Heavy-flavor transport and hadronization in proton-proton collisions

Andrea Beraudo

INFN - Sezione di Torino

Quark Matter 2023, Houston, 3-9 September 2023

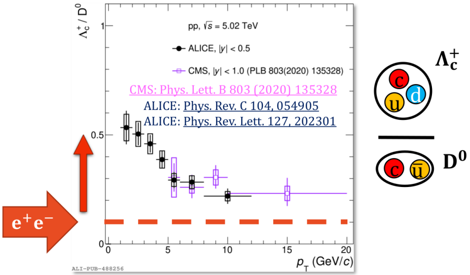
Istituto Nazionale di Fisica Nucleare

Outline

- Motivation: unexpected results in HF hadrochemistry in pp collisions
- Basic idea[1]: small fireball undergoing *local* color neutralization (LCN)
- Model implementation and initial-state description
- Predictions for charmed-hadron production
- Small QGP droplet vs color-reconnections: really different pictures?
- Further perspectives

[1] In collaboration with D. Pablos, A. De Pace, F. Prino, M. Monteno and M. Nardi. For details see Eur.Phys.J.C 82 (2022) 7, 607 and 2306.02152 [hep-ph]

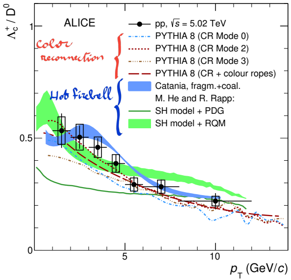
The experimental motivation: HF production in pp collisions



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

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

The experimental motivation: HF production in pp collisions

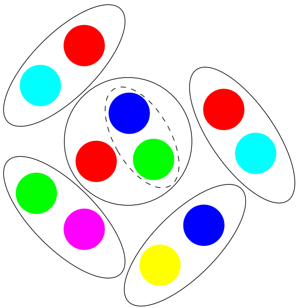


- Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data. Breaking of factorization of hadronic cross-sections in pp collisions

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

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

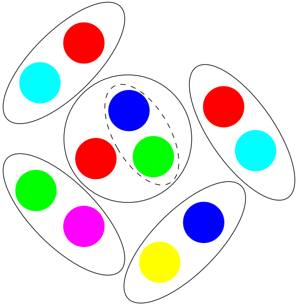
Local Color Neutralization (LCN): basic ideas



Even in pp collision a small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark).

- 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



Even in pp collision a small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark).

- 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: $2 \rightarrow 1 \rightarrow N$ process

- 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

Numerical implementation

Once a c quarks reaches a fluid cell at $T_H = 155$ MeV recombined it with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight

$$n \approx g_s\, g_I\, \frac{T_H M^2}{2\pi^2} K_2\left(\frac{M}{T_H}\right)$$

Numerical implementation

Once a c quarks reaches a fluid cell at $T_H = 155$ MeV recombined it with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight

$$n \approx g_s \, g_I \, \frac{T_H M^2}{2\pi^2} K_2 \left(\frac{M}{T_H} \right)$$

2. Extract its thermal three-momentum in the LRF of the fluid;

Numerical implementation

Once a c quarks reaches a fluid cell at $T_H = 155$ MeV recombined it with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight

$$n \approx g_s\, g_I\, \frac{T_H M^2}{2\pi^2} K_2\left(\frac{M}{T_H}\right)$$

2. Extract its thermal three-momentum in the LRF of the fluid;
3. Boost the thermal particle to the LAB frame and recombine it with the HQ, constructing the cluster $\mathcal{C}$;

Numerical implementation

Once a c quarks reaches a fluid cell at $T_H = 155$ MeV recombined it with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight

$$n \approx g_s \, g_I \, \frac{T_H M^2}{2\pi^2} K_2 \left(\frac{M}{T_H} \right)$$

2. Extract its thermal three-momentum in the LRF of the fluid;
3. Boost the thermal particle to the LAB frame and recombine it with the HQ, constructing the cluster $\mathcal{C}$;
4. Evaluate cluster mass $M_{\mathcal{C}}$. If $M_{\mathcal{C}}$ is smaller than lightest charmed hadron in that channel ($\sim$10% cases) go back to point 1, otherwise go to point 5;

Numerical implementation

Once a c quarks reaches a fluid cell at $T_H = 155$ MeV recombined it with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight

$$n \approx g_s\, g_I\, \frac{T_H M^2}{2\pi^2} K_2\left(\frac{M}{T_H}\right)$$

2. Extract its thermal three-momentum in the LRF of the fluid;
3. Boost the thermal particle to the LAB frame and recombine it with the HQ, constructing the cluster $\mathcal{C}$;
4. Evaluate cluster mass $M_{\mathcal{C}}$. If $M_{\mathcal{C}}$ is smaller than lightest charmed hadron in that channel ($\sim$10% cases) go back to point 1, otherwise go to point 5;
5. Introduce intermediate cutoff $M_{\rm max} \approx 4$ GeV (as in HERWIG) and simulate cluster decay, depending on its invariant mass:

Numerical implementation

Once a c quarks reaches a fluid cell at $T_H = 155$ MeV recombined it with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight

$$n \approx g_s \, g_I \, \frac{T_H M^2}{2\pi^2} K_2 \left(\frac{M}{T_H} \right)$$

2. Extract its thermal three-momentum in the LRF of the fluid;
3. Boost the thermal particle to the LAB frame and recombine it with the HQ, constructing the cluster $\mathcal{C}$;
4. Evaluate cluster mass $M_{\mathcal{C}}$. If $M_{\mathcal{C}}$ is smaller than lightest charmed hadron in that channel ($\sim$10% cases) go back to point 1, otherwise go to point 5;
5. Introduce intermediate cutoff $M_{\mathrm{max}} \approx 4$ GeV (as in HERWIG) and simulate cluster decay, depending on its invariant mass:
   - Light clusters ($M_{\mathcal{C}} < M_{\mathrm{max}}$) undergo isotropic two-body decay in their own rest frame, as in HERWIG;

Numerical implementation

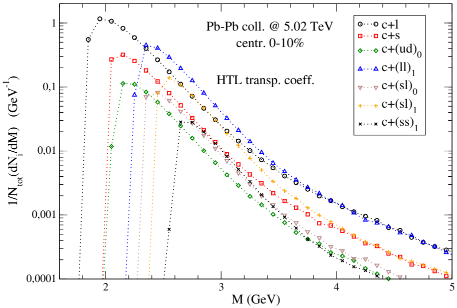
Once a c quarks reaches a fluid cell at $T_H = 155$ MeV recombined it with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight
$$n \approx g_s\, g_I\, \frac{T_H M^2}{2\pi^2} K_2\left(\frac{M}{T_H}\right)$$
2. Extract its thermal three-momentum in the LRF of the fluid;
3. Boost the thermal particle to the LAB frame and recombine it with the HQ, constructing the cluster $\mathcal{C}$;
4. Evaluate cluster mass $M_{\mathcal{C}}$. If $M_{\mathcal{C}}$ is smaller than lightest charmed hadron in that channel ($\sim$10% cases) go back to point 1, otherwise go to point 5;
5. Introduce intermediate cutoff $M_{\rm max} \approx 4$ GeV (as in HERWIG) and simulate cluster decay, depending on its invariant mass:
   - Light clusters ($M_{\mathcal{C}} < M_{\rm max}$) undergo isotropic two-body decay in their own rest frame, as in HERWIG;
   - Heavier clusters ($M_{\mathcal{C}} > M_{\rm max}$) undergo string fragmentation into N hadrons, as in PYTHIA.

Cluster mass distribution

Species	g_s	g_I	M (GeV)	h_c
l	2	2	0.33000	D^0, D^+
s	2	1	0.50000	D_s^+
$(ud)_0$	1	1	0.57933	Λ_c^+
$(ll)_1$	3	3	0.77133	Λ_c^+
$(sl)_0$	1	2	0.80473	Ξ_c^0, Ξ_c^+
$(sl)_1$	3	2	0.92953	Ξ_c^0, Ξ_c^+
$(ss)_1$	3	1	1.09361	Ω_c^0, Ξ_c^+

(masses taken from PYTHIA 6.4)

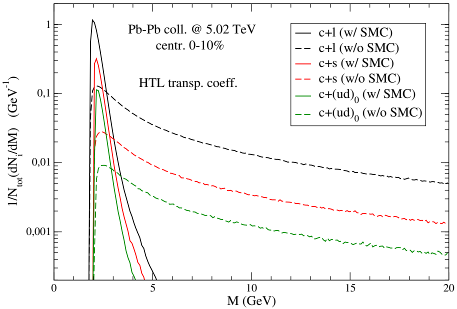


- Cluster mass distribution is steeply falling, most clusters are light and undergo a two-body decay $\mathcal{C} \to h_c + \pi/\gamma$;
- This arises from Space-Momentum Correlation: charm momentum usually parallel to fluid velocity $\longrightarrow$ recombination occurs *locally* between quite collinear partons;

Cluster mass distribution

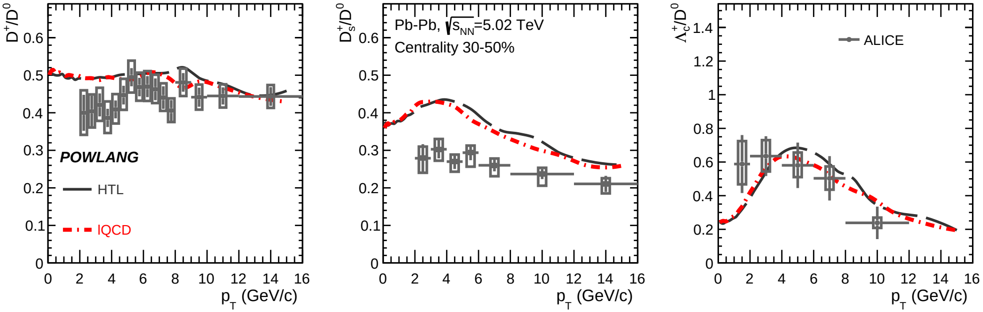
Species	g_s	g_I	M (GeV)	h_c
l	2	2	0.33000	D^0, D^+
s	2	1	0.50000	D_s^+
$(ud)_0$	1	1	0.57933	Λ_c^+
$(ll)_1$	3	3	0.77133	Λ_c^+
$(sl)_0$	1	2	0.80473	Ξ_c^0, Ξ_c^+
$(sl)_1$	3	2	0.92953	Ξ_c^0, Ξ_c^+
$(ss)_1$	3	1	1.09361	Ω_c^0, Ξ_c^+

(masses taken from PYTHIA 6.4)



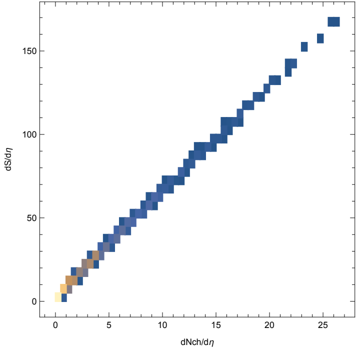
- Cluster mass distribution is steeply falling, most clusters are light and undergo a two-body decay $\mathcal{C} \to h_c + \pi/\gamma$;
- This arises from Space-Momentum Correlation: charm momentum usually parallel to fluid velocity $\longrightarrow$ recombination occurs *locally* between quite collinear partons;
- Cross-check: remove SMC by randomly selecting light parton from a different point on the FO hypersurface $\longrightarrow$ long high-$M_\mathcal{C}$ tail

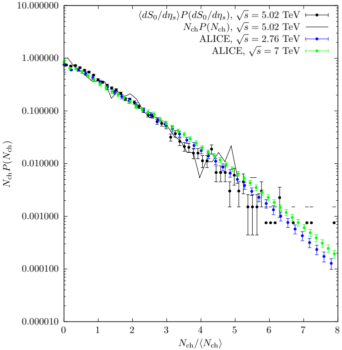
Results in AA collisions



- Enhanced HF baryon-to-meson ratios up to intermediate p_T nicely reproduced, thanks to formation of *small invariant-mass* charm+diquark clusters
- 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

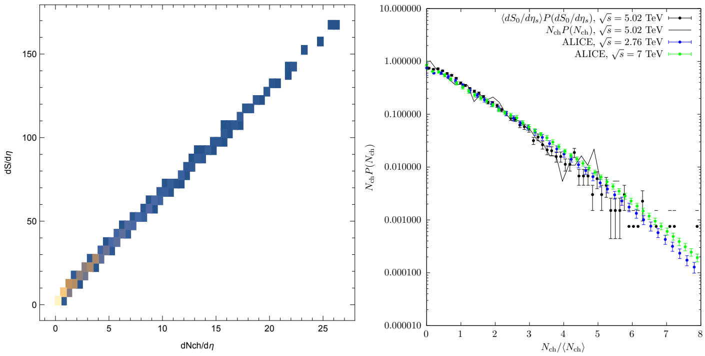
Addressing pp collisions...





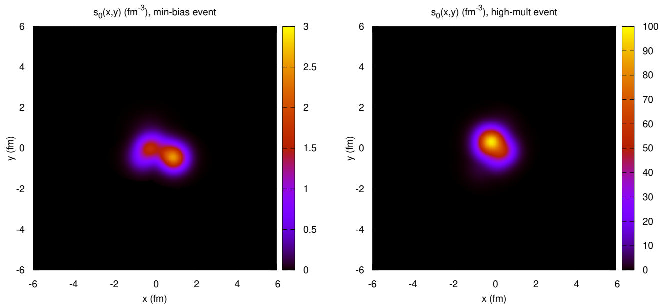
- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);

Addressing pp collisions...



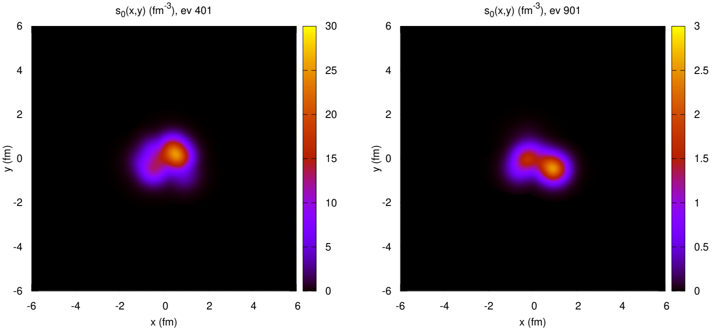
- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity ($dN_{ch}/d\eta$), $S \approx 7.2 N_{ch}$. $P(N_{ch})$ satisfying KNO scaling nicely reproduced;

Addressing pp collisions...



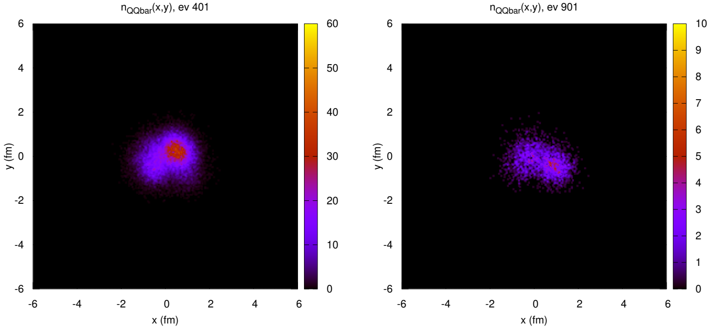
- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity ($dN_{\rm ch}/d\eta$), $S \approx 7.2 N_{\rm ch}$. $P(N_{\rm ch})$ satisfying KNO scaling nicely reproduced;
- Samples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

Why in-medium hadronization also in pp?



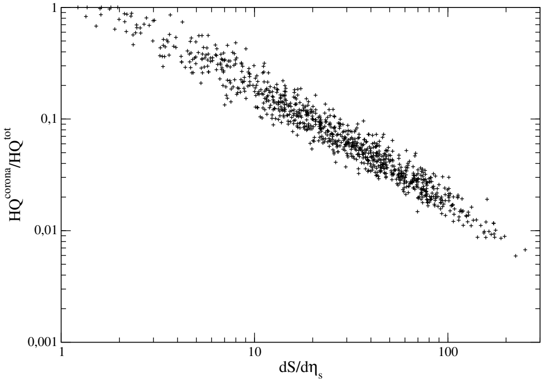
$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events

Why in-medium hadronization also in pp?

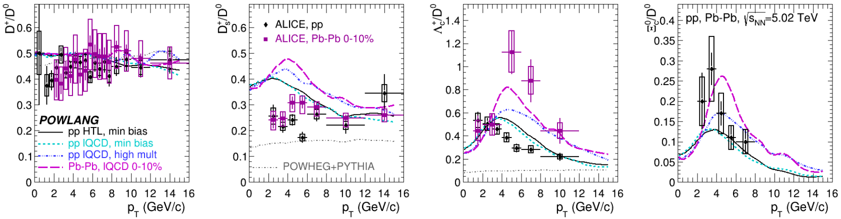


$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events

Why in-medium hadronization also in pp?



$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events $\longrightarrow$ only about 5% of $Q\overline{Q}$ pairs initially found in fluid cells below T_c

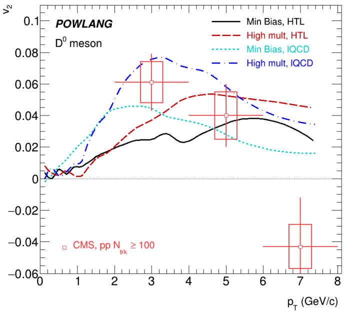


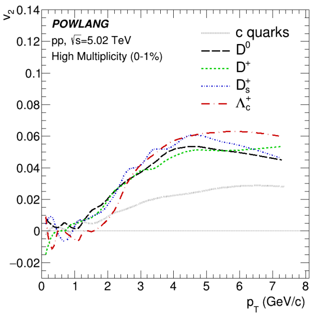
First results for particle ratios[2]:

- 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): $\langle u_\perp \rangle^{\rm mb}_{\rm pp} \approx 0.33$, $\langle u_\perp \rangle^{\rm hm}_{\rm pp} \approx 0.53$, $\langle u_\perp \rangle^{0-10\%}_{\rm PbPb} \approx 0.66$

[2]In collaboration with D. Pablos, A. De Pace, F. Prino et al., 2306.02152 [hep-ph]

Results in pp: elliptic flow

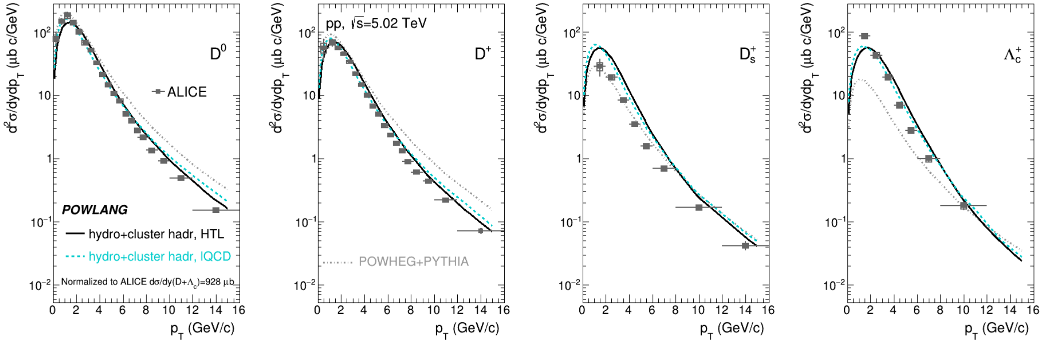




Response to initial elliptic eccentricity $(\langle\epsilon_2\rangle^{\mathrm{mb}} \approx \langle\epsilon_2\rangle^{\mathrm{mh}} \approx 0.31) \longrightarrow$ non-vanishing v_2 coefficient

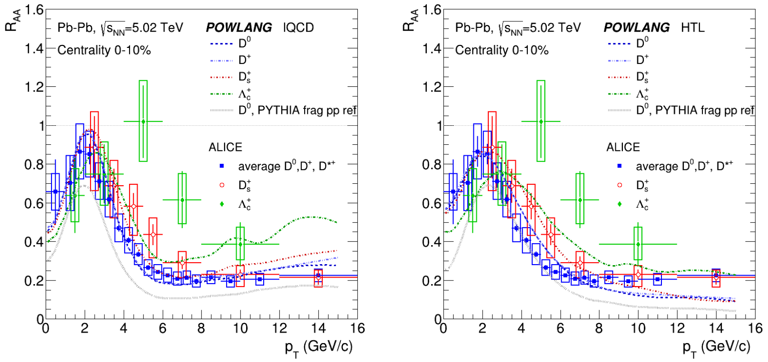
- Differences between minimum-bias and high-multiplicity results only due to longer time spent in the fireball $(\langle\tau_H\rangle^{\mathrm{mb}} \approx 1.95$ fm/c vs $\langle\tau_H\rangle^{\mathrm{hm}} \approx 2.92$ fm/c)
- Mass ordering at low p_T $(M_{qq} > M_q)$
- Sizable fraction of v_2 acquired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

Relevance to quantify nuclear effects



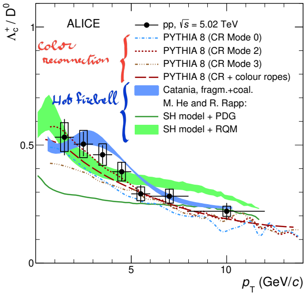
- Slope of the spectra in pp collisions better described including medium effects

Relevance to quantify nuclear effects



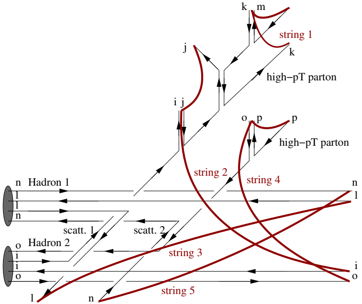
- Slope of the spectra in pp collisions better described including medium effects
- Inclusion of medium effects in minimum-bias pp benchmark fundamental to better describe charmed hadron R_{AA}, both the radial-flow peak and the species dependence

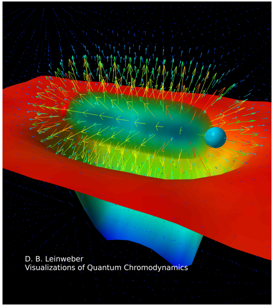
Looking for alternative (?) explanations: Color Reconnection (CR)



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).

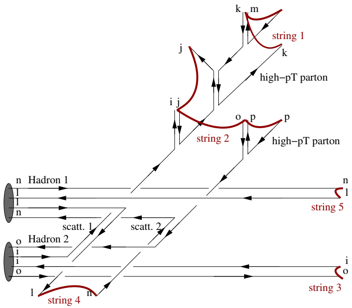
Looking for alternative (?) explanations: Color Reconnection (CR)





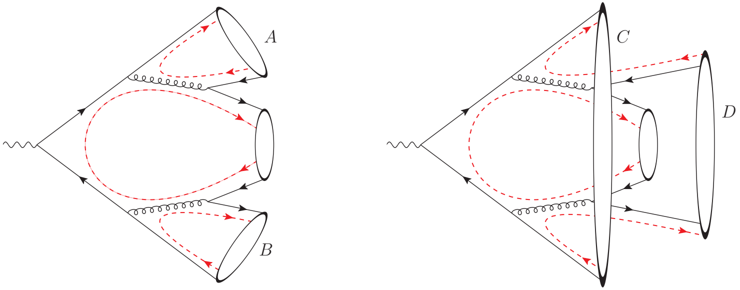
Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap

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



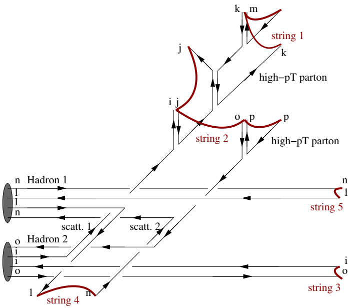
Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap and give rise to a rearrangement of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

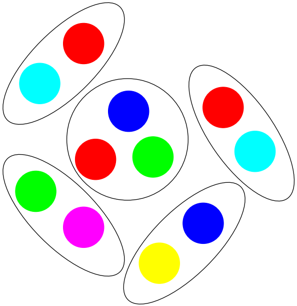
Looking for alternative (?) explanations: Color Reconnection (CR)



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 and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass). Analogous possibility implemented in HERWIG.

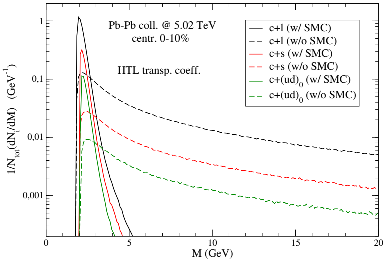
Looking for alternative (?) explanations: Color Reconnection (CR)

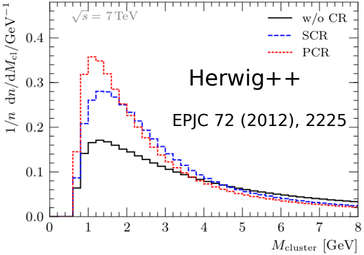




Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap and give rise to a rearrangement of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

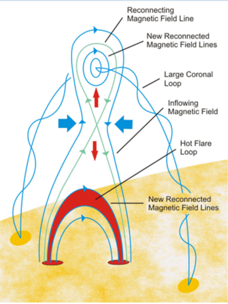
Looking for alternative (?) explanations: Color Reconnection (CR)

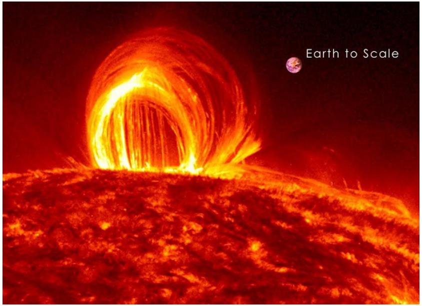




Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass). Analogous possibility implemented in HERWIG. CR vs LCN in a small fireball: two really different pictures? Effect on the cluster mass distribution is the same.

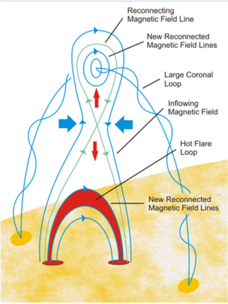
CR = no QGP formation?

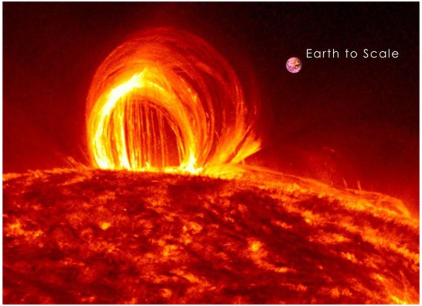




Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

CR = no QGP formation?

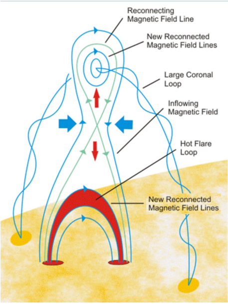


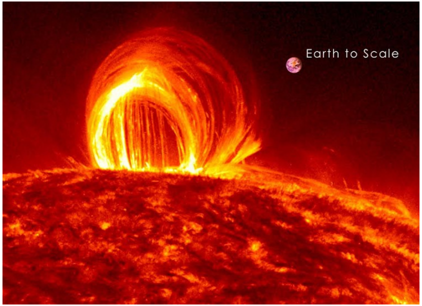


Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

- Still not completely understood in the case of electrodynamic plasmas

CR = no QGP formation?

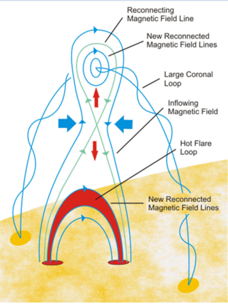


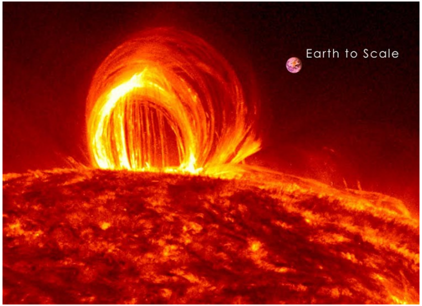


Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

- Still not completely understood in the case of electrodynamic plasmas
- however, the existence of a plasma with *finite electric resistivity* (either from collisions of from a collective flow) looks a *necessary condition* for magnetic reconnection to occur

CR = no QGP formation?





Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

- Still not completely understood in the case of electrodynamic plasmas
- however, the existence of a plasma with *finite electric resistivity* (either from collisions of from a collective flow) looks a *necessary condition* for magnetic reconnection to occur

Is CR possible without the formation of a QGP with *finite color conductivity?*

Conclusions and perspectives

- 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;

Conclusions and perspectives

- 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_{AA} and non-vanishing v_2 coefficient;

Conclusions and perspectives

- 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_{AA} and non-vanishing v_2 coefficient;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events

Conclusions and perspectives

- 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;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events
- Independent, strong indications that the collective phenomena observed in small systems have the same origin as those measured in heavy-ion collisions

Conclusions and perspectives

- 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_{AA} and non-vanishing v_2 coefficient;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events
- Independent, strong indications that the collective phenomena observed in small systems have the same origin as those measured in heavy-ion collisions
- Do alternative explanations really exclude the formation of a small deconfined fireball?

Conclusions and perspectives

- 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;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events
- Independent, strong indications that the collective phenomena observed in small systems have the same origin as those measured in heavy-ion collisions
- Do alternative explanations really exclude the formation of a small deconfined fireball?
- Extension to pA collisions and to beauty production in progress