Big Questions on Small Systems

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Heavy quarks carry information about early stage of collisions:

- Charm(c) and bottom(b) quarks are massive
- Formation takes place only early in the collision
- Sensitivity to initial gluon density and gluon distribution

Selected results on HF and Quarkonia

R.Rapp, D.Blaschke, P.Crochet, Prog. in Nuclear and Particle Physics 65, 209, 2010
Why they are good probes?

Heavy Quarks : Why good probes?

Large Mass : $m_{c,b} \gg \Lambda_{QCD}$

Are hard probes, even at low $p_T$

Do not change flavor while interacting with the QCD medium, although the phase-space distribution does change

$\tau_{\text{prod}} \sim 1/2m \sim 0.1 \text{ fm} \ll \tau_{QGP} \sim 5-10 \text{ fm}$

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{\text{Yield} (A + A)}{\text{Yield} (p + p) \times \langle N_{\text{coll}} \rangle}$$

• Knowing system properties in a simple way
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile of the medium

• Heavy-ion (AA) collisions
  - hard processes : calibrated probe
  - transported through the whole evolution of the system
  - suppression provides density measurements
sQGP and Heavy Quarks : implications in small systems

-- Previously QGP was felt to be a weakly interacting system of quarks and gluons

-- Experimental results from heavy ions (A+A) @RHIC showed a new picture
  → Hot, strongly interacting nearly perfect &
  → Almost opaque relativistic liquid → strongly coupled QGP → “sQGP”

-- LHC program added more to our understanding
  → Critical studies done to understand the evolution
    between p+p, p+A collisions (small systems) & A+A collisions
  → High energies at LHC → huge excess of Hard Probes (Jets,
    Electroweak particles & Heavy-Flavors (HF) ,
    including Quarkonia family(c c & b b bound states)
  → Elastic scattering of Heavy Quarks in the “sQGP”
    → important element for understanding HF at collider energies
Heavy quarks in pp and pA collisions

pp : test understanding of heavy-quark production

- parton level production processes
  - LO contributions:
    - gluon fusion, quark-antiquark annihilation
  - NLO contributions: gluon splitting, flavor excitation
  - also complex mechanisms, like, Multi Parton Interactions (MPI)

- understand perturbative QCD calculations where theoretical uncertainties are due to
  - renormalization and factorization scales
  - quark masses

- production mechanisms via differential measurements
  - multiplicity dependence of heavy-flavor production cross sections
  - angular correlation measurements

- pp collisions act as a reference for pA and AA collisions

pA collisions : Useful as there is no QGP expected while there are some high density effects

- Nuclear modification of Parton Density Functions
- Saturation and shadowing effects
- Energy loss in Cold Nuclear Matter (CNM)
- Multiple binary collisions and $k_T$ broadening
- Help to compare AA collisions
• Left plot: the electrons from semi-leptonic decays of HF hadrons at mid-rapidity in Pb-Pb collisions

• Right plot shows the pQCD calculations in agreement with data at forward rapidity in pp collisions
yields of leptons from heavy-flavor decays show suppression at high-pT in central Pb-Pb collisions, compared with binary scaled pp collisions.

less suppression in more peripheral collisions
**D⁰ mesons in pA collisions : LHC**

ALICE, PHYSICAL REVIEW C 94, 054908 (2016)

LHCb, JHEP 1710 (2017) 090

- ALICE $R_{pA}$ data are consistent with 1 within uncertainties
- We see no major modification in pPb and also similar with LHCb
- We need more precise data to be able to separate between the models
D mesons in AA collisions: LHC

ALICE, Pb+Pb 2.76 TeV, JHEP 03 (2016) 081

CMS, Pb+Pb 5.02 TeV, CMS-PAS-HIN-16-001

• Similar suppression in Pb+Pb at 2.76 TeV and 5.02 TeV
Consistent with various models

But we need more precise data to extract detailed underlying mechanism from the various models
The dAu collisions → consistent or larger than 1

High-pT suppression observed in central Au+Au collisions

Final-state effect due to the formation of a hot and dense medium

Cu+Cu → smaller suppression than central Au+Au collisions due to the smaller size of the system created in the collisions of the lighter Cu nuclei

We see clear systematic difference between the two sets of $R_{AA}$ results

Hence showing that the suppression is stronger in Pb+Pb collisions for the same centrality class

HF-muons
**Different Particle Species**

**Phenix, d+Au**

PRL 112, 252301 (2014)

**ALICE, CMS**


**Medium studies**

- **More suppression for bottomonia**
  - Sequential suppression, consistent with predictions from hadronic comover effects, is observed in pPb, indicating the presence of final-state effects in pPb collisions

**HF & J/ψ**

- J/ψ and open charm at backward rapidity have larger difference compared to forward rapidity

- Maybe related to the longer time this cc state requires to traverse the nuclear matter or the larger density of co-moving particles after the initial collision at backward rapidity

- This comparison motivates that additional CNM effect, nuclear breakup, significantly affects J/ψ production at mid and backward rapidity

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Bottomonia flow?

Studies of $J/\psi \nu_2$ at RHIC and LHC energies have provided important elements toward the understanding on the production mechanisms and thermalization of charm quarks. Bottomonia has an advantage since it is a cleaner probe. A brief discussion has been provided for $Y(1S) \nu_2$, which can become the new probe for QGP, including the necessity of studies for small systems.

ALICE and CMS

ArXiv: 1812.06772 (December 2018) YELLOW REPORT

(CERN) Yellow Report on Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Bottomonia flow at LHC

Studies of $J/\psi v_2$ at RHIC and LHC energies have provided important elements toward the understanding on the production mechanisms and thermalization of charm quarks. Bottomonia has an advantage since it is a cleaner probe. A brief discussion has been provided for $\Upsilon(1S) v_2$, which can become the new probe for QGP, including the necessity of studies for small systems.

ALICE and CMS

➢ Both CMS and ALICE results show that the geometry of the medium has little influence on the Upsilon (1S) yields and that recombination is not a dominant process in the production

➢ Path-length dependence of Upsilon (1S) suppression is small

simultaneous description of HF decay $R_{AA}$ and $v_2$ is a challenge
-- can constrain energy loss models
strong evidence for the collective nature of the long-range correlations observed in pp collisions at LHC

Bottom quarks have less elliptic flow in high multiplicity p+p collisions unlike light and charm quarks
Unanswered Questions and next steps

- Heavy quarks are particularly good probes to study the properties of hot QCD matter

- pp data are important baseline measurements
  - examine interplay of soft and hard processes

- pA which is more than just a control
  - needed to study the CNM effects in various x ranges

- AA collisions: for understanding dense/hot QCD matter
  - strong interaction of heavy quarks with the QCD medium

- But do we understand Pb+Pb at 2.76 TeV and 5.02 TeV?

- The role of shadowing effect?

- Flow in pp collisions?

- Next steps:
  - New differential measurements to constrain models and address open questions
  - Need more statistics, better precision & extended coverage (in terms of \( p_T \)), Run3/HL-LHC

- Bottomonia production studies in pA collisions helps in understanding CNM effects
  - for “small systems” less deeply bound bottomonia states and large chance to escape
  - such measurements in pA will help us to understand the initial state correlations

DD and N.Dutta, Int.J.Mod.Phys. A33 (June 2018) no.16, 1850092
D.Das, IJMPA Vol. 36, No. 24, 2130014 (2021)
MORE
Comparisons at LHC

\[
\frac{dN}{d\phi} = \frac{N_0}{2\pi} \left(1 + 2v_1 \cos(\varphi - \Psi_1) + 2v_2 \cos(\varphi - \Psi_2) + \ldots\right)
\]
Measuring heavy-flavor particles

Heavy-Flavor (HF) hadrons decay via weak interaction:
- decay length $c \tau \sim$ few 100 $\mu$m
- measure decay products
- signal on invariant mass distribution
- difficulty is in understanding the background
- need good event mixing and vertex information

Measurements of electrons and muons from heavy flavor decays:
- $D \rightarrow e/\mu + X$, $BR \sim 10\%$
- $B \rightarrow e/\mu + X$, $BR \sim 11\%$