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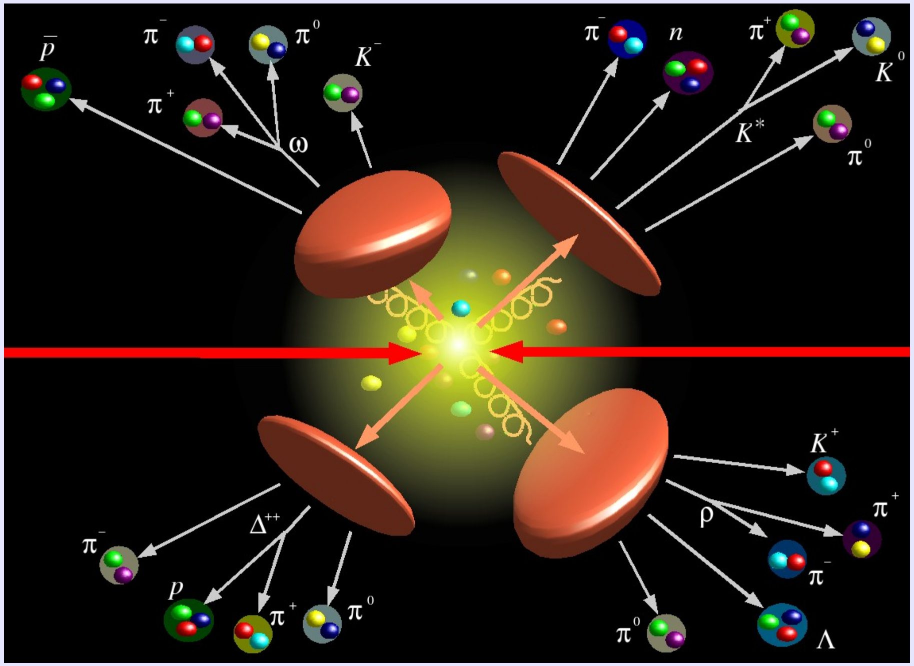
Hadron formation in relativistic nuclear collisions and the QCD phase diagram

OUTLINE

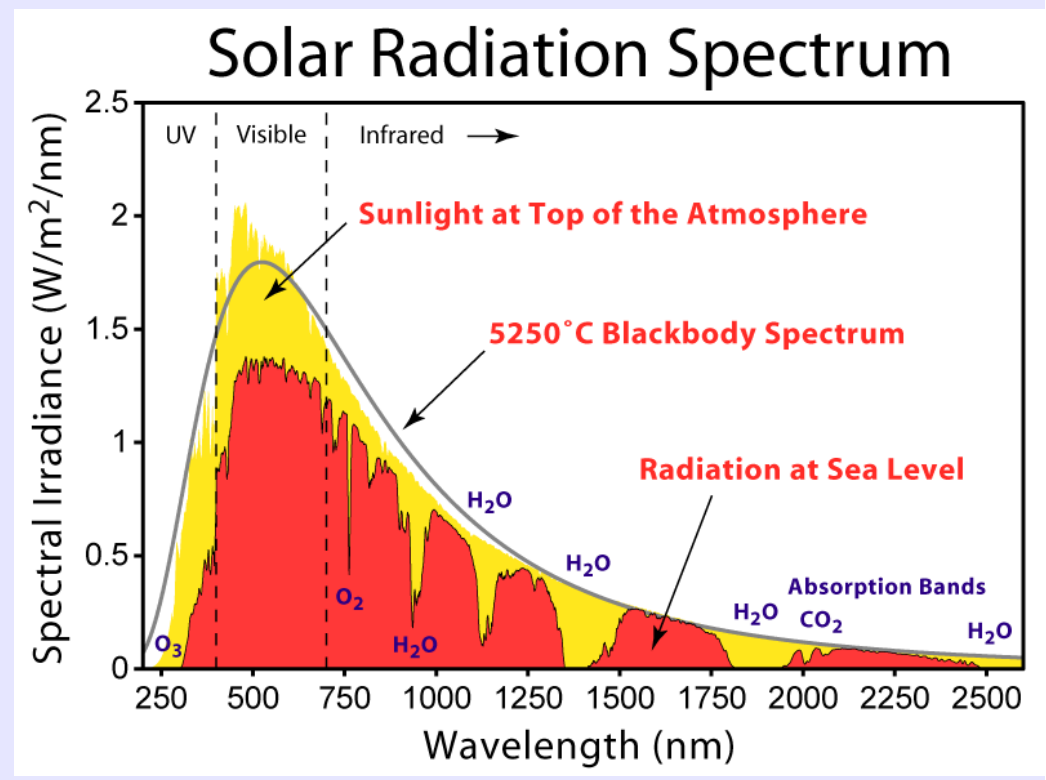
- Introduction
- Chemical freeze-out: small vs large
- Hadronization and QCD phase diagram
- Centrality dependence at the LHC
- Conclusions

NN 2015 - Catania

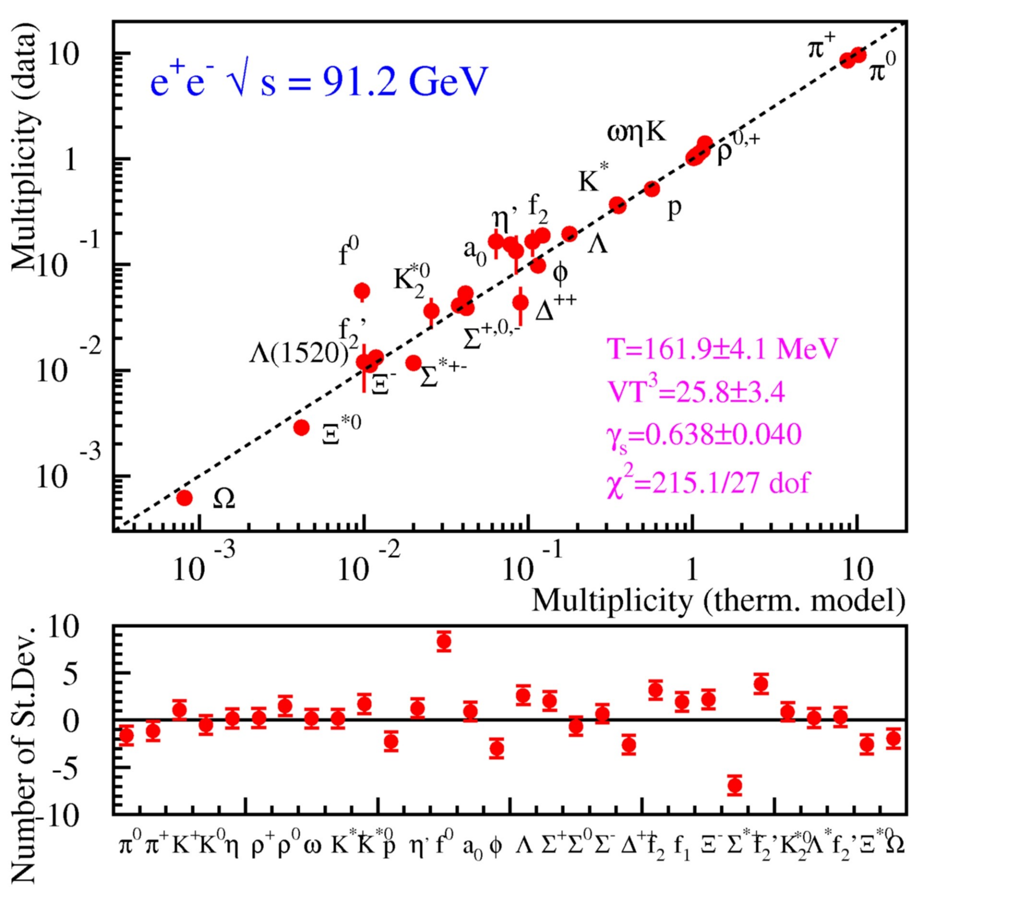
Hadron formation in high energy collisions

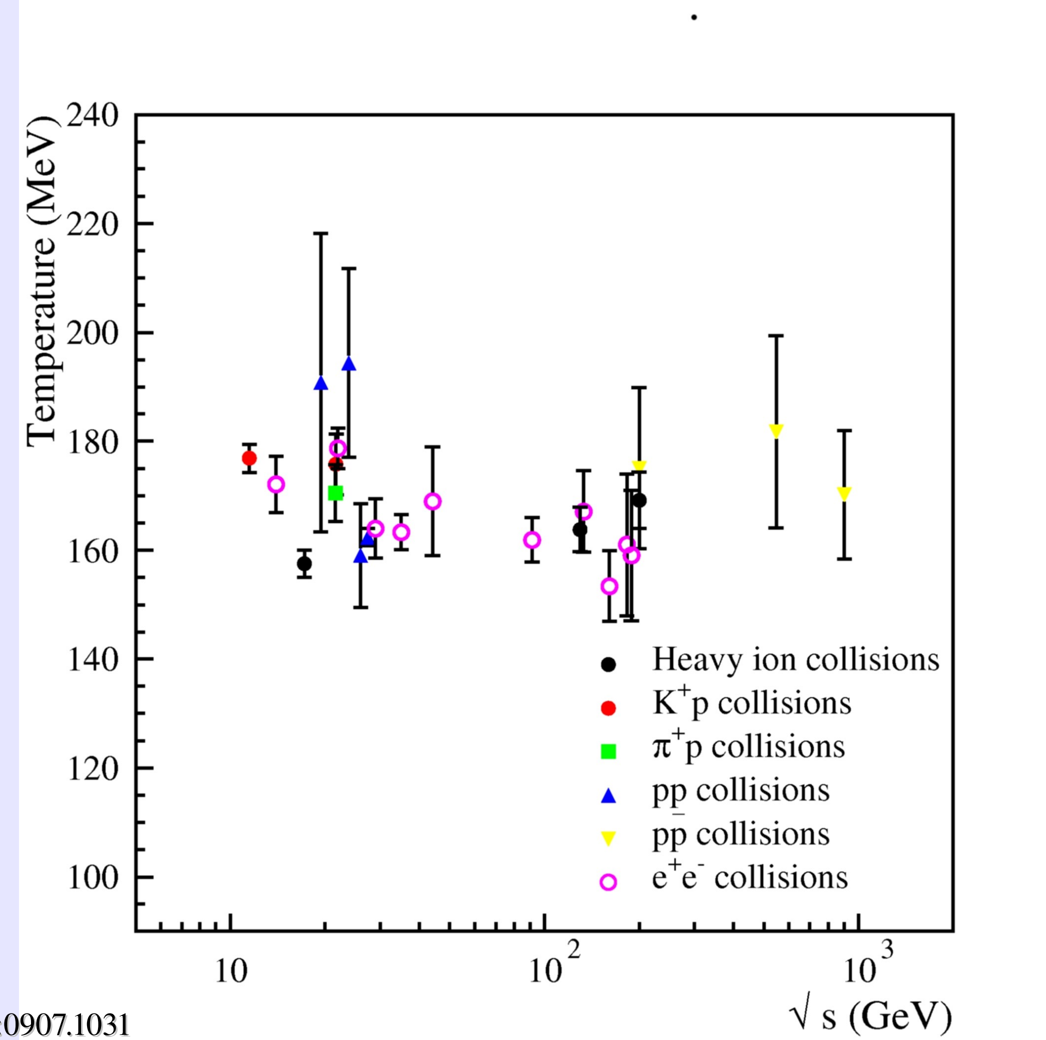


Problem approached with a statistical ansatz (Statistical Hadronization Model) in both elementary (e+e-, pp, …) and heavy ion collisions.
Idea: particle multiplicities are frozen at a common comoving critical temperature *T*



Universal temperature in elementary collisions

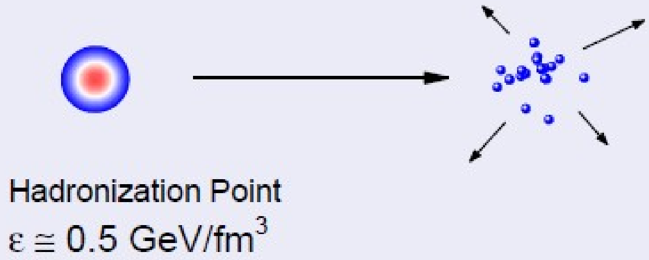




F. B., R. Fries in *Relativistic heavy ion physics*, Landolt-Boernstein 1-23 arXiv:0907.1031

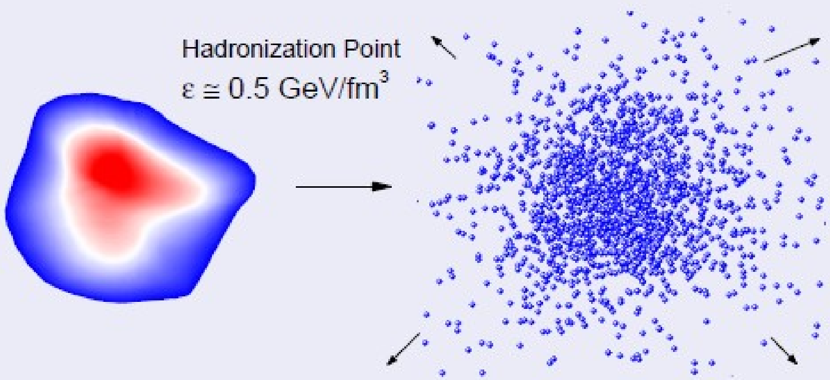
Small vs large

Elementary Collisions



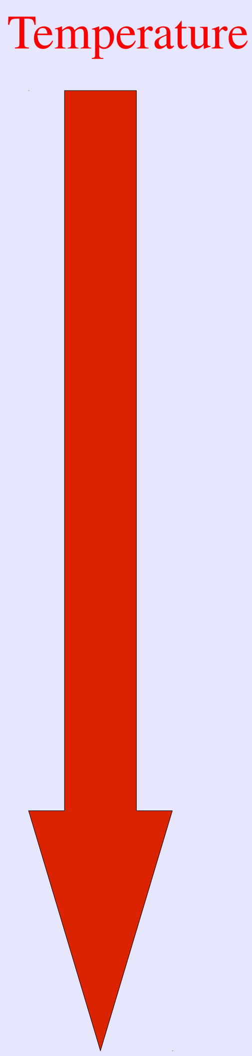
- Hadrons are born into equilibrium.
- They are few and escape the reaction volume immediately.

Heavy Ion Collisions



- Hadrons are born into equilibrium.
- They need more time to escape the reaction volume.
- They can undergo inelastic collisions.

Dictionary



Hadronization
The process of hadron formation <-> QCD "phase transition"

LCEP = Latest Chemical Equilibrium Point – of a hadron gas
If hadronization occurs near or at chemical equilibrium, this is the point where chemical equilibrium ceases because of the collisions in an expanding hadron gas

Chemical freeze-out
The (in principle particle-dependent) point where particle abundances freeze

Kinetic freeze-out
The (approximate) point where elastic interactions cease

Freeze-out conditions

Particle interactions in an expanding, approximately hydrodynamical system, cease when

$$\tau_{\rm scatt} = \frac{1}{n\sigma\langle v\rangle} > \tau_{\rm exp} = \frac{1}{\partial\cdot u}$$

For a sphere, the expansion time is *R/3(dR/dt)* and if *dR/dt* ~ mean velocity, the above inequality becomes:

$$\frac{1}{n\sigma\langle v\rangle} > \frac{R}{3\langle v\rangle} \implies \frac{1}{n\sigma} > \frac{R}{3}$$

Therefore, freeze-out occurs when

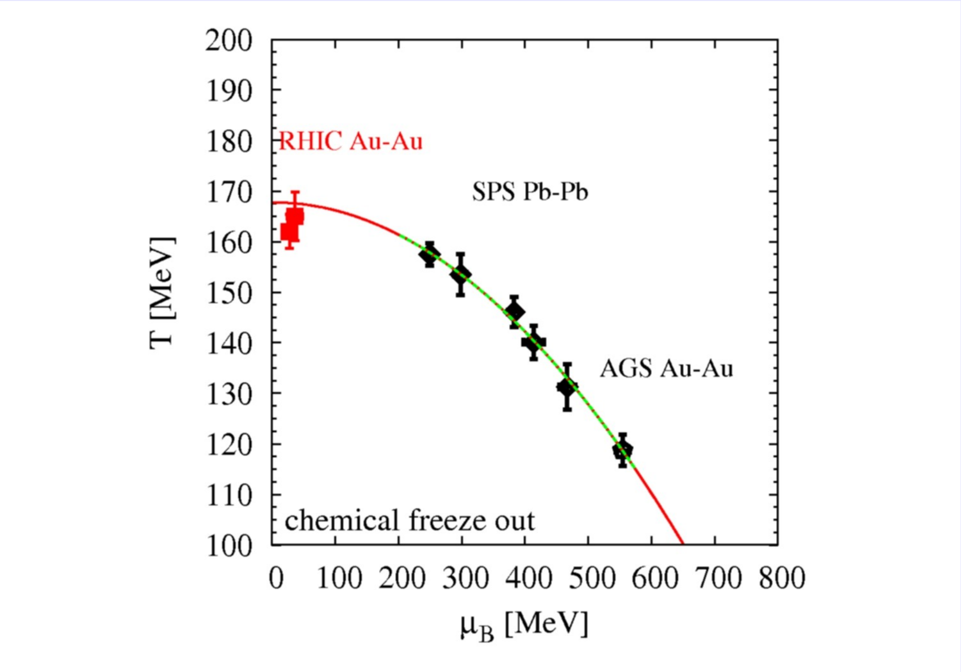
$$R_{\rm fo} = \sqrt{\frac{N\sigma}{4\pi}}$$ with a density $$n_{\rm fo} = \frac{N}{\frac{4\pi}{3}R_{\rm fo}^3} = 3\sqrt{\frac{4\pi}{N}}\frac{1}{\sigma^{3/2}}$$

Therefore, the larger the multiplicity, the larger the freeze-out radius and the lower the particle density.
If one starts with a large number of particles at the hadronization, the system will take more time to decouple, and this will happen at a lower density.

If $n_{fo} > n_{had}$ decoupling is instantaneous, otherwise it is not.

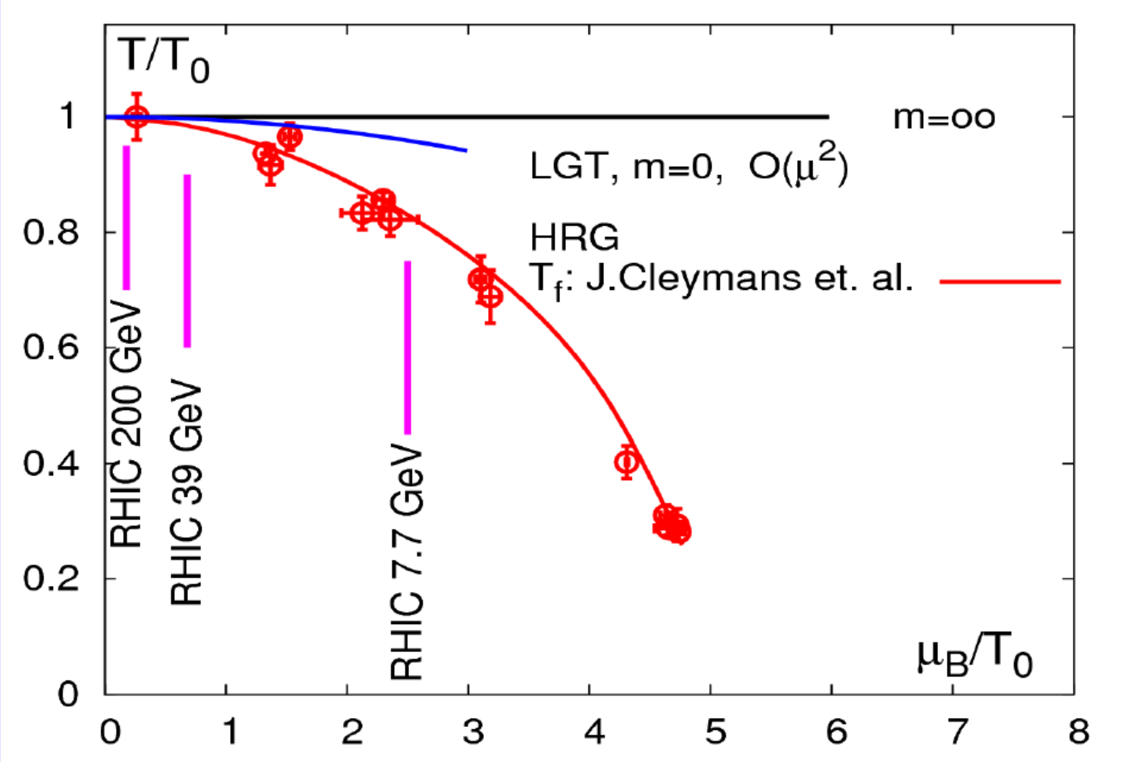
Chemical Freeze-Out vs QCD critical line from relativistic heavy ion collisions

Colliding nuclei at different energies we obtain different chemical Freeze-out points



A. Andronic, P. Braun-Munzinger, J.Stachel
J. Cleymans, K. Redlich, W. Florkowski, W. Broniowski,

Extrapolated T-μ critical line is flatter than the CFO curve



Taking inelastic interactions into account

Estimate the effect of inelastic hadronic rescattering with a hadronic transport code

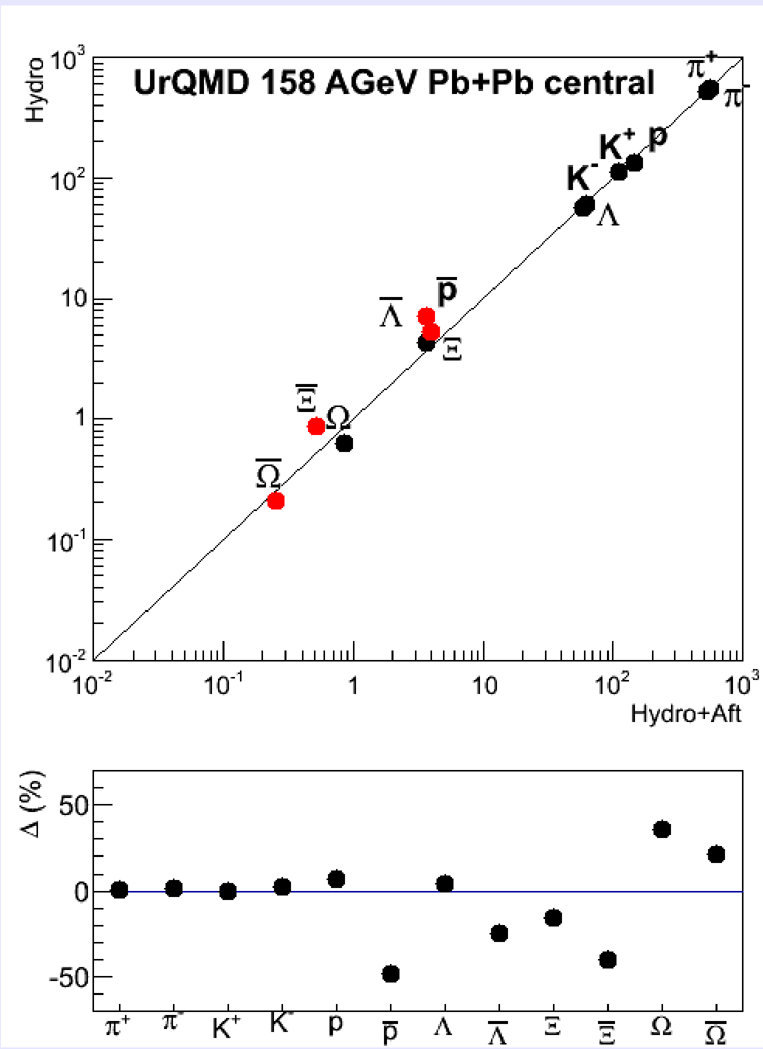
- Run the transport code URQMD (isochronous CF particlization after all cells have fallen below 850 MeV/fm^3)
- For each particle species, calculate the modification factor = yield after cascade/CF yield
- Use the modification factors to correct the theoretical statistical model predicted yields

Effect of post-hadronization collisions (afterburner)

F.B., M. Bleicher, T. Kollegger, M. Mitrovski, T. Schuster and R. Stock, Phys. Rev. C 85 (2012) 044921

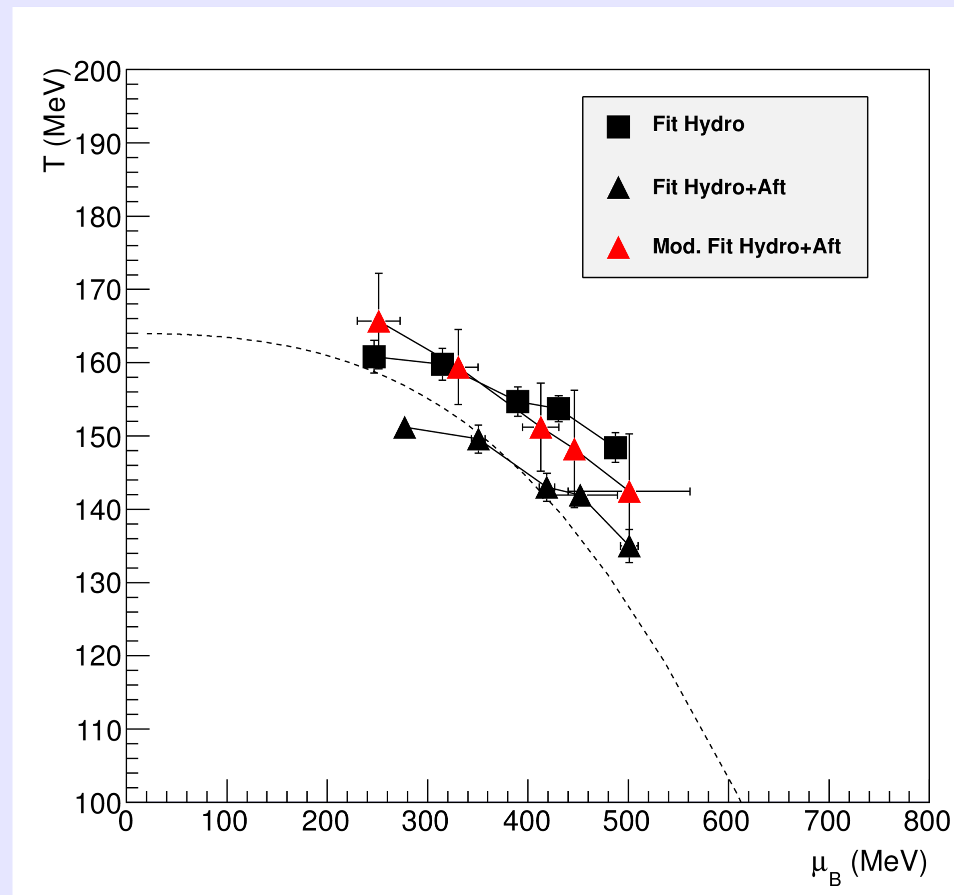
In the particle composition:

Considerable antibaryon loss (at large μ)



In the multiplicity fit

- Temperature shift by ~ 10 MeV
- Sizeable worsening of fit quality

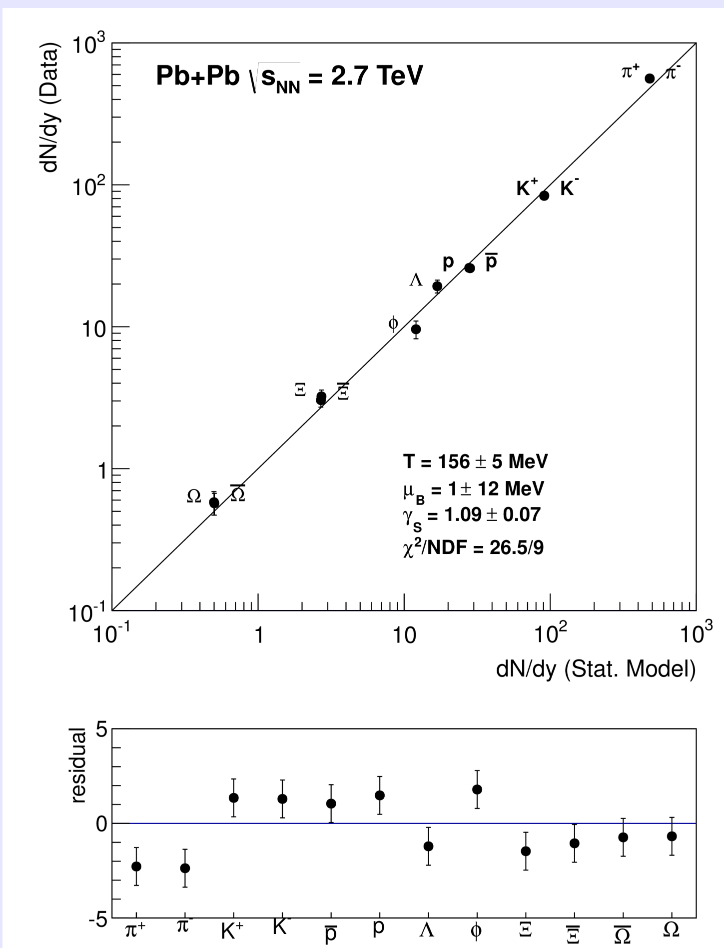


Effect of post-hadronization collisions at the LHC

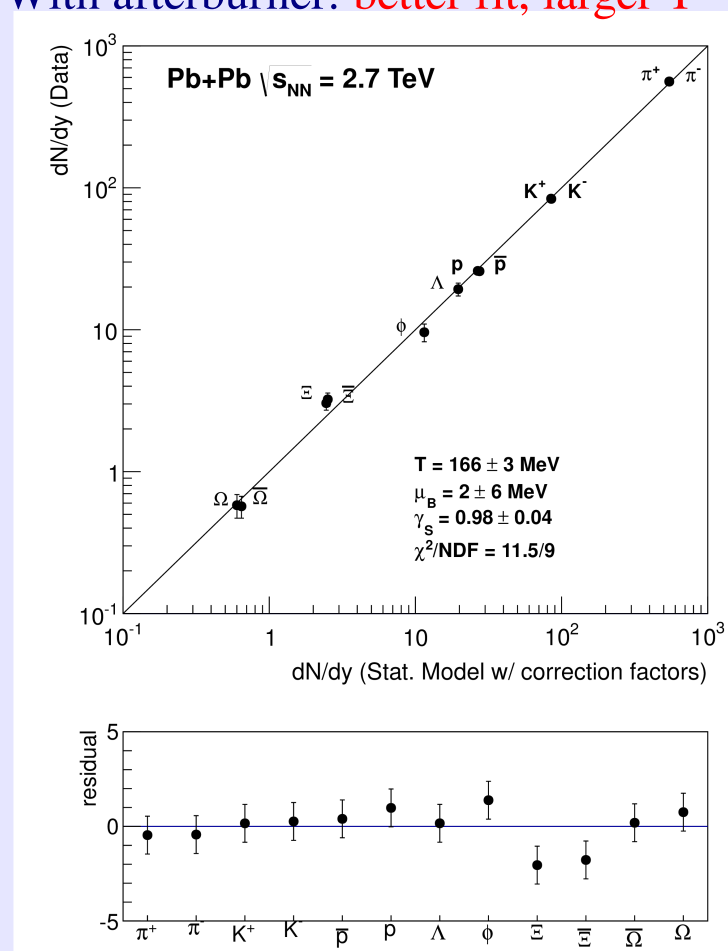
p/π puzzle at LHC: measured value in central collisions sizeably overpredicted by the statistical model extrapolations and deviating from the plain SHM

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl. Phys. A904-905, 535c (2013)

Without afterburner



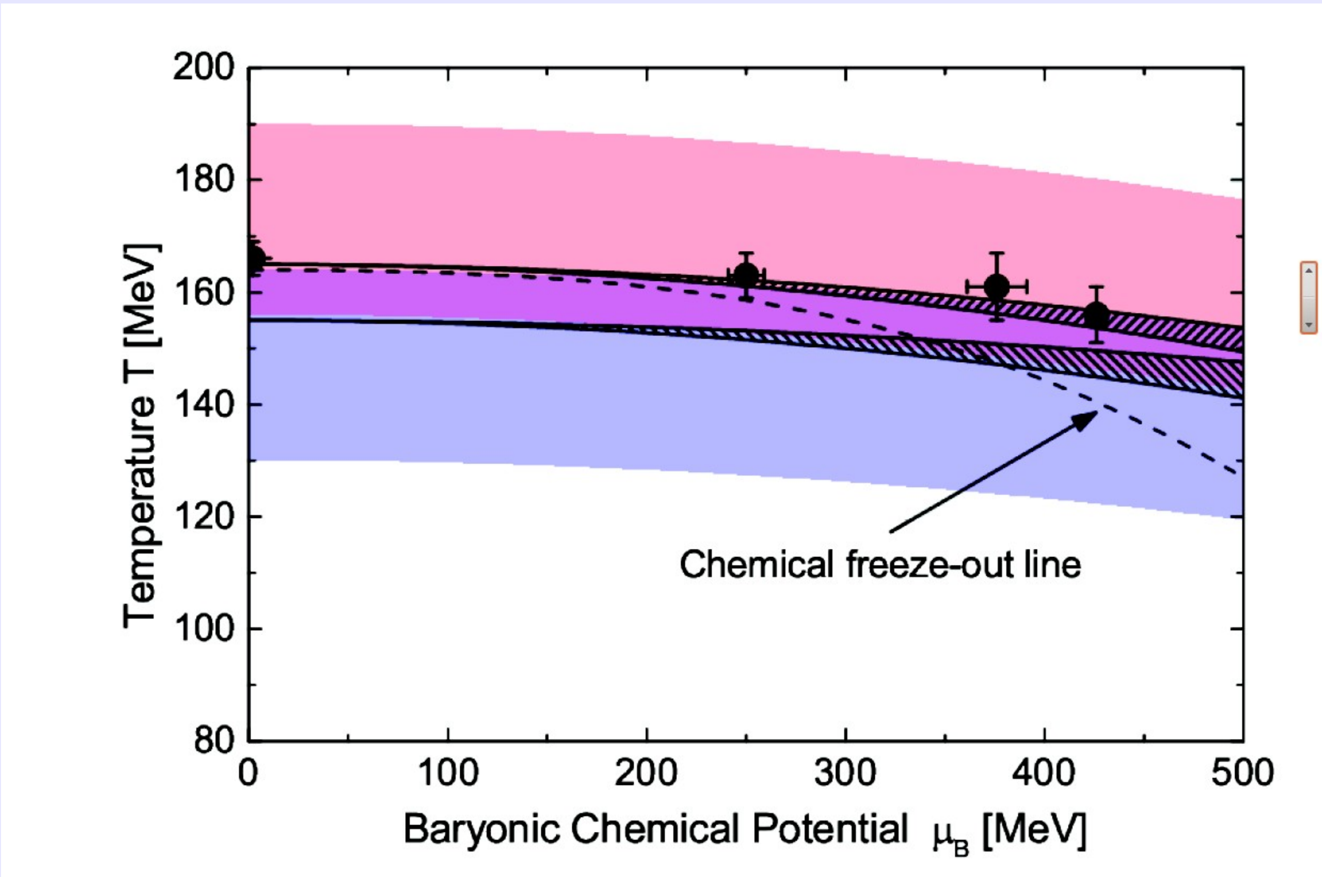
With afterburner: better fit, larger T



F.B., M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer and R. Stock, Phys. Rev. Lett. 111 (2013) 082302

Comparing reconstructed LCEP's with lattice QCD in central collisions

F.B., M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer and R. Stock, Phys. Rev. Lett. 111 (2013) 082302



	T(MeV)	μ_B(MeV)	γ_S	χ^2/NDF
Pb-Pb 20% central $\sqrt{s_{\rm NN}} = 2.7$ TeV				
Std. fit	156 ± 5	1 ± 12	1.09 ± 0.07	26.5/9
Mod. fit	166 ± 3	2 ± 6	0.98 ± 0.04	11.5/9
Pb-Pb 5% central $\sqrt{s_{\rm NN}} = 17.3$ GeV				
Std. fit	151 ± 4	266 ± 9	0.91 ± 0.05	26.9/11
Mod. fit	163 ± 4	250 ± 9	0.83 ± 0.04	20.4/11
Pb-Pb 5% central $\sqrt{s_{\rm NN}} = 8.7$ GeV				
Std. fit	148 ± 4	385 ± 11	0.78 ± 0.06	17.9/9
Mod. fit	161 ± 6	376 ± 15	0.72 ± 0.06	25.9/9
Pb-Pb 5% central $\sqrt{s_{\rm NN}} = 7.6$ GeV				
Std. fit	140 ± 1	437 ± 5	0.91 ± 0.01	22.4/7
Mod. fit	156 ± 5	426 ± 4	0.81 ± 0.00	14.7/7

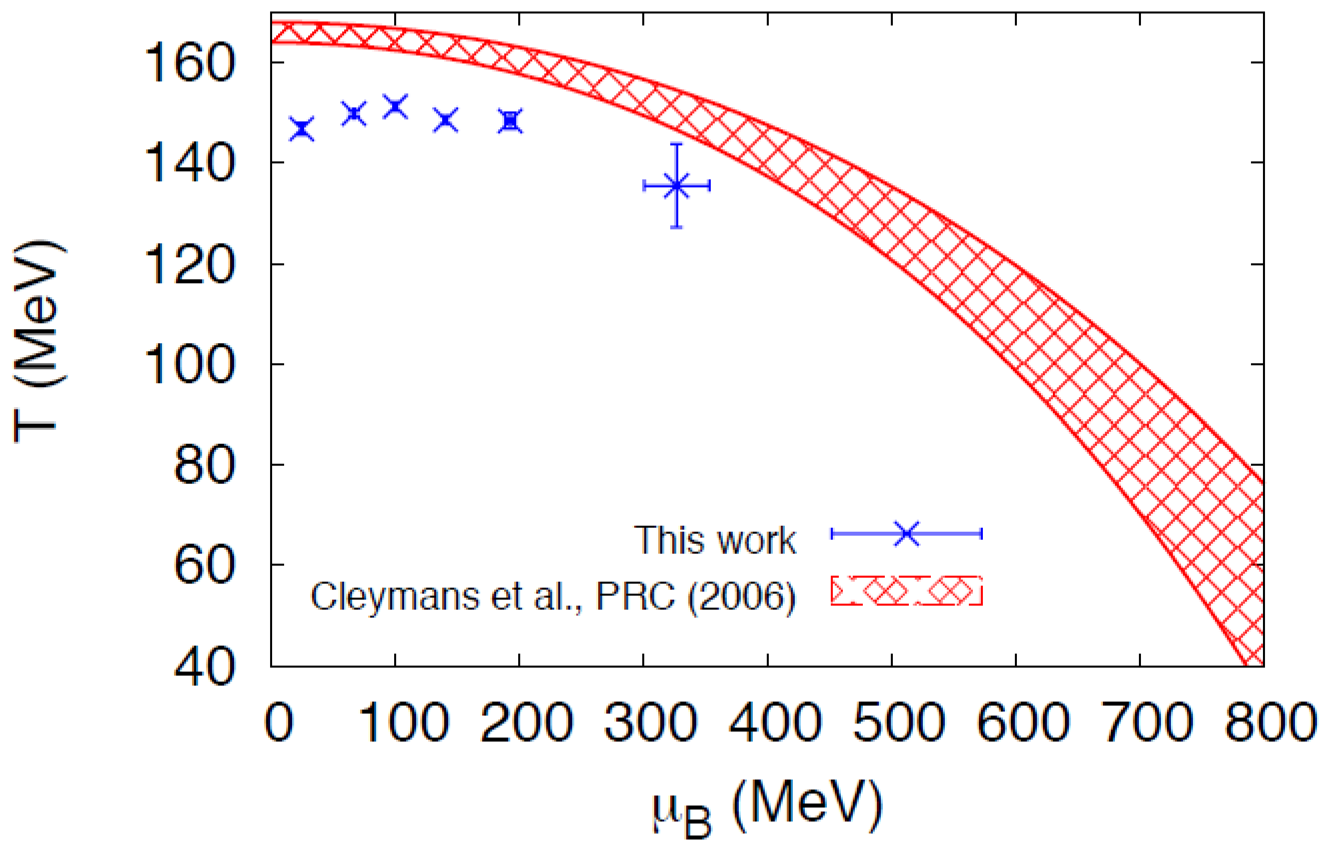
Lattice calculations from

F. Karsch, J. Phys. G 38, 124098 (2011); S. Borsanyi et al., ibidem 124101

G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, JHEP 1104, 001 (2011)

Reconstructed LCEP using fluctuation of conserved charge

P. Alba et al. Phys. Lett. B 738 (2014) 305



Recent calculation of the curvature of the QCD pseudo-critical line

C. Bonati, M. D'Elia et al., Phys. Rev. D 90 (2014) 11, 114025

$$T_c(\mu_B) = T_c(0)\left[1 - \kappa\left(\frac{\mu_B}{T_c(0)}\right)^2\right]$$

with:

$$\kappa = 0.013(2)$$

Take $T_c(0)$=166, then at lowest SPS energy
μ_B/Tc = 426/166 = 2.566
And

$T_c(426)$ = 151.8 MeV

To be compared with ours 156+-5

	T(MeV)	μ_B(MeV)	γ_S	χ^2/NDF
Pb-Pb 20% central $\sqrt{s_{NN}} = 2.7$ TeV				
Std. fit	156 ± 5	1 ± 12	1.09 ± 0.07	26.5/9
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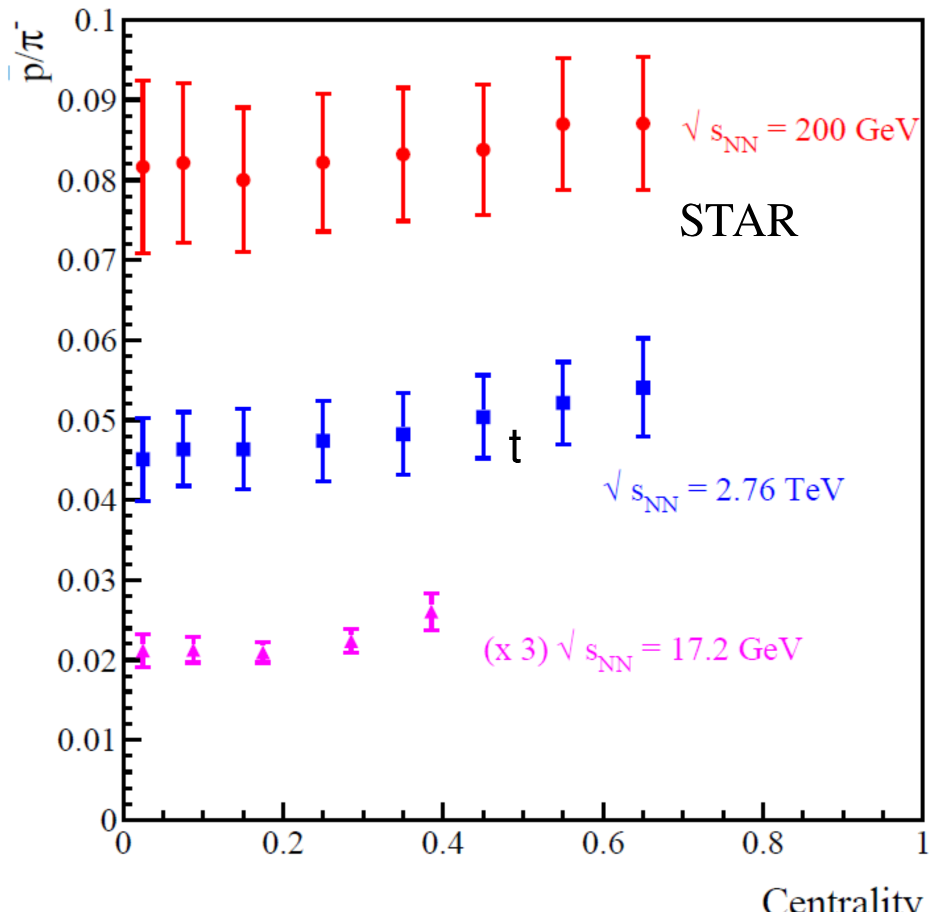
Freeze-out and centrality

F.B., M. Bleicher, E. Grossi, J. Steinheimer and R. Stock, Phys. Rev. C 90 (2014) 054907

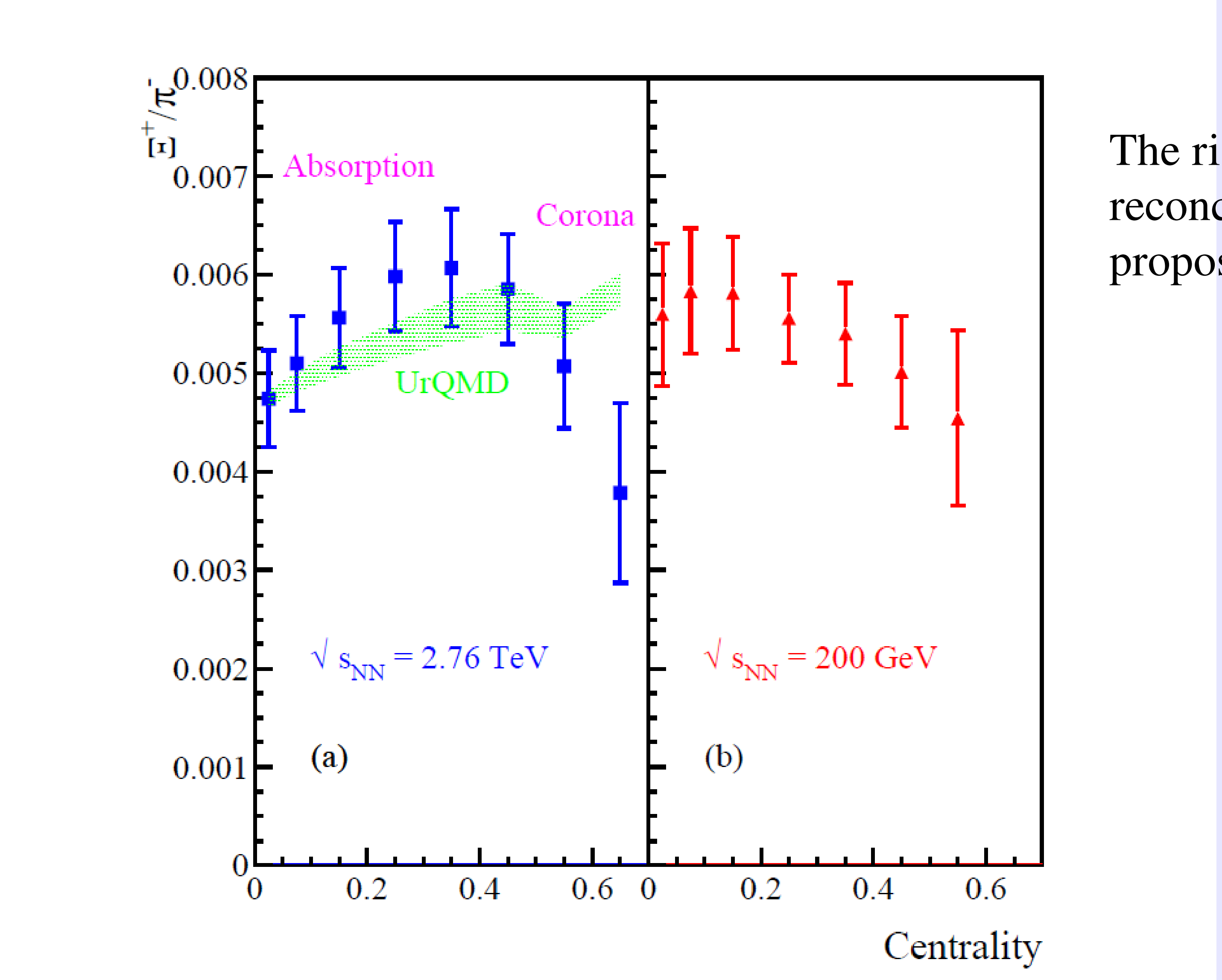
See also X. Zhu, F. Meng, H. Song, Y. X. Liu, Phys. Rev. C 91 (2015) 3, 034904
H.Song, S.~Bass and U.~W.~Heinz, Phys. Rev. C 89 (2014) 3, 034919

If the picture is correct, we should expect some centrality-dependent effect



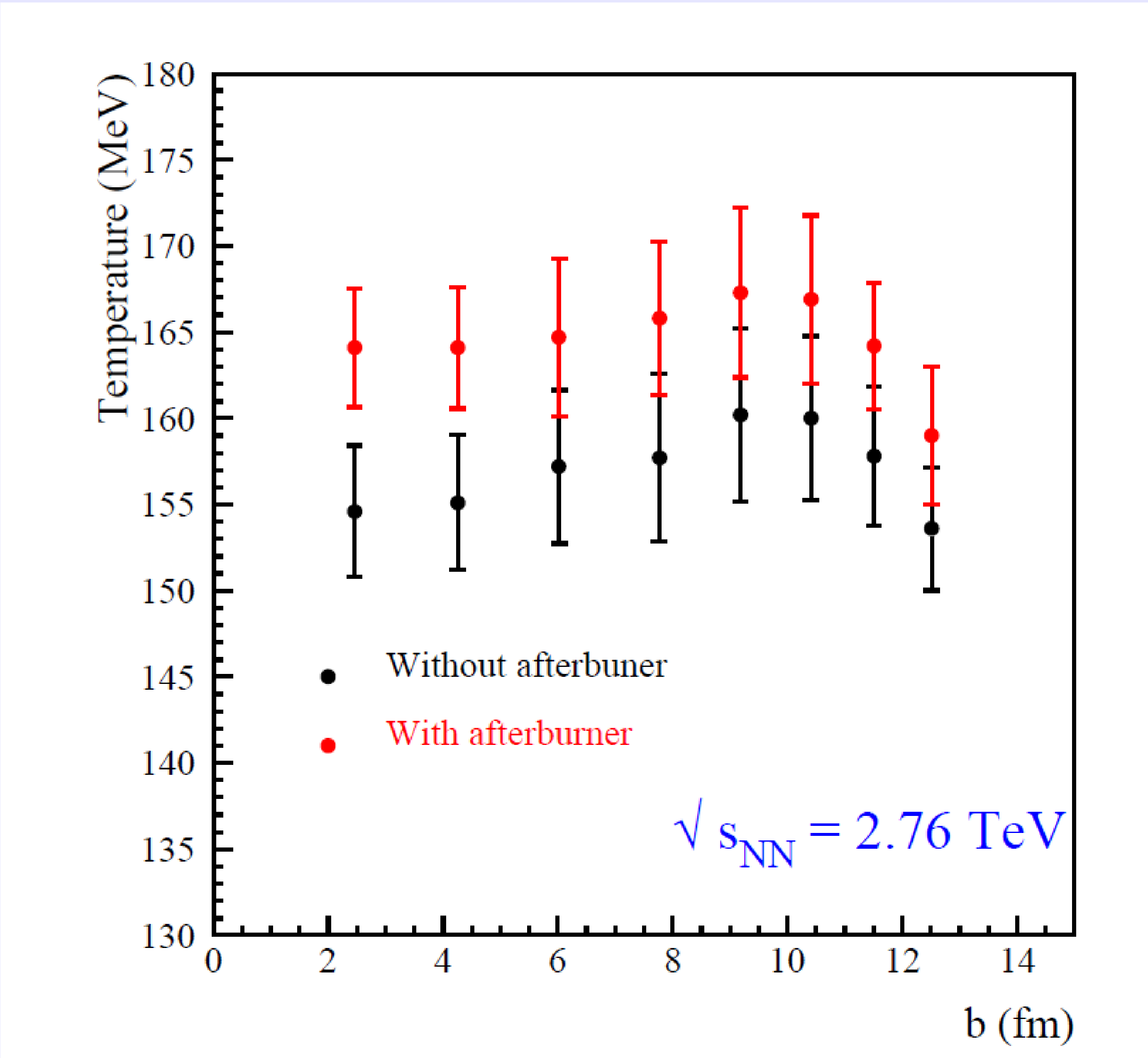
$$n_{\rm fo} = \frac{N}{\frac{4\pi}{3} R_{\rm fo}^3} = 3\sqrt{\frac{4\pi}{N}} \frac{1}{\sigma^{3/2}}$$

Freeze-out and centrality (2)



The rise at the LHC difficult to reconcile with previously proposed pictures

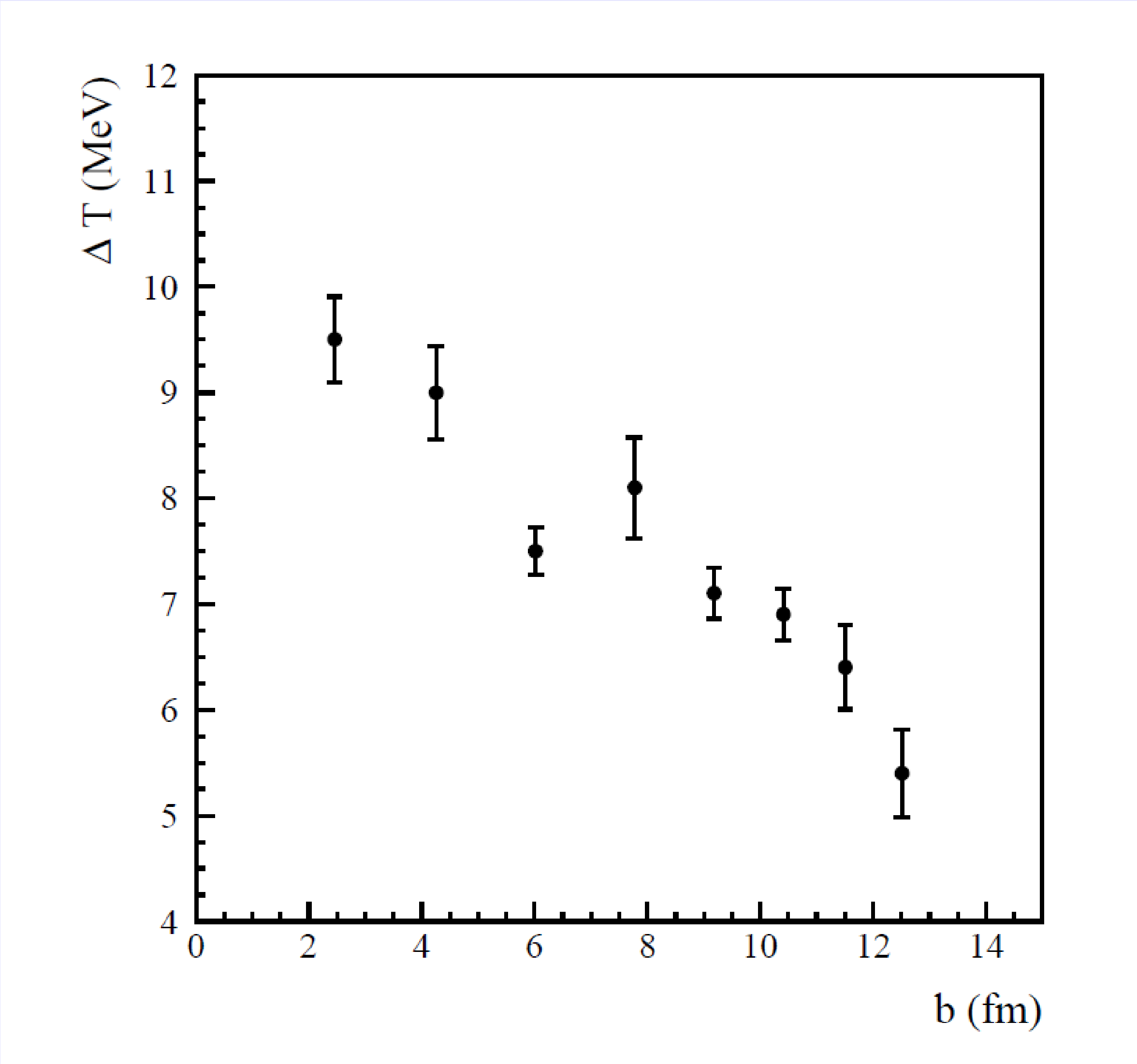
The results



Red:
reconstructed LCEP

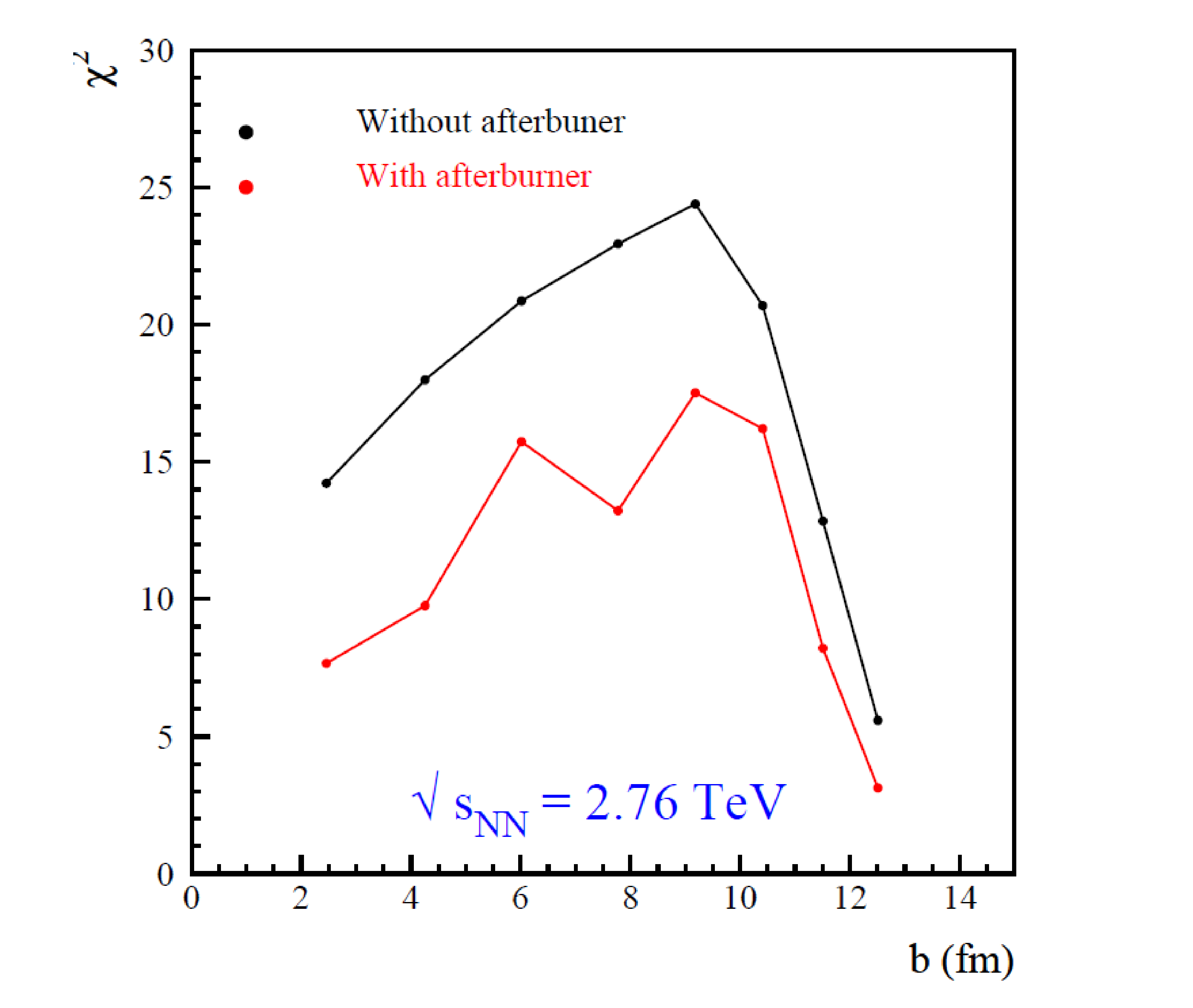
Black:
chemical freeze-out

The temperature shift



Difference between CF and LCEP (assuming full correlation between the T errors of the two fits)

The fit quality



Conclusions

- Convincing evidence that in relativistic AA collisions

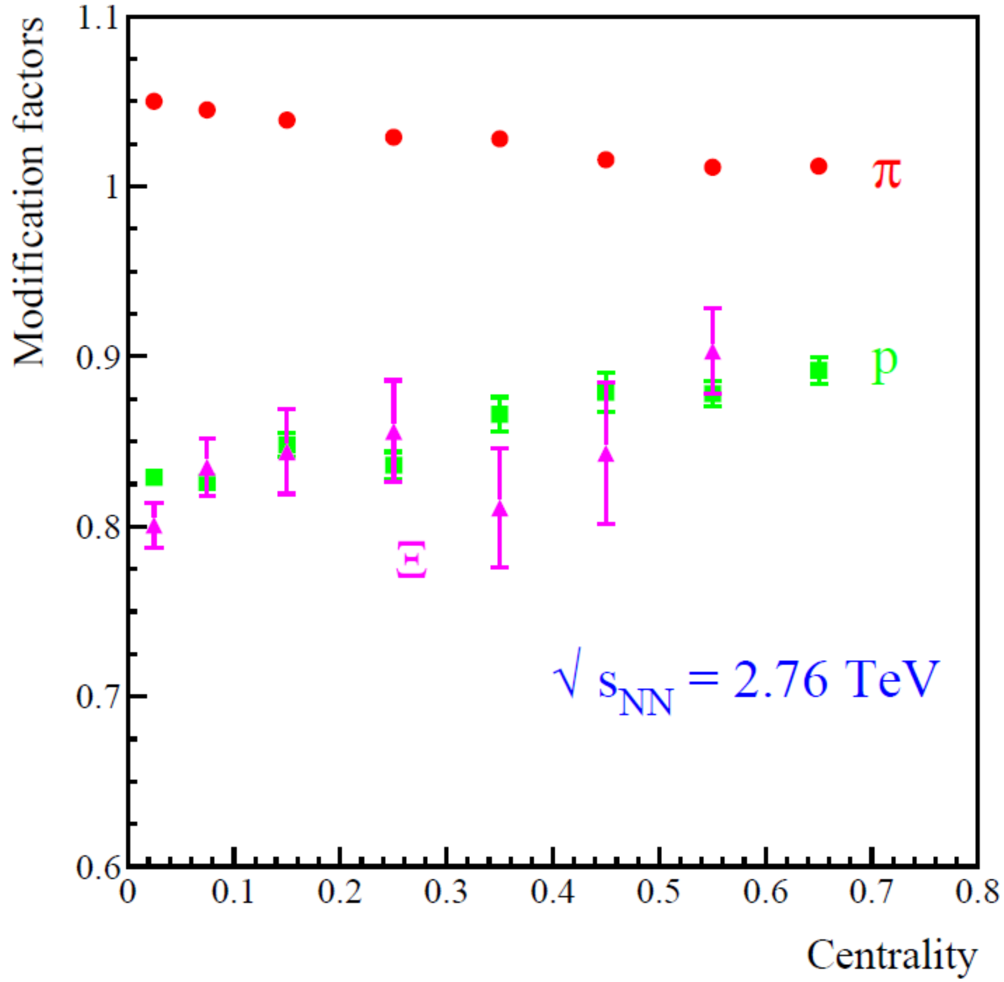
  Chemical freeze-out *follows* Chemical equilibrium (≅ hadronization)

- Corrections to the assumed chemically equilibrated yields improve fit quality and make the hadronization curve much closer in shape to lattice QCD extrapolations

- LCEP Temperature estimated to be 164(4) MeV at zero μ_B

- We are looking forward to new and improved calculations of the modification factors to check if we can achieve an even better fit

URQMD modification factors



Temperature	μ_B	χ^2/dof
158.2 ± 2.2 MeV	0 (fixed)	2.52/8

Particle	Calculated	Fitted with SHM
π^+	528±37	542.4
π^-	529±37	542.4
K^+	100.0±7.7	95.63
K^-	101.0±7.7	95.63
p	33.7±2.4	33.31
$\bar{p}$	30.9±2.2	33.31
Λ	18.9±1.6	18.45
Ξ^-	2.79±0.19	2.744
Ξ^+	2.79±0.19	2.744
$\Omega+\bar{\Omega}$	0.94±0.15	0.9498

Example: most central collisions

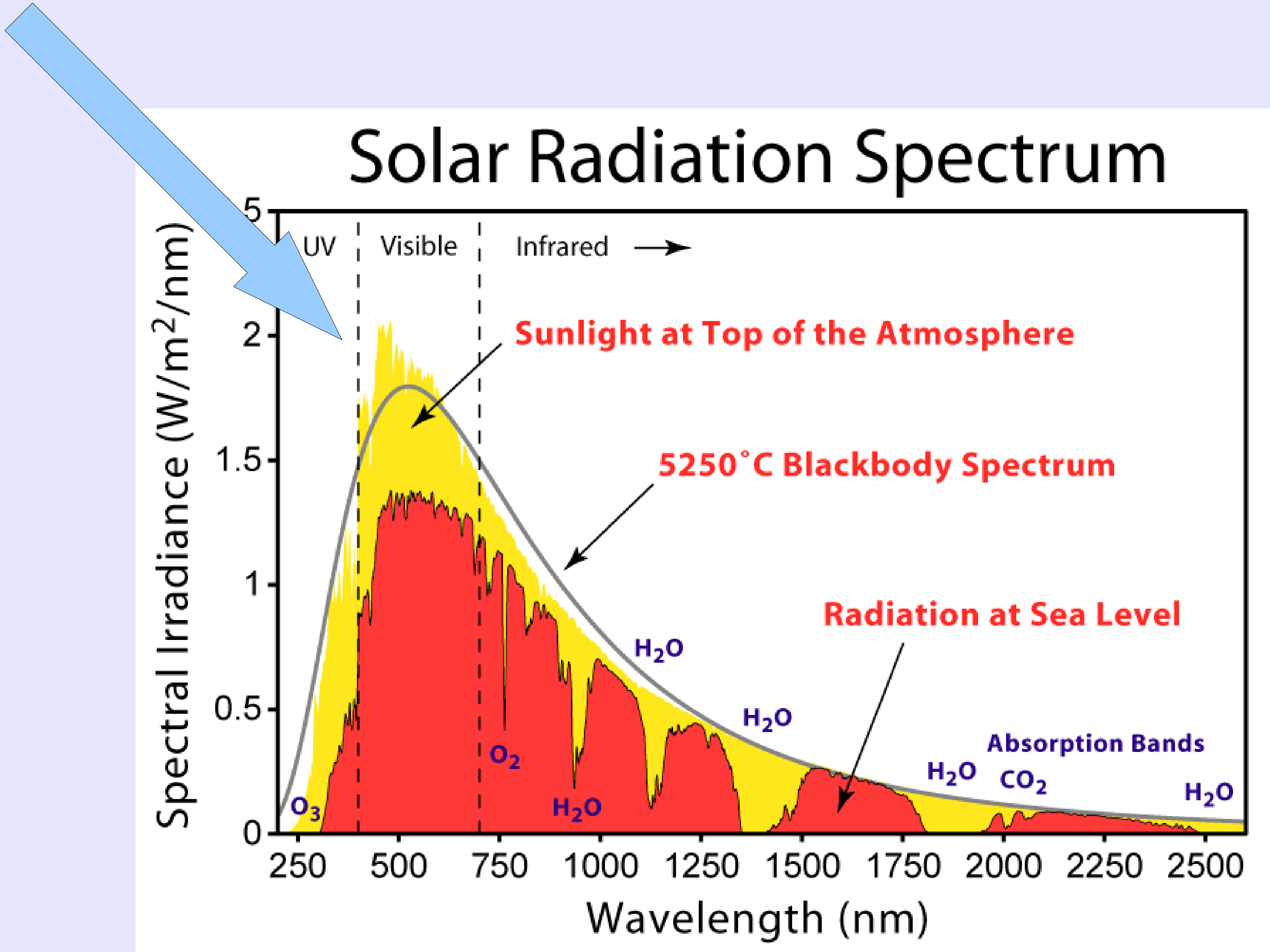
WITHOUT AFTERBURNER

Particle	Fit value	Measured	Error	Residual	Deviation
pi+	645.66336	733.00000	54.00000	-1.6173	-13.5267
pi-	645.66336	732.00000	52.00000	-1.6603	-13.3718
K+	121.16360	109.00000	9.00000	1.3515	10.0390
K-	121.16360	109.00000	9.00000	1.3515	10.0390
p	36.64025	34.00000	3.00000	0.8801	7.2059
pbar	36.64025	33.00000	3.00000	1.2134	9.9351
Lambda	21.55261	26.10000	2.80000	-1.6241	-21.0990
Xi	3.42681	3.57000	0.27000	-0.5303	-4.1785
Xibar	3.42681	3.47000	0.26000	-0.1661	-1.2603
Omega	1.23685	1.26000	0.22000	-0.1052	-1.8718

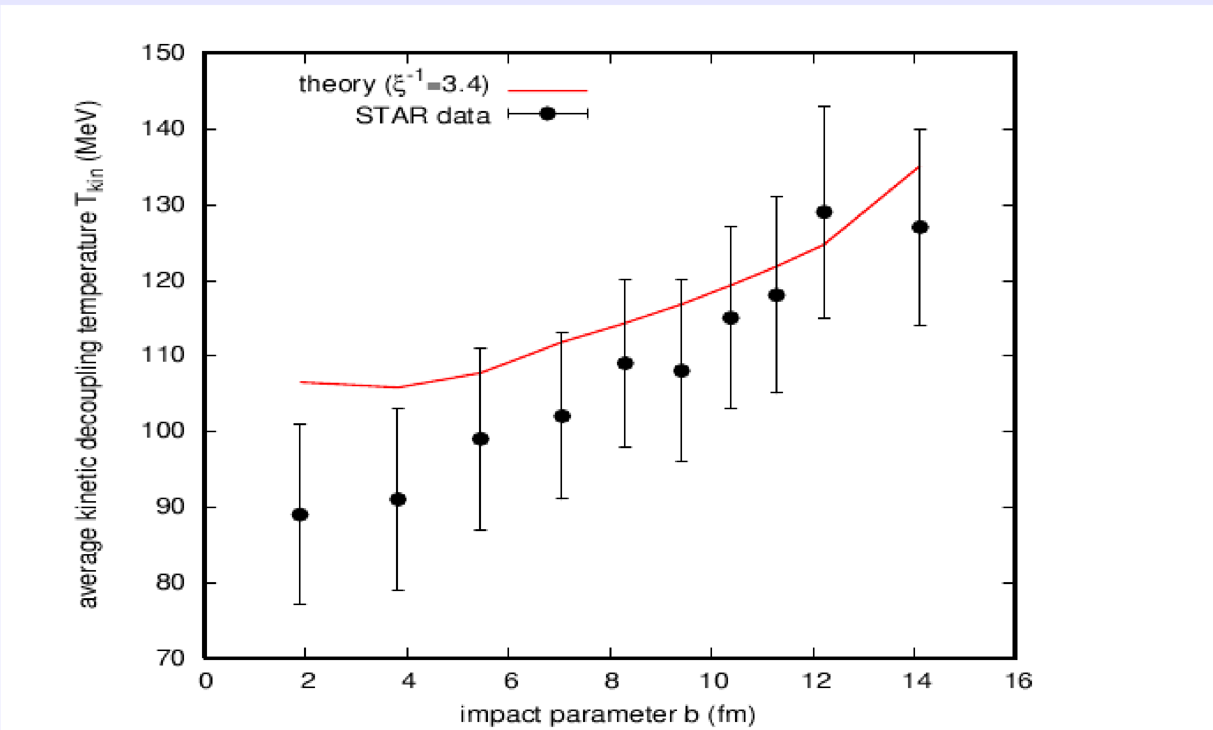
WITH AFTERBURNER

Particle	Fit value	Measured	Error	Residual	Deviation
pi+	683.20419	733.00000	54.00000	-0.9221	-7.2886
pi-	683.20419	732.00000	52.00000	-0.9384	-7.1422
K+	116.84625	109.00000	9.00000	0.8718	6.7150
K-	116.84625	109.00000	9.00000	0.8718	6.7150
p	35.92854	34.00000	3.00000	0.6428	5.3677
pbar	35.92854	33.00000	3.00000	0.9762	8.1510
Lambda	22.38628	26.10000	2.80000	-1.3263	-16.5893
Xi	3.38422	3.57000	0.27000	-0.6881	-5.4895
Xibar	3.38422	3.47000	0.26000	-0.3299	-2.5346
Omega	1.44410	1.26000	0.22000	0.8368	12.7486

We must see the details at some point

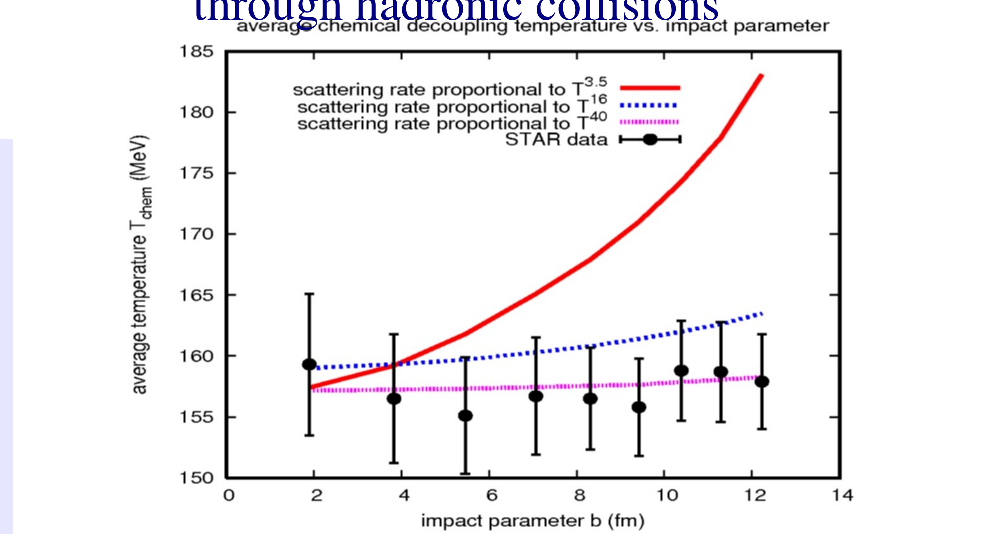


Freeze-out and centrality

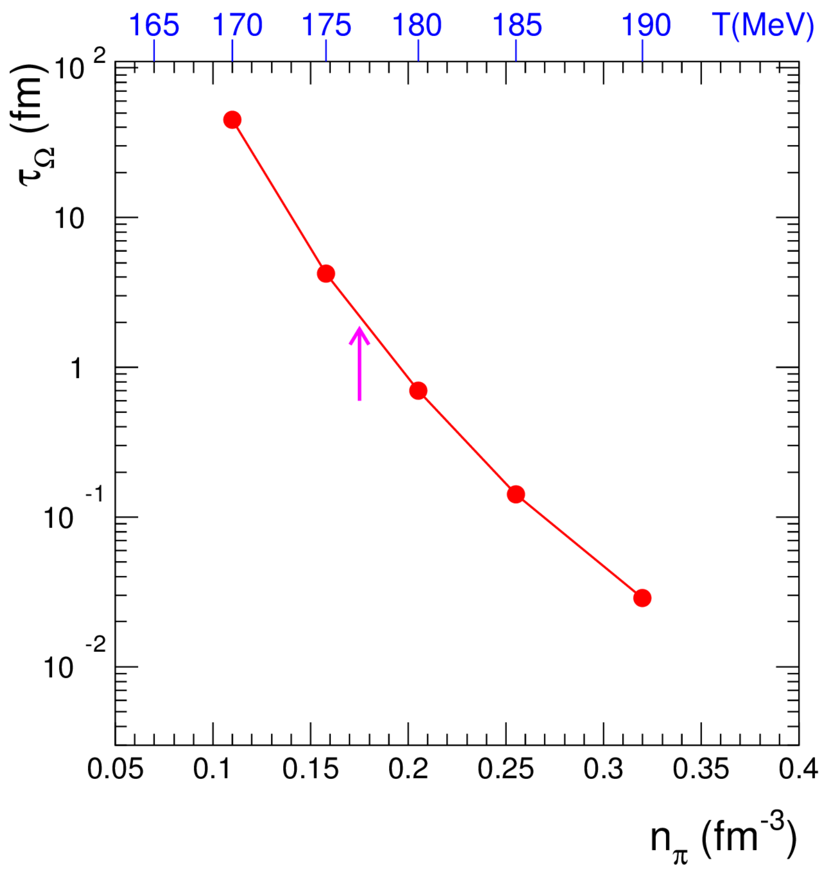


Kinetic freeze-out (at RHIC energy) DOES vary significantly as a function of centrality, whereas chemical does not.

Interpretation: if kinetic decoupling occurs in the expanding hadron gas stage, it MUST depend on the geometry, roughly on Surface/Volume ratio. On the other hand, chemical seems NOT to depend, which is an indication that equilibrium is not achieved through hadronic collisions



U. Heinz, G. Kestin, CPOD 2006 nucl-th: 0612105



165
170
175
180
185
190
T(MeV)
10 2
10
1
10 -1
10 -2
τ_Ω (fm)
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
n_π (fm^-3)