New developments in EPOS

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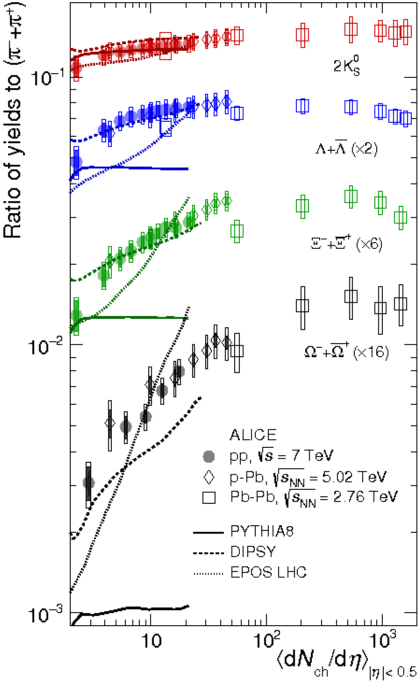
Current activities:

- ☐ Consistent implementation of HF
- ☐ Saturation and factorization
- ☐ **Statistical hadronization, results pp, PbPb**
- ☐ Low energies (BES)
- ☐ EPOS+PHSD



ALICE
Nature physics 2017

Strangeness enhancement "rediscovered"

1 EPOS Introduction

Conceptually very different compared to other models (Pythia, Herwig...)

Heavily based on S-matrix theory

(S related to T via $S_{fi} = \delta_{fi} + i(2\pi)^4 \delta(p_f - p_i) T_{fi}$)

- □ **Lorentz invariance**
- □ **Unitarity**
- □ **Analyticity (=>crossing symmetry)**

Asymptotic form of T

$$T(s,t) = \beta(t)\, s^{\alpha(t)} \approx \beta(t)\, s^{\alpha(0)+\alpha'(0)\,t}$$

This form is extremely important!

After Fourier transform:

- **soft contribution:** $T_{\mathrm{soft}} = \beta(b)\,(x^{+}x^{-}s_{pp})^{\alpha(b)}$
- **pQCD contribution:** $T_{\mathrm{ladder}} = \sum \beta(b)\,(x^{+}x^{-}s_{pp})^{\alpha(b)}$

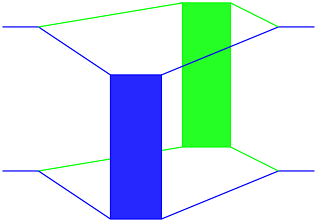
(fit of numerical calculation of pQCD calculations)

Starting point: Unitarity

$$2s\,\sigma_{\mathrm{tot}} = \frac{1}{\mathrm{i}}\mathrm{disc}\,T_{\mathrm{el}}$$

Basic assumption :
Multiple "Pomerons"

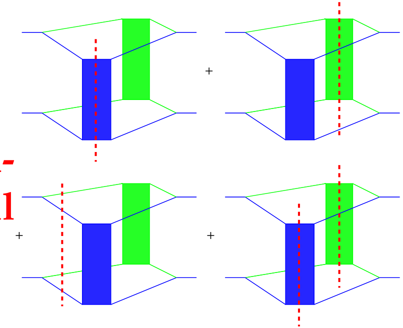
$$iT_{\mathrm{el}} = \sum_k \frac{1}{k!}\left\{iT_{\mathrm{Pom}} \times ... \times iT_{\mathrm{Pom}}\right\}$$



Evaluate

$$\frac{1}{i}\mathrm{disc}\left\{iT_{\mathrm{Pom}}\times ...\times iT_{\mathrm{Pom}}\right\}$$

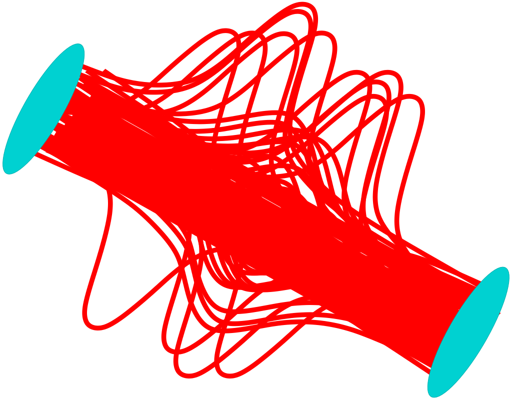
using "cutting rules" :



A "cut" multi-Pomeron diagram amounts to the sum of all possible cuts

Summing uncut contributions
=> Multiple scattering weights (n-fold integrals, n up to 10^7)
=> Sampled via Markov chains

High multiplicity pp or AA: Many cut Pomerons => Many kinky strings



=> core + corona

core => hydro evolution => statistical decay

2 News

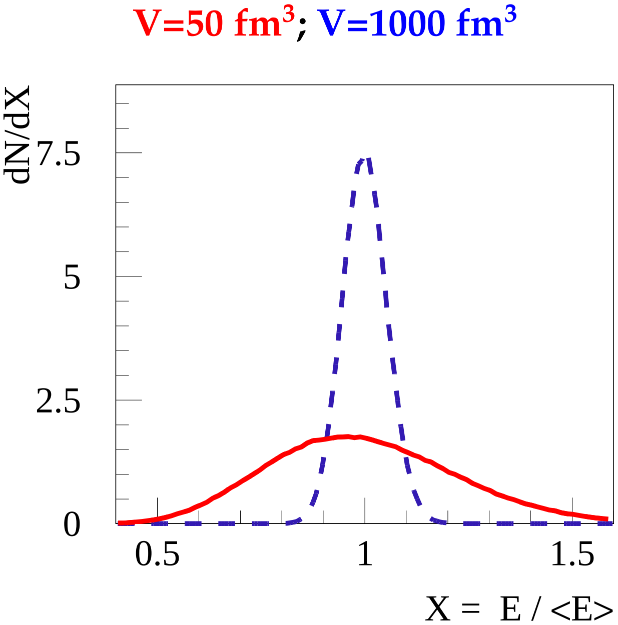
2.1 Microcanonical hadronization of plasma droplets

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

- **Energy and flavor conservation**
  (important for small systems)

- **Extremely fast**

Grand canonical decay, T = 130 MeV



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)

- **Hagedorn integral method can be made very efficient at large n (new)**, but it is VERY time consuming at small n

- **LIPS method very fast for small n**, gets time consuming at large n

- **around $n \approx 30 - 40$ both methods work (=> checks)**

Hagedorn integral method

The phase-space integral:

$$\phi_{\mathrm{NRPS}}(M, m_1, \ldots, m_n)$$
$$= (4\pi)^n \int \prod_{i=1}^{n} p_i^2 \, \delta(E - \sum_{i=1}^{n} E_i) \, W(p_1, \ldots, p_n) \prod_{i=1}^{n} dp_i,$$

with the "**random walk function**" W (angular integral)

$$W(p_1, \ldots, p_n) := \frac{1}{(4\pi)^n} \int \delta(\sum_{i=1}^{n} p_i \times \vec{u}_i) \prod_{i=1}^{n} d\Omega_i$$

New: Very efficient procedures to compute W for large n with high precision

We obtain (Werner, Aichelin 94)

$$\phi(M, m_1, \ldots, m_n) = \int_0^1 dr_1 \ldots \int_0^1 dr_{n-1} \psi(r_1, ..., r_{n-1})$$

$$\psi = \frac{(4\pi)^n \, T^{n-1}}{(n-1)!} \prod_{i=1}^{n} p_i \, E_i \, W(p_1, \ldots, p_n),$$

with $z_i = r_i^{1/i}$, $x_i = z_i x_{i+1}$, $s_i = x_i T$, $t_i = s_i - s_{i-1}$,
$E_i = t_i + m_i$, $T = M - \sum_{i=1}^{n} m_i$

Suited for MC via Markov chains **if *W* is known**

2.2 Grand canonical limit

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 $E_k dE_k = pdp$, and using $K_1(z) = z \int_1^\infty \exp(-zx)\sqrt{x^2-1}dx$, 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 $M = \bar{E}$.

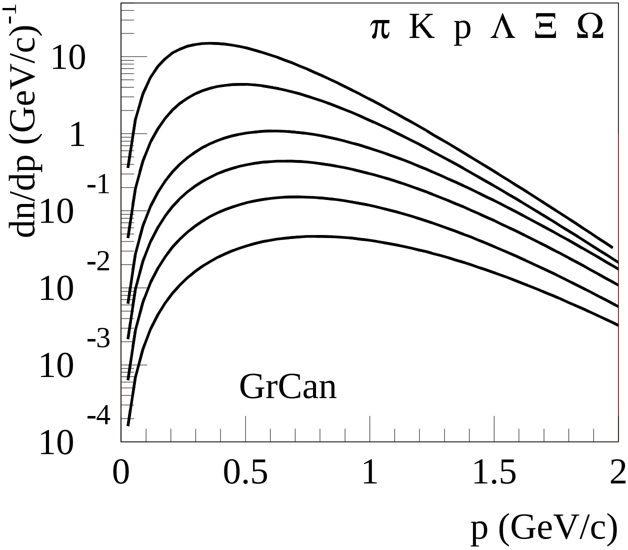
2.3 Comparing GC et MiC decay

We consider a complete set of hadrons ($\approx$ 400, PDG list)

We check the effect of

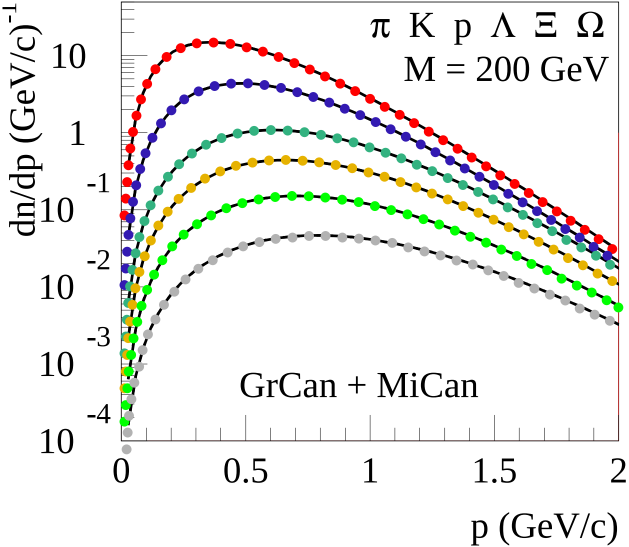
- □ **energy conservation**
- □ **flavor conservation**

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

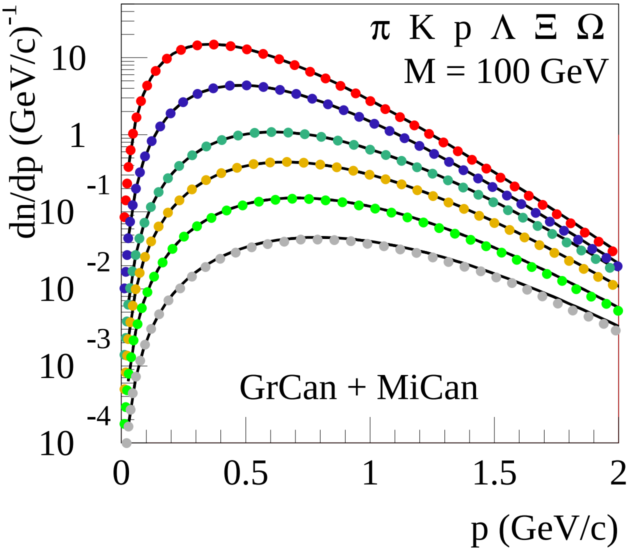


V=350 fm^3

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

good test for
Metropolis proposal

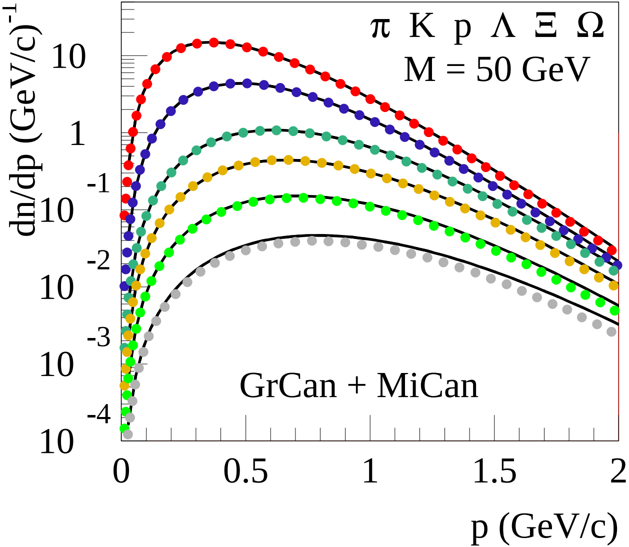
GC+MiC decay, E/V= 0.57 GeV/fm^3 M=100 GeV



V=350/2 fm^3

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

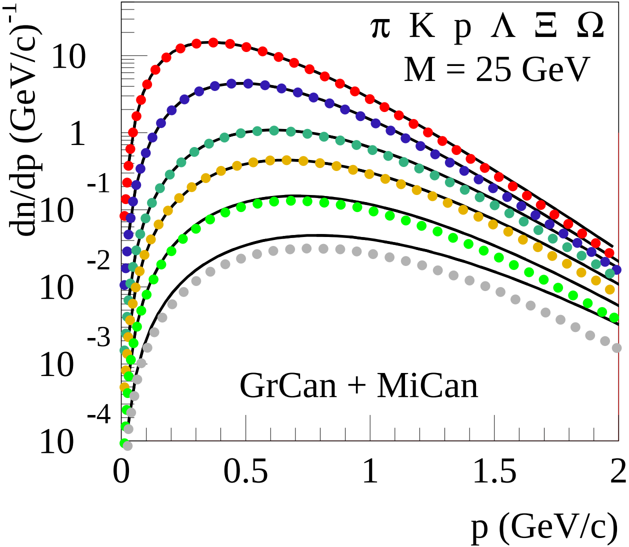
GC+MiC decay, E/V= 0.57 GeV/fm^3 M=50 GeV



V=350/4 fm^3

$\times 1$

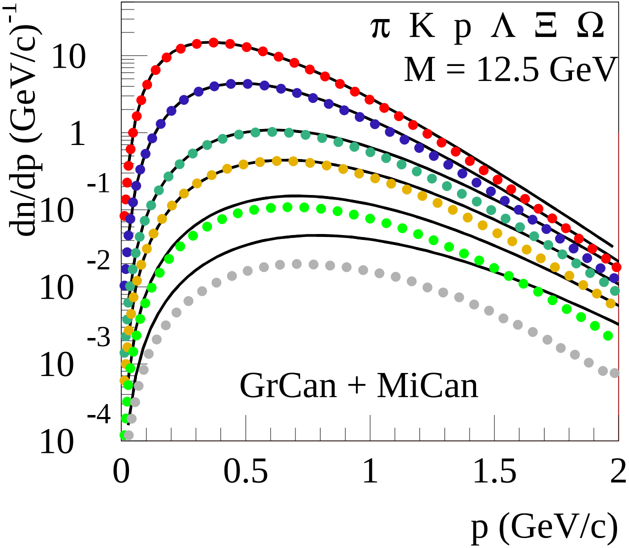
GC+MiC decay, E/V= 0.57 GeV/fm^3 M=25 GeV



V=350/8 fm^3

$\times 2$

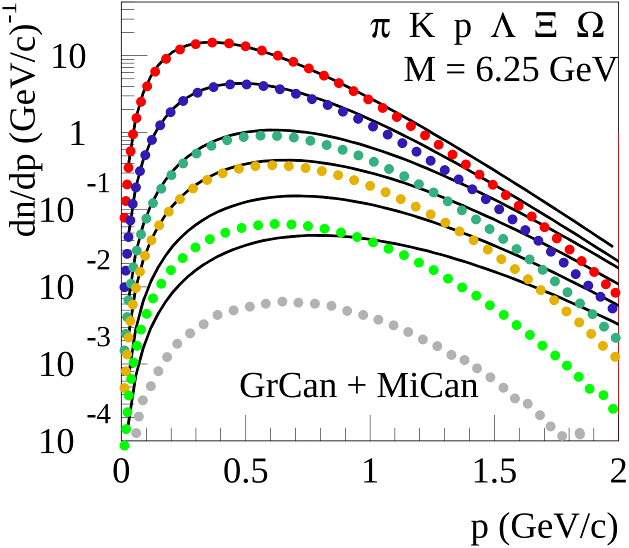
GC+MiC decay, E/V= 0.57 GeV/fm^3 M=12.5 GeV



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

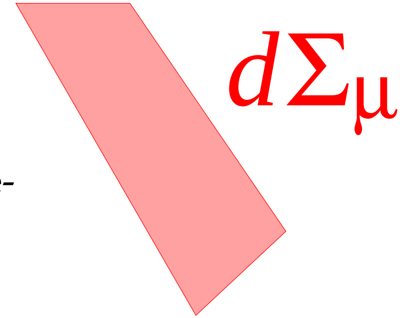
×8

2.4 Hadronization on hyper-surface

Hypersurface element:

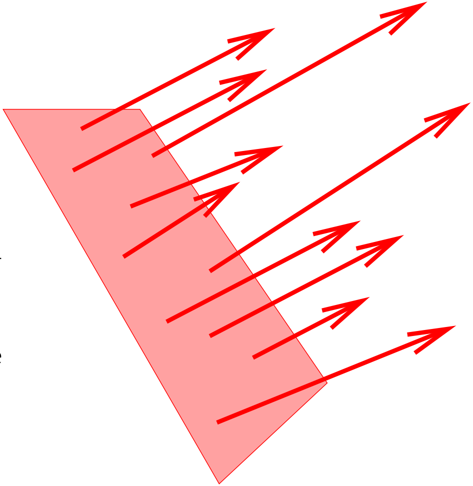
$$d\Sigma_\mu = \varepsilon_{\mu\nu\kappa\lambda} \frac{\partial x^\nu}{\partial \tau} \frac{\partial x^\kappa}{\partial \varphi} \frac{\partial x^\lambda}{\partial \eta} \, d\tau \, d\varphi \, d\eta$$

$x^0 = \tau \cosh \eta$, $x^1 = r \cos \varphi$, $x^2 = r \sin \varphi$, $x^3 = \tau \sinh \eta$ with $r = r(\tau, \varphi, \eta)$, representing the **FO condition**.



GC particle production via Cooper-Frye

$$E\frac{dn}{d^3p} = \int d\Sigma_\mu p^\mu f(up),$$



assuming that "matter" is a thermalized resonance gas

(adding δf for viscous hydro, close to equilibrium)

Our approach:

Flow of momentum vector dP^{μ} and conserved charges dQ_A through the surface element:

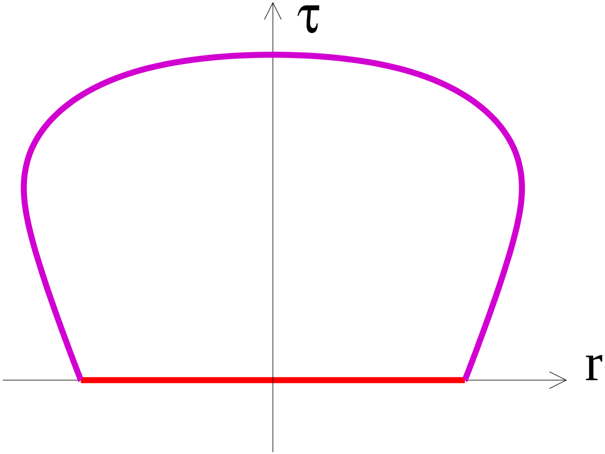
$$\begin{aligned} dP^{\mu} &= T^{\mu\nu} d\Sigma_{\nu}, \\ dQ_A &= J_A^{\nu} d\Sigma_{\nu}. \end{aligned}$$

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

Momentum and charges are conserved :

$$\int_{\Sigma_{\mathrm{FO}}} dP^\mu = P^\mu_{\mathrm{ini}},$$

$$\int_{\Sigma_{\mathrm{FO}}} dQ_A = Q_{A\,\mathrm{ini}}$$



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

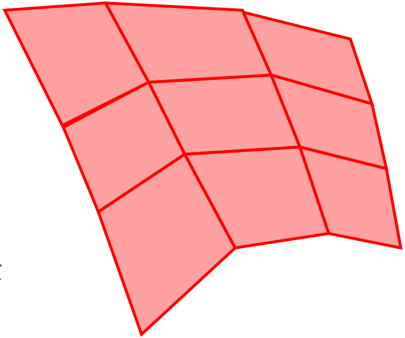
$$M = \int_{\text{surface area}} dM,$$

with

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

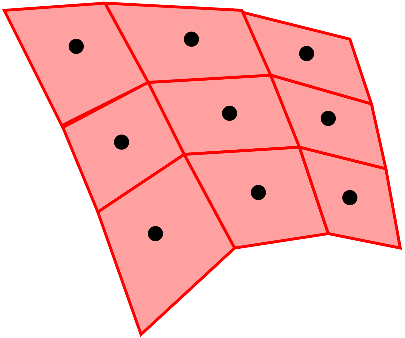
knowing for each element four-velocity

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



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

The effective mass decays microcanonically



Particles are distributed on the hyper-surface

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

according to the distribution

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

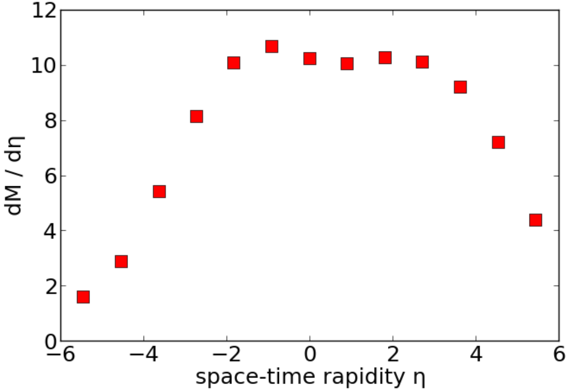
and they are boosted according to the four-velocity

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

2.5 Hadronization in pp

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

Effective mass vs η



Event with 6 Pomerons

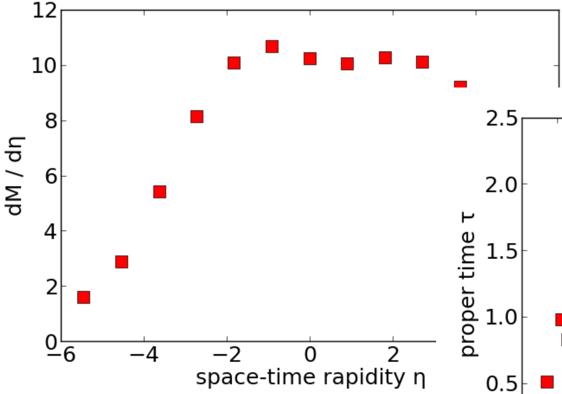
(~ 3 × minimum bias)

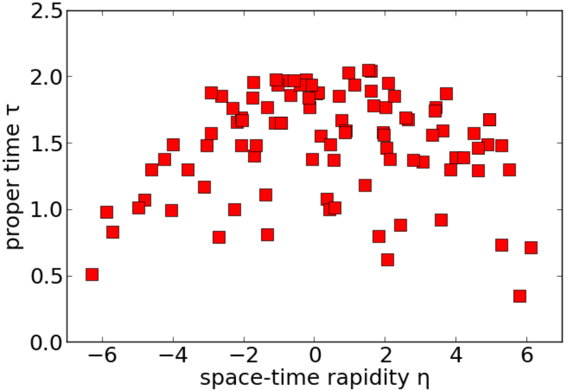
$E_{\text{core}} \approx 2300\text{GeV}$

Effective mass vs η

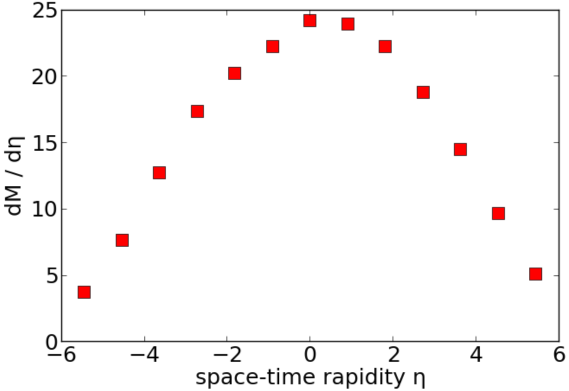
Event with 6 Pomerons
(~ 3 ×minimum bias)

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





Effective mass vs η



Event with 12 Pomerons

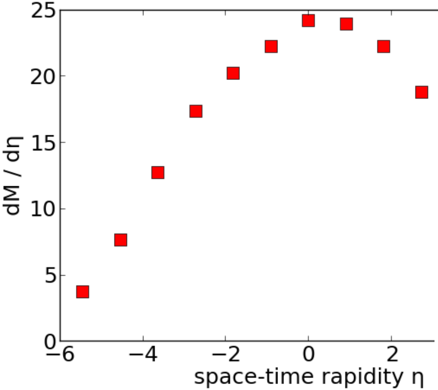
($\sim 6 \times$ minimum bias)

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

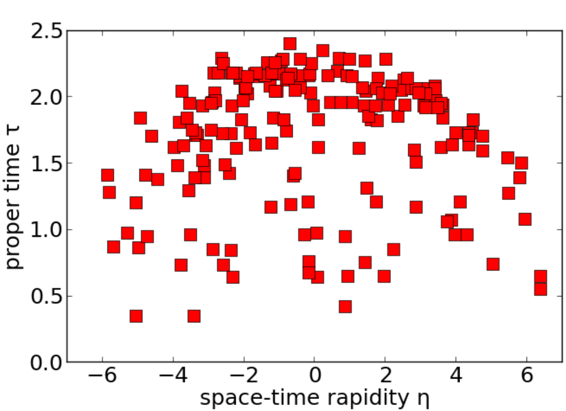
Effective mass vs η

Event with 12 Pomerons

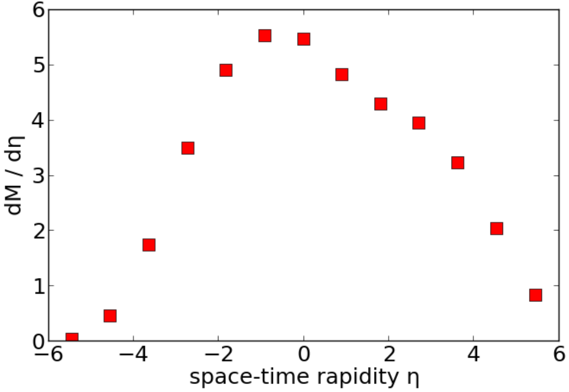
(~ 6 × minimum bias)



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



Effective mass vs η



Event with 2 Pomerons
(~ minimum bias)

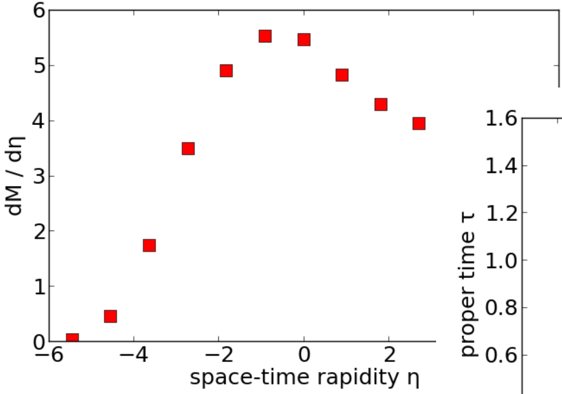
$E_{\text{core}} \approx 430\text{GeV}$

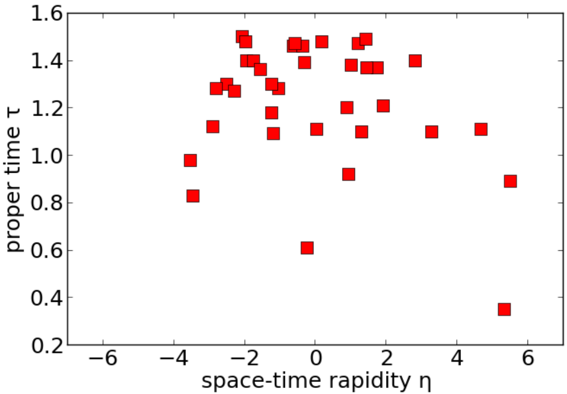
Effective mass vs η

Event with 2 Pomerons

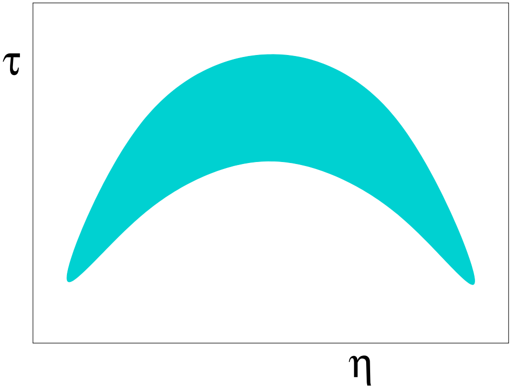
(~ minimum bias)

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

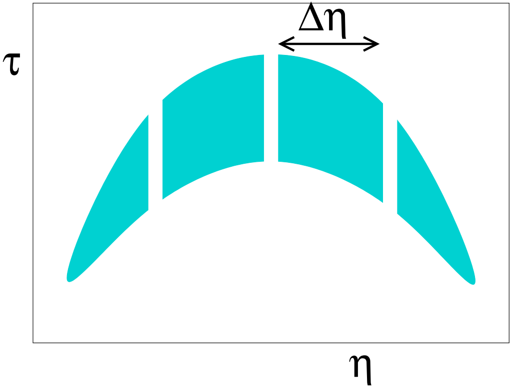




Decaying object extended in space-time



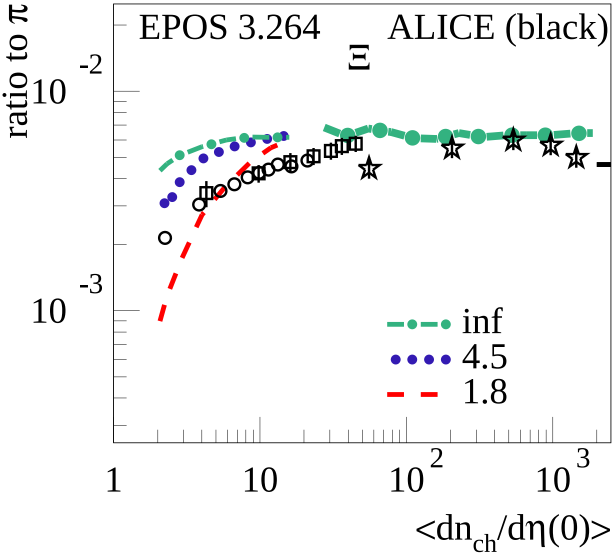
Does is decay as single effective mass M?



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

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

Xi to pion ratio

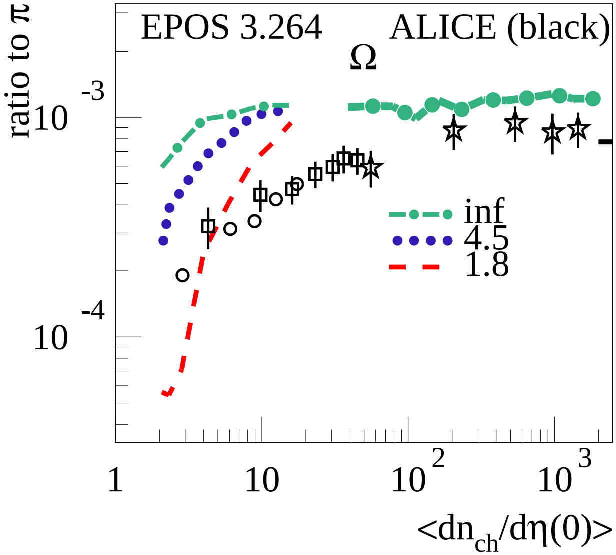


different choices of $\Delta\eta$

$\Delta\eta = \infty$: almost flat

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

Omega to pion ratio



different choices of $\Delta\eta$

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

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

3 Summary

- **New microcanonical hadronization procedure** **(big and small systems)**
  - **Very efficient, possible for "big" systems**
  - **Coincides with GC for M>10-50GeV**
  - **Results for yields vs multipicity depend on correlation width $\Delta\eta$**
  - **Large $\Delta\eta$: little effect,**
    small $\Delta\eta$: yields drop too fast (only in pp range)