Multiple scattering in EPOS: Implications for charm production

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D-meson multiplicity vs charged multiplicity

Significant deviation from the diagonal (linear increase) in particular for large $p_t$

ALICE arXiv:1505.00664v1
PYTHIA 8.157
Already understanding a linear increase is a challenge!

(Only recent Pythia versions can do)

Even much more the deviation from linear (towards higher values)
Trying to understand these data in the EPOS framework:

Two important issues:

- Multiple scattering
- Collectivity
EPOS: Based on multiple scattering and flow

Several steps:

1) Initial conditions:
   Gribov-Regge multiple scattering approach, elementary object = Pomeron = parton ladder, using saturation scale $Q_s \propto N_{part} \hat{s}^\lambda$ (CGC)

2) Core-corona approach to separate fluid and jet hadrons

3) Viscous hydrodynamic expansion, $\eta/s = 0.08$

4) Statistical hadronization, final state hadronic cascade

Initial conditions: **Marriage pQCD+GRT+energy sharing**

(Drescher, Hladik, Ostapchenko, Pierog, and Werner, Phys. Rept. 350, 2001)

For pp, pA, AA:

\[
\sigma_{\text{tot}} = \sum_{\text{cut } P} \int \sum_{\text{uncut } P} \int (\text{squared amplitude})
\]

\[\frac{d\sigma_{\text{exclusive}}}{d\hat{s}} \propto \text{cut Pom} : G = \frac{1}{2\hat{s}} 2\text{Im} \left\{ \mathcal{FT}\{T\} \right\}(\hat{s}, b), \quad T = i\hat{s} \sigma_{\text{hard}}(\hat{s}) \exp(R_{\text{hard}}^2 t)\]

Nonlinear effects considered via saturation scale \( Q_s \propto N_{\text{part}} \hat{s}^\lambda \)
\[ \sigma^{\text{tot}} = \int d^2 b \int \prod_{i=1}^{A} d^2 b_i^A d z_i^A \rho_A(\sqrt{(b_i^A)^2 + (z_i^A)^2}) \]
\[ \prod_{j=1}^{B} d^2 b_j^B d z_j^B \rho_B(\sqrt{(b_j^B)^2 + (z_j^B)^2}) \]
\[ \sum_{m_1 l_1} \cdots \sum_{m_{AB} l_{AB}} (1 - \delta_{0 \Sigma m_k}) \int \prod_{k=1}^{AB} \left( \prod_{\mu=1}^{m_k} dx_{k,\mu}^+ dx_{k,\mu}^- \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^+ d\tilde{x}_{k,\lambda}^- \right) \left\{ \prod_{k=1}^{AB} \left( \frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, |\vec{b} + \vec{b}_\pi^A - \vec{b}_\tau^B|) \right) \right. \]
\[ \left. \prod_{\lambda=1}^{l_k} -G(\tilde{x}_{k,\lambda}^+, \tilde{x}_{k,\lambda}^-, s, |\vec{b} + \vec{b}_\pi^A - \vec{b}_\tau^B|) \right) \]
\[ \prod_{i=1}^{A} \left( 1 - \sum_{\pi(k) = i} x_{k,\mu}^+ - \sum_{\pi(k) = i} \tilde{x}_{k,\lambda}^+ \right) \alpha \prod_{j=1}^{B} \left( 1 - \sum_{\tau(k) = j} x_{k,\mu}^- - \sum_{\tau(k) = j} \tilde{x}_{k,\lambda}^- \right) \alpha \} \]
Core-corona procedure (for pp, pA, AA):

Pomeron $\Rightarrow$ parton ladder $\Rightarrow$ flux tube (kinky string)

String segments with high pt escape $\Rightarrow$ corona, the others form the core = initial condition for hydro depending on the local string density.
Core => Hydro evolution (Yuri Karpenko)

Israel-Stewart formulation, $\eta - \tau$ coordinates, $\eta/S = 0.08$, $\zeta/S = 0$

\[
\partial_{;\nu} T^{\mu\nu} = \partial_{\nu} T^{\mu\nu} + \Gamma^{\mu}_{\nu\lambda} T^{\nu\lambda} + \Gamma^{\nu}_{\nu\lambda} T^{\mu\lambda} = 0
\]

\[
\gamma (\partial_t + v_i \partial_i) \pi^{\mu\nu} = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} + I_{\pi}^{\mu\nu}
\]

\[
\gamma (\partial_t + v_i \partial_i) \Pi = -\frac{\Pi - \Pi_{\text{NS}}}{\tau_\Pi} + I_{\Pi}
\]

- $T^{\mu\nu} = \epsilon u^{\mu} u^{\nu} - (p + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}$
- $\partial_{;\nu}$ denotes a covariant derivative,
- $\Delta^{\mu\nu} = g^{\mu\nu} - u^{\mu} u^{\nu}$ is the projector orthogonal to $u^{\mu}$,
- $\pi^{\mu\nu}$, $\Pi$ shear stress tensor, bulk pressure

Freeze out: at 168 MeV, Cooper-Frye $E \frac{dn}{d^3p} = \int d\Sigma \rho^\mu f(\nu p)$, equilibrium distr

Hadronic afterburner: UrQMD

Marcus Bleicher, Jan Steinheimer
Results

Detailed studies of **pt spectra** and **azimuthal anisotropies** (dihadron corr., $v_n$) in pp, pA:


In the following: An example of an **asymmetric space-time evolution** (high mult pp event, 7TeV)
energy density [GeV/fm$^3$] \( (\eta_s = 0.0, \tau = 0.10 \text{ fm/c} ) \)
energy density [GeV/fm$^3$] \((\eta_s = 0.0, \tau = 0.29 \text{ fm/c})\) \(J_0\)
energy density [GeV/fm$^3$] \( (\eta_s = 0.0, \tau = 0.48 \text{ fm/c}) \)
energy density [GeV/fm³] \( (\eta_s = 0.0, \tau = 0.68 \text{ fm/c}) \)
energy density $[\text{GeV/fm}^3]$ \((\eta_s = 0.0, \tau = 0.87 \text{ fm/c})\) J 0
energy density [GeV/fm$^3$] \( (\eta_s = 0.0 , \tau = 1.06 \text{ fm/c}) \) J 0
energy density [GeV/fm$^3$] \((\eta_s = 0.0, \tau = 1.25 \text{ fm/c})\) J 0
energy density $[\text{GeV/fm}^3]$ \hspace{1em} (\eta_s = 0.0, \tau = 1.44 \text{ fm/c}) \hspace{1em} J_0
energy density [GeV/fm$^3$] ($\eta_s = 0.0$, $\tau = 1.63$ fm/c) $J_0$
energy density [GeV/fm$^3$] \( (\eta_s = 0.0, \tau = 1.83 \text{ fm/c}) \) J 0
energy density $[\text{GeV/fm}^3]$ \hspace{1cm} (\eta_s = 0.0 \text{, } \tau = 2.02 \text{ fm/c}) \hspace{1cm} J_0
energy density $[\text{GeV/fm}^3]$ ($\eta_s = 0.0$, $\tau = 2.21 \text{ fm/c}$)
pp @ 7TeV EPOS 3.119

energy density [GeV/fm$^3$]

\( \eta = 0.0, \tau = 2.40 \, \text{fm/c} \)
energy density \([\text{GeV/fm}^3]\) \(\eta_s = 0.0, \tau = 2.59 \text{ fm/c}\) $J_0$
Charm – multiplicity correlations

**Notations** (always at midrapidity)  (D-meson = average $D^+, D^0, D^{*+}$)

- $N_{ch}$: Charged particle multiplicity
- $N_{D1}$: D-meson multiplicity for $1 < p_t < 2 \text{ GeV/c}$
- $N_{D2}$: D-meson multiplicity for $2 < p_t < 4 \text{ GeV/c}$
- $N_{D4}$: D-meson multiplicity for $4 < p_t < 8 \text{ GeV/c}$
- $N_{D8}$: D-meson multiplicity for $8 < p_t < 12 \text{ GeV/c}$
Heavy quark ($Q$) production in EPOS multiple scattering framework

as light quark production
(but non-zero masses: $m_c = 1.3, m_b = 4.2$

In any of the ladders

- during SLC (space-like cascade)
- during TLC (time-like cascade)
- in Born

Implemented by Benjamin Guiot, UTFSM, Valparaiso (former PhD student in Nantes)
Multiple scattering (EPOS3, basic):

\[ N_{Di} \propto N_{ch} \propto N_{Pom} \]

"Natural" linear behavior
(first approximation)

In the following: \[ N_{Pom} \text{ as reference} \]
The actual calculation (EPOS basic)

Indeed essentially a linear increase

... even more than linear!

(in particular for large $p_t$)
More than linear increase amazing:

$D$ multiplicities increase less than $N_{ch}$ vs $N_{Pom}$

How to understand $N_{D8}(N_{ch})$ more than linear?
But crucial: Fluctuations

$N_{ch}$ and $N_{Pom}$ are correlated, but not one-to-one

(=> two-dimensional probability distribution)
We define normalized multiplicities

\[ n = \frac{N}{\langle N \rangle} \]

for \( n_{ch} \) and \( n_{Di} \)

In the following we consider fixed values \( n_{ch}^* \)
of normalized charged multiplicities
Consider $n_{D1}$ for some given $n_{ch}^*$

\[ n_{D1} = \sum_{N_{Pom}} \text{prob}(N_{Pom}, n_{ch}^*) \times n_{D1}(N_{Pom}, n_{ch}^*) \approx n_{ch}^* \]

having used

\[ n_{D1}(N_{Pom}, n_{ch}^*) \approx n_{ch}^* \]
The precise calculation:
(red point)

on the diagonal!
Perfectly linear!
Now $n_{D8}$ for given $n_{ch}^*$

\[ n_{D8} = \sum_{N_{Pom}} \text{prob}(N_{Pom}, n_{ch}^*) \times n_{D8}(N_{Pom}, n_{ch}^*) > n_{ch}^* \]

because $n_{D8}(N_{Pom}, n_{ch}^*)$ increases strongly towards small $N_{Pom}$
The precise calculation:
(red point)

above the diagonal!
non-linear!
More than linear increase since

- The number of Pomerons fluctuates for given multiplicity

- \( N_{D8} \) increases strongly towards small \( N_{\text{Pom}} \) for given multiplicity

\[ \Rightarrow \text{it is favored to produce high } p_t \text{ D mesons for fewer (and more energetic) Pomerons} \]
The effect is actually too small!

Too little deviation from the diagonal in particular for large $p_t$
But anyhow, basic EPOS (w/o hydro) reproduces neither spectra nor correlations

=> full approach (EPOS w hydro + cascade)

(with or without hadronic cascade makes no difference)
Significant non-linear increase!
How to understand the increased non-linearity?

Little change for $n_{Di}$
(as expected)

But significant reduction of $n_{ch}$
Not the charm production is increased with increasing “collision activity”

but the charged particle multiplicity is reduced when including a hydrodynamical expansion

Collision activity = Pomeron number
Why such a multiplicity reduction?

**Basic EPOS:**

Pomerons > Strings > String fragmentation

(independent of event activity)

**Full model:**

Pomerons > Strings > Fluid, collectivity

(collective energy increases with event activity)
Why is the non-linearity of $N_{Di}(N_{ch})$ more pronounced at high pt?

Naive expectation:
$N_{ch}$ reduction should affect all pt ranges in the same way...
Pt dependence

Broader $N_{\text{Pom}}$ distribution with hydro + strongly dropping $n_{D8}$ makes big effect
Summary

Significant non-linear increase of $N_{Di}(N_{ch})$ (in particular for high pt) understandable in terms of multiple scattering and flow