Event-by-event extraction of kinetic and chemical freeze-out properties in the CBM experiment

V. Vovchenko, I. Kisel, D. Anchishkin
for the CBM collaboration

DPG Spring Meeting

Heidelberg, Germany
23 March 2015

Outline

- Introduction
- Simplest model: temperature from Boltzmann distribution
- Correction procedure for acceptance and reconstruction efficiency
- Longitudinal flow from Blast-Wave model
- Hadron-resonance gas model at chemical freeze-out
- Summary

Introduction

CBM experiment

- A future fixed target experiment at FAIR facility.
- Up to 10^7 Au+Au collisions per second at 4-35A GeV.

Main task: Extract parameters of theoretical models on-line (in addition to off-line) from measured data

Usual procedure

$$\text{Theoretical model } (T, \mu_B, V, \sigma_{NN}, ...) \Rightarrow \omega_p \frac{dN}{d^3p} \text{ (observable)}$$

Our idea: solve the inverse problem on-line

Inverse problem

$$\text{Observable } \omega_p \frac{dN}{d^3p} \Rightarrow \text{model parameters } (T, \mu_B, V, \sigma_{NN}, ...)$$

Implementation as a package in CBMROOT

Boltzmann momentum distribution

Static thermal fireball

Momentum spectrum in y and m_T (c.m. frame)

$$\frac{dN}{m_T dm_T dy d\varphi} = \frac{gV}{(2\pi)^3} m_T \cosh y \, \exp\left[-\frac{m_T \cosh y}{T}\right]$$

Boltzmann momentum distribution

Static thermal fireball

Momentum spectrum in y and m_T (c.m. frame)

$$\frac{dN}{m_T dm_T dy d\varphi} = \frac{gV}{(2\pi)^3} m_T \cosh y \, \exp\left[-\frac{m_T \cosh y}{T}\right]$$

How to extract model parameters from experiment?

Method of moments: relation between $\langle m_T \rangle$ and T

Lab frame, 4π acceptance:

$$\langle m_T \rangle_{4\pi} = \frac{\int dy \int_0^\infty dp_t \, p_t \, m_T \, \cosh(y - y_{c.m.}) \, e^{-m_T \cosh(y-y_{c.m.})/T} m_T}{\int dy \int_0^\infty dp_t \, p_t \, m_T \cosh(y - y_{c.m.}) \, e^{-m_T \cosh(y-y_{c.m.})/T}}$$

$y_{c.m.}$ – mid-rapidity, $m_T = \sqrt{p_t^2 + m^2}$

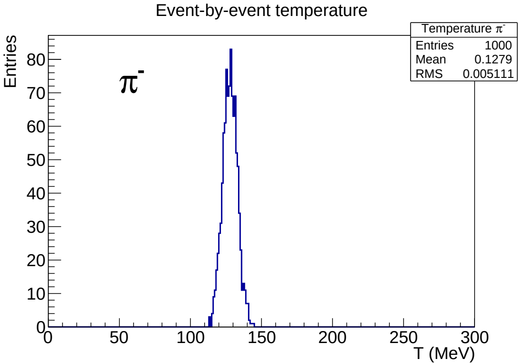
Solving equation for T at given $\langle m_T \rangle$ provides solution for inverse problem

Method of moments is not the only option but is simple and works consistently also on low statistics present in event-by-event analysis

Test calculation

Test calculation for 4π acceptance using toy MC generator

- 1000 events with Boltzmann generator of pions (300 π^- per event)
- Use MC tracks with particle identification
- $\langle m_T \rangle$ is determined event-by-event and also from set of events
- Equation for T is solved using bisection method



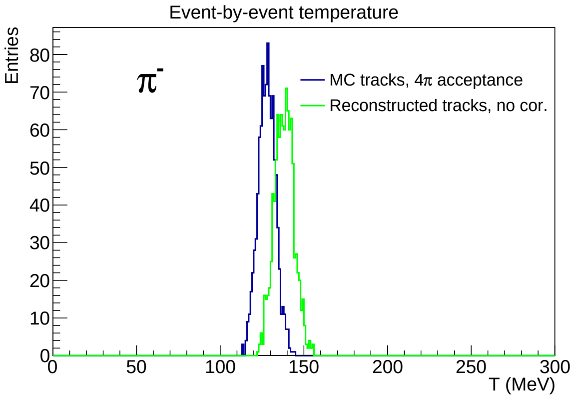
Over 1000 events

Theory: $T = 128\ MeV$, Extracted: $T = (127.9 \pm 0.2(stat.))\ MeV$

Limitations for reconstructed particles

We can only work with tracks within acceptance and which have limited momentum accuracy

Using reconstructed particles from KF Particle Finder which were identified as primary pions



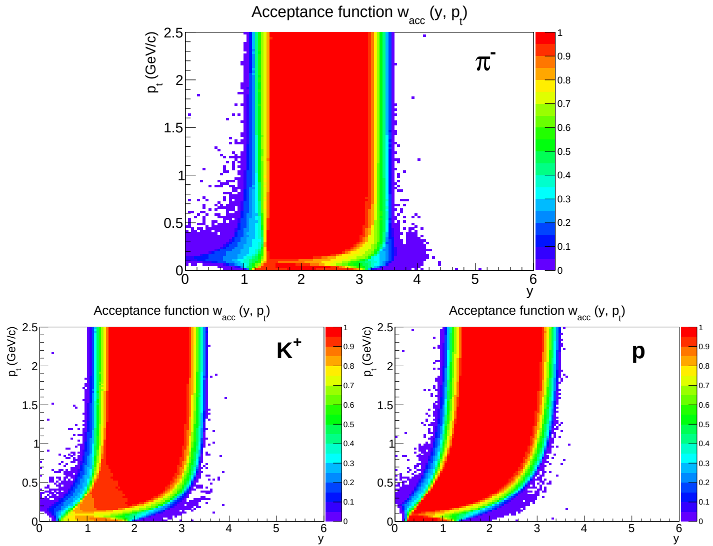
4π acceptance, MC Tracks: $T = (127.9 \pm 0.2)\ MeV$

Reconstructed tracks: $T = (138.2 \pm 0.2)\ MeV$

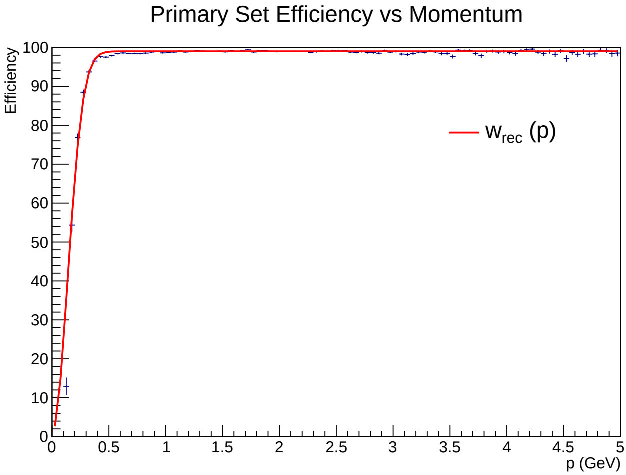
Correction for acceptance and reconstruction efficiency is needed!

Acceptance function

Calculate acceptance probability in (y, p_t) bins.



Reconstruction efficiency correction



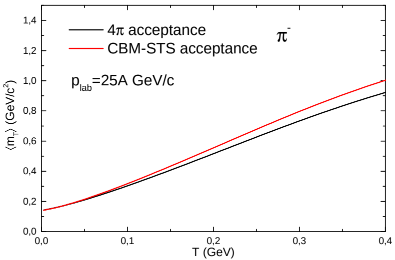
Analytical parametrization

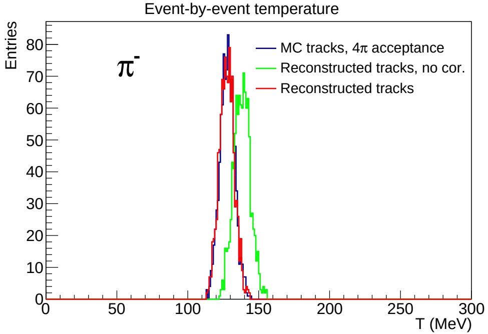
- $w_{rec}(p) = p_0 + p_1 \exp\left(\frac{-p^2}{2p_2^2}\right)$

Correction for reconstructed particles

Correction for momentum spectrum

$$(\omega_p dN/d^3p)_{model} \to (\omega_p dN/d^3p)_{model}\, w_{acc}(y,p_t)\, w_{rec}(p)$$





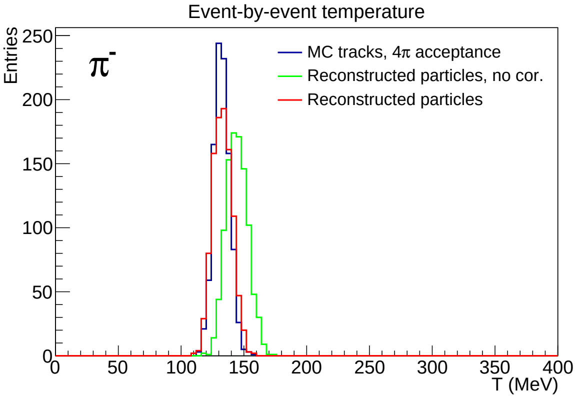
Acceptance	T (MeV)
Theory	128.0
4π-MC	127.9 ± 0.2
Reco. uncor.	138.2 ± 0.2
Reco.	127.5 ± 0.2

Errors (1000 events):

$\Delta T_{stat} = 0.16$ MeV

$\Delta T_{mom} = 0.01$ MeV

UrQMD-3.4, Au+Au, $p_{\text{lab}} = 25A\ GeV/c$, 1000 central events



Over 1000 events (only stat. errors):

Acceptance	T (MeV)
4π-MC	134.3 ± 0.2
Reco. uncor.	144.7 ± 0.2
Reco.	133.7 ± 0.2

Same trend for π^+, $K^\pm$ and also for PHSD events.

Longitudinal flow within Blast-Wave model

Include longitudinal flow: a sum over longitudinally boosted thermal sources

Momentum spectrum with longitudinal flow

$$\frac{dN}{m_T dm_T dy d\phi}(y, m_T, \phi) \to \int_{-\eta_{\max}}^{\eta_{\max}} d\eta \, \frac{dN}{m_T dm_T dy d\phi}(y - \eta, m_T, \phi).$$

E. Schnedermann, J. Sollfrank, U. Heinz, Phys. Rev. C 48, 2462 (1993)

Rapidity distribution is not very sensitive to T.

Longitudinal flow within Blast-Wave model

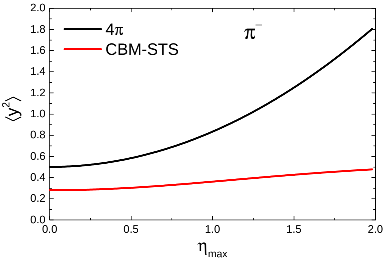
Include longitudinal flow: a sum over longitudinally boosted thermal sources

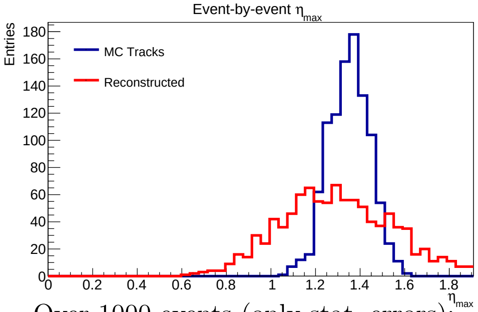
Momentum spectrum with longitudinal flow

$$\frac{dN}{m_T dm_T dy d\phi}(y, m_T, \phi) \to \int_{-\eta_{\max}}^{\eta_{\max}} d\eta \, \frac{dN}{m_T dm_T dy d\phi}(y - \eta, m_T, \phi).$$

E. Schnedermann, J. Sollfrank, U. Heinz, Phys. Rev. C 48, 2462 (1993)

Rapidity distribution is not very sensitive to T.





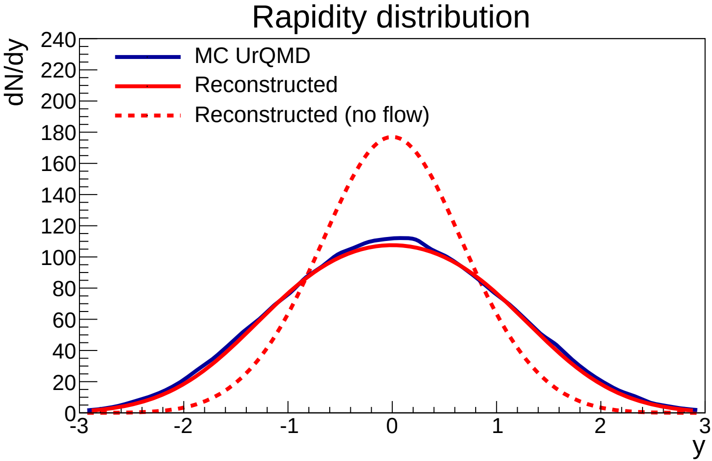
$\langle y^2 \rangle$ monotonic w.r.t. $\eta_{\max}$

Over 1000 events (only stat. errors):

4π-MC	$\eta_{\max} = 1.35 \pm 0.01$
Reconstructed	$\eta_{\max} = 1.30 \pm 0.02$

Longitudinal flow within Blast-Wave model

1000 events



Inclusion of longitudinal flow needed to describe dN/dy.

Full UrQMD rapidity distribution in 4π acceptance described well with the reconstructed one using only reconstructed particles.

Hadron-resonance gas (HRG) at freeze-out model

Allows to extract thermal parameters at chemical freeze-out

Key assumptions

- Matter is thermalized at chemical freeze-out
- Same T and μ_B at all freeze-out space-time points
- Hadron yields according to statistical distribution

J. Cleymans, H. Satz, Z. Phys. C57, 135 (1993).

Density of thermal hadrons

$$n_i = \frac{g_i}{(2\pi)^3} \int d^3p \left\{\exp[(\omega_p^i - \mu_i)/T] \pm 1\right\}^{-1}$$

$$\mu_i = B^i \mu_B + Q^i \mu_Q + S^i \mu_S, \quad \omega_p^i = \sqrt{m_i^2 + p^2}.$$

Total hadron density – thermal + resonance decays

$$n_i^{tot} = n_i + \sum_{j \neq i} Br(j \to i) n_j.$$

Total yields are defined by volume V: $N_i = V n_i$.

HRG model: Toy Monte Carlo generator

Toy Monte Carlo generator

1. For given T, μ_B and V calculate total average N_i for all stable particles.
2. In each event number of particle species i calculated according to Poisson's distribution with mean N_i.
3. Thermal p_t and Gaussian rapidity y.

Implemented as event generator for testing.

Event-by-event extraction of T and μ_B by fitting multiplicity ratios of observables, e.g. π^+, π^-, K^+, K^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$ etc.

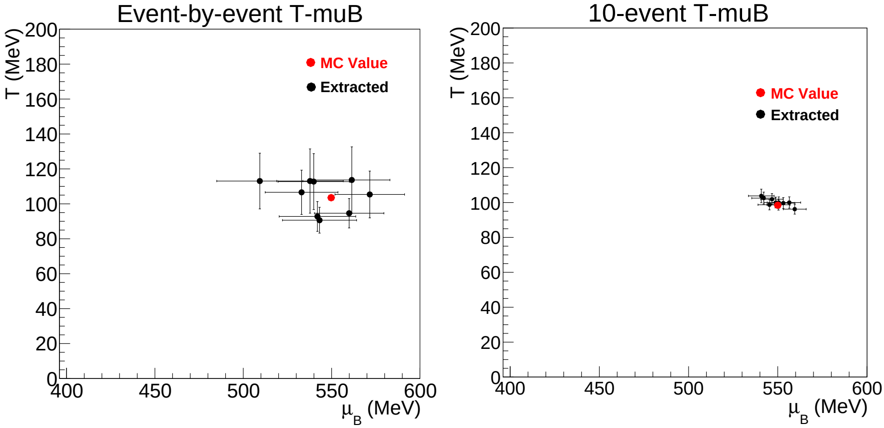
We minimize χ^2

$$\chi^2 = \sum_{ratios} \frac{(\phi_i^{\mathrm{HRG}} - \phi_i^{\mathrm{exp}})^2}{\sigma_i^2}$$

HRG model: Toy Monte Carlo generator

Fit to π^-/π^+, K^-/K^+, K^+/π^+ and p/π^-

Event-by-event fit | Fit to 10-event batches



MC Values: $T = 100$ MeV, $\mu_B = 550$ MeV.

At higher statistics rare probes can also be included.

Summary

1. A package to extract the parameters of theoretical models in CBM experiment is implemented.
2. Extraction of parameters of Boltzmann distribution with and without longitudinal flow is performed.
3. Correction for acceptance and reconstruction efficiency is performed.
4. Chemical freeze-out parameters are extracted from HRG model.

Plans

- Optimization.
- Add other models.

Summary

1. A package to extract the parameters of theoretical models in CBM experiment is implemented.
2. Extraction of parameters of Boltzmann distribution with and without longitudinal flow is performed.
3. Correction for acceptance and reconstruction efficiency is performed.
4. Chemical freeze-out parameters are extracted from HRG model.

Plans

- Optimization.
- Add other models.

Thanks for your attention!