



## 62<sup>nd</sup> International Winter Meeting on Nuclear Physics

19 - 23 January 2026  
Bormio, Italy

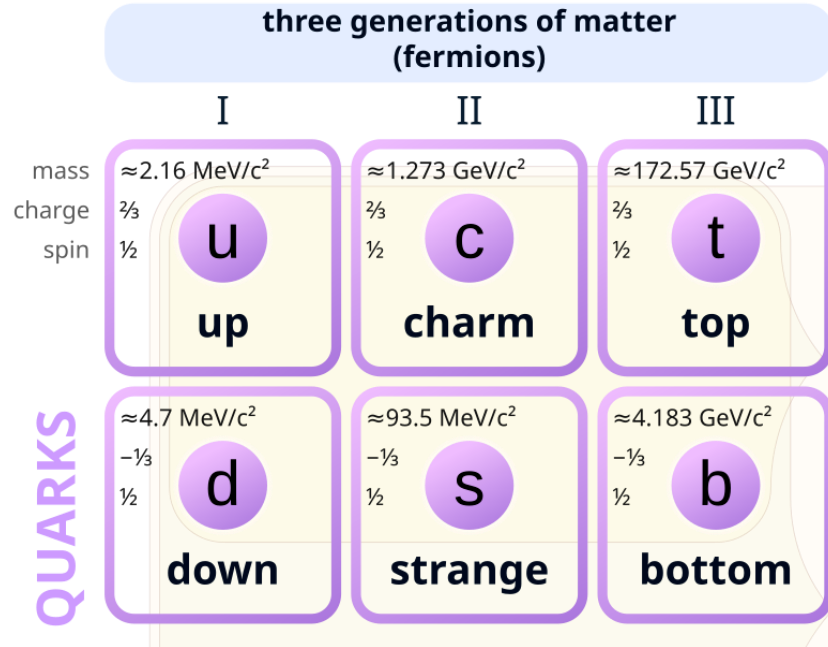
# How charm quarks reveal fundamental properties of QCD

Silvia Masciocchi  
GSI and Uni Heidelberg  
January 23, 2026

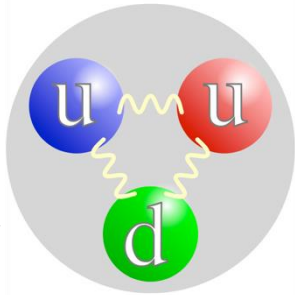


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# Quarks



# Quarks



## Hadronization

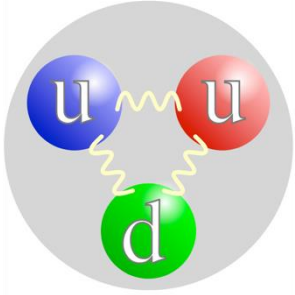
String fragmentation ...  
... baryon production !

three generations of matter (fermions)

|        | I                              | II                              | III                              |
|--------|--------------------------------|---------------------------------|----------------------------------|
| mass   | $\approx 2.16 \text{ MeV}/c^2$ | $\approx 1.273 \text{ GeV}/c^2$ | $\approx 172.57 \text{ GeV}/c^2$ |
| charge | $\frac{2}{3}$                  | $\frac{2}{3}$                   | $\frac{2}{3}$                    |
| spin   | $\frac{1}{2}$                  | $\frac{1}{2}$                   | $\frac{1}{2}$                    |
|        | <b>u</b><br>up                 | <b>c</b><br>charm               | <b>t</b><br>top                  |
|        | <b>d</b><br>down               | <b>s</b><br>strange             | <b>b</b><br>bottom               |

QUARKS

# Quarks

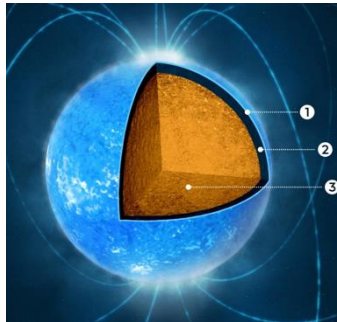
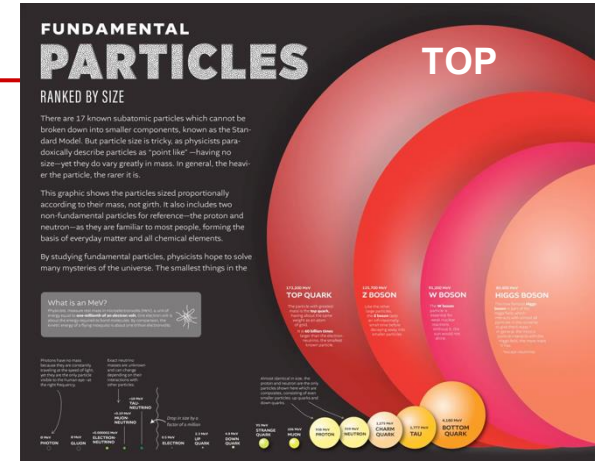


## Hadronization

String fragmentation ...  
... baryon production !

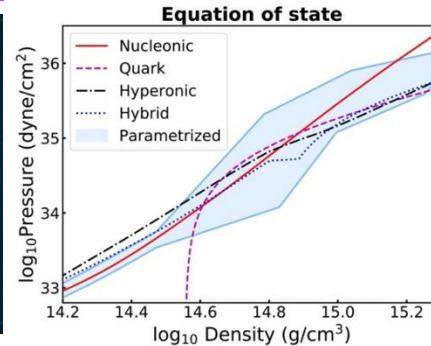
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|        | <b>d</b><br>down               | <b>s</b><br>strange             | <b>b</b><br>bottom               |
|        | $\approx 4.7 \text{ MeV}/c^2$  | $\approx 93.5 \text{ MeV}/c^2$  | $\approx 4.183 \text{ GeV}/c^2$  |
|        | $-\frac{1}{3}$                 | $-\frac{1}{3}$                  | $-\frac{1}{3}$                   |
|        | $\frac{1}{2}$                  | $\frac{1}{2}$                   | $\frac{1}{2}$                    |

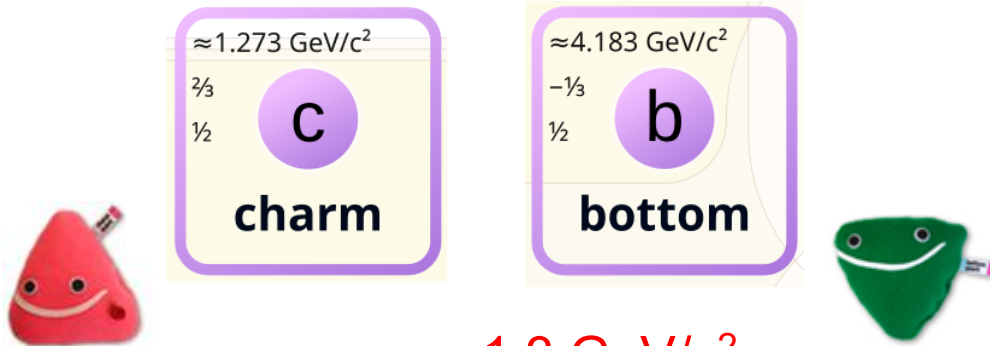


## Neutron stars

Anna Watts  
19/01/26



# Heavy quarks (HQ): charm and beauty



$$m_{\text{charm}} \sim 1.3 \text{ GeV}/c^2$$
$$m_{\text{beauty}} \sim 4.2 \text{ GeV}/c^2$$

Quarks images from <http://www.particlezoo.net/>

- $m_c, m_b \gg \Lambda_{\text{QCD}} \rightarrow$  **hard probes** (even at low momentum  $\neq$  jets)
- Production: **Large  $Q^2$**  processes:  $Q^2 > (2m_{c,b})^2$

$$\text{Very short formation times} = \frac{\hbar}{4m_{c(b)}} \approx 0.05(0.01) \text{ fm}/c$$

**Perturbative QCD** applicable

# QCD

$$\begin{aligned} L_{QCD} = & -\frac{1}{4} F_{\mu\nu}^{(a)} F^{(a)\mu\nu} \\ & + i \sum_q \bar{\psi}_q^i \gamma^\mu (D_\mu)_{ij} \psi_q^j \\ & - \sum_q m_q \bar{\psi}_q^i \psi_{qi} \end{aligned}$$

# QCD

$$L_{QCD} = -\frac{1}{4} F_{\mu\nu}^{(a)} F^{(a)\mu\nu} \\ + i \sum_q \bar{\psi}_q^i \gamma^\mu (D_\mu)_{ij} \psi_q^j \\ - \sum_q m_q \bar{\psi}_q^i \psi_{qi}$$



# QCD

$$L_{QCD} = -\frac{1}{4} F_{\mu\nu}^{(a)} F^{(a)\mu\nu} + i \sum_q \bar{\psi}_q^i \gamma^\mu (D_\mu)_{ij} \psi_q^j - \sum_q m_q \bar{\psi}_q^i \psi_{qi}$$



Lattice  
QCD

Perturbative  
QCD

Lots of effective,  
empirical, quasi-  
phenomenological, MC  
stuff

- HQ production cross sections
- Baryon/meson ratios
- D-light femtoscopy
  
- HQ energy loss
- Charmed current

pQCD

Hadronization  
Hadron interaction

Quark-gluon plasma  
Full dynamic exploration



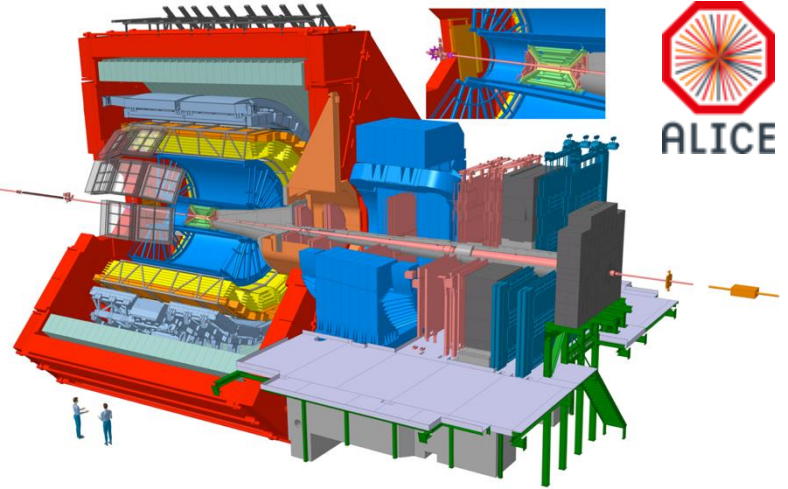
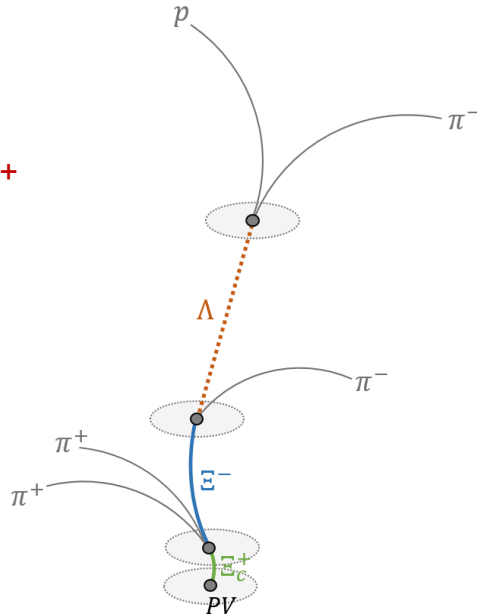
SFB1225

# Open heavy-flavor hadrons

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+$
- $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\Lambda_c^+ \rightarrow p K_S^0$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$

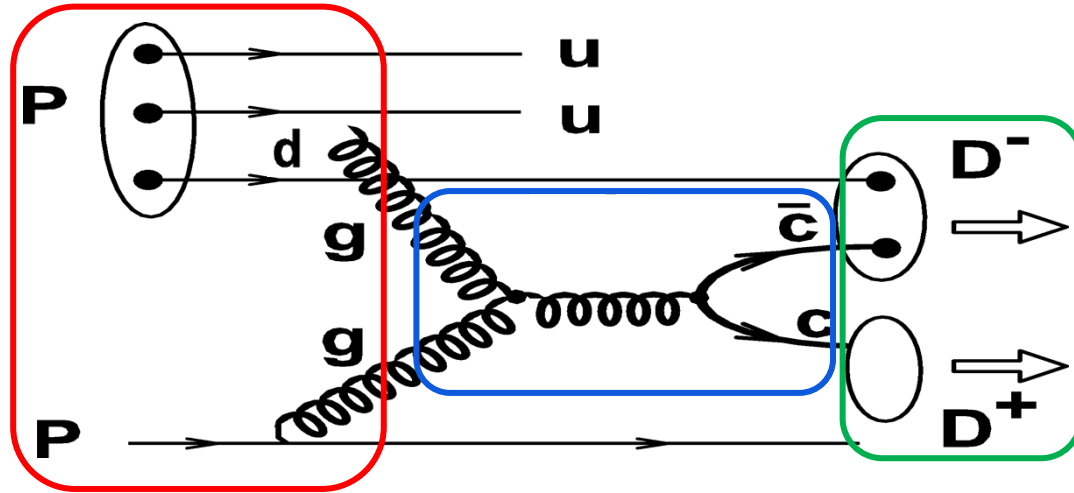
$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$

$\sigma_T \approx 100 \mu\text{m}$



# Heavy quark production: hadron-hadron collisions

Production cross section computed using the QCD **factorization theorem**



**PDFs** →  
parton level



$ij \rightarrow c\bar{c}$   
2-to-2 process  
**pQCD**

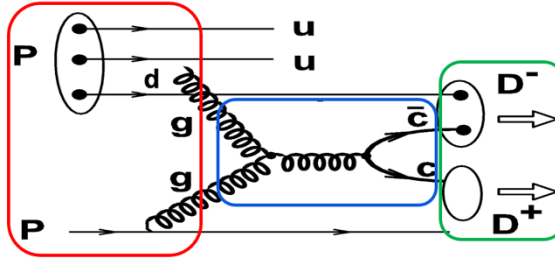


**Hadronization**  
Soft scale (MC,  
phenomenology)

Sketch modified  
from PLB 724  
(2013) 108

# Heavy quark production

Production cross section computed using the QCD factorization theorem:



$$\frac{d\sigma}{dp_T}^{pp \rightarrow H_c X} = \sum_{i,j=q,\bar{q}g} f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \frac{d\sigma^{ij \rightarrow c\bar{c}}}{dp_T} D_{c \rightarrow H_c}(z_c = p_{H_c}/p_c, \mu_f^2)$$

## PDFs

Parton distribution functions relative to the colliding protons (or nPDF for nuclei)

Parton hard scattering cross section of  $c\bar{c}$  pair production

## pQCD

Charm hadronization fractions

- HQ production cross sections
- Baryon/meson ratios
- D-light femtoscopy
  
- HQ energy loss
- Charmed current

pQCD

Hadronization  
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Full dynamic exploration



# Heavy quark production: test of perturbative QCD

PRODUCTION (in proton-proton) well described by perturbative QCD expansion in a series in powers of the strong coupling constant  $\alpha_S$

Next-to-leading order:

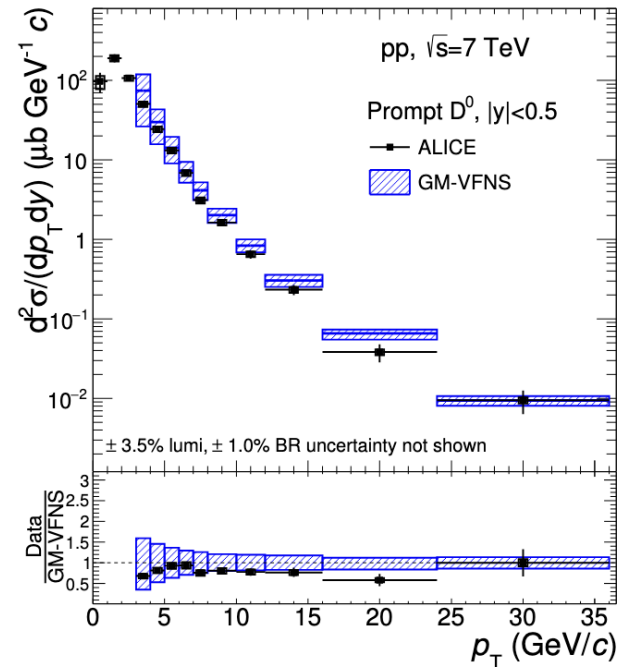
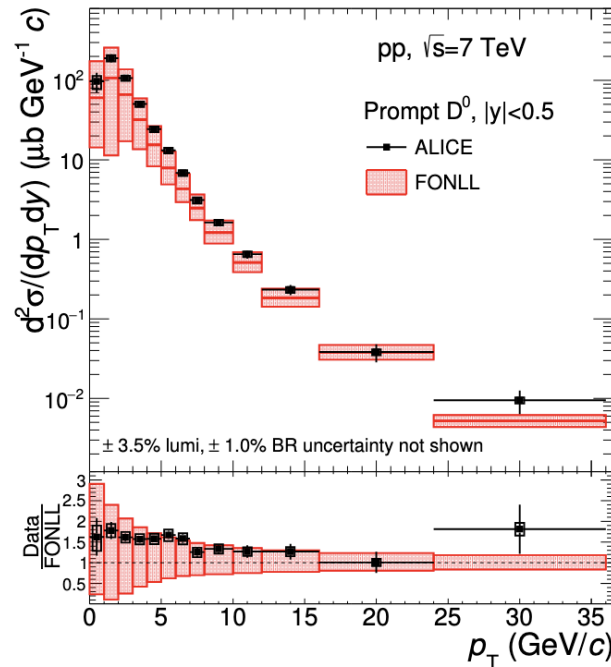
Fixed-Order Next to Leading Log (FONLL)

Cacciari, Greco, Nason  
JHEP 05 (1998) 007  
JHEP 10 (2012) 137

General Mass Variable Flavor Number Scheme GM-VFNS

Kniehl, Kramer, Schienbein, Spiesberger  
Phys. Rev. D71 (2005) 014018,

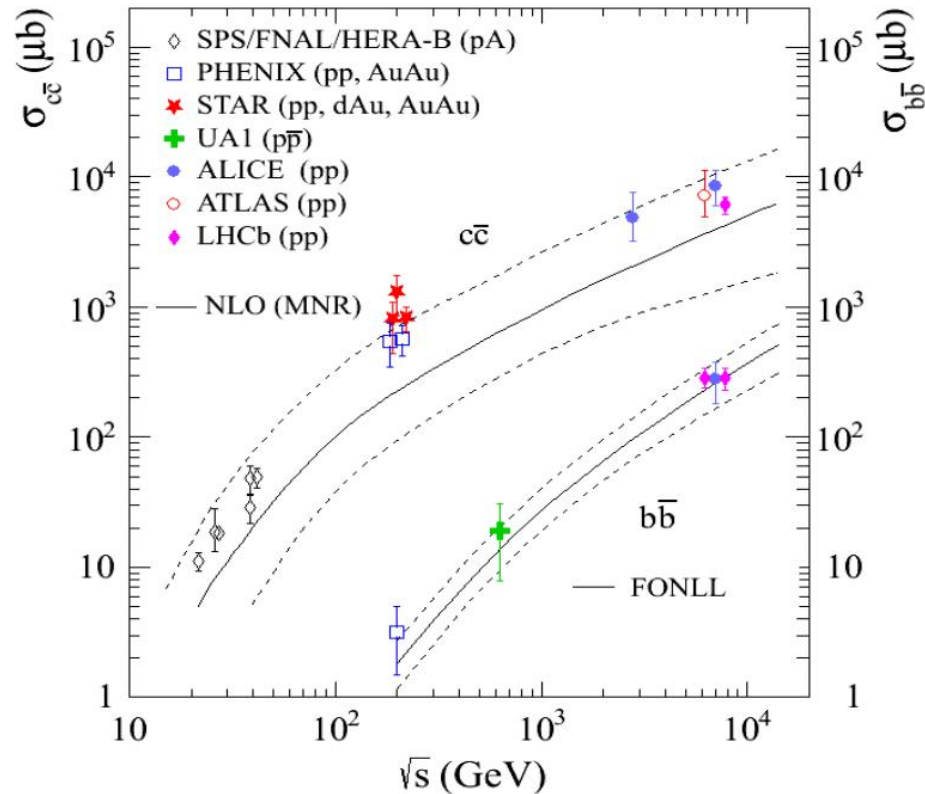
$\mu_f$ : factorisation scale  $\rightarrow$  large uncertainties



# Heavy quark TOTAL production cross section

## Test of perturbative QCD

Recent plots for charm in PRD 105, L011103 (2022) and for beauty in JHEP 05 (2021) 220



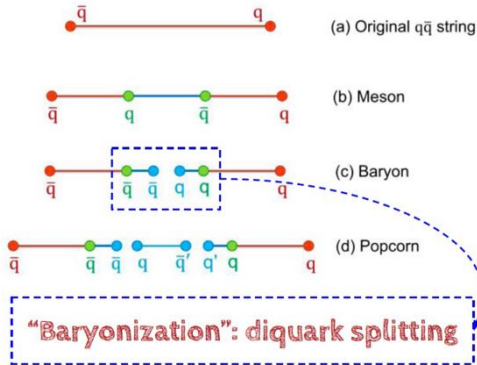
# Hadronization

So fundamental and still pretty not understood

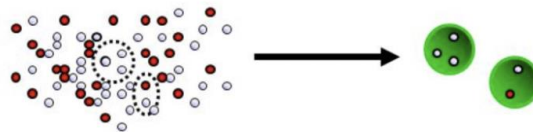
Baryon creation challenges string fragmentation: “ad hoc” solutions implemented

## String fragmentation

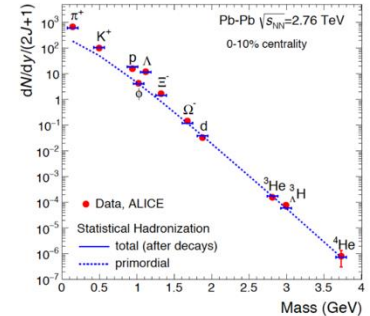
e.g. PYTHIA



## Coalescence



## Statistical hadronization



Vacuum



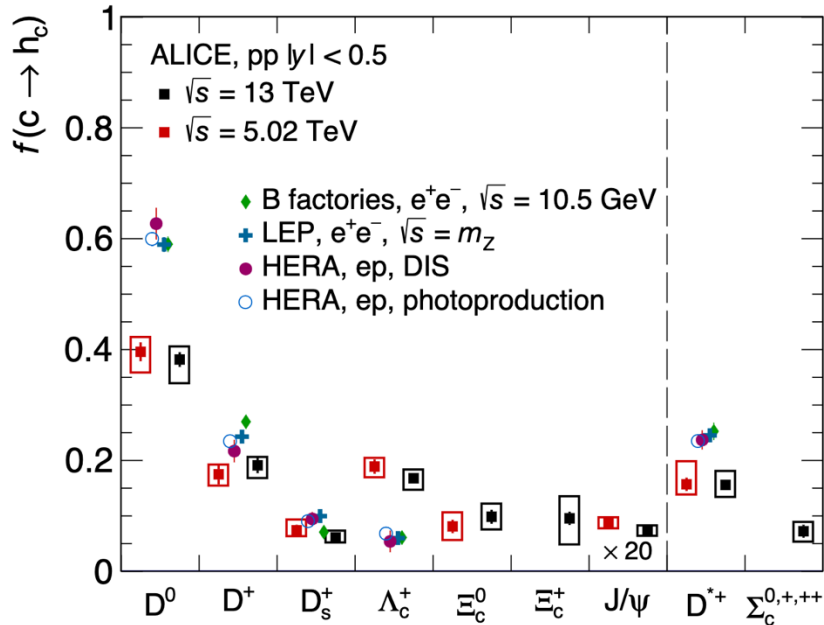
(Extended) (dense)  
partonic medium

→ See how charm helps exploring hadronization

# Hadronization

$$D_{c \rightarrow H_c}(z_c = p_{H_c}/p_c, \mu_f^2)$$

Hadronization or fragmentation fractions  
Precisely measured in electron-positron, electron-proton collisions  
Assumed to be universal

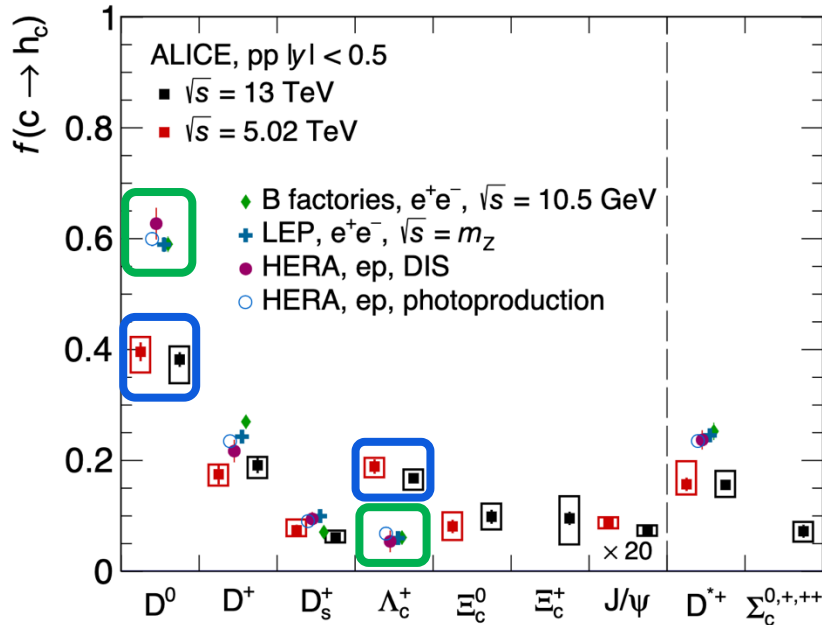


ALICE Collaboration,  
JHEP 12 (2023) 086

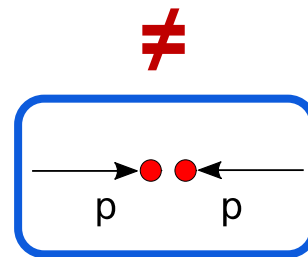
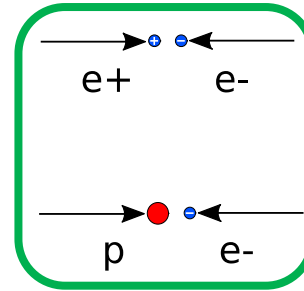
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Hadronization or fragmentation fractions  
 Precisely measured in electron-positron, electron-proton collisions  
 Assumed to be universal



ALICE Collaboration,  
 JHEP 12 (2023) 086



LHC:  
 Charm hadronization  
 fractions in pp (and  
 p-Pb) are **different**  
 from ee and ep

Influence of the  
 partonic environment !

# Hadronization: baryon & meson yields

Hadron A

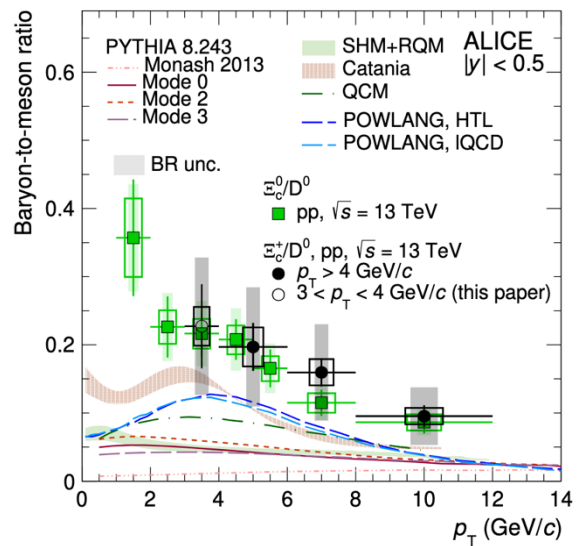
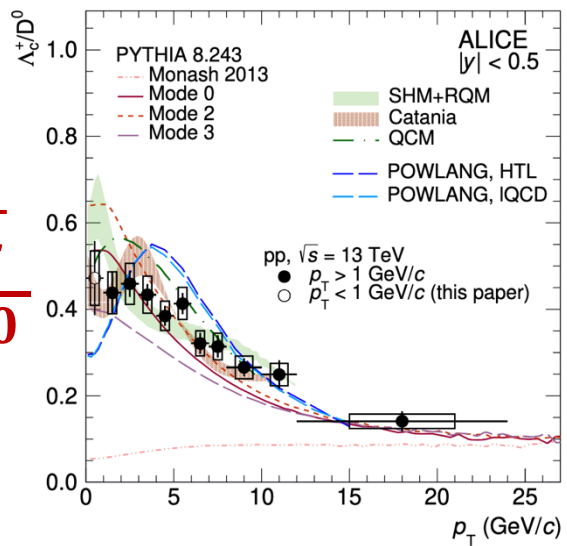
$$\frac{d\sigma}{dp_T}^{pp \rightarrow H_c X} = \sum_{i,j=q,\bar{q}g} f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \frac{d\sigma^{ij \rightarrow c\bar{c}}}{dp_T} D_{c \rightarrow H_c}(z_c = p_{H_c}/p_c, \mu_f^2) \quad \text{A}$$

Hadron B

$$\frac{d\sigma}{dp_T}^{pp \rightarrow H_c X} = \sum_{i,j=q,\bar{q}g} f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \frac{d\sigma^{ij \rightarrow c\bar{c}}}{dp_T} D_{c \rightarrow H_c}(z_c = p_{H_c}/p_c, \mu_f^2) \quad \text{B}$$



$\frac{\Lambda_c^+}{D^0}$



$\frac{\Xi_c^{0,+}}{D^0}$

Models:  
Fragmentation  
Coalescence  
Statistical  
hadronization

ALICE Collaboration,  
JHEP 12 (2023) 086

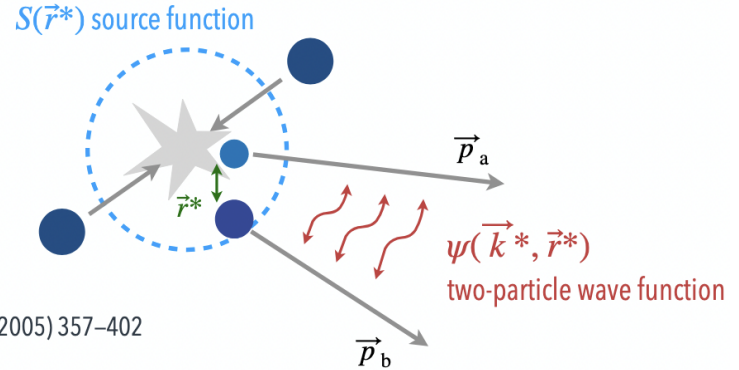
# Correlation function between D and light-flavor mesons

Femtoscopy technique: based on the *correlation function (CF)*

$$C(\vec{k}^*) = \underbrace{\mathcal{N} \frac{N_{\text{pairs}}^{\text{same}}(k^*)}{N_{\text{pairs}}^{\text{mixed}}(k^*)}}_{\text{Experiment}} = \underbrace{\int S(\vec{r}^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3r^*}_{\text{Theory}}$$

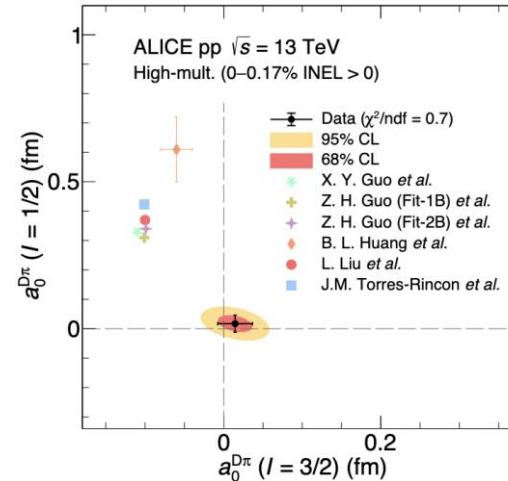
Koonin-Pratt equation

M. Lisa, S. Pratt et al, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357–402



$D\pi$  and  $DK$  measured:

- Shallow interaction between charm and light-flavor hadrons
- Scattering length of residual strong interaction compatible with 0



Phys.Rev.D 110 (2024) 3, 032004

- HQ production cross sections
- Baryon/meson ratios
- D-light femtoscopy
  
- HQ energy loss
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pQCD

Hadronization  
Hadron interaction

Quark-gluon plasma  
Full dynamic exploration



# Outline

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- HQ production cross sections
- Baryon/meson ratios
- D-light femtoscopy
  
- HQ energy loss
- Charmed current

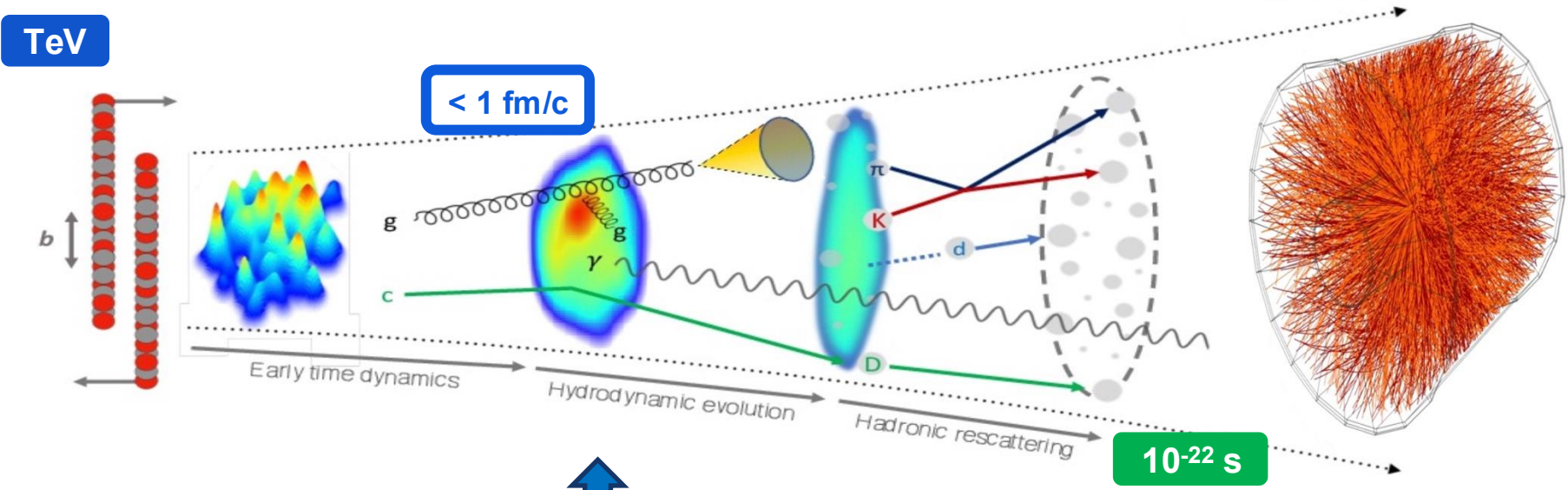
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# Heavy-ion collision evolution



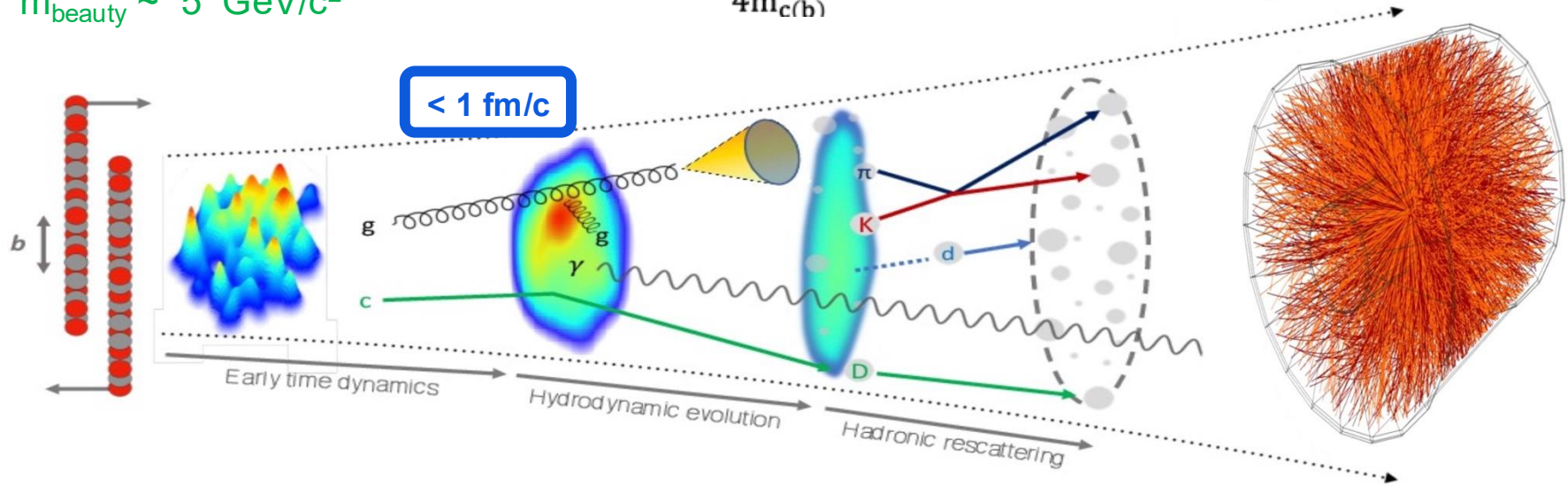
Viscous hydrodynamic description

# Heavy quarks: special probes of the QGP

$m_{\text{charm}} \sim 1.5 \text{ GeV}/c^2$

$m_{\text{beauty}} \sim 5 \text{ GeV}/c^2$

$$\text{Formation time} = \frac{\hbar}{4m_{c(b)}} \approx 0.05(0.01) \text{ fm}/c$$

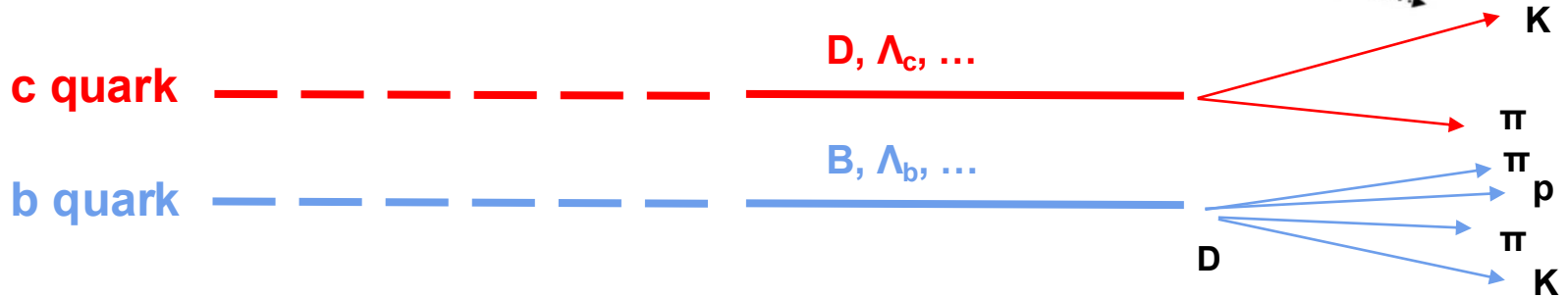
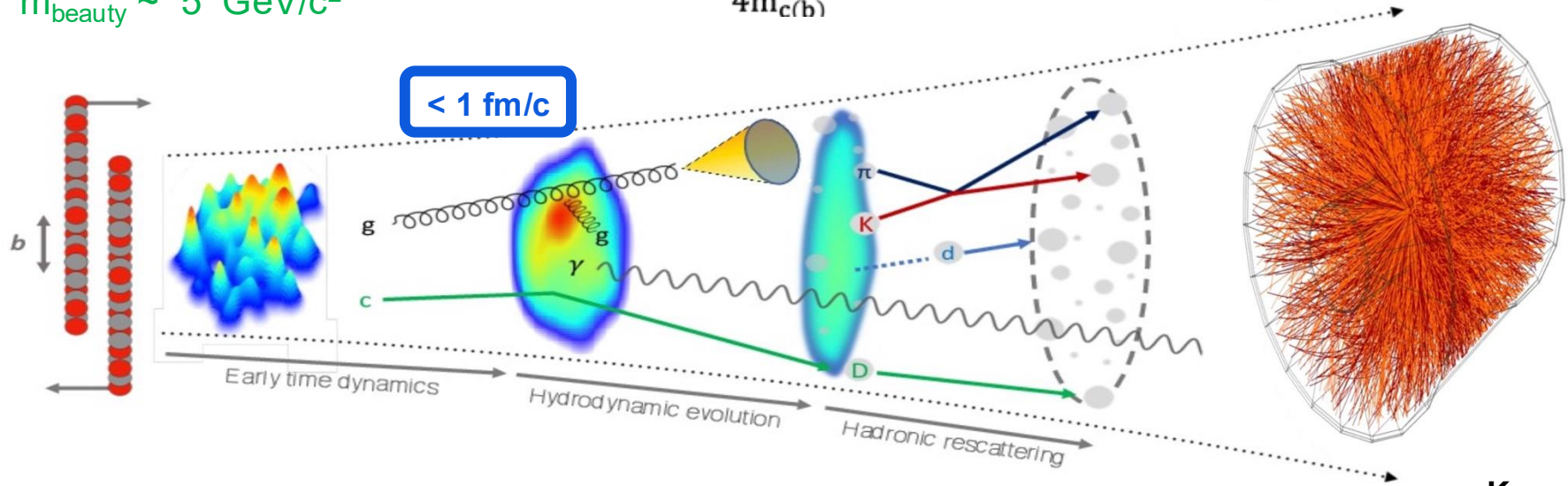


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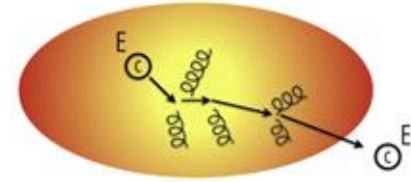
$$\text{Formation time} = \frac{\hbar}{4m_{c(b)}} \approx 0.05(0.01) \text{ fm}/c$$



# Heavy quarks: external probes only or part of the medium?

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- **External probes:** energy loss in the QGP  
Transport models (Browning particles in medium)  
Transport coefficients, e.g. spatial diffusion  $D_s$

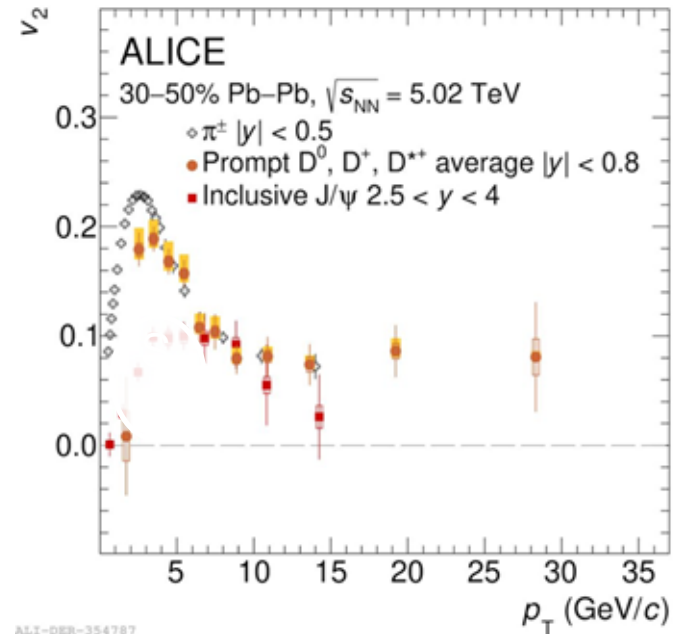
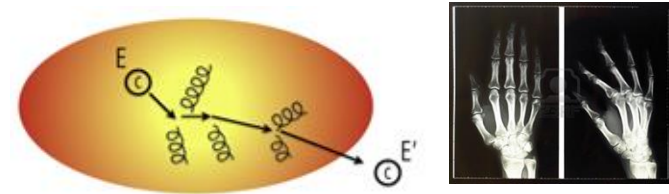


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- **External probes**: energy loss in the QGP  
Transport models (Browning particles in medium)  
Transport coefficients, e.g. spatial diffusion  $D_s$

- Do they show feature of the collective behavior?  
YES  $\rightarrow$  charm hadron elliptic flow ( $v_2$ )

- **Pions**
- **D mesons**



ALICE PLB 813 (2021) 136054

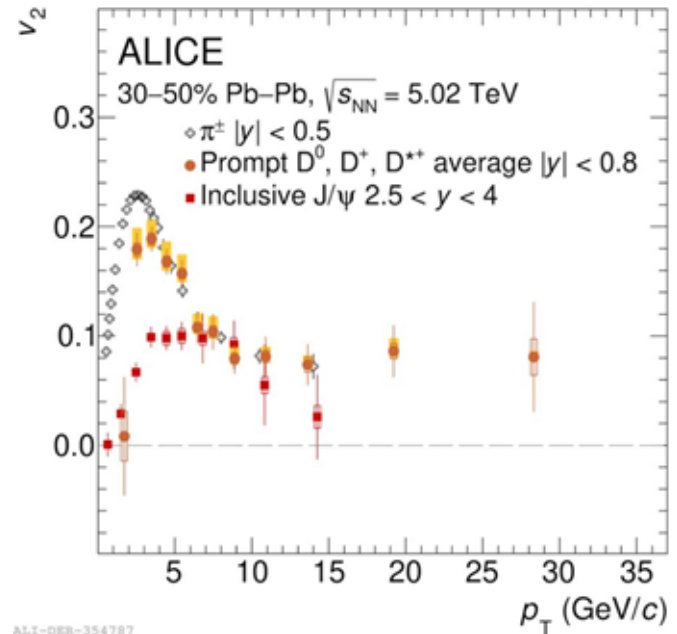
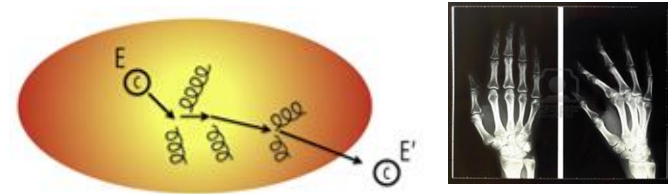
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YES  $\rightarrow$  charm hadron elliptic flow ( $v_2$ )

- **Pions**
- **D mesons**
- **J/ $\psi$**

$\rightarrow$  Do heavy quarks  
thermalize in the QGP?



Thermalization: if particles have enough time to interact with each other, they eventually relax to thermal equilibrium (at least locally)

Questions: charm (beauty) quarks interact with partons in the QGP

- How strongly?
- Long enough to approach local kinetic\* equilibrium within the QGP lifetime?



(\*) HF far from chemical equilibrium (hard production!), fugacity factor needed  
Kinetic equilibrium: particle momentum follows a Maxwell-Boltzmann distribution

Thermalization: if particles have enough time to interact with each other, they eventually relax to thermal equilibrium (at least locally)

Questions: charm (beauty) quarks interact with partons in the QGP

- How strongly?
- Long enough to approach local kinetic\* equilibrium within the QGP lifetime?

## Let's try and do it!

At low  $p_T$ , a window to study equilibration processes



Federica Capellino  
PhD and now postdoc (SFB PI)

[Link](#)



Rossana Facen  
master and now PhD

[Link](#)

(\*) HF far from chemical equilibrium (hard production!), fugacity factor needed  
Kinetic equilibrium: particle momentum follows a Maxwell-Boltzmann distribution

- Consider additional current of charm quarks  
N (charm + anti-charm) conserved

$$N_+^\mu \equiv \frac{N_Q^\mu + N_{\bar{Q}}^\mu}{2}$$

Adopt hydrodynamic approach:

- Current expression:

$$N^\mu = n u^\mu + v^\mu$$

*HQ density*                      *HQ diffusion current*

- Conservation of  $Q\bar{Q}$  pairs:

$$\partial_\mu N^\mu = 0$$

- Equation of motion for the diffusion current:

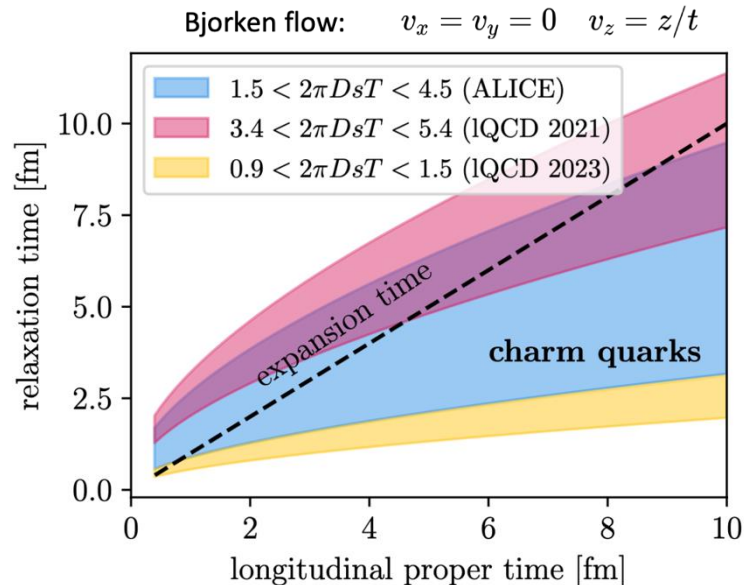
$$\tau_n \partial_t v^i + v^i = \kappa_n \nabla^i \left( \frac{\mu}{T} \right)$$

*HQ relaxation time*                      *HQ diffusion coefficient*

# Charm-quark relaxation time

Compute relaxation time and diffusion coefficient for charm quarks by integrating the first moment of the Fokker-Planck equation, and match with hydrodynamics:

$$\tau_n \propto D_s \quad \text{spatial diffusion coefficient (QCD property)}$$



In simplified picture (Bjorken flow):

charm relaxation time < QGP expansion time

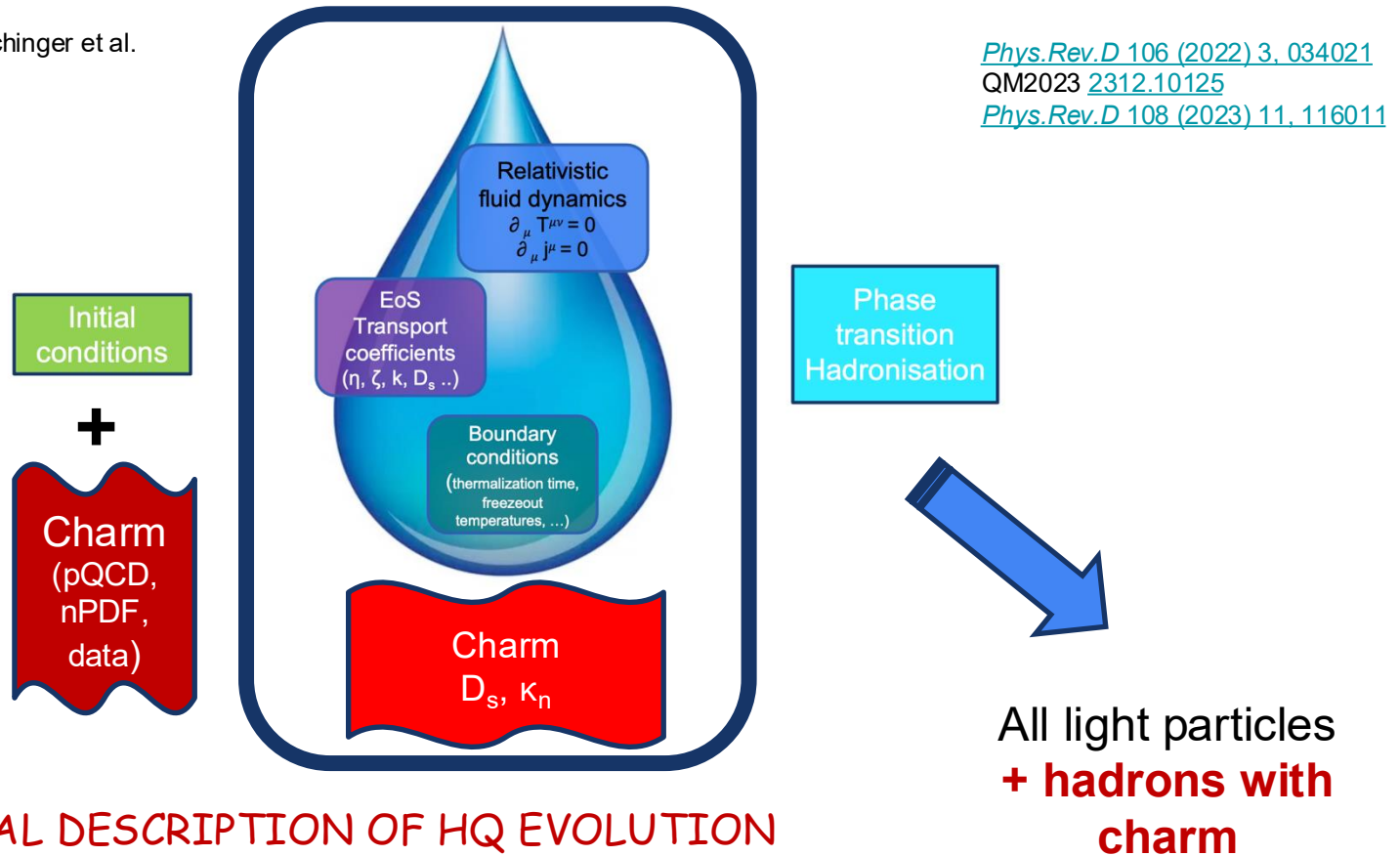
→ fluid-dynamic description looks appropriate!



[Phys.Rev.D 106 \(2022\) 3, 034021](#)  
QM2023 [2312.10125](#)

# Implementation in fluid-dynamic framework: Fluidum

PRC 100, 014905 (2019) Flierchinger et al.



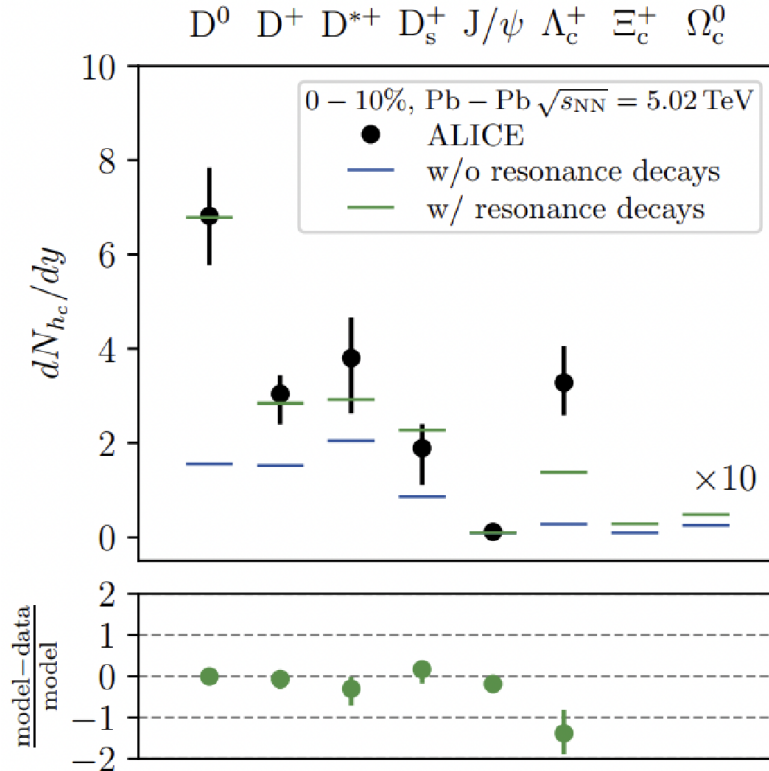
[Phys.Rev.D 106 \(2022\) 3, 034021](#)  
[QM2023 2312.10125](#)  
[Phys.Rev.D 108 \(2023\) 11, 116011](#)

FULLY DYNAMICAL DESCRIPTION OF HQ EVOLUTION

# Fluid dynamic description: particle total yield

Charm hadron yields:

- Cooper-Frey at  $T_{fo} = 156.5$  MeV
- Plus resonance decays (DPG, FastReso)



ALICE JHEP 01 (2022) 174  
 ALICE (2023), arXiv:2303.13361 [nucl-ex]  
 ALICE PLB 839, 137796 (2023)  
 ALICE PLB 827, 136986 (2022)

[Phys.Rev.D 108 \(2023\) 11, 116011](#)

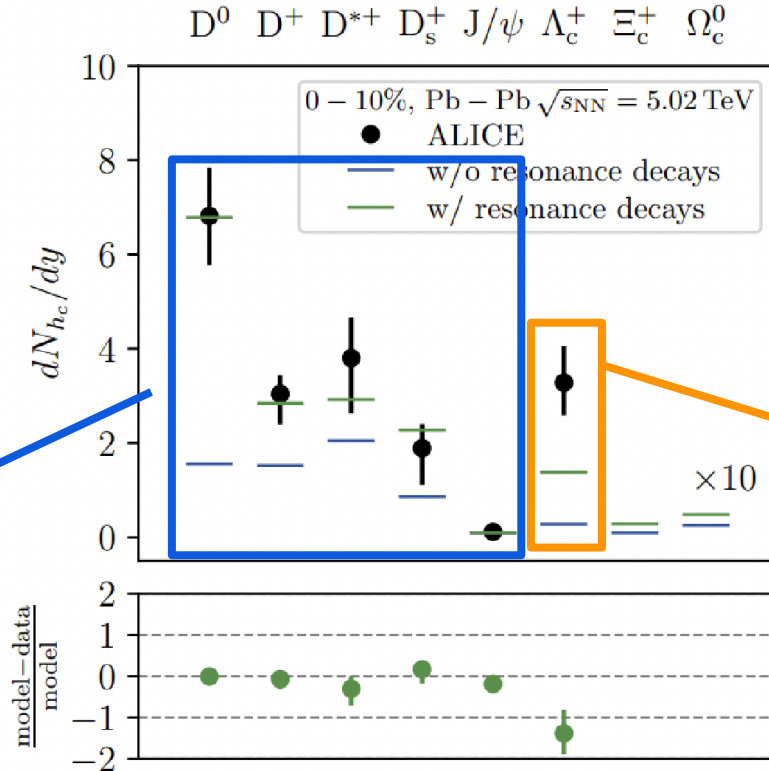
# Fluid dynamic description: particle total yield

Charm hadron yields:

- Cooper-Frey at  $T_{fo} = 156.5$  MeV
- Plus resonance decays (DPG, FastReso)



Very good agreement with data for mesons



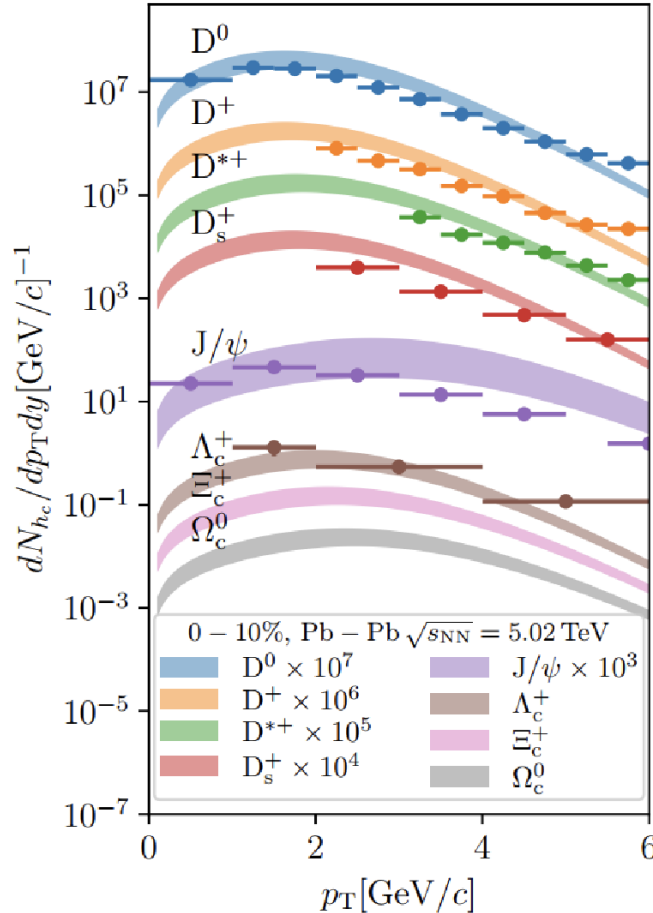
$\Lambda_c$  hadronization?  
Missing resonances?

ALICE JHEP 01 (2022) 174  
ALICE (2023), arXiv:2303.13361 [nucl-ex]  
ALICE PLB 839, 137796 (2023)  
ALICE PLB 827, 136986 (2022)

[Phys.Rev.D 108 \(2023\) 11, 116011](https://arxiv.org/abs/2205.11601)

# Fluid dynamic description: particle spectra

Preliminary transverse momentum spectra:  
Cooper-Frey at  
 $T_{fo} = 156.5$  MeV  
+ resonances



[Phys.Rev.D 108 \(2023\) 11, 116011](https://arxiv.org/abs/2303.13361)

ALICE JHEP 01 (2022) 174  
ALICE (2023), arXiv:2303.13361 [nucl-ex]  
ALICE PLB 839, 137796 (2023)  
ALICE PLB 827, 136986 (2022)

HQs not in kinetic equilibrium at the beginning of the QGP hydro phase, and at freezeout:

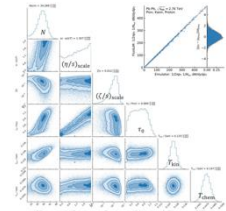
$$f \sim \underbrace{e^{-E/T} e^{\mu/T}}_n + \underbrace{\delta f}_{\nu^\mu}$$

$\delta f$  affect the HQ hadron integrated yields and spectra!  
→ Charm multiplicities depends on Ds ! Unphysical!

Computation of out-of-equilibrium corrections at initial times and at freeze-out

<https://arxiv.org/pdf/2510.25601>  
Just submitted to PRD

- Correct HQ hadron yields and  $p_T$  spectra
- Bayesian fit to data from RHIC and LHC
- Extraction of  $D_s(T)$  and  $\tau_n$

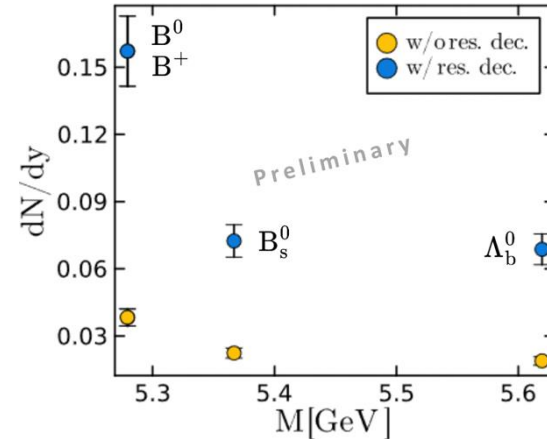
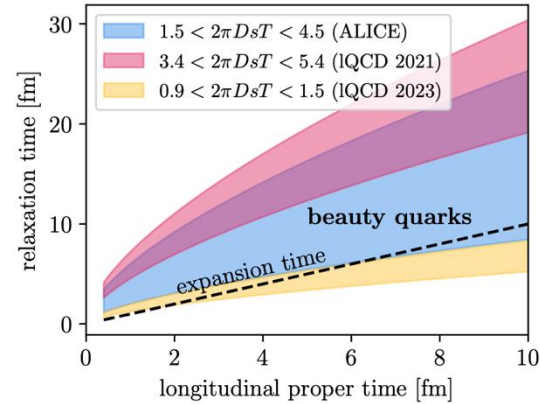


# Coming next: beauty quark

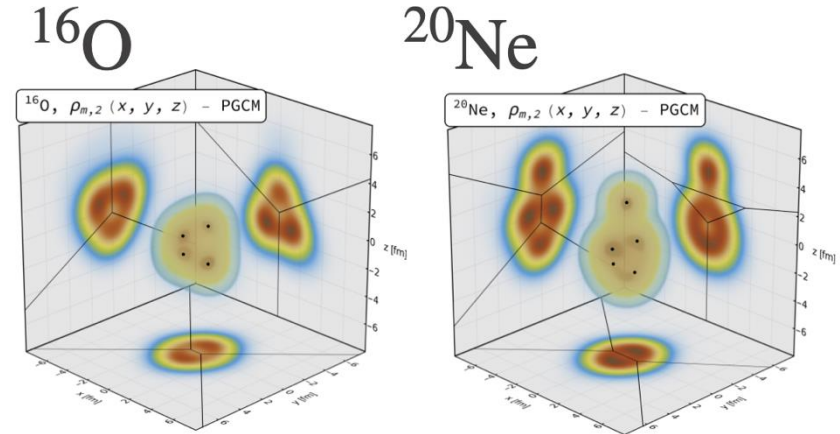
- $m_b \gg m_c$ : larger relaxation time!  
chance to thermalize?

What would “partial” thermalization mean?

- First computations:  
Integrated yields (uncertainty on higher resonances!)  
Spectra for non-prompt charm hadrons



- LHC 2025  
oxygen-oxygen and neon-neon collisions
- LHC Run 5: other ions  
Xe, In, Kr, Ca, Ar, O
- Smaller systems → lower temperature  
→ shorter QGP lifetime

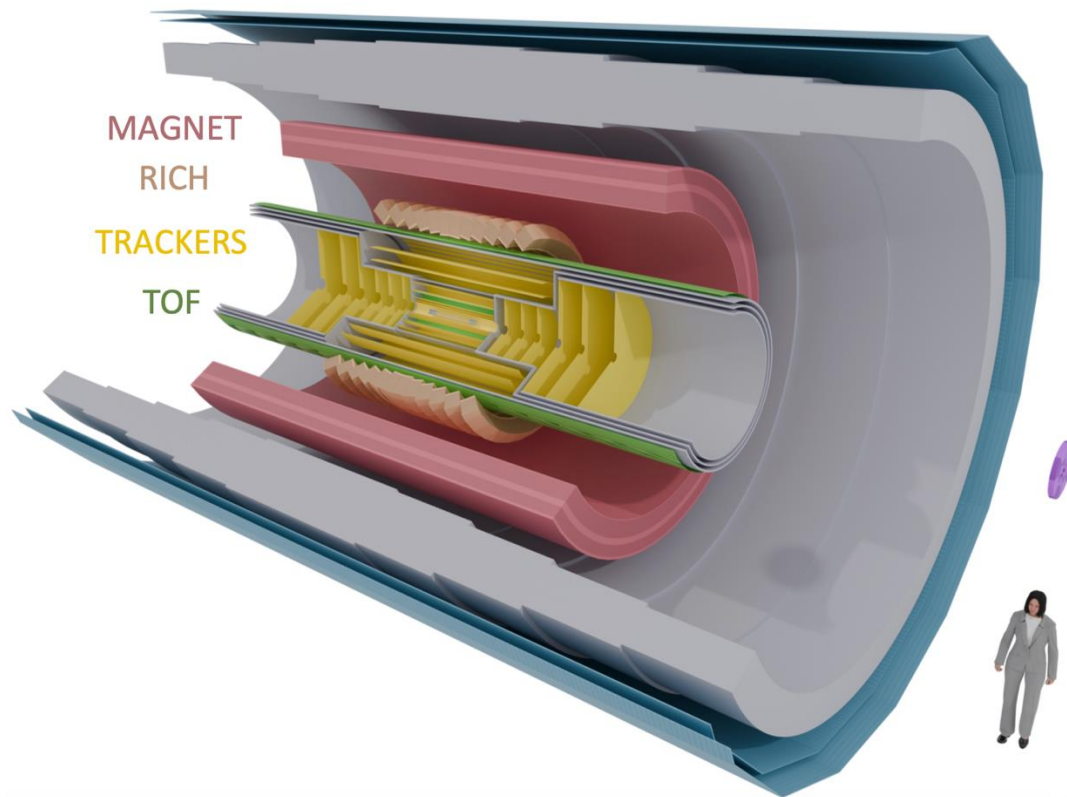
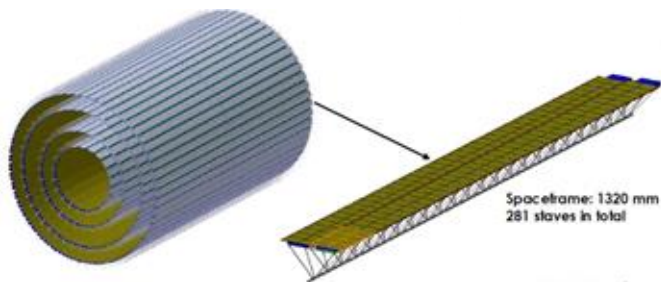


Study the fluid dynamic description of the HQ evolution as a function of system size and medium temperature  
→ See a breakdown of the description?  
→ Limits of applicability (T, energy density, lifetime)

# Outlook

Fabulous statistics from LHC Run 3 and Run 4 !!!  
13 nb<sup>-1</sup> until 2033

Wonder ALICE 3 from 2036



**Spare**

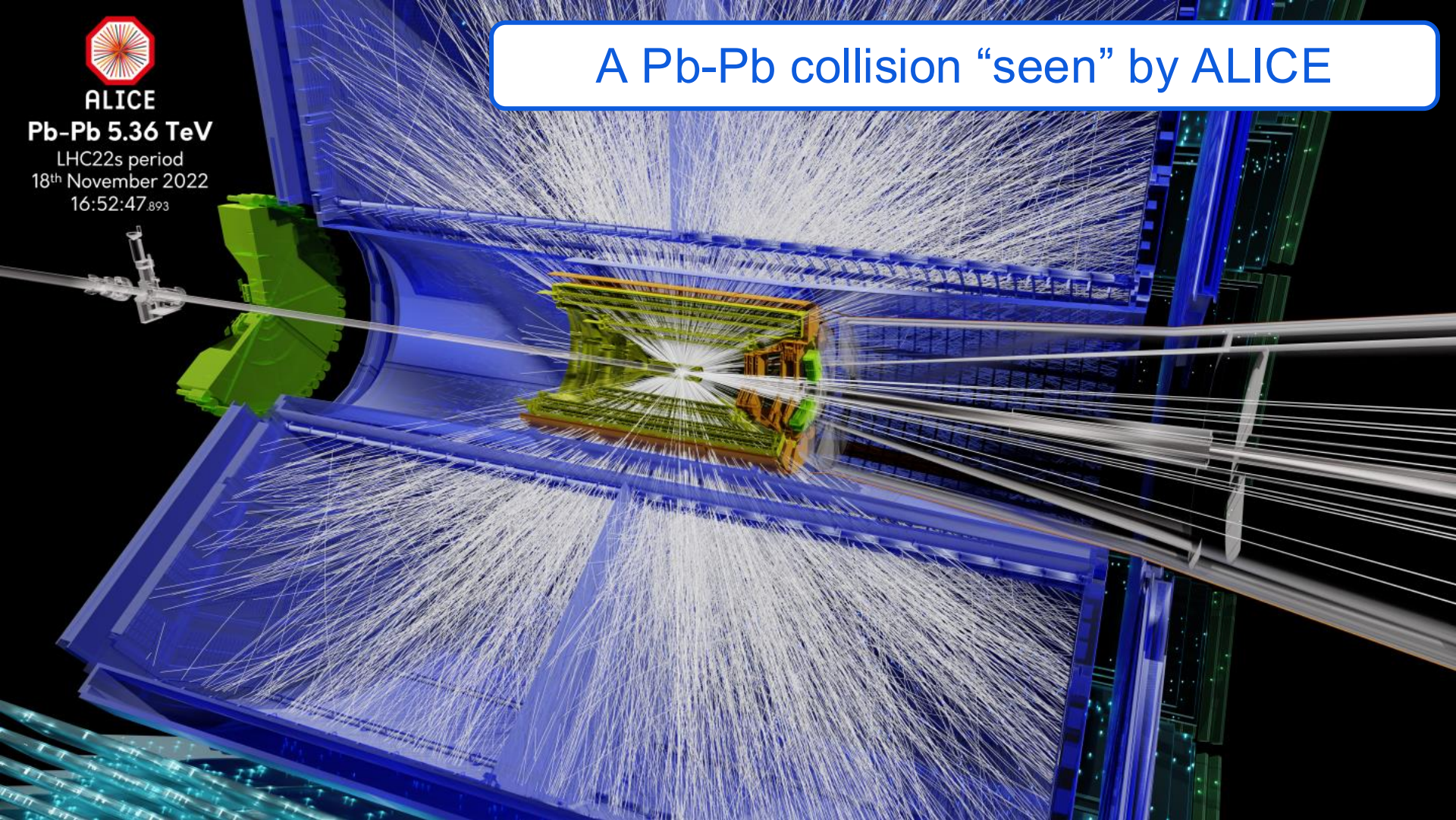


ALICE

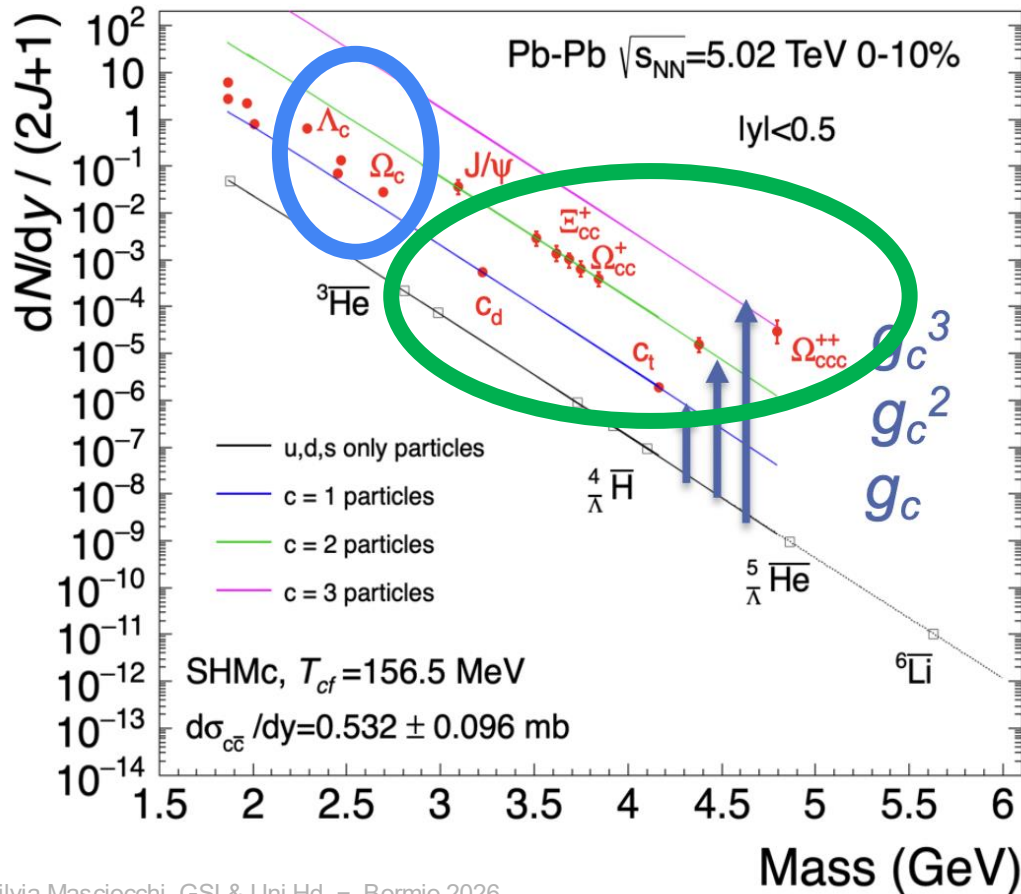
Pb-Pb 5.36 TeV

LHC22s period  
18<sup>th</sup> November 2022  
16:52:47.893

# A Pb-Pb collision “seen” by ALICE



# Future goals: multi-charm hadrons and charm nuclei



Down to  $p_T = 0$  GeV/c:

- $\Lambda_c^+$  (udc)

New – LHC Run 3+4:

- $\Sigma_c^{0,+,++}$  (ddc, udc, uuc)
- $\Xi_c^0$  (dsc)
- $\Xi_c^+$  (usc)
- $\Omega_c^0$  (ssc)

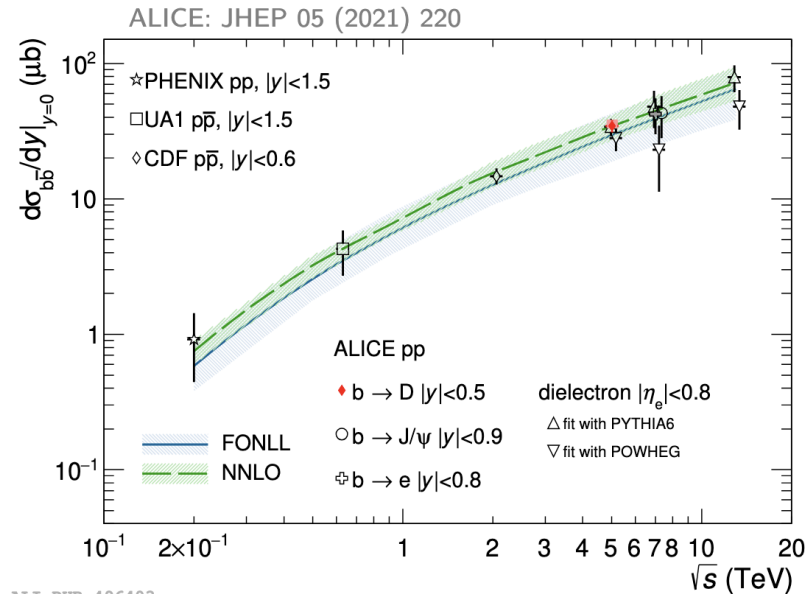
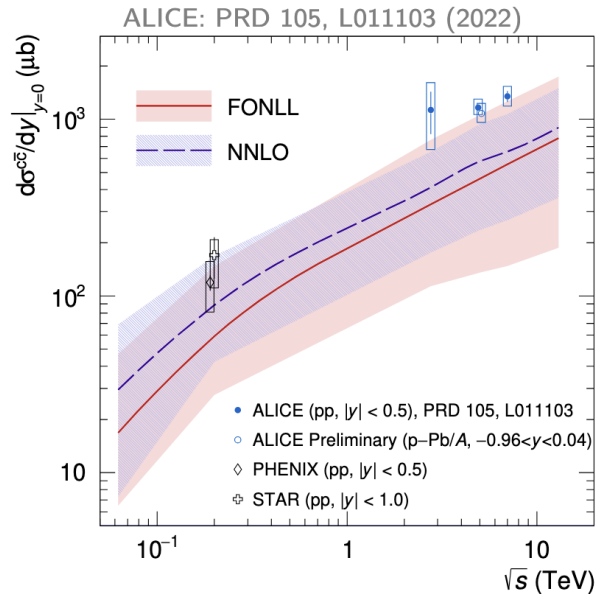
Further – ALICE 3:

- $\Xi_{cc}^{++}$  (ucc)
- $\Xi_{cc}^+$  (dcc)
- $\Omega_{cc}^+$  (scc)
- $\Omega_{ccc}^{++}$  (ccc)
- $C_d$
- $C_t$

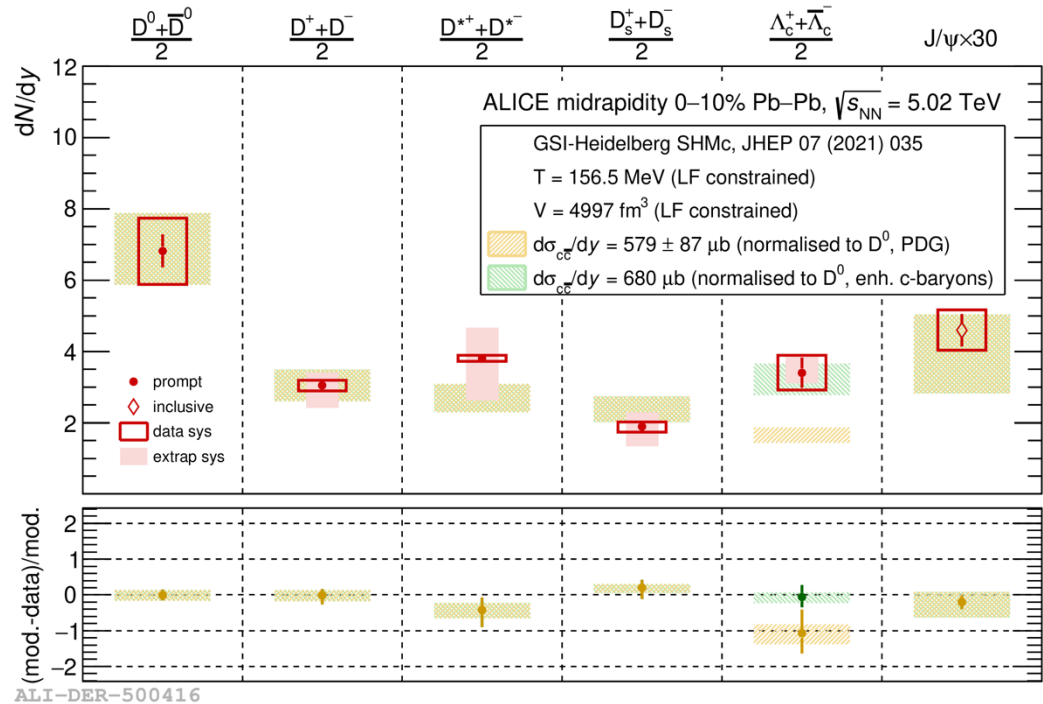
**NEW  
FRONTIERS**

# Heavy quark TOTAL production cross section

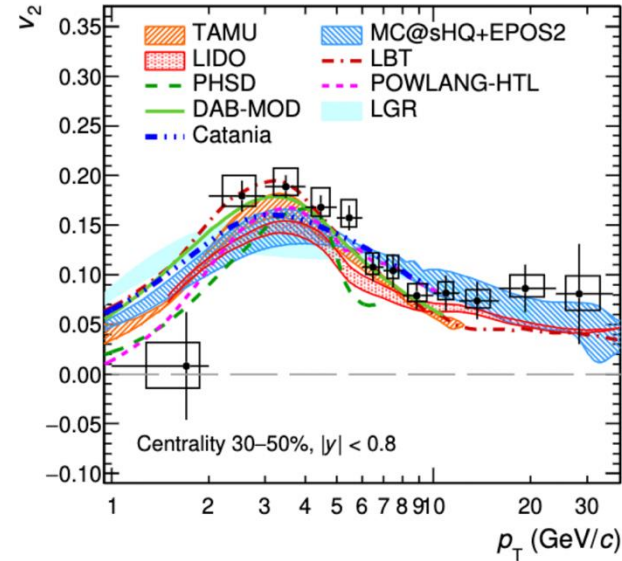
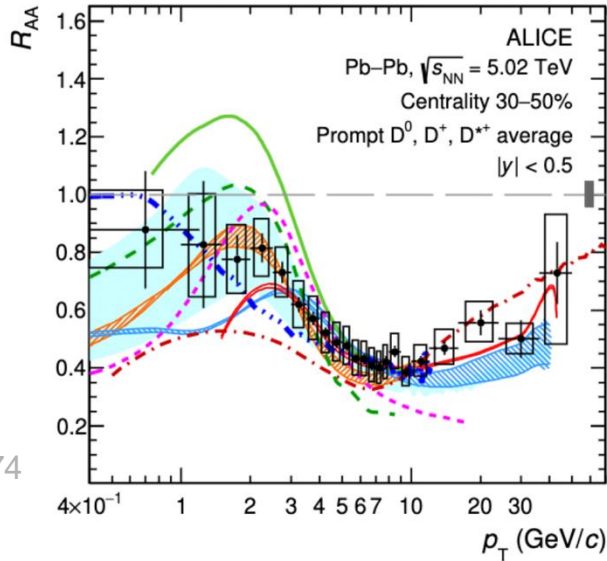
## Test of perturbative QCD



# Statistical hadronization model with charm



# More than energy loss



JHEP 01 (2022) 174

EMMI RAPID REACTION TASK FORCE (2016-2018)

Extraction of Heavy-Flavor Transport Coefficients in QCD Matter

*Andronic, Averbeck, Gossiaux, Masciocchi, Rapp*

Nucl.Phys.A 979 (2018) 21-86