sPHENIX

Cheng-Wei Shih, for the sPHENIX Collaboration

National Central University

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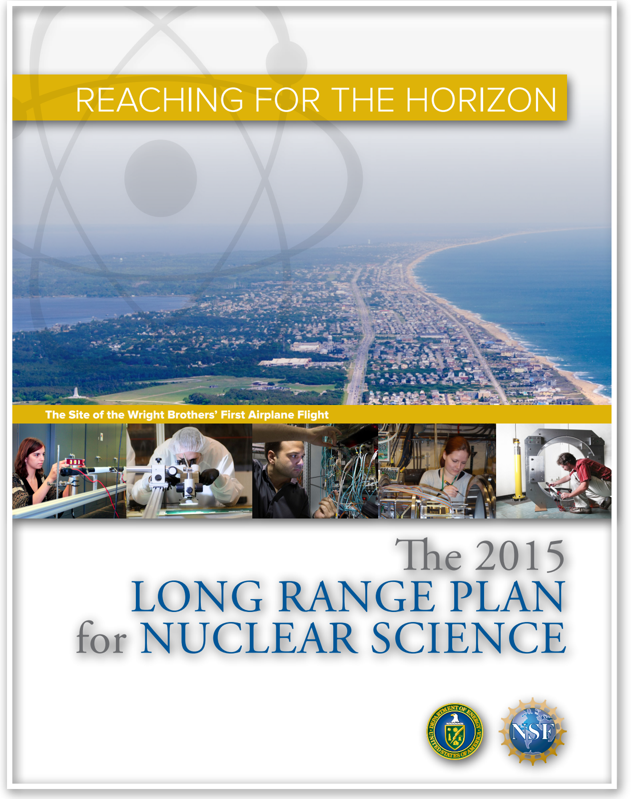
國立中央大學
National Central University

sPHENIX

The sPHENIX experiment

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.**

2012: Proposal released
2015: LRP recommendation

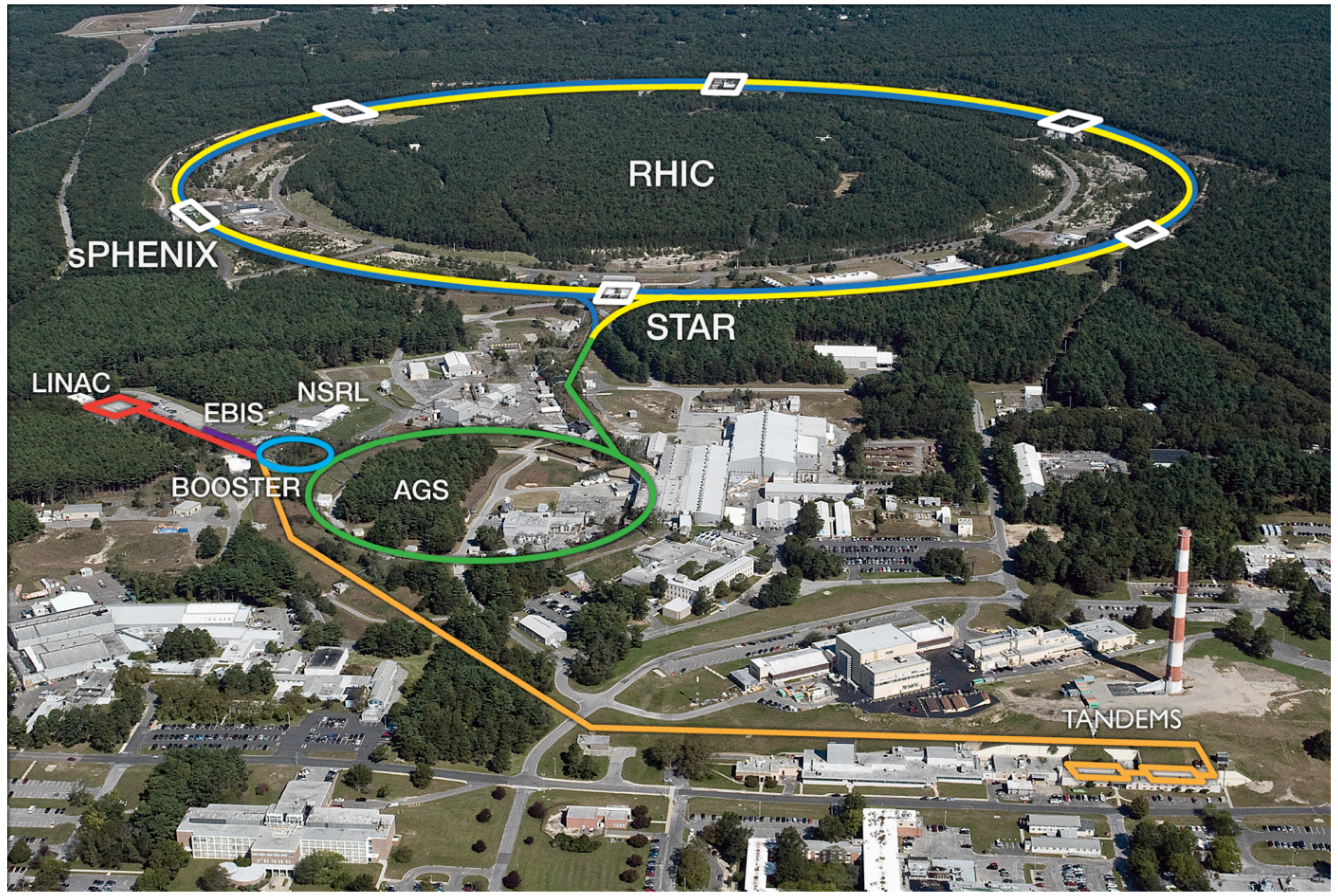
2012 - 2023: Ten-year preparation for detector construction

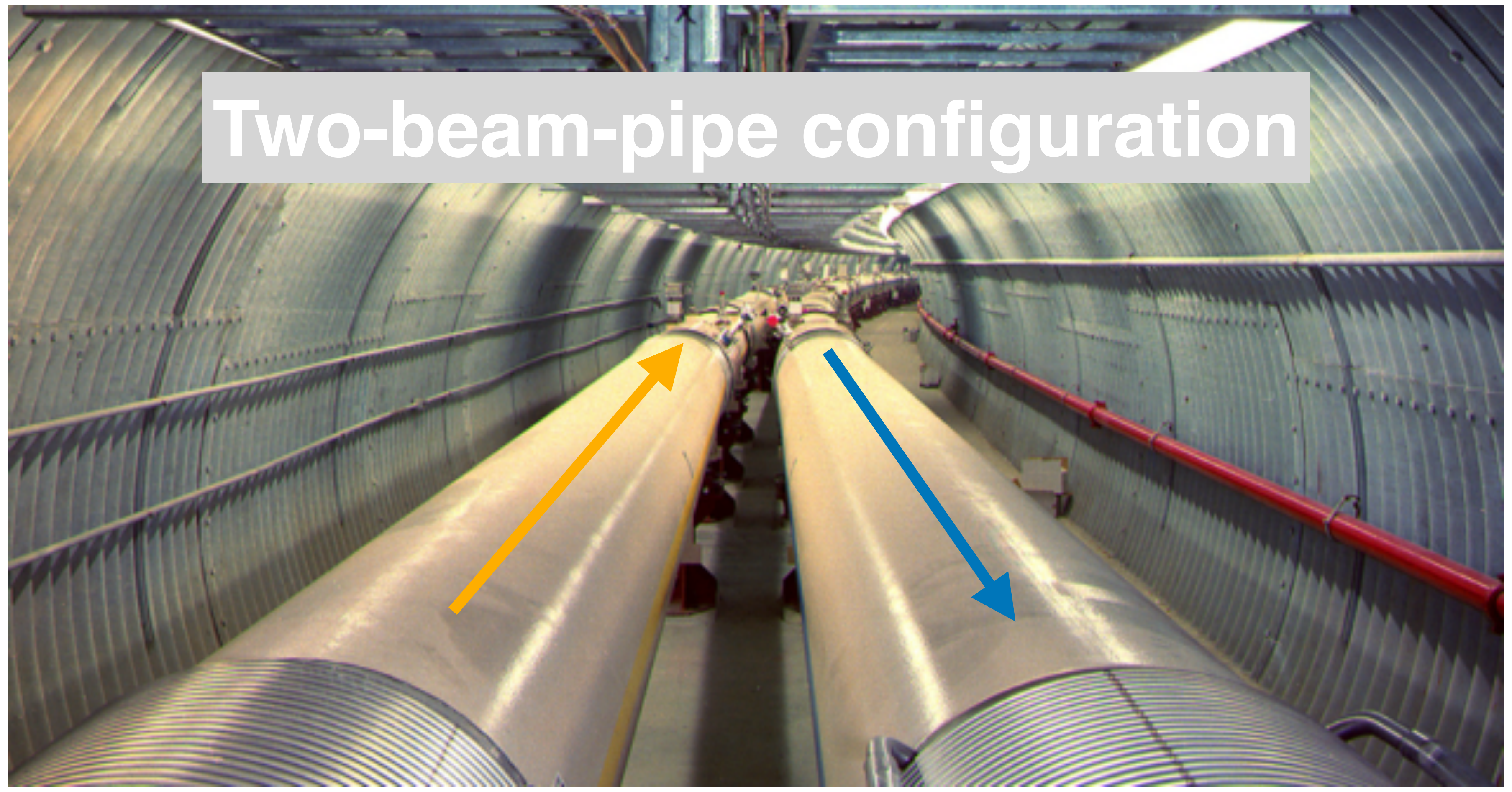
2023 - 2026: Three-year data taking
(polarized p+p and Au+Au collision systems)

2026 - 203?: Full analysis phase

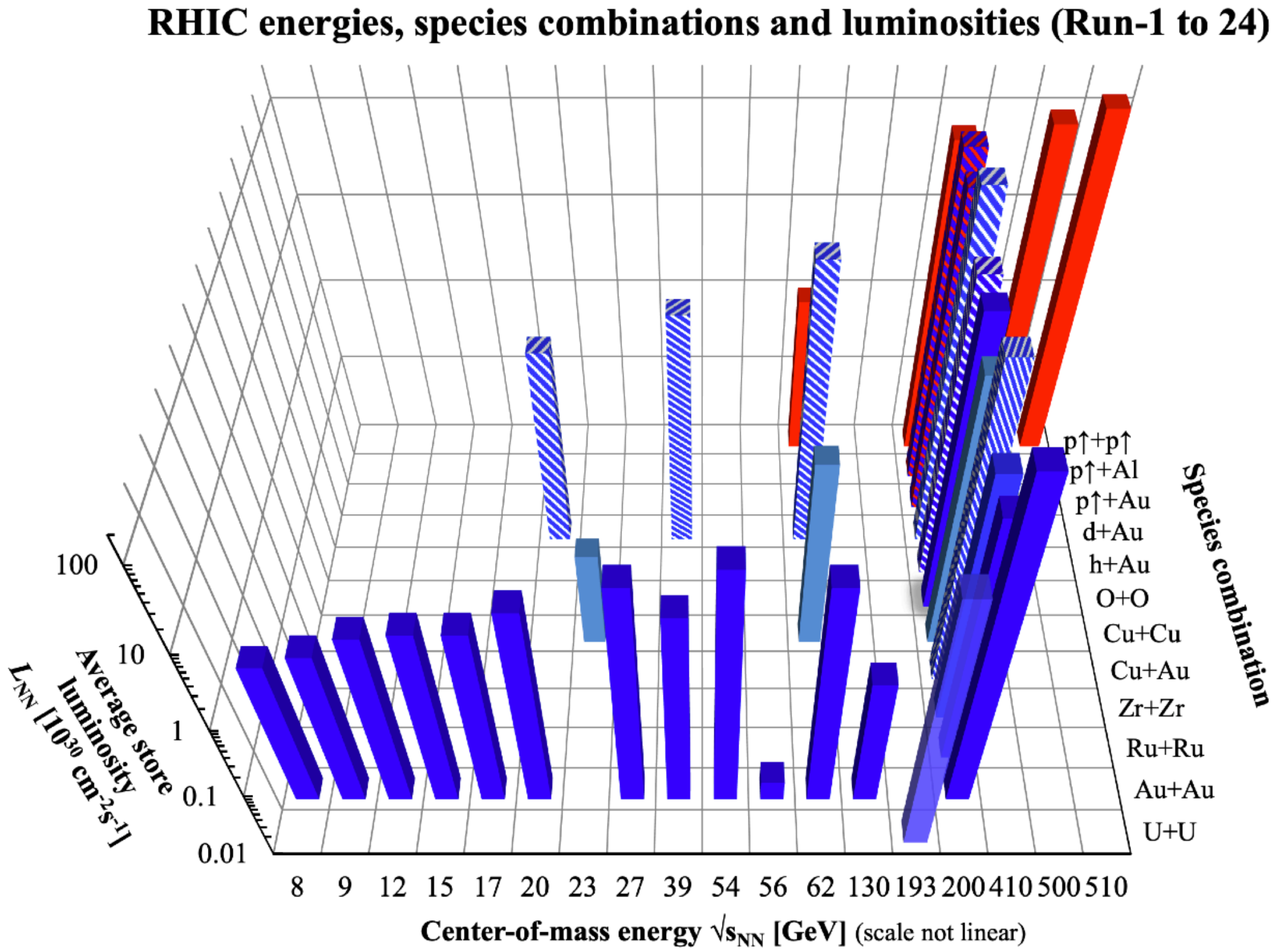
sPHENIX detector @ RHIC

Relativistic Heavy Ion Collider (RHIC)



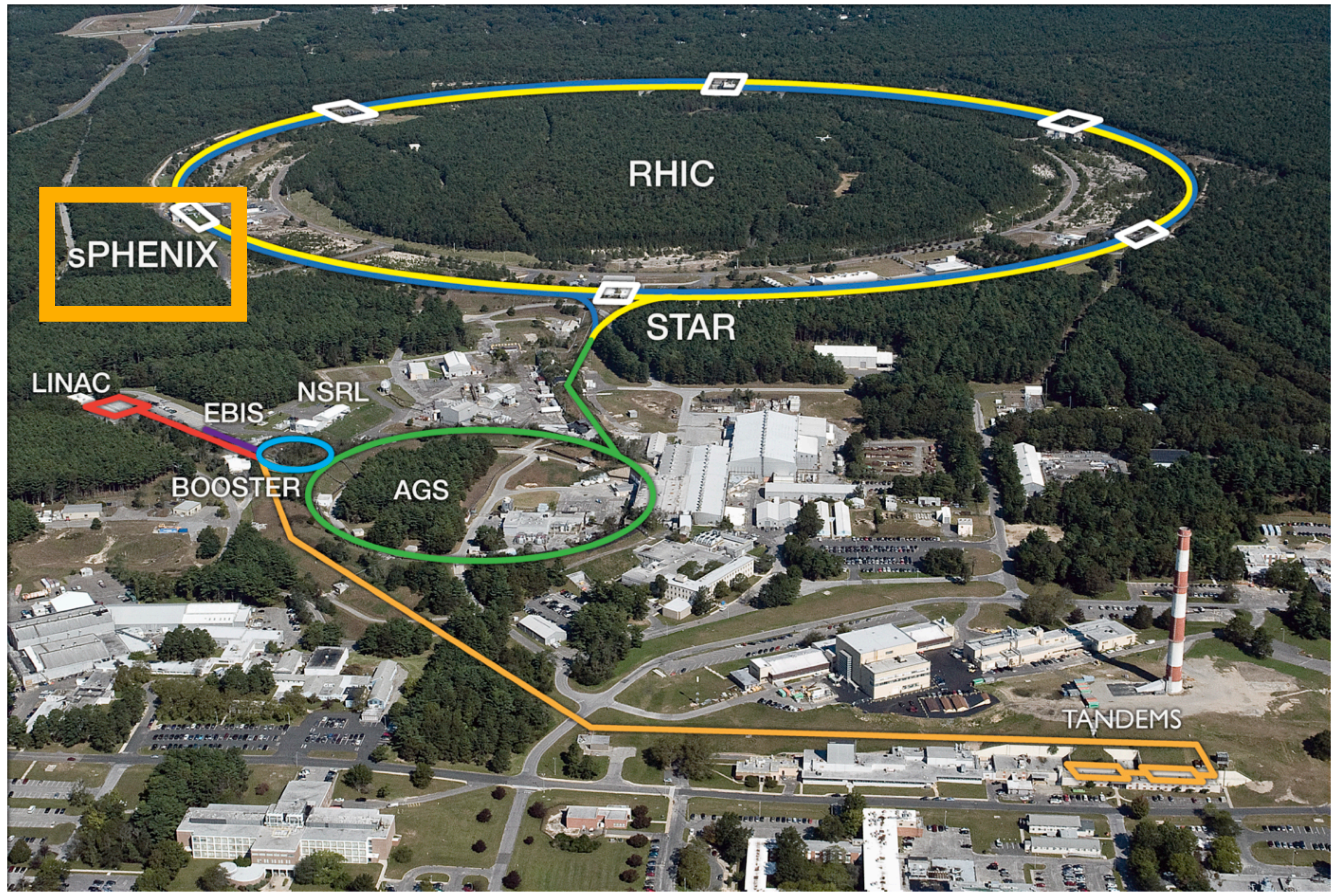


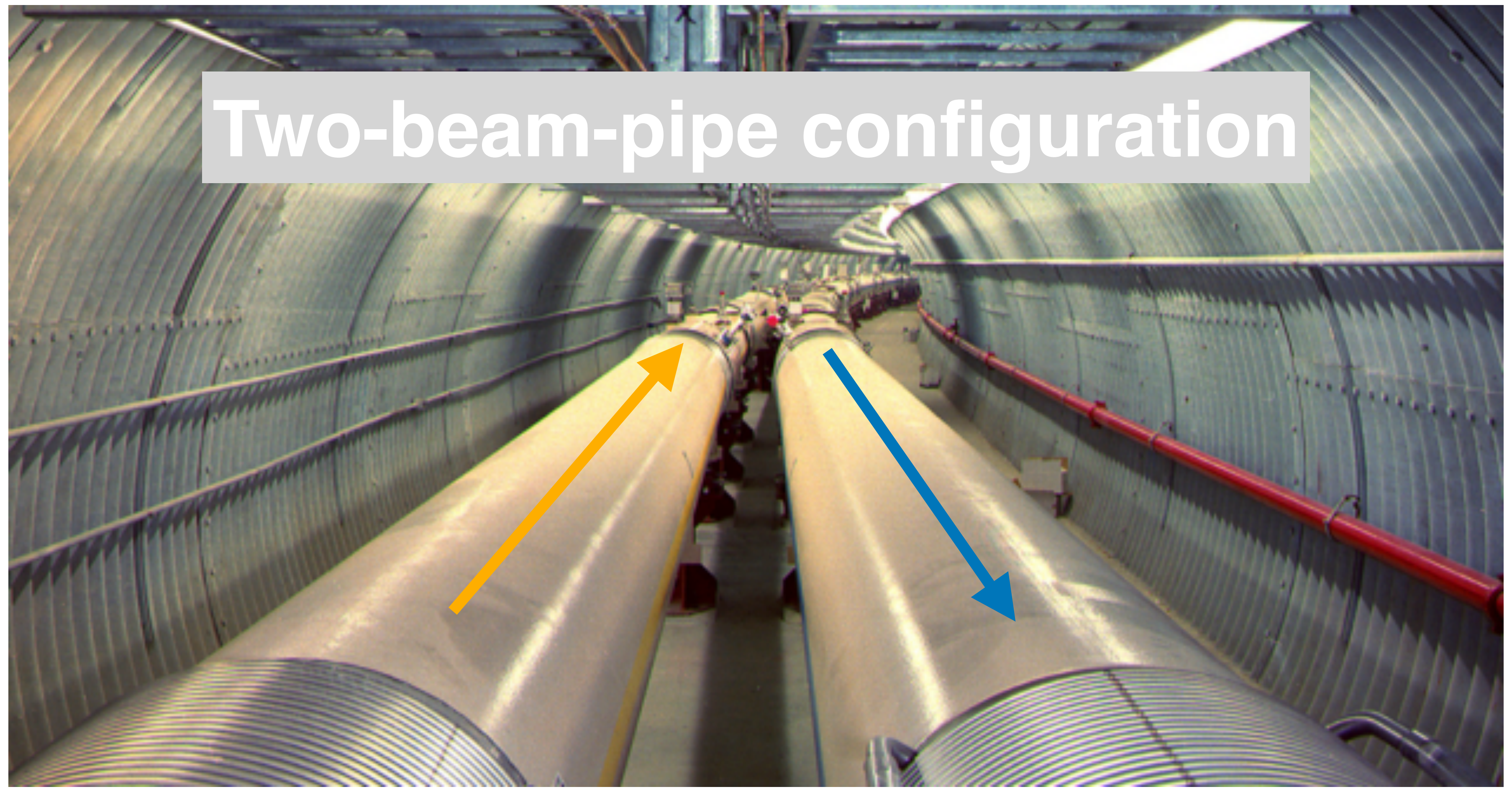
- **Location**: Brookhaven National Lab, Long Island, NY, USA
- **Circumference**: 3.83 km
- **Collision species**: p+p, p+Au, Au+Au up to U+U
- **Collision energy**: $\sqrt{s_{NN}}$ = 7 - 200 GeV (p+p 510 GeV)
- **The world's only machine colliding polarized-proton beams**
- **Operation**: year 2000 to January 28, 2026
- **Future**: hadron beam reuse for the future Electron-Ion Collider at BNL



RHIC: a highly versatile particle collider

Relativistic Heavy Ion Collider (RHIC)





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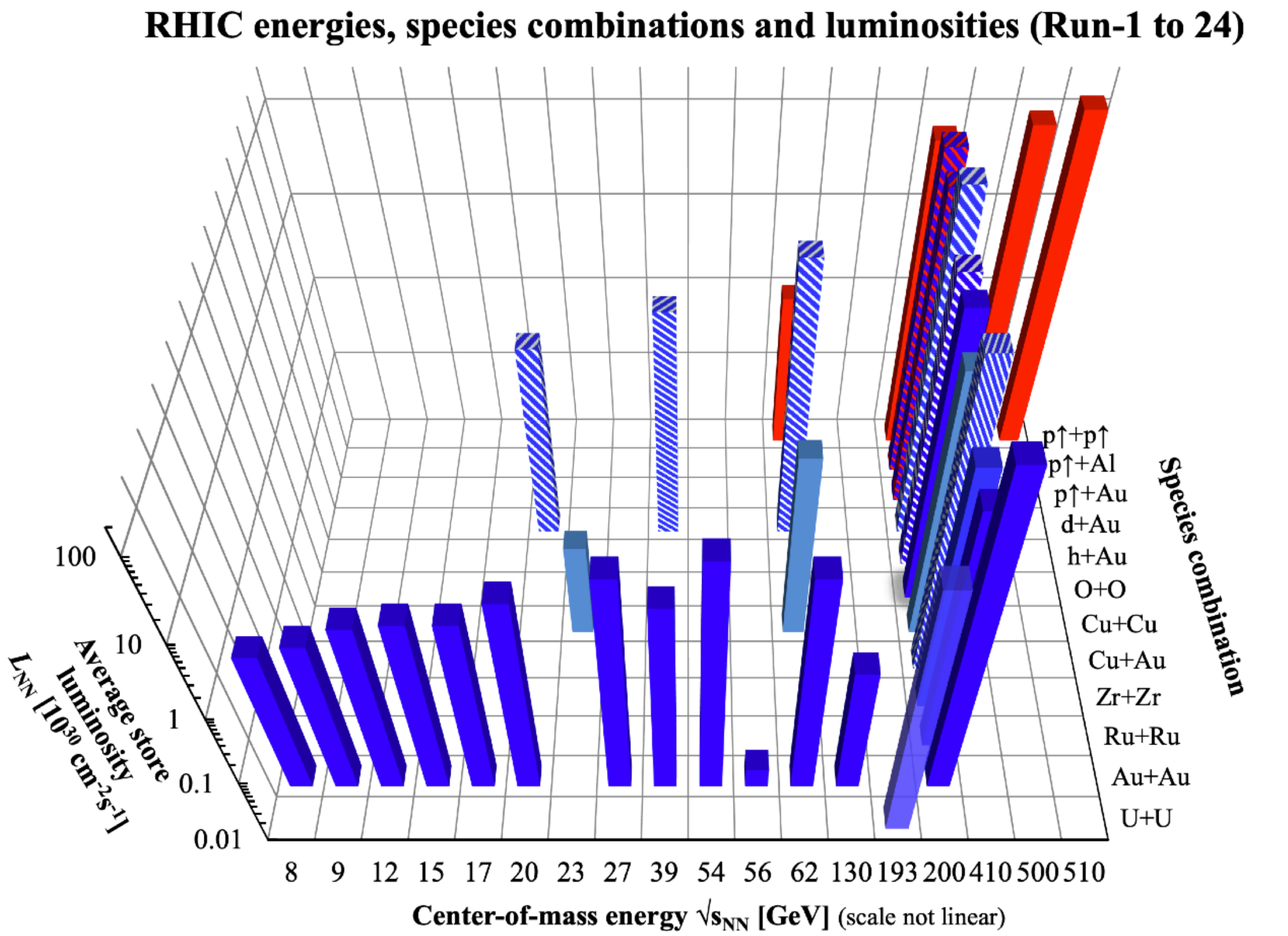
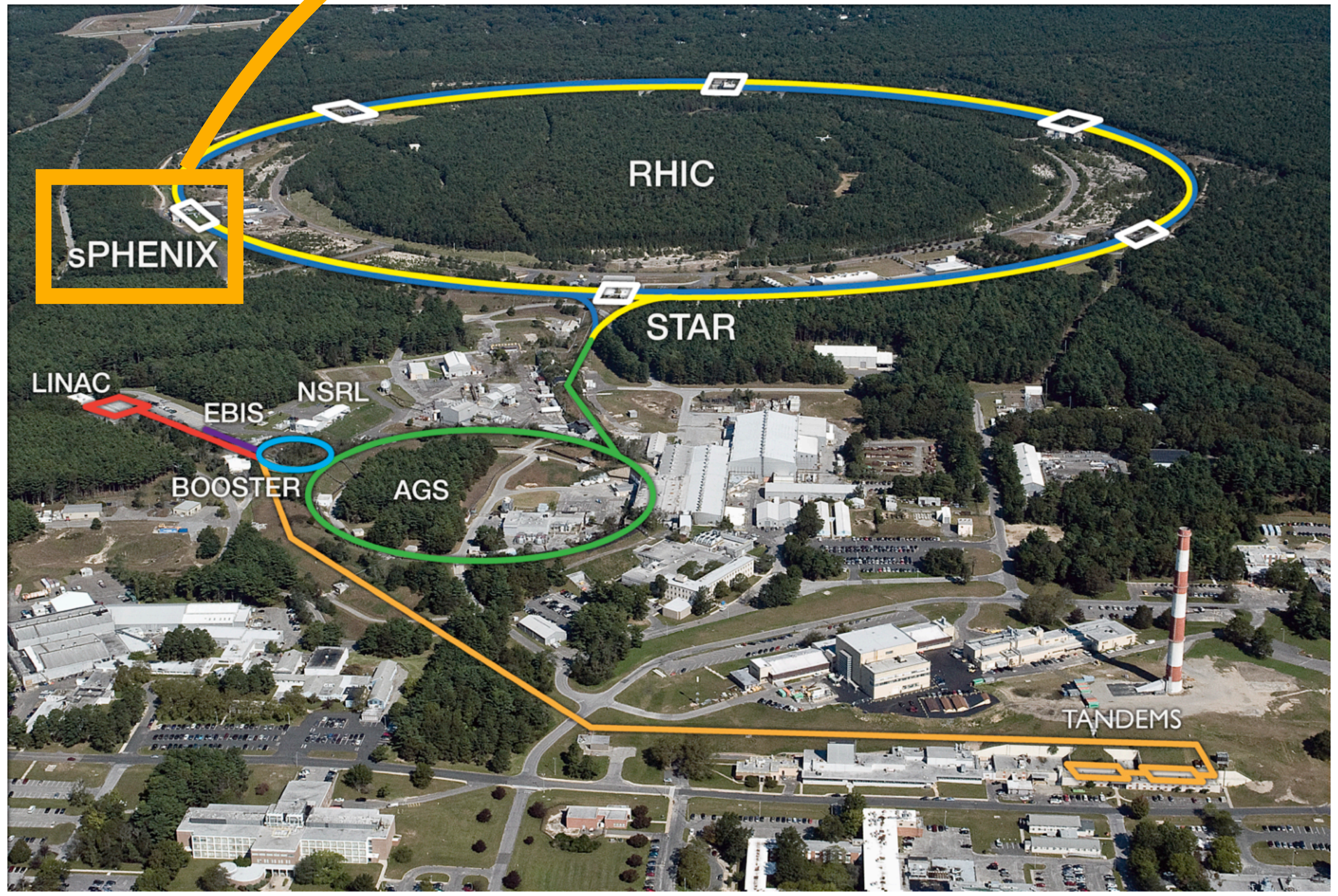
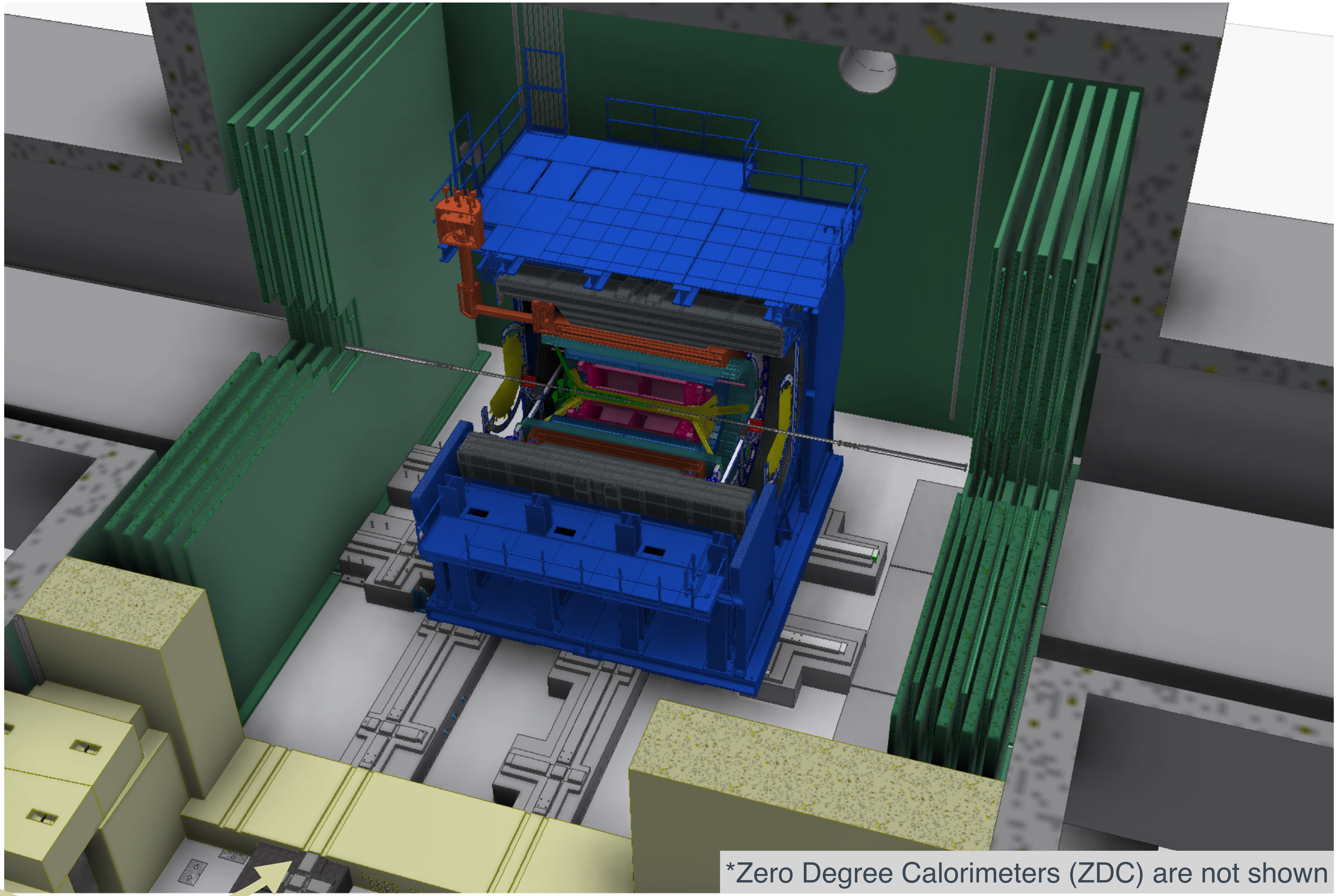


RHIC: a highly versatile particle collider

The sPHENIX experiment

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





Portable shield wall

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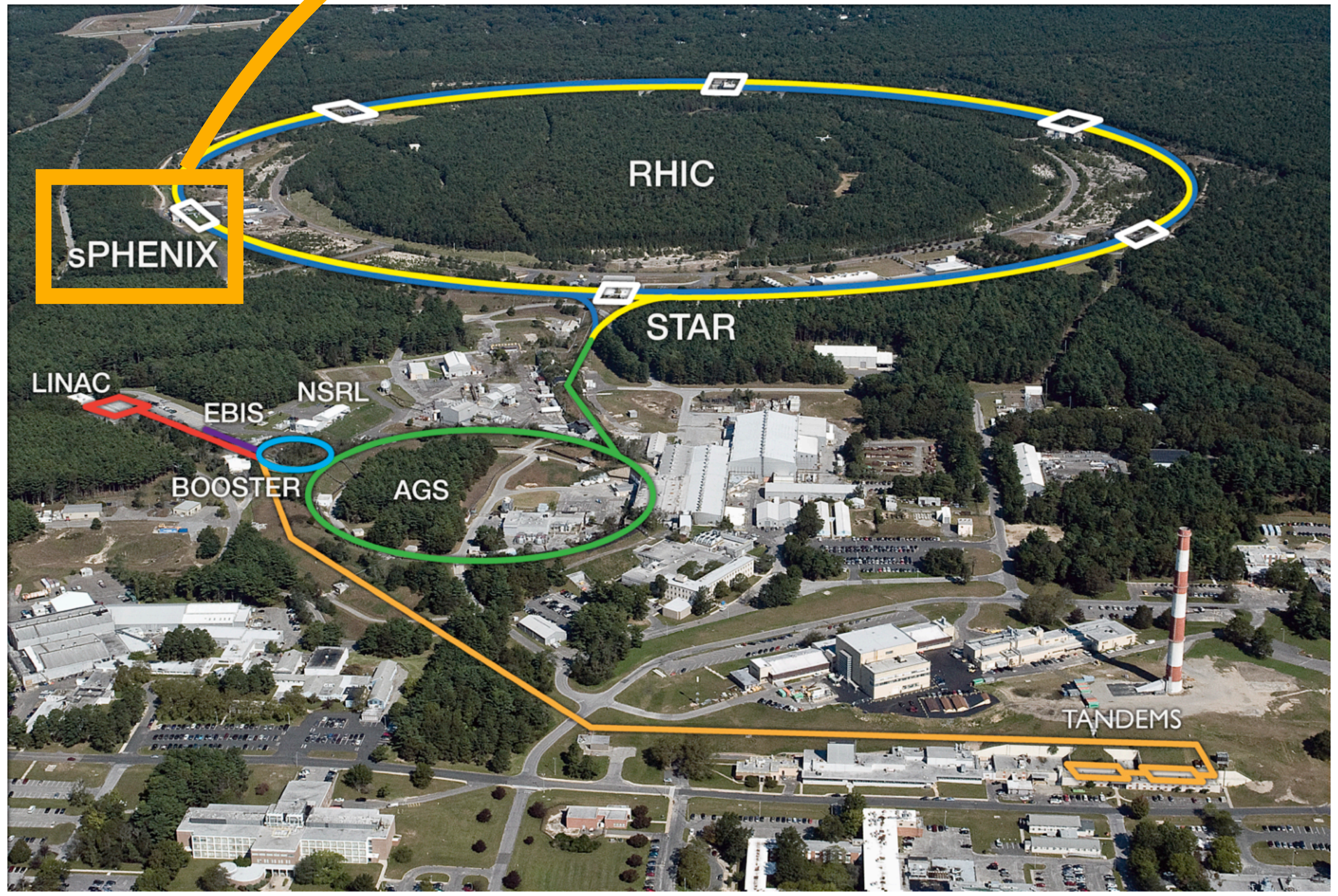

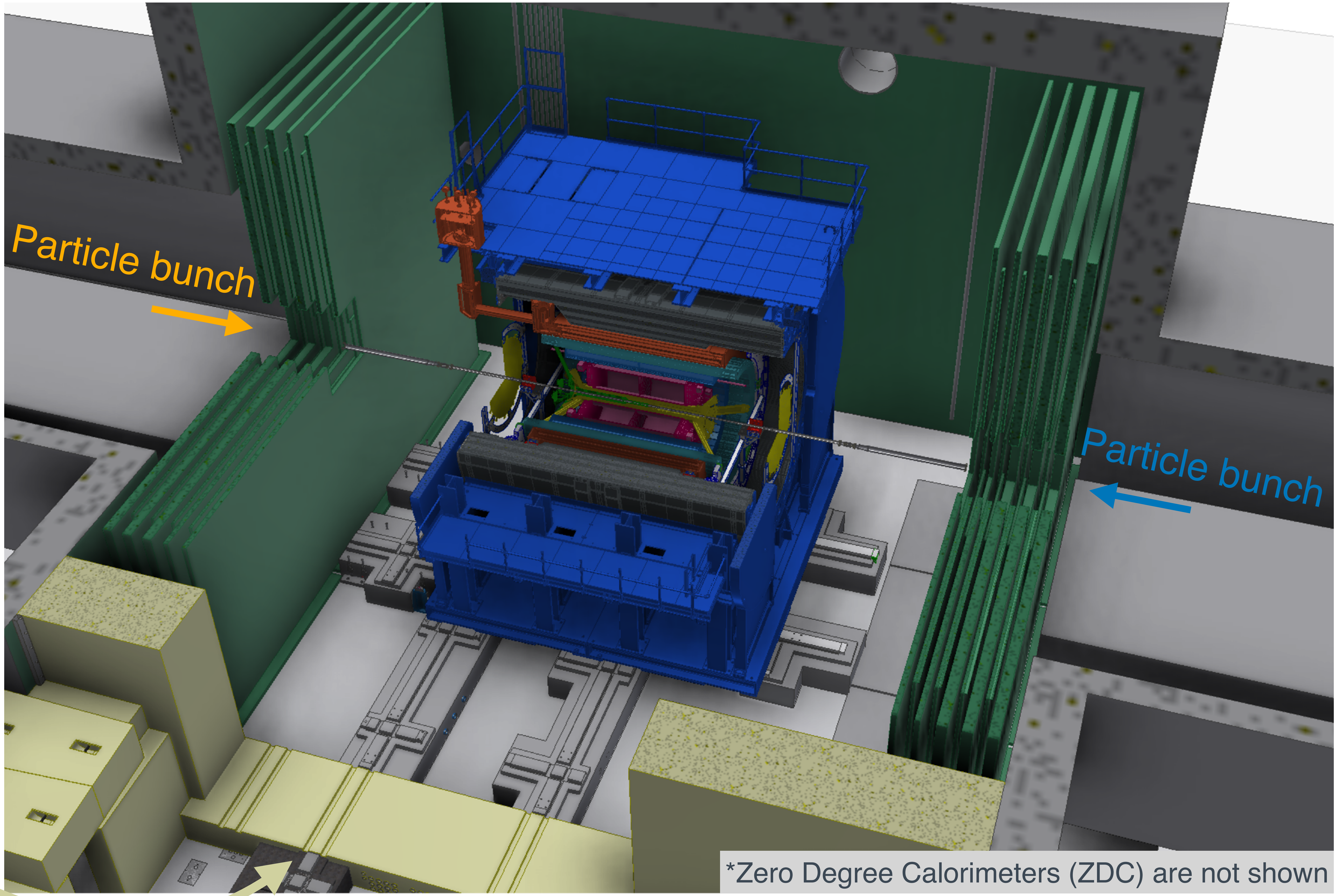

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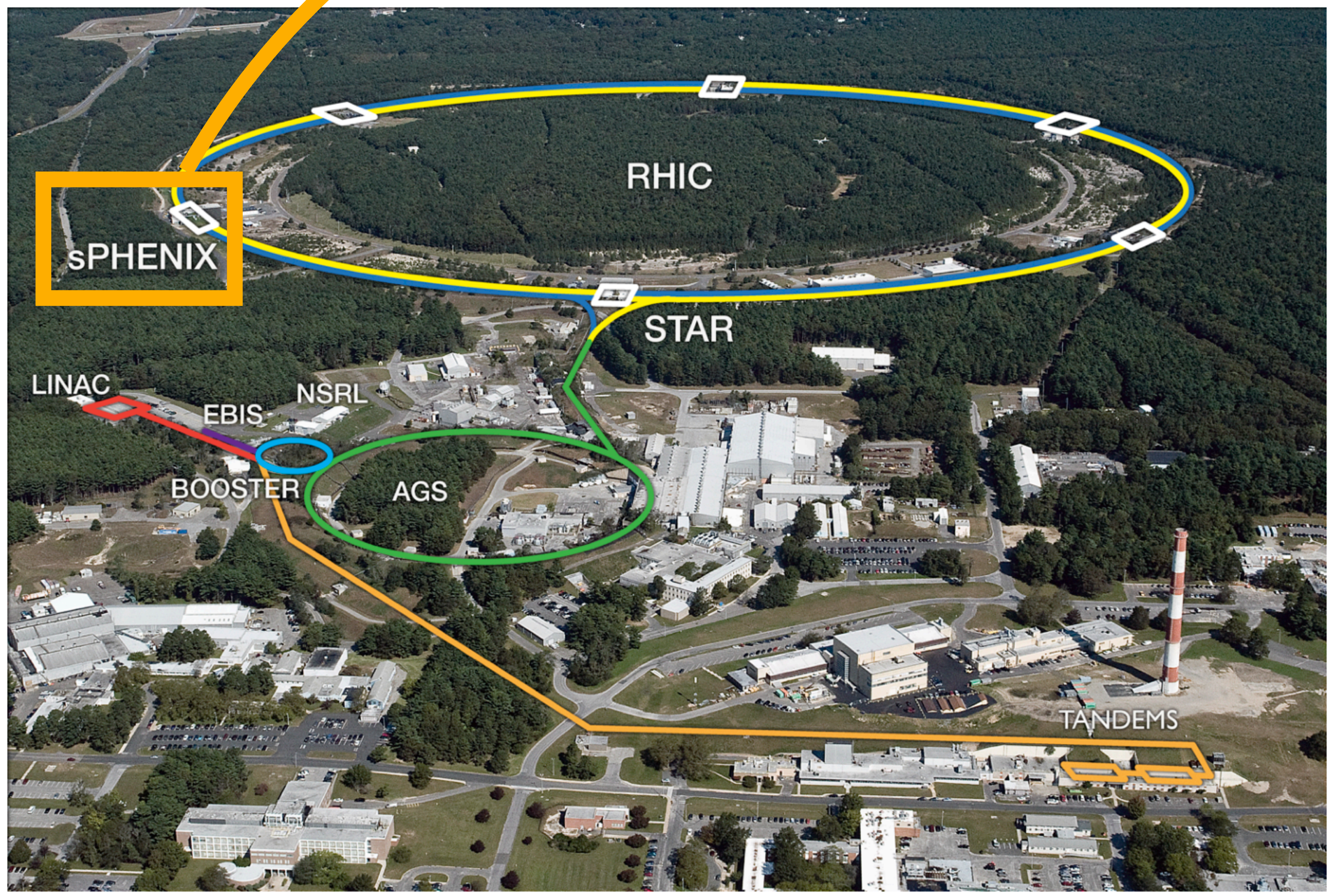

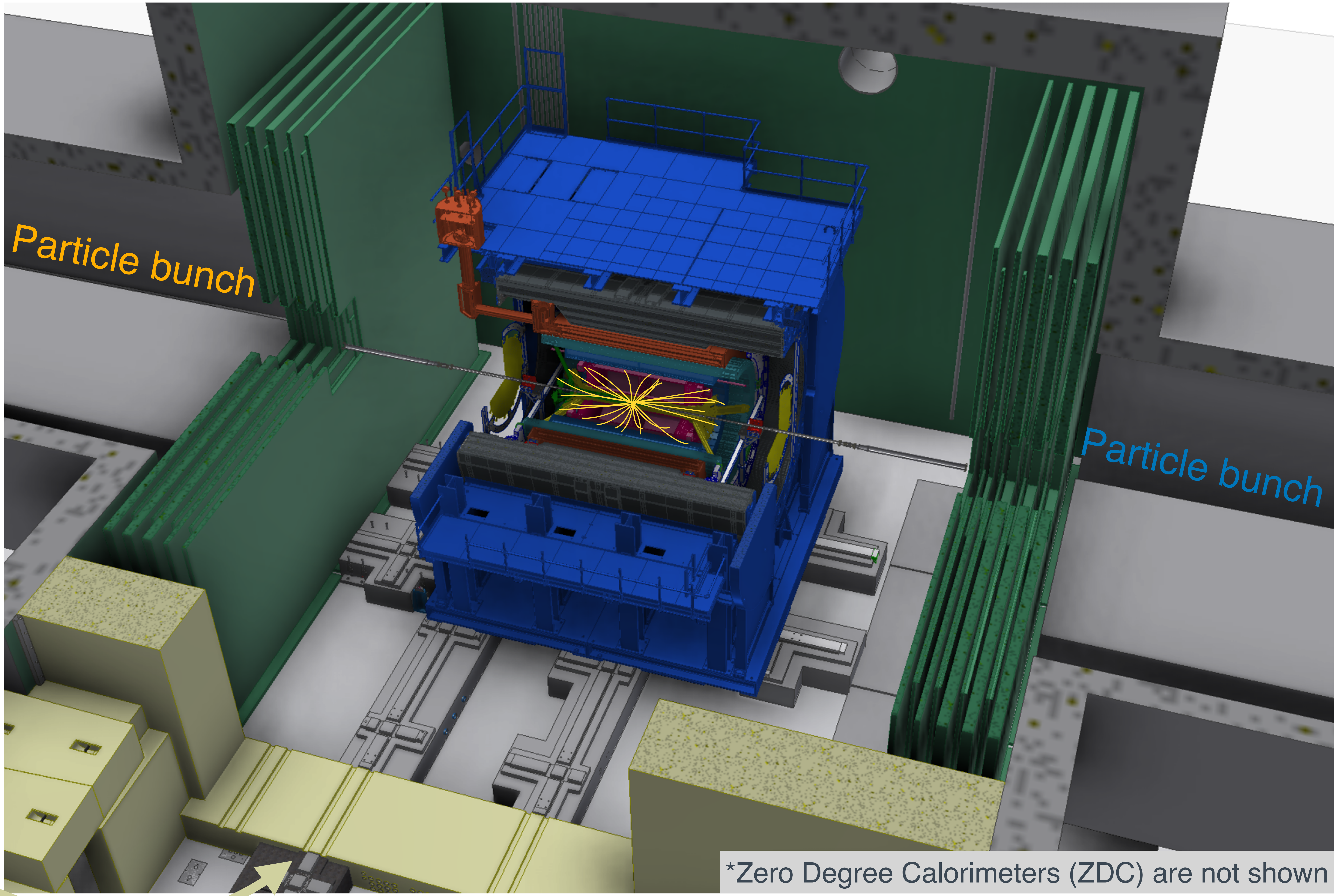

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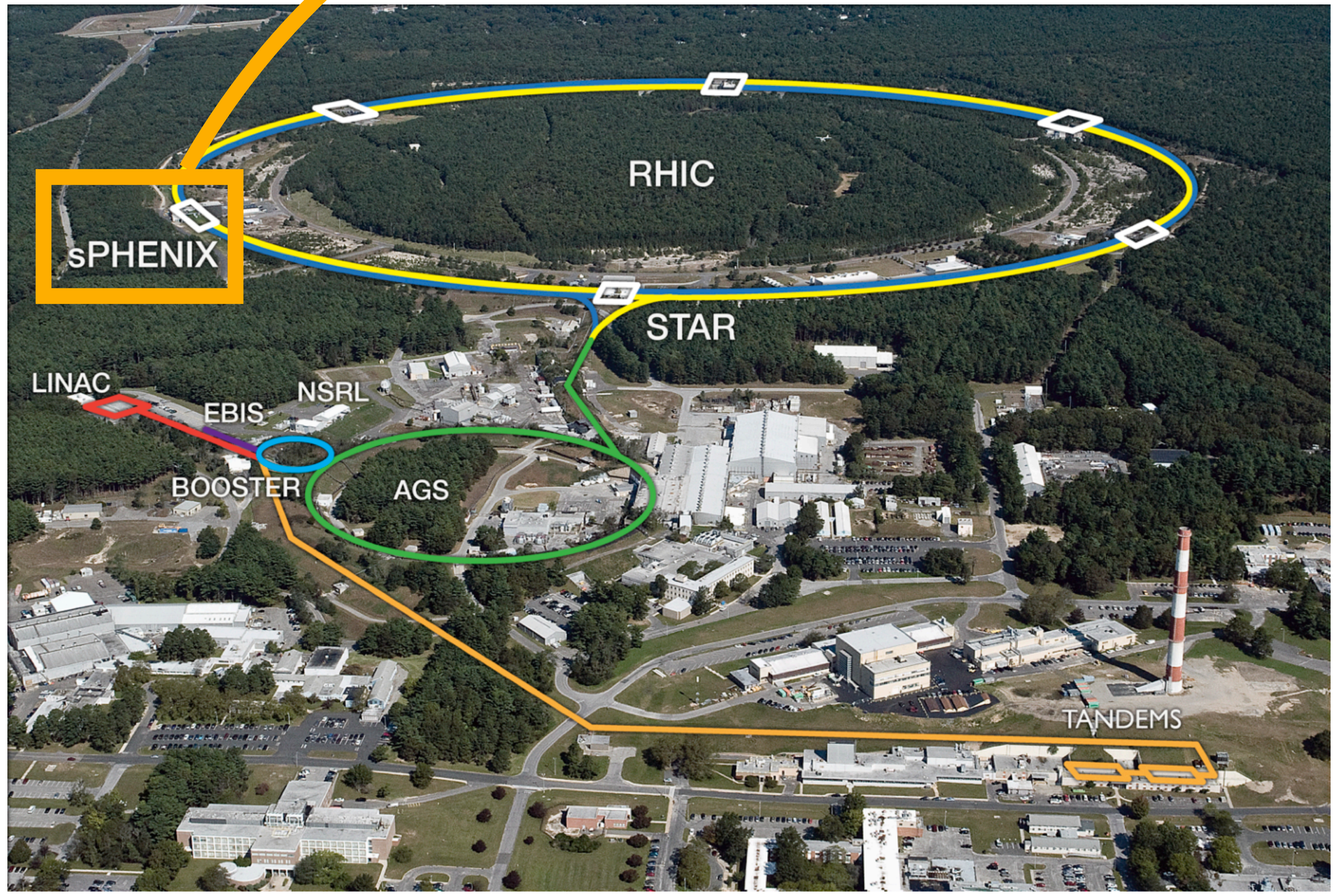
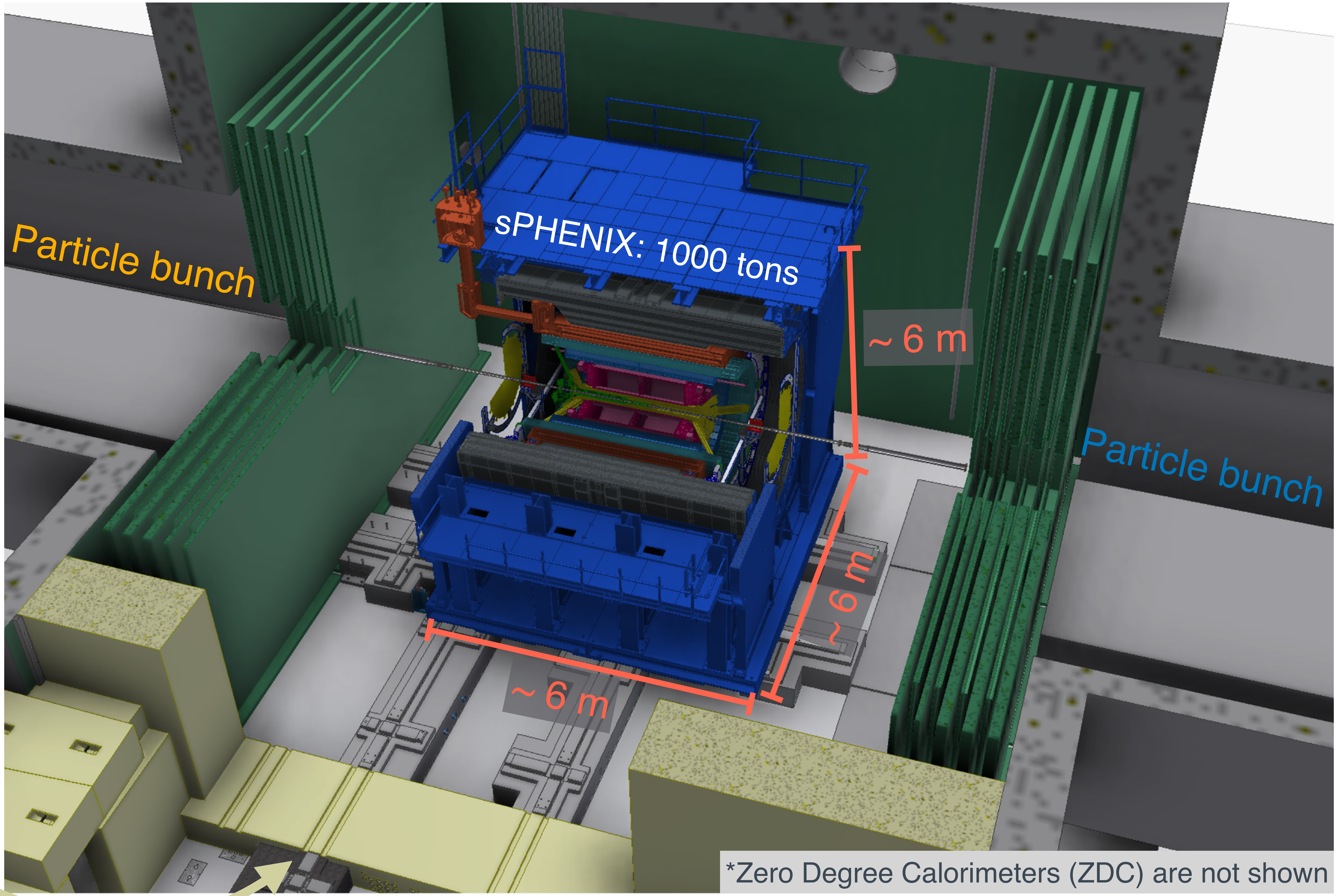




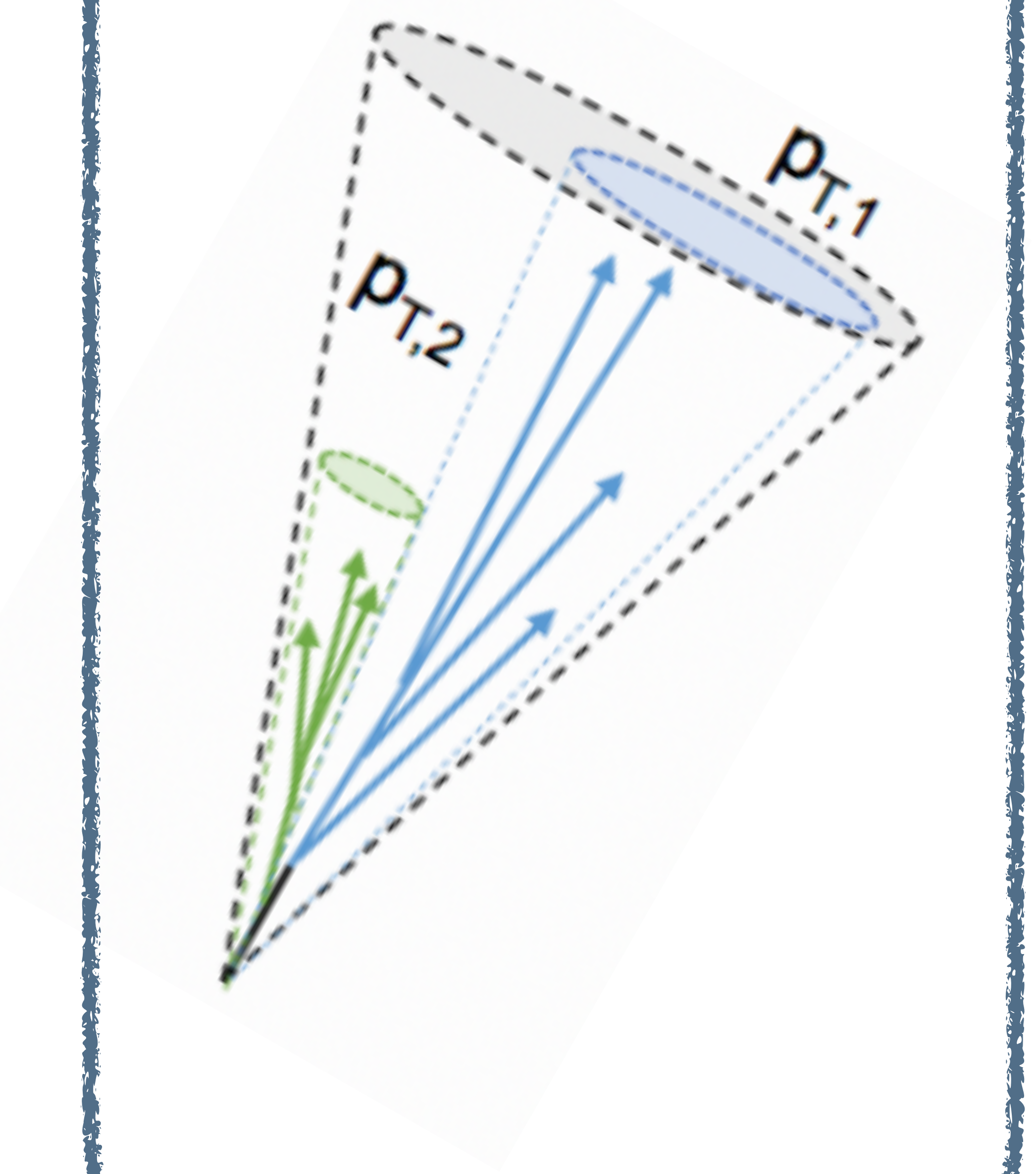
Portable shield wall

*Zero Degree Calorimeters (ZDC) are not shown

sPHENIX physics program

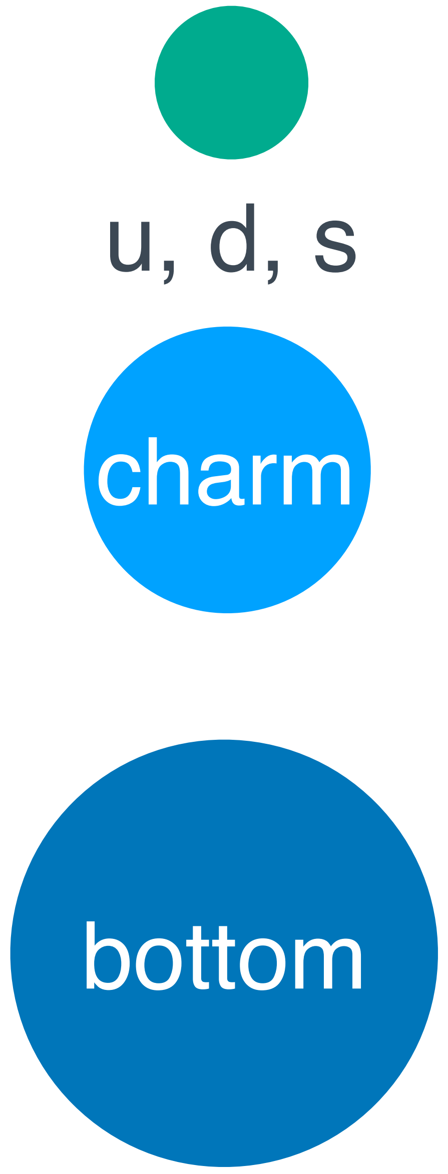
Jet Physics

Jet correlations & Jet structure



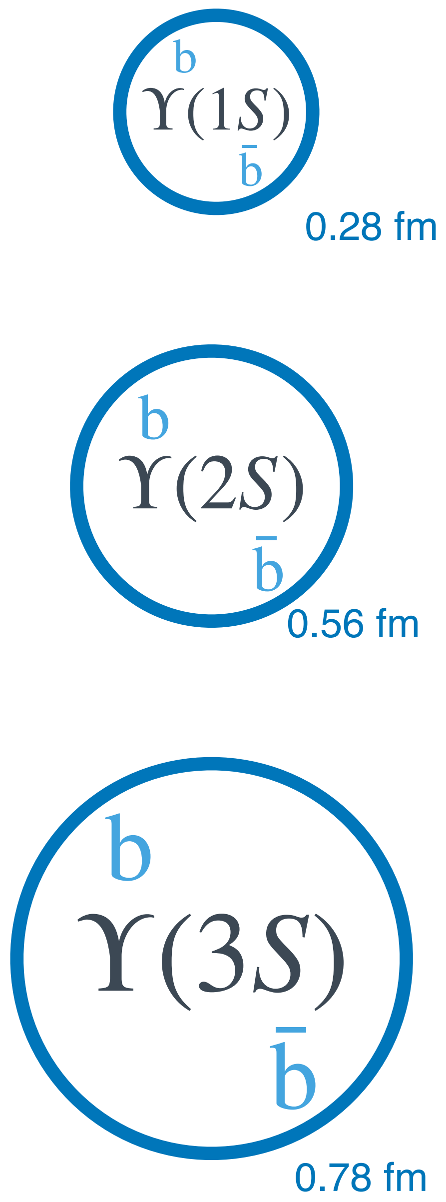
Heavy Flavor

Parton energy loss



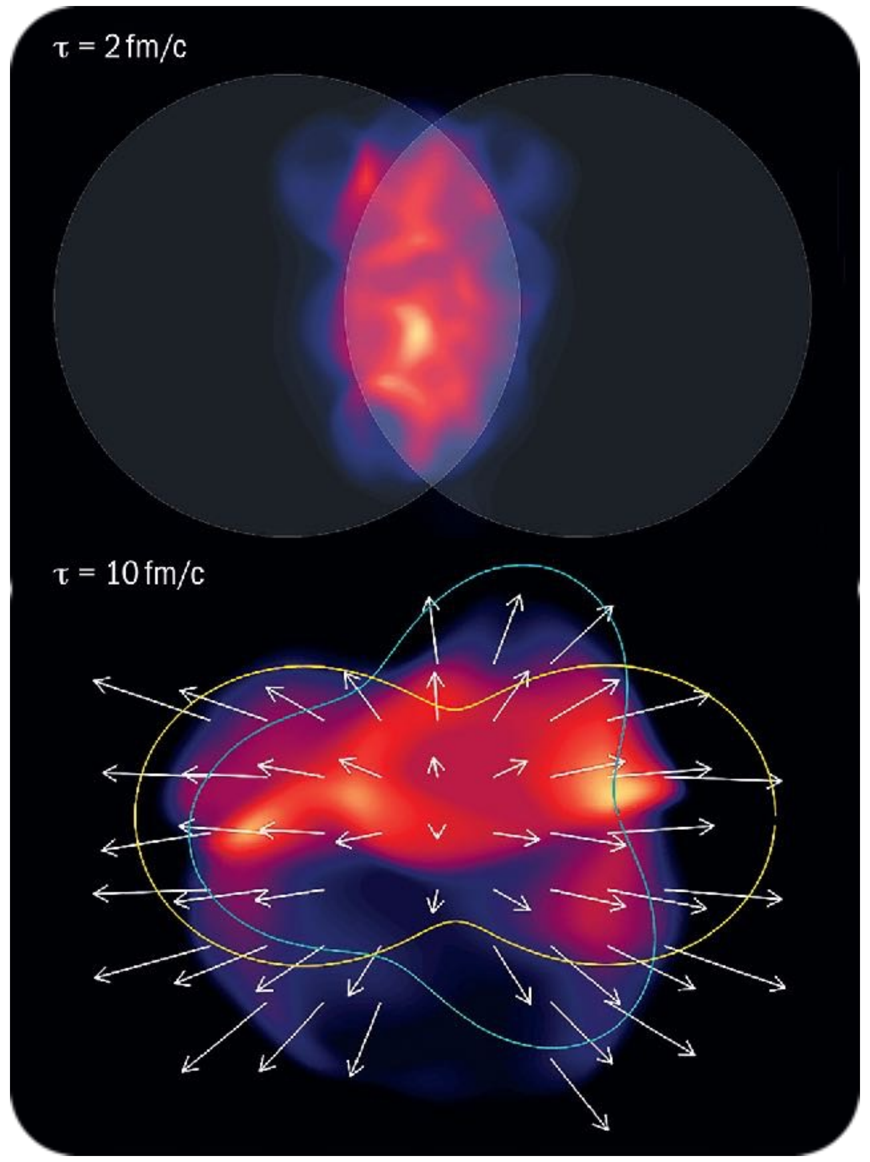
Quarkonium Spectroscopy

Sequential quarkonia melting



Bulk physics

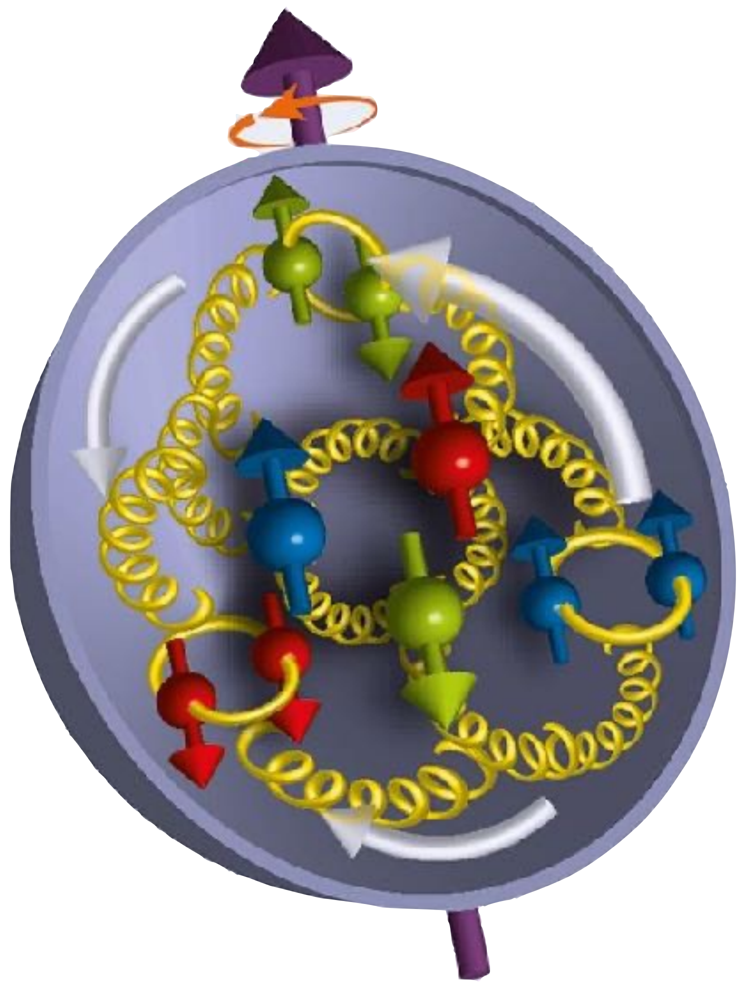
Global and collective properties of medium



MUSIC arXiv:1209.6330

Cold QCD

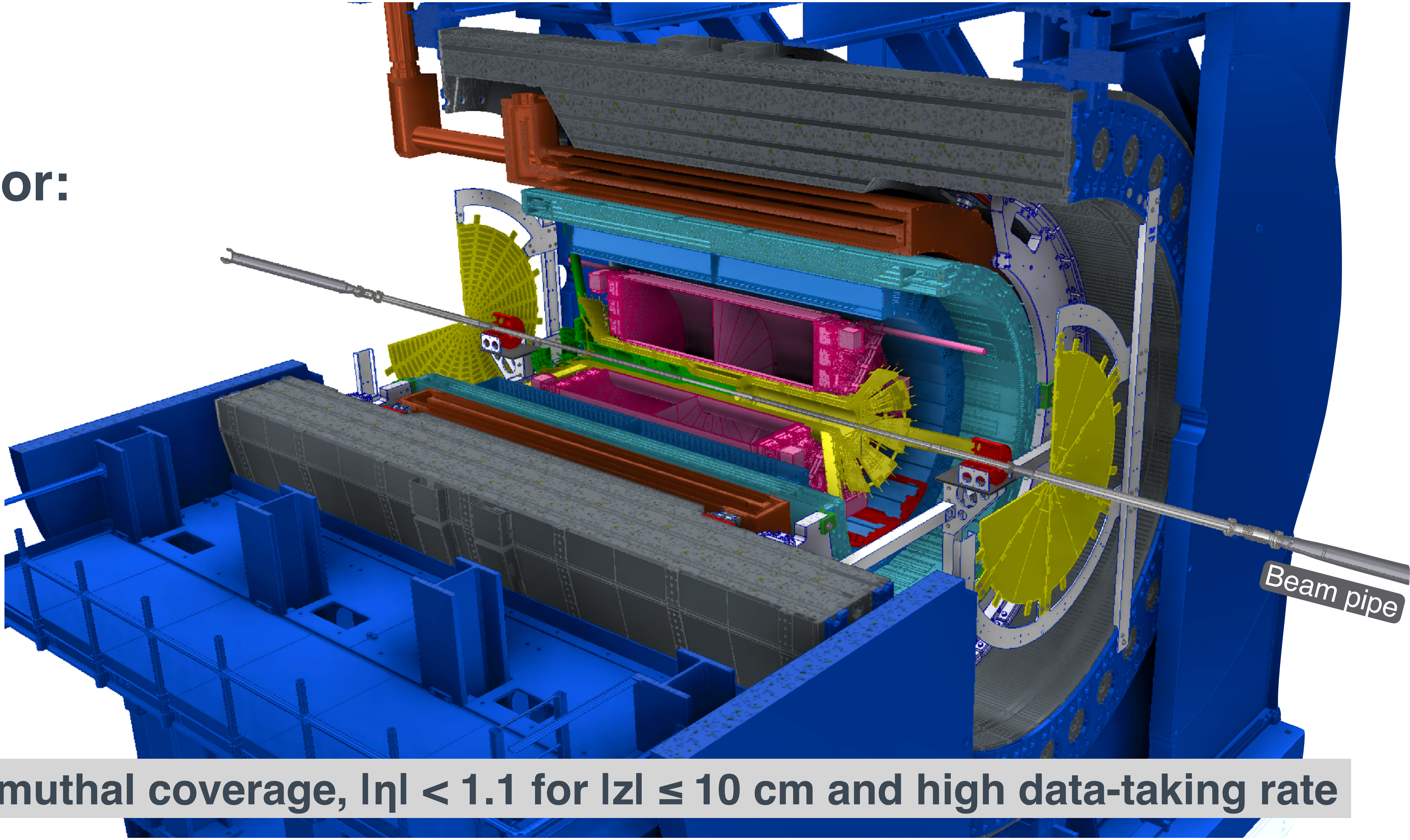
Proton spin & Nucleon structure



sPHENIX serves as the central and essential component to complete science mission of RHIC to reveal the nature of the QGP

sPHENIX detector

sPHENIX detector:
11 subsystems

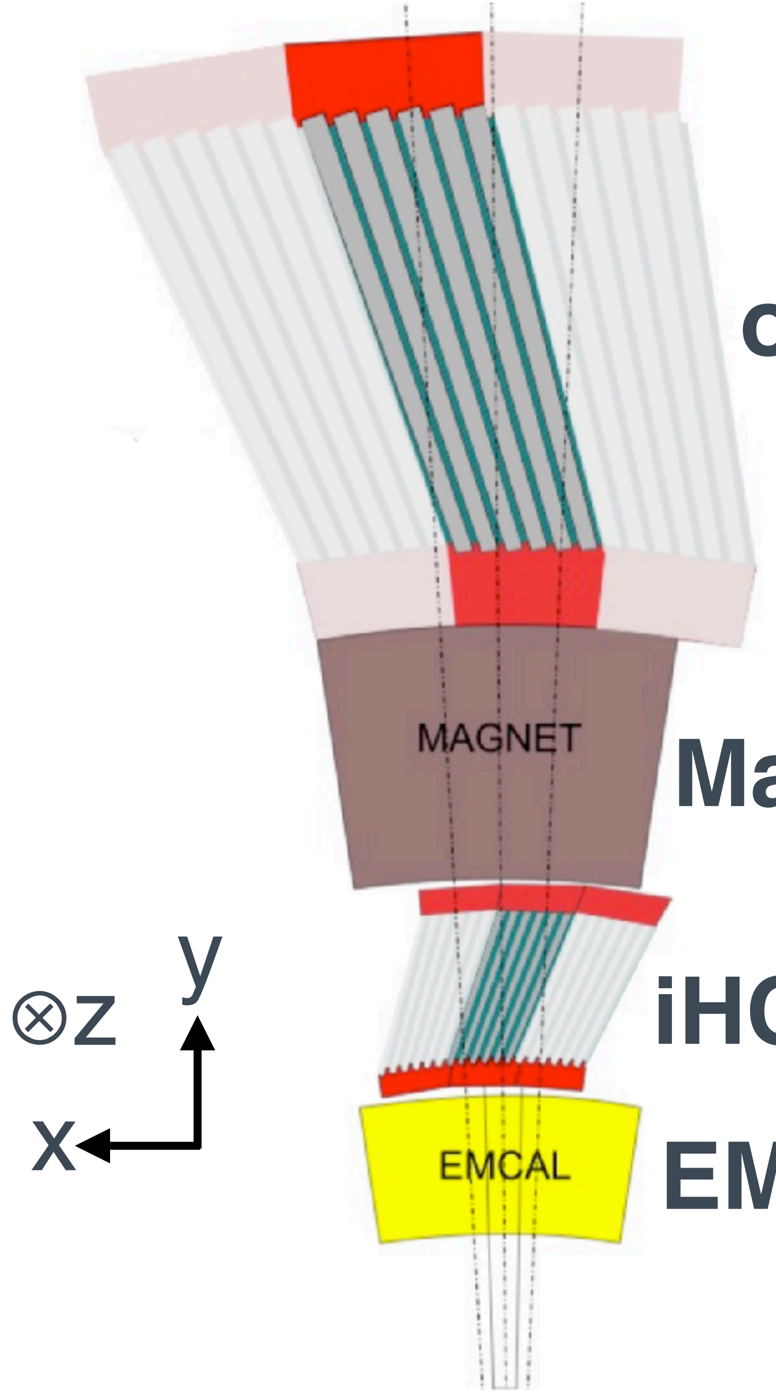


sPHENIX: Full azimuthal coverage, $|\eta| < 1.1$ for $|z| \leq 10$ cm and high data-taking rate

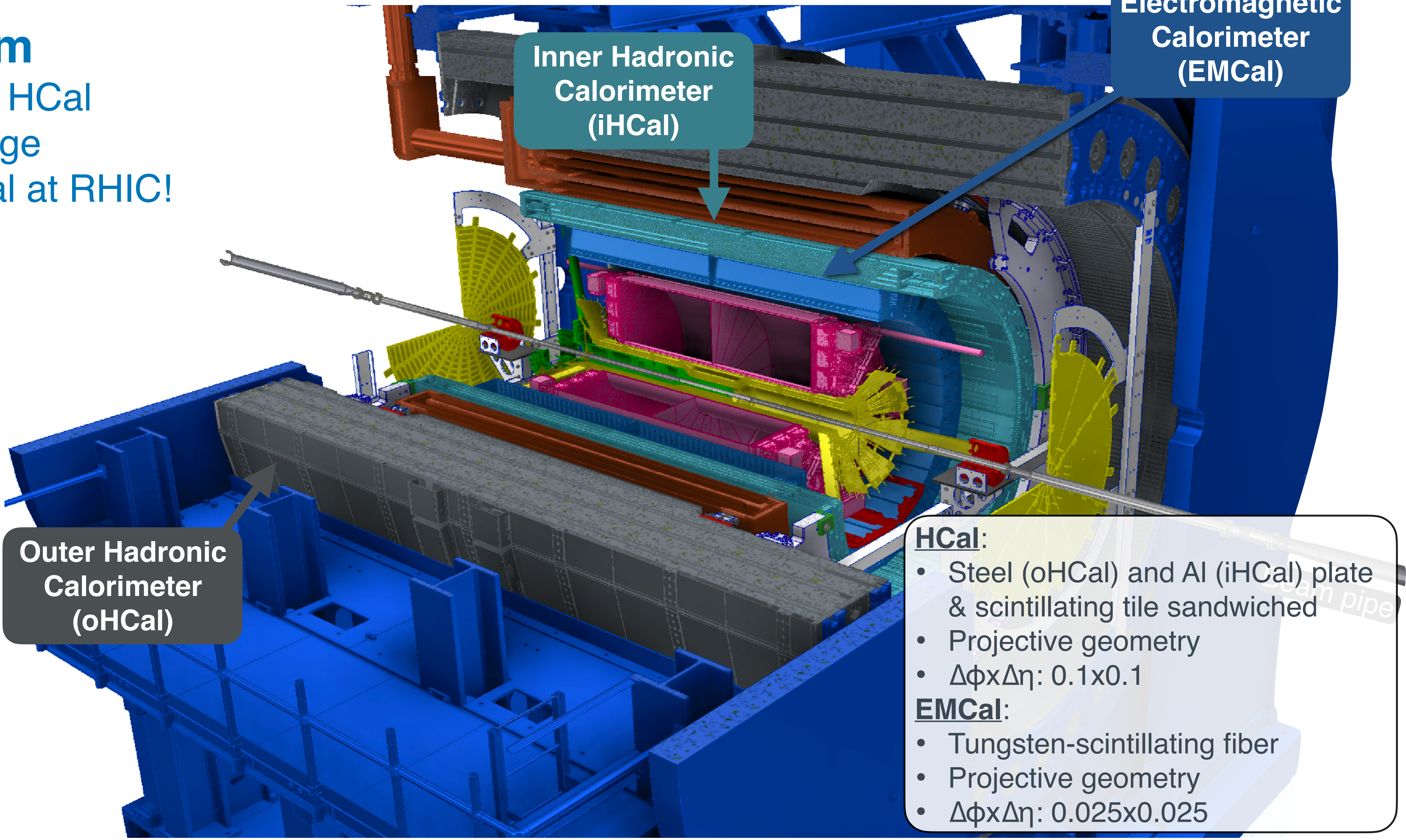
sPHENIX detector

Calorimeter system

- Mid-rapidity EMCal & HCal
- Full azimuthal coverage
- First mid-rapidity HCal at RHIC!



Sampling calorimeter
~ 5 λ_i in total



HCal:
- Steel (oHCal) and Al (iHCal) plate & scintillating tile sandwiched
- Projective geometry
- $\Delta\phi \times \Delta\eta$: 0.1x0.1

EMCal:
- Tungsten-scintillating fiber
- Projective geometry
- $\Delta\phi \times \Delta\eta$: 0.025x0.025

sPHENIX detector

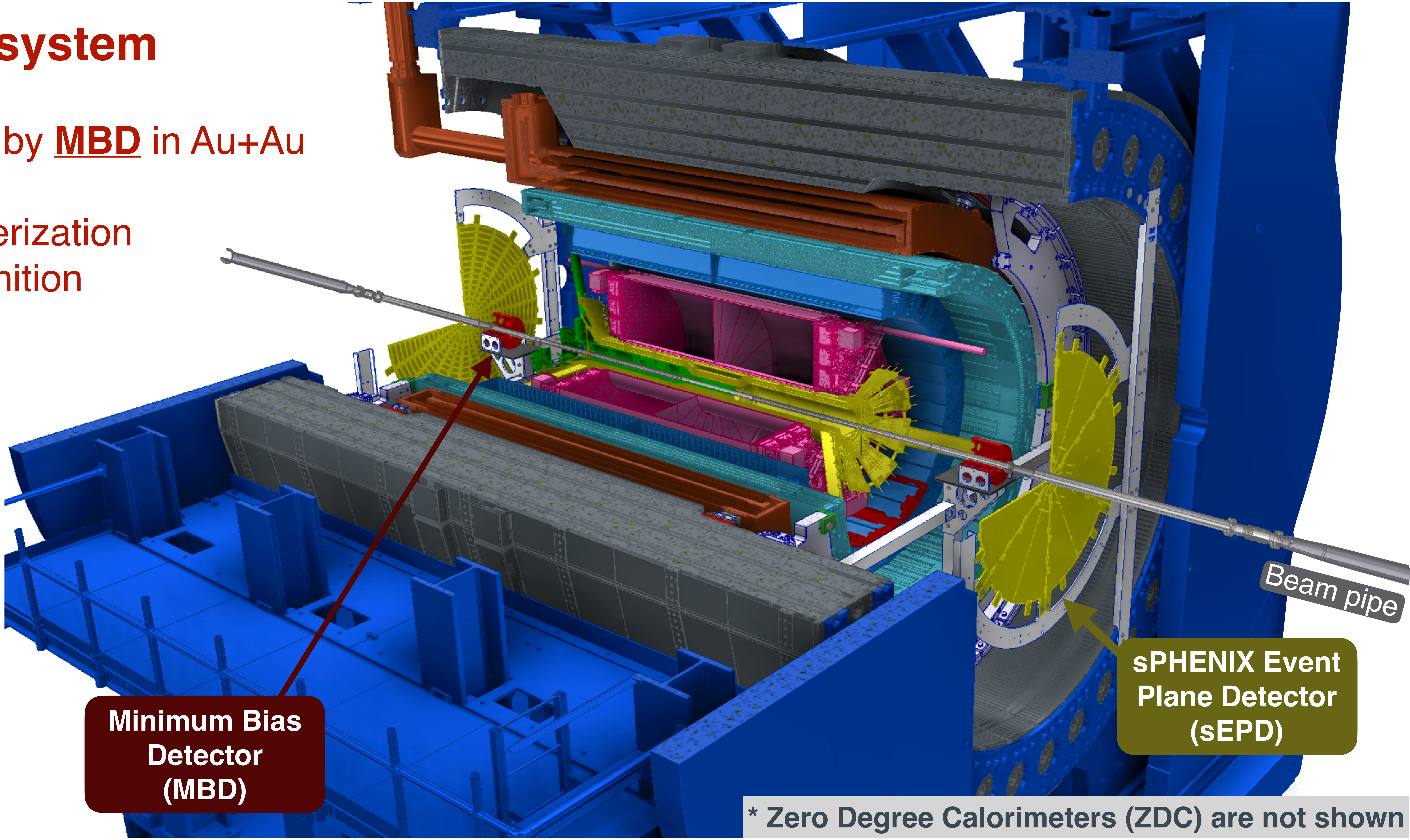
Tracking system

- MVTX: Vertex reconstruction
- INTT: Track-bunch crossing association
- TPC: Momentum measurement
- TPOT: TPC-distortion calibration

sPHENIX detector

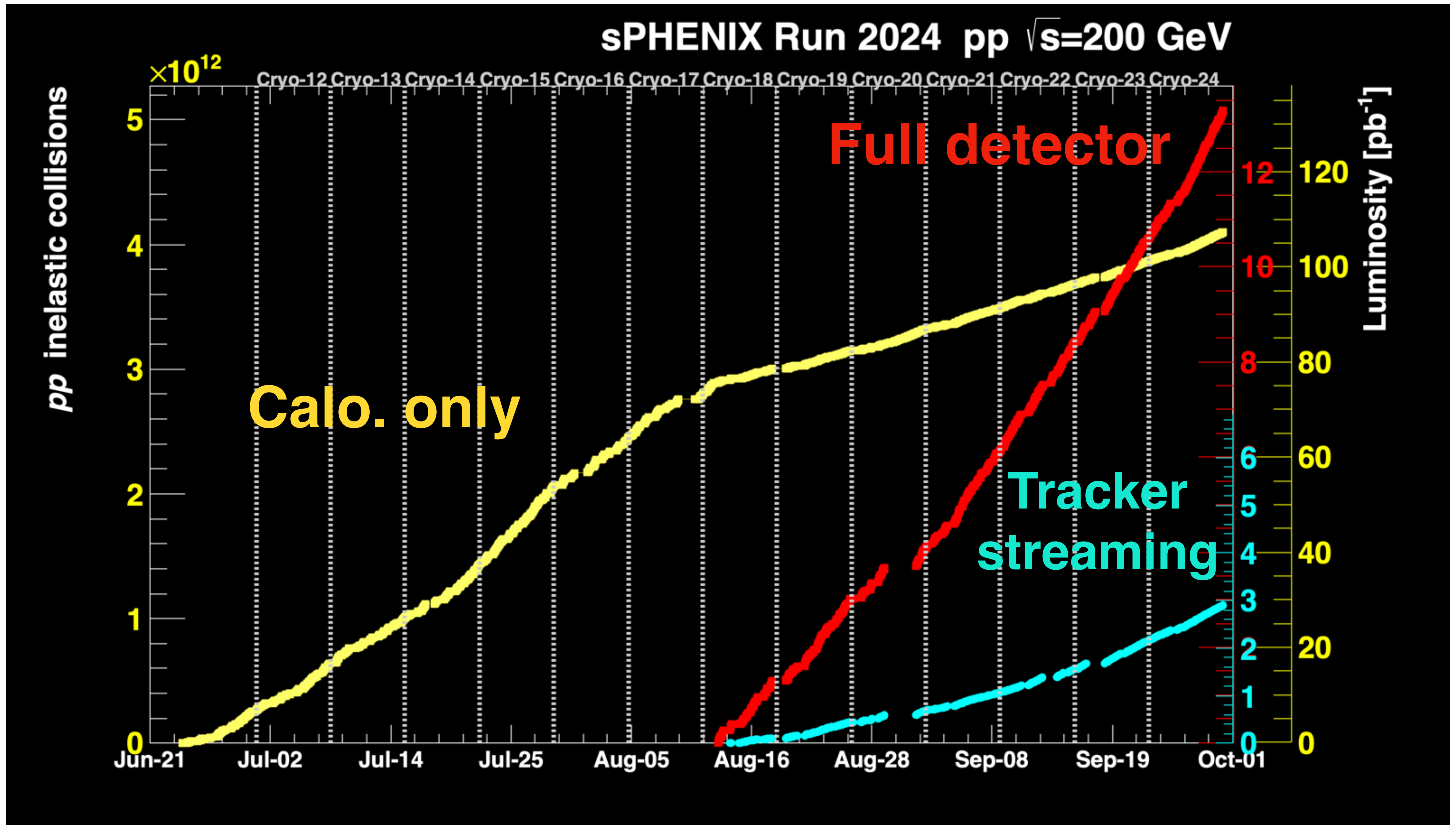
Forward detector system

- MBD + sEPD + ZDC
- Minimum bias trigger by **MBD** in Au+Au and p+p collisions
- Global event characterization
  - Minimum bias definition
  - Event centrality
  - Reaction plane



sPHENIX data taking 2024

Year	Request		Reality		
	Weeks	Run plan	Weeks	Species	Goal
2024	28 weeks	$p^{\uparrow}+p^{\uparrow}$ $p^{\uparrow}+Au$	24	$p^{\uparrow}+p^{\uparrow}$	Au+Au baseline and spin, cold-QCD measurments
			3	Au+Au	Commissioning of TPC and MVTX*



Polarized proton-proton collisions in Run 2024

- **Calorimeter only data: 107.4 pb^{-1} → 240% of Run Goal**
- **Full detector data: 13.28 pb^{-1} → 30% of Run Goal**
- **Tracker streaming data: 2.90 pb^{-1} → 65% of Run Goal**

*Run24 sPHENIX Au+Au data also used for physics analyses

sPHENIX data taking 2024

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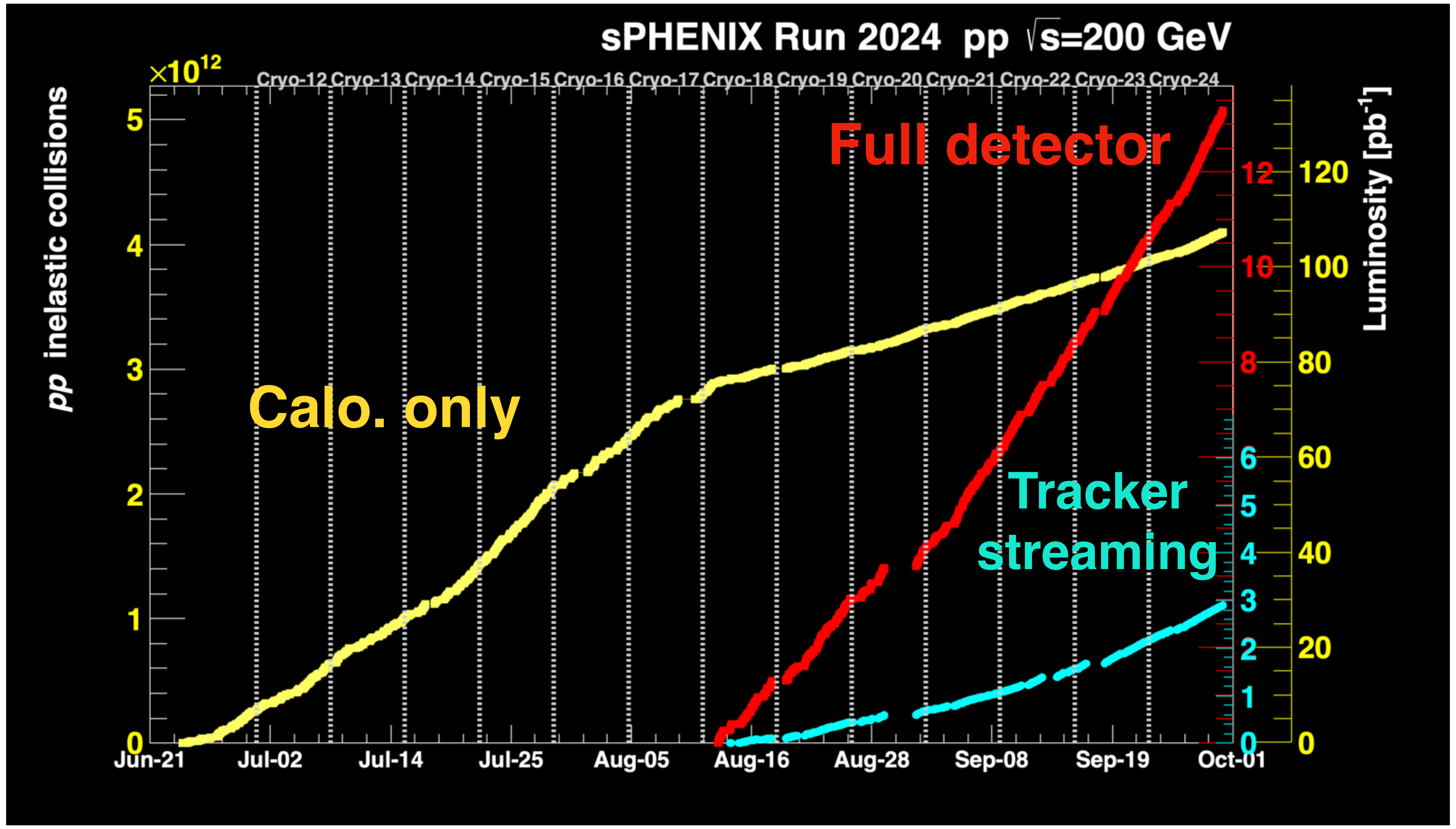

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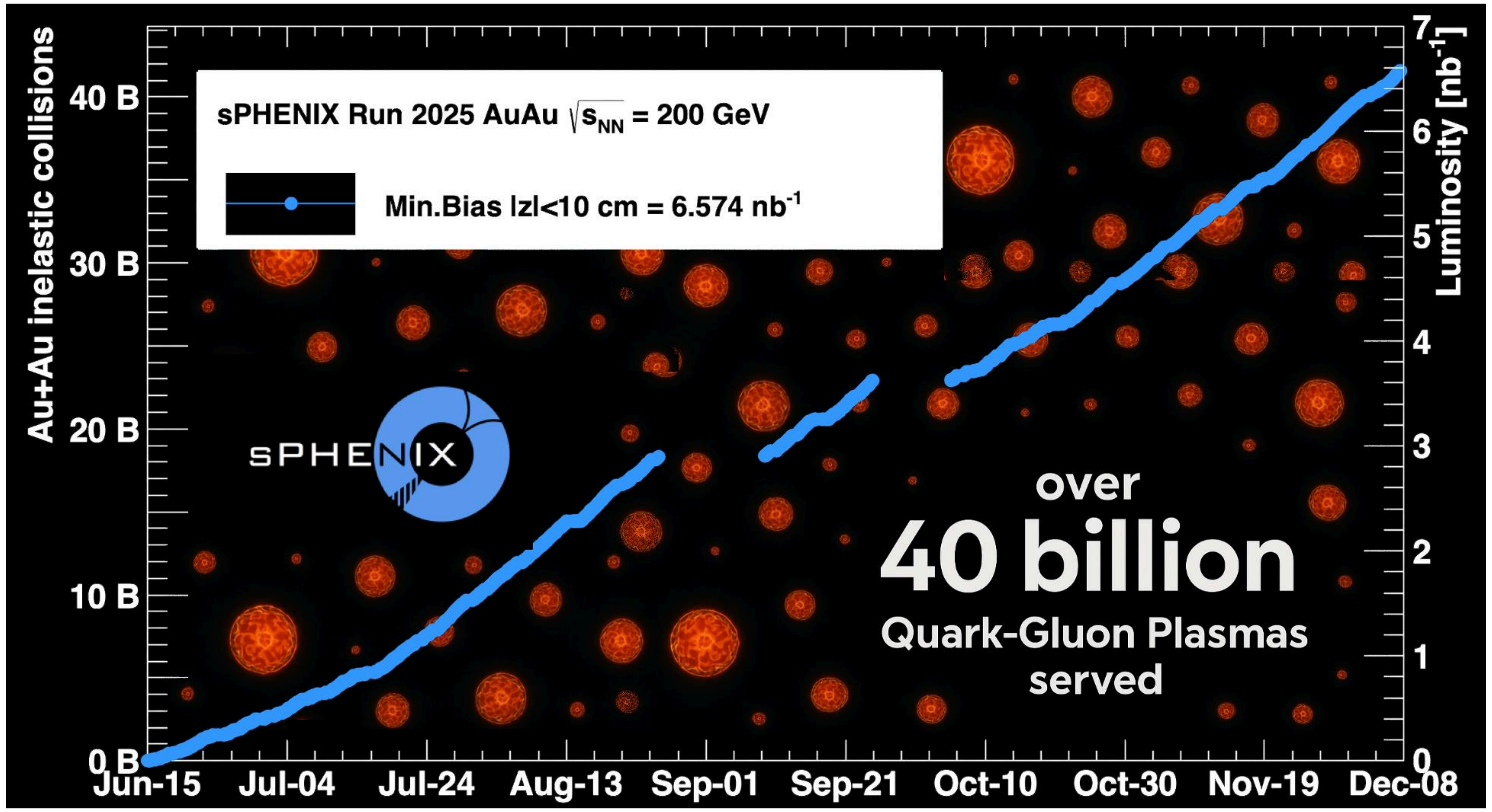
This talk: focus on results using Run24 data

*Run24 sPHENIX Au+Au data also used for physics analyses

sPHENIX data taking 2025

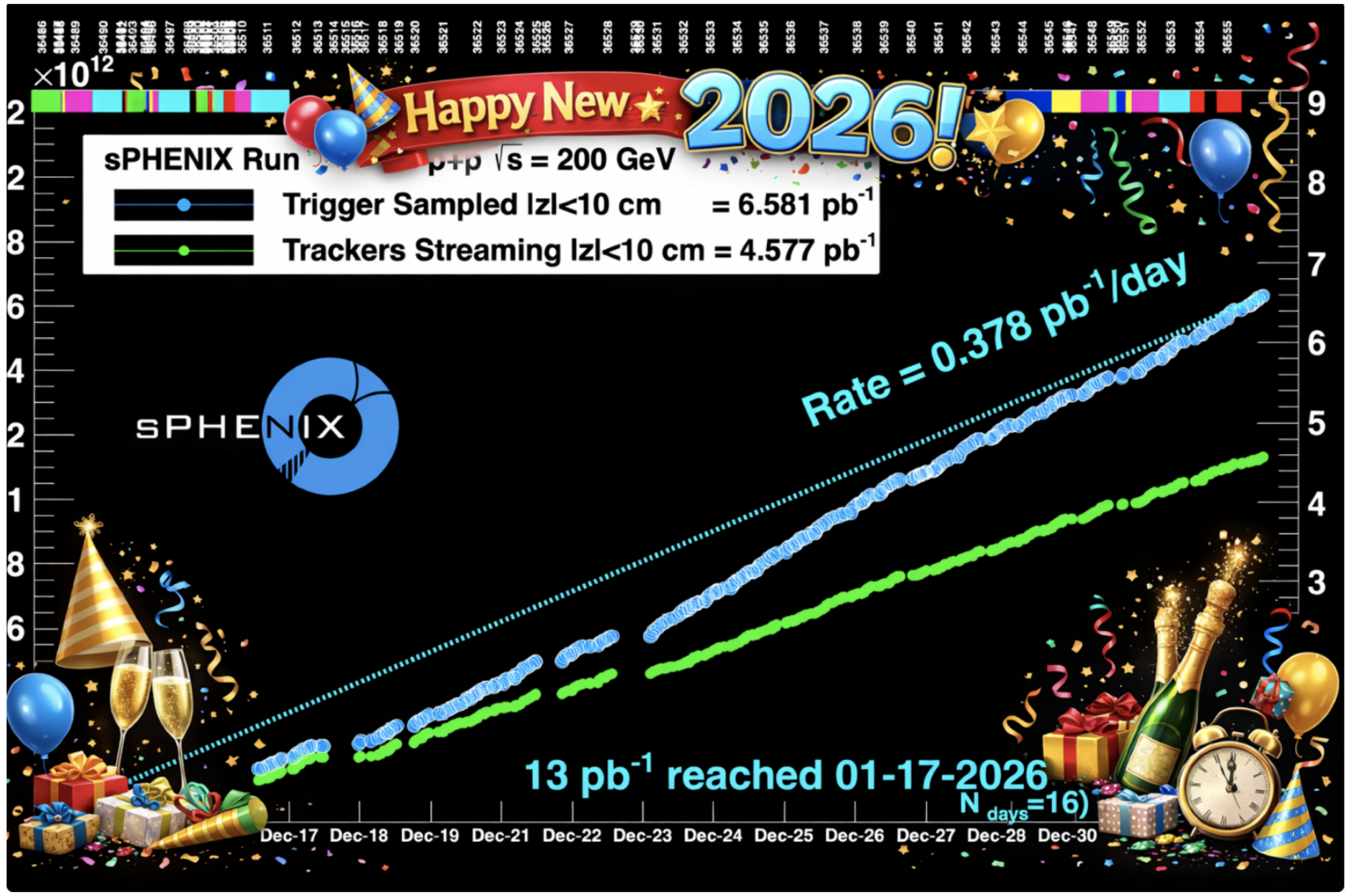
Year	Request		Reality		
	Weeks	Run plan	Weeks	Species	Goal
2025 2026	28 weeks	Au+Au	25	Au+Au	Golden Au+Au dataset
			6	p↑+p↑	Additional full-detector p+p data

Au+Au collision data taking



6.574 nb^{-1} achieved → 94% of Run Goal

p+p collision data taking **on going!**



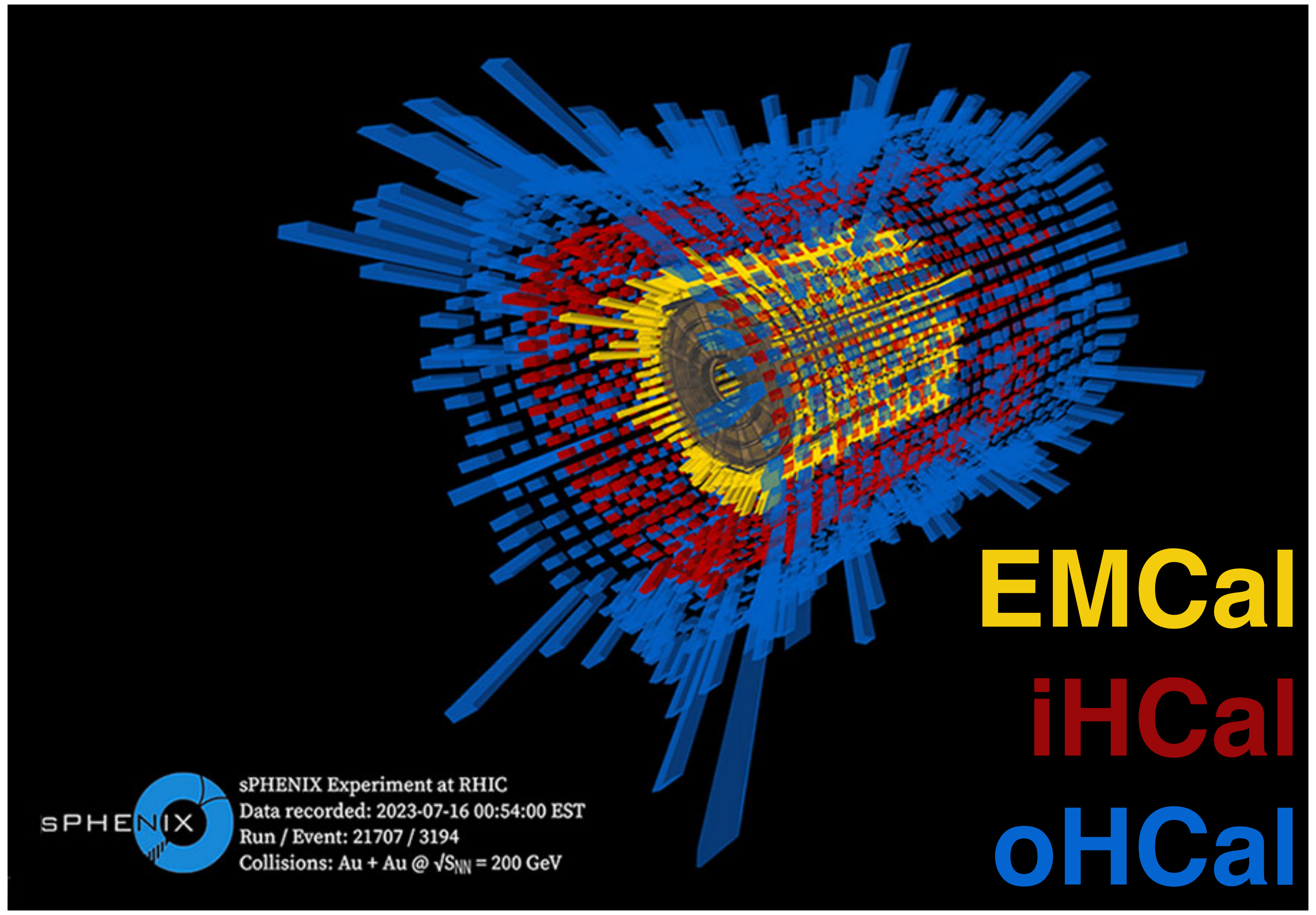
Run25 p+p collision data taking on going!

Bulk physics measurements at sPHENIX

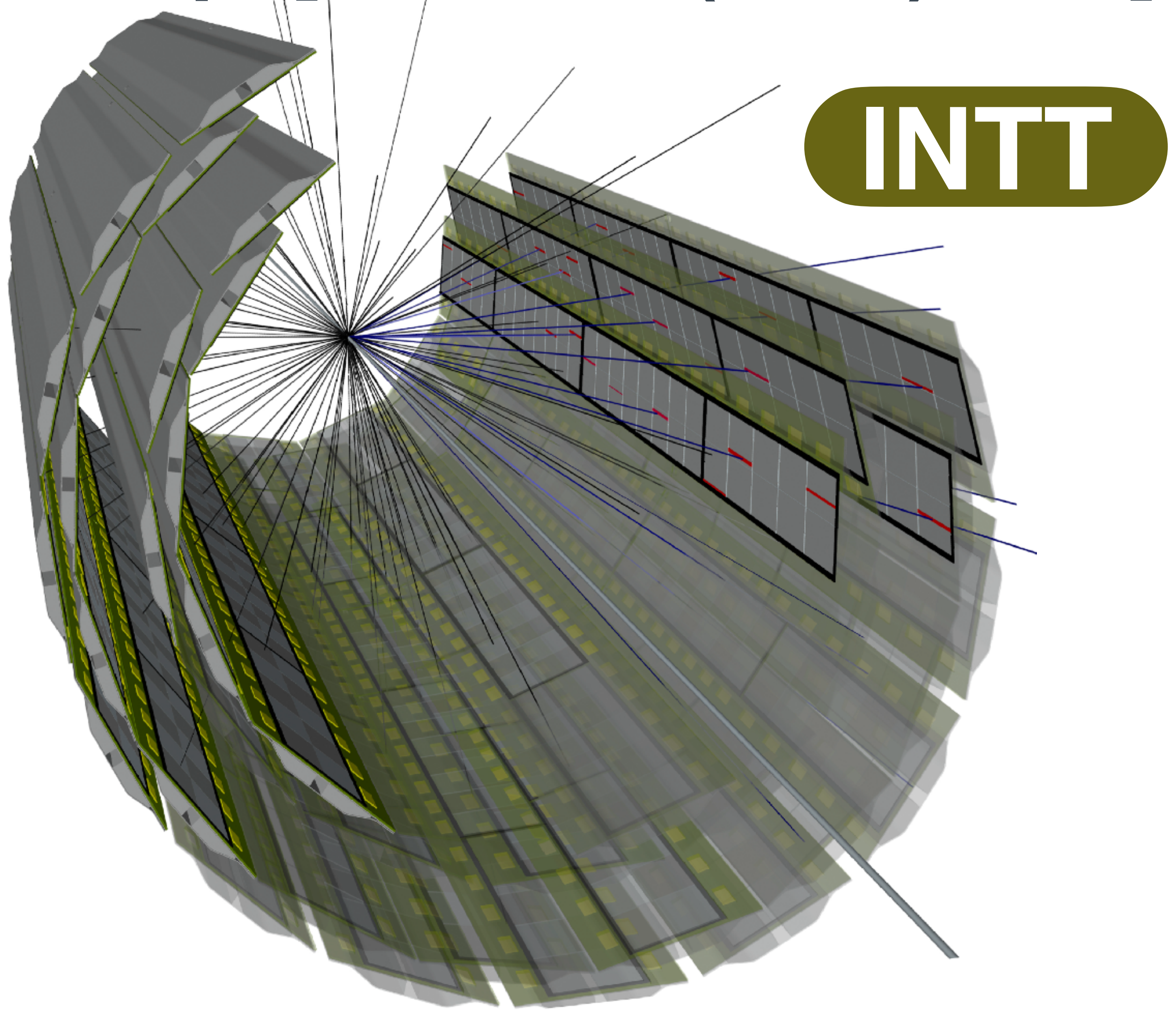
w/ Run24 Au+Au collision data

- **Energy ($dE_T/d\eta$) and particle ($dN_{ch}/d\eta$) densities**: dependence on colliding systems, energies, and geometry place constraints on theories
- sPHENIX is expected to match the previous experimental measurements at RHIC
- These first sPHENIX measurements serve as standard candles to validate performance
- First physics publications

$dE_T/d\eta$ - [PRC 112 (2025), 024908]



$dN_{ch}/d\eta$ - [JHEP 08 (2025), 075]

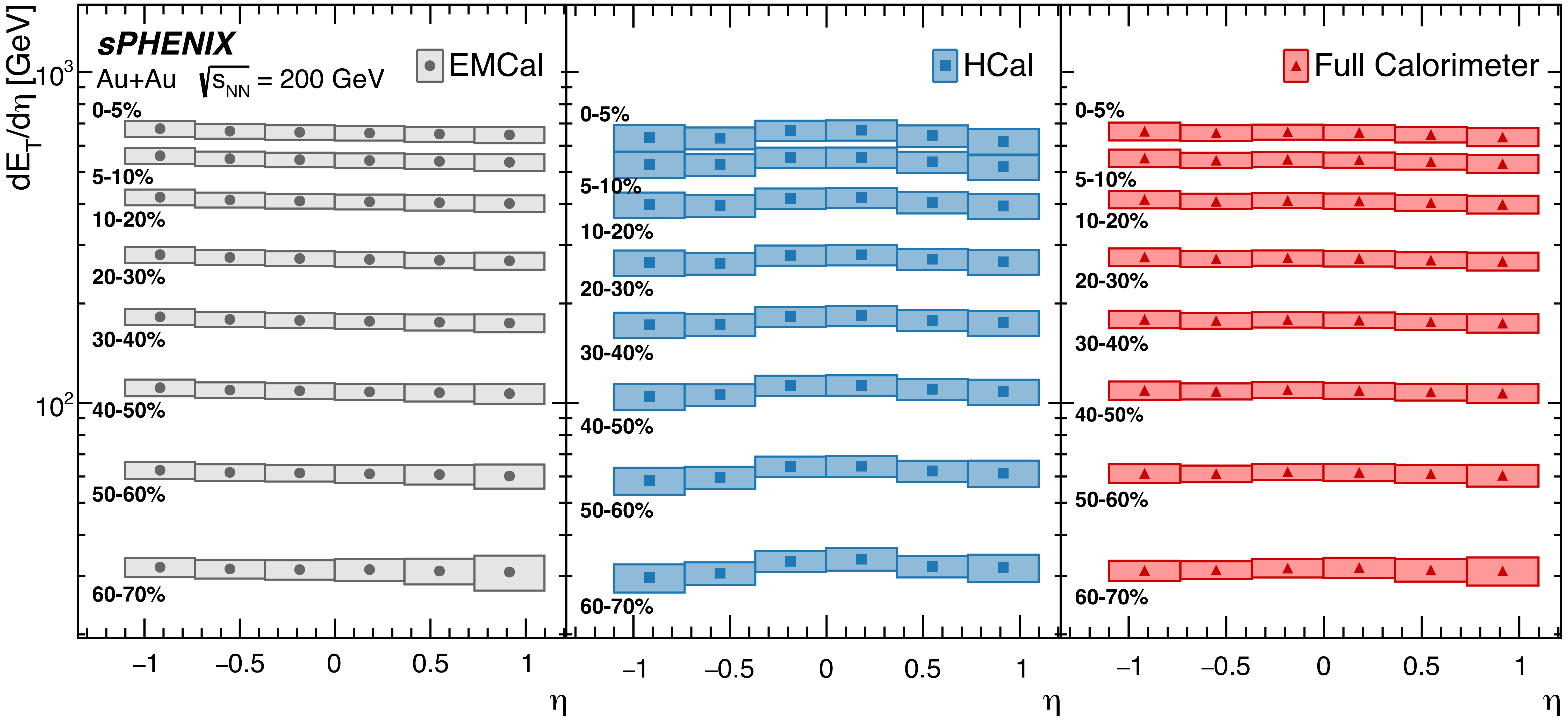


Measurement of $dE_T/d\eta$ in Au+Au collisions

- $dE_T/d\eta$: Transverse energy per unit pseudorapidity, estimating the initial energy density
- Calorimeter-based standard candle measurement
- Measured by the sPHENIX full barrel calorimeter system, EMCal + HCal (separated and combined)
- **$dE_T/d\eta$ in particle level**: Correction factors applied to detector-level $dE_T/d\eta$, to account for detector acceptance, low-p_T charged particles, losses in the magnet region, etc

w/ Run24 Au+Au collision data

sPHENIX Final! - [PRC 112 (2025), 024908]



Excellent agreement between EMCal and HCal measurements

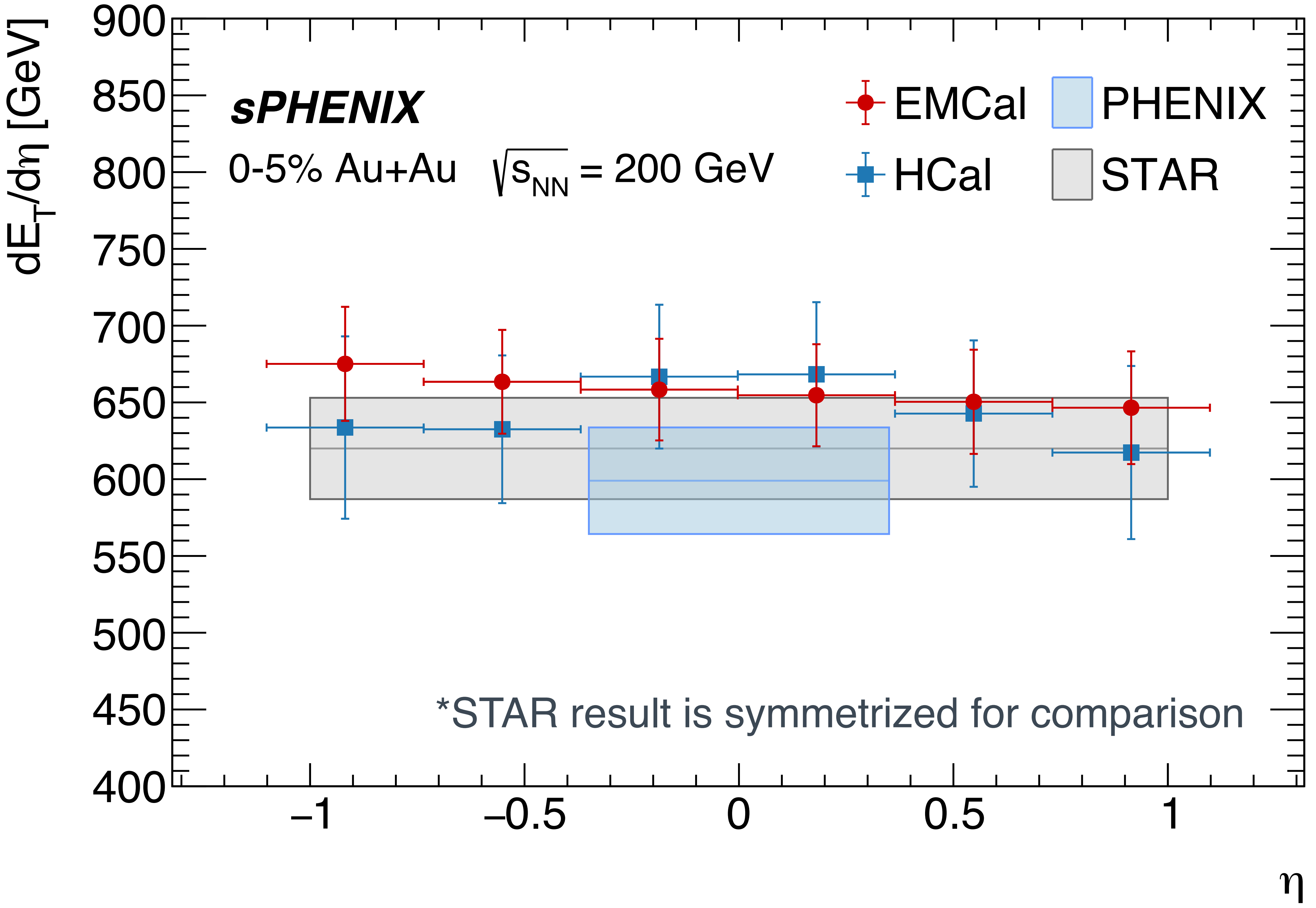
Sensitive to energy deposited from different particle species

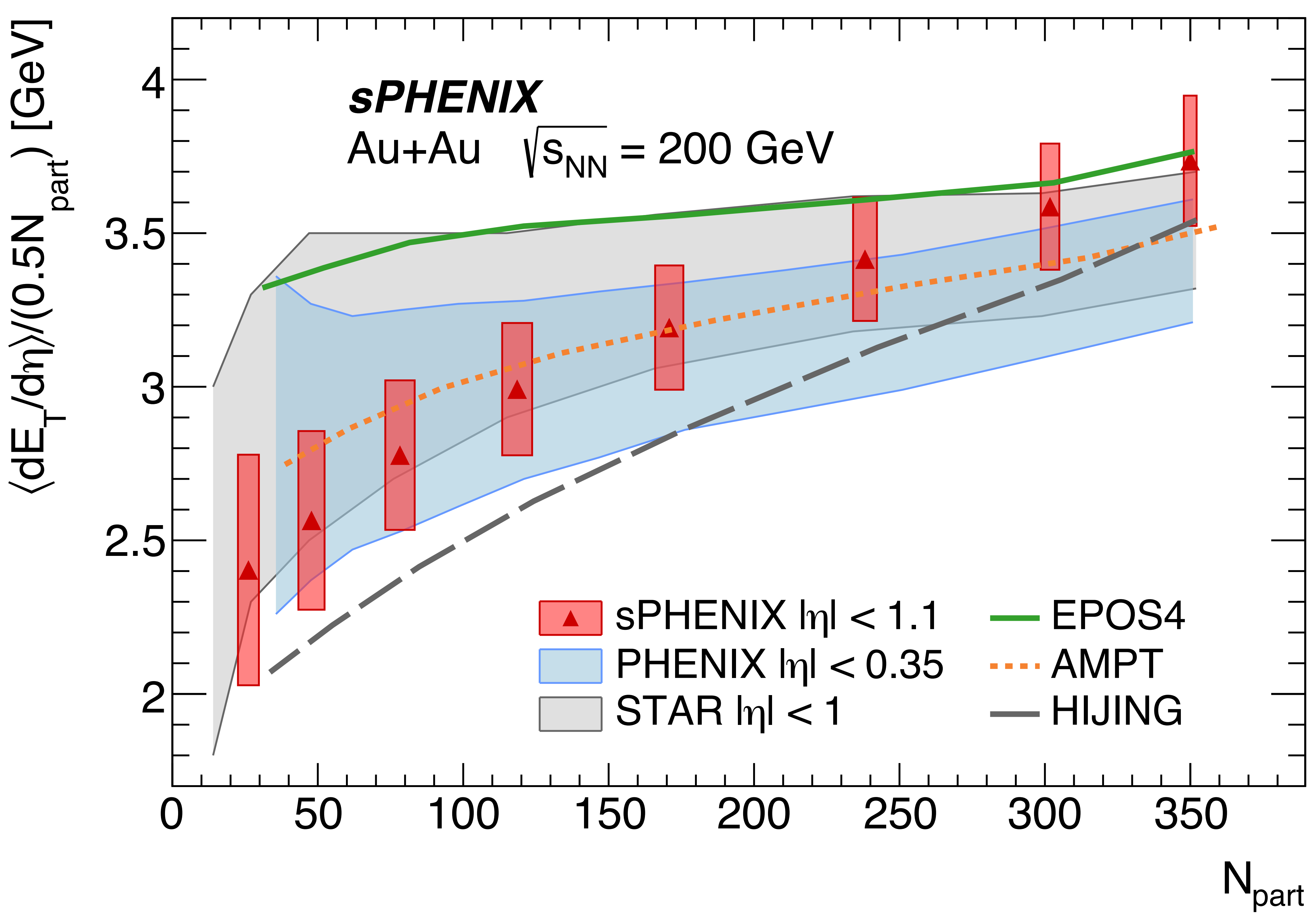
Measurement of $dE_T/d\eta$ in Au+Au collisions

sPHENIX

sPHENIX Final! - [PRC 112 (2025), 024908]

w/ Run24 Au+Au collision data

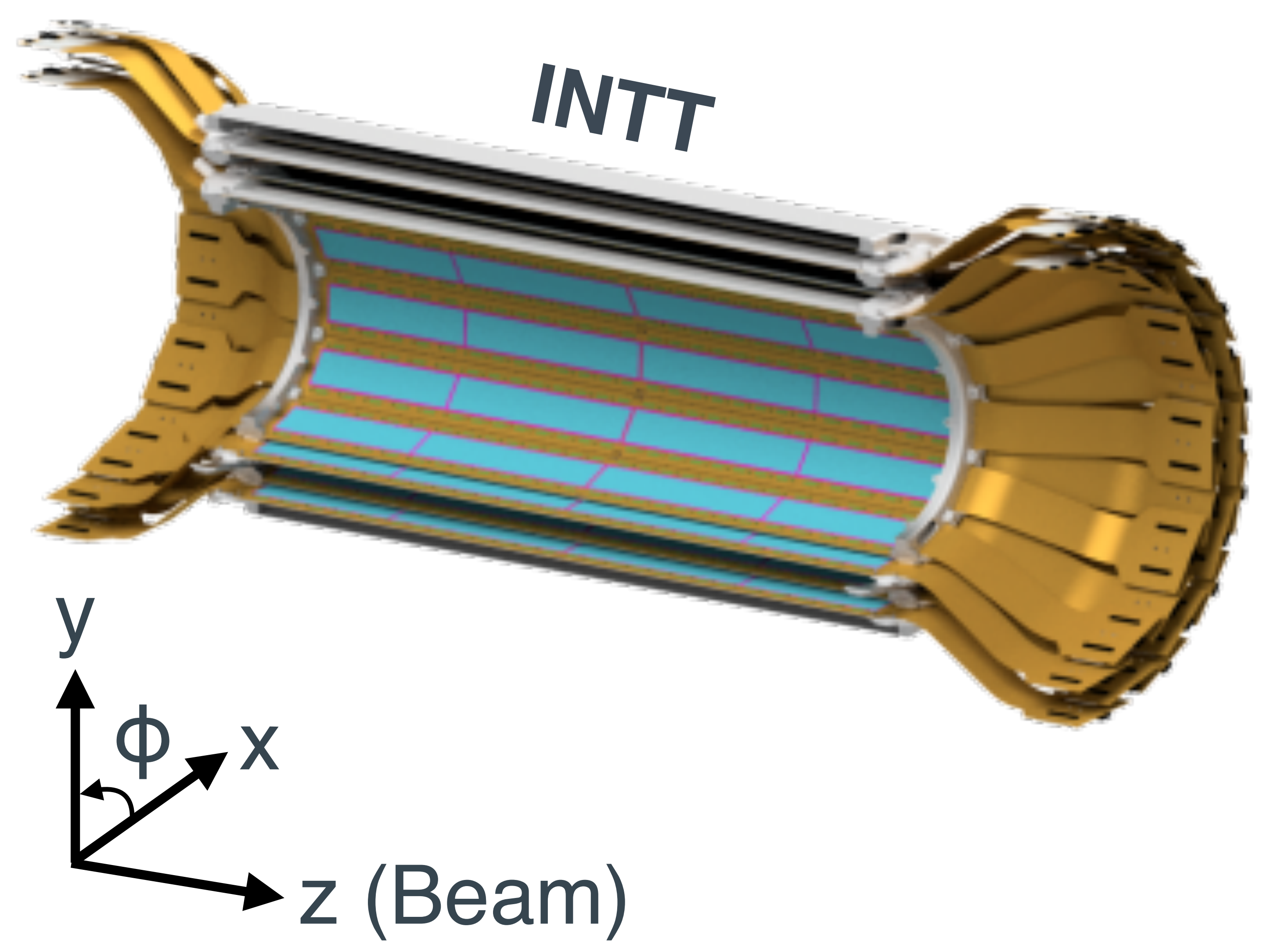


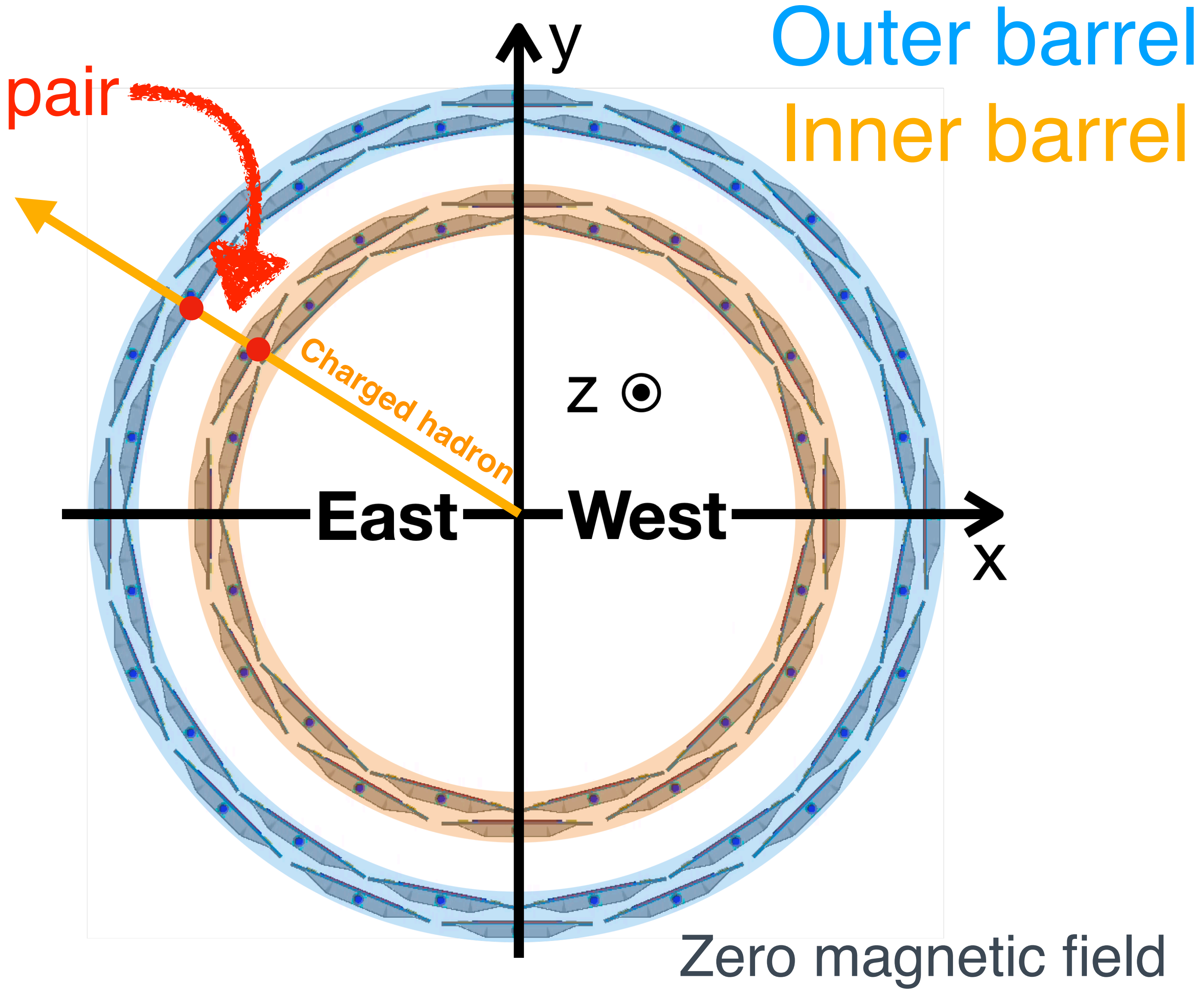


- sPHENIX measurements of $dE_T/d\eta$ as a function of η and normalized $dE_T/d\eta$ as a function of N_{part}, are consistent with previous RHIC measurements
- The sPHENIX measurement offers additional granularity in η and improved uncertainties in peripheral events, and is best described by the AMPT model

Measurement of $dN_{ch}/d\eta$ in Au+Au collisions

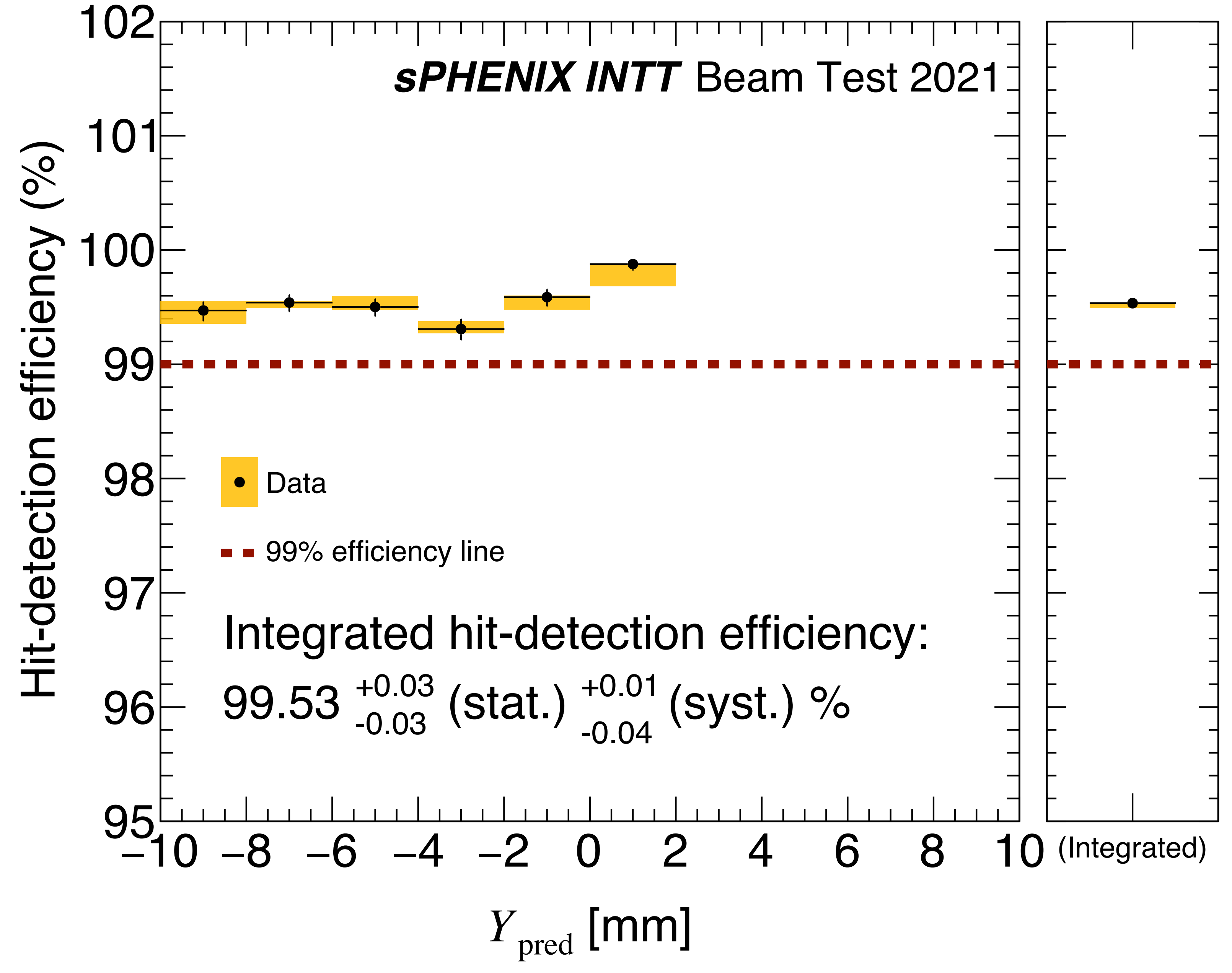
- $dN_{ch}/d\eta$: Charged hadron multiplicity per unit pseudorapidity tracing total entropy production
- Tracking-based standard candle measurement
- Charged hadron yields extracted by counting INTT cluster pairs





$$\Delta\phi = \phi_{\text{inner}} - \phi_{\text{outer}}$$
$$\Delta\eta = \eta_{\text{inner}} - \eta_{\text{outer}}$$
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

INTT beam test - [arXiv:2509.00908]

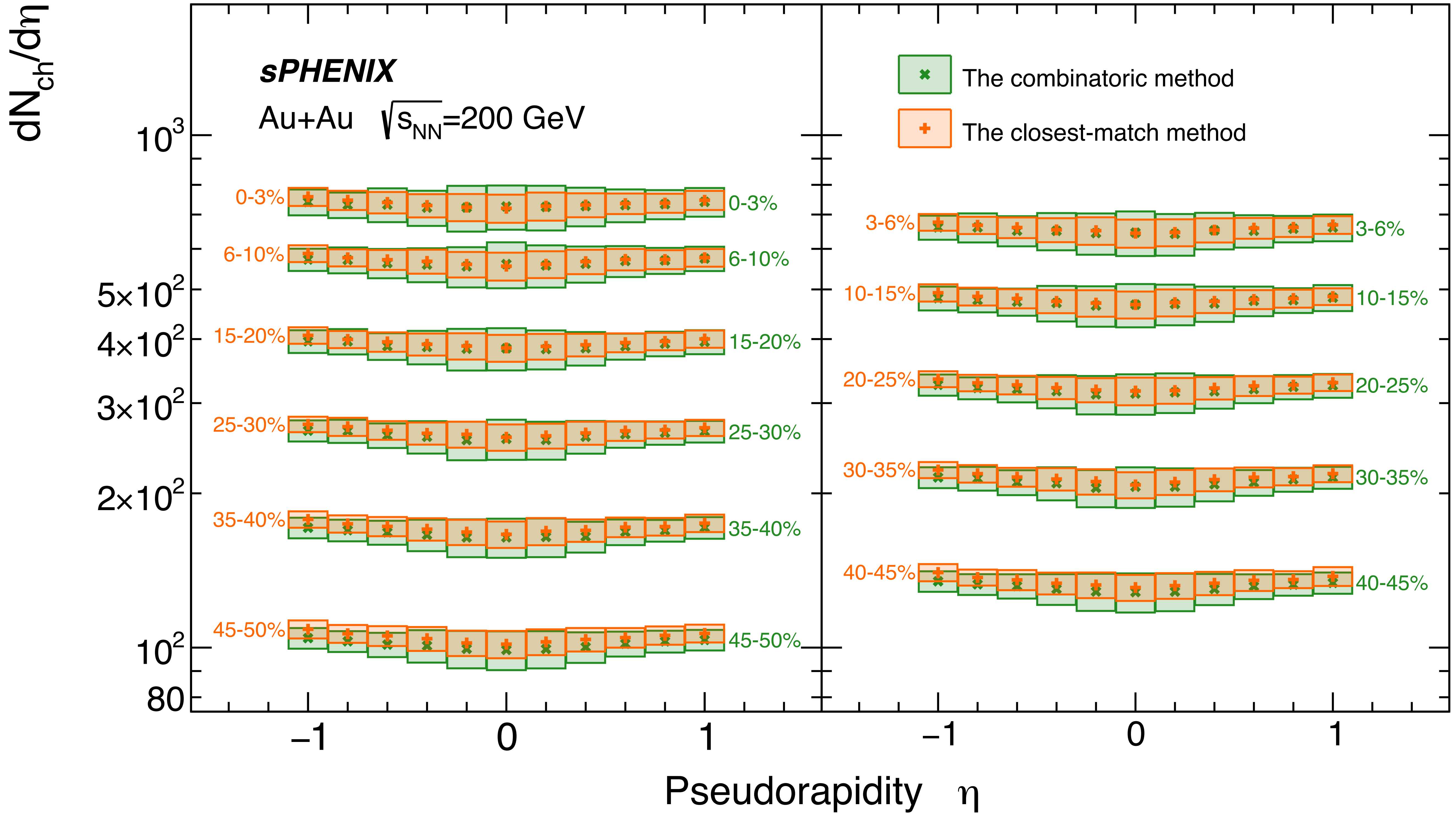


Hit-detection efficiency > 99% confirmed in beam test

Measurement of $dN_{ch}/d\eta$ in Au+Au collisions

w/ Run24 Au+Au collision data

- **Two analysis methods developed**
  - **The combinatoric method**: combinatorial background subtraction by rotating inner-layer clusters by π in ϕ
  - **The closest-match method**: counting the smallest angular-separation cluster pairs
- Corrections applied to account for detector acceptance, reconstruction efficiency, etc



sPHENIX Final! - [JHEP 08 (2025), 075]

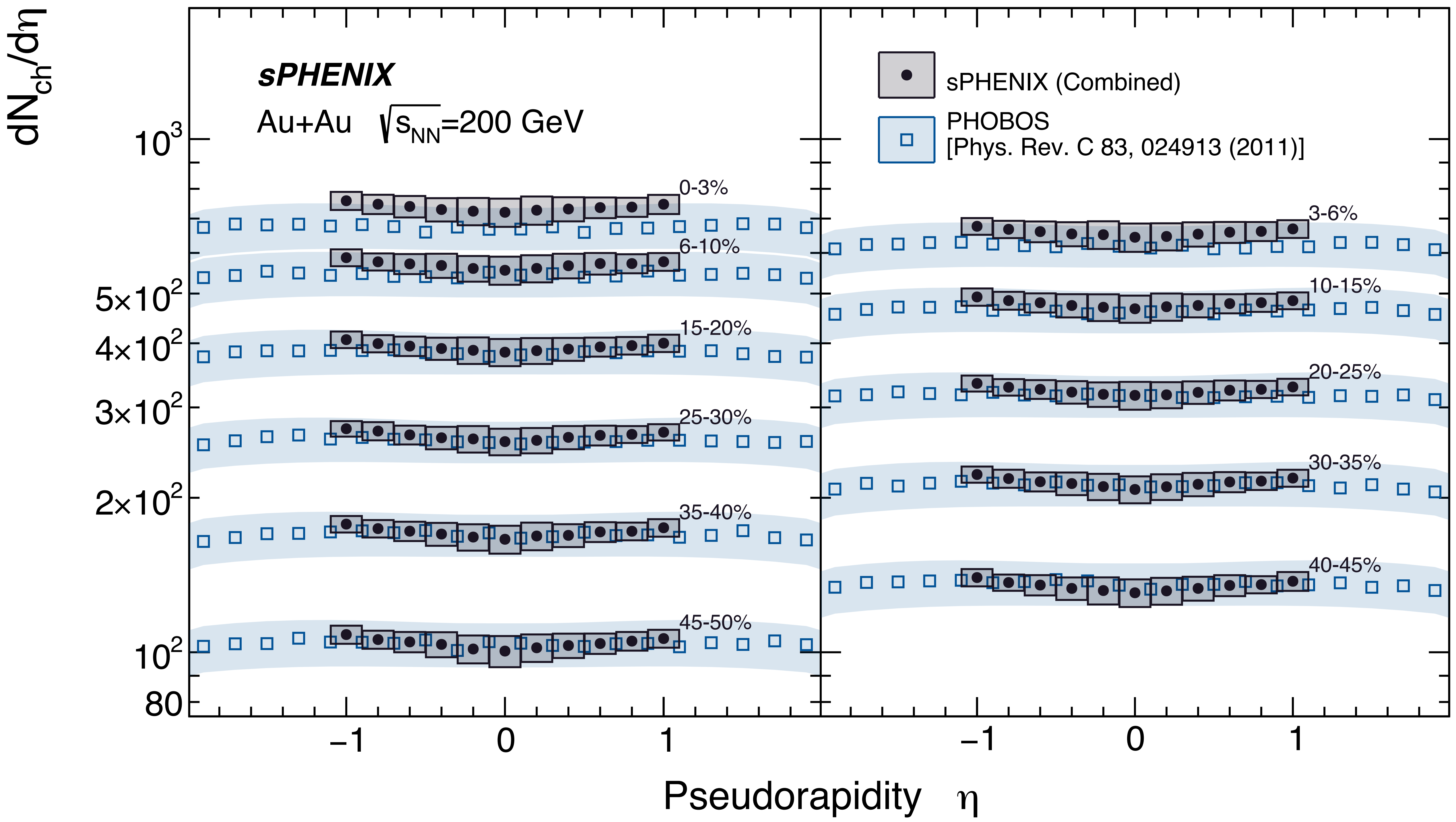
Results from the two methods are consistent with each other, and are statistically combined

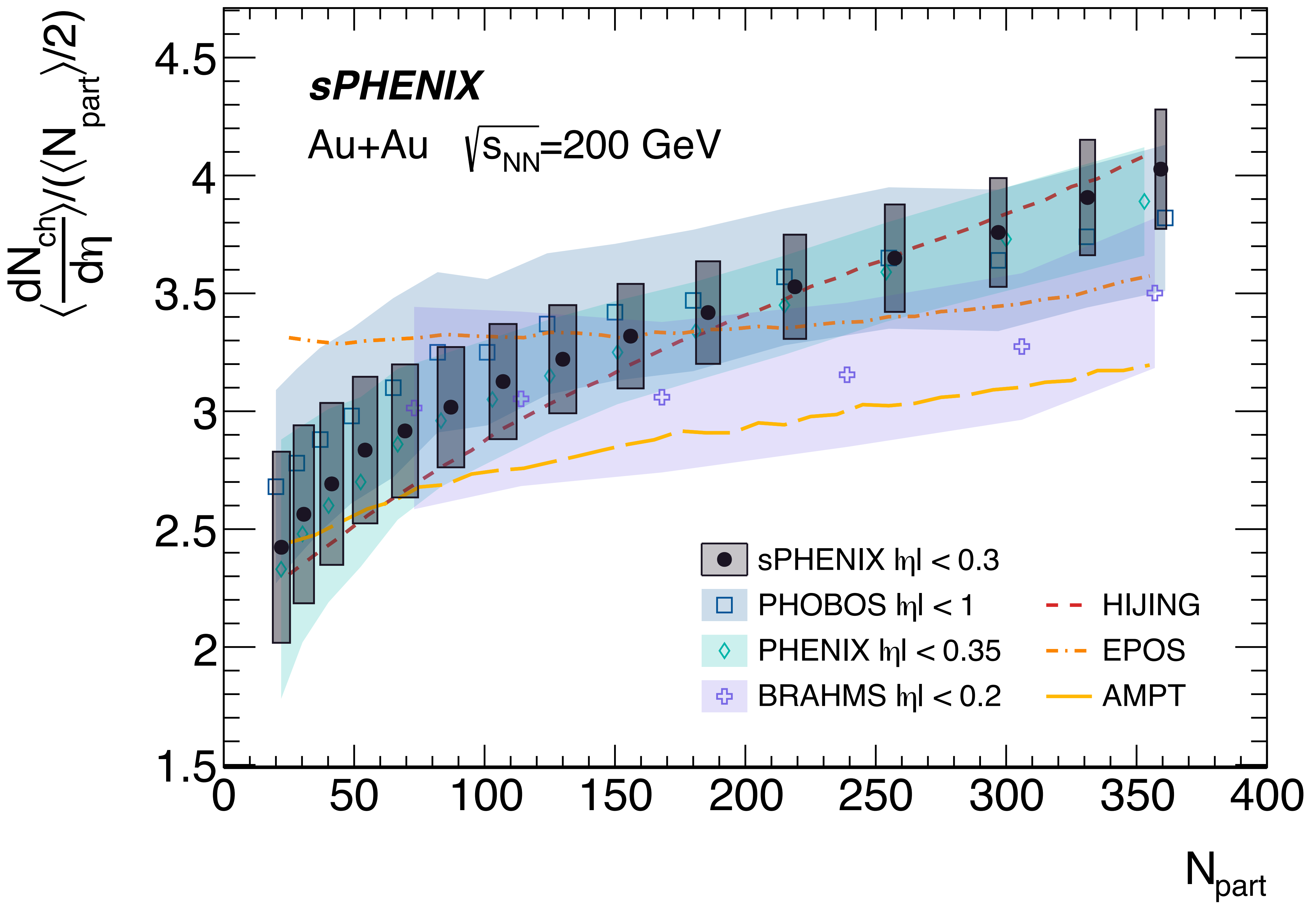
Measurement of $dN_{ch}/d\eta$ in Au+Au collisions

sPHENIX

sPHENIX Final! - [JHEP 08 (2025), 075]

w/ Run24 Au+Au collision data



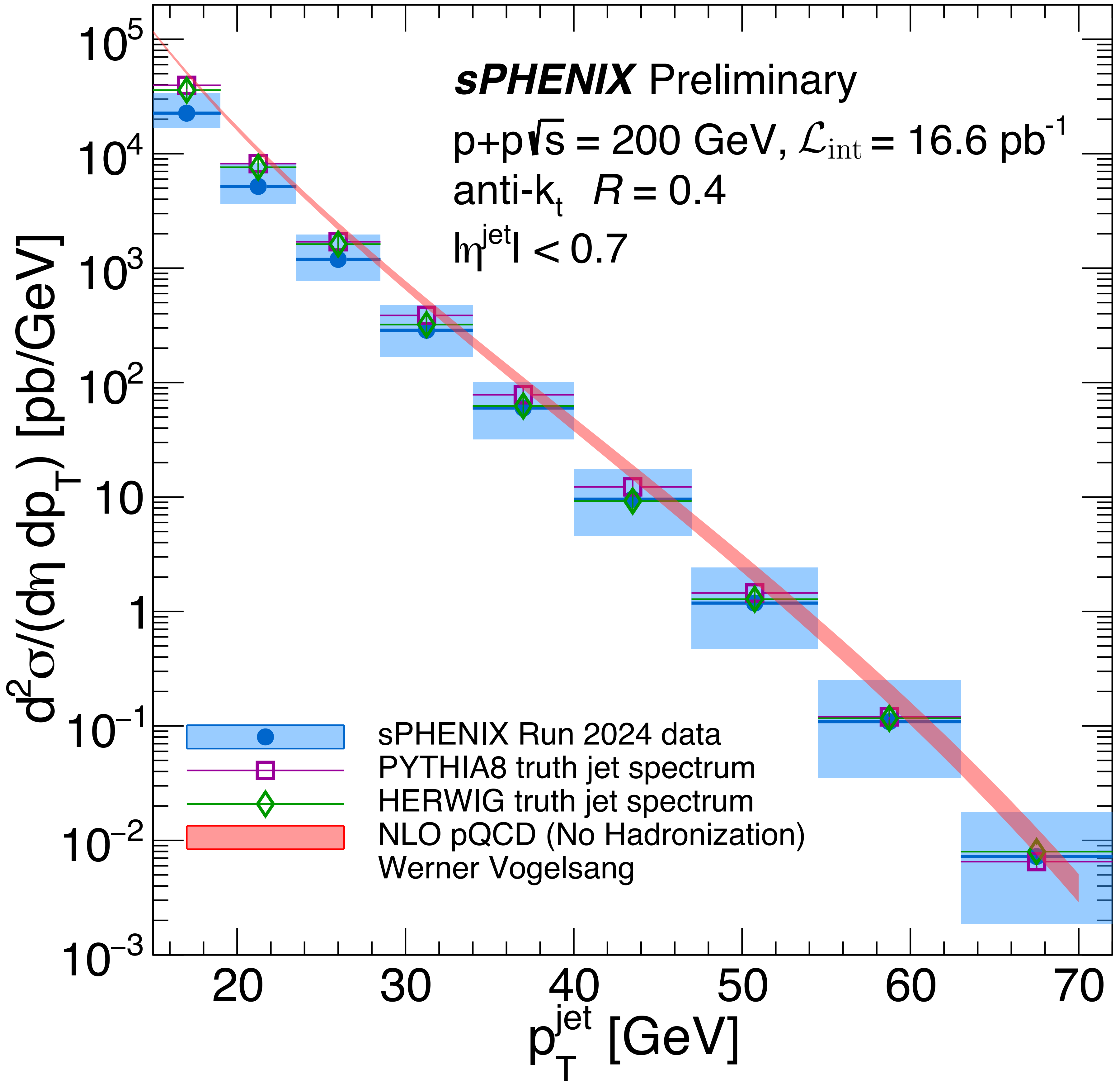


- **sPHENIX measurements, $dN_{ch}/d\eta$ as a function of η, and average $dN_{ch}/d\eta$ normalized by the number of participant pairs as a function of N_{part}, are consistent with previous RHIC measurements**
- **The sPHENIX $dN_{ch}/d\eta$ results offer improved uncertainties in mid-centrality events, and are best described by the HIJING model**

Jet measurement in p+p collisions with sPHENIX

w/ Run24 p+p collision data

[sPHENIX Jet conf. note]

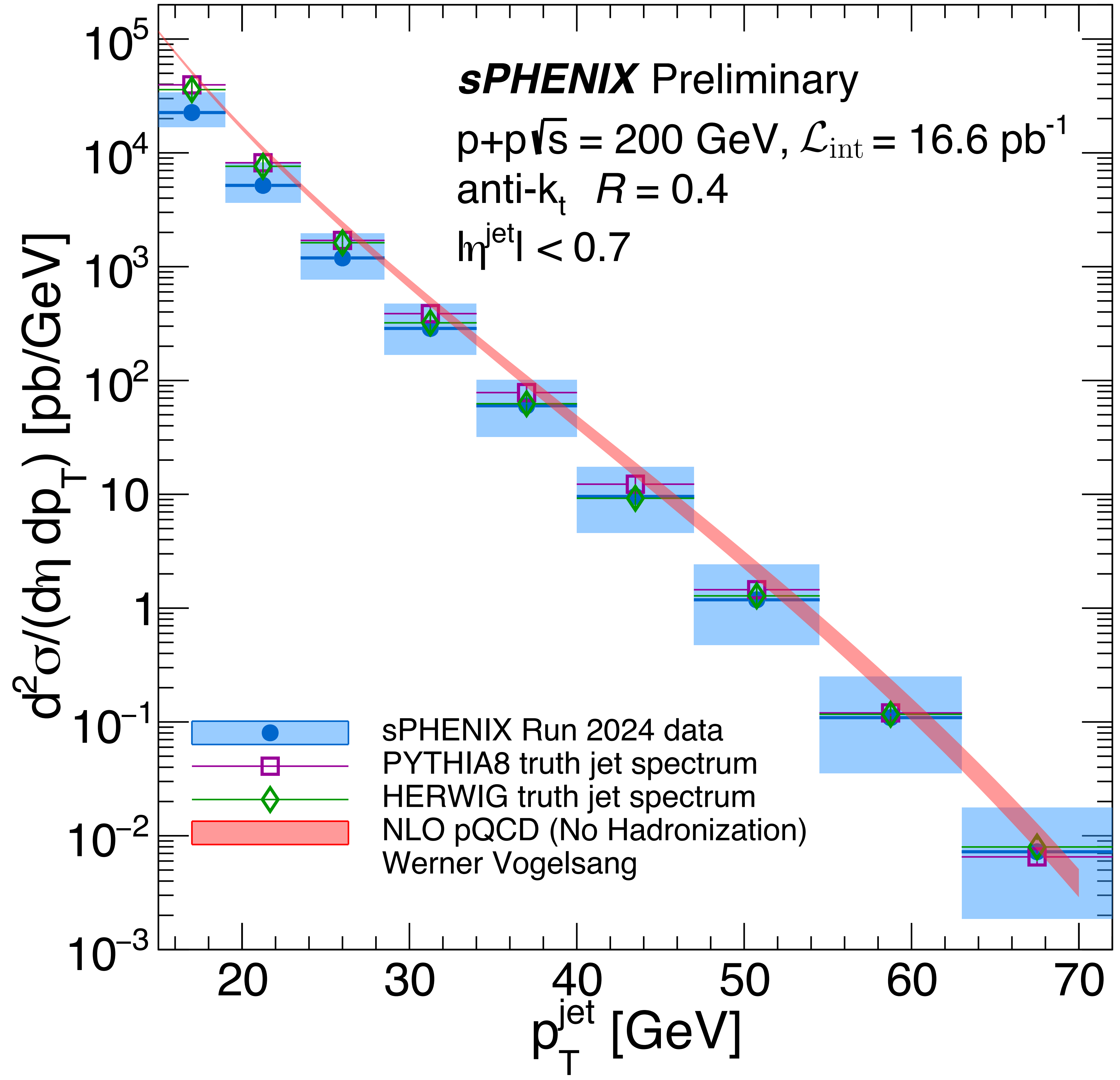


- Jets are multiscale probes of the QGP
- In p+p, jets test pQCD, useful for jet calibration, understanding jet resolution
- Anti-k_T jets, clustered from calorimeter towers
- Unfolded cross section of jet cone size R=0.4
- Syst. unc. dominated by jet energy scale uncertainty on the hadronic response (from test beam) and is expected to have significant improvement with future in-situ hadronic shower studies

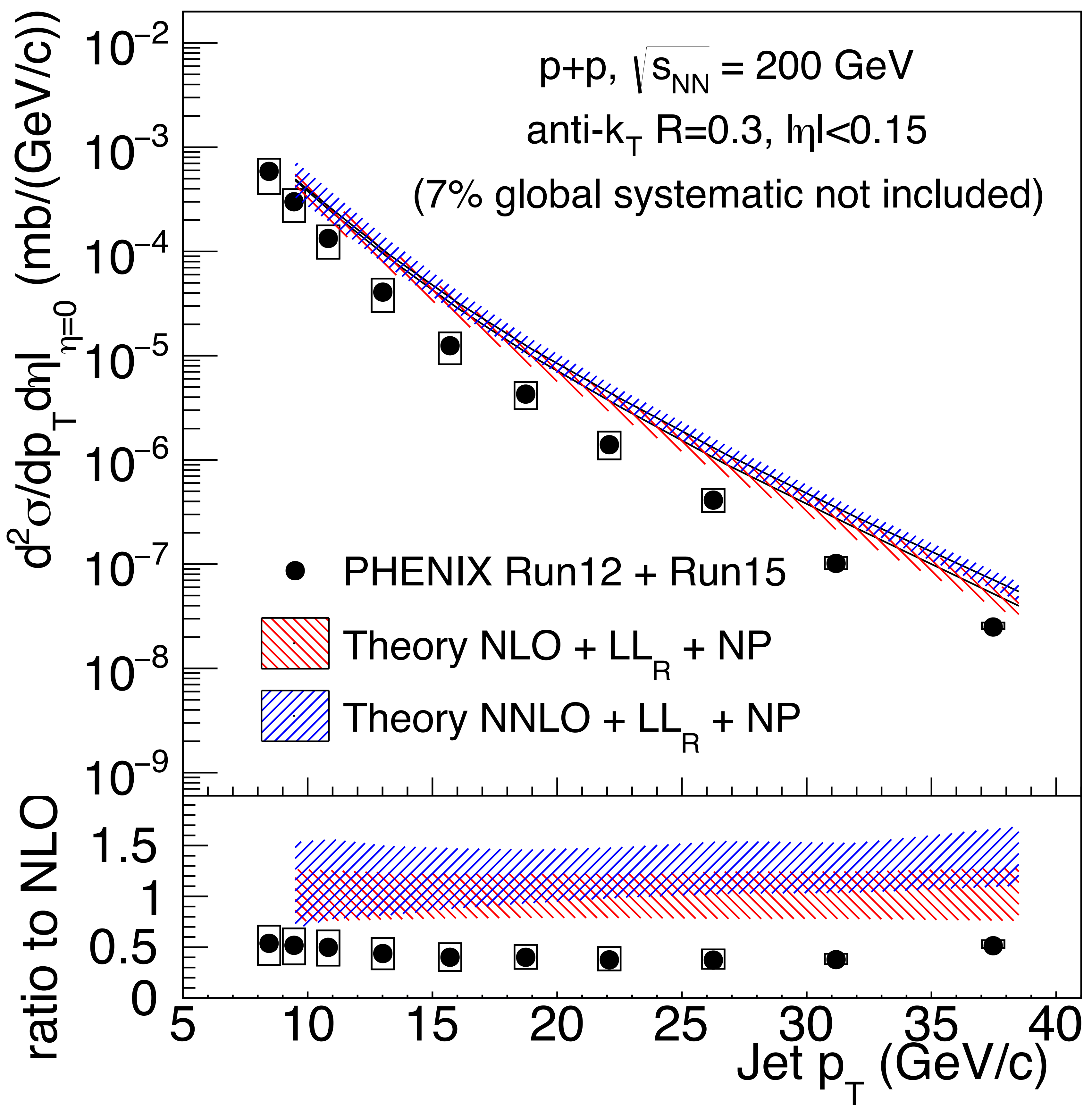
First jet measurement using EMCal and HCal at mid-rapidity at RHIC
Good agreement with PYTHIA8 prediction within the systematic uncertainty

Jet measurement in p+p collisions with sPHENIX

[sPHENIX Jet conf. note]



[PHENIX result]

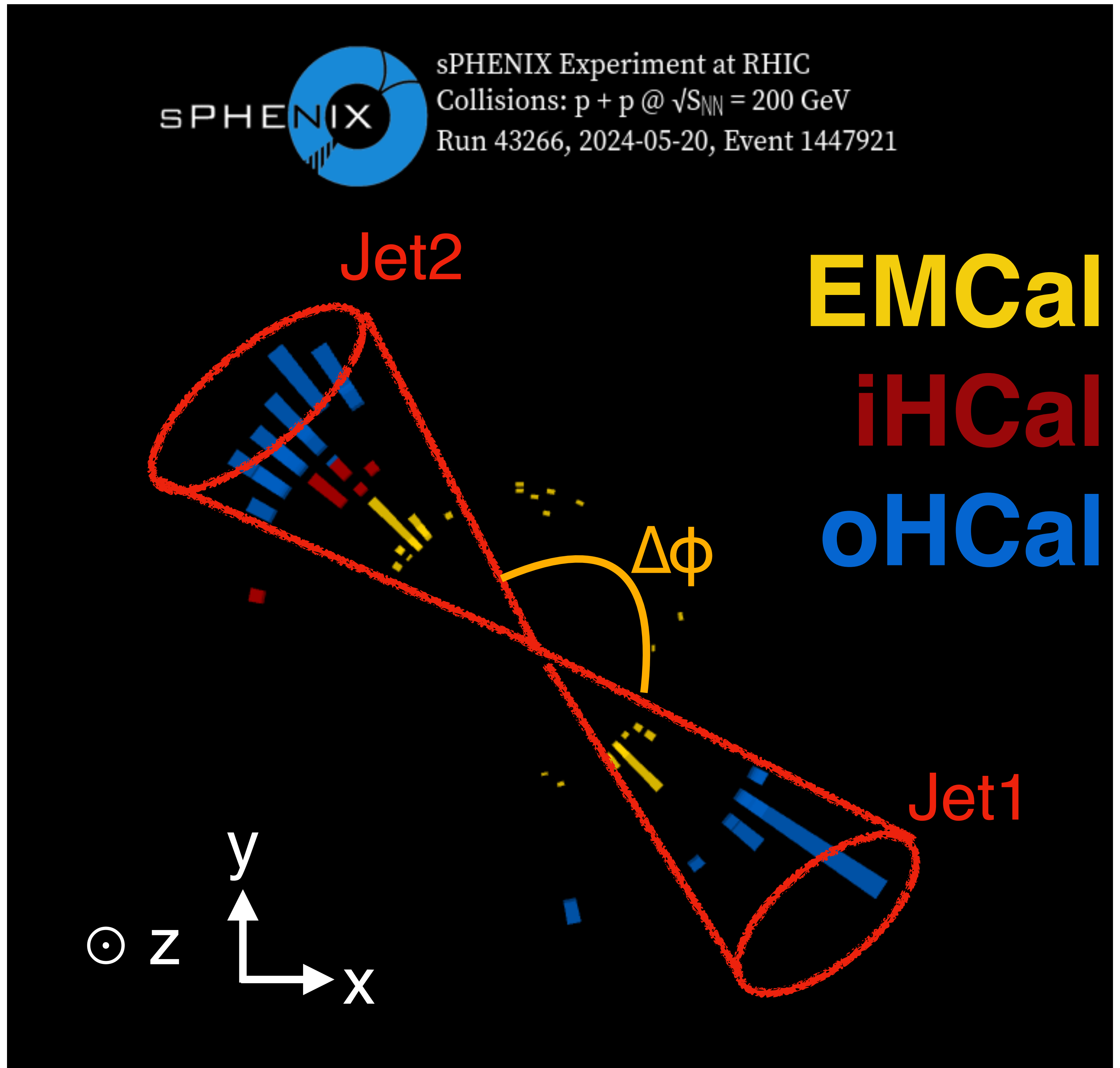


With only 15% of the total Run24 p+p statistics, sPHENIX result offers better kinematic reach than any previous RHIC measurements

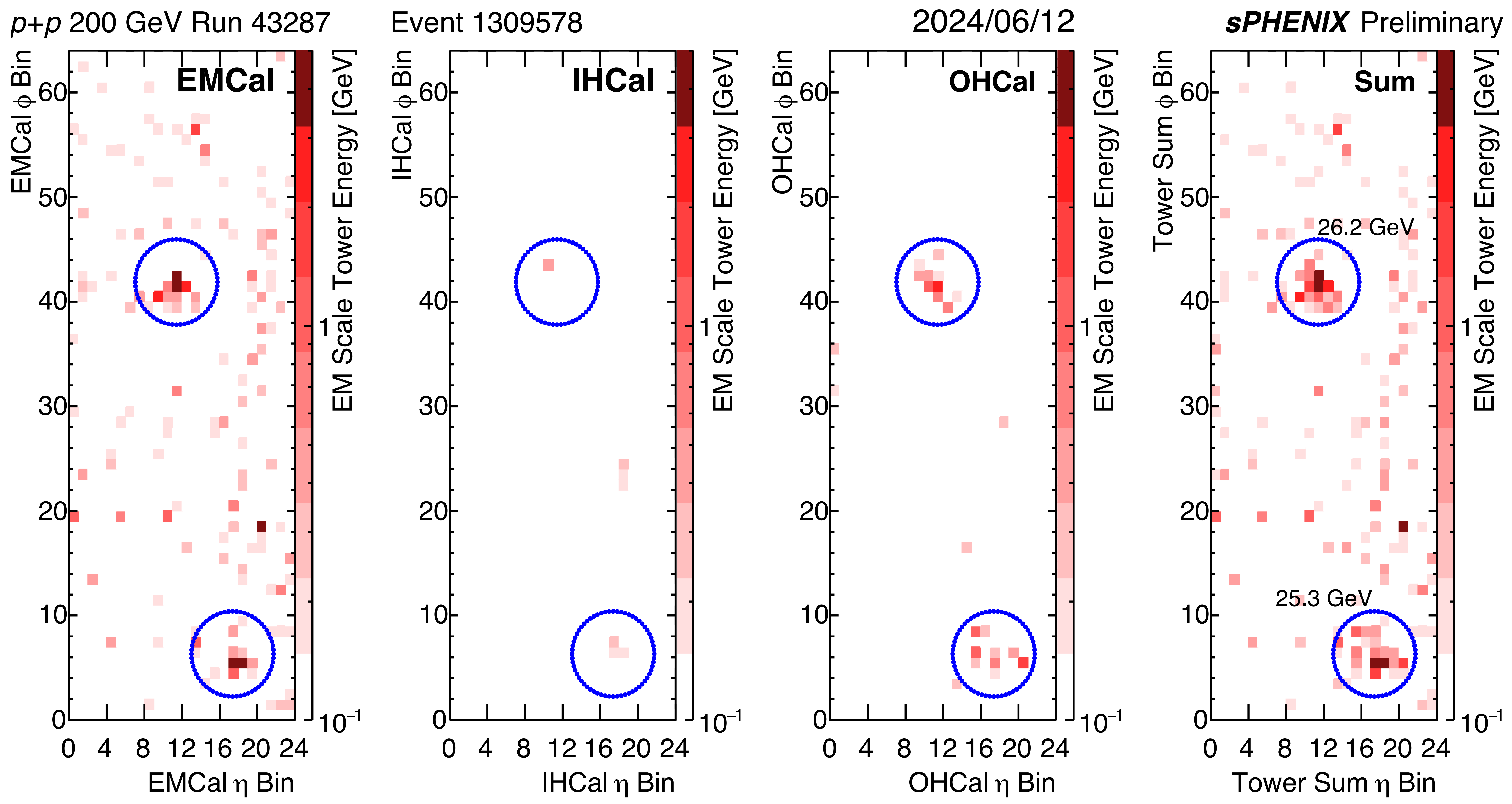
Di-jet measurement at sPHENIX

w/ Run24 p+p collision data

$x_J = p_{T,2}/p_{T,1}$, where $p_{T,1}$ is the leading jet



A di-jet event in p+p collisions

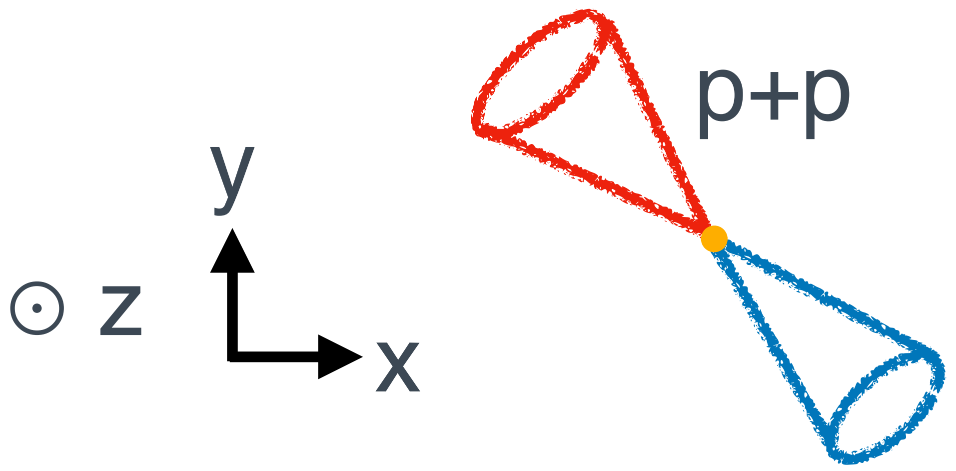


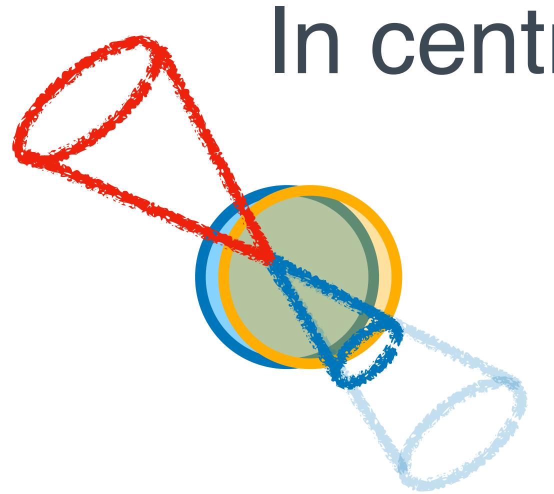
In this particular event, $x_J = 25.3$ GeV$/26.2$GeV $= 0.96$

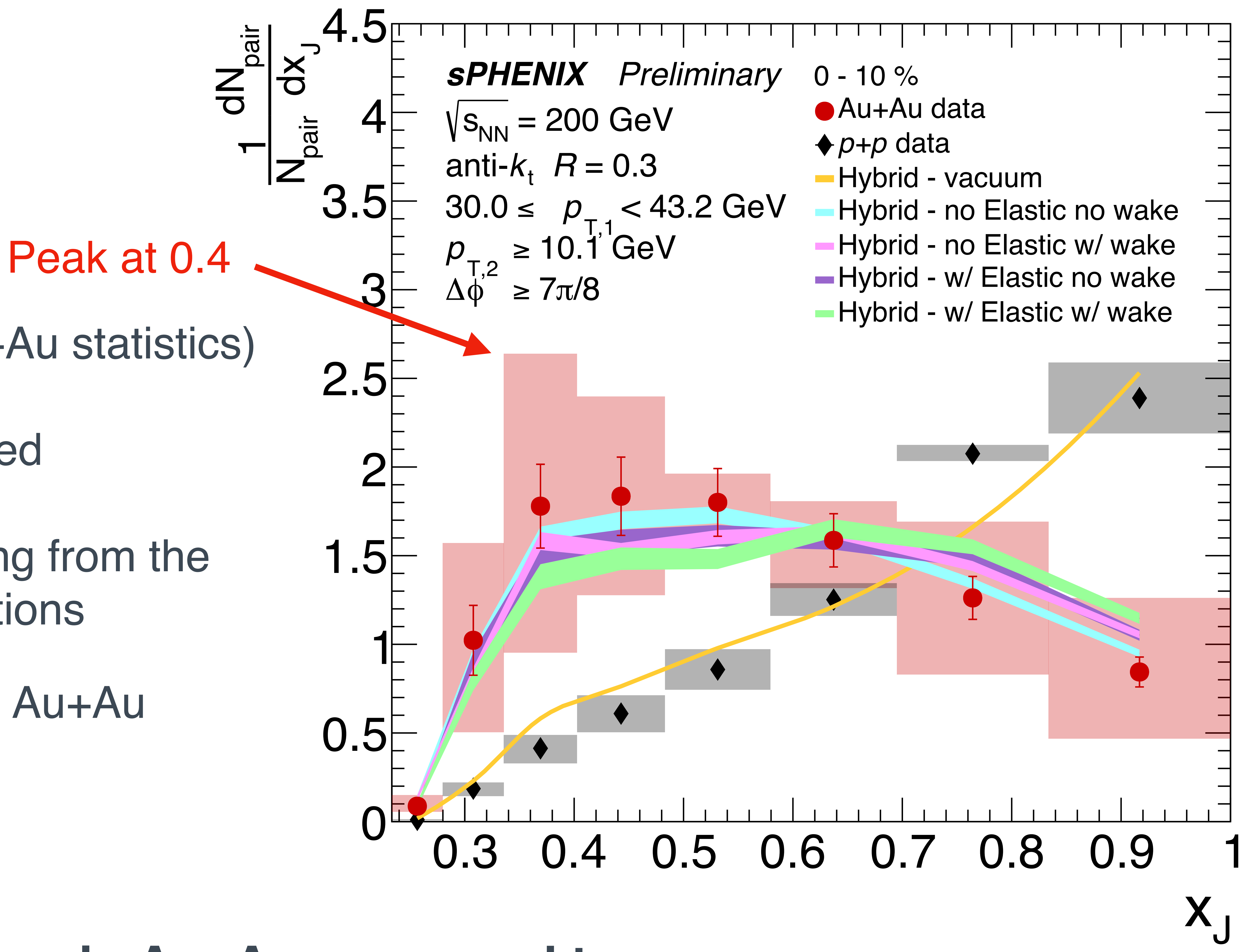
Di-jet imbalance measurement

w/ Run24 p+p and Au+Au collision data

- Anti-k_T jets, jet cone size R = s0.3
- $|\Delta\phi| \geq 7\pi/8$, $30 \leq p_{T,1} \leq 43.2$ GeV
- 2D unfolding in $p_{T,1}$ and $p_{T,2}$
- Au+Au data: ~0.1 nb^{-1} (1.5% of total sPHENIX Au+Au statistics)
- Jets in Au+Au collisions: underlying event subtracted
- Di-Jet imbalance in Au+Au collision primarily coming from the two jets experiencing different in-medium modifications







Significant modification in Au+Au compared to pp
The first jet-quenching measured by sPHENIX!

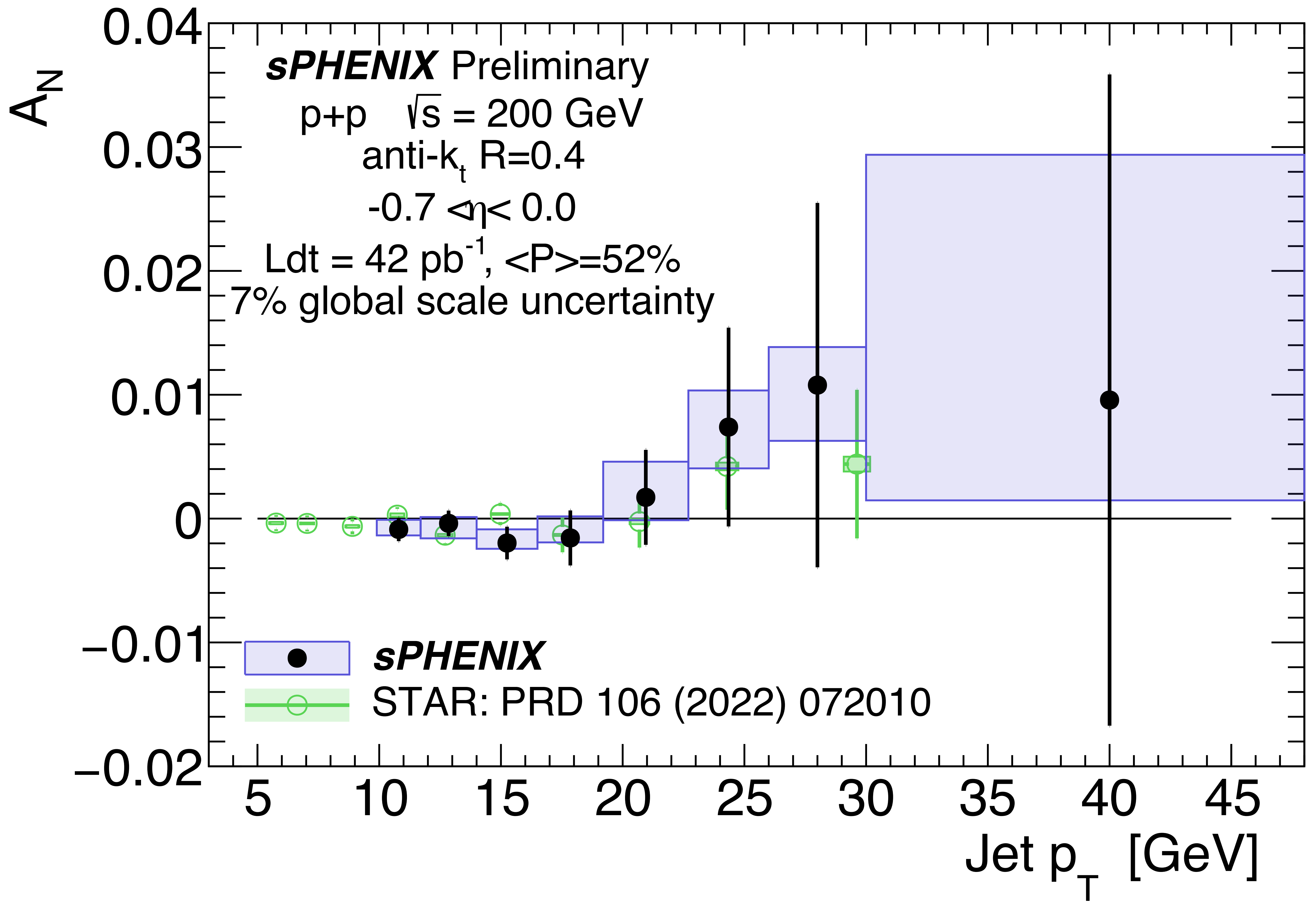
Inclusive jet transverse single spin asymmetry (TSSA)

w/ Run24 p+p collision data

Utilizing the unique capability of colliding polarized proton beams at RHIC!

$$A_N \propto \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

- Inclusive jet TSSA is expected to be primarily sensitive to initial-state effects → test theories and better understand the role of parton-gluon correlations in the proton
- A fraction of full sPHENIX Run24 p+p data analyzed
- Major systematic uncertainty: Jet energy scale uncertainty

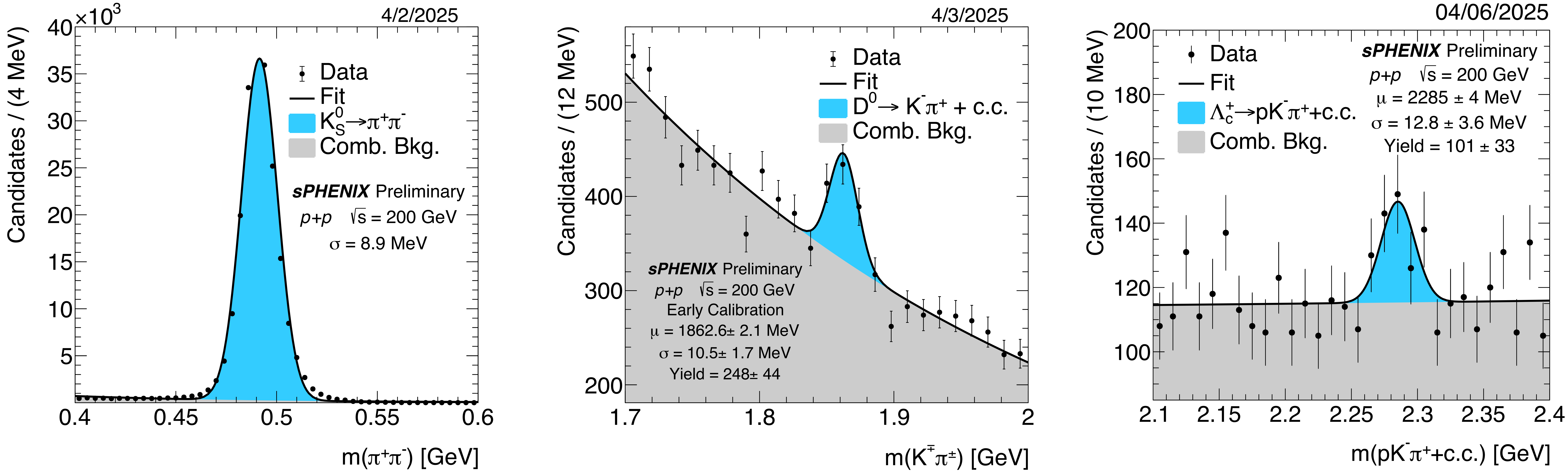


sPHENIX inclusive jet TSSA consistent with zero and agrees with STAR measurement

Full tracking performance

w/ Run24 p+p collision data

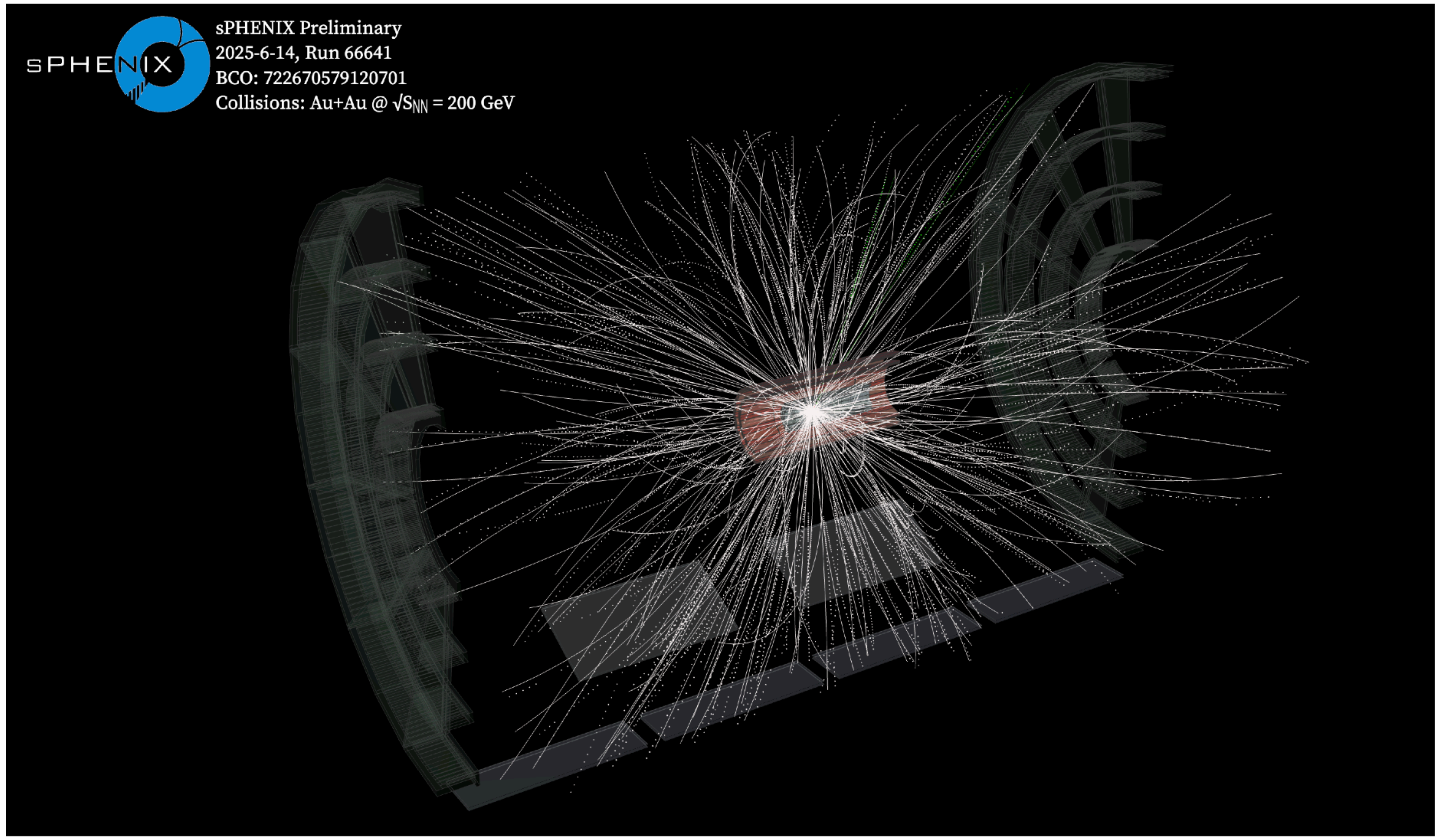
sPHENIX tracking: two silicon trackers + one gas detector → extremely complex system
(interplay between detector alignment, TPC calibration, silicon-TPC matching, timing matching, detection efficiency)

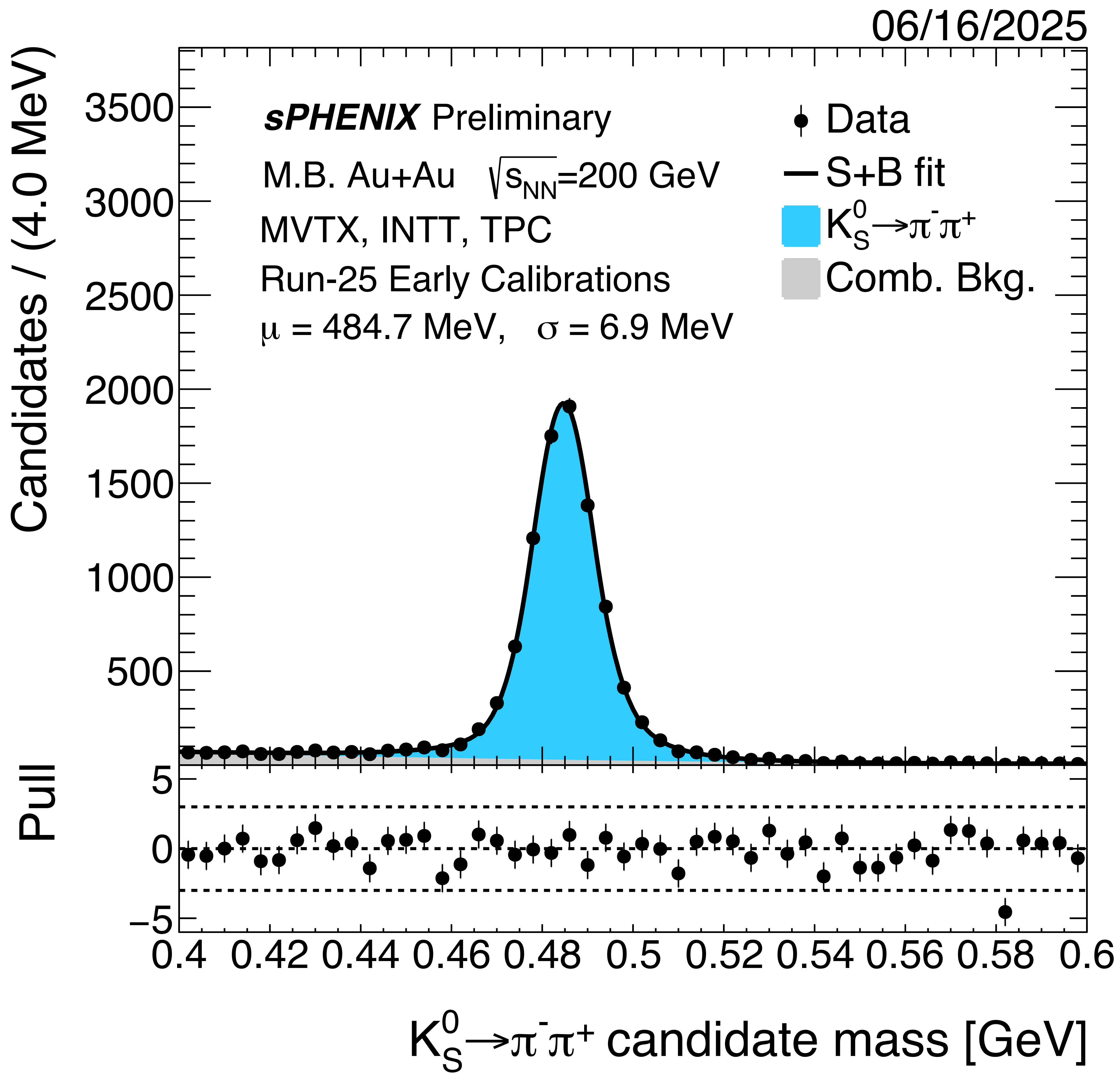


- From ~1 hour of p+p streaming data and very early stage calibrations
- Several resonances observed: K_s^0, D^0 and Λ_c^+, etc
- Progressing on heavy flavor analysis, but still more work to do understand the detector and improve the results

K_s^0 in Run25 Au+Au collisions

w/ Run25 Au+Au collision data





With a few seconds of Au+Au collision data, we see a clean k_s^0 peak!

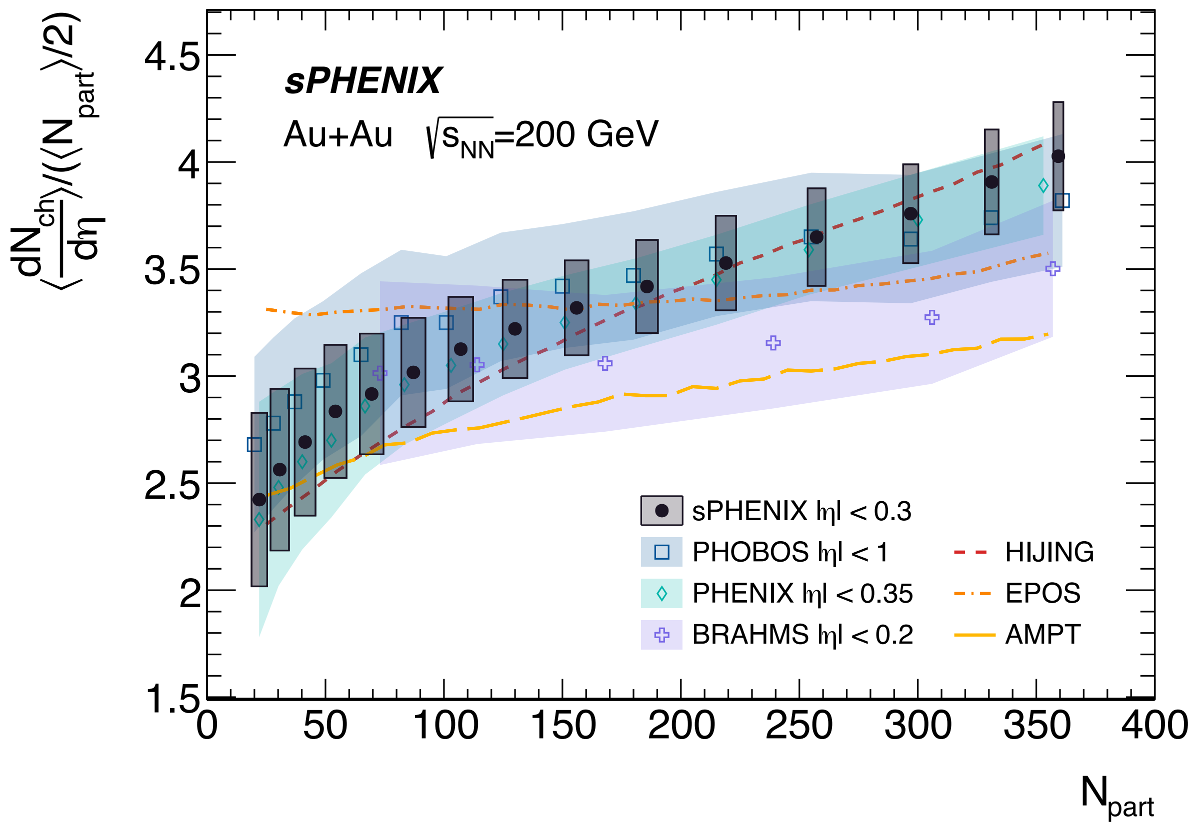
NCU contributions to sPHENIX (post hardware preparation)

- Publications with direct contribution
  - C.W. Shih et al. (sPHENIX INTT Group). "*Beam test results of the Intermediate Silicon Tracker for sPHENIX*". arXiv:2509.00908. (submitting to NIM-A)
  - M. I. Abdulhamid et al. (sPHENIX Collaboration). "*Measurement of charged hadron multiplicity in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the sPHENIX detector*". JHEP 08 (2025), 075.
    - Analysis contact
    - The first-ever physics publication from sPHENIX (9 days earlier than the $dE_T/d\eta$ paper)
  - Y.Akiba et al. (sPHENIX INTT Group). "*The Ladder and Readout Cables of Intermediate Silicon Strip Detector for sPHENIX*". Nucl. Instrum. Meth. A, 1082:171020, 2026.

- Current focus
  - sPHENIX MBD triggered cross section measurement
  - Preparation of the INTT barrel NIM paper
  - sPHENIX silicon-seeding study for the heavy flavor objects
  - Muon identification in sPHENIX using ML (see Shan-Yu's poster)
  - Energy regression using ML for improving electron energy resolution, and more

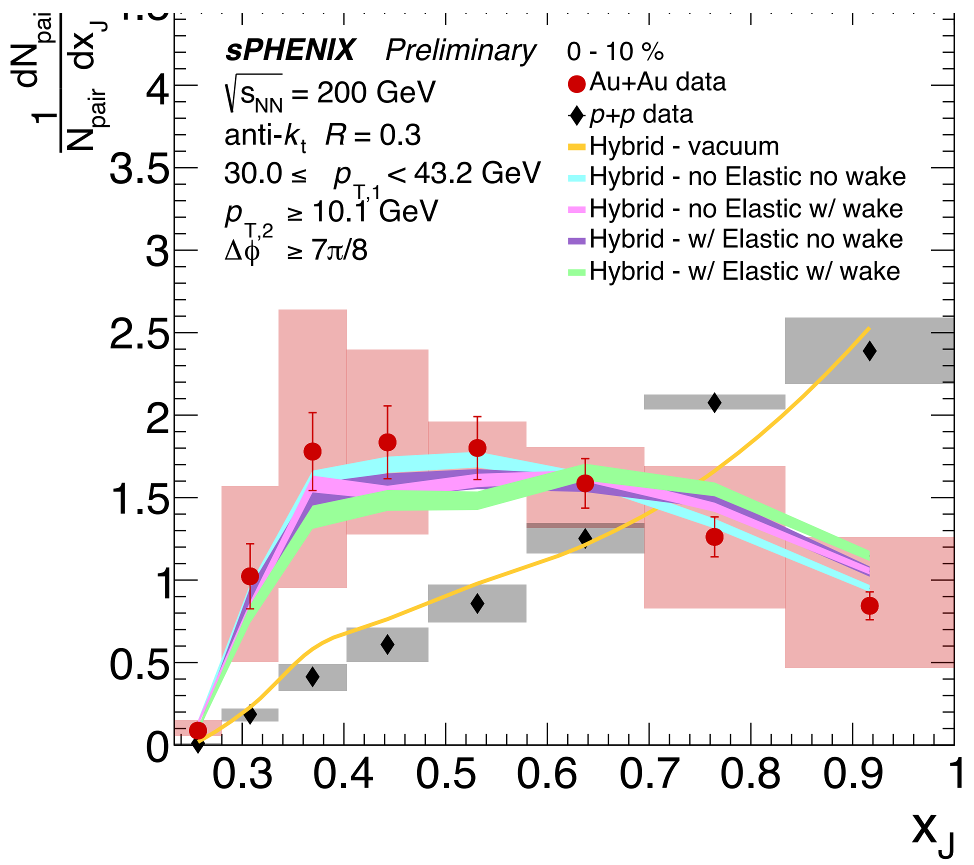
Summary

- sPHENIX completed construction in 2023, and its data-taking will end on Jan 20, 2026
  - Abundant Au+Au collision and polarized p+p collision data collected



- First physics publications: $dE_T/d\eta$ and $dN_{ch}/d\eta$:
  - Offering improved uncertainties and validating the detector performance

- First preliminary jet measurements:
  - Inclusive jet cross section, jet energy loss, inclusive jet TSSA



- Preliminary particle resonances observed by the sPHENIX tracking system
  - K_s^0, D^0 and Λ_c^+, etc

- NCU joined the sPHENIX collaboration in 2019, and has since been an active memeber in the collaboration and actively involved in the INTT business
  - 3 papers published (one under review)
  - First physics paper ever from sPHENIX

Thank you for your attention!

sPHENIX Run25 start party

BACKUP

sPHENIX data taking timeline

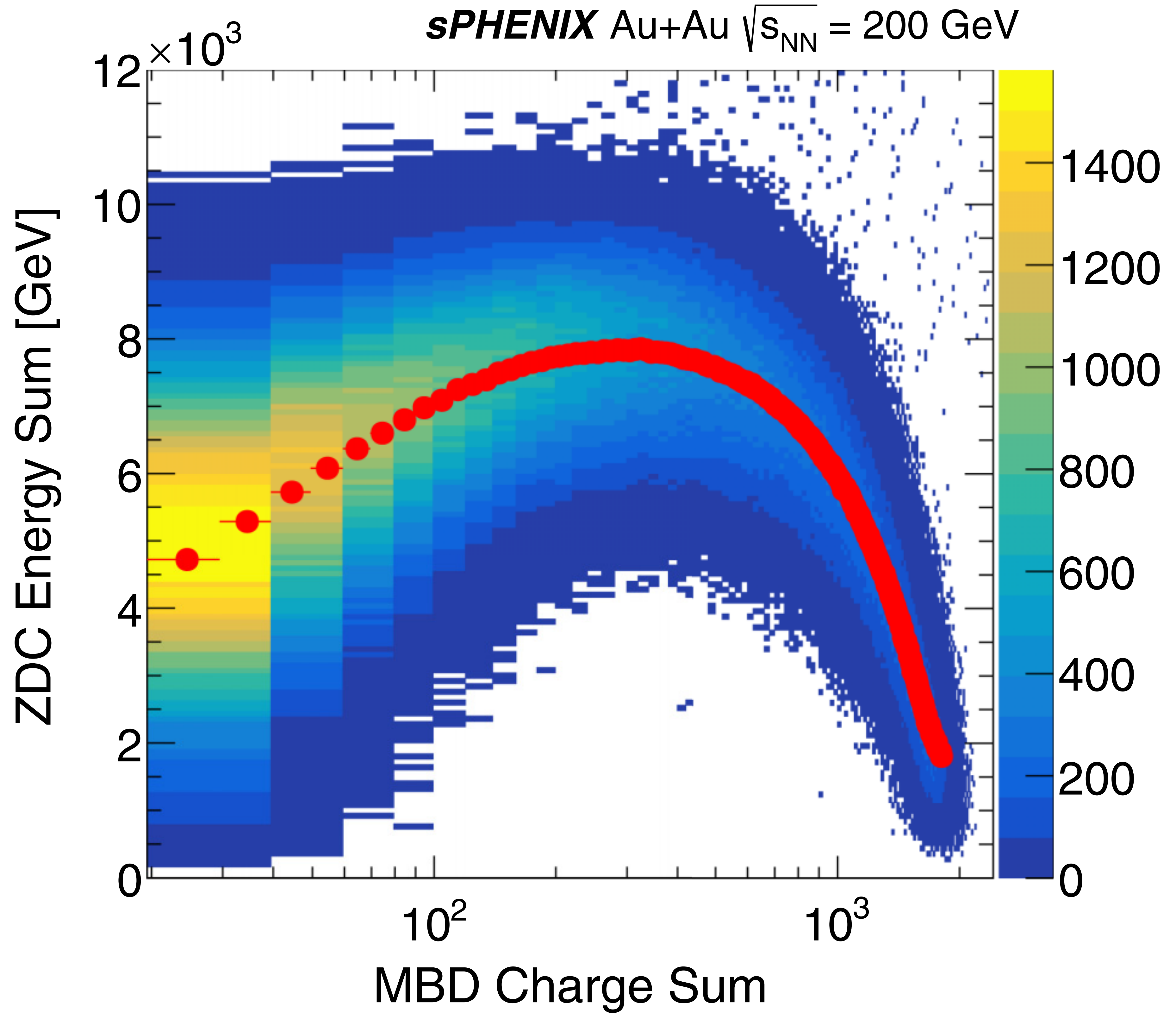
Year	Request		Reality		
	Weeks	Run plan	Weeks	Species	Goal
2023	28 weeks	Au + Au	10.5*	Au + Au	Commissioning and RHIC standard candles
2024	28 weeks	$p^{\uparrow}+p^{\uparrow}$ $p^{\uparrow}$+Au	24	$p^{\uparrow}+p^{\uparrow}$	Au+Au baseline and spin, cold-QCD measurments
			3	Au+Au	Commissioning of TPC and MVTX
2025 2026	28 weeks	Au+Au	25	Au+Au	Golden Au+Au dataset
			6	$p^{\uparrow}+p^{\uparrow}$	Additional full-detector p+p data

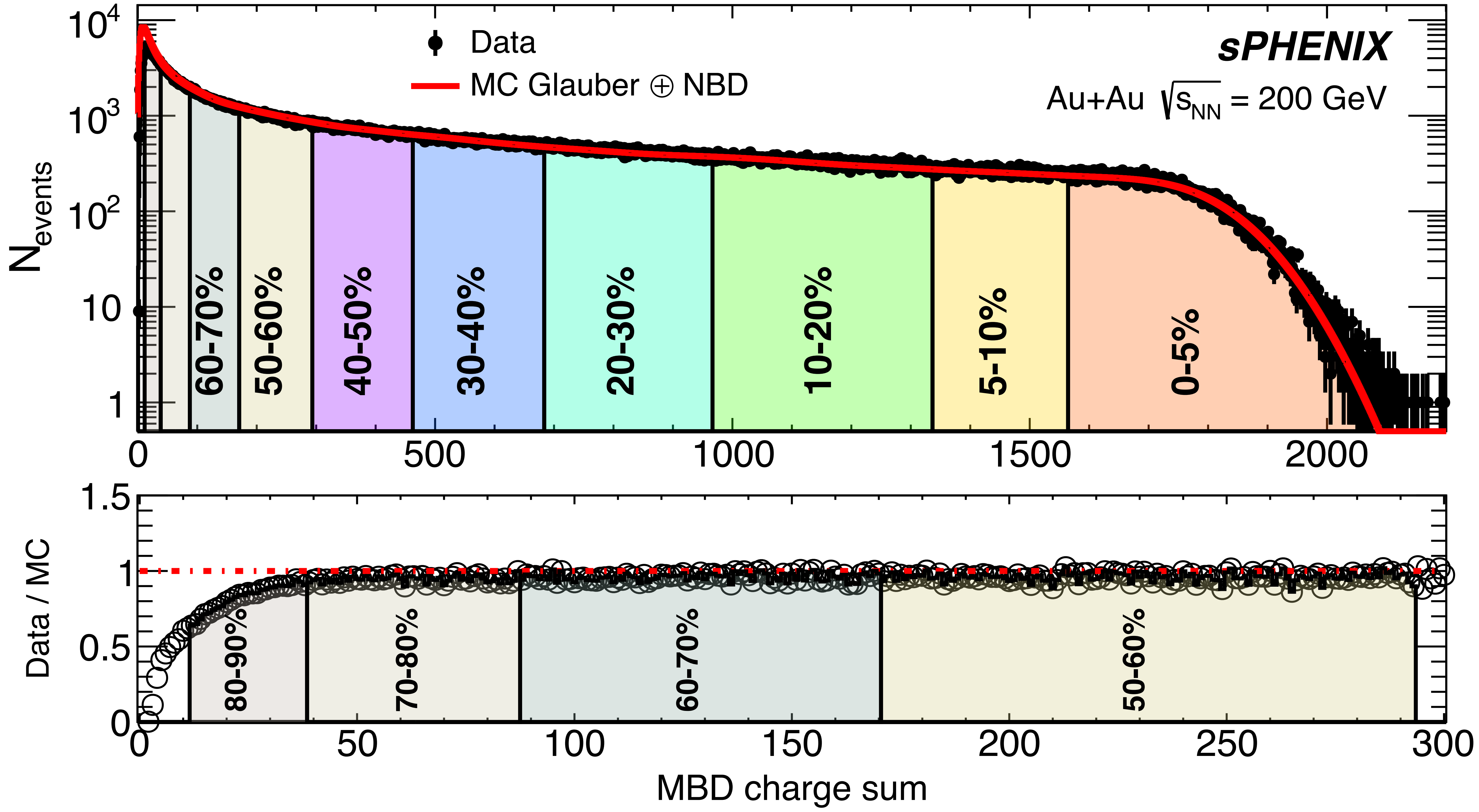
*Due to the accelerator failure

Au+Au collision, Global event characterization

w/ Run24 Au+Au data

Event characterized using MBD and ZDC





A characteristic decrease in the total ZDC energy observed at both high and low MBD charge sum

Full minimum bias selection efficiecny down to over 70%

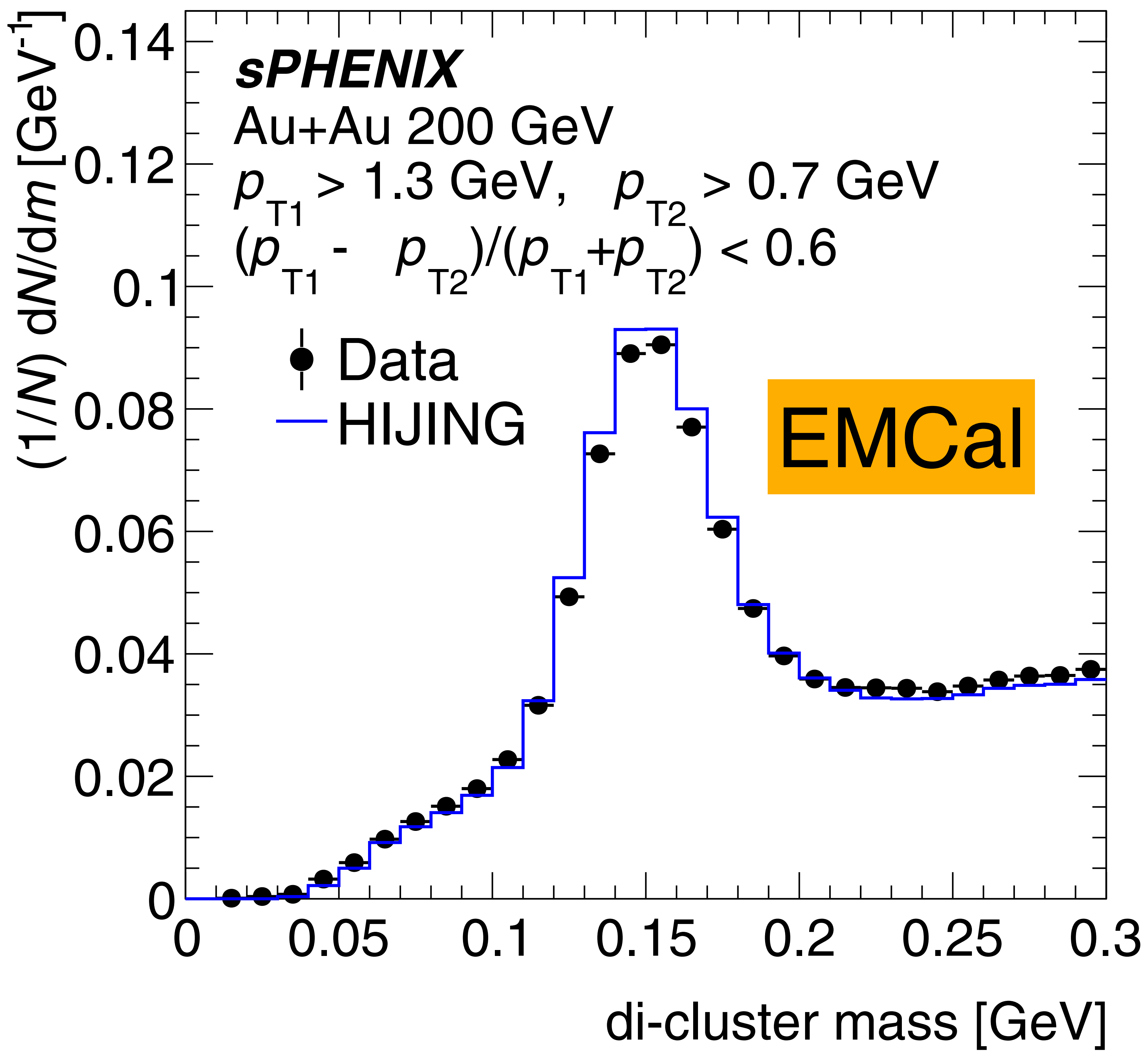
*MBD charge is calibrated such that one MIP is set at unity

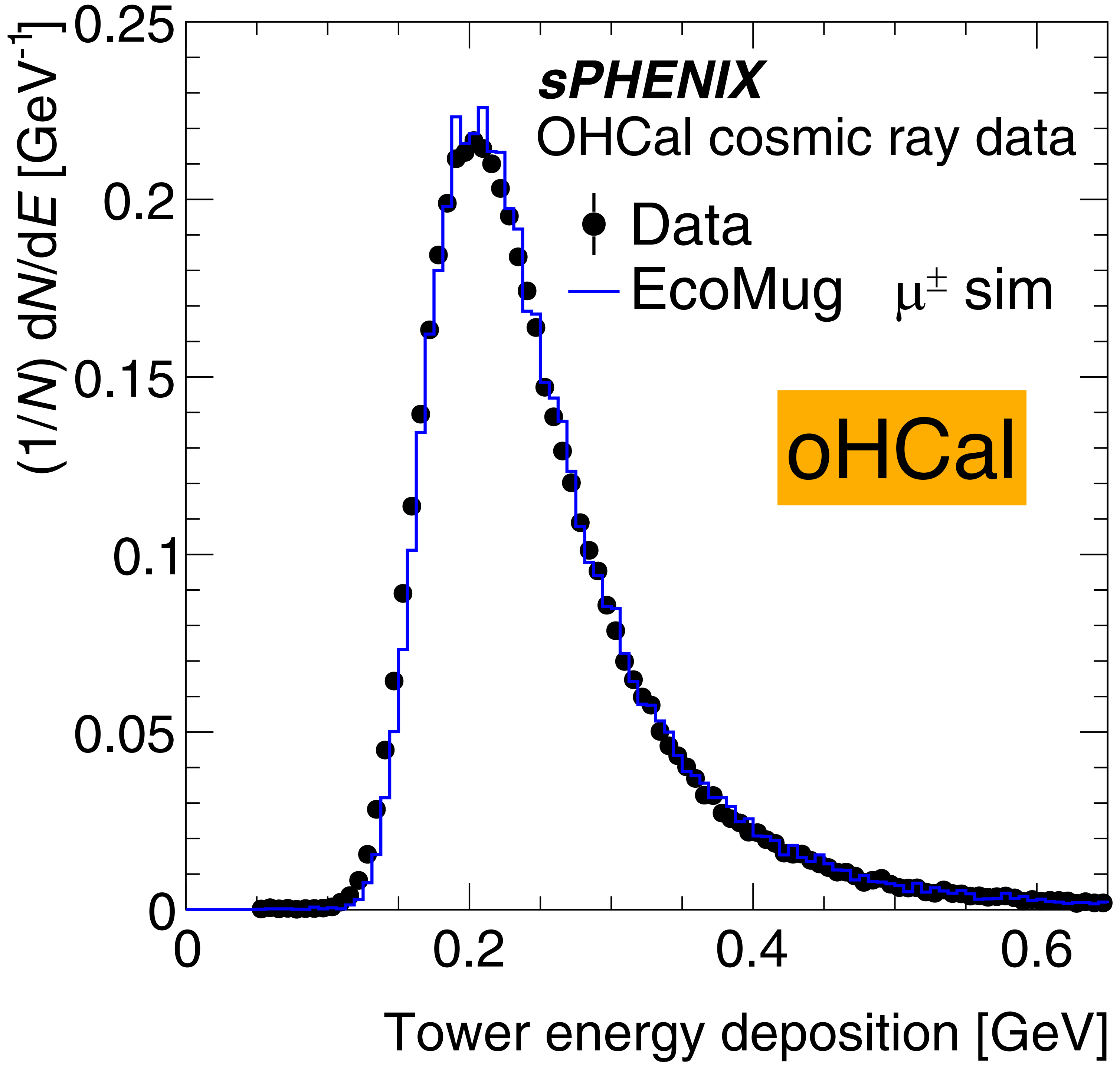
Energy calibrations for sPHENIX calorimeters

w/ Run24 Au+Au collision data

- **Energy calibration**
  - **EMCal**: matching $\pi^0 \rightarrow \gamma\gamma$ mass peak between data and simulation
  - **HCal**: matching the observed MIP peak from cosmic ray muons between data and simulation & an additional factor applied for correcting the measured scintillator MIP energy to an estimated energy deposition in both scintillator and absorber

sPHENIX Final! - [PRC 112 (2025), 024908]





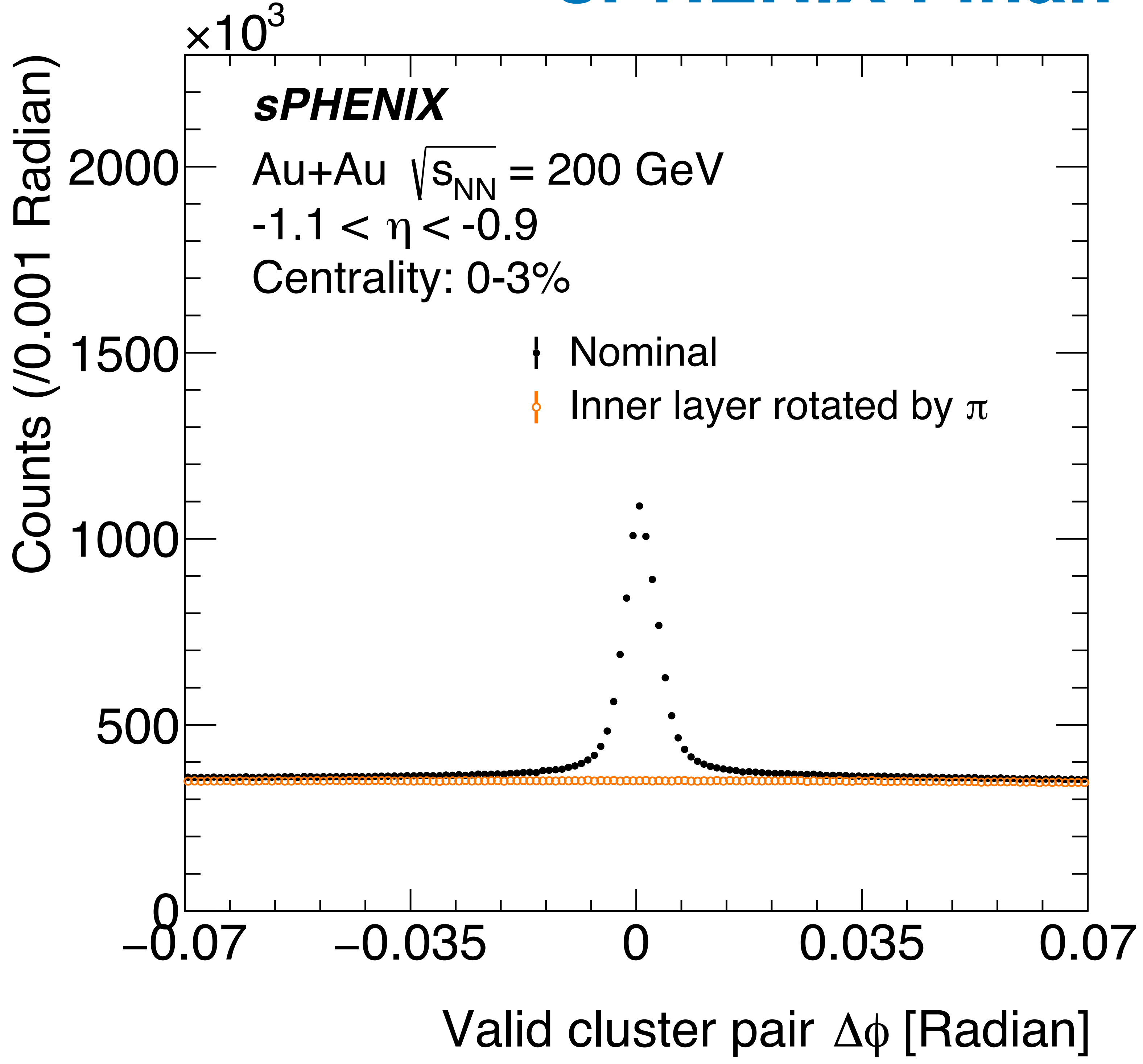
Counting the tracklets using INTT

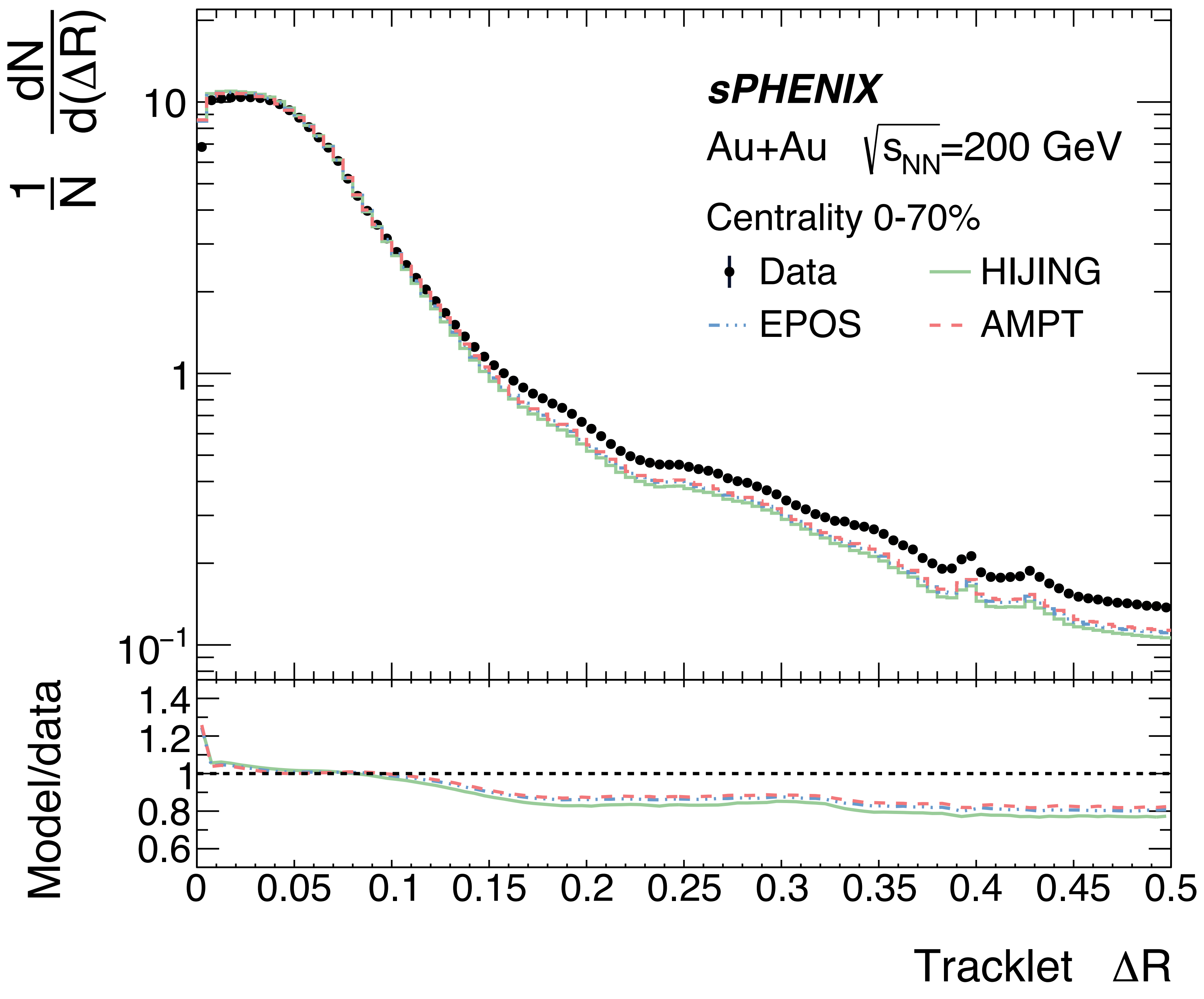
w/ Run24 Au+Au collision data

- **Two analysis methods developed**
  - **The combinatoric method (follows PHENIX [1] and PHOBOS [2] publications)**: combinatorial background subtraction by rotating inner-layer clusters by π in ϕ
  - **The closest-match method (guided by CMS measurements [3])**: counting the smallest angular-separation cluster pairs

[1]: PRL 86 (2001) 3500
[2]: PRC 83 (2011) 024913
[3]: PLB 861 (2025) 139279

sPHENIX Final! - [JHEP 08 (2025), 075]





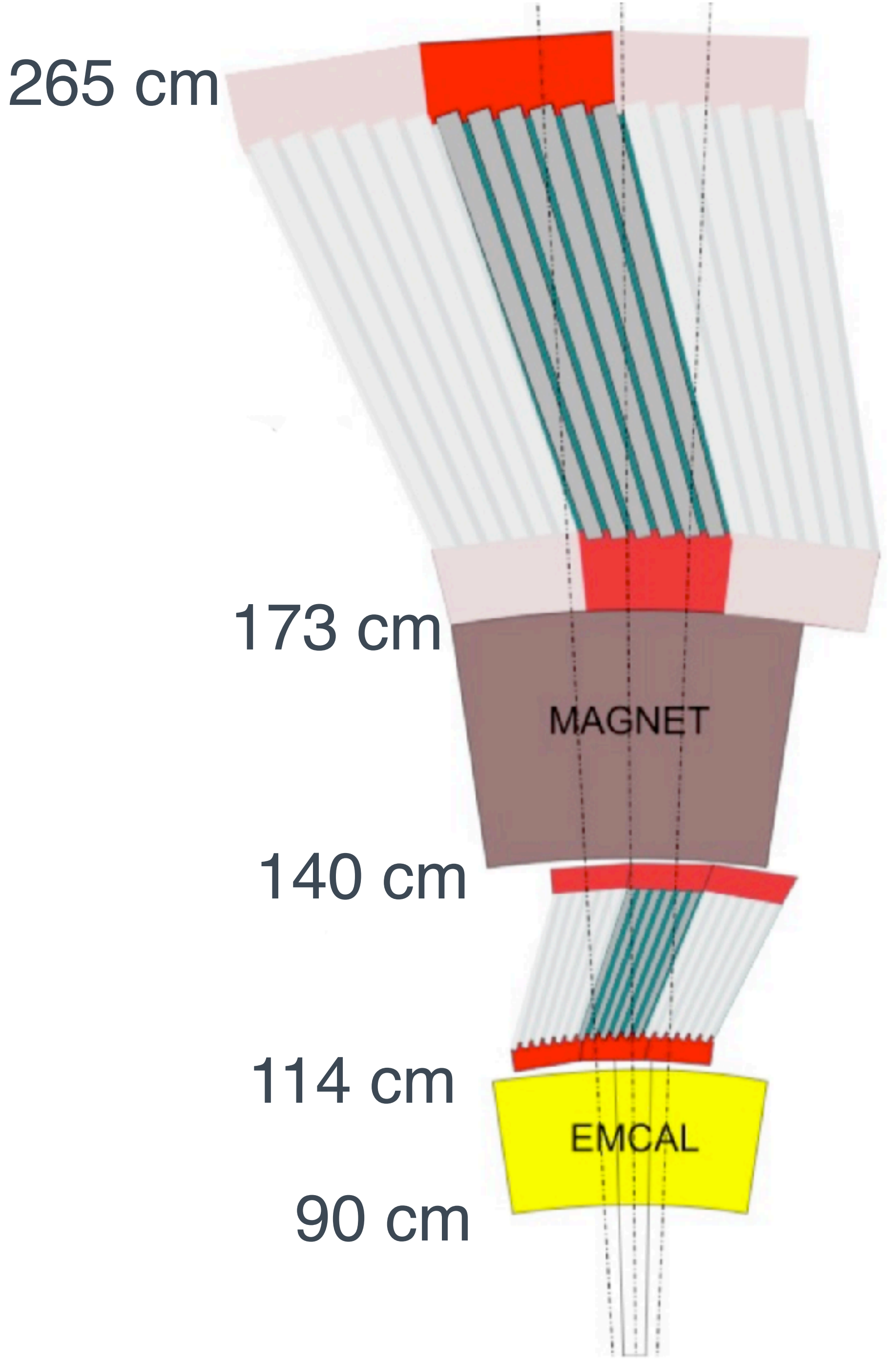
sPHENIX Collaboration

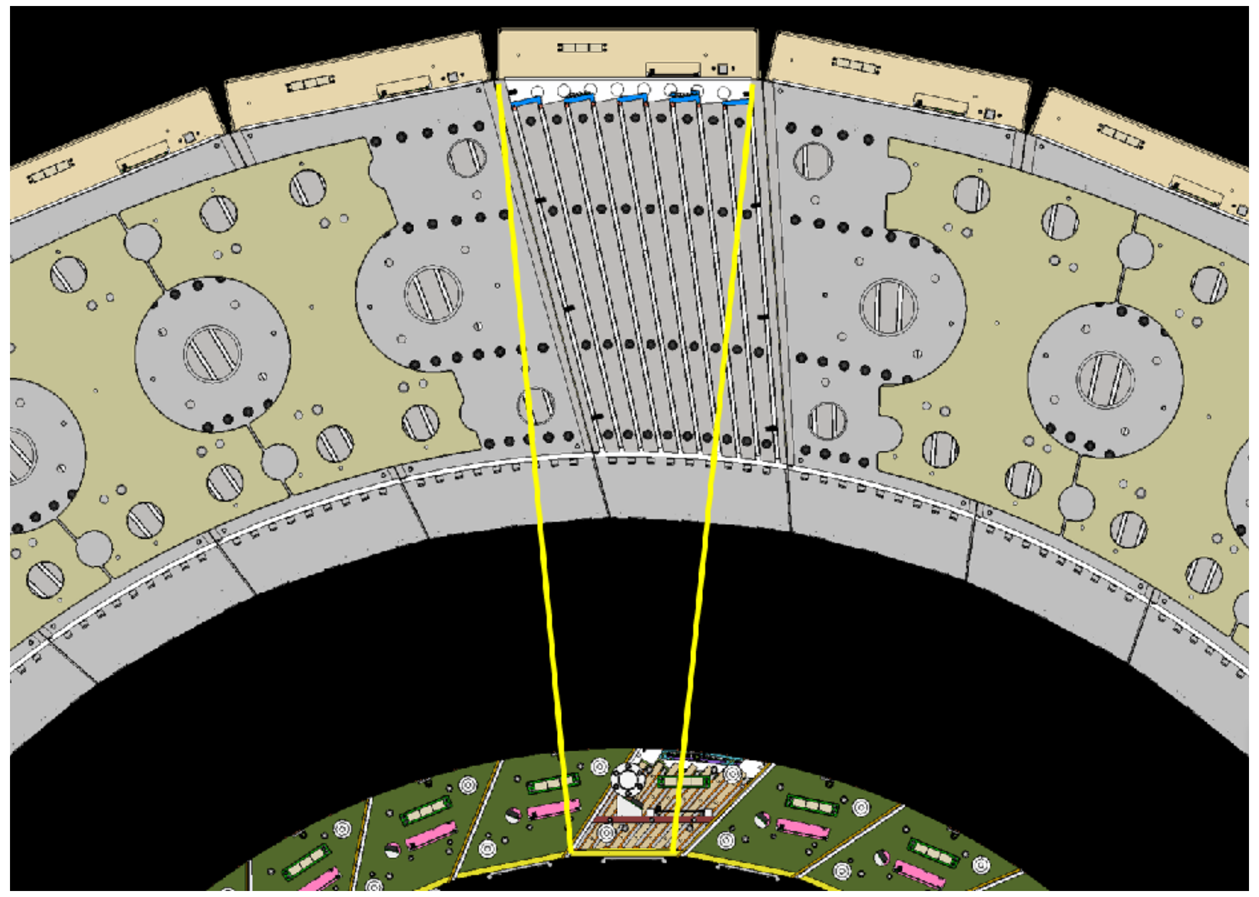
- **Encouraging diversity is a priority for our collaboration**

sPHENIX calorimeter system - HCal

- Metal-plate scintillating-tile sampling calorimeter
- Tilted plates arrangement of HCal: jets traverse at least four scintillator tiles

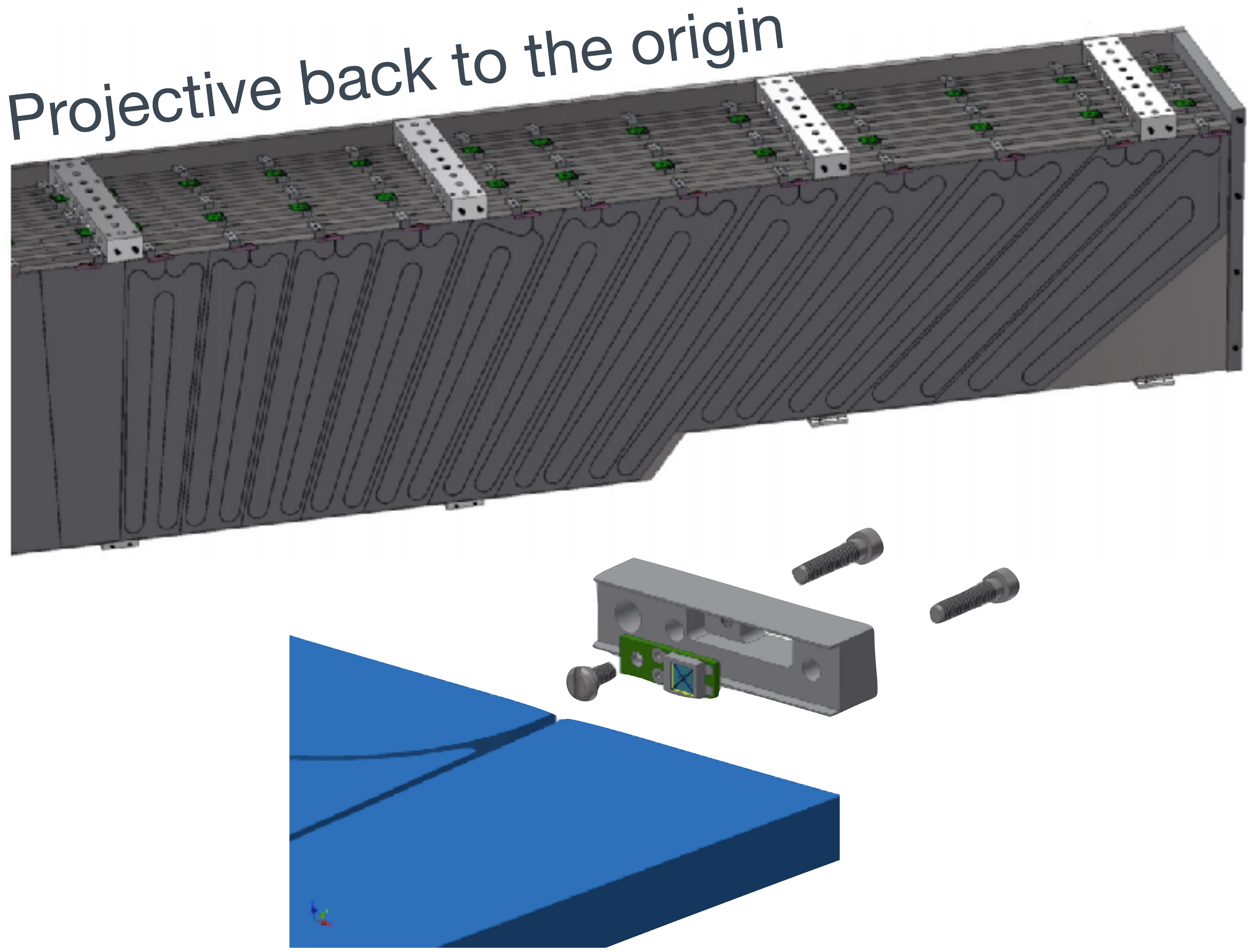
sPHENIX calorimeter system
- **~ 5 λ_i in total**
- **Common readout: SiPM**





Total channel		~ 3k
Outer	Absorber	Steel
	Tilted	-12^0
Inner	Absorber	Aluminum
	Tilted	$+32^0$
$\Delta\eta \times \Delta\phi$		~ 0.1 x 0.1
Energy resolution*		13.5% + (64.9% / $\sqrt{E}$)

*HCal+EMCal combined for hadrons

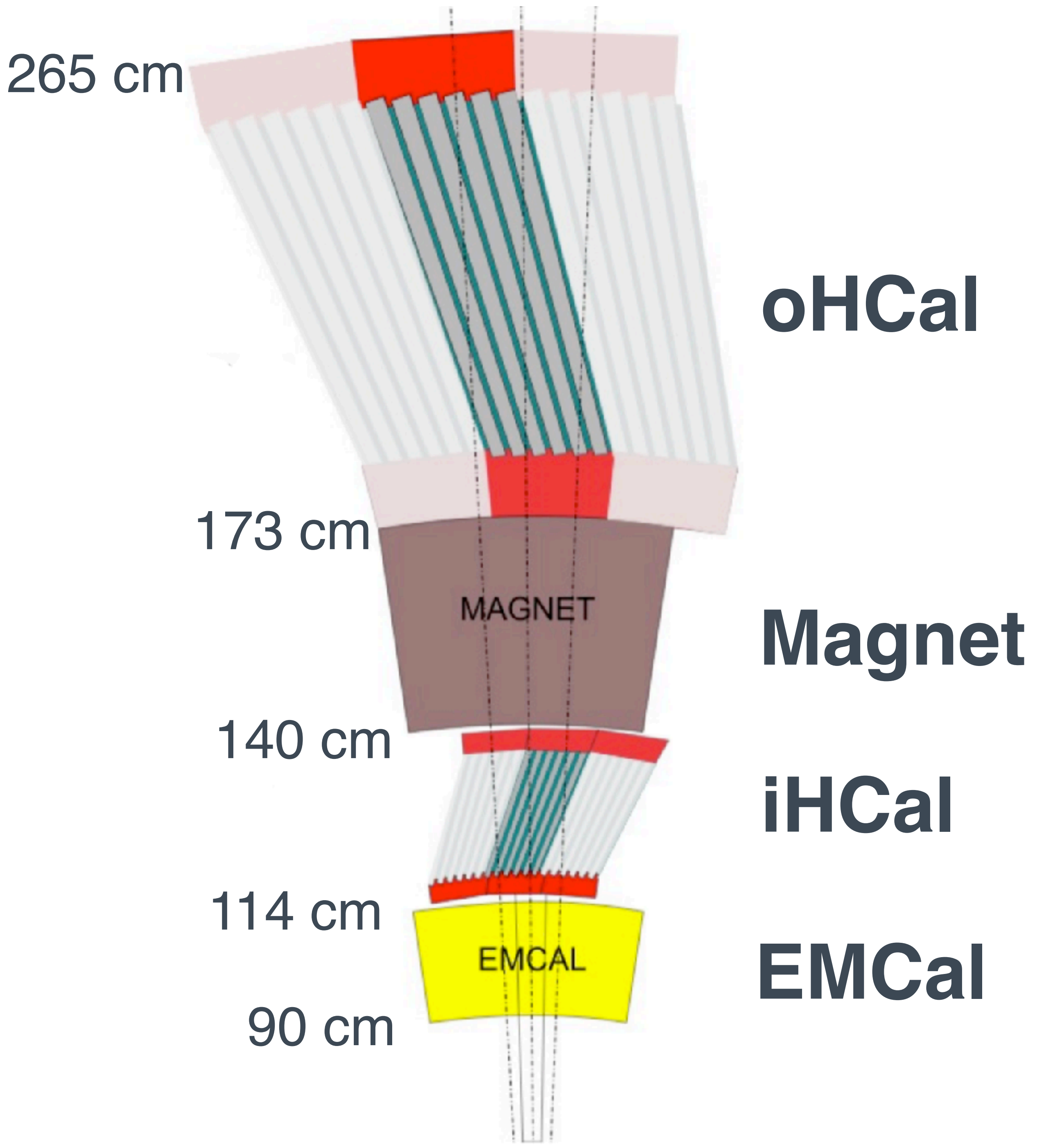


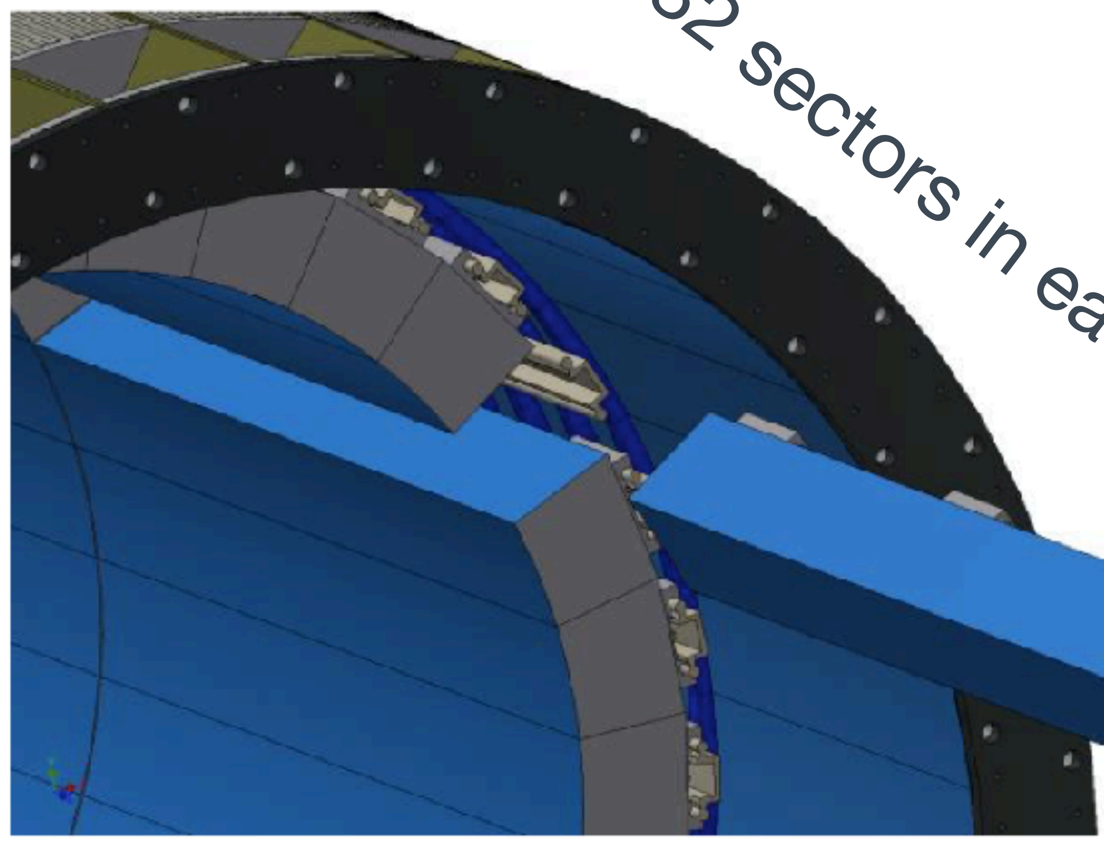
WLS fiber embedded in scintillator plate

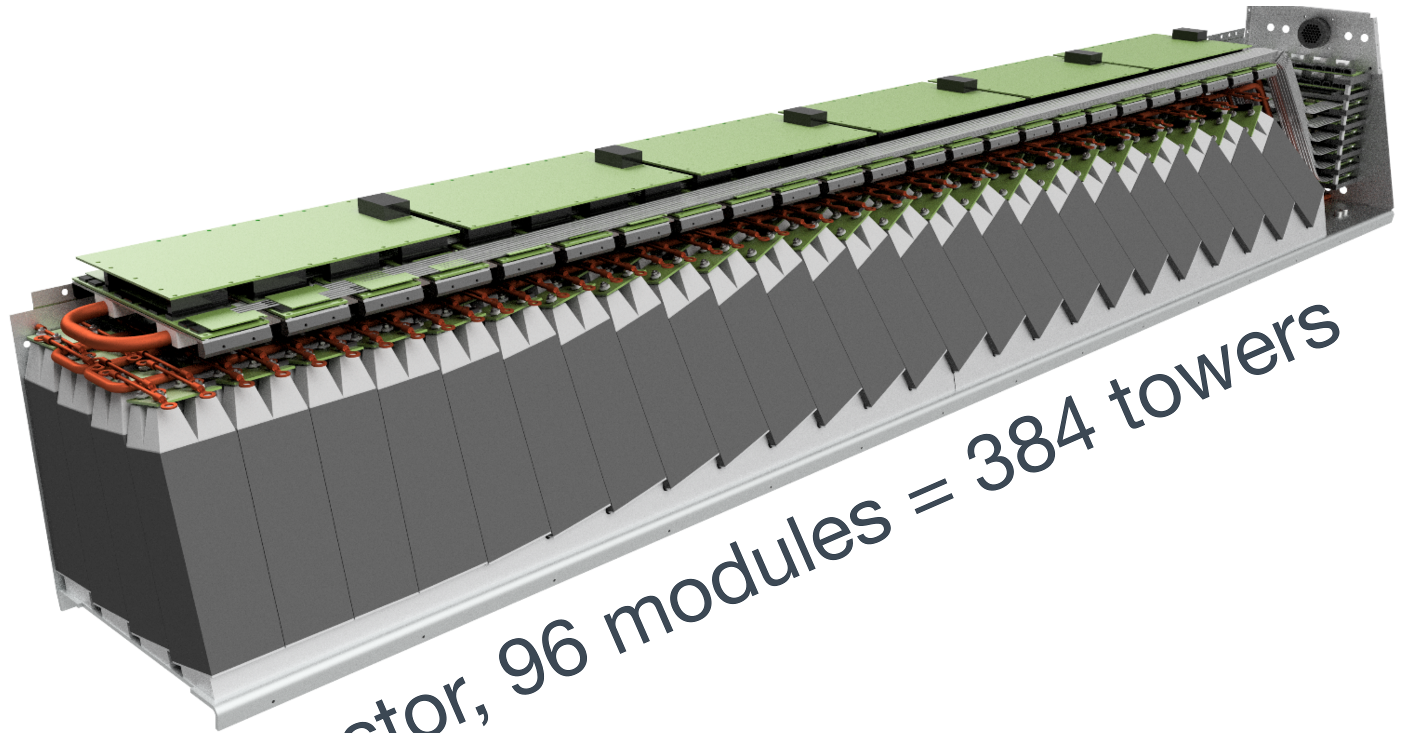
sPHENIX calorimeter system - EMCal

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

sPHENIX calorimeter system
- **~ 5 λ_i in total**
- **Common readout: SiPM**

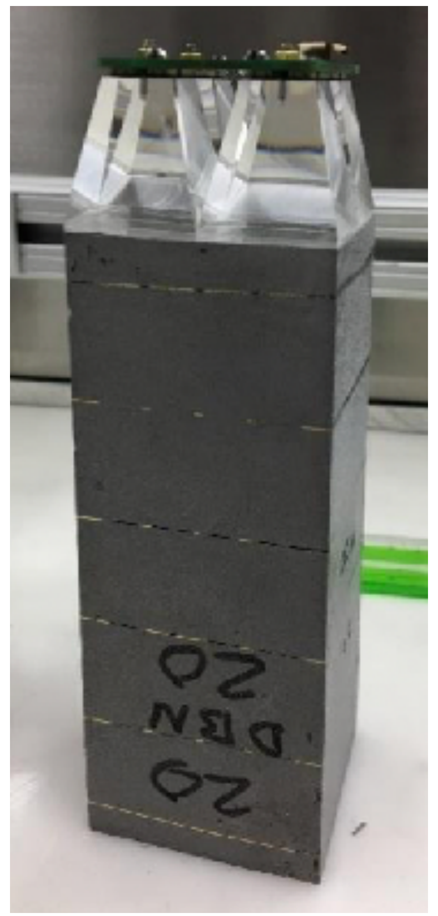




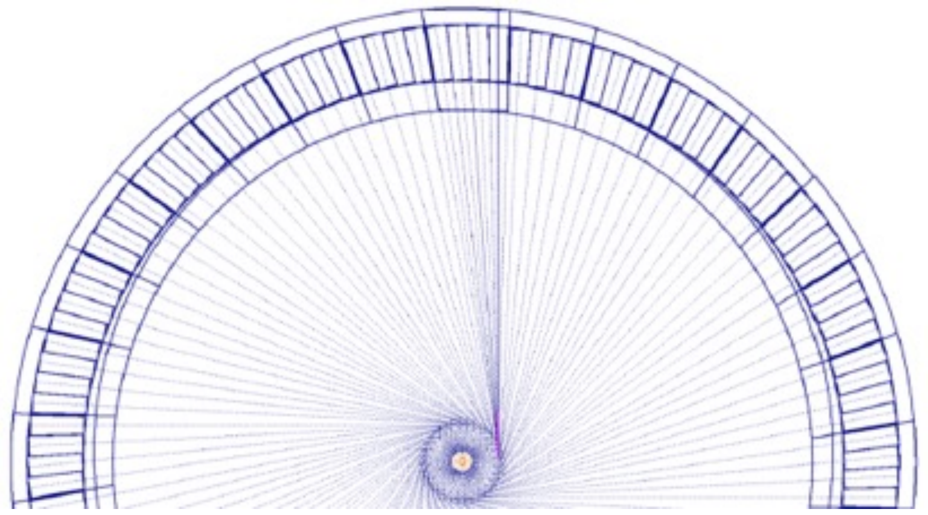


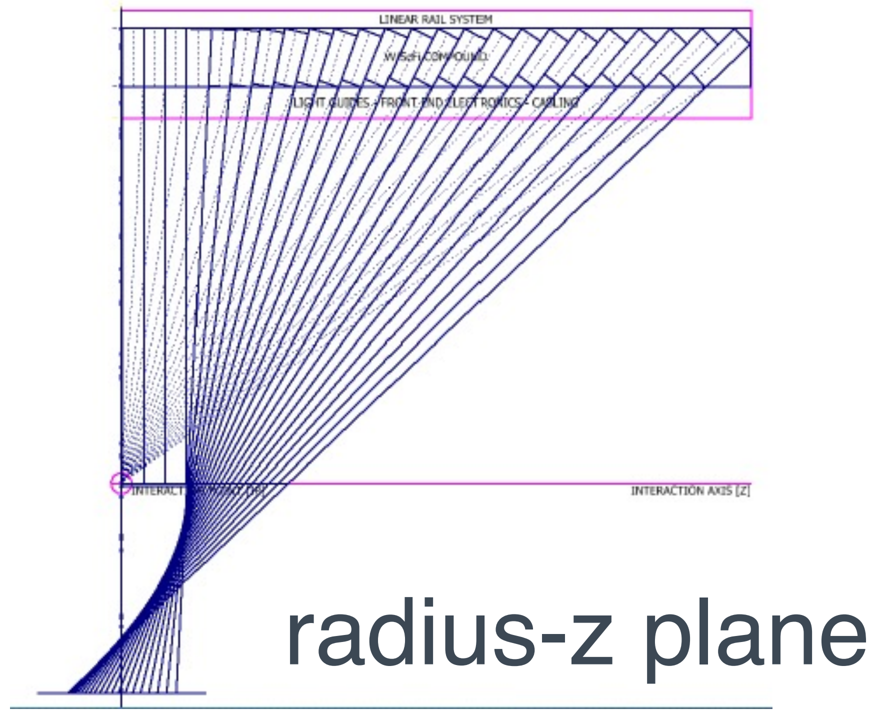
EMCal: SCIFI calorimeter

Module, 4 towers



x-y plane

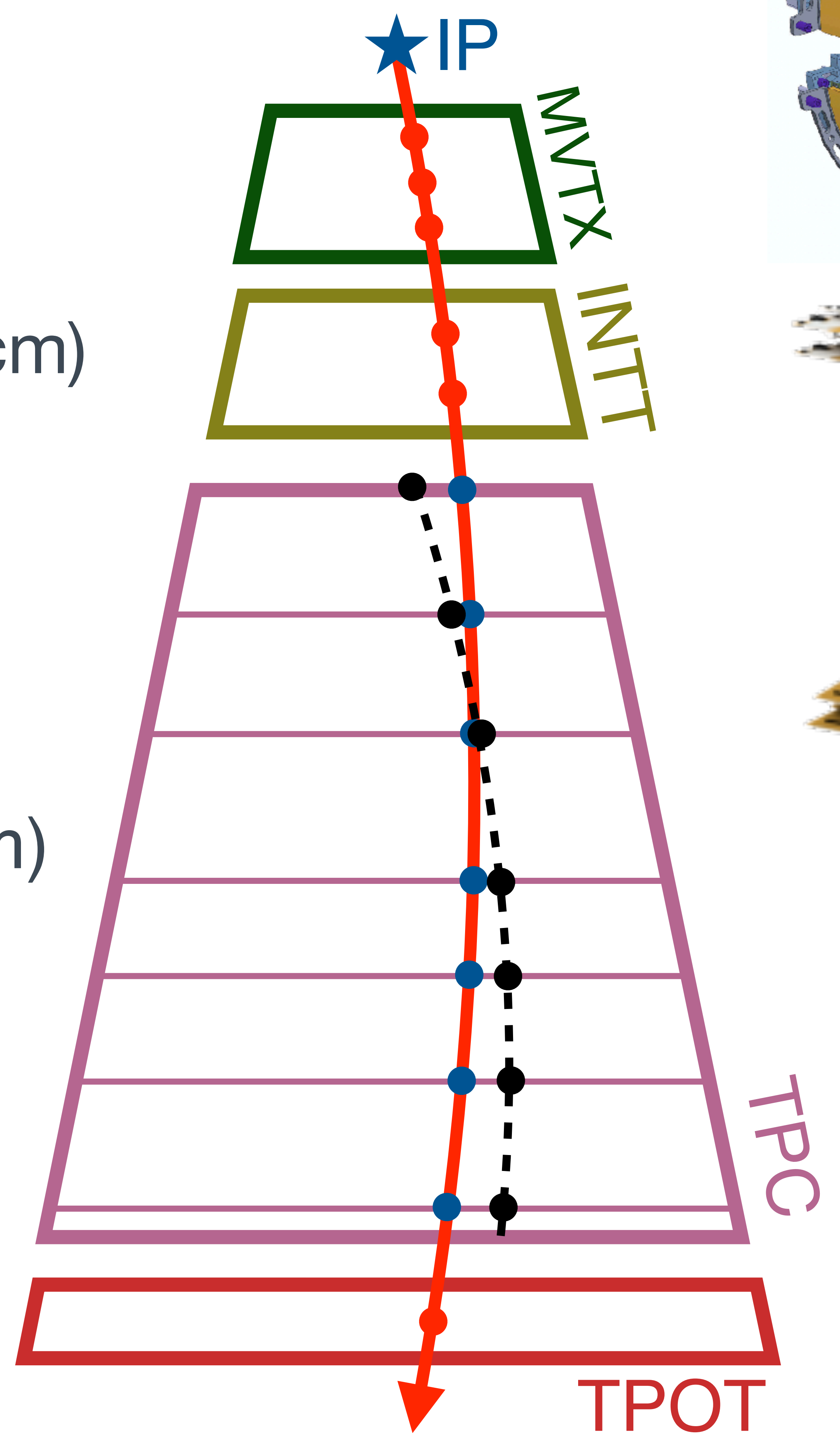


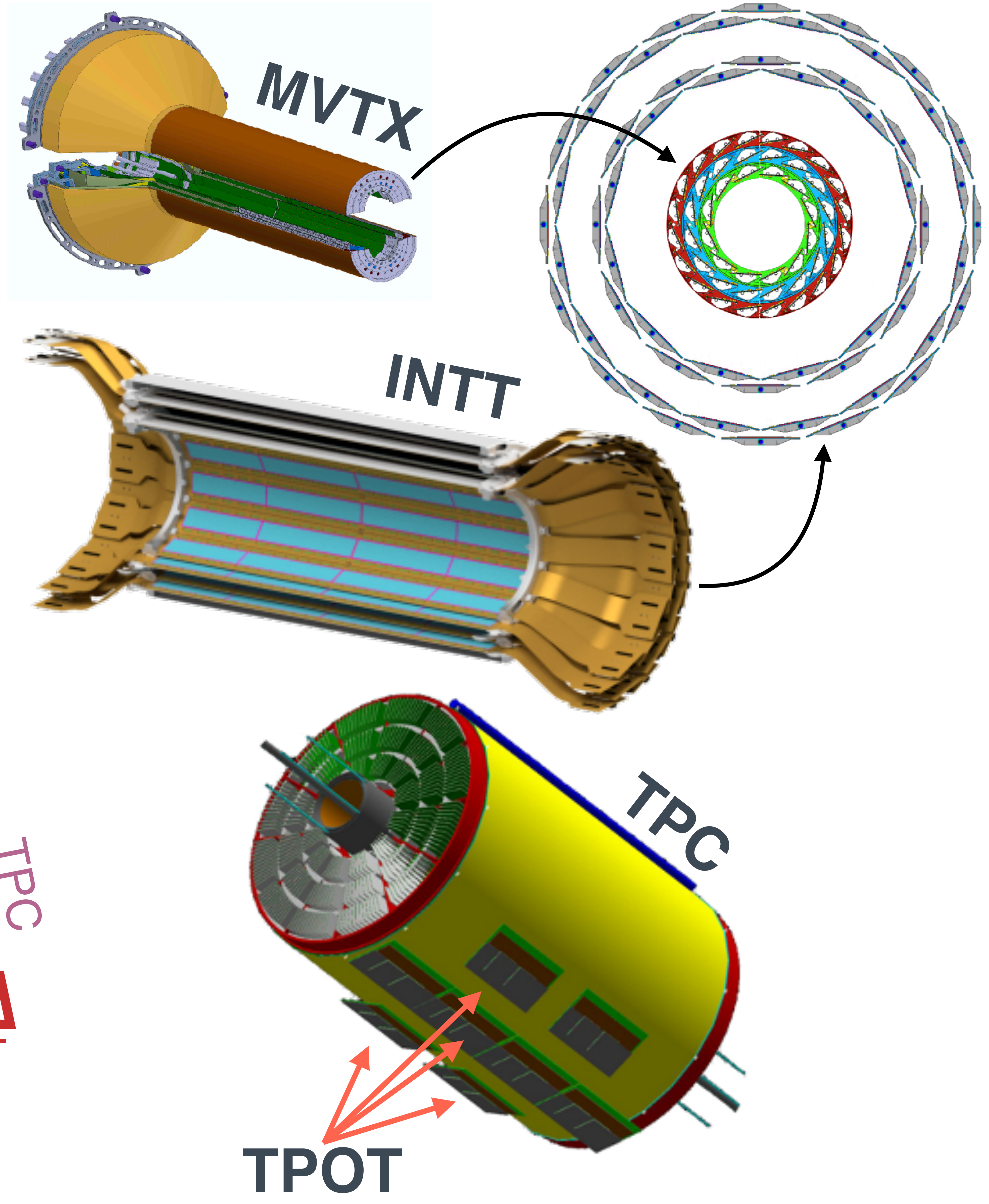


Modules are approximately projective back to IP in ϕ and η

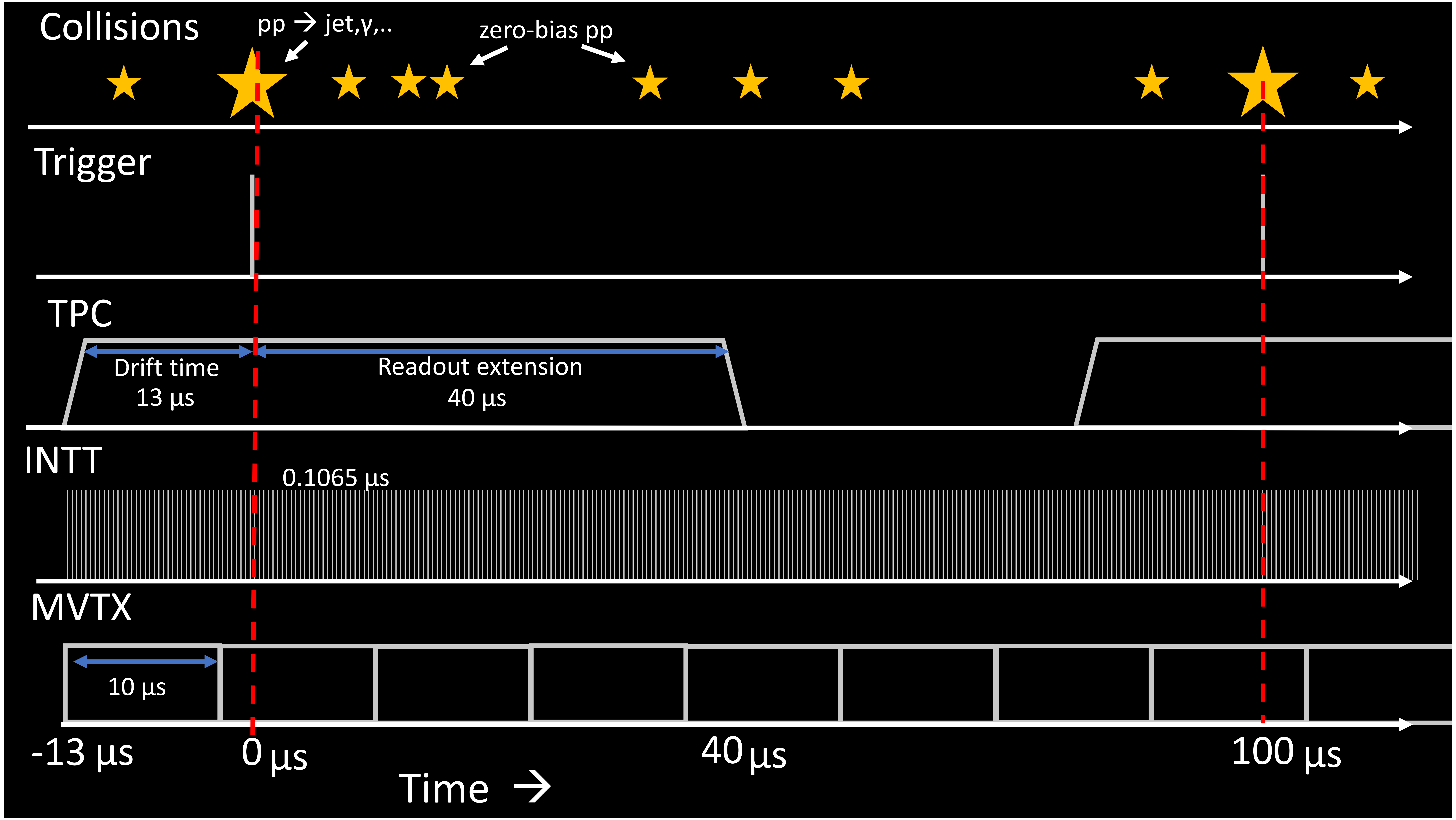
sPHENIX tracking system

- MVTX, MAPS-based Vertex Detector (2.3 < r < 3.9 cm)
  - 3 layers with cell size 27 µm x 29 µm
  - Superb vertex - O(10 micron) in rϕ, and z
- INTT, Intermediate Silicon Tracker (7 < r < 11 cm)
  - 2 layers of silicon strip sensors (78 µm pitch)
  - Surprior timing resolution for track-bunch crossing association
- TPC, Time Projection Chamber (20 < r < 80 cm)
  - Compact GEM-based TPC
  - Precise momentum measurement
- TPOT, TPC Outer Tracker (one spatial point)
  - 8 Micromegas-based detectors
  - Calibration for beam-induced distortions of the electron drift inside the TPC



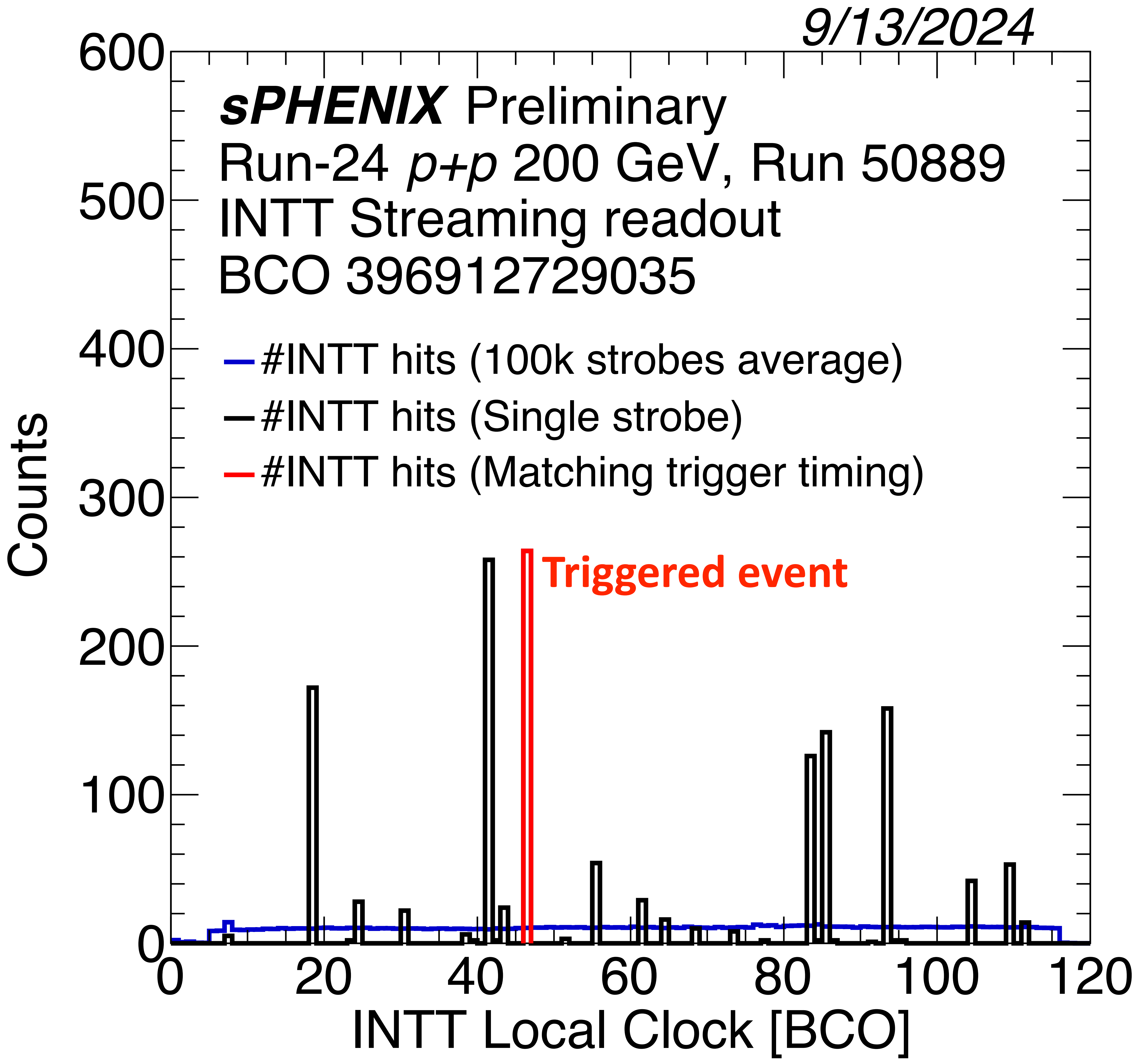


The streaming system of sPEHNIX trackers



Triggered vs. Streaming readout

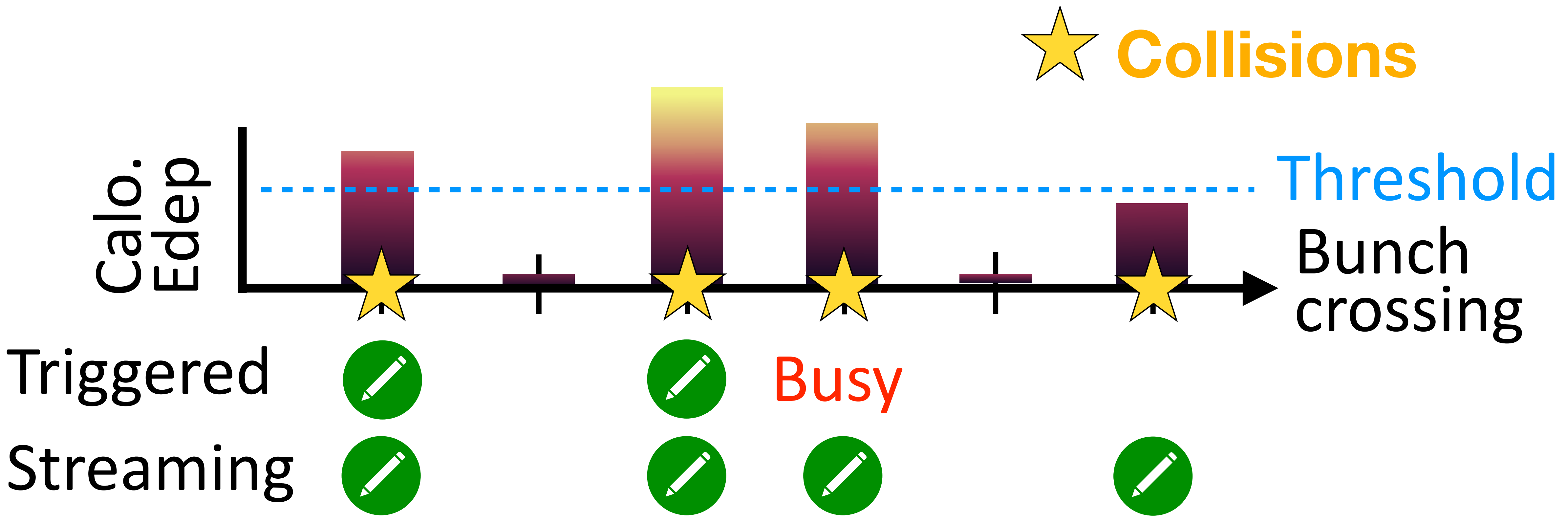
sPHENIX calorimeters: triggered only, sPHENIX tracking system triggered/streaming capable



Why streaming readout mode?

Triggered mode: Keeps events only if the triggers are fired (e.g., EMCal photon trigger)

Streaming mode: Keeps events as long as the particle hits are detected by sPHENIX tracking system → **Crucial for heavy-flavor physics!** (e.g., D^0 production)



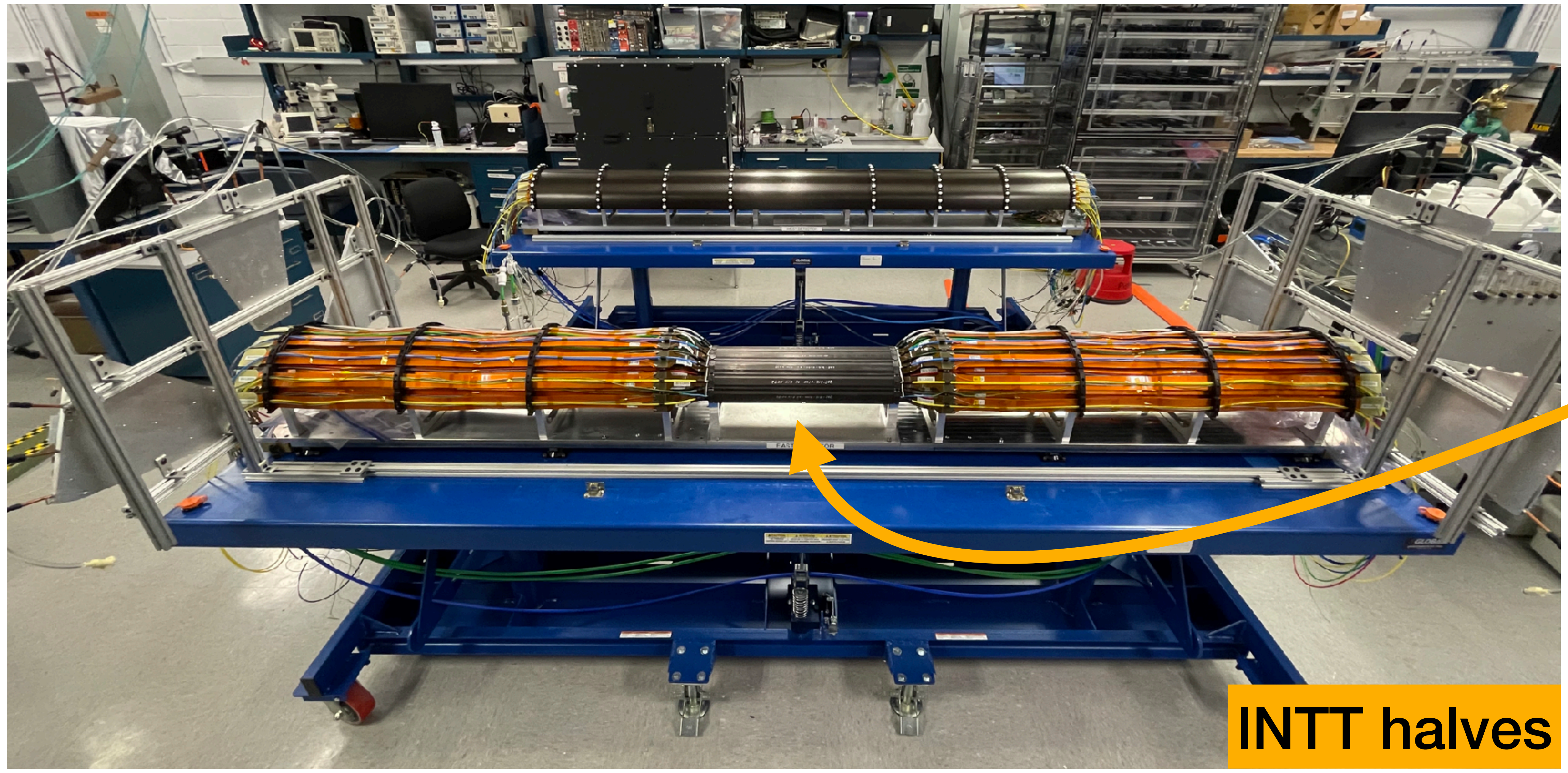
13 additional events recoded by INTT in this single time frame!

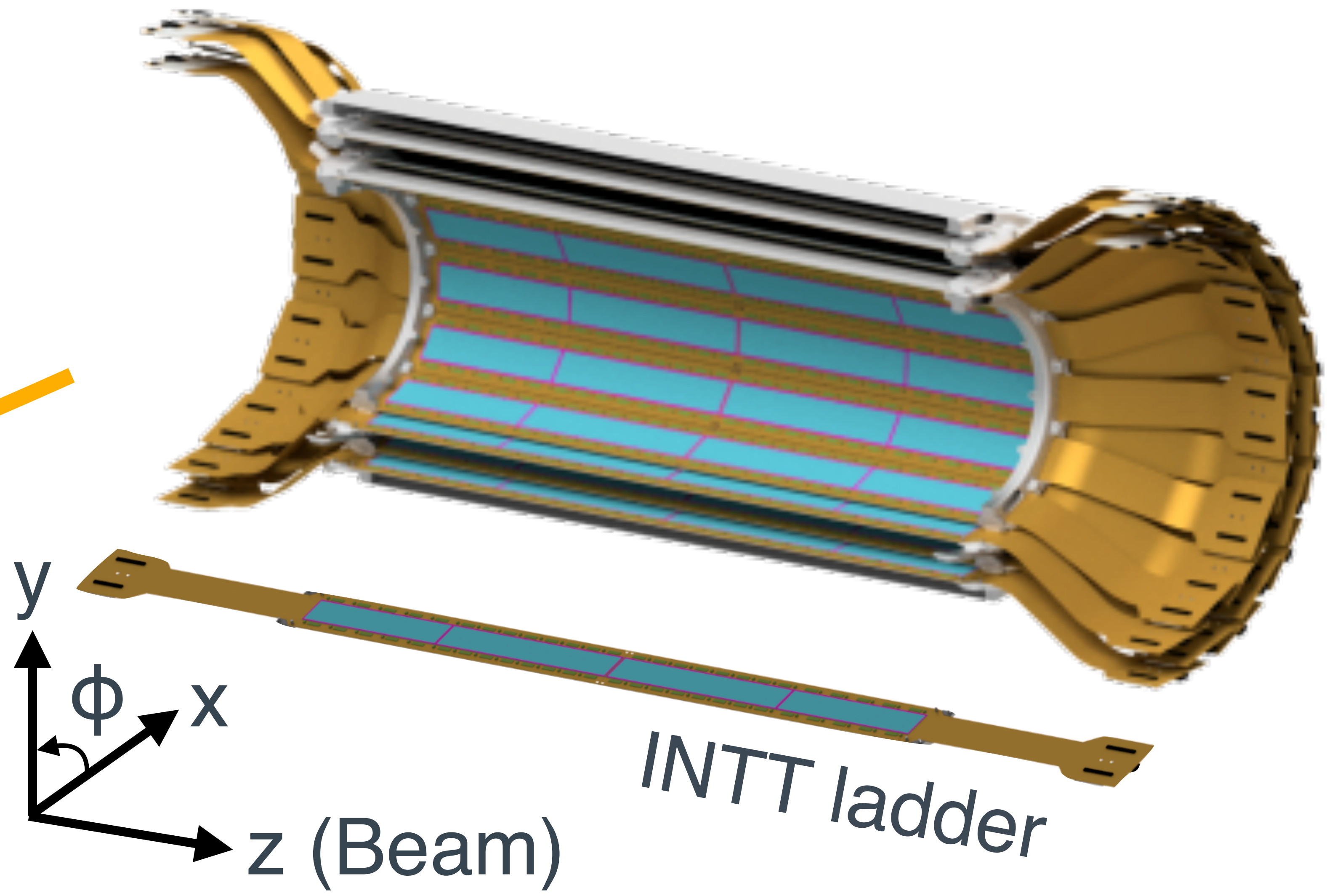
Intermediate Silicon Tracker (INTT)

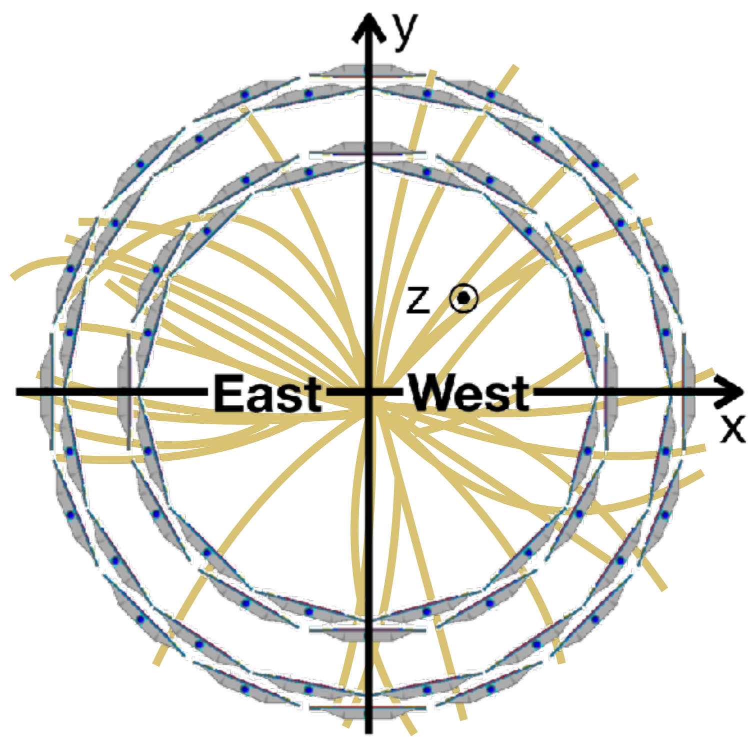
- Strip pitch 78 μm → Excellent spatial resolution in ϕ angle
- Between the MVTX and TPC → Bridge their tracks
- Superior timing resolution in sPHENIX tracking system
  → Associate tracks with individual RHIC bunch crossings
- Streaming readout capability
  →Record all collision events

Element	**Value**
Number of ladders	56
Barrel radial distance to the beam line	7.2 and 7.8 cm (Inner layer) 9.7 and 10.3 cm (Outer layer)
Radiation length (per ladder)	1.14% $[X/X_0]$
Active area (per ladder)	$45.6 \times 2\,\mathrm{cm}^2$
Number of channels (per ladder)	6,656
Channel strip pitch	78 μm
Channel strip length	16 mm (strips within ±13.0 cm along the beam axis) 20 mm (otherwise)

INTT specifications

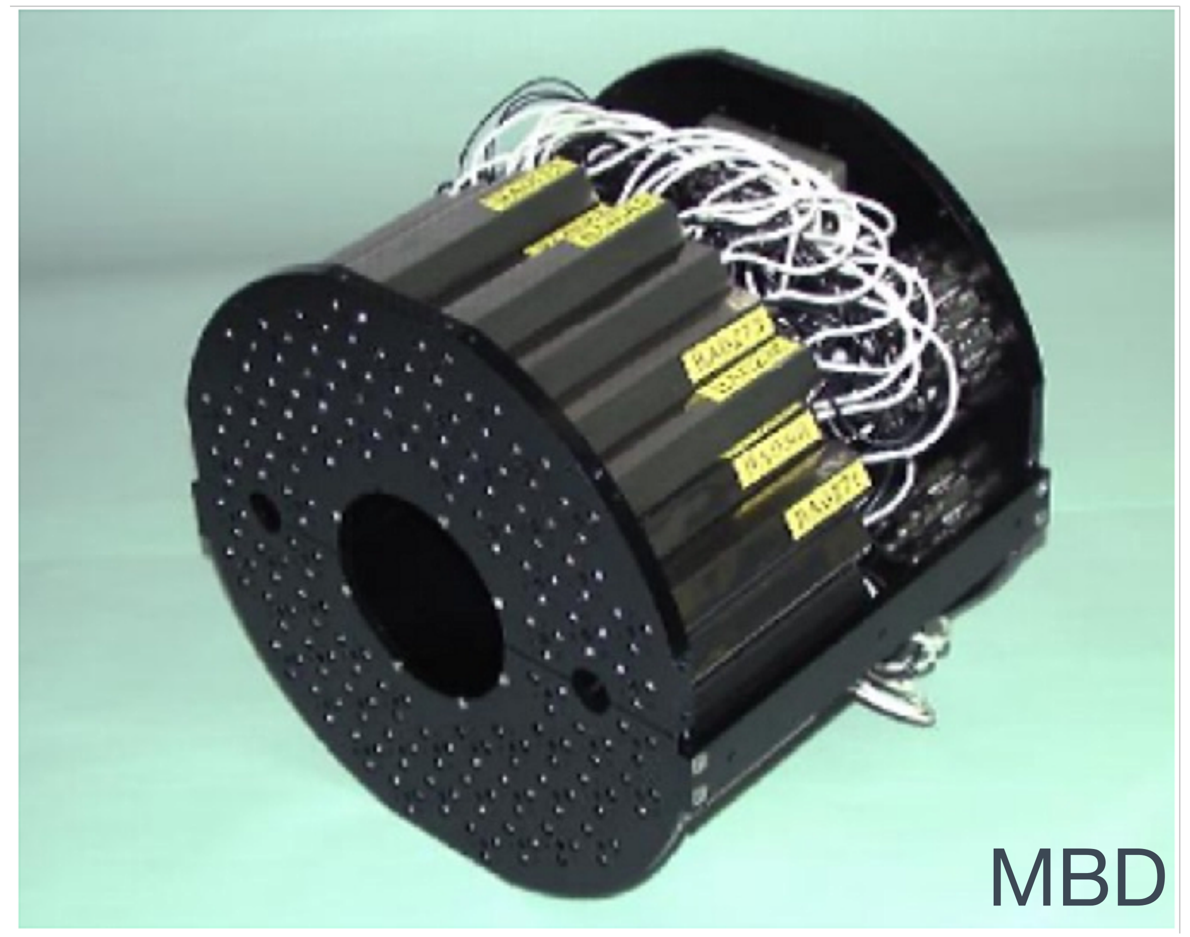


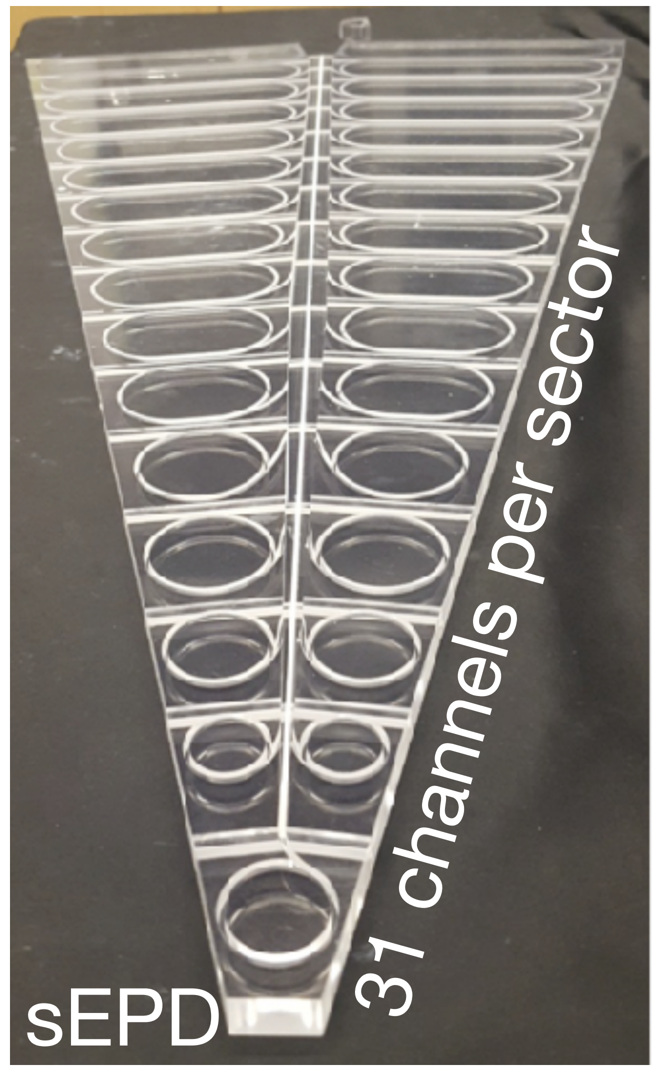




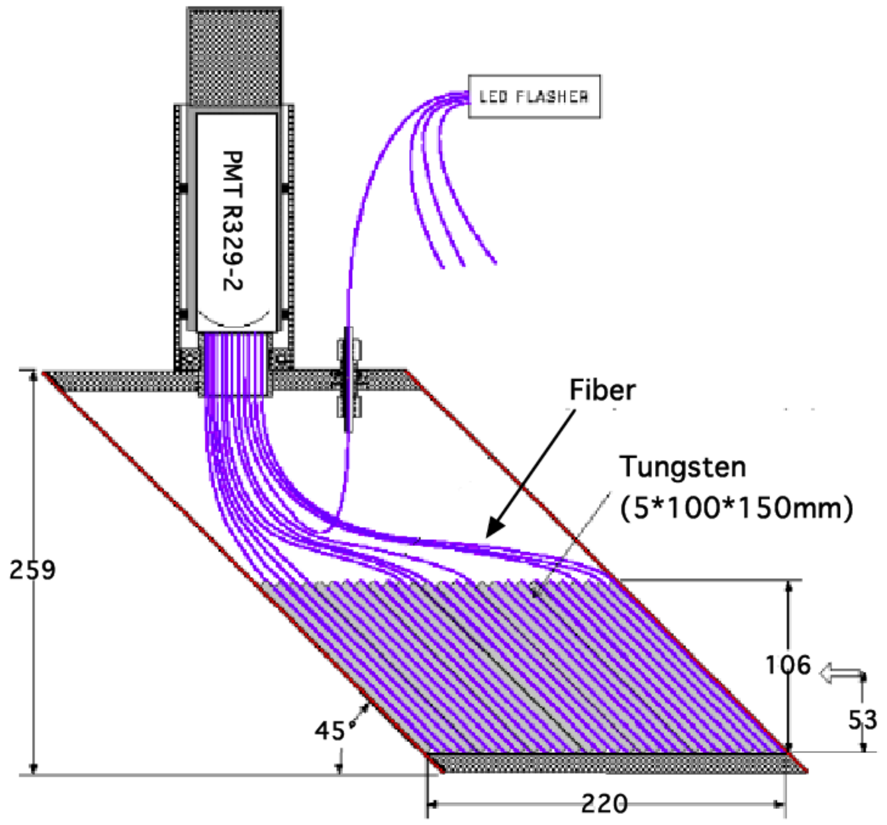
sPHENIX forward detectors

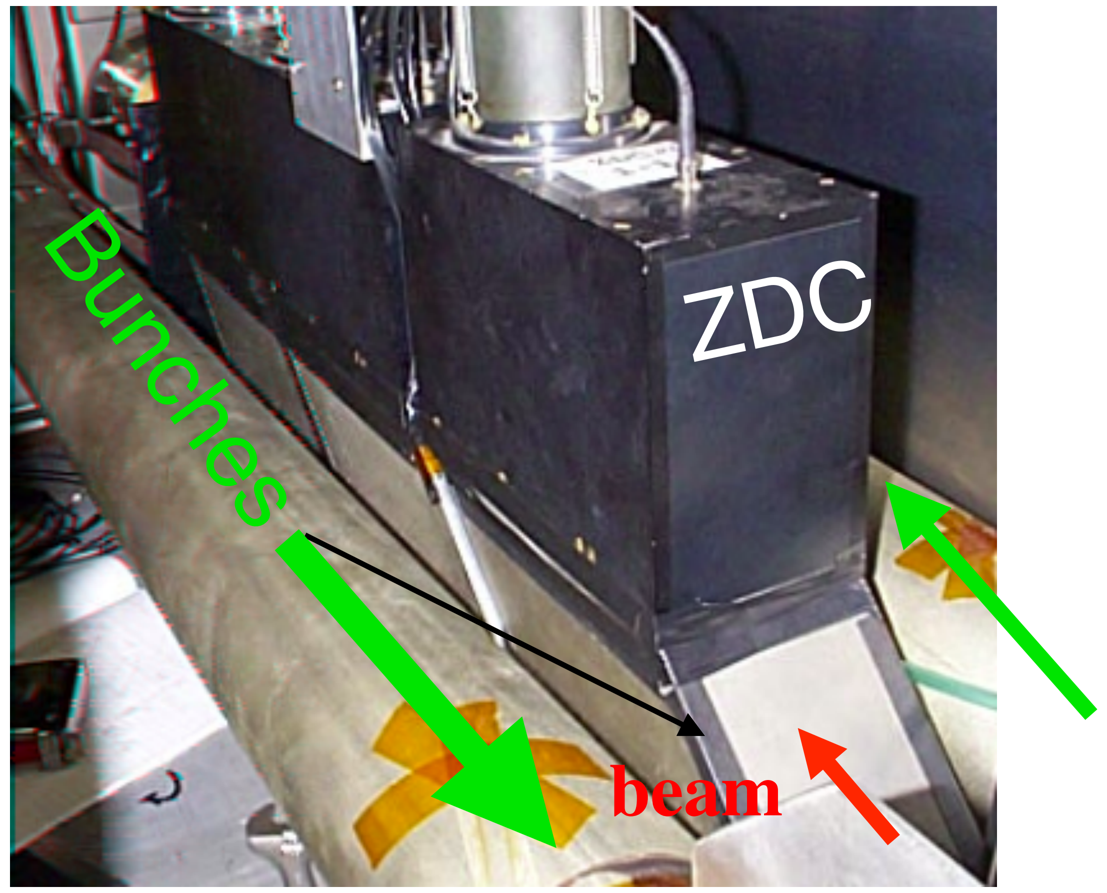
- **MBD**: Minimum Bias Detector (3.51 < |η| < 4.61)
  - Refurbished PHENIX Beam-Beam Counter
  - 3 concentric rings of PMTs on each side
  - Min. Bias. trigger and global event characterization
- **sEPD**: sPHENIX Event Plane Detector (2.0 < |η| < 4.9)
  - Bigger version of STAR EPD (4.6 < r < 90 cm)
  - 2 wheels of scintillator w/ embedded WLS fibers
  - Improve the event plane determination significantly
- **ZDC**: Zero Degree Calorimeter*
  - Reuse of the PHENIX ZDC complex
  - Located at ±18.5 m from IP
  - Global event characterization
  - Local polarimeter in polarized proton-proton collisions





ZDC (Zero Degree Calorimeter)





*The ZDC complex comprises ZDC, Shower Max Detector (SMD) and veto counters

Measurement of $dE_T/d\eta$ in Au+Au collisions

sPHENIX Final! - [PRC 112 (2025), 024908]

Uncertainty source [%]	EMCal-Only	HCal-Only	Full calorimeter
Calibration	2.6	2.7	2.1
Hadronic response	4.1	6.6	4.7
Modeling	1.4–2.1	2.5–3.8	1.6–2.2
Zero suppression thres.	1.0–5.8	0.2–0.3	0.8–4.4
z-vertex resolution	0.3–0.4	0.1–0.2	0.2–0.3
Acceptance	0.2–0.5	0.2–0.6	0.1–0.3
Total	5.3–8.1	7.7–8.3	5.6–7.4

- Overview of major systematic uncertainties contributing to the $dE_T/d\eta$ measurements
- The uncertainty ranges: η-averaged variation for different centrality classes

Measurement of $dN_{ch}/d\eta$ in Au+Au collisions

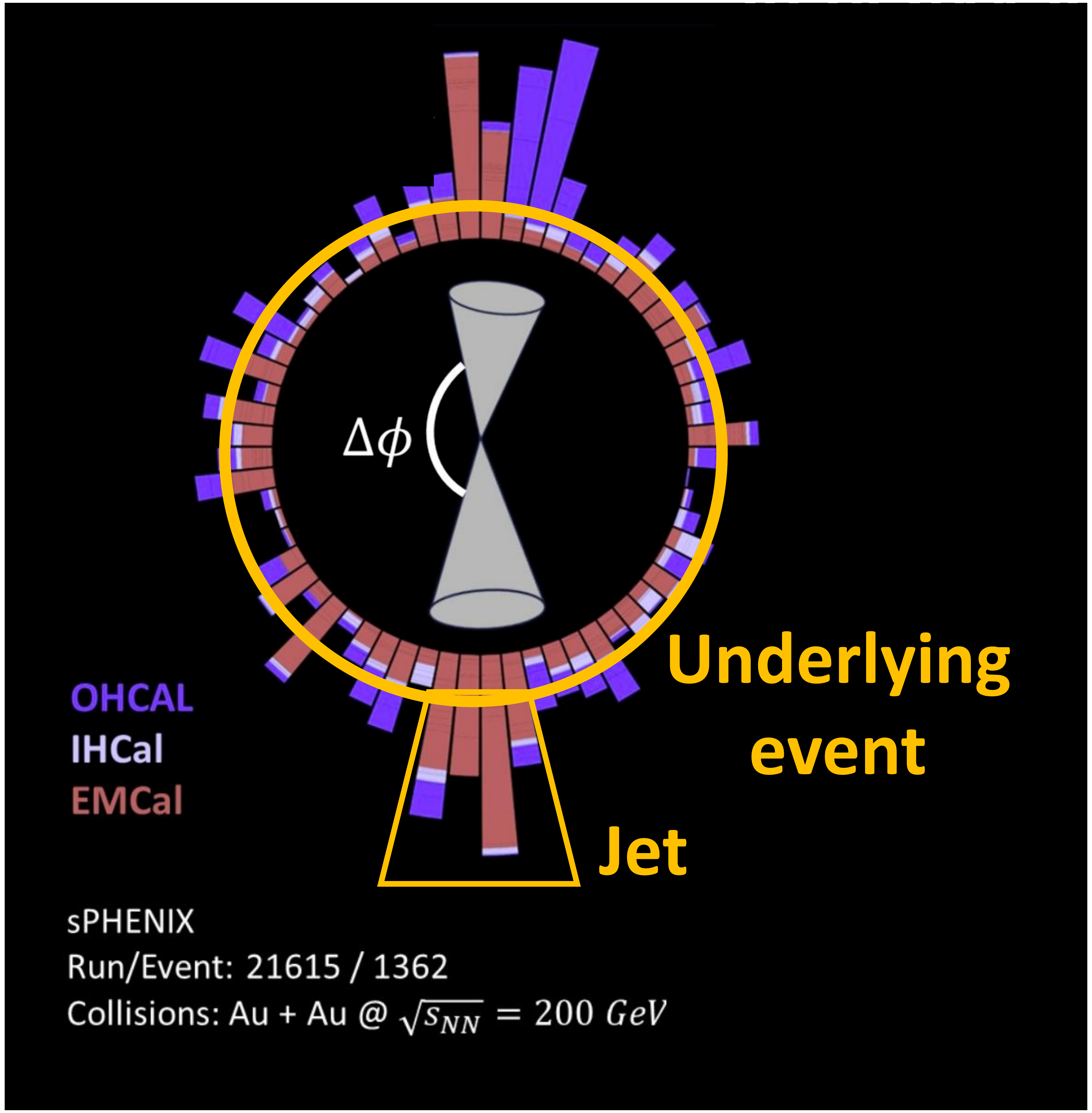
sPHENIX

sPHENIX Final! - [JHEP 08 (2025), 075]

Source	The combinatoric method [%]	The closest-match method [%]
Simulation statistics	0.1–0.6	0.2–0.9
Cluster ADC selection	3.8–8.8	2.8–5.4
Cluster ϕ-size selection	<0.1	<0.2
Tracklet reconstruction criteria	0.7–1.2	<1.7
Machine and detector stability	<1.0	0.1–1.6
Model dependence	0.5–5.7	1.6–3.8
Secondaries	<2.6	<3.2
Detector misalignment	0.5–0.9	—
Total	4.1–10.3	3.5–6.9
Correlated uncertainty in the weighted average result	3.5%–7.9%	
Uncorrelated uncertainty in the weighted average result	$<0.9\%$	
Total uncertainty in the weighted average result	3.5%–7.9%	

- Systematic uncertainties from various sources, with the range indicating the minimum and maximum uncertainty magnitudes across all η bins and centrality classes
- The combination strategy separates the correlated and uncorrelated uncertainties. The weighted average of $dN_{ch}/d\eta$ is based on the uncorrelated uncertainties

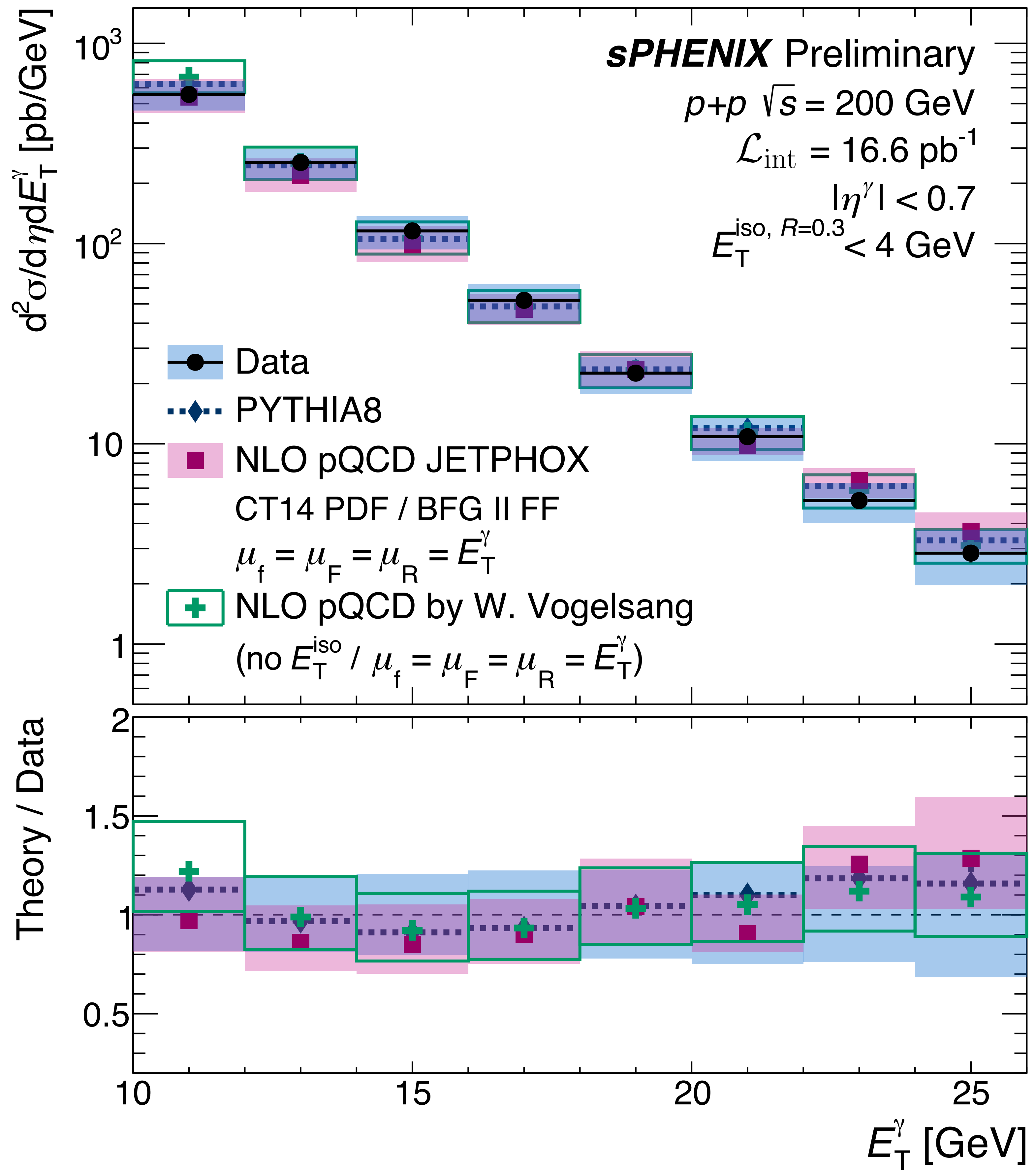
Underlying event subtraction in Au+Au collisions



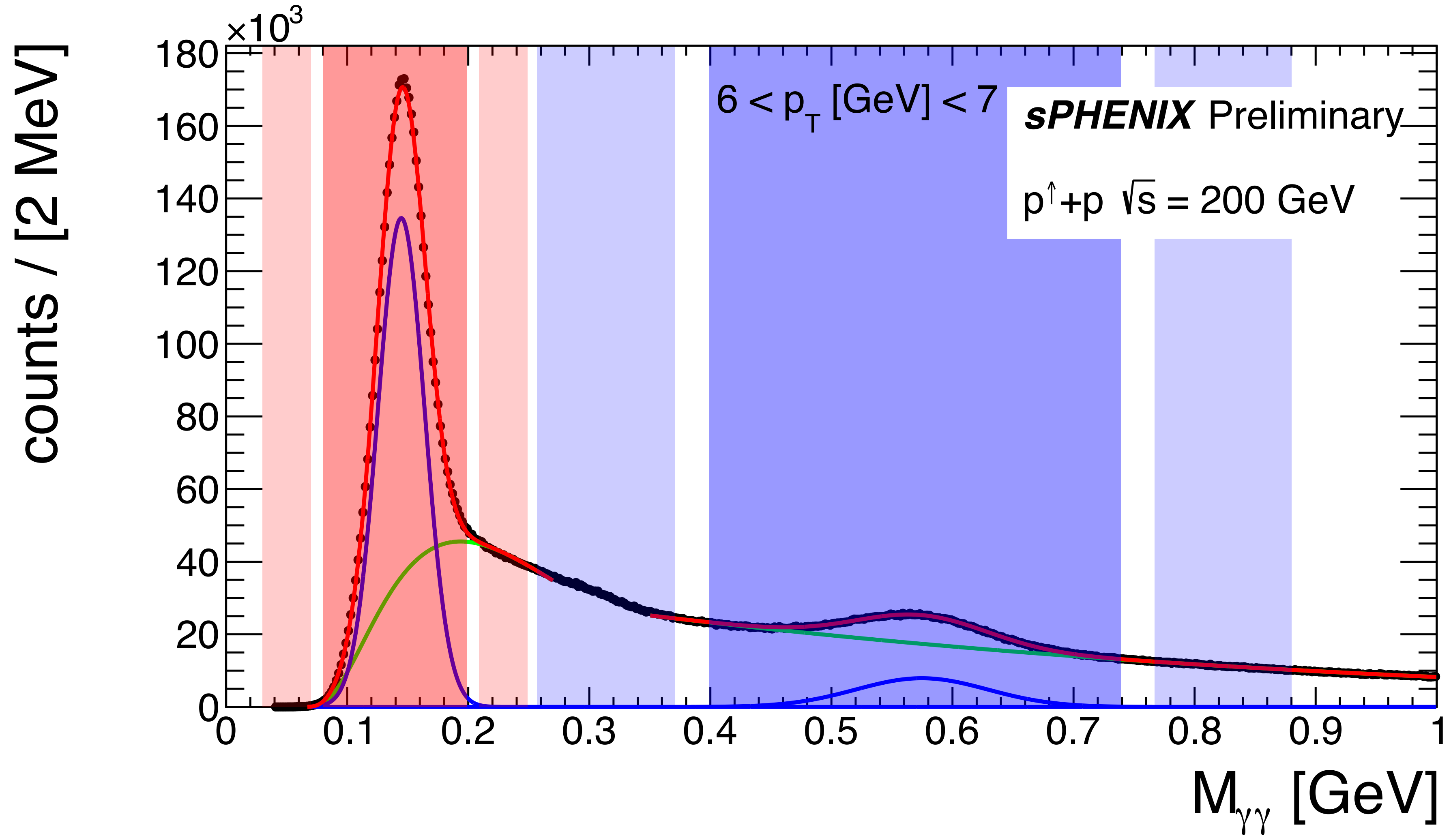
The photon business at sPHENIX

Differential cross-section of isolated prompt photons in p+p collisions

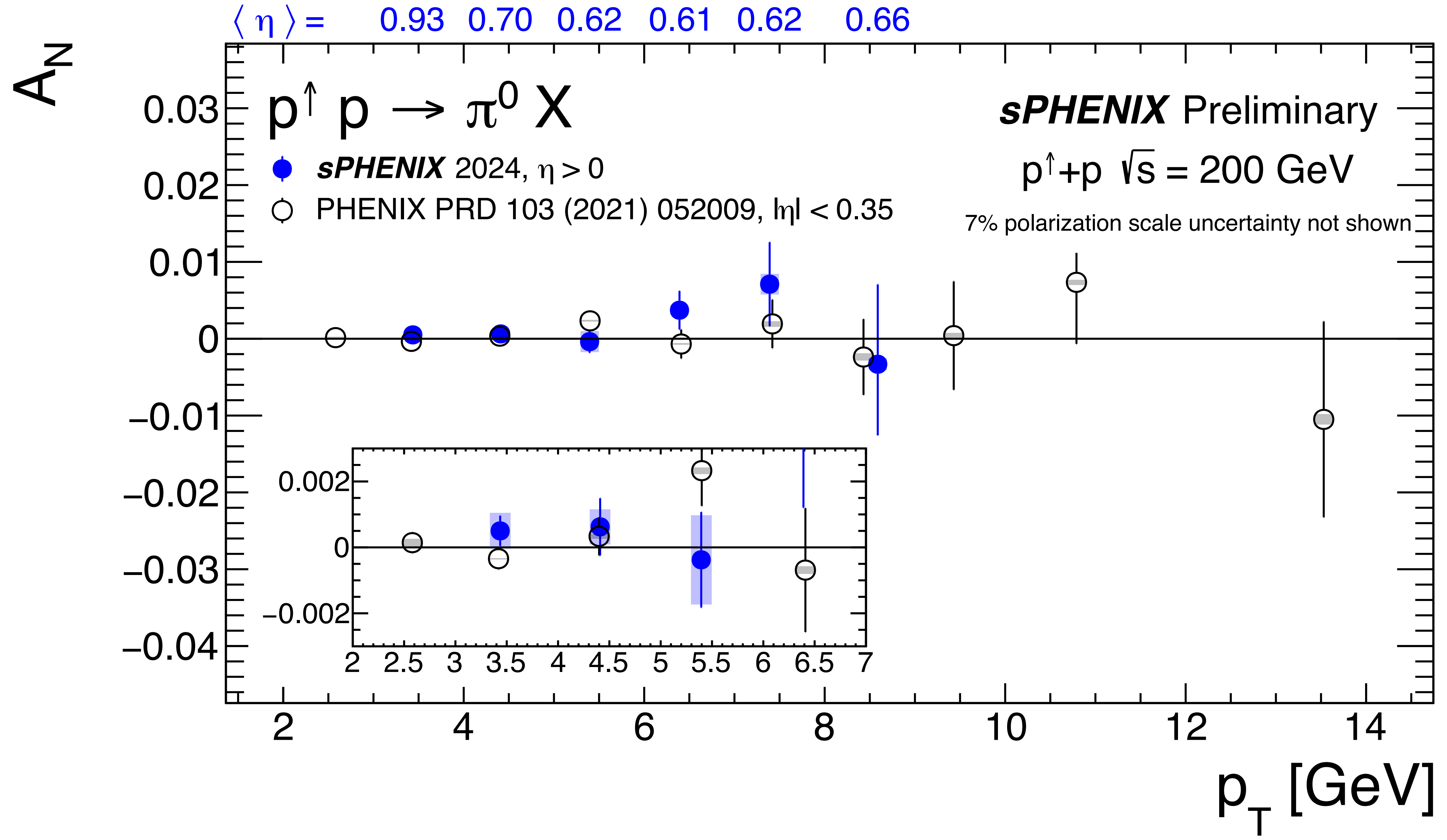
Calo. only measurement
ABCD method for signal extraction



π0 and η signals observed



Neutral meson TSSA



Theoritical models

- **HIJING**, a Heavy Ion Jet Interaction Generator, uses an MC Glauber model of the nucleus-nucleus collision geometry and perturbative QCD to model hard scatterings as parton minijets. The model includes multiparton interactions, and initial and final state radiation effects. HIJING uses the Dual Parton Model for soft interactions and the Lund string model for hadronization

- **AMPT**, A Multi-Phase Transport model, includes explicit interactions between initial minijet partons and final-state hadronic interactions. It extends HIJING by evolving initial partons with Zhang's parton cascade (ZPC) procedure and the ART model for the last stage of parton hadronization

- **EPOS4**, based on Gribov-Regge theory, includes nuclear effects such as Cronin transverse momentum broadening, parton saturation, screening, as well as high-density effects that lead to collective hadronization in hadron-hadron scattering