Heavy Hadron Production in pp Collisions

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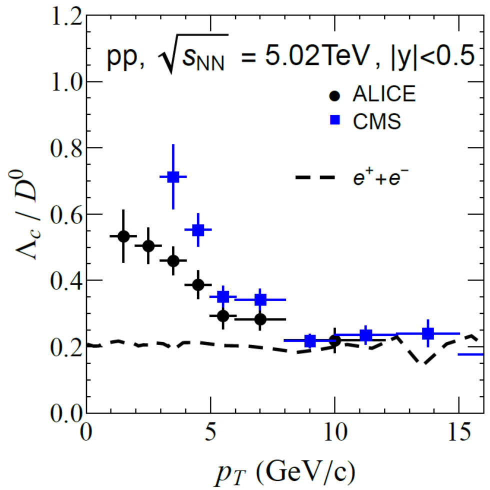
Why should we study heavy hadrons in pp collisions?

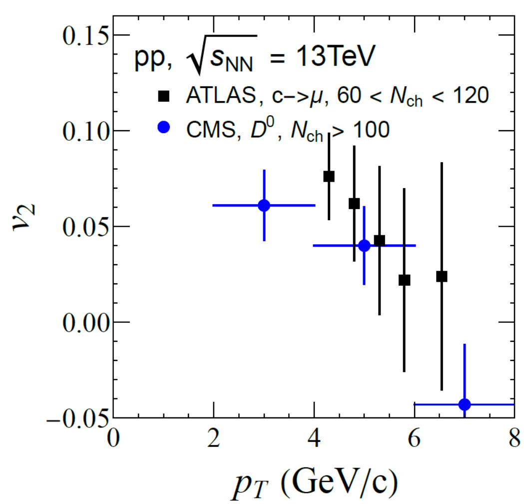
Experimental surprises:

Λ_c / D^0 ratio



are fragmentation functions not universal?

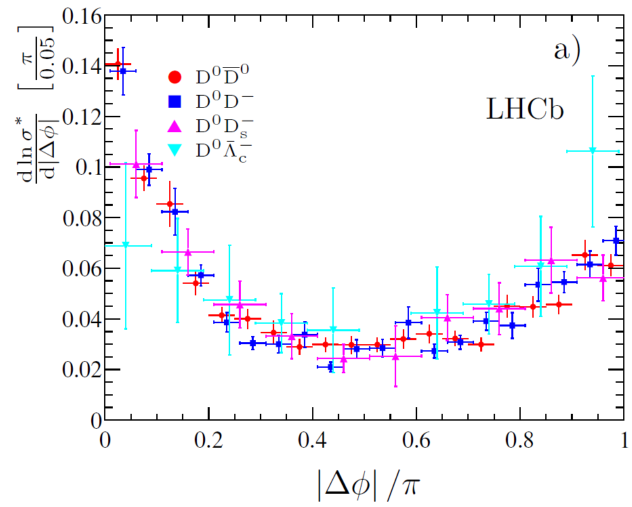
elliptic flow v_2



pQCD: v_2 =0
Where does the finite v_2 come from?

azimuthal $\Delta\varphi(p_D, p_{Dbar})$

JHEP06(2012)141

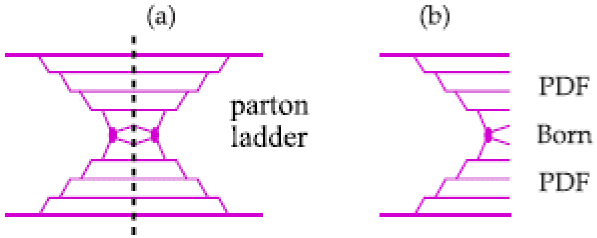


What causes this structured correlation function?

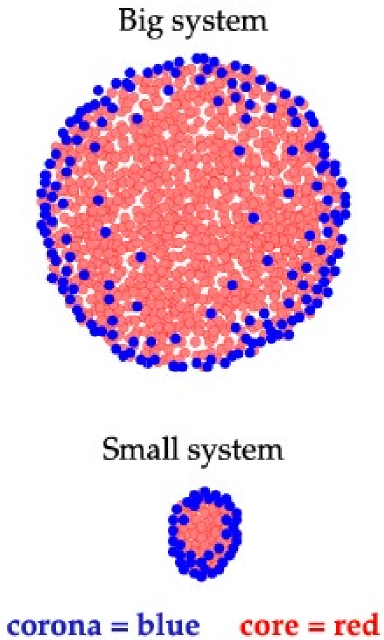
EPOS4 (→ Klaus Werner on Thursday)

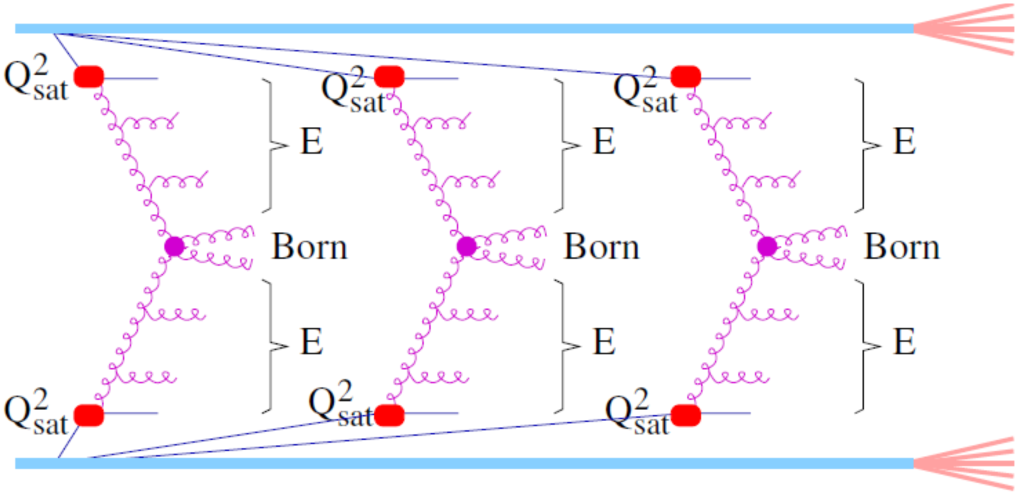
EPOS4: general purpose event generator for heavy ion collisions at RHIC and LHC

All scattering are rigorously treated in parallel
Overall energy conservation and factorisation
binary scaling
Saturation



Core (QGP) and corona contributions



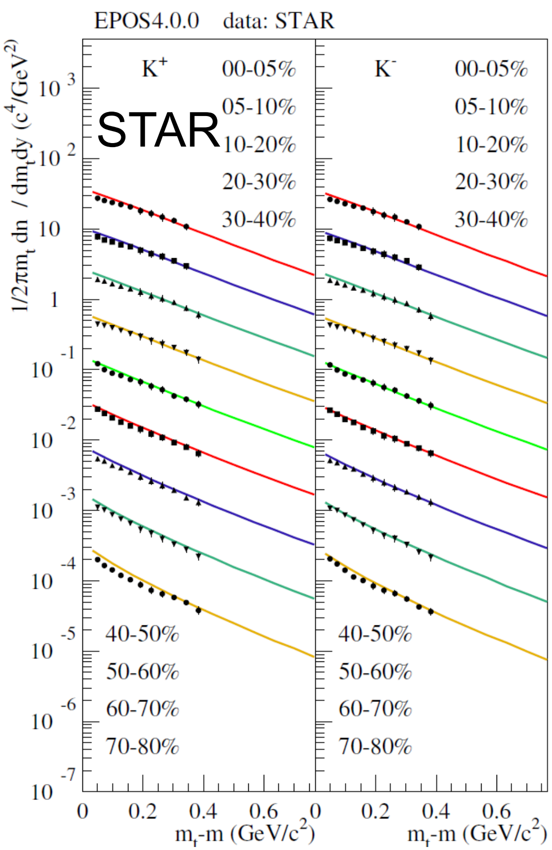


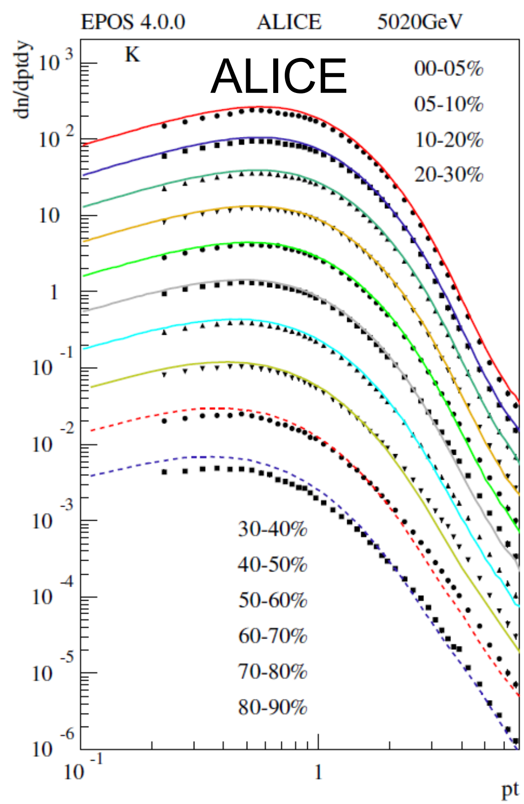
PRC 108 (2023), 064903   PRC 108 (2023), 034904, 2310.09380 [hep-ph]

EPOS4 results in light hadron sector

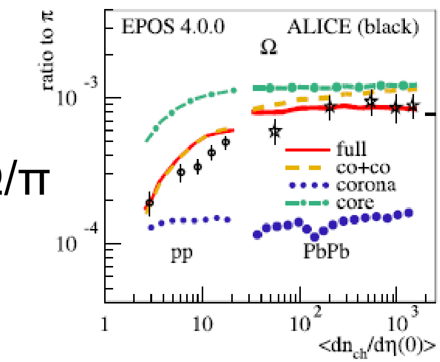
EPOS4 describes the light meson sector

Even rare baryons

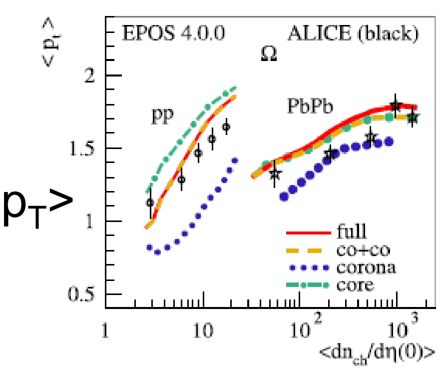




Ω/π



$<p_T>$



EPOS4HQ – extension for heavy quark physics

EPOS 4 | EPOS4HQ

heavy quarks are created at the interaction points

a QGP is created if energy density > 0.57 GeV/fm^2

EPOS 4	EPOS4HQ
No further interaction	heavy quarks interact with the QGP elastic and inelastic collisions
e^+e^- fragmentation function → hadrons	hadronization by fragmentation and coalescence (for Q/Qbar in the QGP) when the light quarks hadronize

hadronic interactions described by UrQMD

Microcanonical description of heavy quarks. We can follow each Q individually from creation through hadronization until they are part of heavy hadrons

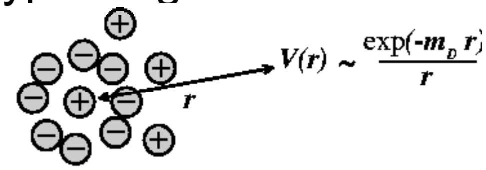
all fluctuations are kept

allows to trace back the D meson observables to the properties of Q at production

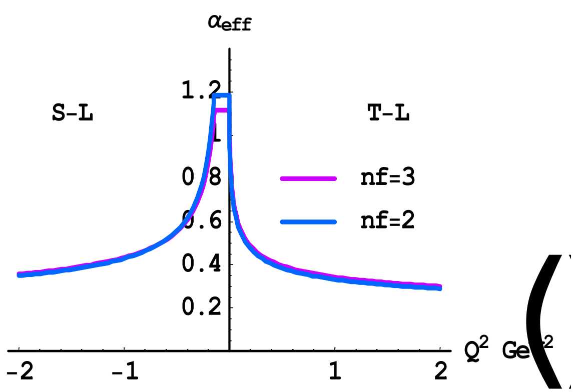
EPOS4HQ – elastic HQ-parton scattering

The interaction between HQ and q and g is described by Born type diagrams

$$\frac{d\sigma_F}{dt} = \frac{g^4}{\pi(s-M^2)^2}\left[\frac{(s-M^2)^2}{(t-\kappa m_D^2)^2} + \frac{s}{t-\kappa m_D^2} + \frac{1}{2}\right]$$



q/g is randomly chosen from a Fermi/Bose distribution with the local hydro temperature
coupling constant and infrared screening are input



Peshier NPA 888, 7
based on universality constraint of Dokshitzer

If t is small ($\sqrt{t}$<<T) : Born has to be replaced by a hard thermal loop (HTL) approach
For $\sqrt{t}$>T Born approximation is (almost) ok

(Braaten and Thoma PRD44,2625) for QED: effective propagator

$$\frac{1}{t-\kappa m_D}$$

with κ that energy loss indep. of the artificial scale t* which separates the regimes
Extension to QCD (PRC78:014904)

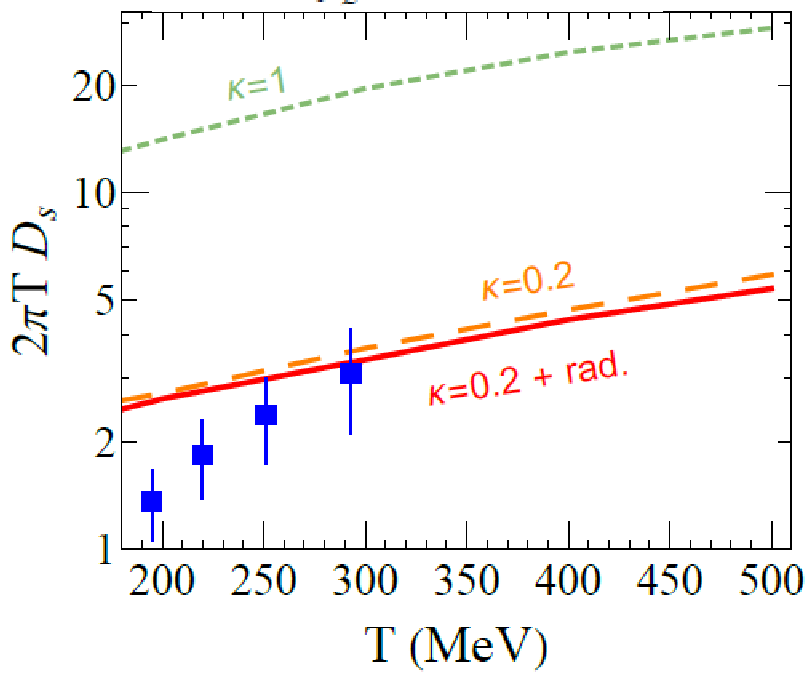
EPOS4HQ – elastic scattering

Independence of the energy loss on the intermediate scale t^* requires

$m_D \rightarrow \kappa\, m_D$ with **$\kappa \approx 0.2$**

In the calculations we include all the other channels and gluon interactions

$$D_s = \lim_{p_Q \to 0} T/(M_Q \eta_D)$$



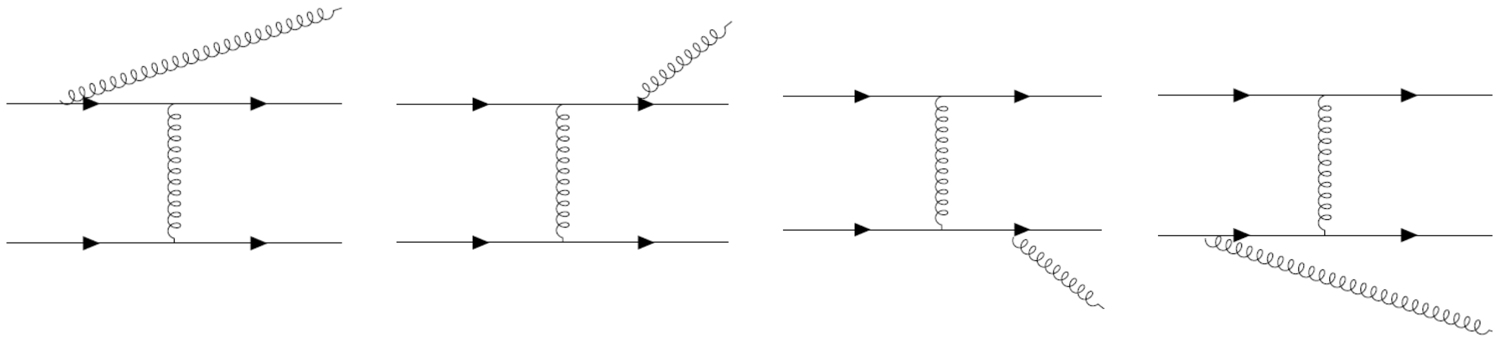
Approach can be checked against lattice calculations

Better agreement as compared to pQCD with a effective thermal mass in gluon propagator

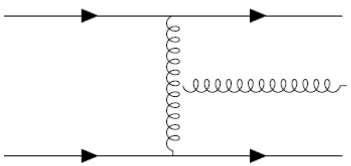
EPOS4HQ - inelastic cross section

QED like

PRD89(2014)074018



genuine QCD



At large $\sqrt{s}$ cross section factorizes

$$\frac{d^5\sigma_{\mathrm{rad}}}{dx\, d^2l_T\, d^2k_T} \approx \frac{x(1-x)\,|\mathcal{M}_{\mathrm{el}}|^2}{4(2\pi)^2(s-m_Q^2)} \underbrace{P_g}_{\text{g-emission prob.}} \underbrace{\frac{1}{\sqrt{\Delta_a}}\Theta(B^+)}_{\text{phase space}}$$

Same elastic matrix element as for elastic coll;

$$P_g(x,\vec{k}_T,\vec{\ell}_T;M) = \frac{C_A\alpha_s}{\pi^2}\frac{1-x}{x}\Bigg(\underbrace{\frac{\vec{k}_T}{\vec{k}_T^2+x^2M^2}}_{\text{from Q}} - \underbrace{\frac{\vec{k}_T-\vec{\ell}_T}{(\vec{k}_T-\vec{\ell}_T)^2+x^2M^2}}_{\text{from g}}\Bigg)^2$$

x=ω/E

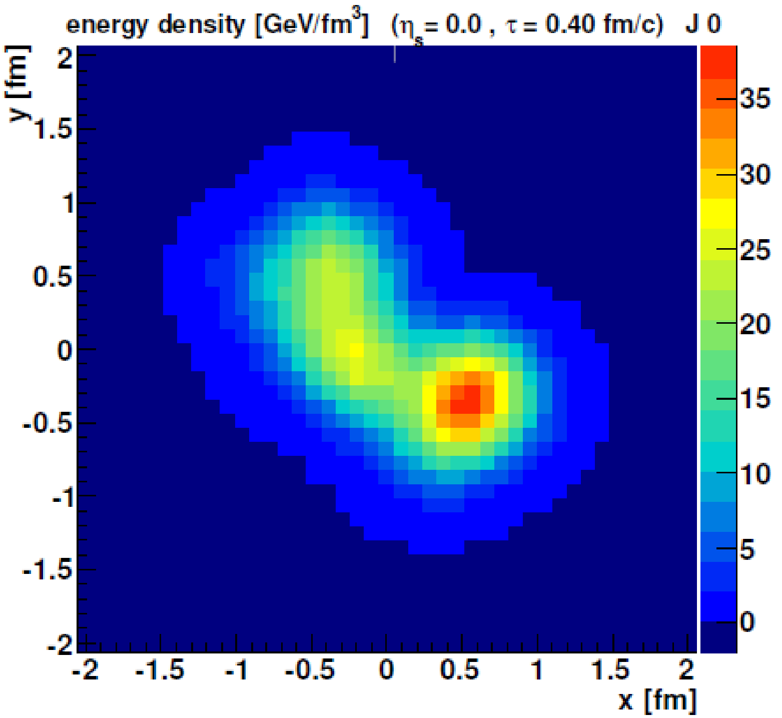
no divergencies

pp in EPOS4HQ

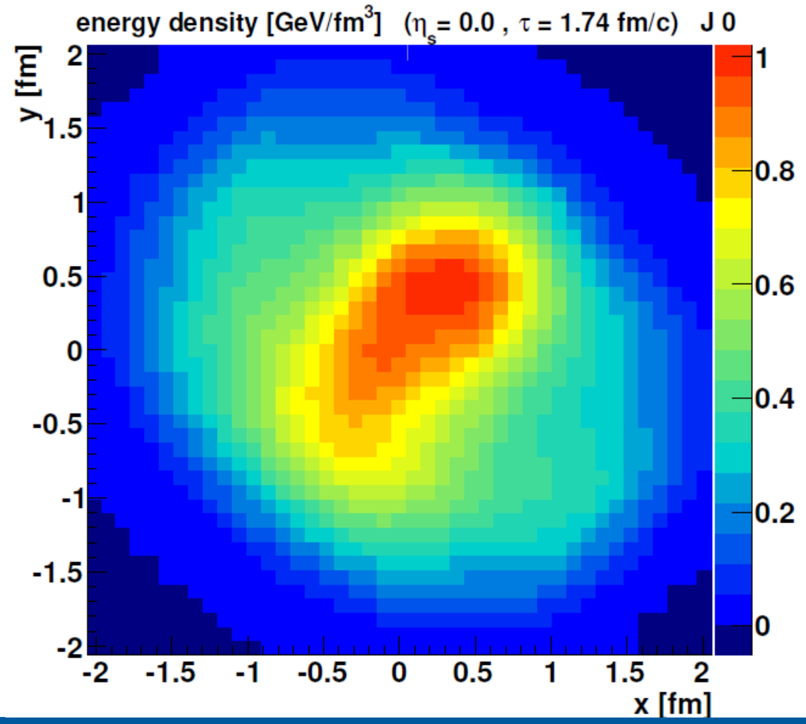
EPOS4HQ applied to pp: QGP is created if energy density > 0.57 GeV/fm^2

Energy density in the transverse plane of a typical pp event
(each event looks differently)

Initial



close to hadronization



EPOS4HQ Hadronization

Quantal density matrix approach $P_m = Tr(\rho_m \rho)$ in Wigner density formalism

Wigner density obtained by
Solution of Schrödinger eq. → rms radius → 3d harm. Osc. wf with same rms

$$\frac{dN}{d^3\mathbf{P}} = g_H \sum_{N_c} \int \prod_{i=1}^{k} \frac{d^3\mathbf{p}_i}{(2\pi)^3} f_i(\mathbf{p}_i) W_m(\mathbf{p}_1, .., \mathbf{p}_i) \times \delta^{(3)}\left(\mathbf{P} - \sum_{i=1}^{k} \mathbf{p}_i\right),$$

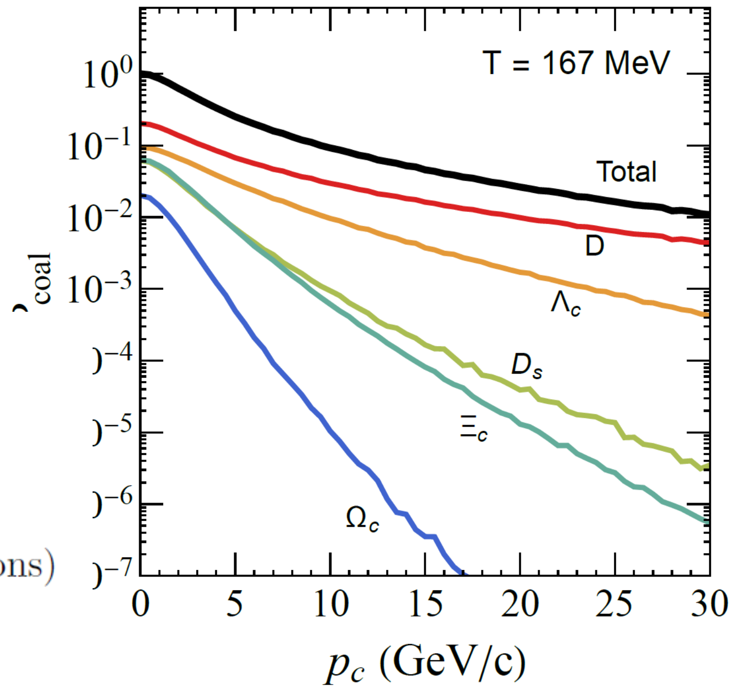
$f_1(\mathbf{p}_1) = (2\pi)^3 \delta^{(3)}(\mathbf{p}_c - \mathbf{p}_1)$

$f_i(\mathbf{p}_i)$ for $i > 1$ drawn from thermal distribution

$W_m(\mathbf{p}_1, .., \mathbf{p}_i) = (2\sqrt{\pi}\sigma_m)^3 e^{-\sigma_m^2 {p_r}^2}$

Wigner density of the heavy hadron m in momentum space

g_H degeneracy factor of color and spin. $k = 2(3)$ for mesons (baryons)



Applied when the QGP reaches $\varepsilon = 0.57$ GeV/fm^3

If not hadronized by coalescence → hadronization by fragmentation

p_T spectra for pp

Spectra at creation and before hadronization very similar

→ Little momentum loss in the QGP

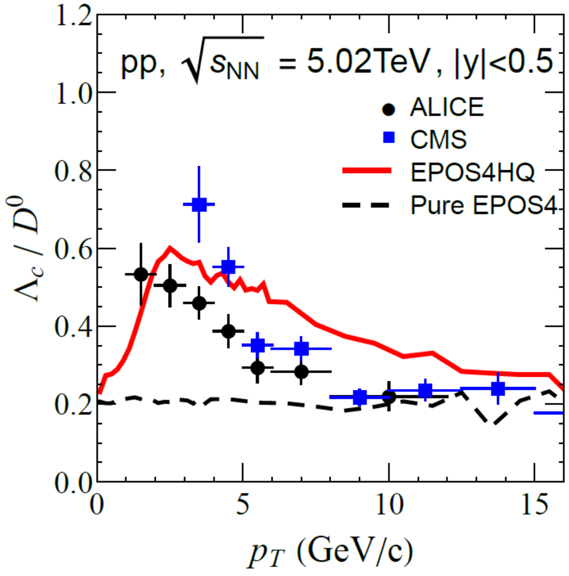
Momentum loss due to hadronization much larger

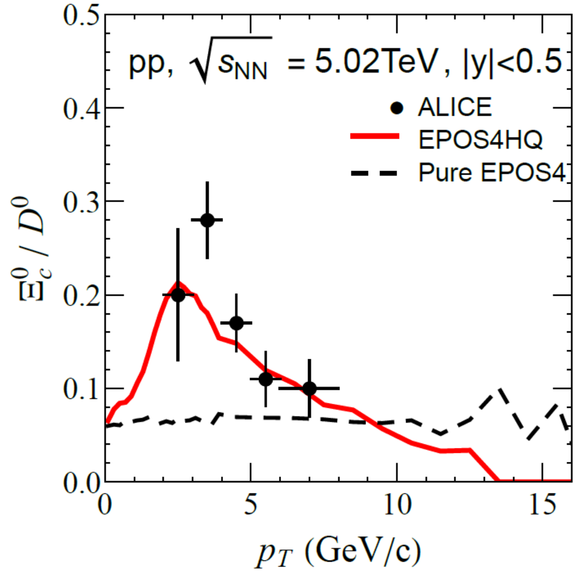
Final spectrum agrees with QCD based FONLL calculations

All measured spectra of mesons and baryons reproduced

But: Momentum spectrum not sensitive to the existence of a QGP

Yield ratios

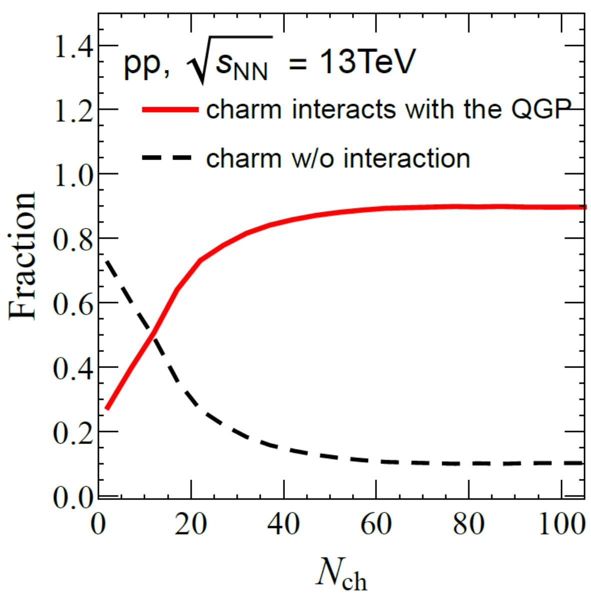




With increasing N_{ch}
more Q pass a QGP
Saturates at $N_{ch} \approx 40$

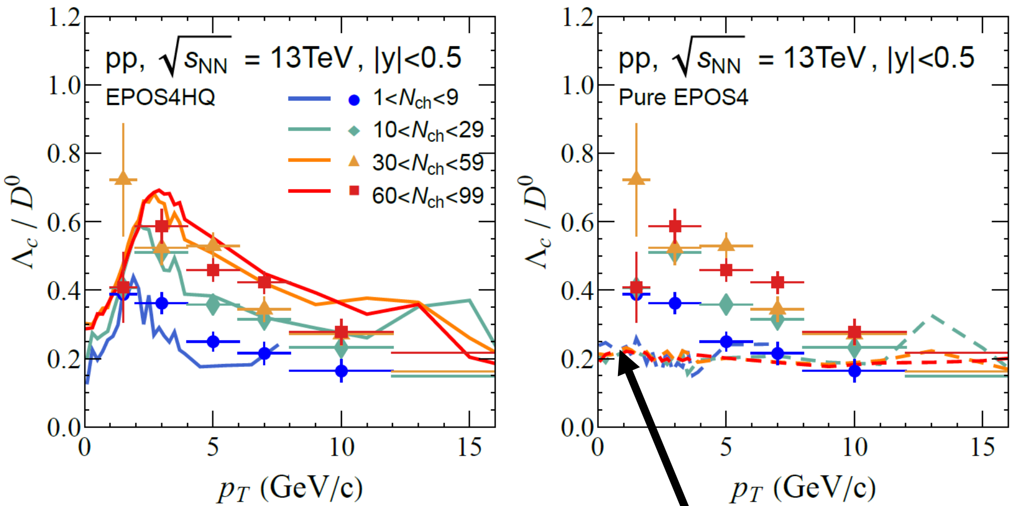
e^+e^- : ratio is constant in p_T = pure EPOS4

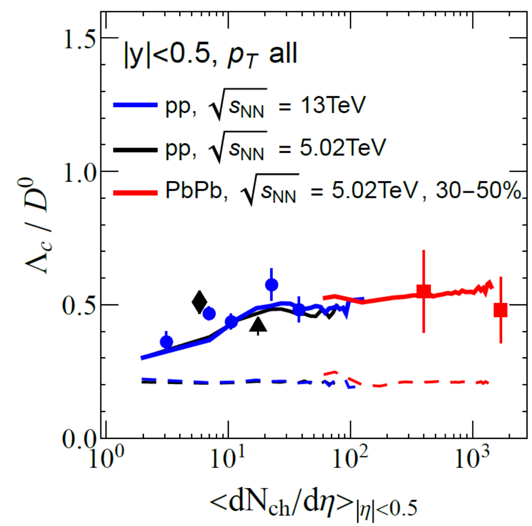
Interaction with QGP enhances ratio at low p_T
hadronization produces more baryons



Yield ratios

N_{ch} dependence of the enhancement is confirmed by experiment





Flat distribution in pure EPOS4

Also experimental enhancement saturates at at $N_{ch} \approx 40$

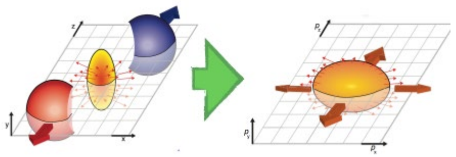
Yield ratios are a strong indication that a QGP is formed

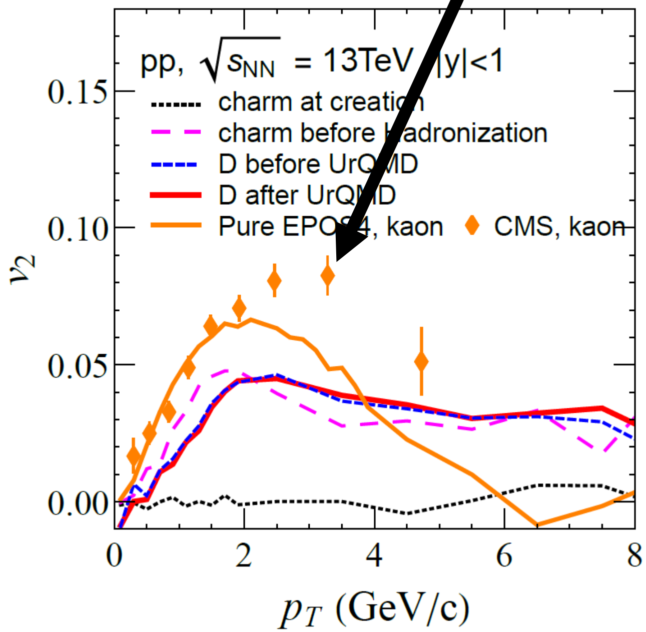
Elliptic flow v_2

$$\frac{dN}{d\phi} \propto 1 + 2v_1 cos\phi + 2v_2 cos(2\phi).....$$

Φ=azimuthal angle wrt reaction plane

Light hadrons show a finite v_2 created by fluctuations of the energy density and hydro expansion





At low p_T :

Spatial eccentricity

→ Anisotropy in azimuthal momentum space

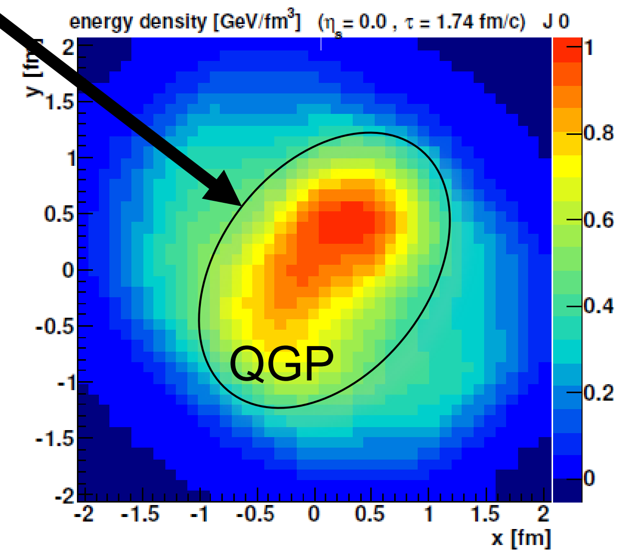
→ $v_2(p_T)$ for low p_T

At high p_T :

$v_2(p_T)$ due to path length difference

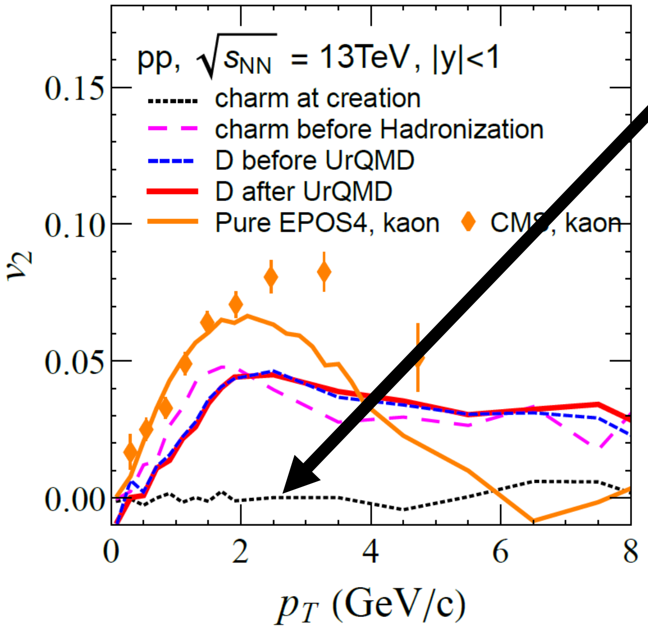
→ Different eloss in QGP)

One EPOS4 pp event



Elliptic flow v_2

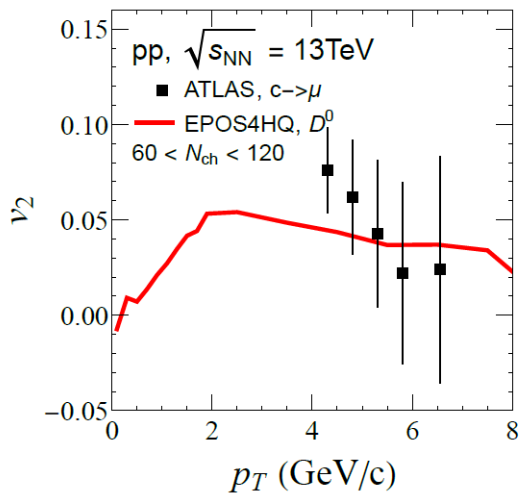
For heavy mesons: Form of $v_2(p_T)$ similar but value is smaller

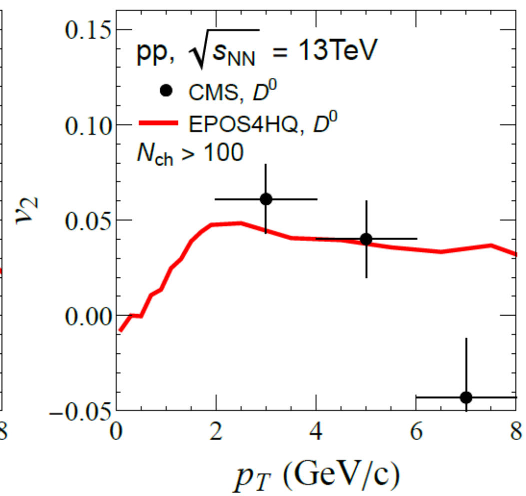


initially heavy quarks are produced in hard processes $M >> \Lambda_{QCD}$

→ no finite elliptic flow expected

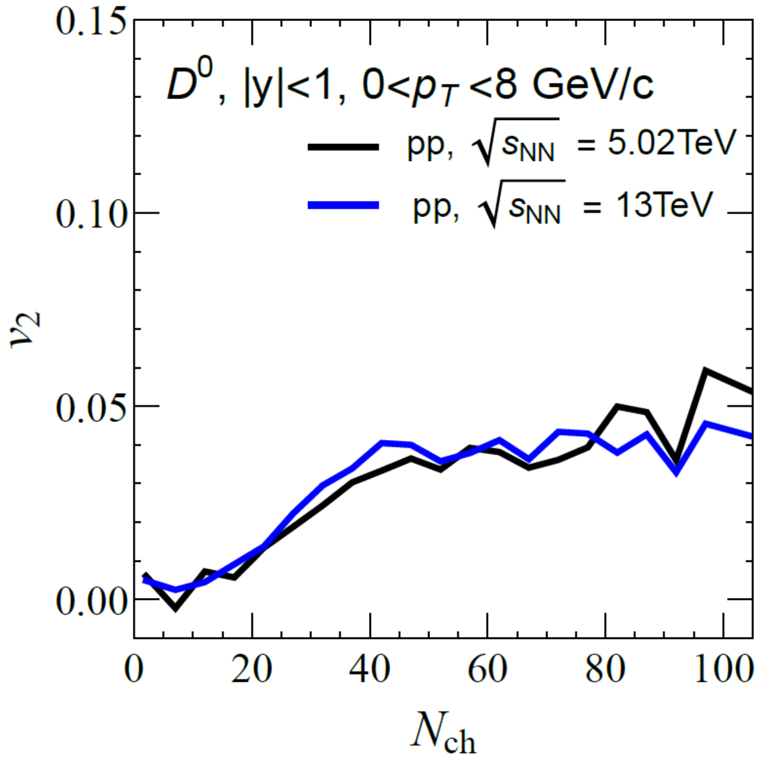
In EPOS4HQ the interaction with the QGP creates this flow even in pp.





$v_2(p_T > 5$ GeV) is up to now the only way the measure the energy loss of heavy quarks in a QGP produced in a pp collision

Elliptic flow v_2



v_2 depends on N_{ch}

saturates when all heavy quarks pass a QGP ($N_{ch} \approx 40$)

Is not beam energy dependent
But less than v_2 of light hadrons

The finite v_2 of heavy hadrons (initially =0!!) as well as its p_T dependence is another strong indication that a QGP is formed in pp collisions

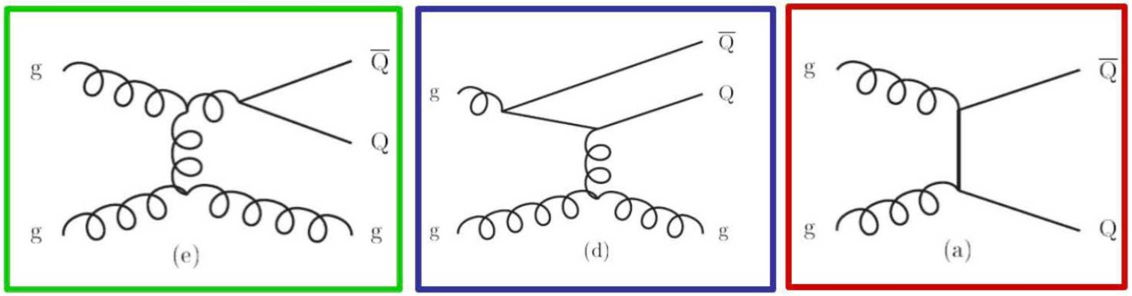
Correlations between Q and Qbar

Correlations between Q and Qbar are important

- if one wants to study/understand D Dbar correlation
- if one wants to study hidden heavy flavour mesons like J/ψ
- if one wants to understand the p_T distributions of heavy hadrons

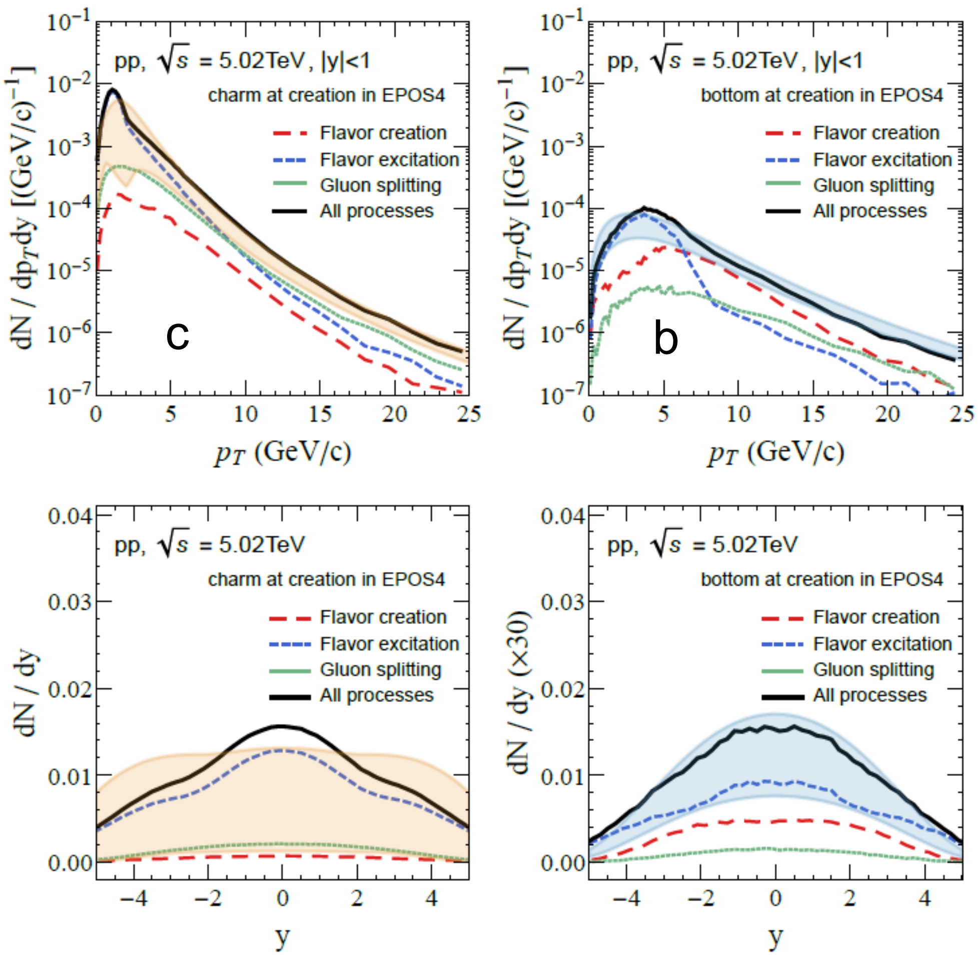
FONLL only single particle p_T spectrum
Pythia ISR and FSR can be added
EPOS4HQ separates the three different production mechanisms

gluon splitting time like	gluon excitation space like	flavour creation hard process (Born)



Correlations between Q and Qbar

p_T and y distribution depend on creation mechanism



Shaded :FONLL

For b and c quarks the contributions are different

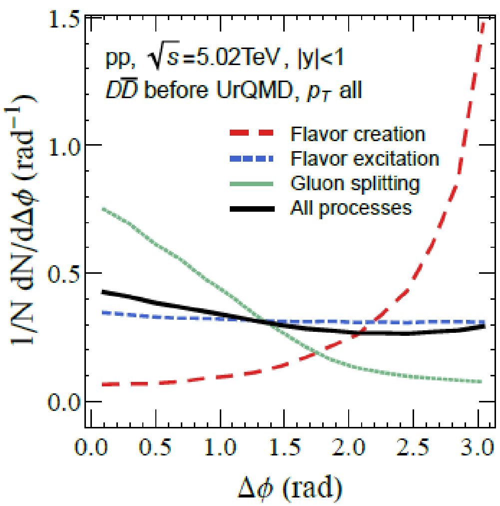
High p_T c → gluon splitting

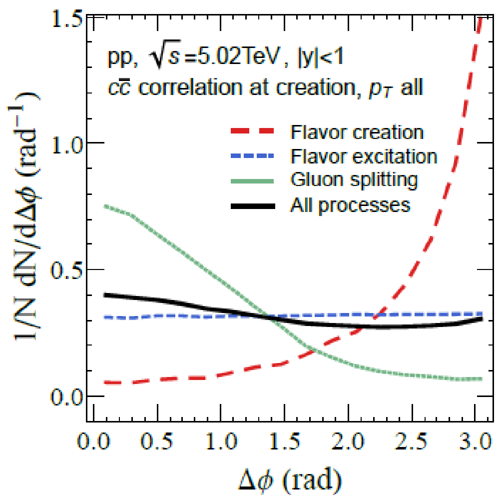
High p_T b → flavor creation (more energy avail.)

low p_T flavor excitation

Spectra (sum of all contributions) agree with FONLL

Correlations between Q and Qbar





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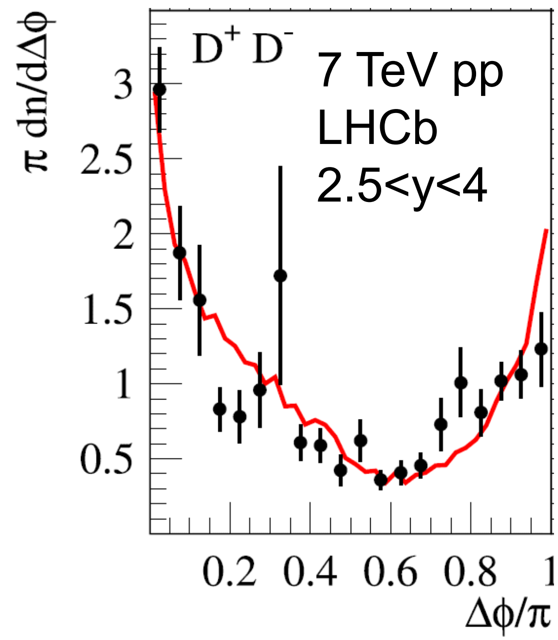


The different production mechanisms of QQbar pairs well seen in the azimuthal correlations and explain the structured experimental data

agree with experiment

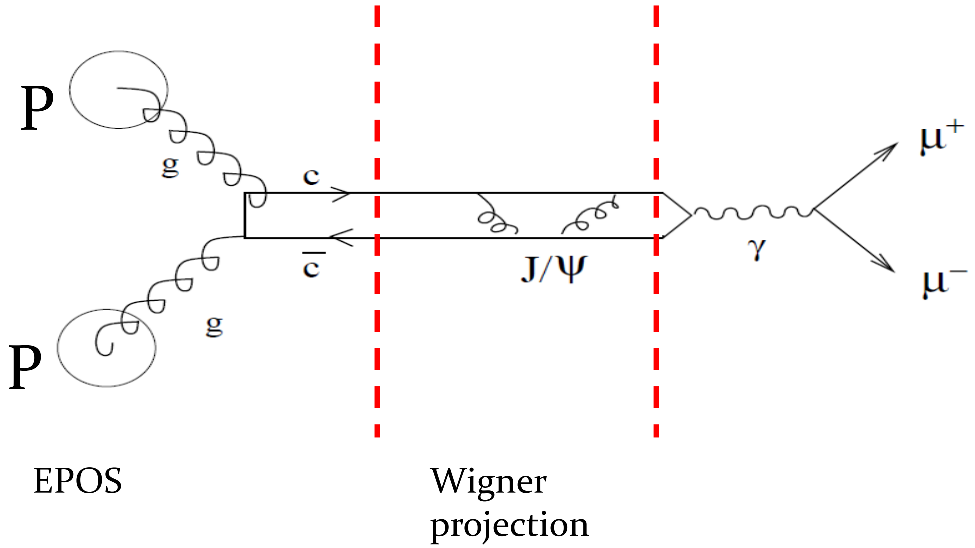
Correlations between Q and Qbar

Correlations between c and cbar show also up in quarkonium production

How to describe a bound state like a c-cbar in QCD?

It involves low momenta and needs non perturbative input ➔ assumptions.

Our approach: Wigner density formalism (as successful at lower energies)



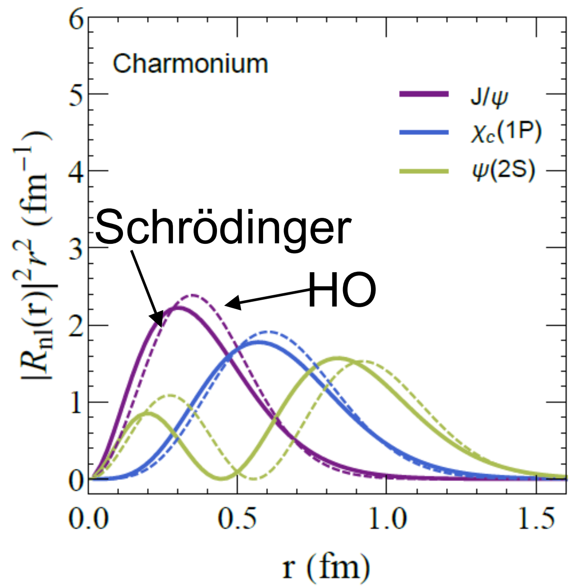
Correlations between Q and Qbar

$$\left[-\frac{1}{2\mu}\left(\frac{d^2}{dr^2}+\frac{2}{2}\frac{d}{dr}\right)+\frac{l(l+1)}{2\mu r^2}+V(r)\right]R_{nl}(r)=ER_{nl}(r)$$

$V(r) = -\alpha/|\mathbf{r}| + \sigma|\mathbf{r}|$ with $\alpha = 0.513$,$\sigma = 0.17\mathrm{GeV}^2$, $m_c = 1.5\mathrm{GeV}$, $m_b = 5.2\mathrm{GeV}$.
$\mathbf{r} = \mathbf{r}_i - \mathbf{r}_j$
$\psi(\mathbf{r}) = R_{nl}(r)Y_{l,m}(\theta,\phi)$.

Wave fct converted into a 3d harmonic oscillator wave fct with same spin and same rms radius

Wave fct
→ density matrix
→ Wigner density $W_{nl}(r,p)$



Correlations between Q and Qbar

Initial Wigner density of the Q Qbar pair at creation:

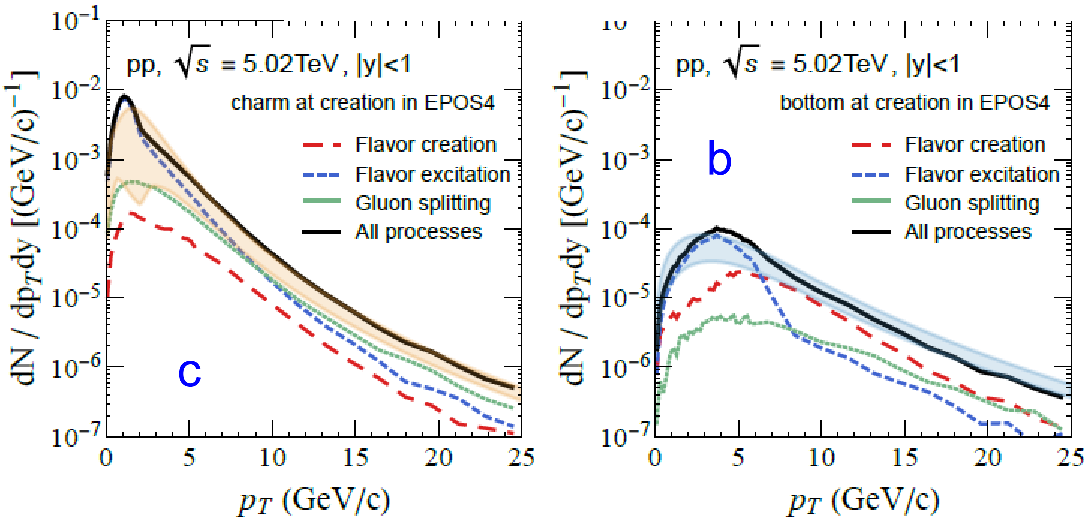
$$W^{(2)}(\mathbf{P},\mathbf{r},\mathbf{p}) \sim r^2 \exp\left(-\frac{r^2}{2\sigma^2_{Q\bar{Q}}}\right) f^{\mathrm{EPOS4}}_{Q\bar{Q}}(\mathbf{P},\mathbf{p})$$

P,p given by EPOS4

$$\sigma_{c\bar{c}} = 0.4\mathrm{fm}\ ;\ \sigma_{b\bar{b}} = 0.2\mathrm{fm}$$

Probability that quarkonium m with quantum number n,l is produced

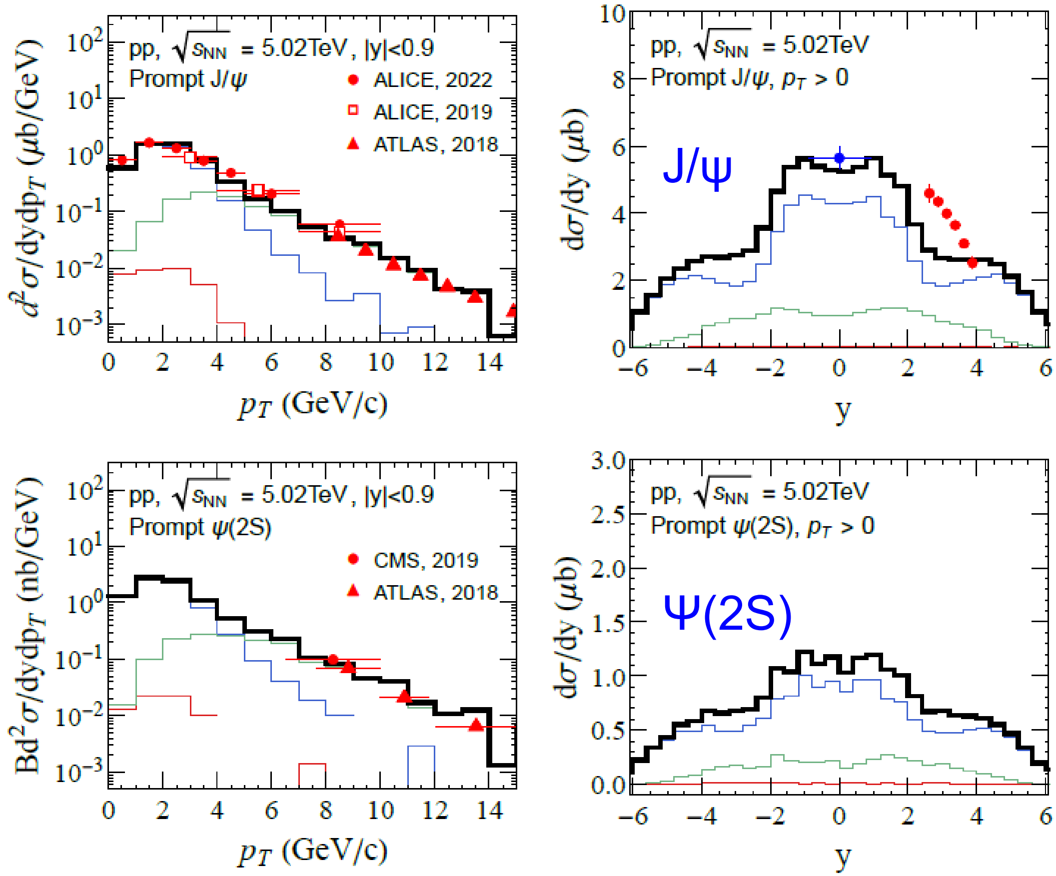
$$\frac{dP^m_{nl}}{d^3\mathbf{P_{cm}}} = \sum \int \frac{d^3r d^3p}{(2\pi)^6} W^m_{nl}(\mathbf{r},\mathbf{p}) W^{(2)}(\mathbf{P_{cm}},\mathbf{r},\mathbf{p})$$



In c-cbar and b-bbar different creation processes act differently

Correlations between Q and Qbar

Prompt J/ψ spectrum and contribution of the different Q Qbar creation processes



high p_T :
dominated by gluon splitting

flavor creation does not play a role

low p_T :
Dominated by flavor excitation

Without understanding the correlations one cannot understand J/ψ production

Conclusion

Q Qbar physics added to EPOS4 ($\varepsilon > \varepsilon_0$ = 0.57 GeV/fm^3 → QGP)

if applied to pp and assuming that

Qqbar interact with QGP with elastic and inelastic collisions

Q and Qbar in the QGP can hadronize by coalescence (density matrix)

v_2 well reproduced (interaction of Q with the QGP)

meson/baryon ratio well reproduced (hadronization of c cbar by coalescence)

p_T spectra and c cbar correlations little affected by QCP

It seems that pp collisions are by far not elementary but complex many body reactions

Three production mechanisms identified (which explain the exp data)

create different correlations between Q and Qbar

→ p_T spectra of heavy mesons is superposition of the three

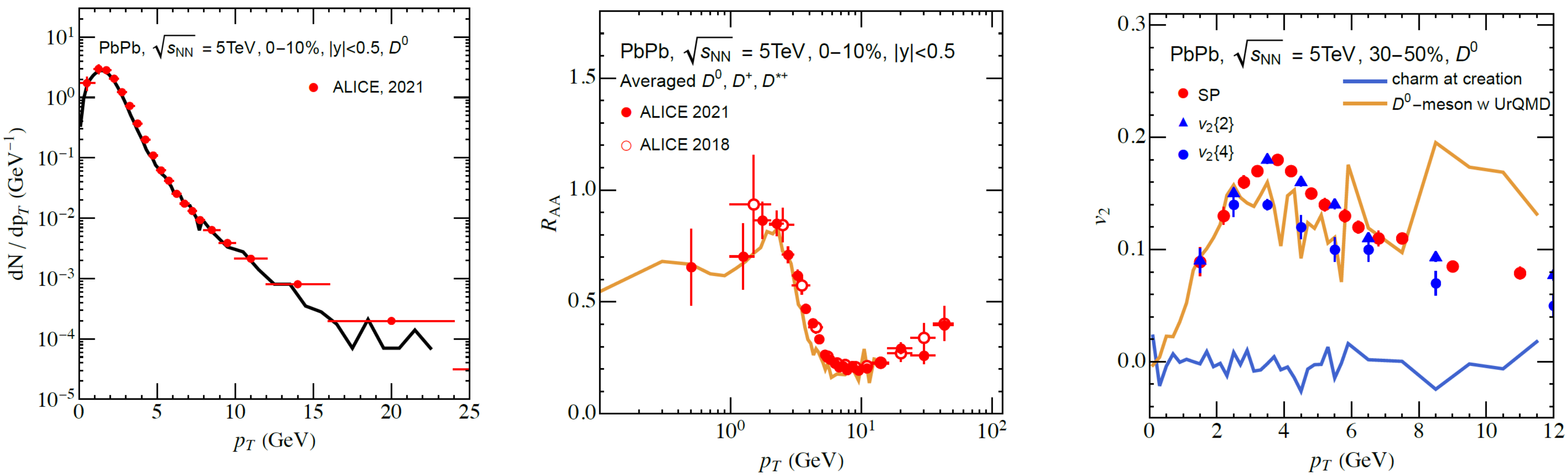
J/ψ production (described by density matrix approach)

→ p_T spectra not understandable without these correlations

pp: perspective to study different aspects of QGP/QCD in detail

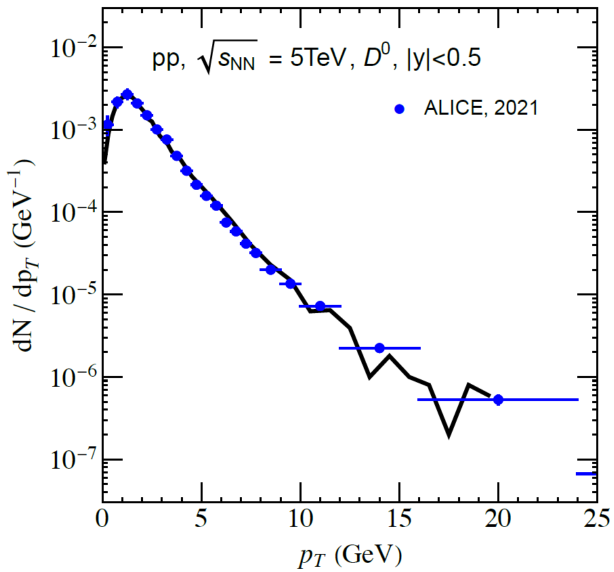
HQ interactions with QGP verified by D meson results

D mesons test the energy loss and v_2 of heavy quarks in a QGP
energy loss tests the initial phase
v_2 the late stage of the expansion
Two mechanisms : collisional energy loss: PRC78 (2008) 014904
radiative energy loss: PRD89 (2014) 074018

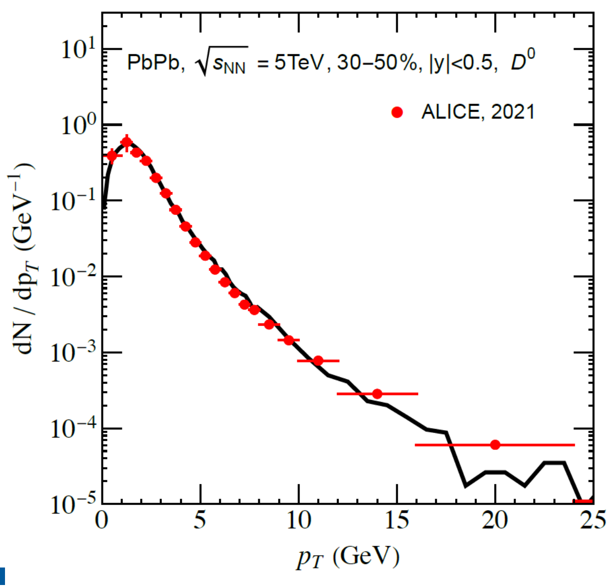


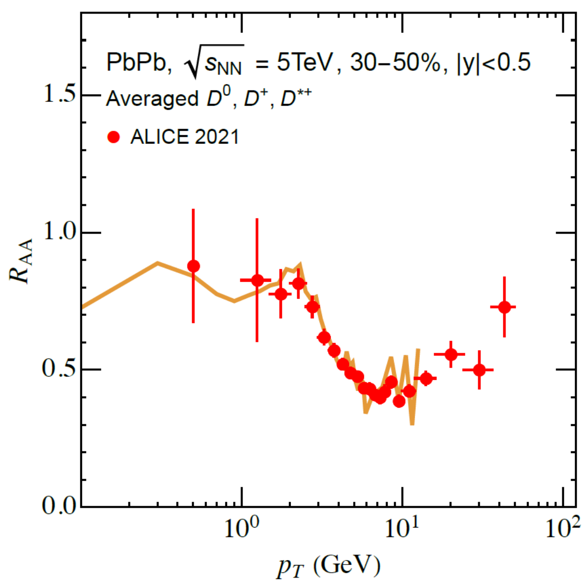
EPOS4HQ reproduces dN/dp_T, R_{AA} and v_2 quite well
→ Heavy quark dynamics in QGP medium under control

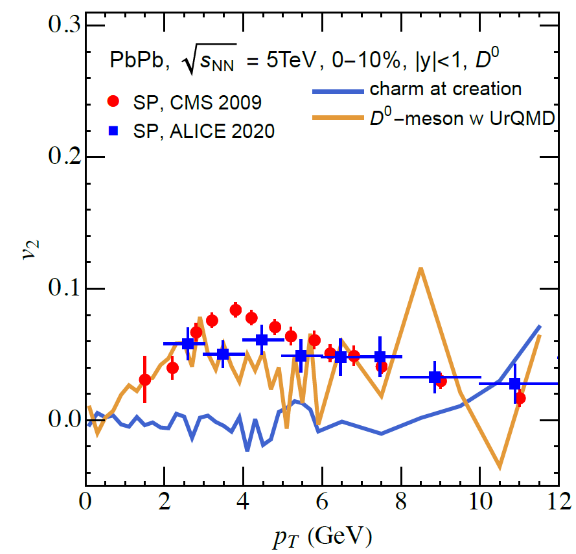
Open heavy flavor results in pp and AA from EPOS4



Energy loss of Q in medium can be controlled by comparing open Heavy flavour results with experiment







J/ψ creation in heavy ion collisions

$\Gamma^{\Phi}(t)$ expressed in Wigner and classical phase space density:

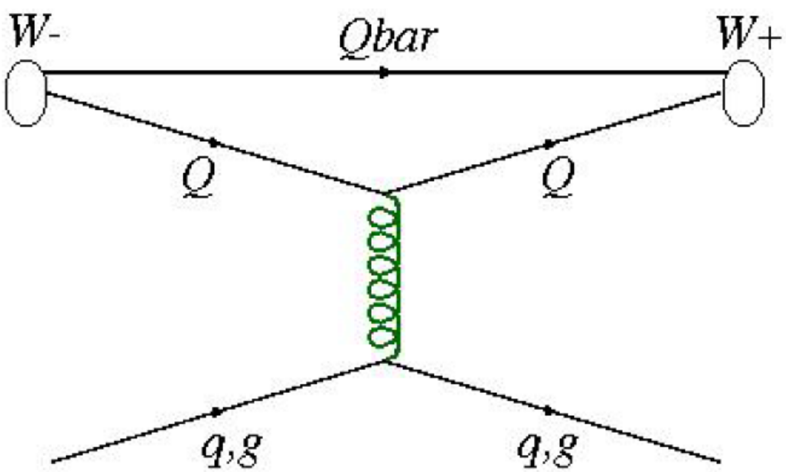
$$\Gamma^{\Phi}(t) = \frac{dP^{\Phi}(t)}{dt} = \frac{d}{dt}Tr[\rho^{\Phi},\rho_N(t)] \approx \frac{d}{dt}\prod \frac{d^3r_i d^3p_i}{(2\pi)^{3N}} W^{\Phi}(\mathbf{r},\mathbf{p})W^{c}(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N})$$

If the collisions are point like in time and if $W^{\Phi}(\mathbf{r_1},\mathbf{r_2},\mathbf{p_1},\mathbf{p_2})$ is time independent

(1,2 are charm quark, n=number of collision of i and j, $t_{ij}(n)$=time of n-th collision of ij) :

$$\Gamma^{\Phi}(t) = \sum_n \sum_{i=1,2} \sum_{j\geq 3} \delta(t-t_{ij}(n)) \prod_N \frac{d^3r_i d^3p_i}{(2\pi)^{3N}} W^{\Phi}(\mathbf{r},\mathbf{p})[\underbrace{W^{c}(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N},t+\epsilon)}_{W^+} - \underbrace{W^{c}(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N},t-\epsilon)}_{W^-}]$$

t-ε

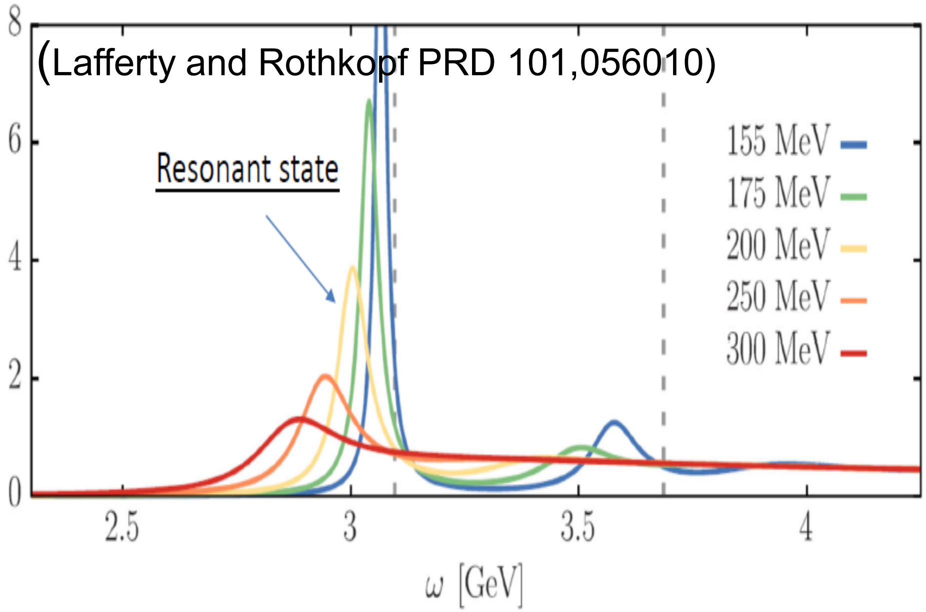


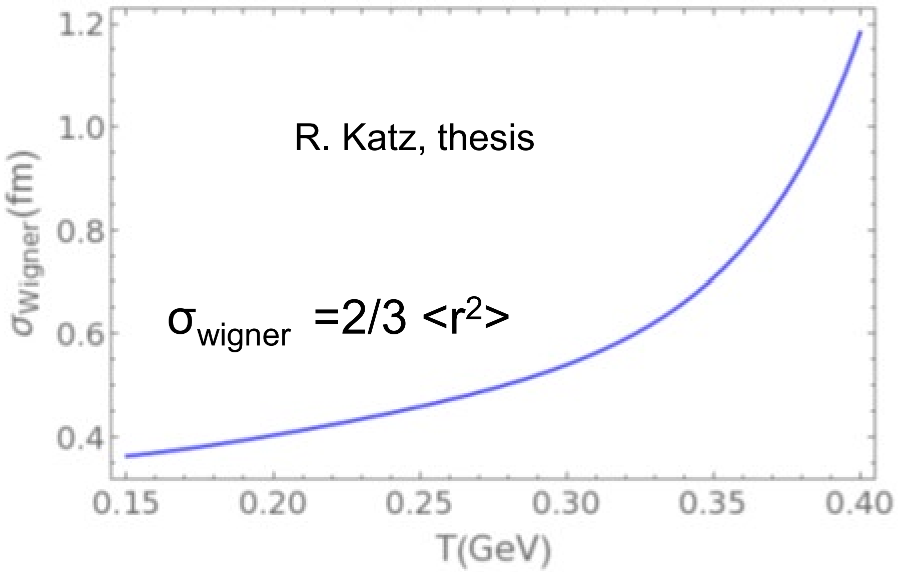
t+ε

QGP parton

J/ψ creation in heavy ion collisions

Lattice calc: $W^{\Phi}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{p}_1, \mathbf{p}_2)$ depends on the temperature and hence on time





This creates an additional rate, called local rate

$$\Gamma_{loc} = (2\pi\hbar)^3 \int d^3r d^3p \, W_{Q\bar{Q}}(\mathbf{r}, \mathbf{p}, t) \dot{W}_{\Phi}(\mathbf{r}, \mathbf{p}, T(t)).$$

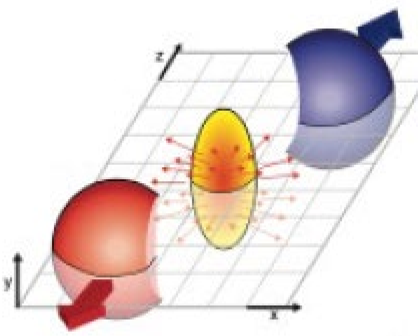
Final multiplicity of J/ in heavy-ion coll with a dissociation temperature

$$P(t) = P^{prim}(t_{init}) + \int_{t_{init}}^{t} [\Gamma_{coll}(t') + \Gamma_{loc}(t')] dt' \quad \rightarrow \quad P(t \rightarrow \infty)$$ = asympt. multiplicity

Influence of the Corona

EPOS 2 show two classes of particles of initially produced particles:

- Core particles which become part of QGP
- Corona particles from the surface of the interaction zone
  (energy density too low, no collision after production → like pp)
  importent for high pt and for v2



Confirmed by centrality dependence of multiplicity

For elementary particles it is easy to define corona and core particle (2306.10277)

For J/ψ mesons we use as working description:

Corona J/ψ are those where none of its constituents suffers from a momentum change of $q > q_{thres}$. Larger q would destroy a J/ψ.

Our approach and open quantum systems

Von Neuman eq.

$$\partial\rho_N/\partial t = -\frac{i}{\hbar}[H,\rho_N] \qquad H = H_{1,2} + H_{N-2} + U_{1,2} \qquad U_{1,2} = \Sigma_j V_{1,j} + \Sigma_j V_{2,j}$$

Prob. to find quarkonium $P^\Phi(t) = \mathrm{Tr}[\rho^\Phi \rho_N(t)]$ with $[\rho^\Phi, H_{1,2}] = 0 \quad [\rho^\Phi, H_{N-2}] = 0$

Quarkonium rate: $$\frac{dP^\Phi(t)}{dt} = \Gamma^\Phi(t) = \frac{-i}{\hbar} Tr[\rho^\Phi[U_{1,2},\rho_N(t)]]$$

$$\partial\rho_N(t)/\partial t = -\frac{i}{\hbar}\Sigma_j[K_j,\rho_N(t)] - \frac{i}{\hbar}\Sigma_{k>j}[V_{jk},\rho_N(t)].$$

Interaction: coll. heavy quarks – partons: $$-\frac{i}{\hbar}\Sigma_{k>j}[V_{jk},\rho_N(t)] \equiv \langle \Sigma_{k>j}\Sigma_n \delta(t - t_{jk}(n)) \cdot (W_N^c(\{\mathbf{r}\},\{\mathbf{p}\},t+\epsilon) - W_N^c(\{\mathbf{r}\},\{\mathbf{p}\},t-\epsilon))\rangle.$$

yields

$$\frac{dP^\Phi(t)}{dt} = \Gamma^\Phi(t) = h^3 \frac{d}{dt}\int \prod_j^N d^3r_j d^3p_j W_{12}^\Phi W_N^c(t) = h^3 \int \prod_i^N d^3\mathbf{r}_j d^3\mathbf{p}_j \; W_{12}^\Phi \frac{\partial}{\partial t} W_N^c(t)$$

Lindblad eq. (open quantum systems) in the quantal Brownian motion regime

$$\frac{d}{dt}\rho(t) = -i\left[\frac{p^2}{M} + \Delta H, \rho\right] + \sum_n \int \frac{d^3k}{(2\pi)^3}\left[C_n(\vec{k})\rho C_n^\dagger(\vec{k}) - \frac{1}{2}\left\{C_n^\dagger(\vec{k})C_n(\vec{k}),\rho\right\}\right]$$

Miura, Akamatsu , 2205.15551

Wigner Density Formalism

c-cbar interaction depends on relative p and r only, → plane wave of CM

Starting point: Wave function (w.f.) of the relative motion of state i: $|\Phi_i>$

w.f. → density matrix $|\Phi_i><\Phi_i|$

Wigner density of $|\Phi_i>$: $\Phi_i^W(\mathbf{r},\mathbf{p}) = \int d^3y e^{i\mathbf{p}\cdot\mathbf{y}} < \mathbf{r} - \frac{1}{2}\mathbf{y}|\Phi_i><\Phi_i|\mathbf{r} + \frac{1}{2}\mathbf{y} > .$

(close to classical phase space density)

$$\mathrm{R} = \frac{\mathrm{r}_1 + \mathrm{r}_2}{2}, \quad \mathrm{r} = \mathrm{r}_1 - \mathrm{r}_2,$$

$$\mathrm{P} = \mathrm{p}_1 + \mathrm{p}_2, \quad \mathrm{p} = \frac{\mathrm{p}_1 - \mathrm{p}_2}{2}.$$

$$n_i(\mathbf{R},\mathbf{P}) = \sum_{\text{all } c\bar{c} \text{ pairs}} \int \frac{d^3r d^3p}{((2\pi)^3} \Phi_i^W(\mathbf{r},\mathbf{p}) \prod_{\text{all other particles}} \int \frac{d^3r_j d^3p_j}{(2\pi)^{3(N-2)}} \rho_N^W(\mathbf{r_1},\mathbf{p_1}....\mathbf{r_N},\mathbf{p_N})$$

$$\Rightarrow \quad \frac{dn_i}{d^3P} = \int \frac{d^3R}{(2\pi)^3} n_i(\mathbf{R},\mathbf{P})$$

The results are obtained using a relativ. formulation

pp: In momentum space given by tuned PYTHIA

In coordinate space $\sim r^2 \exp\left(-\frac{r^2}{2\delta^2}\right)$ $\quad \delta^2 = \langle r^2 \rangle /3 = 4/(3m_c^2)$