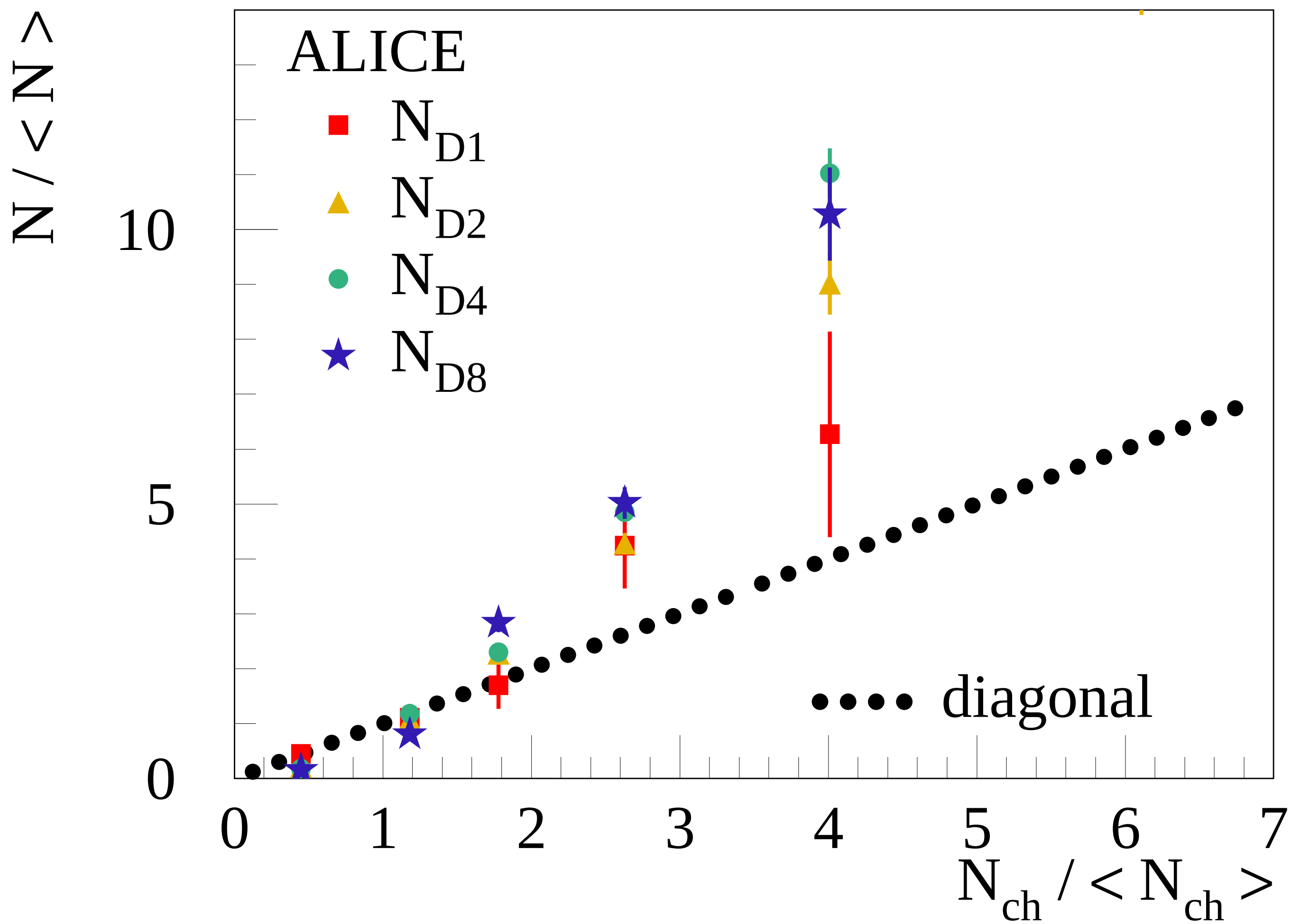
Multiple scattering in EPOS: Implications for charm production

K.W. in collaboration with

B. Guiot, Iu. Karpenko, T. Pierog

D-meson multiplicity vs charged multiplicity

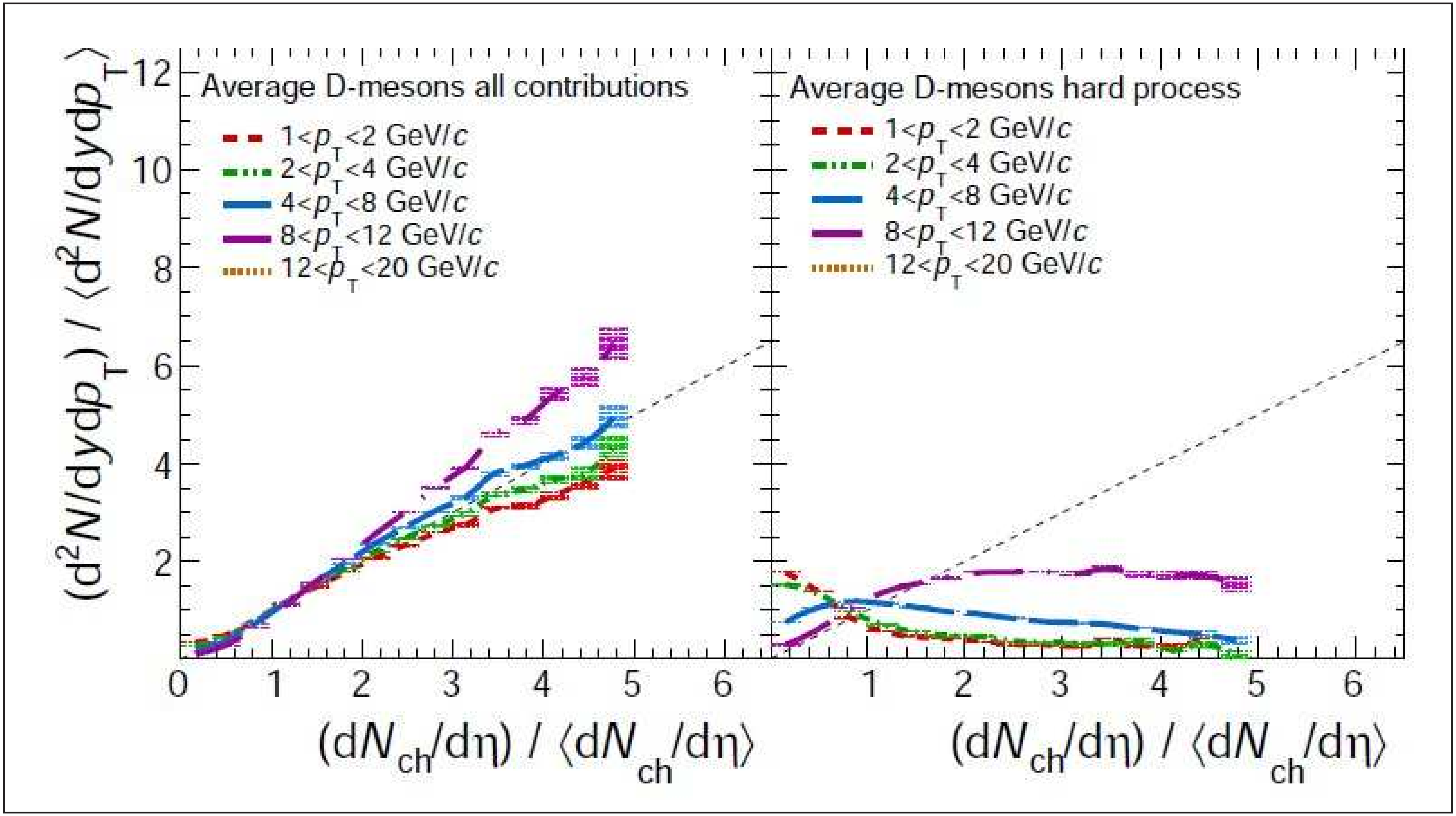


Significant deviation from the diagonal (linear increase)

in particular for large p_t

ALICE arXiv:1505.00664v1

PYTHIA 8.157


Average D-mesons all contributions
1<p_T<2 GeV/c
2<p_T<4 GeV/c
4<p_T<8 GeV/c
8<p_T<12 GeV/c
12<p_T<20 GeV/c
Average D-mesons hard process
(d²N/dydp_T) / ⟨d²N/dydp_T⟩
(dN_ch/dη) / ⟨dN_ch/dη⟩

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

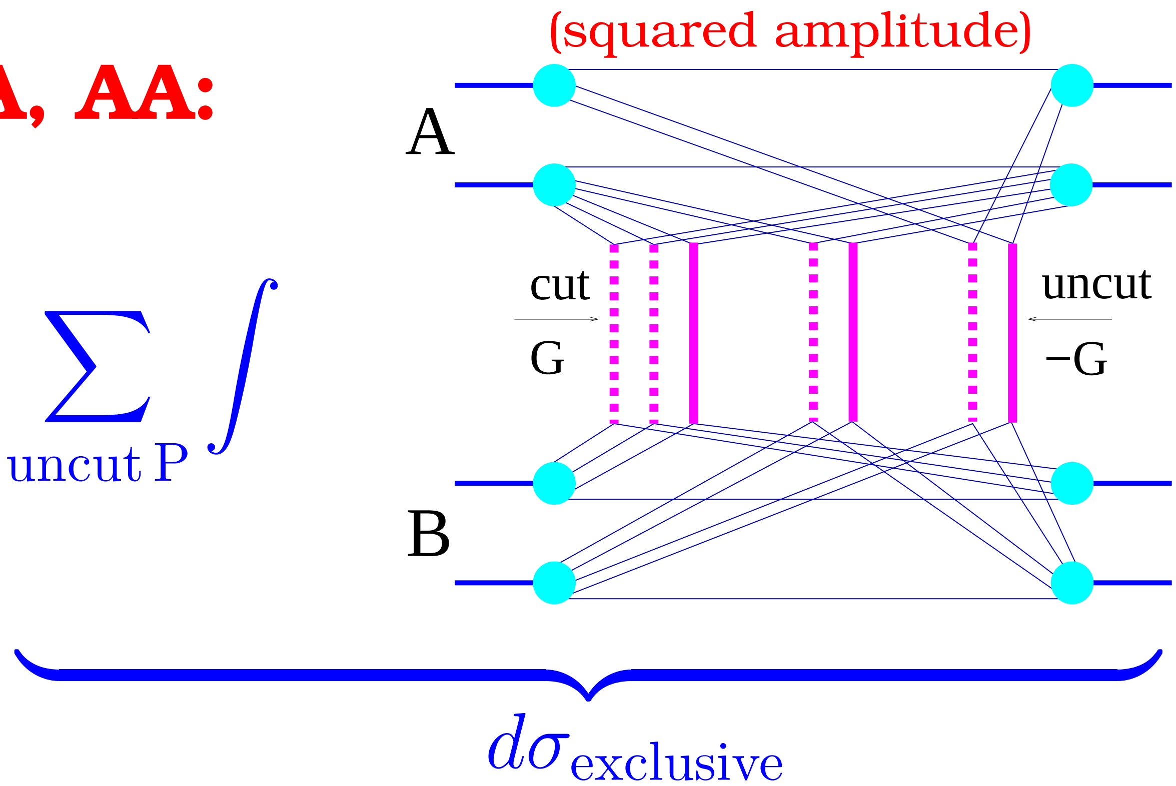
arXiv:1312.1233 , arXix:1307.4379

Initial conditions: Marriage pQCD+GRT+energy sharing

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

For pp, pA, AA:

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



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

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

$$\sigma^{\text{tot}} = \int d^2b \int \prod_{i=1}^{A} d^2b_i^A\, dz_i^A\, \rho_A\Big(\sqrt{(b_i^A)^2 + (z_i^A)^2}\Big)$$

$$\prod_{j=1}^{B} d^2b_j^B\, dz_j^B\, \rho_B\Big(\sqrt{(b_j^B)^2 + (z_j^B)^2}\Big)$$

$$\sum_{m_1 l_1} \ldots \sum_{m_{AB} l_{AB}} (1 - \delta_{0\Sigma m_k}) \int \prod_{k=1}^{AB} \Bigg(\prod_{\mu=1}^{m_k} dx_{k,\mu}^{+} dx_{k,\mu}^{-} \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^{+} d\tilde{x}_{k,\lambda}^{-} \Bigg) \Bigg\{$$

$$\prod_{k=1}^{AB} \Bigg(\frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^{+}, x_{k,\mu}^{-}, s, |\vec{b} + \vec{b}_{\pi(k)}^{A} - \vec{b}_{\tau(k)}^{B}|)$$

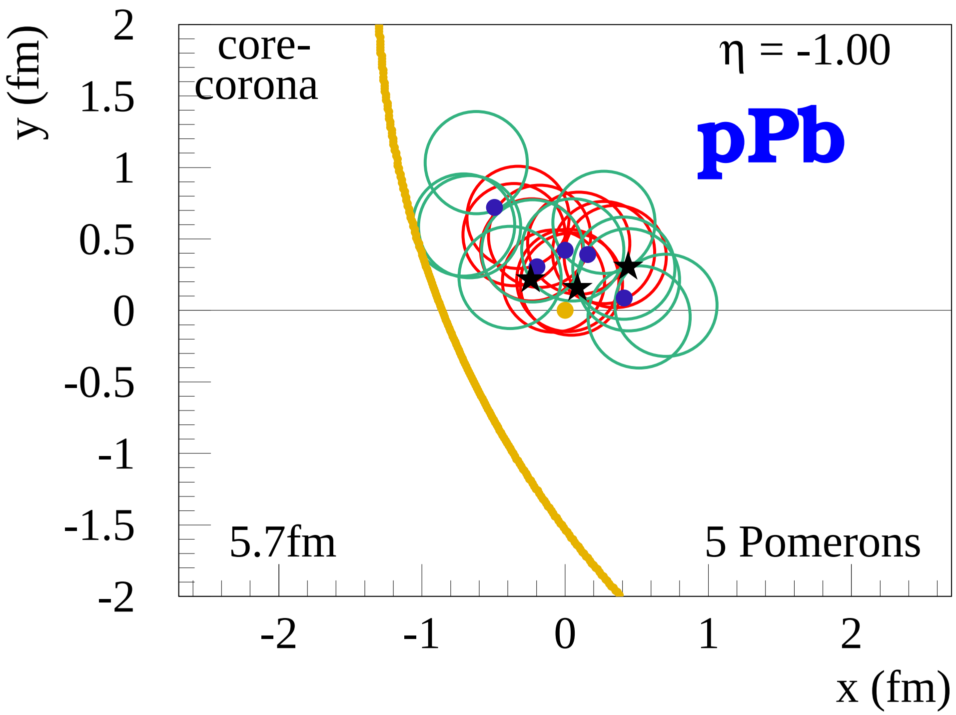
$$\prod_{\lambda=1}^{l_k} -G(\tilde{x}_{k,\lambda}^{+}, \tilde{x}_{k,\lambda}^{-}, s, |\vec{b} + \vec{b}_{\pi(k)}^{A} - \vec{b}_{\tau(k)}^{B}|) \Bigg)$$

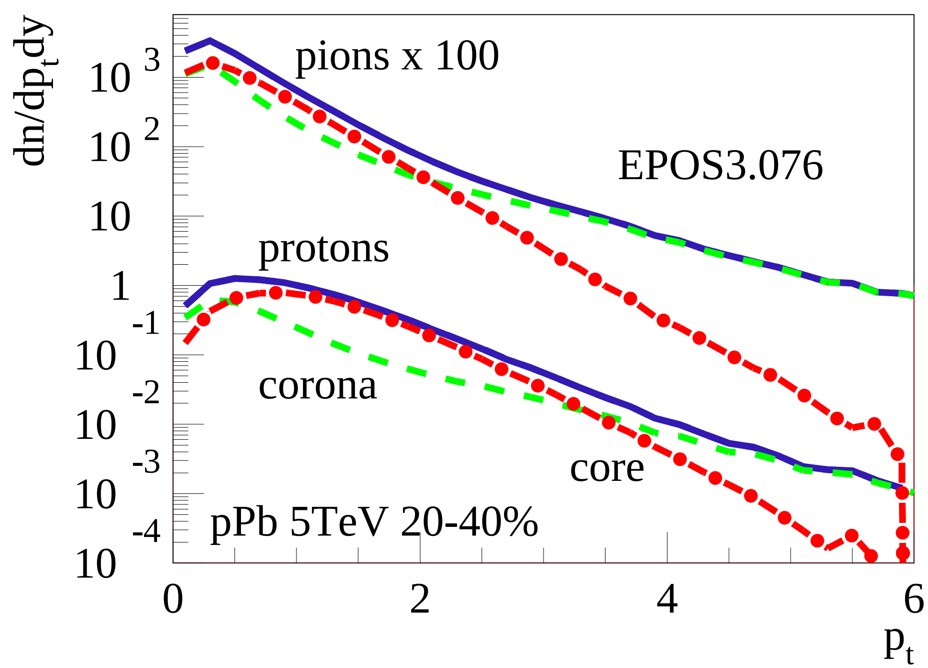
$$\prod_{i=1}^{A} \Bigg(1 - \sum_{\pi(k)=i} x_{k,\mu,}^{+} - \sum_{\pi(k)=i} \tilde{x}_{k,\lambda}^{+} \Bigg)^{\alpha} \prod_{j=1}^{B} \Bigg(1 - \sum_{\tau(k)=j} x_{k,\mu}^{-} - \sum_{\tau(k)=j} \tilde{x}_{k,\lambda}^{-} \Bigg)^{\alpha} \Bigg\}$$

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

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

String segments with high pt 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, $\eta/S = 0.08$, $\zeta/S = 0$

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

$$\gamma\left(\partial_t + v_i \partial_i\right) \pi^{\mu\nu} = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\rm NS}}{\tau_\pi} + I^{\mu\nu}_\pi \qquad \gamma\left(\partial_t + v_i \partial_i\right) \Pi = -\frac{\Pi - \Pi_{\rm NS}}{\tau_\Pi} + I_\Pi$$

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

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

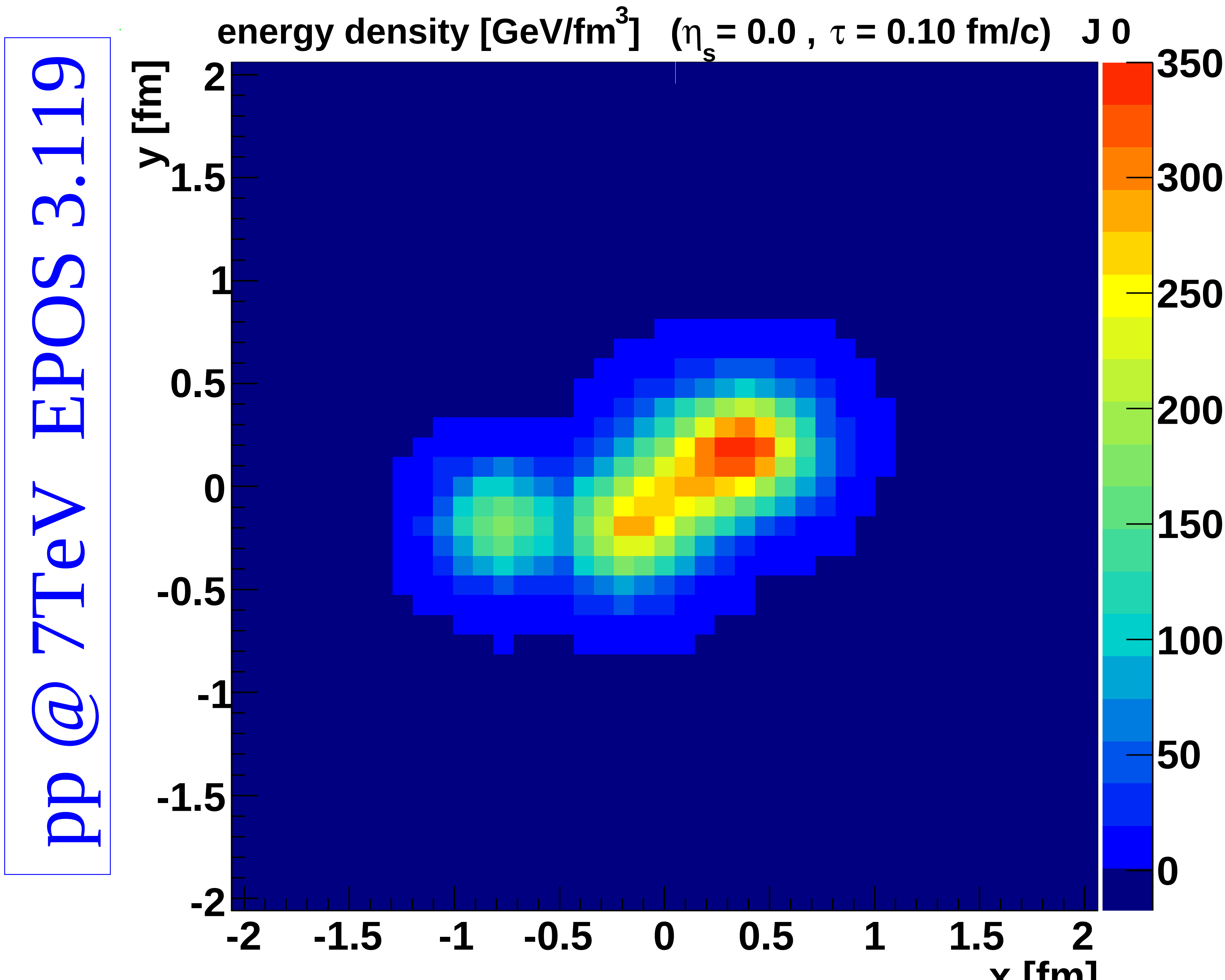
Marcus Bleicher, Jan Steinheimer

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 follwing : An example of an
asymmetric space-time evolution (high mult pp event, 7TeV)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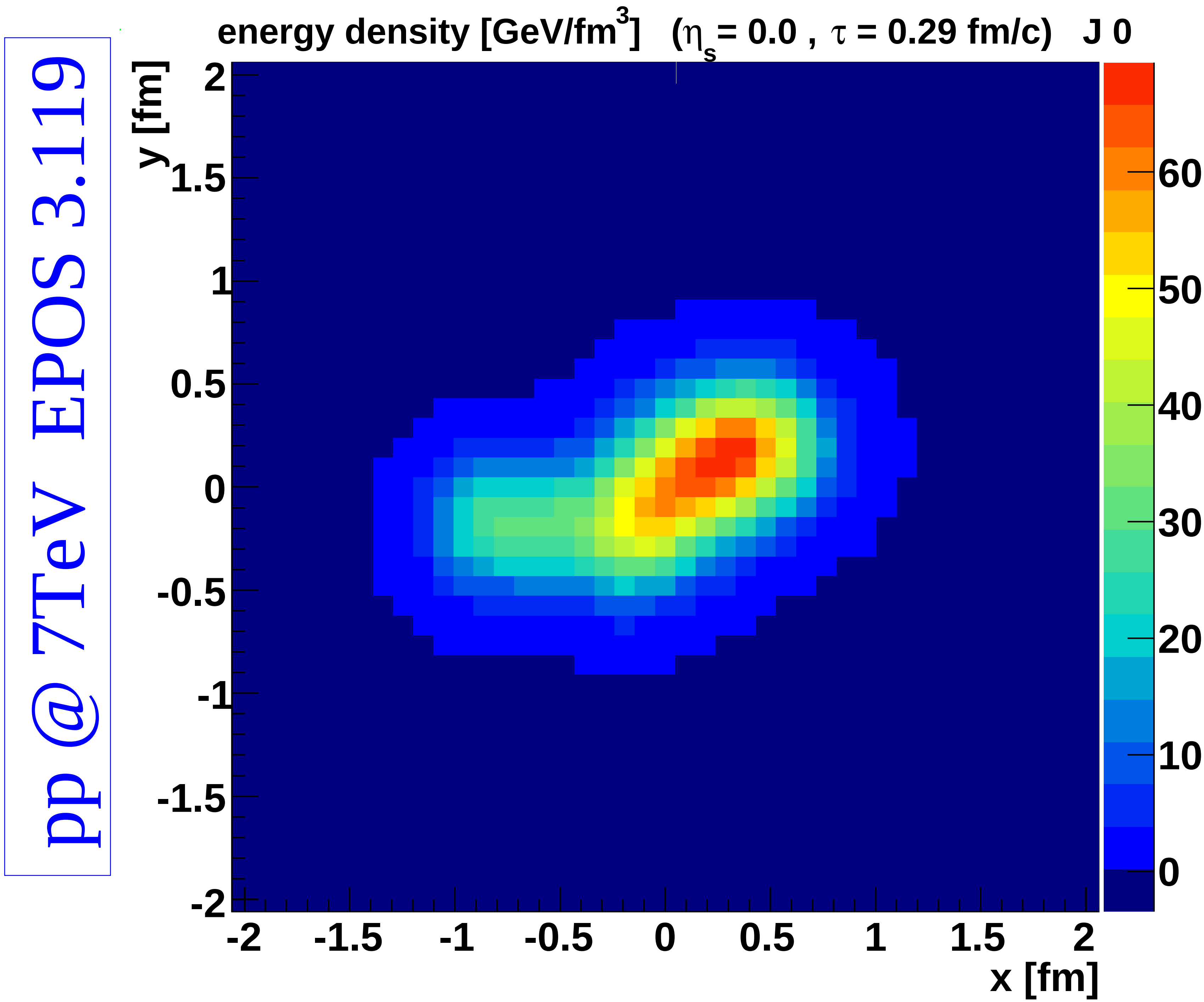
energy density [GeV/fm^3] (η_s = 0.0 , τ = 0.10 fm/c) J 0
y [fm]
x [fm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
350
300
250
200
150
100
50
0



pp @ 7TeV EPOS 3.119
energy density [GeV/fm^3] (η_s = 0.0 , τ = 0.29 fm/c) J 0
y [fm]
x [fm]
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1.5
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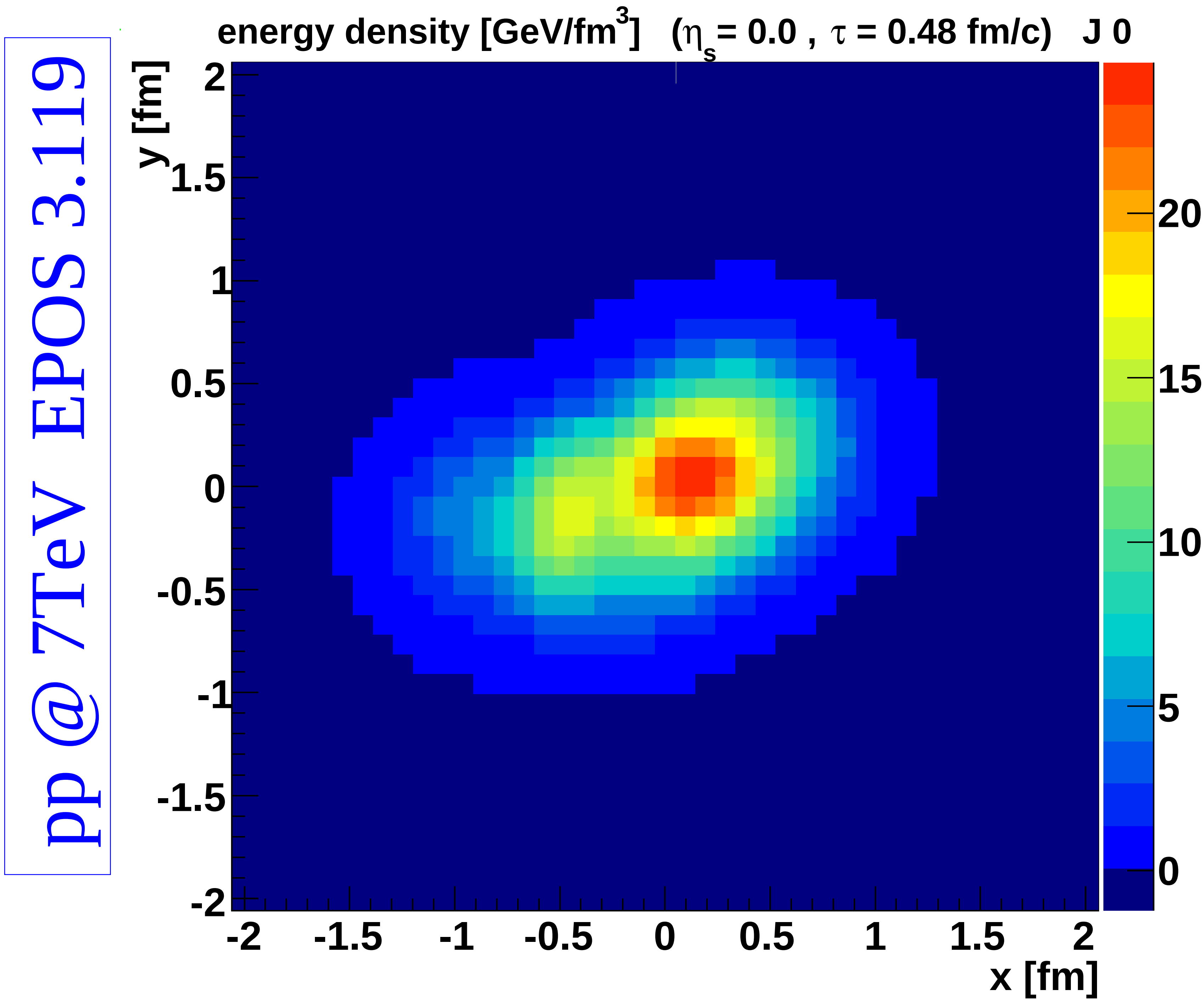
0.5
0
-0.5
-1
-1.5
-2
60
50
40
30
20
10
0


energy density [GeV/fm^3] (η_s= 0.0 , τ = 0.48 fm/c) J 0
pp @ 7TeV EPOS 3.119
y [fm]
x [fm]
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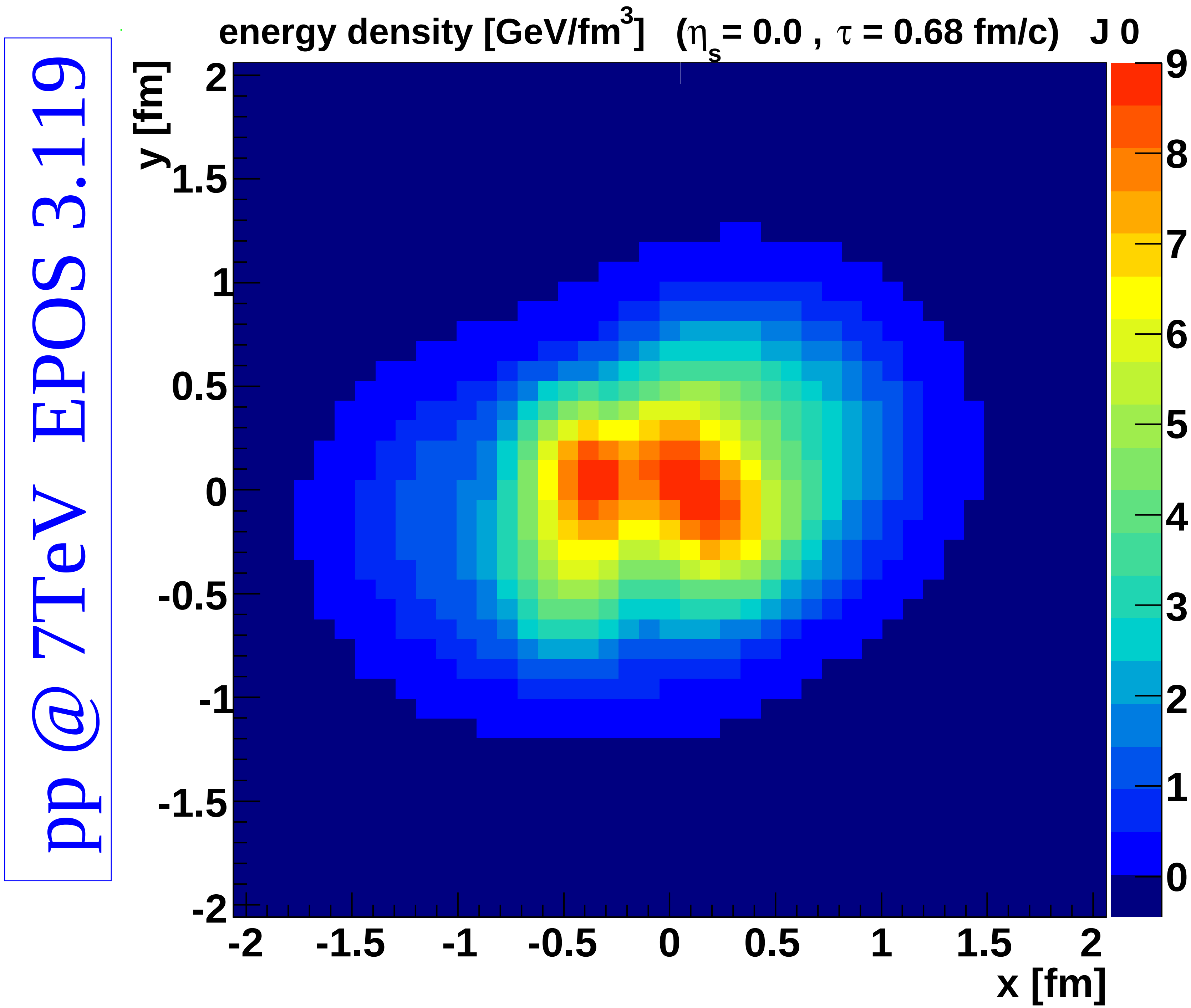
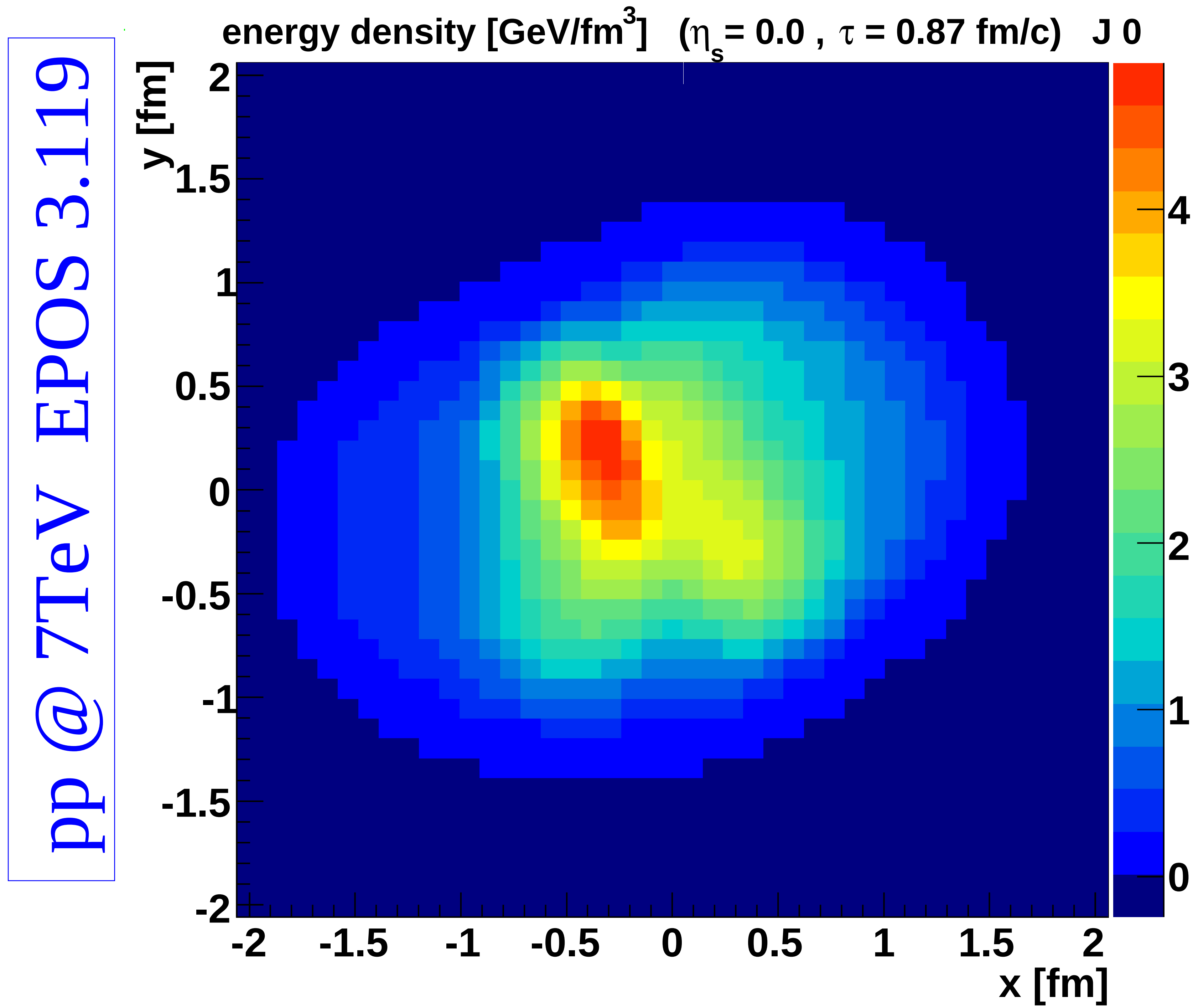
-1.5
-1
-0.5
0
0.5
1
1.5
2
0
5
10
15
20

)-14


pp @ 7TeV EPOS 3.119
energy density [GeV/fm^3] (η_s= 0.0 , τ = 0.68 fm/c) J 0
y [fm]
x [fm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
9
8
7
6
5
4
3
2
1
0


energy density [GeV/fm^3] (η_s = 0.0 , τ = 0.87 fm/c) J 0
pp @ 7TeV EPOS 3.119
y [fm]
x [fm]
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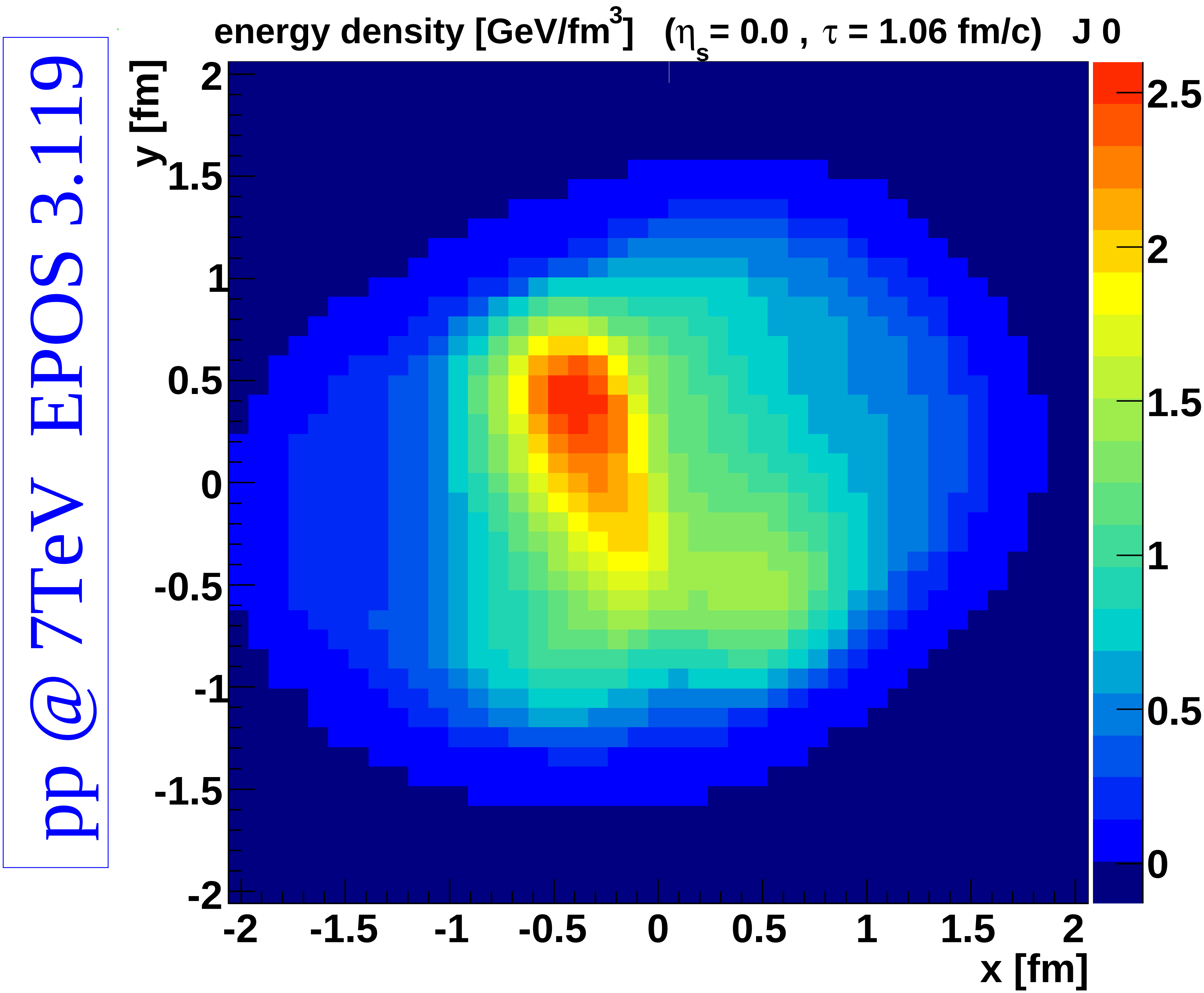
1
0.5
0
-0.5
-1
-1.5
-2
4
3
2
1
0


energy density [GeV/fm^3] (η_s = 0.0 , τ = 1.06 fm/c) J 0
pp @ 7TeV EPOS 3.119
y [fm]
x [fm]
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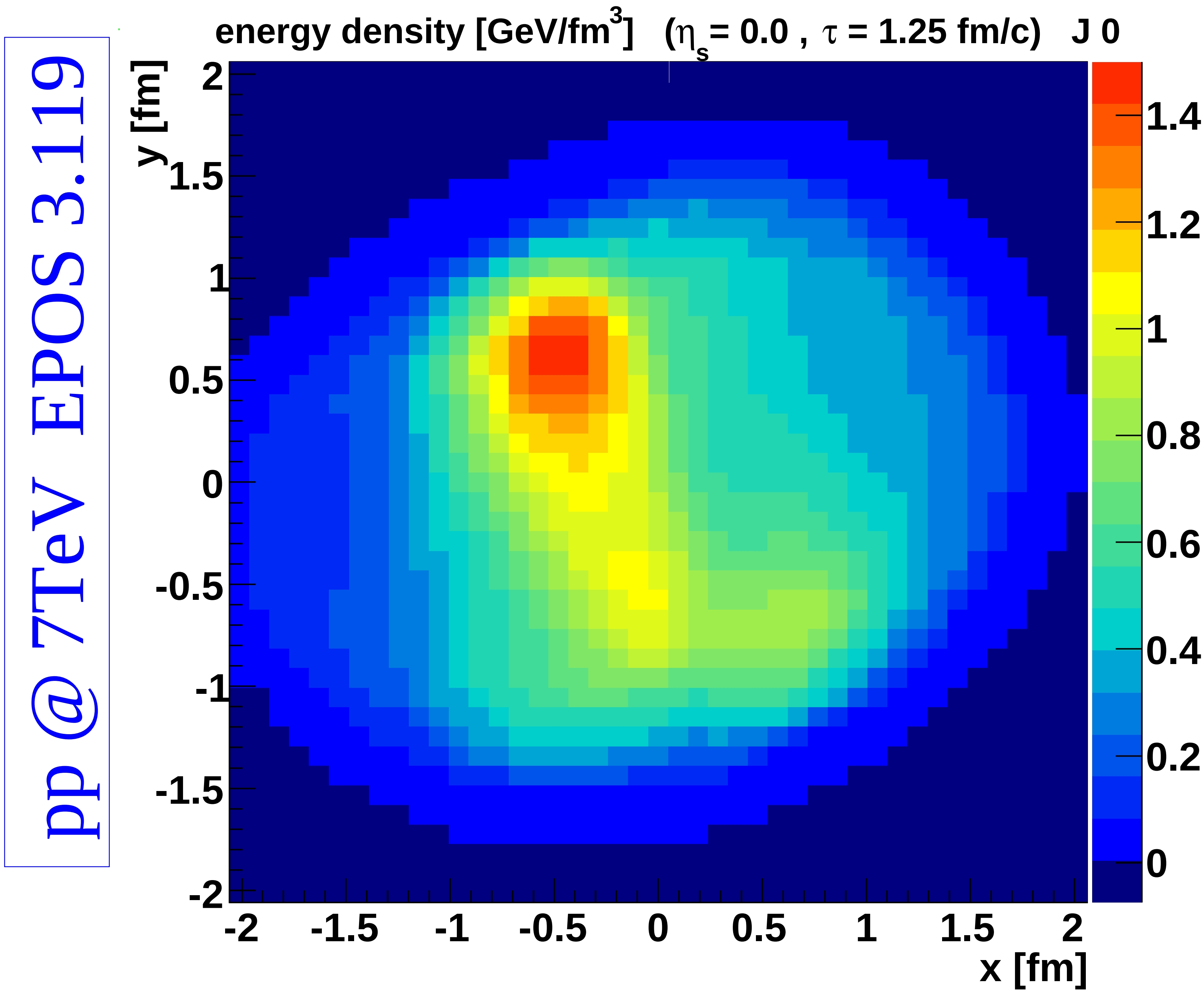
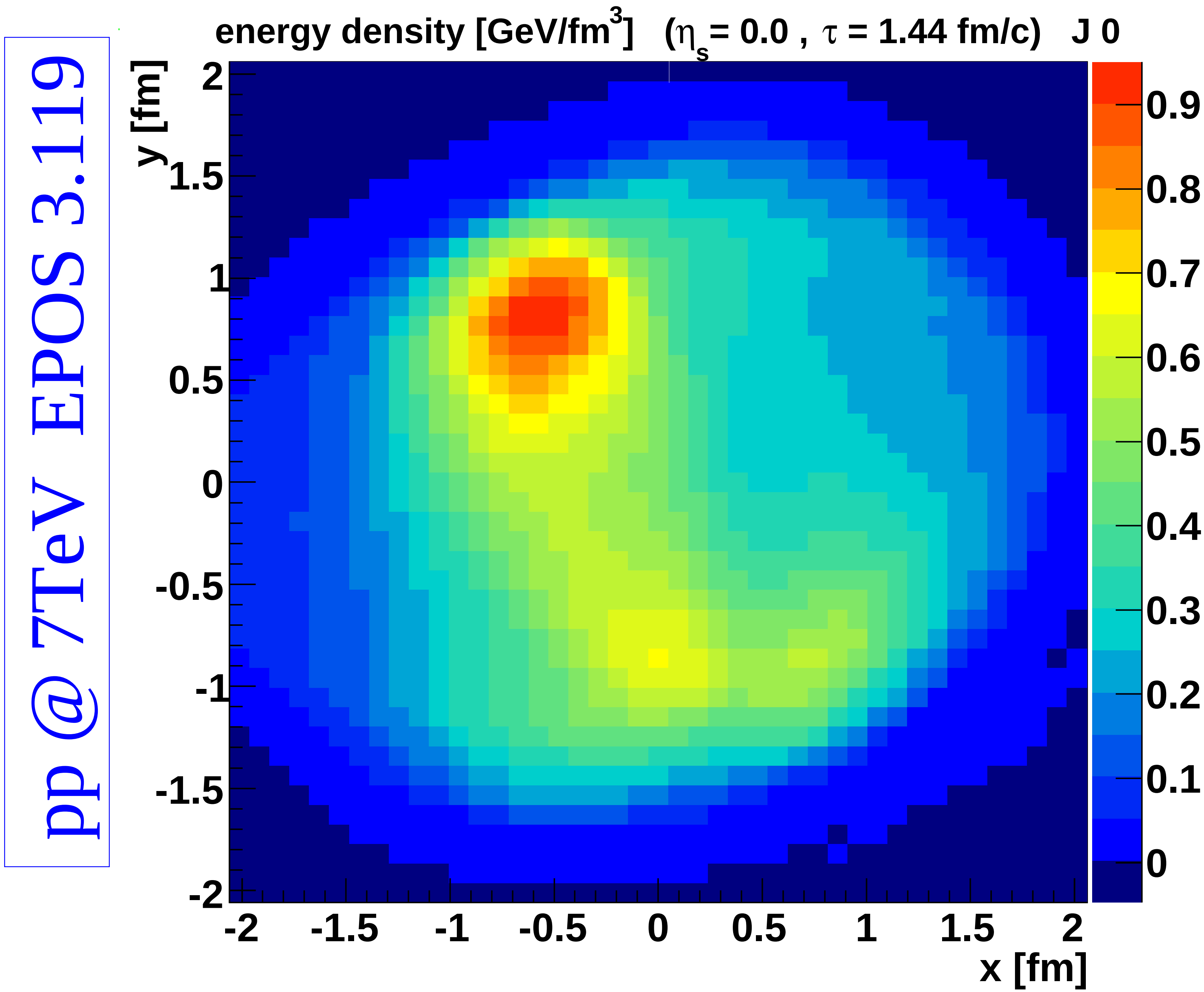
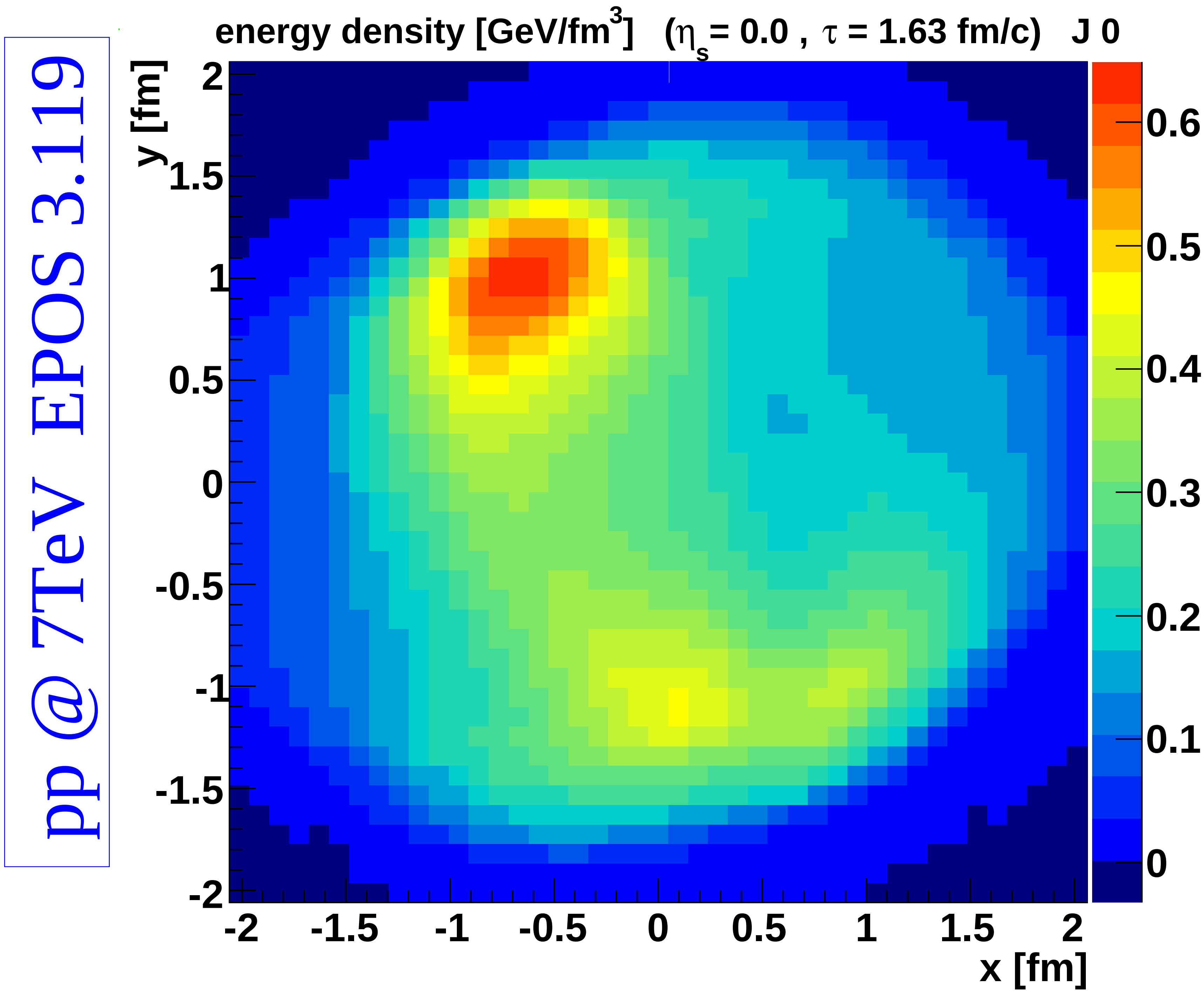
1.5
1
0.5
0
-0.5
-1
-1.5
-2
2.5
2
1.5
1
0.5
0

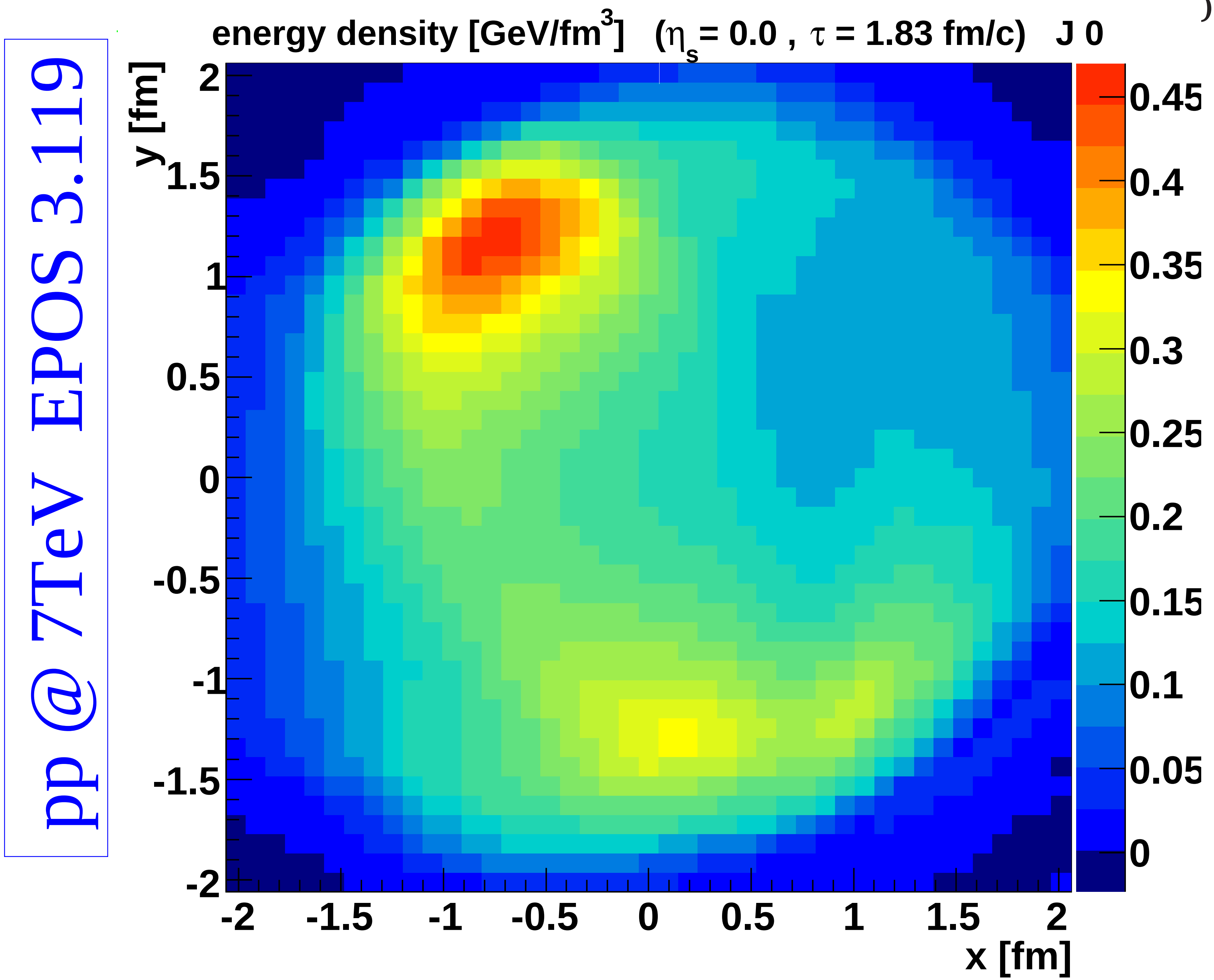


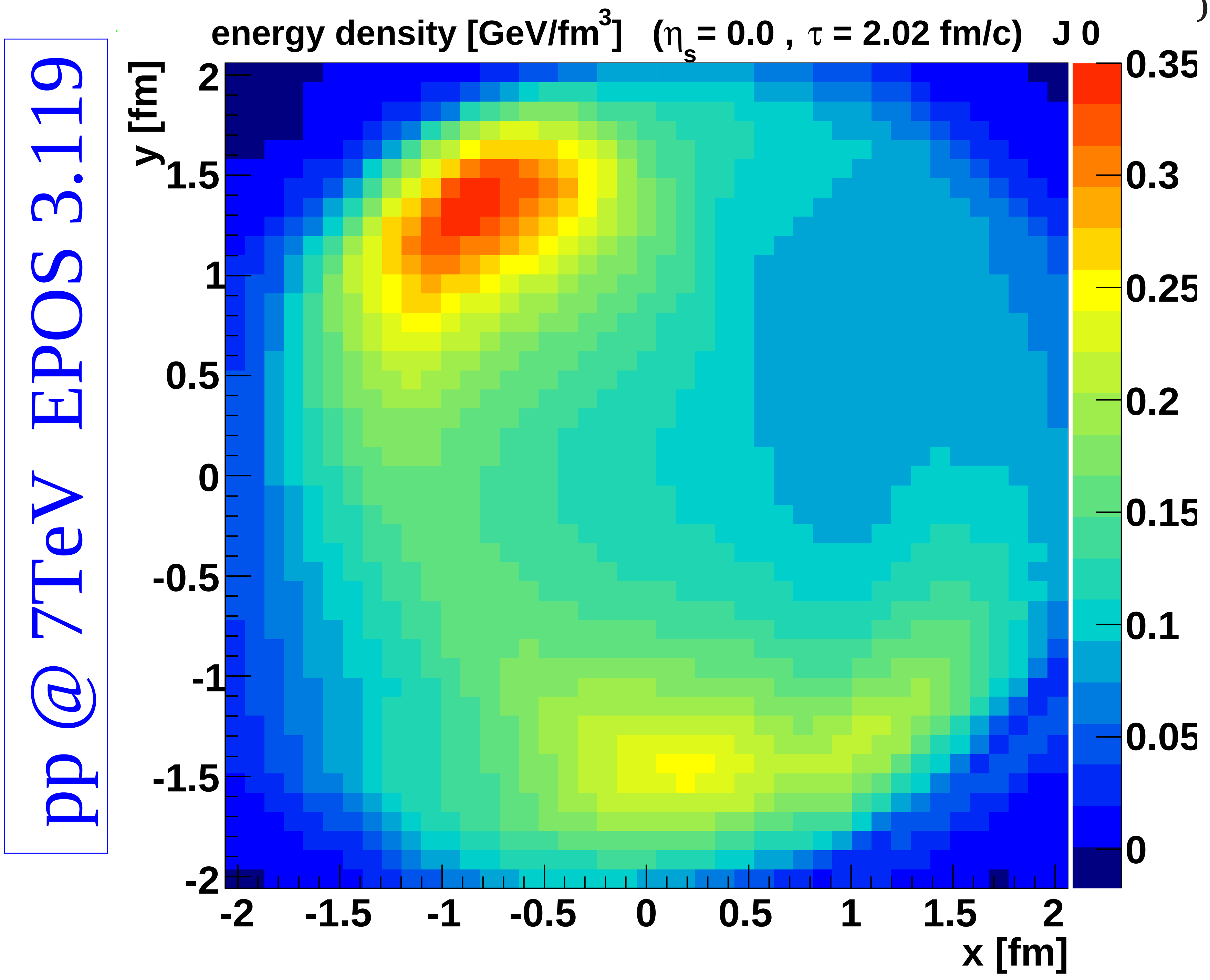
energy density [GeV/fm^3] (η_s = 0.0 , τ = 1.25 fm/c) J 0
pp @ 7TeV EPOS 3.119
y [fm]
x [fm]



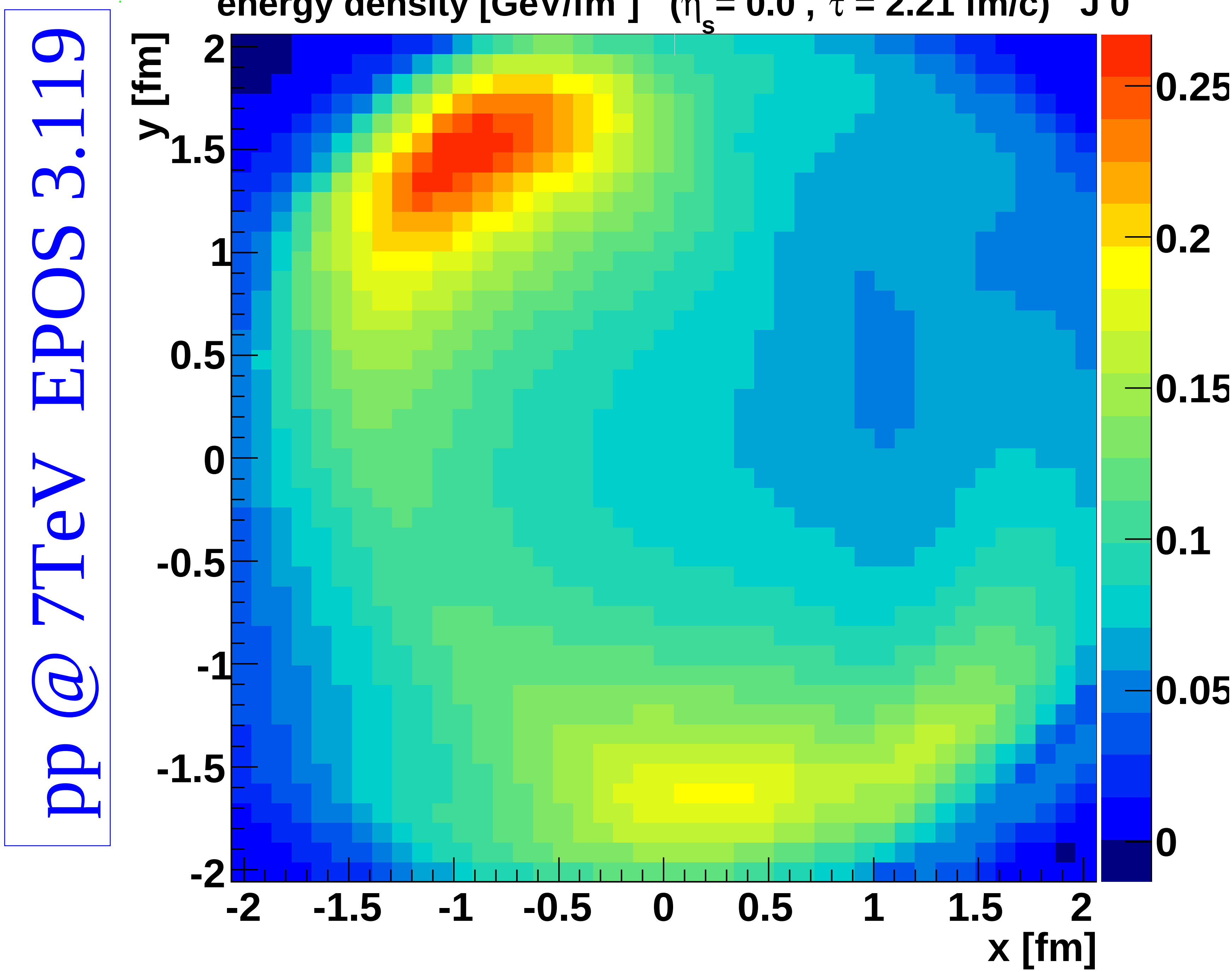
energy density [GeV/fm^3] (η_s = 0.0 , τ = 1.44 fm/c) J 0
pp @ 7TeV EPOS 3.119
y [fm]
x [fm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

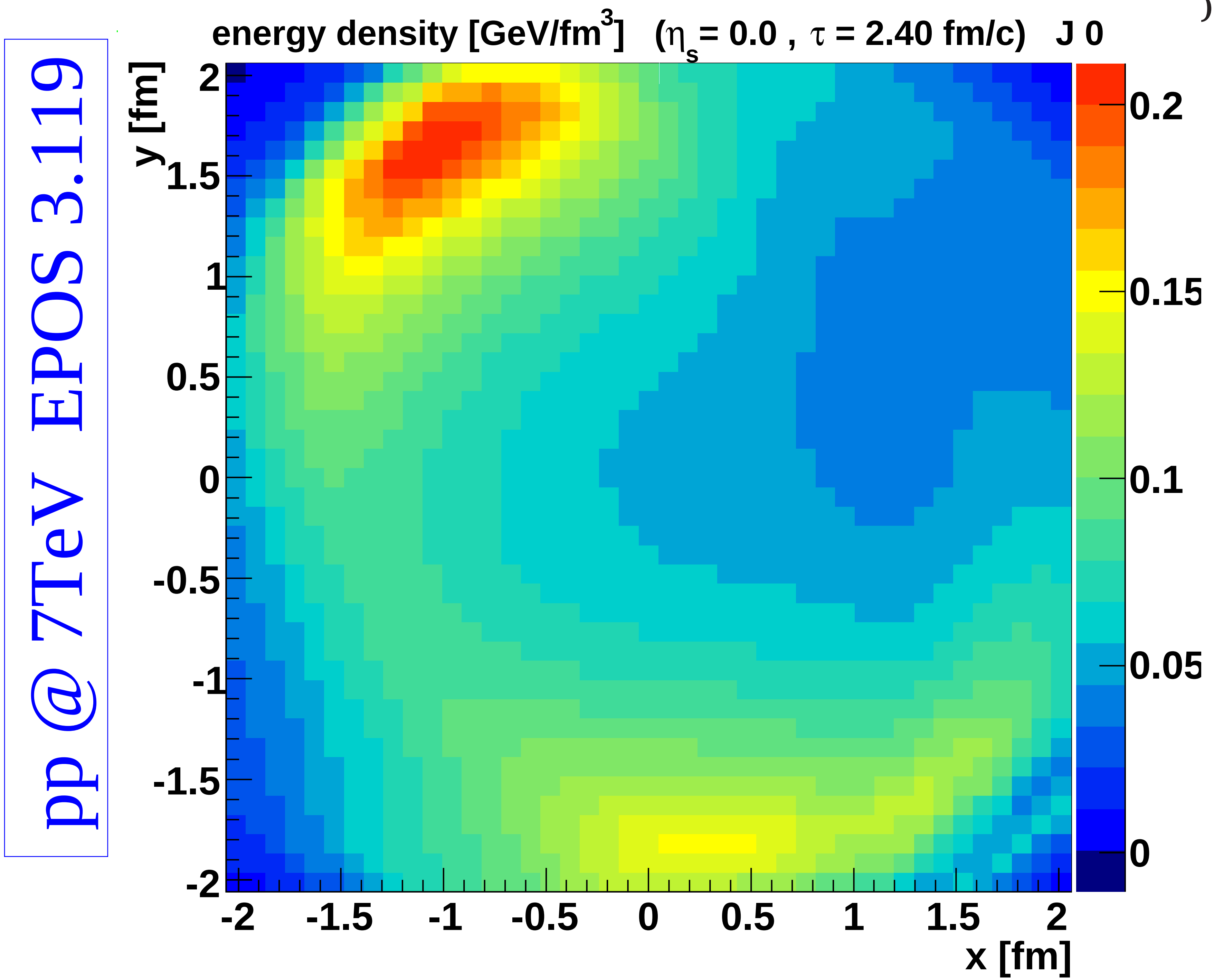

energy density [GeV/fm^3] (η_s = 0.0 , τ = 1.63 fm/c) J 0
pp @ 7TeV EPOS 3.119
y [fm]
x [fm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.6
0.5
0.4
0.3
0.2
0.1
0


pp @ 7TeV EPOS 3.119
energy density [GeV/fm^3] (η_s= 0.0 , τ = 1.83 fm/c) J 0
y [fm]
x [fm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0



pp @ 7TeV EPOS 3.119
energy density [GeV/fm^3] (η_s = 0.0 , τ = 2.02 fm/c) J 0
y [fm]
x [fm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0


pp @ 7TeV EPOS 3.119
energy density [GeV/fm^3] (η_s = 0.0 , τ = 2.21 fm/c) J 0
y [fm]
x [fm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.25
0.2
0.15
0.1
0.05
0



pp @ 7TeV EPOS 3.119
energy density [GeV/fm^3] (η_s= 0.0 , τ = 2.40 fm/c) J 0
y [fm]
x [fm]
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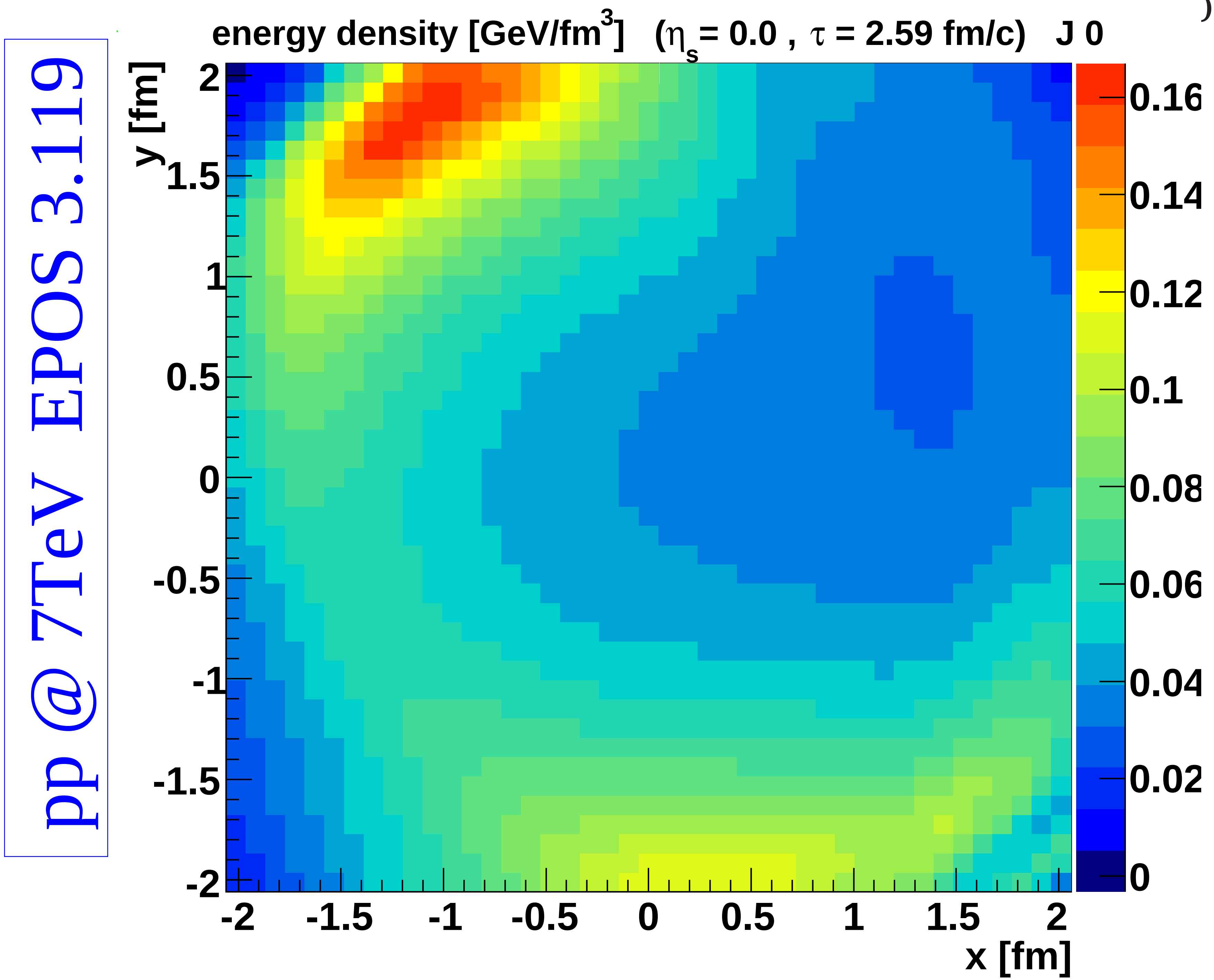
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.2
0.15
0.1
0.05
0


pp @ 7TeV EPOS 3.119
energy density [GeV/fm³] (ηs = 0.0 , τ = 2.59 fm/c) J 0
y [fm]
x [fm]
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-1.5
-1
-0.5
0
0.5
1
1.5
2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16

Charm – multiplicity correlations

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

N_{ch}: Charged particle multiplicity

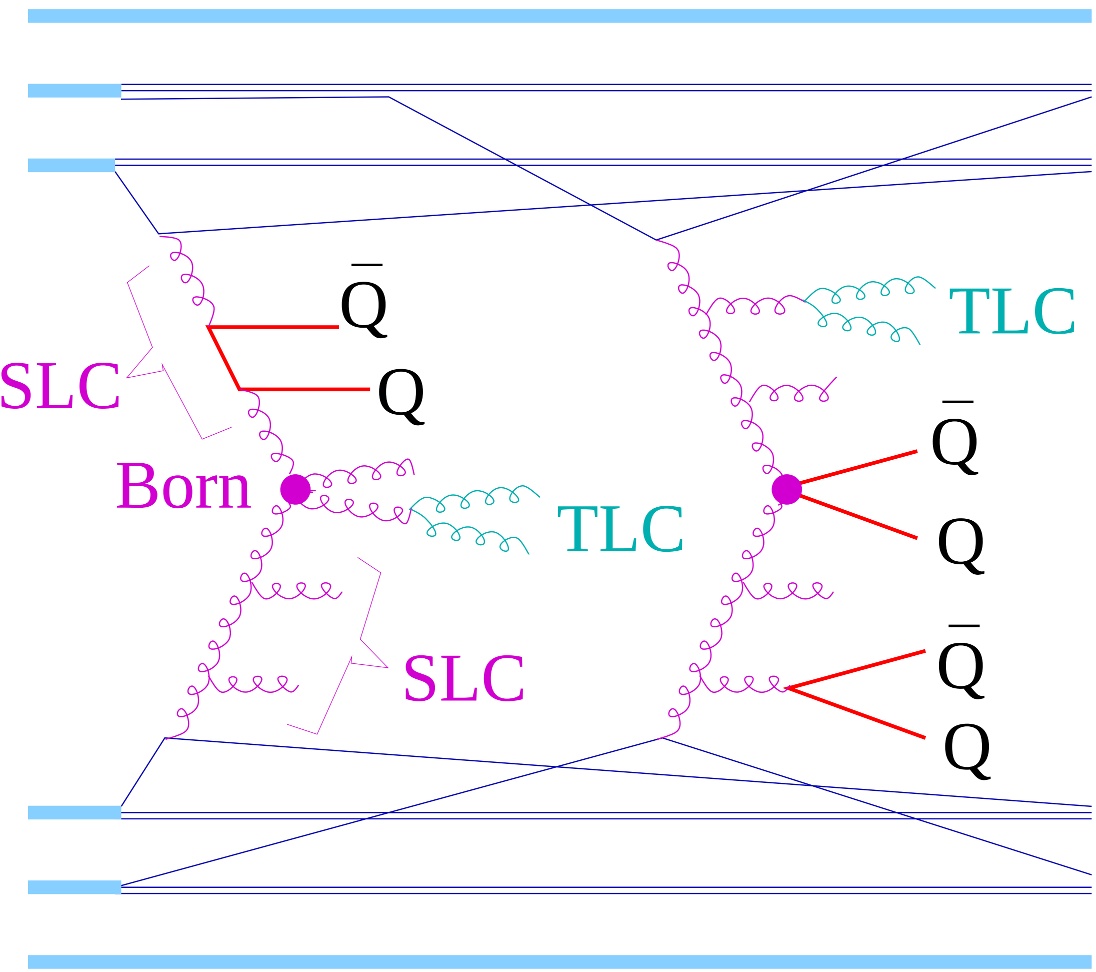
N_{D1}: D-meson multiplicity for $1 < p_t < 2\,\mathrm{GeV/c}$

N_{D2}: D-meson multiplicity for $2 < p_t < 4\,\mathrm{GeV/c}$

N_{D4}: D-meson multiplicity for $4 < p_t < 8\,\mathrm{GeV/c}$

N_{D8}: D-meson multiplicity for $8 < p_t < 12\,\mathrm{GeV/c}$

Heavy quark (Q) production in EPOS multiple scattering framework



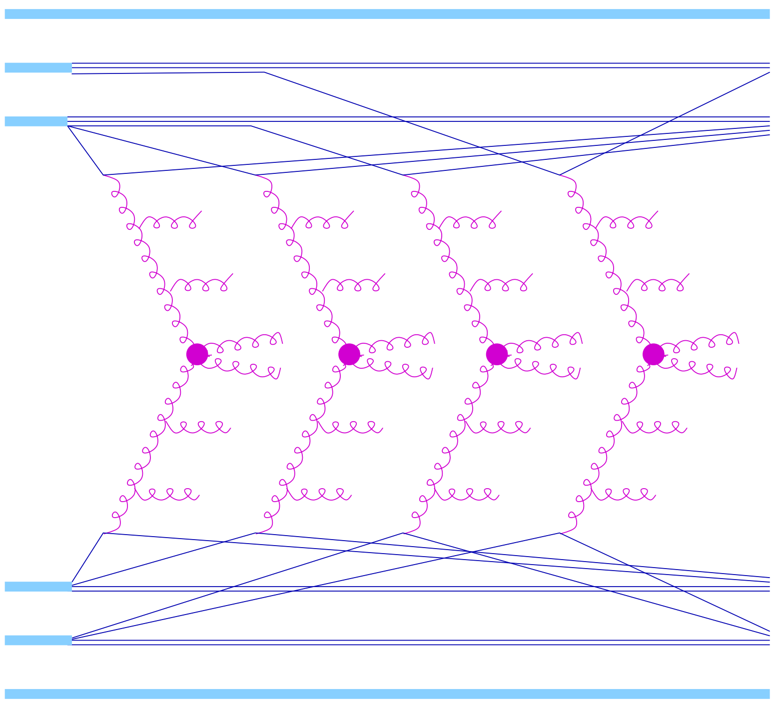
as light quark production
(but non-zero masses : $m_c = 1.3$, $m_b = 4.2$)

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):



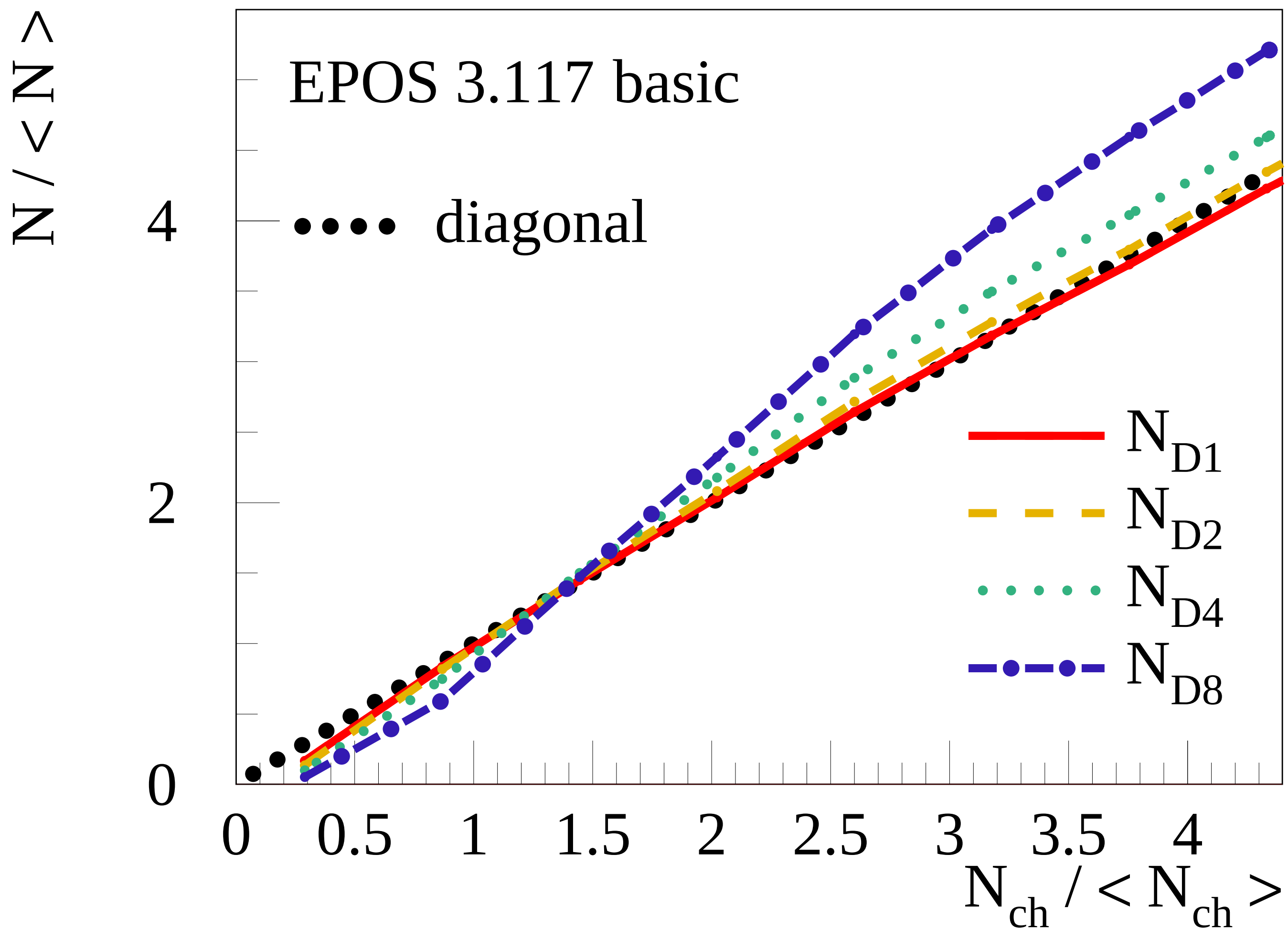
$$N_{\boldsymbol{Di}} \propto N_{\mathbf{ch}} \propto N_{\mathbf{Pom}}$$

"Natural" linear behavior

(first approximation)

In the following: N_{Pom} **as reference**

The actual calculation (EPOS basic)

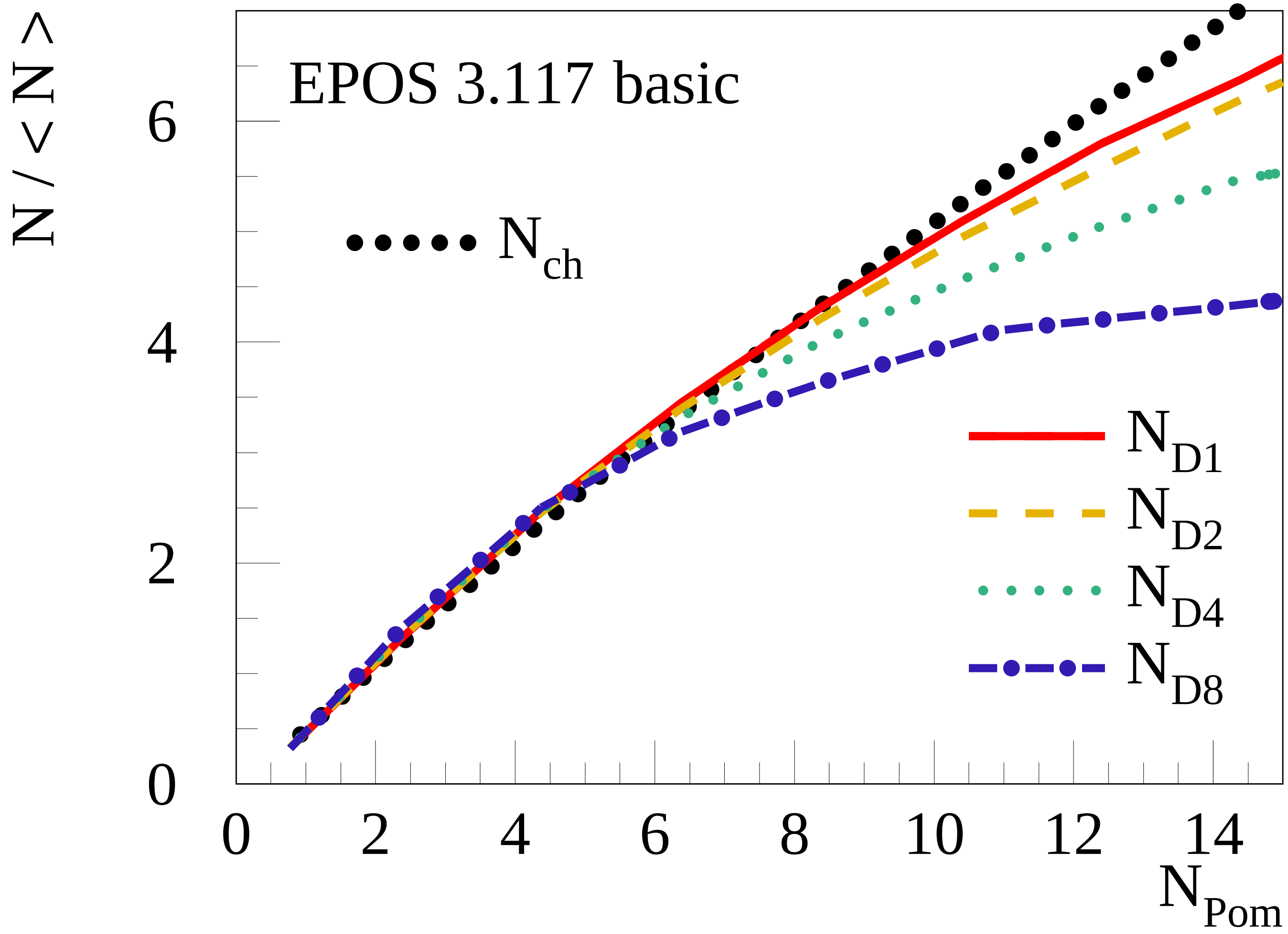


Indeed essentially a linear increase

... even more than linear !

(in particular for large p_t)

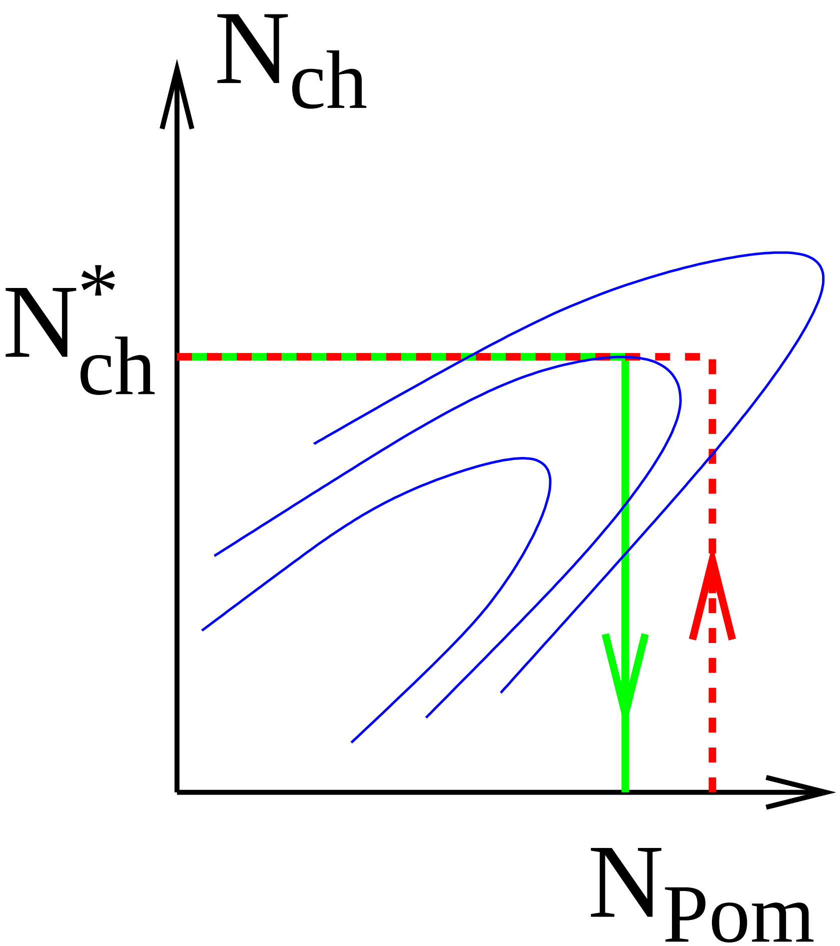
More than linear increase amazing :



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

How to understand $N_{D8}(N_{\mathrm{ch}})$ more than linear ?

But crucial: Fluctuations



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

(=> two-dimensional probability distribution)

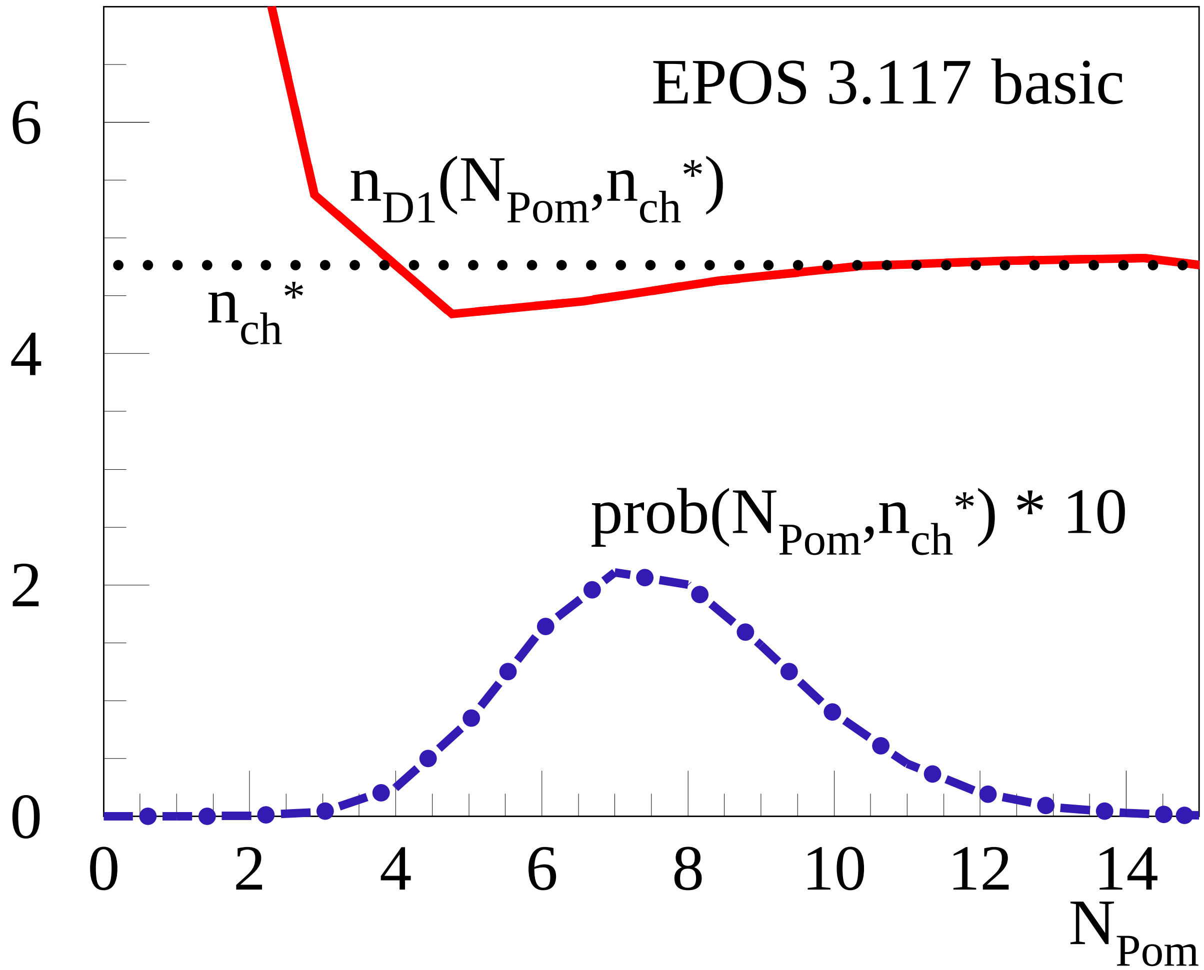
We define normalized multiplitities

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

for n_{ch} **and** n_{Di}

In the following we consider fixed values ${n_{\mathrm{ch}}}^{*}$ **of normalized charged multiplicities**

Consider n_{D1} for some given $n_{\text{ch}}{}^*$



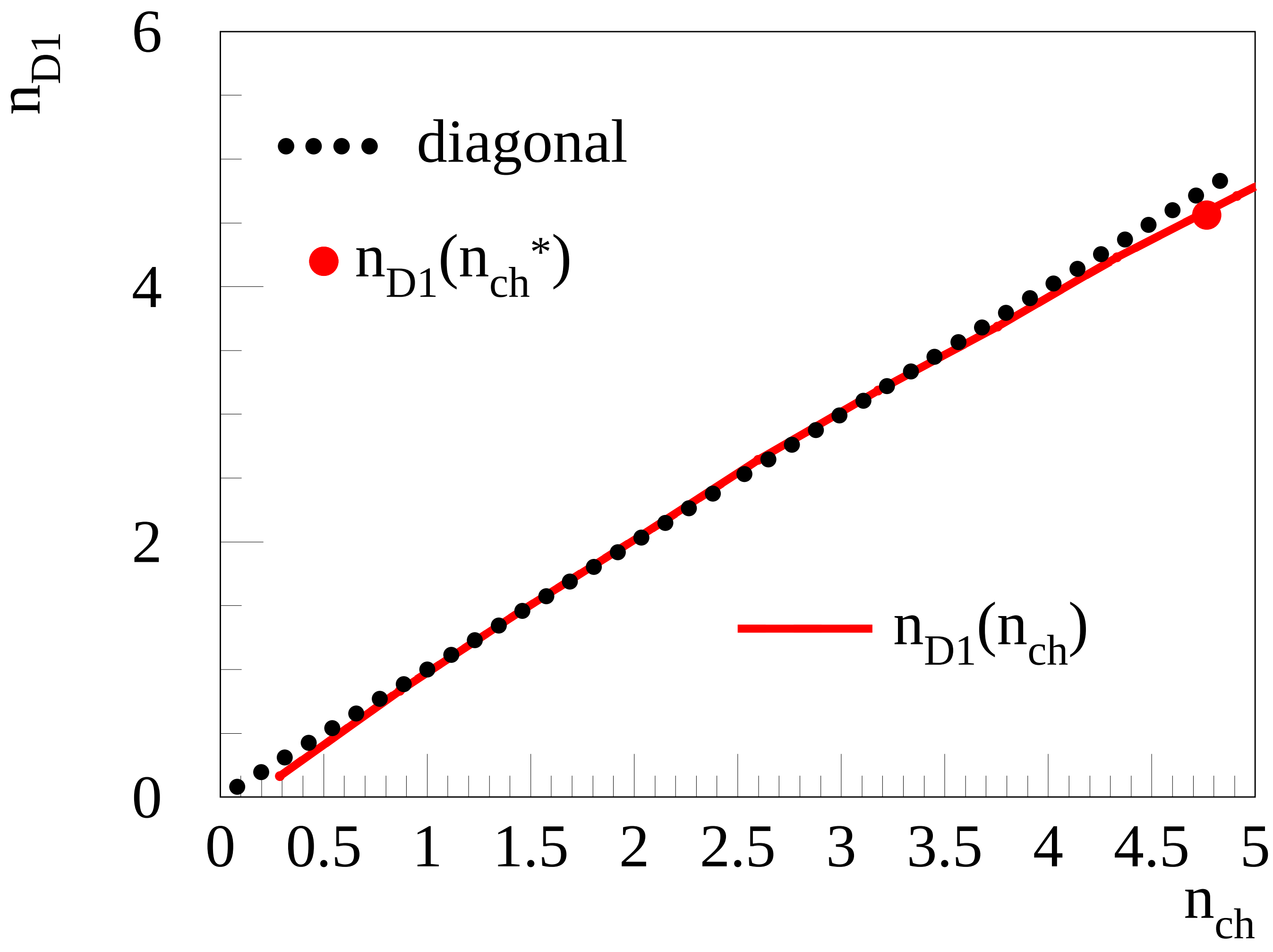
$$n_{D1} = \sum_{N_{\text{Pom}}} \text{prob}(N_{\text{Pom}}, n_{\text{ch}}{}^*) \times n_{D1}(N_{\text{Pom}}, n_{\text{ch}}{}^*) \approx n_{\text{ch}}{}^*$$

having used

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

The precise calculation:

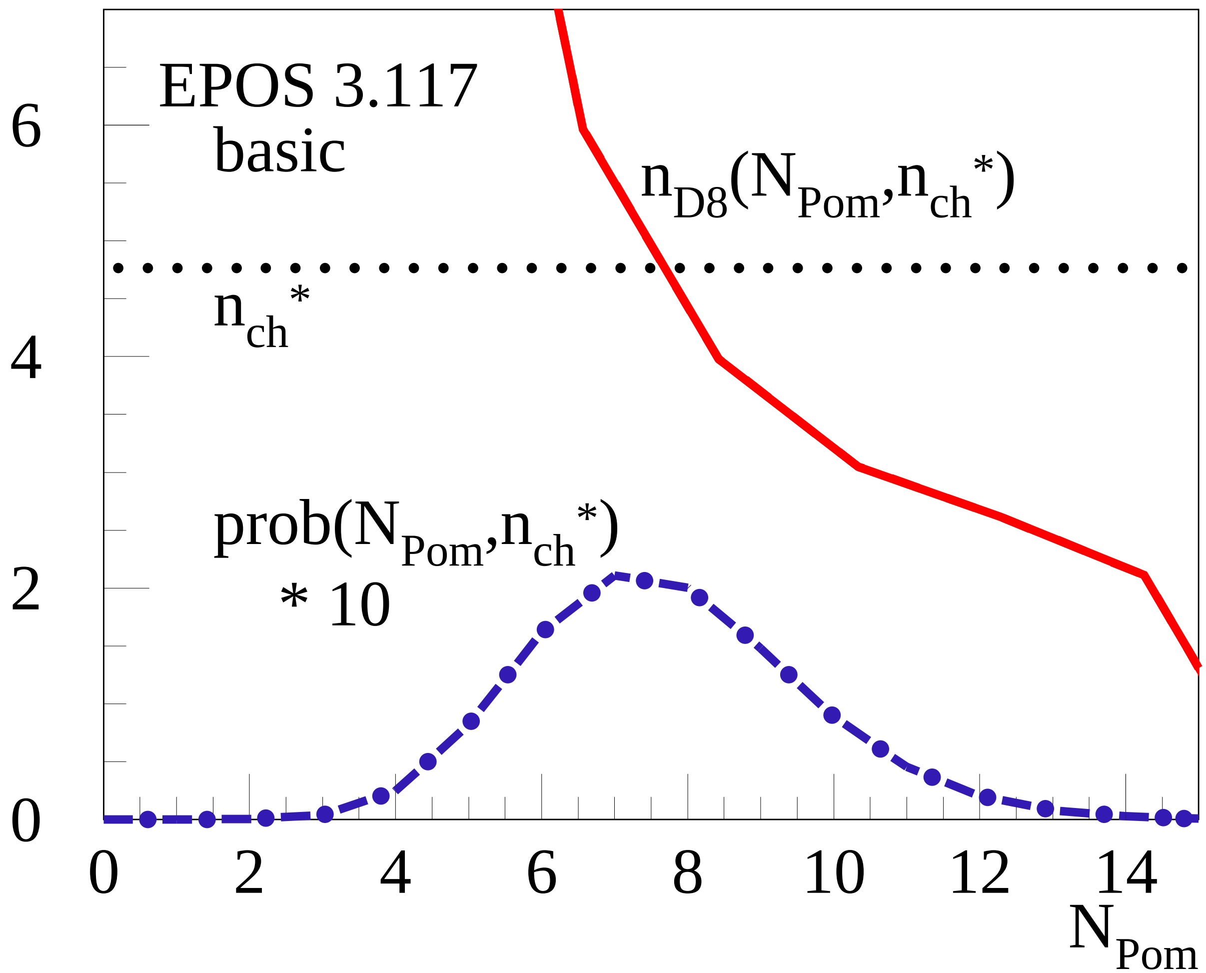
(red point)



on the diagonal!

Perfectly linear!

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

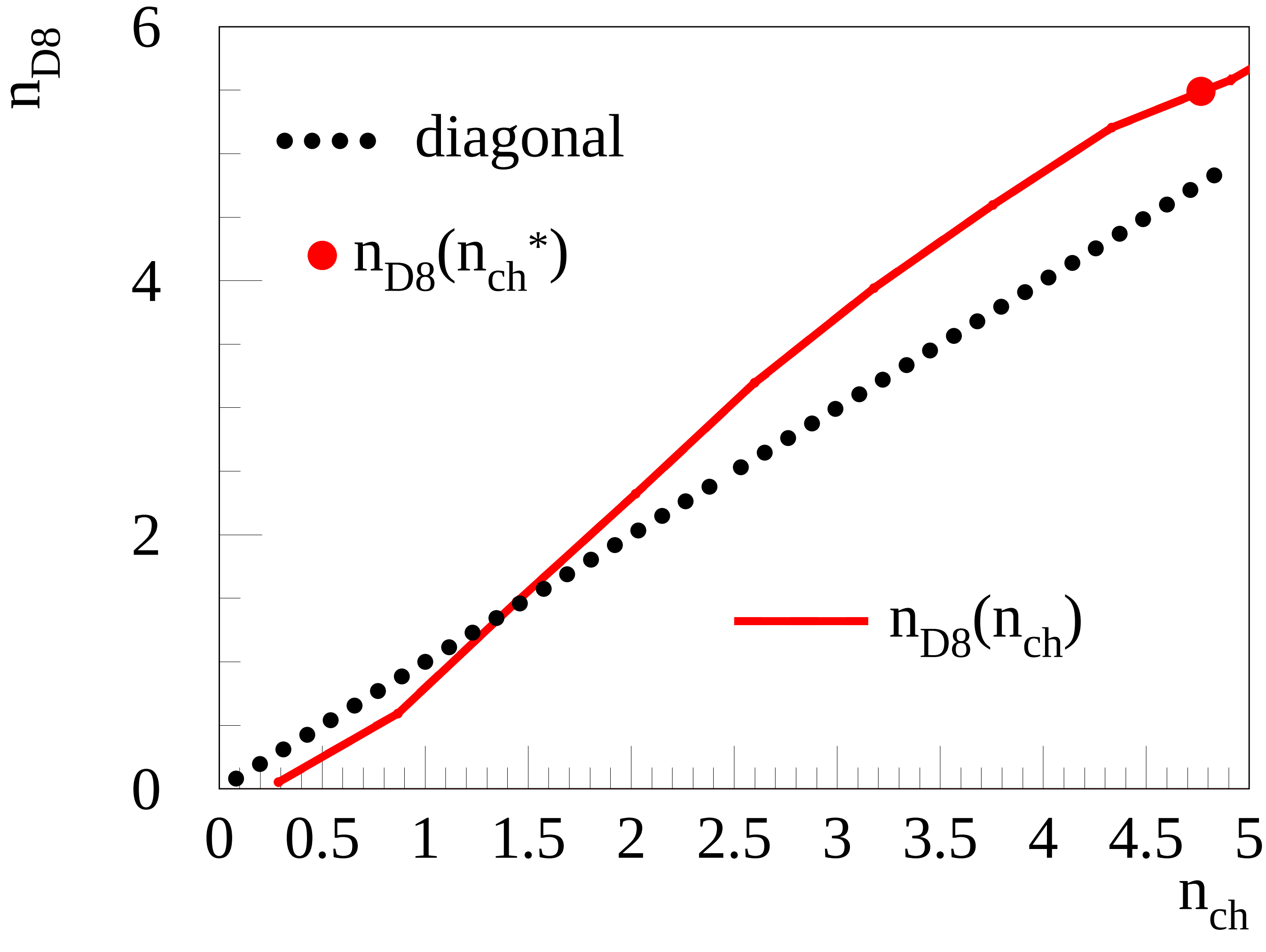


$$n_{D8} = \sum_{N_{\rm Pom}} \mathrm{prob}(N_{\rm Pom}, n_{\rm ch}{}^{*}) \times n_{D8}(N_{\rm Pom}, n_{\rm ch}{}^{*}) > n_{\rm ch}{}^{*}$$

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

The precise calculation:

(red point)



above the diagonal!

non-linear!

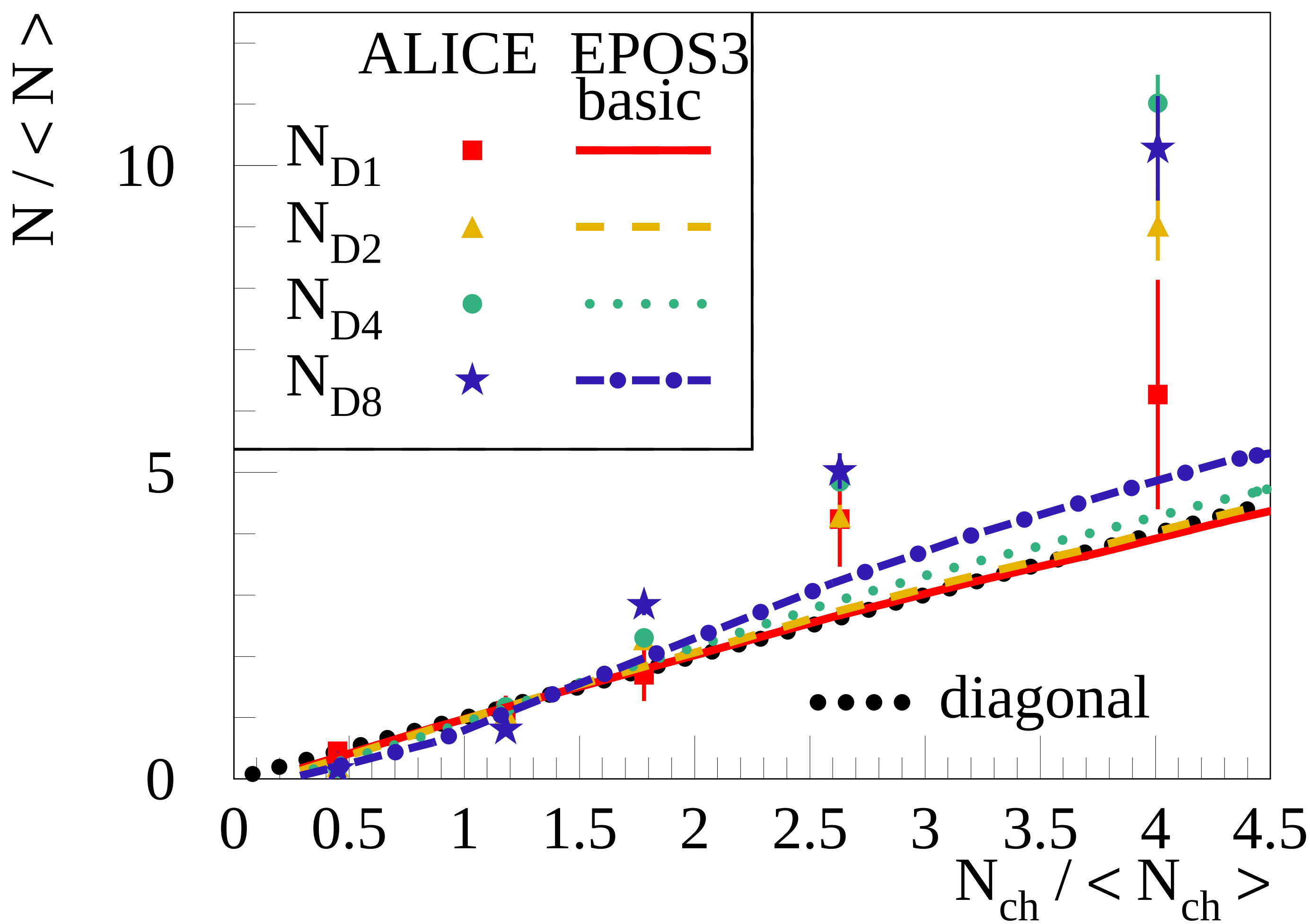
More than linear increase since

- 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

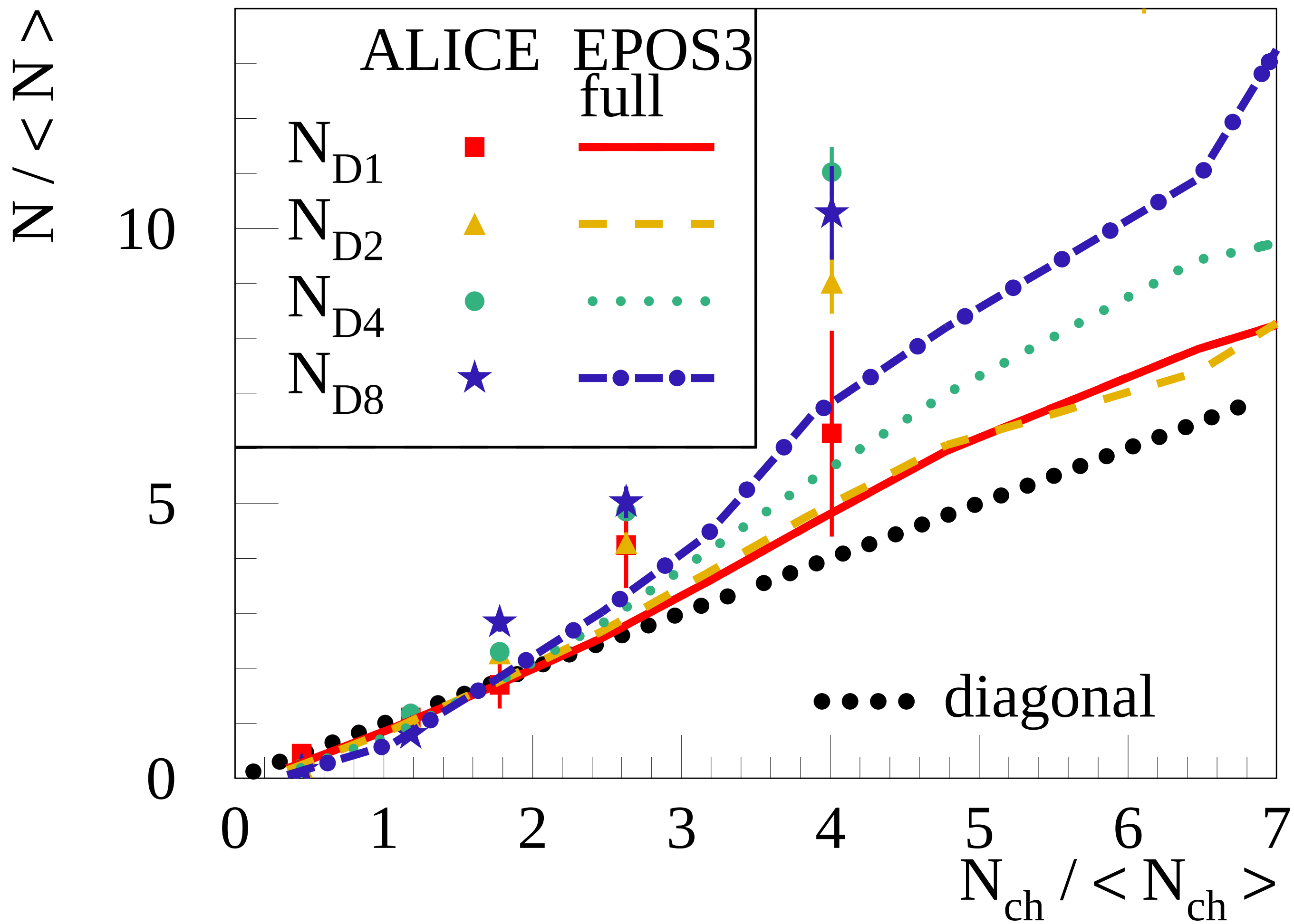
in particular for large p_t

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

=> full approach (EPOS w hydro + cascade)

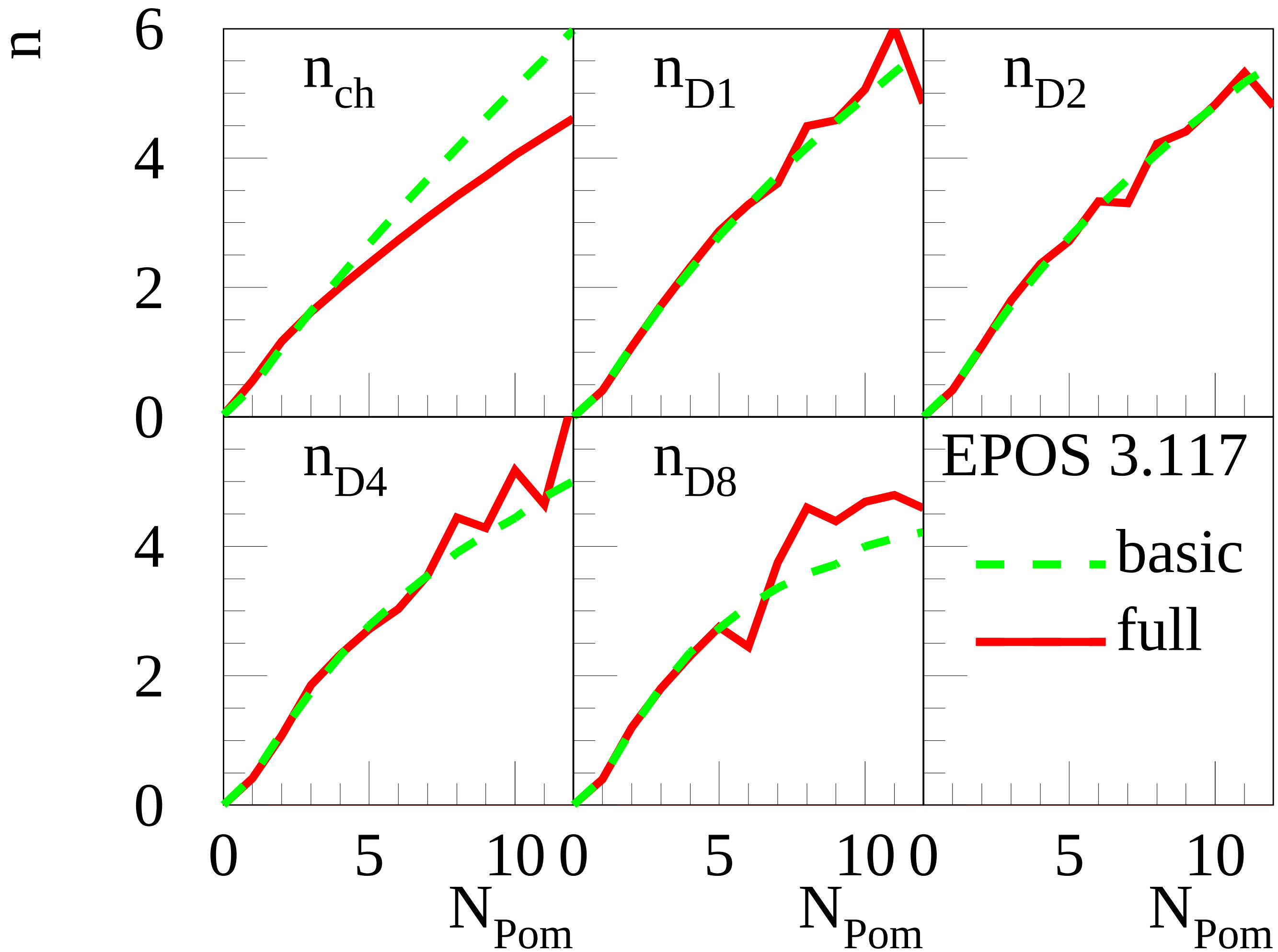
(with or without hadronic cascade makes no difference)

Full EPOS3



Significant non-linear increase!

How to understand the increased non-linearity?



Little change for n_{Di}

(as expected)

But significant reduction of $n_{\rm ch}$

Not the charm production is increased with increasing "collision activity"

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

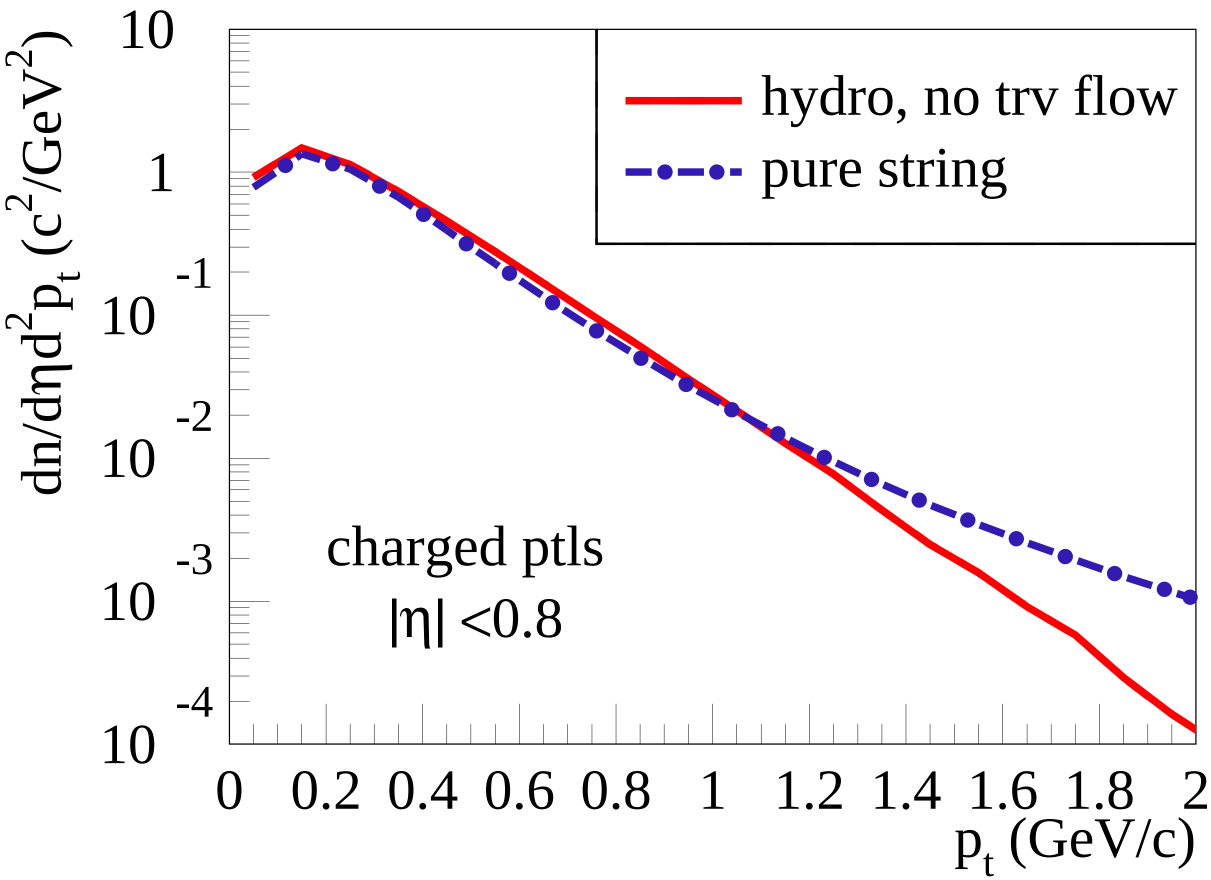
Collision activity = Pomeron number

Why such a multiplicity reduction?

Basic EPOS:
Pomerons > Strings
> String fragmentation

(independent of event activity)

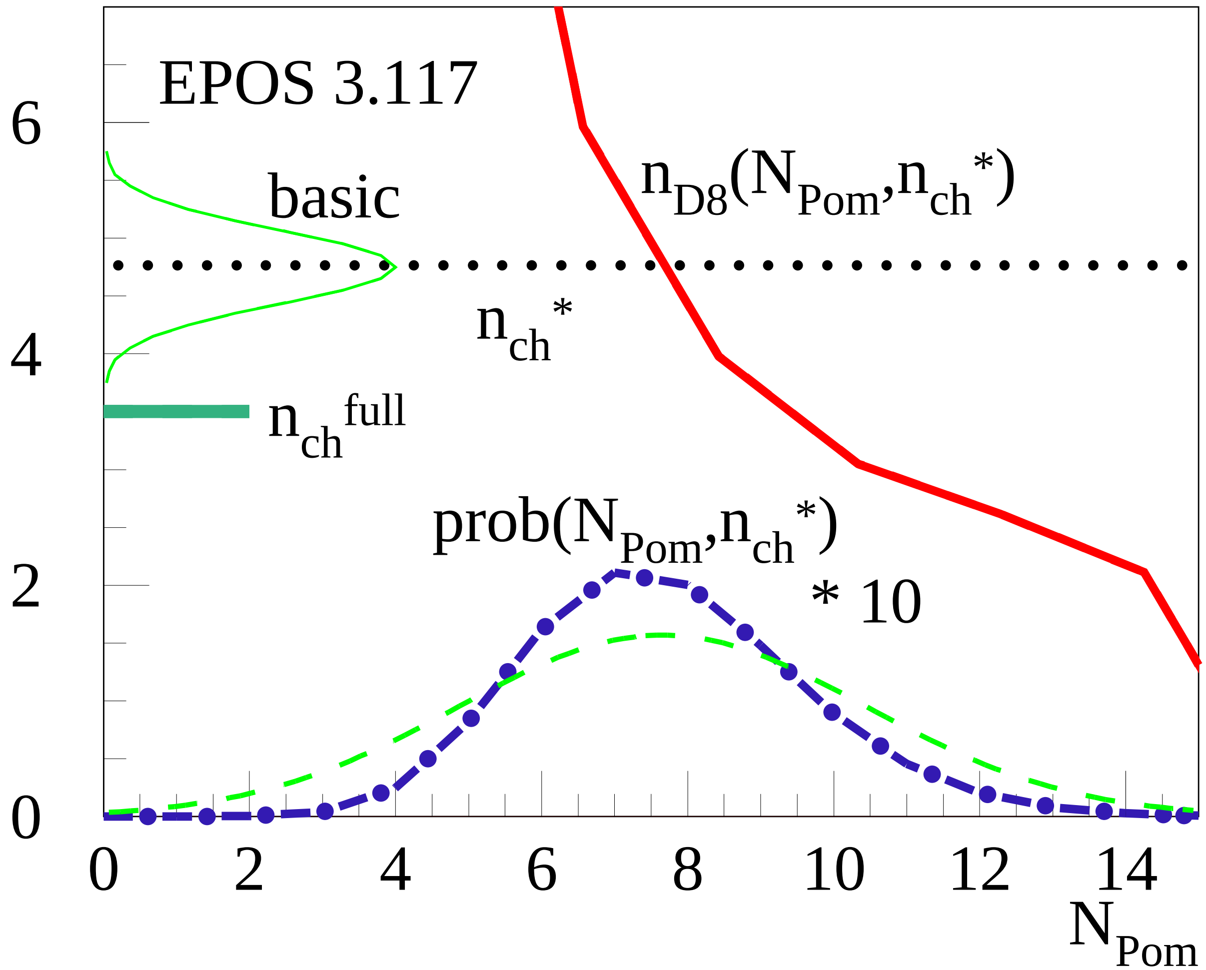
Full model:
Pomerons > Strings
> Fluid, collectivity
(collective energy increases with event activity)



Why is the non-linearity of $N_{Di}(N_{\mathrm{ch}})$ more pronounced at high pt ?

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

Pt dependence



Broader N_{Pom} distribution with hydro

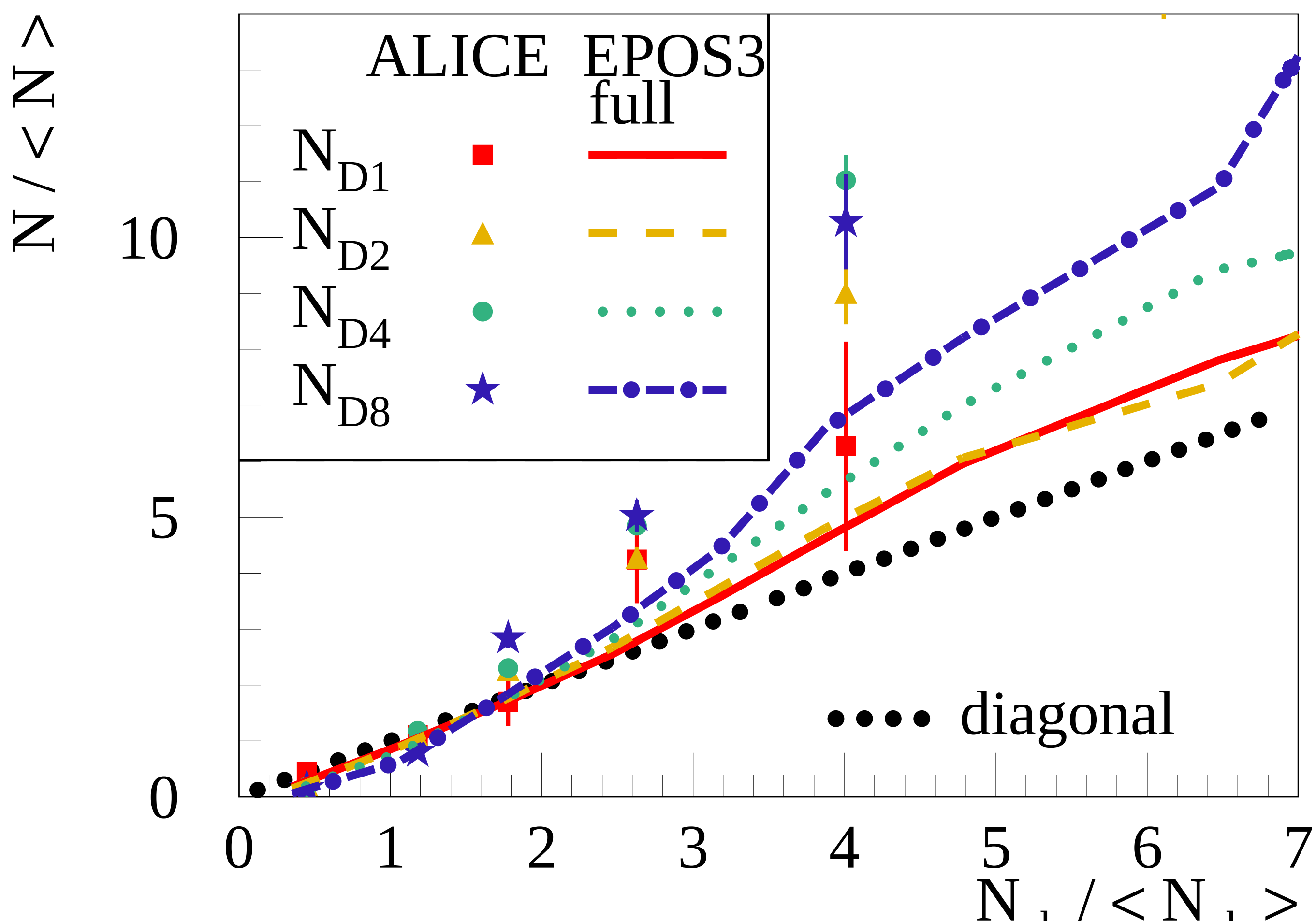
+ strongly dropping n_{D8}

makes big effect

Summary

Significant non-linear increase of $N_{Di}(N_{\mathrm{ch}})$

(in particular for high pt)



understandable in terms of multiple scattering and flow