Open heavy flavour probes at RHIC and LHC

Andrea Dainese
(INFN Padova, Italy)
Outline of the Talk

- Introduction: HF probes of the medium
- Calibrating HF probes: pp results (see back-up)
- HF production in nucleus-nucleus (and proton-nucleus)
  - Semi-leptonic decays
  - D mesons
  - B and b-jets
- HF azimuthal anisotropy
- Outlook: detector upgrades at RHIC and LHC
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What’s special about heavy quarks: probes through the full system history

- Large mass ($m_c \sim 1.5$ GeV, $m_b \sim 5$ GeV) → produced in large virtuality $Q^2$ processes at the initial stage of the collision with short formation time $\Delta t < 1/2m \sim 0.1$ fm $< \tau_{QGP} \sim 5-10$ fm

- Characteristic flavour, conserved in strong interactions
  - Production in the QGP is subdominant
  - Interactions with QGP don’t change flavour identity

- Uniqueness of heavy quarks: cannot be “destroyed/created” in the medium → transported through the full system evolution

- Effective probes of:
  - The mechanisms of quark-medium interaction: energy loss (and gain)
  - The strength of the collective expansion of the system
The parton palette and the properties of QCD energy loss

Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium gluons

\[ \Delta E(\varepsilon_{\text{medium}}; C_R, m, L) \]

\( C_R \): colour charge dep.
\( m \): mass dependence

\[ \Delta E_g > \Delta E_{c=q} > \Delta E_b \]

q: colour triplet
u,d,s: \( m \sim 0, \ C_R = 4/3 \)
g: colour octet
g: \( m = 0, \ C_R = 3 \)
Q: colour triplet
c: \( m \sim 1.5 \ \text{GeV}, \ C_R = 4/3 \)
b: \( m \sim 5 \ \text{GeV}, \ C_R = 4/3 \)

See e.g.:
From energy loss to $R_{AA}$

$\Delta E_g > \Delta E_{c=q} > \Delta E_b$

What is the expected $R_{AA}$ pattern?
- No trivial relation between $\Delta E$ and $R_{AA}$
- Need to account for different steepness of partonic $p_T$ spectrum and different fragmentation functions

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$
From energy loss to $R_{AA}$

1. Comparing D and B: $R_{AA}^D < R_{AA}^B$ (below 30 GeV/c)
   - For essentially all mechanisms / models
   - Small effect from partonic $p_T$ steepness and fragmentation (at LHC)

Radiative E loss

- $\alpha_s = 0.4$
- $\text{Charm } dN/dy = 1750$
- $\text{Bottom } dN/dy = 2900$
- $\text{Charm } dN/dy = 2900$
- $\text{Bottom } dN/dy = 2900$

$B$ ($m_b \sim 5$ GeV)
$D$ ($m_c \sim 1.5$ GeV)

Radiative E loss

- $q = 10$
- $q = 25$
- $q = 100$

Collisional E loss

- Wicks, Gyulassy, “Last Call for LHC Predictions” workshop, 2007
- Cacciari et al., “Last Call for LHC Predictions” workshop, 2007
- Greco et al., “Last Call for LHC Predictions” workshop, 2007
From energy loss to $R_{AA}$

1. Comparing D and B: $R_{AA}^D < R_{AA}^B$ (below 30 GeV/c)

2. Comparing $\pi$ and D: $R_{AA}^\pi \leq R_{AA}^D$ (below 30 GeV/c)

- Pions at LHC originate predominantly from gluons, below 10-15 GeV/c
- Since $R_{AA}$ rises with $p_T$, the softer $p_T$ spectrum and fragmentation of gluons tend to reduce the impact on $R_{AA}$ of their larger energy loss (colour charge)
- Predictions range from a moderate difference to almost no difference

M. Djordjevic and M. Djordjevic, PRL112 (2014) 042302
A. Buzzatti et al., NPA904-905 (2013) 779c
The observed nuclear modification can have a contribution from initial-state effects, not related to the hot QCD medium.

High parton density in high-energy nuclei leads to reduction/saturation/shadowing of the PDFs at small $x$ (and small $Q^2$)

$$\frac{dN_{PbPb}^D}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes P(\Delta E) \otimes D_{c \to D}(z)$$

Nuclear modification of PDFs

see e.g. Eskola et al. JHEP0904(2009)065
Heavy flavour $v_2$: a two-fold observable

- **Low $p_T$:** do heavy quarks take part in the "collectivity"?
  - Due to their large mass, $c$ and $b$ quarks should "feel" less the collective expansion
  - Need frequent interactions with large coupling to build $v_2$
  - $v_2^b < v_2^c$

- **High $p_T$:** probe path length dependence of HQ energy loss

![Graphs showing $v_2$ vs. $p_T$ for different particles](image)

- J. Aichelin et al. in arXiv:1201.4192
- J. Uphoff et al. in arXiv:1205.4945
### Summary of available measurements: AA

<table>
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<tr>
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<th>PHENIX</th>
<th>STAR</th>
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Originally compiled by Z. Conesa dV
### Summary of available measurements: p(d)A

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- Outlook: detector upgrades at RHIC and LHC
Inclusive measurement \((c+b)\) using non-photonic electrons

Same suppression as for light-flavour hadrons above 5 GeV/\(c\)

Smaller suppression at 2-3 GeV/\(c\), but cannot conclude on mass effects

W. Xie (QM2012)

see also Phys. Rev. Lett. 98, 192301 (2007)

HF-decay $e$ and $\mu$ in d-Au at RHIC

- Low-$p_T$ electrons (mid-$y$) and muons (backward $y$) largely enhanced
  - More than expected from anti-shadowing?
  - Significant role of (mass-dependent?) $k_T$ broadening?

$\rightarrow$ Au-Au high-$p_T$ suppression is a final state effect

PHENIX, PRL109 82012) 242301

N. Apadula (WWND2013)
Low-\(p_T\) electrons (mid-\(y\)) and muons (backward \(y\)) largely enhanced
- More than expected from anti-shadowing?
- Significant role of (mass-dependent?) \(k_T\) broadening?

\(\rightarrow\) Au-Au high-\(p_T\) suppression is a final state effect
\(\rightarrow\) Simple(istic?) “propagation” of initial state effects (with \(R_{dA}^2\)) gives consistent “final-state-only \(R_{AA}\)” for \(\pi\) and e also at low \(p_T\)

PHENIX, PRL109 82012) 242301

A.Dion (QM2014)
Lower energy RHIC runs give the unique opportunity to study the onset of the suppression

\( R_{AA} \) at 62 GeV obtained with reference data from ISR

Large uncertainties show the need for a high-stat RHIC pp run at 62 GeV
HF-decay e and $\mu$ at LHC: $R_{AA}$ vs $p_T$

- Electrons and muons from D+B $\rightarrow$ e,$\mu$ decays

- Comparable suppression at central ($|y|<0.6$) and forward (2.5$<y<$4) rapidity

- Suppression by a factor about 2 up to 18 GeV/c
  - Dominated by beauty at such high $p_T$
  - Note: $p_T^{\text{hadron}} \sim 2 p_T^{\text{lepton}}$

A.Festanti (QM2014)
HF-decay \( \mu \) in p-Pb at LHC

**HF-decay muon** \( R_{pA} (p_T>2 \text{ GeV/c})$: 
- Consistent with unity in p-going direction (small \( x \) in the Pb)
- Somewhat enhanced in Pb-going direction (large \( x \) in the Pb)

**HF-decay electron** \( R_{pA} \) consistent with unity

**pQCD+Shadowing (EPS09) can describe the data**

\( \rightarrow \) Pb-Pb high-\( p_T \) suppression is a final state effect

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R.Russo, S.Li (QM2014), Eskola et al., JHEP 0904 (2009) 065

INT-Workshop, Seattle, 30.09.14

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Charm: D mesons at RHIC

- STAR: $D^0$ $R_{AA}$ in Au-Au and U-U at RHIC
  - Without secondary vertex reco ($\sim$800M Au-Au events)
  - Suppressed by a factor $\sim$3 at high $p_T$ in central Au-Au
  - Large enhancement at 1.5 GeV/c: radial flow + coalescence?

STAR Preliminary

Charm: D mesons at LHC

- First $D_{AA}$ measurement in heavy-ion collisions with data from LHC 2010 run (0-20% centr.).
- Extended with LHC 2011 run, from 1 to 30 GeV/c.
- Factor ~5 suppression at ~10 GeV/c in 0-7.5% centr.

ALICE, JHEP 09 (2012) 112

Z. Conesa (QM2012)
D mesons in p-Pb at LHC

- D meson $R_{pA}$ consistent with unity (and with 0.5 at 1 GeV/c…)
  - pQCD+Shadowing (EPS09) or $k_T$ broadening and CNM E loss, and Colour Glass Condensate can describe the data
- Pb-Pb high-$p_T$ suppression is a final state effect

ALICE, arXiv:1405.3452
PHENIX and STAR have measured the total charm cross section (using electrons and D mesons down to $p_T=0$)

- Example: D mesons at low $p_T$
  - Below 1 GeV/c the vertexing method becomes inefficient, the brute-force combinatorics becomes better if very large stat is available

A matter of statistics:
- STAR used a sample of 800M Au-Au collisions
- ALICE Run-1 sample is of about 50M Pb-Pb collisions
- Run-2 might allow a first measurement; precision with Runs-3 and 4
Looking for colour charge dependence: D mesons vs. pions at RHIC and LHC

\[ R_{AA} \]

\[ \text{STAR PRL108, 072302 (2012)} \]

\[ \text{Pb-Pb, } s_{NN} = 2.76 \text{ TeV} \]

- \( R_{AA} \) of D and pions consistent within current uncertainties
- Hint for D > \( \pi \) in 2-5 GeV/c?
  - Below 2 GeV/c: no direct comparison, \( \pi \) not expected to scale with \( N_{\text{coll}} \)
- Is it consistent with the colour charge dependence?
D mesons vs. pions at LHC

- Calculation by M. Djordjevic (rad+coll energy loss) can describe both $R_{AA}$
- Shows strong colour charge effect in partonic $R_{AA}$ ($g$ vs. light and $c$)

Suggests that colour charge effect helps to describe the observed $R^{D}_{AA} \sim R^{\pi}_{AA}$

M. Djordjevic and M. Djordjevic, PRL112 (2014) 042302
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Beauty $R_{AA}$ at LHC

**CMS:**
- Larger suppression at higher $p_T$ in min. bias
- Centrality dep. in next slide

**ALICE:**
- Indication of $R_{AA}<1$ for electron $p_T>3$ GeV/c

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CMS-PAS-HIN-12-014

A. Festanti (QM2014)
CMS measured b-jets with $p_T>80$ GeV/c in Pb-Pb and p-Pb

- Same $R_{AA}$ for b-jets as for q/g-jets, as expected at this $p_T$
CMS measured b-jets with $p_T > 80$ GeV/c in Pb-Pb and p-Pb

- Same $R_{AA}$ for b-jets as for q/g-jets, as expected at this $p_T$
- $R_{pA}$ consistent with unity: no strong initial-state effects
Looking for mass dependence: \( R_{AA} \) of D and B at the LHC

- **D mesons (ALICE) and J/\(\psi\) from B decays (CMS)**

  Similar \( p_T \) for B and D:
  - B \( p_T \) \( \sim \) 11 GeV (FONLL +EvGen)
  - D \( p_T \) \( \sim \) 10 GeV

- **First clear indication of**: \( R_{AA}^B > R_{AA}^D \)

A. Festanti (QM2014)
Looking for mass dependence: $R_{AA}$ of D and B at the LHC

- D mesons (ALICE) and $J/\psi$ from B decays (CMS)

Similar $<p_T>$ for B and D:
- $B <p_T> \sim 11$ GeV (FONLL +EvGen)
- $D <p_T> \sim 10$ GeV

Described by model calculations with $\Delta E_c > \Delta E_b$
- Also WHDG, Aichelin et al., Vitev, TAMU
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Heavy Flavour $v_2$ at RHIC and LHC

- Electrons from HF show a $v_2$ of up to 0.15 at RHIC (PHENIX, STAR)

- D meson $v_2$ in 30-50%: ~0.2 in 2-6 GeV/c
  - Comparable with charged particle $v_2$

- What is the origin of this $v_2$? c quark flow? coalescence?

- Much more to learn with future data
Comparison with models at LHC

- Models without HQ interactions with expanding medium underestimate $v_2$ (WHDG, POWLANG), but are among the best for $R_{AA}$
- Max $v_2 \sim 0.15-0.20$ is best described by models that include **collisional energy loss** of heavy quarks in expanding medium (BAMPS, UrQMD, TAMU, MC@sHQ); they also include a component of **recombination**
- Suggests that these mechanisms play a role in HQ-medium interactions
**p-Pb at LHC: more than a control experiment?**

**e-h correlations in high-mult collisions**

- **Correlation between HF-decay electrons and hadrons in (high-multiplicity) – ((low-multiplicity) p-Pb collisions:** a “double ridge” similar to what observed for hadron-hadron collisions.

- Resembles the structure that in AA is interpreted in terms of collective flow.

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**Graphical representation:**

1. **HFe-h**
   - Correlation for HF-decay electrons and hadrons, showing a “double ridge” pattern.

2. **h-h**
   - Correlation for hadron-hadron collisions, illustrating a similar structure.

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**References:**

- D.Caffarri, HP2013
- ALICE, PLB719 (2013) 29
For hadrons, a flow-like mass ordering is observed.

Alternative interpretations include initial-state effects (Color Glass Condensate) and “vacuum QCD” effects (color reconnection of strings).

Heavy flavour can provide important additional information.

p-Pb at LHC: more than a control experiment?

e-h correlations in high-mult collisions

- Work by ALICE, arXiv:1307.3237
- D. Caffarri, HP2013
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Heavy flavour: a central topic for upgrades of all HI experiments!
- c/b decay leptons
- Low-\(p_T\) D, D_s, B
- HF baryons
- ...

Already online: PHENIX VTX, STAR HFT

Planned for 2018-19: ALICE new ITS and MFT
PHENIX: Vertex Tracker (VTX)

Electron $R_{AA}$

Electron $v_2$

Projections $5 \times 10^9$ evts

M. Rosati, QM2012
D meson $R_{CP}$

- 200 GeV Au+Au Collisions at RHIC
- $(D^0, 500M$ minimum bias events; $|y|<0.5$)
- $R_{CP}$ vs. Transverse Momentum $p_T$ (GeV/c)
- N_part scaling
- N_bin scaling
- Charged hadron $R_{CP}$
- Expected errors on $D^0$ $R_{CP}$

D meson $v_2$

- 200 GeV Au+Au Collisions
- $(D^0, 500M$ min bias events; $|y|<0.5$)
- $v_2$ vs. Transverse Momentum $p_T$ (GeV/c)
- Hydro
- Charged hadrons
- $v_2(c) = v_2(q)$
- $v_2(c) = 0$

Projections $0.5 \times 10^9$ evts

J. Bielcik, Moriond2013
ALICE Upgrade: Heavy flavour $R_{AA}$

Present data at $p_T \sim 10$ GeV

Upgrade: Charm and beauty $R_{AA}$ down to $p_T \sim 0$ using $D^0$ and B-decay $J/\psi$

ALICE, CERN-LHCC-2013-024
ALICE Upgrade: Heavy flavour flow

Present data on charm $v_2$

Upgrade: Charm and beauty $v_2$ down to $p_T \sim 0$ using prompt and B-decay $D^0$

ALICE, PRL 111 (2013) 102301

ALICE, CERN-LHCC-2013-024

Input values from BAMPS model: C. Greiner et al. arXiv:1205.4945
ALICE Upgrade: HF “hadrochemistry”

- $\Lambda_c \rightarrow pK\pi$ and $D_s \rightarrow KK\pi$ ($c\tau=60$ and 150 $\mu$m) measured with good precision in ALICE with upgrades and 10/nb

$\Lambda_c/D$ enhancement (full detector sim.)

![Graph showing $\Lambda_c/D$ enhancement](image)

- ALICE Upgrade Pb-Pb, $\sqrt{s_{NN}} = 5.5$ TeV
  - $L_{int} = 10$ nb$^{-1}$, centrality 0-20%
- ALICE $\Lambda/K^0_s$ param (2.76 TeV)
- Ko et al. (200 GeV)
- TAMU, Rapp et al. (2.76 TeV)

![Graph showing D$^0$ and D$^+_s$ $R_{AA}$](image)

- ALICE Upgrade Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
  - $L_{int} = 10$ nb$^{-1}$, centrality 0-10%
- $D^0 \rightarrow K\pi^+$
- $D^+_s \rightarrow KK\pi^+$ (stat. only)

2011 data

ALICE, CERN-LHCC-2013-024
Instead of a summary …

… questions for discussion

Properties of energy loss

◆ Colour charge dependence of radiative E loss: how to observe to determine it in a model-independent way?
◆ First hint of mass dependence of energy loss? Can precise measurements given information on the radiated gluon properties (angular distribution, formation time…)?
◆ How to Relative weight of radiative and collisional energy loss?

Collectivity and hadronization

◆ Are HQs flowing (radial, elliptic)? If, yes, what do we learn?
◆ What are the signals of HQ coalescence? Which measurements to make a final statement?

Medium properties

◆ Which properties can be accessed (uniquely) with HQs?
◆ Which theoretical approaches are most sensitive? Is theory ready?
Thank You!
EXTRA SLIDES
Radiative energy loss: colour charge dependence ...

Example: BDMPS-Z formalism

\[
\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}
\]

transport coefficient

Radiated-gluon energy distrib.:

\[
\omega \frac{dI}{d\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q}L^2}{\omega}}
\]

\[C_R = \text{Casimir coupling factor: } 4/3 \text{ for } q, \ 3 \text{ for } g\]

\[\rightarrow \text{Colour charge dependence of radiative energy loss}\]

\[
\Delta E_g > \Delta E_{c=q}
\]
... and mass dependence

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$
  $\rightarrow$ “dead cone” effect

- Dead cone implies lower energy loss (Dokshitzer-Kharzeev, 2001):
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppresses high-$\omega$ tail

$$\omega \left. \frac{dI}{d\omega} \right|_{\text{HEAVY}} = \omega \left. \frac{dI}{d\omega} \right|_{\text{LIGHT}} \times \left( 1 + \left( \frac{m_Q}{E_Q} \right)^2 \frac{1}{\theta^2} \right)^{-2}$$

$\Delta E_c > \Delta E_b$

Mass dependence in collisional energy loss

**Example: Langevin formalism**

- Langevin equation gives momentum ($p$) evolution vs. time ($t$):

  $$ dp = -\Gamma(p) \, p \, dt + \sqrt{2D(p + dp)} \, dt \, \rho $$

  - Loss term $\rightarrow$ energy loss
  - Gain term $\rightarrow$ flow (radial, elliptic)

- Both $\Gamma$ (drag) and $D$ (diffusion) $\sim 1/m_Q$

Thermal relaxation rate $A \sim \Gamma$:

![Graph showing the thermal relaxation rate $A$ as a function of temperature $T$]

- $\Delta E_c > \Delta E_b$

He, Rapp, Fries, PRC86 (2012) 014903
Heavy flavour production in pp

- Example pQCD calculation: Fixed Order Next-to-Leading Log

\[
\frac{d\sigma}{dp_T} = A(m)\alpha_s^2 + B(m)\alpha_s^3 + G(m, p_T) \left[ \alpha_s^2 \sum_{i=0}^{\infty} a_i [\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i [\alpha_s \log(\mu/m)]^i \right]
\]

FONLL: Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033

\[ \mu \approx p_T \]

[coincides with NLO for low \( p_T \) (total cross section); more accurate at high \( p_T \)]

- Describes consistently energy dependence of total cross sections
- Charm (beauty) x10 (100) from 0.2 to 2.76 TeV
pp: pQCD calculations vs data
Charm $p_T$-differential cross section

200 GeV

STAR preliminary $p+p \sqrt{s}=200$ GeV

- Charm production described within uncertainties
- Consistently at upper limit of theoretical band from 0.2 to 7 TeV
  - also at 0.5, 1.96 and 2.76 TeV (not shown)
  - deviation below 1 GeV?

STAR, PRD 86 (2012) 72013 (200 GeV)
Z. Ye (QM2013)

7 TeV

ALICE, JHEP01 (2012) 128
pp: pQCD calculations vs data

Beauty $p_T$-differential cross section

1.96 TeV

7 TeV

- Beauty production described very well by central value of calculation
pp: pQCD calculations vs data
HF-decay lepton $p_T$-differential cross section

- HF-decay electrons and muons at central and forward $y$
- FONLL: “$b > c$” for $p_T > 4$ (5) GeV/c at RHIC (LHC)
Clear and consistent centrality dependence for

- $R_{AA}$ of muons at forward rapidity (ALICE)
- $R_{CP}$ of muons at central rapidity (ATLAS)

No sign of $p_T$ dependence from 4 to 12 GeV/c
Three main physics topics that are unique of the upgraded ALICE detector:

1. **Heavy-flavour transport parameters in the QGP**
   - Heavy-quark diffusion coefficient ($\rightarrow$ QGP equation of state, viscosity of the QGP fluid), via precise HQ $v_2$
   - Heavy-quark thermalization and hadronization in the QGP, via $v_2$ and baryons
   - Mass dependence of parton energy loss in QGP medium

2. **Low-mass dielectrons: thermal photons and vector mesons from the QGP**
   - Photons from the QGP ($\gamma \rightarrow e^+e^-$) $\rightarrow$ map temperature during system evolution
   - Modification of $\rho$ spectral function ($\rho \rightarrow e^+e^-$) $\rightarrow$ chiral symmetry restoration

3. **Charmonia ($J/\psi$ and $\psi'$) down to zero $p_T$**
   - Only the comparison of the two states can shed light on the suppression/regeneration mechanism
   - Study QGP-density dependence with measurements at central and forward rapidity
Requirements:

1. High tracking precision at low $p_T$.
2. High-rate capability to exploit envisaged Pb luminosity increase of LHC.

ALICE Upgrade strategy (2018)

- High tracking precision at low $p_T$
- High-rate capability to exploit envisaged Pb luminosity increase of LHC

- New Inner Tracking System
  - Improve precision $x3(\phi), x6(z)$
  - Separation of displaced (di)muons from B

- New Muon Forward Tracker
  - Separation of displaced (di)muons from B

- Upgraded DAQ/HLT/Offline
  - Record Pb data at 50 kHz
  - Integrate $L_{int} = 10 \text{ nb}^{-1}$ after LS2
  - ($10^{11}$ minimum-bias Pb-Pb events)

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ALICE Upgrade: HF suppression and flow

- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

**Prompt $D^0$ and Non-prompt $J/\psi$ $R_{AA}$**

**Prompt and non-prompt $D^0$ $v_2$**

Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945
Heavy flavour in-medium hadronization?

- Baryon/meson enhancement and strange-enh. \( \rightarrow \) most direct indication of light-quark hadronization in a partonic system
- Measure this in the HF sector! Does it hold for charm?
- Charm baryons (\( \Lambda_c \)) and charm-strange mesons (\( D_s \))

\[ \frac{p}{\pi} \]

\[ \frac{\Lambda_c}{D} \]

\[ D_s \text{ vs } D \]

\[ L_s=200 \text{ GeV} \]

Ko et al. PRC79

Rapp et al. arXiv:1204.4442
### ALICE Upgrade: HF physics reach

<table>
<thead>
<tr>
<th>Observable</th>
<th>$p_T^{\text{min}}$ (GeV/c)</th>
<th>Statistical uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heavy Flavour</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D meson $R_{AA}$</td>
<td>0</td>
<td>0.3%</td>
</tr>
<tr>
<td>$D_s$ meson $R_{AA}$</td>
<td>$&lt; 2$</td>
<td>3%</td>
</tr>
<tr>
<td>D meson from B decays $R_{AA}$</td>
<td>2</td>
<td>2%</td>
</tr>
<tr>
<td>J/$\psi$ from B $R_{AA}$</td>
<td>1</td>
<td>5%</td>
</tr>
<tr>
<td>$B^+$ yield</td>
<td>3</td>
<td>10% ( &gt; 3 GeV/c)</td>
</tr>
<tr>
<td>$\Lambda_c$ $R_{AA}$</td>
<td>2</td>
<td>15%</td>
</tr>
<tr>
<td>Charm baryon-to-meson ratio</td>
<td>2</td>
<td>15%</td>
</tr>
<tr>
<td>$\Lambda_b$ yield</td>
<td>7</td>
<td>20% (7–10 GeV/c)</td>
</tr>
<tr>
<td>D meson elliptic flow ($v_2 = 0.2$)</td>
<td>0</td>
<td>3%</td>
</tr>
<tr>
<td>$D_s$ meson elliptic flow ($v_2 = 0.2$)</td>
<td>$&lt; 2$</td>
<td>8%</td>
</tr>
<tr>
<td>D from B elliptic flow ($v_2 = 0.1$)</td>
<td>2</td>
<td>20%</td>
</tr>
<tr>
<td>J/$\psi$ from B elliptic flow ($v_2 = 0.1$)</td>
<td>1</td>
<td>30%</td>
</tr>
<tr>
<td>$\Lambda_c$ elliptic flow ($v_2 = 0.15$)</td>
<td>3</td>
<td>20% (3–6 GeV/c)</td>
</tr>
</tbody>
</table>
pp reference at 2.76 TeV via $\sqrt{s}$-scaling (ALICE D mesons and electrons)

- Scale the 7 TeV cross sections by the 2.76/7 factor from FONLL, with full theoretical uncertainty
  - relative scaling uncertainty: 30% $\rightarrow$ 5% in the $p_t$ range 2 $\rightarrow$ 16 GeV/c
- Validated by comparing to measured cross section at 2.76 TeV (fewer $p_t$ bins)

$$R_{AA}(p_t) = \frac{1}{\left\langle T_{AA} \right\rangle} \frac{dN_{AA}}{dp_t} / \frac{d\sigma_{pp}}{dp_t}$$

Averbeck et al., arXiv:1107.3243
LHC: comparison with models ($R_{AA}$)

- Several models based on E-loss and heavy-quark transport describe qualitatively the measured light, charm, and beauty $R_{AA}$

**charm**

**“light”**

**beauty**

ALICE, JHEP 09 (2012) 112

CMS-PAS-HIN-12-014
D \( R_{AA} \) at RHIC and LHC

- \( D R_{AA} \) similar at RHIC and LHC at 5-6 GeV/c
- Looks quite different at 1-2 GeV/c:
  - Could it be shadowing + recombination + radial flow? (stronger effect at RHIC because of steeper \( dN/dp_T \))
  - Two transport models (TAMU and Duke) with these ingredients predict maximum \( R_{AA} \) ~1.3-1.5 at RHIC and ~0.7-0.8 at LHC
High-multiplicity pp and p-Pb collisions

- LHC energy and luminosity allow for study of pp and p-Pb collisions with very high particle multiplicity
  - e.g. pp or p-Pb events with same multiplicity as non-central nucleus-nucleus at RHIC energy

- Look for similar effects as seen in nucleus-nucleus!
- E.g. characteristic patterns in two-particle correlations

PbPb

(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{\text{off}}^{\text{PbPb}} < 260$

- $1 < p_{T}^{\text{trig}} < 3$ GeV/c
- $1 < p_{T}^{\text{assoc}} < 3$ GeV/c
Two-particle correlations: near-side ridge

- Near-side ridge (long-range correlation in $\eta$ at $\Delta \phi = 0$) observed in high-multiplicity pp and p-Pb (CMS)

(b) MinBias, $1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$

(d) $N>110$, $1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$

**pp, min. bias**

**pp, high-multiplicity**

Pronounced structure at large $\Delta \eta$ around $\Delta \phi \sim 0$!
Two-particle correlations: near-side ridge

- Near-side ridge (long-range correlation in $\eta$ at $\Delta \phi = 0$) observed in high-multiplicity pp and p-Pb (CMS)

Pb-Pb

p-Pb, high-multiplicity

(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{\text{offline}} < 260$

$1 < p_{\text{trig}}^T < 3$ GeV/c

$1 < p_{\text{assoc}}^T < 3$ GeV/c

(b) CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 \leq N_{\text{offline}} < 260$

$1 < p_{\text{trig}}^T < 3$ GeV/c

$1 < p_{\text{assoc}}^T < 3$ GeV/c

CMS, PLB 724 (2013) 213
Two-particle correlations: double-ridge!

- Idea: subtract the “pp-like” structure of low-multiplicity p-Pb from the structure of high-multiplicity p-Pb
- Double ridge discovered by ALICE, followed by ATLAS
- Resembles the structure that in Pb-Pb is attributed to collective flow
Quantifying the modulation: $v_2$

- $v_2$ vs. $p_T$ and multiplicity with various methods
- Similar pattern in p-Pb and Pb-Pb
- $v_2$ rises to 2 GeV, then ~flattens out to 5

CMS, PLB 724 (2013) 213
Is it flow in p-Pb?
Look at identified particles

Pb-Pb

- Mass ordering, interpreted in terms of collective radial and elliptic flow
Is it flow in p-Pb?
Look at identified particles

**Pb-Pb**

- Mass ordering, interpreted in terms of collective radial and elliptic flow

**p-Pb, high-multiplicity**

- Clear indication for mass ordering in p-Pb
- Resembles Pb-Pb and supports “flow” picture
Possible interpretations

- High-multiplicity p-Pb presents several aspects that in Pb-Pb are explained by collective flow of an expanding medium.

- Models including hydrodynamical expansion can describe the observations (e.g. EPOS)

\[
\begin{align*}
v_2^{2PC, sub} & \propto 2PC, sub \\
\text{ALICE} & \\
p-Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV} \\
(0-20\%) - (60-100\%) & \\
\text{Near side gap: } \Delta \eta < 0.8 &
\end{align*}
\]

\[
\begin{align*}
EPOS 3.074 & \\
\text{p} & \text{p} \\
\text{EPOS: Klaus Werner, arXiv:1307.4379} &
\end{align*}
\]
Possible interpretations

- High-multiplicity p-Pb presents several aspects that in Pb-Pb are explained by collective flow of an expanding medium.
- Hydrodynamical expansion.
- Alternative explanation (1): Initial-state effect, CGC (Colour Glass Condensate) many-gluon processes can yield correlations.

Dusling, Venugopalan, PRD 87, 094034 (2013)
Possible interpretations

- High-multiplicity p-Pb presents several aspects that in Pb-Pb are explained by collective flow of an expanding medium
- Hydrodynamical expansion
- Alternative explanation (1): Initial-state effect
- Alternative explanation (2): MPI (multi-parton interactions) and “colour reconnection” (as implemented in PYTHIA8) can induce flow-like effects

see e.g. Ortiz et al, PRL111, 042001 (2013)
Possible interpretations

- High-multiplicity p-Pb presents several aspects that in Pb-Pb are explained by collective flow of an expanding medium
- Hydrodynamical expansion
- Alternative explanation (1): Initial-state effect
- Alternative explanation (2): MPI and “colour reconnection”

These results are clearly intriguing, several interpretations are being put forward, and new measurements from the experiments will provide stringent tests for theory