Charm production: constraints to transport models and charm diffusion coefficient with ALICE

Luuk Vermunt* (Universität Heidelberg), for the ALICE Collaboration

* luuk.vermunt@cern.ch
Open heavy-flavour production plays a **unique role** in heavy-ion physics:

- Production restricted to **early collision stages** and retain a "memory" of their evolution through the QGP

- Good theoretical control on the production (**perturbative QCD**) and transport through the medium (**diffusion treatment**)

- Heavy quarks **retain their flavour and mass identity**; can be "tagged" by the measurement of heavy-flavour hadrons
Charm-hadron analyses conducted in the central barrel ($|y|<0.5$), using:

- Inner Tracking System
- Time Projection Chamber
- Time-of-Flight detector
- V0 detectors

Charm measurements in Pb–Pb collisions:

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
- $\Lambda_c^+ \rightarrow K_S^0 \ p \rightarrow \pi^+ \pi^- \ p$
- $c \rightarrow \mu^\pm X$

Data samples used:

- Pb–Pb 5.02 TeV 2015: $\mathcal{L}_{\text{int}} \sim 13 \mu b$ (MB)
- 2018: $\mathcal{L}_{\text{int}} \sim 130 \mu b$ (0–10%) $\sim 56 \mu b$ (30–50%)
- Xe–Xe 5.44 TeV 2017: $\mathcal{L}_{\text{int}} \sim 0.3 \mu b$ (MB)

Muon Spectrometer (for $c \rightarrow \mu^\pm X$)
Regions of interest

**Low momenta**
- Heavy quarks interact via elastic rescatterings
- Diffusion approach via Langevin dynamics
- Approach thermalisation
- nPDF and shadowing

**Intermediate momenta**
- Probes the heavy quark hadronisation mechanisms
- Via fragmentation and/or recombination?

**High momenta**
- Heavy quarks interact via gluon radiation
- Quark mass and path-length dependence?
Nuclear modification factor: non-strange D

- Increasing suppression (for $p_T > 3 \text{ GeV/c}$) for more central collisions due to **increasing density, size, and lifetime** of the medium.

- Because of interplay of many different effects, **model comparison required** to interpret these single D-meson measurements.

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**New:** JHEP 01 (2022) 174

Pb–Pb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
Average $D^0, D^+, D^{*+}$

$|y| < 0.5$

0–10%  30–50%  60–80%  p–Pb

Nuclear modification factor: $D_{s}^{+}$ and $\Lambda_{c}^{+}$

Hint of hierarchy, $R_{AA}(\Lambda_{c}^{+}) > R_{AA}(D_{s}^{+}) > R_{AA}(D)$ for $p_T > 4$ GeV/c in most central collisions → Indication of modified hadronisation mechanisms; interplay with radial flow?
Azimuthal anisotropies: D mesons

**Positive $D$ $v_2$ and $v_3$ in 0–10% and 30–50%**

→ Charm participates in collective expansion

Positive $D_s^+$ $v_2$ in $2 < p_T < 8$ GeV/$c$ in 30–50% with significance of 6.4σ

→ Current uncertainties too large to draw conclusion about potential difference w.r.t. non-strange D
Charm-quark transport models

Most charm-quark transport models able to describe both the $R_{AA}$ and $v_2$

→ Use comparison to understand which physics effects are relevant
→ Use comparison to estimate the spatial diffusion coefficient

TAMU: PRL 124, 042301 (2020)
LIDO: PRC 98, 064901 (2018)
POWLANG: EPJC 75 (2015) 3, 121
PHSD: PRC 93, 034906 (2016)
LBT: PLB 777 (2018) 255-259
DAB-MOD: PRC 96, 064903 (2017)
Catania: PRC 96, 044905 (2017)
MC@sHQ: PRC 91, 014904 (2015)
LGR: EPJC 80 (2020) 7, 671

$R_{AA}$: JHEP 01 (2022) 174
$v_2$: PLB 813 (2021) 136054

Luuk Vermunt | Quark Matter 2022 | 07/04/2022
Radiative energy loss important to describe intermediate and high $p_T$
→ Small impact on low $p_T$ region
Physics effects in models

Hadronisation via recombination important to describe low and intermediate $p_T$

$\rightarrow$ D meson “picks up” the $v_2$ of the light quark
Spatial diffusion coefficient

Constraining the spatial diffusion coefficient via the data-to-model agreement

→ Using $R_{AA}$ (with $\chi^2/\text{ndf} < 5$) and $v_2$ (with $\chi^2/\text{ndf} < 2$) non-strange D measurements
→ TAMU, MC@sHQ, LIDO, LGR, and Catania “selected”

$\rightarrow 1.5 < 2\pi D_s T_c < 4.5$
$\rightarrow \tau_{\text{charm}} \approx 3-8 \text{ fm/c}$
What do leptons from HF decays teach us?

$R_{AA}$ of HF decay $\mu^{\pm}$ and $e^{\pm}$ (see backup) reasonably well described by transport models → Some tension for PHSD (no radiative e-loss) with forward muons, but describes $e^{\pm}$ at midrapidity

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Similar $R_{AA}$ for $\mu^{\pm}$ from heavy-flavour decays in Pb–Pb and Xe–Xe collisions at similar $\langle dN_{\text{ch}}/d\eta \rangle$ → Possibility to further constrain model calculations

ALI-PUB-495151

MC@SHQ: PRC 89, 014905 (2014) PHSD: PRC 93, 034906 (2016)
What do $D_S^+$ and $\Lambda_C^+$ teach us?

$R_{AA}$ of $D_S^+$ and $\Lambda_C^+$ reasonably well described by models including charm recombination

$\rightarrow$ Tension SHMc due to somewhat schematic corona description
Charm-strange to probe hadronisation

The $D_s^+/D^0$ ratio is **higher** in $2 < p_T < 8$ GeV/c in 0–10% (30–50%) Pb-Pb by $2.3\sigma$ ($2.4\sigma$)

Described by models including strangeness enhancement and fragmentation + recombination
Charm baryons to probe hadronisation

The $\Lambda_c^+/D^0$ ratio is **enhanced** in $4 < p_T < 8$ GeV/c for central Pb–Pb wrt pp collisions by $3.7\sigma$

→ Also seen for baryon-to-meson ratios with **light-flavour particles**

→ Data is described by TAMU. The shapes of the Catania and SHMc predictions agree qualitatively
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→ Also seen for baryon-to-meson ratios with light-flavour particles
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Can the enhancement be explained as an **interplay between radial flow & recombination**, i.e. a different redistribution of $p_T$ between baryons and mesons?
$p_T$-integrated $\Lambda_c^+/D^0$ ratio

![Graph showing $\Lambda_c^+/D^0$ ratio for different collision systems.]

- $\Lambda_c^+/D^0$ ratio for $pp$, $\sqrt{s} = 5.02$ TeV
- $p$-$Pb$, $\sqrt{s_{NN}} = 5.02$ TeV
- $Au$-$Au$, $\sqrt{s_{NN}} = 200$ GeV

Source: STAR, PRL 124 (2020) 172301
$p_T$-integrated $\Lambda_c^+/D^0$ ratio

New and precise estimates by ALICE at low and high multiplicities

Hint of flat trend with multiplicity
**$p_T$-integrated $\Lambda_c^+/D^0$ ratio**

New and precise estimates by ALICE at low and high multiplicities

Hint of flat trend with multiplicity

→ Reproduced by fragm+recomb and SHM predictions (including new charm-baryon states for the latter)
New and precise estimates by ALICE at low and high multiplicities

Hint of flat trend with multiplicity
→ Reproduced by fragm+recomb and SHM predictions (including new charm-baryon states for the latter)

Is the $p_T$ differential $\Lambda_c^+ / D^0$ enhancement just a consequence of radial flow and recombination?

ALICE

- $pp, \sqrt{s} = 13$ TeV
- $pp, \sqrt{s} = 5.02$ TeV
- $p-Pb, \sqrt{s_{NN}} = 5.02$ TeV
- $Pb-Pb, \sqrt{s_{NN}} = 5.02$ TeV
- $Au-Au, \sqrt{s_{NN}} = 200$ GeV

$\left< dN_{ch}/d\eta \right>_{|\eta|<0.5}$


L. Stritto, 07/04/21, 16:00
Statistical hadronisation of charm

SHMc (charm quarks fully thermalised in the QGP)
→ Distributed into hadrons at phase boundary according to **thermal weights**

Measured yields of **open-charm mesons compatible** with SHMc

Measured yield of $\Lambda_c^+$ **underestimated**
→ Described in case of an enhanced charm-baryon resonance spectrum
Conclusion

ALICE performed precise heavy-flavour measurements with Run 2 Pb–Pb data

→ Charm mesons **down to** $p_T = 0$

→ **Charm-strange** mesons and **charm baryons** to low $p_T$
  → No $p_T$ integrated $\Lambda_c^+/D^0$ enhancement with multiplicity

→ Beauty production also accessed, via non-prompt D mesons and $e^{\pm}$ from beauty decays

What did we learn so far?

→ Charm quarks interact with medium via **collisional and radiative processes**

→ Charm quarks participate in the collective motion, i.e. are **thermalised**

→ Charm quarks hadronise via **recombination** (in addition to fragmentation)
What’s next?

Wide ALICE upgrade program for LHC Run 3 and 4, crucial for HF measurements

→ Continuous readout at **50 kHz interaction rate** for Pb–Pb collisions

→ **Improved tracking precision** by a factor 3–6
→ New silicon Inner Tracking System

The near future will bring us **new** and **more precise** HF measurements down to **low** $p_T$, stay tuned...

Thank you for your attention!
Additional slides
Experimental techniques: charm hadrons

Fully reconstructed charm hadrons (in ALICE):

1. Heavy-flavour candidates defined by combining pairs/triplets of charged tracks at midrapidity.
2. Apply kinematical and geometrical selections on displaced decay-topology.
4. Signal extracted via an invariant-mass analysis.
5. Yield corrected for efficiency (MC simulations) and feed-down from b-hadron decays (pQCD predictions).

![Graph showing the mass spectrum of D^+ to K^+π^+ decay]

Counts / (6 MeV/c²)

- D^+ → K^+π^+π^+ with 5 < p_T < 5.5 GeV/c and charge conj.

μ = 1872 ± 1 MeV/c²
σ = 9 ± 1 MeV/c²
S = 5476 ± 369

\( M(K\pi\pi) \) (GeV/c²)

D^+: 311.8 μm
D_S^+: 151.2
D^0: 122.9
Λ_c^+: 60.7
D^{*+}: 2.4 \cdot 10^{-6}
Experimental techniques: HF leptons

- Partial reconstruction via semileptonic decays
  \[ \rightarrow c, b \rightarrow e^\pm X \]
  \[ \rightarrow c, b \rightarrow \mu^\pm X \]

- Exploiting
  \[ \rightarrow \text{identification of } e^\pm \text{ at midrapidity} \]
  \[ \rightarrow \text{tracking of } \mu^\pm \text{ at forward rapidity} \]
  \[ \rightarrow \text{subtraction of hadron contamination and non-HF leptons} \]
  \[ \rightarrow \text{separation of charm and beauty } e^\pm \text{ via impact parameter } d_0 \]
Experimental techniques: azimuthal anisotropies

$v_2$ measured with the **Scalar-Product** (SP) method

$$v_n\{\text{SP}\} = \frac{\langle \mathbf{u}_n \cdot Q_{n}^{A*}\rangle}{\sqrt{\langle Q_{n}^{A} \cdot Q_{n}^{A} \rangle}} \left/ \sqrt{\frac{\langle Q_{n}^{B} \cdot Q_{n}^{C*} \rangle}{\langle Q_{n}^{B} \cdot Q_{n}^{C*} \rangle}} \right.$$ 

$$Q_n = \left( \sum_{k=0}^{N_{\text{tracks}}} \cos(n\varphi_k) + \sum_{k=0}^{N_{\text{tracks}}} \sin(n\varphi_k) \right)$$

$$\mathbf{u}_n = (\cos(n\varphi_D), \sin(n\varphi_D))$$

- Since per-particle identification of D mesons not possible, two component (signal, background) **fit** of $v_n$ vs. **invariant mass** performed:

$$v_n^{\text{tot}}(M) = \frac{S}{S+B}(M) \cdot v_n^{\text{signal}} + \frac{B}{S+B}(M) \cdot v_n^{\text{bkg}}(M)$$
Azimuthal anisotropies ($v_2$)

$$E \frac{d^3N}{dp_T} = \frac{1}{2\pi p_T dp_T dy} \left\{ 1 + \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)] \right\}$$

$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$  

second harmonic coefficient  

elliptic flow  

Asymmetry between the in-plane and out-of-plane directions.
Azimuthal anisotropies ($v_3$)

\[
E \frac{d^3N}{dp_T} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left\{ 1 + \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)] \right\}
\]

$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$

third harmonic coefficient

triangular flow

Event-by-event fluctuations in initial distributions of participant nucleons in the overlap region
- Sensitive to the shear viscosity over entropy density ratio, $\eta/s$.

Prompt $D^0$, $D^+$, $D^{**}$ average, $|y|<0.8$
- $0$–$10\%$
- $30$–$50\%$

Syst. from data
Syst. from B feed-down
Heavy versus light/charm versus beauty

\( p_T < 3-4 \text{ GeV}/c \): Mass ordering.
- \( v_2(\Upsilon) \lesssim v_2(e \leftrightarrow b) \approx v_2(J/\Psi) < v_2(D) < v_2(\pi^{\pm}) \)
- \( \rightarrow \) Interplay between anisotropic flow and isotropic expansion of system (radial flow).

\( 4 < p_T < 8 \text{ GeV}/c \): No. constituent quark scaling.
- \( v_2(J/\Psi) < v_2(D) \approx v_2(\pi^{\pm}) ( < v_2(p) ) \)
- \( v_2(\Upsilon) < v_2(e \leftrightarrow b) \)
- \( \rightarrow \) Supports hypothesis of hadronisation via quark coalescence.

\( p_T > 8 \text{ GeV}/c \): Compatible coefficients.
- \( v_2(J/\Psi) \approx v_2(D) \approx v_2(\pi^{\pm}) ( \approx v_2(p) ) \)
- \( \rightarrow \) Supports hypothesis of similar path-length dependence of in-medium energy loss.
Charm-hadron flow carried by light quarks

Test of $n$-quark scaling and recombination mechanisms

→ quark flow obtained by interpolating $v_n(J/\Psi)$ and $v_n(\pi)$

→ assuming:

\[
v_n^\pi(p_T^\pi) = 2 \ast v_n^q(p_T^\pi/2) \\
v_n^D(p_T^D) = v_n^q(p_T^q) + v_n^c(p_T^c)
\]

→ Good description of $D^0$ flow when light quark carries a large fraction (i.e. $p_T^q/p_T^D = 0.4$) of $D$ meson $p_T$
Heavy versus light versus theory

Perturbative QCD calculations describe reasonably well the measured $v_2$, “confirming”

- the **quadratic path length dependence** of radiative energy loss;
- the expected mass dependence due to the **dead-cone effect**.

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opacity expansion model

soft-collinear effective theory
Heavy versus light/charm versus beauty

\[ R_{AA}(D) > R_{AA}(LF) \text{ for } p_T < 8 \text{ GeV/c} \]

\[ R_{AA}(\text{charm}) < R_{AA}(\text{beauty}) \]

\[ R_{AA}(D) \approx R_{AA}(J/\psi) \text{ for } p_T \gtrsim 10 \text{ GeV/c} \]

\[ R_{AA}(D) \sim R_{AA}(J/\psi) \text{ for } p_T \gtrsim 2 \text{ GeV/c} \]
Heavy versus light versus theory

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opacity expansion model

soft-collinear effective theory
Heavy flavour decay leptons

$R_{AA}$ of HF decay muons and electrons reasonably well described by most transport models

→ Some tension for PHSD (no radiative e-loss) with forward muons, but describes $e^{\pm}$ at midrapidity
Charm-quark transport models: ingredients

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But more importantly: different implementations and input parameters.