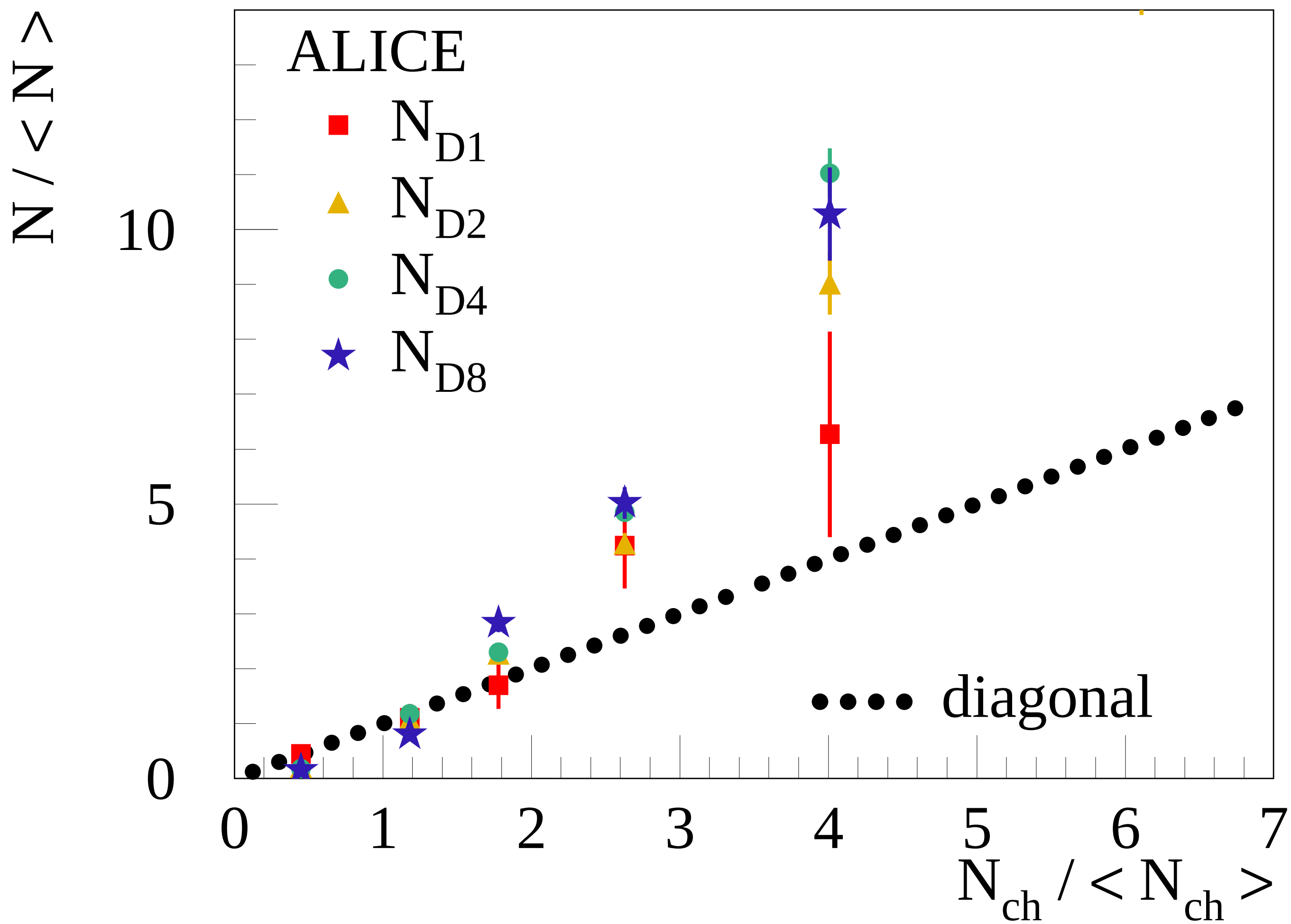
Charm production in high multiplicity pp events

K.W. in collaboration with

B. Guiot, Iu. Karpenko, T. Pierog

D-meson multiplicity vs charged multiplicity

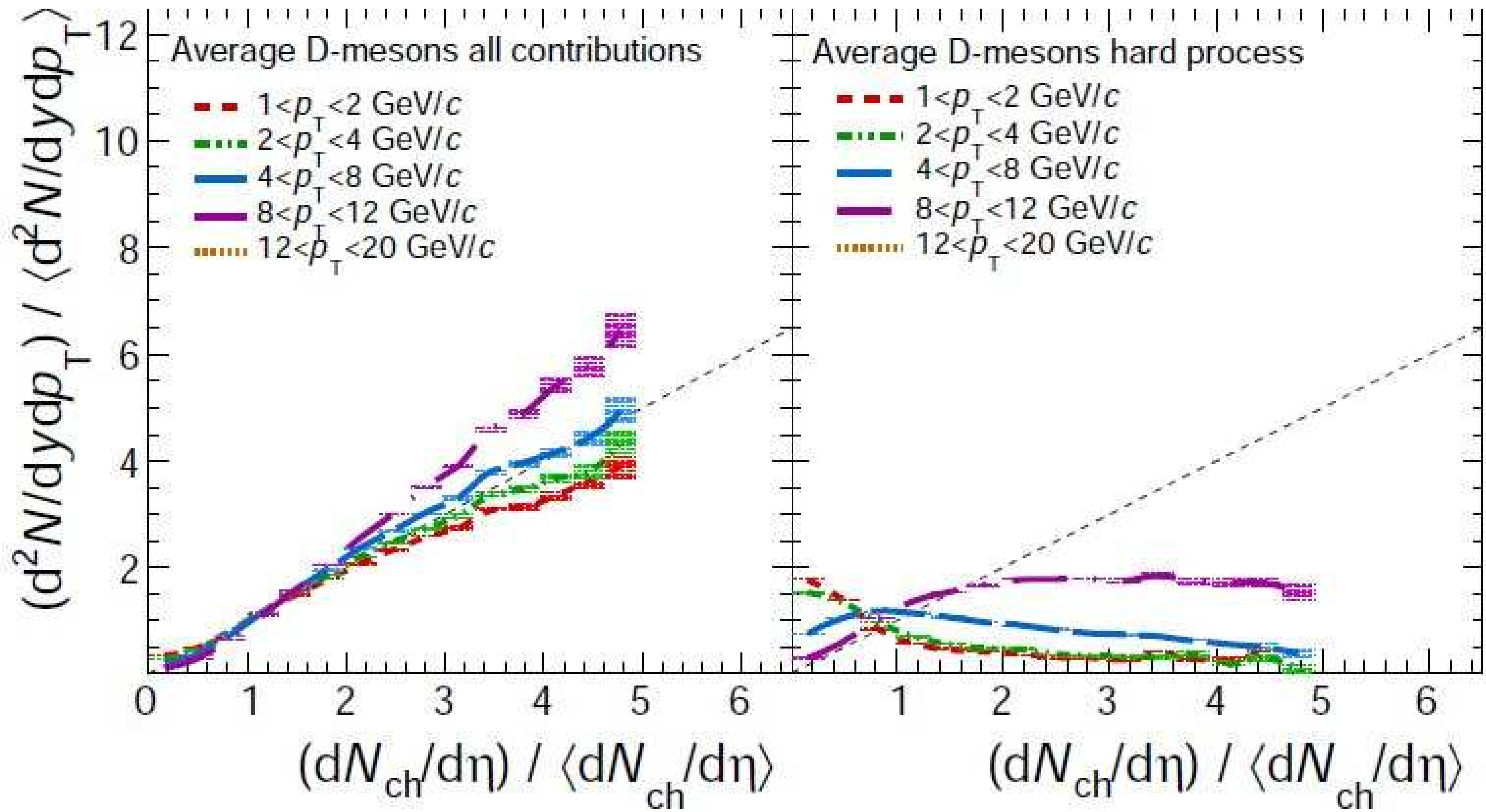


Significant deviation from the diagonal (linear increase)

in particular for large p_t

ALICE arXiv:1505.00664v1

PYTHIA 8.157


Average D-mesons all contributions
1<pT<2 GeV/c
2<pT<4 GeV/c
4<pT<8 GeV/c
8<pT<12 GeV/c
12<pT<20 GeV/c
Average D-mesons hard process
(d2N/dydpT) / ⟨d2N/dydpT⟩
(dNch/dη) / ⟨dNch/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:

For ALL reactions: Same procedure, several stages

- ☐ Initial conditions:
  Gribov-Regge multiple scattering approach,
  elementary object = Pomeron = parton ladder,
  using saturation scale $Q_s \propto N_{part}\,\hat{s}^{\lambda}$ (CGC)
- ☐ Core-corona approach
  to separate fluid and jet hadrons
- ☐ Viscous hydrodynamic expansion, $\eta/s = 0.08$
- ☐ Statistical hadronization, final state hadronic cascade

arXiv:1312.1233 , arXix:1307.4379

1 Multiple scattering

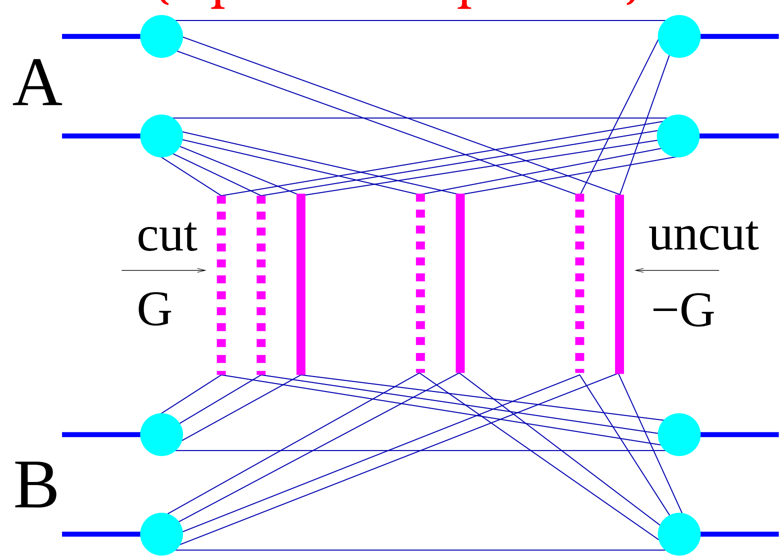
Initial conditions: Marriage pQCD+GRT+energy sharing

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

For pp, pA, AA:

(squared amplitude)

$$\sigma^{\mathrm{tot}} = \underbrace{\sum_{\mathrm{cut\,P}} \int \sum_{\mathrm{uncut\,P}} \int}_{d\sigma_{\mathrm{exclusive}}}$$



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

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

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

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

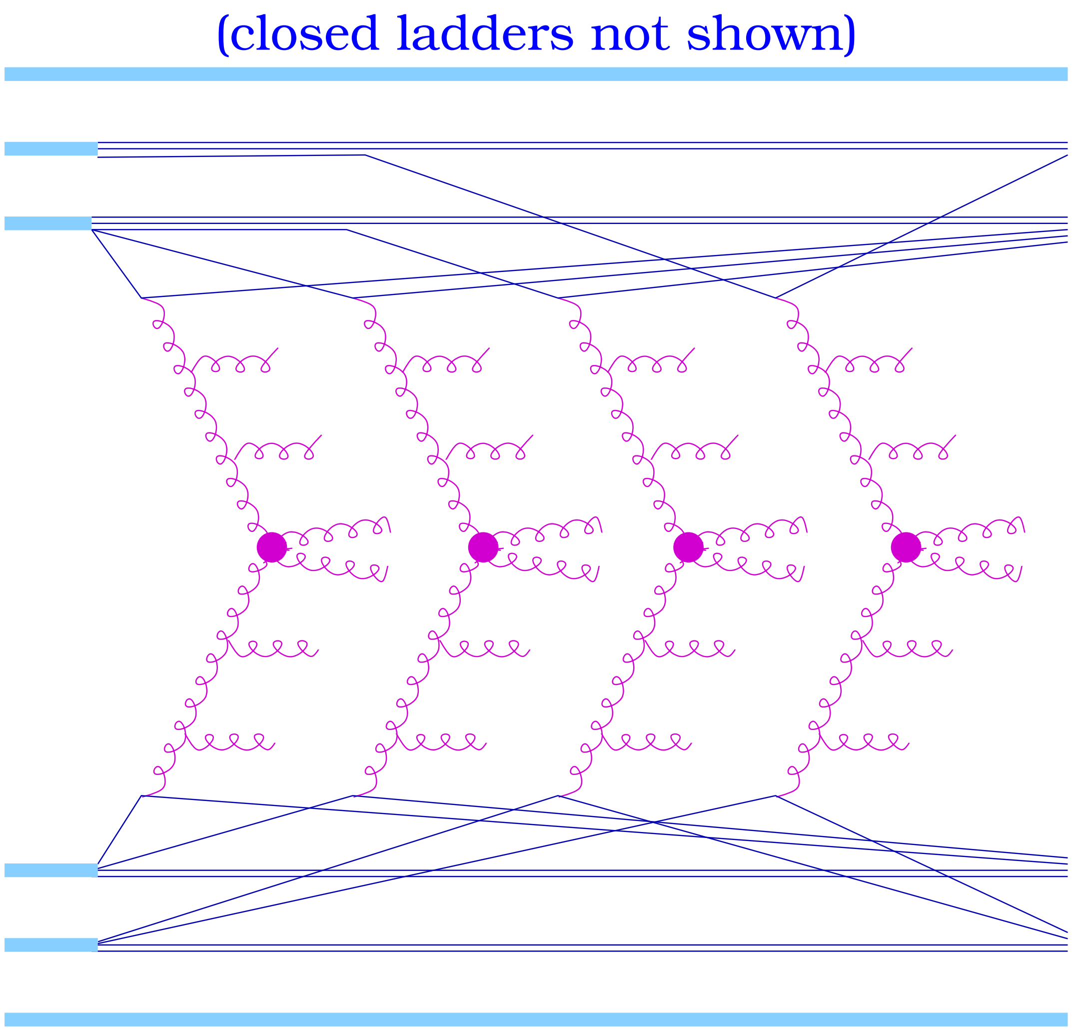
$$\sum_{m_1 l_1} \dots \sum_{m_{AB} l_{AB}} (1-\delta_{0\Sigma m_k}) \int \prod_{k=1}^{AB} \Bigg(\prod_{\mu=1}^{m_k} dx_{k,\mu}^+ dx_{k,\mu}^- \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^+ d\tilde{x}_{k,\lambda}^- \Bigg) \Bigg\{$$

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

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

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

From parton ladders to flux tubes



Many collisions in parallel

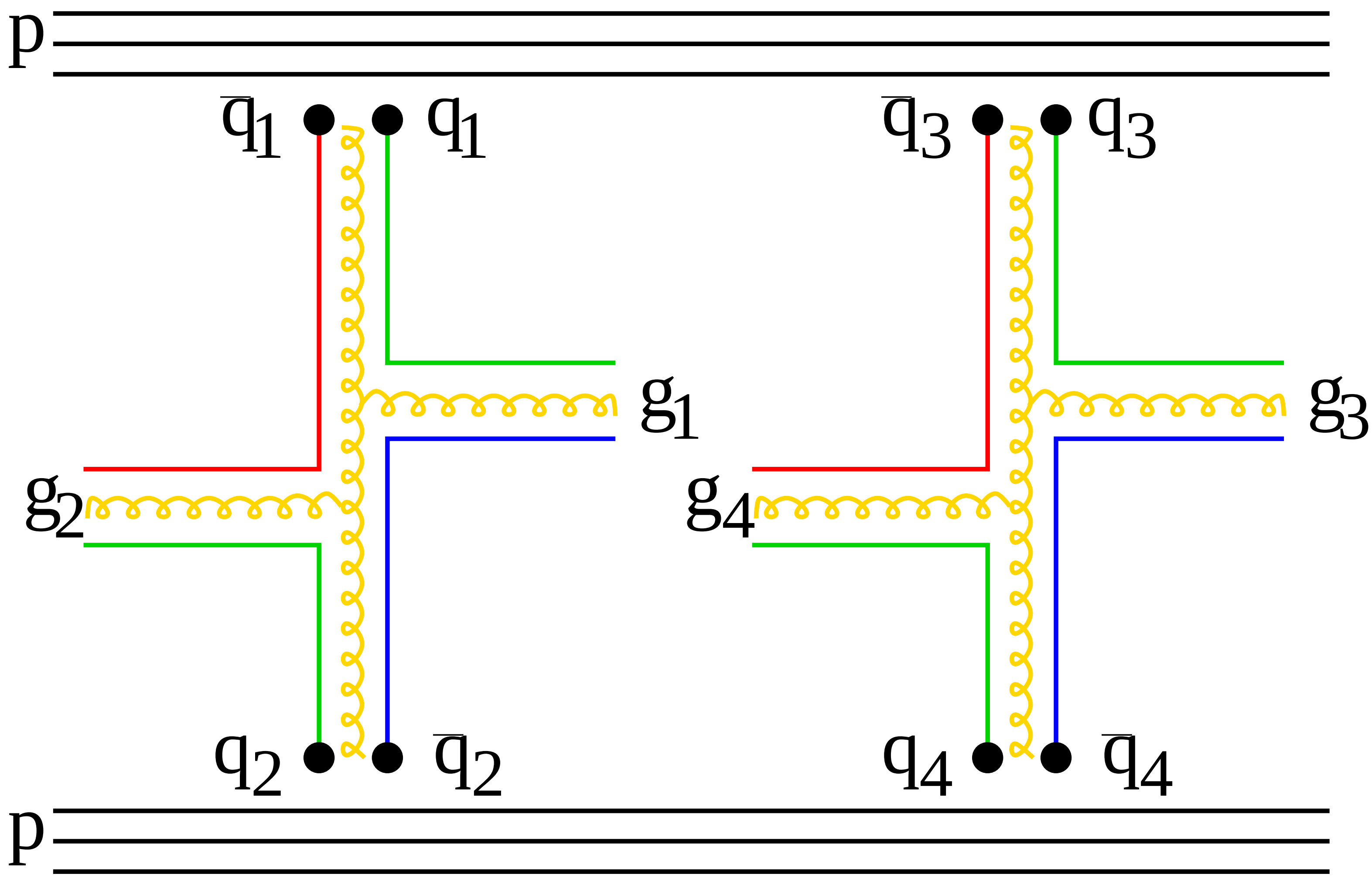
Single scattering

= hard elementary scattering including IS + FS radiation

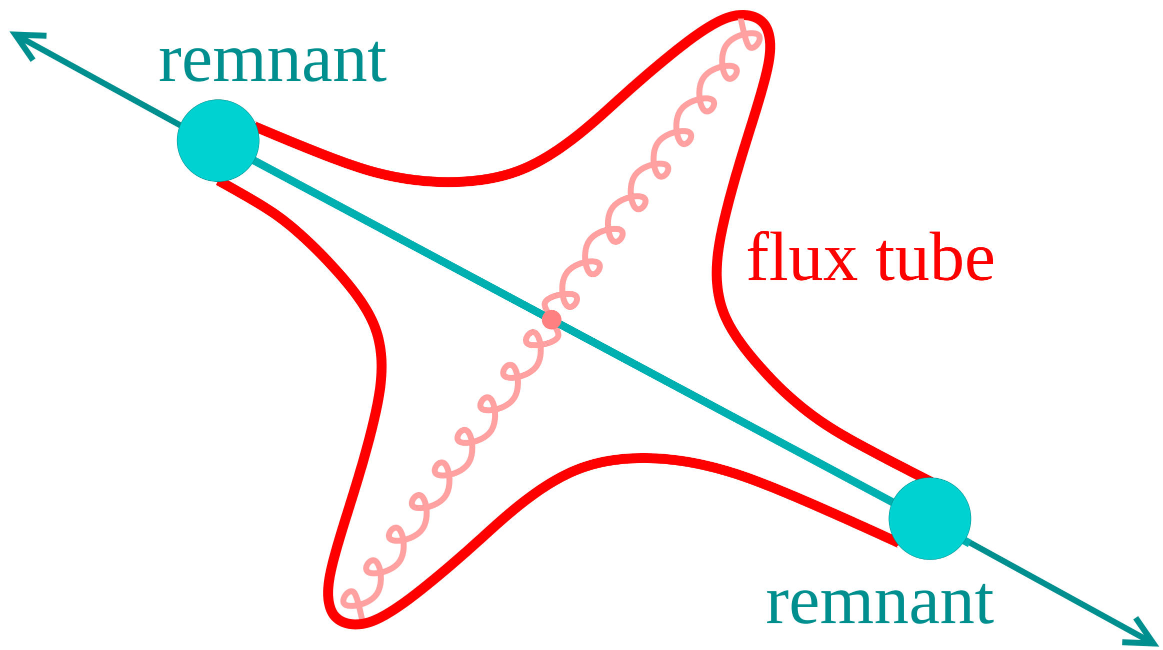
= parton ladder

= color flux tubes

parton ladders => color flux tubes => kinky strings

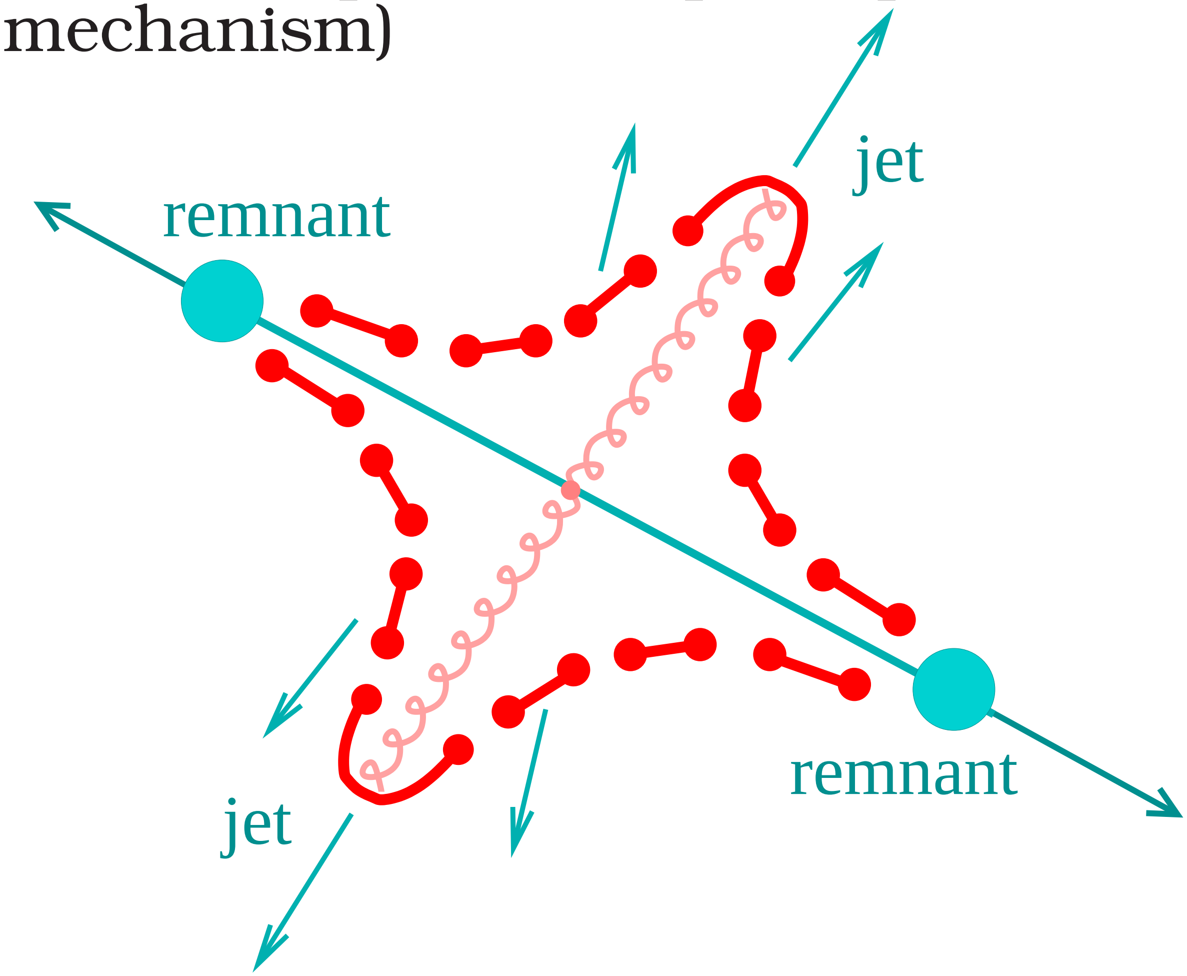


Space-time picture: kinky strings



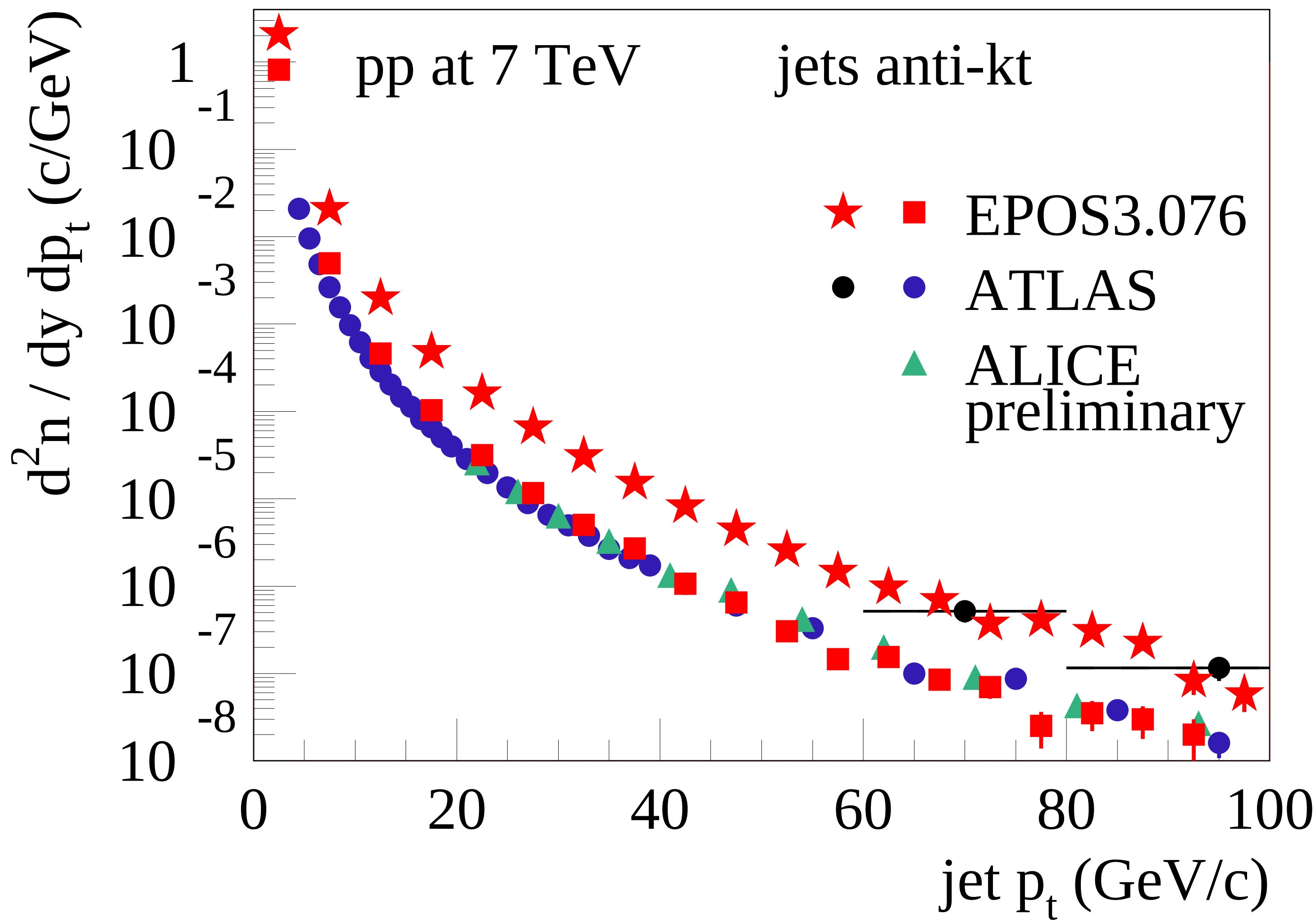
here no IS radiation, only hard process producing two gluons

Strings expand and break
via the production of quark-antiquark pairs
(Schwinger mechanism)

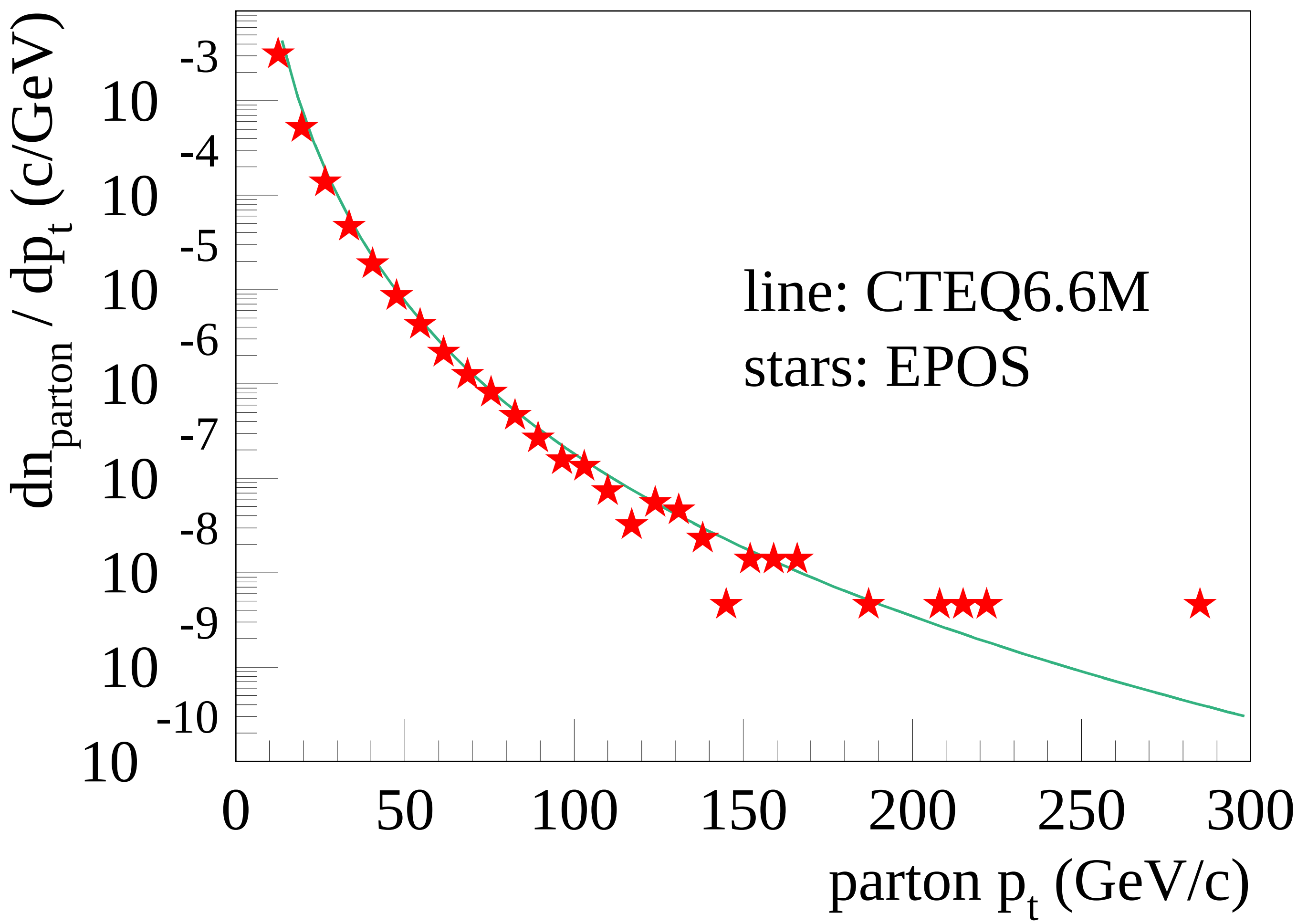


String segment = hadron. Close to “kink”: jets

Check: jet production in pp at 7 TeV



Comparison with parton model calculation using CTEQ PDFs for pp at 7 TeV



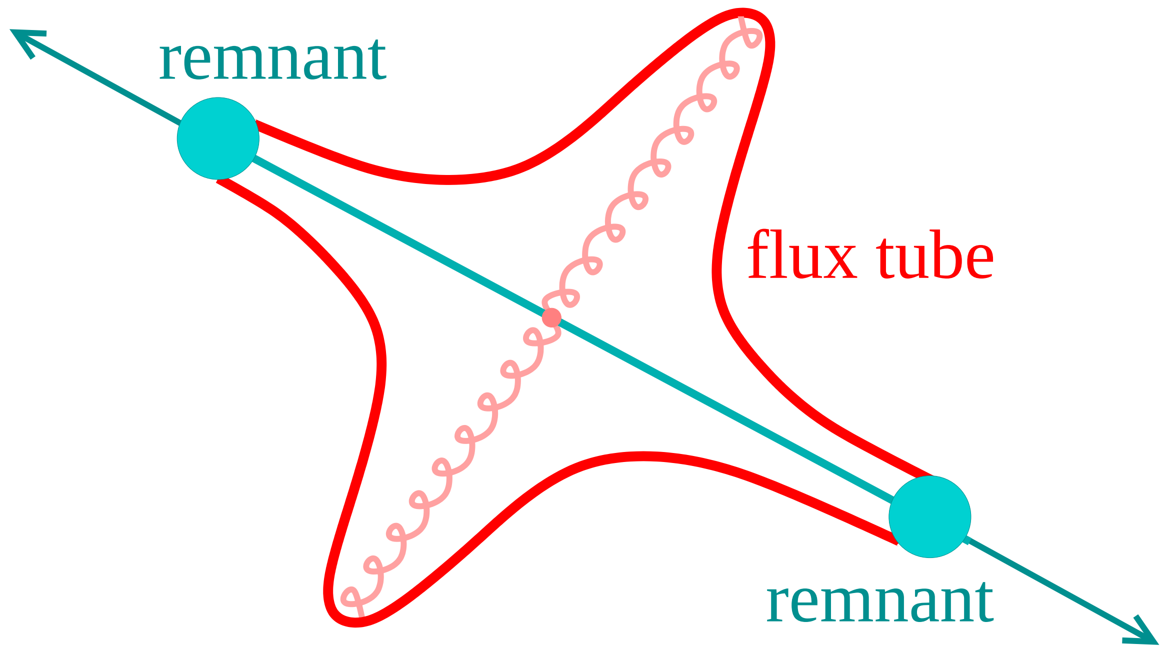
Heavy ion collisions
or high energy & high multiplicity pp events:

- the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently

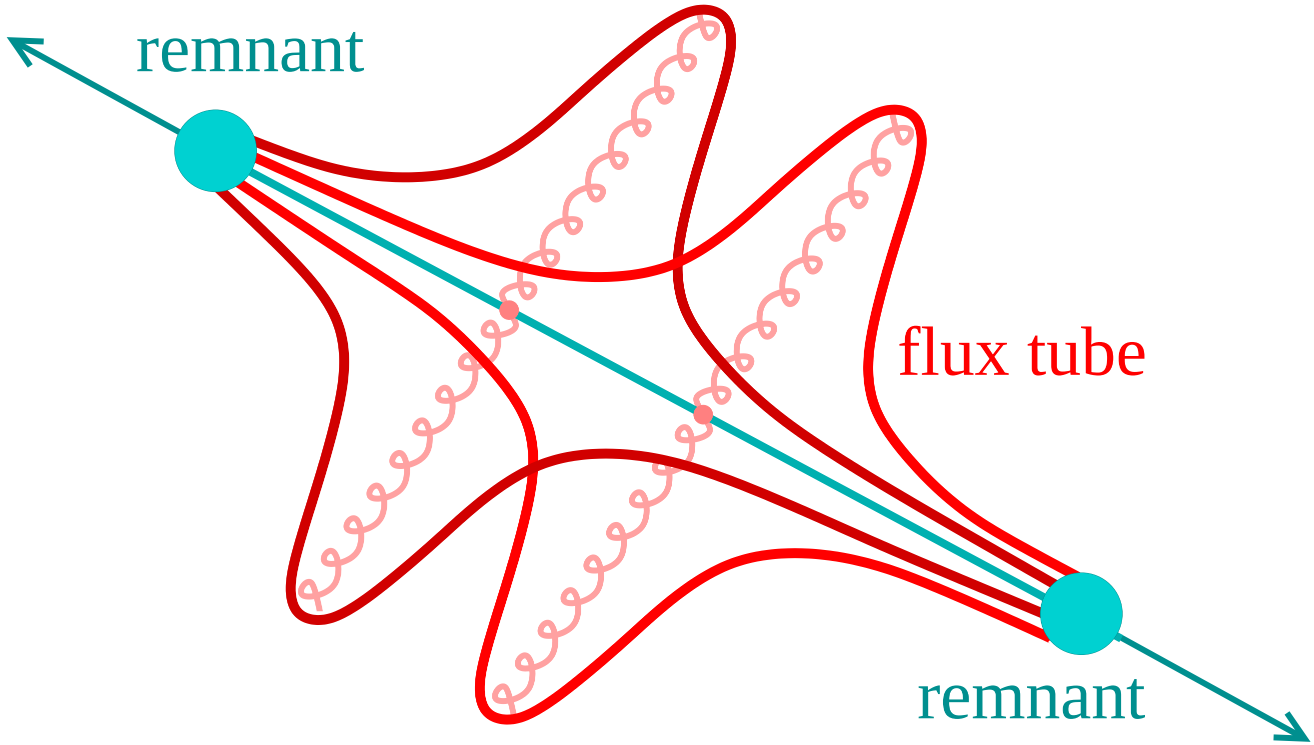
Some string pieces will constitute bulk matter, others show up as hadrons (jets)

These are the same strings (all originating from hard processes at LHC) which constitute BOTH jets and bulk !!

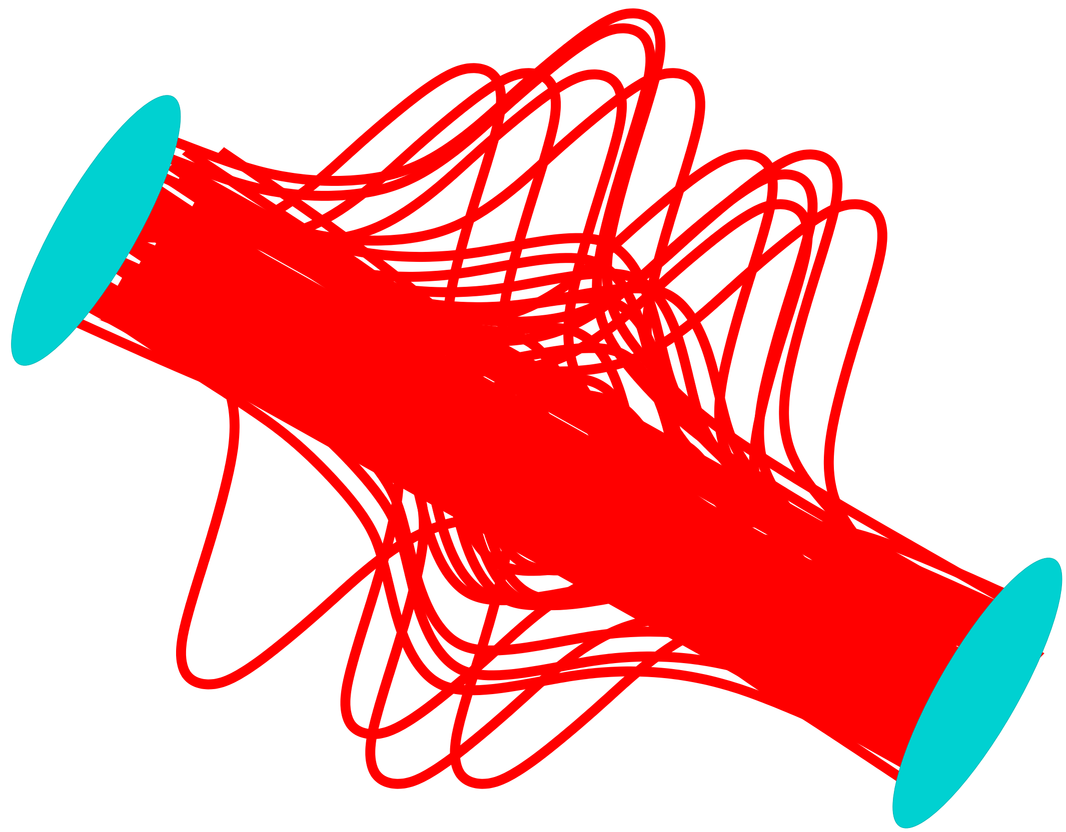
again: single scattering => 2 color flux tubes



... two scatterings => 4 color flux tubes



... many scatterings (high multiplicity pp)
=> many color flux tubes

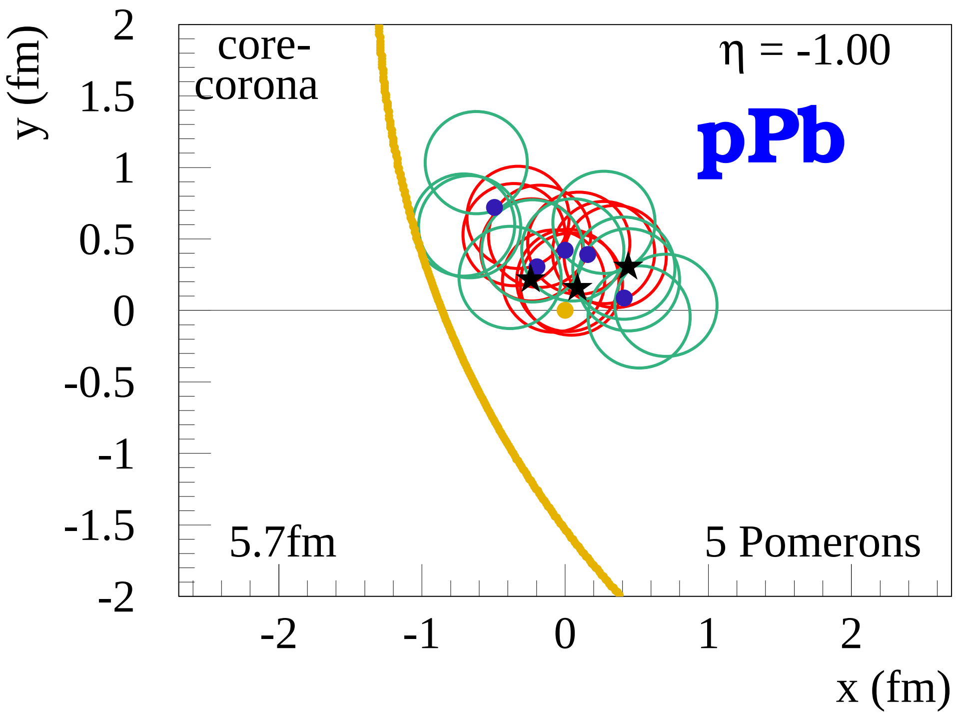


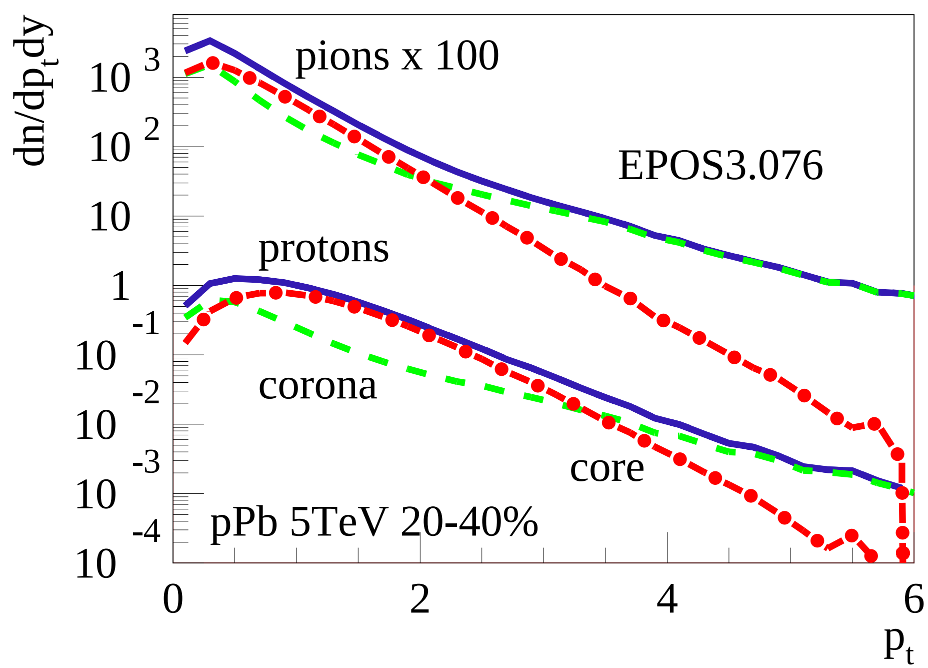
=> matter + escaping pieces (jets)

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, $\eta/S=0.08$, $\zeta/S=0$

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

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

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

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

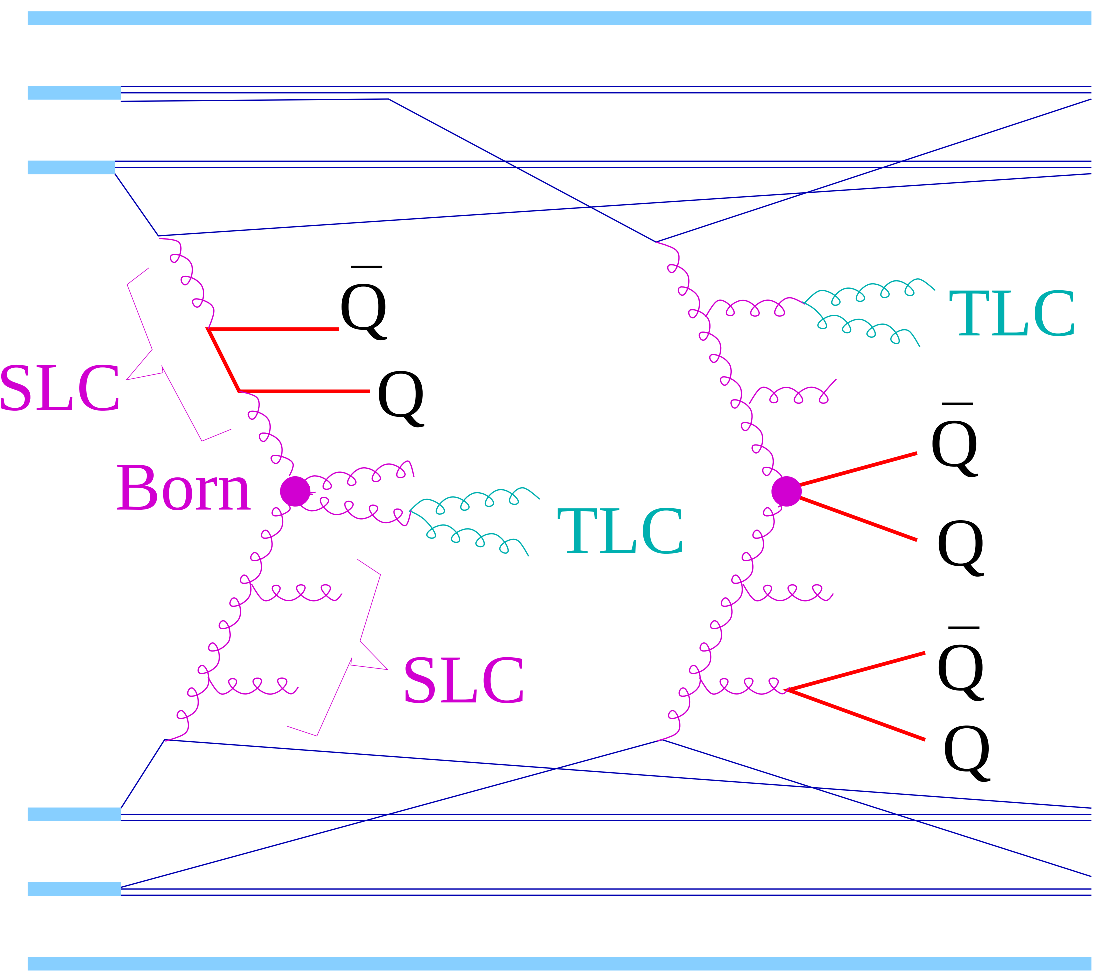
2 Multiple scattering and charm production

Notation:

q = light quark (u,d,s)

Q = heavy quark (c,b)

Heavy quark production in EPOS multiple scattering framework



as light quark production

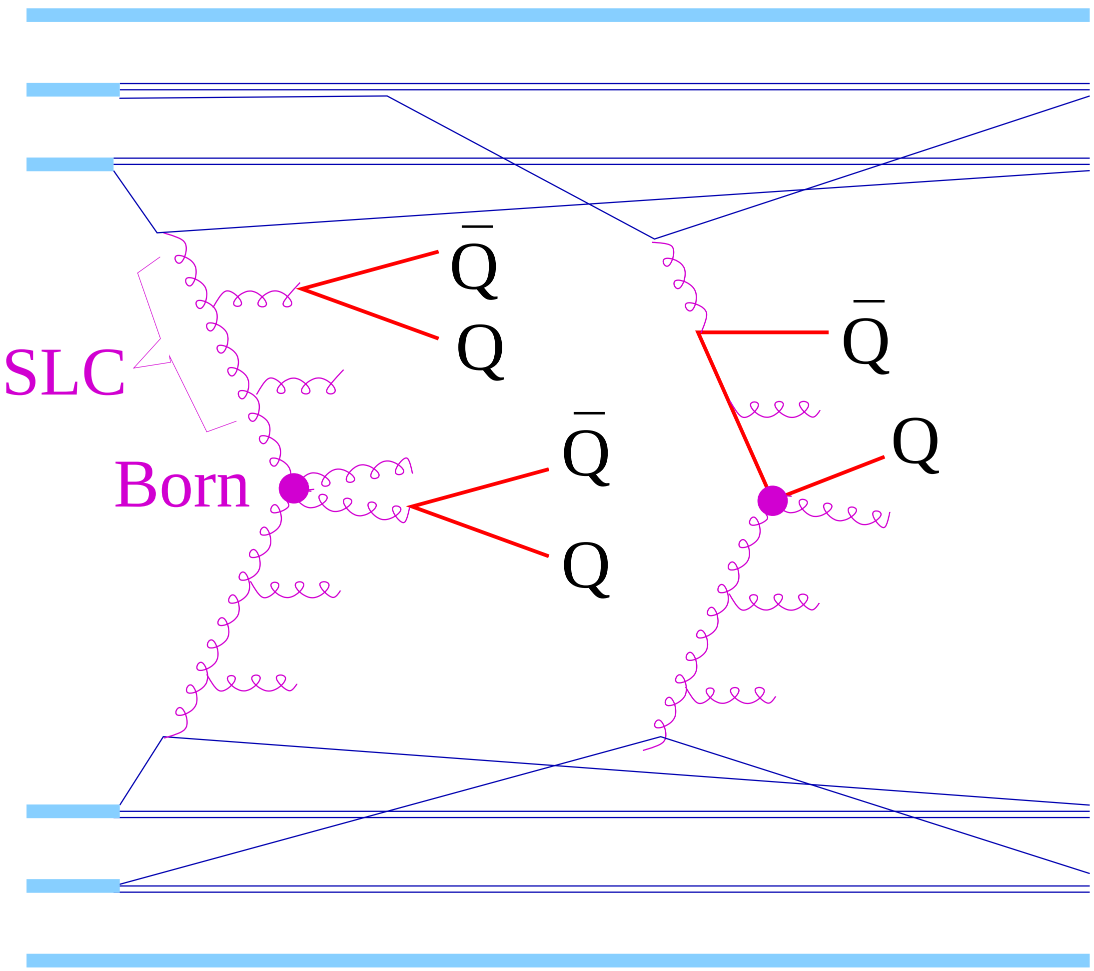
In any of the ladders

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

but m_Q non-zero

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

Remarks



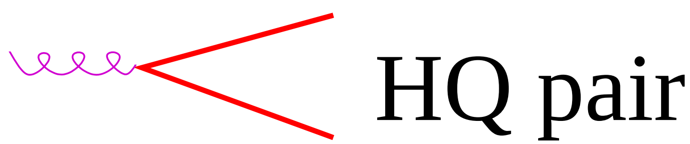
- **TLC may be initiated by a parton**
  - **from Born process**
  - **from SLC**
- **Splittings in SLC may provide Q or $\bar{Q}$ in Born**

Heavy quark masses play a role

- **in matrix elements**

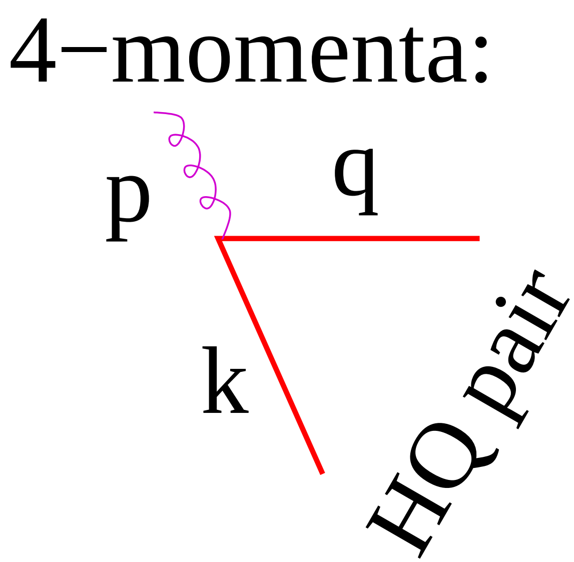
- **as condition in TLC splitting:**

  $g \longrightarrow Q\bar{Q}$ **requires** $Q^2 > (2m_Q)^2$



(Q^2= virtuality of mother)

- **as condition in SLC splitting:**



Energy-momentum conservation:
$q = p - k$

Technicalities:
We suppose

$$p = (E, 0, 0, E).$$

We define

$$\begin{aligned} n &= (1/2E, 0, 0, -1/2E), \\ k_t &= (0, k_x, k_y, 0). \end{aligned}$$

We get

$$p^2 = n^2 = pk_t = nk_t = 0,\ pn = 1.$$

$$\rightarrow k = xp + \frac{k^2 - k_t^2}{2x} n + k_t.$$

We define $Q^2 = -k^2$.

The virtuality of the TL parton is assumed to be m_Q^2, so

$$q^2 = k^2 - 2pk = -Q^2 + \frac{Q^2 + k_t^2}{x} = m_Q^2 \; (\mathrm{using}\ \mathrm{Q}^2 = -\mathrm{k}^2)$$

$$\rightarrow -k_t^2 = Q^2 - xQ^2 - xm_Q^2 > 0$$

which implies

$$\boxed{x < \frac{Q^2}{Q^2 + m_Q^2},}$$

suppressing large x.

As starting virtuality of the TLC, we use

$$Q^2_{\mathrm{ini}} = (\alpha p_t)^2$$

with a coefficient α in the range 1-2.

Our favorite value is

$$\alpha = 2$$

In particular B-meson data in *pp* favor $\alpha = 2$, otherwise there is little producion during the TLC, and spectra are too low compared to data.

Note: Contrary to the light quarks, there appear no HQs

- ☐ **initially in the in colliding hadrons**
- ☐ **in string fragmentation**
- ☐ **in QGP hadronization**

For all details concerning HQ production in EPOS see PhD thesis of Benjamin Guiot, Nantes 2014

3 Flow in small systems

- ☐ **Radial flow**
- ☐ **Flow asymmetries (v2, v3 etc)**

Radial flow in pPb (similar in pp) **:**

We will compare EPOS3 with data

and also with

EPOS LHC

LHC tune of EPOS1.99, :
same GR, but uses **parameterized flow**
T. Pierog et al, arXiv:1306.5413

AMPT

Parton + hadron cascade **-> some collectivity**
Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang and S. Pal, Phys. Rev. C 72, 064901 (2005).

QGSJET

GR approach, **no flow**
S. Ostapchenko, Phys. Rev. D74 (2006) 014026

CMS: Multiplicity dependence of pion, kaon, proton pt spectra

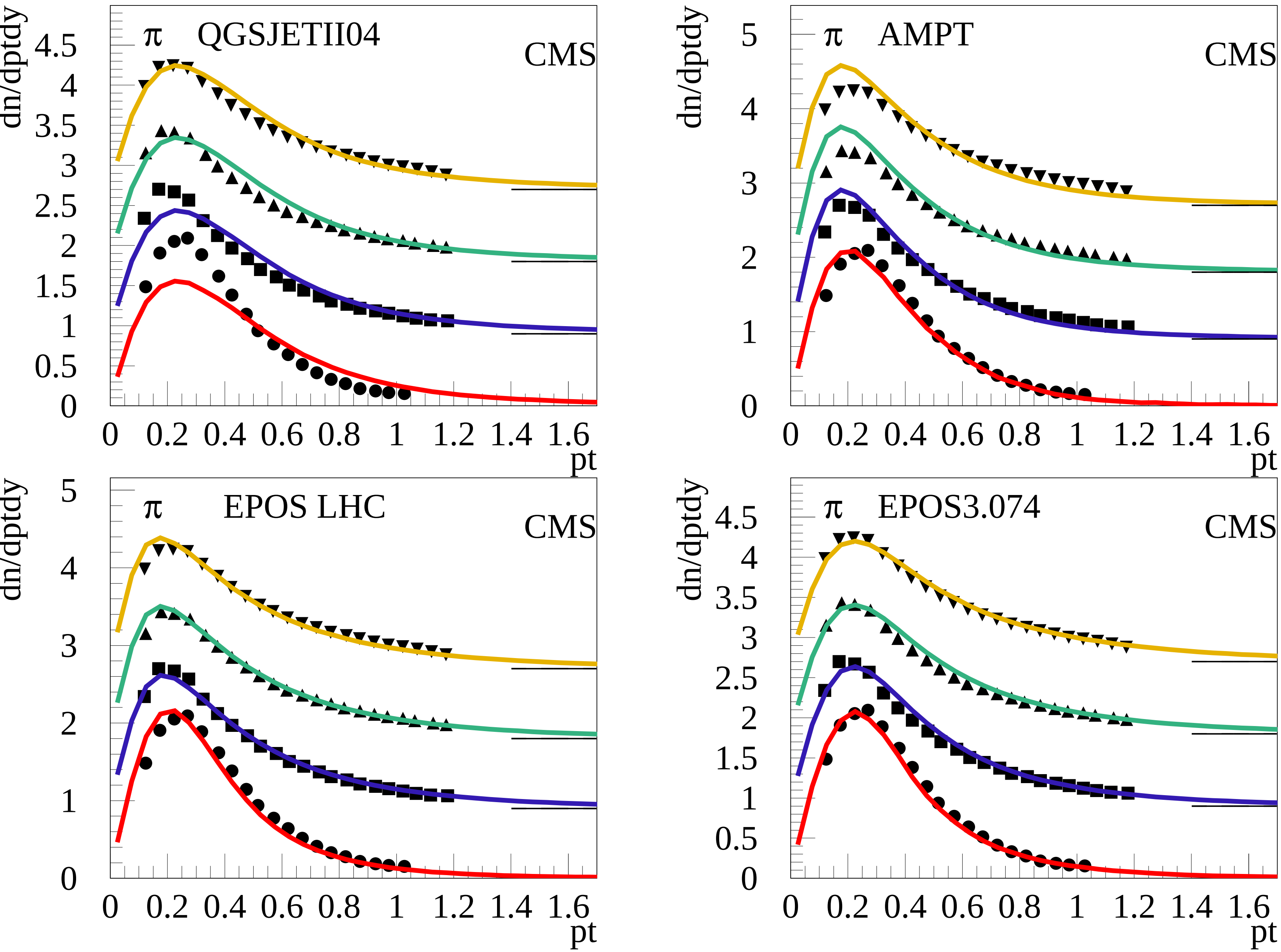
CMS, arXiv:1307.3442

We plot 4 multiplicity classes:

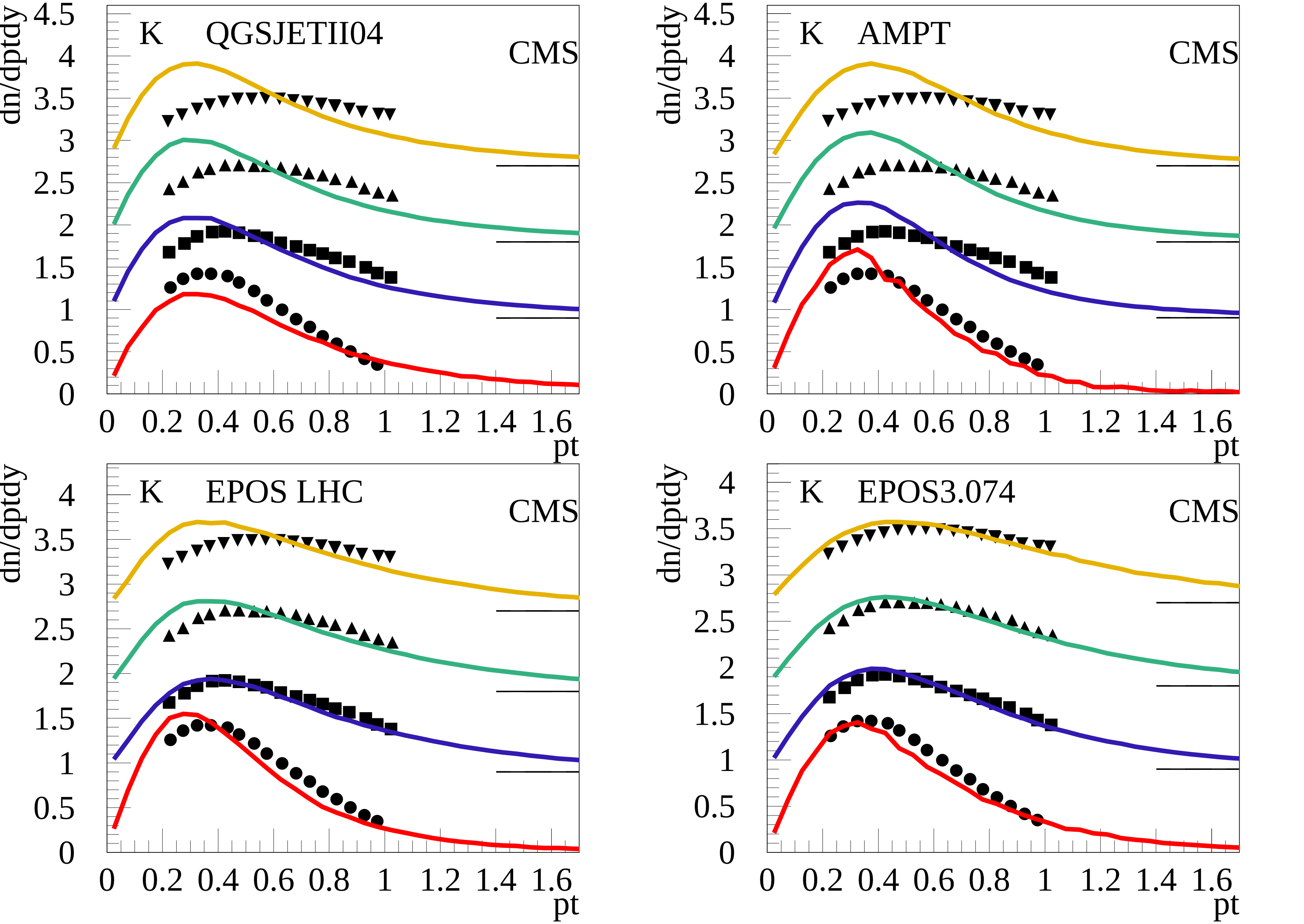
$\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$ = 8, 84, 160, 235 (in $|\eta| < 2.4$)

Multiplicity = "event activity" measure

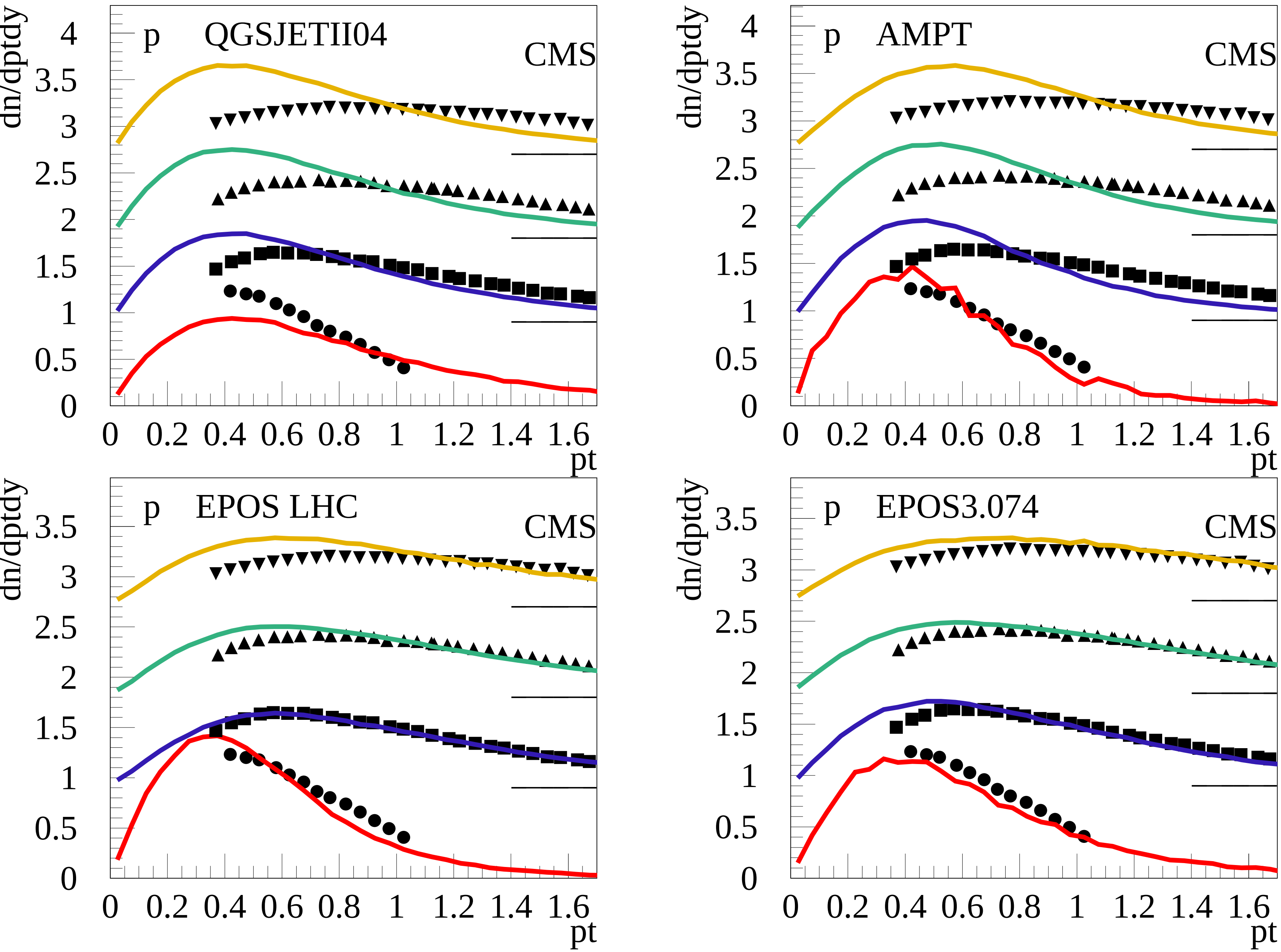
(rather than b)



Little change with multiplicity for pions



Kaon spectra change with multiplicity

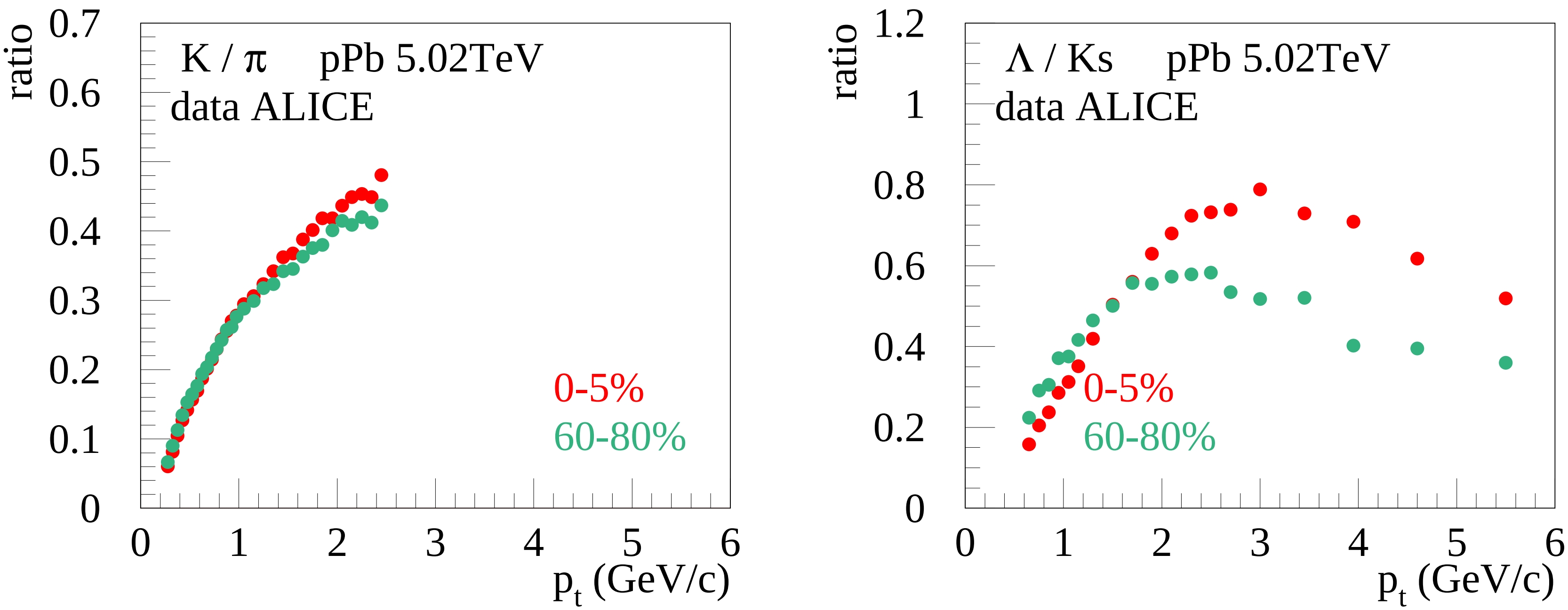


Strong variation of proton spectra => flow helps

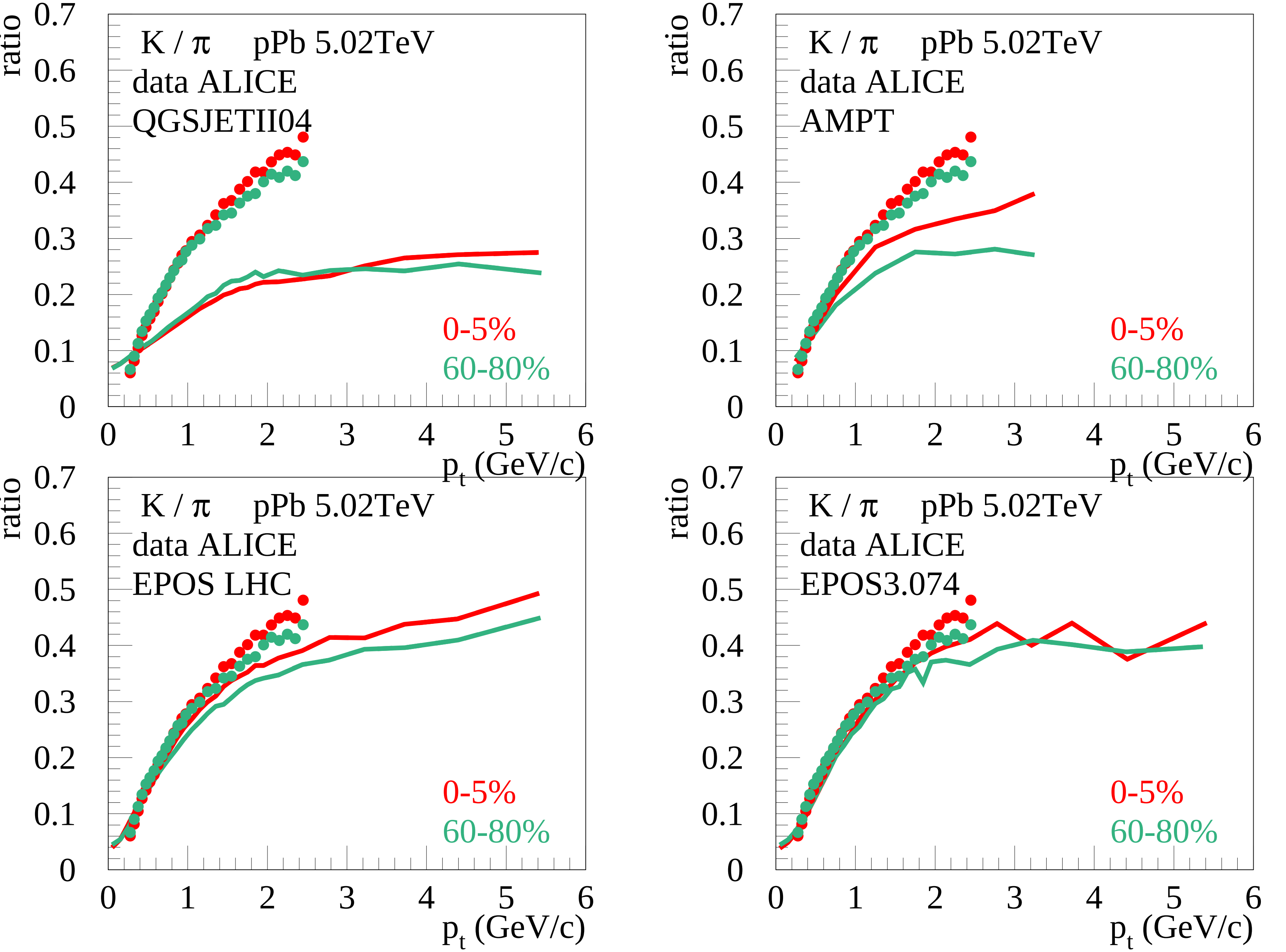
ALICE: compare pt spectra for identified particles in different multiplicity classes: 0-5%,...,60-80%

(in $2.8 < \eta_{\mathrm{lab}} < 5.1$) Phys. Lett. B728 (2014) 25, arXiv:1307.6796

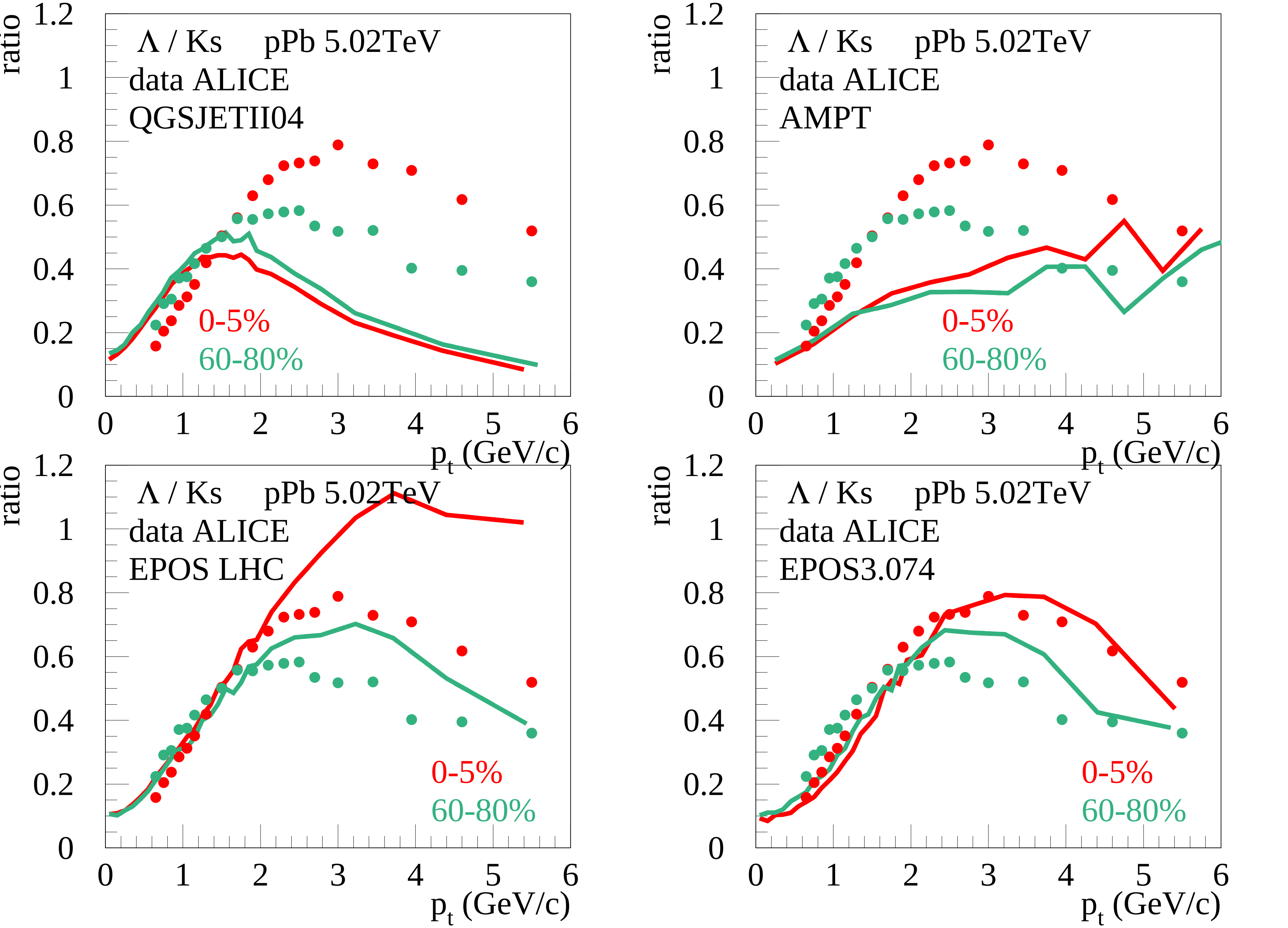
Useful : ratios (K/pi, p/pi...)



Significant variation of lambda/K – like in PbPb



No multiplicity dependence (not trivial to get the peripheral right)



Significant multiplicity dependence. Flow helps

4 Charm – multiplicity correlation

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

$N_{\rm ch}$: Charged particle multiplicity

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

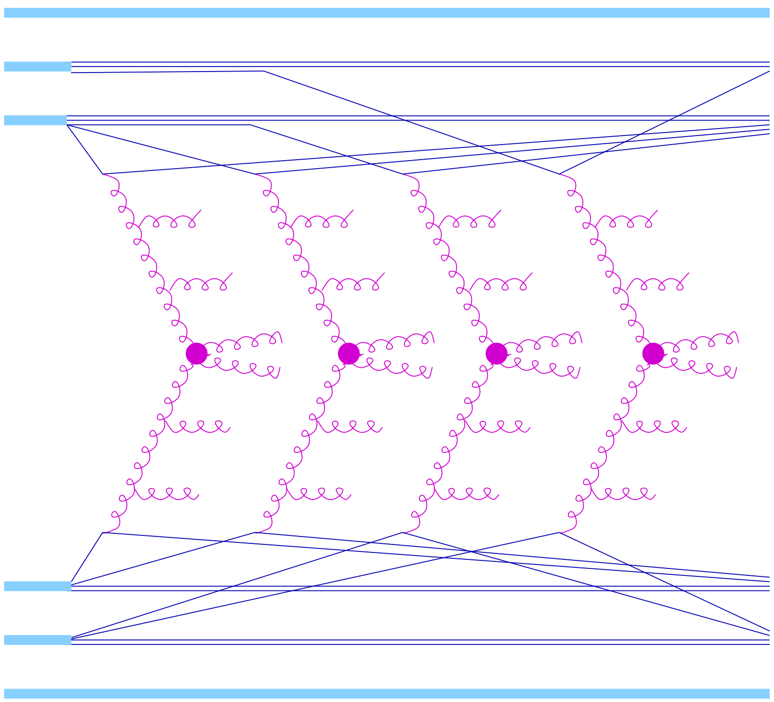
N_{D2}: D-meson multiplicity for $2 < p_t < 4\,\mathrm{GeV/c}$

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

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

Multiple scattering approach

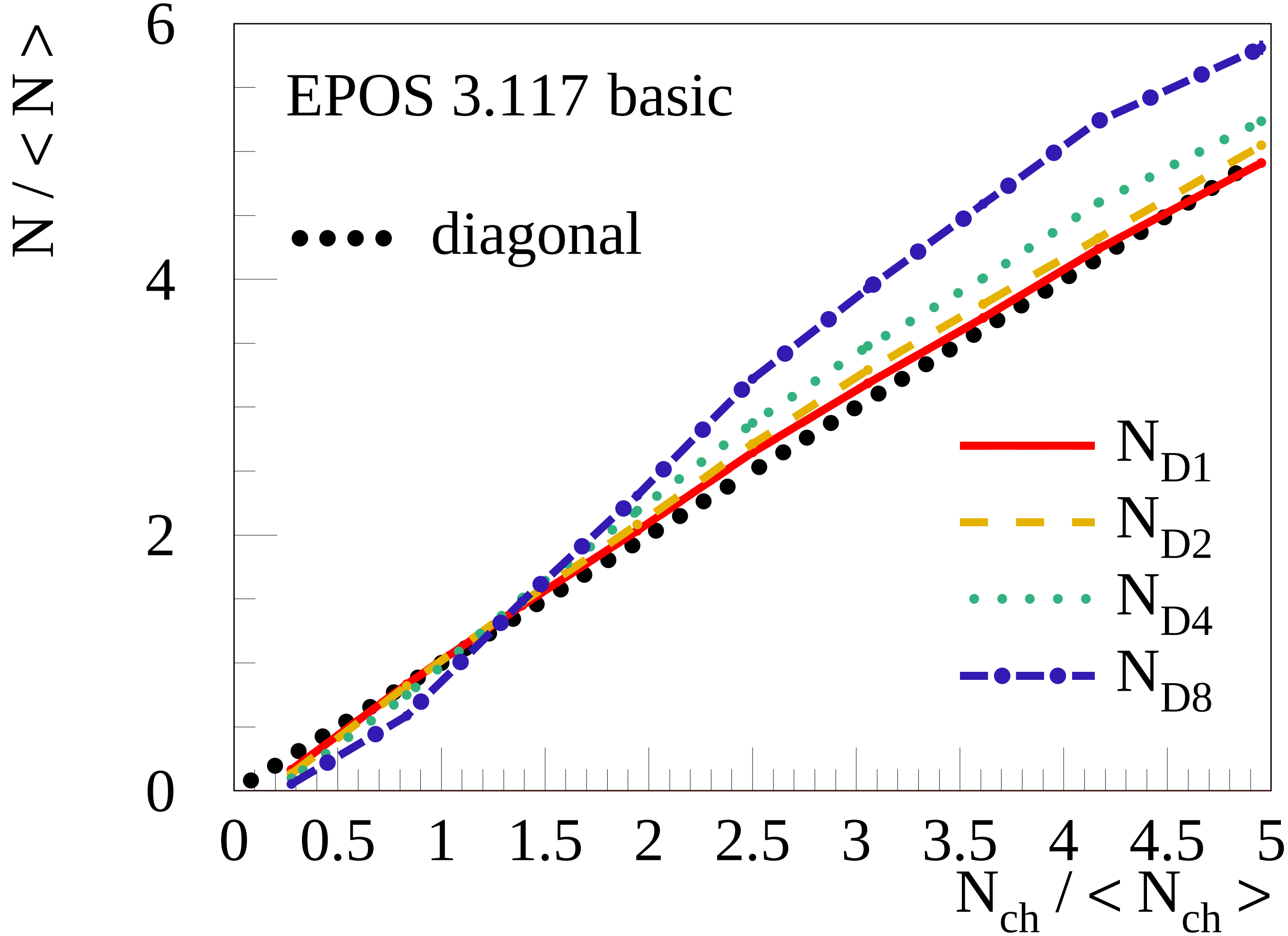
(EPOS3, basic)



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

"Natural" linear behavior (first approximation)

The actual calculation:

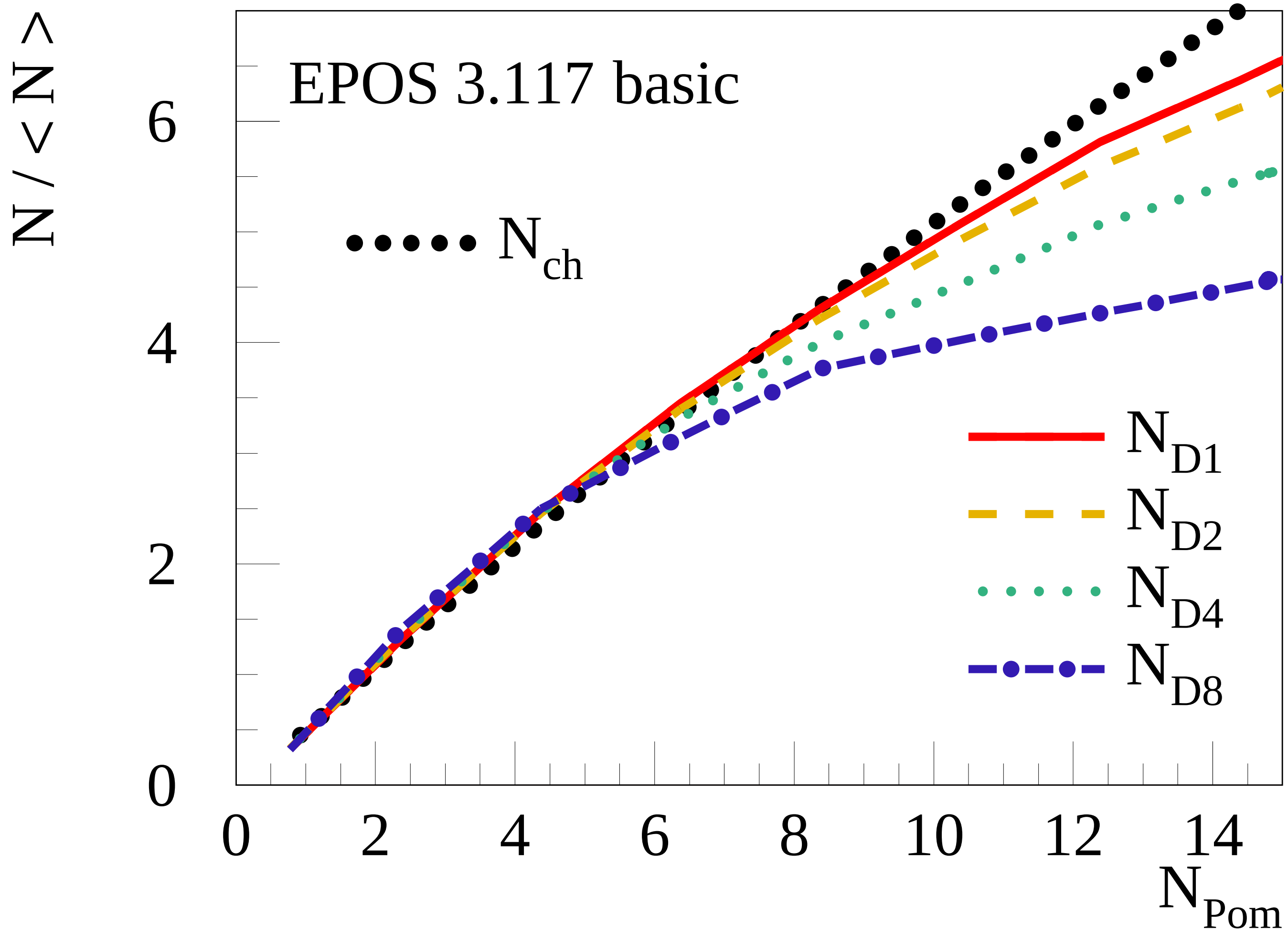


Indeed essentially a linear increase

But some deviation

(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 ?

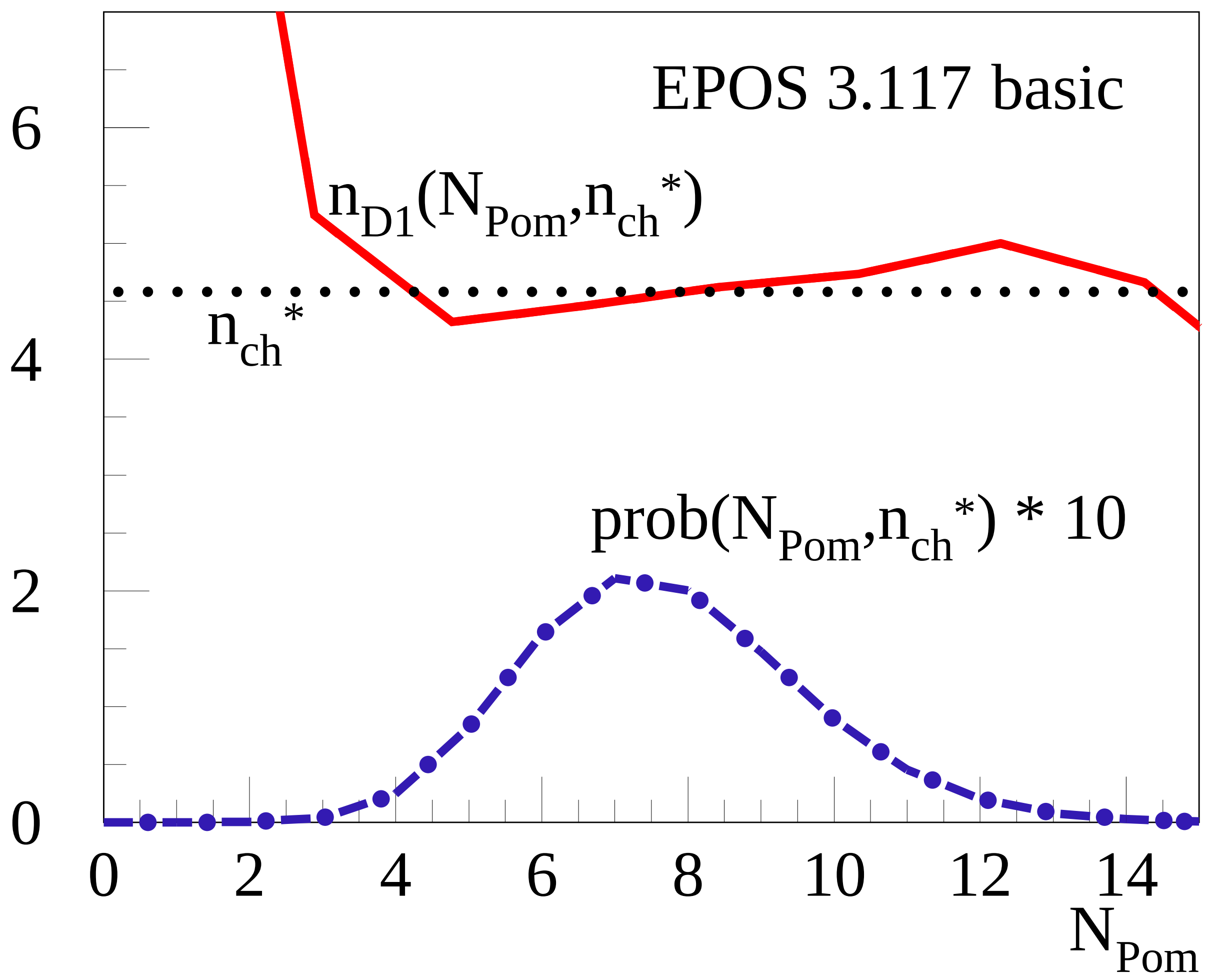
We define normalized multiplitities

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

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 $n_{\text{ch}}{}^*$



$n_{D1}(n_{\text{ch}}{}^*)$ may be written as sum

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

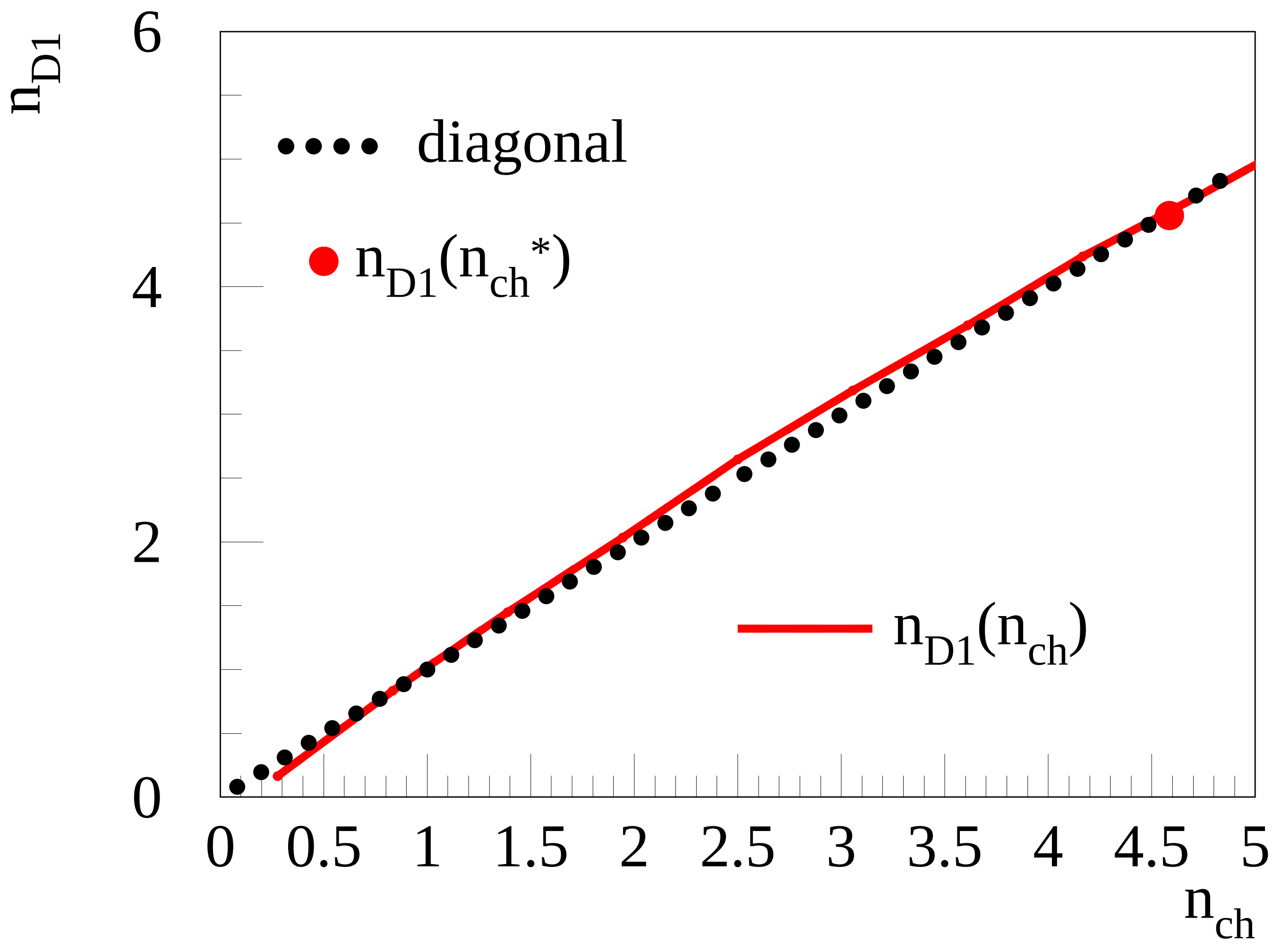
$$\approx n_{\text{ch}}{}^*$$

having used

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

The precise calculation:

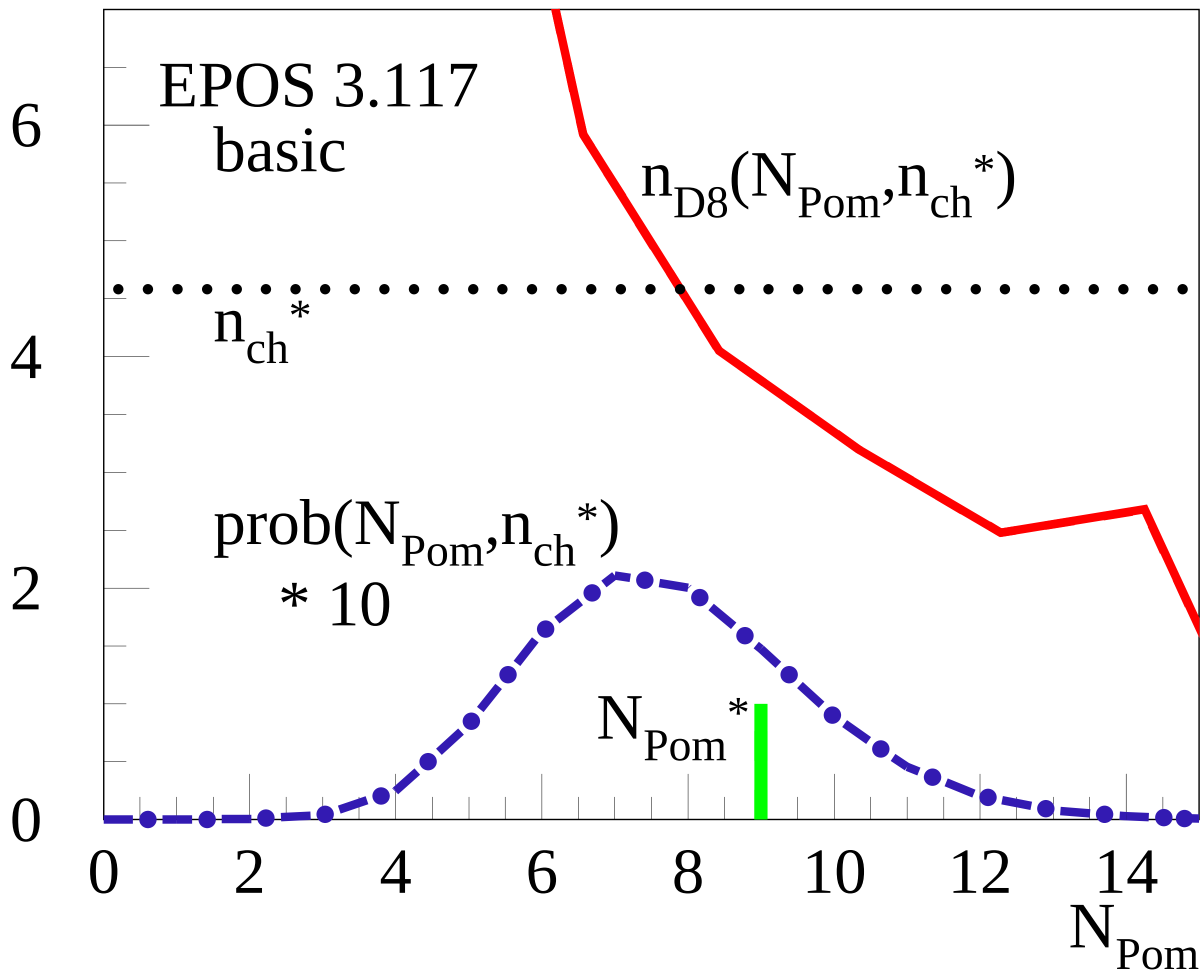
(red point)



on the diagonal!

Perfectly linear!

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



$n_{D8}(n_{ch}{}^*)$ may be written as sum

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

$> n_{ch}{}^*$

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

Def $N_{Pom}{}^*$: $n_{ch}(N_{Pom}{}^*) = n_{ch}{}^*$

$N_{Pom}{}^*$ to the right w.r.t the maximum

${N_{\rm Pom}}^*$ to the right w.r.t the maximum. Proof:
Here $N = N_{\rm ch}$. And N^{**} is such that $p({N_{\rm Pom}}^*, N^{**}) > p(N_{\rm Pom}, N^{**})$

$$
\begin{aligned}
N({N_{\rm Pom}}^*) &= \sum_N N\, p(N)\, p({N_{\rm Pom}}^*, N) \\
&= N^{**}\, p(N^{**})\, p({N_{\rm Pom}}^*, N^{**}) \\
&\quad +(N^{**}-1)\ \underbrace{p(N^{**}-1)\, p({N_{\rm Pom}}^*, N^{**}-1)}_{BIG} + \ldots \\
&\quad +(N^{**}+1)\ \underbrace{p(N^{**}+1)\, p({N_{\rm Pom}}^*, N^{**}+1)}_{SMALL} + \ldots \\
&< N^{**}
\end{aligned}
$$

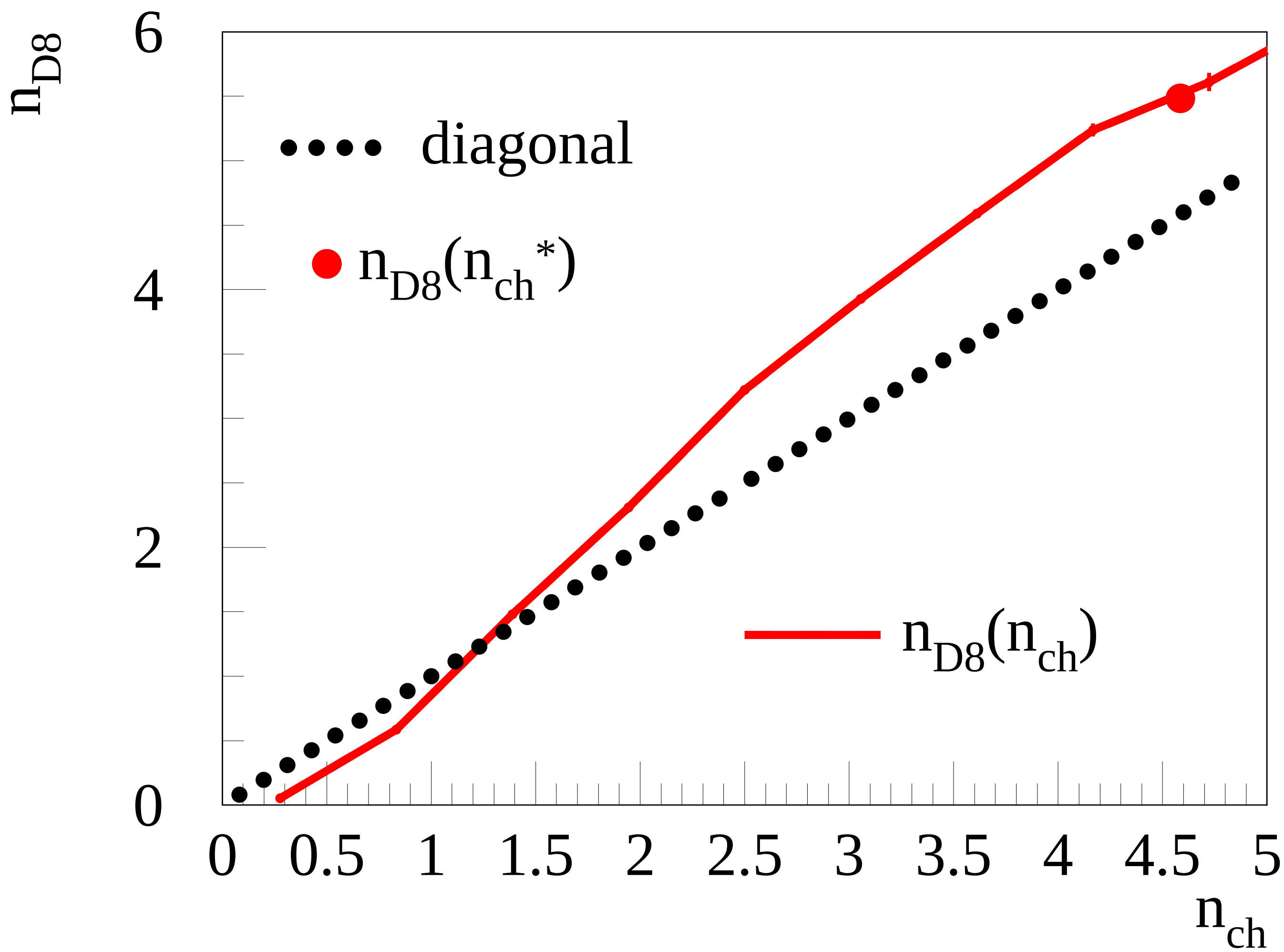
(since $p(N)$ drops rapidly with N). So

$$
{n_{\rm ch}}^* = n_{\rm ch}({N_{\rm Pom}}^*) < {n_{\rm ch}}^{**}
$$

The Pomeron number distribution for fixed ${n_{\rm ch}}^*$ is shifted to the left w.r.t. the distr for fixed ${n_{\rm ch}}^{**}$, and the value $N_{\rm Pom}$ corresponding to the maximum is smaller than ${N_{\rm Pom}}^*$.

The precise calculation:

(red point)



above the diagonal!

non-linear!

More than linear increase since

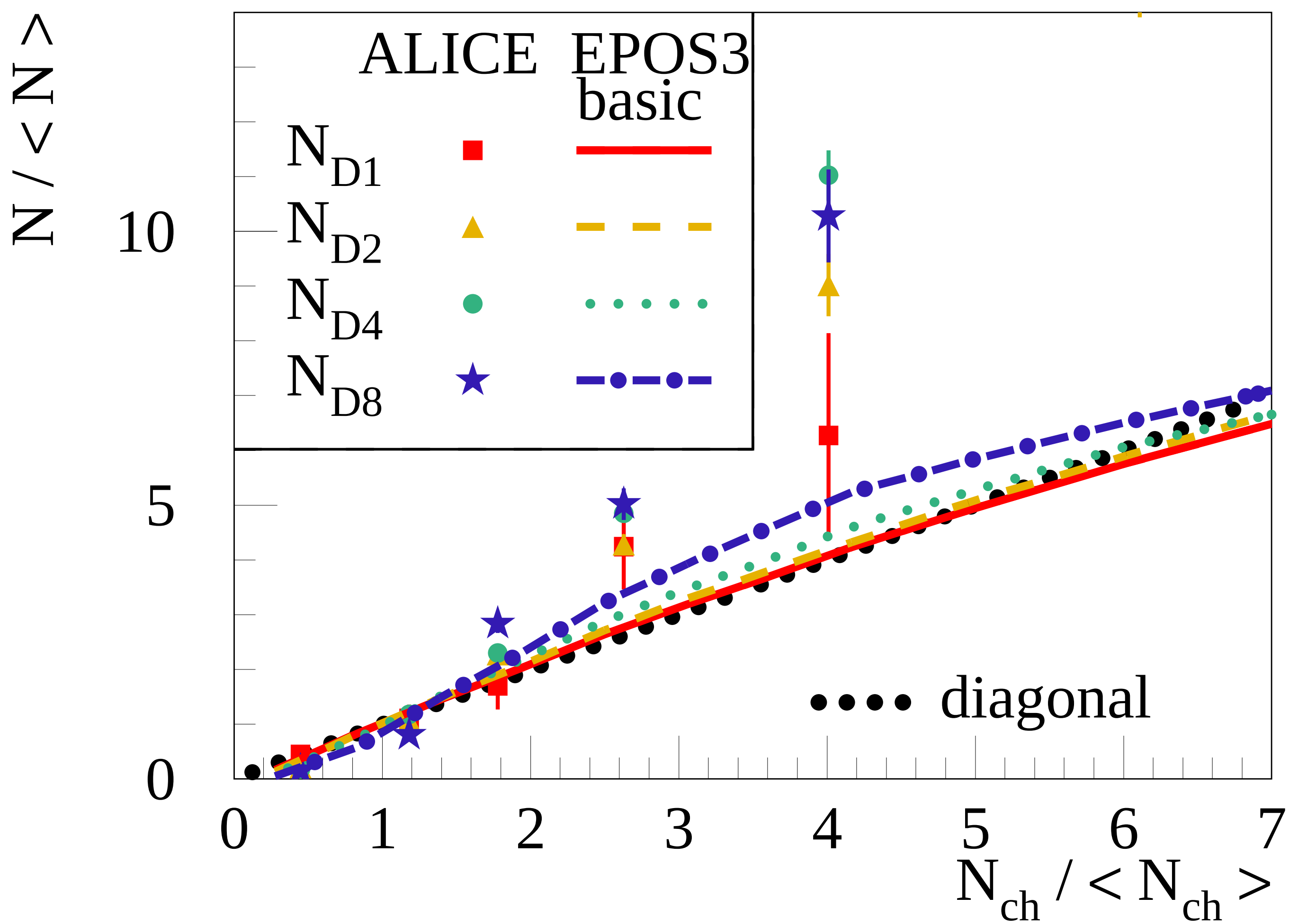
- **The number of Pomerons fluctuates for given multiplicity**

- **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

But the effect is small!

The effect is actually too small!



Too little deviation from the diagonal

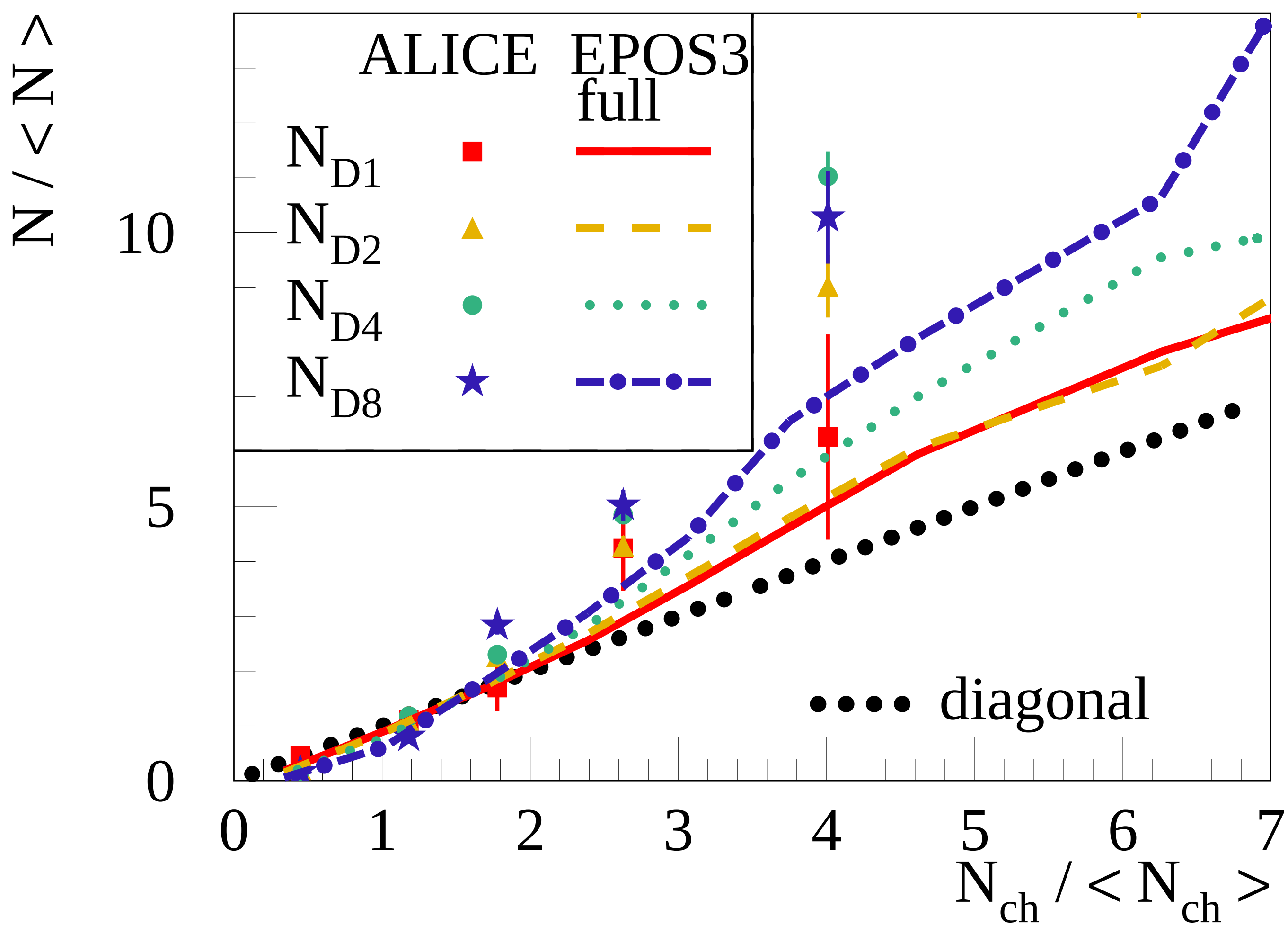
in particular for large p_t

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

=> full approach (EPOS w hydro + cascade)

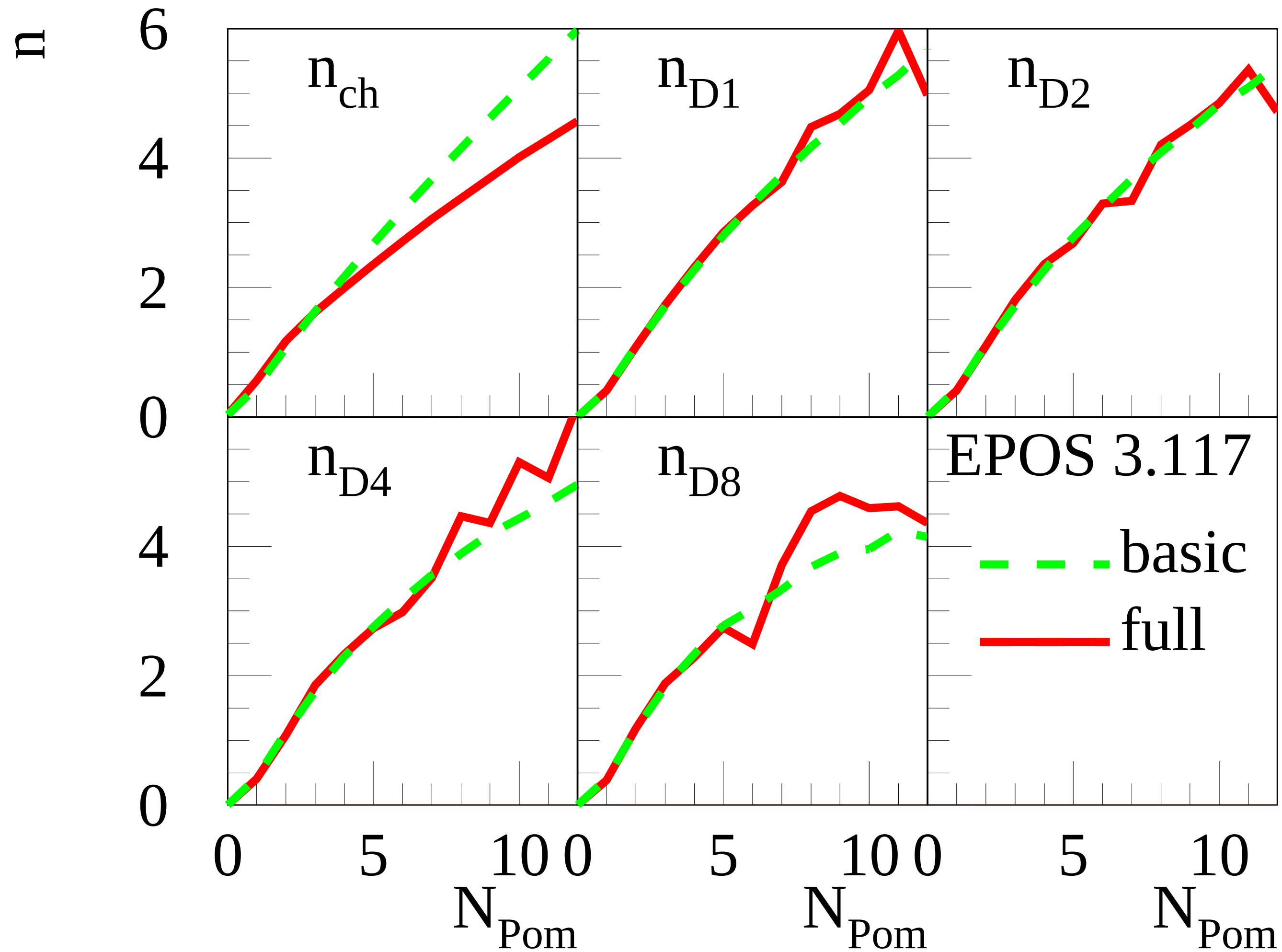
(with or without hadronic cascade makes no difference)

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"

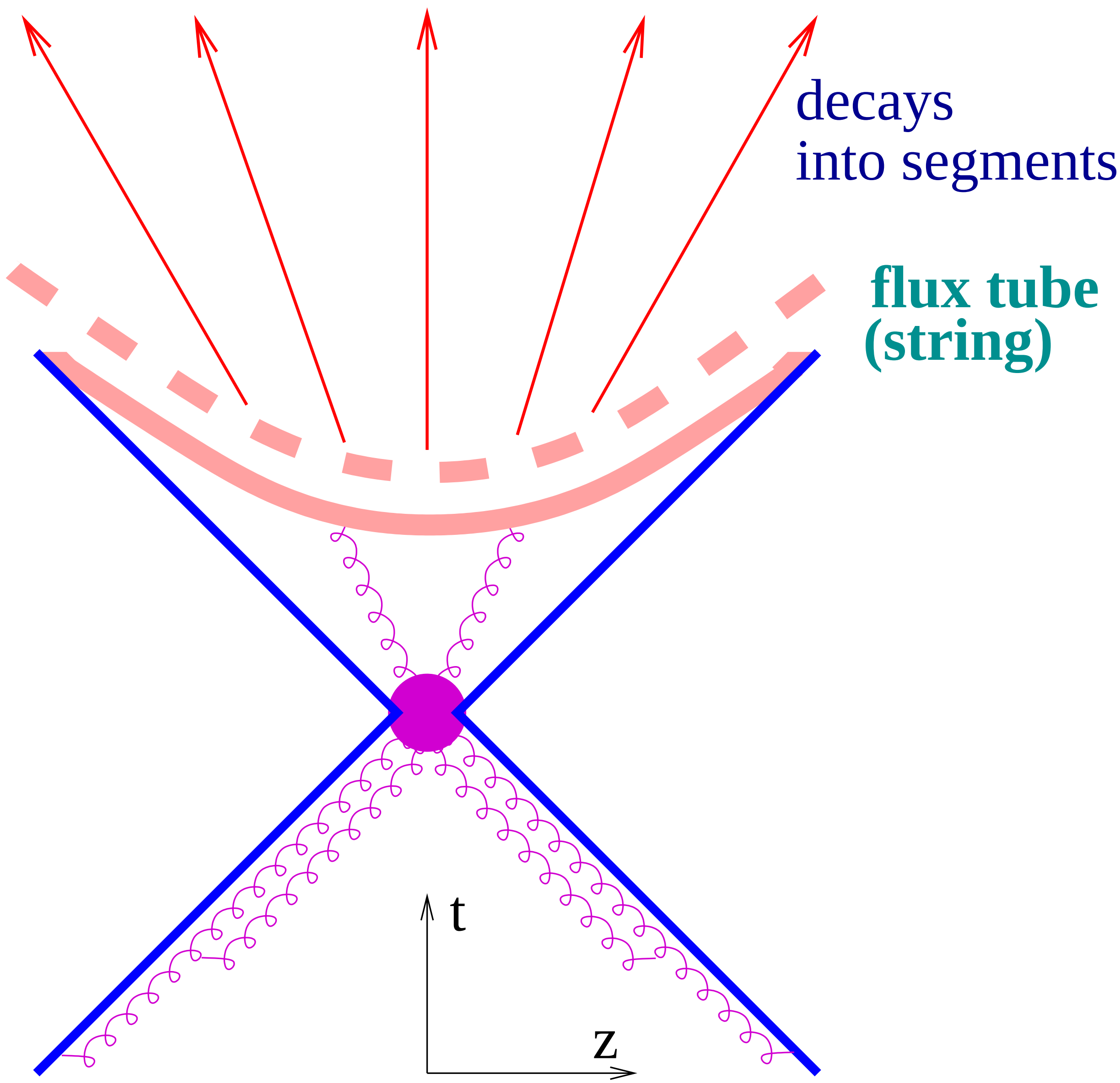
but the charged particle multiplicity is reduced when including a hydrodynamical expansion

Collision activity = Pomeron number

Why such a multiplicity reduction?

Basic EPOS = string fragmentation

=> Bjorken-like expansion



String approach:

density drops as $\frac{1}{\tau}$

as free longitudinal flow from a point source,
=> energy E^* in the Bjorken frame ($y = \eta_s$):

$$\frac{dE^*}{d\eta_s} = \text{constant}$$

Hydrodynamic expansion:

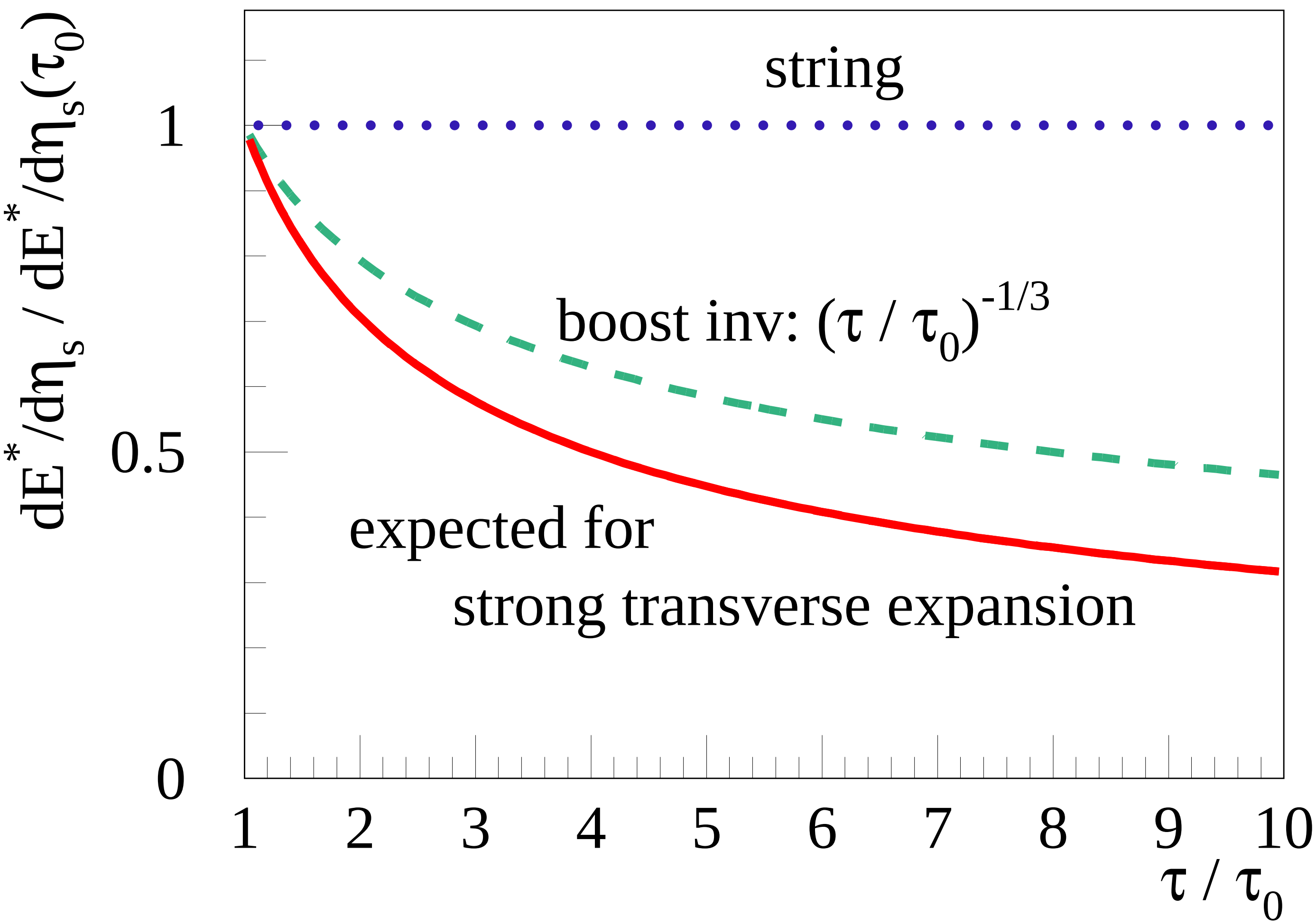
energy density drops as $$\frac{1}{\tau^{4/3}}$$

in case boost invariant ideal hydro, so the energy drops as

$$\frac{dE^*}{d\eta_s} \propto \frac{1}{\tau^{1/3}}$$

or even faster
in case of additional strong radial flow!

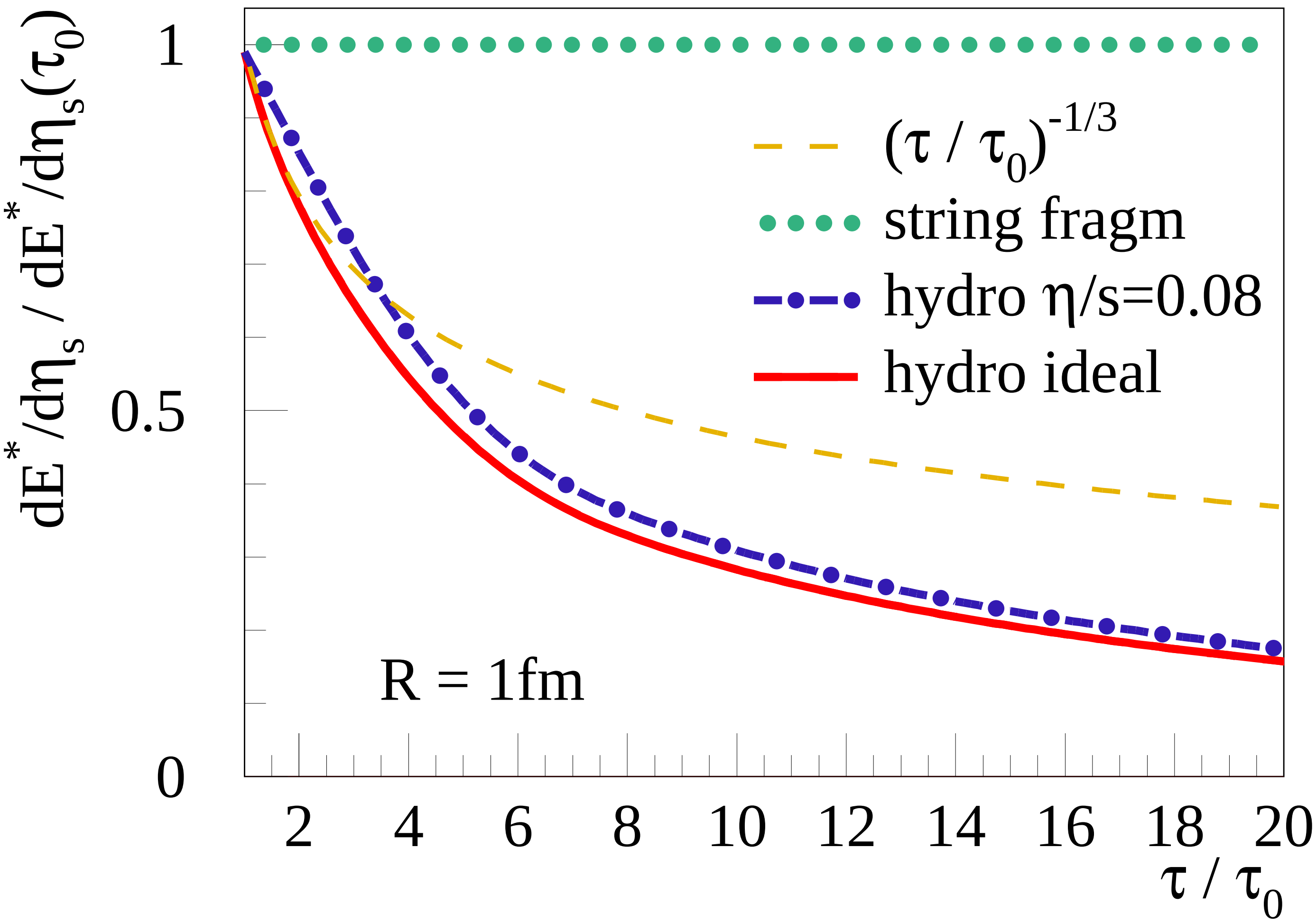
The different expansion scenarios



Strong transverse expansion realized in pp

big reduction factor

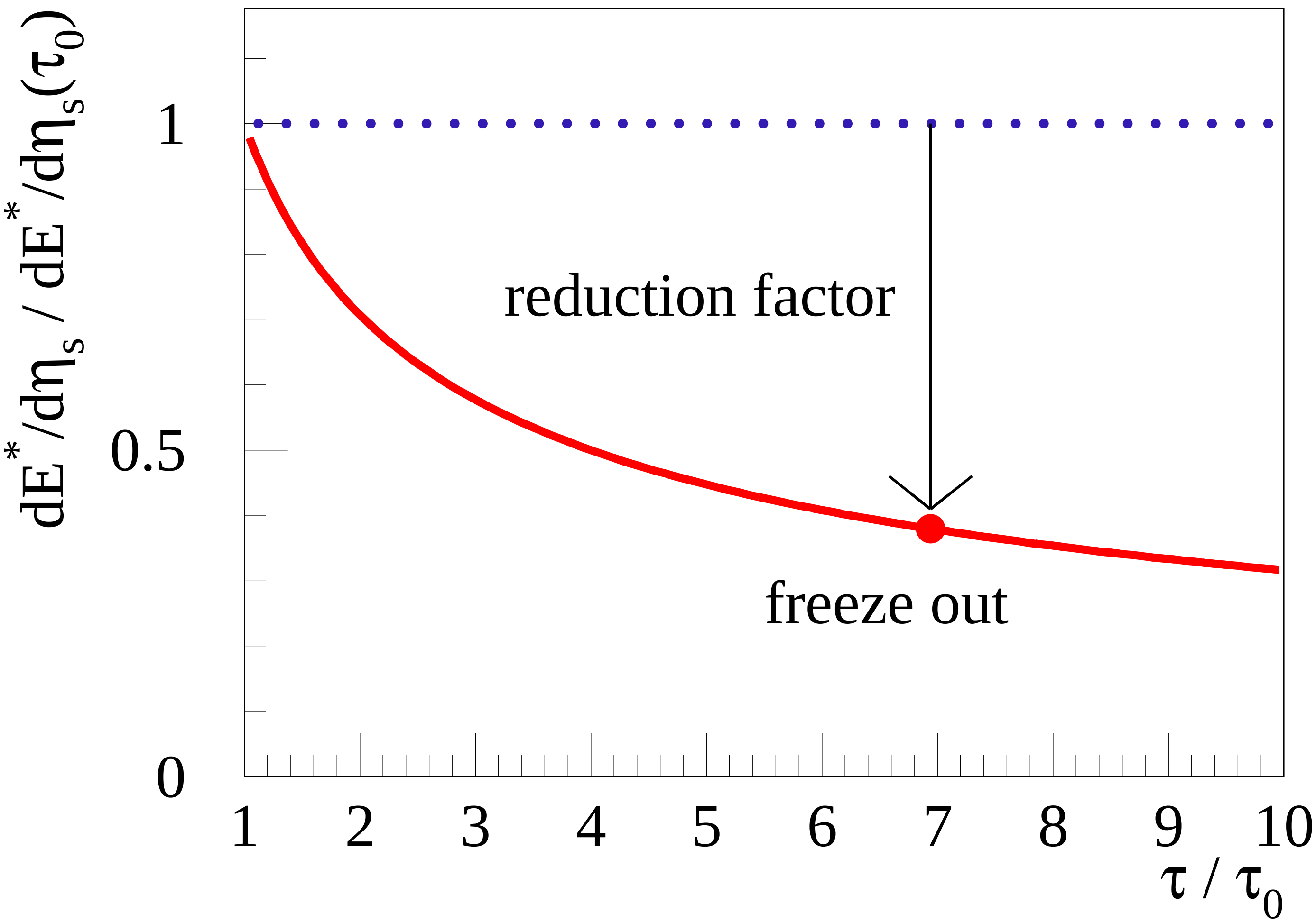
Actual calculation (2D hydro)



Significant drop

small viscosity effect

Reduction factor at freeze-out



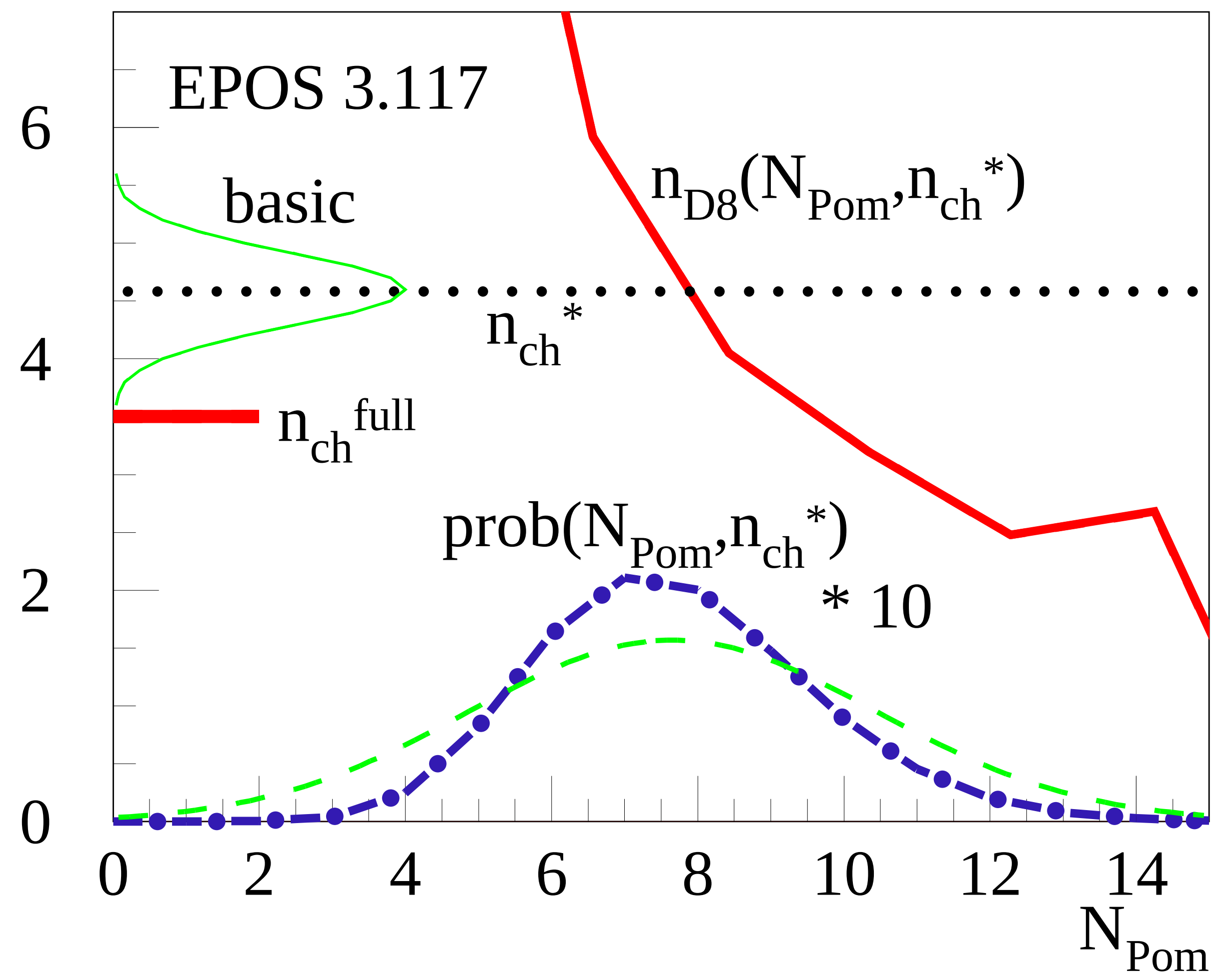
translates into the non-linearity of $N_{D,i}(N_{\mathrm{ch}})$

info about τ_0

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

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

Pt dependence

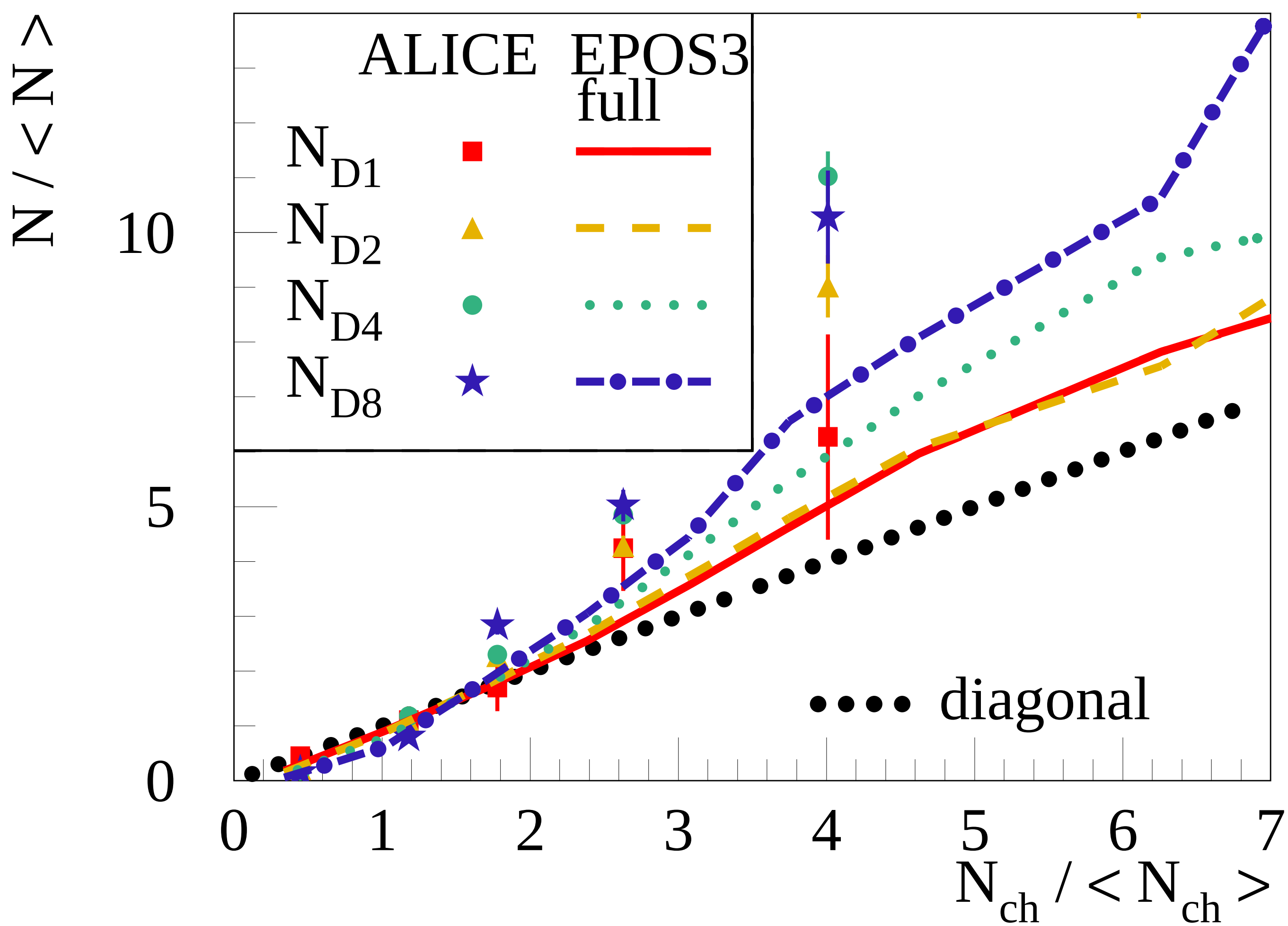


Broader N_{Pom} distribution with hydro

+ strongly dropping n_{D8}

makes big effect

Full EPOS3



Significant non-linear increase!

Bigger effect for high pt

Summary

We analyze D-meson multiplicity vs charged multiplicity in terms of EPOS3.

EPOS w/o hydro provides a roughly linear increase, due to the multiple scattering scheme.

Considering the hydro phase, we find a non-linear behavior, more pronounced at high pt,

due to a "multiplicity reduction" of the charged multiplicity. Fluctuations play an important role.