WPCF-Resonance 2023 Workshop Catania

Resonance production with EPOS4 and the role of collectivity in elementary collisions

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Outline:

- ☐ **EPOS4 in the context of 50 years of pQCD**
- ☐ **Hadrons and resonances (p, Ξ, Ω, ϕ, K^{*0})**
  effect of core/corona and hadronic cascade

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 ($\sigma_{\mathrm{incl}}^{AB} = AB \times \sigma_{\mathrm{incl}}^{\mathrm{single\,Pom}}$)**
- ☐ **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 = pQCD parton ladder**
- **With energy sharing! (GR^+)**
  crucial for MC applications
- **Problem: violates AGK (and binary scaling)**

Solution: EPOS4 = GR^+ & pQCD & saturation

- **Take into account saturation in a very particular way**
- **Redefine link Pomeron <-> pQCD parton ladder**
- **Fully recovers AGK (and geometric properties which follow)**

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/2310.09380.pdf**
    (46 pages, systematic and complete presentation of the theoretical basis,
    combining S-matrix theory, pQCD, saturation,
    many proven statements)
  - ▷ **https://arxiv.org/pdf/2306.10277.pdf**
    (Microcanonical hadronization, core-corona in EPOS4)

☐ **EPOS4 general structure** (Possible at “high energies”)

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

▷ **Secondary scatterings (at t > 0)**
- core-corona procedure (New methods)
- hydro evolution [1]
- microcanonical decay (New)
- hadronic rescattering [2]

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[1]) I. Karpenko et al, Computer Physics Communications 185, 3016 (2014), K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys. Rev. C 89, 064903 (2014), 1312.1233,

[2]) S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 225 (1998), M. Bleicher et al., J. Phys. G25, 1859 (1999)

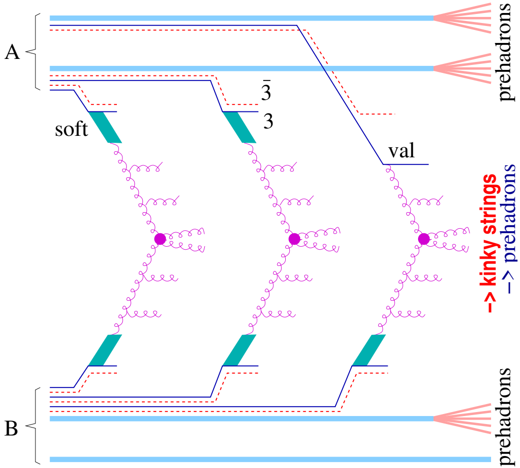
EPOS4: From Pomerons to prehadrons

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

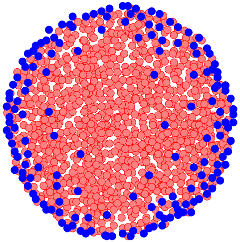
EPOS4: Core-corona separation

(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

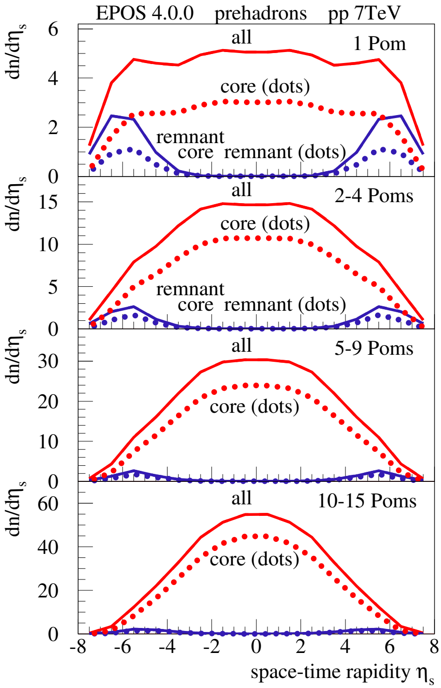
The corona prehadrons become simply hadrons and propagate with reduced energy

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 core (arXiv:2306.10277)
based on energy-momentum flow through hypersurface

- **Real hadronization (not transition fluid-particles)**
  (sudden statistical decay)
- **Energy-momentum and flavor conservation**
  (important for small systems)
- **Extremely fast**
  (major technical impovements in EPOS4)

Based on flow of momentum vector dP^{μ} and conserved charges dQ_A through the surface element $d\Sigma_{\mu}$ †

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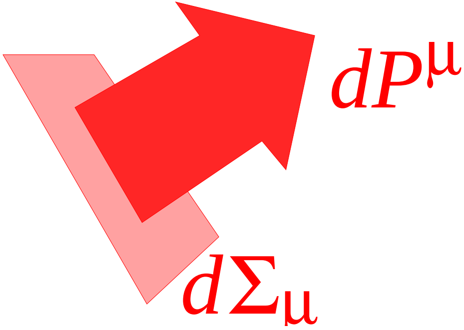
†) $d\Sigma_{\mu} = \varepsilon_{\mu\nu\kappa\lambda} \frac{\partial x^{\nu}}{\partial \tau} \frac{\partial x^{\kappa}}{\partial \varphi} \frac{\partial x^{\lambda}}{\partial \eta} \, d\tau \, d\varphi \, d\eta$

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

$$dP^{\mu} = T^{\mu\nu} d\Sigma_{\nu}$$
$$dQ_A = J_A^{\nu} d\Sigma_{\nu}$$

with conserved charges
$A \in \{C, B, S\}$



Construct an effective mass
by summing surface elements:
$M = \int_{\text{surface area}} dM,$

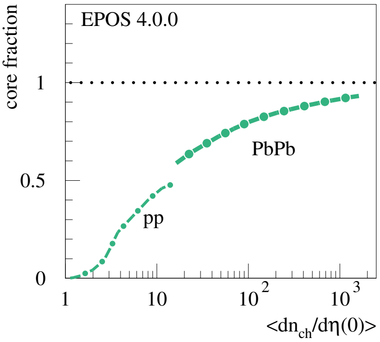
Decay M microcanonically

"give back" flow by placing particles on Σ following $dM/d\tau d\varphi d\eta$
and boosting them according to $U^{\mu}(\tau, \varphi, \eta) = dP^{\mu}/dM$

details: arXiv:2306.10277

Core + corona results - multiplicity dependencies

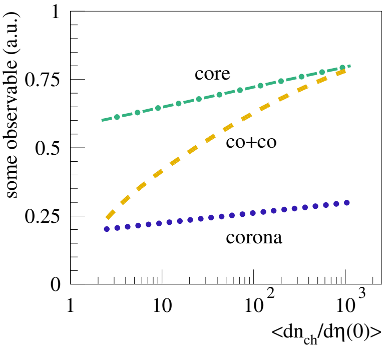
Core fraction



Almost continuous!

see DCCI2, Y. Kanakubo et al
Phys. Rev. C 105 (2022) 2, 024905

Core + corona (co+co) results (sketch)



Transition from corona core

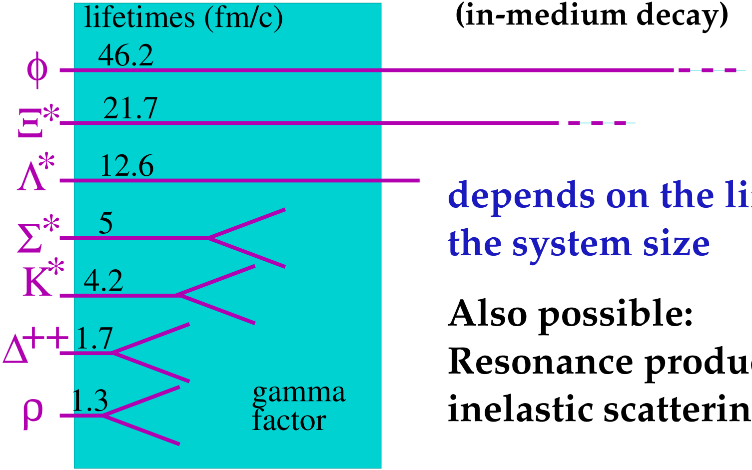
Attention ! Core and corona curve continuous ... or not (depends on variable)

On top: effects from hadronic cascade (UrQMD, S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 225 (1998), M. Bleicher et al., J. Phys. G25, 1859 (1999))

Results on resonance (hadron) production

resonances may be suppressed in the hadronic stage

(in-medium decay)

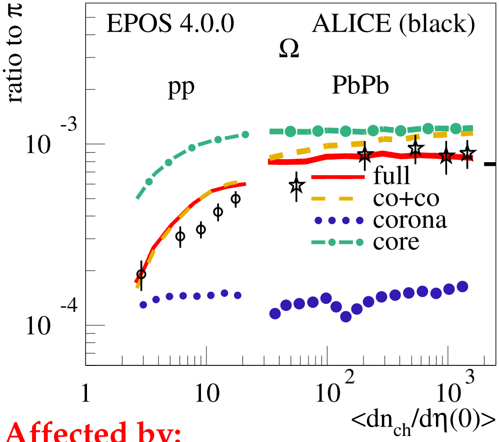


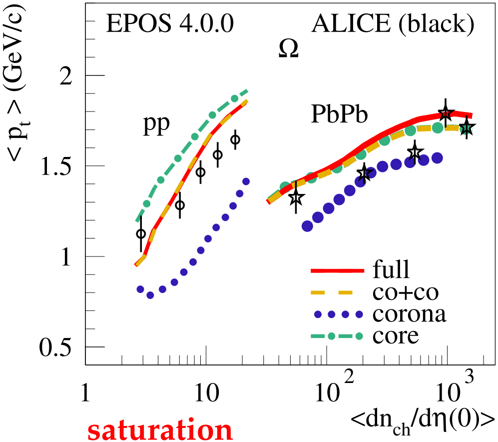
depends on the lifetime and the system size

Also possible:
Resonance production,
inelastic scattering

Core/corona very important

continuous curve **jump**





Affected by:

core-corona (very much)

microcanonical

hadronic cascade

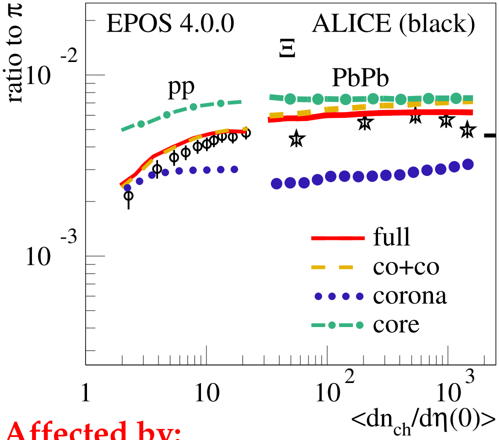
saturation

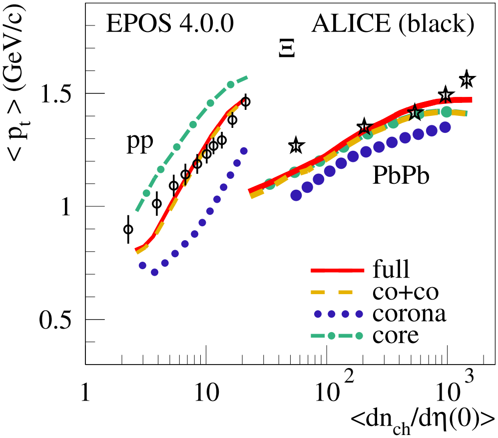
flow

core-corona

("full" means with UrQMD)

continuous curve **jump**





Affected by:

core-corona

microcanonical

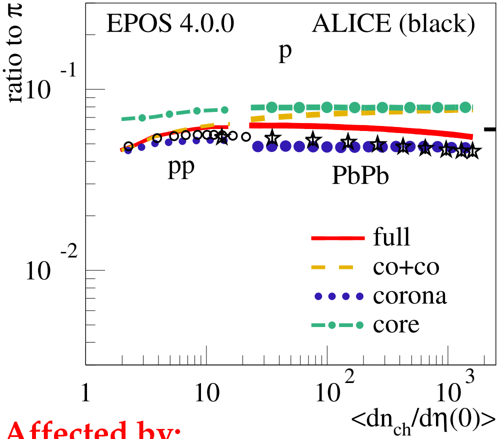
hadronic cascade

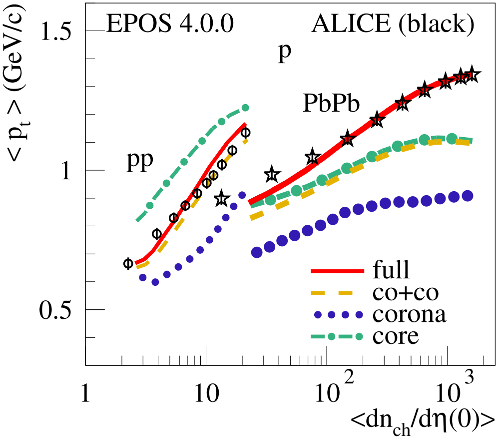
saturation

flow

core-corona

continuous curve **jump**





Affected by:

core-corona (somewhat)

microcanonical small effect

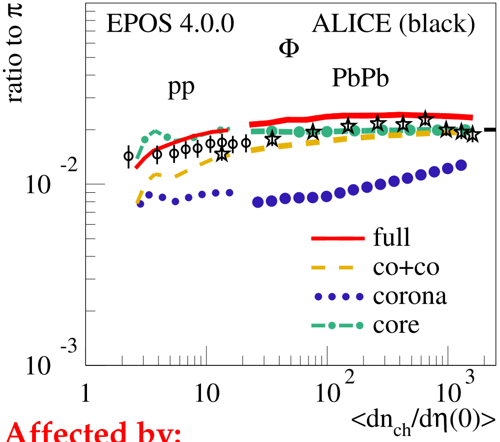
hadronic cascade

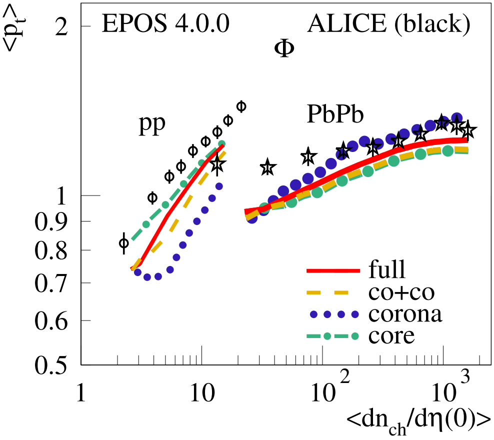
saturation, flow

core-corona

hadronic cascade (big effect)

continuous curve **jump**





Affected by:

core-corona

microcanonical small effect

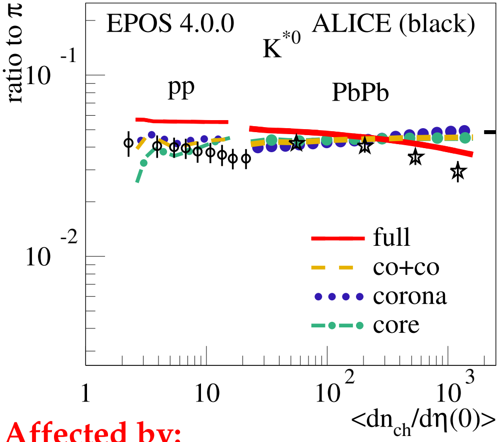
hadronic cascade, creation!!

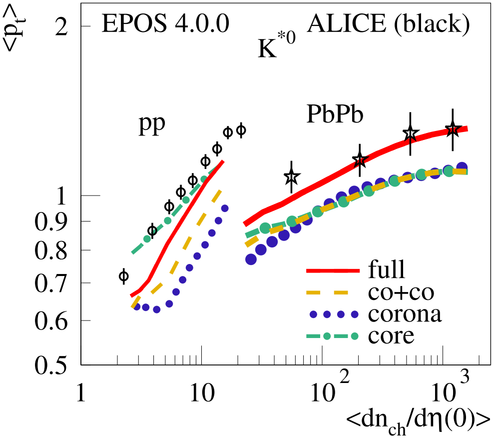
saturation

flow

PbPb: core < corona

continuous curve **jump**





Affected by:

core-corona little effect

microcanonical little effect

hadronic cascade, drop

saturation

flow

hadronic cascade, increase

To summarize:

- **EPOS4 (primary interactions) combines in a particular way** (finally free of contradictions)
  - **S-matrix approach with energy sharing (GR$^+$)**
  - **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** (new)
- **Resonance production: a wealth of information, allowing to disentangle and better understand the different ingredients**
  - **Core (Flow) => mini plasma in pp!!**
  - **Corona (Non-flow)**
  - **Hadronic cascade** **more resonances?**
  - **K^{*0} problem in pp** **contact me**