Heavy-Ion Physics: Mini-Big Bangs in the Lab

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Outline

• Studying QGP in nuclear collisions
• What can we learn from heavy quarks in nuclear collisions?
• Experimental toolkit
• Open charm and charmonium
  • a brief and incomplete selection of heavy-ion charm results
• Summary & outlook
Nuclei as Heavy As Bulls ...

“It would be interesting to explore new phenomena by distributing high energy or high nucleon density over a relatively large volume”, T.D. Lee (1974)

Ultrarelativistic heavy-ion collisions allow the creation of a hot and dense state of matter

➢ use heavy ions to scan through the QCD phase diagram

- RHIC Au+Au at $\sqrt{s_{NN}} = 7.7 – 200$ GeV
- and U+U at $\sqrt{s_{NN}} = 193$ GeV
- LHC Pb+Pb at $\sqrt{s_{NN}} = 2.76 – 5$ TeV
- $\gamma$ between 100 - 2500
Studying the Quark-Gluon Plasma

• What are the dynamical properties of a such strongly interacting many-body system?
  • energy loss mechanisms
• what is the strength of the collective expansion
  • do quarks thermalize?

➢ Look for probes that are produced early, interact with the medium, and experience the full evolution

Typical time scales at RHIC:
• heavy ions cross in ~ 0.3 fm/c (LHC: ~10^{-3} fm/c)

Paul Sorensen (BNL)
Experimental Observables: Energy Loss

• Measure suppression patterns
  - probes travel through and strongly interacting with the medium

• Nuclear Modification Factor $R_{AA}$
  - quantify medium effects
  - “zero hypothesis”: scale $p+p$ to $A+A$ with $N_{coll}$

\[
R_{AA}(p_T) = \frac{d^2N_{AA}/dp_Td\eta}{\langle N_{AA}_{coll} \rangle d^2N_{pp}/dp_Td\eta}
\]

• Hard processes:
  - $R_{AA} = 1$ in the absence of nuclear effects or $R_{AA} < 1$ due to energy loss in the medium
  - competing mechanism may push $R_{AA}$ up, e.g. Cronin effect, radial flow

• Soft processes: expect $R_{AA} < 1$
  - particle production scales with $N_{part}$
Experimental Observables: Collective Flow

- Measure collective flow with respective to reaction plane.
  - elliptic flow \( v_2 \): 2\(^{nd} \) Fourier coefficient

  ➢ For a thermalized system, expect initial coordinate-space anisotropy to be reflected in momentum-space anisotropy
  - particularly prominent in non-central collisions

- Gain information on degree of thermalization of medium
  - \( v_2 \) is sensitive to viscosity \( \eta/s \)

- At low \( p_T \): \( v_2 > 0 \)
  - evidence for collective hydrodynamical expansion
    - QGP evolves as a nearly perfect liquid

- At high \( p_T \): \( v_2 > 0 \)
  - due to path-length dependent E-loss of hard partons

\[
\frac{dN(p_T, y)}{d\phi} \propto 1 + 2v_2 \cos(2(\phi - \Psi))
\]
Heavy Flavors as Probes

- Charm and Bottom quarks are **heavy**
  - \( m_c \sim 1.3 \text{GeV}/c^2, \ m_b \sim 4.2 \text{GeV}/c^2 > \Lambda_{\text{QCD}}, T_{\text{QGP}} \)

- What does this heaviness imply ...
  - \( m_{c,b} > \Lambda_{\text{QCD}} \): production described in perturbative QCD
  - \( m_{c,b} > T_{\text{QGP}} \): thermal contribution from QGP negligible.

- Produced through hard scattering, early in heavy-ion collisions
  - final multiplicities set by initial hard production
Heavy Flavors as Probes

• Typical time scales in the evolution ...
  • Heavy ion crossing ~ 0.3 fm/c (at RHIC)
  • $J/\psi$ formation time $\tau \sim 1/2m_c < 0.1$ fm/c
  • QGP thermalization time $\sim 0.3 - 0.6$ fm/c
  • QGP life time $\sim 5 - 10$ fm/c

production and potential modification in the medium at different time scales.

Heavy flavors can serve as well-calibrated probes
  • experience the full evolution of the QGP
  • flow, energy loss, and dissociation
Measuring Heavy Flavor Particles

Open Heavy Flavor Measurements

- **semi-leptonic decays** $D \to K \ell \nu_{\ell}$
  - large branching ratio
  - single $e^\pm, \mu^\pm$: indirect access to kinematics
  - background from conversions and light hadron decays

- **hadronic decays** $D \to K\pi$ and $D^* \to D\pi$
  - small branching ratio
  - full topological reconstruction: direct access to kinematics
  - if not secondary vertex: large combinatorial background; need vertex detector!

- $B \to J/\psi \to \ell^+\ell^-$
  - non-prompt $J/\psi$ measurement
  - vertex and EM/muon detectors

Quarkonia

- Leptonic decays, e.g. $J/\psi \to e^+e^-, \mu^+\mu^-$
  - need EM/muon detector
The Experimental Toolbox

• Colliding Systems: A+A, p+p, and p+A
  • compare hot nuclear medium (in A+A) to baseline (from p+p)
  • disentangle initial state effects (p+A) from final state observations (A+A)

• Perform Heavy Quark Tomography
  • calibrated probe: heavy flavors mostly produced in initial hard scattering, calculable in pQCD
  • compare light quarks with charm and bottom to disentangle parton energy loss mechanisms
  • compare open charm hadron yields to study hadronization

• Considerable theoretical and experimental efforts have been underway
  • with recent detector upgrades
  • and new upgrades planned in the near future
Heavy Ion Experiments at RHIC & LHC

- **STAR**
  - dielectrons
  - dimuons (MTD, 2014-)
  - TPC + Heavy Flavor Tracker (2014-2016)

- **PHENIX (-2016)**
  - dielectrons
  - dimuons at forward rapidity
  - VTX (2011) and FVTX (2012)

- sPHENIX (2022+)
  - excellent Y reconstruction

- **ALICE**
  - dielectrons
  - dimuons
  - TPC + Inner Tracker System (ITS)

- **ATLAS**
  - dimuons
  - inner detector (ID) tracking system

- **CMS**
  - dimuons
  - inner tracker

- **LHCb (2015)**
  - fixed target & collider mode
  - low-$p_T$ quarkonia at forward rapidity
Medium Interactions: Probing Energy Loss

Mechanisms for parton energy loss in QCD medium

- **Collisional**: collisions with medium gluons
  \[ \Delta E \sim \log(E) \] L

- **Radiative**: medium-induced gluon radiation
  - **Low energy**: incoherent radiation (Gunion-Bertsch)
    \[ \Delta E \sim EL/\lambda_{\text{mfp}} \]
  - **Intermediate energy**: coherent radiation (BDMPS-Z)
    \[ \Delta E \sim \sqrt{EL} \]
  - **High energy**: "thin media", mostly produced outside QGP (not significant contribution)
    \[ \Delta E \sim L^2 \]

Dead cone effect:
- gluon radiation modified by the mass of parent quark
  - radiation for angles \( \theta < m/E \) is suppressed
  - effectively reduces radiative energy loss for heavy quarks

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]
From Energy Loss to $R_{AA}$

Measurements at RHIC

- $R_{AA} > 1$ for $p_T \sim 1.5\,\text{GeV/c}$ – enhancement ...
  indications of charm coalescence with a radially flowing medium?

- $R_{AA} < 1$ at high $p_T > 4\,\text{GeV/c}$ - significant suppression
  - strong charm-medium interactions
    - $R_{AA}(D) \sim R_{AA}(\pi)$

- Do we understand the initial interactions, i.e. “Cold Nuclear Matter” effects? more on that later ...

*STAR: PRL 113 (2014) 142301; QM15*
From Energy Loss to $R_{AA}$

Measurements at LHC

- $R_{AA}(\pi) \leq R_{AA}(D)$

Djordjevic  [PRL112 (2014) 042302]

Inherently quantitative solution:

- despite charged hadrons at LHC predominantly from gluons,
- jet fragmentation distorts bare fragmentation patterns

- net effect: moderate to no difference
Comparing Bottom to Charm $R_{AA}$

At RHIC first results from PHENIX

- B mesons identified via displaced (non-prompt) $J/\psi$

At LHC results from ALICE & CMS

- $R_{AA}(B) > R_{AA}(D)$

**ALICE, CMS 2.76 TeV**

CMS: EPJC77 (2017) 252
ALICE: JHEP 11 (2015) 205
Heavy Flavor Flow

*Analogy by Jamie Nagle (UC Boulder)*

“No putting a rock in a stream and watch if the stream can drag it along”

- **Low $p_T$:** do heavy quarks take part in flow?
  - if so, what is the mechanism? Coalescence?

- **High $p_T$:** probe path length dependence of energy loss
  - additional measure of energy loss
  - in-plane vs. out-of-plane
  - test models that include heavy flavor interactions in an expanding medium
Open Charm Flow ... at LHC

Recall flow measurement:
extract medium properties from motion of heavy quarks in medium (Brownian motion), e.g. diffusion coefficient

Recall nuclear modification measurements:
D-meson $R_{AA}$ suppression at high $p_T$ $\Rightarrow$
strong charm-medium interactions

- at LHC: $D^0 v_2$ compatible with light flavor $v_2$
- indications of thermalized charm?
... and $D^0 v_2$ at RHIC

- Low-$p_T$ $v_2$ is especially sensitive to the partonic medium:
  - scattering strength, transport properties

- What do we observe at low $p_T$ at RHIC ...
  - mass ordering for $p_T < 2$ GeV/$c$ (hydrodynamic behavior)
  - $v_2$ follows similar NCQ scaling as observed for light hadrons for $(m_T - m_0) < 1$ GeV/$c^2$

- Evidence of charm flow similar to that of the medium
  suggests charm quarks may have achieved thermalization
Open Charm and Strangeness \( \text{... } D_S \)

- \( D_S \) yield is sensitive to strangeness production and hadronization mechanism
  - strangeness enhancement observed in heavy-ion collisions from SPS to LHC
- If formation dominated by in-medium recombination with light quarks ...
  ➢ then what is the effect on yield?
  ➢ Model description agrees within uncertainties at low \( p_T \)
    - but, at high \( p_T \) under predicts because it does not include inelastic processes (gluon radiation)

**At LHC ...**

\[ R_{AA} = \frac{N_{\text{AA}}}{N_{\text{pp}}} \]

- Average \( D^0, D^+, D^{*+}, |y|<0.5 \)
- with \( p_T \)-extrapolated pp reference
- \( D^*_s, |y|<0.5 \)

**At RHIC ...**

- \( D_s \) (Run 14)
- Extrapolated error from \( p+p \) ref.
- \( D^0 \) (Run 10+11)
- Au+Au 10-40%

RHIC \( R_{AA} \) of \( D_s \) higher than 1, but statistically not significant
Quarkonia in Strongly Interacting QGP

- Sensitive to color screening of quark potential
  - QGP consists of deconfined color charges
  - proposed as a QGP signature in the mid-80s by Matsui & Satz PLB 178 (1986) 416

- $r_d(T)$ decreases with increasing $T$
  - if $r_d(T)$ falls below screening radius $r_i$ for quarkonium state $i$, then $q\bar{q}$ cannot bind ...
    - $i = \psi'$, $X_c$, $J/\psi$, ..., $\Upsilon(1S)$ cannot exist

- Suppression of different states determined by $T_{med}$ and $E_{bind}$
  - sequential quarkonium dissociation points $T_i$ specify temperature of the QGP

- QGP thermometer

PPC 2017 (Corpus Christi, TX) - May 24, 2017
Frank Geurts (Rice Univ., Houston TX)
A More Complicated Picture Emerges

- Measured J/\Psi yields include significant feeddown contributions
  - prompt: \(~10\%\) from \(\psi(2S)\) and \(~30\%\) from \(X_c\) decays
  - non-prompt: B mesons carry 10-25\% of charmonium yield

- Contributions from Cold Nuclear Medium effects
  - enhancement mechanisms, Cronin effect
  - suppression mechanisms, e.g. gluon shadowing (nPDFs), nuclear absorption, initial state energy loss
    - systematic studies to measure effective absorption cross section

- Contributions from hot & dense medium effects
  - recombination from uncorrelated charm pairs

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Eskola et al. JHEP 04 (2009) 065
J/ψ in Hot Nuclear Matter

- J/ψ \( R_{AA} \) for \( p_T > 0 \) GeV/c: smaller at RHIC than LHC \( \Rightarrow \) more recombination at LHC
- J/ψ \( R_{AA} \) for \( p_T > 5 \) GeV/c: larger at RHIC than LHC \( \Rightarrow \) stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe the data
Sequential Suppression in Bottomonium

- $\Upsilon$ measurements
  - negligible recombination effect
    - @RHIC: $\sigma_{cc} \sim 800 \mu$b $\gg \sigma_{bb} \sim 1-2 \mu$b
  - less co-mover absorption predicted
    - $\Upsilon(1S)$ tightly bound, thus large kinematic threshold
    - expect $\sigma_{\Upsilon_{abs}} \sim 0.2 \mu$b $< \sigma_{J/\psi_{abs}}$
  - Lin & Ko, PLB 503 (2001) 104
  - low production rate

- $\Upsilon$ suppression pattern supports sequential melting
Summary & Outlook

• Heavy flavors are excellent probes to study hot and dense nuclear matter
  • HF is created earlier in the system and experiences the full evolution
• Considerable body of data available
  • with different colliding systems
  • at RHIC and LHC energies
• Significant theoretical interest and effort
• Recent detector upgrades are delivering very promising results
  • paired with spectacular increases in delivered luminosities by the accelerators
• Expect new detector upgrades to improve vertex and calorimetry performance
  • both at RHIC and LHC

➢ These are exciting times for
  “Nuclei and Flavors as Heavy as Bulls ... “
Backup Slides
Cold Nuclear Matter Effects ...

Look for initial state (CNM) effects to $R_{p(d)A}$ in d+Au (RHIC) or p+Pb (LHC)

• Open heavy-flavor: Measurements at RHIC of $e^\pm$ in d+Au
  • could the difference at low $p_T$ between light and heavy flavor be attributed to CNM effects?

system-size study incl. Cu+Cu

- smooth evolution from d+Au to Au+Au for both versus $p_T$ and $N_{\text{part}}$
Open Heavy Flavor: CNM at Forward Rapidity

PHENIX $\mu^-$ measurements at forward and backward rapidities in d+Au

Peripheral Collisions
- no significant modifications

Central Collisions
- suppression at forward $y$
- enhancement at backward $y$
  - EPS09 nPDF calculations cannot describe backward $y$
  - Other CNM effects?

Final state parton recombination

Peripher al Collisions

Central Collisions
J/ψ in Cold Nuclear Matter

Compare $R_{dA}$ measurements of J/$\psi$ with open heavy flavor
be mindful of the different kinematics

• Expect sensitivity to the same effects as seen in $R_{dA}$ of $\mu^-$
  ➢ consistency in the forward rapidity

• However, in backward rapidity J/ψ shows additional effect of breakup
  • beyond the underlying HF $\mu^-$
  • backward rapidity = A-going direction, higher particle densities
  ➢ Recent comparisons with $\psi'$ suggest importance of co-mover dissociation
Comparing $R_{AA}$ and $v_2$ to Models

- Constrain models by comparing to both collective flow and nuclear modification

- **DUKE**: Langevin simulation
  - transport properties tuned to LHC
  - $(2\pi T)D=7$
  - doesn’t describe magnitude of $v_2$

- **SUBATECH**: pQCD
  - re-summation with hard thermal loops
  - $(2\pi T)D=2-4$
  - good agreement for both $v_2$ and $R_{AA}$

- **TAMU**: non-perturbative T-matrix
  - $(2\pi T)D=2 – 7$
  - good agreement with $v_2$ at low $p_T$
  - model favors including of $c$ quark diffusion in the medium