Workshop on the tuning of hadronic interaction models
Jan 22 – 25, 2024, University Wuppertal

EPOS4 overview

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EPOS4 is designed as a general purpose approach,
with conceptual problems of earlier EPOS versions being solved.

Presently, we focus on tests against a very large amount of data for many systems (pp, pA, AA) at many energies, to get an overall picture.

Concerning CR applications, there are still some technical "issues" to be considered.

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** (inclusive, hard)
  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**
  H.J. Drescher, M. Hladik, **Sergey Ostapchenko**, **Tanguy Pierog**, K. Werner **(2001)**

- ☐ **Using: Pomeron = pQCD parton ladder**

- ☐ **With energy sharing! (GR^+)**
  crucial for MC applications

- ☐ **Problem: violates AGK (and binary scaling and factorization)**

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)
  - ▷ paper on **EPOS4 results on RHIC BES**
    and paper on **EPOS4HQ** just submitted

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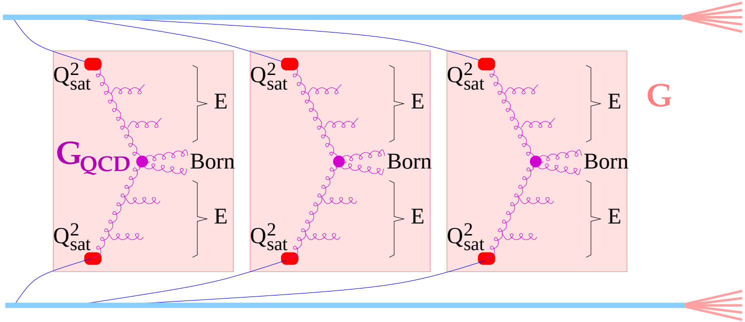
[1]) I. Karpenko et al, Computer Physics Communications 185, 3016 (2014), K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys. Rev. C 89, 064903 (2014), 1312.1233,

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

Primary scatterings: connecting GR$^+$ and pQCD

Expressing G in terms of G_{QCD}; $G = G_{\mathrm{QCD}}$ not working in case of energy sharing



G = imaginary part of T-matrix over s in impact parameter representation ("cut diagram")

Not trivial to recover AGK (->binary scaling, factorization)

solution : $$G(x) = \frac{1}{R_{\mathrm{deform}}(N_{\mathrm{conn}}, x)} \times G_{\mathrm{QCD}}(\, Q^2_{\mathrm{sat}}(N_{\mathrm{conn}}, x)\, ,\; x)$$

N_{conn} = number of Pomerons connected to same nucleons (in AA)

R_{deform} = modification of Pomeron's energy distribution ($x = s_{\mathrm{Pom}}/s$)

details: https://arxiv.org/pdf/2310.09380.pdf, **early work**: K. Werner, F.-M. Liu, and T. Pierog, Phys. Rev. C 74, 044902 (2006), K. Werner, B. Guiot, I. Karpenko, and T. Pierog, J. Phys. Conf. Ser. 458, 012020 (2013), T. Pierog and K. Werner, Acta Phys. Polon. Supp. 8, 1031 (2015).

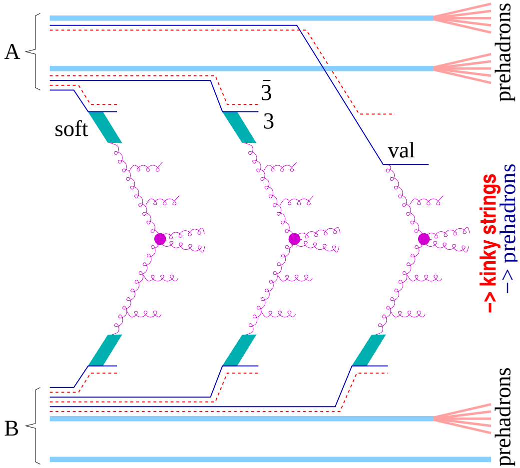
EPOS4: From Pomerons to prehadrons

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

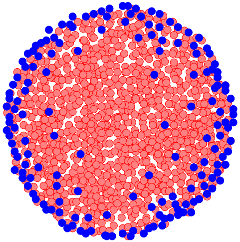
EPOS4: Core-corona separation

(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", which will be treated via hydrodynamics and decays eventually microcanonically (NEW)

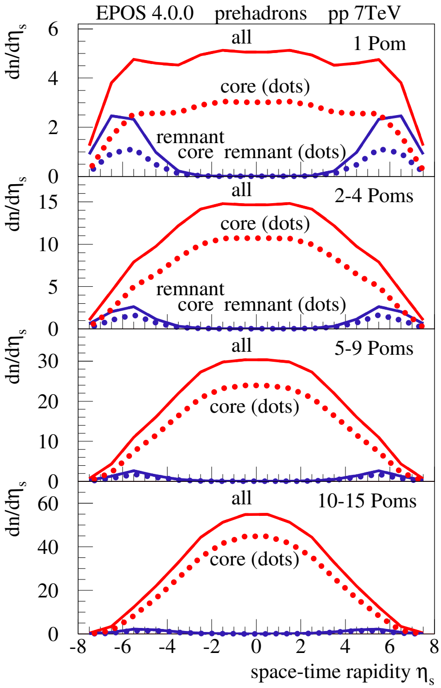
The corona prehadrons become simply hadrons and propagate with reduced energy

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 hypersurface element $d\Sigma_\mu$ †
(hypersurface Σ defined via constant energy density)

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

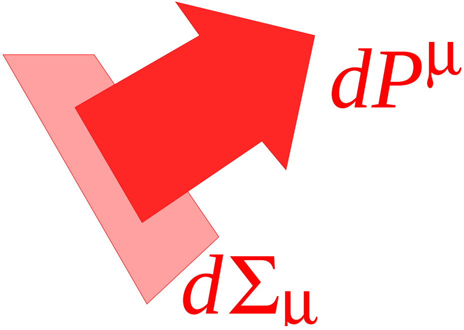
Surface: $x^0 = \tau \cosh \eta$, $x^1 = r \cos \varphi$,$x^2 = r \sin \varphi$, $x^3 = \tau \sinh \eta$, with $r = r(\tau, \varphi, \eta)$

$$dP^{\mu} = T^{\mu\nu} d\Sigma_{\nu}$$
$$dQ_A = J^{\nu}_{A} d\Sigma_{\nu}$$

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

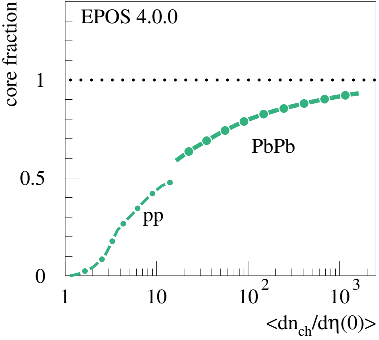


"give back" flow by placing particles on Σ following $dM/d\tau d\varphi d\eta$ and boosting them according to $U^{\mu}(\tau, \varphi, \eta) = dP^{\mu}/dM$

details: arXiv:2306.10277

Core + corona results - multiplicity dependencies

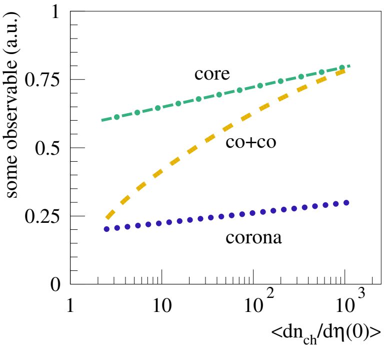
Core fraction



Almost continuous!

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

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



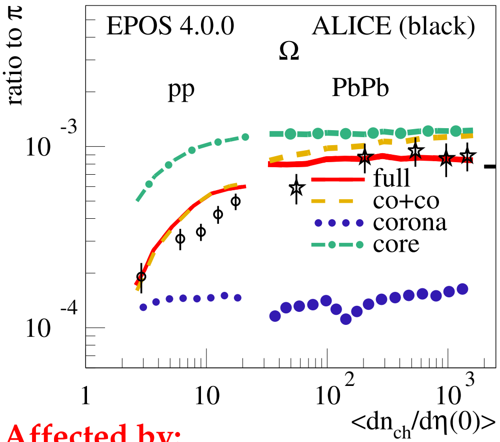
Transition from corona core

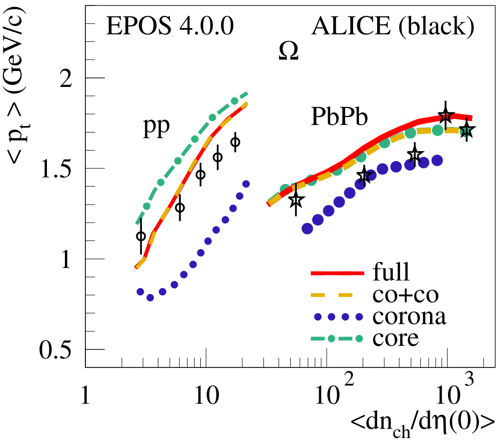
Attention ! Core and corona curve continuous ... or not (depends on variable)

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))

continuous curve

jump





Affected by:

core-corona

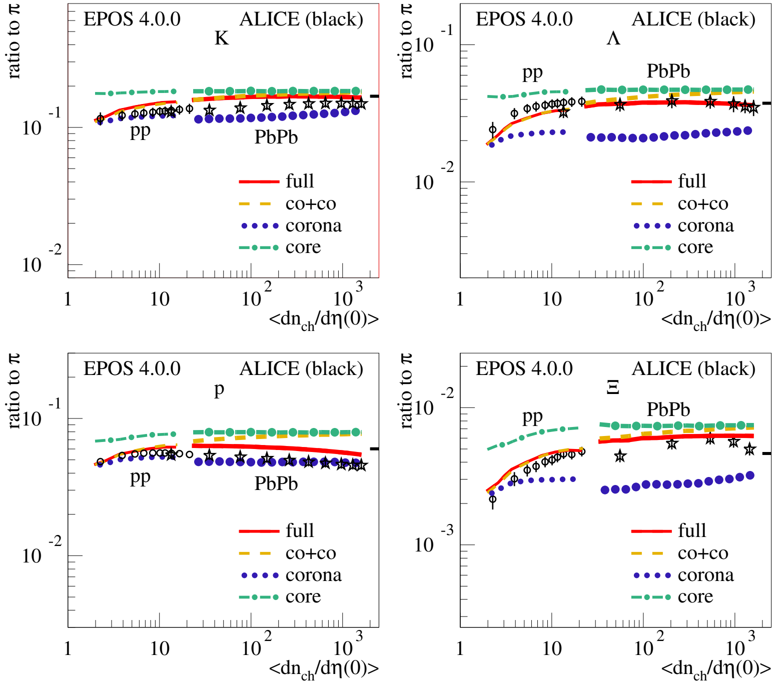
microcanonical

hadronic cascade (UrQMD)

saturation

flow

core-corona



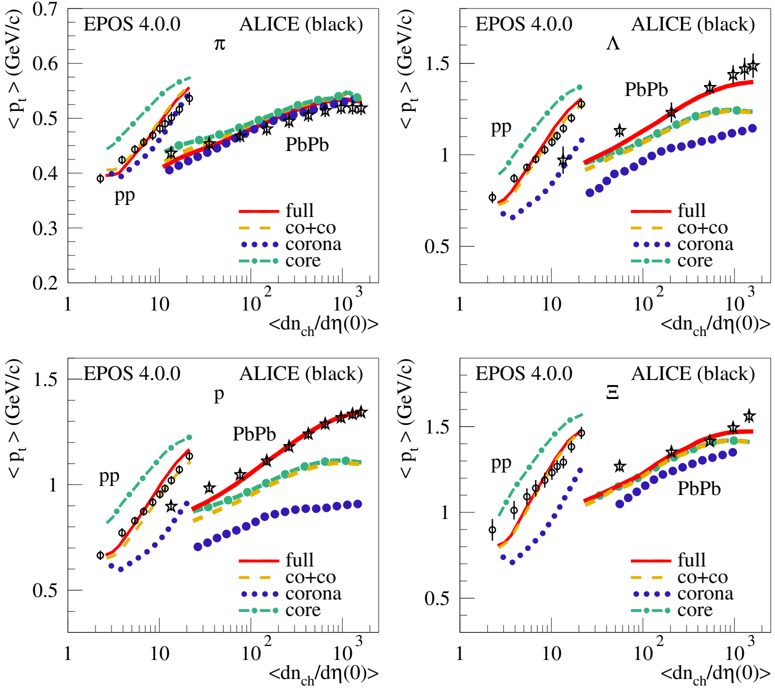
continuous curves

Affected by:

core-corona

microcanonical

hadronic cascade



discontinuities

curves affected by:

saturation

flow

core-corona

hadronic cascade

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** (in a very particular way)
- **Secondary interactions** (using prehadrons from primary interactions)
  - **core-corona, hydro evolution**
  - **microcanonical decay** (new)
- **Multiplicity dependencies: a wealth of information, allowing to disentangle and better understand different phenomena, as**
  - **Core-corona separation, radial flow, saturation effects, hadronic rescattering**
- **Possible CR applications: a fast version exists, PFE (parameterized fluid expansion), but there are still "technical issues".**