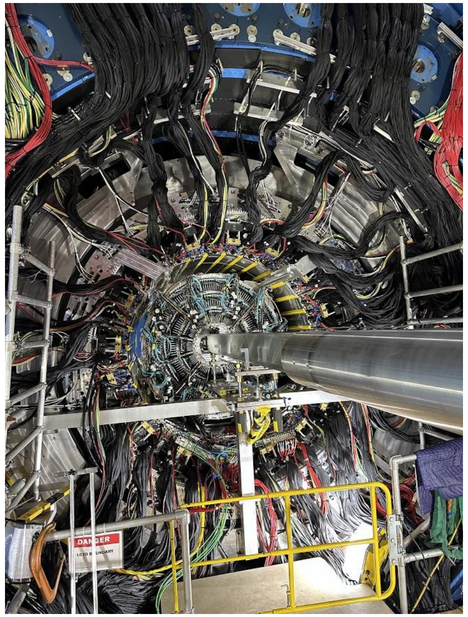
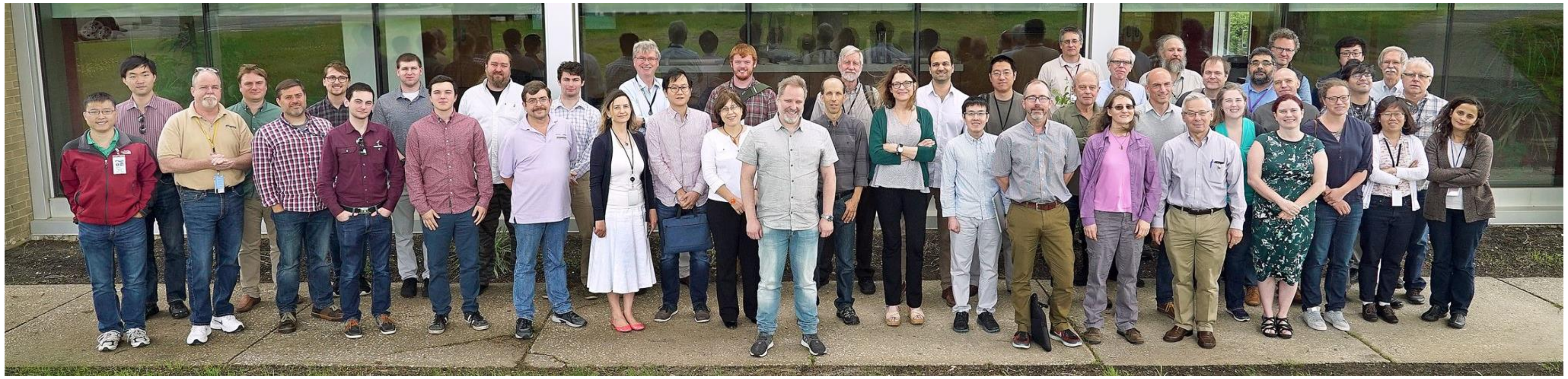
sPHENIX Highlights



TK Hemmick for sPHENIX Collaboration

RHIC/AGS User's Meeting -- June 13th, 2024

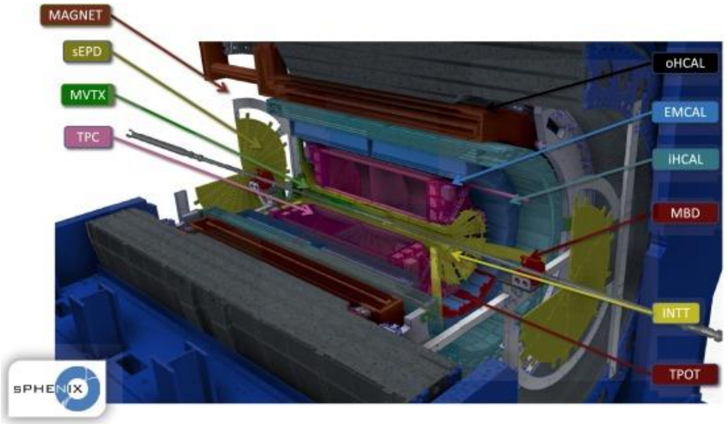


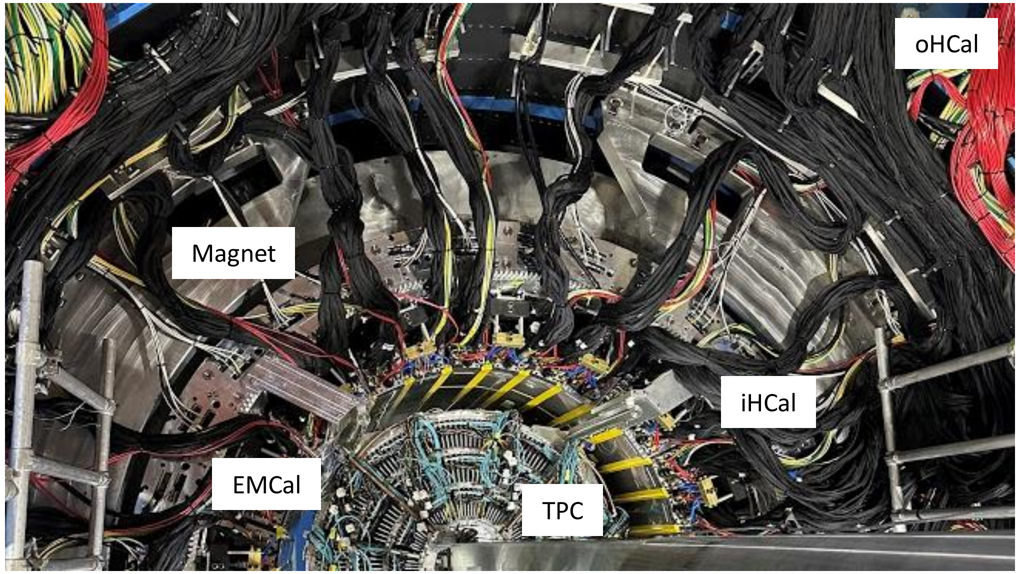
Stony Brook University

~195 Scientists from 47 Institutions

sPHENIX

Outline





- The sPHENIX detector completed installation and mostly completed commissioning during the 2023 Au+Au at $\sqrt{s}$ = 200 GeV.

- A limited dataset from this run has yielded two preliminary results:
  - v_2 of neutral pions as a function of centrality.
  - $\frac{dE_T}{d\eta}$ measured calorimetrically using EM and Hadronic calorimetry

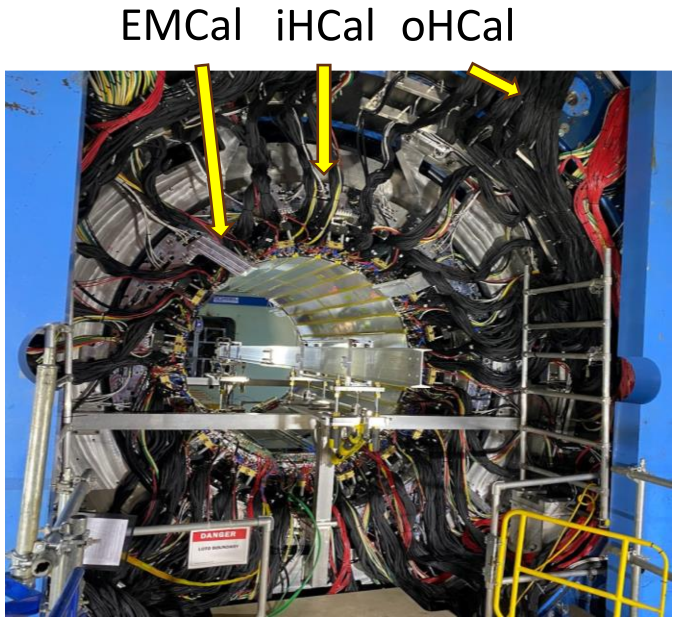
- These results highlight the bright future of the sPHENIX program.

NOTE: Explanations are targeted at the level of students and questions are ENCOURAGED!

sPHENIX Subsystems for Analysis

Three concentric calorimeter layers, electromagnetic calorimeter (EMCal), inner hadronic calorimeter (iHCal) and outer hadronic calorimeter (oHCal) with full azimuth ($0 < \phi < 2\pi$) and large ($|\eta| < 1.1$) coverage.

Provides a total depth of 4.9 hadronic interaction lengths.



sPHENIX technical design report:
https://indico.bnl.gov/event/7081/attachments/25527/38284/sphenix_tdr_20190513.pdf

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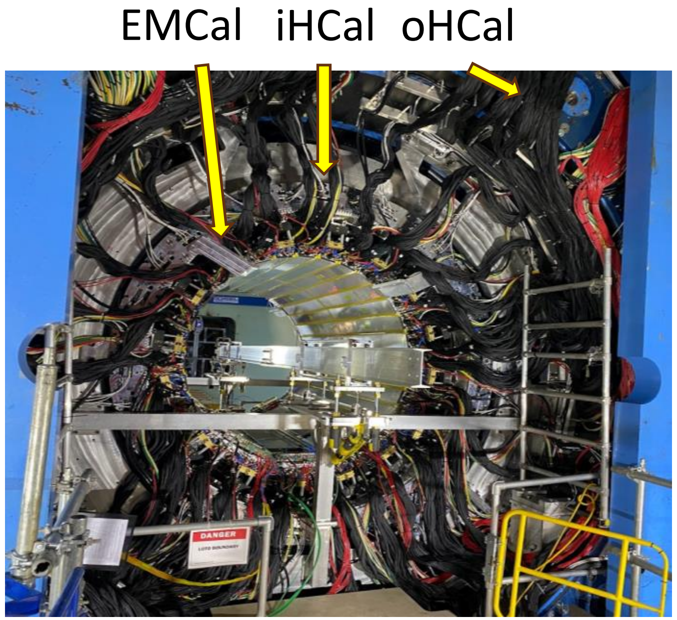

EMCal:

- Calibrated with π^0 mass peak in η rings
- Tungsten powder absorber & scintillating fibers
- Tower size $\Delta\eta \times \Delta\varphi = 0.024 \times 0.024$

HCal:

- Calibrated with cosmic muons
- Al (inner)/steel (outer) absorber plates & scintillating tiles
- Tower size $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

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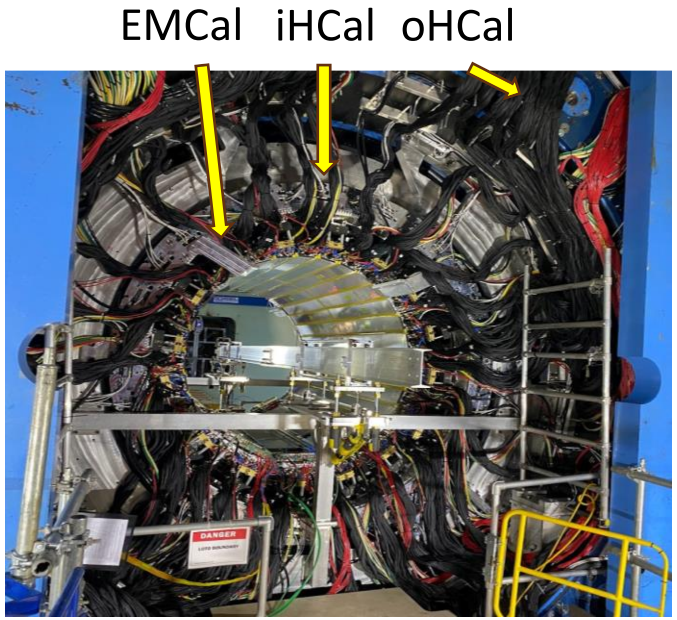
Provides a total depth of 4.9 hadronic interaction lengths.

Minbias Detector (MBD):

- Covers 3.51 < $|\eta|$ < 4.61 on both sides of the interaction point, labeled “North” and “South” sides
- Quartz Bars readout via Photomultiplier Tubes
- Provides MB triggering, z vertex determination and centrality determination



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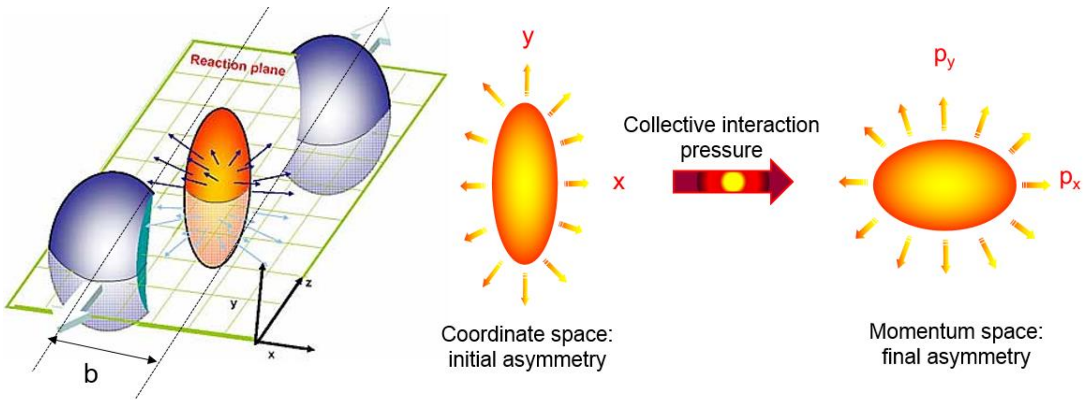
Anisotropic Azimuthal Flow

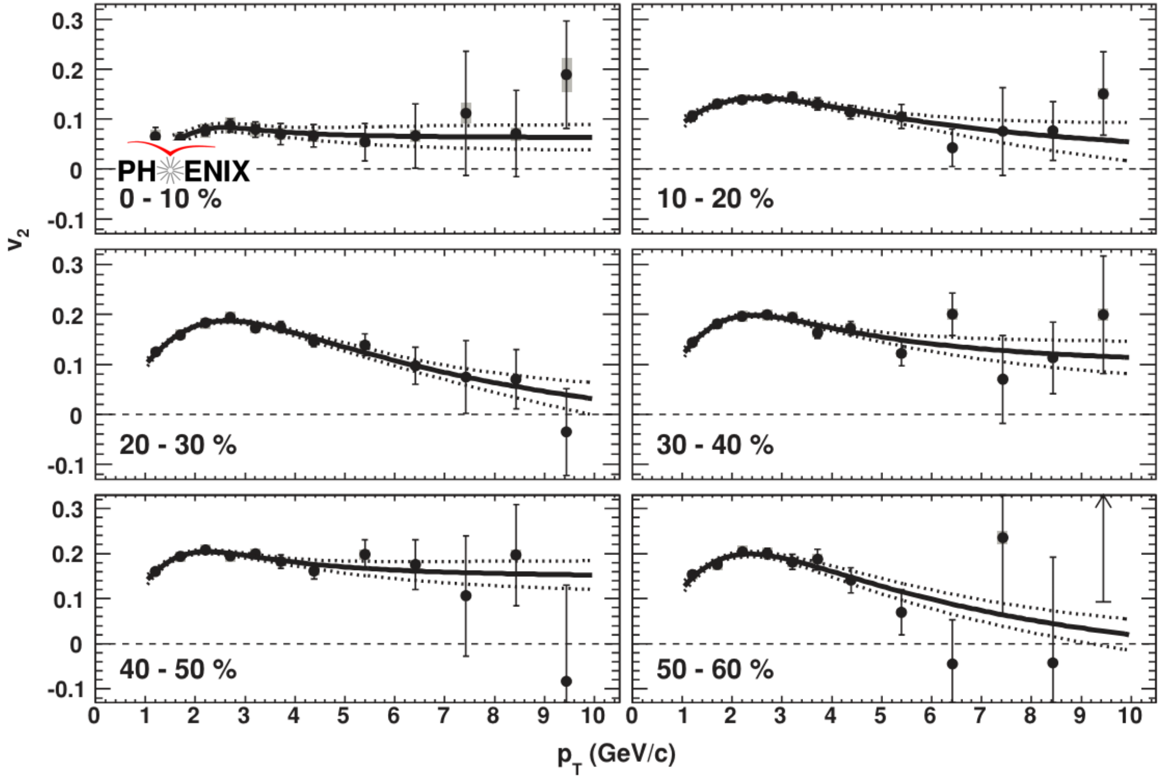
- The direction of the reaction plane offset breaks the initial state azimuthal symmetry.
- Particle yields in the azimuthal direction can be expressed as a Fourier Series ($\varphi \equiv \phi - \psi_{RP}$):

$$\frac{d^3N}{dp_T dy d\varphi} = \frac{d^2N}{dp_T dy}\left(\sum_{n=0}^{\infty} v_n(p_T, y)\cos n\varphi\right)$$

- "Lumpiness" in initial state transforms into pressure gradients driving anisotropic flow.
- v_2 characterizes the elliptic flow contribution to anisotropic flow



Previous measurements of $\pi^0 v_2$:



arXiv:1006.3740

Data Selection

Commissioning data from Run 2023 with calorimeters and MBD in normal operating mode used in analyses of $\pi^0 v_2$ and $dE_T/d\eta$:

$\pi^0 v_2$ analysis

- 4.23M events
- Prioritized high statistics of EMCal clusters
- EMCal + MBD subsystems
- Centrality intervals 0-60% as determined by MBD

$dE_T/d\eta$ analysis

- 249k events
- Prioritized full acceptance of calorimeters
- EMCal + HCal + MBD subsystems
- Centrality intervals 0-60% as determined by MBD

$\pi^0\ v_2$ via Scalar Product Method

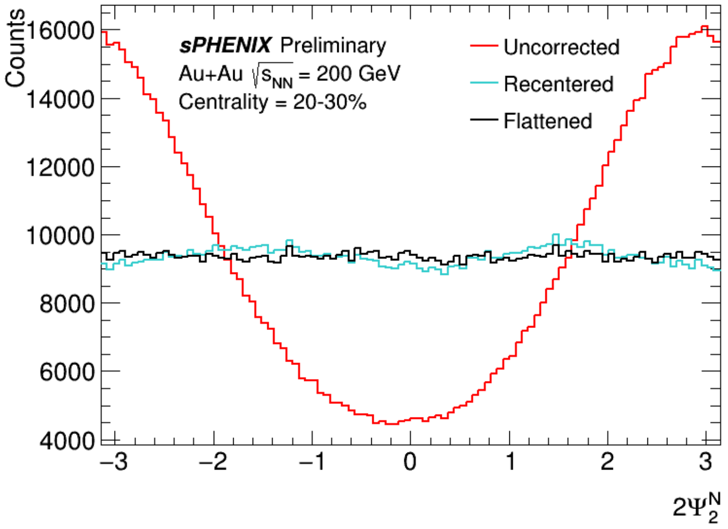
Scalar Product method:

$$v_2\{SP\} = Re\frac{\left\langle \vec{q}_{2,j}\vec{Q}_2^{S|N*} \right\rangle}{\sqrt{\vec{Q}_2^S \vec{Q}_2^{N*}}}$$

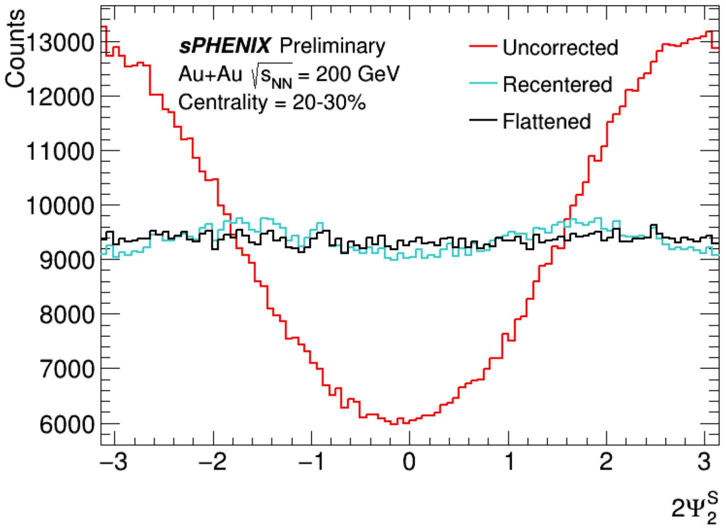
$q_{2,j} = e^{2i\phi_j}$: q-vector of a π^0 candidate found from EMCal diphoton clusters

$\vec{Q}_2 = \frac{1}{\sum_j w_j}\sum_j w_j \vec{q}_{2,j}$: reference flow vectors measured by the north and south sides of the MBD, weights from MBD PMTs' charge

North



South



Q_2 corrected for detector asymmetry with first recentering and then flattening to yield a flat distribution for Ψ_2 over many events

Scalar Product methodology: arXiv:nucl-ex/0206001
2^{nd} order correction methodology: doi:10.7916/d8-t50g-tn57

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π^0 invariant mass peaks

EMCal diphoton pair criteria:

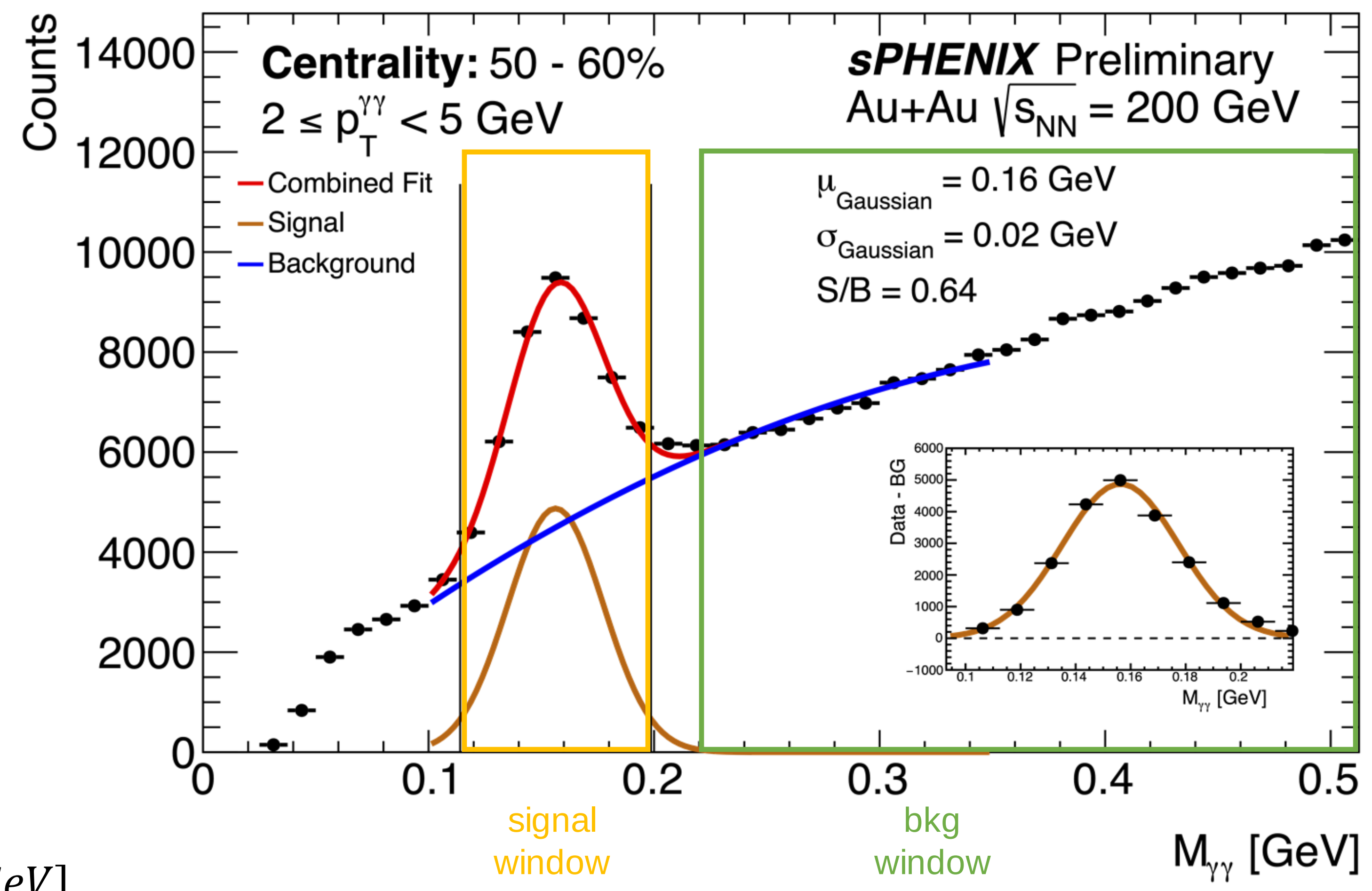
1. Cluster $E_{Core} > 1GeV$
2. Cluster $\chi^2 < 4$
3. $\alpha = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.5$

Low asymmetry discriminates against combinatorial pairs

π^0 v_2 background subtraction:

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

v_2^M from signal window $[\mu - 2\sigma, \mu + 2\sigma]$
v_2^{BG} from background window $[\mu + 3\sigma, 0.5\ GeV]$
S/B ratio calculated in signal window $[\mu - 2\sigma, \mu + 2\sigma]$



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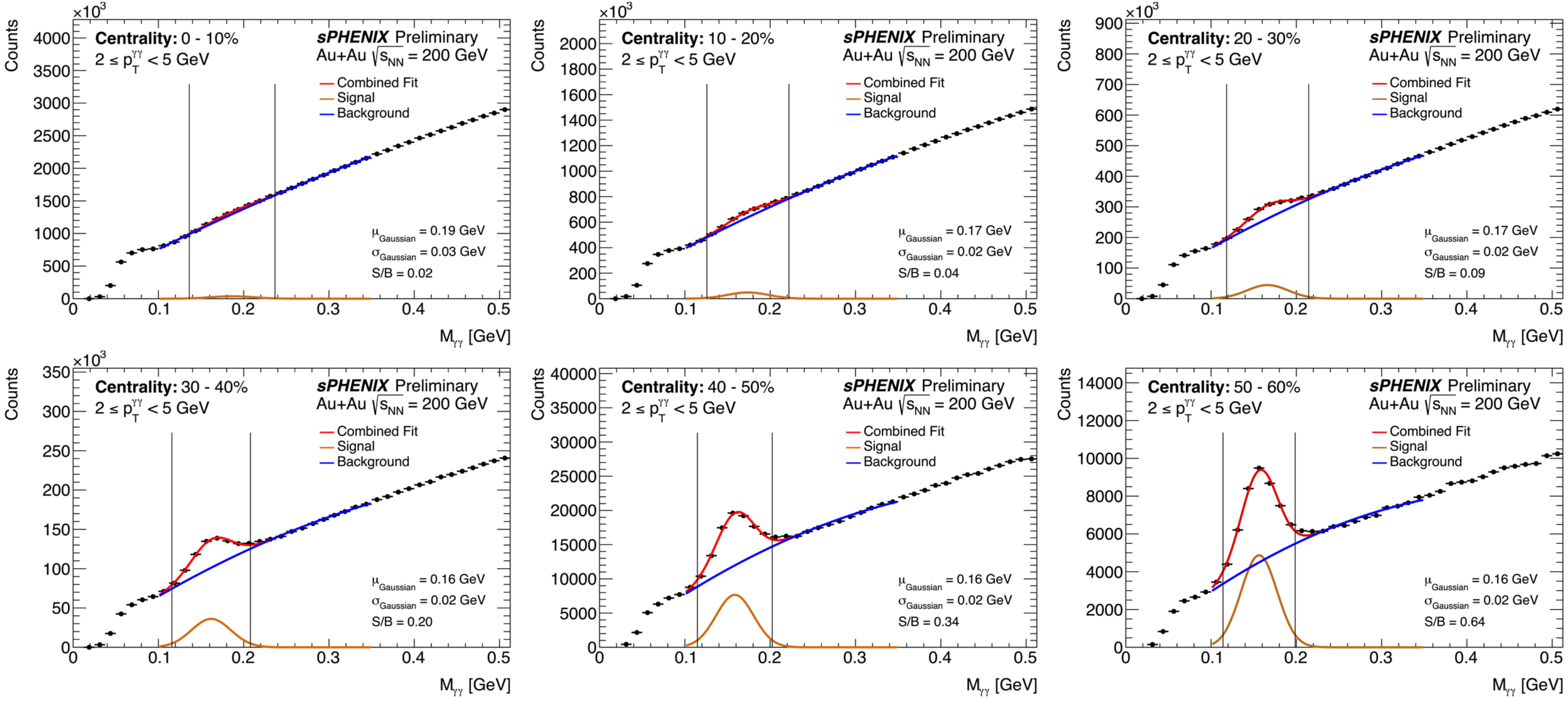
π^0 mass peaks vs. Centrality



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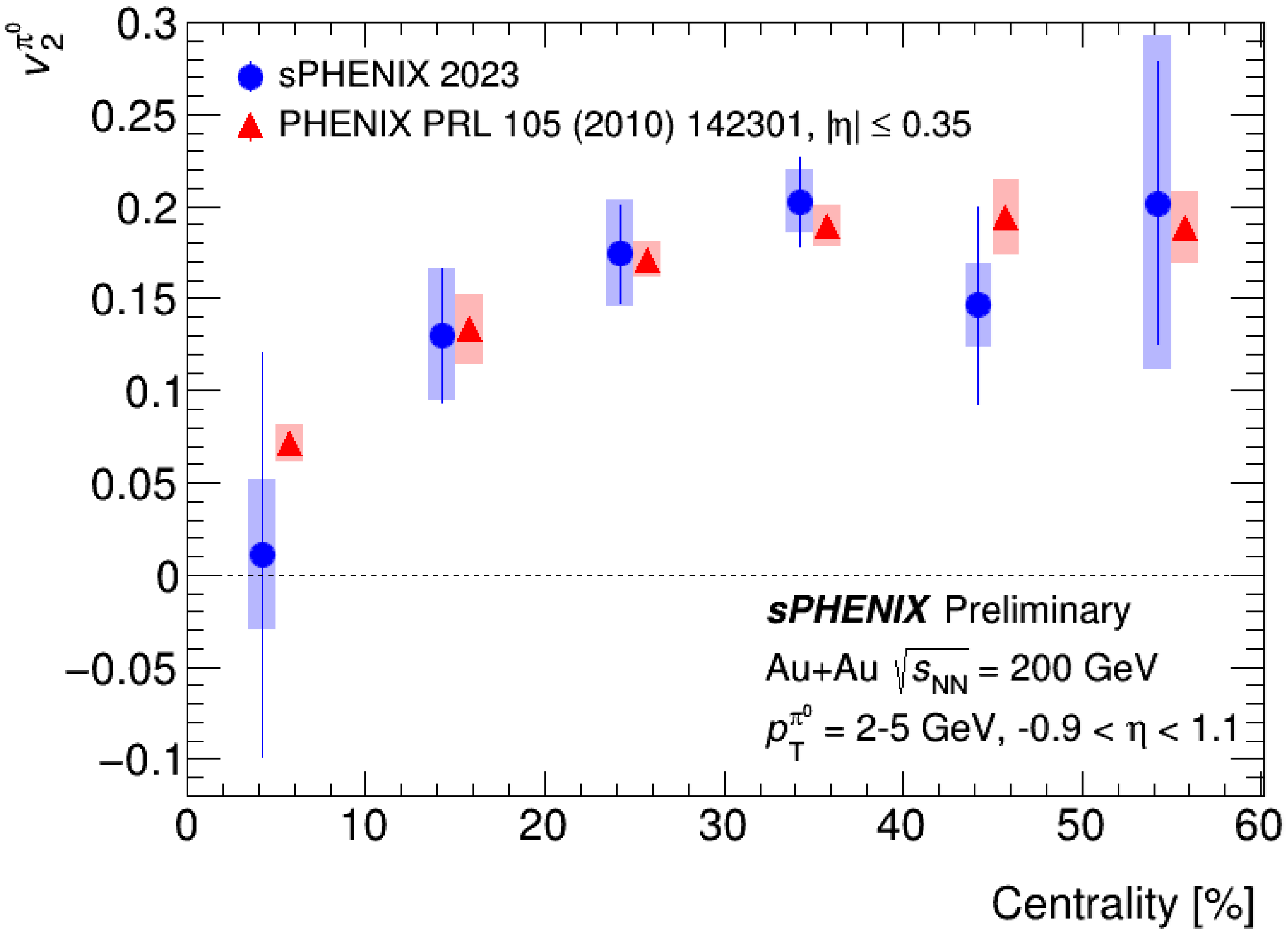
π^0 v_2 results vs. Literature

sPHENIX

Successful extraction of π^0 v_2 from sPHENIX Run 2023 Commissioning dataset with very limited statistics.

Excellent agreement to PHENIX measurement for all centralities.

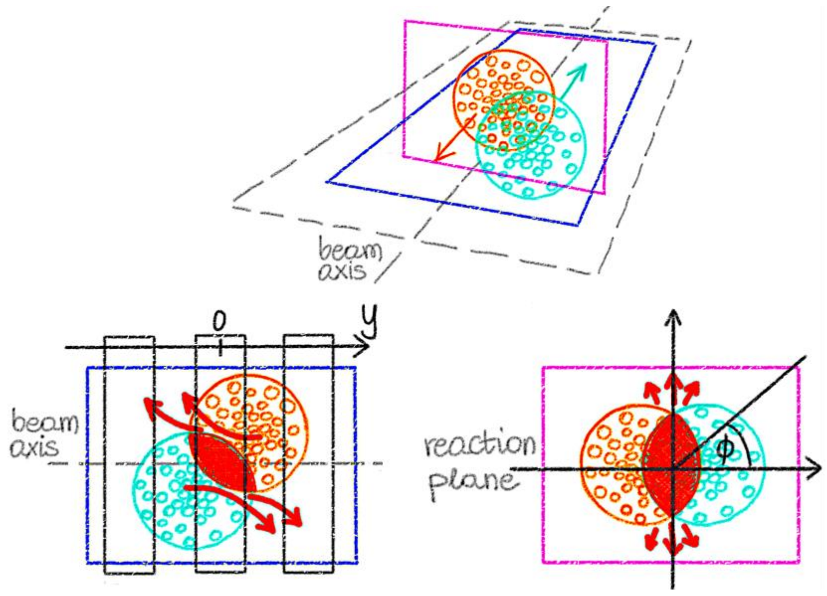


PHENIX measurement: arXiv:1006.3740

sPH-CONF-BULK-2024-01

Longitudinal Expansion and $\varepsilon_{BJ}\tau$ via $\frac{dE_T}{d\eta}$

Longitudinal expansion of QGP medium via measurement of $dE_T/d\eta$:

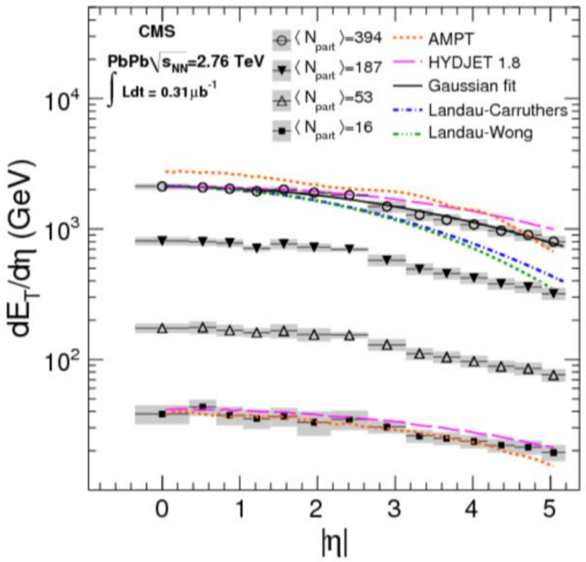


arXiv:2402.10183

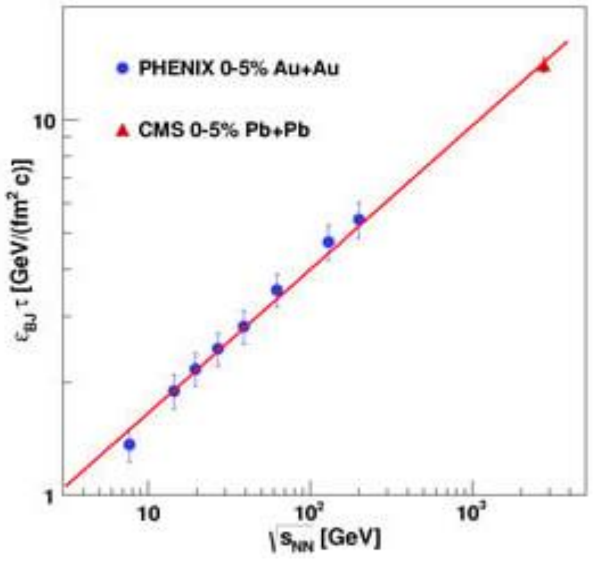
Initial energy density via measurement of $dE_T/d\eta$:

HIC collisions at RHIC and the LHC have measured Bjorken energy densities greater than energy densities predicted from Lattice QCD for the transition from hadron gas to QGP

Previous measurements of $dE_T/d\eta$ and ϵ_{Bj} via $dE_T/d\eta$:



arXiv:1205.2488



Nucl Phys A 956 (2016) 842-845

$dE_T/d\eta$ correction factors

Reconstruct total E_T from each calorimeter layer's measurement of $\sum E_{T,tower}(\eta)$:

- Correction factors needed to correct for detector acceptance/effects
- Created using HIJING events reweighted to match particle spectra from PHENIX and STAR

PHENIX particle spectra: arXiv:1304.3410
STAR particle spectra: arXiv:nucl-ex/0606014

$dE_T/d\eta$ correction factors

sPHENIX

Reconstruct total E_T from each calorimeter layer's measurement of $\sum E_{T,tower}(\eta)$:

- Correction factors needed to correct for detector acceptance/effects
- Created using HIJING events reweighted to match particle spectra from PHENIX and STAR

Correction factor:

$$C(\eta) = \frac{\sum E_{T,tower}(\eta)}{\sum E_{T,particle}(\eta)}$$

- $E_{T,tower} = E_{tower} sin(\theta)$ for each calorimeter in simulation
- $E_{T,particle} = E_{particle} \sin(\theta)$ for all collision final state particles within the detector's acceptance

- Factors show the amount of energy each calorimeter layer sees of the total collision energy

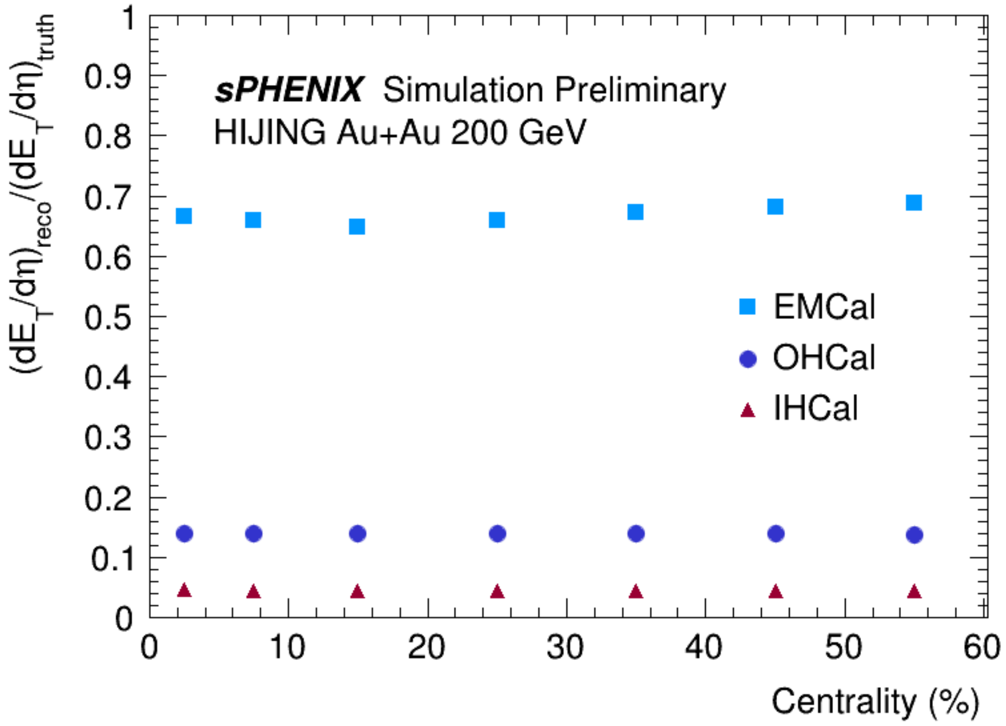
PHENIX particle spectra: arXiv:1304.3410
STAR particle spectra: arXiv:nucl-ex/0606014

sPH-CONF-BULK-2024-02

$dE_T/d\eta$ correction factors

Reconstruct total E_T from each calorimeter layer's measurement of $\sum E_{T,tower}(\eta)$:

- Correction factors needed to correct for detector acceptance/effects
- Created using HIJING events reweighted to match particle spectra from PHENIX and STAR



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- $E_{T,particle} = E_{particle} \sin(\theta)$ for all collision final state particles within the detector's acceptance

- Factors show the amount of energy each calorimeter layer sees of the total collision energy

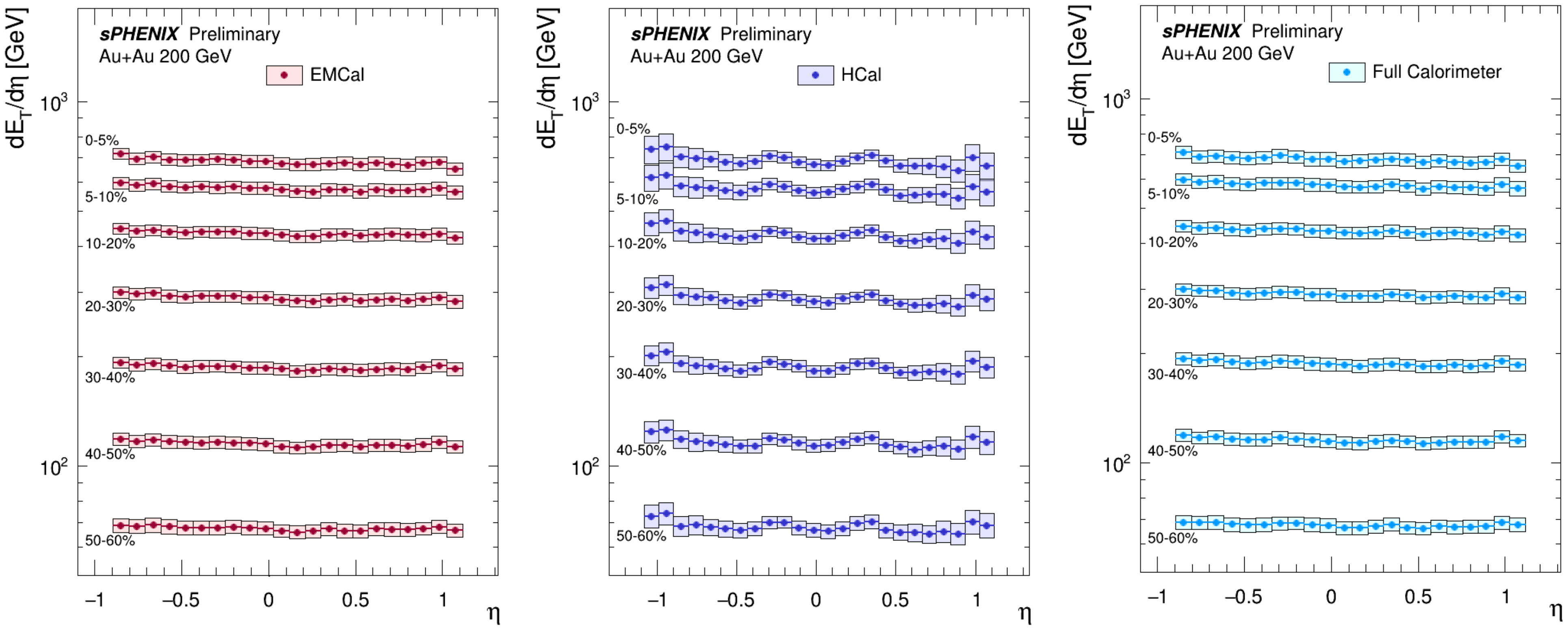
- EMCal sees 66% of truth $\frac{dE_T}{d\eta}$
- IHCal / OHCal see 4% / 14% respectively

PHENIX particle spectra: arXiv:1304.3410
STAR particle spectra: arXiv:nucl-ex/0606014

sPH-CONF-BULK-2024-02

$dE_T/d\eta$ calorimeter results

Fully corrected $dE_T/d\eta$ from $\frac{dE_T}{d\eta}(\eta) = \frac{\sum E_{T,tower}(\eta)}{C(\eta)}$



Strong dependence on centrality and good agreement between EMCal, HCal and full calorimeter results

Systematic uncertainties for data driven validation of hadronic response and calorimeter resolution not evaluated in present analysis

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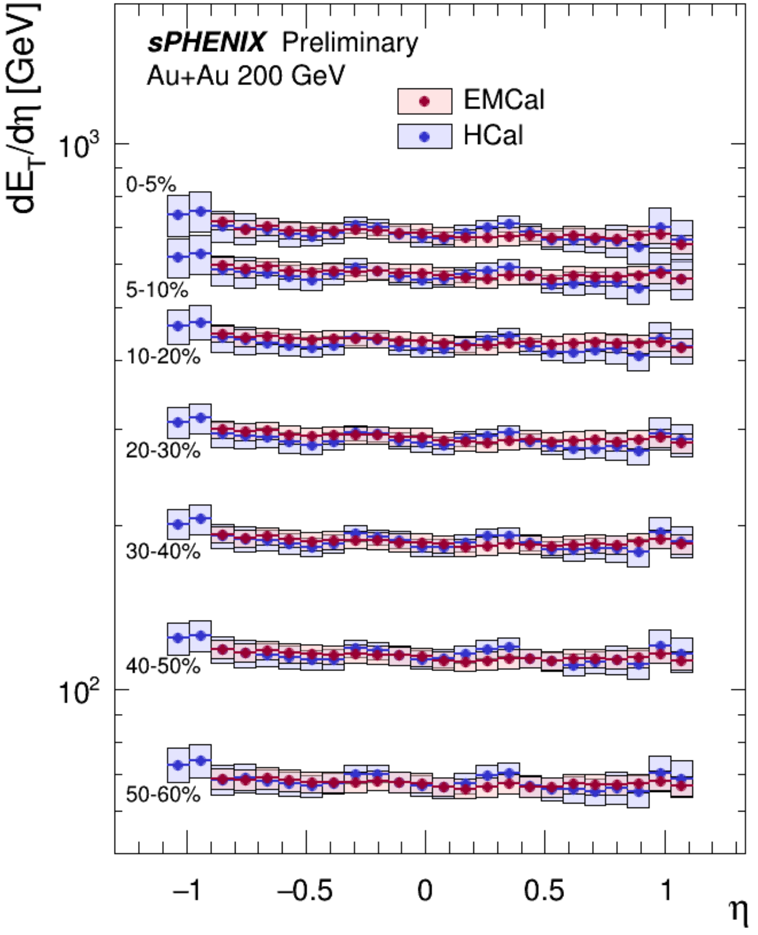
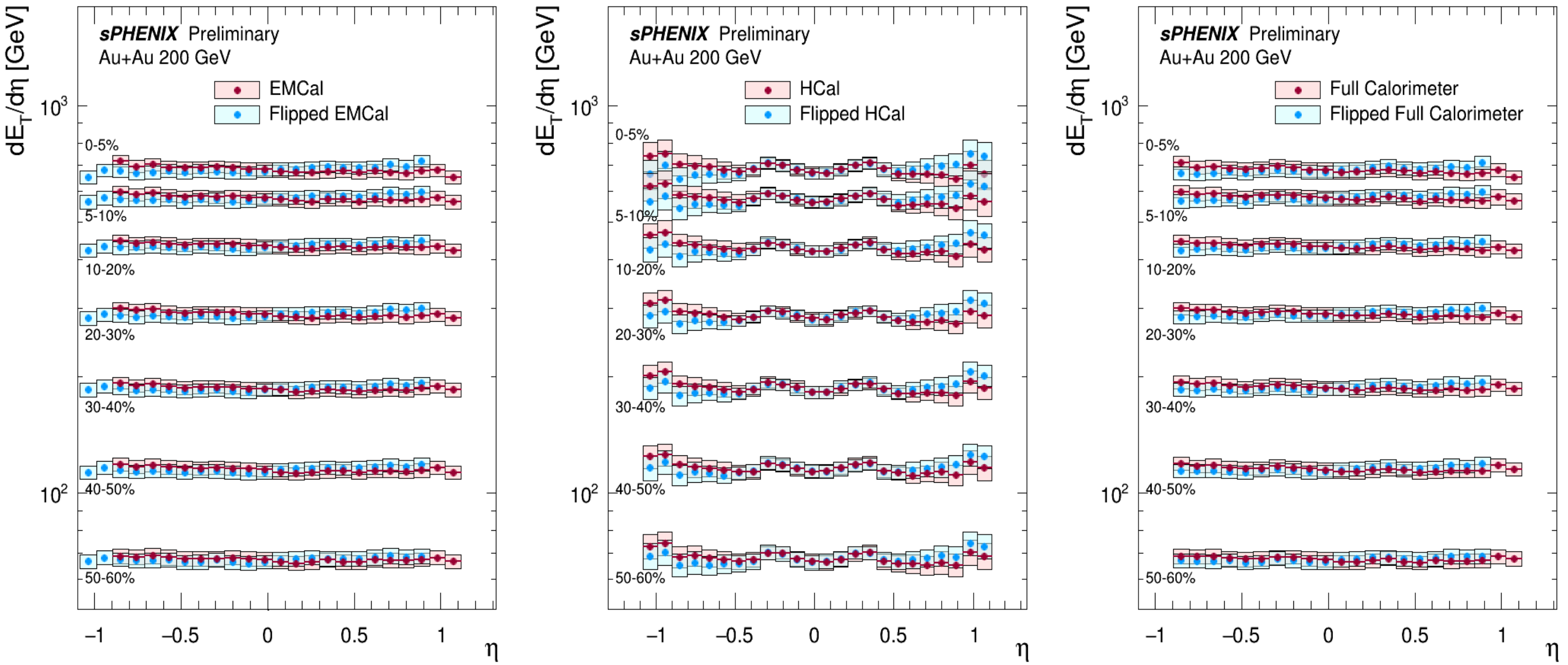
$dE_T/d\eta$ calorimeter results

sPHENIX

Good agreement between EMCal and HCal!!





EMCal, HCal and full calorimeter results all symmetric about $\eta = 0$ within uncertainties!

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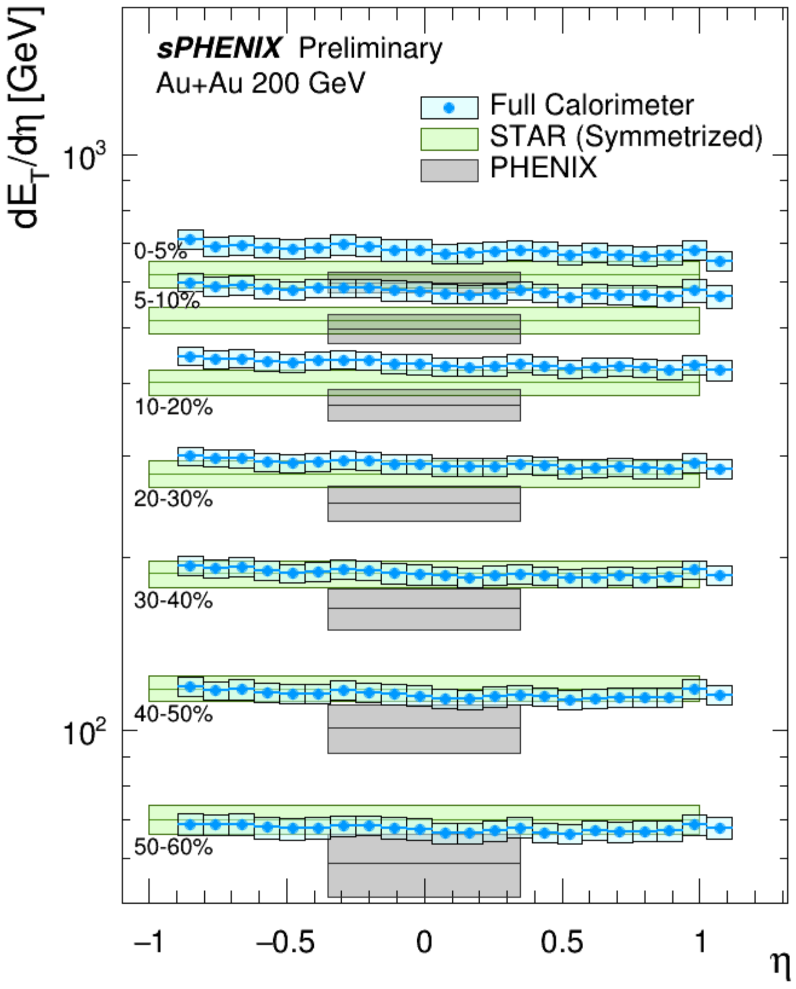
$dE_T/d\eta$ comparison to Literature

Comparison of sPHENIX full calorimeter $dE_T/d\eta$ measurements to previous STAR/PHENIX measurements

sPHENIX results are consistently higher than the results from PHENIX for all centrality bins but agree within uncertainties for mid-central bins 30-60%

sPHENIX results are above the STAR results in the centrality range of 0-10% but agree in other centralities

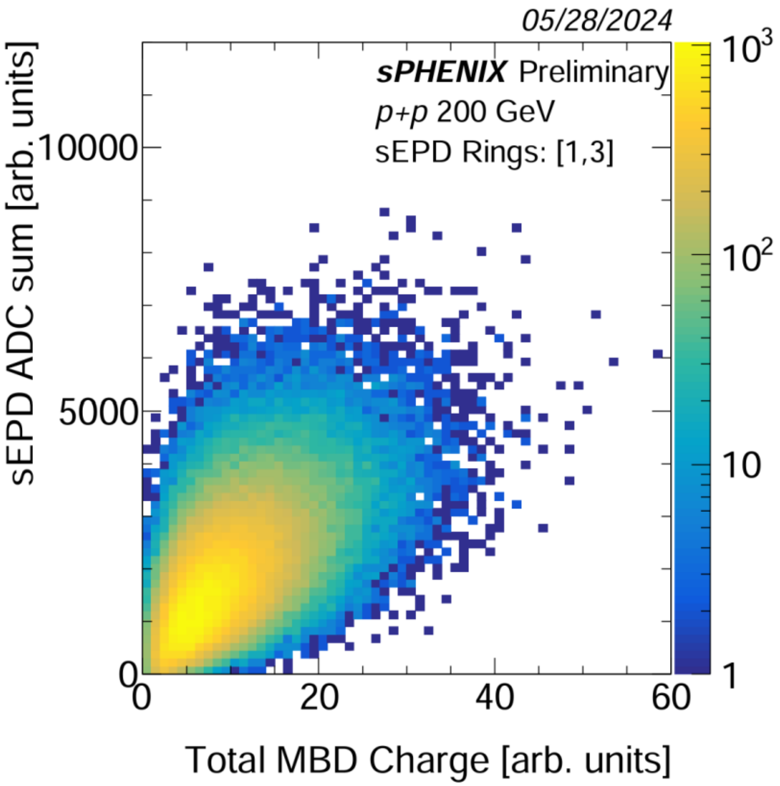
Presented are sPHENIX centrality intervals from preliminary centrality calculations which will be updated before finalizing centrality selections and reporting quantities like <Npart>



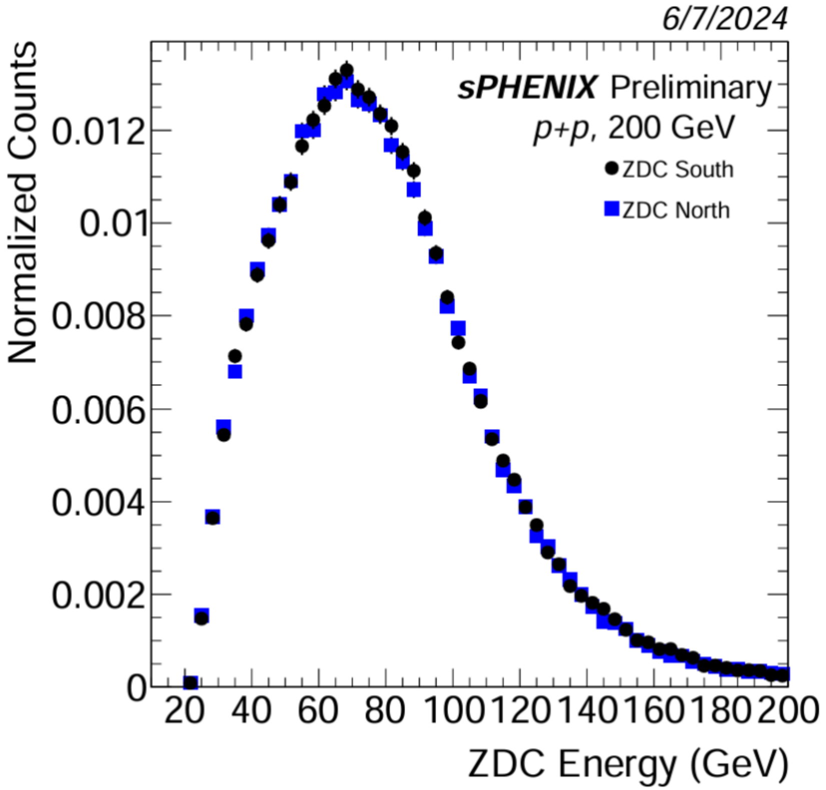
PHENIX measurement: arXiv:1509.06727
STAR measurement: arXiv:nucl-ex/0407003

sPH-CONF-BULK-2024-02

sPHENIX is not just Calorimeters! Event Characterization:



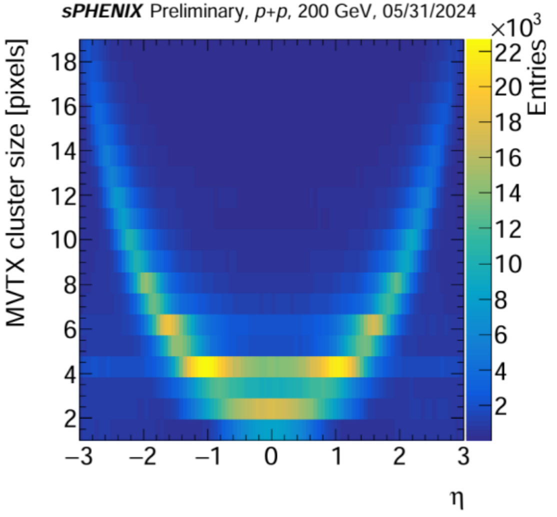
sPHENIX Event Plane Detector (sEPD)

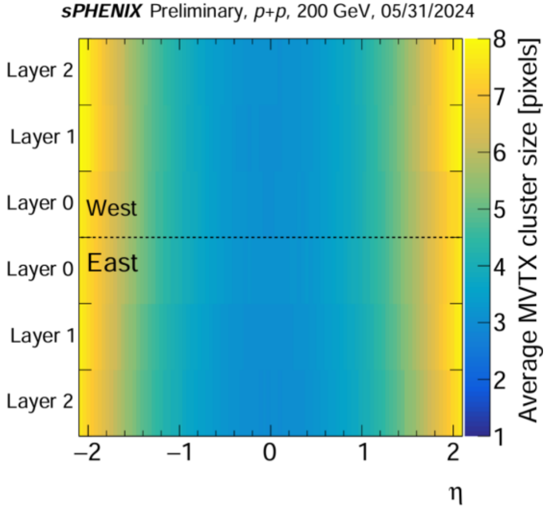


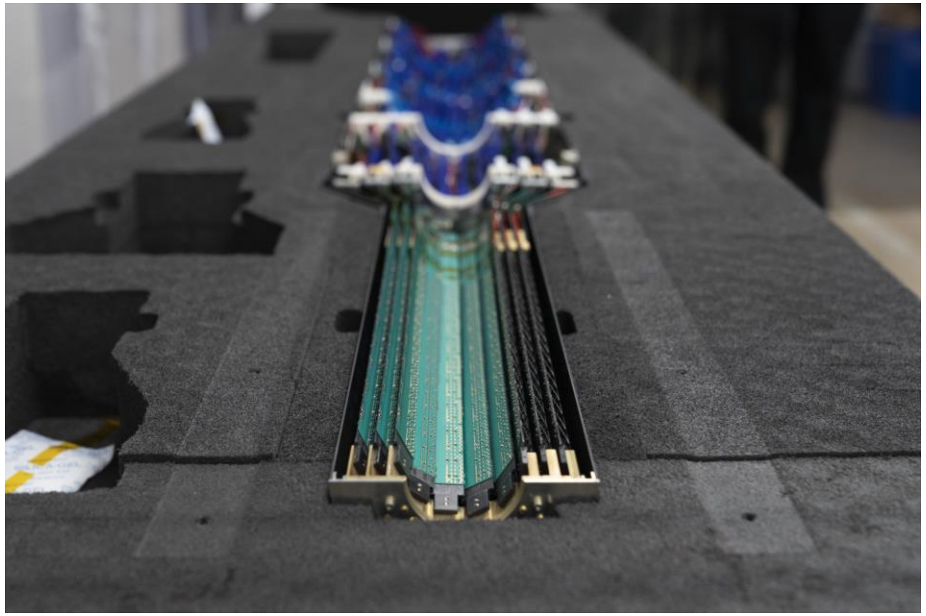
Zero Degree Calorimeters (ZDC)

Tracking MVTX & INTT:

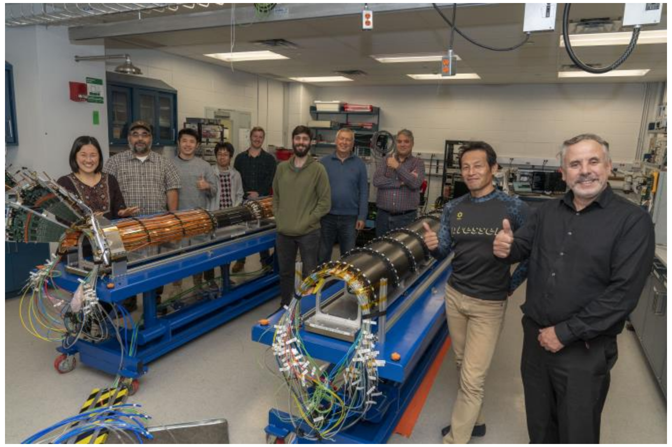
- Multiplicity and VerTeX Detector

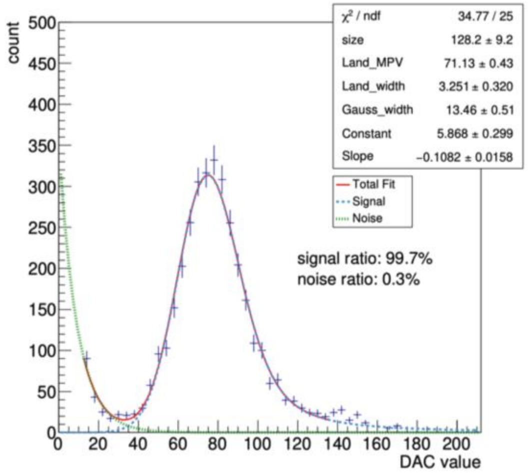


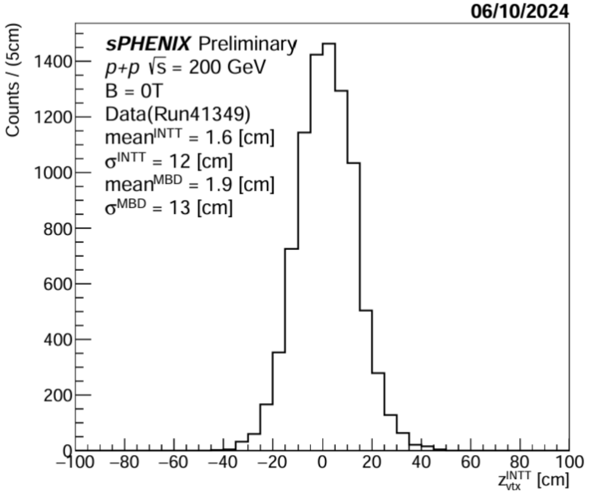




- Intermediate Silicon Tracker

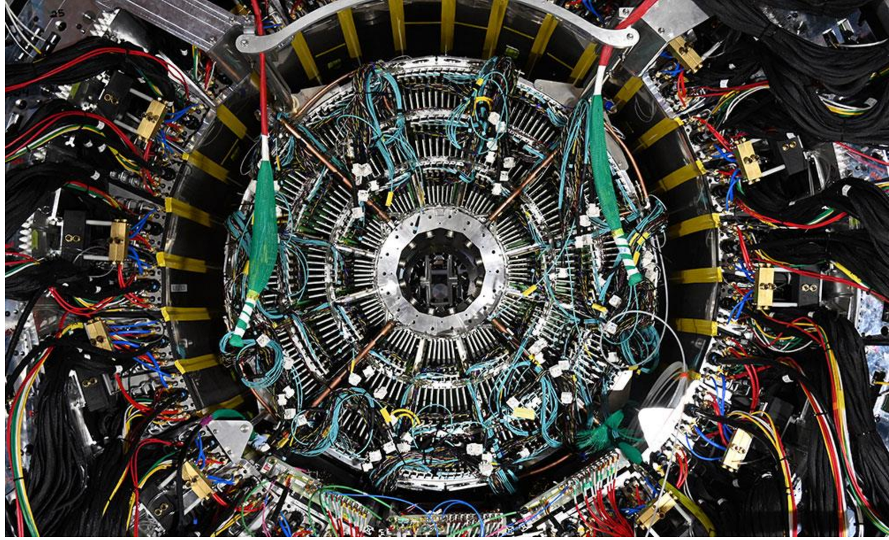


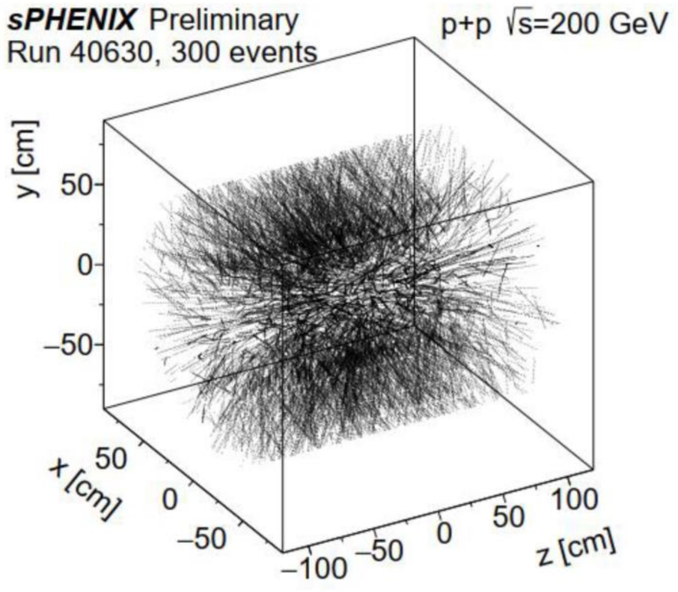




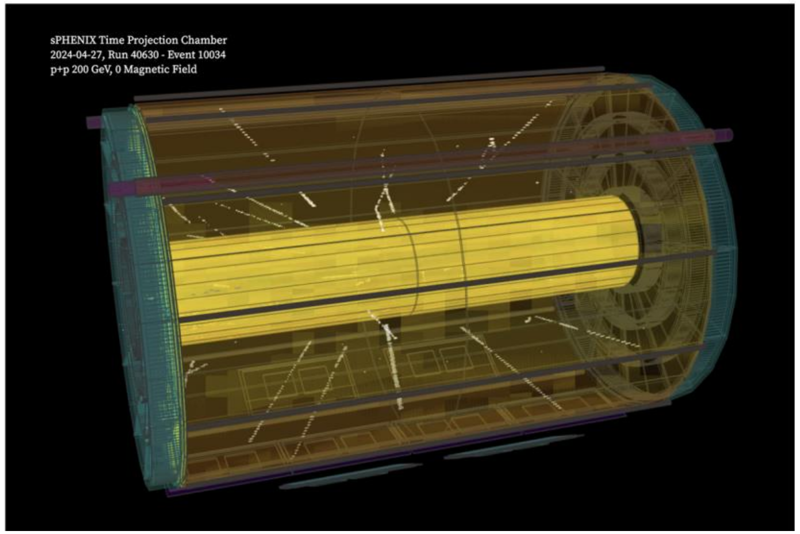
$Signal : 99.7\%\ noise : 0.3\%$

Time Projection Chamber (TPC):

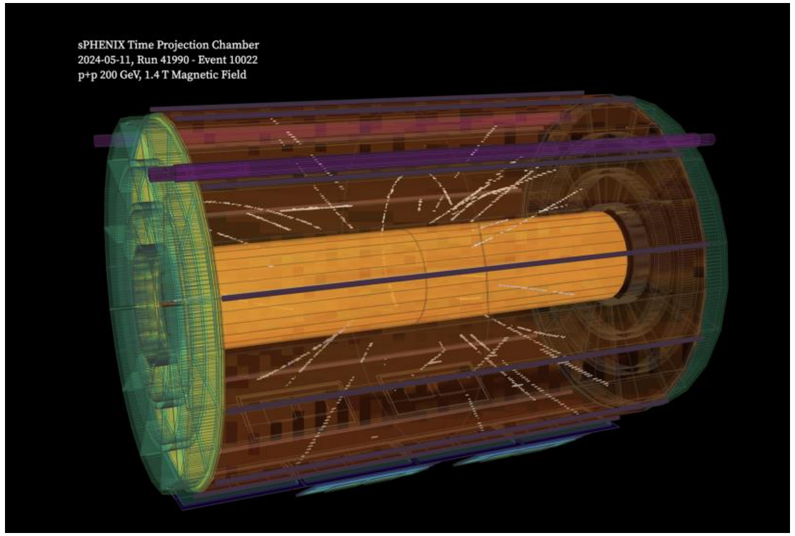




300 pp Collisions

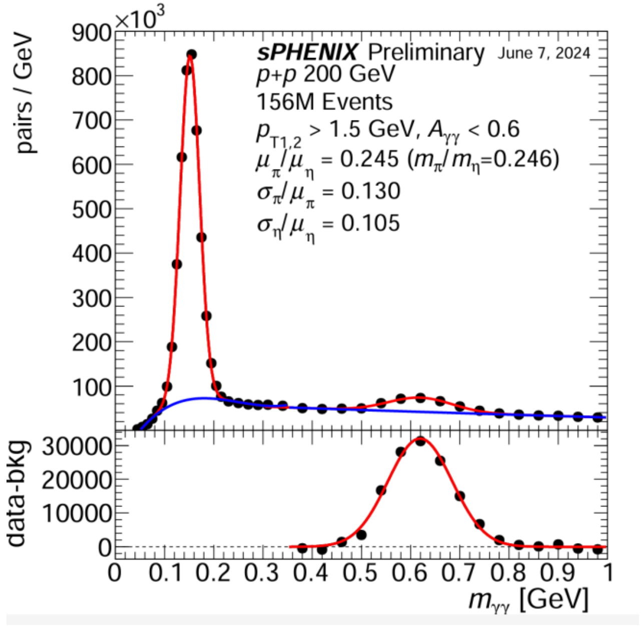


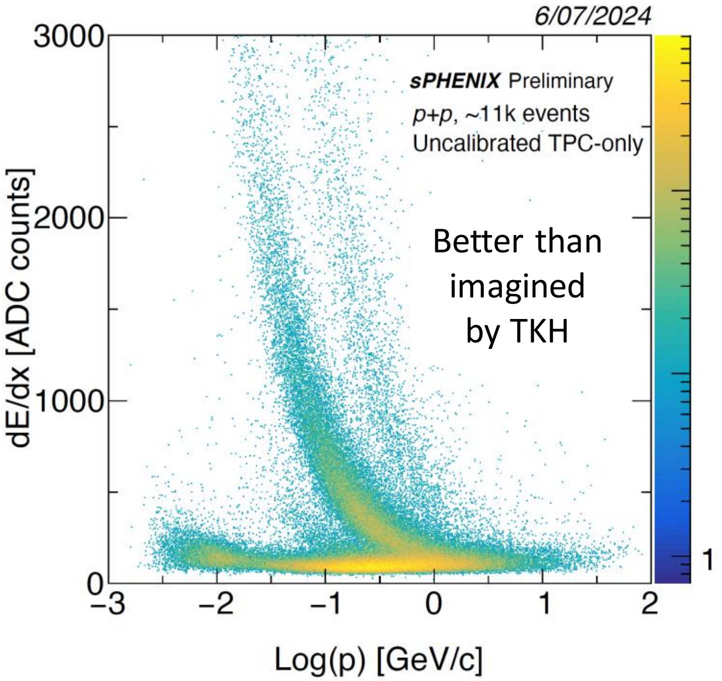
Single Collision (Field Off)

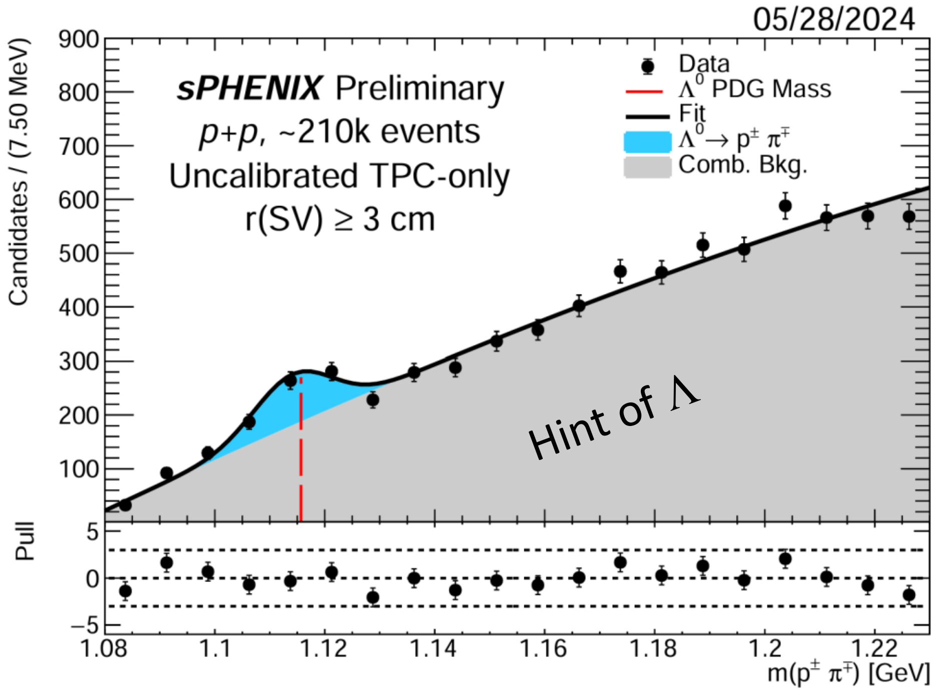


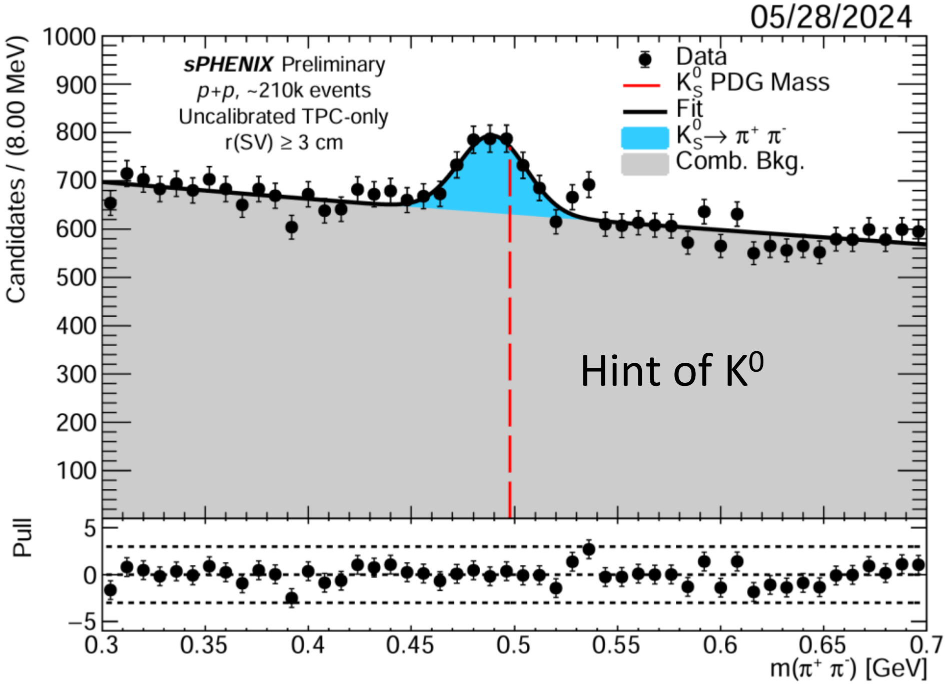
Single Collision (Field On)

Tantalizing Fresh Results









- We are poised for an excellent run.
- Many results await collection & analysis
- The enthusiasm within and beyond sPHENIX is palpable.

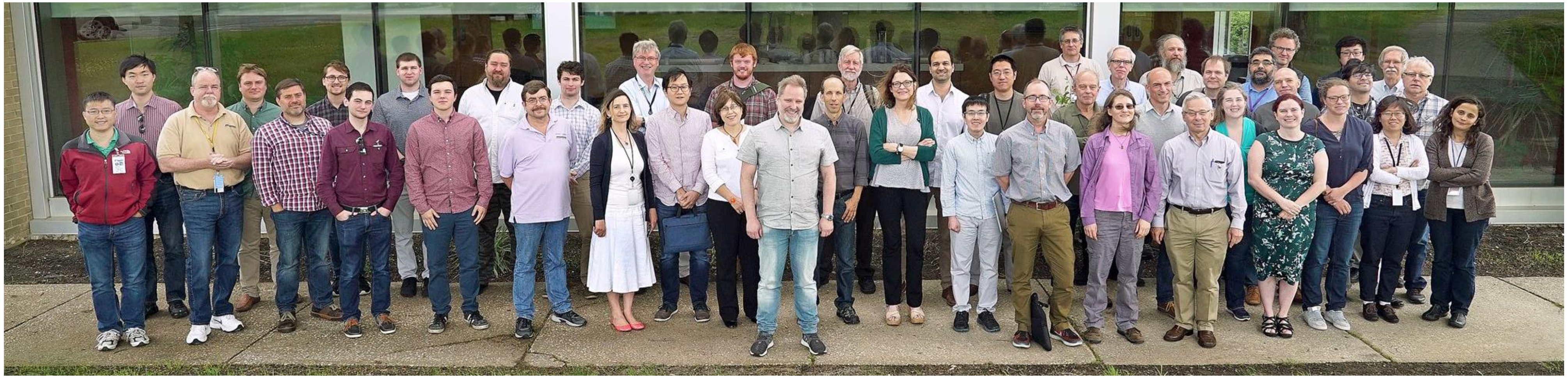
Summary and outlook

Two complementary measurements of sPHENIX's ability to probe the collective behavior of the QGP are presented using commissioning data from Run 2023

sPH-CONF-BULK-2024-01 sPH-CONF-BULK-2024-02

Find these first results and all other current and future sPHENIX results at https://www.sphenix.bnl.gov/PublicResults!

sPHENIX is poised for an exciting future!



Backup

Corrections to reference flow vectors

Ψ_2 calculated from: $\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{Q_x}{Q_y}\right)$

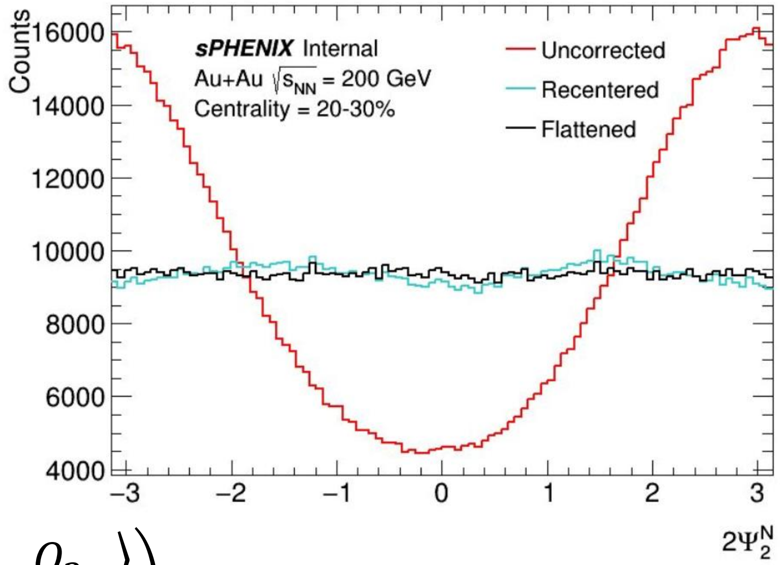
Uncorrected distribution: Inherent asymmetry in MBD results in bias in Ψ_2

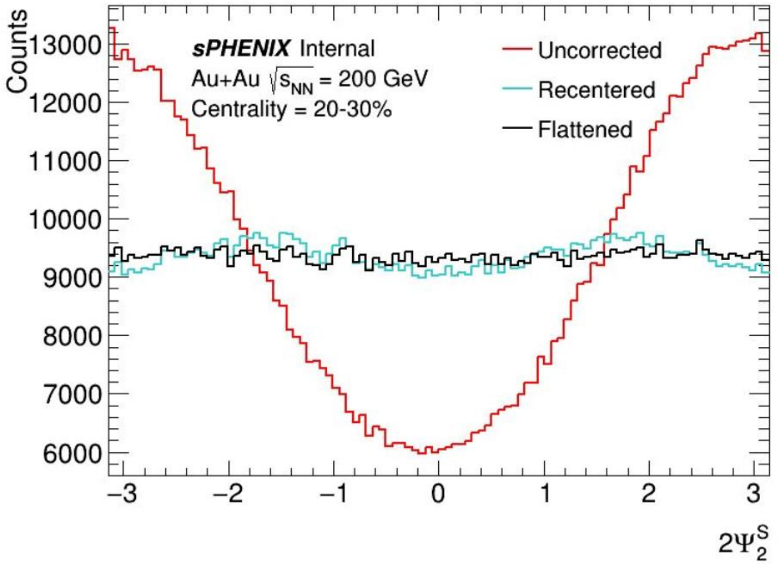
Recentered distribution:

$$\vec{Q}_{2,recentered} = \vec{Q}_{2,raw} - \left\langle \vec{Q}_{2,raw} \right\rangle$$

applied to raw Q_2

Flattened distribution:
mean corrected Q_2 multiplied by the normalized inverse square root of the covariance matrix :





$$\frac{1}{\sqrt{N}}\begin{pmatrix} \langle Q_{2,y}^2\rangle + D & -\langle Q_{2,x}Q_{2,y}\rangle \\ -\langle Q_{2,x}Q_{2,y}\rangle & \langle Q_{2,x}^2\rangle + D \end{pmatrix}$$

$$D = \sqrt{\langle Q_{2,x}^2\rangle\langle Q_{2,y}^2\rangle - \langle Q_{2,x}Q_{2,y}\rangle^2}\,,\ N = D\left(\langle Q_{2,x}^2\rangle + \langle Q_{2,y}^2\rangle + 2D\right),$$

$Q_{2,y} = Im(Q_2)$ and $Q_{2,x} = Re(Q_2)$

π^0 v_2 uncertainties

- Statistical uncertainties determined from subsampling routine (k=30)
  - Event pool uniformly and randomly divided into 30 samples and π^0 v_2 is measured for each sample via SP method
  - Statistical uncertainty is calculated as the standard deviation of the π^0 v_2 distribution

- Systematic uncertainties from EMCal calibration, signal and bkg windows
  - Large contribution from EMCal calibration uncertainties to total systematic uncertainties
  - Calibration uncertainties include:
    - statistical uncertainties on π^0 calibration
    - absolute scale uncertainty
    - uncertainties on method to balance tower response within calibrated η rings of the EMCal

$dE_T/d\eta$ uncertainties

- Systematic uncertainties account for nearly all of the measurement uncertainty (statistical uncertainties are very small ($< 1\%$))

- Greatest contributions to systematic uncertainty:
  1. MC hadronic response modeling uncertainty found by varying the GEANT physics configuration
  2. MC reweighting methodology tested by reweighting different MC generators (AMPT/EPOS) and comparing reweighted AMPT/EPOS results to reweighted HIJING results
  3. MC reweighting rapidity dependence tested by reweighting HIJING dataset to PHENIX/STAR particle spectra measured at central rapidity versus BRAHMS particle spectra measured as a function of rapidity

Systematic uncertainties for calorimeter hadronic response and energy resolution missing from present results

Systematic Uncertainties			
	EMCal	OHCal	Full Calo
Calibration	1.4-1.6	0.9-1.1	1.1-1.3
Hadron Resp.	2.8	2.8	2.8
MC reweight.	1.5-1.6	1.7-3.0	2.1-2.7
ZS	0.1-1.7	0.6-0.7	0.2-1.4
Accept.	0.3-0.9	0.7-1.3	0.3-0.9
Global	0.1-0.3	0.03-0.1	0.1-0.2
Total	3.8-4.1	3.6-4.4	3.8-4.1