Implications of LHCb measurements and future prospects

Hadronization in small system

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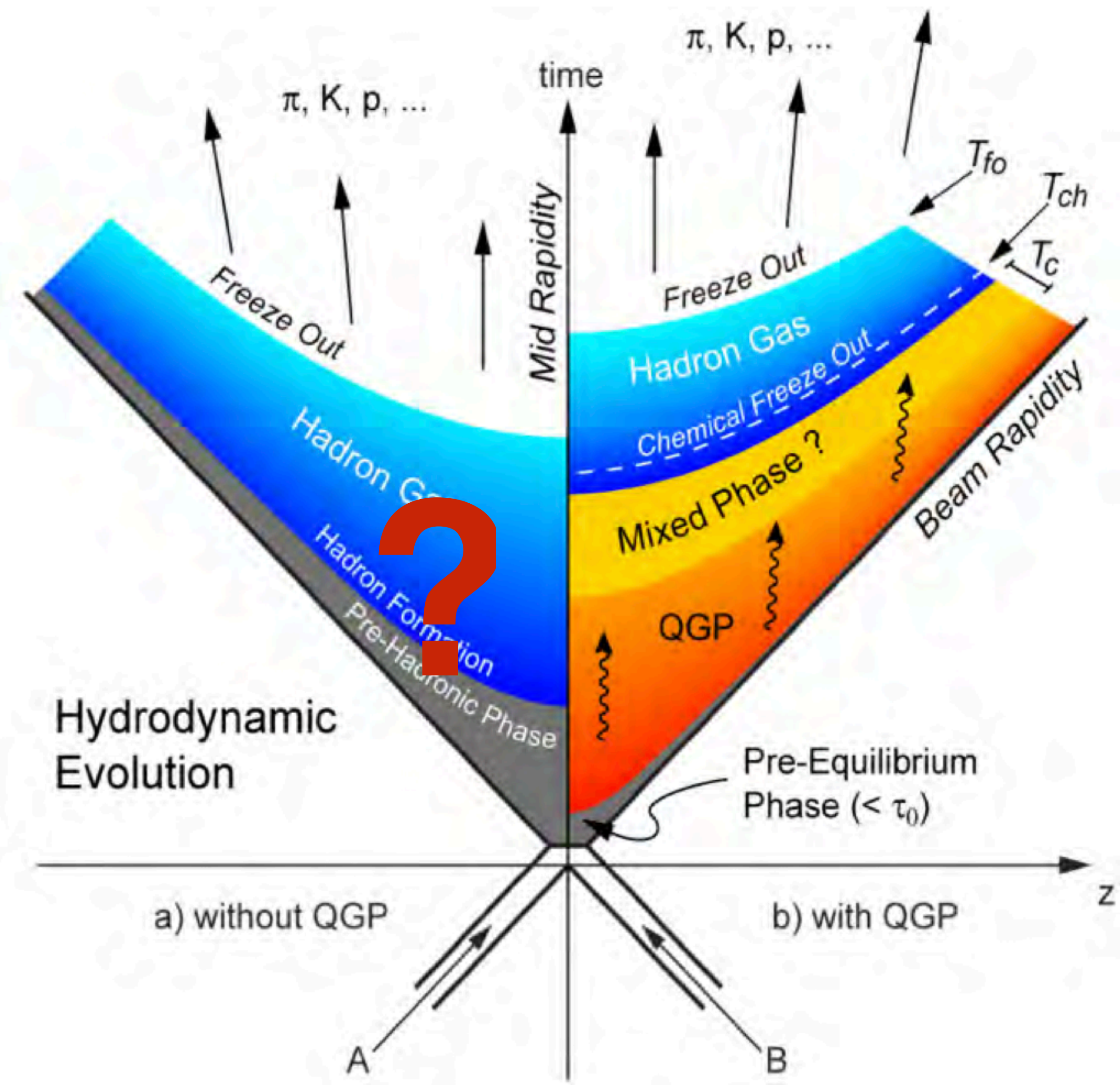
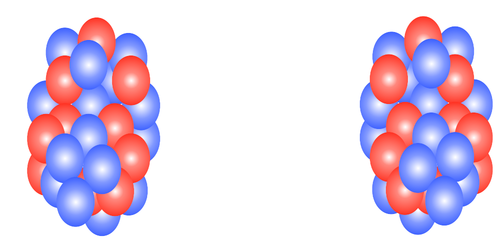
25/10/2023

I. Small system vs. Large system

p p

$pp, pPb, dAu, \ldots$





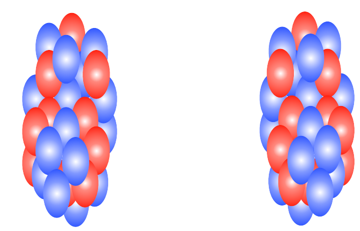
Pb Pb

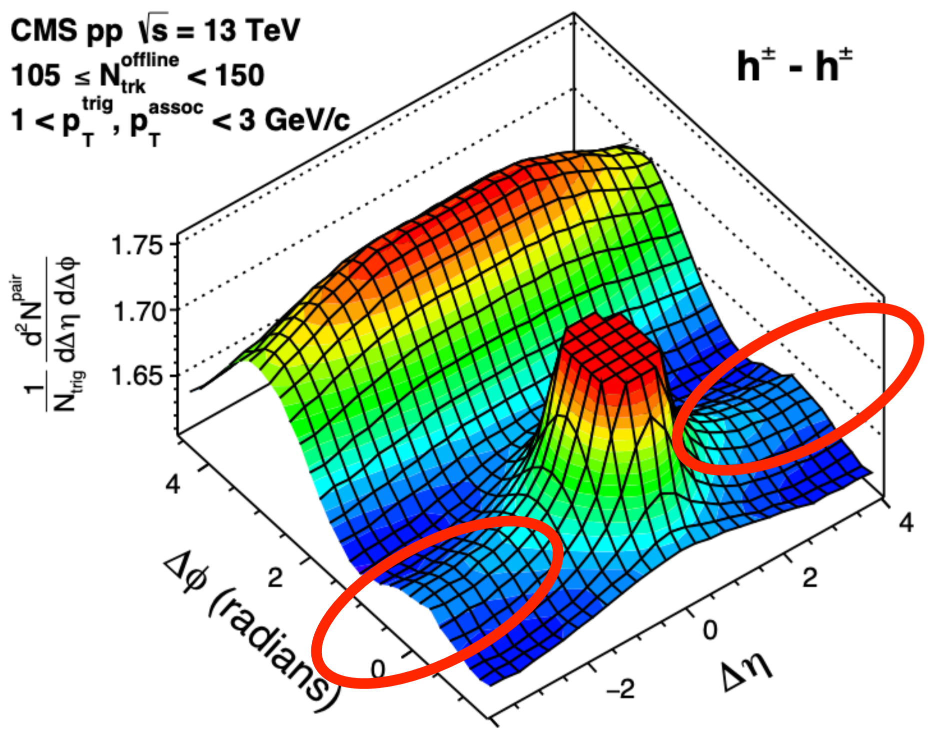
$PbPb, AuAu, \ldots$

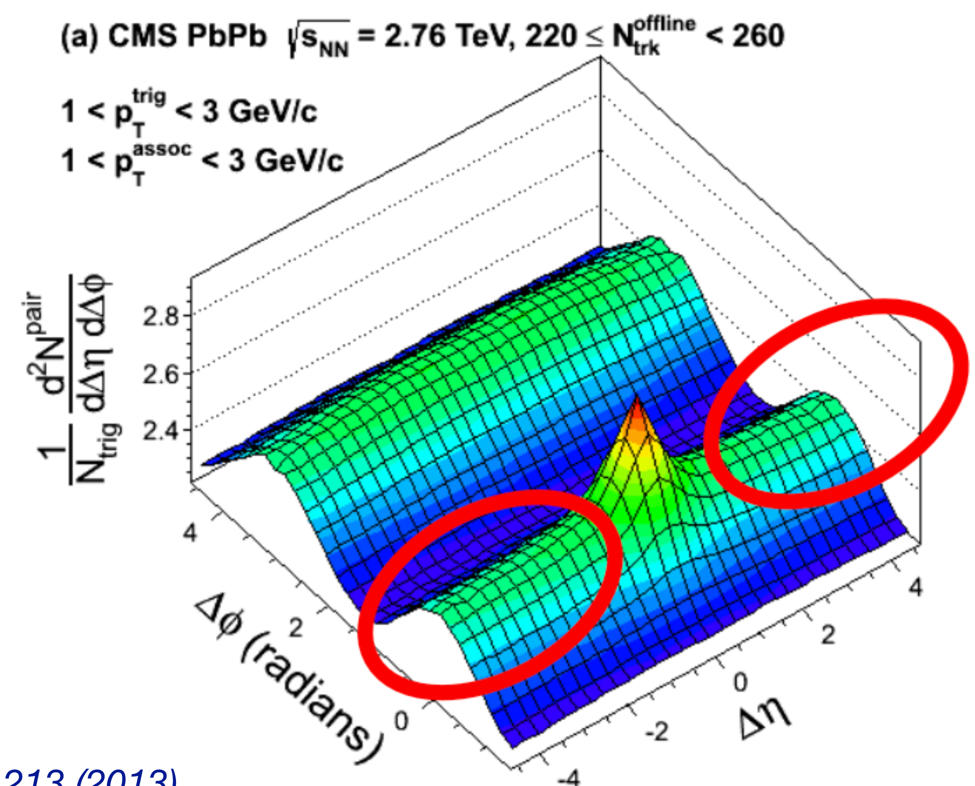
Deconfined QCD matter or QGP created in pp collisions?

I. Small system vs. Large system

1. Long-range two-particle correlation





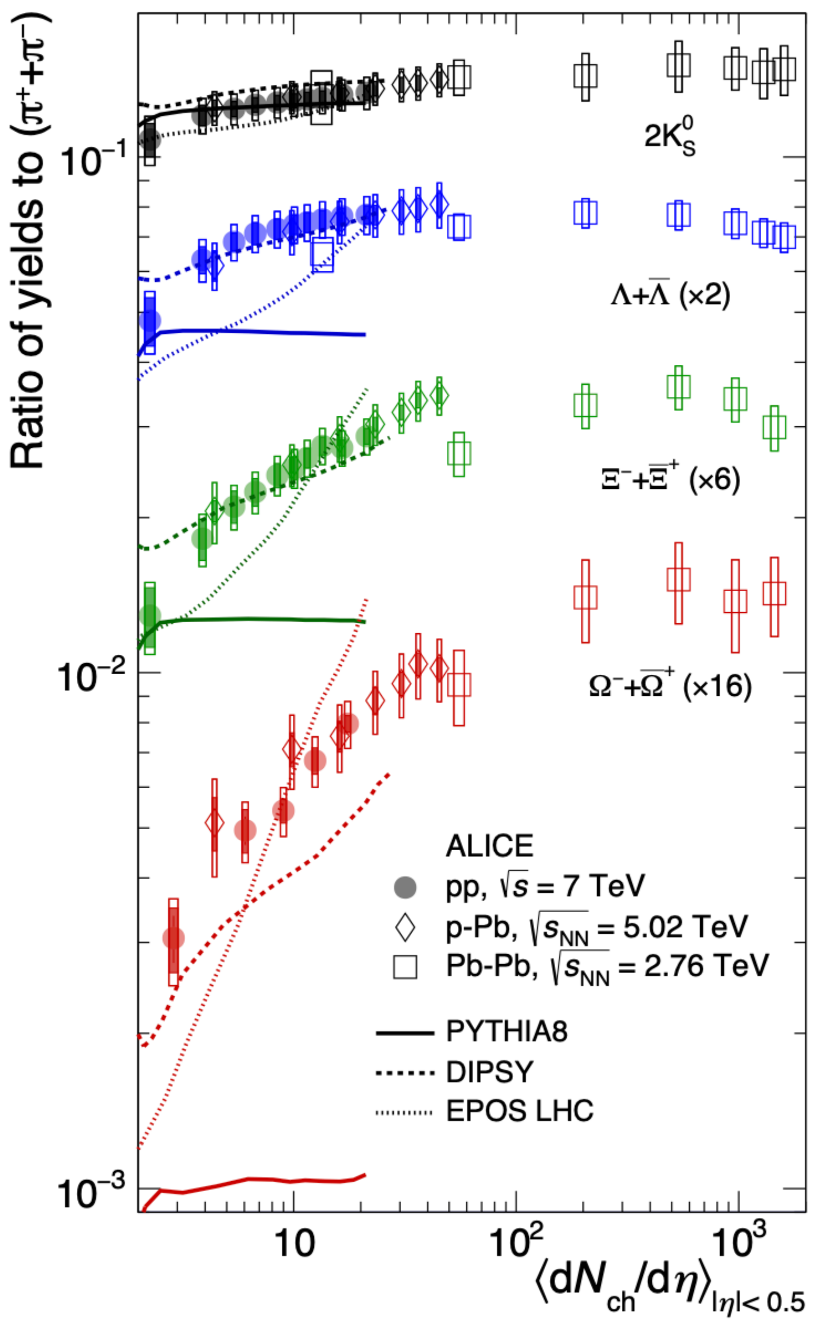


CMS, PLB 724, 213 (2013)
And PLB 765, 193-220 (2017)

✤ *Observation of long-range correlations (near-side “ridge”), in high-multiplicity pp collisions. —>. Indication of collectivity in small systems*

I. Small system vs. Large system

2. Strangeness enhancement

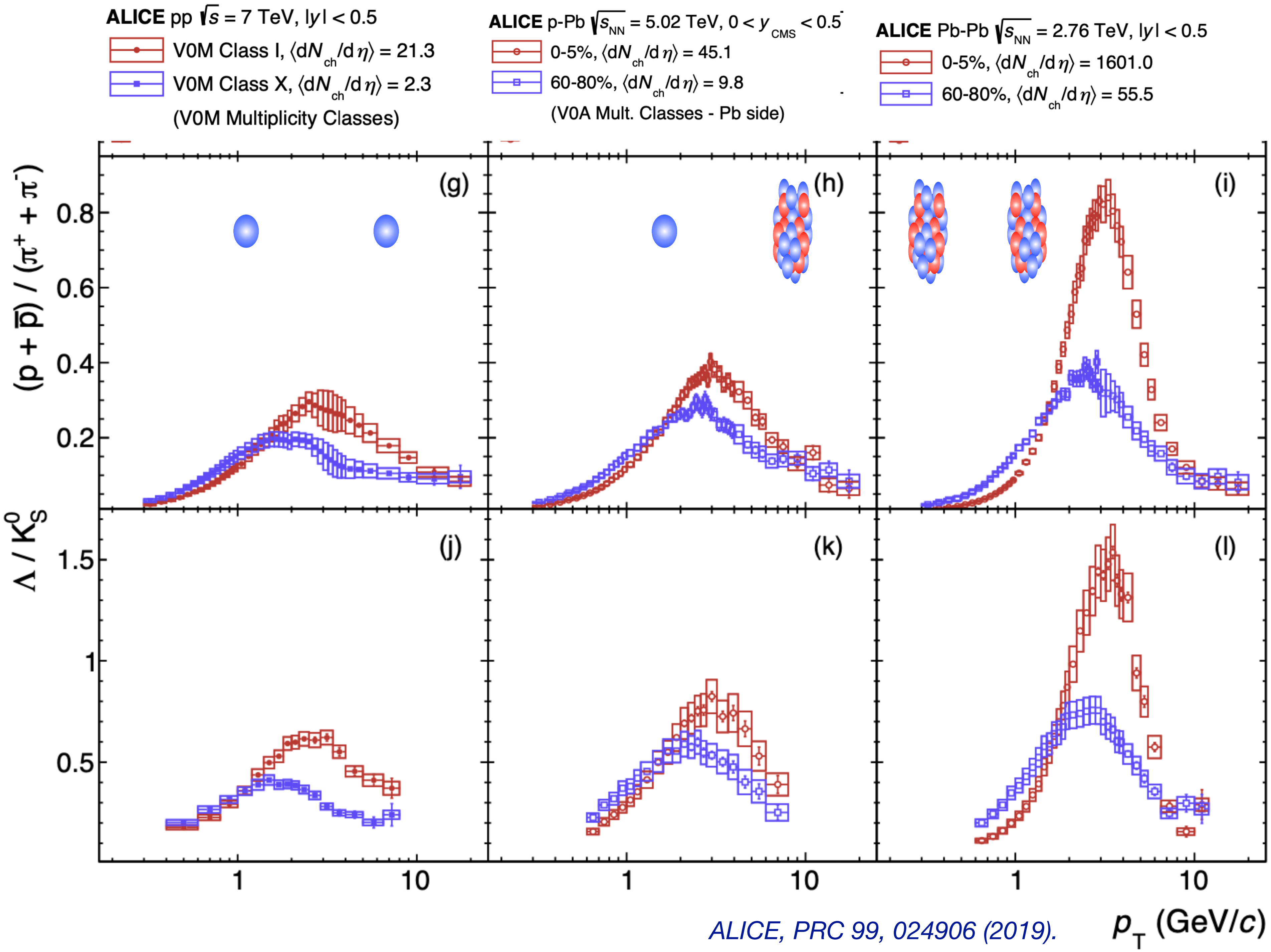


ALICE, Nature Phys. 13, 535–539 (2017)

✤ *Smooth transition with multiplicity from small to large system.*

I. Small system vs. Large system

3. Baryon / meson ratio

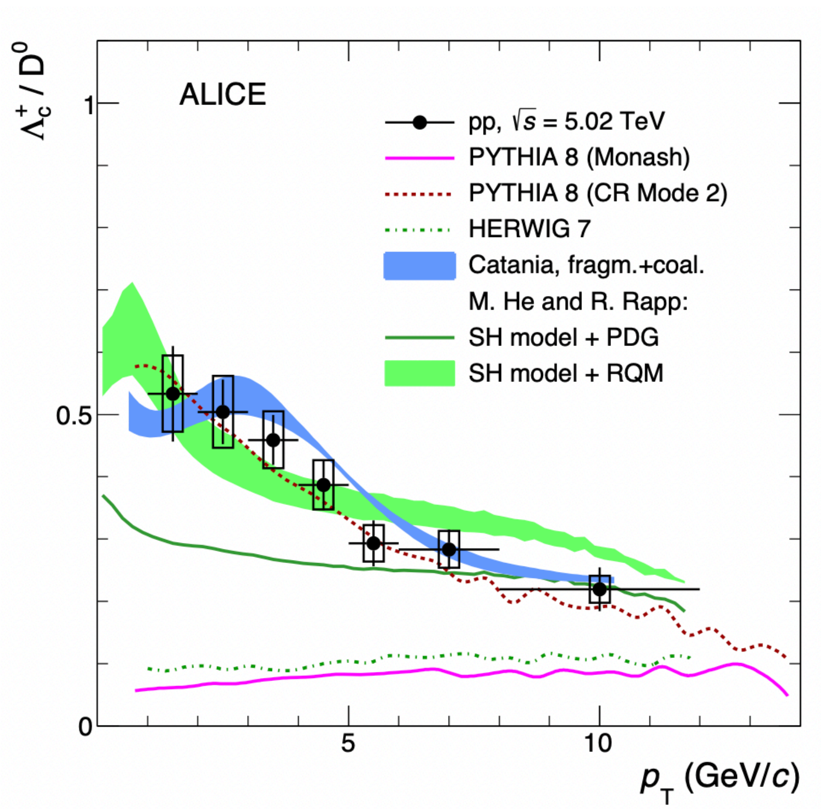


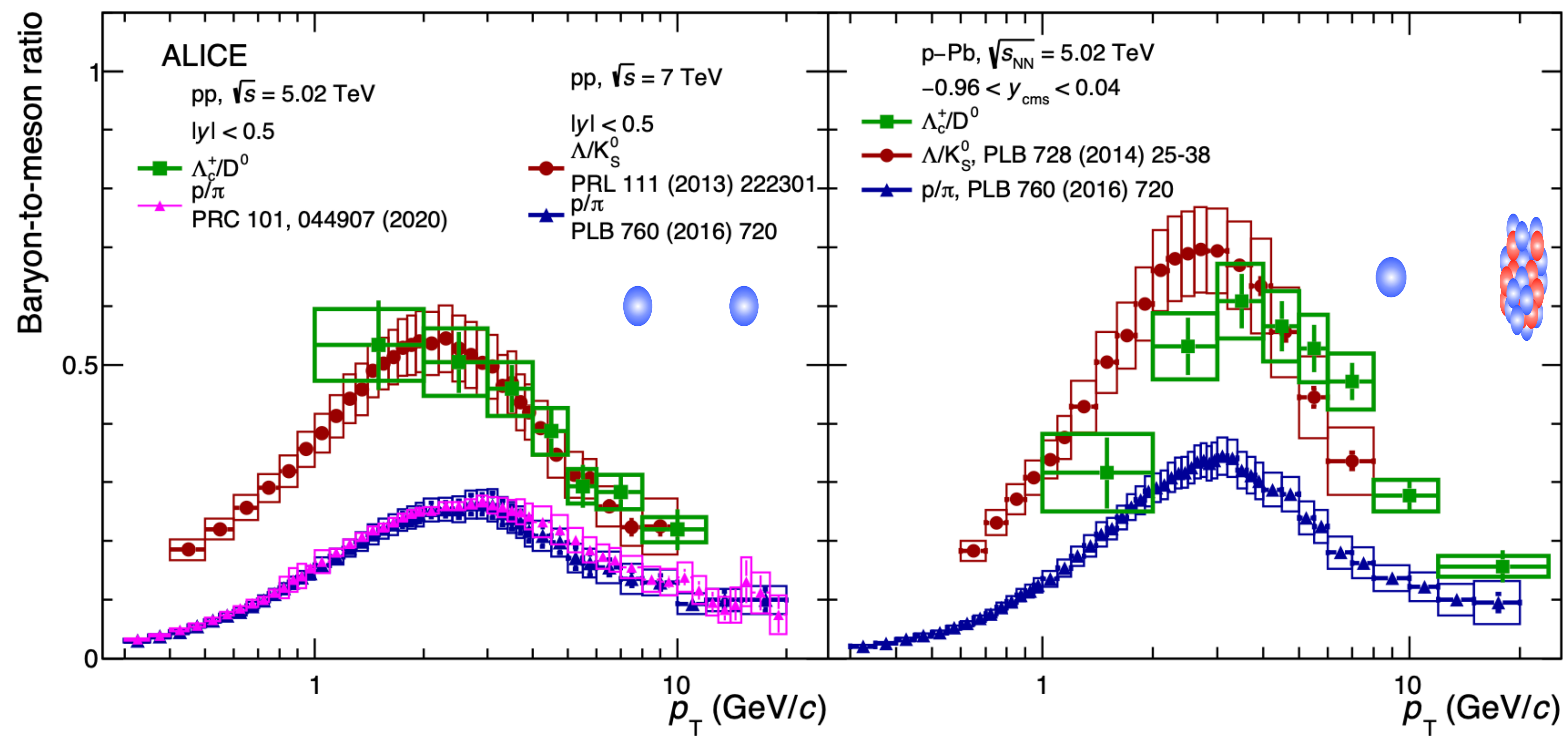
ALICE, PRC 99, 024906 (2019).

✤ *Indicate the hadronization mechanism may changed in high-multiplicity pp collisions and same as the AA collsions.*

I. Small system vs. Large system

4. Heavy flavor ratio





ALICE, PRL 127, 202301 (2021).

✤ *Hadronization mechanism changed in heavy flavor sector too!*

I. Small system vs. Large system

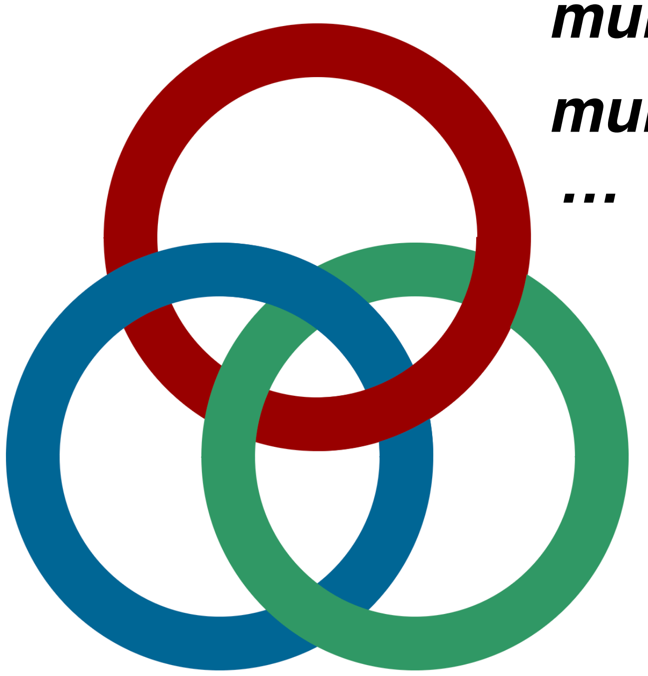
Many measurements to investigate the properties of small system: **Benjamin's talk**

Collectivity

multiplicity dependent vn

multi-particle cumulant

…



Particle productions

Strangeness enhancement

Baryon to meson ratio

Heavy flavor probes

Enhancement of $\Lambda_c/D^0,\ \Xi_c/D^0,\ldots$

Elliptic flow of D

Study the hadronization mechanism in small system is improtant to particle production, dis., in the meantime, to probe the hot and dense QCD medium!

I. Hadronizarion process

Hadronization: the degree of freedom changes from quarks/gluons to hadrons

Hadronization is a non-perturbative process and can only be studied via models!

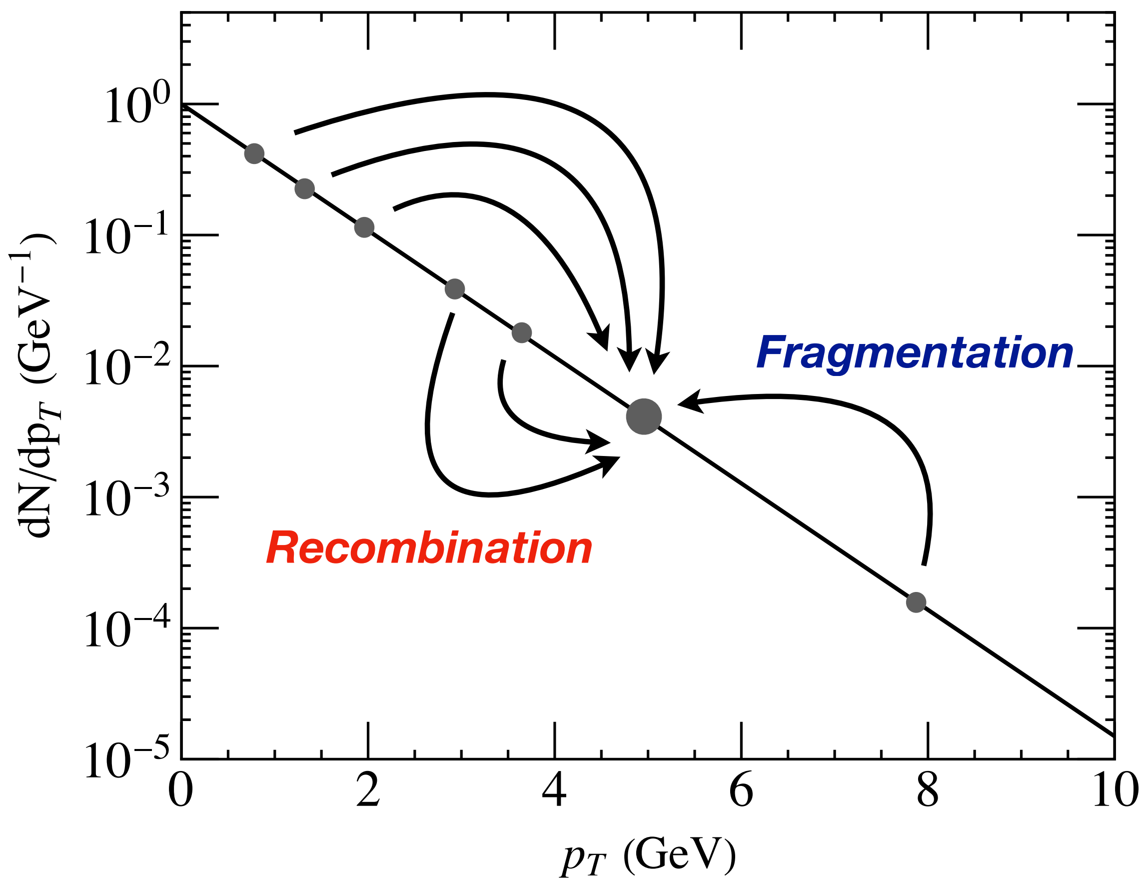
Fragmentation:

$$\sigma_H \propto f_i^A(x_1,\mu_F) f_j^B(x_2,\mu_F) \otimes \sigma_{ij\to Q\bar{Q}+X} \otimes \mathscr{D}_{Q\to H}$$ *Fragmentation function*

Recombination:

Enhancement of Baryon / Meson Ratio; Quark Number Scaling of Elliptic flow.

Play an important role in heavy ion collisions.



Low momentum flavor hadronizes via recombination, while high momentum through the fragmentation!

So, how about the small system?

I. Heavy flavor hadronizarion in small system

Heavy flavor can be a nice probe:

- ✦ *Mc, Mb >>* Λ_{QCD}, *produced by hard scattering, described by pQCD.*
- ✦ *Number is conserved during the evolution.*
- ✦ *Evolution (energy loss/gain) in the QGP is well studied.*
- ✦ *Hadronization probability can be managed partly based on heavy flavor effective theory.*
- ✦ *Few excited states compared to light hadrons.*

TAMU(SHM), Catania, Torino, PYTHIA8 with CR model.

M. He and R. Rapp, Phys. Lett. B 795, 117 (2019);
V. Minissale, S. Plumari, and V. Greco, Phys. Lett. B 821, 136622 (2021);
A. Beraudo, A. De Pace, D. Pablos, F. Prino, M. Monteno, and M. Nardi, (2023), arXiv:2306.02152 [hep-ph].
J. Christiansen, P. Skands, JHEP 08 (2015) 003

—> EPOS4HQ

JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, arXiv: 2310.08684*

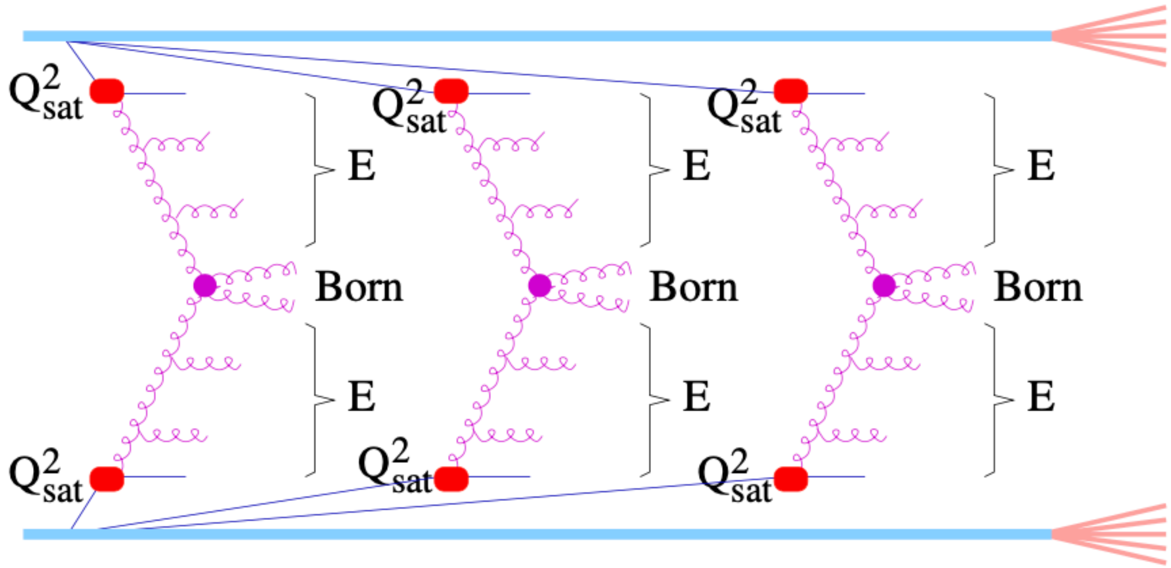
II. EPOS4

EPOS4: A Monte Carlo tool for simulating high-energy scatterings

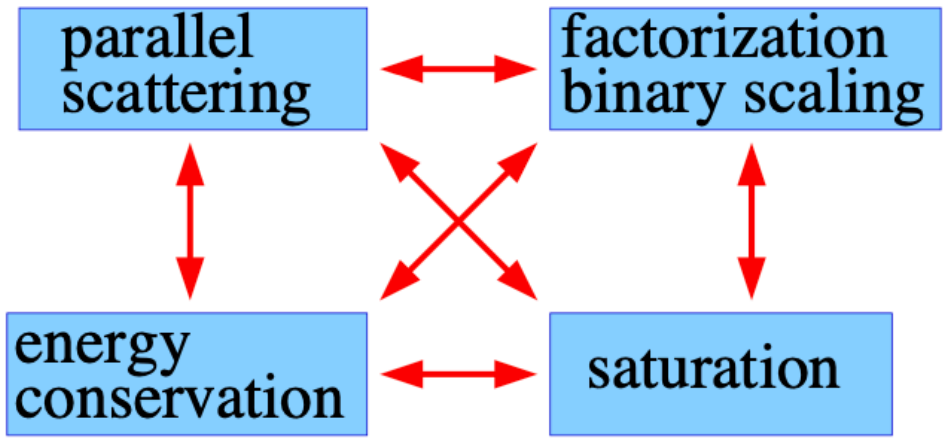
*An abbreviatation of **E**nergy conserving quantum mechanical multiple scattering approach, based on **P**arton (parton ladders), **O**ff-shell remnants, and **S**aturation of parton ladders.*

https://klaus.pages.in2p3.fr/epos4/

K. Werner. arXiv: 2301.12517



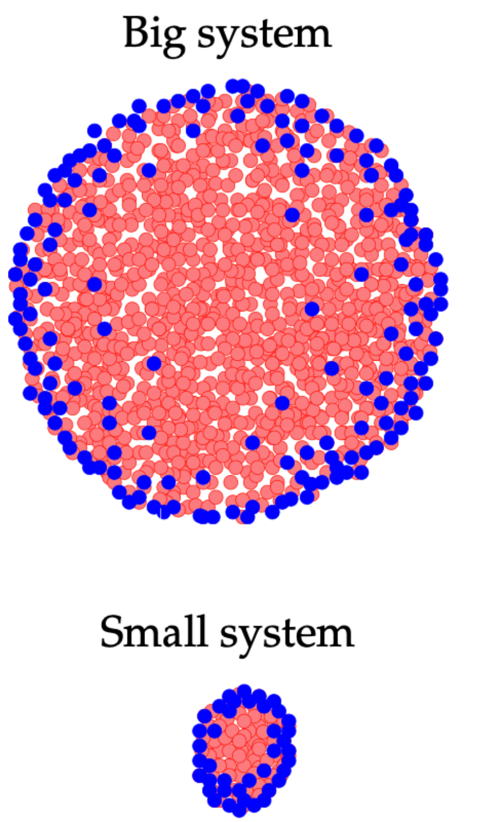
e.g. three parallel scatterings



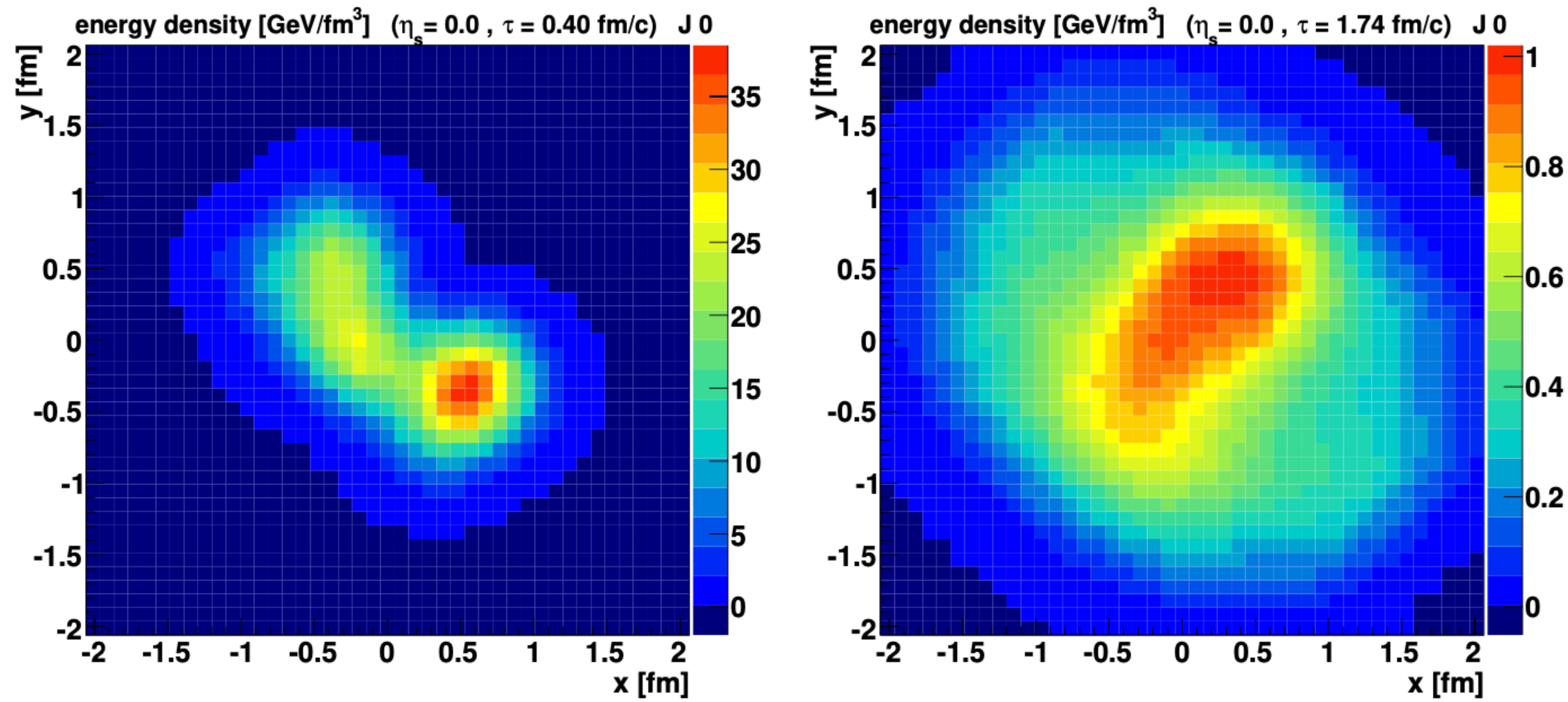
S-matrix theory (to deal with parallel scatterings happens in high energy collisions)

Consistently accommodate these four crucial concepts is realized in the EPOS4!

II. EPOS4: core-corona picture



corona = blue   core = red



JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, arXiv: 2310.08684*

If the energy loss is bigger than the energy of the prehadron, it is considered to be a “core”

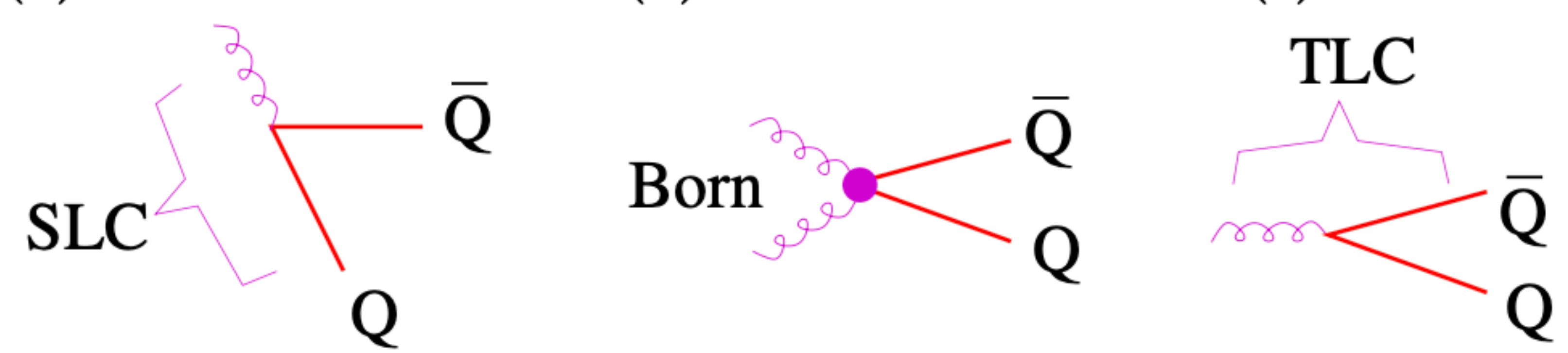
If the energy loss is smaller than the energy, the prehadron escapes, it is called “corona”

Core: hydrodynamics;   Corona: hadronic phase

The energy density is larger than the critical energy density ϵ_0

—> deconfined QCD matter!

II. EPOS4HQ: heavy quark production

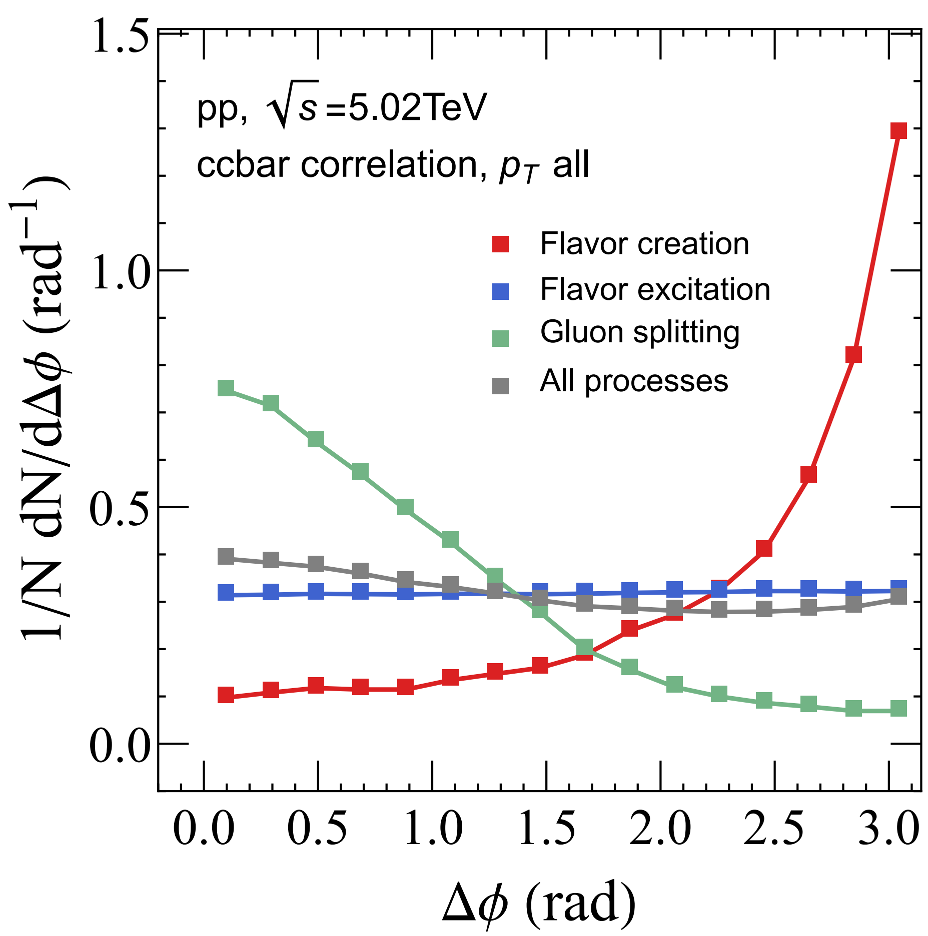


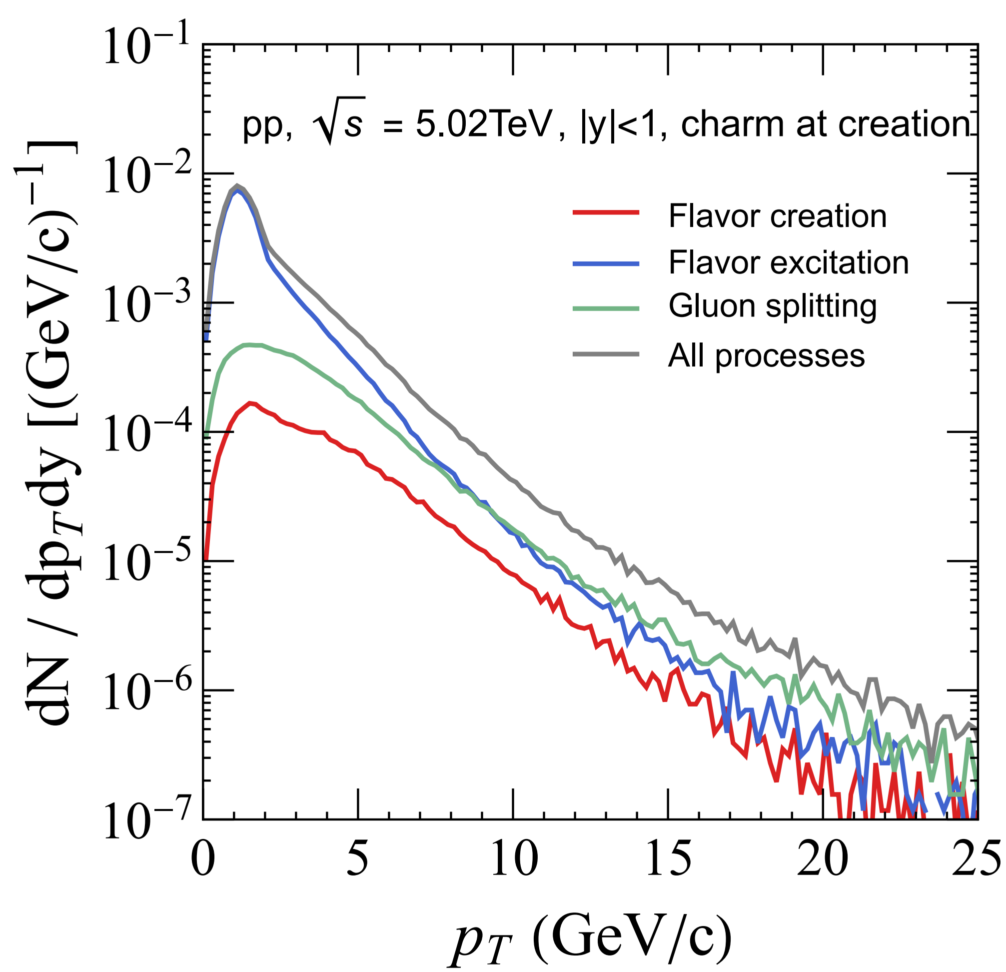
Space-like cascade

$$g + g \rightarrow Q + \bar{Q}$$
$$q + \bar{q} \rightarrow Q + \bar{Q}$$

Time-like cascade

K. Werner. arXiv: 2306.02396

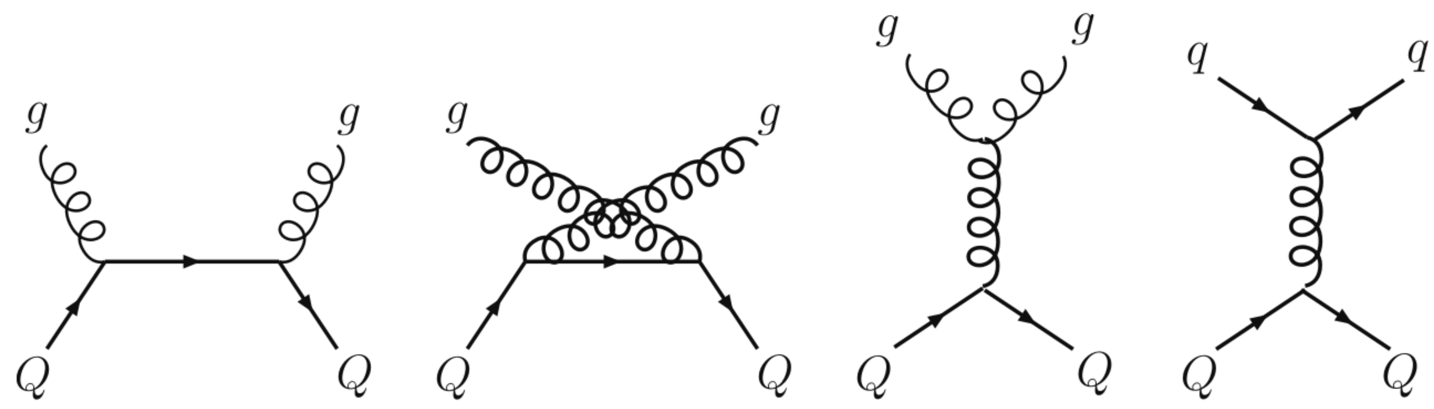




II. EPOS4HQ: heavy quark evolution

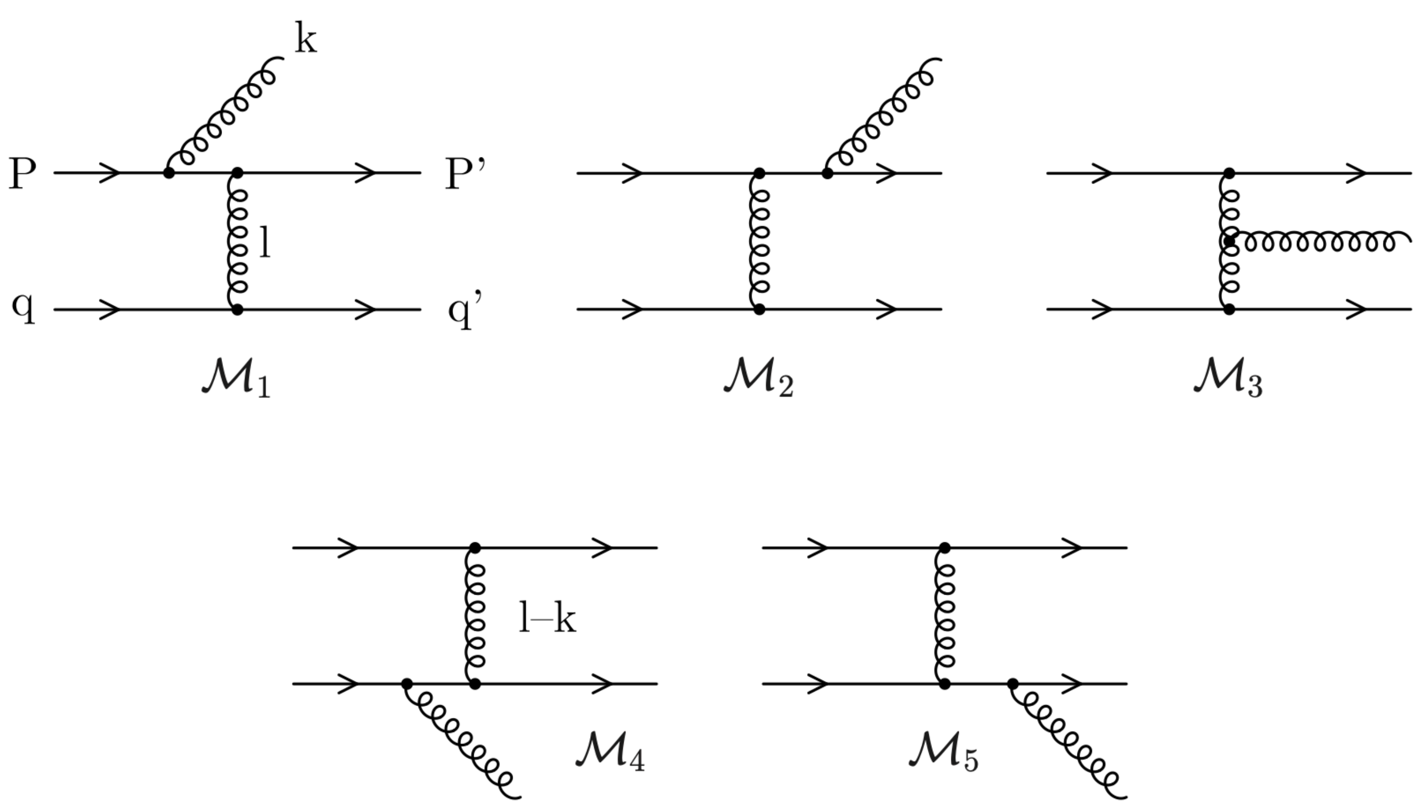
Both collisional and radiative energy loss are included

The interaction between heavy quark Q and q and g is described:



P.B. Gossiaux. J. Aichelin. Phys.Rev.C 78 (2008) 014904.

Gluon emission of heavy quarks created by the interaction with light quarks:



J. Aichelin, P. B. Gossiaux, and T. Gousset, Phys. Rev. D 89, 074018 (2014)

II. EPOS4HQ: hadronization

When the local energy density is lower than critical value (T~165MeV)

Heavy quark hadronize via coalescence + fragmentation!

$$\frac{dN}{d^3\mathbf{P}} = g_H \int \prod_{i=1}^{k} \frac{d^3p_i}{(2\pi)^3 E_i} p_i \cdot d\Sigma_i F(\mathbf{p}_1, \ldots, \mathbf{p}_k) W_m(\mathbf{p}_1, \ldots, \mathbf{p}_k)\, \delta^{(3)}\left(\mathbf{P} - \sum_{i=1}^{N} \mathbf{p}_i\right),$$

Determine the coalescence probability $P_{coal.}$*:* $1 - P_{coal.}$ *for fragmentation*

$D^0, D^+, D_s^+, \Lambda_c, \Xi_c, \Omega_c, \ldots$ *Charmonium and multi-charm states are neglected!*

We only deal with ground states, and the contributions from excited states (no matter they are P-or D-waves,…) are encoded in an overall momentum independent factor $\mathscr{F}$ *!*

For ground states:

$$W(r,p) = 8e^{-\frac{r^2}{\sigma^2} - p^2\sigma^2}.$$

$$W(\rho, \lambda, p_\rho, p_\lambda) = 8^2 e^{-\frac{\rho^2}{\sigma_\rho^2} - p_\rho^2\sigma_\rho^2} e^{-\frac{\lambda^2}{\sigma_\lambda^2} - p_\lambda^2\sigma_\lambda^2}.$$

$$\sigma^2 = \frac{2}{3}\langle r^2 \rangle$$

σ are given by their mean radius calculated by two-body Dirac equation!

How to estimate this factor $\mathscr{F}$*?*

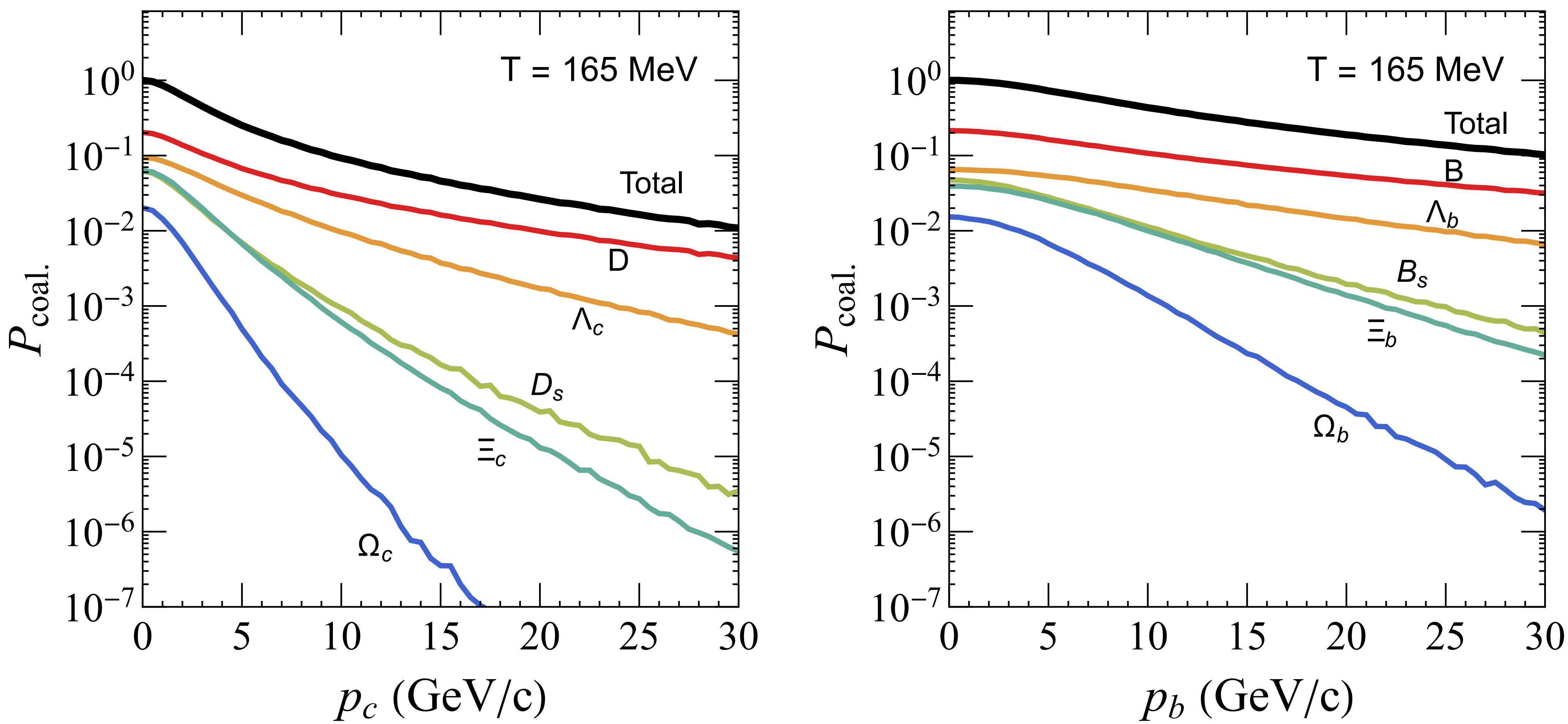
II. EPOS4HQ: hadronization

For the excited states/resonance states:
we include all hadrons [see backup slides]
(missing baryons predicted by the potential model) *D. Ebert, et al. Phys.Rev.D 84 (2011) 014025.*

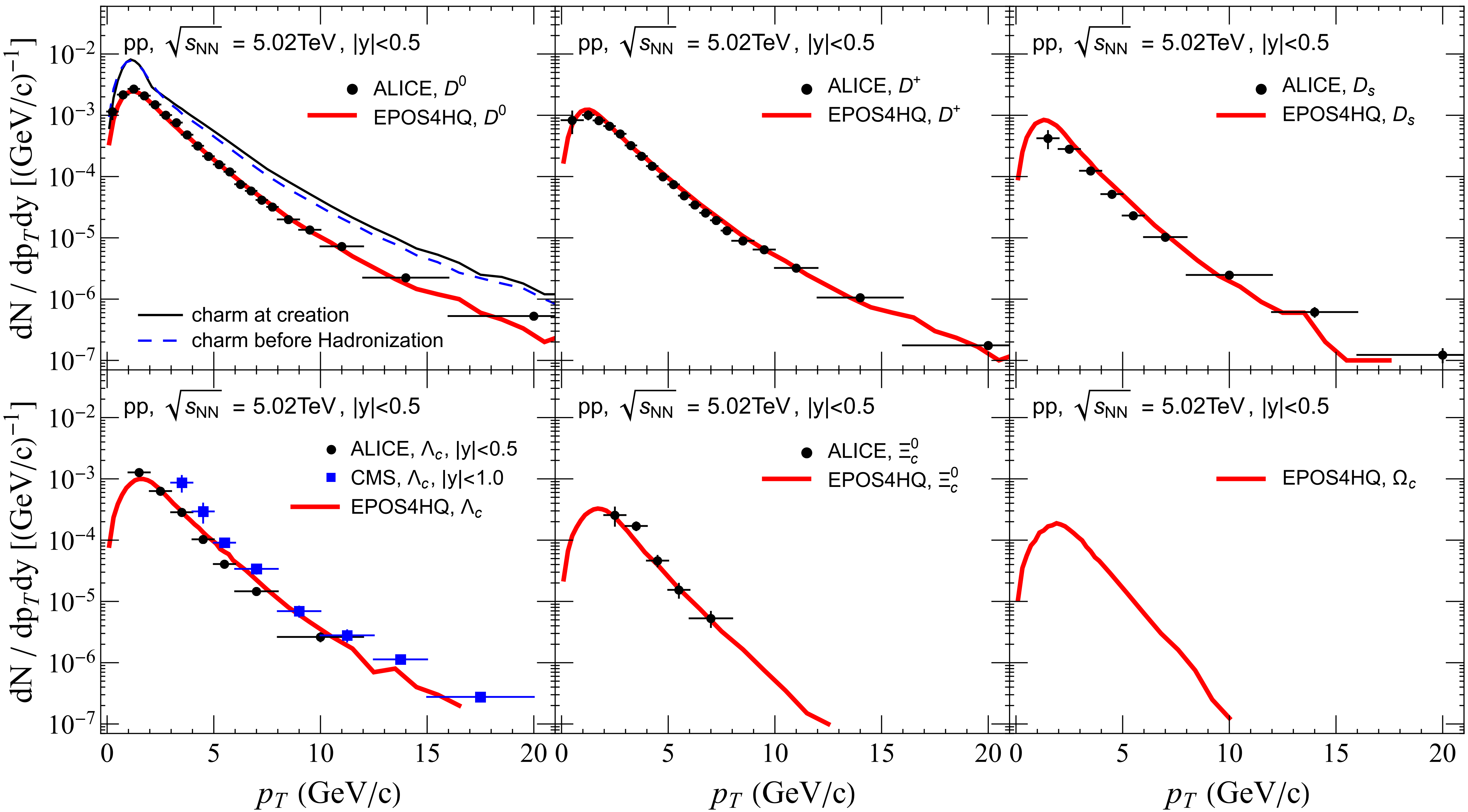
The yield of the excited states to the ground state is given by the thermal ratio:

$$n_i = \frac{d_i}{2\pi^2} m_i^2 T_H K_2\left(\frac{m_i}{T_H}\right) \ ,$$

e.g. $\frac{D^{*+}}{D^0} = \frac{D^{*+}}{D^0 + D^{*0} + D^{*+}68\,\%} = \frac{1.42}{1 + 1.42 + 1.42 * 0.68} = 0.419$



II. EPOS4HQ: results-spectra

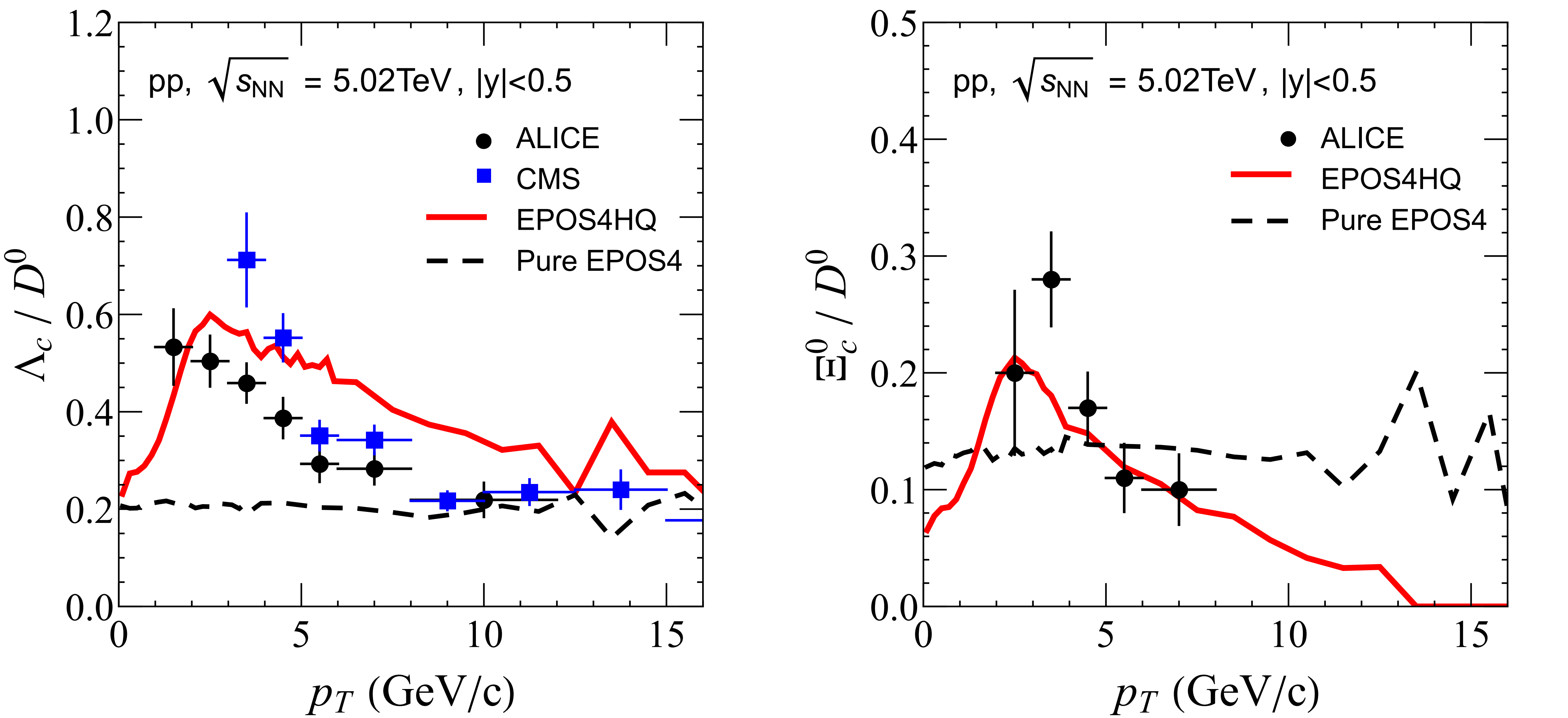


Heavy quark energy loss is very small.

JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, arXiv: 2310.08684*

EPOS4HQ reproduces spectra of different charmed hadrons quite well !

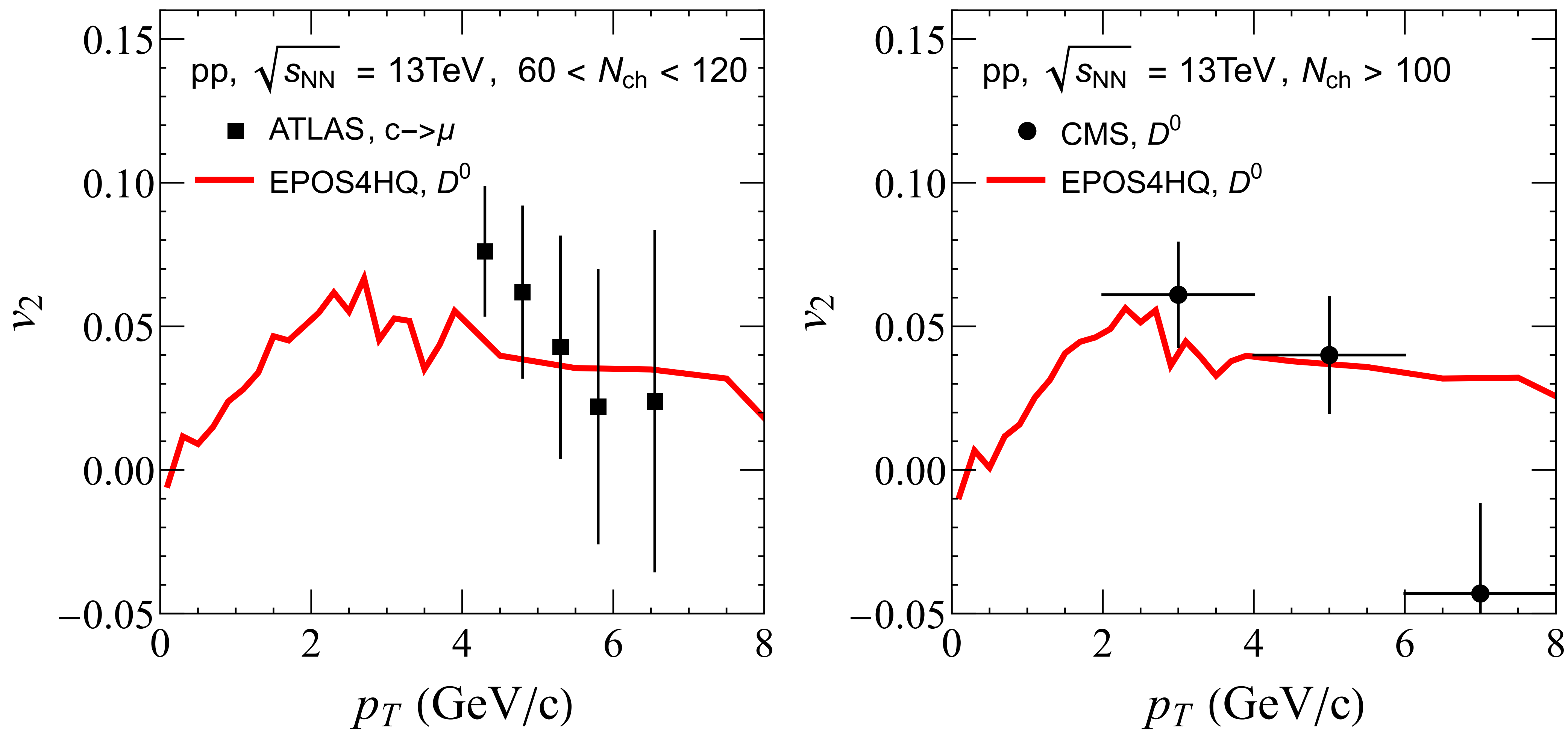
II. EPOS4HQ: results-yield ratio



JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, arXiv: 2310.08684*

The yield ratio between charmed baryon to meson can be described via: coalescence + fragmentation !

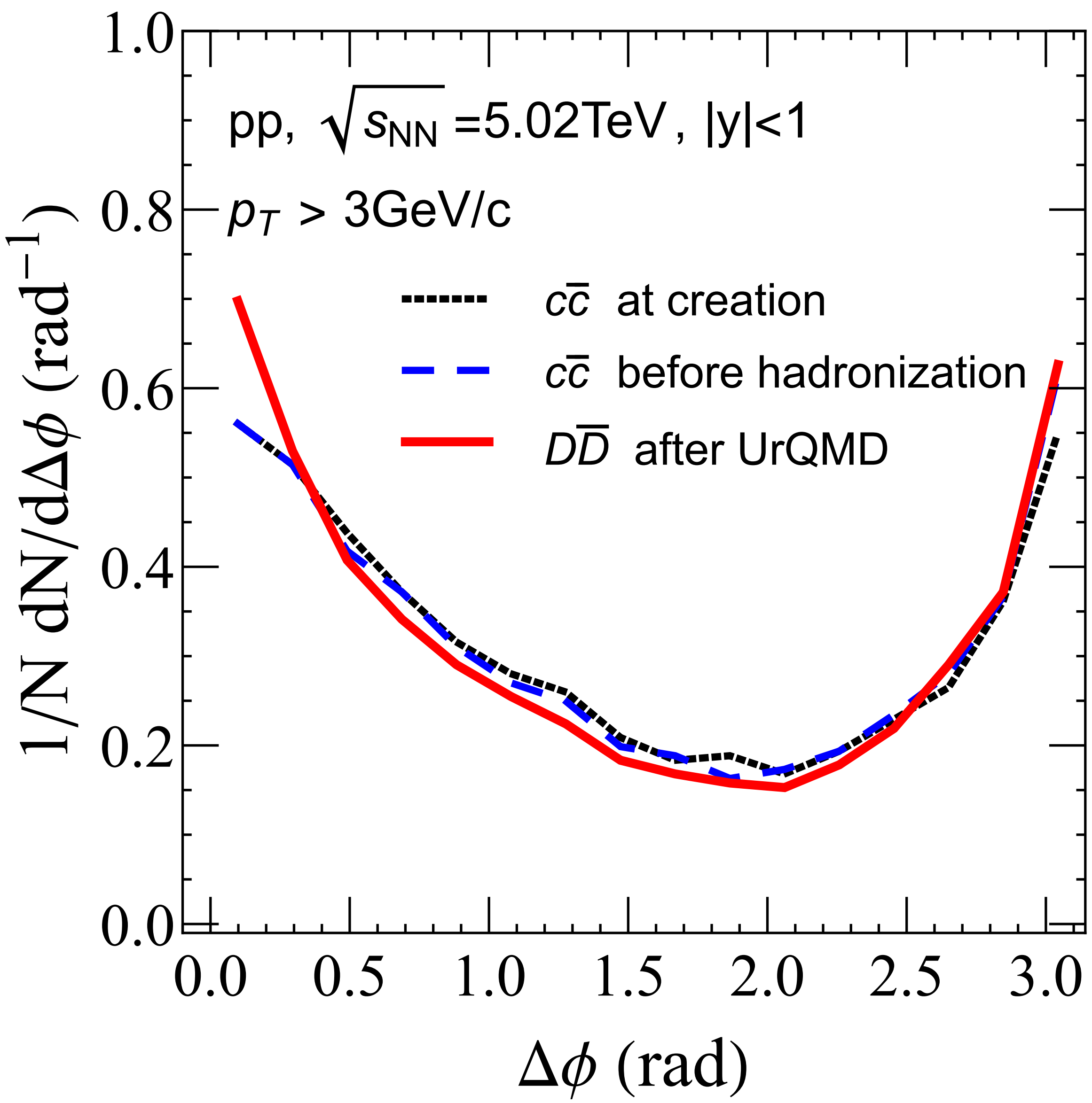
II. EPOS4HQ: results-elliptic flow



JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, arXiv: 2310.08684*

EPOS4HQ can well describe the elliptic flow of D meson!

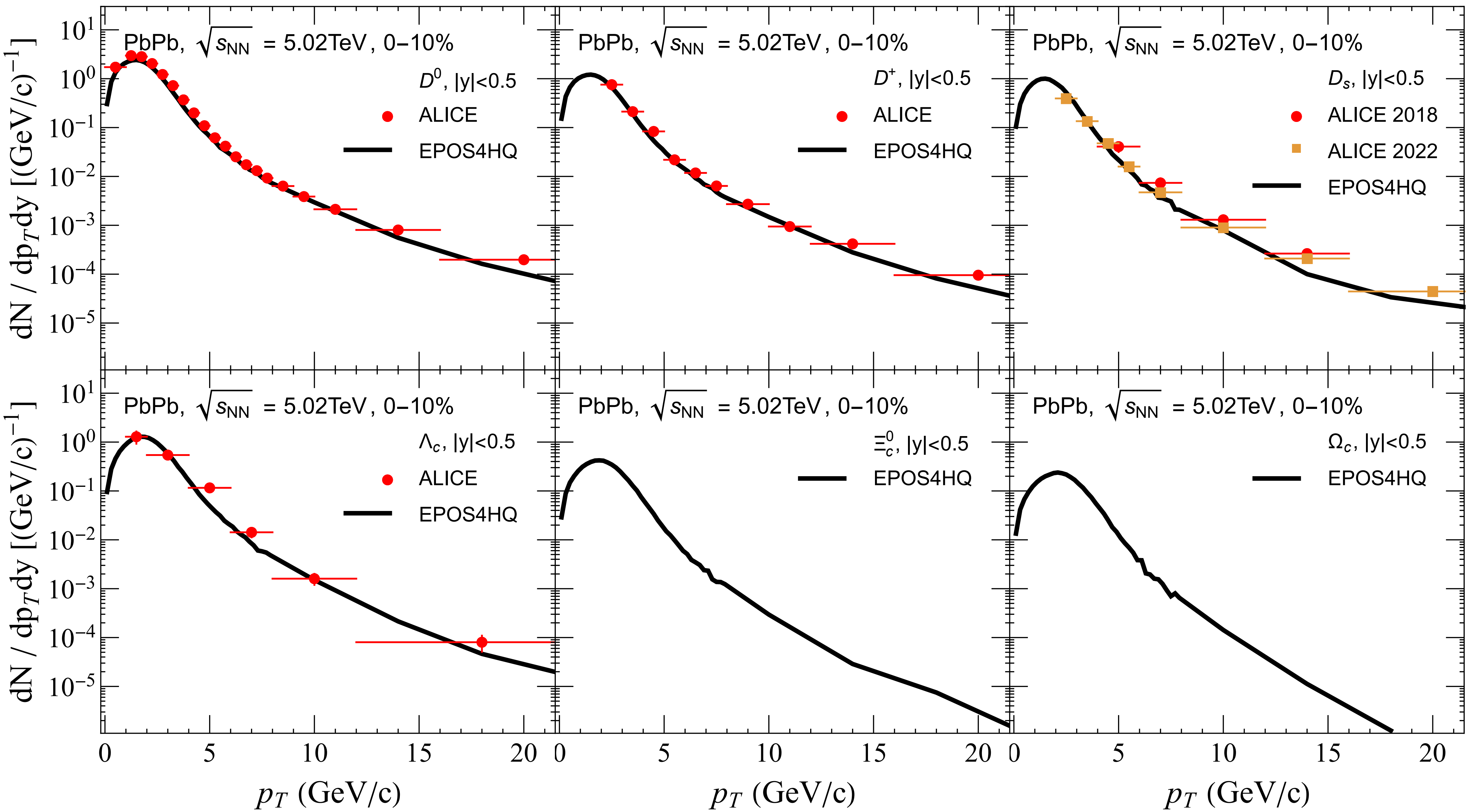
II. EPOS4HQ: results-correlations



***JZ**, J.Aichelin, P.B. Gossiaux, K.Werner, arXiv: 2310.08684*

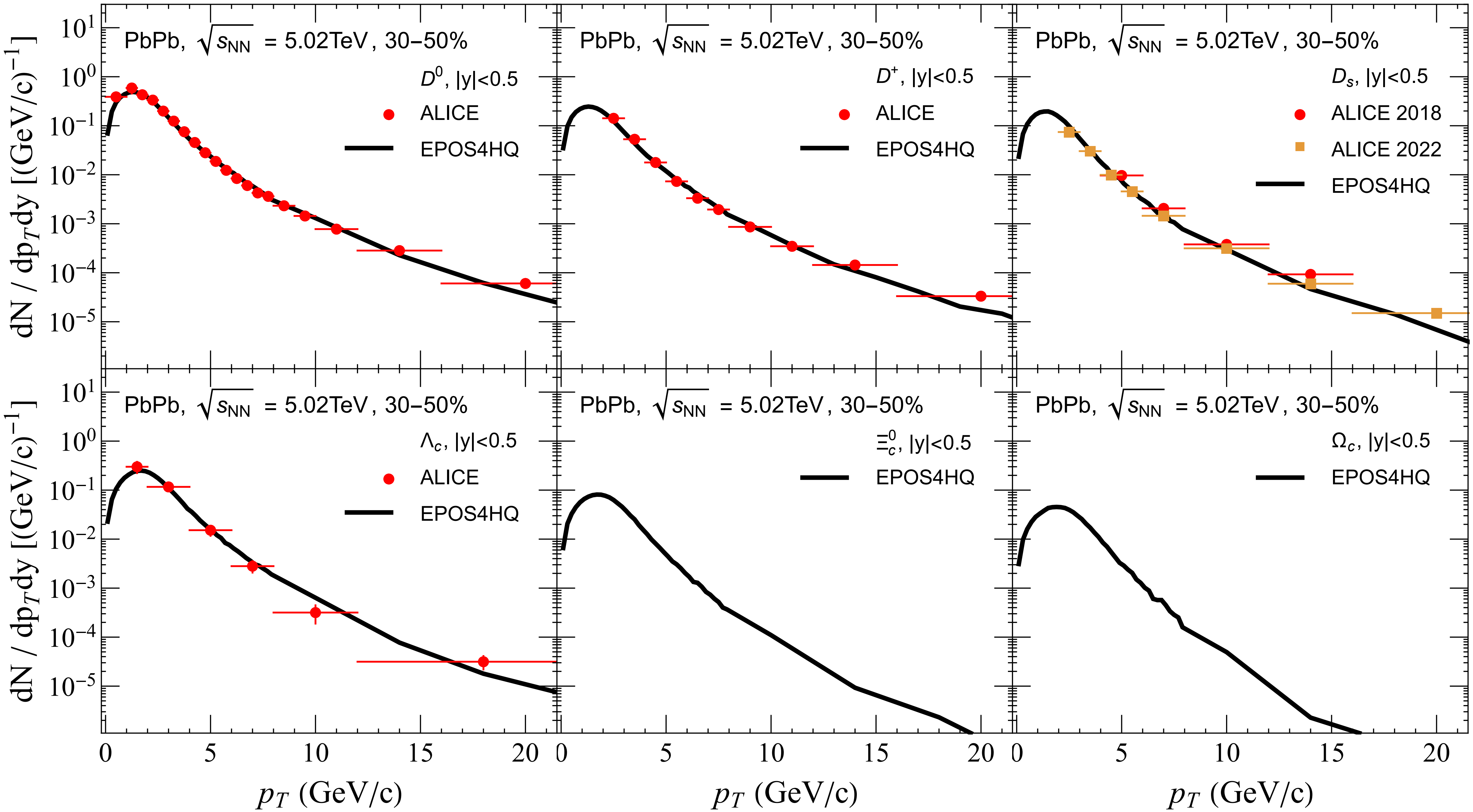
Small modification to the correlations!

II. EPOS4HQ: for large system



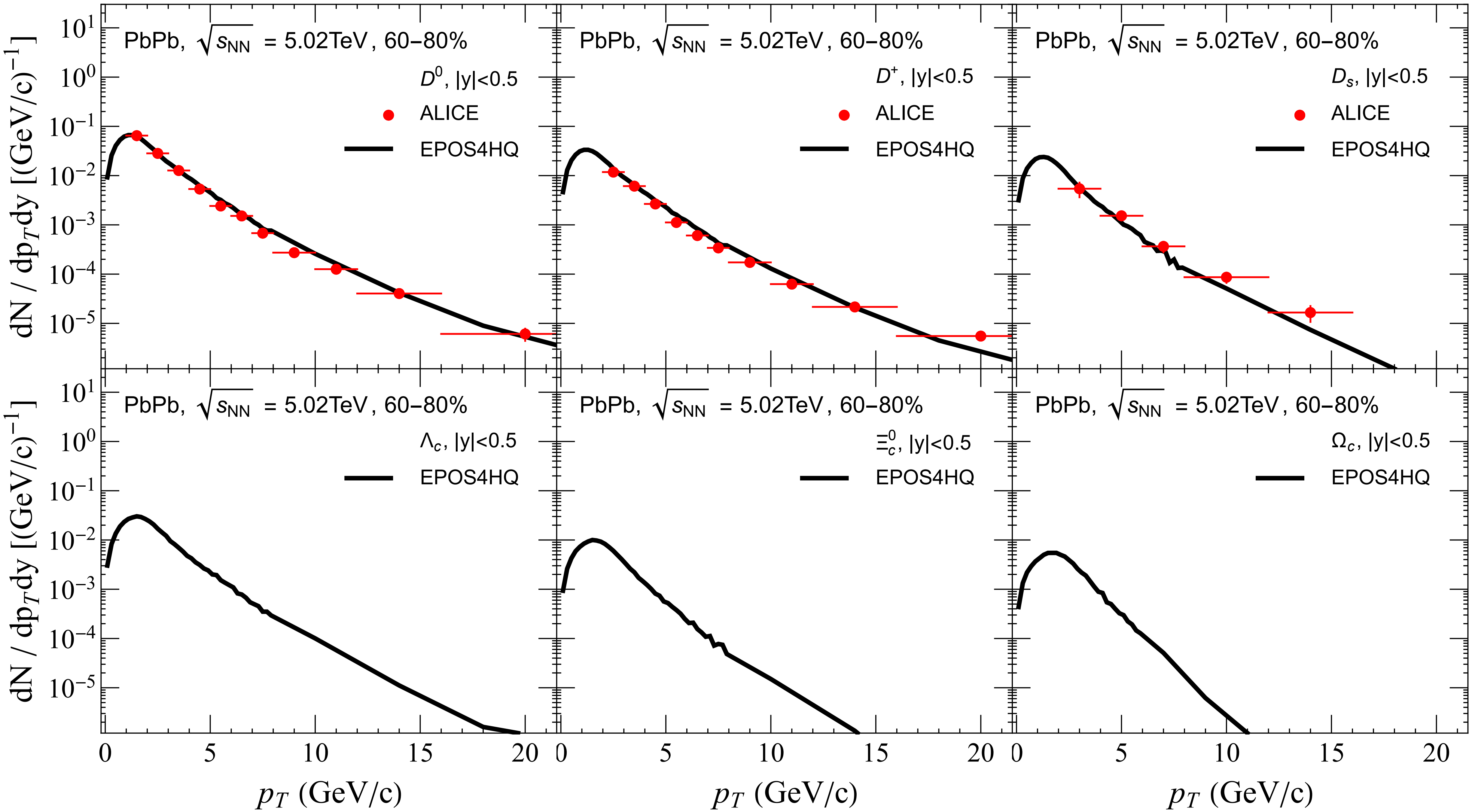
JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, in preparation…*

II. EPOS4HQ: for large system



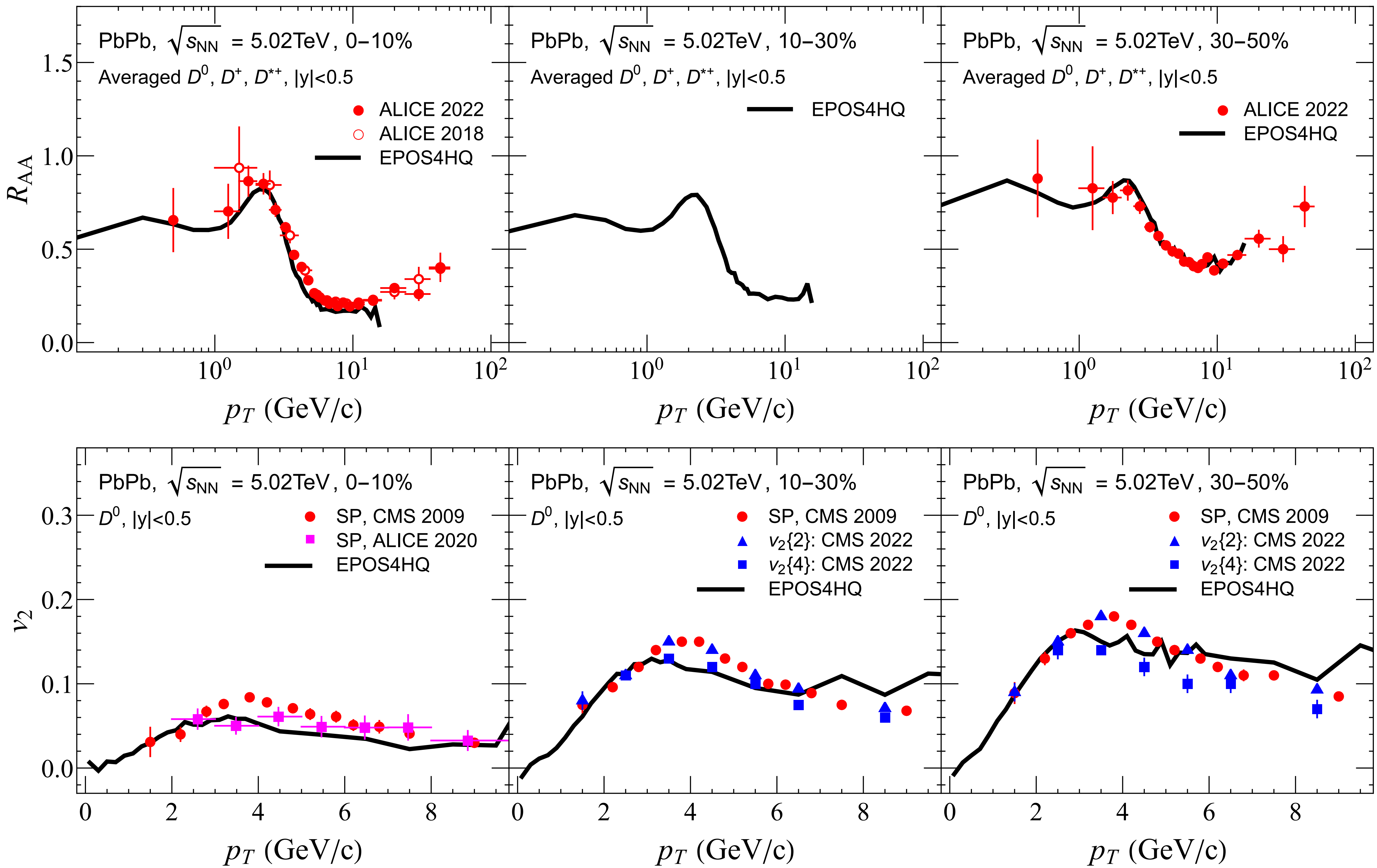
JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, in preparation…*

II. EPOS4HQ: for large system



JZ, J.Aichelin, P.B. Gossiaux, K.Werner, in preparation…

II. EPOS4HQ: for large system



JZ, J.Aichelin, P.B. Gossiaux, K.Werner,
in preparation…

III. Summary

- *Based on the newly developed EPOS4 framework, which reproduces the light hadron observables in pp as well as in heavy-ion collisions, we bulit a new branch to investigate the heavy flavor physics, which is named EPOS4HQ.*

- *The yield of all charmed hadrons (D^0, D^+, D_s, Λ_c, Ξ_c, and Ω_c), the elliptic flow v_2, and the correlation of heavy flavor hadrons are studied in pp collisions, employing the EPOS4HQ.*

- *Our results show that independent of the system size, all observables can be well understood assuming that there is system-independent critical energy density for the creation of a QGP.*

- *pPb collisions*

- *Exotic states production in pp collisions*

Thanks for your attention!

Charmed mesons

D *17 states*

Charmed Mesons (C = + −1)
D+ −
D0
D*(2007)0
D*(2010)+ −
D*(0)(2400)0
D*(0)(2400)+ −
D(1)(2420)0
D(1)(2420)+ −
D(1)(2430)0
D*(2)(2460)0
D*(2)(2460)+ −
D(2550)0
D*(J)(2600)
D*(2640)+ −
D(2740)0
D(2750)
D(3000)0

D_s *10 states*

Charmed, Strange Mesons (C = S = +−1)
D(s)+−
D*(s)+−
D*(s0)(2317)+−
D(s1)(2460)+−
D(s1)(2536)+−
D(s2)(2573)+−
D*(s1)(2700)+−
D*(s1)(2860)+−
D*(s3)(2860)+−
D(sJ)(3040)+−

Particle data Group

Charmed baryons

Λ_c

38 states

TABLE II: Masses of the Λ_Q ($Q = c, b$) heavy baryons (in MeV).

$I(J^P)$	Qd state	$Q=c$		$Q=b$	
		M	M^{exp} [1]	M	M^{exp} [1]
$0(\frac{1}{2}^+)$	$1S$	2286	2286.46(14)	5620	5620.2(1.6)
$0(\frac{1}{2}^+)$	$2S$	2769	2766.6(2.4)?	6089	
$0(\frac{1}{2}^+)$	$3S$	3130		6455	
$0(\frac{1}{2}^+)$	$4S$	3437		6756	
$0(\frac{1}{2}^+)$	$5S$	3715		7015	
$0(\frac{1}{2}^+)$	$6S$	3973		7256	
$0(\frac{1}{2}^-)$	$1P$	2598	2595.4(6)	5930	
$0(\frac{1}{2}^-)$	$2P$	2983	$2939.3(^{1.4}_{1.5})$?	6326	
$0(\frac{1}{2}^-)$	$3P$	3303		6645	
$0(\frac{1}{2}^-)$	$4P$	3588		6917	
$0(\frac{1}{2}^-)$	$5P$	3852		7157	
$0(\frac{3}{2}^-)$	$1P$	2627	2628.1(6)	5942	
$0(\frac{3}{2}^-)$	$2P$	3005		6333	
$0(\frac{3}{2}^-)$	$3P$	3322		6651	
$0(\frac{3}{2}^-)$	$4P$	3606		6922	
$0(\frac{3}{2}^-)$	$5P$	3869		7171	
$0(\frac{3}{2}^+)$	$1D$	2874		6190	
$0(\frac{3}{2}^+)$	$2D$	3189		6526	
$0(\frac{3}{2}^+)$	$3D$	3480		6811	
$0(\frac{3}{2}^+)$	$4D$	3747		7060	
$0(\frac{5}{2}^+)$	$1D$	2880	2881.53(35)	6196	
$0(\frac{5}{2}^+)$	$2D$	3209		6531	
$0(\frac{5}{2}^+)$	$3D$	3500		6814	
$0(\frac{5}{2}^+)$	$4D$	3767		7063	
$0(\frac{5}{2}^-)$	$1F$	3097		6408	
$0(\frac{5}{2}^-)$	$2F$	3375		6705	
$0(\frac{5}{2}^-)$	$3F$	3646		6964	
$0(\frac{5}{2}^-)$	$4F$	3900		7196	
$0(\frac{7}{2}^-)$	$1F$	3078		6411	
$0(\frac{7}{2}^-)$	$2F$	3393		6708	
$0(\frac{7}{2}^-)$	$3F$	3667		6966	
$0(\frac{7}{2}^-)$	$4F$	3922		7197	
$0(\frac{7}{2}^+)$	$1G$	3270		6598	
$0(\frac{7}{2}^+)$	$2G$	3546		6867	
$0(\frac{9}{2}^+)$	$1G$	3284		6599	
$0(\frac{9}{2}^+)$	$2G$	3564		6868	
$0(\frac{9}{2}^-)$	$1H$	3444		6767	
$0(\frac{11}{2}^-)$	$1H$	3460		6766	

arXiv: 1105.0583

Σ_c

54 states

TABLE III: Masses of the Σ_Q ($Q = c, b$) heavy baryons (in MeV).

$I(J^P)$	Qd state	$Q=c$		$Q=b$	
		M	M^{exp} [1]	M	M^{exp} [1]
$1(\frac{1}{2}^+)$	$1S$	2443	2453.76(18)	5808	5807.8(2.7)
$1(\frac{1}{2}^+)$	$2S$	2901		6213	
$1(\frac{1}{2}^+)$	$3S$	3271		6575	
$1(\frac{1}{2}^+)$	$4S$	3581		6869	
$1(\frac{1}{2}^+)$	$5S$	3861		7124	
$1(\frac{3}{2}^+)$	$1S$	2519	2518.0(5)	5834	5829.0(3.4)
$1(\frac{3}{2}^+)$	$2S$	2936	$2939.3(^{1.4}_{1.5})$?	6226	
$1(\frac{3}{2}^+)$	$3S$	3293		6583	
$1(\frac{3}{2}^+)$	$4S$	3598		6876	
$1(\frac{3}{2}^+)$	$5S$	3873		7129	
$1(\frac{1}{2}^-)$	$1P$	2799	$2802(^{4}_{7})$	6101	
$1(\frac{1}{2}^-)$	$2P$	3172		6440	
$1(\frac{1}{2}^-)$	$3P$	3488		6756	
$1(\frac{1}{2}^-)$	$4P$	3770		7024	
$1(\frac{1}{2}^-)$	$1P$	2713		6095	
$1(\frac{1}{2}^-)$	$2P$	3125		6430	
$1(\frac{1}{2}^-)$	$3P$	3455		6742	
$1(\frac{1}{2}^-)$	$4P$	3743		7008	
$1(\frac{3}{2}^-)$	$1P$	2798	$2802(^{4}_{7})$	6096	
$1(\frac{3}{2}^-)$	$2P$	3172		6430	
$1(\frac{3}{2}^-)$	$3P$	3486		6742	
$1(\frac{3}{2}^-)$	$4P$	3768		7009	
$1(\frac{3}{2}^-)$	$1P$	2773	2766.6(2.4)?	6087	
$1(\frac{3}{2}^-)$	$2P$	3151		6423	
$1(\frac{3}{2}^-)$	$3P$	3469		6736	
$1(\frac{3}{2}^-)$	$4P$	3753		7003	
$1(\frac{5}{2}^-)$	$1P$	2789		6084	
$1(\frac{5}{2}^-)$	$2P$	3161		6421	
$1(\frac{5}{2}^-)$	$3P$	3475		6732	
$1(\frac{5}{2}^-)$	$4P$	3757		6999	
$1(\frac{1}{2}^+)$	$1D$	3041		6311	
$1(\frac{1}{2}^+)$	$2D$	3370		6636	
$1(\frac{3}{2}^+)$	$1D$	3043		6326	
$1(\frac{3}{2}^+)$	$2D$	3366		6647	
$1(\frac{3}{2}^+)$	$1D$	3040		6285	
$1(\frac{3}{2}^+)$	$2D$	3364		6612	
$1(\frac{5}{2}^+)$	$1D$	3038		6284	
$1(\frac{5}{2}^+)$	$2D$	3365		6612	
$1(\frac{5}{2}^+)$	$1D$	3023		6270	
$1(\frac{5}{2}^+)$	$2D$	3349		6598	
$1(\frac{7}{2}^+)$	$1D$	3013		6260	
$1(\frac{7}{2}^+)$	$2D$	3342		6590	
$1(\frac{3}{2}^-)$	$1F$	3288		6550	
$1(\frac{5}{2}^-)$	$1F$	3283		6564	
$1(\frac{5}{2}^-)$	$1F$	3254		6501	
$1(\frac{7}{2}^-)$	$1F$	3253		6500	
$1(\frac{7}{2}^-)$	$1F$	3227		6472	
$1(\frac{9}{2}^-)$	$1F$	3209		6459	
$1(\frac{5}{2}^+)$	$1G$	3495		6749	
$1(\frac{7}{2}^+)$	$1G$	3483		6761	
$1(\frac{7}{2}^+)$	$1G$	3444		6688	
$1(\frac{9}{2}^+)$	$1G$	3442		6687	
$1(\frac{9}{2}^+)$	$1G$	3410		6648	
$1(\frac{11}{2}^+)$	$1G$	3386		6635	

Charmed baryons

38 states

Ξ_c

TABLE IV: Masses of the Ξ_Q $(Q = c, b)$ heavy baryons with the scalar diquark (in MeV).

		$Q=c$		$Q=b$	
$I(J^P)$	Qd state	M	$M^{\rm exp}$ [1]	M	$M^{\rm exp}$ [1]
$\frac{1}{2}(\frac{1}{2}^+)$	$1S$	2476	$2470.88(^{34}_{80})$	5803	5790.5(2.7)
$\frac{1}{2}(\frac{1}{2}^+)$	$2S$	2959		6266	
$\frac{1}{2}(\frac{1}{2}^+)$	$3S$	3323		6601	
$\frac{1}{2}(\frac{1}{2}^+)$	$4S$	3632		6913	
$\frac{1}{2}(\frac{1}{2}^+)$	$5S$	3909		7165	
$\frac{1}{2}(\frac{1}{2}^+)$	$6S$	4166		7415	
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2792	2791.8(3.3)	6120	
$\frac{1}{2}(\frac{1}{2}^-)$	$2P$	3179		6496	
$\frac{1}{2}(\frac{1}{2}^-)$	$3P$	3500		6805	
$\frac{1}{2}(\frac{1}{2}^-)$	$4P$	3785		7068	
$\frac{1}{2}(\frac{1}{2}^-)$	$5P$	4048		7302	
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2819	2819.6(1.2)	6130	
$\frac{1}{2}(\frac{3}{2}^-)$	$2P$	3201		6502	
$\frac{1}{2}(\frac{3}{2}^-)$	$3P$	3519		6810	
$\frac{1}{2}(\frac{3}{2}^-)$	$4P$	3804		7073	
$\frac{1}{2}(\frac{3}{2}^-)$	$5P$	4066		7306	
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3059	3054.2(1.3)	6366	
$\frac{1}{2}(\frac{3}{2}^+)$	$2D$	3388		6690	
$\frac{1}{2}(\frac{3}{2}^+)$	$3D$	3678		6966	
$\frac{1}{2}(\frac{3}{2}^+)$	$4D$	3945		7208	
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3076	3079.9(1.4)	6373	
$\frac{1}{2}(\frac{5}{2}^+)$	$2D$	3407		6696	
$\frac{1}{2}(\frac{5}{2}^+)$	$3D$	3699		6970	
$\frac{1}{2}(\frac{5}{2}^+)$	$4D$	3965		7212	
$\frac{1}{2}(\frac{5}{2}^-)$	$1F$	3278		6577	
$\frac{1}{2}(\frac{5}{2}^-)$	$2F$	3575		6863	
$\frac{1}{2}(\frac{5}{2}^-)$	$3F$	3845		7114	
$\frac{1}{2}(\frac{5}{2}^-)$	$4F$	4098		7339	
$\frac{1}{2}(\frac{7}{2}^-)$	$1F$	3292		6581	
$\frac{1}{2}(\frac{7}{2}^-)$	$2F$	3592		6867	
$\frac{1}{2}(\frac{7}{2}^-)$	$3F$	3865		7117	
$\frac{1}{2}(\frac{7}{2}^-)$	$4F$	4120		7342	
$\frac{1}{2}(\frac{7}{2}^+)$	$1G$	3469		6760	
$\frac{1}{2}(\frac{7}{2}^+)$	$2G$	3745		7020	
$\frac{1}{2}(\frac{9}{2}^+)$	$1G$	3483		6762	
$\frac{1}{2}(\frac{9}{2}^+)$	$2G$	3763		7032	
$\frac{1}{2}(\frac{9}{2}^-)$	$1H$	3643		6933	
$\frac{1}{2}(\frac{11}{2}^-)$	$1H$	3658		6934	

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Ξ_c

54 states

TABLE V: Masses of the Ξ_Q $(Q = c, b)$ heavy baryons with the axial vector diquark (in MeV).

		$Q=c$		$Q=b$
$I(J^P)$	Qd state	M	$M^{\rm exp}$ [1]	M
$\frac{1}{2}(\frac{1}{2}^+)$	$1S$	2579	2577.9(2.9)	5936
$\frac{1}{2}(\frac{1}{2}^+)$	$2S$	2983	2971.4(3.3)	6329
$\frac{1}{2}(\frac{1}{2}^+)$	$3S$	3377		6687
$\frac{1}{2}(\frac{1}{2}^+)$	$4S$	3695		6978
$\frac{1}{2}(\frac{1}{2}^+)$	$5S$	3978		7229
$\frac{1}{2}(\frac{3}{2}^+)$	$1S$	2649	2645.9(0.5)	5963
$\frac{1}{2}(\frac{3}{2}^+)$	$2S$	3026		6342
$\frac{1}{2}(\frac{3}{2}^+)$	$3S$	3396		6695
$\frac{1}{2}(\frac{3}{2}^+)$	$4S$	3709		6984
$\frac{1}{2}(\frac{3}{2}^+)$	$5S$	3989		7234
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2936	2931(6)	6233
$\frac{1}{2}(\frac{1}{2}^-)$	$2P$	3313		6611
$\frac{1}{2}(\frac{1}{2}^-)$	$3P$	3630		6915
$\frac{1}{2}(\frac{1}{2}^-)$	$4P$	3912		7174
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2854		6227
$\frac{1}{2}(\frac{1}{2}^-)$	$2P$	3267		6604
$\frac{1}{2}(\frac{1}{2}^-)$	$3P$	3598		6906
$\frac{1}{2}(\frac{1}{2}^-)$	$4P$	3887		7164
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2935	2931(6)	6234
$\frac{1}{2}(\frac{3}{2}^-)$	$2P$	3311		6605
$\frac{1}{2}(\frac{3}{2}^-)$	$3P$	3628		6905
$\frac{1}{2}(\frac{3}{2}^-)$	$4P$	3911		7163
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2912		6224
$\frac{1}{2}(\frac{3}{2}^-)$	$2P$	3293		6598
$\frac{1}{2}(\frac{3}{2}^-)$	$3P$	3613		6900
$\frac{1}{2}(\frac{3}{2}^-)$	$4P$	3898		7159
$\frac{1}{2}(\frac{5}{2}^-)$	$1P$	2929	2931(6)	6226
$\frac{1}{2}(\frac{5}{2}^-)$	$2P$	3303		6596
$\frac{1}{2}(\frac{5}{2}^-)$	$3P$	3619		6897
$\frac{1}{2}(\frac{5}{2}^-)$	$4P$	3902		7156
$\frac{1}{2}(\frac{1}{2}^+)$	$1D$	3163		6447
$\frac{1}{2}(\frac{1}{2}^+)$	$2D$	3505		6767
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3167		6459
$\frac{1}{2}(\frac{3}{2}^+)$	$2D$	3506		6775
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3160		6431
$\frac{1}{2}(\frac{3}{2}^+)$	$2D$	3497		6751
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3166		6432
$\frac{1}{2}(\frac{5}{2}^+)$	$2D$	3504		6751
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3153		6420
$\frac{1}{2}(\frac{5}{2}^+)$	$2D$	3493		6740
$\frac{1}{2}(\frac{7}{2}^+)$	$1D$	3147	3122.9(1.3)	6414
$\frac{1}{2}(\frac{7}{2}^+)$	$2D$	3486		6736
$\frac{1}{2}(\frac{3}{2}^-)$	$1F$	3418		6675
$\frac{1}{2}(\frac{5}{2}^-)$	$1F$	3408		6686
$\frac{1}{2}(\frac{5}{2}^-)$	$1F$	3394		6640
$\frac{1}{2}(\frac{7}{2}^-)$	$1F$	3393		6641
$\frac{1}{2}(\frac{7}{2}^-)$	$1F$	3373		6619
$\frac{1}{2}(\frac{9}{2}^-)$	$1F$	3357		6610
$\frac{1}{2}(\frac{5}{2}^+)$	$1G$	3623		6867
$\frac{1}{2}(\frac{7}{2}^+)$	$1G$	3608		6876
$\frac{1}{2}(\frac{7}{2}^+)$	$1G$	3584		6822
$\frac{1}{2}(\frac{9}{2}^+)$	$1G$	3582		6821
$\frac{1}{2}(\frac{9}{2}^+)$	$1G$	3558		6792
$\frac{1}{2}(\frac{11}{2}^+)$	$1G$	3536		6782

Charmed baryons

54 states

Ω_c

TABLE VI: Masses of the Ω_Q ($Q = c, b$) heavy baryons (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$0(\frac{1}{2}^+)$	$1S$	2698	2695.2(1.7)	6064	6071(40)
$0(\frac{1}{2}^+)$	$2S$	3088		6450	
$0(\frac{1}{2}^+)$	$3S$	3489		6804	
$0(\frac{1}{2}^+)$	$4S$	3814		7091	
$0(\frac{1}{2}^+)$	$5S$	4102		7338	
$0(\frac{3}{2}^+)$	$1S$	2768	2765.9(2.0)	6088	
$0(\frac{3}{2}^+)$	$2S$	3123		6461	
$0(\frac{3}{2}^+)$	$3S$	3510		6811	
$0(\frac{3}{2}^+)$	$4S$	3830		7096	
$0(\frac{3}{2}^+)$	$5S$	4114		7343	
$0(\frac{1}{2}^-)$	$1P$	3055		6339	
$0(\frac{1}{2}^-)$	$2P$	3435		6710	
$0(\frac{1}{2}^-)$	$3P$	3754		7009	
$0(\frac{1}{2}^-)$	$4P$	4037		7265	
$0(\frac{1}{2}^-)$	$1P$	2966		6330	
$0(\frac{1}{2}^-)$	$2P$	3384		6706	
$0(\frac{1}{2}^-)$	$3P$	3717		7003	
$0(\frac{1}{2}^-)$	$2P$	4009		7257	
$0(\frac{3}{2}^-)$	$1P$	3054		6340	
$0(\frac{3}{2}^-)$	$2P$	3433		6705	
$0(\frac{3}{2}^-)$	$3P$	3752		7002	

TABLE VI: (continued)

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$0(\frac{3}{2}^-)$	$4P$	4036		7258	
$0(\frac{3}{2}^-)$	$1P$	3029		6331	
$0(\frac{3}{2}^-)$	$2P$	3415		6699	
$0(\frac{3}{2}^-)$	$3P$	3737		6998	
$0(\frac{3}{2}^-)$	$4P$	4023		7250	
$0(\frac{5}{2}^-)$	$1P$	3051		6334	
$0(\frac{5}{2}^-)$	$2P$	3427		6700	
$0(\frac{5}{2}^-)$	$3P$	3744		6996	
$0(\frac{5}{2}^-)$	$4P$	4028		7251	
$0(\frac{1}{2}^+)$	$1D$	3287		6540	
$0(\frac{1}{2}^+)$	$2D$	3623		6857	
$0(\frac{3}{2}^+)$	$1D$	3298		6549	
$0(\frac{3}{2}^+)$	$2D$	3627		6863	
$0(\frac{3}{2}^+)$	$1D$	3282		6530	
$0(\frac{3}{2}^+)$	$2D$	3613		6846	
$0(\frac{5}{2}^+)$	$1D$	3297		6529	
$0(\frac{5}{2}^+)$	$2D$	3626		6846	
$0(\frac{5}{2}^+)$	$1D$	3286		6520	
$0(\frac{5}{2}^+)$	$2D$	3614		6837	
$0(\frac{7}{2}^+)$	$1D$	3283		6517	
$0(\frac{7}{2}^+)$	$2D$	3611		6834	
$0(\frac{3}{2}^-)$	$1F$	3533		6763	
$0(\frac{5}{2}^-)$	$1F$	3522		6771	
$0(\frac{5}{2}^-)$	$1F$	3515		6737	
$0(\frac{7}{2}^-)$	$1F$	3514		6736	
$0(\frac{7}{2}^-)$	$1F$	3498		6719	
$0(\frac{9}{2}^-)$	$1F$	3485		6713	
$0(\frac{5}{2}^+)$	$1G$	3739		6952	
$0(\frac{7}{2}^+)$	$1G$	3721		6959	
$0(\frac{7}{2}^+)$	$1G$	3707		6916	
$0(\frac{9}{2}^+)$	$1G$	3705		6915	
$0(\frac{9}{2}^+)$	$1G$	3685		6892	
$0(\frac{11}{2}^+)$	$1G$	3665		6884	

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