Recent

PHENIX Heavy-Flavor Results (incl. c and b flow)

Dan Richford for the PHENIX Collaboration
2024 AGS/RHIC Users Meeting
9:40 a.m., Wednesday, June 12, 2024
Overview
Anisotropic flow mechanisms

• Path-length dependent dissociation
• Charm equilibration and J/ψ regeneration
• Primordial J/ψ equilibration

Introduction
Broad Study of Light-Flavor Hadrons in Small and Large Systems at Multiple Centrality Classes & Broad Study of Flow in Small Systems at Multiple Centrality Classes
Charged Hadron Production in p+Al, d+Au, 3He+Au, Cu+Au, Au+Au, U+U (PRC 109 054910 [2024])

Nuclear Modification Factor

- Small systems on left, large on right
- Central on top, peripheral on bottom

Comprehensive look at PHENIX Data and Analysis
2-Particle Correlation $v_2$

$v_2$ in p+Au, d+Au, 3He+Au
(PR.C 107 024907 [2024])

$v_2$ in Small Systems
- Extending prior central result (PRC 105 024901)
- greater $v_2$ for more peripheral collisions

Comprehensive look at PHENIX Data and Analysis
Midrapidity Heavy-Flavor Measurement
Flavor Determination Using the VTX, DC/PC, RICH, EMCal

- $|\eta| < 0.35$
- $\Delta\phi = \pi$
- Electron-ID: RICH, EMCal
- Track projection of electrons back to the primary vertex
- ID HF electrons based on $DCA_T$ (lifetime)

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<tr>
<td>$\Lambda^+_b (\bar{\Xi}^0_b)$</td>
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FIG. 7. The measured invariant yield for (black markers) $+2-1$ electrons (brown) and the refolded electrons from charm (green) and bottom (blue) hadron decays. The sum of these three distributions in the decay-electron space are predicted by applying corresponding decay matrices to the same data. The response matrix or decay matrix assigns a probability distribution to the final result.

MSTP(91) = 1, PARP(91) = 1.5, MSTP(33) = 1, PARP(31) = 2.5.

Using

$$\frac{N}{d^3p}$$

This unfolding procedure is a likelihood-based approach that uses the Markov-chain Monte-Carlo method. This unfolding procedure is a likelihood-based approach that uses the Markov-chain Monte-Carlo method. This unfolding procedure is a likelihood-based approach that uses the Markov-chain Monte-Carlo method. This unfolding procedure is a likelihood-based approach that uses the Markov-chain Monte-Carlo method. This unfolding procedure is a likelihood-based approach that uses the Markov-chain Monte-Carlo method. This unfolding procedure is a likelihood-based approach that uses the Markov-chain Monte-Carlo method.
Improvement over last analysis:
6x more data!
Larger active VTX area for tracking
Extended $p_T$ results down to 1 GeV/c
Reduced systematic uncertainties

Heavy-Flavor Invariant Yield

- Centrality classes scaled for clarity
MCMC repeats the process through multiple iterations until the background DCA. Each source of uncertainty is discussed below. Figure 8 shows the contribution of each systematic uncertainty source. For the measured data and the unfolding procedure, likelihood calculation in the unfolding method. A 5% uncertainty introduction large statistical fluctuations in the unfolded distribution, but the DCA and DCA due to negative correlations of adjacent bins.

The systematic uncertainties are independently evaluated to statistical limitations. The yield. Figure 8 compares contributions due to negative correlations of adjacent bins.

Without additional information, the unfolding procedure introduces large statistical fluctuations in the unfolded distribution is fit with the refolded components within 1 to 100.

Background normalization \( \text{of the nominal value, and the unfolding} \) normalizes the background DCA \( \ln T \) and, where \( T = \ln (0, \text{which dominates the likelihood}) \) and \( \ln \theta \) represents the selection uncertainty. Estimates of background normalization are obtained, the same response matrices are applied to the template. For each background source, the difference between the unfolding result using nominal-background templates and that with a modified-background template is taken as the systematic uncertainty.
AuAu 200 Gev @ different centrality classes (PRC 109 044907)

Charm-Hadron Invariant Yield
- Centrality classes scaled for clarity
- pp reference scaled by TAA

Suppression for all centrality classes
- Greater for more-central events
AuAu 200 Gev @ different centrality classes (PRC 109 044907)

Bottom Hadron Invariant Yield
- Centrality classes scaled for clarity
- pp reference scaled by TAA

Mass ordering
- less than charm

Suppression for all centrality classes
- Greater for more-central events
\begin{align*}
R_{AA}^{c \rightarrow e} &= \frac{(1 - F_{AuAu})}{(1 - F_{pp})} R_{AA}^{HF} \\
R_{AA}^{b \rightarrow e} &= \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF},
\end{align*}

\begin{itemize}
\item Large charm suppression above 3.5-4 GeV/c
\item Bottom suppression above 1-2 GeV/c
\end{itemize}
Result

- Greater HF suppression in central collisions
Heavy-Flavor Flow
HF v₂ at midrapidity

\[ v^\text{meas}_2 = \langle \cos(2 \cdot (\phi_i - \Psi)) \rangle \]

- c + b together
- consistent with prior measurement without Silicon Vertex detector tracking
- Clear collective motion
- Small uncertainty

Min. bias Au+Au \( \sqrt{s_{\text{NN}}} = 200 \text{GeV} \)

- Run2014 (with VTX)
- PRC84,044905 (w/o VTX)

Additional Details: Nuc. Phys. A 982 663
c-, b-separation from unfolding leads to flow measurement at midrapidity
• measure $v_2$ in flavor-enriched $DCA_T$ regions
Charm electron $v_2$

- Comparison to prior charged hadron measurement
- Less elliptic flow below 3 GeV/c
Bottom electron $v_2$

- Comparison to prior charged hadron measurement
- Less elliptic flow below 4 GeV/c
HF Muon Flow @ Forward Rapidity

**Flavor Determination Using the FVTX, MuTr**
- $1.2 < |\eta| < 2.2$
- $\Delta \phi = 2\pi$
- Muon-ID: MuID
- Track projection of muons back to the primary vertex
- $DCA_R$

$$v_2^{HF} = \frac{1}{F^{HF}} (v_2^\mu - (1 - F^{HF})v_2^{LF})$$
HF-inclusive muon $v_2$
- Comparison to prior charged hadron measurement
- less elliptic flow below 4 GeV/c
- Consistent with results at midrapidity!

[Graph showing elliptic flow $v_2$ vs. $p_T$ for different particle types and rapidity values.]

Open Heavy Flavor Elliptic Flow

https://indico.cern.ch/event/1139644/contributions/5456502/
PHENIX data and analysis are comprehensive and sophisticated
• Many reaction types from pp to UU, and mixed

HF Production and c-, b-separation result in Au+Au shows significant improvement from prior result
• More statistics, less uncertainty
• Clear suppression of charm and bottom hadrons in QGP, varying by centrality and $n_{Part}$

Clear HF $v_2$ at midrapidity and forward rapidity
• Agreement between the two probes
• Separate c, b $v_2$ shows mass-ordering

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Backup Slides
Geometric and Momentum Anisotropy and Measure of Event Activity

The figure shows the BBC Au-going charge distribution in MB d+Au events (upper curves) and the distribution in the subset of events where there is a single neutron spectator present (lower curves). The lowest curve (blue) in each set represents events with no spectator neutrons. The distributions are color-coded by the number of binary collisions, with darker colors indicating higher collision numbers. The x-axis represents the number of binary collisions, ranging from 0 to 35, and the y-axis shows the number of events per decade, ranging from $10^{-3}$ to 1. The distribution peaks at lower collision numbers and decreases as the number of collisions increases.

The figure also includes a legend with the average number of collisions, $<N_{coll}>$, for different centrality classes: 2.6, 4.3, 5.8, 7.5, 9.3, 11.3, 13.4, 15.5, and 18.1. This information is used to identify the centrality classes associated with each data point in the distribution.
The measured values of identified charged hadron primary yields should be corrected for the geometric acceptance. The measured values of identified charged-hadron yields are therefore, the veto cut was introduced for better separation of the hadron signals from TOF. The PID and veto cuts are standard for the PHENIX detector [14, 17]. This section describes the reconstruction efficiency, and analysis cuts have been taken into account. The measured momentum and the path length. Black solid lines represent PID cuts, based on Eq. 2, which were used for hadron identification.重建效率, and分析切割已经考虑在内。测量到的粒子的动量和路径长度。黑线表示用 Eq. 2 基于的 PID 切割，用于识别粒子。
Light Flavor Invariant Yield

- Small systems (black=pAl, pink=3HeAu)
- Large systems (green=CuAu, red=UU)
- Centrality classes scaled for clarity

Charged hadrons of different collision systems @ different centrality classes (PRC 109 054910)
v2 in small systems @ different centrality classes (PRC 107 024907)
v2 in small systems @ different centrality classes (PRC 107 024907)

0.2
0.4
v2

20%-40%

40%-60%

60%-88%

PHENIX PRC.105.024901
- 3x2PC:BF
- 3x2PC:BB
This analysis
- 3x2PC:BF
- 3x2PC:BB

AMPT 5%-10%
- 3x2PC:BF
- 3x2PC:BB

PHENIX
- Participant Plane

He+Au 200 GeV 0%-5%

He+Au 200 GeV 5%-10%

He+Au 200 GeV 10%-20%

He+Au 200 GeV 20%-40%

He+Au 200 GeV 40%-60%

He+Au 200 GeV 60%-88%

FIG. 5. Second-harmonic azimuthal anisotropy \( v_2 \) \{3x2PC\} in (a) 0%–5%, (b) 5%–10%, (c) 10%–20%, (d) 20%–40%, (e) 40%–60%, and (f) 60%–88% centrality \( d + Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) with the FVTXS-CNT-FVTXN (BF) and BBCS-FVTXS-CNT (BB) detector combinations as a function of \( p_T \). The solid (black) squares are shifted for visibility. The bands around the (black) squares and (black) circles show the systematic uncertainties. The bands around the dashed (red) and dotted (blue) curves show statistical uncertainties in the AMPT calculations with the 3x2PC method. The solid (green) curves show \( v_2 \) in AMPT using the parton participant plane.

In \( d + Au \) collisions, this trend is not observed because of the limited statistical precision. Figure 9 shows that a point-by-point comparison among the different collision systems can be made with the 3x2PC method using both the BB and BF detector combinations by plotting \( v_2 \) as a function of charged-particle multiplicity \( dN_{ch} d\eta \) at midrapidity. The values of \( dN_{ch} d\eta \) are obtained from Ref. [31].

In \( 2 < p_T < 2.5 \text{ GeV/c} \), \( v_2 \{BB\} \) shows an increasing trend towards the low \( dN_{ch} d\eta \) side; the peripheral \( p + Au \) data points

FIG. 6. Second-harmonic azimuthal anisotropy \( v_2 \) \{3x2PC\} in (a) 0%–5%, (b) 5%–10%, (c) 10%–20%, (d) 20%–40%, (e) 40%–60%, and (f) 60%–88% centrality \( He+Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) with the FVTXS-CNT-FVTXN (BF) and BBCS-FVTXS-CNT (BB) detector combinations as a function of \( p_T \). The solid (black) squares are shifted for visibility. The bands around the (black) squares and (black) circles show the systematic uncertainties. The bands around the dashed (red) and dotted (blue) curves show statistical uncertainties in the AMPT calculations with the 3x2PC method. The solid (green) curves show \( v_2 \) in AMPT using the parton participant plane.
Prior Result: Au+Au HF

AuAu 200 Gev @ different centrality classes (PRC 109 044907)

Prior Result
PRC 93 034904

Fig. 19

Prior Result:
PRC 93 034904

Simulation of background components

![Graph showing fractions of signal, photonic, and nonphotonic backgrounds](image-url)

- **Signal component** in isolated electron candidates as a function of track candidates
- **Photonic background**
- **Nonphotonic background**

The isolation cut is applied. The modeling of these backgrounds is described in Ref. [25]. After subtracting these backgrounds, the remaining signal component is the inclusive heavy flavor (HF), namely the Drell-Yan process are found to be negligibly small compared to the total background. The non-photonic backgrounds for MB Au+Au, are estimated by the full GEANT-3 simulation of the PHENIX detector.
Unfolding constraint: FNP

Unfolding: 

The isolation cut is applied. The modeling of these backgrounds is described in the text and in Ref. [33]. The fraction of nonphotonic electrons (NP) are estimated by the full GEANT simulation of the PHENIX detector. After the isolation cut, the DCA distributions are matched backgrounds are determined by the RICH and VTX swap method as described in Sec. III C 1. The detailed flavor electrons to photonic electrons as from the photonic electron yields and the fraction of heavy-flavor electrons (heavy-flavor electrons) is calculated based on the invariant yields of (photonic) electrons. The photonic electron yield is calculated related to the invariant yields of heavy-flavor electrons and decay electron tracks are reconstructed and analyzed with the same analysis cuts used measured by PHENIX and decay electron tracks are reconstructed and analyzed with the same analysis cuts used.

The invariant yield of heavy-flavor electrons is calculated related to the invariant yields of heavy-flavor electrons and decay electron tracks are reconstructed and analyzed with the same analysis cuts used measured by PHENIX and decay electron tracks are reconstructed and analyzed with the same analysis cuts used.

The efficiency and acceptance cancel out in this subtraction process. The fractions of signal component in isolated electron candidates as a function of $p_T$ for different centrality classes in Au+Au are shown in Fig. 3. After the isolation cut, the DCA distributions are matched backgrounds are determined by the RICH and VTX swap method as described in Sec. III C 1. Note that the efficiency and acceptance cancel out in this subtraction process. The fractions of signal component in isolated electron candidates as a function of $p_T$ for different centrality classes in Au+Au are shown in Fig. 3. After the isolation cut, the DCA distributions are matched backgrounds are determined by the RICH and VTX swap method as described in Sec. III C 1. Note that the efficiency and acceptance cancel out in this subtraction process.

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The efficiency and acceptance cancel out in this subtraction process.
Comparison to STAR: Au+Au HF

AuAu 200 Gev @ different centrality classes (PRC 109 044907)

Comparison to STAR:

**PHENIX**

**Au+Au, min. bias**

$\sqrt{s_{NN}}=200 \text{ GeV}$

Comparison to Star

*Figure 15. Nuclear modification factor $R_{AA}$ as a function of $p_T$. The collision centrality is characterized by the number of participants increases. The high-$p_T$ region (5.0–7.0 GeV/$c$) shows a clear suppression of charm hadrons when the number of participants increases. The high-$p_T$ region (2.6–3.0 GeV/$c$) shows an increasing suppression of both charm and bottom hadrons with increasing collision centrality.*
Comparison to Models

$\sqrt{s_{NN}} = 200$ GeV

$R_{AA}$ vs. $p_T^e$ for $c \rightarrow e$ and $b \rightarrow e$

Different centrality classes (PRC 109 044907)

Comparison to Models

Models include:
- D → e (DGLV)
- B → e (DGLV)
- D → e (SUBATECH)
- B → e (SUBATECH)
- D → e (T-Matrix)
- B → e (T-Matrix)

Note: The graph shows the nuclear modification factor $R_{AA}$ for charm and bottom quark decays, comparing PHENIX data to various theoretical models.
$n_{\text{Part}}$ scaling: Au+Au HF

AuAu 200 GeV @ different centrality classes (PRC 109 044907)
HF Flow (possible rapidity effect?)

**HF-inclusive Electron $v_2$ @ Midrapidity**

- Min. bias Au+Au $\sqrt{s_{NN}}=200$ GeV
- $e^-$ from open heavy flavor

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**HF-inclusive Muon $v_2$ @ Forward Rapidity**

- $|\eta|<0.35$, $HF\rightarrow e$ (PRL98.172301)
- Charged hadron
- $HF\rightarrow \mu$

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**Remarks:**

- The result is qualitatively consistent with the expected mass ordering of energy loss for quarks ($q$) and gluons ($g$).
- Both collisional and radiative loss mechanisms suggest less energy loss with increasing collision centrality for charm decays.
- The $v_2$ is sensitive to the energy loss of particles in small collision systems at RHIC.
- The mass dependence of azimuthal anisotropy for light particles in small collision systems at RHIC is an intriguing observation.
- To see the extension of this phenomenon in heavy quark particles, we measured the bottom production.
- Suppression and significant azimuthal anisotropy for charm are reported from RHIC and LHC experiments.
- The DCA distributions are measured for charm and bottom components, and misidentified hadrons.
- Background electrons from Ke3 decays and random association with VTX hits are estimated by event-driven methods and the PHENIX detector simulation.
- The DCA is defined as the distance of closest approach (DCA) of electrons to the collision vertex.
- The VTX provides precise tracking information for high multiplicity events.
- The DCA analysis performs a statistical separation of electrons from charm and bottom decays utilizing the different decay lengths measured by a silicon vertex detector (VTX).
- The main sources of backgrounds are photon conversions, Dalitz decays of pions ($\pi^0$), and $\eta$ mesons.

**Figures:**

- **Fig. 1.** DCA distribution of electrons for minimum bias Au+Au collisions. The result from this analysis is consistent with the expected mass ordering of energy loss for quarks and gluons.
- **Fig. 2.** Inclusive electron $v_2$ vs $p_T$ and azimuthal anisotropy for light particles in small collision systems at RHIC.
HF Flow: Muons (constituent parts of equation)

- Tuned PYTHIA+GEANT4 embedded in Au+Au to get hadron and muon fractions
- Extract the contribution of open heavy flavor muons \( F_{HF} \)
- Determine heavy flavor muon \( v_2 \) in the inclusive muon sample:

![Graph showing counts vs. \( p_T \) with data points and fitted lines]

**Extracting Heavy Flavor**