Heavy-flavour meson and baryon production in high-energy nucleus-nucleus collisions

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Heavy-particle diffusion: physics motivation

Goal: getting access to the microscopic properties of the background medium in which the Brownian particle propagates

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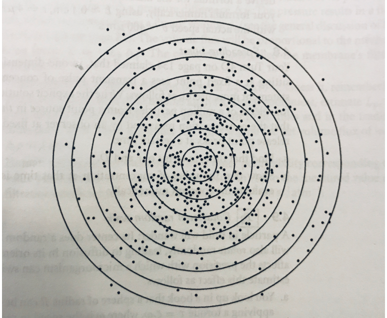

Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

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

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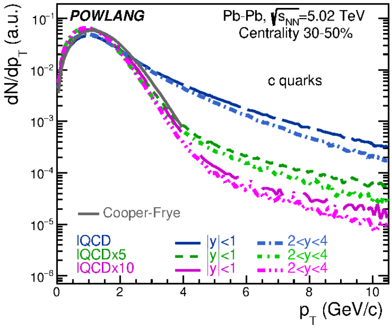

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$$\mathcal{N}_A = \frac{\mathcal{R}T}{6\pi a \eta D_s} \approx 5.5 - 7.2 \cdot 10^{23}$$

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

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

A crucial difference

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

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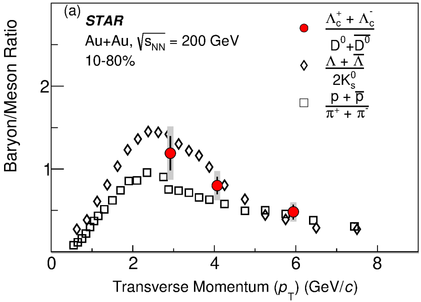
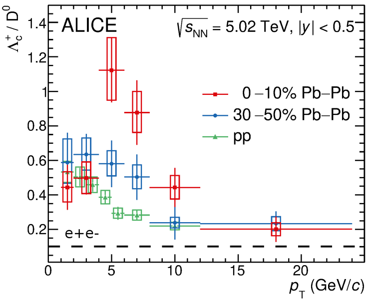
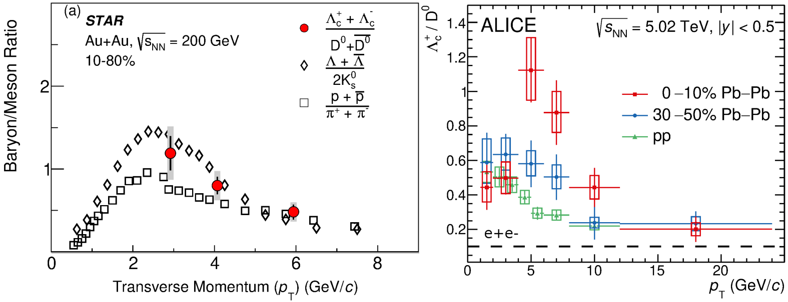
- possible thermal mass-shift (here neglected)
- hadronization (impossible to neglect)
  - source of systematic uncertainty in extracting transport coefficients;
  - an issue of interest in itself: how quark $\rightarrow$ hadron transition changes in the presence of a medium (the topic of this talk)





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

HF hadronization: experimental findings



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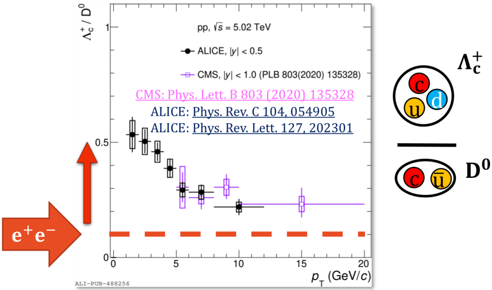

Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data

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

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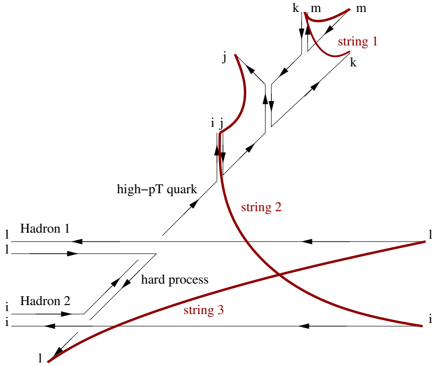

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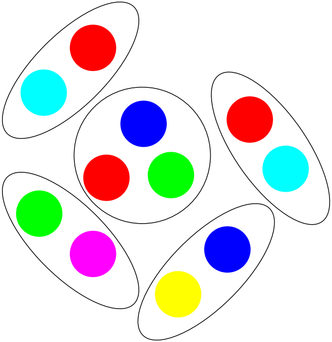

- in "elementary collisions": from the hard process, shower stage, underlying event and beam remnants;
- in heavy-ion collisions: from the hot medium produced in the collision. NB Involved partons closer in space in this case and this has deep consequence!

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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   - 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^+
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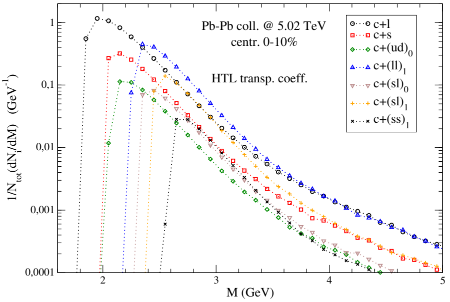
$(ss)_1$	3	1	1.09361	Ω_c^0, Ξ_c^+

(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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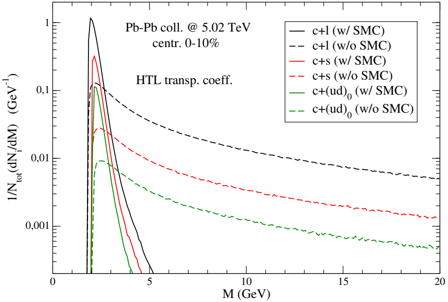

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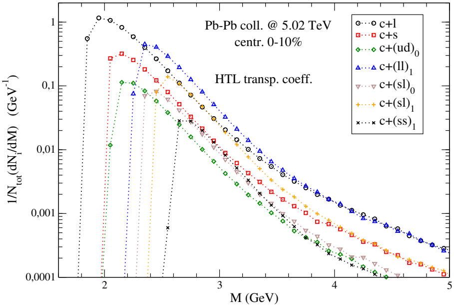
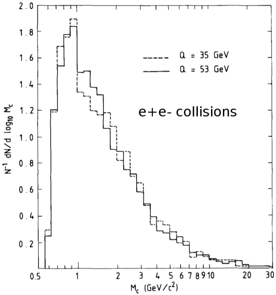
- This arises from Space-Momentum Correlation: charm momentum usually parallel to fluid velocity $\longrightarrow$ recombination occurs between quite collinear partons;
- Cross-check: remove SMC by randomly selecting light parton from a different point on the FO hypersurface $\longrightarrow$ long high-$M_{\mathcal{C}}$ tail

On the suppression of high-mass clusters





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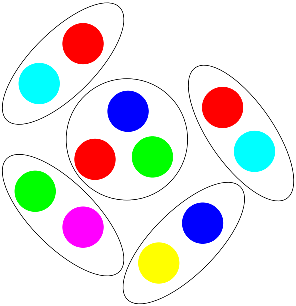

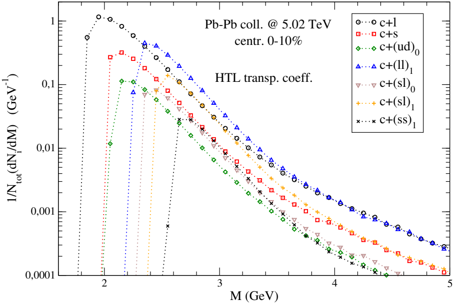

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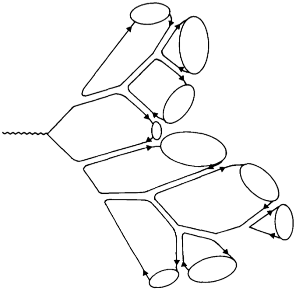

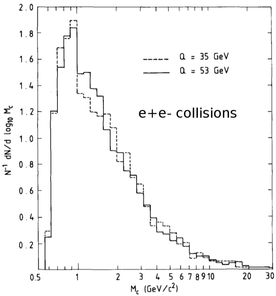

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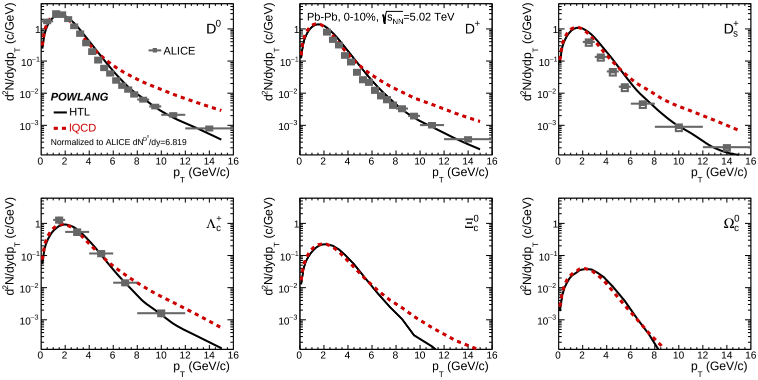
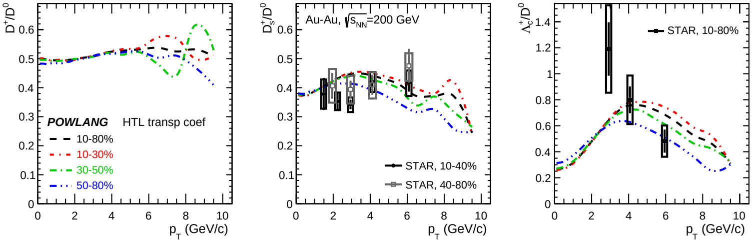
- In our model this is due to the SMC arising from recombining nearby partons;
- In Herwig, in e^+e^- collisions, this is due to the angular ordered parton shower (*pre-confinement*)



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: hadron ratios



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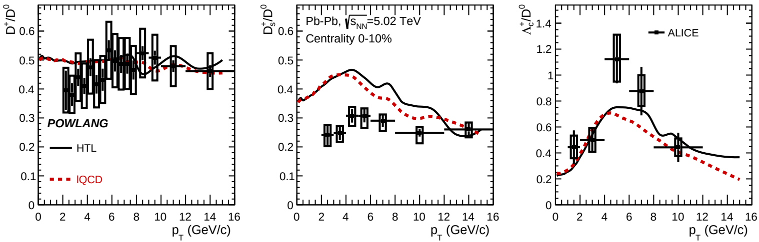

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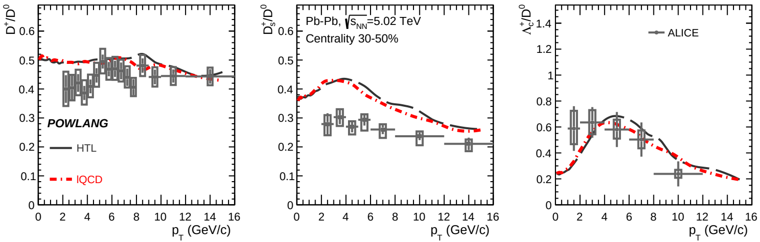

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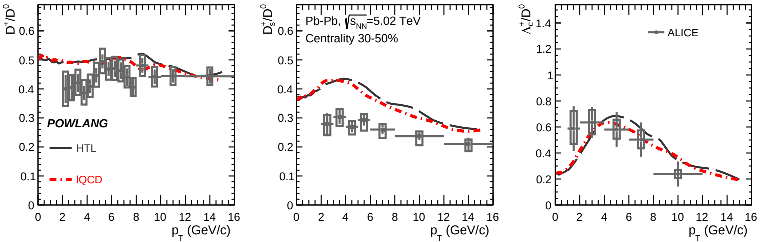

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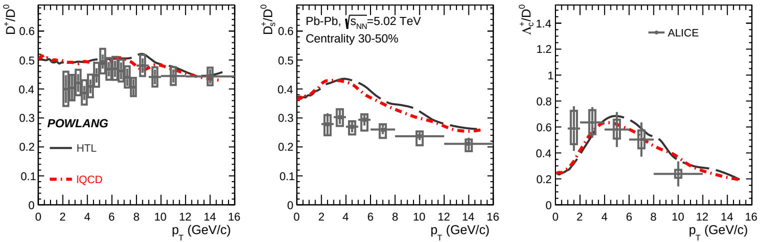

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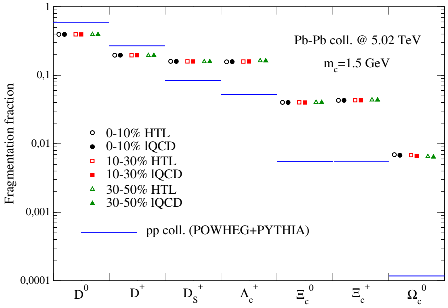
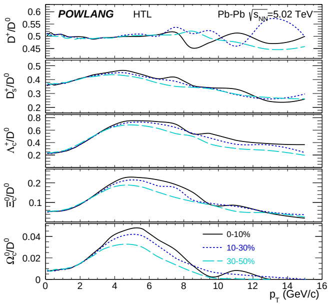
NB We have not attempted a tuning of the parameters to fit the data, e.g. quark and diquark masses taken from default values in PYTHIA

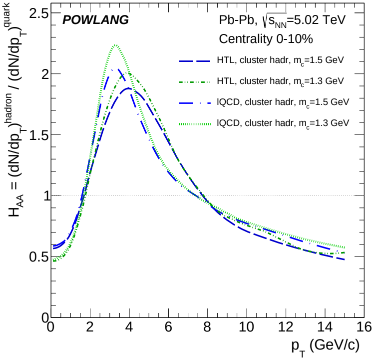
Results: fragmentation fractions

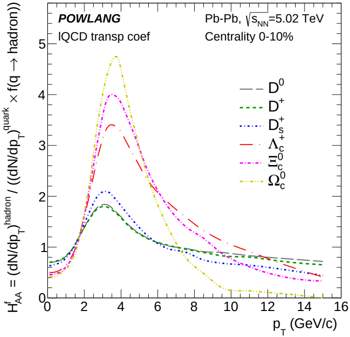




- FF's in AA collisions pretty independent from the centrality, leading simply to a reshuffling of the p_T-distribution (stronger radial flow of charmed baryons in central events);
- Strong enhancement of charmed baryon production wrt theoretical predictions by default tunings of QCD generators in pp collisions

How much flow acquired at hadronization?

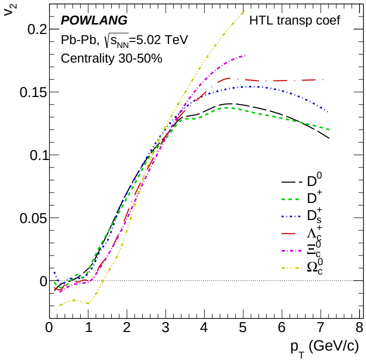


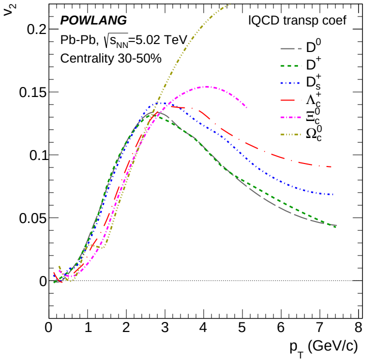


Big enhancement of charmed hadron production at intermediate p_T

- SMC efficient mechanism to transfer flow from the fireball to the charmed hadrons;
- stronger signal for heaviest charmed baryons due to the larger radial flow of the heaviest diquarks

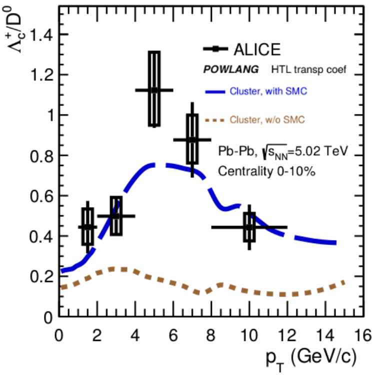
Results: elliptic flow

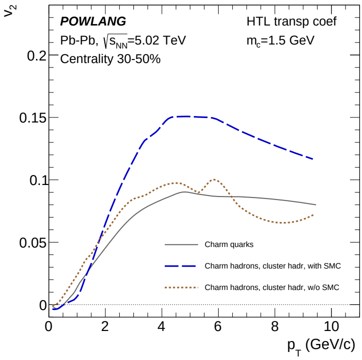




Two different bands for charmed mesons and baryons arising in our model from the higher mass of diquarks involved in the recombination process (mass scaling rather than quark-number scaling)

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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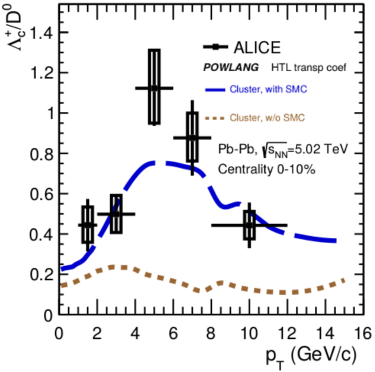

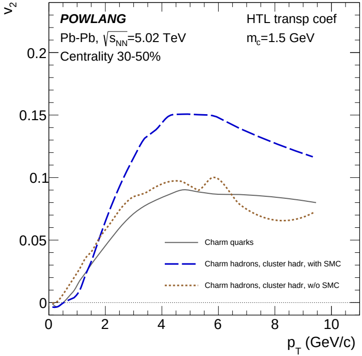

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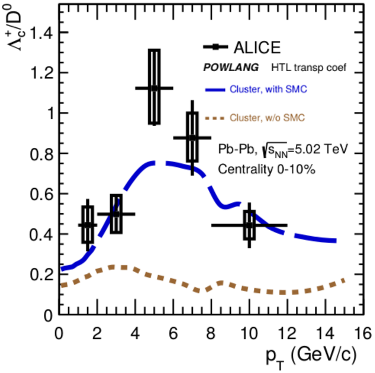

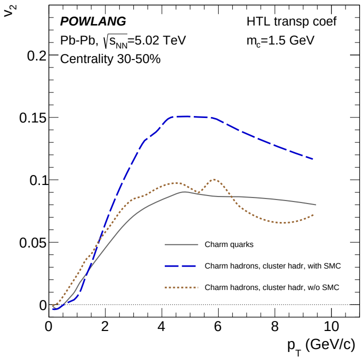

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- No big enhancement of the charmed hadron v_2
- Larger invariant mass of the formed cluster $\longrightarrow$ fragmentation into a larger number of hadrons as a standard Lund string, with no modified HF hadrochemistry

Some comments

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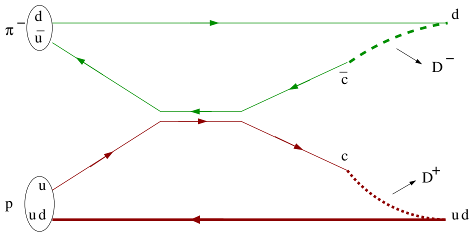
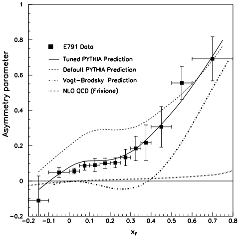
Crucial point: formation of quite light color-singlet clusters undergoing in most cases a decay into a charmed hadron plus a very soft particle. Ingredient already necessary in the past to describe peculiar effects in charm hadroproduction at Fermilab and SPS (e.g. $\pi^- + p$ collisions)



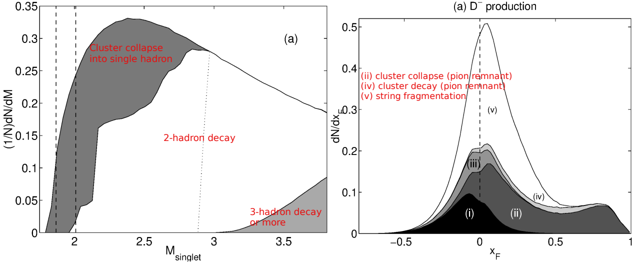


Second endpoint boosts the string along the direction of the beam-remnant (*beam-drag effect*), leading to an asymmetry in the rapidity distribution of D^+/D^- mesons

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

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. Ingredient already necessary in the past to describe peculiar effects in charm hadroproduction at Fermilab and SPS (e.g. $\pi^- + p$ collisions)



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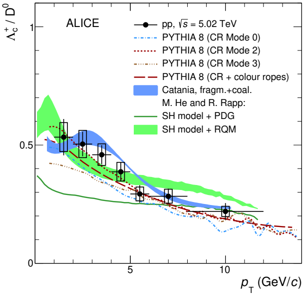
NB Small invariant-mass string can collapse into a single hadron: non-universal flavor composition (E. Norrbin and T. Sjostrand, EPJC 17 (2000) 137)!

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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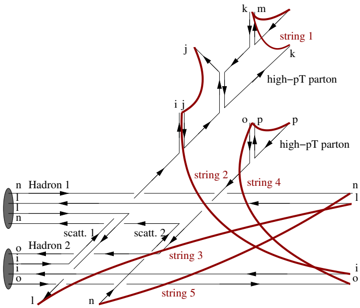

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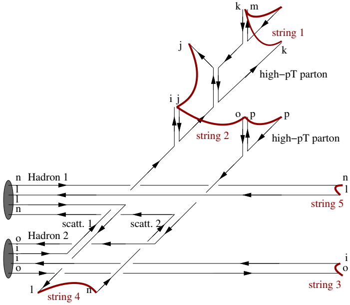
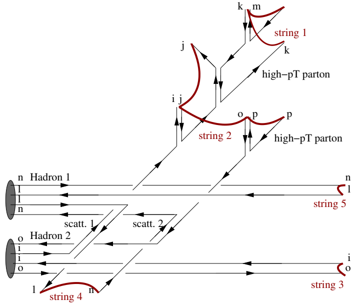
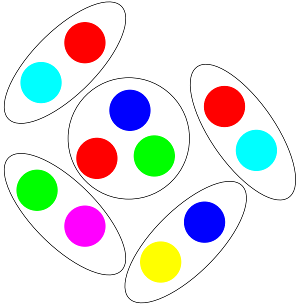


Charmed baryon enhancement in *pp* collisions can be accounted for in PYTHIA introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap and give rise to a rearrangement of color connections to minimize their length.

On color-reconnections and *pp* collisions





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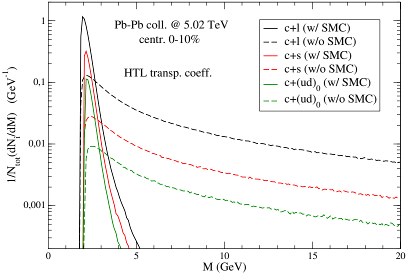

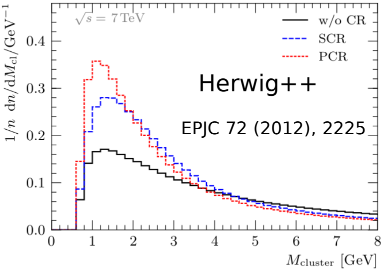

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- The generalization of the results to the *pp* and *pA* case is currently in progress.