Exploring Quark-Gluon Plasma through soft and hard probes, 29-31 May 2023, Belgrade, Serbia

Low-pt and high-pt probes in the EPOS4 framework

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The EPOS4 project

- ☐ **NOT provide "another model" to study flow**
- ☐ **BUT a "complete" event generator**
  - ▷ **to do normal pp physics**
    (total cross section, light flavor spectra, jets, charm,...)
  - ▷ **which in addition accounts for collective effects in small systems**
  - ▷ **which in addition can handle nuclear scatterings from LHC to RHIC**

To check if we get a consistent overall picture

- **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

  - **a full general purpose approach, public, and testable**

  - **tested (by myself) for 4 GeV - 13000 GeV,**
    pp to PbPb, light / heavy flavor, collective / hard

- **Papers:**

  - **https://arxiv.org/pdf/2301.12517.pdf**
    will be updated from v1 to v2 very soon

  - **many more coming soon**
    checkout https://klaus.pages.in2p3.fr/epos4/physics/papers

☐ Work in progress:

▷ **EPOS4+HQ (heavy flavor)**

- basic observables (R_{AA}, v_2)

- charm flow in pp

- charmed baryon enhancement in pp

with Jiaxing Zhao, Jorg Aichelin, Pol-Bernard Gossiaux

▷ **EPOS4+JETS**

with Alexander Lind, Jorg Aichelin, Pol-Bernard Gossiaux, Iurii Karpenko, Damien Vintache

▷ **EPOS3+PHSD**

- hydro versus transport

with Mahbobeh Jafarpour, Elena Bratkovskaya, Vadym Voronyuk

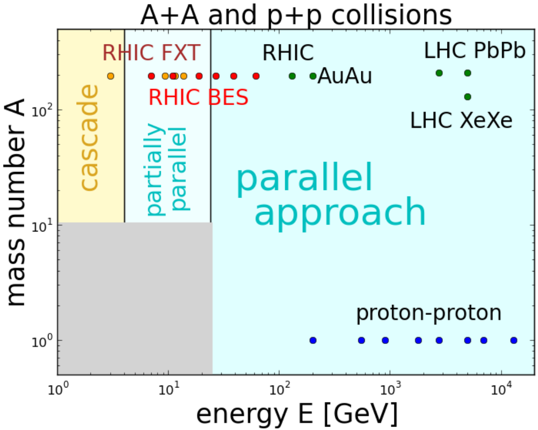
☐ EPOS4 general structure

▷ **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).

Parallel vs sequential scattering



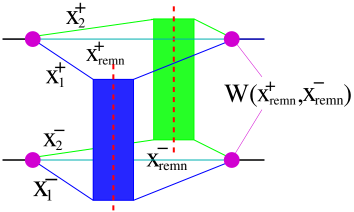
Points (besides FXT): Epos comparisons to data

From very elementary time scale arguments: parallel scheme needed everywhere beyond 25 AGeV, partly beyond 4AGeV

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

Very compact summary (details: https://arxiv.org/pdf/2301.12517.pdf)

- **Start: elastic scattering T-matrix T for pp scattering**
- **= product of "elementary" T-matrices** (parton-parton scatterings)
  pp->AA trivial: product of T-matrices per NN pair
- **Connection to inelastic:**
  optical theorem / cutting rules
  cross section = sum of products of
  "cut Pomerons"
- **cut Pomeron = squared**
  inelastic amplitude
  ends up as two
  (or more) **kinky strings**



two cut Pomerons
(QCD inside)

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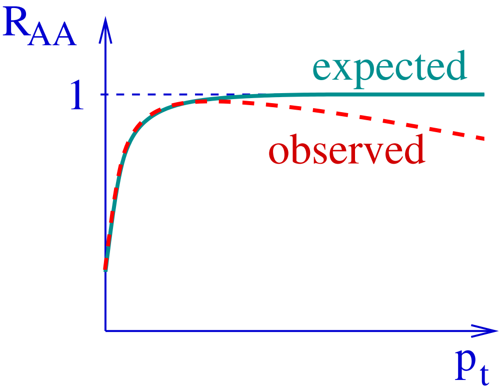
*) Relation S-matrix - T-matrix: $\mathbf{S}_{fi} = \delta_{fi} + i(2\pi)^4\delta(p_f - p_i)\mathbf{T}_{fi})$
$T = \mathcal{F}[\mathbf{T}_{ii}]/(2s)$ (Fourier transform w.r.t. to transv. momentum , depends on b)

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**
- **but without new (good) ideas this is not the case**
  (like in EPOS LHC)

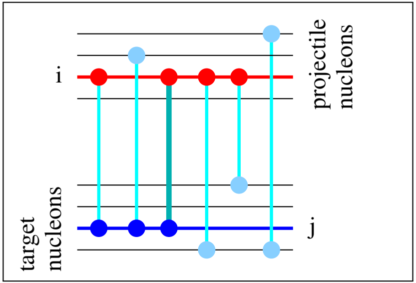


The problem is the energy sharing among Pomerons.

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 variable: the Pomeron's squared CMS energy fraction

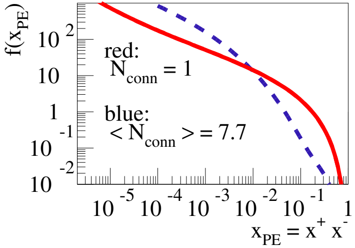
$$x_{\mathrm{PE}} = x^+ x^- \approx s_{\mathrm{Pom}} / s_{\mathrm{tot}}$$

x_{PE}-distribution $f(x_{\mathrm{PE}})$ determines p_t distributions of partons

The x_{PE} distributions $f(x_{\mathrm{PE}})$ depend on N_{conn}

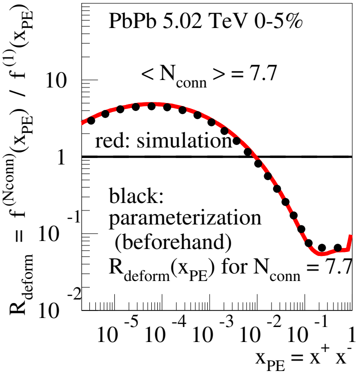
Large N_{conn} => large x_{PE} suppressed, small x_{PE} enhanced

We will use the notation $f^{(N_{\mathrm{conn}})}(x_{\mathrm{PE}})$



We define the "deformation" of $f^{(N_{\mathrm{conn}})}(x_{\mathrm{PE}})$ relative to the reference $f^{(1)}(x_{\mathrm{PE}})$

$$R_{\mathrm{deform}} = \frac{f^{(N_{\mathrm{conn}})}(x_{\mathrm{PE}})}{f^{(1)}(x_{\mathrm{PE}})}$$



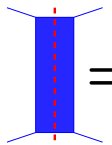
We are able to parameterize the "deformation" beforehand(!)
(iterative process, converges fast)
for all systems, all centrality classes

So R_{deform} can be considered to be known, it is tabulated.

We compute and tabulate $G_{\mathrm{QCD}}(Q^2, x^+, x^-, s, b)$, DGLAP parton ladder, with low virtuality cutoff Q^2 (=> G_{QCD} accessible via interpolation)

Now we can define the "box", called "cut Pomeron" and named $G(x^+, x^-, s, b)$

the crucial building block used in the multi-Pomeron expessions (pp,AA)



(and make the link with pQCD):

For each cut Pomeron, for given $x^{\pm}$, s, b, and N_{conn}, we postulate:

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

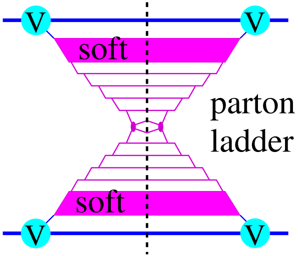
G does not depend on N_{conn}, Q_{sat}^2 depends on x^+, x^-, N_{conn}
(n is a normalization depending linearly on N_{conn})

which perfectly solves the "R_{AA} problem", the model can be used to study hight p_t and low p_t phenomena

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

EPOS4 factorization mode (1 Pom) and EPOS4 PDFs

Based on cut single Pomeron diagrams (composed of soft parts + parton ladder),



we may compute (and tabulate) PDFs, corresponding to half of the diagram

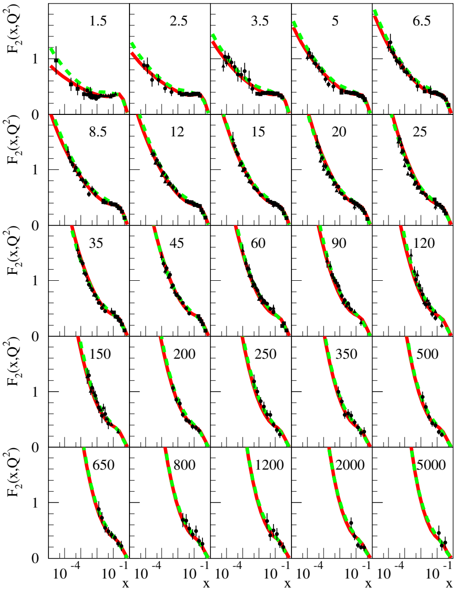
including Pomeron-nucleon coupling,
excuding the Born process

and then express the di-jet cross sections in terms of the PDFs

$$E_3 E_4 \frac{d^6\sigma_{\mathrm{dijet}}}{d^3p_3 d^3p_4} = \sum_{kl} \int\!\!\int dx_1 dx_2\, f^k_{\mathrm{PDF}}(x_1,\mu_F^2)\, f^l_{\mathrm{PDF}}(x_2,\mu_F^2)$$

$$\frac{1}{32 s \pi^2} \bar{\sum} |\mathcal{M}^{kl\to mn}|^2 \delta^4(p_1+p_2-p_3-p_4)$$

Electron-proton scattering F_2 vs x



To check our f_{PDF}, we can compute

$$F_2 = \sum_k e_k^2 \, x \, f_{\mathrm{PDF}}^k(x, Q^2)$$

with

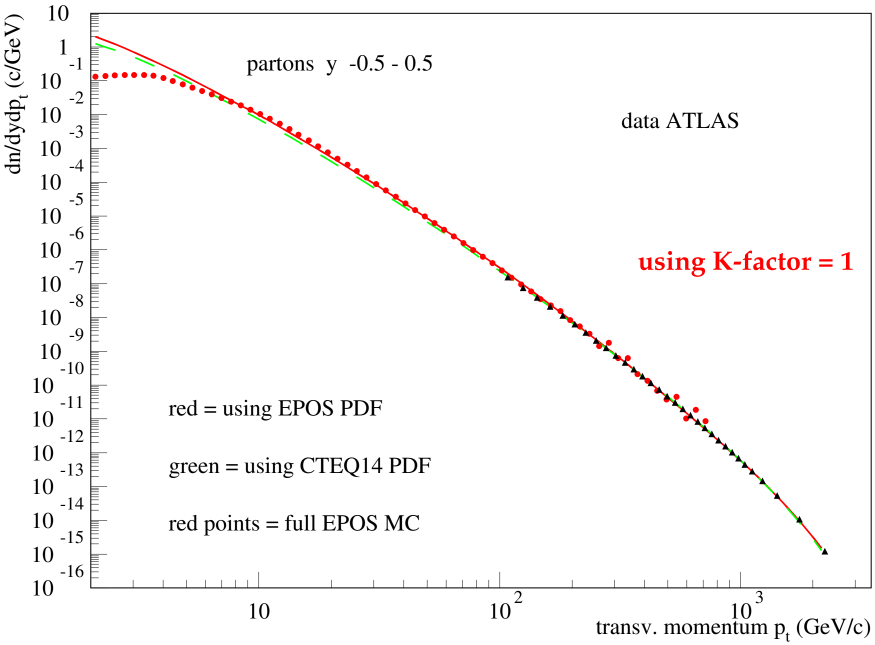
$$x = x_B = \frac{Q^2}{2pq}$$

in the EPOS framework,

and compare with data from ZEUS, H1

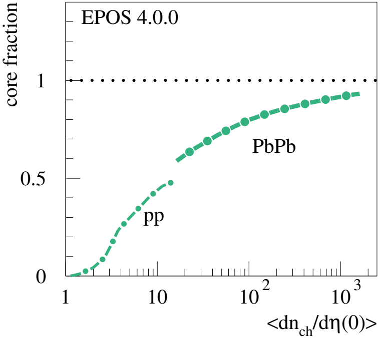
and with calculations based on CTEQ14(5f)

Jet cross section vs pt for pp at 13 TeV



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

Core fraction



Core: microcanonical

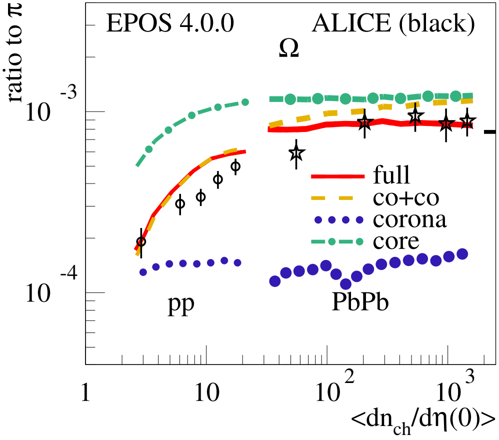
NEW FO concept
NEW numerical methods
used for pp and AA

Microcanonical core alone does not work!
Check
in the following

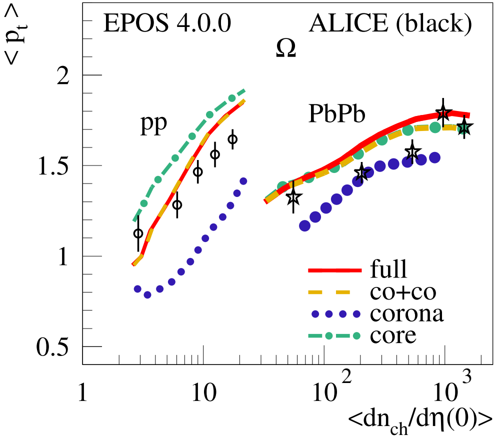
- ☐ **hadron to pion ratios**
- ☐ **mean pt**

versus multiplicity
in core-corona approach

continuous curve



jump



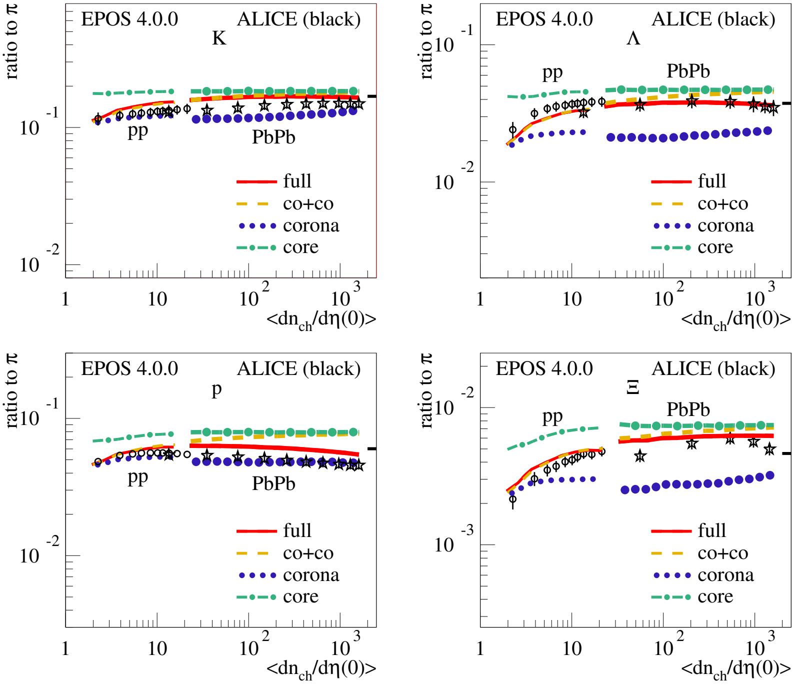
core-corona effect

+ microcanonical effect

core-corona effect

saturation effect

+ flow effect


EPOS 4.0.0
ALICE (black)
K
pp
PbPb
full
co+co
corona
core
ratio to π
<dn_ch/dη(0)>
Λ
p
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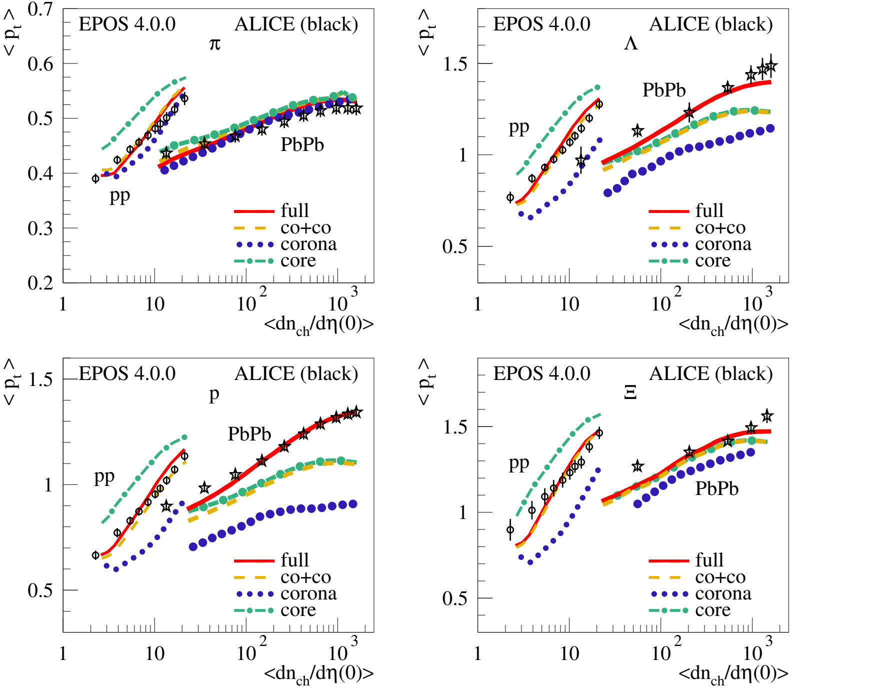

EPOS 4.0.0
ALICE (black)
π
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EPOS 4.0.0
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EPOS 4.0.0
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Ξ
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Multiplicity dependence of charm production

saturation and flow effect

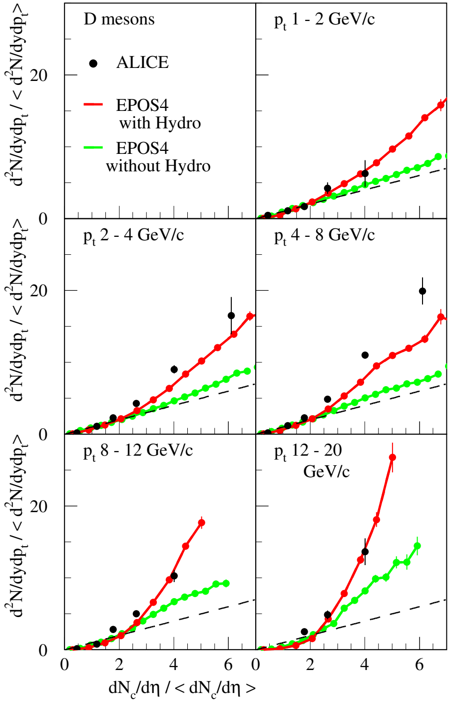
pp 7TeV

Self-normalized *D* meson multiplicity

for different transverse momentum ranges

versus self-normalized charged particle multiplity,

compared to ALICE data



To summarize:

EPOS4 allows (for the first time!) to accommodate simultaneously

Energy conservation + Parallel scattering + factOrization + Saturation

Now we can do in one single (“general purpose”**) approach**

- **“normal” pp physics (high pt jets etc) (where factorization comes into play)**
- **high multiplicity pp events (where saturation plays a crucial role)**
- **AA scattering at LHC and RHIC**

https://indico.ihep.ac.cn/event/19061/attachments/67272/80883/04_Wenrner_0404.pdf
https://1drv.ms/v/s!AlNBqFZ7zFxojXnwBcsy_6qkBiwk?e=4JDsa6