Heavy quarks as a probe of QGP

Klaus Reygers, Kai Schweda
Physikalisches Institut
Universität Heidelberg / GSI Darmstadt
Building Blocks of Matter

1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.

2) Gluons hold quarks together to form hadrons:

   - meson
   - baryon

3) Gluons and quarks, or partons, typically exist in a color singlet state: confinement.
Time Scales

- **QGP life time**
  \[ 10 \text{ fm/c} \approx 3 \cdot 10^{-23} \text{ s} \]

- **thermalization time**
  \[ 0.2 \text{ fm/c} \approx 7 \cdot 10^{-25} \text{ s} \]

- **formation time**
  (e.g. charm quark):
  \[ \frac{1}{2m_c} = 0.08 \text{ fm/c} \approx 3 \cdot 10^{-25} \text{ s} \]

- **collision time**
  \[ \frac{2R}{\gamma} = 0.005 \text{ fm/c} \approx 2 \cdot 10^{-26} \text{ s} \]
Outline

• Introduction
• Charm-quark production in pp
• Charm-quark production in Pb-Pb
• Summary
Erste Bleikollisionen in ALICE!

ALICE is designed for

- Highest multiplicities $dN/d\eta$ up to 6000
- Excellent tracking & particle identification
down to lowest momentum $\sim 100$ MeV/c
Heavy - flavor: a unique probe

\[ m_{c,b} \gg \Lambda_{QCD} : \text{new scale} \]
\[ m_{c,b} \approx \text{const.}, \ m_{u,d,s} \neq \text{const.} \]

**initial conditions:**

\[ \sigma_{c\bar{c}}, \sigma_{b\bar{b}} \]

test pQCD, \( \mu_R, \mu_F \)

probe gluon distribution

**early partonic stage:**

diffusion (\( \gamma \)), drag (\( \alpha \))

flow, jets, correlations

probe thermalization

**hadronization:**

chiral symmetry restoration

confinement

statistical coalescence

\( J/\psi \) enhancement / suppression

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Mass in the Standard Model (I)

• From the Higgs mechanism (fundamental) for vector bosons:

\[ M_{W^+} = M_{W^-} = \frac{1}{2} v g \]

\[ M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2} \]

• \( v = 246 \text{ GeV} \), is vacuum expectation of the Higgs field

• \( g \) and \( g' \) are coupling constants
Mass in the Standard Model (II)

- From Yukawa coupling to the Higgs field (‘put in by hand’) for charged fermions, e.g. electron:

\[ m_e = \frac{\lambda_e v}{\sqrt{2}} \]

- \( \lambda_e \) is free parameter

- Higgs decay: \( \Gamma(h \rightarrow ee) \propto \lambda_e^2 \)
- Check experimentally for heaviest fermions (b-quark and tau-lepton)
Mass of the proton

- 3 quarks: uud
- Each quark weighs less than 10 MeV
- But: protons weighs 938 MeV!
- Yukawa coupling of fermions to the Higgs field generates < 1% of proton mass

- 99% comes from kinetic energy of bound quarks and thus from strong interactions
Where does all the charm go?

- **Total charm cross section:** open-charmed hadrons, e.g. $D^0, D^+, D^{*+}, \Lambda_c$, ... and $c, b \rightarrow e(\mu) + X$

- Quarkonia, e.g. $J/\psi$ carries $\approx 1\%$ of total charm
Heavy-quark detection

Open-charm reco. in ALICE

\[ D^0 \rightarrow K\pi \]
\[ D^+ \rightarrow K\pi\pi \]
\[ D^* \rightarrow D^0\pi \]
\[ D_s \rightarrow KK\pi \]

Under study:
\[ D^0 \rightarrow K\pi\rho \]
\[ \Lambda_c \rightarrow pK\pi \]
\[ \Lambda_c \rightarrow \Lambda\pi \]
\[ \Lambda_c \rightarrow K^0_S\pi \]

plot: courtesy of D. Tlusty.

- \( D^0 \rightarrow K^- + \pi^+ \), \( c \tau = 123 \ \mu m \)
- **displaced decay vertex is signature of heavy-quark decay**

14 Jun 2013  
QGP lecture  
10/36
Charm-quark production pp collisions
Open-charm spectra from pp @ 7 TeV


covers spectrum from 1 up to 24 GeV/c
Open-charm cross section

ALICE, arXiv:1205.4007 [hep-ex];
J. Wilkinson, bachelor thesis, Univ. Heidelberg (2011);
S. Stiefelmaier, bachelor thesis, Univ. Heidelberg (2012);

- LHC: First collider measurements at TeV scale
- ATLAS & LHCb agree with ALICE
- 10x more charm at LHC than at RHIC
  (larger factors at high-\(p_T\): \(10^4 - 10^5\))
P_v: fraction of D-mesons in vector state (V) to all mesons (V+S),
\[ P_v = \frac{V}{V+S} \]
- World average:
\[ P_v = 0.60 \pm 0.01 \]
- Stat. model, T=164 \pm 10 MeV: \( P_v = 0.58 \pm 0.13 \), agrees with data
- HQET predicts
\[ P_v = \frac{3}{3+1} = 0.75 \]
Charm hadronization, cont’ed

- $P_v$ independent on collision energy and system
- Charm quark does not remember how it was created
- In hindsight, justifies factorization Ansatz
- Charm hadronization described by stat. model
- N.B. Lund fragm. + Clebsch-Gordan coupling: $P_v = 0.63$
- HQEFT ($m=\infty$), mass differences negligible,
  NOT justified for charm
  but exp. checked for B mesons ($\Delta m/m = 40 \text{ MeV}/5000 \text{ GeV}$)
Charm-quark production Pb-Pb collisions
Energy loss in the medium


\[
z = \frac{p(h)}{p_{\text{parton}}}
\]

Fast parton (i.e. charm quark) propagates in the medium
Loses energy due to gluon bremsstrahlung + elastic collisions
Appears as D-meson at lower momentum wrt pp collisions
→ probe QGP
Parton energy loss

Access medium properties: transport coefficients

\[ \hat{q} = \frac{\langle p_T^2 \rangle}{L} \]  
transverse momentum diffusion rate

\[ \hat{e} = \frac{\langle \Delta E \rangle}{L} \]  
elastic energy loss rate
Nuclear Modification Factor - $R_{AA}$

$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \cdot \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$

- define $R_{AA}$, expect unity in the absence of nuclear effects (for hard processes)
- $N_{\text{coll}} = \text{number of binary nucleon-nucleon collisions}$
- at RHIC, suppression of factor $\sim 5$
- at LHC, suppression of factor $\sim 6$
- strong medium effects!
AdS/CFT correspondence

- Maldacena conjecture: string theory and conformal QFT mathematically equivalent
- heavy-quark energy loss modeled by embedding a string in AdS space
- Prediction: **strong suppression** for charm, **small** for beauty

Charm nuclear modification factor


- In Pb-Pb collisions: Charmed hadrons are suppressed by factor $\sim 3-4$ when compared to simple binary collision scaling from $pp$. 

14 Jun 2013 QGP lecture
Charm: Nuclear Modification

- In Pb-Pb collisions: Suppression by factor ~5 when compared to simple binary scaling from pp
- Covers 1 – 36 GeV/c
- pp reference measured only up to 24 GeV/c + extrapolation
Comparison to other hadrons

- Mass ordering in RAA?
  \( J/\psi \leftrightarrow B \) (upper)
  \( D \) (middle)
  \( \pi \) (lower)

- \( \gamma, W, Z \)-bosons:
  \( R_{AA} \approx 1 \) (!)
  checks normalization, does not probe the medium

ALICE, arXiv:1203.2160 [nucl-ex],
Vector bosons: some remarks

• $\gamma$: no color charge $\rightarrow$ does not interact with the QGP medium

• $W^\pm$ and $Z$: decay before QGP is formed, into lepton pairs ($ee$, $\mu\mu$, $\tau\tau$); $\rightarrow$ decay daughters do not interact with the medium

• $R_{AA}$ expected to be unity – and observed!
Model calculations

- Rising $R_{AA}$ solely due to spectrum in pp
- Still have to learn from theory about medium properties, i.e. $q_{hat}$, $e_{hat}$
- Not an initial state effect
- To be checked with p+Pb collisions (2013)
Anisotropy Parameter $v_2$

Coordinate-space-anisotropy ⇔ Momentum-space-anisotropy

\[ \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]

\[ v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right) \]

Initial/final conditions, EoS, degrees of freedom
• Substantial $v_2$ of charm, comparable to charged hadrons
v_2 - Model calculations

- Models needs to simultaneously describe v_2 and R_{AA}
- Stringent constraint, gets tougher with more precision/data
Next steps

- Extract power spectrum of $v_n$, like WMAP*
- Compare pp high multiplicity vs Pb+Pb
- Mach cone vs medium response for heavy-quarks (well defined probes)
- $\eta/s$

*WMAP data: The NASA/WMAP Science team; http://map.gsfc.nasa.gov/media/080997/index.html.
Heavy – quark Correlations

- Charm and anti-charm quarks created in pairs and thus correlated
- Look for modifications in Pb+Pb collisions
- Study transport properties / thermalization

Heavy quark Correlations*

- CMS trigger: inspected 200 x 10⁹ p+p collisions
- B–Bbar, establish correlations exist in p+p!
- Look out for modifications in Pb+Pb

Upgrading the Inner Detector

- upgrade Concept recently approved by the ALICE Collaboration
- targeted for 2017-2018 LHC shutdown
- Conceptual Design Report CERN-LHCC-2012-005
Lesson learnt

• 99% of all visible mass comes from breaking of chiral symmetry in strong interactions

• Heavy quarks (charm and bottom) are unique probes of a QGP

• LHC is the ultimate machine for characterizing QGP by hard probes (heavy quarks, jets, ...)

• Parton energy loss gives in QGP gives access to QGP transport coefficients (qhat, ehat)

• Observable is nuclear modification factor $R_{AA}$

• Control measurement: Vector boson ($\gamma, W, Z$) $R_{AA} = 1$
ALICE - Jetzt geht’s los!