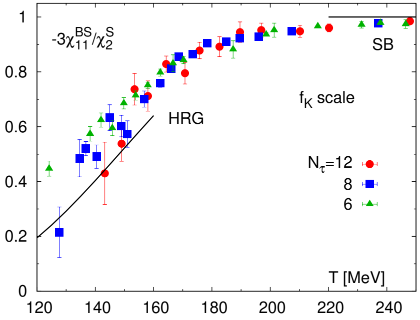
Hadronization in small and large systems

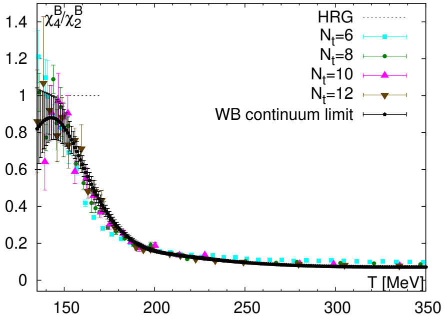
Andrea Beraudo

INFN - Sezione di Torino

LHCP 2024, Boston, 3-7 June 2024

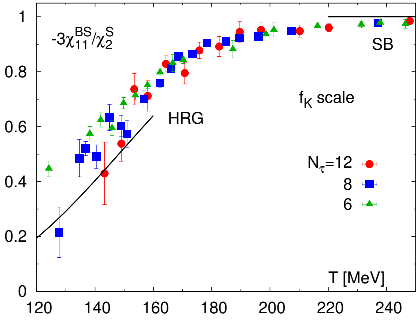
Premise: which are the carriers of conserved charges?

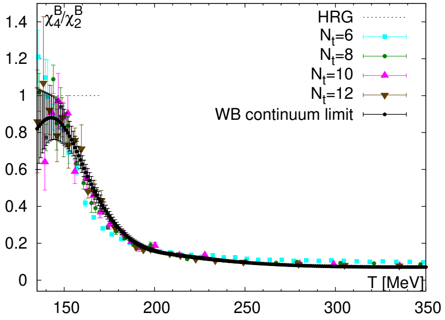




- In the QGP strangeness carried by quarks with $|B|=1/3$, PRD 86, 034509 (2012)
- $\chi_4^B/\chi_2^2 = B^2$, with $|B|=1$ (HG) or $|B|=1/3$ (QGP), PRL 111, 062005 (2013)

Premise: which are the carriers of conserved charges?

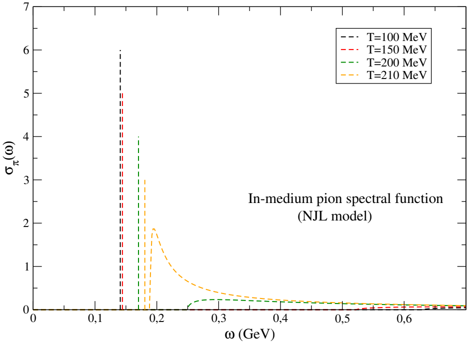


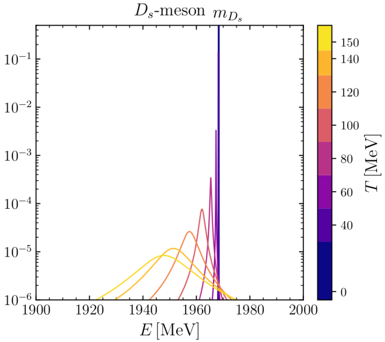


- In the QGP strangeness carried by quarks with $|B|=1/3$, PRD 86, 034509 (2012)
- $\chi_4^B/\chi_2^2 = B^2$, with $|B|=1$ (HG) or $|B|=1/3$ (QGP), PRL 111, 062005 (2013)

One would expect a sharp change in the nature of these carriers...
However, lQCD data show that also this change is very smooth!

What is a hadron around the QCD crossover?

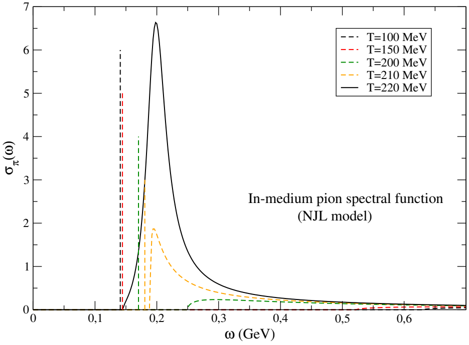


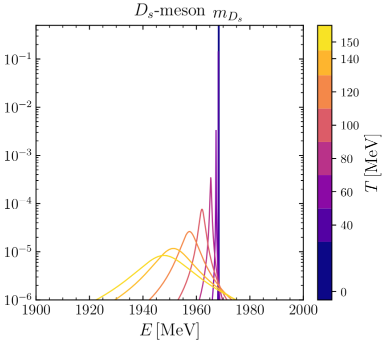


- At $T = 0$ hadrons are stable eigenstates of H_{QCD}
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?

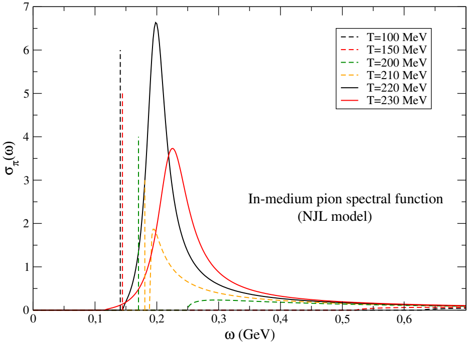


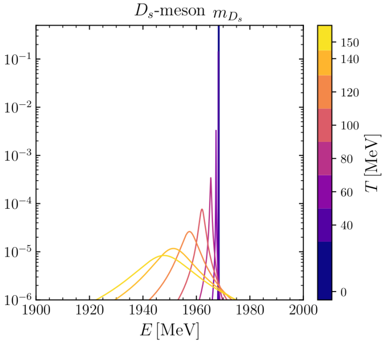


- At $T = 0$ hadrons are stable eigenstates of $H_{\rm QCD}$
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?

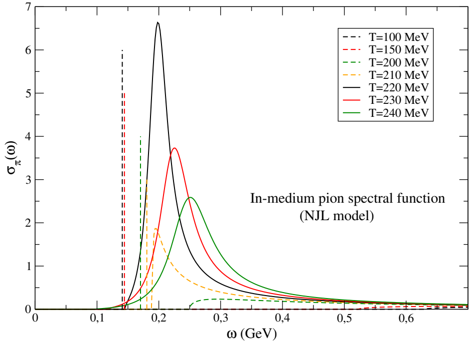


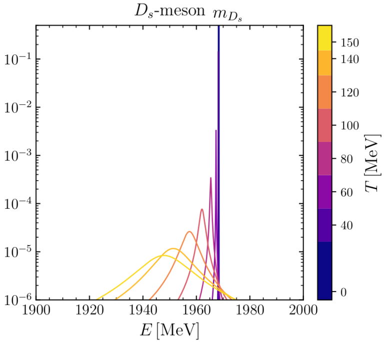


- At $T = 0$ hadrons are stable eigenstates of H_{QCD}
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?

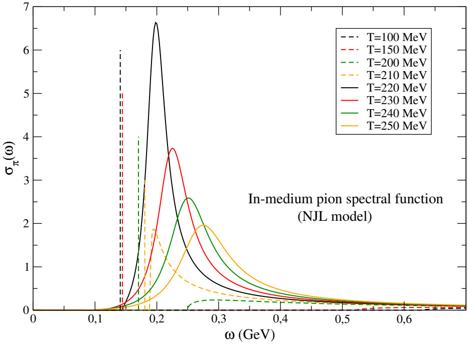


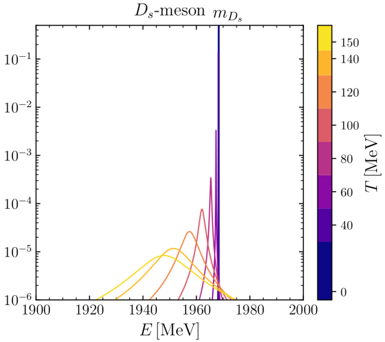


- At $T = 0$ hadrons are stable eigenstates of $H_{\rm QCD}$
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?

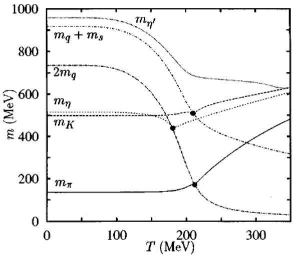


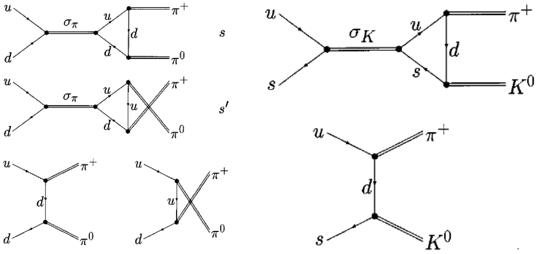


- At $T = 0$ hadrons are stable eigenstates of $H_{\rm QCD}$
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

Light sector: hadronization in effective chiral Lagrangians



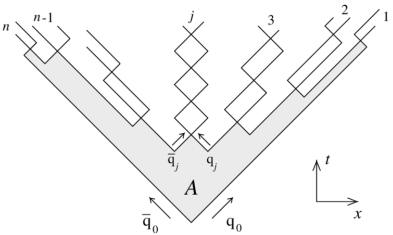


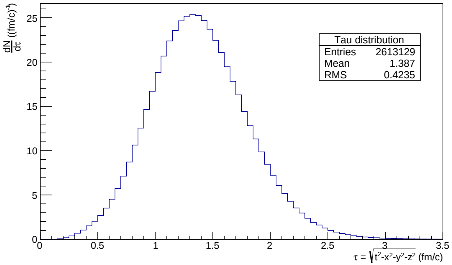
From $N_f = 2+1$ NJL Lagrangian (P. Rehberg et al, PRC 53 (1995) 410)

- Different Mott temperatures for the different hadrons, below which the decay channel $H \to q_1 + \overline{q}_2$ gets closed (non-universal hadronization temperature?)
- Hadronization, modeled as $q_1 + \overline{q}_2 \to H_1 + H_2$ process (exact *four-momentum conservation* $\neq$ coalescence) , takes time to occur:

$$\tau_u^{-1}(T_H) = \langle \sigma_{u\bar{u}} v \rangle \rho_{\bar{u}} + \langle \sigma_{u\bar{d}} v \rangle \rho_{\bar{d}} + \langle \sigma_{u\bar{s}} v \rangle \rho_{\bar{s}} \approx (2-3 \text{ fm/c})^{-1}$$
$$\tau_s^{-1}(T_H) = \langle \sigma_{s\bar{u}} v \rangle \rho_{\bar{u}} + \langle \sigma_{s\bar{d}} v \rangle \rho_{\bar{d}} + \langle \sigma_{s\bar{s}} v \rangle \rho_{\bar{s}} \approx (3-4 \text{ fm/c})^{-1}$$

Hadronization does not occur suddenly

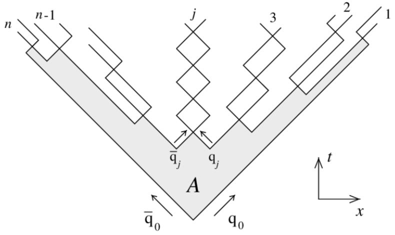


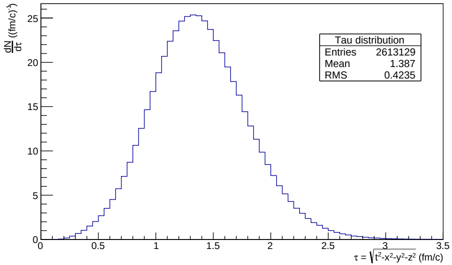


Also in string-fragmentation model (PYTHIA) primary hadron production takes time to occur, $\langle\tau\rangle \approx 1.3$ fm/c, however only recently model builders started investigating its implications (S. Ferreres-Solé and T. Sjostrand, EPJC 78 (2018) 11, 983)

- Probably irrelevant in e^+e^- collisions
- Important to consider if a dense medium (big or small), *with its own time scales* (lifetime, interaction rate, expansion rate...), is formed.

Hadronization does not occur suddenly





Also in string-fragmentation model (PYTHIA) primary hadron production takes time to occur, $\langle\tau\rangle \approx 1.3$ fm/c, however only recently model builders started investigating its implications (S. Ferreres-Solé and T. Sjostrand, EPJC 78 (2018) 11, 983)

- Probably irrelevant in e^+e^- collisions
- Important to consider if a dense medium (big or small), *with its own time scales* (lifetime, interaction rate, expansion rate...), is formed.

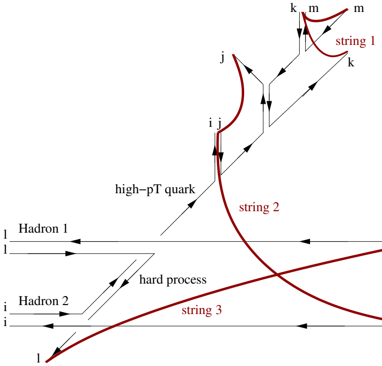
Notice that in most cases in HIC's hadronization is modeled as an instantaneous process (e.g. Cooper-Frye particlization or standard coalescence approaches)

Hadronization models: common features

Grouping colored partons into color-singlet structures: strings (PYTHIA), clusters (HERWIG), hadrons/resonances (coalescence/recombination).

Hadronization models: common features

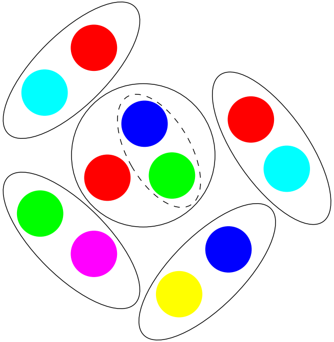
Grouping colored partons into color-singlet structures: strings (PYTHIA), clusters (HERWIG), hadrons/resonances (coalescence/recombination). Partons taken



- in "elementary collisions" (what is elementary?): from the hard process, shower stage, underlying event and beam remnants;

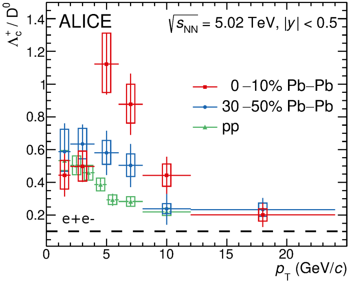
Hadronization models: common features

Grouping colored partons into color-singlet structures: strings (PYTHIA), clusters (HERWIG), hadrons/resonances (coalescence/recombination). Partons taken



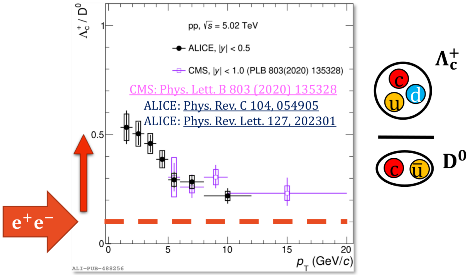
- in "elementary collisions" (what is elementary?): from the hard process, shower stage, underlying event and beam remnants;
- in heavy-ion collisions (only?): from the hot medium produced in the collision.
  NB Involved partons closer in space in this case and this has deep consequence!

Why the title of this talk?



- Strong enhancement of charmed baryon/meson ratio *both in AA and pp collisions*, incompatible with hadronization models tuned to reproduce e^+e^- data.

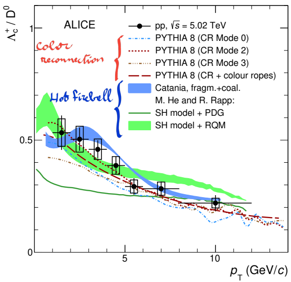
Why the title of this talk?



- Strong enhancement of charmed baryon/meson ratio *both in AA and pp collisions*, incompatible with hadronization models tuned to reproduce e^+e^- data. Breaking of factorization of *inclusive* hadronic cross-sections in *pp* collisions

$$d\sigma_h \neq \sum_{a,b,X} f_a(x_1)\, f_b(x_2) \otimes d\hat{\sigma}_{ab\to c\bar{c}X} \otimes D_{c\to h_c}(z)$$

Why the title of this talk?



- Strong enhancement of charmed baryon/meson ratio *both in AA and pp collisions*, incompatible with hadronization models tuned to reproduce e^+e^- data. Breaking of factorization of *inclusive* hadronic cross-sections in *pp* collisions

$$d\sigma_h \neq \sum_{a,b,X} f_a(x_1)\, f_b(x_2) \otimes d\hat{\sigma}_{ab\to c\bar{c}X} \otimes D_{c\to h_c}(z)$$

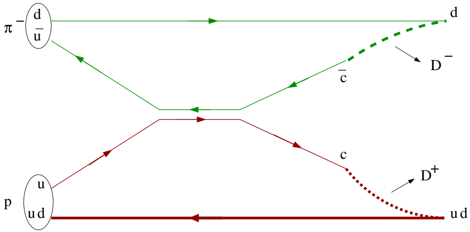
- Recent theory attempts to explain the data either based on Color Reconnection (CR) or on the formation of a small fireball: really different pictures?

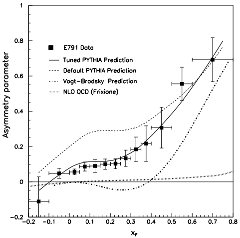
Non-universality of hadronization: not the first observation

Breaking of factorization already observed in fixed target experiments at Fermilab and SPS (e.g. $\pi^- + p$ collisions) in the production of charmed hadrons sharing a valence (di-)quark with the beam or target remnant (D^-/D^+, D_s^-/D_s^+, $\Lambda_c^+/\overline{\Lambda}_c^-$)

Non-universality of hadronization: not the first observation

Breaking of factorization already observed in fixed target experiments at Fermilab and SPS (e.g. $\pi^- + p$ collisions) in the production of charmed hadrons sharing a valence (di-)quark with the beam or target remnant (D^-/D^+, D_s^-/D_s^+, $\Lambda_c^+/\overline{\Lambda}_c^-$)



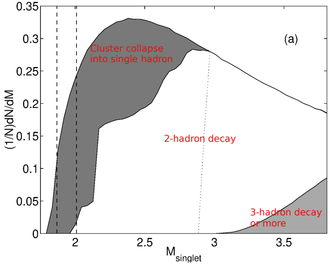


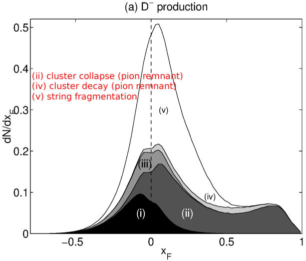
Second endpoint boosts the string along the direction of the beam-remnant (*beam-drag effect*), leading to an asymmetry in the rapidity distribution of D^-/D^+ mesons

$$A = \frac{\sigma_{D^-} - \sigma_{D^+}}{\sigma_{D^-} + \sigma_{D^+}}$$

Non-universality of hadronization: not the first observation

Breaking of factorization already observed in fixed target experiments at Fermilab and SPS (e.g. $\pi^- + p$ collisions) in the production of charmed hadrons sharing a valence (di-)quark with the beam or target remnant (D^-/D^+, D_s^-/D_s^+, $\Lambda_c^+/\overline{\Lambda}_c^-$)



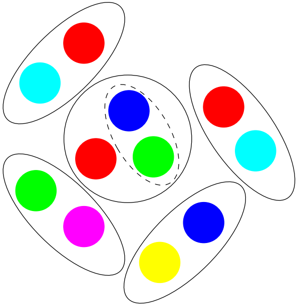


Second endpoint boosts the string along the direction of the beam-remnant (*beam-drag effect*), leading to an asymmetry in the rapidity distribution of D^-/D^+ mesons

$$A = \frac{\sigma_{D^-} - \sigma_{D^+}}{\sigma_{D^-} + \sigma_{D^+}}$$

Major contribution to asymmetry from collapse of a *very light cluster* into a single hadron (E. Norbin and T. Sjostrand, PLB 442 (1998) 407 and EPJC 17 (2000) 137)!

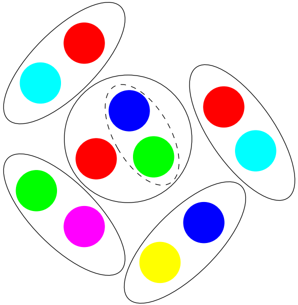
Local Color Neutralization (LCN): basic ideas



Both in AA and pp collisions a big/small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark, favoring baryon production).

- Why? screening of color-interaction, minimization of energy stored in confining potential
- Implication: recombination of particles *from the same fluid cell* $\longrightarrow$ Space-Momentum Correlation (SMC), recombined partons tend to share a common collective velocity

Local Color Neutralization (LCN): basic ideas



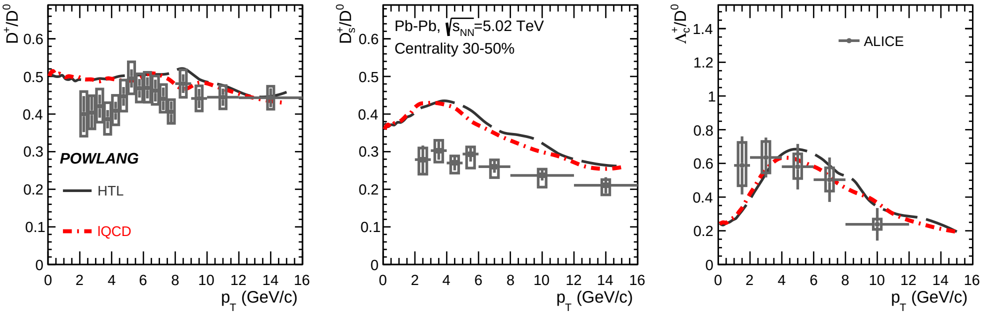
Both in AA and pp collisions a big/small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark, favoring baryon production).

- Why? screening of color-interaction, minimization of energy stored in confining potential
- Implication: recombination of particles *from the same fluid cell* $\longrightarrow$ Space-Momentum Correlation (SMC), recombined partons tend to share a common collective velocity

Color-singlet structures are thus formed, eventually undergoing decay into the final hadrons: $2 \to 1 \to N$ process, usually a charmed hadron plus a very soft particle

- Exact four-momentum conservation;
- No direct bound-state formation, hence no need to worry about overlap between the final hadron and the parent parton wave-functions

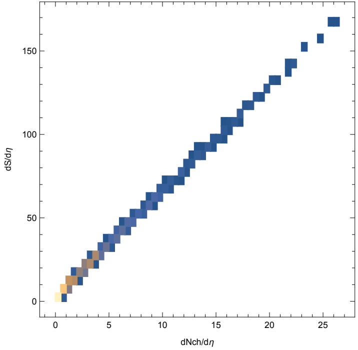
Results in AA collisions

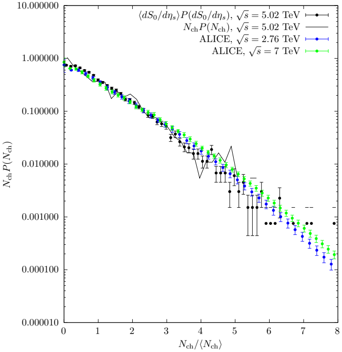


- Enhanced HF baryon-to-meson ratios up to intermediate p_T nicely reproduced, thanks to formation of *small invariant-mass* charm+diquark clusters[2]
- Smooth approach to e^+e^- limit ($\Lambda_c^+/D^0 \approx 0.1$) at high p_T: high-M_c clusters fragmented as Lund strings, as in the vacuum

[2] A.B. et al., EPJC 82 (2022) 7, 607

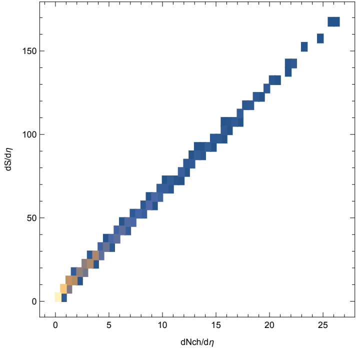
Addressing pp collisions...

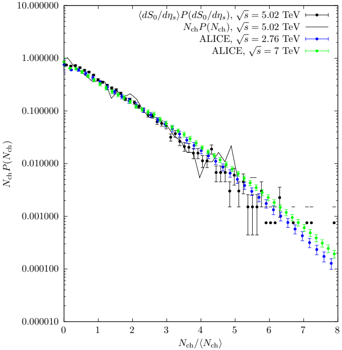




- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);

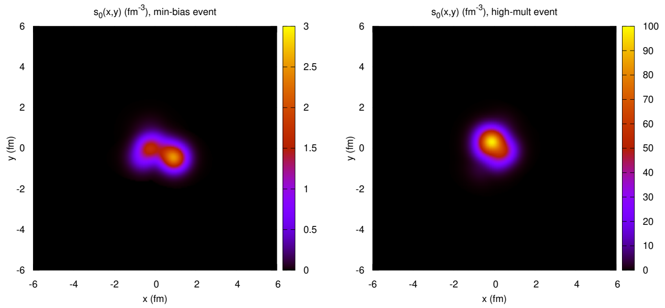
Addressing pp collisions...





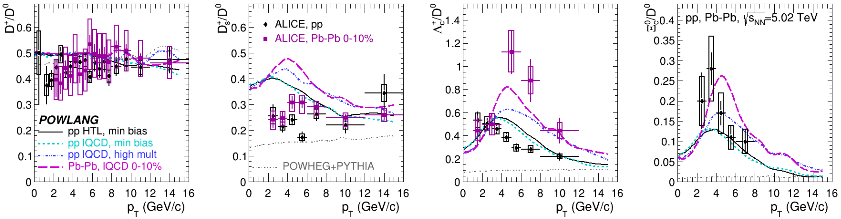
- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity ($dN_{ch}/d\eta$), $S \approx 7.2 N_{ch}$. $P(N_{ch})$ satisfying KNO scaling nicely reproduced;

Addressing pp collisions...



- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity ($dN_{\rm ch}/d\eta$), $S \approx 7.2N_{\rm ch}$. $P(N_{\rm ch})$ satisfying KNO scaling nicely reproduced;
- Samples of 10^3 minimum-bias ($\langle dS/dy\rangle_{\rm mb} \approx 37.6$, tuned to experimental $\langle dN_{\rm ch}/d\eta\rangle$) and high-multiplicity ($\langle dS/dy\rangle_{0-1\%} \approx 187.5$) events used to simulate HQ transport and hadronization.

Results in pp: particle ratios

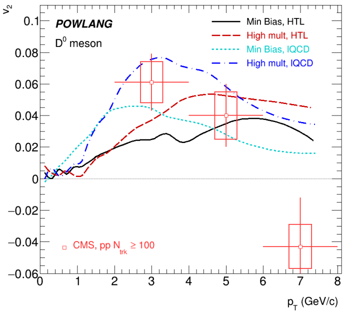


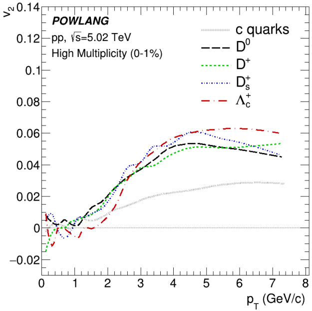
First results for particle ratios[3]:

- POWHEG+PYTHIA standalone strongly underpredicts baryon-to-meson ratio
- Enhancement of charmed baryon-to-meson ratio *qualitatively* reproduced if propagation+hadronization in a small QGP droplet is included
- Multiplicity dependence of radial-flow peak position (just a reshuffling of the momentum, without affecting the yields): $\langle u_\perp \rangle_{\rm pp}^{\rm mb} \approx 0.33$, $\langle u_\perp \rangle_{\rm pp}^{\rm hm} \approx 0.53$, $\langle u_\perp \rangle_{\rm PbPb}^{0-10\%} \approx 0.66$

[3] In collaboration with D. Pablos, A. De Pace, F. Prino et al., PRD 109 (2024) 1, L011501

Results in pp: elliptic flow

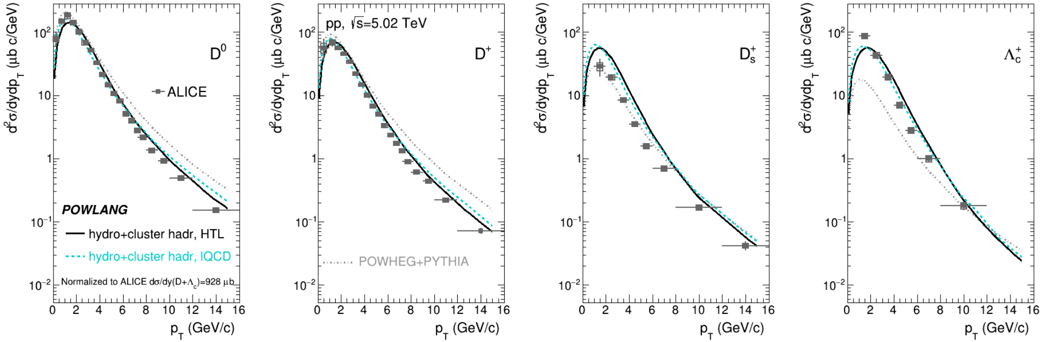




Response to initial elliptic eccentricity ($\langle\epsilon_2\rangle^{\rm mb} \approx \langle\epsilon_2\rangle^{\rm mh} \approx 0.31$) $\longrightarrow$ non-vanishing v_2 coefficient

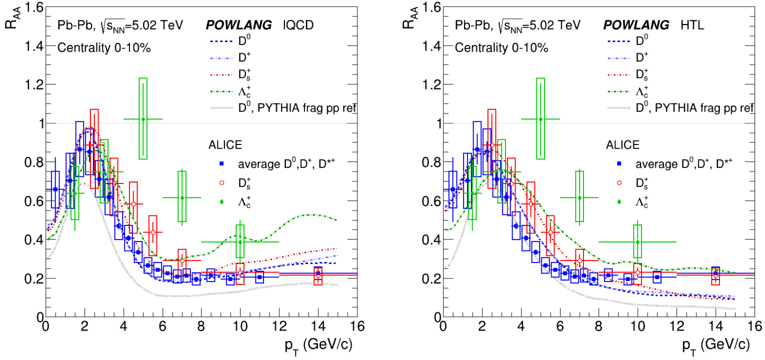
- Differences between minimum-bias and high-multiplicity results only due to longer time spent in the fireball ($\langle\tau_H\rangle^{\rm mb} \approx 1.95$ fm/c vs $\langle\tau_H\rangle^{\rm hm} \approx 2.92$ fm/c)
- Mass ordering at low p_T ($M_{qq} > M_q$)
- Sizable fraction of v_2 acquired at hadronization

Relevance to quantify nuclear effects



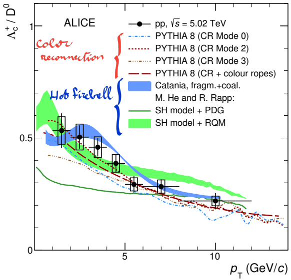
- Slope of the spectra in pp collisions better described including medium effects

Relevance to quantify nuclear effects



- Slope of the spectra in pp collisions better described including medium effects
- Inclusion of medium effects in minimum-bias pp benchmark fundamental to better describe charmed hadron R_{AA}, both the radial-flow peak and the species dependence

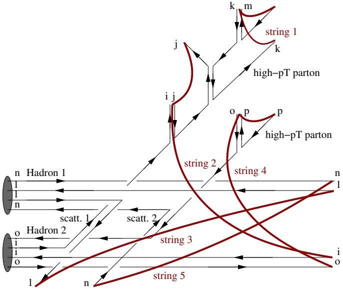
Looking for alternative (?) explanations: Color Reconnection (CR)

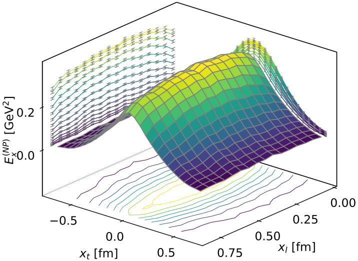


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR).

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

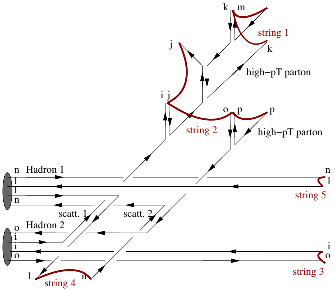


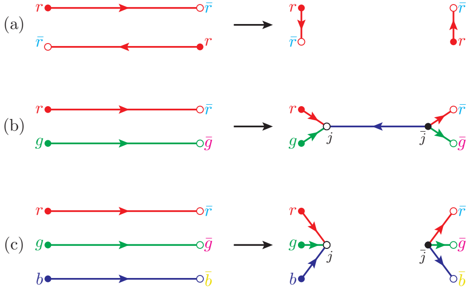


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4]

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

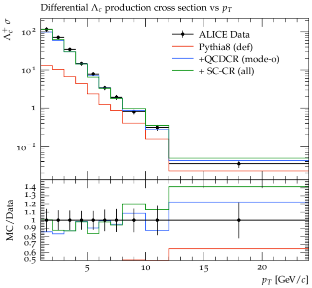


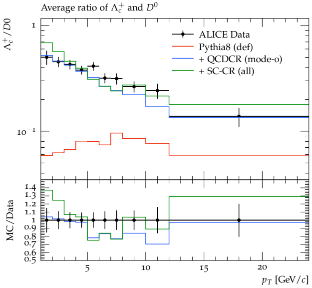


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4] and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass).

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

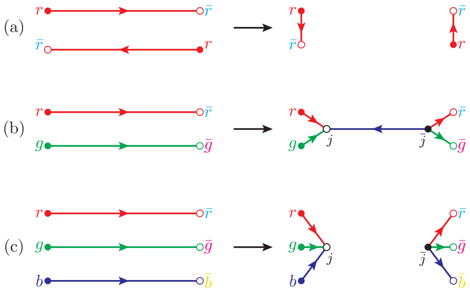


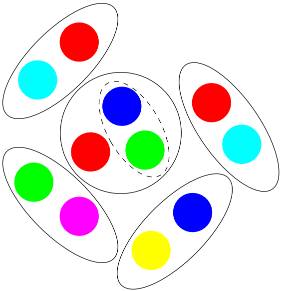


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4] and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass). Enhanced charmed baryon production correctly reproduced.

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

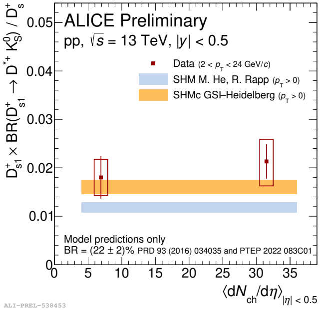


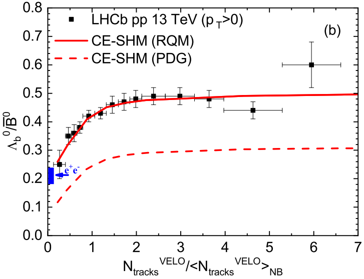


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4] and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass). Enhanced charmed baryon production correctly reproduced. CR vs LCN in a small fireball: two really different pictures?

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

HF statistical hadronization



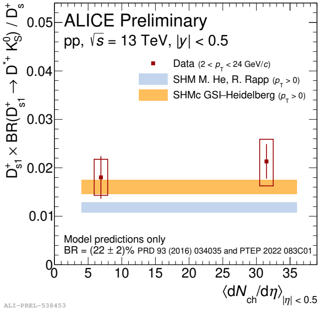


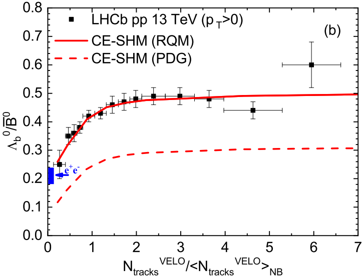
$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j] \,, \quad \text{with} \quad z_j = (2J_j+1)\frac{VT_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H})$$

Statistical description of HF production (Y. Dai, S. Zhao and M. He, 2402.03692) accounting for

- Deviation from chemical equilibrium (quark fugacities)

HF statistical hadronization



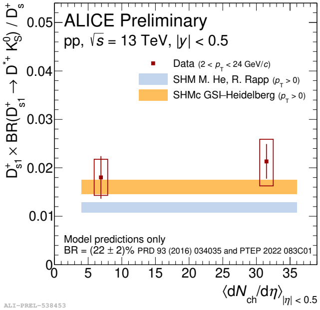


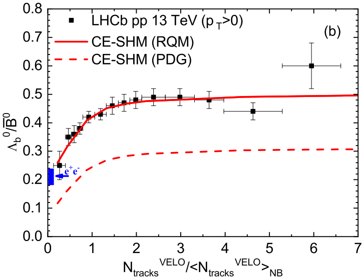
$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j]\,, \quad \text{with} \quad z_j = (2J_j+1)\frac{VT_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H})$$

Statistical description of HF production (Y. Dai, S. Zhao and M. He, 2402.03692) accounting for

- Deviation from chemical equilibrium (quark fugacities)
- Exact charge conservation within correlation volume V

HF statistical hadronization





$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp\Big[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j\Big], \quad \text{with} \quad z_j = (2J_j+1)\frac{VT_H}{2\pi^2} m_j^2 K_2\Big(\frac{m_j}{T_H}\Big)$$

Statistical description of HF production (Y. Dai, S. Zhao and M. He, 2402.03692) accounting for

- Deviation from chemical equilibrium (quark fugacities)
- Exact charge conservation within correlation volume V
- Enlarged set of hadronic resonance wrt PDG

Summary and open questions/challenges

- No doubt that a medium affecting the way hadronization occurs is formed also in proton-proton collisions

Summary and open questions/challenges

- No doubt that a medium affecting the way hadronization occurs is formed also in proton-proton collisions
- Various models developed to describe this process, different names but important common features: formation of small-mass color-singlet clusters, space-momentum correlation, enhanced collective flow and baryon production

Summary and open questions/challenges

- No doubt that a medium affecting the way hadronization occurs is formed also in proton-proton collisions
- Various models developed to describe this process, different names but important common features: formation of small-mass color-singlet clusters, space-momentum correlation, enhanced collective flow and baryon production
- The same Local Color-Neutralization (LCN) model developed to describe medium-modification of HF hadronization in AA collisions has been applied to the pp case;

Summary and open questions/challenges

- No doubt that a medium affecting the way hadronization occurs is formed also in proton-proton collisions
- Various models developed to describe this process, different names but important common features: formation of small-mass color-singlet clusters, space-momentum correlation, enhanced collective flow and baryon production
- The same Local Color-Neutralization (LCN) model developed to describe medium-modification of HF hadronization in AA collisions has been applied to the pp case;
- LCN model coupled to transport calculations in a small fireball provides a consistent description of several HF observables: shape of the p_T-distributions, enhanced baryon-to-meson ratio, charmed-hadron $R_{\rm AA}$ and non-vanishing v_2 coefficient

Summary and open questions/challenges

- No doubt that a medium affecting the way hadronization occurs is formed also in proton-proton collisions
- Various models developed to describe this process, different names but important common features: formation of small-mass color-singlet clusters, space-momentum correlation, enhanced collective flow and baryon production
- The same Local Color-Neutralization (LCN) model developed to describe medium-modification of HF hadronization in AA collisions has been applied to the pp case;
- LCN model coupled to transport calculations in a small fireball provides a consistent description of several HF observables: shape of the p_T-distributions, enhanced baryon-to-meson ratio, charmed-hadron $R_{\rm AA}$ and non-vanishing v_2 coefficient
- A cross-fertilization between different communities will be welcome (lattice-QCD, QCD event generators, nuclear physics...) and necessary to achieve a deeper understanding of hadronization