

# Heavy Hadron Production in pp Collisions

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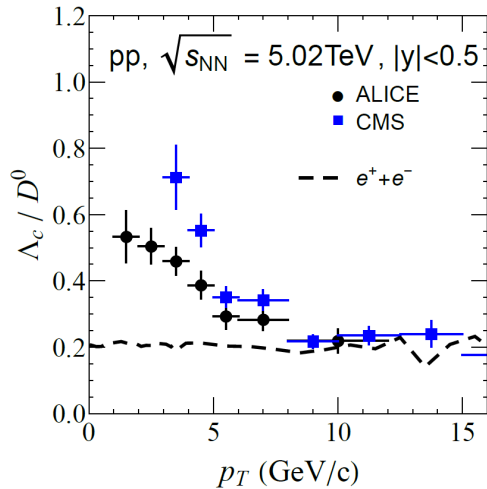
QNP2024 - The 10th International Conference on Quarks and Nuclear Physics

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# Why should we study heavy hadrons in pp collisions?

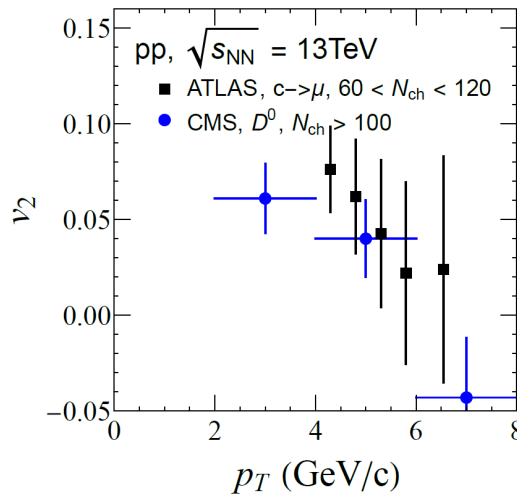
Experimental surprises:

$\Lambda_c / D^0$  ratio



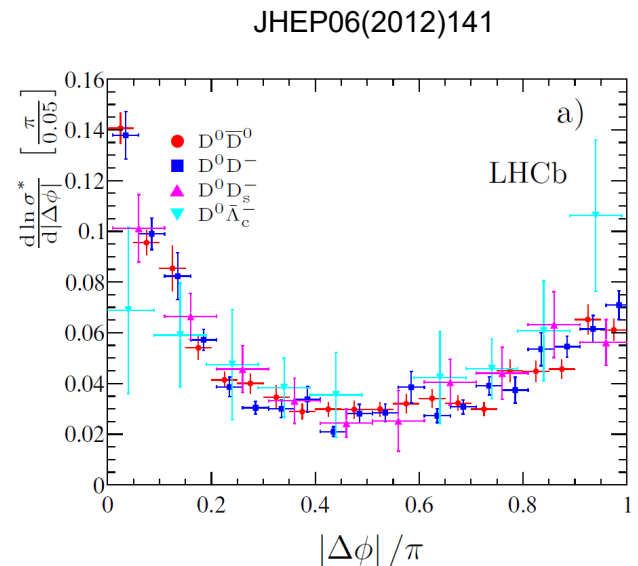
are fragmentation functions not universal?

elliptic flow  $v_2$



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

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

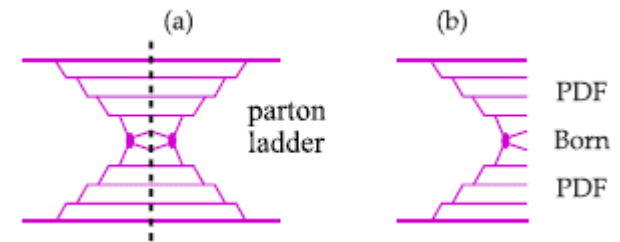


What causes this structured correlation function?

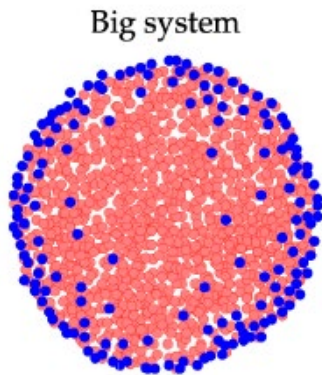
# EPOS4 (→ see literature)

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

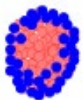
All scattering are rigorously treated in **parallel**  
Overall **energy conservation** and factorisation  
**binary scaling**  
**Saturation**



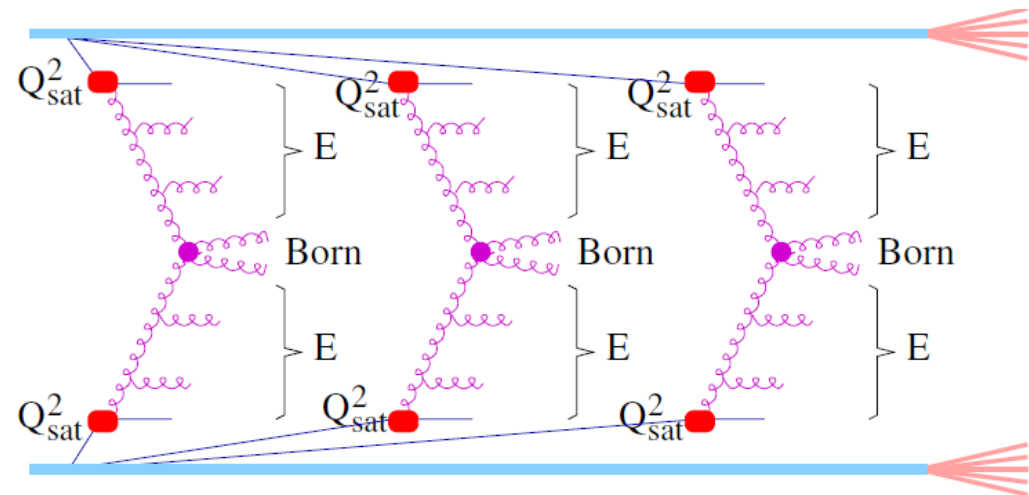
Core (QGP) and corona contributions



Small system



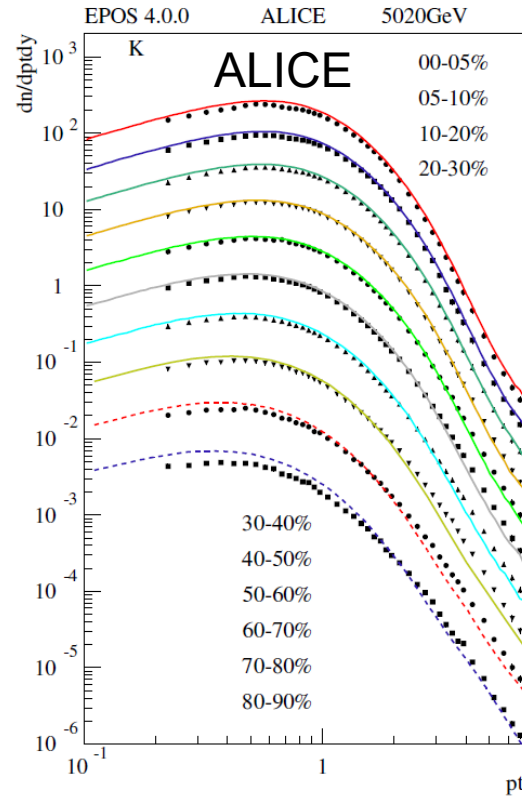
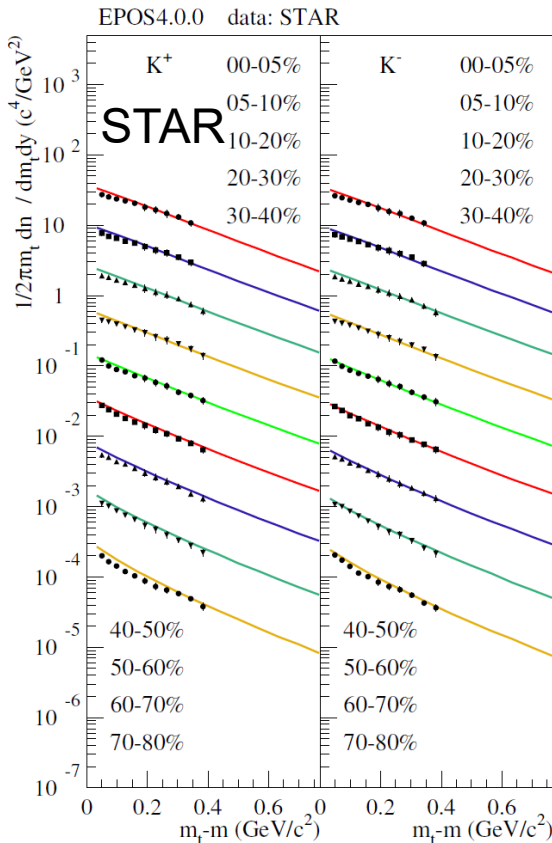
corona = blue core = red



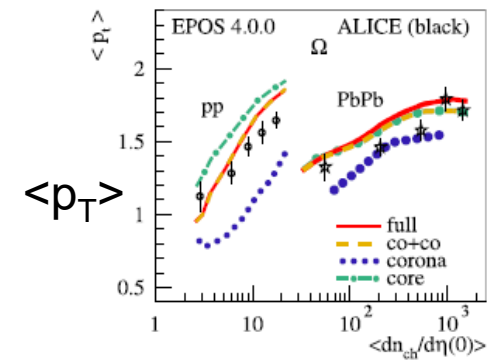
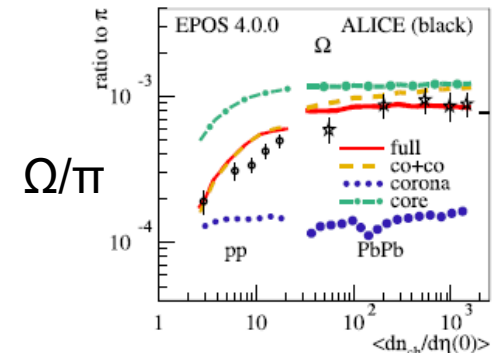
PRC 108 (2023), 064903 PRC 108 (2023), 034904, 2310.09380 [hep-ph]

# EPOS4 results in light hadron sector

EPOS4 describes the light meson sector



Even rare baryons



# EPOS4HQ – extension for heavy quark physics

## EPOS 4

heavy quarks are created at the interaction points  
a QGP is created if energy density  $> 0.57 \text{ GeV/fm}^2$

No further interaction

$e^+e^-$  fragmentation function  $\rightarrow$  hadrons

## EPOS4HQ

heavy quarks interact with the QGP  
**elastic and inelastic collisions**

hadronization by fragmentation and  
**coalescence** (for Q/Qbar in the QGP)  
when the light quarks hadronize

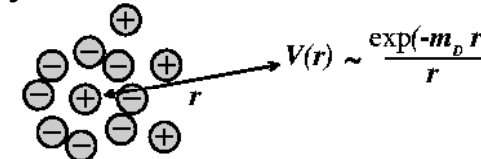
hadronic interactions described by UrQMD

**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

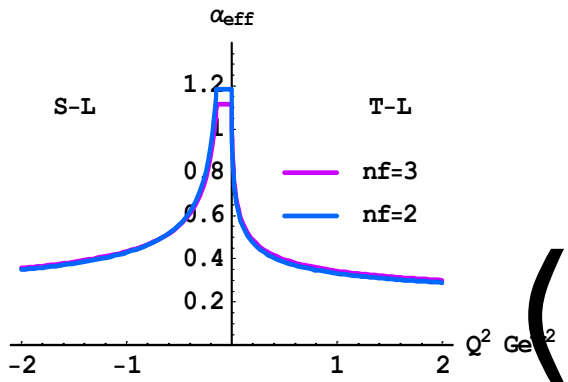
**allows to trace back** the D meson observables to the properties of Q at production

# 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 ( $\sqrt{t} \ll T$ ): 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

$$\frac{1}{t - \kappa m_D^2}$$

with  $\kappa$  that energy loss indep. of **the artificial scale**  
 $t^*$  which separates the regimes

Extension to QCD (PRC78:014904)

# EPOS4HQ – elastic scattering

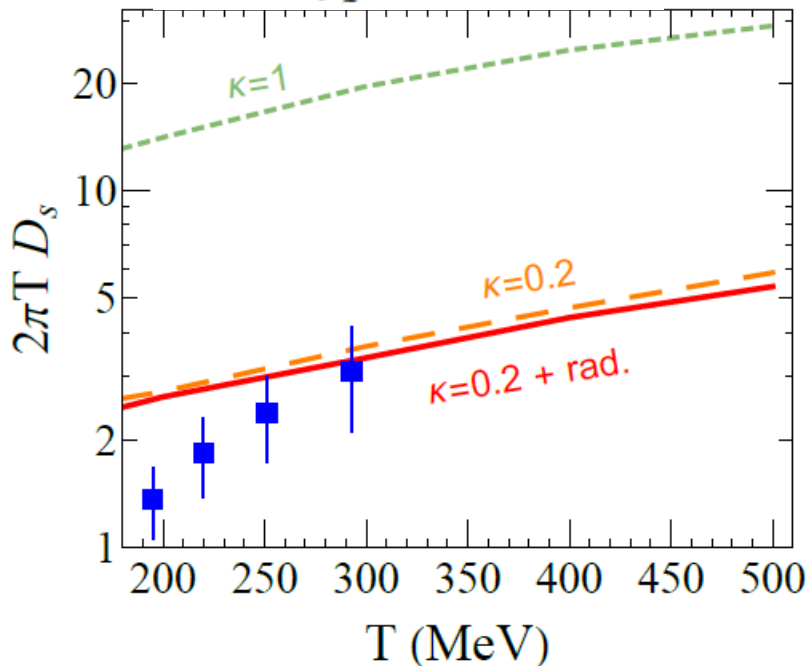
Independence of the energy loss on the intermediate scale  $t^*$  requires

$m_D \rightarrow \kappa m_D$  with

$\kappa \approx 0.2$

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

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



Approach can be checked against lattice calculations

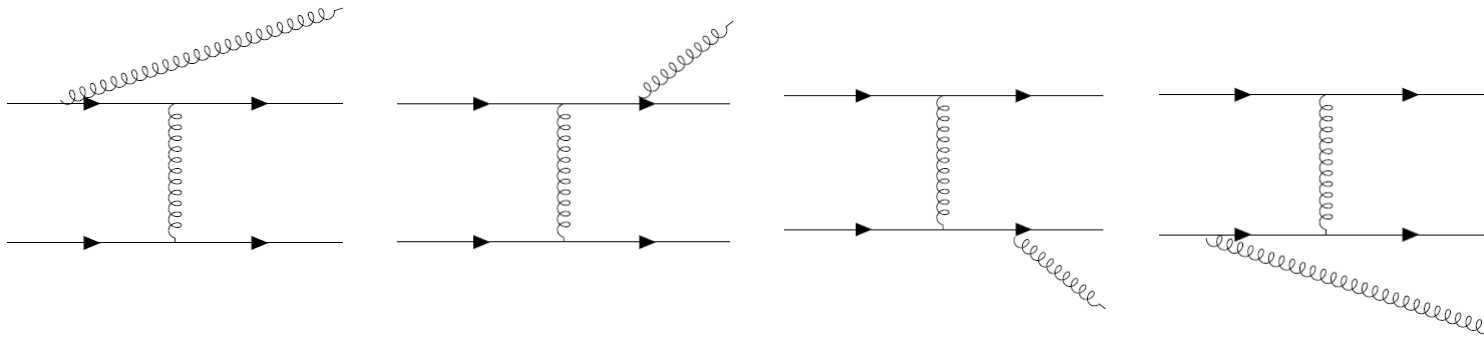
Better agreement as compared to pQCD with a effective thermal mass in gluon propagator

Olaf Kaczmarek et al, Phys.Rev.Lett. 130 (2023) 23, 231902

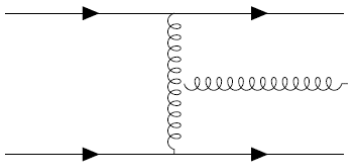
# EPOS4HQ - inelastic cross section

QED like

PRD89(2014)074018



genuine QCD



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

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

Same elastic matrix element as for elastic coll;

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

no divergencies

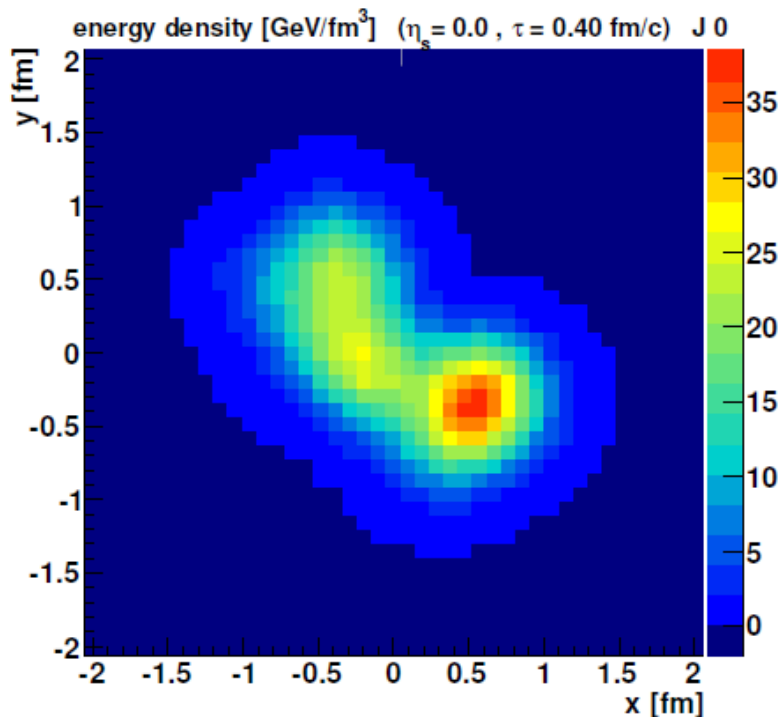


# pp in EPOS4HQ

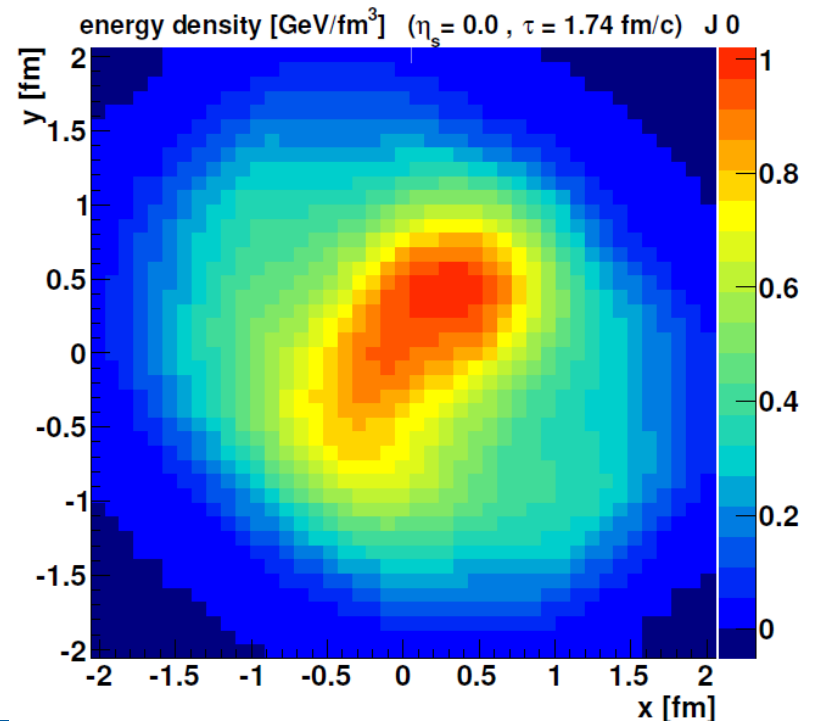
EPOS4HQ applied to pp: QGP is created if energy density  $> 0.57 \text{ GeV}/\text{fm}^2$

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  $P_m = \text{Tr}(\rho_m \rho)$  in Wigner density formalism

Wigner density obtained by

Solution of Schrödinger eq.  $\rightarrow$  rms radius  $\rightarrow$  3d harm. Osc. wf with same rms

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

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

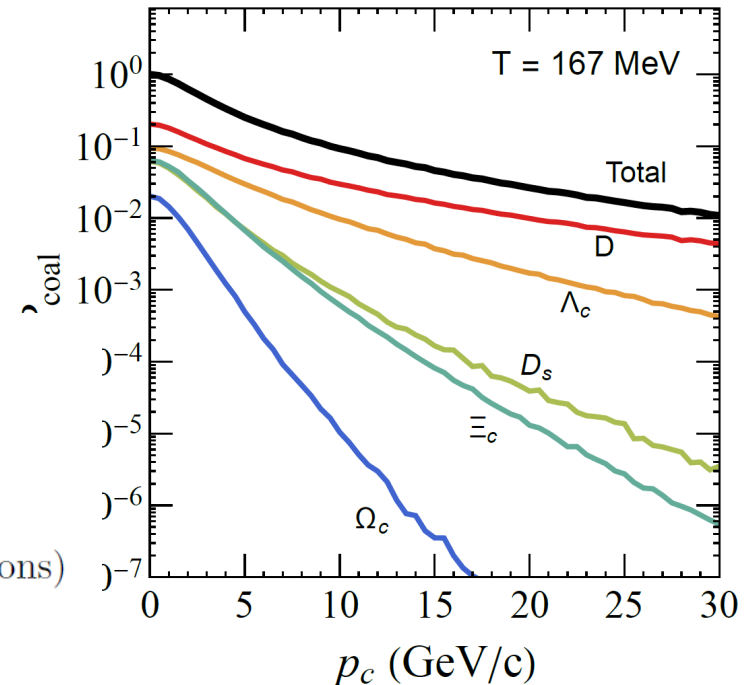
$f_i(\mathbf{p}_i)$  for  $i > 1$  drawn from thermal distribution

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

Wigner density of the heavy hadron  $m$  in momentum space

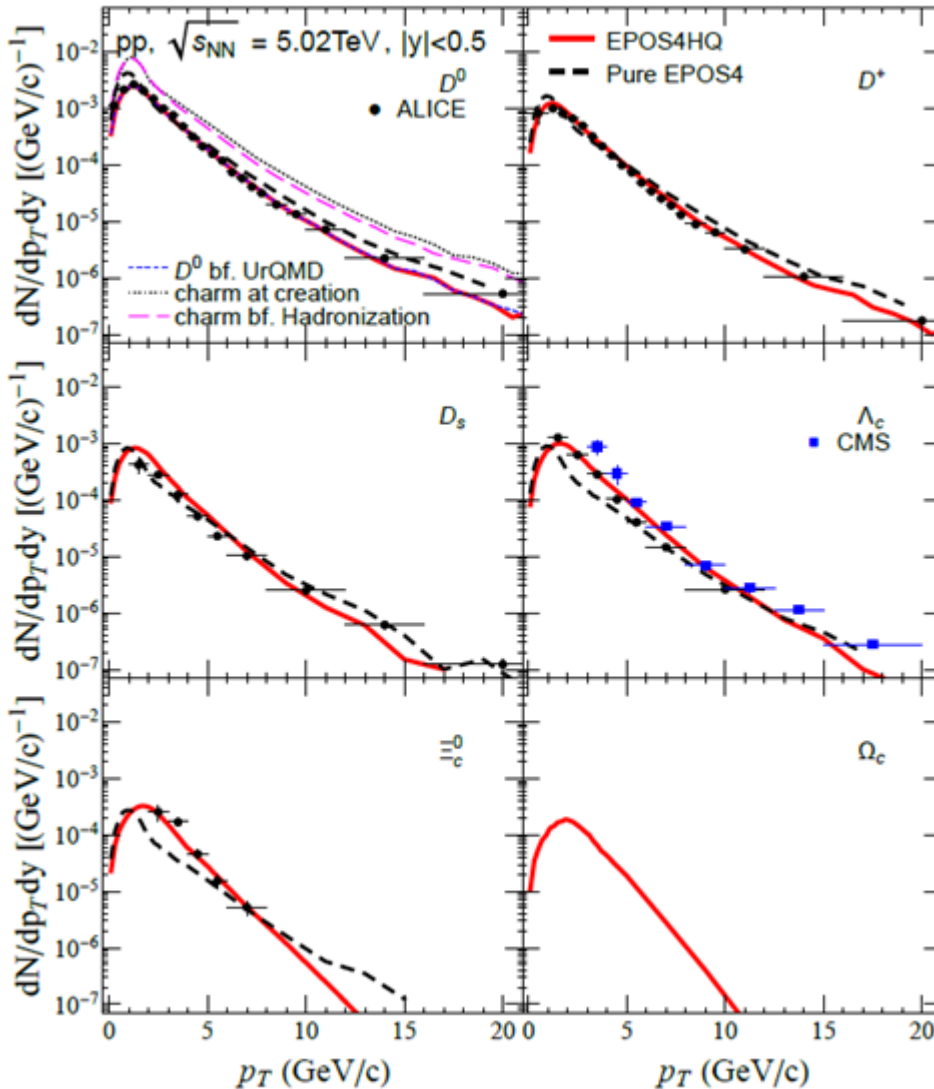
$g_H$  degeneracy factor of color and spin.  $k = 2(3)$  for mesons (baryons)

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



If not hadronized by coalescence  $\rightarrow$  hadronization by fragmentation

# $p_T$ spectra for pp



Spectra at creation and before hadronization very similar

→ Little momentum loss in the QGP

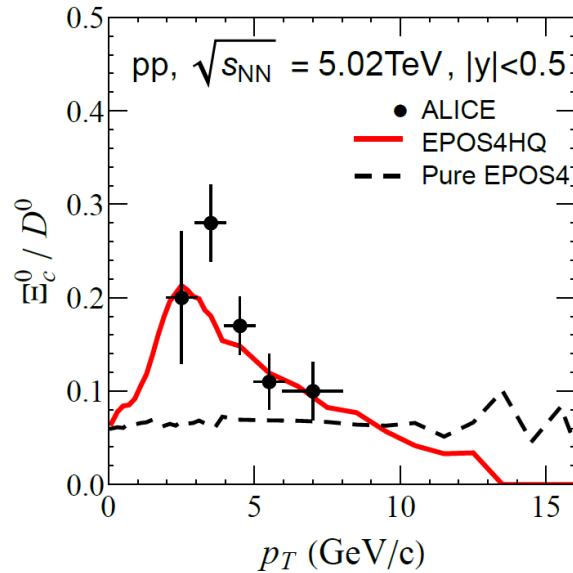
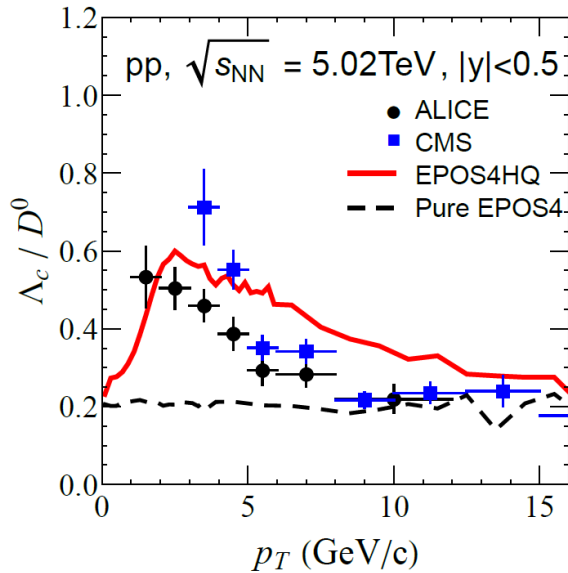
Momentum loss due to hadronization much larger

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**

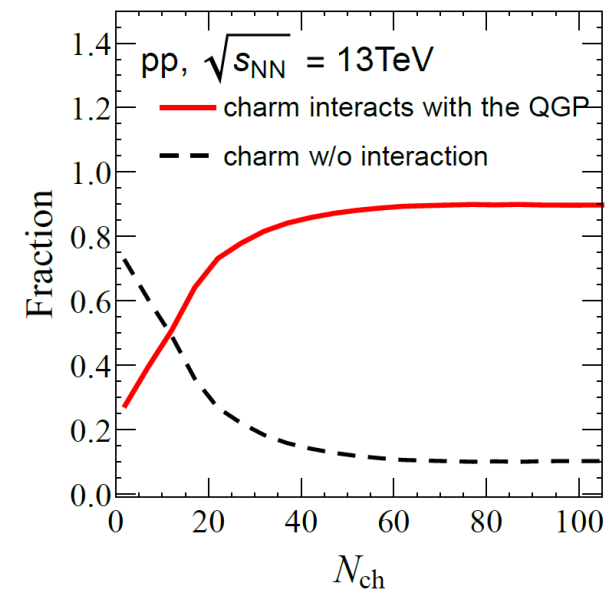
# Yield ratios



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

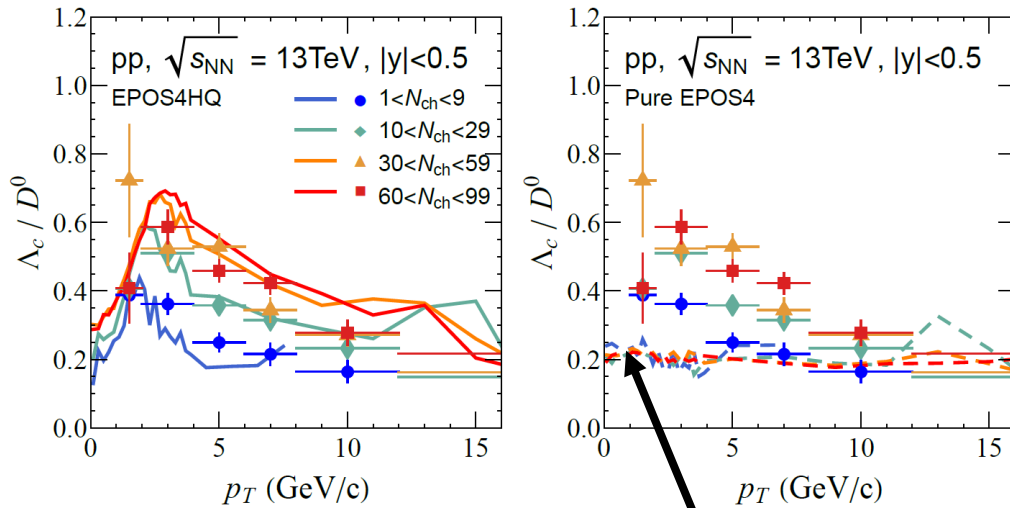
$e^+e^-$  : ratio is constant in  $p_T$  = pure EPOS4

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

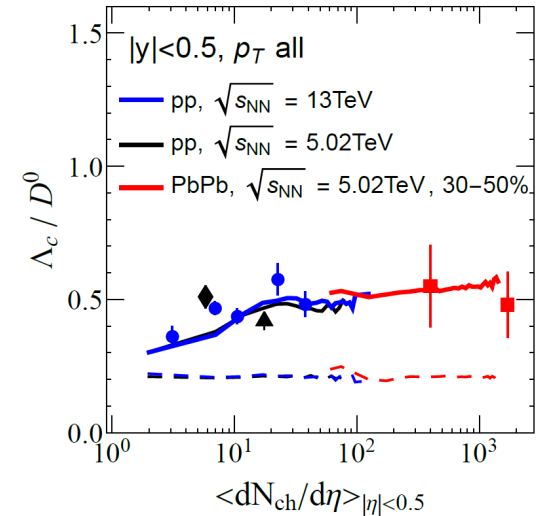


# Yield ratios

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



Flat distribution in pure EPOS4



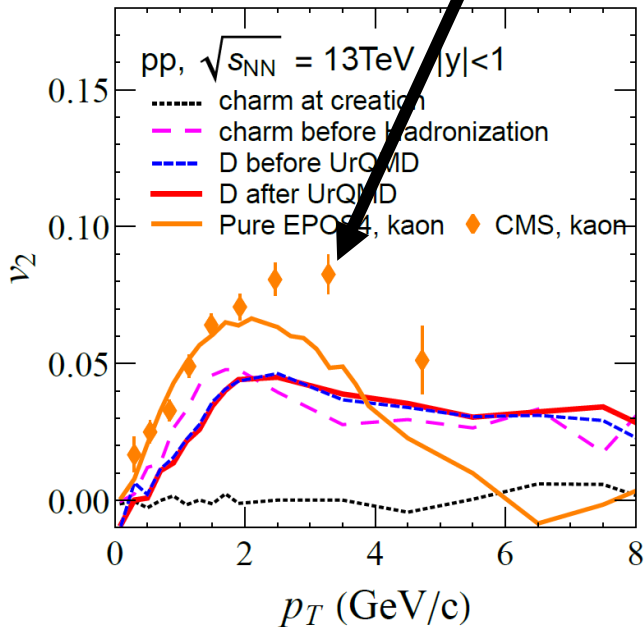
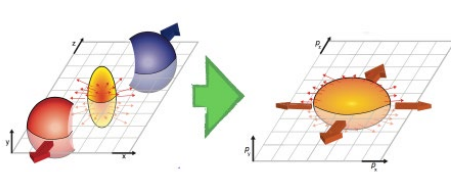
Also experimental enhancement saturates at at  $N_{ch} \approx 40$

Yield ratios are a strong indication that a QGP is formed

# Elliptic flow $v_2$

$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos\phi + 2v_2 \cos(2\phi) \dots \quad \Phi = \text{azimuthal angle wrt reaction plane}$$

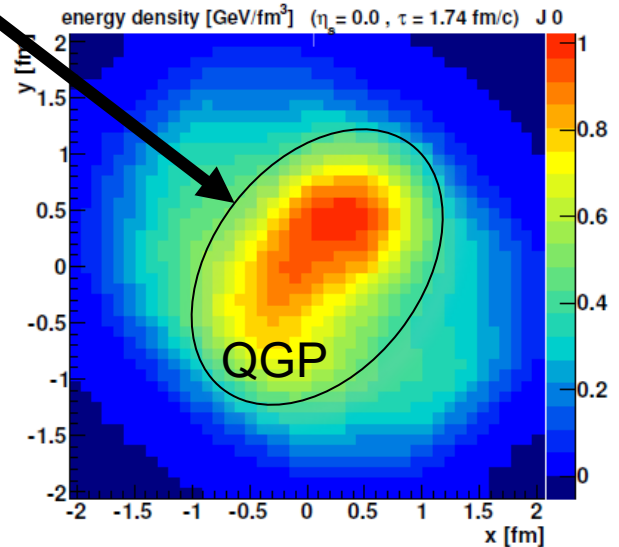
**Light hadrons** show a finite  $v_2$  created by fluctuations of the energy density and hydro expansion



At **low**  $p_T$  :  
**Spatial eccentricity**  
 → Anisotropy in azimuthal momentum space  
 →  $v_2(p_T)$  for low  $p_T$

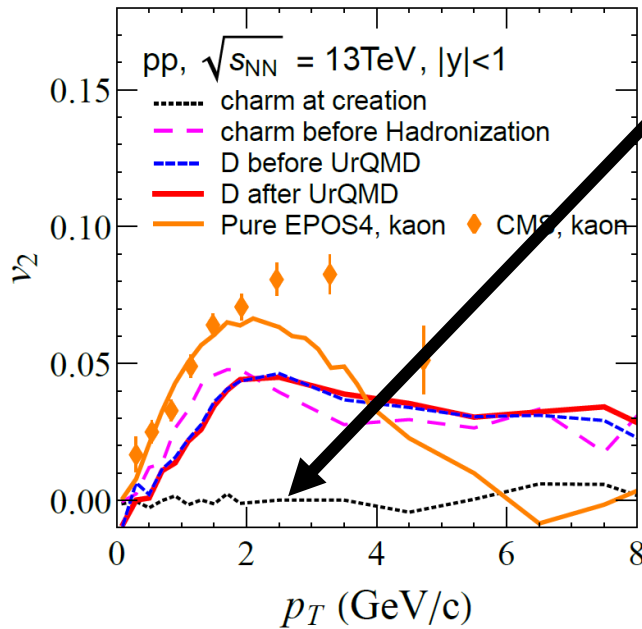
At **high**  $p_T$  :  
 $v_2(p_T)$  due to **path length difference**  
 → Different loss in QGP)

One EPOS4 pp event



# Elliptic flow $v_2$

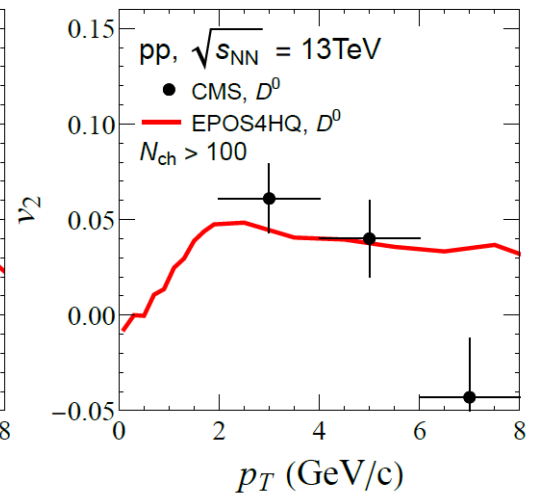
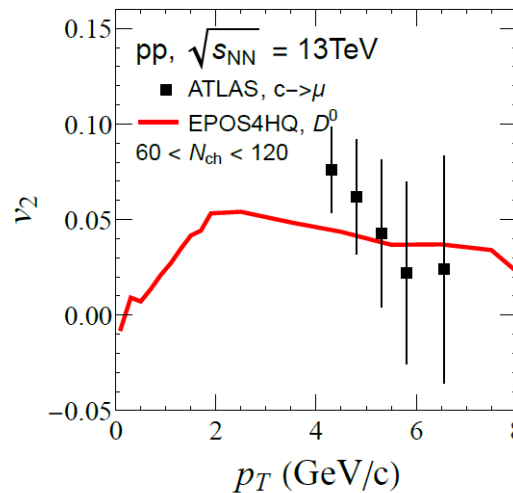
For heavy mesons: Form of  $v_2(p_T)$  similar but value is smaller



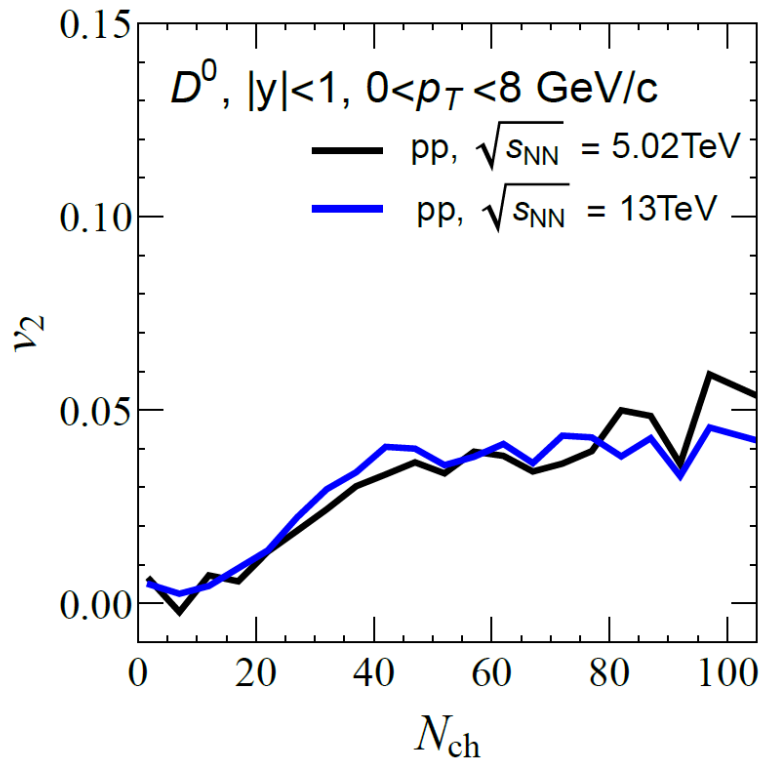
initially heavy quarks are produced in hard processes  $M \gg \Lambda_{\text{QCD}}$   
 $\rightarrow$  no finite elliptic flow expected

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

$v_2(p_T > 5 \text{ GeV})$  is up to now the only way to 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

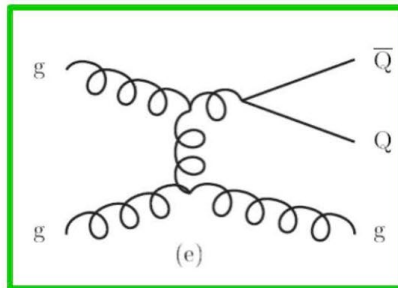
if one wants to understand the  $p_T$  distributions of heavy hadrons

FONLL only single particle  $p_T$  spectrum

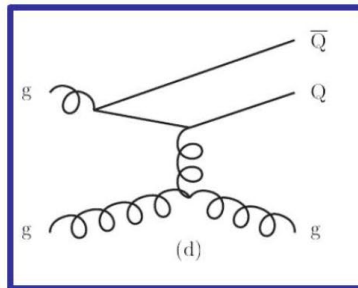
Pythia ISR and FSR can be added

EPOS4HQ separates **the three different production mechanisms**

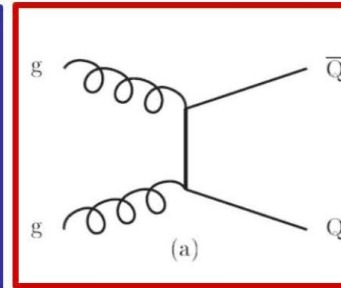
gluon splitting  
time like



gluon excitation  
space like

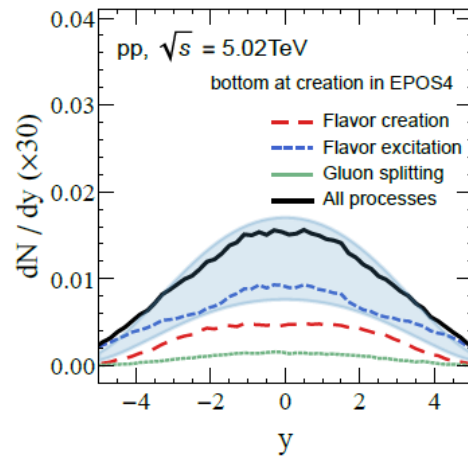
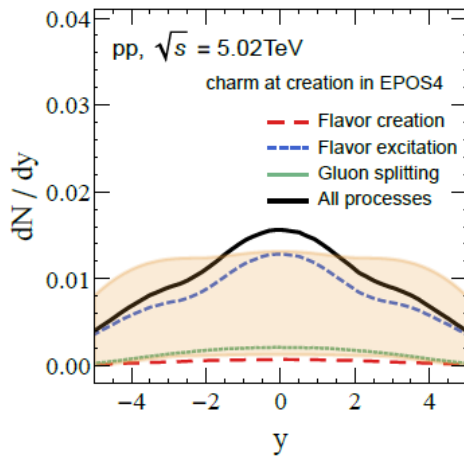
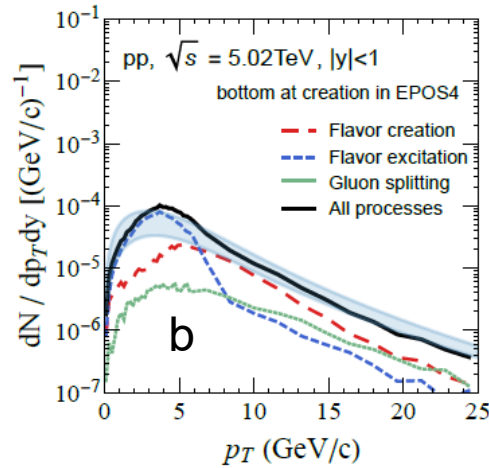
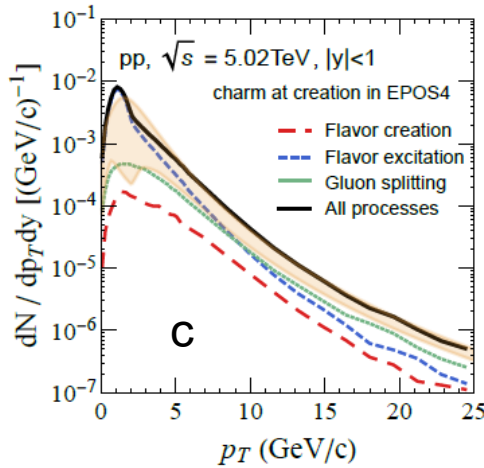


flavour creation  
hard process (Born)



# Correlations between Q and Qbar

$p_T$  and  $y$  distribution depend on creation mechanism



For b and c quarks the contributions are different

High  $p_T$  c  $\rightarrow$  gluon splitting

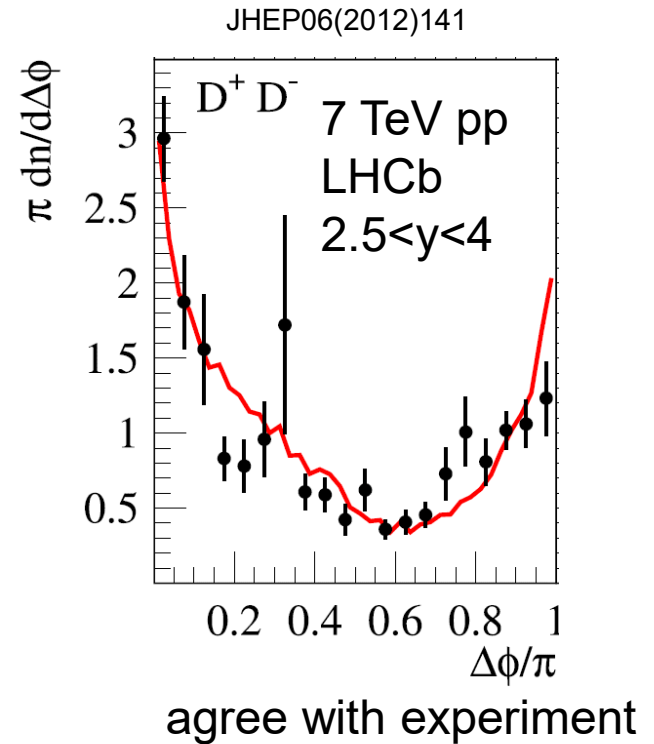
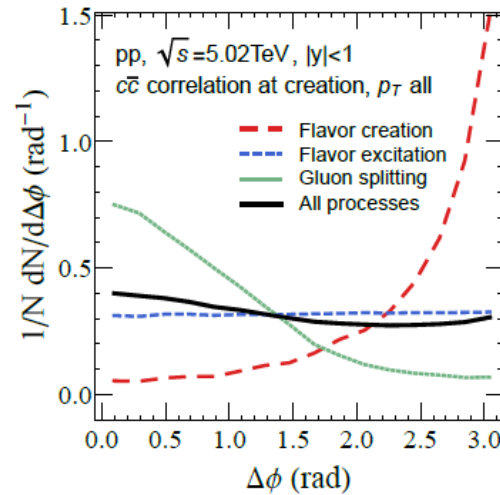
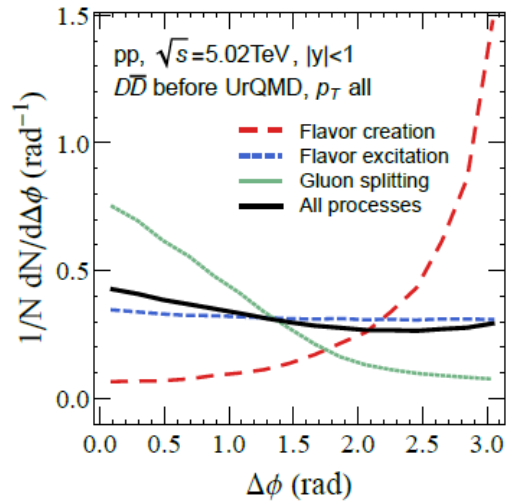
High  $p_T$  b  $\rightarrow$  flavor creation  
(more energy avail.)

low  $p_T$  flavor excitation

Spectra (sum of all contributions) agree with FONLL

Shaded :FONLL

# Correlations between Q and Qbar



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

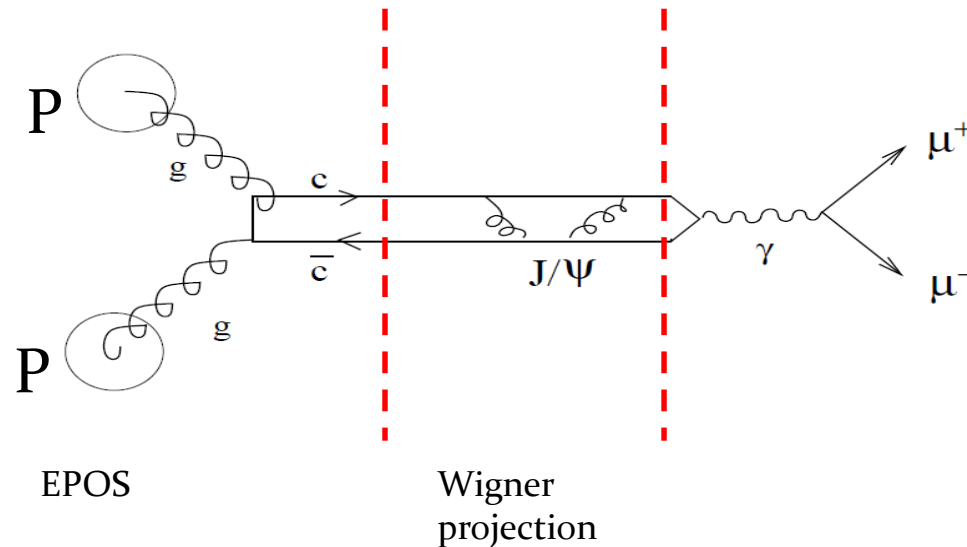
# Correlations between Q and Qbar

Correlations between  $c$  and  $c\bar{c}$  show also up in quarkonium production

How to describe a **bound** state like a  $c\bar{c}$  in QCD?

It involves low momenta and needs **non perturbative** input  $\rightarrow$  assumptions.

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



# Correlations between Q and Qbar

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

$V(r) = -\alpha/|r| + \sigma|r|$  with  $\alpha = 0.513$ ,  $\sigma = 0.17\text{GeV}^2$ ,  $m_c = 1.5\text{GeV}$ ,  $m_b = 5.2\text{GeV}$ .

$\mathbf{r} = \mathbf{r}_i - \mathbf{r}_j$

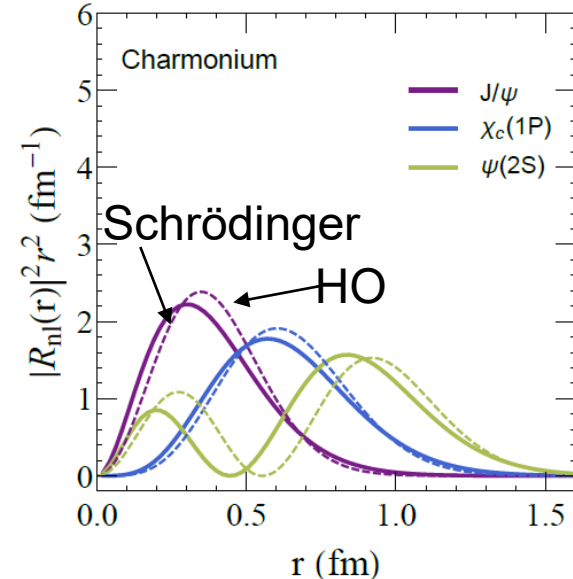
$\psi(\mathbf{r}) = R_{nl}(r)Y_{l,m}(\theta, \phi)$ .

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:

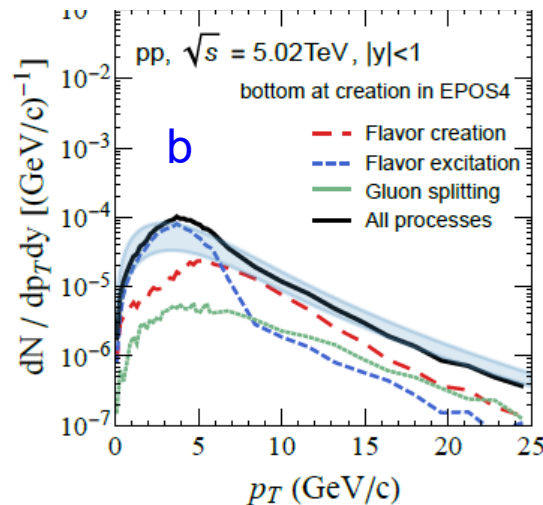
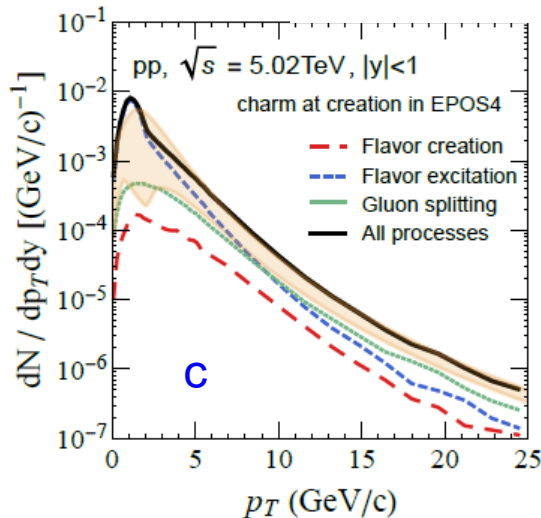
$$W^{(2)}(\mathbf{P}, \mathbf{r}, \mathbf{p}) \sim r^2 \exp\left(-\frac{r^2}{2\sigma_{Q\bar{Q}}^2}\right) f_{Q\bar{Q}}^{\text{EPOS4}}(\mathbf{P}, \mathbf{p})$$

P,p given by EPOS4

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

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

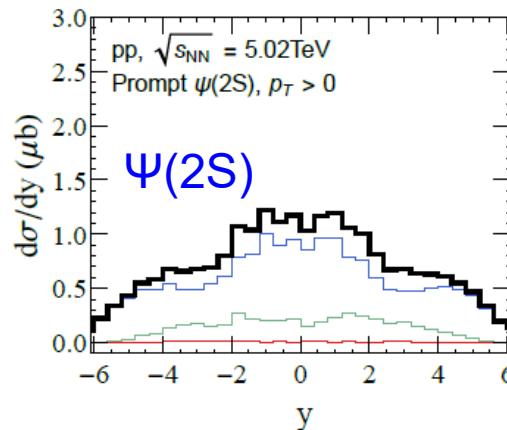
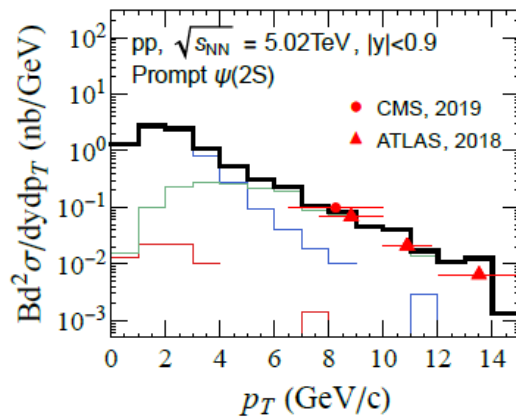
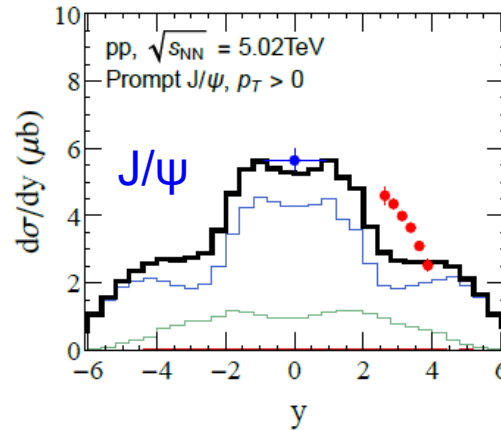
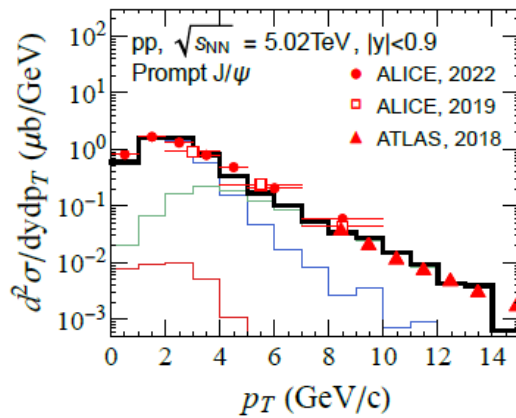
$$\frac{dP_{nl}^m}{d^3\mathbf{P}_{\text{cm}}} = \sum \int \frac{d^3r d^3p}{(2\pi)^6} W_{nl}^m(\mathbf{r}, \mathbf{p}) W^{(2)}(\mathbf{P}_{\text{cm}}, \mathbf{r}, \mathbf{p})$$



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

# Correlations between Q and Qbar

Prompt  $J/\psi$  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  $J/\psi$  production

# Conclusion

Q Qbar physics added to EPOS4 ( $\epsilon > \epsilon_0 = 0.57 \text{ GeV/fm}^3 \rightarrow \text{QGP}$ )

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/ $\psi$  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

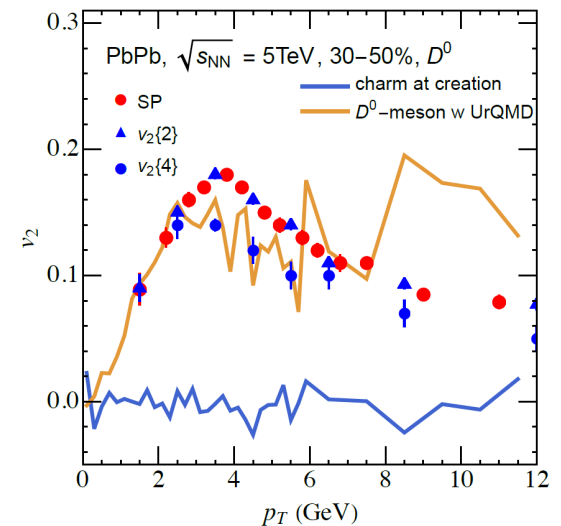
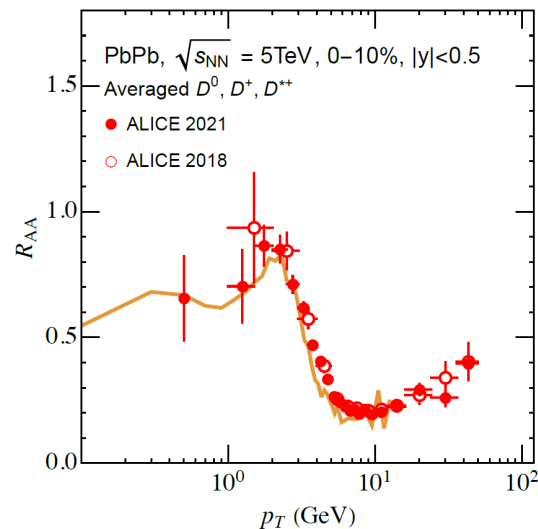
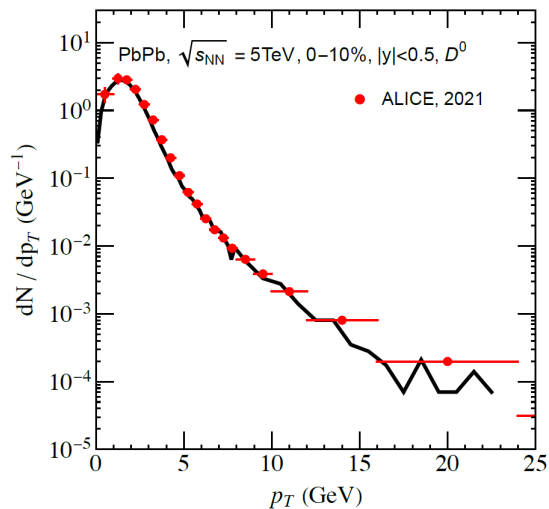
D mesons test the energy loss and  $v_2$  of heavy quarks in a QGP

energy loss tests the **initial phase**

$v_2$  the **late stage** of the expansion

Two mechanisms : collisional energy loss: PRC78 (2008) 014904

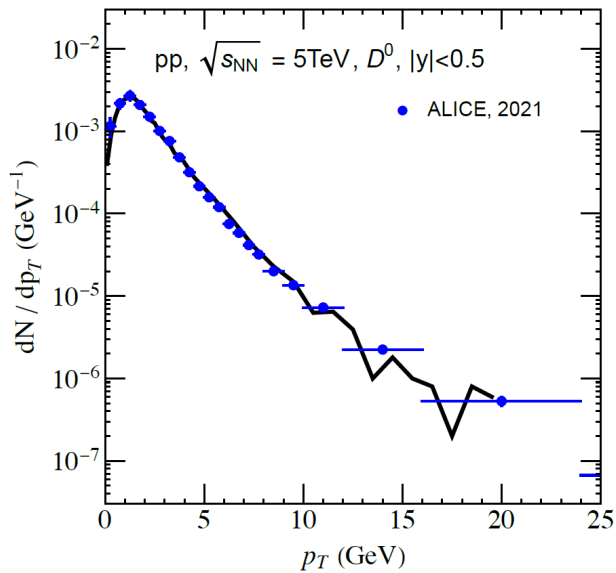
radiative energy loss: PRD89 (2014) 074018



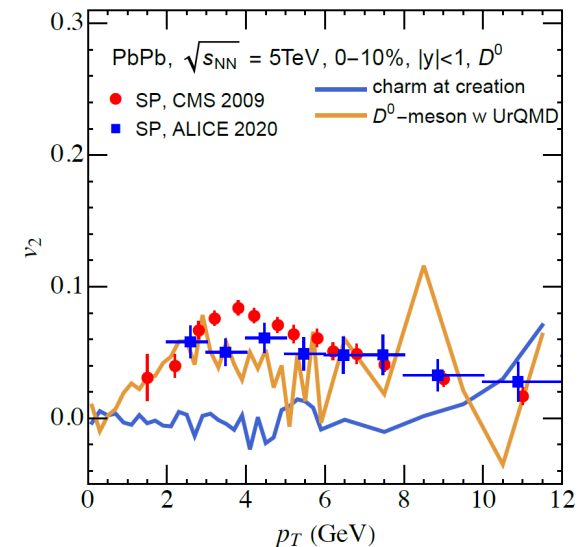
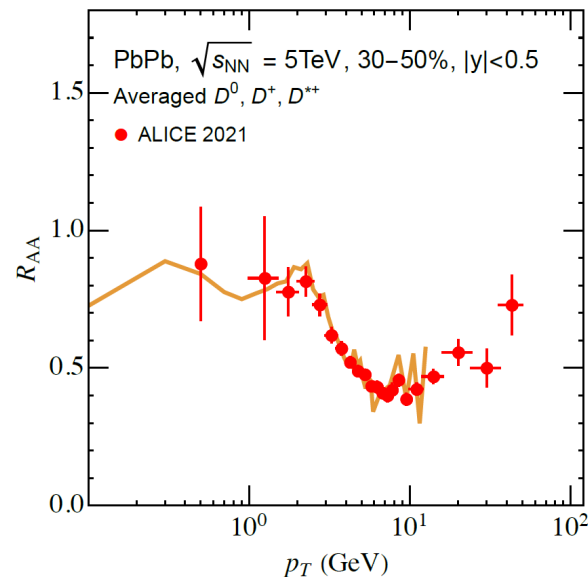
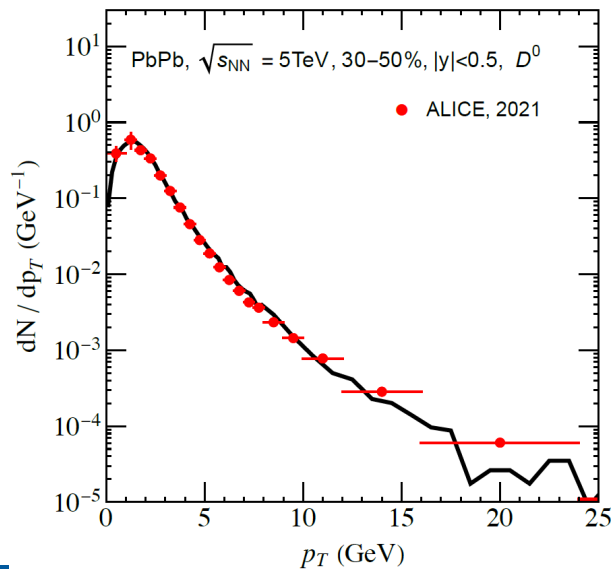
EPOS4HQ reproduces  $dN/dp_T$ ,  $R_{AA}$  and  $v_2$  quite well

→ 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



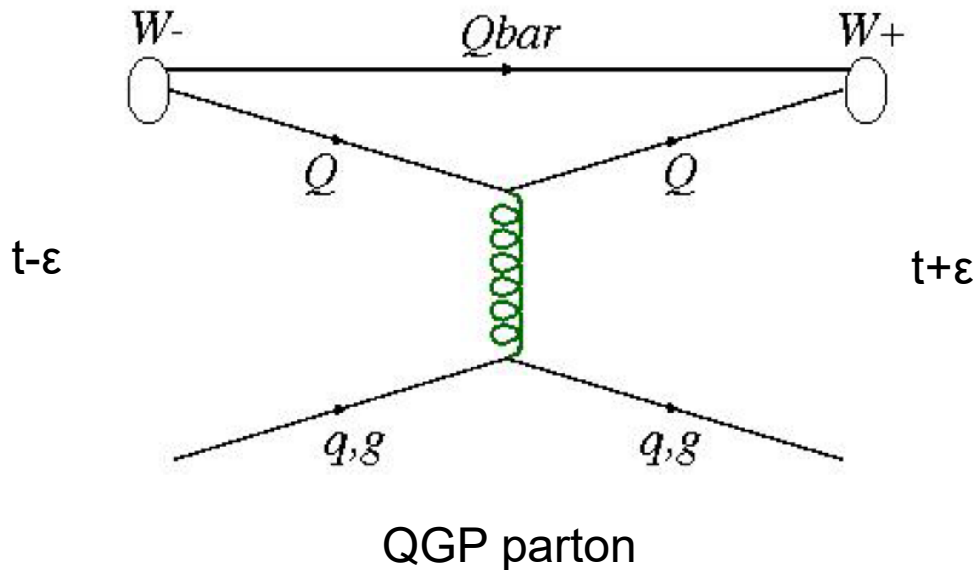
# J/ψ creation in heavy ion collisions

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

$$\Gamma^\Phi(t) = \frac{dP^\Phi(t)}{dt} = \frac{d}{dt} \text{Tr}[\rho^\Phi, \rho_N(t)] \approx \frac{d}{dt} \prod \frac{d^3 r_i d^3 p_i}{(2\pi)^{3N}} W^\Phi(\mathbf{r}, \mathbf{p}) W^c(\mathbf{r}_1, \mathbf{p}_1, \dots, \mathbf{r}_N, \mathbf{p}_N)$$

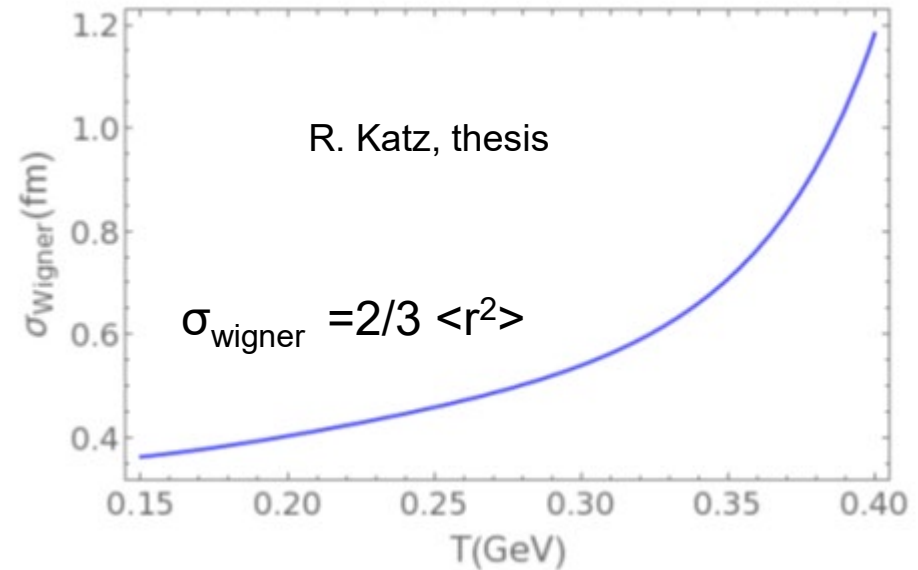
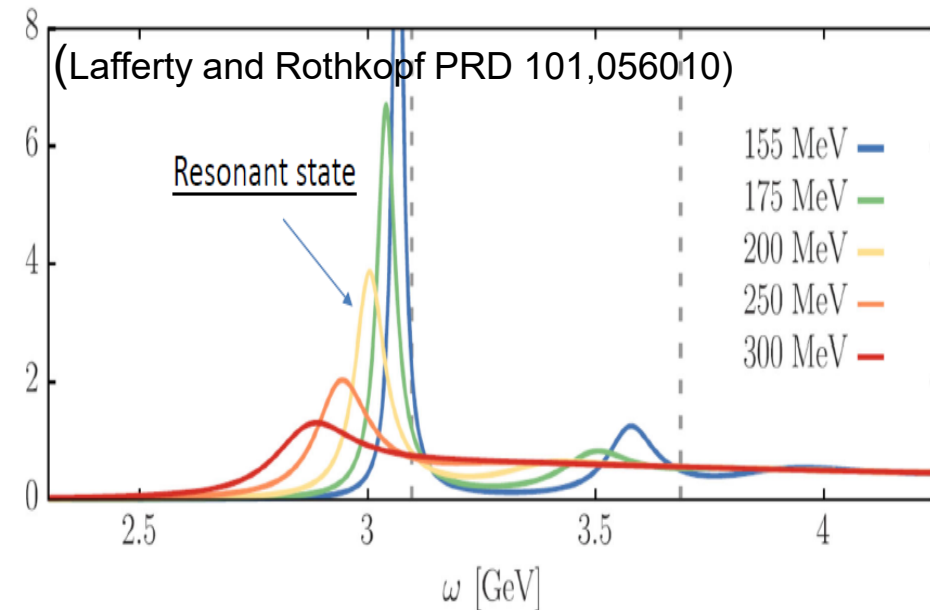
If the collisions are point like in time and if  $W^\Phi(\mathbf{r}_1, \mathbf{r}_2, \mathbf{p}_1, \mathbf{p}_2)$  is time independent (1,2 are charm quark, n=number of collision of i and j,  $t_{ij}(n)$ =time of n-th collision of ij) :

$$\Gamma^\Phi(t) = \sum_n \sum_{i=1,2} \sum_{j \geq 3} \delta(t-t_{ij}(n)) \prod_N \frac{d^3 r_i d^3 p_i}{(2\pi)^{3N}} W^\Phi(\mathbf{r}, \mathbf{p}) \left[ \underbrace{W^c(\mathbf{r}_1, \mathbf{p}_1, \dots, \mathbf{r}_N, \mathbf{p}_N, t + \epsilon)}_{W^+} - \underbrace{W^c(\mathbf{r}_1, \mathbf{p}_1, \dots, \mathbf{r}_N, \mathbf{p}_N, t - \epsilon)}_{W^-} \right]$$



# 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/ψ in heavy-ion coll with a dissociation temperature

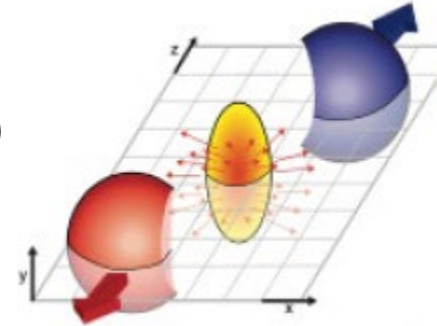
$$P(t) = P^{prim}(t_{init}) + \int_{t_{init}}^t [\Gamma_{coll}(t') + \Gamma_{loc}(t')] dt' \rightarrow P(t \rightarrow \infty) = \text{asympt. multiplicity}$$

# 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) important for high  $p_t$  and for  $v_2$

Confirmed by centrality dependence of multiplicity



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

For  $J/\psi$  mesons we use as working description:

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

# Our approach and open quantum systems

Von Neuman eq.

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

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

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

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

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

yields

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

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

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

# Wigner Density Formalism

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

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

w.f.  $\rightarrow$  density matrix  $|\Phi_i\rangle\langle\Phi_i|$

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

(close to classical phase space density)

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

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

$$n_i(\mathbf{R}, \mathbf{P}) = \sum_{\text{all } c\bar{c} \text{ pairs}} \int \frac{d^3r d^3p}{((2\pi)^3)} \Phi_i^W(\mathbf{r}, \mathbf{p}) \prod_{\text{all other particles}} \int \frac{d^3r_j d^3p_j}{(2\pi)^{3(N-2)}} \rho_N^W(\mathbf{r}_1, \mathbf{p}_1 \dots \mathbf{r}_N, \mathbf{p}_N)$$

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

The results are obtained using a relativ. formulation

pp: In momentum space given by tuned PYTHIA

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