Multiplicity dependence of charm production and parton saturation

K.W. in collaboration with

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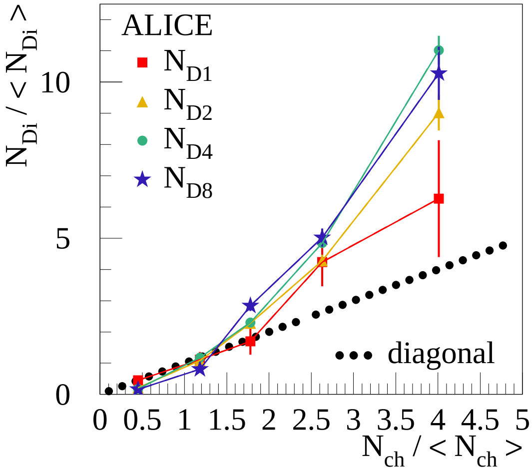
D multiplicity vs charged multiplicity in pp



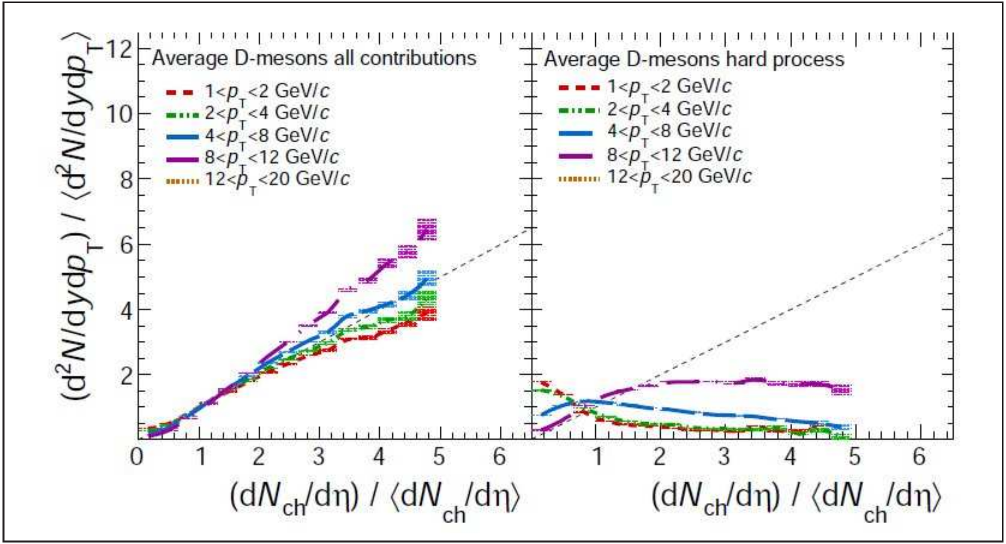
ALICE JHEP 09 (2015) 148, arXiv:1505.00664v1

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
(d²N/dydp_T) / ⟨d²N/dydp_T⟩
(dN_ch/dη) / ⟨dN_ch/dη⟩
Average D-mesons hard process
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
(dN_ch/dη) / ⟨dN_ch/dη⟩

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

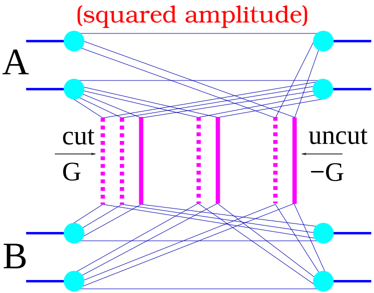
arXiv:1312.1233 , arXix:1307.4379

Initial conditions: Marriage pQCD+GRT+energy sharing

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

For pp, pA, AA:

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



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

Nonlinear effects considered via saturation scale Q_s

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

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

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

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

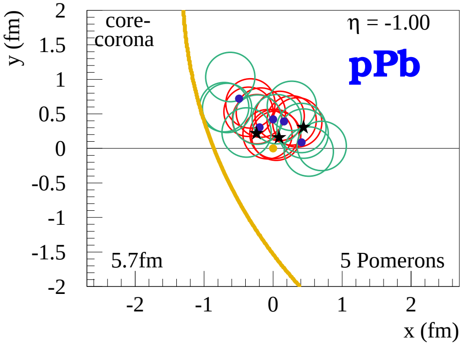
$$\prod_{\lambda=1}^{l_k} -G(\tilde{x}^+_{k,\lambda}, \tilde{x}^-_{k,\lambda}, s, |\vec{b} + \vec{b}^A_{\pi(k)} - \vec{b}^B_{\tau(k)}|) \Bigg)$$

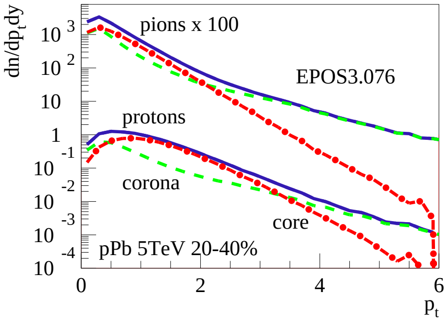
$$\prod_{i=1}^{A} \Big(1 - \sum_{\pi(k)=i} x^+_{k,\mu,} - \sum_{\pi(k)=i} \tilde{x}^+_{k,\lambda} \Big)^{\alpha} \prod_{j=1}^{B} \Big(1 - \sum_{\tau(k)=j} x^-_{k,\mu} - \sum_{\tau(k)=j} \tilde{x}^-_{k,\lambda} \Big)^{\alpha} \Bigg\}$$

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

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

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

- ☐ $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,
- ☐ $\partial_{;\nu}$ 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*)

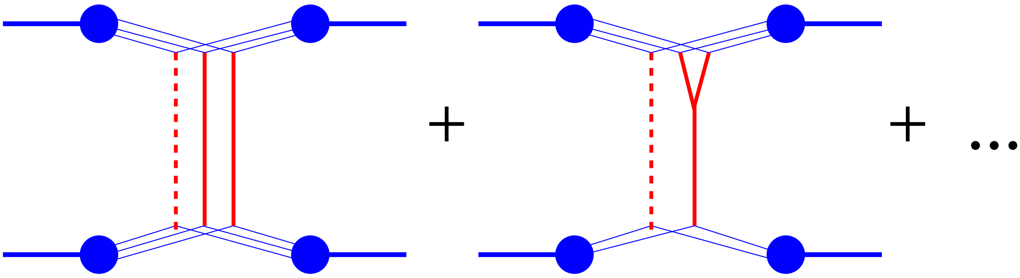
$$G \approx G_{\rm fit} = \alpha\,(x^+)^\beta (x^-)^{\beta'}$$

($x^\pm$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)

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[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!

(-) technical challenge

(Pomerons not independent any more)

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_{eff}) in order to fit cross sections

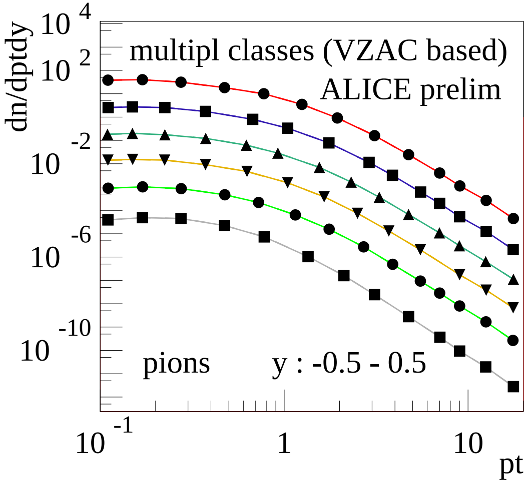
Step 2 Introduce saturation scale via

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

affecting the internal structure

(We will see what to take to k)

A crucial test:
Multiplicity dependence of spectra at high p_t



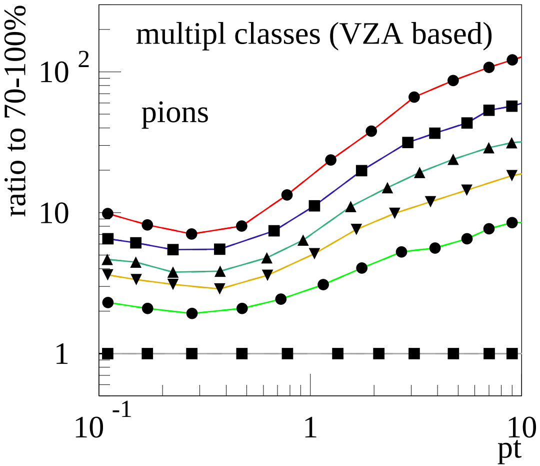
preliminary ALICE data

(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

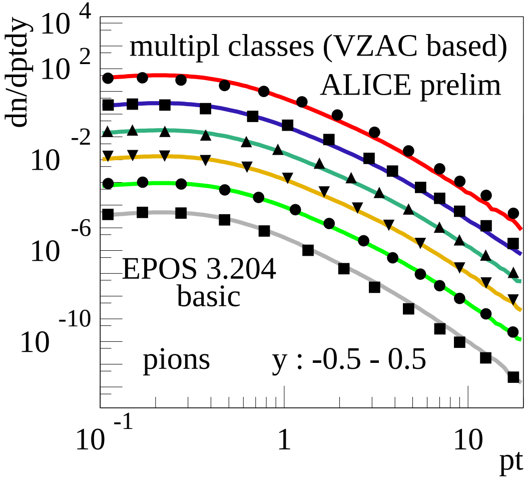
Same data - ratio to 70-100%



non-trivial:

spectra get harder with multiplicity

Comparing ALICE data with EPOS calculations

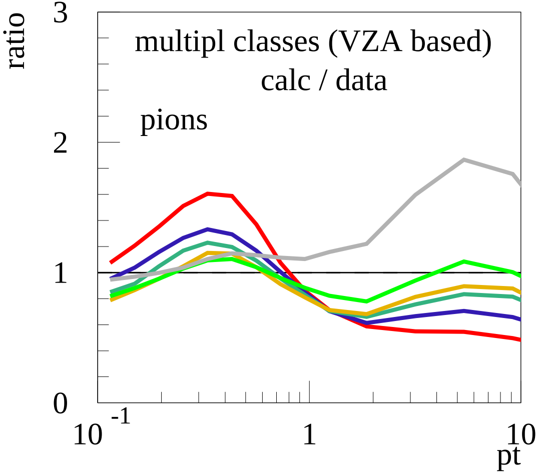


(preliminary ALICE data digitalized from B.A.Hess, talk at MPI@LHC 2015 Trieste November 27, 2015)

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}

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

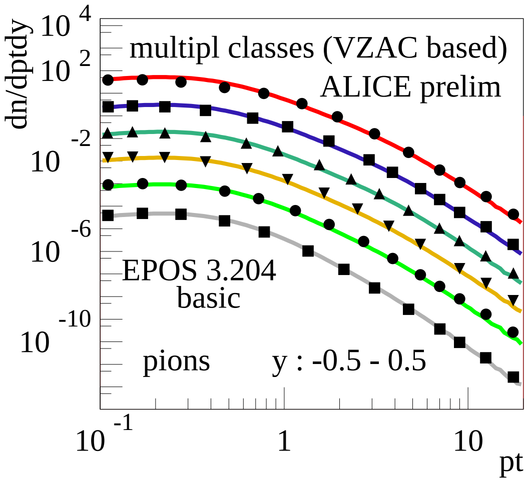
with

$$k = k_0\,{N_{\mathrm{Pom}}}^{0.75}$$

higher Q_s^2 with increasing Pomeron number

(like N_{part} dependence in pA)

Comparing ALICE data with EPOS calculations

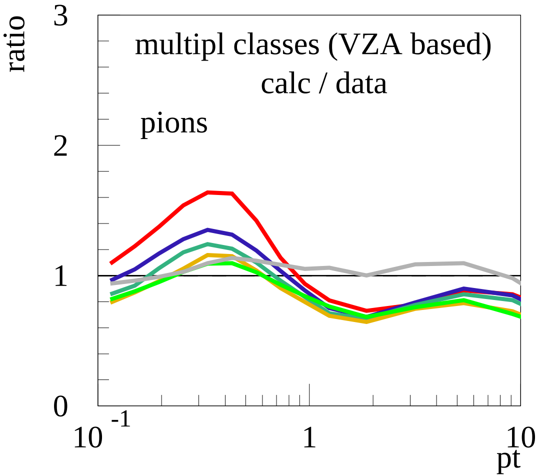


using

$$k = k_0 \, N_{\mathrm{Pom}}^{\;\;0.75}$$

=> much better

Ratio calculation / data



Still finetuning and tests needed, but we use

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

with

$$k = k_0\, N_{\mathrm{Pom}}{}^{A_{\mathrm{sat}}}, \quad A_{\mathrm{sat}} = 0.75$$

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 $1 < p_t < 2\,\mathrm{GeV/c}$

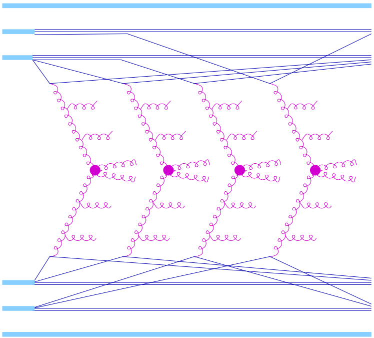
N_{D2}: D-meson multiplicity for $2 < p_t < 4\,\mathrm{GeV/c}$

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

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

We use also $\boldsymbol{n = N/\langle N\rangle}$

Multiple scattering (EPOS3, basic):



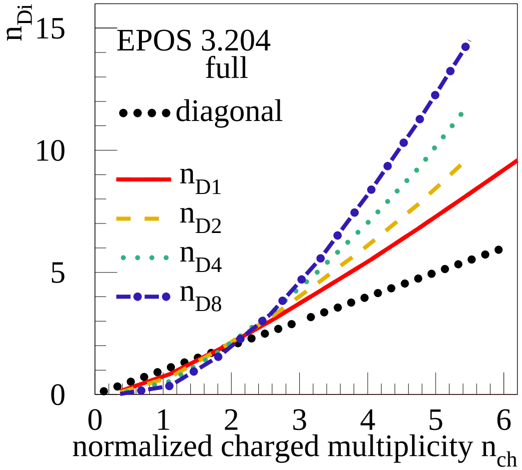
$$N_{Di} \propto N_{\mathrm{ch}} \propto N_{\mathrm{Pom}}$$

"Natural" linear behavior

(first approximation)

The actual calculations

n_{Di} vs n_{ch}



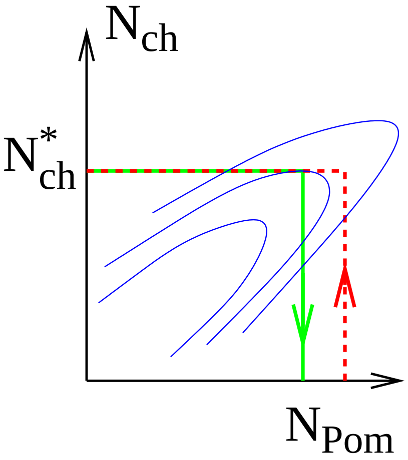
... even more than linear increase!

(in particular for large p_t)

New Q_s procedure helps!

Why this pt dependence ?

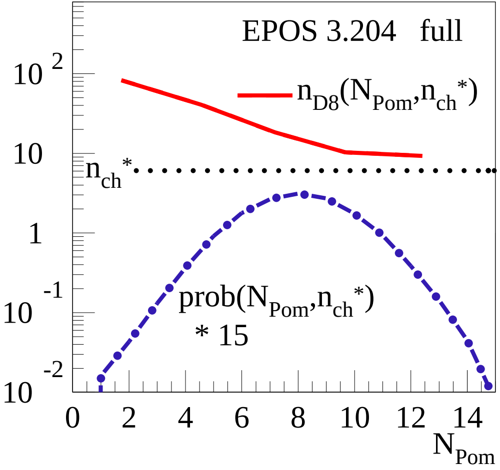
Crucial: Fluctuations



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

(=> two-dimensional
probability distribution)

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



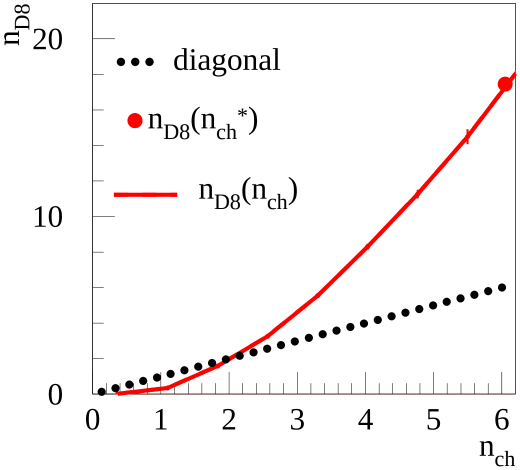
$$n_{D8} = \sum_{N_{Pom}} \text{prob}(N_{Pom}, n_{ch}{}^*) \times n_{D8}(N_{Pom}, n_{ch}{}^*)$$

$$>> n_{ch}{}^*$$

n_{D8} increases strongly towards small N_{Pom} !!!

much more than n_{D1}

The precise calculation (red point)



significantly above the diagonal!

strongly non-linear!

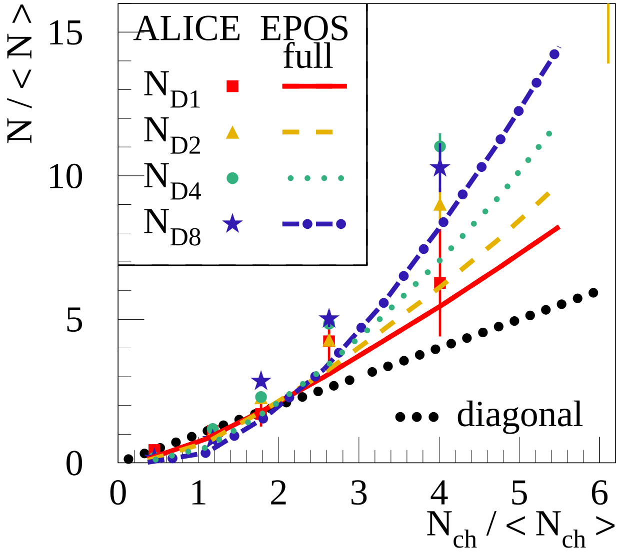
Strong non-linear increase (of $n_{D8}(n_{\mathrm{ch}})$) since

- **Pomerons harder with increasing multiplicity (larger Q_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

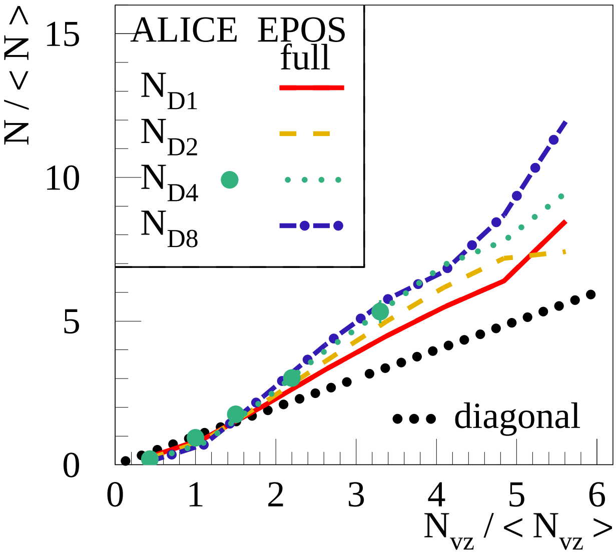


Taking charged-particle multiplicity at forward/backward rapidity

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

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

Vzero multiplicity : Smaller increase

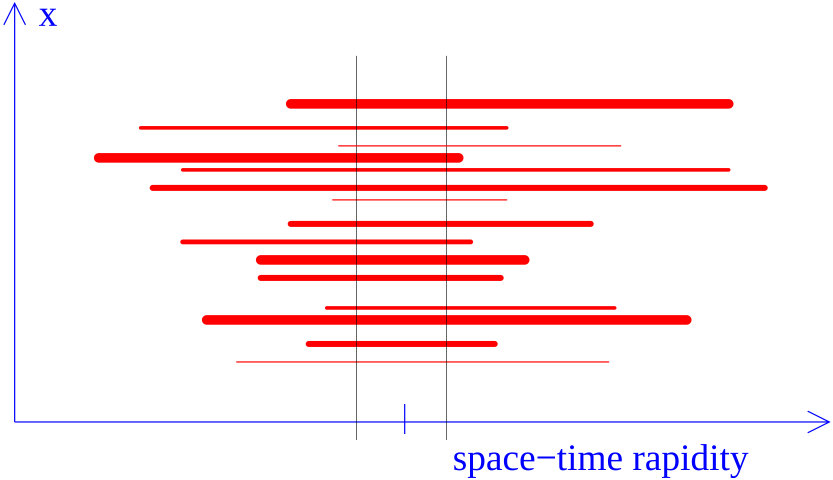


as in the data

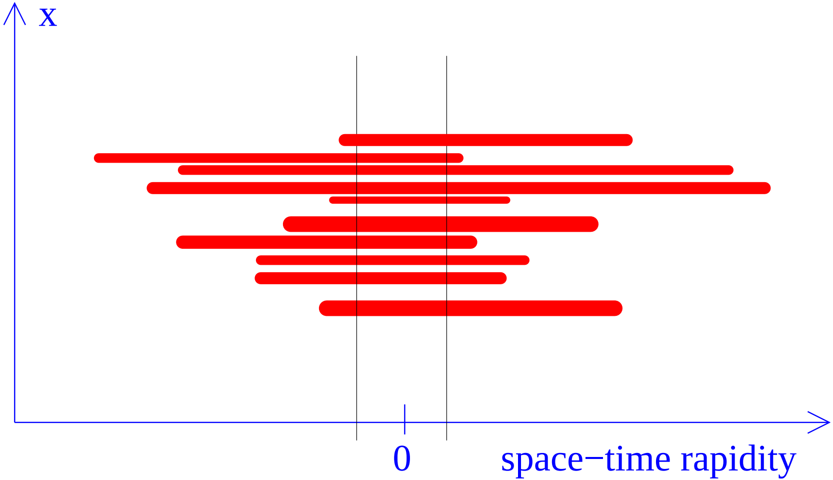
Why this difference

between n_{ch} and n_{vz} ?

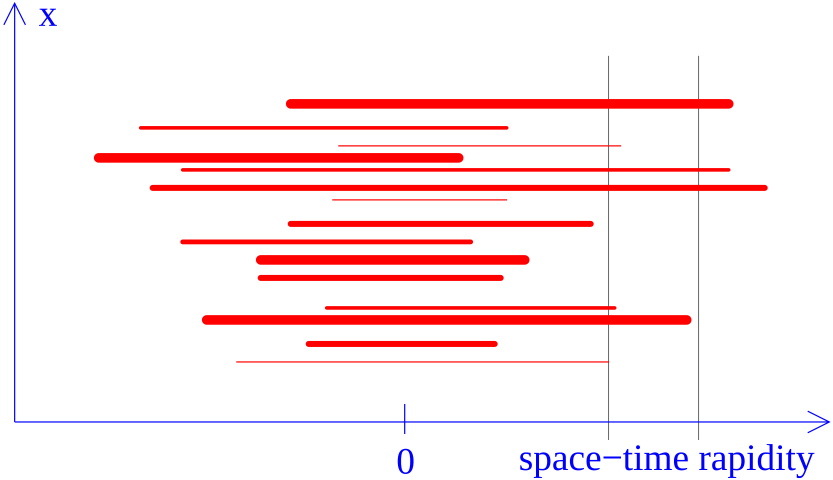
In case of n_{ch}, almost all Pomerons cover the corresponding central rapidity range



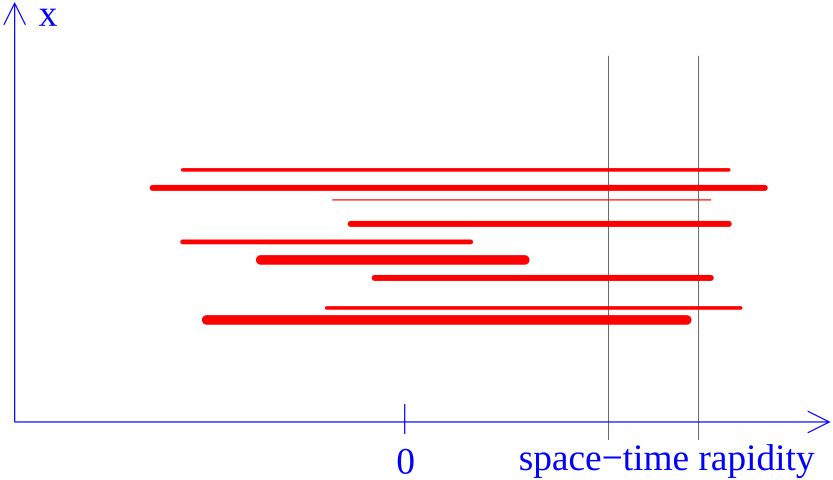
to keep n_{ch} fixed for smaller N_{Pom} requires harder Pomerons
(no other way)



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



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**
- **Provides increasing Pomeron hardness with increasing multiplicity (ALICE multipl dependence of spectra)**
  (different origin compared to Pythia)
- **Explains strong increase of high pt charm production vs multiplicity, and the modest increase in case of forward multiplicity.**
- **These (charm) data do not teach us much about charm production, but are extremely useful to understand multiple scattering**