First physics measurements in Au+Au collisions from sPHENIX

Emma McLaughlin for sPHENIX Collaboration

June 4th, 2024

Columbia University
in the City of New York

First physics measurements and signatures of the QGP

- sPHENIX is a brand new state of the art detector at RHIC which completed installation in 2023

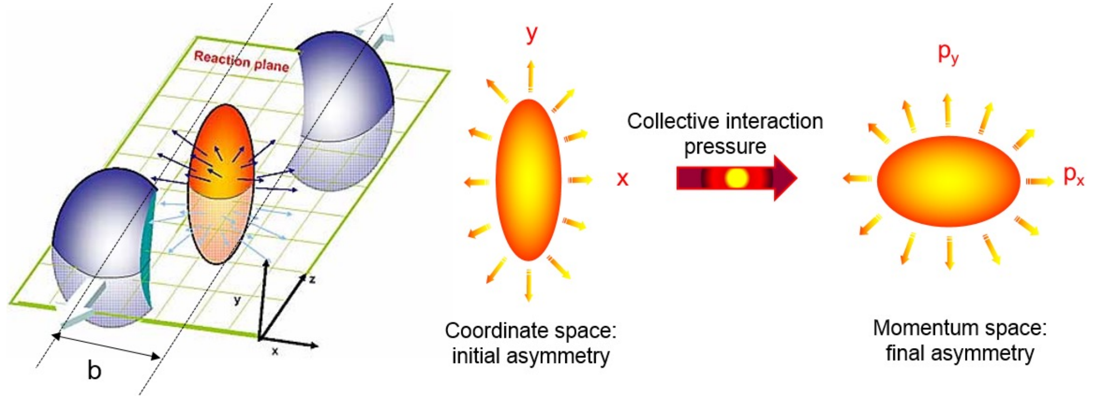
- From Run 2023, sPHENIX has a limited dataset from commissioning running with calorimeter and Minbias detector is normal operating mode

- This dataset is used here as an exercise to re-measure a number of “standard candles” from the RHIC program

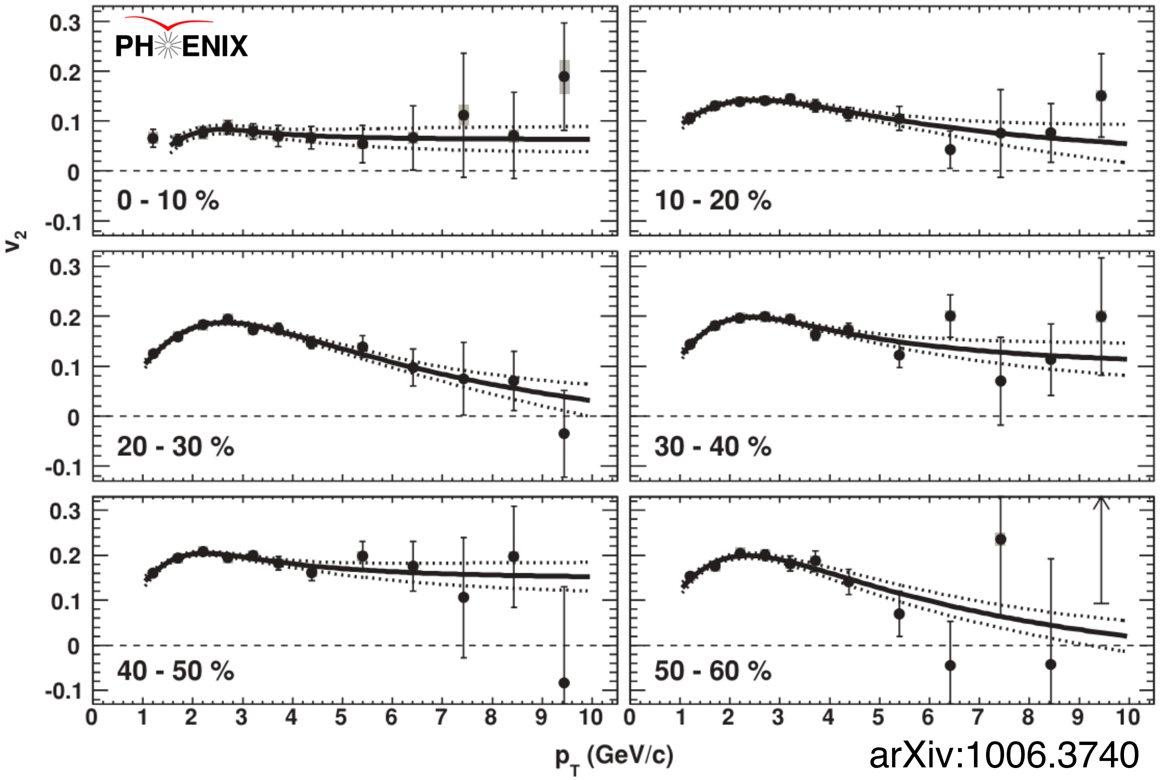
First physics measurements and signatures of the QGP

Collective flow via measurement of $\pi^0 v_2$:

- Through the HIC evolution lumpiness in initial state transform into pressure gradients driving anisotropic flow
- v_2 characterizes the elliptic flow contribution to anisotropic flow
- Evidence for the QGP's strongly interacting fluid nature



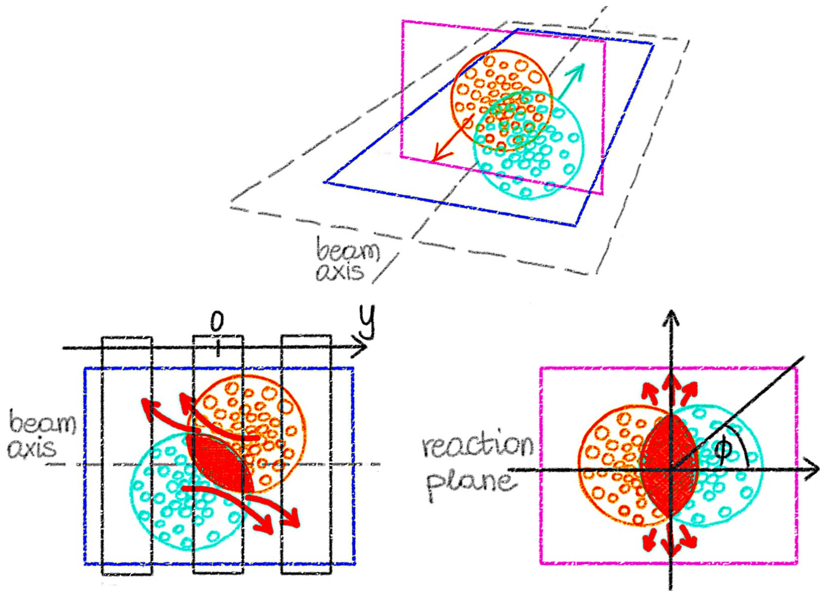
Previous measurements of $\pi^0 v_2$:



arXiv:1006.3740

First physics measurements and signatures of the QGP

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

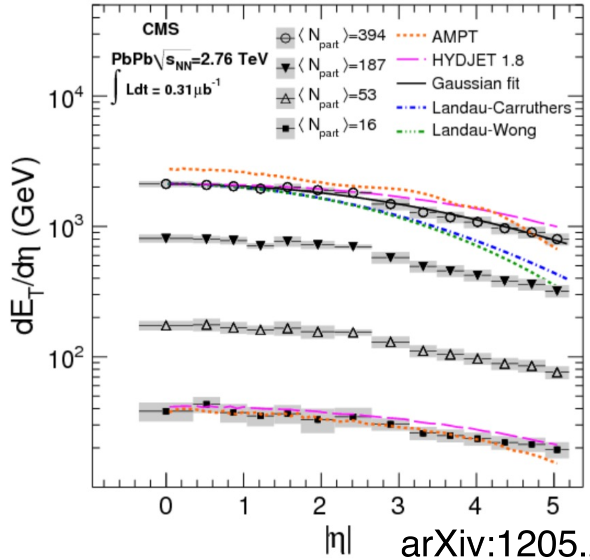


arXiv:2402.10183

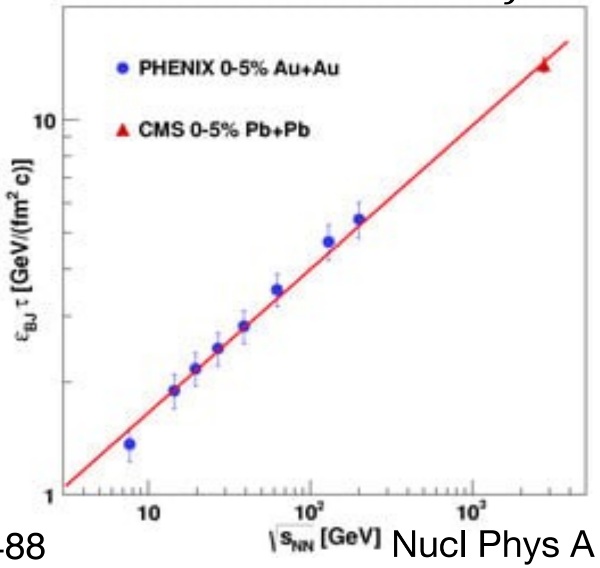
Initial energy density via measurement of $dE_T/d\eta$:

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



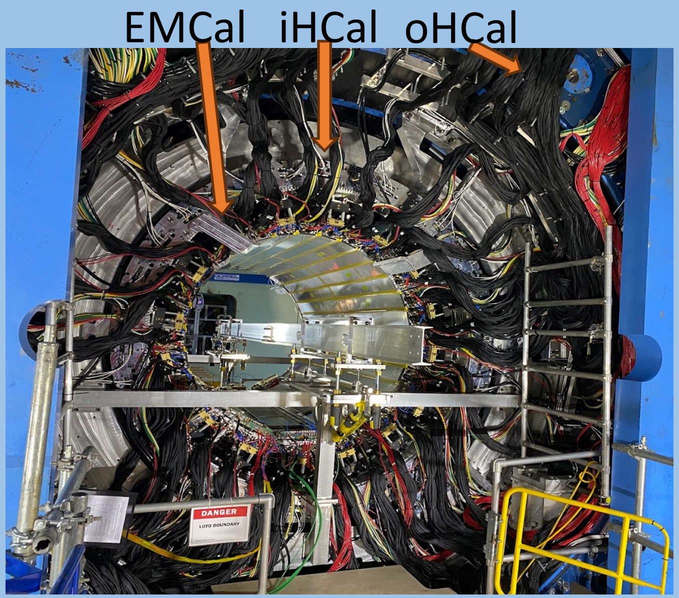
Nucl Phys A 956 (2016) 842-845

sPHENIX Subsystems

For a full overview of the sPHENIX detector, please see sPHENIX overview talk given by Rachid Nouicer

Three concentric calorimeter layers, electromagnetic calorimeter (EMCal), inner hadronic calorimeter (IHCal) and outer hadronic calorimeter (OHCal) with $0 < \phi < 2\pi$ and $|\eta| < 1.1$ range

sPHENIX calorimeter system has total depth of 4.9 hadronic interaction lengths



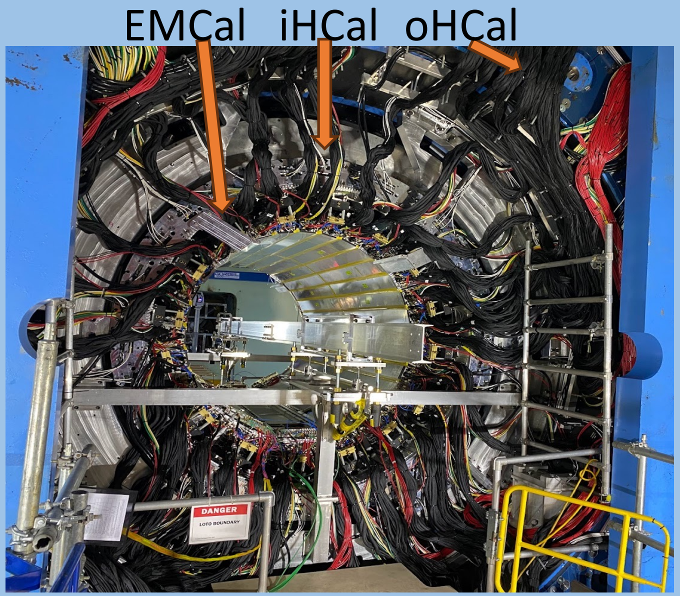
sPHENIX technical design report:
https://indico.bnl.gov/event/7081/attachments/25527/38284/sphenix_tdr_20190513.pdf

sPHENIX Subsystems

For a full overview of the sPHENIX detector, please see sPHENIX overview talk given by Rachid Nouicer

Three concentric calorimeter layers, electromagnetic calorimeter (EMCal), inner hadronic calorimeter (IHCal) and outer hadronic calorimeter (OHCal) with $0 < \phi < 2\pi$ and $|\eta| < 1.1$ range

sPHENIX calorimeter system has total depth of 4.9 hadronic interaction lengths



EMCal:

- Calibrated with π^0 mass peak in η rings
- Tungsten powder absorber & scintillating fibers
- Tower size Δη × Δϕ = 0.024 × 0.024

HCal:

- Calibrated with cosmic muons
- Al (inner)/steel (outer) absorber plates & scintillating tiles
- Tower size Δη × Δϕ = 0.1 × 0.1

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

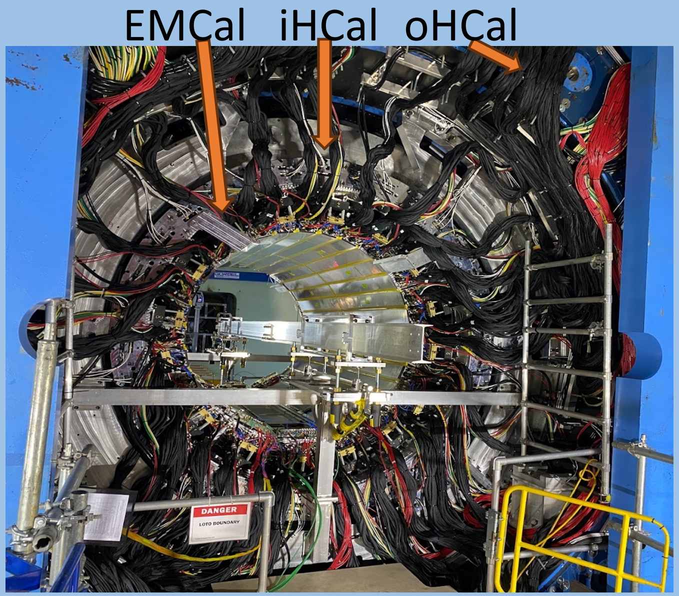
sPHENIX Subsystems

For a full overview of the sPHENIX detector, please see sPHENIX overview talk given by Rachid Nouicer

Three concentric calorimeter layers, electromagnetic calorimeter (EMCal), inner hadronic calorimeter (IHCal) and outer hadronic calorimeter (OHCal) with $0 < \phi < 2\pi$ and $|\eta| < 1.1$ range

sPHENIX calorimeter system has 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
- Comprised of Photomultiplier Tube (PMT) counters
- Provides MB triggering, z vertex determination and centrality determination



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

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

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

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

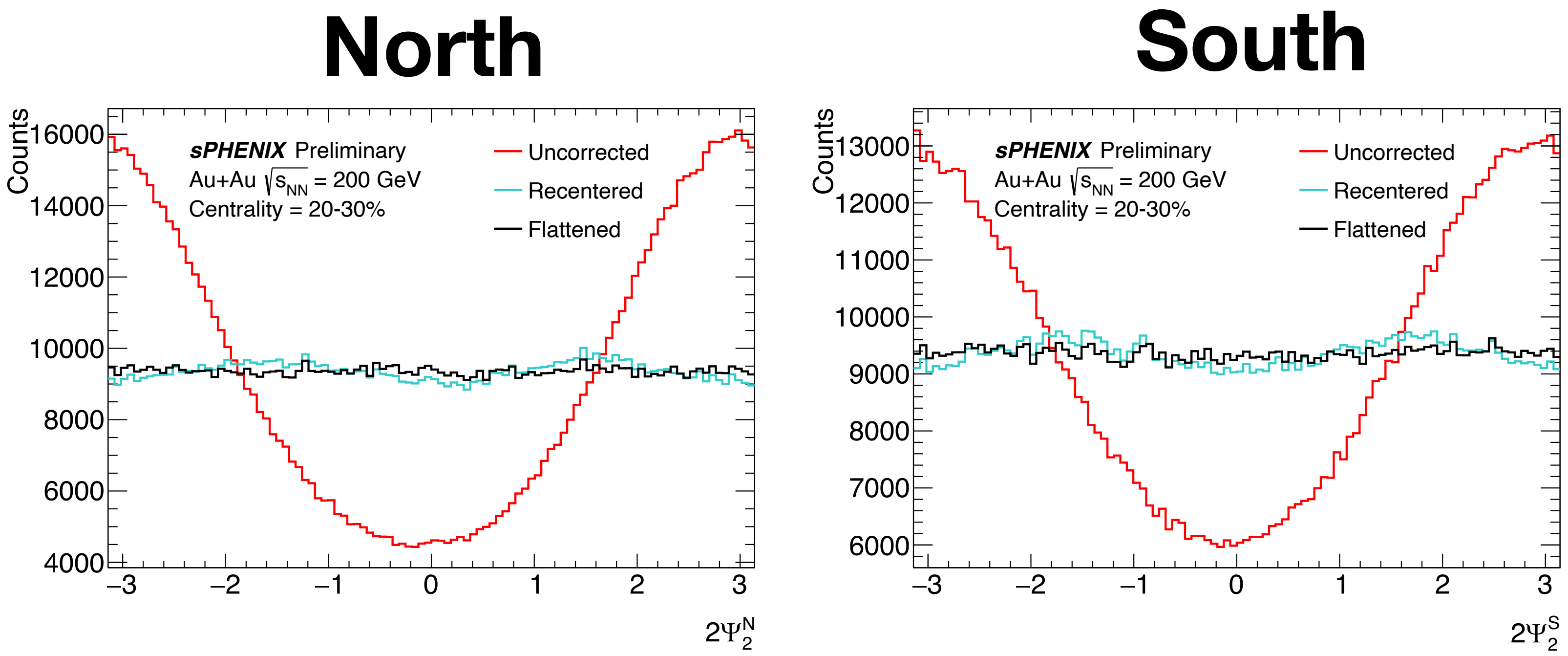
π^0 v_2 via Scalar Product Method

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



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

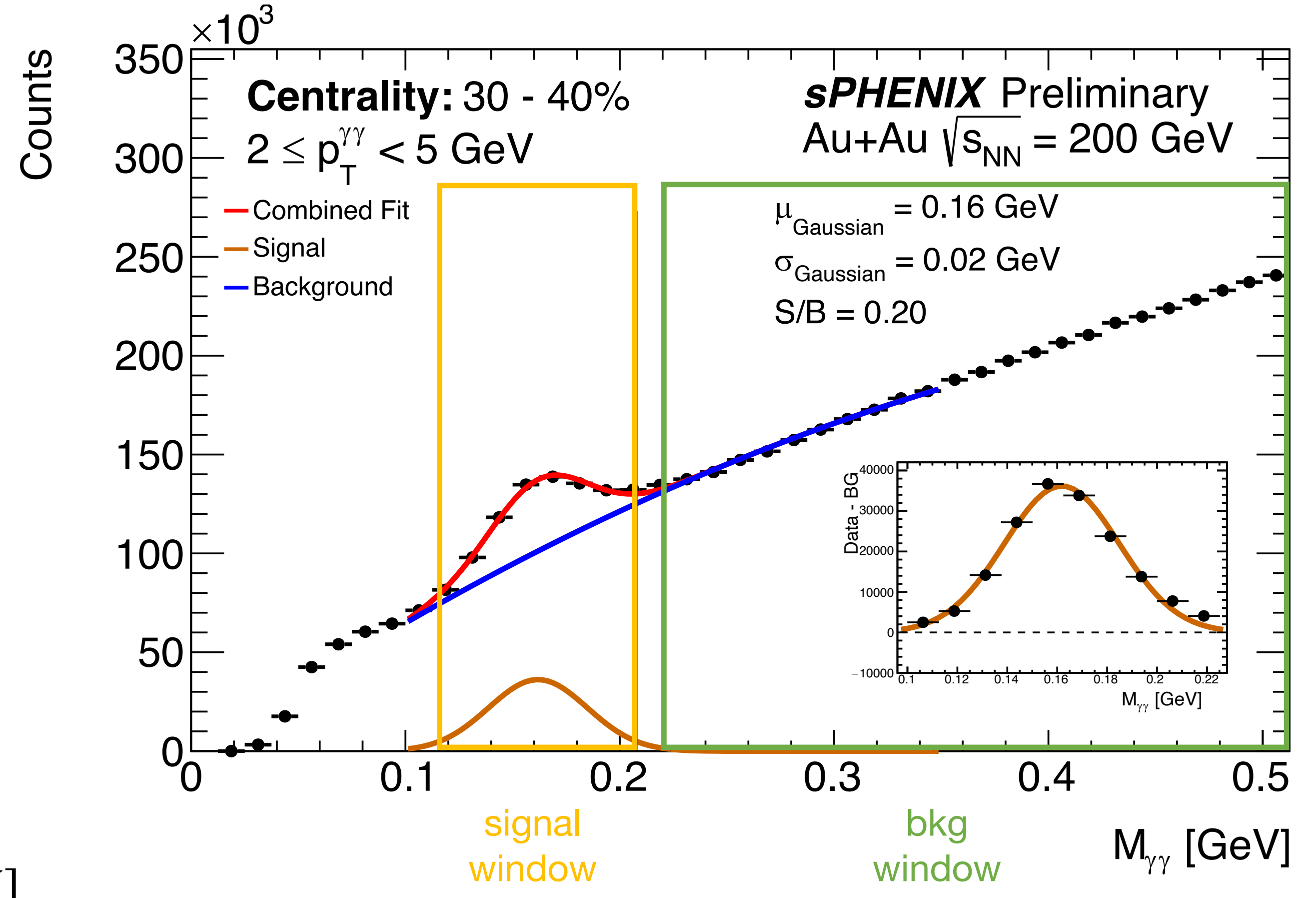
Scalar Product methodology: arXiv:nucl-ex/0206001
2nd order correction methodology: doi:10.7916/d8-t50g-tn57

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 non π^0 diphoton 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 $[\mu - 2\sigma, \mu + 2\sigma]$

π^0 invariant mass peaks

EMCal diphoton pair criteria:

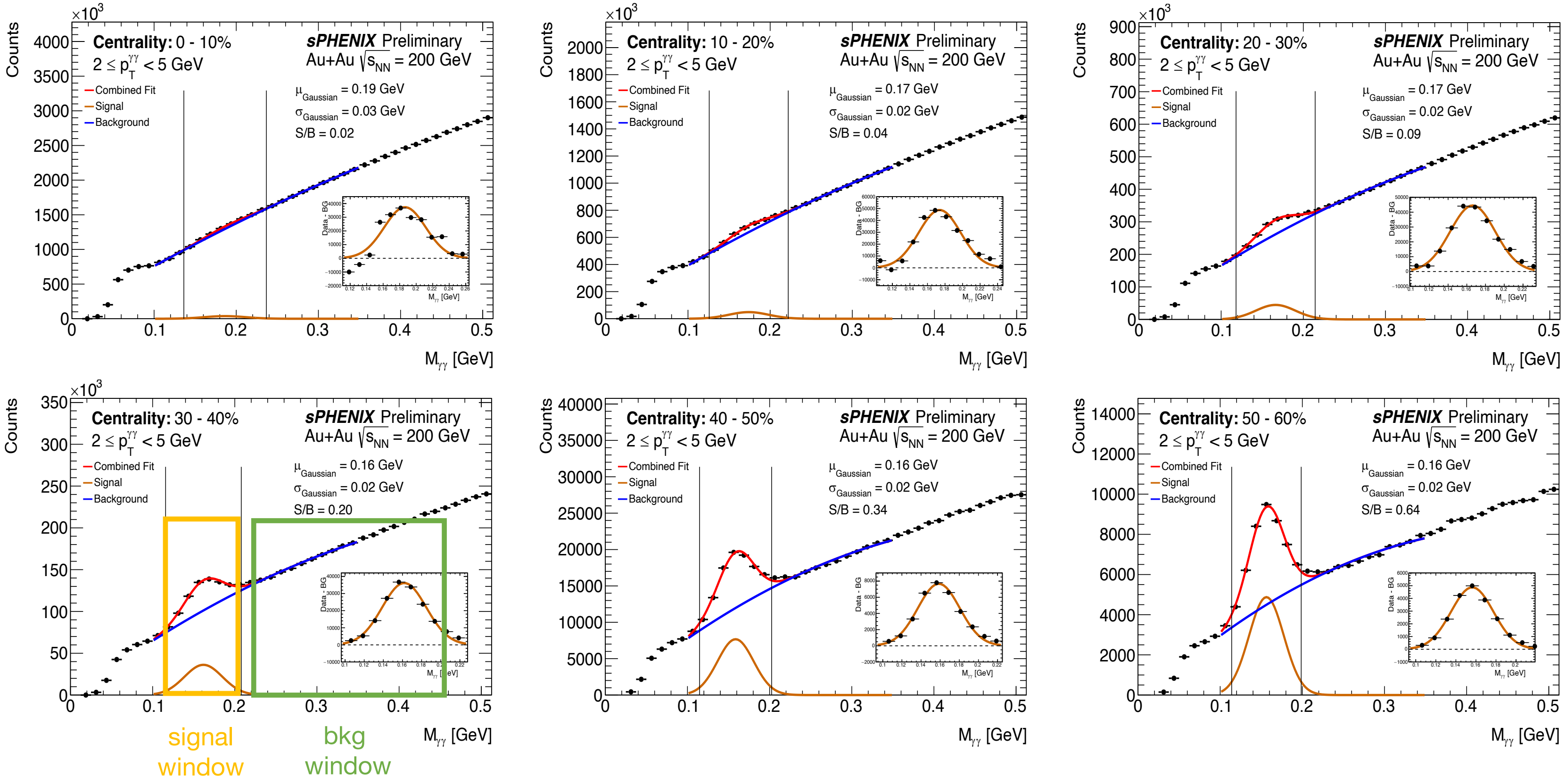
1. Cluster $E_{Core} > 1GeV$
2. Cluster $\chi^2 < 4$
3. $\alpha = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.5$

Low asymmetry discriminates against non π^0 diphoton pairs

π^0 v_2 background subtraction:

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

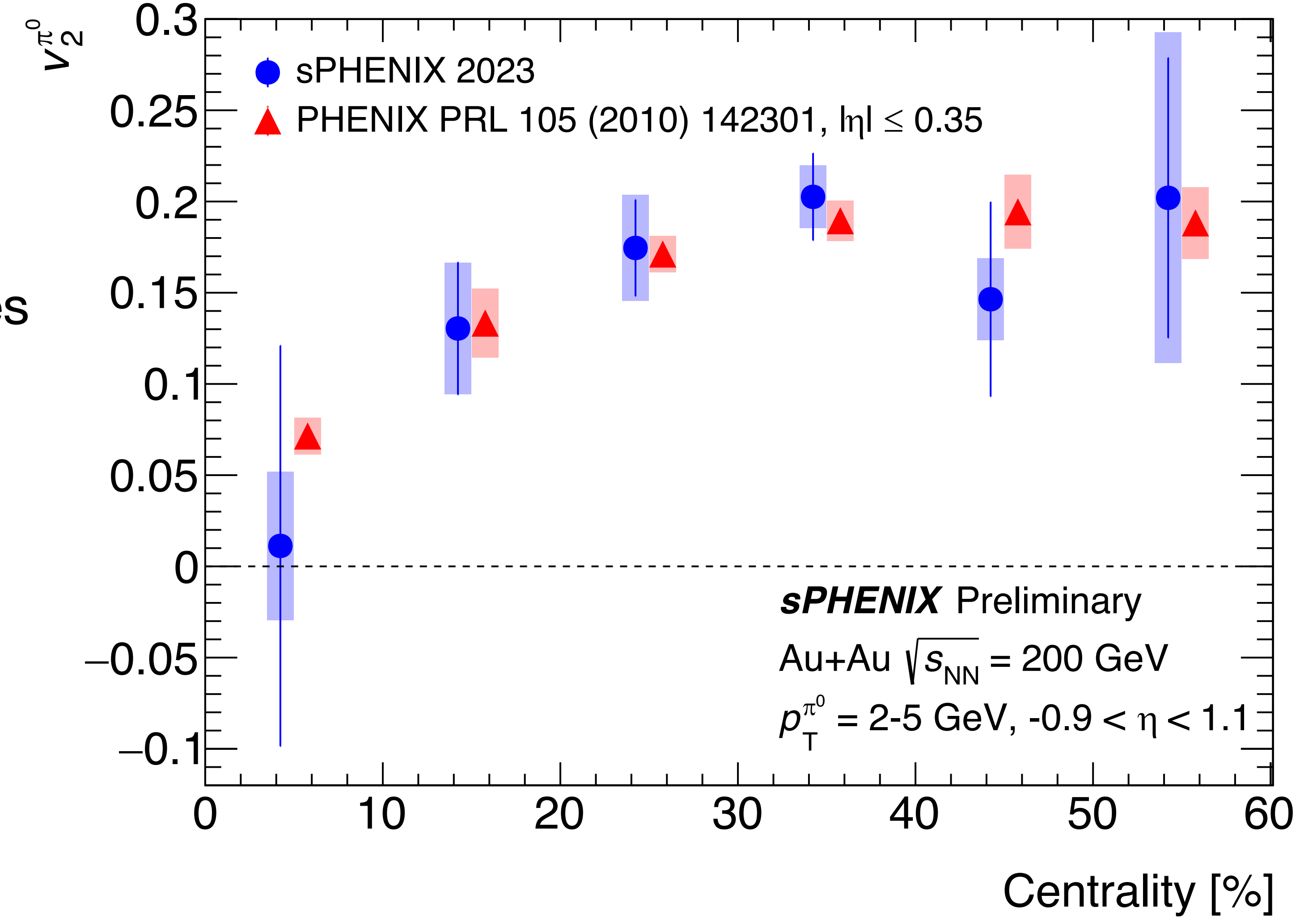
v_2^M from signal window $[\mu - 2\sigma, \mu + 2\sigma]$
v_2^{BG} from background window $[\mu + 3\sigma, 0.5\ GeV]$
S/B ratio calculated in signal window $[\mu - 2\sigma, \mu + 2\sigma]$



π^0 v_2 results

Good agreement between sPHENIX measurement of π^0 v_2 and previous PHENIX measurement for all centralities in this analysis!

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



$dE_T/d\eta$ 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

sPH-CONF-BULK-2024-02

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

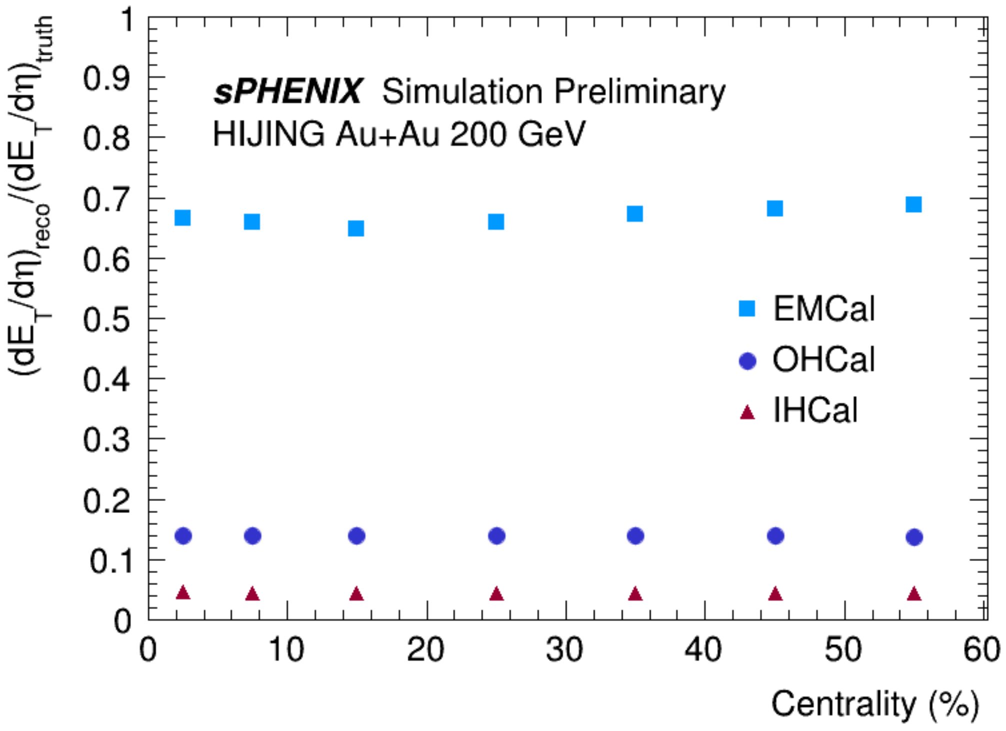
PHENIX particle spectra: arXiv:1304.3410
STAR particle spectra: arXiv:nucl-ex/0606014

$dE_T/d\eta$ correction factors

sPH-CONF-BULK-2024-02

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

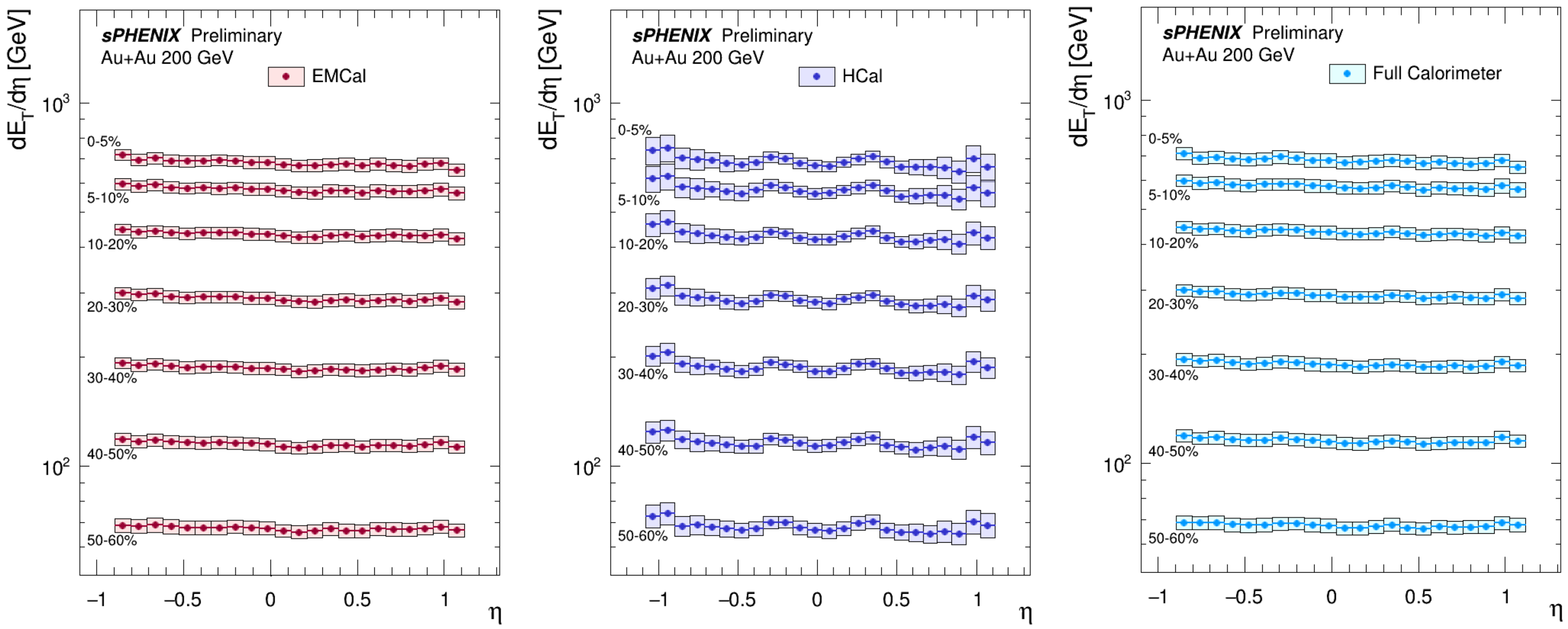
- Factors show the amount of energy each calorimeter layer sees of the total collision energy

EMCal sees ~66% of truth $dE_T/d\eta$! IHCal and OHCal see 4% and 14% of truth $dE_T/d\eta$

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

$dE_T/d\eta$ calorimeter results

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



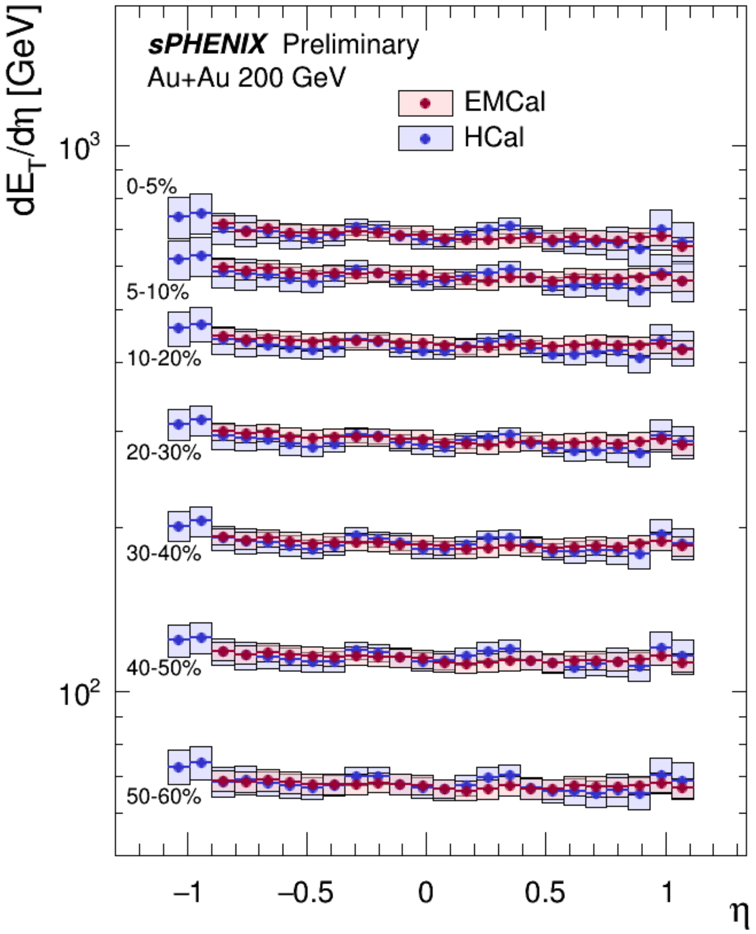
Strong dependence on centrality and good agreement between EMCal, HCal and full calorimeter results

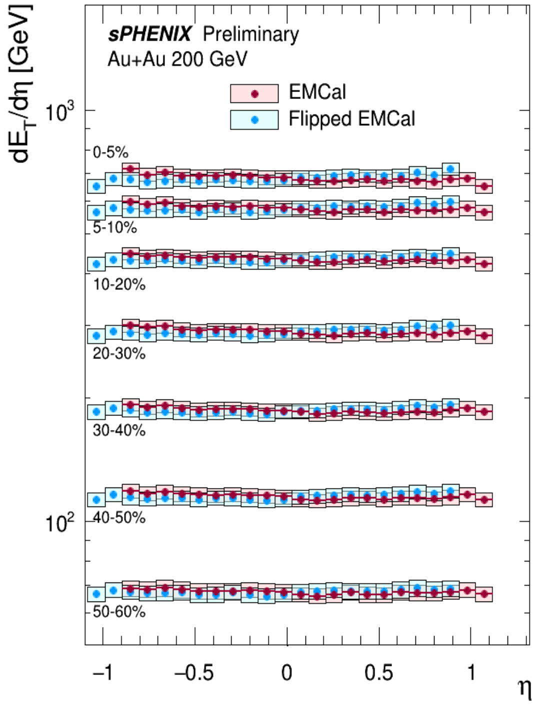
Systematic uncertainties for data driven validation of hadronic response and calorimeter resolution not evaluated in present analysis

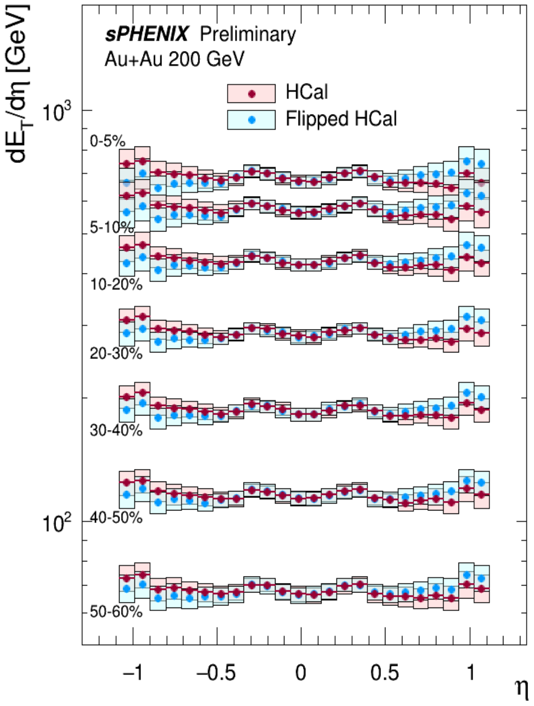
$dE_T/d\eta$ calorimeter results

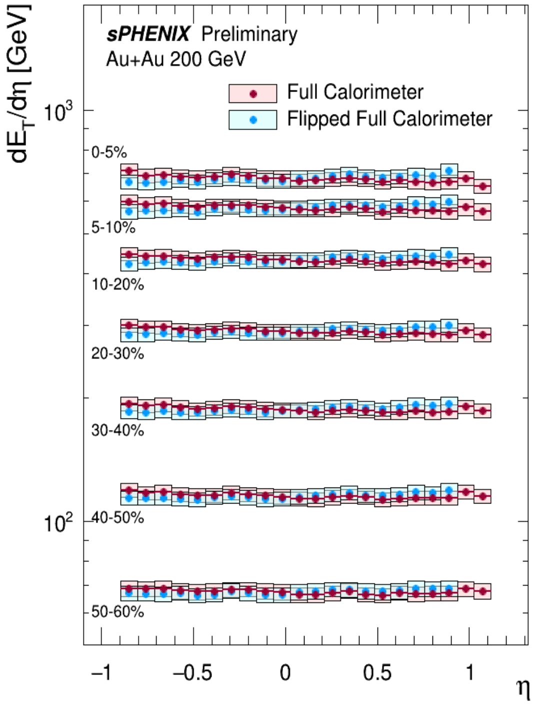
sPH-CONF-BULK-2024-02

Good agreement between EMCal and HCal!!









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

$dE_T/d\eta$ detector comparison

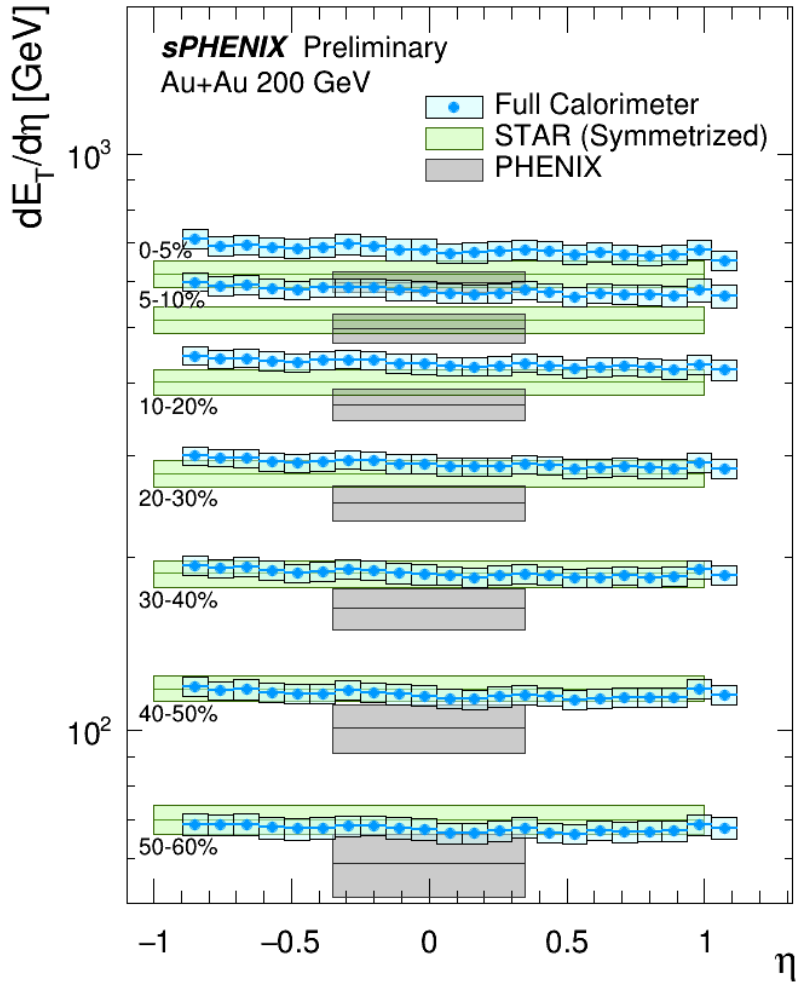
sPH-CONF-BULK-2024-02

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 are in agreement in other centrality intervals

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

Summary and outlook

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

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

Through these analyses using Run 2023 commissioning data, sPHENIX has been able to exercise the readout, reconstruction, calibration and analysis of data at the level of rigor appropriate for physics measurements

sPHENIX is ready to make measurements from physics data of the currently ongoing Run 2024!

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

Backup

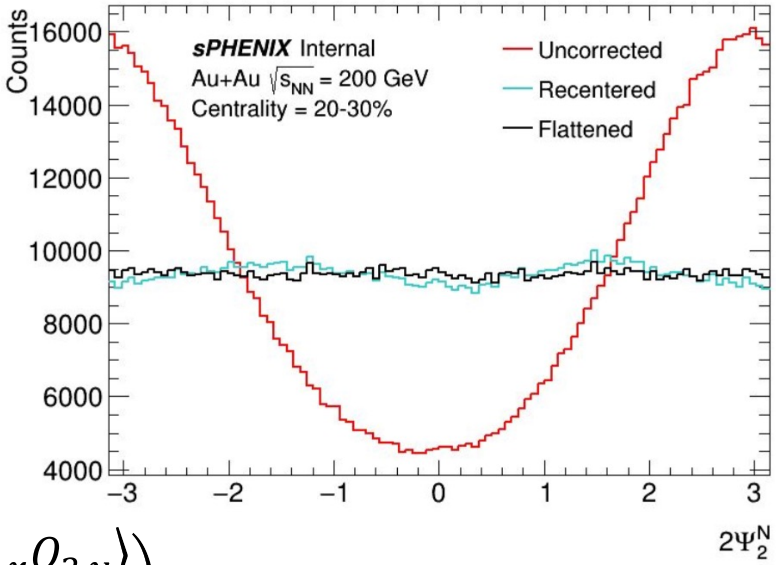
Corrections to reference flow vectors

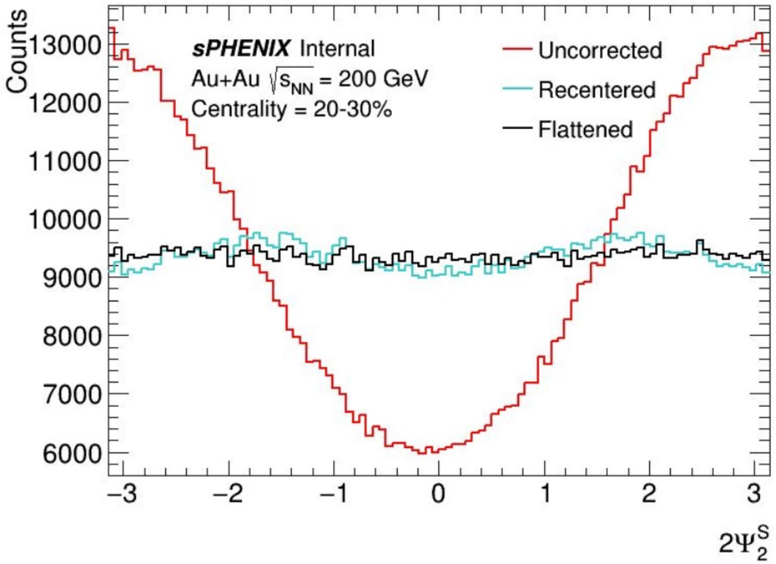
Ψ_2 calculated from: $\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{Q_x}{Q_y}\right)$

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

Recentered distribution:
$\vec{Q}_{2,recentered} = \vec{Q}_{2,raw} - \langle\vec{Q}_{2,raw}\rangle$
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 $Q_{2,x} = Re(Q_2)$

2nd order correction methodology: doi:10.7916/d8-t50g-tn57

$\pi^0\ v_2$ uncertainties

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

sPHENIX

- 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**