EPOS and EPOS3

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with

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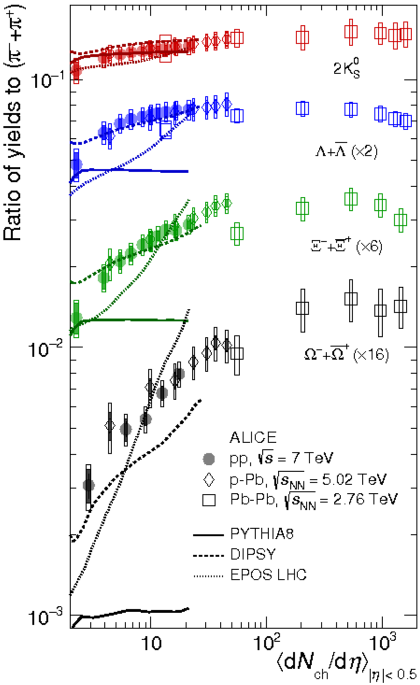
Current activities (2017-2020)

(towards EPOS4, replacing EPOS3 and EPOS LHC)

- ☐ **Consistent implementation of HF**
- ☐ **Accommodate multiple scattering, saturation, and factorization**
  (deeply connected)
  Crucial to understand nowadays pp results
- ☐ **Microcanonical hadronization**
  (EPOS3 : GC, EPOS LHC n-body decay)
- ☐ **Understanding energy dependence**
  (-> Lower energies, BES)
- ☐ **Understanding thermalization**
  (EPOS+PHSD, quantum statistical approach, replaces hydro)

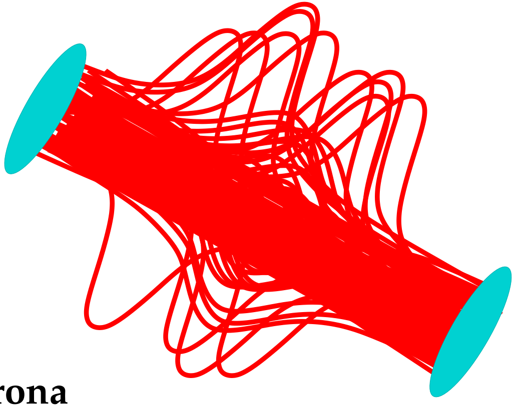


ALICE
Nature physics 2017

Strangeness enhancement "rediscovered"

In EPOS: High multiplicity pp or AA:

Many cut Pomerons => Many kinky strings



=> core + corona

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

Microcanonical hadronization of plasma droplets

- **No need to match dynamical part of hydro evolution**
  (sudden statistical decay)

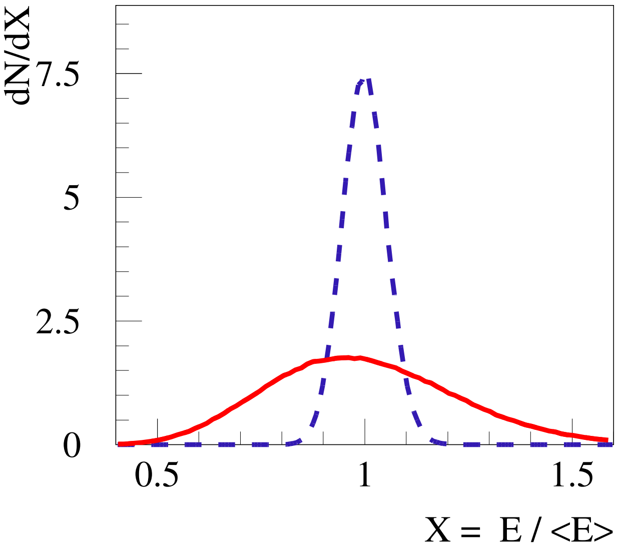
- **Energy and flavor conservation**
  (works for big and small systems)

- **Extremely fast**
  (faster than approximate GC method)

- **Useful for EPOS CR**
  (fast version, based on parameterized hypersurfaces)

Grand canonical decay, T = 130 MeV

V=50 fm^3; **V=1000 fm^3** (energy conservation always violated)



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** $E_i = \sqrt{p_i^2 + m_i^2}$

Microcanonical decay

$$dP \propto d\Phi_{\mathrm{NRPS}} = \delta(M - \Sigma E_i)\,\delta(\Sigma \vec{p}_i)\,\prod_{i=1}^{n} d^3 p_i$$

- □ Hagedorn 1958 methods to compute Φ_{NRPS}
- □ Lorentz invariant phase space (LIPS) (James 1968)
- □ Hagedorn methods used for decaying QGP droplets (Werner, Aichelin, 1994, Becattini 2003)
- □ 2012 (Bignamini,Becattini,Piccinini) compute Φ_{NRPS} via the Lorentz invariant phase space (LIPS)
- □ **our recent work:**
  Major technical improvements => very fast
  Allows to treat small and big systems

Grand canonical limit

Often wrongly referred to as "The statistical model"

For very large M we should recover the "grand canonical limit" for single particle spectra:

$$f_k = \frac{g_k V}{(2\pi\hbar)^3} \exp\left(-\frac{E_k}{T}\right),$$

The average energy is

$$\bar{E} = \sum_k \frac{g_k V}{(2\pi\hbar)^3} \int_0^\infty E_k \exp\left(-\frac{E_k}{T}\right) 4\pi p^2 dp$$

Changing variables via $E_k dE_k = p dp$, and employing modified Bessel functions via $K_1(z) = z \int_1^\infty \exp(-zx)\sqrt{x^2-1}dx$, and $3\,K_2(z) = z^2 \int_1^\infty \exp(-zx)\sqrt{x^2-1}^3 dx$

=>

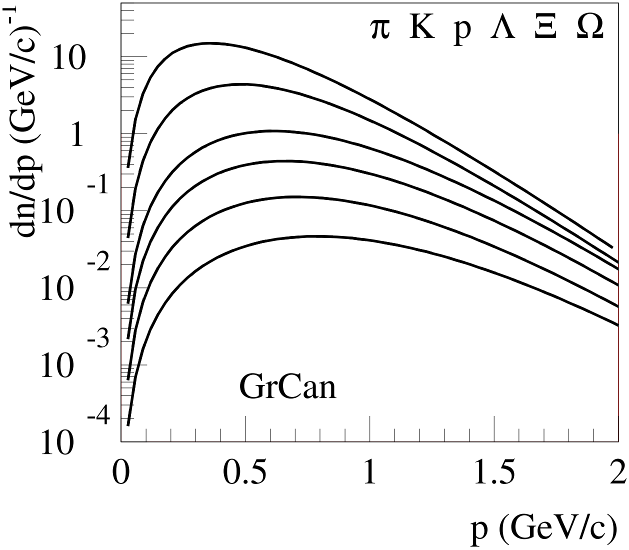
$$\bar{E} = \sum_k \frac{4\pi g_k V}{(2\pi\hbar)^3} m_k^2 T \left(3TK_2(\frac{m_k}{T}) + m_k K_1(\frac{m_k}{T}) \right).$$

The microcanonical decay of an object of mass M and volume V should converge (for $M \to \infty$) to the GC single particle spectra

with T obtained from $M = \bar{E}$.

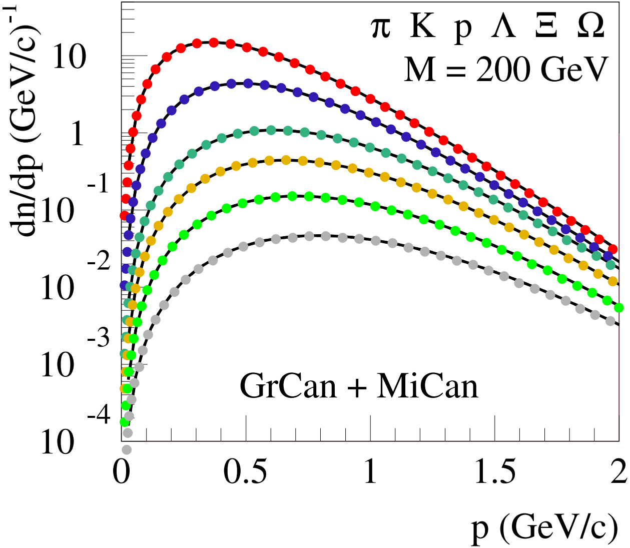
We will check it ...

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



V=87.5 fm^3

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

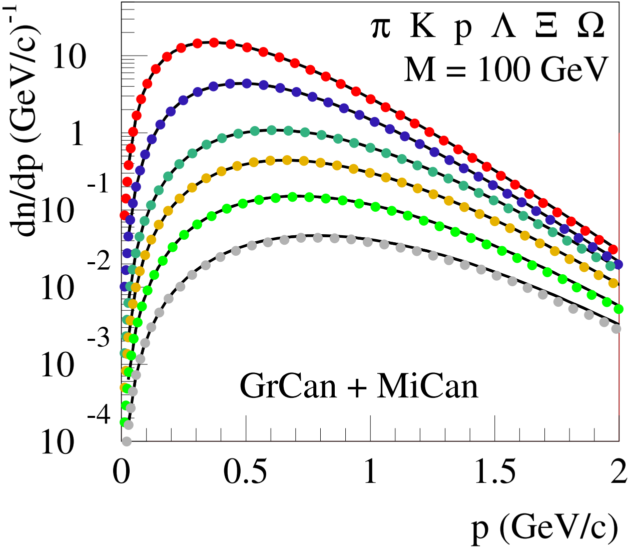


V=350 fm^3

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

good test for
Metropolis proposal

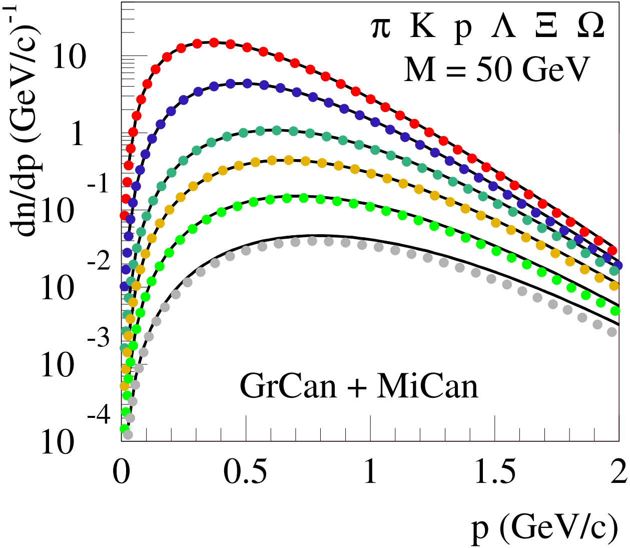
GC+MiC decay, E/V= 0.57 GeV/fm^3 **M=100 GeV**



V=350/2 fm^3

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

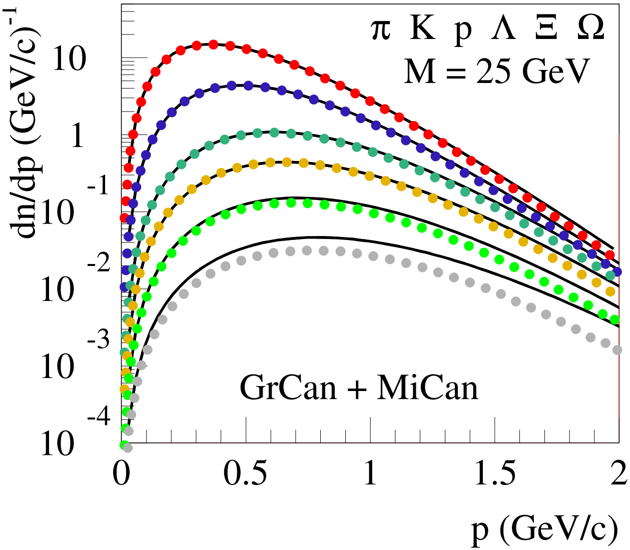
GC+MiC decay, E/V= 0.57 GeV/fm^3 M=50 GeV



V=350/4 fm^3

×1

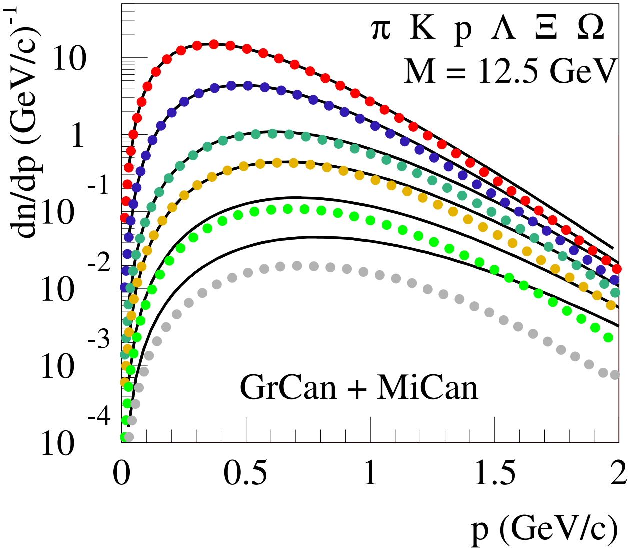
GC+MiC decay, E/V= 0.57 GeV/fm^3 M=25 GeV



V=350/8 fm^3

×2

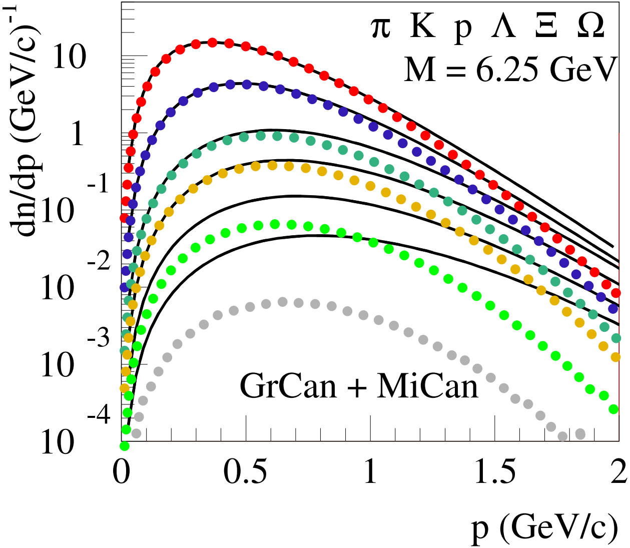
GC+MiC decay, E/V= 0.57 GeV/fm^3 M=12.5 GeV



V=350/16 fm^3

×4

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



V=350/32 fm^3

×8

Expanding system -> Hadronization on hyper-surface

Hyper-surface element (in space-time):

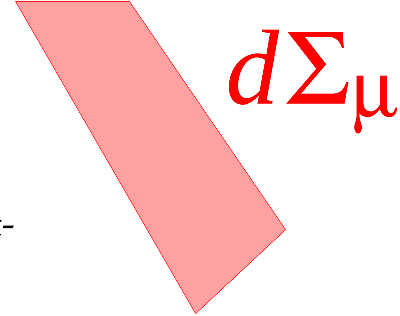
$$d\Sigma_\mu = \varepsilon_{\mu\nu\kappa\lambda} \frac{\partial x^\nu}{\partial \tau} \frac{\partial x^\kappa}{\partial \varphi} \frac{\partial x^\lambda}{\partial \eta} \, d\tau \, d\varphi \, d\eta$$

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:

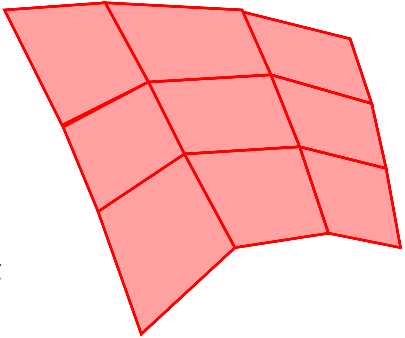
$$M = \int_{\textbf{surface area}} dM,$$

with

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

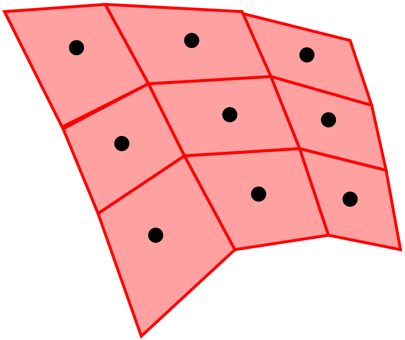
knowing for each element four-velocity

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



The four-velocity U^{μ} is NOT equal to the fluid velocity u^{μ}!

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

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

Should be parameterized or tabulated for EPOS CR

Hadronization in pp at 7TeV

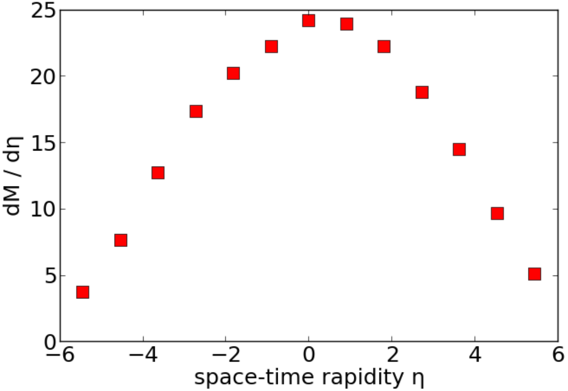
- ☐ **What are the effective masses produced in pp?**
- ☐ **Where are they produced in space and time?**

Effective mass vs η

Event with 12 Pomerons

($\sim 6 \times$ minimum bias)

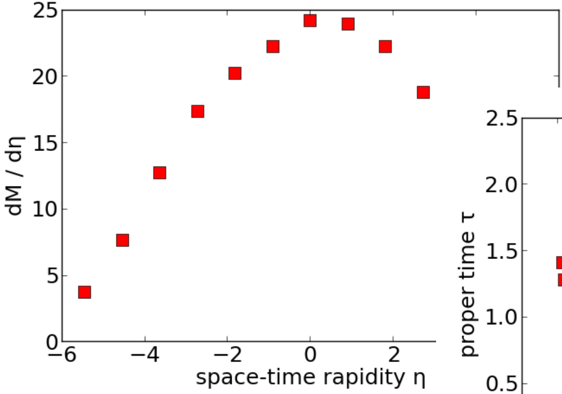
$E_{\text{core}} \approx 3700\text{GeV}$

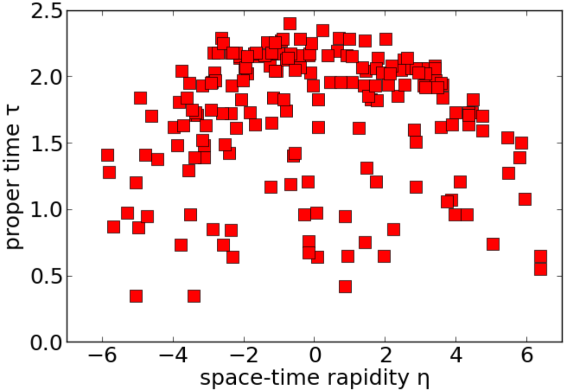


Effective mass vs η

Event with 12 Pomerons
(~ 6 × minimum bias)

$E_{\text{core}} \approx 3700\text{GeV}$

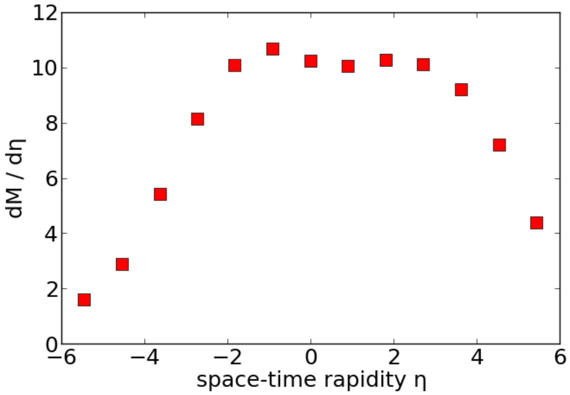




Effective mass vs η

Event with 6 Pomerons

(~ 3 × minimum bias)

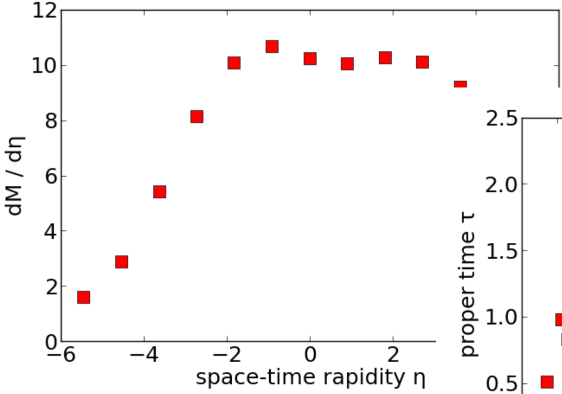


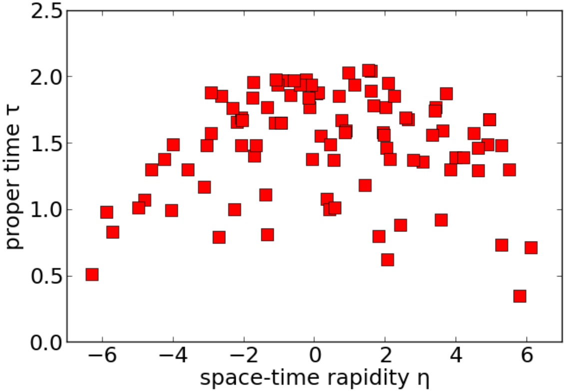
$E_{\text{core}} \approx 2300\text{GeV}$

Effective mass vs η

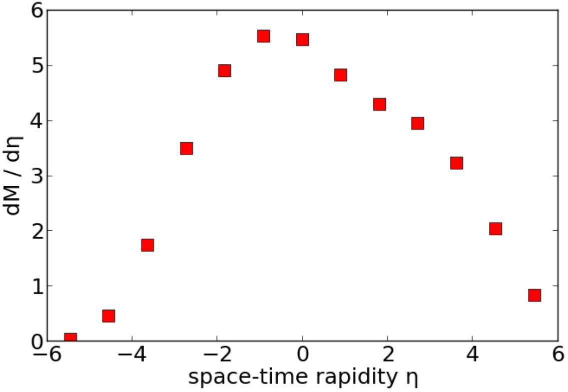
Event with 6 Pomerons
($\sim 3\ \times$minimum bias)

$E_{\text{core}} \approx 2300\text{GeV}$





Effective mass vs η



Event with 2 Pomerons

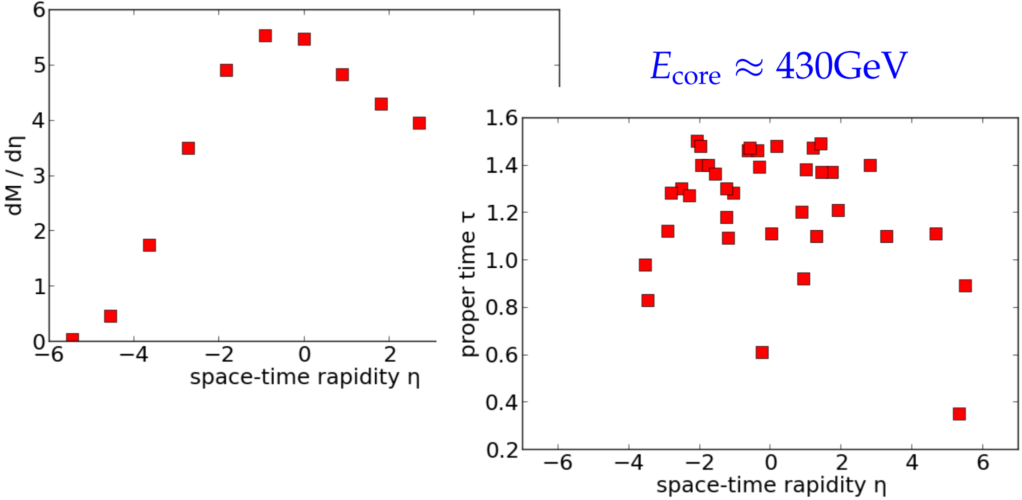
(~ minimum bias)

$E_{\rm core} \approx 430\text{GeV}$

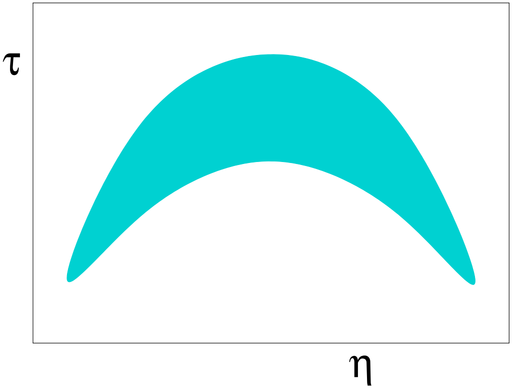
Effective mass vs η

Event with 2 Pomerons
(~ minimum bias)

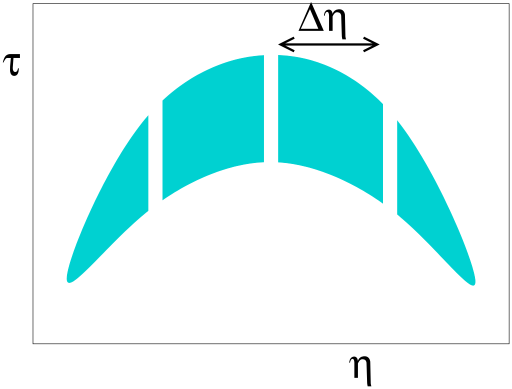
$E_{core} \approx 430\text{GeV}$



Decaying object extended in space-time



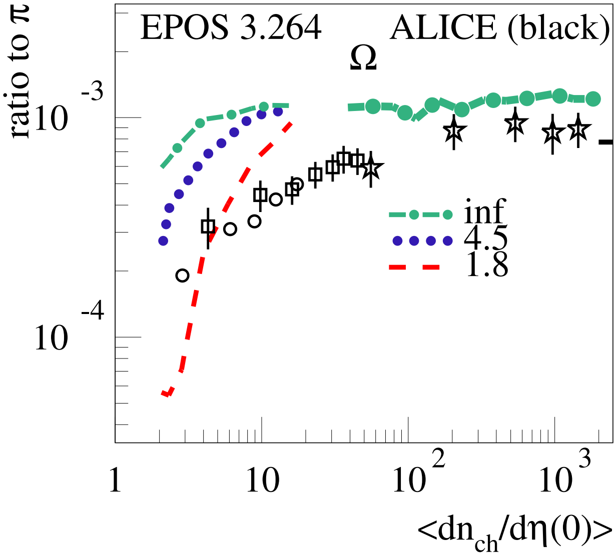
Does is decay as single effective mass M?



... or as several independent objects of width $\Delta\eta$

We will try several choices of $\Delta\eta$

Omega to pion ratio



different choices of $\Delta\eta$

$\Delta\eta = \infty$: drops slightly

$\Delta\eta = 1.8$: drops quickly around $dn/d\eta = 10$

1 Summary

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

  – **Very efficient, possible for “big” systems**

  – **Results for yields vs multipicity depend on correlation width $\Delta\eta$ -> large values favoured**
  (but anyway corona part is needed)

  – **Method may be extended to build “fast version”, compatible with the “normal” one**