Measurement of Bulk Properties with sPHENIX from the 2023 RHIC Run

Ron Belmont
University of North Carolina at Greensboro

International Conference on High Energy Physics
18–24 July 2024

Outline

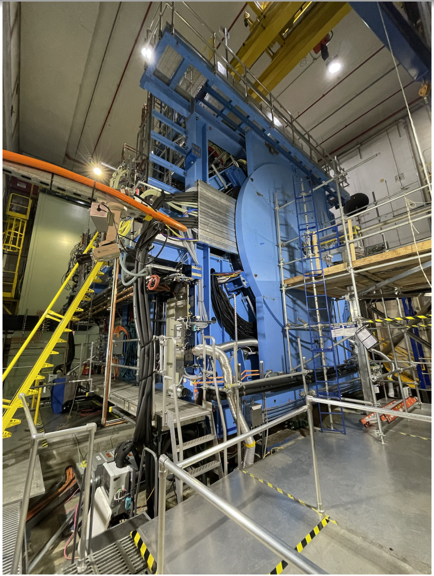
- The sPHENIX detector completed installation and mostly completed commissioning during the 2023 Au+Au at $\sqrt{s_{NN}} = 200$ GeV

- Unfortunately, Run 2023 was cut short, with only 11 cryo-weeks delivered out of 24 cryo-weeks planned

- Nevertheless, a limited dataset from this run has yielded two preliminary results:
  —v_2 of neutral pions as a function of centrality
  sPH-CONF-BULK-2024-01
  —$dE_T/d\eta$ measured calorimetrically using EM and Hadronic calorimetry
  sPH-CONF-BULK-2024-02

- These results highlight that the sPHENIX physics program is well under way, using "bread and butter" physics measurements to fully establish proper detector operation and calibration

sPHENIX

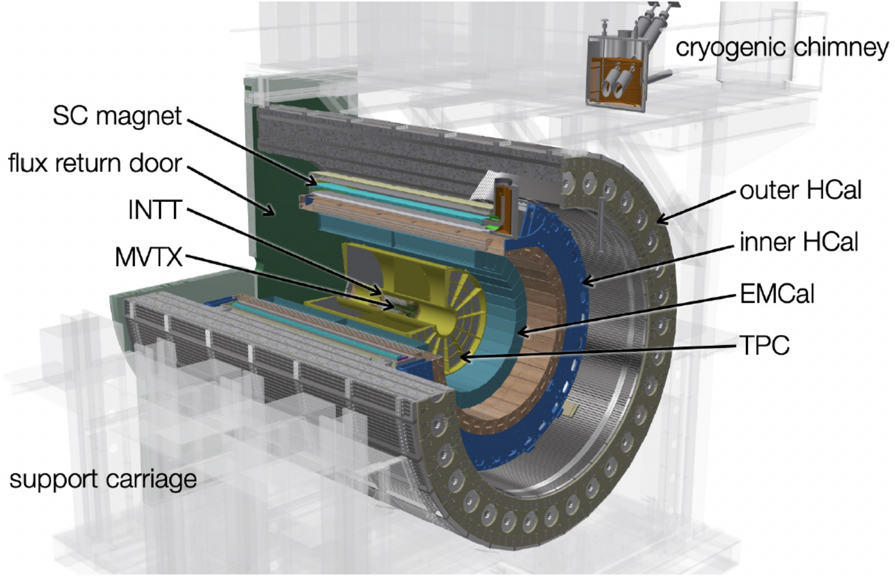


Conceived in 2012, sPHENIX was identified in the 2015 DOE Nuclear Physics Long Range Plan as essential for achieving the goal of studying the microscopic properties of the QGP

With assembly completed in 2023, sPHENIX is a state-of-the-art jet and upsilon detector

In overall design, it closely resembles general purpose particle physics detectors like CMS and ATLAS
—First detector at RHIC with hadronic calorimetry

sPHENIX



Full calorimetry (i.e. both electromagnetic and hadronic)

High-precision tracking (3 layers of Si pixels, 2 layers of Si strips, time projection chamber and TPC outer tracker)

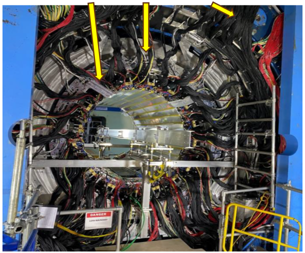
Event characterization (min bias detector, event plane detector, zero degree calorimeter)

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 pseudorapidity ($\eta < 1.1$) coverage

Provides a total depth of 4.9 hadronic interaction lengths

EMCal iHCal oHCal



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

EMCal:

- Calibrated with π^0 mass peak in pseudorapidity rings
- Tungsten powder absorber and 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 and scintillating tiles
- Tower size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

Data Selection

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

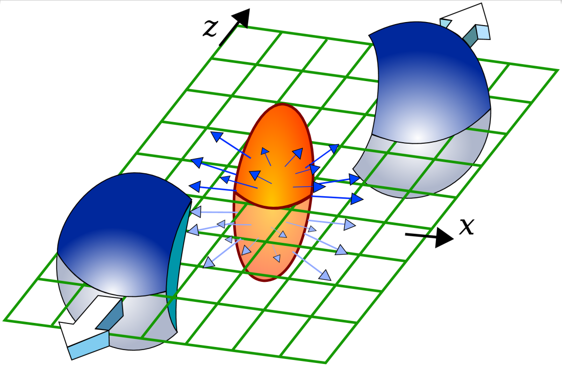
π^0 v_2 analysis

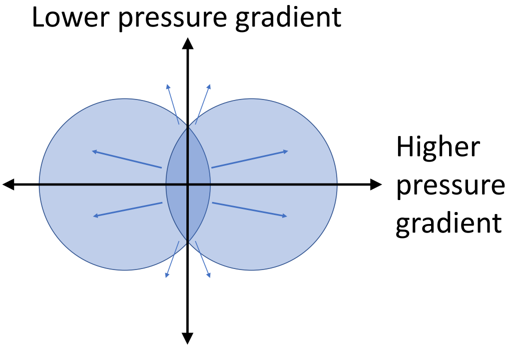
- 4.23M events
- Prioritized high statistics of EMCal clusters
- EMCal + MBD subsystems
- Centrality intervals 0–60% as determined by MBD

$dE_T/d\eta$ analysis

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

Azimuthal anisotropy measurements





$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

Hydrodynamics translates initial shape (including fluctuations) into final state distribution
In $A{+}A$, the shape is mostly elliptical, so $n = 2$ dominates

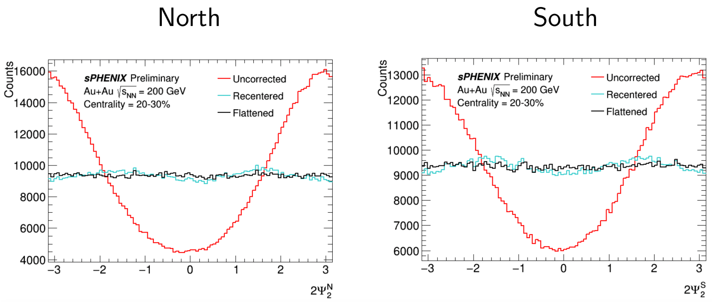
π^0 v_2 via Scalar Product Method

Scalar Product Method:

$$v_2\{SP\} = Re\frac{\left\langle q_{2,j} Q_2^{N|S*} \right\rangle}{\sqrt{Q_2^S Q_2^{N*}}}$$

$q_{2,j} = e^{i2\phi_j}$: flow vector of a π^0 candidate found from EMCal diphoton clusters

$Q_2 = \frac{1}{\sum_k w_k} \sum_k w_k e^{i2\phi_k}$: reference flow vectors measured by the north and south sides of the MBD, using PMT charge as weight



Q_2 corrected for acceptance with recentering and then flattening

Note that ψ_2 used only as diagnostic, not in calculation of v_2

π^0 Invariant Mass Peaks

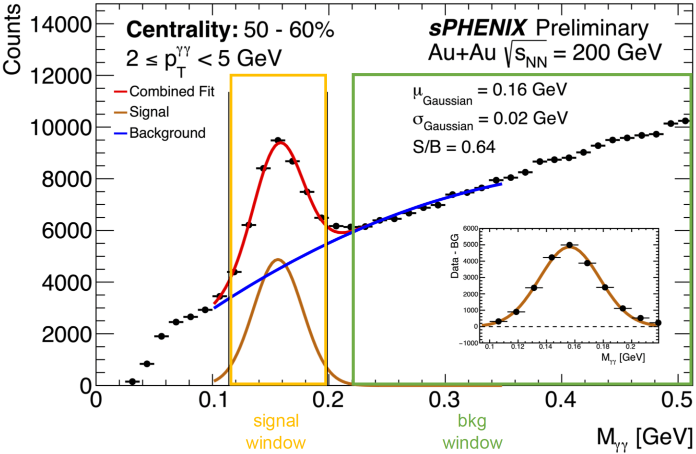
π^0 v_2 background subtraction:

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

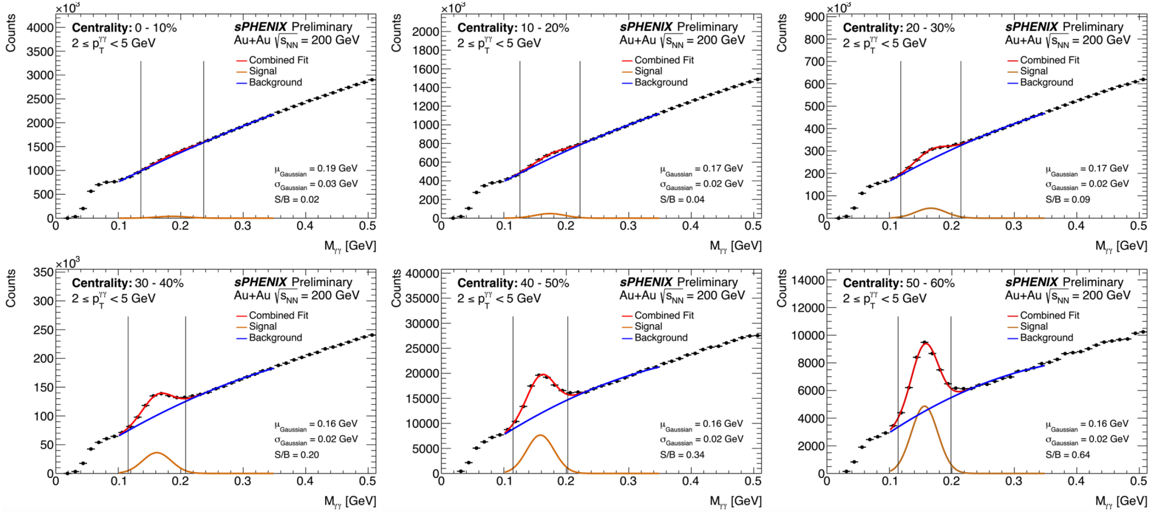
v_2^{FG} from signal window
$[\mu - 2\sigma, \mu + 2\sigma]$

v_2^{BG} from background window
$[\mu + 3\sigma, 0.5 \text{ GeV}]$

S/B ratio calculated in signal window
$[\mu - 2\sigma, \mu + 2\sigma]$



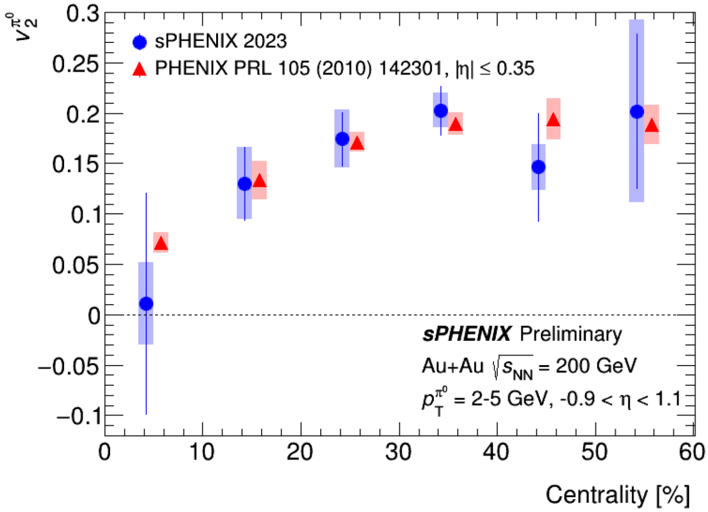
π^0 Mass Peaks vs Centrality



π^0 v_2 vs Centrality

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

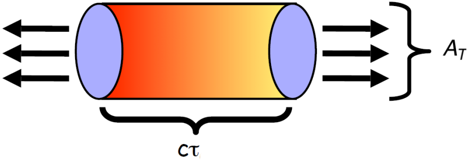
Excellent agreement to PHENIX measurement for all centralities



Longitudinal Expansion and ε_{Bj} via $dE_T/d\eta$

The Bjorken picture of impact is the applicable one at RHIC energies, so we use the Bjorken formula to estimate the energy density
—J. Bjorken, PRD 27, 140 (1983)

$$\begin{aligned}\varepsilon_{\text{nuclear matter}} &\approx 0.15\ \text{GeV/fm}^3\\ \varepsilon_{\text{proton}} &\approx 0.5\ \text{GeV/fm}^3\\ \varepsilon_{\text{critical}} &\approx 1.0\ \text{GeV/fm}^3\\ \varepsilon_{\text{RHIC}} &\approx 5.4\ \text{GeV/fm}^3\end{aligned}$$



$$\varepsilon = \frac{1}{\tau A_T}\frac{dE_T}{dy}$$

$$\begin{aligned}\tau &= \text{characteristic time}\\ A_T &= \text{transverse area of the system}\\ E_T &= \text{total transverse energy}\\ &= \textstyle\sum_i \sqrt{p_{T,i}^2 + m_i^2}\\ &= \textstyle\sum_i E_i \sin\theta_i\end{aligned}$$

Note: A_T is easy to reliably estimate (centrality) while τ is highly model-dependent (hydro), so $\varepsilon\tau$ is often quoted instead

$dE_T/d\eta$ Correction Factors

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

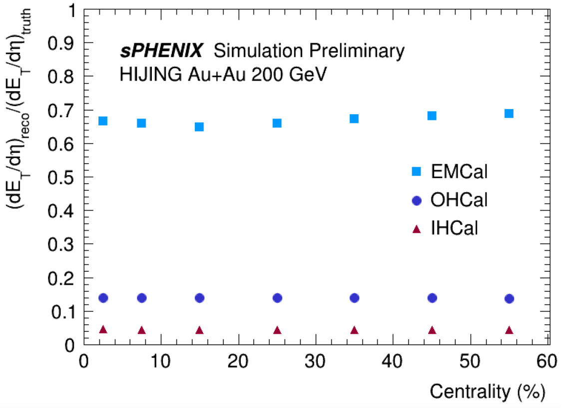
Correction factors needed to correct for detector acceptance/effects

Created using HIJING events reweighted to match particle spectra from PHENIX and STAR
—PHENIX: PRC 88, 024906 (2013)
—STAR: PRL 98, 062301 (2007)

Correction factor:

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

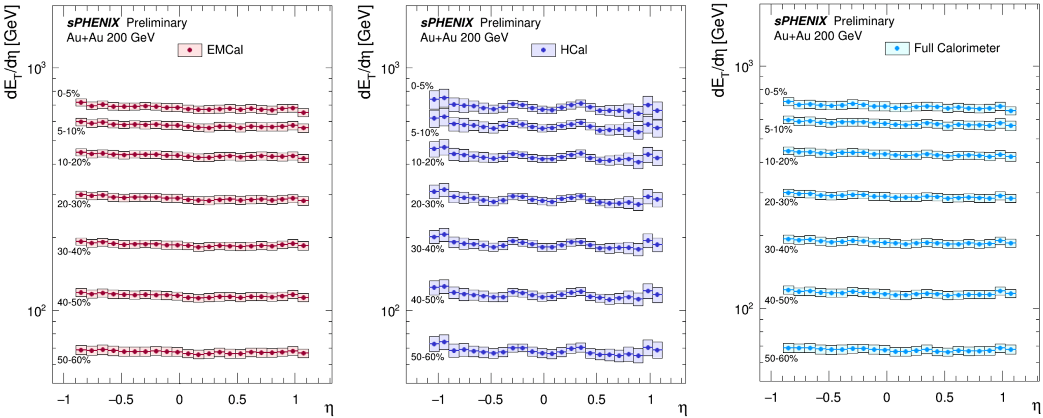
Factors show the amount of energy each calorimeter layer sees of the total collision energy



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

$dE_T/d\eta$ Calorimeter Results

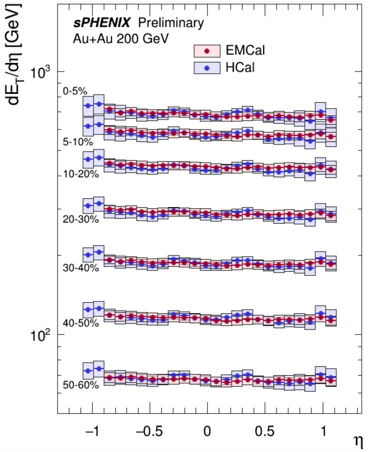
Fully corrected $dE_T/d\eta$

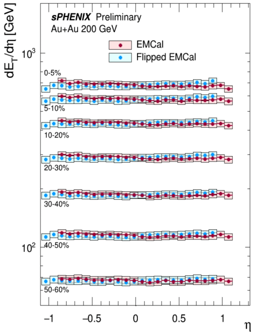


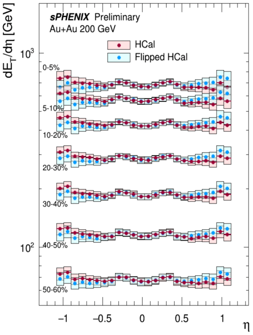
Strong dependence on centrality and good agreement between EMCal, HCal, and full calorimeter results

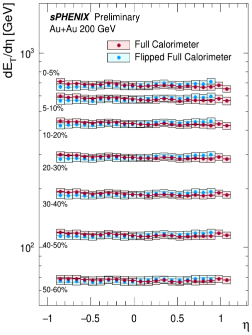
$dE_T/d\eta$ Calorimeter Results

Good agreement between EMCal and HCal









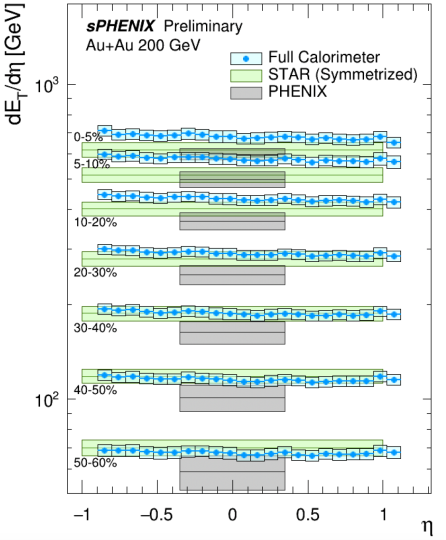
EMCal, HCal, and full calorimeter results all symmetric about $\eta = 0$ within uncertainties

$dE_T/d\eta$ Comparison to Literature

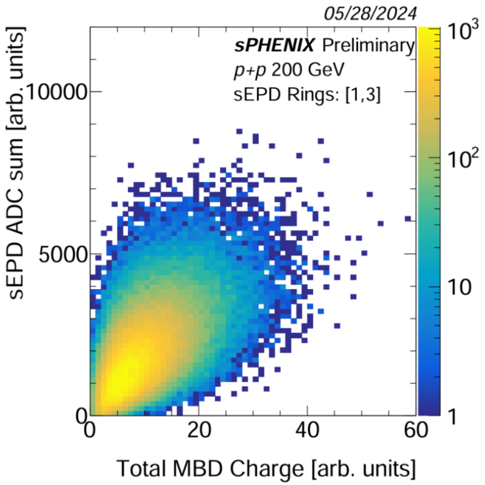
sPHENIX results are consistently higher than the results from PHENIX (PRC 93, 024901 (2016)) for all centrality bins but agree within uncertainties for mid-central bins 30–60%

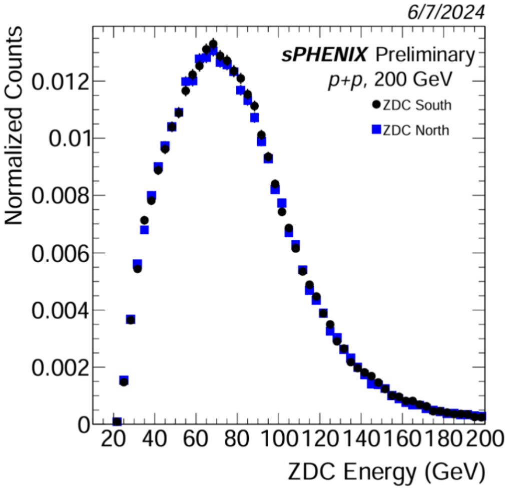
sPHENIX results are above the STAR (PRC 70, 054907, (2004)) results in the centrality range of 0–10% but agree in other centralities

Centrality definition will be finalized, and then we will also report derived quantities like $\langle N_{part} \rangle$



sPHENIX event characterization (Run 2024 Preview)





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
  —https://www.sphenix.bnl.gov/sPH-CONF-BULK-2024-01
  —https://www.sphenix.bnl.gov/sPH-CONF-BULK-2024-02
- Find these first results and all other current and future sPHENIX results at https://www.sphenix.bnl.gov/PublicResults
- See also "Intelligent experiments through real-time AI: Fast Data Processing and Autonomous Detector Control for sPHENIX and future EIC detectors" by Jakub Kvapil tomorrow morning (19 July 2024) in the Computing and Handling Data session!
- The sPHENIX dream is now the sPHENIX reality, with many more exciting results on the way!

Intermission

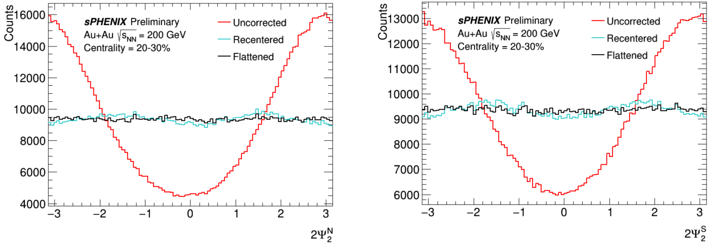
Additional Information

π^0 v_2 via Scalar Product Method

Uncorrected distribution: Inherent asymmetry in MBD results in bias in ψ_2

$$2\psi_2 = \arctan\left(\frac{Q_{2,y}}{Q_{2,x}}\right)$$

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



Flattened distribution: mean corrected $\vec{Q}_2$ multiplied by the normalized inverse square root of the covariance matrix:

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

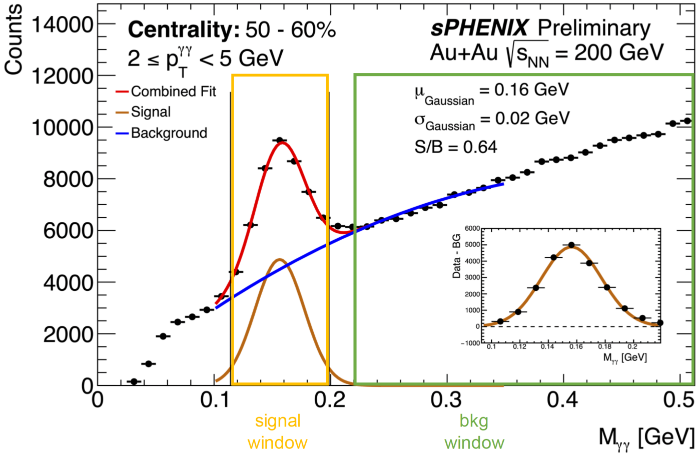
$$D = \sqrt{\langle Q_{2,x}^2 \rangle \langle Q_{2,y}^2 \rangle - \langle Q_{2,x}Q_{2,y} \rangle^2}$$
$$N = D\left(\langle Q_{2,x}^2 \rangle + \langle Q_{2,y}^2 \rangle + 2D\right)$$

π^0 Invariant Mass Peaks

EMCal diphoton pair criteria:

1. Cluster $E_{core} > 1$ GeV
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 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**