Heavy-Flavor Transport in QCD Matter

ECT* Trento 2630 April 2021

HADRONIZATION in MC@sHQ (Nantes)

PB Gossiaux

- Coalescence (Main ref.: PHYSICAL REVIEW C **79**, 044906 (2009))
- Global hadronization algorithm : fragmentation + coalescence
- No Baryon up to now
- Some recent update

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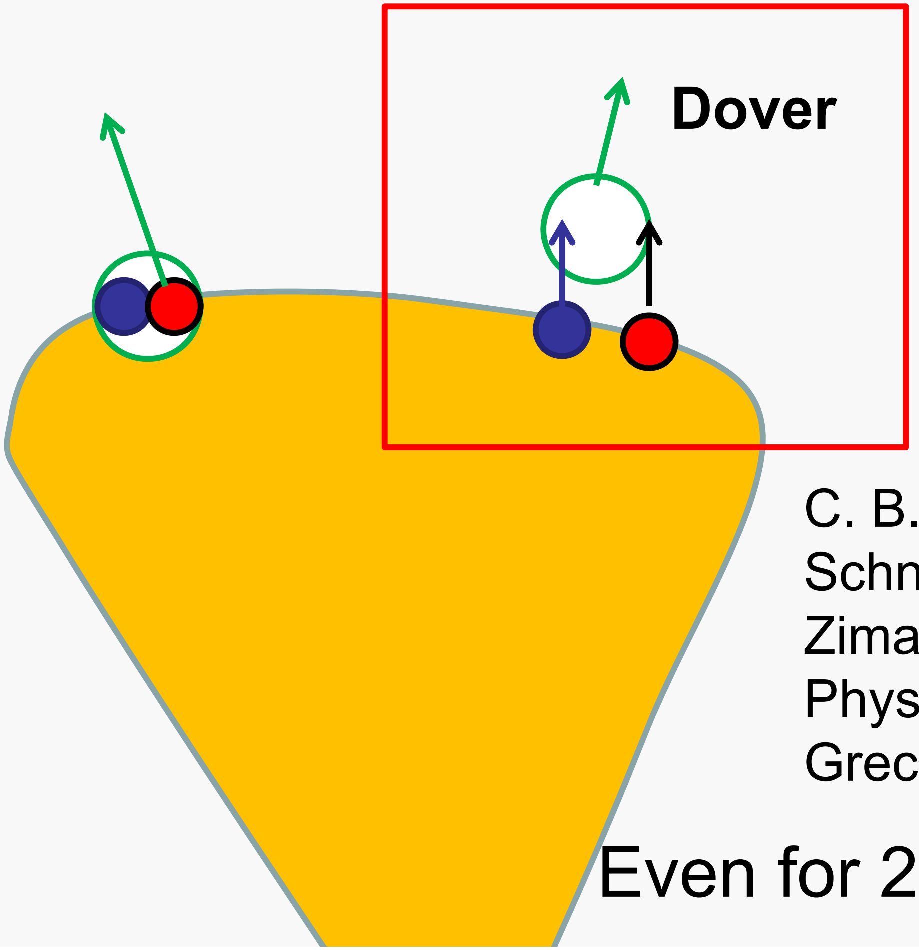
I don’t like it, but I use it

2 physical pictures for coalescence

Lin et Molnar (03) et de Fries, Müller, Nonaka and Bass (03)



2->1

C. B. Dover, U. W. Heinz, E. Schnedermann, and J. Zimanyi,
Phys. Rev. C **44**, 1636 (1991).
Greco (2003).

Even for 2->1, several ways

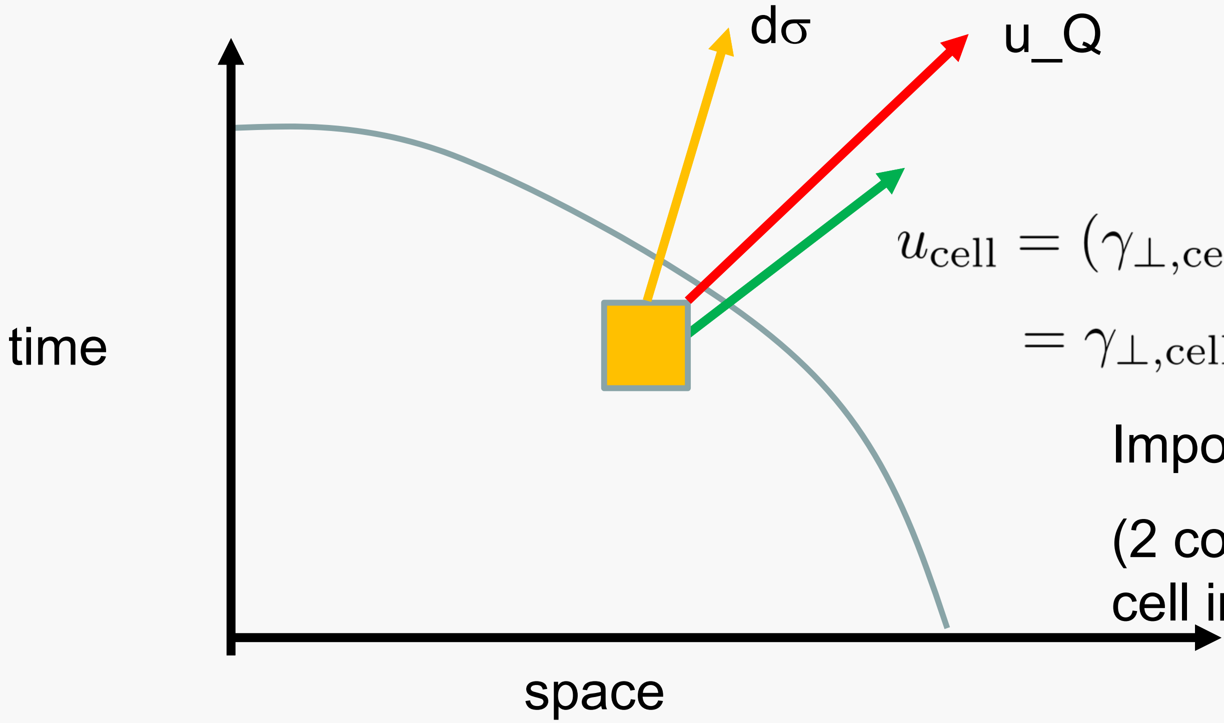
$$N_{\Phi=D,B} = \int p_Q \cdot d\sigma_1 p_q \cdot d\sigma_2 \frac{d^3 p_Q}{(2\pi\hbar)^3 E_Q} \frac{d^3 p_q}{(2\pi\hbar)^3 E_q}$$

A delta distribution $\longrightarrow$ $$\times \boxed{f_Q(x_Q, p_Q)} \boxed{f_q(x_q, p_q)} f_\Phi(x_Q, x_q; p_Q, p_q).$$

Locally thermalized

Various covariant quantities

$$d\sigma_\mu \equiv \tau_f d^2 x_\perp d\eta (\cosh\eta, -\vec{\nabla}_\perp \tau_f(\vec{x}_\perp), \sinh\eta)$$



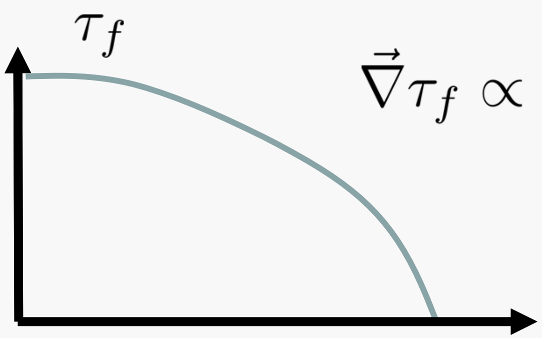
$$u_{\rm cell} = (\gamma_{\perp,\rm cell}\cosh\eta, \vec{u}_{\perp,\rm cell}, \gamma_{\perp,\rm cell}\sinh\eta)$$
$$= \gamma_{\perp,\rm cell}\left(\cosh\eta, \vec{\beta}_{\perp,\rm cell}, \sinh\eta\right)$$

Important product: $d\sigma \cdot u_{\rm cell}$

(2 colinear, then, hadronize in the cell irrespective of the hypersurface)

Several profiles:

« implosive »



$\vec{\nabla}\tau_f \propto -\vec{e}_\rho$ in $d\sigma^\mu$ while $\vec{u}_\perp \propto +\vec{e}_\rho$ => some skewness

$$d\sigma \cdot u_{\rm cell} \propto \gamma_{\perp,\rm cell}(1 + \beta_{\perp,\rm cell}|\tau_f'(x_\perp)|$$

Dover vs Gossiaux (spatial)

Dover

Coall. Prob:= D_{sp} x D_p

$$C(x_1,x_2;p_1,p_2)=\alpha^C_{1,2}\exp\left[\frac{(x_1-x_2)^2}{2R_C^2}\right] \times\exp\left[\frac{(p_1-p_2)^2-(m_1-m_2)^2}{2P_C^2}\right], \quad (2.14)$$

Particles far away can coalesce !!!

Gaussian space (Gossiaux)

$$f_\Phi(x_Q,x_q;p_Q,p_q) = \exp\left(-\frac{\|\vec{x}_{q,\mathrm{ref}\,Q}\|^2}{2R_c^2}\right) \times \tilde{f}_\Phi(p_Q,p_q)$$

$$= \exp\left(\frac{\Delta x^2 - (\Delta x\cdot u_Q)^2}{2R_c^2}\right) \times \tilde{f}_\Phi(p_Q,p_q)$$

2.2.1 (Dover)

2.2.2 (Gossiaux)

$$N_\Phi(x_Q;p_Q) = g_q \int_{p_q\cdot\hat{d\sigma}(x_Q)>0} \frac{d^3p_q}{E_q}\, p_q\cdot\hat{d\sigma}(x_Q)\, e^{-\frac{u_{\mathrm{cell}}(x_Q)\cdot p_q}{T}} \left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 \tilde{f}_\Phi(p_Q,p_q) \quad (29)$$

$$N_\Phi(x_Q;p_Q) = g_q \int_{p_q\cdot\hat{d\sigma}(x_Q)>0} \frac{d^3p_q}{E_q}\, \frac{p_q\cdot\hat{d\sigma}(x_Q)}{\boxed{u_Q\cdot\hat{d\sigma}(x_Q)}}\, e^{-\frac{u_{\mathrm{cell}}(x_Q)\cdot p_q}{T}} \left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 \tilde{f}_\Phi(p_Q,p_q) \quad (48)$$

The only difference

Dover vs Gaussian (momentum)

I. Gaussian p (2.3.1)

$$\tilde{f}_\Phi(\vec{p}_Q,\vec{p}_q) = \exp\left(-\frac{\|\vec{q}\|^2}{2\Lambda_{\rm cm}^2}\right) = \exp\left(-\frac{\|\vec{p}_{q,{\rm ref}\,Q}\|^2}{2m_q^2\alpha_g^2}\right) \quad (58)$$

$$\Lambda_{\rm cm} = \frac{m_q m_Q}{m_q+m_Q}\alpha_g \quad (57)$$

Then (also using normalisation)

$$\boxed{N_\Phi(x_Q;p_Q) = g_q\int_{p_q\cdot\hat{d\sigma}(x_Q)>0}\frac{d^3p_q}{E_q}\,p_q\cdot\hat{d\sigma}(x_Q)\,e^{-\frac{u_{\rm cell}(x_Q)\cdot p_q}{T}}\left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3\tilde{f}_\Phi(p_Q,p_q)} \quad (29/48)$$

$$\underbrace{\left(\frac{\sqrt{2\pi}(m_q+m_Q)}{m_Q m_q \alpha_g}\right)^3}_{c_g}\exp\left(-\frac{\|\vec{p}_{q,{\rm ref}\,Q}\|^2}{2m_q^2\alpha_g^2}\right)$$

with $\|\vec{p}_{q,{\rm ref\,Q}}\|^2 = m_q^2\left[(u_Q\cdot u_q)^2-1\right]$

Dover (x) -Gaussian (p)

$$\boxed{N_\Phi(x_Q;p_Q) = \tilde{c}_g g_q\int_{u_q\cdot\hat{d\sigma}(x_Q)>0}\frac{d^3u_q}{u_0}\,u_q\cdot\hat{d\sigma}(x_Q)\,e^{-\left(\frac{m_q}{T}u_{\rm cell}(x_Q)\cdot u_q+\frac{(u_Q\cdot u_q)^2-1}{2\alpha_g^2}\right)}} \quad (60)$$

with $\tilde{c}_g = \left(\frac{(m_q+m_Q)}{\sqrt{2\pi}m_Q\alpha_g}\right)^3$

Gossiaux (x) - Gaussian (p): $u_q\cdot\hat{d\sigma}(x_Q) \to \frac{u_q\cdot\hat{d\sigma}(x_Q)}{u_Q\cdot\hat{d\sigma}(x_Q)}$

Dover vs Gaussian (momentum)

II Dover (2.3.2)

$$\tilde{f}_\Phi(p_Q, p_q) = \exp\left(-\left(\frac{m_Q m_q}{(m_q+m_Q)\Lambda_d}\right)^2 (u_q \cdot u_Q - 1)\right) \quad (63)$$

with $\Lambda_d = \frac{m_q m_Q}{mq + m_Q}\alpha_d$

Then (also using normalisation) $\left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 = \left(\frac{m_Q+m_q}{m_Q m_q}\right)^3 \times \frac{1}{4\pi\alpha_d^2 K_2\left(\frac{1}{\alpha_d^2}\right) e^{\frac{1}{\alpha_d^2}}}$

$$\boxed{N_\Phi(x_Q; p_Q) = g_q \int_{p_q\cdot\hat{d\sigma}(x_Q)>0} \frac{d^3p_q}{E_q} p_q \cdot \hat{d\sigma}(x_Q)\, e^{-\frac{u_{\text{cell}}(x_Q)\cdot p_q}{T}} \left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 \tilde{f}_\Phi(p_Q, p_q)} \quad (29/48)$$

Dover (x) - Dover (p)

$$\boxed{N_\Phi(x_Q; p_Q) = \tilde{c}_d g_q \int_{u_q\cdot\hat{d\sigma}(x_Q)>0} \frac{d^3u_q}{u_0} u_q \cdot \hat{d\sigma}(x_Q)\, e^{-\left(\frac{m_q}{T}u_{\text{cell}}(x_Q)+\frac{u_Q}{\alpha_d^2}\right)\cdot u_q} \quad (73)}$$

with $\tilde{c}_g = \left(\frac{m_Q+m_q}{m_Q}\right)^3 \times \frac{1}{4\pi\alpha_d^2 K_2\left(\frac{1}{\alpha_d^2}\right)}$

$$u_q \cdot \hat{d\sigma}(x_Q) \to \frac{u_q\cdot\hat{d\sigma}(x_Q)}{u_Q\cdot\hat{d\sigma}(x_Q)}$$

Gossiaux (x) - Dover(p) **(our favorite)**

Calibration: section 2.4

Assuming u_{cell} oriented along $d\sigma$

4 combinations

$$N_{\Phi,D,G}(x_Q u_{\rm cell}\cdot u_Q) = \tilde{c}_g g_q \int \frac{d^3u_q}{u^0} u_q\cdot u_{\rm cell}\, e^{-\left(\frac{m_q}{T}u_q\cdot u_{\rm cell}+\frac{(u_Q\cdot u_q)^2-1}{2\alpha_g^2}\right)} \quad (75)$$

$$N_{\Phi,D,D}(x_Q; u_{\rm cell}\cdot u_Q) = \tilde{c}_d g_q \int \frac{d^3u_q}{u^0} u_q\cdot u_{\rm cell}\, e^{-\left(\frac{m_q}{T}\,u_{\rm cell}+\frac{u_Q}{\alpha_d^2}\right)\cdot u_q}. \quad (76)$$

space momentum

$$N_{\Phi,Gx,G}(x_Q; u_{\rm cell}\cdot u_Q) = \tilde{c}_g g_q \int \frac{d^3u_q}{u^0}\frac{u_q\cdot u_{\rm cell}}{u_Q\cdot u_{\rm cell}}\, e^{-\left(\frac{m_q}{T}u_q\cdot u_{\rm cell}+\frac{(u_Q\cdot u_q)^2-1}{2\alpha_g^2}\right)} \quad (77)$$

$$\boxed{N_{\Phi,Gx,D}(x_Q; u_{\rm cell}\cdot u_Q) = \tilde{c}_d g_q \int \frac{d^3u_q}{u^0}\frac{u_q\cdot u_{\rm cell}}{u_Q\cdot u_{\rm cell}}\, e^{-\left(\frac{m_q}{T}\,u_{\rm cell}+\frac{u_Q}{\alpha_d^2}\right)\cdot u_q} \quad (78)}$$

One needs to fix the parameters (m_q and Λ_{xxx} / $\boxed{\alpha_{d/g}}$)

Same value for b & c

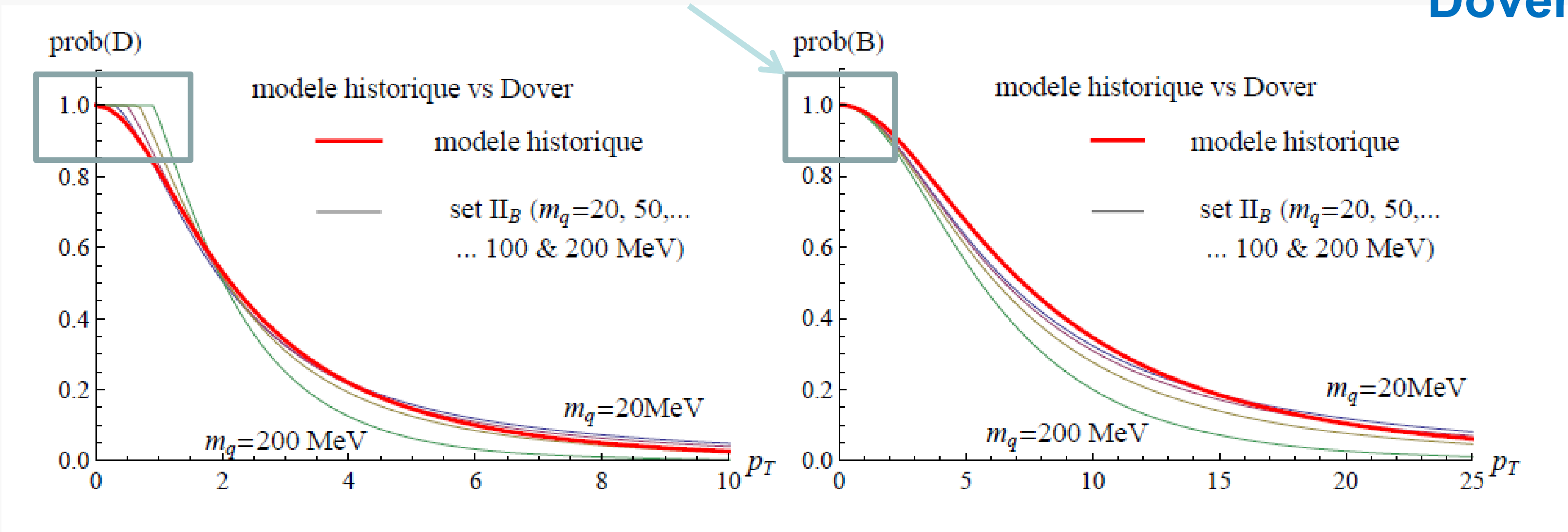
Calibration: section 2.4.5 (& 2.4.3)

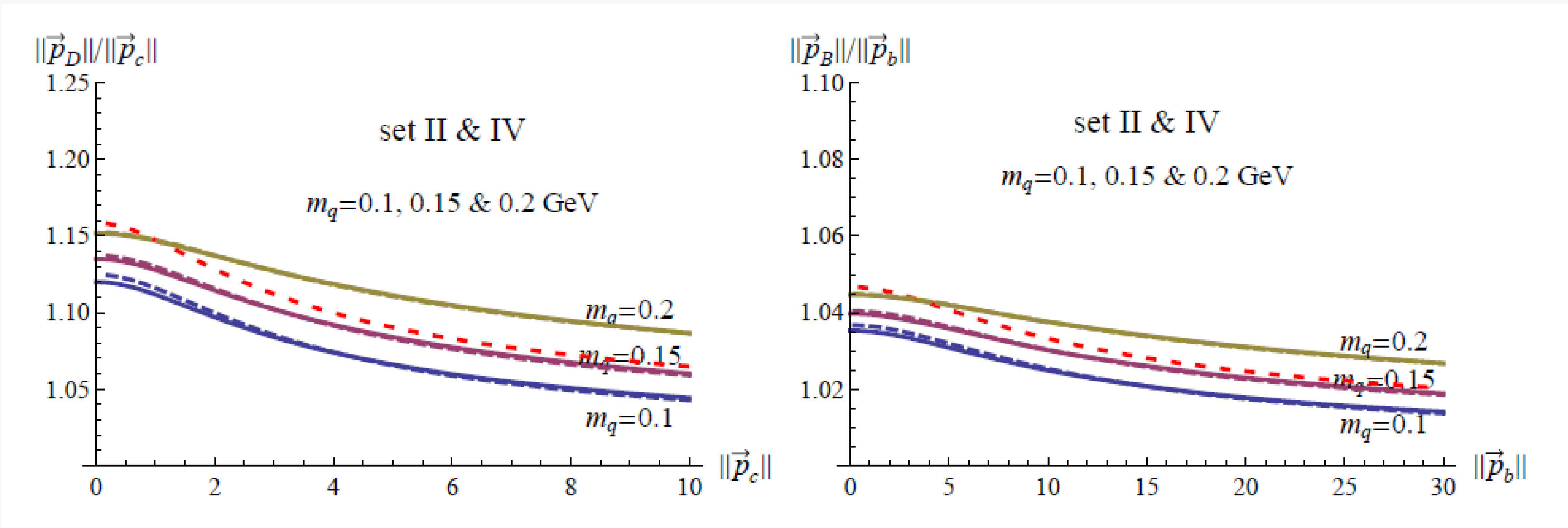
Assuming: u_{cell} oriented along $d\sigma$ and general p_Q

And Gossiaux spatial

Parameters tuned such that prob b->B is = 1 through coalescence

Dover p (set II)





$$\boxed{m_q \approx 100 \text{ MeV} \quad \text{et} \quad \alpha_d = 0.876 \ (\text{set } \mathrm{II}_{ter})}$$

Optimal wrt historical model

Summary 2009

In our approach, we take:

- Gossiaux factor in "spatial" coordinates $= \boxed{\exp\left(\frac{\Delta x^2 - (\Delta x \cdot u_Q)^2}{2R_c^2}\right)} \times \tilde{f}_\Phi(p_Q, p_q)$

- (Modified) Dover in momentum space:

$$\tilde{f}_\Phi(p_Q, p_q) = \exp\left(-\left(\frac{m_Q m_q}{(m_q + m_Q)\Lambda_d}\right)^2 (u_q \cdot u_Q - 1)\right)$$

with $\Lambda_d = \frac{m_q m_Q}{mq + m_Q} \alpha_d$

- Normalization of the coalescence probability writes: $\left(\frac{R_c}{\sqrt{2\pi}\hbar}\right)^3 = \left(\frac{m_Q + m_q}{m_Q m_q}\right)^3 \times \frac{1}{4\pi\alpha_d^2 K_2\left(\frac{1}{\alpha_d^2}\right) e^{\frac{1}{\alpha_d^2}}}$

- Parametric choice is $\boxed{m_q \approx 100 \text{ MeV} \quad \text{et} \quad \alpha_d = 0.876 \ (\text{set } \mathrm{II}_{\mathrm{ter}})}$

Optimal wrt hist. model, but other choices could be made

General (section 2.5) **Assuming: $u_q \cdot d\sigma > 0$ (space-like surface)**

Gossiaux spatial

Depends on 3 invariant quantities

$$N_{\Phi,Gx,D}(x_Q;p_Q) = \left(\frac{m_Q+m_q}{m_Q}\right)^3 \frac{m_q g_q}{\alpha_d^2 T K_2\left(\frac{1}{\alpha_d^2}\right)} \times \left(\mu + \frac{u_{\rm cell}\cdot \hat{d\sigma}}{u_Q \cdot \hat{d\sigma}}\right) \times \frac{K_2(D)}{D^2}$$

with $D = \frac{m_q}{T} \times \sqrt{1 + 2\mu u_{\rm cell}\cdot u_Q + \mu^2}$ and $\mu = \frac{T}{m_q \alpha_d^2}$

After normalization

$$\mathrm{prob}_\Phi(x_Q;p_Q) = \max\left(ff \times \mathrm{prob}_\Phi(x_Q;p_Q,\hat{d\sigma}=u_{\rm cell}), 1\right)$$

$$\mathrm{prob}_\Phi(x_Q;p_Q,\hat{d\sigma}=u_{\rm cell}) = \left(\mu + \frac{1}{u_Q\cdot u_{\rm cell}}\right)\left(\frac{m_Q+m_q}{m_Q}\right)^3 \frac{m_q g_q}{T} \frac{K_2(D)/D^2}{K_2\left(\frac{1}{\alpha_d^2}\right)/\frac{1}{\alpha_d^2}}$$

Fig 2 of PRC79

$$ff = \frac{\mu + \frac{u_{\rm cell}\cdot\hat{d\sigma}}{u_Q\cdot\hat{d\sigma}}}{\mu + \frac{1}{u_Q\cdot u_{\rm cell}}}$$ Flux factor

Caviats

1) m_q probably too small

2) Coalescence -> « average » D meson (chemistry not taken into account)

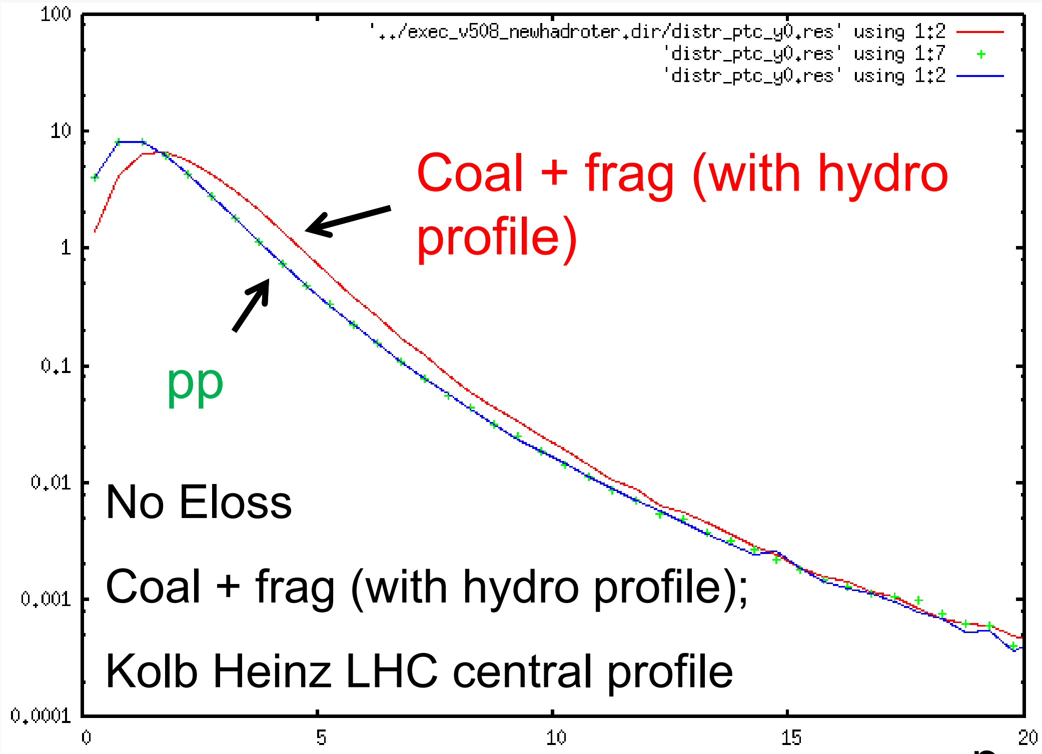
Hadronization algorithm

1) For pp: use p_T-frag ($y_D=y_c$ and $\mathbf{p}_{TD}=z\,\mathbf{p}_{Tc}$)

2) For pA or AA:
   1) Perform sampling criteria (coal or frag) in the fluid cell rest frame
   2) When fragmentation is chosen perform the same fragmentation as in pp, **staying in the lab frame**

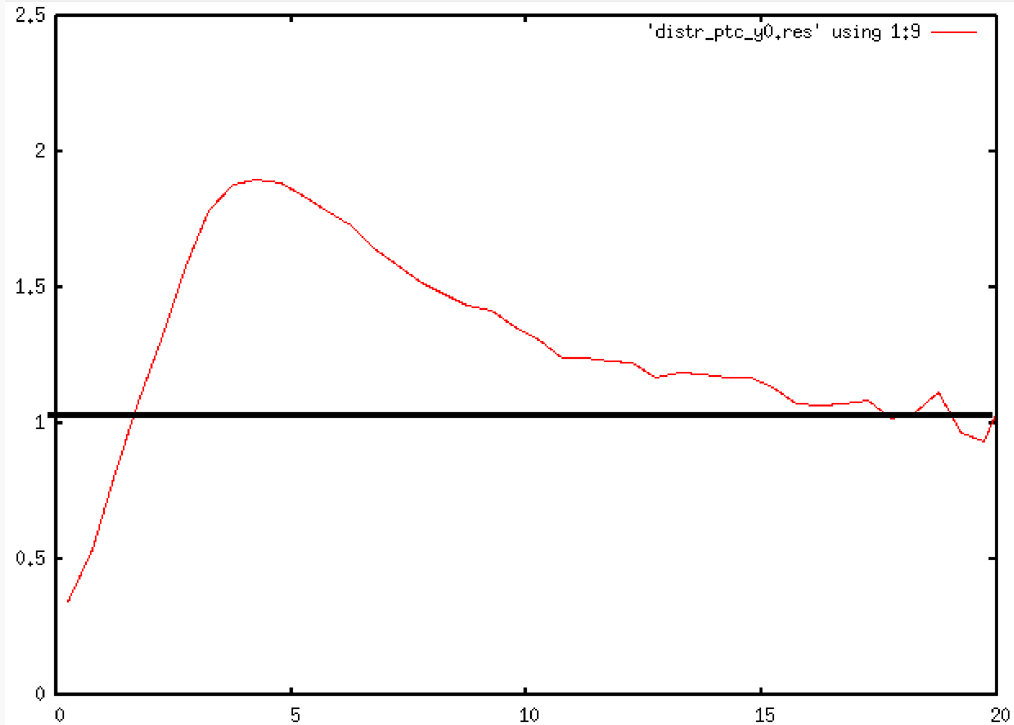
This allows to preserve the rapidity invariance as well as Q (ratio) =1 if no Eloss (and no shadowing)…(NOT SO TRIVIAL !!!) Then looking for the coal + frag case:

dN_D/dp_T



p_T

$Q_D(p_T)$



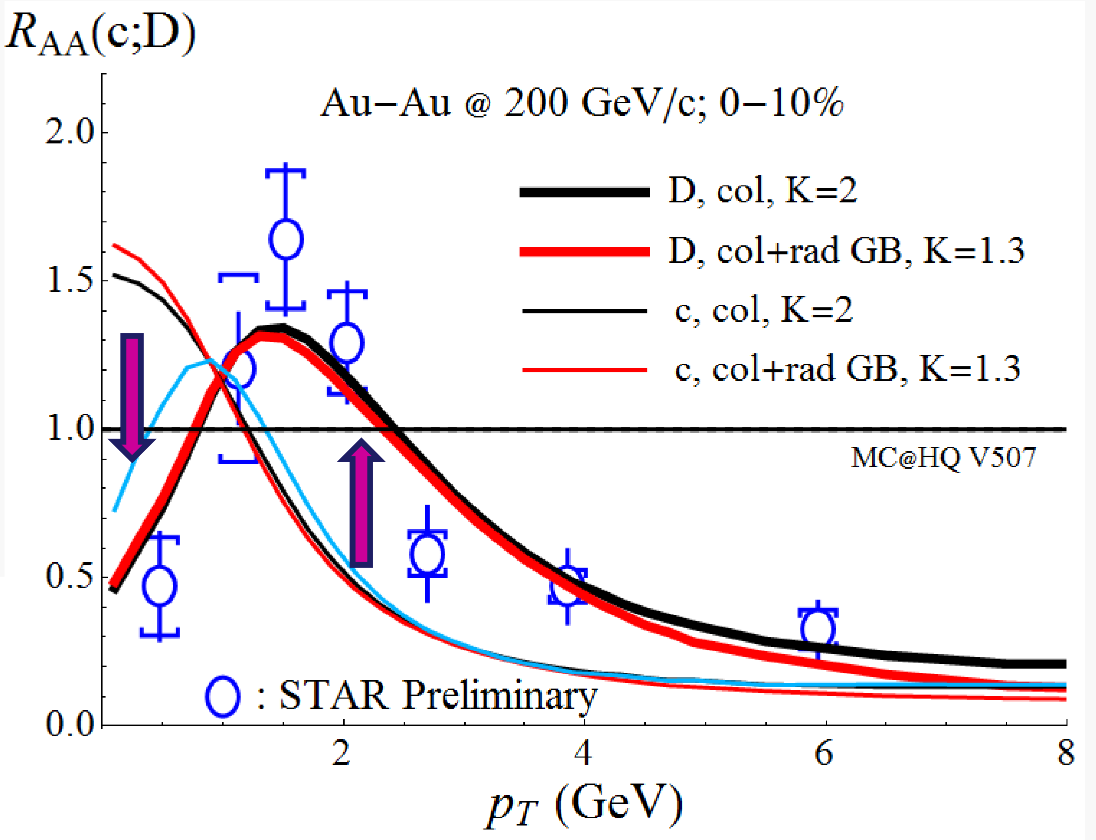
p_T

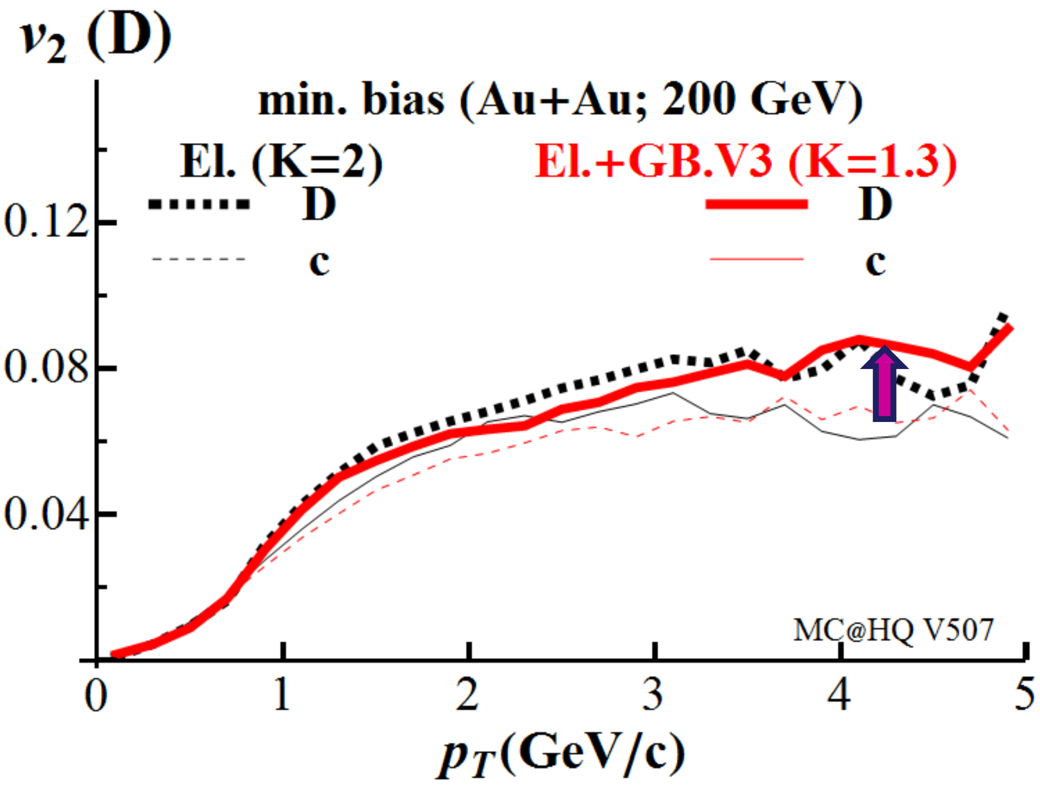
While boost invariance is preserved as well for boost invariant QGP (checked but not shown)

some effects on HQ evolution

Basic observables (RHIC)

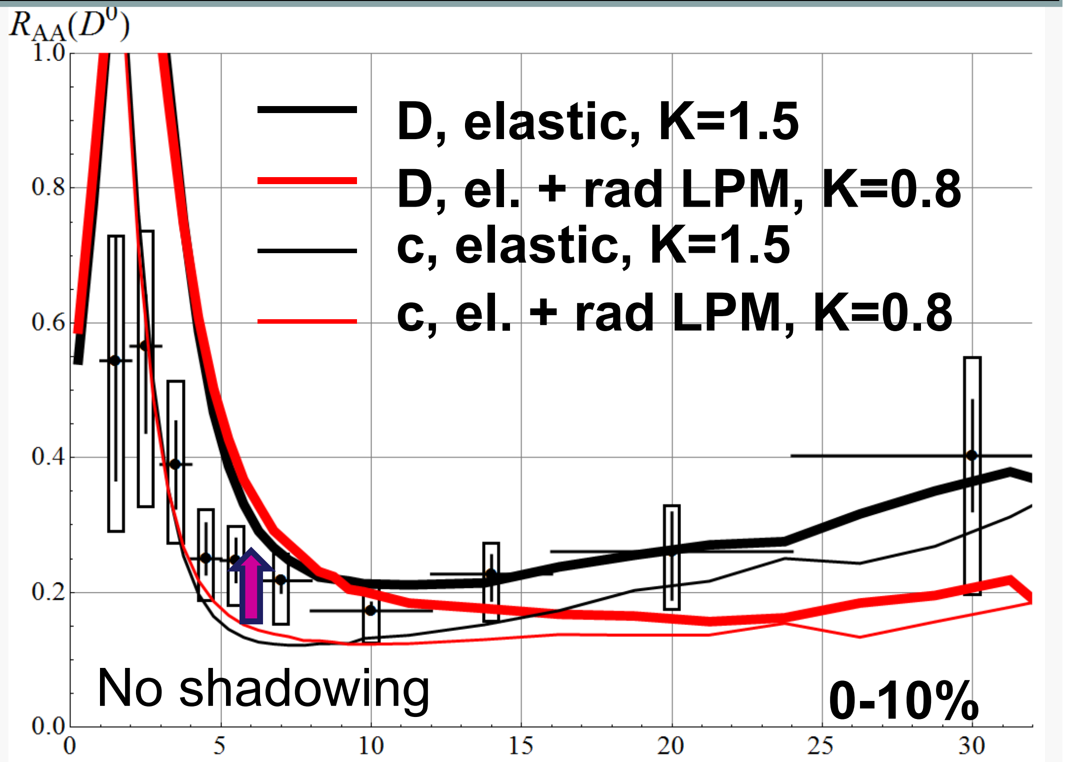
Kolb Heinz hydro



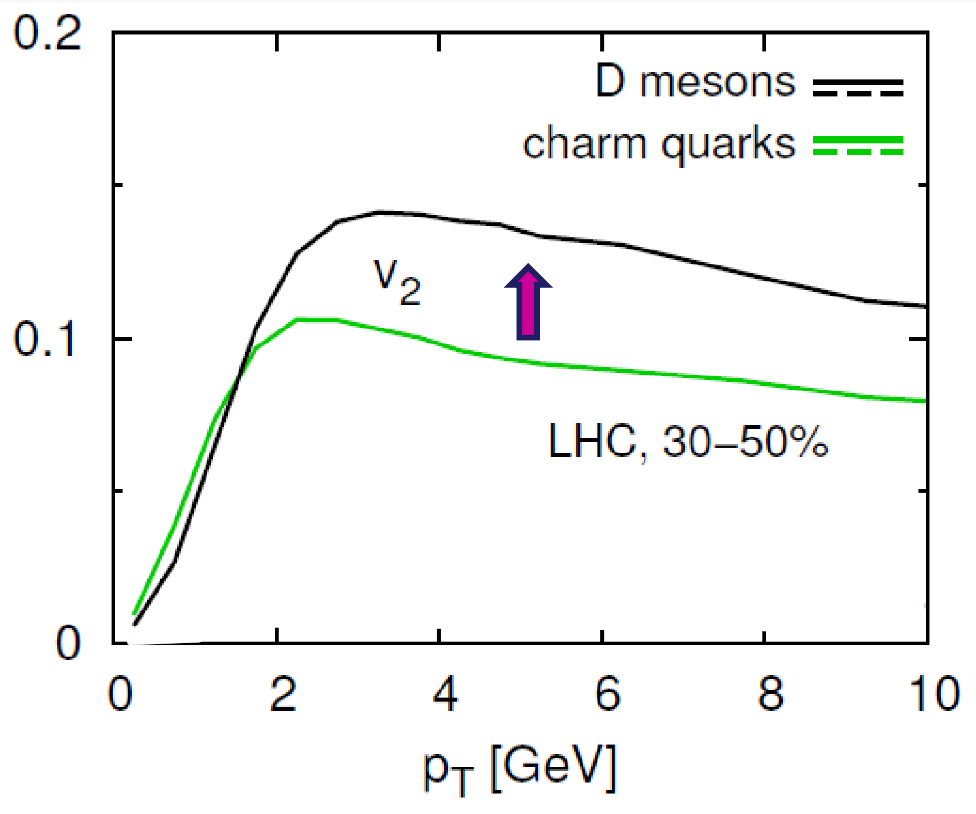


Large effects from coalescence (especially in the R_{AA})… to be studied in a more systematic way

Basic observables (LHC 2.76 TeV)



EPOS2



Large effects from coalescence for both observables

Sharing at EMMI RRTF and since then…

H_{AA} observable

R. Rapp et al. / Nuclear Physics A 979 (2018) 21–86 43

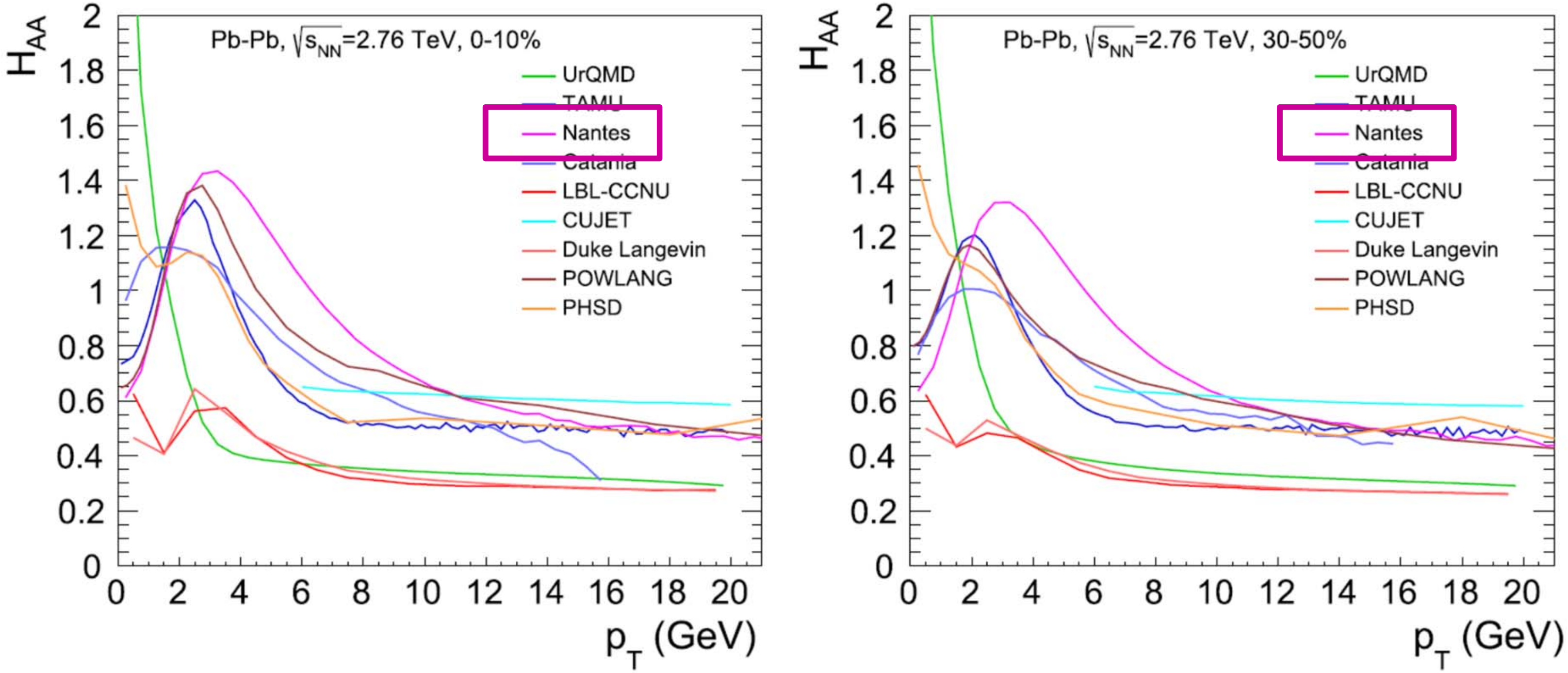


Fig. 14. Comparison of the ratio of D-meson to charm-quark p_T spectra, $H_{AA}(p_T = p_t)$, just after and before hadronization, respectively, in central (left panel) and semi-central (right panel) Pb–Pb(2.76 TeV) collisions for the results from the elastic pQCD*5 QGP transport simulations and individual hadronization procedures within the various bulk evolution models.

$$H_{AA} = \frac{dN_D^{\mathrm{hadro}}}{\boxed{dN_c}}$$

Just before hadronization

- Nantes has the largest H_{AA} in the low p_T region
- Possible reason : m_q chosen artificially too small
- => In the cocktail, compensates for larger Eloss
- Important to revisit

Other constrains / issues

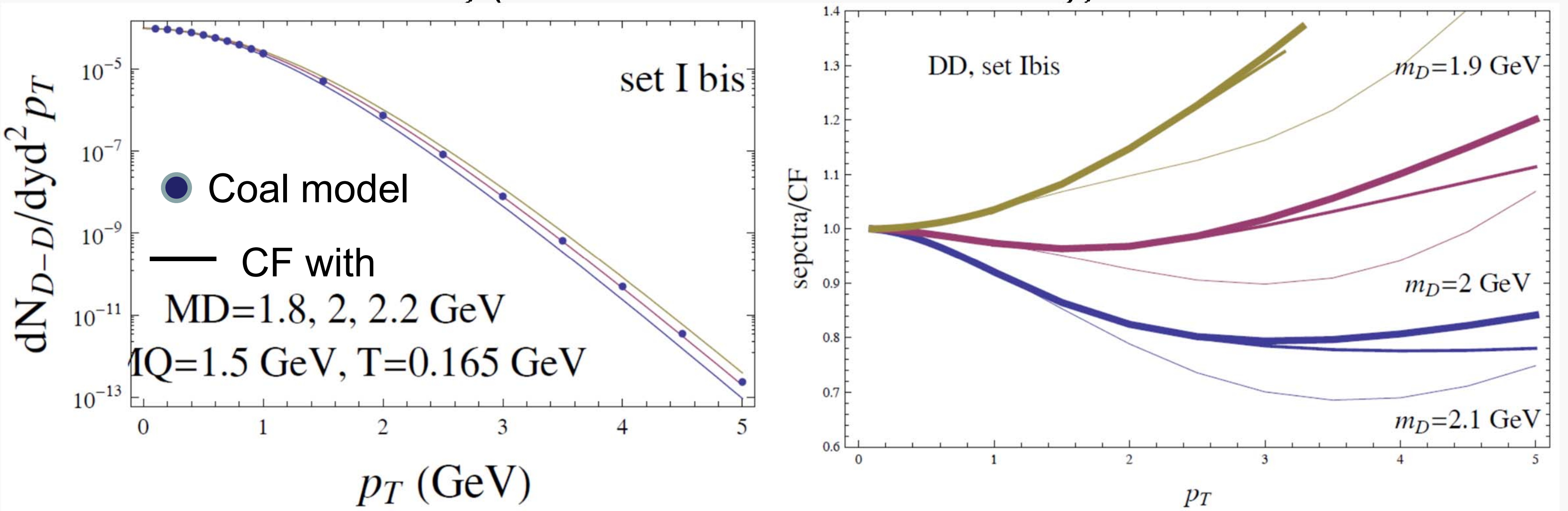
- Energy conservation issue => concrete consequence : coalescence spectrum depends on the frame where the Q+q -> H “conversion” is performed.

- Equilibrium limit : Taking both statistical distribution for q and Q, one expects to recover the Cooper – Frye spectrum.

Imposing further constrains on the coalescence model

Basic Criteria (BC): Starting from some equilibrated and uniform (in space) distribution of c-quarks, it sounds rather natural to require from any sound hadronization model that it leads to some Cooper – Frye distribution of the generated D-mesons, with the correct physical mass of 1.87 GeV.

In fig below, we see how well/bad the BC is satisfied for **Dover** model of coalescence, with m_q=200 MeV and α_d=0.532 (what we call set Ibis), for the simple case of a uniform fireball with 0 fluid velocity (consider the thickest curves only).

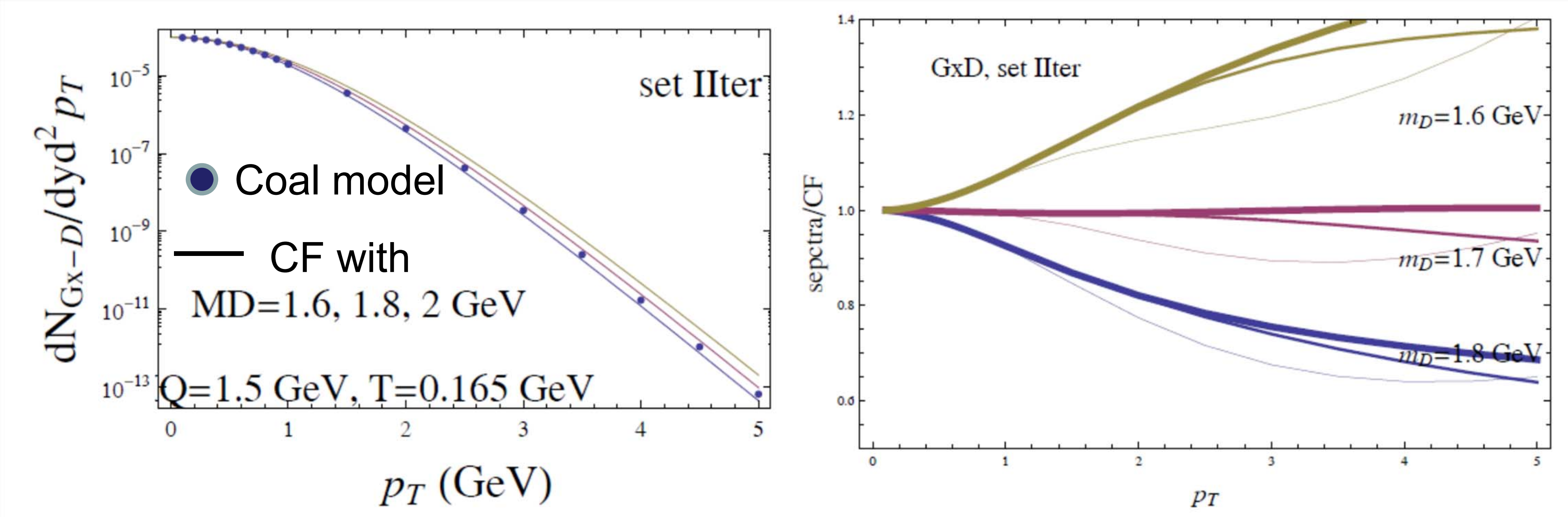


Although the global shape seems ok (left panel) after a global normalisation, precise ratio with any CF spectrum of given mass m_D shows deviation ./. unity of the order of 20% in the p_T range 0-4 GeV, so that the BC cannot be considered to be satisfied even for a simple FB model. This invalidates the most common coalescence Model !!!

<u>N.B.:</u>**Validation should be made at the level of the ratio, not on the global shape !**

Imposing further constrains on the coalescence model

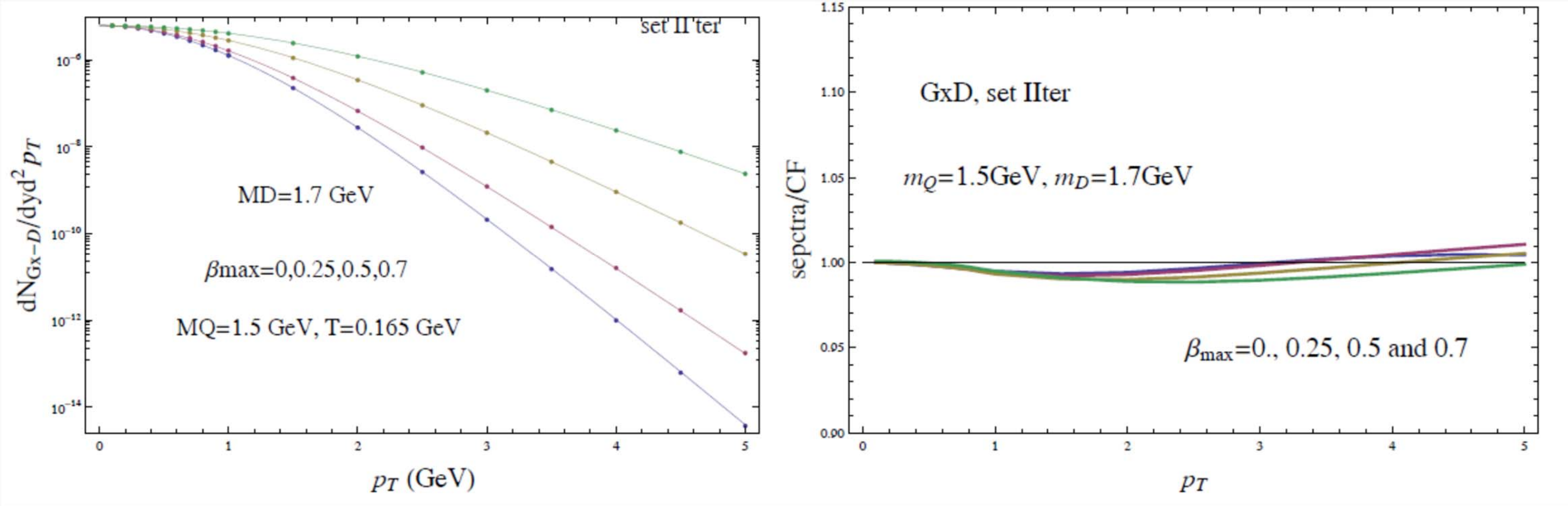
We now consider the coalescence model of Gossiaux et al, where the spatial part of the coalescence probability depends on the q-Q distance measured in the Q rest frame. In the plots below, we see that with the « standard » parameters considered for the coalescence probability (m_q=100 MeV, α_d=0.876), the D-meson spectrum ensuing from coalescence follows a CF-like shape, with however a wrong effective mass value of m_D^{eff}=1.7GeV



N.B.: Technically, the coalescence spectrum is obtained through analytival calculation, transforming the 6-fold integration on $\mathbf{p}_Q$ & $\mathbf{p}_q$ in some integration on $\mathbf{P}_T$ and Y (transverse momentum and rapidity of the Qq pair) as well as on the relative momentum, which is performed explicitly. In MC simulations, one needs to put the Qq « on shell » by assigning the physical m_D mass to the selected Qq pair for a given Q. This can be done (f.i.) either in the fluid frame or in the lab frame. It appears that the consequence of the wrong effective mass m_D^{eff} (1.7GeV) in the BC calibration it that the dN_D/dp_T in dynamical simulations depends on the prescription used for performing the coalescence.

Imposing further constrains on the coalescence model

We should also notice that once a Cooper Frye spectrum shape is achieved for a « basic » fireball, it appears that the agreement is preserved for more involved FB, for instance when imposing transverse velocity α r x β_{max}, for various values of β_{max} as illustrated below.

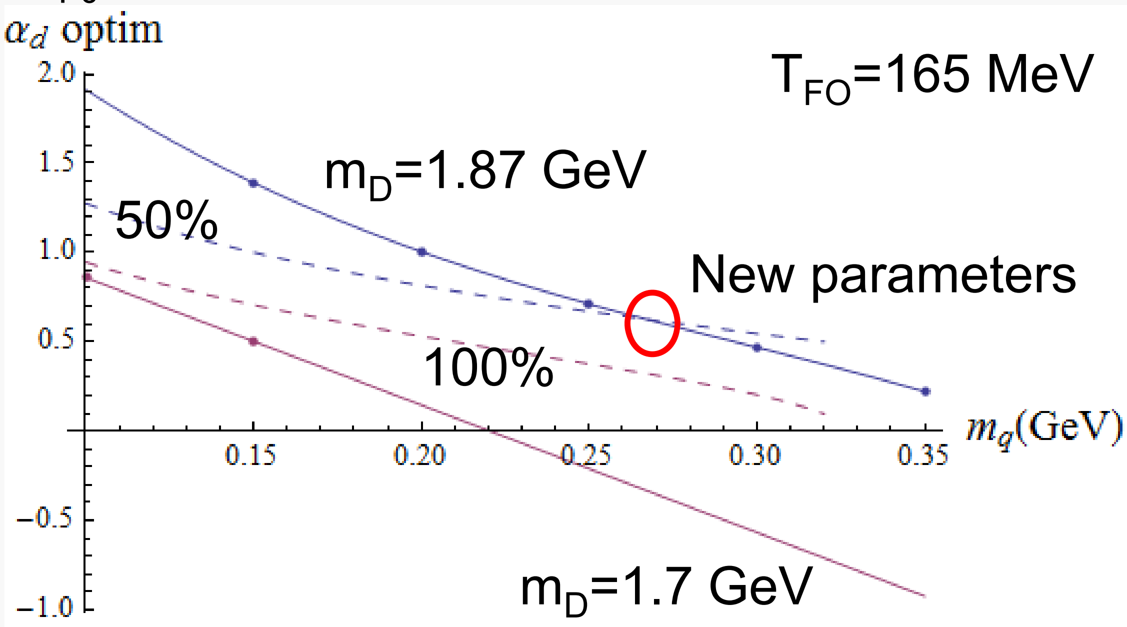


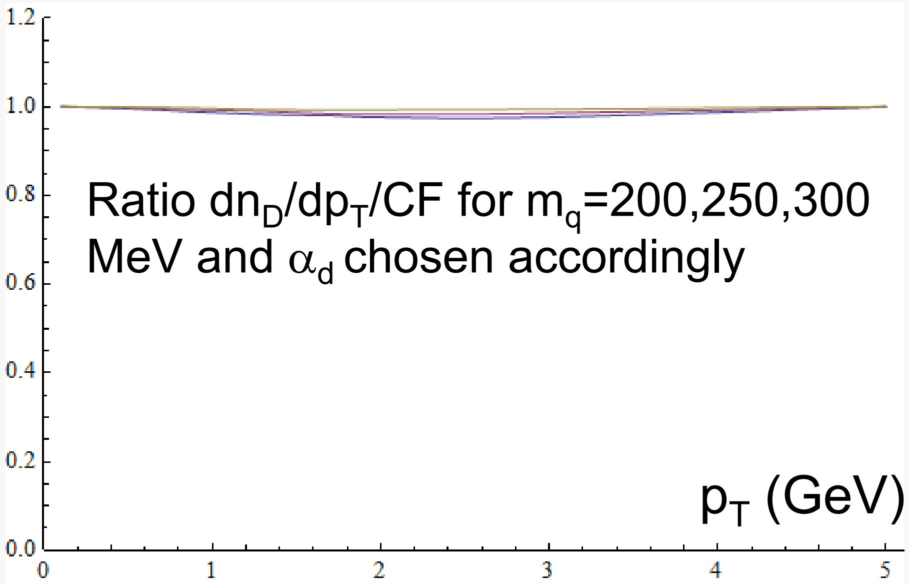
We thus conclude that the coalescence model used by Gossiaux at al. has the potentiality to match the BC, although:

- It does lead to the correct CF spectrum, i.e. not to the one with the correct D-meson mass
- There is, to our understanding, no underlying dynamical ground why it should be the case.

Imposing further constrains on the coalescence model

In order to get the « best set » for our coalescence model, we thus seek the values of (m_q,α_d) compatible with a CF spectrum of physical D-meson mass (1.87 GeV). For T_{F0}=165 MeV, those are located on the blue curve of the fig below.



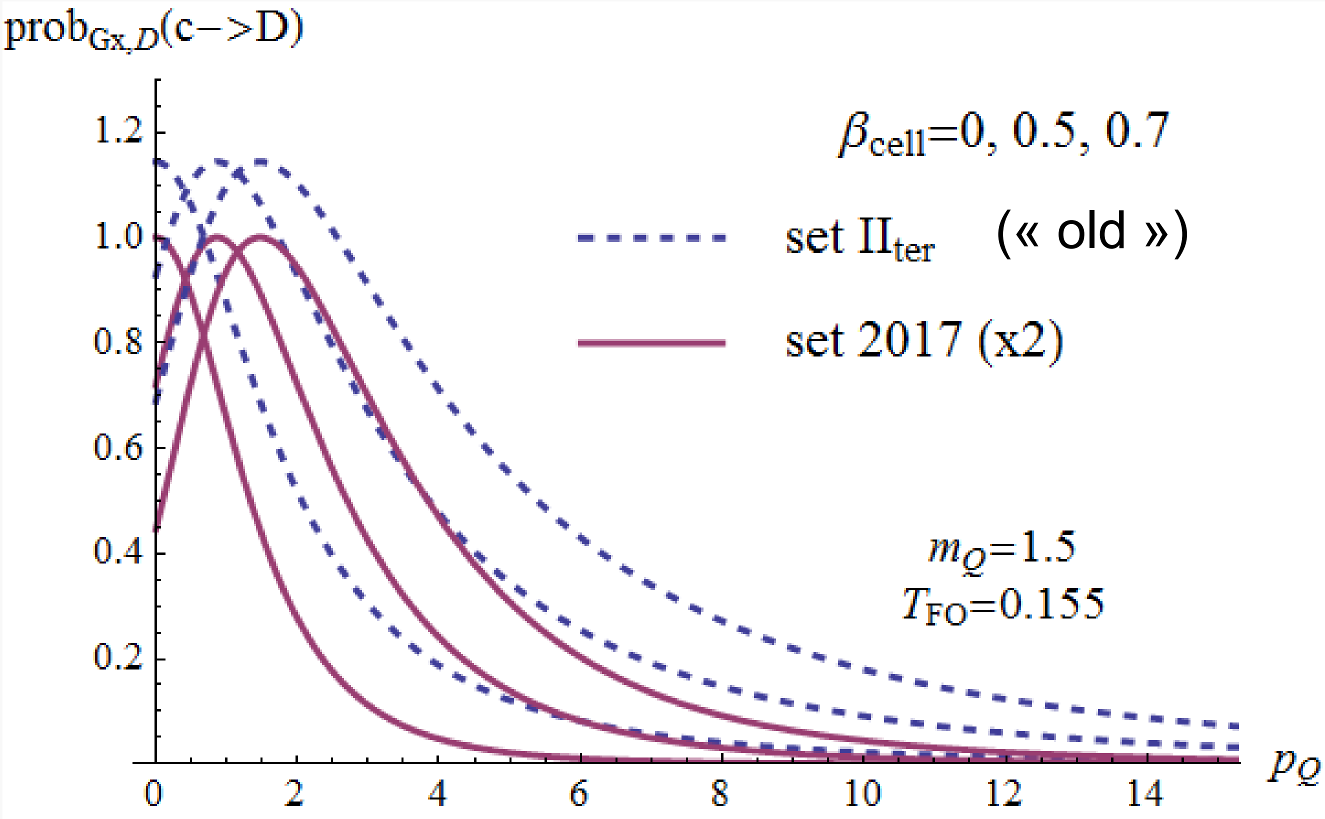


We moreover require an absolute value of the coalescence probability -> mesons to be 50% for some c-quark at rest in the fluid (dashed blue curve), the other 50%, corresponding to coalescence -> baryon. This leads to m_q=267 MeV and α_d= 0.627 for and T_{FO}=165 MeV and to m_q=292 MeV and α_d= 0.510 for and T_{FO}=155 MeV (referred to as « sets 2017 » or coal IV), i.e. values of m_q closer to the constituent mass value chosen by other groups.

N.B.: For this new sets, the dN_D/dpT obtained in dynamical simulations do not depend on the prescription used for coalescence (in fluid or in lab), which can be considered as a BC2

Imposing further constrains on the coalescence model

We now show the coalescence probability as a function of p_c for the « old » and new set of parameters, for 3 values of cell velocity (dS is chosen such that it is (1,**0**) in fluid rest frame).



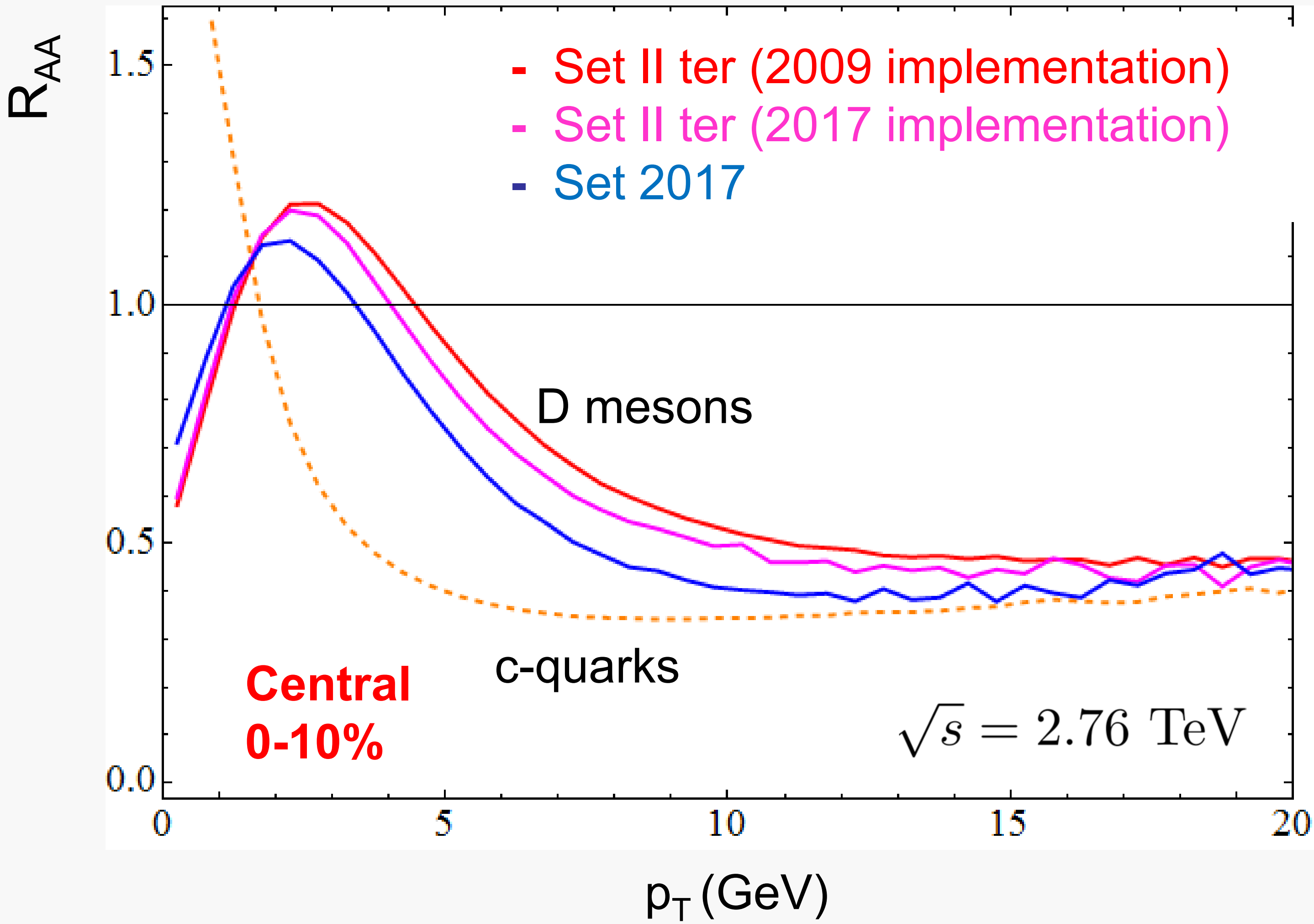
N.B.1: Larger m_q reduces the probability to find a q at finite velocity, and hence the coalescence probability at intermediate p_T.

N.B.2: finite cell velocity shifts the coal. prob. towards larger momentum.

Consequences for EMMI

With EPOS2 as a background and pQCD x 5 as an Eloss model.

Various implementations of hadronization for same underlying c-quark evolution



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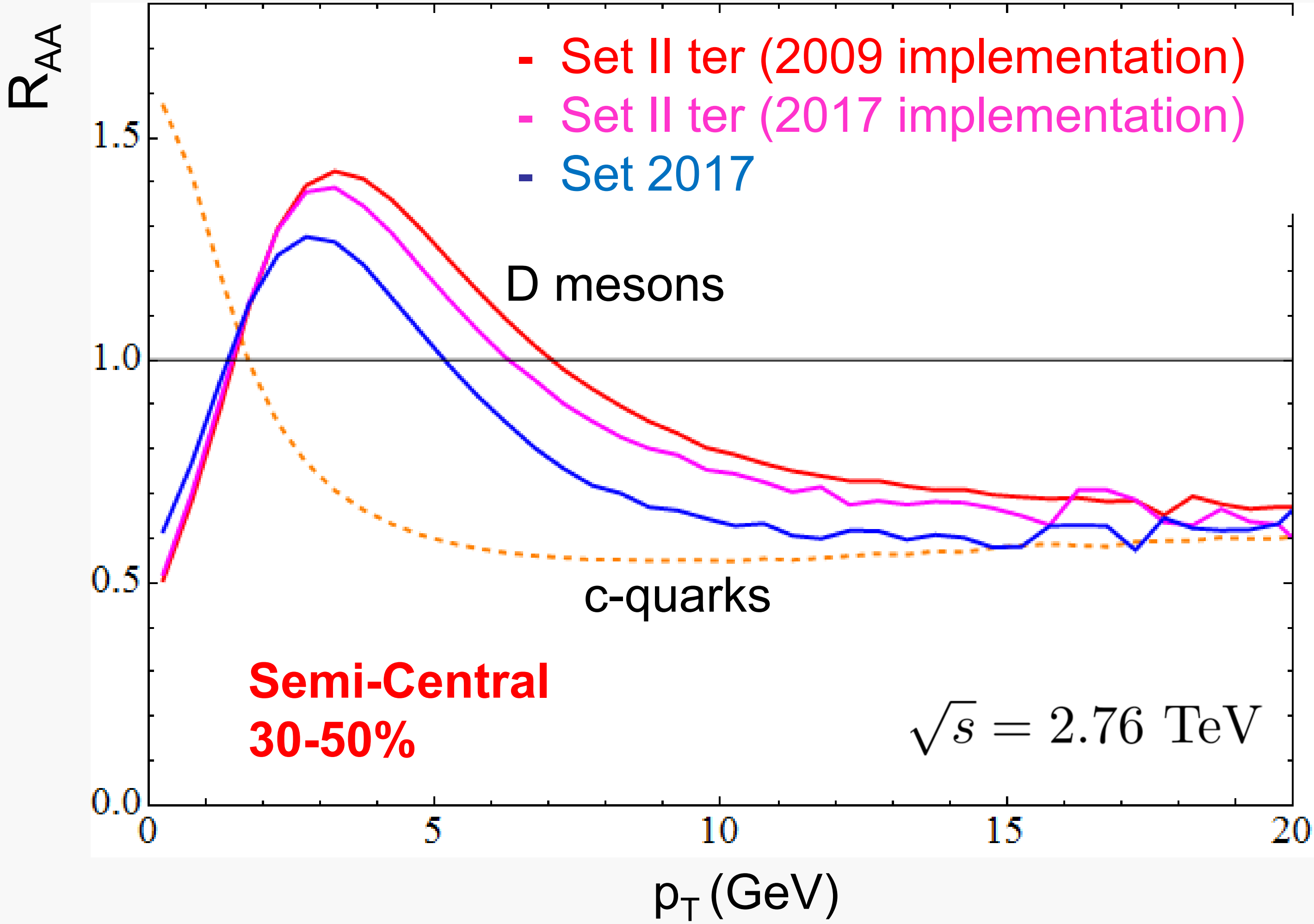

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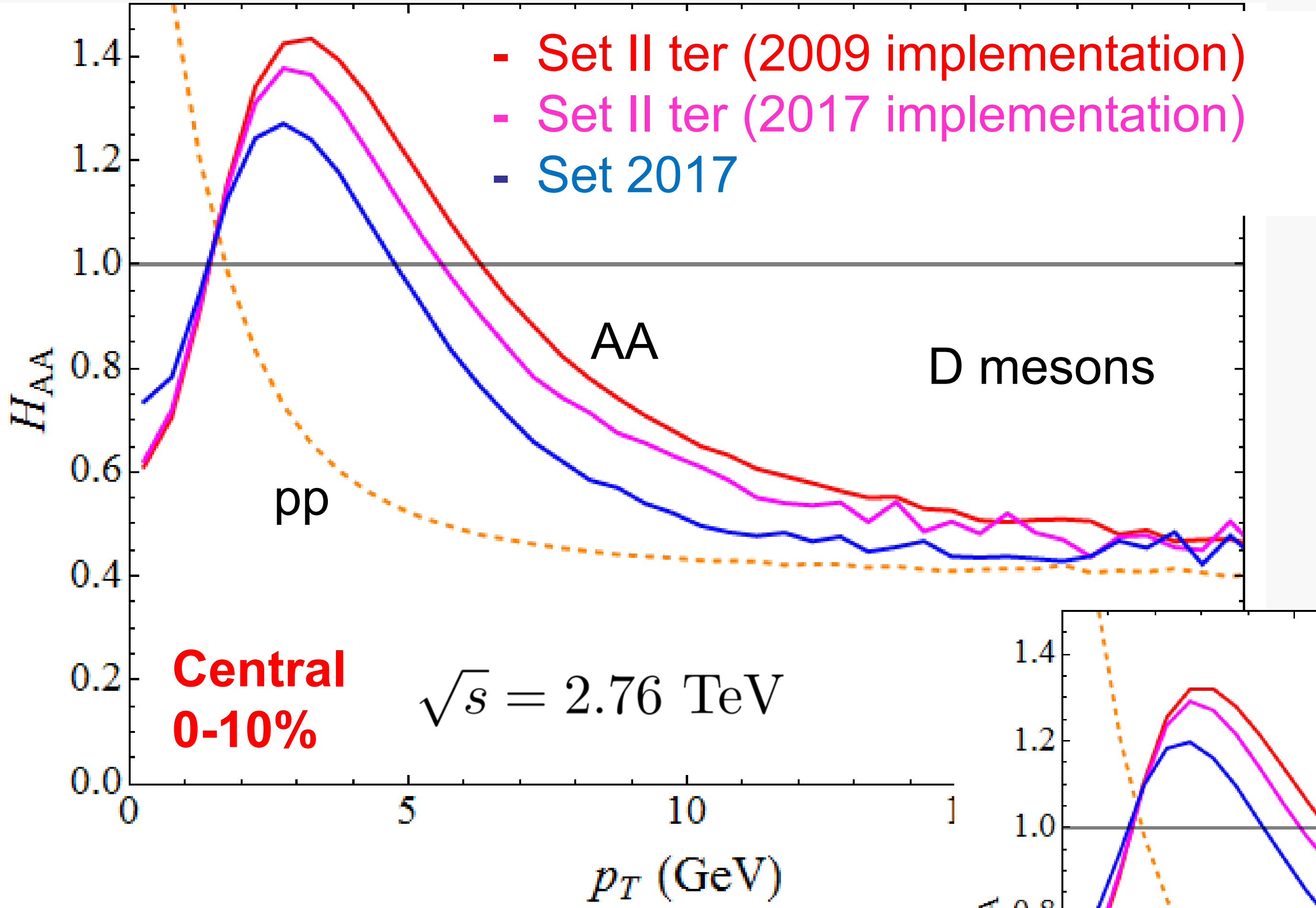
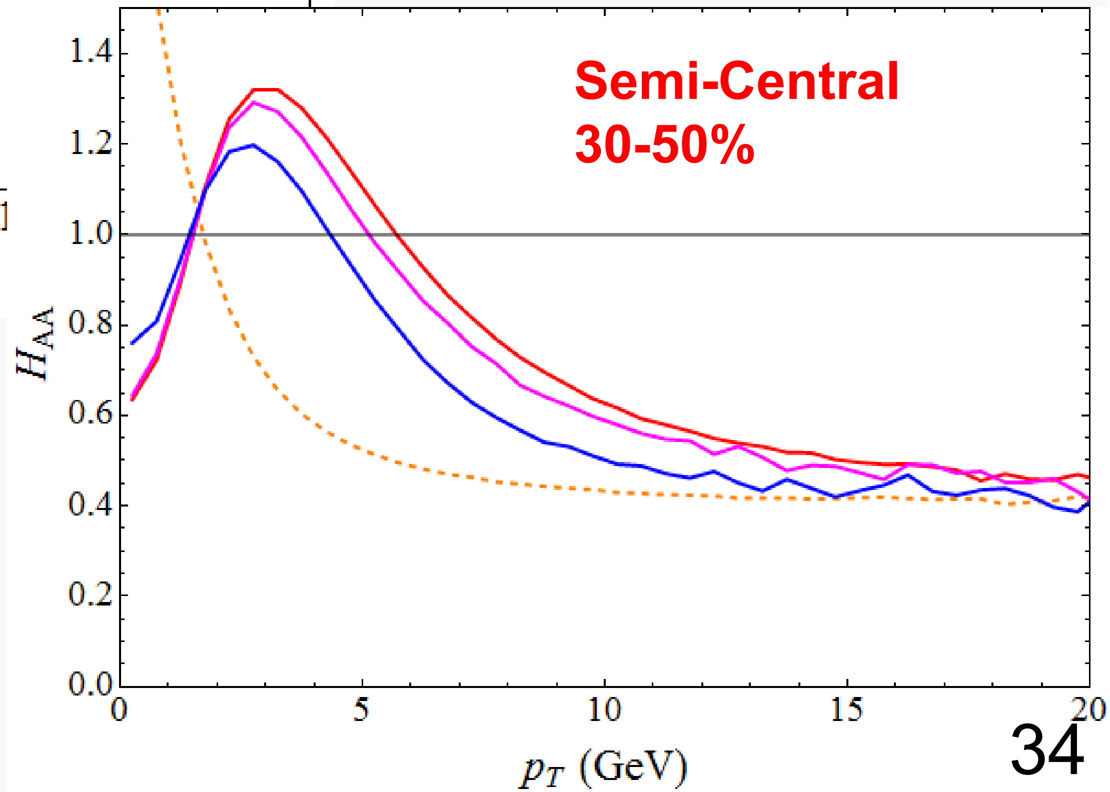
With EPOS2 as a background and pQCD x 5 as an Eloss model.

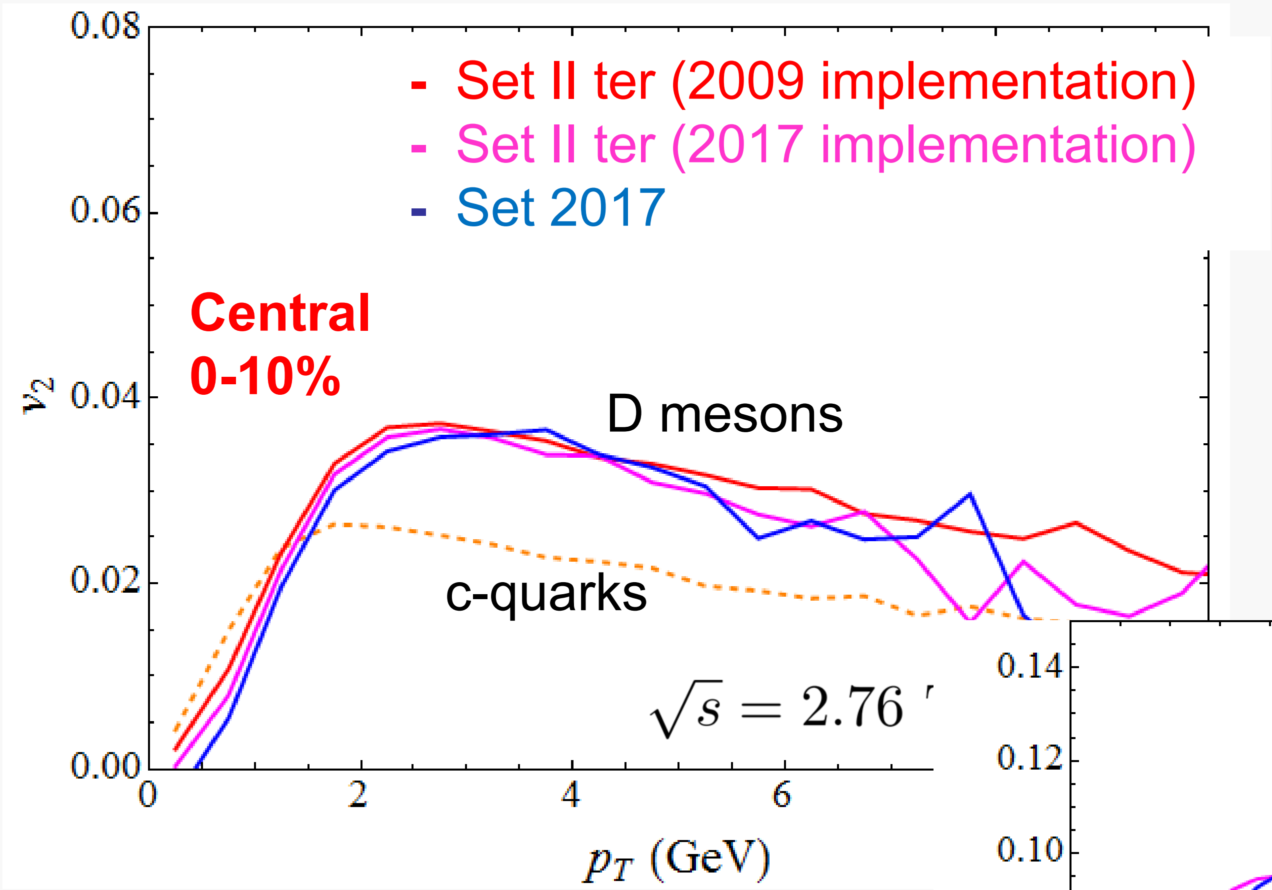


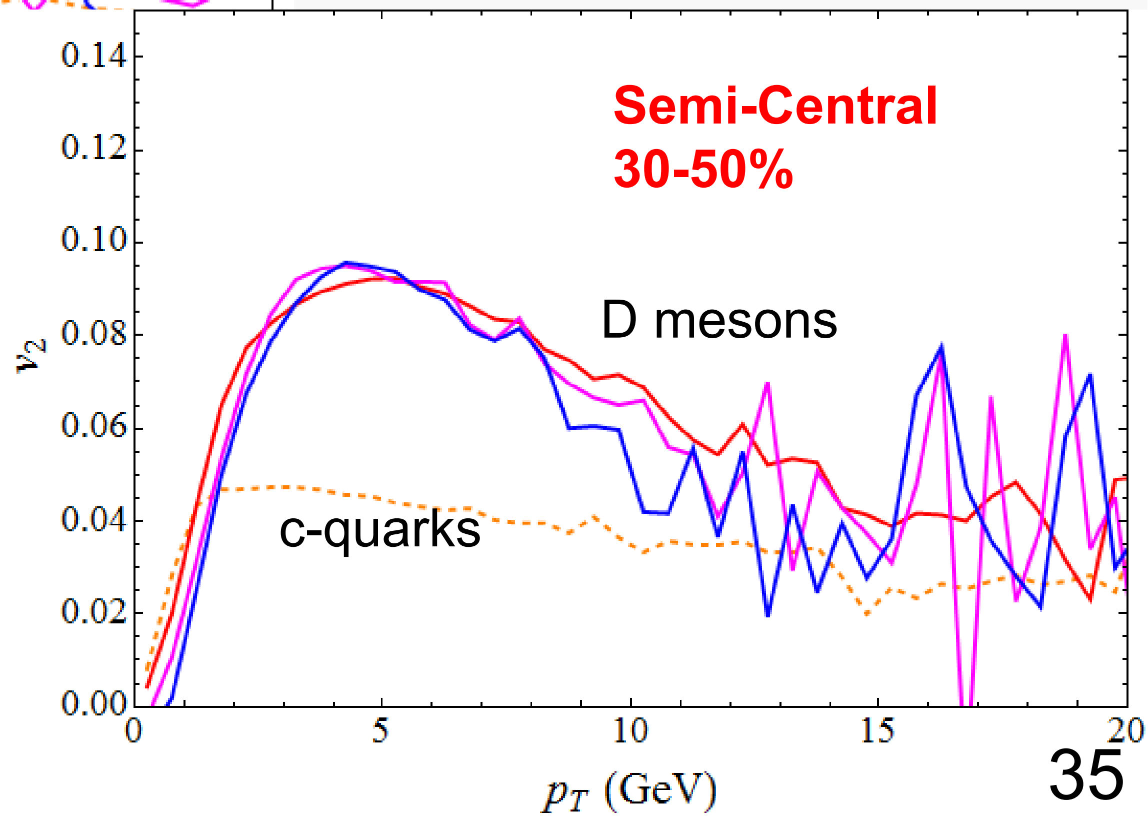


Adopting a set of parameters compatible with the Basic Criteria leads to a reduction of the H_{AA} (which becomes now compatible with the largest H_{AA} from other groups: Catania, Powlang) => reduction of uncertainty band. Flow velocities play a significant role as well.

Consequences for EMMI

With EPOS2 as a background and pQCD x 5 as an Eloss model.



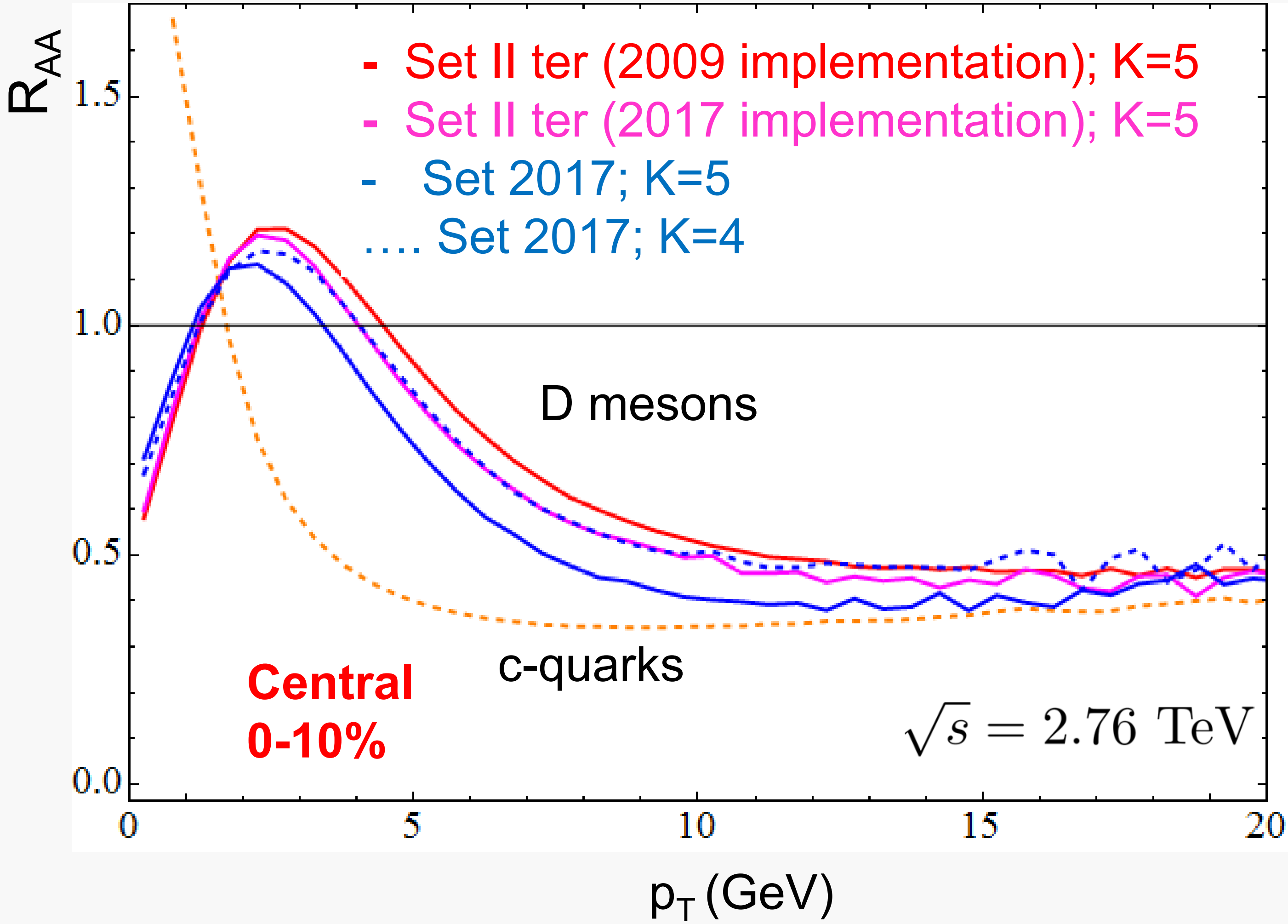


Adopting a set of parameters compatible with the Basic Criteria leads to a reduction of the v_2 at large p_T. At intermediate p_T, some compensation happens (f.i., the larger m_q mass compensates for the smaller coalescence probability)

Consequences for EMMI

With EPOS2 as a background and pQCD x 5 as an Eloss model.

Let us assume that set II ter (2017 implementation) would be tuned to exp. Data for pQCD x 5 ⇔ …

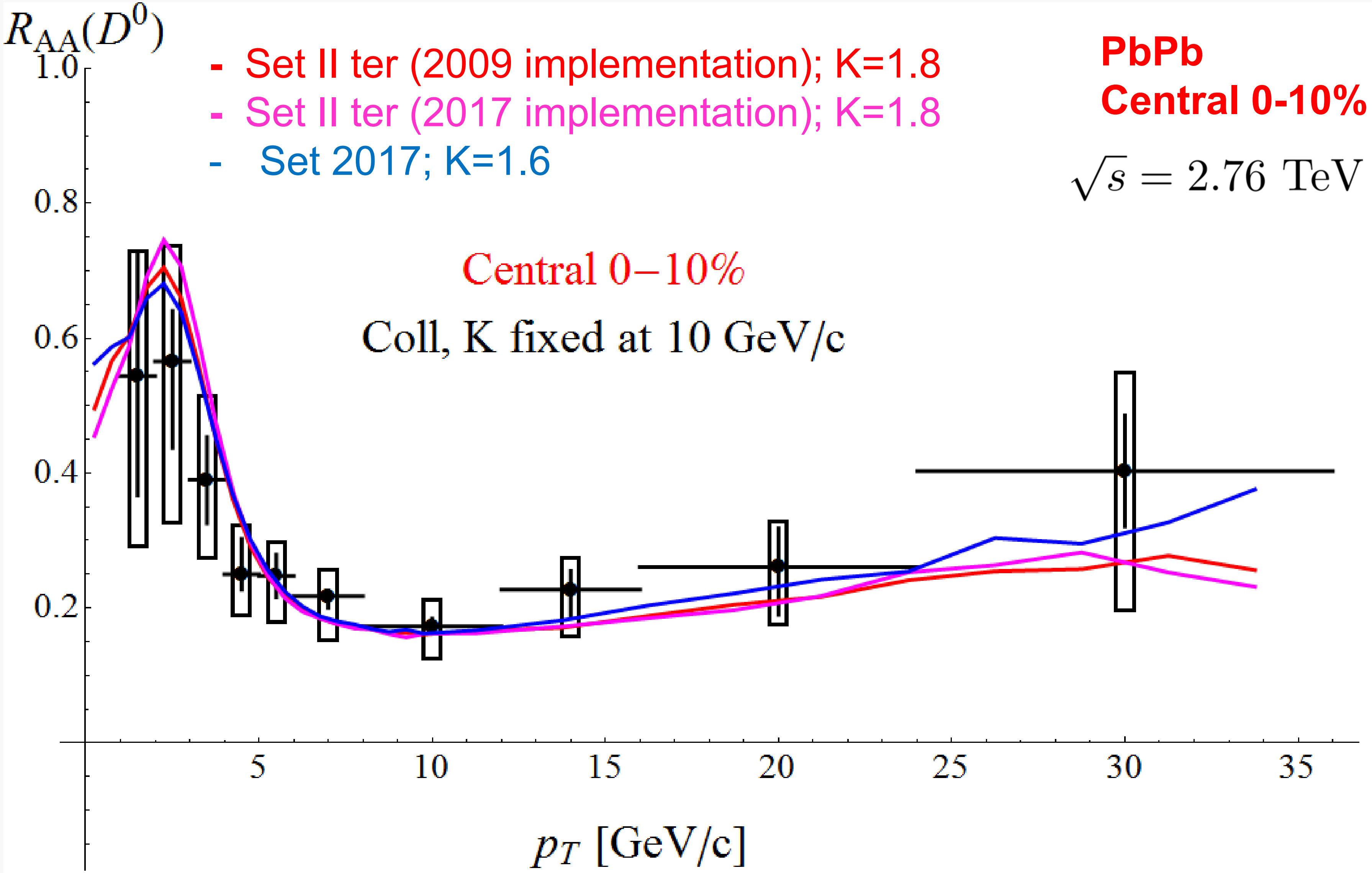


… Then we would need to apply « only » a factor x4 for the model with set 2017 for coalescence… **=> -20% for the transport coefficients extraction (main conclusion)**

Test in MC@HQ + EPOS2

With EPOS2 as a background and running α_s as an Eloss model.

Let us tune the K to exp. Data at p=10 GeV/c

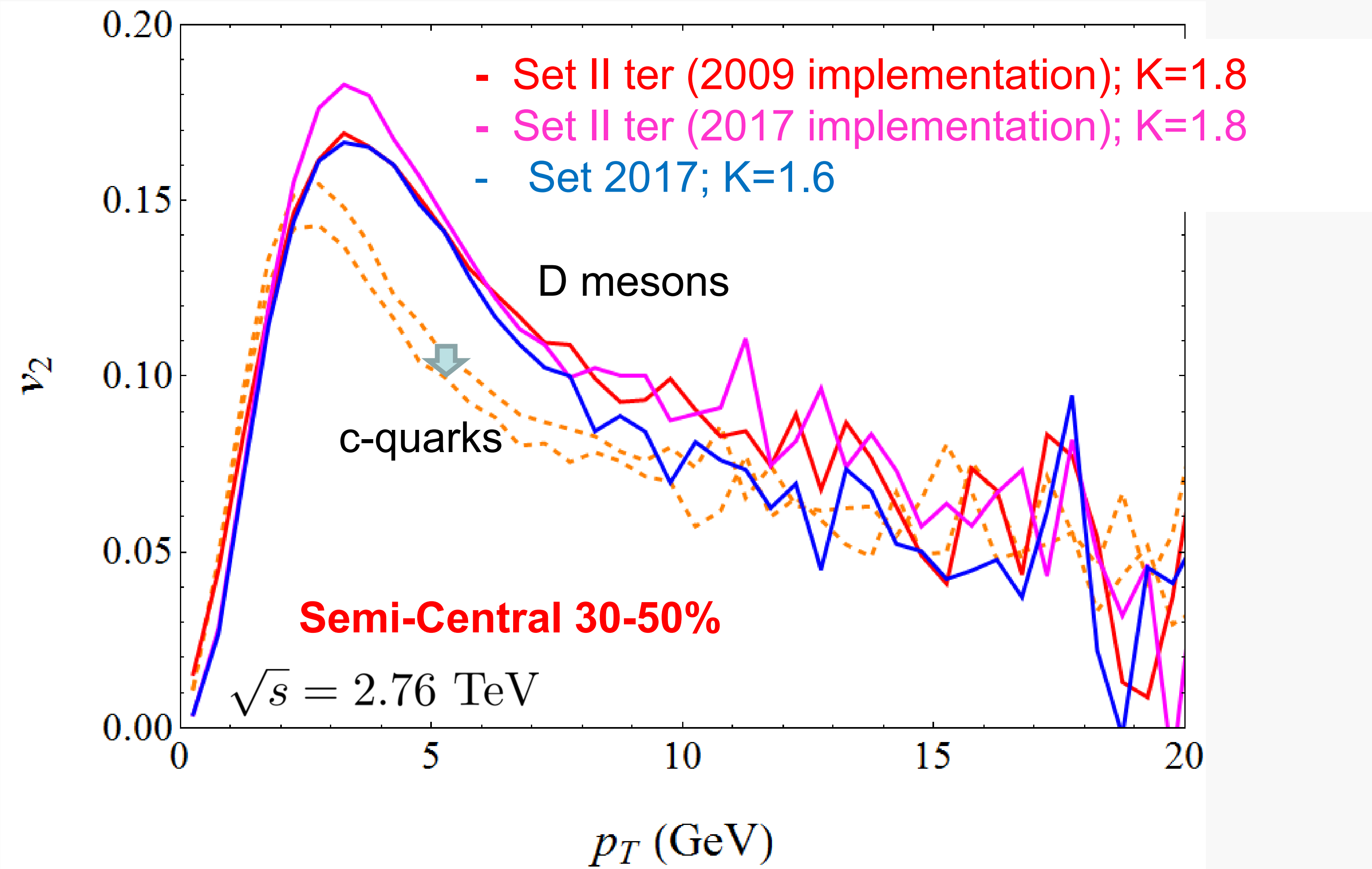


… Then we would need to apply « only » a factor x1.6 for the model with set 2017 for coalescence instead of K=1.8… **=> -12% for the transport coefficients extraction**

Test in MC@HQ + EPOS2

With EPOS2 as a background and running α_s as an Eloss model.

Then, let us look at consequences for the v2:



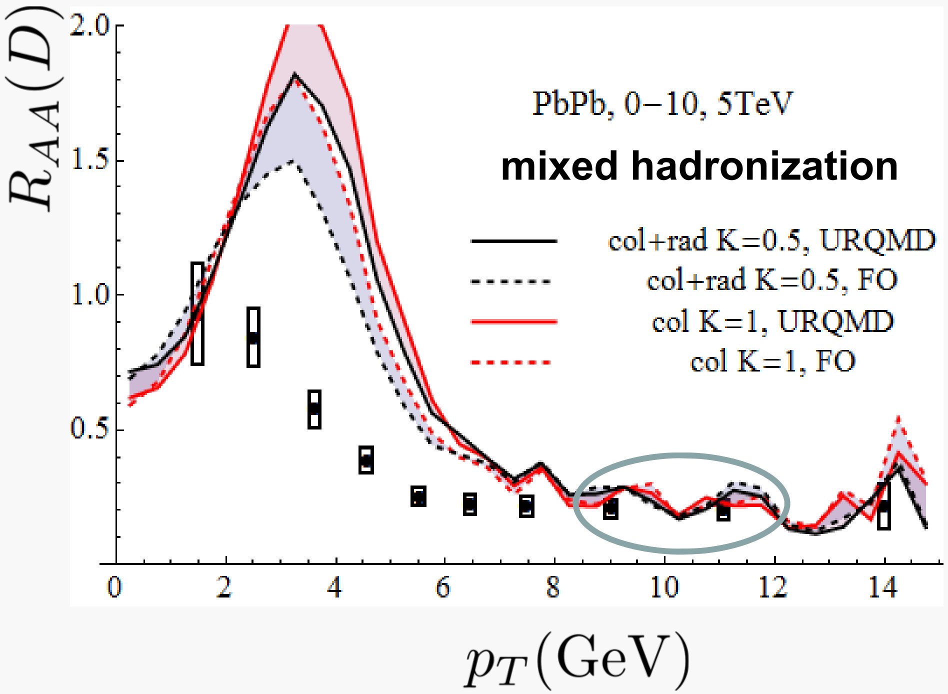
Comparing with the previous implementation (red), we observe faster decrease of the v_2 at large p_T (which seems to be observed in the data as well)

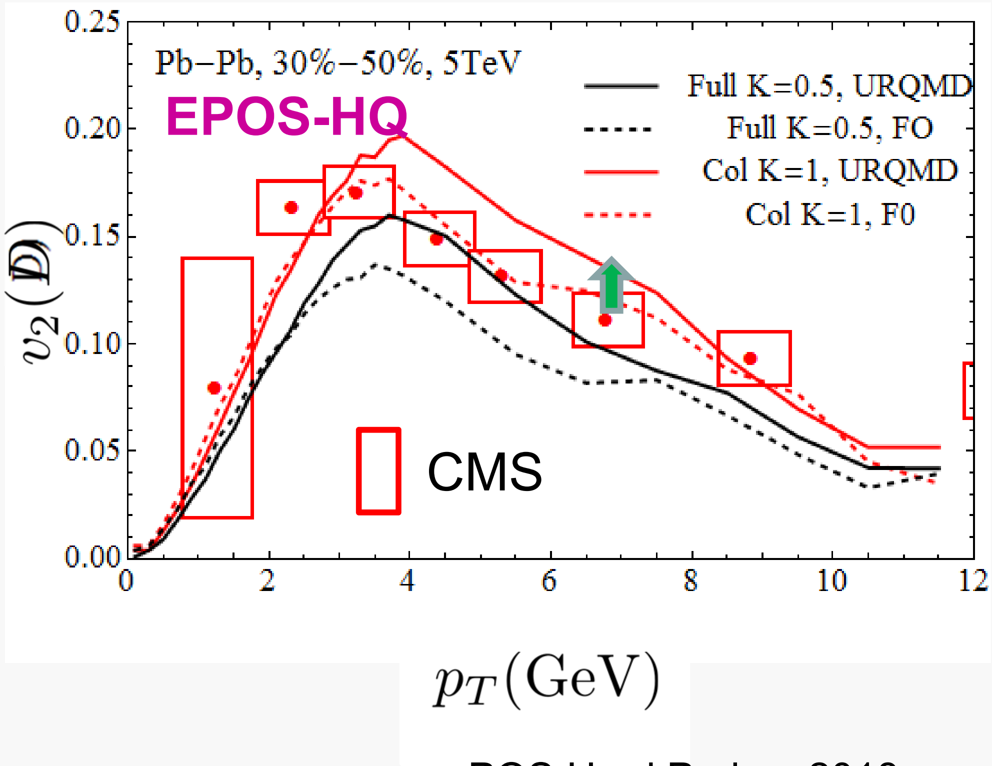
Conclusion and future

- Coalescence model of Nantes confronted with basic criteria (BC) to produce Cooper Frye spectrum in equilibrated case: ok, but one needs to change the parameters (m_q now needed to be of the order of 300 MeV for m_Q=1.5 GeV)
- Consequences @ LHC with realistic hydro : 10-15% reduction of the optimized drag coefficient.
- In short term future: one needs to generalize the hadronization model for the production of Ds and Λ_c (competitive coalescence)
- It would be good to compare the genuine basic parameters (m_q, width – α_d --, global normalisation ?) in ICM.
- In mid/long term future: extraction of parameters in instantaneous coalescence is pretty phenomenological => one needs to develop hadronization models more deeply rooted to microscopic principles.

Role of hadronic phase

- In EPOS-HQ : EPOS3 + MC@HQ + URQMD (not until then)





POS Hard Probes 2018

- Preliminary (still problems with the flow bump)