ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

INFN
Istituto Nazionale di Fisica Nucleare

A personal

Overview on hadronization of quarks in proton-proton and e^+e^- collisions

baryons

heavy-flavour

p-Pb and Pb-Pb

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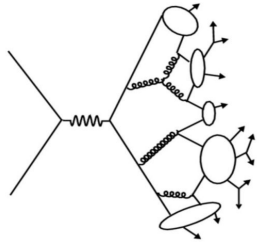
MESON 2023
17th International Workshop on Meson Physics
22nd - 27th June 2023, Kraków, Poland

Hadronization

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

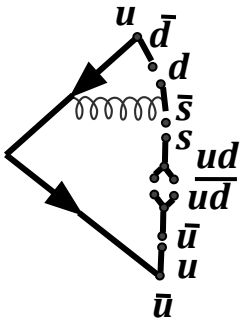


- **No first-principle description of hadron formation**
  - Non-perturbative problem, not calculable with QCD
  - Necessary to resort to models and make use of phenomenological parameters

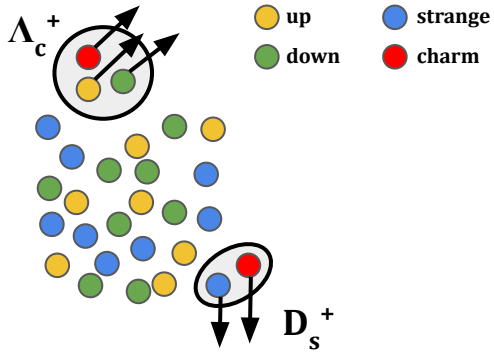
- **Different mechanisms depending on the system size**
  - e^+e^-, pp collisions: fragmentation
  - heavy-ion collision (e.g. Au–Au, Pb–Pb): coalescence in the quark-gluon plasma (QGP) → a few references in this talk

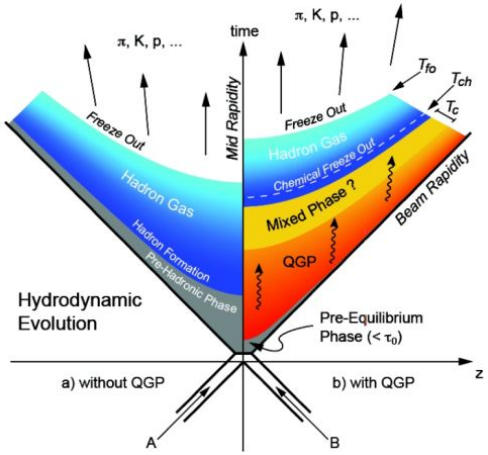
Focus of this talk

Fragmentation



Coalescence





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

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e^+e^- collisions

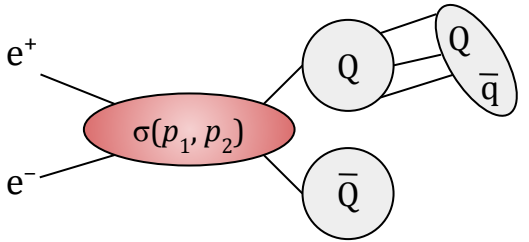
- "Vacuum-like" system
- Hadronization described with string models

Factorization approach

$$\frac{\mathrm{d}\sigma^{\mathrm{H_c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{H_c}}}(p_{\mathrm{T}};\mu_{\mathrm{F}},\mu_{\mathrm{R}}) = \frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(p_1,p_2,\mu_{\mathrm{F}},\mu_{\mathrm{R}}) \otimes D_{\mathrm{c}\to\mathrm{H_c}}(z=p_{\mathrm{H_c}}/p_{\mathrm{c}},\mu_{\mathrm{F}})$$

Hard scattering cross section (perturbative calculations)

Fragmentation function (hadronization)



Hadron production at large Q^2 - pp collisions

Factorization approach

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

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

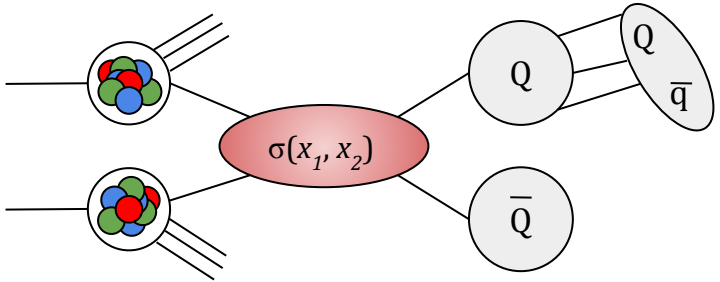
e^+e^- collisions

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

Multi-parton interactions (**MPIs**)

p p

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



Independent fragmentation

- **Fragmentation functions** assumed **universal** among collision systems and **constrained** from **e^+e^-** and **e^-p measurements**

Hadronization: string models

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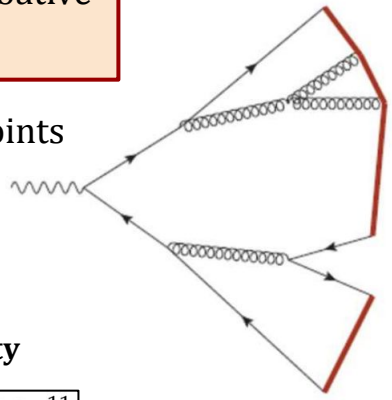
Event generators: final stage of parton shower interfaced with non-perturbative hadronization models



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

κ: string tension

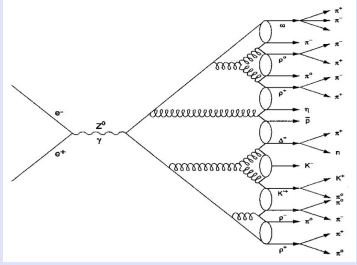
$$P(\text{string breaking}) \propto \exp\left(-\frac{\pi m_{\mathrm{T,q}}^2}{\kappa}\right) = \exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa}\right)\exp\left(-\frac{\pi p_{\mathrm{T,q}}^2}{\kappa}\right)$$

Tunneling probability

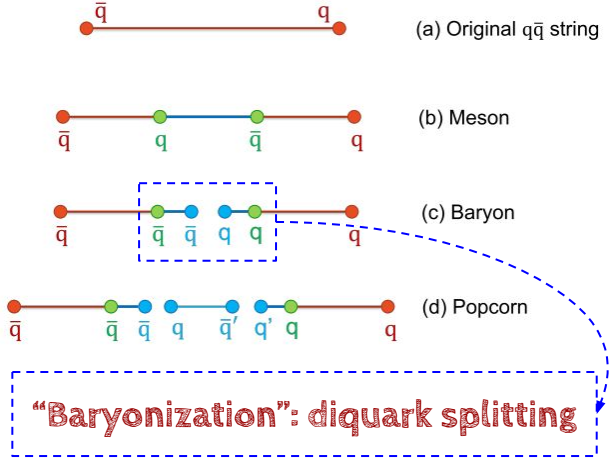
$$\mathrm{u} : \mathrm{d} : \mathrm{s} : \boxed{\mathrm{c}} \simeq 1 : 1 : 1/3 : \boxed{10^{-11}}$$

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

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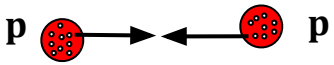
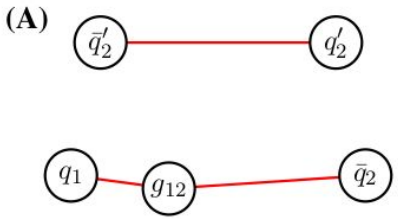
JHEP 08 (2015) 003



- 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

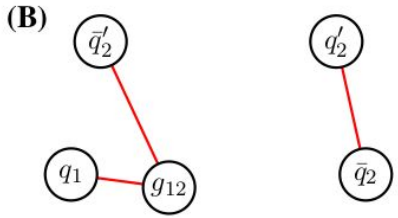
$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

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 Monash

PYTHIA

Success of the independent fragmentation

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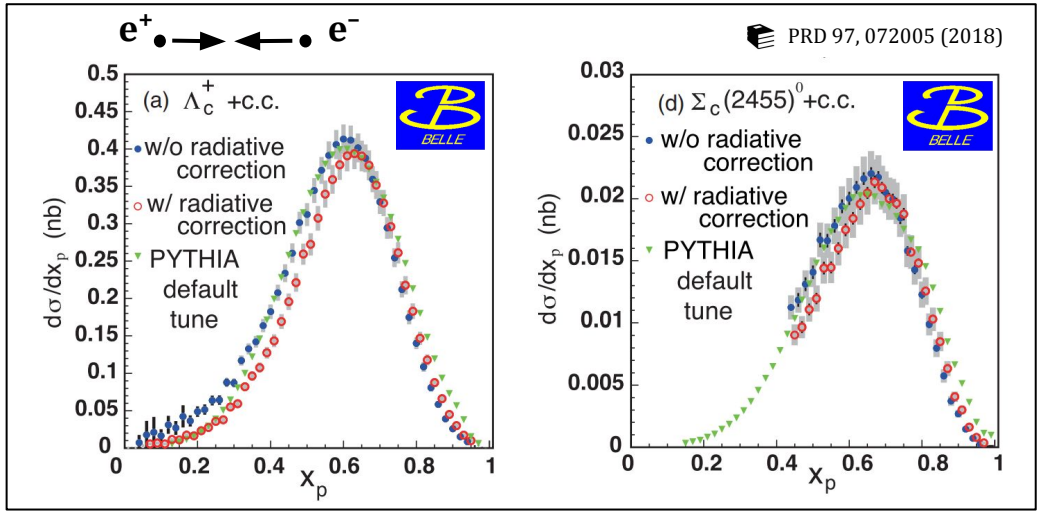
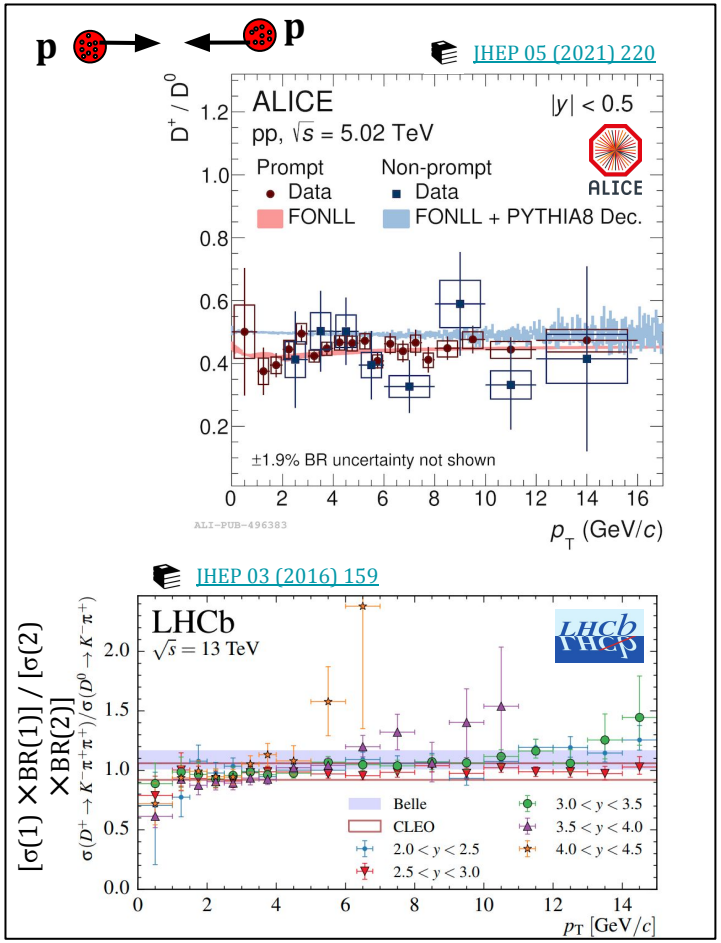


- **Charm-hadron** production in **e⁺e⁻** collisions described by **PYTHIA**
- **Heavy-flavour meson-to-meson** ratios in **pp** collisions:
  - no significant p_T-dependence
  - **described** by models based on **factorization** and with **fragmentation functions** constrained **from e⁺e⁻** collisions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



Bugs in our ears - strangeness enhancement

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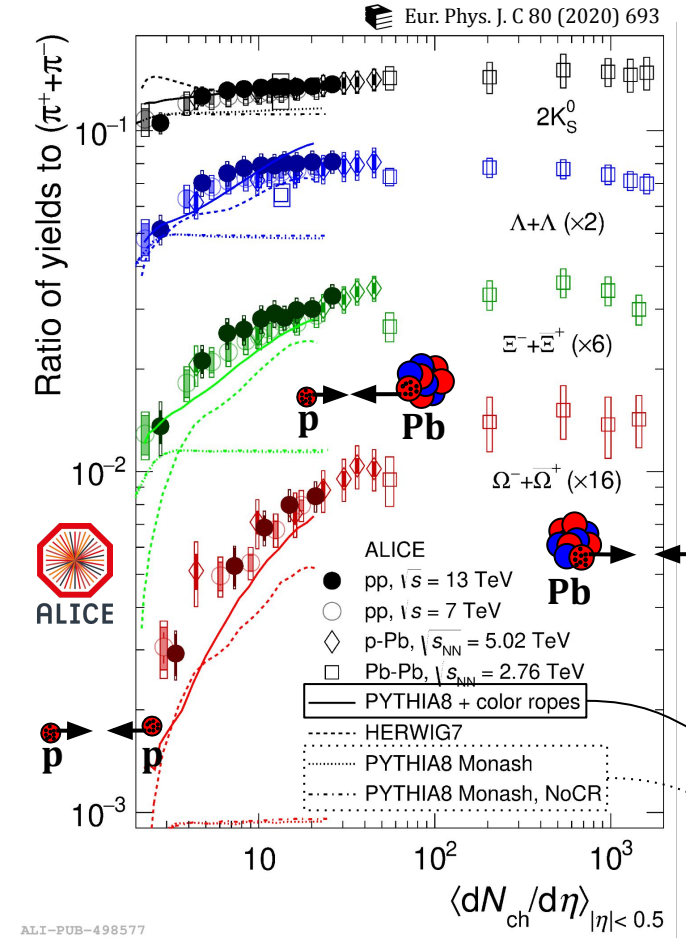
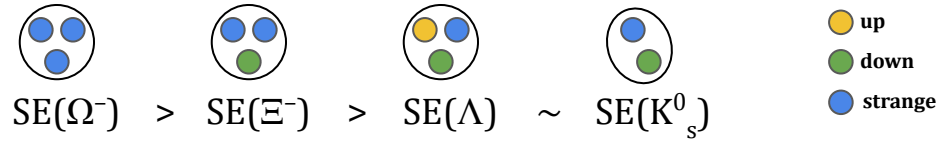


- **Strangeness enhancement** (SE): yield-ratio between (multi-)strange hadrons and $\pi^{\pm}$ larger in heavy-ion collisions than minimum-bias pp collisions
- **Strange-content hierarchy** → not a meson-baryon matter!



Historically considered a key signature of QGP formation…

… but data show a **smooth trend from pp to Pb–Pb collisions**

Ropes: strangeness production favoured by string increased tension due to overlapping strings (parallel, antiparallel)

PYTHIA Monash: MPIs + string fragmentation

Bugs in our ears - strangeness enhancement

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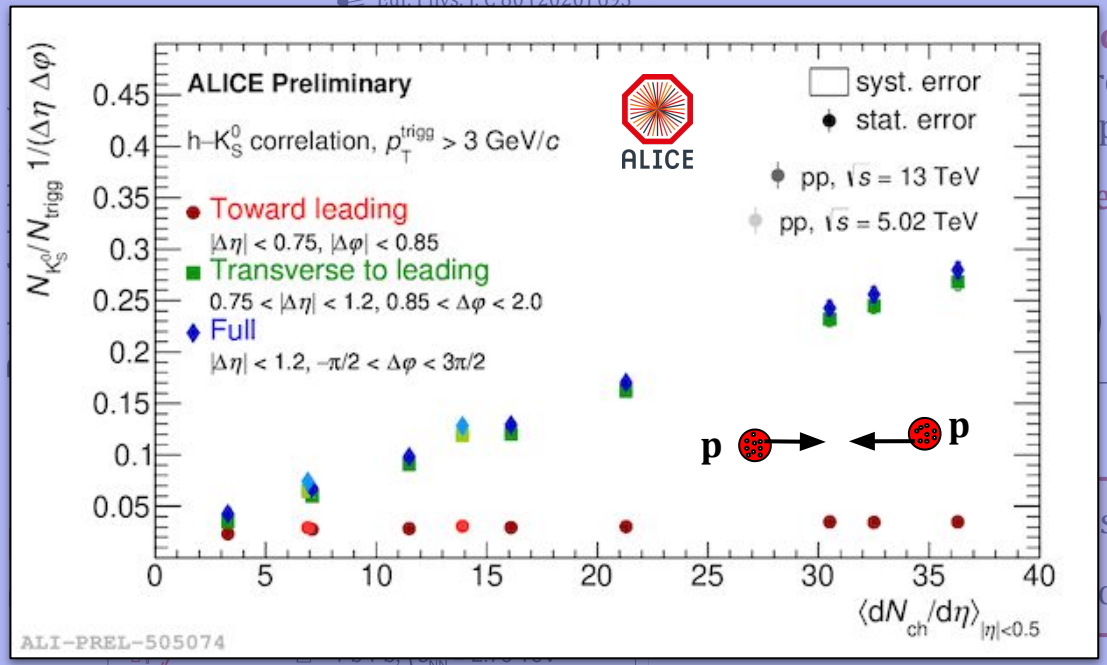

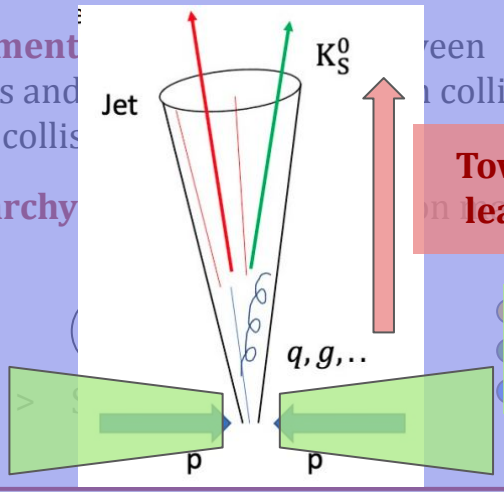

Towards leading

Transverse to leading

- Trigger (leading) particle: highest p_T → ~ jet axis
- Proxy of quark from hard scattering

- Normalized K^0_s yields per trigger particle vs. event multiplicity
- Full and out-of-jet K^0_s yield increasing with multiplicity
- In-jet contribution ~flat

Same for jets with Ξ particles!

The underlying event covers a crucial role to explain the strangeness production in pp collisions at the LHC

Bugs in our ears - baryon enhancement

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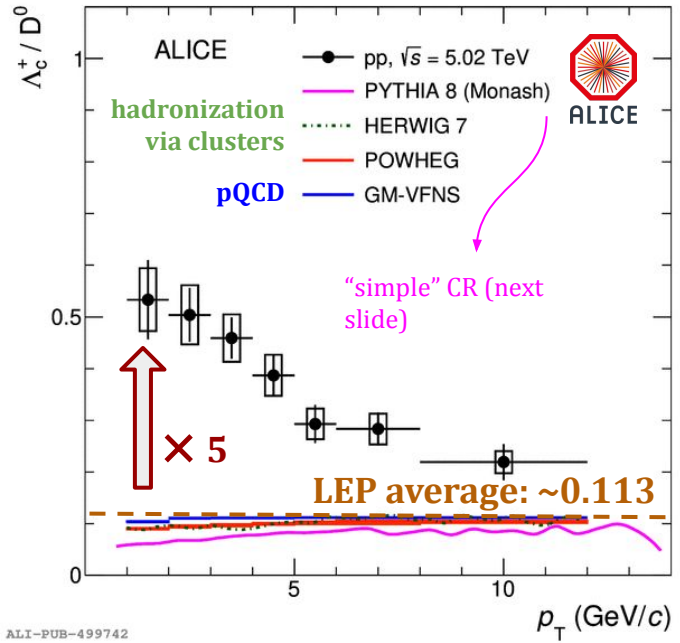
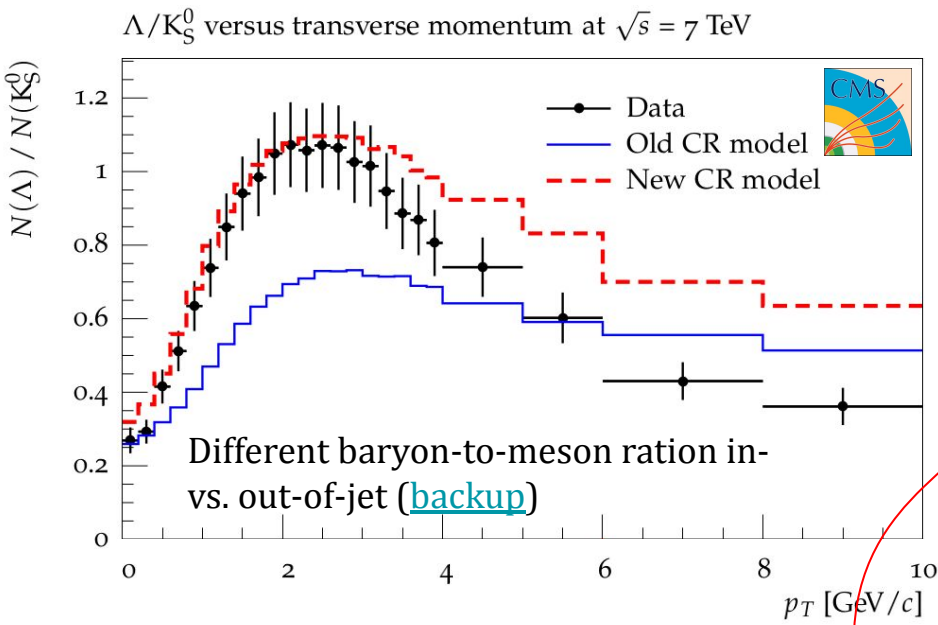
PRC 104 (2021) 054905 PRL 127 (2021) 202301



JHEP 08 (2015) 003

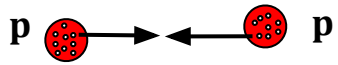


- Significant **baryon-to-meson** ratio **enhancement** in **pp** compared to **e⁺e⁻** collisions
- **Pythia** predictions and **pQCD**-based calculations based of **factorization** and **fragmentation functions** tuned on **e⁺e⁻ underestimate** the results in pp collisions

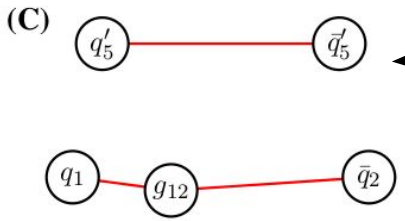
"New" colour reconnection (CR) model better describes the data

“Baryonization” in pp collisions - CR beyond leading color

JHEP 08 (2015) 003



No CR

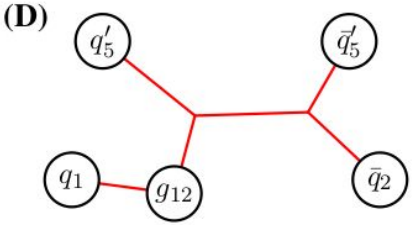


CR beyond Leading Color approximation (CR-BLC)

- “**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
  → 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, according to 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

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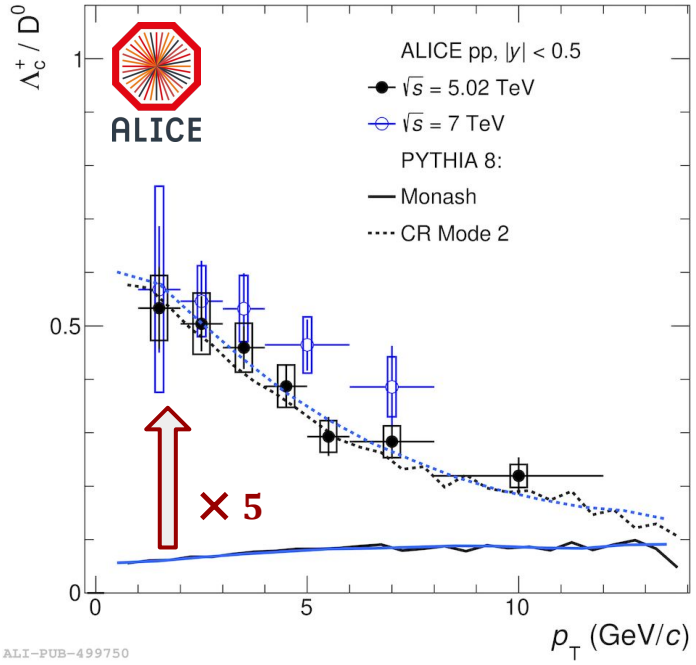
p p

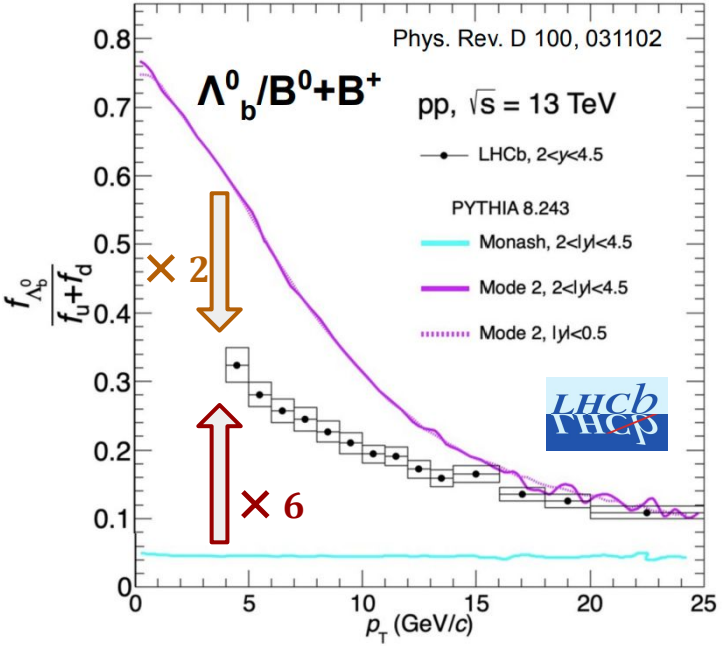
CMS

Λ_c^+/D^0 at midrapidity in backup

Phys. Rev. C 104 (2021) 054905



Phys. Rev. D 100, 031102



- PYTHIA **Monash** predictions **underestimate** the measurement up to **~5x, 6x**
- **CR Mode 2 agrees** with Λ_c^+/D^0 at $|y| < 0.5$
- CR Mode 2 estimates a $\Lambda_b^0/(B^0 + B^+)$ about **2x larger**

Any "obvious" explanation (parton and/or heavy-quark density)**?**

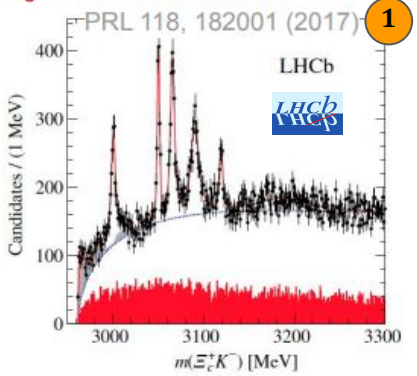
Charm "baryonization" - different approaches

p p

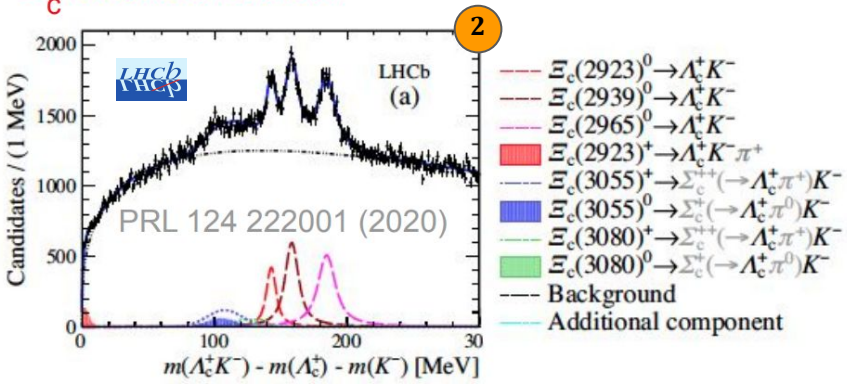
SHM+RQM PLB 795 (2019) 117-121 — Statistical approach

- Hadron formation driven by the mass at a hadronization temperature T_H → **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

Ω_c excited states

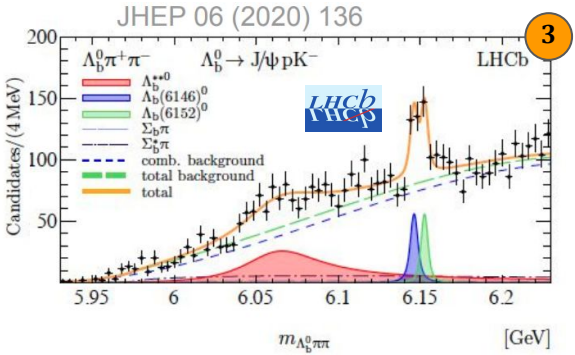


Ξ_c excited states



Do these states exist?

Λ_b excited states



Many new hadrons popping up!

4 5 6 … … and more!

Charm "baryonization" - different approaches

p p

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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

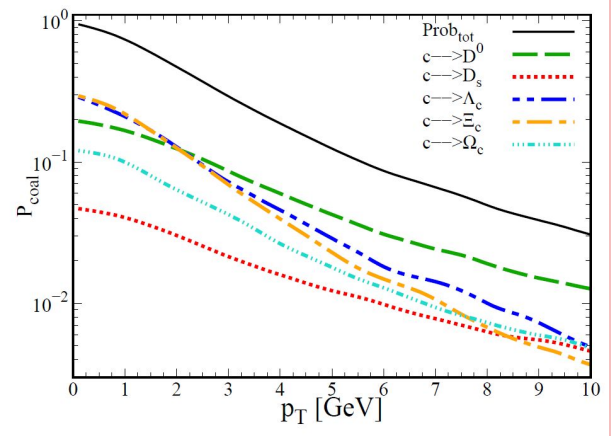
Quark Coalescence Mechanism (QCM) Eur. Phys. J. C (2018) 78: 344

- **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

Statistical approach + coalescence

Catania coalescence model PLB 821, 136622 — Fragmentation + coalescence

- **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 $[m_{H^*}/m_H]^{3/2} \times \exp(-\Delta E/T)$



Charm "baryonization" - different approaches

p → ← p

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SHM+RQM PLB 795 (2019) 117-121

Statistical approach

- Hadron formation driven by the mass at a hadronization temperature T_H → **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
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n_i [$\times 10^{-4}$ fm^{-3}] (T_H [MeV])	Λ_c^+	$\Xi_c^{0,+}$	Ω_c^0
	0.3310	0.0874	0.0064
	0.6613	0.1173	0.0144

Quark Coalescence Mech

- **Thermal weights** to
  and vector mesons
- **Hadron p_T- spectru**
  from the hard scatte
  nearby in phase-spa

- **Different hadronization mechanisms in pp collisions compared to e^+e^- collisions**
- **Assumption of independent fragmentation (or better "hadronization") no more valid**

Catania coalescence model PLB 821, 136622

Fragmentation + coalescence

- **Thermalised system** of u, d, s and gluons
- Charm quark can hadronize either via **fragmentation** or **coalescence**
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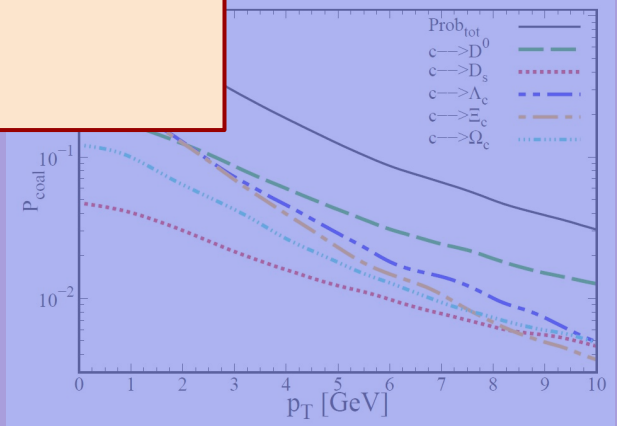

Λ_c^+/D^0 ratio in pp at the LHC vs. model predictions

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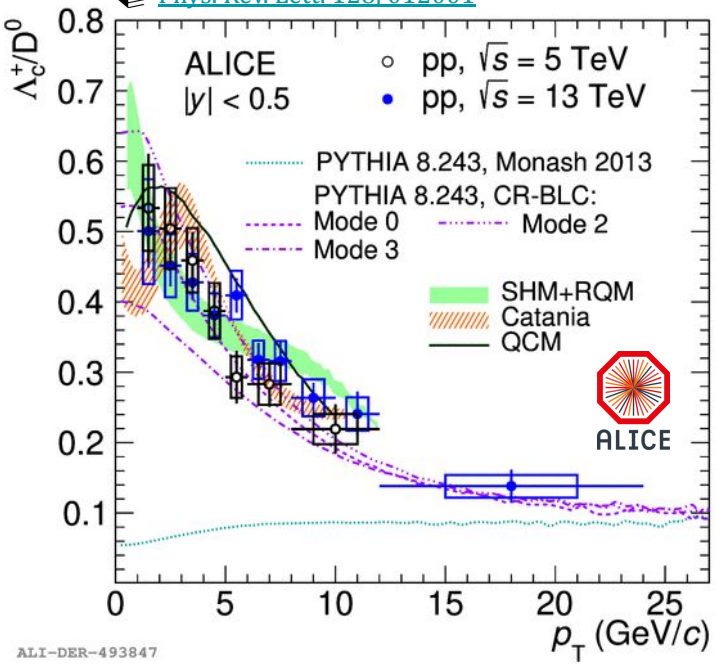
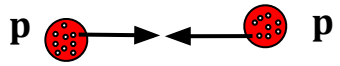
Phys. Rev. Lett. 128, 012001





They all foresee baryon enhancement

	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
- **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 e^+e^- and pp collisions

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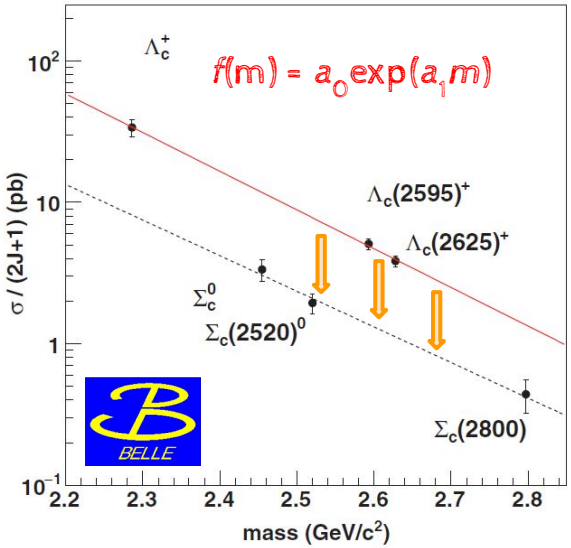
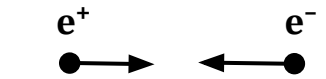
Phys. Rev. D 97, 072005



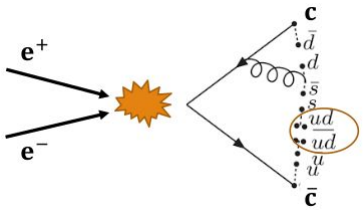


$\sqrt{s}$ = 10.52 GeV

(PYTHIA 8)

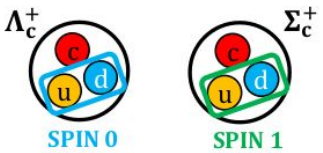
$m(\mathrm{ud})_0 = 579\ \mathrm{MeV}/c^2$

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

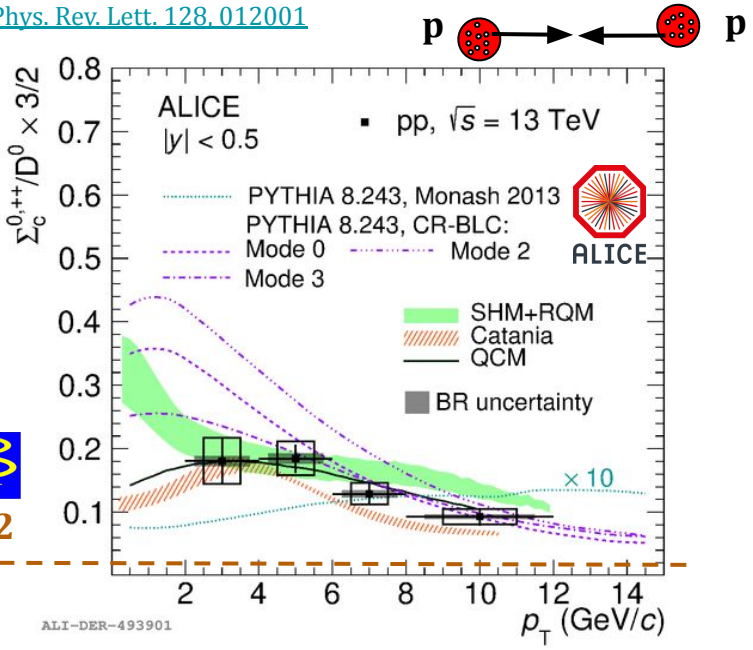


- Σ_c states **suppressed** by ~3-4 than Λ_c ones
- String model: penalty due to the **diquark mass**!
  - $\Lambda_c^+(I=0)$: c-$(\mathrm{ud})_0$
  - $\Sigma_c^+(I=1)$: c-$(\mathrm{ud})_1$

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



Phys. Rev. Lett. 128, 012001



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

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

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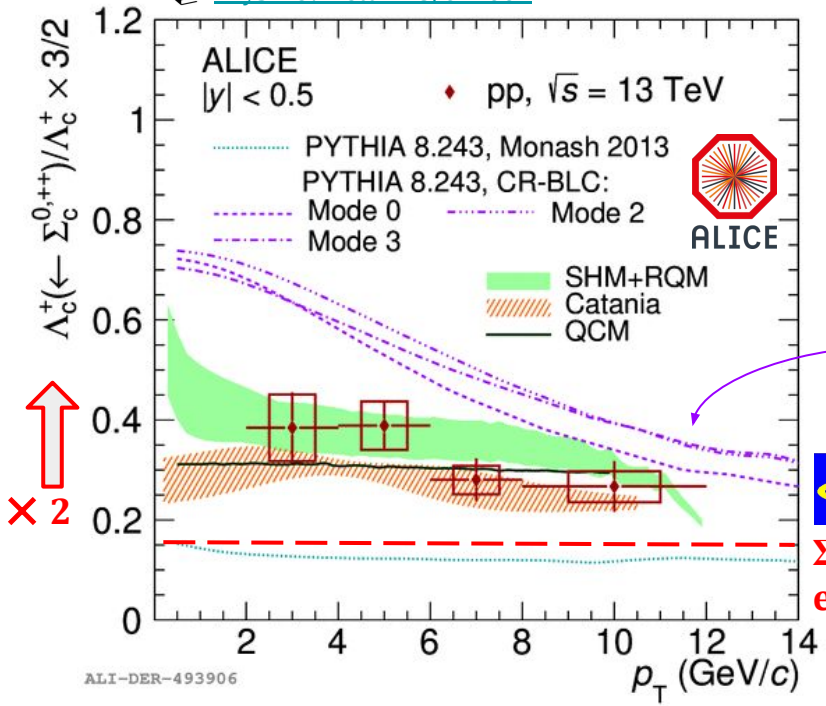
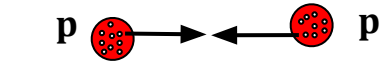
Phys. Rev. Lett. 128, 012001



× 2

$\Sigma_c^{0,+,++}/\Lambda_c^+ \sim 0.17$
e^+e^-



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

  $(2 \leq p_T < 12\ \text{GeV}/c)$ **0.38 ± 0.06 ± 0.06**

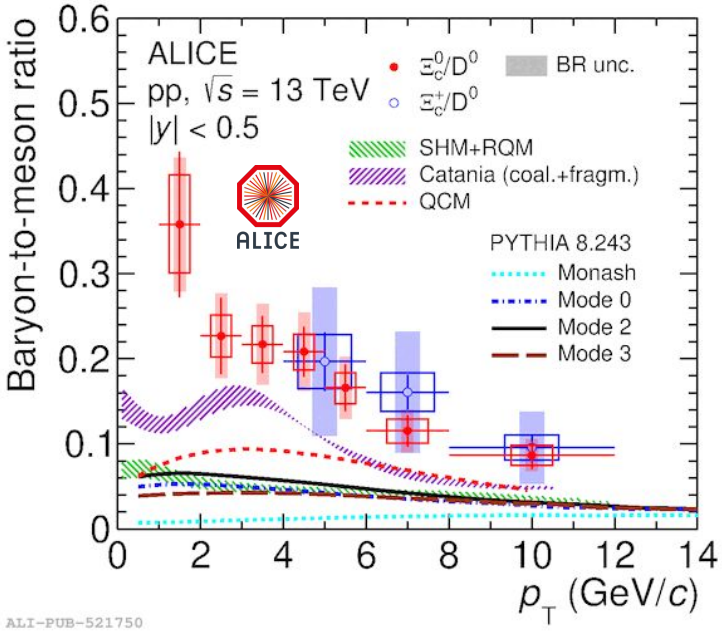
- ~2 times larger than e^+e^- → relative increase of $\Sigma_c^{0,+,++}$
- $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratio **overestimated** by **CR-BLC**

Default parameter **tunes not fully describing** the **inclusive prompt** Λ_c^+ **production**?

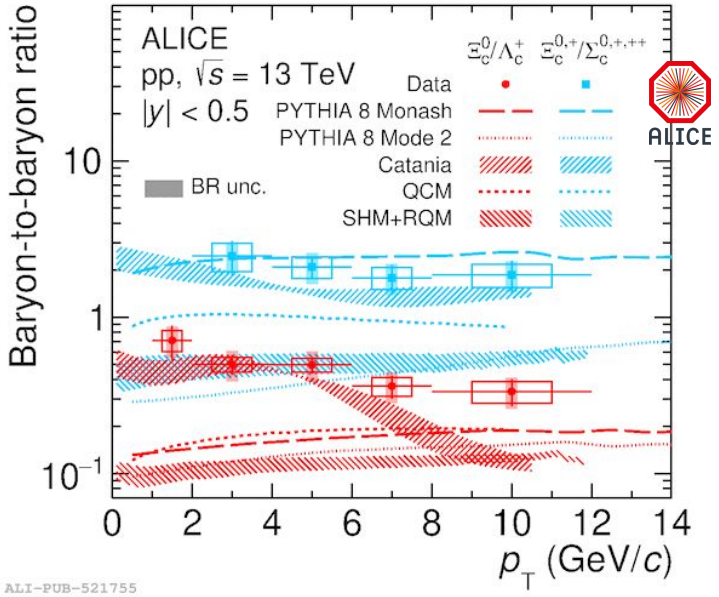
Inputs from production **measurements** of **excited c-baryons**? (e.g. $\Lambda_c^+(2595)$, $\Lambda_c^+(2625)$, $\Lambda_c^+(2880)$, $\Lambda_c^+(2940)$)

New: **c-diquark** role **crucial**. **Re-tuning needed**?

$\Xi_c^{0,+}$ 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 (JHEP 05 (2021) 220)
  → are baryons "strange"?
- **$\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ described by 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-baryon enhancement - fragmentation fractions

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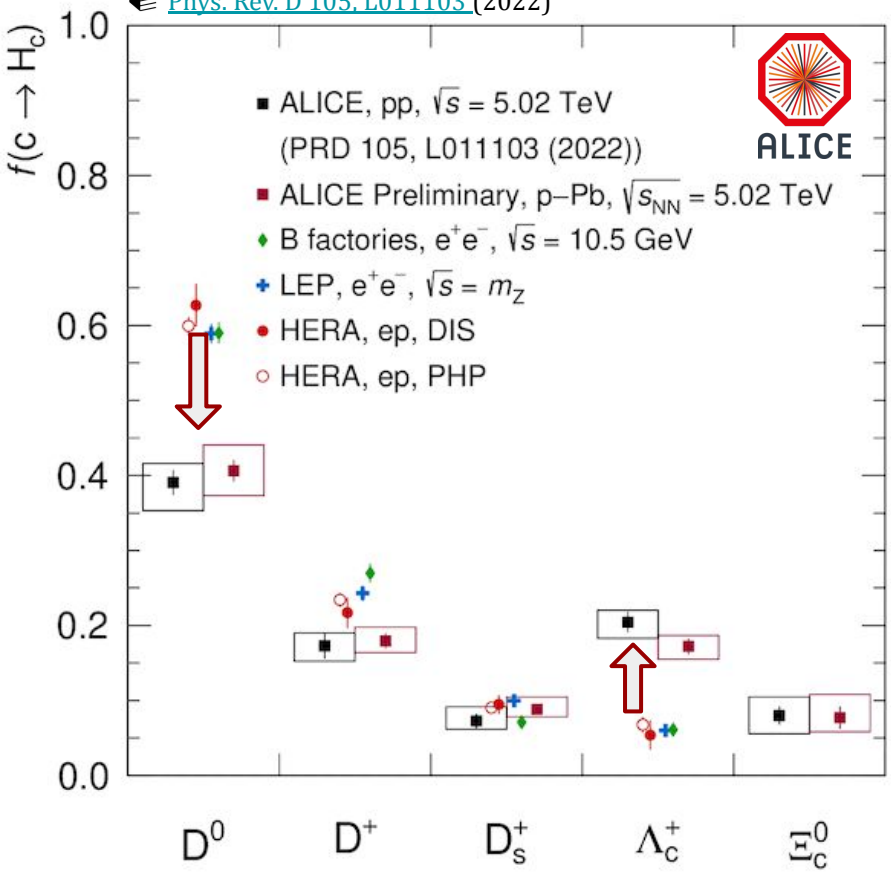
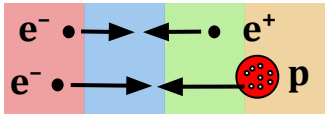
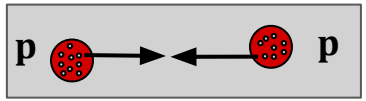
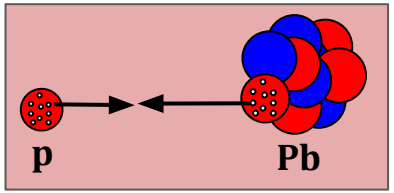
Phys. Rev. D 105, L011103 (2022)



ALI-PREL-541012







Baryon enhancement at the LHC

D mesons: ↓↓↓ ×1.4-1.6 with respect to e^+e^-
Λ_c^+ baryon: ↑↑↑ ×~ 3 with respect to e^+e^-

Evidence of for **different fragmentation fractions** at the LHC and e^+e^- (ep) collisions at lower $\sqrt{s}$

Independent fragmentation picture not valid in partonic-color-rich environment

HF production ratios in pp vs. multiplicity

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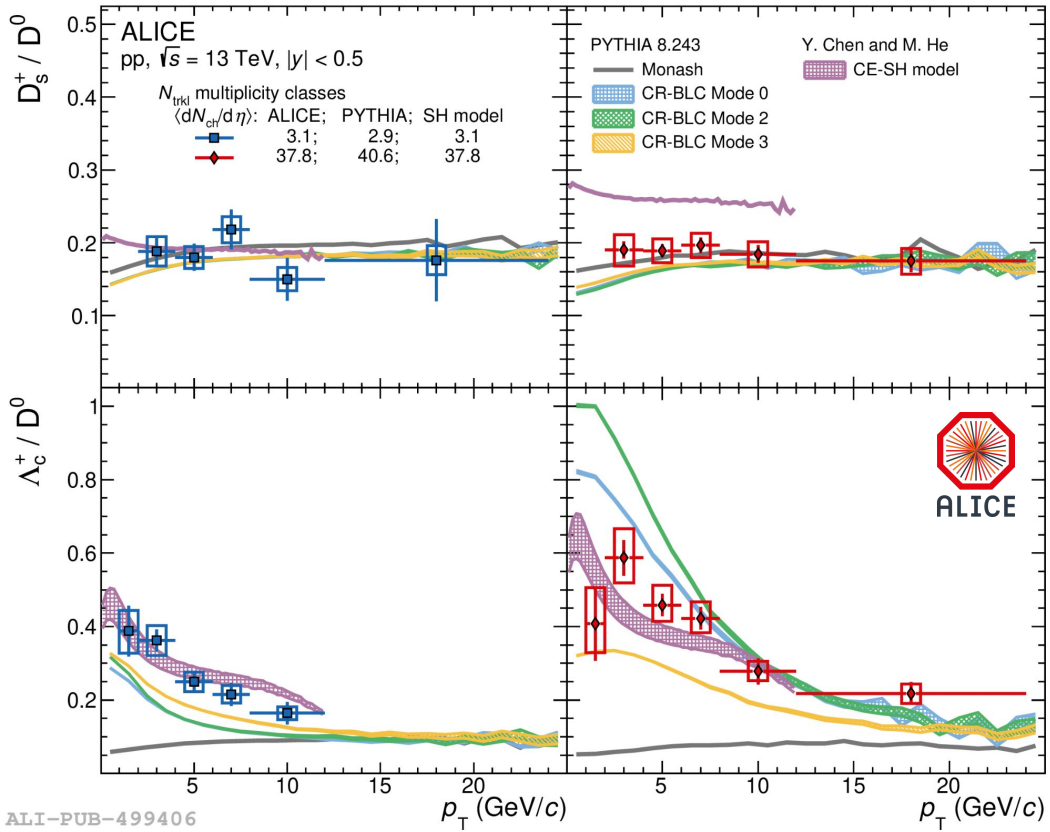
Phys. Lett. B 829 (2022) 137065



ALI-PUB-499406

Studies **vs. multiplicity**:

- **insights** into the **multi-parton interactions**
- **interplay** between **hard and soft mechanisms** in particle production

D_s^+/D^0 ratio

- **Flat in p_T** and in **multiplicity**
- **Described by all PYTHIA tunes** (Monash included) **and CE-SH model** at **low mult.**
- **Overestimated** at **high mult.** by **CE-SH**

Λ_c^+/D^0 ratio

- **Decreasing in p_T**, p_T dependence described by PYTHIA BR-BLC modes at all event multiplicities
- Ratio **described CE-SH** model and significantly underestimated by Monash

HF production ratios in pp vs. multiplicity

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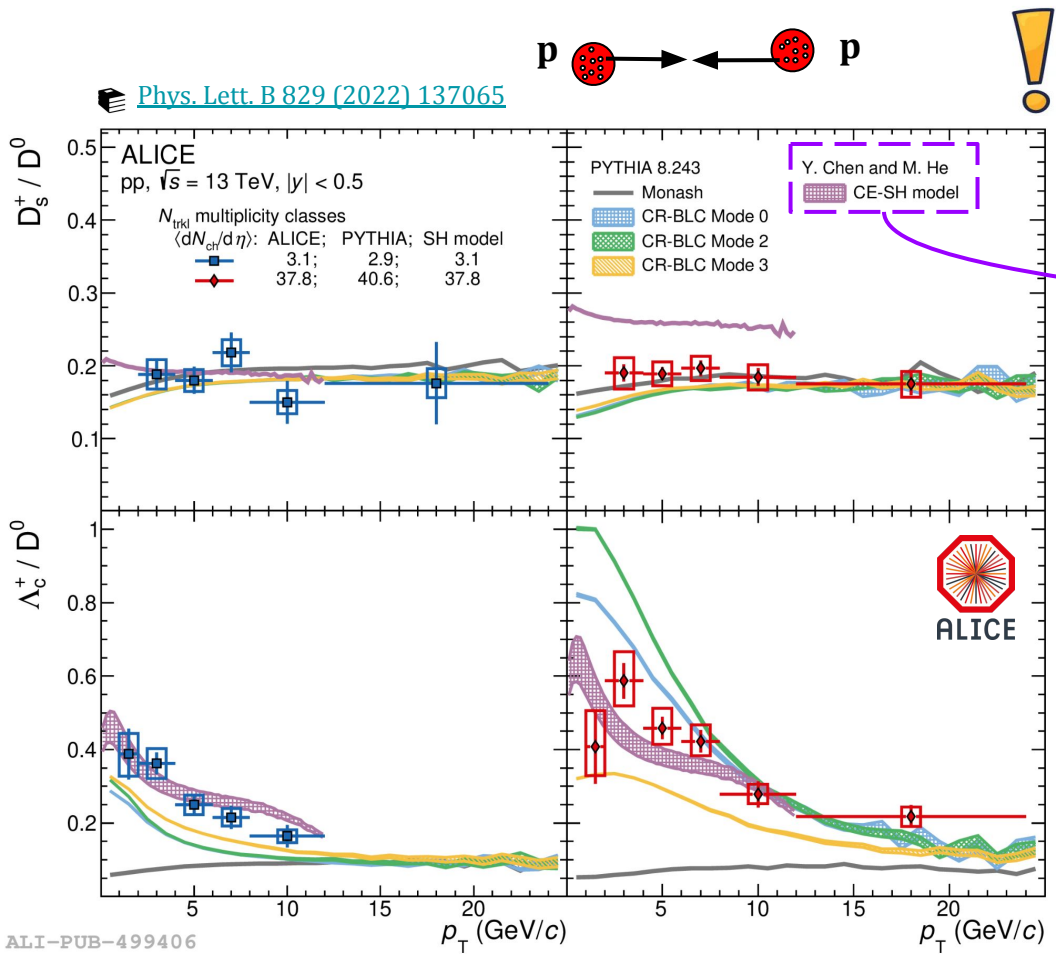


Studies **vs. multiplicity**:

- **insights** into the **multi-parton interactions**
- **interplay** between **hard and soft mechanisms** in particle production

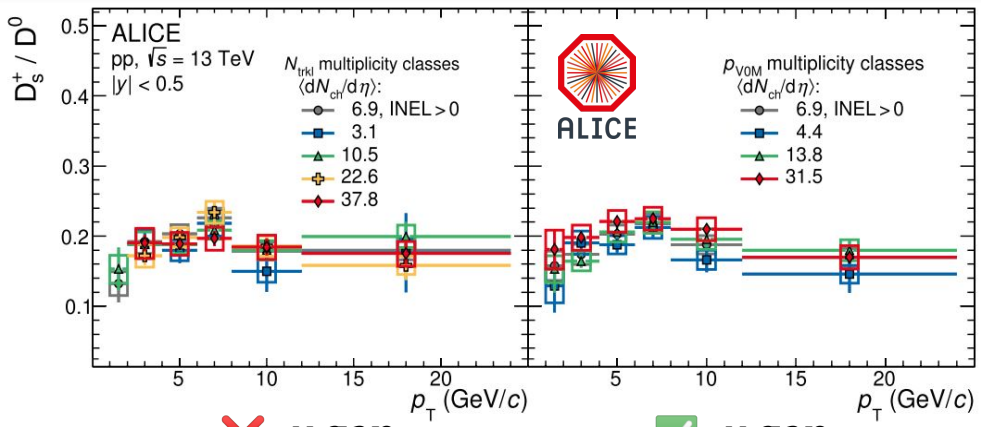
CE-SH model

- **SHM+RQM** model in pp collisions with grand-canonical ensemble (GCE) **generalized** to the **canonical** one (CE) →global (GCE) to **local** (CE) **charge conservation**
- Explore how **dependence vs. multiplicity** can be explained as an **increasing canonical suppression** from high **to low system size**

Phys. Lett. B 815 (2021) 136144

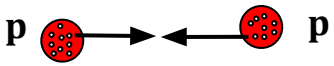
Strangeness enhancement in HF sector in pp collisions

Phys. Lett. B 829 (2022) 137065



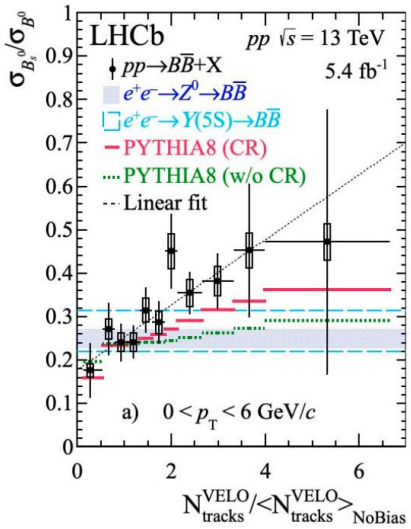
❌ *y* gap ✅ *y* gap

D_s^+/D^0

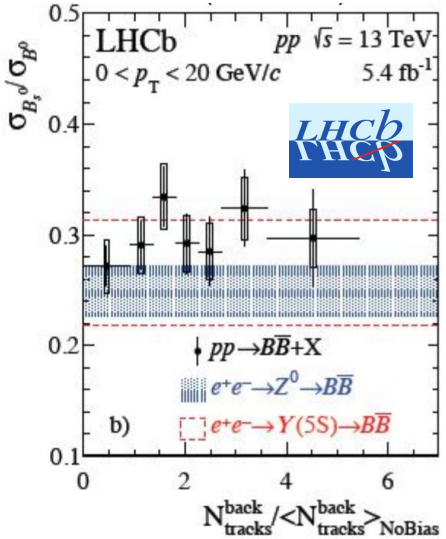


B_s^+/B^0 arXiv:2204.13042

❌ *y* gap



✅ *y* gap



Strangeness enhancement in HF sector in pp collisions

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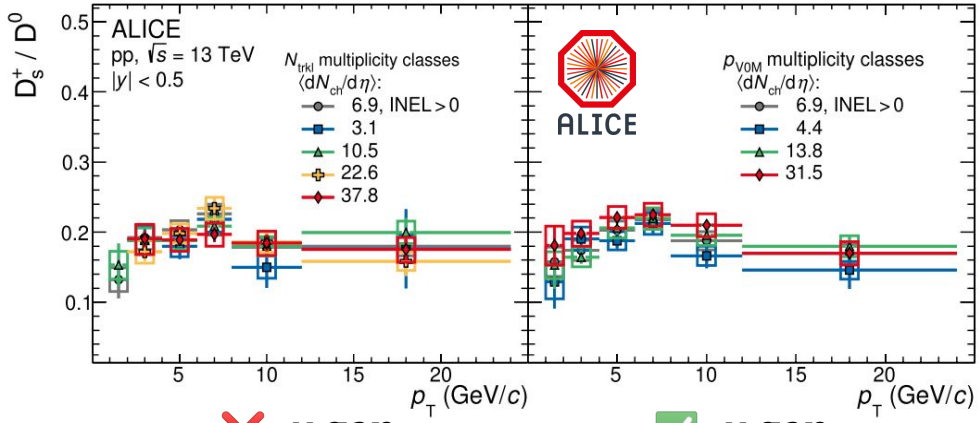
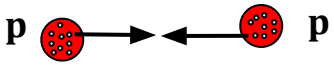
Phys. Lett. B 829 (2022) 137065



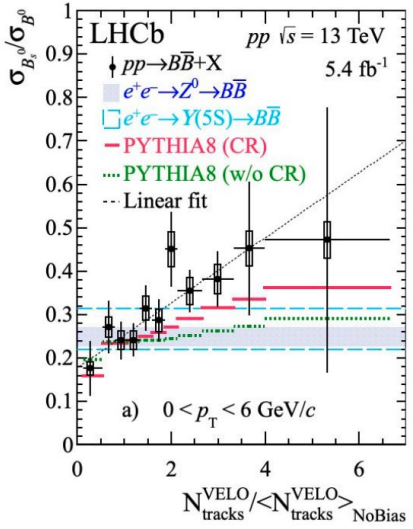
❌ *y* gap ✅ *y* gap

D_s^+/D^0

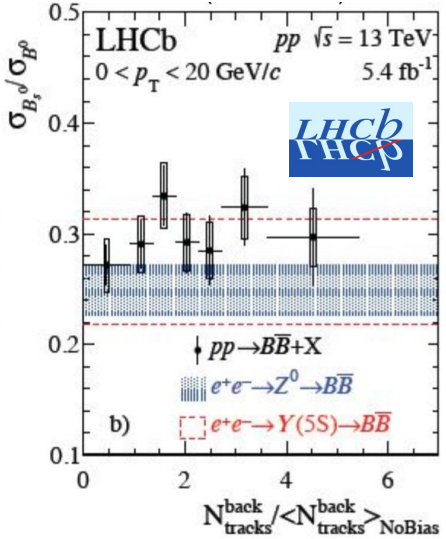


B_s^+/B^0 arXiv:2204.13042

❌ *y* gap



✅ *y* gap



❌ *y* gap between measurement and multiplicity estimation

- **No strangeness enhancement** in the **charm** sector vs. mult.
- **Strangeness enhancement** in the **beauty** sector vs. mult.

Charm baryon-to-meson ratio vs. multiplicity

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

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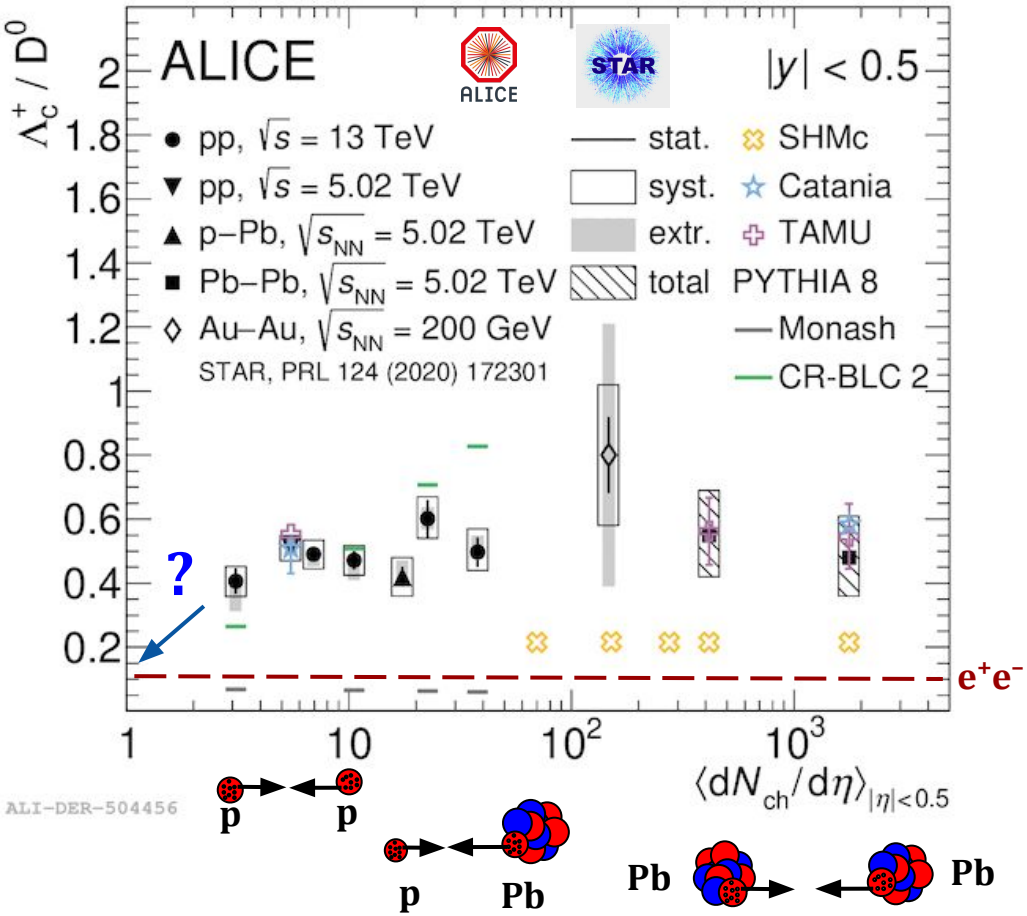


No evidence of **multiplicity dependence** of p_T-**integrated** Λ_c^+/D^0 ratio across collision systems, contrary to what shown by p_T-differential ones (backup)

- 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

Lowest multiplicities in pp collisions not yet covered

- possible to recover e^+e^-?
- looking forward to new LHC data!

Conclusions

Did you understand how quark hadronize in e^+e^- collisions?

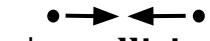
I think so!

Great! And in pp collisions?

mmh… not really…

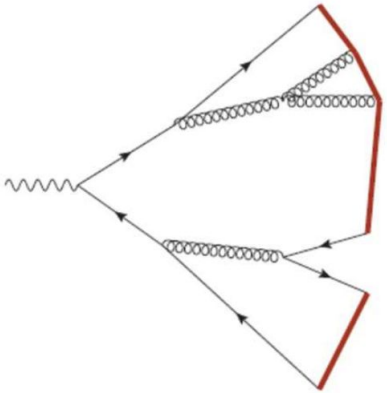
oh… what a pity…

Conclusions

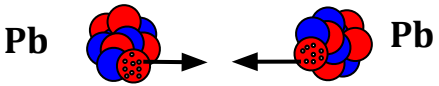


e^+e^- collisions

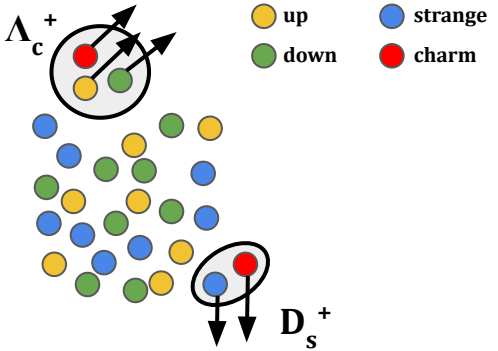
- "**Vacuum**-like" system
- **Hadronization** described by **string models**
  - Lund fragmentation: quark and diquark pairs popping up from QCD potential in the string



2 extremely different scenarios



- **QGP**: complex system with **partonic d.o.f**
- Equilibrium and collectivity
- **Hadronization** is **modified**



Conclusions

e^+e^- collisions

- pp collisions: environment rich of quarks and gluons which alter hadronization
- **Independent fragmentation** scenario **violated** already in pp collisions
- Still **far from** a complete **agreement** between **experiments** and **models** (strangeness enhancement, baryon enhancement, evolution with event multiplicity, …)

~~- Bigger e^+e^-, not far from vacuum~~
~~- Many independent hard scatterings (at least for HF)~~

p p

MPIs, system size

Pb Pb

pp collisions: the correct trait d'union?

The end

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MESON 2023

17th International Workshop on Meson Physics

22nd - 27th June 2023, Kraków, Poland

Thanks to A. Dainese, A. Rossi, C. Terrevoli, S. Trogolo, V. Zaccolo for the useful discussions and suggestions!

*"This work is **(partially)** supported by ICSC – Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by European Union – NextGenerationEU".*

Backup

Baryon-to-meson ratio of strangeness in vs. out-of-jet

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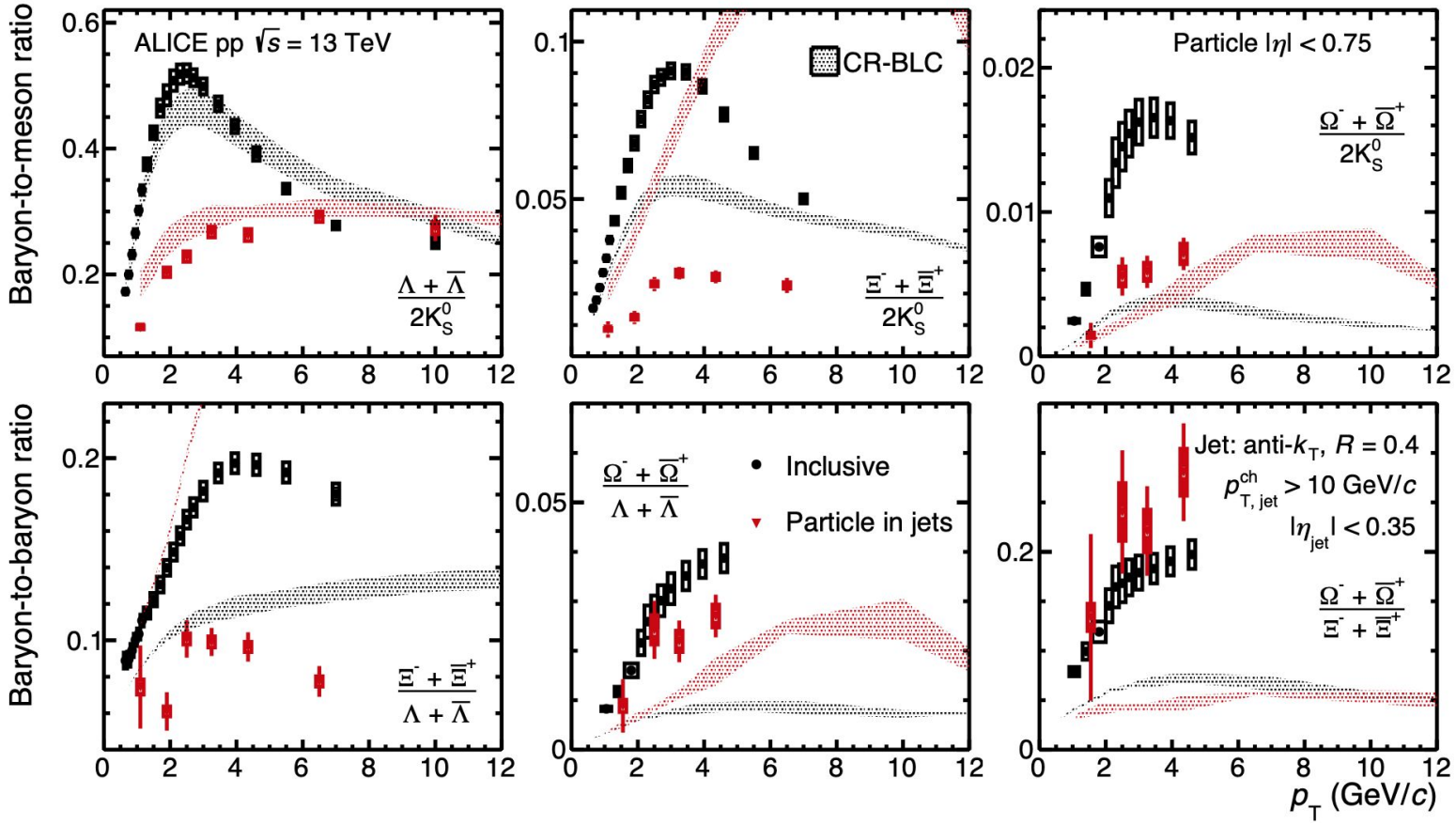

https://arxiv.org/abs/2211.08936

Back to main

Bugs in our ears - strangeness enhancement in b-sector

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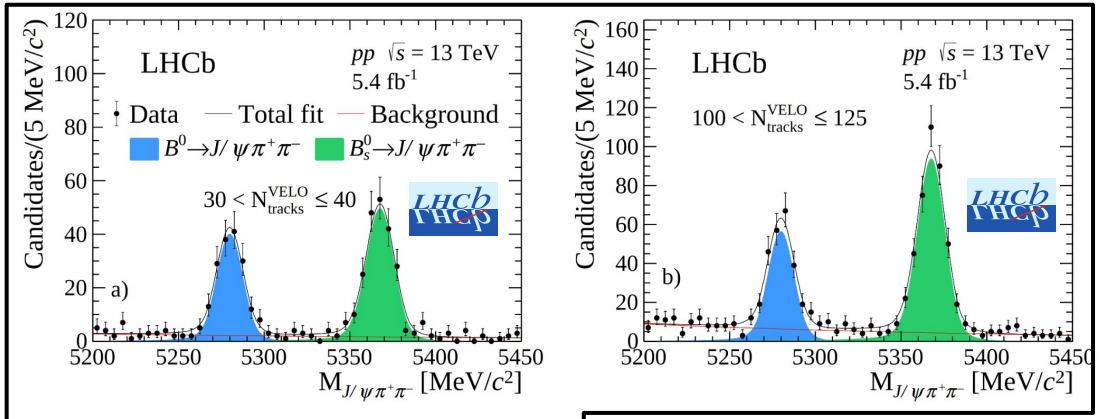
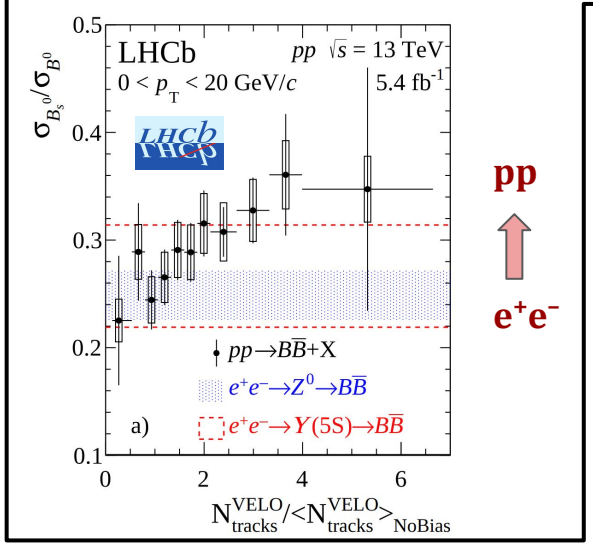
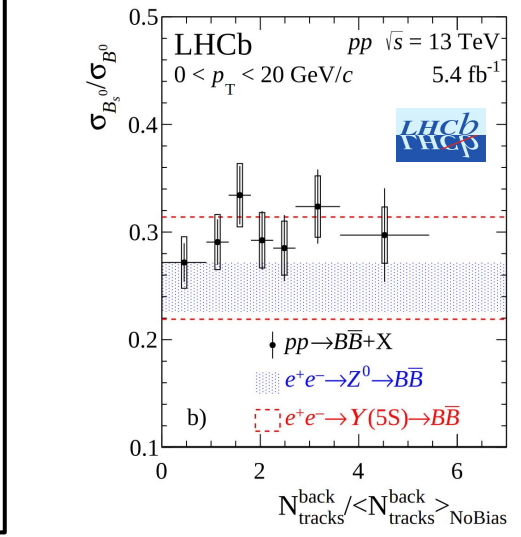




pp

e^+e^-



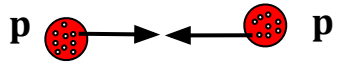
arXiv:2204.13042

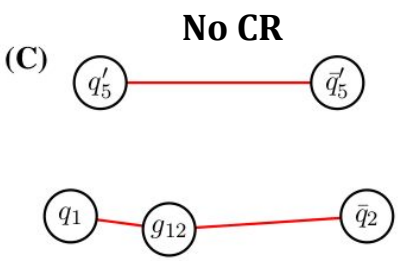
$B^0 \rightarrow J/\psi\pi^+\pi^-$ $B^0_s \rightarrow J/\psi\pi^+\pi^-$

- Beauty-quark production from hard scattering
- **Increase** of **strange-hadron** production **with multiplicity** in the **same *y* range** ($2 < y < 5$)
  - enhanced B^0_s/B^0 hadronization via coalescence?
  - increase of B^0_s/B^0 at low p_T due to local particle density?
    → autocorrelations
- **Flat trend** if **multiplicity** is estimated with a ***η*-gap** ($-3.5 < \eta < -1.5$)

“Baryonization” in pp collisions - CR beyond leading color

JHEP 08 (2015) 003





CR beyond Leading Color approximation (CR-BLC)

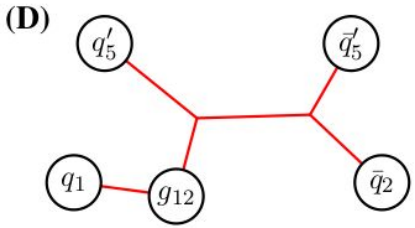
- “**Simplified QCD**” with 9 color indices to determine the string formation
- **String length minimization** over **all possible configurations**, even those beyond the Leading Color topology
  → Monash: only CR among LC
- Enhanced leading color among MPIs and beam remnants

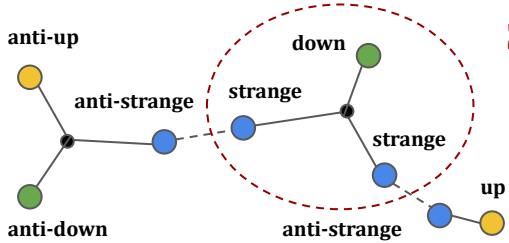
Conditions for color reconnections:

- **Invariant mass** of string *j*-th must 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, according to the time dilation due to the relative boost
  →**Mode 0, 2, 3**: different “severity” on this condition

PYTHIA

CR-BLC: junctions





Ξ^- via junction

Baryon-to-meson ratio for charm and beauty

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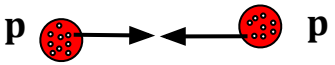

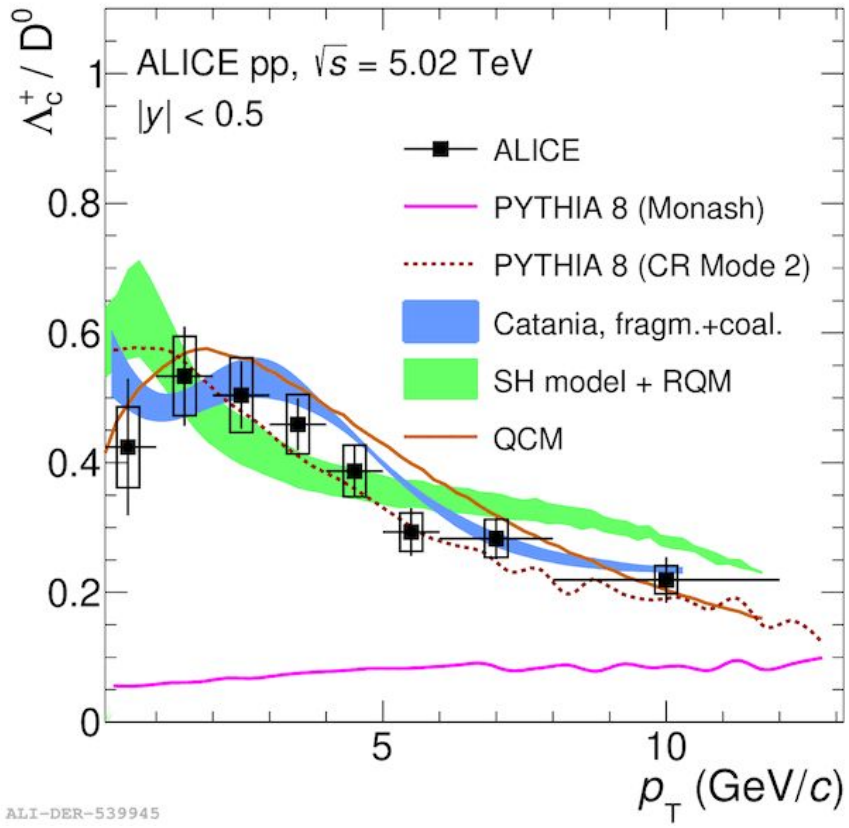

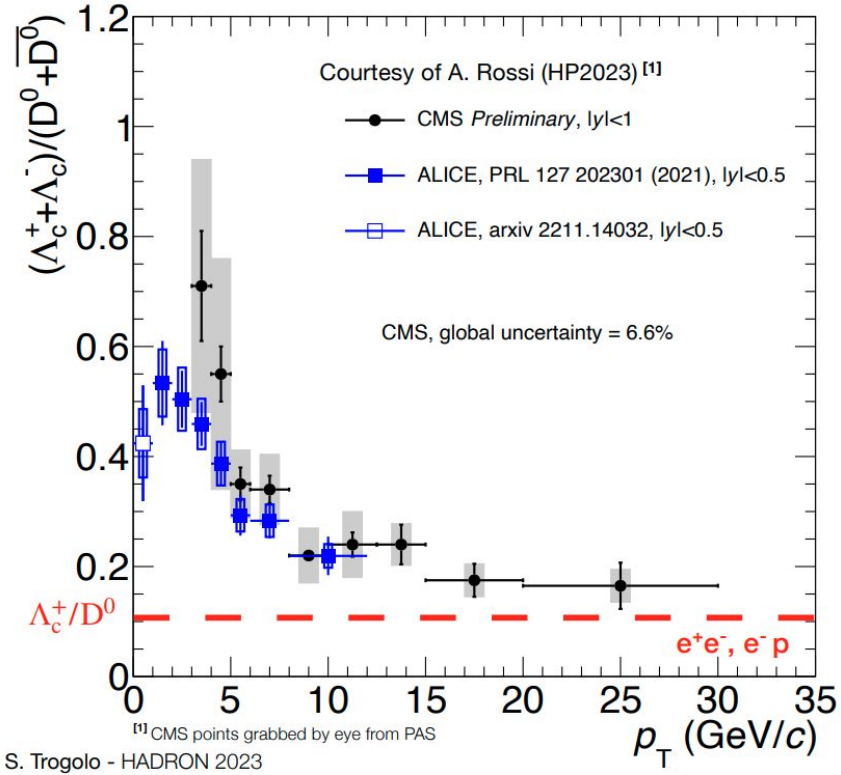

https://agenda.infn.it/event/33110/contributions/198233/attachments/106532/150101/Trogolo_HADRON_2023_final.pdf

Baryon-to-meson ratio for charm and beauty

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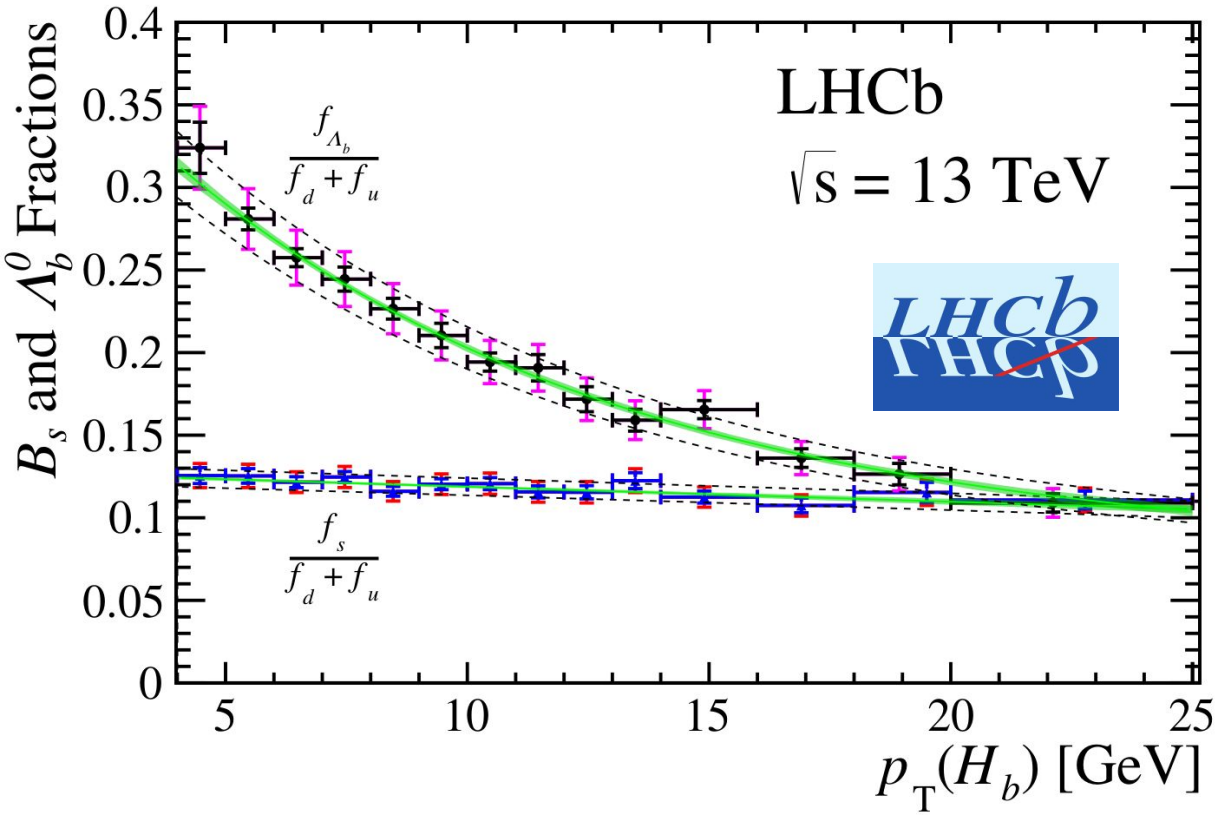
p p

Phys. Rev. D 100, 031102



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

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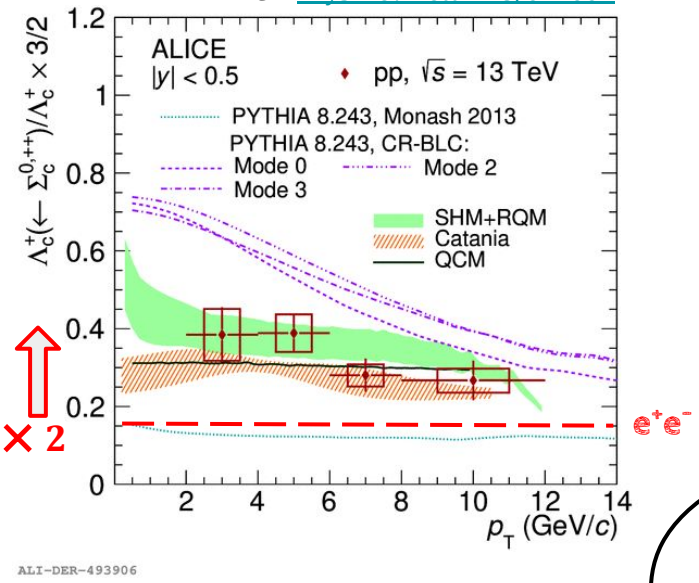
ALICE: Phys. Rev. Lett. 128, 012001



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

$$(2 \leq p_T < 12\ \text{GeV}/c)\quad 0.38 \pm 0.06 \pm 0.06$$

- ~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 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/)

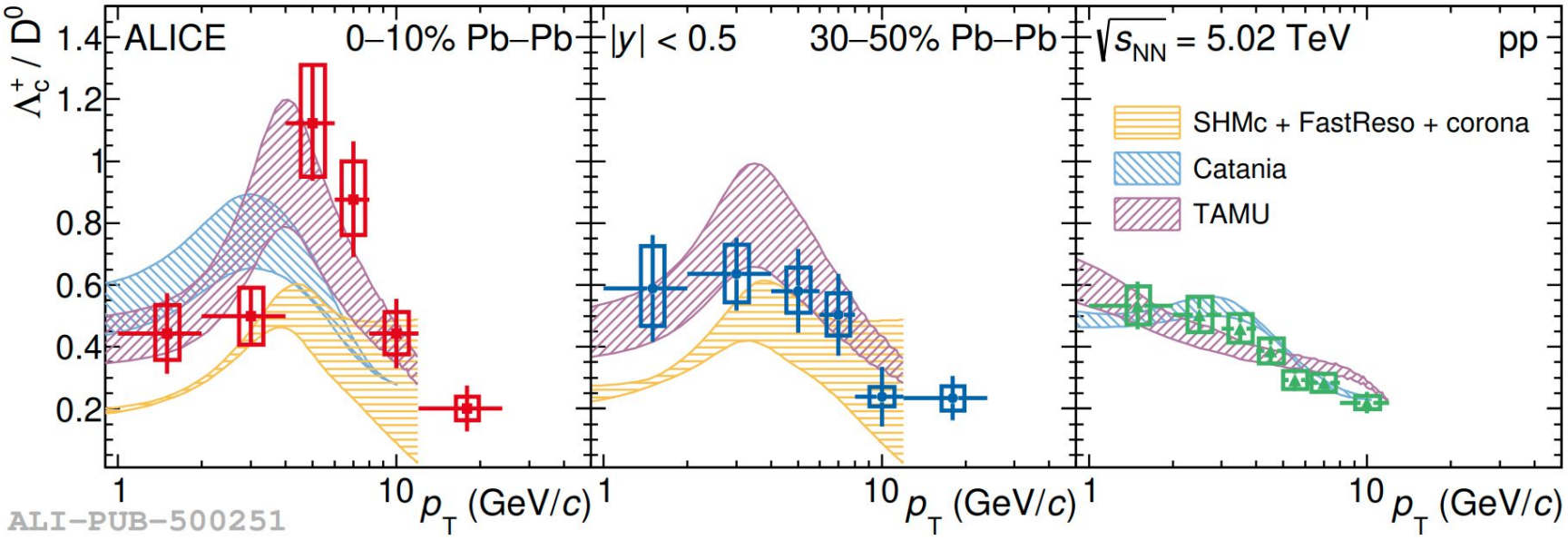
Junction baryons (e.g, from CR) are expected to be different

- 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

Λ_c^+/D^0 ratio at the LHC

mfaggin@cern.ch



Λ_c^+/D^0 ratio at the LHC

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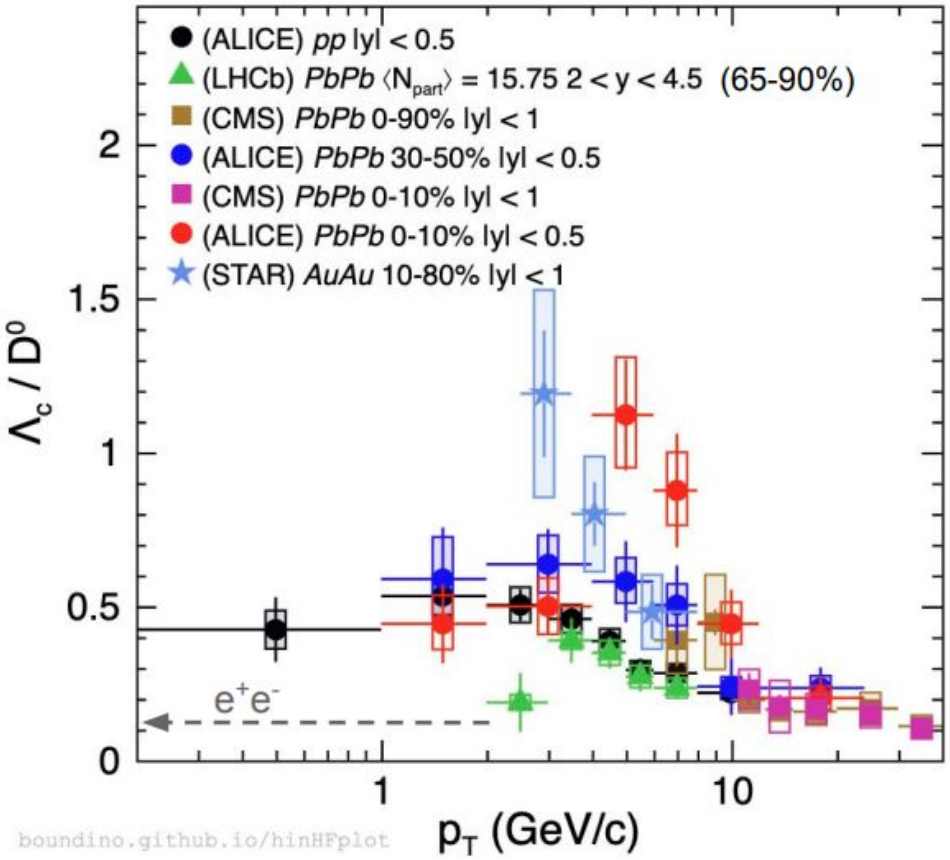


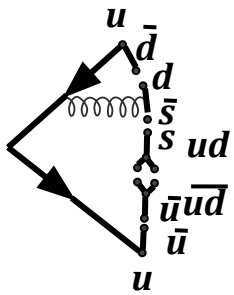
Significant evolution of p_T-differential yields

Biggest jump from e^+e^- to pp

"Radial-flow" like peak ← coalescence?

Large ratio also at STAR, "shifted" in p_T w.r.t. LHC

ALICE pp, PRL 127 (2021) 202301
LHCb Pb-Pb, arXiv:2210.06939
CMS Pb-Pb, CMS-PAS-HIN-21-004
ALICE Pb-Pb, arXiv:2112.08156
STAR Au-Au, PRL 124 (2020) 172301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