Medium modification of hadronization: different implementations of recombination

Andrea Beraudo, in collaboration with A. De Pace, D. Pablos, F. Prino, M. Monteno and M. Nardi

INFN - Sezione di Torino

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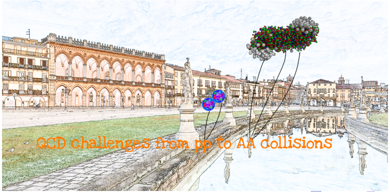
Istituto Nazionale di Fisica Nucleare



Heavy-particle diffusion: physics motivation

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- Perrin (1909): proving the *granular structure of matter* and providing an estimate of the Avogadro number

$$\mathcal{N}_A = \frac{\mathcal{R}T}{6\pi a \eta D_s} \approx 5.5 - 7.2 \cdot 10^{23}$$

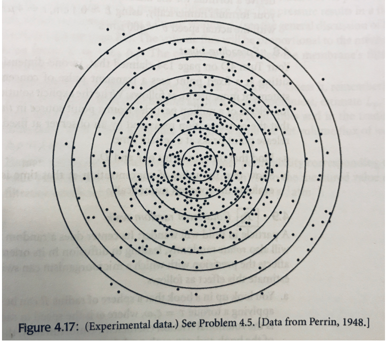

Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

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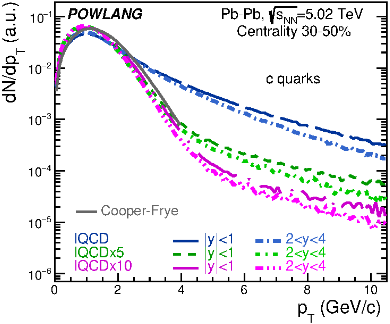

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$$\mathcal{N}_A = \frac{\mathcal{R}T}{6\pi a \eta D_s} \approx 5.5 - 7.2 \cdot 10^{23}$$

- 100 years later: getting an estimate of similar accuracy of some transport coefficients, like e.g. the momentum broadening

$$\kappa = \frac{2T^2}{D_s}$$

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In HF studies in nuclear collisions the nature of the Brownian particle changes during its propagation through the medium

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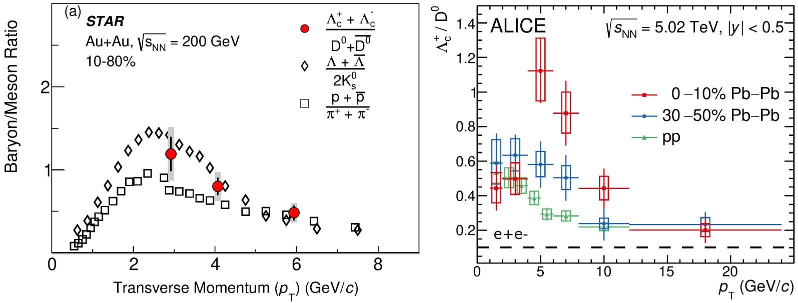
- possible thermal mass-shift (here neglected)
- hadronization (impossible to neglect)
  - source of systematic uncertainty in extracting transport coefficients;
  - an issue of interest in itself: how quark $\rightarrow$ hadron transition changes in the presence of a medium (the topic of this talk)

HF hadronization: experimental findings



Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data

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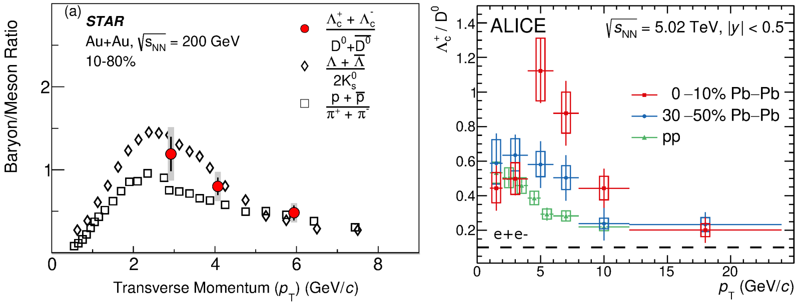

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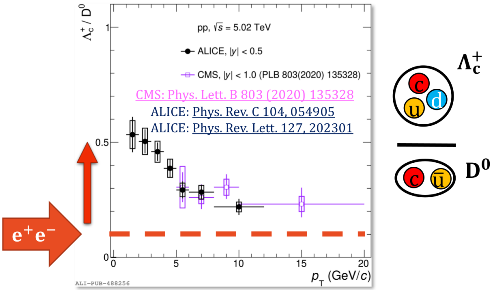

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- pattern similar to light hadrons
- baryon enhancement observed also in *pp* collisions: is a dense medium formed also there? Breaking of factorization description in *pp* collisions

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

Hadronization models: common features

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

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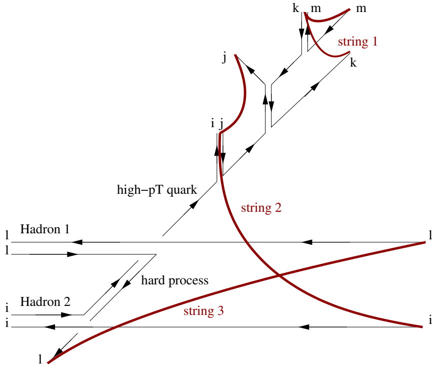

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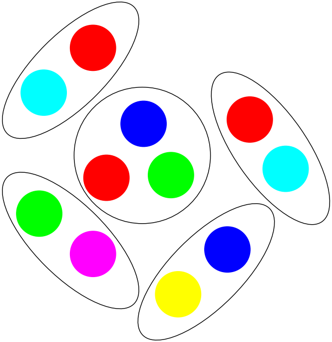
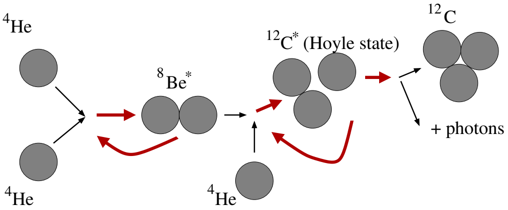
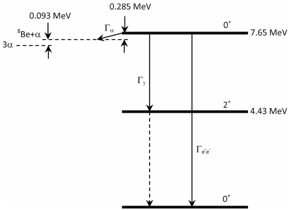


- in “elementary collisions”: from the hard process, shower stage, underlying event and beam remnants;
- in heavy-ion collisions: from the hot medium produced in the collision. NB Involved partons closer in space in this case and this has deep consequence!

A warning from nucleosynthesis





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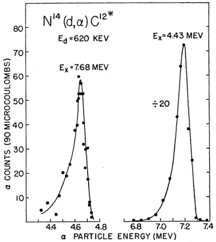

Selected for a Viewpoint in *Physics*
PRL **106,** 192501 (2011) PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

***Ab Initio* Calculation of the Hoyle State**

Evgeny Epelbaum,[1] Hermann Krebs,[1] Dean Lee,[2] and Ulf-G. Meißner[3,4]
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(Received 24 February 2011; published 9 May 2011)

The Hoyle state plays a crucial role in the helium burning of stars heavier than our Sun and in the production of carbon and other elements necessary for life. This excited state of the carbon-12 nucleus was postulated by Hoyle as a necessary ingredient for the fusion of three alpha particles to produce carbon at stellar temperatures. Although the Hoyle state was seen experimentally more than a half century ago nuclear theorists have not yet uncovered the nature of this state from first principles. In this Letter we report the first *ab initio* calculation of the low-lying states of carbon-12 using supercomputer lattice simulations and a theoretical framework known as effective field theory. In addition to the ground state and excited spin-2 state, we find a resonance at −85(3) MeV with all of the properties of the Hoyle state and in agreement with the experimentally observed energy.

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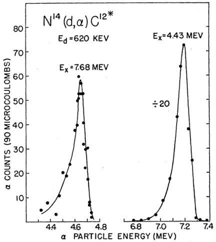

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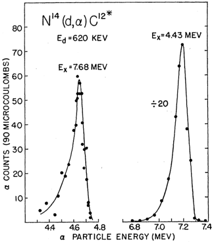

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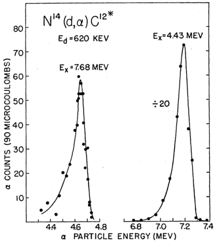

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None of the above conditions is fully under control in the quark to hadron transition

Our new hadronization model

Once a c quarks reaches a fluid cell at $T_H = 155$ MeV it is recombined 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

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

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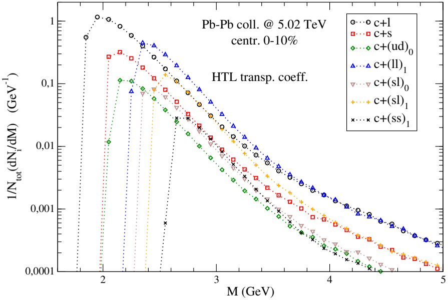
   - Heavier clusters ($M_{\mathcal{C}} > M_{\rm max}$) undergo string fragmentation into N hadrons, as in PYTHIA.

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 $\mathcal{C} \to h_c + \pi/\gamma$;
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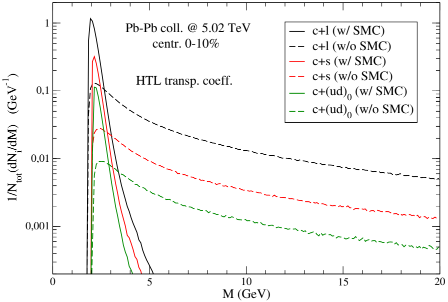

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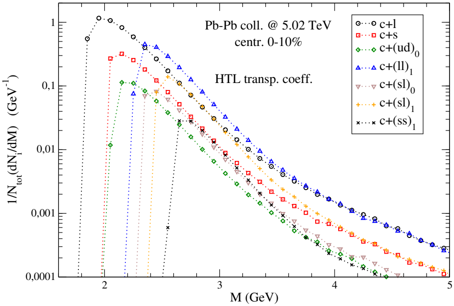
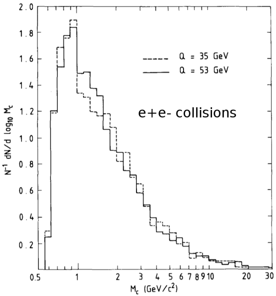
- Cross-check: remove SMC by randomly selecting light parton from a different point on the FO hypersurface $\longrightarrow$ long high-$M_{\mathcal{C}}$ tail

On the suppression of high-mass clusters





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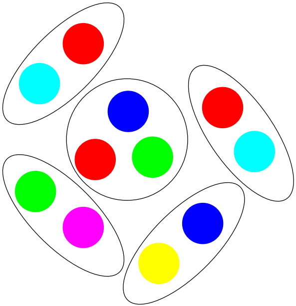

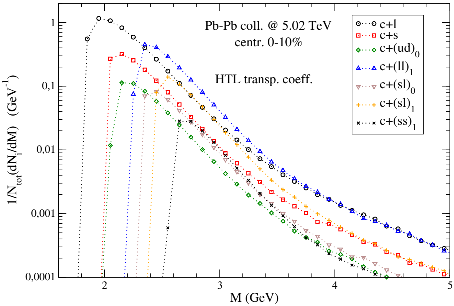

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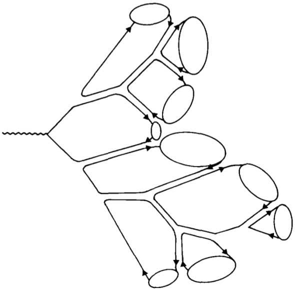

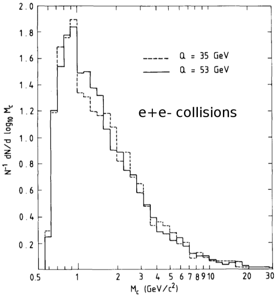

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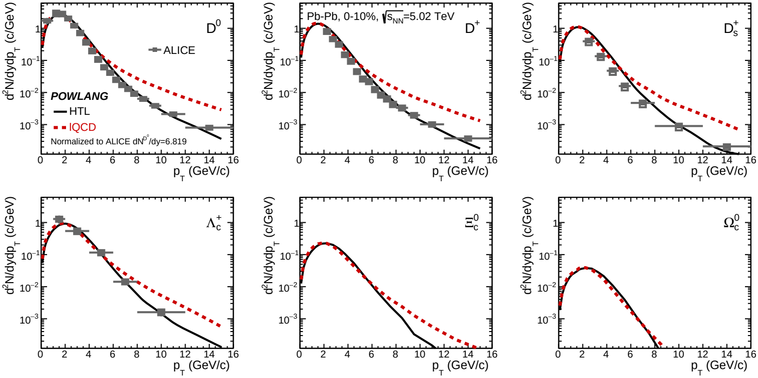
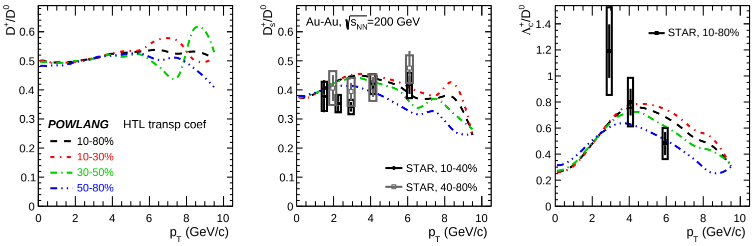
- In our model this is due to the SMC arising from recombining nearby partons;
- In Herwig, in e^+e^- collisions, this is due to the angular ordered parton shower (*pre-confinement*)

Results in AA: charmed-hadron p_T-distributions

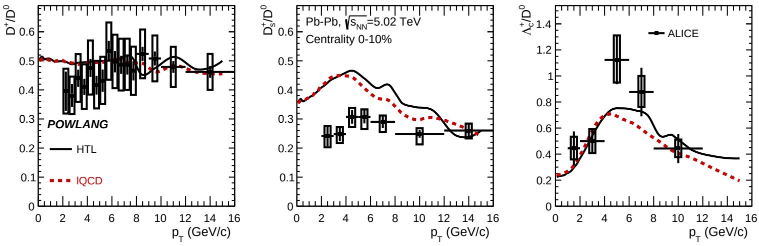


Charmed hadron p_T-spectra normalized to integrated D^0-yield per event. At high p_T better agreement with experimental data for curves including momentum dependence of the transport coefficients (HTL curves)

Results in AA: hadron ratios



- Qualitative agreement with STAR results;



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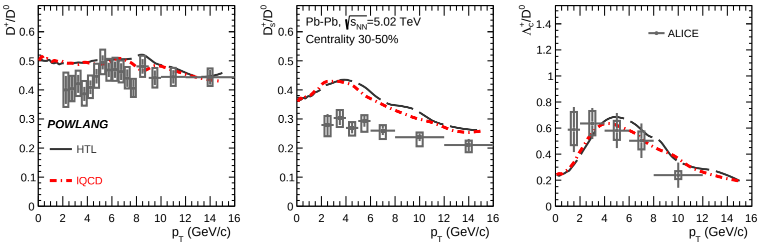

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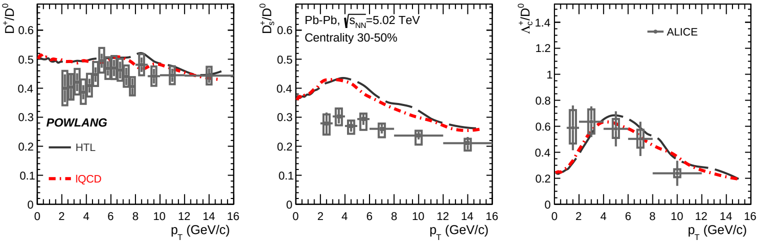

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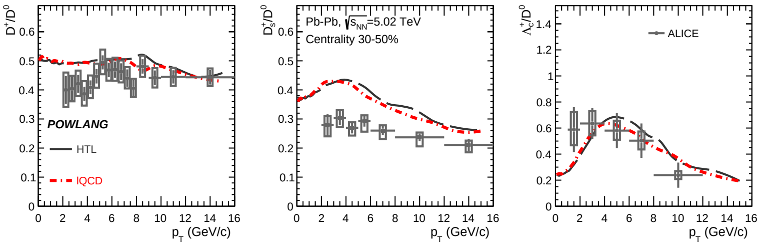

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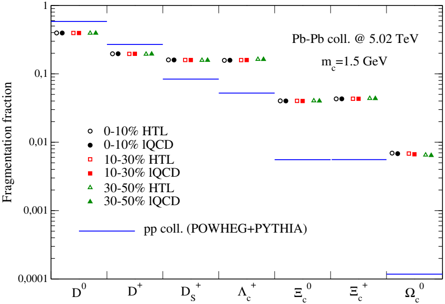
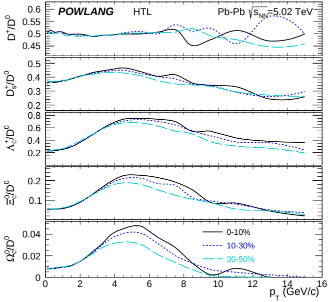
NB We have not attempted a tuning of the parameters to fit the data, e.g. quark and diquark masses taken from default values in PYTHIA

Results in AA: fragmentation fractions





- FF's in *AA* collisions pretty independent from the centrality, leading simply to a reshuffling of the p_T-distribution (stronger radial flow of charmed baryons in central events);
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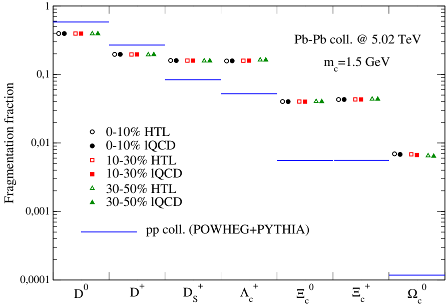

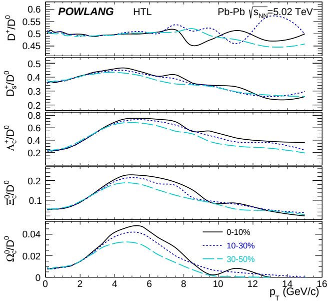

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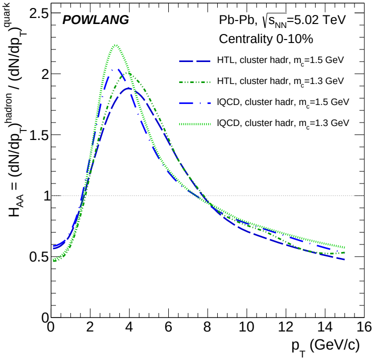
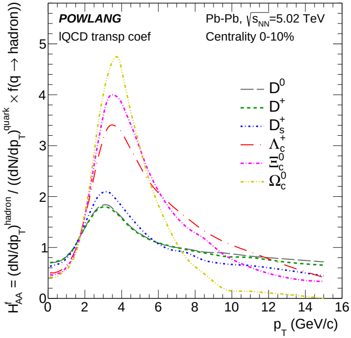
NB Model predictions for pp collisions displayed in the following

How much flow acquired at hadronization?

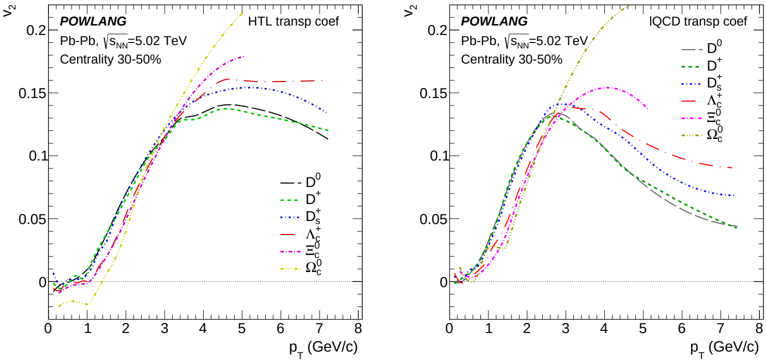




Big enhancement of charmed hadron production at intermediate p_T

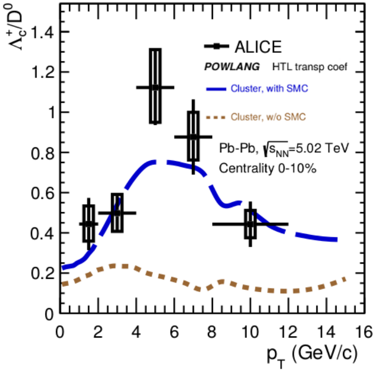
- SMC efficient mechanism to transfer flow from the fireball to the charmed hadrons;
- stronger effect for charmed baryons due to the larger radial flow of diquarks (mass ordering)

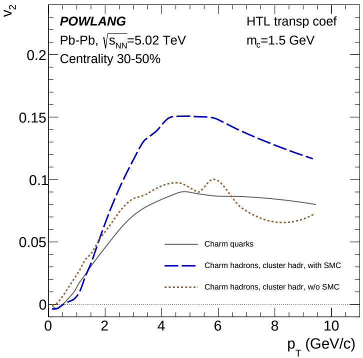
Results in AA: elliptic flow



Two different bands for charmed mesons and baryons arising in our model from the higher mass of diquarks involved in the recombination process (mass scaling rather than quark-number scaling)

The role of SMC





Explore the role of SMC's combining the HQ with a thermal particle chosen from a different point on the FO hypersurface $\longrightarrow$ recombining partons no longer collinear, hence:

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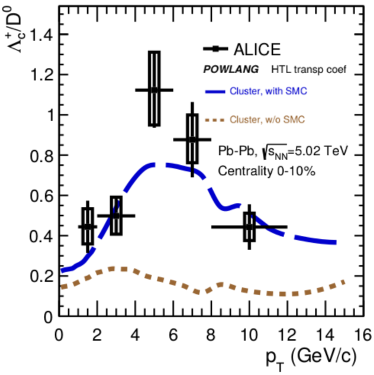

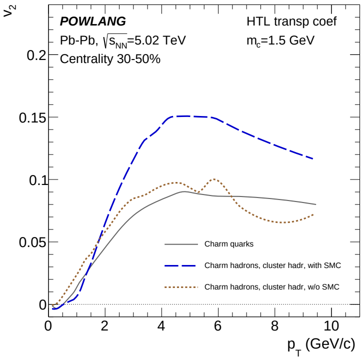

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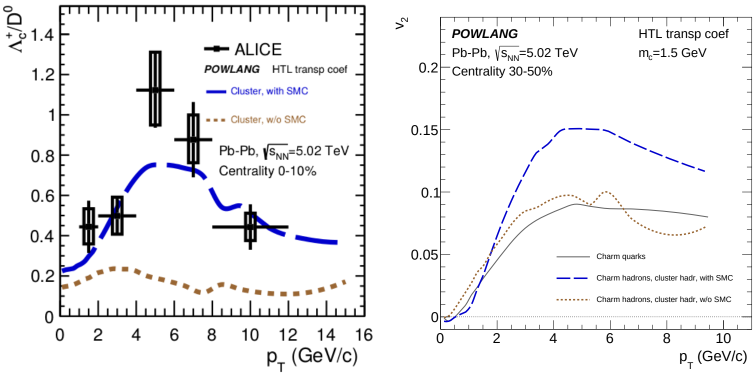

Explore the role of SMC's combining the HQ with a thermal particle chosen from a different point on the FO hypersurface $\longrightarrow$ recombining partons no longer collinear, hence:

- No big enhancement of the charmed hadron v_2
- Larger invariant mass of the formed cluster $\longrightarrow$ fragmentation into a larger number of hadrons as a standard Lund string, with no modified HF hadrochemistry

Some comments

Crucial point: formation of quite light color-singlet clusters undergoing in most cases a decay into a charmed hadron plus a very soft particle.

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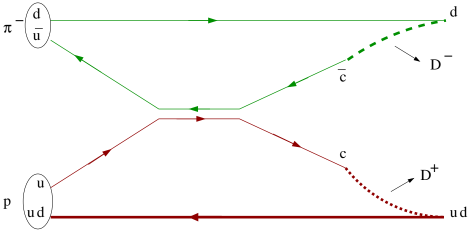

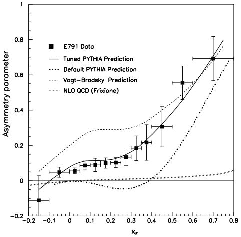

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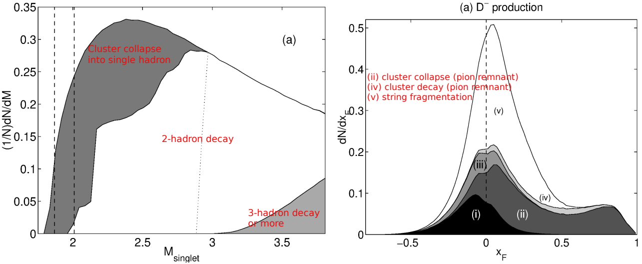

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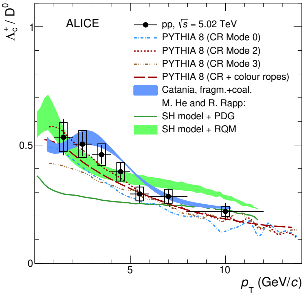
NB Small invariant-mass string can collapse into a single hadron: non-universal flavor composition (E. Norrbin and T. Sjostrand, EPJC 17 (2000) 137)!

On color-reconnections and *pp* collisions



Charmed baryon enhancement in *pp* collisions can be accounted for in PYTHIA introducing the possibility of color-reconnection (CR).

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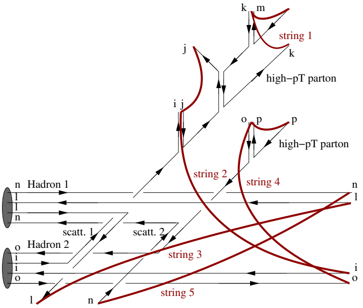

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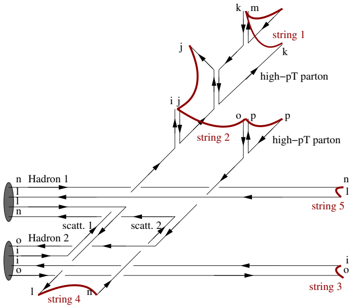

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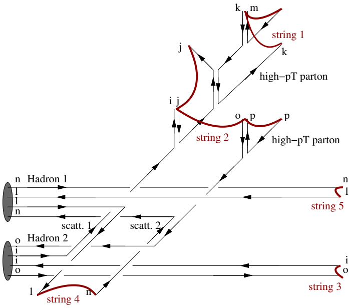

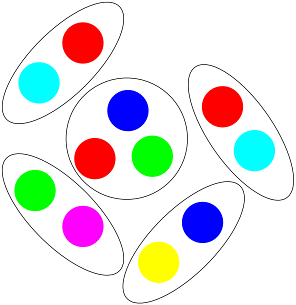

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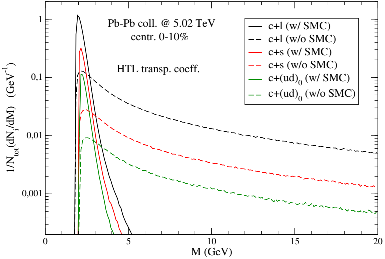

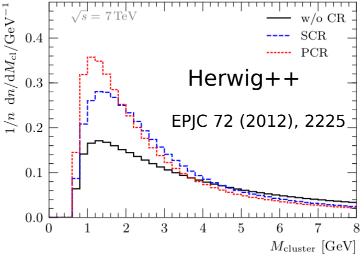

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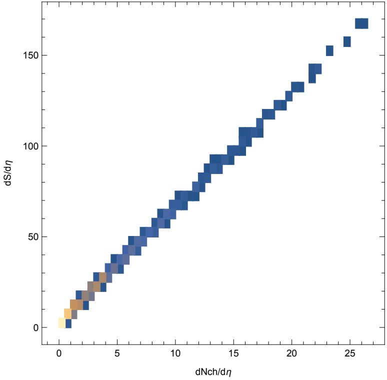
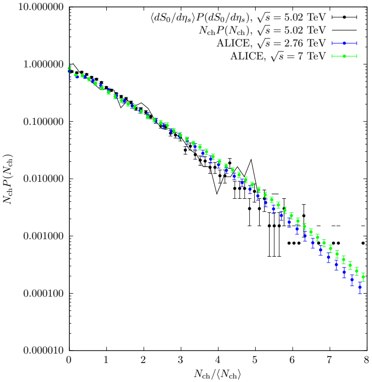
Addressing pp collisions in our model





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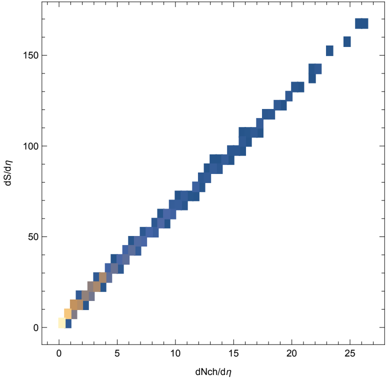

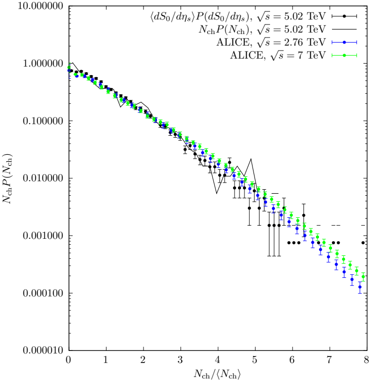

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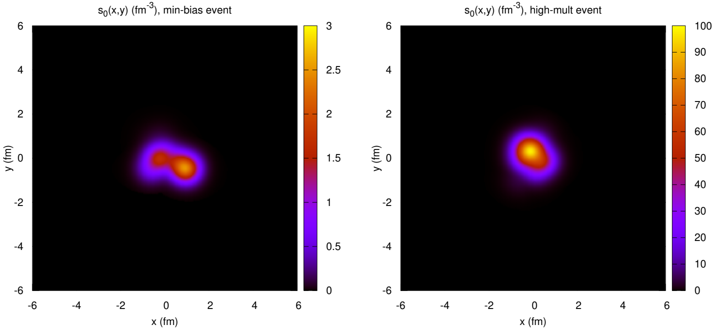

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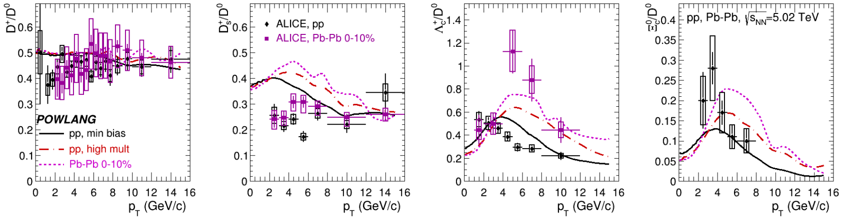
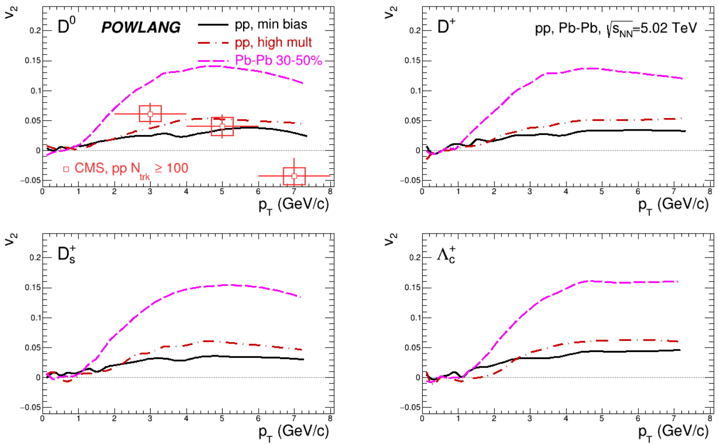
- Samples of 10^3 minimum-bias ($\langle dS/dy\rangle_{\rm mb} \approx 37.6$) and high-multiplicity ($\langle dS/dy\rangle_{0-1\%} \approx 187.5$) events used to simulate HQ transport and hadronization

Results in pp: particle ratios



- Enhancement of charmed baryon/meson ratio *qualitatively* reproduced
- Multiplicity dependence of the radial-flow peak position observed (just a reshuffling of the momentum, without affecting the yields)

Results in pp: elliptic flow



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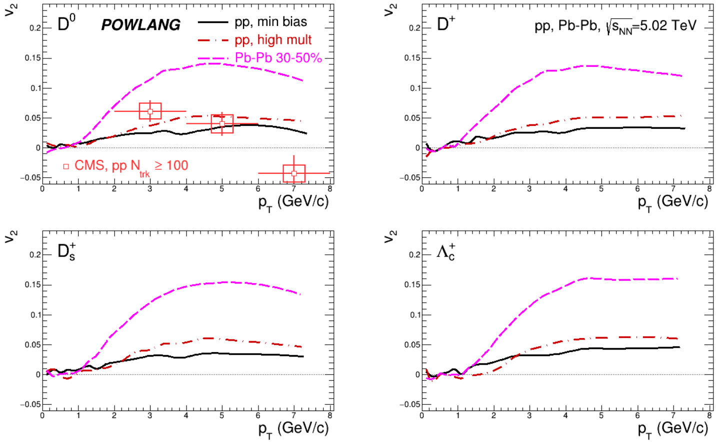

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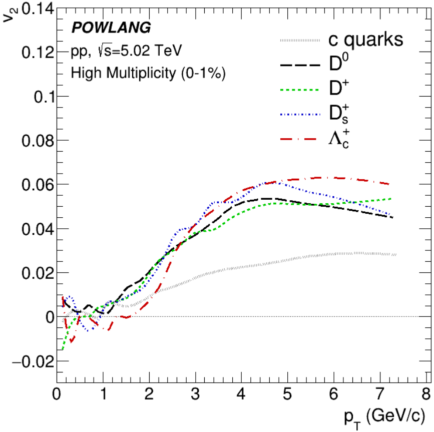

- Non-vanishing v2 even in minimum-bias pp
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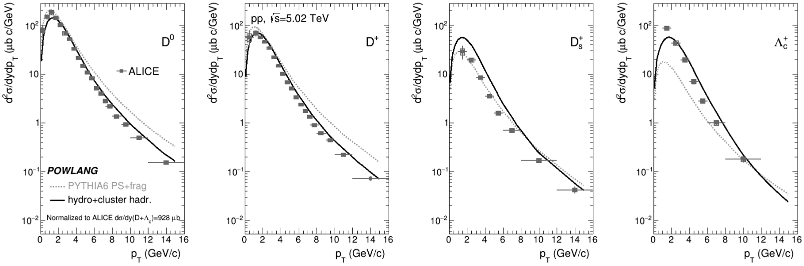
- Sizable fraction of v_2 acquired at hadronization

Relevance for the R_{AA} in nuclear collisions



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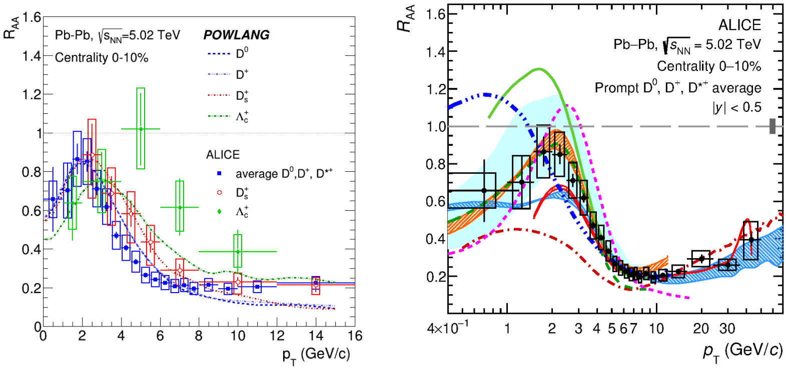

- Slope of the spectra in pp better described including medium effects
- Inclusion of medium effects in minimum-bias pp benchmark fundamental to better describe charmed hadron R_{AA} (left panel vs magenta curve in the right panel), both the radial-flow peak and the species dependence

In summary

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- The generalization of the results to the *pp* and *pA* case is currently in progress and first results have been displayed