# Probing QCD-based model predictions with charm-hadron production measurements with ALICE at the LHC

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# Heavy quarks: a unique probe for high-density QCD

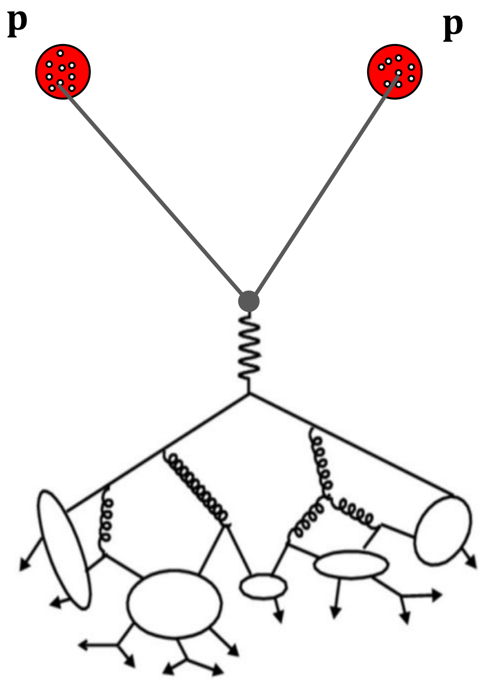
- Charm and beauty quarks: $m_c$~1.3 GeV/$c^2$, $m_b$~4.2 GeV/$c^2$
- Significantly larger than $\Lambda_{QCD}$ (~200 MeV)
  → Produced in hard scattering processes among partons

**Charm-** and **beauty- quarks dynamic** tested via **measurements** of **charm-** and **beauty- hadron production**

pp collisions

- Test of pQCD calculations
  - heavy-quark production
  - parton distribution functions (PDFs)
  - hadronization

- No first-principle description of hadronization
  - Non-perturbative problem, pQCD calculations not applicable
  - Necessary to resort to models and make use of phenomenological parameters



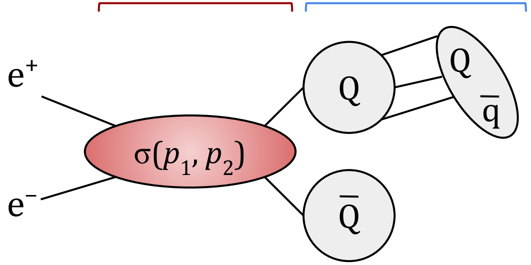
# Hadron production at large $Q^2$ - $e^+e^-$ collisions

**$e^+e^-$ collisions**

- "Vacuum-like" system
- Hadronization described with string models

**Factorization approach**

$$\frac{d\sigma^{H_c}}{dp_T^{H_c}}(p_T;\mu_F,\mu_R) = \underbrace{\frac{d\sigma^c}{dp_T^c}(p_1,p_2,\mu_F,\mu_R)}_{\text{Hard scattering cross section (perturbative calculations)}} \otimes \underbrace{D_{c\rightarrow H_c}(z = p_{H_c}/p_c,\mu_F)}_{\text{Fragmentation function (hadronization)}}$$



# Hadron production at large $Q^2$ - pp collisions

**Factorization approach**

$$\frac{d\sigma^{H_c}}{dp_T^{H_c}}(p_T;\mu_F,\mu_R) = \underbrace{PDF(x_1,\mu_F)\cdot PDF(x_2,\mu_F)}_{\text{Parton distribution functions (PDFs)}}\otimes\underbrace{\frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_F,\mu_R)}_{\text{Hard scattering cross section (pQCD)}}\otimes\underbrace{D_{c\to H_c}(z=p_{H_c}/p_c,\mu_F)}_{\text{Fragmentation function (hadronization)}}$$

$e^+e^-$ collisions

- "Vacuum-like" system
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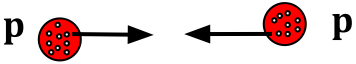
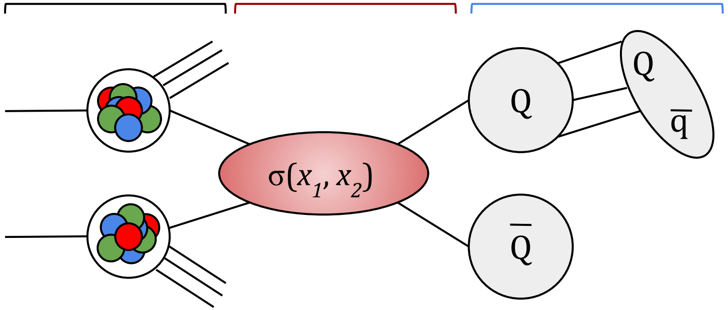
Multiparton interactions (**MPIs**)



- Superimposition of many independent parton-parton collisions?
- Changes in hadronization due to the surrounding color charges and those from MPI?

- Fragmentation functions assumed universal across collision systems and constrained from $e^+e^-$ and $e^-p$ measurements



Independent fragmentation

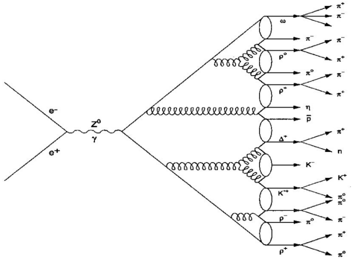
# Hadronization in event generators: clusters and strings

**Event generators**: final stage of parton shower interfaced with non-perturbative hadronization models

## **Cluster decay**
(HERWIG)

Eur. Phys. J. C 76 no. 4, (2016) 196

- Parton shower evolved up to a softer scale
- All gluons forced to split in q$\bar{q}$ pairs
- Color-singlet clusters of partons identified following the color flow
- Cluster decays into hadrons according to the available phase space



# Hadronization in event generators: clusters and strings

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**Event generators**: final stage of parton shower interfaced with non-perturbative hadronization models

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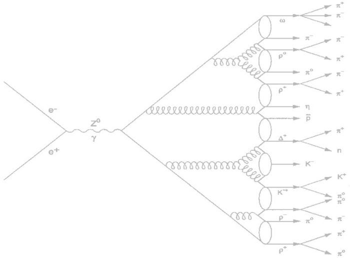


**String fragmentation**
(e.g. Lund model in PYTHIA)

Phys. Rept. 97 (1983) 31–145
Eur. Phys. J. C 78 no. 11

- Strings: colour-flux tubes between q and $\bar{q}$ endpoints
  - gluons: kinks
- Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs

**Tunneling probability**

$$P(\text{string breaking}) \propto \exp\left(-\frac{\pi m_{\mathrm{T,q}}^2}{\kappa}\right) = \exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa}\right) \exp\left(-\frac{\pi p_{\mathrm{T,q}}^2}{\kappa}\right)$$

$$\mathrm{u} : \mathrm{d} : \mathrm{s} : \boxed{\mathrm{c}} \simeq 1 : 1 : 1/3 : \boxed{10^{-11}}$$

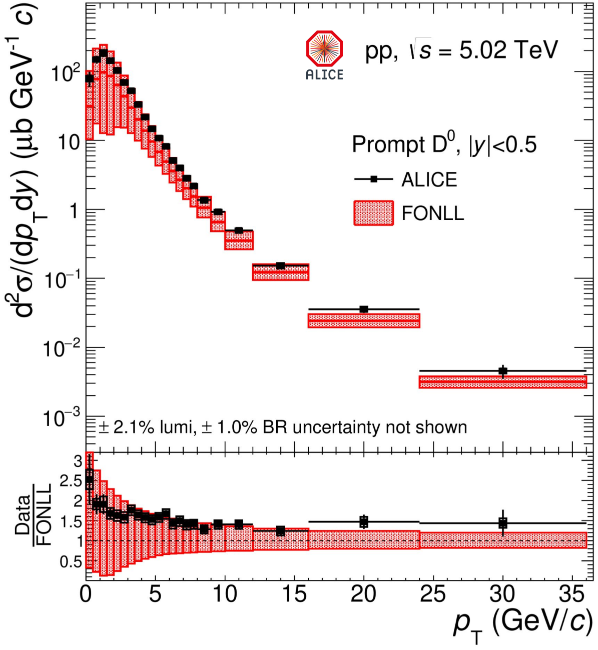
charm mostly produced in the hard scattering

# The success of factorization and independent fragmentation (1/2)

Eur.Phys.J. C79 (2019) no.5, 388

- Factorization in terms of squared momentum transfer $Q^2$: collinear factorization
- At LHC energies, calculations available in:
  - general-mass variable-flavour-number scheme (GM-VFNS) approach
  - fixed order plus next-to-leading logarithms (FONLL) approach

both having NLO accuracy with all-order resummation of next-to-leading logarithms



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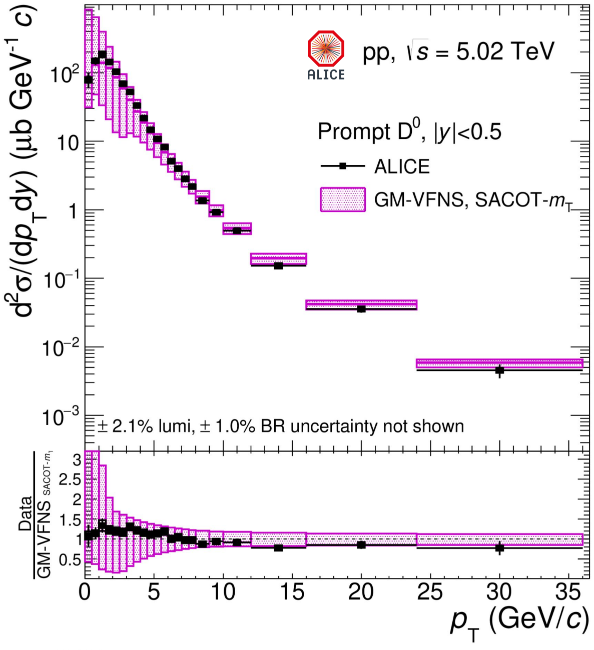


ALI-PUB-314123

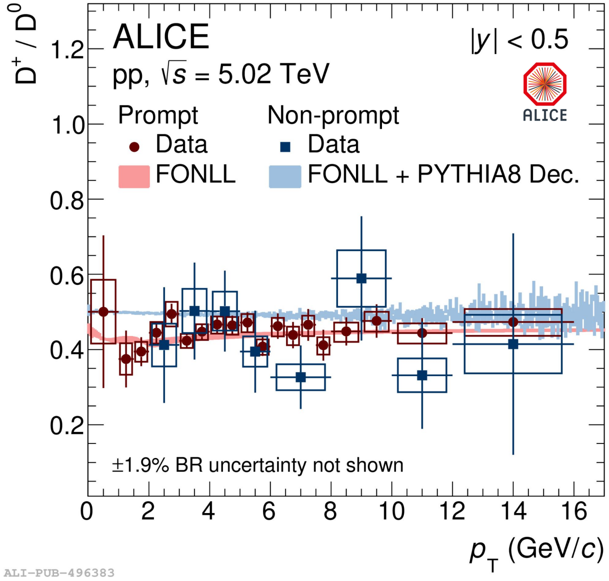
D-meson measurements described by model predictions

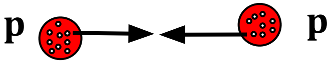
→ Theoretical uncertainties: (i.) renormalization and factorization scales; (ii.) c-, b-quark mass; (iii.) PDFs

→ main source of theoretical uncertainty: scales for perturbative calculations (up to ~100%)

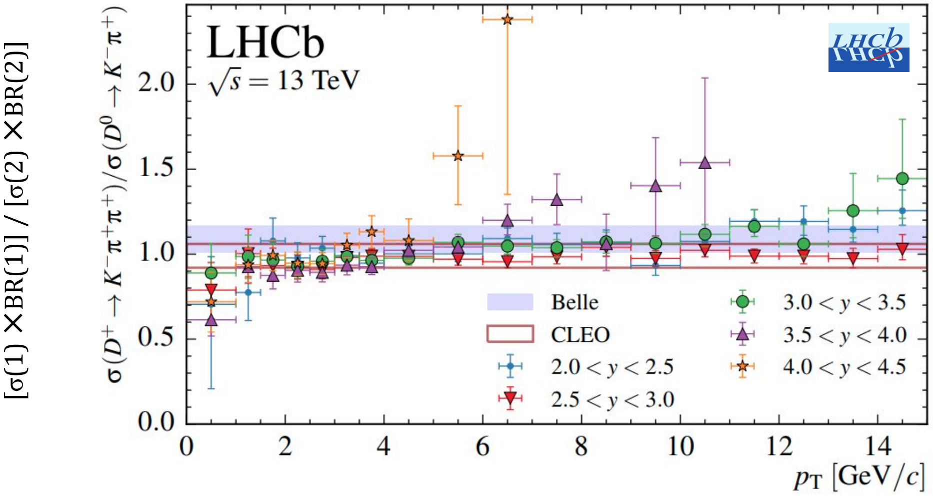
# The success of factorization and independent fragmentation (2/2)

JHEP 05 (2021) 220





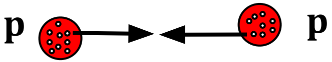
JHEP 03 (2016) 159



- Charm-hadron production in $e^+e^-$ collisions described by PYTHIA (backup)
- Heavy-flavour meson-to-meson ratios in pp collisions:
  - no significant $p_T$-dependence
  - described by models based on factorization and with fragmentation functions constrained from $e^+e^-$ collisions
  - compatible with results in $e^+e^-$ collisions

# Hadronization in PYTHIA 8 - colour reconnection with MPIs

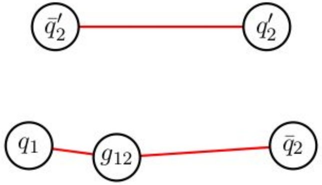
JHEP 08 (2015) 003



pp collisions

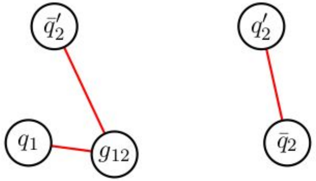
PYTHIA

**No CR**



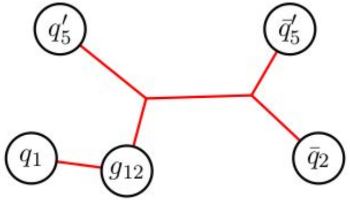
- Initial state not insensitive to strong force (coloured partons, beam remnants)
- MPIs crucial to explain underlying event
- No CR: partons from different MPIs do not interact

PYTHIA 8 default tune



**Colour reconnection (CR)** within **Leading Color**

- CR allowed among partons from different MPIs to minimize string length
- Implemented in PYTHIA 8 Monash



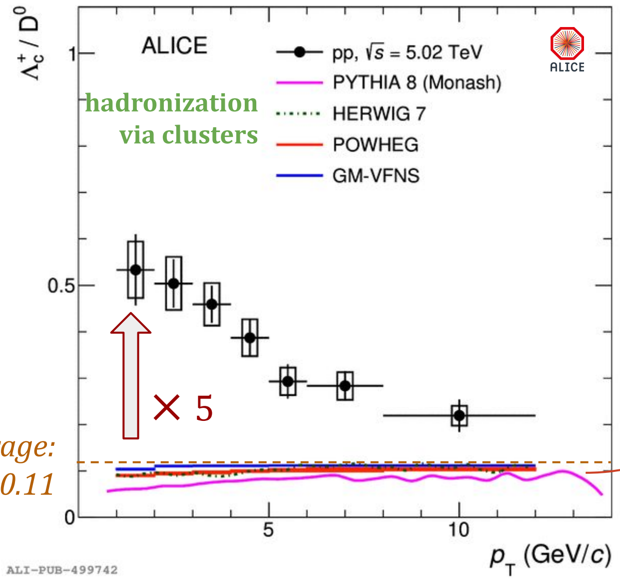
**CR beyond Leading Color** approximation **(CR-BLC)**

- String length minimization over all possible configurations, even those beyond the LC topology
- Enhanced leading color among MPIs and beam remnants
  - baryon production enhanced by junctions

# The baryon enhancement in the charm sector

p p

PRC 104 (2021) 054905  PRL 127 (2021) 202301  LEP: Eur. Phys. J. C (2015) 75:19



hadronization via clusters

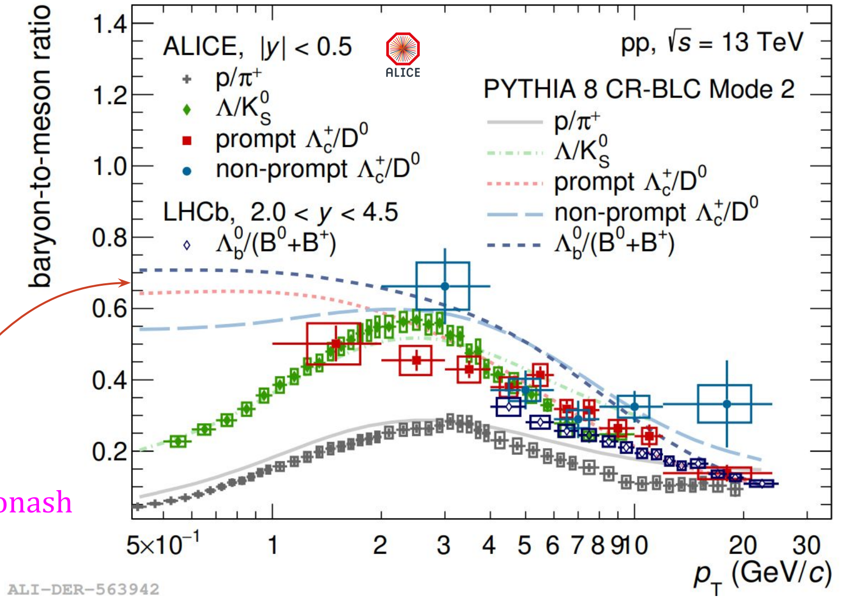
× 5

LEP average: ~0.11

junctions enabled

PYTHIA 8 Monash

Phys. Rev. D 108, 112003 (2023)



- Significant baryon-to-meson ratio enhancement in pp compared to e$^+$e$^-$ collisions
- PYTHIA 8 Monash predictions and pQCD-based calculations based on factorization and fragmentation functions tuned on e$^+$e$^-$ underestimate the results in pp collisions
- PYTHIA 8 predictions with junctions better describe the measured $\Lambda_c^+/D^0$ at $|y| < 0.5$
  - Beauty baryon-to-meson ratio at forward rapidity not well described

# Charm production at mid-*y* in pp collisions at $\sqrt{s}$ = 13 TeV (1/2)

JHEP12 (2023) 086

*"Charm production and fragmentation fractions at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV"*

## *Contents*

1. Most precise and granular measurements of $p_T$-differential production cross section of prompt $D^0$, $D^+$, $D^{*+}$, $D_s^+$ mesons at mid-*y* in pp at $\sqrt{s}$ = 13 TeV
2. Extended measurements down to lower $p_T$ values of prompt $\Lambda_c^+$- and $\Xi_c^+$-baryon production cross sections at mid-*y* in pp at $\sqrt{s}$ = 13 TeV
3. Measurement of the $c\bar{c}$ production cross section and charm-quark fragmentation fractions at mid-*y* in pp at $\sqrt{s}$ = 13 TeV
    a. based on the sum of $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, $\Xi_c^{0,+}$, J/ψ cross sections
    b. first measurement of $\Xi_c^+$ and $\Sigma_c^{0,+,++}$ fragmentation fractions at mid-*y* in pp collisions

## *Goals*

1. Overview of charm-hadron production measurements with ALICE at mid-*y* in pp collisions
2. Provide new inputs to:
    a. test the validity of the factorization approach and independent fragmentation
    b. constrain gluon PDF at low Bjorken-*x*
    c. further study the baryon enhancement at the LHC

# Charm production at mid-$y$ in pp collisions at $\sqrt{s}$ = 13 TeV (1/2)

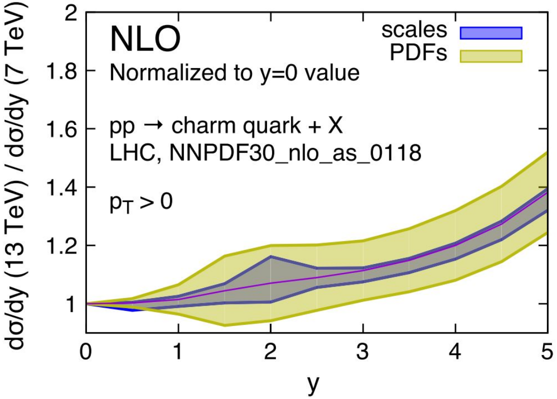
JHEP12 (2023) 086

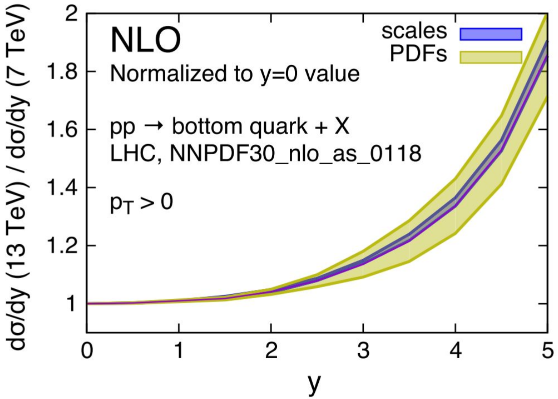
*"Charm production and fragmentation fractions at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV"*

1. Most precise and granular measurements of $p_T$-differential production cross section of prompt $D^0$, $D^+$, $D^{*+}$, $D_s^+$ mesons at mid-$y$ in pp at $\sqrt{s}$ = 13 TeV

Cacciari, Mangano, Nason: Eur. Phys. J. C (2015) 75:610

Constrain gluon PDF

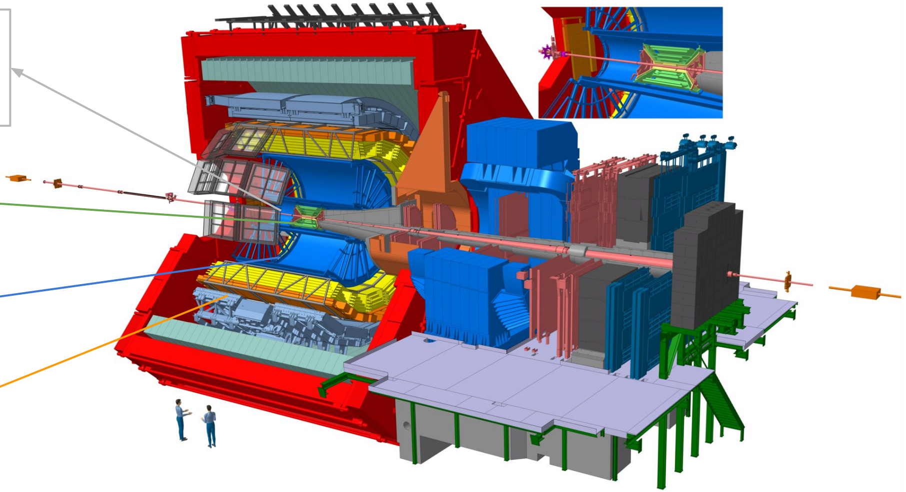




- Double ratio in rapidity and energy: scale and mass uncertainties reduced → PDF uncertainties dominant
- Low ($\lesssim 10^{-5}$) and high ($\gtrsim 10^{-2}$) Bjorken-$x$ regime accessible with measurements at $p_T \lesssim 2$ GeV/$c$ and $p_T \gtrsim 30$ GeV/$c$, respectively

# The ALICE detector in Run 1 and Run 2

Central barrel: $|\eta| < 0.9$
Muon spectrometer: $-4 < \eta < -2.5$



**V0**
*Trigger, centrality*

**Inner Tracking System (ITS)**
*Tracking, vertexing (primary, secondary HF)*

**Time Projection Chamber (TPC)**
*Tracking, PID via dE/dx*

**Time-Of-Flight (TOF)**
*PID via time of flight*

## *Charm-hadron decay channels*

$D^0 \to K^-\pi^+$
$D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$
$D^+ \to K^-\pi^+\pi^+$
$D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$
$D_{s1}^+ \to D^{*+}K_s^0$
$D_{s2}^{*+} \to D^+K_s^0$

$\Lambda_c^+ \to pK^-\pi^+, pK_s^0$
$\Xi_c^0 \to \Xi^-e^+\nu_e$
$\Xi_c^0 \to \Xi^-\pi^+$
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$
$\Sigma_c^{0,++} \to \Lambda_c^+\pi^{-,+}$
$\Omega_c^0 \to \Omega^-\pi^+$

## *Datasets*

| | |
|---|---|
| pp $\sqrt{s}$ = 5.02 TeV | $\to \mathcal{L}_{int} \sim 19\ nb^{-1}$ (MB) |
| pp $\sqrt{s}$ = 7 TeV | $\to \mathcal{L}_{int} \sim 5.9\ nb^{-1}$ (MB) |
| pp $\sqrt{s}$ = 13 TeV | $\to \mathcal{L}_{int} \sim 32\ nb^{-1}$ (MB) |
| p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV | $\to \mathcal{L}_{int} \sim 287\ \mu b^{-1}$ (MB) |
| Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV | $\to \mathcal{L}_{int} \sim 130\ \mu b^{-1}$ (0-10%) |
| | $\to \mathcal{L}_{int} \sim 56\ \mu b^{-1}$ (30-50%) |

new results in pp collisions at $\sqrt{s}$ = 13 TeV in JHEP12 (2023) 086

# Charm-hadron reconstruction (in a nutshell)

1. ***Track selections***
   - ○ ITS-TPC matched tracks → selection of *primaries* (ALICE-PUBLIC-2017-005)
   - ○ particle identification (PID)

2. ***Secondary-vertex reconstruction***
   - ○ Impact parameter resolution to primary vertex ~ 75 μm @ $p_T$ = 1 GeV/*c*
   - ○ Evaluation of topological variables
     - → intrinsic displacement ($c\tau(\mathrm{D}^+) \sim 310\ \mu\mathrm{m}$)

3. ***Topological selections***
   - ○ Separate signal from background candidates exploiting topological variables
     - → BDT exploited for most challenging analyses
   - ○ Measure the reconstructed signal with an invariant-mass analysis

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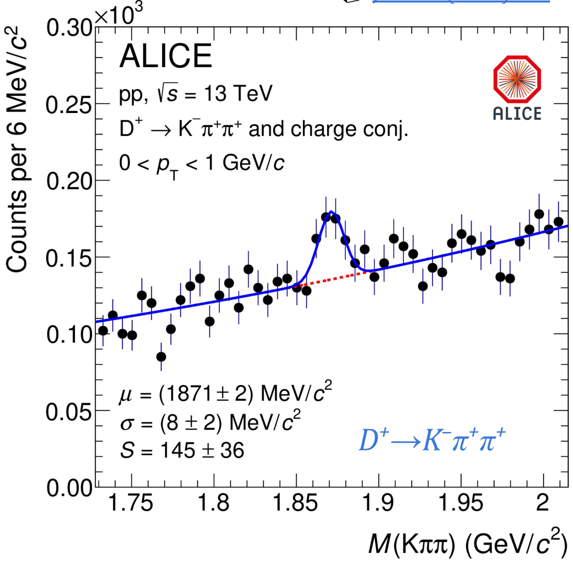

ALI-PUB-567781

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{H}}}{\mathrm{d}p_{\mathrm{T}}}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta p_{\mathrm{T}}} \times \frac{f_{\mathrm{prompt}} \times \boxed{N^{\mathrm{H}+\overline{\mathrm{H}}}_{|y|<y_{\mathrm{fid.}}}}}{c_{\Delta y}(\mathrm{Acc}\times\varepsilon)_{\mathrm{prompt}}} \times \frac{1}{\mathrm{BR}} \times \frac{1}{\mathcal{L}_{\mathrm{int}}}$$

# Prompt D-meson cross section in pp collisions at $\sqrt{s}$ = 13 TeV

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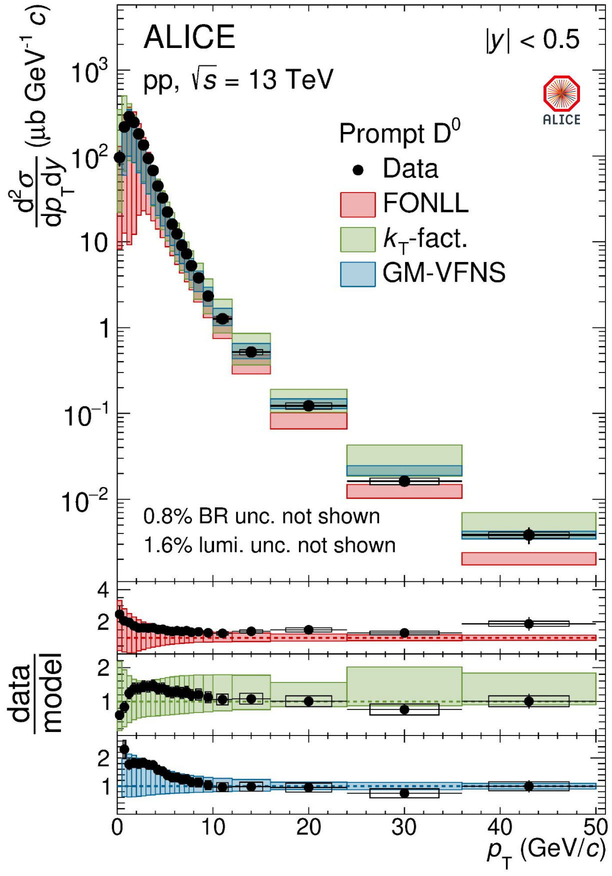

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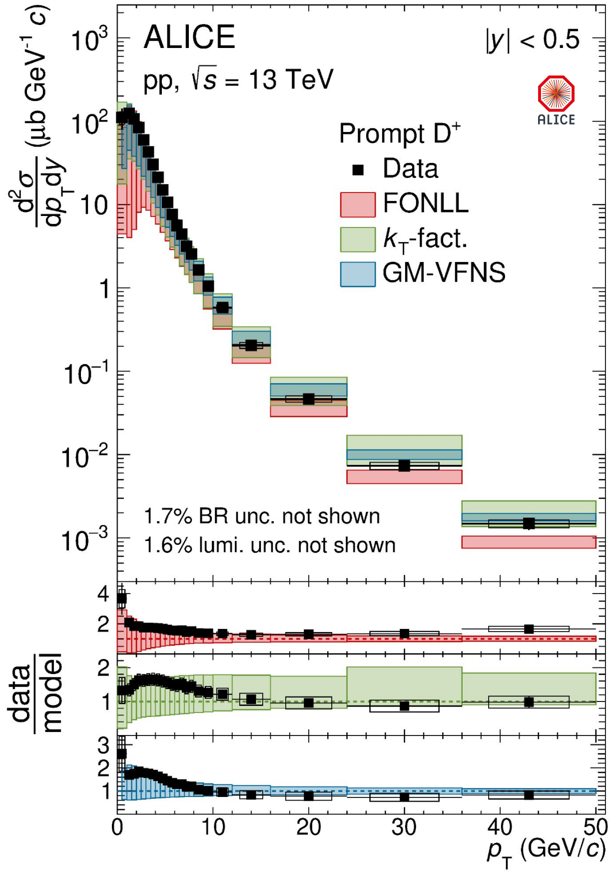

ALI-PUB-567841

Factorization in terms of:

- squared momentum transfer $Q^2$
  → collinear factorization
  - GM-VFNS
  - FONLL
- parton transverse momentum $k_T$
  → $k_T$-factorization

Model **calculations describe** the **measurements** within uncertainties

- measurement on the lower (upper) edge of GM-VFNS and $k_T$-factorization (FONLL) calculations at high $p_T$
- **main** source of **theoretical uncertainty**: **scales** for **perturbative calculations**

# D-meson yield ratios

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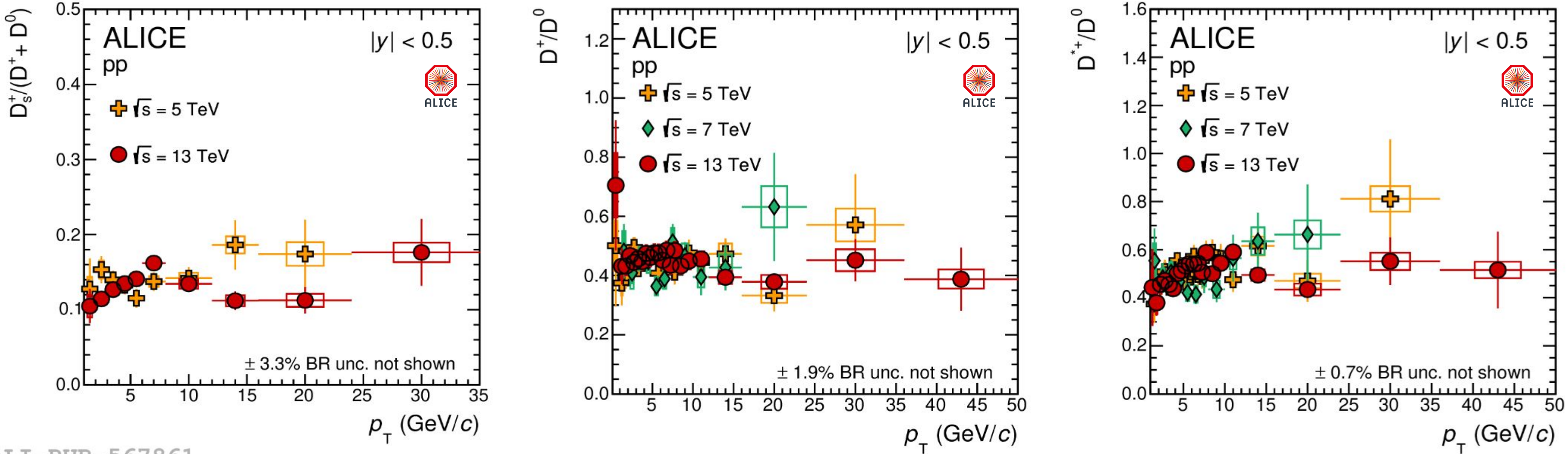


ALI-PUB-567861

- Hint of increasing $D_s/(D^0+D^+)$ vs. $p_T$ for $p_T < 8$ GeV/$c$
- No significant $p_T$ dependence for non-strange D-meson ratios
- The measured yield ratios do not depend significantly on collision energy

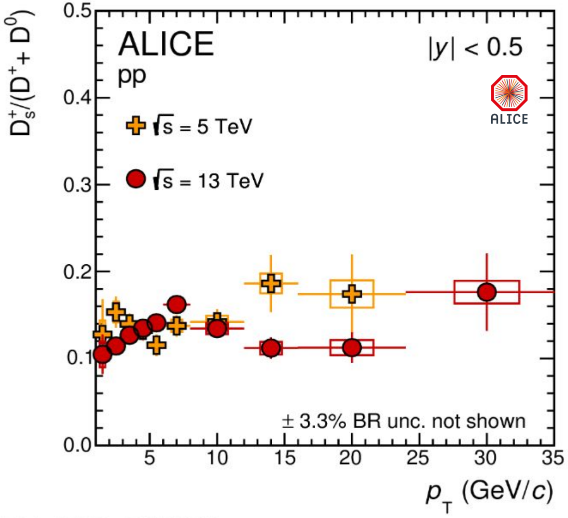
No energy dependence of charm quark **fragmentation functions** into pseudoscalar or vector D mesons, and on strange or non-strange D mesons

*from factorization …*

$$\frac{\dfrac{d\sigma^{H_c^1}}{dp_T^{H_c^1}}(p_T;\mu_F,\mu_R)}{\dfrac{d\sigma^{H_c^2}}{dp_T^{H_c^2}}(p_T;\mu_F,\mu_R)} \sim \frac{D_{c\to H_c^1}(z=p_{H_c^1}/p_c,\mu_F)}{D_{c\to H_c^2}(z=p_{H_c^2}/p_c,\mu_F)}$$

# Charm fragmentation fraction ratio $f_s / (f_u + f_d)$

JHEP12 (2023) 086



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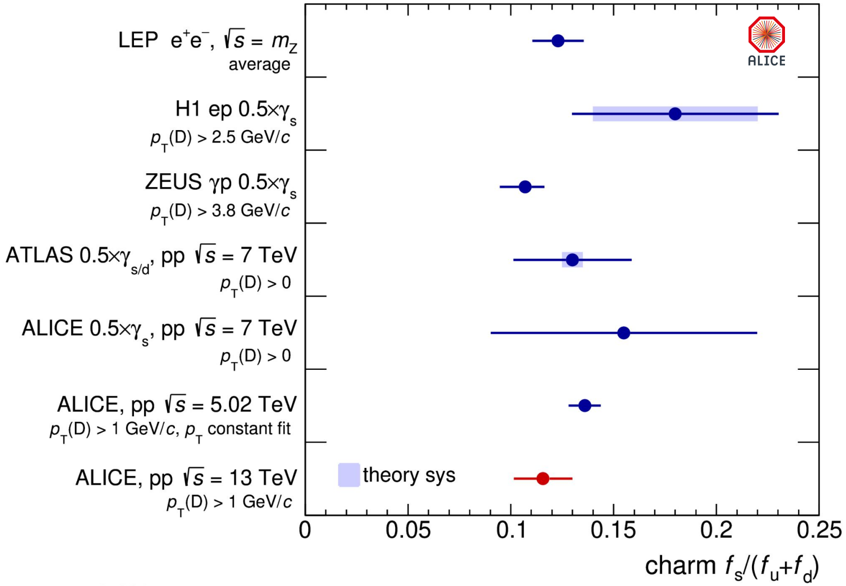

ALI-PUB-567901

- Hint of increasing $D_s/(D^0+D^+)$ vs. $p_T$ for $p_T < 8$ GeV/$c$
- D-meson cross sections for $p_T > 1$ GeV/$c$ used for $f_s / (f_u + f_d)$

$$\left(\frac{f_s}{f_u + f_d}\right)_{\text{charm}} = 0.116 \pm 0.011\,(\text{stat.}) \pm 0.009\,(\text{syst.}) \pm 0.003\,(\text{BR})$$

→ No significant collision-system dependence

| $\mathrm{d}\sigma/\mathrm{d}y\|_{\|y\|<0.5}$ ($\mu$b), $p_T > 1$ GeV/$c$ | |
|---|---|
| $D^0$ | $592 \pm 19\ (\text{stat.})^{+40}_{-42}\ (\text{syst.}) \pm 9\ (\text{lumi.}) \pm 4\ (\text{BR.})$ |
| $D^+$ | $264 \pm 5\ (\text{stat.})^{+20}_{-20}\ (\text{syst.}) \pm 4\ (\text{lumi.}) \pm 5\ (\text{BR.})$ |
| $D_s^+$ | $99 \pm 9\ (\text{stat.})^{+10}_{-11}\ (\text{syst.}) \pm 2\ (\text{lumi.}) \pm 3\ (\text{BR.})$ |

# Charm-hadron production at different collision energies

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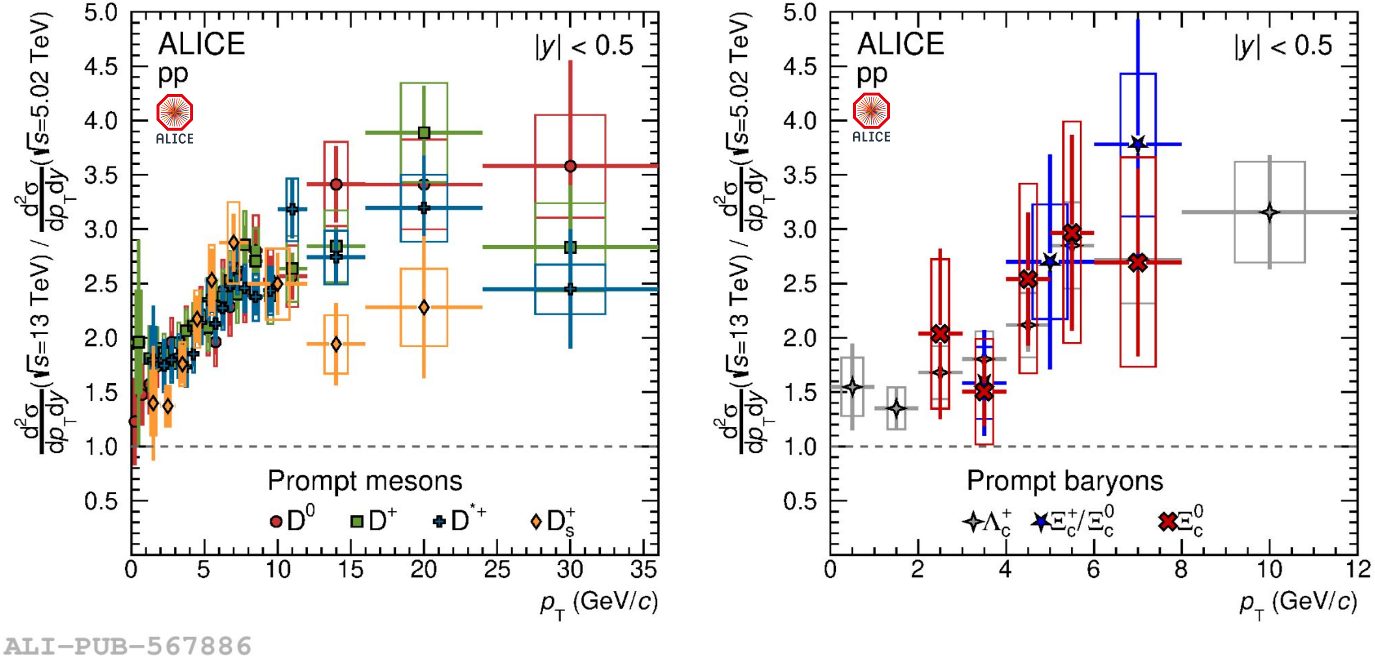


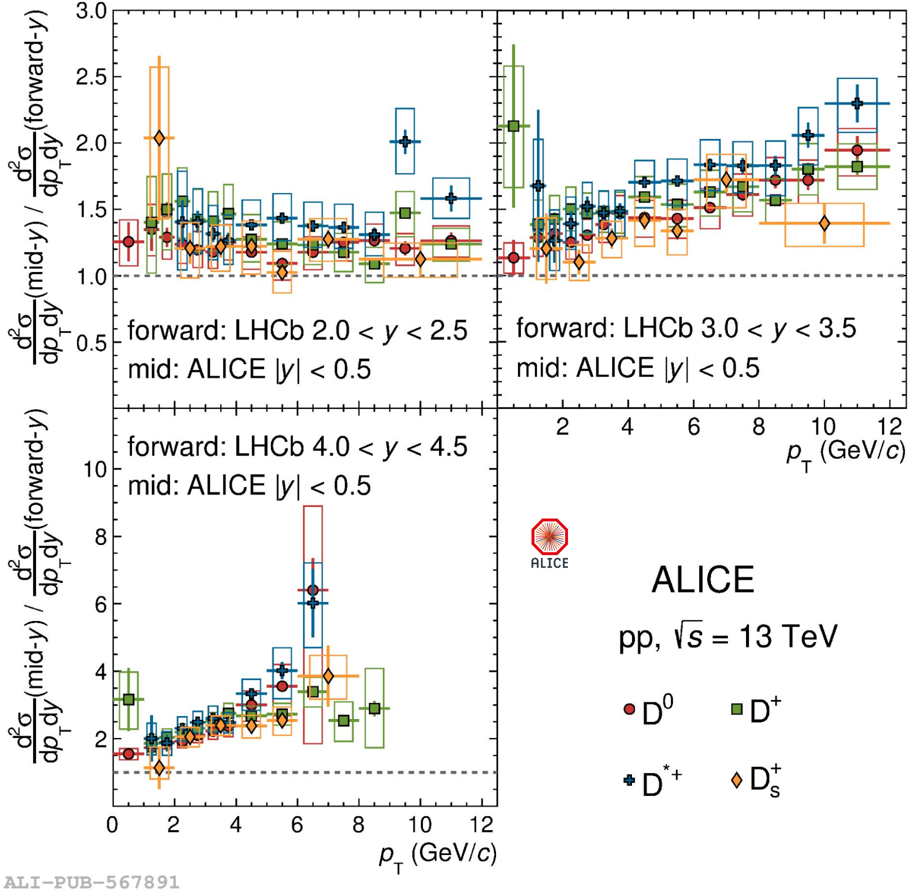
- Cross section ratio of D$^0$, D$^+$, D$^{*+}$ and D$^+_s$ between $\sqrt{s}$ = 13 TeV and $\sqrt{s}$ = 5.02 TeV
- Increasing trend with $p_T$, and compatible values for different species
  - similar for $\Lambda_c^+$ and $\Xi_c^{0,+}$ baryons

Similar $p_T$-spectrum hardening from $\sqrt{s}$ = 5.02 TeV to $\sqrt{s}$ = 13 TeV for charm mesons and baryons

# D-meson cross section ratio mid-*y* / forward-*y*

📚 ALICE: JHEP12 (2023) 086

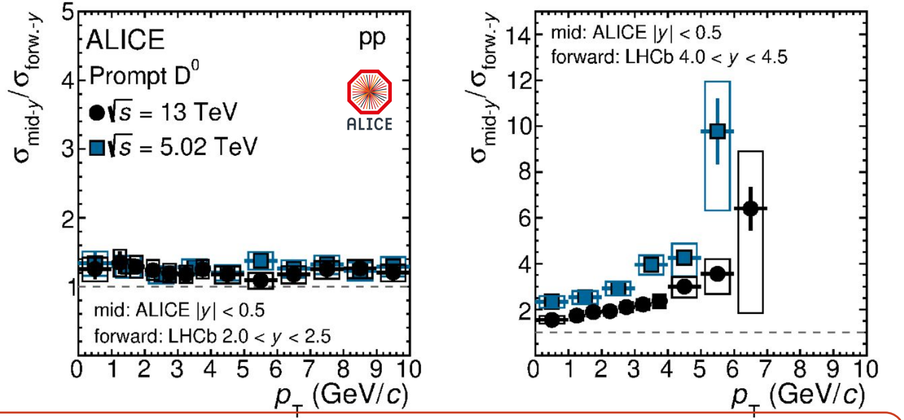
📚 LHCb: JHEP03(2016)159
📚 LHCb: JHEP09(2016)013
📚 LHCb: JHEP05(2017)074

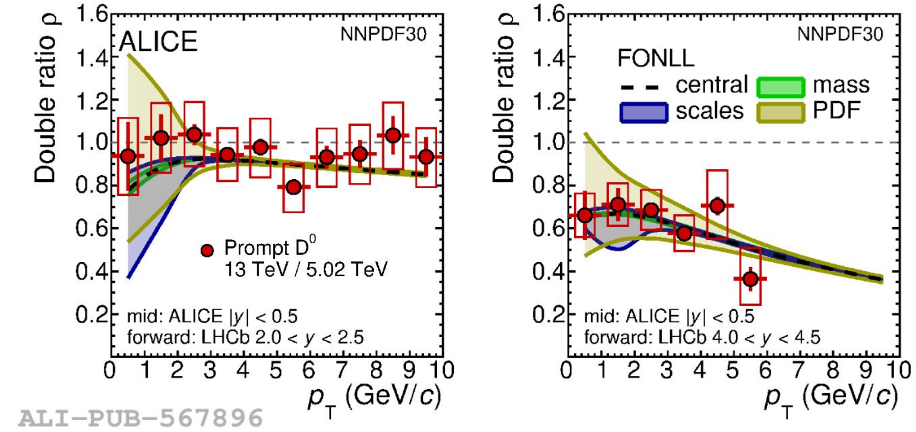


- Mid-*y* / forward-*y* ratio of prompt $D^0$-meson cross section
- Compatible results among D-meson species
- Hint of increasing ratio vs. $p_T$ with increasing rapidity separation between mid- and forward-*y*
    - ○ softer $p_T$ spectrum at forward-*y*

# $D^0$-meson double ratio ($\rho$)

forward: $2.0 < y < 2.5$ forward: $4.0 < y < 4.5$





ALICE: JHEP12 (2023) 086

LHCb: JHEP03(2016)159
LHCb: JHEP09(2016)013
LHCb: JHEP05(2017)074

- Mid-$y$ / forward-$y$ ratio of prompt $D^0$-meson cross section
- Compatible results among D-meson species

---

- Double ratio mid-$y$ / forward-$y$ && 13 TeV/ 5.02 TeV of prompt $D^0$-meson cross section

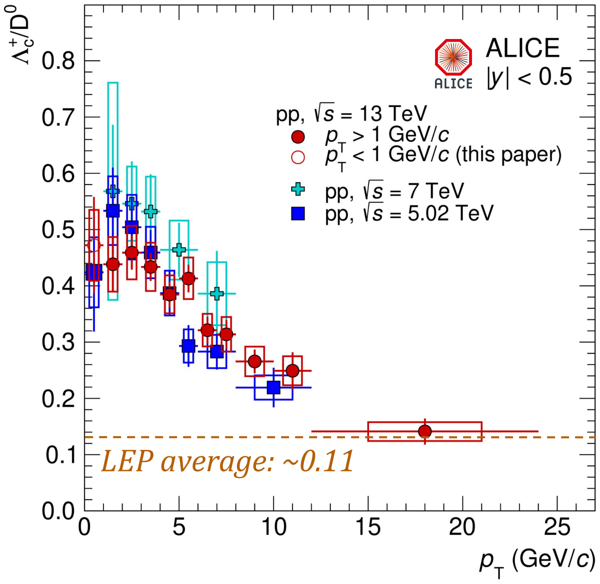
$$\rho = \left(\sigma^{13\,\text{TeV}}_{\text{mid-}y} \Big/ \sigma^{13\,\text{TeV}}_{\text{forward-}y}\right) \Big/ \left(\sigma^{5.02\,\text{TeV}}_{\text{mid-}y} \Big/ \sigma^{5.02\,\text{TeV}}_{\text{forward-}y}\right)$$

- $\rho$ decreasing vs. $p_T$ with increasing rapidity gap
  - different Bjorken-$x$ tested (~$10^{-6}$-$10^{-4}$)
  - harder $p_T$ spectrum at lower energy
- FONLL calculations with NNPDF30 PDFs
- Dominant uncertainties at low $p_T$: NNPDF30 PDFs
  - measurement with ✕~2-3 smaller uncertainties
  - quantitative constraints on gluon PDF possible

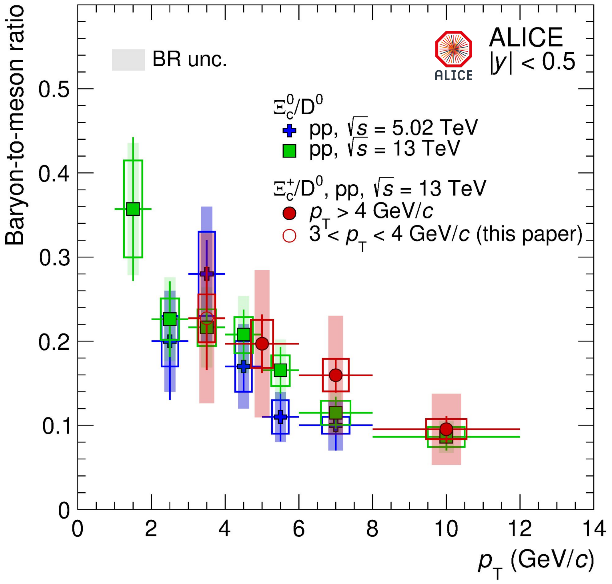
# Baryon-to-meson ratio at mid-$y$

ALICE: JHEP12 (2023) 086

LEP: Eur. Phys. J. C (2015) 75:19



ALI-PUB-567866



ALI-PUB-567871

- Extended measurement of $\Lambda_c^+/D^0$ ($\Xi_c^+/D^0$) baryon-to-meson ratio down to $p_T$ = 0 (3) GeV/$c$ at mid-$y$ in pp at $\sqrt{s}$ = 13 TeV
- No significant energy dependence from 5.02 TeV to 7 TeV and 13 TeV
  - $\Lambda_c^+/D^0$ in pp at the LHC larger than $e^+e^-$ collisions, by a factor of ~5 at low $p_T$

*baryon enhancement*

# Charm “baryonization” in pp collisions - different approaches (1/4)

***SHM+RQM*** PLB 795 (2019) 117-121

Statistical approach

- Hadron formation driven by the mass $m_i$ at a hadronization temperature $T_H$
- Strong feed-down from an augmented set of excited charm baryon states
  - PDG: 5 $\Lambda_c$, 3 $\Sigma_c$, 8 $\Xi_c$, 2 $\Omega_c$
  - RQM: additional (not yet measured) 18 $\Lambda_c$, 42 $\Sigma_c$, 62 $\Xi_c$, 34 $\Omega_c$
    - → some discovered by LHCb

Total angular momentum degeneracy **2J + 1**

$$n_i = \frac{\boxed{d_i}}{2\pi^2} m_i^2 T_H K_2 \left( \frac{m_i}{T_H} \right)$$

| $n_i$ [×$10^{-4}$ fm$^{-3}$] ($T_H$ [MeV]) | $\Lambda_c^+$ | $\Xi_c^{0,+}$ | $\Omega_c^0$ |
|---|---|---|---|
| **PDG (170)** | 0.3310 | 0.0874 | 0.0064 |
| **RQM (170)** | 0.6613 | 0.1173 | 0.0144 |

# Charm “baryonization” in pp collisions - different approaches (2/4)

mfaggin@cern.ch

**Statistical approach**

## ***SHM+RQM***

PLB 795 (2019) 117-121

- Hadron **formation driven by** the **mass** $m_\mathrm{i}$ at a hadronization temperature $T_\mathrm{H}$
- Strong **feed-down** from an **augmented set of excited charm baryon states**
    - PDG: 5 $\Lambda_c$, 3 $\Sigma_c$, 8 $\Xi_c$, 2 $\Omega_c$
    - RQM: additional (not yet measured) 18 $\Lambda_c$, 42 $\Sigma_c$, 62 $\Xi_c$, 34 $\Omega_c$
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Total angular momentum degeneracy **2J + 1**

$$n_i = \frac{d_i}{2\pi^2} m_i^2 T_\mathrm{H} K_2 \left( \frac{m_i}{T_\mathrm{H}} \right)$$

| $n_\mathrm{i}$ [×$10^{-4}$ fm$^{-3}$]<br>($T_\mathrm{H}$ [MeV]) | $\Lambda_c^+$ | $\Xi_c^{0,+}$ | $\Omega_c^0$ |
|---|---|---|---|
| **PDG (170)** | 0.3310 | 0.0874 | 0.0064 |
| **RQM (170)** | 0.6613 | 0.1173 | 0.0144 |

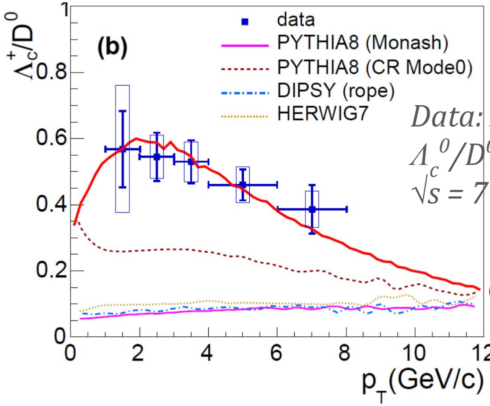
---

## ***Quark Coalescence Mechanism (QCM)***

Eur. Phys. J. C (2018) 78: 344

- **Coalescence** between a **charm quark** (perturbative), and **equal-velocity light quarks** from fragmentation (not perturbative)
- **Thermal weights** to account for **relative production** of scalar and vector mesons

**Statistical approach + coalescence**



*Data: ALICE $\Lambda_c^0/D^0$ in pp at $\sqrt{s}$ = 7 TeV*

***QCM***

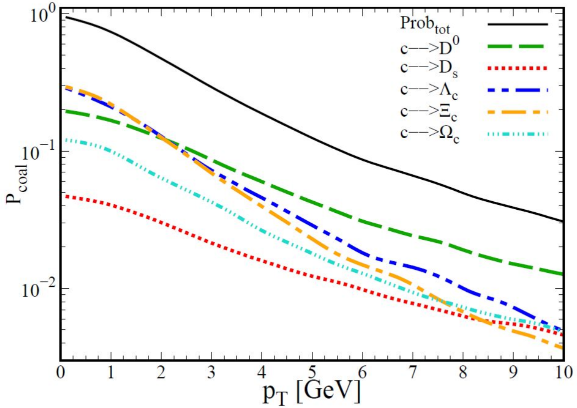
# Charm “baryonization” in pp collisions - different approaches (3/4)

***Catania coalescence model***

📚 PLB 821, 136622

**Thermalised system + fragmentation + coalescence**

- Thermalised system of u, d, s and gluons
- Charm quark can hadronize either via fragmentation or coalescence with light quarks from the bulk
- Charm hadronization into ground and (PDG) excited states
    - ○ Statistical “penalty” weight $[m_{H*}/m_{H}]^{3/2} \times \exp(-\Delta E/T)$



# Charm “baryonization” in pp collisions - different approaches (4/4)

mfaggin@cern.ch

### *Catania coalescence model*

PLB 821, 136622

Thermalised system + fragmentation + coalescence

- Thermalised system of u, d, s and gluons
- Charm quark can hadronize either via fragmentation or coalescence with light quarks from the bulk
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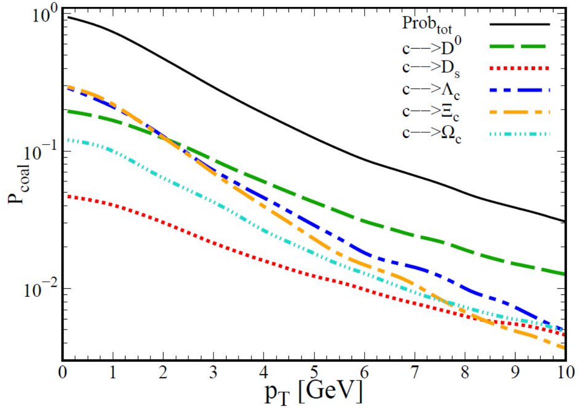

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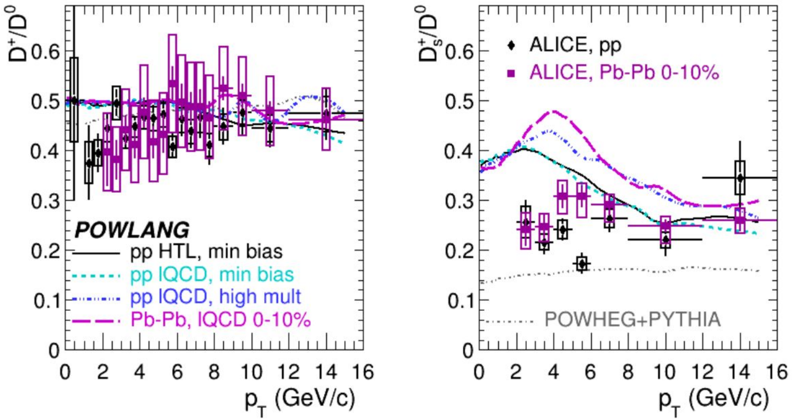
### *POWLANG*

https://arxiv.org/abs/2306.02152

- Small, deconfined and expanding fireball in pp collisions
- Charm quark subject to rescattering and hadronization
  - charm recombination with light quarks, as in heavy-ion collisions
  - presence of diquark excitations, promoting the formation of charm baryons



Thermalised system + coalescence

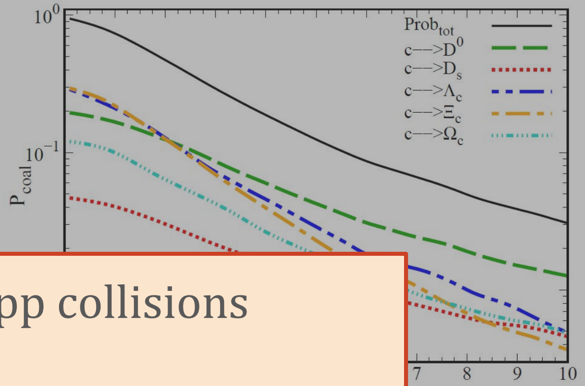
# Charm “baryonization” in pp collisions - different approaches (4/4)

### *Catania coalescence model*

PLB 821, 136622

Thermalised system + fragmentation + coalescence

- Thermalised system of u, d, s and gluons
- Charm quark can hadronize either via fragmentation or coalescence with light quarks from the bulk
- Charm hadroni
  - Statistica



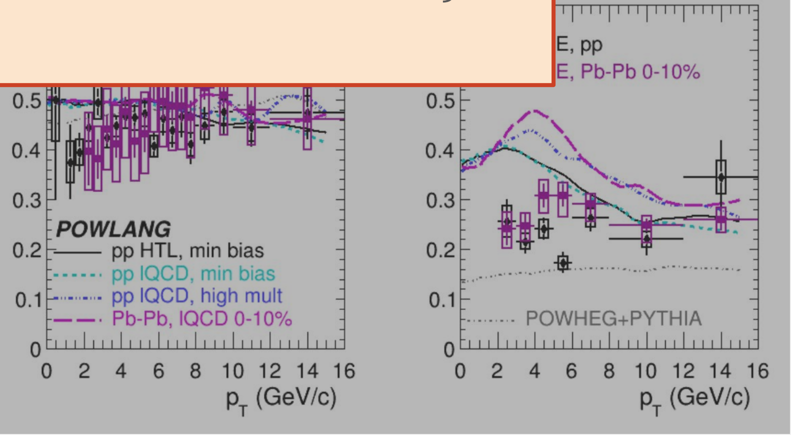
- Different hadronization mechanisms in pp collisions compared to $e^+e^-$ collisions
- Independent fragmentation (or better “hadronization”) no more assumed

### *POWLANG*

http

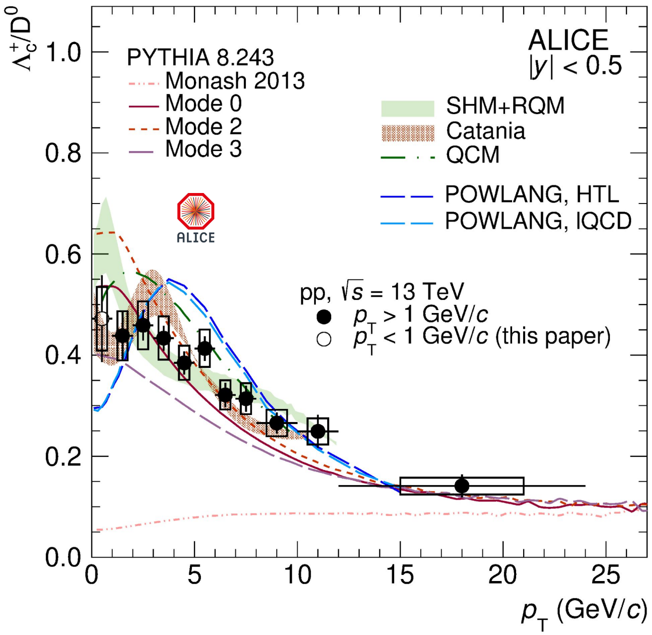
- Small, deconfin
- Charm quark subject to rescattering and hadronization
  - charm recombination with light quarks, as in heavy-ion collisions
  - presence of diquark excitations, promoting the formation of charm baryons

Thermalised system + coalescence



# Measured $\Lambda_c^+/D^0$ ratio vs. model predictions

JHEP12 (2023) 086



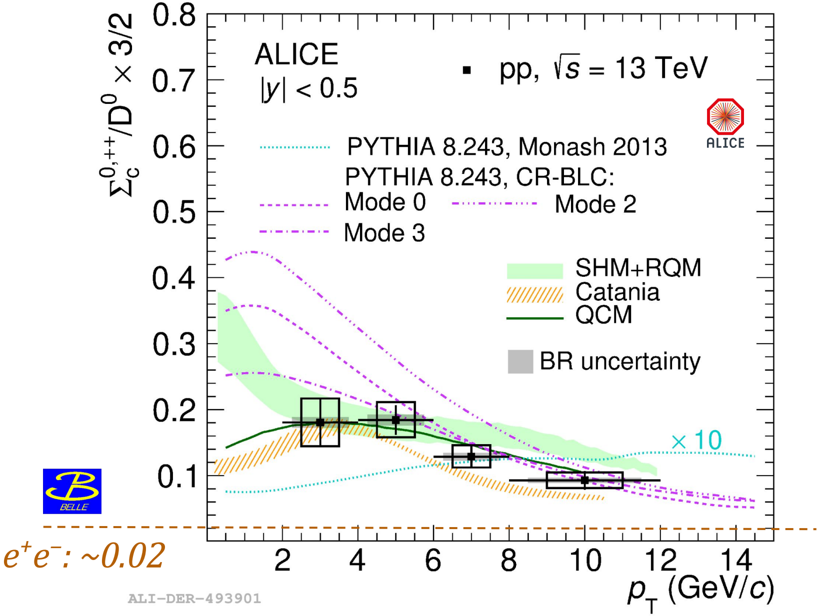
ALI-PUB-567876

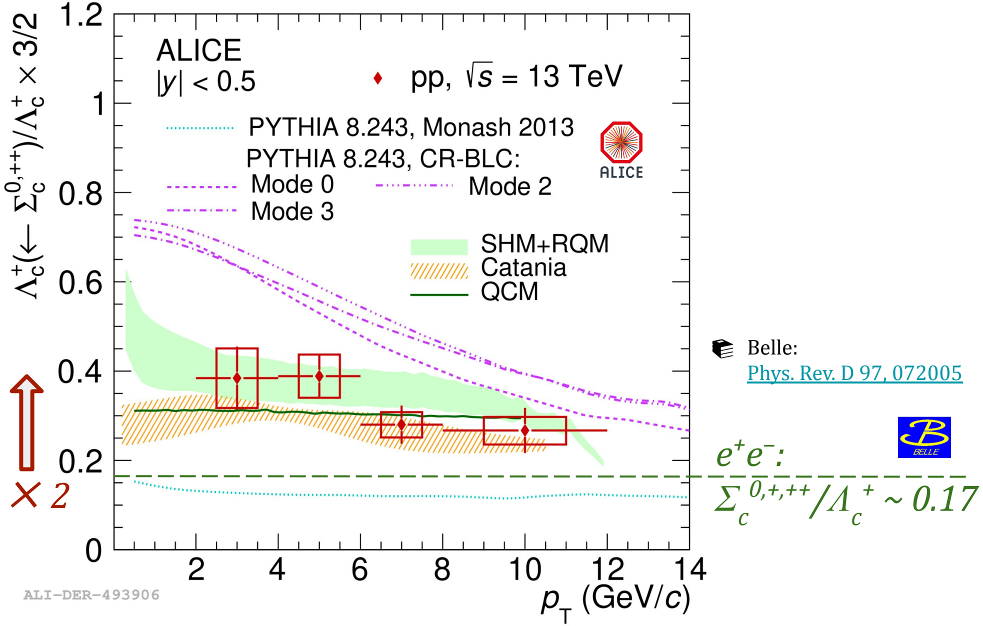
| | Coalescence | Excited baryons | Thermal system / fireball | Thermal component | $\Lambda_c^+/D^0$ |
|---|---|---|---|---|---|
| **CR-BLC** | ❌ | ❌(not explicit) | ❌ | ❌ | ✅ |
| **SHM+RQM** | ❌ | ✅ PDG + RQM | ❌ | ✅ | ✅ |
| **Catania** | ✅ | ✅ PDG | ✅ | ✅ | ✅ |
| **QCM** | ✅ | ❌ (not explicit) | ❌ | ✅ | ❓ slightly higher |
| **POWLANG** | ✅ | ❌ | ✅ | ❌ | ❌ |

- $\Lambda_c^+/D^0$ ratio described within uncertainties by several models despite the different mechanisms assumed
- $\Lambda_c^+/D^0$ ratio underestimated by a factor ~5 at low $p_T$ by PYTHIA 8 Monash
- Maximum at $p_T$~4 GeV/$c$ predicted by POWLANG not observed in data

# $\Sigma_c^{0,+,++}$ production in pp collisions

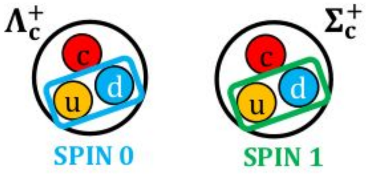
Phys. Rev. Lett. 128, 012001





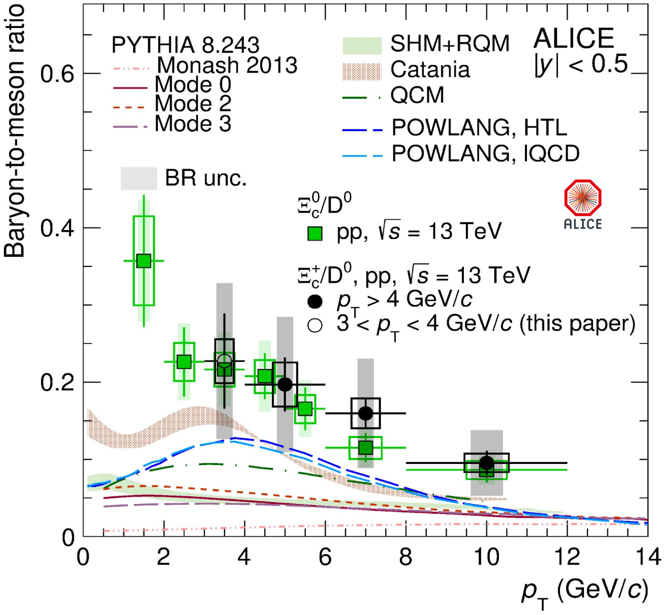
Belle: Phys. Rev. D 97, 072005

- $e^+e^-$: $\Sigma_c$ states suppressed by a factor ~3-4 with respect to $\Lambda_c$ ones → string model: penalty due to $m(ud)_0 > m(ud)_1$
- pp: $\Sigma_c^{0,+,++}/D^0$ underestimated by PYTHIA 8 Monash (larger discrepancy than for $\Lambda_c^+/D^0$), and described by other models
  → no diquark penalty factor assumed
- $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratio overestimated by CR-BLC
  → parameter tuning? Inputs from excited c-baryon measurements?



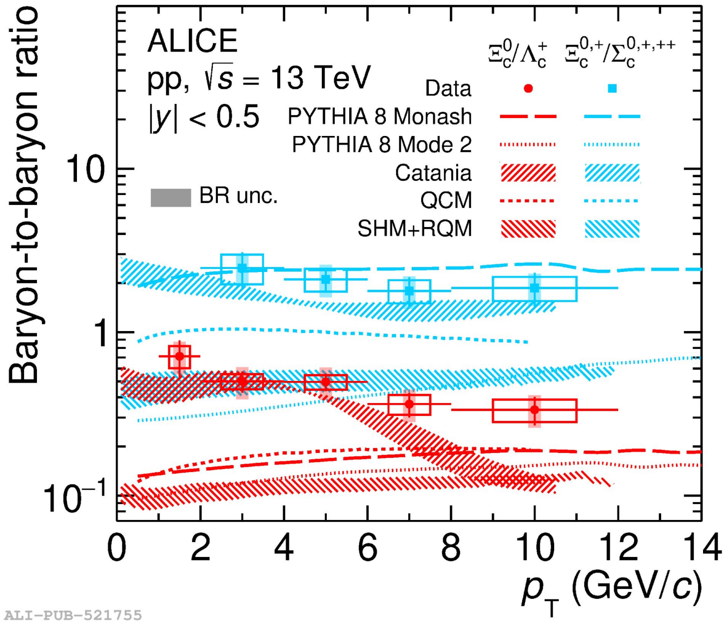
# $\Xi_c^{0,+}/D^0$ ratio vs. model predictions

JHEP12 (2023) 086



ALI-PUB-567881

Phys. Rev. Lett. 128 (2022) 012001



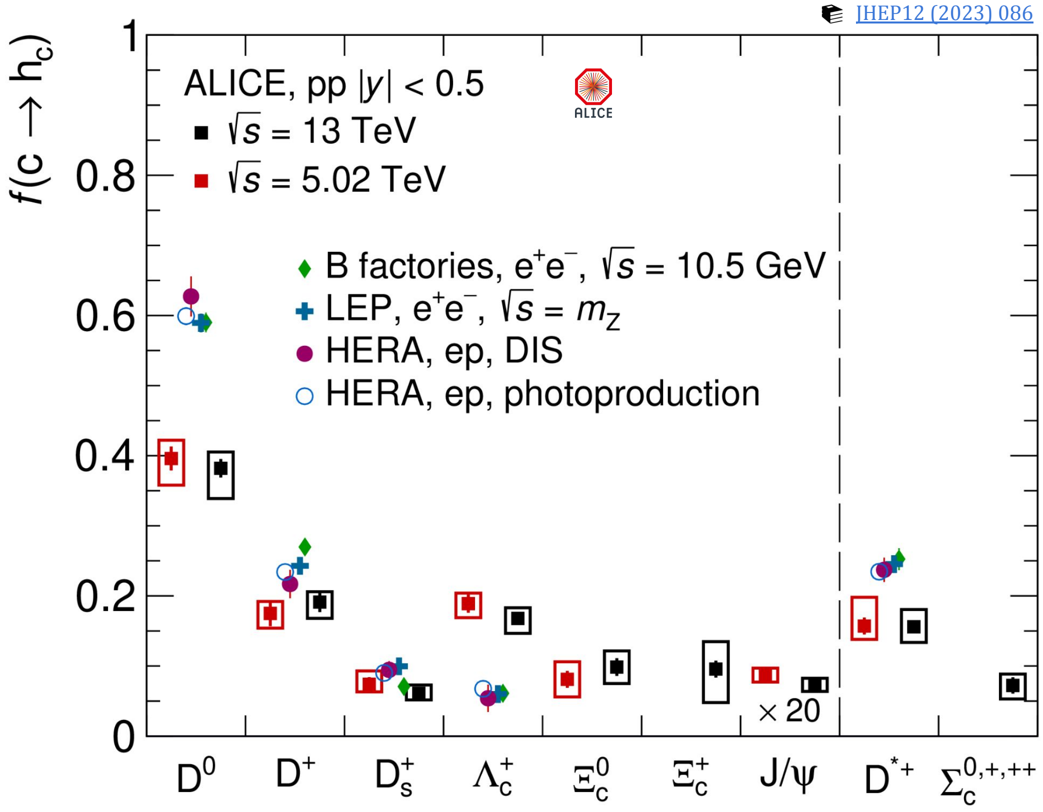
ALI-PUB-521755

- $\Xi_c^{0,+}/D^0$ underestimated by all the models
- $D_s^+/(D^0+D^+)$ in line with $e^+e^-$ results
  → are baryons “strange”?
- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ described by PYTHIA 8 Monash

Strangeness enhancement missing in CR-BLC
→ can it play any role?

Similar suppression in $e^+e^-$ due to similar diquark masses?
→ $m(uu, ud, dd)_1 \approx m(us)_0$

# Charm-quark fragmentation fractions $f(c\rightarrow h_c)$ in pp collisions



JHEP12 (2023) 086

ALI-PUB-567906

$$f(c \rightarrow h_c) = \frac{\sigma(h_c)|_{|y|<0.5}}{\boxed{\sum_i \sigma(h_c^i)|_{|y|<0.5}}}$$

Sum of prompt $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, $\Xi_c^{0,+}$, $J/\psi$ production cross sections

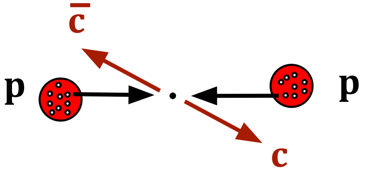
- $f(c \rightarrow \Lambda_c^+)$ larger than $e^+e^-$, $e^-p$ by ×~3
- $f(c \rightarrow D^0)$ lower than $e^+e^-$, $e^-p$ by ×~1.5
- No significant energy dependence in pp collisions

***Baryon enhancement at the LHC***

- Evidence of different fragmentation fractions at the LHC compared to $e^+e^-$ (ep) collisions at lower $\sqrt{s}$
- Independent fragmentation picture not valid in color-rich systems

# $c\bar{c}$ production at mid-*y* in pp collisions

- $p_T$-integrated charm-anticharm production cross section at mid-*y* in pp collisions at $\sqrt{s}$ = 5.02 TeV, 13 TeV measured as the sum of prompt $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, $\Xi_c^{0,+}$, J/ψ cross sections



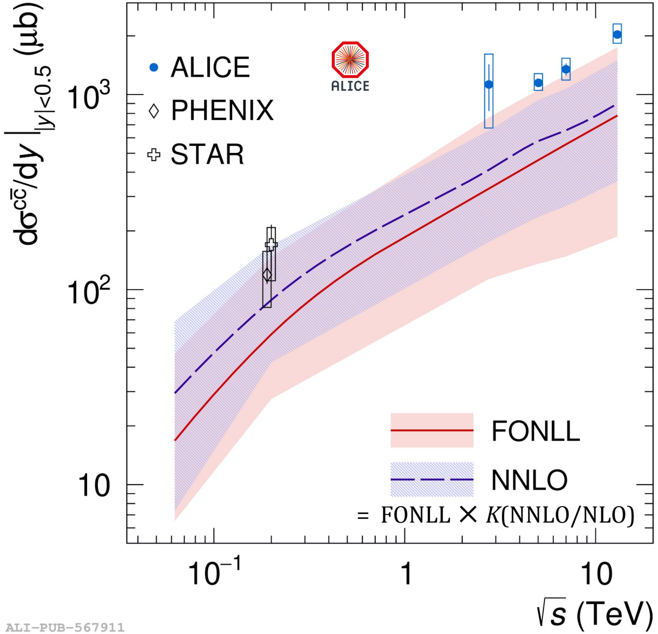
***pp collisions at √s = 5.02 TeV***

$$\left.\frac{d\sigma}{dy}\right|_{|y|<0.5}^{pp,\sqrt{s}=5.02\,\text{TeV}} = 1148 \pm 43\ (\text{stat.})^{+62}_{-65}\ (\text{syst.})^{+98}_{-36}\ (\text{extrap.}) \pm 43\ (\text{BR}) \pm 24\ (\text{lumi.}) \pm 41\ (\text{y})\ \mu\text{b}\,.$$

***pp collisions at √s = 13 TeV***

$$\left.\frac{d\sigma}{dy}\right|_{|y|<0.5}^{pp,\sqrt{s}=13\,\text{TeV}} = 2031 \pm 61\ (\text{stat.})^{+135}_{-141}\ (\text{syst.})^{+196}_{-63}\ (\text{extrap.}) \pm 97\ (\text{BR}) \pm 33\ (\text{lumi.}) \pm 73\ (\text{y})\ \mu\text{b}\,.$$

JHEP12 (2023) 086



ALI-PUB-567911

- Measurement on the upper edge of pQCD calculations
- Possible constraints to theoretical uncertainties

# Summary

JHEP12 (2023) 086

*"Charm production and fragmentation fractions at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV"*

## *Contents*

1. Most precise and granular measurements of $p_T$-differential production cross section of prompt $D^0$, $D^+$, $D^{*+}$, $D_s^+$ mesons at mid-$y$ in pp at $\sqrt{s}$ = 13 TeV
2. Extended measurements down to lower $p_T$ values of prompt $\Lambda_c^+$- and $\Xi_c^+$-baryon production cross sections at mid-$y$ in pp at $\sqrt{s}$ = 13 TeV
3. Measurement of the $c\bar{c}$ production cross section and charm-quark fragmentation fractions at mid-$y$ in pp at $\sqrt{s}$ = 13 TeV
   a. based on the sum of $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, $\Xi_c^{0,+}$, $J/\psi$ cross sections
   b. first measurement of $\Xi_c^+$ and $\Sigma_c^{0,+,++}$ fragmentation fractions at mid-$y$ in pp collisions

## *Results*

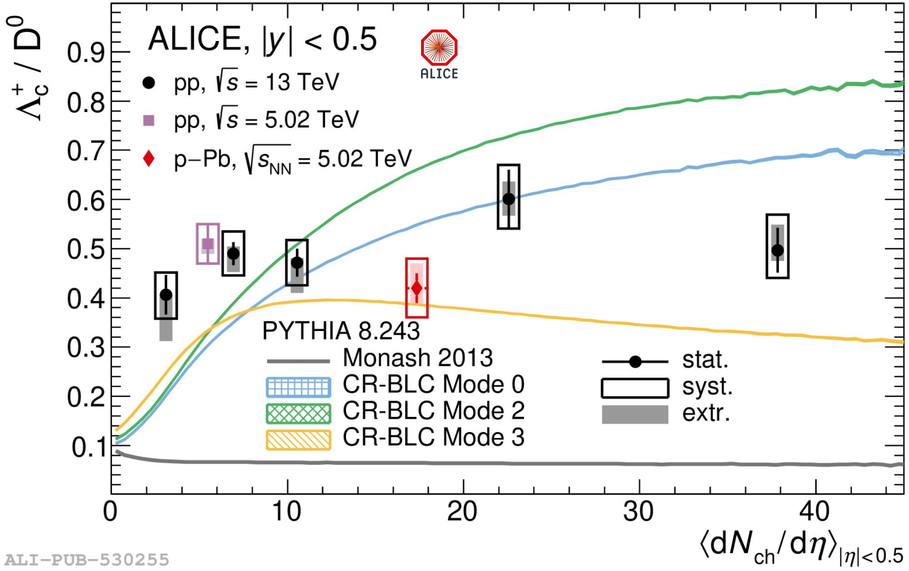
1. pQCD calculations based on factorization successfully describe the $p_T$-differential D-meson production
2. ALICE measurements precise enough to put constraints on theoretical uncertainties (e.g. gluon PDFs at $x \lesssim 10^{-5}$)
3. Baryon enhancement
   - independent fragmentation violated
   - no model providing a satisfactory picture of all the measurements

     → limited predictive power

# Open points - baryon-to-meson ratio vs. rapidity (1/2)

**Charm** baryon-to-meson ratio

PLB 839 (2023) 137796



ALI−PUB−530255

Nuclear Physics, Section B 871 (2013), pp. 1-20

LHCb, pp, √s = 7 TeV, multiplicity-integrated

$2.0 < y < 4.5$

**0.140 ± 0.05**

- No significant dependence vs. multiplicity of the $p_T$-integrated $\Lambda_c^+/D^0$ ratio at mid-$y$ across collision systems
- Model calculations do not catch either the magnitude or the multiplicity evolution
- $p_T$-integrated $\Lambda_c^+/D^0$ ratio at forward-$y$ significantly lower than that at mid–$y$

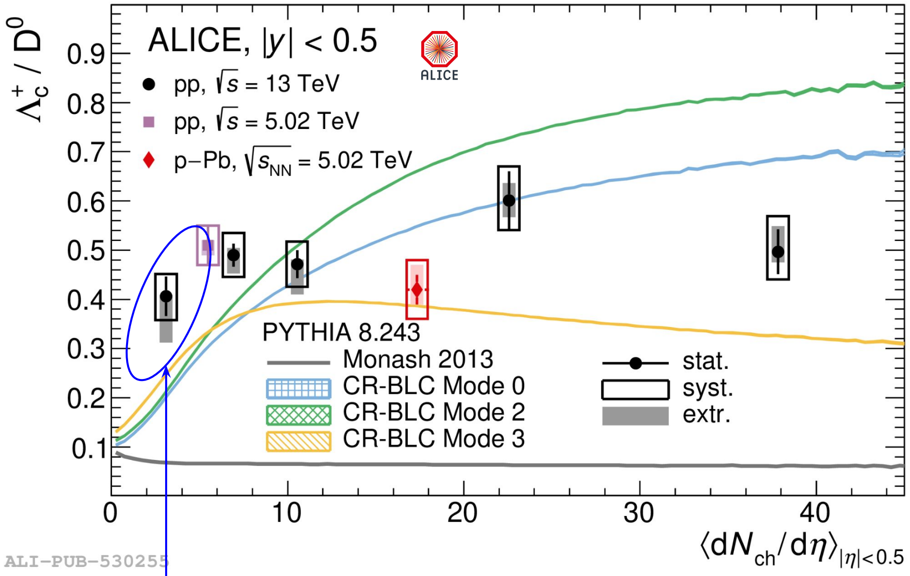
# Open points - baryon-to-meson ratio vs. multiplicity (2/2)

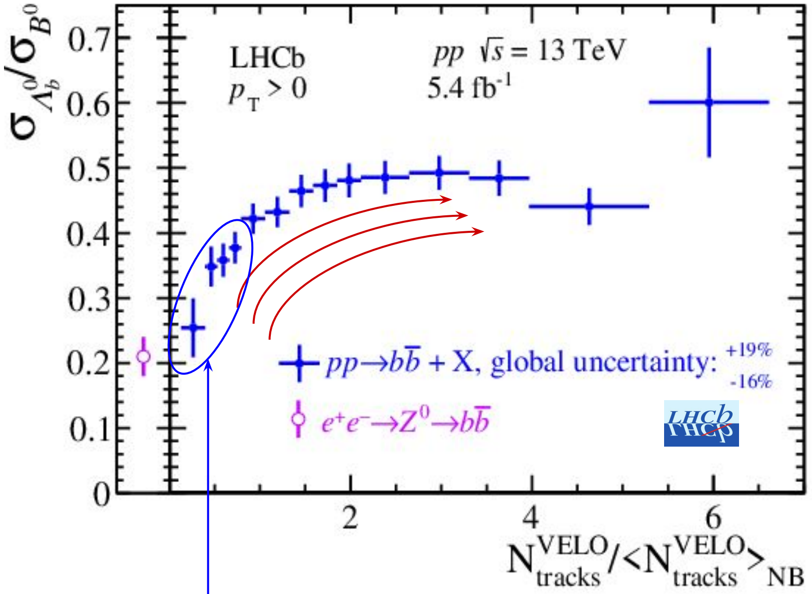
**Charm** baryon-to-meson ratio

PLB 839 (2023) 137796

**Beauty** baryon-to-meson ratio

arXiv:2310.12278

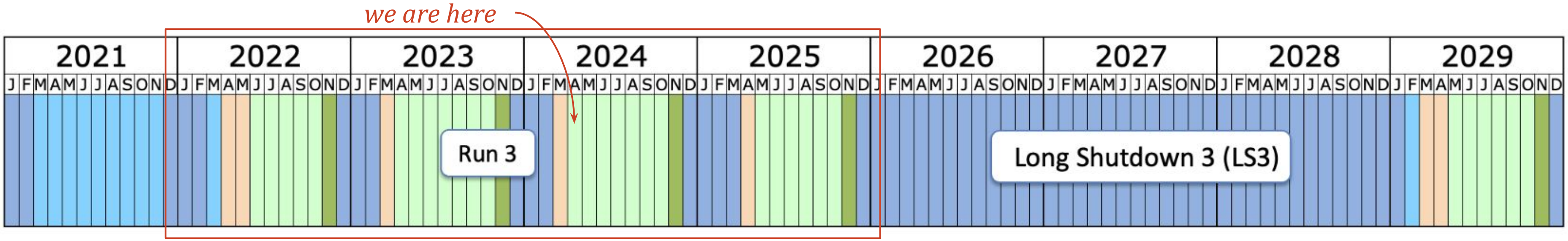


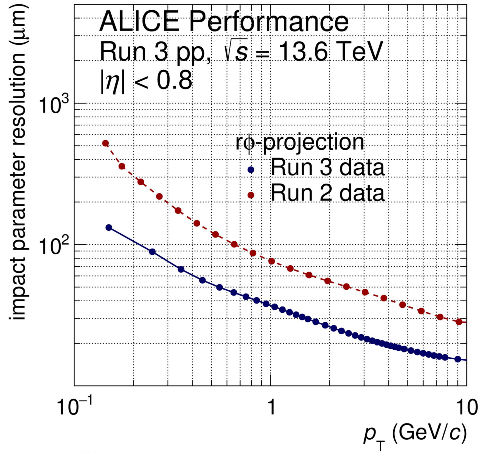


- No significant dependence vs. multiplicity of the $p_T$-integrated $\Lambda_c^+/D^0$ ratio at mid-$y$ across collision systems
- Model calculations do not catch either the magnitude or the multiplicity evolution
- $p_T$-integrated $\Lambda_c^+/D^0$ ratio at forward-$y$ significantly lower than that at mid–$y$
- $p_T$-integrated $\Lambda_b^0/B^0$ ratio at forward-$y$ significantly increasing with multiplicity

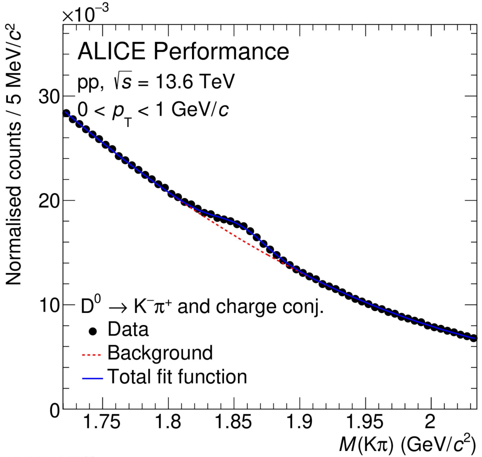
ALICE results not enough differential at low multiplicity

# Outlook - the Run 3 era

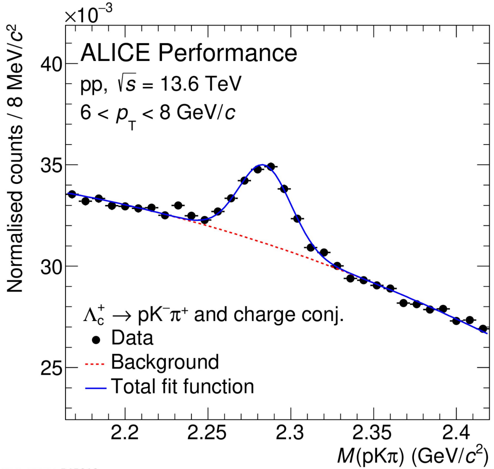




ALI-PERF-558822

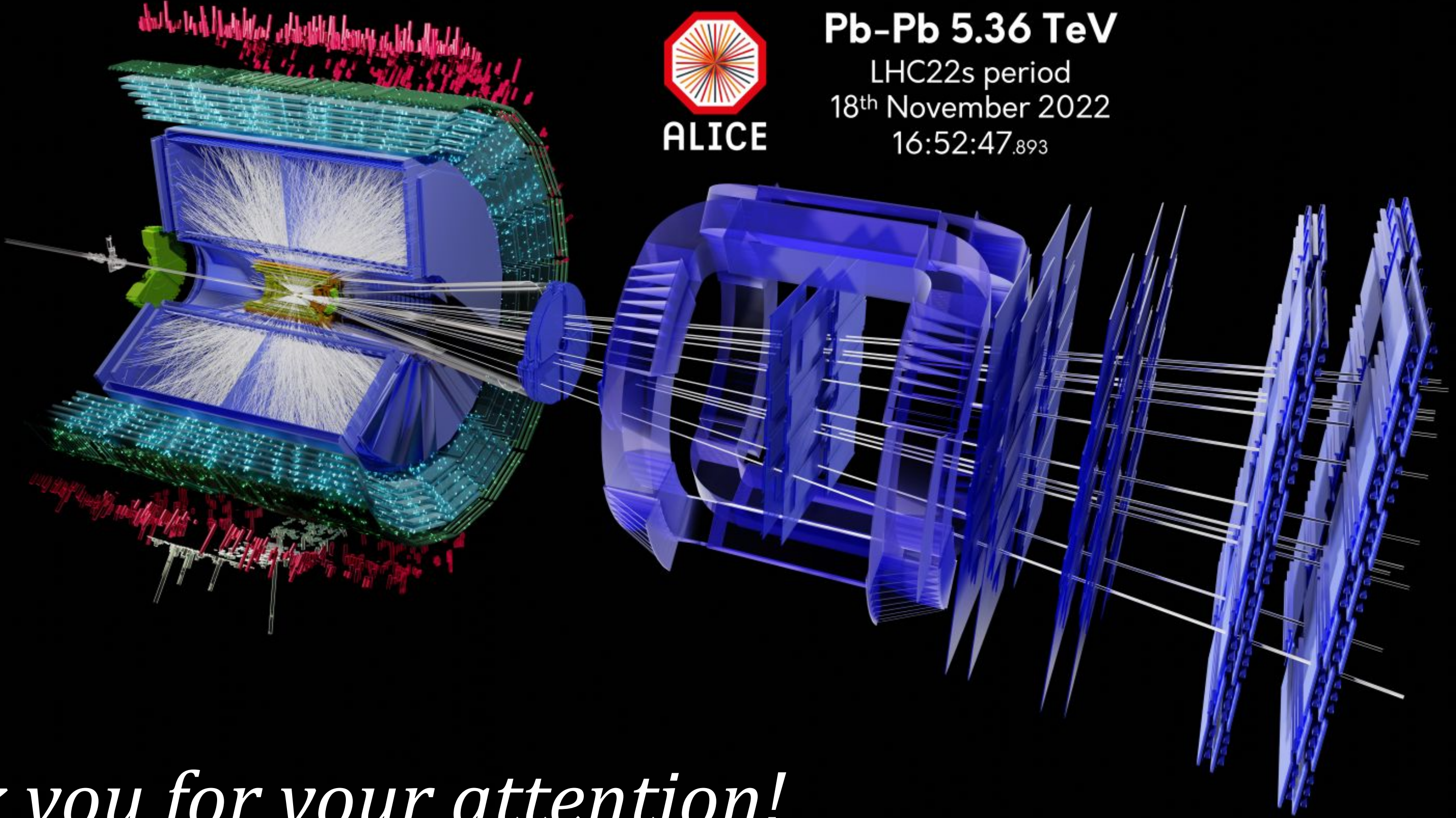


ALI-PERF-545799



ALI-PERF-545812

- Continuous readout → larger statistics than in Run 2 (~30 times more MB from 2022, ~500 times more for specific triggers)
- Improved pointing resolution due to the upgraded Inner Tracking System (ITS)
    - Better signal-to-background separation for heavy-flavour hadron signals



ALICE

**Pb-Pb 5.36 TeV**

LHC22s period

18th November 2022

16:52:47.893

# *Thank you for your attention!*

# Backup

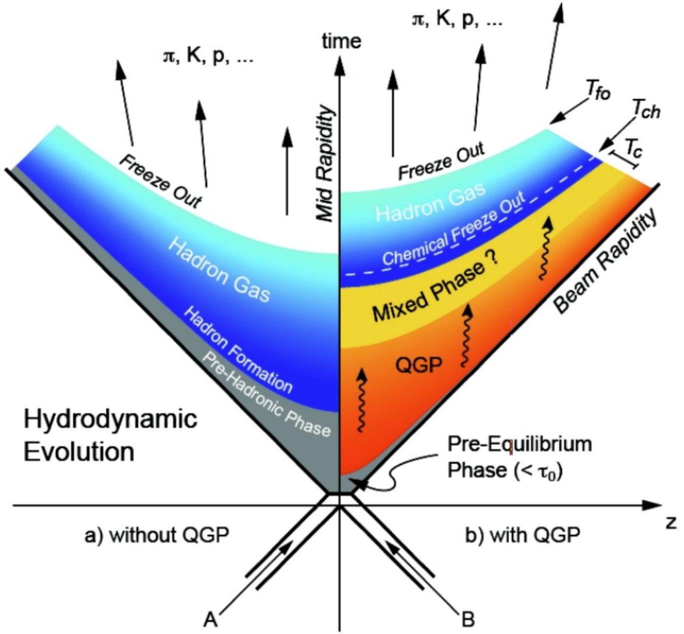
# Heavy quarks: a unique probe for high-density QCD

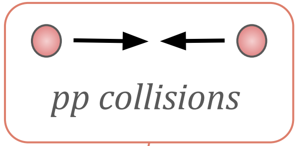
- Charm and beauty quarks: $m_c \sim 1.3\ \mathrm{GeV}/c^2$, $m_b \sim 4.2\ \mathrm{GeV}/c^2$
- Produced in hard scattering processes among partons

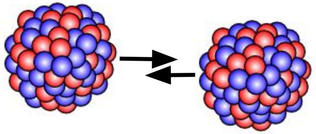
- Ultrarelativistic heavy-ion collisions at the LHC: quark-gluon plasma (QGP)
    - state of matter expected in the first ~ 10 μs after the Big Bang
    - heavy quarks experience the full evolution of the system

**Charm-** and **beauty- quarks dynamic** tested via **measurements** of **charm-** and **beauty- hadron production**

- Reference for Pb–Pb collisions
- **Test of pQCD calculations**
    - heavy-quark production
    - hadronization
    - parton distribution functions (PDFs)



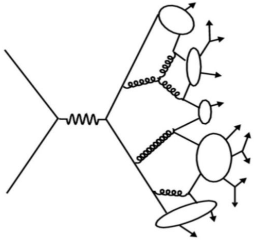

*pp collisions*


*Pb–Pb collisions*

# Hadronization

- **Hadronization**: the mechanism by which quarks and gluons produced in hard partonic scattering processes form the hadrons

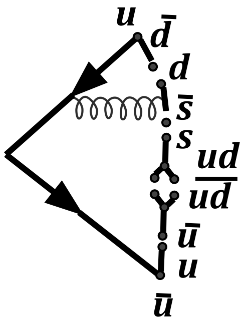
- **No first-principle description of hadron formation**
  - Non-perturbative problem, not calculable with QCD
  - Necessary to resort to models and make use of phenomenological parameters



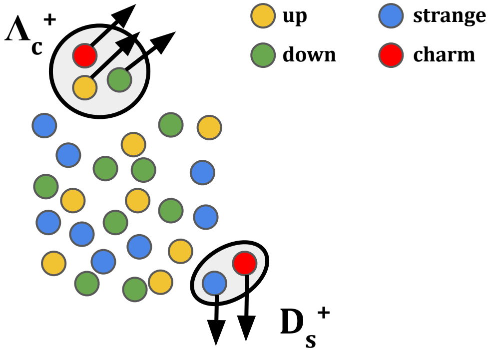
- **Different mechanisms depending on the system size**
  - $e^+e^-$, pp collisions: fragmentation
  - heavy-ion collision (e.g. Au–Au, Pb–Pb): coalescence in the quark-gluon plasma (QGP)

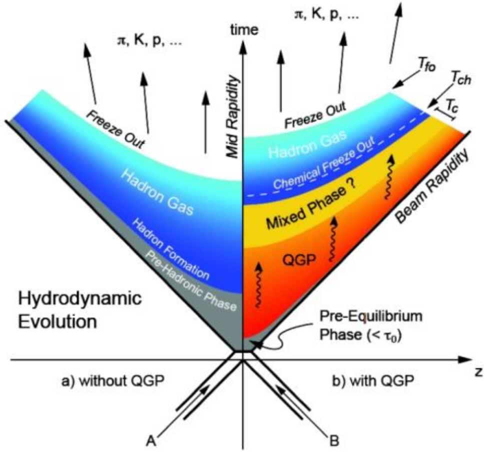
*Focus of the talk*

**Fragmentation**



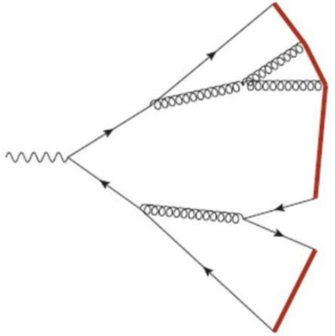
**Coalescence**





# Hadronization: string models

**Event generators**: final stage of parton shower interfaced with non-perturbative hadronization models



## String fragmentation
(e.g. Lund model in PYTHIA)

Phys. Rept. 97 (1983) 31–145
Eur. Phys. J. C 78 no. 11

- Strings: colour-flux tubes between q and qbar endpoints
- Gluons: kinks along the string
- Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs

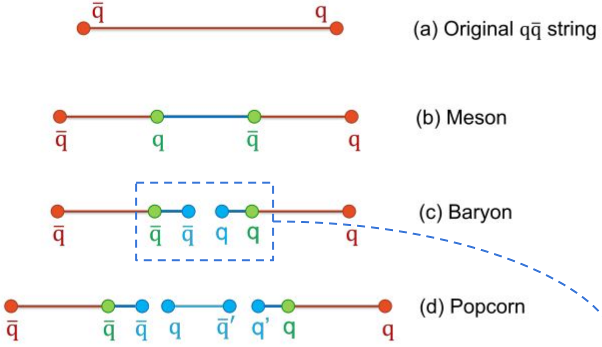
**$\kappa$: string tension**

$$P(\text{string breaking}) \propto \exp\left(-\frac{\pi m_{\mathrm{T,q}}^2}{\enclose{circle}{\kappa}}\right) = \exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa}\right)\exp\left(-\frac{\pi p_{\mathrm{T,q}}^2}{\kappa}\right)$$

**Tunneling probability**

$$\mathrm{u:d:s:}\boxed{\mathrm{c}} \simeq 1:1:1/3:\boxed{10^{-11}} \rightarrow$$

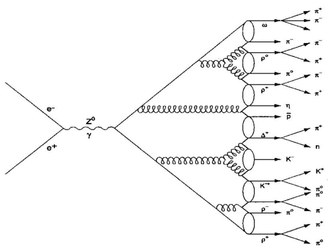
charm mostly produced in the hard scattering



**"Baryonization": diquark splitting**

## Cluster decay
(HERWIG)

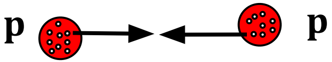
Eur. Phys. J. C 76 no. 4, (2016) 196



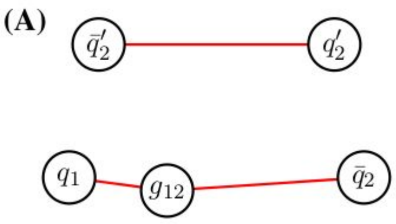
- Parton shower evolved up to a softer scale
- All gluons force to split in qqbar pairs
- Colour-singlet clusters of partons identified following the colour flow
- Cluster decays into hadrons according to the available phase space

# Default hadronization in PYTHIA event generator

JHEP 08 (2015) 003



- Initial state not insensitive to strong force (coloured partons, beam remnants)
- MPI → crucial to explain underlying event



**No CR**
Partons from different MPIs do not interact

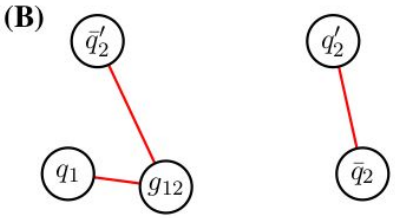
$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$$

uncorrelated quarks

Subleading topologies

Baryon! (singlet)
Probability = 1/27

**Leading Color** topology: incoherent addition of the 3 quarks → 3 color strings connected to the beam remnant



**CR within Leading Color**

- CR allowed among partons from different MPIs to minimize string length
- Implemented in PYTHIA 8 Monash

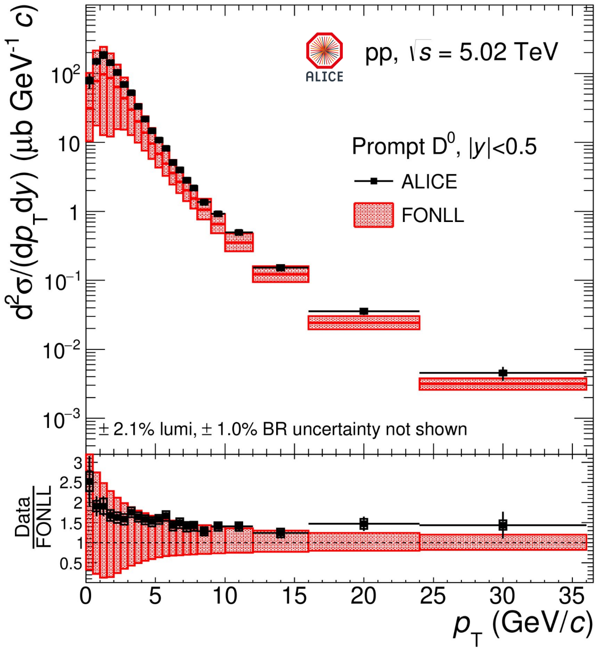
**PYTHIA**

# The success of factorization and independent fragmentation (1/2)

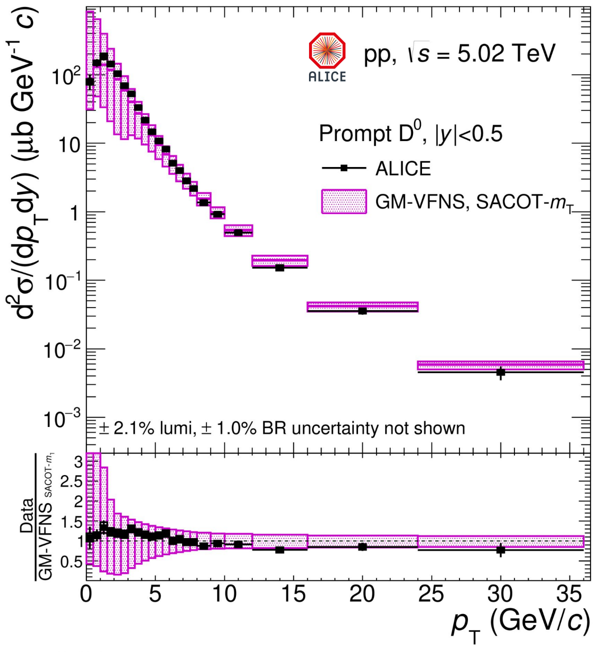
Eur.Phys.J. C79 (2019) no.5, 388

- Factorization in terms of squared momentum transfer $Q^2$: collinear factorization
- At LHC energies, calculations available in:
  - general-mass variable-flavour-number scheme (GM-VFNS) approach
  - fixed order plus next-to-leading logarithms (FONLL) approach

both having NLO accuracy with all-order resummation of next-to-leading logarithms



ALI-PUB-314115



ALI-PUB-314123

**Measurements described by model predictions**

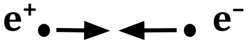
→ Theoretical uncertainties: (i.) scale; (ii.) c-, b-quark mass; (iii.) PDFs

→ **main** source of **theoretical uncertainty**: **scale** for **perturbative calculations**

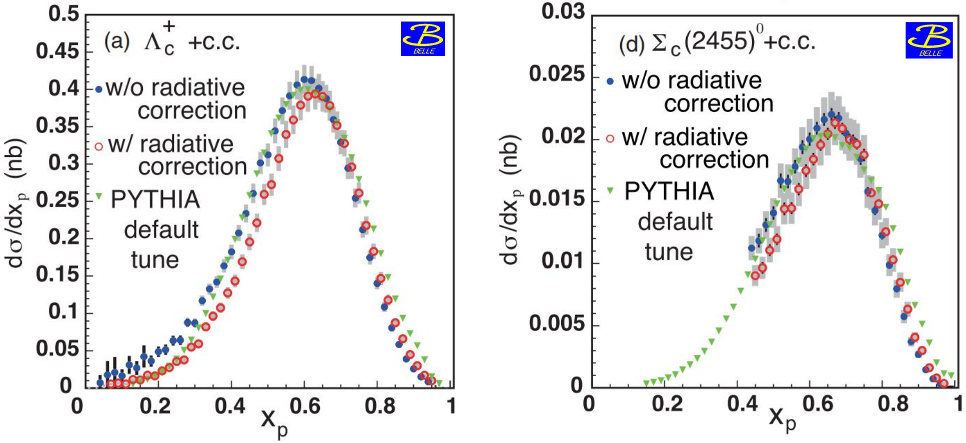
*“At lower $p_T$ values, where we can only rely on the fixed-order NLO QCD calculation, the scale dependence reaches values in the range of ~100 % in the case of the charm quark, and of ~50 % for the bottom quark.”*

Cacciari, Mangano, Nason: Eur. Phys. J. C (2015) 75:610

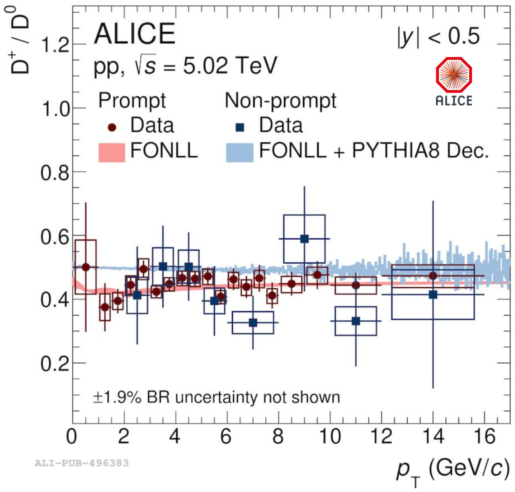
# The success of factorization and independent fragmentation (2/2)



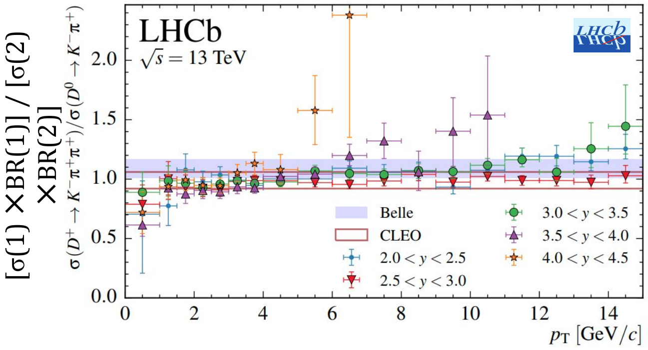
PRD 97, 072005 (2018)



JHEP 05 (2021) 220



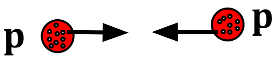
JHEP 03 (2016) 159

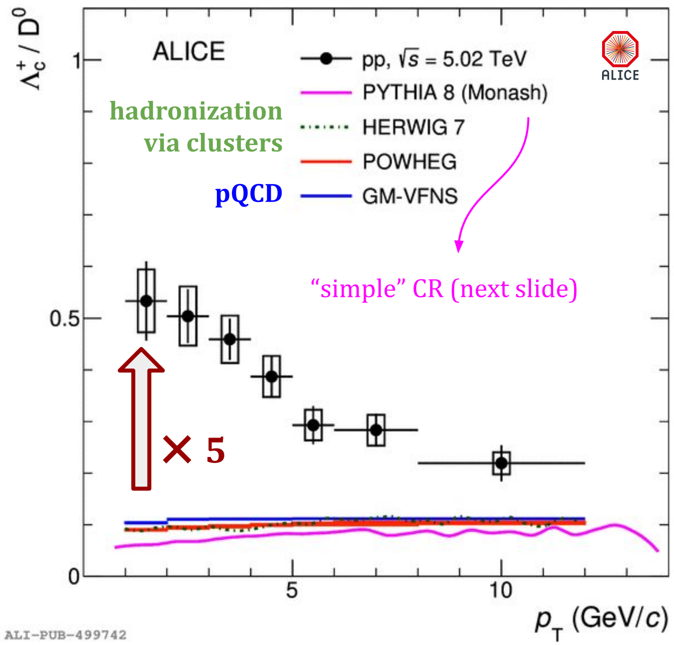


- Charm-hadron production in $e^+e^-$ collisions described by PYTHIA
- Heavy-flavour meson-to-meson ratios in pp collisions:
    - no significant $p_T$-dependence
    - described by models based on factorization and with fragmentation functions constrained from $e^+e^-$ collisions
    - compatible with results in $e^+e^-$ collisions

# Bugs in our ears - baryon enhancement in pp collisions

PRC 104 (2021) 054905    PRL 127 (2021) 202301    JHEP 08 (2015) 003



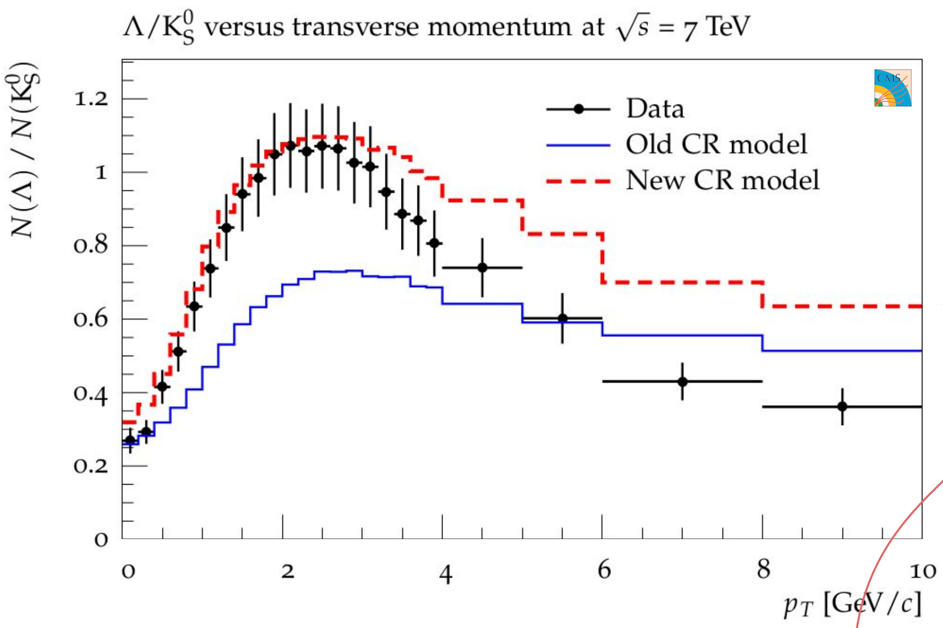


**hadronization via clusters**

**pQCD**

“simple” CR (next slide)

**× 5**

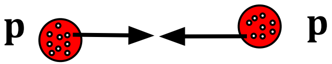


- Significant baryon-to-meson ratio enhancement in pp compared to $e^+e^-$ collisions
- *PYTHIA* predictions and pQCD-based calculations based of factorization and fragmentation functions tuned on $e^+e^-$ underestimate the results in pp collisions

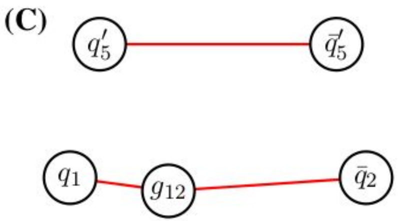
! **“New” colour reconnection (CR)** *model better describes the data*

# “Baryonization” in pp collisions - CR beyond leading color

JHEP 08 (2015) 003



**No CR**

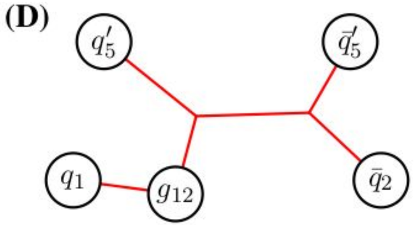


**CR beyond Leading Color approximation (CR-BLC)**

- “Simplified QCD” with 9 color indices to determine the string formation
- String length minimization over all possible configurations, even those beyond the Leading Color topology
→ PYTHIA 8 Monash: only CR among LC
- Enhanced leading color among MPIs and beam remnants

**PYTHIA**

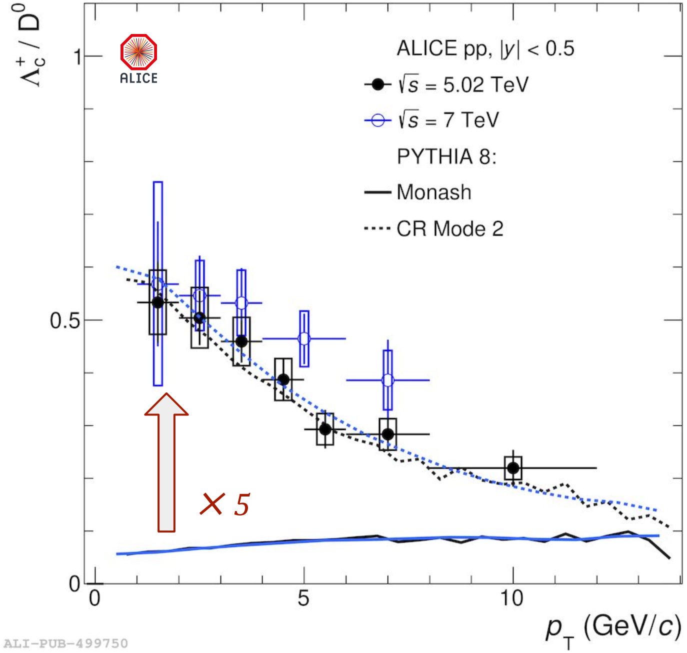
**CR-BLC**: junctions



- Conditions for color reconnections:
  - Invariant mass of string j-th must be above a threshold $m_0$
$C = m_{0j}/m_0 > 1$ : enhanced reconnections
  - Causality: two strings must resolve each other between formation and hadronization, considering the time dilation due to the relative boost
→Mode 0, 2, 3: different “severity” on this condition

# Baryon-to-meson ratio for charm and beauty

Phys. Rev. C 104 (2021) 054905



Phys. Rev. D 100, 031102

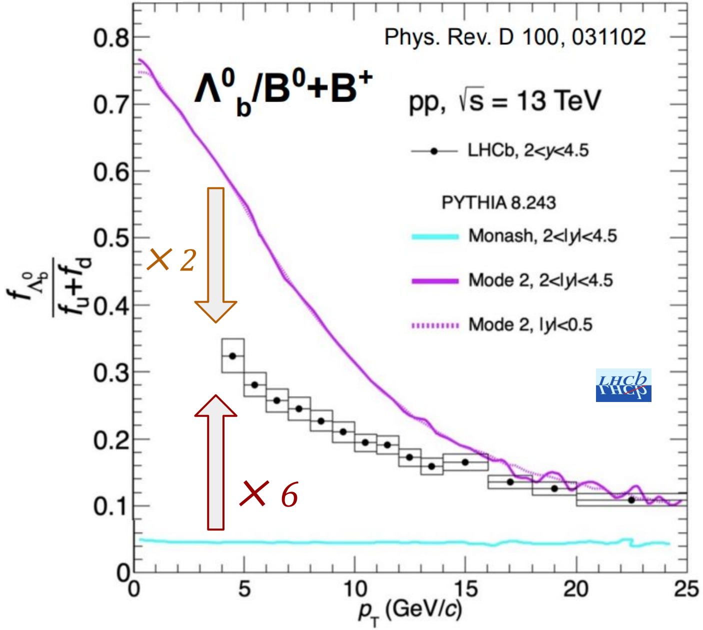


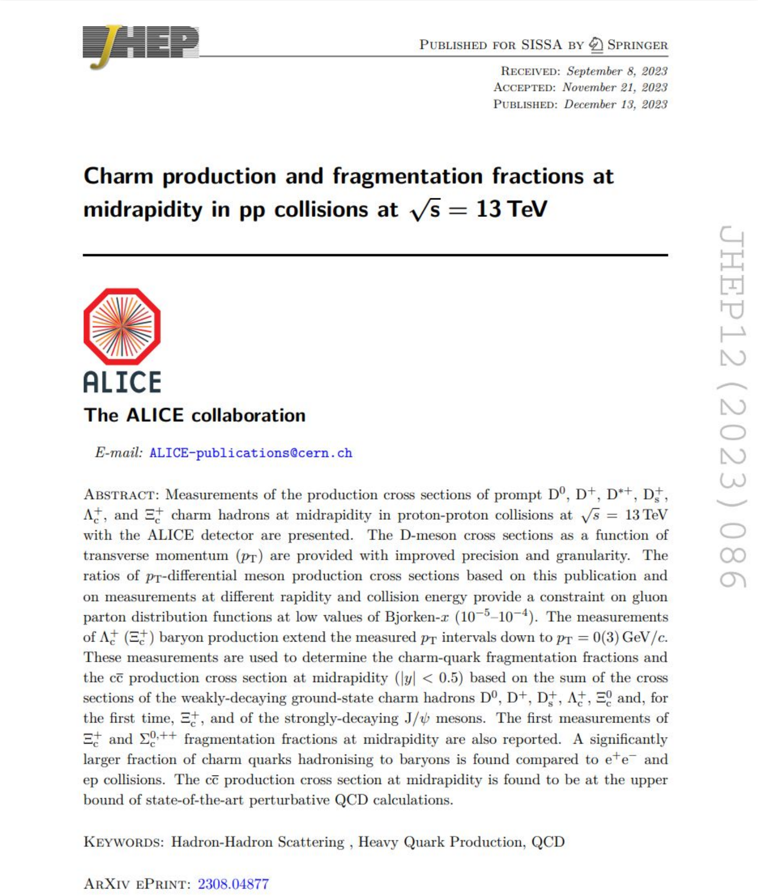
Figure from "*Hadronization mechanism (via heavy-flavor hadrons): Experiment*"
A. Rossi, Hard Probes 2023 (link)

- PYTHIA 8 Monash predictions underestimate the measured $\Lambda_c^+/D^0$ at midrapidity up to ~5x
- CR Mode 2 agrees with $\Lambda_c^+/D^0$ at $|y| < 0.5$

- Beauty baryon-to-meson ratio at forward rapidity not well described

# Charm production at mid-*y* in pp collisions at $\sqrt{s}$ = 13 TeV (1/2)

JHEP12 (2023) 086



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Received: *September 8, 2023*
Accepted: *November 21, 2023*
Published: *December 13, 2023*

**Charm production and fragmentation fractions at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV**

**The ALICE collaboration**

*E-mail:* ALICE-publications@cern.ch

Abstract: Measurements of the production cross sections of prompt $\mathrm{D}^0$, $\mathrm{D}^+$, $\mathrm{D}^{*+}$, $\mathrm{D}_s^+$, $\Lambda_c^+$, and $\Xi_c^+$ charm hadrons at midrapidity in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ALICE detector are presented. The D-meson cross sections as a function of transverse momentum ($p_\mathrm{T}$) are provided with improved precision and granularity. The ratios of $p_\mathrm{T}$-differential meson production cross sections based on this publication and on measurements at different rapidity and collision energy provide a constraint on gluon parton distribution functions at low values of Bjorken-$x$ ($10^{-5}$–$10^{-4}$). The measurements of $\Lambda_c^+$ ($\Xi_c^+$) baryon production extend the measured $p_\mathrm{T}$ intervals down to $p_\mathrm{T} = 0(3)\,\mathrm{GeV}/c$. These measurements are used to determine the charm-quark fragmentation fractions and the $\mathrm{c\bar{c}}$ production cross section at midrapidity ($|y| < 0.5$) based on the sum of the cross sections of the weakly-decaying ground-state charm hadrons $\mathrm{D}^0$, $\mathrm{D}^+$, $\mathrm{D}_s^+$, $\Lambda_c^+$, $\Xi_c^0$ and, for the first time, $\Xi_c^+$, and of the strongly-decaying $\mathrm{J}/\psi$ mesons. The first measurements of $\Xi_c^+$ and $\Sigma_c^{0,++}$ fragmentation fractions at midrapidity are also reported. A significantly larger fraction of charm quarks hadronising to baryons is found compared to $\mathrm{e^+e^-}$ and ep collisions. The $\mathrm{c\bar{c}}$ production cross section at midrapidity is found to be at the upper bound of state-of-the-art perturbative QCD calculations.

Keywords: Hadron-Hadron Scattering , Heavy Quark Production, QCD

ArXiv ePrint: 2308.04877

JHEP12(2023)086

## *Contents*

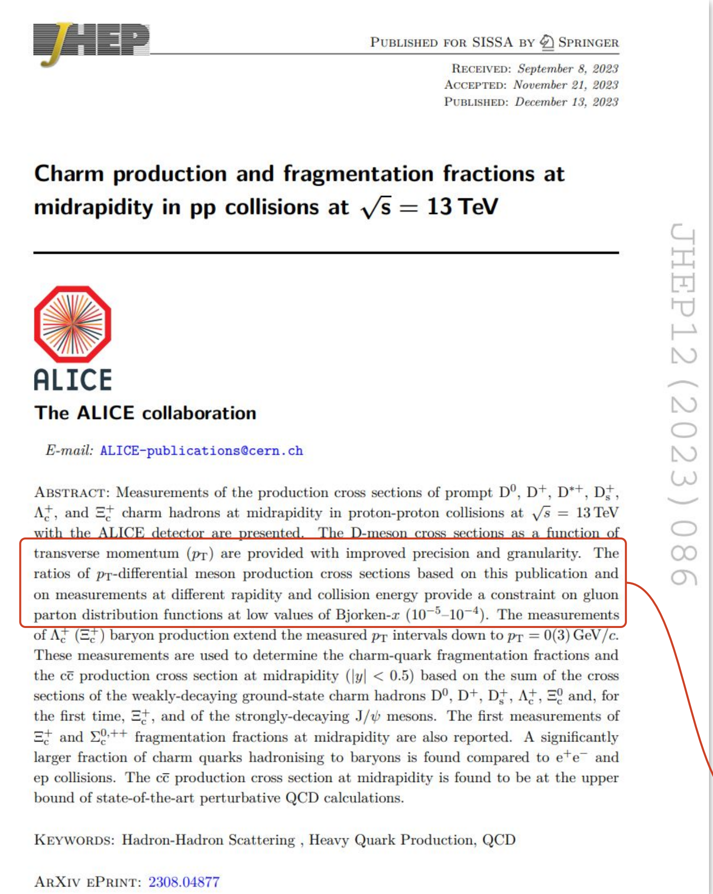
1. Most precise and granular measurements of $p_T$-differential cross section of prompt $D^0$, $D^+$, $D^{*+}$, $D_s^+$ mesons at mid-*y* in pp at $\sqrt{s}$ = 13 TeV
2. Extended measurements down to lower $p_T$ values of prompt $\Lambda_c^+$- and $\Xi_c^+$-baryon cross sections at mid-*y* in pp at $\sqrt{s}$ = 13 TeV
3. Measurement of the ccbar cross section and charm-quark fragmentation fractions at mid-*y* in pp at $\sqrt{s}$ = 13 TeV
   a. based on the sum of $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, $\Xi_c^{0,+}$, $J/\psi$ cross sections
   b. first measurement of $\Xi_c^+$ and $\Sigma_c^{0,+,++}$ fragmentation fractions at mid-*y* in pp collisions

## *Goals*

1. Overview of charm-hadron production measurements with ALICE at mid-*y* in pp collisions
2. Provide new inputs to:
   a. test the validity of the fragmentation approach and independent fragmentation
   b. constrain gluon PDF at low Bjorken-*x*
   c. study further the baryon enhancement at the LHC

# Charm production at mid-$y$ in pp collisions at $\sqrt{s}$ = 13 TeV (2/2)

JHEP12 (2023) 086



JHEP

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RECEIVED: *September 8, 2023*
ACCEPTED: *November 21, 2023*
PUBLISHED: *December 13, 2023*

## Charm production and fragmentation fractions at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV

ALICE
**The ALICE collaboration**

*E-mail:* ALICE-publications@cern.ch

ABSTRACT: Measurements of the production cross sections of prompt $D^0$, $D^+$, $D^{*+}$, $D_s^+$, $\Lambda_c^+$, and $\Xi_c^+$ charm hadrons at midrapidity in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ALICE detector are presented. The D-meson cross sections as a function of transverse momentum ($p_T$) are provided with improved precision and granularity. The ratios of $p_T$-differential meson production cross sections based on this publication and on measurements at different rapidity and collision energy provide a constraint on gluon parton distribution functions at low values of Bjorken-$x$ ($10^{-5}$–$10^{-4}$). The measurements of $\Lambda_c^+$ ($\Xi_c^+$) baryon production extend the measured $p_T$ intervals down to $p_T = 0(3)$ GeV/$c$. These measurements are used to determine the charm-quark fragmentation fractions and the $c\bar{c}$ production cross section at midrapidity ($|y| < 0.5$) based on the sum of the cross sections of the weakly-decaying ground-state charm hadrons $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, $\Xi_c^0$ and, for the first time, $\Xi_c^+$, and of the strongly-decaying J/$\psi$ mesons. The first measurements of $\Xi_c^+$ and $\Sigma_c^{0,++}$ fragmentation fractions at midrapidity are also reported. A significantly larger fraction of charm quarks hadronising to baryons is found compared to $e^+e^-$ and ep collisions. The $c\bar{c}$ production cross section at midrapidity is found to be at the upper bound of state-of-the-art perturbative QCD calculations.

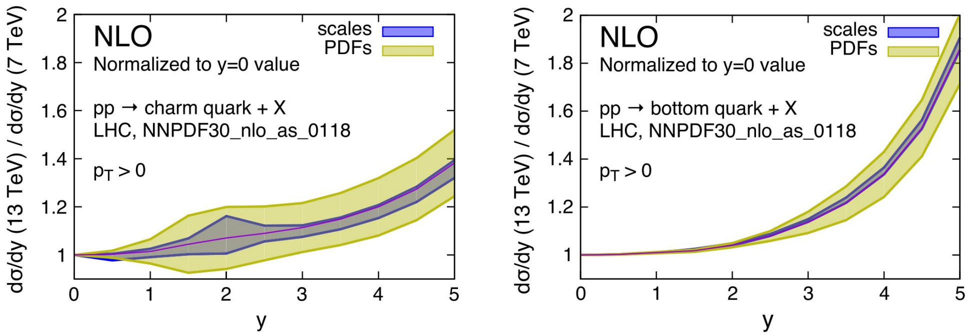
KEYWORDS: Hadron-Hadron Scattering , Heavy Quark Production, QCD

ARXIV EPRINT: 2308.04877

JHEP12(2023)086

1. Most precise and granular measurements of $p_T$-differential cross section of prompt $D^0$, $D^+$, $D^{*+}$, $D_s^+$ mesons at mid-$y$ in pp at $\sqrt{s}$ = 13 TeV

Cacciari, Mangano, Nason: Eur. Phys. J. C (2015) 75:610

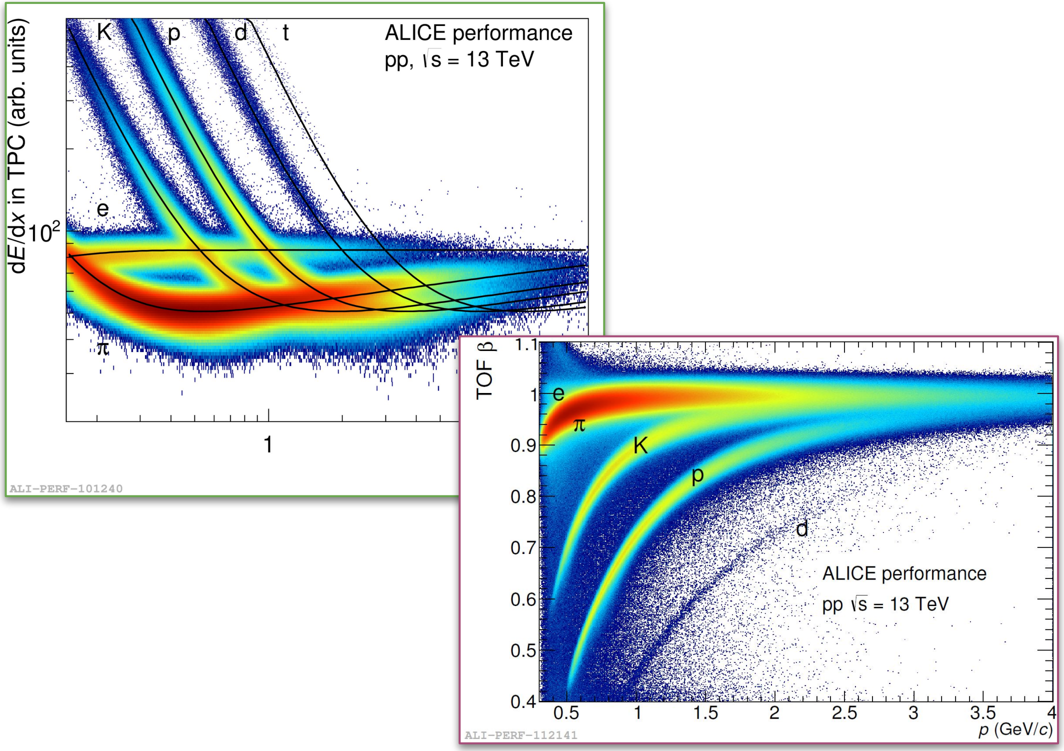


- *Double-ratio in rapidity and energy*: scale and mass uncertainties reduced → *PDF uncertainties dominant*
- Low ($\lesssim 10^{-5}$) and high ($\gtrsim 10^{-2}$) Bjorken-$x$ regime accessible with measurements at low $p_T$ and $p_T \gtrsim 30$ GeV/$c$, respectively

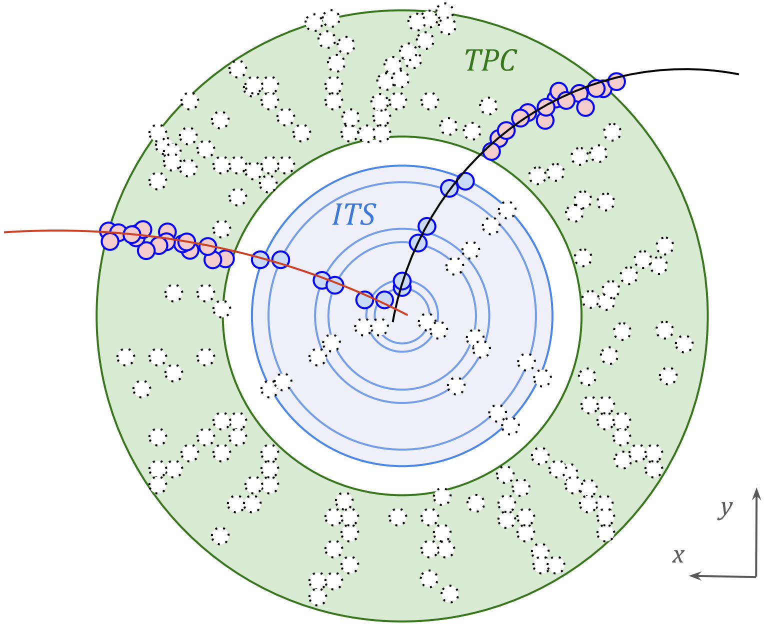
The ratios of $p_T$-differential meson production cross sections based on this publication and on measurements at different rapidity and collision energy provide a constraint on gluon parton distribution functions at low values of Bjorken-$x$ ($10^{-5}$–$10^{-4}$).

# Charm-hadron reconstruction (1/3)

1. ***Track selections***
    - ITS-TPC matched tracks →isolation of *primaries* (ALICE-PUBLIC-2017-005)
    - particle identification (PID) in **TPC (d*E*/dx)** and **TOF (time-of-flight)**



$D^0 \rightarrow K^- \pi^+$

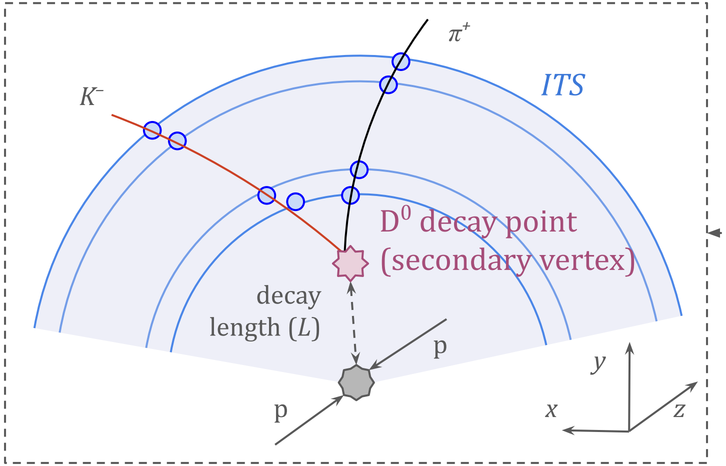


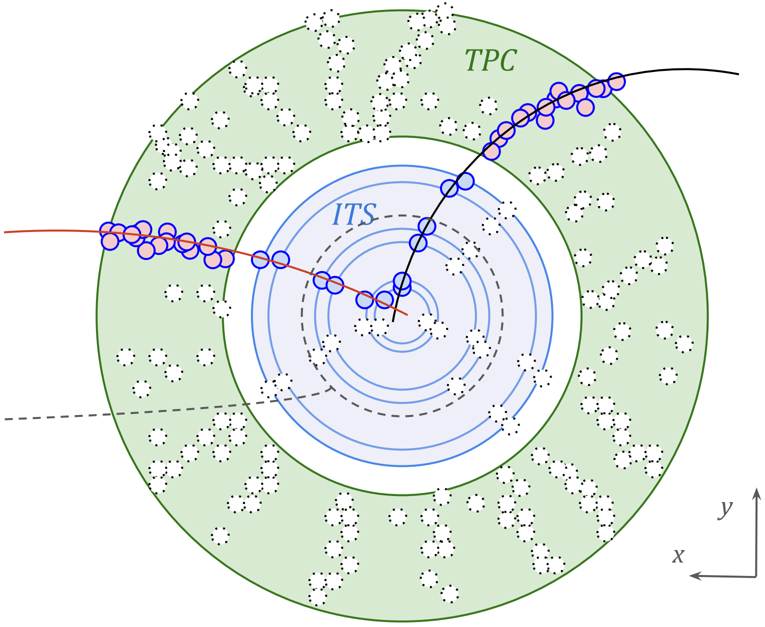
# Charm-hadron reconstruction (2/3)

1. ***Track selections***
   - ITS-TPC matched tracks →isolation of *primaries* (ALICE-PUBLIC-2017-005)
   - particle identification (PID) in **TPC (d*E*/dx)** and **TOF (time-of-flight)**

2. ***Secondary-vertex reconstruction***
   - $D^0$ decay-point reconstruction
     - → separate from primary vertex (PV)
     - → pointing resolution to PV ~ 75 μm @ $p_{\mathrm{T}} = 1$ GeV/$c$
   - Calculation of topological variables
     - → *intrinsic displacement* ($c\tau(D^0) \sim 123$ μm)

$D^0 \rightarrow K^- \pi^+$





# Charm-hadron reconstruction (3/3)

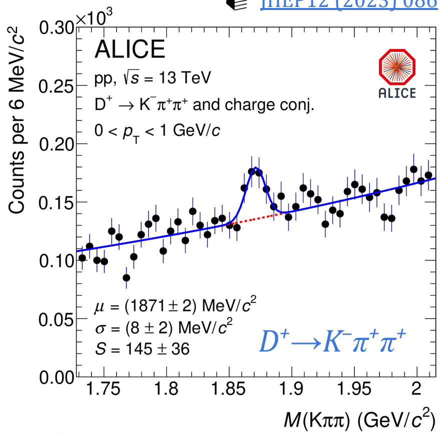
1. ***Track selections***
    - ITS-TPC matched tracks →isolation of *primaries* (ALICE-PUBLIC-2017-005)
    - particle identification (PID) in **TPC (d*E*/dx)** and **TOF (time-of-flight)**

2. ***Secondary-vertex reconstruction***
    - $D^0$ decay-point reconstruction
        - → separate from primary vertex (PV)
        - → pointing resolution to PV ~ 75 μm @ $p_T$ = 1 GeV/$c$
    - Calculation of topological variables
        - → *intrinsic displacement* ($c\tau(D^0)$ ~ 123 μm)

3. ***Topological selections***
    - Separate signal from background candidates exploiting topological variables
        - → BDT exploited in some analyses
    - Measure the reconstructed signal with an invariant-mass analysis

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{H}}}{\mathrm{d}p_{\mathrm{T}}}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta p_{\mathrm{T}}} \times \frac{f_{\mathrm{prompt}} \times \boxed{N^{\mathrm{H}+\overline{\mathrm{H}}}_{|y|<y_{\mathrm{fid.}}}}}{c_{\Delta y}(\mathrm{Acc}\times\varepsilon)_{\mathrm{prompt}}} \times \frac{1}{\mathrm{BR}} \times \frac{1}{\mathcal{L}_{\mathrm{int}}}$$

JHEP12 (2023) 086



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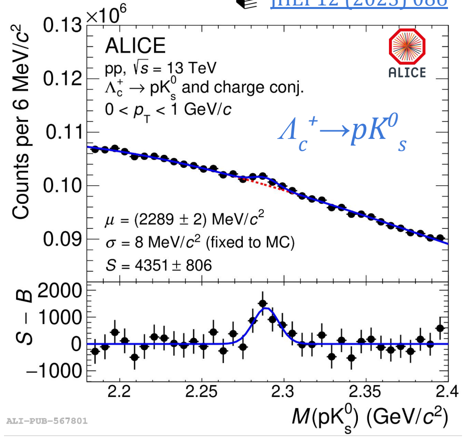
JHEP12 (2023) 086



ALI-PUB-567801

# Charm-hadron cross section measurement

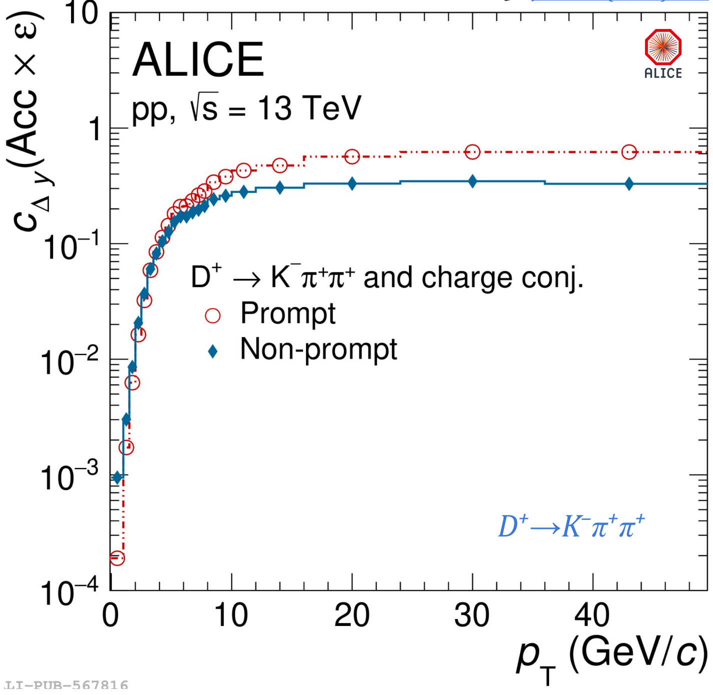
$$\left.\frac{\mathrm{d}\sigma^{\mathrm{H}}}{\mathrm{d}p_{\mathrm{T}}}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta p_{\mathrm{T}}} \times \frac{\overset{\text{③}}{f_{\mathrm{prompt}}} \times \overset{\text{①}}{N^{\mathrm{H}+\overline{\mathrm{H}}}_{|y|<y_{\mathrm{fid.}}}}}{\underset{\text{②}}{\boxed{c_{\Delta y}(\mathrm{Acc}\times\varepsilon)_{\mathrm{prompt}}}}} \times \underset{\text{④}}{\frac{1}{\mathrm{BR}}} \times \underset{\text{⑤}}{\frac{1}{\mathcal{L}_{\mathrm{int}}}}$$

1. ***Reconstructed signal***
   - from invariant-mass analysis (previous slide)
2. ***Acceptance × efficiency for prompt signal***
   - PYTHIA 8 simulations
3. ***Fraction of prompt reconstructed signal***
   - b-quark production from FONLL
   - b-hadron production with fragmentation fractions from LEP for b→B mesons [1] and from LHCb for b→$\Lambda_b^0$ [2]
   - b-hadron decay kinematics with PYTHIA 8
4. ***Branching ratio***
5. ***Integrated luminosity***
   - $\mathcal{L}_{\mathrm{int}} \sim 32\ \mathrm{nb}^{-1}$

②

$$= \frac{N_{\mathrm{reco.}}|_{|y|<y_{\mathrm{fid.}}}(p_{\mathrm{T}}^{\mathrm{reco.}})}{N_{\mathrm{gen.}}|_{|y|<0.5}(p_{\mathrm{T}}^{\mathrm{gen.}})}$$

JHEP12 (2023) 086



[1] Phys. Rev. D 100 (2019) 031102

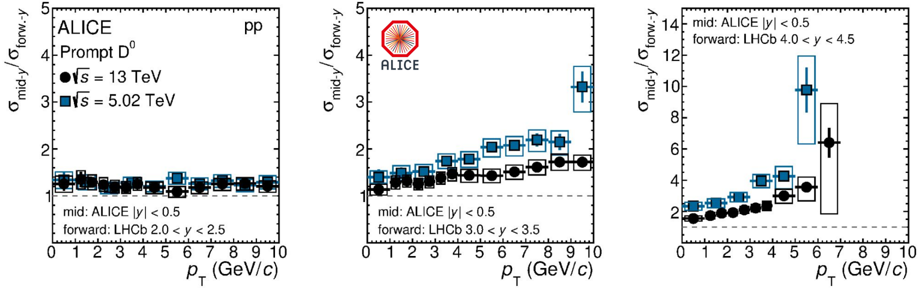
[2] Eur. Phys. J. C 75 (2015) 19

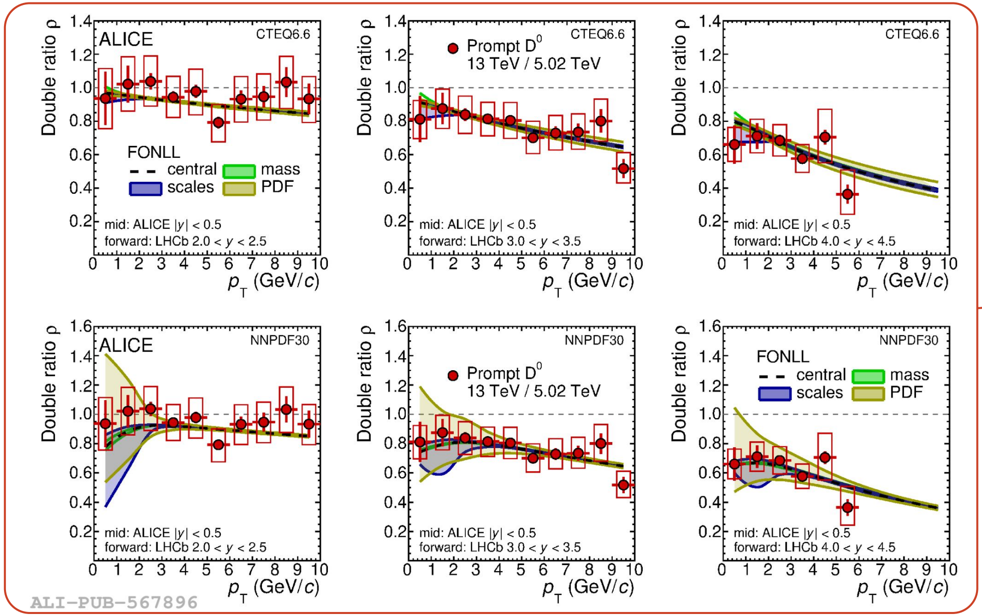
# $D^0$-meson double ratio ($\rho$)

mfaggin@cern.ch

ALICE: JHEP12 (2023) 086

LHCb: JHEP03(2016)159
LHCb: JHEP09(2016)013
LHCb: JHEP05(2017)074





- Ratio mid-$y$ / forward-$y$ of prompt $D^0$-meson cross section
- Compatible results among D-meson species

---

- Double ratio mid-$y$ / forward-$y$ && 13 TeV/ 5.02 TeV of prompt $D^0$-meson cross section

$$\rho = \left(\sigma^{13\,\text{TeV}}_{\text{mid-}y} \Big/ \sigma^{13\,\text{TeV}}_{\text{forward-}y}\right) \Big/ \left(\sigma^{5.02\,\text{TeV}}_{\text{mid-}y} \Big/ \sigma^{5.02\,\text{TeV}}_{\text{forward-}y}\right)$$

- $\rho$ decreasing vs. $p_T$ with increasing rapidity gap
  - different Bjorken-$x$ tested ($\sim 10^{-6}$-$10^{-4}$)
  - harder $p_T$ spectrum at lower energy
- FONLL calculations with CTEQ6.6 and NNPDF30 PDFs
- Dominant uncertainties at low $p_T$: NNPDF30 PDFs
  - measurement with ✕~2-3 smaller uncertainties
  - quantitative constraints on gluon PDF possible

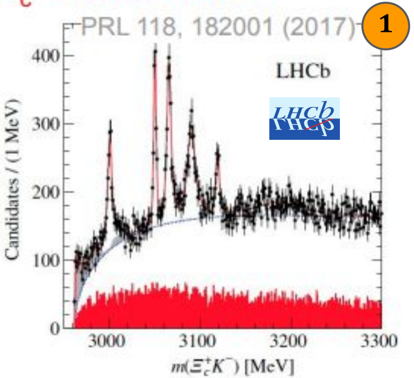
# Charm “baryonization” in pp collisions - different approaches

**Statistical approach**

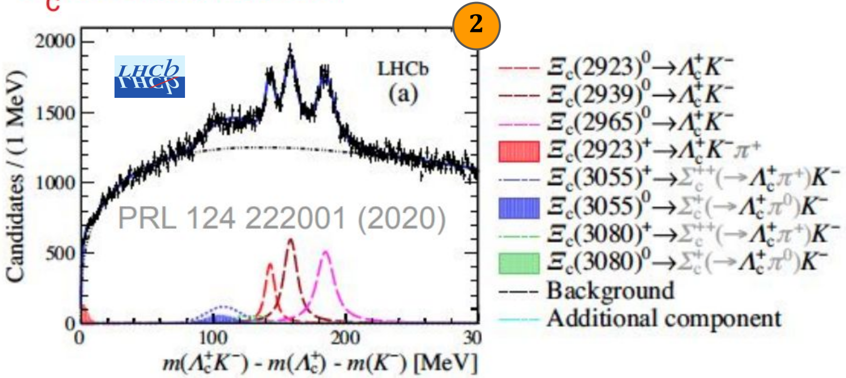
***SHM+RQM*** PLB 795 (2019) 117-121

- Hadron formation driven by the mass at a hadronization temperature $T_H$
- Strong **feed-down** from an **augmented set of excited charm baryon states**
  - PDG: 5 $\Lambda_c$, 3 $\Sigma_c$, 8 $\Xi_c$, 2 $\Omega_c$
  - RQM: additional (not yet measured) 18 $\Lambda_c$, 42 $\Sigma_c$, 62 $\Xi_c$, 34 $\Omega_c$

$\Omega_c$ excited states

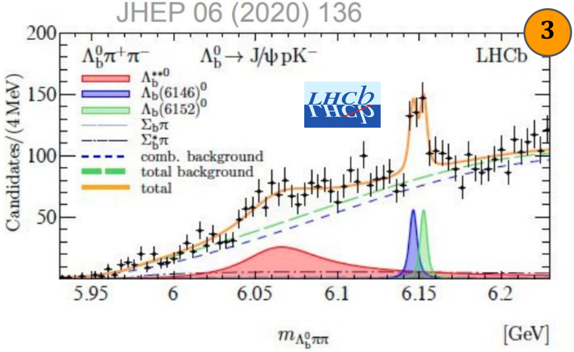


$\Xi_c$ excited states



*Do these states exist?*

$\Lambda_b$ excited states



*Many new hadrons popping up!*

④ ⑤ ⑥ … … and more!

# Charm “baryonization” in pp collisions - different approaches (2/4)

Statistical approach

***SHM+RQM*** PLB 795 (2019) 117-121

- Hadron formation driven by the mass $m_i$ at a hadronization temperature $T_H$
- Strong **feed-down** from an **augmented set of excited charm baryon states**
    - ○ PDG: 5 $\Lambda_c$, 3 $\Sigma_c$, 8 $\Xi_c$, 2 $\Omega_c$
    - ○ RQM: additional (not yet measured) 18 $\Lambda_c$, 42 $\Sigma_c$, 62 $\Xi_c$, 34 $\Omega_c$

Total angular momentum degeneracy **2J + 1**

$$n_i = \frac{\enclose{circle}{d_i}}{2\pi^2} m_i^2 T_{\mathrm{H}} K_2\left(\frac{m_i}{T_{\mathrm{H}}}\right)$$

| $n_i$ [$\times 10^{-4}$ fm$^{-3}$] ($T_H$ [MeV]) | $\Lambda_c^+$ | $\Xi_c^{0,+}$ | $\Omega_c^0$ |
|---|---|---|---|
| **PDG (170)** | 0.3310 | 0.0874 | 0.0064 |
| **RQM (170)** | 0.6613 | 0.1173 | 0.0144 |

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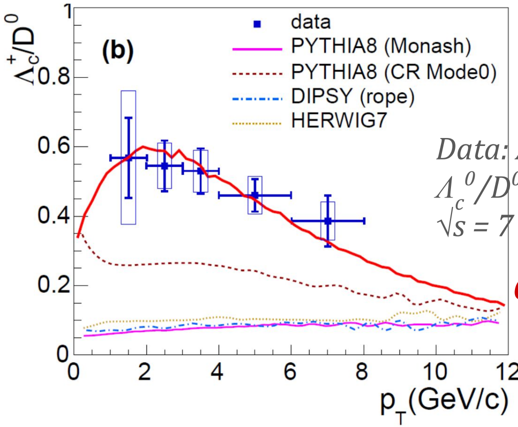
***Quark Coalescence Mechanism (QCM)*** Eur. Phys. J. C (2018) 78: 344

- Low $p_T$ charm hadrons conceived as coalescence between a charm quark (perturbative), with light quarks from fragmentation (not perturbative)
- Co-moving approximation: charm quark coalesces with an equal-velocity light quark (quark pair) to produce a meson (baryon)
- **Thermal weights** to account for **relative production** of scalar and vector mesons



*Data: ALICE $\Lambda_c^0/D^0$ in pp at $\sqrt{s}$ = 7 TeV*

***QCM***

Statistical approach + coalescence

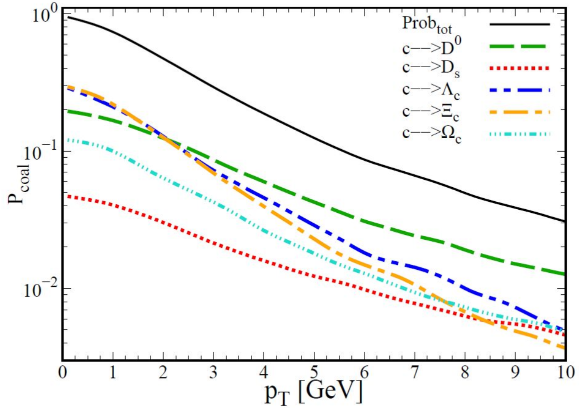
# Charm “baryonization” in pp collisions - different approaches (4/4)

## *Catania coalescence model*

PLB 821, 136622

Thermalised system + fragmentation + coalescence

- **Thermalised system** of u, d, s and gluons
- Charm quark can hadronize either via **fragmentation** or **coalescence** with light quarks from the bulk
- Charm hadronization into ground and (PDG) excited states
    - The latter ones increase the abundance of the former ones
    - Statistical “penalty” weight $[m_{H*}/m_H]^{3/2} \times \exp(-\Delta E/T)$



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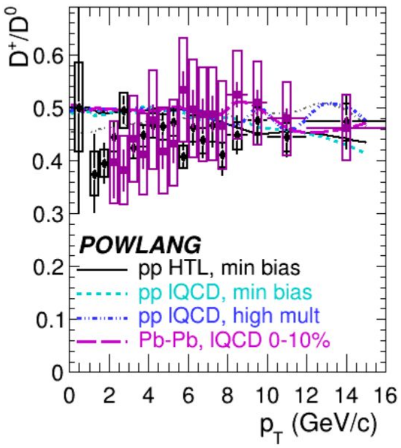
## *POWLANG*

https://arxiv.org/abs/2306.02152

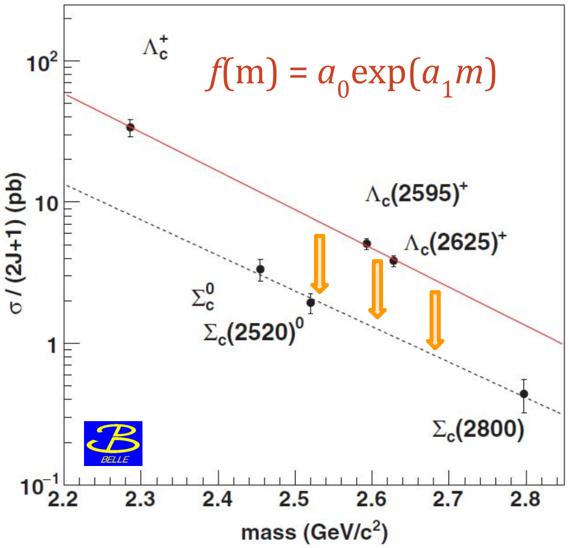
Thermalised system + coalescence

- Small, deconfined and expanding fireball in pp collisions
- Charm quark subject to rescattering and hadronization
    - local color neutralization
        - → charm recombining with light quarks from the system
        - → same processes as in heavy-ion collisions
    - presence of diquark excitations, promoting the formation of charm baryons
- Predictions employing transport coefficients calculated by weak-coupling (Hard-Thermal-Loop, HTL) and the most recent lattice-QCD (lQCD) calculations

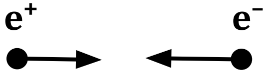


# $\Sigma_c^{0,+,++}$ production in $e^+e^-$ and pp collisions

Phys. Rev. D 97, 072005

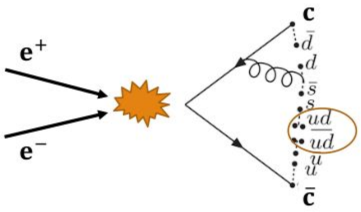


$f(m) = a_0\exp(a_1 m)$



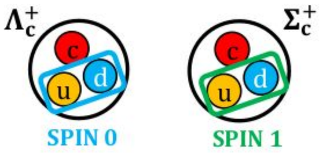
$\sqrt{s}$ = 10.52 GeV

(PYTHIA 8)
$m(\mathrm{ud})_0 = 579\ \mathrm{MeV}/c^2$
$m(\mathrm{ud})_1 = 771\ \mathrm{MeV}/c^2$

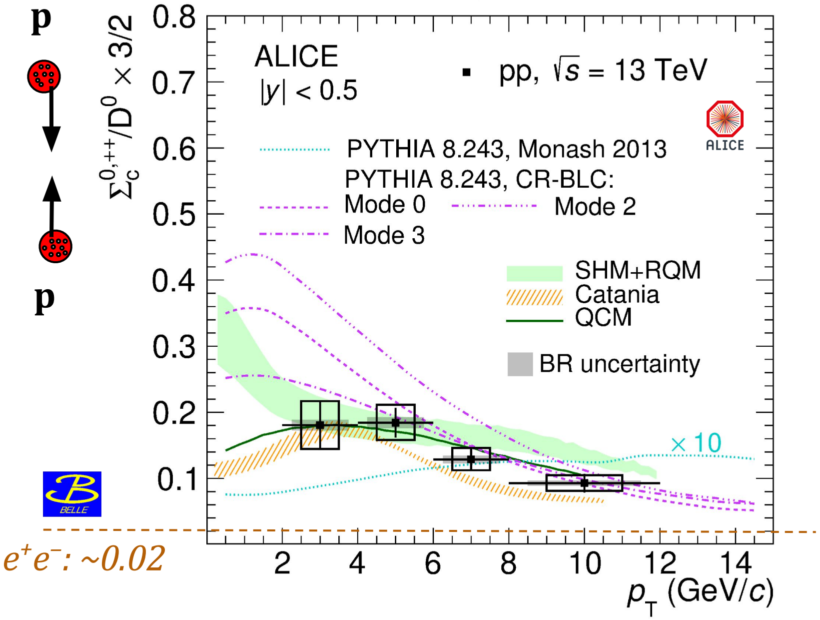


- $\Sigma_c$ states suppressed by ~3-4 than $\Lambda_c$ ones
- String model: penalty due to the diquark mass
  - $\Lambda_c^+(I=0)$: c-$(\mathrm{ud})_0$
  - $\Sigma_c^+(I=1)$: c-$(\mathrm{ud})_1$

→ Penalty due to $m(\mathrm{ud})_0 > m(\mathrm{ud})_1$



Phys. Rev. Lett. 128, 012001

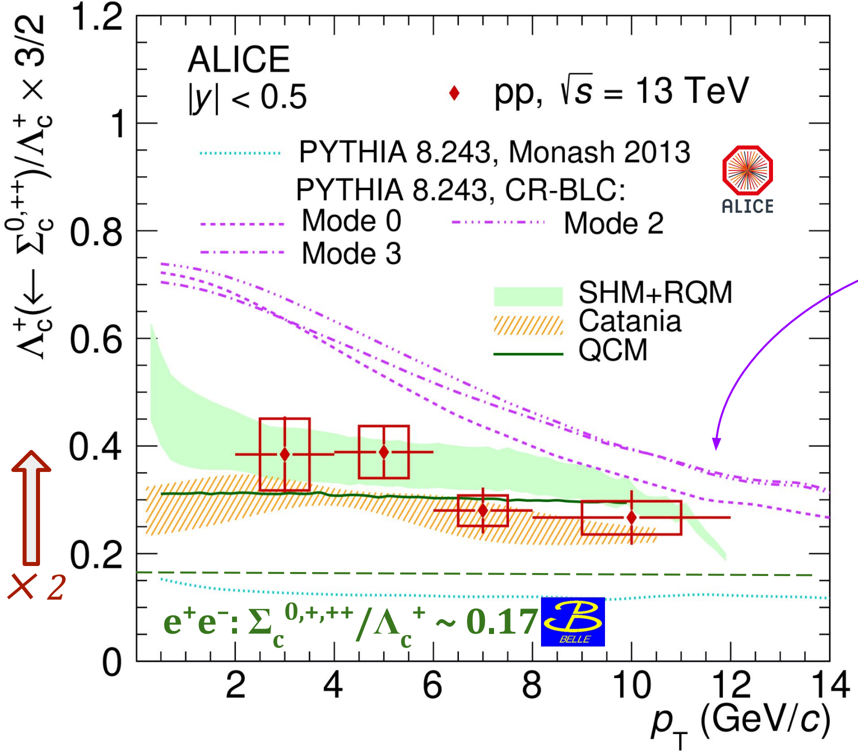


ALI-DER-493901

- $\Sigma_c^{0,+,++}/D^0$ underestimated by PYTHIA 8 Monash (larger discrepancy than for $\Lambda_c^+/D^0$)
- $\Sigma_c^{0,+,++}/D^0$ ratio described within uncertainties by other models
  →no diquark penalty factor assumed

# $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})$ production in pp collisions at the LHC

Phys. Rev. Lett. 128, 012001



ALI-DER-493906

- Fraction of prompt $\Lambda_c^+$ production from $\Sigma_c^{0,+,++}$ decays at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV at the LHC:

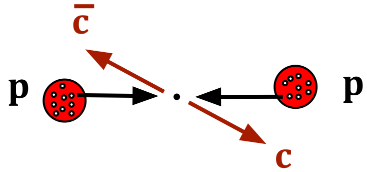
  $(2 \leq p_T < 12$ GeV/$c)$ $0.38 \pm 0.06 \pm 0.06$

- ~2 times larger than $e^+e^-$ → relative increase of $\Sigma_c^{0,+,++}$
- $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratio overestimated by CR-BLC

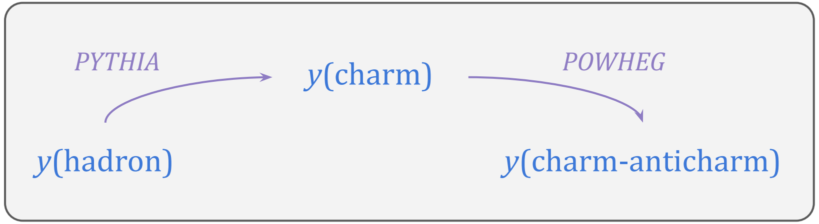
- Default parameter tunes not fully describing the inclusive prompt $\Lambda_c^+$ production?
- New: c-diquark role crucial in CR_BLC modes. Re-tuning needed?
- Inputs from production measurements of excited c-baryons? (e.g. $\Lambda_c^+(2595)$, $\Lambda_c^+(2625)$, $\Lambda_c^+(2880)$, $\Lambda_c^+(2940)$)

# $c\bar{c}$ production at mid-$y$ in pp collisions

- Charm-anticharm production cross section at midrapidity in pp collisions at $\sqrt{s}$ = 5.02 TeV, 13 TeV measured as the sum of prompt $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$, $\Xi_c^{0,+}$, J/$\psi$ cross sections



*Rapidity correction factor: ~ 1.04*



***pp collisions at $\sqrt{s}$ = 5.02 TeV***

$$\left.\frac{d\sigma}{dy}\right|_{|y|<0.5}^{pp,\sqrt{s}=5.02\ \mathrm{TeV}} = 1148 \pm 43\ (\mathrm{stat.})^{+62}_{-65}\ (\mathrm{syst.})^{+98}_{-36}\ (\mathrm{extrap.}) \pm 43\ (\mathrm{BR}) \pm 24\ (\mathrm{lumi.}) \pm 41\ (\mathrm{y})\ \mu\mathrm{b}\,.$$

***pp collisions at $\sqrt{s}$ = 13 TeV***

$$\left.\frac{d\sigma}{dy}\right|_{|y|<0.5}^{pp,\sqrt{s}=13\ \mathrm{TeV}} = 2031 \pm 61\ (\mathrm{stat.})^{+135}_{-141}\ (\mathrm{syst.})^{+196}_{-63}\ (\mathrm{extrap.}) \pm 97\ (\mathrm{BR}) \pm 33\ (\mathrm{lumi.}) \pm 73\ (\mathrm{y})\ \mu\mathrm{b}\,.$$

- Measurement on the upper edge of pQCD calculations
- Possible constraints to theoretical uncertainties

JHEP12 (2023) 086