The 220th HENPIC Seminar

中国高能核物理网络论坛
HIGH ENERGY NUCLEAR PHYSICS IN CHINA

HENPIC

Heavy flavor production in high-energy proton-proton and heavy-ion collisions in EPOS4 framework

Jiaxing Zhao

12/19/2024

HFHF Helmholtz Forschungsakademie Hessen für FAIR

CRC-TR 211 Strong-interaction matter under extreme conditions

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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Outline

- Introduction of the heavy flavor probes
- Heavy flavor production in heavy-ion collisions in EPOS4
- Heavy flavor production in p-p collisions in EPOS4
- System size dependence of energy loss and correlations
- Summary

Heavy flavor probes

$m_c \sim 1.5\mathrm{GeV}, \mathrm{m_b} \sim 4.7\mathrm{GeV}$

✦ $\tau_c \sim 1/m_c, \tau_b \sim 1/m_b < \tau_0 \sim 1fm/c$, “see” full system evolution.

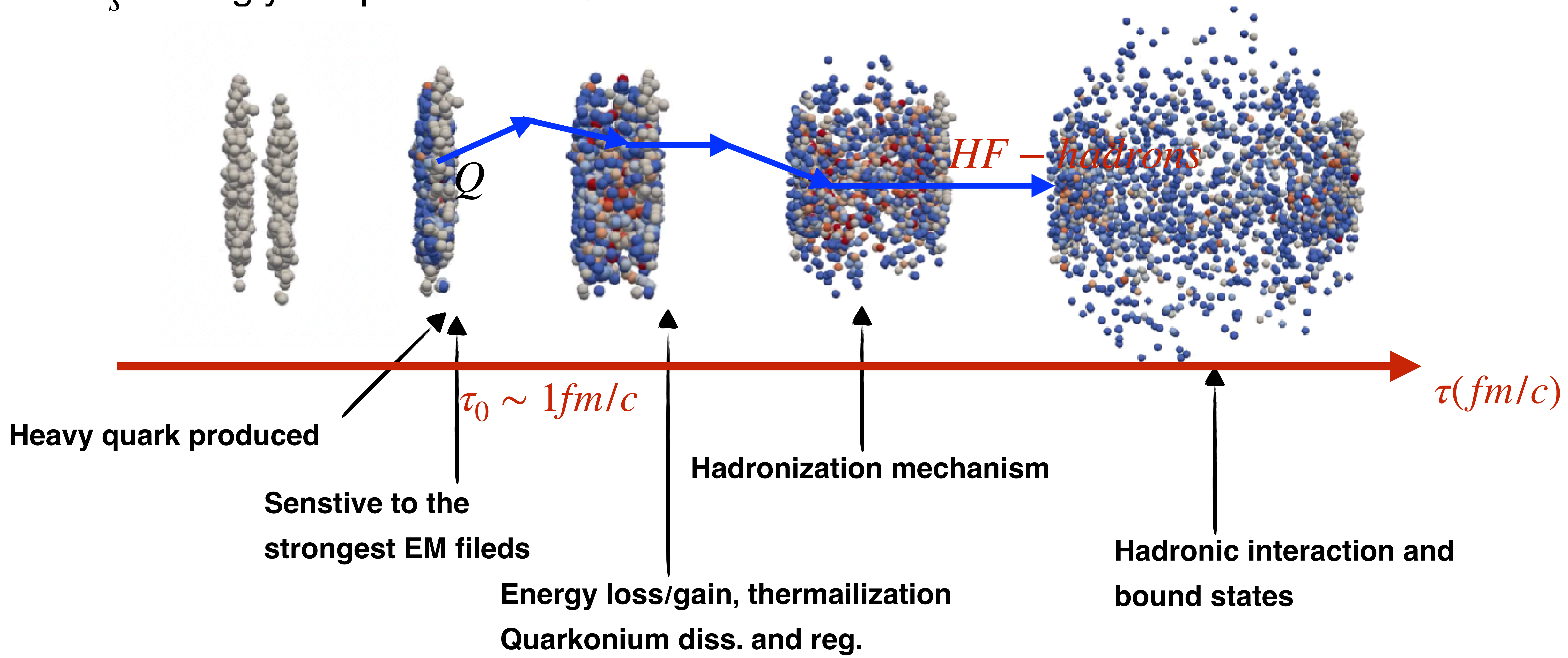
✦ $\tau_c, \tau_b < \tau_B \approx R/\gamma \sim 0.1fm/c$, feel strong electromagnetic fields in HICs.

✦ $m_c, m_b \gg \Lambda_{QCD}$, produced by hard scattering, pQCD.

✦ $m_c, m_b \gg T$, number is conserved during the evolution (thermal production can be neglected).

✦ $m \gg T \sim q$, can be treated as a Brownian particle.

✦ Small $\mathscr{D}_s$. strongly coupled to the QGP.



Heavy quark produced

Senstive to the strongest EM fileds

Energy loss/gain, thermailization
Quarkonium diss. and reg.

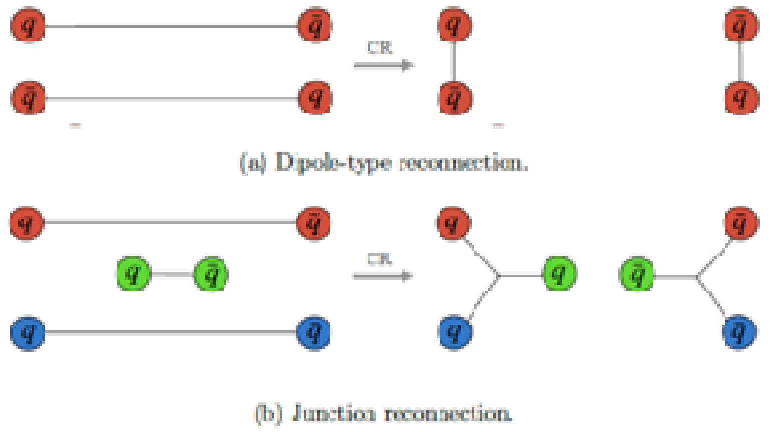
Hadronization mechanism

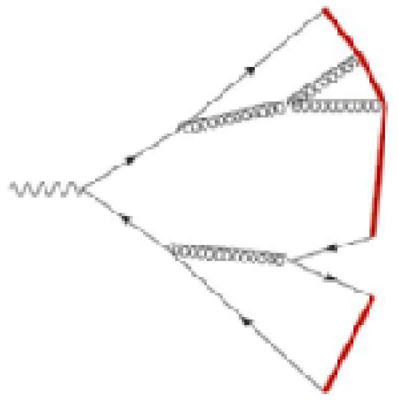
Hadronic interaction and bound states

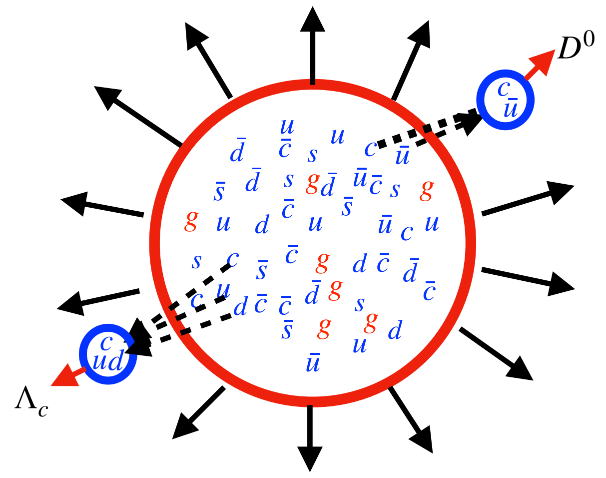
State of art

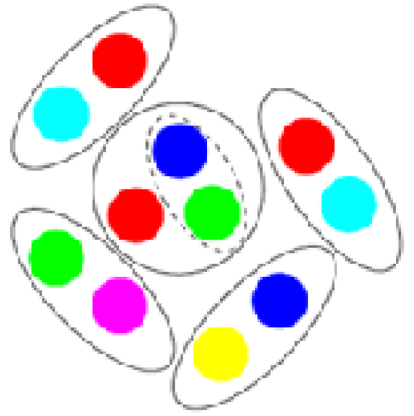
In the theoretical side, there are many models to describe heavy flavor energy loss & hadronization:

Catania (coalescence+fragmentation; pp and AA),
CUJET (fragmentation; only AA)
Duke (coalescence+fragmentation; only AA),
EPOS4 (coalescence+fragmentation: pp and AA),
LBT (coalescence+fragmentation; only AA),
Nantes (coalescence+fragmentation; only AA),
PHSD (coalescence+fragmentation; pp and AA),
POWLANG (local color neutralization; pp and AA),
PYTHIA (fragmentation/color reconnection; only pp),
Qufu (equal-velocity combination; only AA),
TAMU (pp-fragmentation; AA-resonance recombination+fragmentation; pp and AA),
Tsinghua (coalescence; only AA).
….



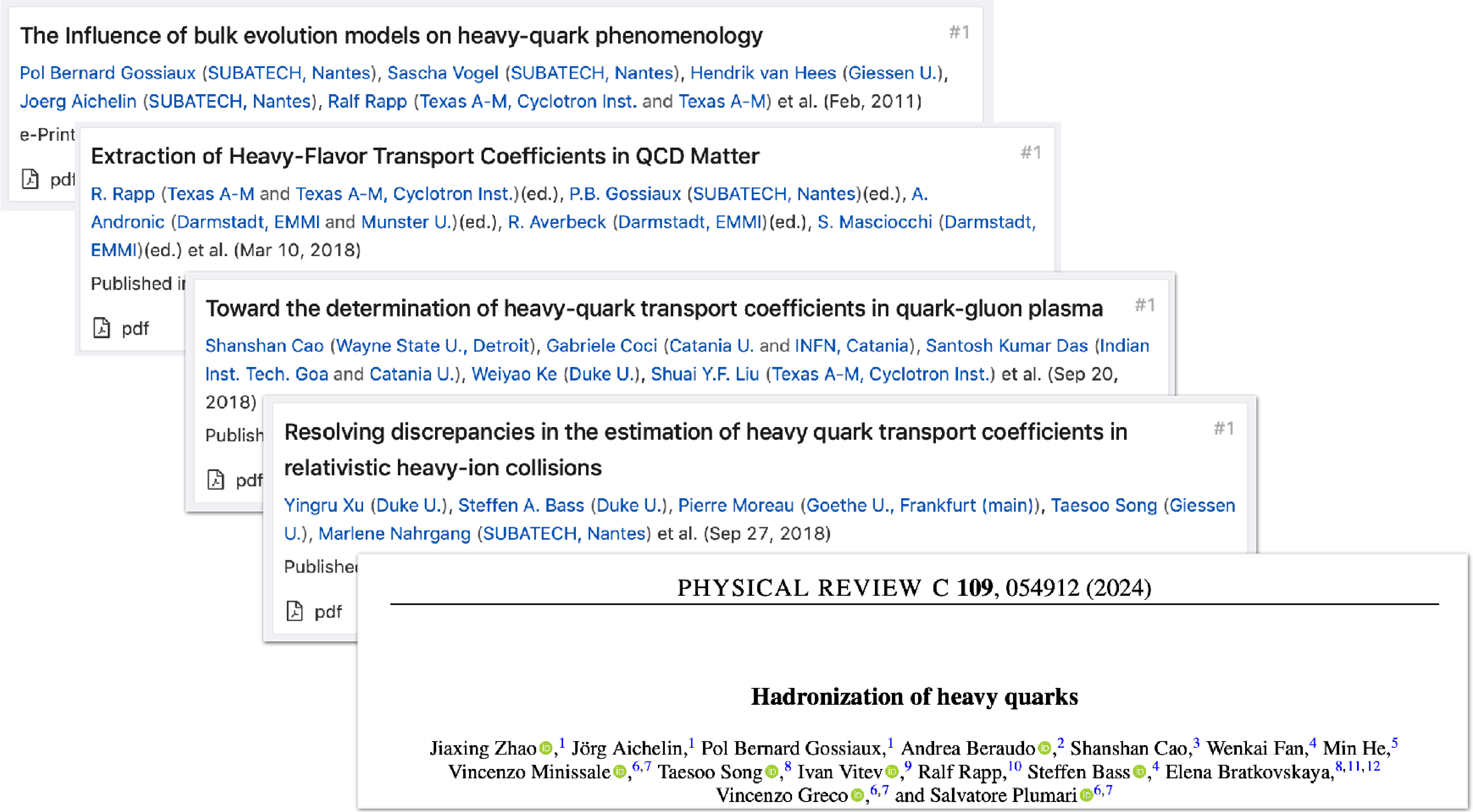






They give a more or less good description of the expermential data.

Heavy flavor energy loss, hadronization model comparison



The Influence of bulk evolution models on heavy-quark phenomenology #1

Pol Bernard Gossiaux (SUBATECH, Nantes), Sascha Vogel (SUBATECH, Nantes), Hendrik van Hees (Giessen U.), Joerg Aichelin (SUBATECH, Nantes), Ralf Rapp (Texas A-M, Cyclotron Inst. and Texas A-M) et al. (Feb, 2011)

e-Print

pd

Extraction of Heavy-Flavor Transport Coefficients in QCD Matter #1

R. Rapp (Texas A-M and Texas A-M, Cyclotron Inst.)(ed.), P.B. Gossiaux (SUBATECH, Nantes)(ed.), A. Andronic (Darmstadt, EMMI and Munster U.)(ed.), R. Averbeck (Darmstadt, EMMI)(ed.), S. Masciocchi (Darmstadt, EMMI)(ed.) et al. (Mar 10, 2018)

Published i

pdf

Toward the determination of heavy-quark transport coefficients in quark-gluon plasma #1

Shanshan Cao (Wayne State U., Detroit), Gabriele Coci (Catania U. and INFN, Catania), Santosh Kumar Das (Indian Inst. Tech. Goa and Catania U.), Weiyao Ke (Duke U.), Shuai Y.F. Liu (Texas A-M, Cyclotron Inst.) et al. (Sep 20, 2018)

Publish

pdf

Resolving discrepancies in the estimation of heavy quark transport coefficients in relativistic heavy-ion collisions #1

Yingru Xu (Duke U.), Steffen A. Bass (Duke U.), Pierre Moreau (Goethe U., Frankfurt (main)), Taesoo Song (Giessen U.), Marlene Nahrgang (SUBATECH, Nantes) et al. (Sep 27, 2018)

Publishe

pdf

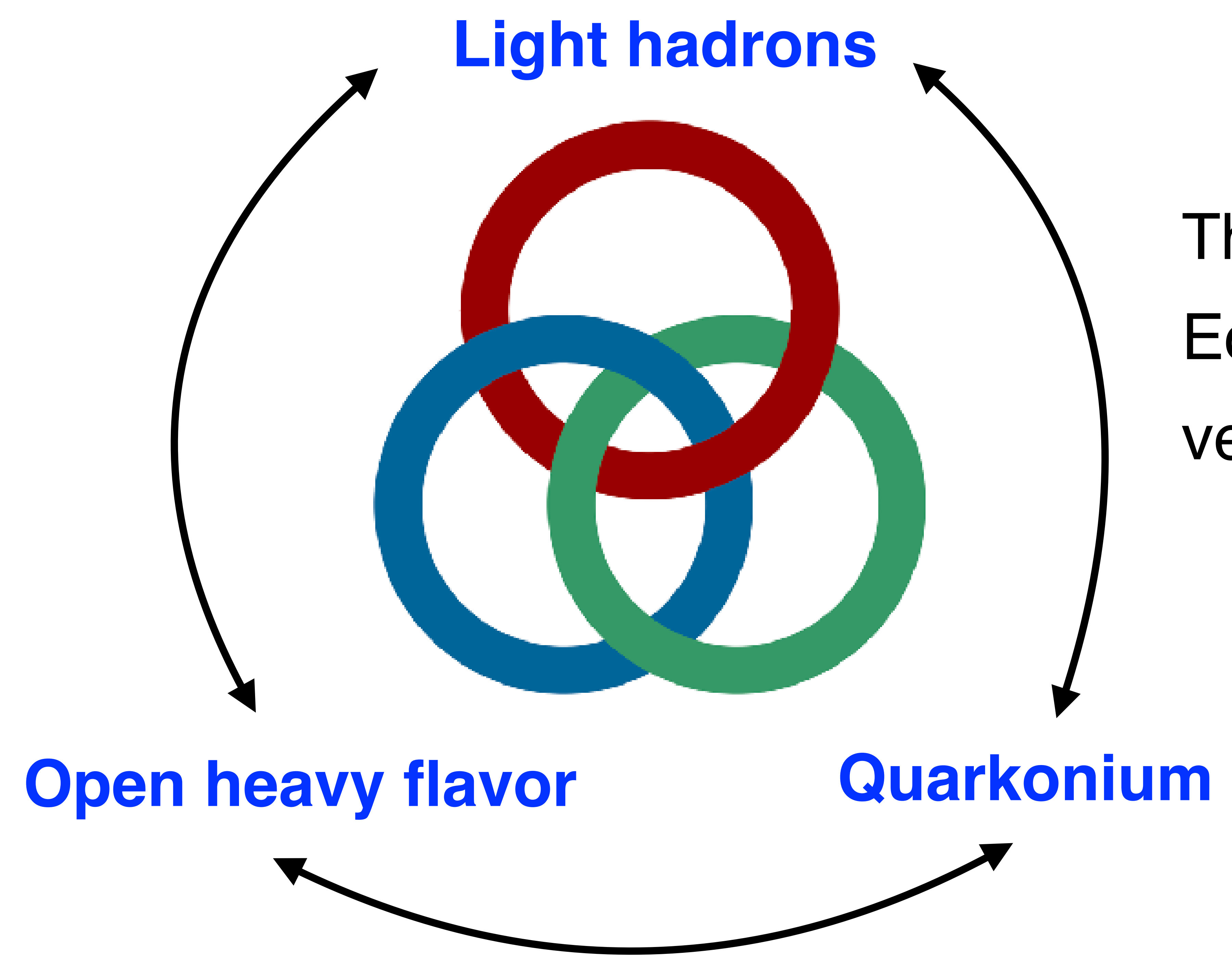
PHYSICAL REVIEW C **109**, 054912 (2024)

Hadronization of heavy quarks

Jiaxing Zhao,[1] Jörg Aichelin,[1] Pol Bernard Gossiaux,[1] Andrea Beraudo,[2] Shanshan Cao,[3] Wenkai Fan,[4] Min He,[5]
Vincenzo Minissale,[6,7] Taesoo Song,[8] Ivan Vitev,[9] Ralf Rapp,[10] Steffen Bass,[4] Elena Bratkovskaya,[8,11,12]
Vincenzo Greco,[6,7] and Salvatore Plumari[6,7]

Bulid a unified framework

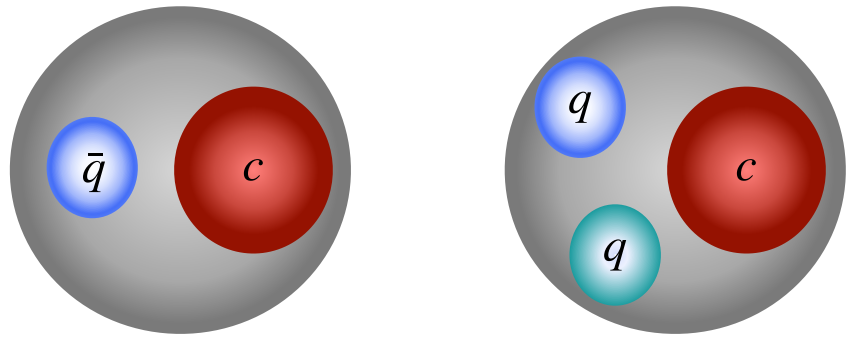
To combine the light with heavy, open heavy flavor with quarkonium!

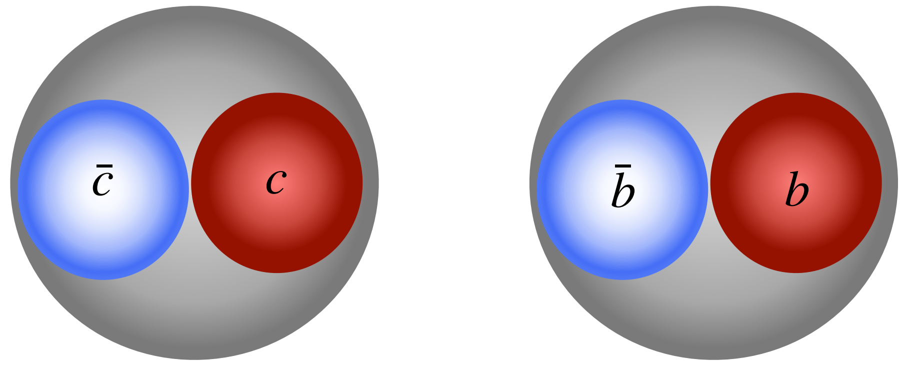


Light hadrons

Open heavy flavor

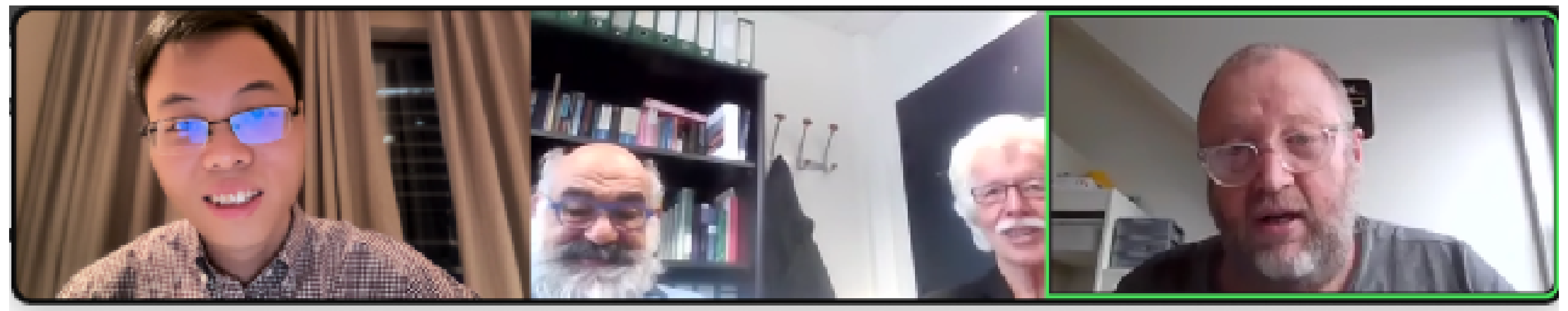
Quarkonium





Thermal medium properties:
EoS, lifetime,temperature,
velocity, shear viscosity…

Heavy quark energy loss
Correlations
Quark number conservation
…



Jiaxing Zhao, Joerg Aichelin, Klaus Werner, Pol Bernard Gossiaux

➡ **EPOS4** gives a good description of both charm and bottom hadrons production in pp & heavy ion collisions, central and peripheral collisions, RHIC and LHC energies!

will be released soon! ***JZ,*** *J.Aichelin, P.B. Gossiaux, K.Werner, Phys.Rev.D 109 (2024) 5, 054011; Phys.Rev.C 110 (2024) 2, 024909; arxiv: 2407.20919.*

EPOS4

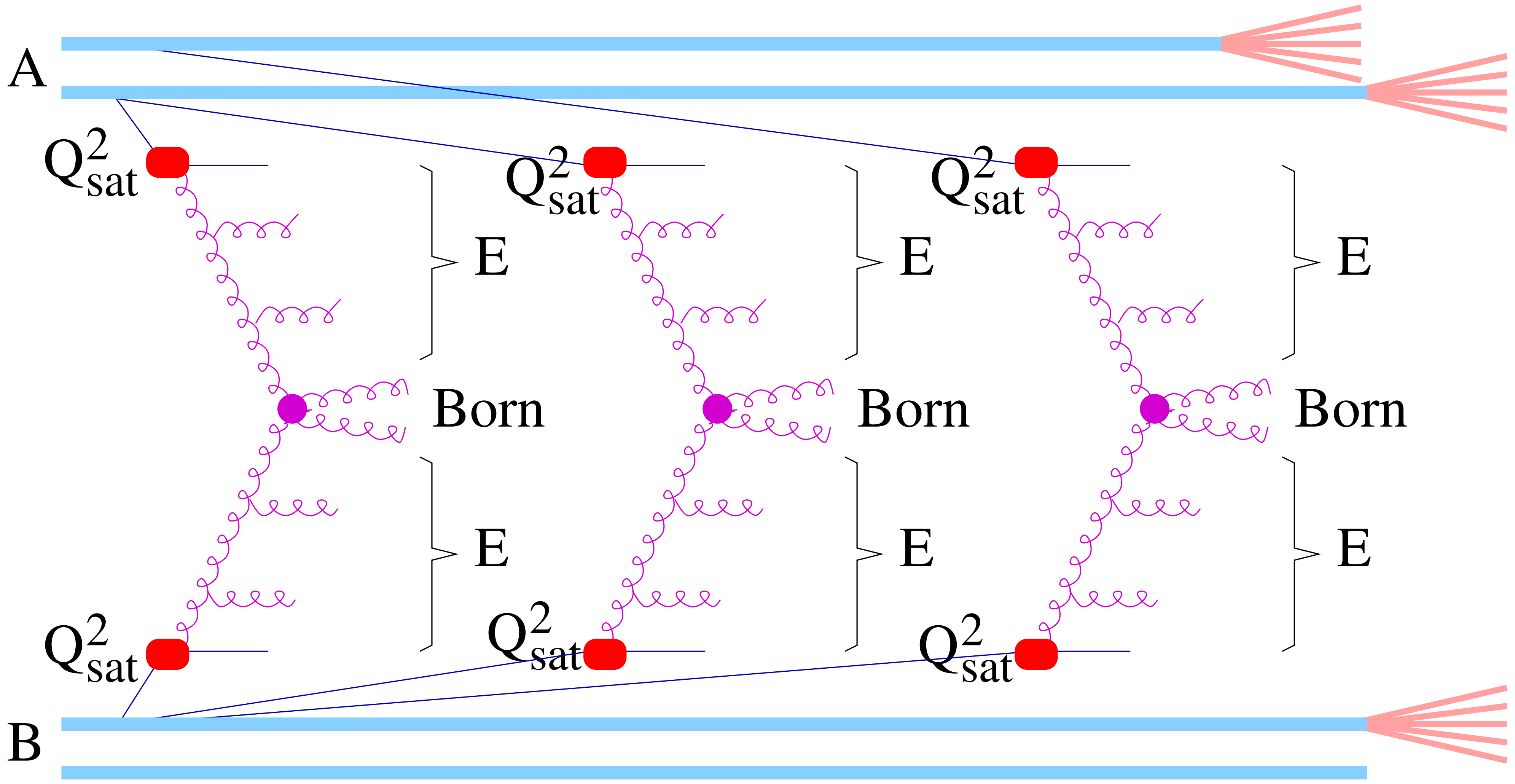
EPOS4: A Monte Carlo tool for simulating high-energy scatterings

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

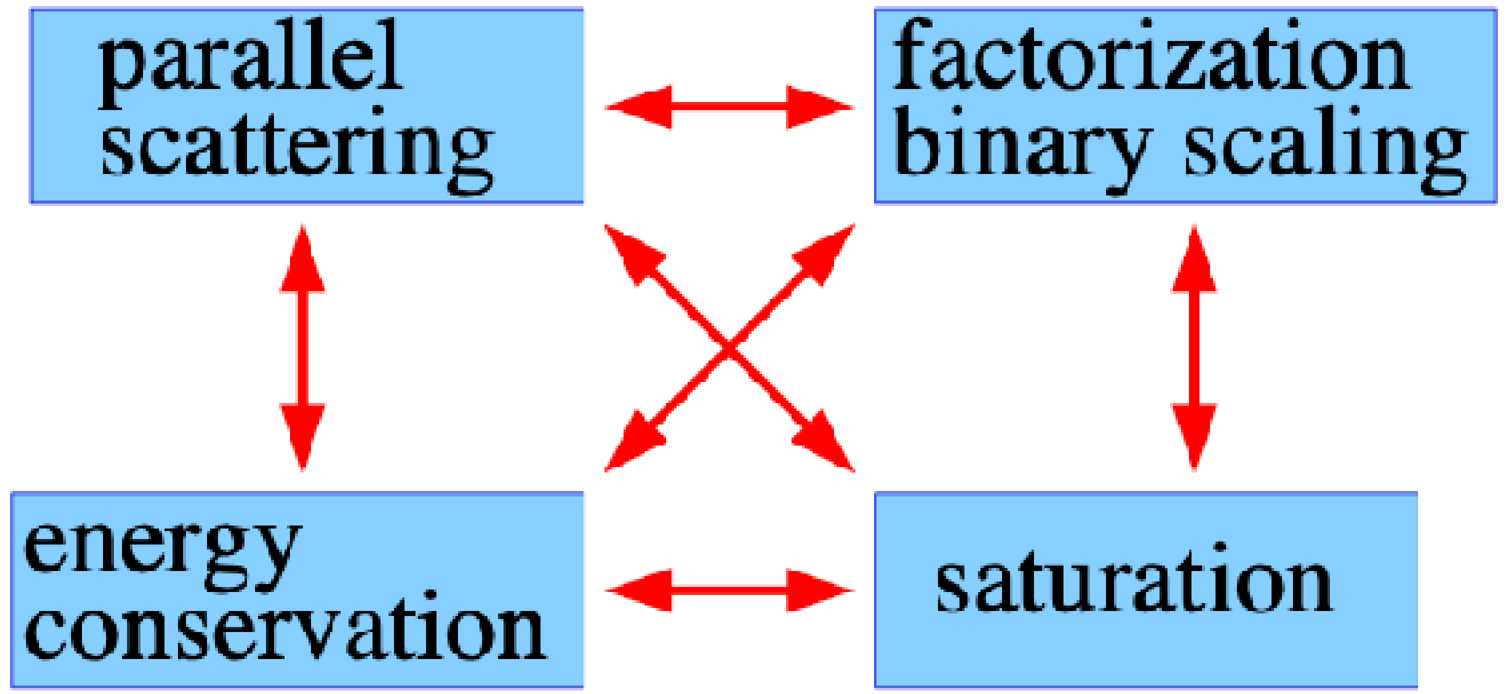
VENUS(1990)—>NEXUS(2000)—> EPOS1(2002)—>EPOS2(2010)—>EPOS3(2013)—>EPOS4(2020)

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.

K. Werner. PRC 108 (2023) 6, 064903
K. Werner, B. Guiot, PRC 108 (2023) 3, 034904
K. Werner, PRC 109 (2024) 1, 014910



e.g. three parallel scatterings



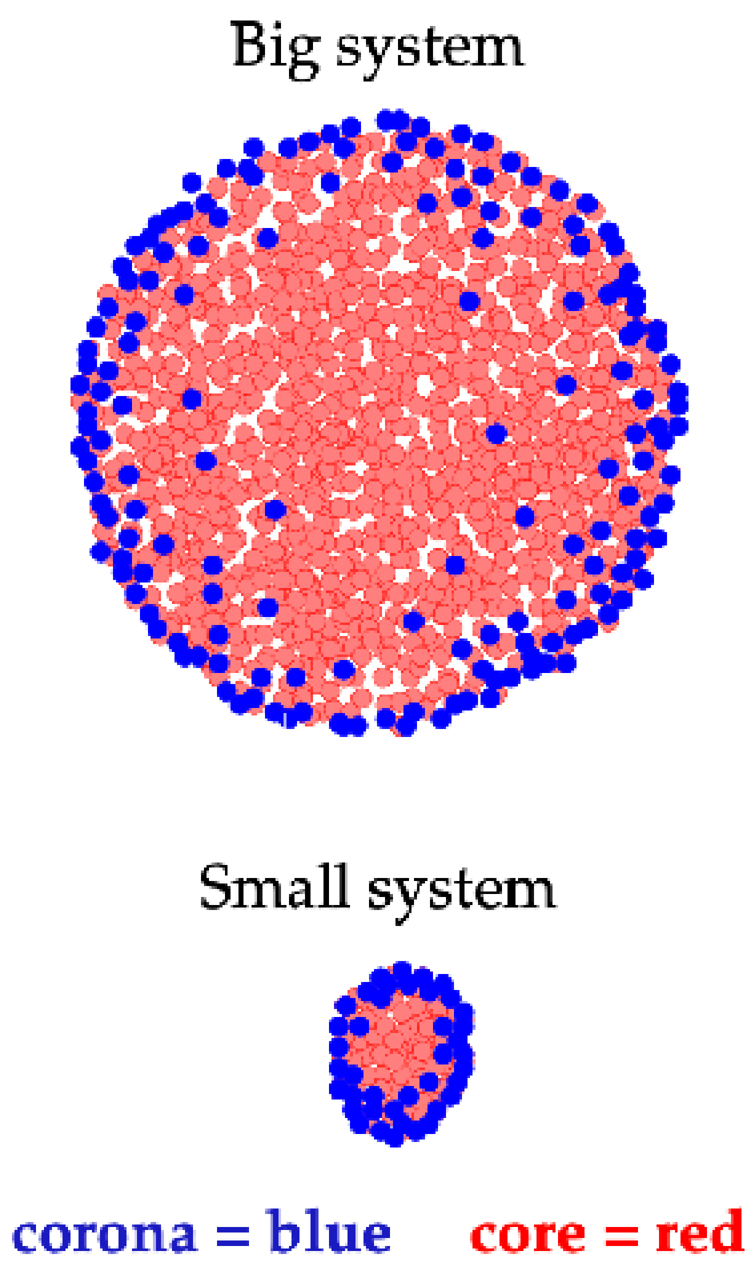
parallel scattering
factorization binary scaling
energy conservation
saturation

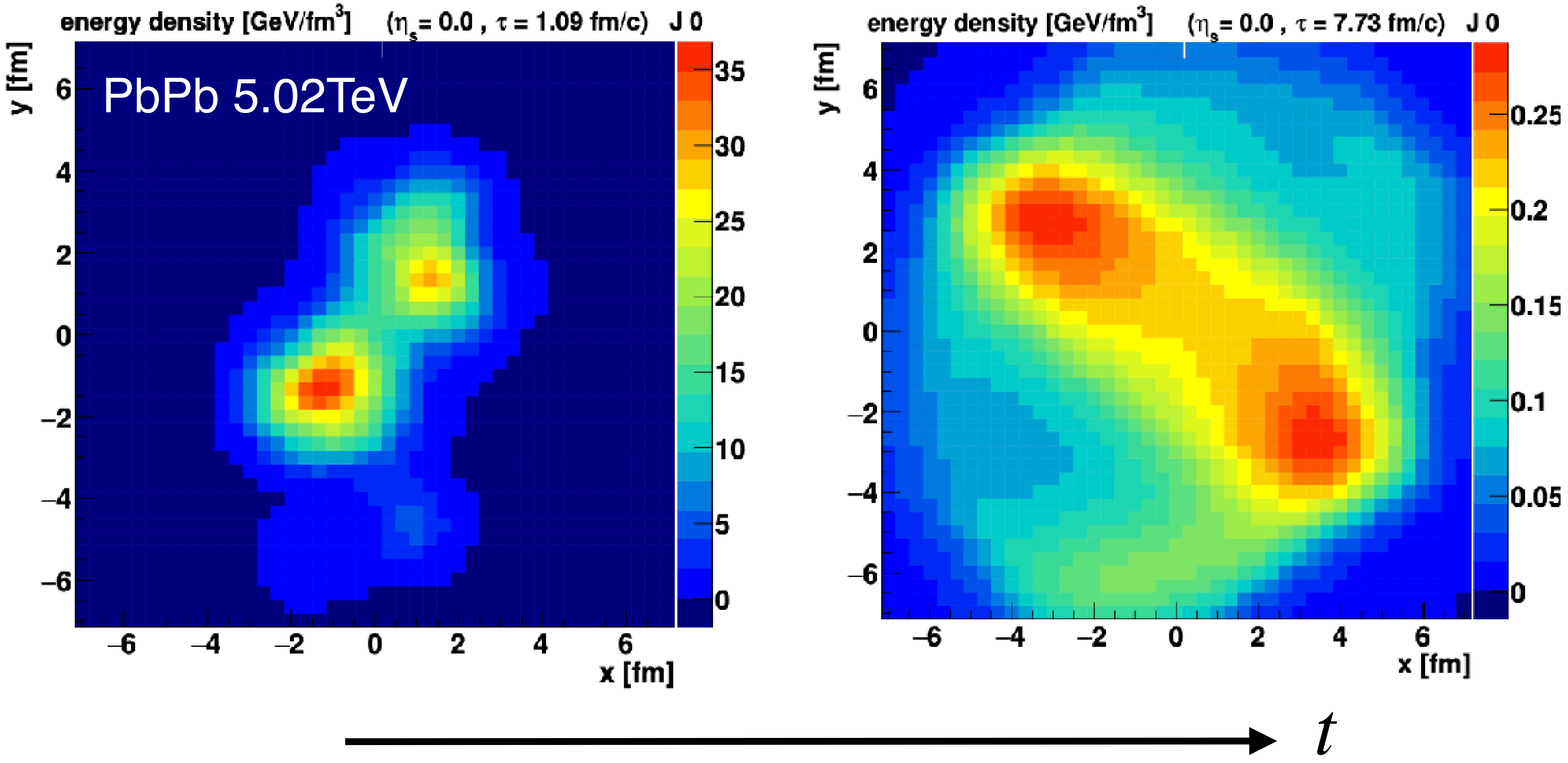
S-matrix theory (to deal with parallel scatterings happens in high energy collisions)

For each one we have a parton evolution according to the DGLAP .

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

EPOS4: core-corona picture





Core: string segment density larger than the critical density and also the transverse momentom of the segment; hydrodynamics (vHLLE);

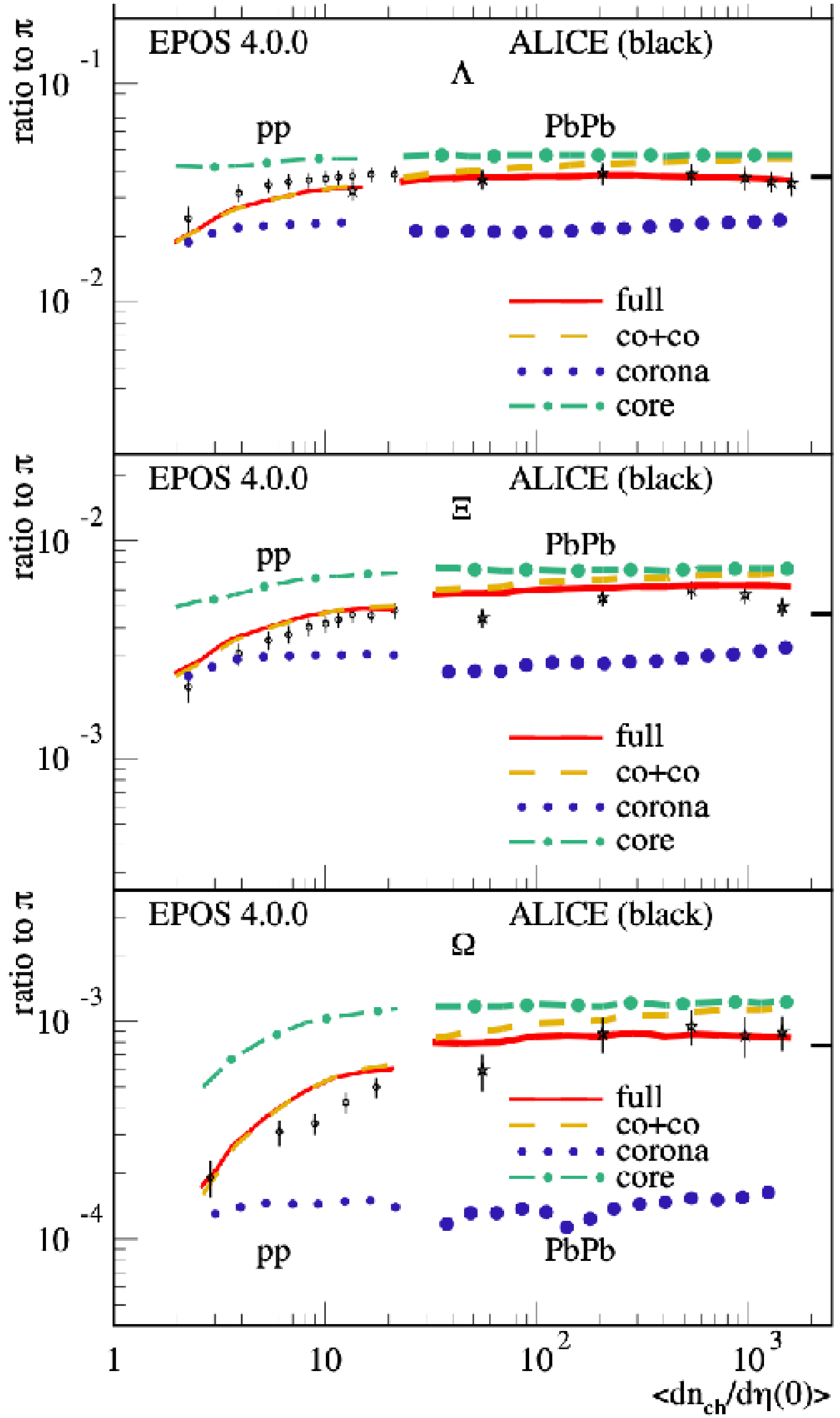
Corona: hadronic phase (UrQMD)

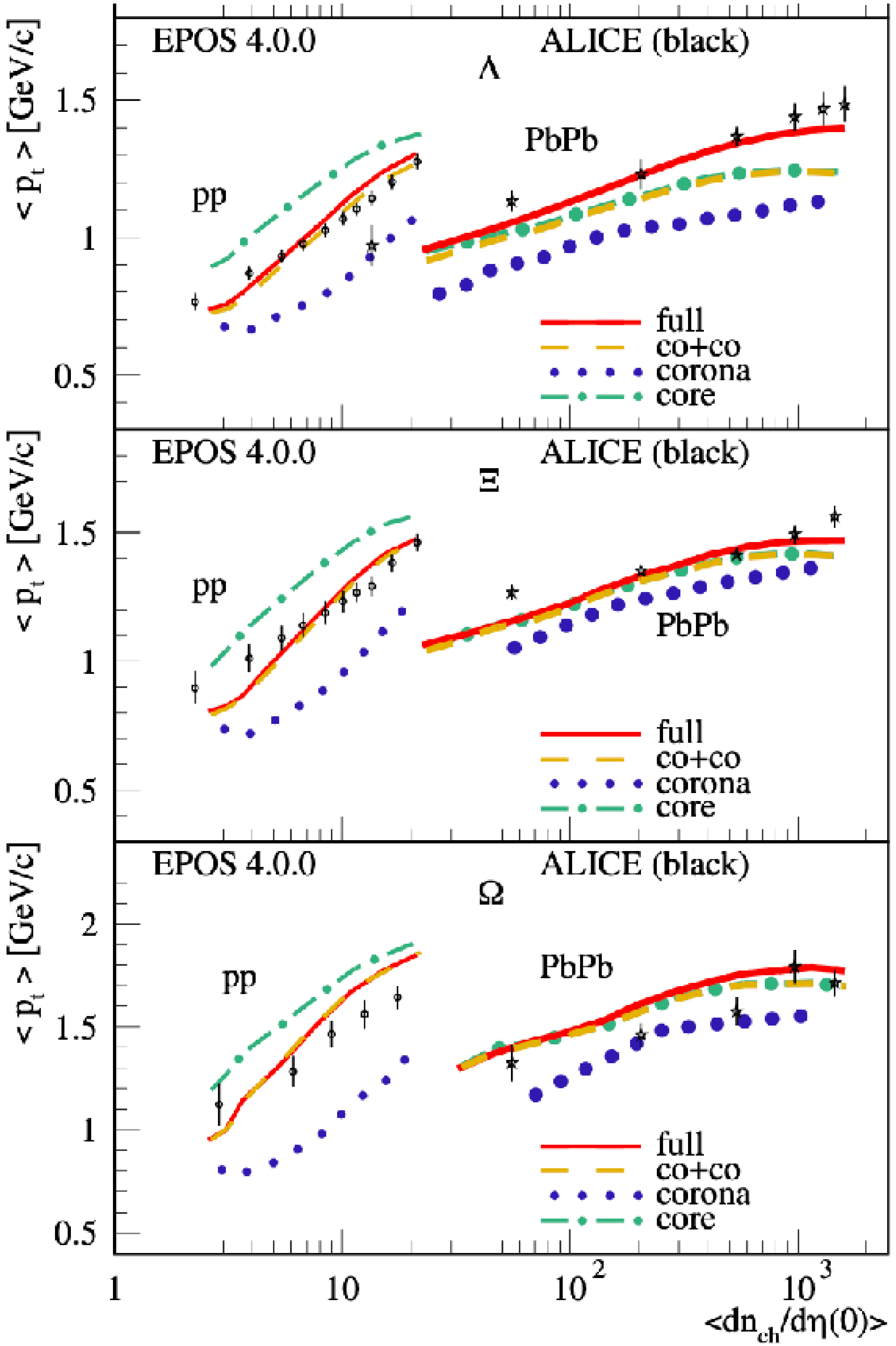
The energy density is larger than the critical energy density ϵ_0 -> deconfined QCD matter!

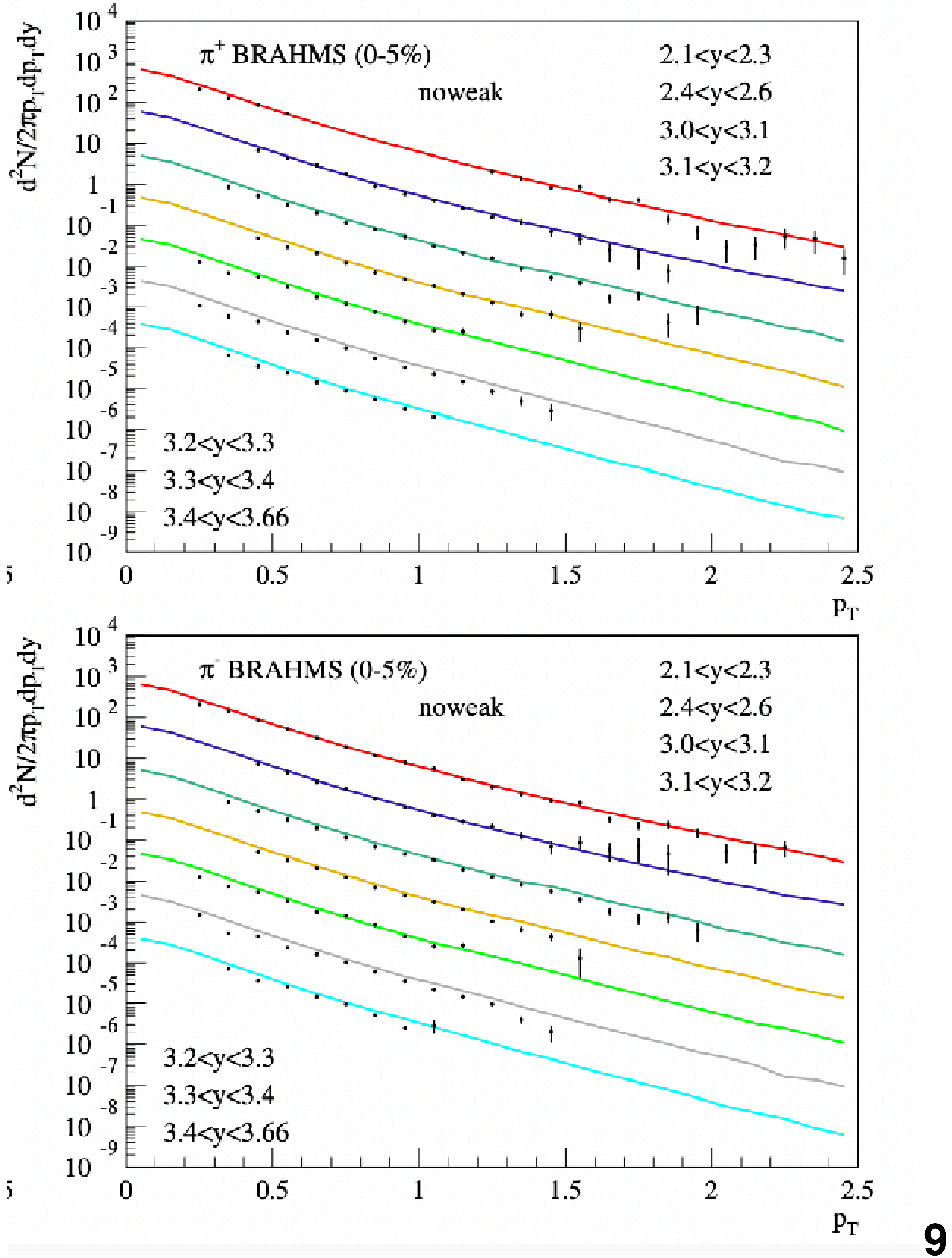
EPOS4: light hadrons production

Light hadrons have been described well from pp to AA by EPOS4!

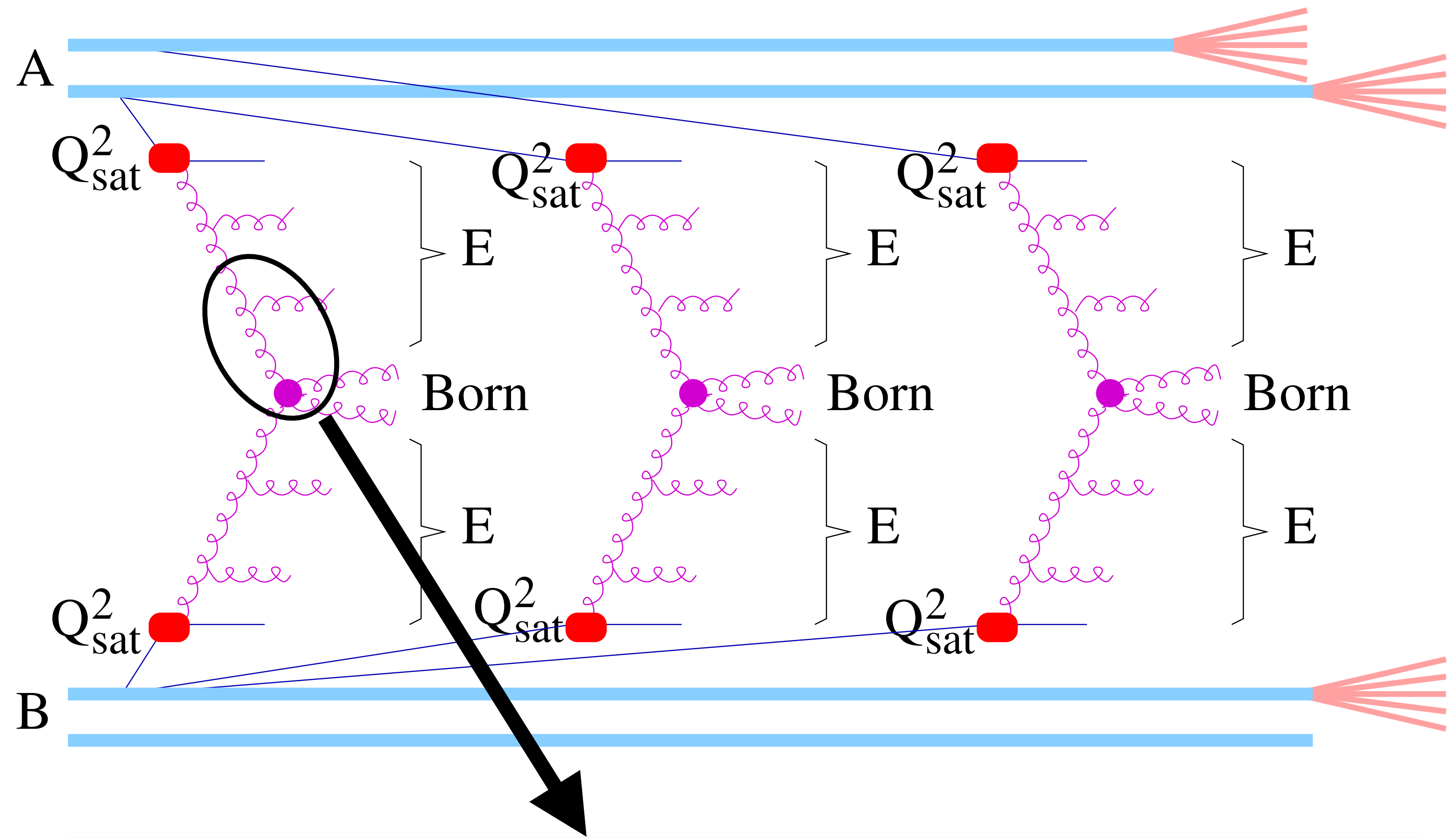
K. Werner, PRC 109 (2024) 1, 014910



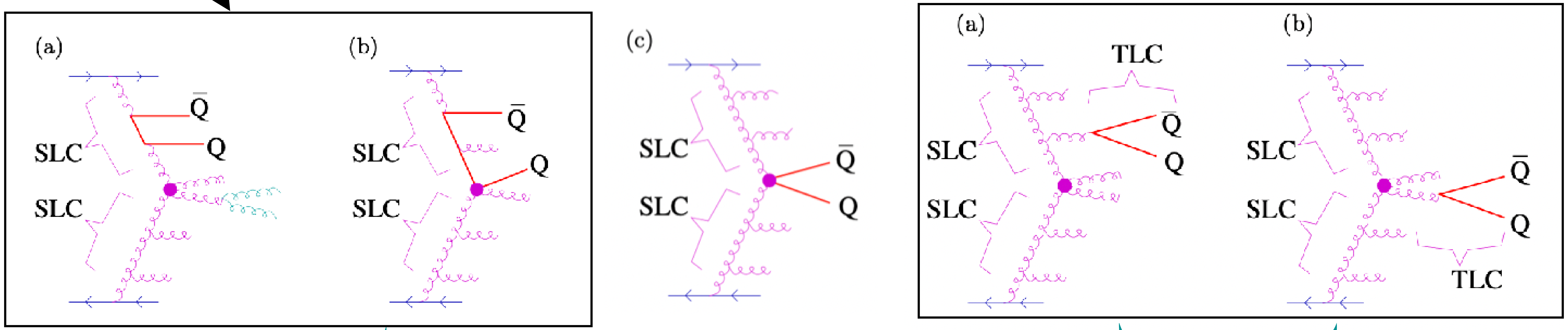




EPOS4: heavy quark production



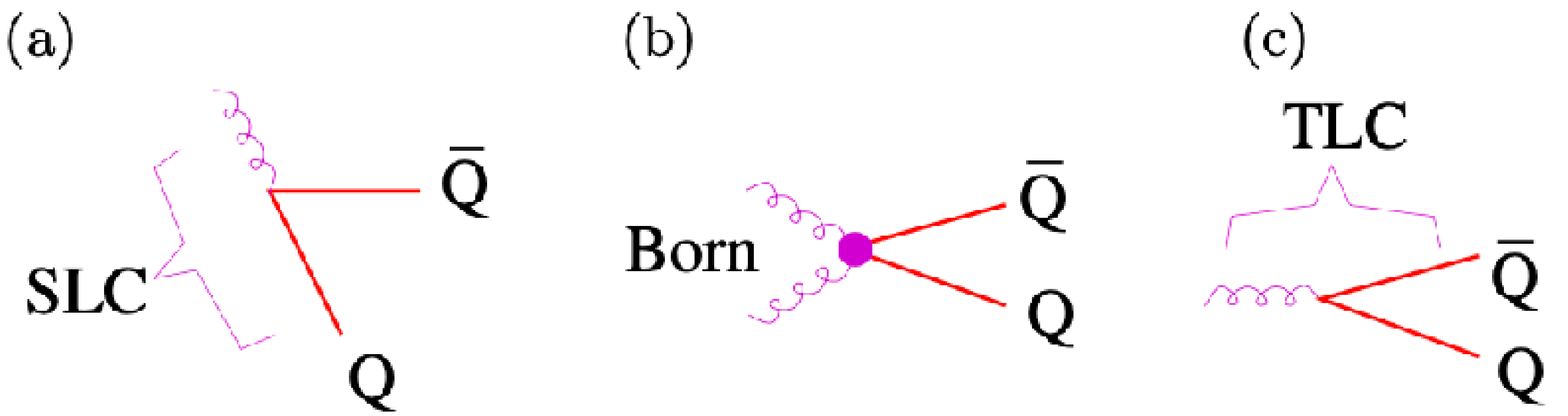
Heavy quarks are produced initially via:



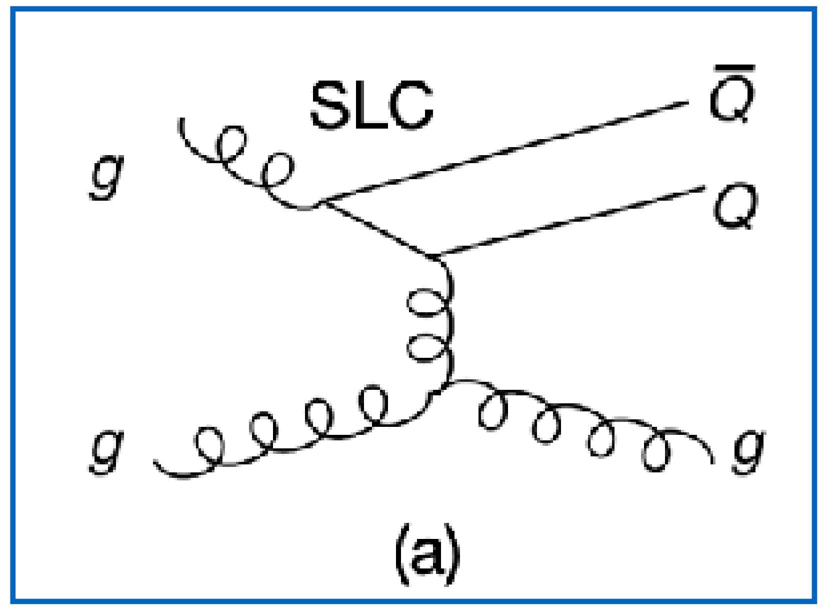
$$g + g \rightarrow Q + \bar{Q}$$
$$q + \bar{q} \rightarrow Q + \bar{Q}$$

Space-like cascade

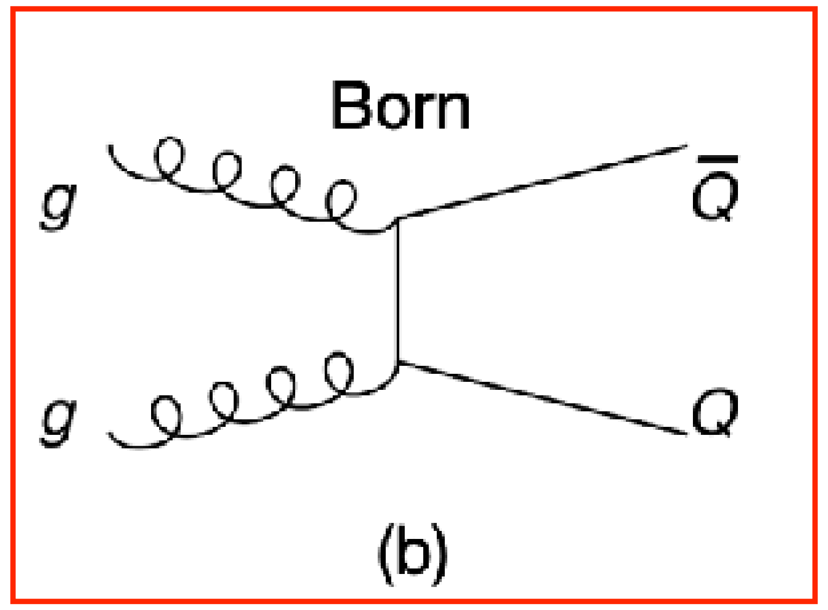
Time-like cascade



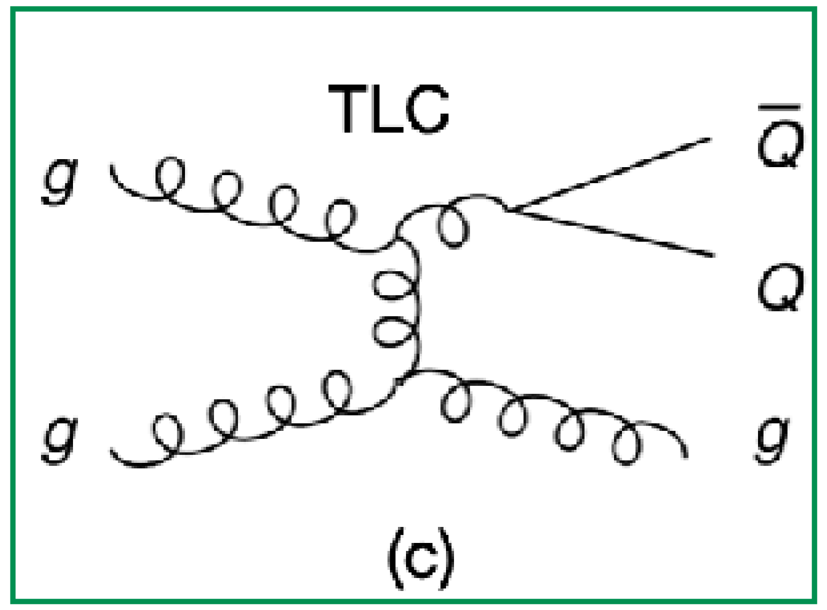
EPOS4: heavy quark production



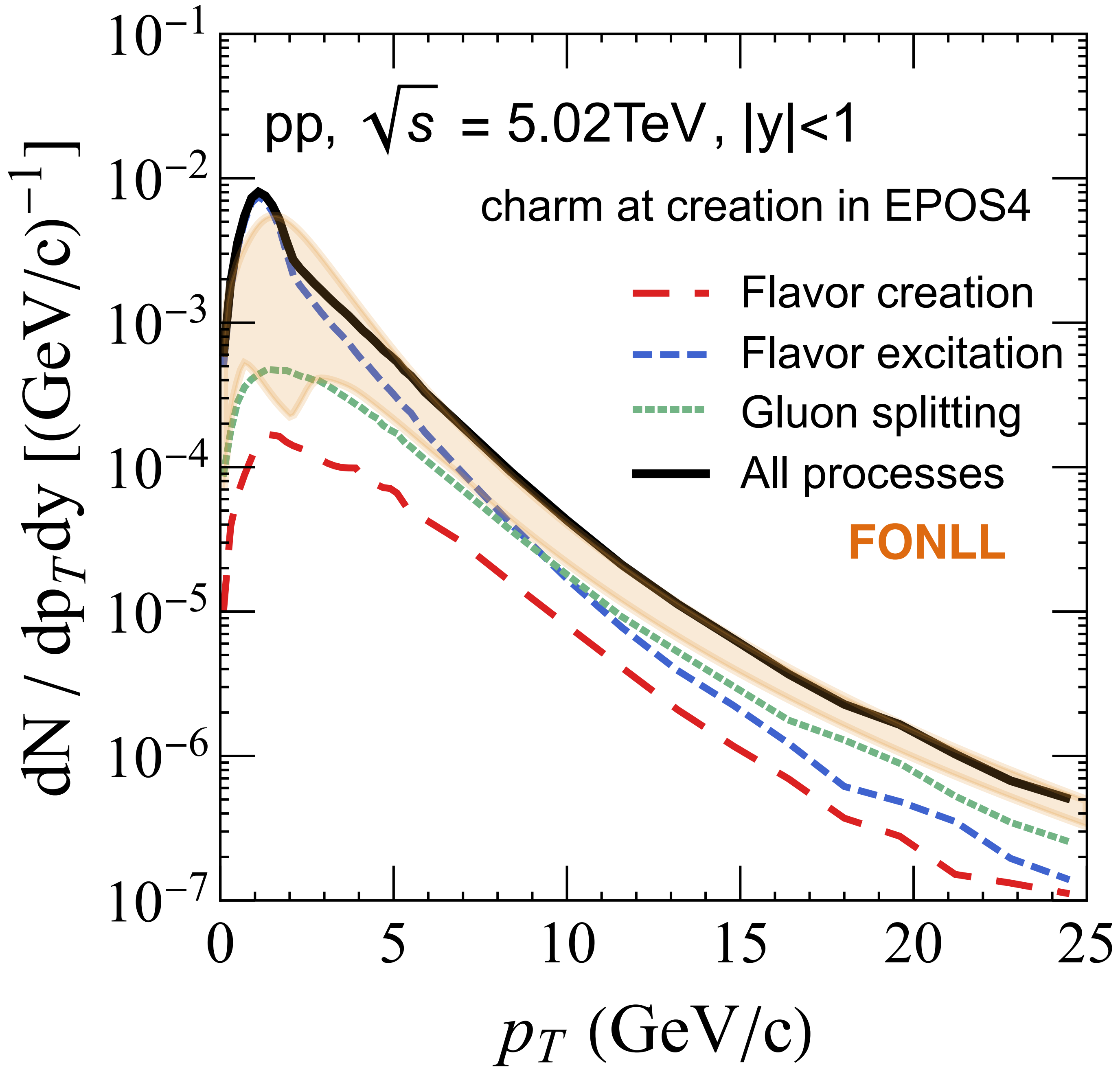
Flavor excitation

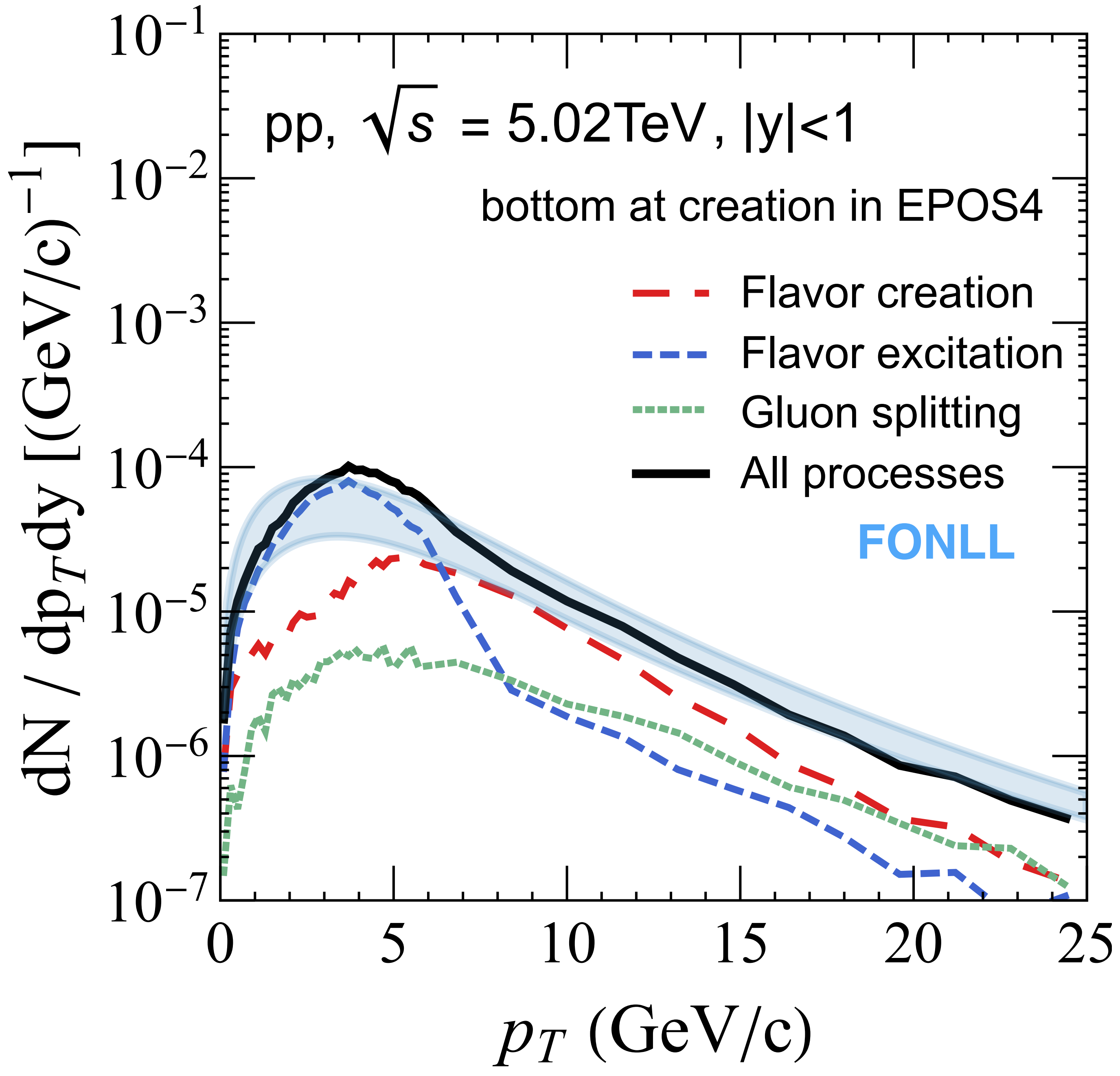


Flavor creation



Gluon splitting





Fixed order next to leading log

Flavor excitation dominates at low p_T while gluon splitting becomes important at high p_T.

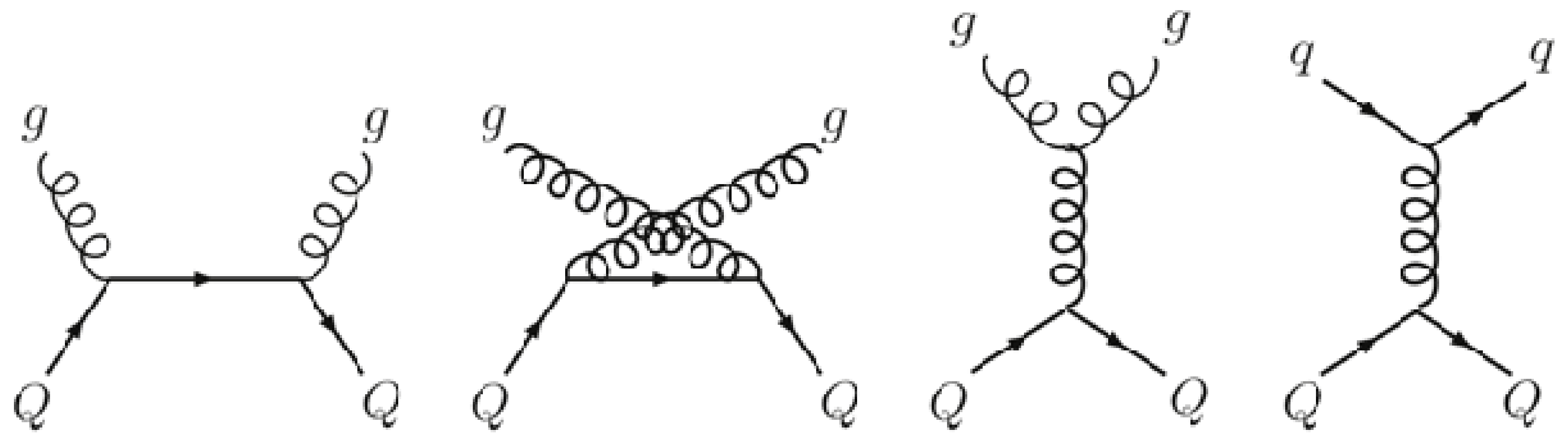
Outline

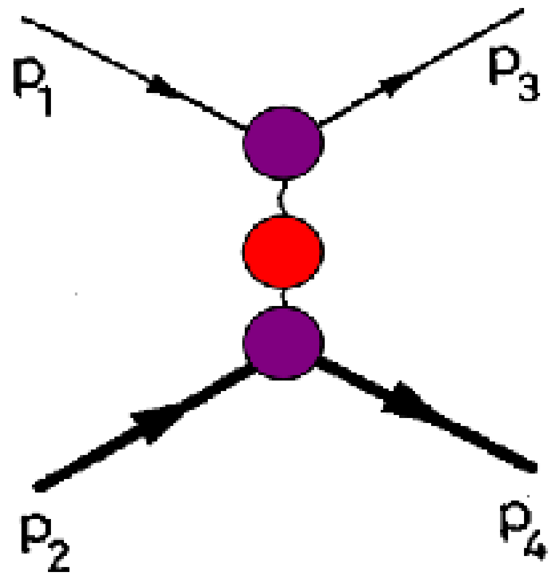
- Introduction of the heavy flavor probes
- **Heavy flavor production in heavy-ion collisions in EPOS4**
- Heavy flavor production in p-p collisions in EPOS4
- System size dependence of energy loss and correlations
- Summary

EPOS4: heavy quark energy loss

Heavy quark is treated as a Brownian particle and its evolution is described by the **Boltzmann equation**

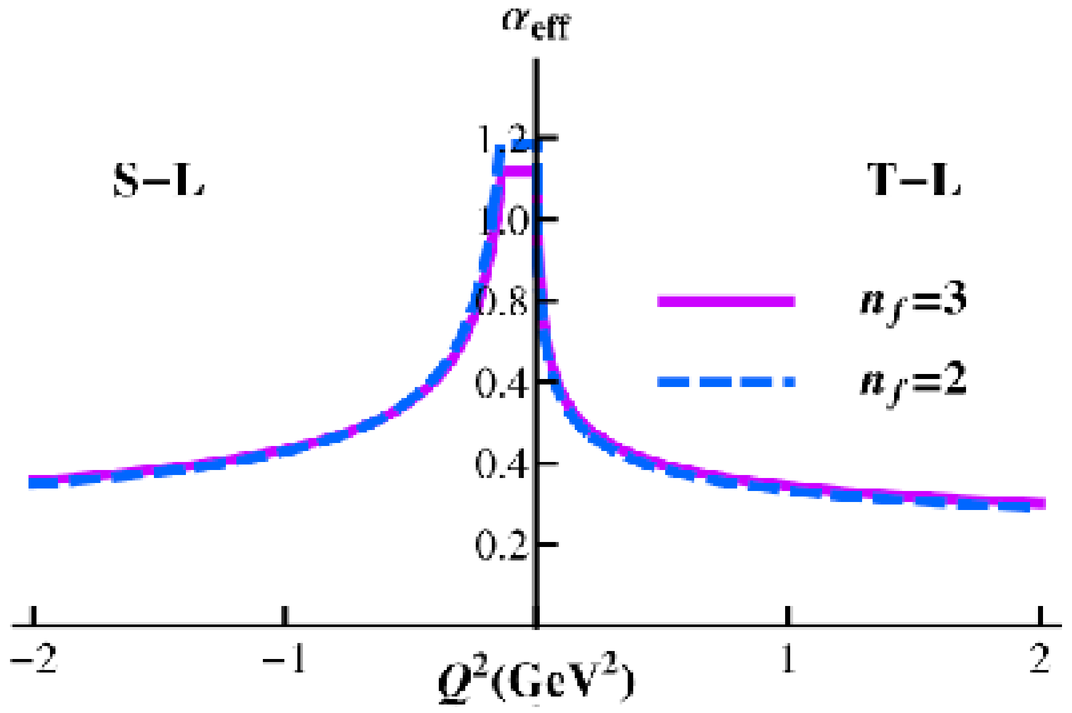
Both collisional and radiative energy loss are included





$$\frac{1}{q^2 - \kappa m_D^2(T)}$$

+ u and s channels

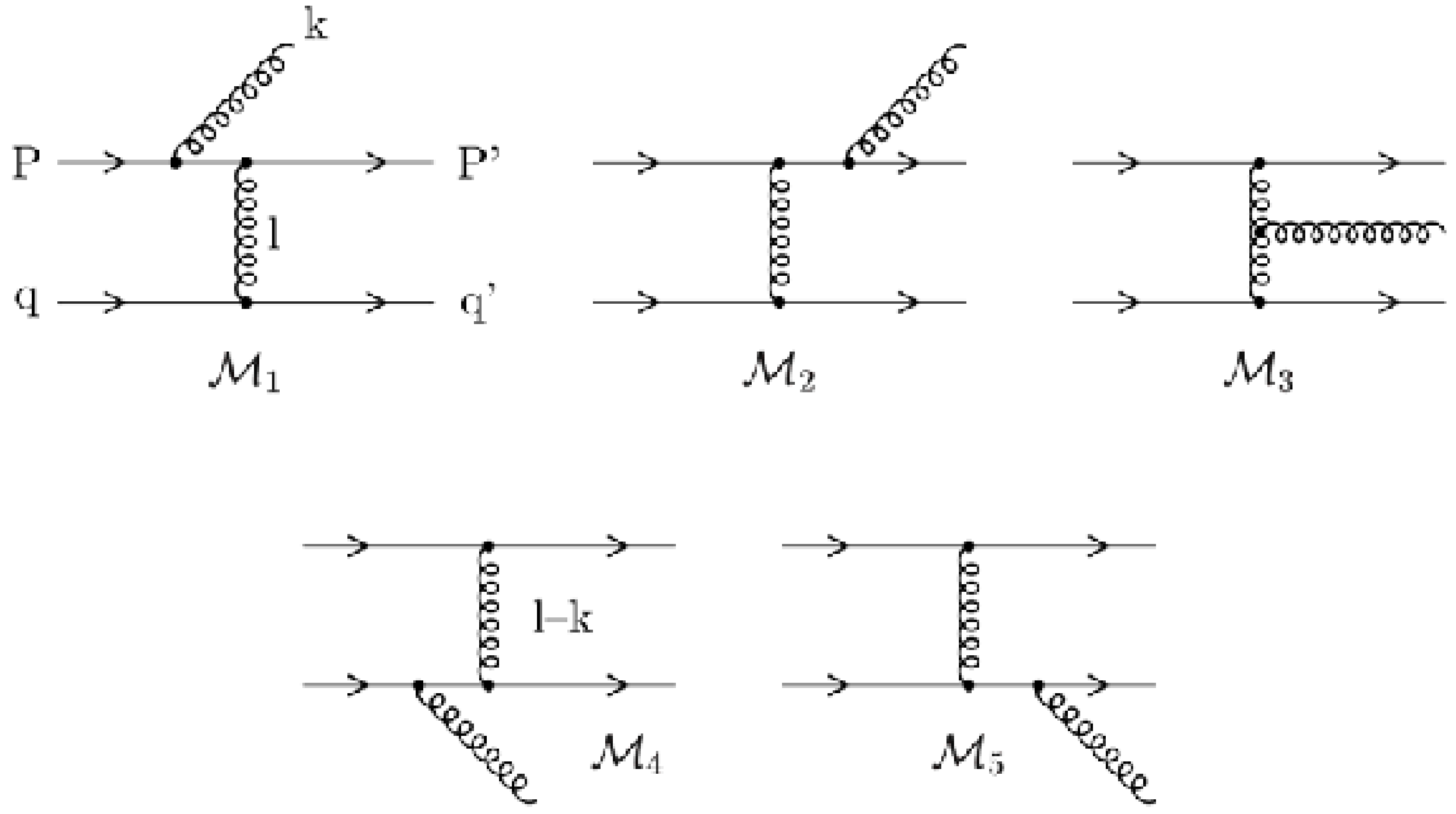


- ➡ IR regulator κm_D^2, where m_D given by HTL
- ➡ Running coupling

$$m_D^2(T) = (1 + \frac{N_f}{6}) 4\pi\alpha_s T^2$$

$$\alpha \to \alpha_{\rm eff}(Q^2) = \frac{4\pi}{\beta_0}\begin{cases} L_-^{-1} \\ \frac{1}{2} - \pi^{-1}{\rm atn}(L_+/\pi) \end{cases} \quad \text{for } Q^2 \lessgtr 0\,,$$

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



$$\frac{d\sigma_{II}^{Qq\to Qgq}}{dx d^2k_t d^2\ell_t} = \frac{d\sigma_{\rm el}}{d^2\ell_t} P_g(x, \vec{k}_t, \vec{\ell}_t)\Theta(\Delta)\,.$$

$$P_g(x, \vec{k}_t, \vec{\ell}_t; M) = \frac{C_A\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\vec{k}_t}{\vec{k}_t^2 + x^2M^2} - \frac{\vec{k}_t - \vec{\ell}_t}{(\vec{k}_t - \vec{\ell}_t)^2 + x^2M^2}\right)^2.$$

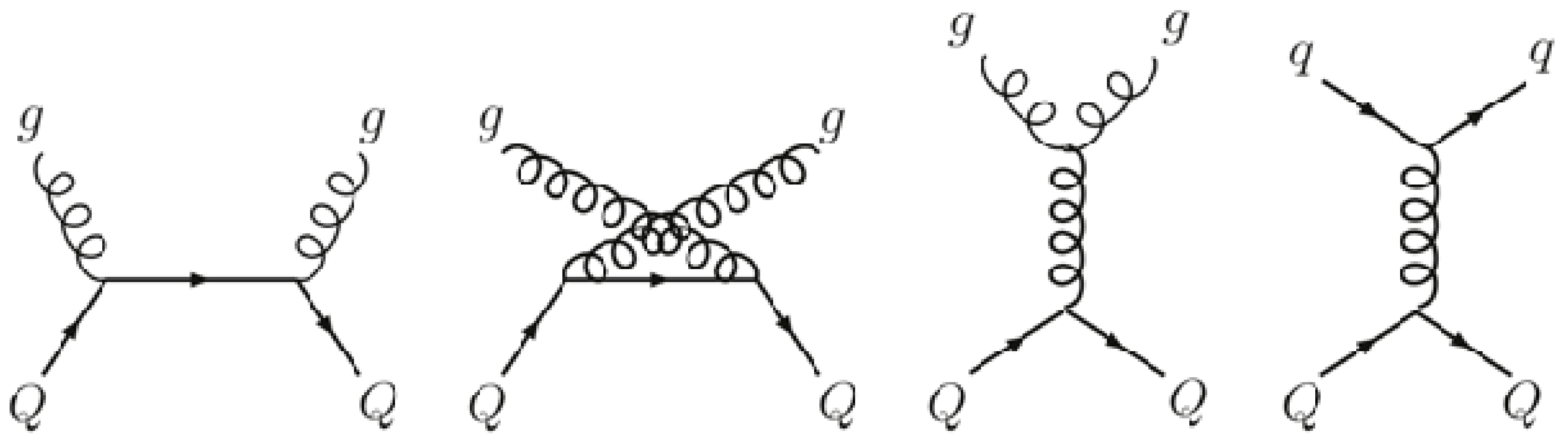
- ➡ Extension of Gunion-Bertsch approximation (massless and high energy)
- ➡ LPM effect for moderate gluon energy

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

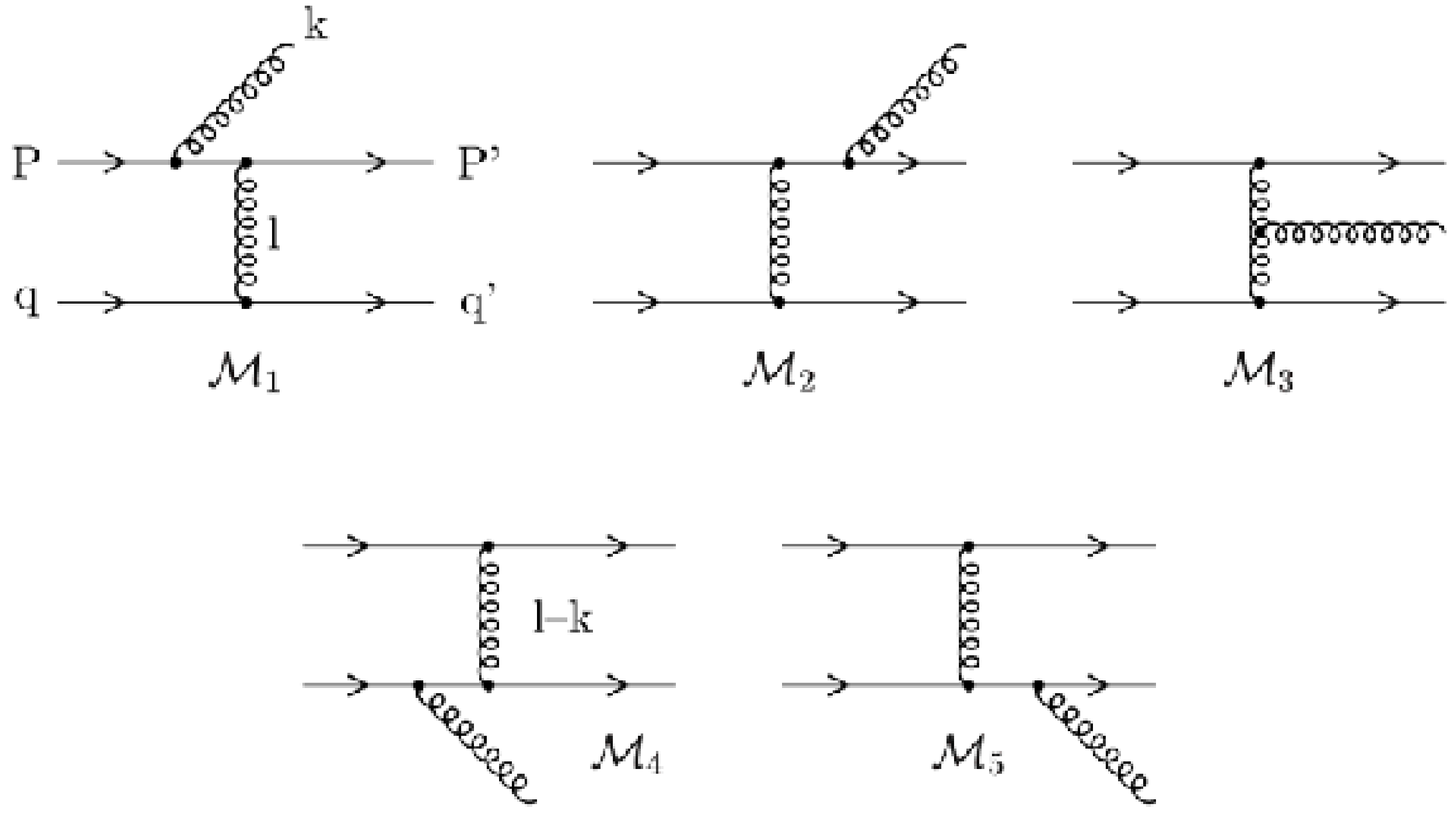
EPOS4: heavy quark energy loss

Heavy quark is treated as a Brownian particle and its evolution is described by the **Boltzmann equation**

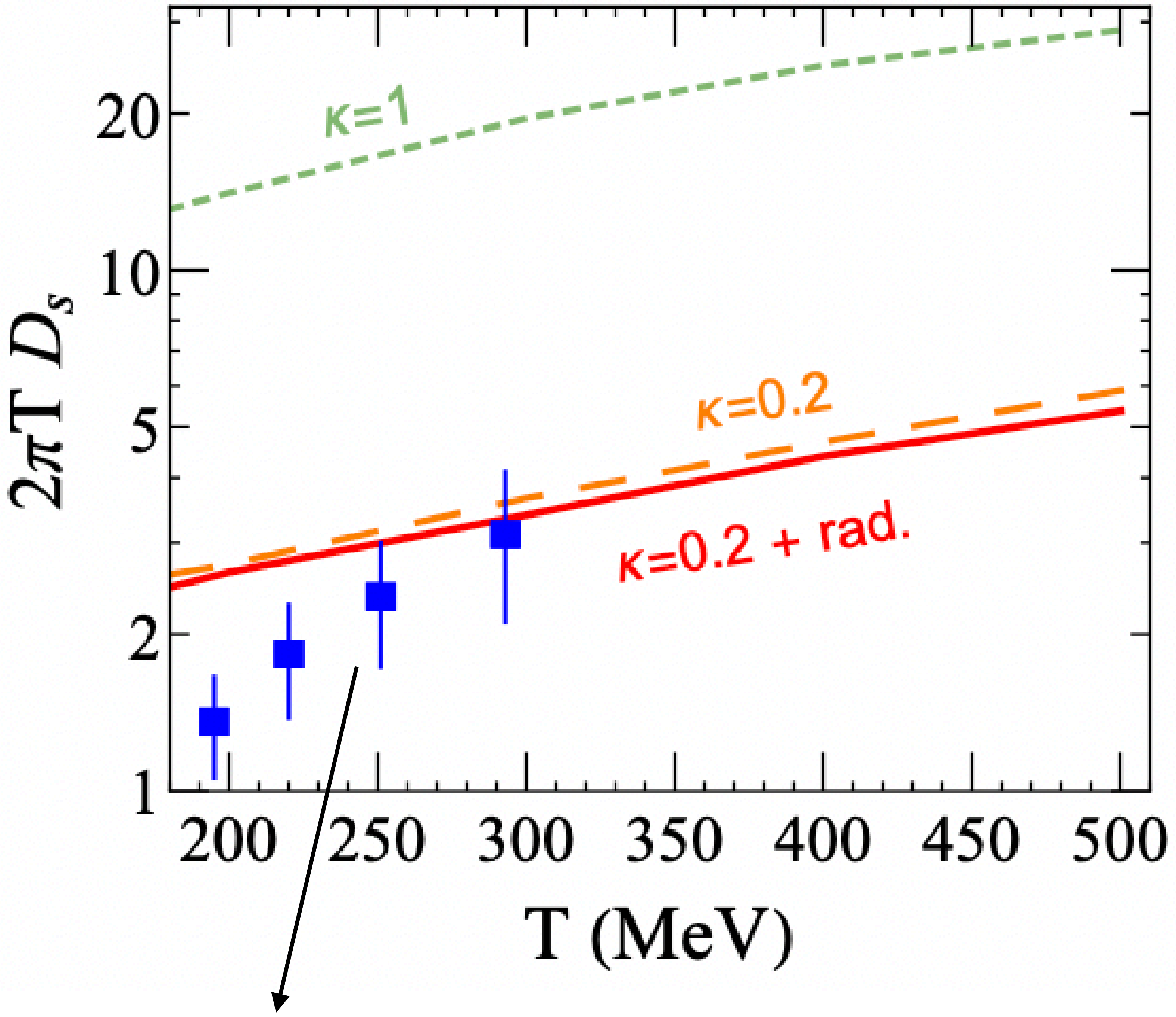
Both collisional and radiative energy loss are included



- ➡ IR regulator κm_D^2, where m_D given by HTL
- ➡ Running coupling

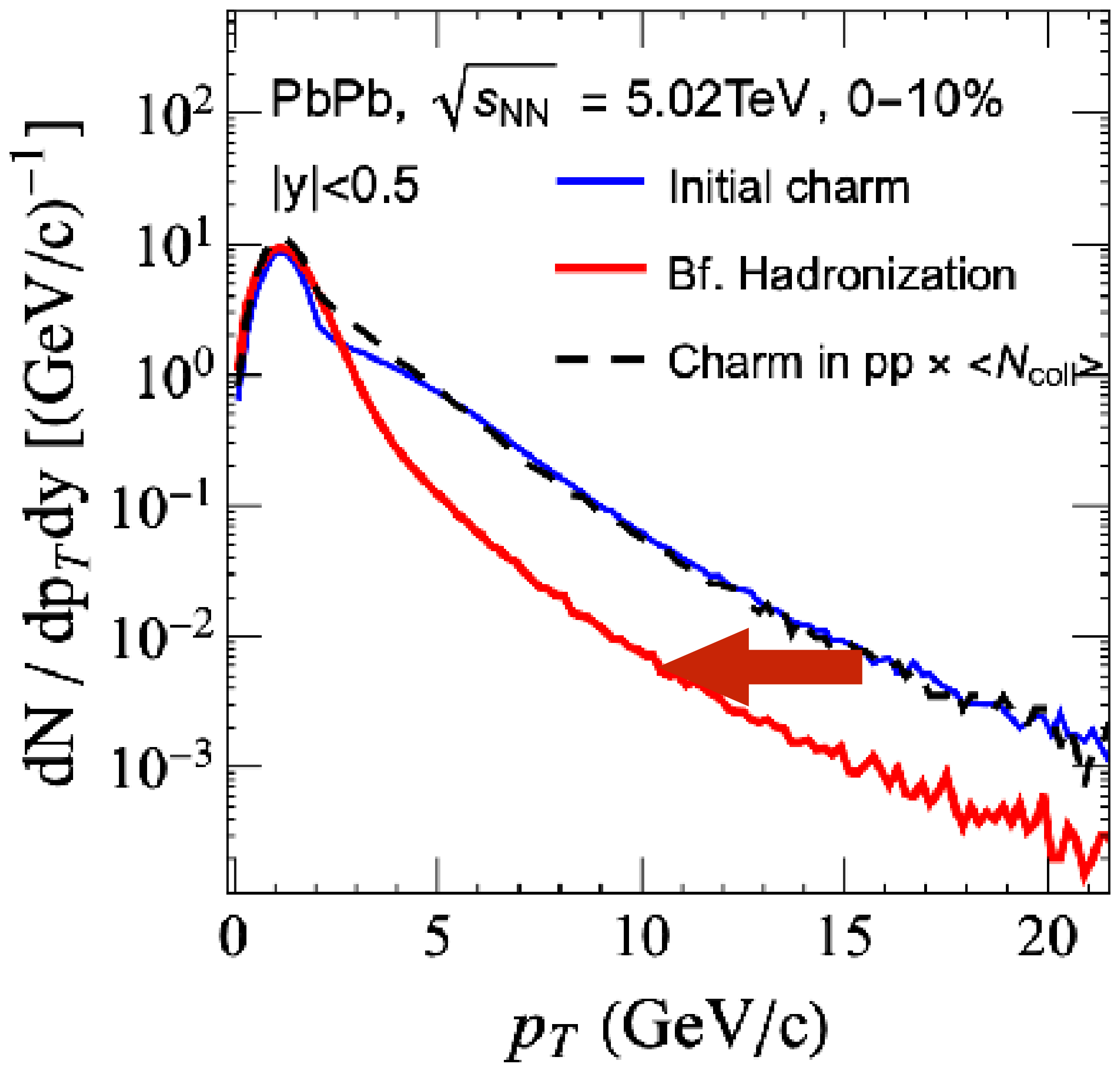


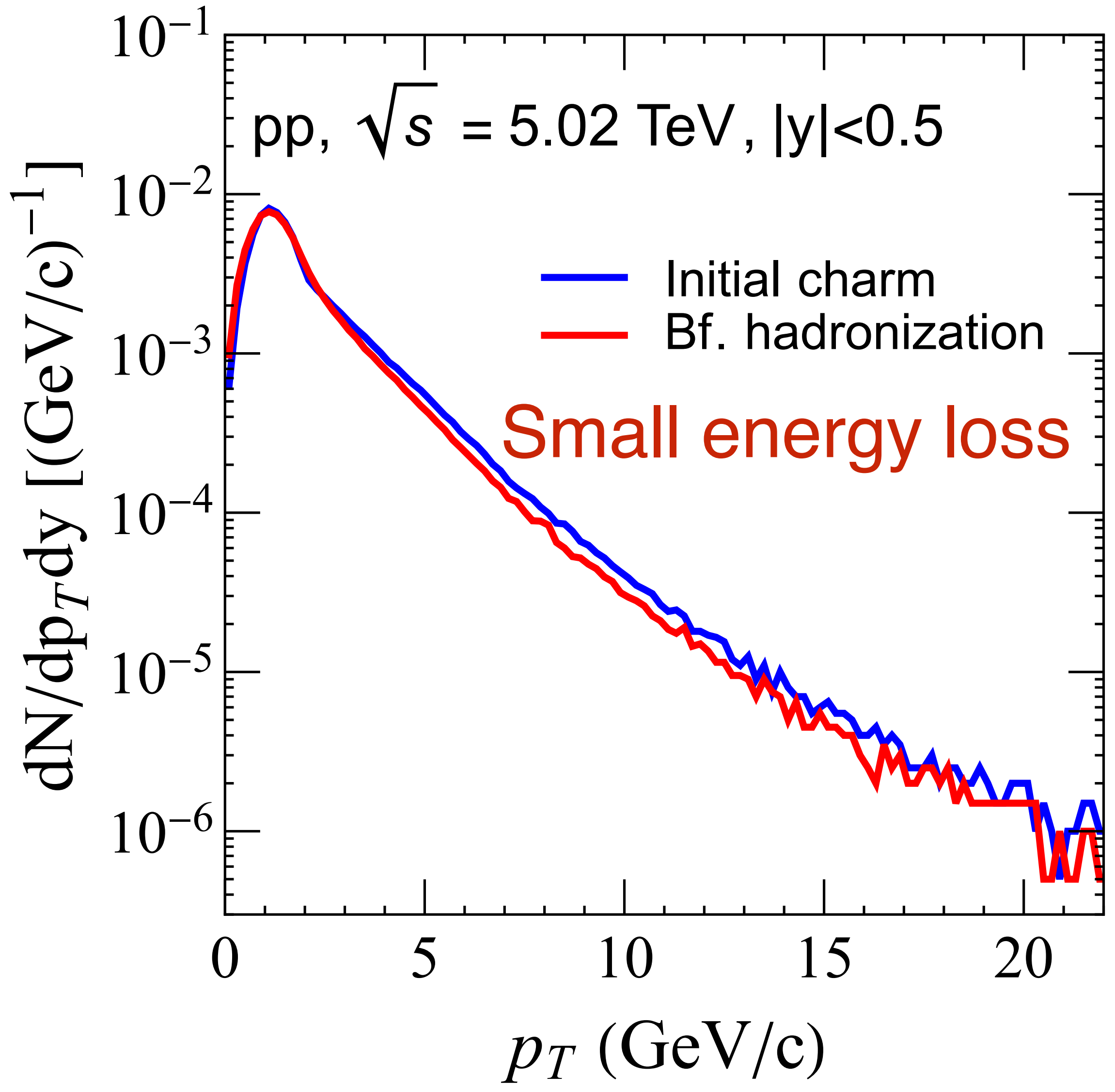
- ➡ Extension of Gunion-Bertsch approximation (massless and high energy)
- ➡ LPM effect for moderate gluon energy



Recent lattice results with dynamic quarks

HotQCD Collaboration, Phys.Rev.Lett. 130 (2023) 23, 231902





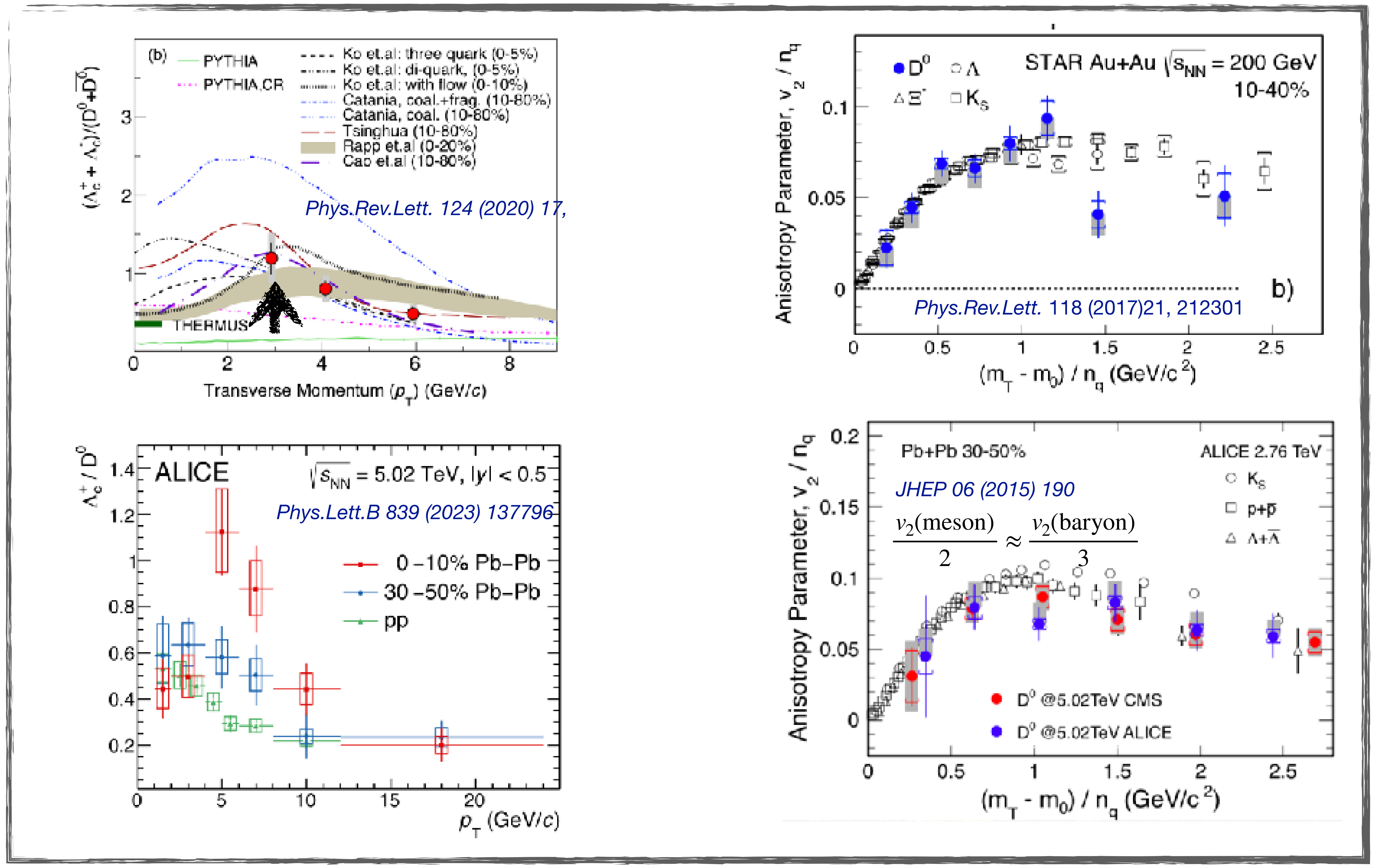
Small energy loss

JZ, *J.Aichelin, P.B. Gossiaux, V. Ozvenchuk, K.Werner, Phys.Rev.C 110 (2024) 2, 024909*

EPOS4: heavy quark hadronization

When the local energy density is lower than the critical value ($T_{FO} \sim 165$ MeV)

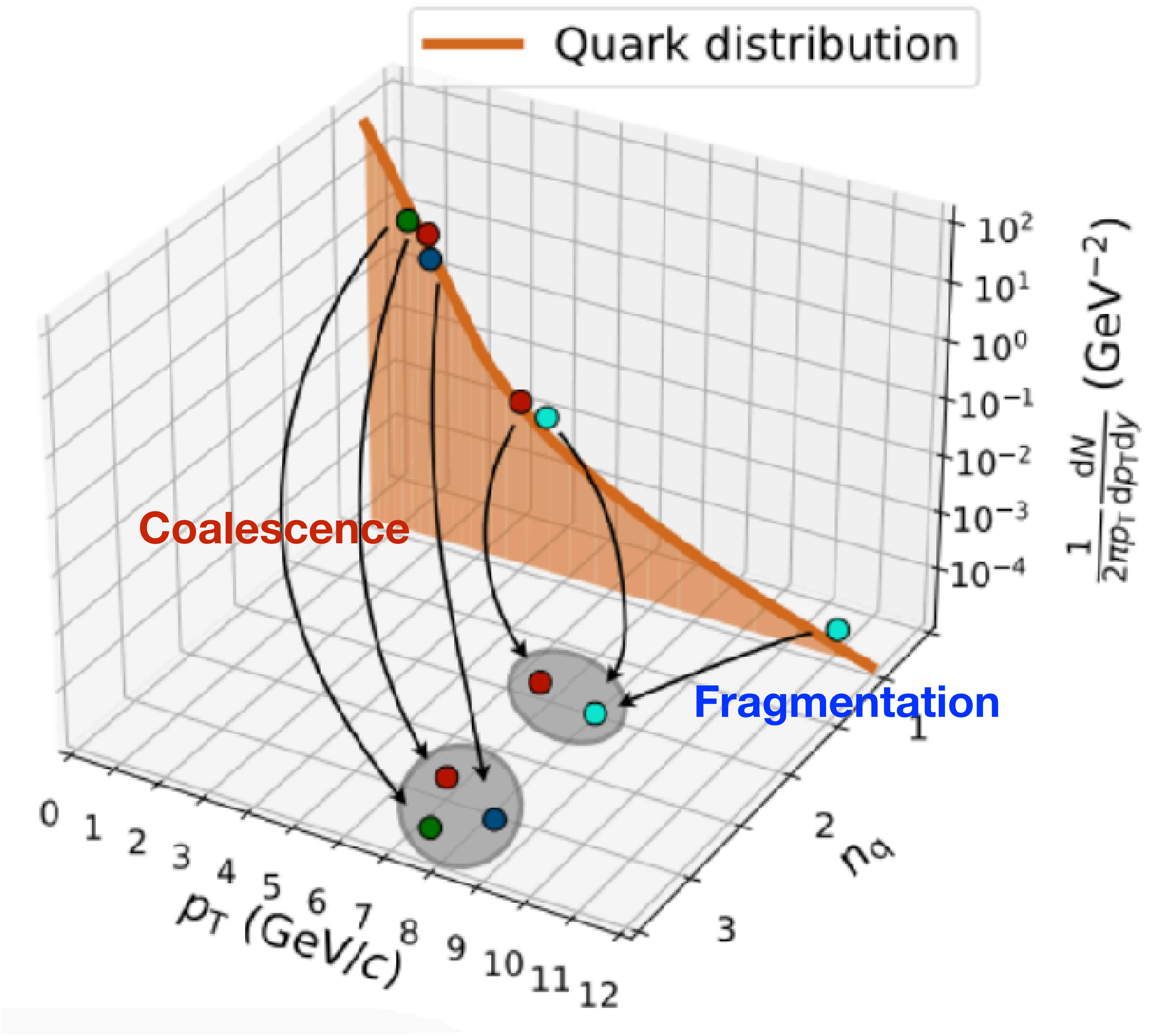
Heavy quarks hadronize into heavy flavor hadrons!


Phys.Rev.Lett. 124 (2020) 17,

Phys.Rev.Lett. 118 (2017)21, 212301

Phys.Lett.B 839 (2023) 137796

JHEP 06 (2015) 190



- Enhancement Baryon / Meson Ratio
- Quark Number Scaling of Elliptic flow

The heavy quark combines with the light quark(s), which are close together in phase space.

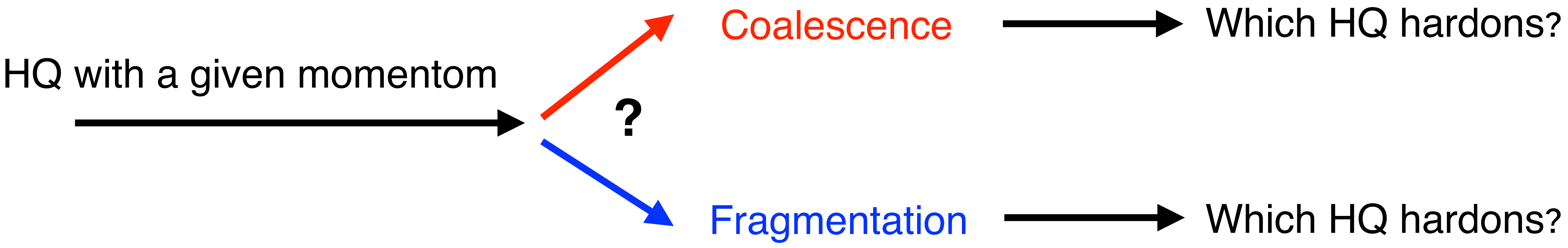
Low p_T heavy quark hadronizes by recombination while high p_T hadronizes by fragmentation.

EPOS4: heavy quark hadronization

When the local energy density is lower than the critical value ($T_{\mathrm{FO}} \sim 165$ MeV)

Heavy quarks hadronize into heavy flavor hadrons!

Heavy quarks hadronize via coalescence + fragmentation in EPOS4!

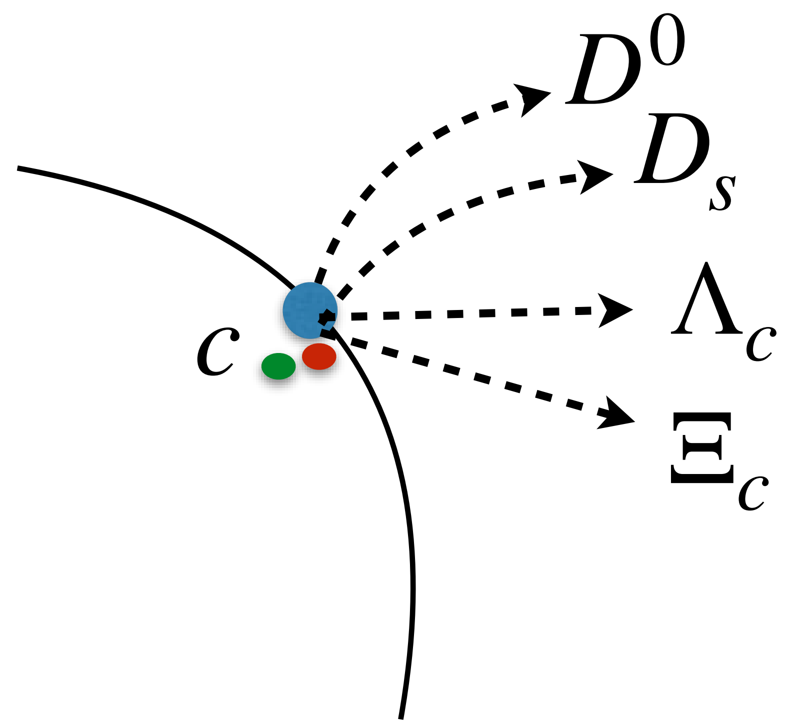


HQ with a given momentom

?

Coalescence → Which HQ hardons?

Fragmentation → Which HQ hardons?



- ➡ Which fragmentation function?
- ➡ How to decide the fragmentation fraction?
- ➡ How to calculate the coalescence probablity?
- ➡ How to decide the coalescence fraction?

EPOS4: heavy quark hadronization

➡ Which fragmentation function?

Works well for e^+e^-, low energy pp,…

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

HeavyQuarkEffectiveTheory-based Fragmentation:

pseudoscalar:

M. Cacciari, P. Nason, and R. Vogt, Phys. Rev. Lett. 95, 122001 (2005), E. Braaten, K.-m. Cheung, S. Fleming, and T. C. Yuan, Phys. Rev. D 51, 4819 (1995).

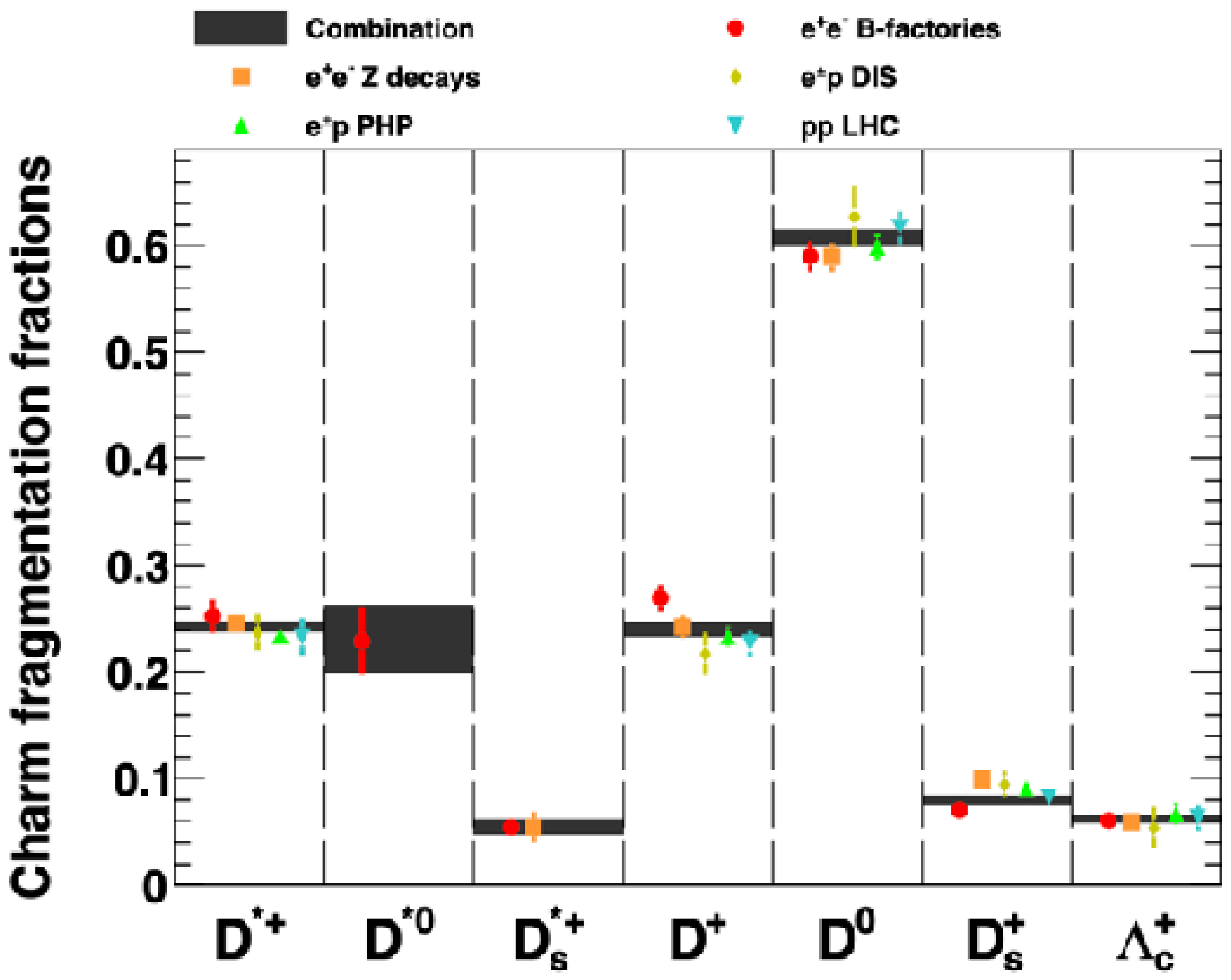
$$\mathscr{D}_{c\to P} \propto \frac{rz(1-z)^2}{[1-(1-r)z]^6}\left[6-18(1-2r)z+(21-74r+68r^2)z^2-2(1-r)(6-19r+18r^2)z^3+3(1-r)^2(1-2r+2r^2)z^4\right]$$

vector meson:

$$\mathscr{D}_{c\to V} \propto \frac{rz(1-z)^2}{[1-(1-r)z]^6}\left[2-2(3-2r)z+3(3-2r+4r^2)z^2-2(1-r)(4-r+2r^2)z^3+3(1-r)^2(3-2r+2r^2)z^4\right]$$

➡ How to decide the fragmentation fraction?

The fragmentation fraction has given by e^+e^-

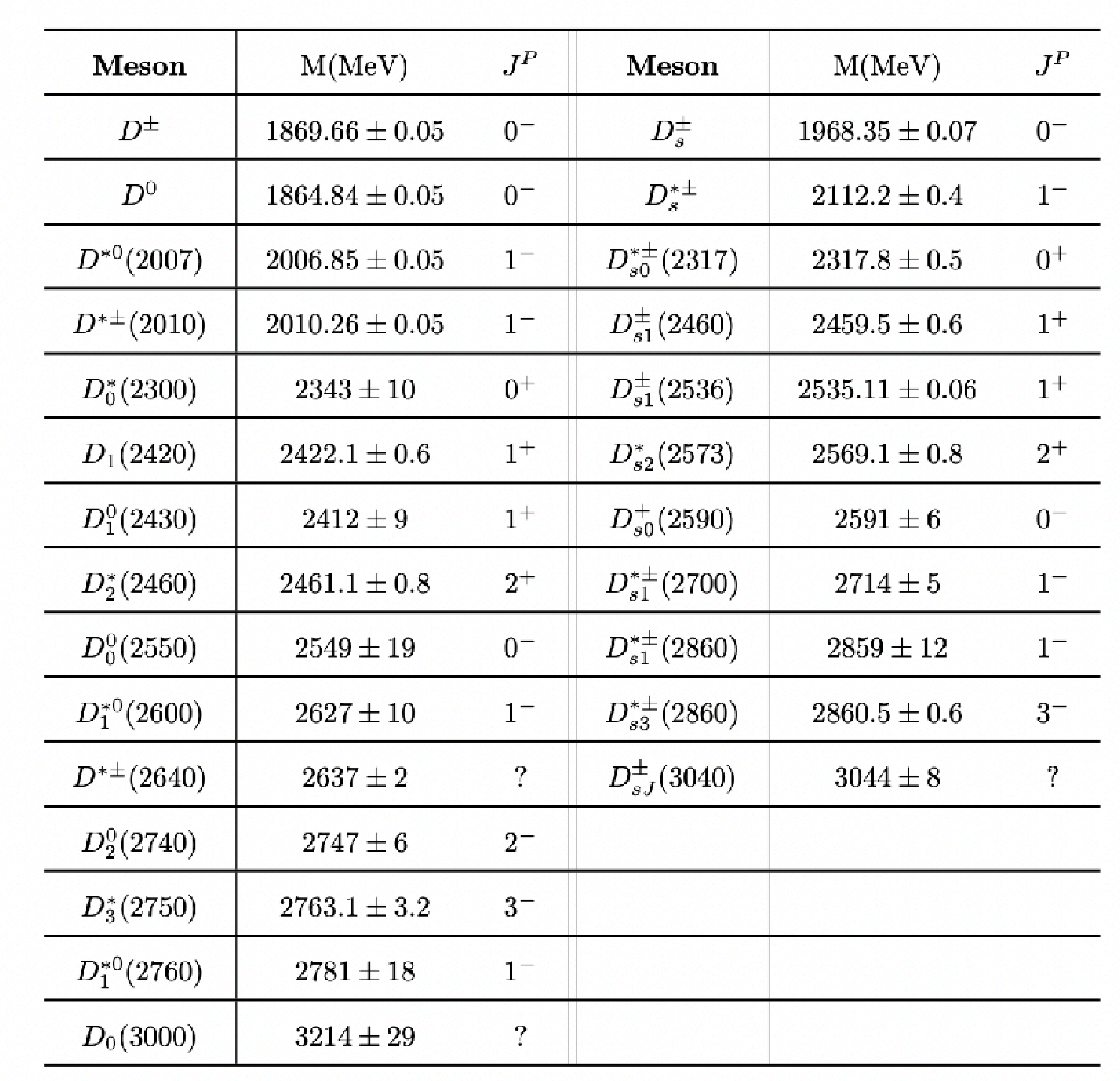


EPOS4: heavy quark hadronization

When the local energy density is lower than the critical value ($T_{\mathrm{FO}} \sim 165$ MeV)

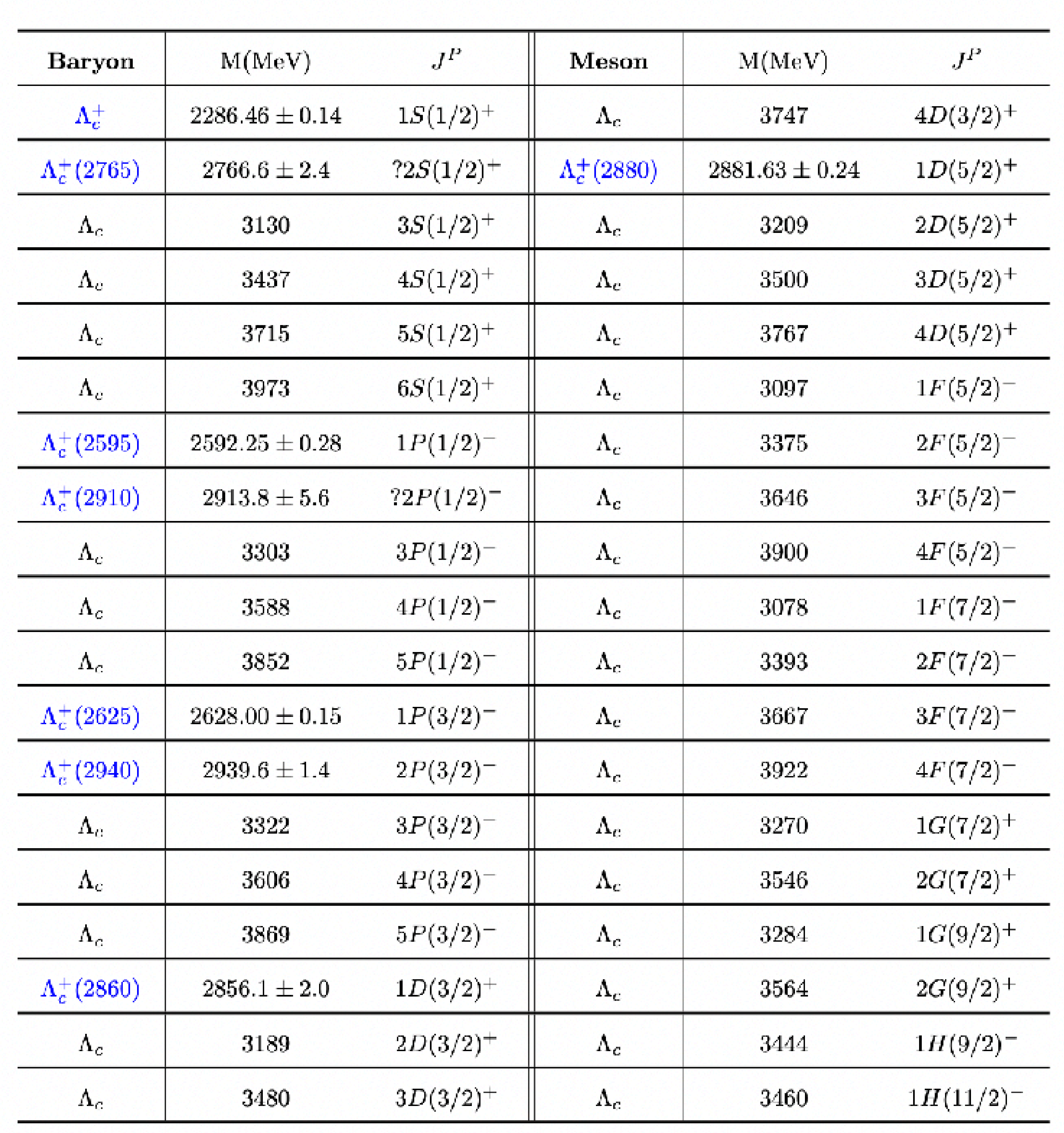
Charmed hadrons from PDG and RQM.

D



Meson	M(MeV)	J^P	Meson	M(MeV)	J^P
$D^\pm$	1869.66 ± 0.05	0^-	$D_s^\pm$	1968.35 ± 0.07	0^-
D^0	1864.84 ± 0.05	0^-	$D_s^{*\pm}$	2112.2 ± 0.4	1^-
$D^{*0}(2007)$	2006.85 ± 0.05	1^-	$D_{s0}^{*\pm}(2317)$	2317.8 ± 0.5	0^+
$D^{*\pm}(2010)$	2010.26 ± 0.05	1^-	$D_{s1}^\pm(2460)$	2459.5 ± 0.6	1^+
$D_0^*(2300)$	2343 ± 10	0^+	$D_{s1}^\pm(2536)$	2535.11 ± 0.06	1^+
$D_1(2420)$	2422.1 ± 0.6	1^+	$D_{s2}^*(2573)$	2569.1 ± 0.8	2^+
$D_1^0(2430)$	2412 ± 9	1^+	$D_{s0}^\pm(2590)$	2591 ± 6	0^-
$D_2^*(2460)$	2461.1 ± 0.8	2^+	$D_{s1}^{*\pm}(2700)$	2714 ± 5	1^-
$D_0^0(2550)$	2549 ± 19	0^-	$D_{s1}^{*\pm}(2860)$	2859 ± 12	1^-
$D_1^{*0}(2600)$	2627 ± 10	1^-	$D_{s3}^{*\pm}(2860)$	2860.5 ± 0.6	3^-
$D^{*\pm}(2640)$	2637 ± 2	?	$D_{sJ}^\pm(3040)$	3044 ± 8	?
$D_2^0(2740)$	2747 ± 6	2^-			
$D_3^*(2750)$	2763.1 ± 3.2	3^-			
$D_1^{*0}(2760)$	2781 ± 18	1^-			
$D_0(3000)$	3214 ± 29	?			

Λ_c



Baryon	M(MeV)	J^P	Meson	M(MeV)	J^P
Λ_c^+	2286.46 ± 0.14	$1S(1/2)^+$	Λ_c	3747	$4D(3/2)^+$
$\Lambda_c^+(2765)$	2766.6 ± 2.4	$?2S(1/2)^+$	$\Lambda_c^+(2880)$	2881.63 ± 0.24	$1D(5/2)^+$
Λ_c	3130	$3S(1/2)^+$	Λ_c	3209	$2D(5/2)^+$
Λ_c	3437	$4S(1/2)^+$	Λ_c	3500	$3D(5/2)^+$
Λ_c	3715	$5S(1/2)^+$	Λ_c	3767	$4D(5/2)^+$
Λ_c	3973	$6S(1/2)^+$	Λ_c	3097	$1F(5/2)^-$
$\Lambda_c^+(2595)$	2592.25 ± 0.28	$1P(1/2)^-$	Λ_c	3375	$2F(5/2)^-$
$\Lambda_c^+(2910)$	2913.8 ± 5.6	$?2P(1/2)^-$	Λ_c	3646	$3F(5/2)^-$
Λ_c	3303	$3P(1/2)^-$	Λ_c	3900	$4F(5/2)^-$
Λ_c	3588	$4P(1/2)^-$	Λ_c	3078	$1F(7/2)^-$
Λ_c	3852	$5P(1/2)^-$	Λ_c	3393	$2F(7/2)^-$
$\Lambda_c^+(2625)$	2628.00 ± 0.15	$1P(3/2)^-$	Λ_c	3667	$3F(7/2)^-$
$\Lambda_c^+(2940)$	2939.6 ± 1.4	$2P(3/2)^-$	Λ_c	3922	$4F(7/2)^-$
Λ_c	3322	$3P(3/2)^-$	Λ_c	3270	$1G(7/2)^+$
Λ_c	3606	$4P(3/2)^-$	Λ_c	3546	$2G(7/2)^+$
Λ_c	3869	$5P(3/2)^-$	Λ_c	3284	$1G(9/2)^+$
$\Lambda_c^+(2860)$	2856.1 ± 2.0	$1D(3/2)^+$	Λ_c	3564	$2G(9/2)^+$
Λ_c	3189	$2D(3/2)^+$	Λ_c	3444	$1H(9/2)^-$
Λ_c	3480	$3D(3/2)^+$	Λ_c	3460	$1H(11/2)^-$

PDG *and D. Ebert, R. Faustov, and V. Galkin, Phys.Rev.D 84 (2011) 014025.*

EPOS4: heavy quark hadronization

When the local energy density is lower than the critical value ($T_{\mathrm{FO}} \sim 165$ MeV)

Charmed hadrons from PDG and RQM.

Σ_c

Baryon	M(MeV)	J^P	Meson	M(MeV)	J^P
Σ_c^{+}	2443.97 ± 0.14	$1S(1/2)^+$	Σ_c	3161	$2P(5/2)^-$
Σ_c	2901	$2S(1/2)^+$	Σ_c	3475	$3P(5/2)^-$
Σ_c	3271	$3S(1/2)^+$	Σ_c	3757	$4P(5/2)^-$
Σ_c	3581	$4S(1/2)^+$	Σ_c	3041	$1D(1/2)^+$
Σ_c	3861	$5S(1/2)^+$	Σ_c	3370	$2D(1/2)^+$
$\Sigma_c(2520)$	2518.41 ± 0.22	$1S(3/2)^+$	Σ_c	3043	$1D(3/2)^+$
Σ_c	2936	$2S(3/2)^+$	Σ_c	3366	$2D(3/2)^+$
Σ_c^{+}	3293	$3S(3/2)^+$	Σ_c	3040	$1D(3/2)^+$
Σ_c	3598	$4S(3/2)^+$	Σ_c	3364	$2D(3/2)^+$
Σ_c	3873	$5S(3/2)^+$	Σ_c	3038	$1D(5/2)^+$
$\Sigma_c(2800)$	2801 ± 5	$1P(1/2)^-$	Σ_c	3365	$2D(5/2)^+$
Σ_c	3172	$2P(1/2)^-$	Σ_c	3023	$1D(5/2)^+$
Σ_c	3488	$3P(1/2)^-$	Σ_c	3349	$2D(5/2)^+$
Σ_c	3770	$4P(1/2)^-$	Σ_c	3013	$1D(7/2)^+$
Σ_c	2713	$1P(1/2)^-$	Σ_c	3342	$2D(7/2)^+$
Σ_c	3125	$2P(1/2)^-$	Σ_c	3288	$1F(3/2)^-$
Σ_c	3455	$3P(1/2)^-$	Σ_c	3283	$1F(5/2)^-$
Σ_c	3743	$4P(1/2)^-$	Σ_c	3254	$1F(5/2)^-$
Σ_c	2798	$1P(3/2)^-$	Σ_c	3253	$1F(7/2)^-$
Σ_c	3172	$2P(3/2)^-$	Σ_c	3227	$1F(7/2)^-$
Σ_c	3486	$3P(3/2)^-$	Σ_c	3209	$1F(9/2)^-$
Σ_c	3768	$4P(3/2)^-$	Σ_c	3495	$1G(5/2)^+$
Σ_c	2773	$1P(3/2)^-$	Σ_c	3483	$1G(7/2)^+$
Σ_c	3151	$2P(3/2)^-$	Σ_c	3444	$1G(7/2)^+$
Σ_c	3469	$3P(3/2)^-$	Σ_c	3442	$1G(9/2)^+$
Σ_c	3753	$4P(3/2)^-$	Σ_c	3410	$1G(9/2)^+$
Σ_c	2789	$1P(5/2)^-$	Σ_c	3386	$1G(11/2)^+$

Ξ_c

Baryon	M(MeV)	J^P	Meson	M(MeV)	J^P
Ξ_c'	2578.2 ± 0.5	$1S(1/2)^+$	Ξ_c	3303	$2P(5/2)^-$
$\Xi_c(2970)$	2964.3 ± 1.5	$2S(1/2)^+$	Ξ_c	3619	$3P(5/2)^-$
Ξ_c	3377	$3S(1/2)^+$	Ξ_c	3902	$4P(5/2)^-$
Ξ_c	3695	$4S(1/2)^+$	Ξ_c	3163	$1D(1/2)^+$
Ξ_c	3978	$5S(1/2)^+$	Ξ_c	3505	$2D(1/2)^+$
$\Xi_c(2645)$	2645.10 ± 0.3	$1S(3/2)^+$	Ξ_c	3167	$1D(3/2)^+$
Ξ_c	3026	$2S(3/2)^+$	Ξ_c	3506	$2D(3/2)^+$
Ξ_c	3396	$3S(3/2)^+$	Ξ_c	3160	$1D(3/2)^+$
Ξ_c	3709	$4S(3/2)^+$	Ξ_c	3497	$2D(3/2)^+$
Ξ_c	3989	$5S(3/2)^+$	Ξ_c	3166	$1D(5/2)^+$
Ξ_c	2936	$1P(1/2)^-$	Ξ_c	3504	$2D(5/2)^+$
Ξ_c	3313	$2P(1/2)^-$	Ξ_c	3153	$1D(5/2)^+$
Ξ_c	3630	$3P(1/2)^-$	Ξ_c	3493	$2D(5/2)^+$
Ξ_c	3912	$4P(1/2)^-$	Ξ_c	3147	$1D(7/2)^+$
Ξ_c	2854	$1P(1/2)^-$	Ξ_c	3486	$2D(7/2)^+$
Ξ_c	3267	$2P(1/2)^-$	Ξ_c	3418	$1F(3/2)^-$
Ξ_c	3598	$3P(1/2)^-$	Ξ_c	3408	$1F(5/2)^-$
Ξ_c	3887	$4P(1/2)^-$	Ξ_c	3394	$1F(5/2)^-$
Ξ_c	2935	$1P(3/2)^-$	Ξ_c	3393	$1F(7/2)^-$
Ξ_c	3311	$2P(3/2)^-$	Ξ_c	3373	$1F(7/2)^-$
Ξ_c	3628	$3P(3/2)^-$	Ξ_c	3357	$1F(9/2)^-$
Ξ_c	3911	$4P(3/2)^-$	Ξ_c	3623	$1G(5/2)^+$
Ξ_c	2912	$1P(3/2)^-$	Ξ_c	3608	$1G(7/2)^+$
Ξ_c	3293	$2P(3/2)^-$	Ξ_c	3584	$1G(7/2)^+$
Ξ_c	3613	$3P(3/2)^-$	Ξ_c	3582	$1G(9/2)^+$
Ξ_c	3898	$4P(3/2)^-$	Ξ_c	3558	$1G(9/2)^+$
Ξ_c	2929	$1P(5/2)^-$	Ξ_c	3536	$1G(11/2)^-$

Baryon	M(MeV)	J^P	Meson	M(MeV)	J^P
Ξ_c	2467.71 ± 0.23	$1S(1/2)^+$	Ξ_c	3945	$4D(3/2)^+$
Ξ_c	2959	$2S(1/2)^+$	Ξ_c	3076	$1D(5/2)^+$
Ξ_c	3323	$3S(1/2)^+$	Ξ_c	3407	$2D(5/2)^+$
Ξ_c	3632	$4S(1/2)^+$	Ξ_c	3699	$3D(5/2)^+$
Ξ_c	3909	$5S(1/2)^+$	Ξ_c	3965	$4D(5/2)^+$
Ξ_c	4166	$6S(1/2)^+$	Ξ_c	3278	$1F(5/2)^-$
$\Xi_c^+(2790)$	2791.9 ± 0.5	$1P(1/2)^-$	Ξ_c	3575	$2F(5/2)^-$
Ξ_c	3179	$2P(1/2)^-$	Ξ_c	3845	$3F(5/2)^-$
Ξ_c	3500	$3P(1/2)^-$	Ξ_c	4098	$4F(5/2)^-$
Ξ_c	3785	$4P(1/2)^-$	Ξ_c	3292	$1F(7/2)^-$
Ξ_c	4048	$5P(1/2)^-$	Ξ_c	3592	$2F(7/2)^-$
$\Xi_c(2815)$	2816.51 ± 0.25	$1P(3/2)^-$	Ξ_c	3865	$3F(7/2)^-$
Ξ_c	3201	$2P(3/2)^-$	Ξ_c	4120	$4F(7/2)^-$
Ξ_c	3519	$3P(3/2)^-$	Ξ_c	3469	$1G(7/2)^+$
Ξ_c	3804	$4P(3/2)^-$	Ξ_c	3745	$2G(7/2)^+$
Ξ_c	4066	$5P(3/2)^-$	Ξ_c	3463	$1G(9/2)^+$
Ξ_c	3059	$1D(3/2)^+$	Ξ_c	3763	$2G(9/2)^+$
Ξ_c	3388	$2D(3/2)^+$	Ξ_c	3643	$1H(9/2)^-$
Ξ_c	3678	$3D(3/2)^+$	Ξ_c	3658	$1H(11/2)^-$

Ω_c

Baryon	M(MeV)	J^P	Meson	M(MeV)	J^P
Ω_c^0	2695.2 ± 1.7	$1S(1/2)^+$	Ω_c	3427	$2P(5/2)^-$
$\Omega_c^0(2770)$	3088	$2S(1/2)^+$	$\Omega_c^+(2880)$	3744	$3P(5/2)^-$
Ω_c	3489	$3S(1/2)^+$	Ω_c	4028	$4P(5/2)^-$
Ω_c	3814	$4S(1/2)^+$	Ω_c	3287	$1D(1/2)^+$
Ω_c	4102	$5S(1/2)^+$	Ω_c	3623	$2D(1/2)^+$
$\Omega_c^0(2770)$	2765.9 ± 2	$1S(3/2)^+$	Ω_c	3298	$1D(3/2)^+$
Ω_c	3123	$2S(3/2)^+$	Ω_c	3627	$2D(3/2)^+$
Ω_c	3510	$3S(3/2)^+$	Ω_c	3282	$1D(3/2)^+$
Ω_c	3830	$4S(3/2)^+$	Ω_c	3613	$2D(3/2)^+$
Ω_c	4114	$5S(3/2)^+$	Ω_c	3297	$1D(5/2)^+$
$\Omega_c^0(3000)$	3000.46 ± 0.25	$?1P(1/2)^-$	Ω_c	3626	$2D(5/2)^+$
Ω_c	3435	$2P(1/2)^-$	Ω_c	3283	$1D(5/2)^+$
Ω_c	3754	$3P(1/2)^-$	Ω_c	3614	$2D(5/2)^+$
Ω_c	4037	$4P(1/2)^-$	Ω_c	3283	$1D(7/2)^+$
Ω_c	2966	$1P(1/2)^-$	Ω_c	3611	$2D(7/2)^+$
Ω_c	3384	$2P(1/2)^-$	Ω_c	3533	$1F(3/2)^-$
Ω_c	3717	$3P(1/2)^-$	Ω_c	3522	$1F(5/2)^-$
Ω_c	4009	$4P(1/2)^-$	Ω_c	3515	$1F(5/2)^-$
Ω_c	3054	$1P(3/2)^-$	Ω_c	3514	$1F(7/2)^-$
Ω_c	3433	$2P(3/2)^-$	Ω_c	3498	$1F(7/2)^-$
Ω_c	3752	$3P(3/2)^-$	Ω_c	3485	$1F(9/2)^-$
Ω_c	4036	$4P(3/2)^-$	Ω_c	3739	$1G(5/2)^+$
Ω_c	3029	$1P(3/2)^-$	Ω_c	3721	$1G(7/2)^+$
Ω_c	3415	$2P(3/2)^-$	Ω_c	3707	$1G(7/2)^+$
Ω_c	3737	$3P(3/2)^-$	Ω_c	3705	$1G(9/2)^+$
Ω_c	4023	$4P(3/2)^-$	Ω_c	3685	$1G(9/2)^+$
Ω_c	3051	$1P(5/2)^-$	Ω_c	3665	$1G(11/2)^+$

EPOS4: heavy quark hadronization

➡ How to calculate the coalescence probablity?

Ground states Wigner density:

$$W(r,p) = \int d^4 y e^{-ipy} \psi(r+\frac{y}{2})\psi(r-\frac{y}{2})$$

Wavefunction

$$W(p_r) \ = \ (2\sqrt{\pi}\sigma)^3 e^{-\sigma^2 p_r{}^2}$$

Width is given by the potential model $\langle r^2 \rangle \ = \ \frac{3}{2}\frac{m_c^2+m_q^2}{(m_c+m_q)^2}\sigma^2$

$$\frac{dN}{d^3\mathbf{P}} = g_H \sum_{N_Q} \int \prod_{i=1}^{k} \frac{d^3 p_i}{(2\pi)^3} f(\mathbf{p}_i) W_H(\mathbf{p}_1, \ldots, \mathbf{p}_i)\, \delta^{(3)}\left(\mathbf{P} - \sum_{i=1}^{N} \mathbf{p}_i\right),$$

thermal light quark distribution

Excited states are involed via the thermal ratio:

$$n_i = \frac{g_i}{2\pi^2} T_{\rm FO} m_i^2 K_2\left(\frac{m_i}{T_{\rm FO}}\right)$$

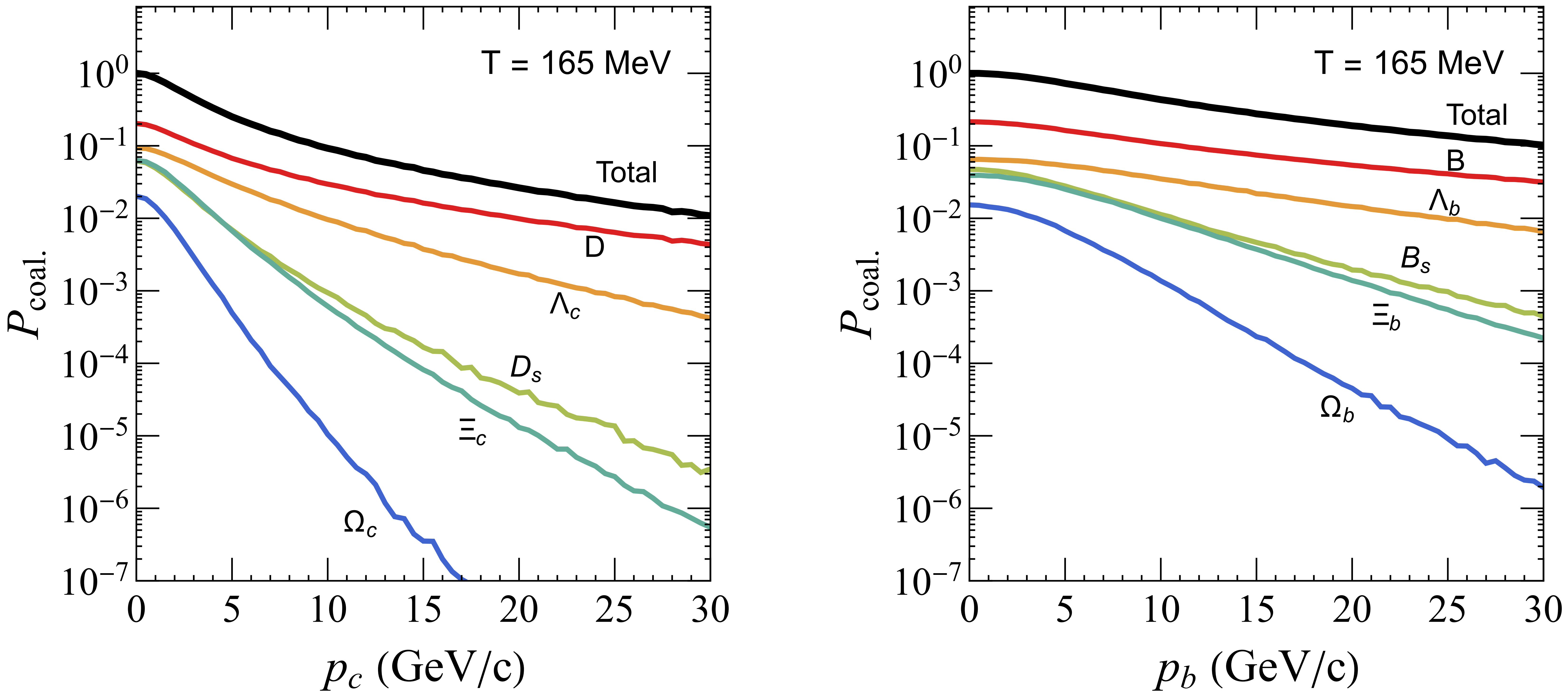
$$R^i = n^i_{\rm excited}/n_{\rm ground} \qquad P^i(p) = R^i \times P_{\rm ground}(p)$$

➡ How to decide the coalescence fraction?

Sample a random number and choose the hadron to coalescence based on their coalescence probability.

EPOS4: heavy quark hadronization

We include almost all hadrons (missing baryons predicted by the potential model; except the rare HF hadrons)

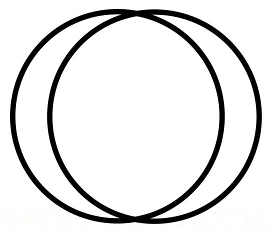


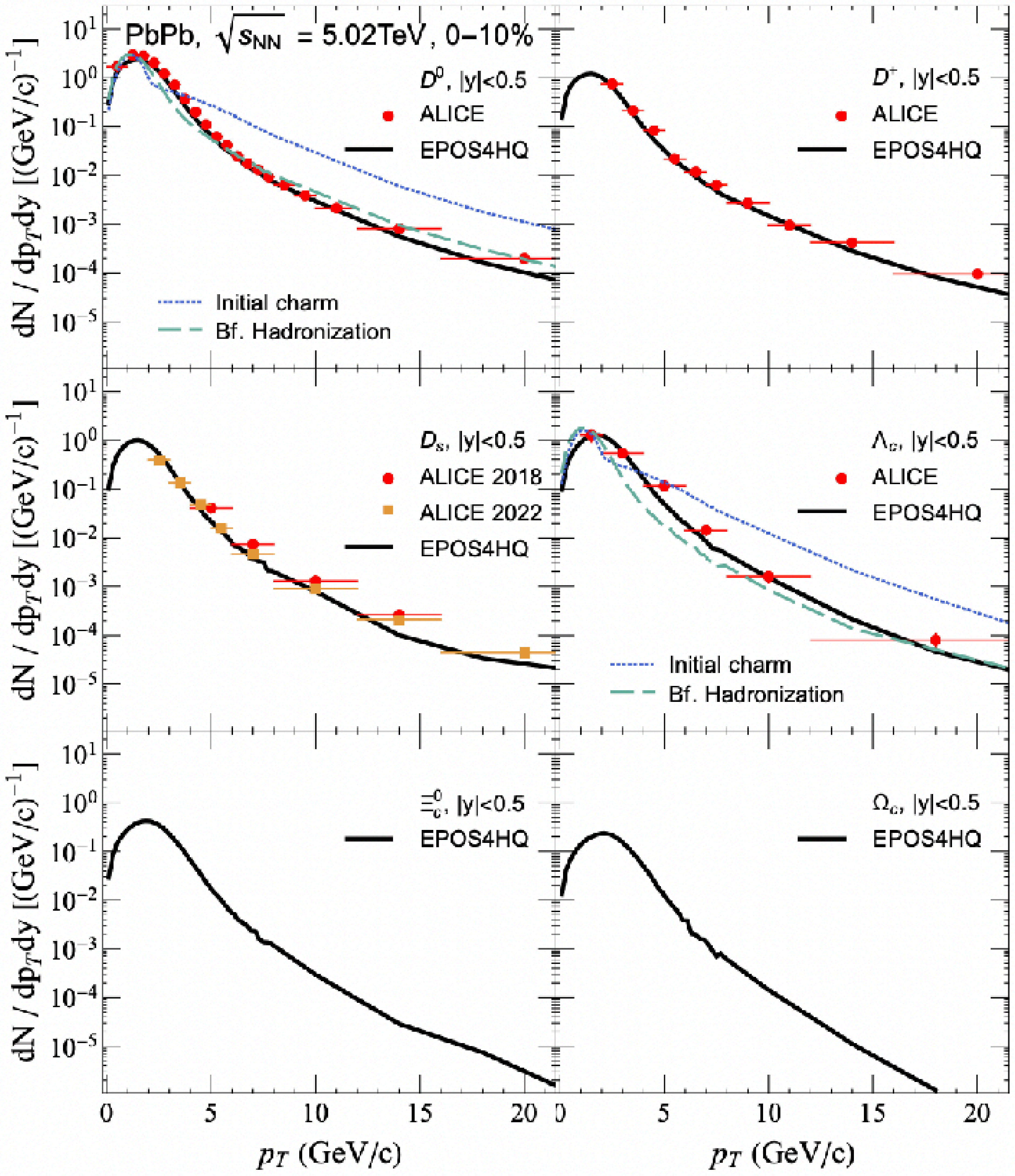
$1 - P_{\mathrm{coal.}}$ for fragmentation

After hadronization, evolution in hadronic phase -> UrQMD

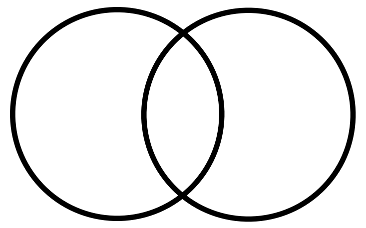
EPOS4: @ Large system (AA)

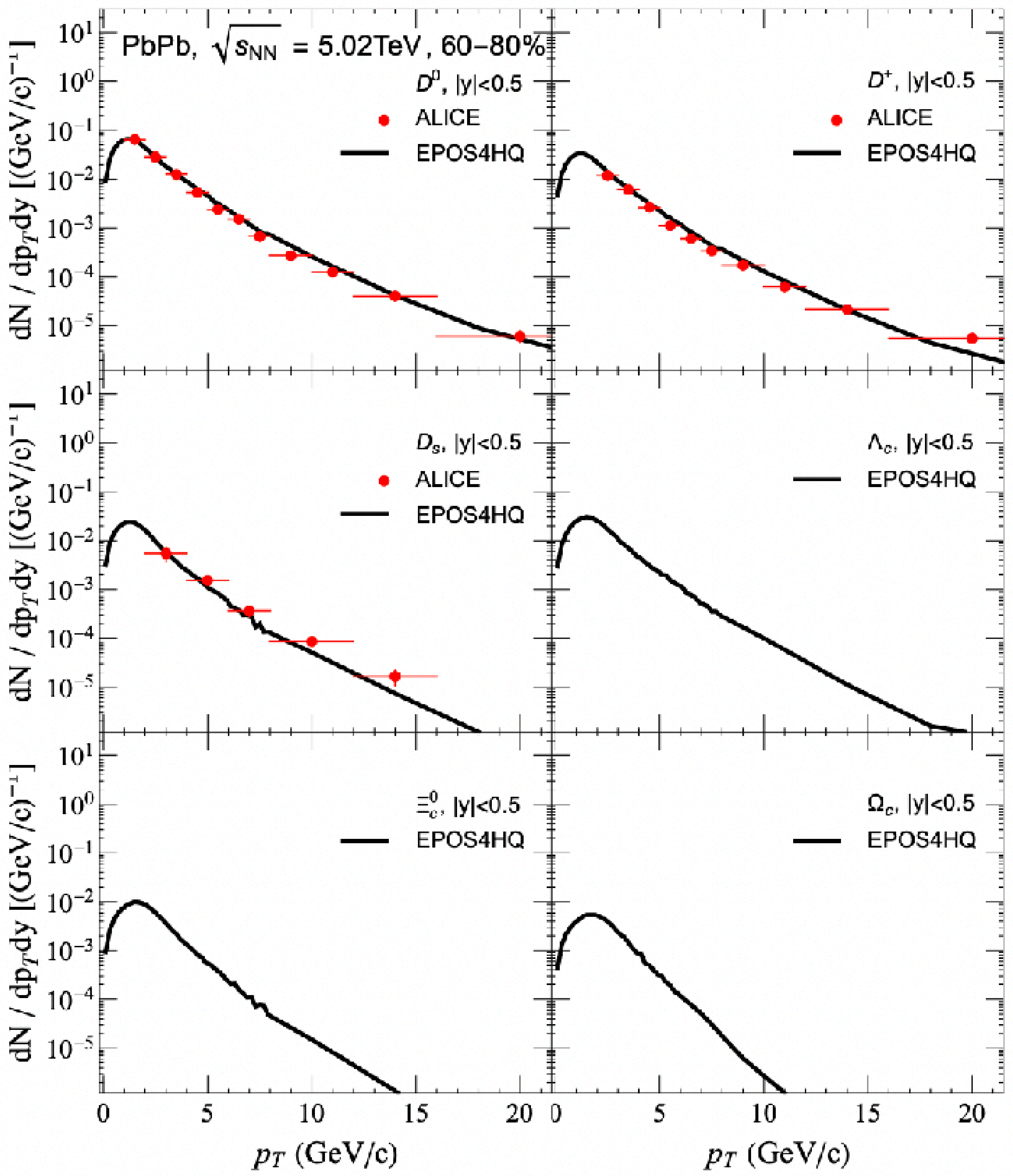
Central collisions





Peripheral collisions





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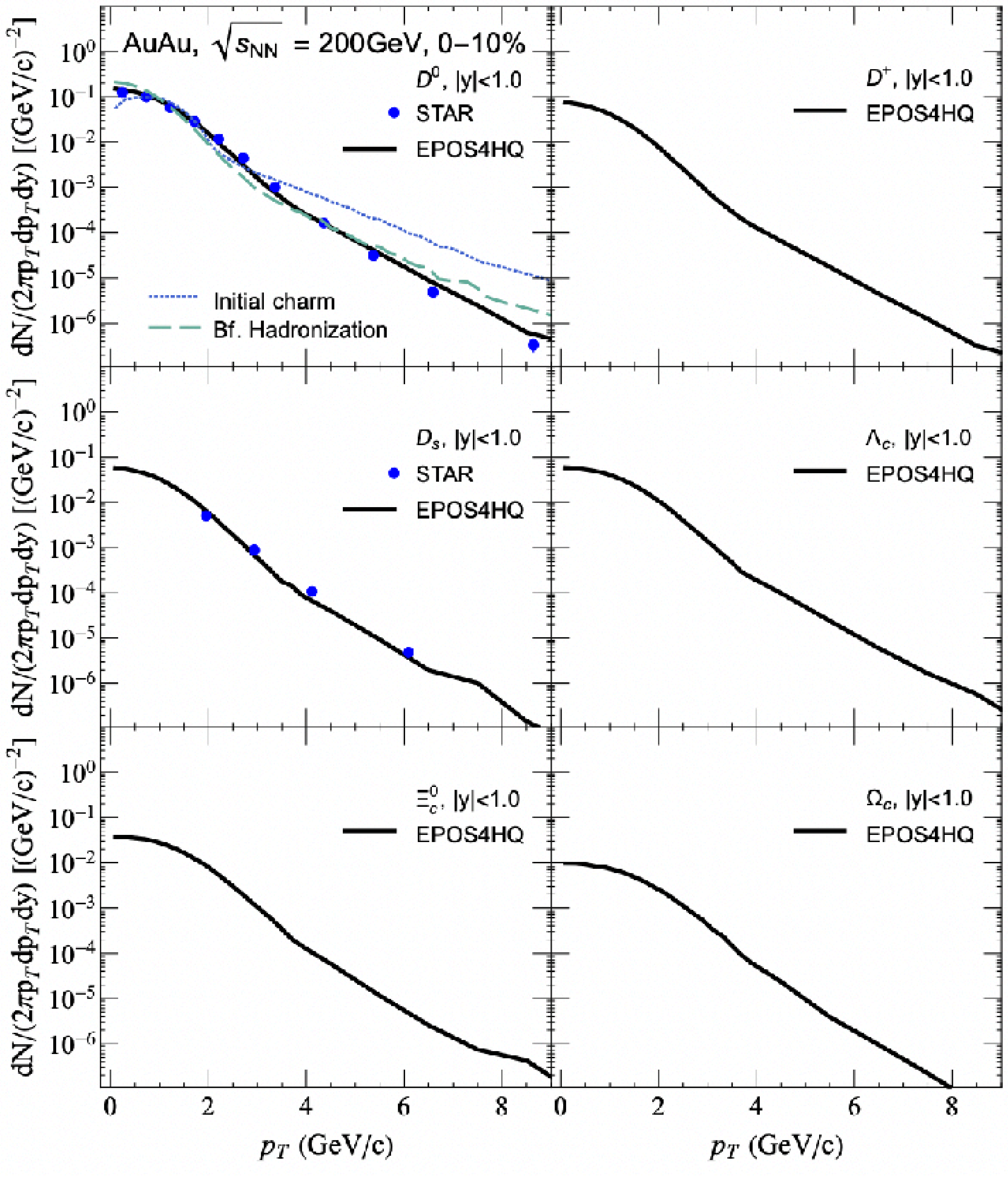
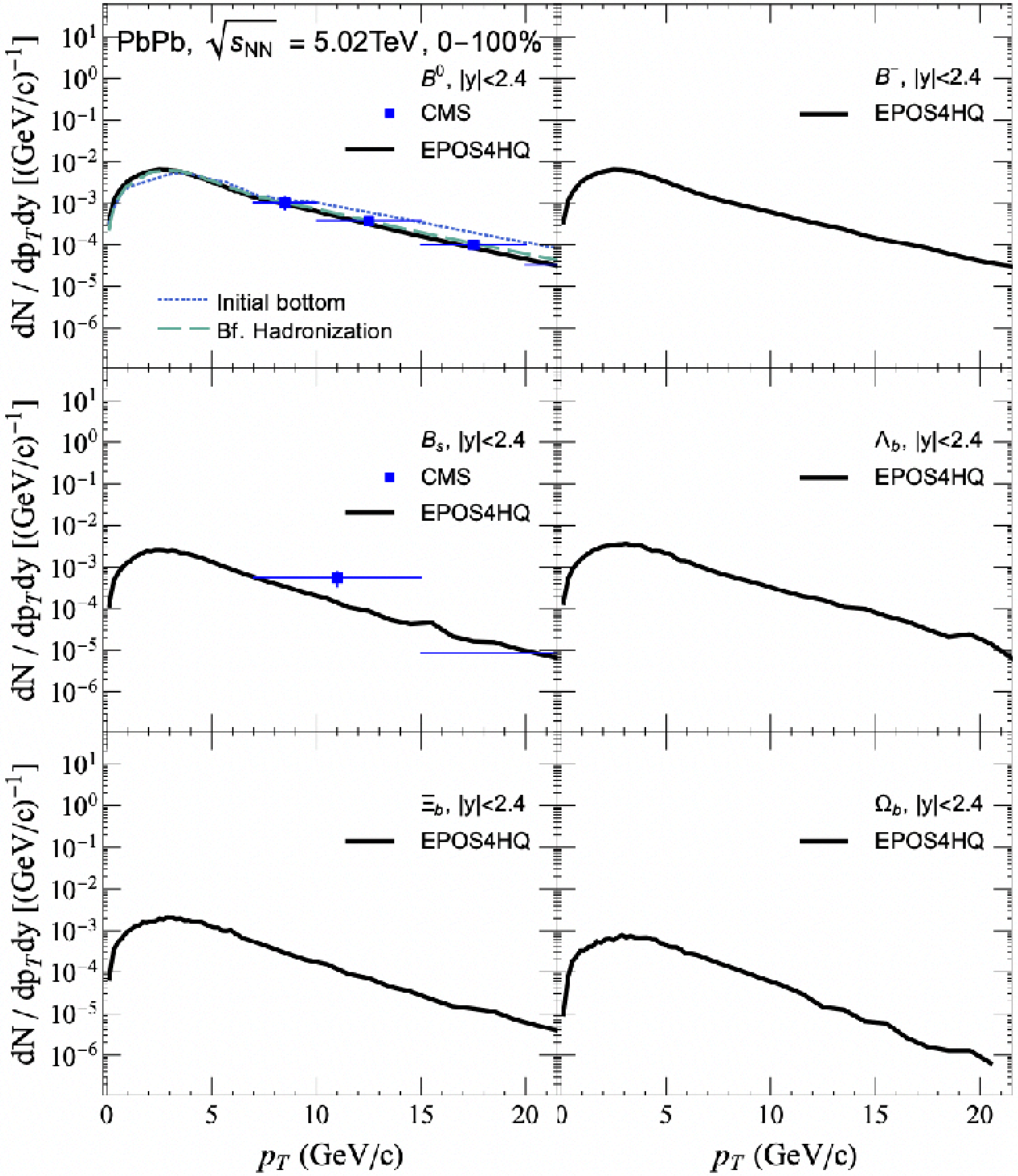
EPOS4: @ Large system (AA)

RHIC energy



Bottom sector



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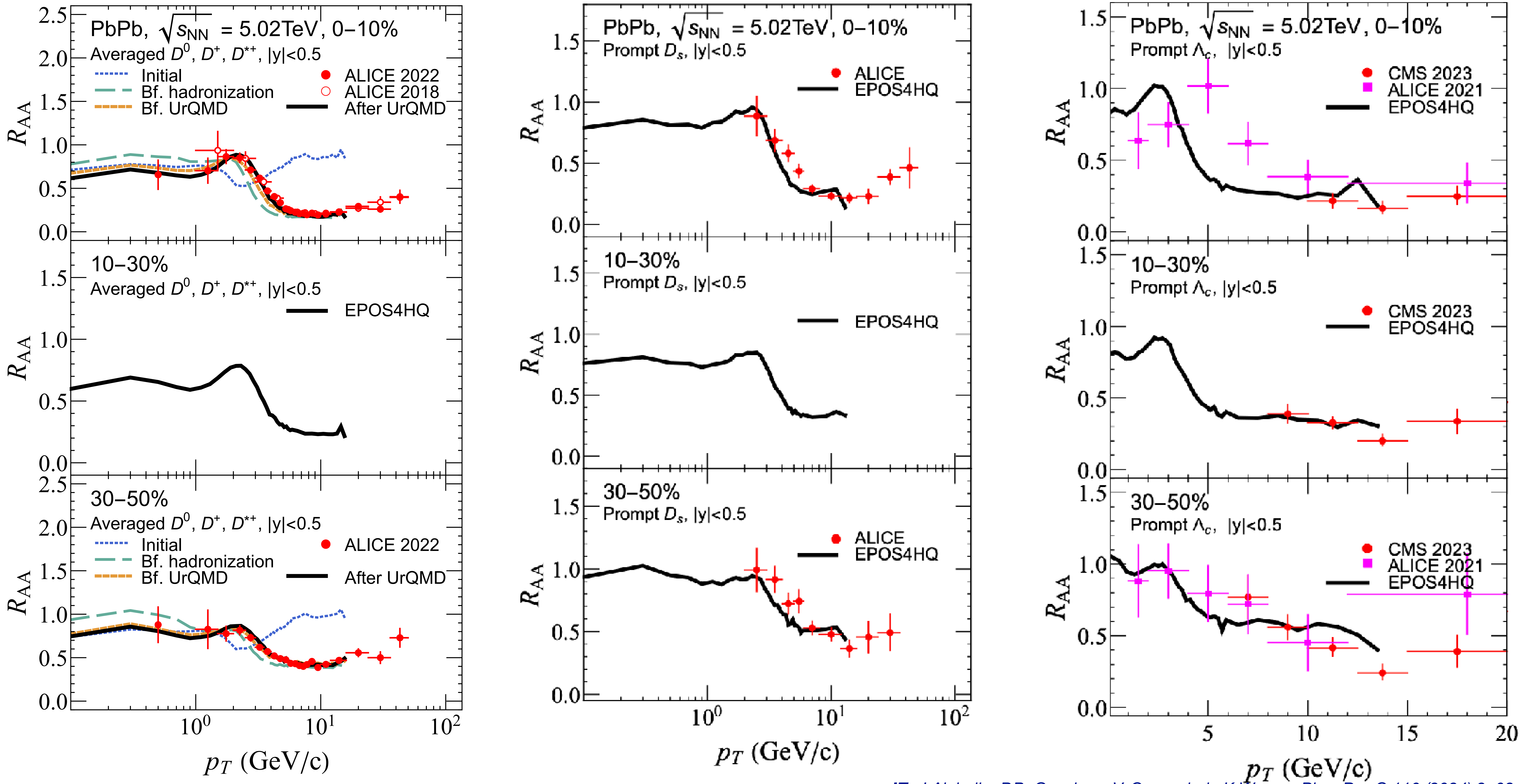
EPOS4: @ Large system (AA)

$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{\mathrm{coll}}\ dN^{pp}/dp_T}$$



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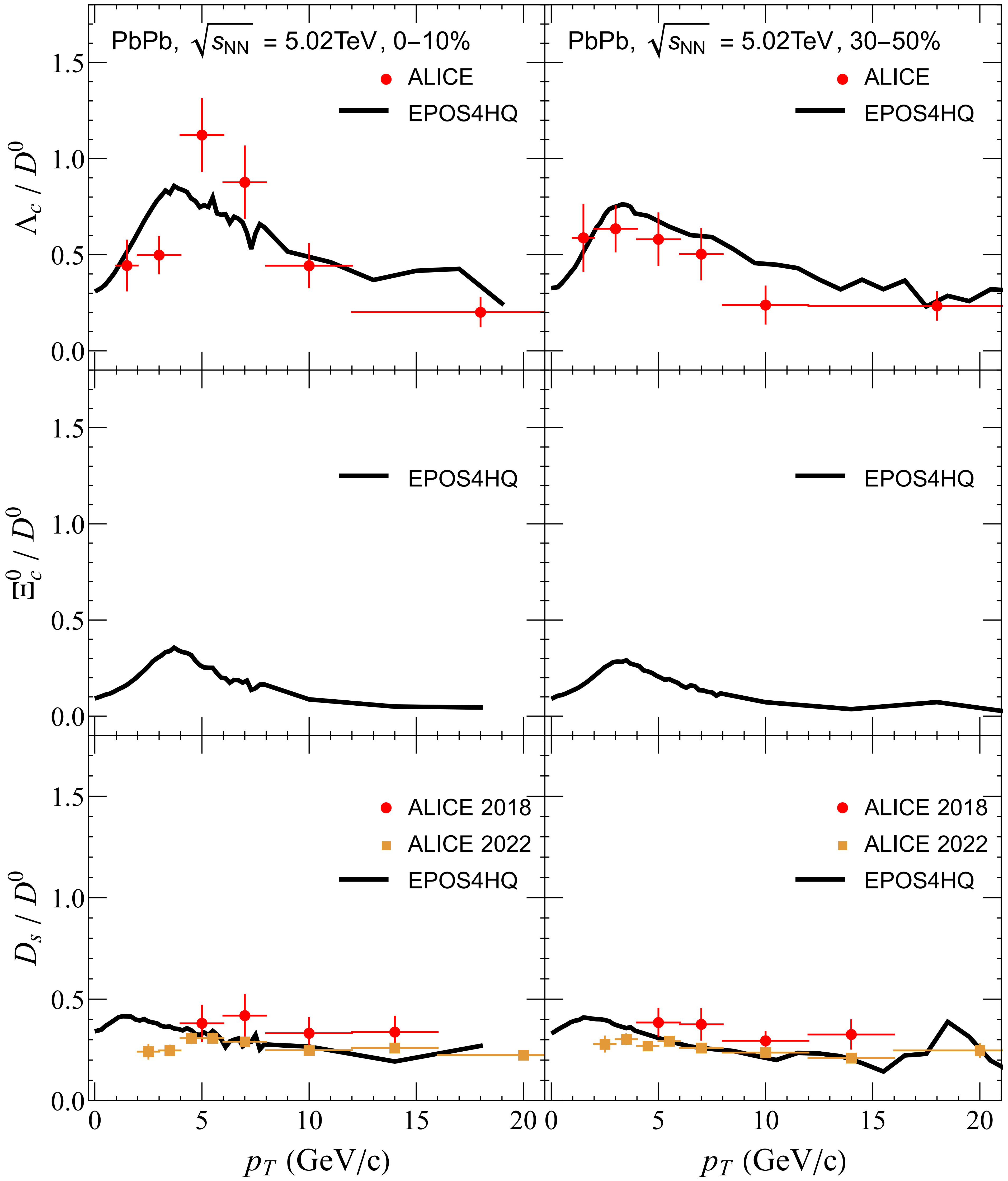
EPOS4: @ Large system (AA)

Yield ratios



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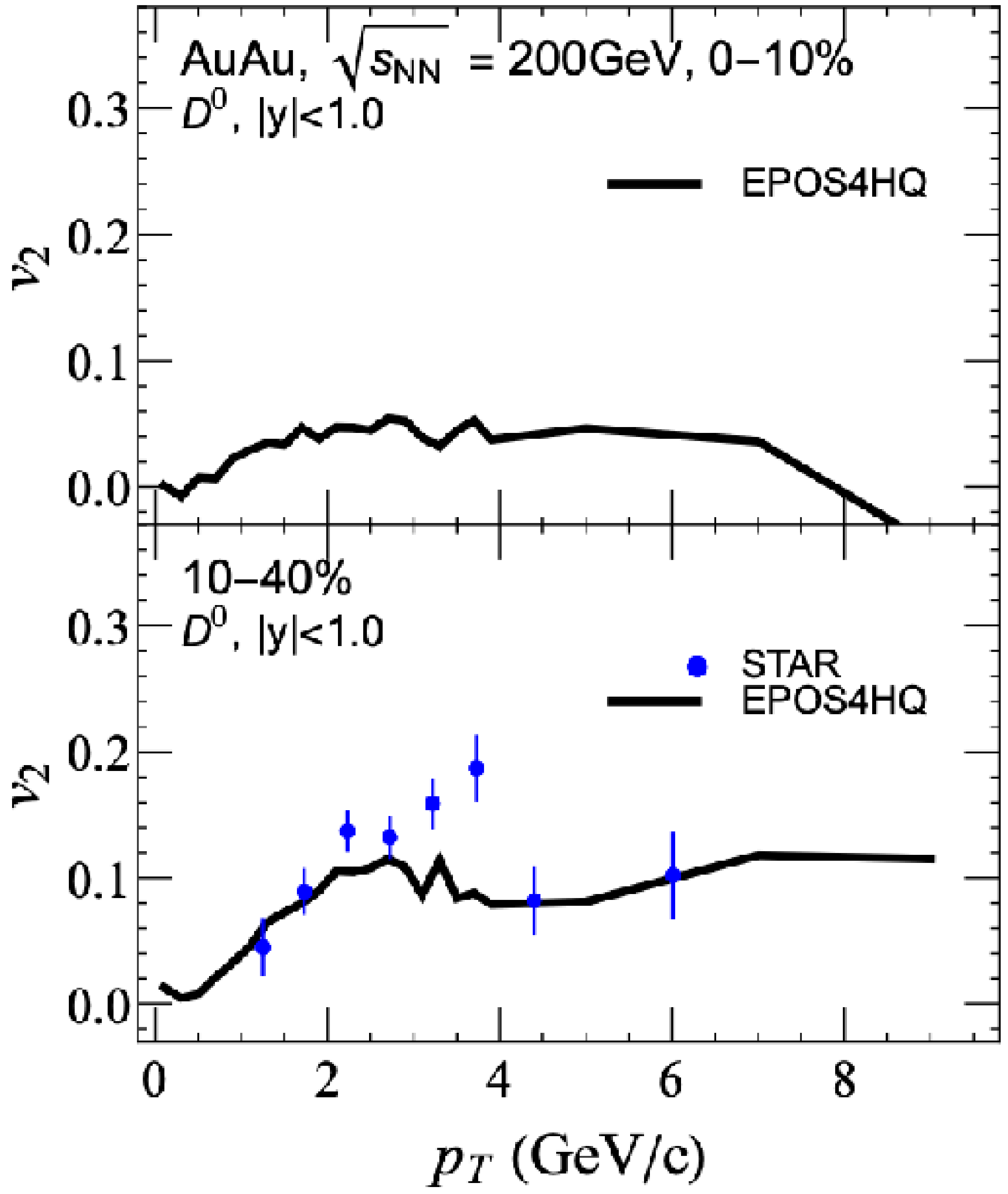
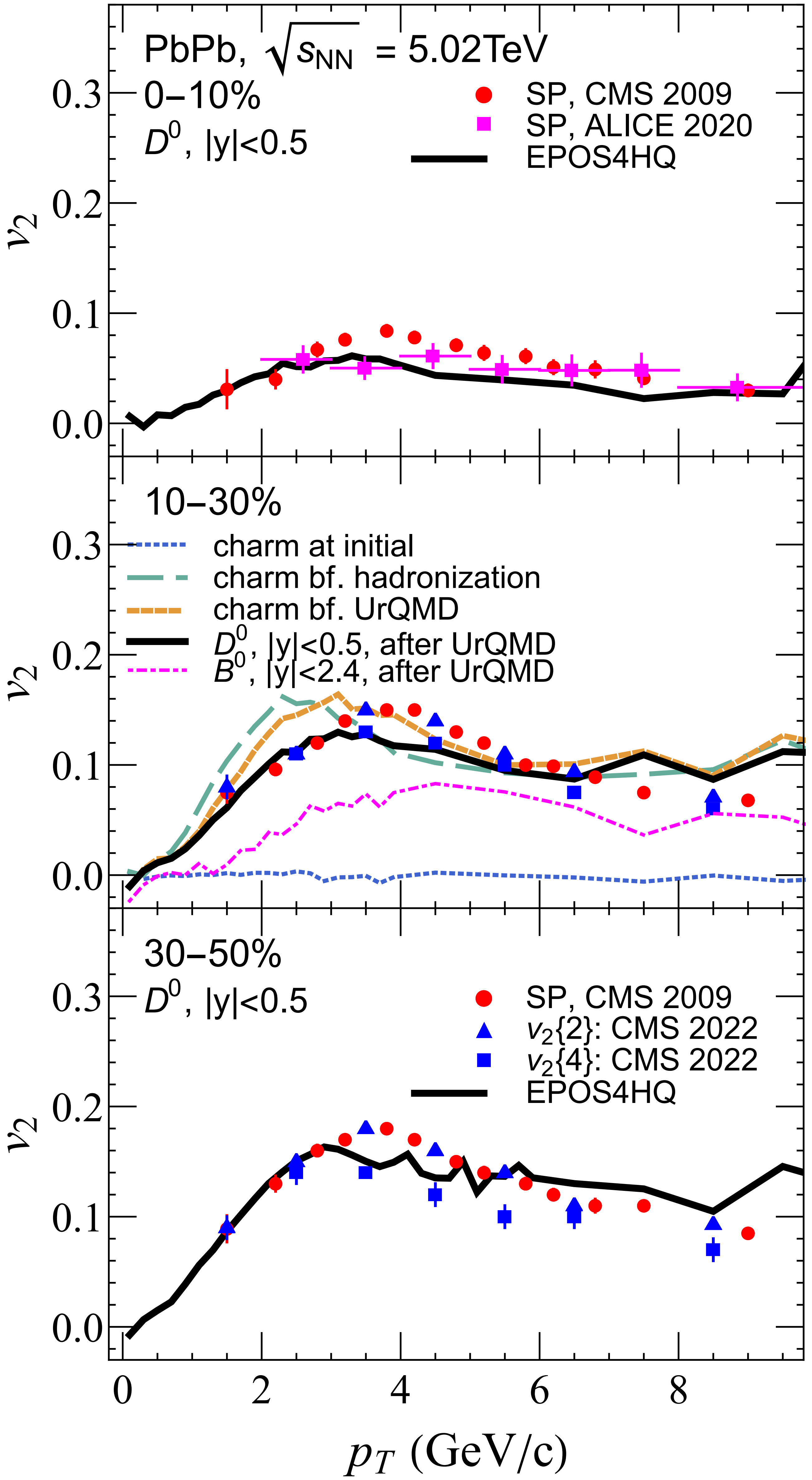
EPOS4: @ Large system (AA)

$v_2 = < \cos[2(\phi - \Psi_2)] >$
or $v_2\{2\}, v_2\{4\}$





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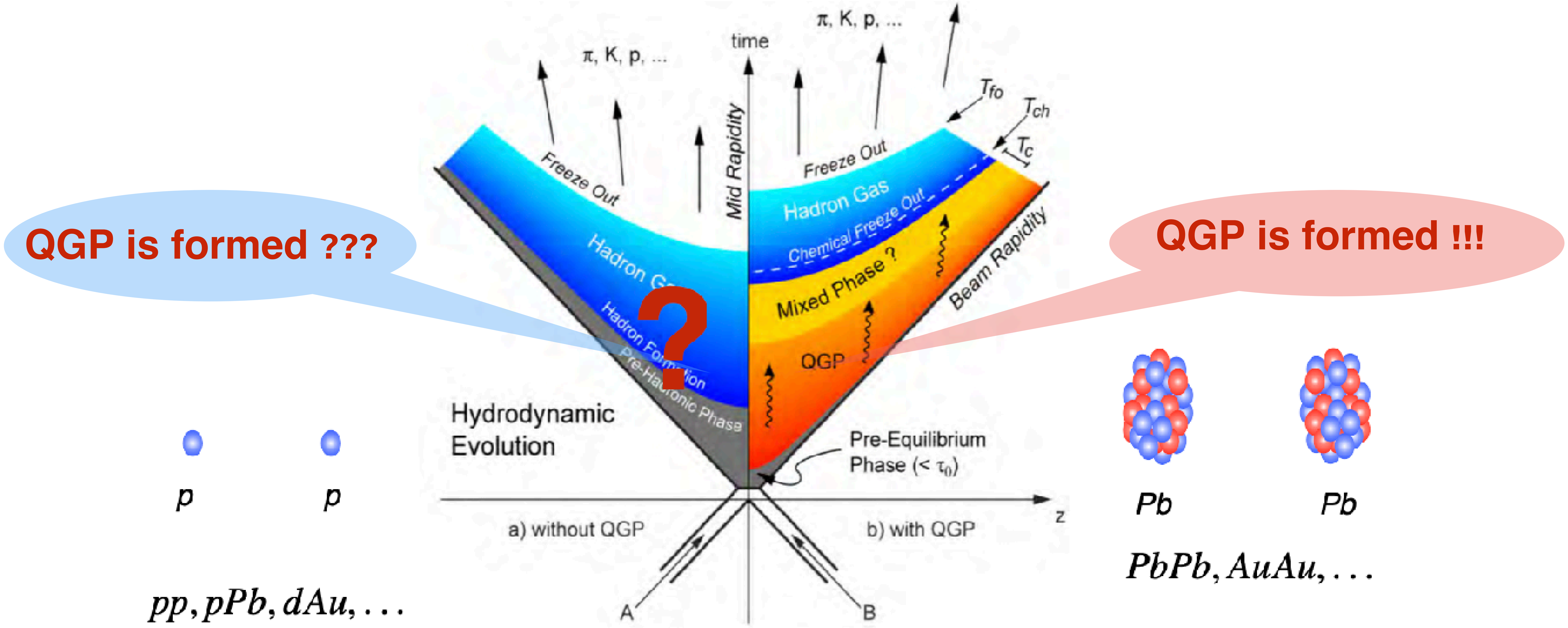
Outline

- Introduction of the heavy flavor probes
- Heavy flavor production in heavy-ion collisions in EPOS4
- **Heavy flavor production in p-p collisions in EPOS4**
- System size dependence of energy loss and correlations
- Summary

proton-proton vs. heavy ion collisions



QGP is formed ???

$pp, pPb, dAu, \ldots$

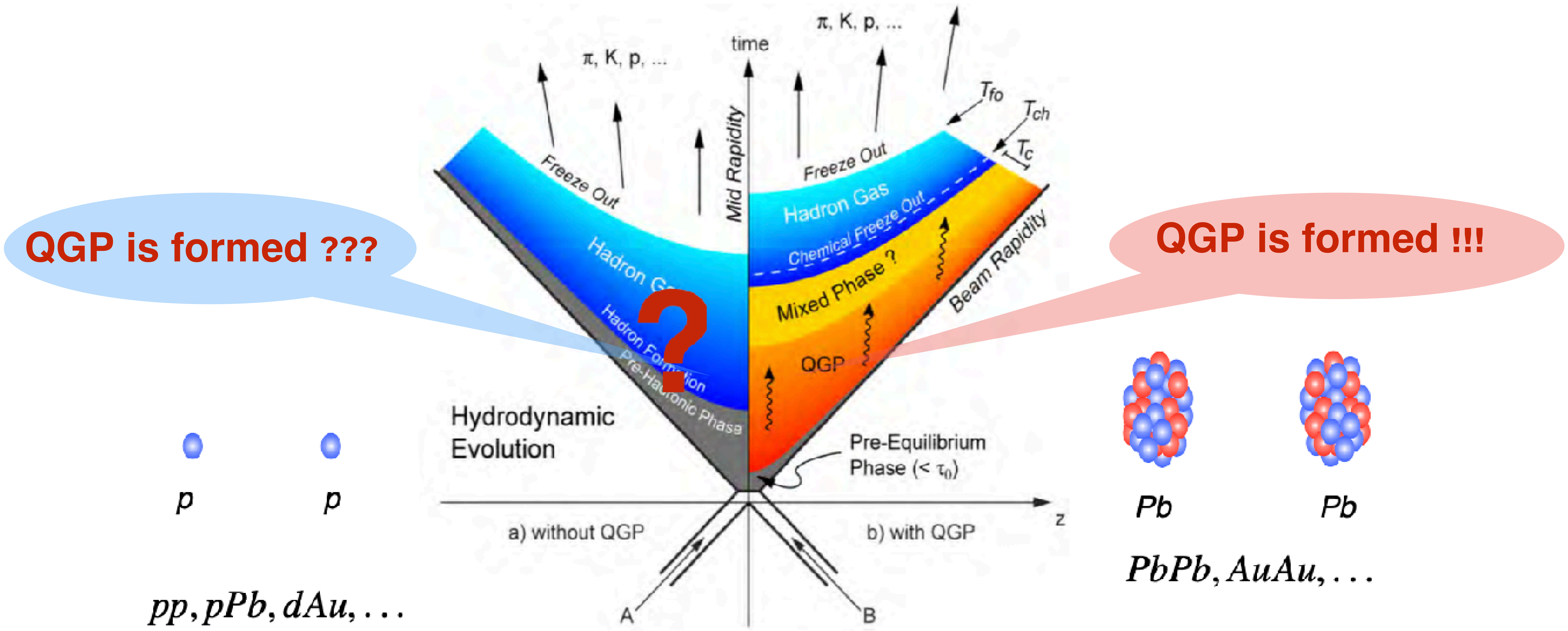
QGP is formed !!!

$PbPb, AuAu, \ldots$

1. Quarkonium suppression
2. Quark number scaling law of the elliptical flow
3. Jet quenching

…

proton-proton vs. heavy ion collisions



1. Long-range two-particle correlation

   Long-range correlations (near-side «ridge») in high-multiplicity pp collisions. -> collectivity in small systems

2. Strangeness enhancement

   Smooth transition with multiplicity from small to large system.

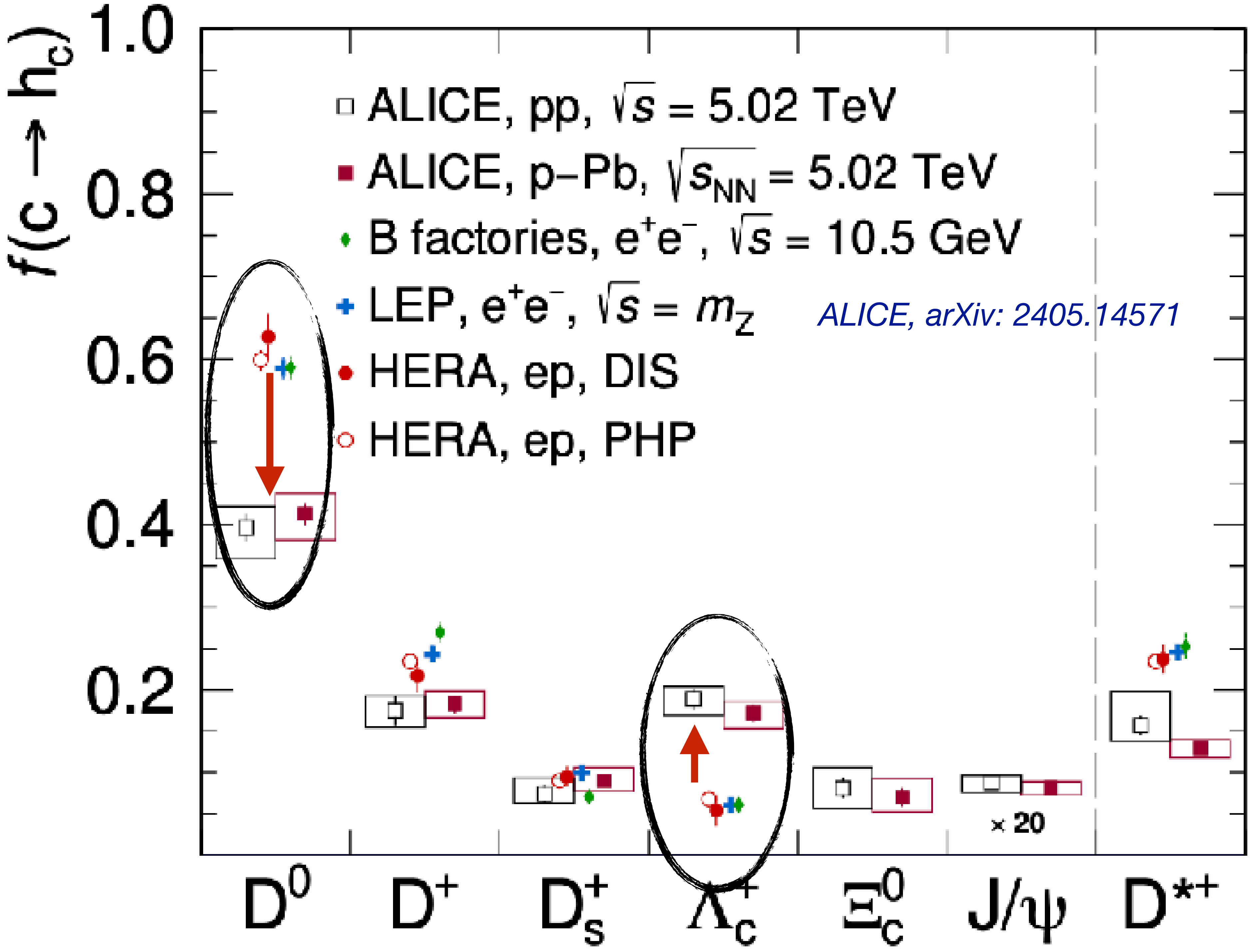
3. Baryon / meson ratio ($\Lambda/K, p/\pi$,..)

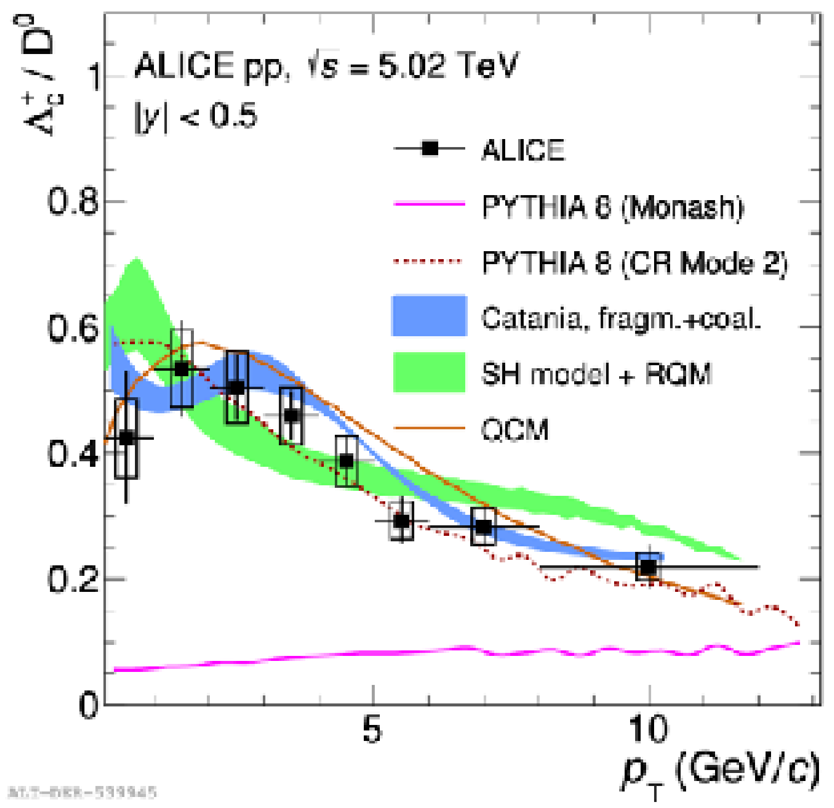
   Hadronization mechanism may be changed in high-multiplicity pp collisions and same as the AA collsions.

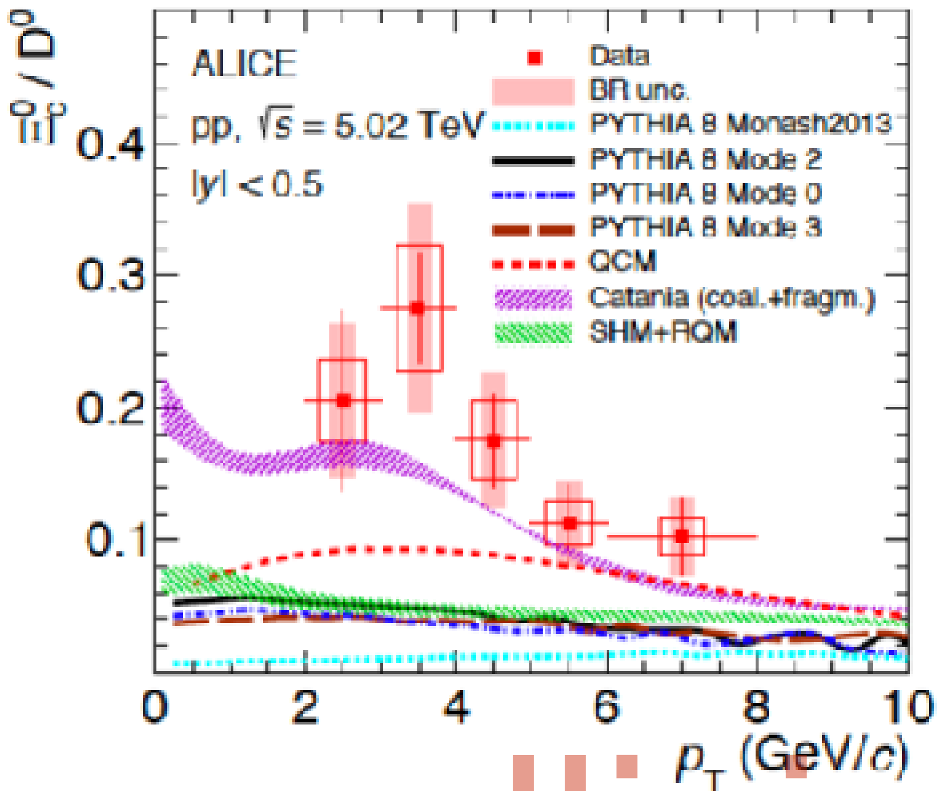
1. Quarkonium suppression
2. Quark number scaling law of the elliptical flow
3. Jet quenching

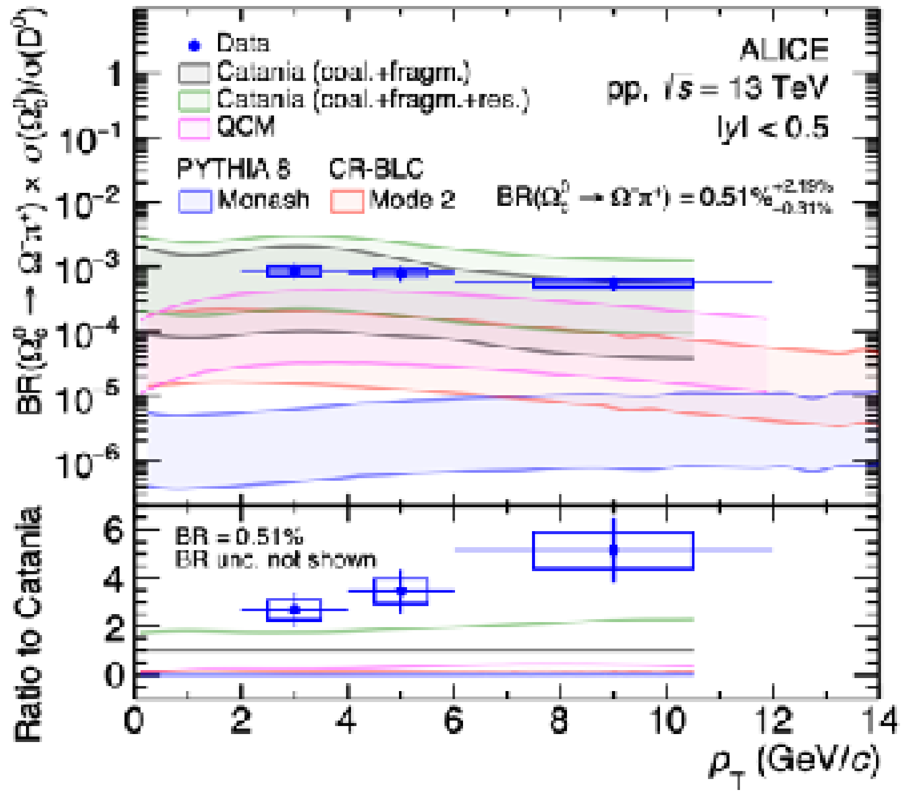
…

Heavy flavor in small system

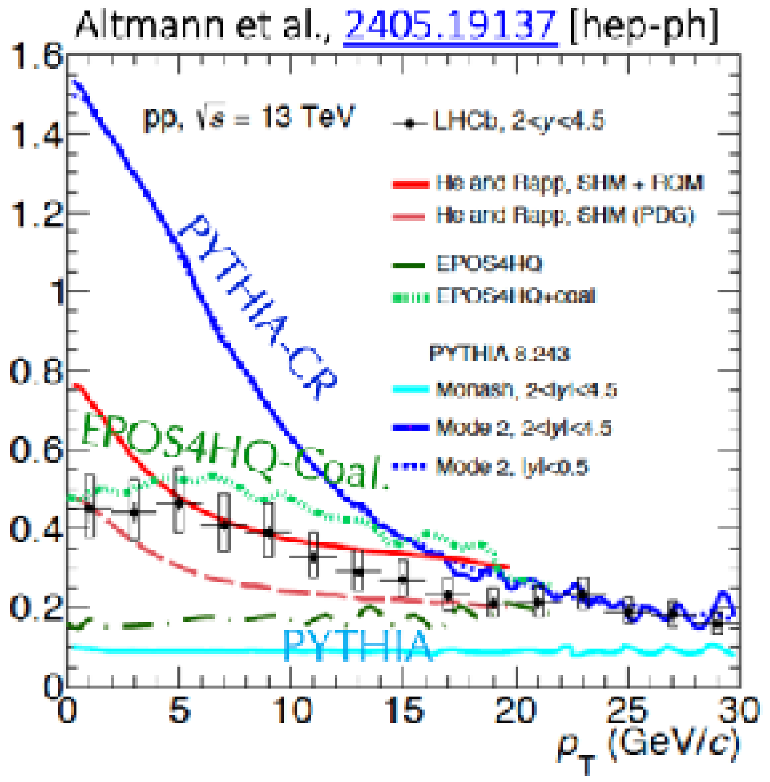


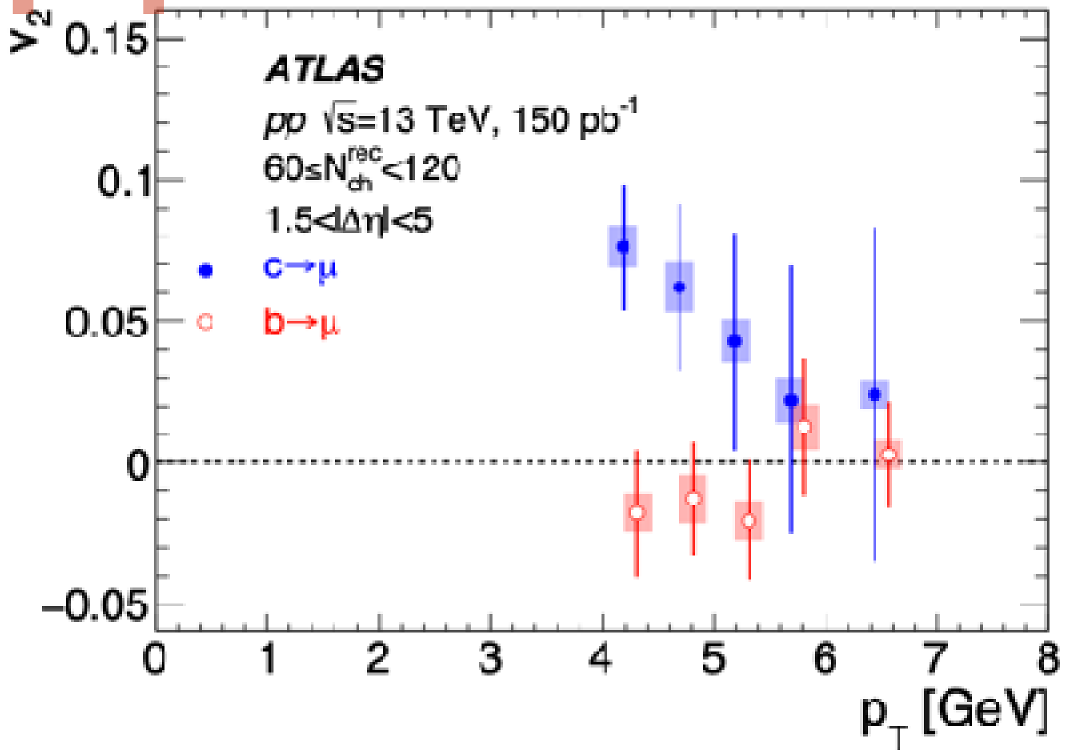


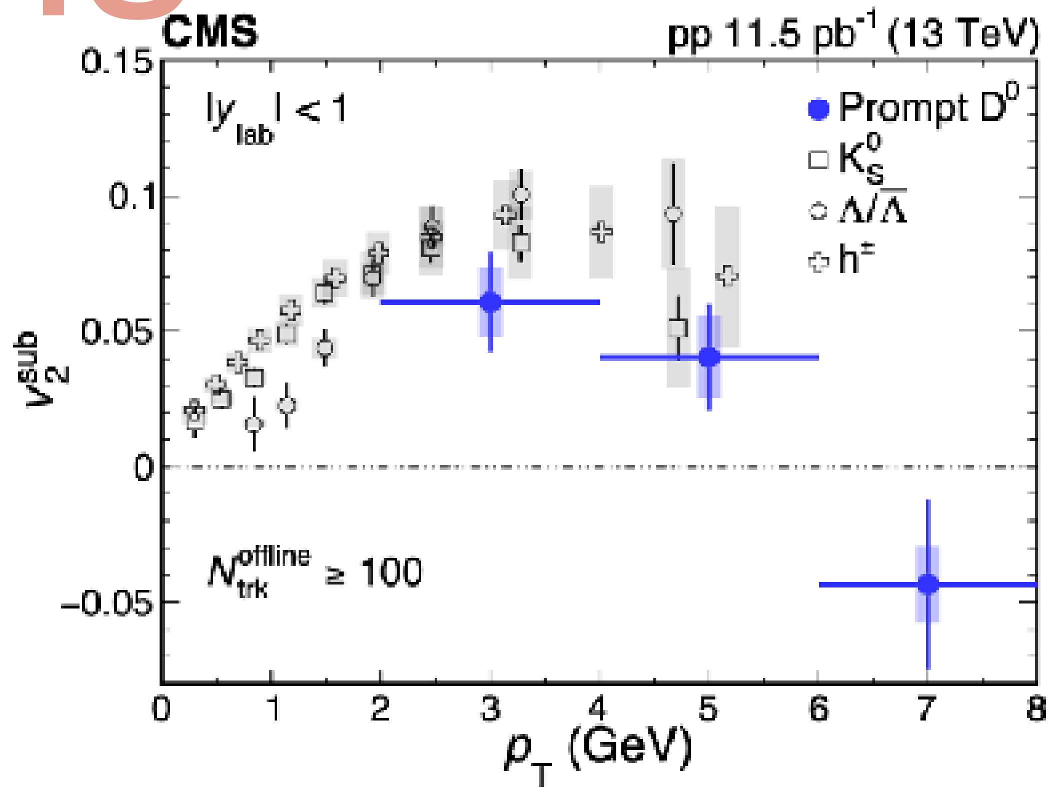




pp collisions



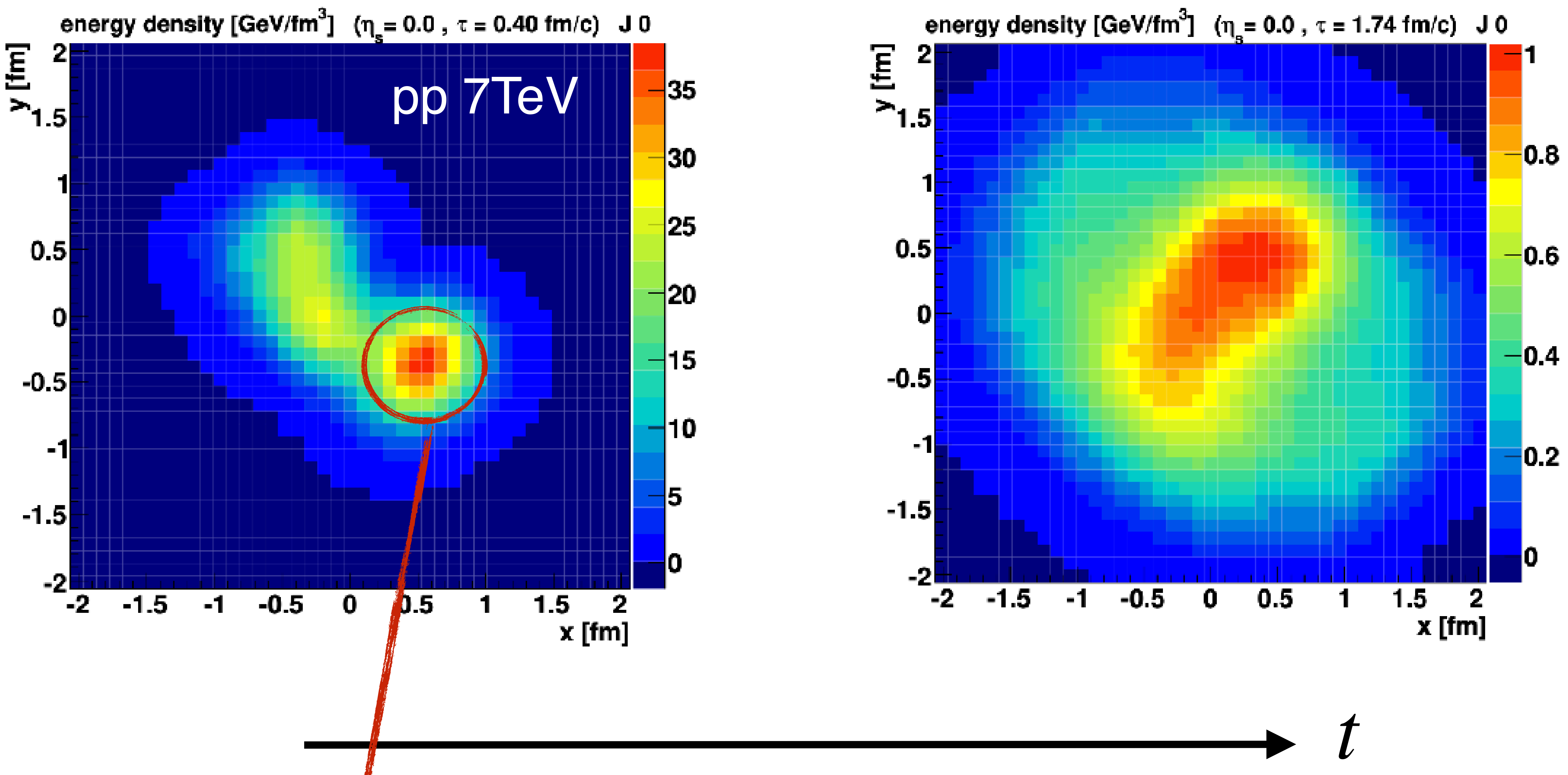




Evidence of different “Fragmentation” Fractions in pp (pPb) at LHC wrt e^+e^- collisions but similar to HICs !

The large Λ_c/D^0, Σ_c/D^0, Ξ_c/D^0,Λ_b/B^0, and v_2 of D indicate a small QGP may be formed.

core-corona picture



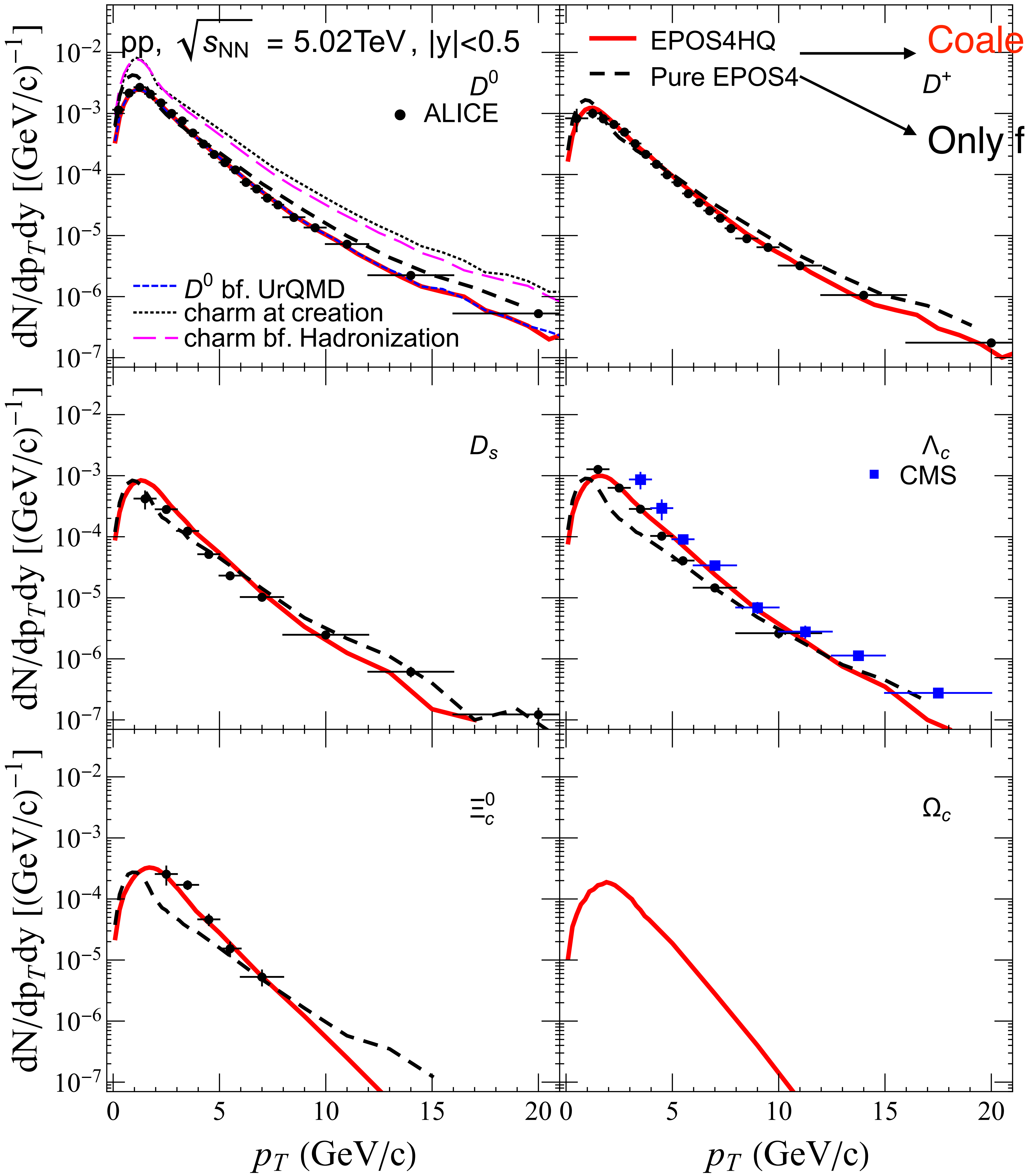
The energy density is larger than the critical energy density ϵ_0 –> deconfined QCD matter!

--> A small QGP is created and its evolution can still be described by the hydrodynamics!

EPOS4: @ small system (pp)

Charm sector

JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, Phys.Rev.D 109 (2024) 5, 054011*



Coalescence+fragmentation

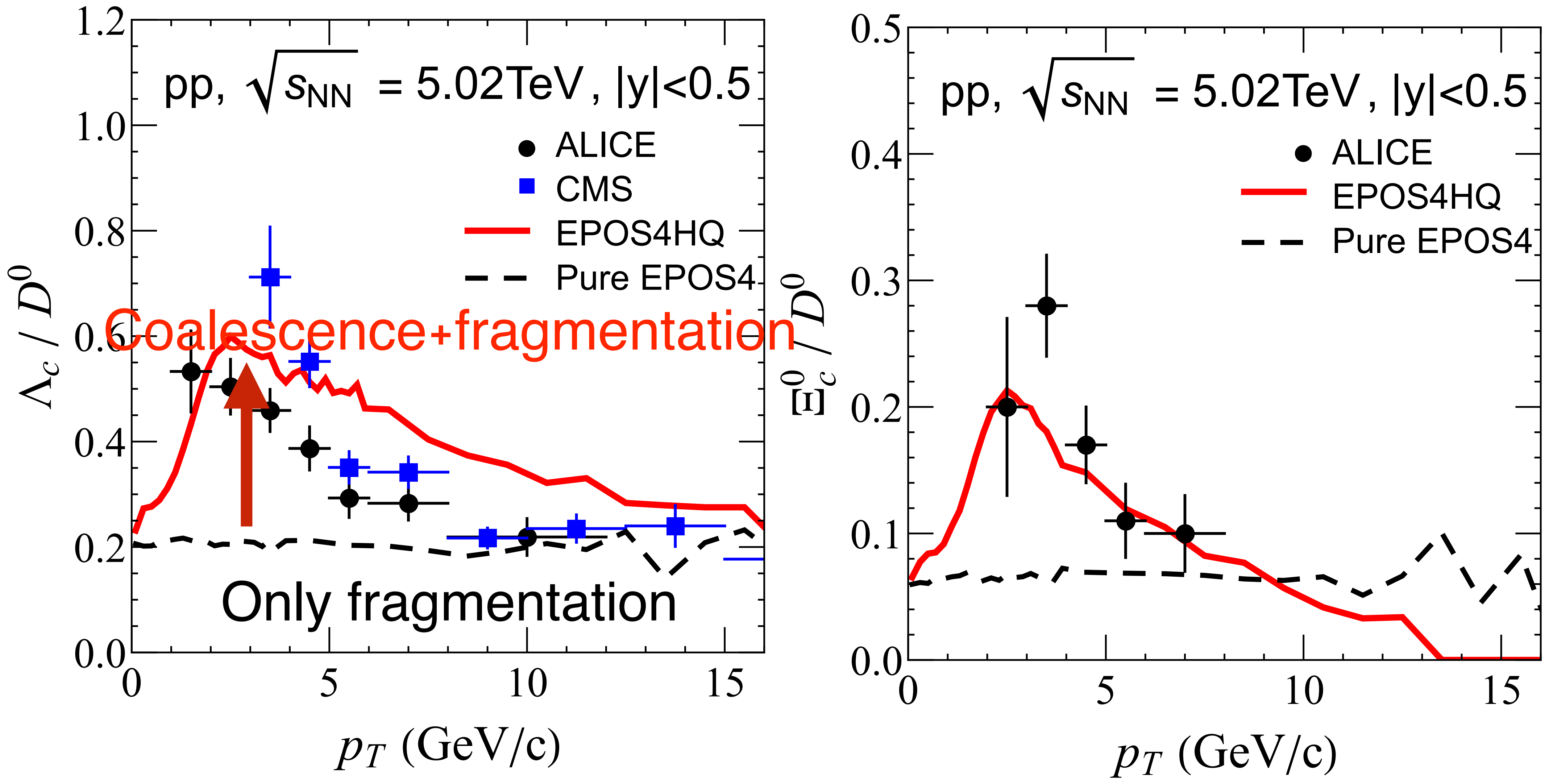
Only fragmentation

- ✦ Small momentum shift in the evolution
- ✦ Momentum loss due to hadronization much larger
- ✦ Charmed baryons are more sensitive to the QGP
- ✦ All measured spectra of charmed hadrons are reproduced

EPOS4: @ small system (pp)

Charm sector

JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, Phys.Rev.D 109 (2024) 5, 054011*



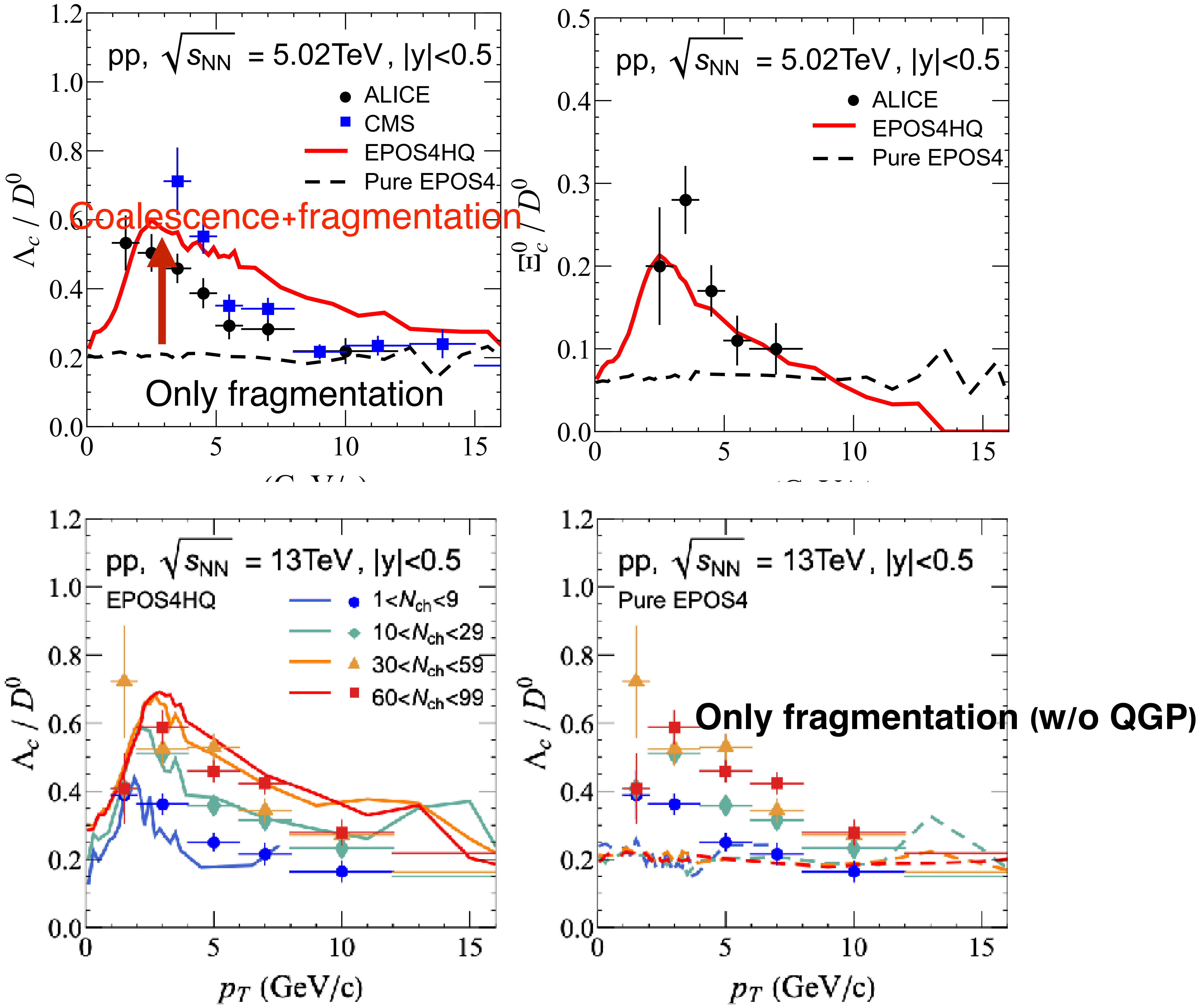
Coalescence+fragmentation

Only fragmentation

EPOS4: @ small system (pp)

Charm sector

JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, Phys.Rev.D 109 (2024) 5, 054011*


Coalescence+fragmentation

Only fragmentation

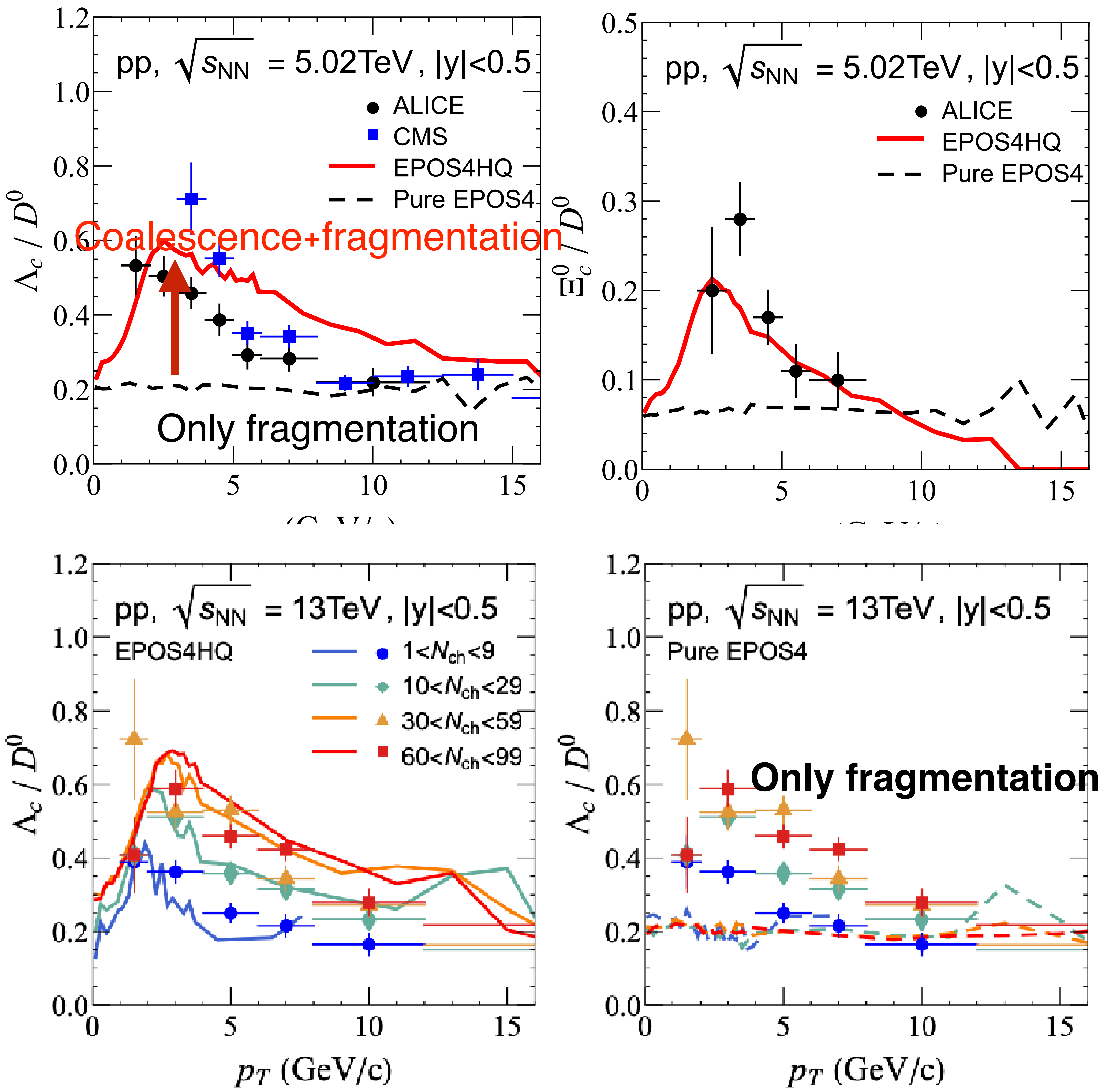
Only fragmentation (w/o QGP)

Multiplicity-dependent enhancement is confirmed by experiment !

EPOS4: @ small system (pp)

Charm sector

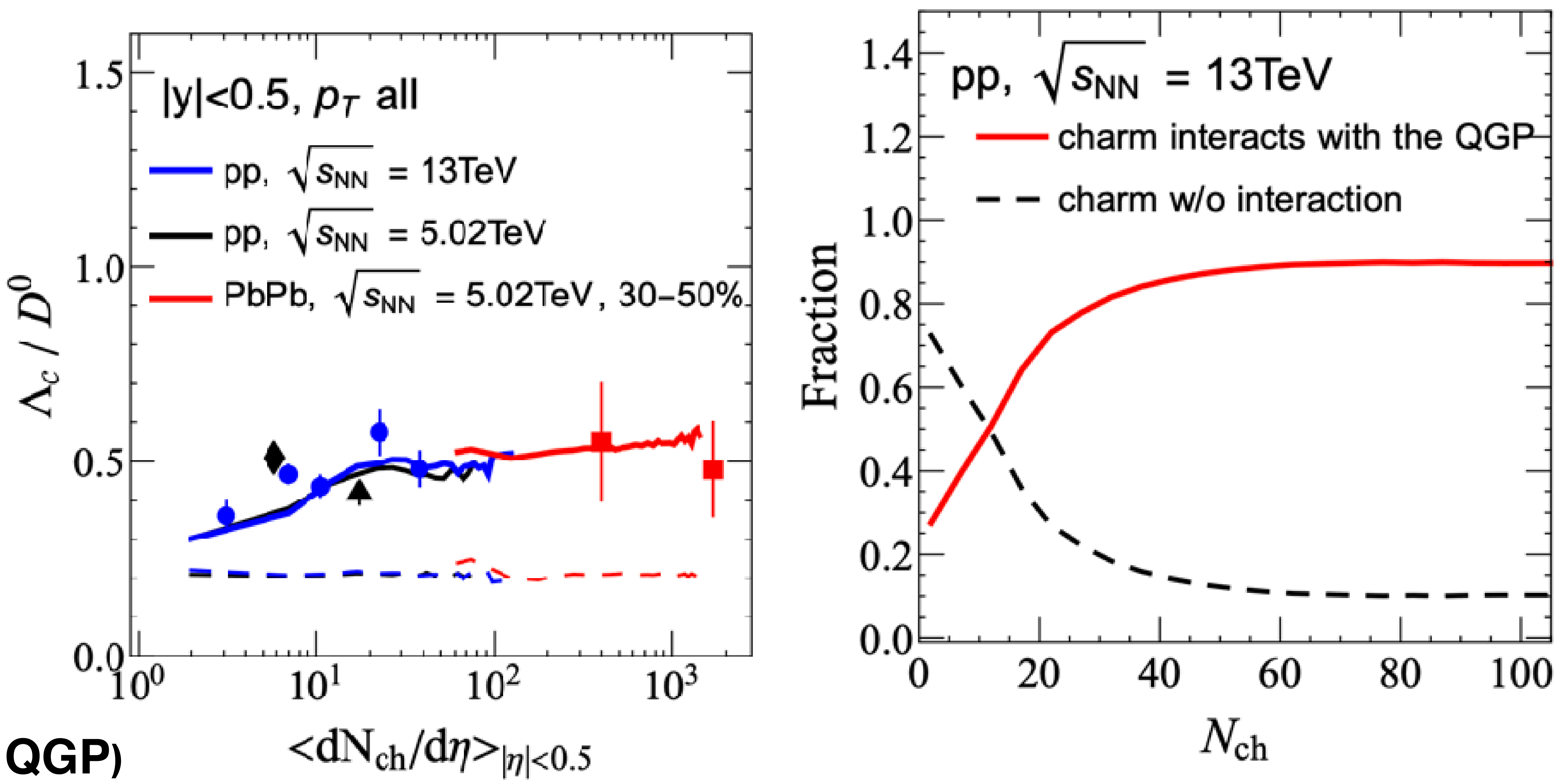
JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, Phys.Rev.D 109 (2024) 5, 054011*



Coalescence+fragmentation

Only fragmentation

Only fragmentation (w/o QGP)



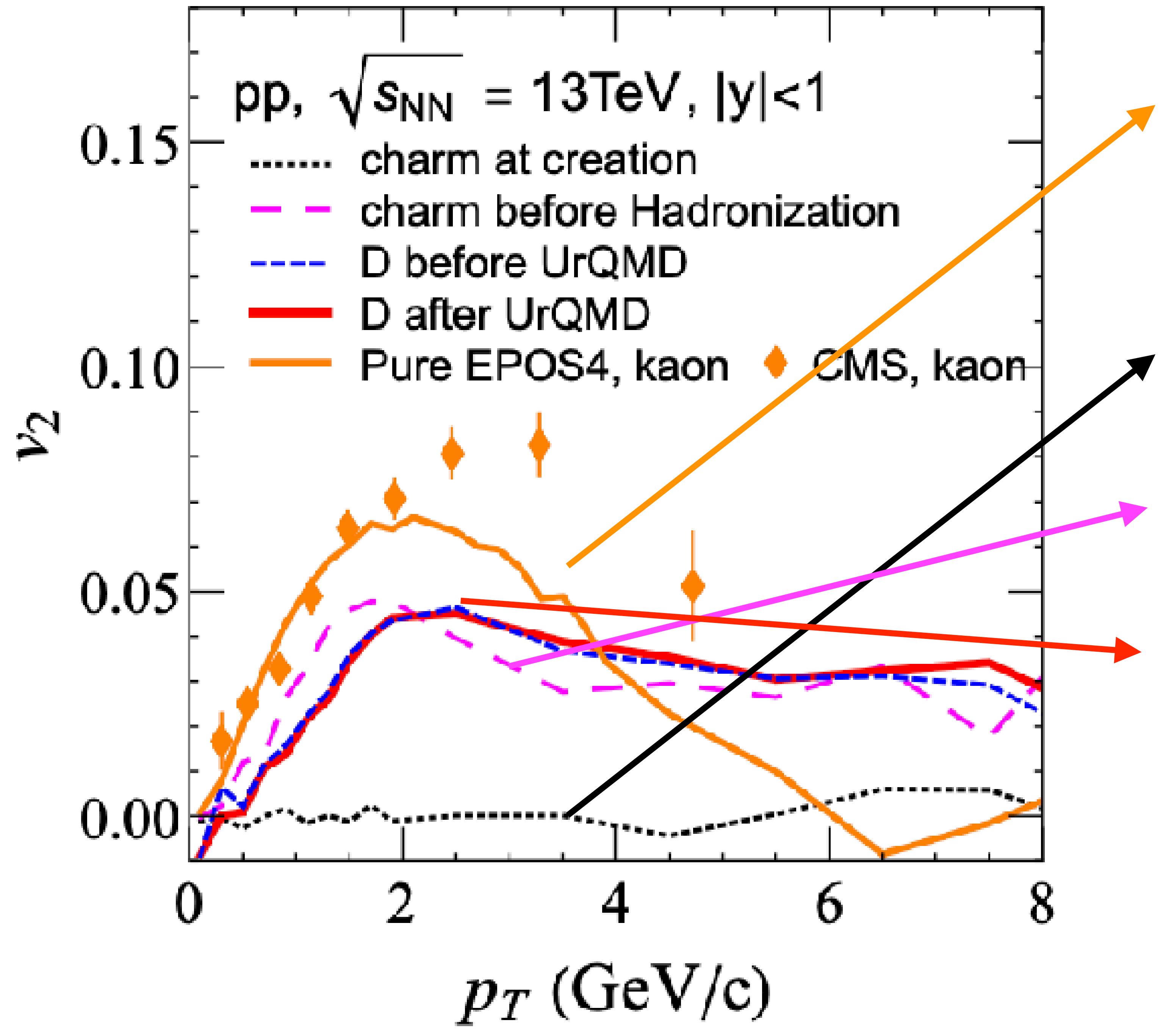
Yield ratios are a strong indication that a QGP is formed in high multiplicity region !

Multiplicity-dependent enhancement is confirmed by experiment !

EPOS4: @ small system (pp)

Charm sector

JZ, *J.Aichelin, P.B. Gossiaux, K.Werner, Phys.Rev.D 109 (2024) 5, 054011*



- ✦ Light hadrons show a finite v2 created by fluctuations of the energy density and hydro expansion
- ✦ Initially charm are produced in hard processes –> no finite elliptic flow expected
- ✦ In EPOS4, the interaction with the QGP creats this flow even in pp collisions.
- ✦ Hadronization and hadronic scattering slightly change the v2

EPOS4: @ small system (pp)

Charm sector

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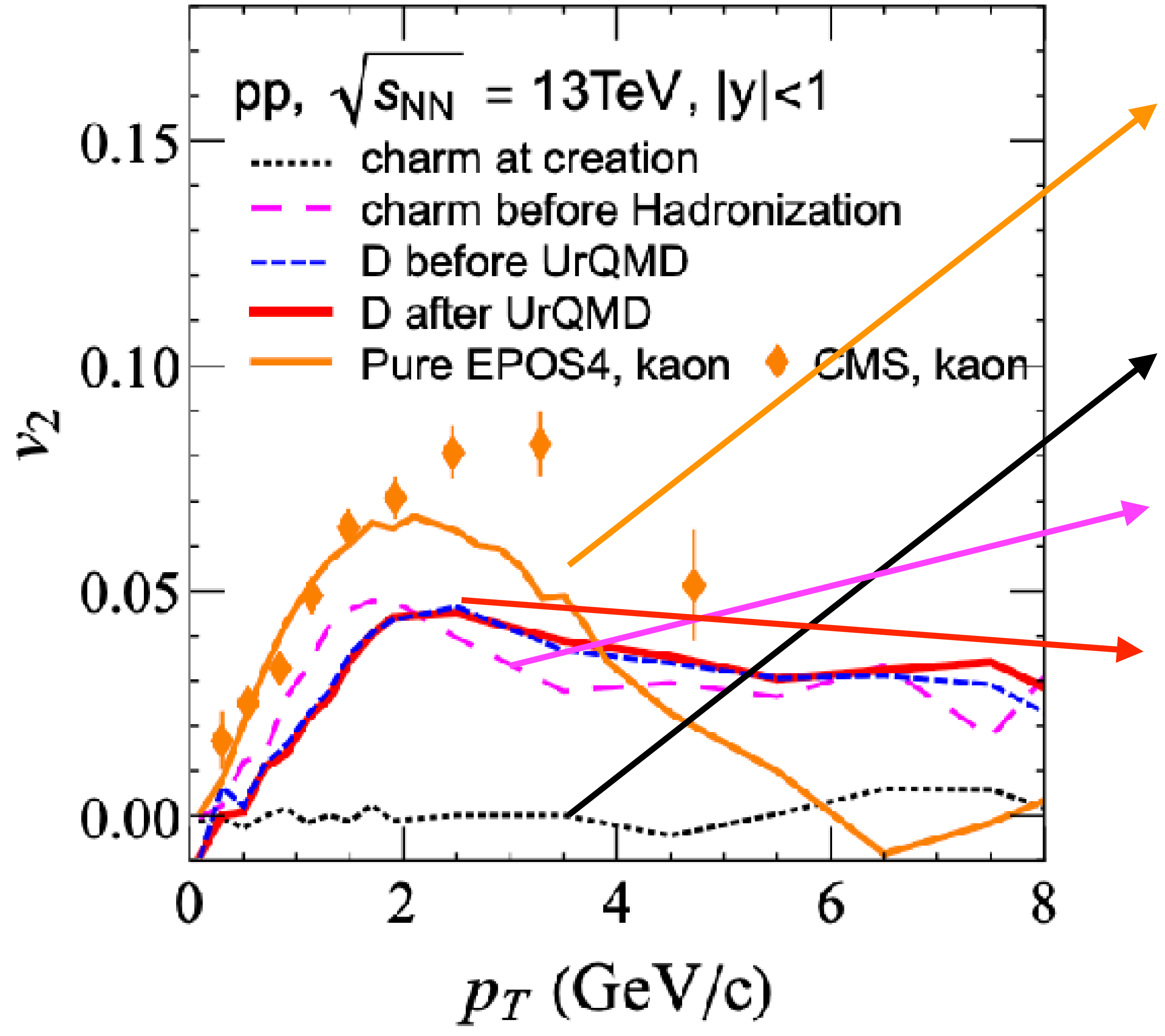

- ✦ Light hadrons show a finite v_2 created by fluctuations of the energy density and hydro expansion
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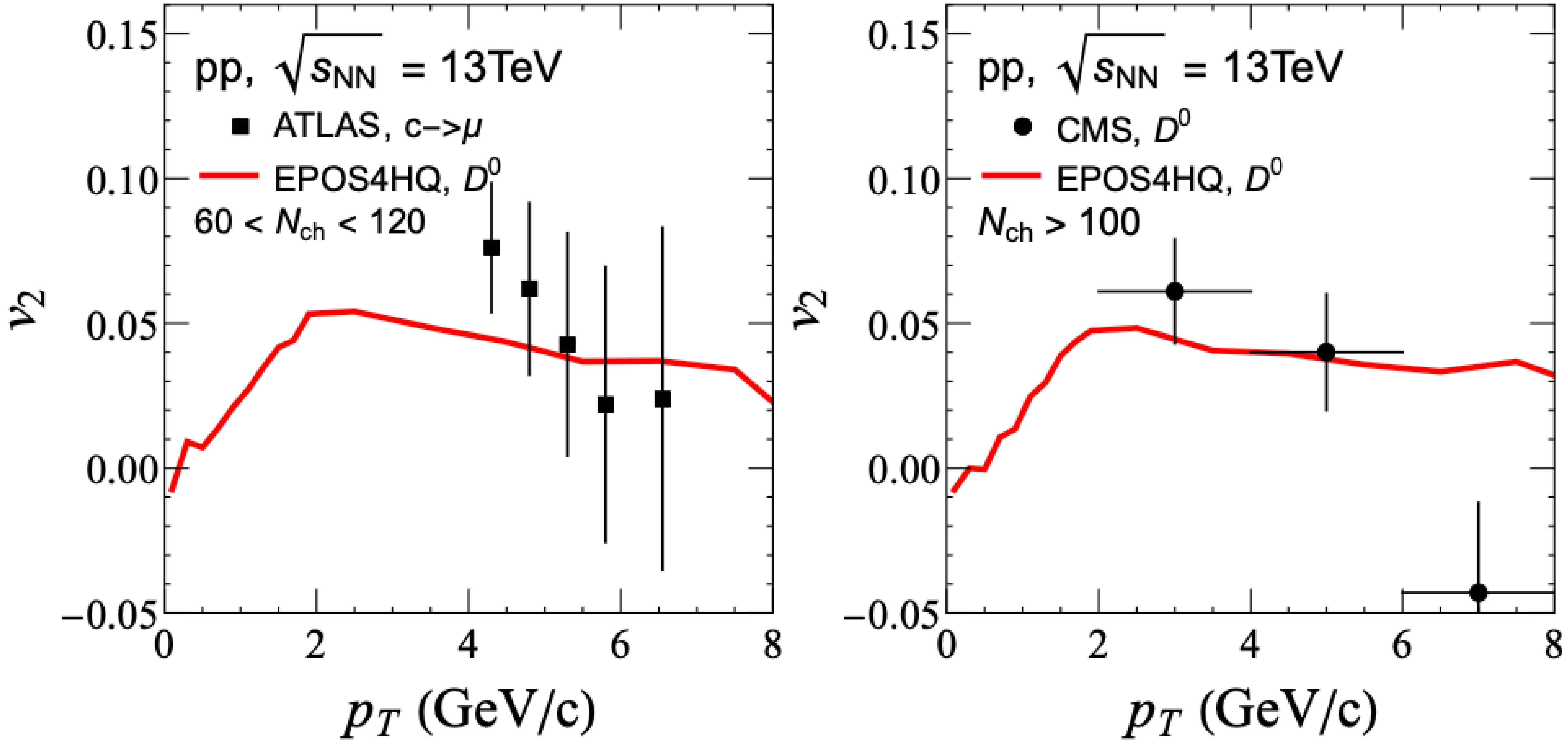
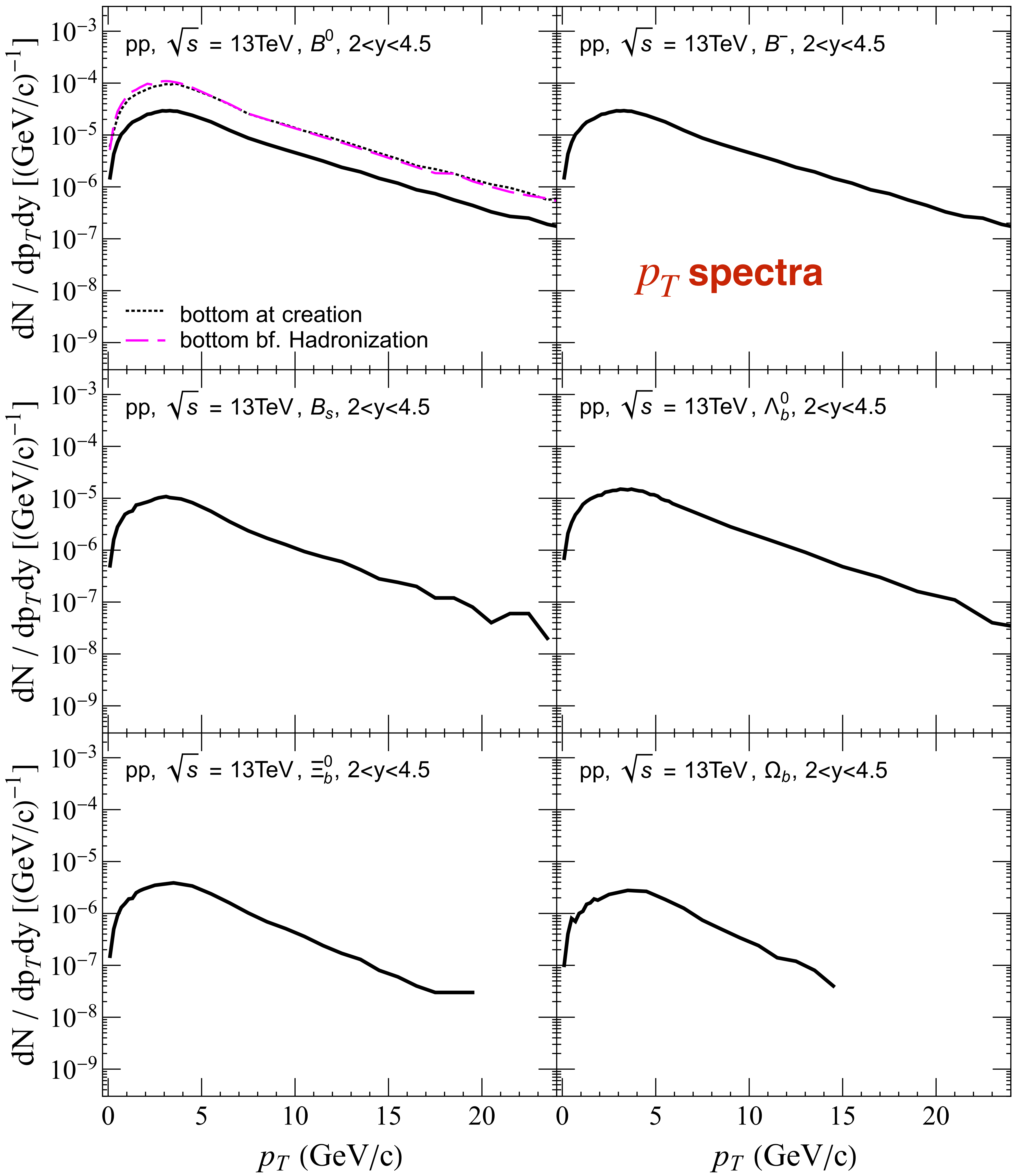
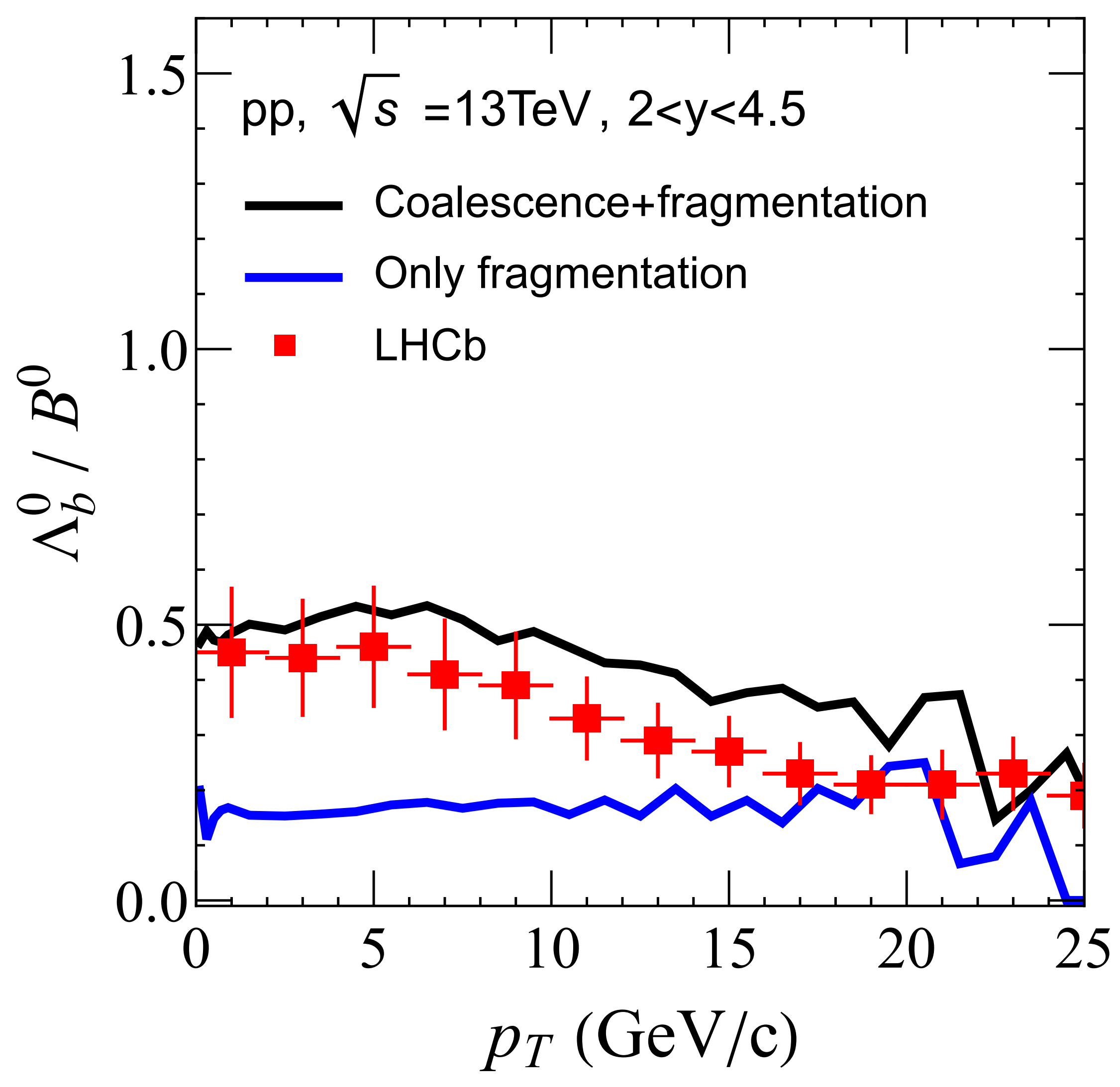


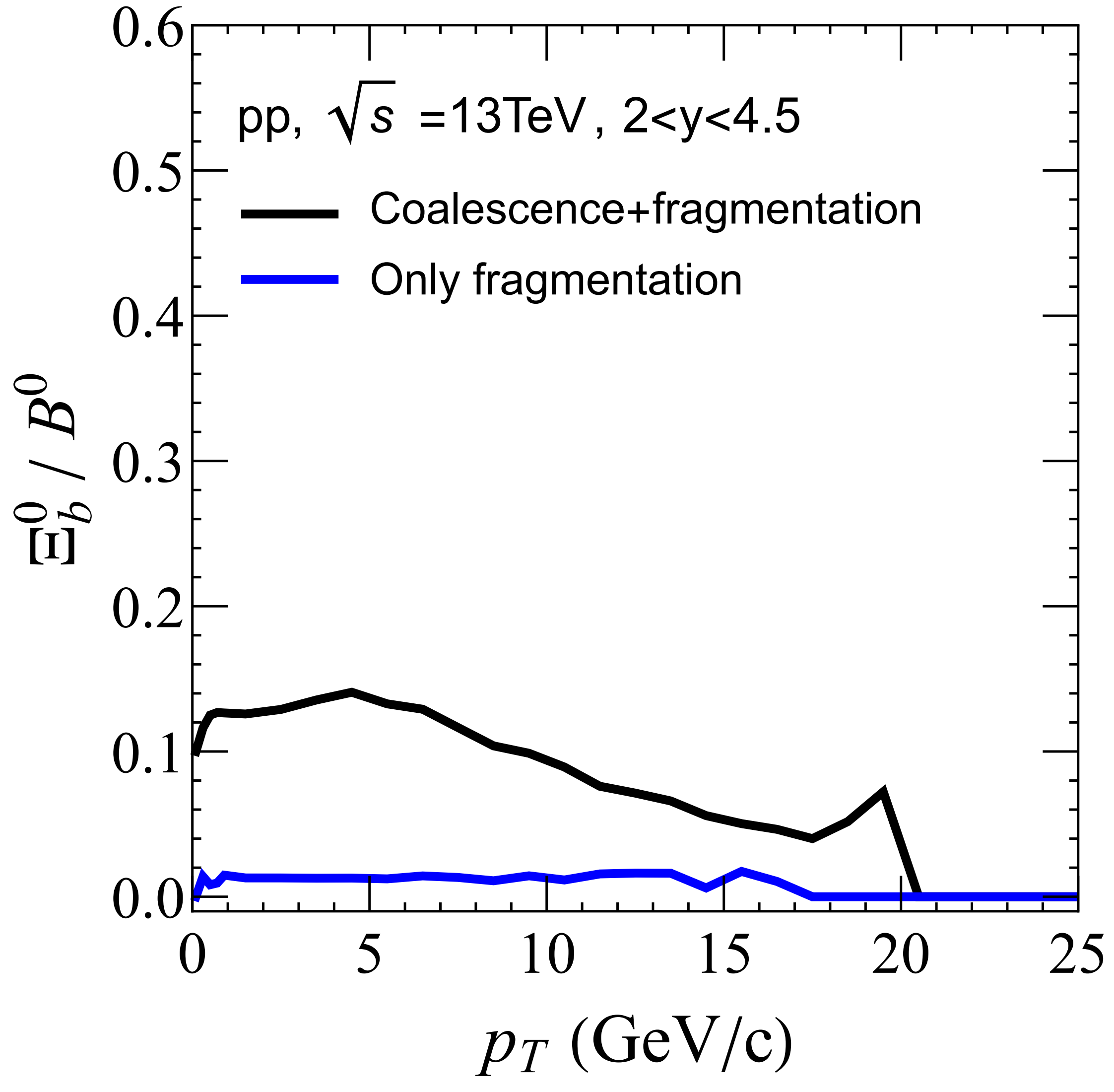
EPOS4: @ small system (pp)

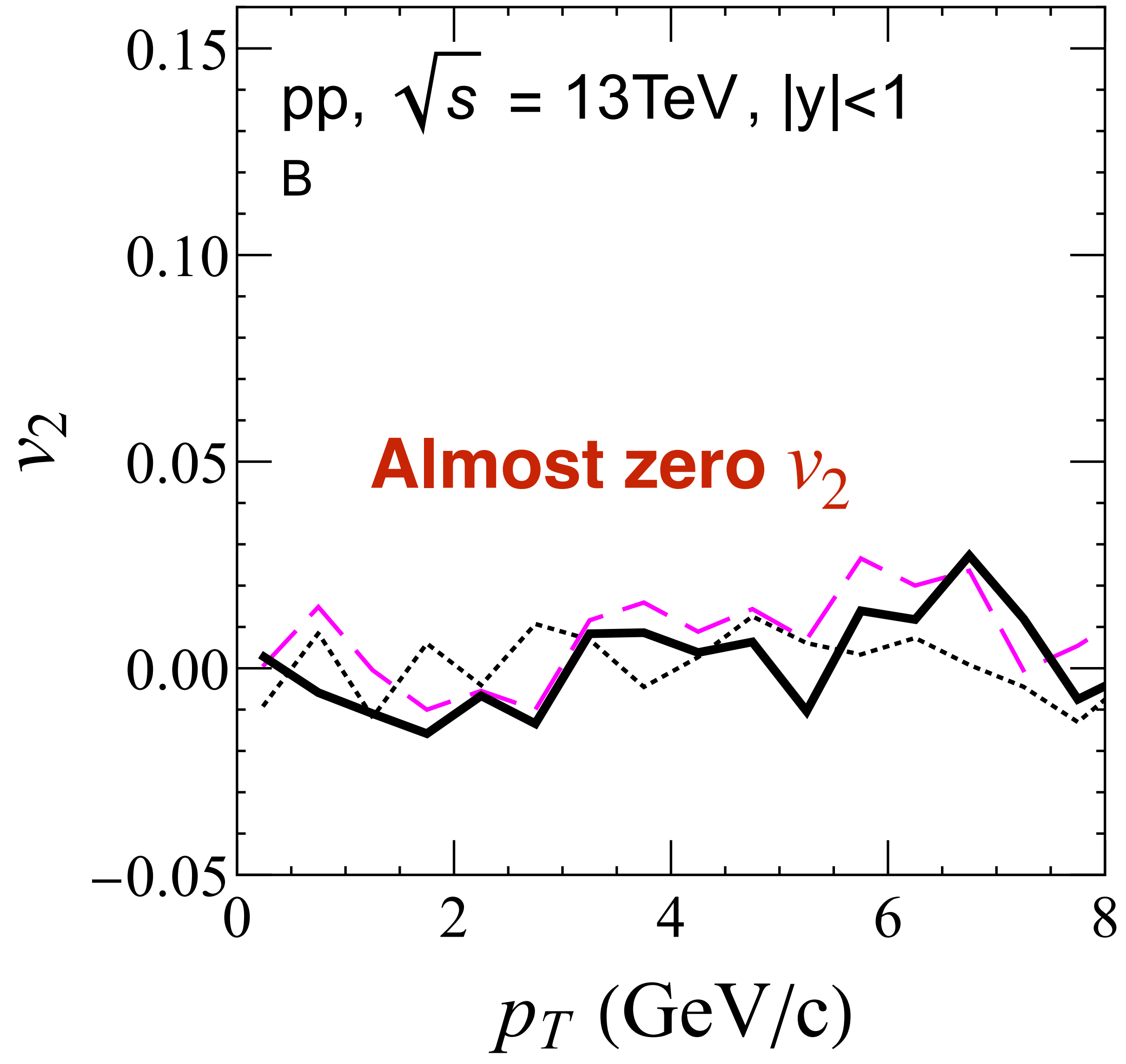
Bottom sector



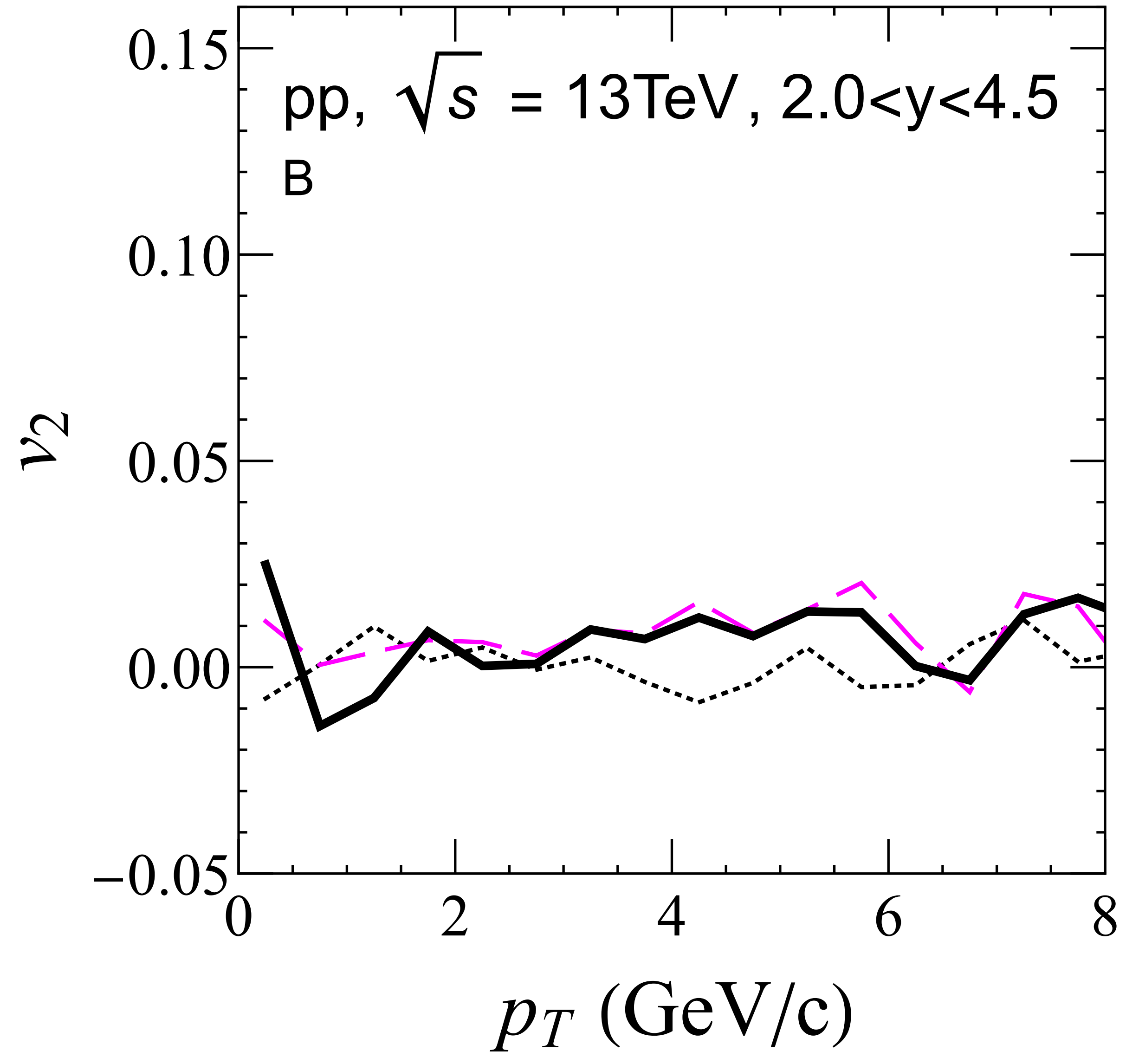
p_T **spectra**







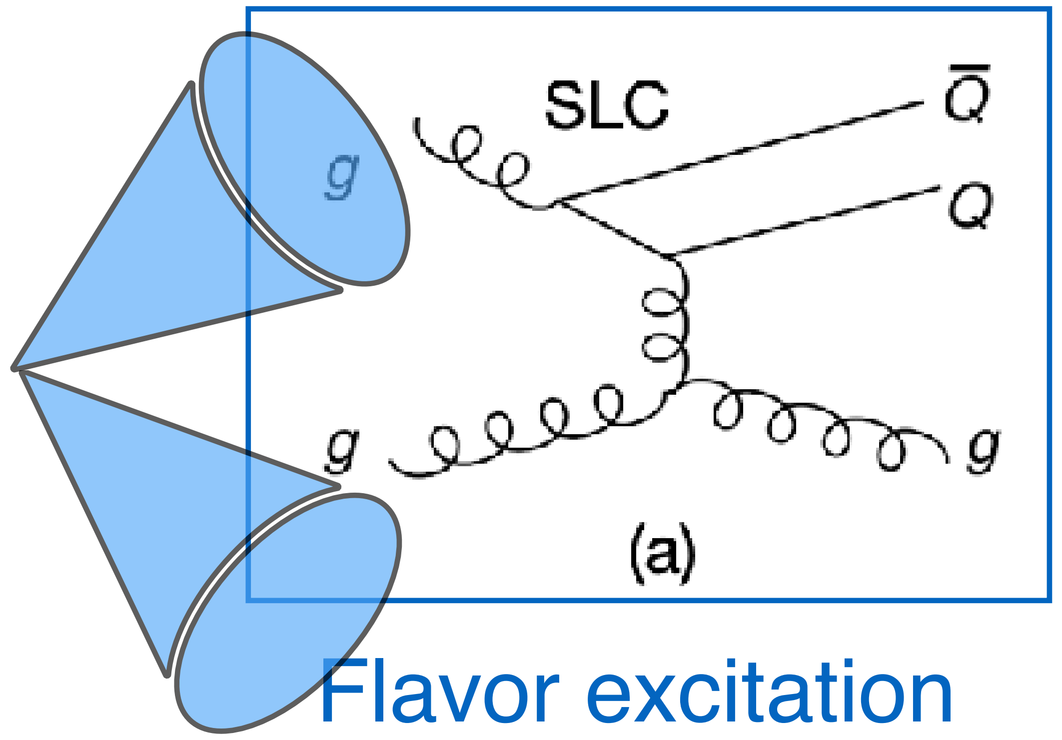
Almost zero v_2



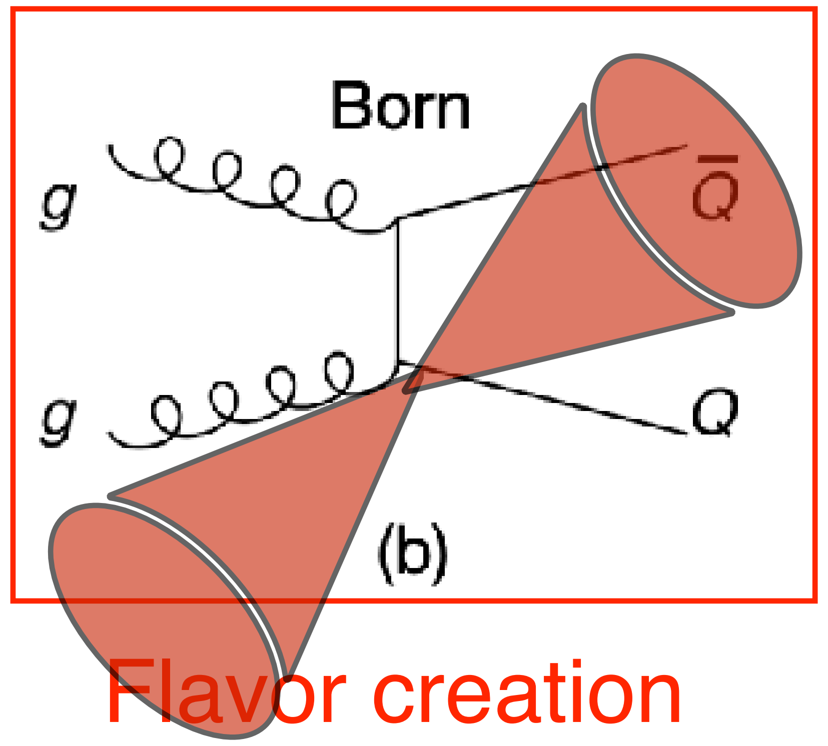
Outline

- Introduction of the heavy flavor probes
- Heavy flavor production in heavy-ion collisions in EPOS4
- Heavy flavor production in p-p collisions in EPOS4
- **System size dependence of energy loss and correlations**
- Summary

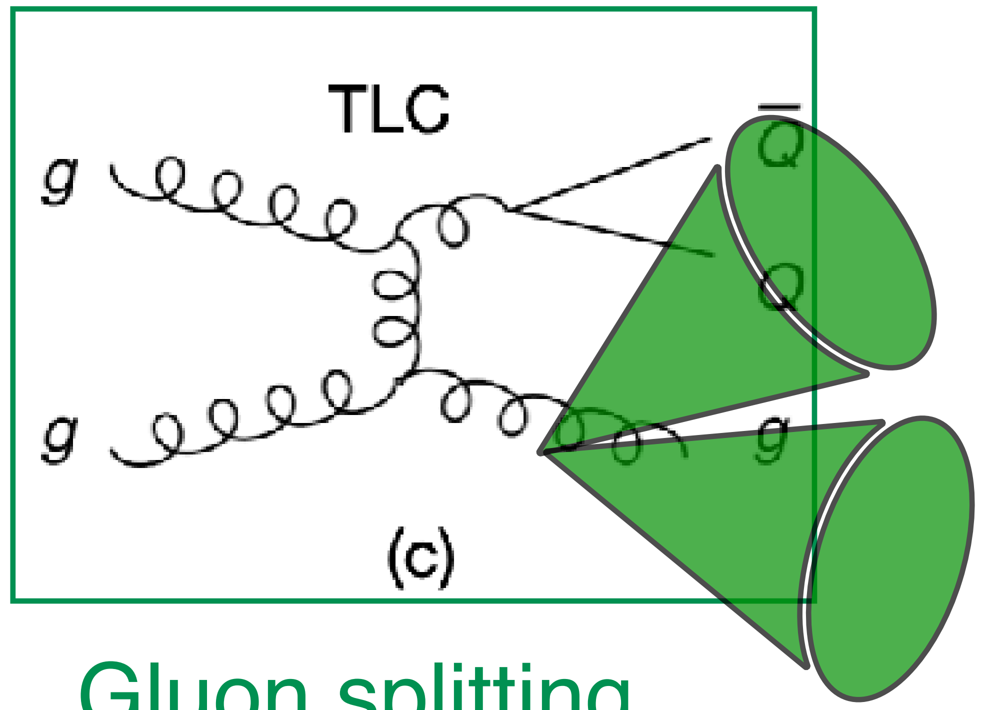
Heavy quark correlations



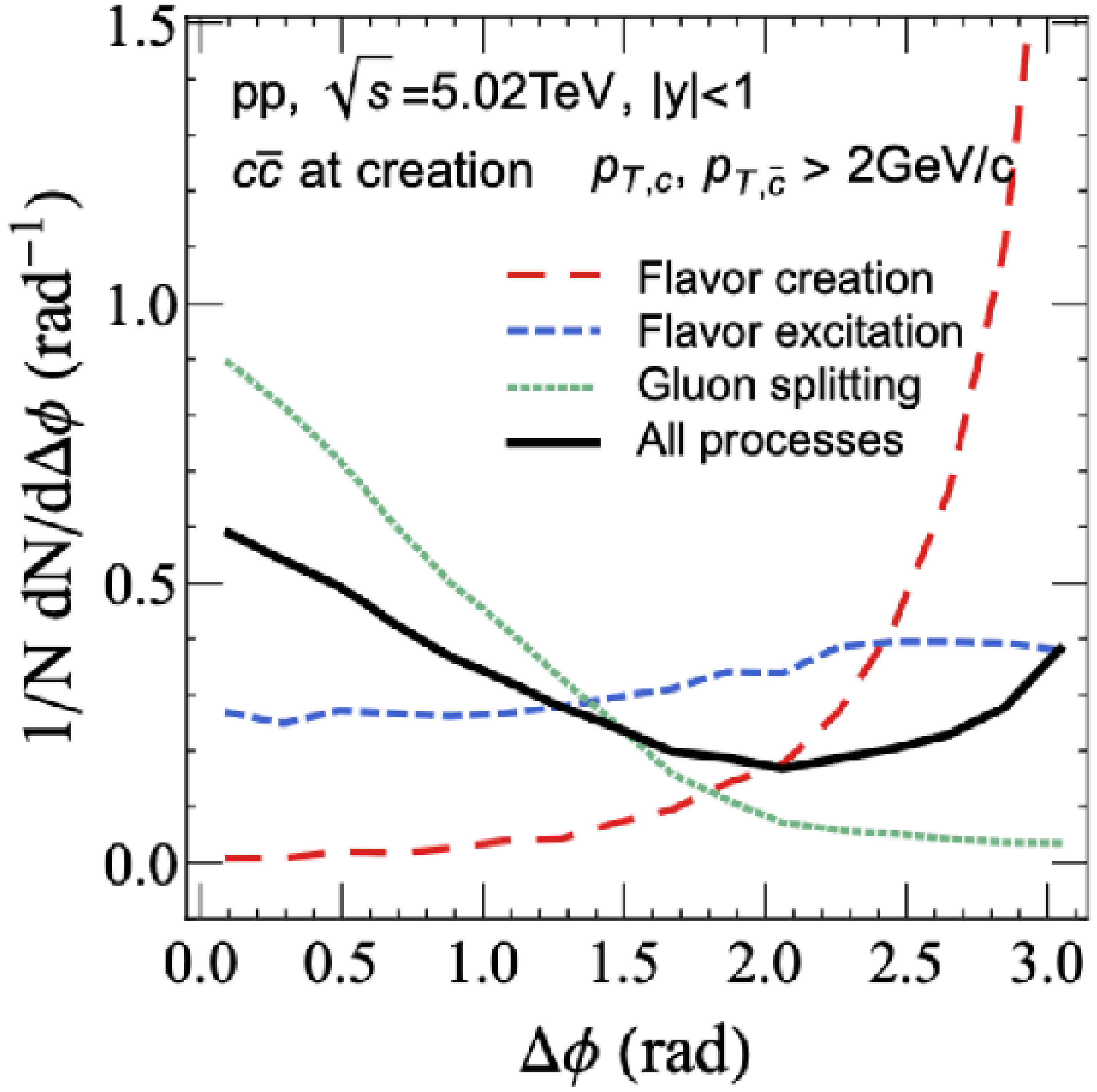
Flavor excitation



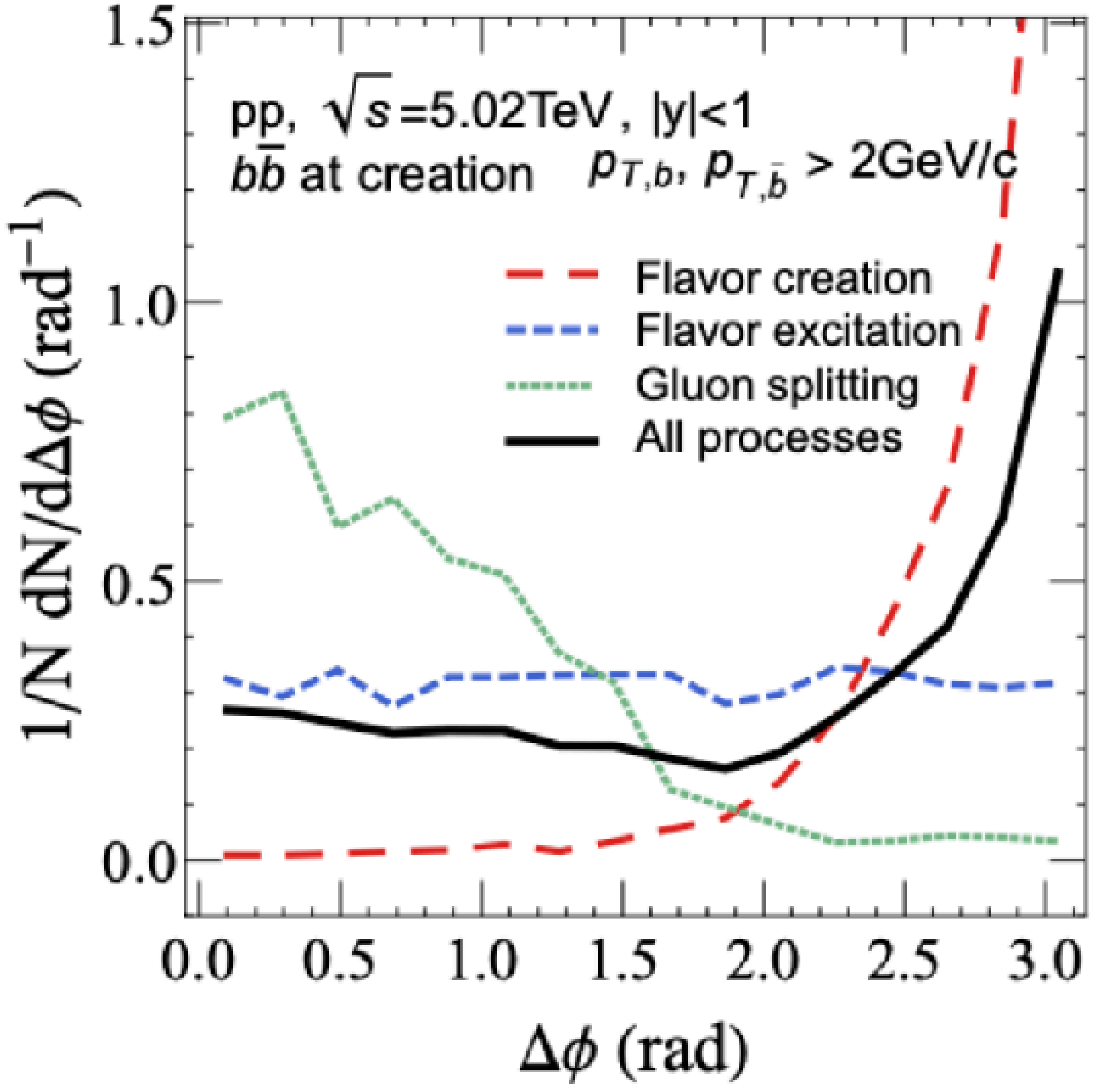
Flavor creation



Gluon splitting

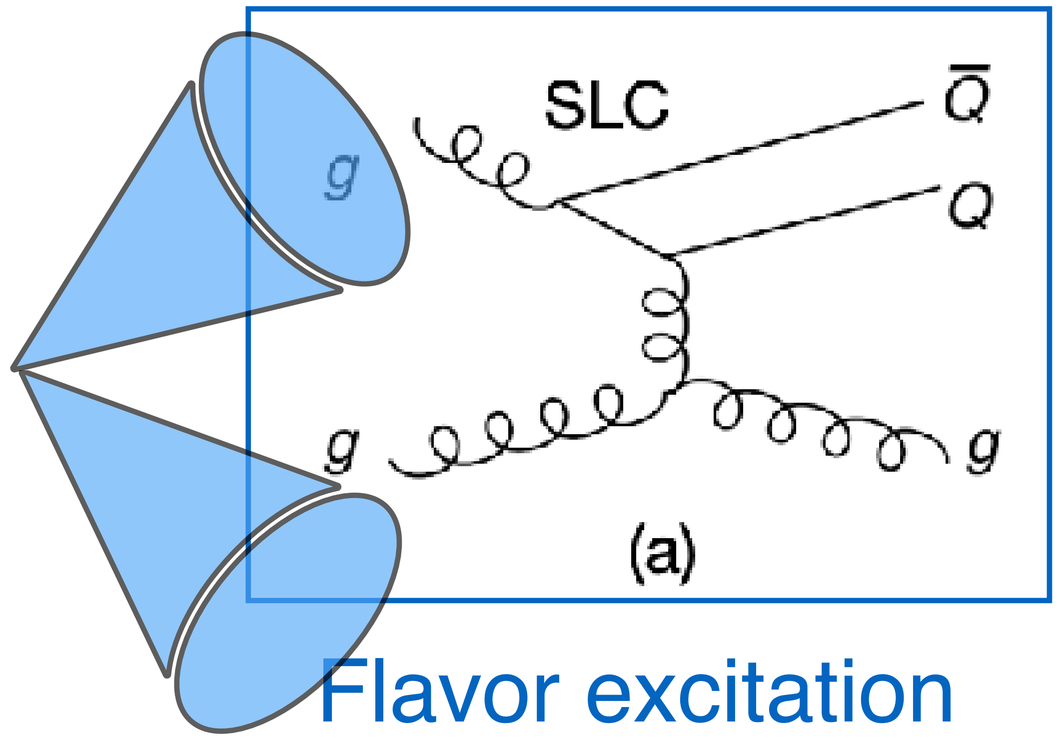


$c\bar{c}$ correlations

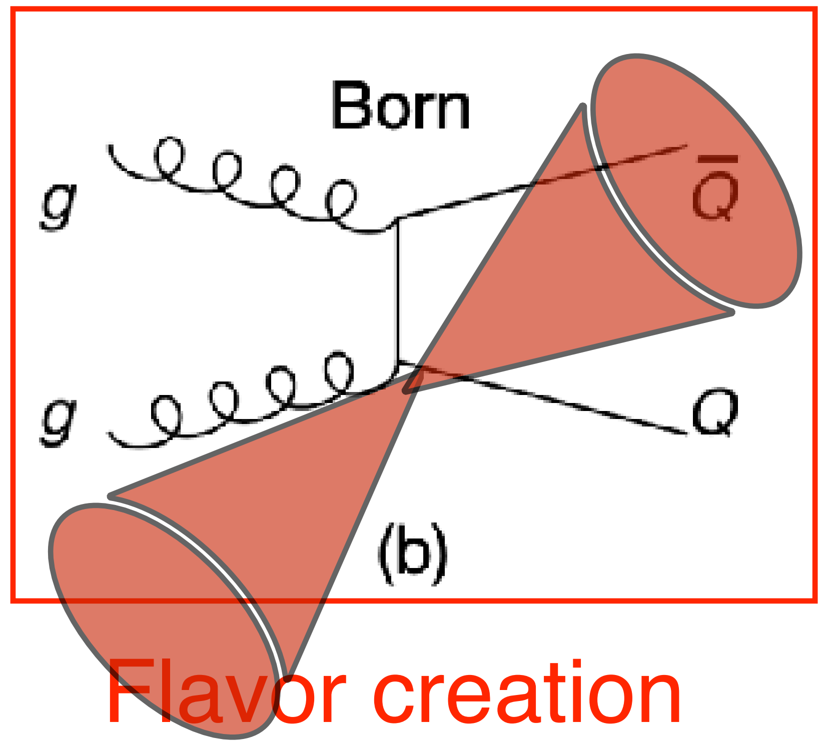


$b\bar{b}$ correlations

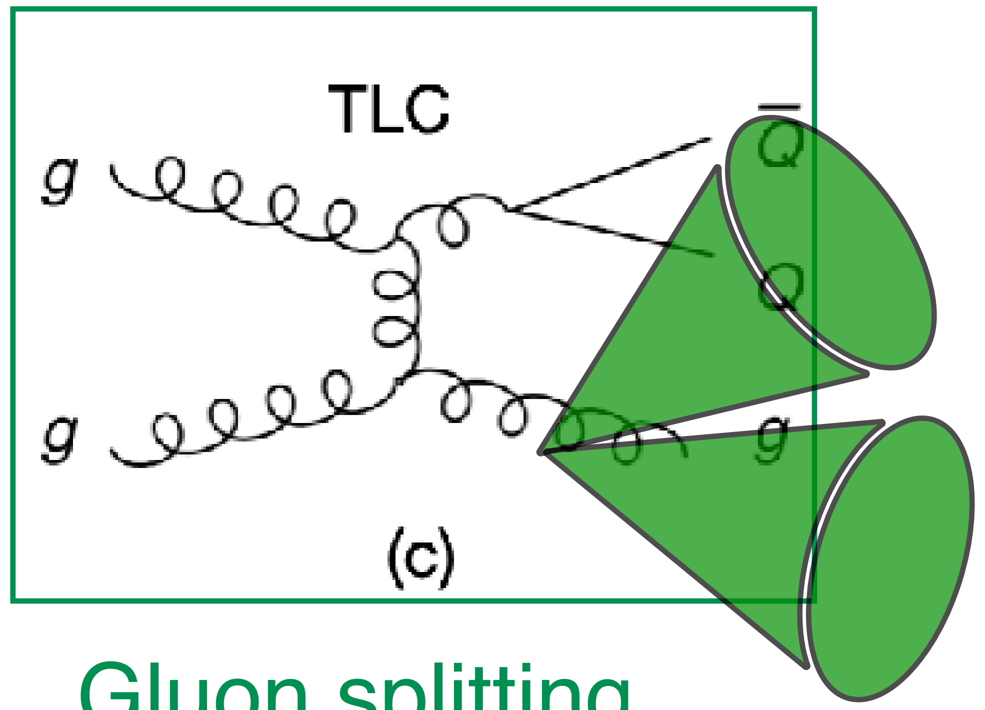
Heavy quark correlations



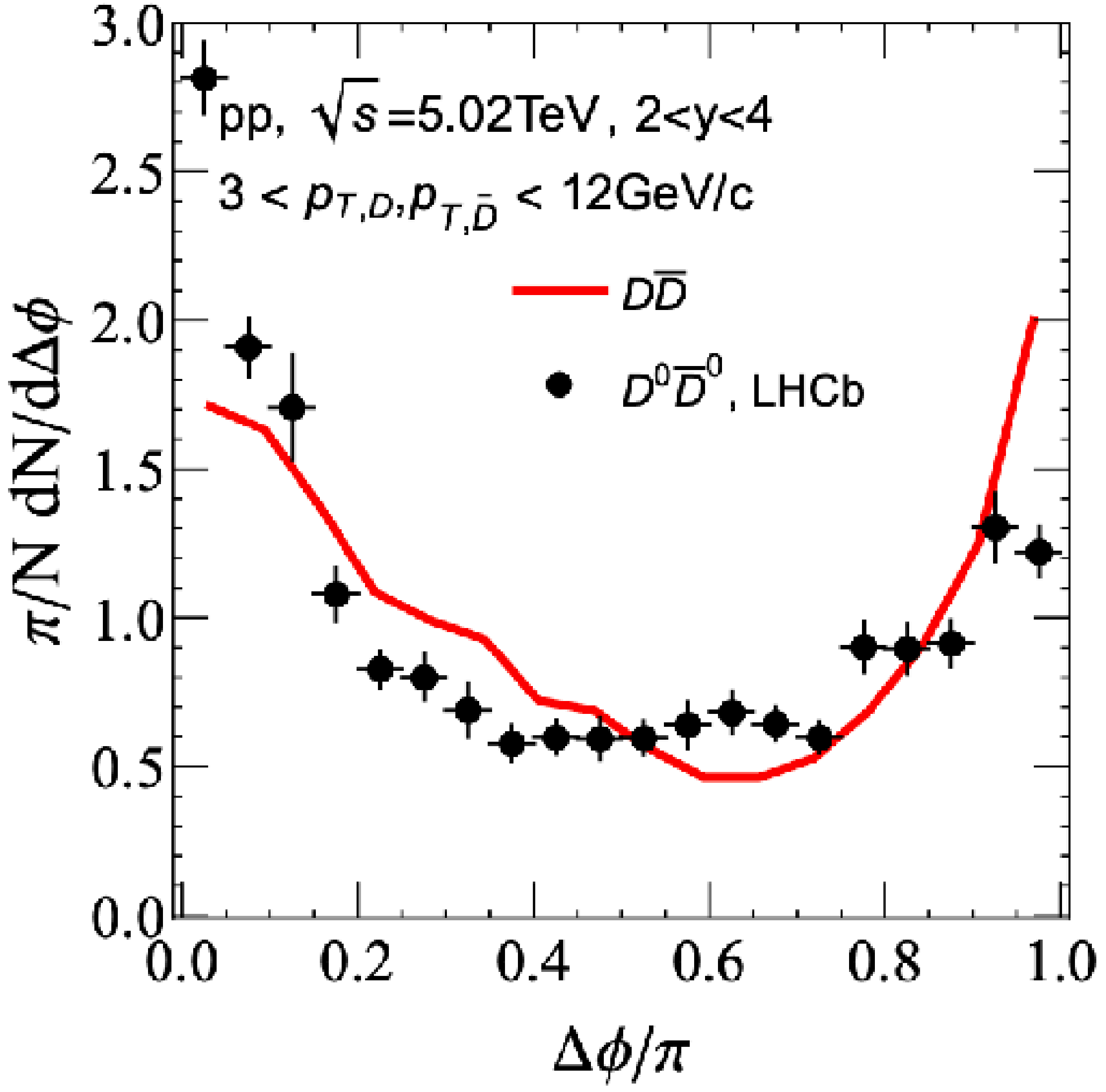
Flavor excitation



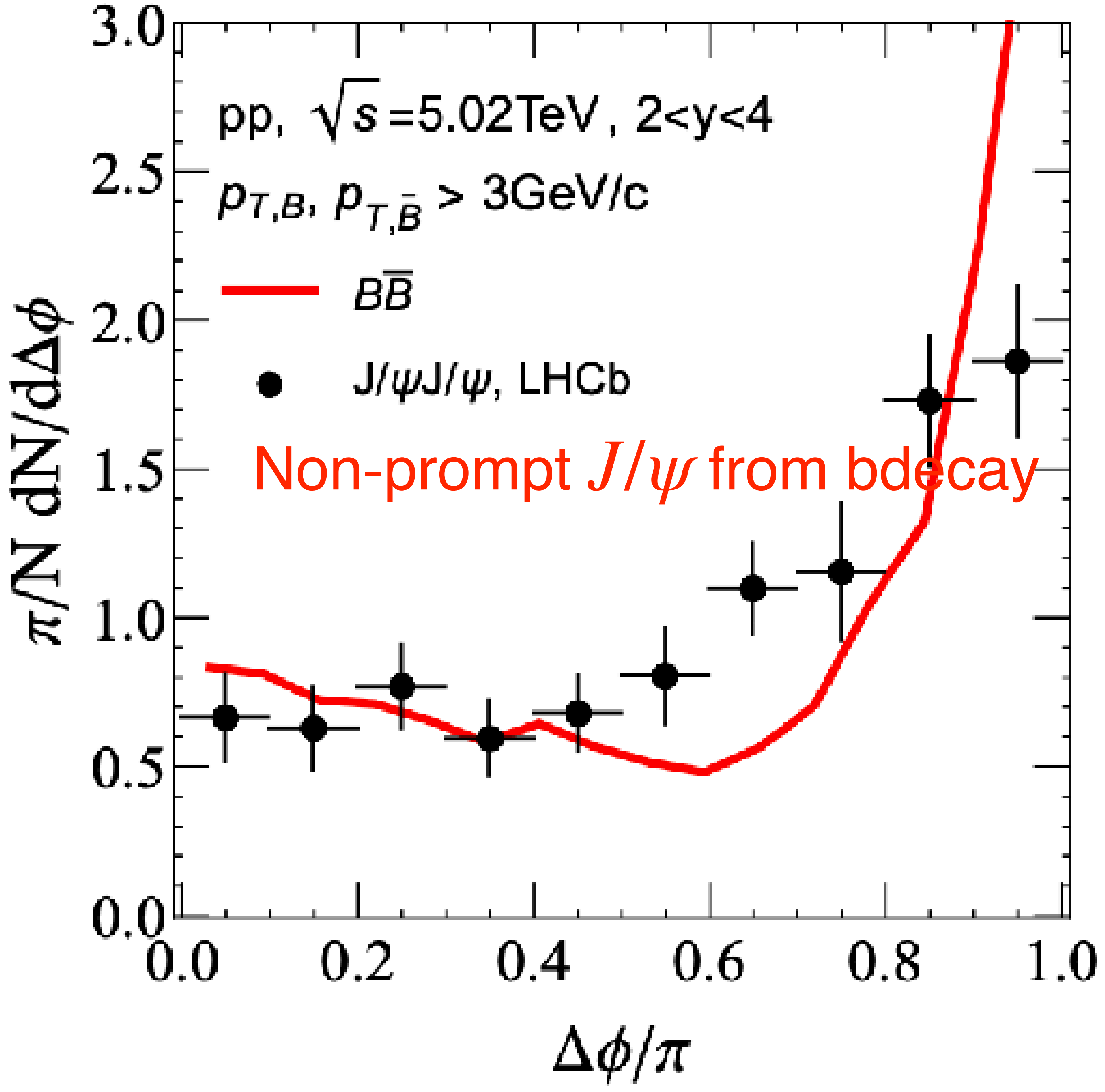
Flavor creation



Gluon splitting



$D\bar{D}$ correlations

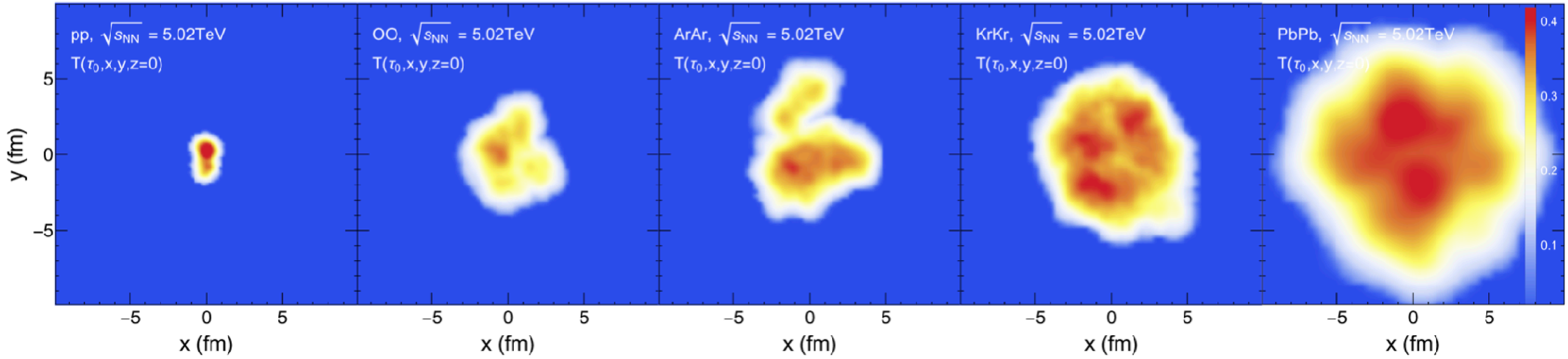


Non-prompt J/ψ from bdecay

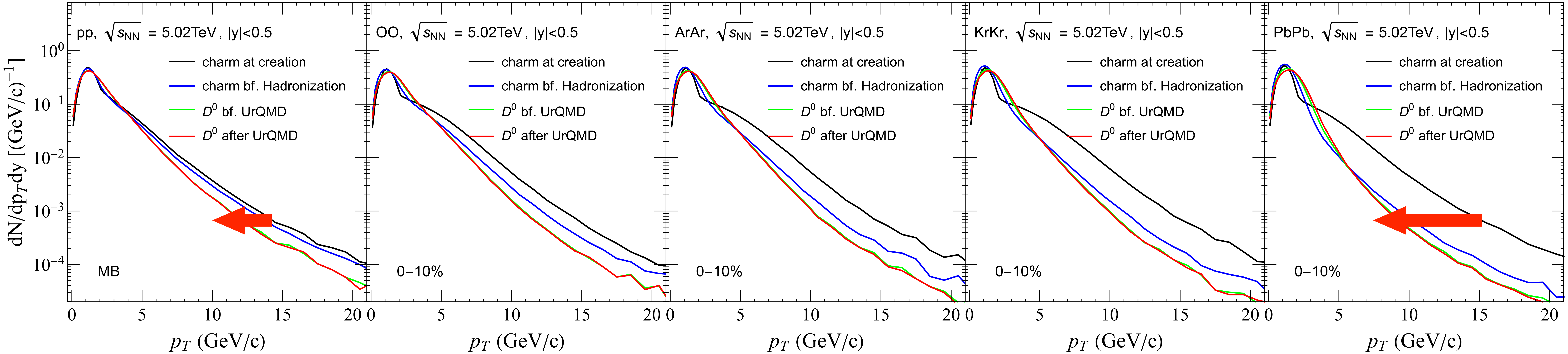
$B\bar{B}$ correlations

System size dependent energy loss

pp, OO, ArAr, KrKr, PbPb 0-10%   ---> to investigate the heavy quark energy loss



Charm quark at creation, after evolution, after hadronization, after UrQMD.



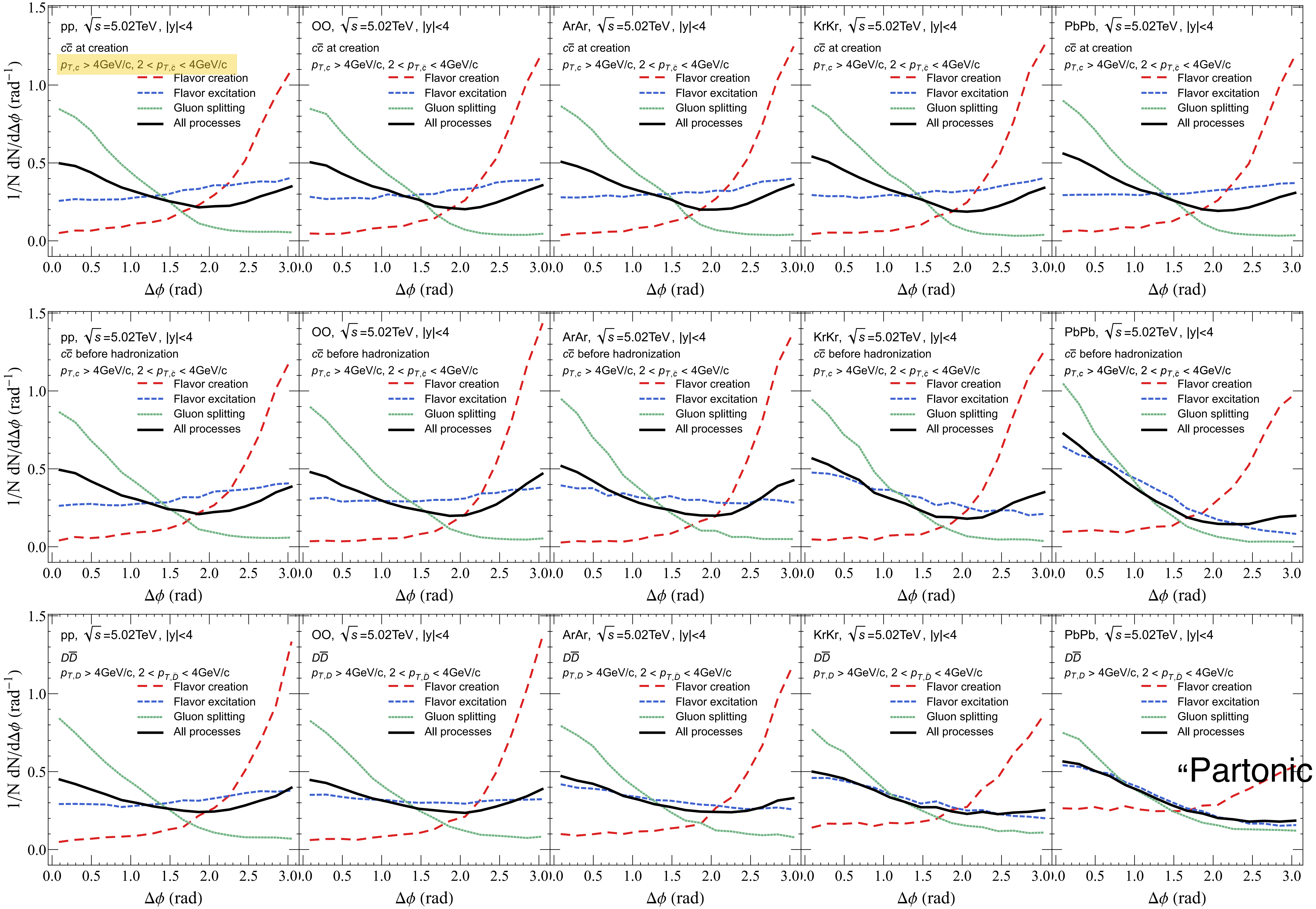
Correlations from different process

Small from the same vertex (correlated) Large

At creation

After energy loss

After hadronization

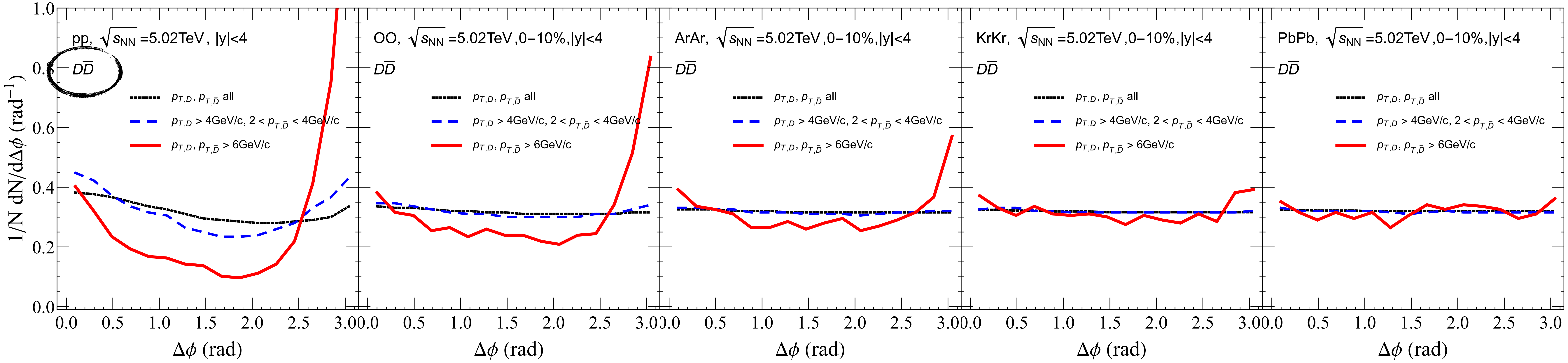


"Partonic wind"

$D\bar{D}$ Correlations

Small

Large

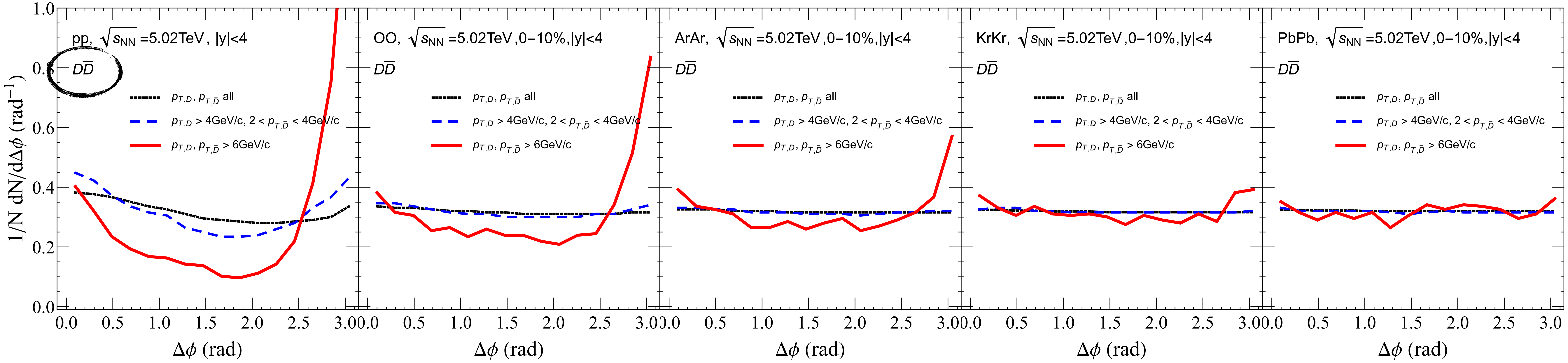


The correlation is washed out by the uncorrelated heavy quark pairs in QGP!

$D\bar{D}$ Correlations

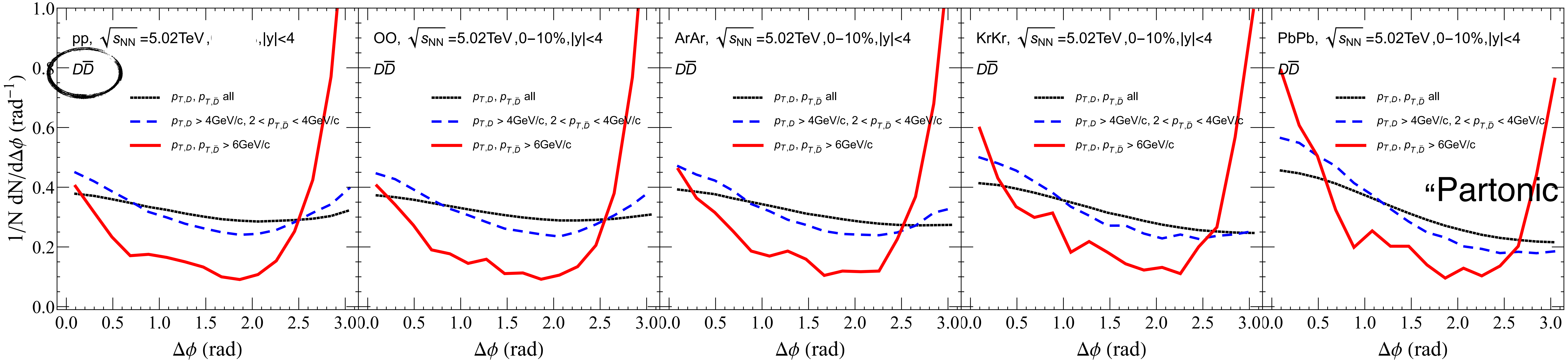
Small

Large



The correlation is washed out by the uncorrelated heavy quark pairs in QGP!

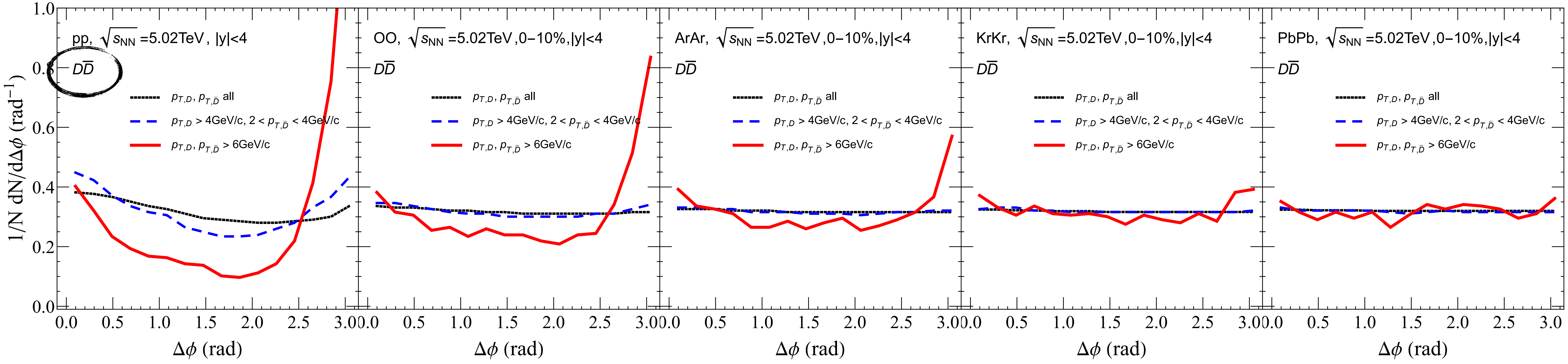
If only consider the correlation from **correlated** heavy quarks: (**hard** to do in the experiment !!!)



“Partonic wind”

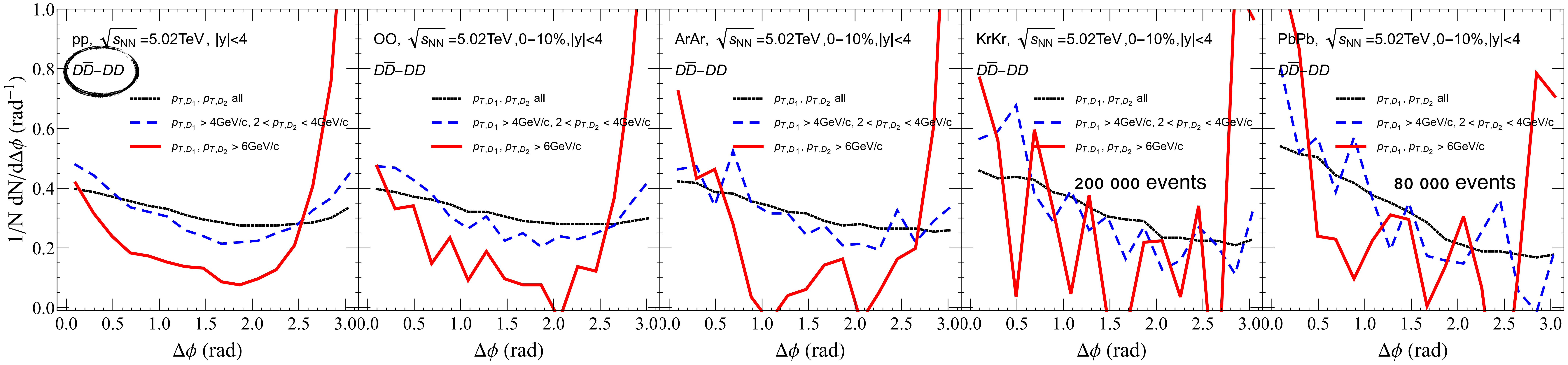
$D\bar{D}$ Correlations

Small | Large



The correlation is washed out by the uncorrelated heavy quark pairs in QGP!

correlation (correlated) = correlation (all) - correlation (uncorrelated): (**easier** to do in the experiment !!!)



It is possible to observe the correlation in the large system by subtracting the DD correlations !

Summary

- Based on the newly developed EPOS4 framework, the yield of all charmed hadrons ($D^0, D^+, D_s, \Lambda_c, \Xi_c, \Omega_c$, also bottom hadrons), the elliptic flow v_2, and the correlation of heavy flavor hadrons are well described in both pp and heavy-ion collisions.

- Our results show that independent of the system size, almost all observables can be well understood in pp collisions assuming that there is system-independent critical energy density for the creation of a QGP —> the existence of a small QGP in high energy pp collisions.

- It is possible to observe the correlation in the large system by subtracting the DD (uncorrelated) correlations !

- EPOS4 is now ready for light and open heavy flavors, and the quarkonium part is coming soon.

On going:

- pA collisions

- Test the hadronization mechanism by considering the influence of the light quark mass, hadronization temperature, baryon diquark structure, and so on.

Thanks for your attention!