Network NA7-HF-QGP

HFHF Theory Retreat 2023

Small systems in EPOS4

(pp scattering at LHC energies)

K. Werner

SUBATECH, Nantes University – IN2P3/CNRS – IMT Atlantique

Nantes, France

Some history

Before QCD

- **Gribov-Regge (GR) approach, for pp, pA, AA**
  V. A. Abramovsky, V. N. Gribov, O. V. Kancheli, L. N. Lipatov **(1967-1973)**
- **S-matrix theory, parallel scattering scheme**
- **Exchanged "objects" are called Pomerons**
- **AGK theorem ($\sigma_{\mathbf{incl}}^{AB} = AB \times \sigma_{\mathbf{incl}}^{\mathbf{single\,Pom}}$)**
- **Infinite energy limit**
  (problematic...)
- **Still used (Glauber MC ...)**
  not necessarily correctly

Perturbative QCD for pp

- **Asymptotic freedom**
  D. Gross, F. Wilczek,H. Politzer **(1973)**
- **DGLAP (linear) evolution**
  V. N. Gribov, L. N. Lipatov **(1973)**
  G. Altarelli, G. Parisi **(1977)**, Y. L. Dokshitzer **(1977)**
- **Factorization** J. Collins, D. Soper, G. Sterman **(1989)**
- **Covers only a small fraction of events**
  High multiplicity events are not covered

Saturation (CGC, low-x physics,...)

- **Nonlinear evolution**
  L. V. Gribov, E. M. Levin, and M. G. Ryskin **(1984)**
  L. D. McLerran and R. Venugopalan **(1994)**, Y. V. Kovchegov **(1996)**, ...

An attempt to couple GR and pQCD

- **NEXUS model, earlier EPOS versions**
  Drescher, H. J. and Hladik, M. and Ostapchenko, S. and Pierog, T. and Werner, K. **(2001)**
- **Using: Pomeron = QCD parton ladder**
- **With energy sharing!**
  crucial for MC applications
- **Problem: violates AGK (and binary scaling)**
- **Solution: take into account saturation**
  in a very particular way (EPOS4)

EPOS4

- **Oct. 2022 EPOS4.0.0 release** (no “official” EPOS3 release)
  https://klaus.pages.in2p3.fr/epos4/
  thanks Laurent Aphecetche for explaining gitlab pages, nextjs etc
  thanks Damien Vintache for managing installation/technical issues

- **Papers** (https://klaus.pages.in2p3.fr/epos4/physics/papers)

  - **https://arxiv.org/pdf/2301.12517.pdf** (EPOS4 Overview)
  - **https://arxiv.org/pdf/2306.02396.pdf** (pQCD in EPOS4)
  - **https://arxiv.org/pdf/2306.10277.pdf**
    (Microcanonical hadronization, core-corona in EPOS4)

  - **very soon: Parallel scattering, saturation, and generalized AGK theorem**
    (44 pages, systematic and complete presentation of the theoretical basis, **combining S-matrix theory, pQCD, saturation,** many proven statements)

☐ EPOS4 general structure

▷ **Primary scatterings (at t = 0)**
parallel scattering approach based on S-matrix theory

▷ **Secondary scatterings (at t > 0)**
- core-corona procedure,
- hydro evolution,
- microcanonical decay,
- hadronic rescattering

Possible at "high energies" (large gamma factors).

EPOS4 S-matrix approach (for parallel scatterings!!!)

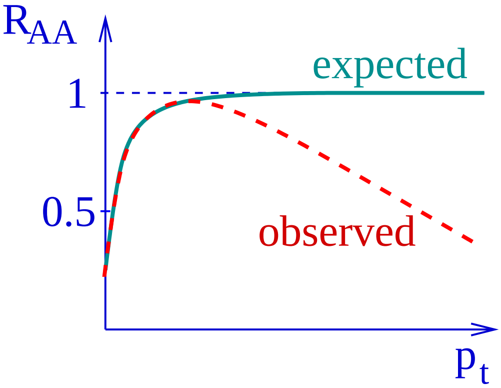
Very compact summary (details: arXiv:2301.12517)

- **Connecting S-matrix approch (parallel scattering) and pQCD:** **assume: Pomeron = pQCD parton ladder**

A major problem

Popular observable: **nuclear modification factor** $R_{AA} = AA/(N_{coll} \times pp)$

- **should be unity for hard probes w/o final state interactions or in pA**

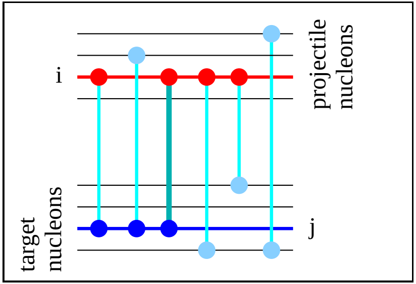


The problem is the energy sharing among Pomerons.

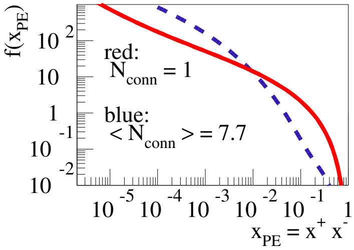
For a given Pomeron, connecting projectile nucleon i and target nucleon j define:

$$N_{\mathrm{conn}} = \frac{N_{\mathrm{P}} + N_{\mathrm{T}}}{2}$$

N_{P} = number of Pomerons connected to i
N_{T} = number of Pomerons connected to j



Crucial variables: the Pomeron's light-cone momentum fractions x^{+} and x^{-}
distributions $f(x^{+}, x^{-})$ determine p_t distributions of partons



$$R_{\mathrm{deform}} = \frac{f^{(N_{\mathrm{conn}})}(x^{+}, x^{-})}{f^{(1)}(x^{+}, x^{-})}$$

We are able to parameterize the "deformation"

How to connect S-matrix approach and pQCD?

- To be quantitative: we use (always) "G" to be the imaginary part of the T-matrix in impact parameter representation divided by $s/2$ (Mandelstam s)
- We need to relate
  - G_{Pom} (single Pomeron expression in S-matrix approach) to
  - G_{QCD} (parton-parton scattering, calculable in pQCD)
- We know: $G_{\mathrm{Pom}} = G_{\mathrm{QCD}}$ does not work
- In the following, for simplicity, use $G = G_{\mathrm{Pom}}$

Better than simply $G = G_{\mathrm{QCD}}$:

$$G(x^+, x^-, s, b) = \frac{1}{R_{\mathrm{deform}}^{(N_{\mathrm{conn}})}(x^+, x^-)} \times n \times G_{\mathrm{QCD}}(Q^2_{\mathrm{sat}}, x^+, x^-, s, b)$$

G does not depend on N_{conn}, but Q^2_{sat} depends on $x^+, x^-, N_{\mathrm{conn}}$
(n is a normalization constant)

which perfectly solves the R_{AA} problem; we recover binary scaling (generalized Abramovskii Gribov Kancheli theorem).

For large N_{conn}, low pt is suppressed, the Pomeron gets "hard".

We need to combine in a particular way parallel scattering, energy sharing, saturation, and pQCD to get a formalism free of contradictions!

Now we can do high pt physics, as "factorization models", but we can do much more...

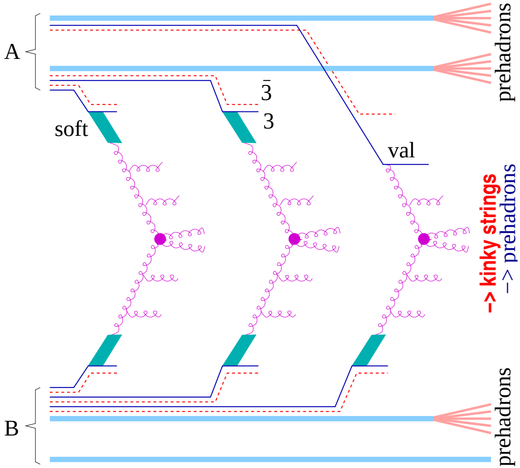
EPOS4: From Pomerons to prehadrons

Very compact summary (details: arXiv:2306.02396)

From multiple Pomeron configurations, after making the link with pQCD, we get
partonic configurations

=> color flow diagrams
=> parton chains
=>kinky strings
=> prehadrons

also: remnants
=> prehadrons



At the end: many prehadrons

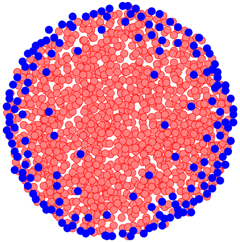
EPOS4: Core-corona separation

(details: arXiv:2306.10277)

We consider all prehadrons (at given τ)

For each one, we estimate its energy loss if it would move out of this system

- **If the energy loss is bigger than the energy of the prehadron, it is considered to be a "core prehadron"**
- **If the energy loss is smaller than the energy, the prehadron escapes, it is called "corona prehadron"**



The core prehadrons constitute "bulk matter" and will be treated via hydrodynamics

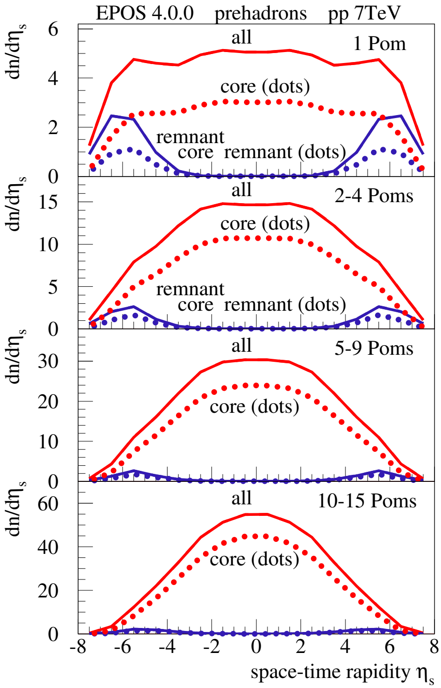
The corona prehadrons become simply hadrons and propagate with reduced energy

The prehadron yield as a function of space-time rapidity,

for different Pomeron numbers in proton-proton collisions at 7 TeV.

prehadrons:
all (red full),
core (red dotted)
remnant (blue full)
core remnant (blue dotted)

For core: compute $T^{\mu\nu}$ and flavor flow vector, then hydro evolution.



Microcanonical hadronization of plasma droplets

(see arXiv:2306.10277)

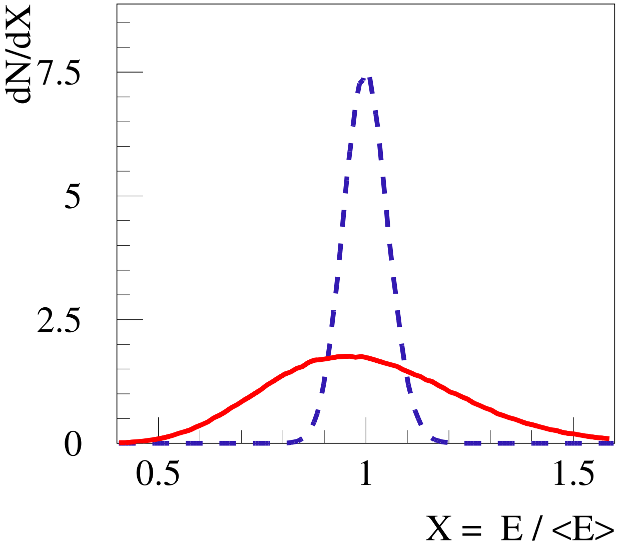
- **Real hadronization (not transition fluid-particles)**
  (sudden statistical decay)

- **Energy and flavor conservation**
  (important for small systems)

- **Extremely fast**
  (major technical impovements in EPOS4)

Grand canonical decay, T = 130 MeV, $f_k = \frac{g_k V}{(2\pi\hbar)^3} \exp\left(-\frac{E_k}{T}\right)$

V=50 fm^3; V=1000 fm^3



Microcanonic decay
of given volume in its CMS into n hadrons

$$dP = C_{\mathrm{vol}}\, C_{\mathrm{deg}}\, C_{\mathrm{ident}} \times \delta(E-\Sigma E_i)\,\delta(\Sigma\vec{p}_i)\prod_A \delta_{Q_A,\Sigma q_{Ai}} \prod_{i=1}^{n} d^3p_i$$

$$C_{\mathrm{vol}} = \frac{V^n}{(2\pi\hbar)^{3n}}\,,\quad C_{\mathrm{deg}} = \prod_{i=1}^{n} g_i\,,\quad C_{\mathrm{ident}} = \prod_{\alpha\in\mathcal{S}} \frac{1}{n_\alpha!}$$

(n_α is the number of particles of species α, $\mathcal{S}$ is the set of particle species)

Different from decay rate of a massive particle (using LIPS), where asymptotic states are defined over an infinitely large volume (see Becattini et al, EPJC35:243-258,2004). **But $E_i = \sqrt{p_i^2 + m_i^2}$**

Microcanonical decay

$$dP \propto d\Phi_{\mathrm{NRPS}} = \delta(M - \Sigma E_i)\,\delta(\Sigma\vec{p}_i)\prod_{i=1}^{n} d^3p_i$$

- ☐ Hagedorn 1958 methods to compute Φ_{NRPS}
- ☐ Lorentz invariant phase space (LIPS) (James 1968)
- ☐ Hagedorn methods used for decaying QGP droplets (Werner, Aichelin, 1994, Becattini 2003)
- ☐ 2012 (Bignamini,Becattini,Piccinini) compute Φ_{NRPS} via the Lorentz invariant phase space (LIPS)
- ☐ **NEW (EPOS4) 2022:**
  - ▷ **Much improved Hagedorn integral method, made very efficient at large n**
  - ▷ **use LIPS method only for small n,** (gets time consuming at large n)

Grand canonical limit

For very large M we should recover the "grand canonical limit" for single particle spectra:

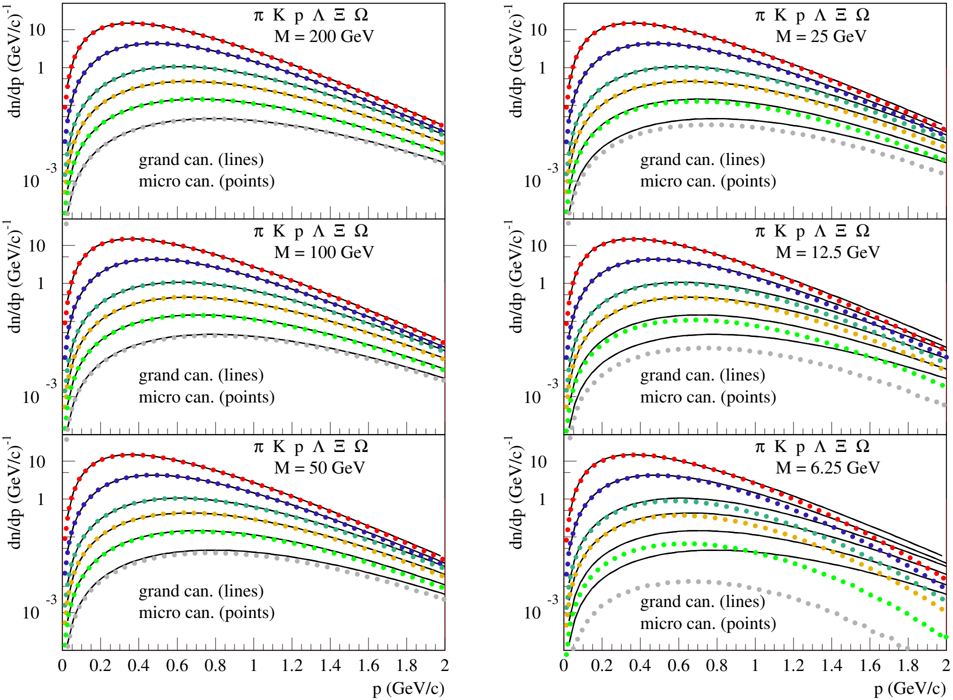
$$f_k = \frac{g_k V}{(2\pi\hbar)^3} \exp\left(-\frac{E_k}{T}\right),$$

The average energy is

$$\bar{E} = \sum_k \frac{4\pi g_k V}{(2\pi\hbar)^3} m_k^2 T \left(3TK_2(\frac{m_k}{T}) + m_k K_1(\frac{m_k}{T})\right).$$

The microcanonical decay of an object of mass M and volume V should converge (for $M \to \infty$) to the GC single particle spectra

with T obtained from $M = \bar{E}$. **$T = 167$ MeV in the following**


π K p Λ Ξ Ω
M = 200 GeV
grand can. (lines)
micro can. (points)
π K p Λ Ξ Ω
M = 25 GeV
grand can. (lines)
micro can. (points)
π K p Λ Ξ Ω
M = 100 GeV
grand can. (lines)
micro can. (points)
π K p Λ Ξ Ω
M = 12.5 GeV
grand can. (lines)
micro can. (points)
π K p Λ Ξ Ω
M = 50 GeV
grand can. (lines)
micro can. (points)
π K p Λ Ξ Ω
M = 6.25 GeV
grand can. (lines)
micro can. (points)
dn/dp (GeV/c)$^{-1}$
p (GeV/c)

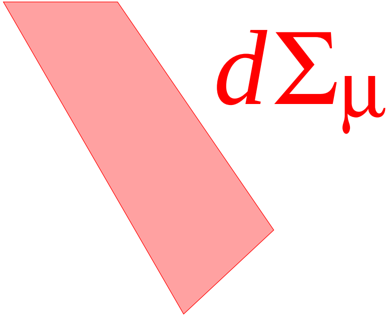
Hadronization on hyper-surface

Hypersurface element:

$$d\Sigma_\mu = \varepsilon_{\mu\nu\kappa\lambda} \frac{\partial x^\nu}{\partial \tau} \frac{\partial x^\kappa}{\partial \varphi} \frac{\partial x^\lambda}{\partial \eta} \, d\tau \, d\varphi \, d\eta$$

Surface:
$x^0 = \tau \cosh \eta$, $x^1 = r \cos \varphi$,
$x^2 = r \sin \varphi$, $x^3 = \tau \sinh \eta$

with $r = r(\tau, \varphi, \eta)$,
representing the
FO condition $\varepsilon = \varepsilon_{\mathrm{FO}}$

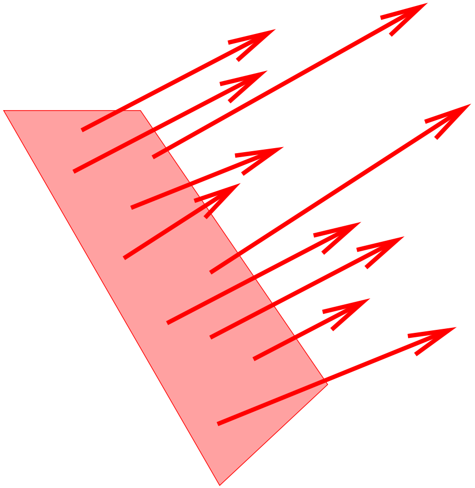


GC particle production via Cooper-Frye

$$E\frac{dn}{d^3p} = \int d\Sigma_\mu p^\mu f(up),$$

assuming a thermalized resonance gas

(adding δf for viscous hydro)



Our approach:

Flow of momentum vector $\boldsymbol{dP^\mu}$ and conserved charges $\boldsymbol{dQ_A}$ through the surface element:

$$\begin{aligned} dP^\mu &= T^{\mu\nu} d\Sigma_\nu, \\ dQ_A &= J^\nu_A d\Sigma_\nu. \end{aligned}$$

(with $A \in \{C, B, S\}$, corresponding electric charge, baryon number and strangeness)

Construct an **effective mass** by summing surface elements:

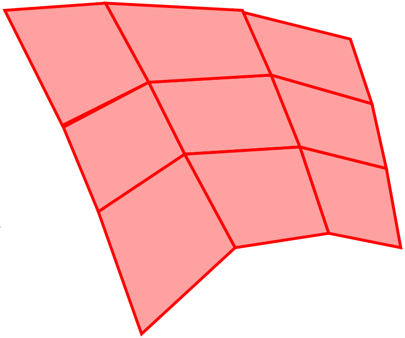
$$M=\int_{\text{surface area}} dM,$$

with

$$dM=\sqrt{dP^{\mu}dP_{\mu}},$$

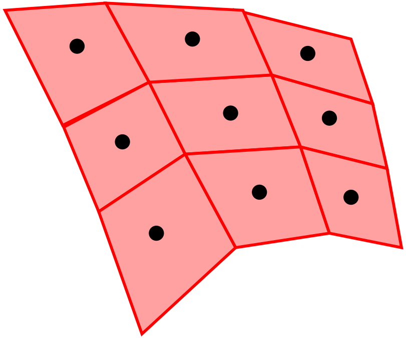
knowing for each element four-velocity

$$U^{\mu}=dP^{\mu}/dM,$$



The four-velocity U^{μ} is NOT equal to the fluid velocity u^{μ}!

The effective mass decays microcanonically



Particles are distributed on the hyper-surface

$$x^{\mu}(\tau, \varphi, \eta)$$

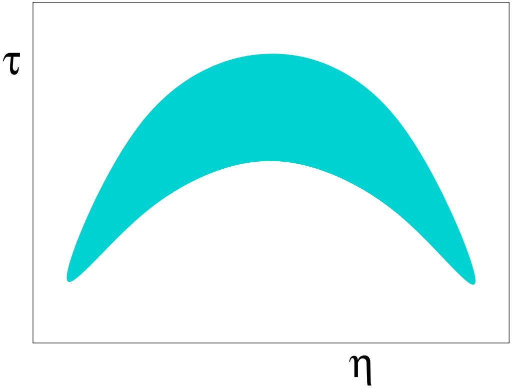
according to the distribution

$$dM(\tau, \varphi, \eta)$$

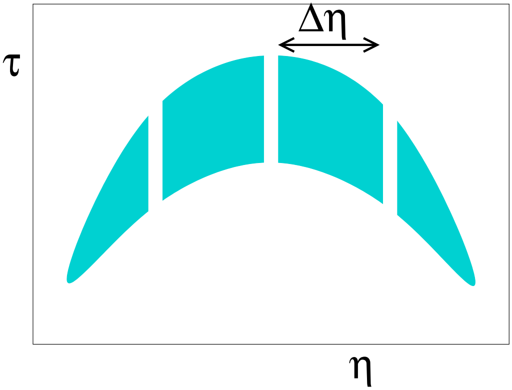
and they are boosted according to the four-velocity

$$U^{\mu}(\tau, \varphi, \eta)$$

Decaying object extended in space-time



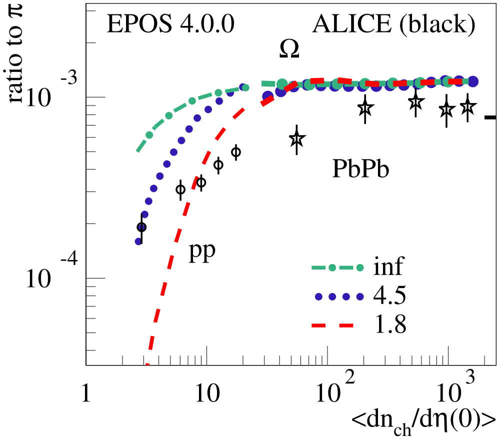
Does is decay as single effective mass M?



... or as several independent objects of width $\Delta\eta$

We will try several choices of $\Delta\eta$

Omega to pion ratio (pure core)



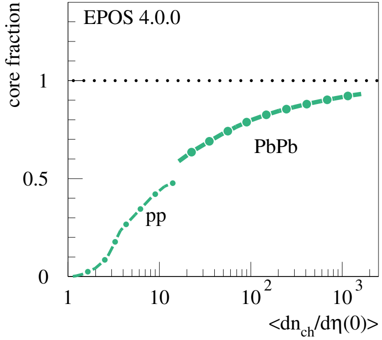
different choices of $\Delta\eta$

$\Delta\eta = \infty$: drops slightly

$\Delta\eta = 1.8$: drops quickly around $dn/d\eta = 10$

Full EPOS4, core + corona, hydro, microcanonical decay: checking multiplicity dependencies

Core fraction



Core: microcanonical

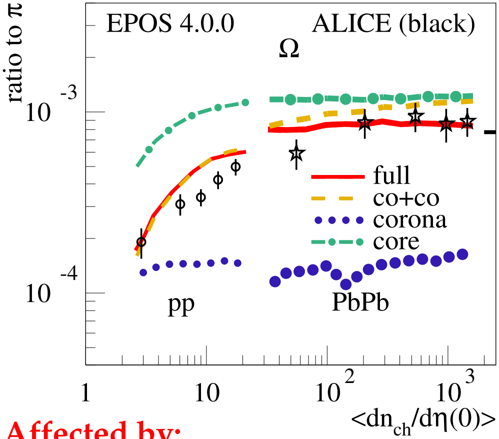
NEW FO concept
NEW numerical methods
used for pp and AA

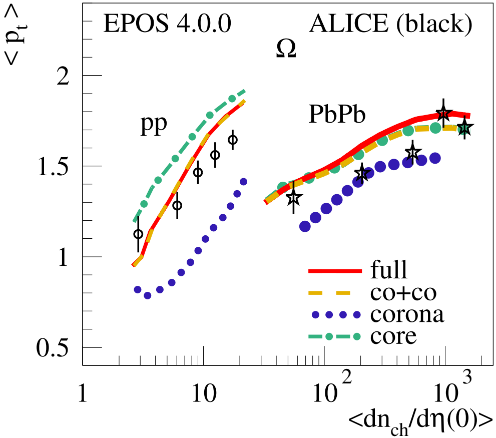
Microcanonical core alone does not work!
Check
in the following

- ☐ hadron to pion ratios
- ☐ mean pt

versus multiplicity
in core-corona approach

continuous curve **jump**





Affected by:

core-corona

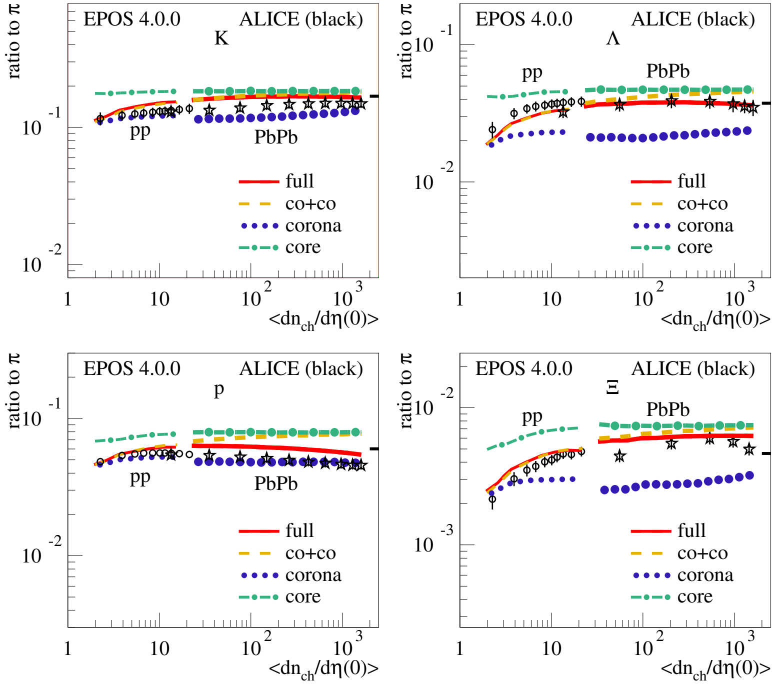
microcanonical

hadronic cascade (UrQMD)

saturation

flow

core-corona



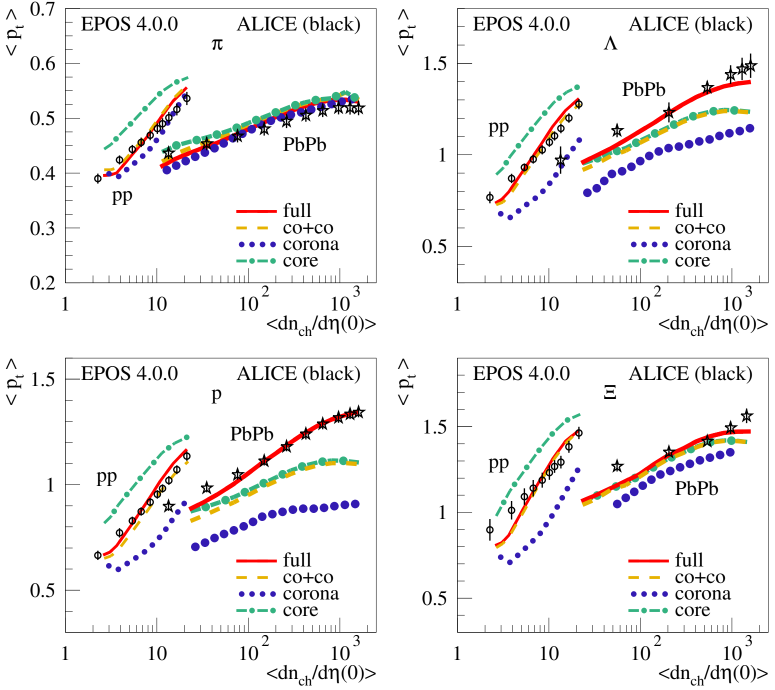
continuous curves

Affected by:

core-corona

microcanonical

hadronic cascade



discontinuities

curves affected by:

saturation

flow

core-corona

hadronic cascade

Multiplicity dependence of charm production

saturation and "hydro" effect

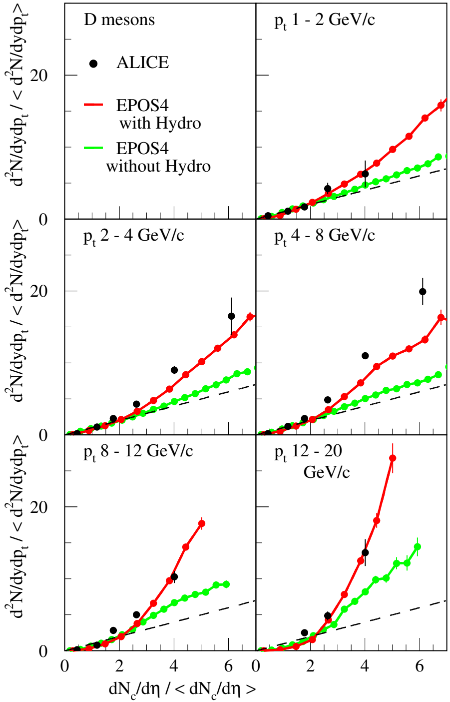
pp 7TeV

Self-normalized
***D* meson multiplicity**

for different transverse momentum ranges

versus self-normalized charged particle multiplity,

compared to ALICE data



To summarize:

- **EPOS4 (primary interactions) combines in a particular way** (finally free of contradictions)
  - **S-matrix approach with energy sharing**
  - **and pQCD** (specifying the Pomeron in terms of pQCD)
  - **by introducing saturation**
- **Secondary interactions** (using prehadrons from primary interactions)
  - **core-corona, hydro evolution**
  - **microcanonical decay** (major improvements)
- **Multiplity dependence of ratios and mean pt for pp and PbPb on the same plot: roughly OK**
  - **Continous curves for ratios**
  - **discontinuities for means pt**