Open heavy-flavour measurements in Pb-Pb collisions with ALICE at the LHC

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Outline

• Strongly interacting matter in extremes
• ALICE experiment
• Recent open heavy-flavour measurements
  - Probes: D mesons and heavy-flavour decay leptons (e and $\mu$)
  - Collision systems
    - pp: test QCD and important baseline for heavy-ion measurements
    - p-Pb: study cold nuclear matter effects (initial state)
    - Pb-Pb: study hot QCD matter (final state); determine medium properties
  - Observables: nuclear modification factor and azimuthal anisotropy

• Conclusions

J. Norman, Wed. afternoon

Overview talk on heavy-flavor probes
J. Stachel, Tue. morning
Study strongly interacting matter under extreme conditions: high temperature and high density.

Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the quark-gluon plasma.

Experimental access via high energy heavy-ion collisions.
Probing hot and dense QCD matter

- “Simplest way” to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - modification of the transverse momentum distribution tells about density profile

- Heavy-ion collision
  - hard processes serve as calibrated probe (pQCD)
  - partons traverse through the medium and interact strongly
  - suppression provides density measurement

General picture
- parton energy loss through medium-induced gluon radiation
- collisions with medium constituents
Heavy quarks are ideal probes

• Symmetry breaking
  - Higgs mass: electro-weak symmetry breaking → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass

• Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP

• Test QCD at transition from perturbative to non-perturbative regime: charm and beauty quarks provide hard scale for QCD calculations

*Formation time:*

$$\tau \sim \frac{1}{2}m_Q \sim 0.1\text{fm} \ll \tau_{\text{QGP}} \sim 5-10\text{ fm}$$

*B. Müller, Nucl. Phys. A750 (2005) 84*
Radiative parton energy loss

- ...depends on
  - medium properties (e.g. density, temperature, mean free path)
    \[ \Rightarrow \text{transport coefficients} (\hat{q}) \]
  - path length in the medium \((L)\)
  - parton properties (colour charge and mass); traversing the medium \(\Rightarrow\) Casimir coupling factor \((C_R)\):
    \[ C_R = 4/3 \text{ for quarks and 3 for gluons} \]

\[
\langle \Delta E_{\text{medium}} \rangle \propto \alpha_s C_R \hat{q} L^2
\]

- Dead-cone effect: gluon radiation suppressed at small angles \((\theta < m_Q/E_Q)\)

- Expectation: \(\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b\)
  mass dependence
Comparison of the production yield in heavy-ion collisions with the one in proton-proton collisions

Nuclear modification factor

\[ R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{bin} \rangle_{AA} \cdot \text{Yield}_{pp}(p_T)} \]

Expectation:

- \( R_{AA} = 1 \) for photons
- \( R_{AA} < 1 \) for hadrons

\[ R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) \]
A Large Ion Collider Experiment

At the CERN Large Hadron Collider

Sub-detector systems
ITS, TPC, TOF, HMPID, TRD, FMD, PMD, T0, V0, ZDC, EMCAL, DCAL, PHOS, Muon arm, DAQ, HLT (High Level Trigger)

- PID over a very broad momentum range (> ~100 MeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage (|\eta| < 0.9) and -4 < \eta < -2.5 in forward region
Trigger and data samples

- Minimum bias, based on interaction trigger:
  - SPD or V0-A side or V0-C side
  - at least one charged particle in 8 $\eta$ units
  - 95% efficient on $\sigma_{\text{inel}}$
- Vertex determination: SPD
- Centrality in Pb-Pb: Glauber fit to V0 signal amplitude
- Single-muon trigger ($p_T > 0.5$ and 4.2 GeV/c)
  - forward muon in coincidence with MB

<table>
<thead>
<tr>
<th>$\sqrt{s_{\text{NN}}}$ (TeV)</th>
<th>Year</th>
<th>Integrated luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.76</td>
<td>2010</td>
<td>10 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>2.76</td>
<td>2011</td>
<td>0.1 nb$^{-1}$</td>
</tr>
<tr>
<td>5.02</td>
<td>2015</td>
<td>202.3 $\mu$b$^{-1}$ (muon data)</td>
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</tbody>
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In addition (not covered in this talk):
- pp collisions at $\sqrt{s} = 0.9, 2.76, 7, 8$ and 13 TeV
- p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ and 8.16 TeV
1. Full reconstruction of open charmed mesons
   e.g.: $D^0 \rightarrow K^- + \pi^+$ \quad BR = 3.89\%, \quad c\tau = 123 \ \mu m$
   - direct clean probe: signal in invariant mass distribution
   - difficulty: large combinatorial background especially in a high multiplicity environment
   - techniques of background subtraction and vertex tracker needed

2. Semi-leptonic decay of D and B mesons
   \begin{align*}
   &c \rightarrow \text{lepton} + X \quad \text{BR} = 9.6\% \\
   &D^0 \rightarrow e^+ + X \quad \text{BR} = 6.87\% \\
   &D^0 \rightarrow \mu^+ + X \quad \text{BR} = 6.5\% \\
   &b \rightarrow \text{lepton} + X \quad \text{BR} = 10.9\%
   \end{align*}
   - robust electron trigger
   - needs handle on photonic electron background

3. Beauty via non-prompt $J/\psi$ and hadronic decays
Typical event display
$Pb-Pb$ at $\sqrt{s_{NN}}$ 5.02 TeV
Above 5 GeV/c strong suppression (factor 4-5) of D-meson yield in central Pb-Pb collisions, compared to binary scaling from pp collisions

First $D_s^+$($c\bar{s}$) measurement in heavy-ion collisions

Expectation: enhancement of strange D-meson yield at intermediate $p_T$ if charm hadronises via recombination in the medium
\( R_{AA} \): light versus heavy-quark hadrons

**JHEP 1603 (2016) 081**

- Slight enhancement of D at low \( p_T \) for 10% most central collisions
- Indication for rising \( R_{AA} \)

**Theoretical interpretation:**
*M.Djordjevic, PRL 112, 042302 (2014)*
Prompt D and B-meson $R_{AA}$ in 2.76 TeV Pb-Pb

- Comparison of prompt D mesons (ALICE) with J/ψ from beauty decays (CMS)
- D and B meson $<p_T> \sim 10$ GeV/c
- Described by theoretical model calculations including quark-mass dependent energy loss ($R_{AA}^D < R_{AA}^B$) in the studied $p_T$ range

Theoretical interpretation:
D mesons: initial-state effects


ALICE

$R_{p\text{Pb}}$ vs. $p_T$ (GeV/c)

- Importantly baseline measurement of **cold nuclear matter effects** (e.g., Cronin effect, nuclear shadowing, gluon saturation)
- D-meson $R_{pA}$ shows consistency with unity and predictions from shadowing and CGC model predictions
- High-$p_T$ suppression of particle yield in Pb-Pb is a final-state effect

Andre Mischke (Utrecht)
Single electron $R_{AA}$ at 2.76 TeV

- Strong suppression of single electron yield up to 18 GeV/c observed in 10% most central Pb-Pb collisions, unlike in p-Pb
  - Substantial energy loss of heavy quarks in the medium

- Constrain theoretical models (with D-meson $R_{AA}$ and $v_2$)
  - Extraction of heavy-quark transport coefficients

Andre Mischke (Utrecht)
Single muon $R_{AA}$ at 2.76 and 5.02 TeV

- Strong suppression in 10% most central collisions reaching a factor $\sim 3$ in $7 < p_T < 12$ GeV/c
- $R_{AA}$ at 5.02 TeV consistent with that at 2.76 TeV in the overlap $p_T$ region
- Suppression increases with increasing centrality
Azimuthal anisotropy (elliptic flow)

Do heavy quarks thermalise in the medium?

- Multiple interactions lead to thermalisation → hydrodynamic behaviour of the system
- Pressure gradient generates collective expansion of the medium → anisotropy in momentum space
- Fourier decomposition:
  \[
  \frac{dN}{d(\varphi - \psi_n)} \propto 1 + 2 \sum_{n=1} v_n \cos(n[\varphi - \psi_n])
  \]
  where \( v_n = \langle \cos(n[\varphi - \psi_n]) \rangle \)

Andre Mischke (Utrecht)
Azimuthal anisotropy of prompt D mesons

- Due to the large mass, long thermalisation process is expected for heavy quarks
  - less influenced by collective expansion
- Indication (3-5σ confidence level) for non-zero charm elliptic flow in the $p_T$ range 2-6 GeV/c
  - Significant interaction of charm quarks with the medium
- Improved measurement with Run-2 data
Comparison with model calculations: D mesons

$R_{AA}$ (0-20%)

$\nu_2$ (30-50%)

Collisional energy loss only

Collisional and radiative energy loss

No final conclusion possible at the moment → more precision data needed
• Simultaneous description of $R_{AA}$ in central collisions and $v_2$ in semi-central collisions is challenging

• $R_{AA}$ and $v_2$ measurements provide constraints on energy-loss models
Summary

• LHC ideal for studying the properties of hot dense QCD matter
  - large volume, long lifetime, high production rates for rare probes

• Heavy quarks are particularly good probes to study transport properties (e.g. drag and diffusion coefficient) and degree of thermalisation
  - $R_{AA}$ and $v_2$ of prompt D mesons and single leptons (run-2 muons)
    • strong suppression of the yield at high $p_T$ (>6 GeV/c) observed in central collisions → more insight on energy-loss mechanisms
    • non-zero elliptic flow → suggest strong re-interactions within the medium

- Quark-mass dependence: $R_{AA}(\pi) \sim R_{AA}(D, \text{single leptons}) < R_{AA}(B \to J/\psi)$

- Precision measurements in extended $p_T$ ranges needed to further constraint theoretical model calculations

• Many more exciting results ahead of us
  - Run-2 Pb-Pb data at $\sqrt{s_{NN}} = 5.02$ TeV and after upgrades in 2019/20
  - p-Pb data taking at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV in 2016

Andre Mischke (Utrecht)
Upgrade of the ALICE Inner Tracker

- 7-layer barrel geometry based on CMOS pixel sensors
- Factor $\sim 3$ improvement in impact parameter resolution
- $\eta$ coverage: $|\eta| \leq 1.22$
- Low material budget; goal
  - $X/X_0 \leq 0.3\%$ for first 3 inner silicon layers
  - $X/X_0 \sim 1\%$ for outer barrel
- Installation in 2019/2020
- Design requirements: event readout rate
  - Pb-Pb: 100 kHz
  - pp: $>400$ kHz

12.5 G-pixel camera ($\sim 10 \text{ m}^2$)

Also upgrade of the Muon Forward Tracker at forward rapidity