





# Istituto Nazionale di Fisica Nucleare ALICE Study of RAA and v2 of non-strange D mesons and D-jet production in **Pb-Pb collisions with ALICE**



Fabrizio Grosa on behalf of the ALICE Collaboration **Politecnico and INFN Torino** European Physical Society - Conference on High Energy Physics 2019



# Ultra-relativistic heavy-ion collisions and quark-gluon plasma

Under extreme conditions of very high temperature and/ or density, quantum chromodynamics (QCD) calculations on the lattice predict a phase transition from the ordinary nuclear matter to a colour-deconfined medium, called quark-gluon plasma (QGP)





The QGP can be recreated in the laboratory via ultrarelativistic heavy-ion collisions

(i) pre-equilibrium

(ii) QGP formation and thermalisation (iii) hadronisation

(iv) freeze out (chemical and kinetic)





### Heavy-flavour hadrons in Pb-Pb collisions



Incoming Heavy Ion Beams

- Properties of in-medium energy loss studied via the nuclear modification factor  $R_{AA} \rightarrow$  quark-mass, colour-charge, path length dependencies
- Study in-medium colour/mass dependent energy loss and modification of internal jet sub-structure with heavy-flavour jets
- Possible modification of the hadronisation mechanism investigated via the measurement of relative abundances of different hadron species

Heavy flavours (HF), i.e. charm and beauty quarks, are mainly produced in hard-scattering processes in shorter time scales compared to the QGP formation time IF probe the entire space-time evolution of the system, loosing energy interacting with the medium constituents via elastic scatterings and gluon radiations





 $dN_{AA}/dp_{T}$  $R_{AA}$  $dN_{pp}/dp_T$ NAA `COII/









# Heavy-flavour hadron azimuthal anisotropies in Pb-Pb collisions

- The initial geometrical anisotropy is converted via multiple interactions into an azimuthally anisotropic distribution in momentum space of the produced particles
- Azimuthal anisotropies can be studied via the Fourier decomposition of the azimuthal distribution of particle momenta

$$E\frac{\mathrm{d}^3 N}{\mathrm{d}p_{\mathrm{T}}} = \frac{1}{2\pi} \frac{\mathrm{d}^2 N}{p_{\mathrm{T}} \mathrm{d}p_{\mathrm{T}} \mathrm{d}y} \left\{ 1 + \sum_{i=1}^{\infty} v_{\mathrm{n}} \cos[\mathrm{n}(\varphi - \Psi_{\mathrm{n}})] \right\}$$

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

second harmonic coefficient, elliptic flow

- Solution Asymmetry between the in-plane (parallel to  $\Psi_2$ ) and out-of plane (orthogonal to  $\Psi_2$ ) regions At low *p*<sub>T</sub>: participation in the collective motion and possible thermalisation of heavy quarks in the medium
- At high *p*<sub>T</sub>: path-length dependence of energy loss















#### **Time Projection Chamber**

Track reconstruction Particle identification via specific energy loss









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- Particle identification via specific energy loss

# Inner Tracking System Track reconstruction Reconstruction of primary and decay vertices







#### **Time Projection** Chamber

- Track reconstruction
- Particle identification via specific energy loss

#### **Inner Tracking System**

- Track reconstruction
- Reconstruction of primary and decay vertices

#### **Time of Flight detector** Particle identification via the

time-of-flight measurement







#### **Time Projection** Chamber

- Track reconstruction
- Particle identification via specific energy loss

#### **V0** detectors

- Trigger
- Centrality estimation
- Event-plane estimation









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# Non-strange D-meson reconstruction in ALICE

[1]	Meson	$M(\text{GeV}/c^2)$	decay	<i>cτ</i> (μm)	BR (%)
_	D <sup>0</sup> (cū)	1.865	$\mathrm{K} extsf{-}\pi^+$	123	3.89
	$D^{+}(c\bar{d})$	1.870	$\mathrm{K} extsf{-}\pi^+\pi^+$	312	8.98
-	$D^{*+}(c\bar{d})$	2.010	$D^0 (\rightarrow K^- \pi^+) \pi^+$	strong decay	2.66

D-meson candidates built combining pairs/triplets of tracks reconstructed at mid-rapidity ( $|\eta| < 0.8$ ) with proper charge



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### Non-strange D-meson and jet reconstruction in ALICE

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- D<sup>0</sup>-tagged jets: D<sup>0</sup> candidate with  $p_T$  > 3 GeV/*c* required to be among the jet constituents
- $\therefore$  K and  $\pi$  tracks replaced by D<sup>0</sup>







# D-meson *R*<sub>AA</sub> in Pb-Pb collisions



Increasing suppression from
peripheral (60-80%) to central
(0-10%) Pb-Pb collisions

SIFEP 1810 (2018) 174





# D-meson *R*<sub>AA</sub> in Pb-Pb collisions



Increasing suppression from peripheral (60-80%) to central (0-10%) Pb-Pb collisions

D mesons Charged pions Charged particles JHEP 1811 (2018) 013  $R_{AA}(D) > R_{AA}(\pi^{\pm})$ for  $p_{\rm T} < 8 \text{ GeV/}c$  $\rightarrow N_{\text{coll}}$  vs.  $N_{\text{part}}$  scaling at low  $p_{\rm T}$ , different fragmentation and initial spectra shapes,

possible mass and Casimir factor effects, different coalescence and radial flow

 $R_{AA}(D) \simeq R_{AA}(\pi^{\pm}) \simeq R_{AA}(charged particles)$  for  $p_T > 8 \text{ GeV}/c$ 











# D-meson abundances in Pb-Pb collisions



For a complete picture also the relative abundance of strange D mesons Ş and the charmed baryons has to be compared in pp and Pb-Pb

EPJ C79 (2019) no 5, 388

No observed modification of the non-strange D-meson relative abundances from pp to Pb-Pb collisions

➡ L. Vermunt 12/07 9:00













### D-meson *R*<sub>AA</sub> in Pb-Pb collisions vs. models



**TAMU:** PLB 735, 445-450 (2014) **PHSD:** PRC 92, 014910 (2015) **POWLANG: EPJC 75, 121 (2015)**  **MC@sHQ+EPOS: PRC 89, 014905 (2014)** *Solutionary Elipsical States and States and* **BAMPS: JPG 42, 115106 (2015)** Section Catania: EPJC 78, 348 (2018)

Low p<sub>T</sub> D-meson *R*<sub>AA</sub> described by transport models based on Boltzmann/ Fokker-Plank/ Langevin equations









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High *p*<sub>T</sub> D-meson *R*<sub>AA</sub> described by pQCD-based models

Solution Djordevic: PRC 92, 024918 (2015) **CUJET3.0: JHEP 02 (2016) 169** SCET: JHEP 03 (2017) 146











# D-meson production in jets in Pb-Pb collisions



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Charged jets D-meson tagged jets

Fint of smaller  $R_{AA}$  for low- $p_T$  D-meson tagged jets compared to higher *p*<sub>T</sub> charged jets





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- Similar *R*<sub>AA</sub> for D-meson tagged jets and D mesons







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- Similar *R*<sub>AA</sub> for D-meson tagged jets and D mesons
- D-jet analysis performed with 2015 data possibility to improve precision and extend *p*<sub>T</sub> coverage with 2018 data sample (x9 more central collisions than 2015 data sample)







# D-meson elliptic flow in Pb-Pb collisions



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D mesons

Charged pions JHEP 1809 (2018) 006 Charged particles JHEP 07 (2018) 103 J/Ψ JHEP 02 (2019) 012

- Positive D-meson  $v_2$  in mid-central Pb-Pb collisions indicates participation of charm quark in the collective motion  $v_2(D) \approx v_2(\pi^{\pm})$  for  $p_T > 3-4$  GeV/c
- Solution  $V_2(D) < v_2(\pi^{\pm}) \text{ for } p_T < 3-4 \text{ GeV}/c$
- <sup>\$</sup>ν<sub>2</sub>(D) > ν<sub>2</sub>(J/Ψ) for p<sub>T</sub> < 6 GeV/c
   explained by charm-quark coalescence
   with flowing light-flavour quarks
   </p>





# Event-shape engineering for the D-meson *v*<sub>2</sub>

The Event-shape engineering (ESE) technique relies on the classification of events according to their eccentricity, using the magnitude of the second-harmonic reduced flow vector:

Solution Measurement of D-meson  $v_2$  in ESE-selected samples indicate a positive correlation between the D-meson *v*<sub>2</sub> and the light-hadron *v*<sub>2</sub>





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### Event-shape engineering for the D-meson v<sub>2</sub> vs. models



- Models based on charmquark transport in an hydrodynamically expanding medium describe reasonably  $q_2$ dependence of elliptic flow
- Variation of D-meson v<sub>2</sub> in ESE-selected samples with respect to unbiased sample similar for different transport parameters (e.g. POWLANG HLT vs. lQCD) pure geometrical effect?

POWLANG: arXiv:1812.08337 LIDO: PRC 98, 064901 (2018) Section 2016 (2016) Section 2017 (2016)









- Non-strange D-meson *R*<sub>AA</sub> in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV shows a strong suppression, increasing with collision centrality
- $R_{AA}$  (D) >  $R_{AA}$  (light hadrons) for  $p_T < 8 \text{ GeV}/c$ quark-mass / colour-charge dependence
- Similar *R*<sub>AA</sub> for D-meson tagged jets and D mesons
- Positive D-meson elliptic flow
  - participation of charm quark in the collective motions
  - $\rightarrow$  at low  $p_T v_2$  (D) >  $v_2 (J/\Psi)$  explained by charmquark coalescence with flowing light-flavour quarks
- ESE technique
  - positive correlation between D and light-hadron *v*<sup>2</sup> reasonably described by transport models







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![](_page_28_Picture_13.jpeg)

![](_page_28_Picture_14.jpeg)

![](_page_29_Picture_0.jpeg)

![](_page_29_Picture_1.jpeg)

### D-meson *R*<sub>AA</sub> in Pb-Pb collisions

![](_page_30_Figure_1.jpeg)

 $\mathbb{P}$  D<sup>0</sup>, D<sup>+</sup>, and D<sup>\*+</sup> R<sub>AA</sub> is compatible within uncertainties

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![](_page_30_Picture_7.jpeg)

![](_page_30_Picture_8.jpeg)

![](_page_30_Picture_9.jpeg)

### D-meson *R*<sub>AA</sub> in Pb-Pb collisions 2018 VS. 2015

![](_page_31_Figure_1.jpeg)

- Improved precision in 2018
- Solution  $\mathbb{S}$  More differential measurement in 2018 allows for a better description of the  $p_{\rm T}$  shape

![](_page_31_Picture_8.jpeg)

![](_page_31_Picture_9.jpeg)

### D-meson v<sub>2</sub> in Pb-Pb collisions 2018 VS. 2015

![](_page_32_Figure_1.jpeg)

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![](_page_32_Figure_4.jpeg)

![](_page_32_Picture_7.jpeg)

![](_page_32_Picture_8.jpeg)

# D-meson elliptic flow in Pb-Pb collisions

#### Solution $P_2$ D-meson $v_2$ measured at mid-rapidity (|y| < 0.8) using the scalar-product (SP) method

$$v_{2}\{\text{SP}\} = \frac{\langle u_{2,\text{D}}Q_{2,\text{A}}^{*}/M_{\text{A}} \rangle}{\sqrt{\frac{\langle Q_{2,\text{A}}/M_{\text{A}}Q_{2,\text{B}}^{*}/M_{\text{B}} \rangle \langle Q_{2,\text{A}}/M_{\text{A}}Q_{2,\text{C}}^{*}/M_{\text{C}} \rangle}}{\langle Q_{2,\text{B}}/M_{\text{B}}Q_{2,\text{C}}^{*}/M_{\text{C}} \rangle}} \text{ where }$$

Figure The  $v_2$  of the signal is extracted from a  $v_2$  vs mass fit:

$$v_2(M) = \frac{S}{S+B}v_2^{\text{sgn}} + \frac{B}{S+B}v_2^{\text{sgn}} + \frac{B}{S+B}v_2^{\text{sgn$$

![](_page_33_Figure_8.jpeg)

![](_page_33_Figure_9.jpeg)

![](_page_33_Figure_10.jpeg)

![](_page_33_Figure_11.jpeg)

![](_page_33_Picture_13.jpeg)

![](_page_33_Picture_14.jpeg)

#### D-meson $v_2$ vs. models

![](_page_34_Figure_1.jpeg)

![](_page_34_Picture_5.jpeg)

![](_page_34_Picture_6.jpeg)

![](_page_34_Picture_7.jpeg)

### Event-shape engineering selection

harmonic reduced flow vector

![](_page_35_Figure_2.jpeg)

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![](_page_35_Picture_6.jpeg)

![](_page_35_Picture_7.jpeg)

![](_page_35_Picture_9.jpeg)

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#### ESE-selected D-meson yields

![](_page_36_Figure_1.jpeg)

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POWLANG: arXiv:1812.08337

![](_page_36_Picture_6.jpeg)

![](_page_36_Figure_7.jpeg)

![](_page_36_Picture_8.jpeg)

#### ESE-selected charged-particle v<sub>2</sub>

![](_page_37_Figure_1.jpeg)

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#### PRC 93, 034916 (2016)

![](_page_37_Figure_6.jpeg)

![](_page_37_Picture_7.jpeg)