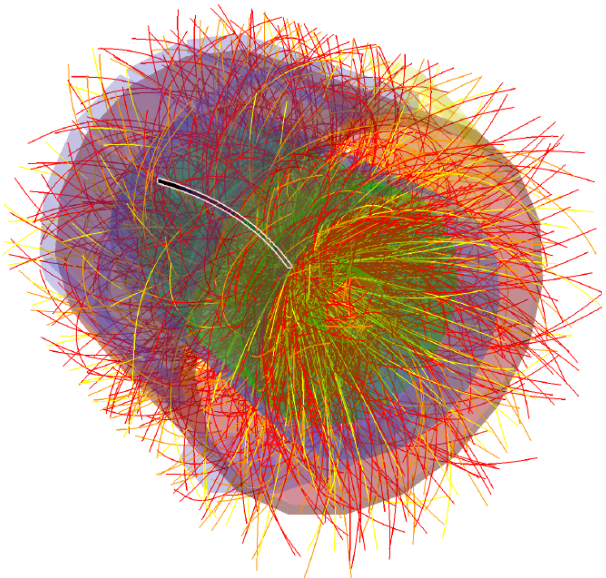
Statistical hadron production



11.02.2019
EMMI Workshop
Probing dense baryonic matter with hadrons: Status and Perspective
GSI

Benjamin Dönigus
Institut für Kernphysik
Goethe Universität Frankfurt

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IKF Institut für Kernphysik Frankfurt

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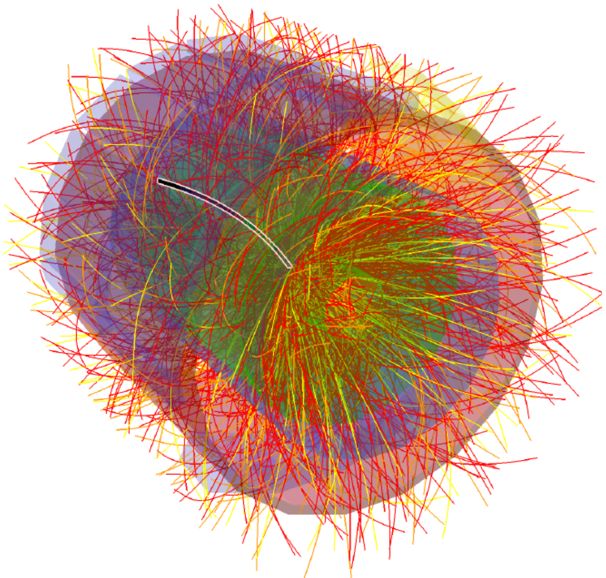

Thanks to
A. Andronic
P. Braun-Munzinger
M. Lorenz
V. Vovchenko

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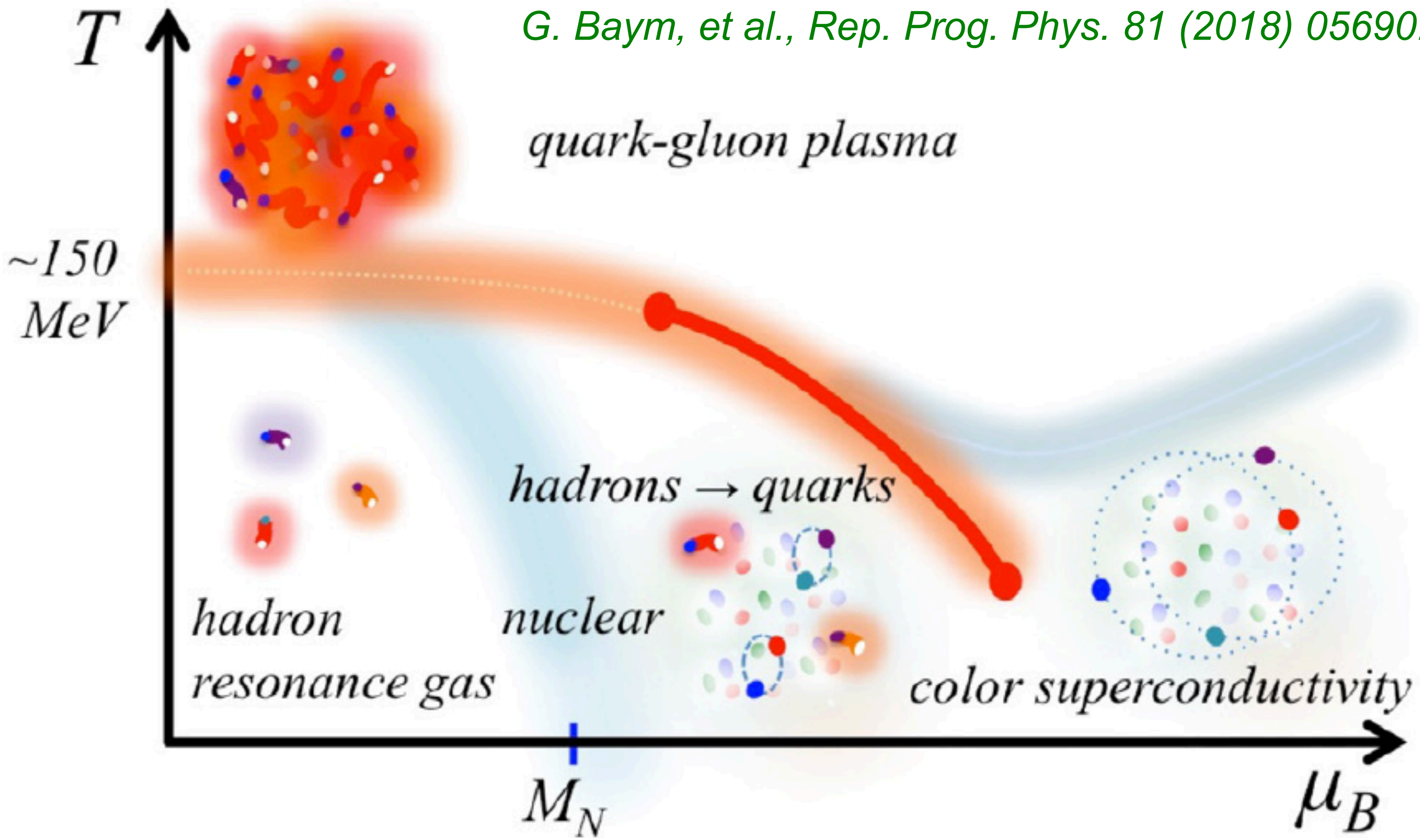
Outline

- Introduction
- From LHC to HADES
- Systematics
- Light nuclei and exotica at FAIR
- Summary

Phase diagram

G. Baym, et al., Rep. Prog. Phys. 81 (2018) 056902



Phase diagram accessible through measurement of hadron production yields

Hadron production yields

A. Andronic

- Large amount of particles measured, many of those newly produced ($E = mc^2$)
- Large variety of hadrons

  $\pi^{\pm}$ $(u\bar{d},\ d\bar{u})$, m=140 MeV

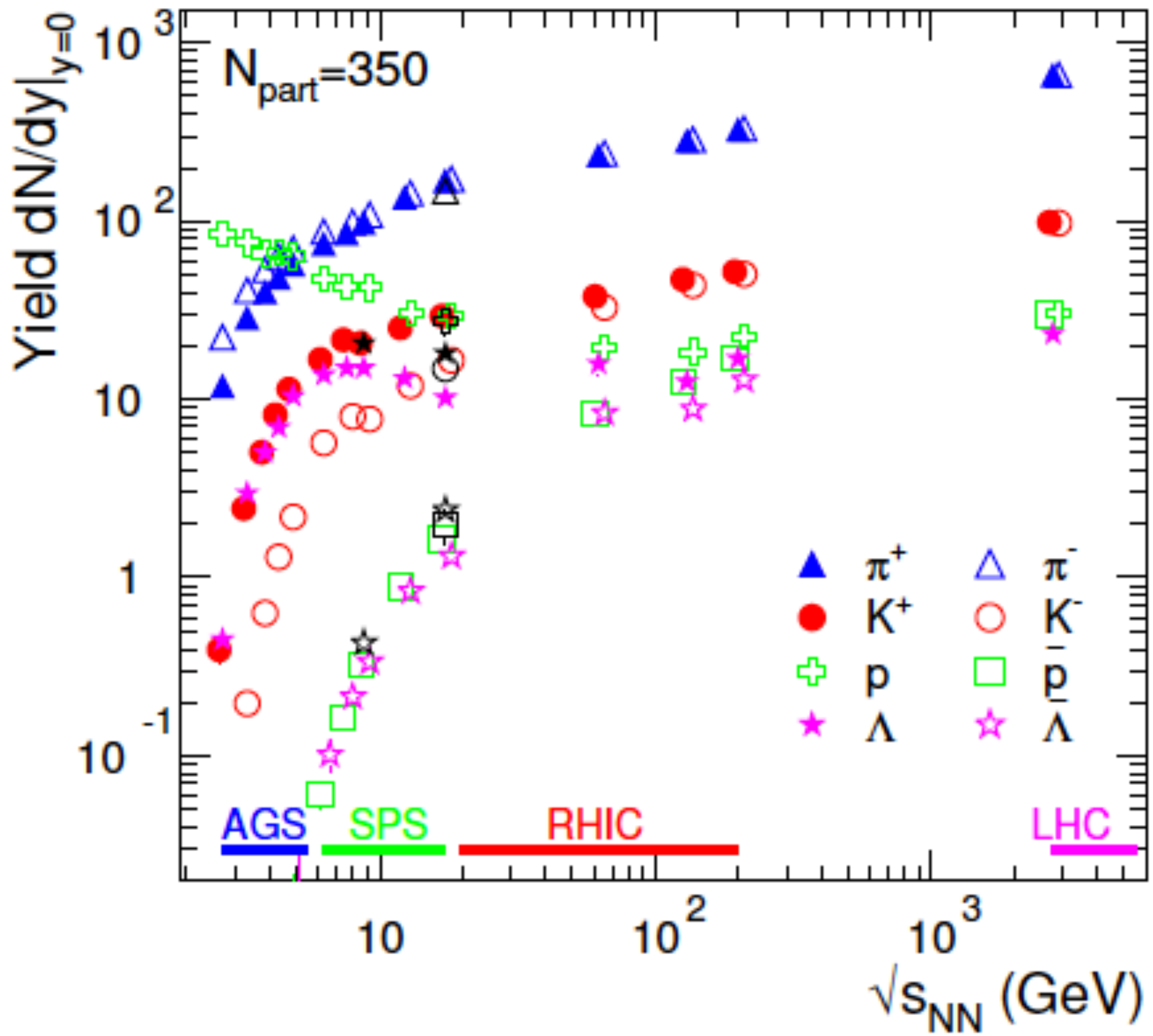
  $K^{\pm}$ $(u\bar{s},\ \bar{u}s)$, m=494 MeV

  p (uud), m=938 MeV

  Λ (uds), m=1116 MeV

  also: $\Xi(dss)$, $\Omega(sss)$...

- Three decades of energy corresponding to three decades of experimental investigation



Thermal model

Simplest approach using a grand-canonical ensemble and its corresponding partition function for specie i (pions, kaons, protons, etc.):

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$g_i = (2J_i + 1)$ spin degeneracy factor; T temperature;

$E_i = \sqrt{p^2 + m_i^2}$ total energy; $+$ for fermions – for bosons

$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials

μ ensure conservation (on average) of quantum numbers, fixed by "initial conditions"

i) isospin: $V_{cons} \sum_i n_i I_{3i} = I_3^{tot}$, with $V_{cons} = N_B^{tot} / \sum_i n_i B_i$

I_3^{tot}, N_B^{tot} isospin and baryon number of the system ($\simeq$0 at high energies)

ii) strangeness: $\sum_i n_i S_i = 0$

iii) charm: $\sum_i n_i C_i = 0$.

Thermal model: yields

Particle densities of each species can be extracted from the partition function as

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

In practise the thermal model codes usually use a particle listing (PDG based) as input and compare the yields with the „best" values of T,μ_B and V, by minimising

$$\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$$

N_i: hadron yield, σ_i: experimental uncertainty (statistical and systemtical)

→ (T, μ_B,V) tests chemical freeze-out (chemical equilibrium)

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Particle listing used in the model is one possible systematic uncertainty of the codes → other important ones in the following

Thermal model fits

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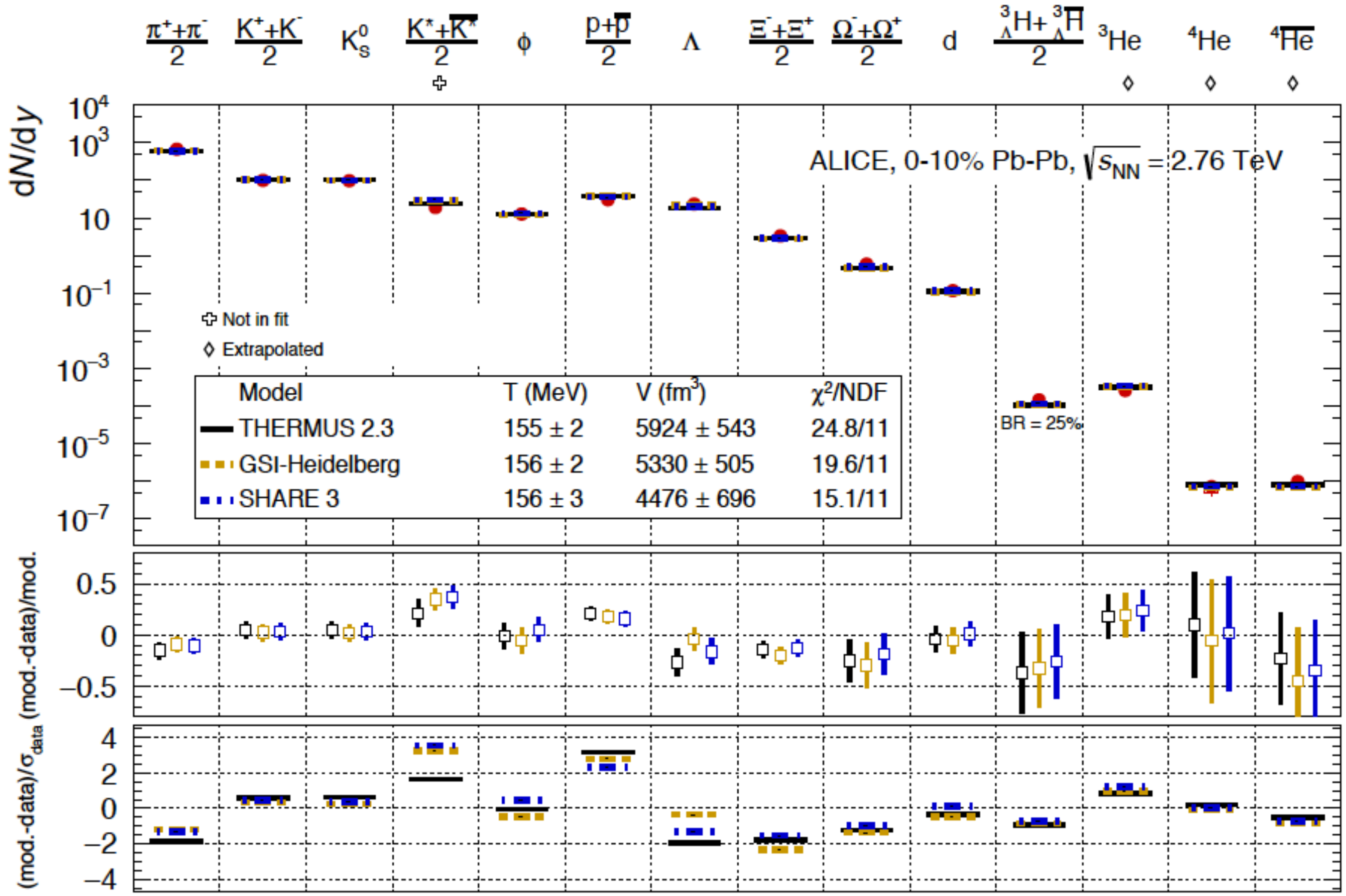
ALICE

THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)



ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

- Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV
- Including nuclei in the fit causes no significant change in T_{ch}

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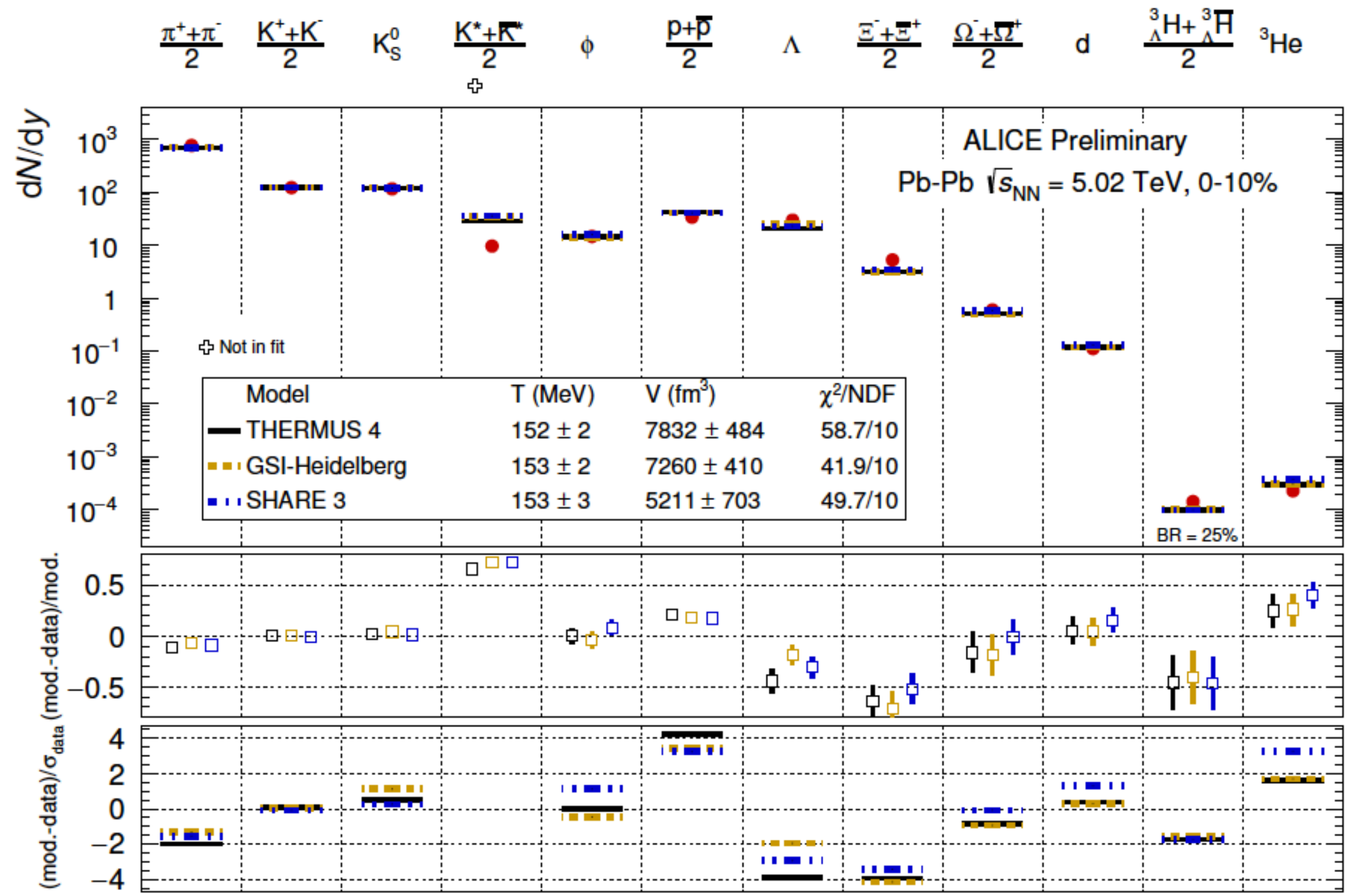
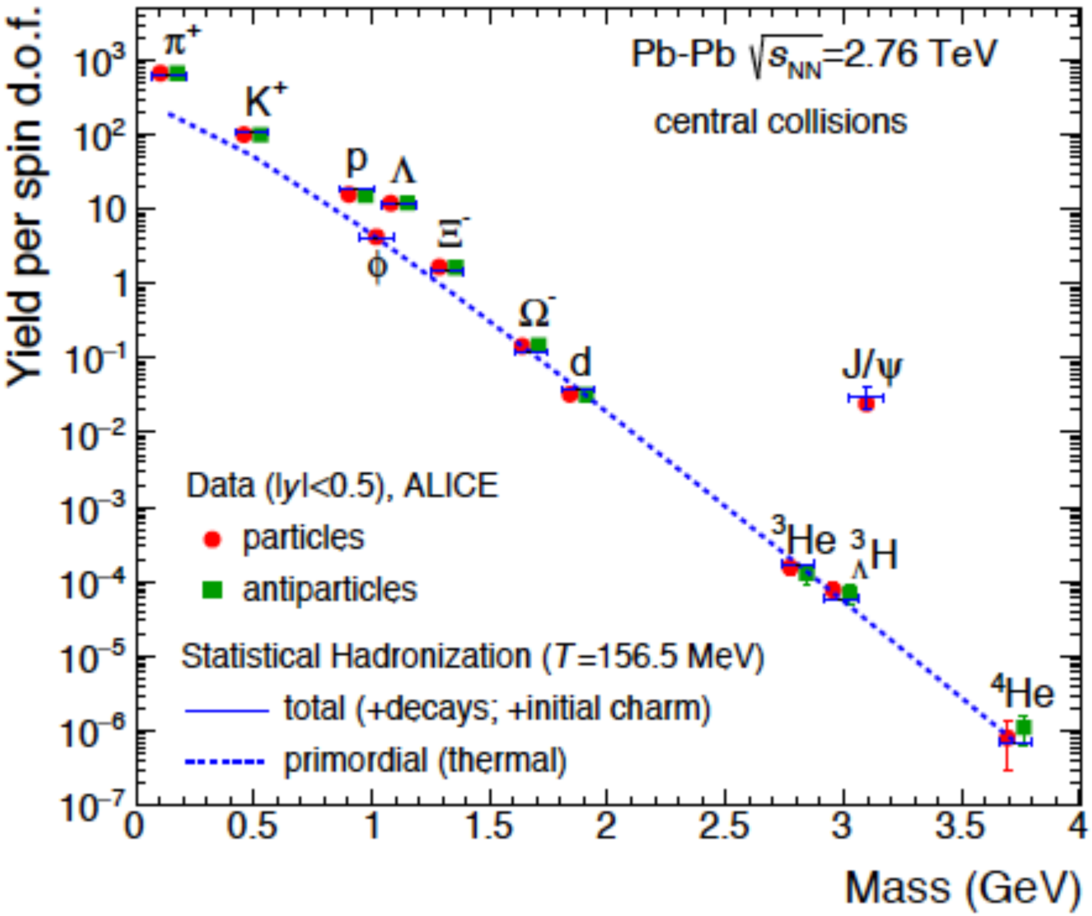


- Different models describe particle yields including light (hyper-)nuclei slightly worse at higher collision energy with a T_{ch} of about 153 MeV
- Including nuclei in the fit causes no significant change in T_{ch}

Fits: different view

A. Andronic



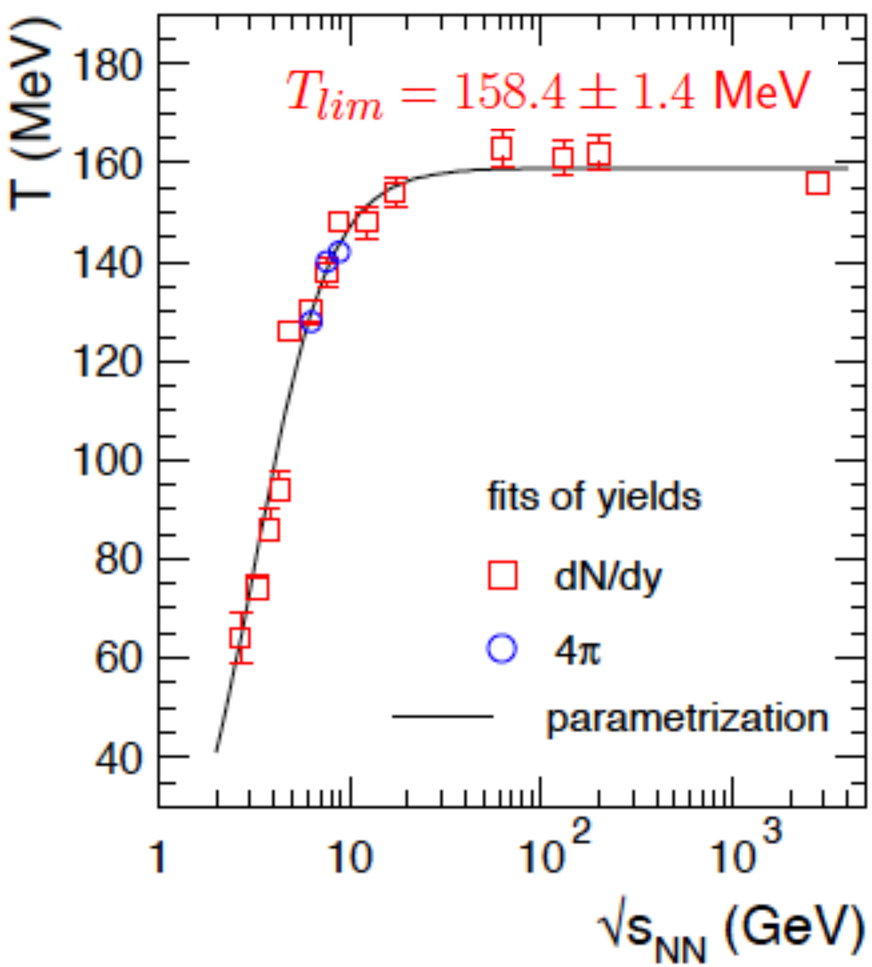
- Excellent agreement over 9 orders of magnitude
- Contribution from resonances significant and depending on the particle type
- Fit of φ, Ω, d, ^{3}He, $^3_\Lambda$H, ^{4}He: T_{ch}=156.0 ± 2.5 MeV (χ^2/ndf=7.4/8)
- Fit of nuclei (d, ^{3}He, ^{4}He): T_{ch}=159 ± 5 MeV
- 3-4 MeV upper bound of syst. uncertainty due to hadron spectrum

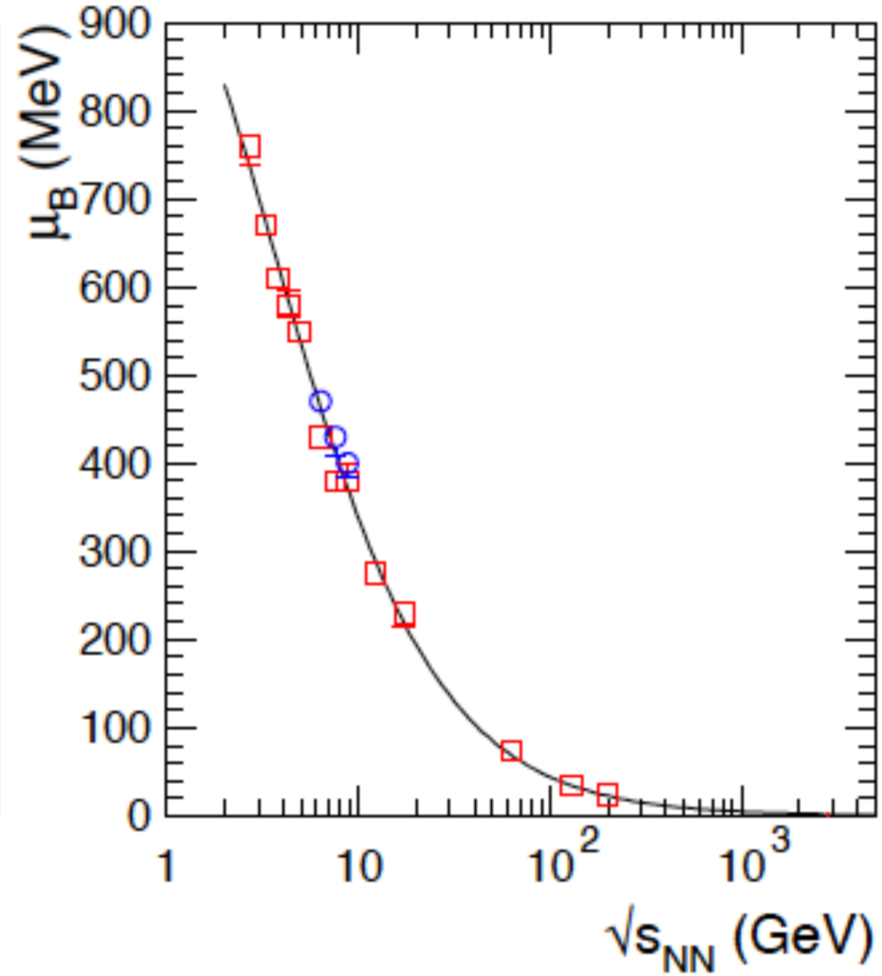
charm quarks, out of chemical equilibrium, undergo statistical hadronization

Parameterization

$$T = T_{lim}\frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}}(\text{GeV}))/0.45)}$$

$$\mu_B[\text{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\text{GeV})}$$

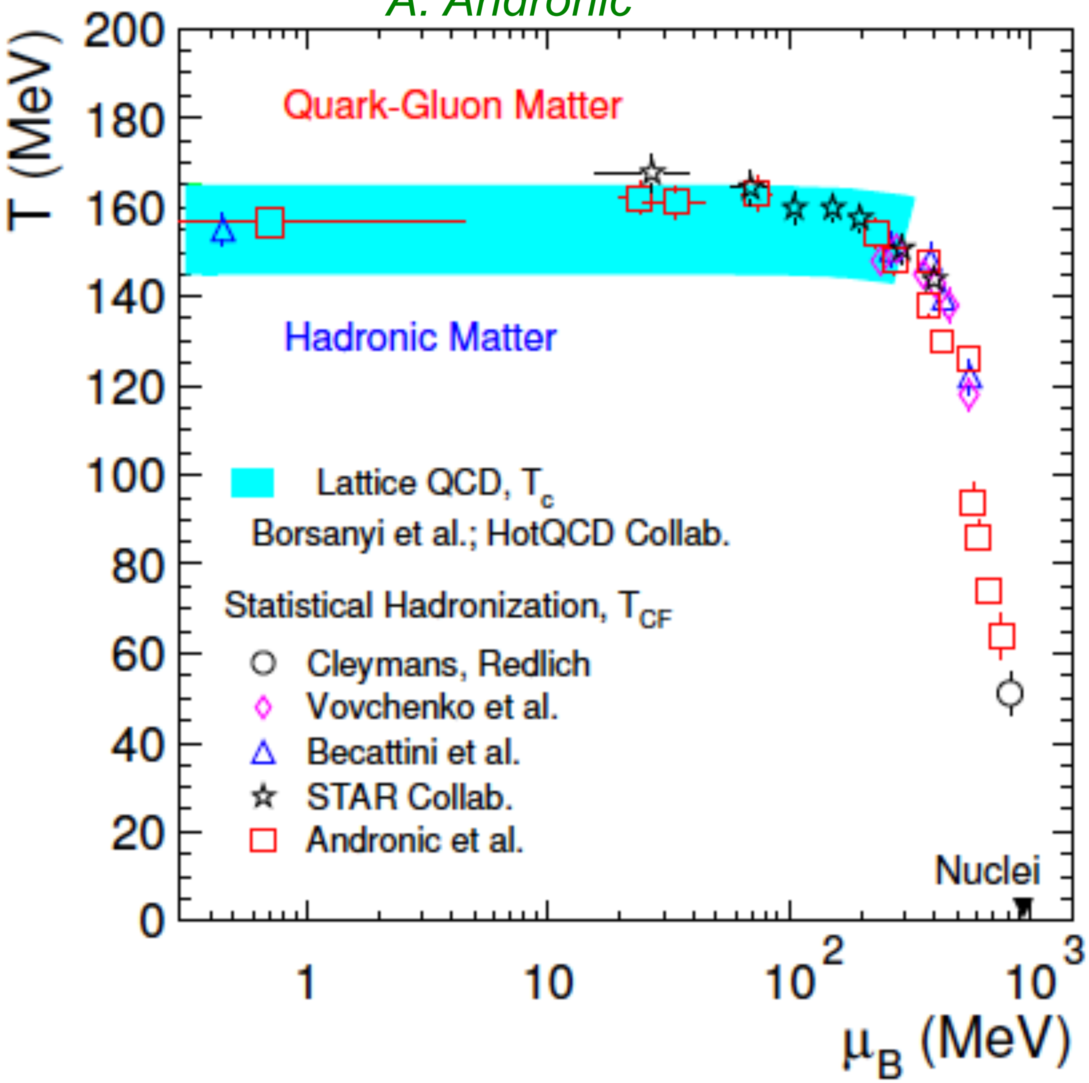




A. Andronic, et al., Phys. Lett. B 673 (2009) 142, with updates

Fits → phase diagram

A. Andronic



- At low μ_B the extracted freeze-out temperatures, and thus T_{lim}, coincide with the pseudo-critical temperature extracted through lattice QCD

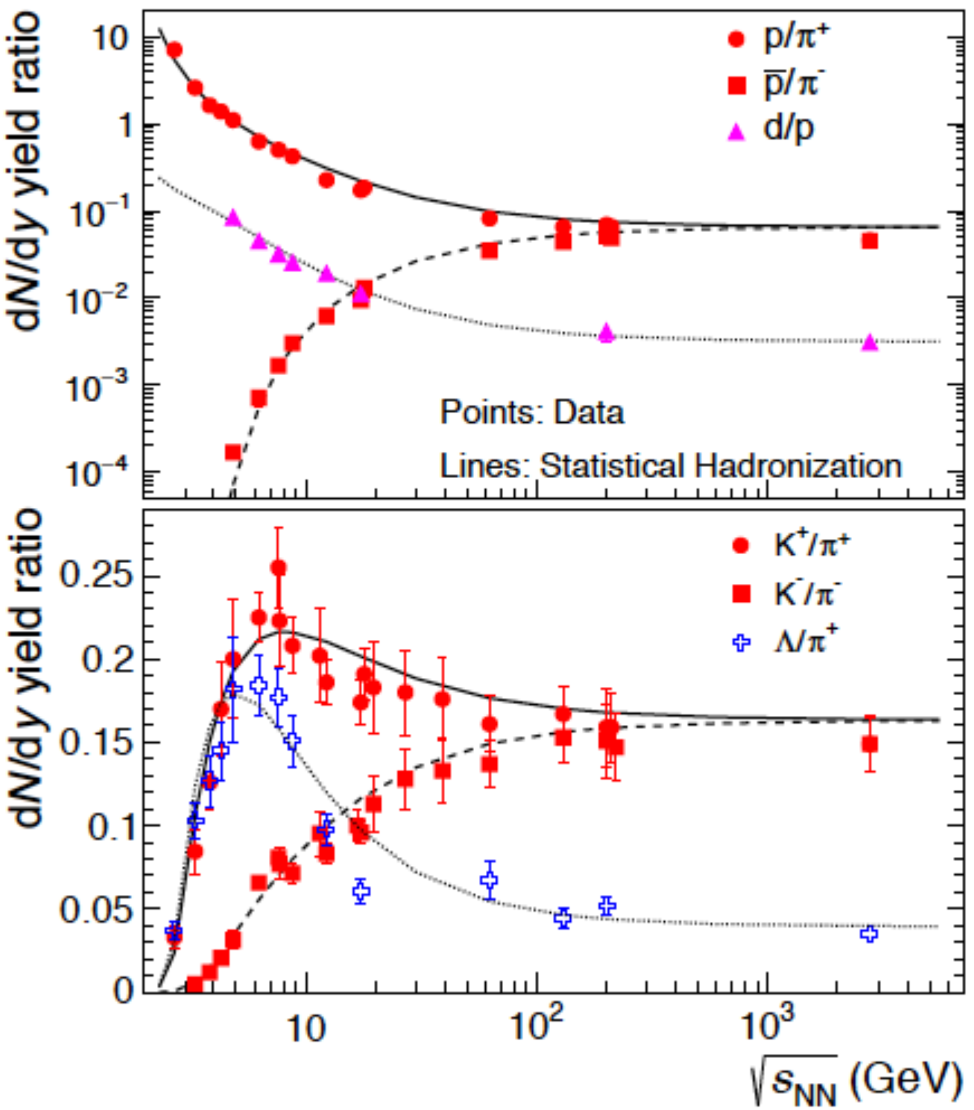
Lattice QCD:
Borsanyi et al., JHEP 1009 (2010) 073, JHEP 1208 (2012) 053
HotQCD, PRD 90 (2014) 094503, PRD 83 (2011) 014504

Statistical model:
Cleymans, Redlich, PRC 59 (1999) 1663
Vovchenko et al., PRC 93 (2016) 064906
Becattini et al., PLB 764 (2017) 241
STAR, PRC 96 (2017) 044904

- In the CBM regime (high-μ_B) one faces a much stronger energy dependence of T

Ratios

A. Andronic



Data:
AGS: E895, E864, E866, E917, E877
SPS: NA49, NA44
RHIC: STAR, BRAHMS
LHC: ALICE
NB: no contribution from weak decays

„structures" described by SHM determined by *T*, μ_B and strangeness conservation

„features" are not necessarily (1st order) phase transition signatures (or chiral symmetry restoration)

Proton anomaly

Possible explanations:

- incomplete hadron spectrum
- chemical non-equilibrium at freeze-out
- modification of hadron abundancies
- separate freeze-out temperatures for strange and non-strange hadrons
- excluded volume interactions
- energy dependent Breit-Wigner T = 155 ± 1.7 MeV
- replace Breit-Wigner by phase shift analysis T = 155.0 MeV

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→ All connected to systematic uncertainties of thermal model approaches

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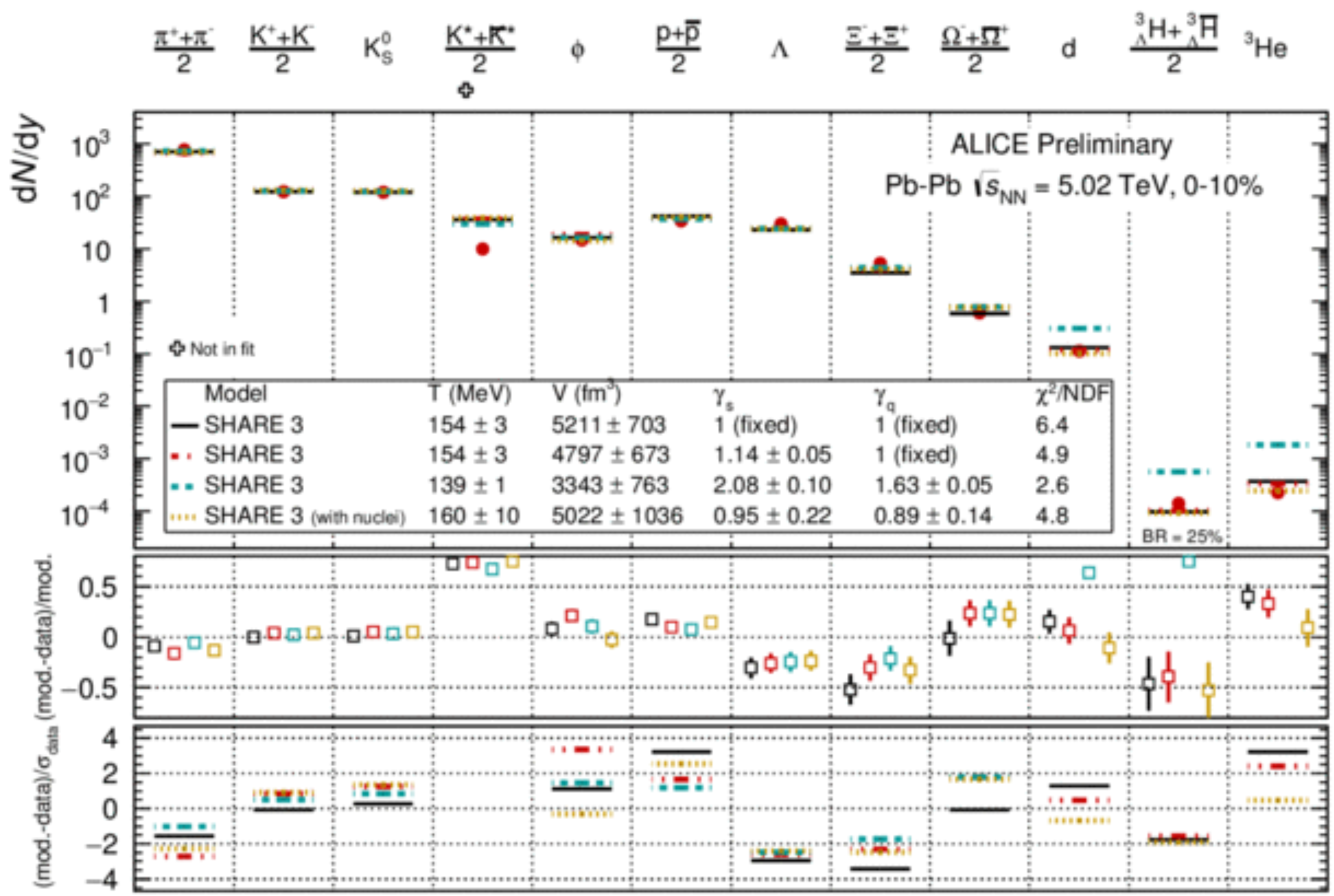
Thermal model: SHARE

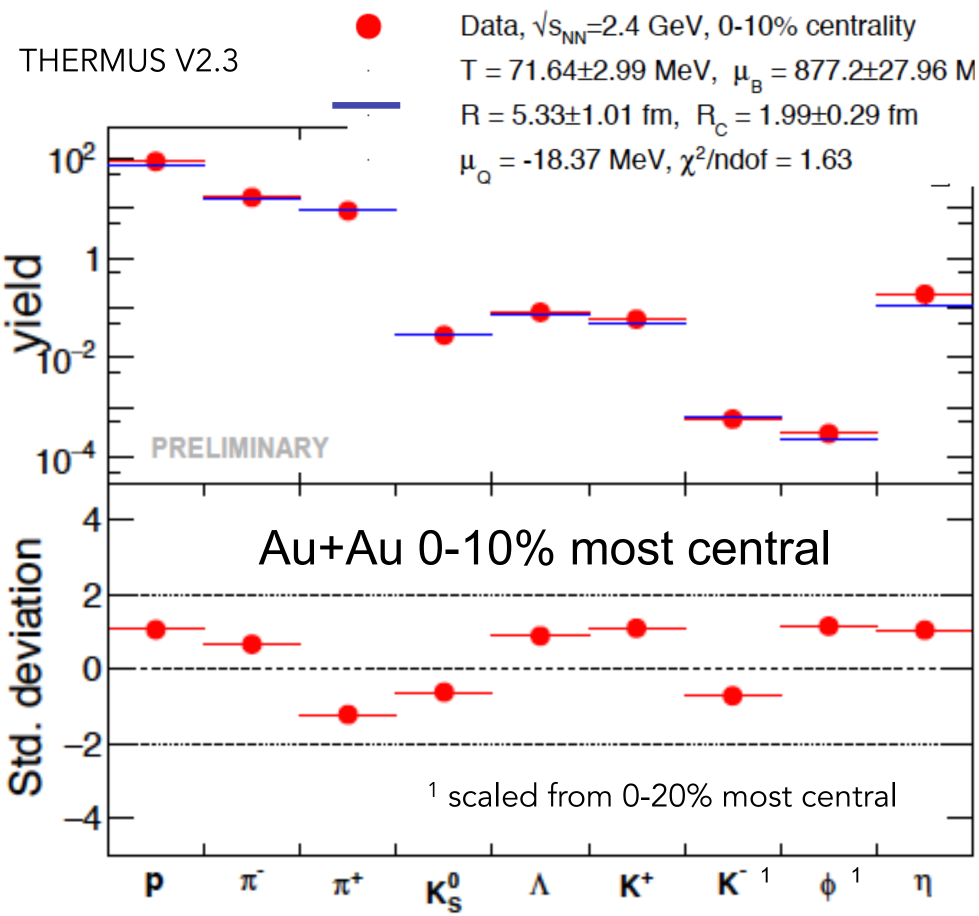
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

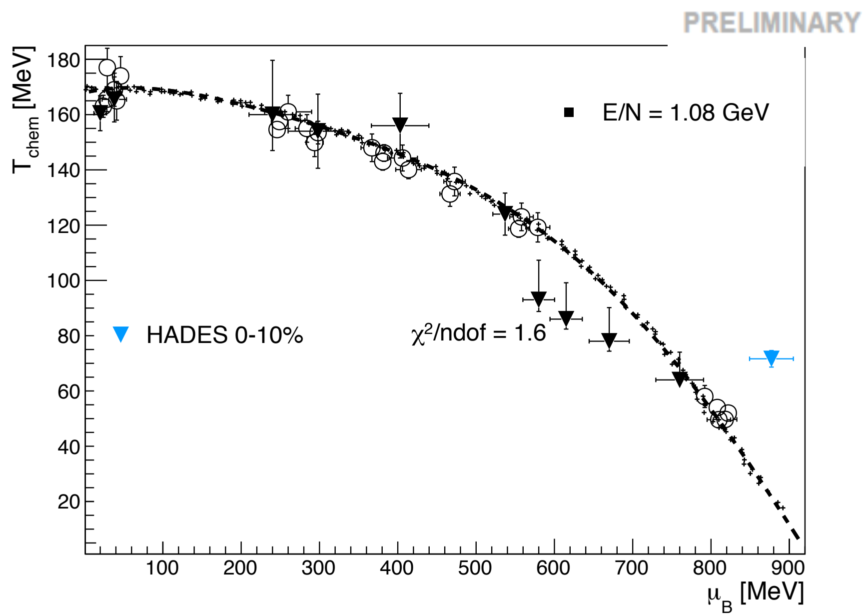


- Non-equilibrium thermal approach leads to better fit
- Observations similar to QM2014 results
- Including nuclei drives a non-equilibrium fit towards the equilibrium values

HADES Au-Au

M. Lorenz





– Freeze-out point stays at higher T and μ_B also for 0-10% most central events

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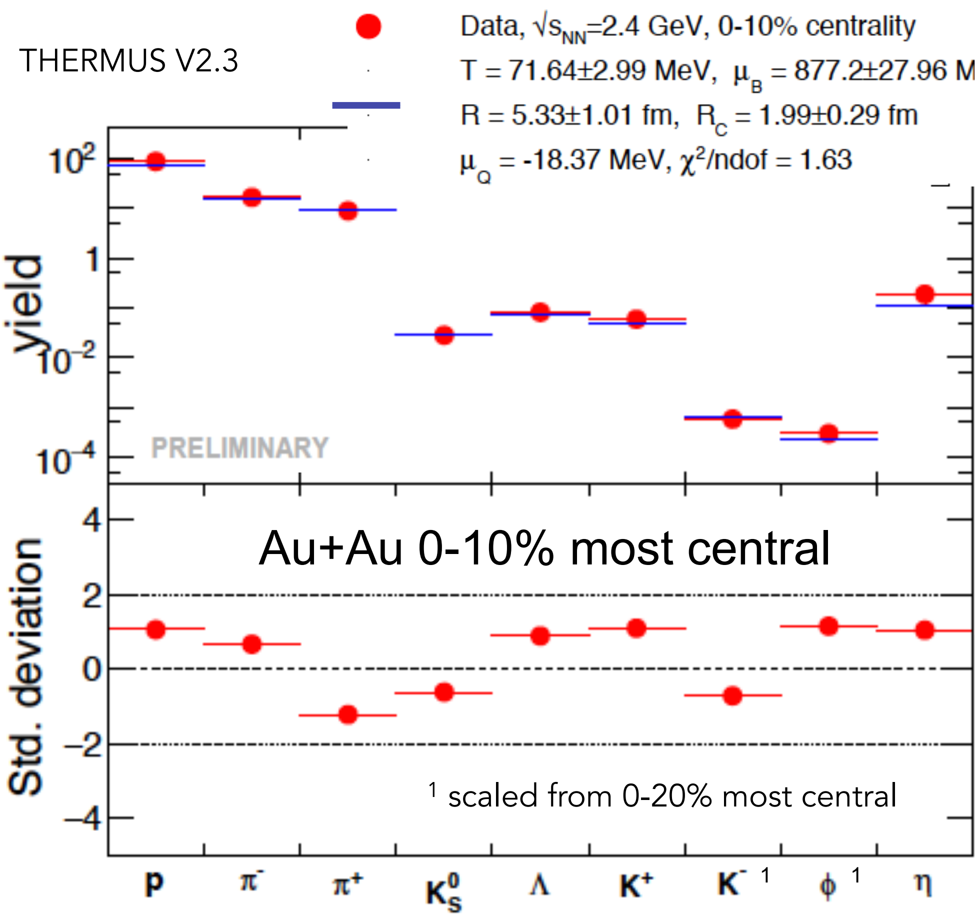

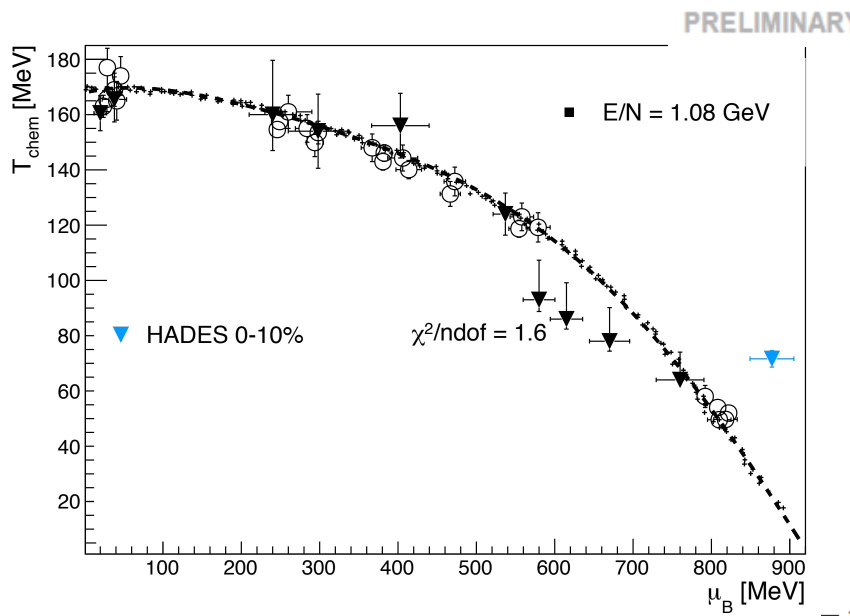

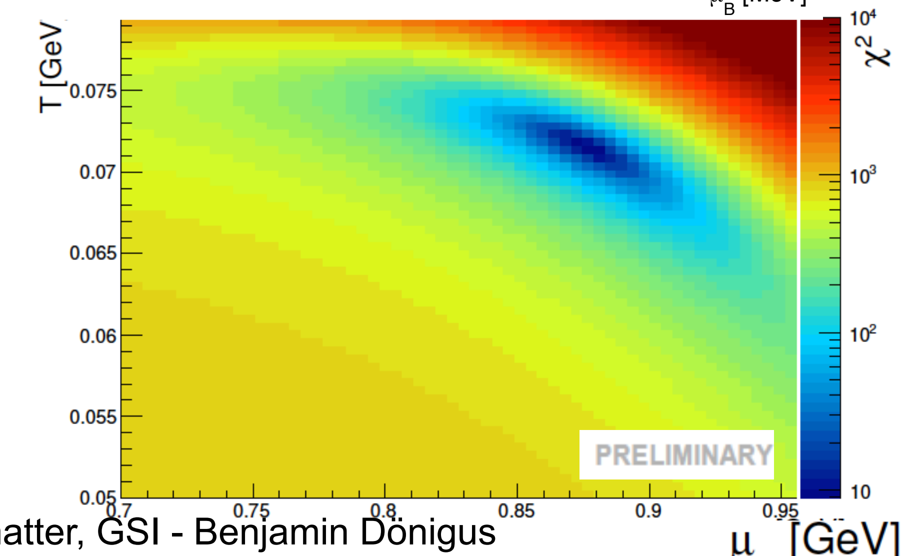

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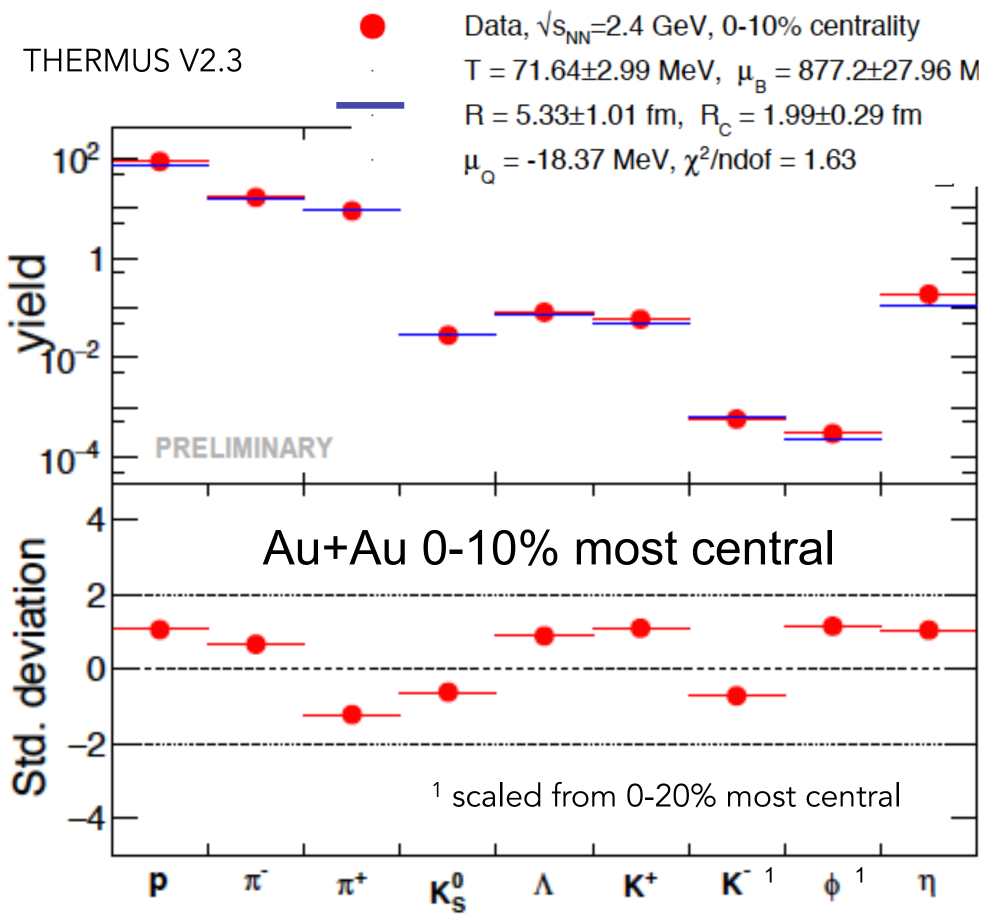
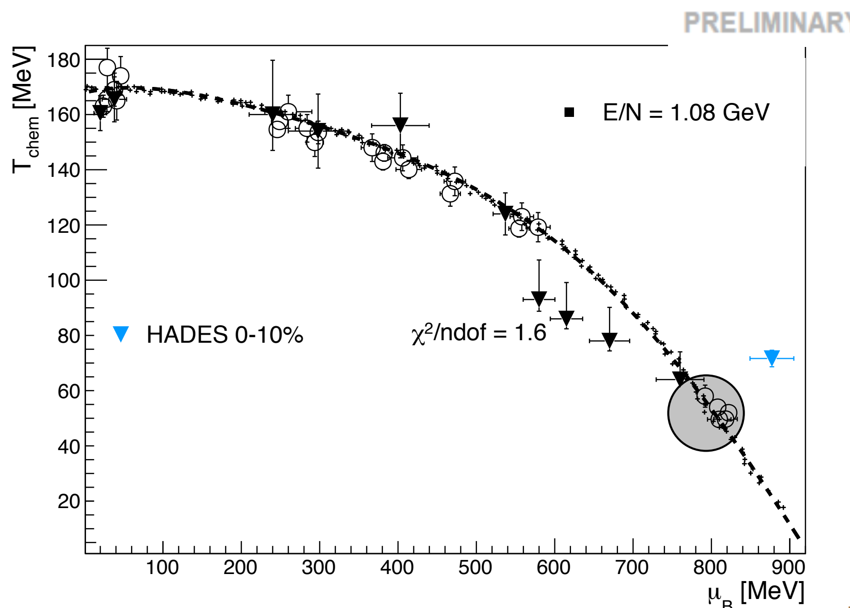
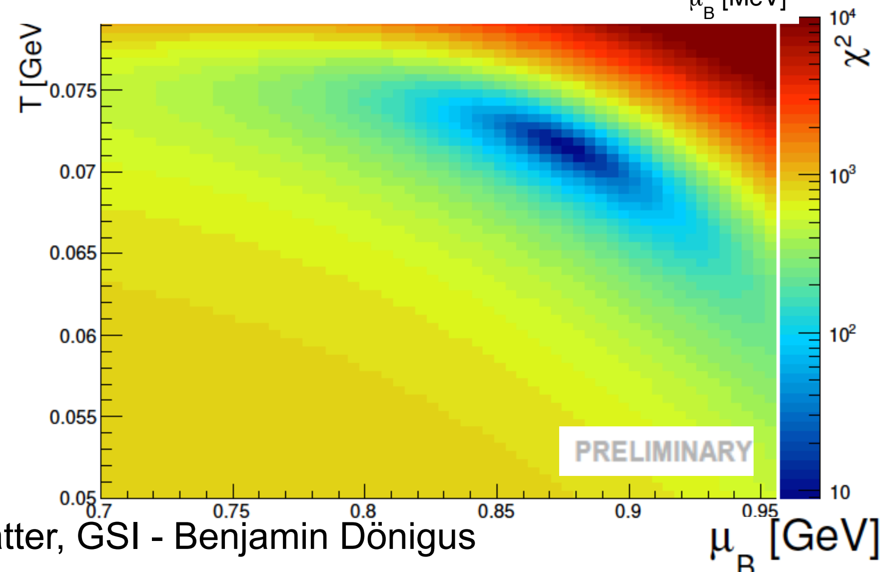


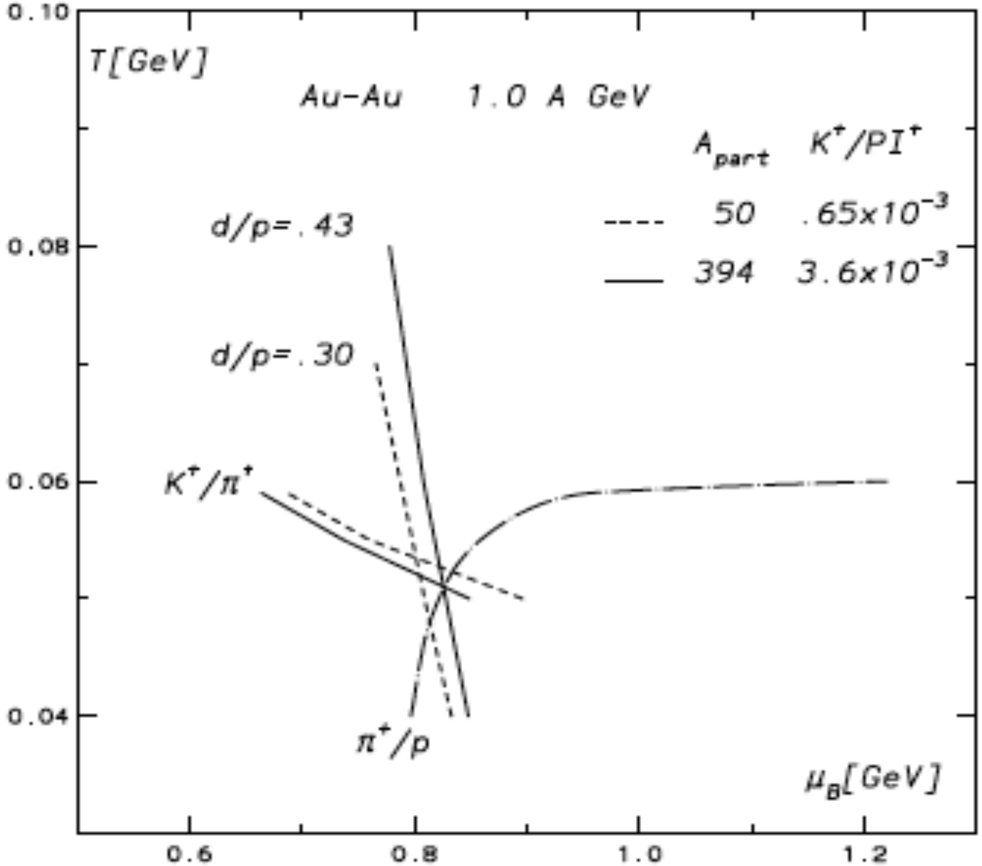


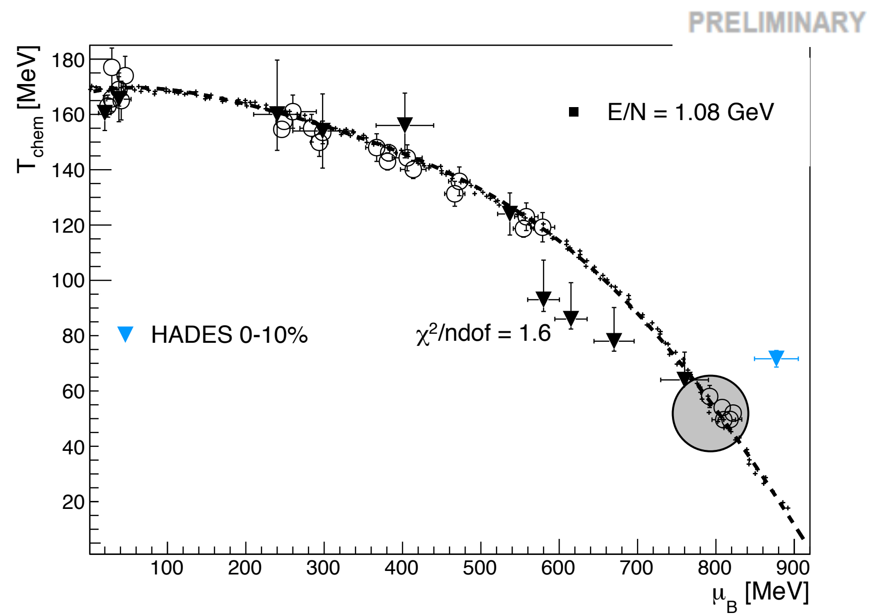


- Freeze-out point stays at higher T and μ_B also for 0-10% most central events
- X^2 scan: no minimum near expected freeze-out
- Which hadron yields drive the fit away?

HADES Au-Au

M. Lorenz





J. Cleymans, H. Oeschler, K. Redlich, Phys.Rev. C59 (1999))

– Freeze-out points previously estimated based on ratios of p, d, K^+, π^+

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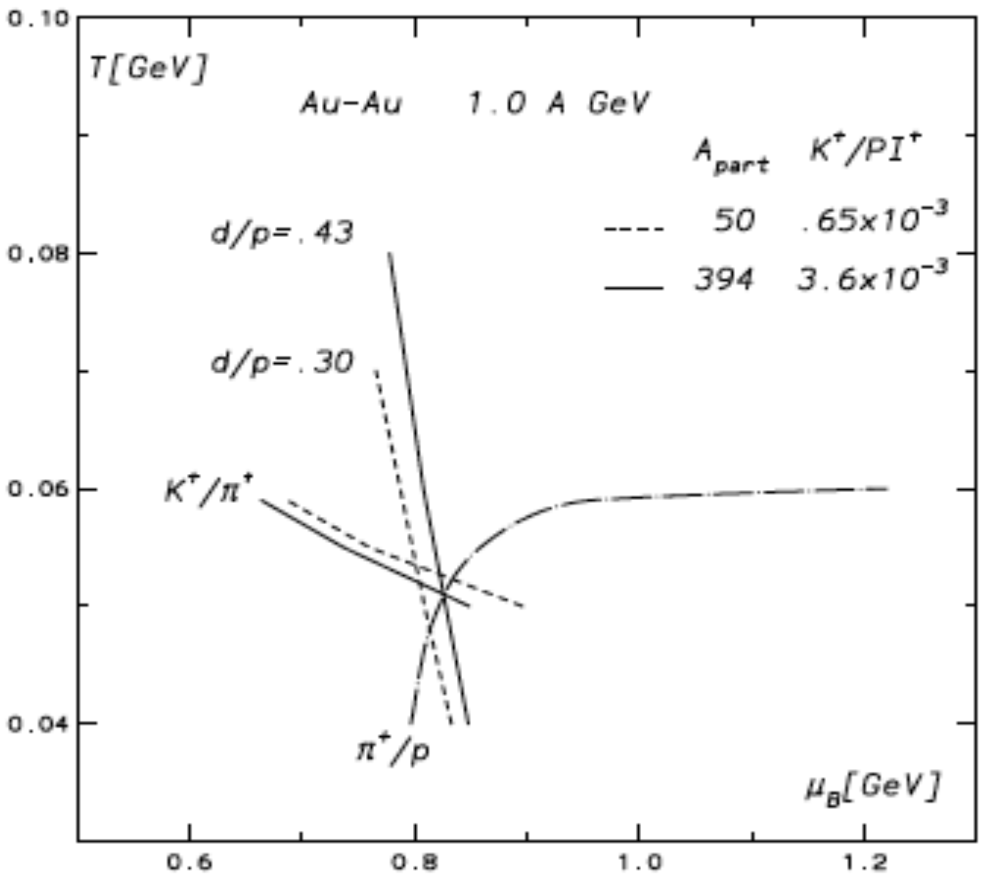

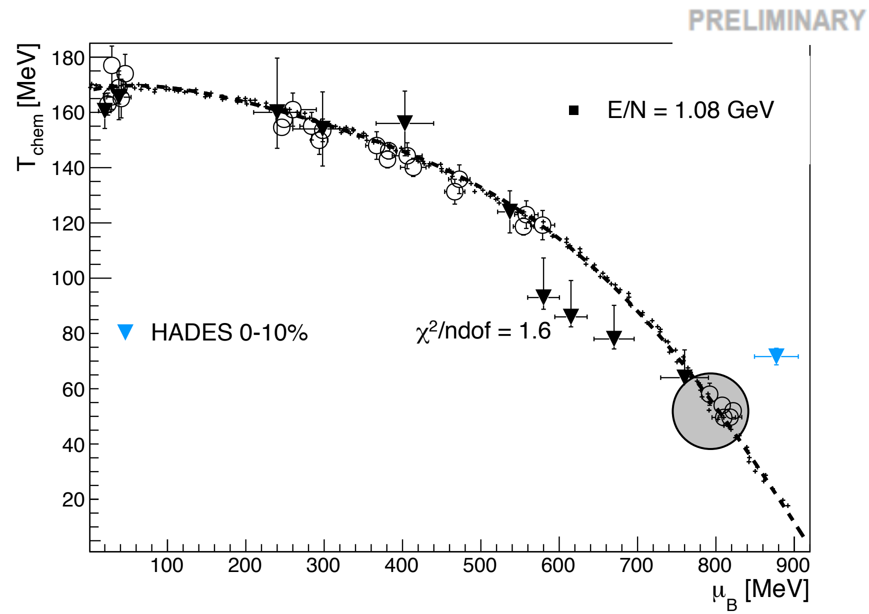

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  Switch to Thermus V3.0 or Thermal-Fist https://github.com/vlvovch/Thermal-FIST

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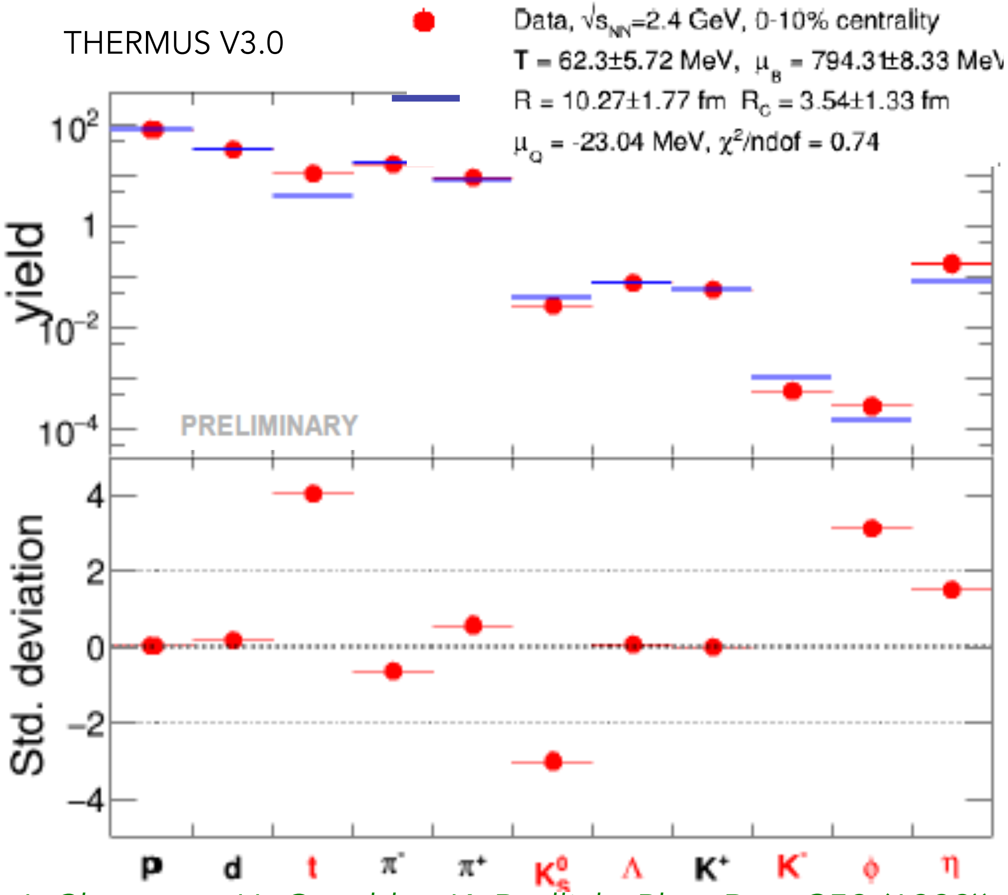
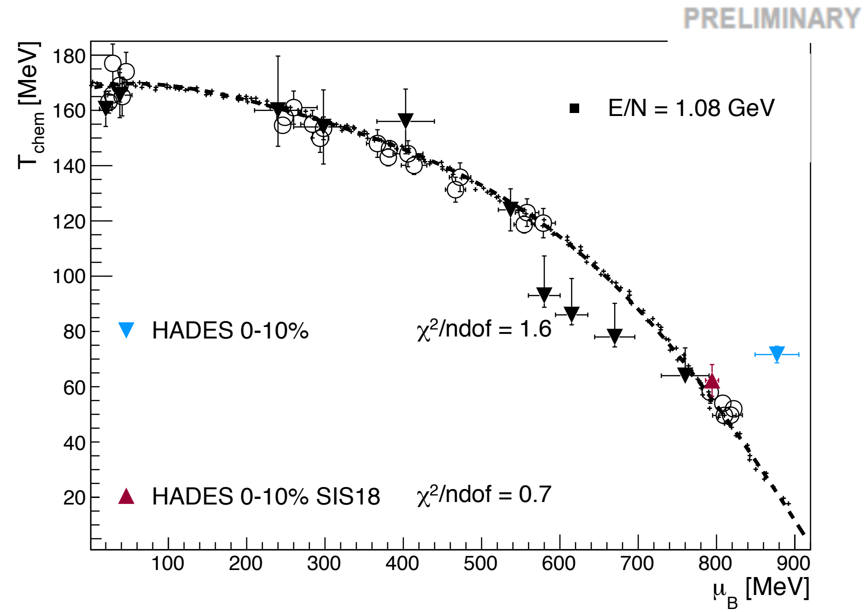
THERMUS V3.0





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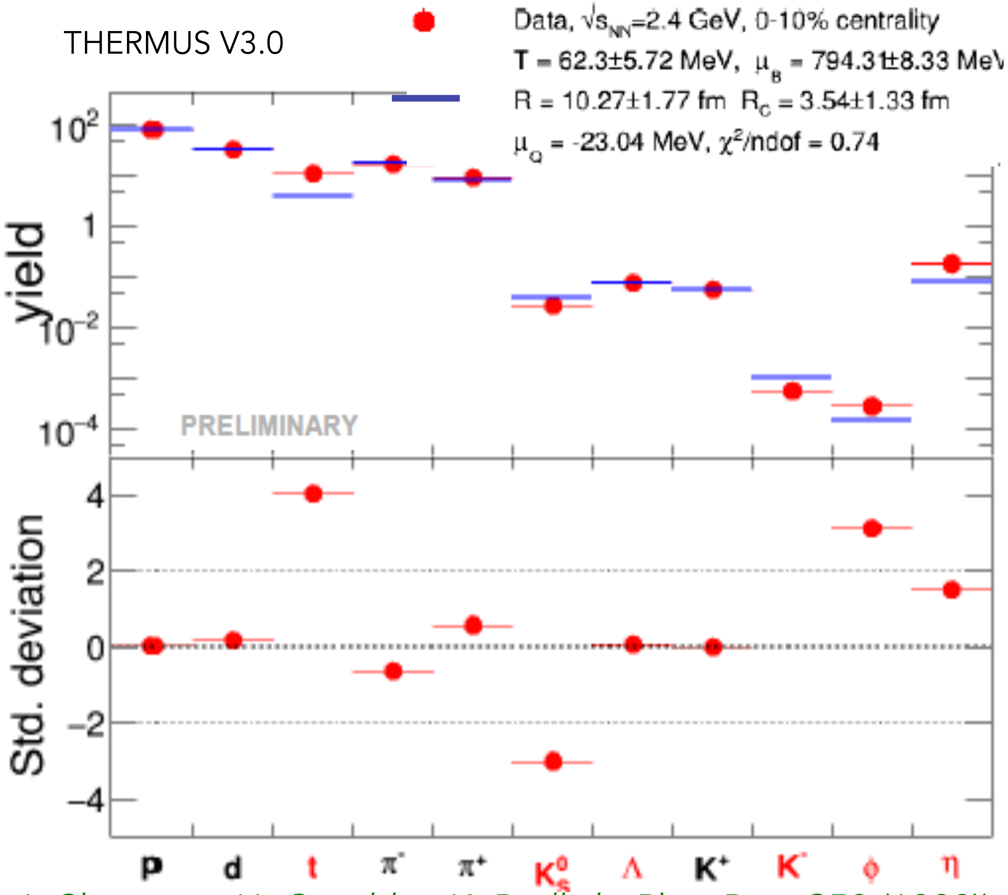

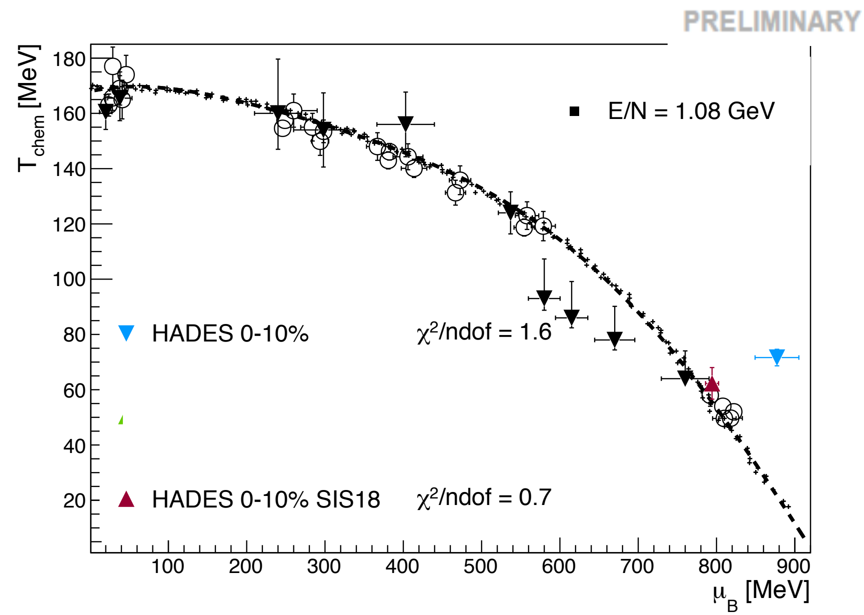

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- E/N=1.08 GeV with or without light nuclei?

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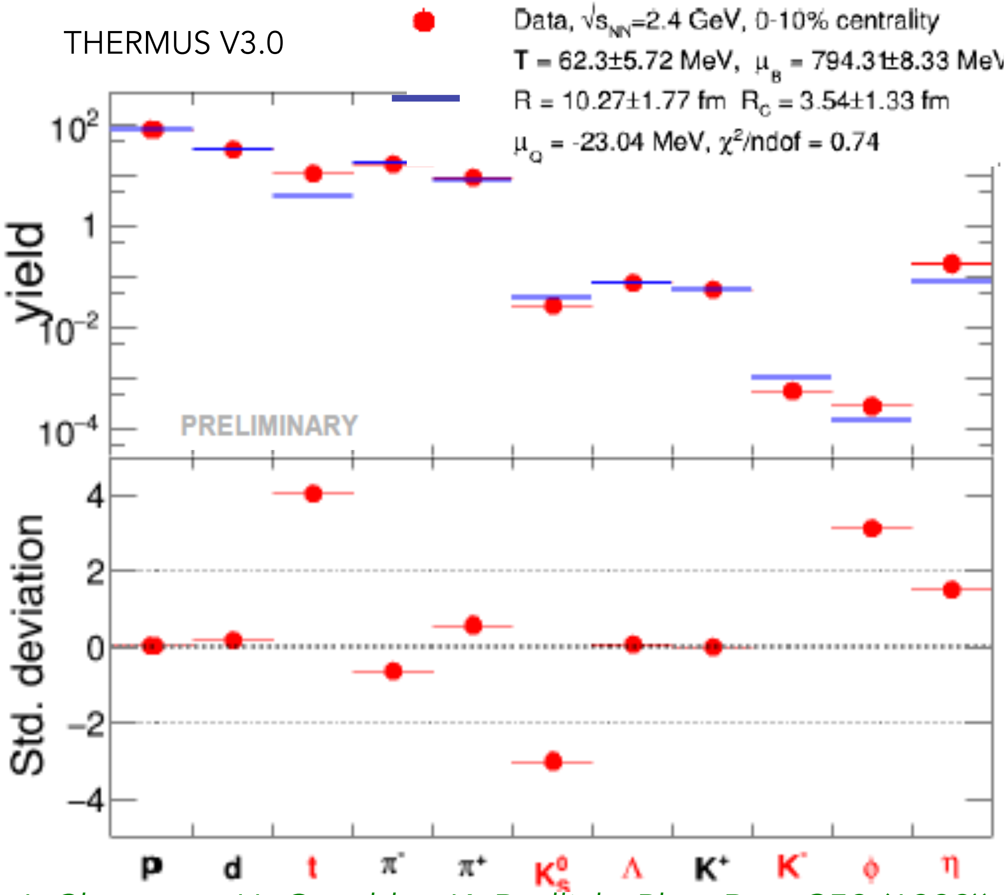
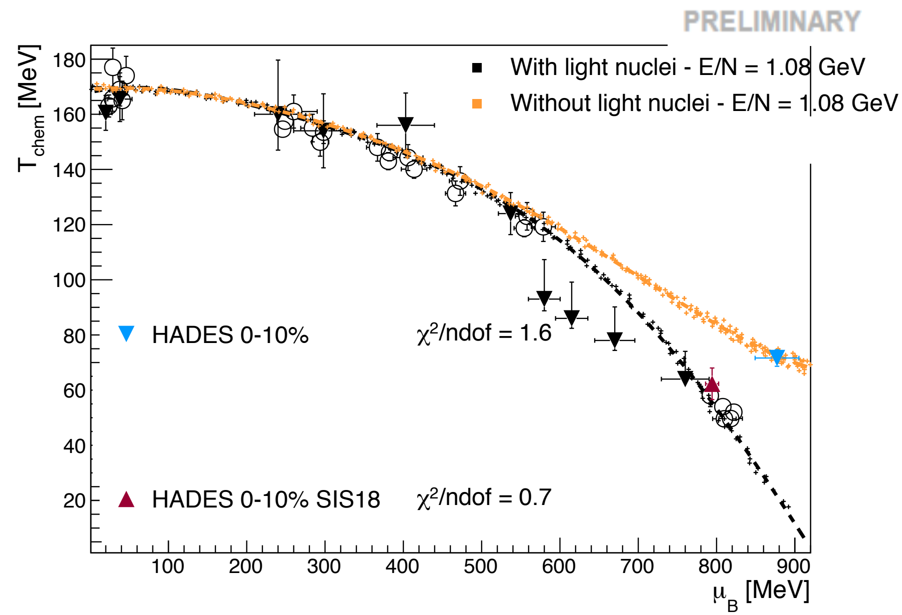
THERMUS V3.0





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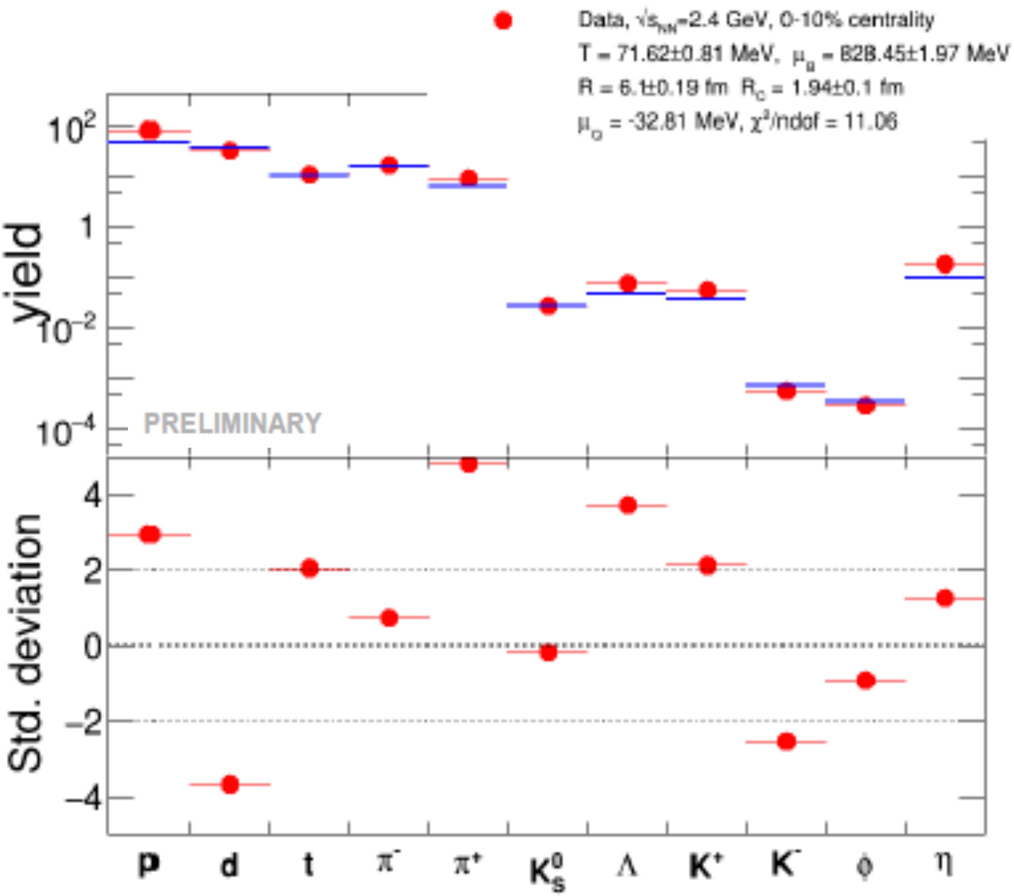

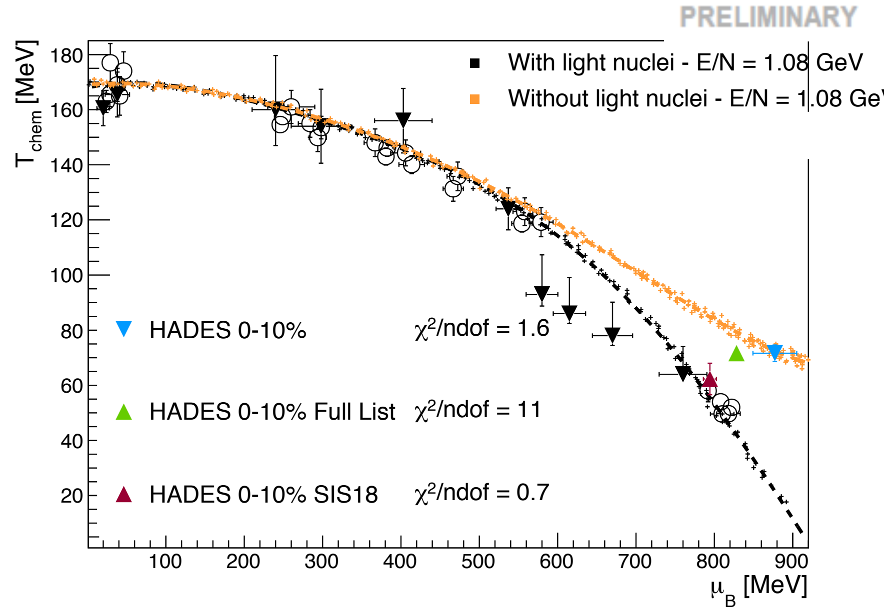

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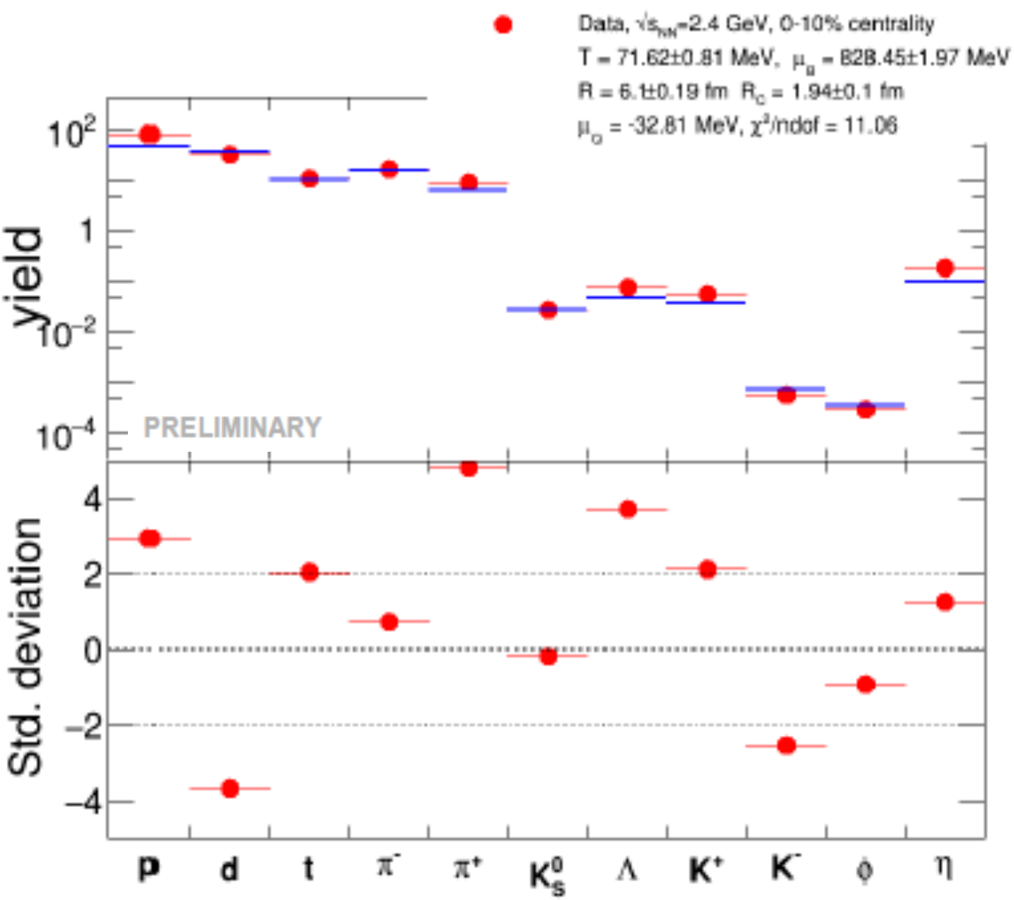

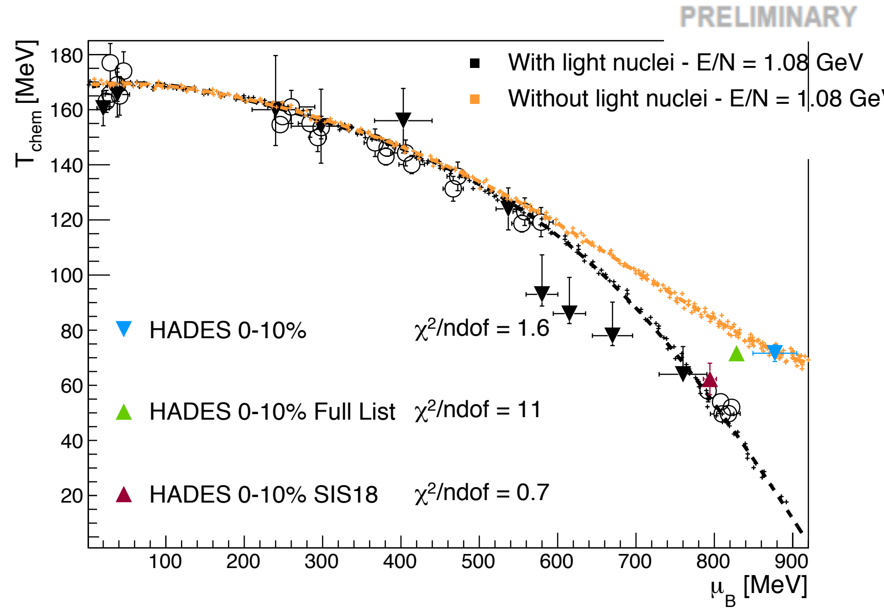

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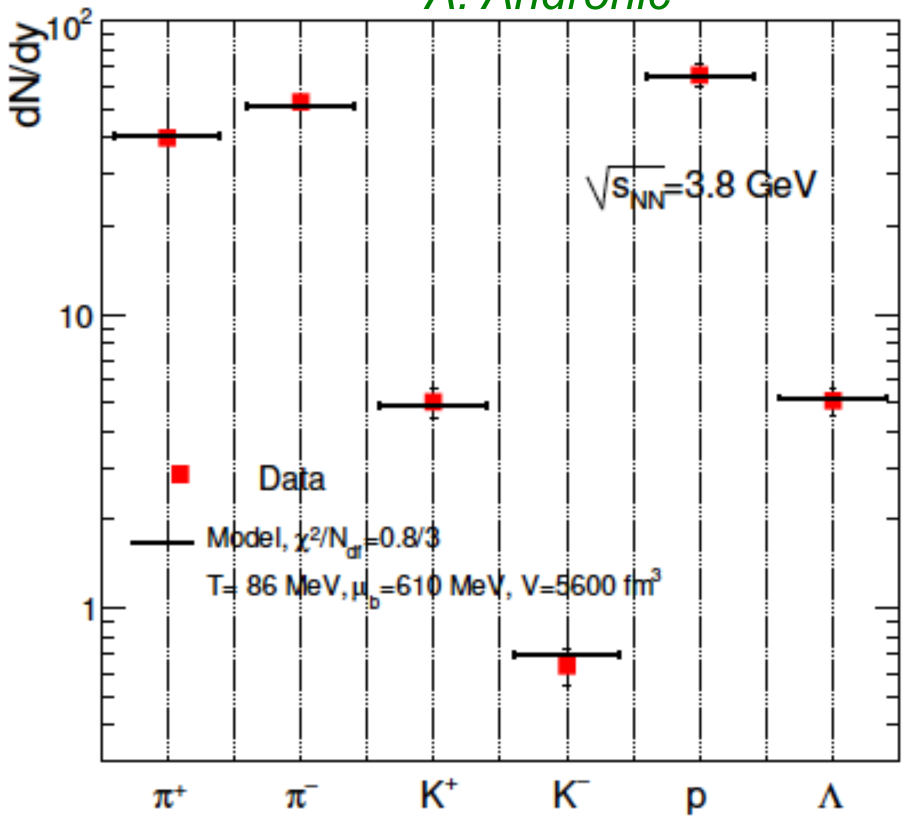
- Fit to complete hadron set gives bad χ^2 (very preliminary triton yield)
- Inclusion of repulsive interactions[1] needed?

[1]V. Vovchenko ,H. Stöcker J.Phys. G44 (2017) no.5, 055103
A. Andronic et al. arXiv:1808.03102

SIS100 energy regime

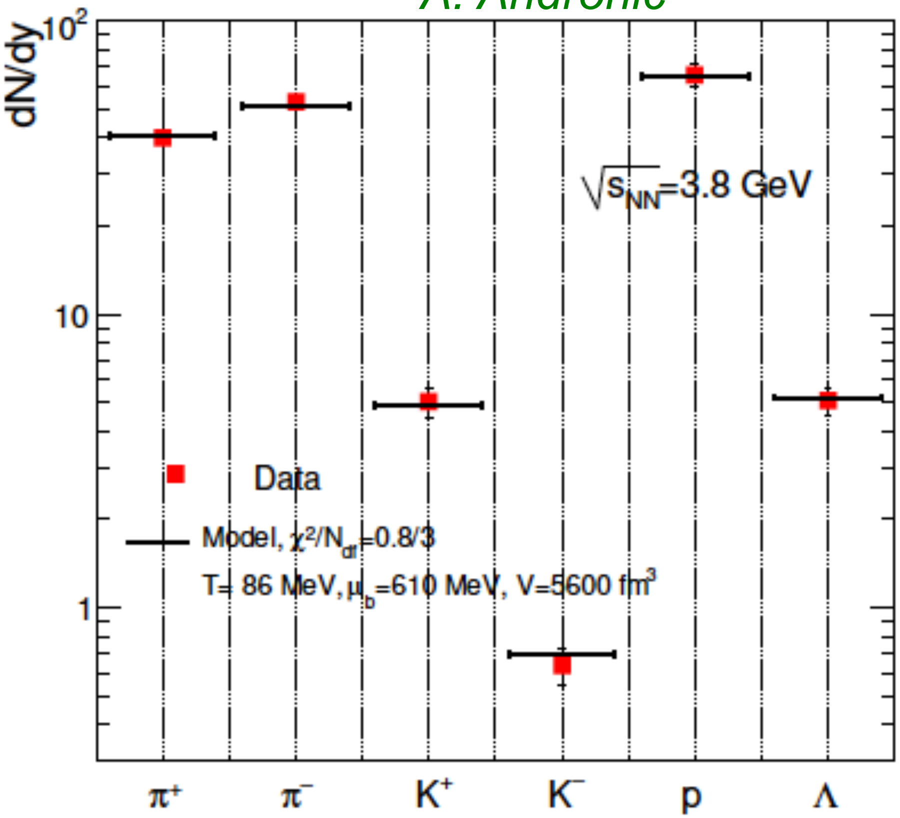
A. Andronic

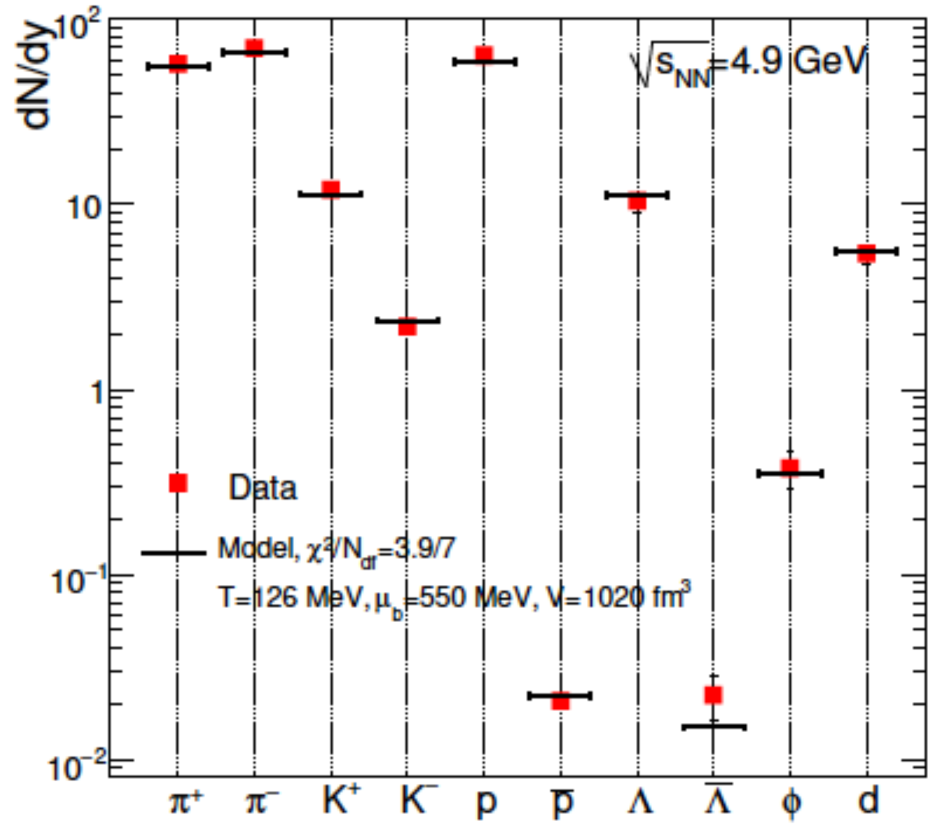


Data situation in the SIS100 energy regime rather scarce
Nevertheless, fits are of good quality
→ precision and number of hadrons should be increased

SIS100 energy regime

A. Andronic





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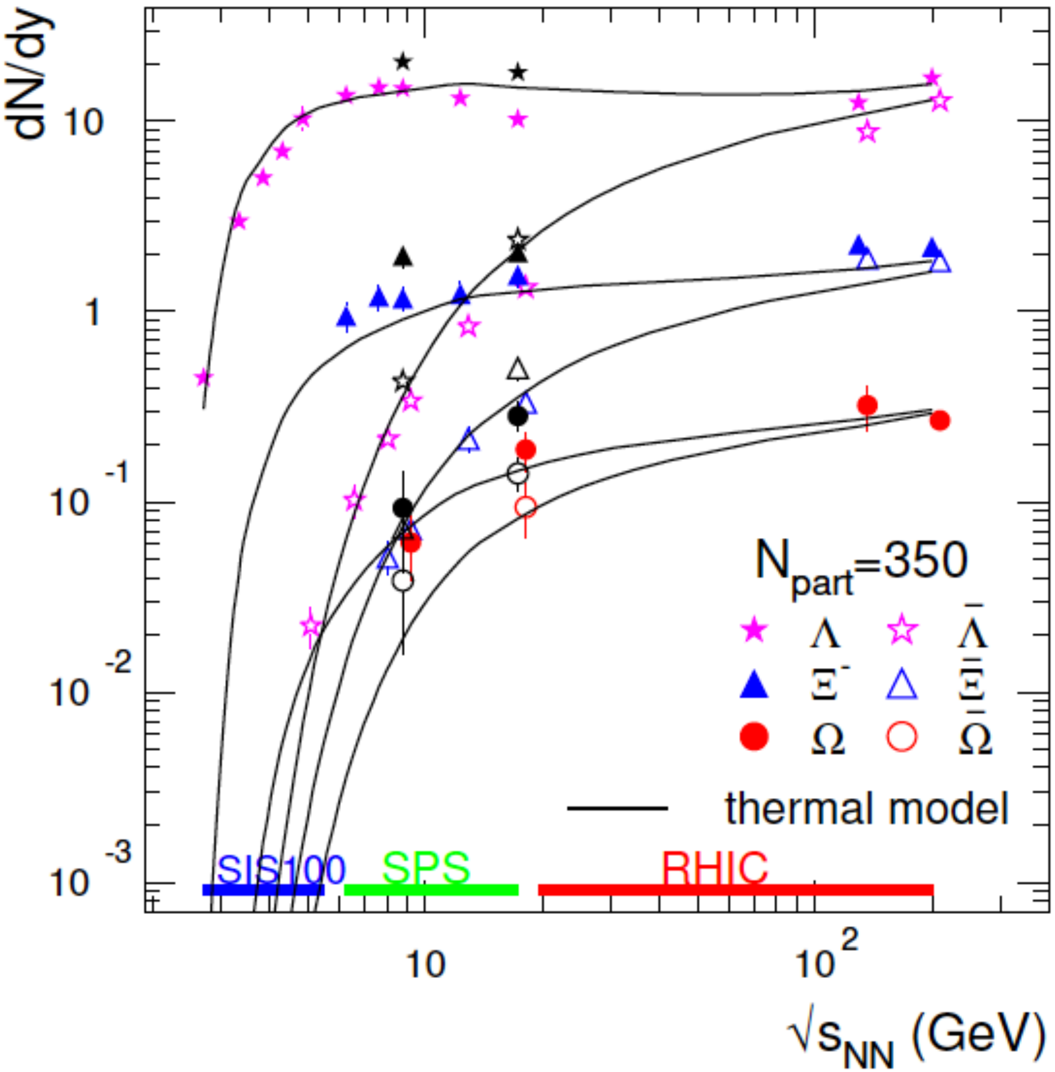
Predictions

A. Andronic



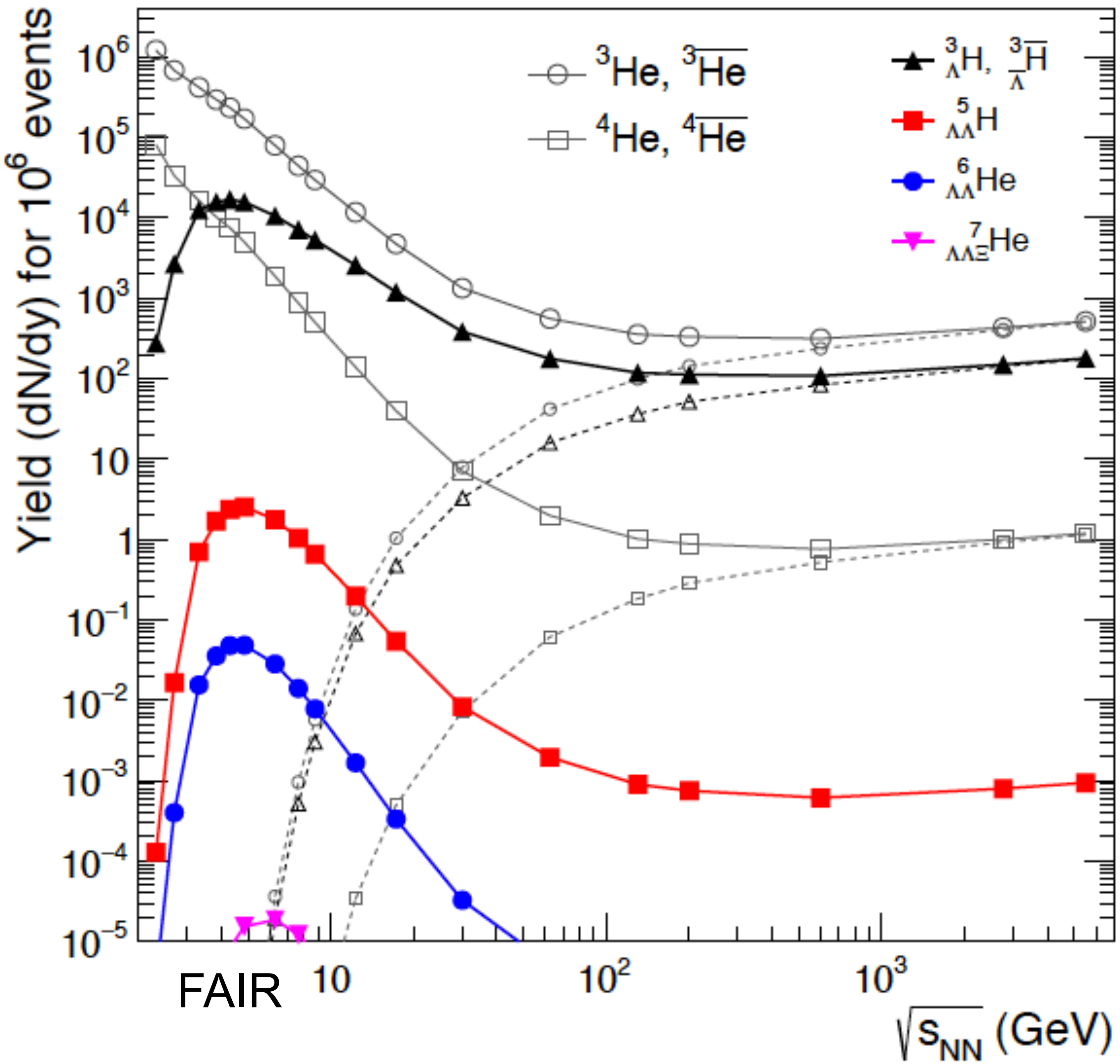
Example:

$dN/dy|_{y=0}$ yields at 8 AGeV:

Λ: 9.0	$\bar{\Lambda}$: $1.4 \cdot 10^{-3}$
Ξ^-: 0.27	$\bar{\Xi}^+$: $3.2 \cdot 10^{-4}$
Ω^-: $5.4 \cdot 10^{-3}$	$\bar{\Omega}^+$: $5.4 \cdot 10^{-5}$

Hypernuclei

A. Andronic



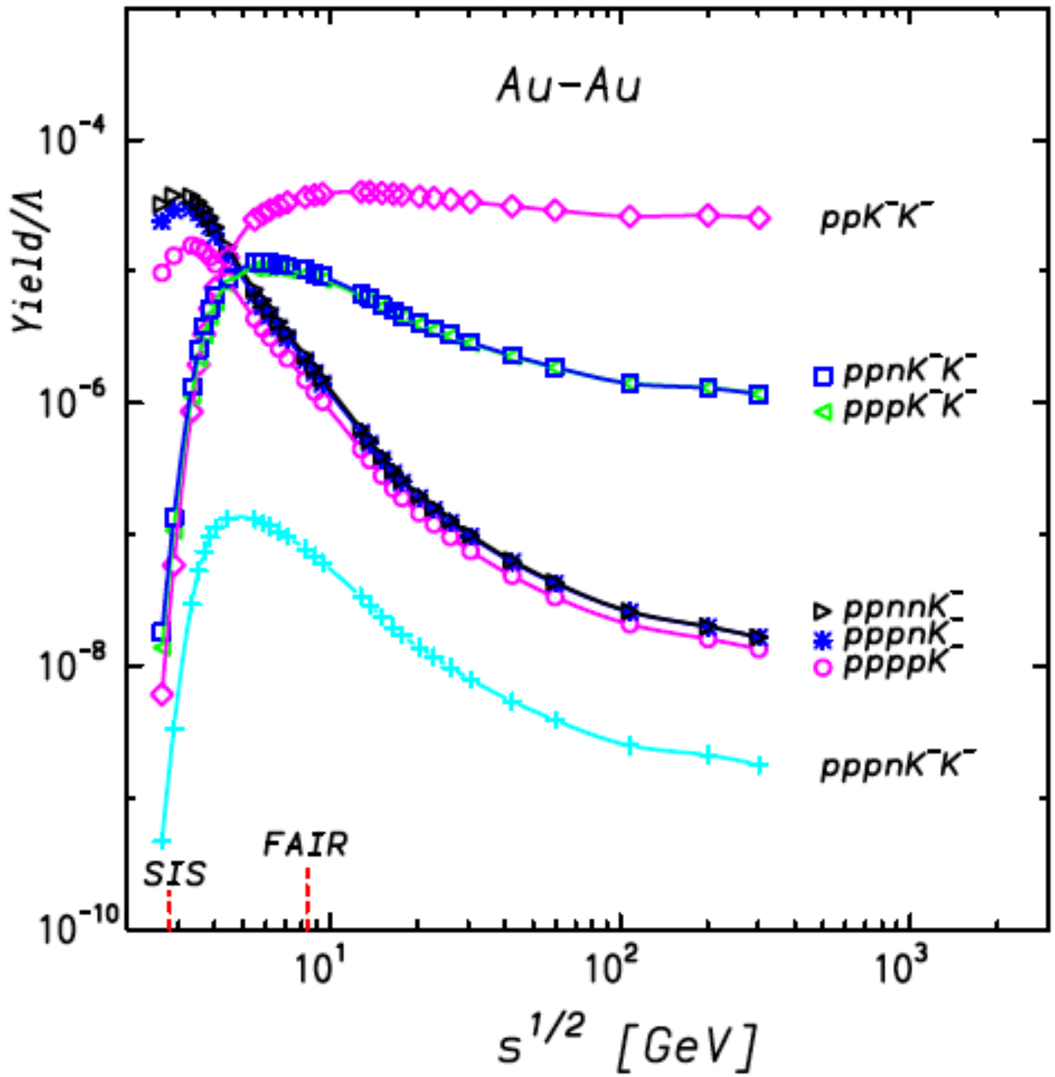
- Hypernuclei production maximum around FAIR energies
- Roughly two orders of magnitude higher $^{3}_{\Lambda}H$ production compared to LHC
- Even hypernuclei with higher strangeness content will be in reach

→ FAIR will be a hypernuclei factory

Exotica

A. Andronic, et al., NPA 765 (2006) 211

- Exotica searches feasible at FAIR energies
- Kaonic bound states have highest production probability in the SIS100 region
- Strange dibaryons of all kinds are also good candidates for searches

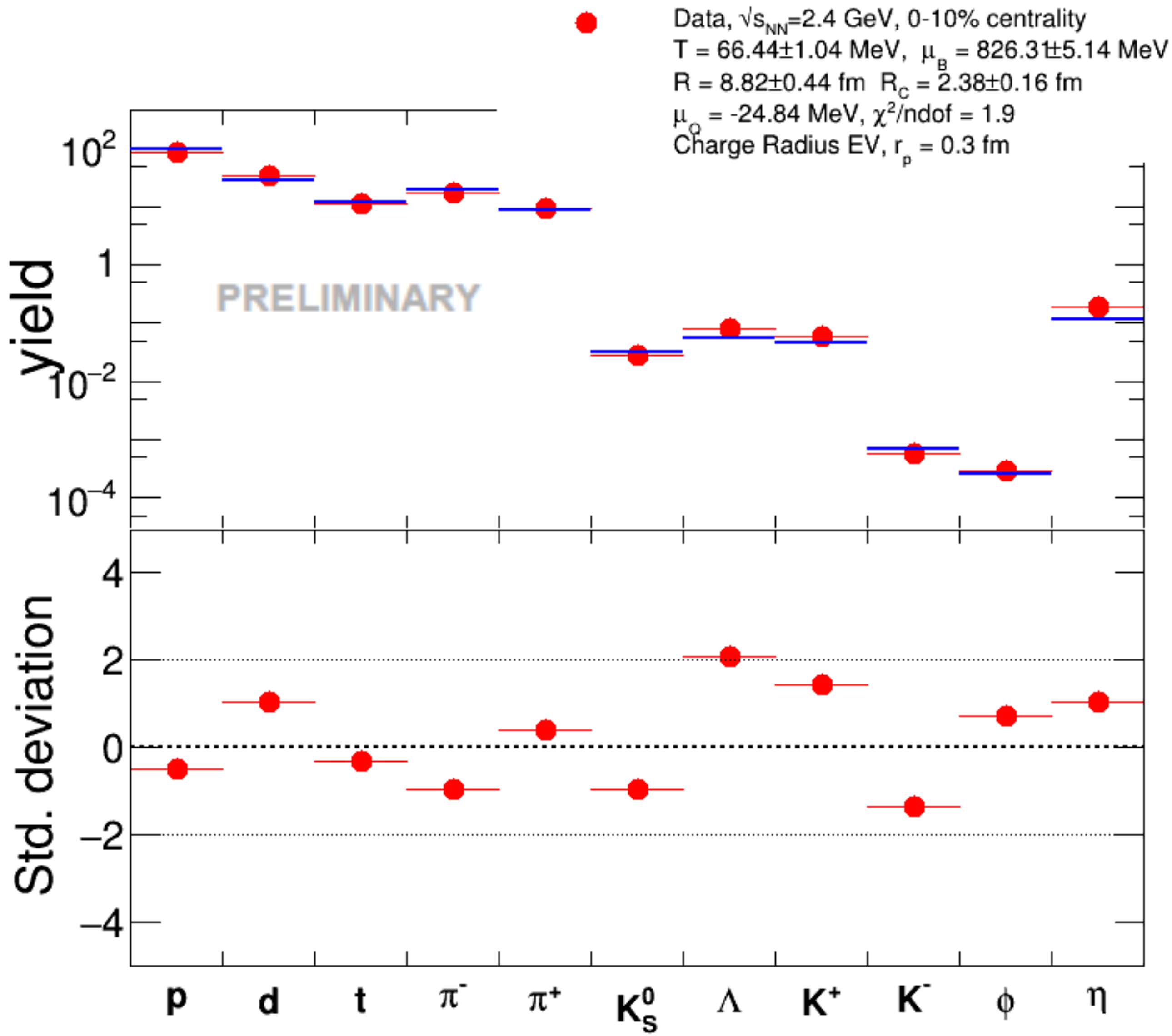


Summary

- The themal model provide a clear way to obtain „experimental points“ in the QCD phase diagram (via fits of *u,d,s* hadron yields)
- Thermal fits work well (AGS – LHC) with 3 parameters (T,μ_B,V) and can describe the current data with a precision of about 10%
- Canonical models work reasonably well in small systems and below threshold (HADES)
- The improved precision of the new data sets are testing the thermal model much stronger than before
- Systematics of the thermal model can lead to better or worse description of the high precision data
- Improved models using eigenvolume corrections, phase shifts or energy dependent Breit-Wigner lead to better fits of the current data (better χ^2/ndf)
- Abundant production of (hyper)nuclei and exotica can be expected from predictions from the thermal model

HADES Au-Au

M. Lorenz



- SHM fit including EV-corrections based on the charge radius of the nuclei describes the same data set rather well

Master thesis J. Stumm

Canonical approach

In particular for small systems as e^+e^- and pp one often uses the canonical ensemble instead of the grand canonical ensemble, i.e. one or more quantum number is no longer conserved on average but needs to be conserved exactly

Often only strangeness-canonical treatment is used which can be modelled by a conservation or correlation Radius R_C in which the quantum number (strangeness) is exactly conserved