ETC* WORKSHOP: "*QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES*"

15 November 2021 — 18 November 2021

Charm and Bottom dynamics: nuclear modification factor R_{AA} and anisotropic flows v_n in event shape selections

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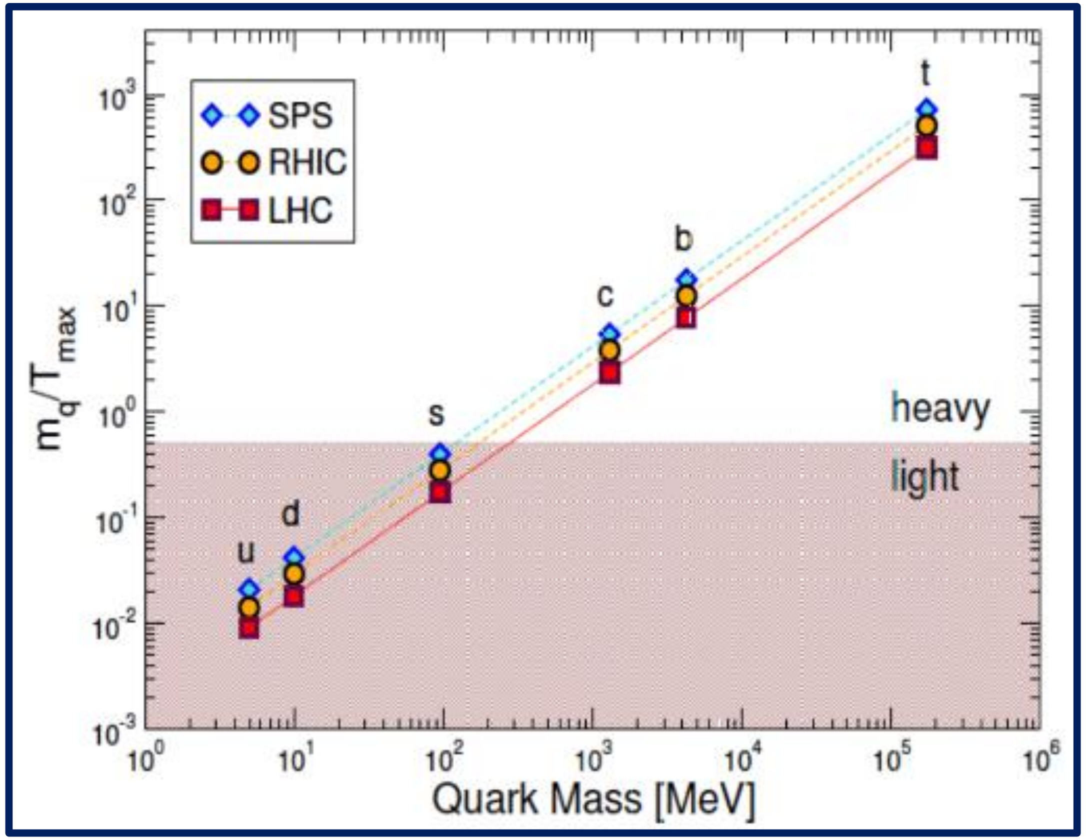
In collaboration with: S. Plumari, Y. Sun, V. Minissale, V. Greco

Outline

- QPM Catania approach to charm quark dynamics
  - $R_{AA}, v_2 \rightarrow$ Spatial diffusion coefficient $D_s(T)$ of charm.
- Initial state fluctuations → Event-Shape-Engineering
  - Anisotropic flows $v_{n(=2,3,4)}$ and their correlations.
- Predictions for bottom quark
  - R_{AA}, v_2 of electrons from semileptonic B-mesons decays.
  - Spatial diffusion coefficient $D_s(T)$ of bottom.
- Extension to off-shell dynamics
  - Impact on transport properties and FDT validity.
  - Energy loss
- Conclusions and new perspectives.

Basic scales of charm and bottom quarks



- $m_{c,b}$ >> Λ_{QCD}
  pQCD initial production
- $m_{c,b}$ >> $T_{RHIC,LHC}$
  negligible thermal production
- τ_0 < 0,08 fm/c << τ_{QGP}
- $\tau_{th} \approx \tau_{QGP}$ >> $\tau_{g,q}$

They experience the full evolution of the QGP.

They carry more informations with respect to their light counterparts.

CATANIA MODEL: QPM APPROACH AND TRANSPORT THEORY

QP-Model fitting lQCD

Non perturbative dynamics → M scattering matrices (q,g → Q) evaluated by Quasi-Particle Model fit to **lQCD thermodynamics**

$$m_g^2(T) = \frac{2N_c}{N_c^2 - 1}\, g^2(T)\, T^2$$

$$m_q^2(T) = \frac{1}{N_c}\, g^2(T)\, T^2$$

g(T) from a fit to ε from lQCD data
→ good reproduction of P, ε-3P, c_s

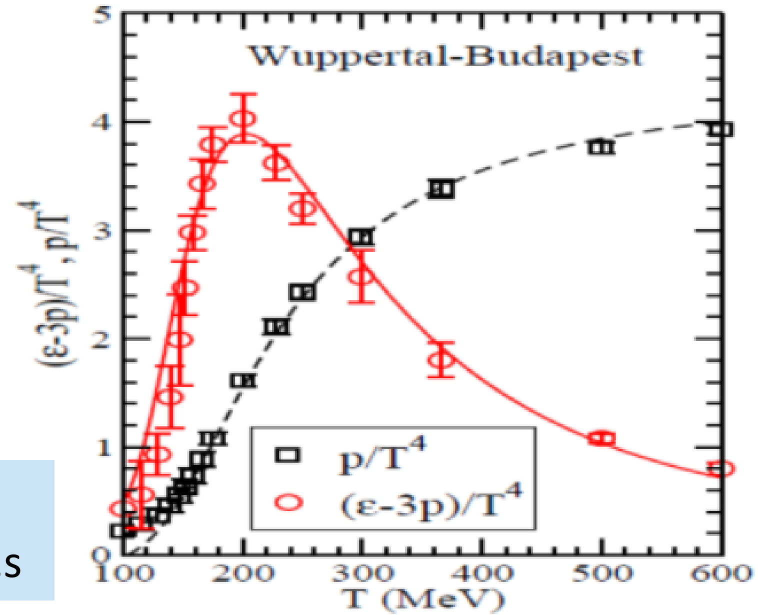
$$g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

λ=2.6
T_s=0.57 T_c

Larger than pQCD especially as T → T_c

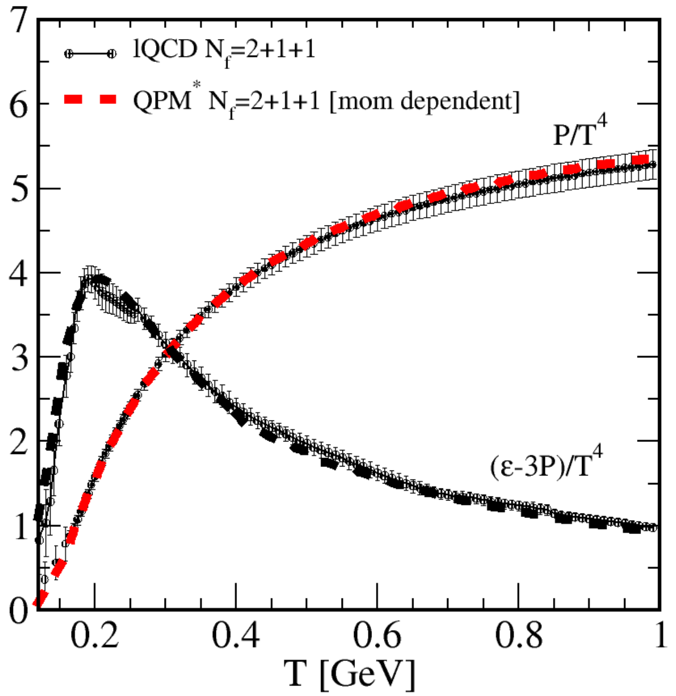
S. Plumari et al, *Phys.Rev.D* 84 (2011) 094004
H. Berrehrah,, PHYSICAL REVIEW C **93**, 044914 (2016)
M.L. Sambataro et al. in preparation

N_f=2+1
Bulk: u,d,s



NEW

Including charm!
N_f=2+1+1
and
mom dependence



Relativistic Boltzmann equation at finite η/s

Bulk evolution

$$p^{\mu}\partial_{\mu}f_{q}(x,p)+m(x)\partial^{x}_{\mu}m(x)\partial^{\mu}_{p}f_{q}(x,p)=C[f_{q},f_{g}]$$
$$p^{\mu}\partial_{\mu}f_{g}(x,p)+m(x)\partial^{x}_{\mu}m(x)\partial^{\mu}_{p}f_{g}(x,p)=C[f_{q},f_{g}]$$

Equivalent to viscous hydro at η/s ≈ 0.1

Free-streaming

field interaction $\varepsilon - 3p \neq 0$

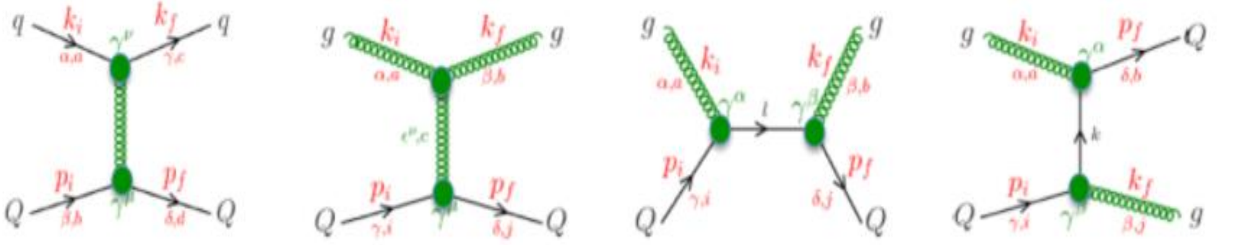
Collision term gauged to some η/s≠ 0

HQ evolution

$$p^{\mu}\partial_{\mu}f_{Q}(x,p)=C[f_{q},f_{g},f_{Q}]$$

$$C[f_q,f_g,f_Q]=\frac{1}{2E_1}\int\frac{d^3p_2}{2E_2(2\pi)^3}\int\frac{d^3p_1'}{2E_1'(2\pi)^3}$$
$$\times[f_Q(p_1')f_{q,g}(p_2')-f_Q(p_1)f_{q,g}(p_2)]$$
$$\times|M_{(q,g)\to Q}(p_1p_2\to p_1'p_2')|$$
$$\times(2\pi)^4\delta^4(p_1+p_2-p_1'-p_2')$$

Feynmann diagrams at first order pQCD for HQs-bulk interaction:



Scattering matrices $M_{g,q}$ by QPM fit to lQCD thermodynamics

Relativistic Boltzmann equation at finite η/s

Bulk evolution

$$p^{\mu}\partial_{\mu}f_q(x,p)+m(x)\partial_{\mu}^{x}m(x)\partial_{p}^{\mu}f_q(x,p)=C[f_q,f_g]$$
$$p^{\mu}\partial_{\mu}f_g(x,p)+m(x)\partial_{\mu}^{x}m(x)\partial_{p}^{\mu}f_g(x,p)=C[f_q,f_g]$$

Equivalent to viscous hydro at η/s ≈ 0.1

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HQ evolution

$$p^{\mu}\partial_{\mu}f_Q(x,p)=C[f_q,f_g,f_Q]$$

Coalescence + fragmentation hadronization ($\varepsilon \rightarrow \varepsilon_c$)

For details: S. Plumari talk [17.30]

$$\frac{dN_h}{d^2p_h}=\sum_f \int dz \frac{dN_f}{d^2p_f} D_{f\rightarrow h}(z)$$

Peterson fragmentation function

C. Peterson, D. Schalatter, I. Schmitt, P.M. Zerwas PRD 27 (1983) 105

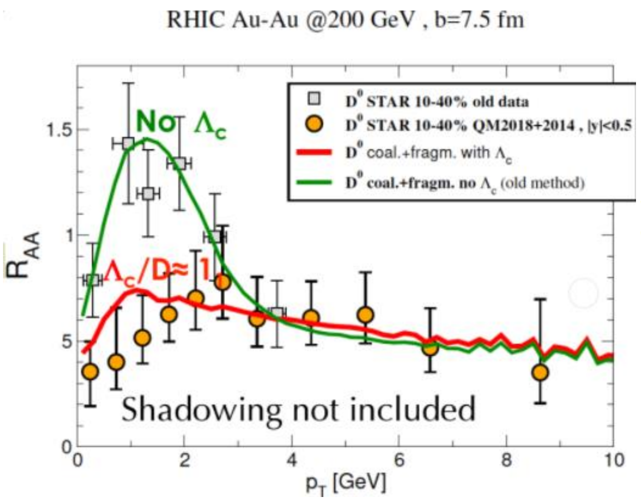
$$\frac{dN_{Hadron}}{d^2p_T}=g_H\int \prod_{i=1}^{n} p_i\cdot d\sigma_i \frac{d^3p_i}{(2\pi)^3} f_q(x_i,p_i) f_W(x_1,\ldots,x_n;p_1,\ldots,p_n)\,\delta\left(p_T-\sum_i p_{iT}\right)$$

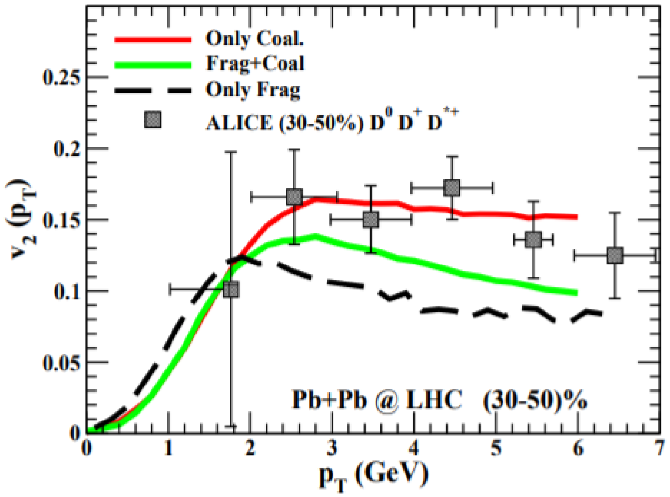
Wigner function

S. Plumari, et al., Eur. Phys. J. C78 no. 4, (2018) 348

$P_{coal} = 1$ for $p = 0$

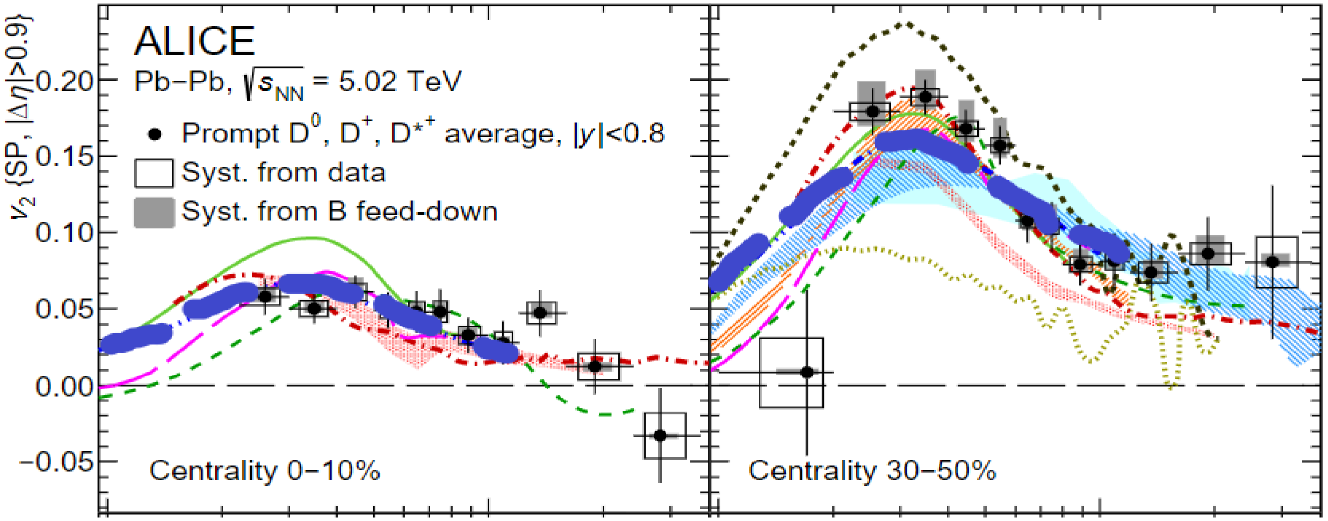
Catania QPM: some prediction for charm…





Scardina et al., PRC 97(2017)

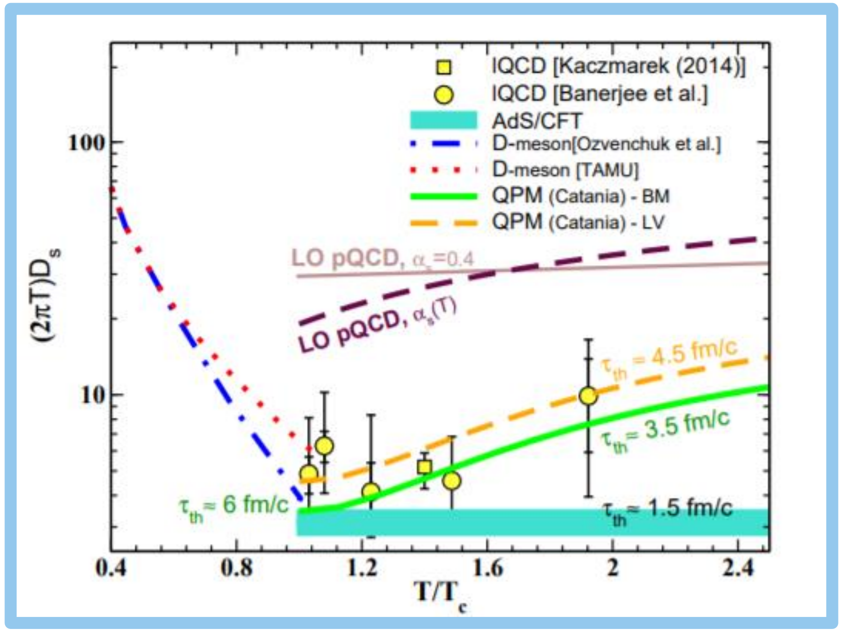
Good description of R_{AA}, v_2 at RHIC & LHC energies within error bars



Catania Model

ALICE collaboration, *Phys.Lett.B* 813 (2021) 136054

Spatial diffusion coefficient of charm quark



Not a model fit to lQCD data!
Results from R_{AA} (p_T), v_2 (p_T)

We have a probe with $\tau_{therm} \approx \tau_{QGP}$

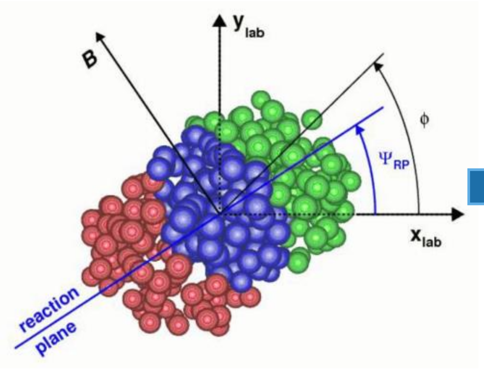
$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8\,\frac{2\pi T D_s}{(T/T_c)^2}\ \mathrm{fm/c}$$

FUTURE:
-Access low p and precision data (detector upgrade);
-Better insight into hadronization;
-***New observables;***
-Bottom.
Main focus of this talk

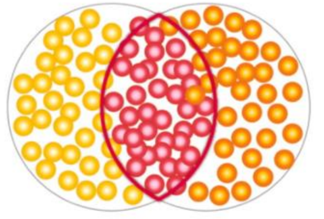
Reviews:
- F. Prino and R. Rapp, JPG(2019)
- X. Dong and V. Greco, Prog.Part.Nucl.Phys. (2019)
- Jiaxing Zhao et al., arXiv:2005.08277

Extension to higher order anisotropic flows $v_n(p_T)$

$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

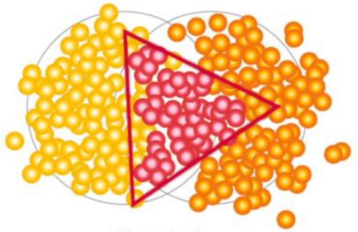


v_2



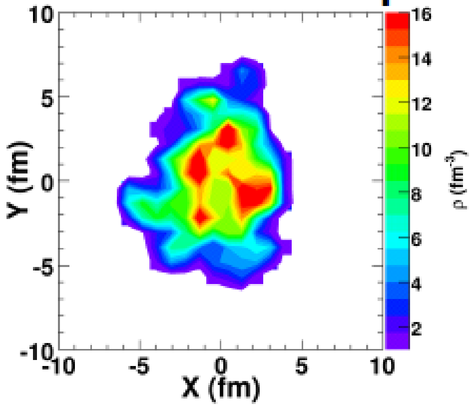
Elliptic flow

v_3



Triangular flow

Not almond shape



$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)]\rangle}{\langle r_\perp^n \rangle} \qquad \Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\varphi)\rangle}{\langle r_\perp^n \cos(n\varphi)\rangle}$$

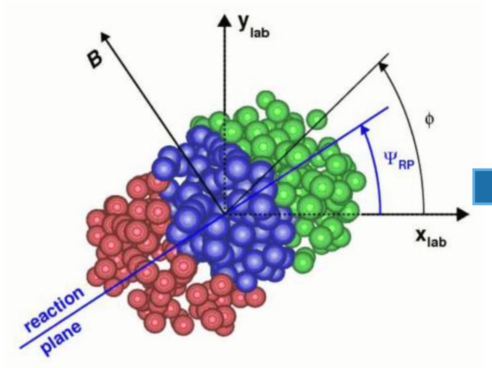
$$r_\perp = \sqrt{x^2 + y^2}, \qquad \varphi = \arctan(y/x)$$

Monte Carlo Glauber for initial condition of partons

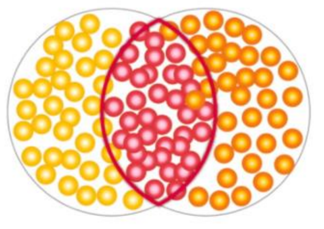
S.Plumari et al, *Phys.Rev.C* 92 (2015) 5

Extension to higher order anisotropic flows $v_n(p_T)$

$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

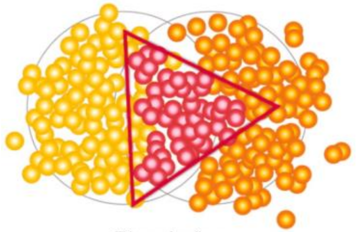


v_2

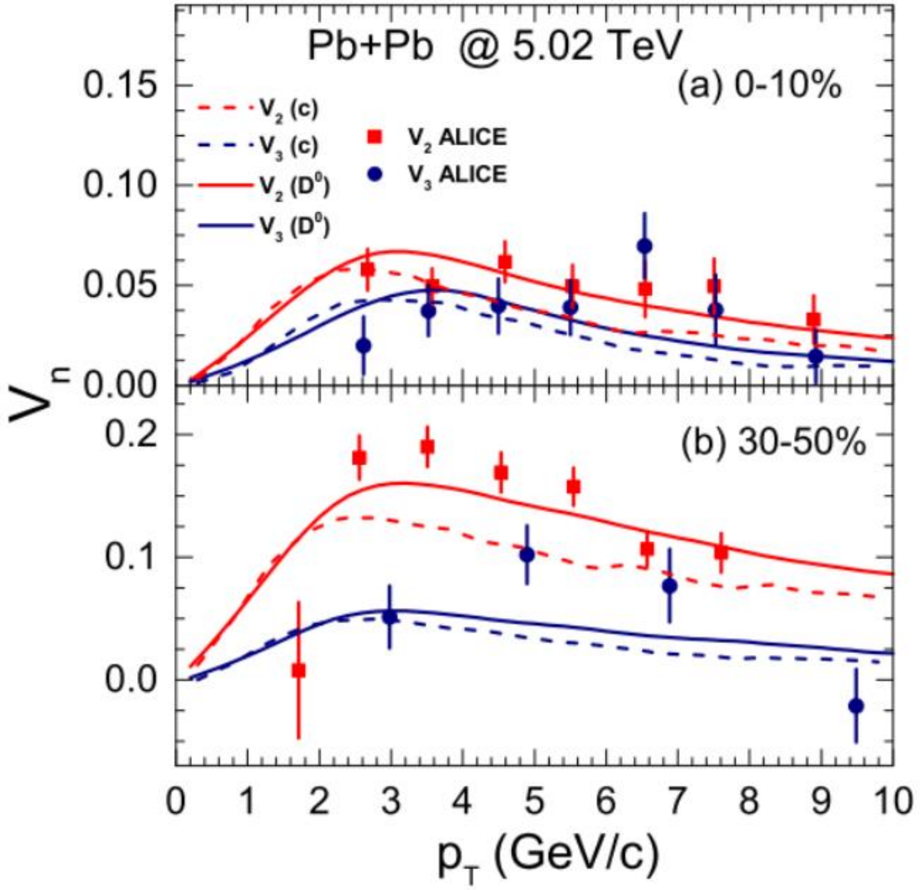


Elliptic flow

v_3



Triangular flow



$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)]\rangle}{\langle r_\perp^n \rangle} \qquad \Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\varphi)\rangle}{\langle r_\perp^n \cos(n\varphi)\rangle}$$

$$r_\perp = \sqrt{x^2 + y^2}, \qquad \varphi = \arctan(y/x)$$

Data taken from ALICE collaboration: *Phys.Lett.B* 813 (2021) 136054

In the more peripheral collision (30-50 % centrality class) → larger v_2 and comparable v_3

- ➢ v_2 mainly generated by the geometry of overlapping region in larger centrality collision
- ➢ v_3 mainly driven by the fluctuation of the triangularity of overlap region at all centrality

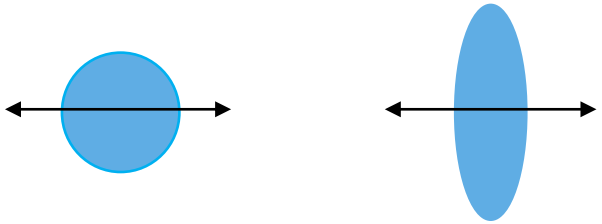
Extension to higher order anisotropic flows $v_n(p_T)$

ESE tecnique and v_n correlations

Selection of events with the same centrality but different initial geometry on the basis of the magnitude of the second-order harmonic reduced flow vector q_2.

$$q_2 = |\vec{Q}_2|/\sqrt{M}$$

$$\vec{Q}_2 = \sum_{j=1}^{M} e^{i2\varphi_j}$$



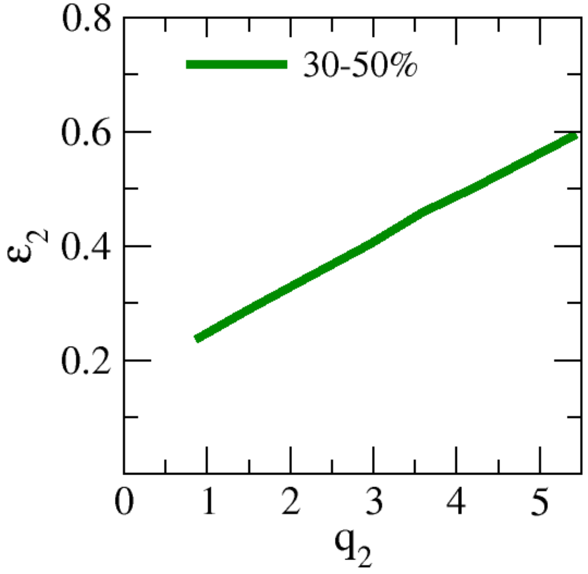
20 % small q_2 20 % large q_2

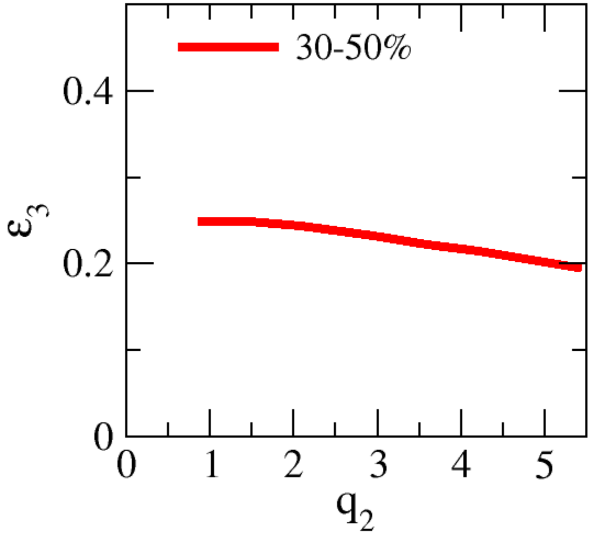
Large $q_2 \rightarrow$ large ε_2

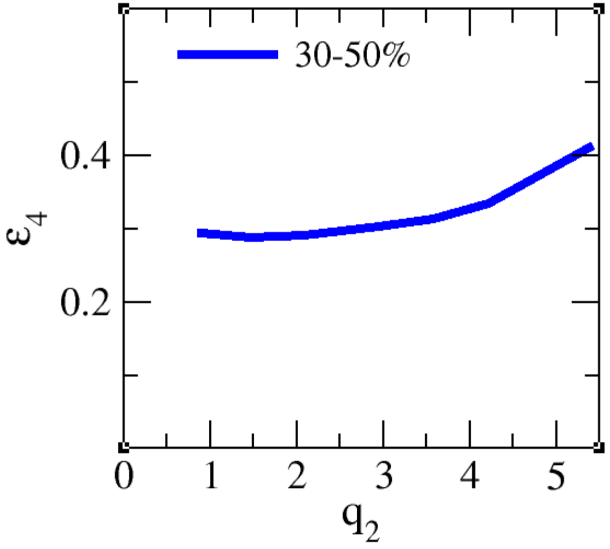
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)] \rangle}{\langle r_\perp^n \rangle} \qquad \Phi_n = \frac{1}{n} \arctan \frac{\langle r_\perp^n \sin(n\varphi) \rangle}{\langle r_\perp^n \cos(n\varphi) \rangle}$$

$$r_\perp = \sqrt{x^2 + y^2}, \qquad \varphi = \arctan(y/x)$$

Pb-Pb 5,02 TeV





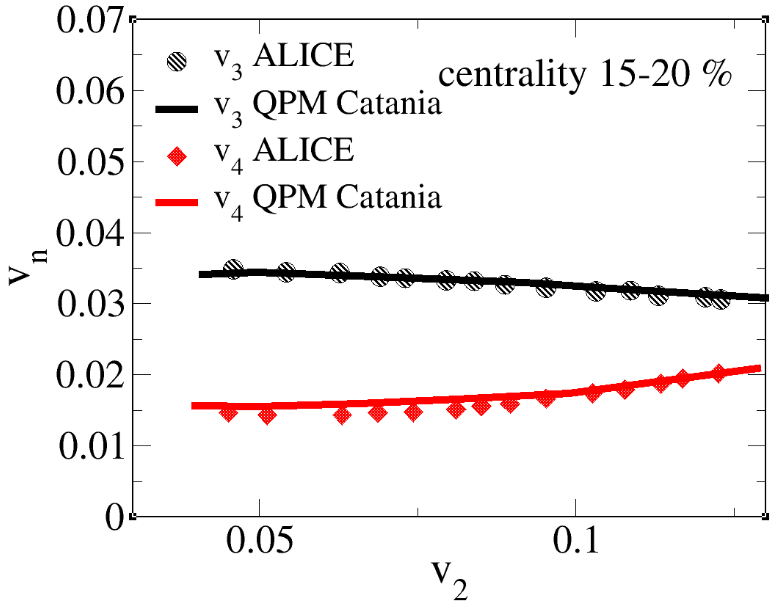


Anti-correlation between ε_2 and ε_3

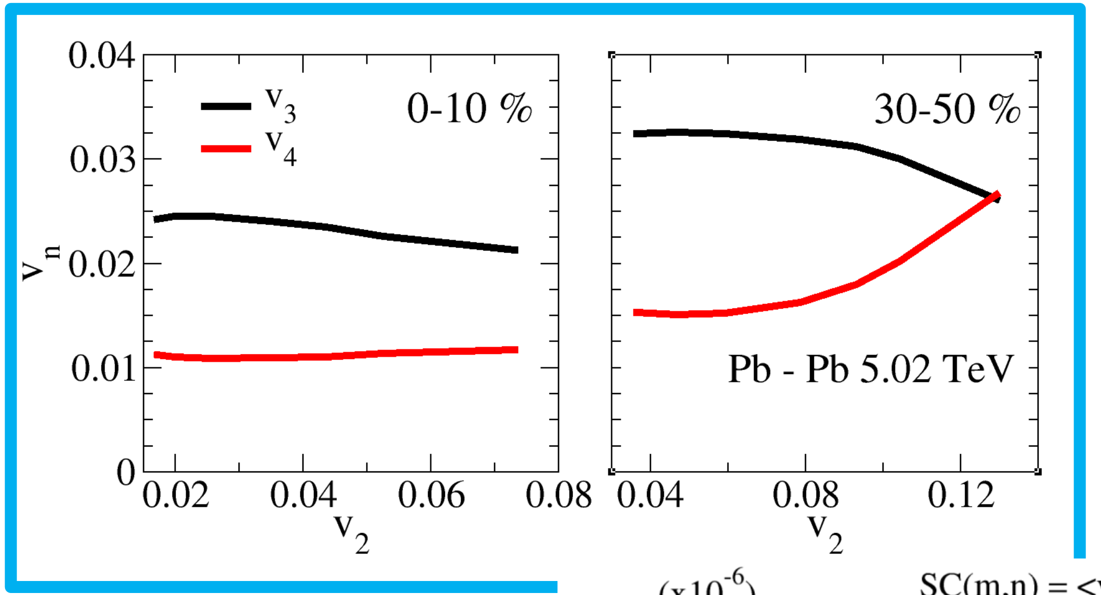
Non-linear correlation between ε_2 and ε_4

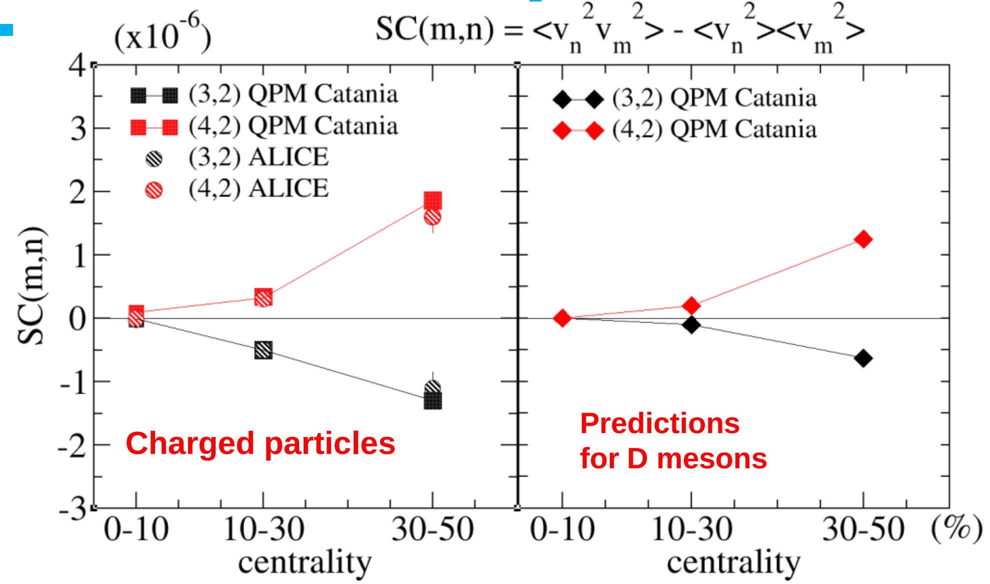
ESE: $v_n - v_m$ correlations

Charged particles



Predictions for D mesons





Correlations between the ε_n and ε_m present in the initial geometry → correlations between flow harmonics different orders, i.e. correlations v_n and v_m

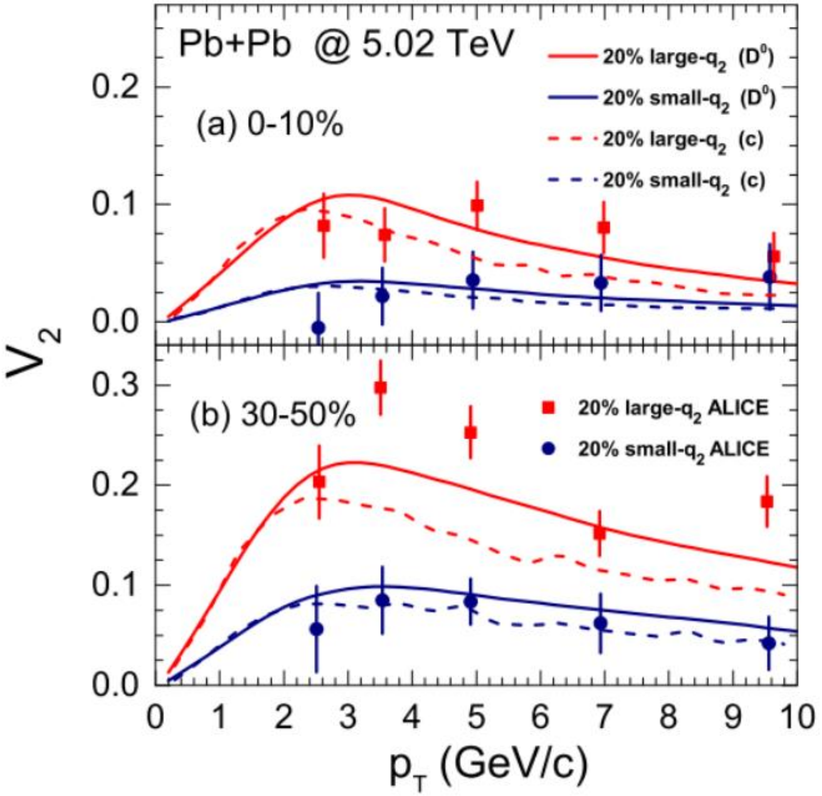
- **Good description of v_n- v_m correlation for bulk**
- **Prediction for similar and weaker correlation between soft and hard particles → NSC(m,n)?**

M.L. Sambataro, Y. Sun et al. in preparation

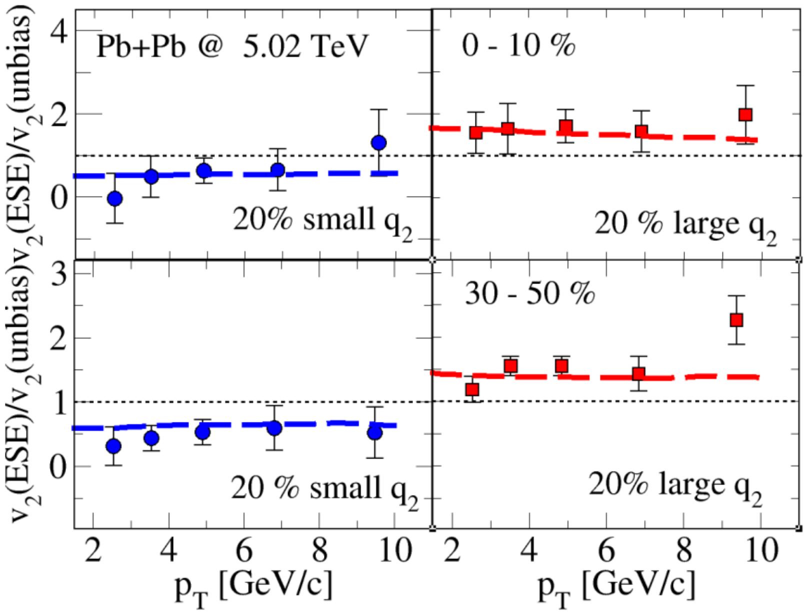
Data taken from: S. Mohapatra *Nucl.Phys.A* 956 (2016) 59-66

ESE: v_2 and spectra (20% small/large q_2)

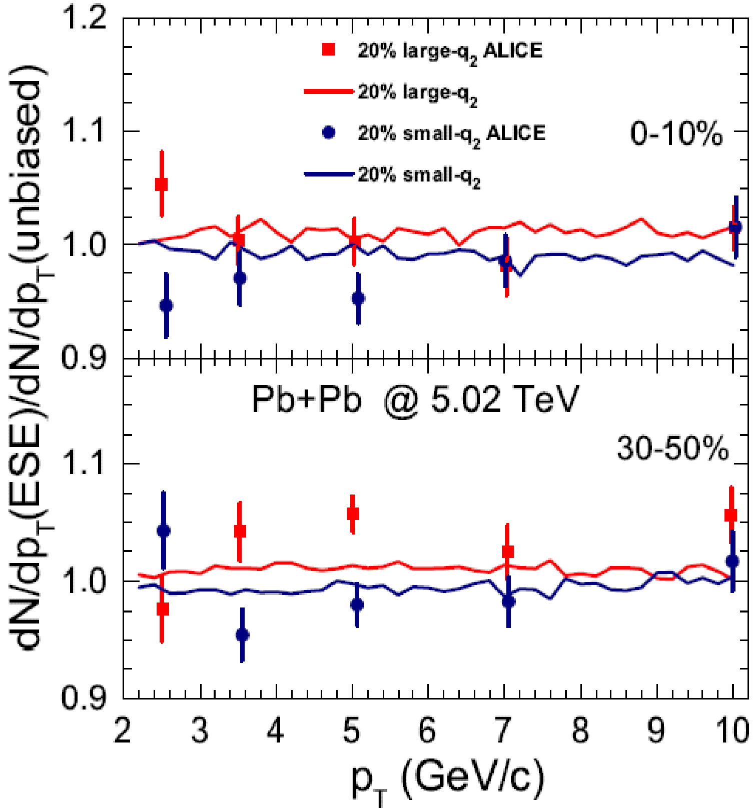
$q_2$selected $v_2(p_T)$



$q_2$selected $v_2(p_T)$ ratio



$q_2$selected spectra ratio

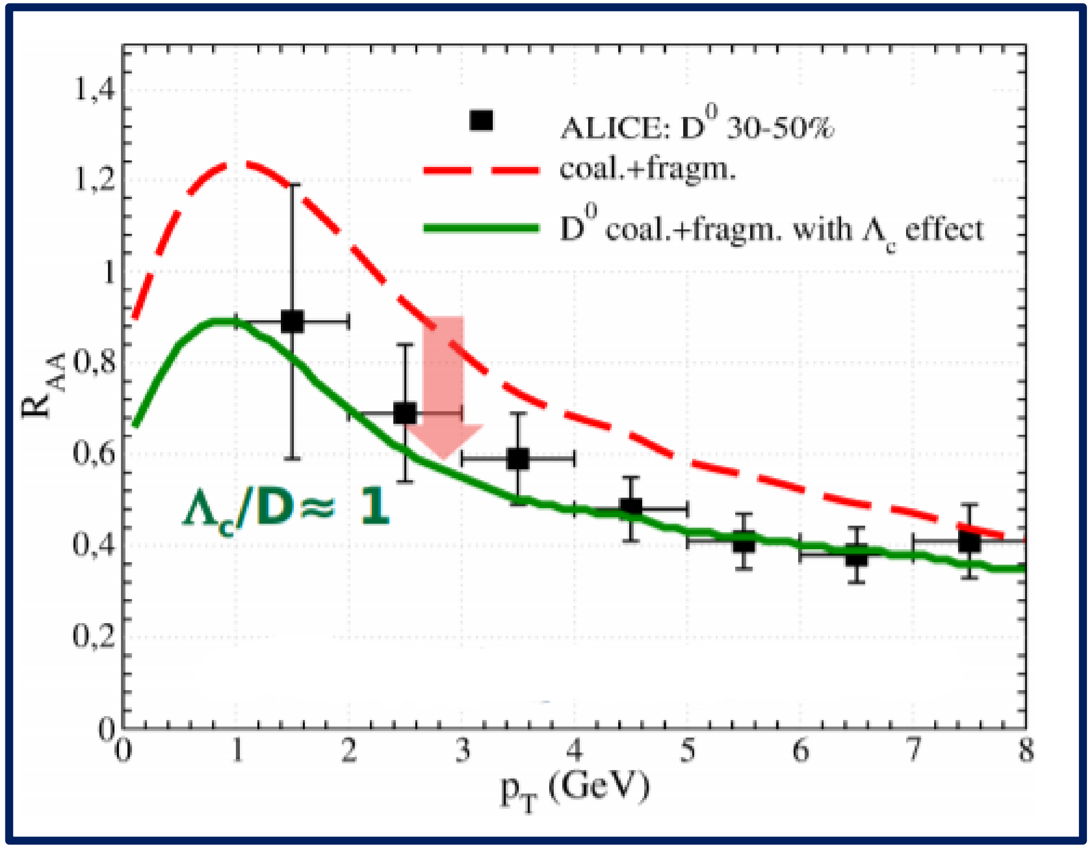


Data taken from ALICE collaboration: *Phys.Lett.B* 813 (2021) 136054

- v_2 (large- q_2 /small- q_2) $\gtrless$ v_2 (unbiased) of about 50% in both 0-10% and 30-50% centrality.
- Spectra ratio of D mesons (ESE selected/unbiased event) → close to unity → small correlation between the radial flow and the azimuthal anisotropy (still missing ev. by ev. fluctuation for coalescence)

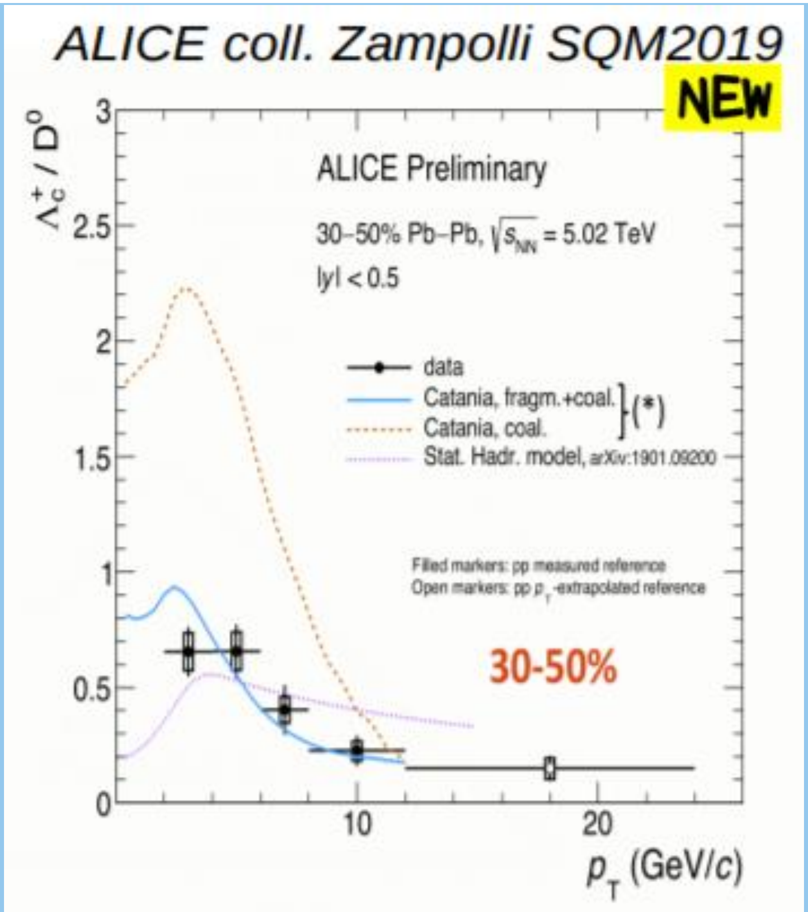
Y. Sun e al. in preparation

D meson: Impact of large Λ_c production on R_{AA}



$D_s(T)$ of charm quark that reproduces R_{AA} and v_2 gives good description of

- **Impact of Λ_C/ D^0**
- **Triangular flow $v_3(p_T)$.**
- **q_2 selected anisotropic flow and spectra.**



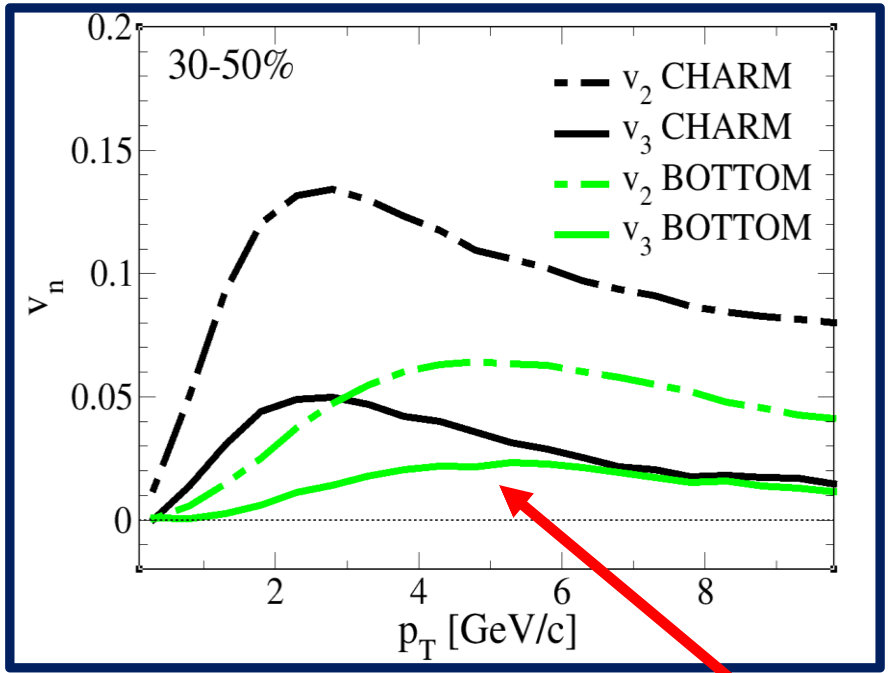
- With the same coalescence plus fragmentation model we describe the Λ_C/ D^0

S. Plumari, et al.,
Eur. Phys. J. C78 no. 4, (2018) 348

Extension to bottom dynamics: R_{AA} and v_n

- Prediction for B meson, electrons from semileptonic B meson decay within a coal + fragm model

Pb + Pb 5,02 TeV



Non-zero v_2, v_3 for bottom quark

No parameters changed
with respect to charm dynamics

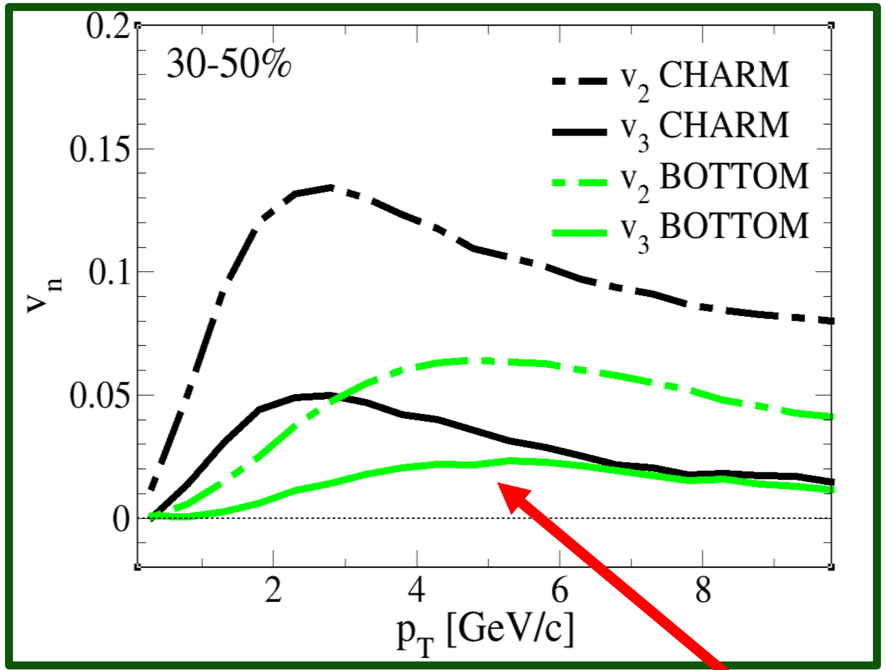
M.L. Sambataro, V. Minissale et al., in preparation

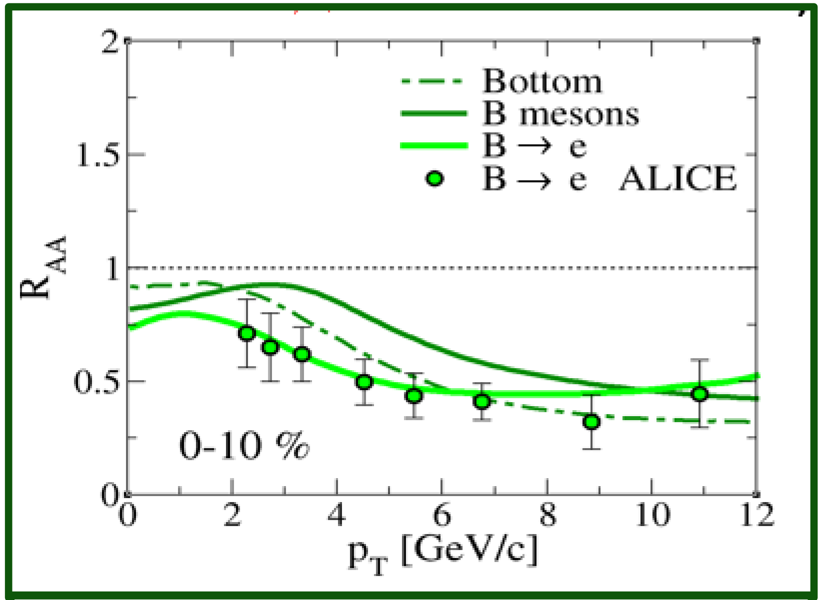
Extension to bottom dynamics: R_{AA} and v_n

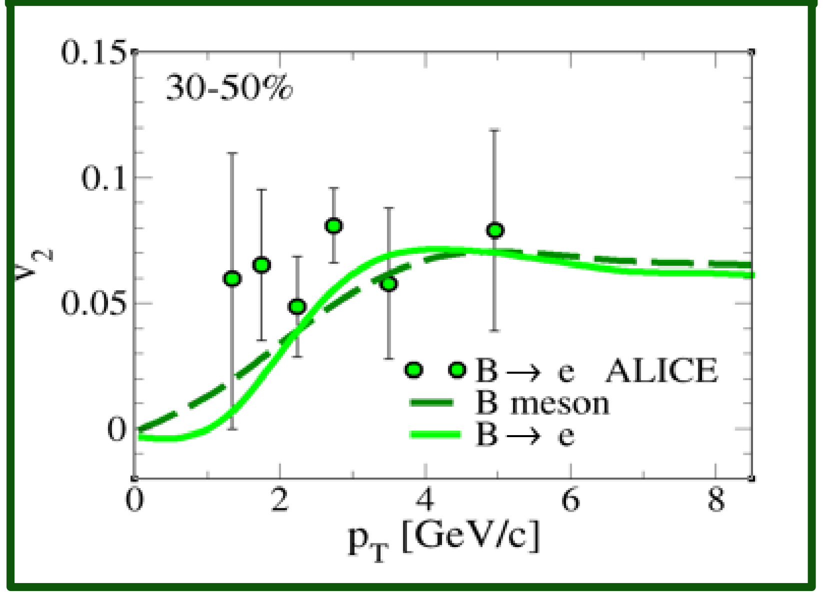
Data taken from Arnaldi HP(2020)

- Prediction for B meson, electrons from semileptonic B meson decay within a coal + fragm model

Pb + Pb 5,02 TeV





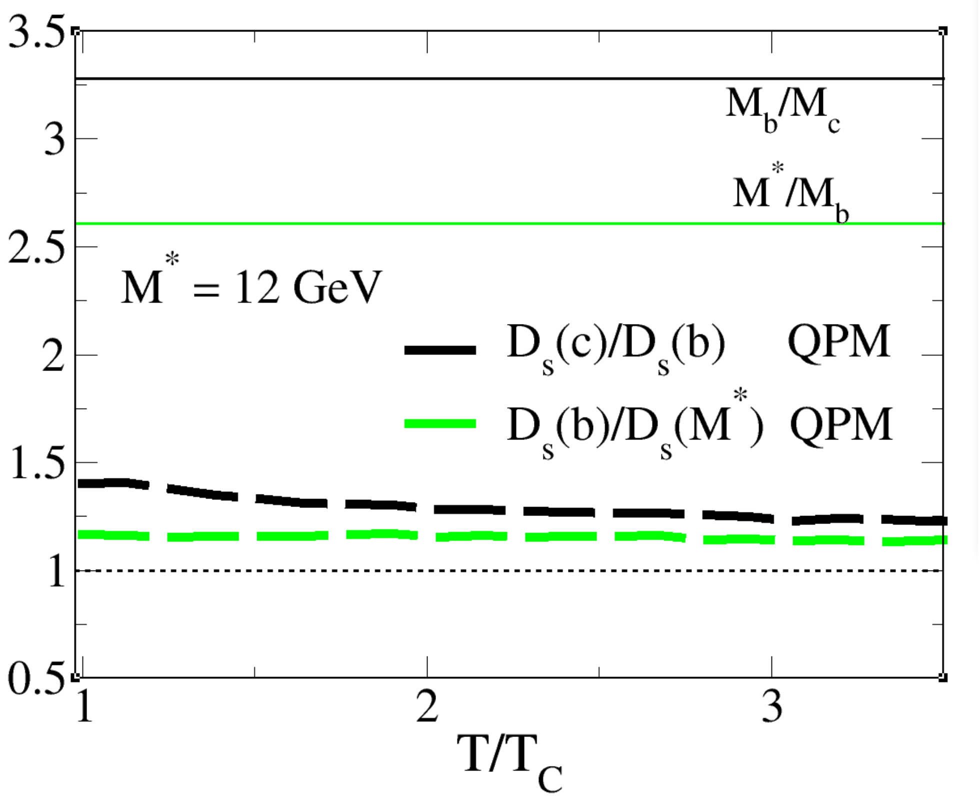


Non-zero v_2, v_3 for bottom quark

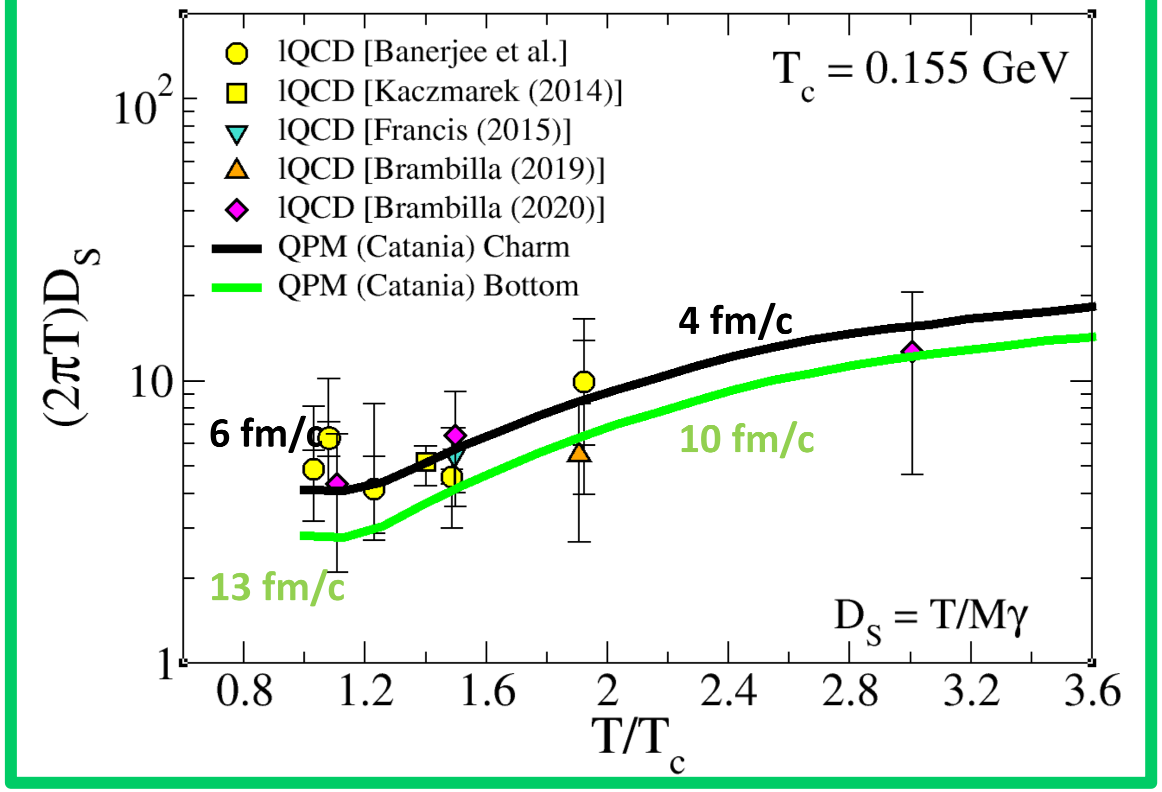
- **R_{AA} and v_2 indicate a strong coupling for bottom with collectively expanding fireball**

M.L. Sambataro, V. Minissale et al., in preparation

Charm quark vs Bottom quark



Spatial diffusion coefficient of bottom quark



Kinetic theory: $\tau_{th}(b)/\tau_{th}(c) \approx \gamma_c/\,\gamma_b \approx M_b/M_c$

$D_s = \frac{T}{M\gamma} = \frac{T}{M}\,\tau_{th}$ ideally M independent (M → ∞)

Results from $R_{AA}\,(p_T)$ and $v_2\,(p_T)$

In QPM approach → D_s(c) is 30-40% larger than D_s(b)
M →∞ limit is not reached for charm

FCC → Bottom fully thermalized

ON-SHELL VS OFF-SHELL
IN A STATIC BOX

Non-perturbative effects: impact of off-shell dynamics QPM vs. DQPM

- Partons are dressed by non-perturbative spectral functions:

$$A_i^{BW}(m_i) = \frac{2}{\pi}\frac{m_i^2\gamma_i^*}{(m_i^2 - M_i^2)^2 + (m_i\gamma_i^*)^2}$$

$$\begin{aligned} C[f] = & \int dm_i A(m_i) \int dm_f A(m_f) \\ & \times \frac{1}{2E_p} \int \frac{d^3\mathbf{q}}{2E_q(2\pi)^3} \int \frac{d^3\mathbf{q}'}{2E_{q'}(2\pi)^3} \int \frac{d^3\mathbf{p}'}{2E_{p'}(2\pi)^3} \\ & \times \frac{1}{\gamma_Q} \sum |\mathcal{M}_Q|^2 (2\pi)^4 \delta^4(p + q - p' - q') \\ & \times [f(\mathbf{p}')\hat{f}(\mathbf{q}', m_f) - f(\mathbf{p})\hat{f}(\mathbf{q}, m_i)] \end{aligned}$$

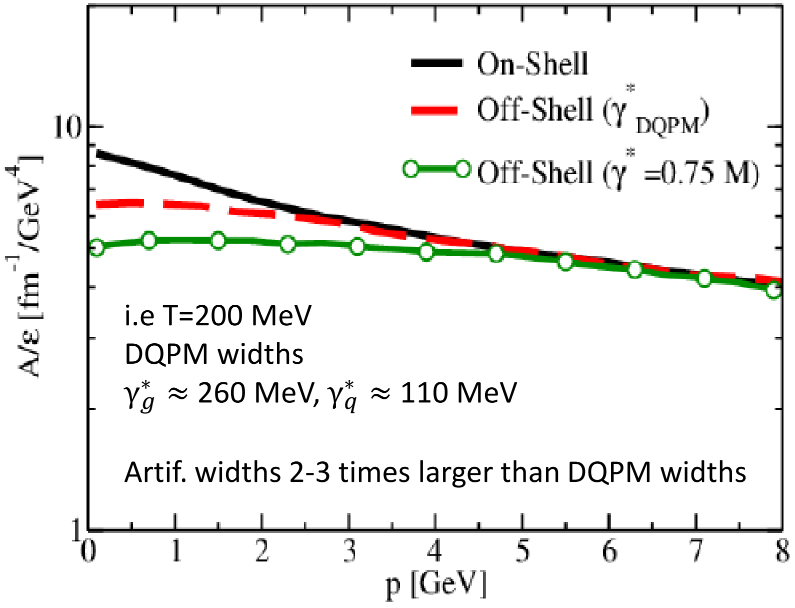
For references: W. Cassing, Nucl.Phys. A831, 215
E. Bratkovskaya, Nucl.Phys. A856, 162
H. Berrehrah, Phys. Rev. C 89(5), 054901
M.L. Sambataro et al., *Eur.Phys.J.C* 80 12, 1140

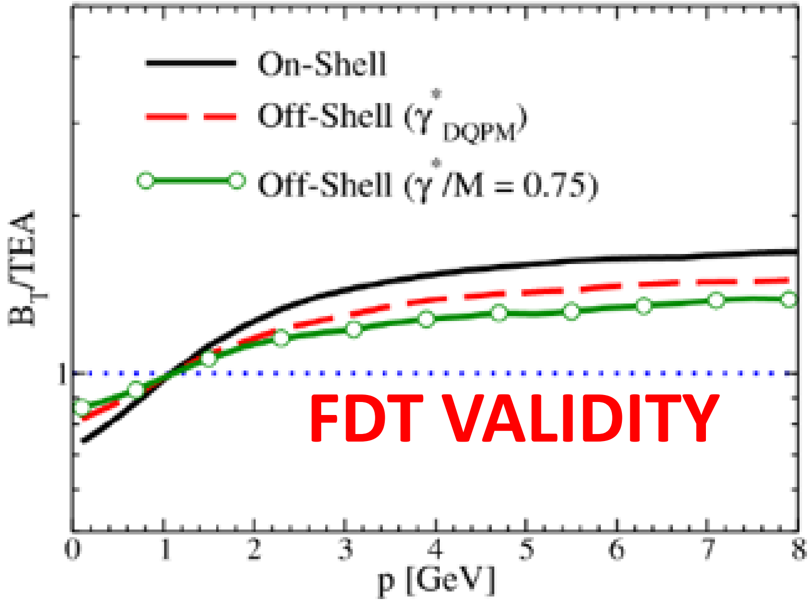
Off-shell≈ PHSD but also larger widths!

BOX CALCULATION [T=200 MeV] FOR CHARM

Bulk is not with the same energy density
The energy density of off-shell case is smaller

- Transport coefficient scales with energy density of the system ε
- Larger breaking for low p region ($p \lesssim$2-3 GeV/c)
  → **larger off-shell effects**
  →30-40% decreasing drag





On-shell vs Off-shell energy loss

BOX CALCULATION [T=200 MeV] FOR CHARM

- Partons are dressed by non-perturbative spectral functions:

$$A_i^{BW}(m_i) = \frac{2}{\pi} \frac{m_i^2 \gamma_i^*}{(m_i^2 - M_i^2)^2 + (m_i \gamma_i^*)^2}$$

Boltzmann equation and off-shell extension

$p^\mu \partial_\mu f_Q = C[f_Q, f_{g,q}]$

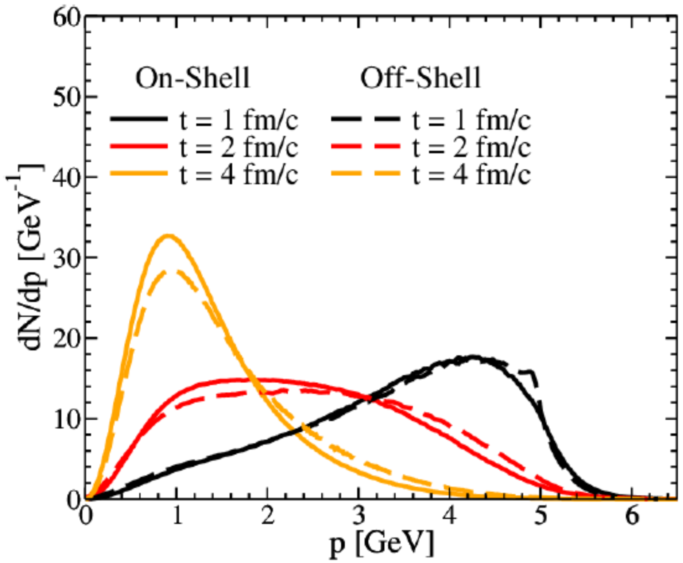
Plasma uniform $\rightarrow p^0 \partial_0 f_Q = C[f_Q, f_{g,q}]$

$\frac{\partial f_Q}{\partial t} = \frac{1}{E_Q} C[f_q, f_g, f_Q]$

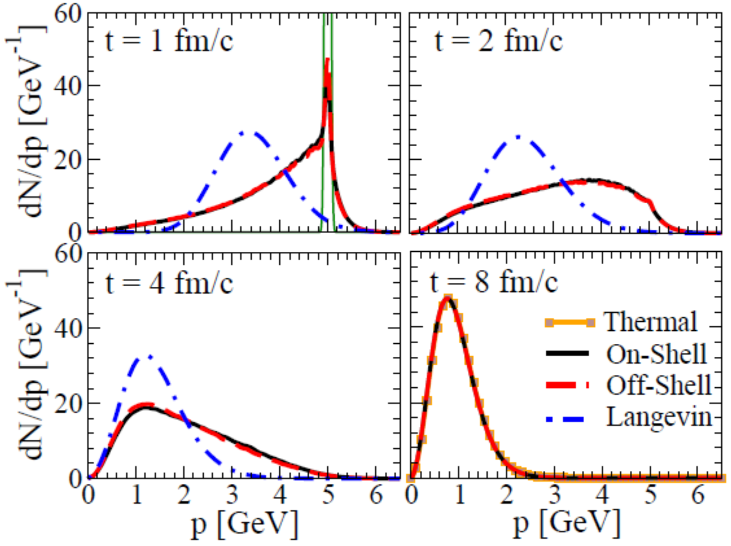
$f(t + \Delta t, p) = f(t, p) + \frac{1}{E_Q} C[f]$

$C[f_q, f_g, f_Q]$ Collision integral calc. both in on-shell and off-shell mode

$\varepsilon_{onshell} = \varepsilon_{offshell}$



+k(p) making
the Drag on-shell=Drag off-shell



The difference between on-shell and off-shell mode can be adsorbed by multiplying scattering matrix for a *k* factor

Conclusions

- $D_S(T)$ reproduces D meson $R_{AA}$and v_2

  → correct predictions for v_3 and q_2 selected anisotropic flow/spectra.

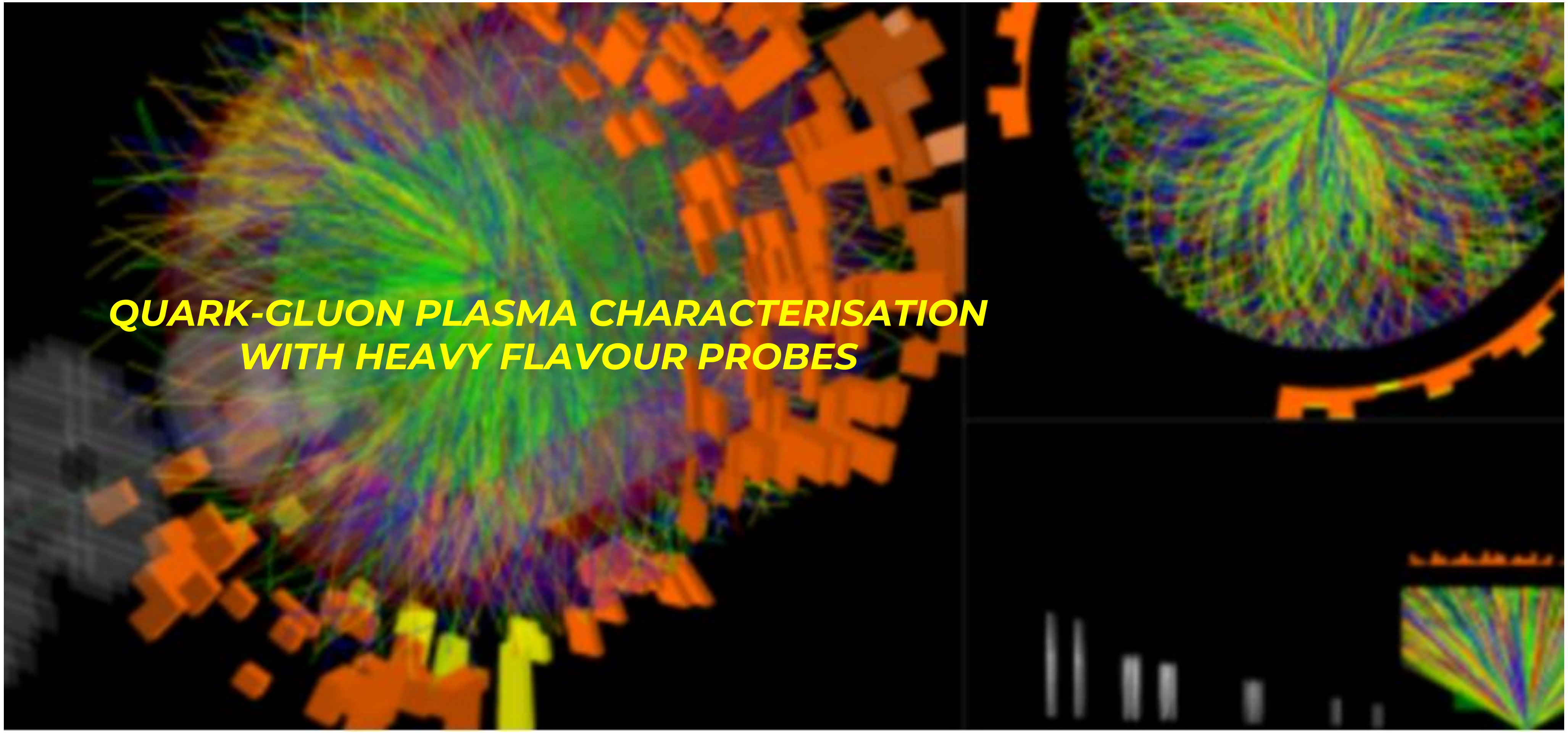
- Extension to bottom quark dynamics:

  → good description of R_{AA}, v_2 of electron from semileptonic B meson decay.

  → $D_S(T)$ of bottom in agreement with lattice QCD data within the still significantly large uncertainties.

- Prediction for significant $v_n - v_m$ correlation of hard particles, similar correlation between v_n of soft and hard particles.

- New perspectives: B meson v_3 and impact of Λ_B / B^0 on B meson R_{AA}.

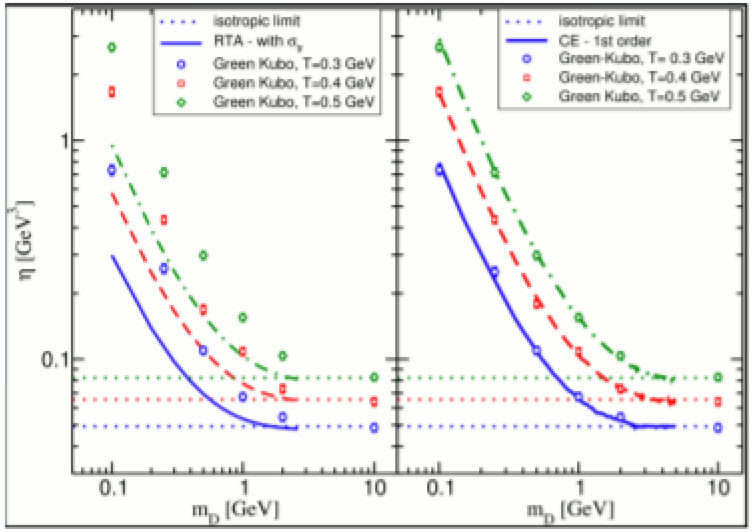


Thanks for your attention!

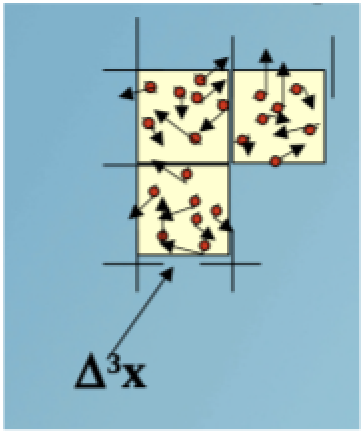
Back-up slides

We evaluate the cross section in each cell α according to the Chapmann-Enskog formula in order to have a fluid at the wanted $\eta/s(T_\alpha)$ (*S. Plumari et al., Phys. Rev. C 86, 054902 (2012)*):

$$\sigma_{\text{tot},\alpha} = \frac{1}{15} \frac{\langle p \rangle_\alpha}{g\left(\frac{m_D}{T_\alpha}\right) n_\alpha} \frac{1}{\eta/s}.$$



Comparison between Relaxation Time Approximation, Chapmann-Enskog and Green-Kubo. In the non-isotropic case CE works better than RTA.



From that we obtain the probability for a $2 \to 2$ collision (*Z. Xu, C. Greiner, Phys. Rev. C 71, 064901 (2005)*):

$$P = v_{\text{rel}} \sigma_{\text{tot}} \frac{\Delta t}{\Delta^3 x}.$$

Non-perturbative effects: impact of off-shell dynamics QPM vs. DQPM

- Partons are dressed by non-perturbative spectral functions:

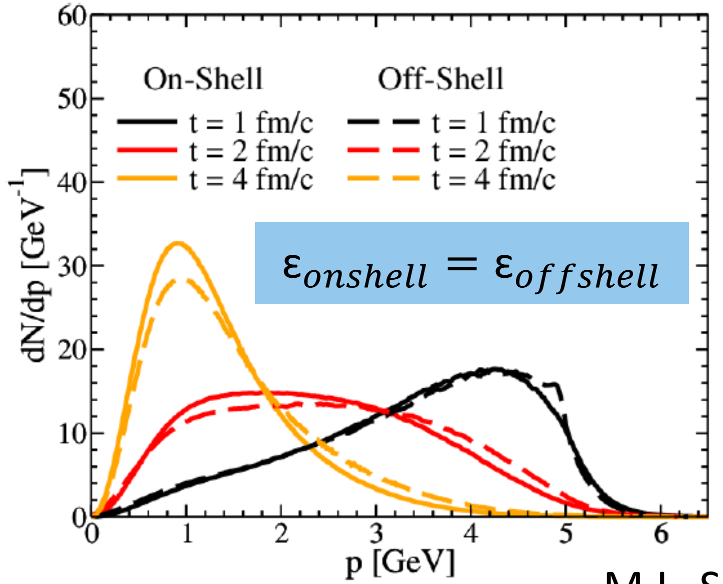
$$A_i^{BW}(m_i) = \frac{2}{\pi} \frac{m_i^2 \gamma_i^*}{(m_i^2 - M_i^2)^2 + (m_i \gamma_i^*)^2}$$

$$\gamma_g(T) = \frac{1}{3} N_C \frac{g^2(T/T_C)T}{8\pi} ln\left[\frac{2c}{g^2(T/T_C)} + 1\right]$$

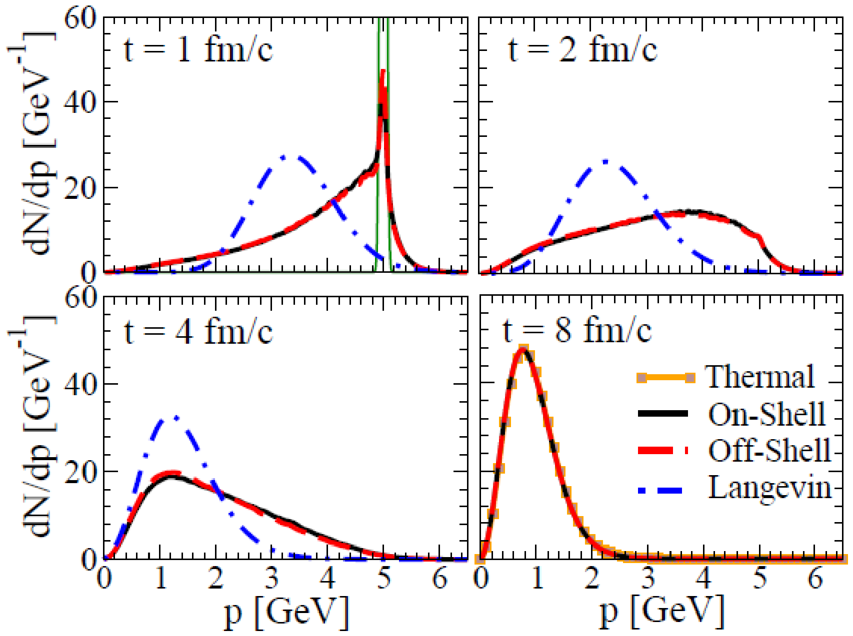
$$\gamma_q(T) = \frac{1}{3} \frac{N_C^2 - 1}{2N_C} \frac{g^2(T/T_C)T}{8\pi} ln\left[\frac{2c}{g^2(T/T_C)} + 1\right]$$

$$C[f] = \int dm_i A(m_i) \int dm_f A(m_f) \times \frac{1}{2E_p} \int \frac{d^3\mathbf{q}}{2E_q(2\pi)^3} \int \frac{d^3\mathbf{q}'}{2E_{q'}(2\pi)^3} \int \frac{d^3\mathbf{p}'}{2E_{p'}(2\pi)^3} \times \frac{1}{\gamma_Q} \sum |\mathcal{M}_Q|^2 (2\pi)^4 \delta^4(p + q - p' - q') \times [f(\mathbf{p}')\hat{f}(\mathbf{q}', m_f) - f(\mathbf{p})\hat{f}(\mathbf{q}, m_i)]$$

Off-shell≈ PHSD



+k(p) making
the Drag off-shell=Drag off-shell



M.L. Sambataro et al., *Eur.Phys.J.C* 80 (2020) 12, 1140