Heavy-flavour production measurements in ALICE

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ALICE

Kruger 2022: Discovery physics at the LHC

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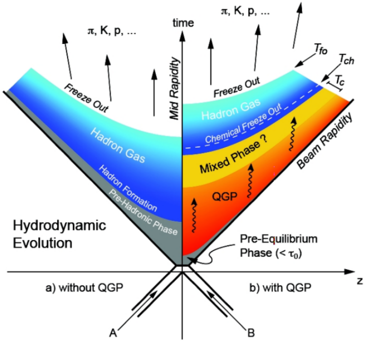
Heavy quarks (charm, beauty), due to their large masses ($m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2)

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

$$d\sigma^{hard}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes d\sigma^{hard}_{ab\to c}(x_a, x_b, Q^2) \otimes D_{c\to C}(z, Q^2)$$

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



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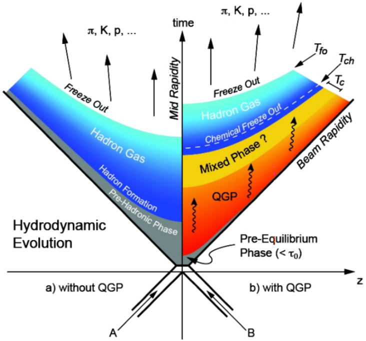

Pb–Pb collisions:

- Heavy quark interaction with the medium constituents
- Study hadronization mechanisms in presence of a medium
  - ▷ Studied through ratios of particle species

Heavy quarks as probes for characterizing relativistic collisions

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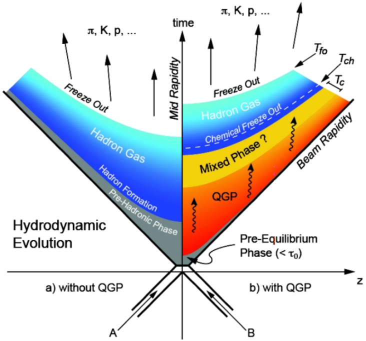

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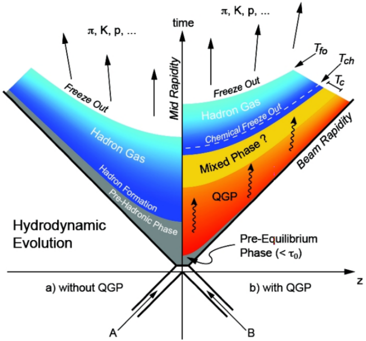
  → **Main focus of this presentation**



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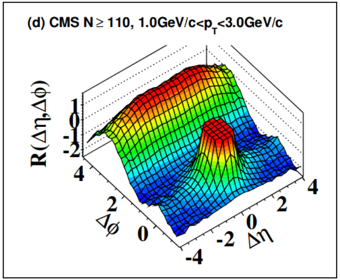

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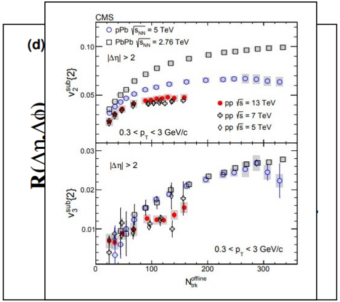
  $\Big\} \Longrightarrow$ collectivity



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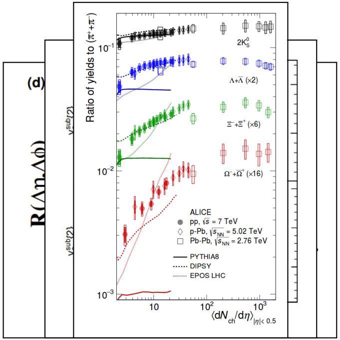

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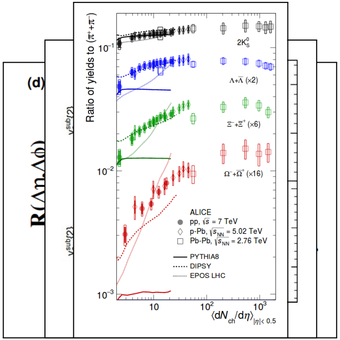
  (Ridge formation and anisotropic flow) $\Longrightarrow$ collectivity

$\downarrow$

These are typical signatures for quark-gluon plasma formation in heavy-ion collisions

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



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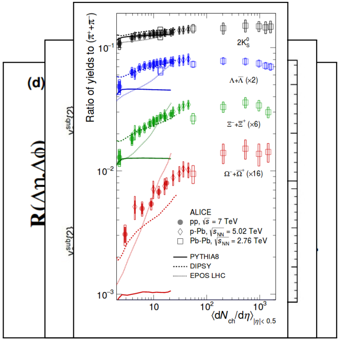

- Give insight into **multiple-parton-interaction (MPI)** and **color reconnection (CR)** in the hadronization mechanisms

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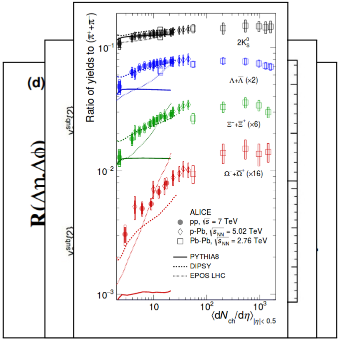
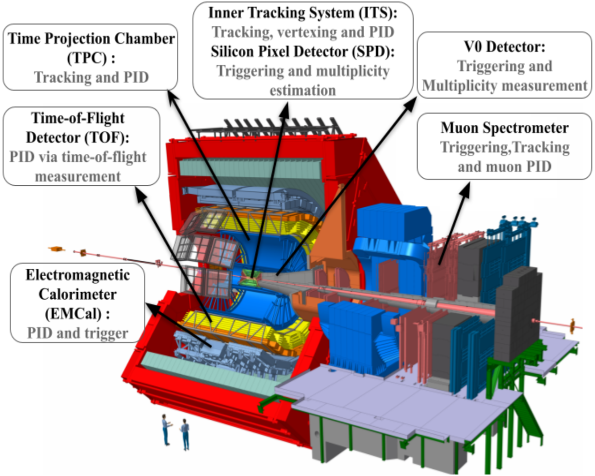


- Give insight into **multiple-parton-interaction (MPI)** and **color reconnection (CR)** in the hadronization mechanisms

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

Open heavy-flavours with the ALICE detector



[P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

Open heavy-flavor production discussed in this talk via:

$\mathbf{D^0} \rightarrow \mathbf{K^-}\pi^+$

$\mathbf{D_s^+} \rightarrow \mathbf{K^-K^+}\pi^+$

$\mathbf{D^+} \rightarrow \mathbf{K^-}\pi^+\pi^+$

$\mathbf{D^*} \rightarrow \mathbf{D^0}\pi^+$

$\mathbf{\Lambda_c^+} \rightarrow \mathbf{pK^-}\pi^+$

$\mathbf{\Lambda_c^+} \rightarrow \mathbf{pK_s^0}$

$\Xi_c^0 \rightarrow \Xi^-\mathbf{e^+}\nu_e$

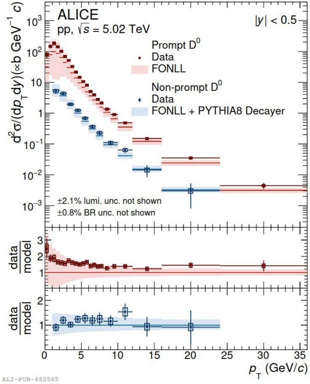
$\Xi_c^0 \rightarrow \Xi^-\pi^+$

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

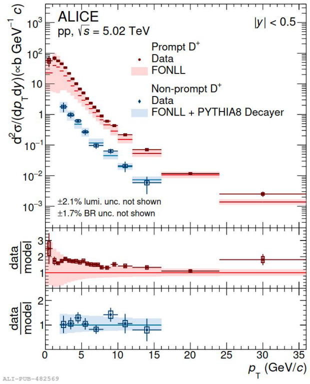
$\mathbf{\Omega_c^0} \rightarrow \mathbf{\Omega^-}\pi^+$

$\mathbf{B, D} \rightarrow \mathbf{e}\nu_e\mathbf{X}$

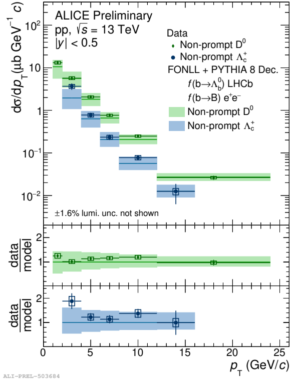
D^0 meson



D^+ meson



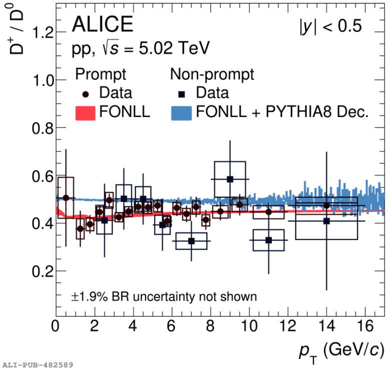
Non-prompt Λ_c^+, D^0



[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)**: [FONLL: JHEP 1210 (2012) 137]
  - $\rightarrow$ Factorization approach with **universal fragmentation functions** from e^+e^- of LEP [EPJC 75 (2015) 1, 19]
  - $\rightarrow$ For non-prompt $D^{0,+}$ & Λ_c^+: **PYTHIA8** used to describe $H_b \rightarrow D\ (\Lambda_c^+)$+X decays and branching ratio

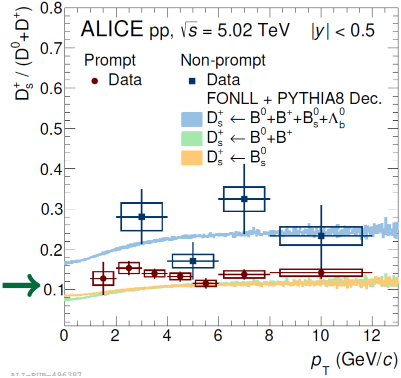
D^+/D^0 :



e^+e^-

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

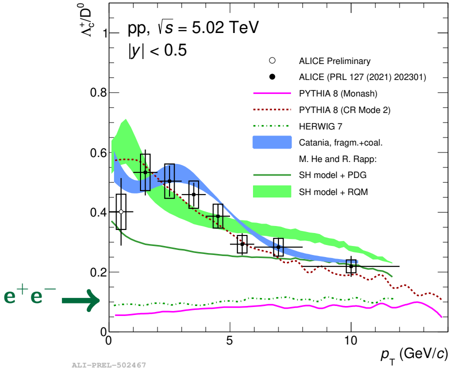
e^+e^-



[ALICE Collaboration, JHEP 05 (2021) 220]

- **Meson-to-meson** ratios **independent** of p_{T} and **collision system** [FONLL: JHEP 1210 (2012) 137]
- **Agreement** with FONLL calculations which assumes **universal fragmentation function** [EPJC 75 (2015) 1, 19]
- $D_s^+/(D^0 + D^+)$ **higher** for **non prompt mesons** $\rightarrow$ substantial B_s^0 **decay** contribution

Λ_c^+/D^0 :



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

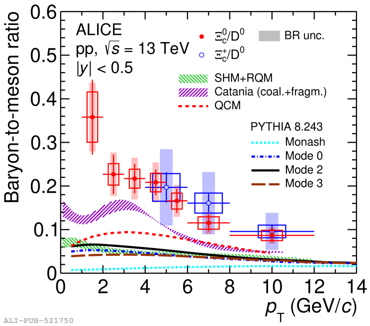
Data is well described by models :

- **PYTHIA 8 CR-BLC (Mode 2)**: Color reconnection beyond the leading color approximation [JHEP 1508 (2015) 003]
  → Enhances production of baryons thanks to new CR topologies
- **Catania Model** [arXiv:2012.12001]
  → Mixed hadron formation: fragmentation + coalescence
- **SHM + RQM** : Statistical Hadronization Model and Relativistic Quark Model [PLB 795 (2019) 117-121]
  → Statistical hadronisation models with augmented set of (not yet observed) excited charm baryon states

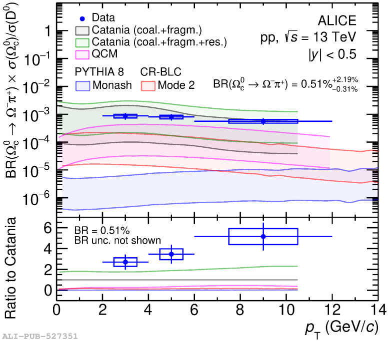
- Strong p_T dependence
- **Higher than value** measured in e^+e^- **collisions** → **fragmentation not universal among different collision systems ?**

Charm fragmentation in pp collisions : $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0

$\Xi_c^{0,+}/D^0$: [ALICE Collaboration, PRL 127, 272001]



Ω_c^0/D^0 : [ALICE Collaboration, arXiv:2205.13993]



p_T dependence **underestimated by models** describing Λ_c^+/D^0

$D_s^+/(D^0 + D^+)$ **compatible** with e^+e^- expectations → what about **strange-charm baryon** hadronization ?

No clear p_T dependence in BR×Ω_c^0/D^0

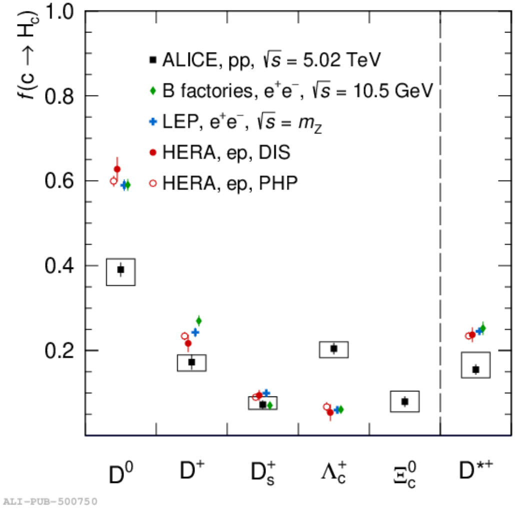
BR($\Omega_c^0 \to \pi^+\Omega^-$) = (0.51 ± 0.07)% from theory calculations [Y. Hsiao et al. EPJC 80, 1066 (2020)]

→ Catania model predictions gets close to the measurements

→ Baryon-enhanced models underestimate the data

[PYTHIA8+CR: JHEP 1508 (2015) 003] [SHM+RQM: PLB 795 (2019) 117-121] [QCM: EPJ C78 no. 4 (2018) 344] [Catania: arXiv:2012.12001]

Charm fragmentation fractions in pp collisions at 5.02 TeV



[ALICE Collaboration, Phys. Rev. D 105 (2022) L011103]

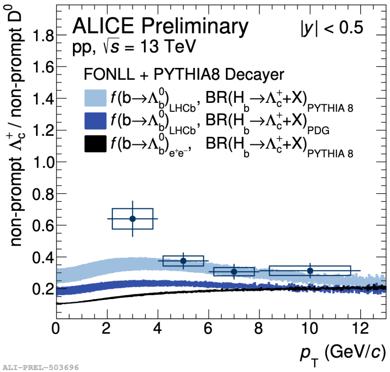
- **Charm Fragmentation Fractions are not universal !!**
- First measurement of f(c$\to \Xi_c^0$)

H_c	$f(c \to H_c)[\%]$
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

($D^{*,+}$ feeds into the D^0 and D^+ mesons)

[B factories: EPJC 76 no. 7 (2016) 397] [LEP: EPJC 76 no. 7 (2016) 397] [HERA: EPJC 76 no. 7 (2016) 397]

Non-prompt Λ_c^+/Non-prompt D^0 :



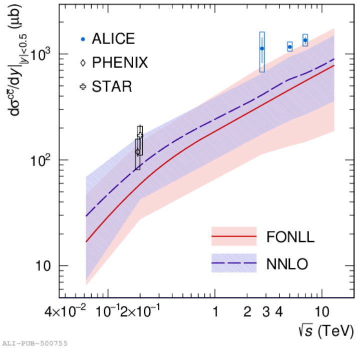
Access to the fragmentation of beauty quark via non-prompt ratio

- FONLL + Pythia 8 and fragmentation fraction f(b→ Λ_b^0) measured by LHCb [FONLL: JHEP 1210 (2012) 137]

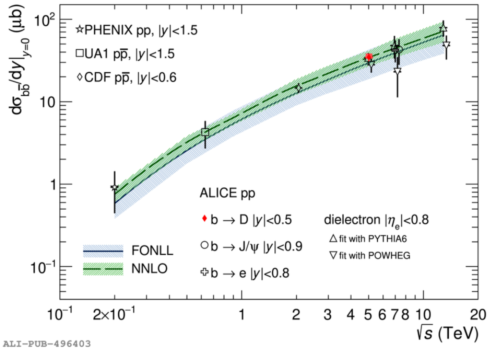
→ Predictions with f(b→ Λ_b^0) measured at e^+e^- underestimate data [LHCb Collaboration, Phys. Rev. D 100, 031102(R)]

- **Similar trend vs p_T as for prompt Λ_c^+/D^0 → hint of larger enhancement at low p_T**

$c\bar{c}$ and $b\bar{b}$ cross section in pp collisions



[ALICE Collaboration, Phys. Rev. D 105 (2022) L011103]



[ALICE Collaboration, JHEP 05 (2021) 220]

Production cross section in **pp collisions at 5.02 TeV** at mid rapidity

$$(\mathrm{d}\sigma^{c\bar{c}}/\mathrm{d}y)_{|y|<0.5} = 1165 \pm 44(\mathrm{stat.}) \pm 134(\mathrm{syst.})\mu\mathrm{b}$$

$$(\mathrm{d}\sigma^{b\bar{b}}/\mathrm{d}y)_{|y|<0.5} = 34.5 \pm 2.4(\mathrm{stat.}) \pm 2.5(\mathrm{syst.})\mu\mathrm{b}$$

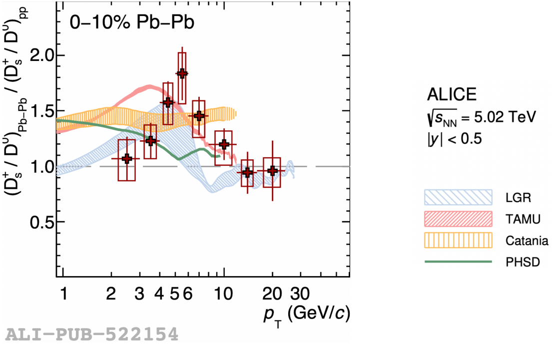
Results **barely on the upper edge** of FONLL and NNLO calculation

Measurements **described well** by FONLL and NNLO calculations

[FONLL: JHEP10(2012) 137], [NNLO: arXiv:1612.05582] [CDF: arXiv:hep-ex/0412071] [PHENIX: arXiv:1005.1627] [STAR: arXiv:1204.4244] [UA1: PLB256(1991)121–128]

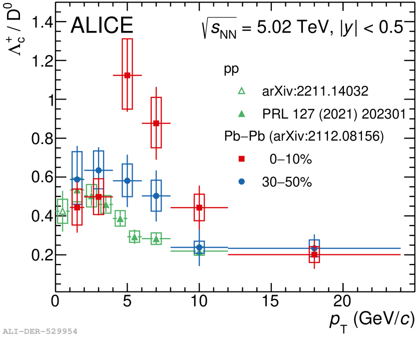
D_s^+/D^0, and Λ_c^+/D_0 in Pb–Pb and pp collisions

Double ratio of D_s^+/D_0 :



[ALICE Collaboration, arxiv:2110.10006]

Λ_c^+/D_0:



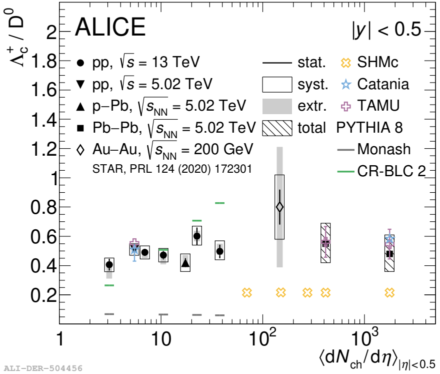
[ALICE Collaboration, arxiv:2112.08156]

- Ratio is higher in $2 < p_T < 8$ GeV/c
  $\rightarrow$ Strangeness enhancement in QGP in Pb–Pb
- Agreement with models that include strangeness enhancement, fragmantation + recombination

- At intermediate p_T: Increasing trend from pp, to semi-central and most central Pb-Pb collisions
- Coalescence? Radial flow?

[TAMU: PRL 124, 042301 (2020)] [PHSD: PRC 93, 034906 (2016)] [LGR: EPJC, 80 7 (2020) 671] [CATANIA: PRC 96, 044905 (2017)]

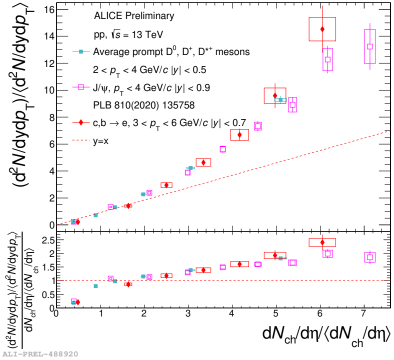
p_T-integrated Λ_c^+/D_0

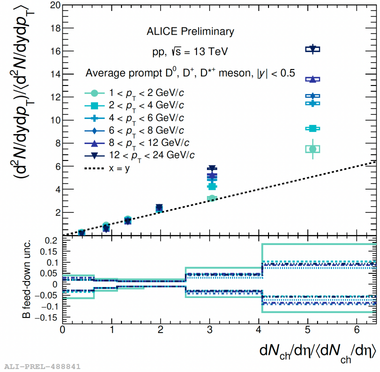


[TAMU: PRL 124, 042301 (2020)];
[PHSD: PRC 93, 034906 (2016)];
[LGR: EPJC, 80 7 (2020) 671];
[CATANIA: PRC 96, 044905 (2017)]

- **No evidence of multiplicity dependence**, from low (pp) to high (central Pb–Pb) multiplicity
- No enhancement of total yield in Pb-Pb with respect to to pp collisions
  - Reproduced by **fragmentation + recombination** and **SHM** predictions
- Is the p_T-differential enhancement a consequence of radial flow and recombination only ?

Self-normalised yields defined as: $$\frac{\mathrm{d}^2 N/\mathrm{d}p_\mathrm{T}\mathrm{d}\eta}{\langle \mathrm{d}^2 N/\mathrm{d}p_\mathrm{T}\mathrm{d}\eta\rangle} = \frac{N^i_\mathrm{HF}/(\epsilon^i \times n^i_\mathrm{events})}{(N^\mathrm{total}_\mathrm{HF})/(\epsilon^\mathrm{total} \times \mathrm{n}^\mathrm{total}_\mathrm{events})}$$



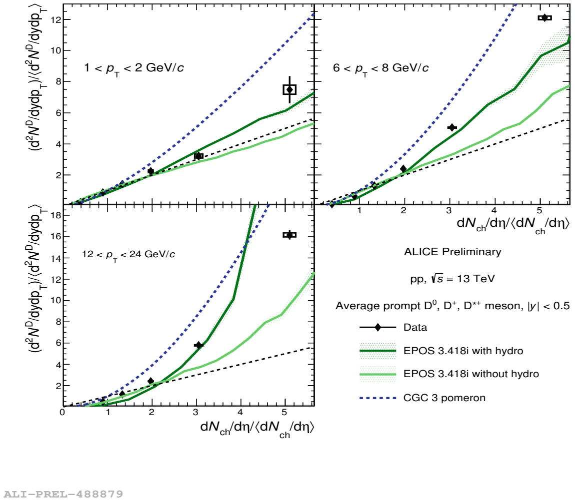


Faster than linear increasing trend and p_T **dependence,** influenced by **momentum dependence** of :

→ jet fragmentation affecting the measured multiplicity

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

- **Precise measurements of charm and beauty cross sections**

- **Charm fragmentation function calculated in pp collisions and compared to e^+e^- collisions**

  $\rightarrow$ **Non-universality** of the **fragmentation functions**

- **Charm hadronization studied in Pb–Pb collisions and pp collisions**

  $\rightarrow$ Models containing hadronization mechanism with recombination$+$ fragmentation tend to describe data well

  $\rightarrow$ More studies are needed to discriminate among different theoretical descriptions

- **HF** self-normalised yield **vs. multiplicity** in **pp collisions**

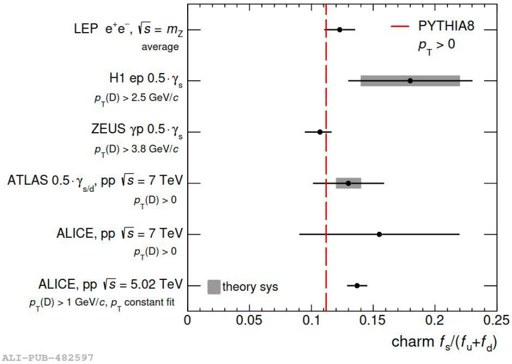
  $\rightarrow$ Faster than linear increasing trend, with strong p_{T} dependence

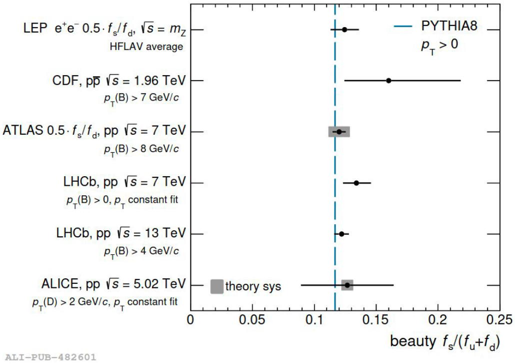
  $\rightarrow$ Compared with model expectation, more studies required

  - **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

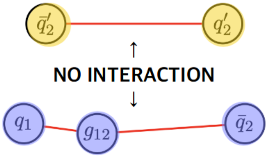




Colour Reconnection (CR) scenario

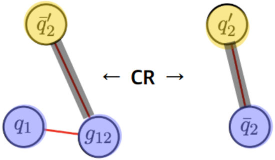
- strings rearranged between partons, so as to **reduce the total string length**
- Partons from different PI can become connected to each other

No CR



Partons created in different MPIs do not interact each other

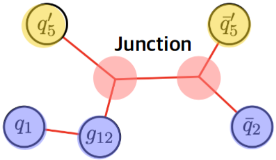
Old CR



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

(Monash tune)

New CR



Minimization of string length over all possible configurations

Reconnections of dipoles $\rightarrow$ junctions structure produces $\rightarrow$ 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]