Bulk Property Measurements With sPHENIX

Hao-Ren Jheng, on behalf of the sPHENIX Collaboration

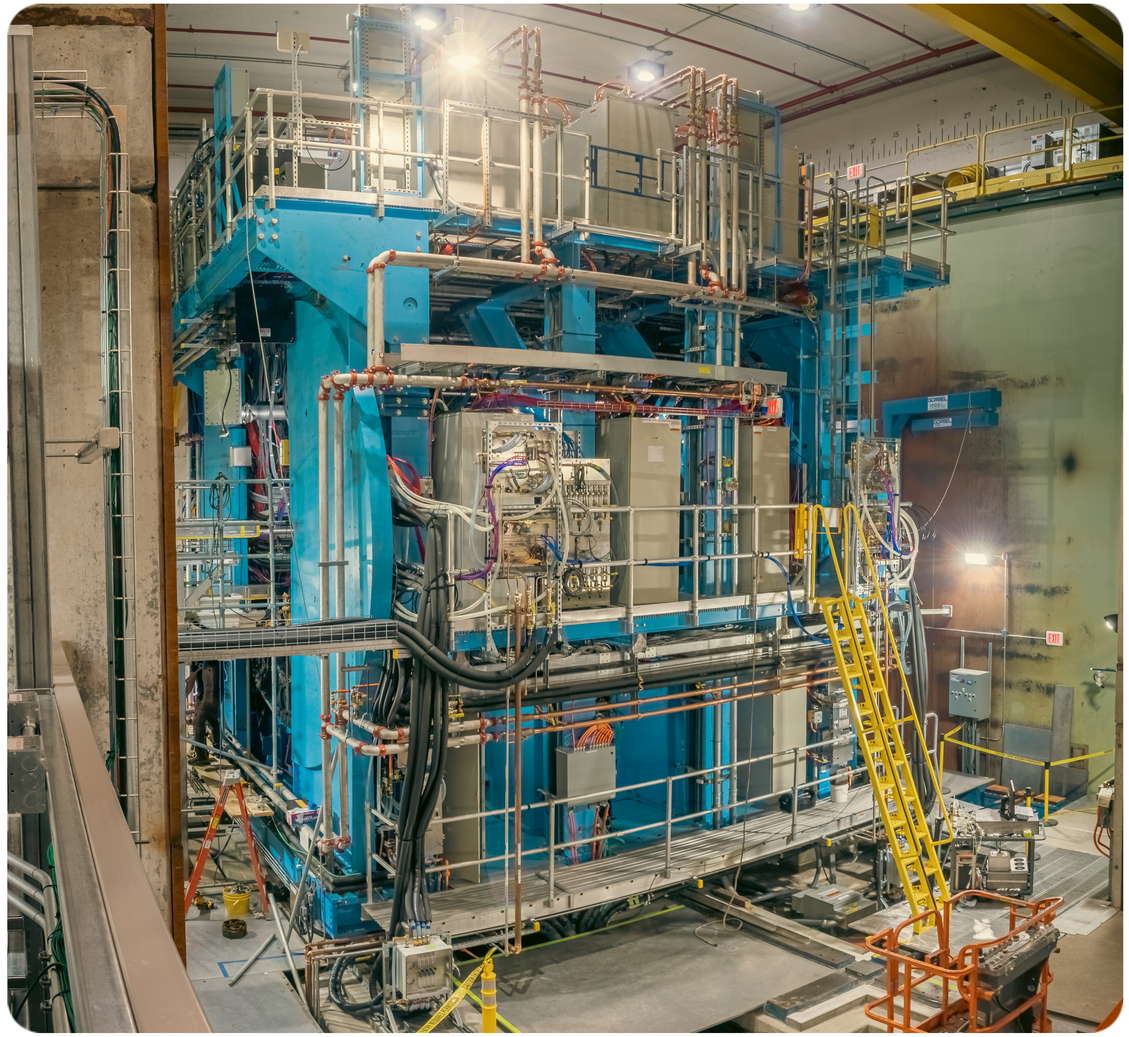
Massachusetts Institute of Technology

Quark Matter 2025

MIT HIG group's work was supported by US DOE-NP

Overview

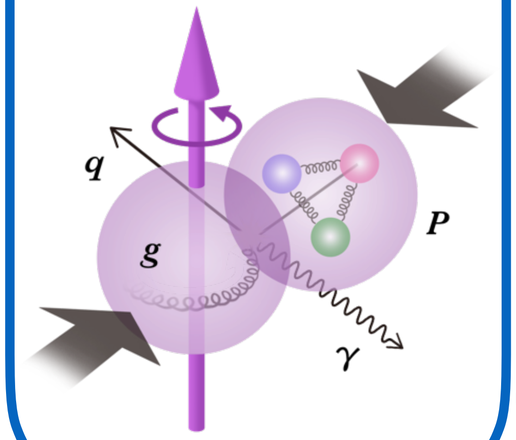
- sPHENIX is a brand-new general-purpose detector at RHIC
  - Completed installation in May 2023
  - Began the commissioning period in preparation for physics data taking in June 2023
  - Has since collected high-quality physics data
- sPHENIX serves as the central and essential component for completing RHIC's science mission to probe the inner workings of the QGP
  - Enables multi-scale probes and provides complementarity with the LHC measurements



sPHENIX Physics Program

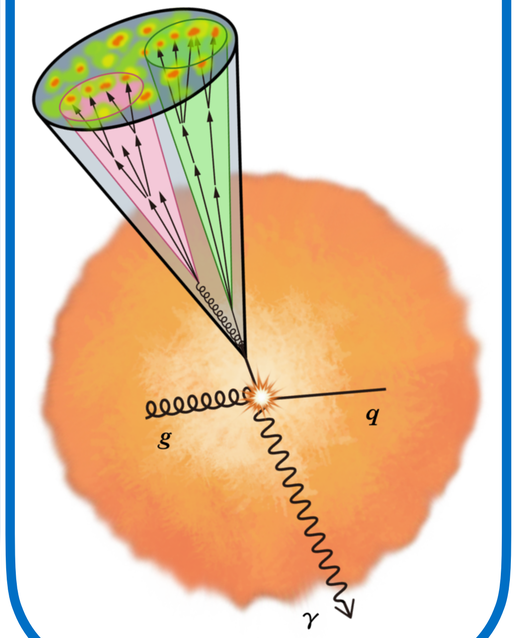
Cold QCD

Study proton spin, transverse momentum, and cold nuclear effects



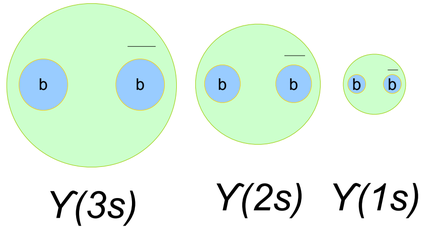
Jet Physics

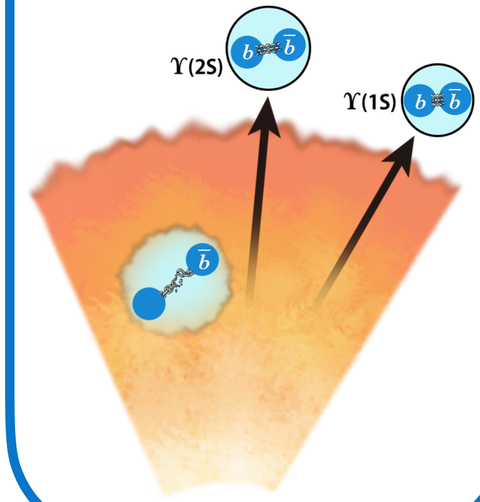
Vary momentum and angular scale of probe



Quarkonia

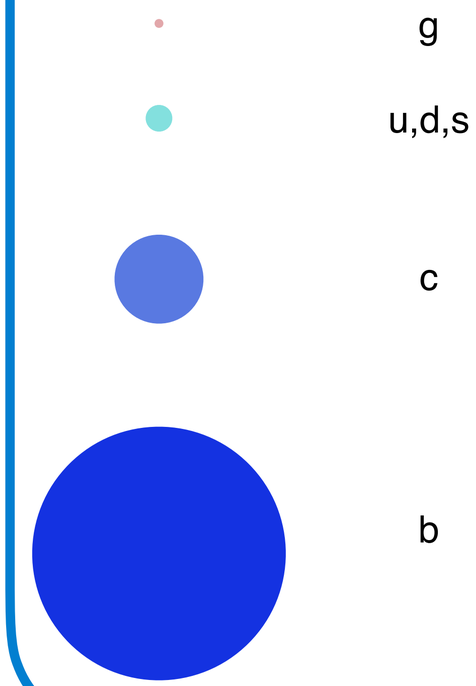
Vary size of probe





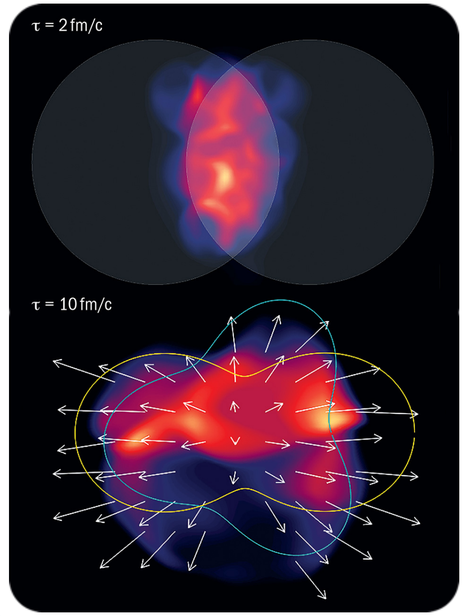
Heavy Flavor

Vary mass and momentum of probe



Bulk

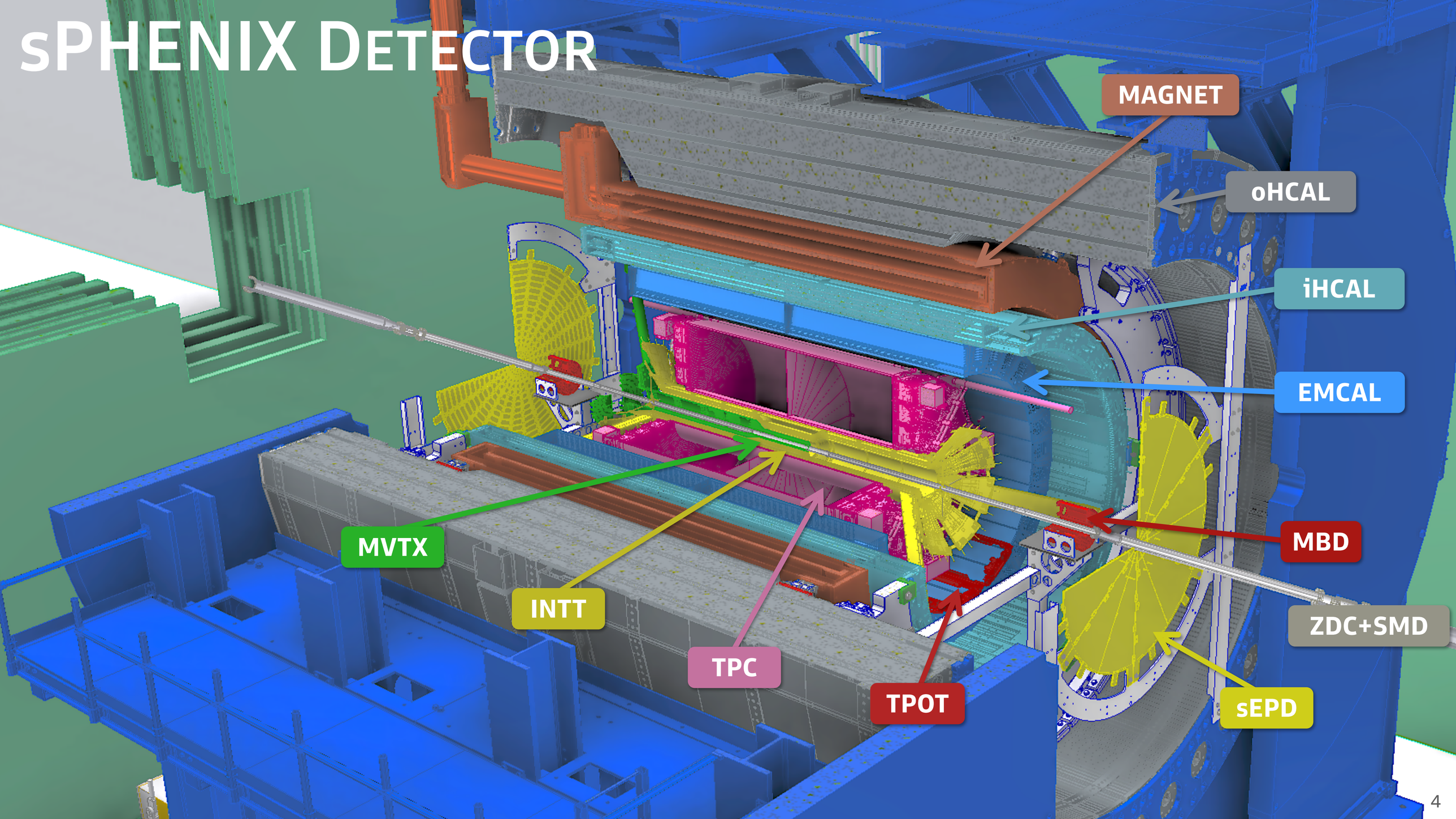
Global and collective properties of medium



Credit: MUSIC arXiv:1209.6330

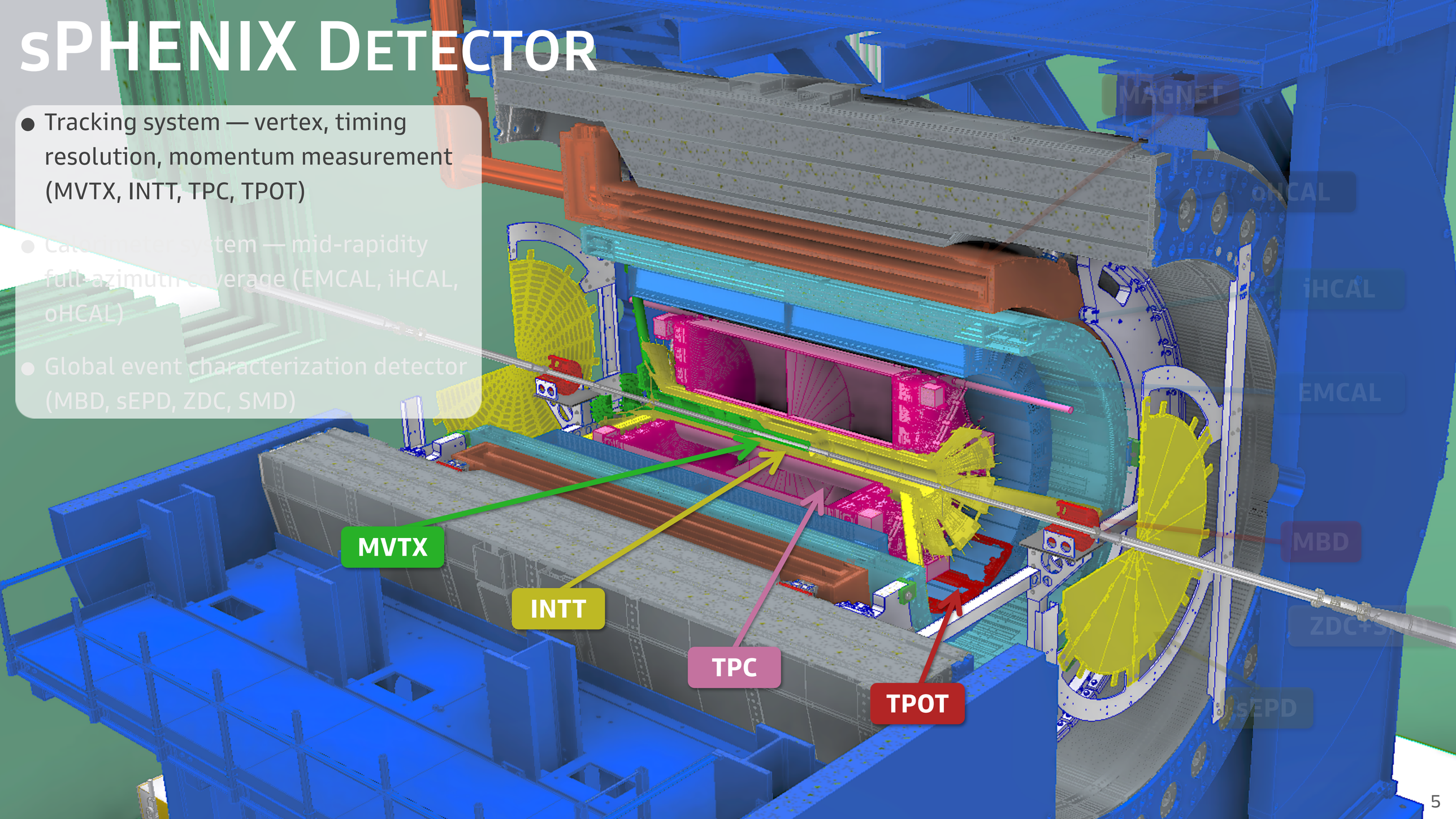
Credit: Misaki Ouchida (Hokkaido University)

sPHENIX Detector



sPHENIX Detector

- Tracking system — vertex, timing resolution, momentum measurement (MVTX, INTT, TPC, TPOT)
- Calorimeter system — mid-rapidity full-azimuthal coverage (EMCAL, iHCAL, oHCAL)
- Global event characterization detector (MBD, sEPD, ZDC, SMD)



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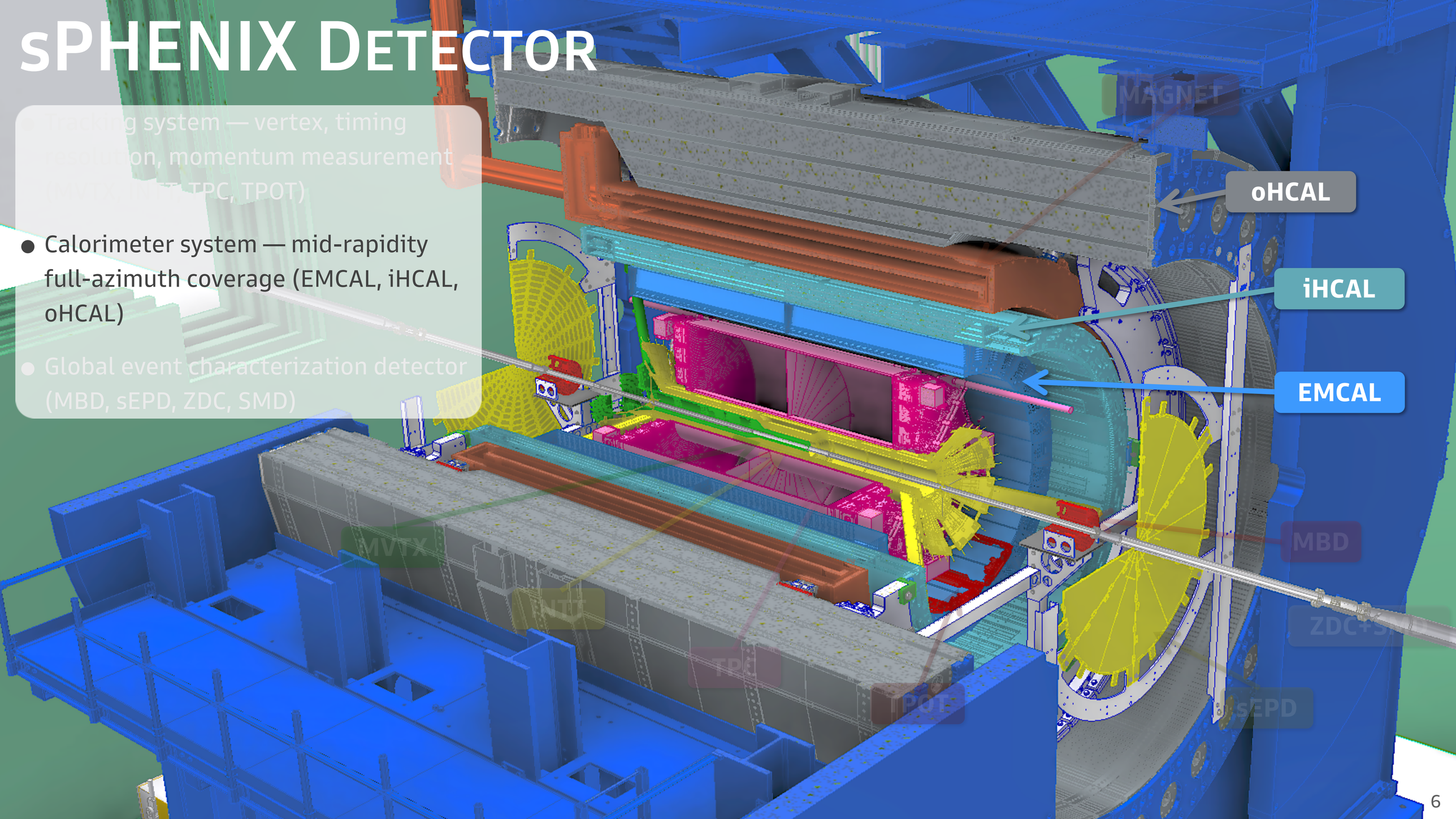

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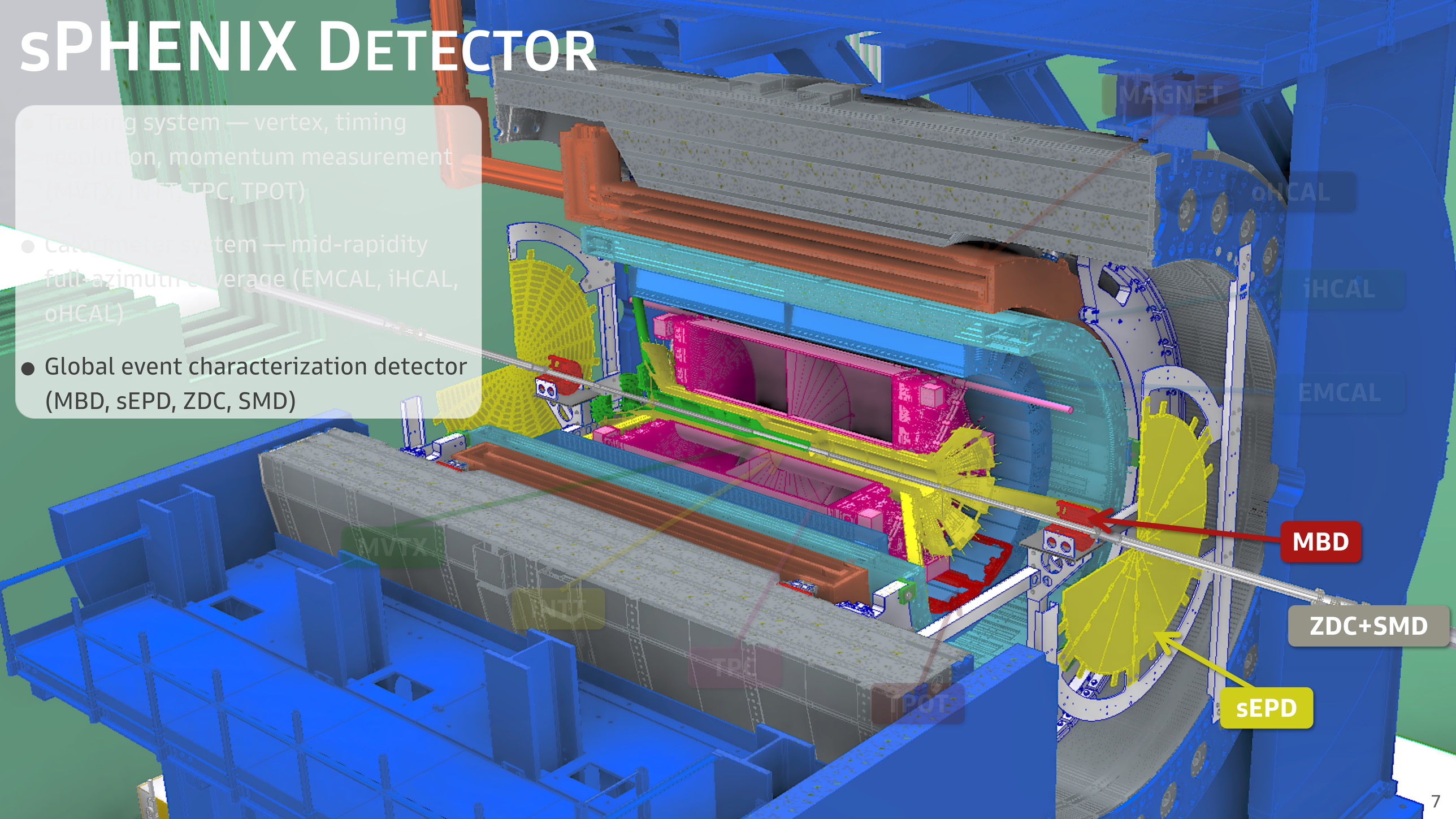
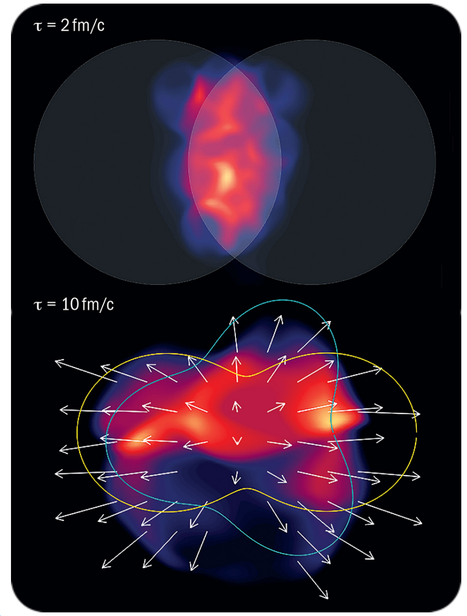


Focus Of This Talk

- New results on the bulk properties from data collected during Run-2023 and -2024
  - ☐ **2 poster presentations in this conference**
    - Long-range two-particle correlation in high-multiplicity p+p collisions: Indico page of the poster
    - Event plane determination with forward detectors: Indico page of the poster
  - ☐ **1 preliminary result**
    - Neutral pion v_2 in Au+Au Collisions: sPH-CONF-BULK-2024-01
  - ☐ **2 physics papers**
    - Measurement of transverse energy per unit pseudorapidity, $dE_T/d\eta$ in Au+Au collisions: [Link to sPHENIX publication, arXiv] [Indico page of the poster]
    - Measurement of charged hadron multiplicity $dN_{ch}/d\eta$ in Au+Au collisions: [Link to sPHENIX publication, arXiv]

Bulk

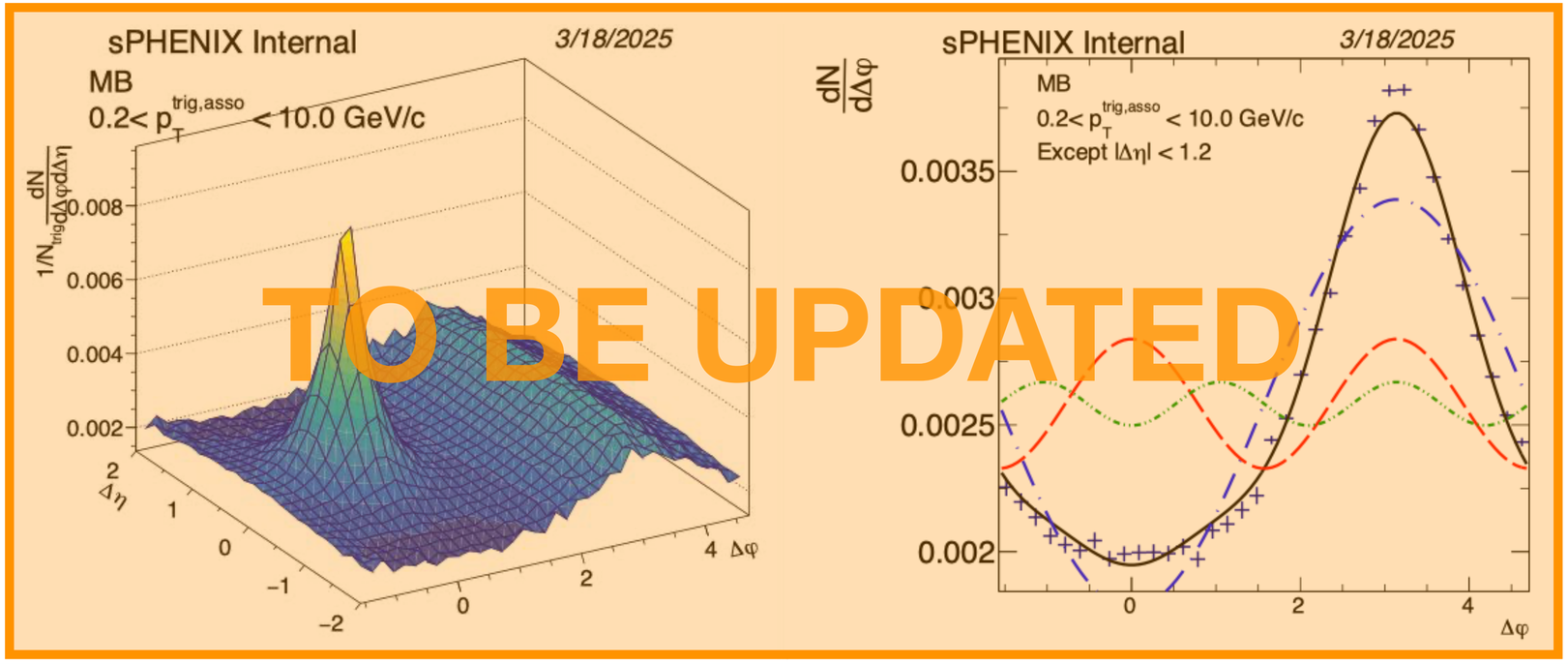
Global and collective properties of medium



Credit: MUSIC arXiv:1209.6330

Two-Particle Correlation In pp Collisions

- Measure long-range two-particle correlations in high-multiplicity pp collisions
  - Using silicon-tracks — validation of the sPHENIX tracking and the performances of two silicon detectors, MVTX and INTT, which provide precise vertexing and timing
- Complementary measurements of the two-particle correlation in pp collisions to PHENIX publications

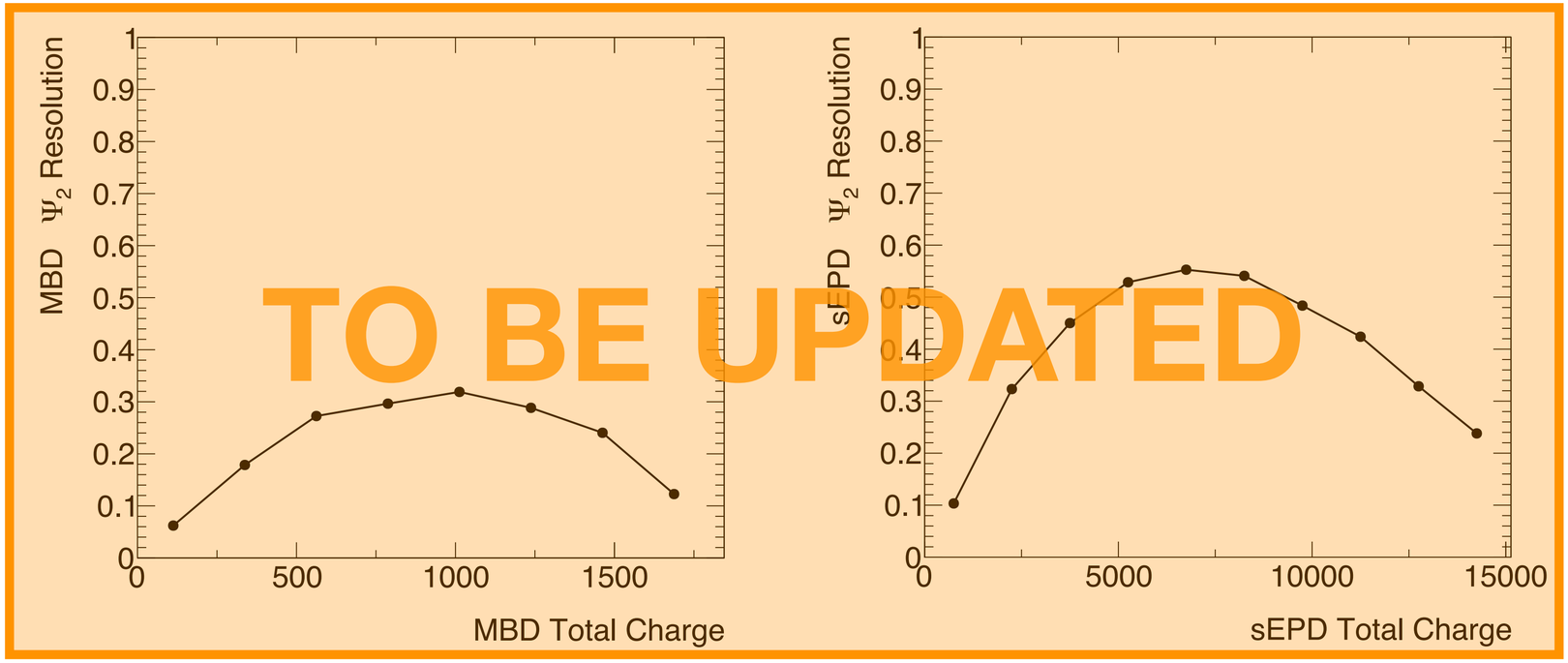


Poster by Yuko Sekiguchi

[Poster # 741]

Event Plane Measurement

- Event plane determination using sPHENIX forward detector, MBD and sEPD
  - Essential inputs to future jet and open heavy-flavor flow measurements
- Plan to combine the tracking system to measure the charged hadron v_2 in Au+Au collisions in Run-2025!

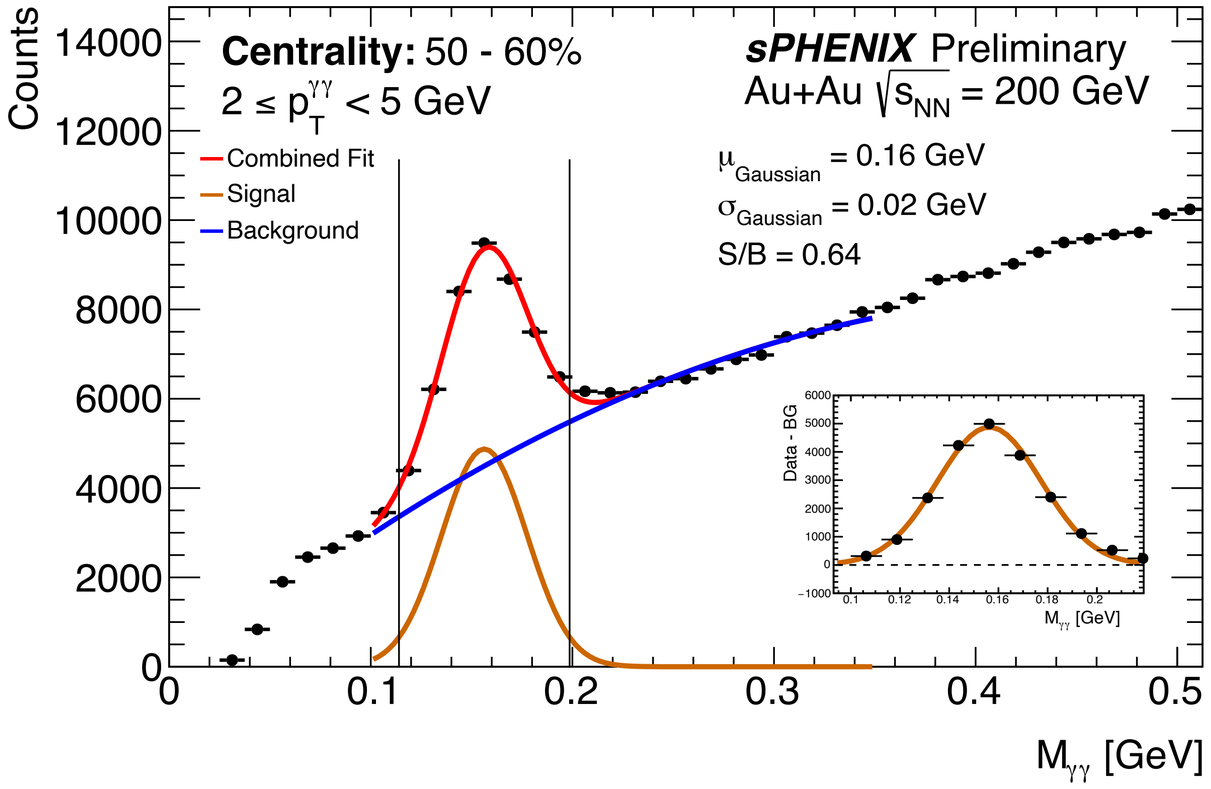


Poster by Ejiro Umaka

[Poster # 824]

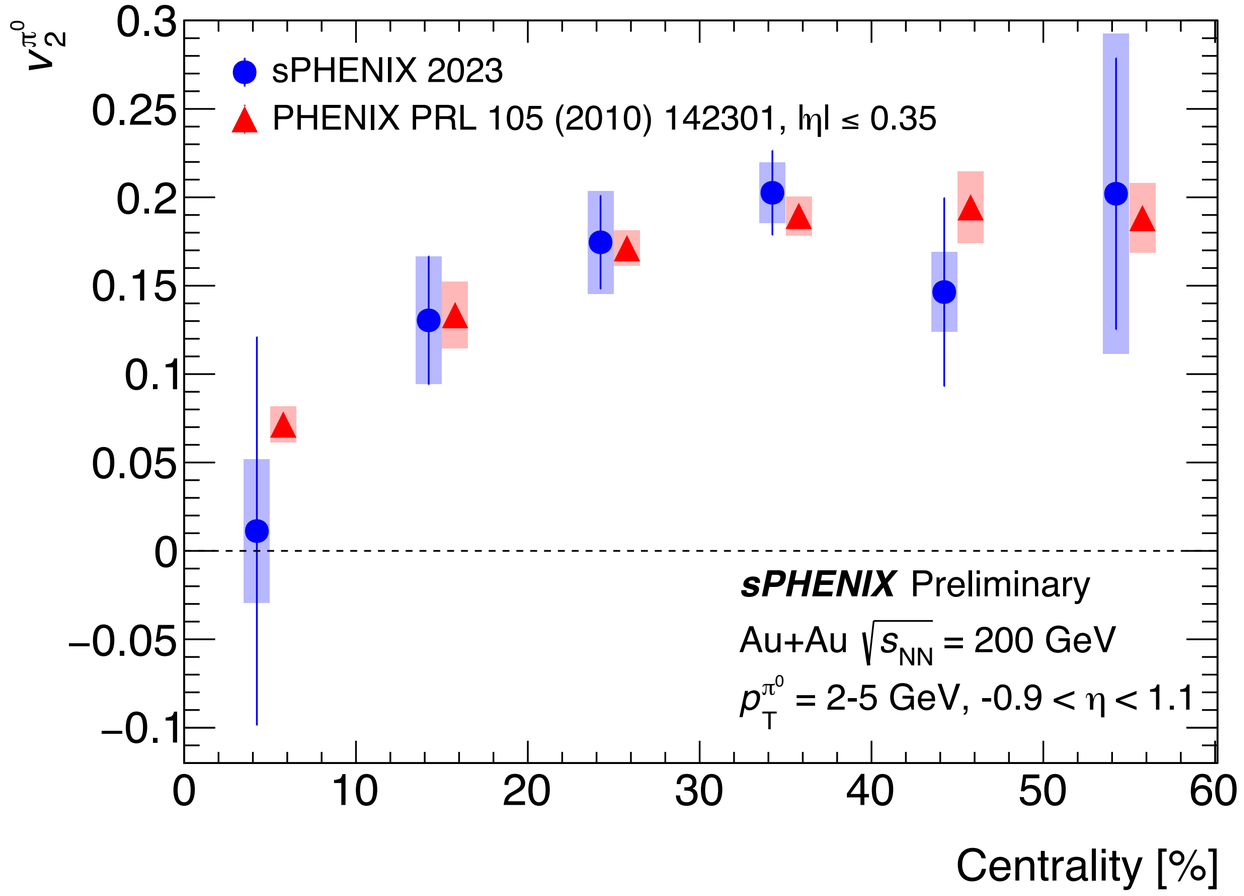
Measurement Of π_0 v_2 In Au+Au Collisions

- Azimuthal anisotropy of π_0 as one of the calorimeter-based standard candle measurements
- EMCAL energy calibration: the energy scale is extracted from the $\pi_0 \to \gamma\gamma$ candidate invariant mass, then set to match simulation after the detector effect smearing
- The reference flow vector is determined by signals in MBD and is propagated to the v_2 calculation



Measurement Of π_0 v_2 In Au+Au Collisions

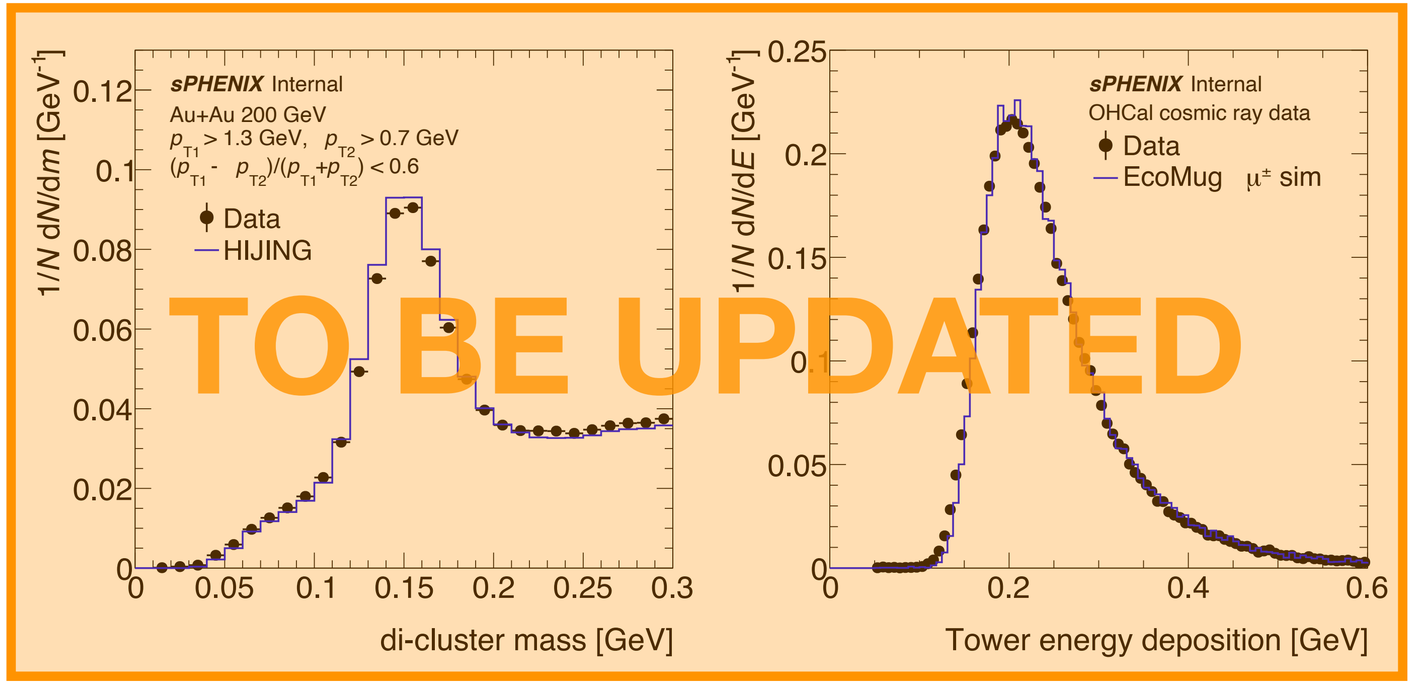
- The π_0 v_2 is measured as a function of centrality
  - v_2 increases with centrality and levels off at around the 30–40% centrality class
- Extraction of π_0 v_2 from Run-2023 commissioning dataset
  - Consistent with the PHENIX measurement, made with much higher statistics, and validates sPHENIX event plane and π_0 reconstruction



Measurement Of $dE_T/d\eta$ In Au+Au Collisions

- The transverse energy per unit pseudorapidity, $dE_T/d\eta$, measured by the full calorimeter system EMCAL + HCAL
  - First $dE_T/d\eta$ measurement with mid-rapidity full azimuthal coverage HCAL at RHIC!

- Energy calibration
  - EMCAL: $\pi_0 \rightarrow \gamma\gamma$ mass peak to match between data and simulation
  - HCAL: compared measured MIP peak from cosmic ray muons in data to simulation



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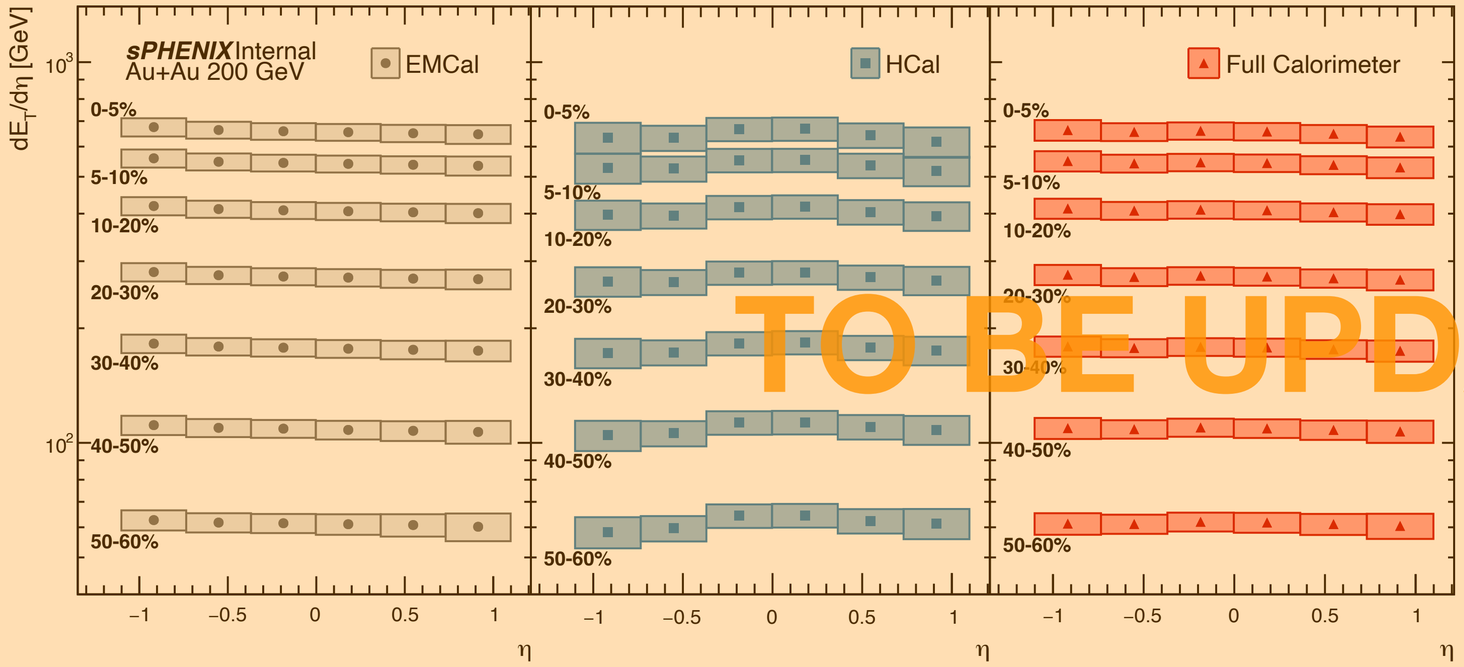
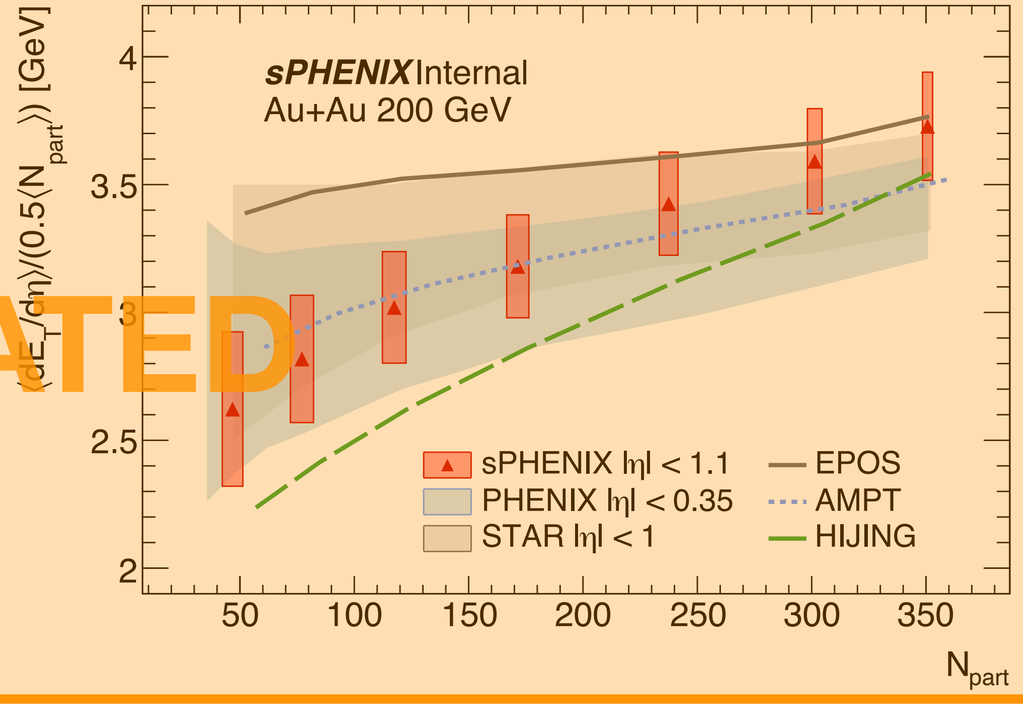




- Excellent consistency between EMCAL and HCAL measurements — sensitive to energy deposit from different particle species and completely independent calibrations
- sPHENIX results are compatible with PHENIX and STAR measurements

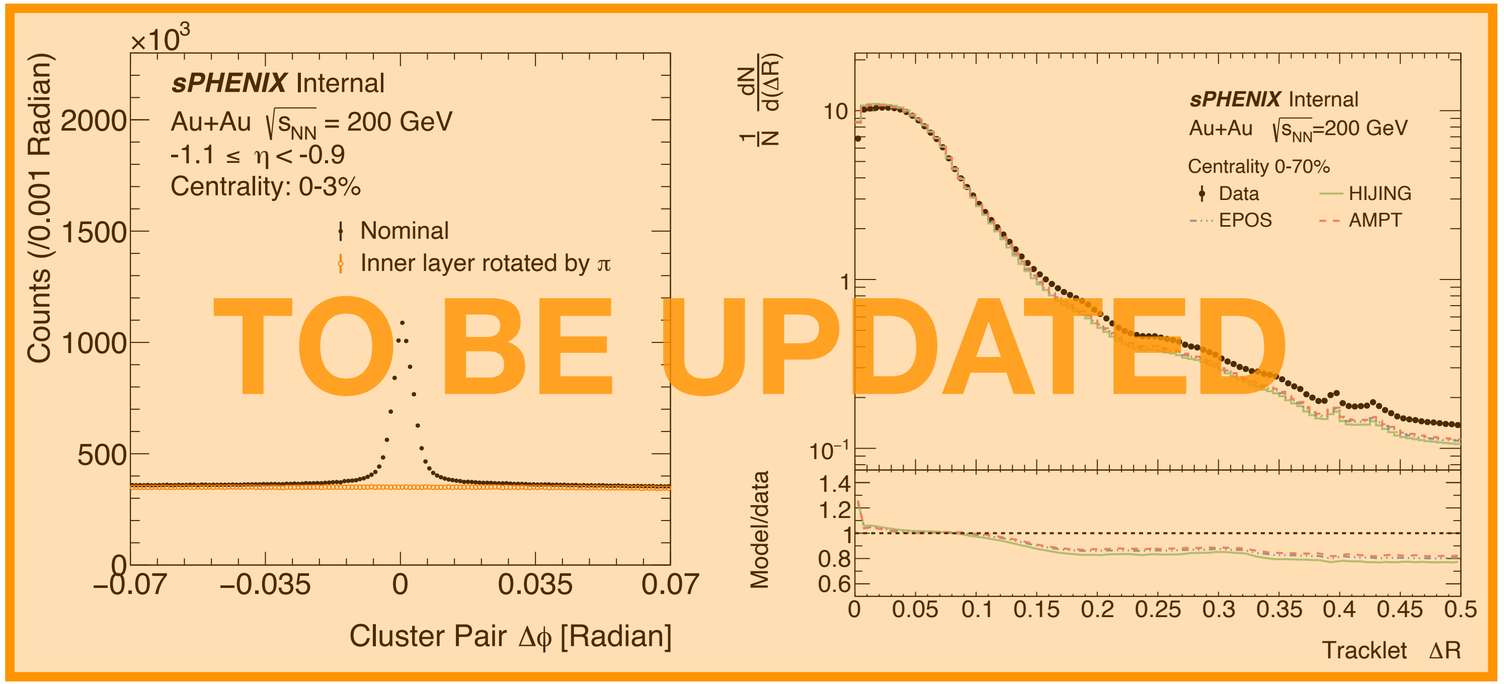
Poster by Emma McLaughlin

[Poster # 1062]

Measurement Of $dN_{ch}/d\eta$ In Au+Au Collisions

- Tracking-based standard candle measurement - Charged hadron multiplicity per unit pseudorapidity, $dN_{ch}/d\eta$, by the Intermediate Silicon Tracker, INTT
  - Counting tracklets, cluster pairs that point back to the event vertex

- Two analysis methods:
  - The combinatoric method: closely follows the PHENIX and PHOBOS publications
  - The closest-match method: adapted from the CMS measurements



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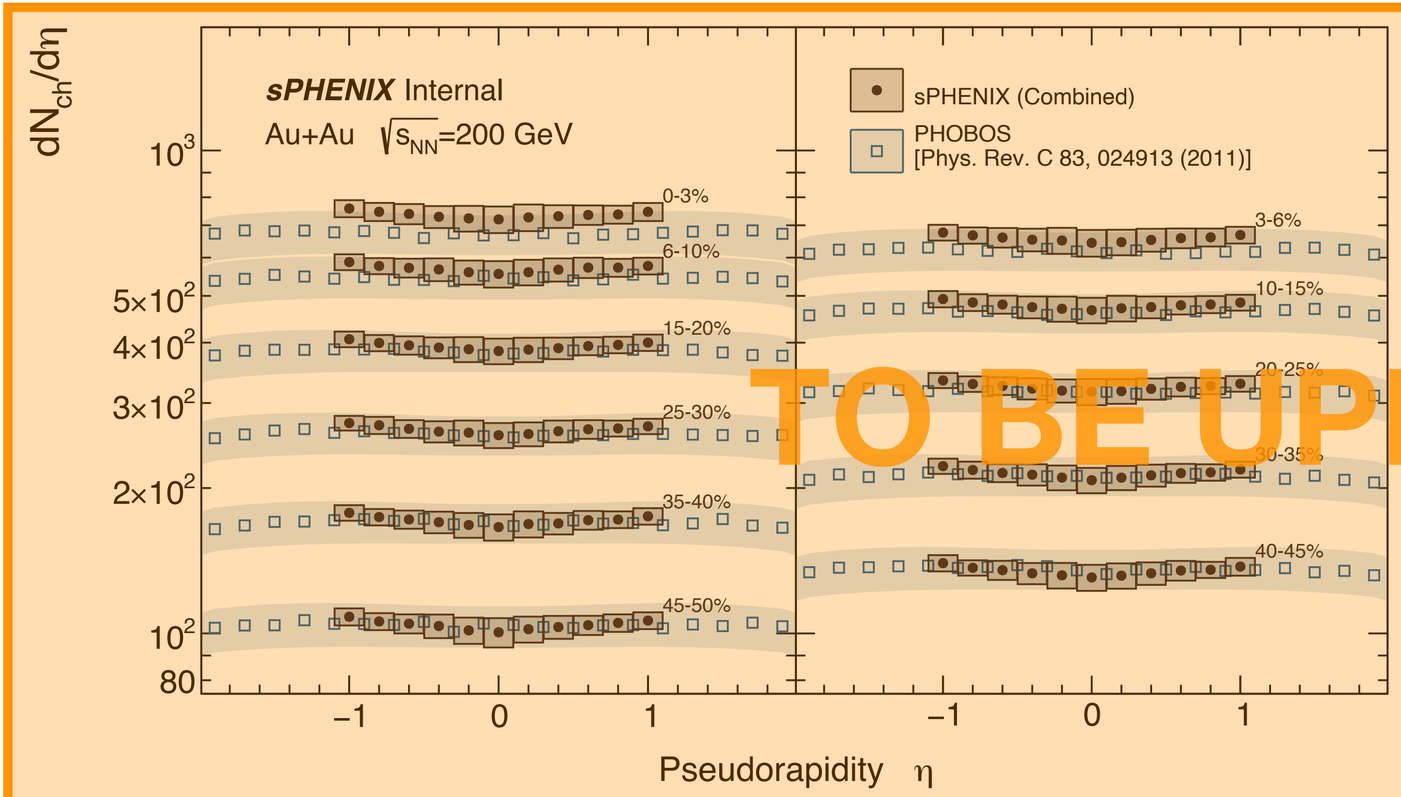
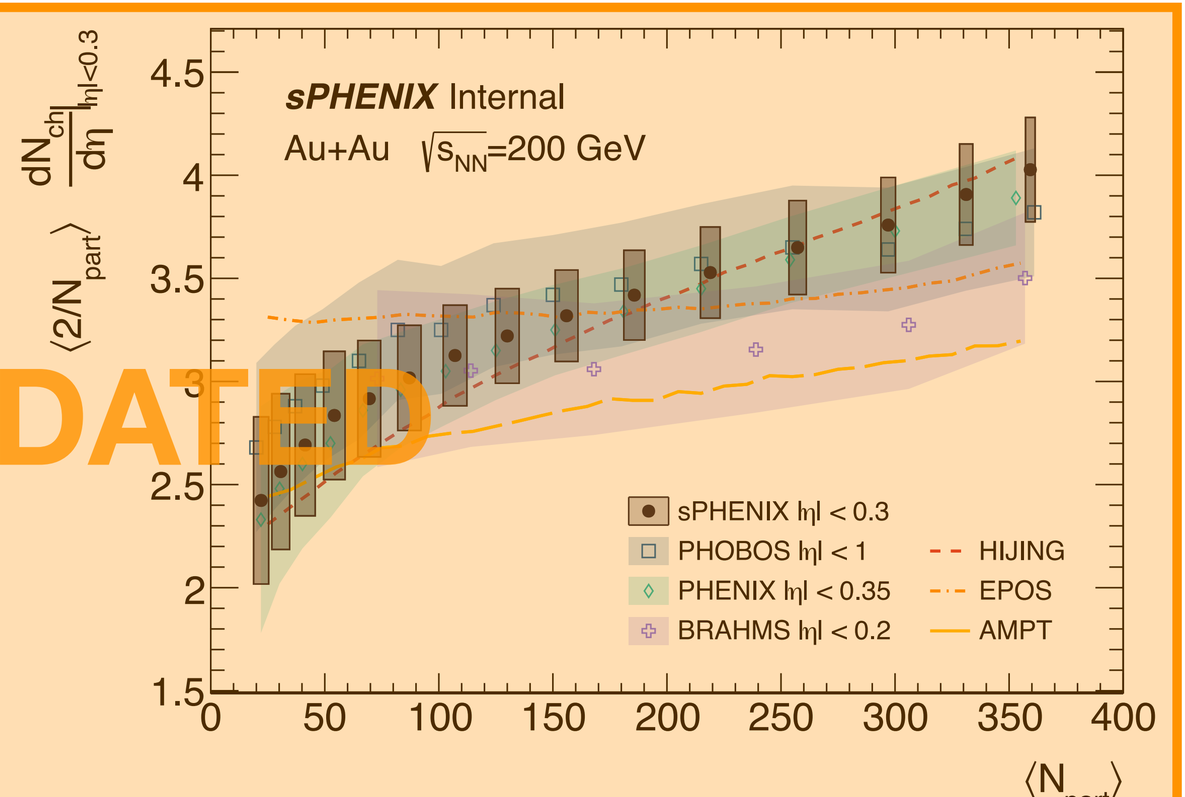


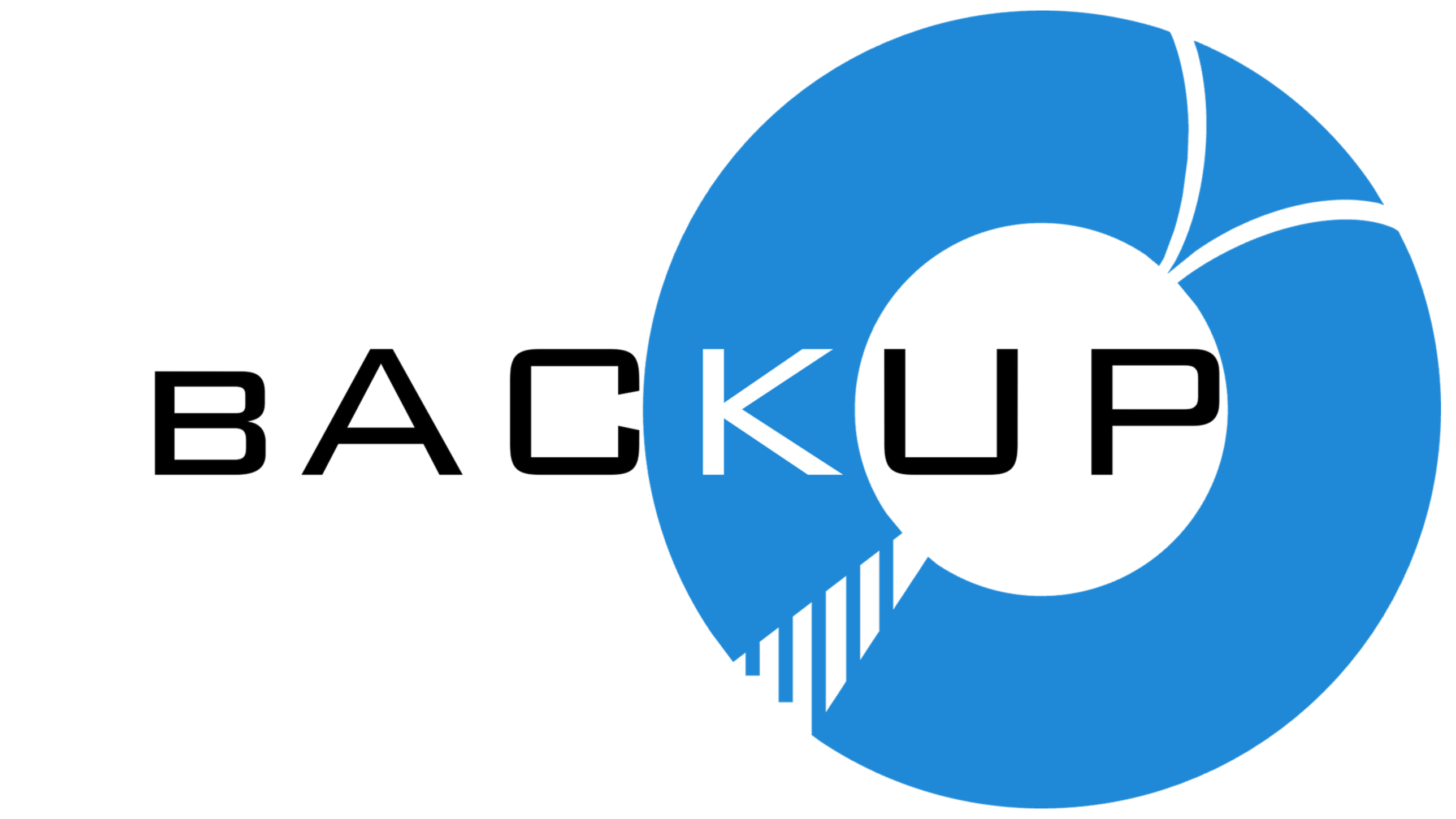


TO BE UPDATED

- Full azimuthal coverage at mid-rapidity, advantageous over PHENIX and PHOBOS
- sPHENIX measurement are consistent with previous RHIC publications from PHOBOS, PHENIX, and BRAHMS

Summary

- Bulk properties by all 3 groups of sPHENIX detector systems
  - Tracking system: two-particle correlation, the charged-hadron multiplicity $dN_{ch}/d\eta$
  - Calorimeter system: the azimuthal anisotropy of π_0, the transverse energy $dE_T/d\eta$
  - Global event characterization system: event plane determination
- Results from measurements of the azimuthal anisotropy of π_0, the transverse energy $dE_T/d\eta$, and the charged-hadron multiplicity $dN_{ch}/d\eta$ are consistent with previous RHIC measurements
  - Provide strong foundation of the broad physics program of sPHENIX!


BACKUP

sPHENIX Detector

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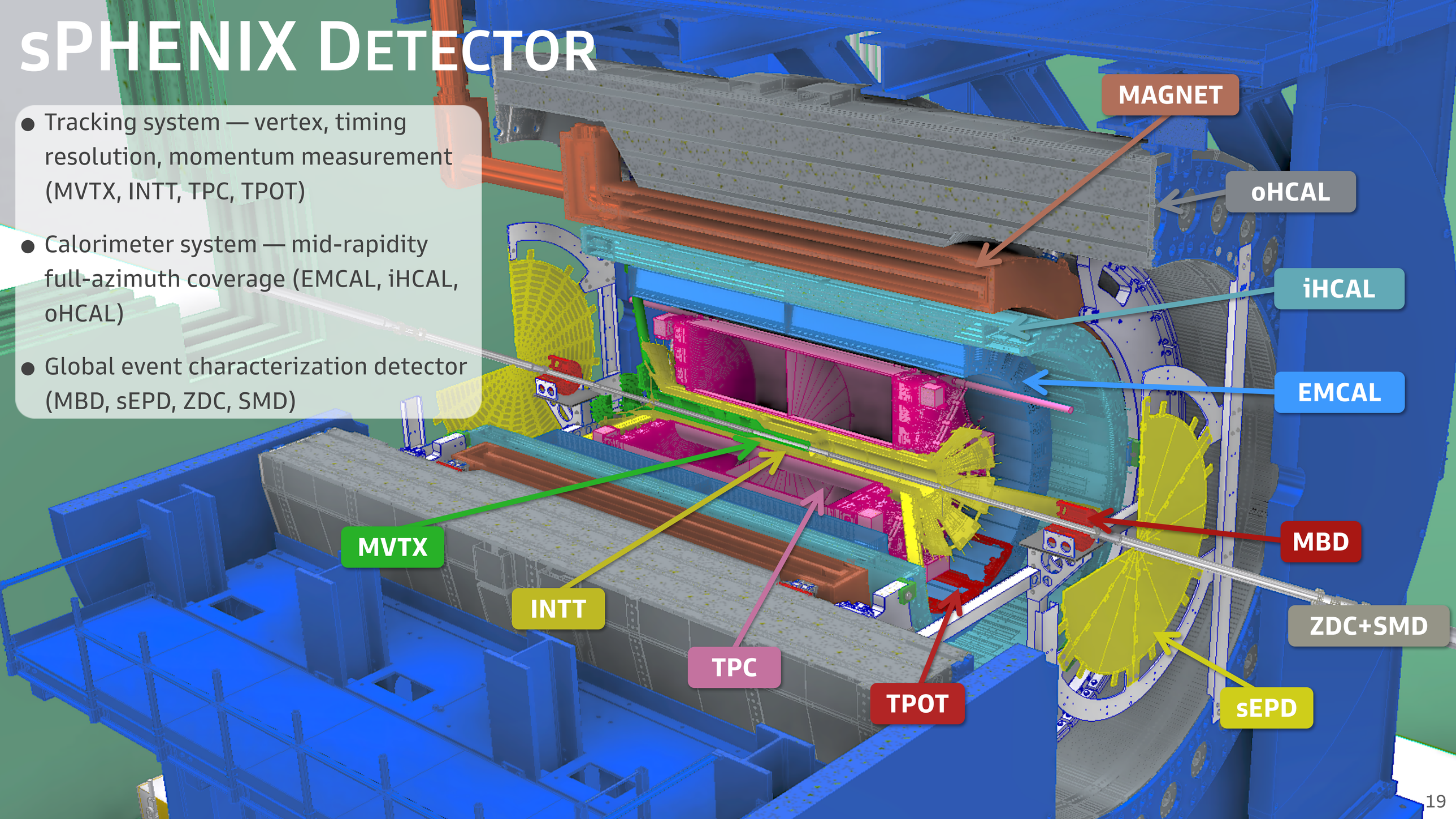
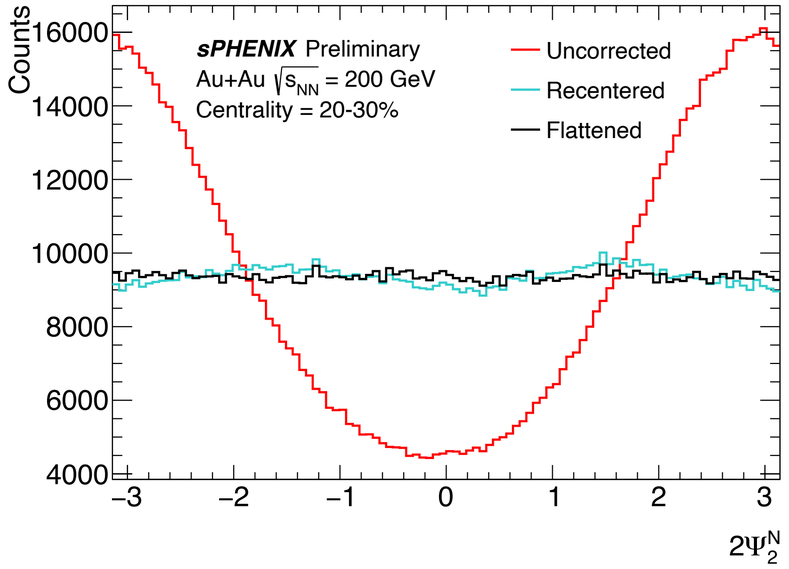
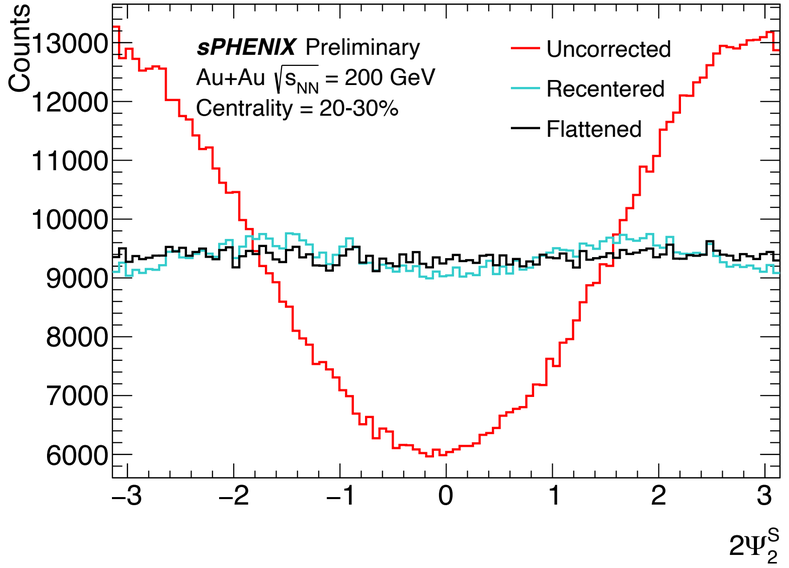
- Calorimeter system — mid-rapidity full-azimuth coverage (EMCAL, iHCAL, oHCAL)
- Global event characterization detector (MBD, sEPD, ZDC, SMD)



Measurement Of π_0 v_2 In Au+Au Collisions

- Scalar product method $v_2\{SP\} = Re\dfrac{\langle q_{2,j}Q_2^{N|S*}\rangle}{\sqrt{Q_2^S Q_2^{N*}}}$
  - $q_{2,j} = e^{i2\phi_j}$: the 2nd-order q-vector of a π_0 candidate in an event with azimuthal angle ϕ_j
  - $Q_2 = \dfrac{1}{\sum_k w_k}\sum_k w_k e^{i2\phi_k}$: the reference flow vector measured by the north and south arms of MBD, weighted by PMT charge
- Q_2 is then corrected for non-uniform acceptance using recentering and then flattening the associated event plane
  - The event plane angle Ψ_2 as a diagnostic and quality assurance





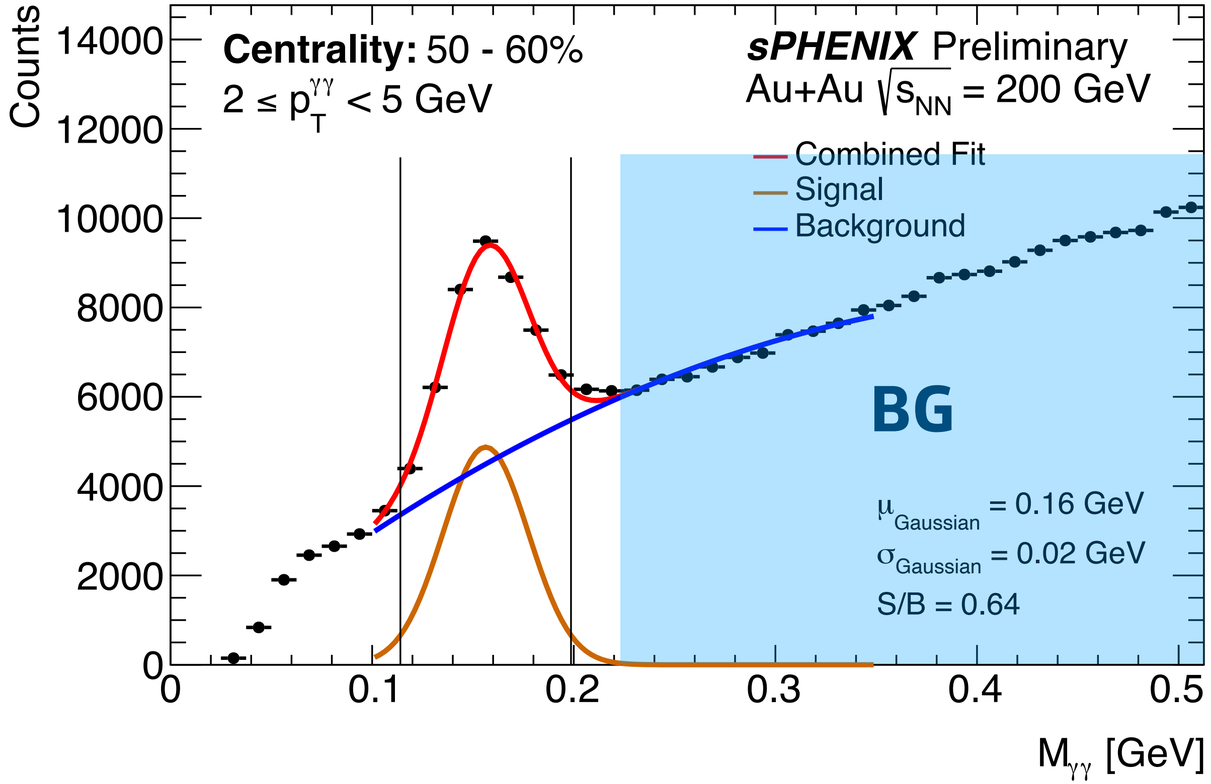
Measurement Of π_0 v_2 In Au+Au Collisions

Background subtraction:

$$v_2^{\pi^0} = v_2^M + \frac{v_2^M - v_2^{BG}}{S/B}$$

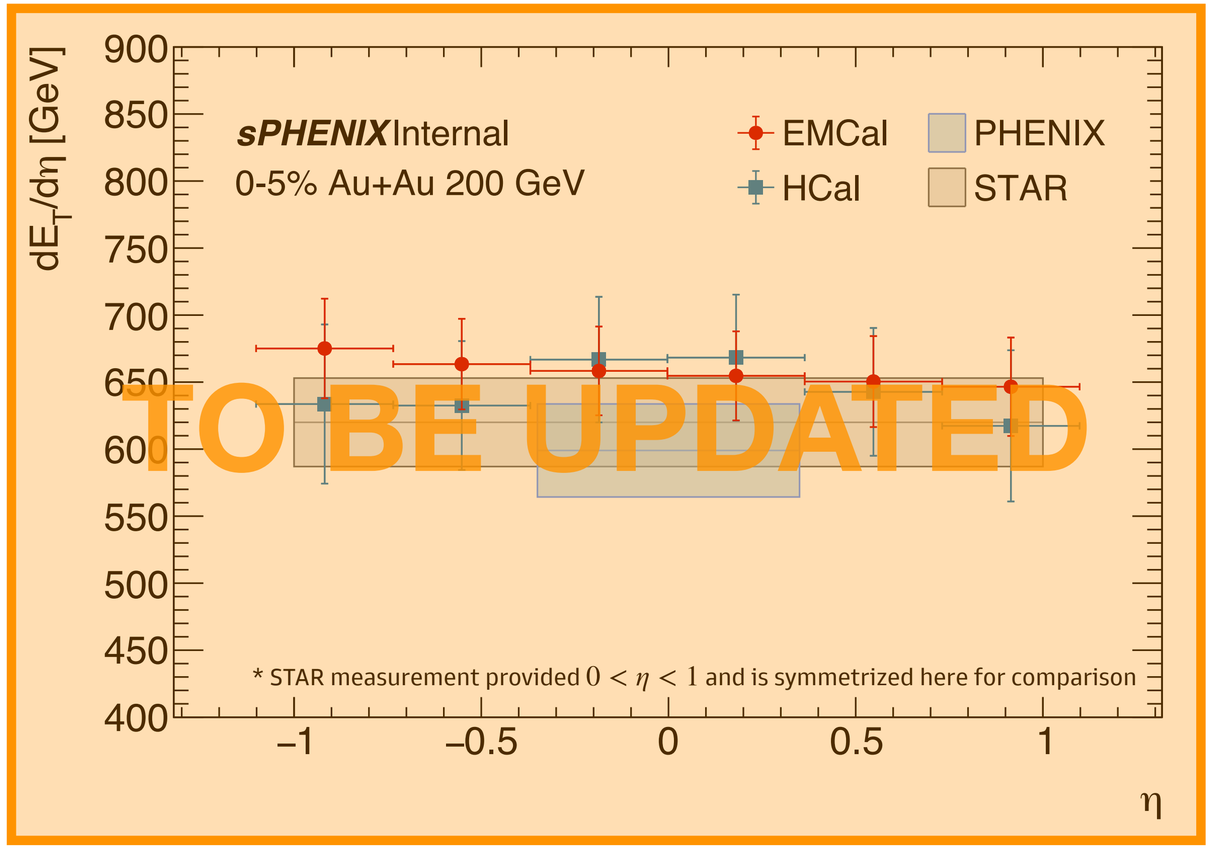
v_2^M: signal, $\mu - 2\sigma < M_{\gamma\gamma} < \mu + 2\sigma$

v_2^{BG}: signal, $\mu + 3\sigma < M_{\gamma\gamma} < 0.5$ GeV



Measurement Of $dE_T/d\eta$ In Au+Au Collisions

- The EMCAL-only and HCAL-only measurements in the most central 0-5% are overlaid to highlight their agreement
  - Sensitive to deposited energy from different particle species and completely independent calibration procedures
- Compatible with PHENIX and STAR, where measurements were performed either only with the electromagnetic calorimetry or a combination of tracks and electromagnetic calorimetry



Measurement Of $dE_T/d\eta$ In Au+Au Collisions

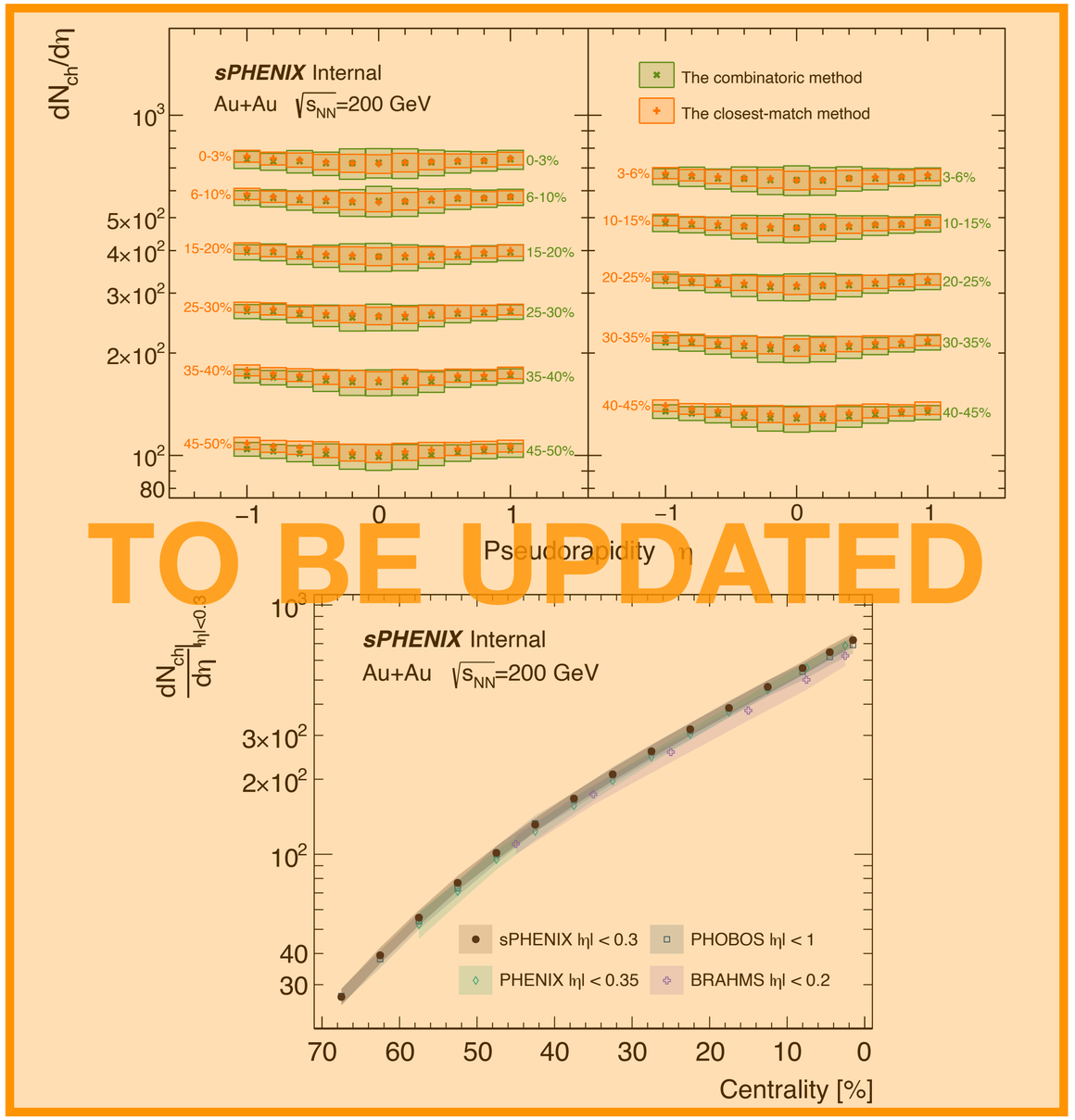
Uncertainty Source [%]	EMCal-Only	HCal-Only	Full Calorimeter
Calibration	2.6	2.7	2.1
Hadronic response	4.1	6.6	4.7
Modeling	1.4–1.8	2.5–3.0	1.6–1.9
Zero suppression thres.	1.0–3.6	0.2–0.3	0.8–2.7
z-vertex resolution	0.3–0.4	0.1–0.2	0.2–0.3
Acceptance	0.2–0.4	0.2–0.4	0.1–0.3
Total	5.3–6.5	7.7–7.9	5.6–6.3

TO BE UPDATED

- Dominant systematic uncertainty is the hadronic response — evaluated by comparing the agreement of the single hadron response between data and simulation in beam tests of prototypes of the sPHENIX calorimeter system
- Second largest uncertainty is the physics modeling — correction factors derived with HIJING and AMPT, and the η-dependent particle spectra measured by BRAHMS

Measurement Of $dN_{ch}/d\eta$ In Au+Au Collisions

- Results from two analysis methods are consistent with each other,
  - Statistically combined, closely following procedures in PDG and the CMS publication, specifically to account for the dominant correlated uncertainty
- $dN_{ch}/d\eta$ at mid-rapidity, $|\eta| < 0.3$, for the sPHENIX measurement is consistent with all previous RHIC results from PHOBOS, PHENIX, and BRAHMS across all centrality intervals



Measurement Of $dN_{ch}/d\eta$ In Au+Au Collisions

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%	

TO BE UPDATED

- Dominant systematic uncertainty is the INTT cluster ADC selection — difference between the two methods because their differing sensitivities to combinatorial backgrounds
- Combination strategy separates the correlated and uncorrelated uncertainties. The weighted averaged of $dN_{ch}/d\eta$ based on the uncorrelated uncertainties