Heavy-flavour productions in the relativistic heavy ion collisions

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

- Heavy-flavour (charm & beauty) production
  - Initial hard scatterings ($M_{\text{HF}} \gg \Lambda_{\text{QCD}}$)
    - Flavour creation, flavour excitation, gluon splitting
  - 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 ($R_{\text{AA}}$), 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 \((\text{PLB 632, 81})\)
    - gluon bremsstrahlung
    - smaller energy loss for heavy than for light quarks due to “dead cone” effect \((\text{PLB 519 (2001) 199.})\)
    - energy loss depends on the colour charge and is larger for gluons than for quarks
  - **Collisional energy loss** \((\text{PLB 649, 139})\)
    - 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
  \[ \frac{dN}{d(\varphi-\psi_{RP})} = ... + N_0(1+2v_2\cos(2(\varphi-\psi_{RP}))) + ... \]

- 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
HF production in pp collisions at RHIC

- Charm and beauty production via electrons are in good agreement with FONLL calculation
HF production in pp collisions at LHC

Productions of leptons (e, µ) from charm + beauty decays in different rapidity ranges are well described by pQCD calculations.
Charm production in pp collisions at LHC

- 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
Beauty production in pp collisions at LHC

B meson production is in good agreement with pQCD calculations.
Beauty jets production in pp collisions at LHC (2)

- b-jet productions in pp collisions at 7 TeV
  - production is well described with MC@NLO in large rapidity regions
Cross section of charm and beauty are in good agreement with pQCD
Beam energy dependence is consistent with pQCD (NLO, FONLL)
Heavy-flavour results in pA 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

$$R_{pPb}(p_T) = \frac{d N_{pPb}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}/dp_T}$$
$R_{dA}$ of $e^{HF}$ & $\mu^{HF}$ at RHIC

- HF production in d+Au at 200 GeV
- mid-, forward & backward
$R_{pPb}$ of D, B and e$^{HF}$ at mid-rapidity at LHC

- $R_{pPb}$ 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 $x$
**$R_{pA}$: RHIC vs. LHC**

- Enhancement of $e^{HF}$ production in 0-20% in d+Au is well reproduced by Blast-wave model [PLB 731 (2014) 51]
- Possible enhancement due to radial flow is predicted smaller at LHC
  - consistent with data
  - due to harder D and B meson $p_T$ at higher collision energy
**R_{pPb} of c-jets and b-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

PLB 754 (2016) 59

**pPb 35 nb^{-1} (5.02 TeV)**

![Graph showing c-jet and b-jet cross sections](image)

- **c-jet**
  - Data: Yellow bars
  - PYTHIA Z2: Blue line

- **b-jet**
  - pPb luminosity uncert.
  - pp reference uncert.

**Huang, Kang, Vitev (Ref. [29])**
D production at forward-backward rapidity

LHCb-CONF-2016-003

- 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**

JHEP 02 (2014) 072

- B->J/Ψ production at $1.5 < \eta < 4.0$ (forward) and $-5 < \eta < -2.5$ (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 AA collisions
D mesons in Au-Au (200 GeV)

- D meson production at 200 GeV in Au-Au collisions
- Total production follow binary scale
- Low $p_T$ (< 2 GeV/c): tend larger than unity
  - recombination, radial flow?
- High $p_T$ (>2 GeV/c): strongly suppressed
  - indicate charm energy loss in the matter
$R_{AA}$ of $e^{HF}$ ($c\rightarrow e$ and $b\rightarrow e$) in Au-Au (200 GeV)

- $R_{AA}$ of $D\rightarrow e$ and $B\rightarrow e$

- Strong suppression both electrons original from charm and beauty indicate charm and beauty energy loss in the matter

- $R_{AA}$ of $B\rightarrow e$ and $D\rightarrow e$ are consistent within current uncertainty
  - not conclude mass dependence of energy loss
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
\(e^{\text{HF}} \& \mu^{\text{HF}}\) production in Pb-Pb collisions (2.76 TeV)

- Strong suppression of \(e^{\text{HF}} (|y|<0.6)\) & \(\mu^{\text{HF}} (2.5<y<4)\) in central collisions
  - similar suppression of \(e^{\text{HF}} \& \mu^{\text{HF}}\) 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
Similar order of suppression of D meson production in 0.2 TeV (Au-Au) and 2.76 TeV (Pb-Pb) in most-central collisions at $2<p_T<6$ GeV/c

- Looks there is difference at low $p_T$
  - recombination, radial flow @ RHIC?
  - shadowing @ LHC?
RHIC vs. LHC: HF->e production

- Similar order of suppression of c->e + b->e production in 0.2 TeV (Au-Au) and 2.76 TeV (Pb-Pb) in most-central collisions at $3<p_T<9$ GeV/c

- Not imply similar HF energy loss between RHIC and LHC
  - combined effect of a denser medium and harder initial $p_T$ spectrum at LHC

arXiv:1509.06888
$R_{AA}$ of B meson decays ($B\to e$ & $B\to J/\Psi$) in LHC

- 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 at $p_T > 8$ GeV/c

- 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/$\Psi$

  - indication of smaller energy loss of beauty than charm
Beauty jet in LHC

- 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 in LHC

- Sub-leading recoil jets
  - larger path-length, primary b-jets from flavour creation
- Toward increasing imbalance with increasing centrality
  - similar imbalance as inclusive dijet
Azimuthal anisotropy of HF (D and e) at RHIC

Non-zero HF $v_2$ (D & e$^{\text{HF}}$) in Au-Au collisions at 200 GeV
- $v_2$ at lower energies (62.4 & 39 GeV) is consistent with zero at $p_T < 2$ GeV/c
  - non-zero light-flavour ($\pi$, k & p) $v_2$ in the energy regions (arXiv:1601.07052)
Azimuthal anisotropy of D mesons in LHC

Non zero D $v_2$ at low $p_T$
- Tends to get large from central (0-10%) to mid-central (30-50%)
  - Hydrodinamical behavior
- Consistent with charged particle $v_2$
- Charm quarks participate to the collective motion of the system
Azimuthal anisotropy of $e^{HF}$ and $\mu^{HF}$ in LHC

$e^{HF}$: arXiv: 1606.00321, $\mu^{HF}$: PLB 753 (2016) 41-56

- 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

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**Comparison of Models**

- **ALICE D**, $D^*$, $D^+$ average, $|y|<0.5$
- **Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV**
- **Centrality 0-20%**

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**ALICE Preliminary**

- **Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV, 0-10% central**
  - with pp ref. from scaled cross section at $\sqrt{s} = 7$ TeV
  - with pp ref. from FONLL calculation at $\sqrt{s} = 2.76$ TeV
  - **BAMPS el.**
  - **BAMPS el. + rad.**
  - **TAMU elastic**
  - **POWLANG**
  - **MC@sHQ+EPOS, Coll+Rad(LPM)**

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**BAMPS**: J. Phys. G 38 (2011) 124152,


**TAMU**: Phys. Rev. C 86 (2012) 014903,

**WHDG**: J. Phys. G38(2011)124114,


**Cao, Qin, Bass**: arXiv:1308.0617
Model calculations are reasonably reproduced D meson $R_{AA}$ in both RHIC (0.2 TeV Au-Au) and LHC (2.76 TeV Pb-Pb)
Comparison with models (3)

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

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

- Heavy-flavour productions in pp collisions at 200 GeV, 2.76 TeV, 7 TeV and 13 TeV
  - The productions are well described by pQCD calculations
- Heavy-ion collisions (Au-Au 200 GeV, Pb-Pb 2.76 & 5.02 TeV)
  - Strong suppression of heavy-flavour yield
    - Clear indication for substantial energy loss of charm and beauty in the hot and dense matter
  - 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