Rencontres QGP France 2023, 26-29/6, 2023
Bagnoles de l'Orne

EPOS4 Overview

& comparison with Pythia/Angantyr

(General Purpose MCs for pp and AA scattering)

K. Werner

SUBATECH, Nantes University – IN2P3/CNRS – IMT Atlantique

Nantes, France

EPOS4

- ☐ **NOT provide "another model" to study flow**

- ☐ **BUT a "complete" (general purpose) 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/
  - **tested for 4 GeV - 13000 GeV,**
    pp to PbPb, light / heavy flavor, collective / hard
- **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** (Hadronization in EPOS4)
- **Papers to come**
  - **Heavy ions collisions from 5TeV down to 4 GeV**
    - understand disappearance of fluid component
    with Maria Stefaniak, Johannès Jahan, Damien Vintache,...

- ▷ **Susceptibilities of conserved quantities in HIC at RHIC**
  with Johannès Jahan
- ▷ **EPOS4 and Rivet analyses**
  with Johannès Jahan, Damien Vintache

☐ **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

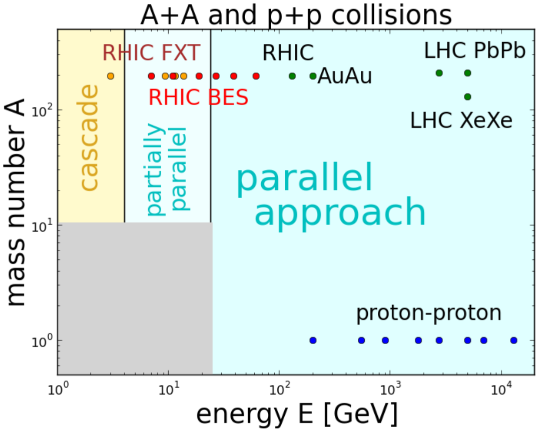
□ EPOS4 general structure

- ▷ **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



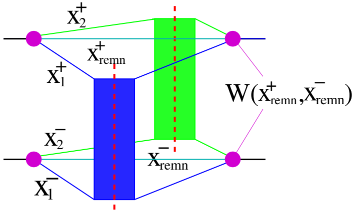
Points (besides FXT): Epos comparisons to data

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: arXiv:2301.12517)

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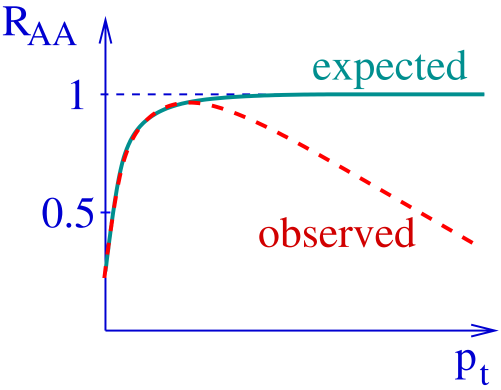
*) Relation S-matrix - T-matrix: $\mathbf{S}_{fi} = \delta_{fi} + i(2\pi)^4\delta(p_f - p_i)\mathbf{T}_{fi})$
$T = \mathcal{F}[\mathbf{T}_{ii}]/(2s)$ (Fourier transform w.r.t. to transv. momentum , depends on b)

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)

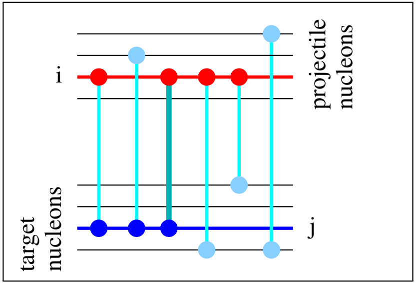


The problem is the energy sharing among Pomerons.

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

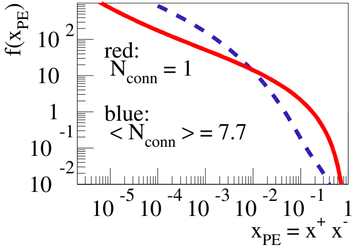
$$x_{\mathrm{PE}} = x^{+}x^{-} \approx s_{\mathrm{Pom}} / s_{\mathrm{tot}}$$

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}

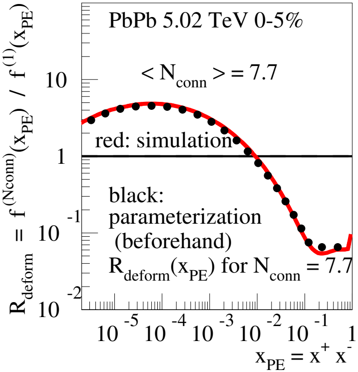
Large N_{conn} => large x_{PE} suppressed, small x_{PE} enhanced

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 $f^{(1)}(x_{\mathrm{PE}})$

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



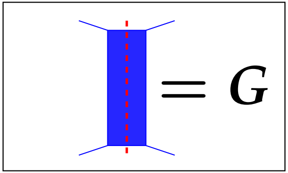
We are able to parameterize the "deformation" beforehand(!)
(iterative process, converges fast)
for all systems, all centrality classes

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 (see arXiv:2306.02396)

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; we recover factorization (generalized Abramovskii Gribov Kancheli cancellations).

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

The model can be used to study hight p_t and low p_t phenomena.

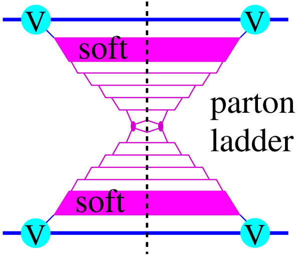
EPOS4 factorization mode (1 Pom) and EPOS4 PDFs

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

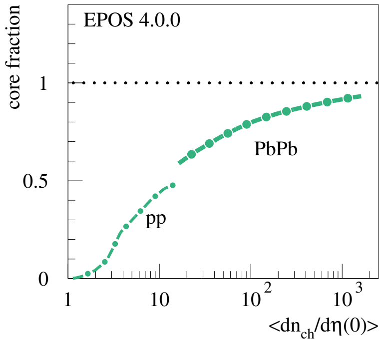
$$E_3E_4\frac{d^6\sigma_{\mathrm{dijet}}}{d^3p_3d^3p_4}=\sum_{kl}\int\!\!\int dx_1dx_2\,f^k_{\mathrm{PDF}}(x_1,\mu_F^2)\,f^l_{\mathrm{PDF}}(x_2,\mu_F^2)$$
$$\frac{1}{32s\pi^2}\bar{\sum}|\mathcal{M}^{kl\to mn}|^2\delta^4(p_1+p_2-p_3-p_4)$$

Almost identical to CTEQ14(5f)

(arXiv:2301.12517: F_2 in ep (HERA) and jet cross sections in pp at 13 TeV)

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

Core fraction



Core: microcanonical

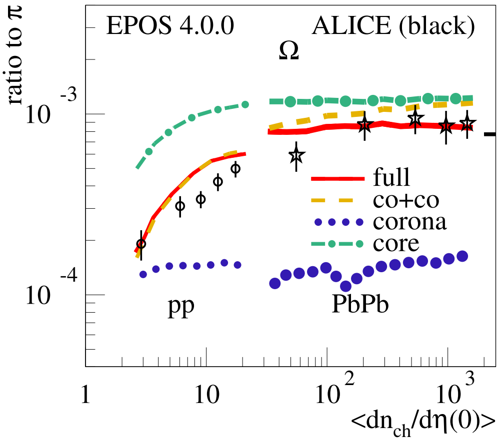
NEW FO concept
NEW numerical methods
used for pp and AA

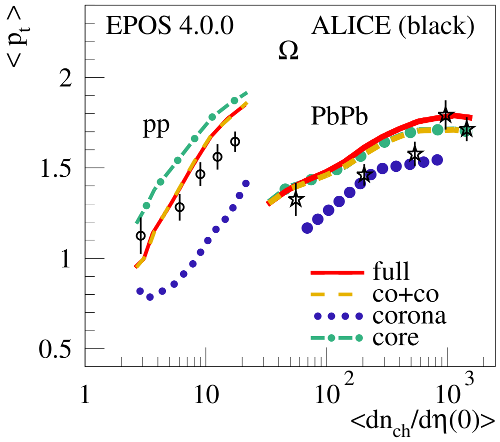
Microcanonical core alone does not work!
Check
in the following

- ☐ hadron to pion ratios
- ☐ mean pt

versus multiplicity
in core-corona approach

continuous curve **jump**





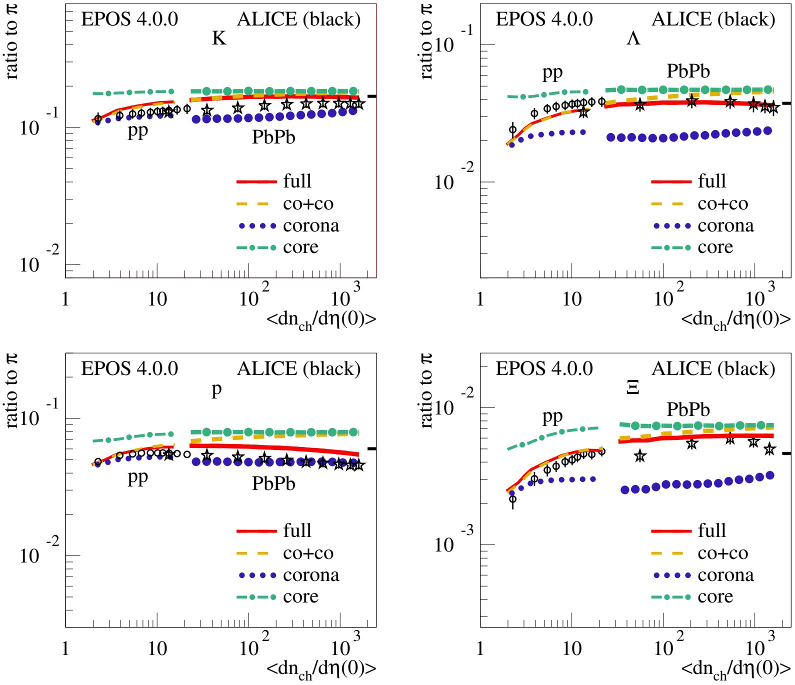
core-corona effect

+ 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)>
EPOS 4.0.0
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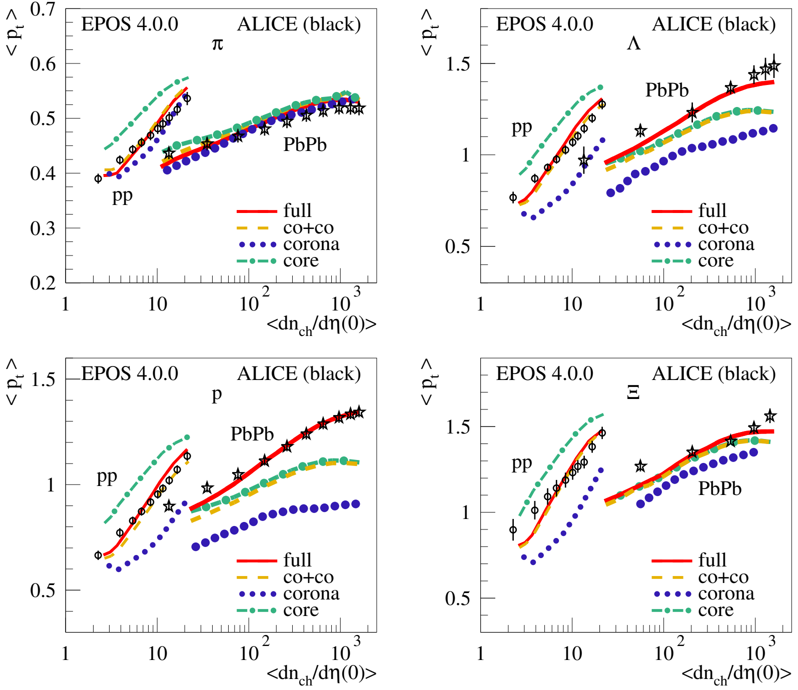
EPOS 4.0.0
ALICE (black)
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Multiplicity dependence of charm production

saturation and flow effect

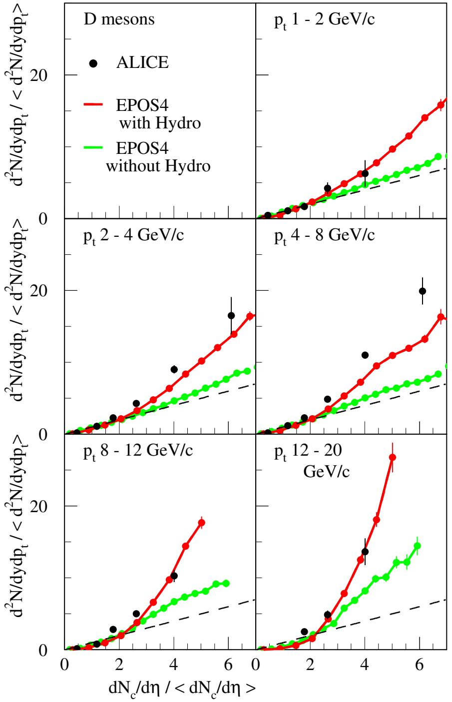
pp 7TeV

Self-normalized *D* meson multiplicity

for different transverse momentum ranges

versus self-normalized charged particle multiplity,

compared to ALICE data



Angantyr

- **Papers** (proposed by Christian Bierlich)
  - ▷ **arXiv:1806.10820 JHEP 10 (2018) 134**
  - ▷ **arXiv:2205.11170 Phys.Lett.B 835 (2022) 137571**

- **Authors**
  - ▷ **Christian Bierlich, Smita Chakraborty, Gösta Gustafson, Leif Lönnblad, Harsh Shah**

- **General structure**
  - ▷ **Basic AA model**
    S-matrix theory (Glauber formalism)
    => independent sub-processes
  - ▷ **String interactions / rescattering**
    - rope model
    - to come: combining ropes with shoving & hadronic cascade

Basic AA model (Glauber model)

- **Elastic scattering S-matrix**

$$S^{AB}(b) = \prod_{i=1}^{A} \prod_{j=1}^{B} S^{ij}(b_j + b - b_i), \quad T^{ij} = 1 - S^{ij}$$

$$\frac{d\sigma_{\mathrm{tot}}^{ij}(b)}{d^2b} = 2T^{ij}, \quad \frac{d\sigma_{\mathrm{abs}}^{ij}(b)}{d^2b} = 2T^{ij} - \left(T^{ij}\right)^2$$

- **Sub-T-matrix** - including nucleon size fluctuations $P(r) \propto r^{k-1} \exp(-r/r_0)$

$$T^{ij} = T(b^{ij}, r_p, r_t) \propto \Theta\left(\sqrt{\frac{(r_p + r_t)^2}{2T_0}} - b^{ij}\right)$$

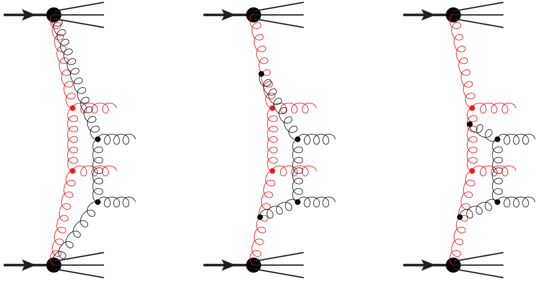
opacity : $T_0 = (1 - e^{-\pi(r_p+r_t)^2/\sigma_t})^\alpha$

No energy-momentum arguments! Independent sub-processes

- **For each pair, probability for absorptive interaction $2T^{ij} - (T^{ij})^2$**
  Two states to distinguish between absorptively and diffractively wounded wounded nucleons.

- **MPI: sub-collisions treated as separate QCD $2 \rightarrow 2$ scatterings**
  Parton densities rescaled according to an overlap function assuming some matter distribution in the colliding protons

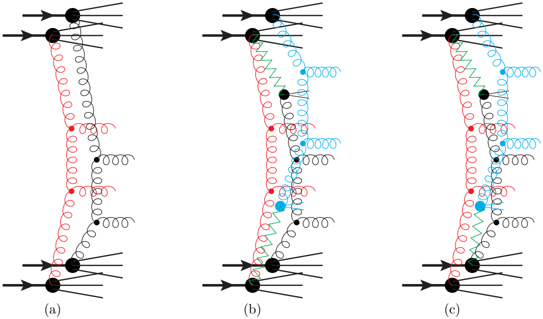
- **Event with two sub-scatterings of type $gg \rightarrow gg$**
  Choice (a) gives wrong multiplicity dependence of mean pt


(a) (b) (c)

Better: additional sub-scatterings colour connected to partons in previous sub-scatterings (b) and (c)

EPOS4: choice (a) + saturation scale

- **AA scattering: two types of NN scatterings**
  - primary in case of not-yet-wounded nucleons (a)
  - secondary in case of already-wounded nucleons (b,c)



Primary: normal PYTHIA MPI scattering

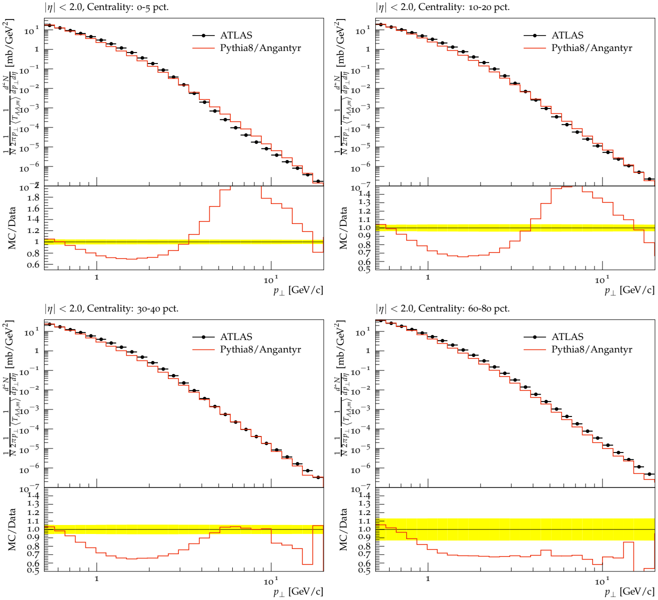
Secondary: diffractive PYTHIA scattering

= IP-N scattering
Pomeron IP = zigzag

EPOS4: same amplitude for wounded / unwounded compensated by "dynamical saturation scale"

- **Interactions ordered wrt increasing NN impact parameter**
- **then treat NN scattering one after the other**
  Several iterations: first absorptive scatterings, primary; second iteration to treat secondary scatterings. If not enough energy, redo / skip

pt distributions charged ptls PbPb 2.76 TeV, different centralities



Very small v2 (no string interactions)

String interactions, rope model

arXiv:2205.11170

- **Adding overlapping string pieces as random walk in color space: add triplet ($q-\bar{q}$) to multiplet an and chose randomly according to nr of states**

$$\{p,q\} \oplus \{1,0\} = \begin{cases} \{p+1,q\} \\ \{p,q-1\} \\ \{p-1,q+1\} \end{cases}$$

- **Breakup one string at the time, string tension:**

$$\kappa_{\mathrm{eff}} = \kappa_{\{p,q\}} - \kappa_{\{p-1,q\}}, \quad \frac{\kappa^{\{p,q\}}}{\kappa^{\{1,0\}}} = \frac{(p^2+pq+q^2+3p+3q)/3}{4/3}$$

(ratio of Casimir operators)

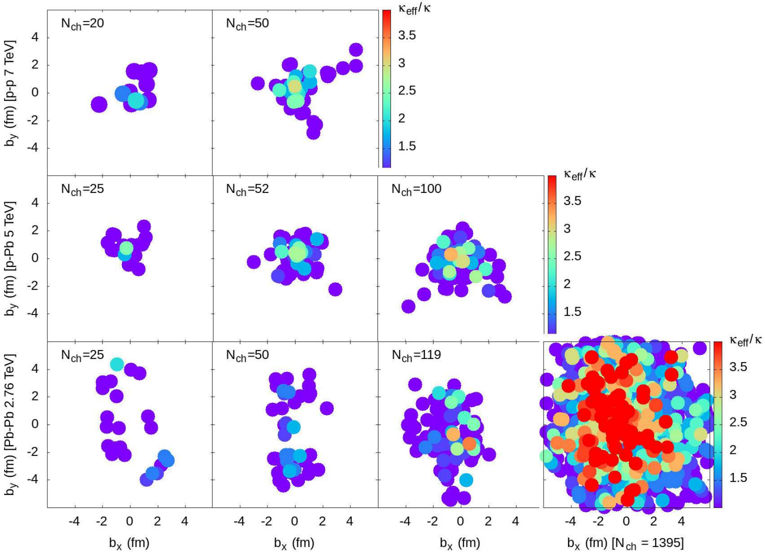
Production points of primary hadrons in impact parameter space

Colored points: κ_{eff}

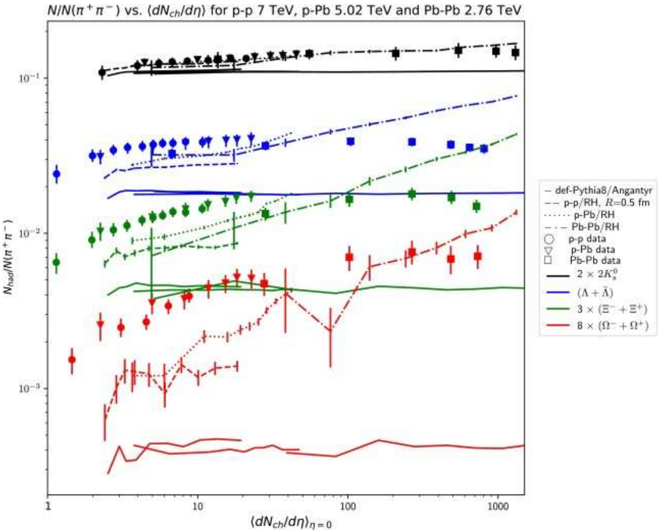
pp 7TeV

pPb 5TeV

PbPb 2.76TeV



Strangeness enhancement, effect of rope picture



arXiv:2205.11170

Still missing:

Repulsion between overlapping strings (shoving)

Hadronic rescattering (at an early stage)

To summarize:

EPOS4 and Angantyr are conceptually fundamentally different.

- ☐ **EPOS: NN collisions strictly parallel, all equal, dynamical saturation scale needed, core-corona, core=hydro**
- ☐ **Angantyr: NN collisons "sequential", wounded nucleons interact diffractively, rope mechanism (+ shoving)**

Who is right? Or ar they (at the end) the same?
(like shoving = hydro etc)

- ☐ **Looking at strangeness enhancement for pp,pA, AA is good**
- ☐ **Looking in addition at <pt> vs multiplicity for pp, pA, AA is better**
- ☐ **Defining a large set of crucial observables (including older ones), at RHIC and LHC, and making systematic comparisons, is needed**