PHENIX Heavy Flavor Production in Heavy-ion Collisions

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PHENIX Collaboration

QWG at Fermilab on Sep. 2003
QGP & Proton Spin

- 2 counter-circulating rings, 3.8 km circumference
- Any nucleus on any other.
- Top energies (each beam):
  - 100 GeV/nucleon Au-Au.

Pioneering High Energy Nuclear Interaction eXperiment
(460 participant from 57 institutions of 12 countries)

- Maximal Set of Observables
  - Photons, Electrons, Muons, ID-hadrons
- Highly Selective Triggering
  - High Rate Capability.
  - Rare Processes.
PHENIX Ability to Study Heavy Flavor

-- electron and muon measurement

- high resolution tracking and momentum measurement from Drift chamber.

Good electron identification from Ring Imaging Cherenkov detector (RICH) and Electromagnetic Calorimeter (EMCal).

- Good momentum resolution and muon identification from \( \mu \)ID and \( \mu \)Trk.

- Yield of Open Charm, Bottom from single leptons.

- flow of charm.

- \( J/\psi, \psi' \)

- Upsilon
Collision Topology

The impact parameter determines the number of nucleons that participate in the collision.

- Soft interactions where production scales with $N_{\text{part}}$
- Hard interactions where production scales with $N_{\text{coll}}$

\[
dN_{ch}/d\eta \big|_{\eta=0} = A \times N_{\text{part}} + B \times N_{\text{bin}}
\]

Wang, Gyulassy: nucl-th/0008014
Kharzeev, Nandi: nucl-th/0012025
Open Charm measurements

Motivation

- Mainly produced from gluon fusion. Sensitive to initial gluon density and gluon distribution
- Energy loss when propagating through dense medium
- Baseline measurement for charmonium suppression

PHENIX has measured charm cross section via single electron in run1 and run2

$$D^0 \rightarrow K^- \ell^+ \nu_e$$
$$\bar{D}^0 \rightarrow K^+ \ell^- \bar{\nu}_\ell$$

$$D^0 \bar{D}^0 \rightarrow e^+ e^- K^+ K^- \nu_e \bar{\nu}_e$$
$$D^0 \bar{D}^0 \rightarrow e^- \mu^+ K^+ K^- \nu_e \nu_\mu$$
$$D^0 \bar{D}^0 \rightarrow \mu^+ \mu^- K^+ K^- \nu_\mu \nu_\mu$$
Inclusive $e^\pm$ spectra from Au+Au at 130 GeV

main sources contributing to the $e^\pm$ spectra

— “photonic” sources
  • conversion of photons from hadron decays in material
  • Dalitz decays of light mesons ($\pi^0$, $\eta$, $\omega$, $\eta'$, $\phi$)

— “non-photonic” sources
  • semi leptonic decays of open charm (beauty)

“non-photonic” sources are picked-up via cocktail methods.
Non-photonic $e^\pm$ spectra from Au-Au at 130 GeV

Comparison with PYTHIA

- tuned to fit SPS, FNAL, ISR data
- ($\sqrt{s} < 63$ GeV)
  $\sigma_{cc} = 330 \, \mu$b for pp at 130 GeV
- scale to Au+Au using the $<N_{\text{coll}}>$ PYTHIA calculation consistent with data.

Charm cross section per binary collision from data

- assumption: all $e^\pm$ are from charm decays
- fitting PYTHIA to data for $p_T > 0.8$ GeV/c
  $\sigma_{c\bar{c}}^{0-10\%} = 380 \pm 60 \pm 200 \mu$b and $\sigma_{c\bar{c}}^{0-92\%} = 420 \pm 33 \pm 250 \mu$b
- consistent with binary scaling (within large uncertainties)
Energy dependence of charm production

PHENIX: PRL 88(2002)192303

NLO pQCD (M. Mangano et al., NPB405(1993)507)

PHENIX data is consistent with the prediction of PYTHIA and NLO pQCD calculation.
Converter method for RUN2 single electron measurement

- $e^\pm$ spectra with converter: $N^c$
- $e^\pm$ spectra without converter: $N$
- if no contribution to $e^\pm$ from non-photonic sources $\rightarrow N/N^c \approx \text{const.}$
- but spectra approach each other with increasing $p_T$
  - indication for strong non-photonic source

![PHENIX Detector - Second Year Physics Run](image)

![Graph](image)

$(e^+e^-)$ yield from Au+Au collisions @ $\sqrt{s_{NN}} = 200$ GeV

**minimum bias**
- with converter
- without converter

**PHENIX preliminary**
Non-photonic $e^\pm$ spectra from Au-Au at 200 GeV

- non-photonic $e^\pm$ yield at 200 GeV
  - larger than at 130 GeV
  - consistent with PYTHIA, assuming binary scaling
  - PYTHIA for pp at 200 GeV: $\sigma_{cc} = 650 \mu b$

- inclusive $e^\pm$ are consistent with binary scaling within the current statistical and systematical uncertainties

- no large suppression observed in $e^\pm$ from charm decay, possibly due to “dead cone” effect which result in less energy loss (Y.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B519(2001)199)
J/ψ Measurement

When Quark-Gluon plasma (QGP) is formed:


A promising signal for the observation of QGP
**J/ψ Signal in RUN2 p-p Collisions at √s=200 GeV**

- One of the baseline for understanding J/ψ production in AuAu collisions.

- Constrain models for J/ψ production (for results and discussion, see Hiroki Seto’s talk in production session)

\[ \frac{\mathrm{d}N}{\mathrm{d}y}|_{y=0} = 1.46\pm0.23\text{(stat)}\pm0.22\text{(sys)}\pm0.15\text{(abs)}\times10^{-6} \]
$J/\psi$ Measurement in Au-Au Collisions at $\sqrt{s_{nn}} = 200$ GeV

- NA50 points normalized to pp point
- Incl. systematic errors
- 90% C.L.
- One standard deviation
- Binary scaling
- Expectation with absorption (4.4 and 7.1 mb)

NA50 points normalized to pp point
Comparison with Model

Disfavor models with enhancement relative to binary collision scaling. Cannot discriminate between models that lead to suppression.
Charm Measurement in RUN3 d-Au Collision at $\sqrt{s_{nn}} = 200\text{GeV}

There’re also suppression or enhancement due to normal nuclear effect:

Gluon (anti)shadowing:

deployment of the small x gluons (very low momentum fraction partons have large size, overlap with neighbors, and fuse to thus enhancing higher population at higher momentum at the expense of lower momentum).

Nuclear absorption:
ccbar dissociation through interaction with nucleons when passing through nucleus.

Nuclear effect can be understood through p-A collisions.
Number of J/$\Psi$’s expected from the d-Au run about 400 for central arm for $e^+e^-$

Number of J/$\Psi$’s expected from the d-Au run (w/o shadowing) is about 1000/arm for $\mu^+\mu^-$
PHENIX Proposal for **Future** Heavy Flavor Measurement in Heavy-ion Collisions

**RUN4**: Au+Au at $\sqrt{s_{nn}}=200\text{ GeV}$ to measure charmonium, open charm with the maximum possible integrated luminosity.

**RUN5**: Si+Si at $\sqrt{s_{nn}}=200\text{ GeV}$ to study charmonium production in a lighter system.

**RUN6**: Au+Au at $\sqrt{s_{nn}}=62.4\text{ GeV}$ to study the energy dependence of charm production.

**RUN8**: Au+Au at $\sqrt{s_{nn}}=200\text{ GeV}$ with Silicon Vertex Detector, which will enable PHENIX in the future runs:

- to have robust measurement of gluon shadowing in p+A collisions
- to measure charm and beauty with $p_t$ above 4GeV/c
- to quantify J/ψ suppression relative to open charm production
- to improve mass resolution of J/ψ and γ to better separate different states

Muon Trigger Upgrade to enable PHENIX consume future high luminosity runs for rare event.
Separation of non-photonic $e^\pm$: cocktail method

- light hadron cocktail input:
  - $\pi^0$ (dominant source at low $p_T$)
    - $p_T$ spectra from PHENIX $\pi^0$, $\pi^\pm$ data
    - power law parameterization
  - other hadrons
    - $m_T$ scaling: $p_T \rightarrow \sqrt{p_T^2 + m_h^2 - m_\pi^2}$
    - relative normalization to $\pi$ at high $p_T$ from other measurements at SPS, FNAL, ISR, RHIC
  - photon conversions
    - material known in acceptance
- excess above cocktail
  - increasing with $p_T$
  - expected from charm decays
Photon converter in Run-2

- additional **photon converter** installed in parts of the 200 GeV run in PHENIX central arms
- 1.7 % $X_0$ brass close to beam line
- additional material increases the number of $e^\pm$ from photon conversions by a fixed factor
- ratio between Dalitz decays and photon conversions is fixed by relative branching ratios $\text{Dalitz}/\gamma\gamma$, which is very similar for $\pi^0$ and $\eta$

- comparison of spectra with and without converter allows for complete separation of contributions from non-photonic and photonic sources
  - complementary to cocktail method
  - completely different systematics
PHENIX has very broad coverage in $x_F$, $p_T$ and $x_2$ by combining
- North Arm
- Central Arm
- South Arm
**Dead Cone Effect**

**Dead Cone effect**:  
- Gluon radiation from a massive parton is suppressed at angles $\theta < Mq/Eq$ (manifestation of causality as $\nu_Q < c$).


- The slower moving quark also samples a more dilute density profile as the medium expands.

→ Reduced energy loss $\Delta E$ since most radiation is in the forward region.
→ Is $\Delta E$ inhibited enough for produced medium to be transparent to heavy quarks ($\lambda_Q > L_N$)?
Flowing D Meson Calculation.

Electron data are consistent with both:

1. Medium transparent to heavy quarks which then fragment into D/B mesons outside the system (scaled Pythia)

2. Highly opaque medium with charm boosted via rescattering and hadronizing in the system

Centrality dependence at 200 GeV

PHENIX preliminary  \( \text{Au+Au @ } \sqrt{s_{NN}} = 200 \text{ GeV} \)

- **0-10 \% central**
  - \( (e^+e^-)/2 \): non-photonic sources
  - PYTHIA: \( pp @ \sqrt{s} = 200 \text{ GeV} \)
  - \( (e^+e^-)/2 \) from charm
  - bin. scaling to Au+Au: \( x \ (975\pm94) \)

- **10-20 \% central**
  - \( (e^+e^-)/2 \): non-photonic sources
  - PYTHIA: \( pp @ \sqrt{s} = 200 \text{ GeV} \)
  - \( (e^+e^-)/2 \) from charm
  - bin. scaling to Au+Au: \( x \ (609\pm66) \)

- **20-40 \% central**
  - \( (e^+e^-)/2 \): non-photonic sources
  - PYTHIA: \( pp @ \sqrt{s} = 200 \text{ GeV} \)
  - \( (e^+e^-)/2 \) from charm
  - bin. scaling to Au+Au: \( x \ (297\pm40) \)

- **40-70 \% central**
  - \( (e^+e^-)/2 \): non-photonic sources
  - PYTHIA: \( pp @ \sqrt{s} = 200 \text{ GeV} \)
  - \( (e^+e^-)/2 \) from charm
  - bin. scaling to Au+Au: \( x \ (71\pm14) \)
Silicon Vertex Tracker in PHENIX

Strawman design under investigation

| | $|\eta|<1.2$ | $1.2<|\eta|<2.4$ |
|---|---|---|
| | $R_1=1.0\text{cm}$ | $R_2=0.5\text{cm}$ | $R_3=2.5\text{cm}$ |
| Be beam pipe $r=2\text{cm}$ |

- **Pixel barrels** (50 $\mu$m x 425 $\mu$m)
- **Strip barrels** (80 $\mu$m x 3 cm)
- **Pixel disks** (50 $\mu$m x 2 mm)

- $\sim$1.0% $X_0$ per layer
- barrel resolution $< 50 \mu$m
- forward resolution $< 150 \mu$m
Charm/Beauty measurements with SVT

- Charm Measurement by barrel + central arm

HIJING Au+Au

Beauty $\rightarrow J/\psi$ in endcap + muon arm

$J/\psi$ from B

direct $J/\psi$

z vertex (cm)

- $\Lambda_c$ vertex (cm)

Beauty $\rightarrow e$ by barrel+central arm

- $D^+ + D^0_s$

- $M_{\text{inv}} (3T)$ [GeV/c]

- $1/N_{\text{ave}} dN_{3T}/dM_{\text{inv}}$ [GeV$^{-1}$]

- $P_T > 3$ GeV/c

- $DCA_{xy}, \mu m$

- Beauty $\rightarrow J/\psi$ in endcap + muon arm

- Beauty $\rightarrow e$ by barrel+central arm

- $J/\psi$ from B

- Direct $J/\psi$

- $z$ vertex (cm)

- $M_{\text{inv}} (3T)$ [GeV/c]

- $1/N_{\text{ave}} dN_{3T}/dM_{\text{inv}}$ [GeV$^{-1}$]

- $P_T > 3$ GeV/c

- $DCA_{xy}, \mu m$

- Au+Au
  - Robust charm/beauty measurement in Au+Au
  - Energy loss of charm at high $P_T$
  - Energy loss of beauty

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Measurement of gluon shadowing with SVT

- Heavy-flavor measurement in p+A
  - Single lepton and J/Ψ with displaced vertex
- Heavy-flavor production via g+g → q+ q̅
- Extracting gluon structure function nuclei, shadowing
  - vertex detector provides broader range in x into predicted shadowing region (x ~ 10^{-2} - 10^{-3})