Charm production in small and large systems

A personal overview

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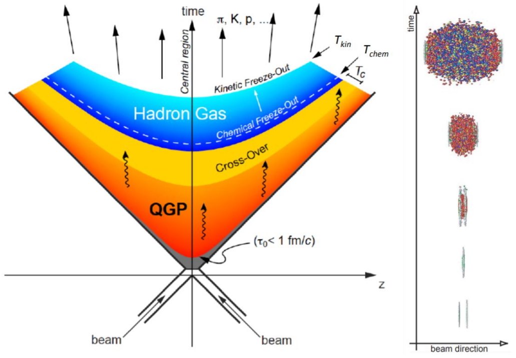
We ♥ baryons

Thanks lot to A. Dainese and A. Rossi for the fruitful discussions!

- Mass of the GeV/c^2 order → **charm** and **beauty** quarks mainly produced only in the **hard scattering processes**

- Pb-Pb collisions:
  - quark gluon plasma (**QGP**) → parton d.o.f.
  - **charm** and **beauty** (production timescale $\Delta\tau \sim 1/Q \sim 1/2m$) **produced before** the **QGP** ($\Delta\tau \sim 1$ fm/c)
  - **full** system **evolution** experienced

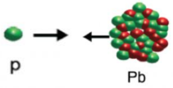


- Measurement of heavy hadrons: access to charm and beauty quark dynamics

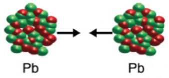
Charm
$m_c \sim 1.3$ GeV/c^2
$\Delta\tau_c \sim 0.08$ fm/c

Beauty
$m_c \sim 4.2$ GeV/c^2
$\Delta\tau_b \sim 0.03$ fm/c

- **Test** of **pQCD** calculations
- **Reference** for heavy-ion collisions

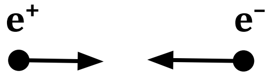


Cold nuclear matter effects
- Modification of PDF in bound nucleons

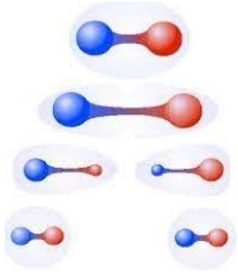


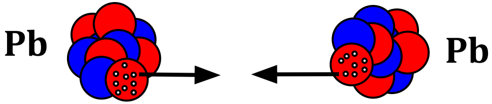
Hot nuclear matter effects
- Energy loss in the QGP
- Collective motion
- Modification of **hadronization**

Charm and beauty hadrons from e^+e^- to Pb-Pb

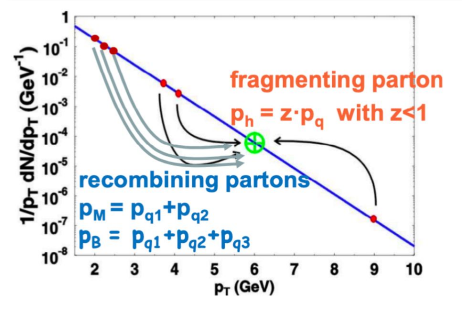


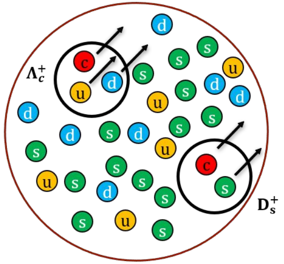
- "**Point-like**" object interaction
- **Fragmentation** in the vacuum





- **QGP**: complex system with **partonic d.o.f**
- Hadronization is modified by **coalescence**





Fragmentation

- Hard scattering: $e^+e^- \rightarrow q\bar{q}$
- Color string: $V_{Cornell}(r) \sim \kappa r$
- New $q\bar{q}$ pairs from multiple string breaking (confinement)

Coalescence

- Heavy quark recombinates with light quarks in the QGP
- Expected increase of hadrons at intermediate-low p_T
- QGP: interplay

Charm and beauty hadrons from pp collisions

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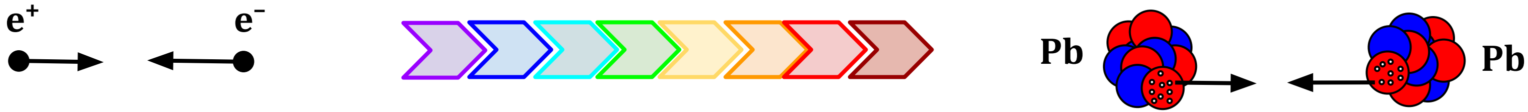
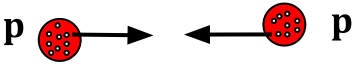


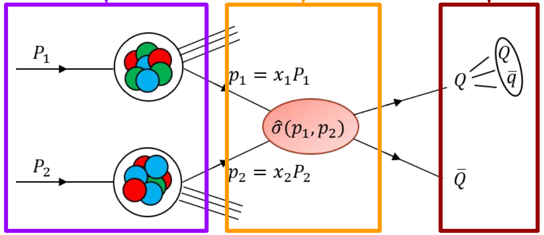


- Superimposition of many "e⁺e⁻" collisions
- Changes in hadronization due the the surrounding color charges and those from MPI?

- Standard description of heavy-quark hadronization based on a **factorization approach**
- **Fragmentation functions** assumed **universal** among collision systems and constrained from e^+e^- and e^-p measurements

$$\frac{\mathrm{d}\sigma^{\mathrm{H_c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{H_c}}}(p_{\mathrm{T}};\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F) \otimes \frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{\mathrm{c}\to\mathrm{H_c}}(z = p_{\mathrm{H_c}}/p_{\mathrm{c}},\mu_F)$$

Parton distribution functions (PDF) | Hard scattering cross section (pQCD) | Fragmentation function (hadronization)



Charm (and beauty) mesons

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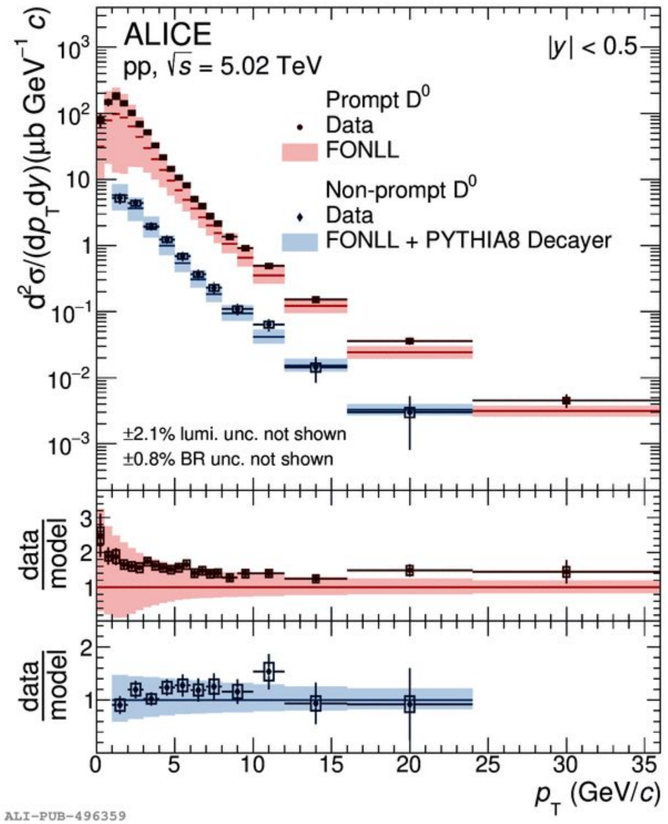
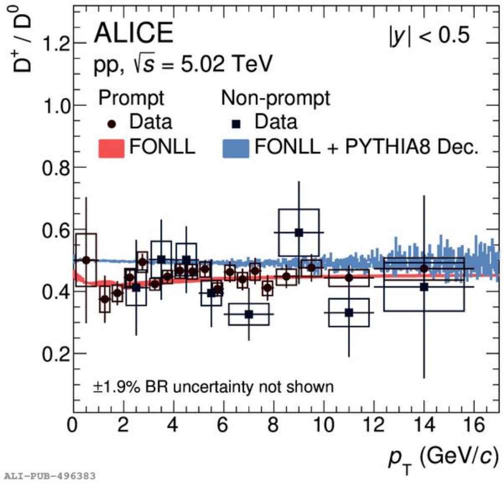
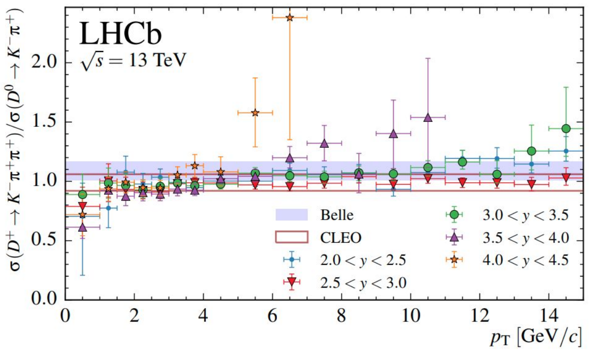
ALICE: JHEP 05 (2021) 220

LHCb: JHEP 03 (2016) 159





NB: [σ(1) ✕BR(1)] / [σ(2) ✕BR(2)]



- **Heavy meson production** described by models based on:
  - **factorization** approach
  - **fragmentation functions** constrained **from e^+e^-, e^-p**
- **Same relative abundances** with those in **e^+e^-** collisions
- **No** significant **p_T** or **collision system** (backup) **dependence**

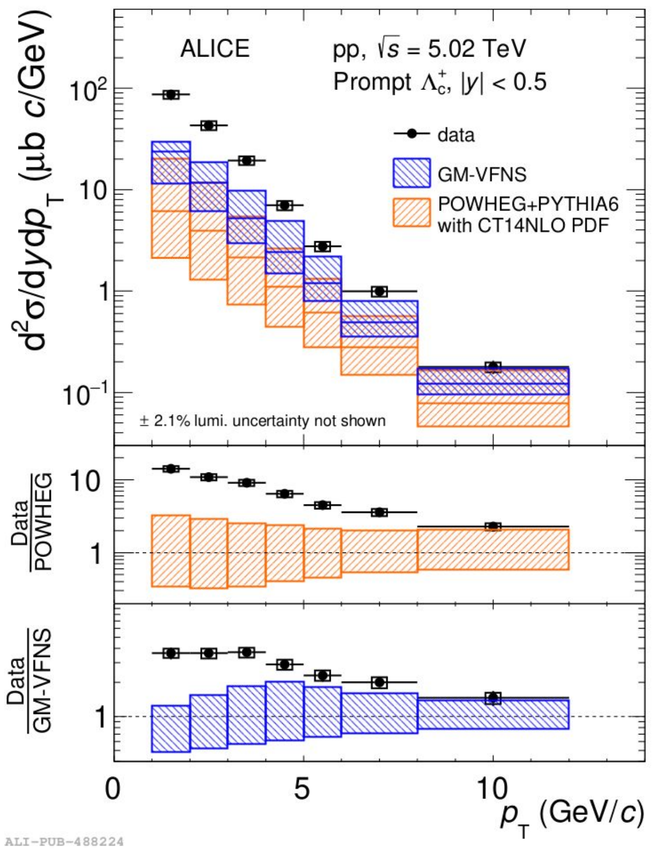
Charm and beauty baryons

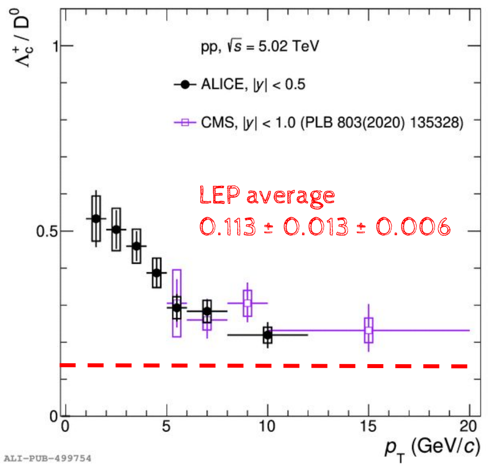
… but the baryons tell us something new!

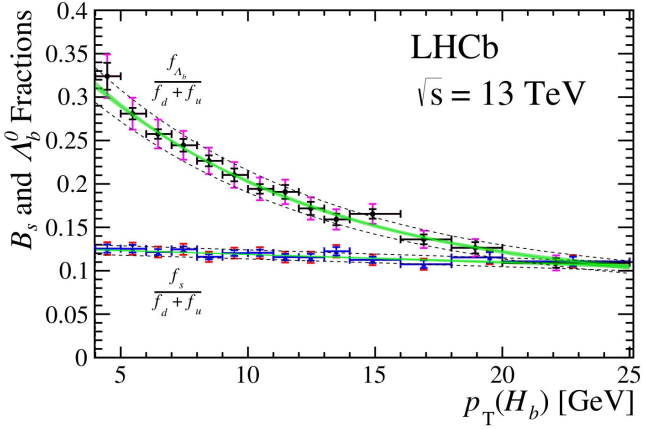
ALICE: Phys. Rev. C 104 (2021) 054905
Phys. Rev. Lett. 127 (2021) 202301

LEP: EPJC 75, 19 (2015)
CMS: Phys. Lett. B 803 (2020) 135328

LHCb: Phys.Rev. D100 (2019) no.3, 031102







- Λ_c^+ production **significantly undershoot** by models tuned to reproduce e^+e^- and e^-p collision results
- **Λ_c^+/D^0** in pp **at mid-*y*** significantly **larger than e^+e^-**
- **Λ_b^0/B** at **forward-*y*** significantly **higher than B meson-to-meson** ratio **at low p_T**

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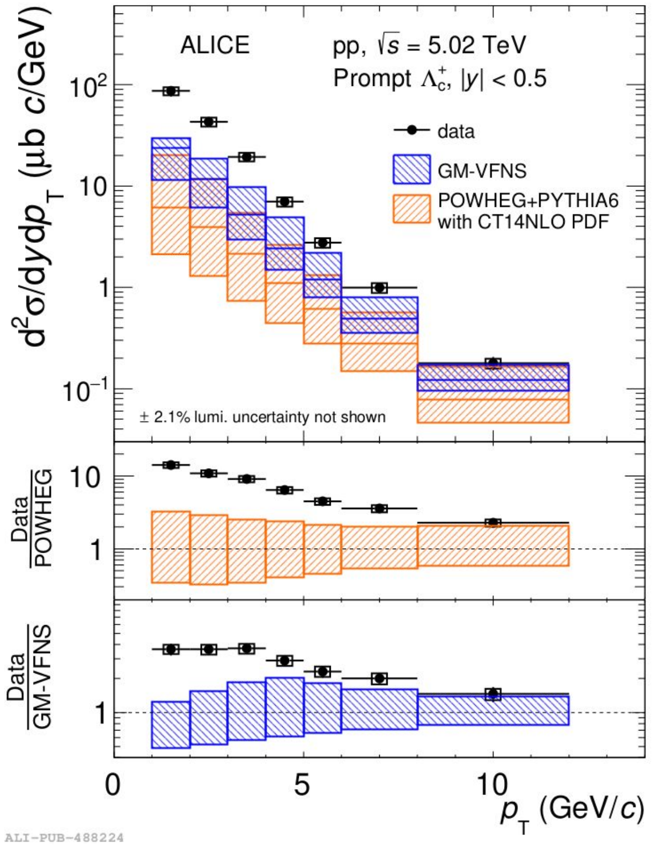
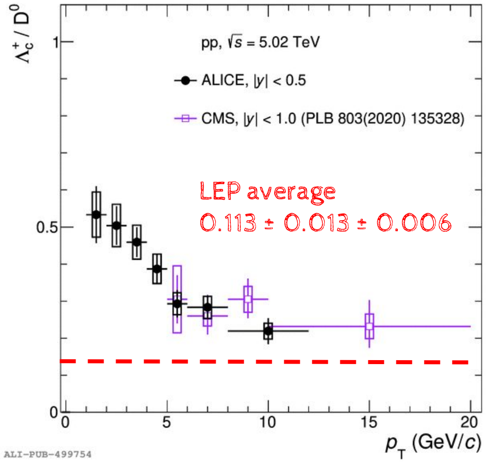
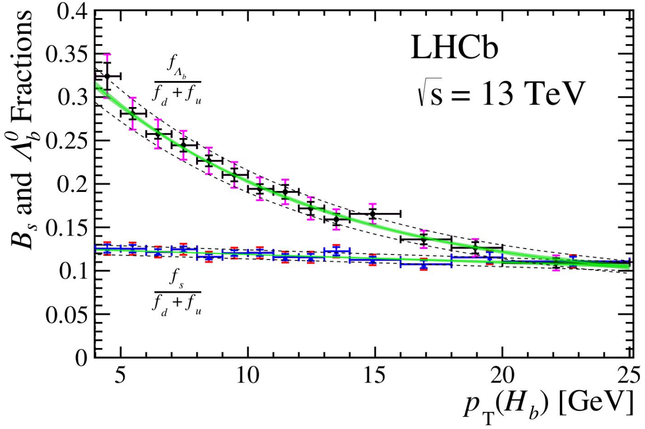


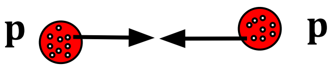


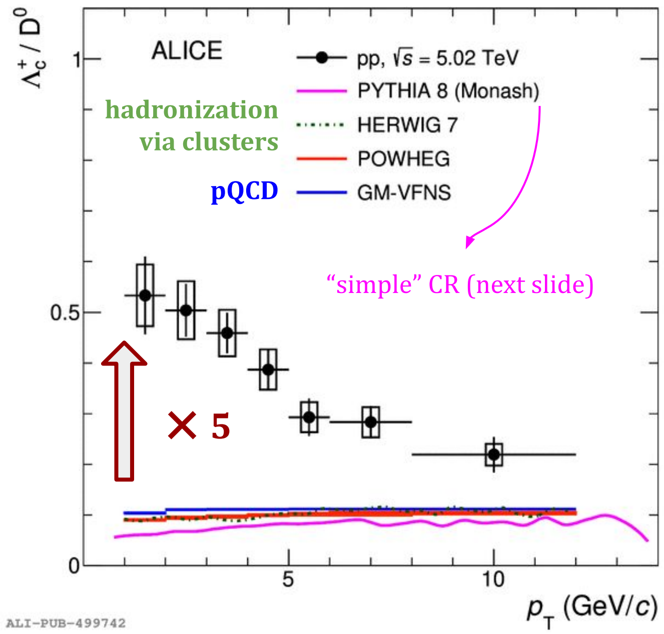


- Does the **factorization** approach **fail**?
- Does the assumption of **universal fragmentation fractions** among collision systems **fail**?
- Do **new hadronization mechanisms** play a role **in pp** collisions **at the LHC**?

Charm “baryonization” - the Lund fragmentation

ALICE: Phys. Rev. C 104 (2021) 054905
Phys. Rev. Lett. 127 (2021) 202301

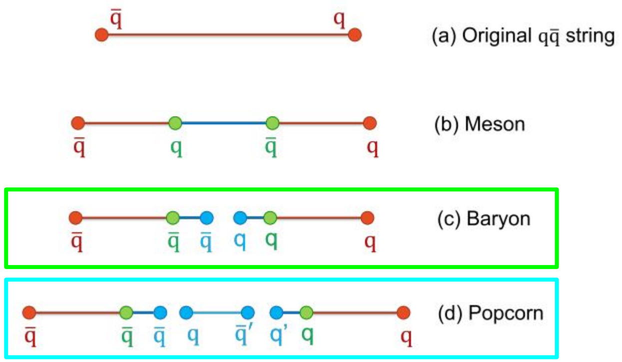




$$P(\text{string breaking}) \propto \exp\left(-\frac{\pi m_{T,q}^2}{\kappa}\right) = \exp\left(-\frac{\pi m_q^2}{\kappa}\right)\exp\left(-\frac{\pi p_{T,q}^2}{\kappa}\right)$$

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

“Tunneling” probability



http://home.thep.lu.se/~torbjorn/talks/durham09.pdf

“[...] Baryon production as if diquark when only one break inside “wrong-colour” region”

“[...] popcorn when several breaks ”

Fragmentation parameters for these simulations (calculations) tuned to previous e^+e^- and e^-p collision

Charm "baryonization" - color reconnection (CR)

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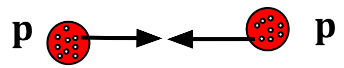
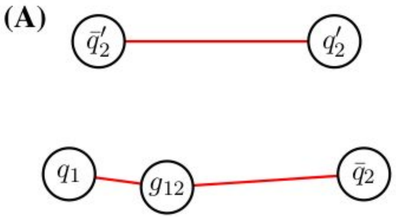


- Initial state not insensitive to strong force (coloured partons, beam remnants)
- MPI → crucial to explain underlying event



No CR

Partons from different MPIs do not interact

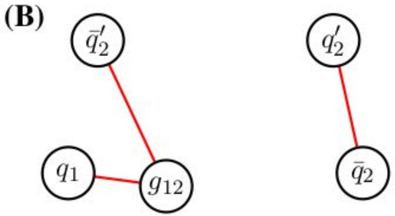
$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$$

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 Monash
- Λ_c^+/D^0 underestimated by a factor ~5 at low p_T

JHEP 08 (2015) 003

Charm "baryonization" - CR beyond leading color

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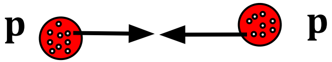
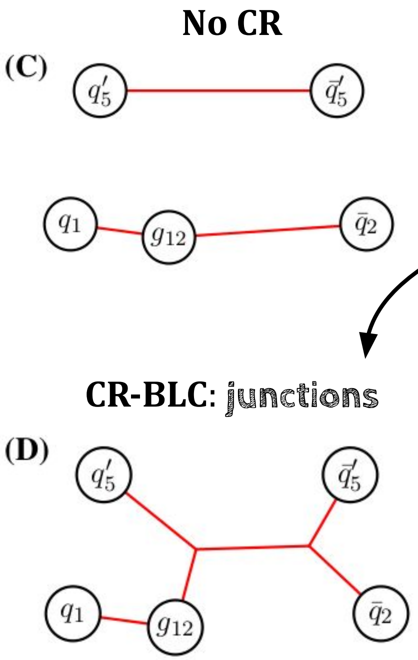


- Initial state not insensitive to strong force (coloured partons, beam remnants)
- MPI → crucial to explain underlying event



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
  → Monash: only CR among LC
- Enhanced leading color among MPIs and beam remnants
- Conditions for color reconnections:
  - Invariant mass of string *j*-th must overcome a threshold m_0
    $C = m_{0j}/m_0 > 1$: enhanced reconnections
  - Causality: two strings must resolve each other between formation and hadronization, according to the time dilation due to the relative boost
    →Mode 0, 2, 3: different "severity" on this condition

JHEP 08 (2015) 003

Charm “baryonization” - statistical approaches and coalescence

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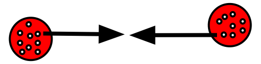


SHM+RQM PLB 795 (2019) 117-121

- Hadron formation driven by the mass at a hadronization temperature $T_H \rightarrow$ stat. weights $n_i \sim m_i^2 T_H K^2(m_i/T_H)$
- Strong feed-down from an augmented set of excited charm baryon states
  - PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
  - RQM: additional (not yet measured) 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

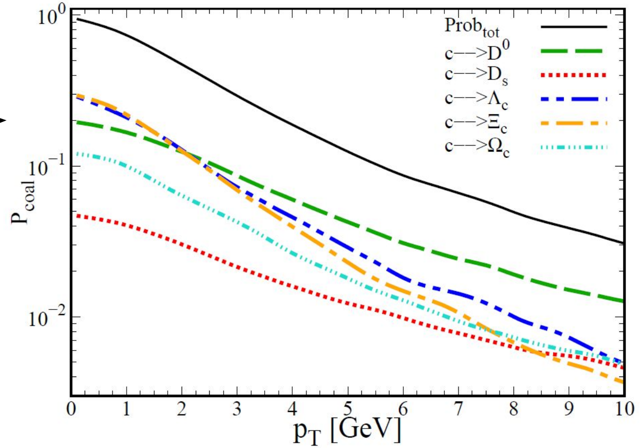
n_i [$\times 10^{-4}$ fm^{-3}] (T_H [MeV])	Λ_c^+	$\Xi_c^{0,+}$	Ω_c^0
PDG (170)	0.3310	0.0874	0.0064
RQM (170)	0.6613	0.1173	0.0144

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

- Thermal weights to account for relative production of scalar and vector mesons
- Hadron p_T- spectrum from recombination of charm quarks from the hard scattering with equal-velocity light quarks in the nearby in phase-space

Catania coalescence model PLB 821, 136622

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



Λ_c^+/D^0 ratio in pp at the LHC vs. model predictions

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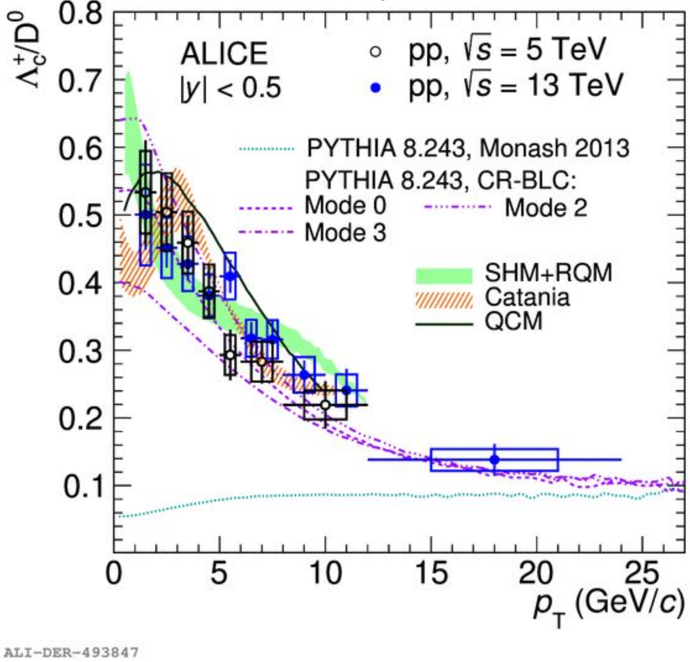
ALICE: Phys. Rev. Lett. 128, 012001



	Coalescence	Excited baryons	Thermal component	Λ_c^+/D^0
CR-BLC	❌	❌ (not explicit)	❌	✅
SHM+ RQM	❌	✅ PDG + RQM	✅	✅
Catania	✅	✅ PDG	✅	✅
QCM	✅	❌ (not explicit)	✅	❓ slightly higher

- Λ_c^+/D^0 ratio underestimated by a factor ~5 at low p_T by Monash → only CR among LC topologies
- **Λ_c^+/D^0 ratio described** within uncertainties **by** other **models** introduced (QCM slightly higher) **despite** the **different mechanisms** assumed

→ **Can we learn something more from other charm baryon measurements in pp collisions?**

$\Sigma_c^{0,+,++}$ production in pp collisions at the LHC

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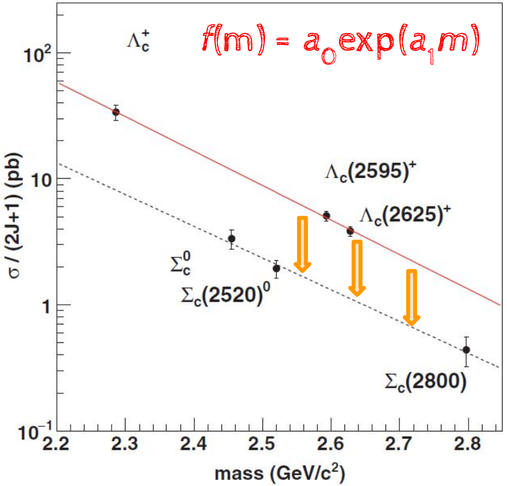
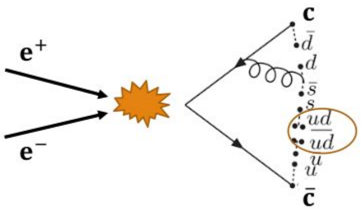
e^+e^- at $\sqrt{s}$ = 10.52 GeV

Phys. Rev. D 97, 072005



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

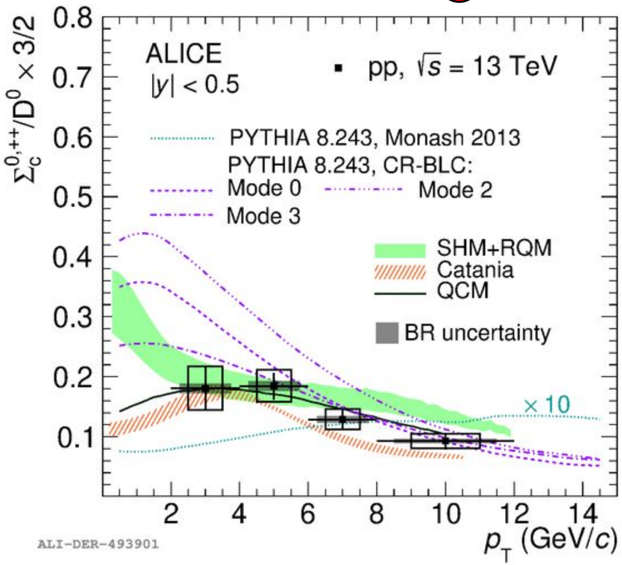


- Σ_c states **suppressed** by ~3-4 than Λ_c ones
- String model: penalty due to the diquark mass!
  - $\Lambda_c^+(I=0)$: c-$(ud)_0$
  - $\Sigma_c^+(I=1)$: c-$(ud)_1$

Penalty due to $m(ud)_0 > m(ud)_1$

Λ_c^+ SPIN 0 Σ_c^+ SPIN 1

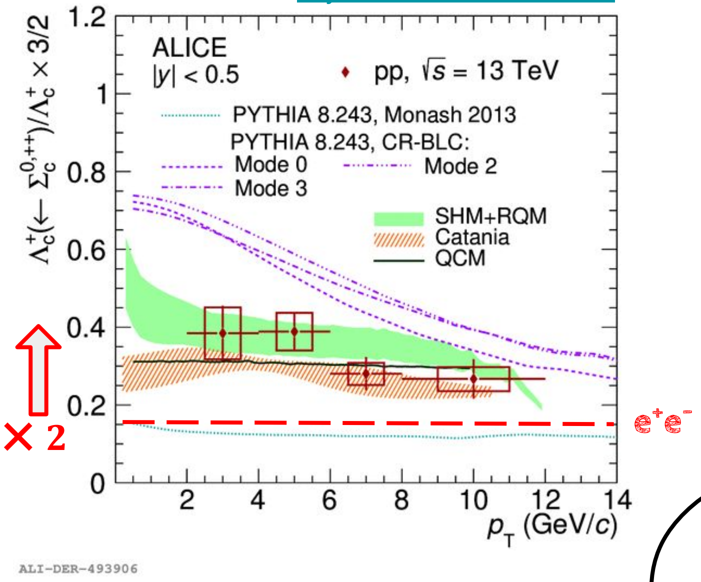
ALICE: Phys. Rev. Lett. 128, 012001



- $\Sigma_c^{0,+,++}/D^0$ **underestimated** by **Monash** (**larger discrepancy** than for Λ_c^+/D^0)
- $\Sigma_c^{0,+,++}/D^0$ **ratio described** within uncertainties **by** other **models** (CR-BLC slightly higher) →no diquark penalty factor assumed

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

ALICE: Phys. Rev. Lett. 128, 012001



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

  $(2 \leq p_T < 12\ \mathrm{GeV}/c)$ **0.38 ± 0.06 ± 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 Λ_c^+ production**?
  - New: **c-diquark** role **crucial**. **Re-tuning needed**?
  - Inputs from production **measurements** of **excited c-baryons**?

https://pdg.lbl.gov/2222/tables/contents_tables_baryons.html

- $\Lambda_c^+(2595)$, $\Lambda_c^+(2625)$, $\Lambda_c^+(2880)$, $\Lambda_c^+(2940)$ decaying into $\Lambda_c^+\pi(\Sigma_c^{0,++})\pi$
- Mass difference with $\Lambda_c^+ \approx$ 300-650 MeV/c^2

P. Skands, PHENO meeting 2021 (https://indico.cern.ch/event/1028933/)

Junction baryons (e.g, from CR) are expected to be different

- In junction fragmentation, two junction legs get combined, one of which can be a c quark → charm diquarks + a quark from a string break.
- Radically new possibility.

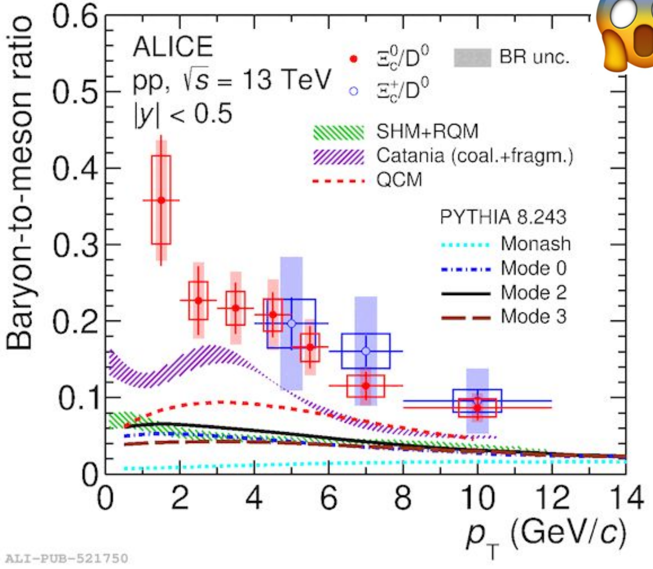
  ~probQQ1toQQ0join = {0.5,0.7,0.9,1.0} really only **guesses**

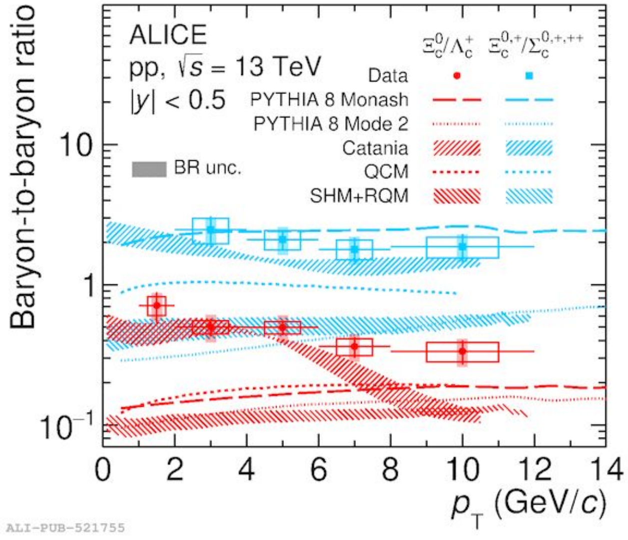
  Controls charm baryons

  But note can be vastly different from that of string-breaks (0.0275)

string breaking suppression in Monash when the heaviest quark is u/d, s, c or b

ALICE: Phys. Rev. Lett. 128 (2022) 012001





- **$\Xi_c^{0,+}/D^0$ underestimated by all the models**
- $D_s^+/(D^0+D^+)$ in line with e^+e^- results
  → are baryons "strange"? JHEP 05 (2021) 220
- **$\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ described by Monash**
  → similar suppression in e+e– due to similar diquark masses? $(m(uu, ud, dd)_1 \approx m(us)_0)$

What about the strangeness enhancement description in these models (missing in CR-BLC)? Does it play a role?

Ω_c^0 production in pp collisions at the LHC

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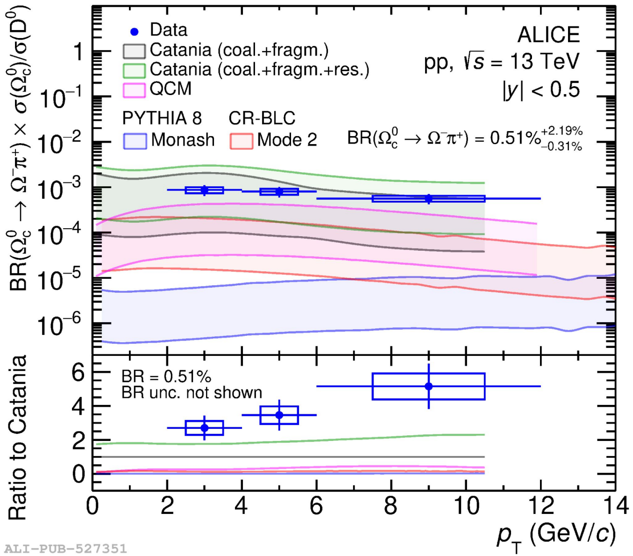

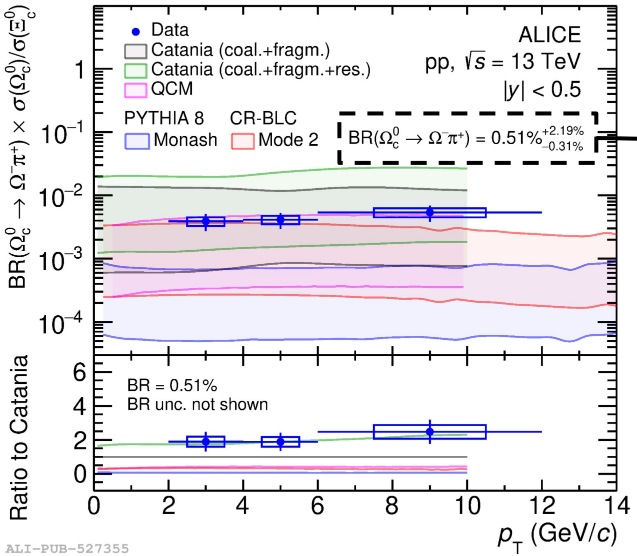

ALICE: arXiv:2205.13993 [nucl-ex]

- Huge BR uncertainty due to lack of measurements
- Envelope of several theoretical calculations

- **CR-BLC underestimates** the **data**
- **Coalescence models** get **closer** to the measurements
- Ω_c^0/Ξ_c^0 described by **Catania** model (coalescence + fragmentation) including **higher-mass resonance** decays

What about the strangeness enhancement description in these models (missing in CR-BLC)? Does it play a role?

$f(\Omega^0_c) \approx f(\Xi^0_c) \approx 10\%$

Sizeable charm hadronization into Ω_c^0 at the LHC?

Charm production in pp as a function of multiplicity

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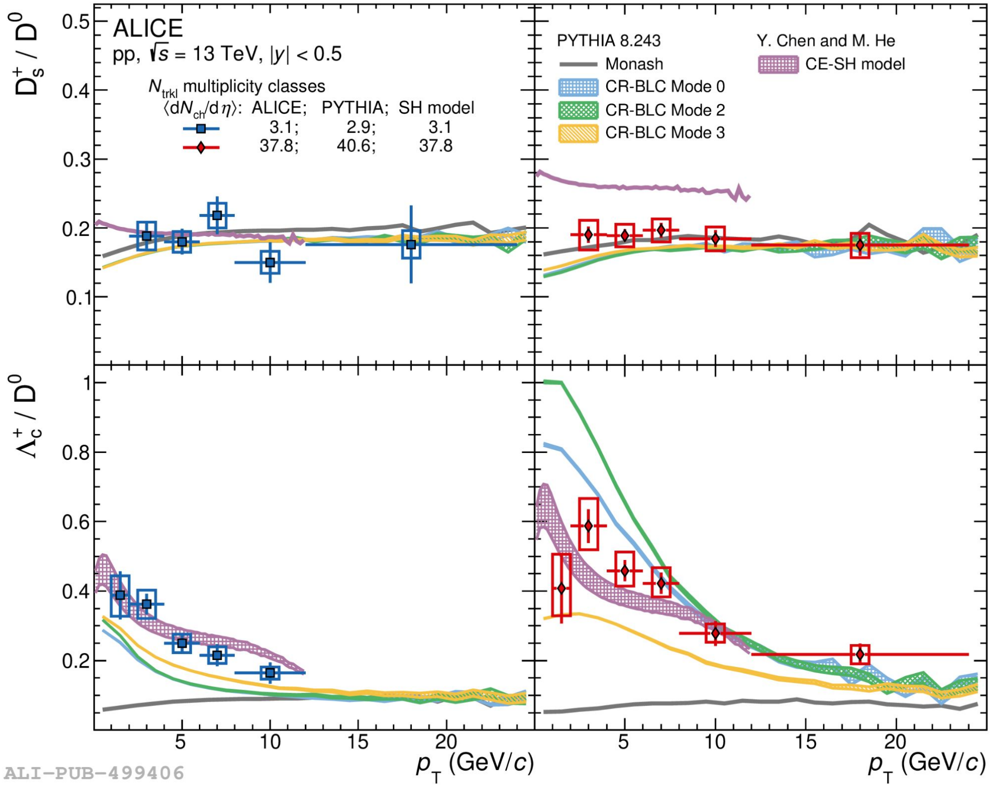
Studies **vs. multiplicity** can provide **insights** into the **multi-parton interactions**, the **interplay** between **hard and soft mechanisms** in particle production



Phys. Lett. B 829 (2022) 137065

- **D_s^+/D^0** ratio **flat in p_T** and in **multiplicity**
- Ratio **described by all PYTHIA tunes** (Monash included) **and CE-SH model** at **low multiplicity**
- Ratio **overestimated** at **high multiplicity** by **CE-SH**

- **Λ_c^+/D^0** ratio **decreasing in p_T** at all event multiplicities
- Ratio **described CE-SH** model and significantly underestimated by Monash
- p_T dependence described by PYTHIA BR-BLC modes

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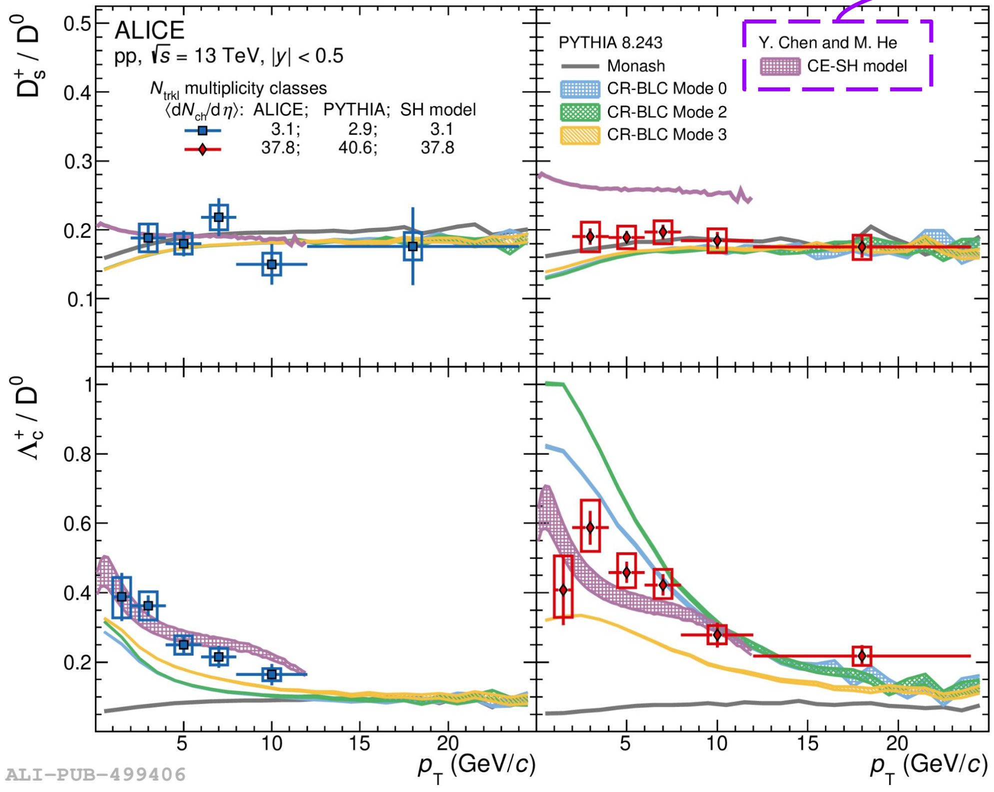

Phys. Lett. B 829 (2022) 137065

CE-SH model (Phys. Lett. B 815 (2021) 136144)

- SHM+RQM model in pp collisions assuming a grand-canonical ensemble (GCE) generalized to the canonical one (CE)
  →global (GCE) to local (CE) charge conservation
- Explore how Λ_c^+/D^0 dependence vs. multiplicity can be explained as an increasing canonical suppression from high to low system size (i.e. multiplicity)

Λ_c^+/D^0 ratio in Pb-Pb collisions

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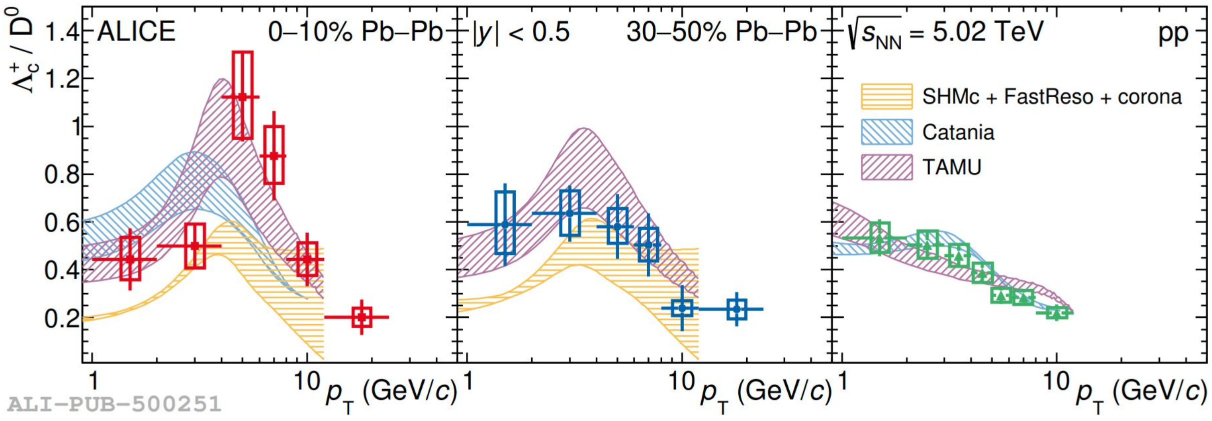
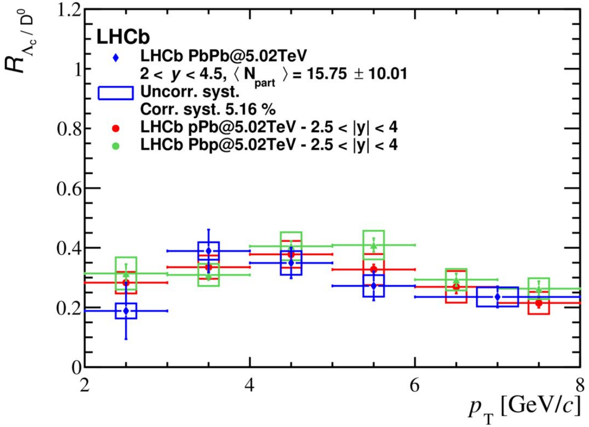
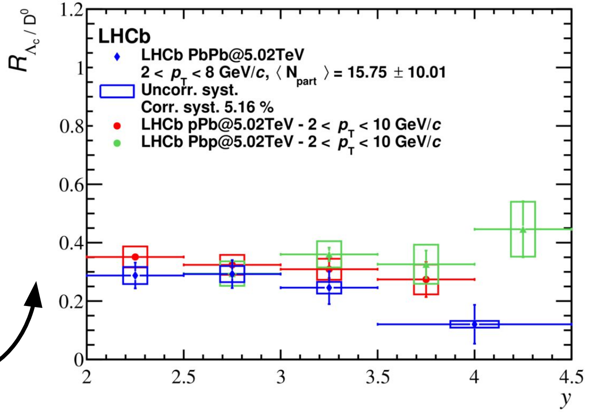
ALICE: arXiv:2112.08156 [nucl-ex]

Central and semicentral Pb-Pb from ALICE!



LHCb: arXiv:2210.06939 [hep-ex]



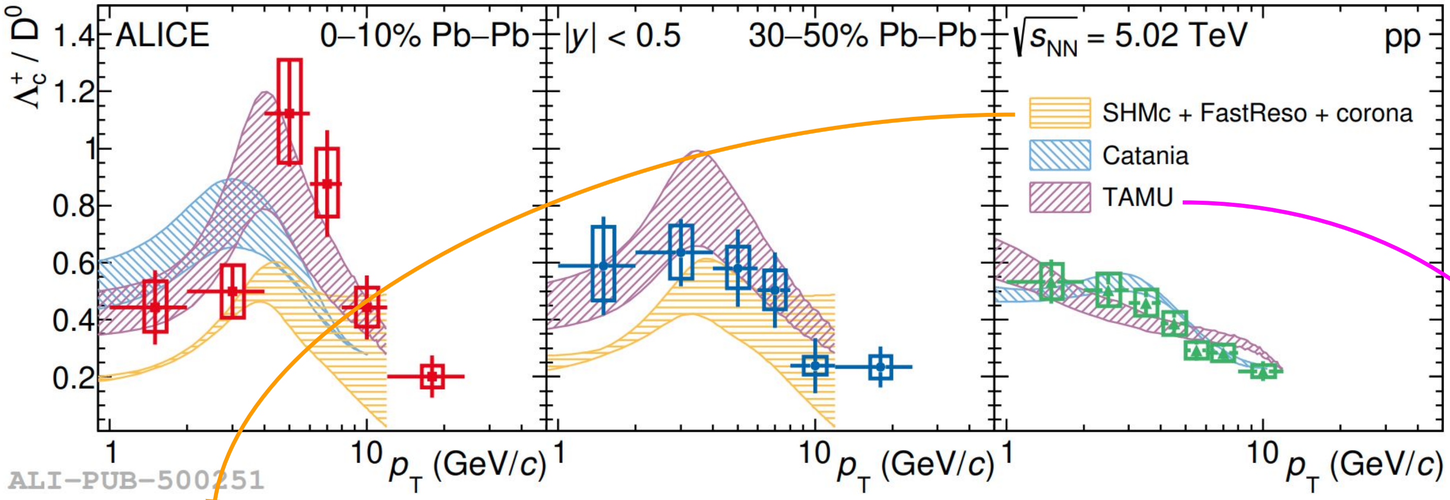


- The Λ_c^+/D^0 ratio is **enhanced** in **$4 < p_T < 8$ GeV/c** for **central Pb–Pb** compared to pp collisions by 3.7σ
- **Also** seen for **baryon-to-meson** ratios with **light-flavour** particles
- Data is described by TAMU. The shapes of the Catania and SHMc predictions agree qualitatively

Peripheral Pb-Pb from LHCb!

Λ_c^+/D^0 ratio in Pb-Pb collisions

ALICE: arXiv:2112.08156 [nucl-ex]



SHMc (JHEP 07 (2021) 035)

- Grand-canonical SHM, where charm quark is an “impurity” with thermal distribution (thermalization)
- Total charm production from hard scatterings fixed by measurements of open charm cross sections

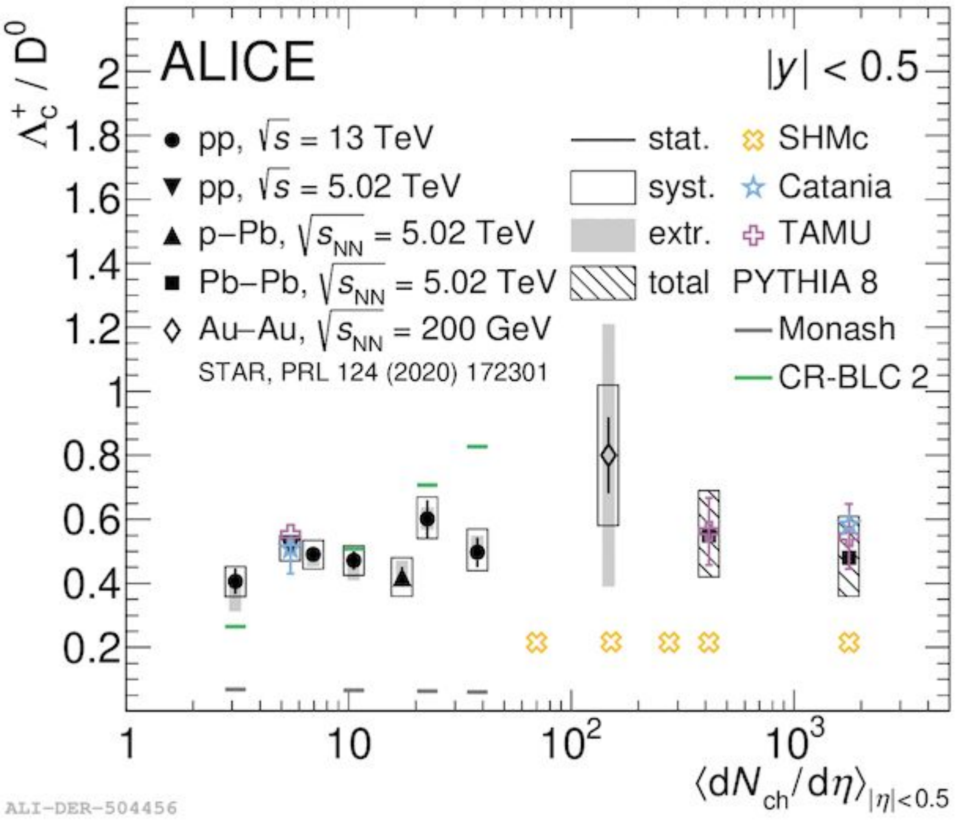
SHM+RQM → extra excited c-baryon contribution

In Pb-Pb Phys. Rev. Lett. **124**, 042301:

- relativistic hydrodynamics model based on Langevin approach
- 4-momentum conserving coalescence
- baryon phase-space distribution from quark and diquark ones →c-diquarks degrees of freedom also here, like in CR-BLC!

Λ_c^+/D^0 ratio at the LHC vs. multiplicity

ALICE: Phys. Lett. B 829 (2022) 137065
arXiv:2112.08156 [nucl-ex]



- p_T-integrated Λ_c^+/D^0 ratio **from pp to Pb-Pb** as a function of multiplicity
- Flat trend vs. multiplicity within uncertainties →**no collision system dependence**

?! →is the p_T-differential enhancement given only by a p_T reshuffling between baryons and mesons due to radial flow and coalescence?

- Ratio described by Catania (fragmentation + coalescence) and TAMU (SHM+RQM + 4-momentum conserving coalescence in Pb-Pb)
- Flat trend also from SHMc, but systematically underestimated
- PYTHIA CR-BLC prediction does not reproduce the trend vs. multiplicity

Conclusions

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- Charm hadron production at the LHC explained by models going beyond a pure fragmentation scenario
  → hadronization is not a universal process among collision systems
- Not a single model able to explain all the baryon-chemistry
- Available measurements still not precise enough to reject / support one model

	Coalescence	Excited baryons	Thermal component	Λ_c^+/D^0	$\Sigma_c^{0,+,++}/D^0$	$\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$	$\Xi_c^{0,+}/D^0$	Ω_c^0/D^0
CR-BLC	❌	❌ (not explicit)	❌	✅	❓ slightly higher	❌	❌	❌
SHM+RQM	❌	✅ PDG + RQM	✅	✅	✅	✅	❌	❌
Catania	✅	✅ PDG	✅	✅	✅	✅	❌	✅ with resonances
QCM	✅	❌ (not explicit)	✅	❓ slightly higher	✅	✅	❌	❌

What next from the experiments?

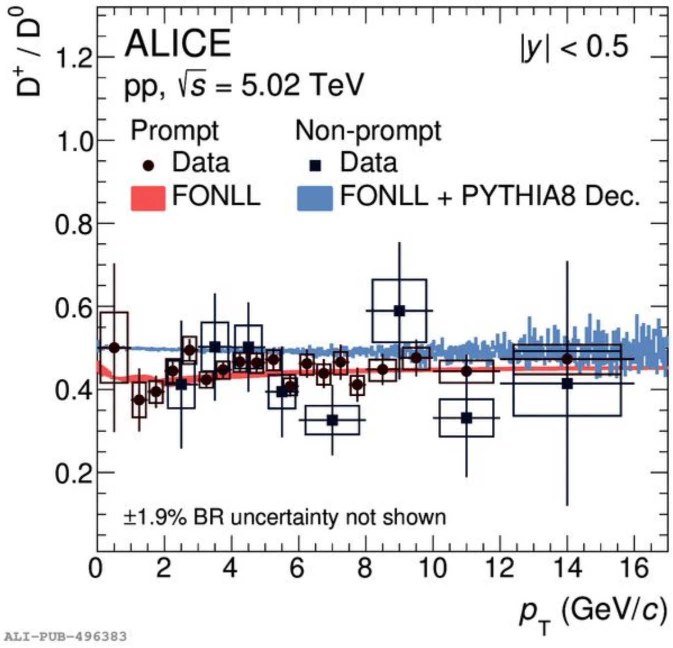
- More precise production measurements in pp and Pb-Pb
- New measurements (e.g. Λ_c^+ resonances)
- Polarization measurements at midrapidity? (LHCb: arXiv:2208.03262 [hep-ex])

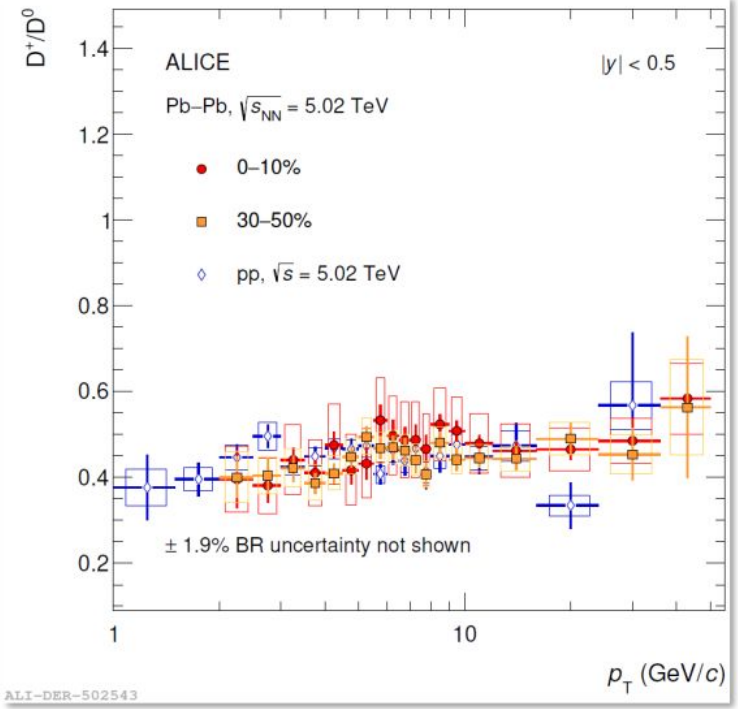
Thank you very much for the attention

Backup

Charm mesons

ALICE: JHEP 05 (2021) 220





Model vs. pp collision results at the LHC

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	Coalescence	Excited baryons	Thermal component	Λ_c^+/D^0	$\Sigma_c^{0,+,++}/D^0$	$\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$	$\Xi_c^{0,+}/D^0$
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SHM+ RQM	❌	✅ PDG + RQM	✅	✅	✅	✅	❌
Catania	✅	✅ PDG	✅	✅	✅	✅	❌
QCM	✅	❌ (not explicit)	✅	❓ slightly higher	✅	✅	❌

JHEP 08 (2015) 003

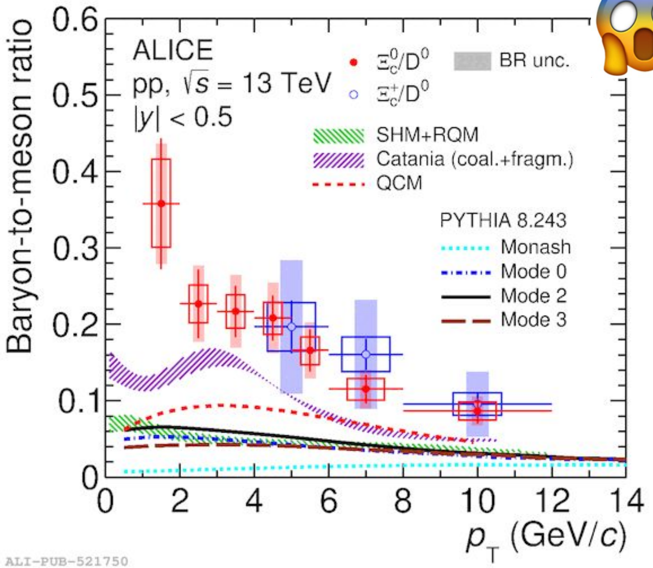
A Model parameters

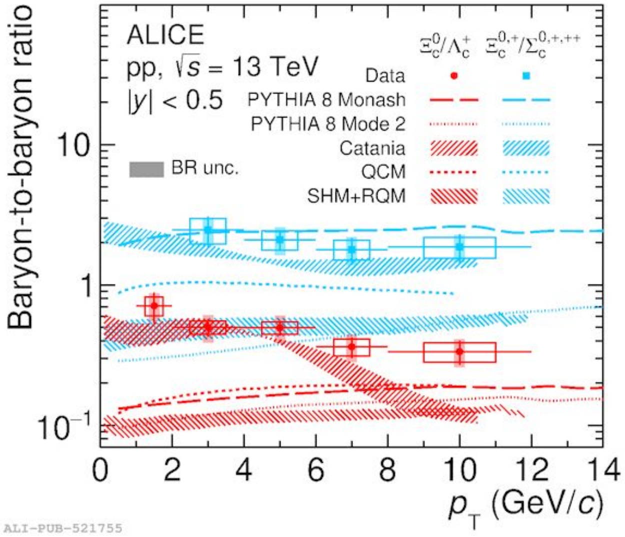
A complete list of all the parameters that differ from the Monash tune for the three different models are listed in the table below.

Parameter	Monash	Mode 0	Mode 2	Mode 3
StringPT:sigma	= 0.335	= 0.335	= 0.335	= 0.335
StringZ:aLund	= 0.68	= 0.36	= 0.36	= 0.36
StringZ:bLund	= 0.98	= 0.56	= 0.56	= 0.56
StringFlav:probQQtoQ	= 0.081	= 0.078	= 0.078	= 0.078
StringFlav:ProbStoUD	= 0.217	= 0.2	= 0.2	= 0.2
StringFlav:probQQ1toQQ0join	= 0.5, 0.7, 0.9, 1.0	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275
MultiPartonInteractions:pT0Ref	= 2.28	= 2.12	= 2.15	= 2.05
BeamRemnants:remnantMode	= 0	= 1	= 1	= 1
BeamRemnants:saturation	-	= 5	= 5	= 5
ColourReconnection:mode	= 0	= 1	= 1	= 1
ColourReconnection:allowDoubleJunRem	= on	= off	= off	= off
ColourReconnection:m0	-	= 2.9	= 0.3	= 0.3
ColourReconnection:allowJunctions	-	= on	= on	= on
ColourReconnection:junctionCorrection	-	= 1.43	= 1.20	= 1.15
ColourReconnection:timeDilationMode	-	= 0	= 2	= 3
ColourReconnection:timeDilationPar	-	-	= 0.18	= 0.073

$\Xi_c^{0,+}$ production in pp collisions at the LHC

Phys. Rev. Lett. 128 (2022) 012001



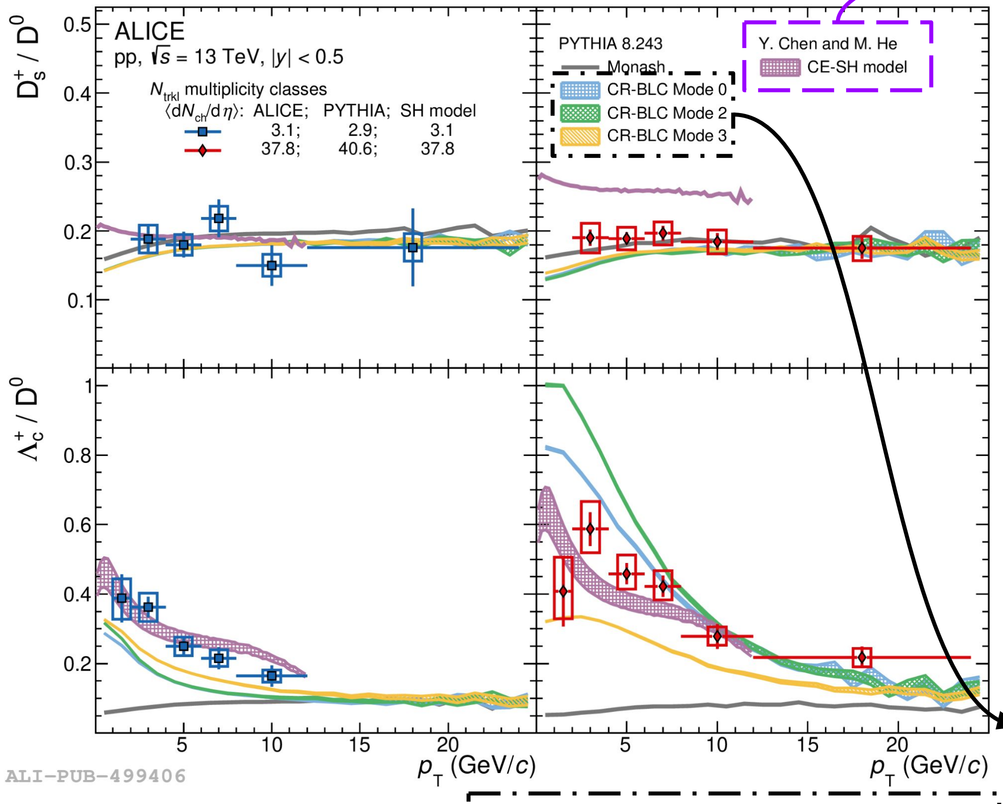


- **$\Xi_c^{0,+}/D^0$ underestimated by all the models**
- $D_s^+/(D^0+D^+)$ in line with e^+e^- results
  → are baryons "strange"? JHEP 05 (2021) 220
- **$\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ described by Monash**
  → similar suppression in e+e– due to similar diquark masses? $(m(\mathrm{uu, ud, dd})_1 \approx m(\mathrm{us})_0)$

"Ξ_c is super interesting. The model in our paper does not have any mechanism for "strangeness enhancement" in the way that ropes do. Your observation is consistent with the fact that our CR model is missing an important ingredient: strangeness enhancement.
[...] I think the strangeness enhancement is evidence that more is going on."

P. Skands, iterations with ALICE PWGHF conveners in 2020 about CR-BLC

Charm production in pp as a function of multiplicity



Phys. Lett. B 829 (2022) 137065

Why Mode 3 Λ_c/D^0 decreasing with increasing multiplicity with Mode 3?

CE-SH model (Phys. Lett. B 815 (2021) 136144)

- SHM+RQM model in pp collisions assuming a grand-canonical ensemble (GCE) generalized to the canonical one (CE)
  →global (GCE) to local (CE) charge conservation
- Explore how Λ_c^+/D^0 dependence vs. multiplicity can be explained as an increasing canonical suppression from high to low system size (i.e. multiplicity)

"Another possibility that comes to mind is that the very highest multiplicities could represent events that do not have so much CR going on. [...] If one looked, e.g., at an imaginary sample with a fixed number of MPI, then events that had a lot of CR would end up at low multiplicities, presumably with high baryon fractions, while events from the same sample with low (stochastic) CR would end up with high multiplicities and presumably low baryon fractions."

P. Skands, iterations with ALICE PWGHF conveners in 2020

Λ_c^+/D^0 ratio in pp and Pb-Pb collisions