Recent developments in EPOS

(the EPOS4 project)

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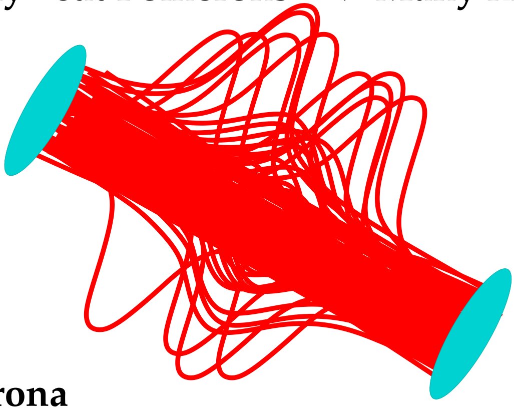
Recent activities (2017-2021)

(EPOS4 project, replacing EPOS3 and EPOS LHC)

- □ **Accommodate consistently multiple scattering S-matrix approch, saturation, and factorization/binary scaling**
  (deeply connected, crucial to understand recent pp,pA results)
- □ **Consistent implementation of HF in this framework**
- □ **Microcanonical hadronization of the "core"**
  (EPOS3 : GC, EPOS LHC n-body decay)
- □ **Understanding energy dependence**
  (-> Lower energies, BES)
- □ **Understanding thermalization**
  (EPOS+PHSD, quantum statistical approach, replaces hydro)

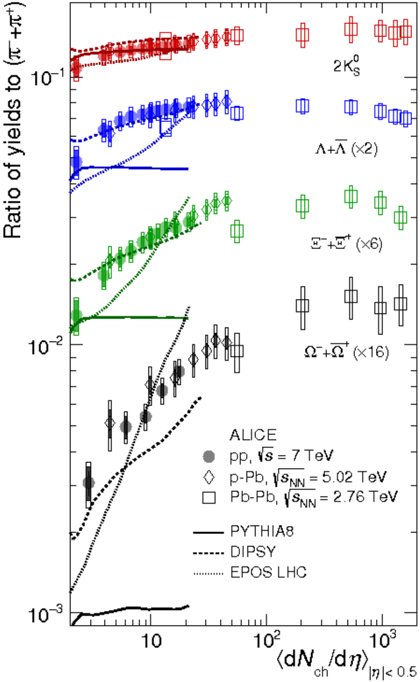
Starting point : S-matrix expressed in terms of Pomerons.
High multiplicity pp, pA, AA:

Many “cut Pomerons” => Many kinky strings



=> core + corona

core => hydro evolution => statistical decay (hadronization)



Core contribution crucial to understand particle production

ALICE
Nature physics 2017

Strangeness enhancement "rediscovered"

pp and pA look similar to AA

Relevant for CR physics?

Core-corona effect in hadron collisions and muon production in air showers
(arXiv:1902.09265v2 13 Mar 2020, Sebastian Baur et al)

Crucial quantity: Electromagnetic to hadronic energy

$$R = \frac{E_{\mathrm{EM}}}{E_{\mathrm{had}}}$$

- ☐ **Strongly correlated with muon yield!**
- ☐ **Energy going into EM cascade is lost for muon production**
  Too big R => Too small muon yield

Values of R:

Toy string model (only u-ubar and ddbar break):

$$R = 0.50$$

Realistic models used for simulations (calibrated with e^+e^-)**:**

$$R \approx 0.41$$

Statistical hadronization (thermal model)

$$R \approx 0.34$$

may help!

in the "Baur et al" paper, a core-corona toy model is used, using the "thermal model" for hadronization. Is this reasonable?

Microcanonical hadronization of plasma droplets

- **In pp and pA the core (plasma part) may be quite small, so the "thermal model" may not work**
- **Energy and flavor conservation play a role**
  => in EPOS4: microcanonical approach
  (equal to the thermal model (GC) in the limit of infinite volume)
- **New methods, extremely fast, work for big systems**
  (faster than approximate GC method)

We discuss here a **static droplet**, but in reality we treat a **flowing object**, with hadronization through a space-time hypersurface (covarant framework using $T^{\mu\nu}$ and $d\Sigma_\nu$)

Microcanonic decay

of given volume in its CMS into n hadrons

$$dP = C_{\mathrm{vol}}\, C_{\mathrm{deg}}\, C_{\mathrm{ident}} \times \delta(E - \Sigma E_i)\, \delta(\Sigma \vec{p}_i) \prod_A \delta_{Q_A, \Sigma q_{A\,i}} \prod_{i=1}^{n} d^3 p_i$$

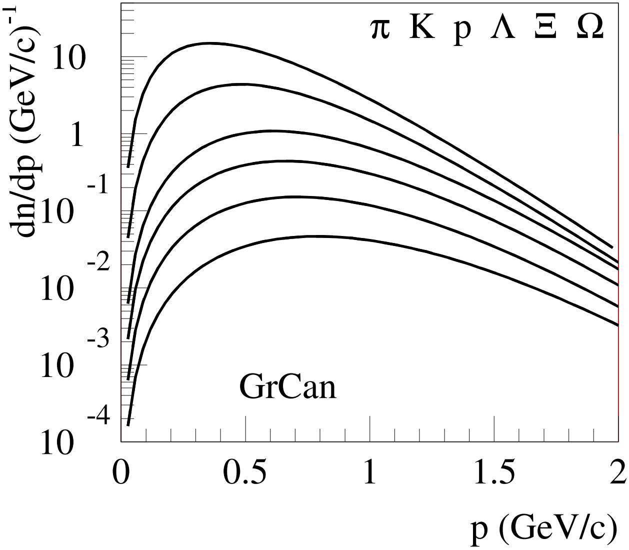
$$C_{\mathrm{vol}} = \frac{V^n}{(2\pi\hbar)^{3n}}\,, \quad C_{\mathrm{deg}} = \prod_{i=1}^{n} g_i\,, \quad C_{\mathrm{ident}} = \prod_{\alpha \in \mathcal{S}} \frac{1}{n_\alpha!}$$

(n_α is the number of particles of species α, $\mathcal{S}$ is the set of particle species)

Different from decay rate of a massive particle (using LIPS), where asymptotic states are defined over an infinitely large volume

(see Becattini et al, EPJC35:243-258,2004). **But** $E_i = \sqrt{p_i^2 + m_i^2}$

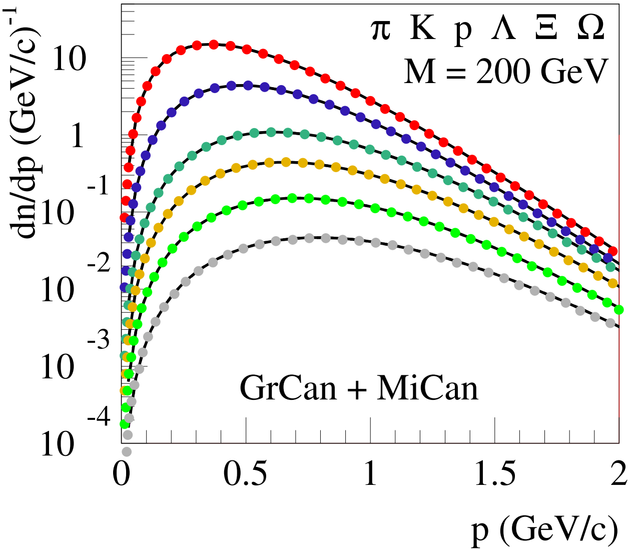
GC decay, E/V= 0.57 GeV/fm^3 T=167 MeV



V=87.5 fm^3

"thermal model"

GC+MiC decay, E/V= 0.57 GeV/fm^3 **E=M=200 GeV**

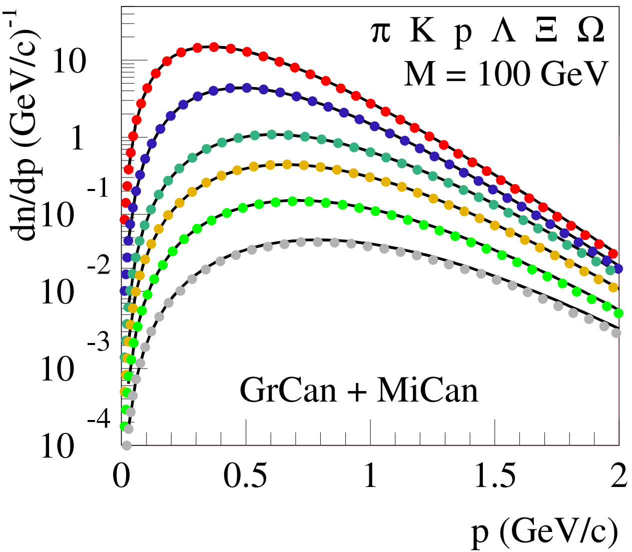


V=350 fm^3

$\times \frac{1}{4}$

good test for
Metropolis proposal

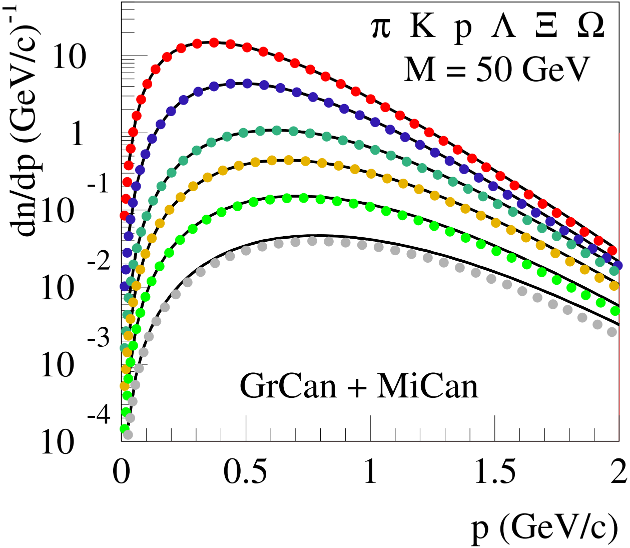
GC+MiC decay, E/V= 0.57 GeV/fm³ M=100 GeV



$V=350/2\ fm^3$

$\times\frac{1}{2}$

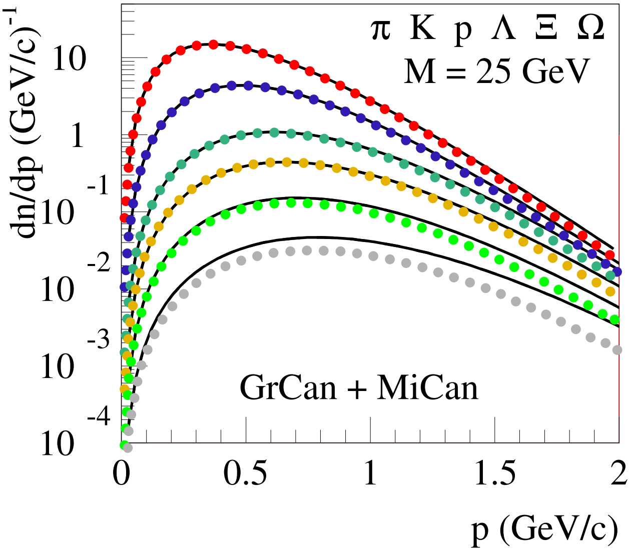
GC+MiC decay, E/V= 0.57 GeV/fm³ M=50 GeV



$V=350/4\ fm^3$

$\times 1$

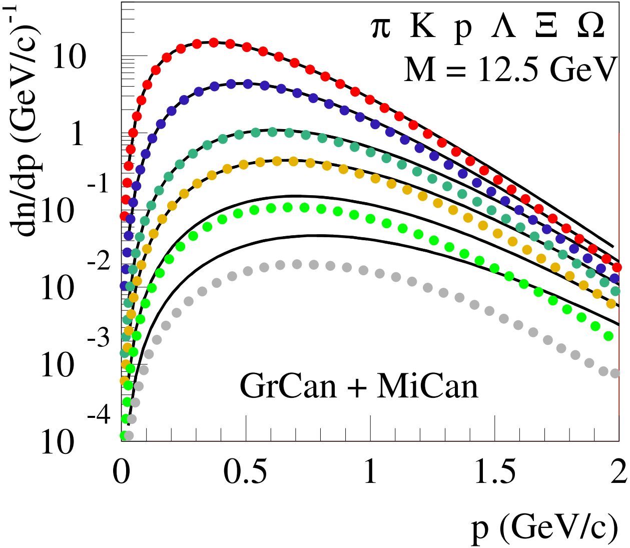
GC+MiC decay, E/V= 0.57 GeV/fm³ **M=25 GeV**



V=350/8 fm³

×2

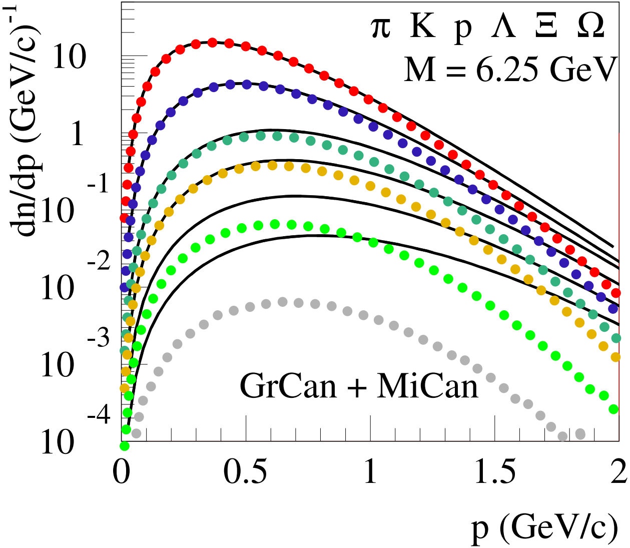
GC+MiC decay, E/V= 0.57 GeV/fm³ M=12.5 GeV



$V=350/16\ fm^3$

$\times 4$

GC+MiC decay, E/V= 0.57 GeV/fm^3 M=6.25 GeV



V=350/32 fm^3

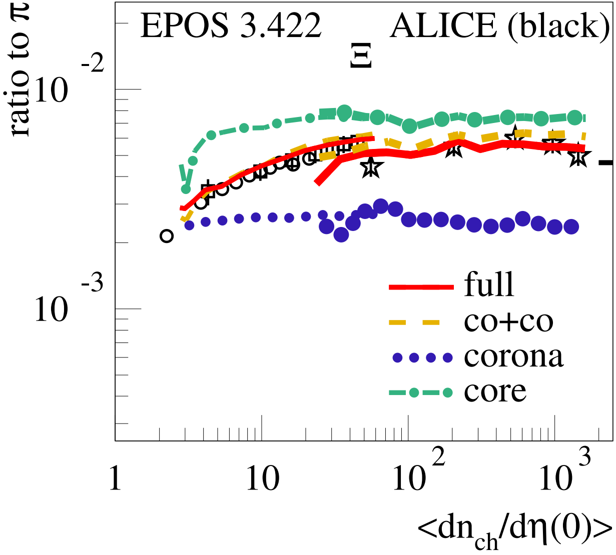
×8

affects heavy particles

(resonances)

p+Pb (5TeV) and PbPb (2.76TeV) results

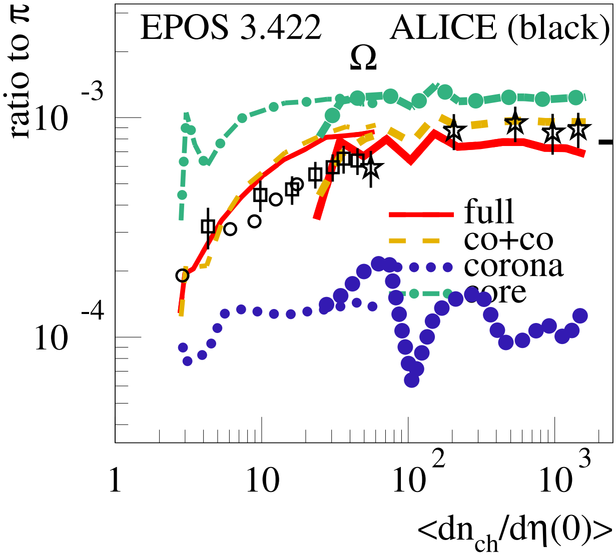
Xi to pion ratio



data from the ALICE Nature paper

even in pA strong core contribution

Omega to pion ratio

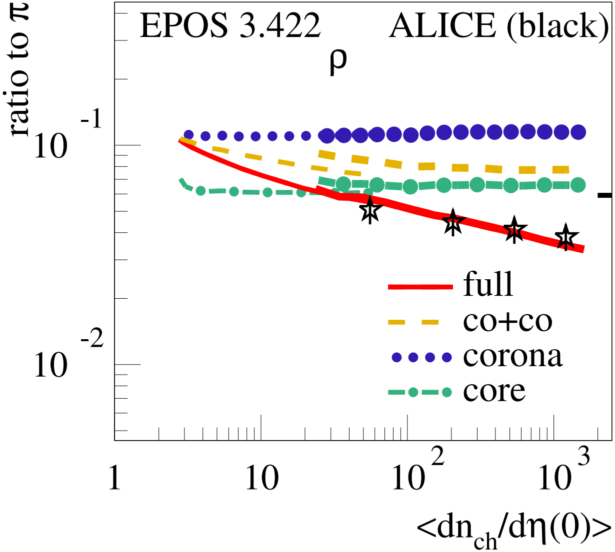


data from the
ALICE Nature paper

even in pA strong
core contribution

core close
to "thermal limit"

Rho to pion ratio



inverse case

core less than corona

Summary

- **New microcanonical hadronization procedure**
  (universal procedure for big and small systems)

  – **Very efficient, possible for "big" systems,**
  so we use it for pp up to AA.

  – **Qualitative understanding of the transition**
  pp -> pA -> AA (concerning yields).

  – **Even in pA, core is important.**
  Core yields close to thermal limit.

Thank you!

Expanding system -> Hadronization on hyper-surface

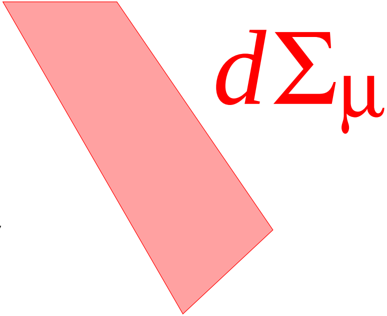
Hyper-surface element (in space-time):

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

Hyper-surface

$$x = \begin{pmatrix} \tau \cosh \eta \\ r \cos \varphi \\ r \sin \varphi \\ \tau \sinh \eta \end{pmatrix}$$

with $r = r(\tau, \varphi, \eta)$ representing the **FO condition**
= constant energy density



Flow of momentum vector dP^{μ} and conserved charges dQ_A through the surface element (with $T^{\mu\nu}$ **from hydro**):

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

(with $A \in \{C, B, S\}$, corresponding electric charge, baryon number and strangeness)

Construct an **effective mass** by summing surface elements:

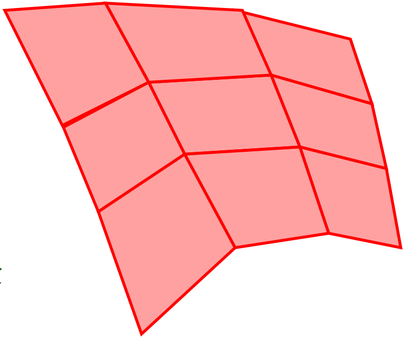
$$M = \int_{\text{surface area}} dM,$$

with

$$dM = \sqrt{dP^\mu dP_\mu},$$

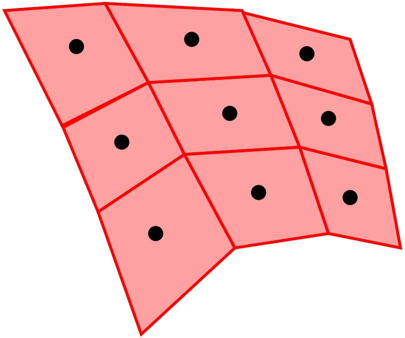
knowing for each element four-velocity

$$U^\mu = dP^\mu / dM,$$



The four-velocity U^μ is NOT equal to the fluid velocity u^μ!
(Only in case of zero pressure)

The effective mass decays microcanonically



Particles are distributed on the hyper-surface

$$x^\mu(\tau, \varphi, \eta)$$

according to the distribution

$$dM(\tau, \varphi, \eta)$$

and they are boosted according to the four-velocity

$$\boldsymbol{U^\mu(\tau, \varphi, \eta)}$$

Should be parameterized or tabulated for EPOS CR