Istituto Nazionale di Fisica Nucleare
Sezione di Catania

WPCF 2023 - XVI Workshop on Particle Correlations and Femtoscopy & IV Resonance Workshop 2023

Charm and Bottom quarks dynamics in Heavy-Ion Collisions: anisotropic flows v_n and their correlations with Event-Shape Engineering technique.

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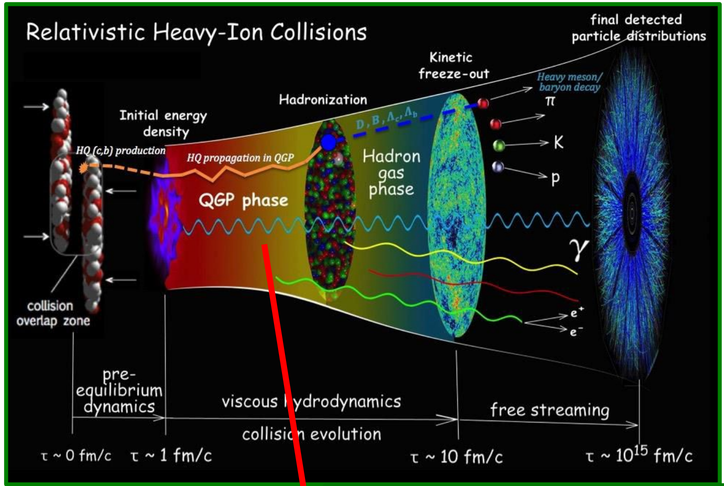
Basic scales of charm and bottom quarks



One of the main probes to signal the <u>Quark-Gluon Plasma</u> properties:
Heavy Quarks

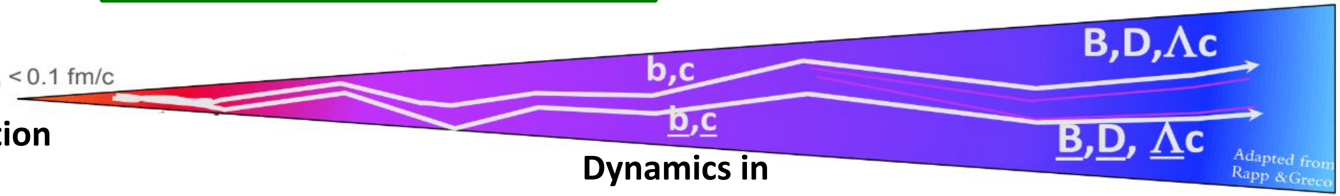
Charm M_c≈1.3 GeV and Bottom M_b≈4.2 GeV

- $m_{c,b} >> \Lambda_{QCD}$
  pQCD initial production
- $m_{c,b} >> T_{RHIC,LHC}$
  negligible thermal production
- $\tau_0 < 0{,}08$ 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.

Initial production $\tau_0 < 0.1$ fm/c



Dynamics in QGP

Hadronization:
Final hadron Spectra and observables

<u>Reviews</u>:
1. X.Dong, V. Greco Prog. Part. Nucl. Phys. 104 (2019),
2. A.Andronic EPJ C76 (2016), 3) R.Rapp, F.Prino J.Phys. G43 (2016)

CATANIA MODEL: QUASI-PARTICLE MODEL AND TRANSPORT THEORY

R_{AA}, v_n and v_n - v_m correlations

in charm sector

Quasi Particle Model (QPM) fitting lQCD

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

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

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

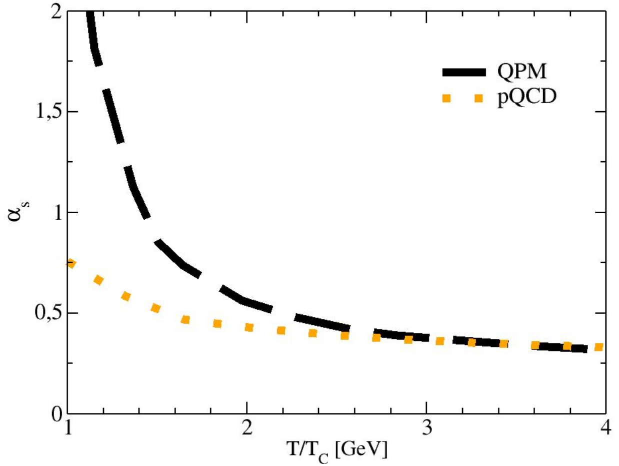
→ **Thermal masses of gluons and light quarks**

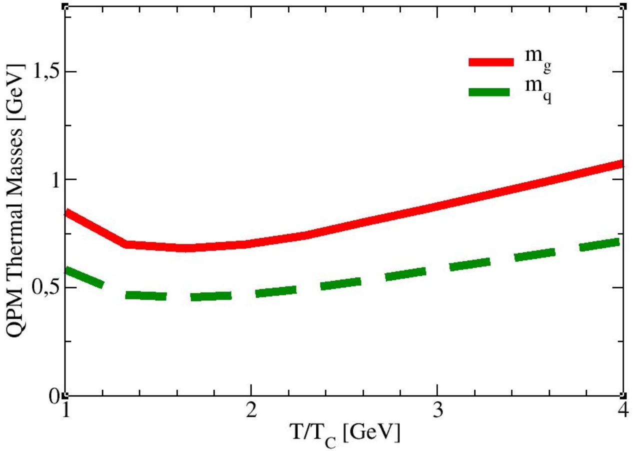
g(T) from a fit to ε from lQCD data → good reproduction of P, ε-3P

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

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)

Relativistic Boltzmann equation at finite η/s

Bulk evolution

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

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

Free-streaming | field interaction $\varepsilon - 3p \neq 0$ | Collision term gauged to some η/s≠ 0

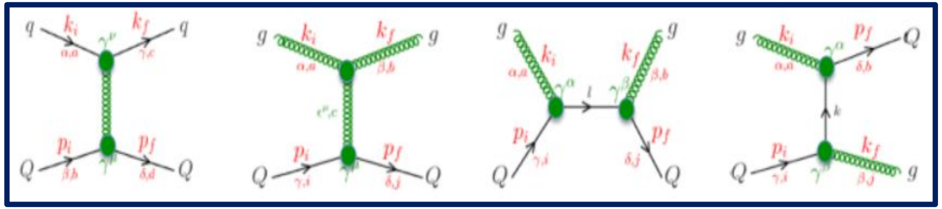
Equivalent to viscous hydro at η/s ≈ 0.1

HQ evolution

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

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

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



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

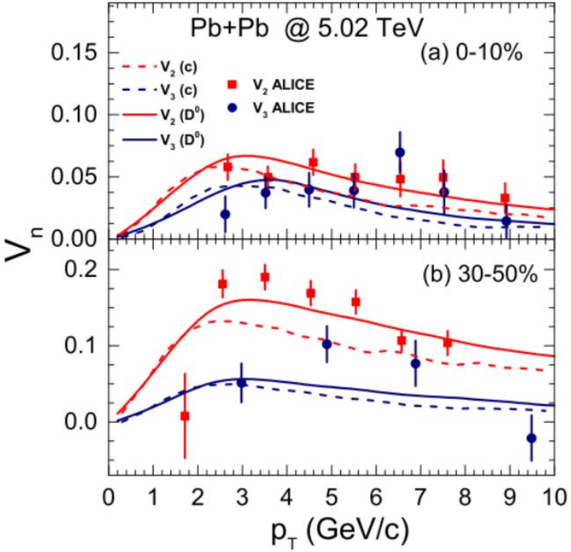
HADRONIZATION: hybrid Coalescence + fragmentation

For details: S. Plumari talk

Information from non-equilibrium: anisotropic flows $v_n(p_T)$

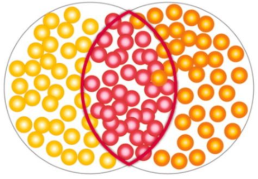
M.L. Sambataro et al., *Eur.Phys.J.C* 82 (2022) 9, 833

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



Elliptic flow v_2

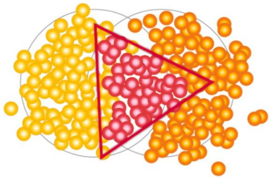
- **asymmetry** between the **in-plane** and **out-of-plane** directions



Elliptic flow

Triangular flow v_3

- event-by-event **fluctuations** in the **initial distributions** of nucleons



Triangular flow

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

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

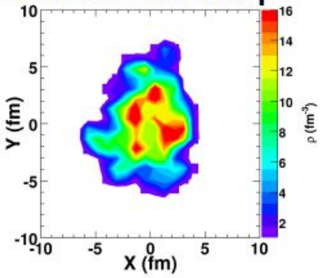
Azimuthal anisotropies depend on

- the interaction and coupling of heavy quarks with the medium;
- the initial conditions of the system, i.e.geometry of the collision;
- **the fluctuations in the distributions of nucleons and gluons within the nuclei**

Monte Carlo Glauber for initial condition of partons

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

Not almond shape

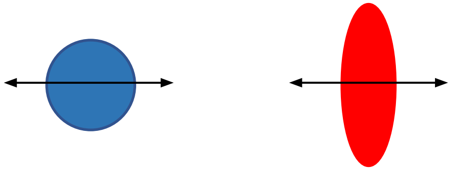


Event-Shape-Engeenering technique

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.

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

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



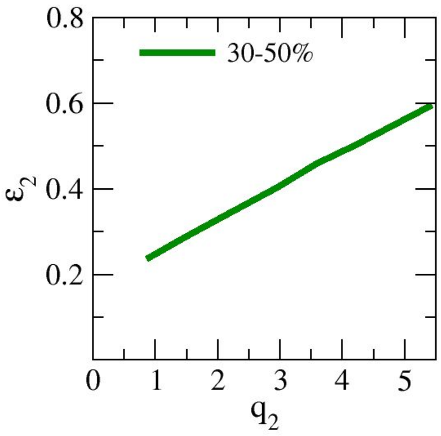
20 % small q_2 20 % large q_2

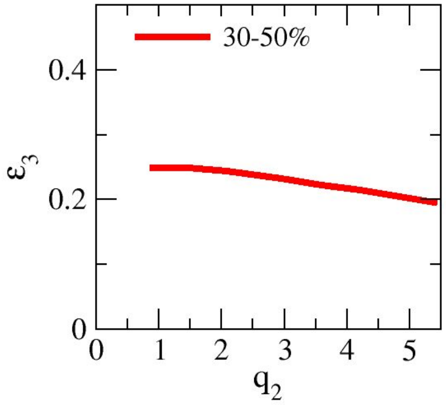
Large $q_2 \rightarrow$ large ε_2

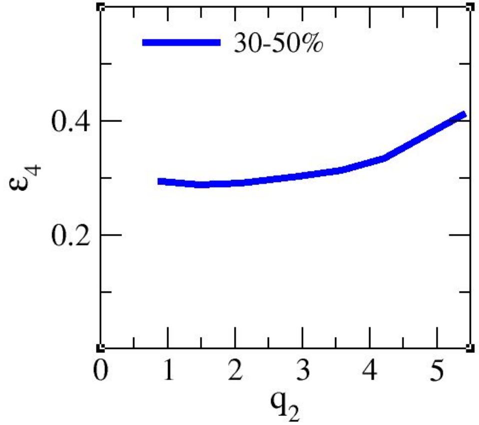
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)] \rangle}{\langle r_\perp^n \rangle} \qquad \Phi_n = \frac{1}{n} \arctan \frac{\langle r_\perp^n \sin(n\varphi) \rangle}{\langle r_\perp^n \cos(n\varphi) \rangle}$$

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

Pb-Pb 5,02 TeV







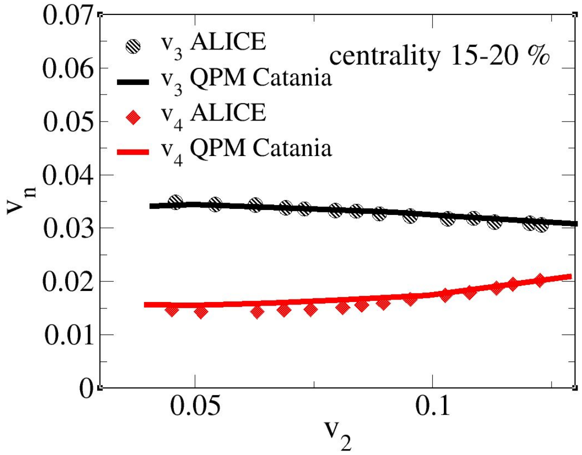
Anti-correlation between ε_2 and ε_3

Non-linear correlation between ε_2 and ε_4

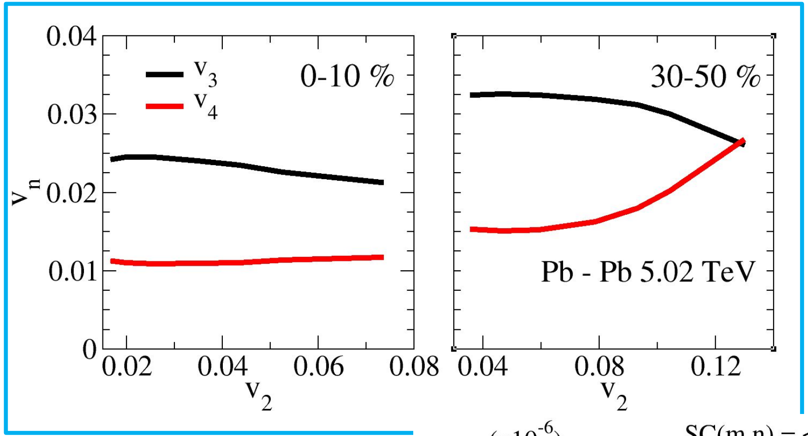
M.L. Sambataro et al., *Eur.Phys.J.C* 82 (2022) 9, 833

ESE: $v_n - v_m$ correlations

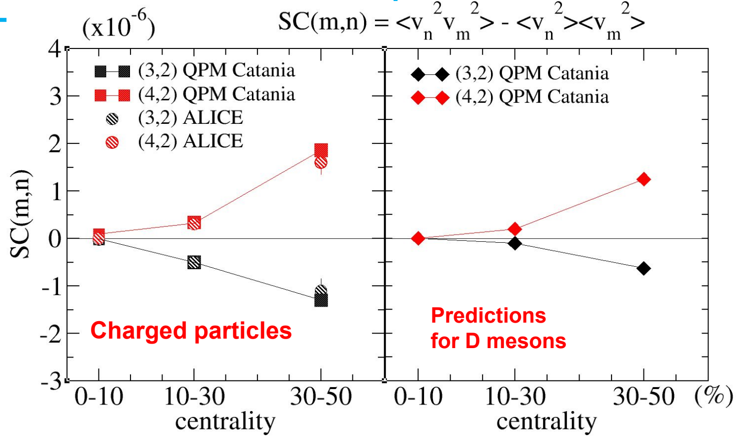
Charged particles



Predictions for D



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**

M.L. Sambataro, *Eur.Phys.J.C* 82 (2022) 9, 833

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

Event-shape-engeenering

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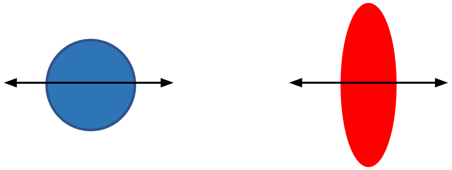


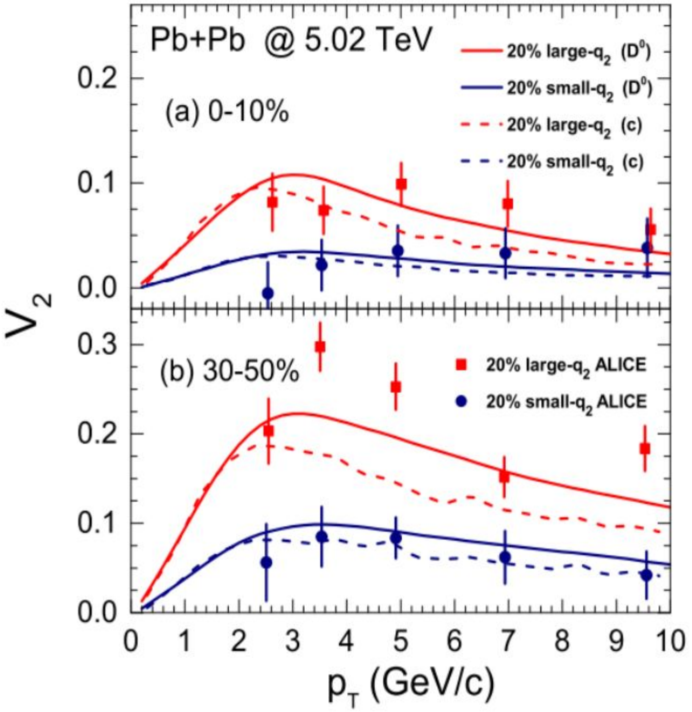
20 % small q_2 20 % large q_2

Large $q_2 \rightarrow$ large ε_2

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

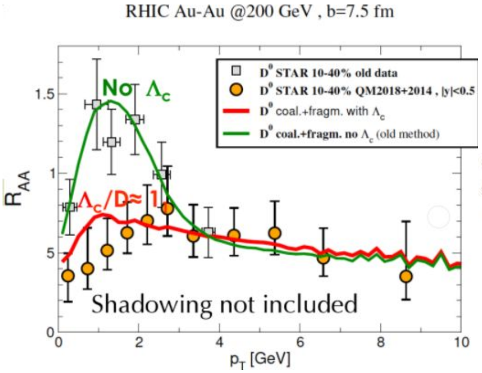
$$r_\perp = \sqrt{x^2 + y^2}, \qquad \varphi = \arctan(y/x)$$

M.L. Sambataro et al., *Eur.Phys.J.C* 82 (2022) 9, 833

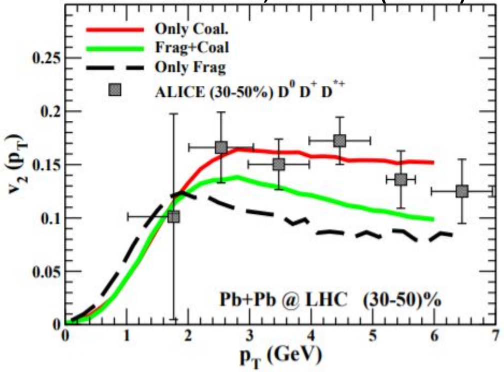


Discrepancy between selected v_2 and unbiased one ~ 50%

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

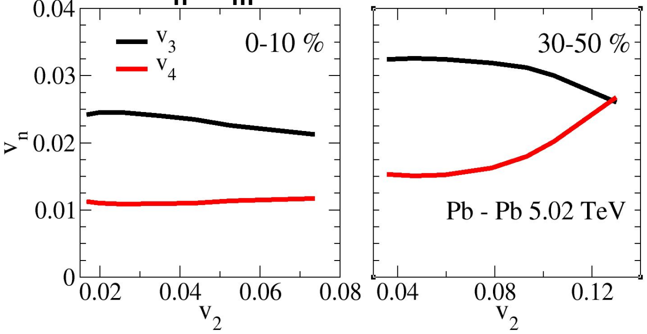
Monte Carlo Glauber for initial condition of partons

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

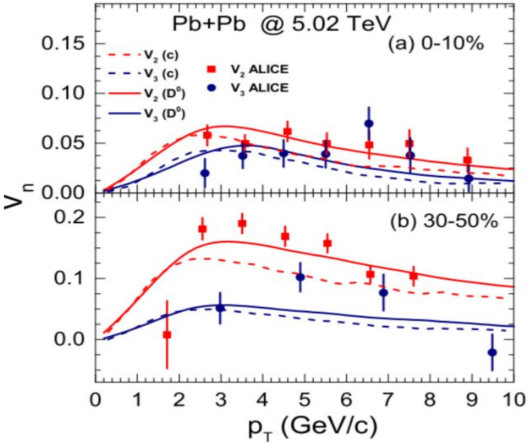
Predictions for D mesons

v_n - v_m correlations

- **Event-Shape Engeenering Technique:**
  Prediction for similar correlation for hard particles wrt bulk



Triangular flow v_3



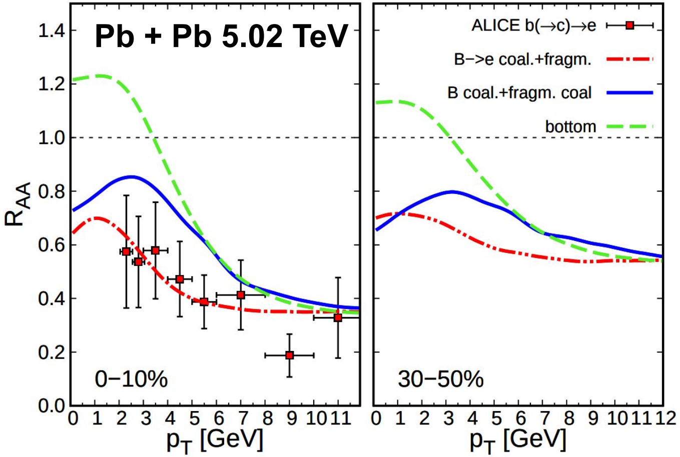
ALICE collaboration, *Phys.Lett.B* 813 (2021) 136054

M.L. Sambataro, et al., *Eur.Phys.J.C* 82 (2022)

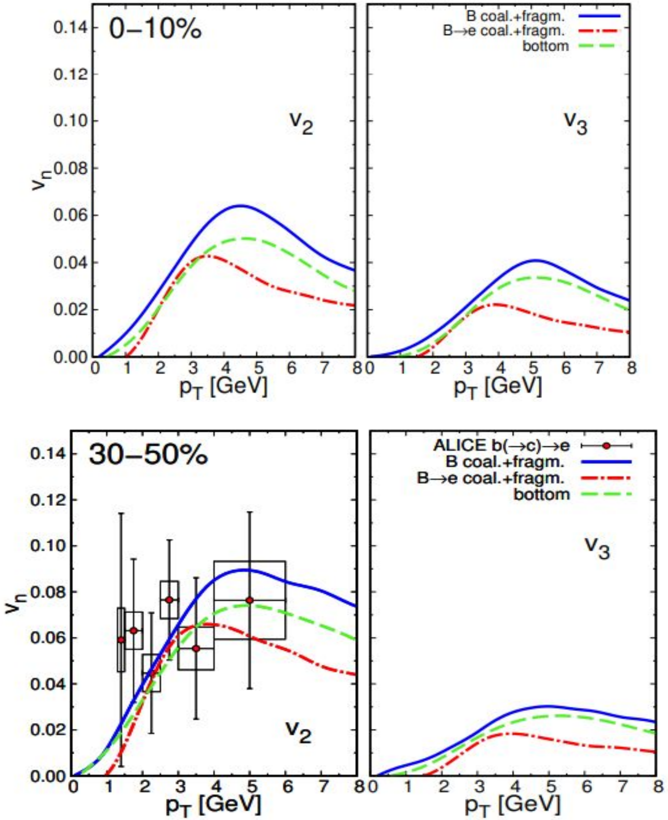
Extension to bottom dynamics: R_{AA} and $v_{(n=2,3)}$

Hadronization with coalescence + fragmentation model

- Prediction for B meson R_{AA} and v_n
- R_{AA} and v_n of electrons from semileptonic B meson decay



No parameters changed with respect to charm dynamics



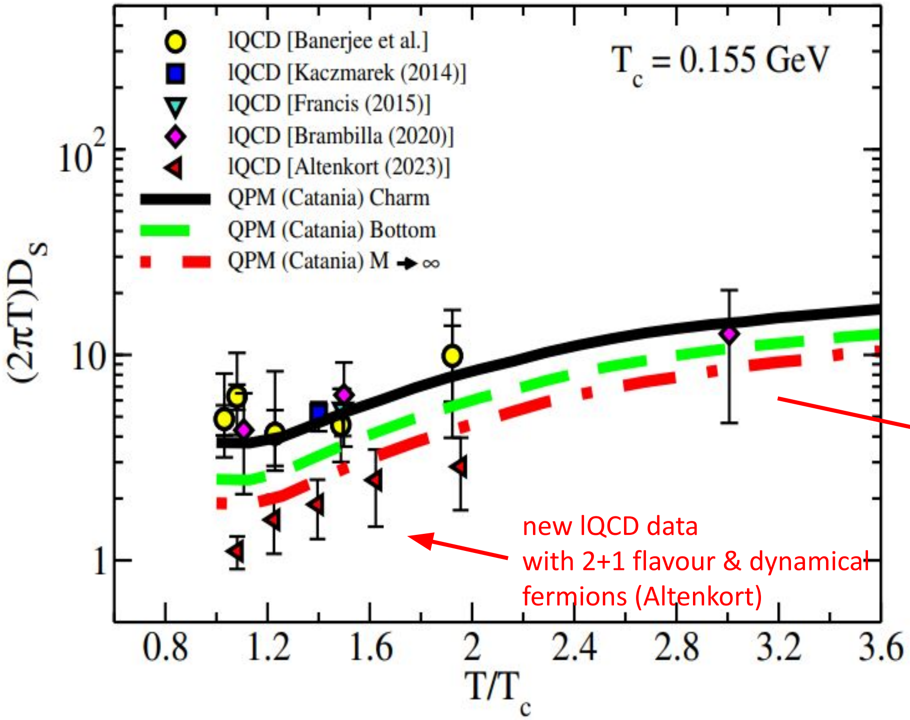
M.L. Sambataro et al., e-Print: 2304.02953

Data from: ALICE coll., arxiv:2211.13985

Compared to charm quark:

- Efficiency of conversion of ε_2 :
  15% smaller for v_2 in most central collisions.
  40% smaller for v_2 at 30−50% centrality.
- Efficiency of conversion of ε_3 :
  30% smaller for v_3 at both 0-10% and 30-50% centralities.

$(2\pi T)D_s$: Charm quark vs Bottom quark



new lQCD data
with 2+1 flavour & dynamical
fermions (Altenkort)

- lQCD data are in $M_Q \to \infty$, so the D_s evaluated is mass independent + quenched medium (data until 2020)
- QPM use finite mass and includes dynamical fermions – D_s saturates only for M>10 GeV.

$$D_s = \frac{T}{M\,\gamma} = \frac{T}{M}\,\tau_{th}$$

Calculations with fictitious super-heavy quark staying in the $M_Q \to \infty$ limit to correctly compare to new lQCD data

From D_s we obtain (in the 1-2T_c range):

- $\tau_{th}(c)$ ~ 5 fm/c
- $\tau_{th}(b)$ ~ 11 fm/c

Good agreement with the new lQCD data including dynamical fermions which are the more pertinent one to compare to.

M.L. Sambataro et al., e-Print: 2304.02953

Conclusions

- **Catania Quasi-Particle model for charm quark**:

  - Good agreement with experimental data for R_{AA} and v_2
  - Extension to higher order anisotropic flows v_n : good description also for triangular flow v_3
  - **Event-Shape Engineering technique:** prediction for significant v_n- v_m correlations for hard particles, similar correlation between soft and hard particles.

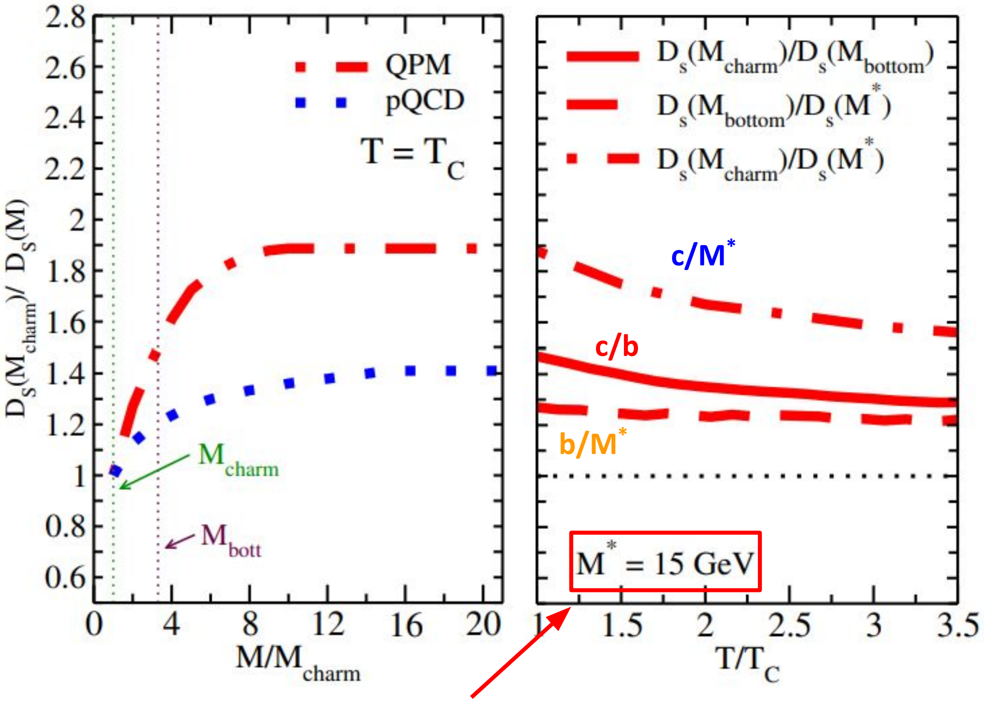
- **Extension to bottom quark dynamics**:

  - Good description of R_{AA} and v_2 of electrons from semileptonic B meson decay
  - Prediction for v_3 different from zero in central and semi-pheripheral collisions.

- **Spatial diffusion coefficient D_s(T) in good agreement with the new lQCD data which include dynamical fermions - the more pertinent one to compare to.**

Thanks for the attention!

$(2\pi T)D_s$ ratios: Charm quark vs Bottom quark



fictitious super-heavy quark staying in the $M_Q \rightarrow \infty$ limit

➢ $D_s(M_{charm})/D_s(M)$ as a function of M/M_{charm} at T_C:

Saturation scale of Ds for M_Q ~ 8 M_{charm} $\gtrsim$ 10 GeV
$Ds(M_{charm})/Ds(M \rightarrow \infty) = 1.9$ for QPM.

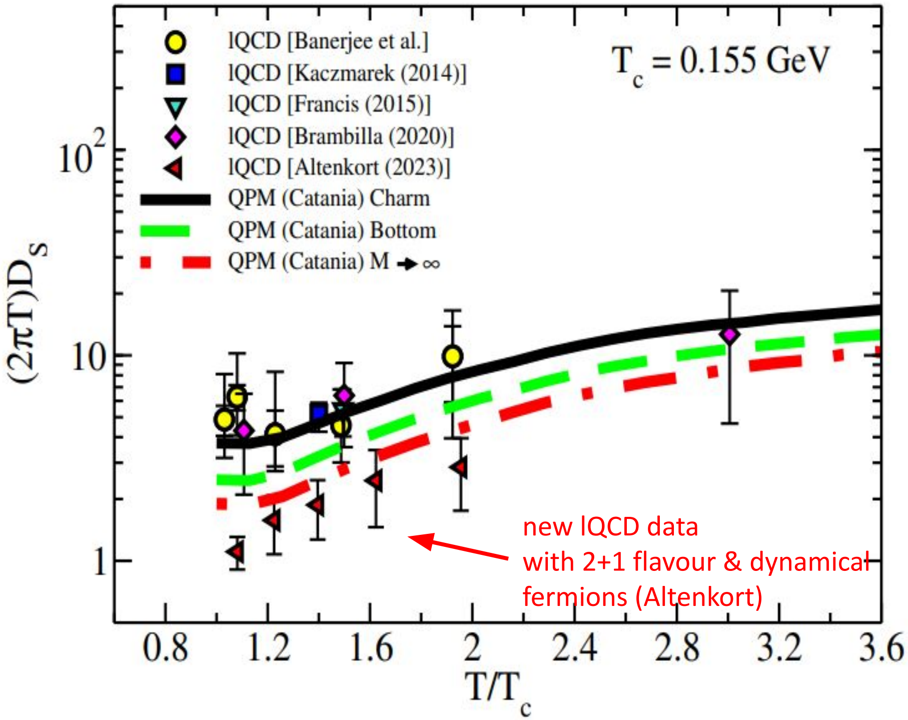
$Ds(M_{charm})/Ds(M \rightarrow \infty) \simeq 1.4$ for pQCD.

➢ Ratios at fixed mass as a function of T:

- **b/M^*: about 25% in all T range**
- **c/b: about 50% at T_C and not smaller than 30%**
- **c/M^*: factor 1.5-2**

M.L. Sambataro et al., e-Print: 2304.02953

$(2\pi T)D_s$: Charm quark vs Bottom quark



- lQCD data are in $M_Q \to \infty$, so the D_s evaluated is mass independent + quenched medium (data until 2020)
- QPM use finite mass and includes dynamical fermions

$$D_s = \frac{T}{M\,\gamma} = \frac{T}{M}\,\tau_{th}$$

From kinetic theory is expected that:

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

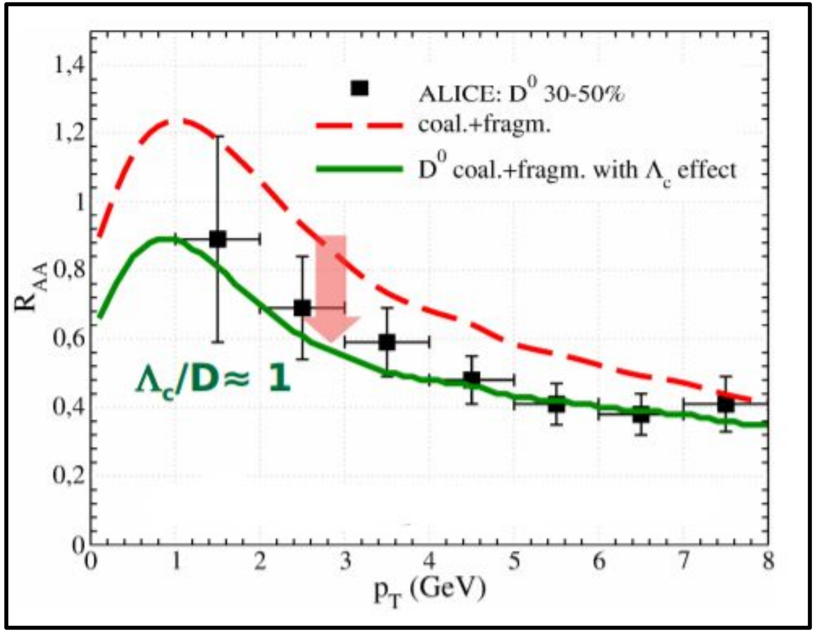
In QPM approach ⟶ $D_s(c)$ is 30-40% larger than $D_s(b)$ (no mass independence)

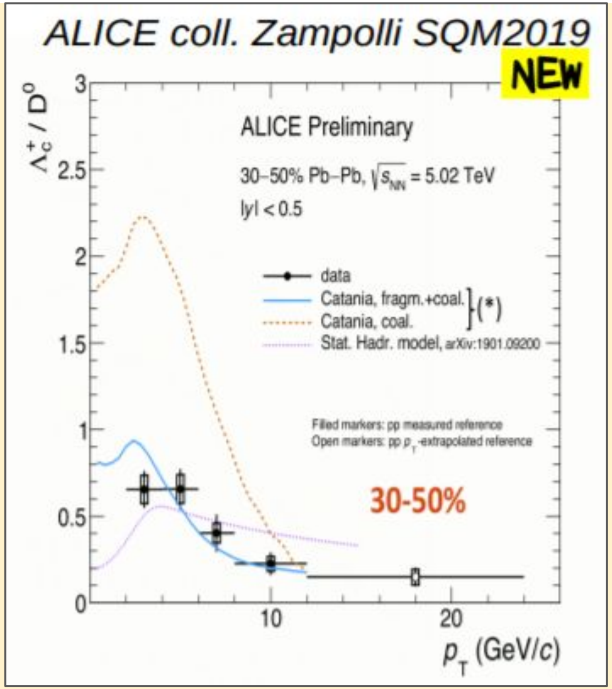
M⟶ ∞ limit is not reached for charm

From D_s we obtain (in the 1-2T_c range):
- $\tau_{th}(c)$ ~ 5 fm/c
- $\tau_{th}(b)$ ~ 11 fm/c breaking w.r.t. the relation: $\tau_{th}(b) = (M_b/M_c)\tau_{th}(c)$ ~ 3.3 $\tau_{th}(c)$ ~ 16.5 fm/c

M.L. Sambataro et al., e-Print: 2304.02953

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

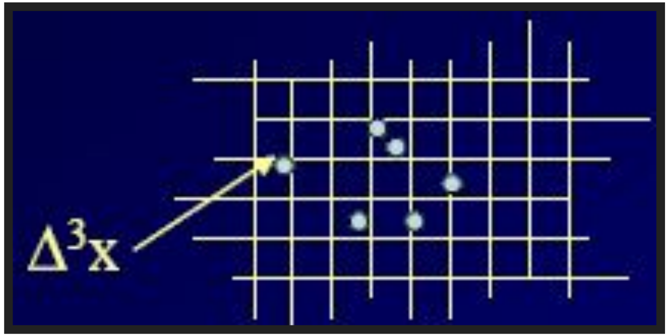
S. Plumari, et al.,
Eur. Phys. J. C78 no. 4, (2018) 348

Numerical solution of Boltzmann Equation

- **Use Test-Particle Method to sample the phase space distribution function**

$$f(\vec{x},\vec{p},t) = \omega \sum_{i=1}^{N_{test}} \delta^{(3)}(\vec{x}-\vec{r}_i(t))\delta^{(3)}(\vec{p}-\vec{p}_i(t))$$

F_i solution of Boltzmann eq.
→ Test particles solve classical Hamilton eq. of motion



$$\begin{cases} \vec{p}_i(t+\Delta t) = \vec{p}_i(t-\Delta t) + 2\Delta t \cdot \left(\frac{\partial \vec{p}_i}{\partial t}\right)_{coll} \\ \vec{r}_i(t+\Delta t) = \vec{r}_i(t-\Delta t) - 2\Delta t \cdot \left[\frac{\vec{p}_i(t)}{E_i(t)}\right] \end{cases}$$

- **Collision Integral mapped through a Stochastic Al**

Δt □ 0 and $\Delta^3 x$ □ 0 : exact solution

$$P_{22} = \frac{\Delta N_{coll}^{2\to 2}}{\Delta N_1 \Delta N_2} = v_{rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

Final phase-space of HQ + bulk parton scattering sampled according to $|M_{QCD}|^2$ □ code test through simulations in a “box”

[Scardina, Colonna, Plumari, and Greco PLB v.724, 296 (2013)]
[Xu and Greiner PRC v. 71, (2005)]

Hybrid Hadronization Model for HQs

✔ **COALESCENCE**: Formula developed for the light sector **[Greco, Ko, Levai PRL 90 (2003)]**

$$\frac{dN_H}{d^2\boldsymbol{P}_T} = g_H \int \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 E_i} p_i \cdot d\sigma_i \, f_{q_i}(x_i, p_i) \, f_W(x_1 \ldots x_n; p_1 \ldots p_n) \, \delta\left(\boldsymbol{P_T} - \sum_i^n p_{T,i}\right)$$

Statistical Factor
Color-spin-isospin

Parton Distribution Functions
(after Boltzmann evolution)

Hadron Wigner Function
(parameters fix according to quark model)
C.-W. Hwang, EPJ C23, 585 (2002)
C. Albertus et al., NPA 740, 333 (2004)

✔ **FRAGMENTATION**: HQs that do not undergo to Coalescence

$$\frac{dN_H}{d^2\boldsymbol{P}_T} = \sum_f \int dz \frac{dN_f}{d^2 p_T} \frac{D_{f\to H}(z)}{z^2}$$

We use Peterson parametrization: $D_H(z) \propto \left[z\left(1 - \frac{1}{z} - \frac{\epsilon_c}{1-z}\right)^2\right]^{-1}$ *Peterson et al. PRD 27 (1983) 105*

Parameter ε_c tuned to reproduce *D* and *B* meson spectra in pp collisions.

Plumari, Minissale, Das , Coci , Greco, EPJ C 78 (2018) no.4

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

 Partons are dressed by non-perturbative spectral functions:

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

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

Evaluated in DQPM approach

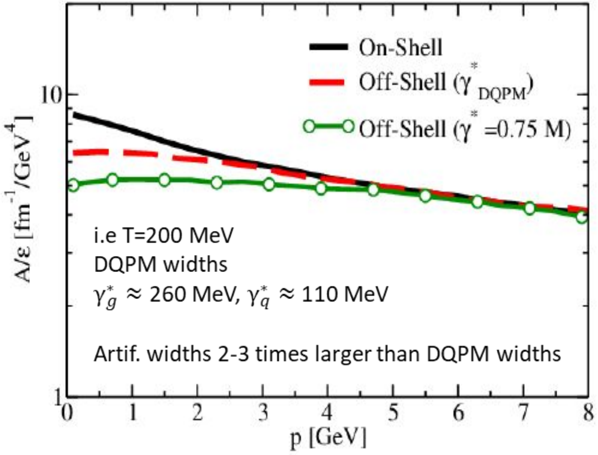
For references: W. Cassing, Nucl.Phys. A831, 215
E. Bratkovskaya, Nucl.Phys. A856, 162
H. Berrehrah, Phys. Rev. C 89(5), 054901
M.L. Sambataro et al., *Eur.Phys.J.C* 80 12, 1140

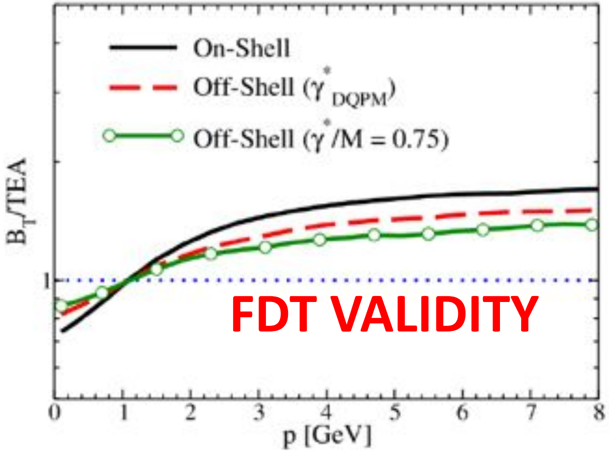
Off-shell ≈ PHSD but also larger widths!

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

BOX CALCULATION [T=200 MeV] FOR CHARM





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

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

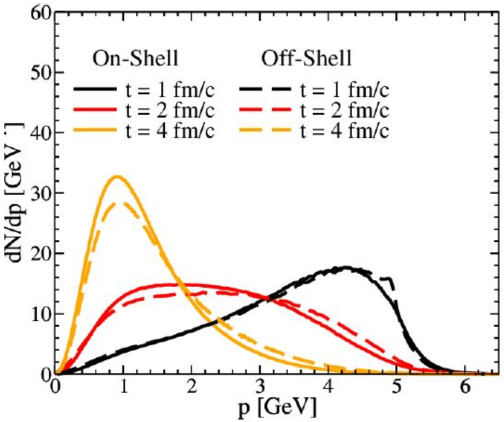
Plasma uniform $\rightarrow$ $p^0 \partial_0 f_Q = C[f_Q, f_{g,q}]$

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

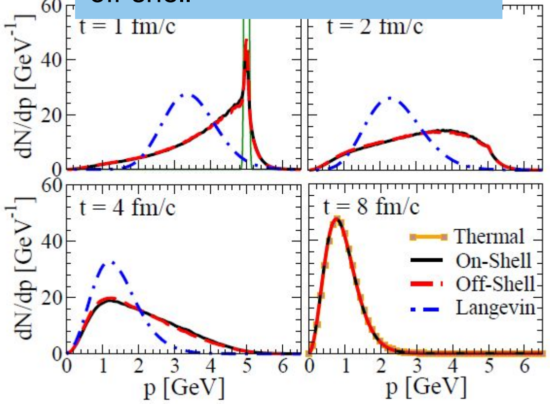
$f(t + \Delta t, p) = f(t, p) + \frac{1}{E_Q} C[f]$

$C[f_q, f_g, f_Q]$ 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