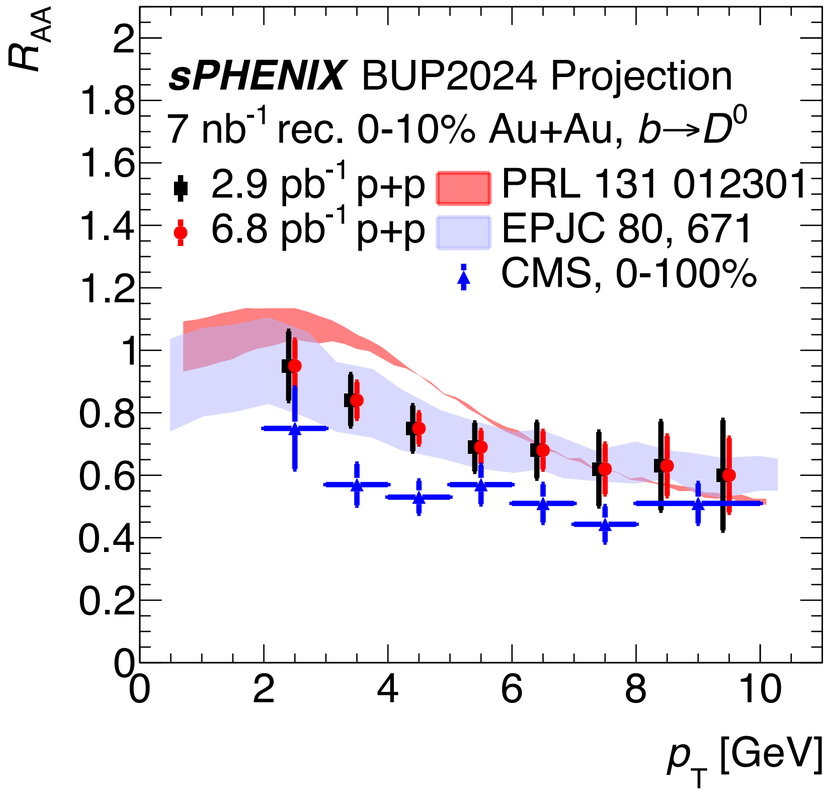
*Streaming readout: regardless trigger, record events as long as the particle hits are detected
Physics of interest: D0 & Λ_c^+ productions, etc.

Highlight of projections (BUP2024)

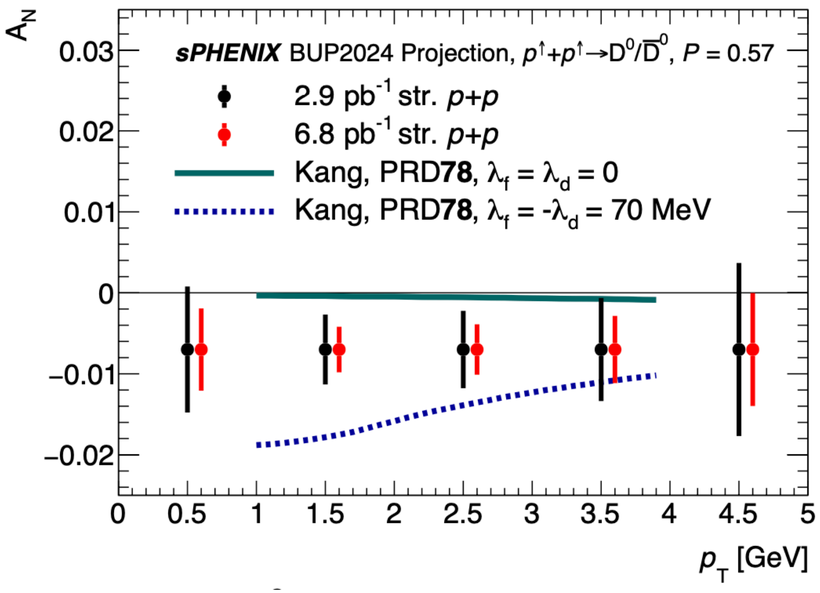
- Projected luminosity based on the delivered luminosity estimated by C-AD
- sPHENIX requests to have AuAu running reaching the statistics of 7 nb^{-1}
- Additional p+p running is planned if the Au+Au luminosity target is met and sufficient physics weeks are available

Upsilon (1S and 2S)





D0 TSSA ($p^{\uparrow} + p^{\uparrow}$)



Precise constrain gluon Sivers TMD functions

1. Distinguishing b/w models
2. Comparisons with LHC (**CMS**)

Summary

- sPHENIX, state-of-the-art jet detector, is the first new collider experiment at RHIC in over twenty years!

- In Run-23, the sPHENIX detector was fully commissioned with beam and cosmic rays
  - The preliminary standard-candle measurements of neutral pion v2 and the $dE_T/d\eta$ show good agreement with that of other experiments

- In Run-24, the large high-quality p+p data was taken, partially meeting the luminosity goals
  - 200% for calo physics program, 30% with TPC, and 65% for HF physics program

- Many analyses with Run-24 data are in progress. Stay tuned! The future for physics with sPHENIX is bright!

- The top priority in Run-25 is to collect a very high luminosity Au+Au dataset (7 nb^{-1}) for the long-envisioned QGP physics program with unique capabilities of sPHENIX at RHIC

Back up

Beam use proposal for Run 2025

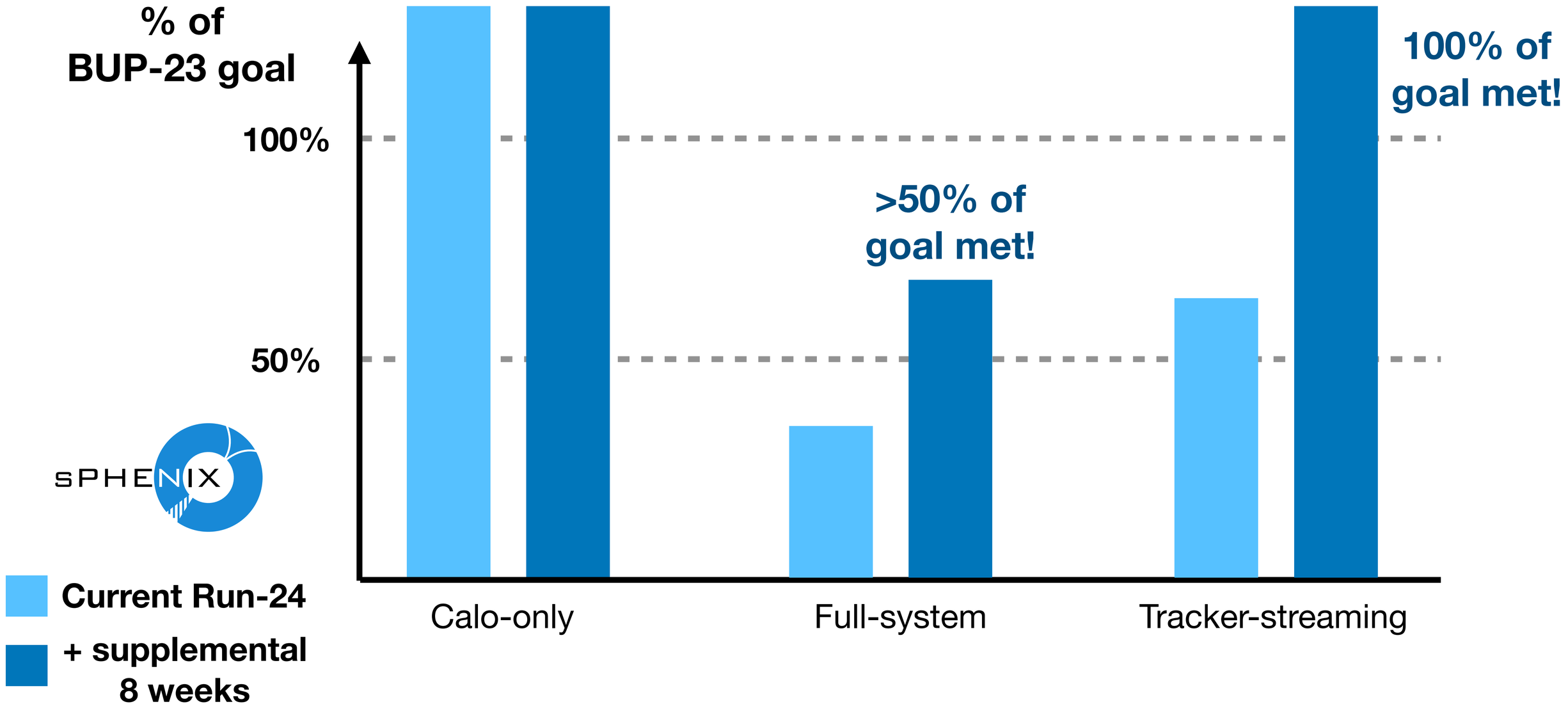
- Projected luminosity based on the delivered luminosity estimated by CA-D
- sPHENIX requests to have AuAu running reaching the statistics of 7 nb^{-1}
- Additional p+p running is planned if the Au+Au luminosity target is met and sufficient physics weeks are available

sPHENIX Physics Target in Run-25: **7 $\mathbf{nb}^{-1}$ (50B events)**		
Collision Species	Cryoweeks	Projected luminosity, $\|z\| < 10$ cm
Au+Au 200 GeV	20	2.4 – 4.2 nb^{-1} recorded
Au+Au 200 GeV	28	3.6 – 6.4 nb^{-1} recorded

If Au+Au luminosity target is met, ordered priority list for additional running:		
Collision Species	Physics weeks	Projected luminosity, $\|z\| < 10$ cm
1. p+p 200 GeV	8	13 pb^{-1} sampled + 3.9 pb^{-1} streaming
2. p+Au 200 GeV	5	80 nb^{-1} sampled + 24 nb^{-1} streaming
3. O+O 200 GeV	2	13 nb^{-1} sampled + 3.9 nb^{-1} streaming

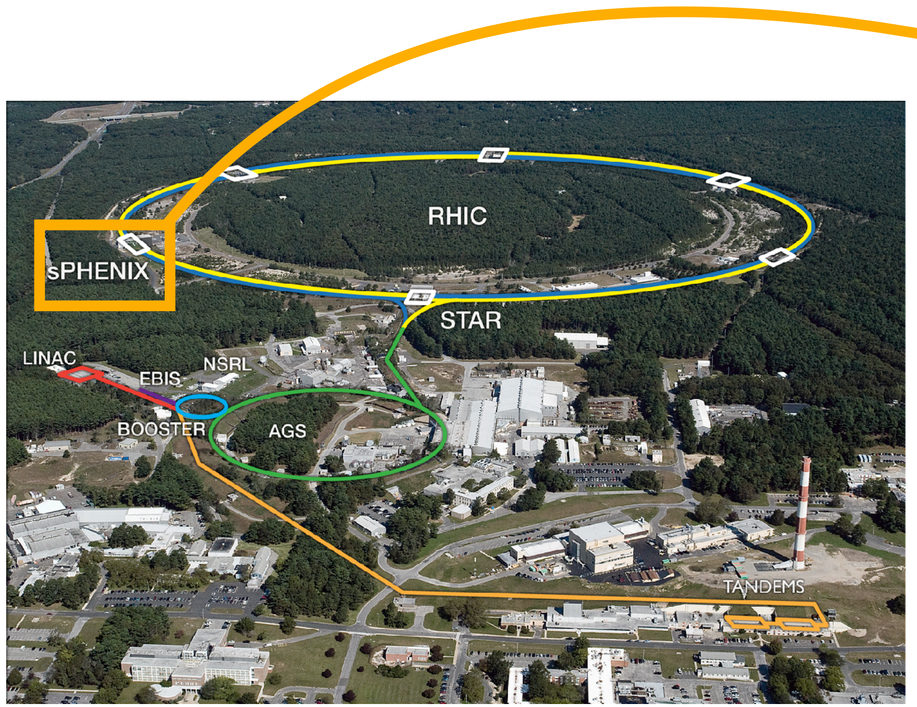
*The dry-weeks 20 (28) assuming 22 (30) weeks are received

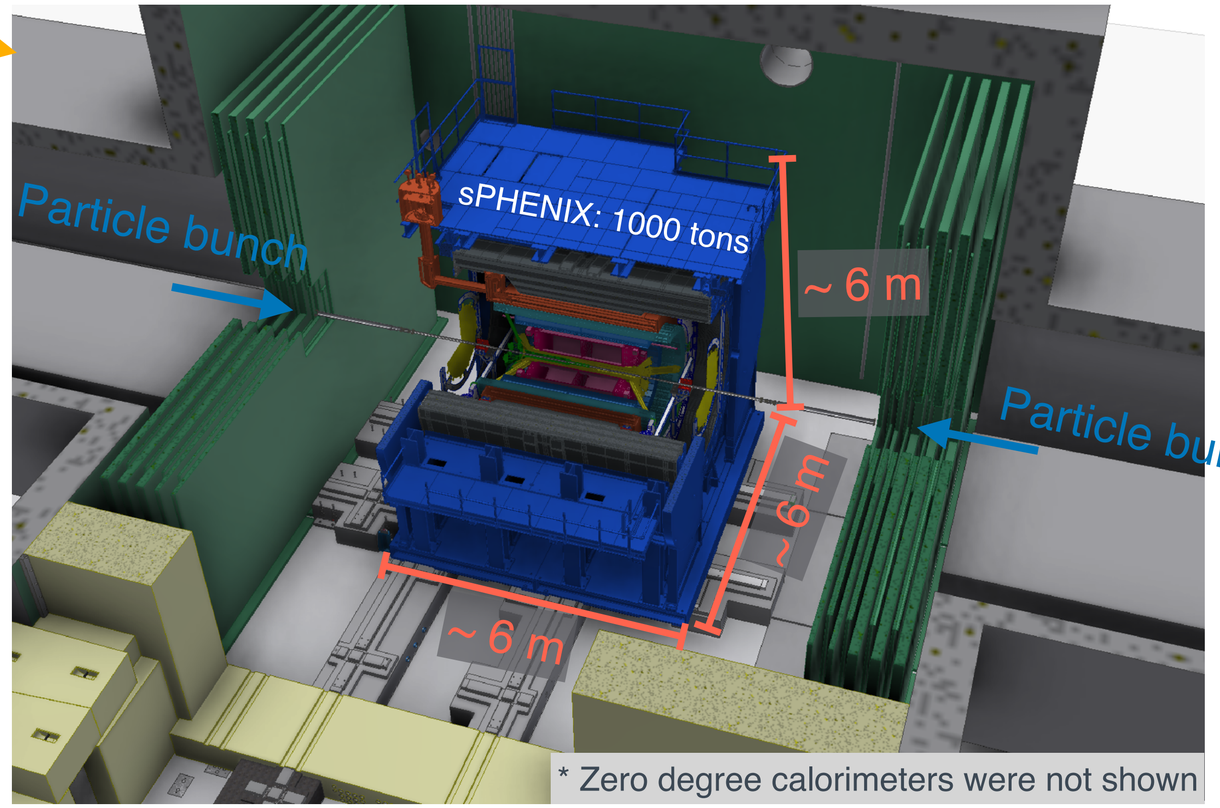
Importance of supplemental p+p running



The sPHENIX detector

sPHENIX, Super Pioneering High Energy Nuclear Interaction eXperiment, at RHIC 1008, USA



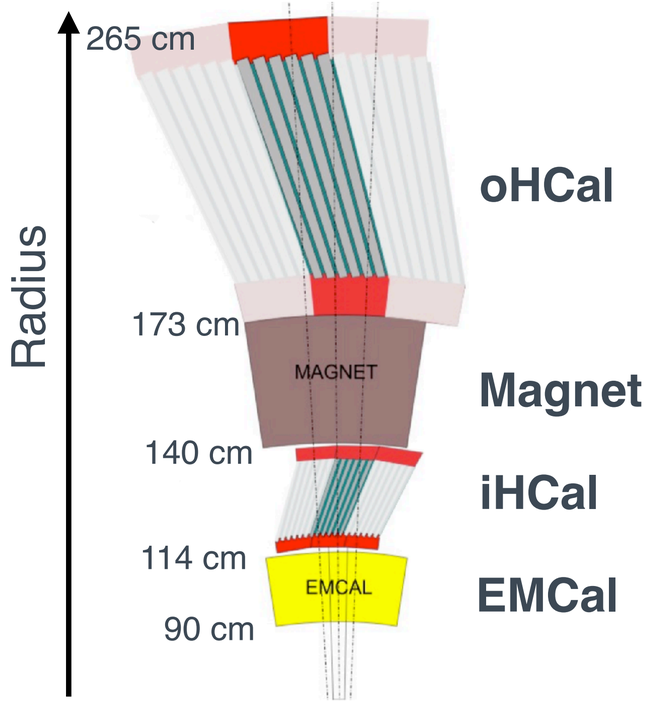


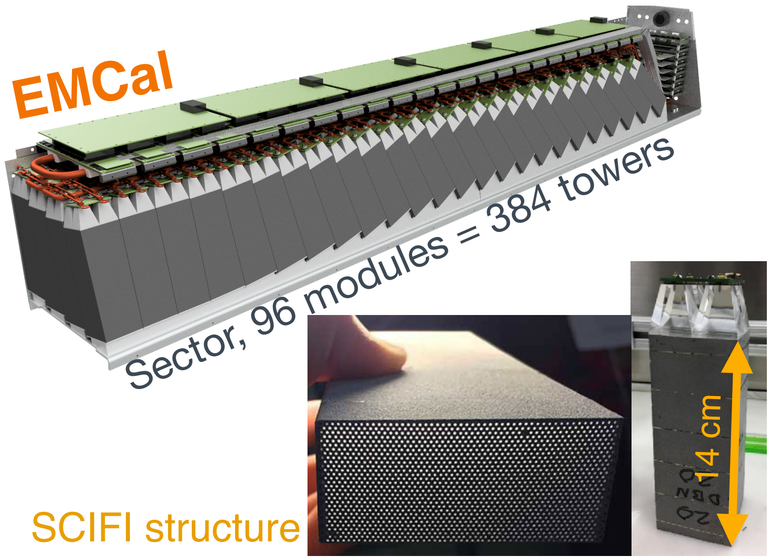
Full barrel calorimeters, 1.4 T solenoid, excellent tracking system and wide coverage

sPHENIX calorimeter system

- First at mid-rapidity at RHIC
- Hadron energy resolution: 13.5% + (64.9% / √E) [beam test paper]

Sampling calorimeters
~ 5 λ_i in total
Common readout: SiPM





- Tungsten-scintillating fiber (SCIFI)
- Radiation length: 18 X_0
- Δη x Δϕ: ~0.025 x 0.025

- Titled plates: jets go through at least 4 scintillator tiles
- Absorber: aluminum (inner) & steel (outer)
- Δη x Δϕ: ~0.1 x 0.1

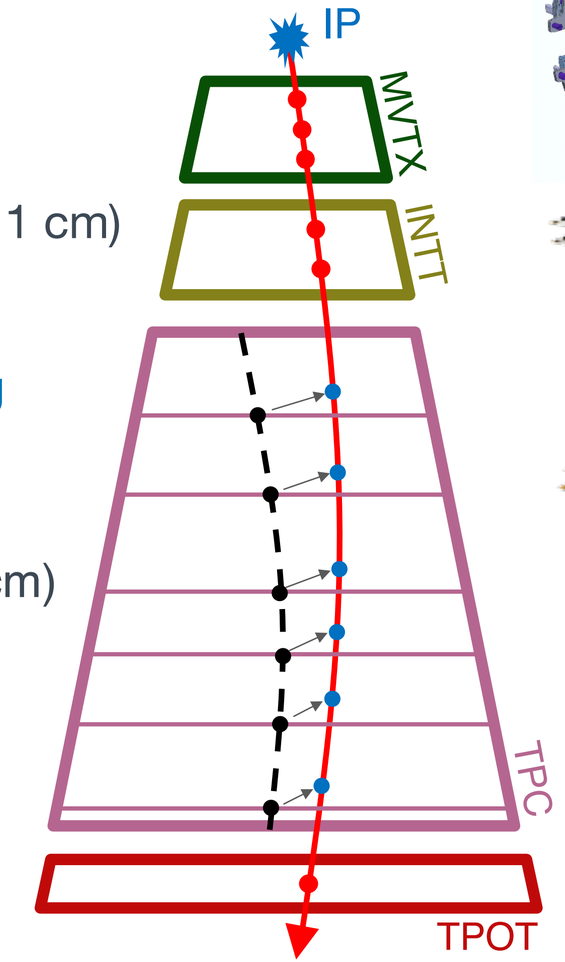
sPHENIX tracking system

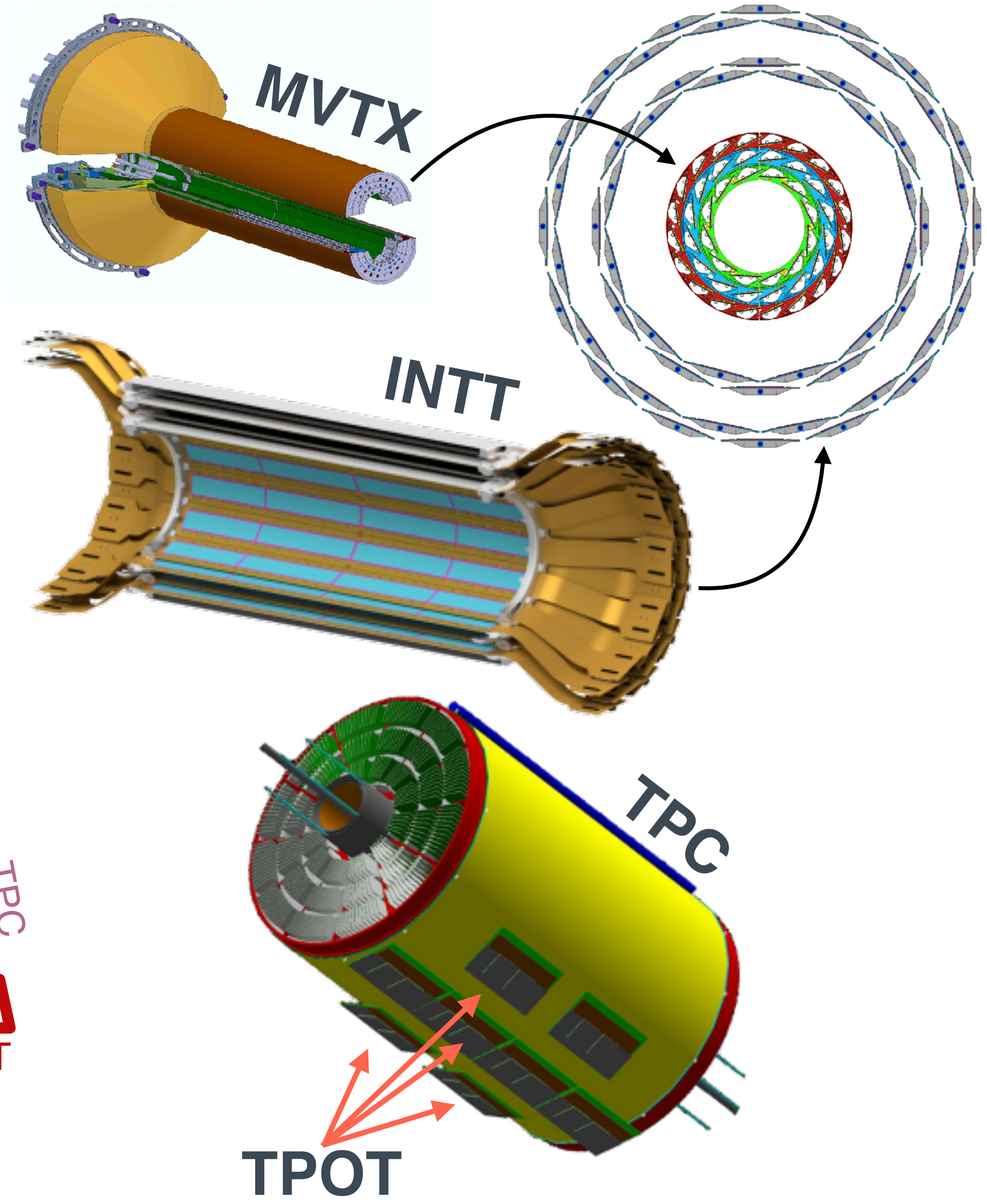
- MVTX, MAPS Vertex Tracker (2.3 < r < 3.9 cm)
  - 3 layers with cell size 27 μm x 29 μm
  - Precise vertex - O(10) micron in rϕ, and z

- INTT, Intermediate Silicon Tracker (7.5 < r < 11 cm)
  - 2 layers of silicon strips (78 μm pitch)
  - NCU & NTU participated since May 2019
  - Precise timing resolution for bunch-crossing identification

- TPC, Time Projection Chamber (30 < r < 80 cm)
  - Compact GEM-based TPC
  - ~ 14 μs drifting time
  - Precise momentum measurement

- TPOT, TPC Outer Tracker (one spacial point)
  - 8 Micromegas-based tracker
  - Calibration of space-charge distortions of TPC



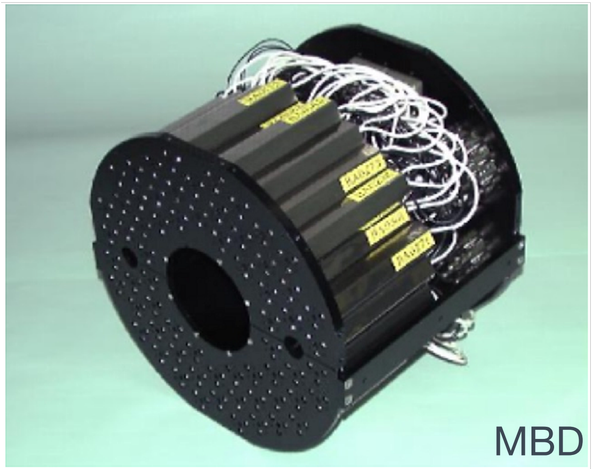


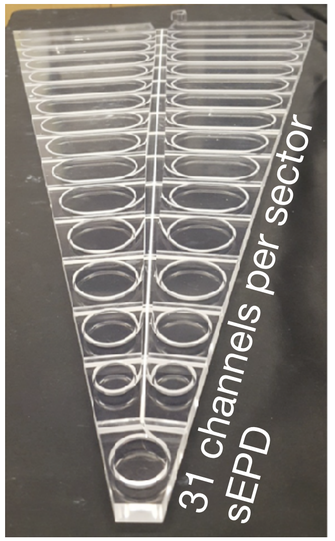
sPHENIX forward detectors

- MBD, Minimum Bias Detector ($3.51 < |\eta| < 4.61$)
  - Reuse of PHENIX Beam-Beam Counter (BBC)
  - 50 ps timing resolution
  - Centrality & luminosity measurements, and Min. Bias. definition

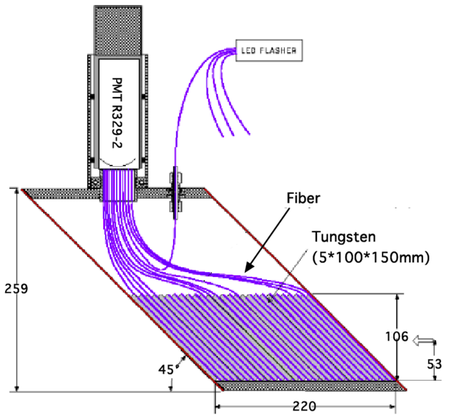
- sEPD, sPHENIX Event Plane Detector ($2.0 < |\eta| < 4.9$)
  - Bigger version of STAR EPD ($4.6 < r < 90$ cm)
  - 2 wheels of scintillator w/ embedded WLS fibers
  - Improve the event plane determination significantly

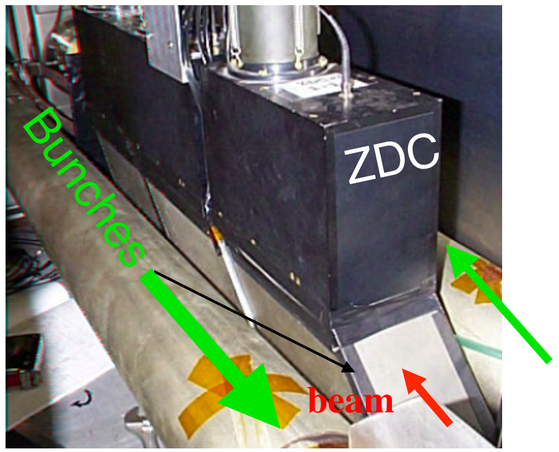
- ZDC, Zero Degree Calorimeter*
  - Reuse of PHENIX ZDC complex
  - Located at ±18.5 m from IP
  - Npart in heavy ion and Local polarimeter $p^{\uparrow}+p^{\uparrow}$





ZDC (Zero Degree Calorimeter)





*the ZDC complex includes Shower Max Detector (SMD) and Veto counter

RHIC termination - Aug 1st 2023

Beam commissioning shut down 8 weeks earlier

- At 12:31 on 1 Aug 2023 a spurious trip of the Quench Interlock System commanded the RHIC power supplies to turn off and for the energy extraction system to begin dissipating the stored energy in the Blue Ring.
- At 12:39 the Cryo control room informed the MCR that the Blue Valve Box in 1004 B was venting Helium to the exterior of the building.

Mail from Haiyan (BNL ALD)

> Since my last email, we have learned that the repair will be significantly more involved than what previously we had hoped for a more optimistic scenario. The damage is more extensive than just a weld as there are multiple shorted Blue circuits, and all are in the same cryo line. The expected access to the valve box will be next Friday, August 11th. The estimate for the repair is 4 weeks or more following that. Given where we are in the calendar, it is therefore prudent that we end Run 2023 and start controlled warm-up now. This plan allows sPHENIX magnet to be cold until at least the end of next week and please work with CAD colleagues on this.

- Commissioning continued with cosmic rays until Oct!
- Bank the funding and expand Run 24

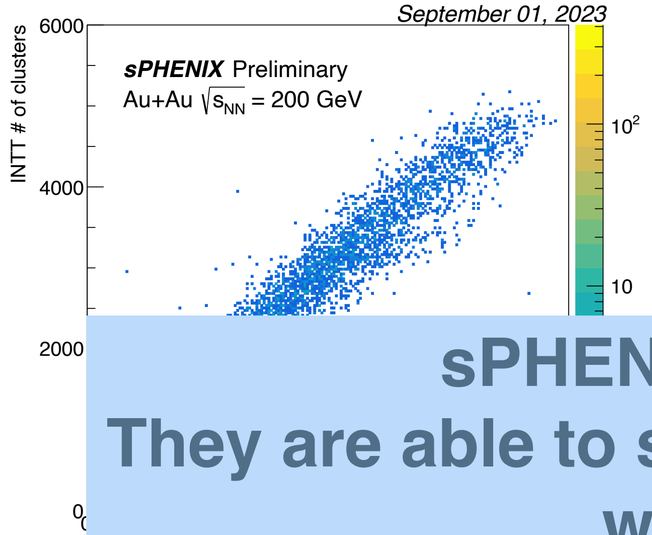
sPHENIX collaboration

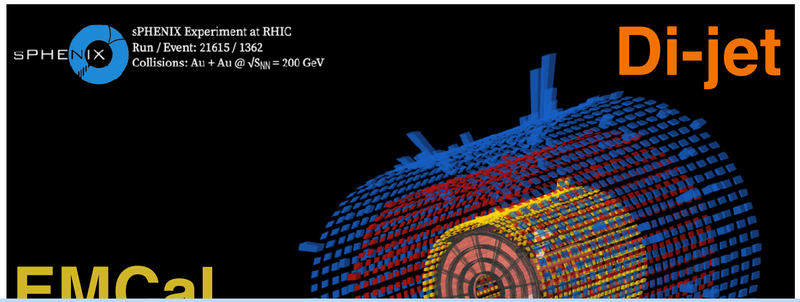
- **Encouraging diversity is a priority for our collaboration**

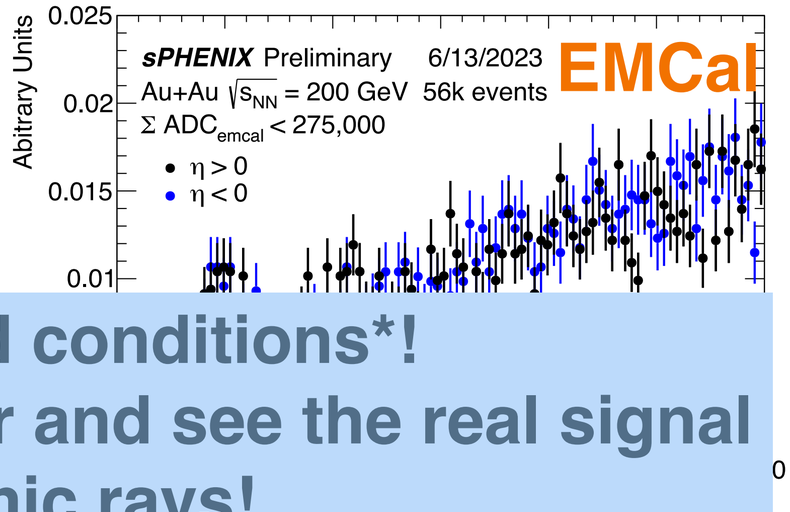
Commissioning in Run 2023

Run 2023 commissioning dataset

With Au+Au collisions



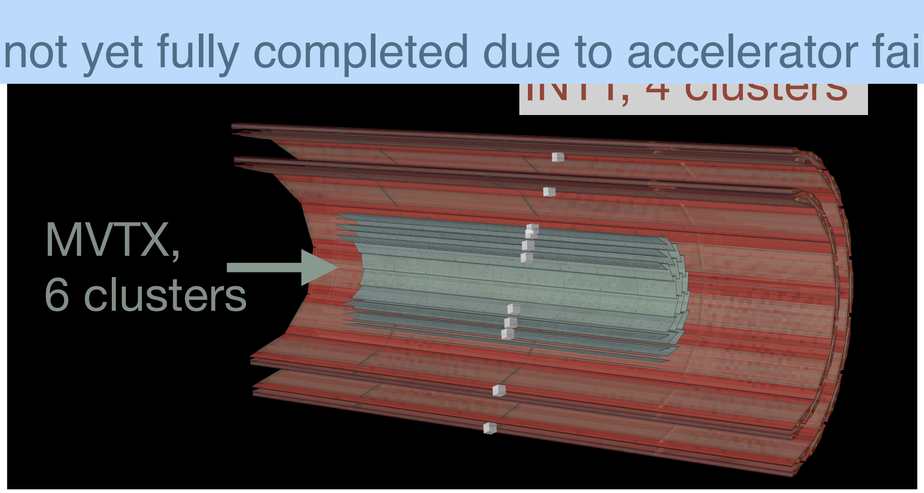


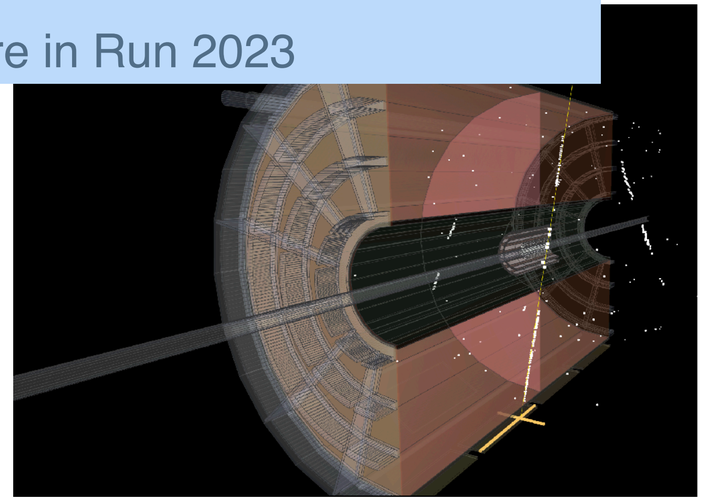


sPHENIX sub-systems are in good conditions*!
They are able to synchronize with each other and see the real signal with either collisions or cosmic rays!

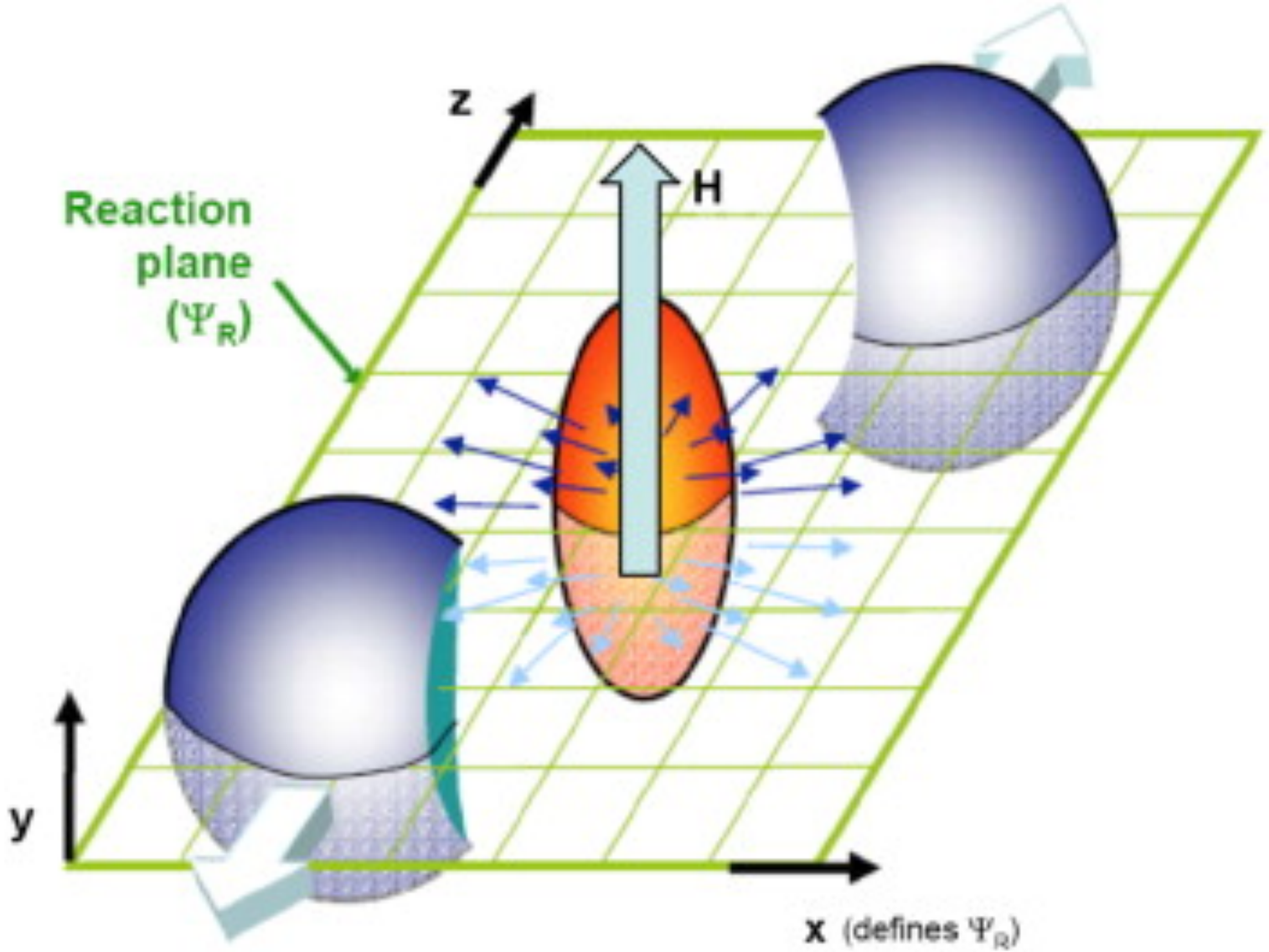
*MVTX & TPC commissioning not yet fully completed due to accelerator failure in Run 2023

With cosmic rays



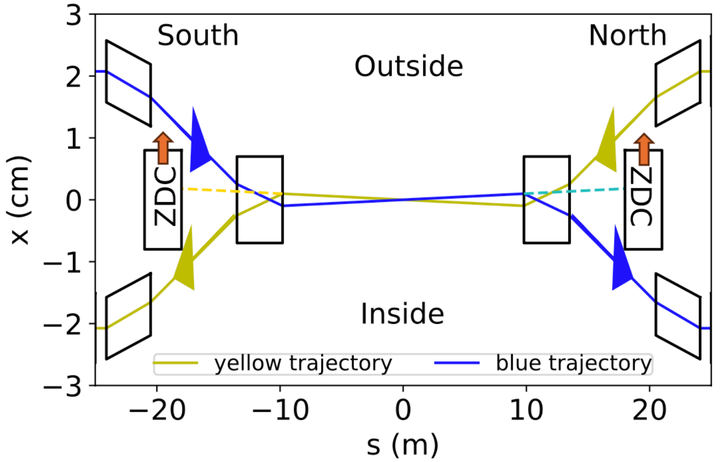


The reaction plane

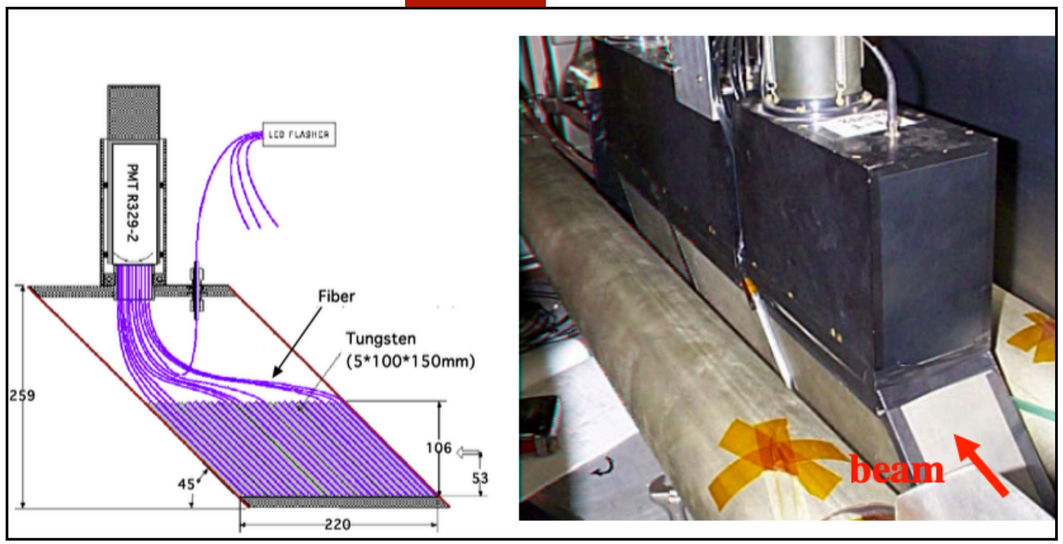


ZDC/SMD/Veto counter

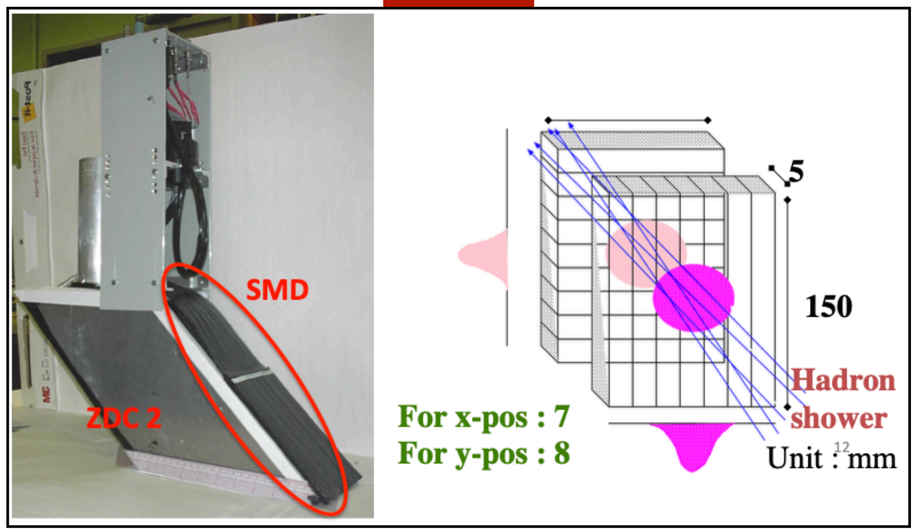
- **Zero Degree Calorimeter (ZDC)**: 3 modules in each side for the energy measurement
- **Shower Max Detector (SMD)**: b/w 1st and 2nd ZDC modules for the position measurement
- **Veto counter**: one in the front and one in the back of ZDC for the charged particle rejection
- The whole sets are located at ±18.5 m away from the interaction point, between beam pipes



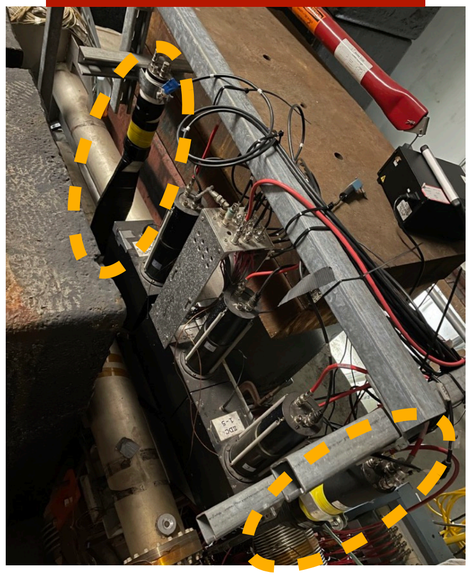
ZDC



SMD



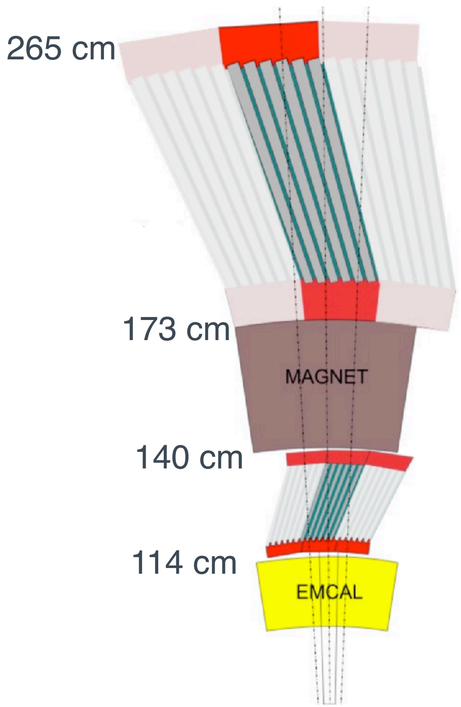
Veto counter



sPHENIX calorimeter system - HCal

- Inner HCal + Outer HCal + EMCal
- First at mid-rapidity at RHIC
- Titled plates: jets go through at least 4 scintillator tiles

Sampling calorimeters
~ 5 λ_i in total
Common readout: SiPM

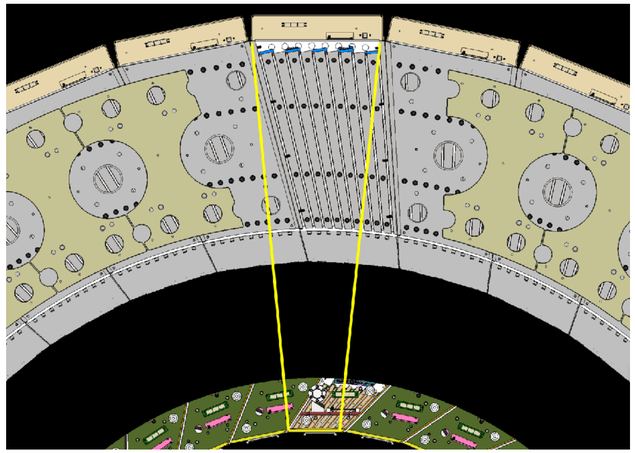


oHCal

Magnet

iHCal

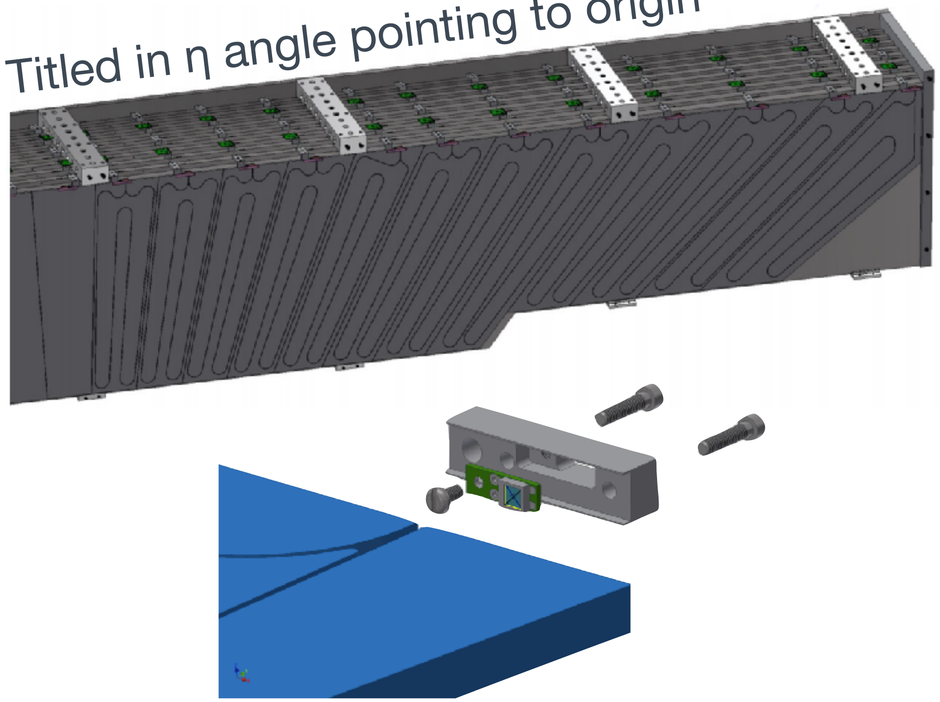
EMCal



Total channel		~ 3k
Outer	Absorber	Steel
	Titled	-12^0
Inner	Absorber	Aluminum
	Titled	+32^0
Δη x Δϕ		~ 0.1 x 0.1
Energy resolution*		13.5% + (64.9% / √E)

*Calorimeters combined

Titled in η angle pointing to origin



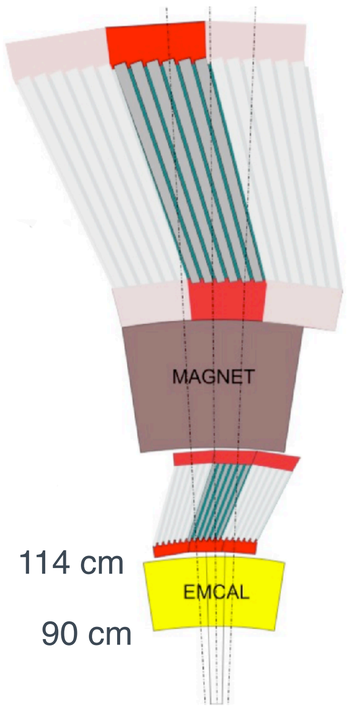
WLS fiber embedded in scintillator plate

Reused by EPIC @EIC

sPHENIX calorimeter system - EMCal

- SCIntillating FIber spaghetti calorimeter (SCIFI)
- $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
- Radiation length: 18 X_0 (14 cm in length per tower)

Sampling calorimeters
~ 5 λ_i in total
Common readout: SiPM

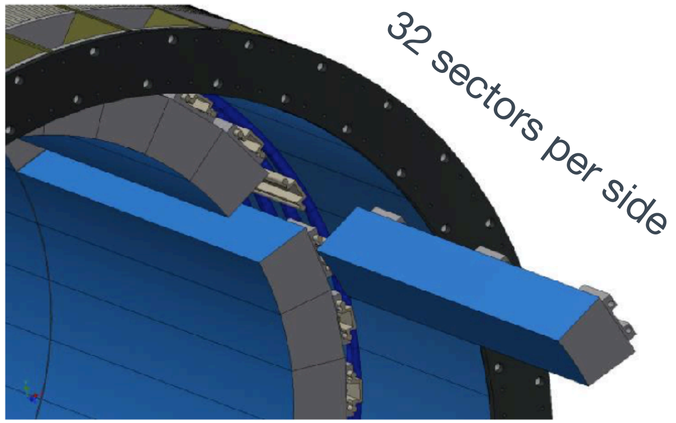


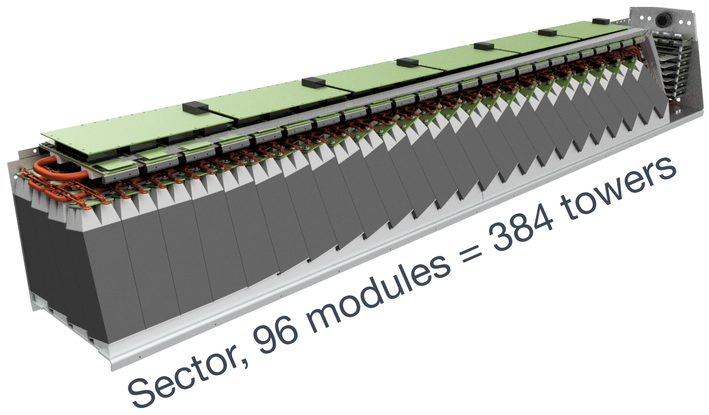
oHCal

Magnet

iHCal

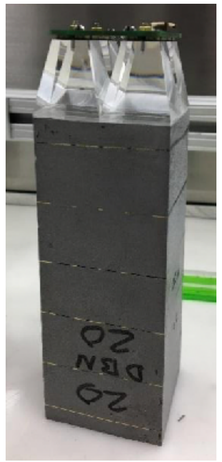
EMCal

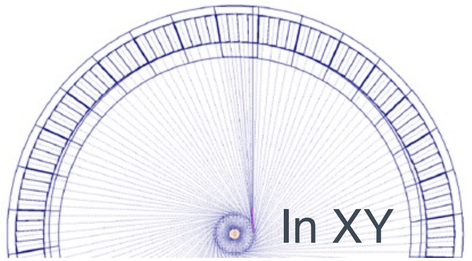


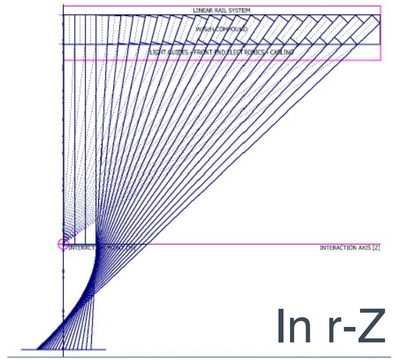


SCIFI calorimeter

Module, 4 towers







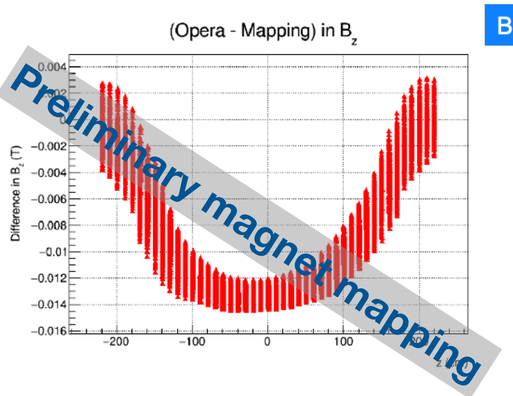
Modules are approximately projective and titled in η and ϕ

Reused by EPIC @EIC

sPHENIX magnet & installation

Former Babar magnet was transported from SLAC to BNL in 2015

Installation: October 7th 2021



B-Field at TPC location = 1.4T

the B-field rows (Bx, By, Bz) :

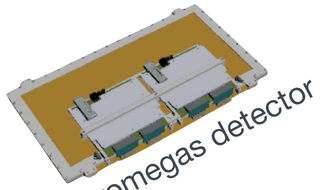
BValT = -1.411592, -0.004703, 0.005511
BValT = -1.401875, 0.004362, 0.005242
BValT = -1.397893, 0.002913, 0.009079
BValT = -1.399307, 0.003422, 0.009062
BValT = -1.406711, 0.006496, 0.008555
BValT = -1.409695, 0.008401, 0.008233
BValT = -1.394770, 0.005816, 0.008268
BValT = -1.396441, 0.005674, 0.008015
BValT = -1.403802, -0.002153, 0.009974
BValT = -1.410893, -0.000813, 0.008565
BValT = -1.395020, 0.001417, 0.005830
BValT = -1.402785, -0.007759, 0.006783

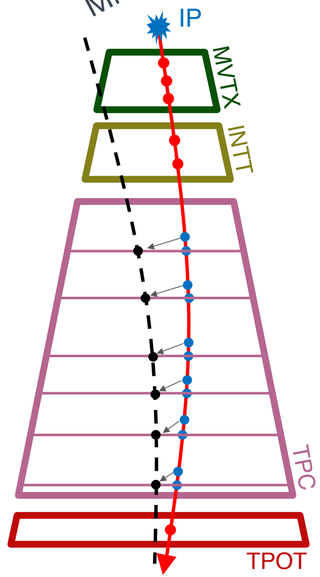
The magnet is ready for sPHENIX!

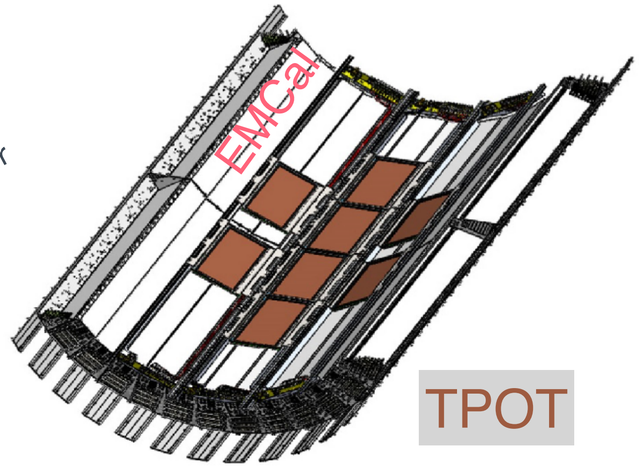
Reused by EPIC @EIC ?

sPHENIX tracking system

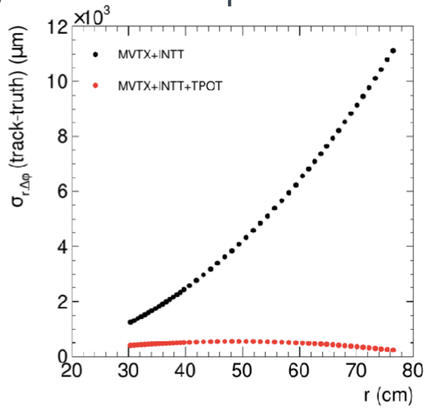
- TPOT, TPC Outer Tracker (one space point)
  - 8 Micromegas-based tracker (2 layers)
  - Resolution: ~ 200 μm (ϕ) and ~ 300 μm (z)





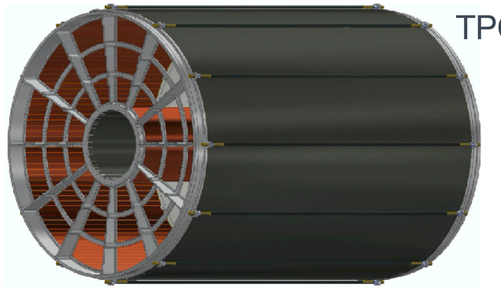


Single-track extrapolation accuracy

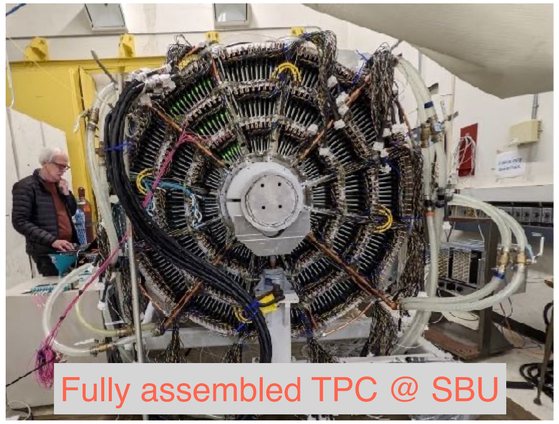


- For the calibration of space-charge distortions of TPC

- TPC, Time Projection Chamber (30 < r < 80 cm)
  - Compact GEM-based TPC
  - Gas: mixture of Argon/CF4
  - Operation voltage: ~ 45 kV
  - Length: 2.11 m (~ 14 μs drift time)

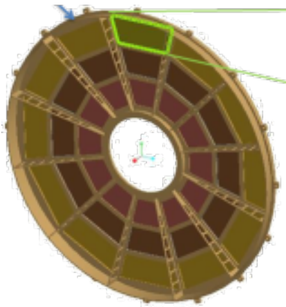


TPC field cage

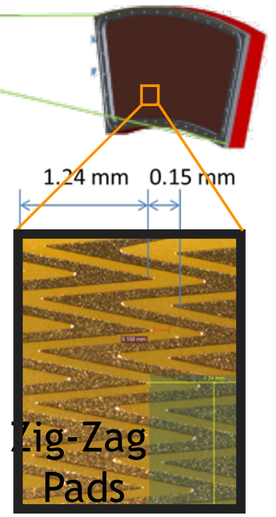


Detection plane

Module



72 modules
2(z), 12(ϕ), 3(r)

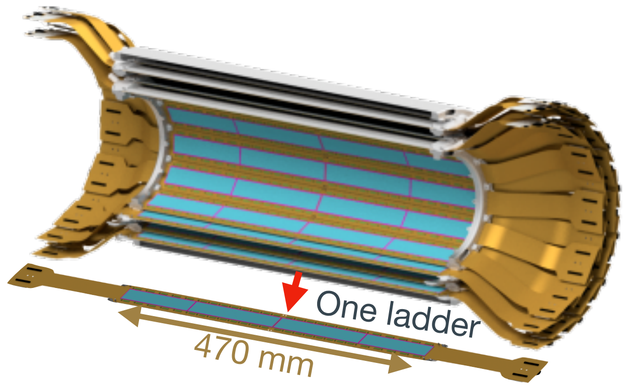


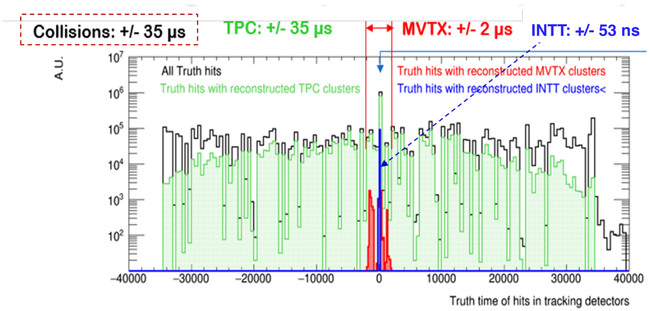
- 48 space points providing precise momentum measurements

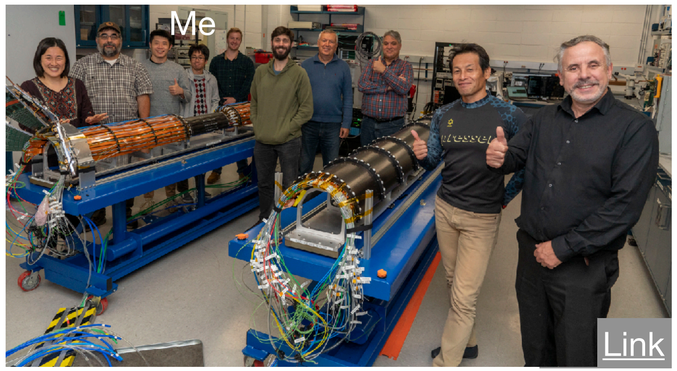
sPHENIX tracking system

- INTT, Intermediate Silicon Tracker (7.5 < r < 11 cm)
  - Inherit from PHENIX FVTX
  - Strip width: 78 μm (~ 370k channels)
  - 320 μm thickness (1.08% X_0)
  - NCU & NTU participated the INTT group since May 2019

2-layer barrel tracker
made of 56 ladders



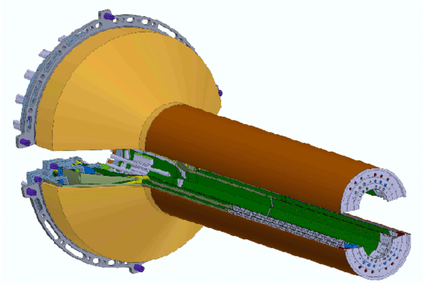


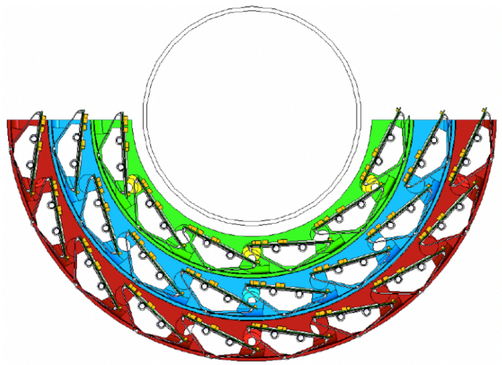


- Precise timing resolution for bunch-crossing identification
- Identify the track timing of TPC and MVTX

- MVTX, MAPS VerTex tracker (2.3 < r < 3.9 cm)
  - Monolithic Active Pixel Sensor
  - Modules from ALICE ITS-2
  - Cell: 27 μm x 29 μm (~0.5M channels)
  - 50 μm thickness (0.3% X_0)

3-layer sensor barrel
made of 48 modules

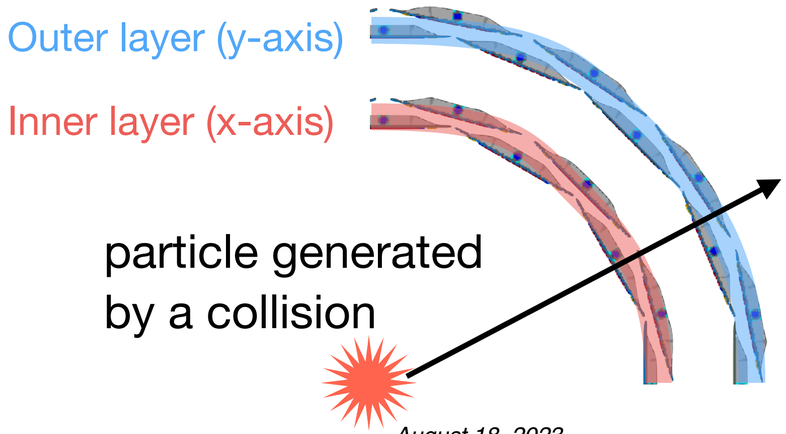


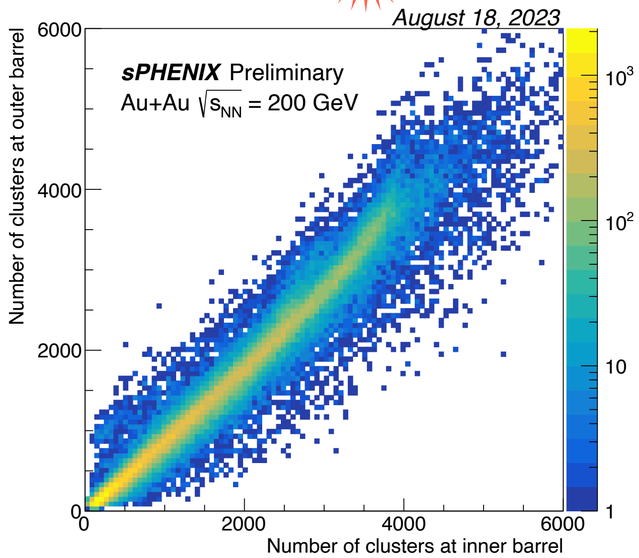


- Superb vertex determination
- Ideal detector for high multiplicity QGP physics study

INTT performance

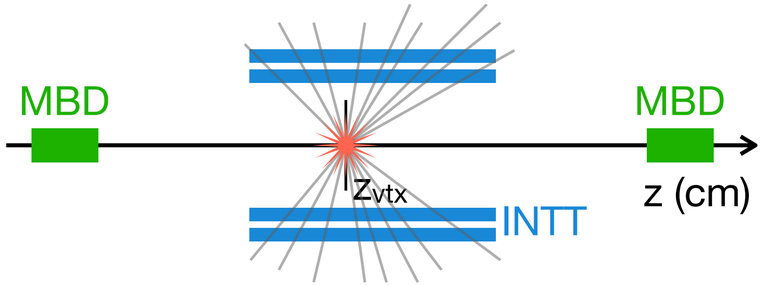
The inner vs outer layers

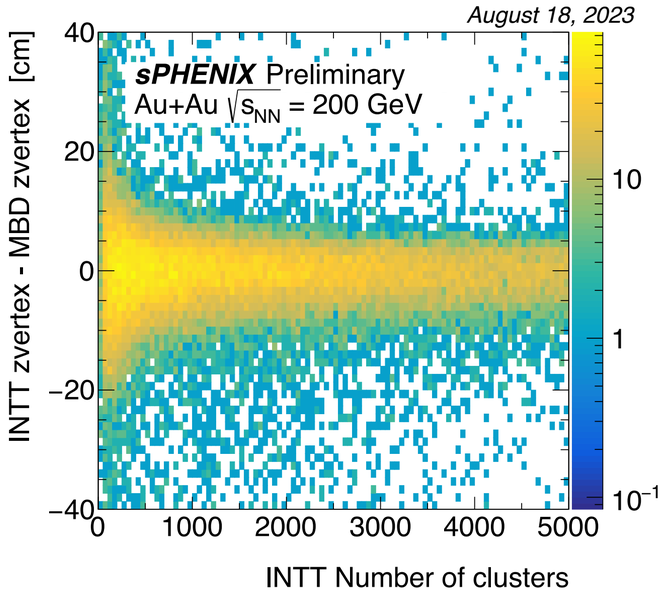




A clear positive correlation was found as expected!

$z_{vtx,\ MBD}$ VS $z_{vtx,\ INTT}$

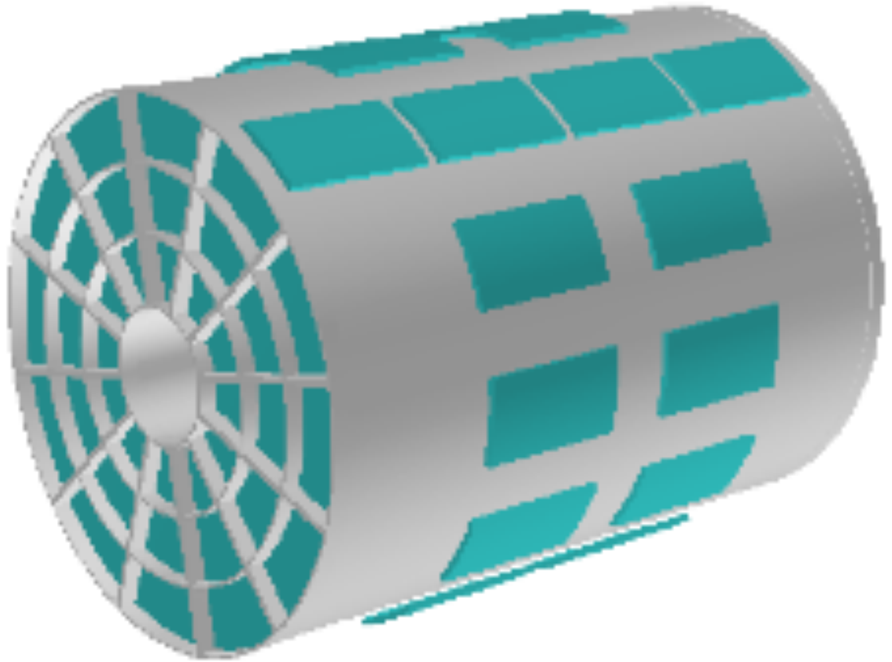




A good agreement of v_{txz} with MBD was confirmed!

TPOT - original design

Original plan (approximately full ϕ coverage)



TPC Zig-Zag pads

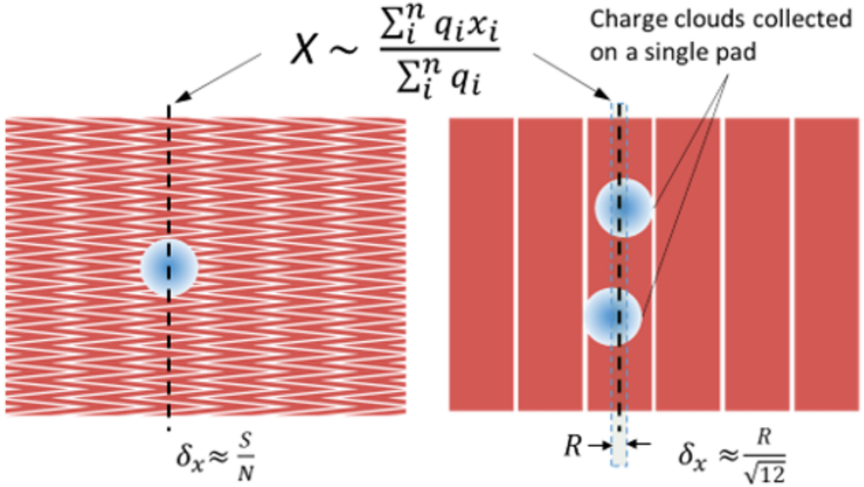
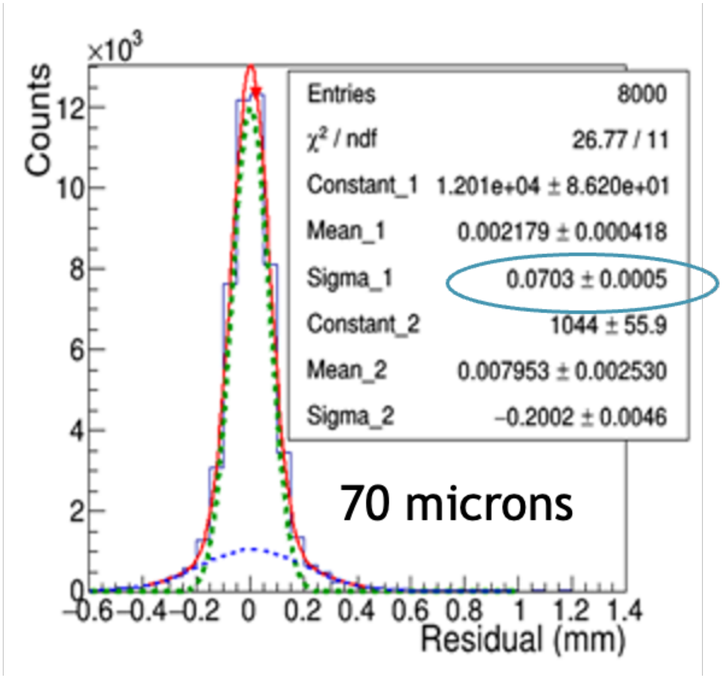


Fig. 1 Sketches of two different readout patterns demonstrate charge sharing and its impact on the centroid calculation and the related position error for a zigzag and rectangular pad geometry. 6 channels are shown for each pattern with the same pitch. (The drawings are to scale.)

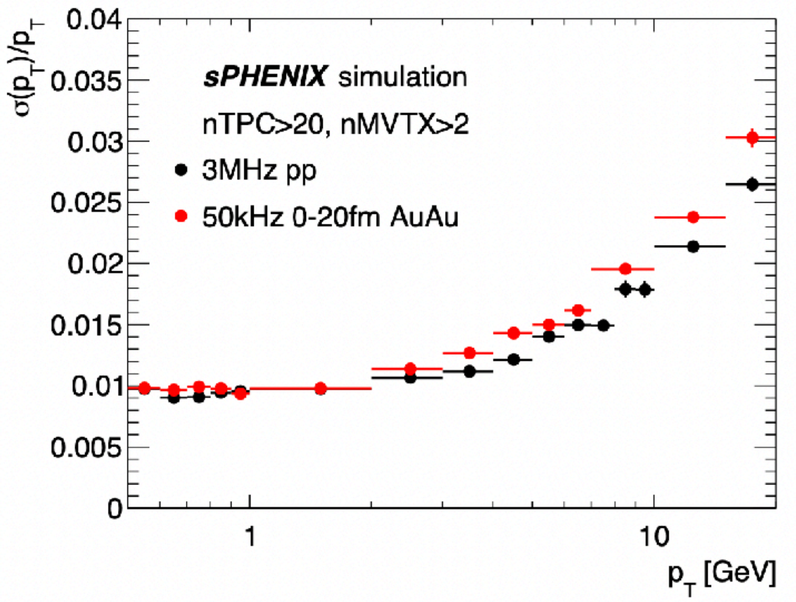


- Low diffusion can cause single pad hits (poor resolution).
- Zig-Zags not only minimize single hits, they achieve resolutions to a smaller fraction of the pitch than rectangles.
- EXTENSIVE studies at BNL lead to several principle conclusions
  - Incursions of nearly 100% are required for good linearity.
  - Tip-to-tip pitch must be controlled relative to avalanche spread.
  - Best linearity when gaps are VERY small (<100 mm).

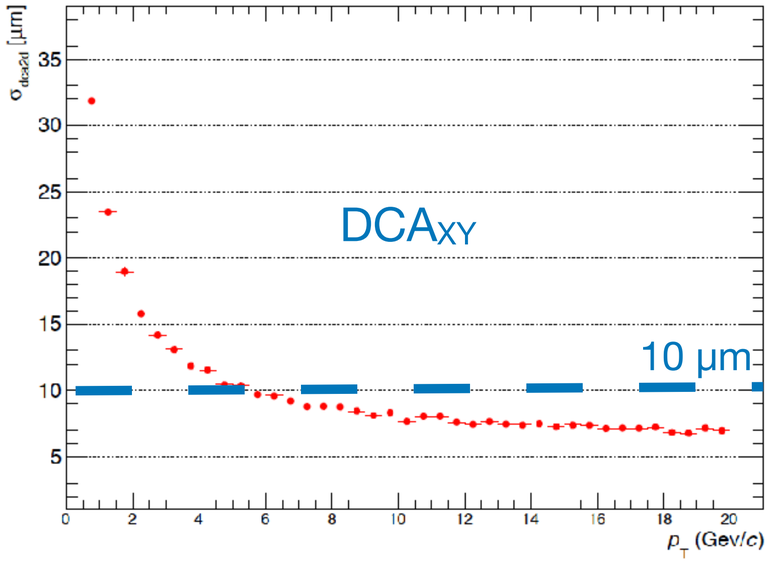
sPHENIX tracking system - 4D tracker

1. MVTX
   - Precise vertex measurement
2. INTT
   - Bridges the tracks of TPC and MVTX
   - High-precision timing for bunch-crossing identification
3. TPC
   - Precise momentum measurement
   - Particle identification (PID) ?
4. TPOT
   - Correction of TPC space-charge distortion

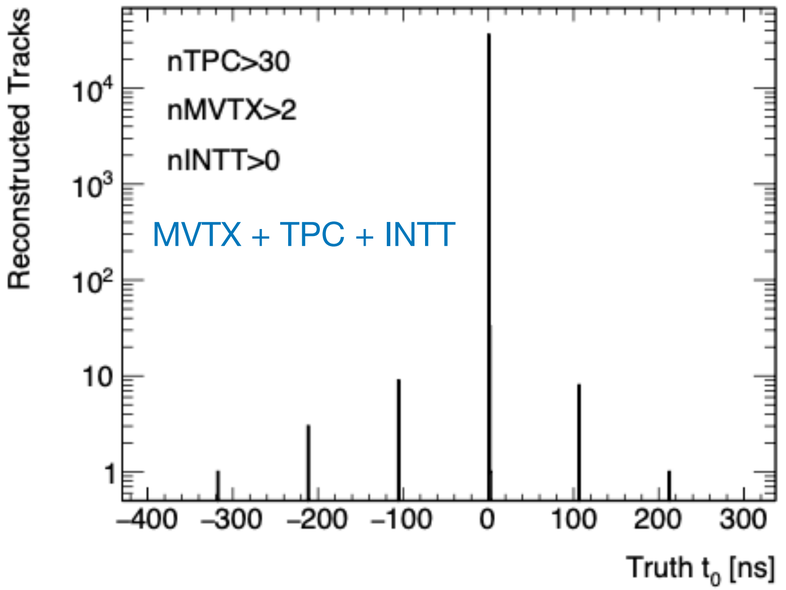
MC - Momentum resolution



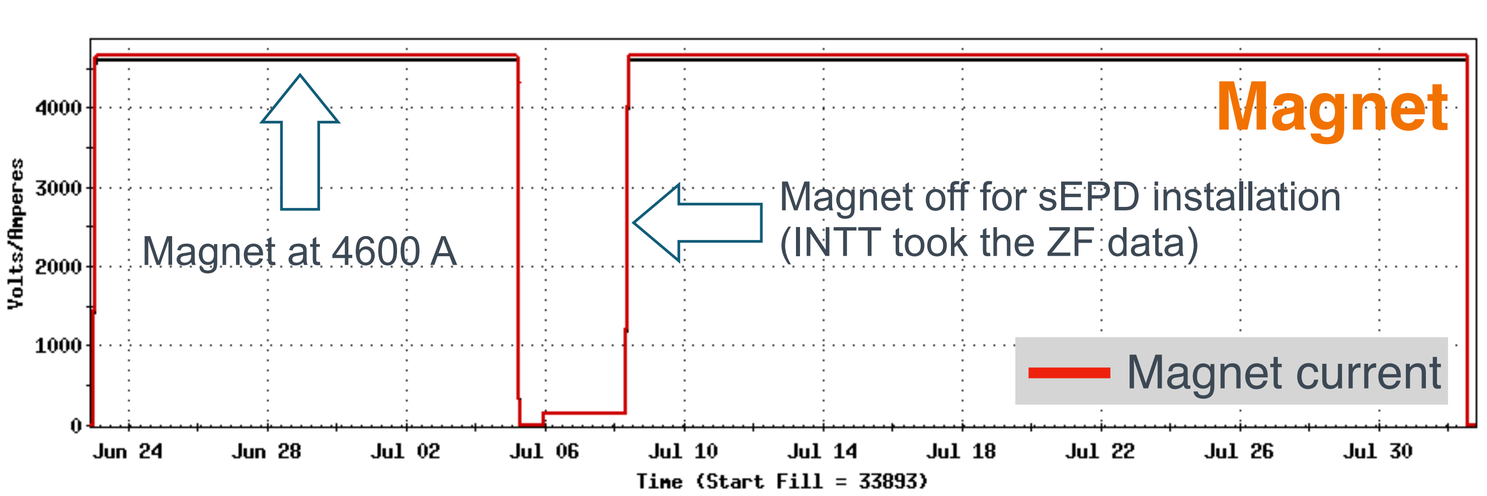
MC - DCA_{XY} resolution

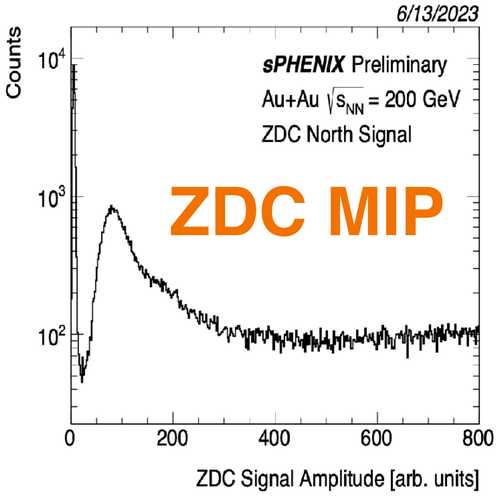


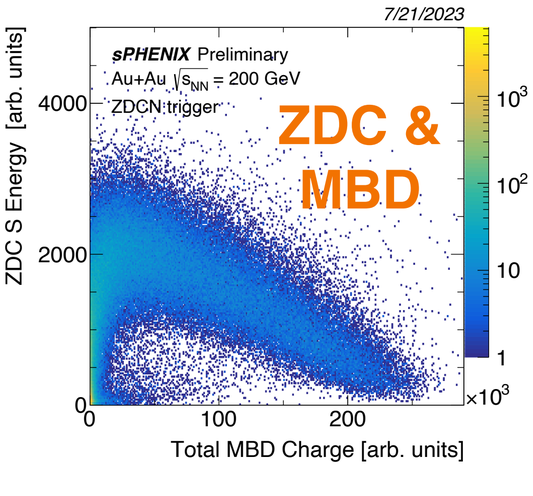
MC - timing resolution



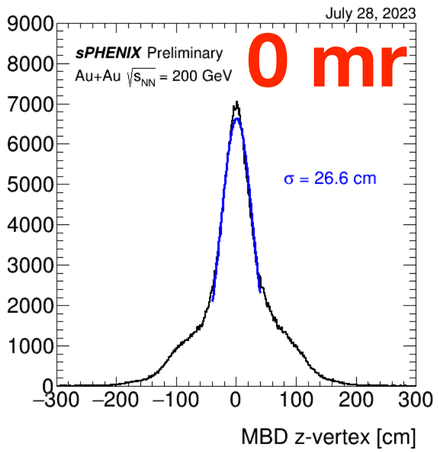
Commissioning status - global

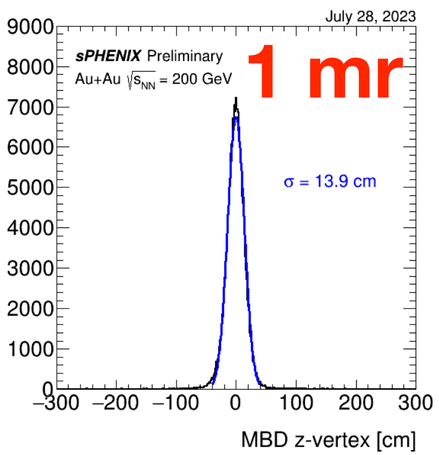


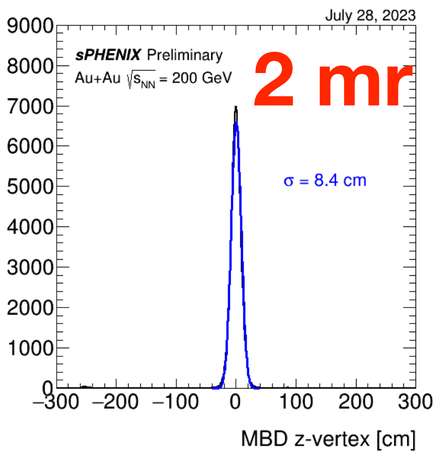




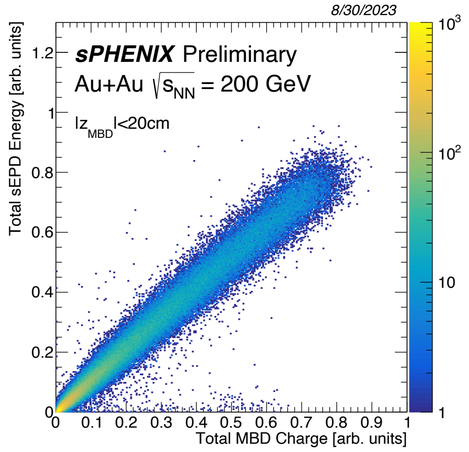
MBD - z vertex with different crossing angles







sEPD & MBD

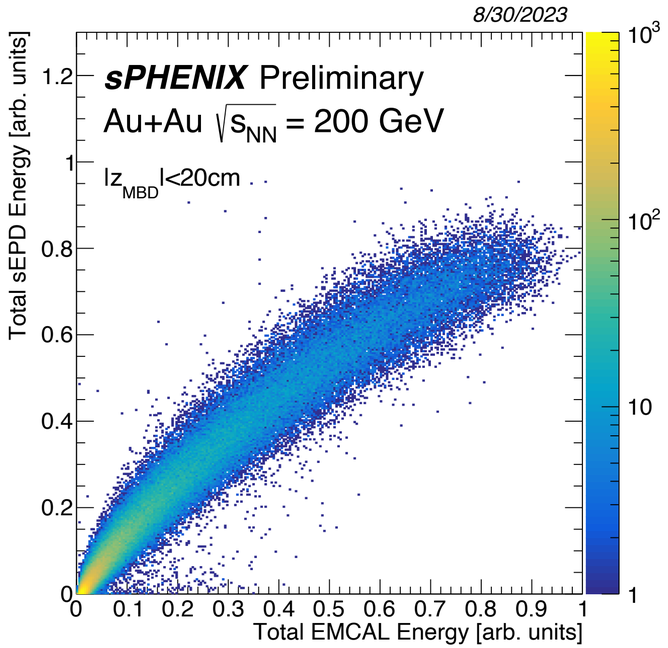


Systems synchronized and able to see the real signal!

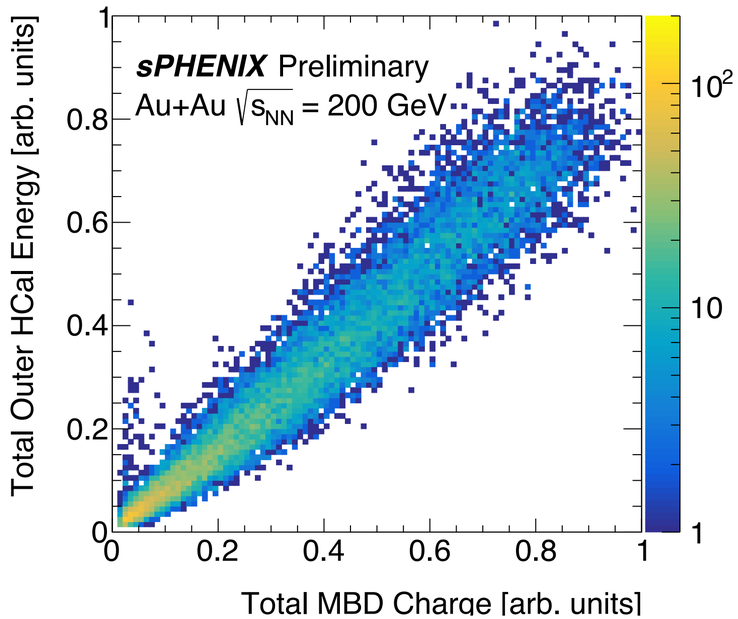
4 out of 11 checked!

Commissioning status - calorimeters

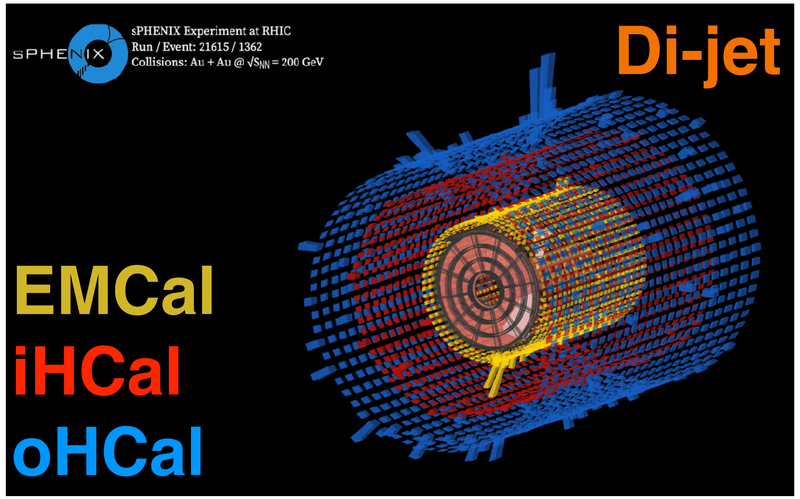
sEPD & EMCal

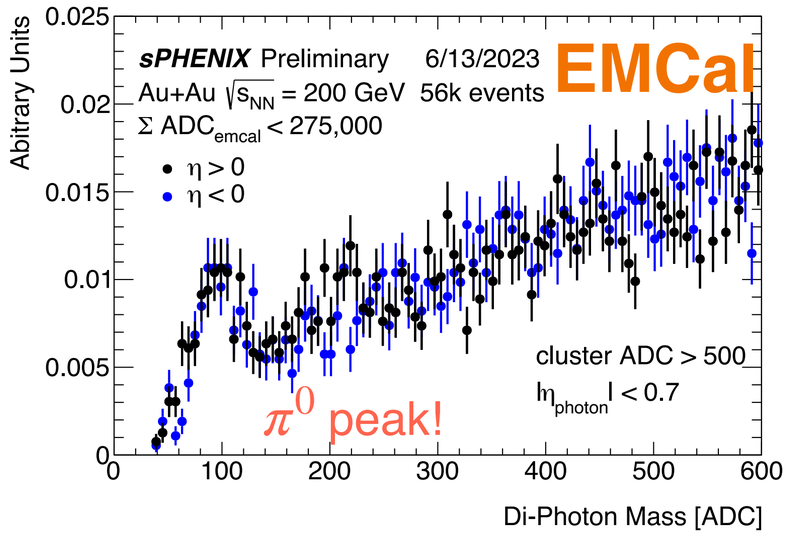


oHCal & MBD



Event display of the sPHENIX calorimeter system

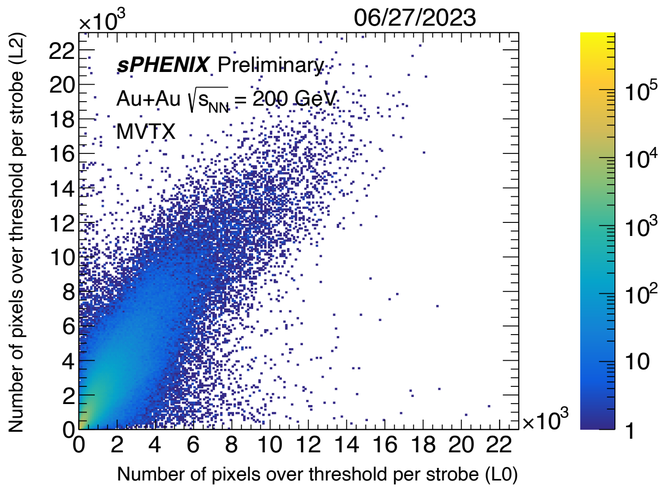


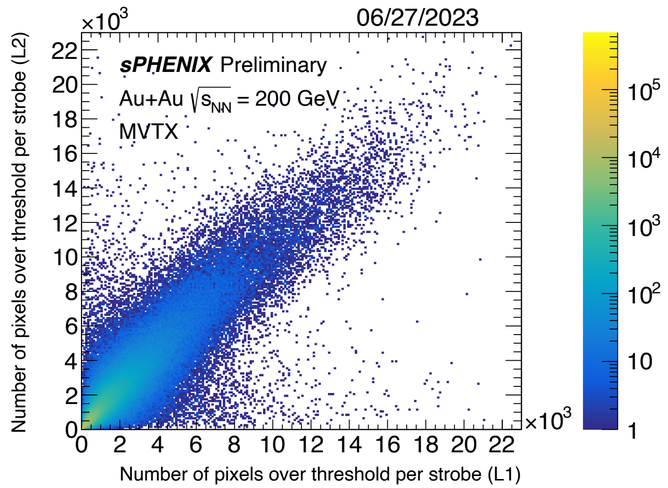


7 out of 11 checked!

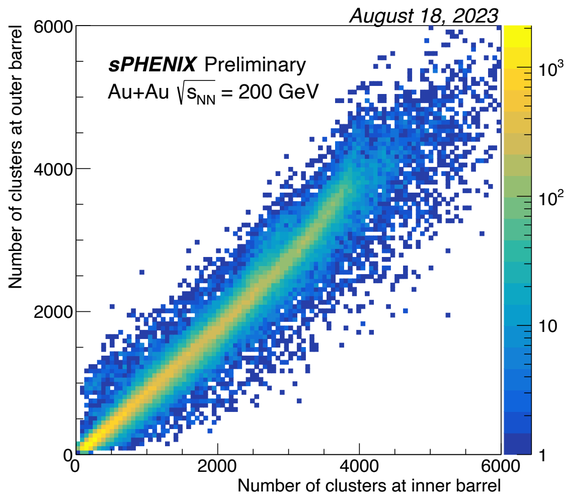
Commissioning status - tracking system

MVTX

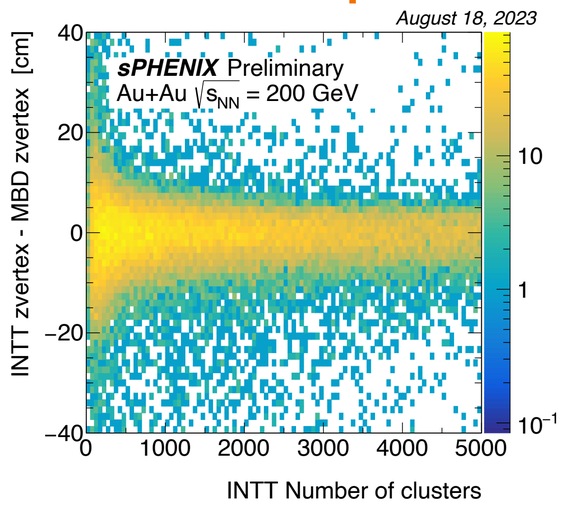




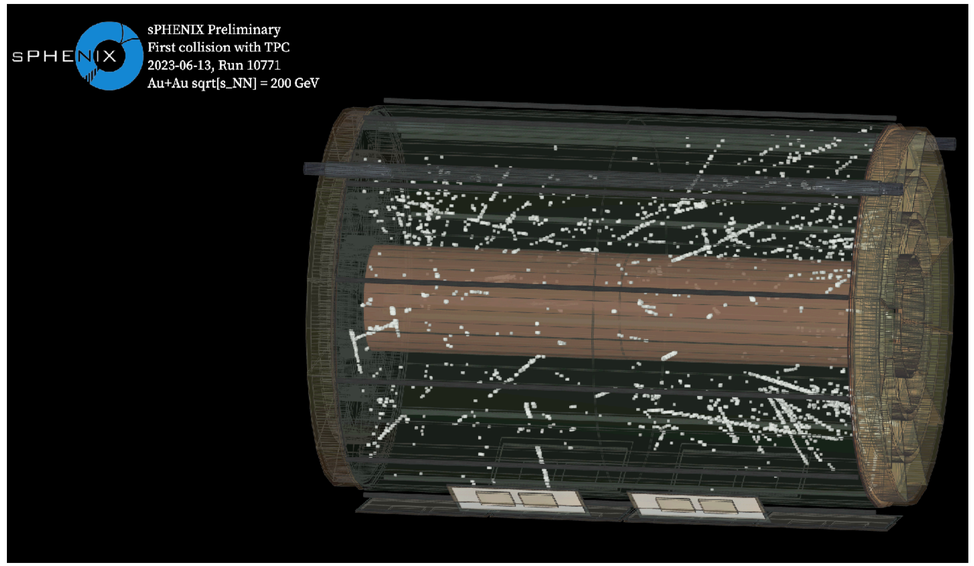
INTT



INTT & MBD Z vertex comparison



Particle tracks from collision visible in raw TPC data



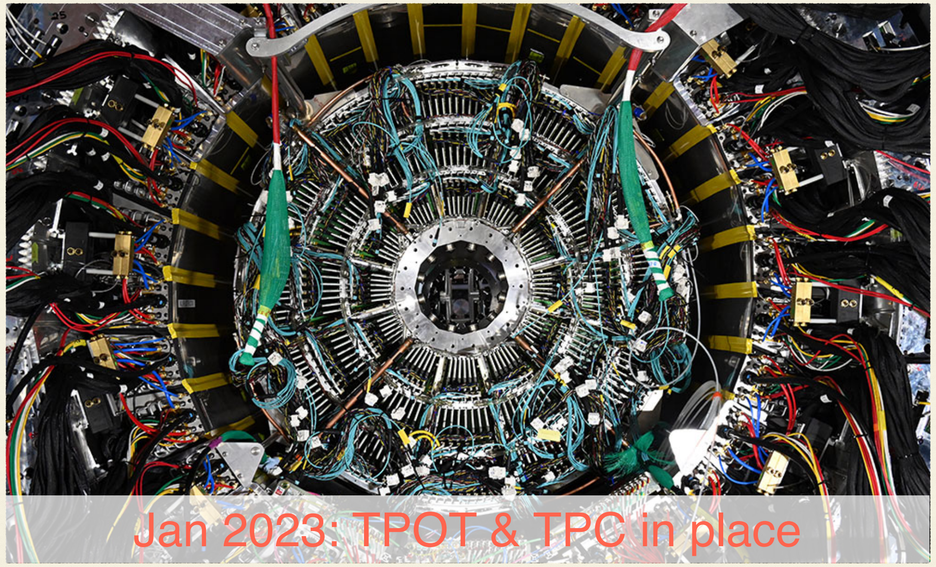
11 out of 11 checked! ✓

The journey of sPHENIX - construction

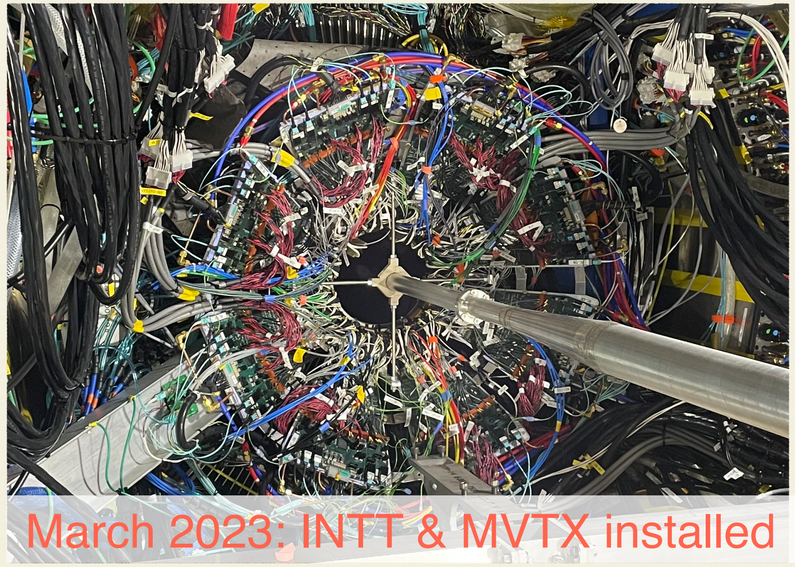
Feb 2022: Cradle, magnet & oHCal

June 2022: iHCal barrel insertion

Dec 2022: EMCal sector installed



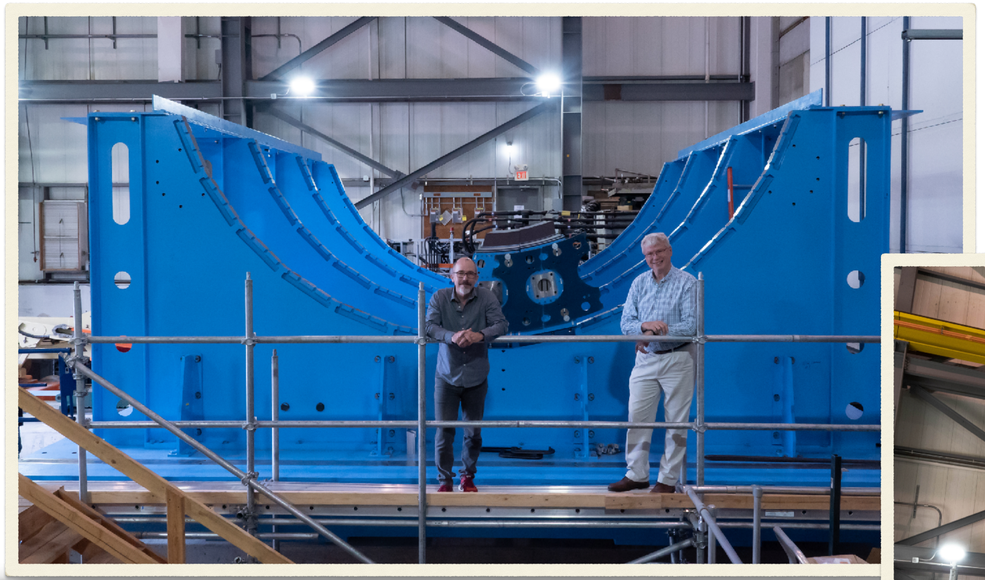
Jan 2023: TPOT & TPC in place



March 2023: INTT & MVTX installed

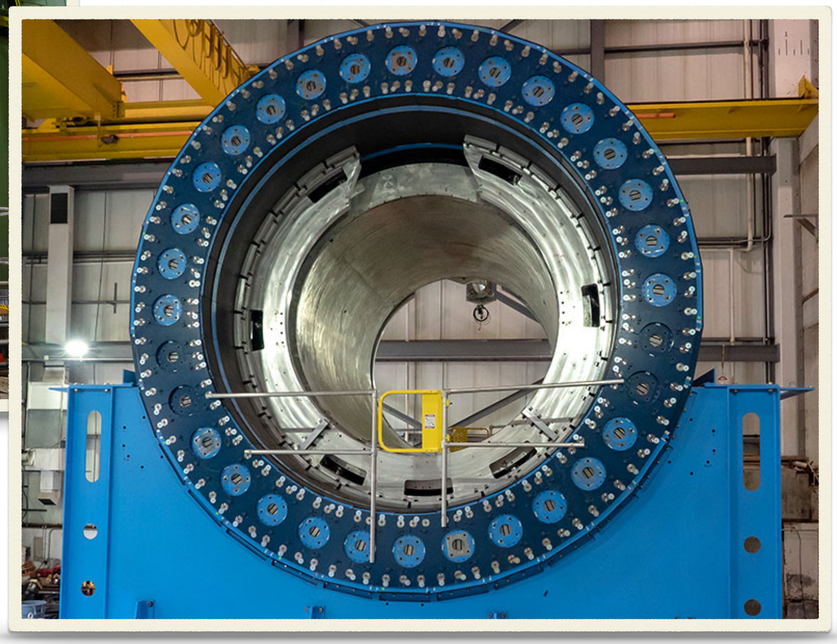
June 2023: sEPD installed

The journey of sPHENIX - construction



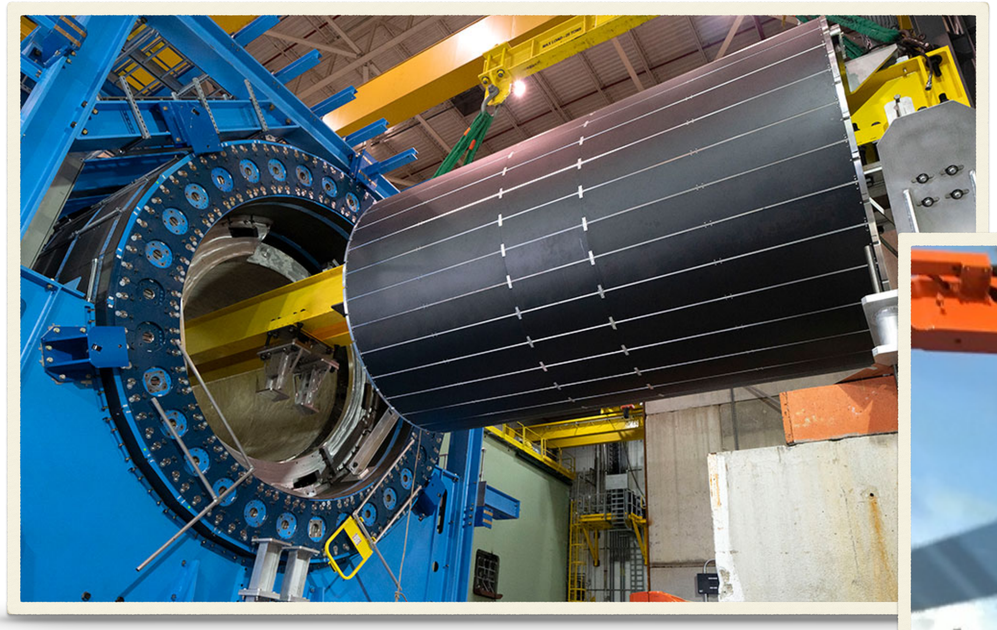
First oHCal sector in placed, June 2021

Magnet installation, Oct 2021



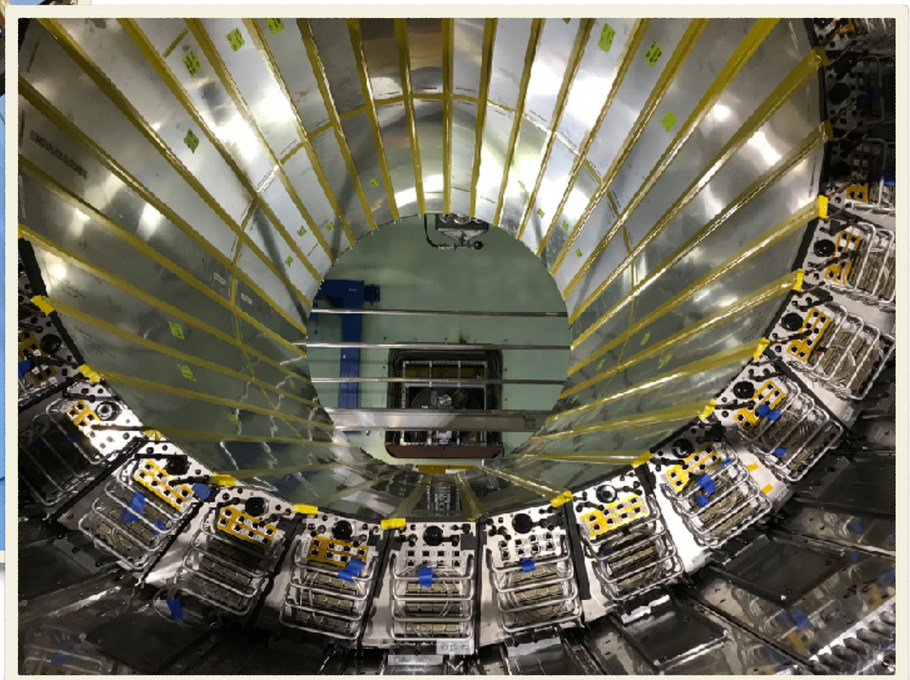
oHCal barrel complete, Feb 2022

The journey of sPHENIX - construction



Full iHCal barrel insertion, June 2022

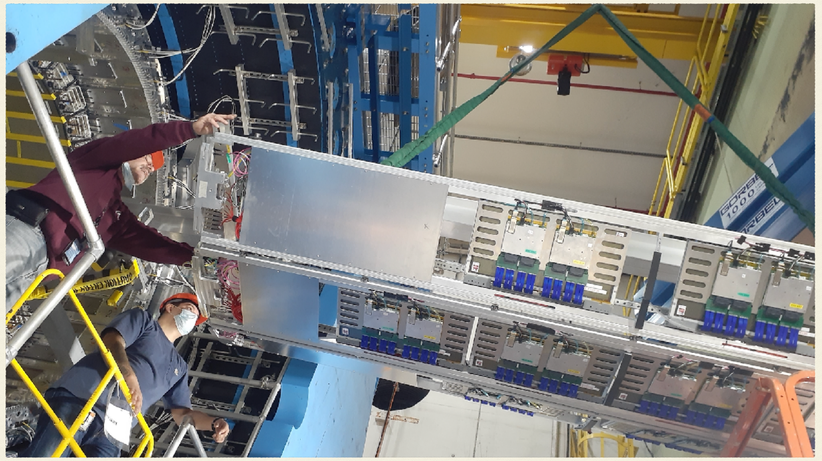
Inserting the EMCal sectors



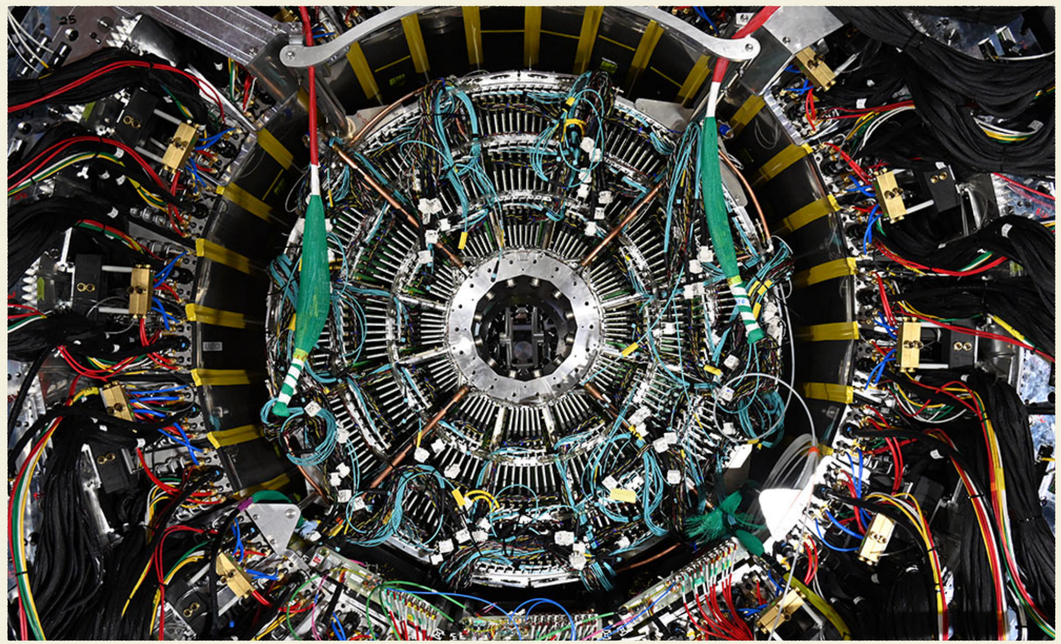
EMCal fully installed, Dec 2022

The journey of sPHENIX - construction

TPOT installation, Dec 2022

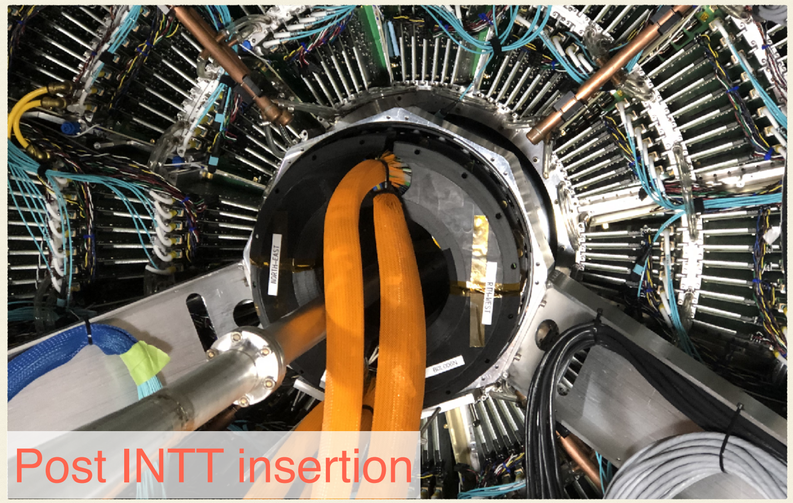


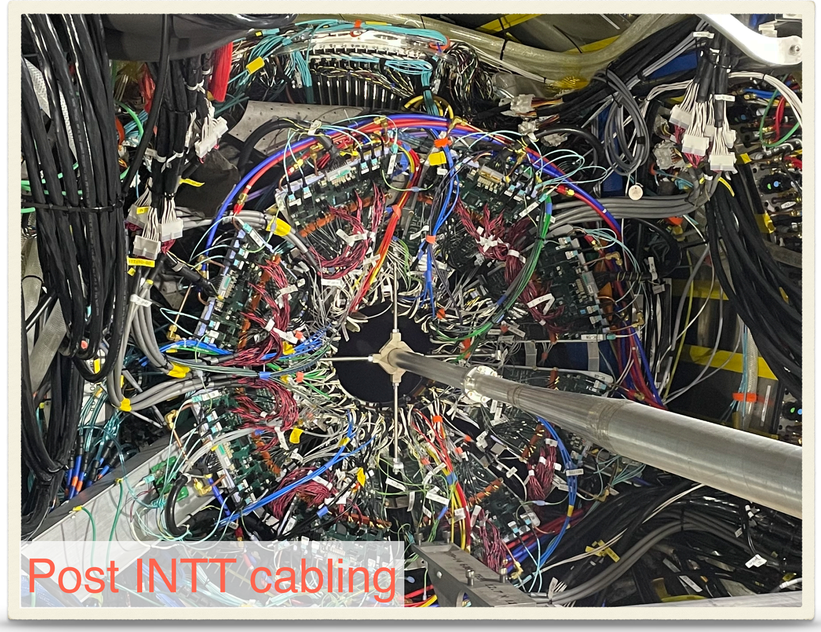
TPC insertion, Jan 2023



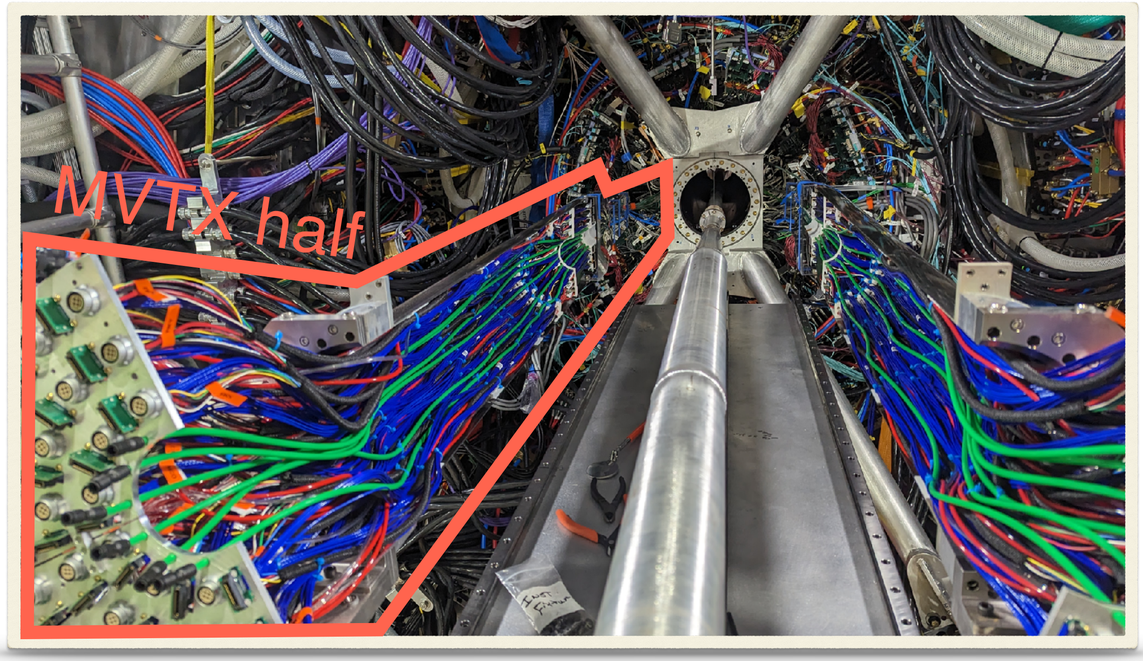
The journey of sPHENIX - construction

INTT insertion, Mar 2023

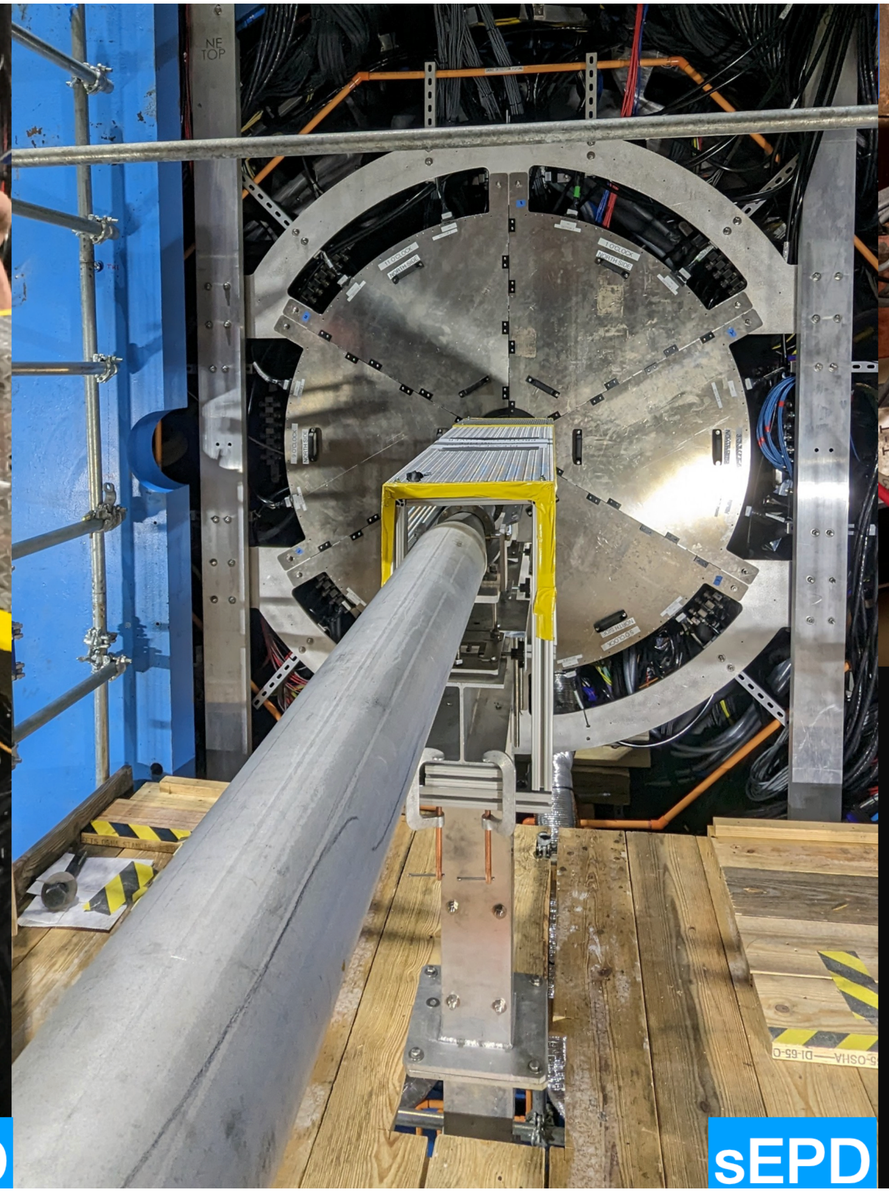


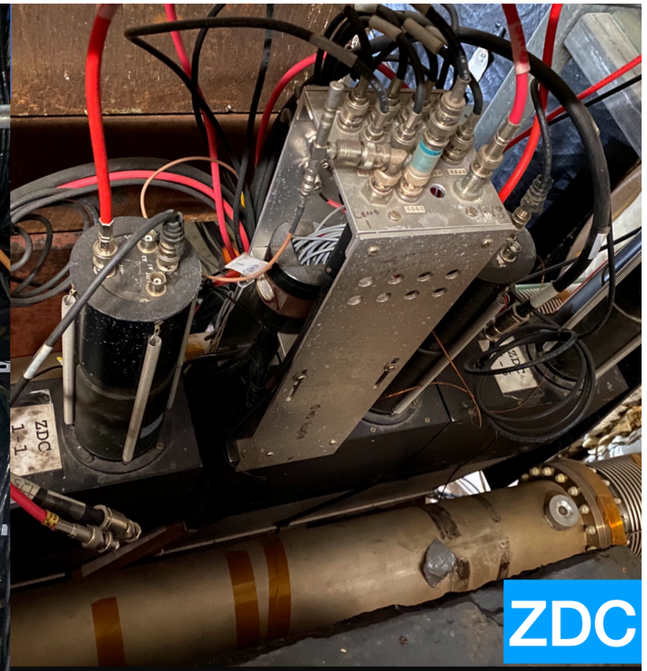


MVTX installed, April 2023



The journey of sPHENIX - construction



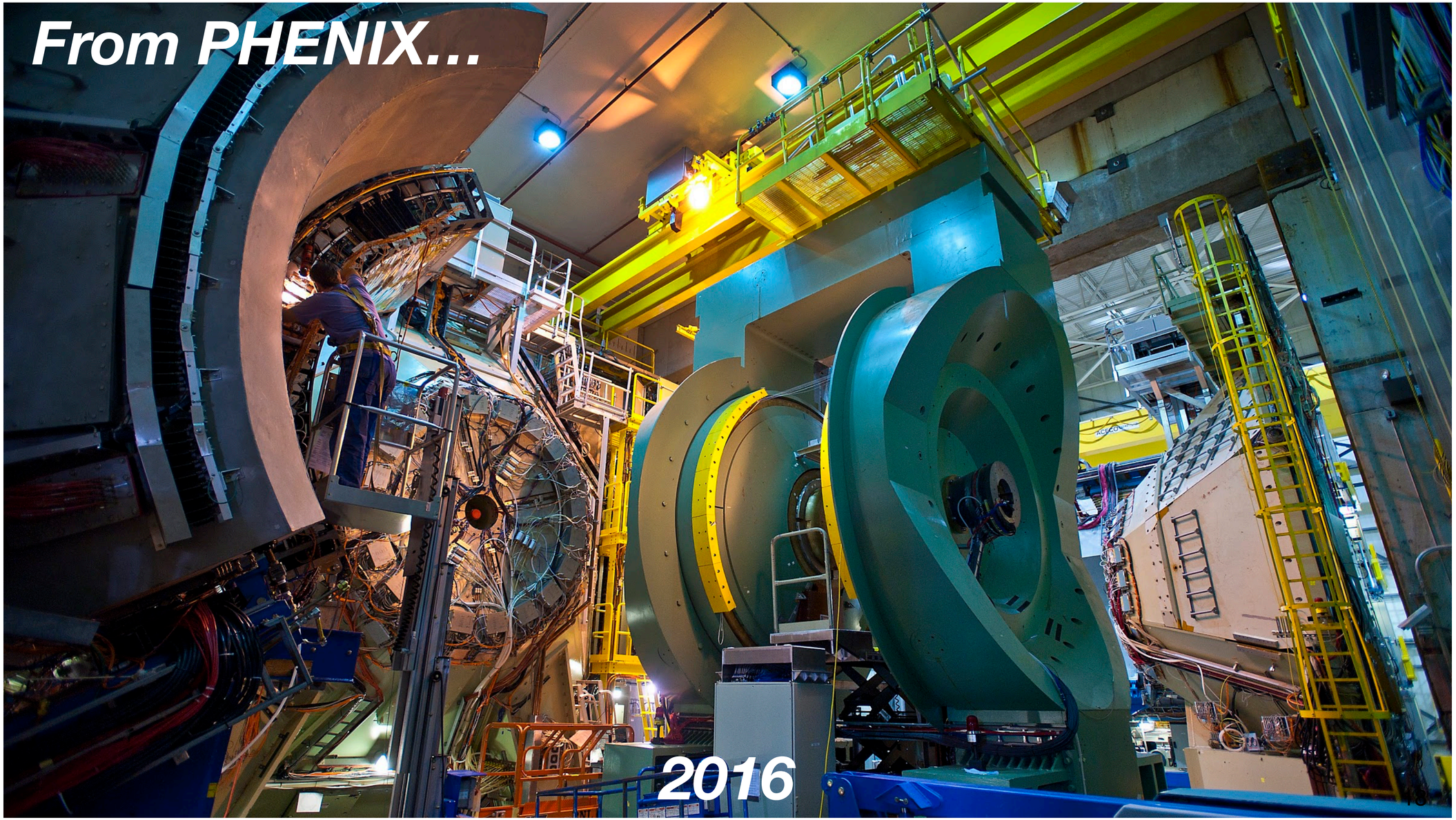


MBD: April 3rd 2023

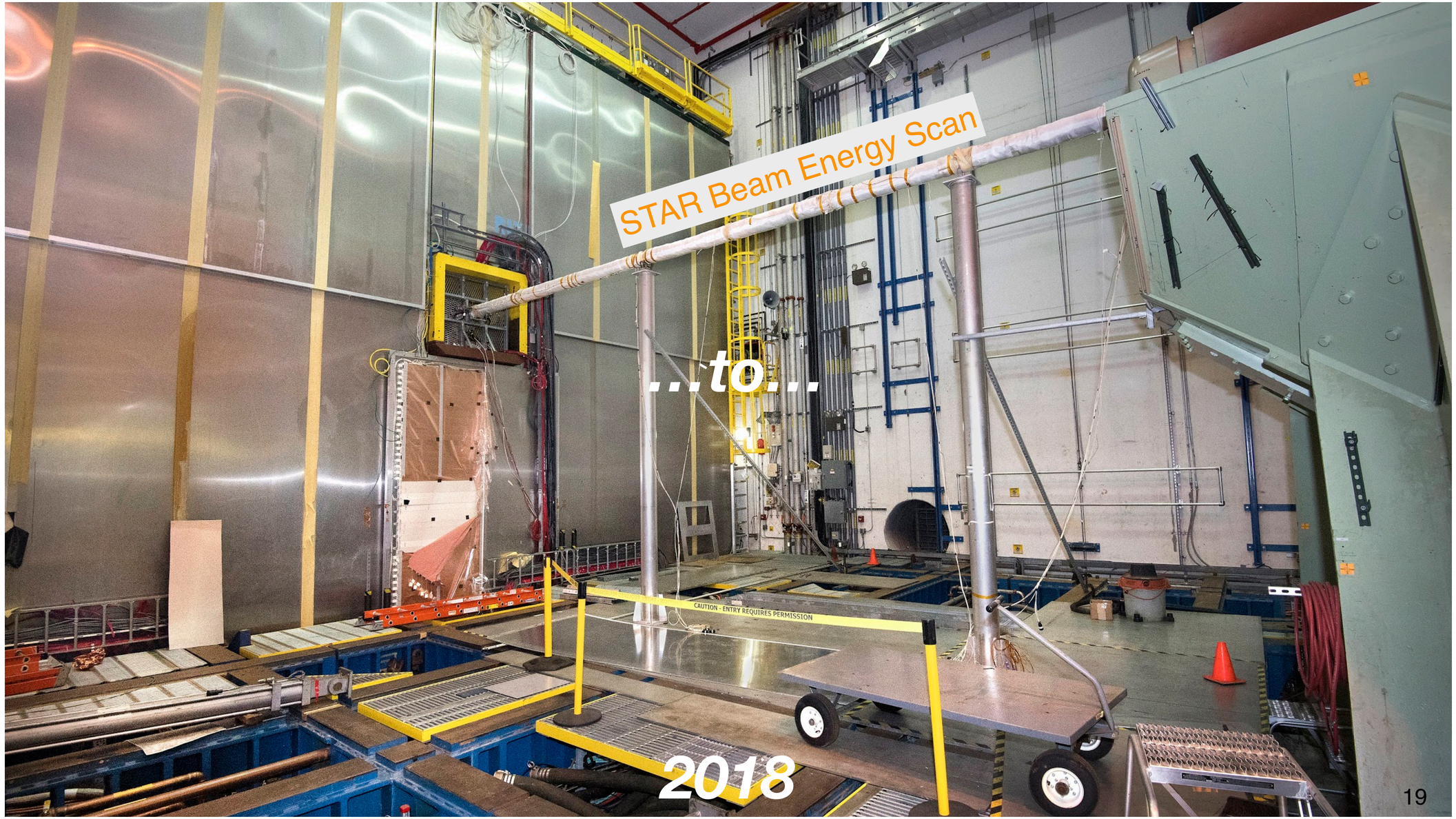
sEPD: June 2023

ZDC: was already for > 10 years

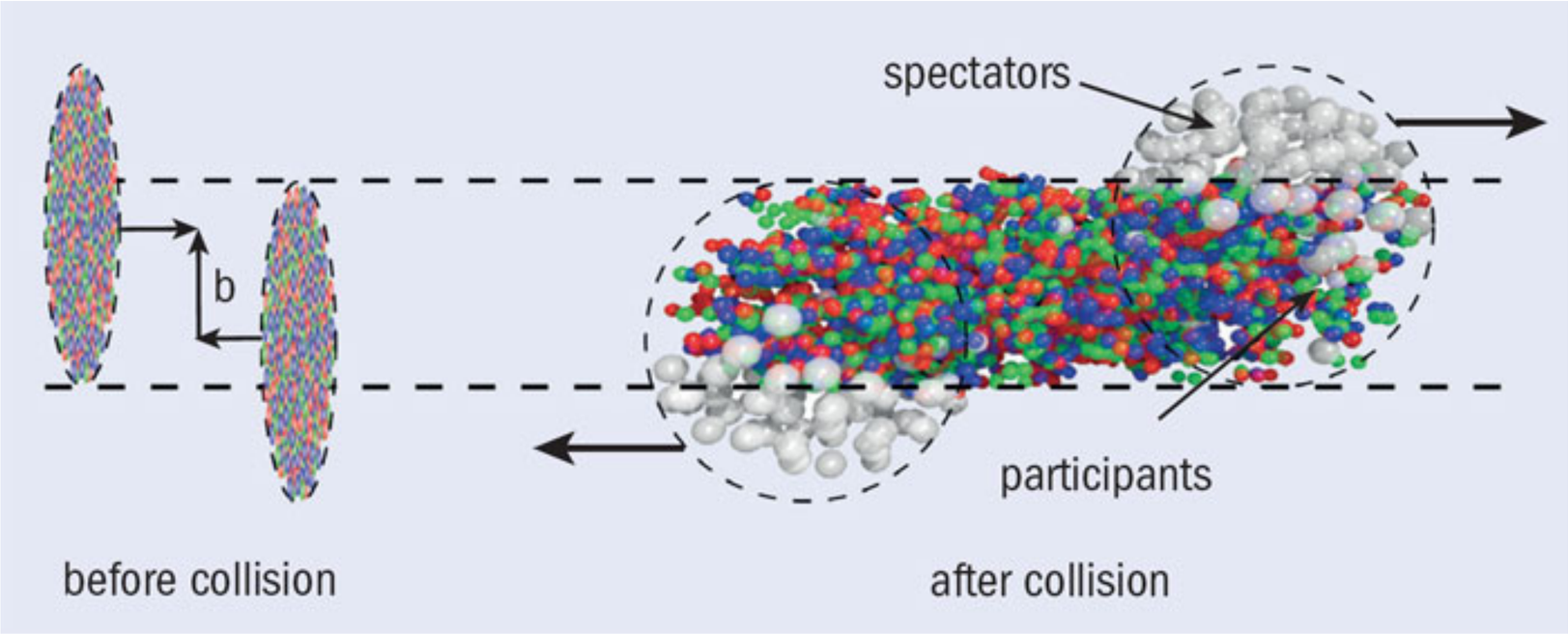
The journey of sPHENIX



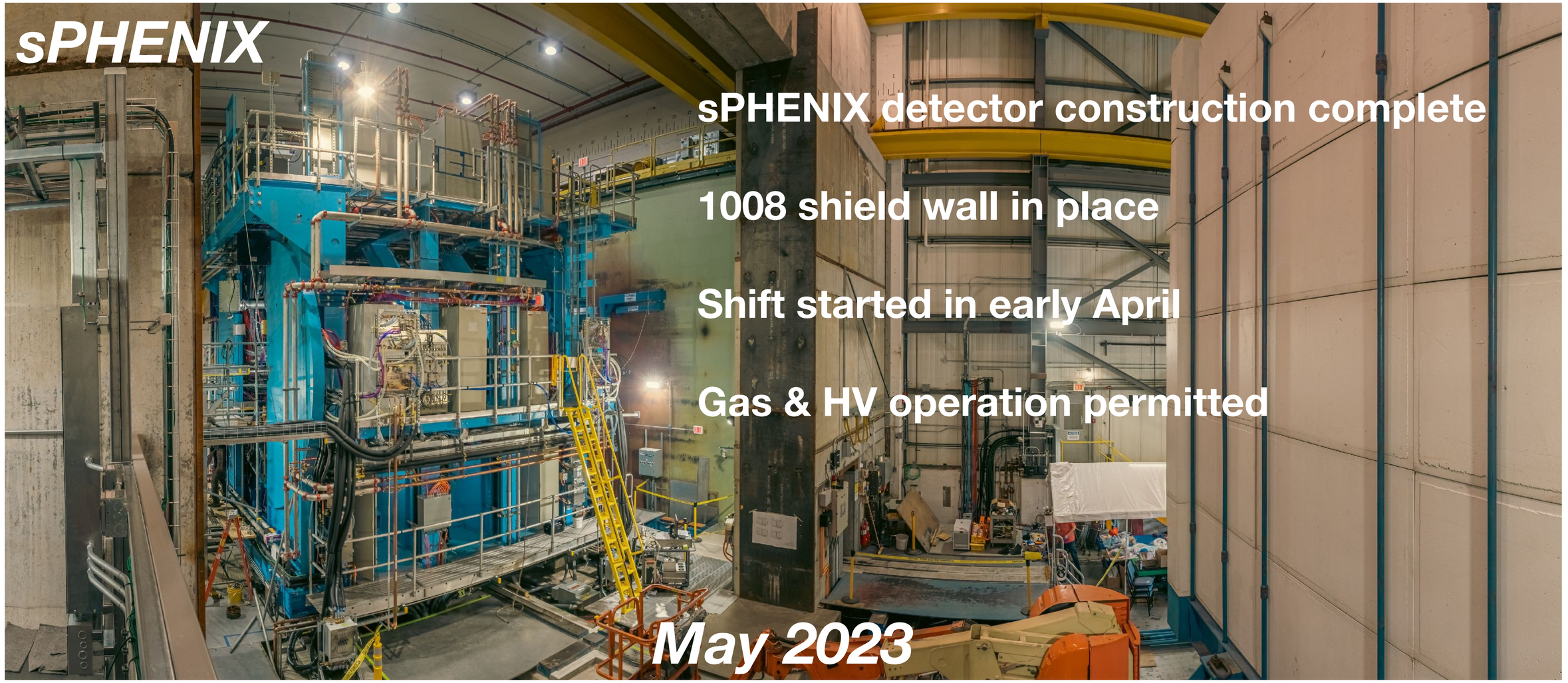
The journey of sPHENIX



Npart


spectators
b
participants
before collision
after collision

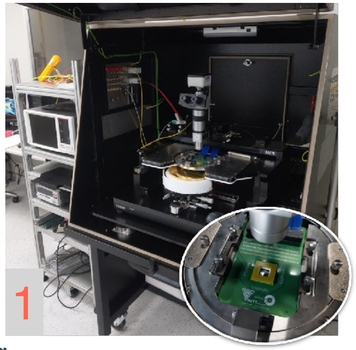
The journey of sPHENIX

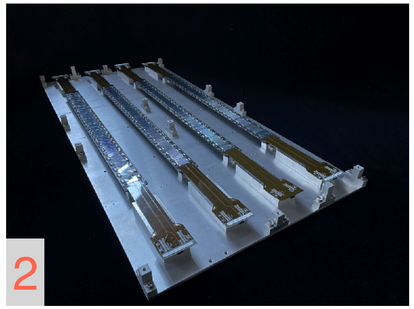


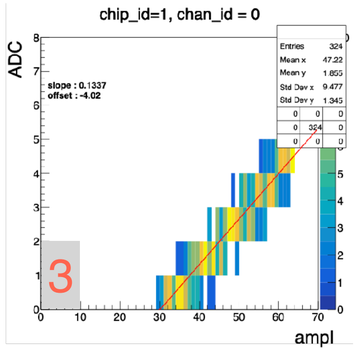
With more than 10 years of preparation, sPHENIX moved from construction phase to the commissioning phase on May 18 2023!

Contributions of Taiwan to sPHENIX

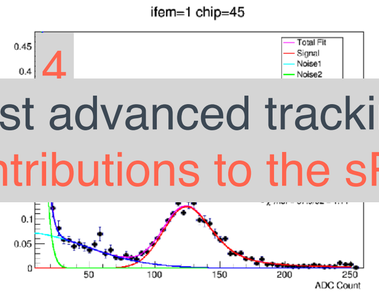
- **NCU and NTU participated in the sPHENIX INTT detector group since May 2019, the R&D phase**
- Contributions:
  1. INTT sensor testing
  2. 1/3 ladder assembly and testing in Taiwan
  3. Ladder classification criteria
  4. Two INTT beam test experiments
  5. On-site INTT barrel construction & commissioning
  6. INTT software development (LV GUI, DB, calib. online analyzer)
  7. 4 times sPHENIX relevant meetings & workshops @ NCU

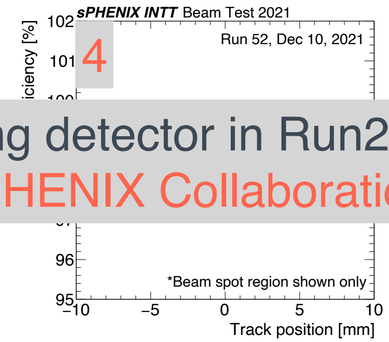






A bit exaggerated in quantifying the contribution, INTT is the most advanced tracking detector in Run23 x Taiwan group did tremendous contributions to the INTT detector → ~10% contributions to the sPHENIX Collaboration (As of Run 23)





10. Contact of sPHENIX spin physics program of 3 weeks
11. Measurement of the MBD cross section → global contribution
12. Run 23 dN/dη pub. → Potentially the first pub. in sPHENIX