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Snapshots of fireballs at freeze-out from heavy-ion collisions at different energies

Ivan Melo (Žilina) & Boris Tomášik (Banská Bystrica)

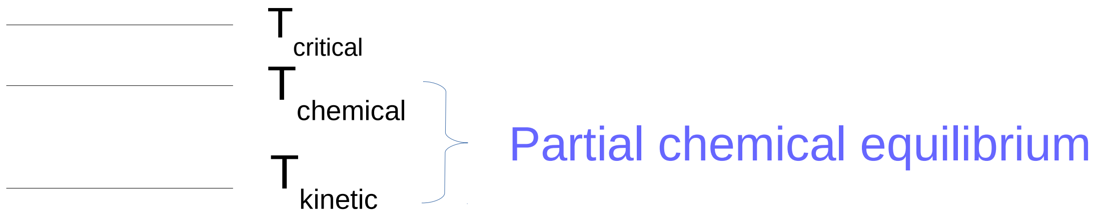
Motivation

Phase diagram of strongly interacting matter can be explored with heavy-ion collisions at various energies

Dependences of various variables on energy E are studied for that purpose

Here we reconstruct T(E) and v_t(E) of the fireball at the moment of the kinetic freeze-out from fits to p_t spectra of *p, anti-p,*π^+*,*π^-*,*K^+*,*K^- from the most central collisions

Scenario with two freeze-outs, chemical and kinetic :



$T_{critical}$

$T_{chemical}$

$T_{kinetic}$

Partial chemical equilibrium

Blast wave model kinetic freeze-out implemented in DRAGON MC tool

P_t spectra fits typically do not include resonance decays

See, e.g., ALICE Collaboration ArXiv:1303.0737[hep-ex]: Centrality dependence of pi,K,p production in Pb-Pb at 2.76 TeV

DRAGON

B. Tomášik, Comp. Phys. Commun. 180 (2009) 1642- 1653.

DRAGON is MC code based on Blast Wave model
+ decays of unstable resonances, 277 hadrons included + possible fragmentation of fireball is included

$$E\frac{d^3N}{dp^3} = \int_\Sigma S(x,p)\,d^4x \qquad S(x,p)\,d^4x = g_i \overbrace{\frac{m_t\cosh(\eta-y)}{(2\pi)^3}}^{\text{Energy of particle}} \overbrace{\left(\exp\left(\frac{p_\mu u^\mu-\mu_i}{T}\right)\pm 1\right)^{-1}}^{\text{Bose/Einstein – Fermi/Dirac}} \underbrace{\theta\left(1-\frac{r}{R}\right)}_{\text{Uniform distribution within R}}$$

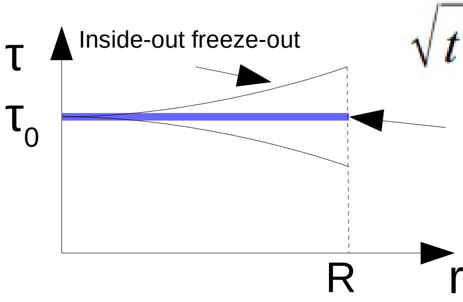
$$\times\, r\,dr\,d\varphi\,\delta(\tau-\tau_0)\,\tau\,d\tau\,d\eta\,.$$

Boost invariant and cylindrically symmetric

$$\eta = \tfrac{1}{2}\ln((t+z)/(t-z))$$

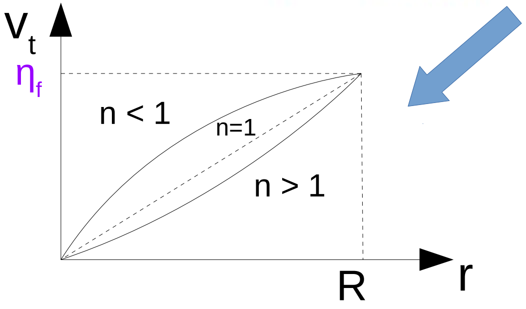
Freeze-out at const proper time

$$\sqrt{t^2-z^2}=\tau_0=const$$



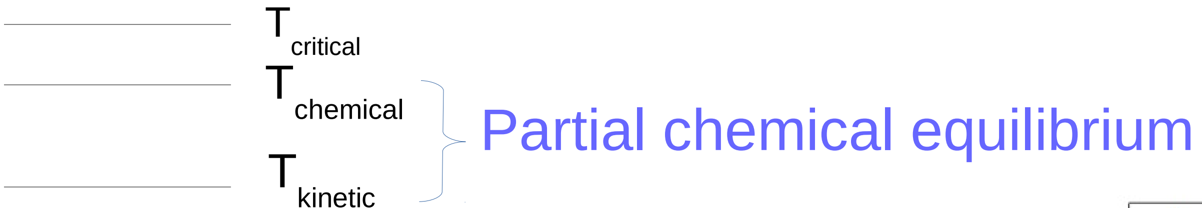
R is radius of fireball at freeze-out

Transverse velocity $v_t = \tanh\eta_t = \eta_f\left(\frac{r}{R}\right)^n$



B. Abelev *et al.* [ALICE collaboration], Phys. Rev. C **88**, 044910 (2013).

$T = T_{kin}$ freeze-out temperature, η_f transverse flow gradient, n profile of transverse velocity



Partial chemical equilibrium

Input data from STAR & ALICE

$T_{chemical}$

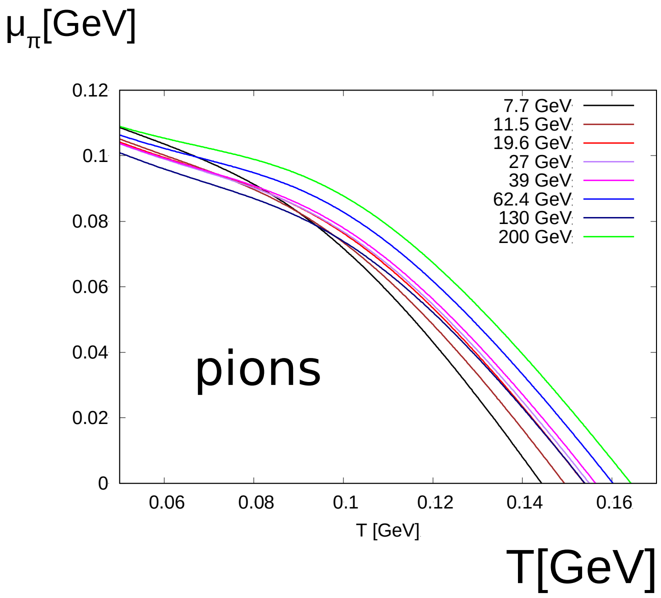
$\sqrt{s_{NN}}$ [GeV]	T [MeV]	μ_B [MeV]	μ_S [MeV]
7.7	144.3	389.2	89.5
11.5	149.4	287.3	64.4
19.6	153.9	187.9	45.3
27	155.0	144.4	33.5
39	156.4	103.2	24.5
62.4	160.3	69.8	16.7
130	154.0	29.0	2.4
200	164.3	28.4	5.6
2760	156.0	0.0	0.0

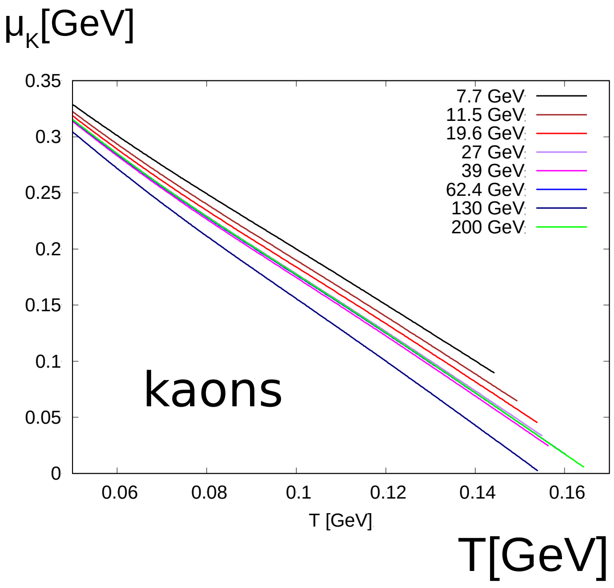
These values reproduce the ratios of hadron multiplicities we take them as input

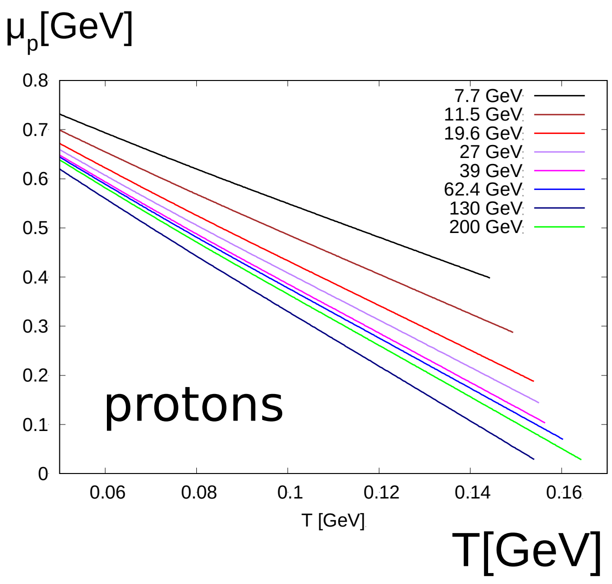
Interactions maintain partial equilibrium between stable hadrons and resonances through which they interact, e.g.

$\rho \leftrightarrow \pi\pi$ $\qquad N_\pi + 2\,N_\rho$ conserved

Pions, kaons, protons and resonances develop chemical potentials below $T_{chemical}$







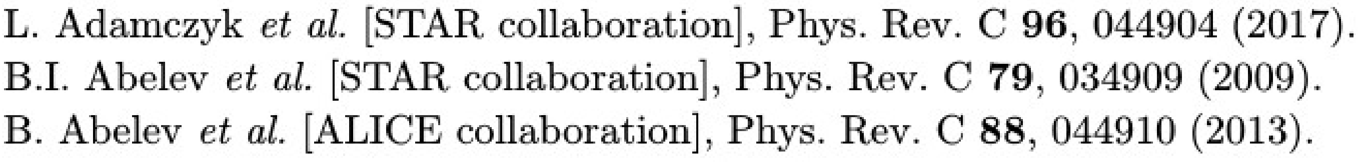
Experimental data

We fitted p_t spectra of *p, anti-p,* π^+, π^-, K^+, K^- from the most central collisions

at $\sqrt{s_{NN}}$ = *7.7, 11.5, 19.6, 27, 39 GeV* STAR [1], $p_t < 2$ GeV

$\sqrt{s_{NN}}$ = *62.3, 130, 200 GeV* STAR [2], $p_t < \sim 0.7 – 1.1$ GeV

and $\sqrt{s_{NN}}$ = *2760 GeV* ALICE [3] $p_t < 2$ GeV



[1] L. Adamczyk *et al.* [STAR collaboration], Phys. Rev. C **96**, 044904 (2017).
[2] B.I. Abelev *et al.* [STAR collaboration], Phys. Rev. C **79**, 034909 (2009).
[3] B. Abelev *et al.* [ALICE collaboration], Phys. Rev. C **88**, 044910 (2013).

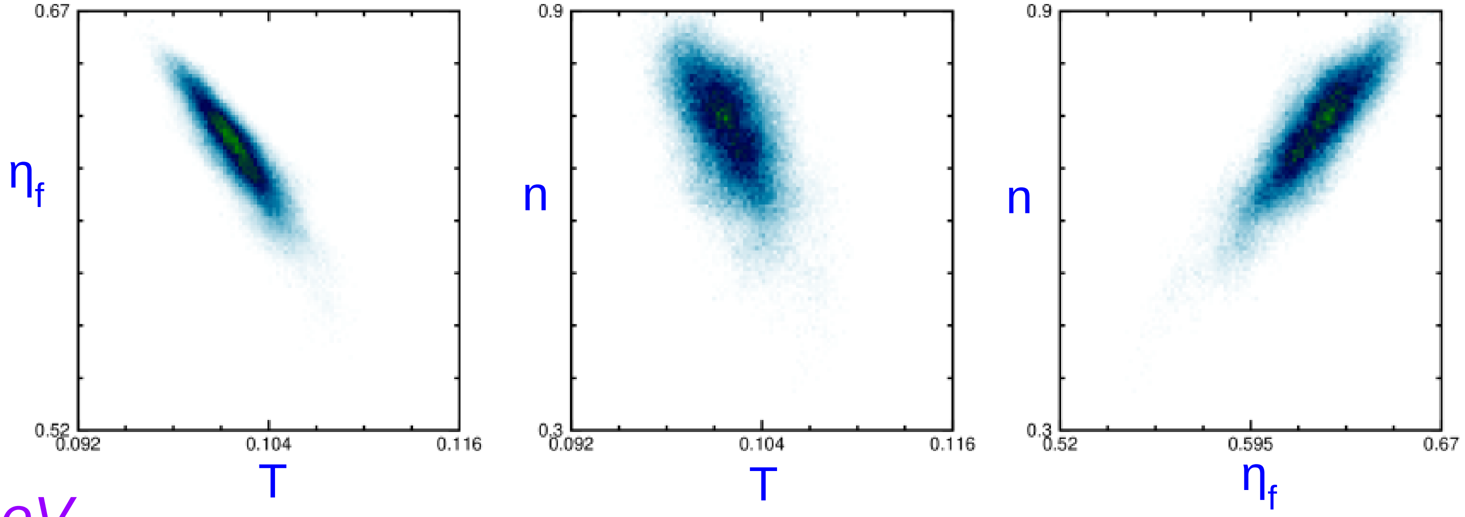
MADAI fitting technique

- The best fit point (T, η_f, n) was found using MADAI package [4], a Monte Carlo exploration of the 3-parameter space weighted by the posterior probability
- First, 400 training points are generated at random
- p_t spectra were generated in each training point with DRAGON (0.5 – 5 hours/point) for each of 6 species, spectrum is normalized independently
- Posterior probability in points other than training points is estimated with Gaussian emulator trained on the training points
- Output of MADAI is the best fit point + uncertainties + correlation matrix among parameters (can be displayed as 2-dim projections of the posterior distribution)

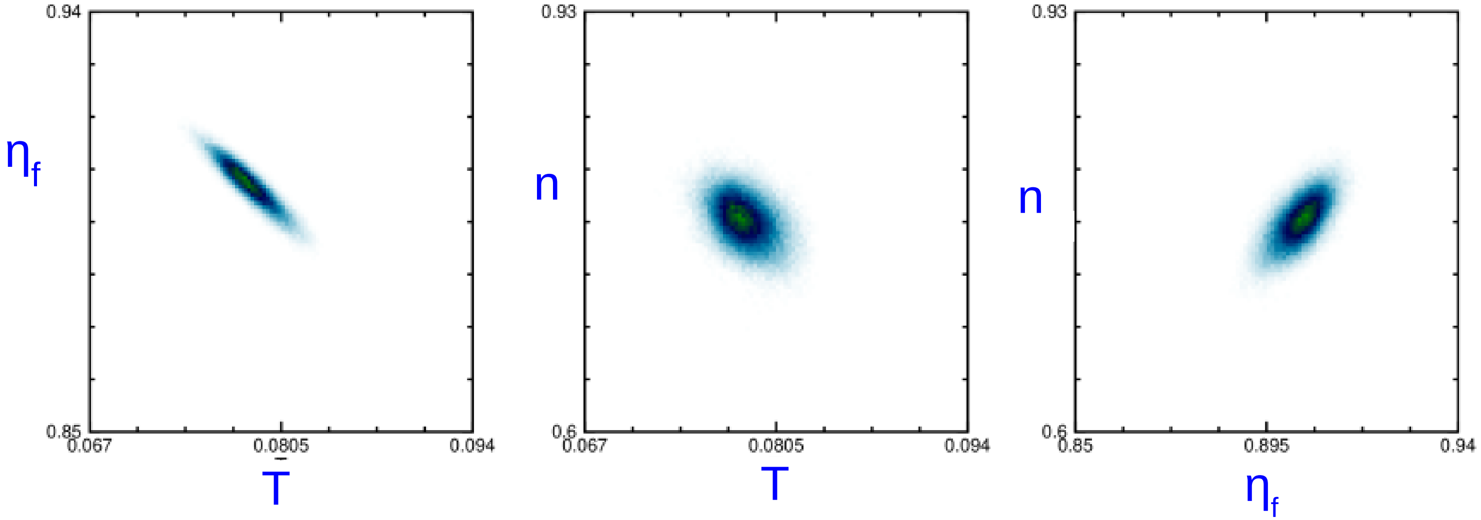
[4] J. Novak, K. Novak, S. Pratt, C. E. Coleman-Smith and R. L. Wolpert Determining Fundamental Properties of Matter Created in Ultrarelativistic Heavy-Ion Collisions, arXiv:1303.5769 [nucl-th] (2013). http://arxiv.org/abs/1303.5769

MADAI: 2-dim projections of posterior probability

$\sqrt{s_{NN}}$ = 7.7 GeV

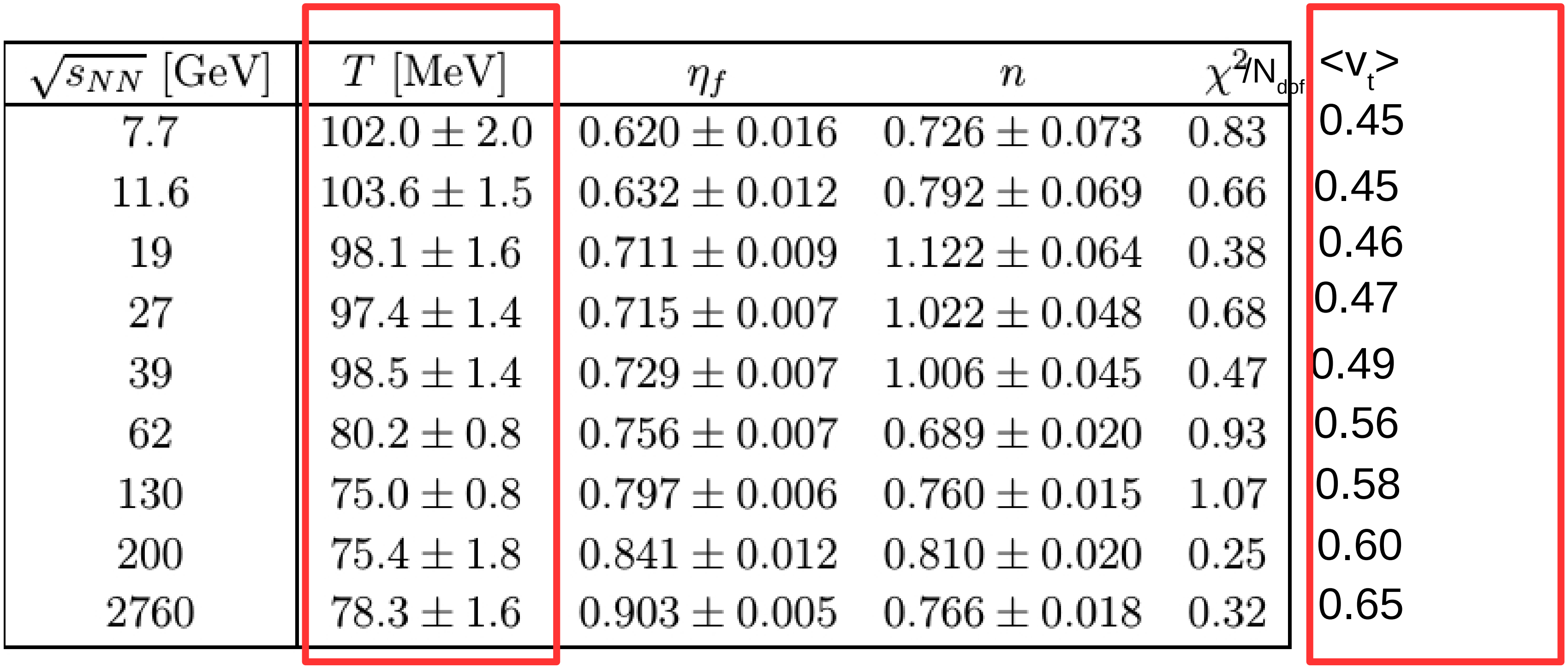


$\sqrt{s_{NN}}$ = 2760 GeV



Best fit parameters

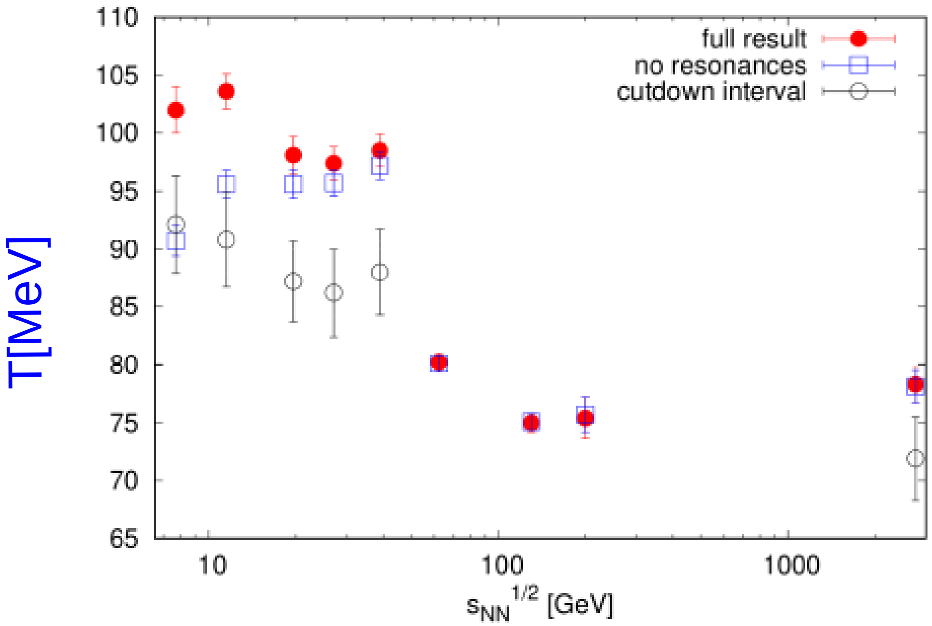
χ^2 fit was performed as an independent check

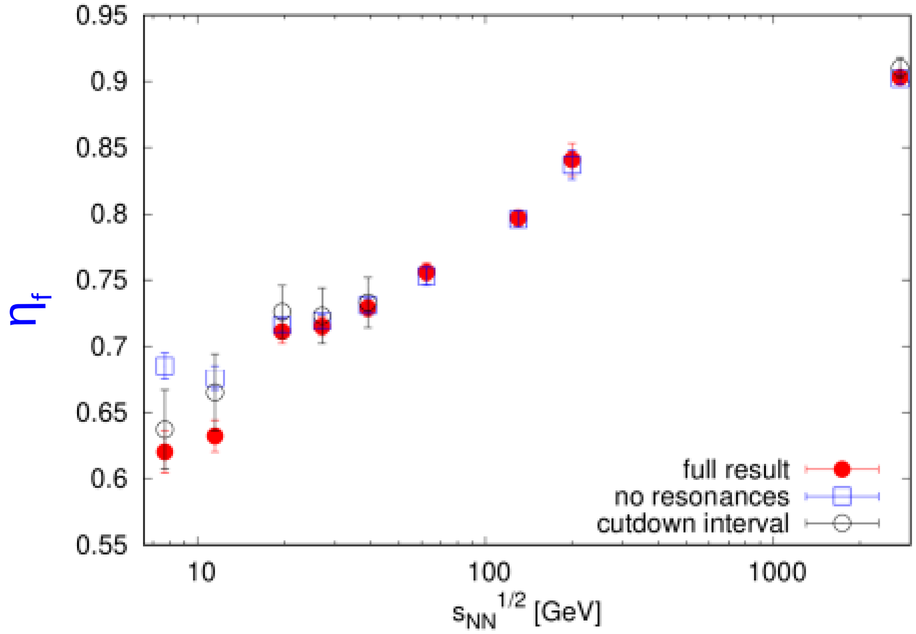


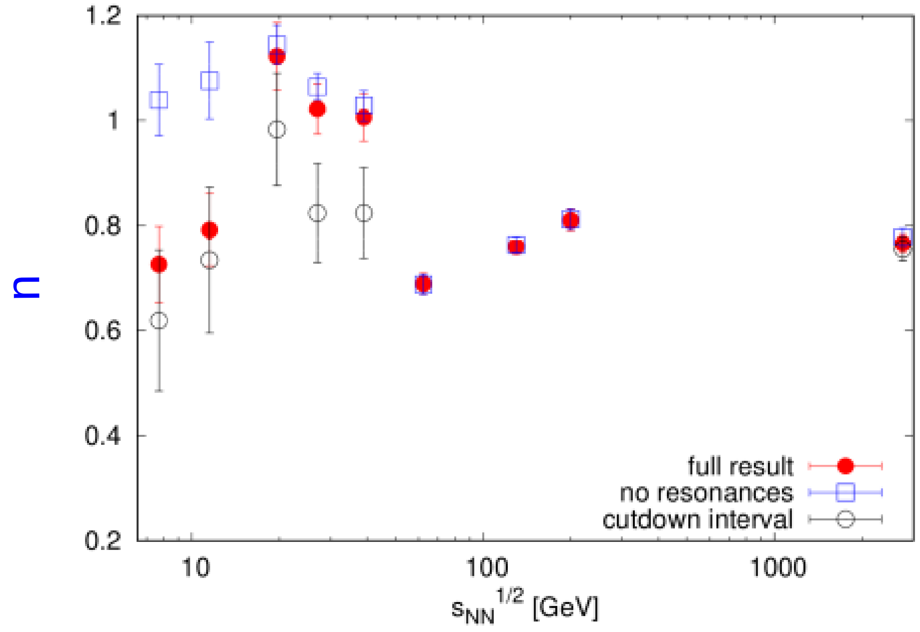
$\sqrt{s_{NN}}$ [GeV]	T [MeV]	η_f	n	χ^2/N_{dof}	$\langle v_t \rangle$
7.7	102.0 ± 2.0	0.620 ± 0.016	0.726 ± 0.073	0.83	0.45
11.6	103.6 ± 1.5	0.632 ± 0.012	0.792 ± 0.069	0.66	0.45
19	98.1 ± 1.6	0.711 ± 0.009	1.122 ± 0.064	0.38	0.46
27	97.4 ± 1.4	0.715 ± 0.007	1.022 ± 0.048	0.68	0.47
39	98.5 ± 1.4	0.729 ± 0.007	1.006 ± 0.045	0.47	0.49
62	80.2 ± 0.8	0.756 ± 0.007	0.689 ± 0.020	0.93	0.56
130	75.0 ± 0.8	0.797 ± 0.006	0.760 ± 0.015	1.07	0.58
200	75.4 ± 1.8	0.841 ± 0.012	0.810 ± 0.020	0.25	0.60
2760	78.3 ± 1.6	0.903 ± 0.005	0.766 ± 0.018	0.32	0.65

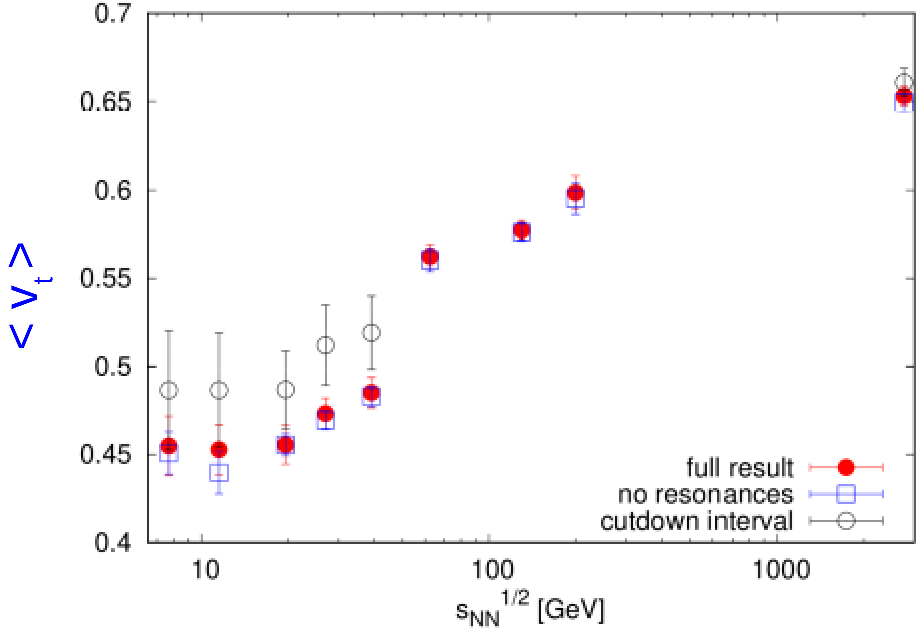
$$v_t = \tanh \eta_t = \eta_f \left(\frac{r}{R}\right)^n \longrightarrow \langle v_t \rangle = \frac{2}{n+2}\eta_f$$

Energy dependence of the freeze-out parameters

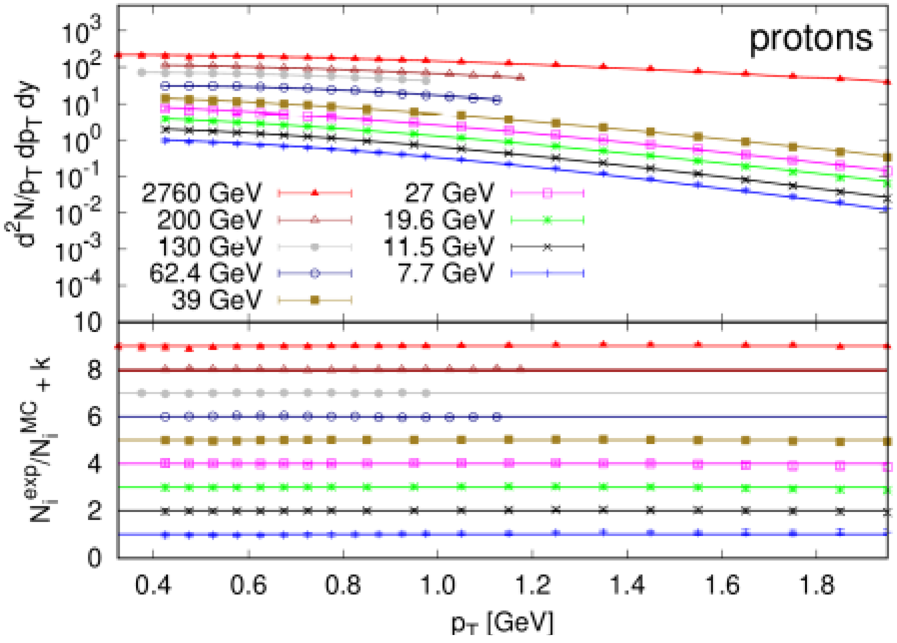




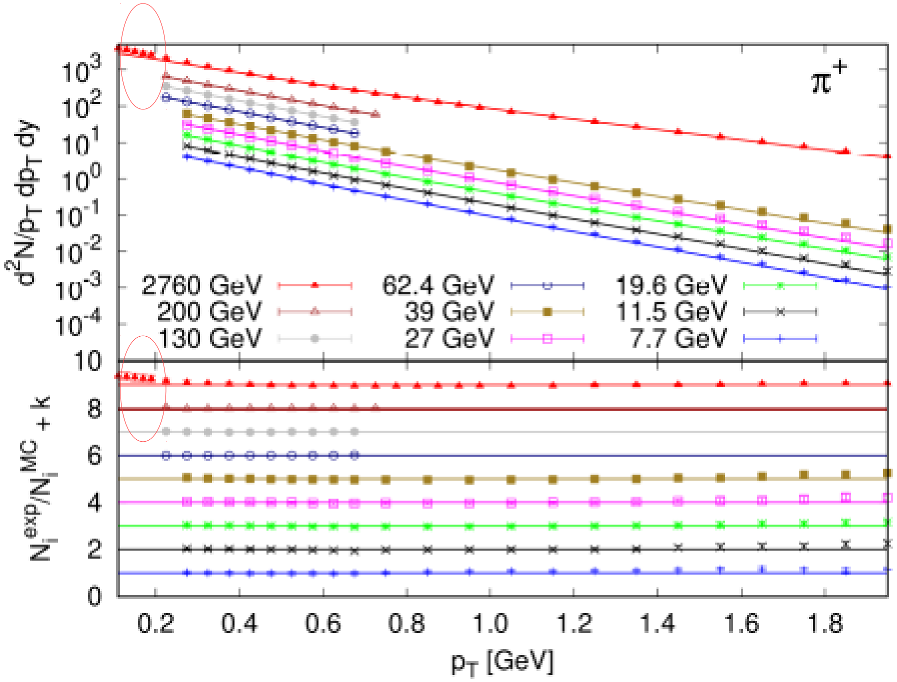




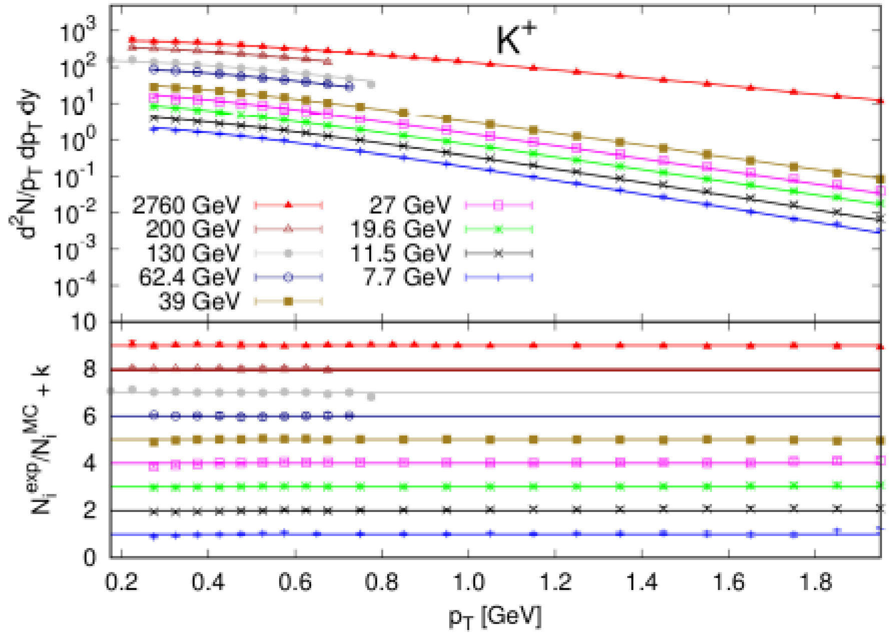
Transverse momentum spectra at different energies
+ ratio data/MC



R



R

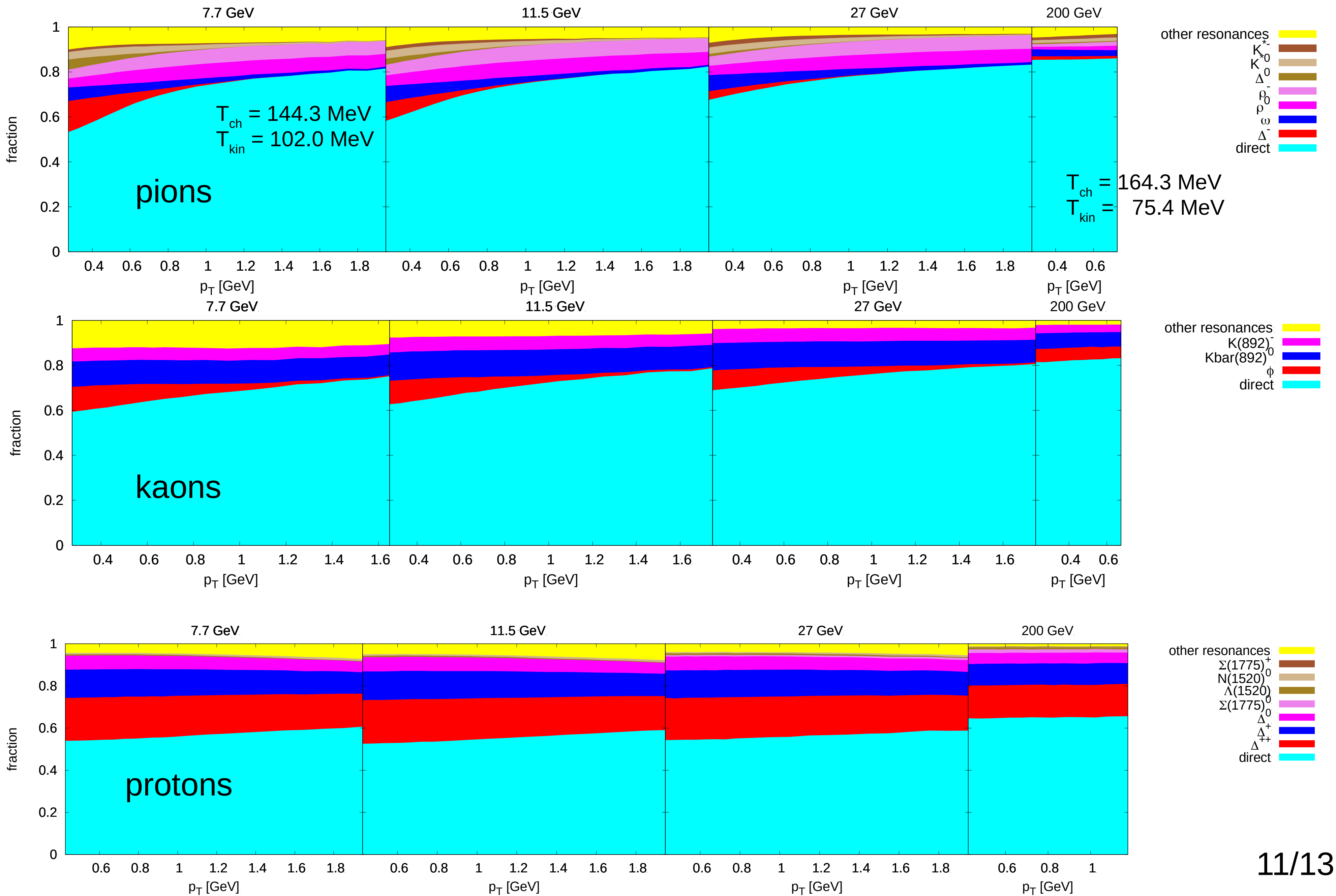


R

ratio R = data/MC + k (k = 0,1,2,...8)
to display all ratios in one Fig.

Anatomy of spectra

Fraction of π-, K-, p coming either from a given resonance or direct production



Anatomy of spectra cont‘d

- Fraction of resonance-produced hadrons goes down as energy goes up

E = 7.7 GeV: T_{ch} = 144.3 MeV
T_{kin} = 102.0 MeV

E = 200 GeV: T_{ch} = 164.3 MeV
T_{kin} = 75.4 MeV

- Fraction of resonance-produced hadrons becomes flat at high energy unlike at low energy

$$\Delta^- \rightarrow n + \pi^- , \qquad m_\Delta = 1\,232 \text{ MeV}$$

Δ- decay happens closely above the threshold, so that daughter particles do not acquire high momentum,

p_t = 227.7 MeV

In combination with small transverse expansion velocity this causes that pions from such decays stay at low pt

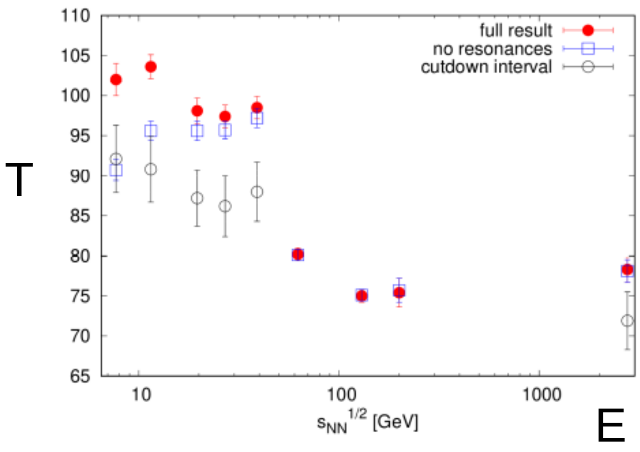
p_t = 500 MeV for 7.7 GeV

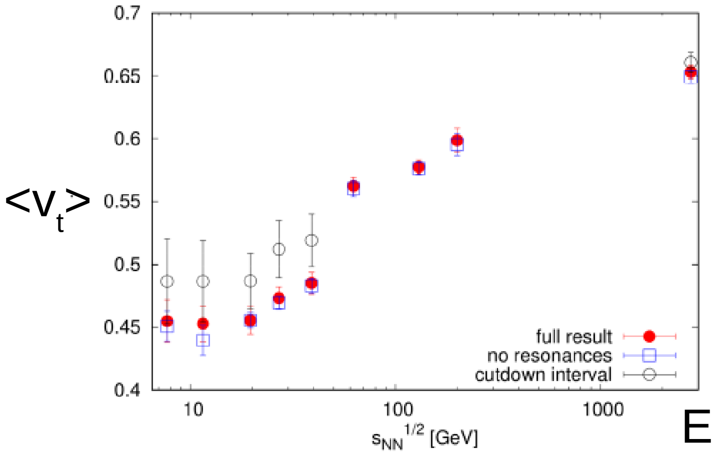
p_t = 1 090 MeV for 200 GeV

The same applies for kaons from the decay of Φ.

Summary

- With increase of collision energy the fireball cools down more and develops stronger transverse expansion





- Although the freeze-out temperature seems to show a sharp step between 39 and 62.4 GeV, it may be connected with different coverage of p_t intervals
- Full results with resonances coincide with those with only directly produced hadrons, i.e. no resonances, except for the two lowest collision energies.
- Lowest p_t pions at LHC are underestimated by the fits (unlike in nonequilibrium Cracow freeze-out model)
- A more comprehensive study which will include the centrality dependence is being elaborated