Heavy flavour in heavy ion collisions
• Heavy quarks produced in the initial stage of the collisions.

• Light quarks and gluons can be produced or annihilated during the entire partonic phase of the medium.

• Heavy quarks preserve their flavour and mass identity while traversing the medium.
What are the observables?

• The properties of the QGP are studied by measuring various final state observables such as multiplicity, particle yields and transverse momentum distribution of particles.

• Nuclear modification factor.

• Jets.

• Azimuthal anisotropy.
Nuclear modification factor

\[ R_{AA}^P = \frac{Y_{AA}^P}{\langle N_{coll} \rangle Y_{pp}^P}, \]

\( \langle N_{coll} \rangle \) average number of binary nucleon-nucleon collisions.

\( Y^P \) is the invariant yield of the particle, \( P \), in A-A (pp) collisions at a AA pp given (same) center-of-mass energy.

\( \langle N_{coll} \rangle \) estimated by the product of the average nuclear overlap function of the nucleus-nucleus collision, calculated with the Glauber model, and the inelastic proton-proton cross section.
Nuclear modification factor

\[ R_{AA}^P = \frac{Y_{AA}^P}{\langle N_{coll} \rangle Y_{pp}^P} , \]

\(<N_{coll}>\) average number of binary nucleon-nucleon collisions.

\(Y^P\) is the invariant yield of the particle, \(P\), in A-A (pp) collisions at a AA pp given (same) center-of-mass energy.

\(<N_{coll}>\) estimated by the product of the average nuclear overlap function of the nucleus-nucleus collision, calculated with the Glauber model, and the inelastic proton-proton cross section

- No QGP, \(R_{AA} = 1\)
- Energy loss \(R_{AA} < 1\) (suppression of yield)
  - can be explained using the mechanism of partonic energy loss via elastic and inelastic collisions in the QCD medium
Nuclear modification factor

- Energy loss
  
  Gluon > light quarks > heavy quarks

  \[ R_{AA}^{\pi^\pm} < R_{AA}^{D} < R_{AA}^{B} \]
Nuclear modification factor

- Energy loss

Gluon > light quarks > heavy quarks

\[ R_{AA}^{\pi^\pm} < R_{AA}^D < R_{AA}^B \]
Nuclear modification factor

- Energy loss
  Gluon > light quarks > heavy quarks
  \[ R_{AA}^{\pi^\pm} < R_{AA}^{D} < R_{AA}^{B} \]
$R_{AA}$ vs centrality

Zero Prompt D

ALICE Preliminary
Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

Filled markers: pp rescaled reference
Open markers: pp $p_T$-extrapolated reference

Average $D^0, D^+, D^{*+}, 0-7.5\%, |y|<0.5$

Average $D^0, D^+, D^{*+}, 30-50\%, |y|<0.5$

ALI-PREL-77059
**$R_{AA}$ vs centrality**

**ALICE Preliminary**

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

- Average $D^0, D^+, D^{*+}, 0-7.5\%, |y|<0.5$
- Average $D^0, D^+, D^{*+}, 30-50\%, |y|<0.5$

Filled markers: pp rescaled reference
Open markers: pp $p_T$-extrapolated reference

$R_{AA}$ vs $p_T$ (GeV/c)

$R_{AA}^D < R_{AA}^B$

Read from CMS-PAS-HIN-12-014

CMS Preliminary Non-prompt $J/\psi$ $R_{AA}$, $6.5 < p_T < 30$ GeV/c $|y|<1.2$

CMS Preliminary Non-prompt $J/\psi$ syst. uncertainties
Proton ion collisions

• To understand the measurements in Pb-Pb collisions, we need to understand cold nuclear matter effects
  – Effects because of the presence of multiple nucleons.

• The parton distribution function of quarks and gluons might be different.

• Partons can lose energy by radiation in the initial state.

• Partons can undergo multiple soft scattering – $k_T$ broadening.

• Use proton-ion collisions to study these effects.
Heavy flavors in ALICE, Kruger, December 2014
S.Masciocchi@gsi.de

Proton - lead results

Proton - proton results

Pb-Pb

P-Pb
$R_{pPb}$ is not due to cold nuclear matter effects at high $p_T$. 

**Nuclear modification factor**

- ALICE b.c $\rightarrow (e^+ + e^-)/2$, TPC-TOF, ALICE reference
- ALICE b.c $\rightarrow (e^+ + e^-)/2$, TPC-EMCal, ALICE reference
- ALICE b.c $\rightarrow (e^+ + e^-)/2$, TPC-EMCal, FONLL reference

**Yield**

- CMS $= 5.02$ TeV, min. bias, $-1.06 < y_{NN} < 0.04$
- Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV, $|y_{NN}| < 0.5$

**Centrality**

- ALICE, D0, D0
- Average D0, D+, D+$^+$

**Shadows**

- FONLL + EPS09 shad.
Jets

• Energetic partons originate in the hard scattering
  – Back-to-back configurations.
• They evolve as parton showers and hadronize.
  – Experimentally observed as back-to-back jets.

• What is a jet??
  – Group of particles emitted in a narrow cone, expected to be originating from the fragmentation of a parton.
Jet quenching

• In QGP, before fragmentation, the partons loose energy in the medium due to gluon radiation and multiple scattering.
  — Jet queching

• Direct measurement of jets is difficult in nuclear collisions due to large background especially for low $p_T$ jets.

• Azimuthal angular correlations of high $p_T$ particles are an alternative probe for these back-to-back jets.

• Particles from a single jet generate an enhances correlation at $\Delta \phi \sim 0$ (near-side).

• Particles originating from back-to-back jet will jet generate an enhances correlation at $\Delta \phi \sim \pi$ (away-side).
Azimuthal angular correlation

- STAR experiment at RHIC measured the $\Delta \phi$ correlation of high $p_T$ hadrons.
  - $p_T^{\text{Trig}} > 4 \text{ GeV/c}$
  - $p_T^{\text{Assoc}} > 2 \text{ GeV/c}$

- Away side suppressed for central Au+Au collisions.

- Interpretation of the results
  - Near side: created from partons produced near the surface of medium.
  - Away side: parton has to travel a significant distance, losing more energy.
Azimuthal angular correlation

In ALICE:

\[ 8 < p_T^{\text{Trig}} < 15 \text{ GeV/c} \]
\[ 4 < p_T^{\text{Assoc}} < 6 \text{ GeV/c} \]

- Quantitative analysis done by measuring the yield on near side and away side \((I_{AA})\).

\[ I_{AA} = \frac{Y_{\text{Pb-Pb}}}{Y_{\text{pp}}} \]
1. Introduction

In central collisions, an away-side suppression ($I_{AA} \approx 0.6$) is observed, which gives evidence for in-medium energy loss. Moreover, the near-side $I_{AA}$ shows an enhancement of about 20-30% above unity, which has not been observed with any significance at RHIC experiments at these momenta. The near-side enhancement suggests that the near-side parton is also subject to medium effects. This could be because of various factors, like a change in the fragmentation function, a possible change of the quark/gluon jet ratio in the final state due to their different coupling to the medium or a bias on the parton $p_T$ spectrum after energy loss due to the trigger particle spectrum. The sensitivity of $I_{AA}$ and $R_{AA}$ to different properties of the medium makes the combination particularly effective in constraining jet quenching models.

Information on how heavy-quarks loose energy and interact with the medium can be obtained by studying the correlations of heavy-flavour hadrons. One of the experimental probes to study heavy quarks are the electrons from their decays. In order to measure $c\bar{c}$ and $b\bar{b}$ correlations, the heavy quark should be identified in both the trigger and away side jets. This would mean either identifying heavy-flavour decay electrons on both sides or identifying a HFE on one side and selecting all hadrons from heavy-flavour decays on the other side. It is experimentally difficult to unambiguously select hadrons from heavy-flavour, and requiring electrons on both side increases the statistical uncertainty. Hence as a first step, the correlations can be obtained for heavy-flavour.

Away side 50% suppressed.
Azimuthal angular correlation in HF??

**Figure 7.21:**

Distribution between HFE and charged hadrons after subtracting uncorrelated background for \(4 < p_T^e < 6 \text{ GeV/c}\) in two \(p_T\) bins for 0-8% and 20-50% most central Pb-Pb collisions at \(p_{NN} = 2.76\) TeV. The distribution in Pb-Pb collisions is compared with the distribution in pp collisions at \(p_{NN} = 7\) TeV. The elliptic flow contributions to the distribution have not been subtracted for 20-50% most central Pb-Pb collisions.

Collisions at \(p_{NN} = 2.76\) TeV, respectively. By taking the integral of the Gaussian distribution of the fit function, the per-trigger near-side yield is obtained. This yield is mainly attributed to the jet fragmentation of heavy quarks. By studying the near-side yield, information on the possible modification of the fragmentation function of heavy quarks in Pb-Pb collisions can be obtained. To measure the change in the fragmentation function due to interaction of heavy quarks with the QGP, the near-side yield in pp collisions is used as a baseline, where no medium effects are expected.

The near-side yield for pp collisions at \(p_{NN} = 7\) TeV is used as a reference measurement instead of the measurement in pp collisions at \(p_{NN} = 2.76\) TeV due to limited statistics available. The difference in the per trigger near-side yield for the two center of mass energies is expected to be small. The uncertainty in this assumption is found to be less than 10% as shown in chapter 6. This justifies the use of the data sample from pp collisions at \(p_{NN} = 7\) TeV as the reference measurement.

The yield from the three datasets, two centrality intervals of Pb-Pb collisions and pp collisions at \(p_{NN} = 7\) TeV, for \(2 < p_T^e < 4\) and \(4 < p_T^h < 6 \text{ GeV/c}\) are shown in Figure 7.22. The yield from semi-central Pb-Pb event is

**Statistics is too poor to understand anything ☹️**

Next LHC run??

**Trigger:** Electrons from B/D decay

**Associated:** Hadrons.