Thermal model description of the particle spectra in the few-GeV energy regime

Szymon Harabasz (TU Darmstadt / GSI) in collaboration with:

Wojciech Florkowski
Jagiellonian University

Tetyana Galatyuk
TU Darmstadt / GSI

Malgorzata Gumberidze
GSI

Radoslaw Ryblewski
IFJ PAN

Piotr Salabura
Jagiellonian University

Joachim Stroth
Goethe-University Frankfurt / GSI

based on: PRC 102 (2020) 5, 054903, arXiv: 2003.12992 [nucl-th]

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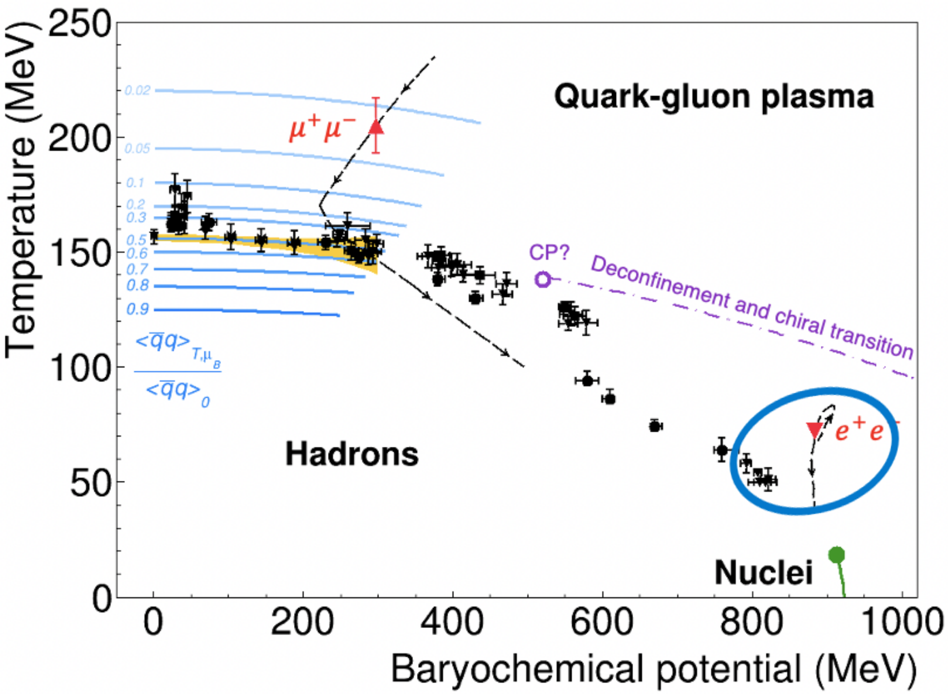
SQM2021

Mapping the phase diagram with the Statistical Hadronization Model



HADES, Nature Phys. 15 (2019) 10, 1040-1045
A. Andronic *et al.*, Nature 561 (2018) no.7723
LQCD: S. Borsanyi *et al.* [Wuppertal-Budapest], JHEP 1009 (2010) 073
LQCD: A. Bazavov *et al.*, PLB 795 (2019) 15-21

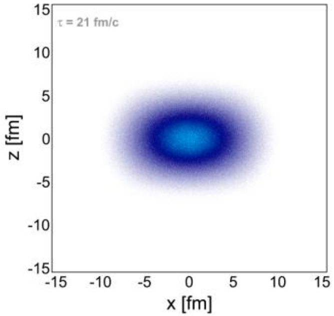
- Is it valid at all to use equilibrium methods at low energies?
  - Particles with strange quarks produced deep below the NN threshold
  - Low number of newly produced particles in the interaction zone: ~40 in central events (mainly pions)
- On the other hand:
  - Original nucleons stopped in the interaction zone (~300 particles in central events)
  - Longer life-time of the system – enough to thermalize

Hydro-inspired models

of particle production at the freeze-out

- **First idea:**
  P. J. Siemens and J. O. Rasmussen, PRL 42 (1979) 880
  - Used for Ne+NaF at $E_{kin}/A = 0.8$ GeV!
  - Thermal source of spherical geometry and spherically symmetric expansion
  - Constant radial velocity (non-physical for $r = 0$?)

Guidance from dynamic models



- Density evolution in Au+Au at $E_{kin}/A = 1.23$ GeV
- Coarse-grained hadronic transport
  T. Galatyuk *et al.*, EPJA 52 (2016) 5, 131
- Spherical symmetry clearly more realistic than boost invariance

- **Modification:**
  E. Schnedermann, J. Sollfrank, U. W. Heinz, PRC 48 (1993) 2462
  - Appropriate for higher-energy collisions (originally S+S at $E_{kin}/A = 200$ GeV)
  - Cylindrically-symmetric geometry and expansion
  - Boost invariance in Z direction – "Bjorken scaling"
  - Velocity profile: $\beta(r) = \beta_{max}(r/r_{max})^n$

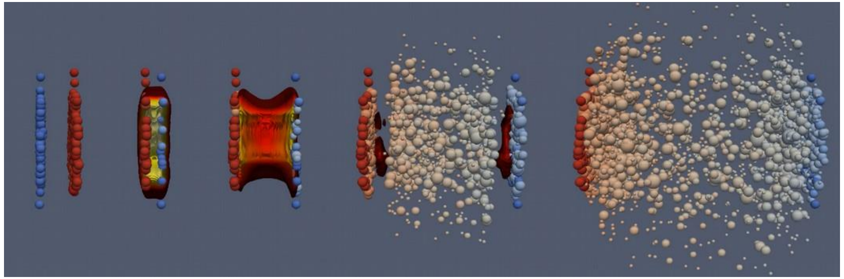
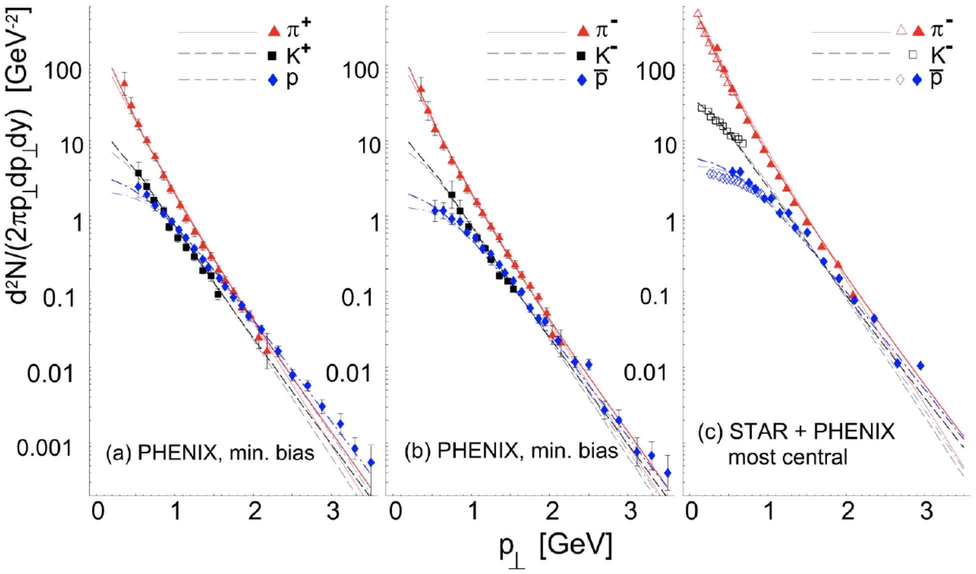


Figure: MADAI collaboration, Hannah Petersen and Jonah Bernhard

Single freeze-out scenario

W. Broniowski and W. Florkowski, PRL 87 (2001) 272302

- Chemical freeze-out coincides with kinetic freeze-out
- Hadron yields are given by the integrals of hadron spectra
- Feed-down from resonance decays included
- Successful at RHIC, does it work at SIS18 energies?
- Idea is implemented in the Thermal Event Generator (Therminator 2)



Resonance treatment

R. Dashen, S. K. Ma and H. J. Bernstein, Phys. Rev. 187 (1969) 345 (1969)
R.Venugopalan, and M. Prakash, Nucl. Phys. A 546 (1992) 718
W. Weinhold, and B. Friman, Phys. Lett. B 433 (1998) 236
Pok Man Lo, Eur. Phys.J. C77 (2017) no.8, 533

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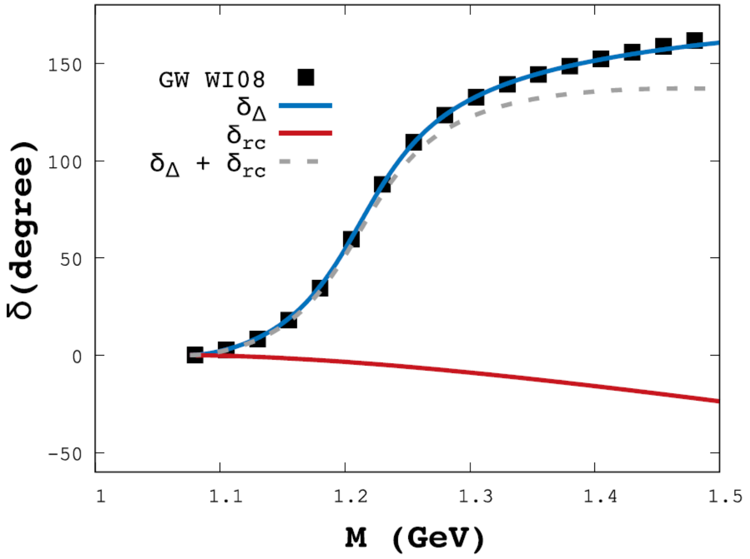
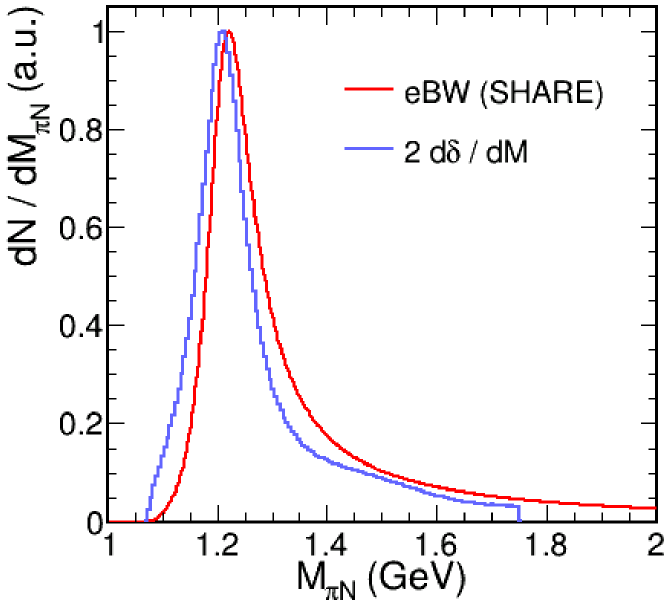
πN phase shift in the P_{33} channel

Pok Man Lo *et al.*, PRC 96, 015207,
GW WI08: R.L. Workman *et al.* PRC 86, 035202



Spectral function: $B_l(M) = 2\frac{d}{dM}\delta_l$



Thermal Event Generator (Therminator 2)

HADES data:
M. Szala, Proceedings of SQM 2019
EPJA 56 (2020) 10, 259
PLB 778 (2018) 403-407
PLB 793 (2019) 457-463

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Ingredients of the method:

M. Chojnacki *et al.*, Comput. Phys. Comm. 103 (2012) 746-773
SH, W. Florkowski, T. Galatyuk *et al.*, PRC 102 (2020) 5, 054903

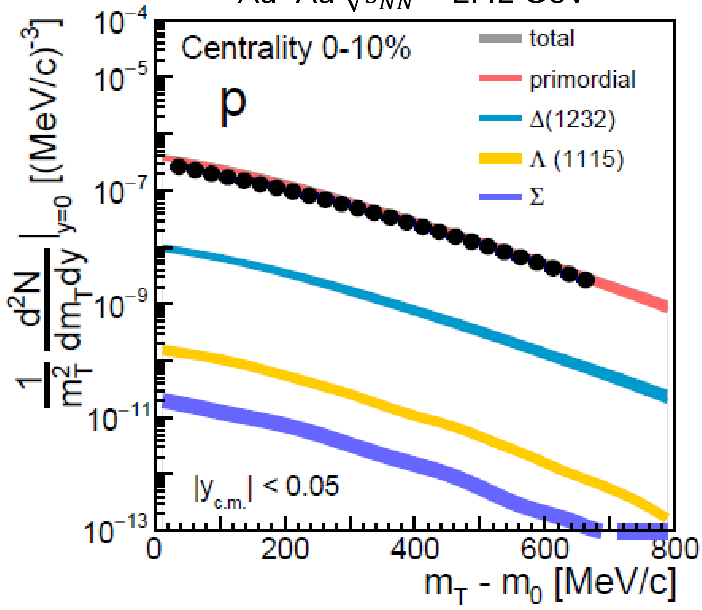
- Single (chemical and kinetic) freeze-out on a **spherically symmetric hypersurface** (Siemens-Rasmussen blast-wave model)
- Fix thermodynamic paremeters with multiplicities of particles:
  — Solve numerically 6 equations for 6 parameters:

protons (incl. those bound in light nuclei):	124.1
π^+:	9.3
π^-:	17.1
K^+:	0.0598
K^-:	0.00056
Λ:	0.0822

→

T = 49.6 MeV
μ_B = 776 MeV
μ_{I3} = -14.1 MeV
μ_S = 123.4 MeV
γ_S = 0.16
R = 16.02 fm

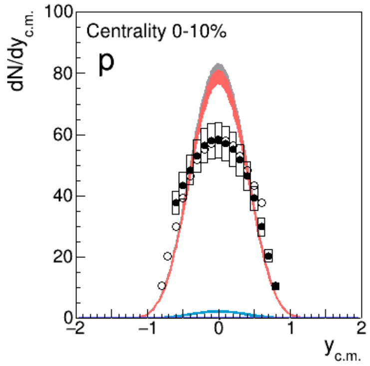
Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV



- Proton m_t spectrum at mid-y is fitted to get the expansion velocity profile: $v = \tanh(Hr)$ with **H = 0.04 fm^{-1}**
- Δ spectral function from πN phase shift

Spectra of bulk particles

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV, 0-10%



T = 49.6 MeV

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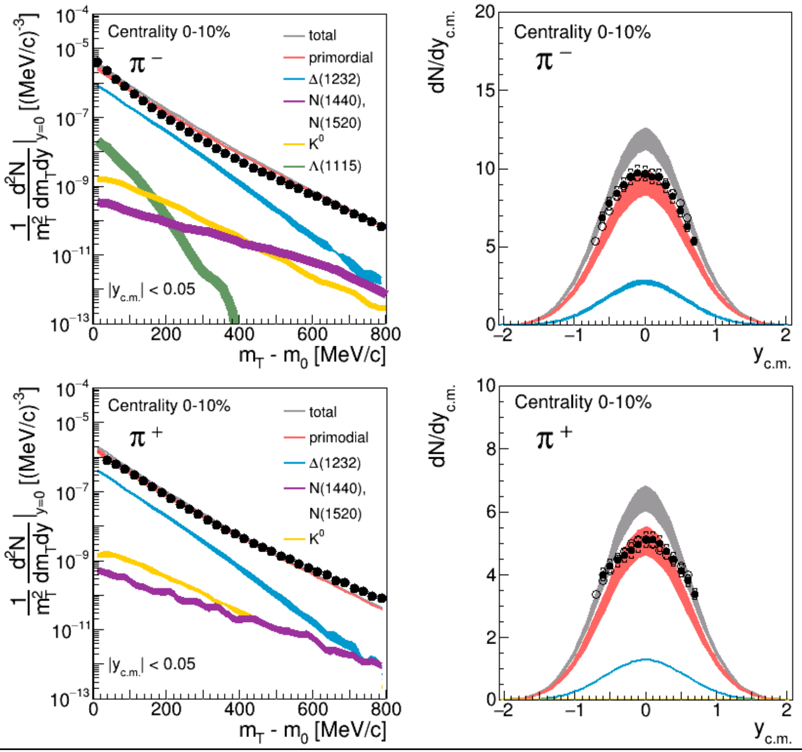
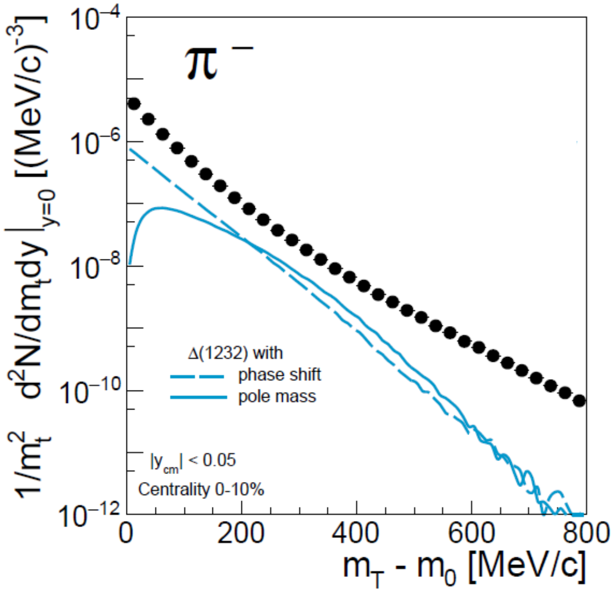
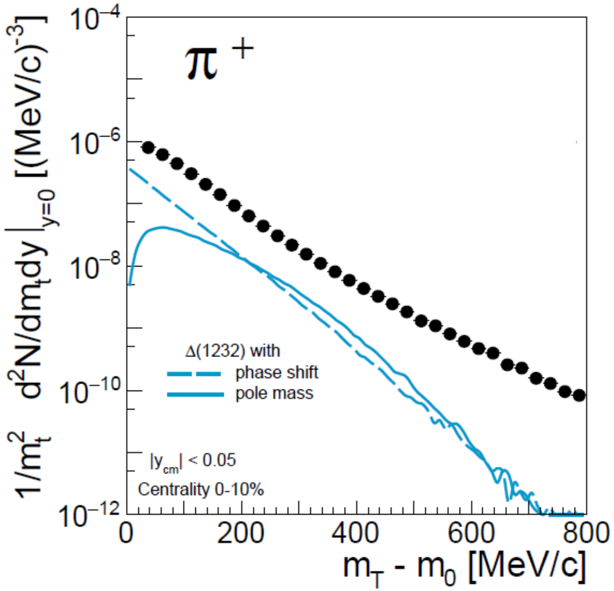


- These spectra are **not fitted**, but **predicted** by the model
- Bands: uncertainty from errors on hadron yields
- Pion slope at high m_t described with T ~ 50 MeV and Hubble
- Rapidity too narrow in the model
  - — Spherical symmetry is not exactly fulfilled
  - — Further improvements are ongoing

Influence of the Δ description on pion spectra





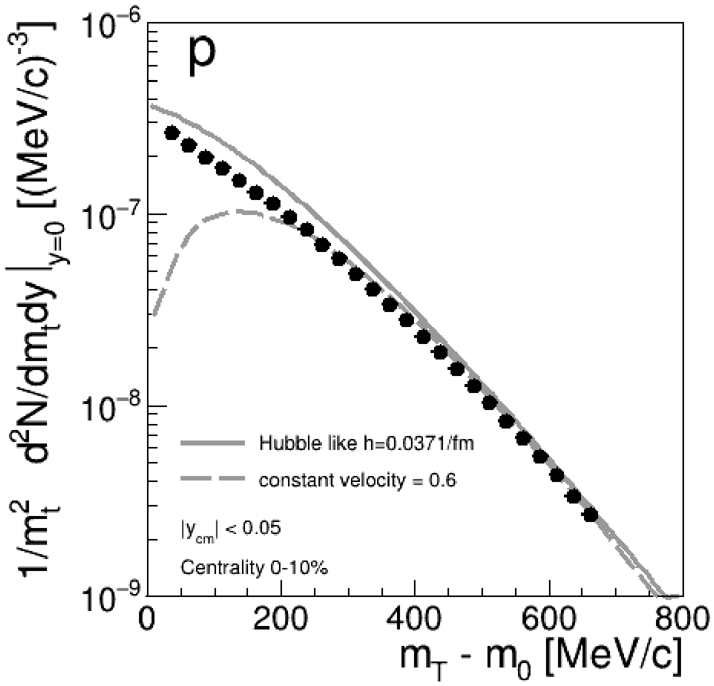
Transverse mass of pions from Δ decay for different spectral functions:

- Δ with fixed mass of 1.232 GeV
- Spectral function from the πN phase shift in the P_{33} channel

Finite Δ width:
→ populate low m_t pions

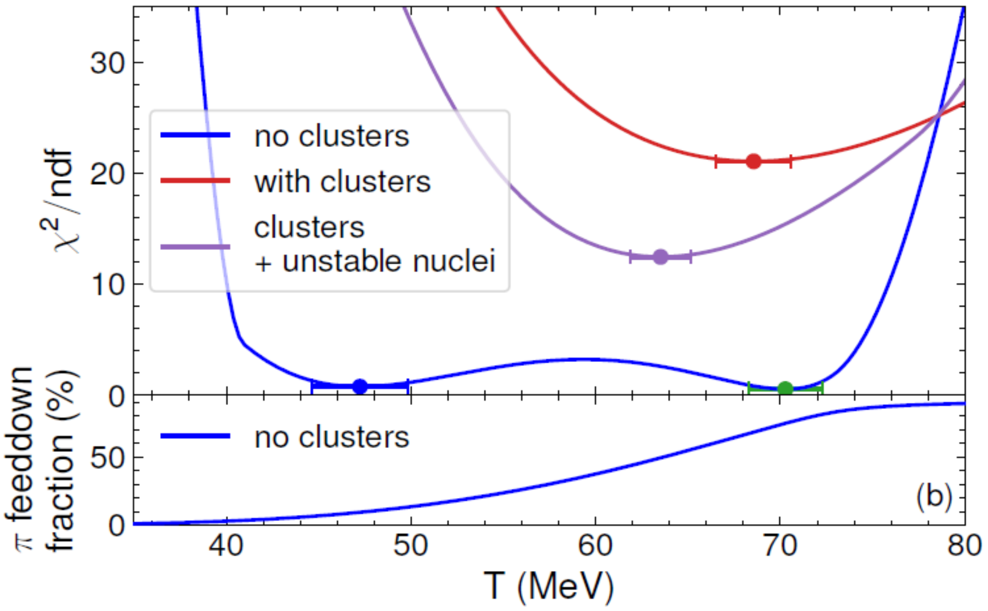
Influence of the velocity profile

- Hubble-like fireball expansion:
$$v(r) = \tanh(Hr)$$
- The parameter *H* fitted to the proton m_t spectra:
$$H \ = \ 0.037\ fm^{-1}$$
- Mean value:
$$\langle v \rangle = \frac{2}{3} HR \left(1 - \frac{1}{5} H^2 R^2 \right) \approx 0.4$$
- Best fit with constant velocity
  — Gives $\langle v \rangle = 0.6$
  — Fails to describe the data at low m_t



Outlook:
other approaches to thermal parameters

A. Motornenko *et al.*, arXiv:2104.06036 [hep-ph]



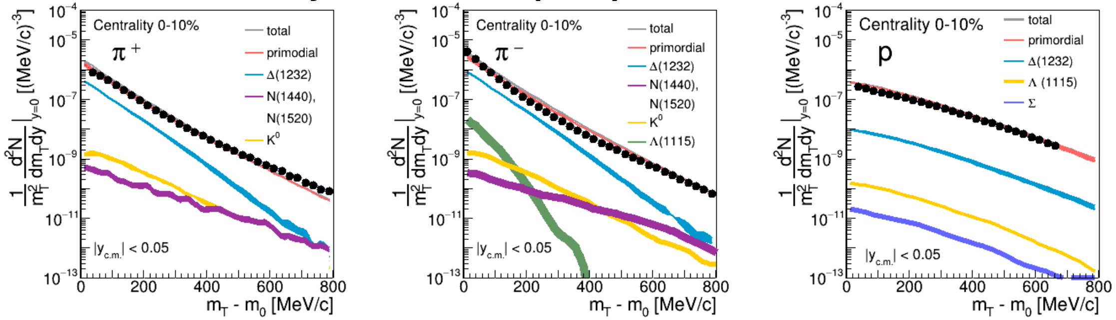
Parameter	Harabasz *et al.* [1]	no clusters low T minimum	no clusters high T minimum	with clusters	with clusters + unstable nuclei
T (MeV)	49.6 ± 1.1	47.2 ± 2.6	70.3 ± 2.0	68.6 ± 2.0	63.5 ± 1.6
R (fm)	16.0	18.9 ± 2.2	6.8 ± 0.9	9.0 ± 0.4	10.4 ± 0.3
μ_B (MeV)	776 ± 3	780.1 ± 3.8	872.1 ± 24.3	786.7 ± 2.9	781.1 ± 3.3
γ_S	0.16 ± 0.02	0.19 ± 0.07	0.05 ± 0.01	0.03 ± 0.01	0.04 ± 0.01
χ^2/N_{df}	$N_{\mathrm{df}} = 0$	1.58/2	1.13/2	105.30/5	62.30/5

- In this manuscript Q/B = 0.4 and total S = 0 are kept as constraints
- We recover parameters needed to run Therminator:
  — μ_{I3} = -21.05 MeV
  — μ_S = 198.63 MeV
- We fix the Hubble constant H and readjust R:
  — H = 0.097 1/fm
  — R = 6.1 fm

Outlook:

other approaches to thermal parameters

Parameters from Phys. Rev. C 102 (2020) 5, 054903



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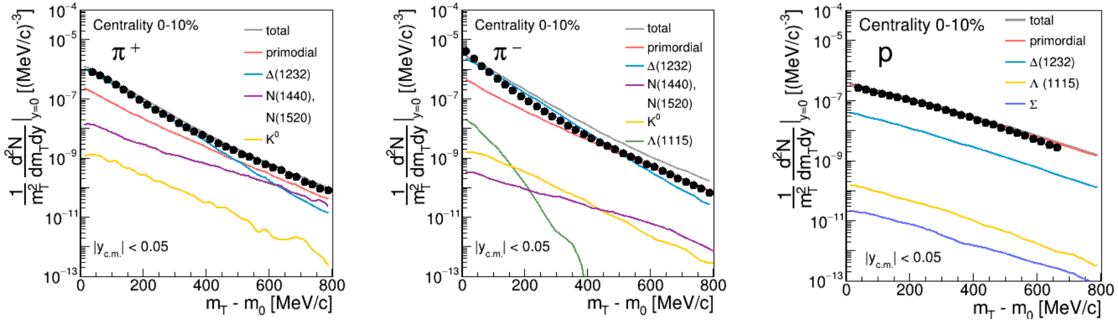


T = 70.3 MeV

μ_B = 876 MeV

μ_{I_3} = -21.5 MeV

μ_S = 198.3 MeV

γ_S = 0.05

R = 6.1 fm

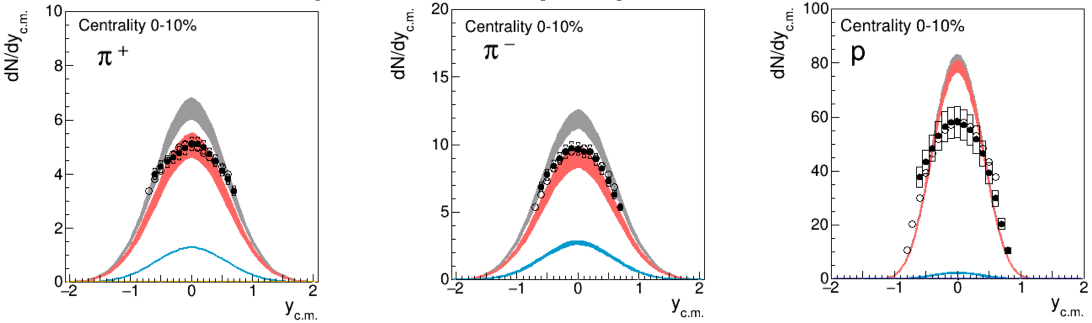
H = 0.097 1/fm

- As expected, stronger contribution of resonance decays in the high-T case
- No grounds to exclude one of the minima by looking qualitatively at the spectra

Outlook:

other approaches to thermal parameters

Parameters from Phys. Rev. C 102 (2020) 5, 054903



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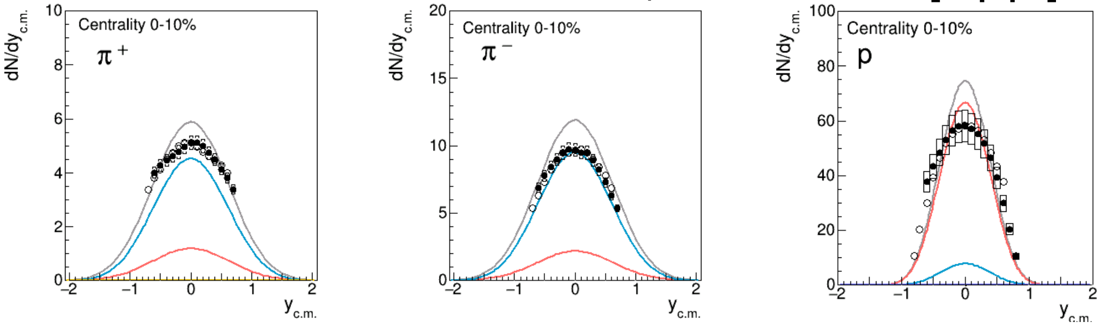

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μ_S = 198.3 MeV

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R = 6.1 fm

H = 0.097 1/fm

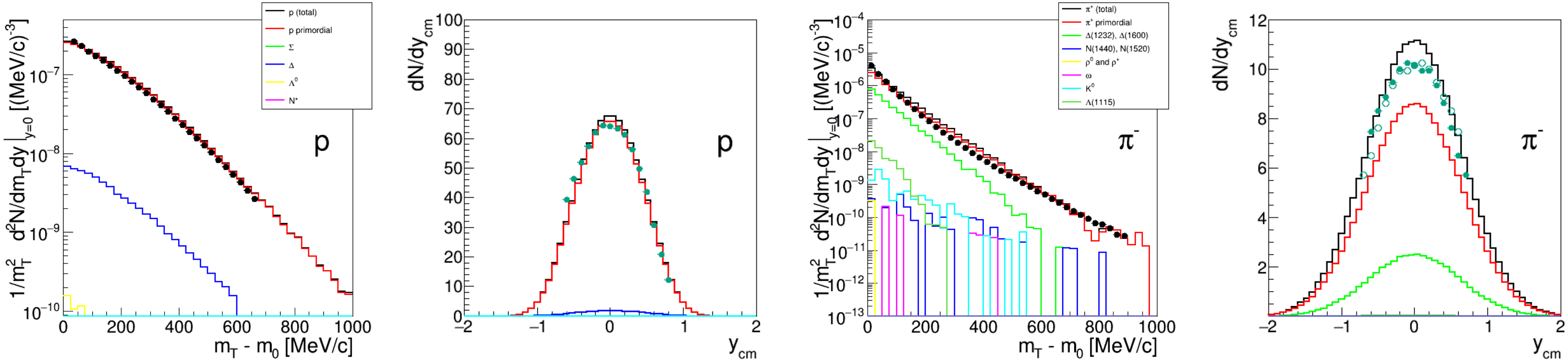
- As expected, stronger contribution of resonance decays in the high-T case
- No grounds to exclude one of the minima by looking qualitatively at the spectra
- No strong influence on the width of *y* spectra
  - — Need to modify the freeze-out hypersurface

Outlook:

moving from spherical to spheroid symmetry

- Transverse momentum spectra are well described, and
- Rapidity spectra are too narrow compared to experiment
  — Expansion in longitudinal direction should be stronger than in transverse direction
- Guidance from dynamic models
  — Freeze-out hypersurface should be narrower in the longitudinal direction

Ongoing work on systematic fitting the shape parameters



Conclusions

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- Statistical hadronization model can describe not only multiplicities, but also spectra of bulk particles produced in heavy-ion collisions in $\sqrt{s_{NN}}$ of few GeV
- Ingredients:
  — Spherical, Siemens-Rasmussen-type fireball expansion
  — Hubble-like velocity profile
  — Sudden freeze-out
  — Careful treatment of baryonic resonances

Outlook:

- Spheroidal instead of spherical symmetry
- Final-state EM interactions
- HBT radii, nucleon coalescence, data from STAR fixed-target, FAIR, NICA…

EXTRA SLIDES

Cooper-Frye formula

F. Cooper and G. Frye, PRD 10 (1974) 186

“Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production”

$$E_p \frac{dN}{d^3p} = \int d^3\Sigma_\mu(x)\, p^\mu\, f(x,p)$$

- Spherically symmetric system:
$$x^\mu = (t(r), r\mathbf{e_r})$$
- Spherical expansion of the "fluid":
$$u^\mu = \frac{1}{\sqrt{1-v^2(r)}}(1, v(r)\mathbf{e_r})$$
- Sudden freeze-out in the "lab" frame ($t = \mathrm{const}(r)$):
$$d^3\Sigma_\mu \equiv \varepsilon_{\mu\alpha\beta\gamma} \frac{\partial x^\alpha}{\partial\zeta} \frac{\partial x^\beta}{\partial\phi} \frac{\partial x^\gamma}{\partial\theta} d\zeta\, d\phi\, d\theta$$
$$= (r^2 \sin\theta\, d\theta\, d\phi\, dr, 0, 0, 0)$$

Parameter of $\zeta \to (t(\zeta), r(\zeta))$

Local thermodynamic equilibrium

$$f(x,p) = \frac{g_s}{2\pi}\left[\Upsilon^{-1} \exp\left(\frac{p_\mu u^\mu}{T}\right) \pm 1\right]^{-1}$$

Fugacity factor:

$$\Upsilon \equiv \gamma_q^{N_q+N_{\bar{q}}} \gamma_s^{N_s+N_{\bar{s}}} \exp\left(\frac{\mu_B B + \mu_S S + \mu_{I_e} I_3}{T}\right)$$

(in this work we assume $\gamma_q = 1$)

- Integrating over the freeze-out hypersurface and phase-space gives back particle multiplicity
- Right sets of assumptions recover the original Siemens-Rasmussen and Schnedermann-Sollfrank-Heinz formulas
- **But we assume Hubble-like expansion:**
$$\boldsymbol{v(r) = \tanh(Hr)}$$