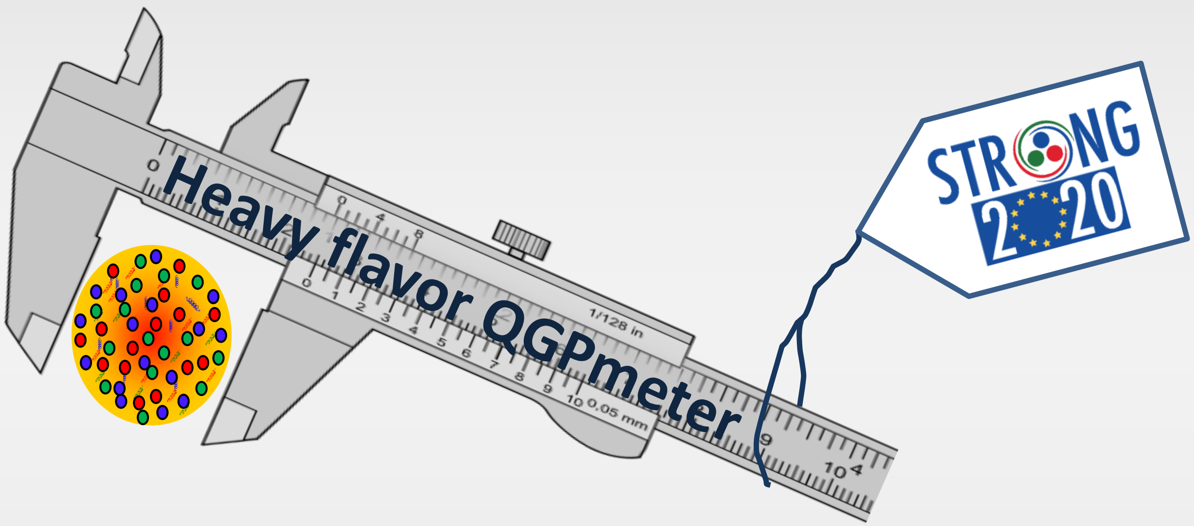
Heavy flavor hadronization with DAB-MOD



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Project developed at the University of São Paulo (Brazil)

<u>with C. Prado, J. Noronha-Hostler, J. Noronha, M. Munhoz, A. Suaide</u>

DAB-MOD: basics

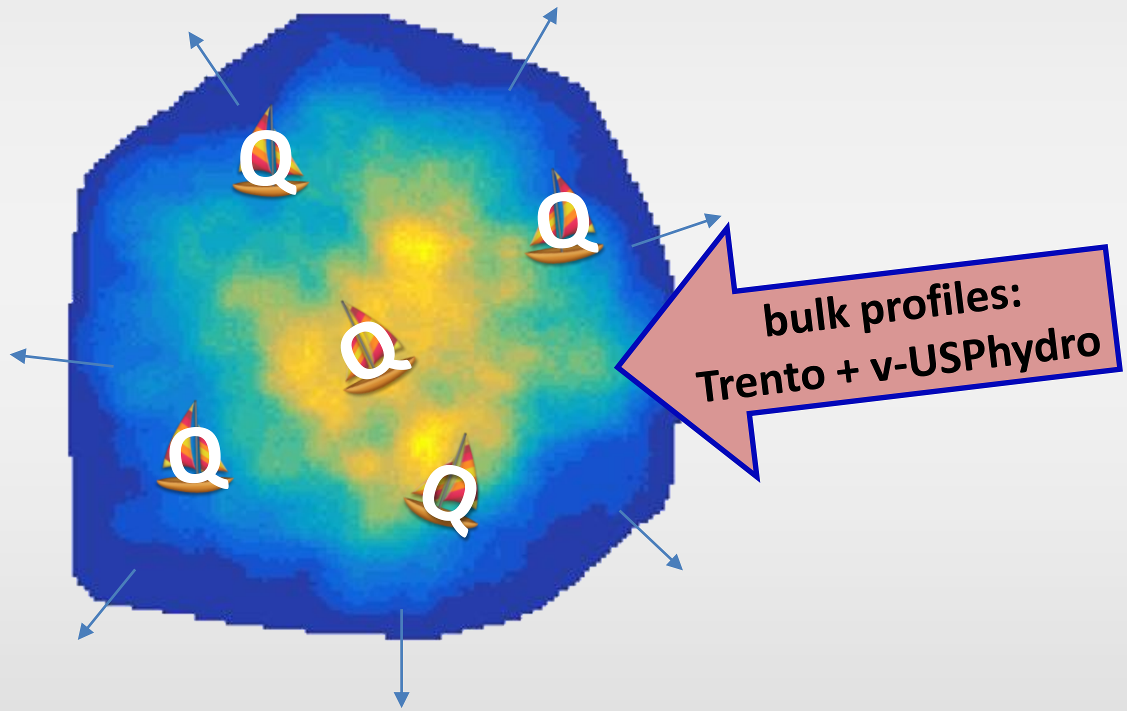
“D and B mesons - modular code”

Heavy quarks evolve on the top of 2d+1 bulk profiles

Transport:
- parametric energy loss
- relativistic Langevin

Hadronization:
- fragmentation
- coalescence

No hadronic rescattering



***Analyses*: -- R_{AA} vs. v_2 -- anisotropies with cumulants -- system size scan --**

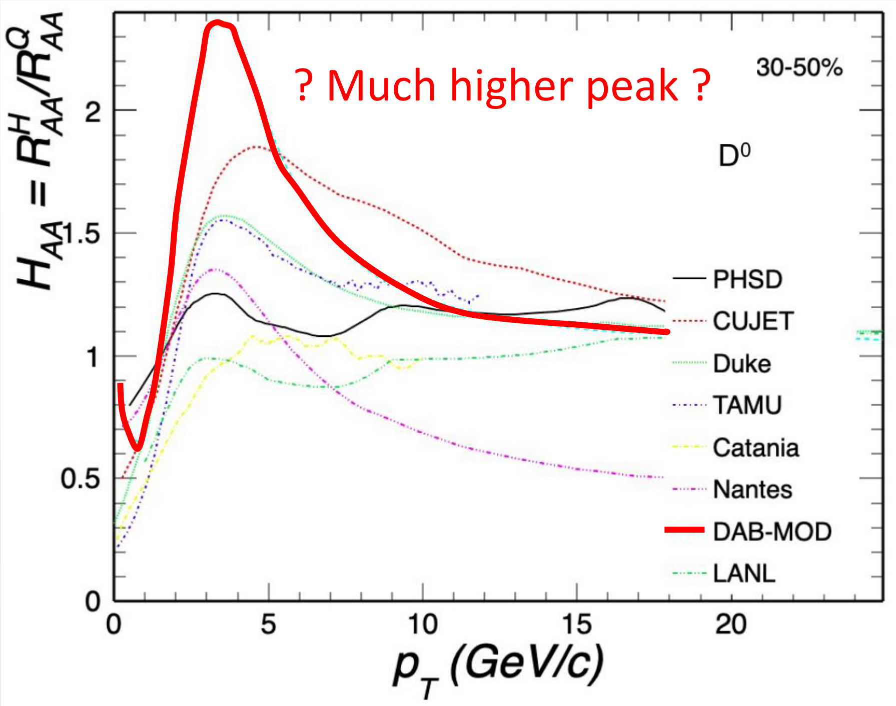
Phys. Rev. C 96, 064903 (2017) [1611.02965], Phys. Rev. C 102, 024906 (2020) [1906.10768], Phys. Rev. C 102, 041901 (2020) [1907.03308]

Hadronization

Each heavy quark propagates until it reaches
a cell where $T \leq T_d = 160$ MeV the « decoupling temperature »

We use a **hybrid coalescence + fragmentation model**

inspired by Cao, Qin, and Bass, Phys. Rev. C92, 024907 (2015)



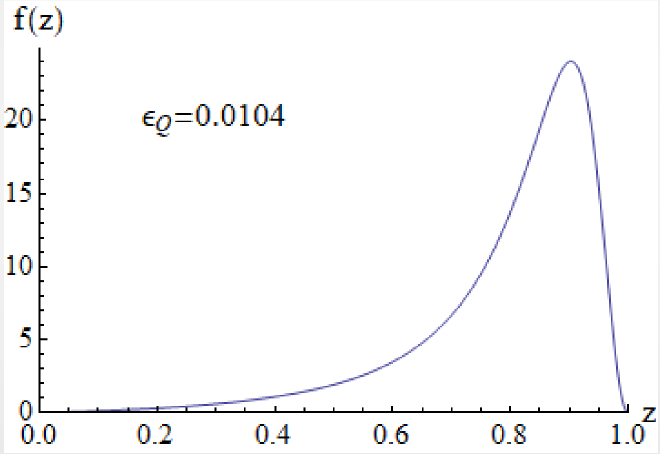
<u>Note</u>:
For DAB-MOD: direct D^0
(no feed-downs)

Fragmentation

Peterson fragmentation function

Peterson, Schlatter, Schmitt, and Zerwas, Phys. Rev. D27, 105 (1983)

We use $$f(z) \propto \frac{1}{z(1 - 1/z - \epsilon_Q/(1-z))^2}$$



To obtain the fraction z of the heavy quark E_Q+p_Q taken by the daughter hadron $E_H + p_H = z(E_Q + p_Q)$

Parameters ε_c and ε_b chosen such as to reproduce the D^0 and B mesons FONLL spectra in pp

Coalescence

Instantaneous projection of states

Dover, Heinz, Schnedermann, and Zimany, Phys. Rev. C44, 1636 (1991)

Heavy meson « M »

Coalescence probability $P_{coal}[q,Q \rightarrow M]$
that a heavy meson of momentum p_M is formed by coalescence of
a heavy quark (p_Q) and a light quark (p_q)

$$\mathrm{P}_{\mathrm{coal}}[q,Q \rightarrow M](\mathbf{p}_Q,\mathbf{u}) = N \int \mathrm{d}^3\mathbf{p}_q \, f_M(\mathbf{p}_q,\mathbf{p}_Q) \; n_q(\mathbf{p}_q,\mathbf{u},T_\mathrm{d}) \, \delta(\mathbf{p}_M - \mathbf{p}_q - \mathbf{p}_Q),$$

global
normalization
factor

probability density:
projection of
the two quark states
onto the meson state

momentum distribution
of the light quarks
at hadronization

Coalescence

Instantaneous projection of states

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Fermi-Dirac distribution of the light quarks in medium cell frame

$$n_q(\mathbf{p}_q,\mathbf{u},T_{\mathrm{d}}) = \frac{g_q}{e^{\sqrt{\mathbf{p}_q^{\mathrm{cell}\,2}+m_q^2}/T_{\mathrm{d}}}+1} = \frac{g_q}{e^{p_q.u/T_{\mathrm{d}}}+1},$$

Local medium cell velocity

light quark momentum in medium cell frame

=> $P_{coal}[q,Q \to M]$ depends on the local flow

Coalescence

Instantaneous projection of states

Dover, Heinz, Schnedermann, and Zimany, Phys. Rev. C44, 1636 (1991)

Heavy meson « M »

Coalescence probability $P_{coal}[q,Q \rightarrow M]$
that a heavy meson of momentum p_M is formed by coalescence of
a heavy quark (p_Q) and a light quark (p_q)

$$\mathrm{P}_{\mathrm{coal}}[q,Q \to M](\mathbf{p}_Q,\mathbf{u}) = N \int \mathrm{d}^3\mathbf{p}_q\, f_M(\mathbf{p}_q,\mathbf{p}_Q)\, n_q(\mathbf{p}_q,\mathbf{u},T_\mathrm{d})\, \delta(\mathbf{p}_M - \mathbf{p}_q - \mathbf{p}_Q),$$

Probability density: projection of the two quark states onto the meson state

$$f_M(\mathbf{p}_q,\mathbf{p}_Q) = g_M\, h_M\, \frac{(2\sqrt{\pi}\sigma)^3}{(2\pi)^3}\, e^{-\mathbf{p}_{\mathrm{rel}}^2\sigma^2},$$

(Only s waves)

relative momentum of the two quarks in the center-of-mass frame

simple harmonic oscillator model for all the meson states

Coalescence

Instantaneous projection of states

Dover, Heinz, Schnedermann, and Zimany, Phys. Rev. C44, 1636 (1991)

Heavy meson « M »

Coalescence probability $P_{coal}[q,Q \rightarrow M]$
that a heavy meson of momentum p_M is formed by coalescence of
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$$\mathrm{P}_{\mathrm{coal}}[q, Q \to M](\mathbf{p}_Q, \mathbf{u}) = N \int \mathrm{d}^3\mathbf{p}_q \, f_M(\mathbf{p}_q, \mathbf{p}_Q) \, n_q(\mathbf{p}_q, \mathbf{u}, T_\mathrm{d}) \, \delta(\mathbf{p}_M - \mathbf{p}_q - \mathbf{p}_Q),$$

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$$f_M(\mathbf{p}_q, \mathbf{p}_Q) = g_M \, h_M \, \frac{(2\sqrt{\pi}\sigma)^3}{(2\pi)^3} \, e^{-\mathbf{p}_{\mathrm{rel}}^2 \sigma^2},$$

(Only s waves)

usual color-spin-isospin statistical factor

New "thermal" factor added by hand (explained in few slides)

Coalescence

Instantaneous projection of states

Dover, Heinz, Schnedermann, and Zimany, Phys. Rev. C44, 1636 (1991)

Heavy baryon « B »

Coalescence probability $P_{coal}[q_1,q_2,Q \rightarrow B]$
that a heavy baryon of momentum p_B is formed by coalescence of
a heavy quark (p_Q) and two light quarks (p_{q1} and p_{q2})

probability density: combining
the two light quarks and the heavy quark
(includes the new thermal factors)

$$\mathrm{P}_{\mathrm{coal}}[q_1, q_2, Q \rightarrow B](\mathbf{p}_Q, \mathbf{u}) = N \int \mathrm{d}^3\mathbf{p}_{q_1}\, \mathrm{d}^3\mathbf{p}_{q_2}\, f_B(\mathbf{p}_{q_1}, \mathbf{p}_{q_2}, \mathbf{p}_Q)\; n_{q_1}(\mathbf{p}_{q_1}, \mathbf{u}, T_\mathrm{d}) \times n_{q_2}(\mathbf{p}_{q_2}, \mathbf{u}, T_\mathrm{d})\, \delta(\mathbf{p}_B - \mathbf{p}_{q_1} - \mathbf{p}_{q_2} - \mathbf{p}_Q),$$

global
normalization
factor

Fermi-Dirac distributions
of the light quarks
in medium cell frame

Footnote

About « combining order invariance » in baryonic case

The probability density for baryons writes:

$$f_B(\mathbf{p}_{q_1}, \mathbf{p}_{q_2}, \mathbf{p}_Q) = g_B\, h_B\, \frac{(2\sqrt{\pi})^6(\sigma_1\sigma_2)^3}{(2\pi)^6}\, e^{-\boldsymbol{p}_{\mathrm{rel1}}^2\sigma_1^2 - \boldsymbol{p}_{\mathrm{rel2}}^2\sigma_2^2},$$

in baryon center of mass frame

with

$$\mathbf{p}_{\mathrm{rel1}} = \frac{m_{q2}\mathbf{p}'_{q_1} - m_{q_1}\mathbf{p}'_{q_2}}{m_{q_1} + m_{q_2}}$$

$$\mathbf{p}_{\mathrm{rel2}} = \frac{m_Q(\boldsymbol{p}'_{q_1} + \mathbf{p}'_{q_2}) - (m_{q_1} + m_{q_2})\mathbf{p}'_Q}{m_{q_1} + m_{q_2} + m_Q},$$

<u>With these formulas one can combine the 3 quarks in any order and get the same result</u>

But in Cao, Qin, and Bass, Phys. Rev. C92, 024907 (2015) : $m_i \to E_i$

$$\mathbf{p}_{\mathrm{rel1}} = \vec{q}_1 \equiv \frac{E_2^{\mathrm{cm}}\vec{p}_1^{\,\mathrm{cm}} - E_1^{\mathrm{cm}}\vec{p}_2^{\,\mathrm{cm}}}{E_1^{\mathrm{cm}} + E_2^{\mathrm{cm}}},$$

$$\mathbf{p}_{\mathrm{rel2}} = \vec{q}_2 \equiv \frac{E_3^{\mathrm{cm}}(\vec{p}_1^{\,\mathrm{cm}} + \vec{p}_2^{\,\mathrm{cm}}) - (E_1^{\mathrm{cm}} + E_2^{\mathrm{cm}})\vec{p}_3^{\,\mathrm{cm}}}{E_1^{\mathrm{cm}} + E_2^{\mathrm{cm}} + E_3^{\mathrm{cm}}},$$

With these formulas:
$P_{coal}[q_1,q_2,Q \to B]$ is different if
we combine the two light quarks first
or the heavy quark and a light quark first

=> <u>Not invariant with combining order !</u>

(Why one type of combination should be better than the other ?)

Coalescence

"Thermal" factors h_M and h_B

Problematic:

Within the "basic" coalescence model (i.e. without the h_M and h_B factors):
the prompt D^+/D^0 and D^{*+}/D^0 ratios are only based on
the color-spin-isospin factors,
with the rest of the probabilities canceling out, e.g.

$$\frac{\mathrm{D^+}_{\text{prompt}}}{\mathrm{D^0}_{\text{prompt}}} = \frac{\mathrm{D^+}_{\text{dir.}} + \mathrm{D}^{*+}_{\text{dir.}}\, Br(\mathrm{D}^{*+} \to \mathrm{D}^+)}{\mathrm{D^0}_{\text{dir.}} + \mathrm{D}^{*0}_{\text{dir.}}\, Br(\mathrm{D}^{*0} \to \mathrm{D}^0) + \mathrm{D}^{*+}_{\text{dir.}}\, Br(\mathrm{D}^{*+} \to \mathrm{D}^0)} = \frac{g_{\mathrm{D}} + 0.307 g_{\mathrm{D}^*}}{g_{\mathrm{D}} + 1.677 g_{\mathrm{D}^*}} \approx \underbrace{0.32}$$

≠ experimental value
~ 0.45 - 0.50 !!
(seems universal to pp, pA, AA:
same underlying mechanism ?)

With:
- prompt = with feed downs included
- « dir. » = direct production from c
- D^0, D^+ → $g_D = 1/36$
- D^{*0}, D^{*+} → $g_{D^*} = 1/12$

Should we consider different radiuses or the differences in energy
to form excited states ?

Coalescence

"Thermal" factors h_M and h_B

<u>Proposition:</u> Adding by hand new "thermal" factors "$\exp[-(m_{excited} - m_{ground})/T_d]$" between energy states of equal quark flavor content

e.g.: $h_{D^{*0}} = \exp[-(m_{D^{*0}} - m_{D^0})/T_d]$

=> not only spin hierarchy but also mass hierarchy between different energy states of equal flavor content

Approximate values at low p_T	Experimental [95, 100, 124–127]	"basic" coalescence	With extra thermal factors
direct $c \to D^0$	in pp: 0.17	0.06	0.10
prompt $c \to D^0$	in pp: 0.55	0.36	0.32
D^+/D^0	0.45 - 0.50	0.32	0.45
D^{*+}/D^0	0.40 - 0.50	0.5	0.4
D_s^+/D^0	0.35	0.31	0.34
D_s^+/D^+	0.75	0.99	0.76
Λ_c^+/D^0	@ RHIC: 1.2 - @ LHC: 0.7	0.74	0.94

TABLE III. The approximate low p_T branching ratios or prompt hadronic ratios obtained with different configurations of the coalescence model (using a typical $|\mathbf{u}| \approx 0.6$) compared to the low p_T experimental data in AA collisions (or pp collisions if specified).

=> Better matches !

Coalescence

“Thermal” factors h_M and h_B

Additional positive effects:

Natural justification for the non consideration of more excited states (such as the J = 2 mesons and J = 5/2 baryons) and antisymmetric states (such as the $J^P = 0^+$ mesons and $J^P = 1/2^-$ baryons) -> they are now suppressed by their larger mass

Notes:

- Motivation for these thermal factors : purely phenomenological, i.e. to improve the ratio fits and the coalescence probabilities
- Need for theoretical justification
- Needs for further tests (e.g. Λ_c^+/D^0 (p_T) ratio, now limited by our fragmentation)

- Alternative to thermal factor ? We tried instead to use larger radiuses => larger widths σ for the excited states → not good

$$f_M(\mathbf{p}_q, \mathbf{p}_Q) = g_M\, h_M\, \frac{(2\sqrt{\pi}\sigma)^3}{(2\pi)^3}\, e^{-\mathbf{p}_{\mathrm{rel}}^2\sigma^2},$$

$$\sigma = 1/\sqrt{\mu\omega}$$

Coalescence

Global normalization factor N

We consider all the meson and baryon symmetric ground and first excited states

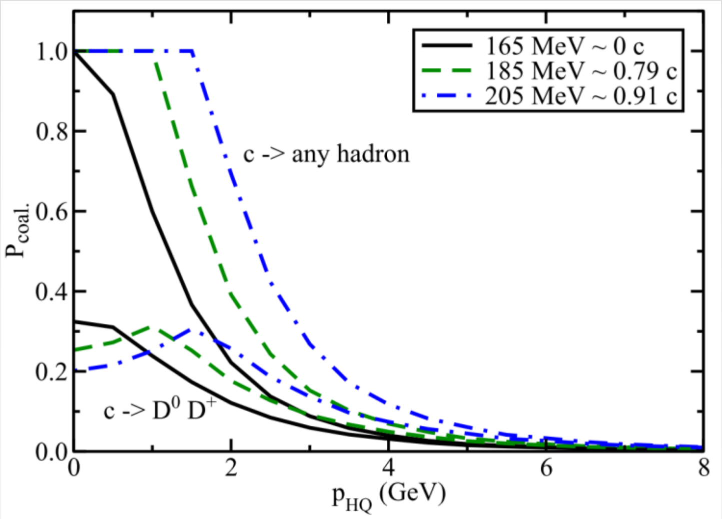
Higher excited states and P states not included

Coalescence

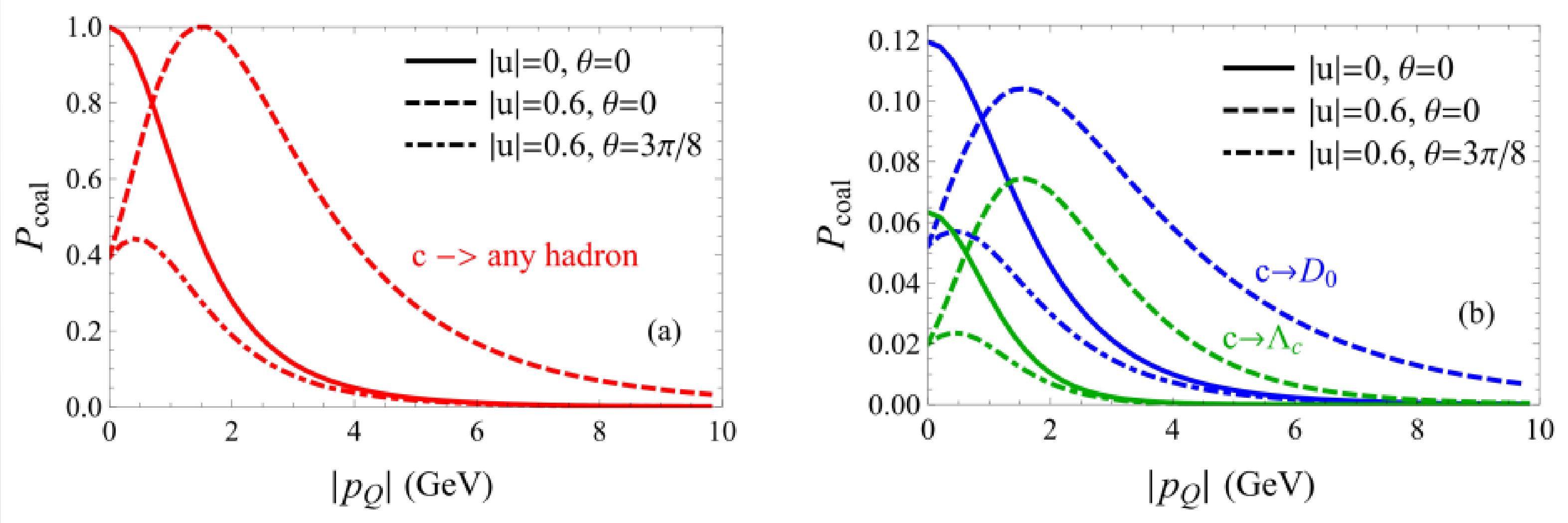
Global normalization factor N

N is often chosen such that
$P_{coal}[c \rightarrow \text{any hadron}](p_Q=0) = 1$
assuming no fragmentation when $p_Q=0$

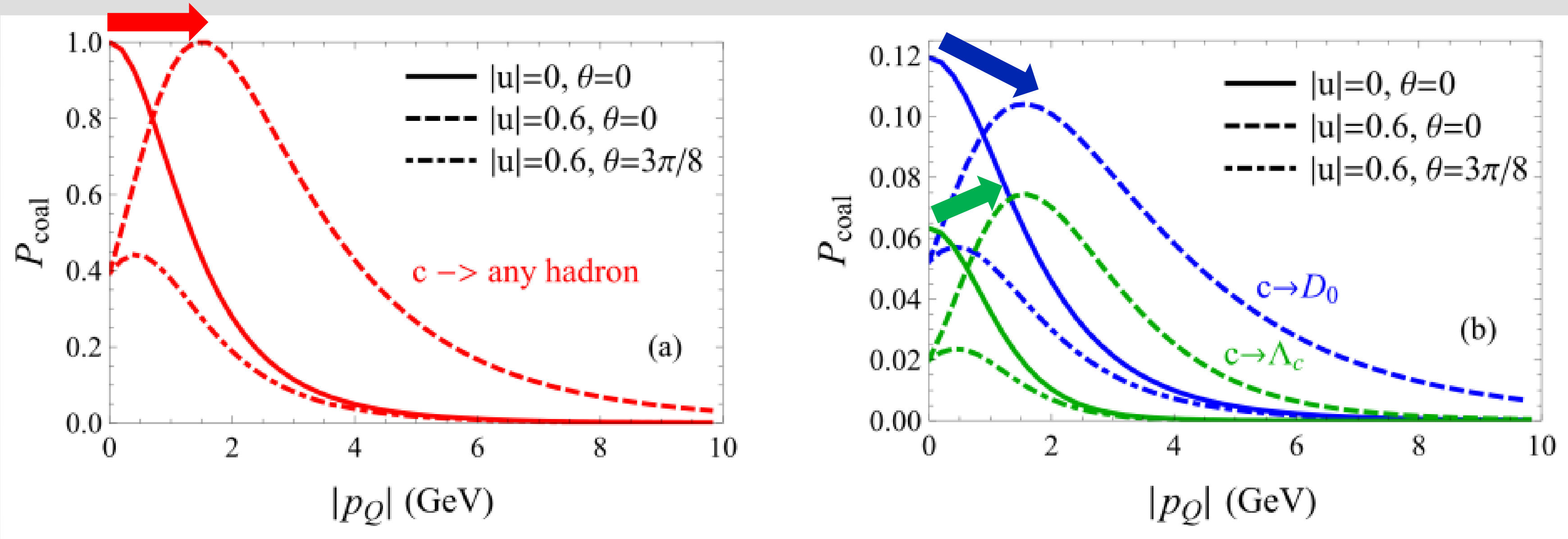
In Cao, Qin, and Bass, Phys. Rev. C92, 024907 (2015):



We assume instead that $P_{coal}[c \rightarrow \text{any hadron}](\mathbf{p}_Q, \mathbf{u}) = 1$ when $\mathbf{v}_Q = \mathbf{u}$
i.e. when the heavy quark is moving together with the light quarks surrounding it.



Coalescence

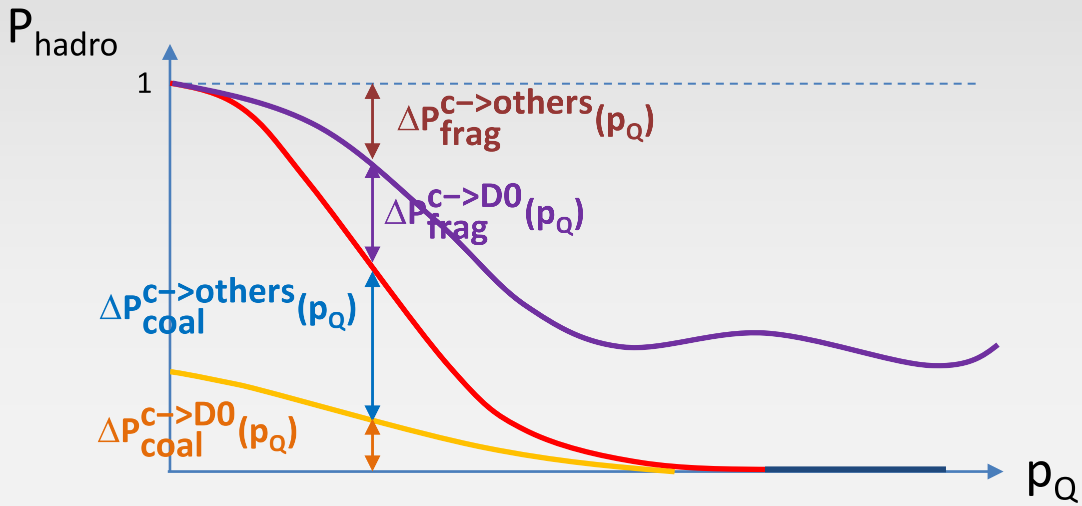


- Larger medium cell velocity |**u**| tends to shift the maximum of P_{coal} toward larger |$\mathbf{p}_Q$|.

- An increasing θ=$|(\widehat{\boldsymbol{v}_Q, \boldsymbol{u}})|$ tends to lower the P_{coal} and restrict the coalescence to heavy quarks with lower |$\mathbf{p}_Q$|.

- With increasing |**u**| the meson production from coalescence tends to decrease whereas the baryon production increases

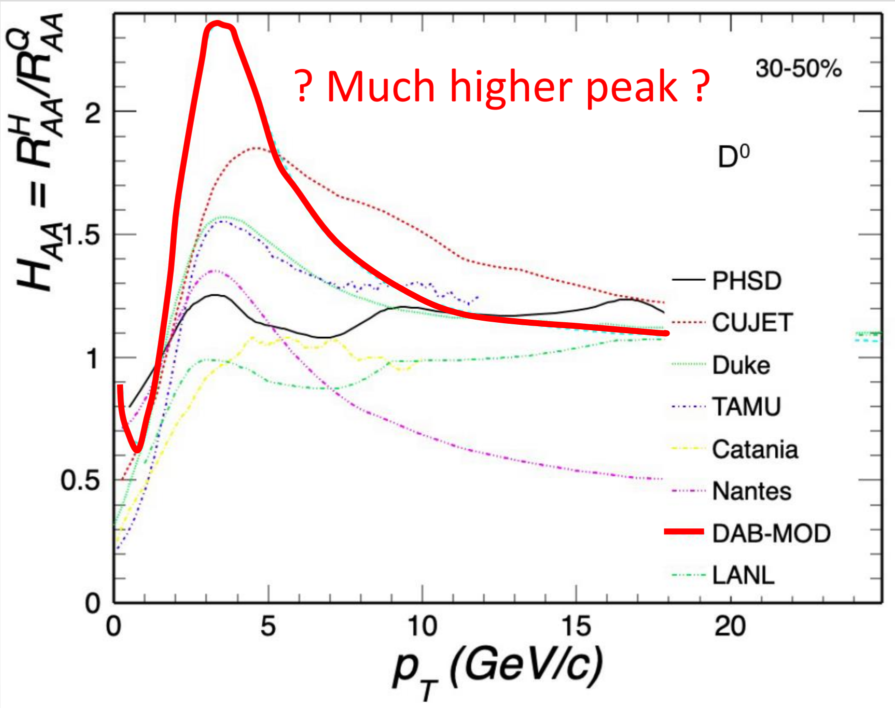
Hadronization



Monte-Carlo procedure to decide if fragmentation or coalescence and into which meson/baryon.

If coalescence: hadron momentum given by the heavy-light quark system $\mathbf{p}_Q + \mathbf{p}_q$.

Hadronization



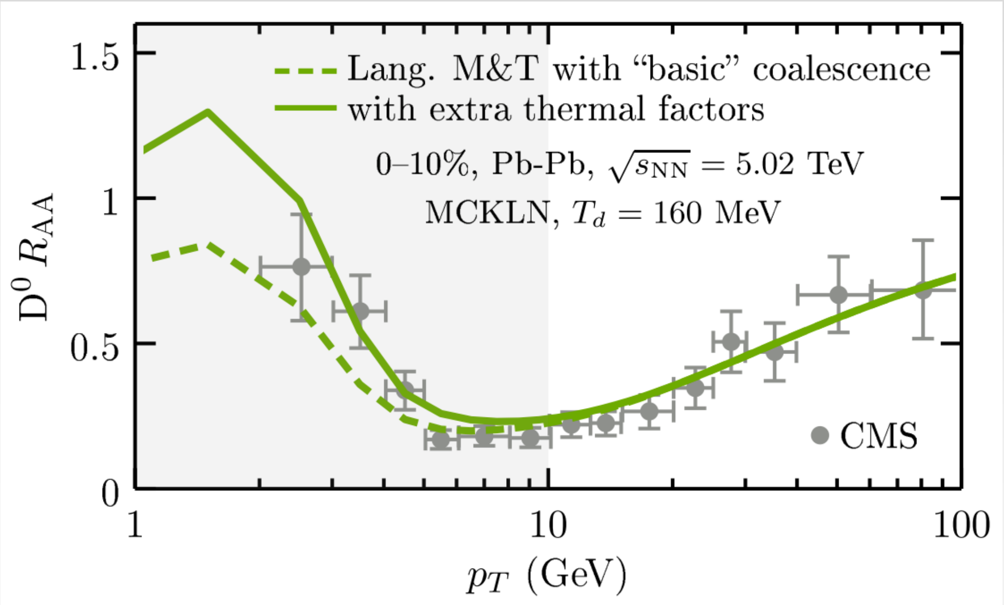
<u>Note</u>:
For DAB-MOD: direct D^0
(no feed-downs)

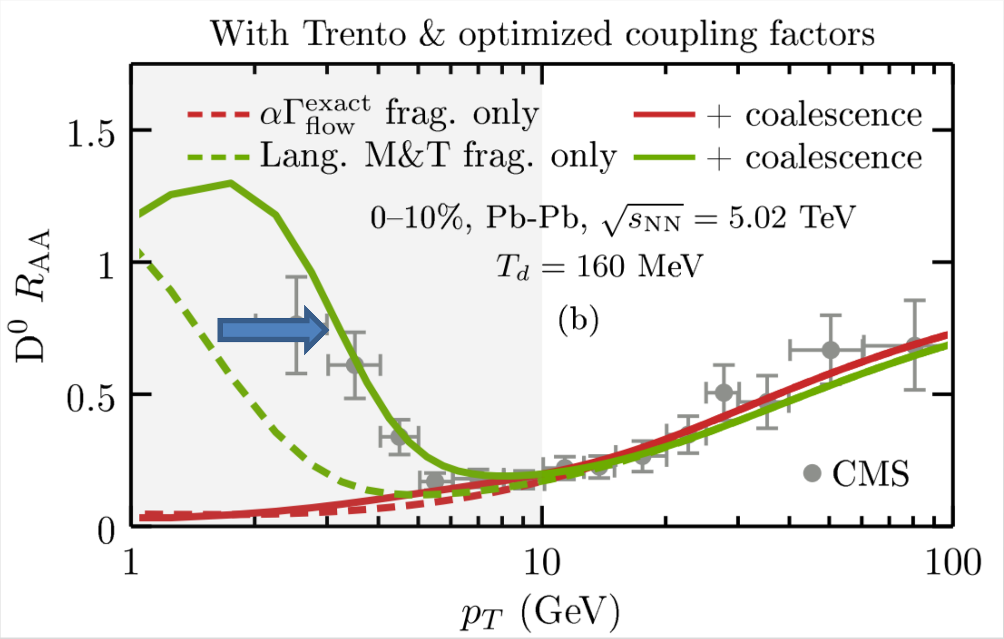
Originates from the combination of

- Thermal factors: reduce the P_{coal} of excited states
- Global normalization factor N such as $P_{coal}[c \rightarrow \text{any hadron}](\mathbf{p}_Q, \mathbf{u}) = 1$ when $\mathbf{v}_Q = \mathbf{u}$

Mechanically increases the production of ground states when coalescence probability is significant

R_{AA}





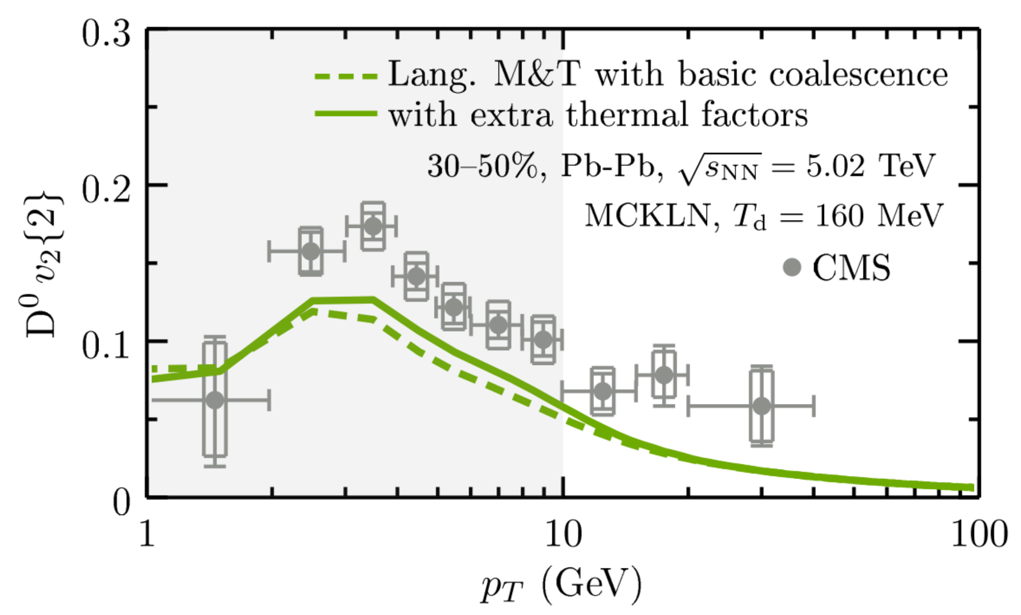
Thermal factors => smaller suppression at low pT

Fragmentation + Coalescence = much better than only fragmentation

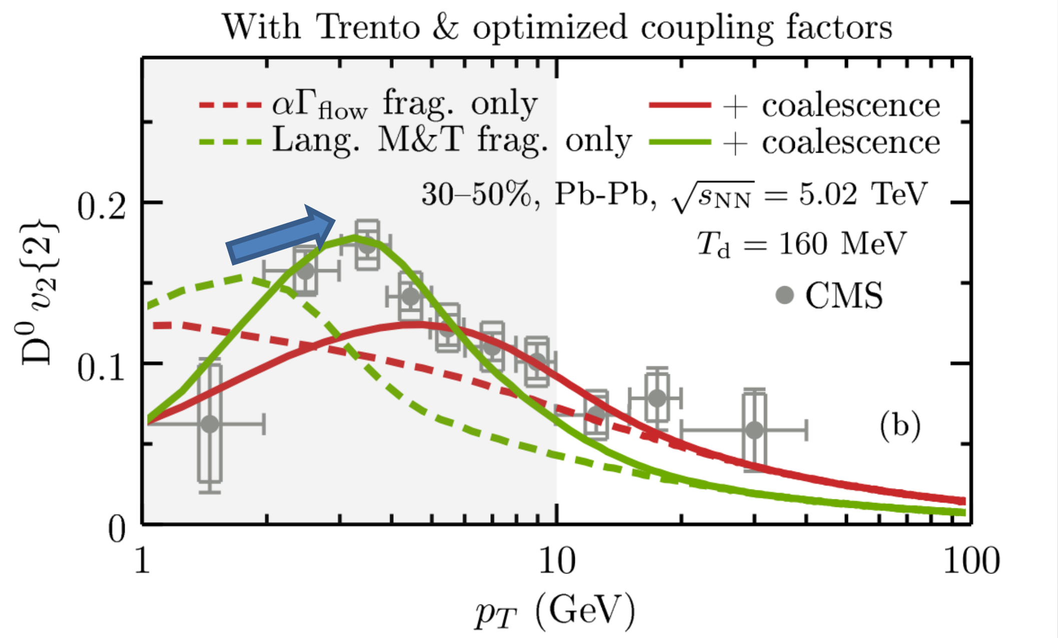
Coalescence effects extend up to 8 GeV

Ref data: arXiv:1708.04962

v_2



Thermal factors =>
slightly more v_n
at low p_T

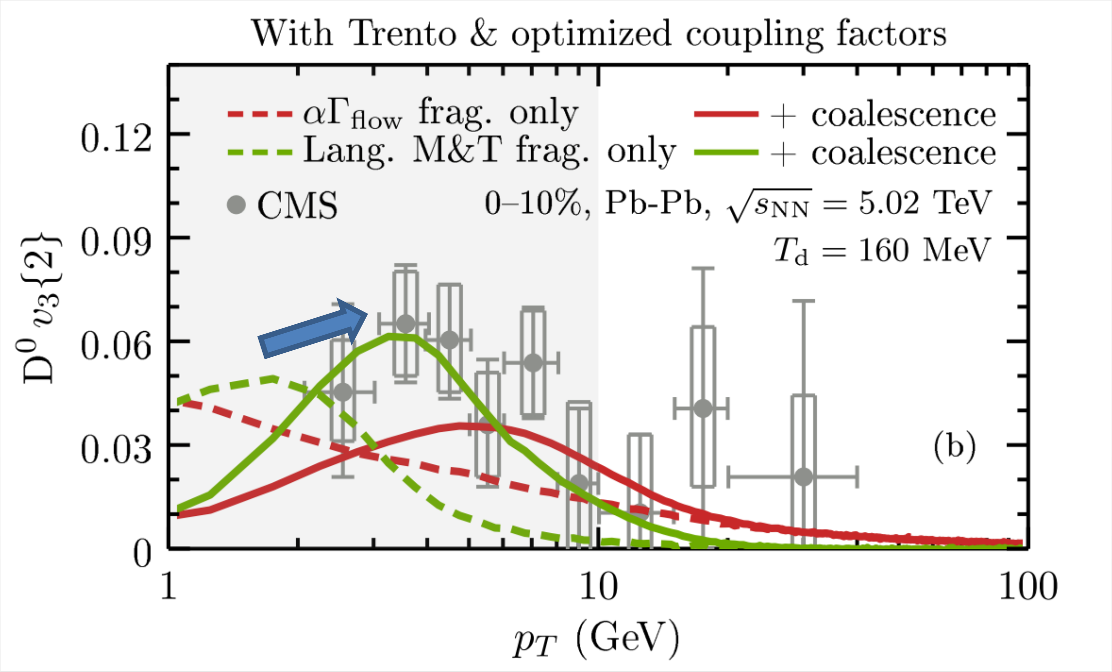


Coalescence
=>
increase v_2 and shift peaks

Coalescence effects
extend up to 15 GeV

Ref data: arXiv:1708.03497

v_3



Coalescence
=>
increase v_3 and shift peaks

Coalescence effects extend up to 15 GeV

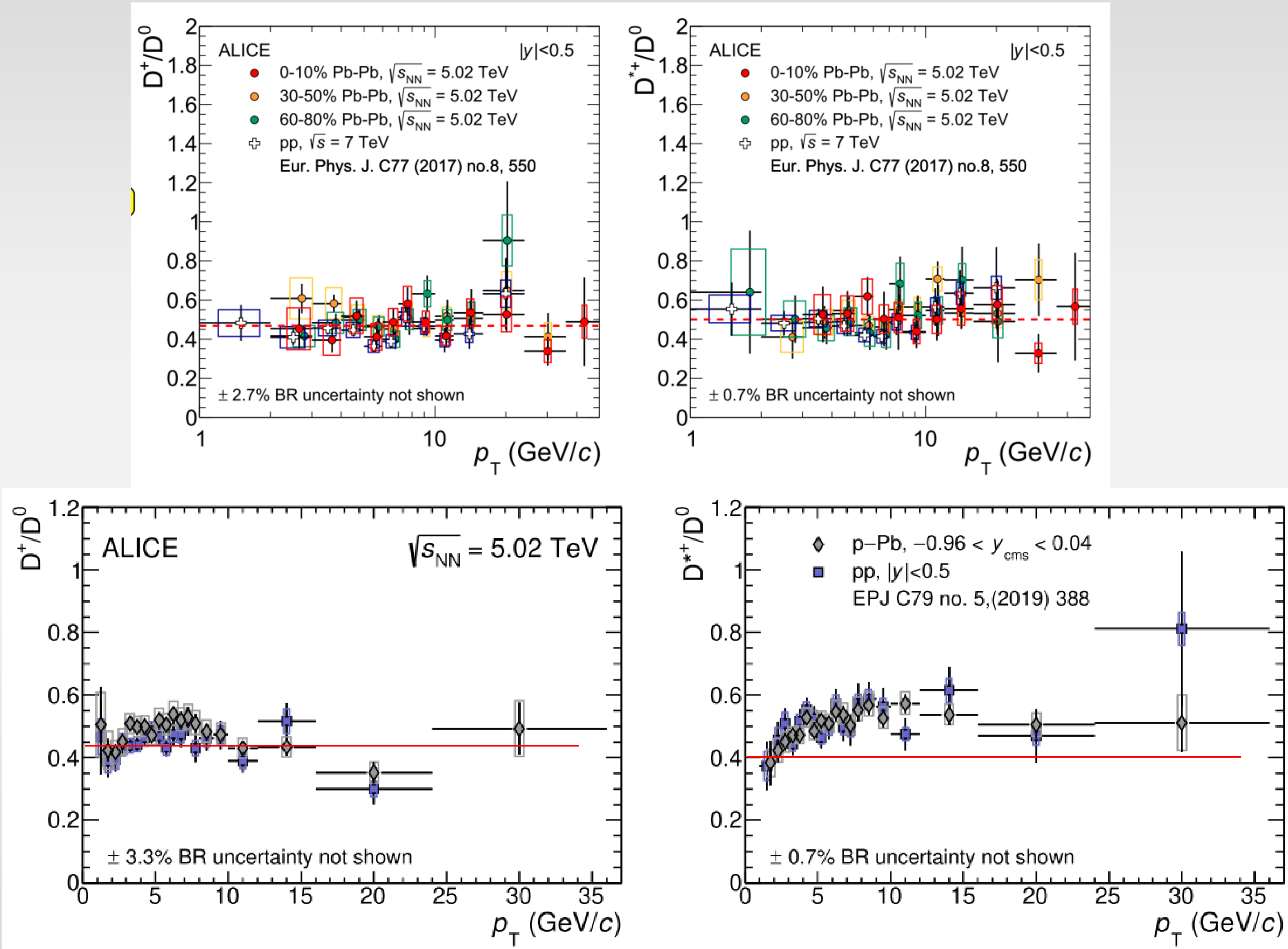
Ref data: arXiv:1708.03497

Thank you !

All details and analysis on hadronization in DAB-MOD:
Katz et al., Phys. Rev. C 102, 024906 (2020) [1906.10768]

Back up

Experimental meson ratios



DAB-MOD: heavy quarks

Initial conditions

- **Large oversampling** of the HQs (statistics)
- Spatial -> following initial bulk densities; p_T -> **FONLL spectra**
- **No shadowing or cold nuclear matter** effects

Transport

- **Parametric Energy loss models** $\frac{dE}{dx} = -f(T,p,x)\,\Gamma_{\rm flow}$

  Where $\Gamma_{\rm flow}$: takes into account the boosts

  Parametrizations $f(T,p,x) = \alpha$ or $f(T,p,x) = \xi T^2$ -> R_{AA} trends ok

or

- **Relativistic Langevin models** $dp_i = -\Gamma(\vec{p})p_i dt + \sqrt{dt}\sqrt{\kappa}\rho_i$

  Two different parametrizations:

  - "**M&T**": from Moore and Teaney, QCD+HTL model $D \propto 1/(2\pi T)$
  - "**G&A**" : from Gossiaux and Aichelin, QCD+HTL model with running coupling and optimized propagator.

Refs: arXiv:1404.6378, arXiv:1609.05171, arXiv:0412346, arXiv:0802.2525

DAB-MOD: heavy quarks

Hadronization

- **Decoupling T_d**: 120 < T_d < 160 MeV -> hadronization uncertainties
- **Fragmentation**: Peterson function $f(z) \propto [z(1 - 1/z - \epsilon_Q/(1-z))]^{-1}$
  to obtain the fraction z of the HQ E_Q+p_Q taken by the hadron E_H+p_H

with or without

- **Light-heavy quark coalescence**
  - Inspired by Dover et al.: instantaneous projection of states
  - Coalescence proba. function of $\vec{p_Q}$, $\overrightarrow{\text{local flow}}$ & angle between
  - To better fit the observed heavy hadron ratios, we included: thermal factors "exp[-($m_{excited}$-m_{ground})/T_d]" between energy states of equal quark content => not only spin but also mass hierarchy between energy states of a hadron type

Final stages

- **No final hadronic re-scattering**

t

Details in: arXiv:1906.10768

Refs: arXiv:1804.09083v1, L. Vermunt SQM 2019 poster, arXiv:1505.01413