Medium modification of HF hadronization: different implementations of recombination

Andrea Beraudo

INFN - Sezione di Torino

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Heavy-particle diffusion: physics motivation

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

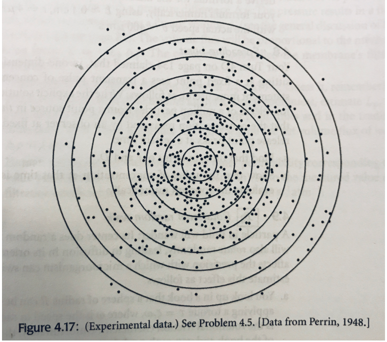

Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

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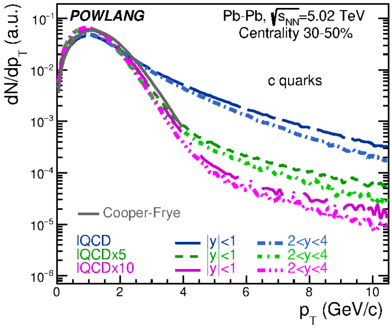

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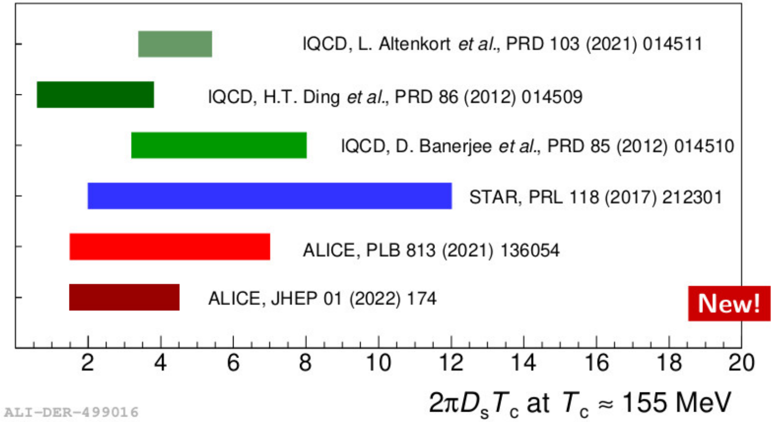
$$\mathcal{N}_A = \frac{\mathcal{R}T}{6\pi a\,\eta\, D_s} \approx 5.5 - 7.2 \cdot 10^{23}$$

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

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

Where do we stand?



Still far from accuracy and precision of Perrin result for $\mathcal{N}_A$...

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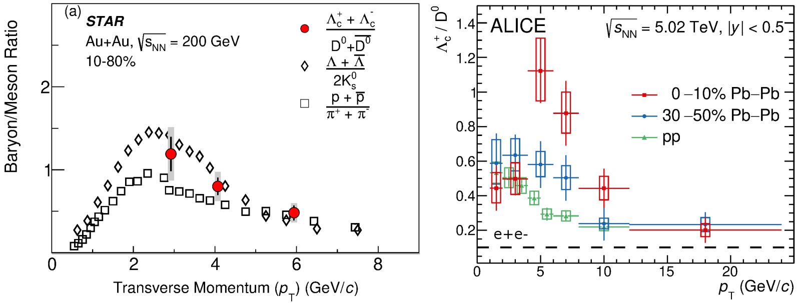
- hadronization (impossible to neglect)
  - source of systematic uncertainty in extracting transport coefficients;
  - an issue of interest in itself: how quark $\rightarrow$ hadron transition changes in the presence of a medium (the topic of this talk)

HF hadronization: experimental findings



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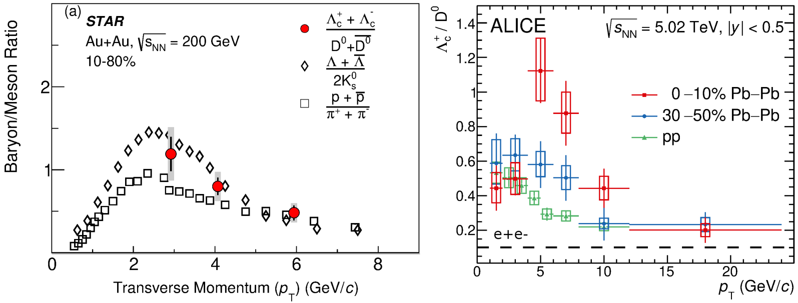

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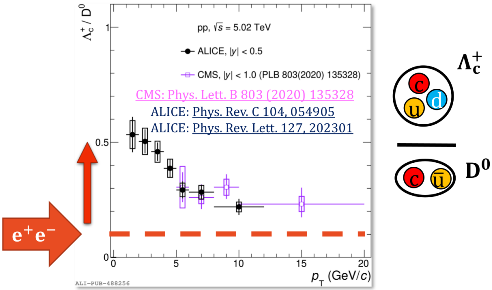

Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data

- 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

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

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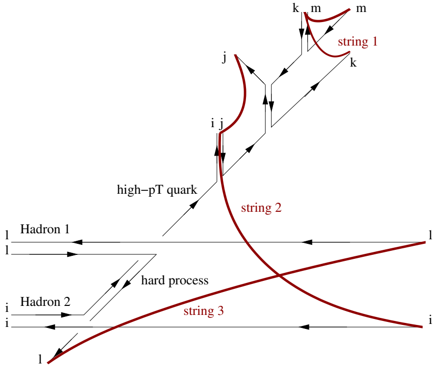

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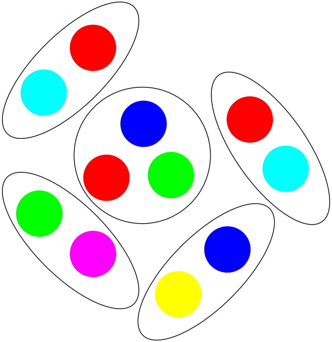
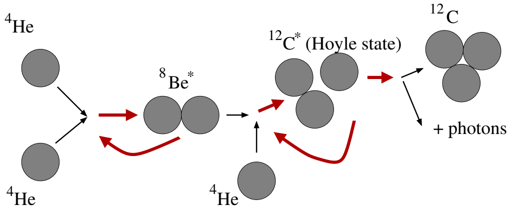
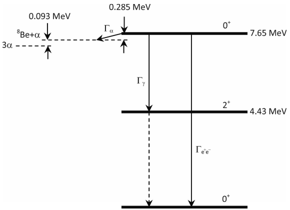


- in "elementary collisions": from the hard process, shower stage, underlying event and beam remnants;
- in heavy-ion collisions: from the hot medium produced in the collision. NB Involved partons closer in space in this case and this has deep consequence!

A warning from nucleosynthesis





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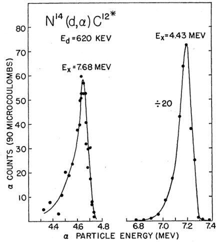

PRL 106, 192501 (2011) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

Ab Initio Calculation of the Hoyle State

Evgeny Epelbaum,[1] Hermann Krebs,[1] Dean Lee,[2] and Ulf-G. Meißner[3,4]
[1]*Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44870 Bochum, Germany*
[2]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[3]*Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*
[4]*Institut für Kernphysik, Institute for Advanced Simulation and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*
(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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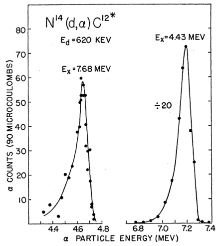

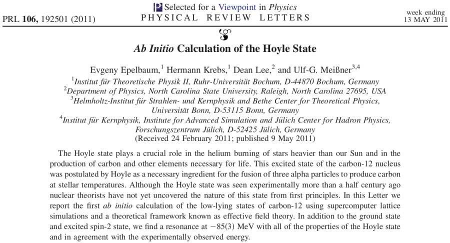

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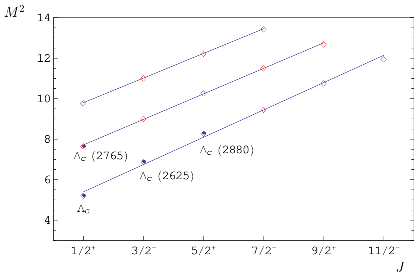

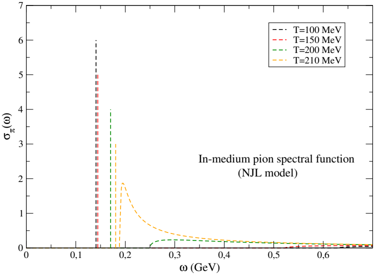

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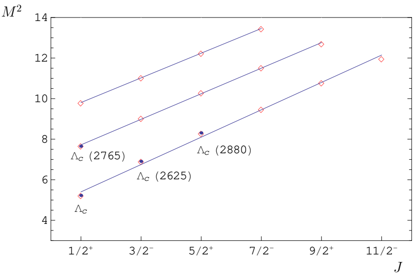

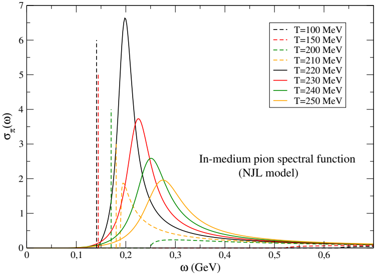

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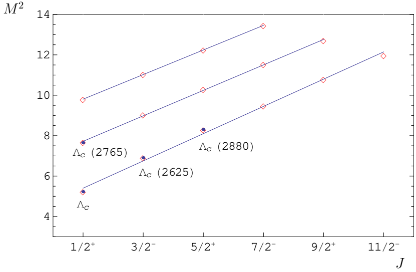

RRM (M. He and R. Rapp)

$c + \bar{q} \rightleftharpoons M$

$Q > 0$, $\Gamma_M \approx 100$ MeV $\gg \Gamma_{exp}$

→ dynamical equilibrium on hadronization hypersurface

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Disclaimer

In the following I will start from a specific *minimal* model of hadronization, based on a *local* color neutralization mechanism, just to illustrate common features and challenges to all approaches[1]

[1] For a quantitative comparison see talk by Jiaxing Zhao

A minimal model of in-medium hadronization

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]).

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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^+
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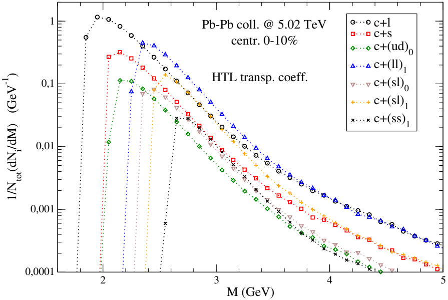
$(sl)_0$	1	2	0.80473	Ξ_c^0, Ξ_c^+
$(sl)_1$	3	2	0.92953	Ξ_c^0, Ξ_c^+
$(ss)_1$	3	1	1.09361	Ω_c^0, Ξ_c^+

(masses taken from PYTHIA 6.4)



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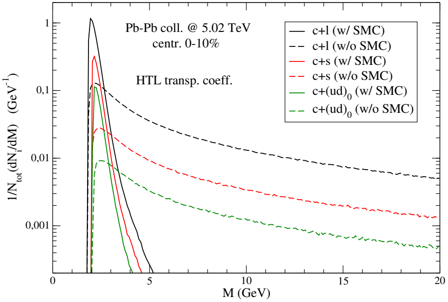

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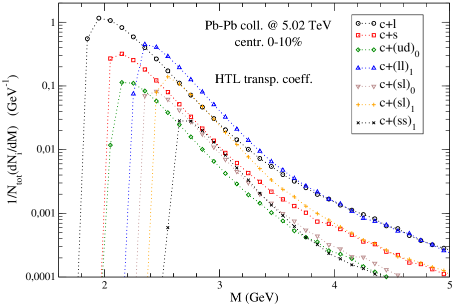
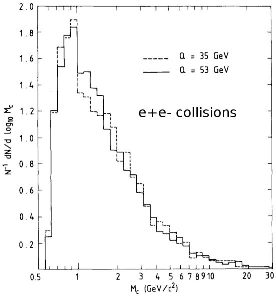
- Cross-check: remove SMC by randomly selecting light parton from a different point on the FO hypersurface $\longrightarrow$ long high-$M_{\mathcal{C}}$ tail

On the suppression of high-mass clusters





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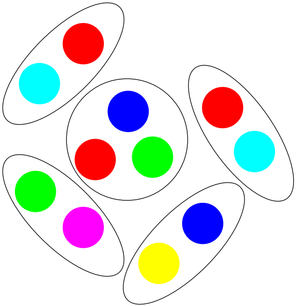

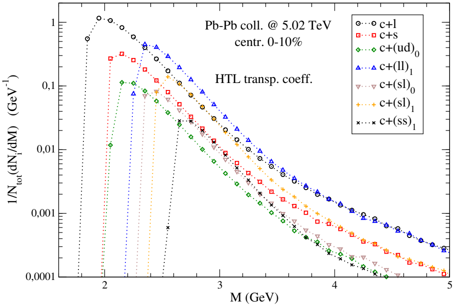

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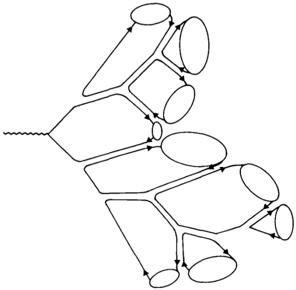

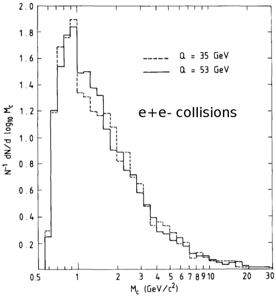

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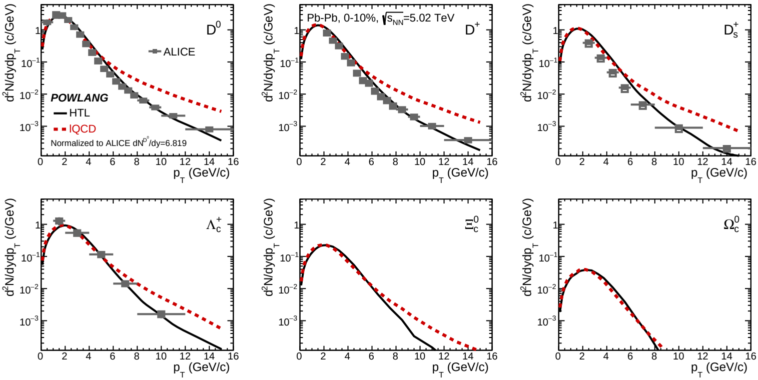
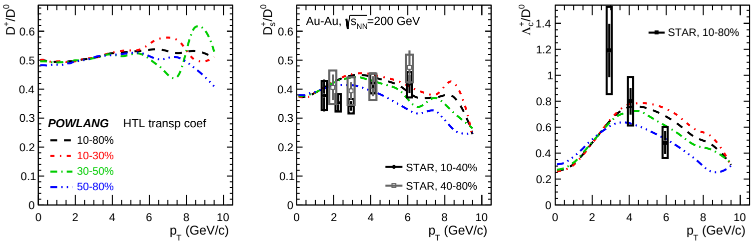
- In Herwig, in e^+e^- collisions, this is due to the angular ordered parton shower (*pre-confinement*)

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



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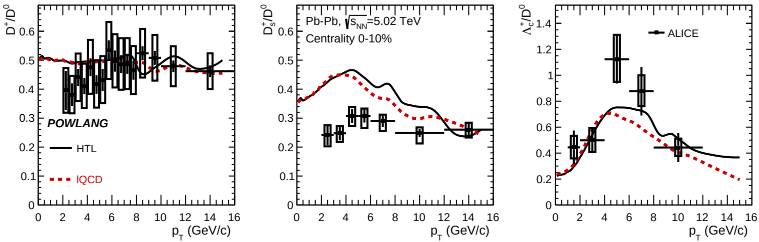

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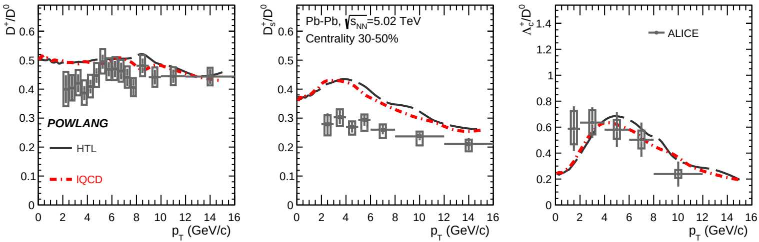

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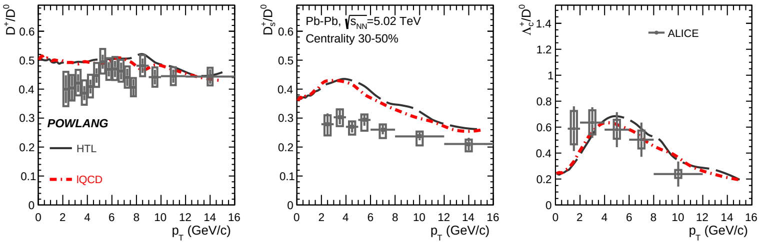

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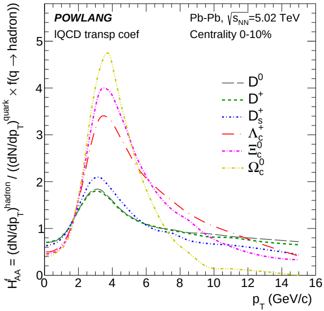
- Mild dependence on the transport coefficients, i.e. on the dynamics in the deconfined phase

How much flow acquired at hadronization?



$$H^f_{AA} \equiv \frac{(dN/dp_T)^{\mathrm{hadron}_f}}{(dN/dp_T)^{\mathrm{quark}}} \frac{1}{f(c \to \mathrm{hadron}_f)}$$

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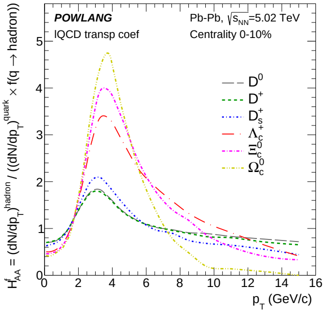

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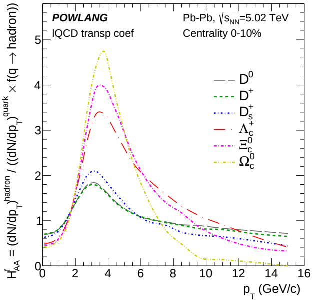

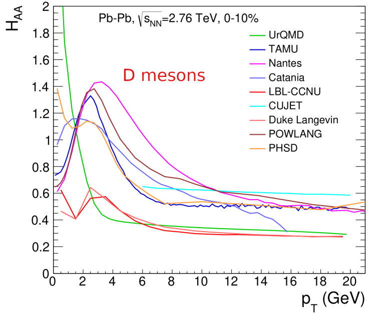

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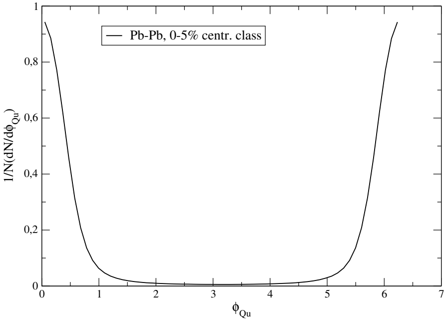
- SMC efficient mechanism to transfer flow from the fireball to the charmed hadrons;
- stronger effect for charmed baryons due to the larger radial flow of diquarks (mass ordering)
- Reshuffling of the spectra from small to intermediate p_T common feature to most recombination models implementing SMC (R. Rapp *et al.*, Nucl.Phys.A 979 (2018) 21)

Why are SMC so effective?



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- This is the case for the present cluster-formation model
- but also for coalescence models, thanks to the quite localized form of the hadron Wigner function:

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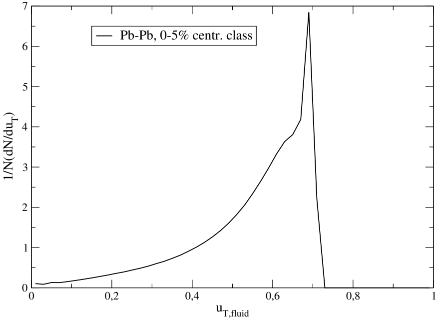

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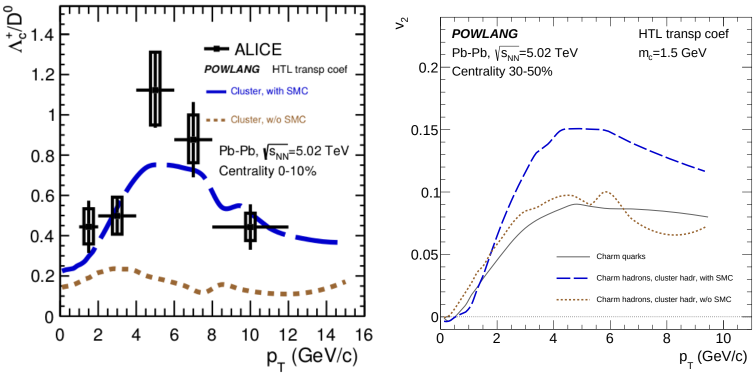
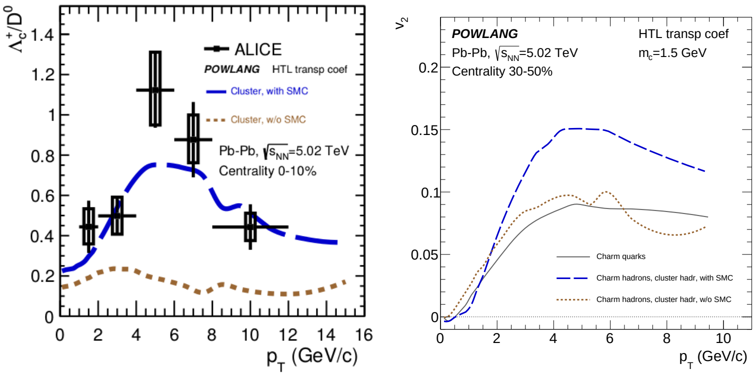


Explore the role of SMC's combining the HQ with a thermal particle chosen from a different point on the FO hypersurface $\longrightarrow$ recombining partons no longer collinear, hence:

The role of SMC



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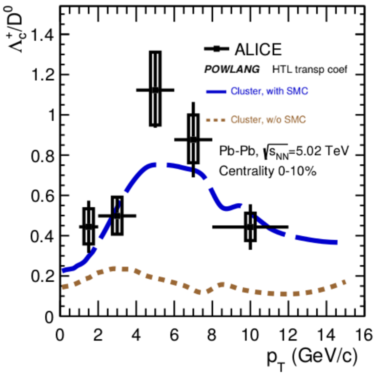

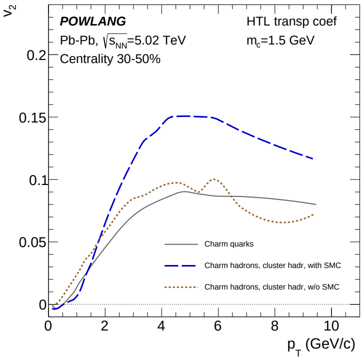

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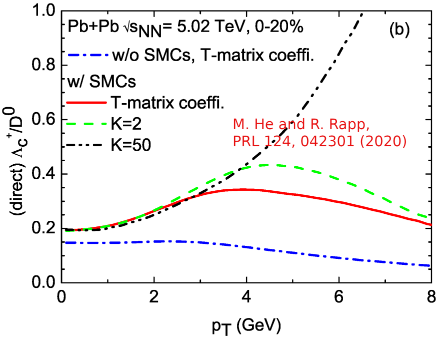

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- Same finding in RRM model

Some comments

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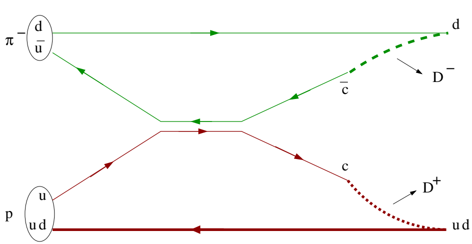

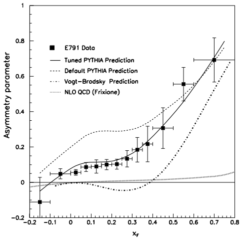

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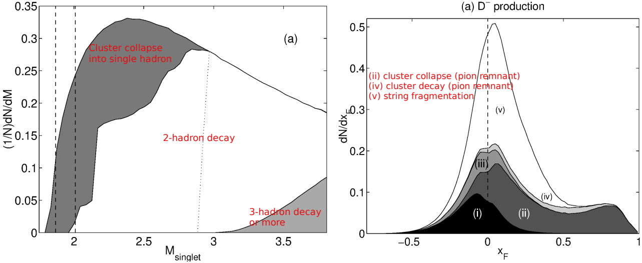

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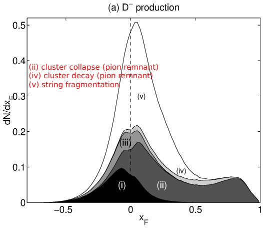

duality arguments, but also with the presence of soft final-state interactions, i.e. the exchange of nonperturbative gluons that can carry some amount of momentum between the low-mass string and the surrounding hadronic system. In the following we will therefore adopt the language of 'gluons' transferring energy and momentum between the strings in a collision, while leaving unanswered the question on the exact nature of those 'gluons'. Specifically, we will not address the possibility of changes in the colour structure of events by such 'gluons'.

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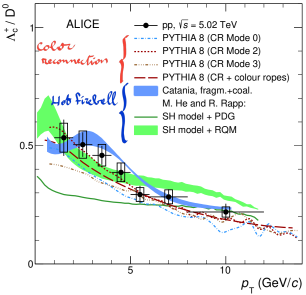
How to conserve four-momentum? Same problem as in coalescence...

On color-reconnections and *pp* collisions



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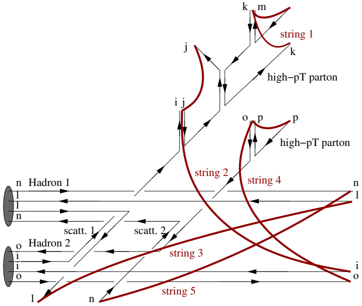

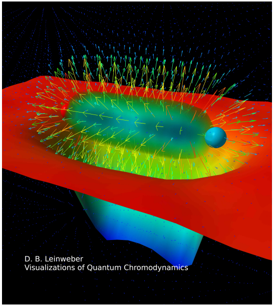

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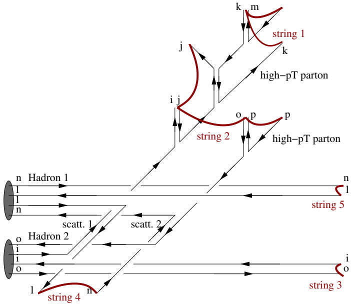

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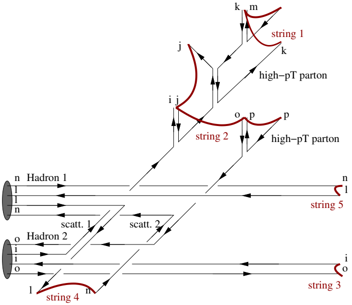

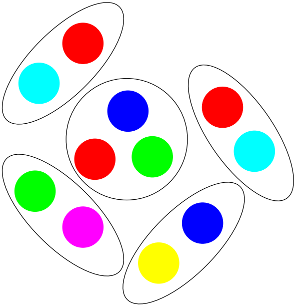

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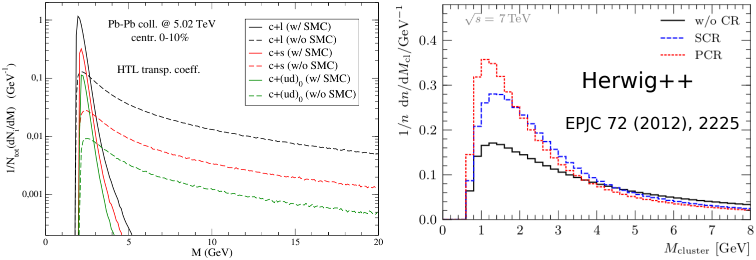

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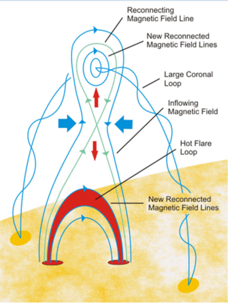
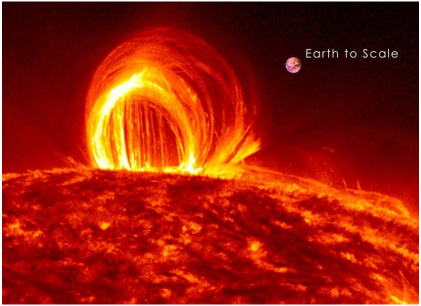
Caveat: reconnection of Abelian gauge fields





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

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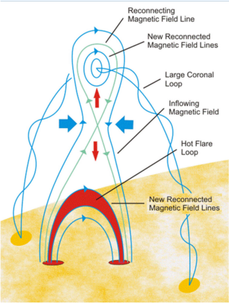

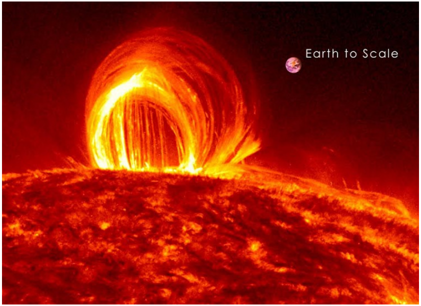

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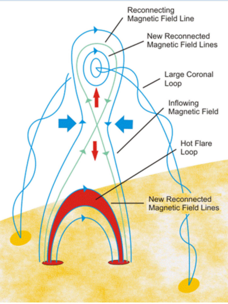

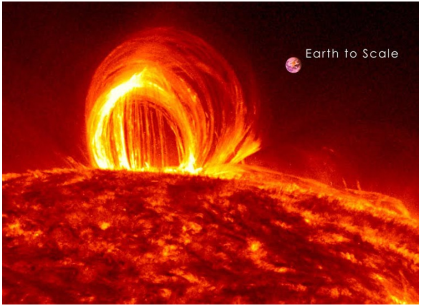

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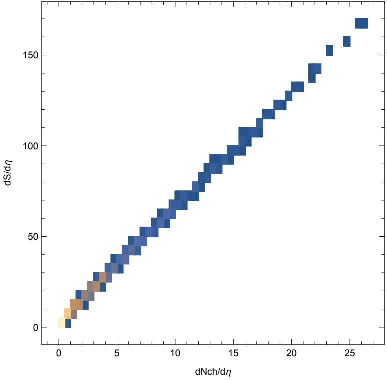
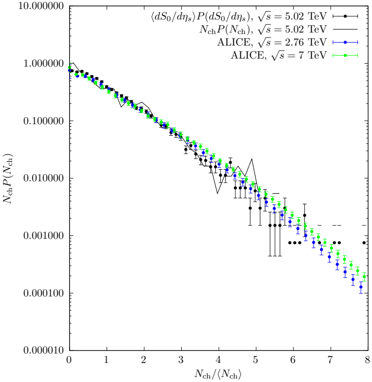
- Not completely understood in the case of electrodynamic plasmas
- Where does the energy stored in the color fields goes? When are reconnected strings formed?

Addressing pp collisions...





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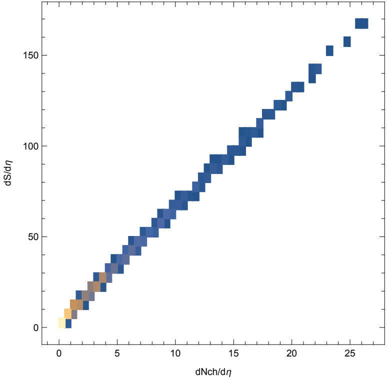

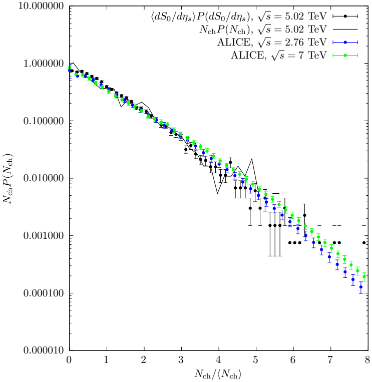

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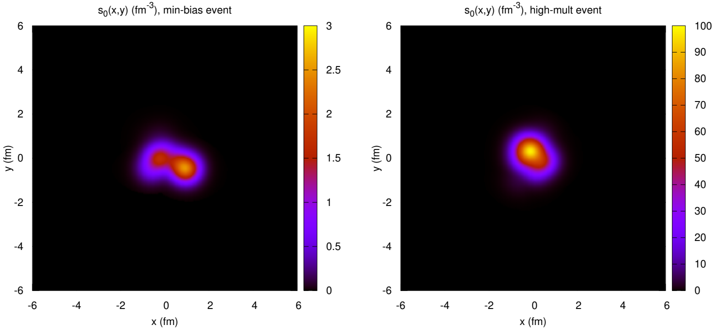

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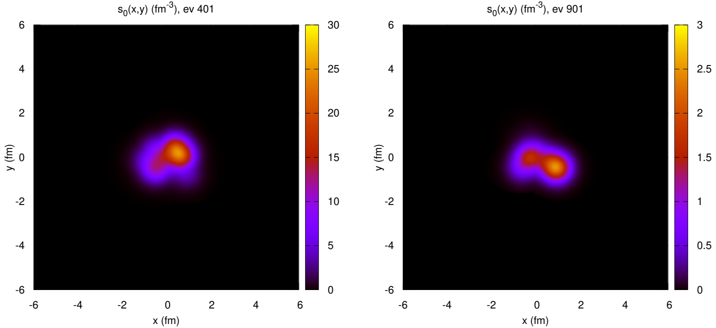
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity ($dN_{\rm ch}/d\eta$), $S \approx 7.2 N_{\rm ch}$
- Samples of 10^3 minimum-bias ($\langle dS/dy \rangle_{\rm mb} \approx 37.6$) and high-multiplicity ($\langle dS/dy \rangle_{0-1\%} \approx 187.5$) events used to simulate HQ transport and hadronization

Why in-medium hadronization also in pp?



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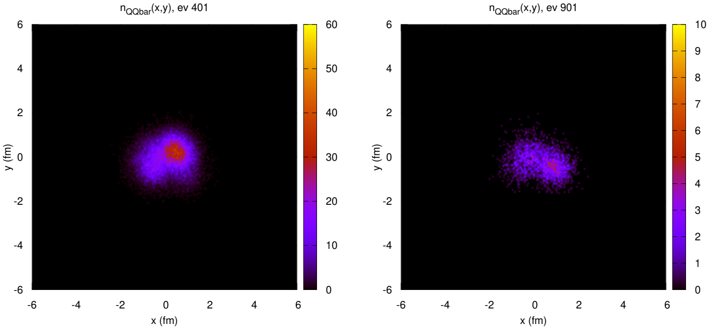

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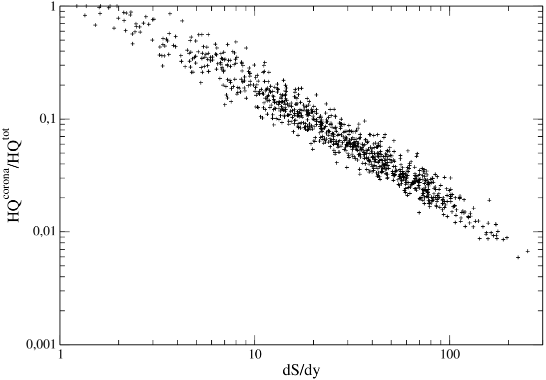

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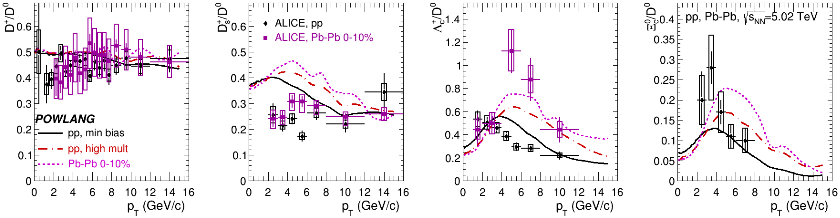
$\longrightarrow$ only about 5% of $Q\overline{Q}$ pairs initially found in fluid cells below T_c

Results in pp: particle ratios

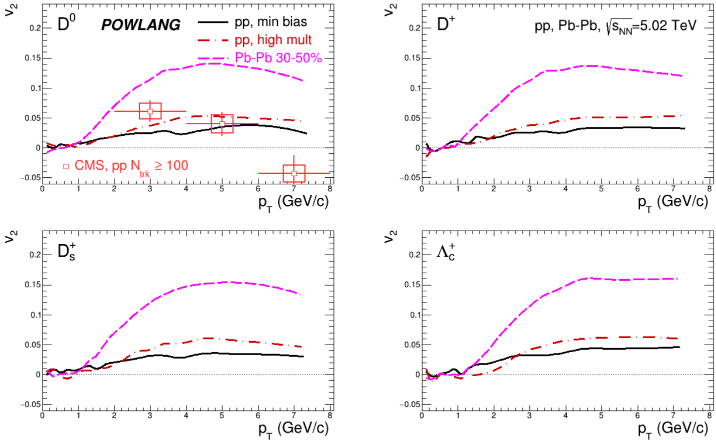


Premilinary results[2]:

- 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)

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

Results in pp: elliptic flow



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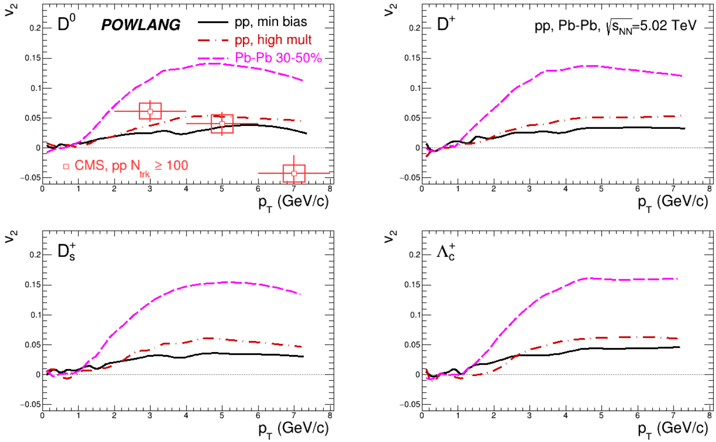

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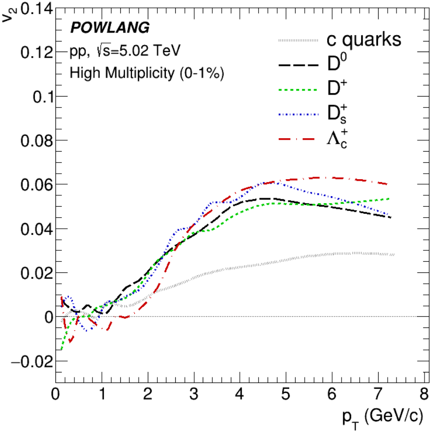
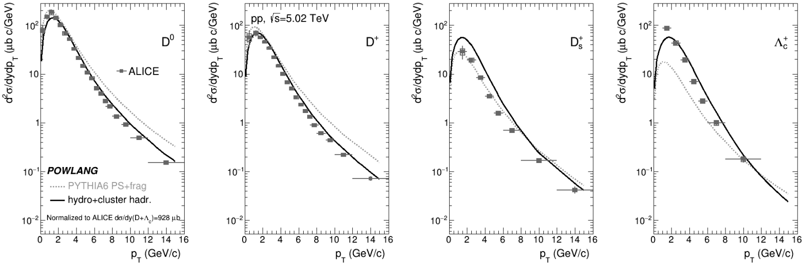


- Non-vanishing v2 even in minimum-bias pp
- D-meson v_2 in high-multiplicity pp in agreement with CMS results
- Sizable fraction of v_2 acquired at hadronization

Relevance for the R_{AA} in nuclear collisions



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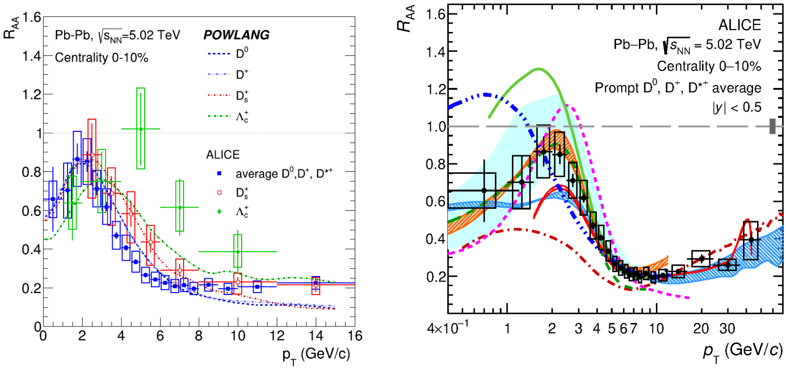

- Slope of the spectra in pp better described including medium effects
- Inclusion of medium effects in minimum-bias pp benchmark fundamental to better describe charmed hadron R_{AA} (left panel vs magenta curve in the right panel), both the radial-flow peak and the species dependence

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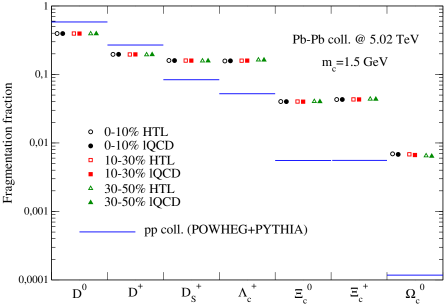
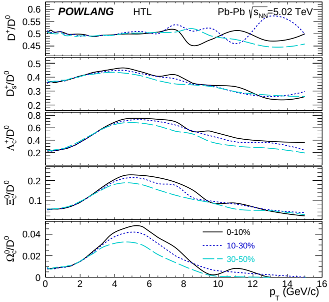
- What is *common* to all microscopic hadronization models?
- Strong implications for the extraction of transport coefficients (same flow reproduced with milder in-medium interaction);
- Consistent modelling of in-medium hadronization also in pA and pp collisions mandatory.

Back-up slides

Results in AA: fragmentation fractions





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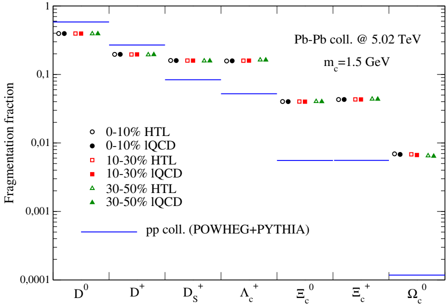

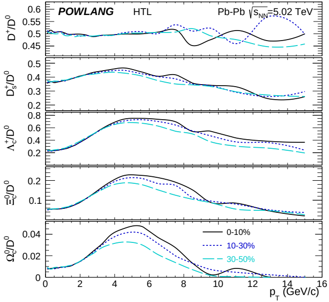

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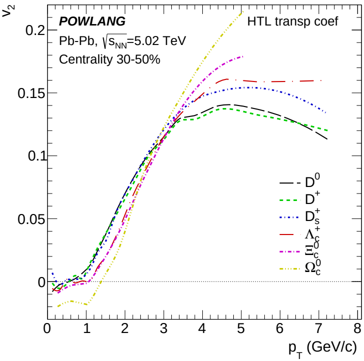
NB Model predictions for pp collisions displayed in the following

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)