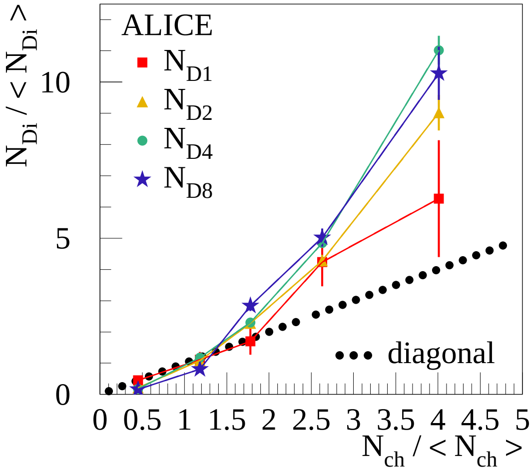
Multiplicity dependence of charm production and parton saturation

K.W. in collaboration with

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

D multiplicity vs charged multiplicity in pp



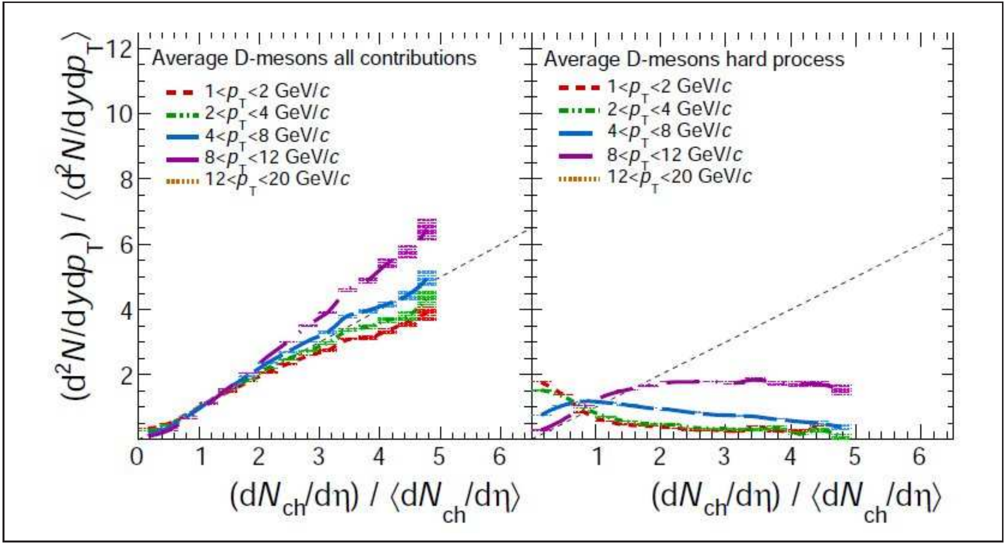
ALICE arXiv:1505.00664v1

Significant deviation from the diagonal (linear increase)

in particular for large p_t

Similar observations for J/Ψ and Υ

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

Important issues:

- **Multiple scattering, parton saturation**
- **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,
Nonlinear effects via saturation scale Q_s

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

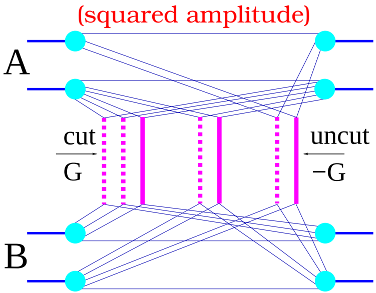
arXiv:1312.1233 , arXix:1307.4379

Initial conditions: Marriage pQCD+GRT+energy sharing

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

For pp, pA, AA:

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



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

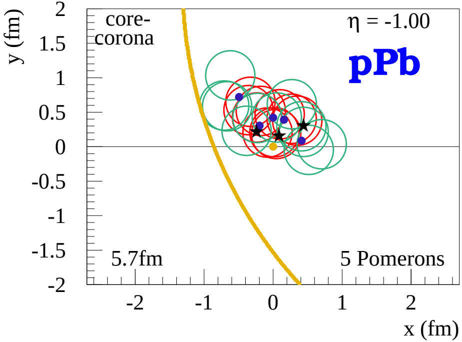
Nonlinear effects considered via saturation scale Q_s

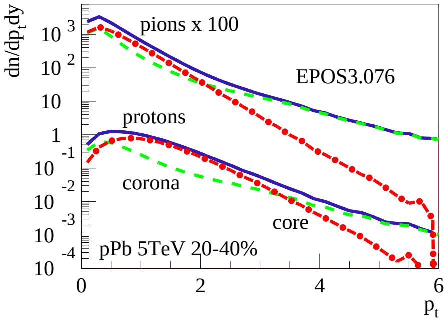
$$
\begin{aligned}
\sigma^{\mathrm{tot}} = \int d^2b \int \prod_{i=1}^{A} d^2b_i^A\, dz_i^A\, \rho_A\Big(\sqrt{(b_i^A)^2 + (z_i^A)^2}\Big) \\
\prod_{j=1}^{B} d^2b_j^B\, dz_j^B\, \rho_B\Big(\sqrt{(b_j^B)^2 + (z_j^B)^2}\Big) \\
\sum_{m_1 l_1} \dots \sum_{m_{AB} l_{AB}} (1 - \delta_{0\Sigma m_k}) \int \prod_{k=1}^{AB}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

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

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

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

- $T^{\mu\nu}=\epsilon u^{\mu}u^{\nu}-(p+\Pi)\Delta^{\mu\nu}+\pi^{\mu\nu}$,
- $\partial_{;\nu}$ 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
- $\pi^{\mu\nu}_{\mathrm{NS}}=\eta(\Delta^{\mu\lambda}\partial_{;\lambda}u^{\nu}+\Delta\nu\lambda\partial_{;\lambda}u^{\mu})-\frac{2}{3}\eta\Delta^{\mu\nu}\partial_{;\lambda}u^{\lambda}$
- $\Pi_{\mathrm{NS}}=-\zeta\partial_{;\lambda}u^{\lambda}$
- $I^{\mu\nu}_{\pi}=-\frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^{\gamma}-[u^{\nu}\pi^{\mu\beta}+u^{\mu}\pi^{\nu\beta}]u^{\lambda}\partial_{;\lambda}u_{\beta}$
- $I_\Pi=-\frac{4}{3}\Pi\partial_{;\gamma}u^{\gamma}$

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

A crucial ingredient: The saturation scale Q_s^2

Single Pomeron contribution G (to the amplitude), computed via pQCD, can be (very well) fitted as*)

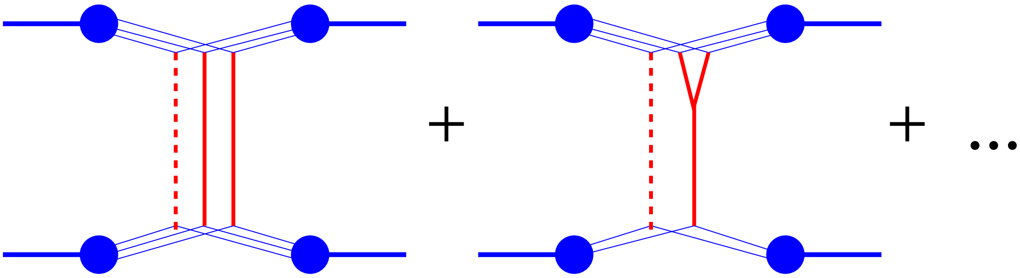
$$G \approx G_{\mathrm{fit}} = \alpha\,(x^+)^{\beta}(x^-)^{\beta'}$$

($x^{\pm}$are light cone momentum fractions)

Extremely useful! Allows analytical calculations of cross sections.

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

Consistency requires adding more diagrams (ladder splitting/fusion, triple Pomeron vertices, gluon fusion in CGC ...)



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

Motivated by model calculations, we treat ladder fusion via adding an exponent [1] :

$$\boldsymbol{G_{\mathrm{fit}} \to G_{\mathrm{eff}} = \alpha\,(x^{+})^{\beta+\varepsilon^{\mathrm{proj}}}(x^{-})^{\beta'+\varepsilon^{\mathrm{targ}}}}$$

("epsilon method") with

$$\varepsilon = \varepsilon(Z),$$

depending on "the number of participating partons":

$$Z^{\mathrm{proj}} = \sum_{\mathrm{proj\,nucleons\,i'}} f_{\mathrm{part}}\left(|\vec{b} + \vec{b_{i'}} - \vec{b_j}|\right)$$

(j is the target nucleon the Pomeron is connected to)

[1] K.Werner, FM.Liu, T.Pierog, Phys.Rev. C74 (2006) 044902

Advantages

- □ Cross section calculations perfectly doable
- □ Energy dependence of σ_{tot}, σ_{el} (and more) correct

Big problems

- □ **Adding ε does not change the internal Pomeron structure**
- □ No binary scaling in pA at high p_t (tails much too low)

Solution

- Introducing a **saturation scale**
  (K. Werner, B. Guiot, Iu. Karpenko, T. Pierog,
  Phys.Rev. C89 (2014) 064903)

Before: Compute G with fixed soft cutoff Q_0
$\rightarrow$ fit $\rightarrow$ add ε exponents

New: Compute G with saturation scale $Q_s \propto Z\,\hat{s}^{\lambda}$
$\rightarrow$ fit   ($\hat{s}$ = Pomeron invariant mass)

varying Q_s changes internal structure!

Still something missing ...

- □ The saturation scale depends on the number of **participating nucleons**,

- □ but NOT on the **number of Pomerons** N_{Pom} (participating parton pairs)

The number of Pomerons represents the event activity in pp, as the number of participating nucleons does in pA.

The final solution

- □ Combining "epsilon method" and saturation scale in a smart way (T. Pierog and K. Werner, procs. EDS 2015, Borgo, France)

Step 1 Compute $G = G(Q_0)$ with fixed soft cutoff Q_0 $\rightarrow$ fit $\rightarrow$ add ε exponents ($\rightarrow G_{\text{eff}}$) in order to fit cross sections

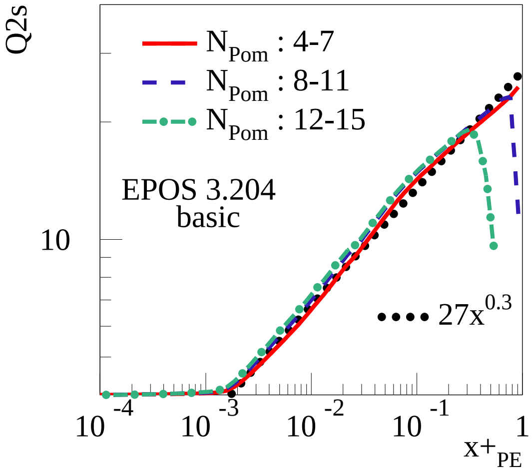
Step 2 Introduce saturation scale via

$$G_{\text{eff}} = k\, G(Q_s)$$

affecting the internal structure

(We will see what to take to k)

The saturation scale Q_s^2



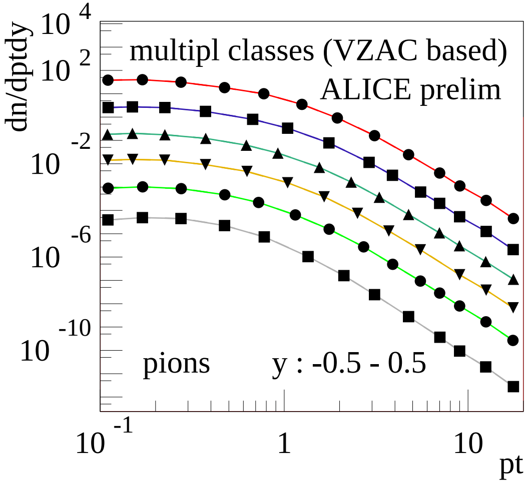
pp at 7 TeV

using $G_{\mathrm{eff}} = k\,G(Q_s)$

with constant k

($x+_{\mathrm{PE}}$ is the LC momentum fraction on the projectile side)

A crucial test:
Multiplicity dependence of spectra at high p_t



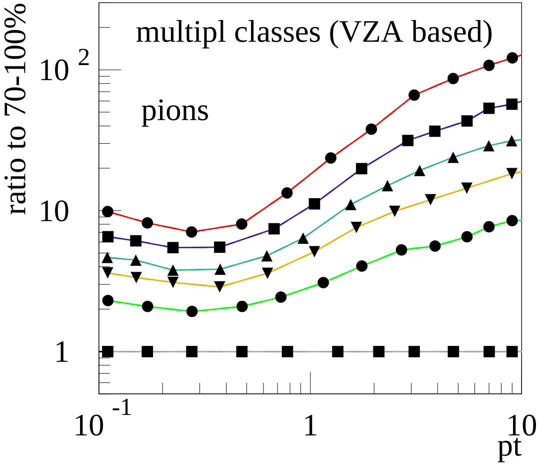
preliminary
ALICE data

(digitalized from B.A.Hess, talk at MPI@LHC 2015 Trieste November 27, 2015)

multiplicity bins
(top to bottom):
0-1%, 1-5%, 10-15%, 20-30%, 40-50%, 70-100%

lines to guide the eye

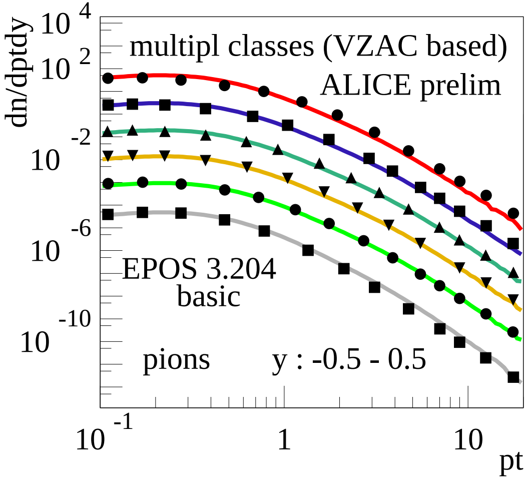
Same data - ratio to 70-100%



non-trivial:

spectra get harder with multiplicity

Comparing ALICE data with EPOS calculations



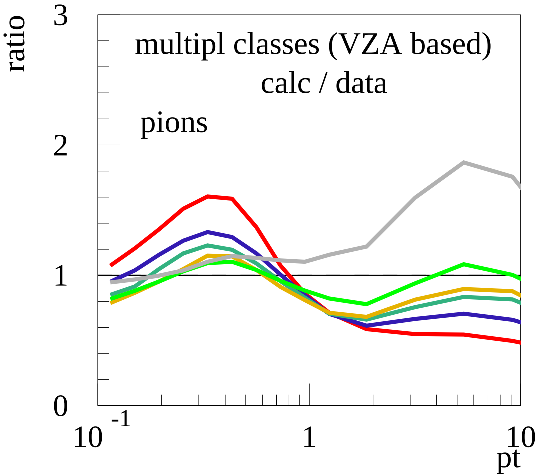
(preliminary ALICE data digitalized from B.A.Hess, talk at MPI@LHC 2015 Trieste November 27, 2015)

multiplicity bins
(top to bottom):
0-1%, 1-5%, 10-15%, 20-30%, 40-50%, 70-100%

Not too bad for a first shot ... but tails are not correct

Comparing ALICE data with EPOS calculations

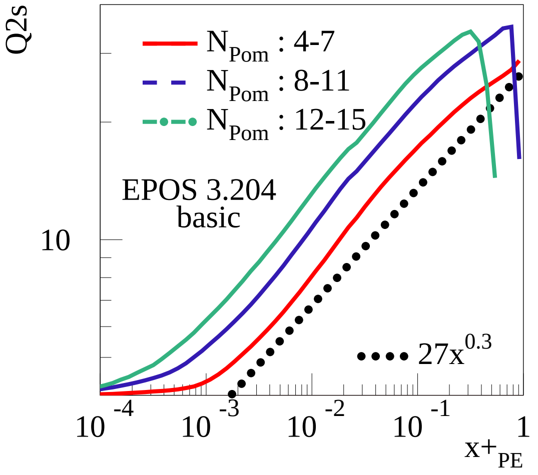
Ratio calculation / data



multiplicity bins : 0-1% (red) , 1-5%, 10-15%, 20-30%, 40-50%, 70-100% (grey)

Tails wrong by factors of two (low pt will be modified by hydro)

Make saturation scale Q_s^2 depending on N_{Pom}



pp at 7 TeV

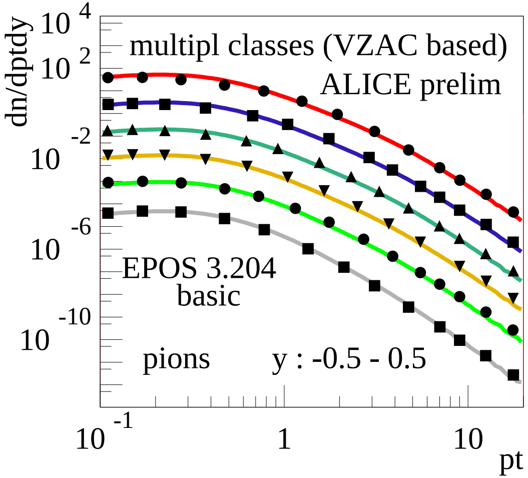
using $G_{\mathrm{eff}} = k\,G(Q_s)$

with

$$k = \left(\frac{N_{\mathrm{Pom}}}{\langle N_{\mathrm{Pom}}\rangle}\right)^{0.75}$$

higher Q_s^2 with increasing Pomeron number (like N_{part} dependence in pA)

Comparing ALICE data with EPOS calculations

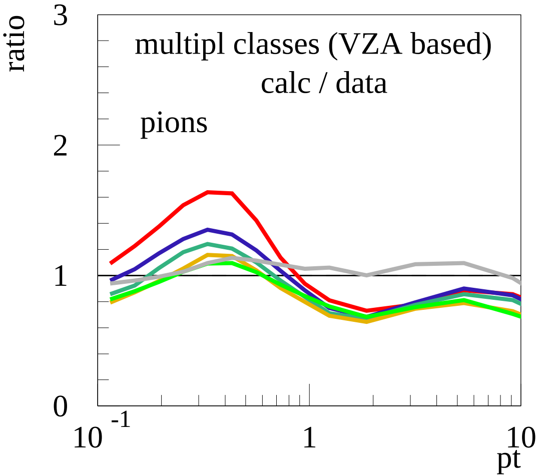


using

$$k = \left(\frac{N_{\mathrm{Pom}}}{\langle N_{\mathrm{Pom}} \rangle} \right)^{0.75}$$

=> much better

Comparing ALICE data with EPOS calculations
Ratio calculation / data



using

$$k = \left(\frac{N_{\mathrm{Pom}}}{\langle N_{\mathrm{Pom}} \rangle} \right)^{0.75}$$

multiplicity bins : 0-1% (red) , 1-5%, 10-15%, 20-30%, 40-50%, 70-100% (grey)

Tails reasonable (low pt will be modified by hydro)

Still finetuning and tests needed, but we use

$$\boldsymbol{G_{\mathrm{eff}} = k\, G(Q_s)}$$

with

$$\boldsymbol{k = \left(\frac{N_{\mathrm{Pom}}}{\langle N_{\mathrm{Pom}}\rangle}\right)^{A_{\mathrm{sat}}}}, \quad A_{\mathrm{sat}} = 0.75$$

to analyse the multiplicity dependence of D-meson production (results depend somewhat on A_{sat})

Remark : This new procedure => EPOS 3.2xx

Charm – multiplicity correlations

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

N_{ch}: Charged particle multiplicity

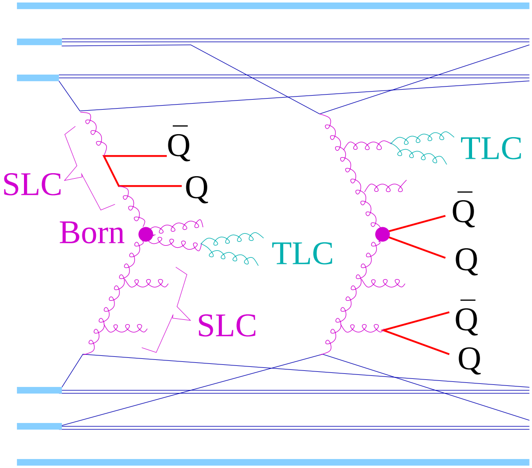
N_{D1}: D-meson multiplicity for $1 < p_t < 2\,\mathrm{GeV/c}$

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

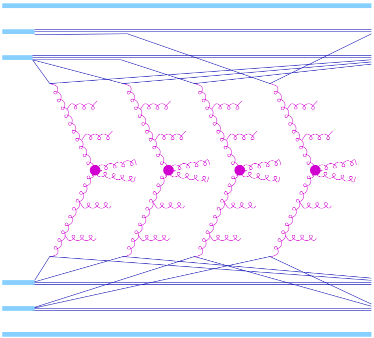


as light quark production
(but non-zero masses : $m_c = 1.3$, $m_b = 4.2$)

In any of the ladders

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

Multiple scattering (EPOS3, basic):



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

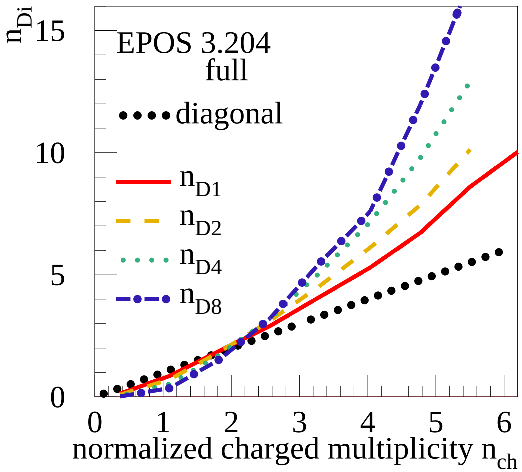
"Natural" linear behavior

(first approximation)

We use $n = N/\langle N \rangle$ for N_{ch} and N_{Di}

The actual calculations

n_{Di} vs n_{ch}



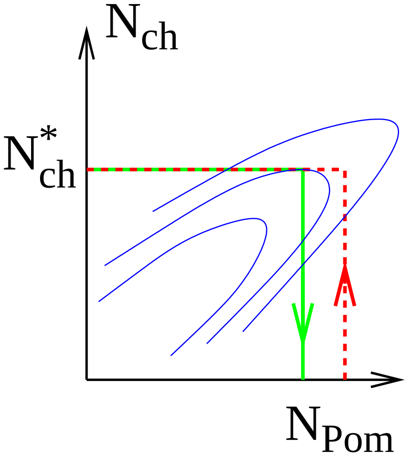
... even more than linear increase!

(in particular for large p_t)

(less for $A_{\rm sat} = 0$)
(much less in EPOS 3.1xx)

Why this pt dependence ?

Crucial: Fluctuations



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

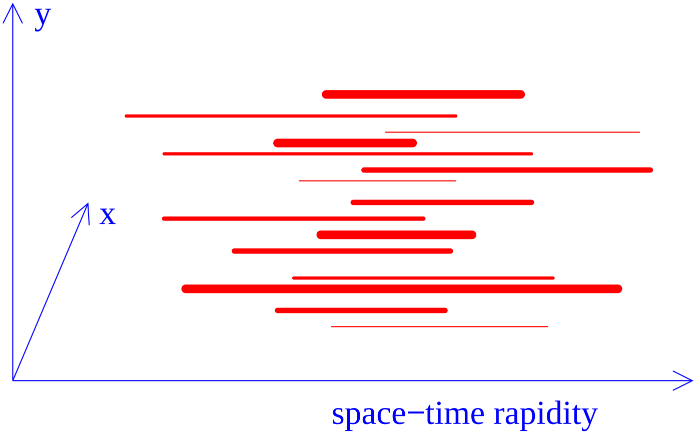
(=> two-dimensional
probability distribution)

In the following, we consider fixed values $N_{\rm ch}{}^{*}$
$\rightarrow$ **fixed** $n_{\rm ch}{}^{*}$

To understand the implications of "fixed n_{ch}"

Strings in multiple scattering event (Schematic view):

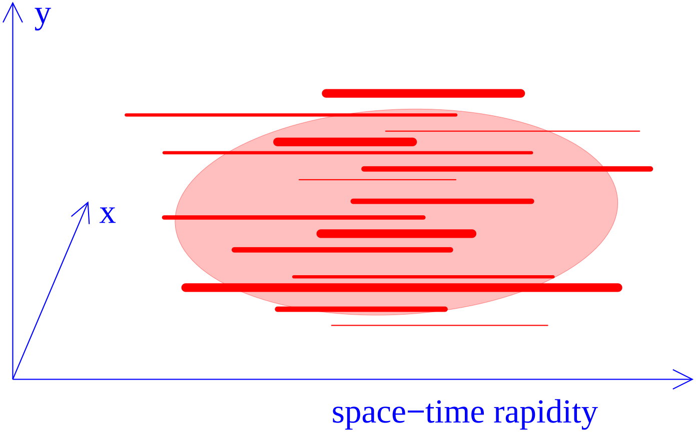
basic EPOS



Strings of
different lengths,
different rapidity
coverage,
different hardness

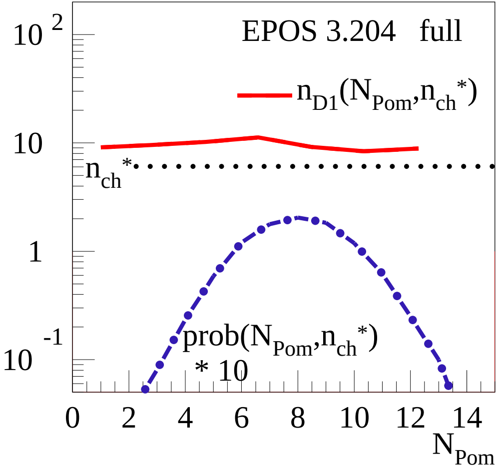
length
~ mass ($\sqrt{x^+x^-s}$)

full EPOS (with hydro) string segments => fluid



but
string properties
- number,
- masses,
- hardnesses
determine initial energy density and final multiplicity

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



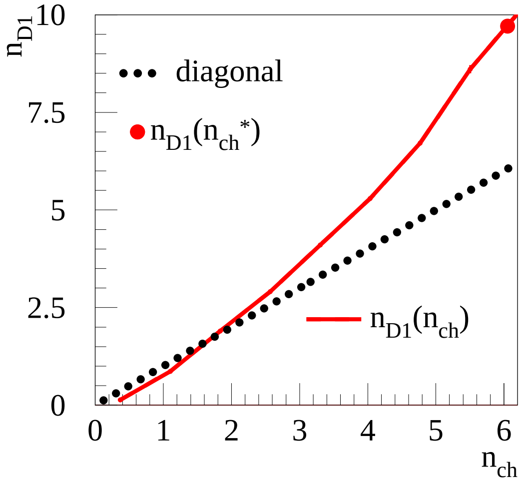
$$\boldsymbol{n_{D1}} = \sum_{N_{\rm Pom}} \text{prob}(N_{\rm Pom}, n_{\rm ch}{}^*) \times n_{D1}(N_{\rm Pom}, n_{\rm ch}{}^*)$$

(60%) $> \boldsymbol{n_{\rm ch}}{}^*$

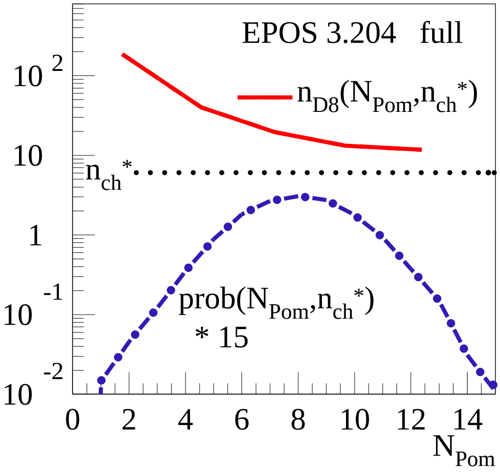
having used

$$n_{D1}(N_{\rm Pom}, n_{\rm ch}{}^*) \quad (60\%) \; > n_{\rm ch}{}^*$$

The precise calculation (red point)



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



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

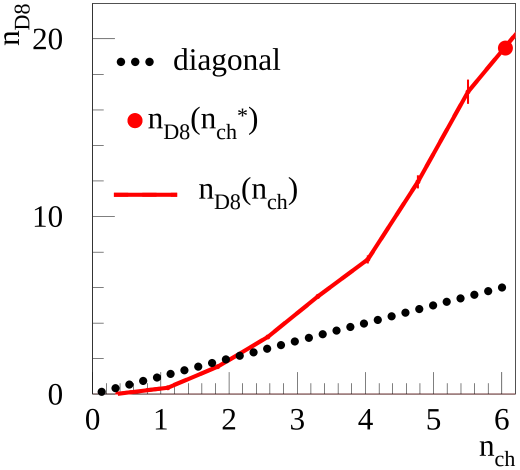
because

$n_{D8} > n_{ch}{}^*$ **at high** N_{Pom}

and

increases strongly towards small N_{Pom}

The precise calculation (red point)



significantly above the diagonal!

strongly non-linear!

How to understand $n_{D8} >> n_{ch}^*$ and why increasing towards small N_{Pom}?

We compute in addition

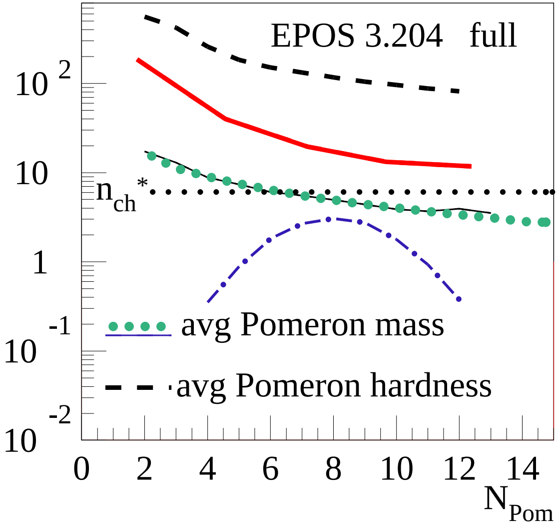
- **The average invariant Pomeron mass for given N_{Pom} and $n_{\mathrm{ch}}{}^{*}$**

- **The average Pomeron hardness**

$$\left(\left\langle p_t^2\right\rangle / \left\langle p_t^2\right\rangle_{\mathrm{ref}} - 1\right) \times 100$$

  for given N_{Pom} and $n_{\mathrm{ch}}{}^{*}$
  (based on string segments)

Pomeron mass and hardness



both increase significantly with decreasing N_{Pom}

red line: n_{D8}

blue dashed-dotted: N_{Pom} distr

correspondence hardness - n_{D8} !!

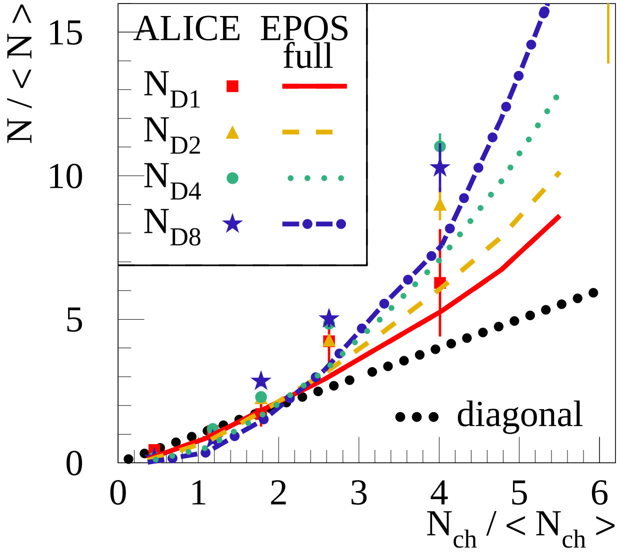
Strong non-linear increase (of $n_{D8}(n_{\mathrm{ch}})$) since

- **Pomerons harder with increasing multiplicity (more screening, higher Q_2^s)**

- **The number of Pomerons fluctuates for given multiplicity and smaller Pomeron numbers imply harder Pomerons**

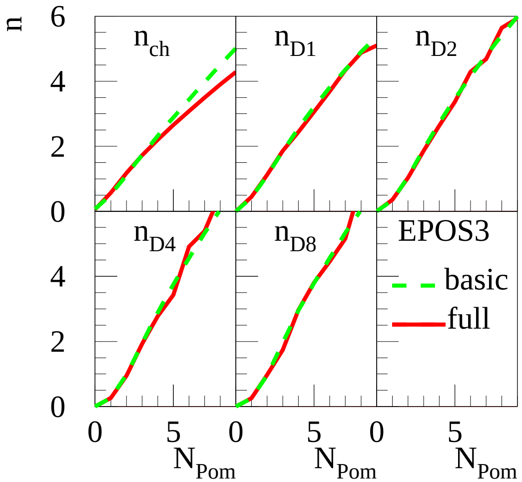
- **note : n_{D8} is nothing but a "Pomeron hardness" measure (even a very sensitive one)**

EPOS 3.204 compared to data



Hydo helps somewhat

(for basic EPOS the increase is somewhat less)



No change for n_{Di}

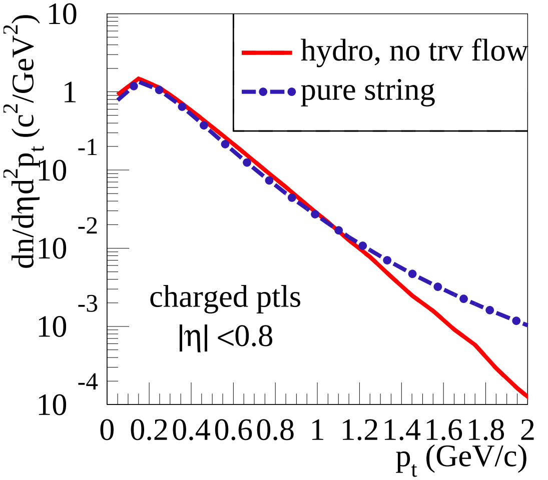
But some reduction of n_{ch}

=> $n_{D8}(n_{ch})$ with hydro is somewhat steeper compared to basic EPOS

Why multiplicity reduction?

Basic EPOS:
Pomerons > Strings
> String fragmentation
(independent of event activity)

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

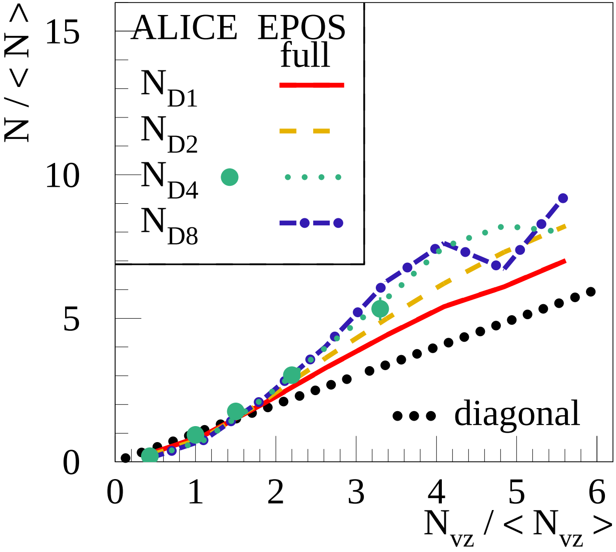


Taking charged-particle multiplicity at forward/backward rapidity

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

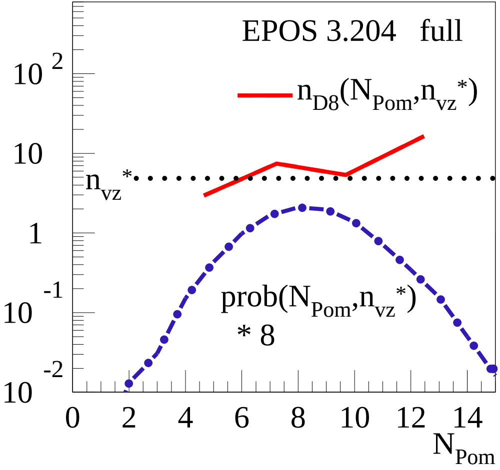
(Vzero multiplicity, N_{vz}**,** n_{vz}**)**

Vzero multiplicity : Smaller increase



as in the data

n_{D8} for given $n_{vz}{}^*$



whereas

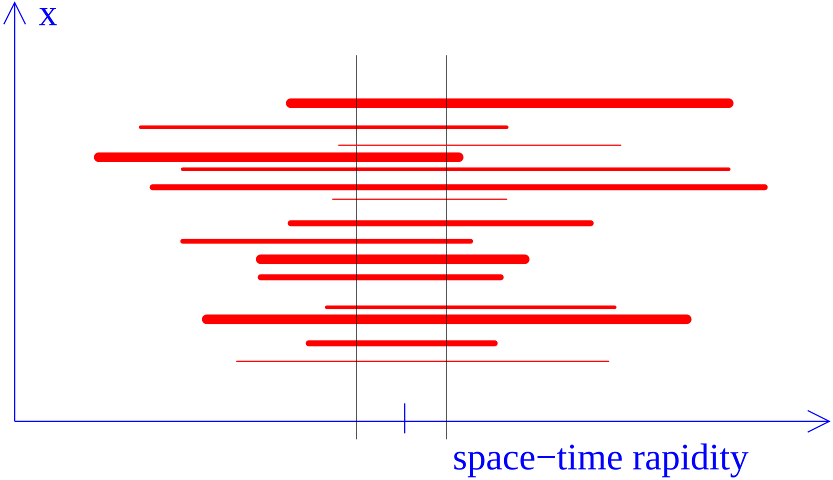
$n_{D8}(N_{\mathrm{Pom}}, n_{\mathrm{ch}}{}^*)$
increases strongly towards small N_{Pom}

$n_{D8}(N_{\mathrm{Pom}}, n_{\mathrm{vz}}{}^*)$
decreases slightly

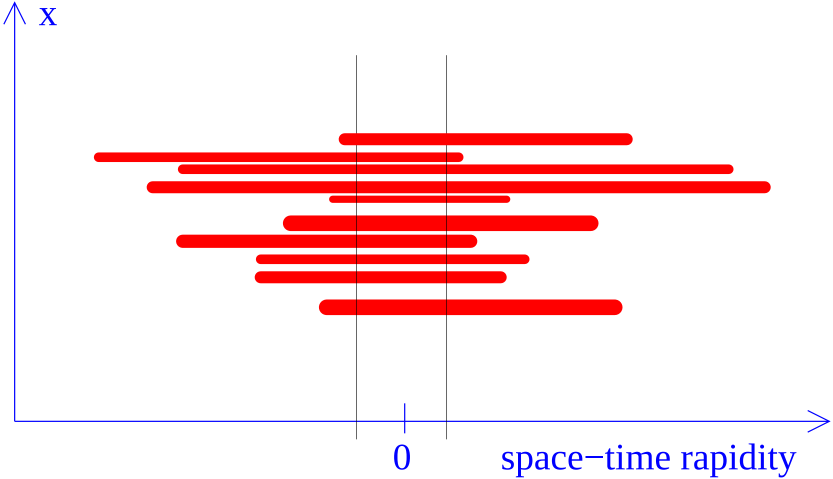
=> Pomerons do not get harder

Why do Pomerons get harder at small N_{Pom} for fixed n_{ch} but not for fixed n_{vz} ?

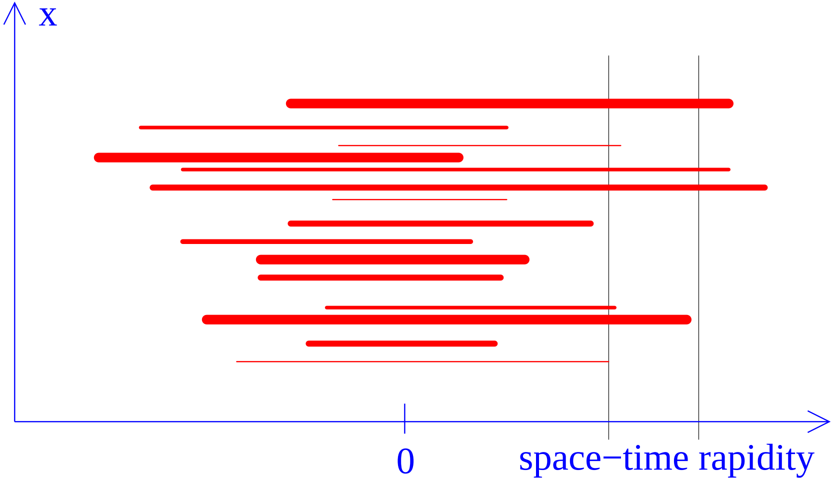
In case of n_{ch}, almost all Pomerons cover the corresponding central rapidity range



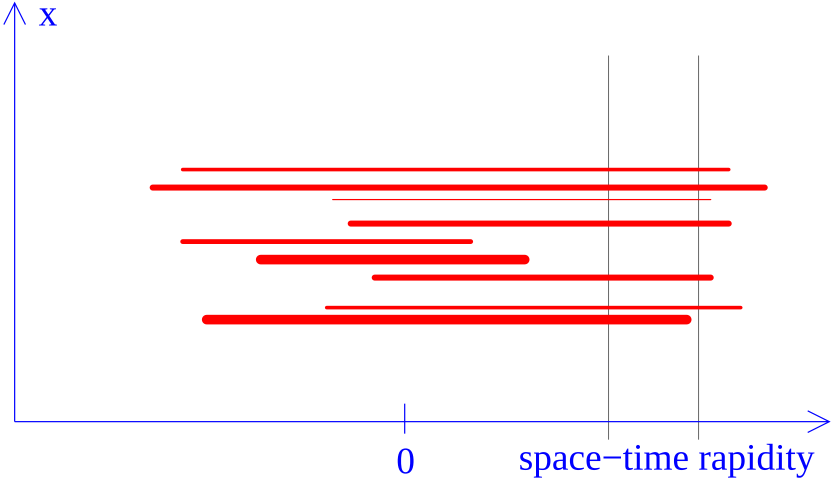
In case of n_{ch}, almost all Pomerons cover the corresponding central rapidity range, so to keep n_{ch} fixed for smaller N_{Pom} requires harder Pomerons (no other way)



In case of n_{vz}, only some Pomerons cover the corresponding forward rapidity range,



In case of n_{vz}, only some Pomerons cover the corresponding forward rapidity range, so to keep n_{vz} fixed for smaller N_{Pom} can be accomodated with more Pomerons covering that rapidity range



Summary

- **New (and final?) major improvement of the multiple scattering scheme in EPOS: Pomeron number dependence of the saturation scale** (**and the corresponding technical improvements which make it possible**)
- **Provides increasing Pomeron hardness with increasing multiplicity** (**ALICE multipl dependence of spectra**)
- **Explains strong increase of high pt charm production vs multiplicity, and the modest increase in case of forward multiplicity.**