Introduction to Heavy-Ion Physics
Part II

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Summer Student Lectures 2019
Recap Lecture 1

- Heavy-ion physics studies quark-gluon plasma (QGP)
  - Deconfined
  - Chiral symmetry restored
- Transition to QGP is expected at $T \sim 150 - 160$ MeV
- Event activity depends on impact parameter $b$
- Centrality estimated by multiplicity (ALICE) / energy (ATLAS/CMS)
• Nucleon-nucleon collisions ($N_{\text{coll}}$) and participating nucleons ($N_{\text{part}}$) estimated with Glauber model
  – Hard processes scale with $N_{\text{coll}}$
  – Soft processes scale with $N_{\text{part}}$
• Nuclear modification factor
  \[ R_{AA} = \frac{dN_{AA} / dp_T}{\langle N_{\text{coll}} \rangle dN_{pp} / dp_T} \]
  – Significant suppression of hadron production in central collisions

How does the medium achieve this suppression?
• Particle production in central collisions is strongly suppressed

How does the medium achieve this suppression?
Energy Loss in the QGP

- QGP: high density of quarks and gluons / color sources
- Traversing quark / gluon feels color fields
- **Collisional energy loss**
  - Elastic scatterings
  - Dominates at low momentum
- **Radiative energy loss**
  - Inelastic scatterings
  - Dominates at high momentum
  - Gluon bremsstrahlung

\[ \Delta E = \Delta E_{\text{coll}} + \Delta E_{\text{rad}} \]
Radiative Energy Loss

• BDPMS formalism
  – Baier, Dokshitzer, Mueller, Peigné, Schiff
  – Infinite energy limit
  – Static medium
  \[ \Delta E \sim \alpha_s C_R \hat{q} L^2 \]

• Energy loss depends on
  – Path length through medium squared
  – Casimir factor
    • \( C_R = 4/3 \) (quarks)
    • \( C_R = 3 \) (gluons)
  – Medium parameter “q hat”

L path length, driven by:
• gluon-gluon self interactions
• quantum interference

\[ \hat{q} = \frac{\mu^2}{\lambda} \]

average transverse momentum transfer

mean free path

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291
Dead Cone Effect

- Due to kinematical constraints, gluon radiation in vacuum suppressed for angles $\theta < m/E = 1/\gamma$ by
  - Massless parton $m = 0 \rightarrow$ no suppression

- Similar effect in the medium
  - Significant for charm and beauty
  - Radiative energy loss reduced by 25% (c) and 75% (b) [$\mu = 1$ GeV/c$^2$]

- Implies quark mass dependence

$$R^\pi_{AA} < R^D_{AA} < R^B_{AA}$$

Charm over light quark suppression vs. $p_T$
Collisional Energy Loss

• For light quarks and gluons

\[ \Delta E_{q,g} \sim \alpha_s C_R \mu^2 L \ln \frac{ET}{\mu^2} \]

• For heavy quarks additional term

\[ \alpha_s^2 T^2 C_R \mu^2 L \ln \frac{ET}{M^2} \]

• Energy loss depends on
  – Path length through medium **linear**
  – Parton type (light or heavy)
  – Temperature T
  – Mass of heavy quark M
  – Medium parameter \( \mu \) (average transverse momentum transfer)
Recap

• We have seen significantly suppression of charged hadron spectra
  – Dominated by light quarks / gluons…
  – … which at low $p_T$ are also produced within the medium

• Energy loss occurs by radiative and collisional processes
• Theoretical calculations extract medium properties like density, average momentum transfer, mean free path, $\hat{q}$

• Calculations more accurate for heavy quarks
• Dependence of energy loss on quark mass expected

*Let’s measure energy loss with heavy quarks!*
Heavy Quarks

- Charm ($m \sim 1.3$ GeV/c$^2$)
- Beauty ($m \sim 4.7$ GeV/c$^2$)
- Produced in hard scattering
- Essentially not produced in the QGP
- Expectation
  
  \[ R^\pi_{AA} < R^D_{AA} < R^B_{AA} \]

- LHC: $\sim 7$ D $> 2$ GeV/c per central event
D⁰ Reconstruction

- D⁰ meson: \( m = 1.87 \text{GeV/c}^2 \); \( c\tau = 123 \text{µm} \)
  - Rather short lived
  - Many decay modes
  - \( D⁰ \rightarrow K\pi \) (branching ratio 3.9%)

- Standard method: invariant mass of opposite charge pairs
  - Per central event (\( D⁰ \rightarrow K\pi, > 2 \text{GeV/c}, \text{incl. efficiencies} \)):
    0.001 compared to \(~700\) K and up to \(~2500\) \(\pi\)
  - Signal over background far too small to extract a peak

- Reduce combinatorial background (see next slides)
  - Topological cuts
  - Particle identification (PID) of K and \(\pi\)
Invariant Mass

- $D^0 \to K\pi$ without PID and without topological cuts

![Graph showing candidates vs. $M_{K\pi}$ distribution](image)

**Graph Details**
- ALICE Preliminary
- p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $L_{int} = 49 \mu$b$^{-1}$
- $D^0 \to K\pi^+$ and charge conj.
- $0 < p_T < 1$ GeV/c

**Observations**
- Peak not visible without cuts
Topological Cuts

3) Require distance of primary and secondary vertex (impact parameter) \([\sim 100 \, \mu m\) challenging for pixel detectors!\]

2) Require that K and \(\pi\) share a secondary vertex

1) Require large impact parameter tracks

4) Require pointing angle \(\theta\) to be small

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Plane transverse to beam

---

Primary vertex

Secondary vertex

---

\(cT \sim 123 \, \mu m\)
• Specific Energy Loss
  – Particles passing through matter loose energy mainly by ionization
  – Average energy loss calculated with Bethe-Bloch formula
  – Identify particle by measuring energy deposition and momentum

• Time Of Flight
  – Particles with the same momentum have slightly different speed due to their different mass
  – Needed flight time precision, e.g. for a particle with $p = 3 \text{ GeV/c}$, flying length 3.5 m
  – $t(\pi) \sim 12 \text{ ns} | t(K) - t(\pi) \sim 140 \text{ ps}$

• Methods can be combined
Invariant Mass with Cuts

- $D^0 \rightarrow K\pi$

PID reduces background, but signal peak stays of same magnitude

D. Caffarri, thesis
Recap: D Meson Yield

- We would like to learn about the energy loss of charm

- Reconstruct D meson decay to $K\pi$
  - Rare signal
  - Combinatorial background reduced with particle identification and topological cuts
  - Invariant mass distribution
  - Background with like-sign combinations
  - Apply fit to extract yield
$D \ R_{AA}$

$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$

$R_{AA}$ vs. centrality

$R_{AA}$ vs. $p_T$

**strong suppression ~ 0.2**

Introduction to Heavy-Ion Physics – Jan Fiete Grosse-Oetringhaus
$\pi R_{AA} \text{ vs. } D R_{AA}$

- Expectation
  \[ R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B} \]

- However
  \[ R_{AA}^{\pi} \approx R_{AA}^{D} \]

- Are the energy loss models wrong?
- Not necessarily
  - Effect expected for $p_T$ close to charm mass ($\sim 1.3 \text{ GeV/c}^2$)
  - Uncertainties on $D R_{AA}$ large for $p_T < 5 \text{ GeV/c}$
  - Fragmentation ($\rightarrow$ hadron) different for gluons and quarks

Let's have a look at particles containing a heavier b…
Comparison B and D

CMS Preliminary CMS, HIN-12-014

PbPb \( \sqrt{s_{NN}} = 2.76 \) TeV

Centrality Dependence

Non-prompt J/\( \psi \)

D is stronger suppressed than B! \( \rightarrow \) hint of quark mass dependence
Summary

Jet Quenching & Energy Loss

- Particle production strongly suppressed in central heavy-ion collisions
  - Mass dependence observed

- Radiative and collisional energy loss
  - Radiative energy loss dominates at high $p_T$ for u, d, c, g
  - Radiative and collisional e-loss play similar role for b quarks

- Theoretical models used to constrain medium properties like density, average momentum transfer, mean free path

$$R^\pi_{AA} \approx R^D_{AA} < R^B_{AA}$$

A dense strongly coupling medium is produced in HI collisions

Measurement of $b \rightarrow J/\psi$ requires displaced vertices. What about $J/\psi$ stemming directly from the interaction?
Quarkonia

How does a quark-gluon plasma affect c-cbar and b-bbar states?
Quarkonia

- $c$-$c\bar{c}$ ($J/\psi$, $\psi'$) and $b$-$b\bar{b}$ ($\Upsilon$, $\Upsilon'$, $\Upsilon''$) from hard process
- High density of quarks and gluons causes screening

- Changes (binding) potential

$$V(r) = -\frac{\alpha}{r} + \sigma r \quad \rightarrow \quad V(r) = -\frac{\alpha}{r} e^{-\mu r} + \sigma r \left[ 1 - e^{-\mu r} \right]$$

- Quarks with distance larger than $1/\mu$ do not see each other
  - Dissociation of $q$-$q\bar{c}$ pair!
  - Quarkonia “melt”
J/ψ Suppression

- Observed at SPS in Pb-Pb collisions ($\sqrt{s_{NN}} = 17$ GeV)
J/ψ Suppression (2)

- ... and at RHIC ($\sqrt{s_{NN}} = 200$ GeV)

Wouldn’t we expect a stronger suppression at larger $\sqrt{s_{NN}}$?
J/ψ Suppression (3)

$R_{AA}$ vs. multiplicity

LHC $\Rightarrow$ RHIC: $\sqrt{s_{NN}}$ 14 times larger ... but the suppression is smaller!
Charm Abundances

- Number of c-cbar pairs increase with cms energy
- In a central event
  - SPS ~0.1 c-cbar
  - RHIC ~10 c-cbar
  - LHC ~100 c-cbar
- c from one c-cbar may combine with cbar from another c-cbar at hadronization to form a J/ψ
J/ψ Regeneration

Dissociation and regeneration work in opposite directions

J/ψ modification vs. energy density

H. Satz

regeneration

sequential suppression

Energy Density
J/ψ Regeneration (2)

- J/ψ regeneration / statistical hadronization models

Other quarkonia states melt at different temperatures
→ QGP thermometer (see backup)
Summary Quarkonia

- High density of color charges in QGP leads to melting of quarkonia (c-cbar and b-bar)

- Large abundance of charm quarks at LHC results in regeneration of the amount of $J/\psi$

- States with smaller binding energies are more suppressed ("QGP thermometer")
Particle Yields

&

Statistical Model

What can particle abundances tell about the transition between QGP and hadrons?
Chemical Freeze-Out

- Hadronization has occurred
- Inelastic collisions stop
- Particle yields fixed

- Elastic collisions may still occur until kinetic freeze-out

- Assume system to be in chemical equilibrium
- Particle yields can be calculated with statistical models
- Calculated in framework of statistical thermodynamics
Statistical Model

- Relativistic ideal quantum gas of hadrons
- Partition function $Z$ for grand-canonical ensemble
  - How is probability distributed between available states?
  - For particle $i$ (out of $\pi, K, p, \ldots$, all known particles)

$$\ln Z_i(T,V,\mu) = \pm g_i V \int \frac{d^3 p}{(2\pi \hbar)^3} \ln \left( 1 \pm \exp \left( - \frac{(E_i(p) - \mu_i)}{T} \right) \right)$$

$$E_i = \sqrt{p^2 + m_i^2}$$

- Temperature
- Spin degeneracy
- Volume
- Chemical potential (conserved quantities)
  $$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$$
  - Baryon number
  - Strangeness
  - Charm
  - Isospin

E.g. NPA722(2006)167
Statistical Model (2)

- Chemical potential constrained with conservation laws
  \[ \mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i \]
  - Sum over considered particles (results depends on particle list)
- 3 free parameters remain (V, T, \( \mu_B \))
- Thermodynamic quantities can be calculated from \( Z \)

\[
\begin{align*}
  n &= \frac{N}{V} = -\frac{1}{V} \frac{\partial (T \ln Z)}{\partial \mu} \\
  P &= \frac{\partial (T \ln Z)}{\partial V} \\
  s &= \frac{1}{V} \frac{\partial (T \ln Z)}{\partial T}
\end{align*}
\]

- Particle densities \( n \)
- Pressure \( P \)
- Entropy \( s \)

- In particle ratios V cancels \( \Rightarrow \) two free parameters (T, \( \mu_B \))

Let’s have a look at the data…
Particle Identification

Direct particle identification

\( \pi K p d \text{ } ^3\text{He} \text{ } ^3\text{H} \)

Large impact parameter

\( K^0_S \rightarrow \pi \pi \) (c\(\tau\) = 2.7 cm)
\( \Lambda \rightarrow p \pi \) (c\(\tau\) = 7.9 cm)

“Kink” in detector volume

\( K \rightarrow \mu \nu \) (c\(\tau\) = 3.7 m)

Invariant mass

\( \phi \rightarrow K K \)
\( K^* \rightarrow K \pi \)

Cascade

\( \Xi \rightarrow \Lambda + \pi \rightarrow p \pi \pi \)
\( \Omega \rightarrow \Lambda + K \rightarrow p \pi K \)
Particle Production: pp vs. PbPb

 Strange hadrons (K, Ξ, Ω) more abundant in Pb-Pb than in pp collisions

- Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV, 0-10%
- pp \( \sqrt{s} = 7 \) TeV

\[
\begin{align*}
\frac{K^+ + K^-}{\pi^+ + \pi^-} & \quad \frac{p+\bar{p}}{\pi^+ + \pi^-} \\
\frac{2\Delta}{K_S} & \quad \frac{\Xi^- + \Xi^+}{\pi^+ + \pi^-} \\
\frac{\Omega^- + \Omega^+}{\pi^+ + \pi^-} & \quad \frac{2d}{p+\bar{p}} \\
\frac{^3He}{d} & \quad \frac{^3H + ^3\bar{H}}{\pi^+ + \pi^-} \quad \text{BR = 25%} \\
\frac{\phi}{K^+ + K^-} & \quad \frac{K^* + \bar{K}^*}{K^+ + K^-}
\end{align*}
\]
Statistical Model at LHC

12 different particles

7 orders of magnitude

Good description of particle production at LHC

$T = 155 \text{ MeV}$
$\mu_B \sim 1 \text{ MeV}$
$V \sim 5000 \text{ fm}^3$
$(200 \times V_{pp})$

<table>
<thead>
<tr>
<th>Model</th>
<th>$T$ (MeV)</th>
<th>$V$ (fm$^3$)</th>
<th>$\chi^2$/NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>THERMUS 2.3</td>
<td>155 ± 2</td>
<td>5924 ± 543</td>
<td>23.6/9</td>
</tr>
<tr>
<td>GSI-Heidelberg</td>
<td>156 ± 2</td>
<td>5330 ± 505</td>
<td>17.4/9</td>
</tr>
<tr>
<td>SHARE 3</td>
<td>156 ± 3</td>
<td>4476 ± 696</td>
<td>14.1/9</td>
</tr>
</tbody>
</table>

ALICE Preliminary
Pb-Pb $s_{NN} = 2.76 \text{ TeV}, 0-10\%$
Temperature increases with $\sqrt{s}$ and reaches plateau of about 160 MeV at $\sqrt{s_{NN}} > 20$ GeV.

Baryochemical potential drops with $\sqrt{s_{NN}}$ → transport of baryon number from nuclei to mid-rapidity is more and more difficult.

arXiv:0911.4931
QCD Phase Diagram

- Fit results from $\sqrt{s_{NN}} = 2$ to 2760 GeV
- Defines chemical freeze-out line in QCD phase diagram

adapted from PRC 73, 034905 (2006)
QCD Phase Diagram (2)

- Statistical model provides $T$ where inelastic collisions stop

Chemical freeze-out temperature $\neq$ phase transition temperature

LHC, RHIC, top SPS energies
Chemical freeze-out close to phase transition

Phase transition from lattice QCD

SPS and below
Chemical freeze-out at lower $T$
Summary
Particle Yields & Statistical Model

• After chemical freeze-out particle composition is fixed
• More than 10 species of hadrons measured at LHC
• Statistical model allows extraction of freeze-out temperature and baryochemical potential
• At high $\sqrt{s_{NN}}$ chemical freeze-out temperature close to phase transition temperature

Statistical models describe hadron production from $\sqrt{s_{NN}} = 2$ to 5040 GeV

Matter created in HI collisions is in local thermal equilibrium
Collective Flow & Hydrodynamics

How does a strongly coupled pressurized system affect particle production?

Collective flow has nothing to do with the particle flow method to reconstruct tracks and jets in ATLAS/CMS
Expansion

• After collision, QGP droplet in vacuum
• Energy density very high
• Strong pressure gradient from center to boundary

• Consequence: rapid expansion ("little bang")
• Partons get pushed by expansion
  → Momentum increases

• Measurable in the transverse plane \((p_T)\)
  – Called radial flow

Longitudinal expansion (in beam direction) not discussed here.
Have a look at for example: [http://www.physi.uni-heidelberg.de/~reygers/lectures/2015/qgp/qgp2015_06_space_time_evo.pdf](http://www.physi.uni-heidelberg.de/~reygers/lectures/2015/qgp/qgp2015_06_space_time_evo.pdf)
Radial Flow

Particle $p_T$ increases
Spectra pushed outwards

Effect larger for $p >> K >> \pi$
$\rightarrow$ mass dependence

$p = m\beta\gamma$
common velocity field ($\beta\gamma$ fixed)
$\rightarrow$ mass dependence

$\pi$ $K$ $p$

$Pb-Pb$, $\sqrt{s_{NN}} = 2.76$ TeV
$pp$, $\sqrt{s} = 2.76$ TeV

$\text{d}^2N/\text{d}p_T \text{d}y$ (arbitrary units)

$\pi$ $K$ $p$

Arbitrary normalization

$p_T$ (GeV/c)
Blast-Wave Fits

- Quantification of radial flow
  - Reproduce basic features of hydrodynamic modeling (discussed later)
- Locally thermalized medium
- Common velocity field
- Instantaneous freeze-out
- All particle species described with three parameters

\[
\frac{1}{m_T} \frac{dN}{dm_T} = \int r \, dr \, m_T \, I_0 \left( \frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_T \cosh \rho}{T_{\text{kin}}} \right) 
\]

- Bessel functions \( I_0 \) \( K_1 \)

\( \rho = \tanh^{-1} \beta_T \left( \frac{r}{R} \right)^n \)

- kinetic freeze-out temperature
- radial flow velocity
- velocity profile

PRC 48, 2462 (1993)
Blast-Wave Fits (2)

Fits describe well at low $p_T$ (high $p_T$, also hard processes)

Peripheral $\rightarrow$ Central

Expansion: $0.35 \text{ c} \rightarrow 0.65 \text{ c}$

$T_{\text{kin}}$: $150 \text{ MeV} \rightarrow 90 \text{ MeV}$

Denser system in central collisions decouples at lower $T$
Overlap of colliding nuclei not isotropic in non-central collisions

Defines reaction plane $\Psi_{RP}$ (spanned by beam axis and impact parameter vector)

→ Pressure gradients dependent on direction

Here: $\frac{dp_x}{dL} > \frac{dp_y}{dL}$
Elliptic Flow (2)

- Spatial anisotropy (almond shape)
  - Quantified by eccentricity $\varepsilon$
    $$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$
  - Pressure gradient larger in-plane
  - Pressure pushes partons
    - More in in-plane than out-of-plane

- Spatial anisotropy converts into momentum-space anisotropy
  - "Faster" particles in-plane
  - Measurable in the final state!
Elliptic Flow (3)

- Particles as a function of $\varphi - \Psi_{RP}$

\[
\frac{dN}{d\varphi} = A(1 + 2v_2 \cos 2(\varphi - \Psi_{RP}))
\]

- Define $v_2 = \langle \cos 2 (\varphi - \Psi_{RP}) \rangle$
  - Second coefficient of Fourier expansion
- $\Psi_{RP}$ common symmetry plane (for all particles)
- What if there were no correlations with $\Psi_{RP}$?
Measuring Elliptic Flow

\[ v_2 = < \cos 2 (\varphi - \Psi_{RP}) > \]

- Reaction plane angle
  - From the particles themselves
    
    \[
    Q_x = \sum_i w_i \cos 2\varphi_i \quad Q_y = \sum_i w_i \sin 2\varphi_i \quad \Psi_{RP} = \tan^{-1}(Q_x, Q_y) / 2
    \]
    
  - \( \Psi_{RP} \) approximates true reaction-plane angle (called event plane)
- Calculation of integrated \( v_2 = < \cos 2 (\varphi - \Psi_{RP}) > \)
- \( v_2(p_T) \) by considering only particles at given \( p_T \)
- Called event plane method, denoted \( v_2\{\text{EP}\} \)
\( \sqrt{s_{NN}} \) Dependence

- Increases with \( \sqrt{s_{NN}} \)
- At LHC \( v_2 \sim 0.06 \)
  - What does that mean?
  
  \[
  \frac{dN}{d\varphi} = A(1 + 2v_2 \cos 2(\varphi - \Psi_{RP}))
  \]
  
  - \( 2v_2 = 12\% \) of particles “move” from out-of-plane to in-plane
Centrality Dependence

- Strong centrality dependence
- $v_2$ largest for 40-50%
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid-central collisions
- Small overlap region in peripheral collisions
Centrality dependence independent of $p_T$.

- Largest $v_2$ for $p_T \sim 3$ GeV/c.
- Low and intermediate $p_T$, $v_2$ caused by collective expansion.
- Large $p_T$, $v_2$ caused by length-dependent jet quenching.
  - Longer path length out of plane than in plane.

$p_T$ Dependence
Recap

• Pressure in dense medium affects momenta
• Isotropic expansion effect called *radial flow*

• Overlap of colliding nuclei causes spatial anisotropy
• Converted into momentum-space anisotropy in medium evolution
• Modulation of observed particles
• Quantified by $v_2 = \langle \cos 2 (\varphi - \Psi_{RP}) \rangle$

**What other methods exist to measure $v_2$?**

**What effect do jet-related particles have on $v_2$?**
B → J/ψ

- B⁺; m = 5.28 GeV; cτ = 492 µm (4 times larger than D)
- B⁰; m = 5.28 GeV; cτ = 455 µm

- B⁺ → J/ψ + X (branching ratio ~ 0.5%)
- B⁰ → J/ψ + X (branching ratio ~ 0.5%)
- J/ψ → μμ (branching ratio ~ 6%)

- Identification by displaced secondary vertex
  - No reconstruction of full decay chain
B Identification

- Most probably transverse b-hadron decay length
  - Transverse because vertex is better known in this direction

  \[ L_{xy} = \frac{\hat{u}^T S^{-1} \vec{r}}{\hat{u}^T S^{-1} \hat{u}} \]

  - \( u \) J/\( \psi \) vector
  - \( r \) primary vertex
  - \( S \) cov. matrices

- Convert to pseudo-proper decay length as estimate of b-hadron decay length (time dilatation)

  \[ l_{J/\psi} = L_{xy} m_{J/\psi} / p_T \]

  - J/\( \psi \) candidate mass and \( p_T \)
Decay Length Distribution

Events vs. $l_{J/\psi}$

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

- $|y| < 2.4$
- $6.5 < p_T < 30$ GeV/c
- Cent. 0-100%

- data
- total fit
- bkgd + non-prompt
- background

$\frac{l_{J/\psi}}{\phi} < 0$
combinatorics
resolution

$\frac{l_{J/\psi}}{\phi} > 0$
combinatorics
resolution
b decays

→ Experimental handle on resolution of $l_{J/\psi}$
Yield Extraction

- (Multi-dimensional) fit to $l_{J/\psi}$ and invariant mass $m_{\mu\mu}$
  - Total number of $J/\psi$ and fraction of displaced $J/\psi$

**Events vs. $l_{J/\psi}$**

**Events vs. $m_{J/\psi}$**

CMS, HIN-12-014
QGP Thermometer

States with lower binding energies more suppressed!