Heavy-flavour production in small systems and its dependence on event multiplicity

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Heavy Flavours from small to large system 2022

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Motivation

Heavy quarks (charm, beauty), due to their large masses ($\mathrm{m_c} \sim 1.3$ GeV/c^2, $\mathrm{m_b} \sim 4.2$ GeV/c^2)

- produced at the early stages of the collision via hard scattering
- production cross-section calculated using factorization theorem

$$d\sigma^{hard}_{AB\to C} = \sum_{a,b} \underbrace{f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2)}_{\text{Parton Distribution Function (PDF)}} \otimes \underbrace{d\sigma^{hard}_{ab\to c}(x_a, x_b, Q^2)}_{\text{Partonic hard scattering cross-section}} \otimes \underbrace{D_{c\to C}(z, Q^2)}_{\text{Fragmentation Function (FF)}}$$

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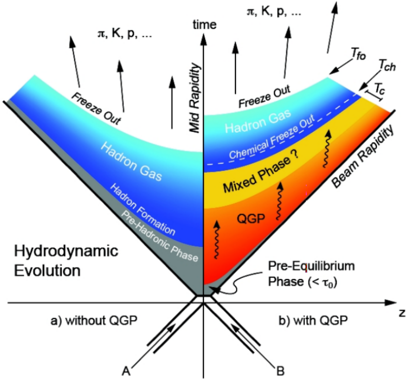
Parton Distribution Function (PDF) | Partonic hard scattering cross-section | Fragmentation Function (FF)

pp collisions:

- Test perturbative QCD calculations
- Baseline reference for heavy-ion studies
- Study hadronization mechanisms in vacuum



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Parton Distribution Function (PDF) — Partonic hard scattering cross-section — Fragmentation Function (FF)

pp collisions:

- Test perturbative QCD calculations
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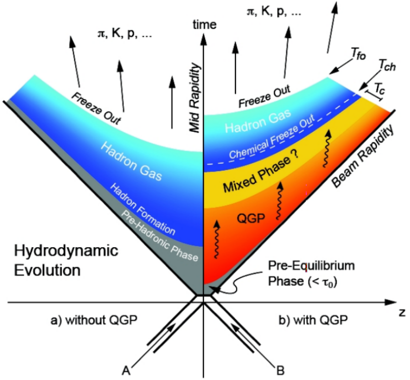
  - → Fragmentation functions assumed universal among collision systems and constrained from e^+e^- collisions
  - → Ratios of particle species → ratios of fragmentation fractions, sensitive to HF quark hadronization



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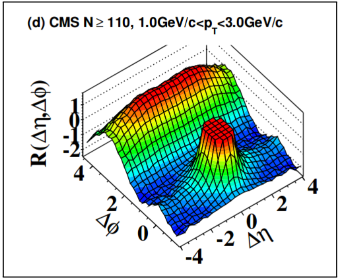

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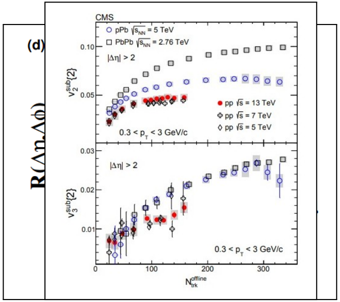

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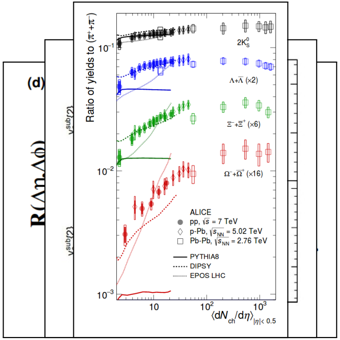

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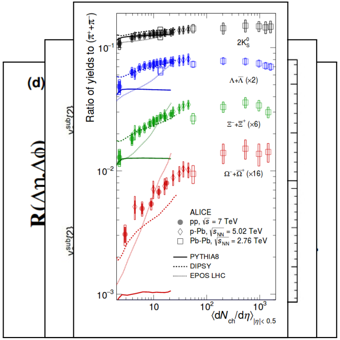
Open question: In small systems, are mechanisms similar to those observed in heavy-ion collisions at play?

[Not discussed in this presentation;
Flow in small systems discussed on Wed 19 by Cvetan. (link)]



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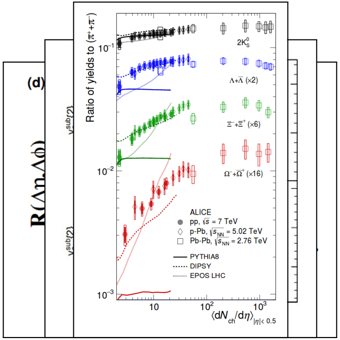

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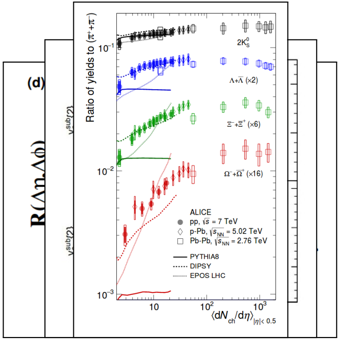
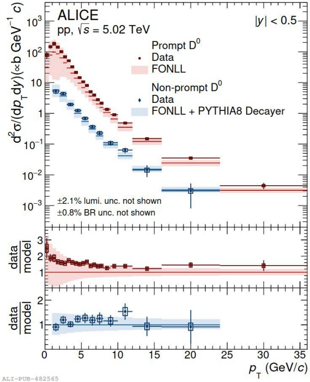


- Give insight into **multiple-parton-interaction (MPI)** and **color reconnection(CR)** in the hadronization mechanisms

- **Understand the interplay of hard and soft processes**
  $\rightarrow$ to search possible connections between small and extended interacting systems.

D^0 meson:



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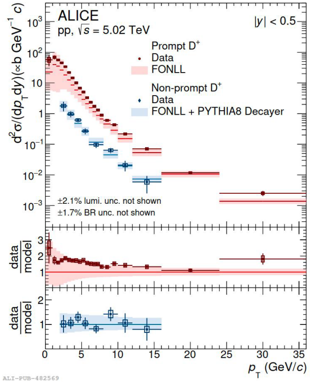

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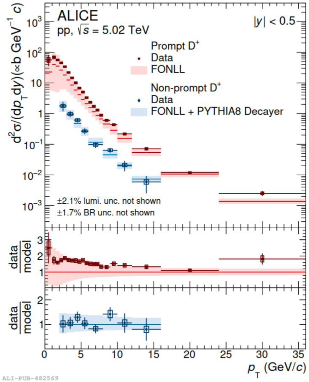
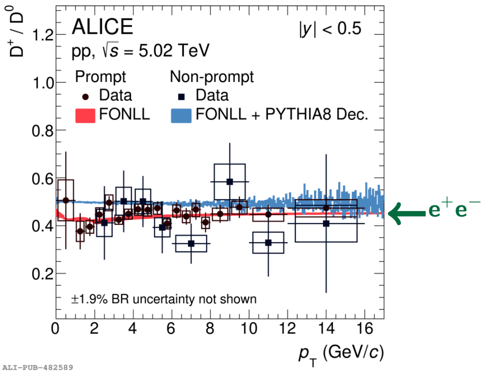


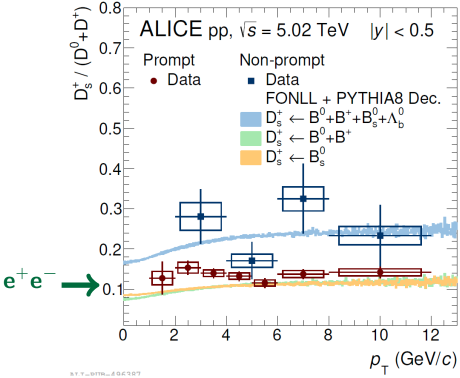
[ALICE Collaboration, JHEP 05 (2021) 220]

- Precise measurement down to $p_T = 0$ for **prompt D^0, D^+**
- **FONLL (Fixed Order with Next-to-Leading Log resummation)**:
  - $\rightarrow$ Factorization approach with **universal fragmentation functions** from e^+e^- of LEP [EPJC 75 (2015) 1, 19]
  - $\rightarrow$ For non-prompt D mesons : **PYTHIA8** used to describe $H_b \rightarrow D+X$ decays and branching ratio

D^+/D^0 :



$D_s^+/(D^0 + D^+)$:

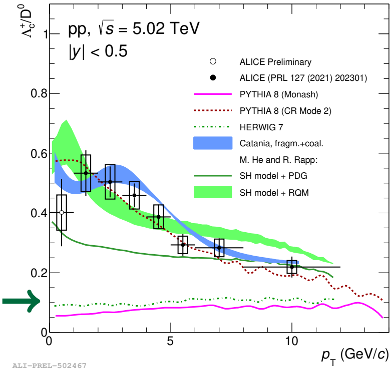


[ALICE Collaboration, JHEP 05 (2021) 220]

- **Meson-to-meson** ratios **independent** of p_{T} and **collision system**
- **Agreement** with FONLL calculations which uses the **universal fragmentation functions**
- $D_s^+/(D^0 + D^+)$ **higher** for **non prompt mesons** $\rightarrow$ substantial $\mathbf{B}_s^0$ **decay** contribution

Λ_c^+/D^0 :

e^+e^- →

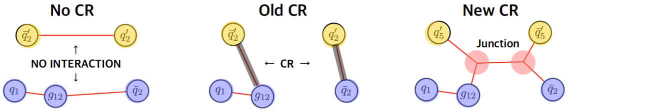


[Alice Collaboration, Phys. Rev. Lett. 127, 202301]

- Strong p_T dependence
- **Higher than value** measured in e^+e^- **collisions** → **fragmentation may not be universal**

Data is well described by models :

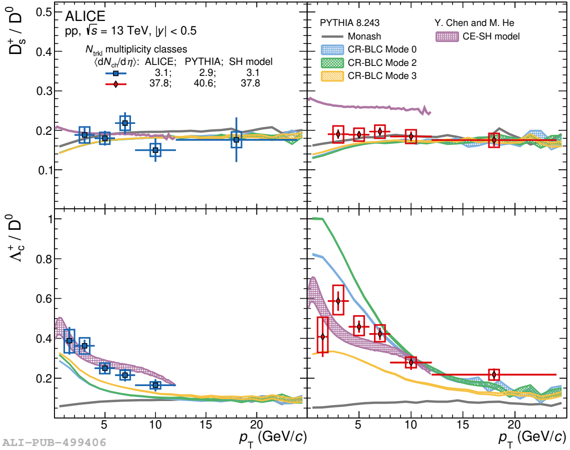
- **PYTHIA 8 color reconnection mechanisms beyond the leading color approximation (CR-BLC) [Mode 2]**
  → Enhances production of baryons thanks to new CR topologies



- **Catania Model**
  → Light quarks (u,d,s) and gluons assumed as thermalised system.
  → Mixed hadron formation: fragmentation + coalescence

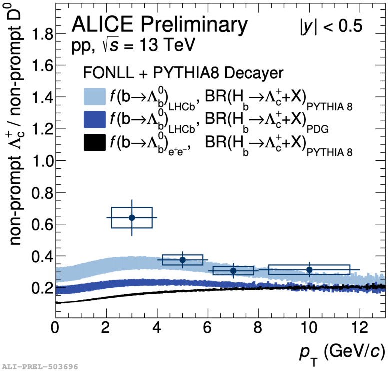
- **Statistical Hadronization Model and Relativistic Quark Model**
  → Hadronization driven by statistical weights governed by hadron masses at a hadronization temperature
  → Strong feed down from augmented set of (not yet observed) excited charm baryon states

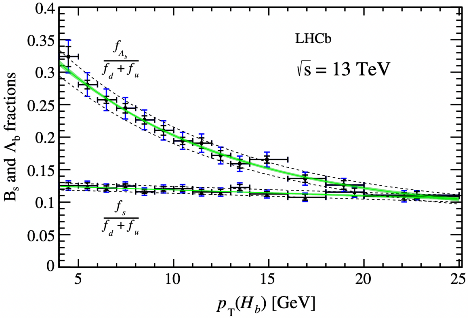
[Alice Collaboration, Phys.Lett.B 829 (2022) 137065]



- D^+/D^0 **:** low and high multiplicity are **compatible** with PYTHIA with Monash and CR-BLC tunes.
- Λ_c^+/D^0 : Significant **increase** from **lowest to highest multiplicity**
- p_{T} and multiplicity dependence qualitatively described by **PYTHIA CR-BLC** and by a **statistical hadronization model**

Beauty baryon-over-meson ratio (non-prompt Λ_c^+/non-prompt D^0)





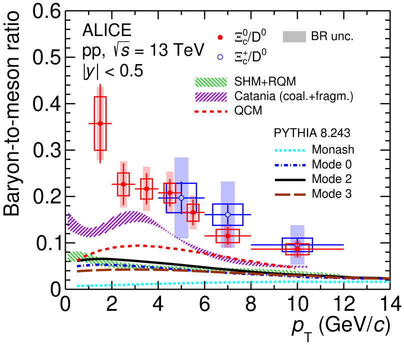
[LHCb Collaboration, Phys. Rev. D 100, 031102(R)]

Non-prompt Λ_c^+/ non-prompt D^0 : Access to the fragmentation of beauty quark via non-prompt ratio

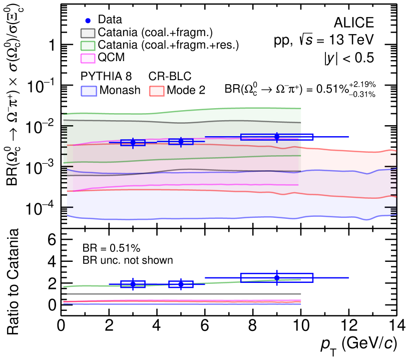
- FONLL + Pythia 8 and fragmentation fraction f(b$\to$ Λ_b^0) measured by LHCb

$\to$ Predictions with f(b$\to$ Λ_b^0) measured at e^+e- underestimate data

- **Similar trend vs p_T as for prompt Λ_c/D^0 $\to$ hint of larger enhancement at low p_T**
- Similar p_T shape as measured by LHCb for Λ_b/B



ALICE Collaboration, PRL 127, 272001



ALICE Collaboration, arXiv:2205.13993

- $\Xi_c^{0,+}/D^0$: p_T dependence and underestimated by models describing Λ_c^+/D^0

→ $D_s^+/(D^0 + D^+)$ compatible with expectations from e^+e^- → Baryons ?

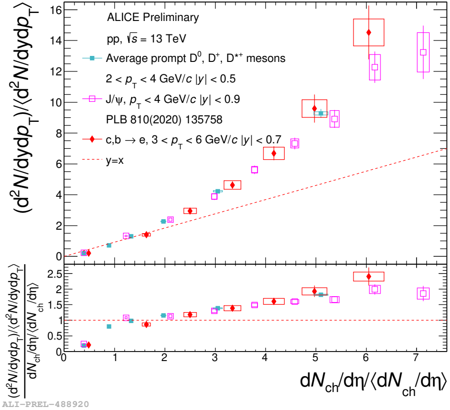
- **Catania (fragm . + coal.) predictions gets close to the measurements**

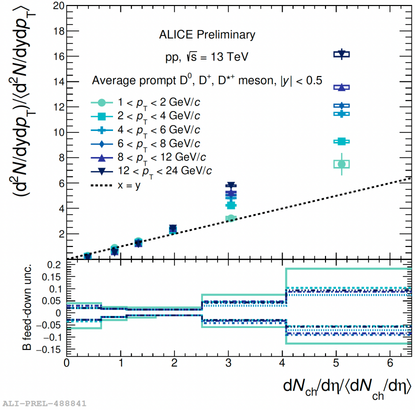
- Ω_c/Ξ_c is better described by coalescence model

[Detailed discussion on hadronization by A.Rossi on Oct 3 (link)]

Self-normalised yields defined as:

$$\frac{d^2N/dp_T d\eta}{\langle d^2N/dp_T d\eta \rangle} = \frac{N^i_{HF}/(\epsilon^i \times n^i_{events})}{(N^{total}_{HF})/(\epsilon^{total} \times n^{total}_{events})}$$





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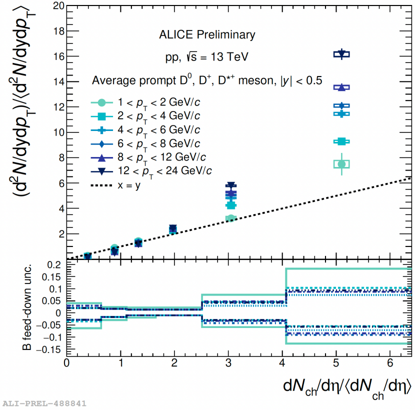
Faster than linear increasing trend and p_T **dependence,** influenced by **momentum dependence** of :

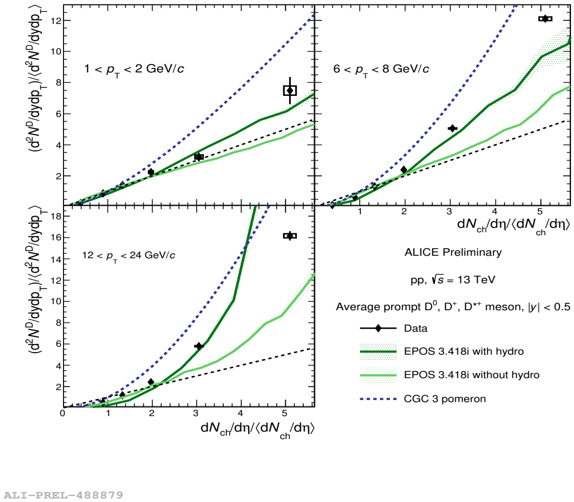
→ jet fragmentation affecting the measured multiplicity

→ fraction of electrons from charm and beauty hadron decays.

High momentum partons → accompanied by larger number of fragments → contribute to high multiplicity



Comparison of self-normalized D-meson yield with model expectations



- **EPOS3 without hydro**
  → underestimates data
- **EPOS3 + Hydro**
  → fairly reproduces data
- **3-Pomeron CGC prediction**
  → overestimates the yield compared to data

3-Pomeron CGC[arXiv:1910.13579]

EPOS [Phys. Rev. C 89, 064903 (2014)]

Summary

- **Enhancement of baryon-over-meson ratio (Λ_c^+/D^0)** $\rightarrow$ in **pp** compared to e^+e^- collisions and **with multiplicity**

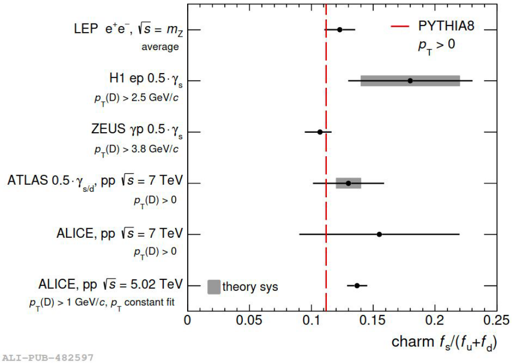
  pQCD models based on factorization approach assuming **universal fragmentation functions** among collision systems **do not describe** charm baryon production in hadronic collisions at the LHC

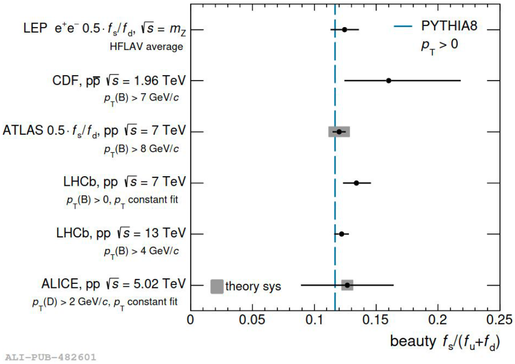
  Additional charm hadronisation mechanisms could happen in pp compared toe^+e^- collisions
  $\rightarrow$ models including enhanced baryon production better describe the ALICE data
  $\rightarrow$ more studies are needed to discriminate among different theoretical descriptions

- **HF** self-normalised yield **vs. multiplicity** in **pp** at $\sqrt{s}$= 13 TeV
  - Faster than linear increasing trend, with strong p_{T} dependence
  - Compared with model expectation
    - **PYTHIA 8.2** (includes MPI and CR),
    - **EPOS3.4** (with and without hydro calculation)
    - **3-Pomeron CGC** (includes multigluon fusion mechanism) models

Back-up

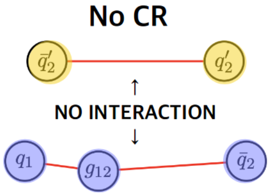
Heavy-flavour production : c and b fragmentation



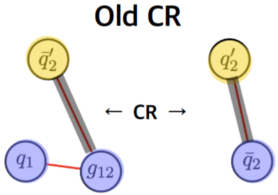


Colour Reconnection (CR) scenario

- strings rearranged between partons, so as to **reduce the total string length**
- Partons from different PI can become connected to each other

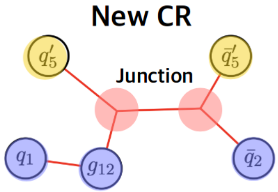


Partons created in different MPIs do not interact each other



partons from lower p_{T} MPI systems are added to the dipoles defined by the higher p_{T} MPI system → in a way that minimizes the total string length

(Monash tune)



Minimization of string length over all possible configurations

Reconnections of dipoles → junctions structure produces → enhances production of baryons

(CR Mode 'X' tune)

CR Mode 2 (Gluon-move model) : Similar to default but only gluons are considered for reconnection. For each gluon all the reconnections to all MPI systems are considered. [ATL-PHYS-PUB-2017-008]