SQM 2024, Strasbourg (France)

Heavy flavor production and collectivity in high energy proton-proton collisions

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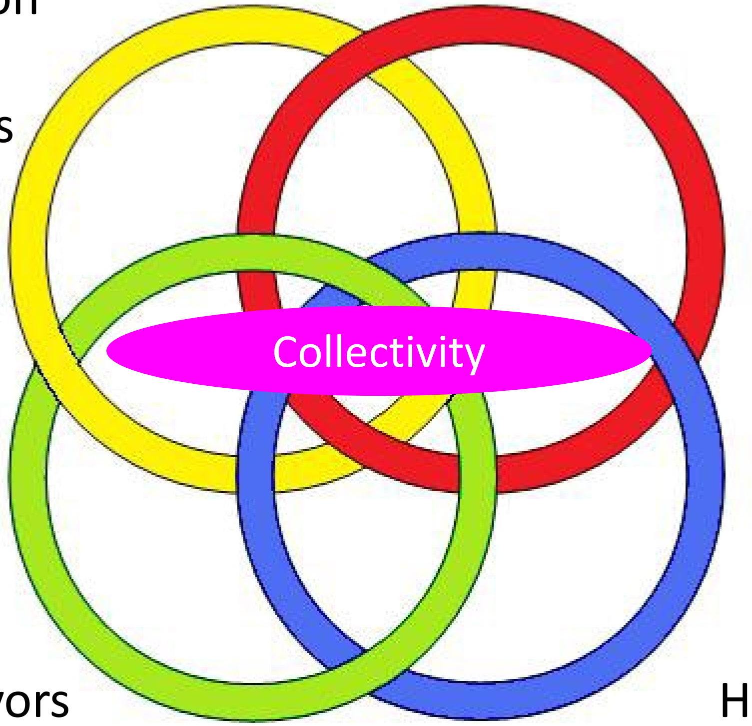
With: J. Aichelin, K. Werner, J. Zhao (main author)

and Pays de la Loire

HF Borromeo's rings of collectivity

Motivation: Studying the collectivity effects in large and small systems as modeled by EPOS4-HQ



HF production
and
correlations

Energy loss
and
coupling with QGP

Collectivity

Open Heavy Flavors
and
Quarkonia

Hadronization

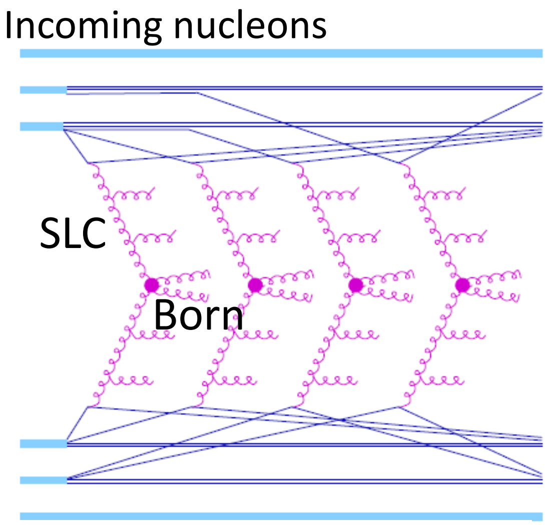
EPOS initial conditions

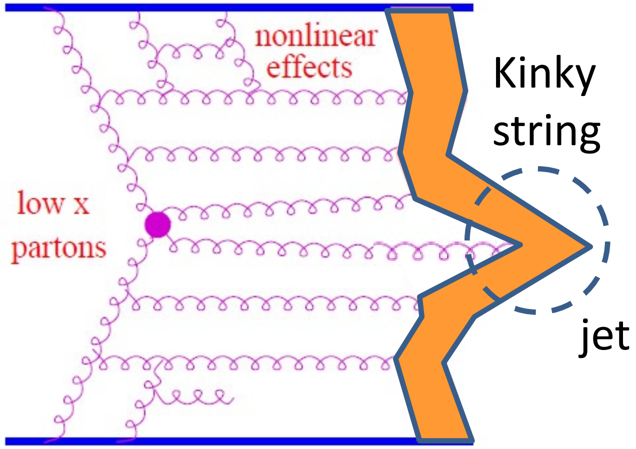
EPOS + Hydro : state of the art framework that encompass pp, pA and AA collisions

EPOS (initial conditions):

- Model based on Gribov-Regge multiple pomeron interactions
- Particle production (including HQ, from EPOS 3 on) in cut (semi-hard) pomerons, seen as partons ladder
- Space like DGLAP evolution with hard Born process
- Soft particles form a flux tube (string, with its own dynamics, incl. string breaking)… lots of them in A-A
- Slow string segments (pre-hadrons), far from the surface, are mapped to fluid dynamic fields
- Hard particles (kinky string) -> jets

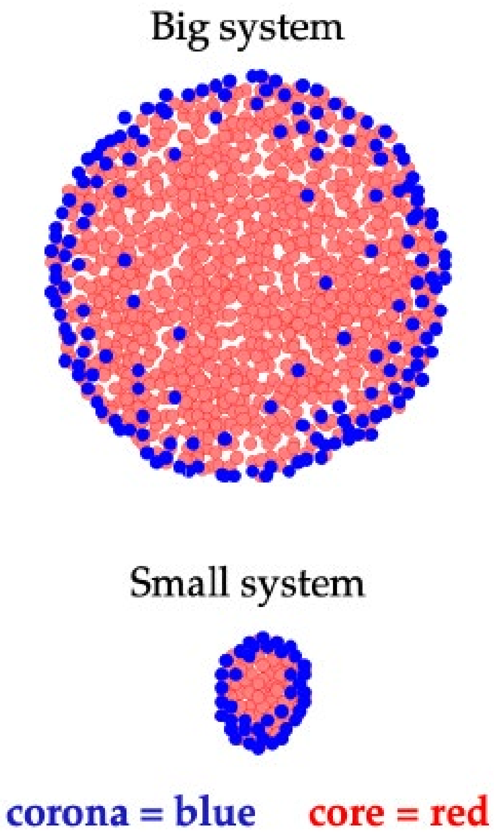
Ref: K. Werner, Iu. Karpenko, M. Bleicher, T. Pierog, and S. Porteboeuf-Houssais Phys. Rev. C 85 (2012), 064907 + many refs in 2023 (*https://klaus.pages.in2p3.fr/epos4/*)



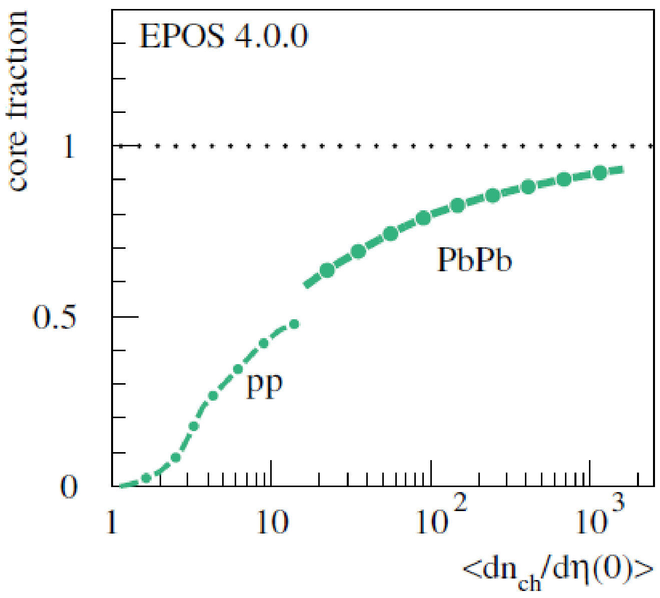


EPOS initial conditions

Simple but efficient initial-stage in EPOS : Core-Corona picture



- If the energy loss is bigger than the energy of the prehadron, it is considered to be part of the "core"
- If the energy loss is smaller than the energy, the prehadron escapes, it is called "corona"
- *Core: hydrodynamics; Corona: hadronic phase*



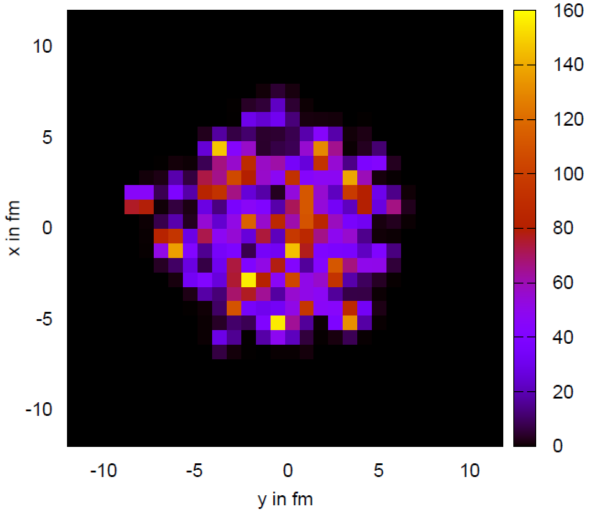
The energy density is larger than the critical energy density ϵ_0 —> deconfined QCD matter and hydro evolution

EPOS + VHHLE hydro as a background for HQ

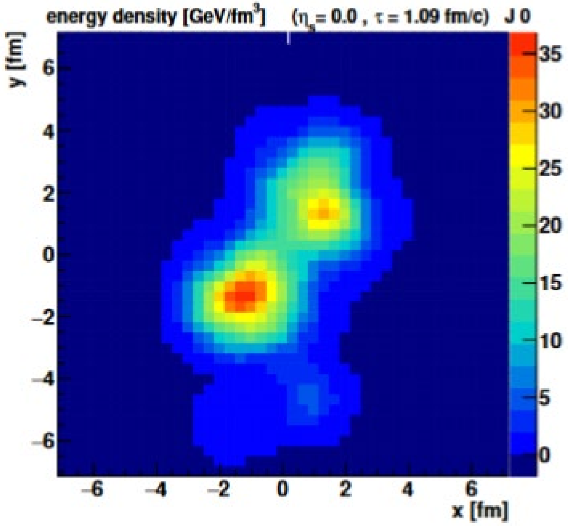
EPOS: state of the art framework that encompass pp, pA and AA collisions

Initial energy density

Beware: ≠ color scales



EPOS Pb-Pb central



EPOS Pb-Pb peripheral

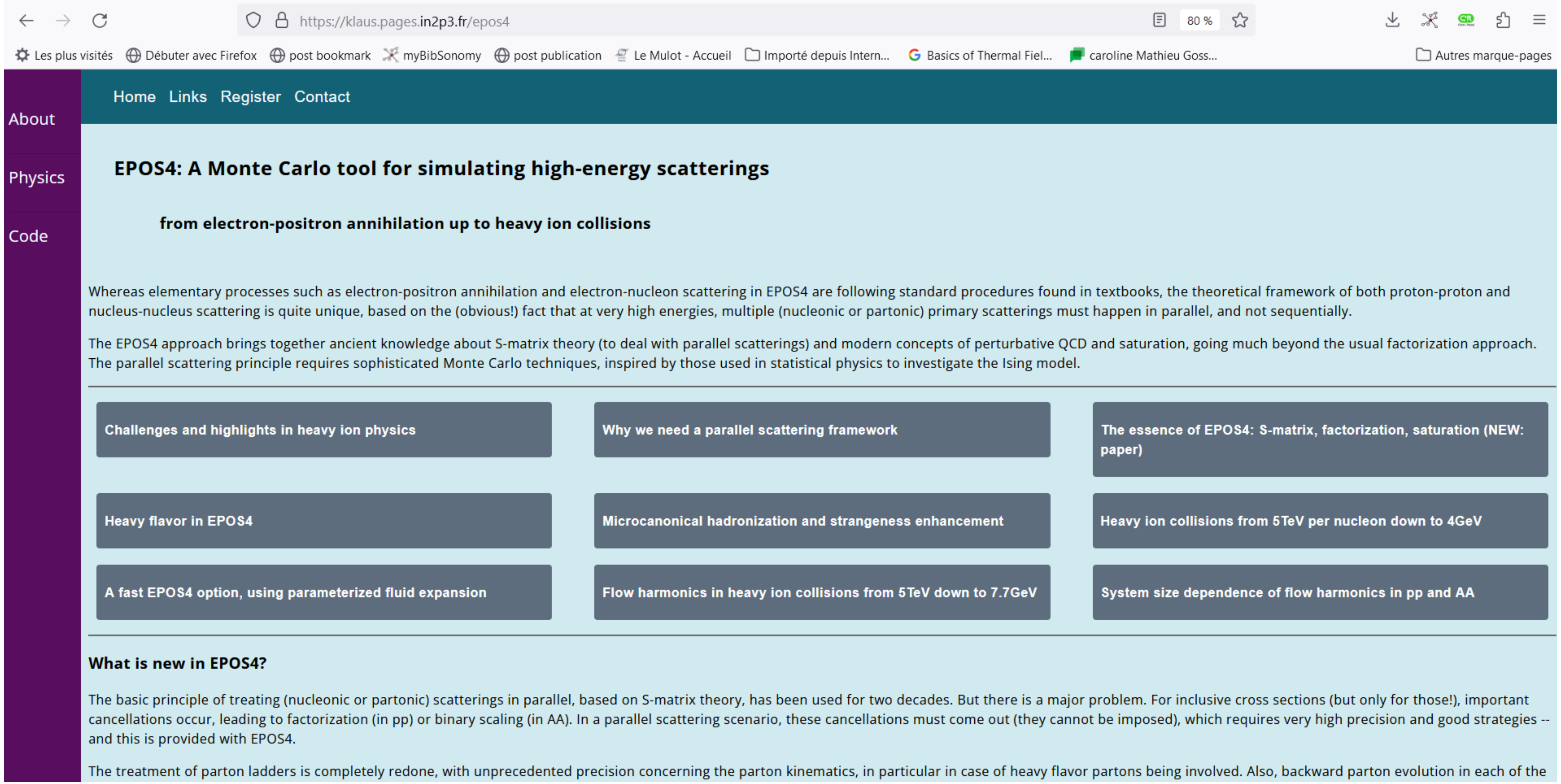
More realistic hydro and initial conditions => original HQ studies such as:

1) fluctuations in HQ observables

2) **correlations between HF and light hadrons**

≈1 year ago: EPOS4

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



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

from electron-positron annihilation up to heavy ion collisions

Whereas elementary processes such as electron-positron annihilation and electron-nucleon scattering in EPOS4 are following standard procedures found in textbooks, the theoretical framework of both proton-proton and nucleus-nucleus scattering is quite unique, based on the (obvious!) fact that at very high energies, multiple (nucleonic or partonic) primary scatterings must happen in parallel, and not sequentially.

The EPOS4 approach brings together ancient knowledge about S-matrix theory (to deal with parallel scatterings) and modern concepts of perturbative QCD and saturation, going much beyond the usual factorization approach. The parallel scattering principle requires sophisticated Monte Carlo techniques, inspired by those used in statistical physics to investigate the Ising model.

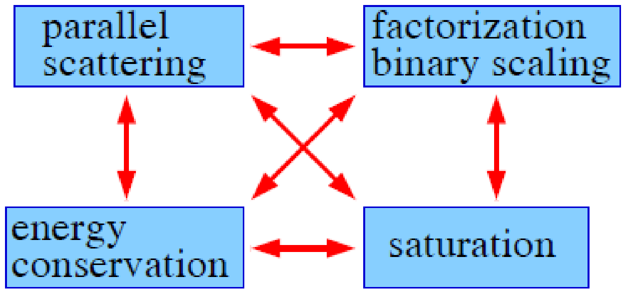
What is new in EPOS4?

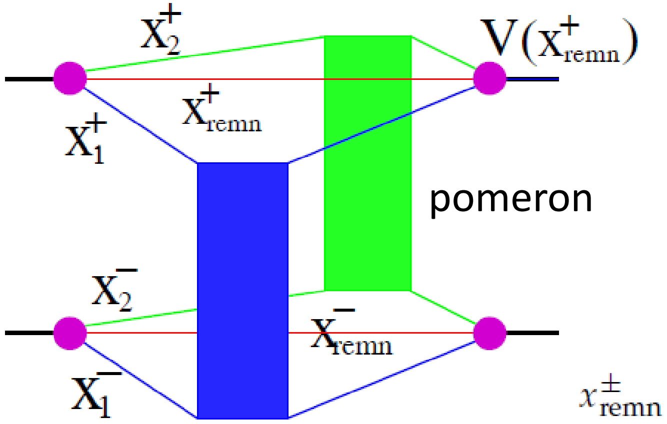
The basic principle of treating (nucleonic or partonic) scatterings in parallel, based on S-matrix theory, has been used for two decades. But there is a major problem. For inclusive cross sections (but only for those!), important cancellations occur, leading to factorization (in pp) or binary scaling (in AA). In a parallel scattering scenario, these cancellations must come out (they cannot be imposed), which requires very high precision and good strategies -- and this is provided with EPOS4.

The treatment of parton ladders is completely redone, with unprecedented precision concerning the parton kinematics, in particular in case of heavy flavor partons being involved. Also, backward parton evolution in each of the

One Novelty in EPOS4: Curing the factorization issue

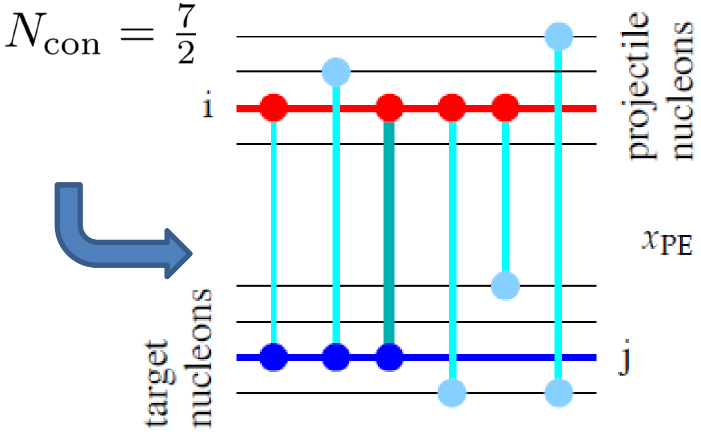
K. Werner. arXiv: 2301.12517





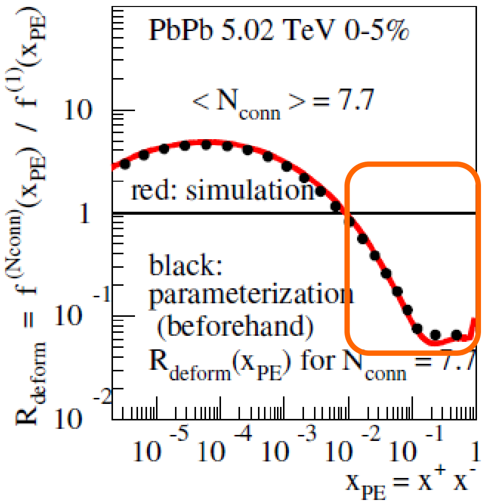
$x_{remn}^{\pm} = 1 - \sum x_i^{\pm}$

Double scattering diagram // energy conservation



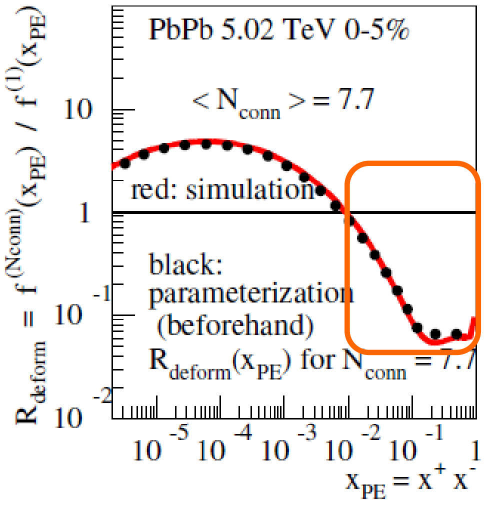
$x_{PE} = x^+ x^- = \frac{M_{Pom}^2}{s}$

Invariant mass of the “hard pomeron” is reduced due to the connection of both projectile and target pomerons to other pomerons



R_{deform}: Depletion of the high pomeron mass frequency due to many energy sharings

One Novelty in EPOS4: Curing the factorization issue



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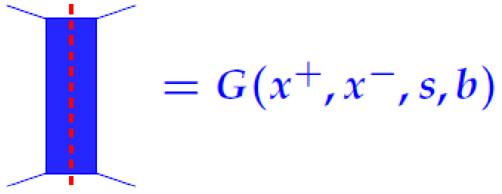


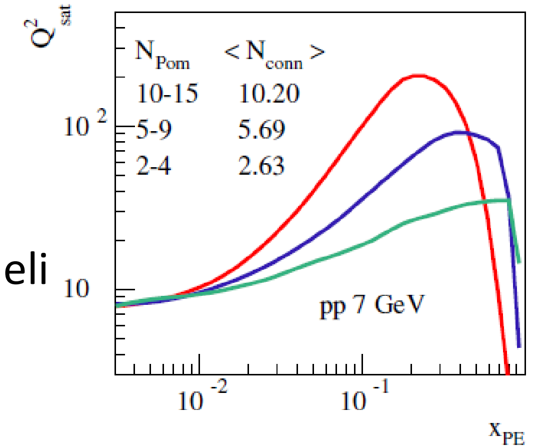
$= G(x^+,x^-,s,b)$

The cut pomeron

The “amazingly simple” solution in EPOS4: define $G(x^+,x^-,s,b) = \dfrac{n}{R_{\mathrm{deform}}(x_{\mathrm{PE}})} G_{\mathrm{QCD}}(Q^2_{\mathrm{sat}},\, x^+,x^-,s,b)$

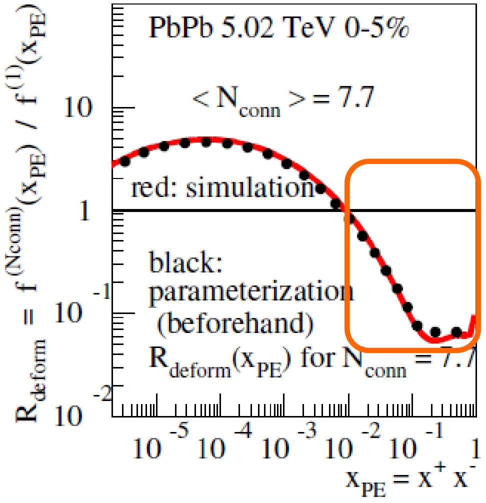
With $Q_{\mathrm{sat}}(N_{\mathrm{conn}},x^+,x^-)$ chosen implicitly such that G does not depend on N_{conn} .

$$\frac{d^2\sigma^{AB\,(N_{\mathrm{conn}})}_{\mathrm{incl}}}{dx^+dx^-} \propto \frac{d\sigma^{\mathrm{single\ Pom}}_{\mathrm{incl}}}{dx^+dx^-}\left[Q^2_{\mathrm{sat}}(N_{\mathrm{conn}},x^+,x^-)\right]$$



- which perfectly warrant the factorization at large p_T; one recovers binary scaling (generalized Abramovskii Gribov Kancheli theorem).
- For large N_{conn}, low p_T is suppressed

One Novelty in EPOS4: Curing the factorization issue



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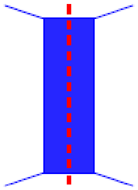

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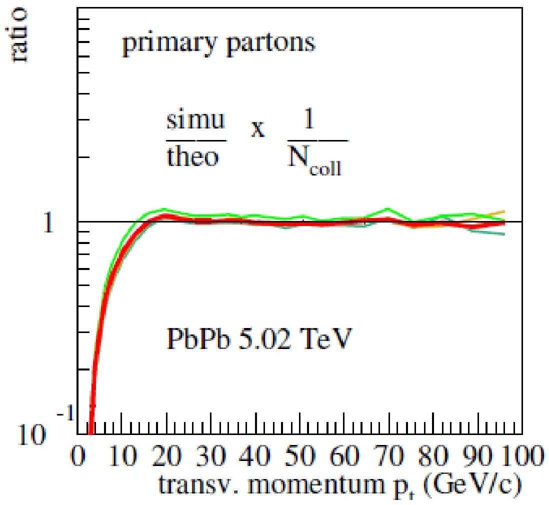
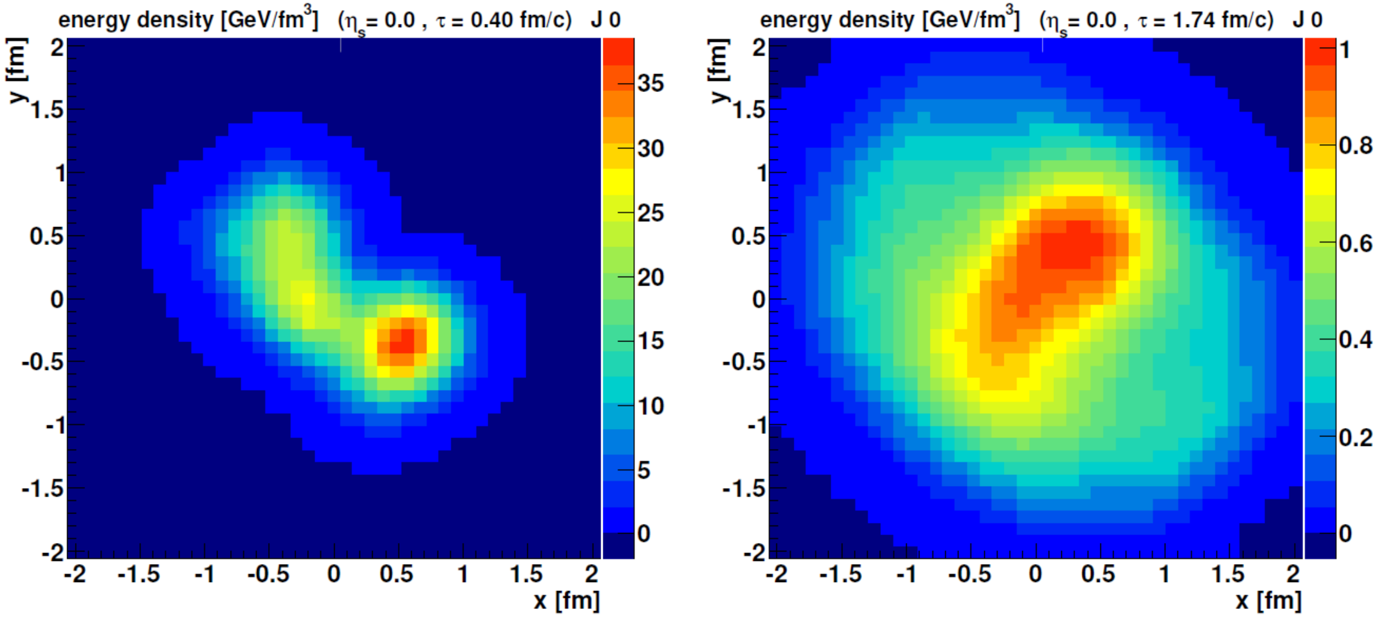


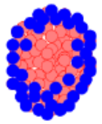
EPOS4 for small systems

EPOS + Hydro : state of the art framework that encompass pp, pA and AA collisions

=> Go and look in pp



Small system



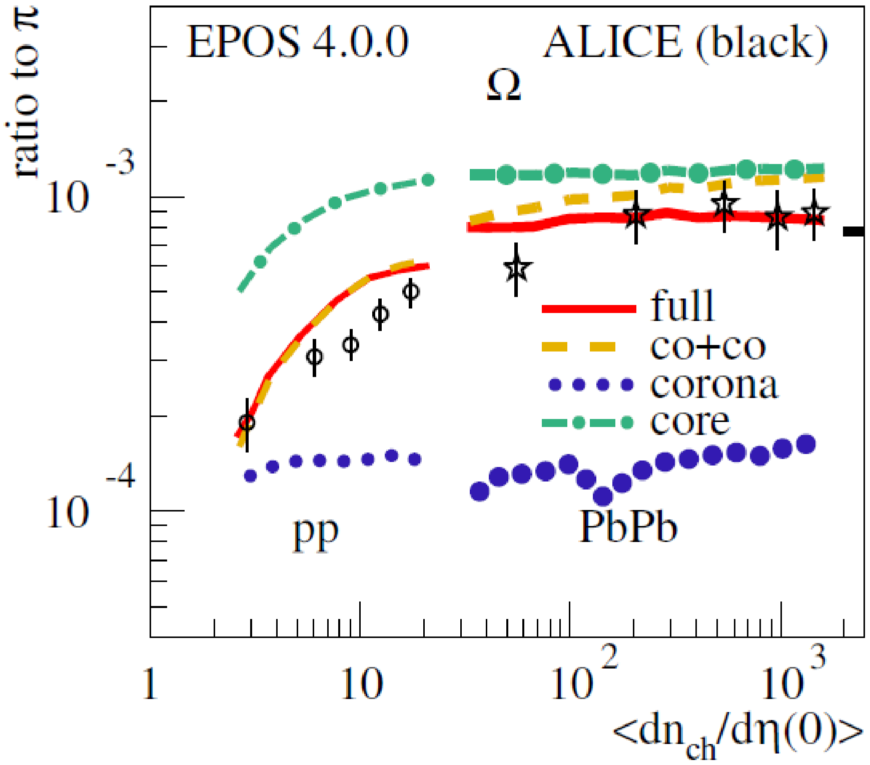
corona = blue **core = red**

The energy density is larger than the critical energy density ϵ_0 —> deconfined QCD matter in pp as well !

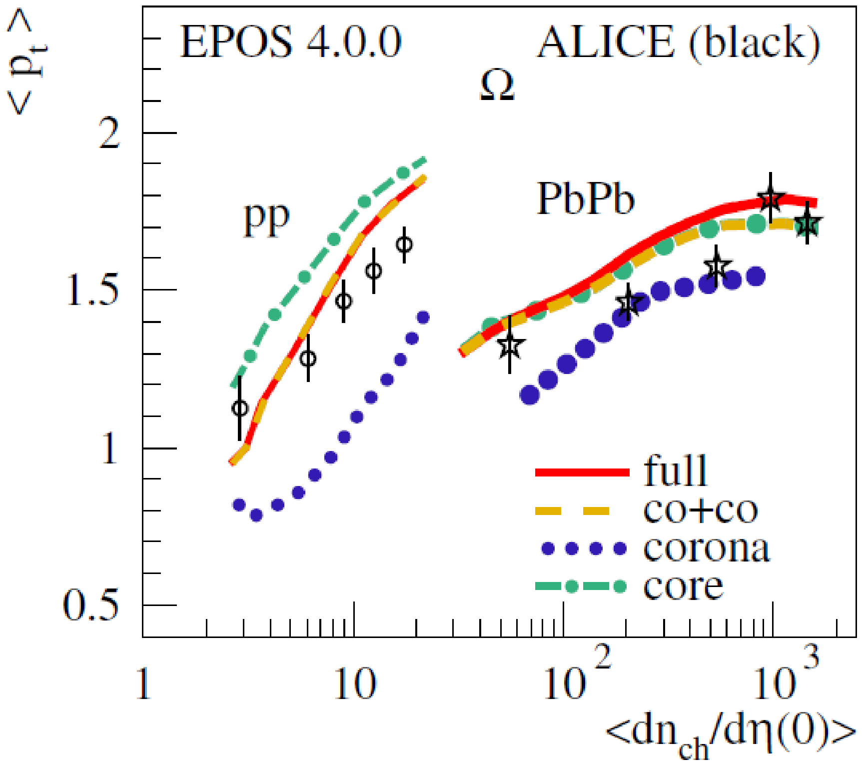
=> In EPOS4, QGP droplet is one of the ingredients of collectivity

Full EPOS4: checking multiplicity dependencies and <p_t>

continuous curve



jump



Affected by:

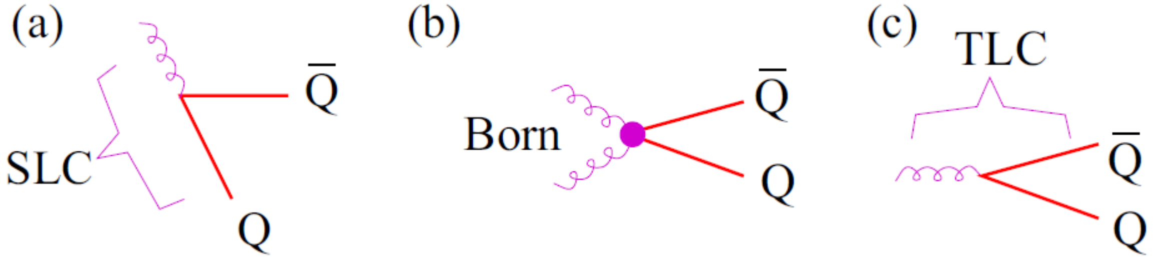
- **core-corona**
- **microcanonical**
- **hadronic cascade (UrQMD)**

- **Saturation**
- **Flow**
- **core-corona**

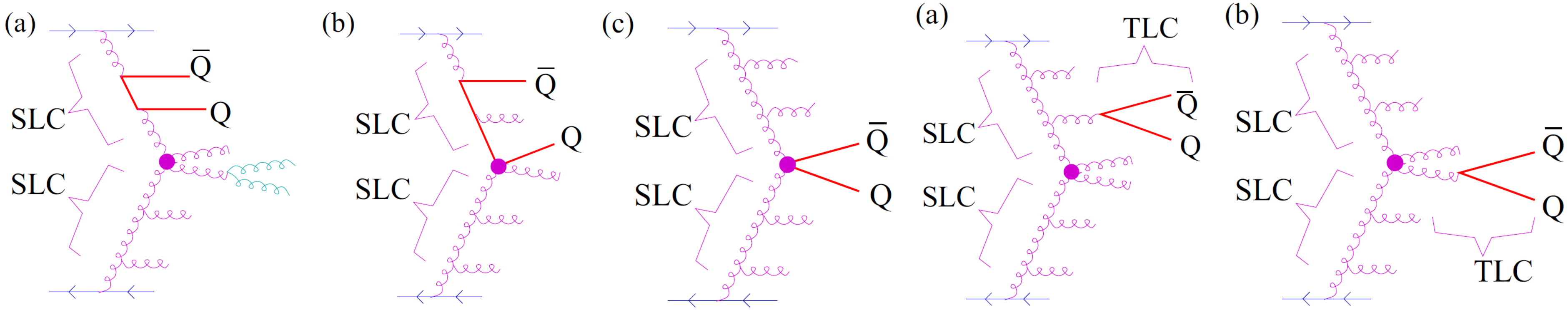
HQ sector: Improved HF production in EPOS4

Initial production of heavy quarks through

K. Werner, B. Guiot, Phys.Rev.C 108 (2023) 3, 034904

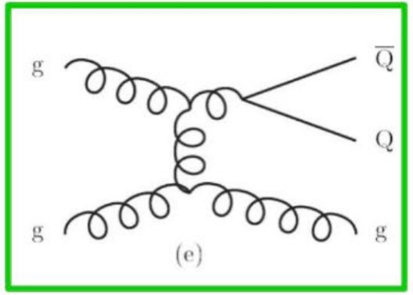


Found in the following “evolutions” :



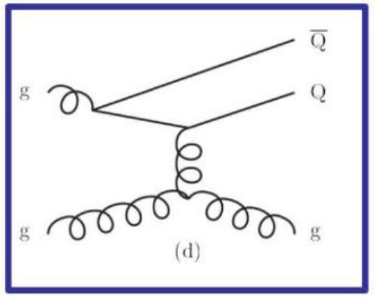
Includes the 3 basic mechanisms present in other MC generator like Pythia

Gluon splitting



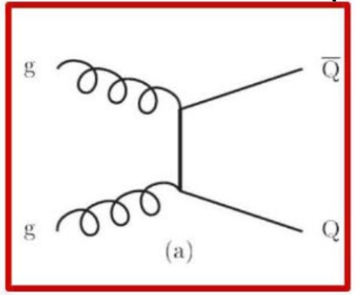
TLC

Flavor excitation



SLC

Flavor creation (LO)

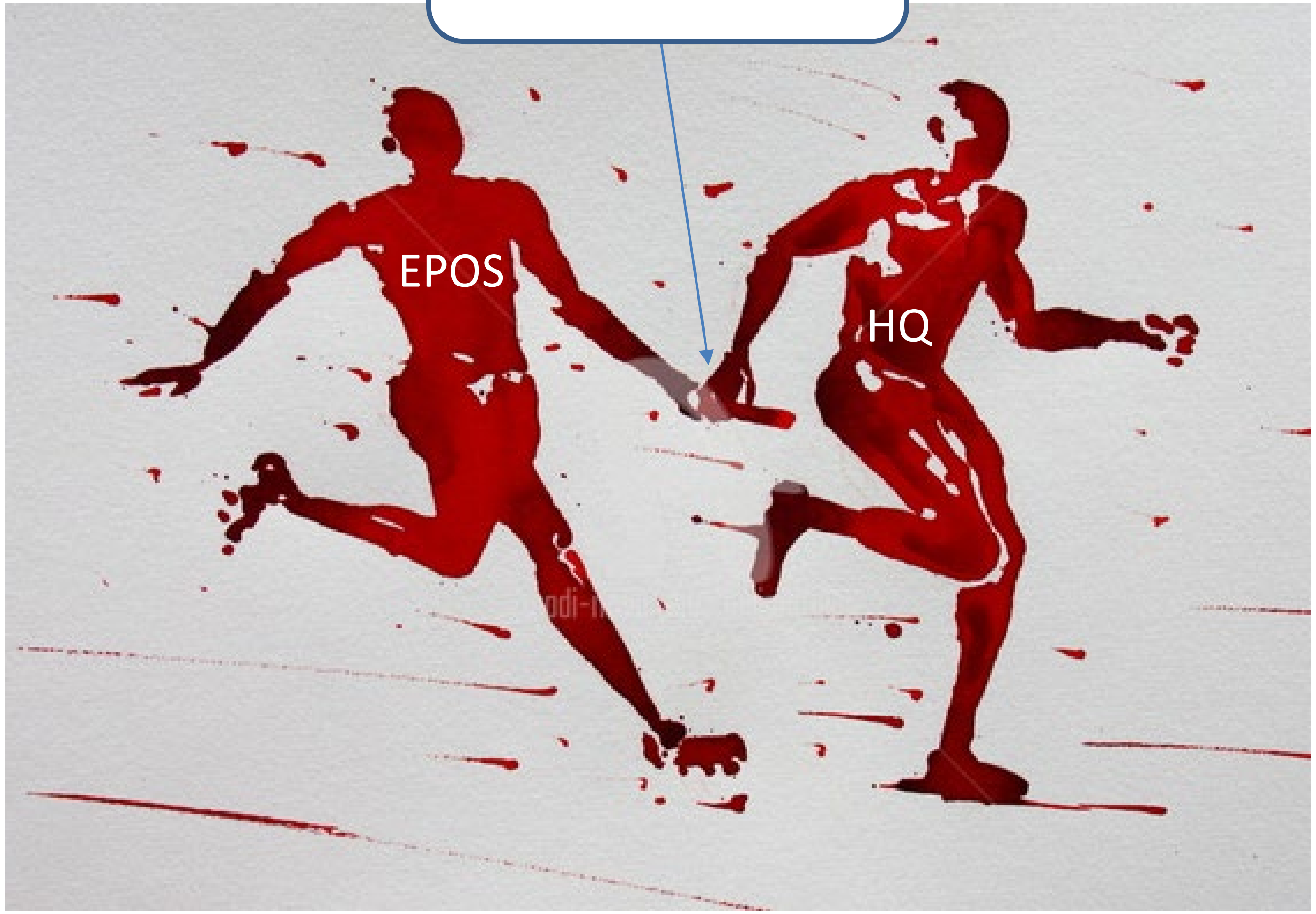


Born

Later hadronized through string breaking in EPOS4

From EPOS4 to (MC@s)HQ

QGP Bulk (t) + initial distribution of HQ

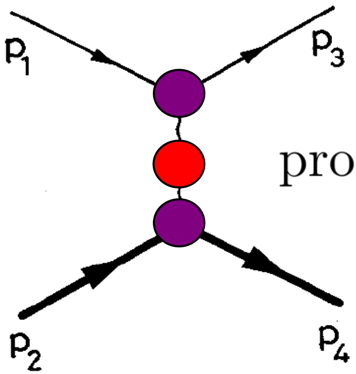


The core energy loss from the HQ part

Colisional component

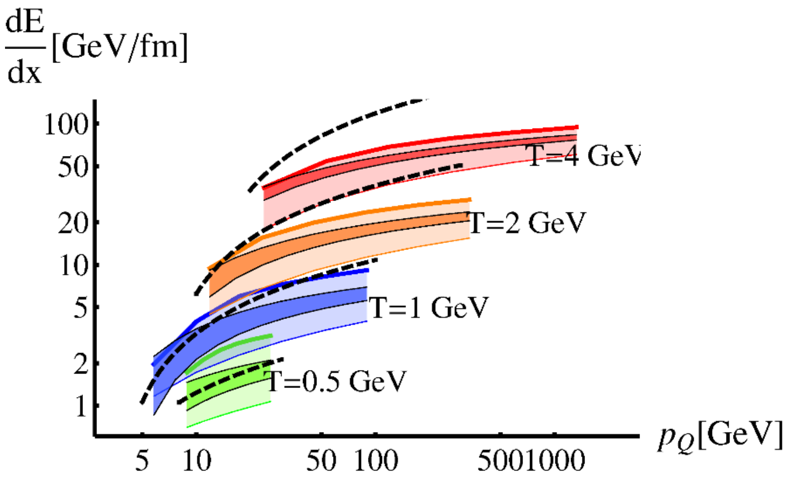
- One-gluon exchange model: reduced IR regulator $\kappa\, m^2_{\mathrm{Dself}}$ in the hard propagator, fixed on HTL Energy loss (maximal insensitivity of dE/dx on q*)
- Running coupling $\alpha_{\mathrm{eff}}(t)$
- self consistent Debye mass

$$m_{\mathrm{Dself}}^2\,(T) = (1+n_f/6)\; 4\pi\alpha_{\mathrm{eff}}(m_{\mathrm{Dself}}^2)T^2$$



$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{\mathrm{Dself}}(T)}$$

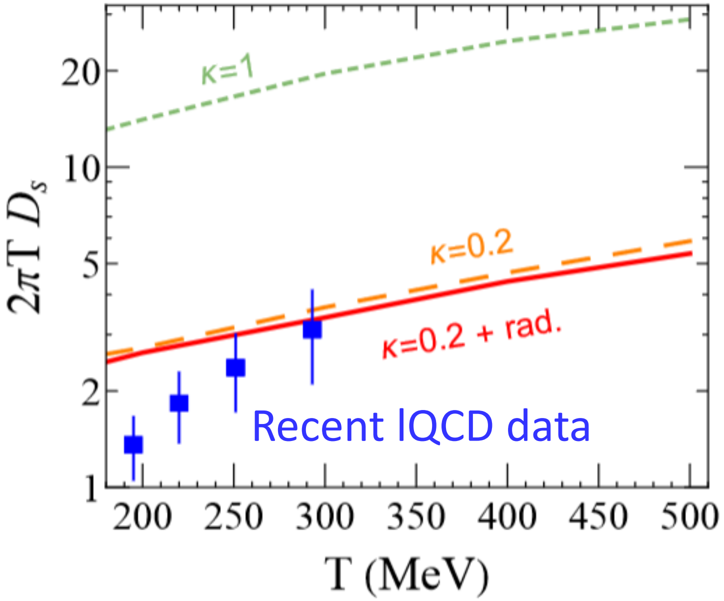
+ u and s channels



Comparison with Peigné-Peshier at finite momentum

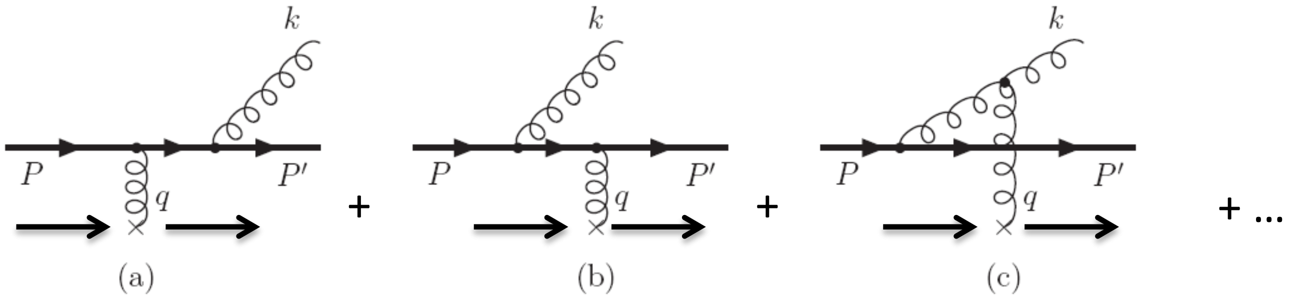
$$D_s = \lim_{p_Q\to 0} T/(M_Q \eta_D)$$

η_D : drag coefficient



The core energy loss from the HQ part

Radiative component



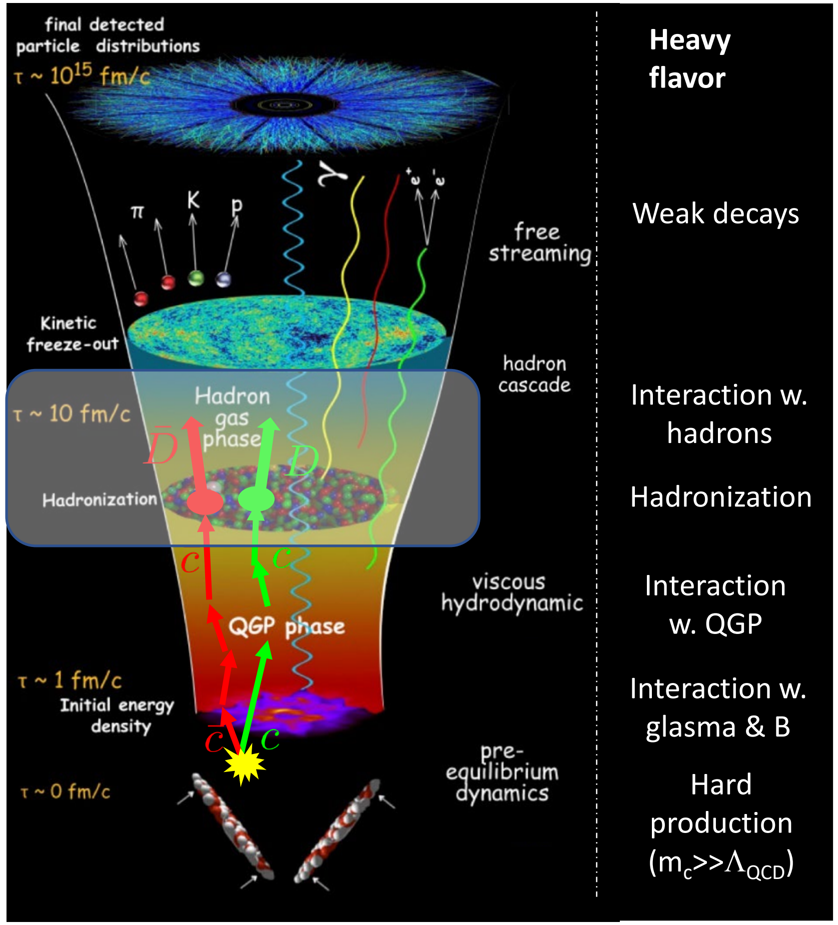
- Extension of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q) distribution of induced gluon radiation per collision (ΔE_{rad} α E L):

$$P_g(x, \mathbf{k}_\perp, \mathbf{q}_\perp, m_Q) = \frac{3\alpha_s}{\pi^2} \frac{1-x}{x} \left(\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2 + x m_Q^2} - \frac{\mathbf{k}_\perp - \mathbf{q}_\perp}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + x m_Q^2} \right)^2$$

- LPM effect for moderate gluon energy

Implemented in EPOS4-HQ through Boltzmann transport

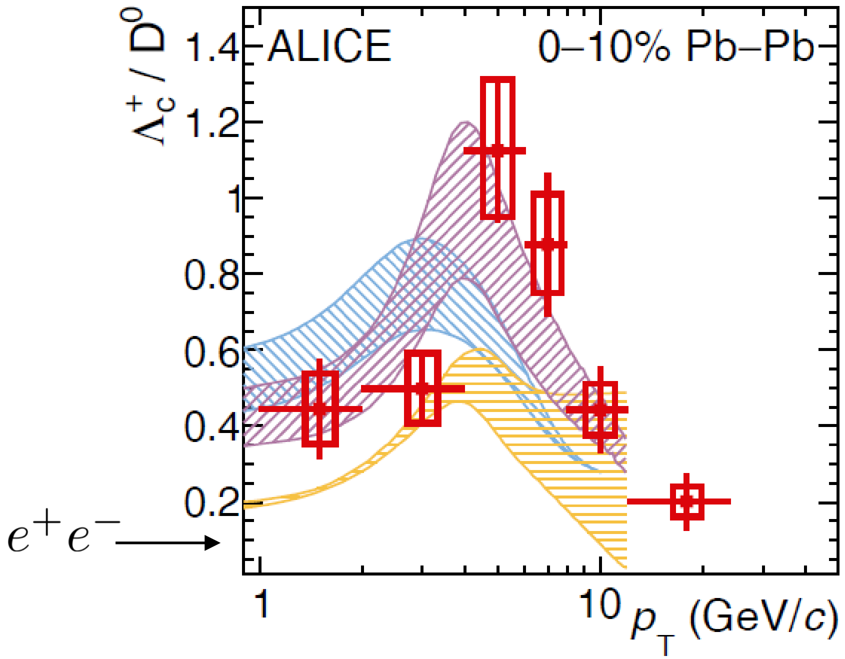
Heavy quarks (Q) as ideal hard probes:



- Evolution in the QGP DOES NOT modify the yield of initial Q and Qbar: Negligible annihilation rate !
- **It only impacts their distribution in momentum**
  - Hence, for usual observables like RAA and v2 … only the initial "1 body" distribution matters

Mostly like in elementary pp collisions…

- **… However hadronization is affected by the QGP**
  - Other mechanism wrt usual fragmentation of HQ in elementary collisions : **coalescence / recombination**



The recombination of heavy quark with some *existing* light quark(s) from the QGP is an essential mechanism at "low" $p_T < 5\text{-}10$ GeV/c…

Mandatory to understand the $\Lambda c/D^0$ ratio

The coalescence + fragmentation hadronization

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

Heavy quarks hadronize via coalescence + fragmentation in EPOS4HQ!

NEW!

EPOS4 with only string fragmentation

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

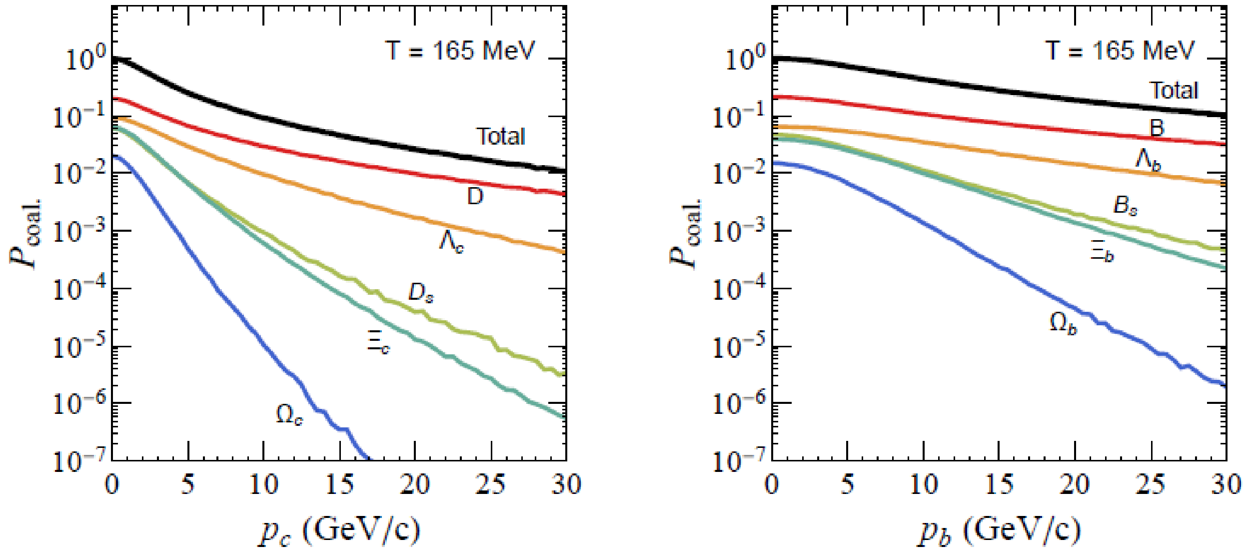
J. Zhao's work

$1 - P_{\mathrm{coal.}}$ *for fragmentation (HQET based fragmentation function)*

We include almost all hadrons (missing baryons predicted by the potential model; 17D,10D_s,38Λ_c,54Σ_c,92Ξ_c,54Ω_c; except the rare HF hadrons)

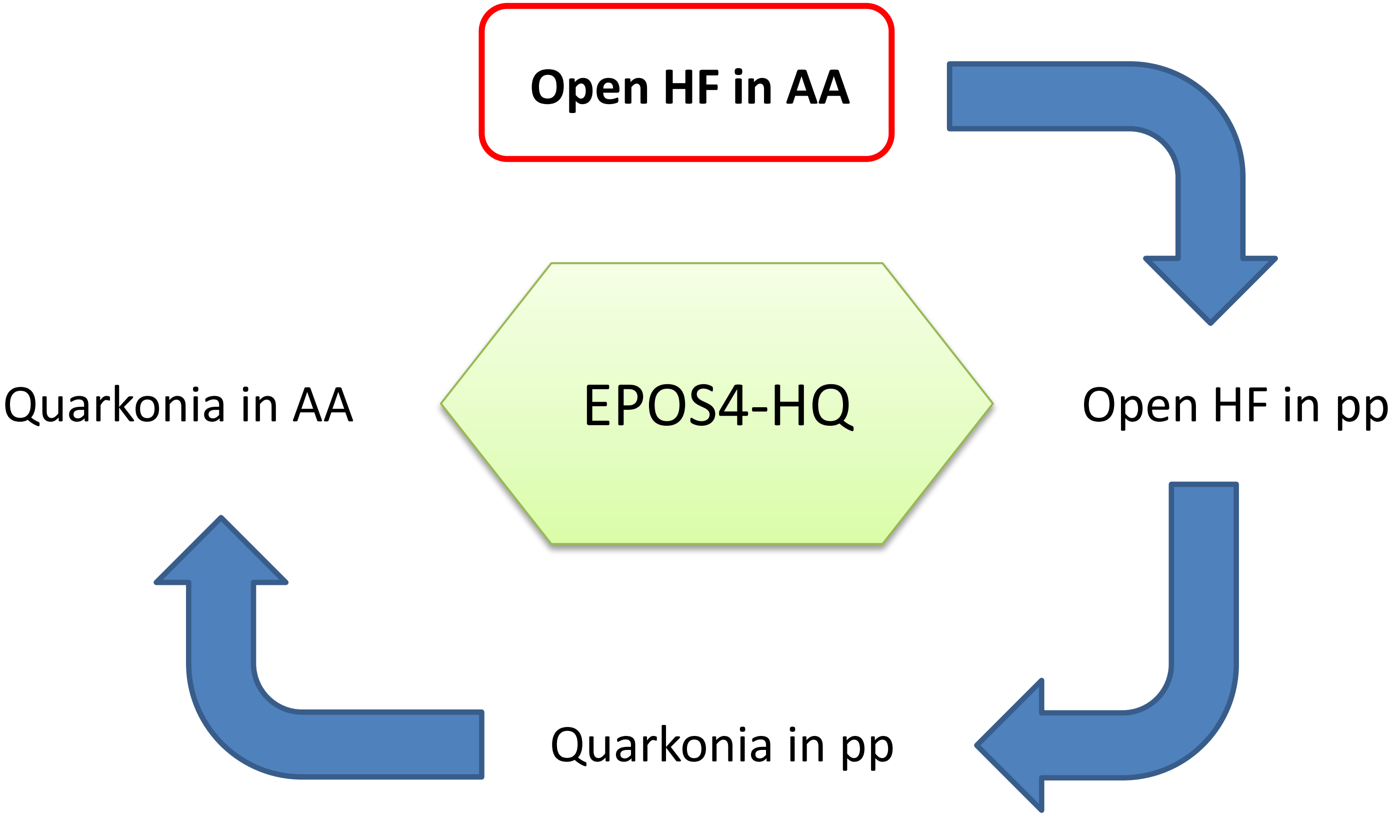
Ground states Wigner density: $W(p_r) = (2\sqrt{\pi}\sigma)^3 e^{-\sigma^2 p_r^2}$ *Width is given by the potential model*

Excited states are involed via the thermal ratio: $n_i = \frac{g_i}{2\pi^2} T_{\mathrm{FO}} m_i^2 K_2\left(\frac{m_i}{T_{\mathrm{FO}}}\right)$ $R^m = n^m_{\mathrm{excited}}/n_{\mathrm{ground}}.$



After hadronization, evolution in hadronic phase —> UrQMD

HF in EPOS4-HQ



Open HF in AA

Open HF in pp

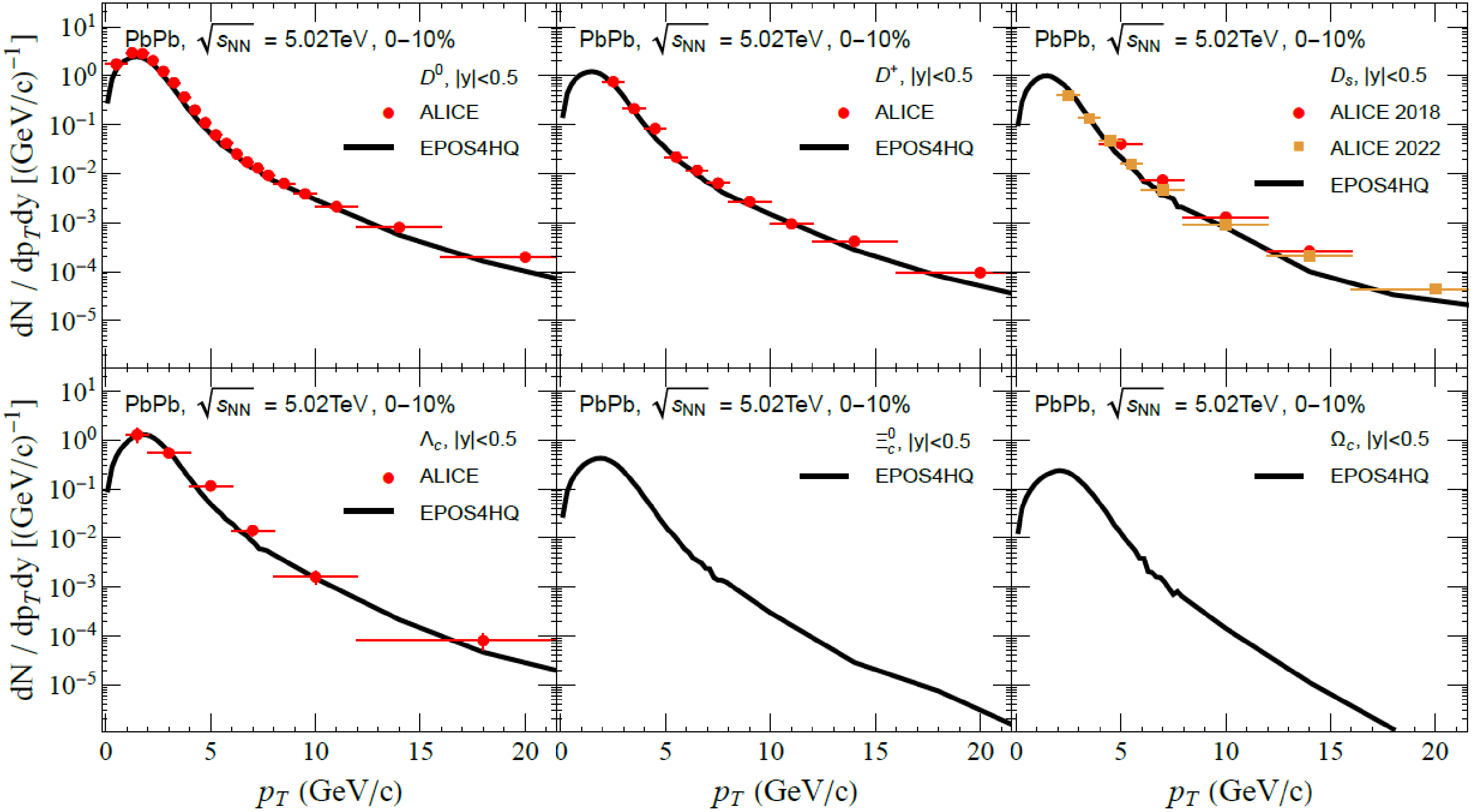
Quarkonia in pp

Quarkonia in AA

EPOS4-HQ

OHF hadrons p_T distributions in EPOS4-HQ

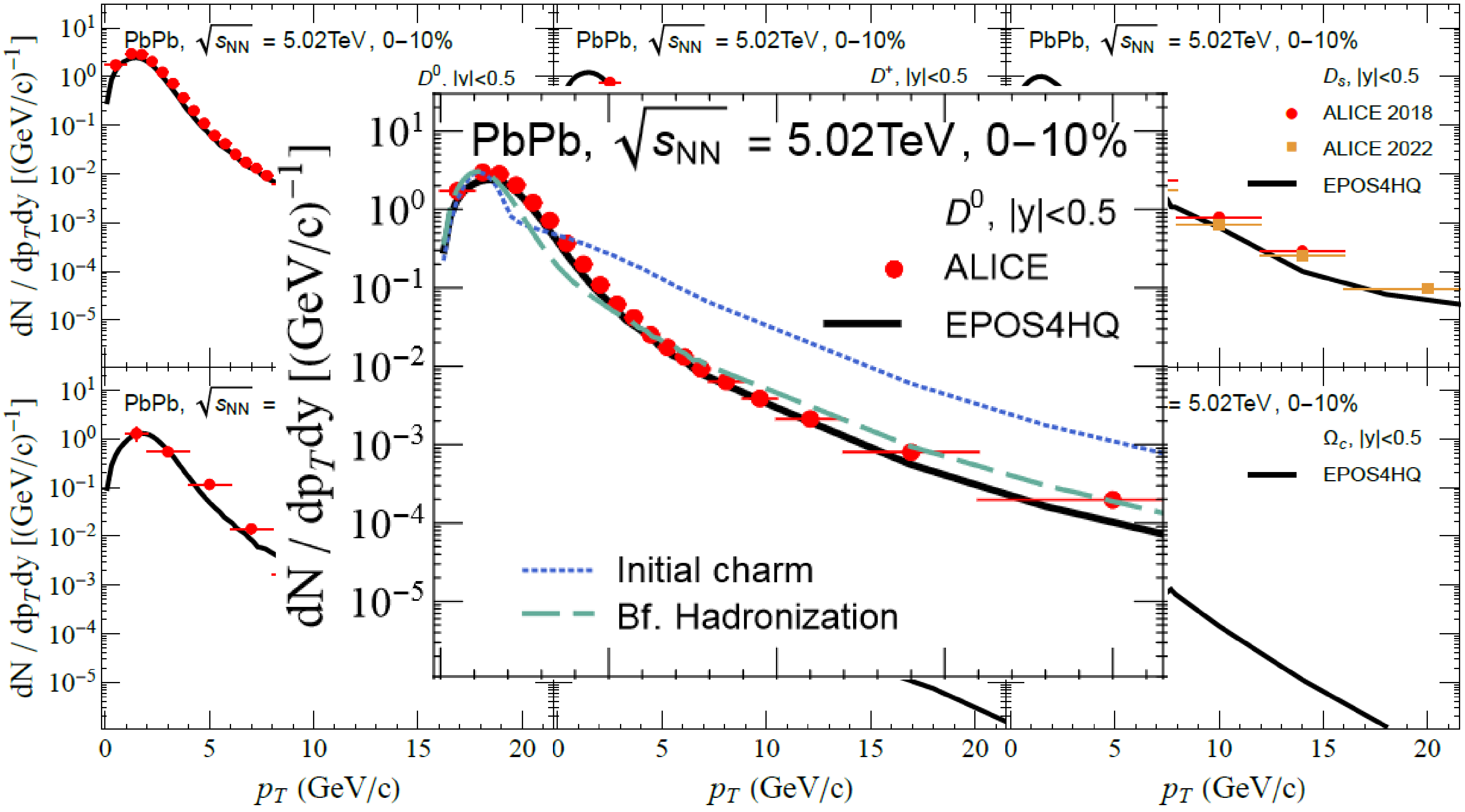
PbPb central @ LHC



Very good agreement for all resonances

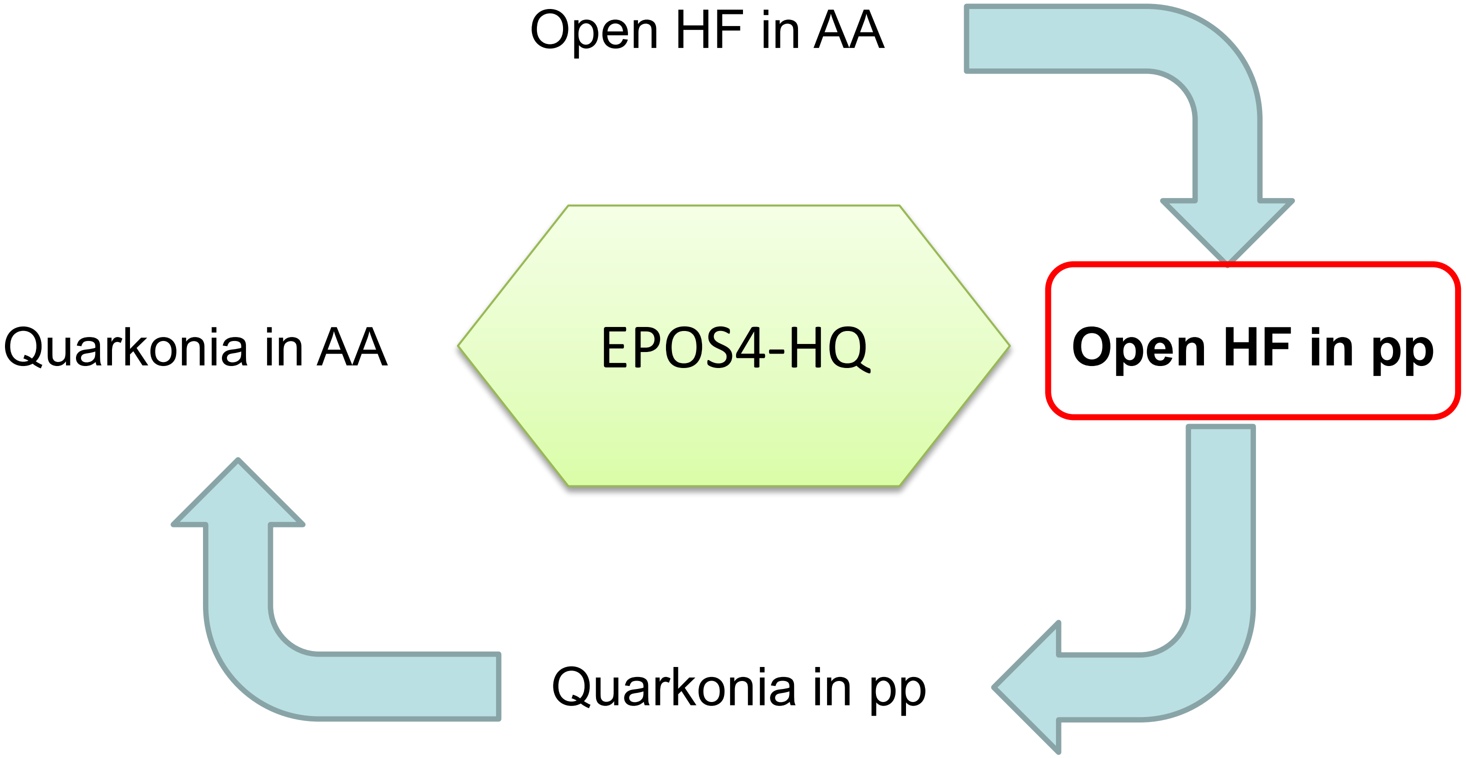
OHF hadrons p_T distributions in EPOS4-HQ

PbPb central @ LHC



Largest effect in AA : Energy loss of c-quarks

HF in EPOS4-HQ



Open HF in AA

Quarkonia in AA

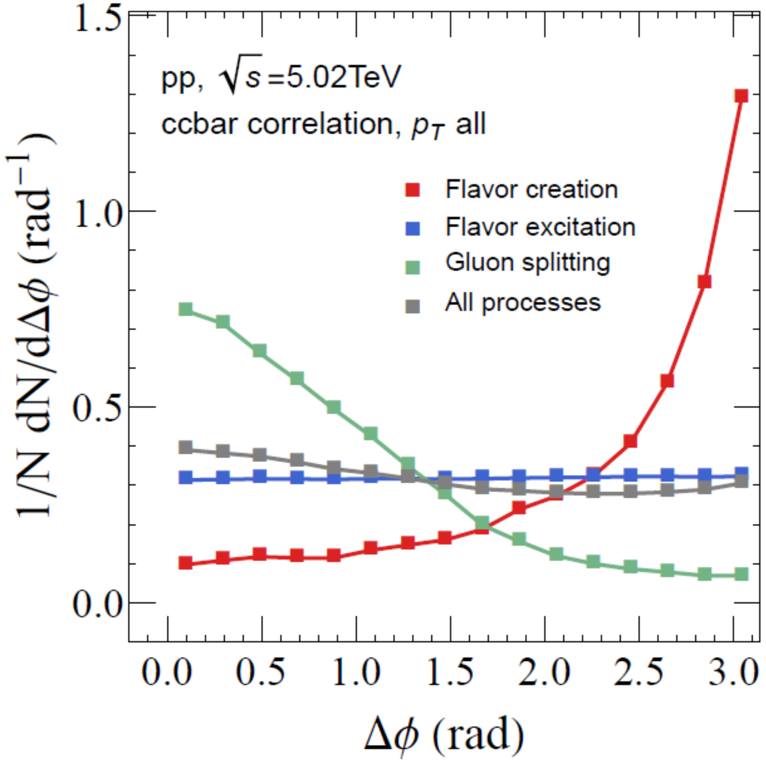
EPOS4-HQ

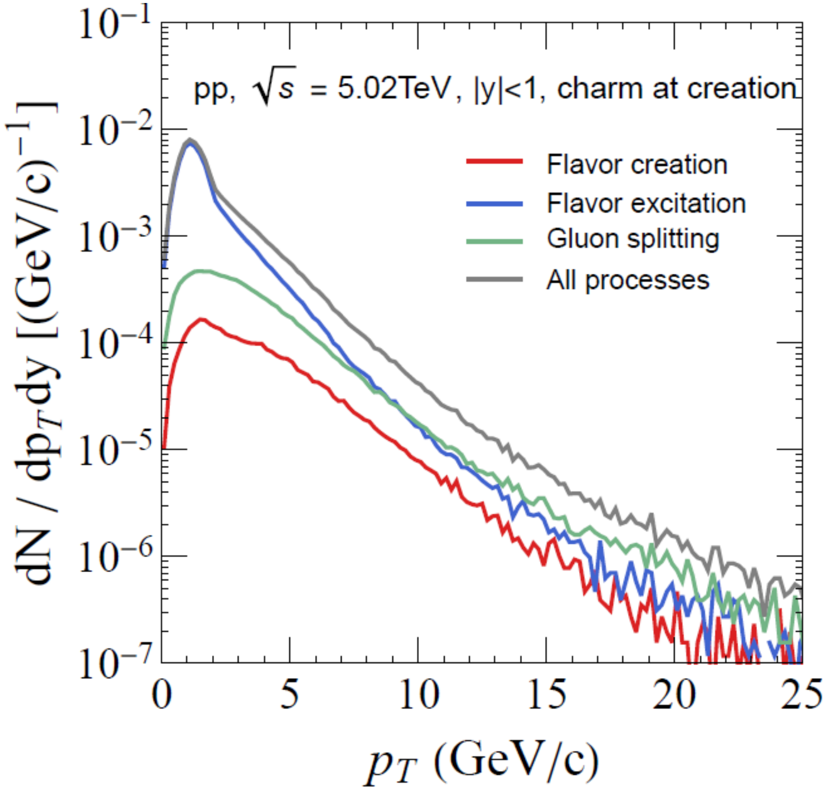
Open HF in pp

Quarkonia in pp

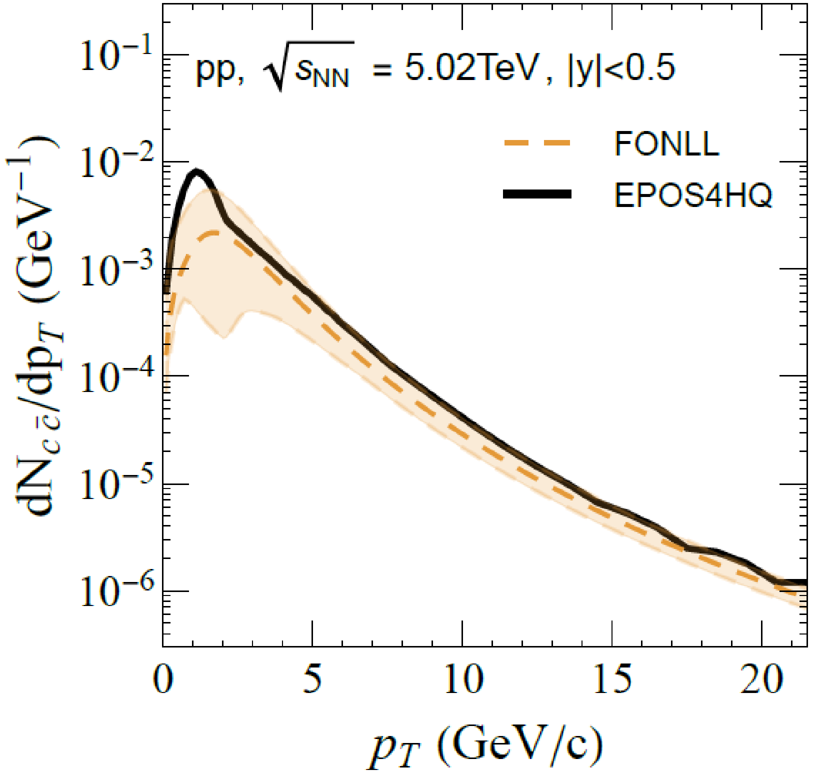
HF production in pp

See *K. Werner. arXiv: 2306.02396*





Dominance of the flavor excitation mechanism at small p_t

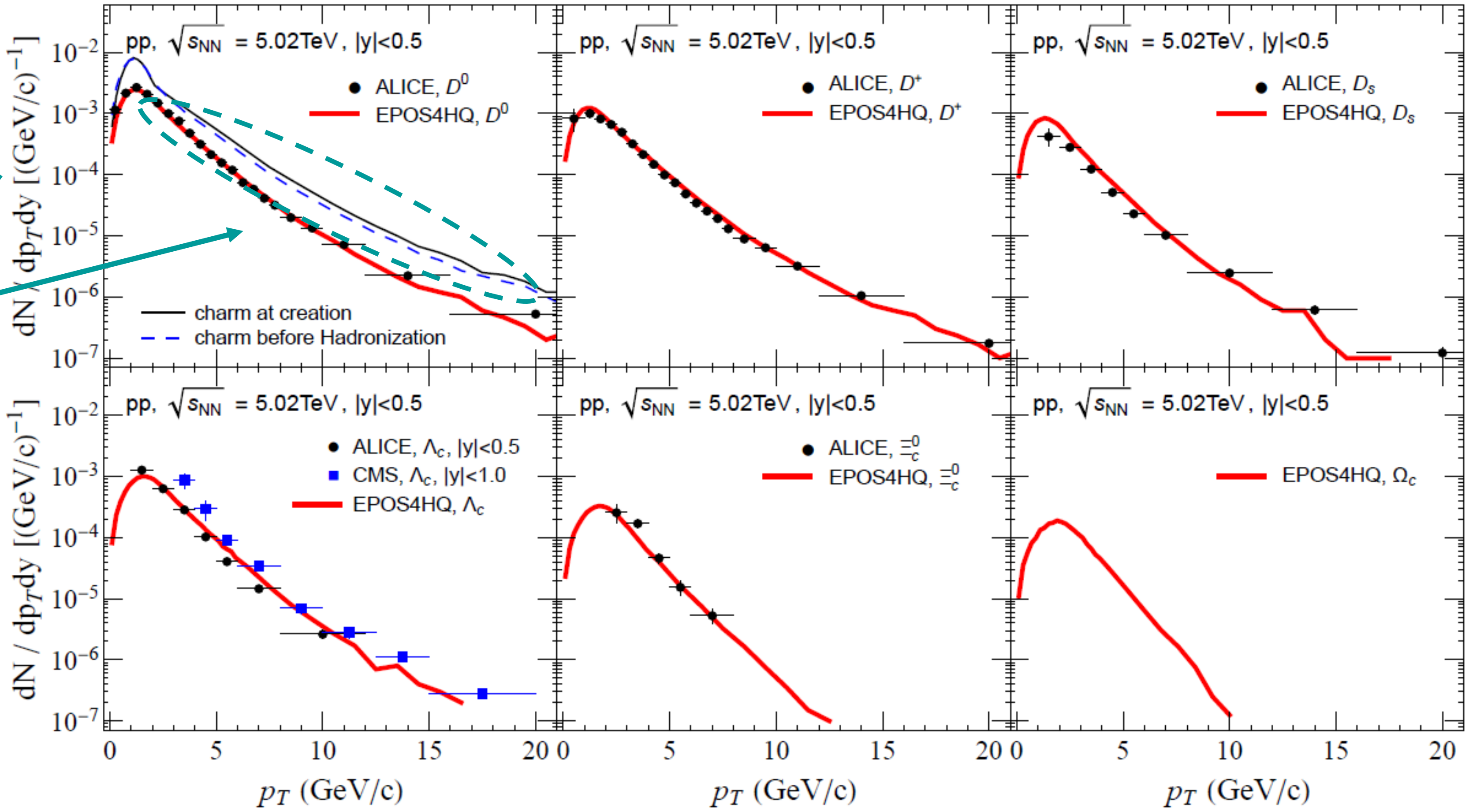


Some overshooting of the FONLL uncertainty band below 1 GeV, but very good agreement at large p_T where FONLL is best justified

Hadrons yield in pp

Heavy flavor as a probe of hot QCD matter produced in proton-proton collisions

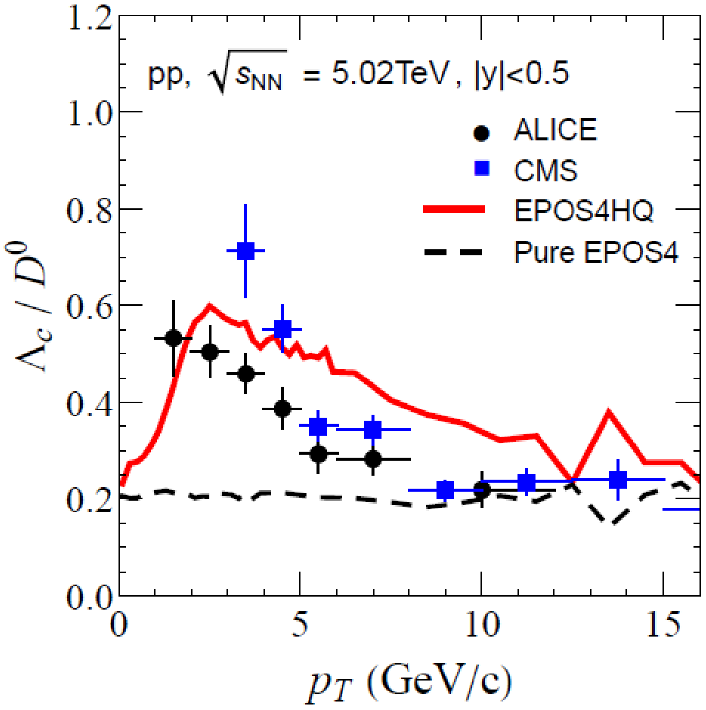
Jiaxing Zhao, Joerg Aichelin, Pol Bernard Gossiaux, and Klaus Werner
Phys. Rev. D **109**, 054011 – Published 6 March 2024

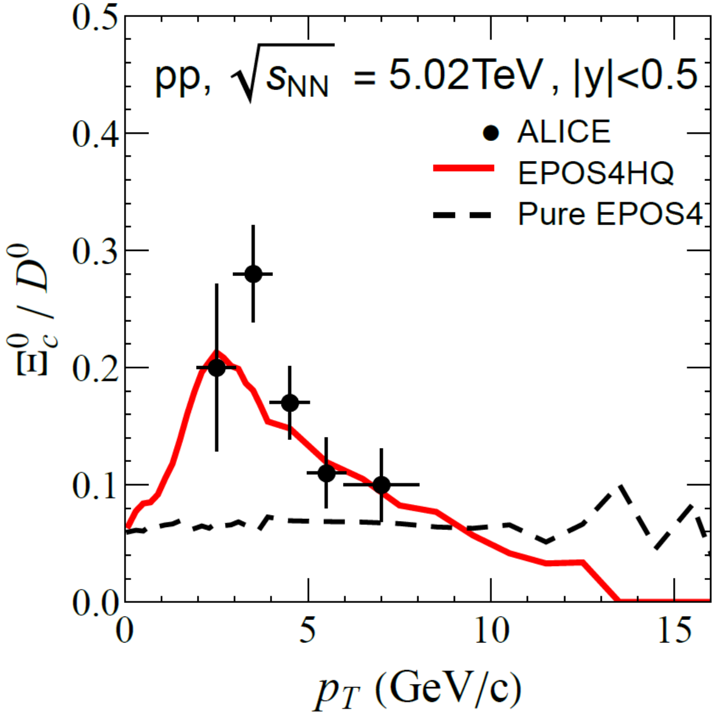


Very small energy loss !

Good agreement in the pp sector, essentially due to the **coalescence + fragmentation hadronization**

Yield ratios in pp

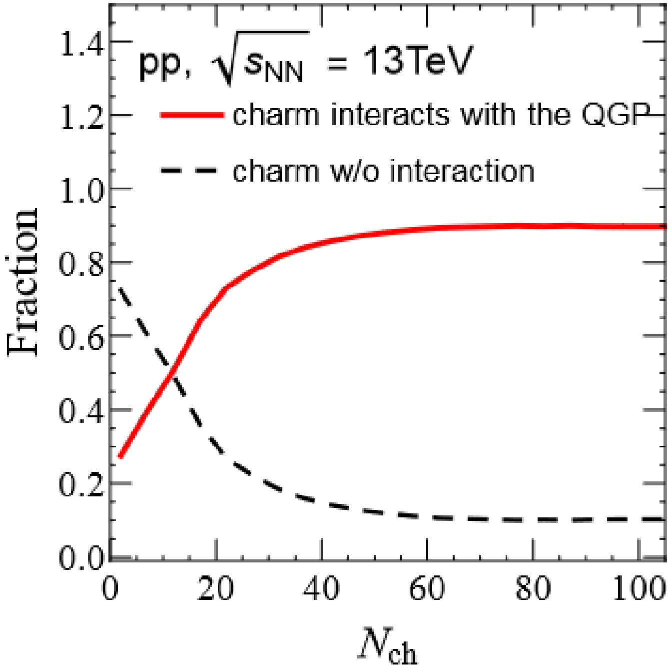


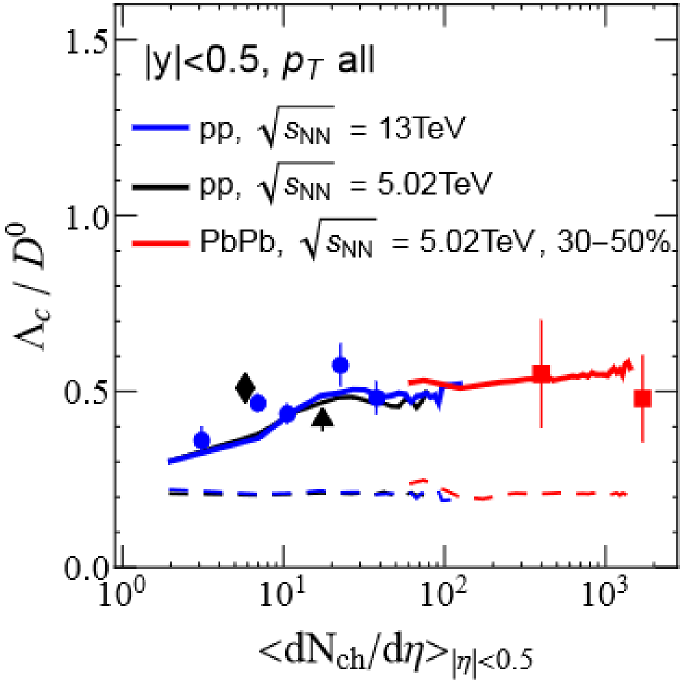


The coalescence + fragmentation hadronization is also successful in describing the yield ratio between charmed baryon to meson !

See as well : M. He and R. Rapp, Phys. Lett. B 795, 117 (2019), V. Minissale, S. Plumari, and V. Greco, Phys. Lett. B 821, 136622 (2021), H.-h. Li, F.-l. Shao, and J. Song, Chin. Phys. C 45, 113105 (2021), A. Beraudo, A. De Pace, D. Pablos, F. Prino, M. Monteno, and M. Nardi, arXiv:2306.02152

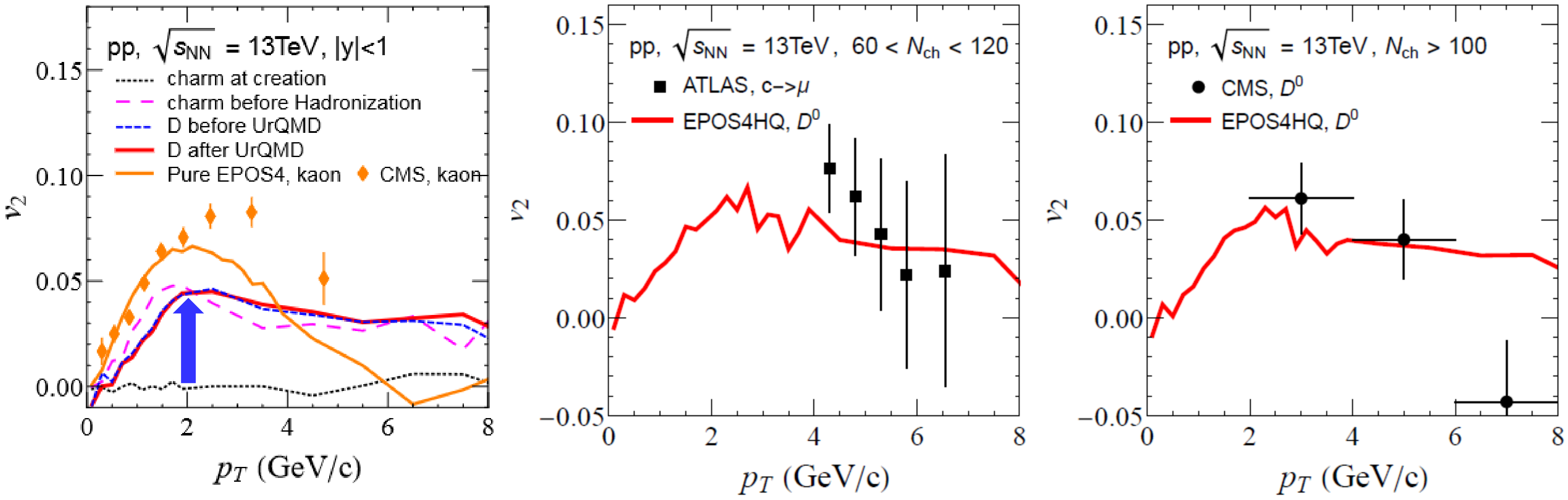
QGP droplet in pp ?

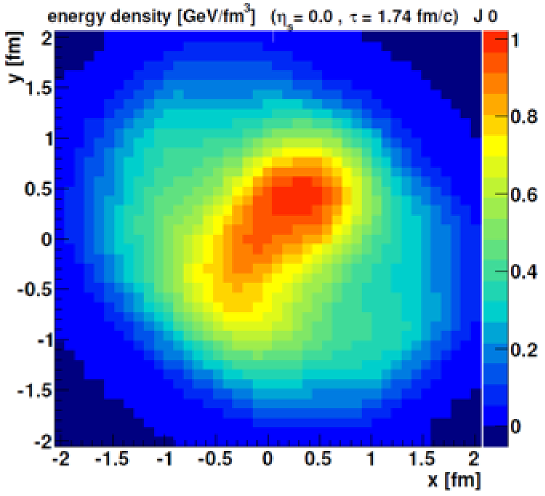




The yield ratio increase with centrality is correlated with the fraction of c quarks which interact with the QGP droplet

Azimuthal distributions in pp: v_2





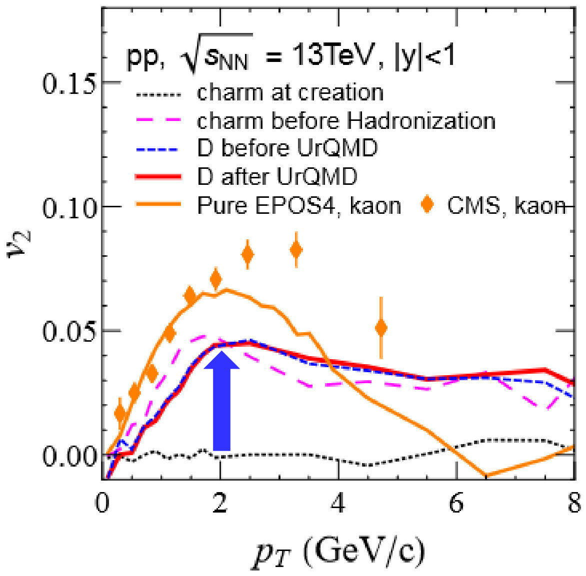
EPOS4HQ describes well the elliptic flow of D meson !

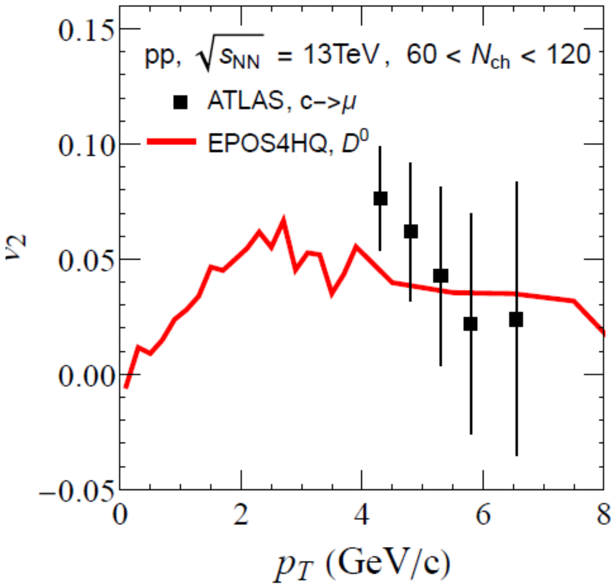
Clear sign of momentum redistribution during the short evolution (only comes through the v_2 in pp)

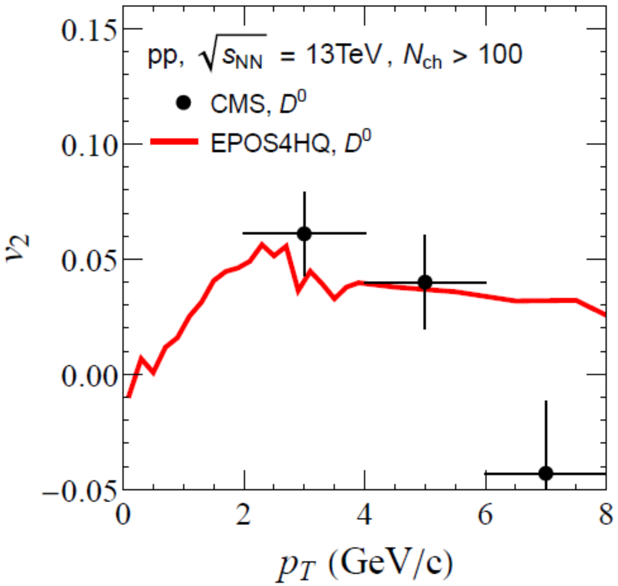
Little effect of the hadronic stage

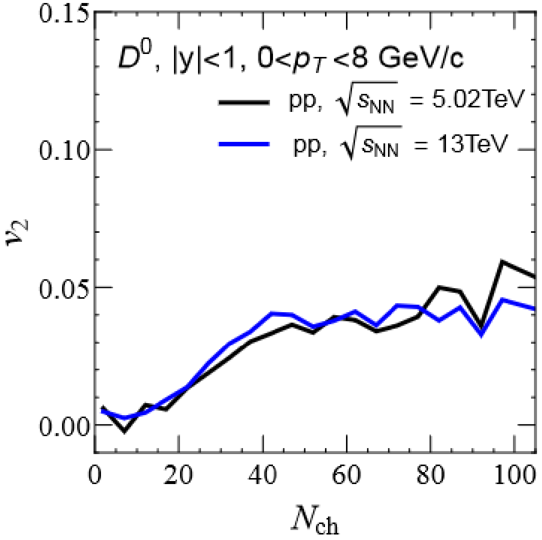
See as well : A. Beraudo, A. De Pace, D. Pablos, F. Prino, M. Monteno, and M. Nardi, arXiv:2306.02152

Azimuthal distributions in pp: v_2









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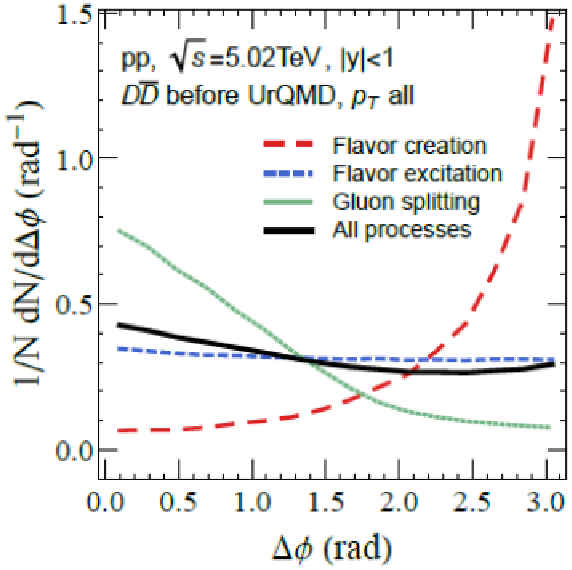
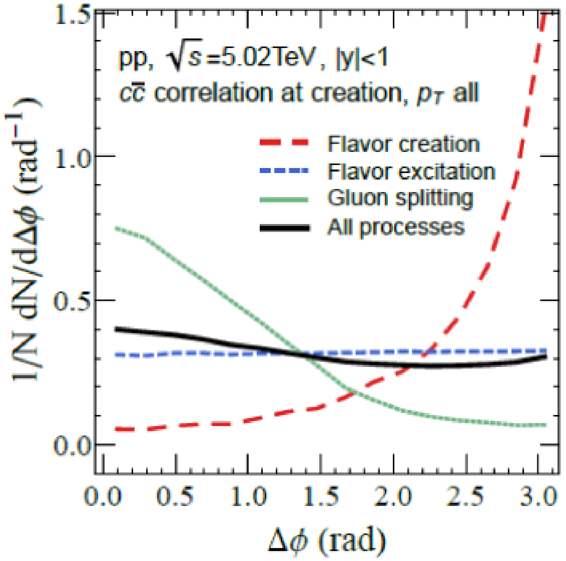
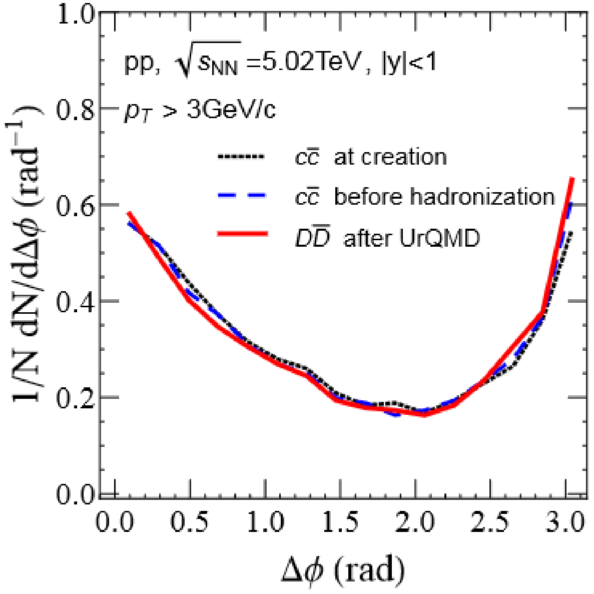
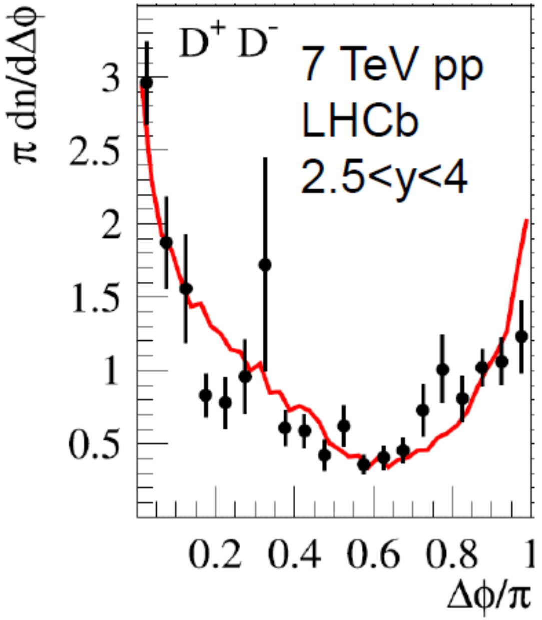
Azimuthal distributions in pp







JHEP06(2012)141



Small modification to the azimuthal correlations => constrain the HQ production process via final $D\overline{D}$ correlations!

Good agreement with the experiment (also for other correlations)

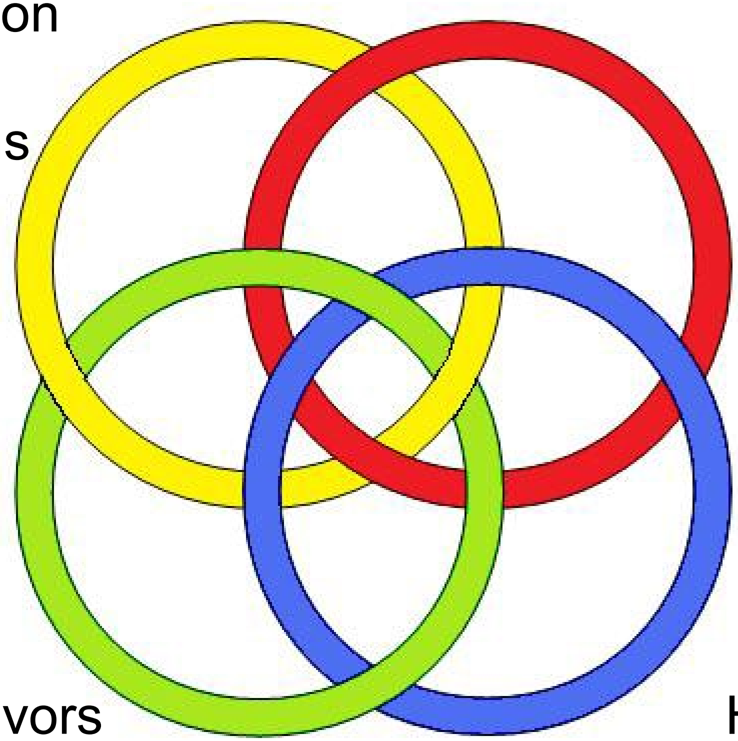
Recap : HF in pp

observable	**HQ energy loss in QGP**	**Coalescence in the presence of a QGP droplet**
Hadron pt spectra	Little effect	**LARGE effect**
Hadron yield ratios	Little effect	**LARGE effect**
v2	**LARGE effect**	Little effect
Azimuthal correlations	Little effect	Little effect

According to EPOS4-HQ: Everything consistent with the production of a short-lived QGP in most active pp collisions at LHC

To come : adding the quarkonia component…

HF Borromeo’s rings



🙂 HF production
and
🙂 correlations

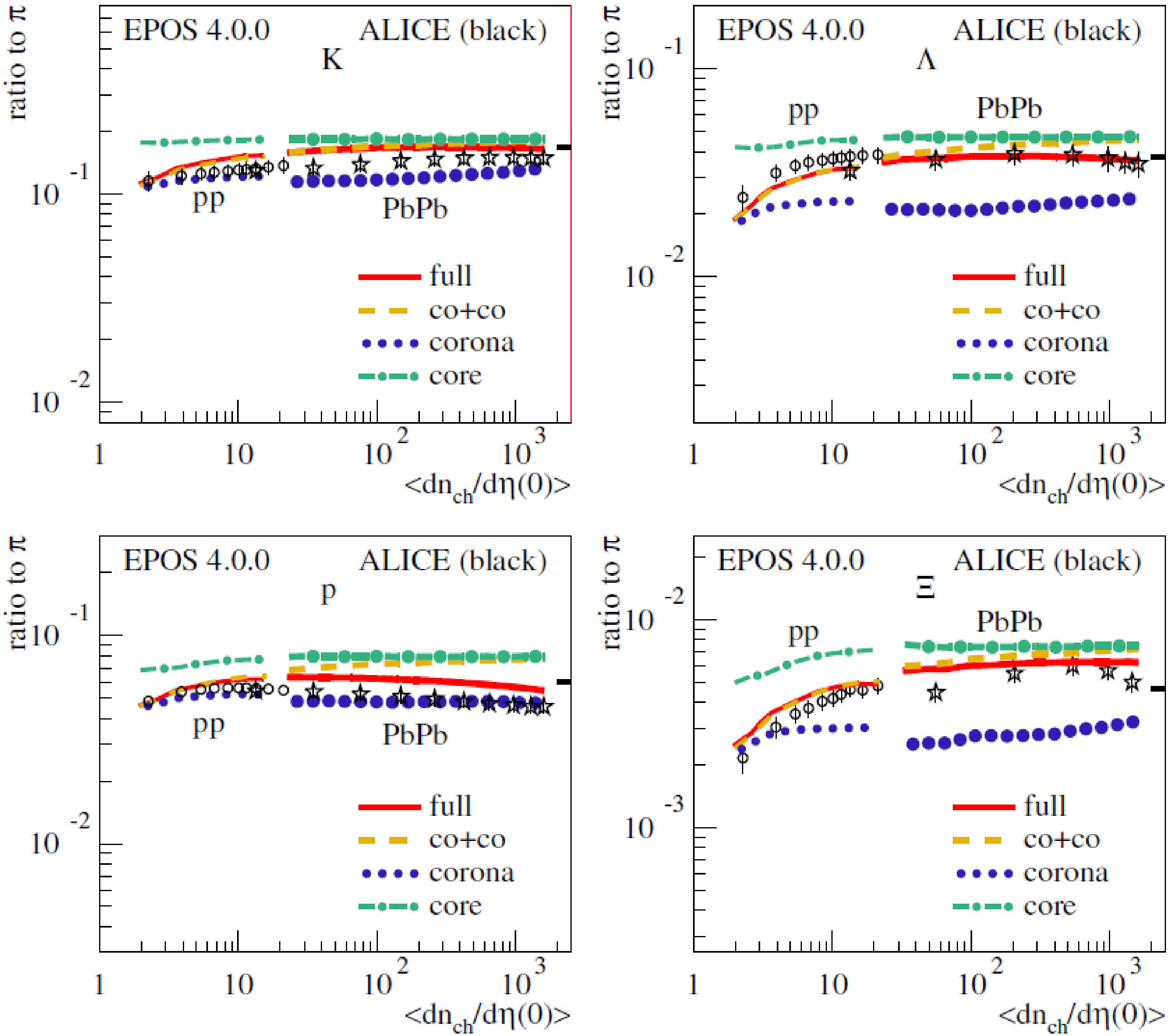
Energy loss 🙂
and
coupling with QGP 🙂

🙂 Open Heavy Flavors
and
Quarkonia

Hadronization 🙂 🙂

Crucial to consider all facets of the problem, as in the new EPOS4-HQ framework

Back up



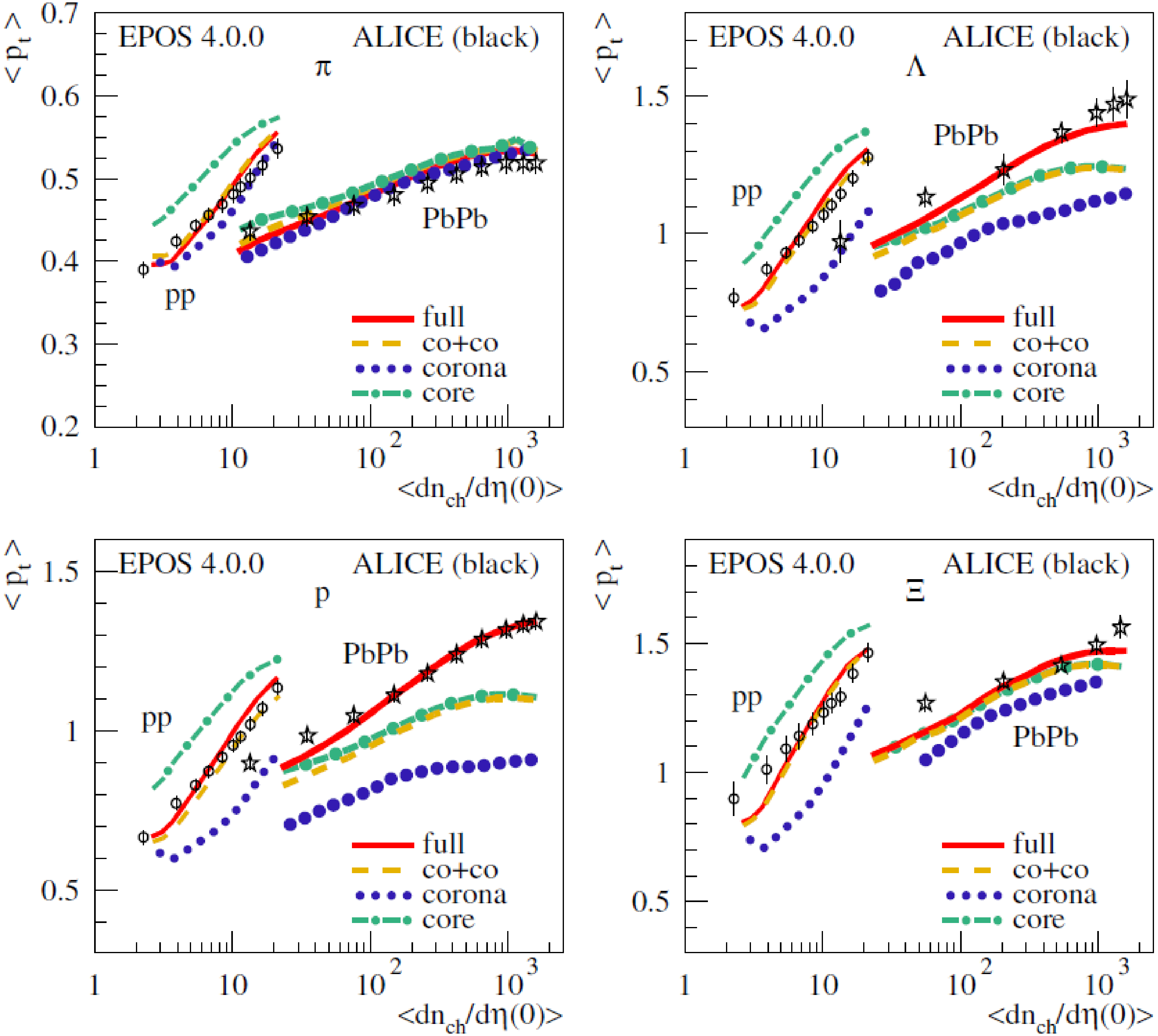
continuous curves

Affected by:

core-corona

microcanonica

hadronic cascade



discontinuities

curves affected by:

saturation

flow

core-corona

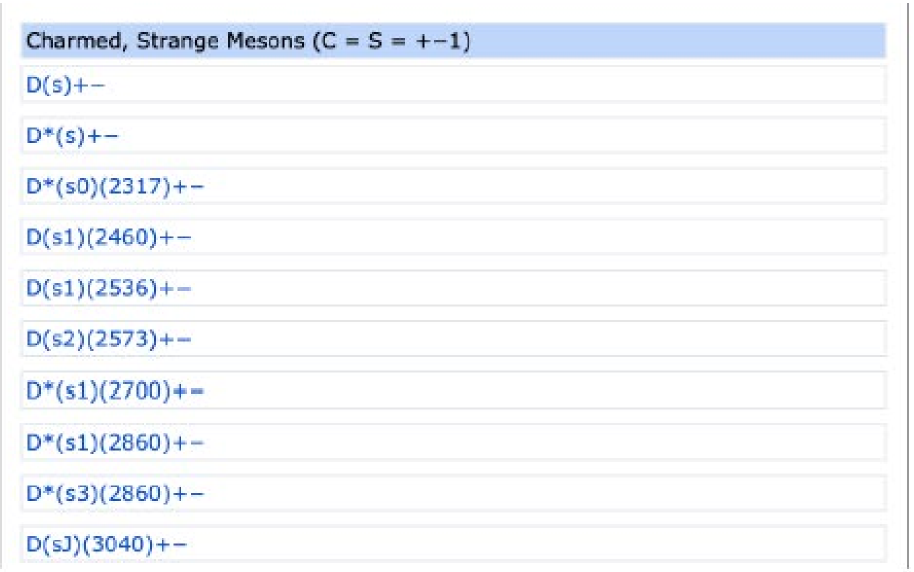
hadronic cascade

Charmed/bottom 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/bottom baryons

38 states

Λ_c

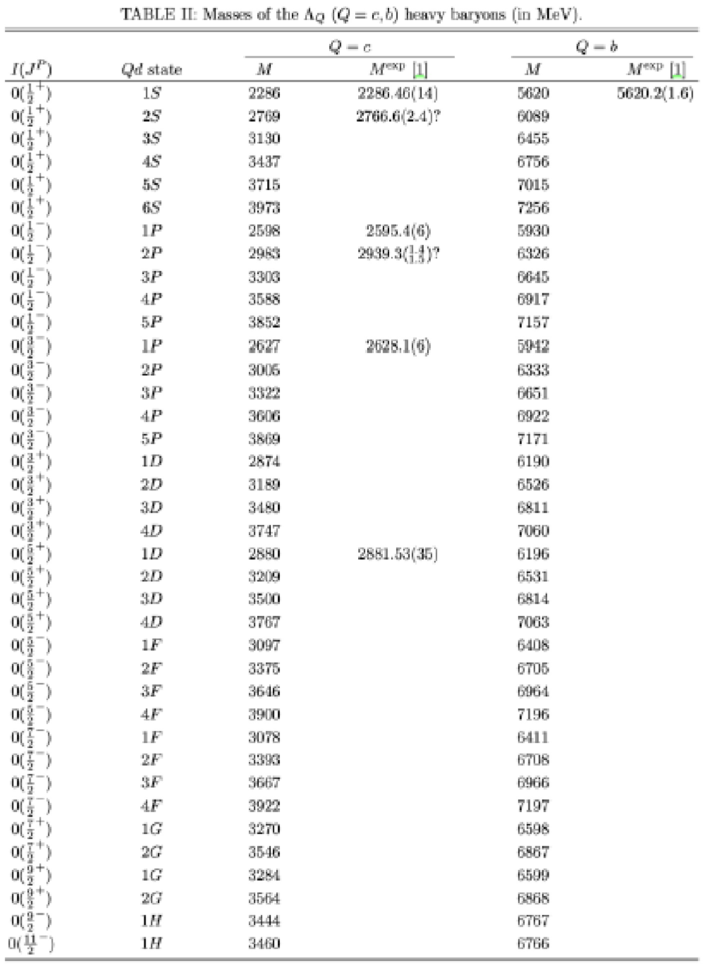


TABLE II: Masses of the Λ_Q ($Q = c, b$) heavy baryons (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	$M^{\rm exp}$ [1]	M	$M^{\rm exp}$ [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

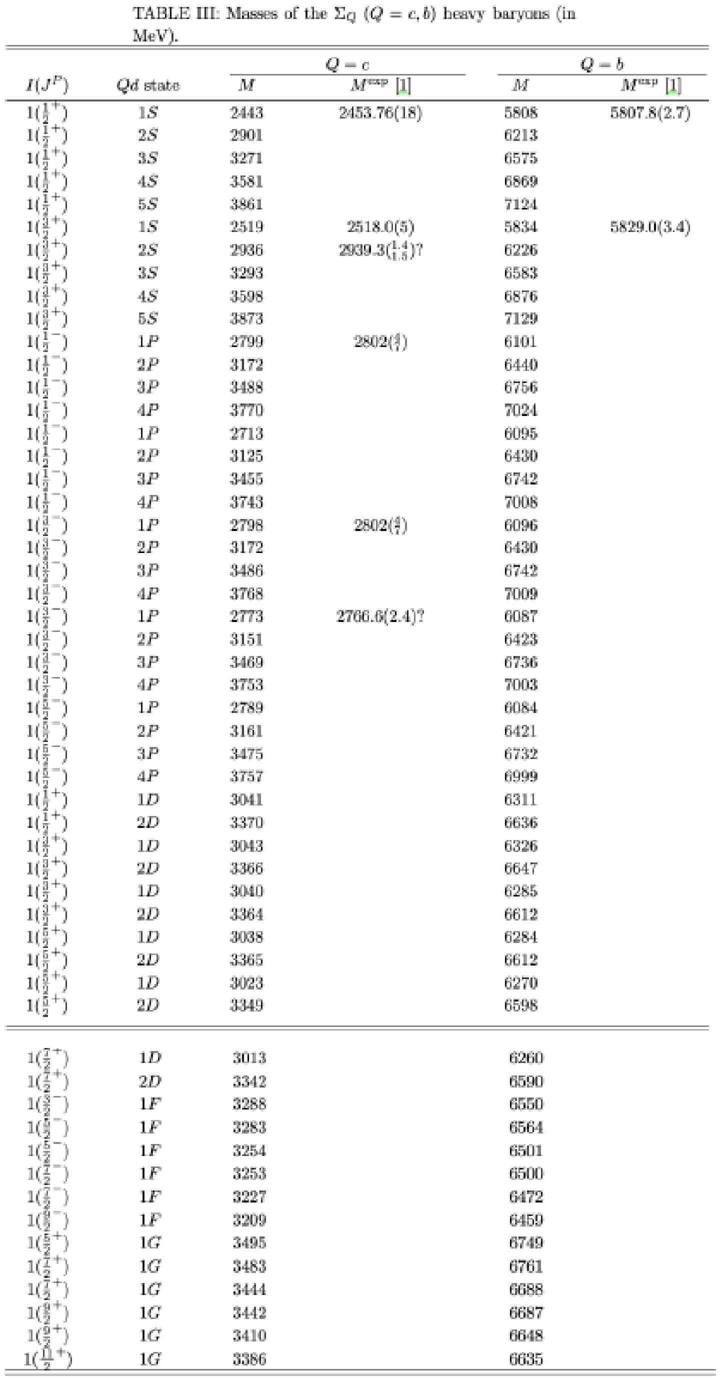


TABLE III: Masses of the Σ_Q ($Q = c, b$) heavy baryons (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	$M^{\rm exp}$ [1]	M	$M^{\rm exp}$ [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/bottom baryons

38 states

Ξ_c

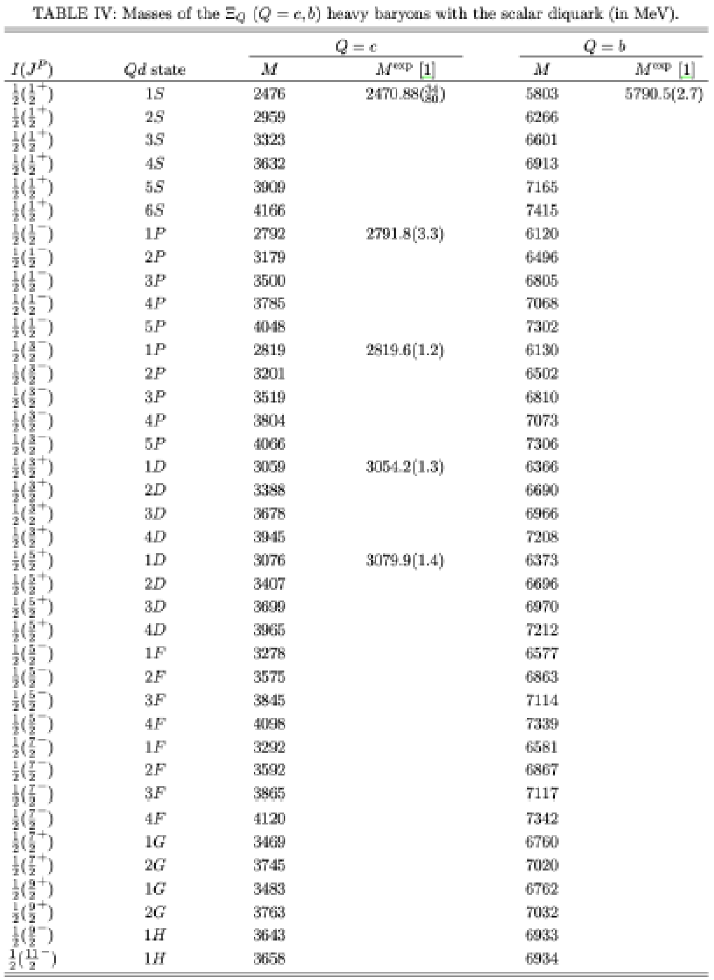


TABLE IV: Masses of the Ξ_Q ($Q = c, b$) heavy baryons with the scalar diquark (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	$M^{\exp}$ [1]	M	$M^{\exp}$ [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	

arXiv: 1105.0583

Ξ_c

54 states

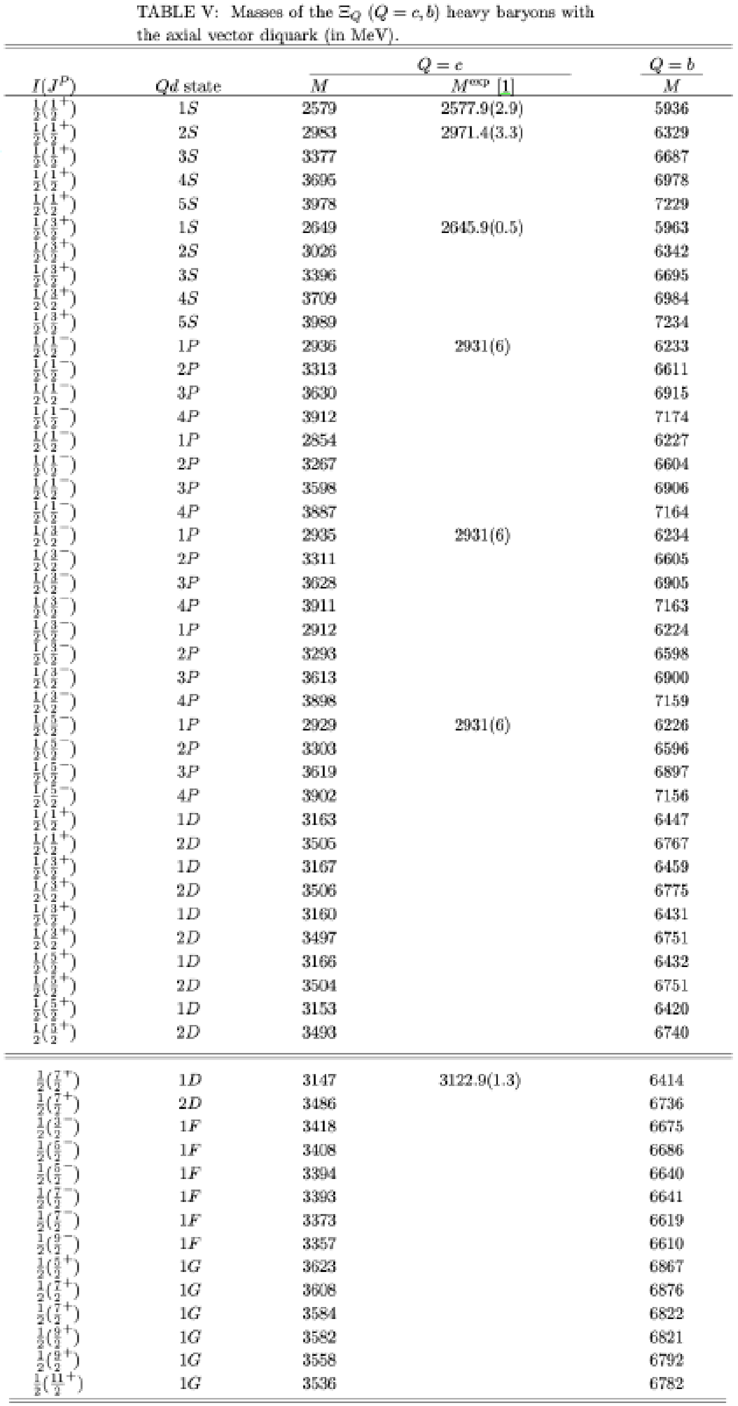


TABLE V: Masses of the Ξ_Q ($Q = c, b$) heavy baryons with the axial vector diquark (in MeV).

		$Q = c$		$Q = b$
$I(J^P)$	Qd state	M	$M^{\exp}$ [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/bottom baryons

54 states

Ω_c

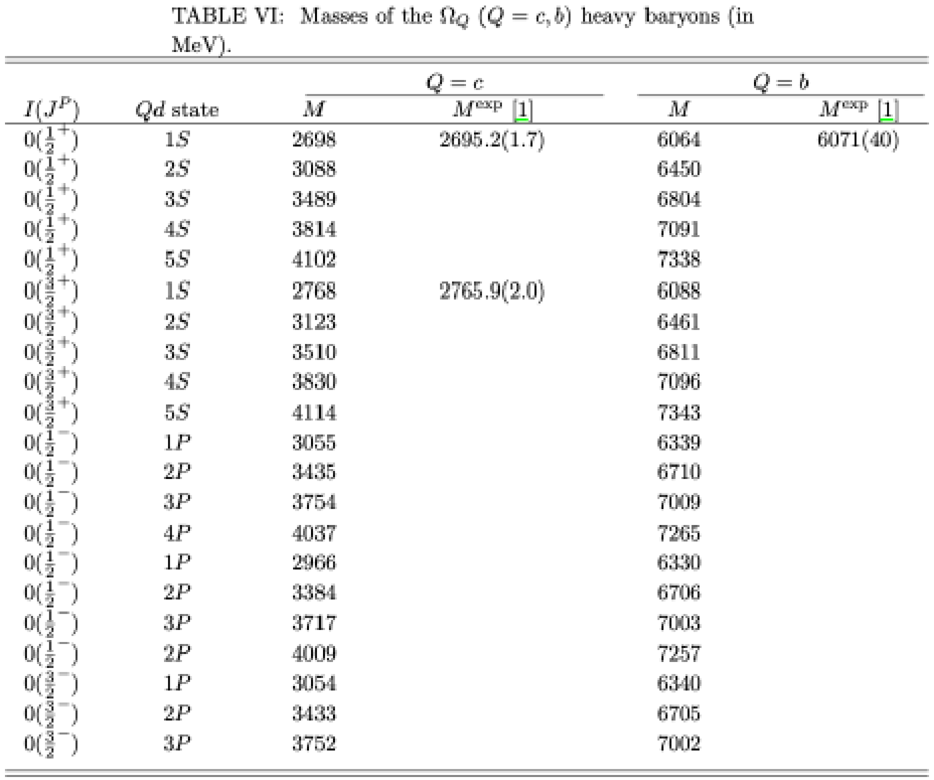


TABLE VI: Masses of the Ω_Q ($Q = c, b$) heavy baryons (in MeV).

$I(J^P)$	Qd state	$Q = c$		$Q = b$	
		M	M^{exp} [1]	M	M^{exp} [1]
$0(\frac{1}{2}^+)$	$1S$	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	

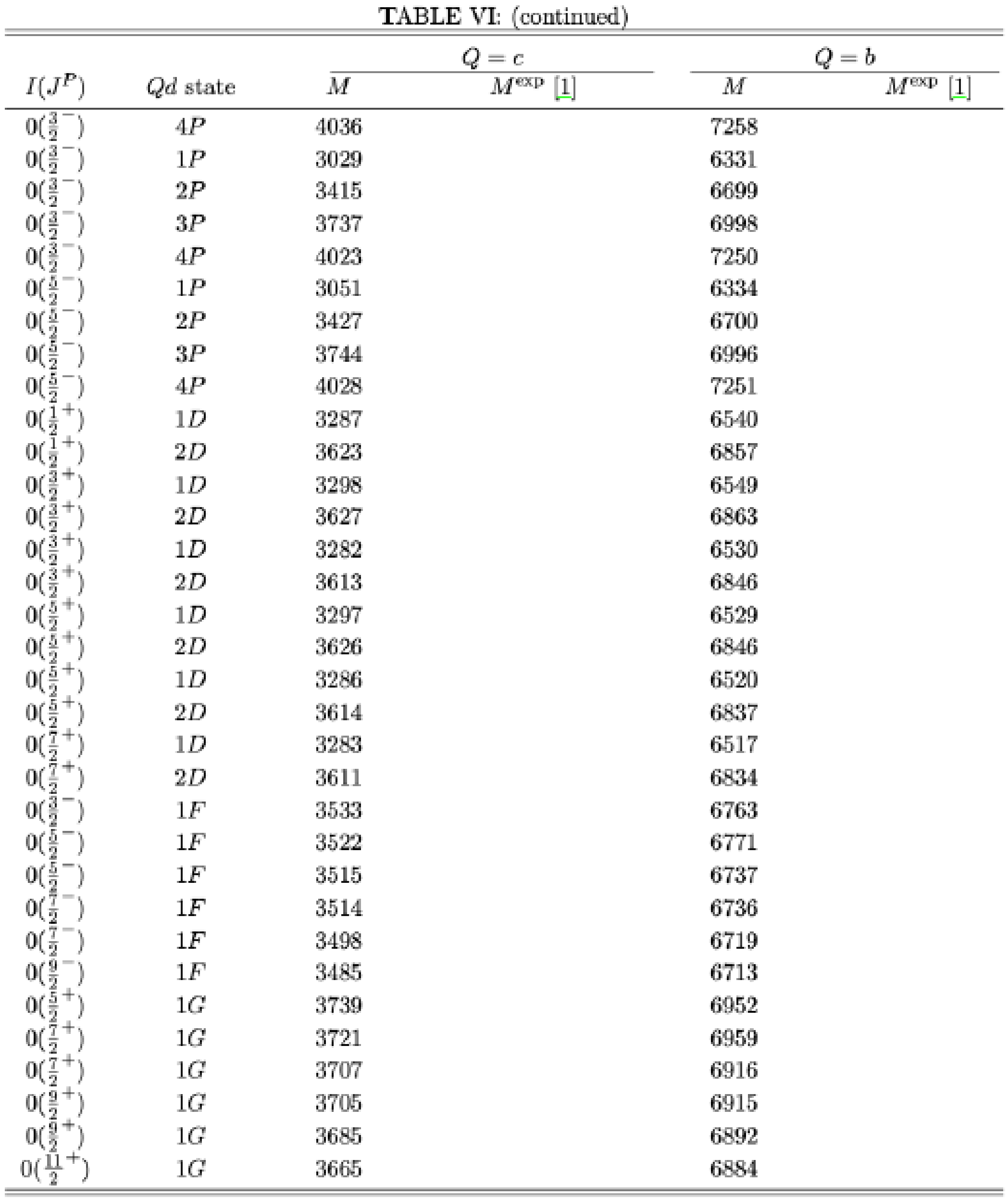
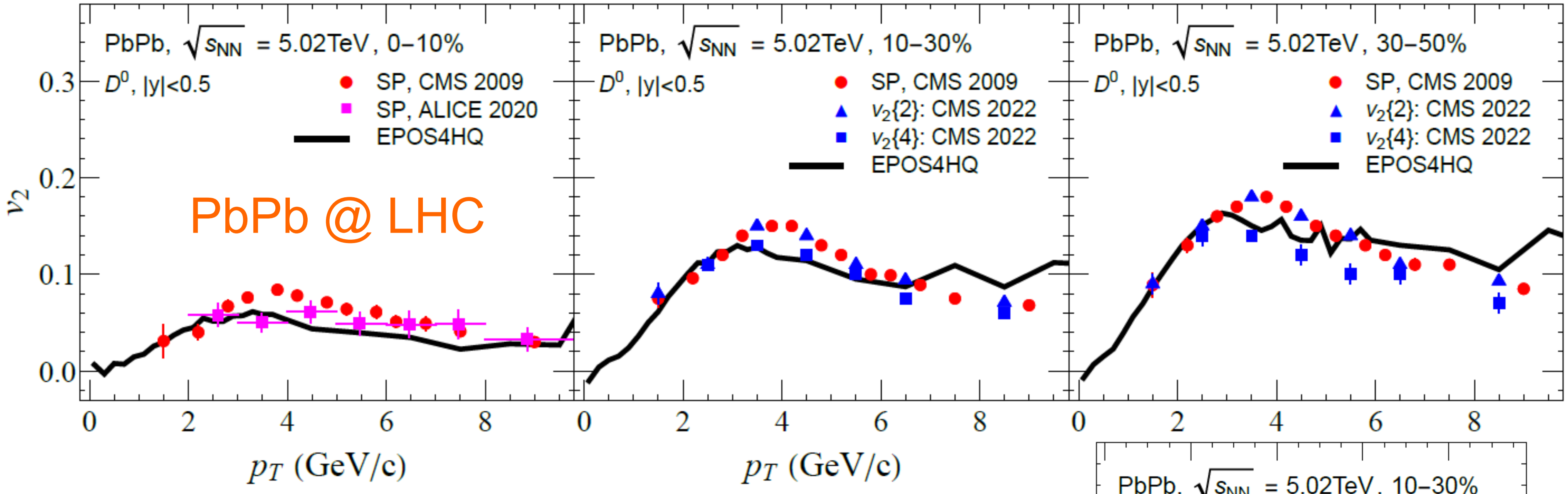


TABLE VI: (continued)

$I(J^P)$	Qd state	$Q = c$		$Q = b$	
		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	

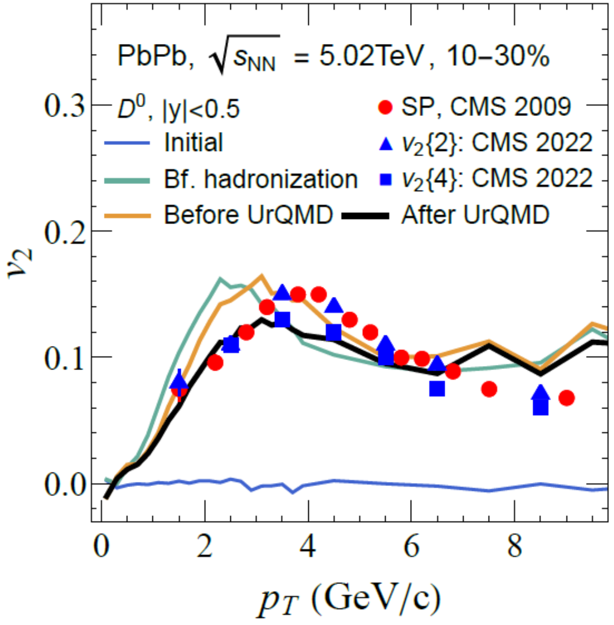
Elliptic flow in EPOS4-HQ



PbPb @ LHC

- Good agreement with data, maybe some excess at large p_T (one should investigate path length anisotropy in the bulk)

- Most of the v_2 generated by the interaction of the c-quarks with the QGP

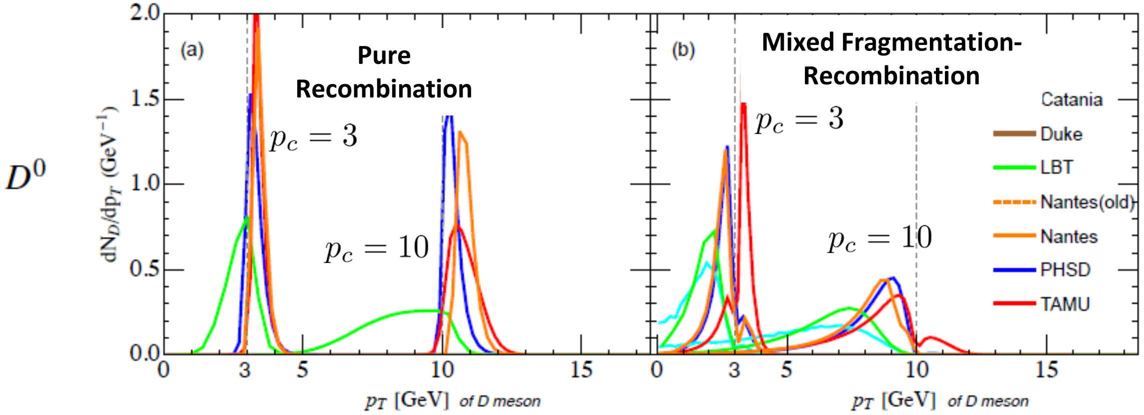


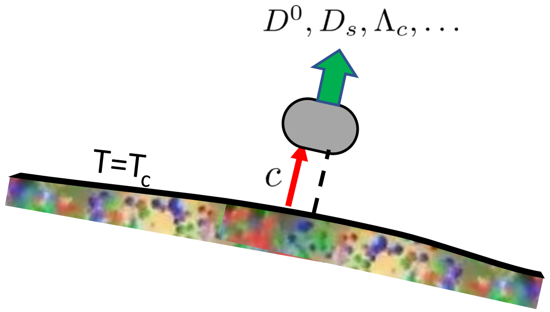
Hadronization of heavy quarks

- **Recent effort of theorists to compare their hadronization schemes at the end of the QGP**

dN_D/dp_T of the direct D^0 meson produced by a c-quark with p_T = 3 GeV *and* 10 GeV

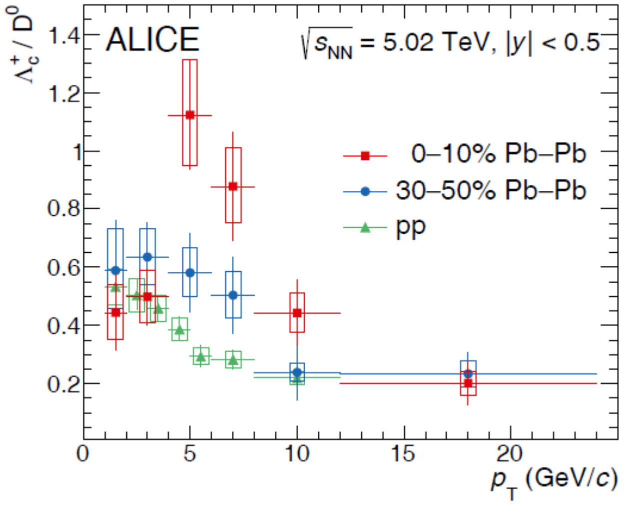
Jiaxing Zhao et al., 2311.10621

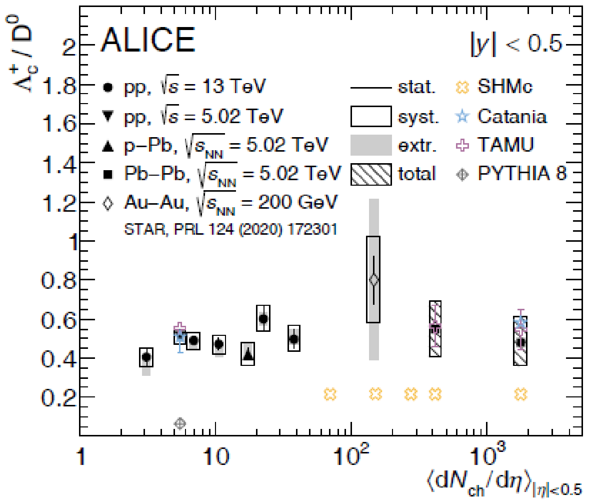


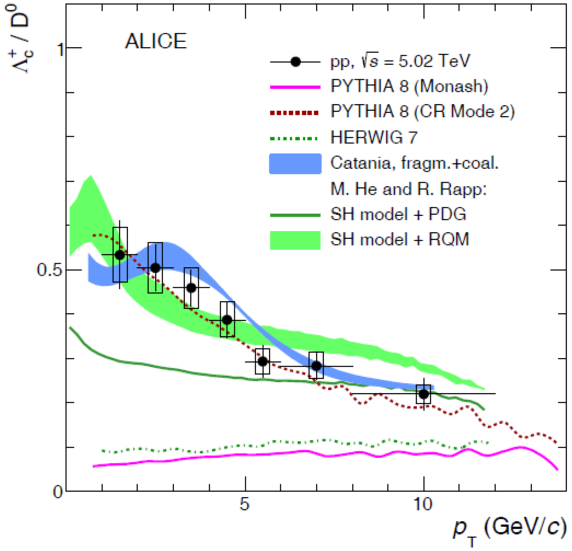


- Diversity => things to learn ! … Hadrochemistry of Heavy Flavor will be a major subject of investigation for ALICE 3.

- But also in small systems like pp (many signs of **collectivity in small systems => QGP ?**)







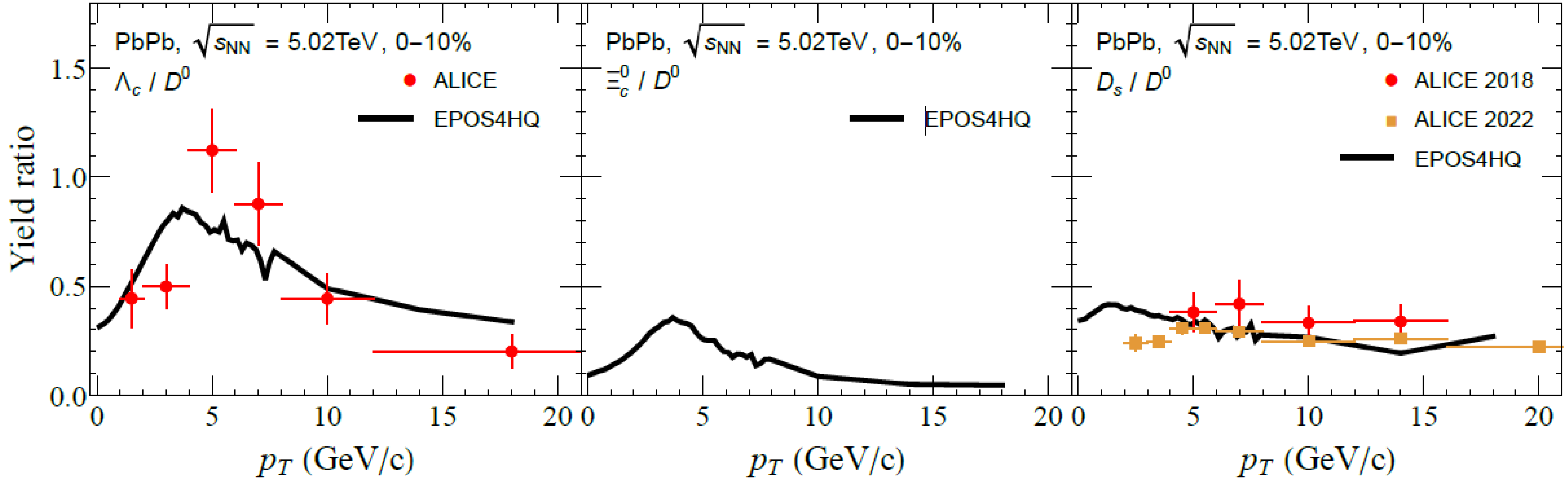
2023: Bundle 4: EPOS4-HQ

Ingredient	B1	B2 (MC@$_s$HQ+EPOS2)	B4 (EPOS4-HQ)
hydro	Kolb Heinz	vHLLE (0 viscosity)	Viscous vHLLE
Init cond (soft)	Glauber	EPOS	EPOS4
Init state fluctuations	No	Yes	Yes
hadronization	Covar. Inst. Coal + frag	Same	New scheme
HQ production	FONLL (p) + Glauber (space)	FONLL (p) + EPOS (space): position of NN interactions	EPOS4
CNM	No shadowing, initial k_T broad.	EPS09	EPOS4
Hadronic interaction	None	None	URQMD

Still no modification of the ELOSS model… maybe as an outcome of the comparison
In the following results : elastic + radiative

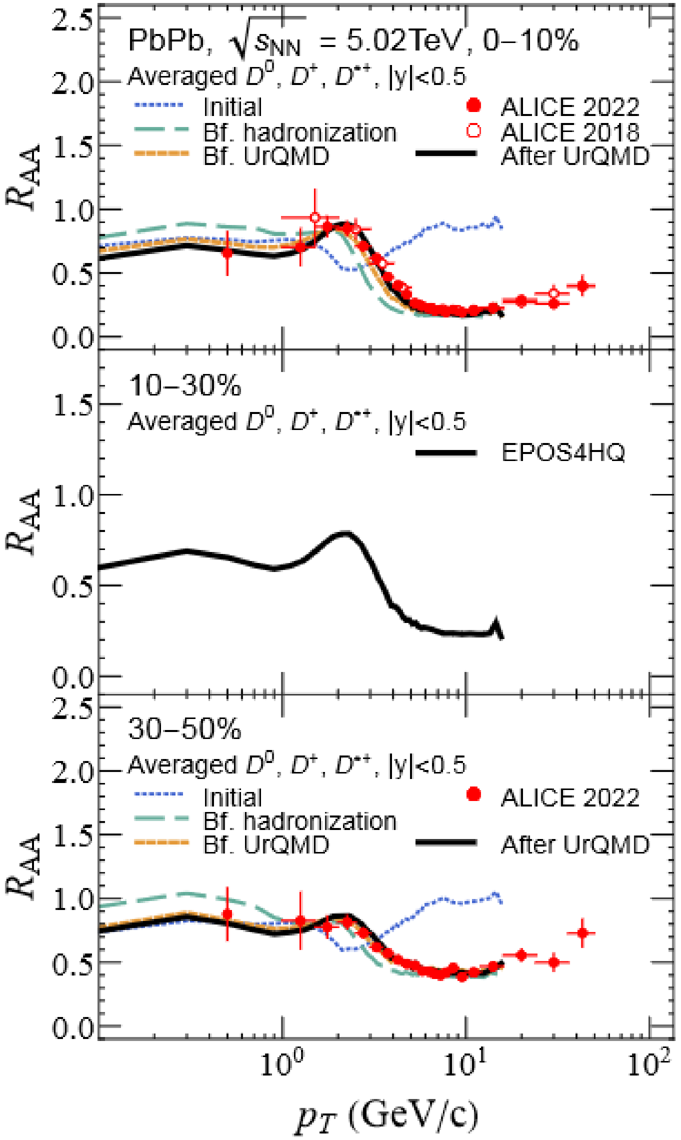
OHF hadrons p_T distributions in EPOS4-HQ

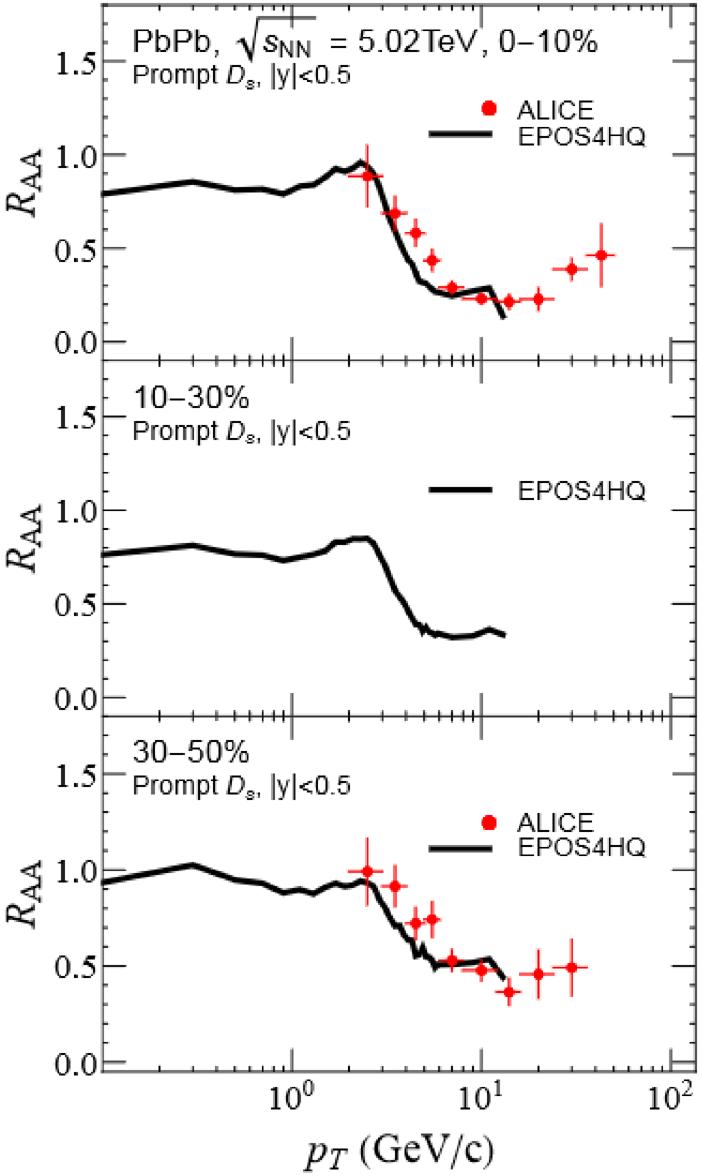
Yield ratios in PbPb @ LHC



- ➢ Experimental trends well reproduced
- ➢ Need for more precise data to improve the hadronization “chemistry”

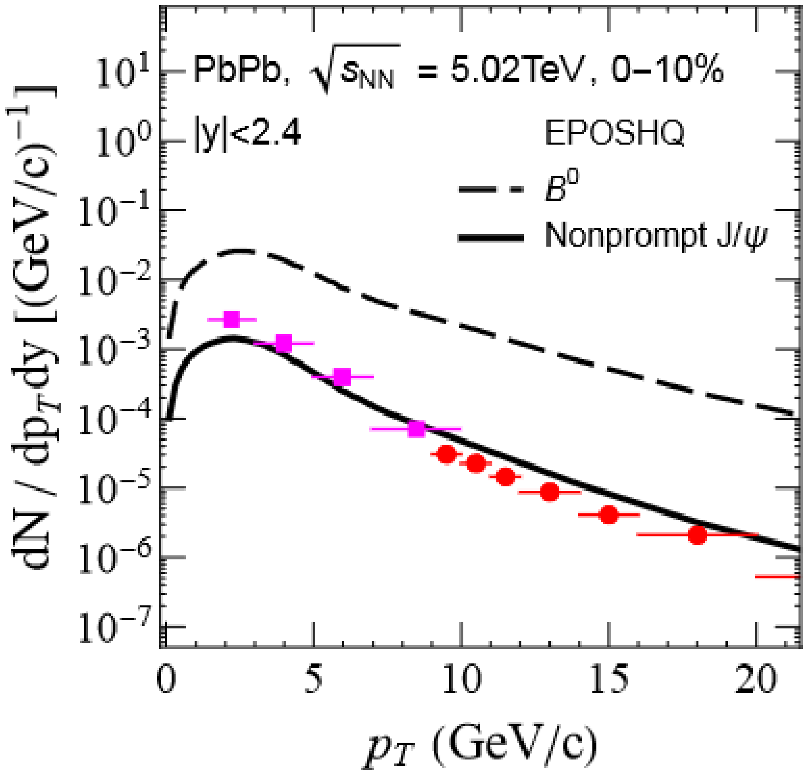
hadrons p_T distributions in EPOS4-HQ

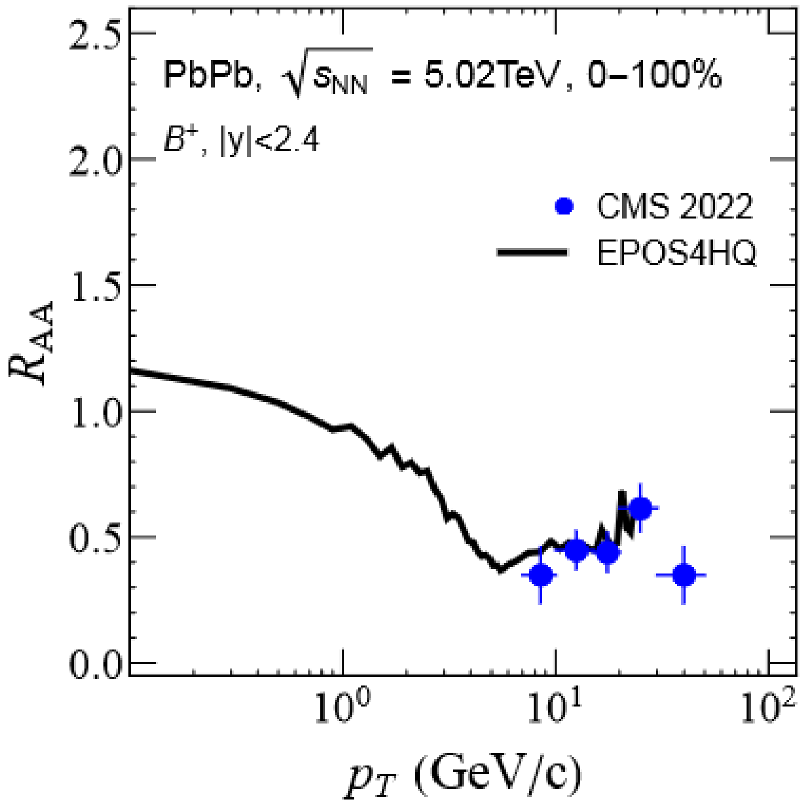




hadrons p_T distributions in EPOS4-HQ

PbPb semi-central @ LHC

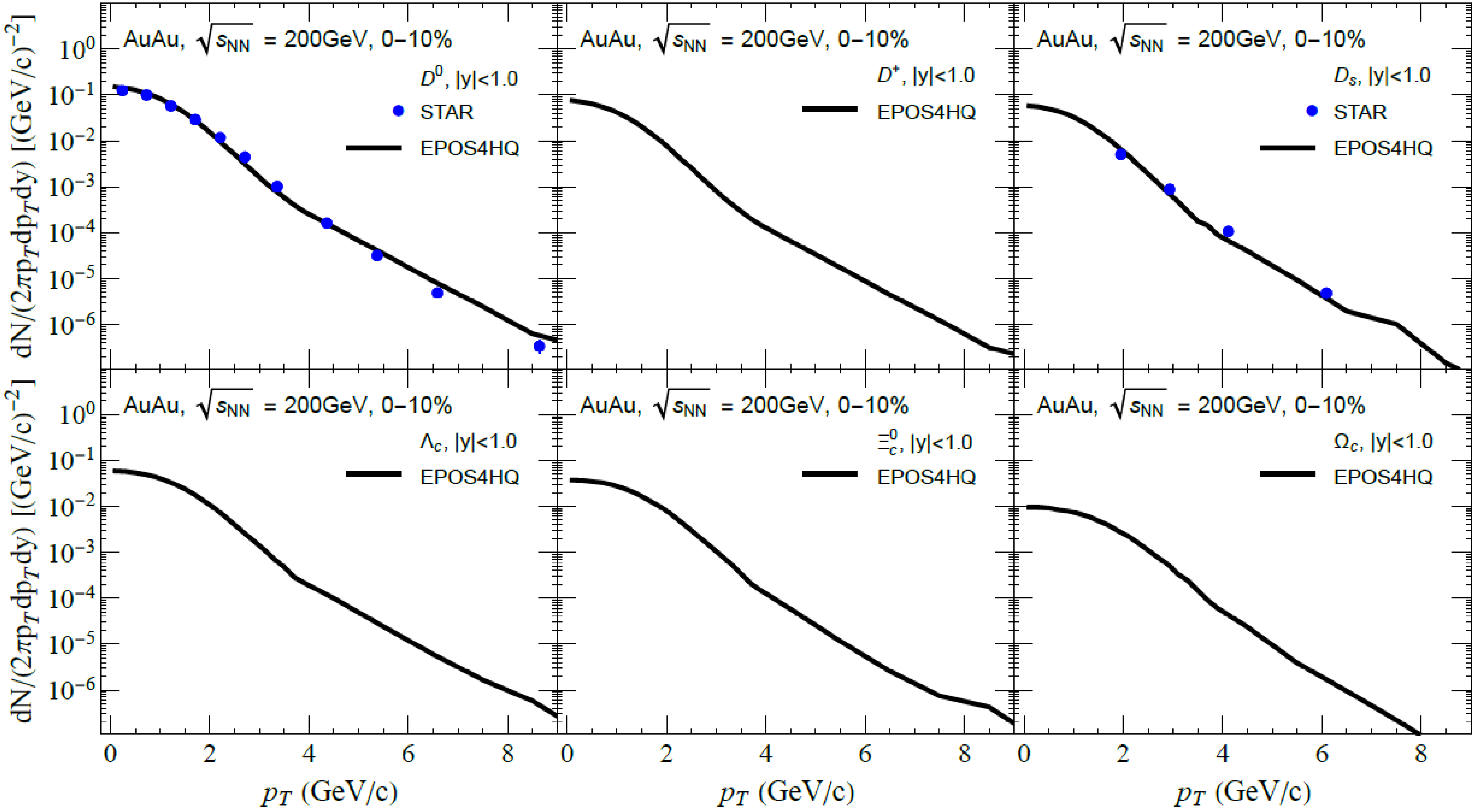




Very good agreement for all resonances

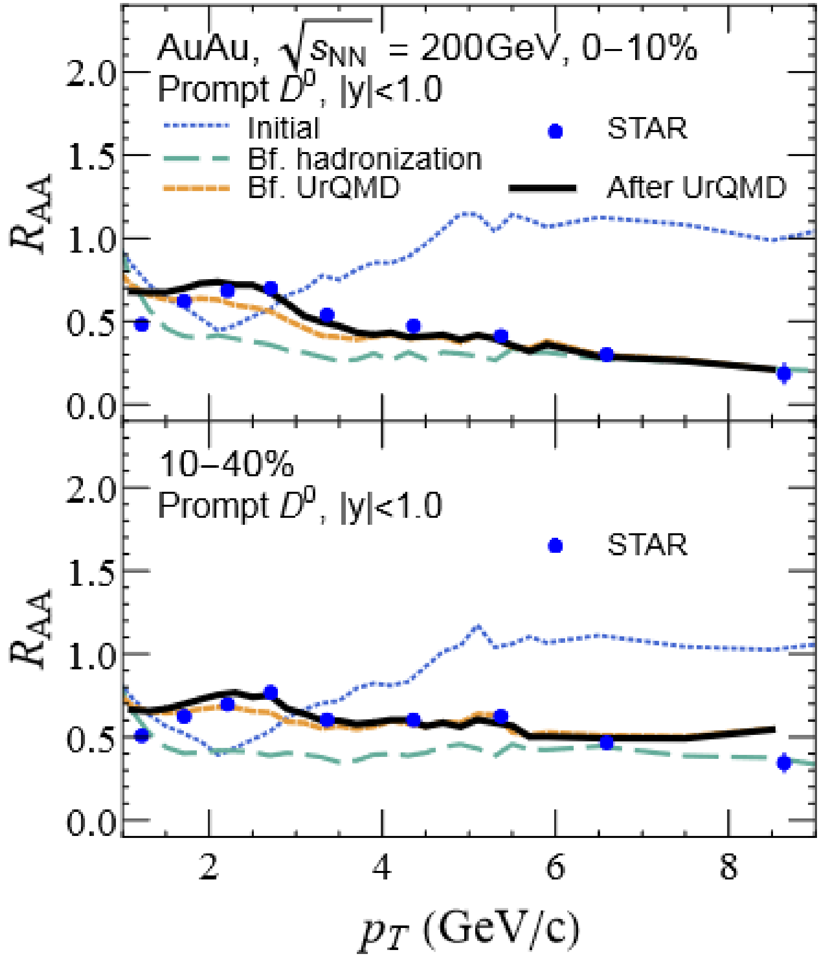
hadrons p_T distributions in EPOS4-HQ

AuAu central @ RHIC



Very good agreement for all resonances

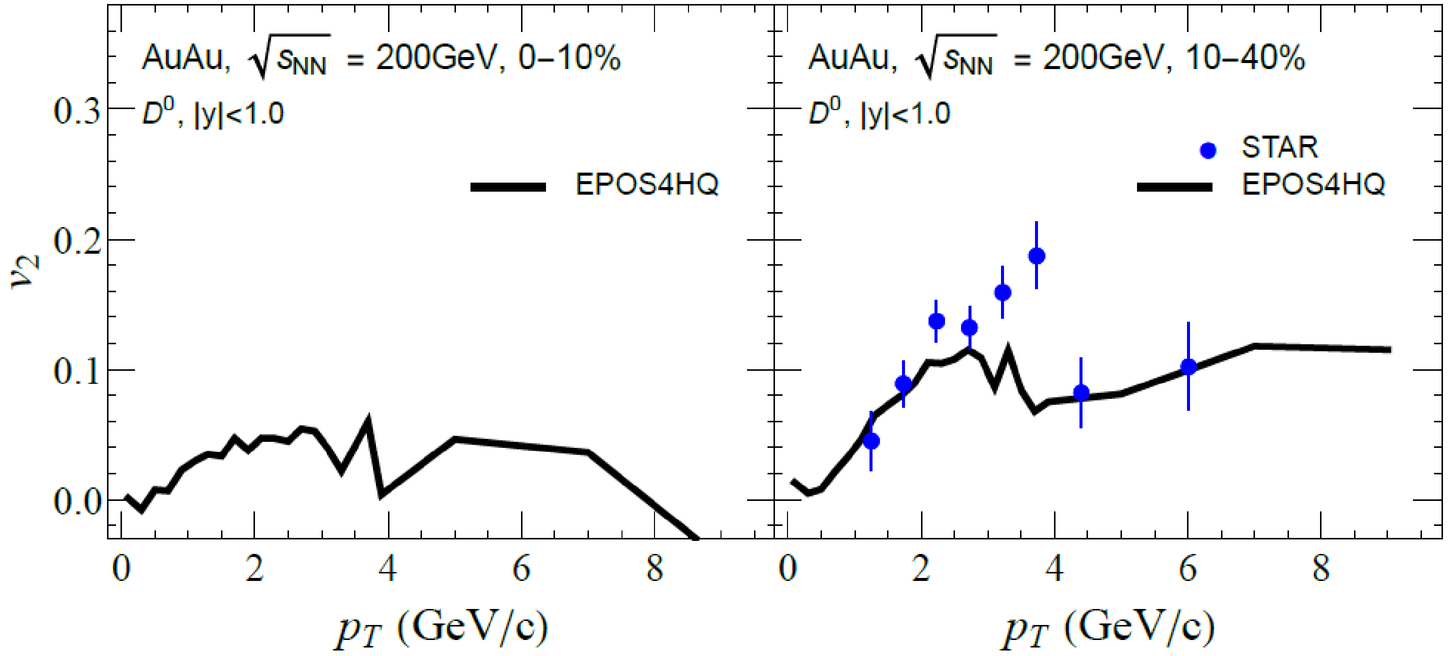
hadrons p_T distributions in EPOS4-HQ



Very good agreement for all resonances

Elliptic flow in EPOS4-HQ

AuAu @ RHIC



- Slight underestimation around 3 GeV/c… probably need sPHENIX data before concluding