

Initial Stages 2023, 19-23/6, 2023, Copenhagen, Denmark

Recent developments of Monte Carlo Models

EPOS4 and Angantyr

(General Purpose MCs for pp and AA scattering)

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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>
 - ▷ <https://arxiv.org/pdf/2306.02396.pdf> ...

 - **Work in progress:**
 - ▷ **EPOS4+HQ (heavy flavor)**
 - basic observables (R_{AA} , v_2)
 - charm flow in pp
 - charmed baryon enhancement in pp
- with Jiaying Zhao, Jorg Aichelin, Pol-Bernard Gossiaux

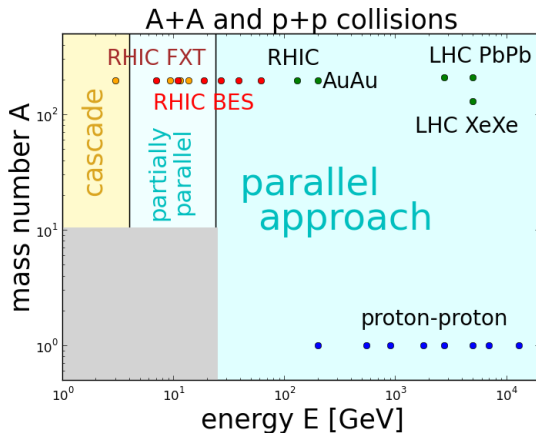
□ EPOS4 general structure

- ▷ **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



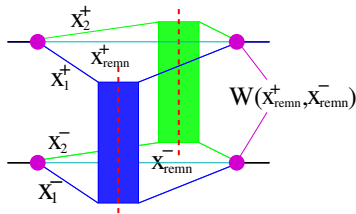
Points
(besides FXT):
Epos
comparisons
to data

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

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)

*) Relation S-matrix - T-matrix: $S_{fi} = \delta_{fi} + i(2\pi)^4 \delta(p_f - p_i) T_{fi}$

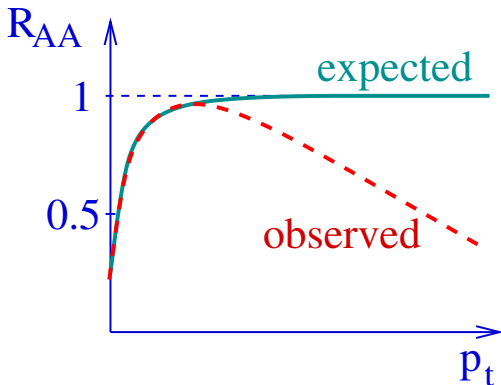
$T = \mathcal{F}[T_{ii}]/(2s)$ (Fourier transform w.r.t. to transv. momentum, depends on b)

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.

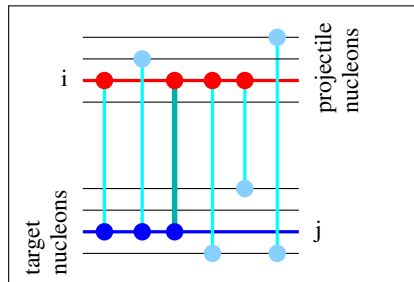
For a given Pomeron, connecting
projectile nucleon i and
target nucleon j

define:

$$N_{\text{conn}} = \frac{N_P + N_T}{2}$$

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

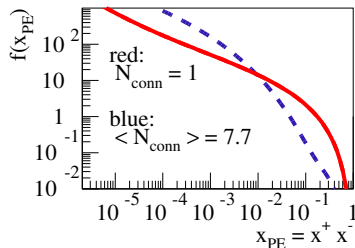
$$x_{\text{PE}} = x^+ x^- \approx s_{\text{Pom}} / s_{\text{tot}}$$

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

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

Large $N_{\text{conn}} \Rightarrow$ large x_{PE} suppressed
small x_{PE} enhanced

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



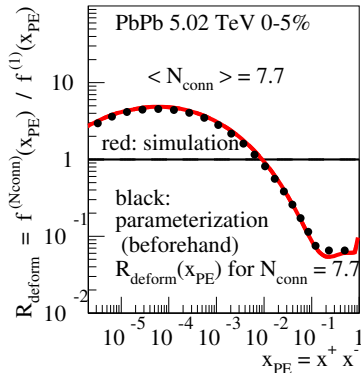
We define the “deformation” of $f^{(N_{\text{conn}})}(x_{\text{PE}})$ relative to the reference $f^{(1)}(x_{\text{PE}})$

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

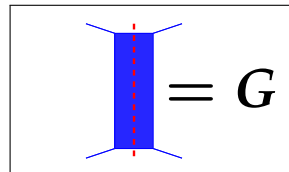
We are able to parameterize the “deformation” beforehand(!) (iterative process, converges fast) for all systems, all centrality classes

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

We compute and tabulate $G_{\text{QCD}}(Q^2, x^+, x^-, s, b)$, 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 expressions (pp,AA)



(and make the link with pQCD):

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

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

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

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

For large N_{conn} , low p_t is suppressed, the Pomeron gets “hard”.

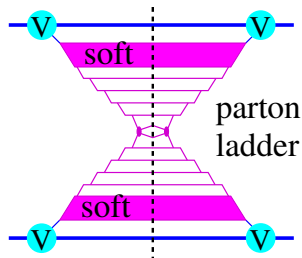
EPOS4 factorization mode (1 Pom) and EPOS4 PDFs

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,
excluding the Born process

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



$$E_3 E_4 \frac{d^6 \sigma_{\text{dijet}}}{d^3 p_3 d^3 p_4} = \sum_{kl} \int \int dx_1 dx_2 f_{\text{PDF}}^k(x_1, \mu_F^2) f_{\text{PDF}}^l(x_2, \mu_F^2)$$

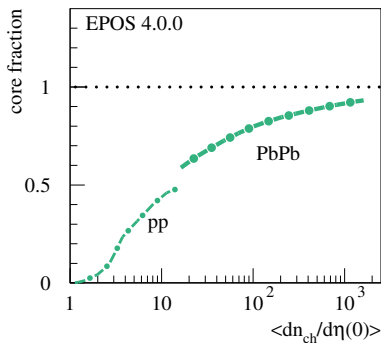
$$\frac{1}{32s\pi^2} \sum_{\bar{}} |\mathcal{M}^{kl \rightarrow mn}|^2 \delta^4(p_1 + p_2 - p_3 - p_4)$$

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

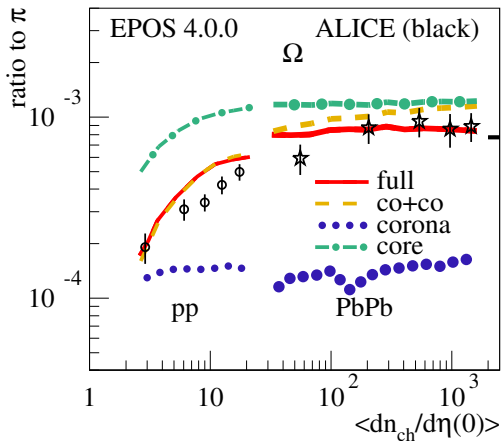
Microcanonical core alone does not work!

Check
 in the following

- hadron to pion ratios
- mean pt

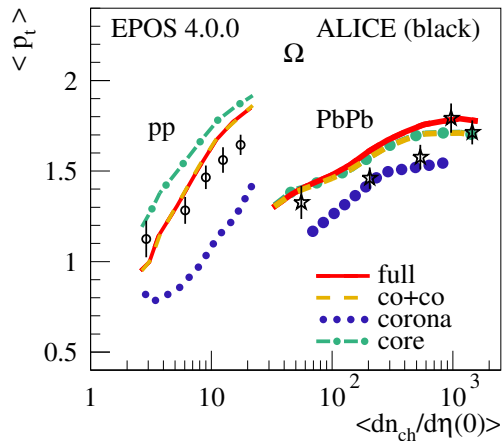
versus multiplicity
 in core-corona
 approach

continuous curve

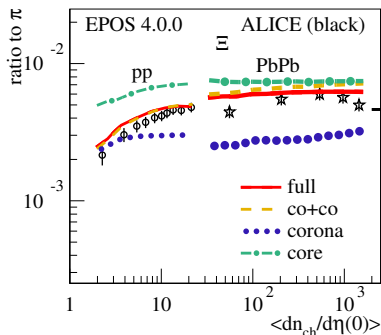
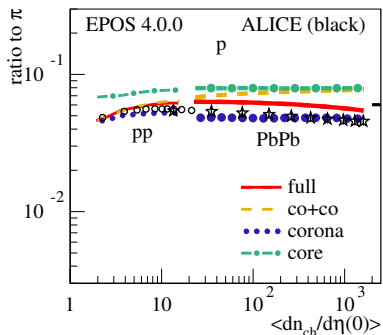
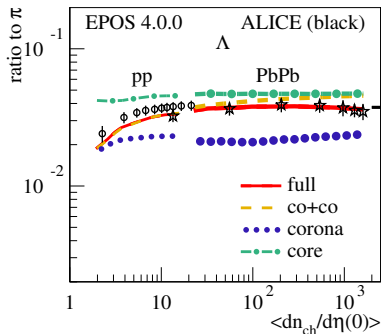
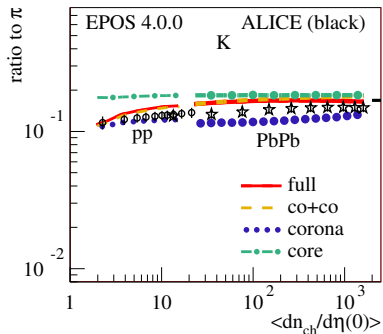


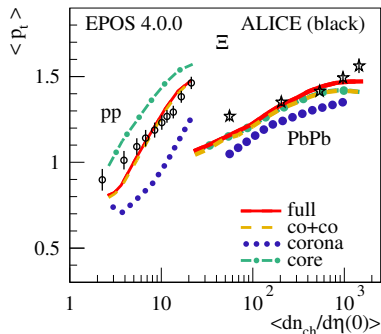
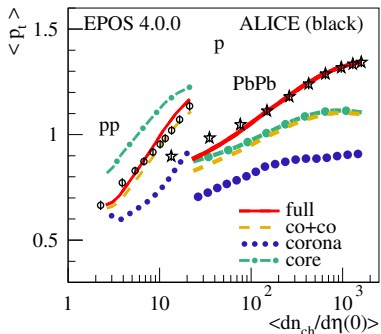
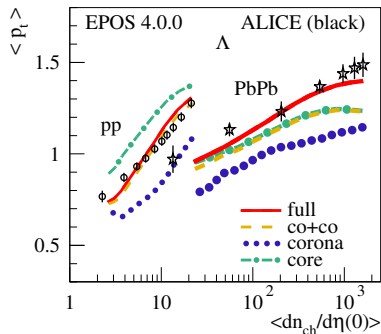
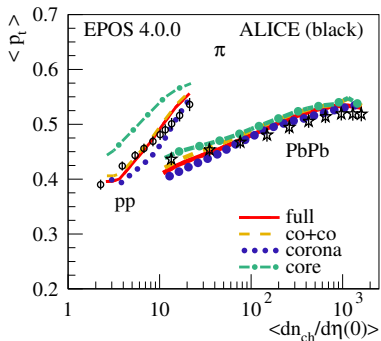
core-corona effect
+ microcanonical effect

jump



core-corona effect
saturation effect
+ flow effect





Multiplicity dependence of charm production

saturation and flow effect

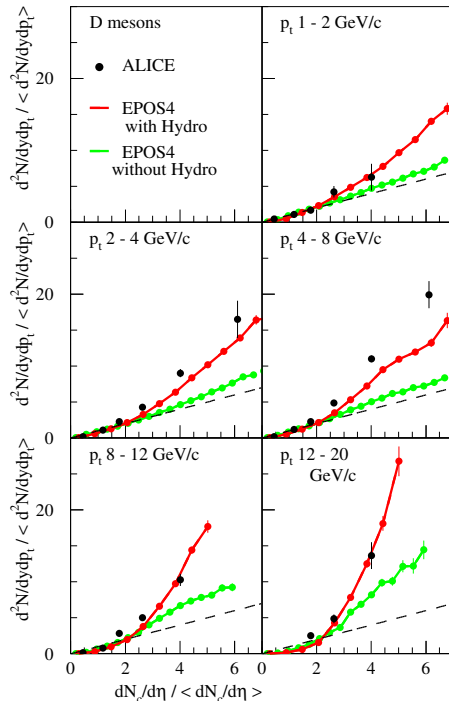
pp 7TeV

Self-normalized D meson
multiplicity

for different transverse
momentum ranges

versus self-normalized charged
particle multiplicity,

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

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

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

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

$$T^{ij} = T(b^{ij}, r_p, r_t) \propto \Theta \left(\sqrt{\frac{(r_p + r_t)^2}{2T_0}} - b^{ij} \right) \quad \text{opacity :} \\ T_0 = (1 - e^{-\pi(r_p + r_t)^2 / \sigma_t})^\alpha$$

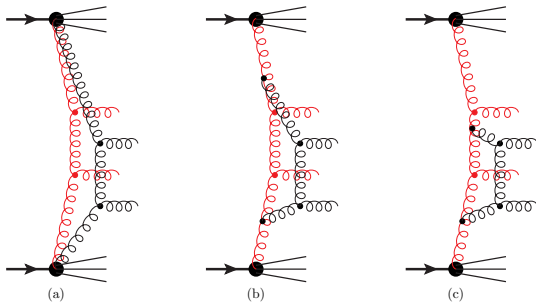
No energy-momentum arguments! Independent sub-processes

- 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

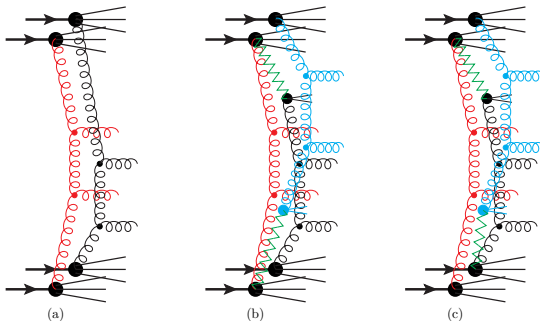
- **Event with two sub-scatterings of type $gg \rightarrow gg$**
Choice (a) gives wrong multiplicity dependence of mean p_t



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

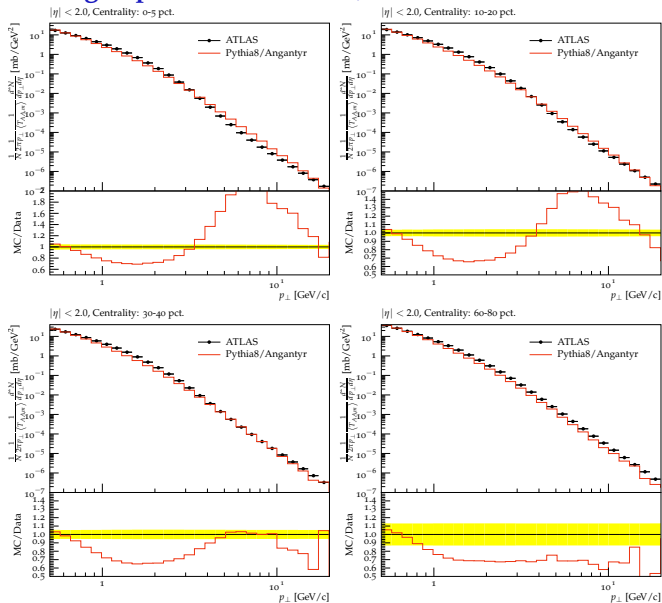
= IP-N scattering
Pomeron IP = zigzag

**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 v_2 (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 n and chose randomly according to nr of states

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

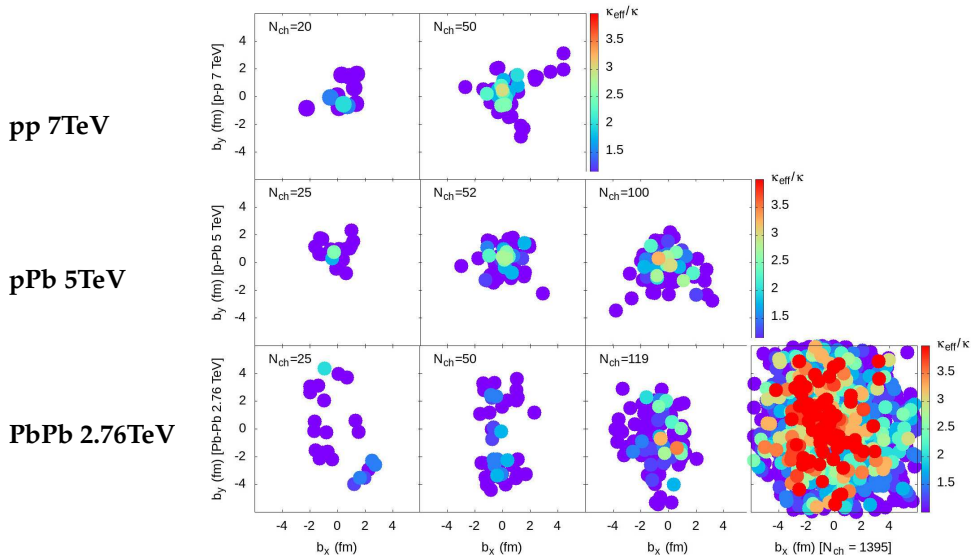
- Breakup one string at the time, string tension:

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

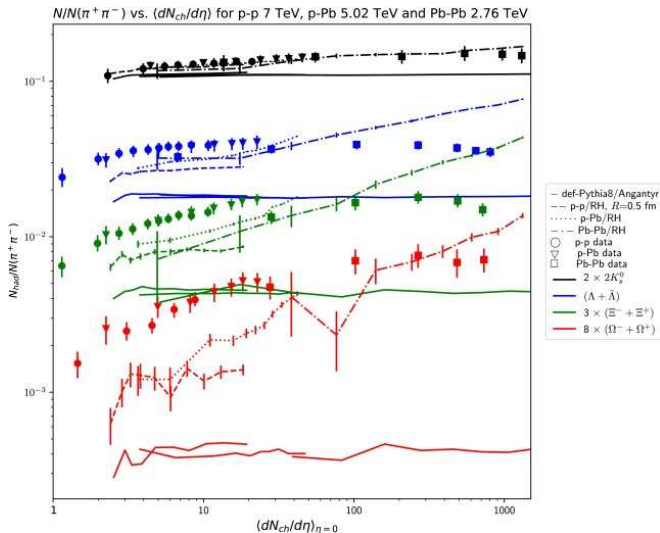
(ratio of Casimir operators)

Production points of primary hadrons in impact parameter space

Colored points: κ_{eff}



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.

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

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

- Looking at strangeness enhancement for pp,pA, AA is good**
- Looking in addition at $\langle pt \rangle$ 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**