Heavy flavor correlations and Quarkonia production in high energy proton-proton collisions in the EPOS4 framework

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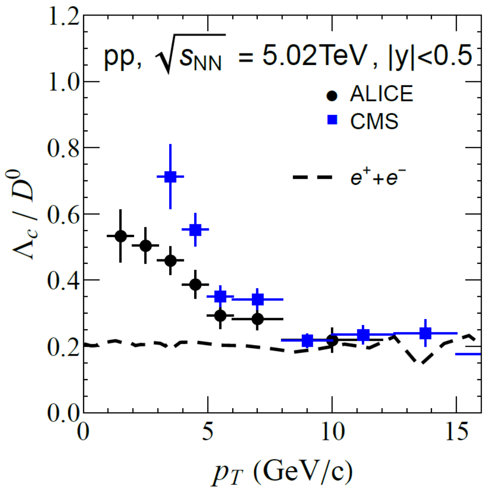
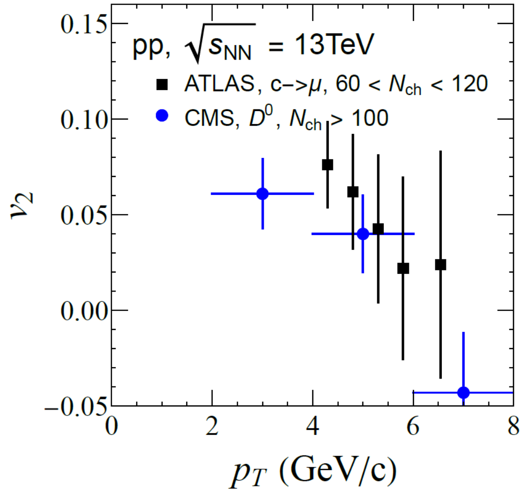
The study of heavy mesons in pp collisions offers big surprises

Λ_c / D^0 ratio



are fragmentation functions not universal?

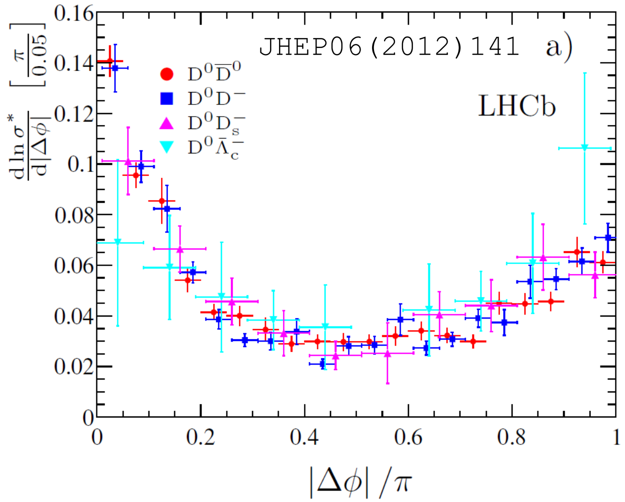
elliptic flow v_2



pQCD: v_2 =0

Where does the finite v_2 come from?

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

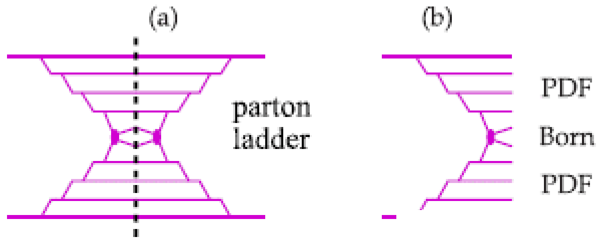


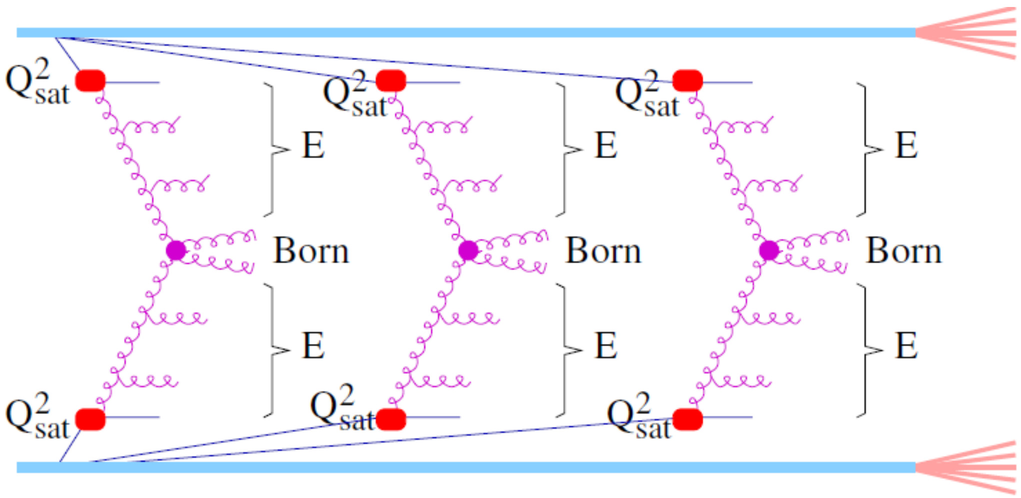
What causes this structured correlation function?

EPOS4 (→ see literature below)

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 for hard processes
Saturation

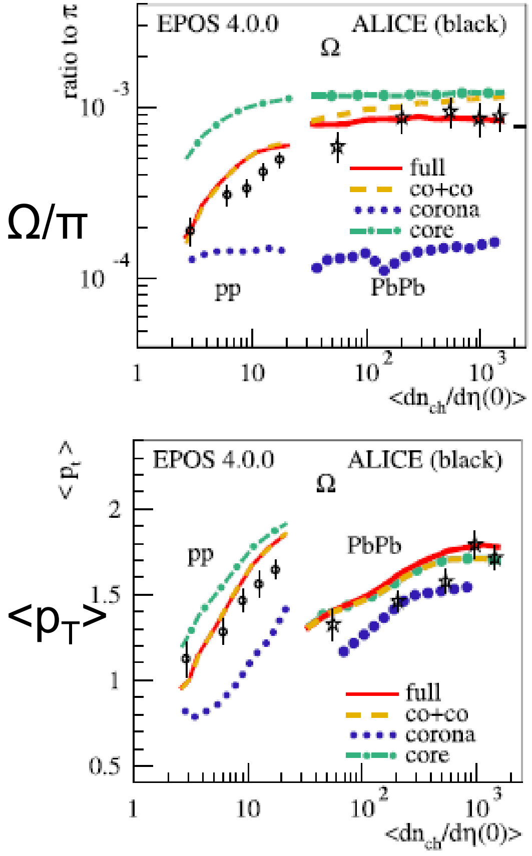




EPOS4 describes well a multitude of observables:

Here those for Ω^-

quite difficult to reproduce



EPOS4:
PRC 108 (2023), 064903 PRC 108 (2023), 034904, 2310.09380 [hep-ph]

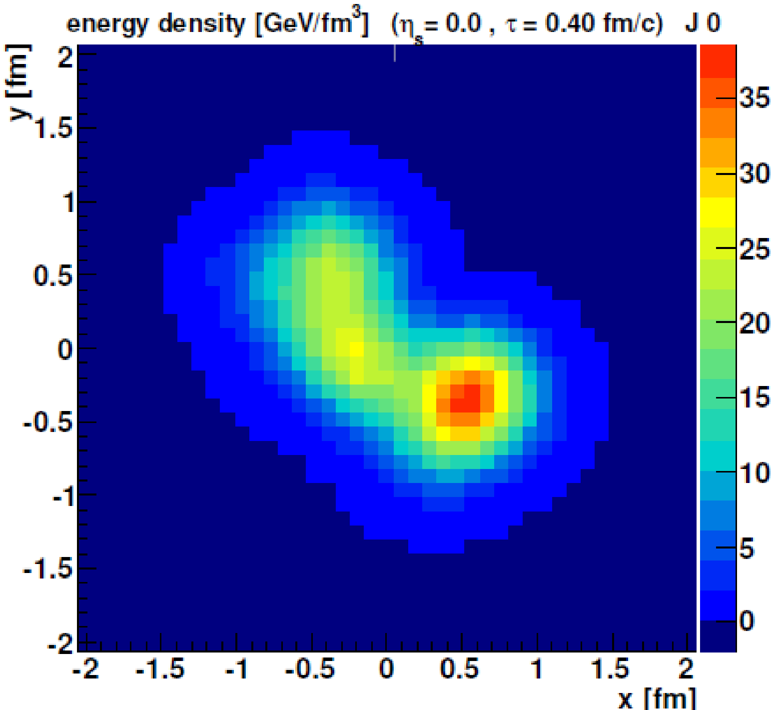
pp in EPOS4HQ

EPOS4(HQ) treats pp collisions like heavy-ion collisions: *

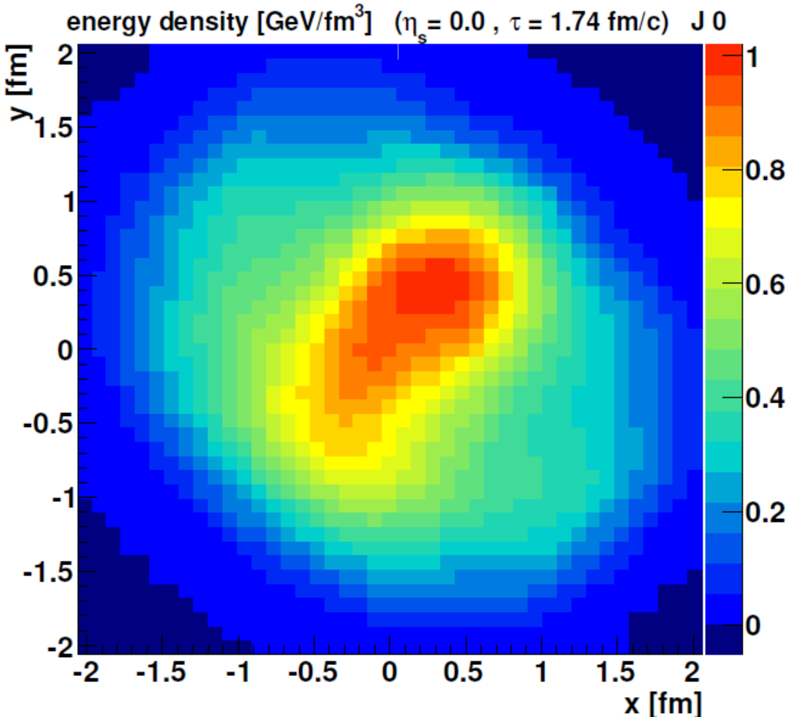
a Quark-Gluon-Plasma is created if energy density > 0.57 GeV/fm^2

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

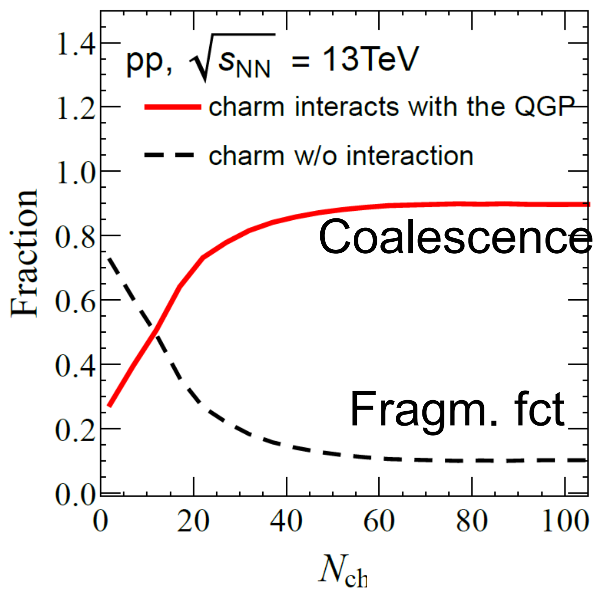
Initial



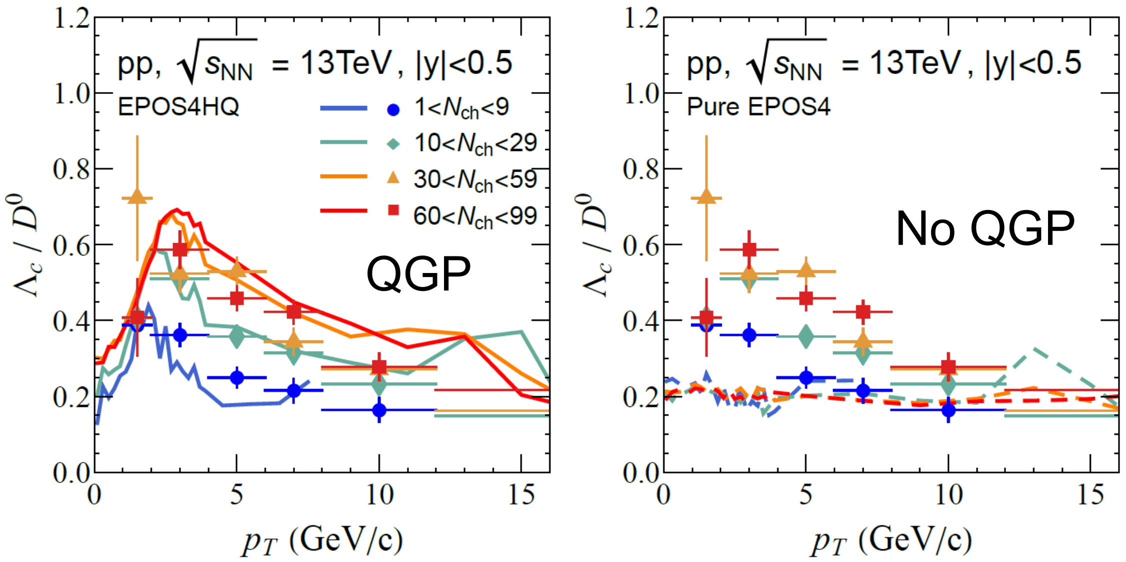
close to hadronization



In high multiplicity pp collisions the critial energy density is reached what makes several experimental observations understandable

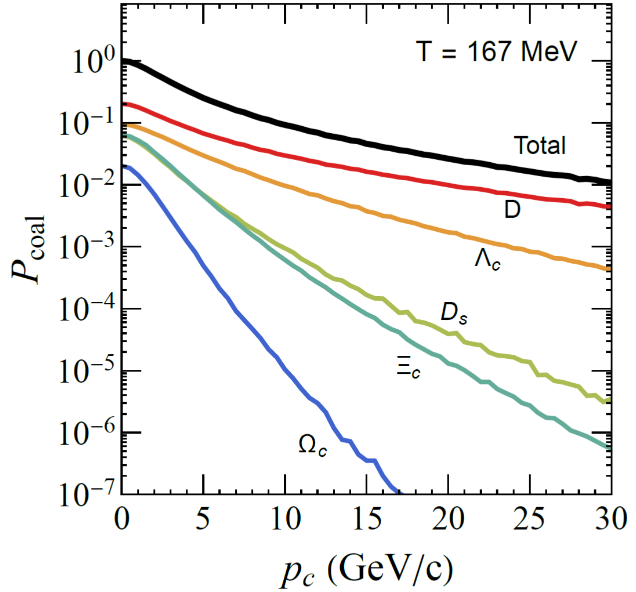


With increasing N_{ch} more Q pass a QGP saturates at $N_{ch} \approx 40$

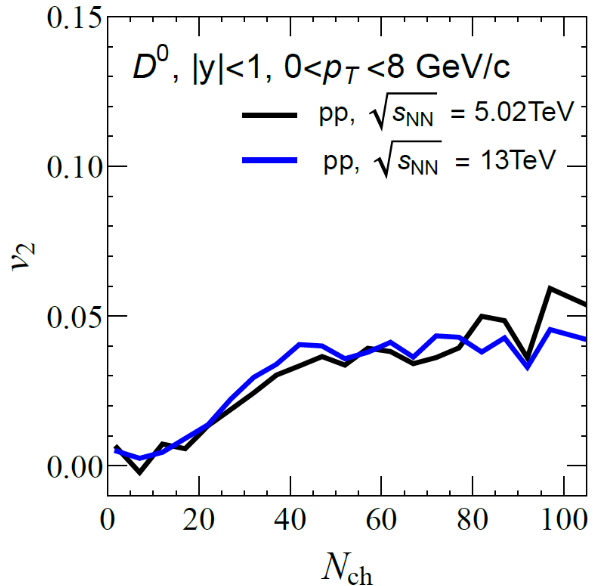


In EPOS4 without QGP: ratio as in e^+e^-

QGP hadronizes by coalescence and not by fragmentation.



v_2 depends on N_{ch} saturates when all heavy quarks pass a QGP ($N_{ch} \approx 40$)



High multiplicity pp collisions seem not to be elementary collisions

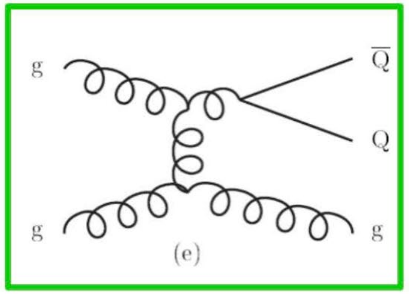
Correlations between Q and Qbar

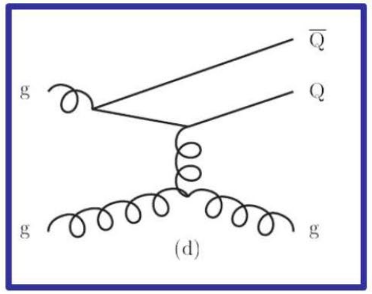
Correlations between Q and Qbar are important

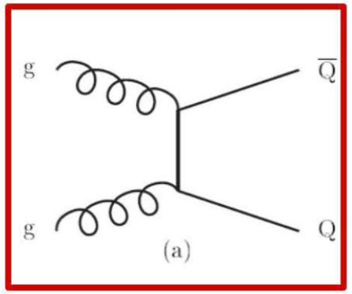
- if one wants to study/understand D Dbar correlation
- if one wants to study hidden heavy flavour mesons like J/ψ
- if one wants to understand the p_T distributions of heavy hadrons

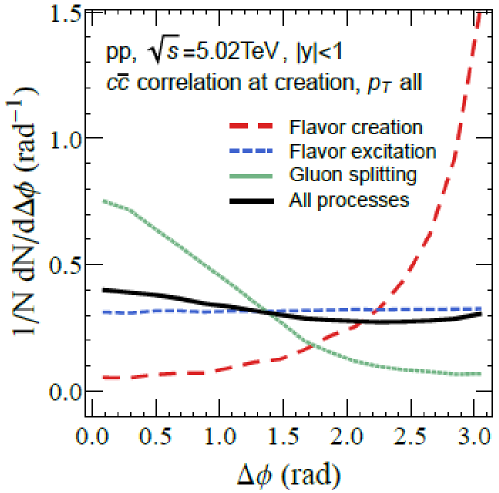
FONLL only single particle p_T spectrum
Pythia ISR and FSR can be added
EPOS4HQ separates the three different production mechanisms

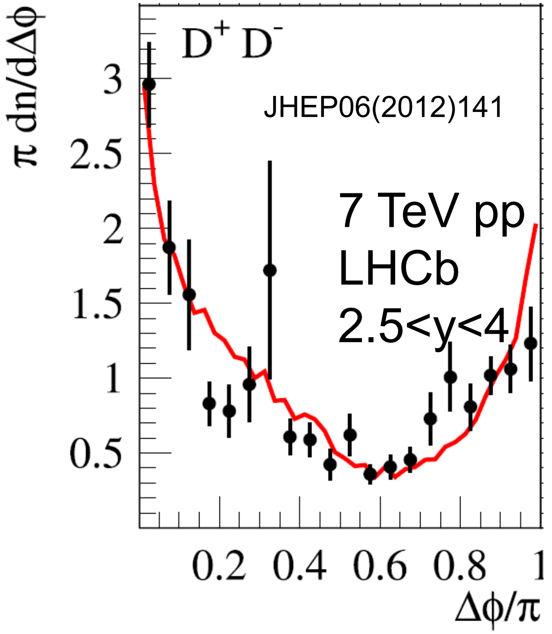
gluon splitting time like	flavor excitation space like	flavour creation hard process (Born)







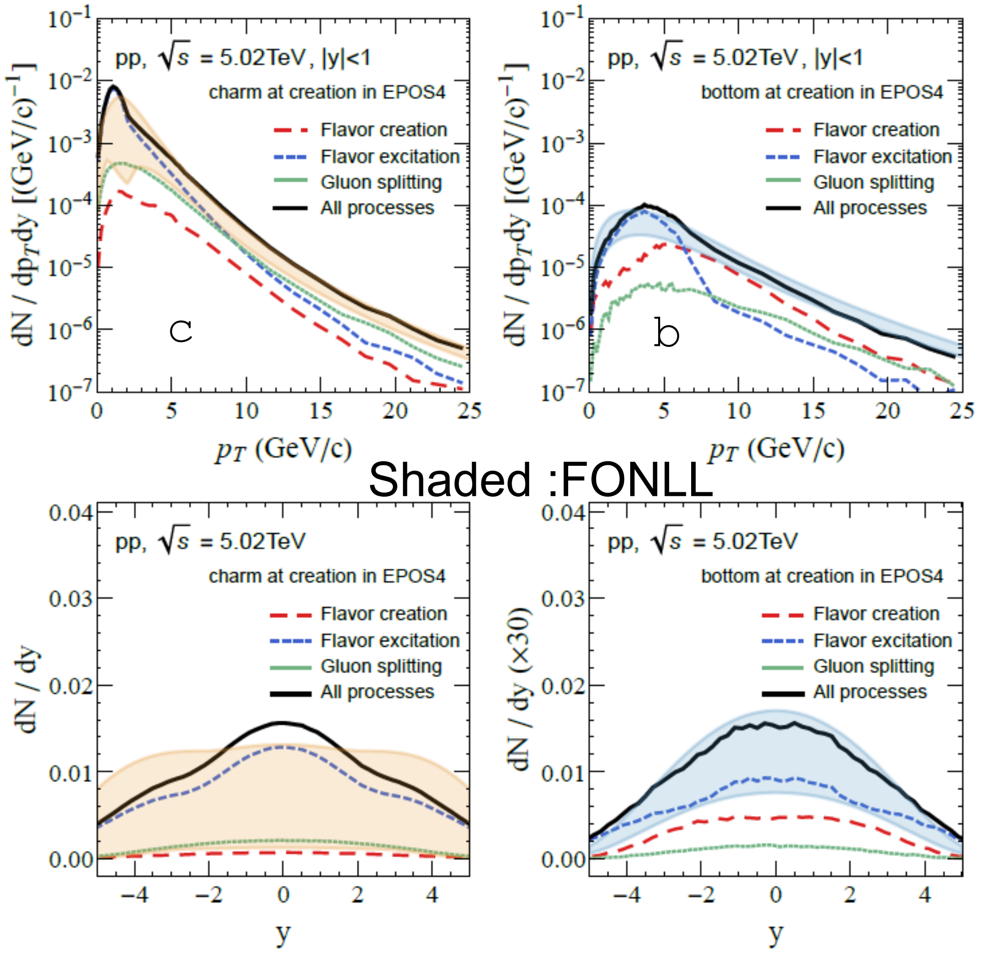




Different QCD processes → different correlations → seen in data

Correlations between Q and Qbar

p_T and y distributions depend on creation mechanism



For b and c quarks the importance of different contributions are different

High p_T c → gluon splitting

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

low p_T flavor excitation dominating

Spectra (sum of all contributions) agree with FONLL (shaded area)

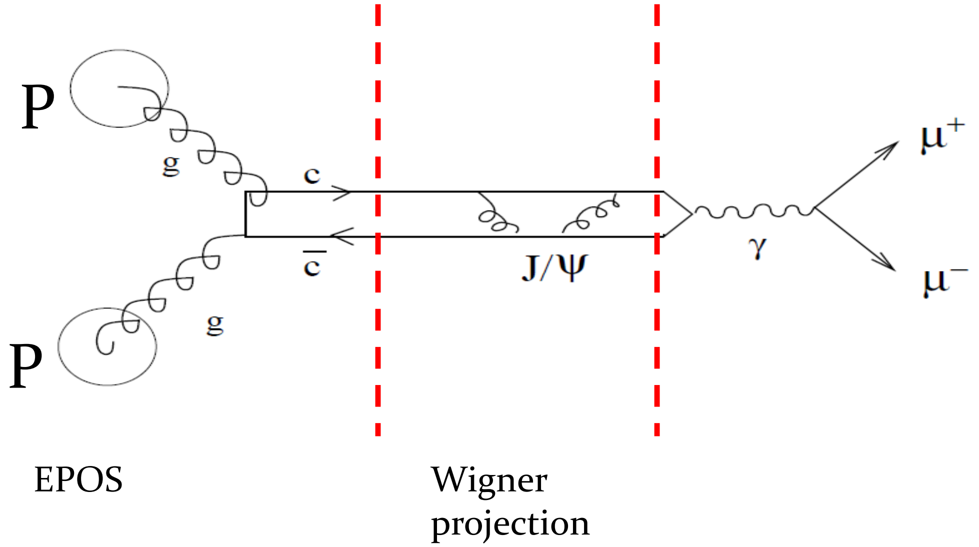
Formation of bound $Q\bar{Q}$ states

Correlations between Q and Qbar 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)



Formation of bound $Q\bar{Q}$ states

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 $\rho_i = |\Phi_i\rangle\langle\Phi_i|$

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

(close to classical phase space density)

The probability to form a state $|\Phi_i\rangle$ if the system is described by $\rho^N = |\psi^N\rangle\langle\psi^N|$

$$P = Tr[\rho^N \rho_i] = \int \prod d^3p_i d^3r_i W^i(\mathbf{r},\mathbf{p}) W^N(\mathbf{r}_1..\mathbf{r}_N, \mathbf{p}_1..\mathbf{p}_N)$$

Where $\mathbf{r},\mathbf{p}$ are relative coordinates.

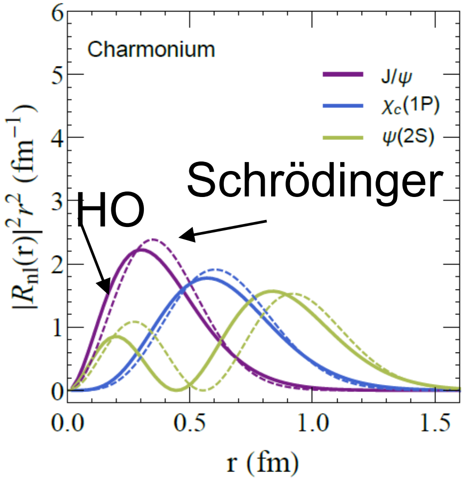
Formation of bound $Q\bar{Q}$ states

Step 1: solution of $Q\bar{Q}$ Schrödinger eq.

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

Step 2: Conversion into a 3d harmonic oscillator wave fct with same spin and rms radius $\psi^{HO}(\mathbf{r})$

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



and conversion into a 2 body Wigner density:

$$W_{nl}(\mathbf{r},\mathbf{p})=\int d^3y\; e^{i\mathbf{p}\mathbf{y}}\langle\mathbf{r}+\mathbf{y}/2|\psi^{HO}\rangle\langle\psi^{HO}|\mathbf{r}-\mathbf{y}/2\rangle$$

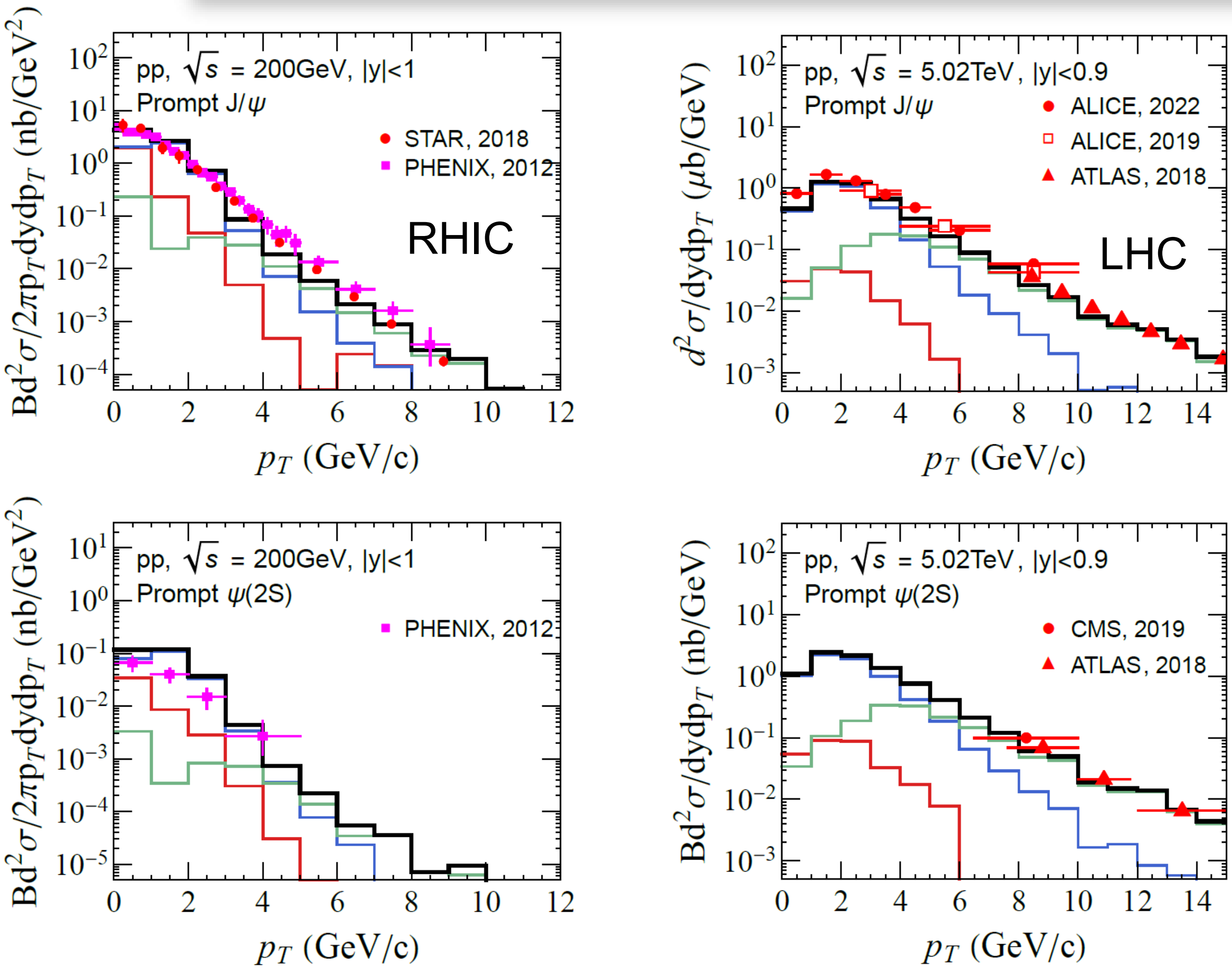
Step 3: Probability that a quarkonium with quantum numbers n,l is produced is given by the overlap integral

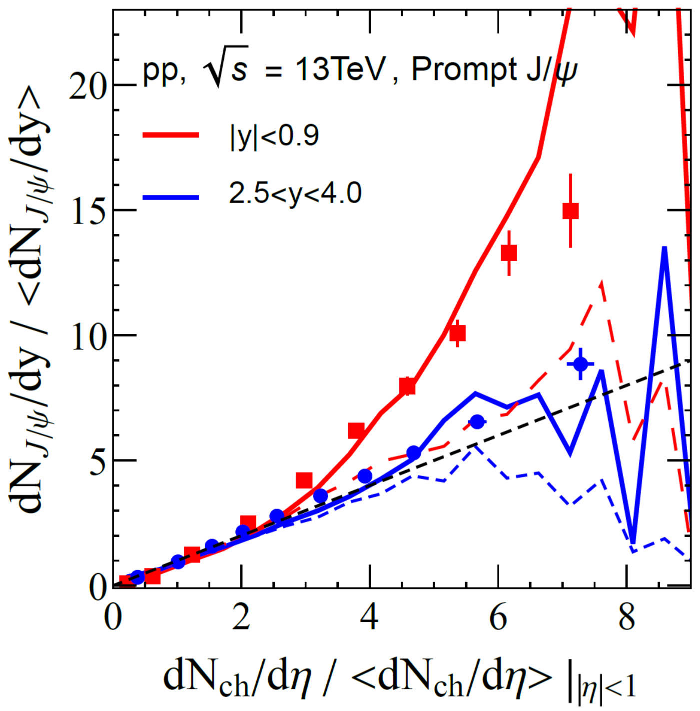
$$\frac{dP^m_{nl}}{d^3\mathbf{P}_{\mathbf{cm}}}=\sum\int\frac{d^3rd^3p}{(2\pi)^6}W^m_{nl}(\mathbf{r},\mathbf{p})W^{(2)}(\mathbf{P}_{\mathbf{cm}},\mathbf{r},\mathbf{p})$$

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

= 2-body $Q\bar{Q}$ phase space distr. by EPOS4

J/ψ and ψ(2s) spectra at RHIC and LHC



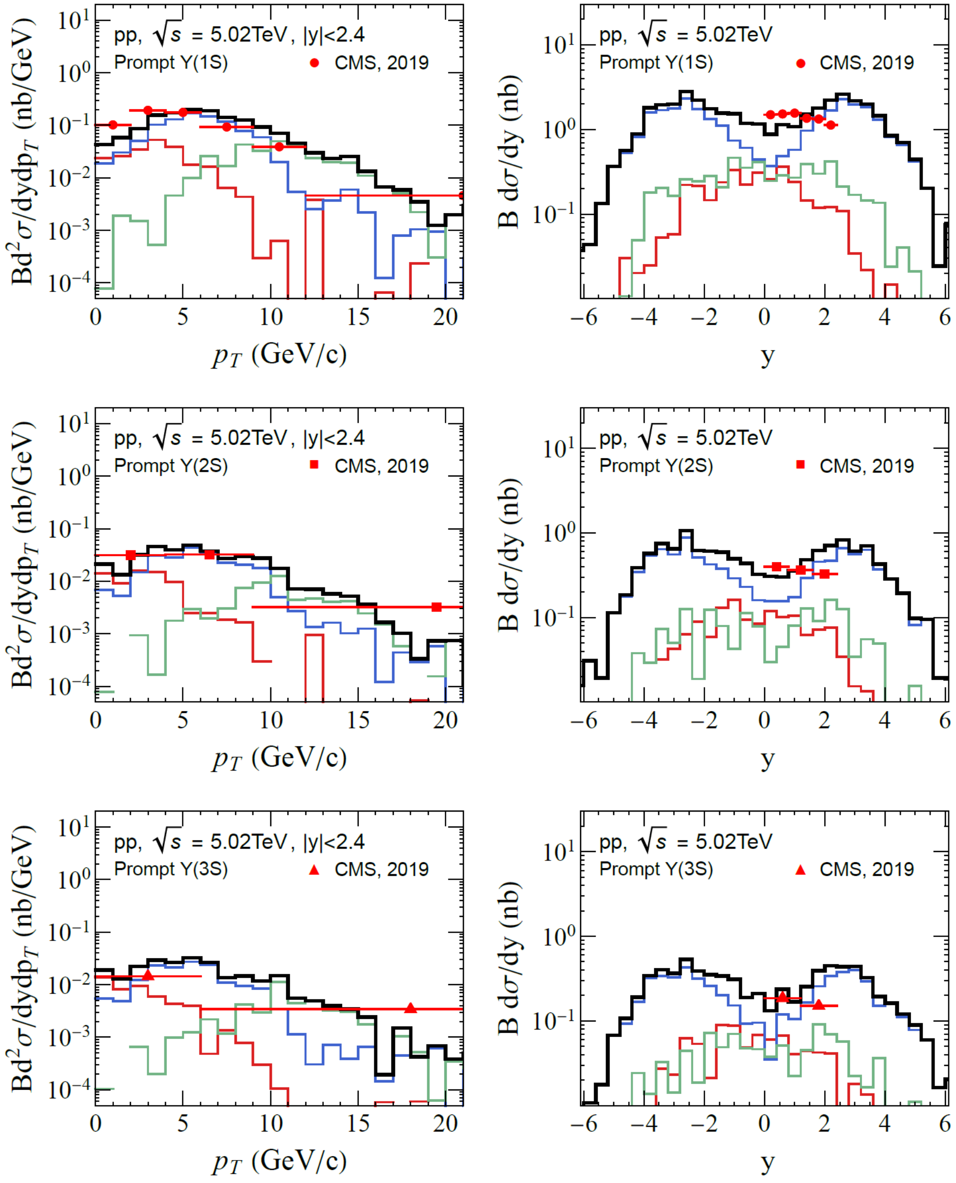


scaled multiplicities at different rapdities

high p_T spectra dominated by gluon splitting
low p_T by flavor excitation

Without understanding of the QCD processes we do not understand the spectra

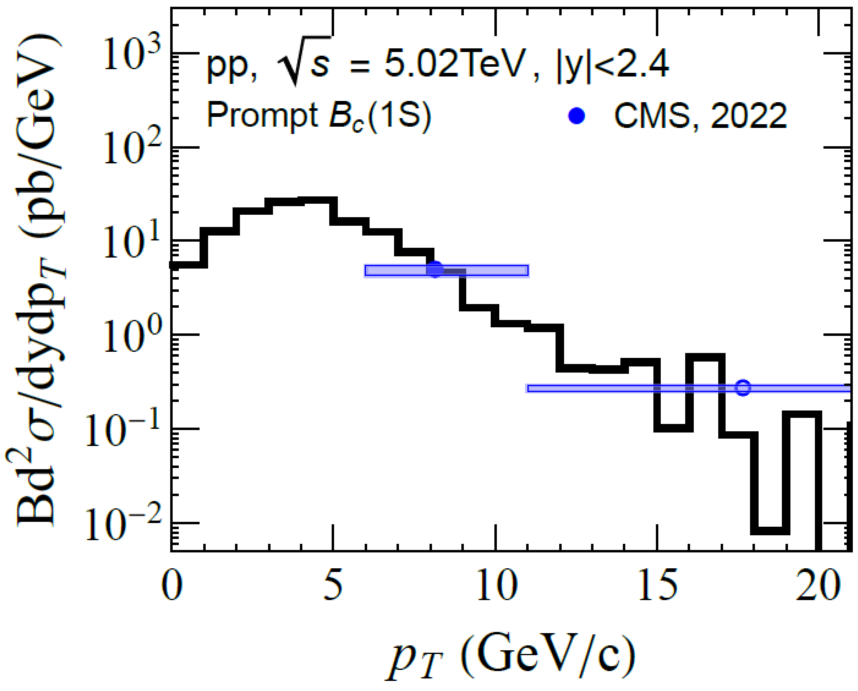
Υ(1),Υ(2),Υ(3) and B_c



high p_T spectra dominated by gluon splitting

in difference to the

high p_T spectra of B mesons, dominated by flavor production



Coming from different production vertices
-> tests the spacial structure of the interaction zone

Conclusion

astonishing heavy flavor results in pp collisions (finite v_2 , $\Lambda_c/D(p_T)$) can be understood if one assumes that in (high multiplicity) pp events, as in heavy ions, a quark gluon plasma is formed if

$$\varepsilon > \varepsilon_0 = 0.57\ \mathrm{GeV/fm^3}$$

The azimuthal $D\bar{D}$ correlation points towards $D\bar{D}$ production by different QCD processes:

In EPOS4HQ The different QCD production processes contribute to the p_T spectra in different ways

high p_T spectra dominated by gluon splitting

low p_T spectra by flavor excitation

the sum of all processes compatible with FONLL

Describing of the production of hidden heavy flavor mesons by a density matrix approach we

reproduce the experimental spectra

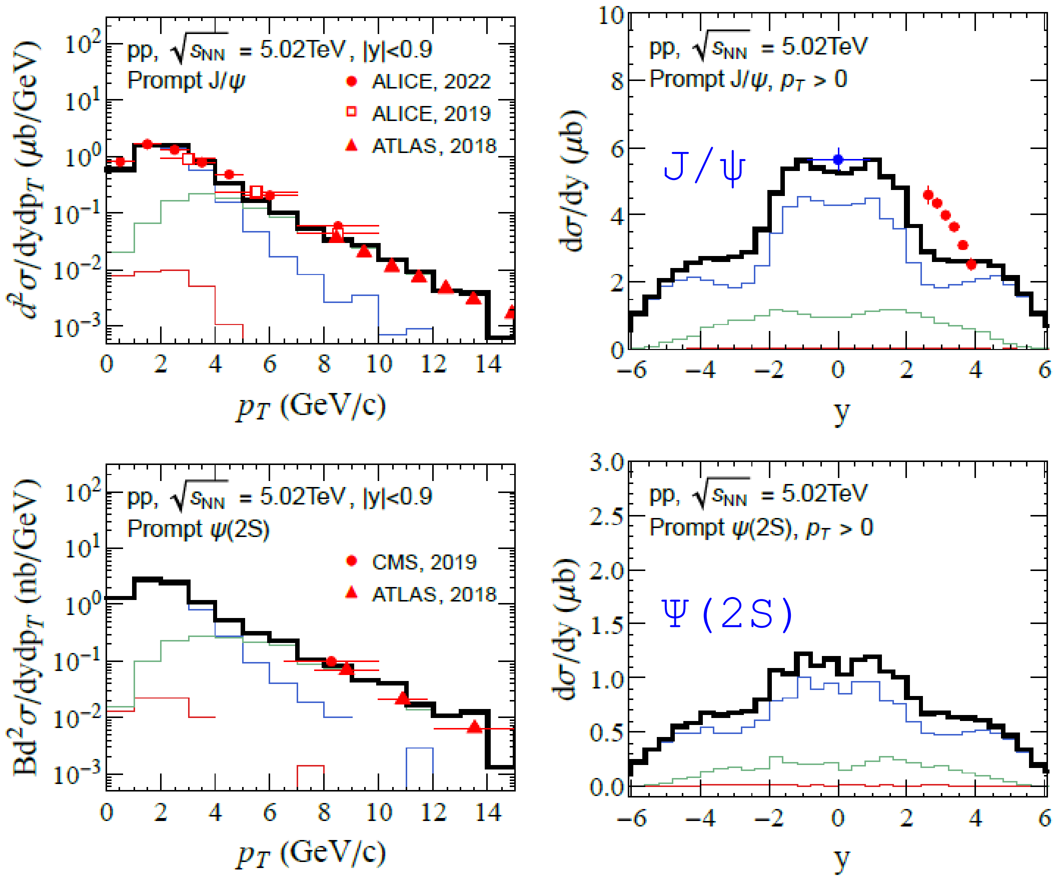
of J/ψ, ψ(2S), Υ(n) and B_c

Detailed analysis shows that the contribution of the QCD processes varies with y and p_T so

run 3 data: perspective to study different aspects of QGP/QCD in detail

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