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Heavy flavor measurements at PHENIX

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Introduction of heavy flavor measurements

**Heavy flavor probe**

> large mass
- \( m_{c,b} \gg \Lambda_{QCD} \gg T_{QGP} \)
- \( 1/2m_{c,b} << \tau_{\text{form}} \)
- hardly generated in QGP
- thorough time evolution

> allows some pQCD calculation

model = pQCD + energy loss model

**QGP physical property**

> HF momentum and space variation → QGP property

> model parameters
- Diffusion constant
- Gluon density
Quark energy loss mechanism in QGP

collisional energy loss
- parton elastic scattering
- Brownian motion via Langevin equation
\[ \frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} \]
\[ \eta_D: \text{friction coefficient} \]
\[ \xi: \text{drift force} \]

radiative energy loss
- Bathe-Heitler for gluon radiation
\[ dP_0 \approx \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{dk^2}{k^2} \]

> Dead-Cone effect
- strong suppression of HF in small-angle radiation
\[ \propto \frac{k^2 dk^2}{(k^2 + \omega^2 \theta^2_0)^2}, (\theta_0 \equiv \frac{M}{E}) \]

> Landau-Pomeranchuk-Migdal effect
- suppression in high density
\[ \propto \frac{\lambda_{path}}{L_{form}} \]

mass ordering
\[ \Delta E_g > \Delta E_{u,d,s} > (?) \Delta E_c > (?) \Delta E_b \]
PHENIX Silicon Vertex Detector (VTX)

- installed in 2011
- 2 pixel layers + 2 strip layers
  \( (\sigma_\phi = 14.4 \, \mu m) \quad (\sigma_\phi = 23 \, \mu m) \)
- reconstruct precise collision vertex

Precise displaced tracking
- Distance of Closest Approach (DCA)
- Transverse DCA of a track is defined as
  \[ \text{DCA}_T = L - R \]
- depends on parent particle life time and mass
- DCA resolution = 60 \( \mu m \) @ 2.5 GeV
- DCA analysis allows separated measurement of bottom and charm

-> focus on single electron tracks from smi-leptonic decay channels
✓ **DCA distribution of electrons**

- $2.00 < p_T^e < 2.50$
- $1.5 < p_T < 5.0$
- no efficiency correction

![Graph showing DCA distribution of electrons](image-url)
DCA distribution of electrons

- $1.5 < p_T < 5.0$
- no efficiency correction

**BG normalization and shape**
- data driven
  > Mis-hadron, Random
- measured yield + Monte Carlo
  > Photonic, $k_{e3}$, $J/\psi$

**Heavy flavor decay electron**
- dominates at $|0.04| < \text{DCA}_T < |0.1|$
Bayesian Inference

Bayesian Inference technique
- Bayes' theory \( P(\theta|x) = \frac{P(x|\theta)\pi(\theta)}{P(x)} \)
- c/b decay electron \( dN/dp_T \), \( DCA_T(p_T) \) from PHYTIA decay matrix
- employ Markov Chain Monte Carlo for sampling

Measured data \( dN/dp_T \), \( DCA_T(p_T) \)

Yield of c/b hadrons -> electron space

\( P(x|\theta)\pi(\theta) \)
Likelihood

Parameter probabilities c/b hadron yields

regularization (smoothness)

sampled with MCMC method

\( 2.5 < p_T < 3.0 \)
\( 3.5 < p_T^c < 4.0 \)
Invariant yield of charm and bottom

Unfolded invariant yield of charm and bottom
Comparison between data and unfolding

Unfolding results agree with measured data well
Bottom electron fraction

Fraction of bottom electrons

\[ F = \frac{(b\rightarrow e)}{(b\rightarrow e + c\rightarrow e)} \]

**p+p data**
- not generate QGP
- agree with FONLL

**Au+Au data (unfolding)**
- difference shape compared to p+p
- significant enhancement at 3 GeV/c
- consistent with p+p for high \( p_T \)
“Calculation of bottom and charm $R_{AA}$”
- published inclusive HF $R_{AA}$ (Run4)
- b-fraction of AuAu and pp (STAR e-h)

$$R_{AA}^{b\rightarrow e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF}$$

$$R_{AA}^{c\rightarrow e} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R_{AA}^{HF}$$

[p_{T} < 4 GeV/c]
- bottom less suppressed than charm

[4 GeV/c < p_{T}]
- similarly suppressed
Nuclear Modification Factor $R_{AA}$

"Calculation of bottom and charm $R_{AA}$"
- published inclusive HF $R_{AA}$ (Run4)
- b-fraction of AuAu and pp(STAR e-h)

\[
R_{AA}^{b\rightarrow e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF} \\
R_{AA}^{c\rightarrow e} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R_{AA}^{HF}
\]

- $[p_T < 4 \text{ GeV/c}]$
- bottom less suppressed than charm
- $[4 \text{ GeV/c} < p_T]$
- similarly suppressed

- first measurements at RHIC
  > uncertainty is large
- need precise measurements to confirm mass ordering of c/b energy loss
  > we are analyzing high statistics and quality data (2014~2016)
Comparison between data and models

**“Collisional energy loss”**
- Depend on diffusion constant $D$
- $D(2\pi T) = 6$ agree with data
- Strong coupling

**“Radiative energy loss”**
- Depend on gluon density in QGP
- $dN_g/dy = 1000 \sim 3500(?)$
- Need more precise measurement...
“High statics and quality data in 2014-2016”
- 2014 Au+Au data x10 statistics compared to 2011
  > broader $p_T$ range (1.0 – 9.0 GeV/c)
  > update invariant yields of HF
    with centrality and angle
  > suppress sys. uncertainty
    with new BG normalization
- 2015 p+p data
  > new base line (same method)

“Analysis goal”
- centrality dependence of $R_{AA}$
- $v_n$ measurements
  > strong constraint to QGP physical property, $D(2\pi T)$, $dN_g/d\eta$
Heavy flavor is important probe for Quark-Gluon Plasma
Quark energy loss mechanism
- Langevin equation → collisional energy loss
- Bathe Heitler → radiative energy loss
Measurement of single electrons from charm and bottom
- used distance of closest approach and Bayesian inference
- bottom suppression is similar to charm at high $p_T$, but smaller than charm at low $p_T$
- compare between data and energy loss models
  - $D(2\pi T) \sim 6$, gluon density = 1000~3500
Future prospects
- high statistics data (~10 times) in 2014
✓ backup
Comparison between data and models
- Yields of $D^0$ can be calculated by unfolding charm yields + PYTHIA
- Unfolding result agree with STAR $D^0$ measurement
  > fit Levy function

\[
\begin{align*}
  f(p_T) &= p_0 \left[ 1 - \frac{(1 - p_1)p_T}{p_2} \right]^{1/(1-p_1)} \\
  &\times \left[ 1.3 \sqrt{2\pi p_4^2 G(p_T, p_3, p_4) + \frac{p_5}{1 + e^{-p_T+3}}} \right].
\end{align*}
\]
DCA distribution
Decay matrix

decay electron pT matrix

\[ P(c \rightarrow e) \]

\[ P(b \rightarrow e) \]
**Bayesian Inference**

[Bayes’ theory]

\[ P(\theta | x) = \frac{P(x | \theta)P(\theta)}{P(x)} \]

- \( P(\theta | x) \): posterior probability
- \( P(x | \theta) \): likelihood
- \( P(\theta) \): prior probability
- \( P(x) \): normalization factor

Prior, \( P(\theta) \)

\[
L = \frac{17}{2}
\begin{pmatrix}
-1 & 1 & 1 & 1 & 1 \\
1 & -2 & 1 & 1 & 1 \\
1 & 1 & -2 & 1 & 1 \\
1 & 1 & 1 & -2 & 1 \\
1 & 1 & 1 & 1 & -1
\end{pmatrix}
\]
Dead-Cone effect

light quark radiation

\[ dP_0 \approx \frac{\alpha_s}{\pi} \frac{C_F}{\omega} \frac{d\omega}{dk_\perp^2} = \frac{\alpha_s}{\pi} \frac{C_F}{\omega} \frac{d\omega}{\theta^2} \]

radiation including mass effect

\[ dP = \frac{\alpha_s}{\pi} \frac{C_F}{\omega} \frac{d\omega}{(k_\perp^2 + \omega^2 \theta_0^2)^2}, \quad \theta_0 = \frac{M}{E} \]

heavy quark radiation

\[ dP_{HQ} = dP_0 \cdot \left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-2} \]
Brownian motion
- Langevin equation
\[ \frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} \]
\( \eta_D \): coefficient of friction, \( \xi \): drift force
- diffusion coefficient
\[ D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{k} \]
Markov Chain
- Markov process = present status depend on previous status only

Algorism
- make a initial input (c/b invariant yields) with PYHIA
- calculate Log likelihood
- compare between present Log likelihood and previous log likelihood
  present > previous  ->  employ present parameters
  present < previous  ->  reject present parameters and employ previous parameters

Metropolis-Hasting Algorism
Diffusion constant
Energy loss model
Quark energy loss mechanism in QGP

+ Collisional energy loss
  - Parton elastic scattering
  - Brownian motion via Langevin equation
    \[ \frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{z} \]
    \( \eta_D \): friction coefficient
    \( \vec{z} \): drift force

+ Radiative energy loss
  - Bathe-Heitler for gluon radiation
  - Landau-Pomeranchuk-Migdal effect
    -> Suppression of radiation in high density
    \[ dP_0 \approx \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d k_\perp^2}{k_\perp^2} \times \frac{\lambda_{\text{path}}}{L_{\text{form}}} \]
  - Dead-Cone effect
    -> Strong suppression of small-angle radiation
    \[ dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 d k_\perp^2}{\left(k_\perp^2 + \omega^2 \theta_0^2\right)^2} \]
    \( \theta_0 \equiv \frac{M}{E} \)

Mass ordering

\[ \Delta E_g > \Delta E_{u,d,s} > (?) \Delta E_c > (?) \Delta E_b \]