Heavy-flavour productions in the relativistic heavy ion collisions at the LHC

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Heavy Flavour (HF) in pp, p-Pb & Pb-Pb

- **Heavy-flavour (charm & beauty) production**
  - Initial hard scatterings \( M_{HF} >> \Lambda_{QCD} \)

- **pp collisions**
  - Test for perturbative QCD (pQCD)
  - Reference for heavy ion collisions (both experiment & theory)

- **Heavy ion collisions**
  - Created in initial parton-parton scatterings
  - Traverse and interact with the hot & dense QCD matter
    - A good probe to study properties of the QCD matter
    - Energy loss \( R_{AA} \), collectivity \( v_2 \), hadronization

- **pA collisions**
  - Control measurement for heavy ion collisions to disentangle initial from final state effects
    - Cold nuclear matter effect on heavy-flavour production
Energy Loss of heavy flavours

- **In-medium parton energy loss**
  - **Radiative energy loss** *(PLB 632, 81)*
    - gluon bremsstrahlung
    - smaller energy loss for heavy than for light quarks due to “dead cone” effect *(PLB 519 (2001) 199.)*
    - energy loss depends on the colour charge and is larger for gluons than for quarks
  - **Collisional energy loss** *(PLB 649, 139)*
    - energy loss via elastic scattering

- **Theoretical predictions:**
  - mass & colour charge dependence of energy loss
  - \( E_{\text{loss}}(g) > E_{\text{loss}}(u,d,s) > E_{\text{loss}}(c) > E_{\text{loss}}(b) \)

\[
R_{AA}^\pi < R_{AA}^D < R_{AA}^B
\]

Nuclear modification factor

\[
R_{AA}(p_T) = \frac{d N_{AA}/dp_T}{\langle T_{AA} \rangle \times d \sigma_{pp}/dp_T}
\]
Azimuthal anisotropy of Heavy flavours

- Elliptic flow
  \[ \frac{dN}{d(\phi - \psi_{RP})} = \ldots + N_0(1+2v_2\cos(2(\phi - \psi_{RP}))) + \ldots \]

- Transfer initial spatial anisotropy to momentum anisotropy
  - macroscopic: hydro model
    => pressure gradient
  - microscopic
    => scattering in the medium

- Low \( p_T \)
  - coupling of heavy quarks with the medium and their thermalization

- Intermediate \( p_T \)
  - Hadronization mechanism (recombination)

- High \( p_T \)
  - Path-length dependence of energy loss

Initial spatial anisotropy

Momentum space anisotropy

of particle emission
Heavy-flavour results in pp collisions
**Charm production in pp collisions**

- D meson production mid- and forward-rapidity is in good agreement with pQCD calculations
  - upper side of the FONLL uncertainty band
  - various energies: 5.02, 7 and 13 TeV
  - from $p_T = 0$ to 100 GeV/c
B meson production is in good agreement with pQCD calculations
- FONLL is better agreement from low $p_T$ to high $p_T$
- PYTHIA overestimates at lower $p_T$
- $b$-jet production is also well represented by a pQCD (NLO)
HF production in pp collisions

**Productions of leptons (e, µ) from charm + beauty decays in different rapidity ranges are also well described by pQCD calculations.**
Heavy-flavour results in p-Pb collisions
p-A collisions

- **Heavy-flavour in p-A collisions**
  - control measurement for heavy-ion collisions to disentangle initial (cold nuclear matter effects) from final state effects

- **Cold nuclear matter effects**
  - nuclear modification of Parton distribution Functions (PDF): shadowing or gluon saturation
    - K.J. Eskola et al., JHEP 0904(2009)65
    - H. Fuji & K. Watanabe, NPA 915 (2013) 1
  - energy loss
    - I. Vitev et al., PRC 75(2007) 064906
  - $k_T$ broadening (Cronin enhancement)
  - multiple collisions
    - A.M. Glenn et al., PLB 644(2007)119

\[
R_{pPb}(p_T) = \frac{dN_{pPb}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}/dp_T}
\]
\( R_{pPb} \) of D mesons, B mesons and e\(^{HF} \) is consistent with unity
- No significant cold nuclear matter effects on heavy-flavour production
- Theoretical calculations with CNM effects are consistent with data
  - predict a small suppression at low \( p_T \) due to gluon saturation at low \( x \)
  - Possible enhancement due to radial flow is predicted small based on Blast-wave model [PLB 731 (2014) 51]
\[ R_{pPb} \text{ of } c\text{-jets and } b\text{-jets at mid-rapidity} \]

CMS-HIN-15-012

- Measured c-jet cross section in p-Pb is consistent with PYTHIA simulation
- \( R_{pPb} \) of b-jet with PYTHIA-based estimation is consistent with unity
  - considering the uncertainty on the PYTHIA reference
D production at forward-backward rapidity

- D⁰ production at forward and backward rapidity
  - forward: p-going, 1.5 < y < -4
  - backward: Pb-going, -5 < y < -2.5
- Significant D⁰ production asymmetry in forward – backward rapidity regions
- Measurements are consistent with a theoretical calculation
  - NLO with CTEQM and EPS09NLO
B→J/Ψ production at forward-backward rapidity

B→J/Ψ production at 1.5 < η < 4.0 (forward) and -5 < η < -2.5 (backward)

- R_{FB} of B→J/Ψ is asymmetry
  - backward yield is suppressed w.r.t. forward yield
- R_{FB} of B→J/Ψ is larger than R_{FB} of prompt J/Ψ
  - indicate cold nuclear matter effect is less pronounced for b hadrons
Heavy-flavour results in Pb-Pb collisions
D mesons in central Pb-Pb collisions

- Strong suppression of D mesons production
  - similar magnitude of suppression in 2.76 and 5.02 TeV
  - suppression observed up to 100 GeV/c at 5.02 TeV
  - $D_s$ tends to larger: a hint of recombination process
- Suggest significant energy loss of charm in the medium
Strong suppression of $e^{HF}$ ($|y|<0.6$) & $\mu^{HF}$ ($2.5<y<4$) in central collisions
- similar suppression of $e^{HF}$ & $\mu^{HF}$ in different rapidity regions
- less suppression in mid-central collisions in both rapidity regions
- high $p_T$: large contribution from beauty
- Suggest significant energy loss of charm and beauty in the medium
$R_{AA}$ of B meson decays ($B\to e$ & $B\to J/\Psi$)

- Suppression of $B\to e$ and $B\to J/\Psi$ at high $p_T$
  - lower $p_T$: tends to follow binary scaling (consistent with unity)
  - high $p_T$ (> 3 GeV/c): $R_{AA} \sim 0.4$-0.5
- Suggestions of beauty energy loss in the dense QCD matter
- The magnitude of D meson suppression is similar to charged particles ($\pi$) within uncertainties
  - can’t conclude on the expectation: $R_{AA}^{D} > R_{AA}^{\pi}$
- $R_{AA}$ of D meson is smaller than $R_{AA}$ of B->J/Ψ
  - indication of smaller energy loss of beauty than charm
- Heavy-flavour jets: allow to address energy loss at parton level
- Observed strong suppression of b-jets in most-central collisions
  - similar magnitude of suppression to inclusive jet
  - high $p_T$ b-jets: largely comes from gluon splitting
Imbalance of pairs of b jets

- Sub-leading recoil jets
  - larger path-length, primary b-jets from flavour creation
- Toward increasing imbalance with increasing centrality
  - similar imbalance as inclusive dijet
Non zero D $v_2$ at low $p_T$
- Tends to get large from central (0-10%) to mid-central (30-50%)
  - Hydrodynamical behavior
- Consistent with charged particle $v_2$
- Charm quarks participate to the collective motion of the system
Azimuthal anisotropy of $e^{HF}$ and $\mu^{HF}$

- Non-zero $v_2$ of $e^{HF}$ at $|y|<0.7$ and $\mu^{HF}$ at $2.5<y<4$
  - the magnitude is compatible in mid- and forward-rapidities
- $v_2$ of $e^{HF}$ measured from $p_T > 0.5$ GeV/c
  - similar $p_T$ dependence to other light hadron $v_2$
- $v_2$ at high $p_T$ $e^{HF}$ and $\mu^{HF}$ reflects beauty
- Charm quarks participate to the collective motion of the system
Comparison with models (1)

JHEP09(2012)112

- Theoretical calculations
  - initial: with/without cold nuclear matter from PDF
  - medium modeling: Hydro, Glauber, parton transportation
  - interaction: radiative, collisional, resonant interaction
  - hadronization: fragmentation, coalescence
- Models represent $R_{AA}$ of D mesons, $e^{HF}$ and $\mu^{HF}$
  - mid- and forward-rapidity regions
  - high $p_T$ leptons ($e, \mu$) mainly from beauty decay

**Theoretical calculations**
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Comparison with models (2)

Theoretical calculations
- initial: with/without cold nuclear matter from PDF
- medium modeling: Hydro, Glauber, parton transportation
- interaction: radiative, collisional, resonant interaction
- hadronization: fragmentation, coalescence

Large suppression and non-zero $v_2$ (at low $p_T$) are represented by models, but simultaneous reproduction of the $R_{AA}$ and $v_2$ is challenging
Comparison with models (3)

- **Experimental result**
  - $R_{AA}(D) < R_{AA}(B\rightarrow J/\Psi)$

- **Theoretical model**
  - radiative + collisional energy loss
  - used two masses (charm and beauty) for calculating $B\rightarrow J/\Psi$ $R_{AA}$
  - result using beauty mass well represents centrality dependence of $R_{AA}(B\rightarrow J/\Psi)$
  - the difference between D meson and $B\rightarrow J/\Psi$ is mainly from mass in this model
Summary

- **Heavy-flavour measurements at LHC**
  - D, B, leptons from heavy flavours, c-jet and b-jet
  - The productions are well described by pQCD calculations in pp collisions

- **Pb-Pb collisions**
  - Strong suppression of heavy-flavour yield
    - Clear indication for substantial energy loss of charm and beauty in the hot and dense matter
      - Not observed such suppression in pPb
    - Results indicate beauty lose smaller energy than charm
  - Non-zero & centrality dependence of $v_2$
    - Suggest strong re-interaction in the medium
  - Heavy flavours observed to be significantly affected by hot and dense QCD medium