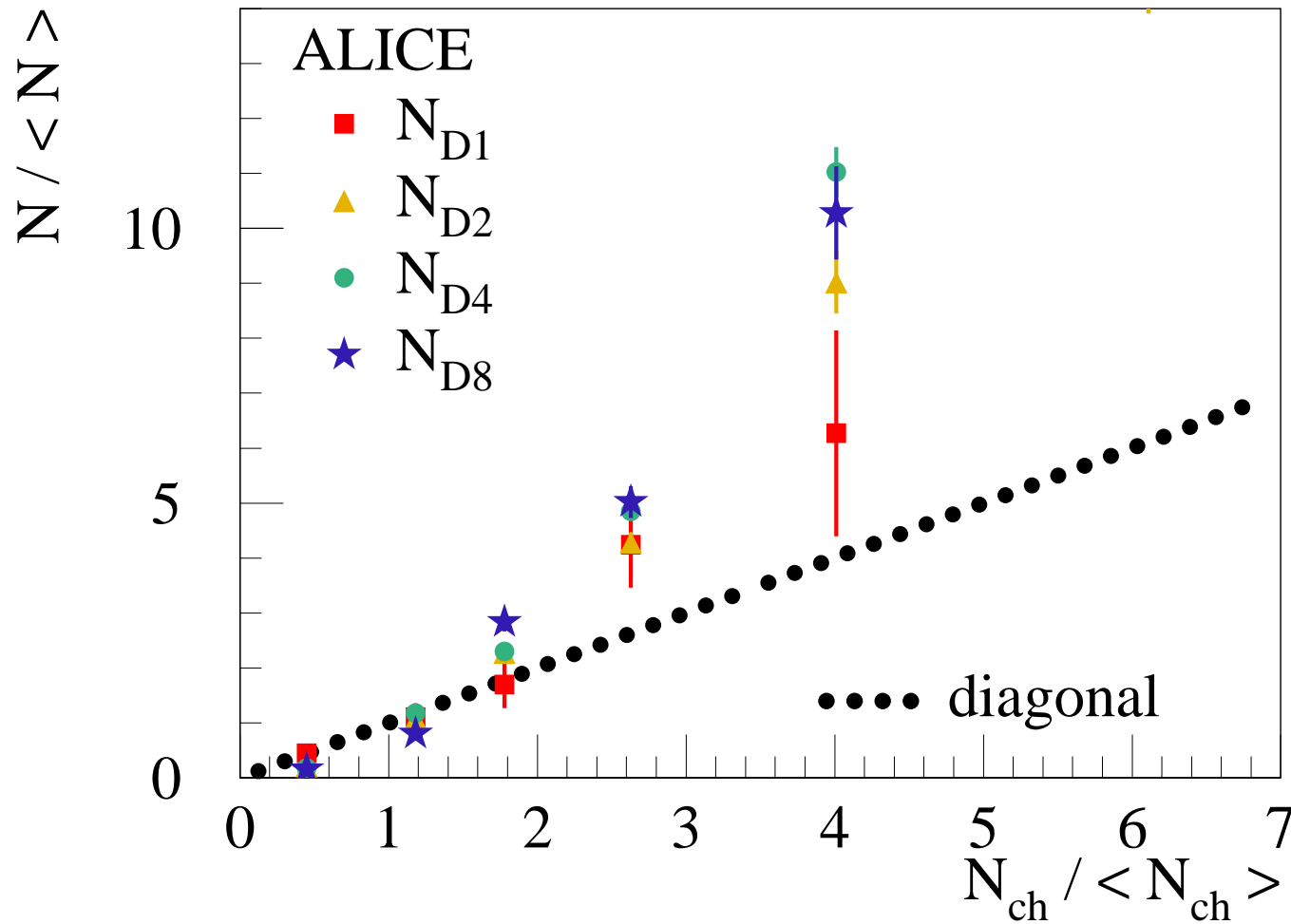


Charm production in high multiplicity pp events

K.W. in collaboration with

B. Guiot, Iu. Karpenko, T. Pierog, G. Sophys

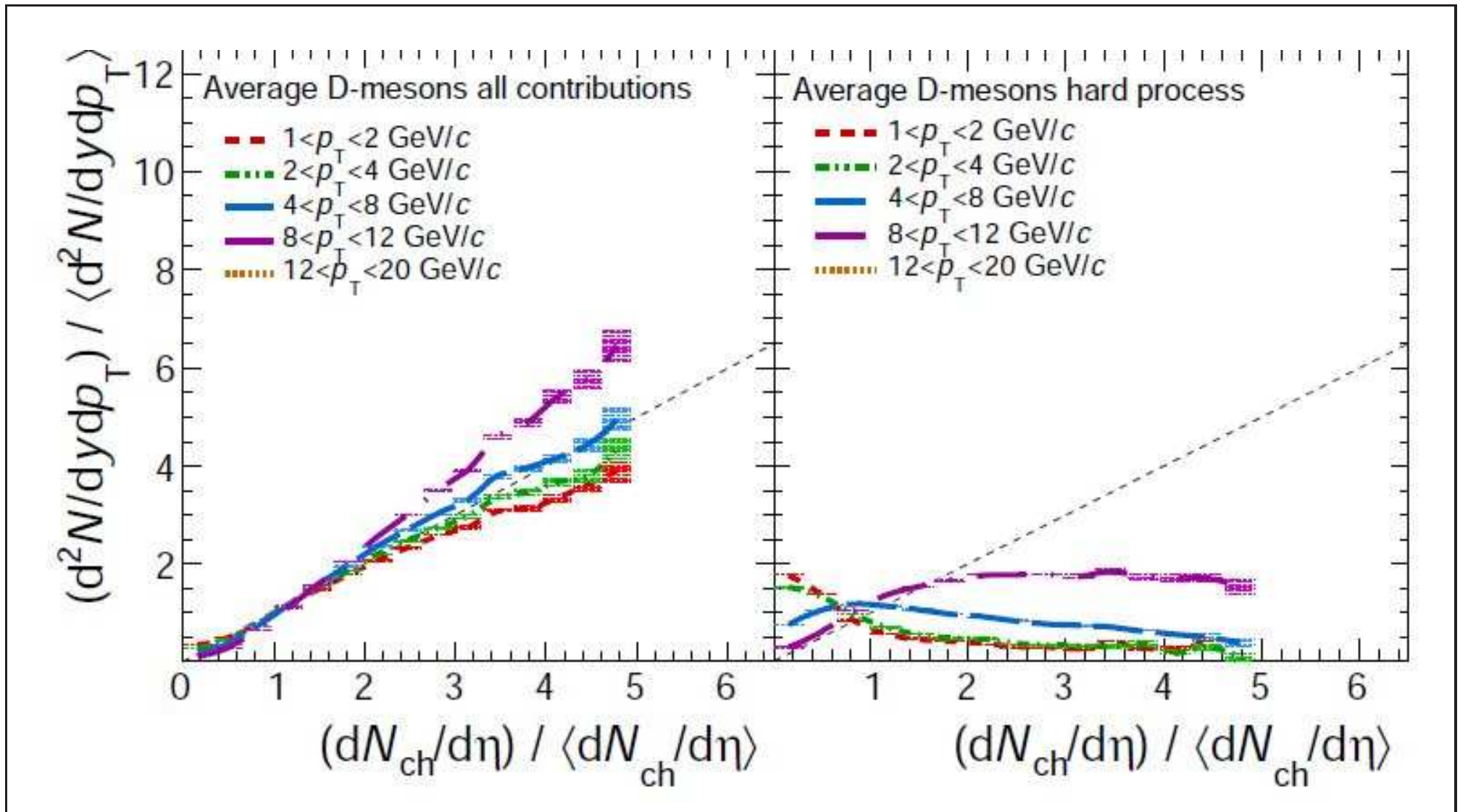
D multiplicity vs charged multiplicity in pp



Significant deviation from the diagonal (linear increase)

in particular for large p_t

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 (even in pp!):

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**, $\eta/s = 0.08$

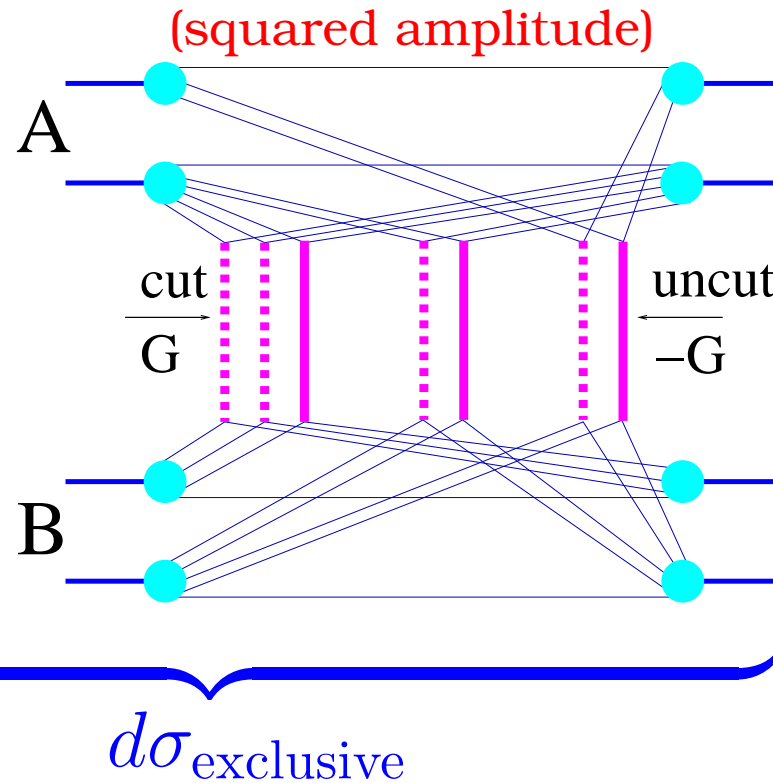
4) Statistical hadronization, final state hadronic cascade

Initial conditions: Marriage pQCD+GRT+energy sharing

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

For pp, pA, AA:

$$\sigma^{\text{tot}} = \sum_{\text{cut P}} \int \sum_{\text{uncut P}} \int$$



$$\text{cut Pom} : G = \frac{1}{2\hat{s}} 2\text{Im} \{ \mathcal{FT} \{ T \} \} (\hat{s}, b), \quad T = i\hat{s} \sigma_{\text{hard}}(\hat{s}) \exp(R_{\text{hard}}^2 t)$$

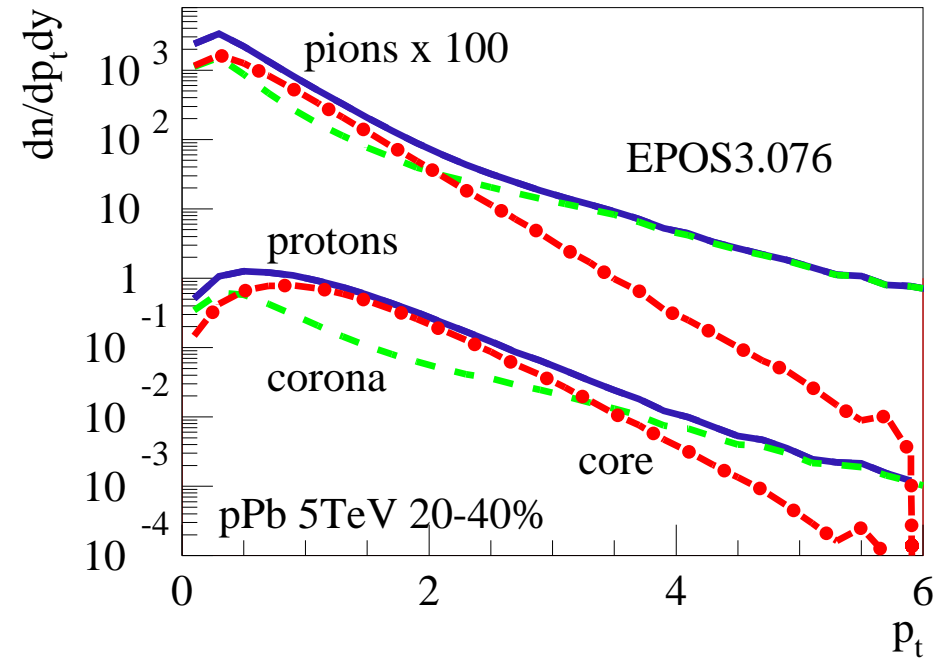
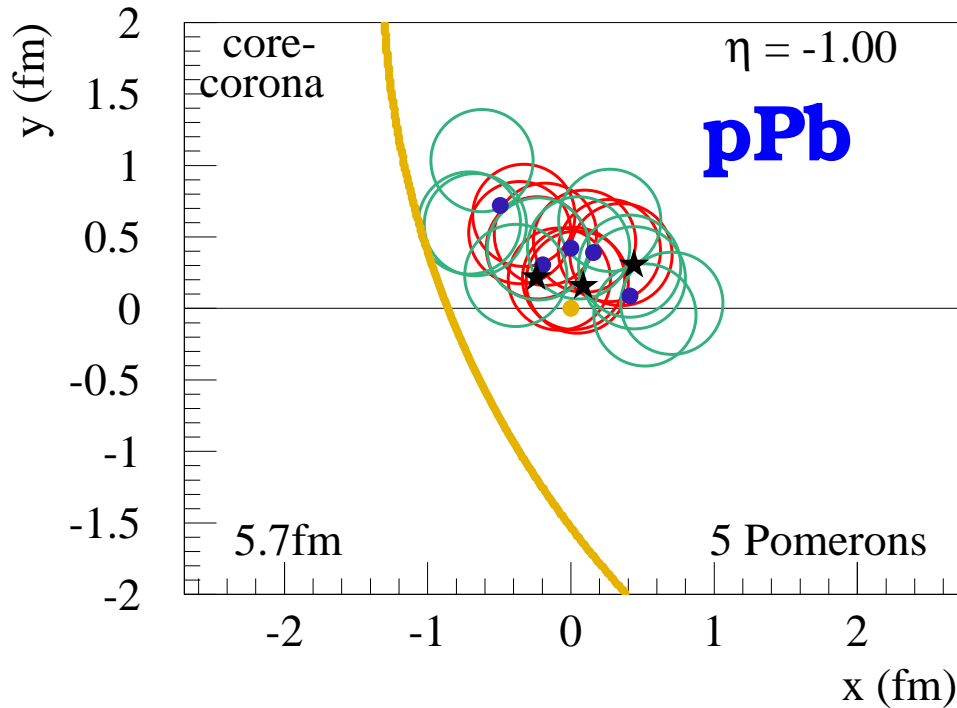
Nonlinear effects considered via saturation scale $Q_s \propto N_{\text{part}} \hat{s}^\lambda$

$$\begin{aligned}
 \sigma^{\text{tot}} = & \int d^2b \int \prod_{i=1}^A d^2b_i^A dz_i^A \rho_A(\sqrt{(b_i^A)^2 + (z_i^A)^2}) \\
 & \prod_{j=1}^B d^2b_j^B dz_j^B \rho_B(\sqrt{(b_j^B)^2 + (z_j^B)^2}) \\
 & \sum_{m_1 l_1} \dots \sum_{m_{AB} l_{AB}} (1 - \delta_{0 \Sigma m_k}) \int \prod_{k=1}^{AB} \left(\prod_{\mu=1}^{m_k} dx_{k,\mu}^+ dx_{k,\mu}^- \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^+ d\tilde{x}_{k,\lambda}^- \right) \left\{ \right. \\
 & \prod_{k=1}^{AB} \left(\frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, |\vec{b} + \vec{b}_{\pi(k)}^A - \vec{b}_{\tau(k)}^B|) \right. \\
 & \left. \left. \prod_{\lambda=1}^{l_k} -G(\tilde{x}_{k,\lambda}^+, \tilde{x}_{k,\lambda}^-, s, |\vec{b} + \vec{b}_{\pi(k)}^A - \vec{b}_{\tau(k)}^B|) \right) \right\} \\
 & \prod_{i=1}^A \left(1 - \sum_{\pi(k)=i} x_{k,\mu}^+ - \sum_{\pi(k)=i} \tilde{x}_{k,\lambda}^+ \right)^\alpha \prod_{j=1}^B \left(1 - \sum_{\tau(k)=j} x_{k,\mu}^- - \sum_{\tau(k)=j} \tilde{x}_{k,\lambda}^- \right)^\alpha \left. \right\}
 \end{aligned}$$

Core-corona procedure (for pp, pA, AA):

Pomeron => parton ladder => flux tube (kinky string)

String segments with high p_t escape => **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, $\eta/S = 0.08$, $\zeta/S = 0$

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma_{\nu\lambda}^\mu T^{\nu\lambda} + \Gamma_{\nu\lambda}^\nu T^{\mu\lambda} = 0$$

$$\gamma (\partial_t + v_i \partial_i) \pi^{\mu\nu} = -\frac{\pi^{\mu\nu} - \pi_{\text{NS}}^{\mu\nu}}{\tau_\pi} + I_\pi^{\mu\nu} \quad \gamma (\partial_t + v_i \partial_i) \Pi = -\frac{\Pi - \Pi_{\text{NS}}}{\tau_\Pi} + I_\Pi$$

- | | |
|--|---|
| <input type="checkbox"/> $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}$, | <input type="checkbox"/> $\pi_{\text{NS}}^{\mu\nu} = \eta (\Delta^{\mu\lambda} \partial_{;\lambda} u^\nu + \Delta^{\nu\lambda} \partial_{;\lambda} u^\mu) - \frac{2}{3} \eta \Delta^{\mu\nu} \partial_{;\lambda} u^\lambda$ |
| <input type="checkbox"/> $\partial_{;\nu}$ denotes a covariant derivative, | <input type="checkbox"/> $\Pi_{\text{NS}} = -\zeta \partial_{;\lambda} u^\lambda$ |
| <input type="checkbox"/> $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ is the projector orthogonal to u^μ , | <input type="checkbox"/> $I_\pi^{\mu\nu} = -\frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^\gamma - [u^\nu \pi^{\mu\beta} + u^\mu \pi^{\nu\beta}] u^\lambda \partial_{;\lambda} u_\beta$ |
| <input type="checkbox"/> $\pi^{\mu\nu}$, Π shear stress tensor, bulk pressure | <input type="checkbox"/> $I_\Pi = -\frac{4}{3} \Pi \partial_{;\gamma} u^\gamma$ |

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

Hadronic afterburner: UrQMD

Marcus Bleicher, Jan Steinheimer

Results

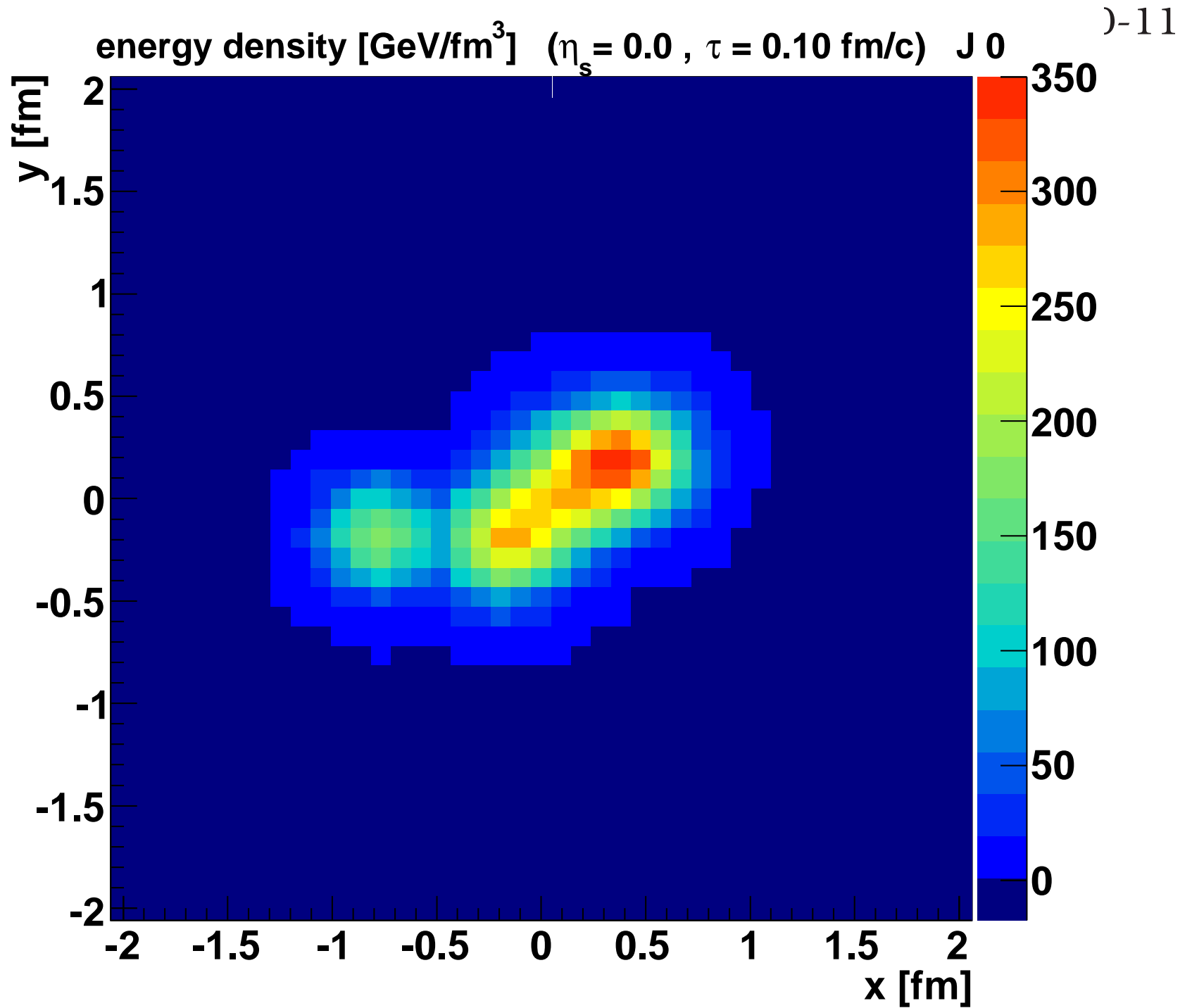
Detailed studies of **pt spectra**
and **azimuthal anisotropies** (dihadron corr., v_n) in pp, pA:

- arXiv:1312.1233 [nucl-th]. Published in Phys.Rev. C89 (2014) 6, 064903.
- arXiv:1307.4379 [nucl-th]. Published in Phys.Rev.Lett. 112 (2014) 23, 232301.
- arXiv:1011.0375 [hep-ph]. Published in Phys.Rev.Lett. 106 (2011) 122004
- arXiv:1004.0805 [nucl-th]. Published in Phys.Rev. C82 (2010) 044904.

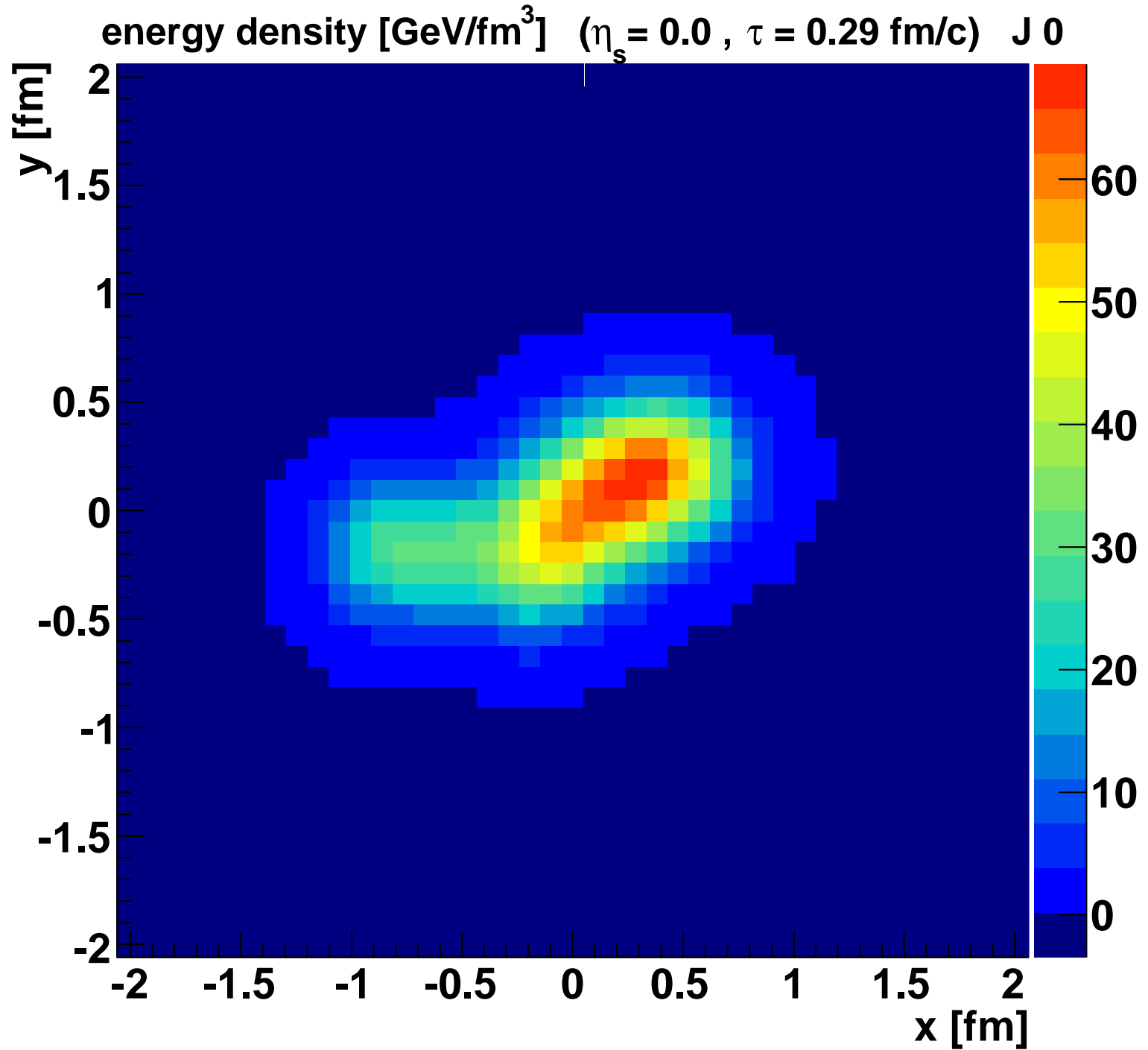
In the following : An example of an

asymmetric space-time evolution (high mult pp event, 7TeV)

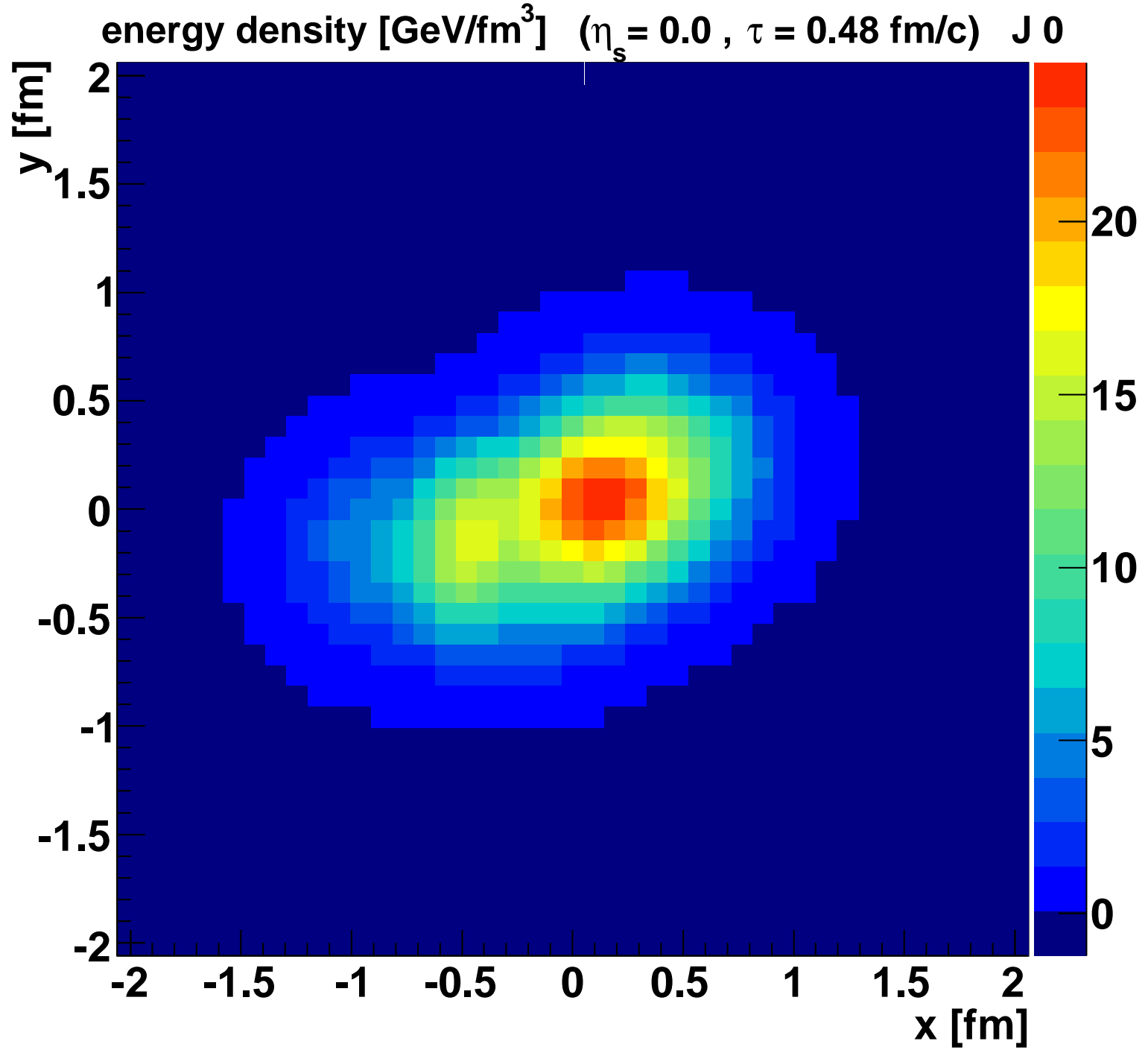
pp @ 7TeV EPOS 3.119



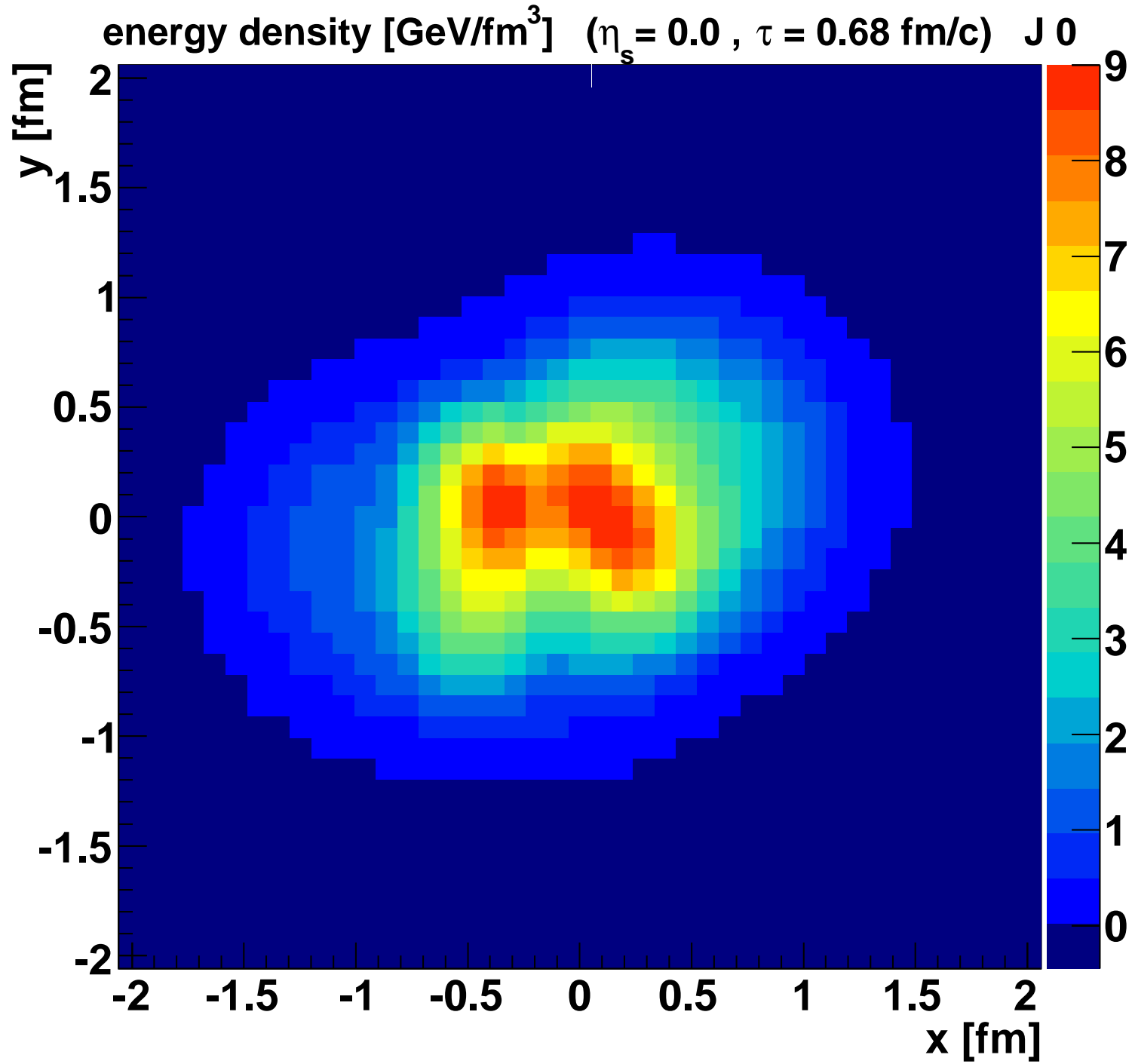
pp @ 7TeV EPOS 3.119



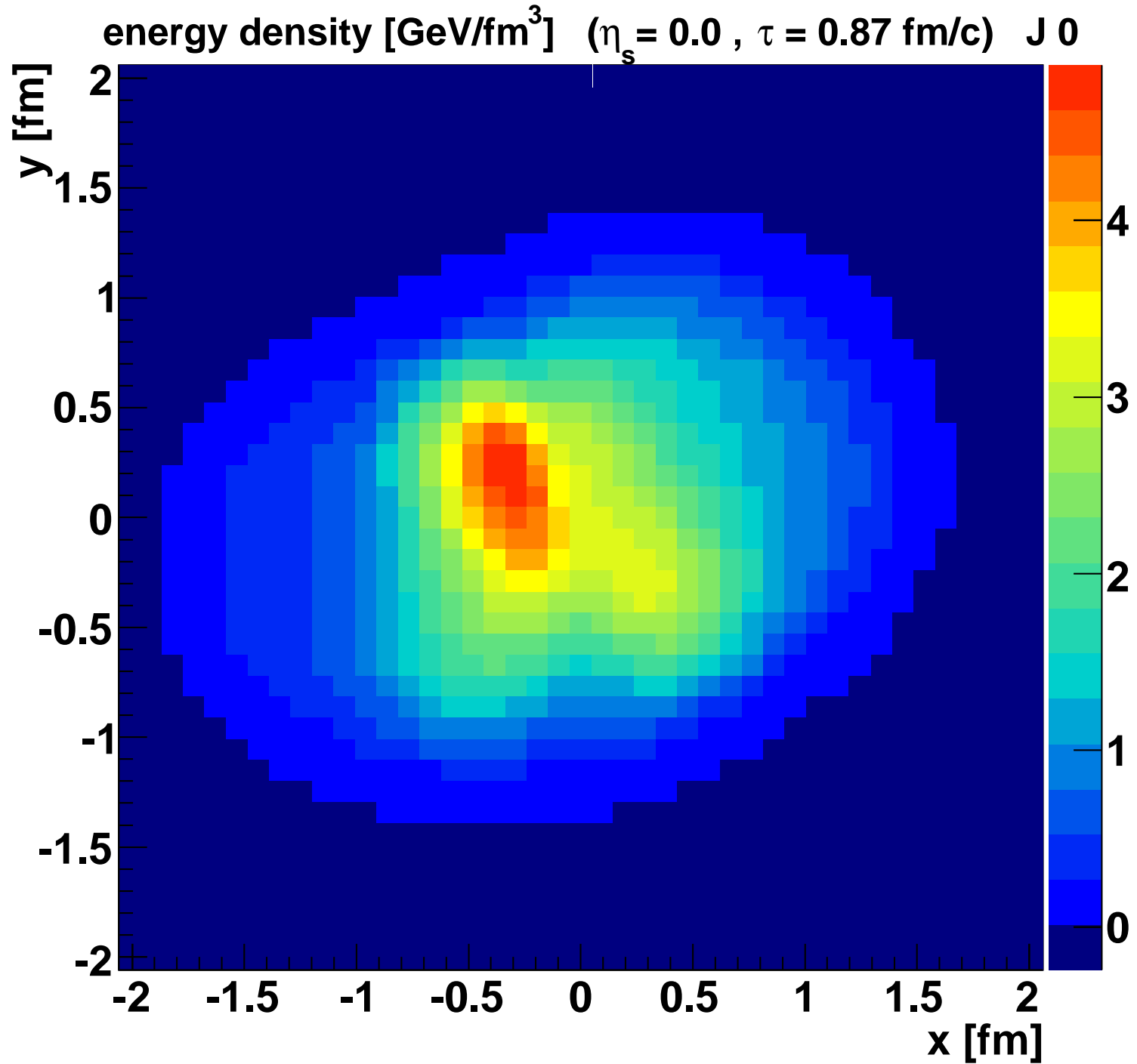
pp @ 7TeV EPOS 3.119



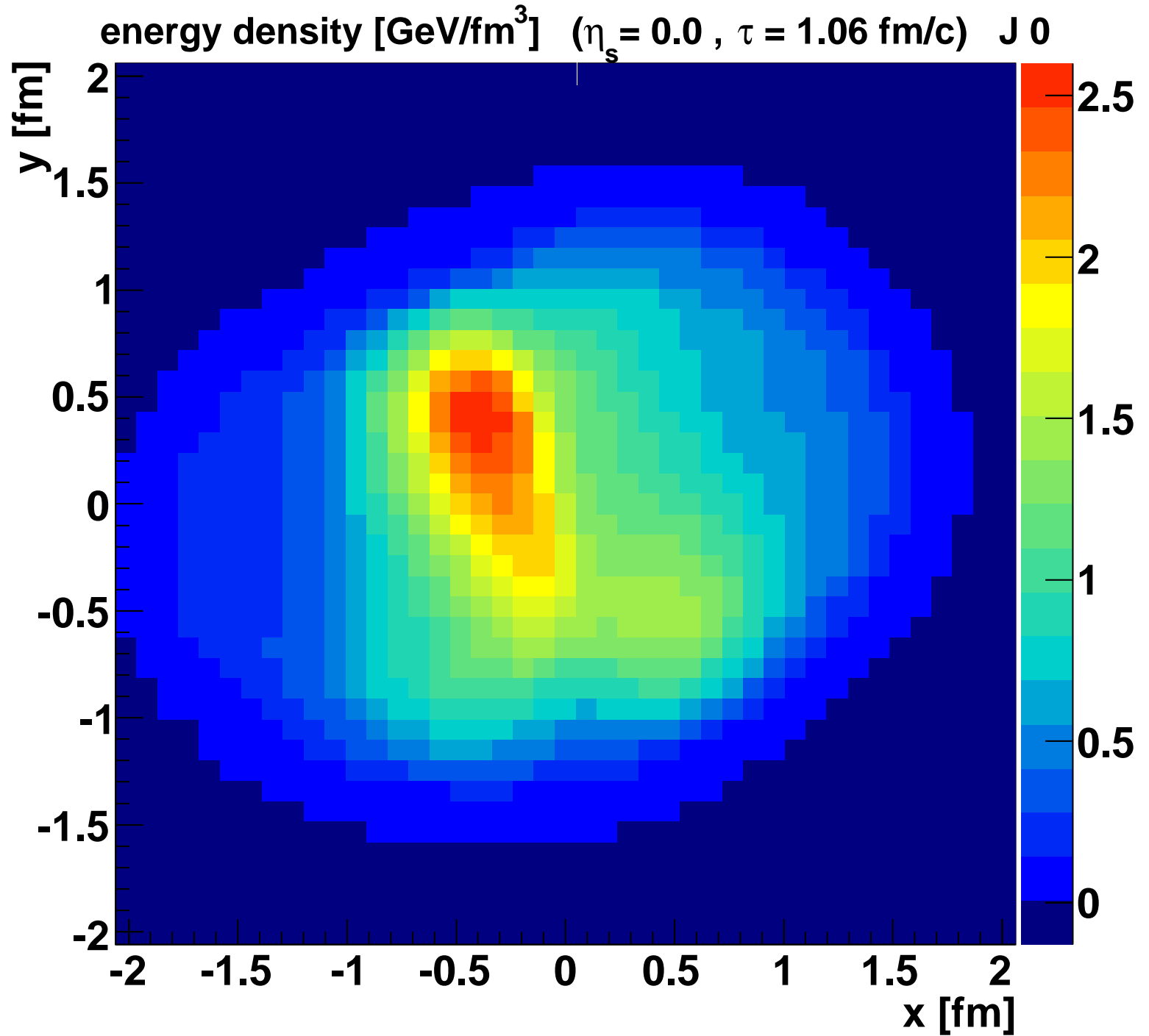
pp @ 7TeV EPOS 3.119



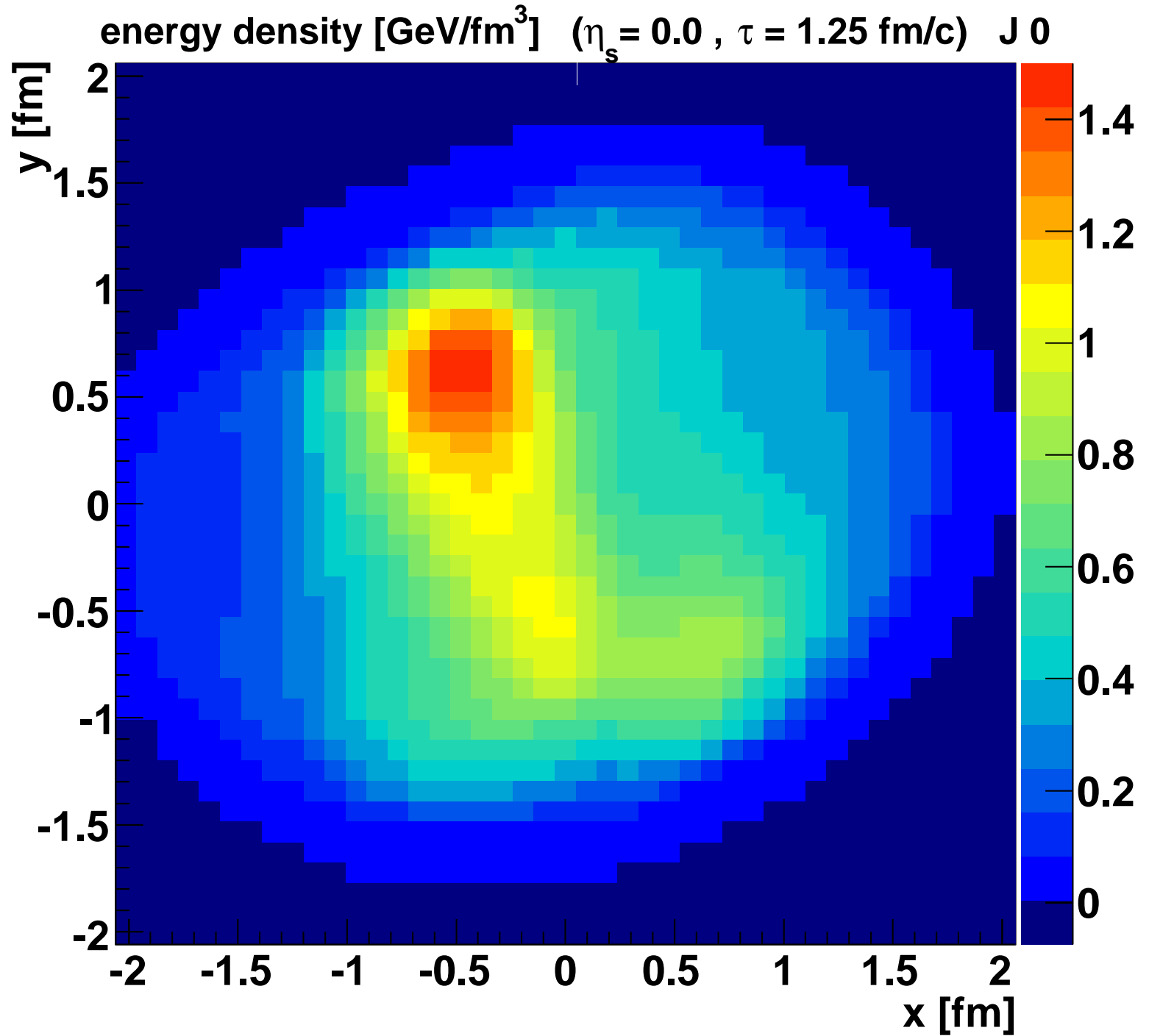
pp @ 7TeV EPOS 3.119



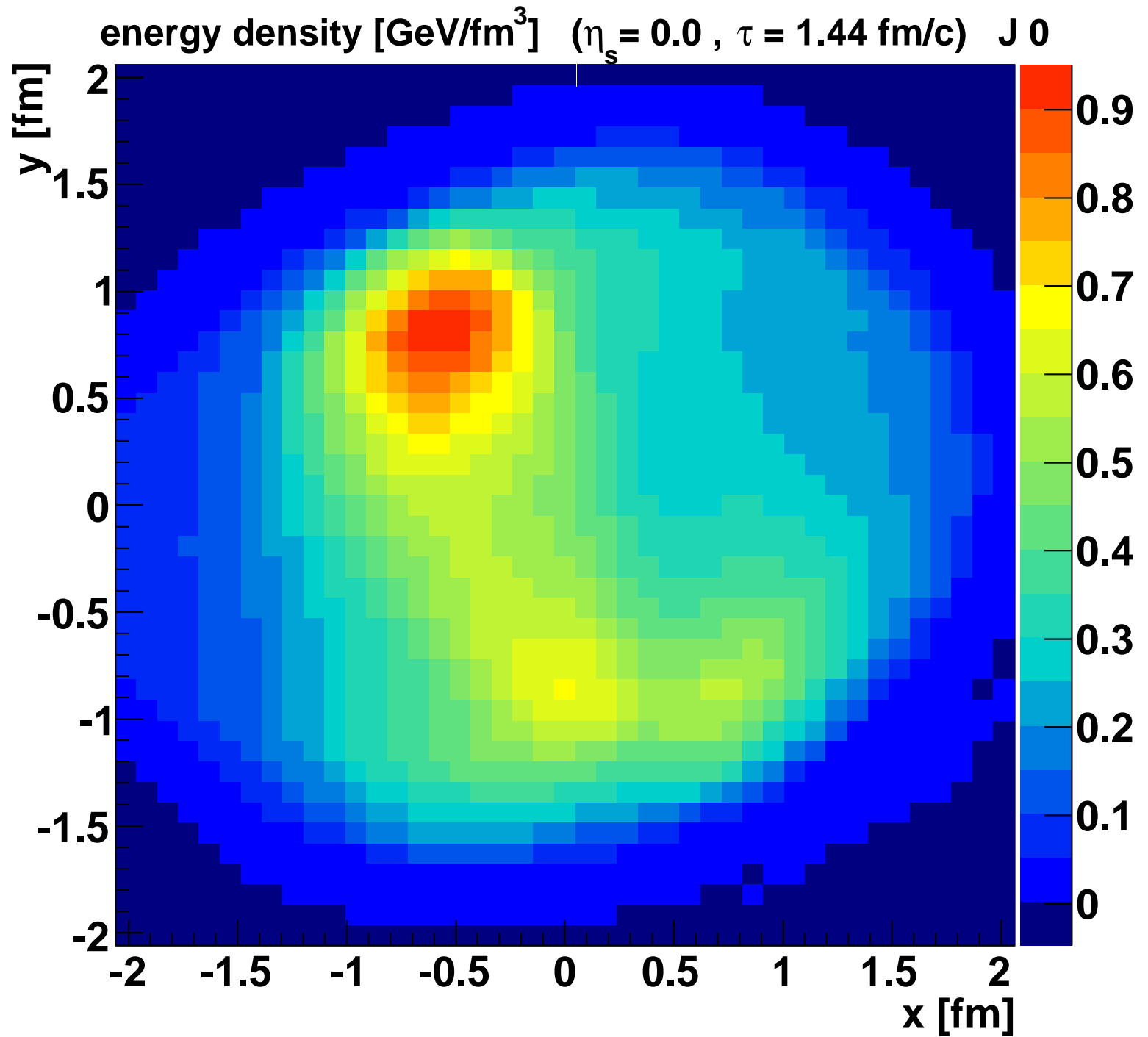
pp @ 7TeV EPOS 3.119



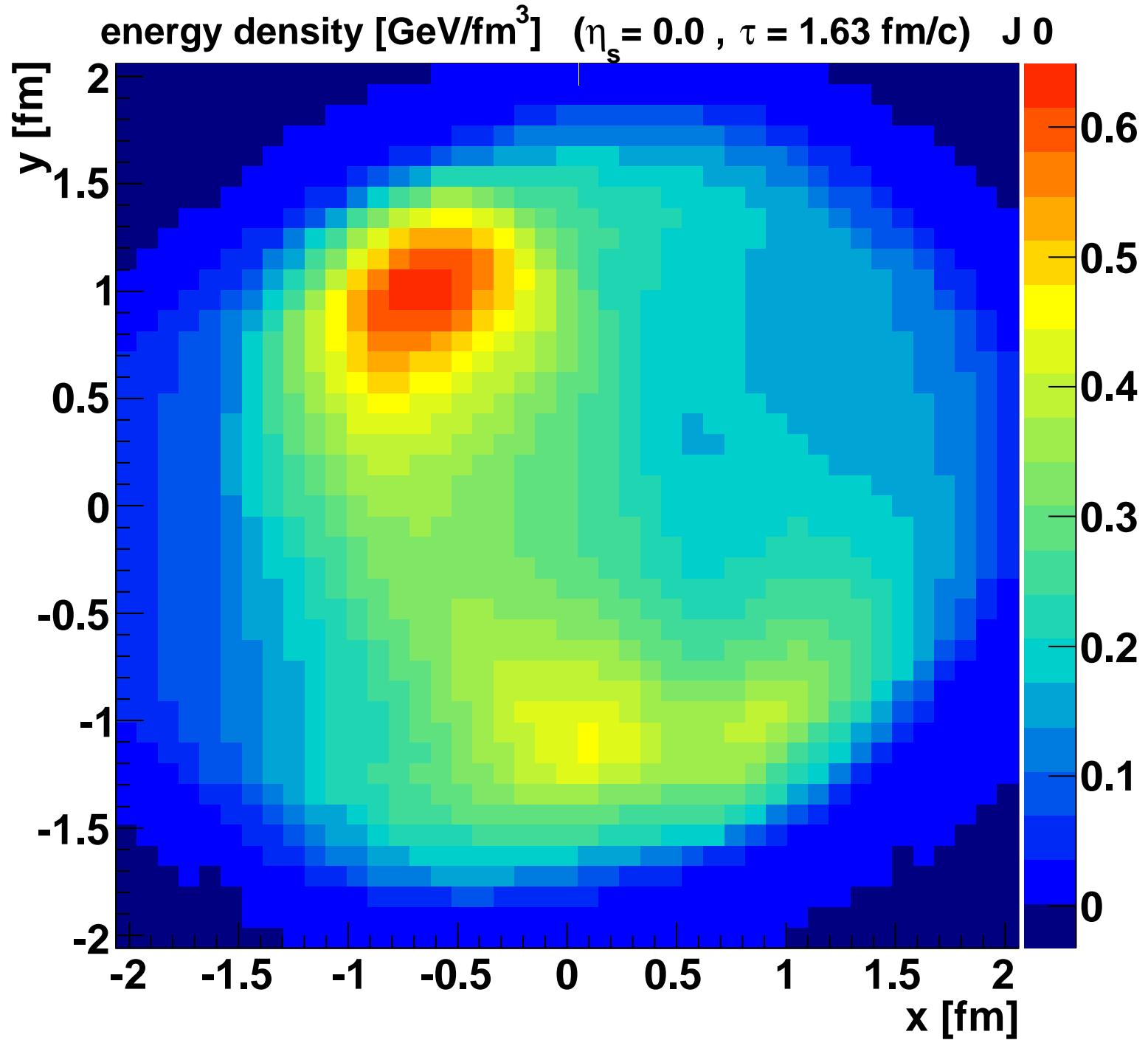
pp @ 7TeV EPOS 3.119



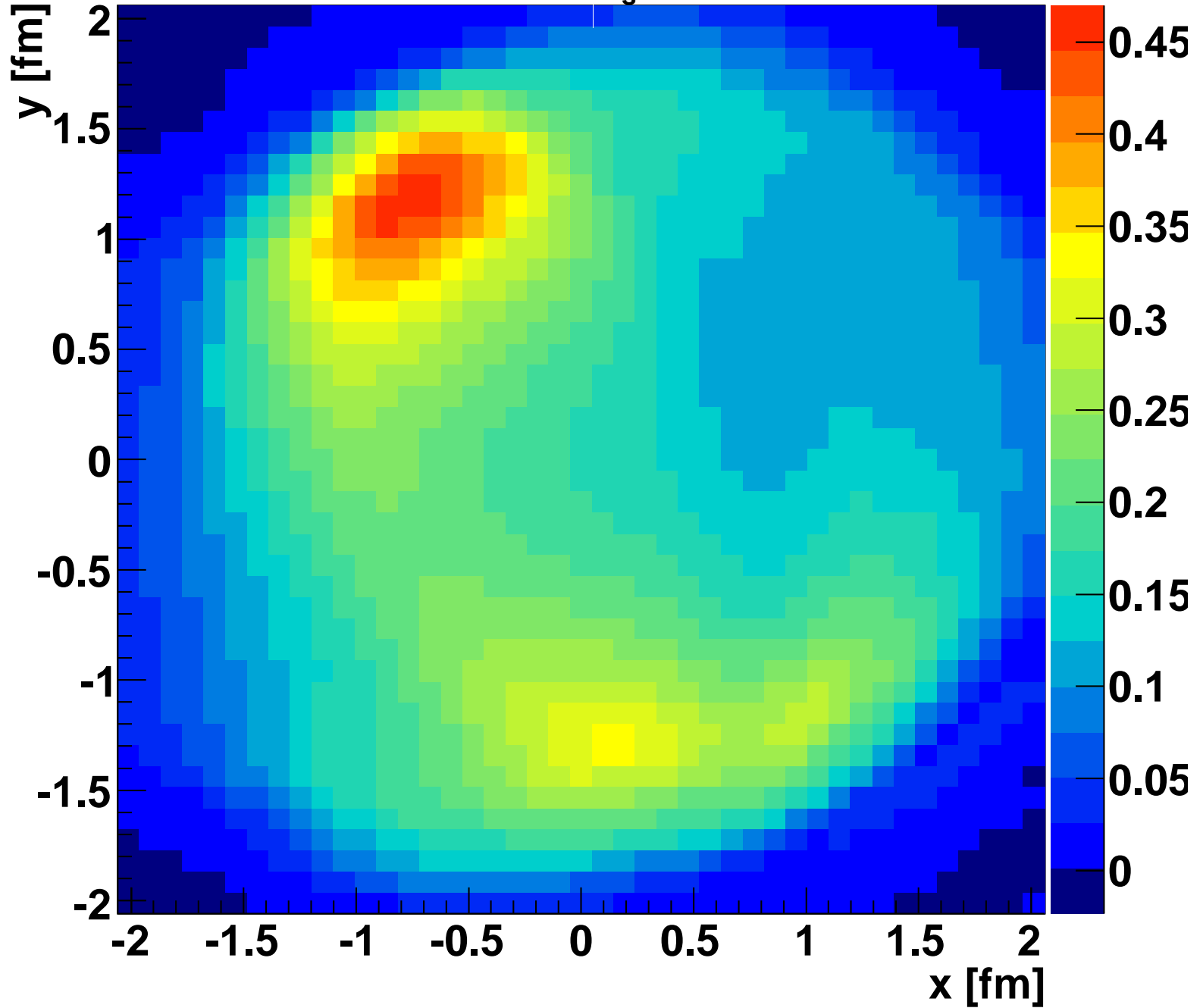
pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119

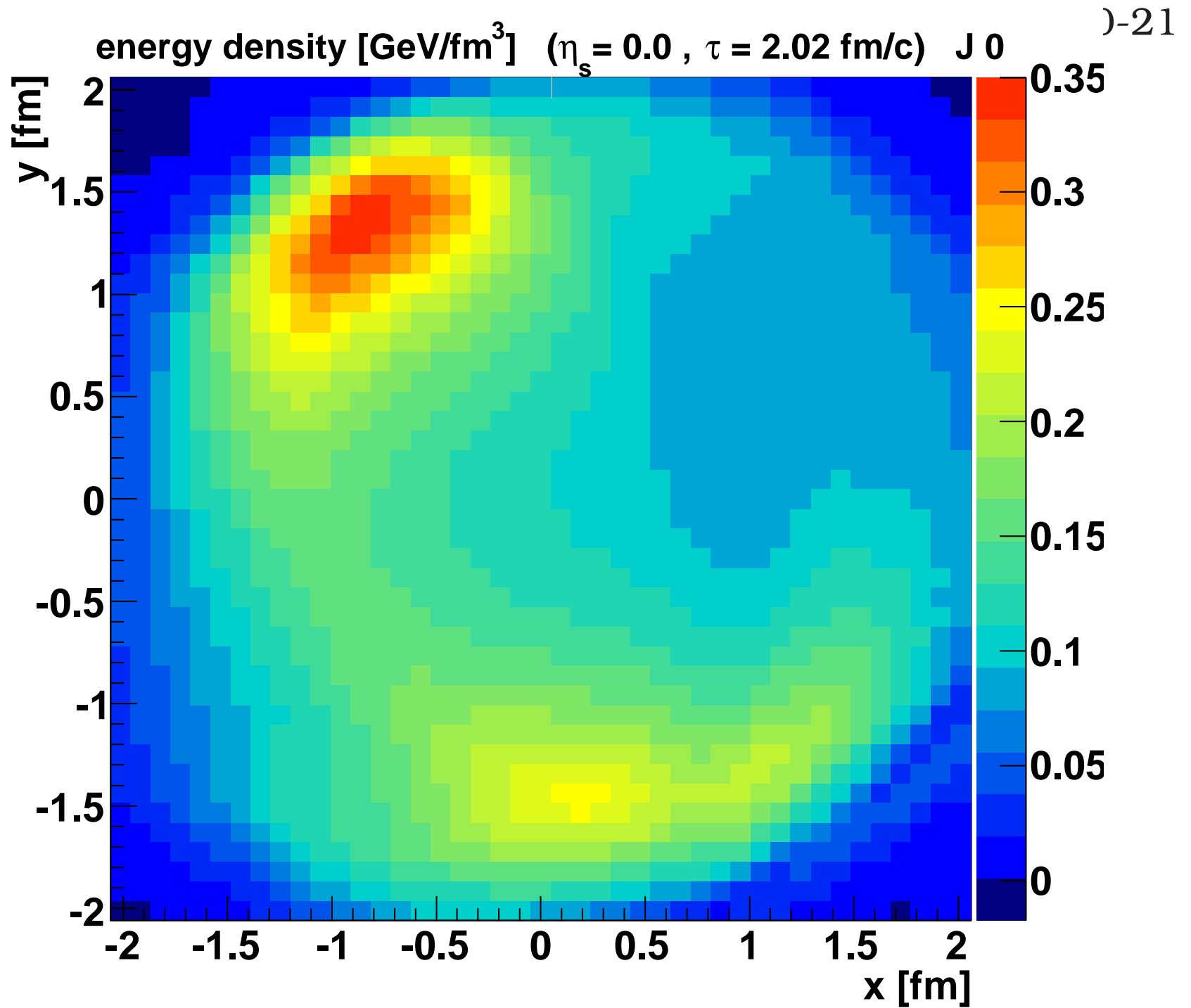


energy density [GeV/fm³] ($\eta_s = 0.0$, $\tau = 1.83$ fm/c) J 0

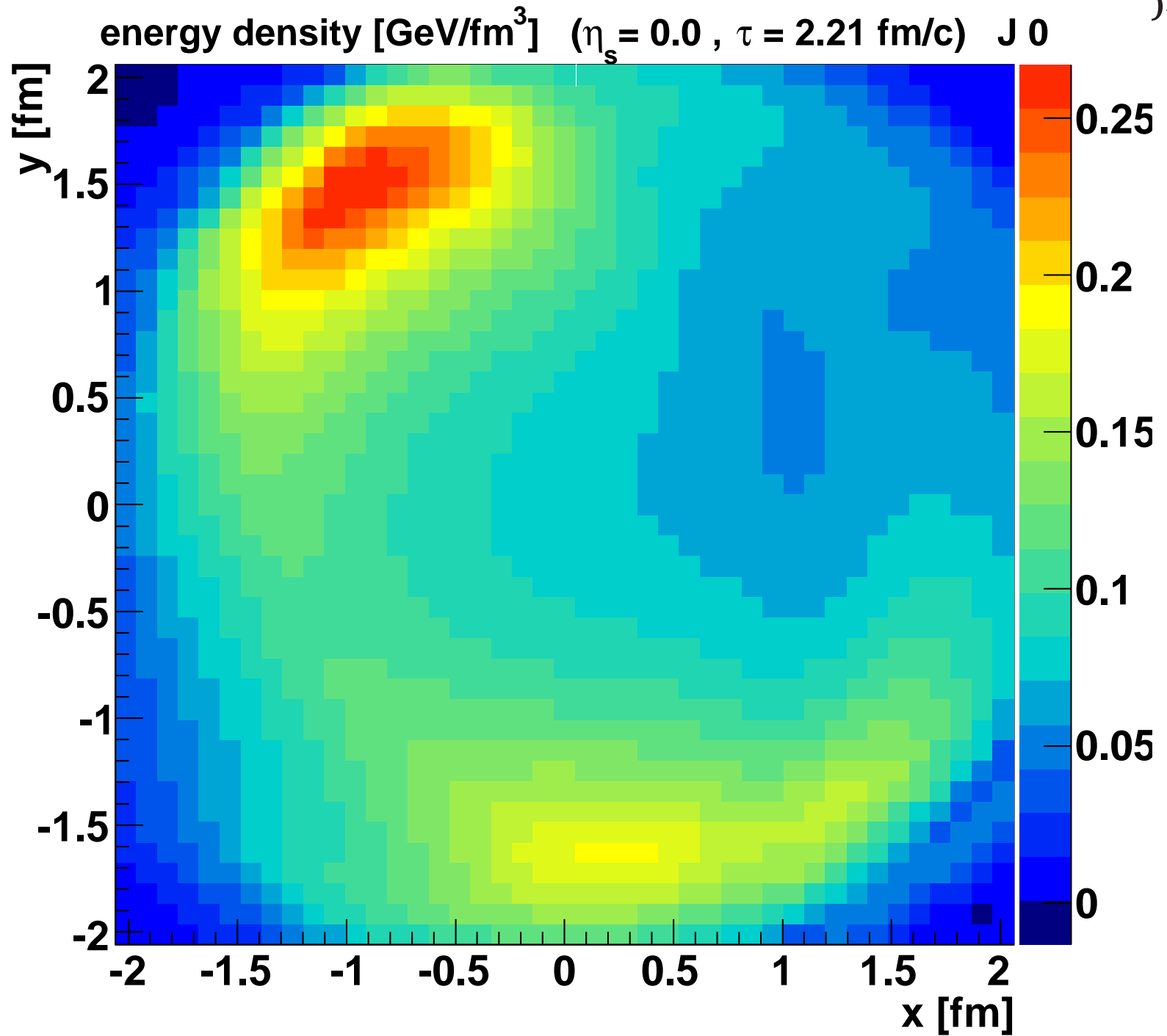


pp @ 7TeV EPOS 3.119

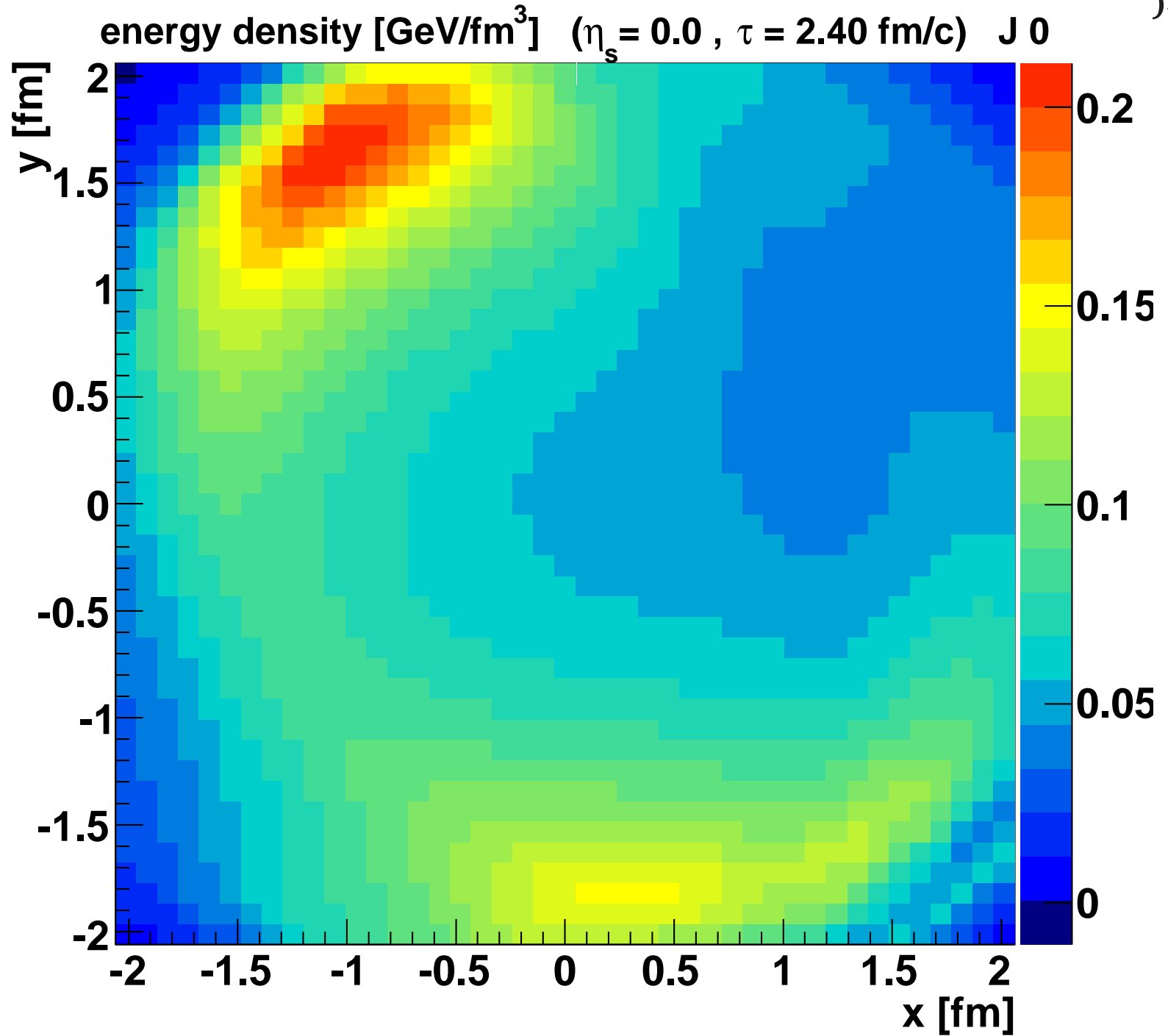
pp @ 7TeV EPOS 3.119



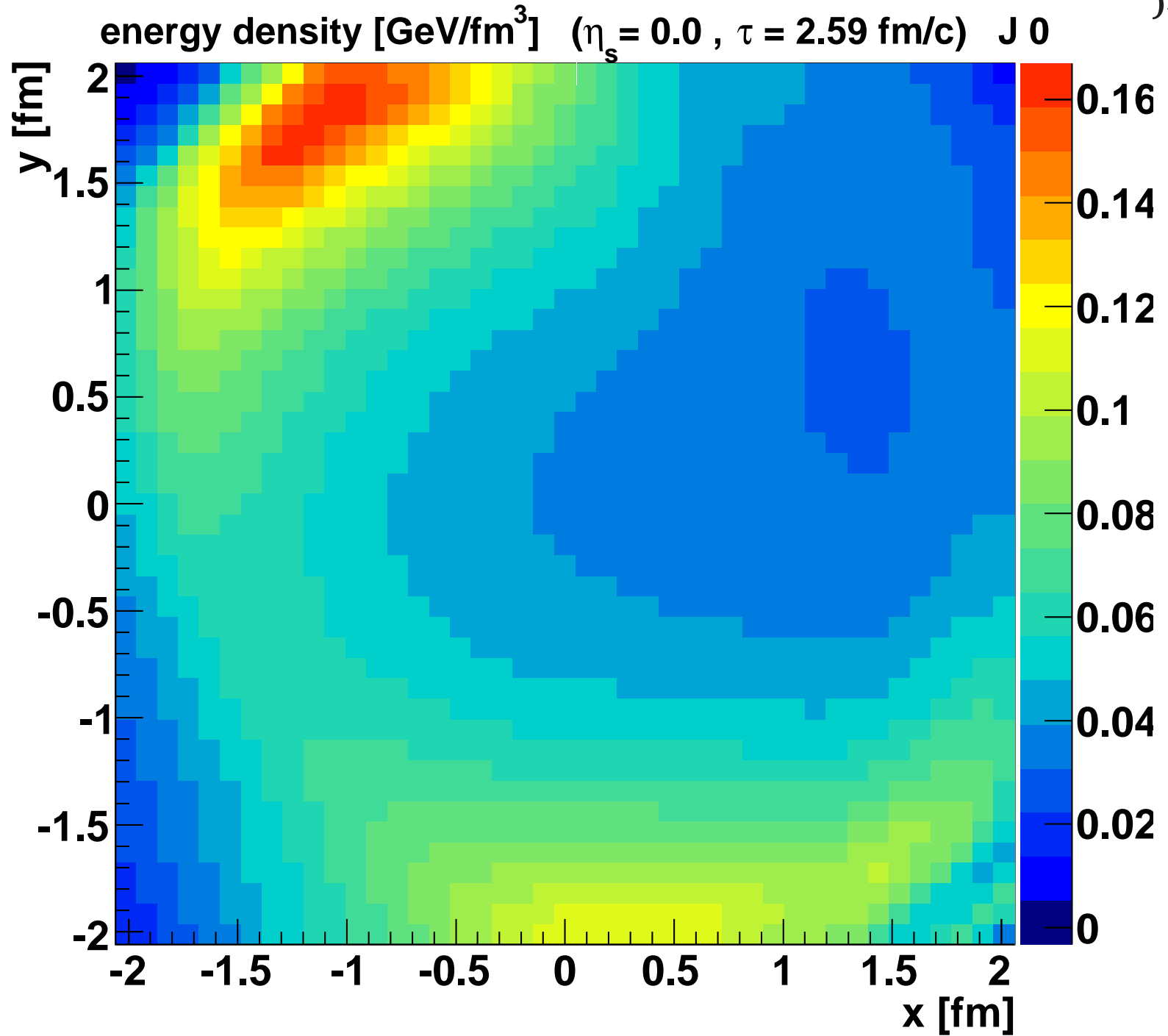
pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



pp @ 7TeV EPOS 3.119



Charm – multiplicity correlations

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

N_{ch} : Charged particle multiplicity

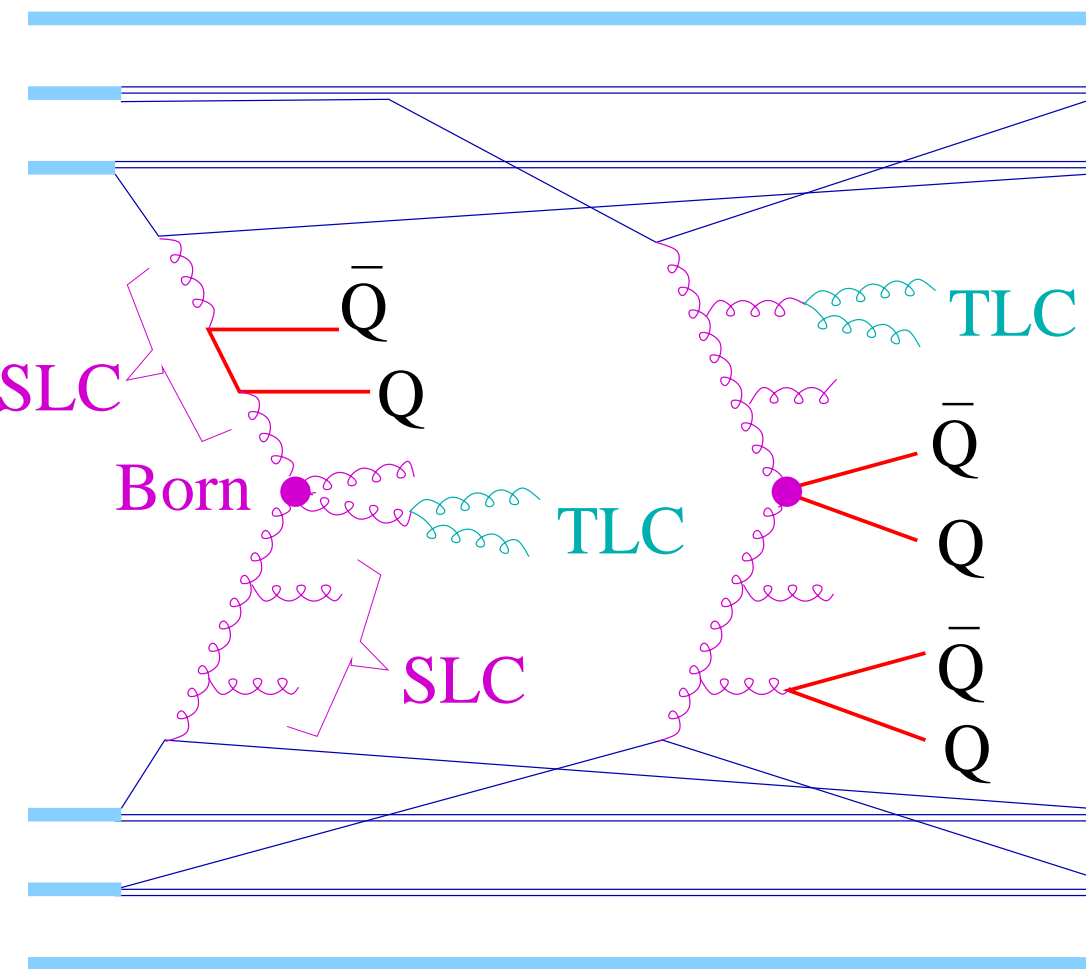
N_{D1} : D-meson multiplicity for $1 < p_t < 2 \text{ GeV}/c$

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 :

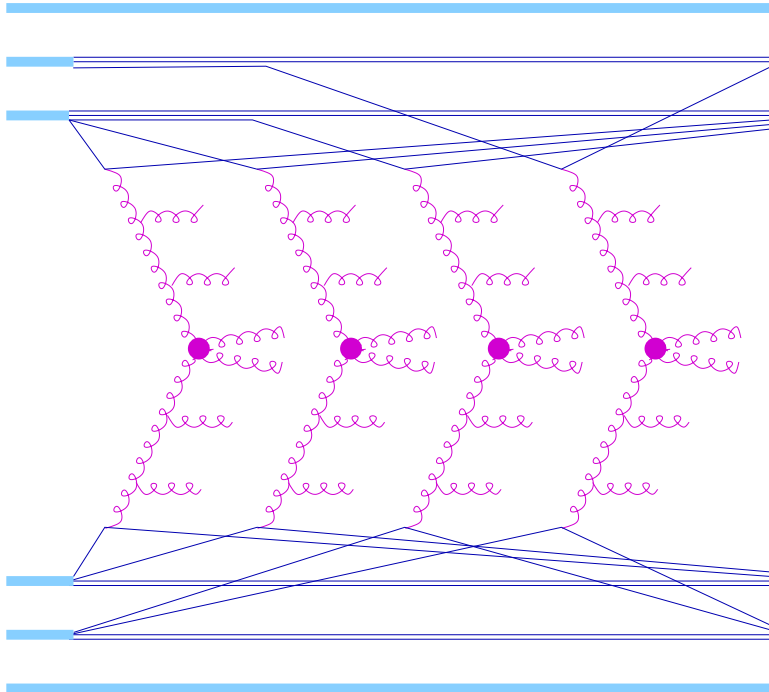
$$m_c = 1.3, m_b = 4.2)$$

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):



$$N_{Di} \propto N_{ch} \propto N_{Pom}$$

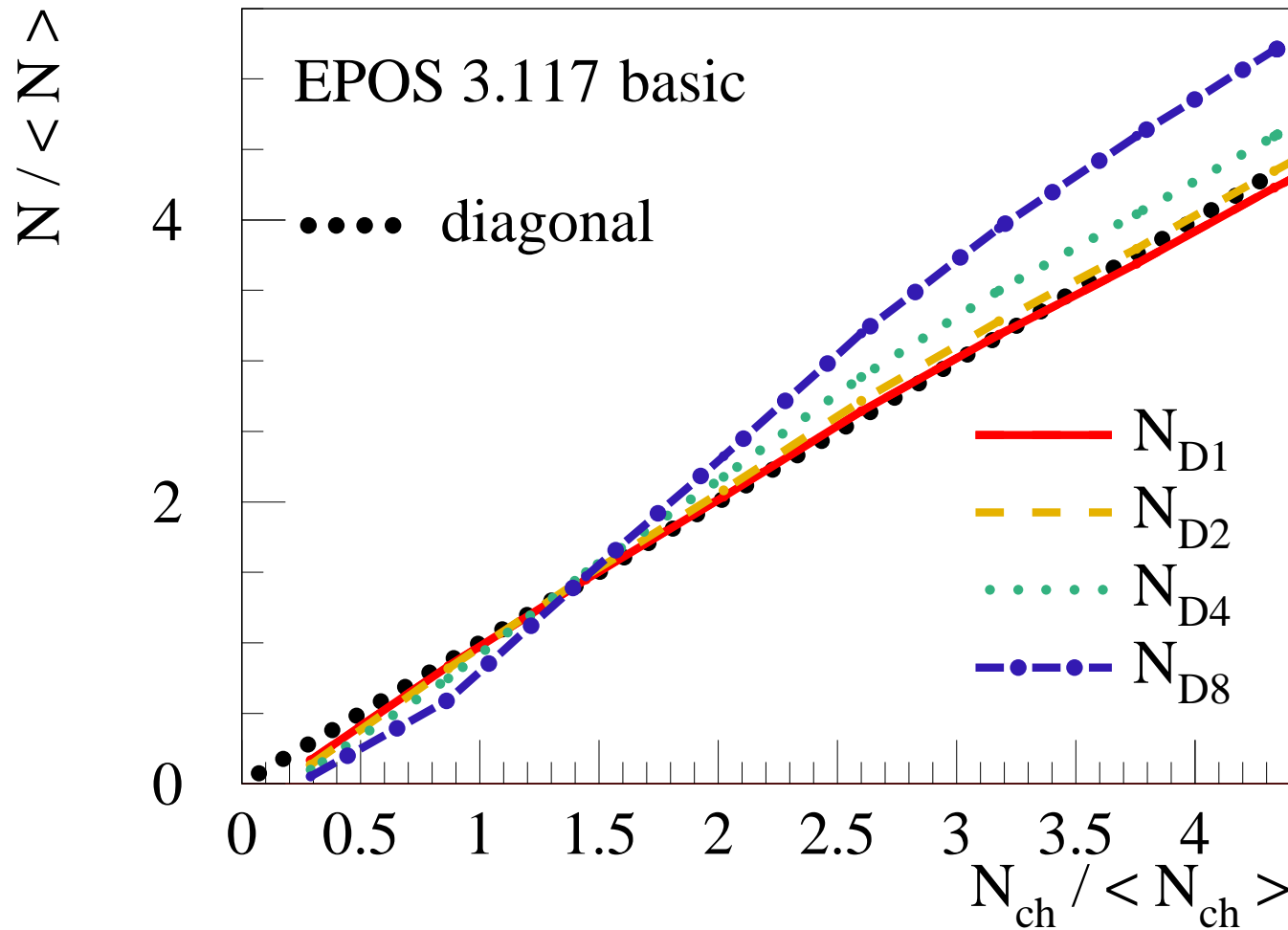
**“Natural” linear
behavior**

(first approximation)

In the following:

N_{Pom} **as reference**

The actual calculation (EPOS basic)

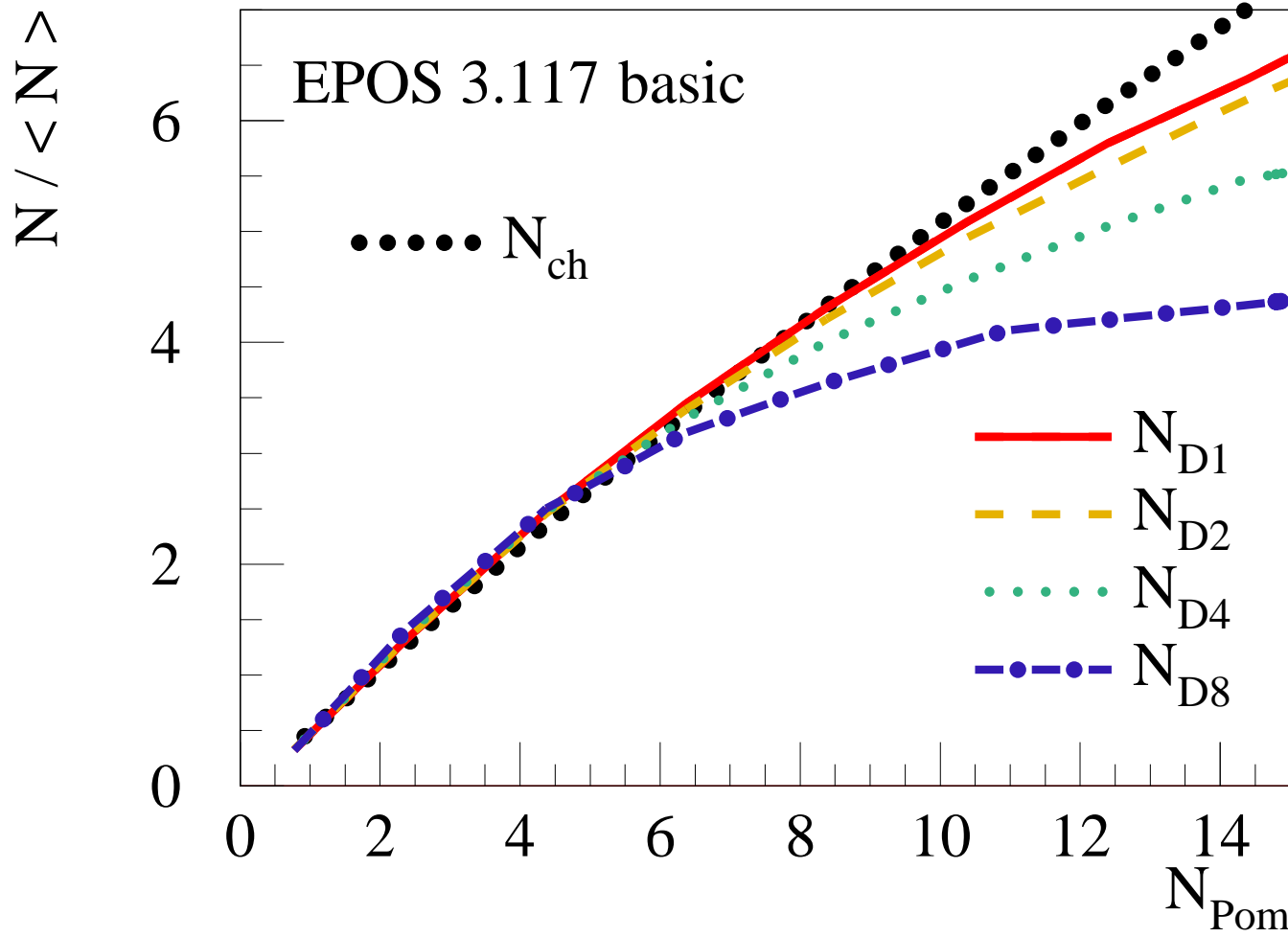


Indeed essentially a linear increase

... even more than linear !

(in particular for large p_t)

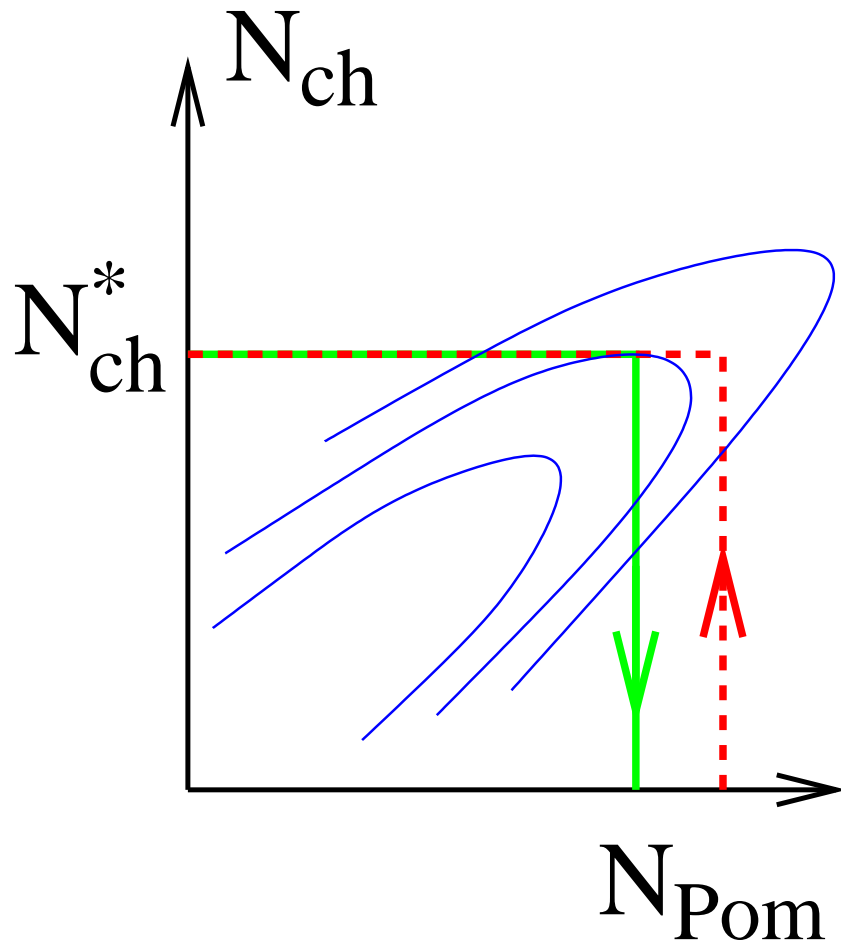
More than linear increase amazing :



**D multiplici-
ties increase
less than N_{ch}
vs N_{Pom}**

**How to un-
derstand
 $N_{D8}(N_{ch})$
more than
linear ?**

But crucial: Fluctuations



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

(=> two-dimensional
probability distribution)

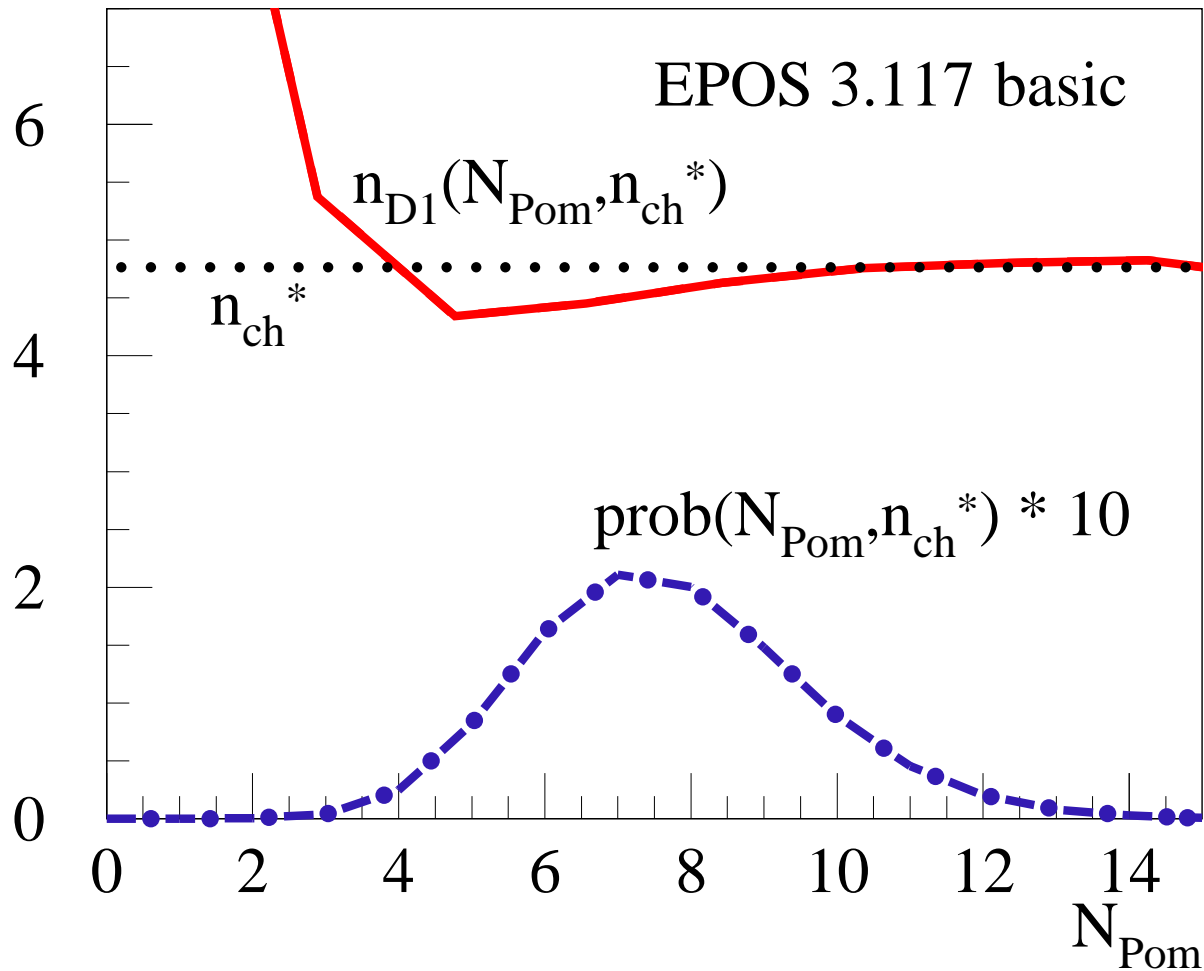
We define normalized multiplicities

$$n = N / \langle N \rangle$$

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}^*



$n_{D1} =$

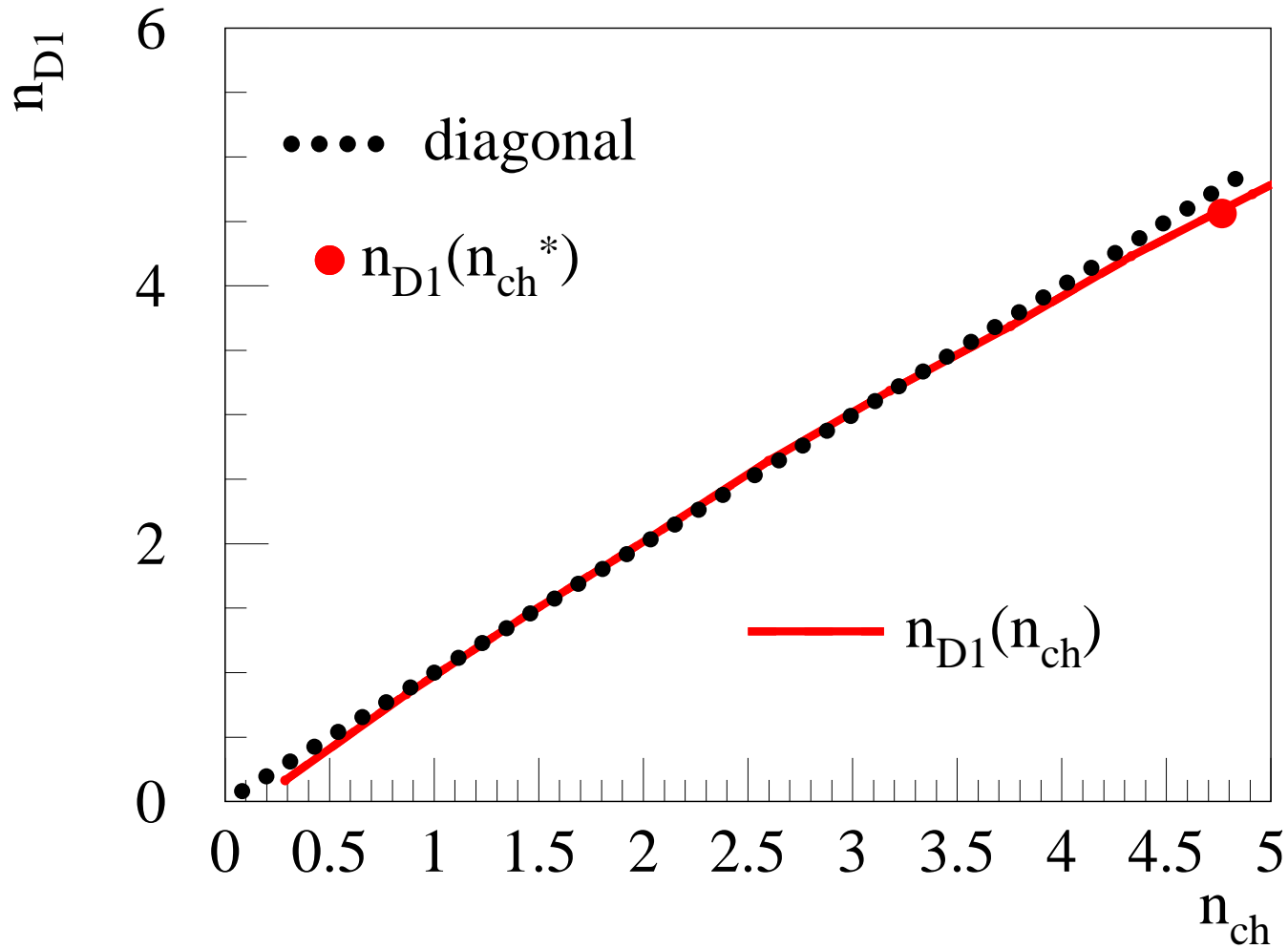
$$\sum_{N_{Pom}} \text{prob}(N_{Pom}, n_{ch}^*) \times n_{D1}(N_{Pom}, n_{ch}^*) \approx n_{ch}^*$$

having used

$$n_{D1}(N_{Pom}, n_{ch}^*) \approx n_{ch}^*$$

The precise calculation:

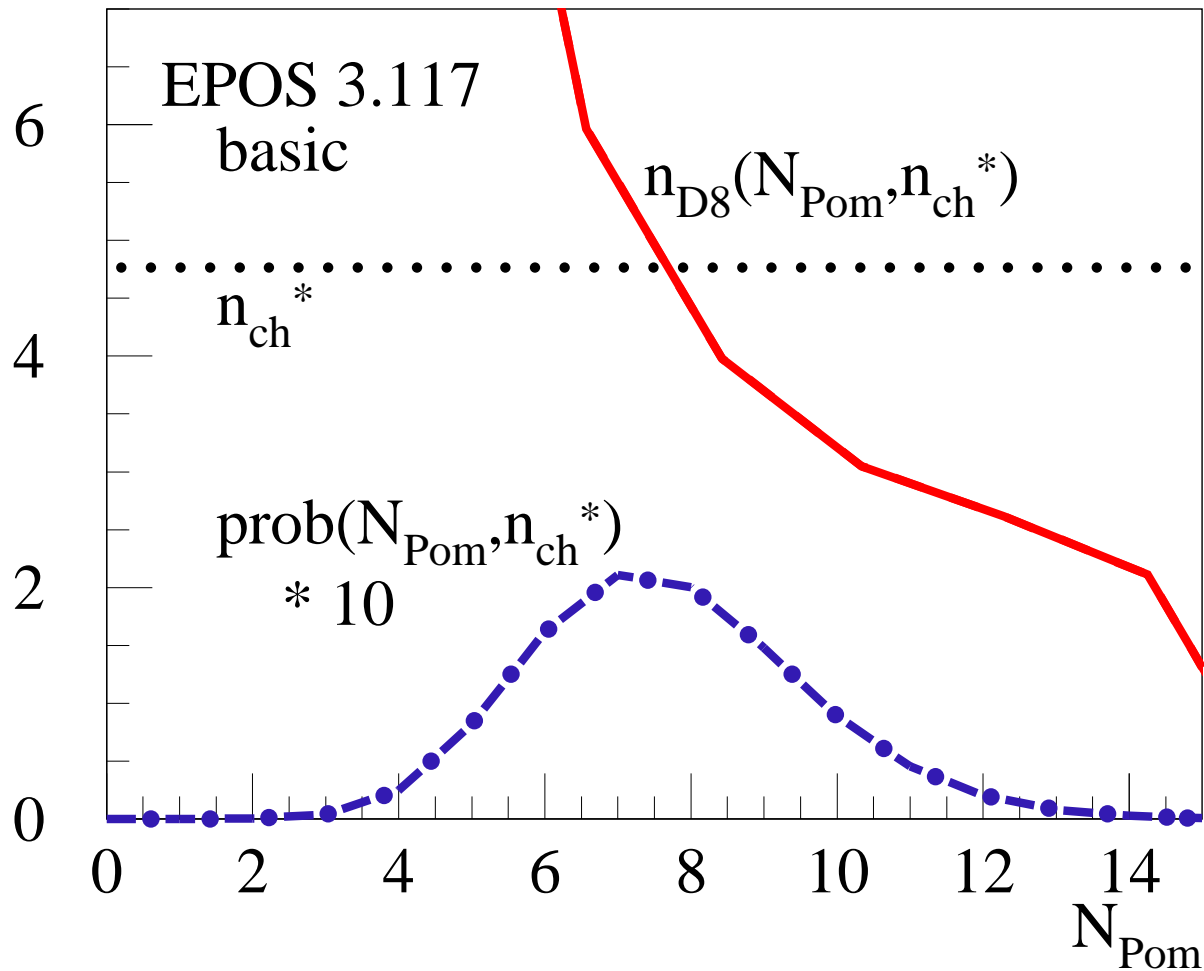
(red point)



**on the
diagonal!**

**Perfectly
linear!**

Now n_{D8} for given n_{ch}^*

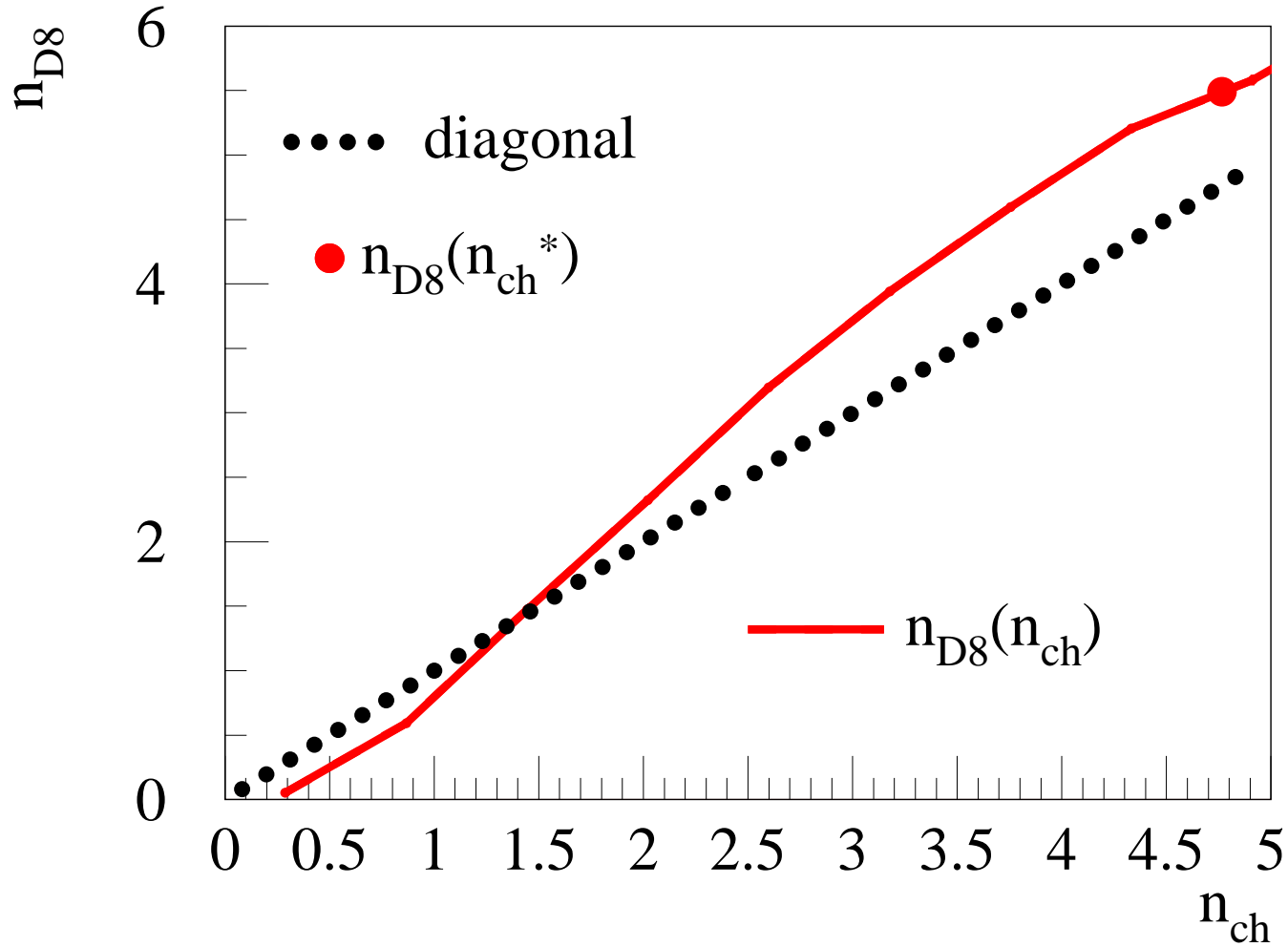


$$n_{D8} = \sum_{N_{Pom}} \text{prob}(N_{Pom}, n_{ch}^*) \times n_{D8}(N_{Pom}, n_{ch}^*) > n_{ch}^*$$

because
 $n_{D8}(N_{Pom}, n_{ch}^*)$
increases strongly
towards small N_{Pom}

The precise calculation:

(red point)



above the diagonal!

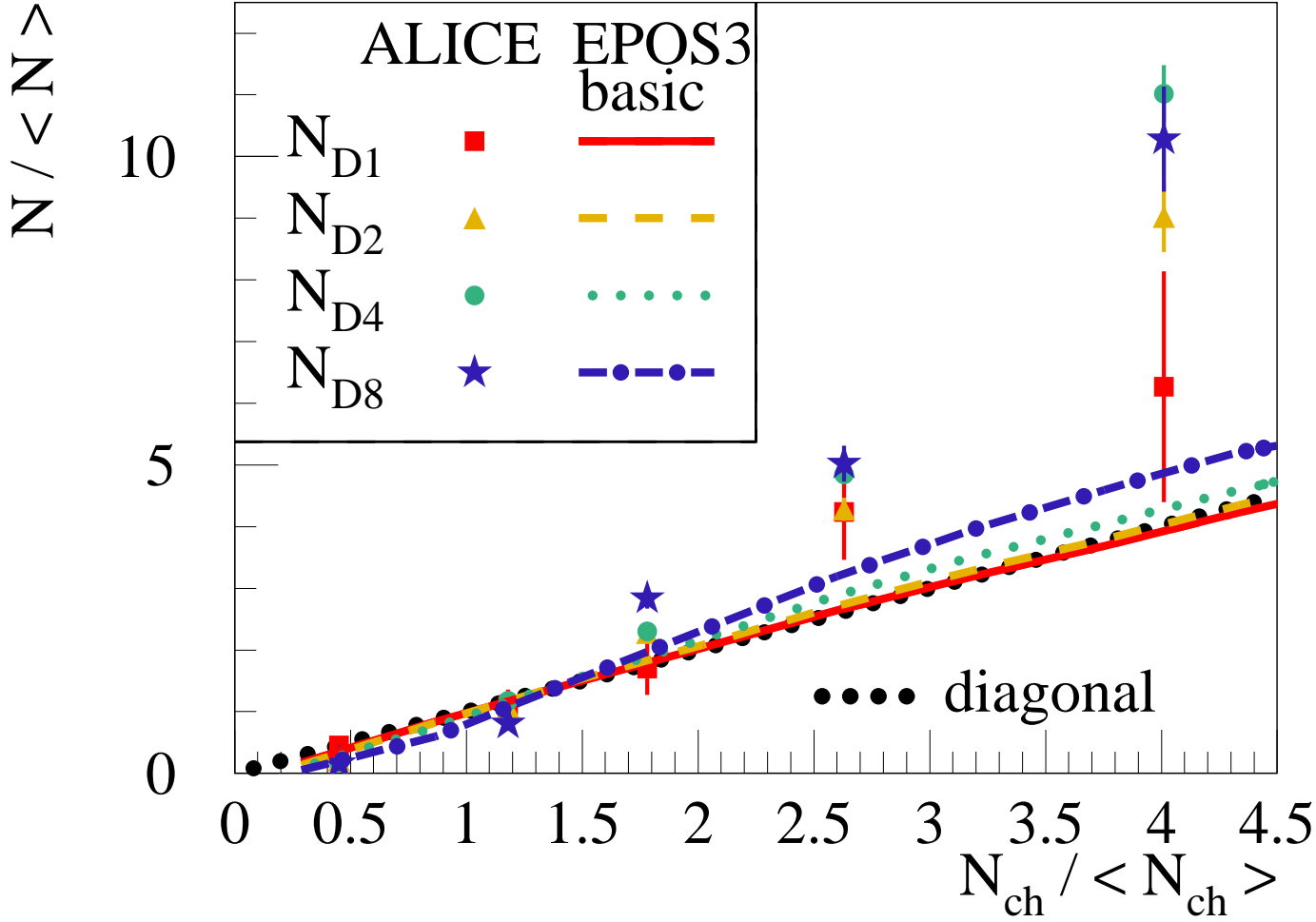
non-linear!

More than linear increase since

- **The number of Pomerons fluctuates for given multiplicity**
- **N_{D8} increases strongly towards small N_{Pom} for given multiplicity**

=> it is favored to produce high p_t D mesons for fewer (and more energetic) Pomerons

The effect is actually too small!



Too little deviation from the diagonal

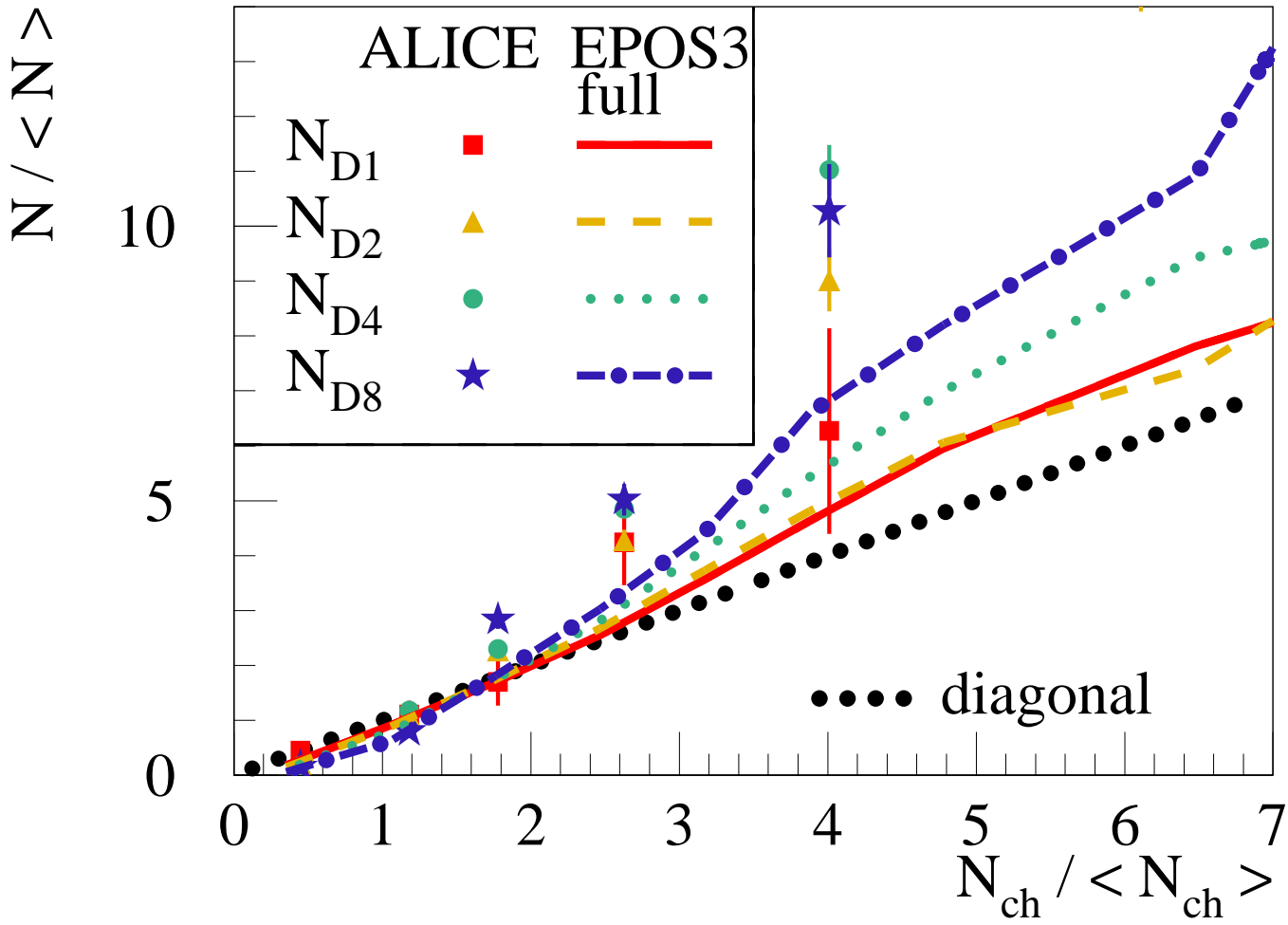
in particular for large p_t

**But anyhow, basic EPOS (w/o hydro)
reproduces neither spectra nor correlations**

=> full approach (EPOS w hydro + cascade)

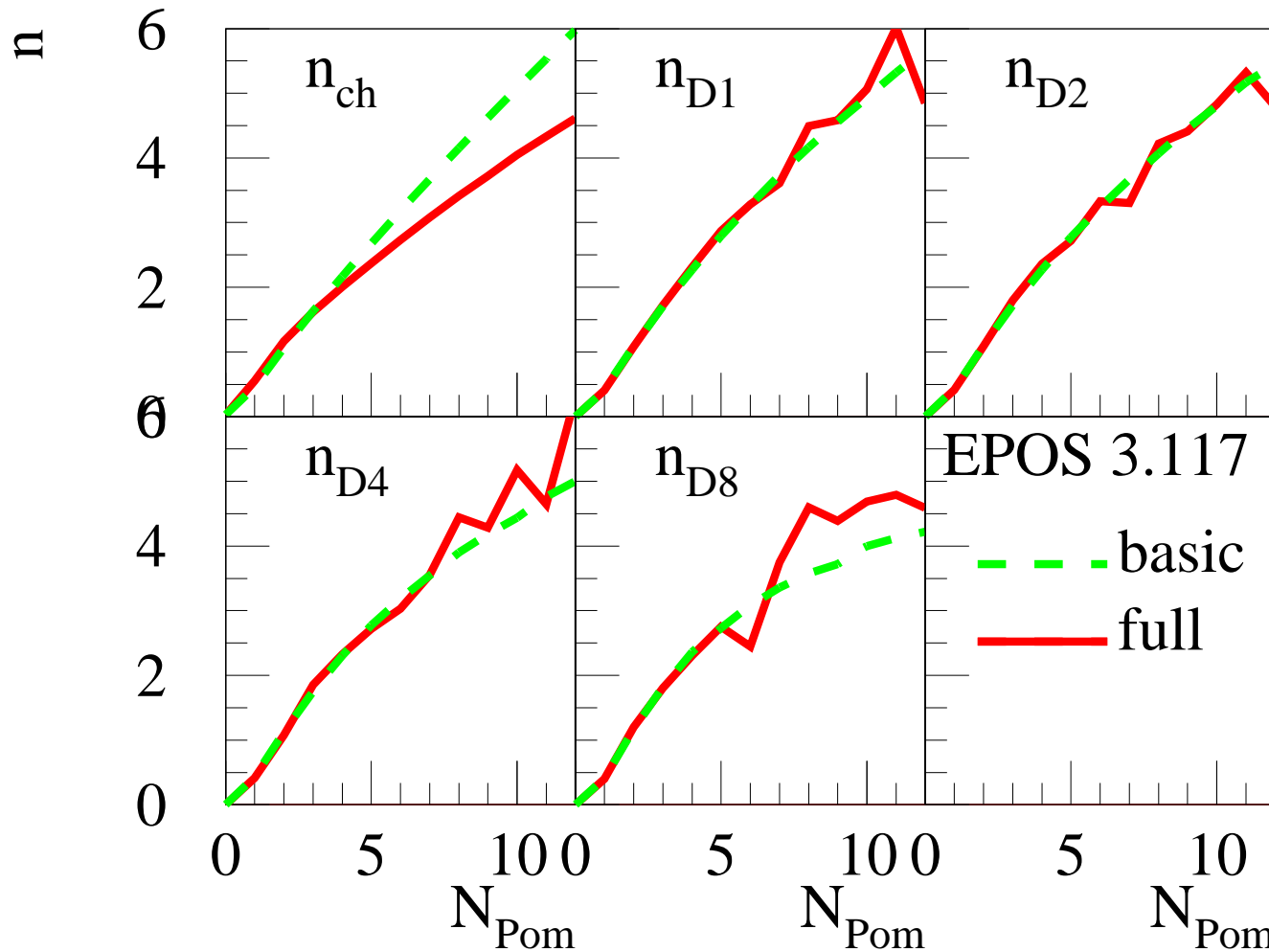
(with or without hadronic cascade
makes no difference)

Full EPOS3



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

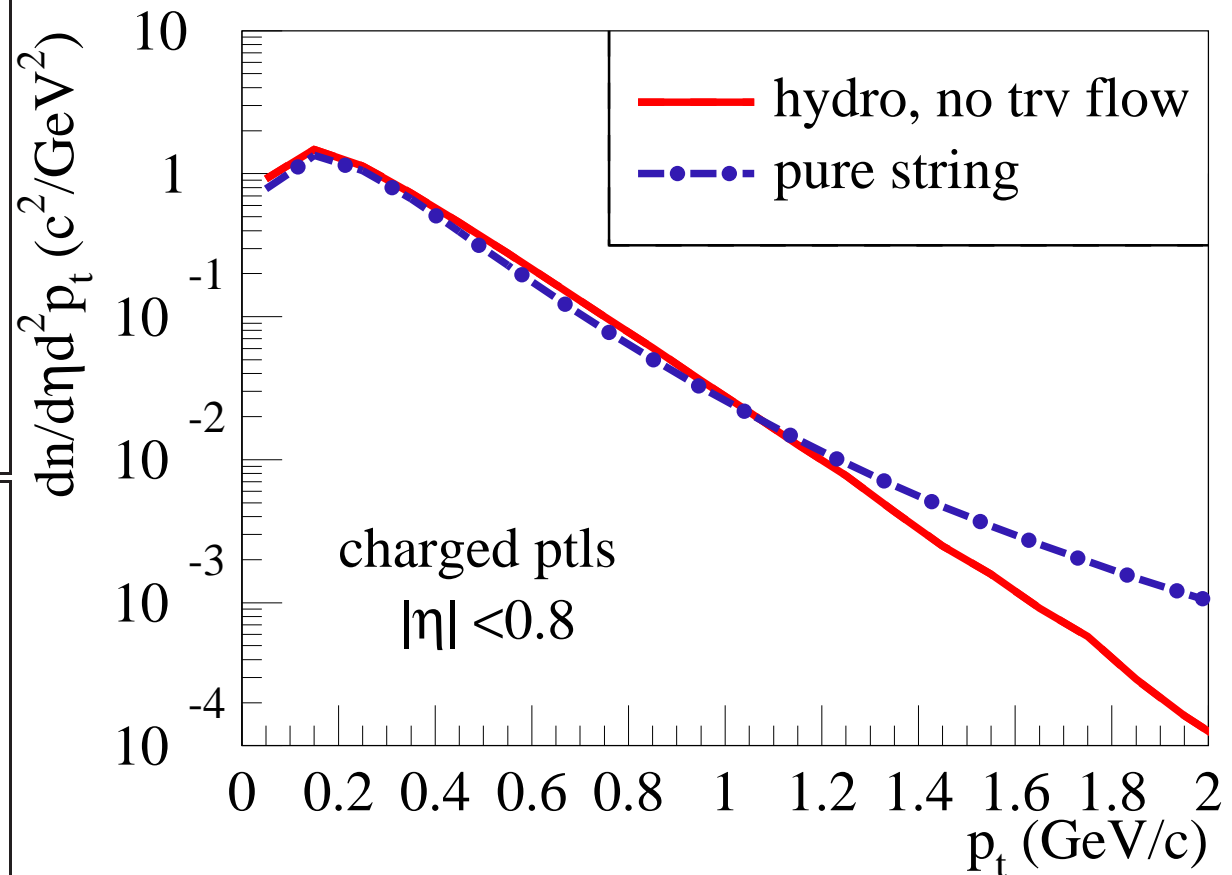
Why such a multiplicity reduction?

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 ?**

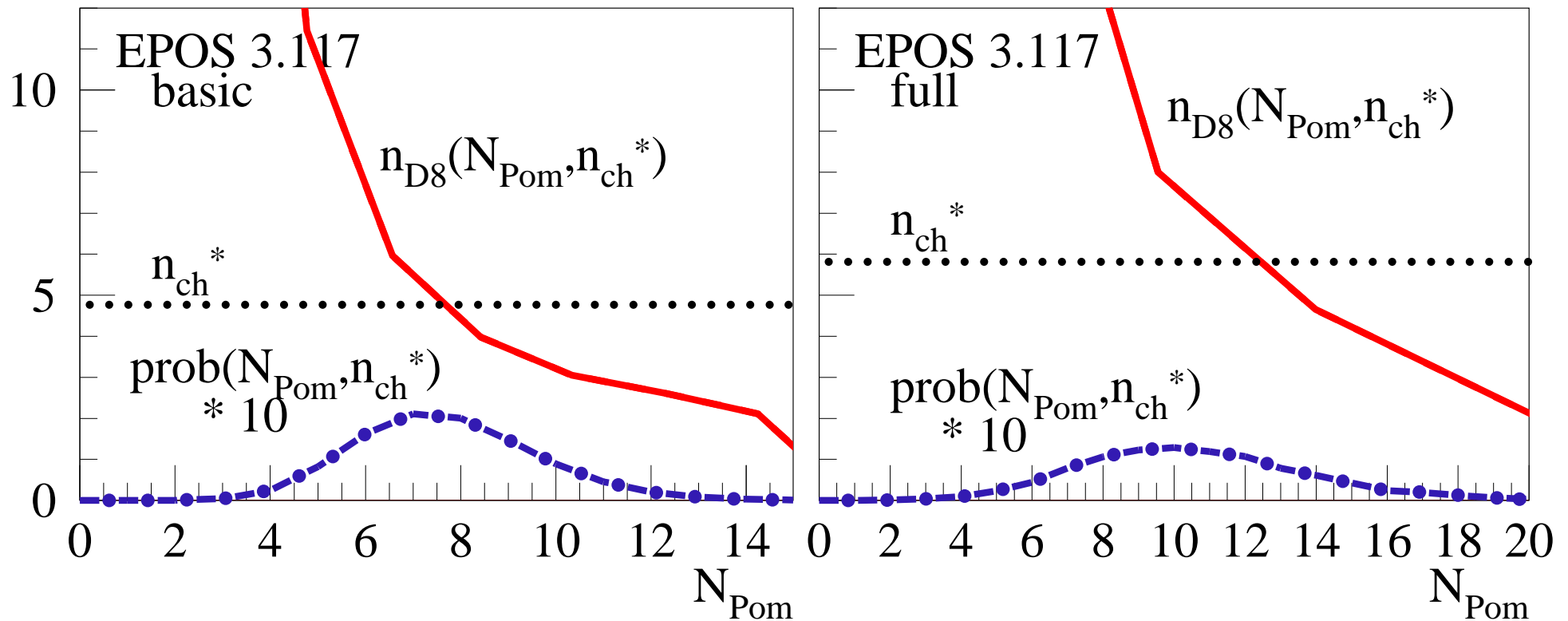
Naive expectation:

N_{ch} reduction should affect all pt ranges in the same way...

High pt

Again n_{D8} for some given n_{ch}^*

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



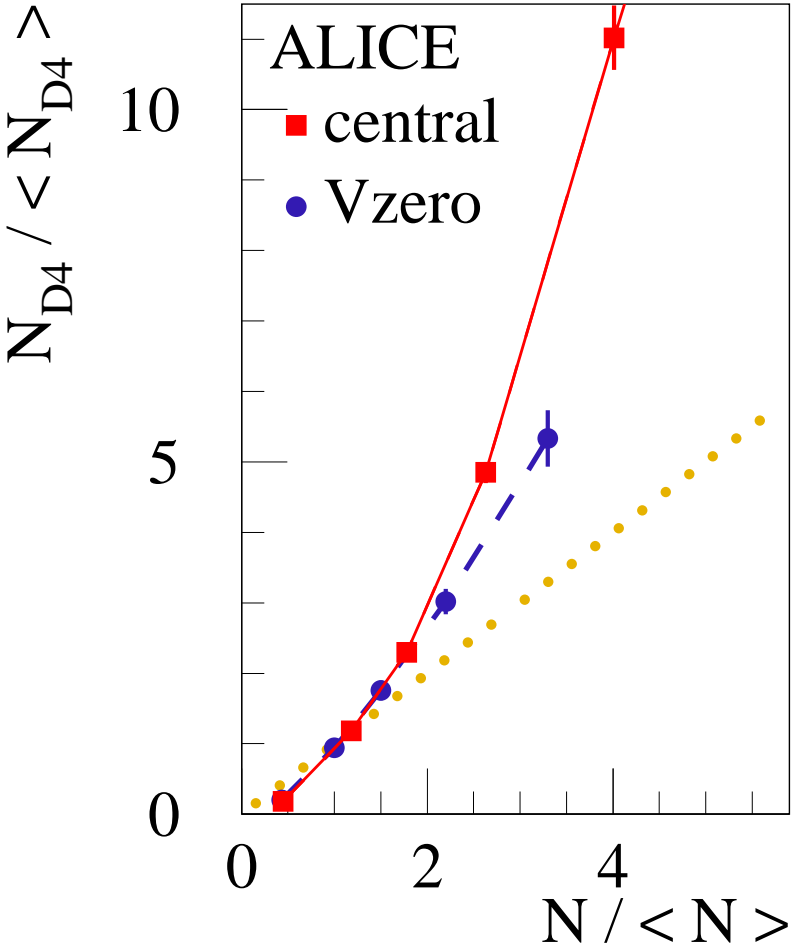
Full: Non-linearity effect enhanced

Taking charged-particle multiplicity at forward/backward rapidity

$$2.8 < \eta < 5.1 \quad \text{and} \quad -3.7 < \eta < -1.7$$

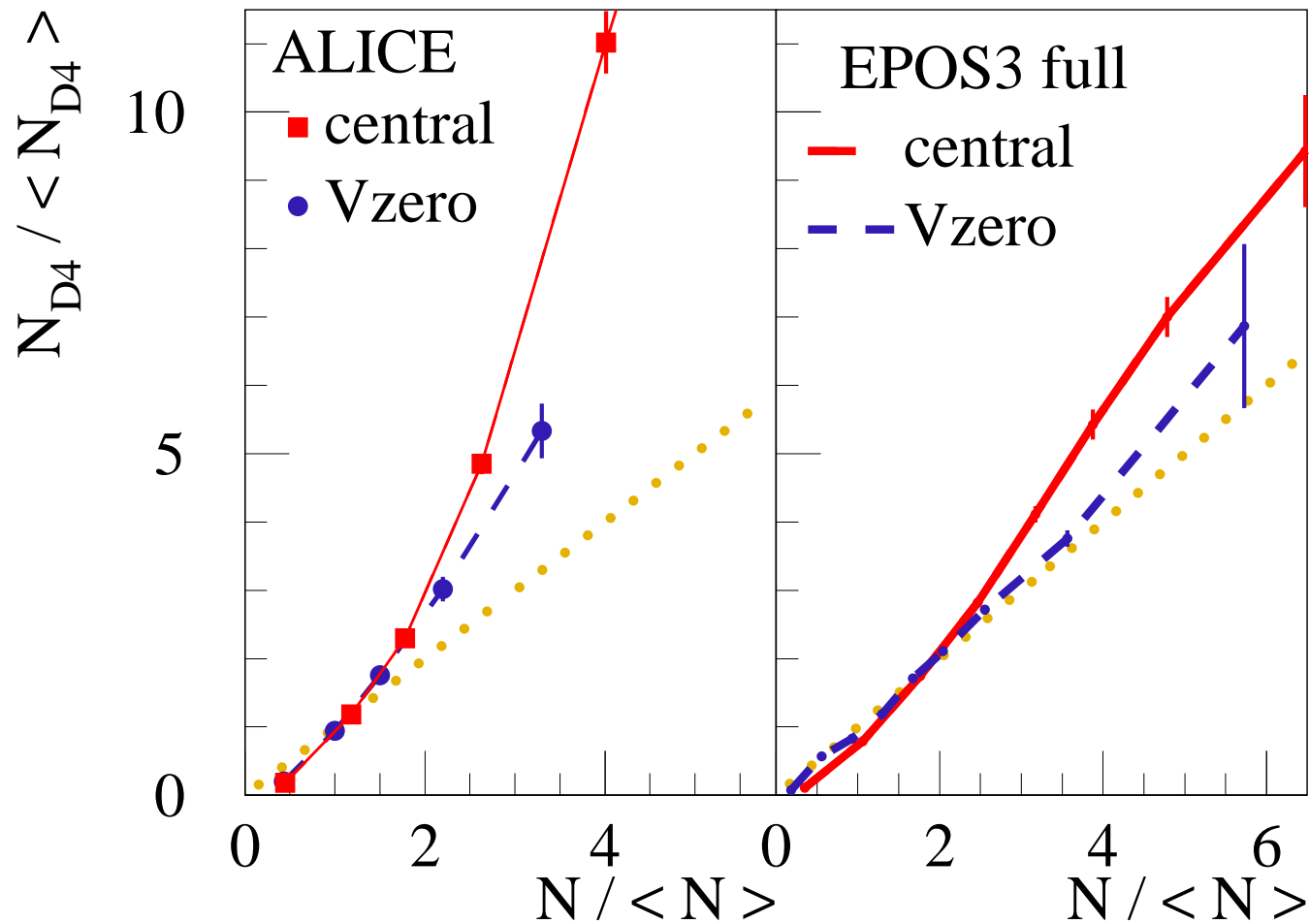
(Vzero multiplicity, N_{vz} , n_{vz})

Forw/backw multiplicity : Smaller increase



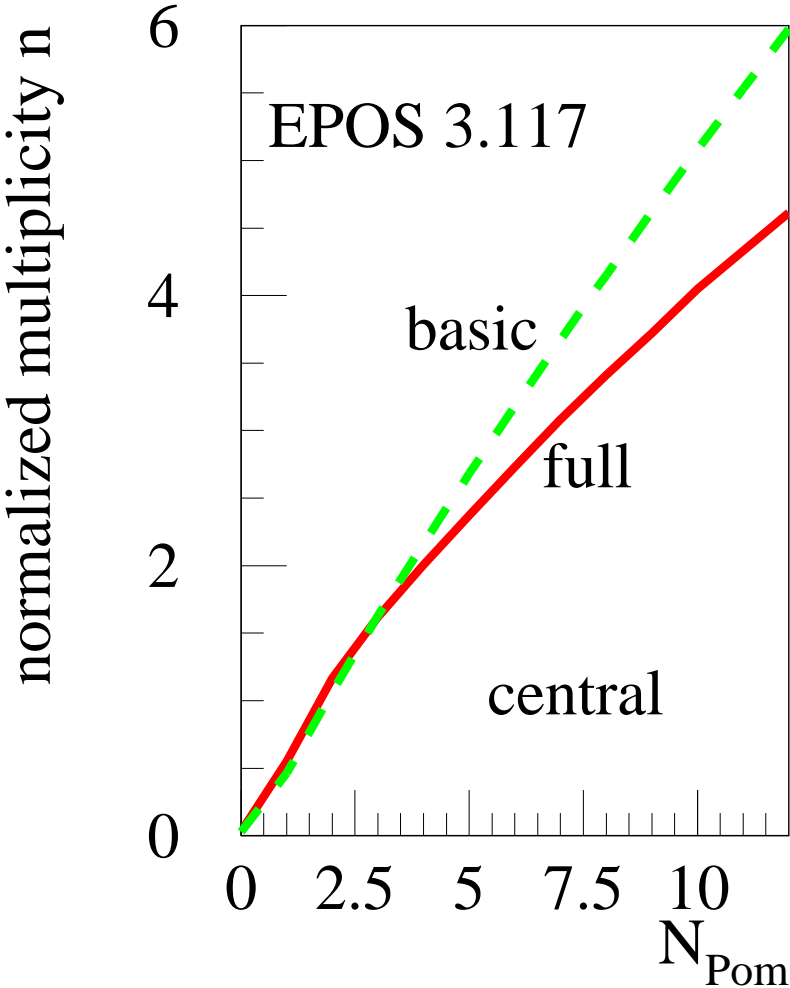
in the data

Forw/backw multiplicity : Smaller increase

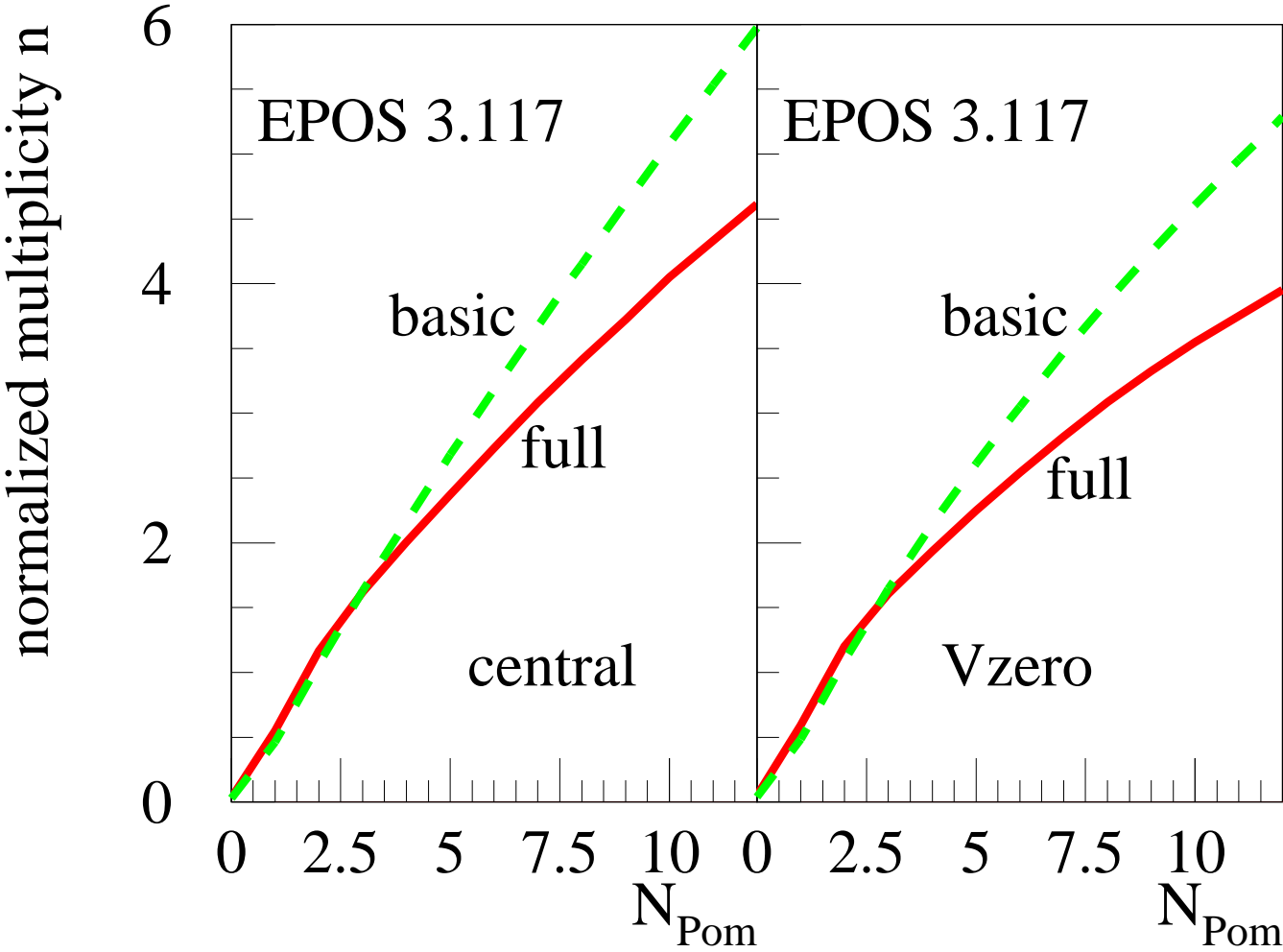


in the data and the simulation

Less “hydro effect” ?

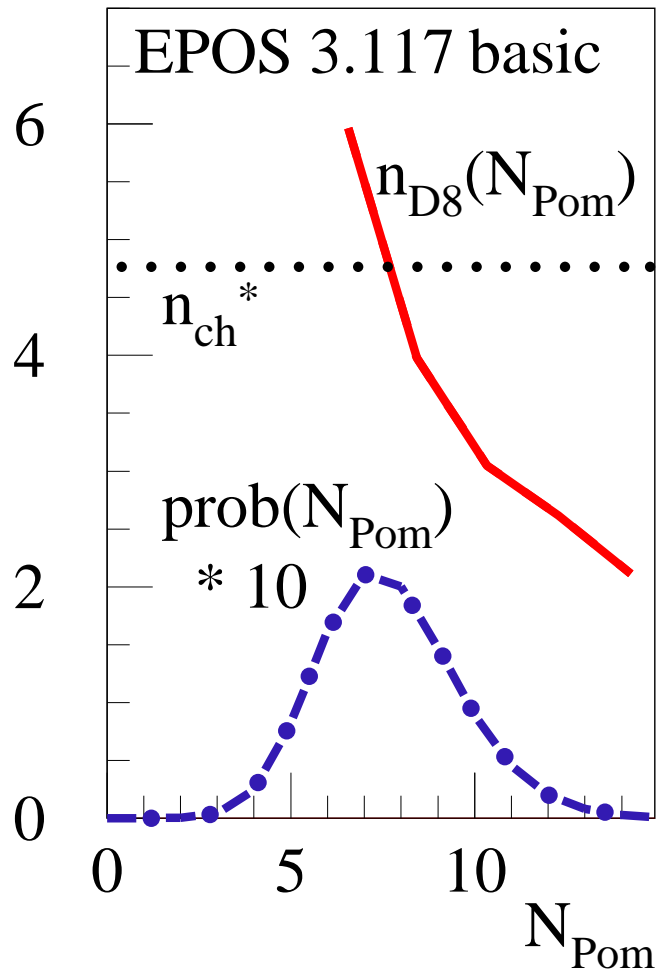


Less “hydro effect” ?



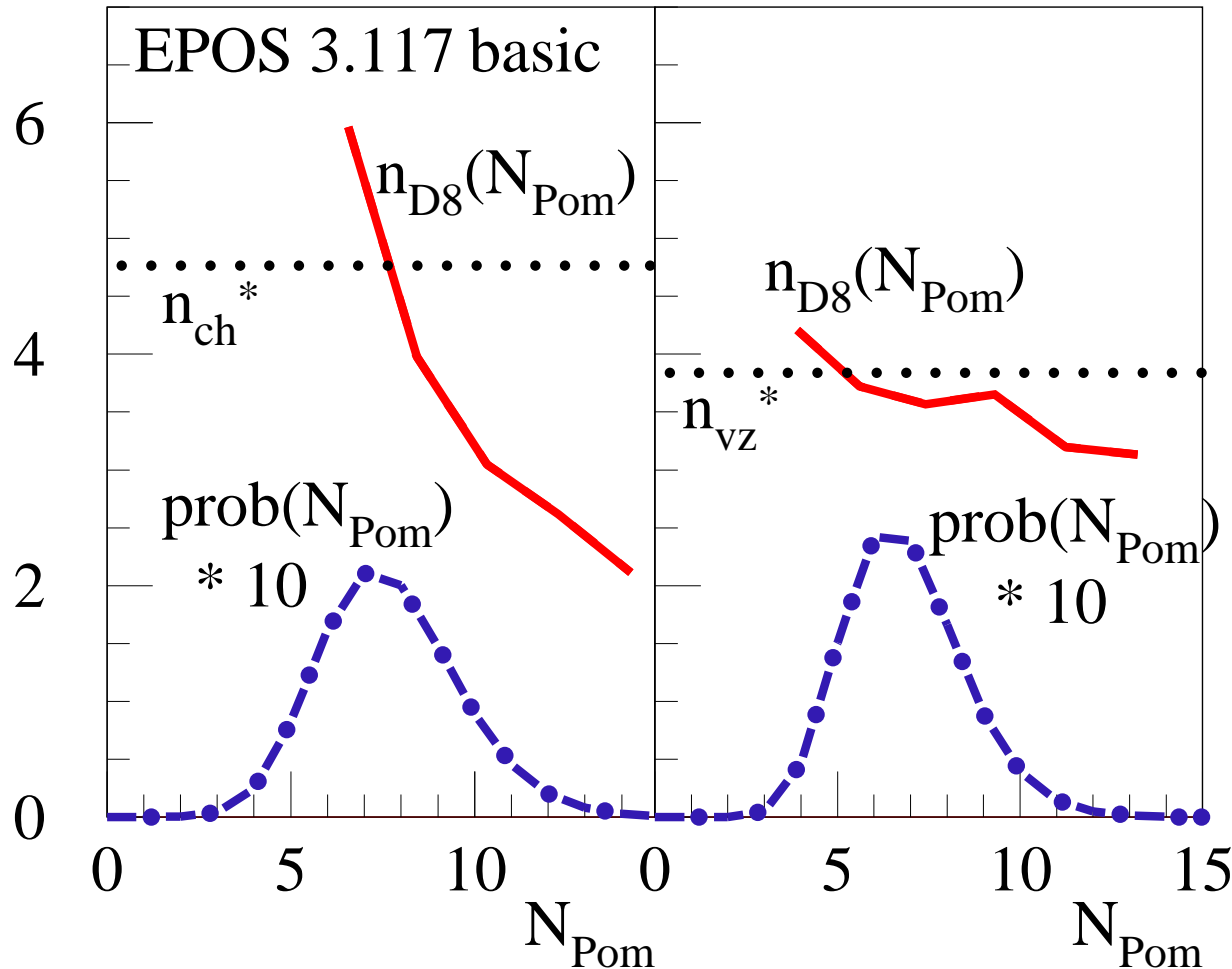
same effect

Less “Pomeron fluctuation effect”? *)



*) drop of $n_{D8}(N_{Pom})$ leads to nonlinear $n_{D8}(n_{ch})$

Less “Pomeron fluctuation effect”?



**$n_{D8}(N_{Pom})$
almost flat
for fixed n_{vz}**

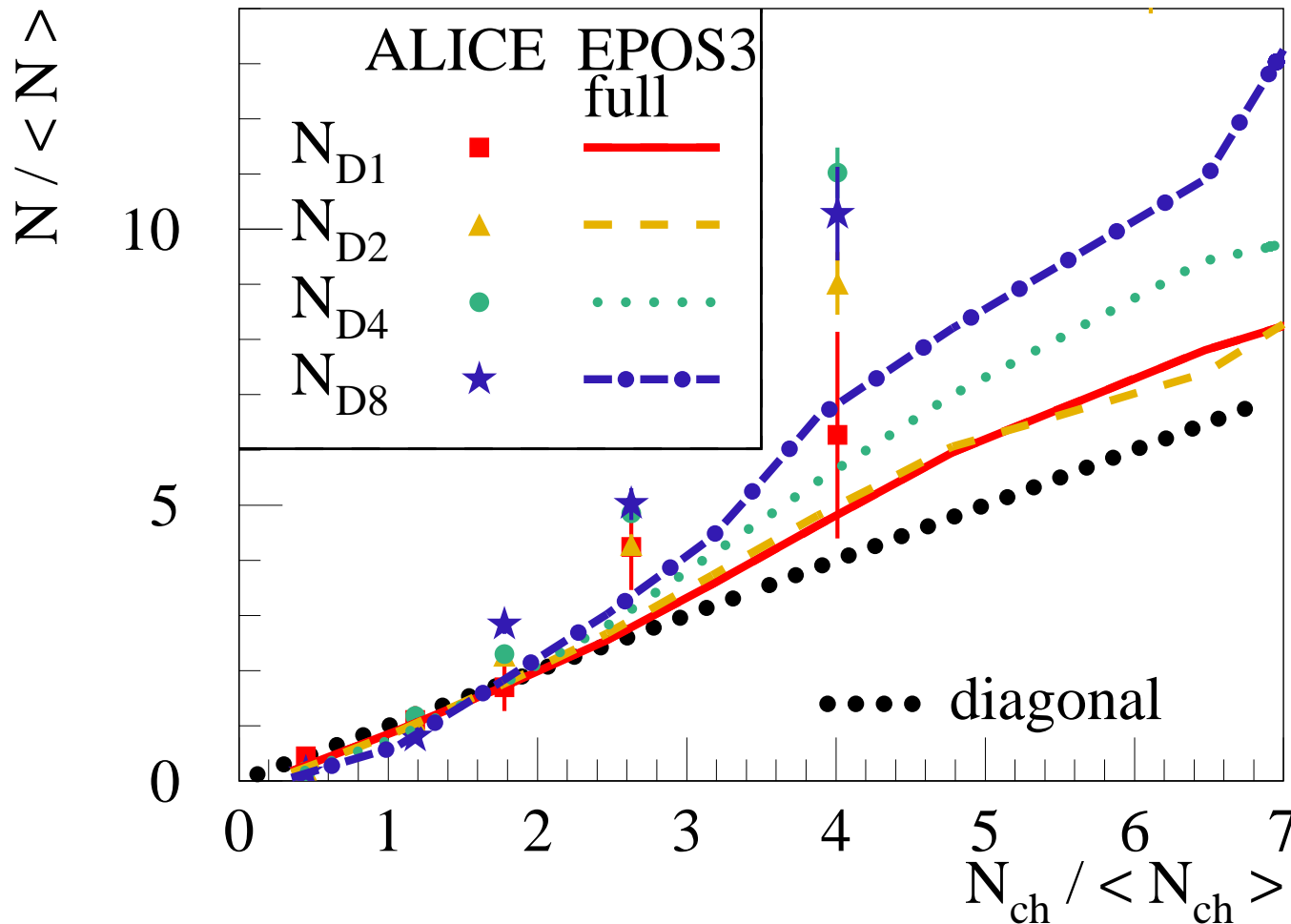
*) drop of $n_{D8}(N_{Pom})$ leads to nonlinear $n_{D8}(n_{ch})$

Summary

Significant non-linear increase

of $N_{Di}(N_{ch})$

(in particular for high pt)



understandable in terms of multiple scattering and flow