Open Charm and Bottom production in Heavy-Ion Collisions: R_{AA} and v_n- v_m correlations within event-shape selection

M.L.Sambataro[1,2] , V.Minissale[1,2], S.Plumari[1,2]and V.Greco[1,2]

[1] Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy;
[2] INFN-Laboratori Nazionali del Sud, Catania, Italy

Quasi-Particle Model (QPM) fitting lQCD

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

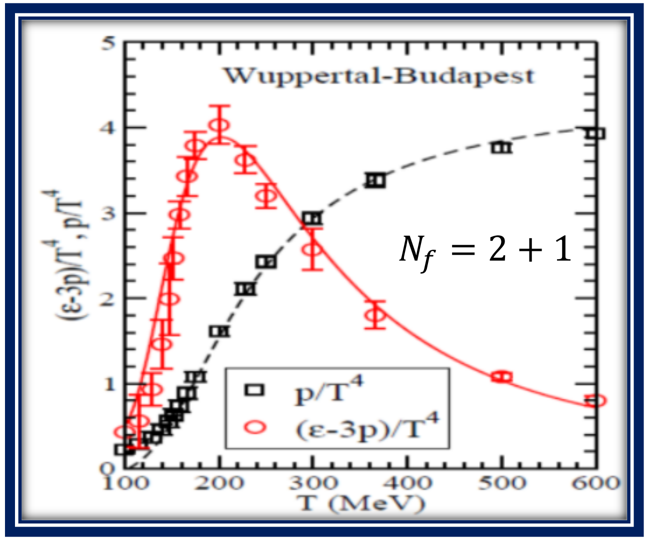
$$m_g^2(T) = \frac{2N_c}{N_c^2-1} g^2(T) T^2$$
$$m_q^2(T) = \frac{1}{N_c} g^2(T) T^2$$

Thermal masses of gluons and light quarks

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

Larger than pQCD especially as T → T_c

g(T) from a fit to ε from lQCD data
→ good reproduction of P, ε-3P
but quark susceptibilities are understimated!



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

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

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

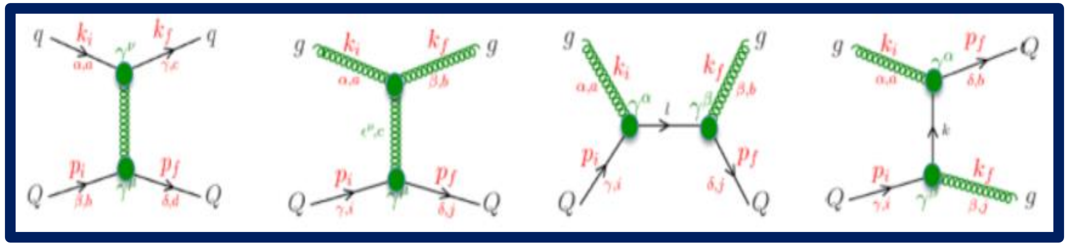
Equivalent to viscous hydro at η/s ≈ 0.1

HQ evolution

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

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

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



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

Predictions for D and B mesons: R_{AA} ,v_n and their correlations within ESE technique

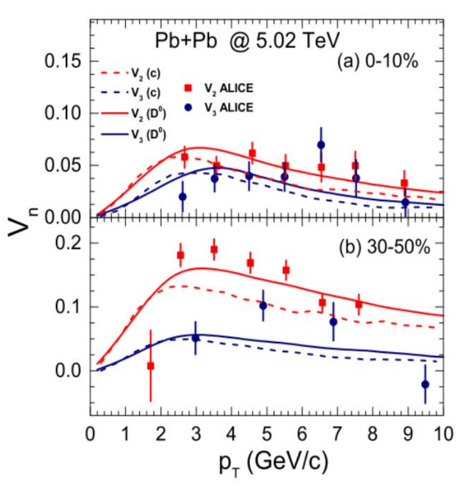
$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

$$v_2 = \langle \cos[2(\varphi - \Psi_2)]\rangle$$

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

$$v_3 = \langle \cos[3(\varphi - \Psi_3)]\rangle$$

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



We use **Monte Carlo Glauber Model** to simulate the initial conditions of partons

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

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

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

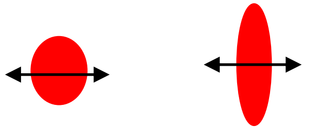
- v_2 mainly generated by the geometry of overlapping region in larger centrality collision
- v_3 mainly driven by the fluctuation of the triangularity of overlap region at all centrality

Event-Shape Engineering 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.

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

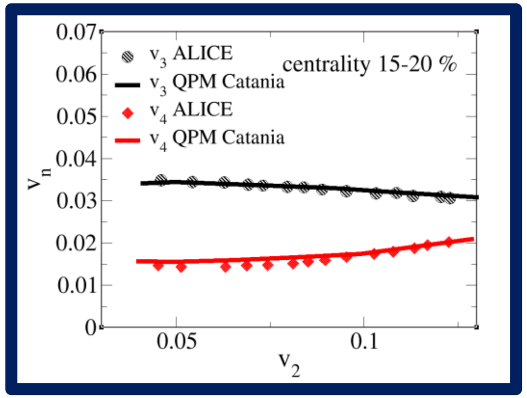
$$\vec{Q}_2 = \sum_{j=1}^{M} e^{i2\varphi_j}$$



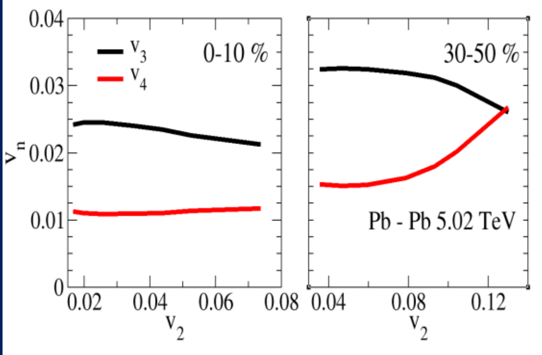
small q_2 large q_2

large q_2 → large ε_2

Charged particles



Predictions for D mesons

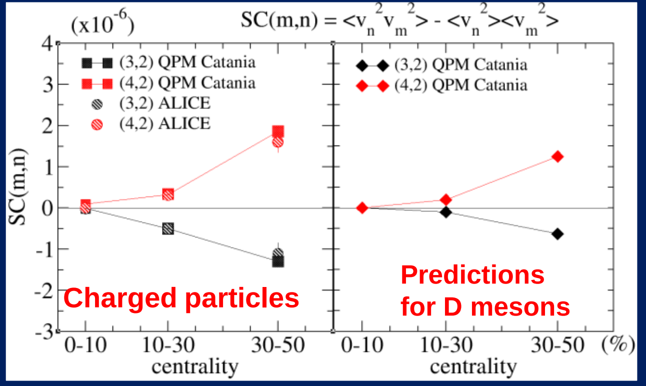


Correlations between the ε_n and ε_m present in the initial geometry $\rightarrow$ correlations between flow harmonics different orders

Similar correlation between hard and bulk particles.

- Quadratic correlation v_2 and v_4
- Anti-correlation v_2 and v_3

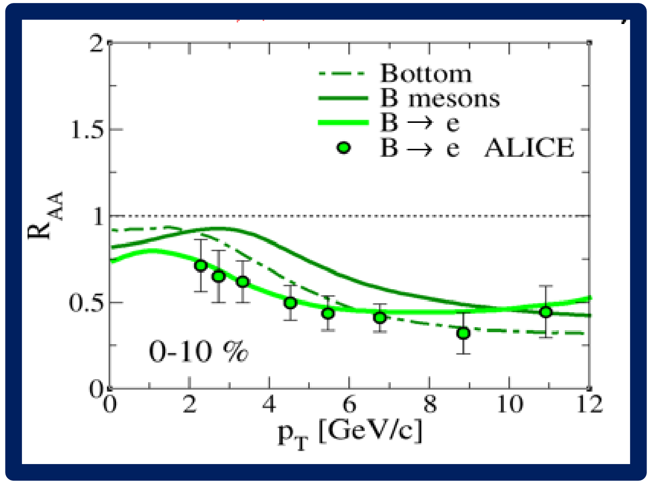
Symmetric cumulant correlator SC(m,n)



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

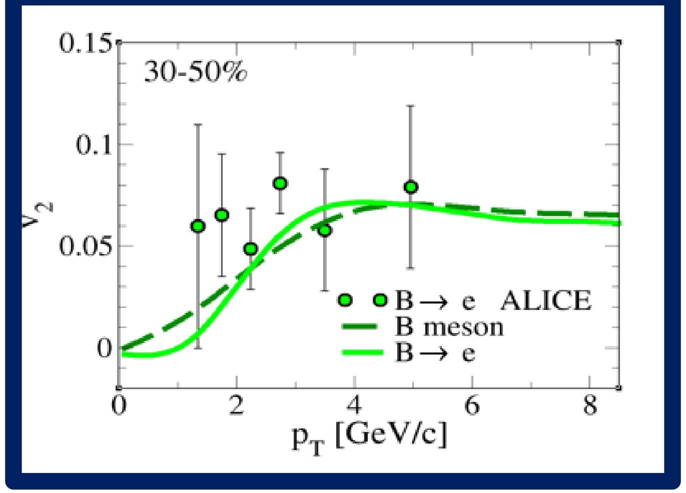
Extension to BOTTOM Dynamics

Nuclear modification factor



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

Elliptic flow

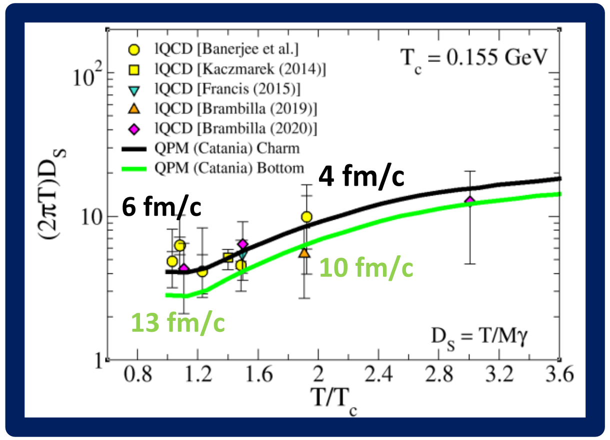


Both R_{AA} and v_2 indicate a **strong coupling for bottom quark with collectively expanding fireball**. We have a good agreement with the ALICE experimental data.

Data taken from Arnaldi HP(2020)

Spatial diffusion coefficient D_s

CHARM vs. BOTTOM



Kinetic theory:

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

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

ideally M independent ($M \rightarrow \infty$)

In QPM approach

D_s(c) is 30-40% larger than D_s(b)

$M \rightarrow \infty$ limit is not reached for charm

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

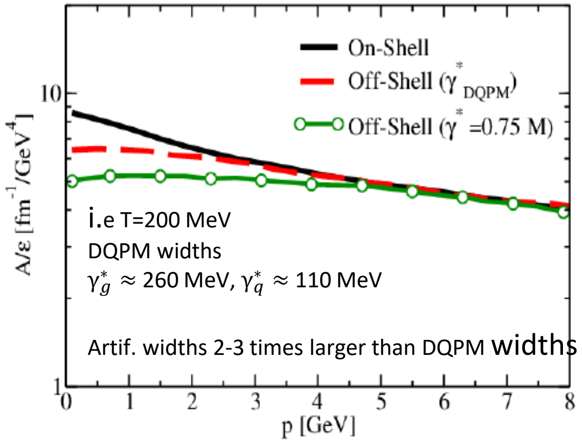
Non-perturbative effects: impact of off-shell dynamics QPM vs. DynamicalQPM

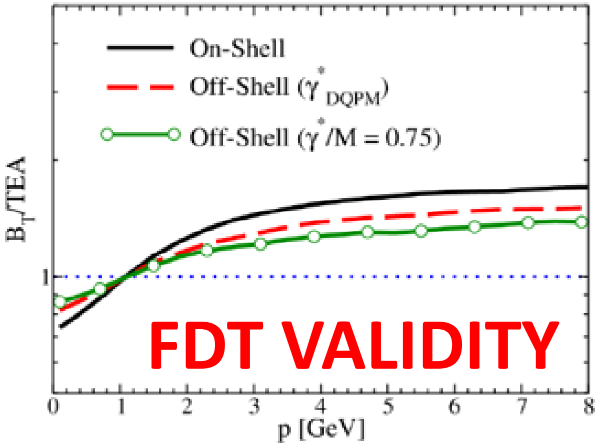
- Partons are dressed by non-perturbative spectral functions

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

- 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

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





BOX CALCULATION [T=200 MeV] FOR CHARM

Temporal evolution of charm quark distribution function

Boltzmann equation and off-shell extension

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

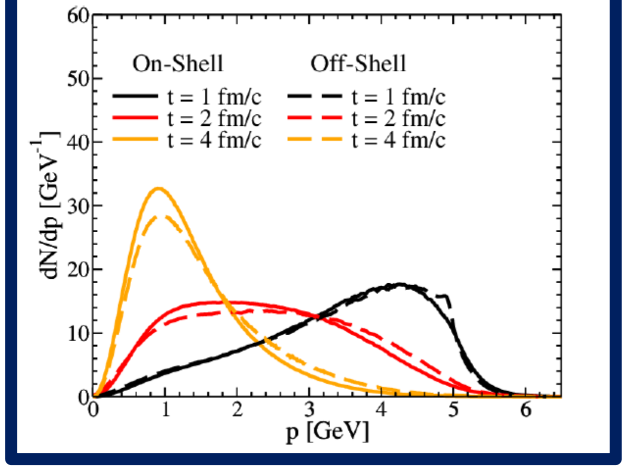
Plasma uniform → $p^0\partial_0 f_Q = C[f_Q, f_{g,q}]$

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

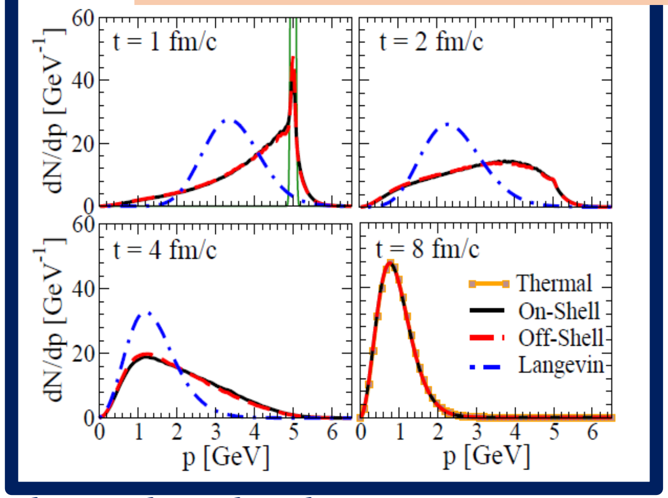
$f(t+\Delta t, p) = f(t,p) + \frac{1}{E_Q} C[f]$

$C[f_q, f_g, f_Q]$ 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!

Standard QPM vs. momentum dependent QPM

$$M_g(T,\mu_q,p) = \left(\frac{3}{2}\right)\left(\frac{g^2(T^\star/T_c(\mu_q))}{6}\left[\left(N_c+\frac{1}{2}N_f\right)T^2+\frac{N_c}{2}\sum_q\frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_g(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2}+m_{\chi g}$$

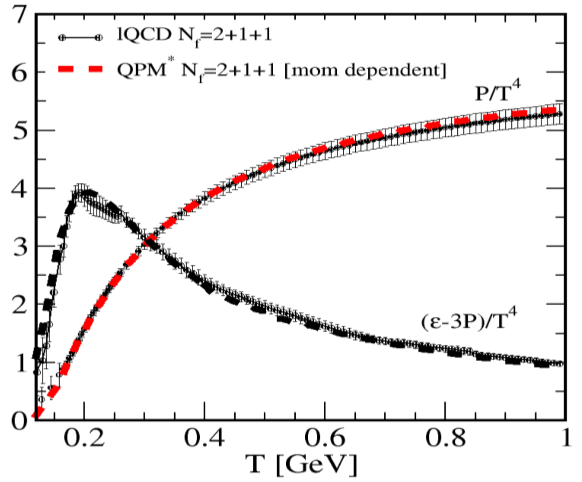
$$M_{q,\bar{q}}(T,\mu_q,p) = \left(\frac{N_c^2-1}{8N_c}g^2(T^\star/T_c(\mu_q))\left[T^2+\frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_q(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2}+m_{\chi q}$$

Momentum dependent factors

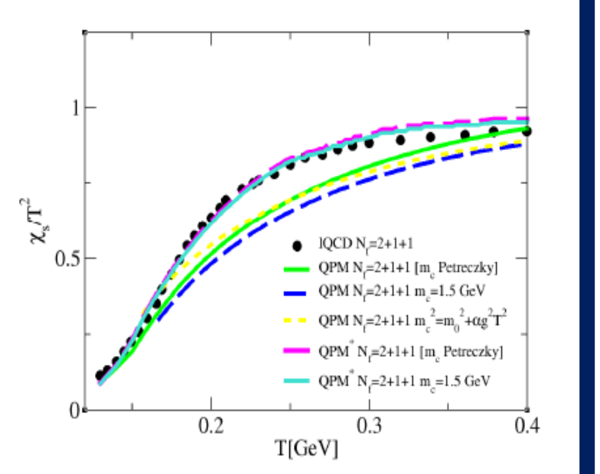
Including charm!
N_f=2+1+1
and
mom dependence

NEW

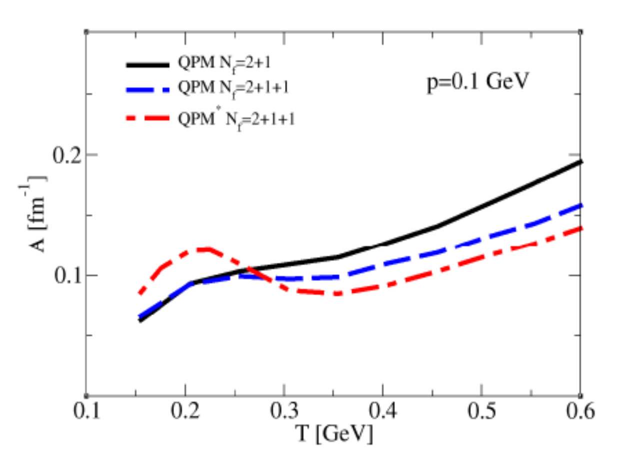
Equation of State

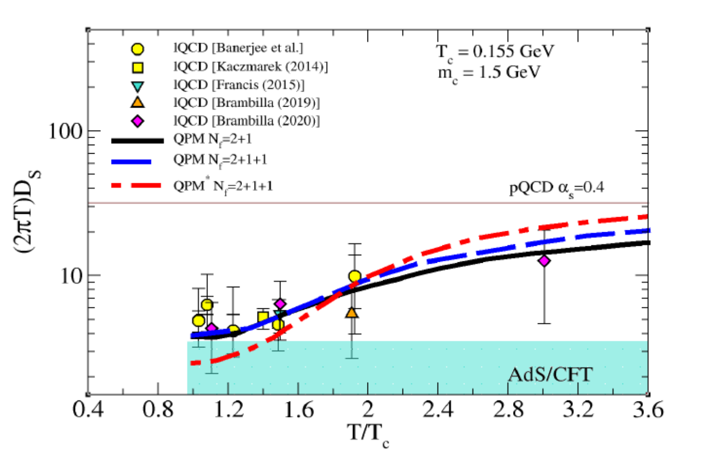


Quark susceptibilities



Drag and spatial diffusion coefficient in the extended QPM





$T/T_c < 2$ → strong non-perturbative behaviour near to T_c similar to the one achieved in strongly coupled theory as AdS/CFT.

high T region → the D_s reaches the pQCD limit quickly than the standard QPM.