Statistical Hadronization and Strangeness

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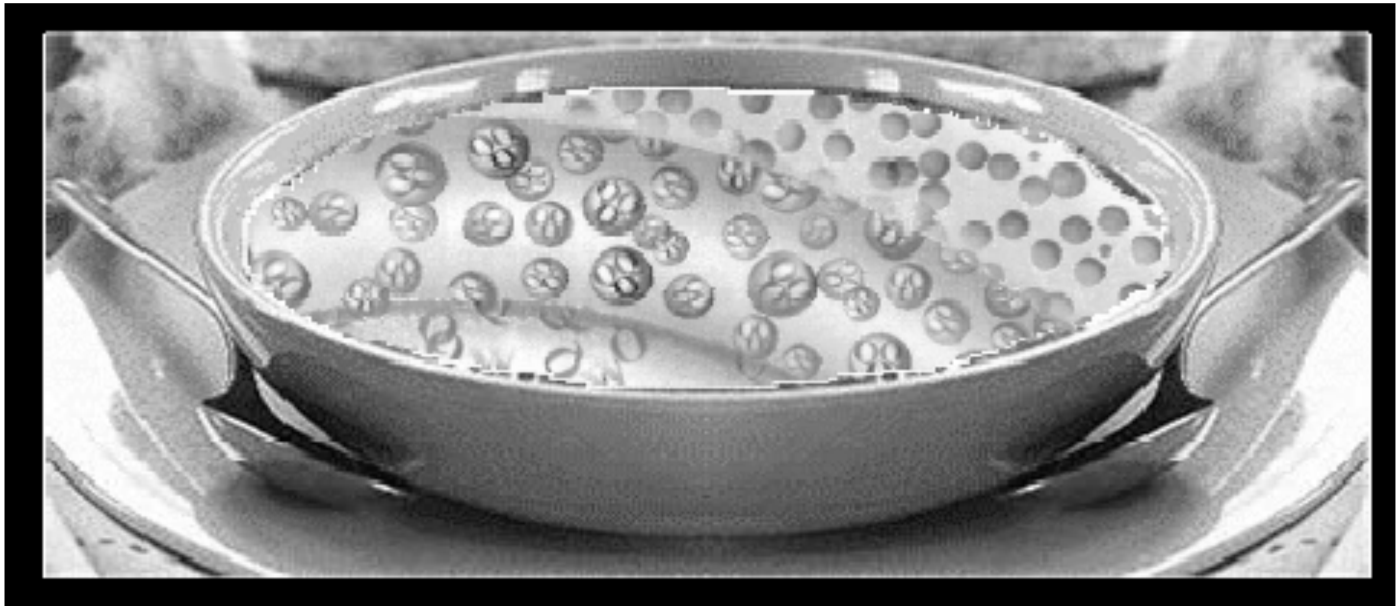
ALICE Experiment 201

Outline

- Introduction
- Collision history
- Excursus: particle identification
- Canonical suppression
- Statistical hadronization model
- Particle abundances – T_{ch}
- Summary

Quark Gluon Plasma



Source: Michael Turner, *National Geographic (1996)*

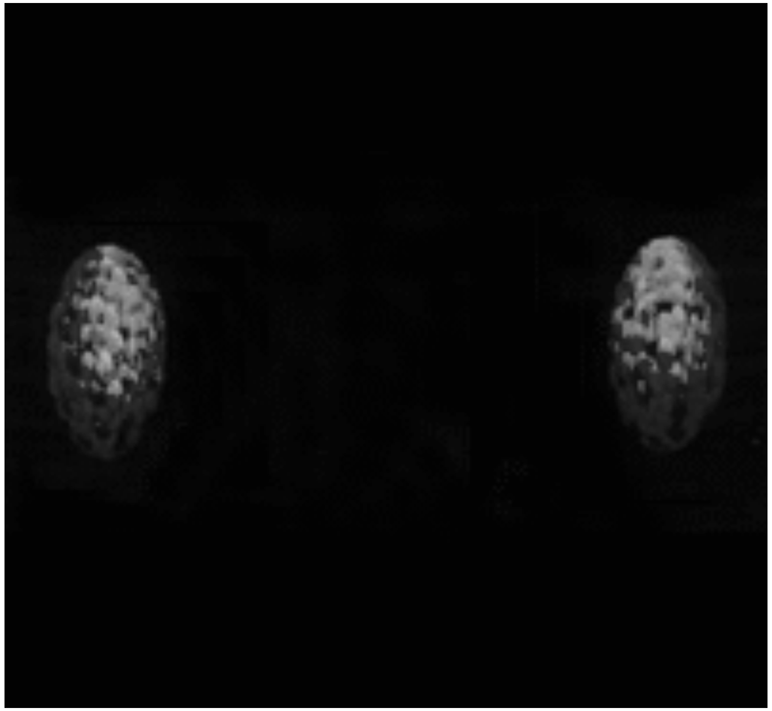
Quark Gluon Plasma:

deconfined and

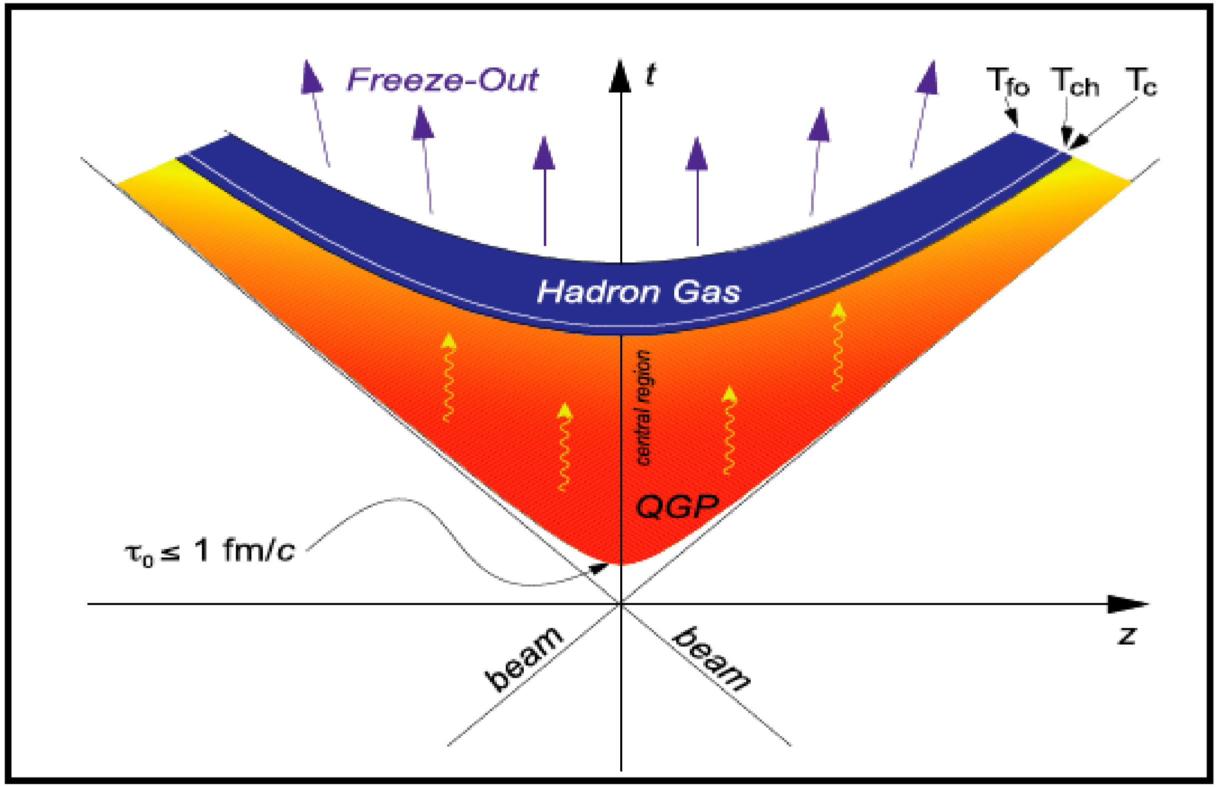
thermalized state of **quarks** and **gluons**

⇒ Study **partonic EoS** at **highest** collider **energies**

High-energy nucleus-nucleus Collisions



Time Scales



Plot: courtesy of R. Stock.

- **QGP life time**
  10 fm/c ≈ $3 \cdot 10^{-23}$ s
- **thermalization time**
  0.2 fm/c ≈ $7 \cdot 10^{-25}$ s
- **formation time**
  (e.g. charm quark):
  $1/2m_c$ = 0.08 fm/c
  ≈ $3 \cdot 10^{-25}$ s
- **collision time**
  $2R/\gamma$ = 0.005 fm/c
  ≈ $2 \cdot 10^{-26}$ s

Temperature scales

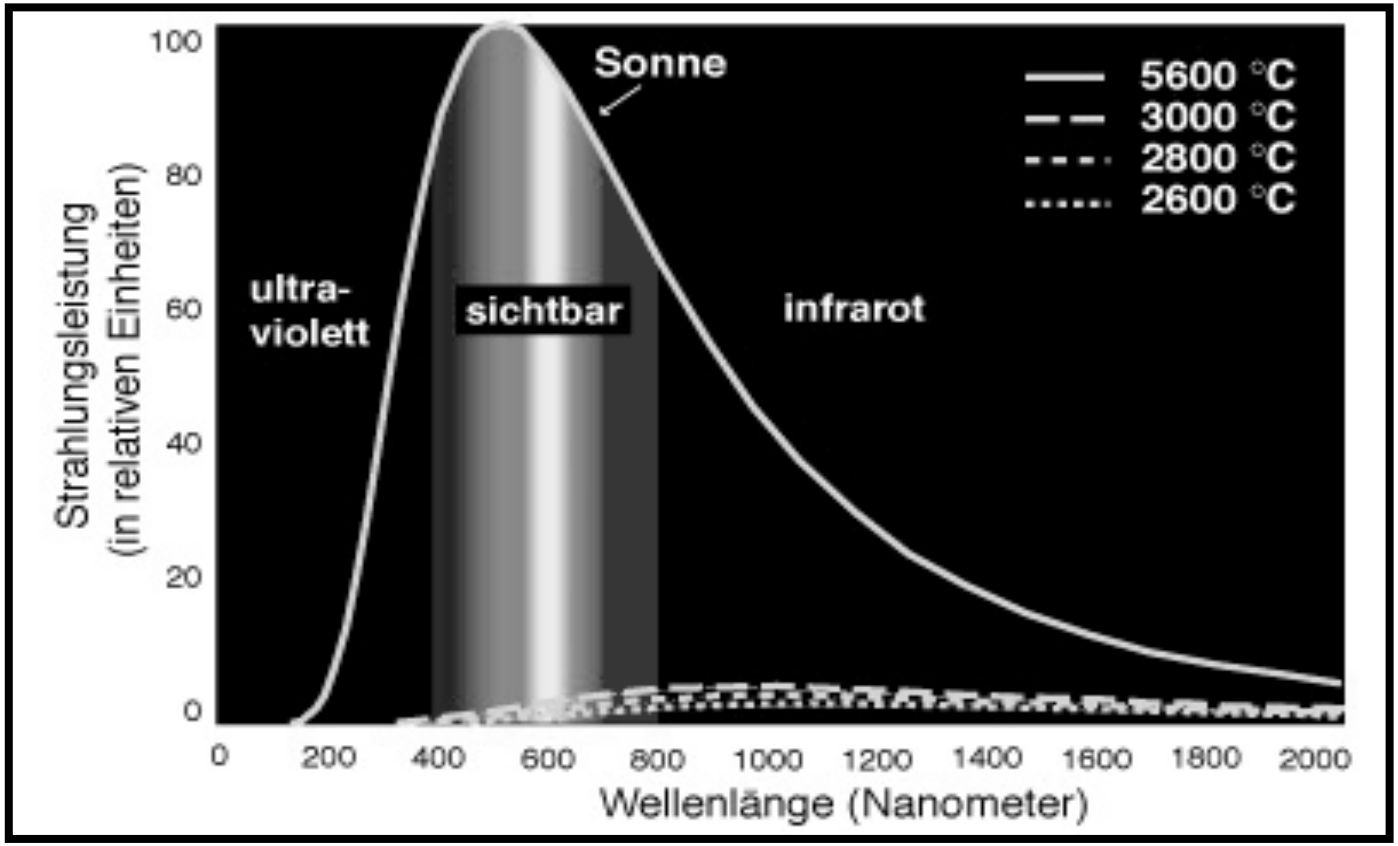
- **T_{max}:** initial temperature at time τ_0, when initial energy density thermalized
- **T_c:** critical temperature, transition from quark-gluon plasma to hadron gas
- **T_{ch}:** chemical freeze-out, inelastic interaction cease particle abundances are fixed
- **T_{fo}:** kinetic freeze-out, elastic interaction cease particle spectra are fixed

N.B.: T_c, T_{ch} and T_{fo} can coincide !

Particle Abundances

or: how to measure a temperature of 2 000 000 000 000 ^{o}C

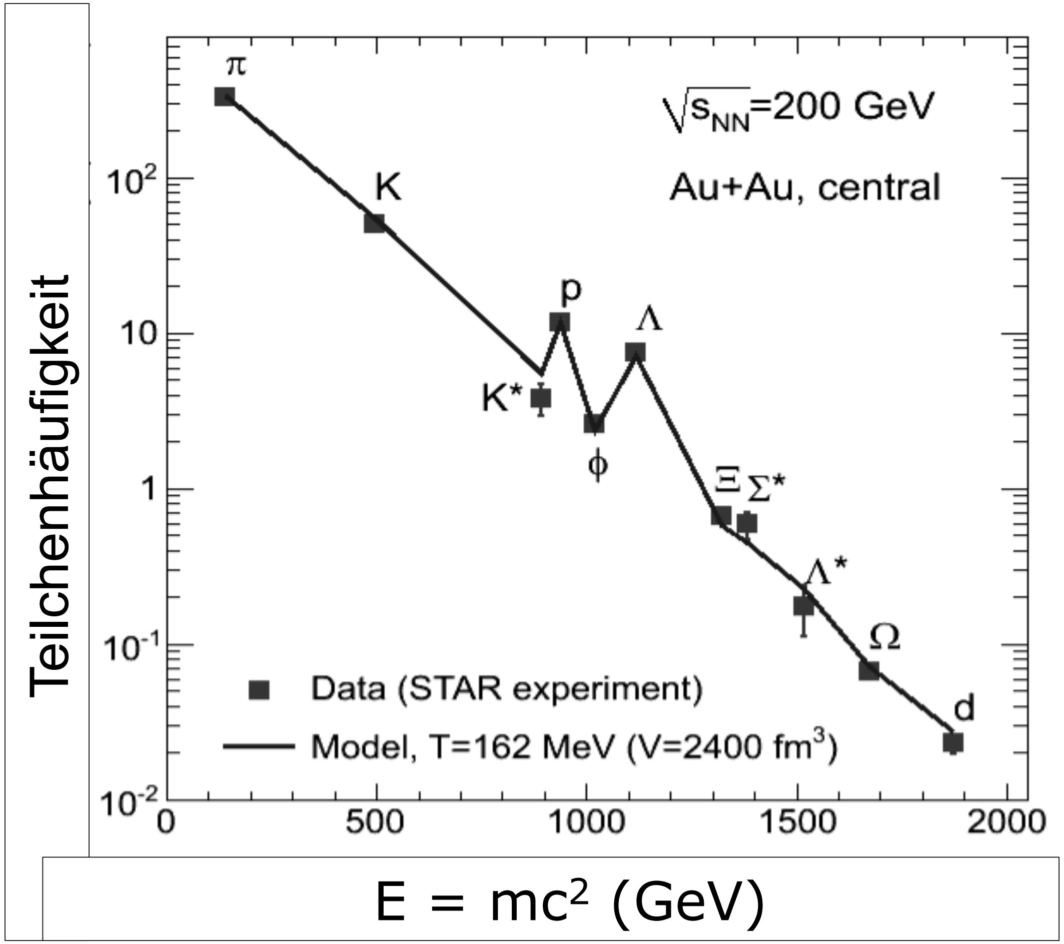
Sonnenspektrum



Graphik: Max-Plack-Institut für Plasmaphysik

Wellenlänge und **Intensität** festgelegt durch Temperatur $\mathbf{T_{Sonne} = 5600\ °C}$

Wie heiss ist die Quelle ?

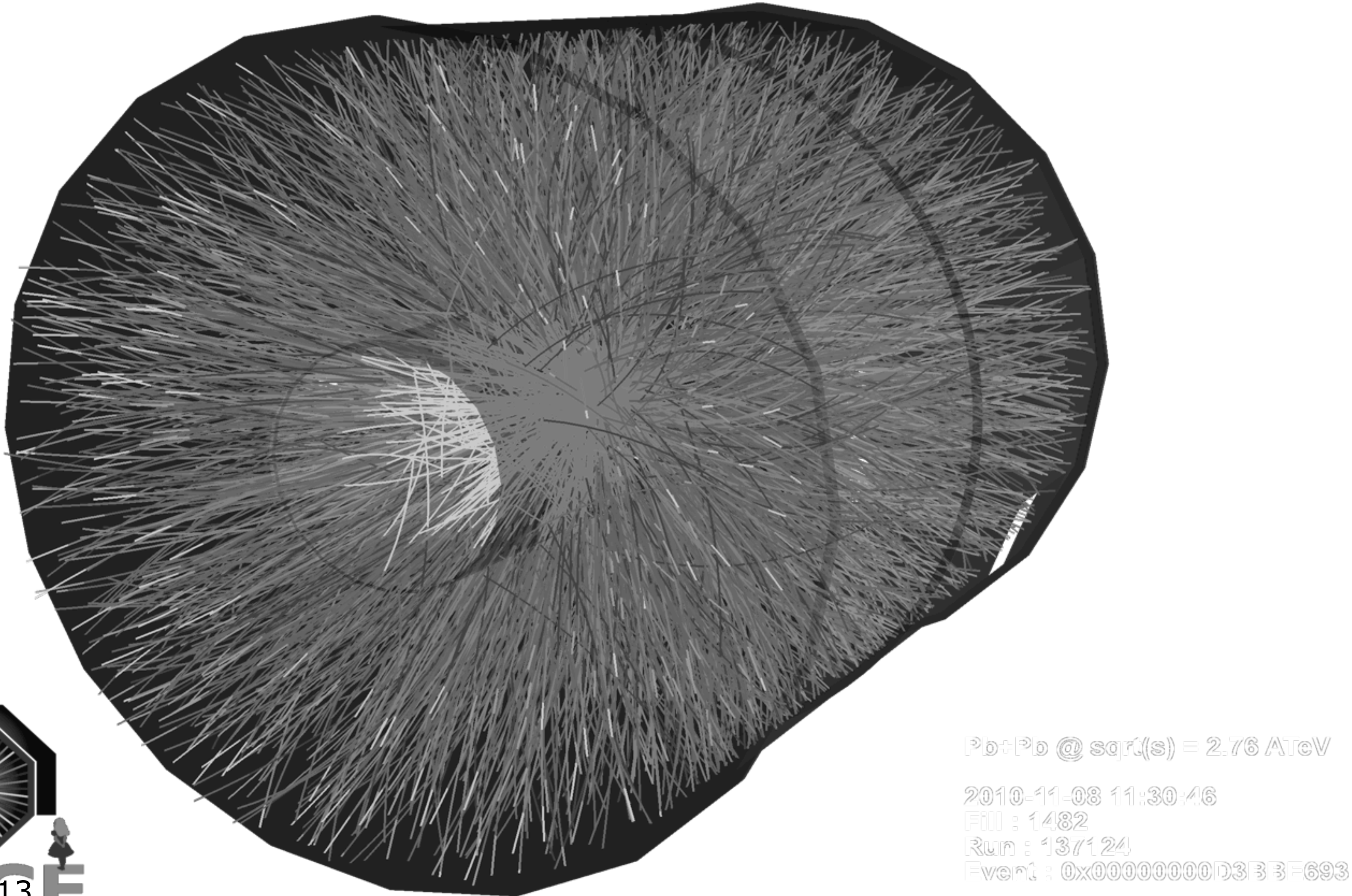


- Lichtquelle ⇒ Teilchenquelle
- Häufigkeit von Teilchen am besten beschrieben durch T = 2 000 000 000 000 ^{o}C (2 Billionen Grad Celsius)

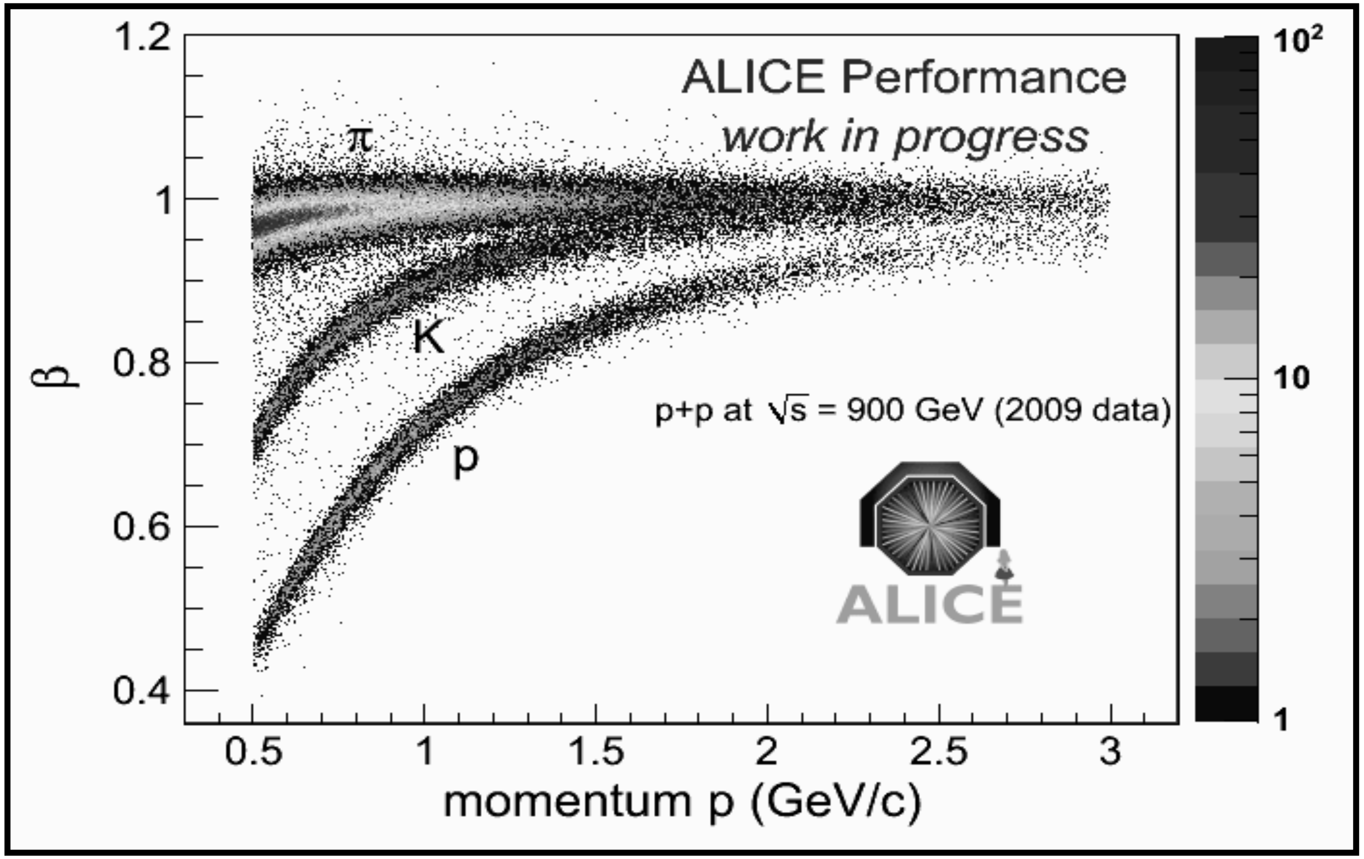
⇒ **100 000** mal **heißer** als im **Innern** der **Sonne !**

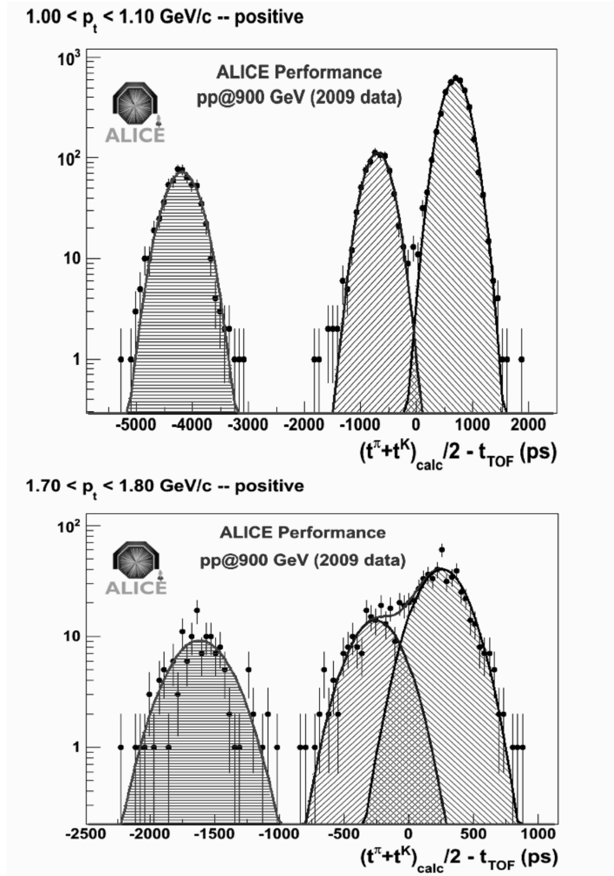
Plot: A. Andronic, GSI Darmstadt

First Pb+Pb collisions in ALICE !



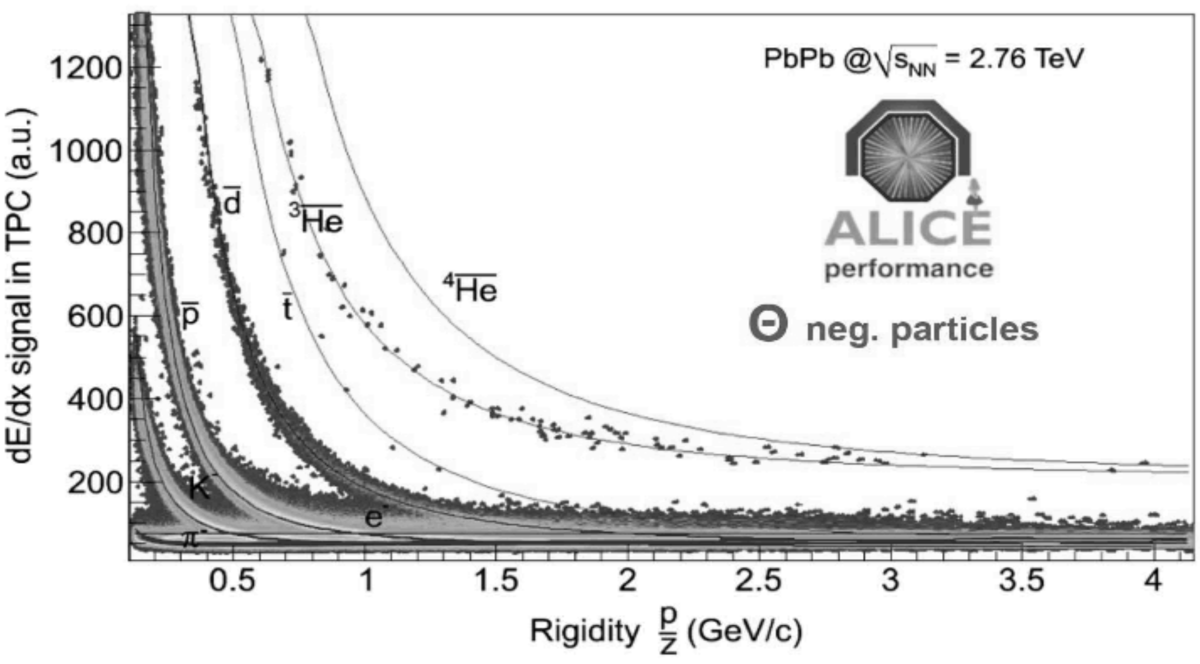
Particle Identification – time of flight





- Time-of-flight resolution ~ 85ps
- Time of flight: separate K from π up to ~ 1.5 GeV

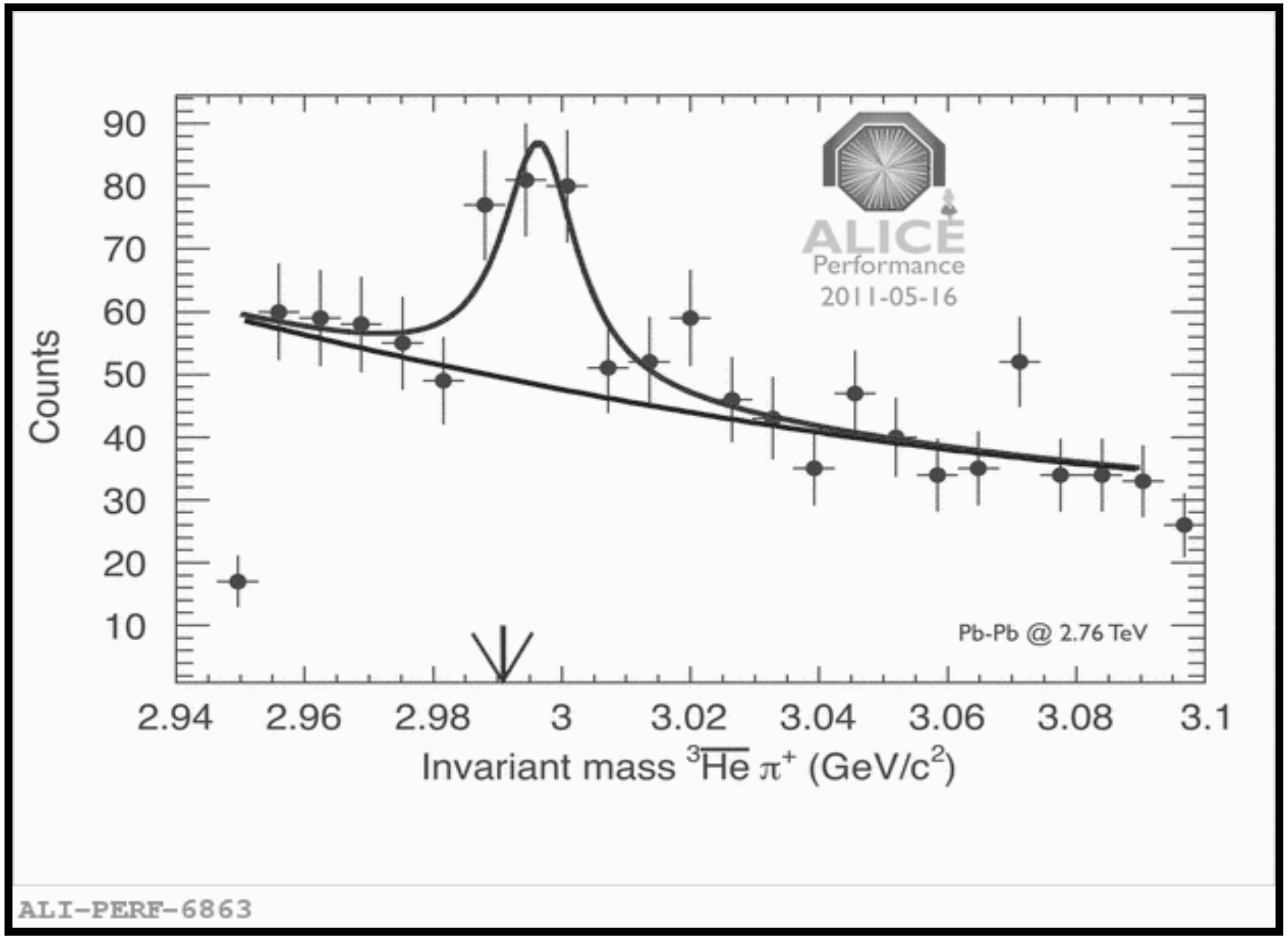
Particle Identification – dE/dx



- dE/dx:
  5% resolution

- TPC dE/dx: separate p from K up to 1.1 GeV/c

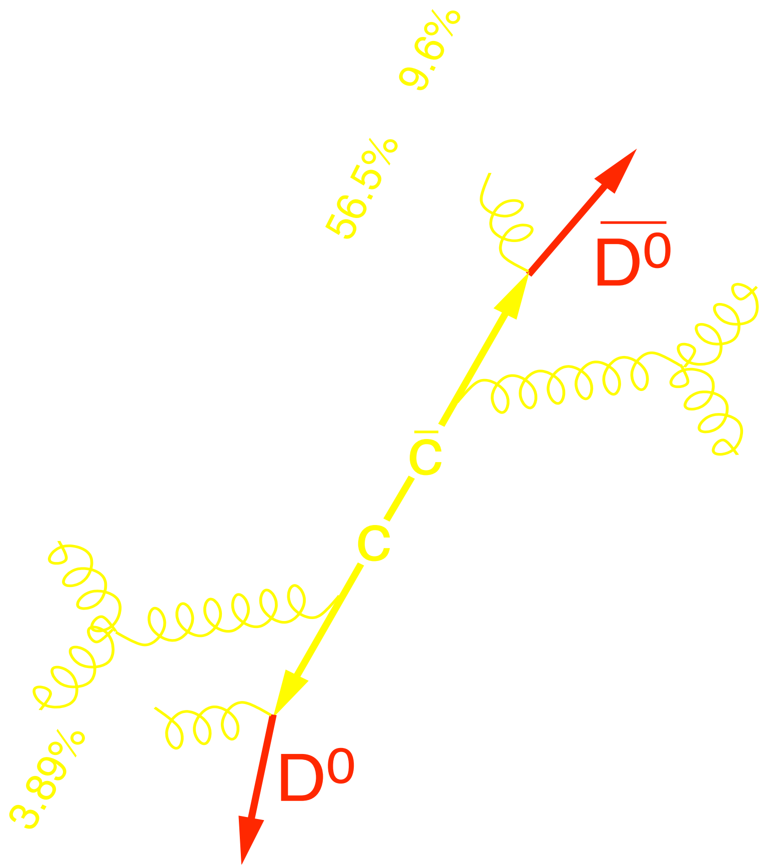
Exotica



- 4 anti-4He candidates
- anti-$^{3}_{\Lambda}$H observed

(anti-)helium trigger:
J. Klein, PhD thesis, in preparation;
F. Muecke, bachelor thesis (2012),
Univ. Heidelberg.

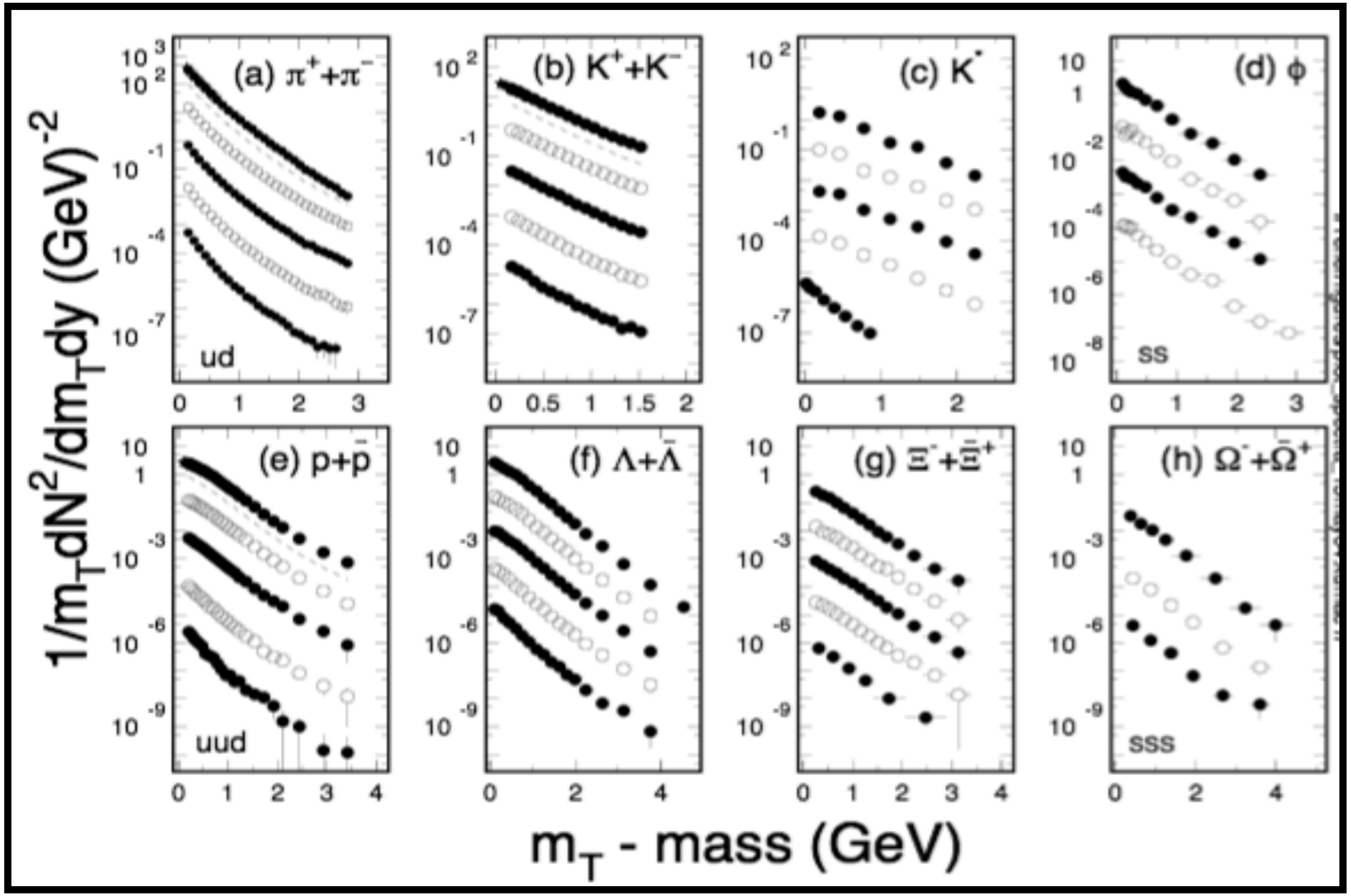
Heavy-quark detection



- golden channel: $D^0 \rightarrow K^- + \pi^+$, $c\tau = 123\ \mu m$
- **displaced** decay **vertex** is **signature** of **heavy-quark decay**

plot: courtesy of D. Tlusty.

STAR year 2 data



White papers - STAR: Nucl. Phys. A757, p102.

Statistical Ensemble

Grand Canonical Ensemble (GC): in a large system, with large number of produced particles, **conservation** of additive quantum numbers (B, S, I_3) can be implemented **on average** by use of **chemical potential** μ

➔ asymptotic realization of exact canonical approach much simpler to compute

Canonical Ensemble (C): in a small system, with small particle multiplicity, **conservation** laws must be implemented **locally** on event-by-event basis

➔severe phase space reduction for particle production "canonical **suppresssion**"

Results of C and GC can be related in a simple way: (Tounsi/Redlich 2001)

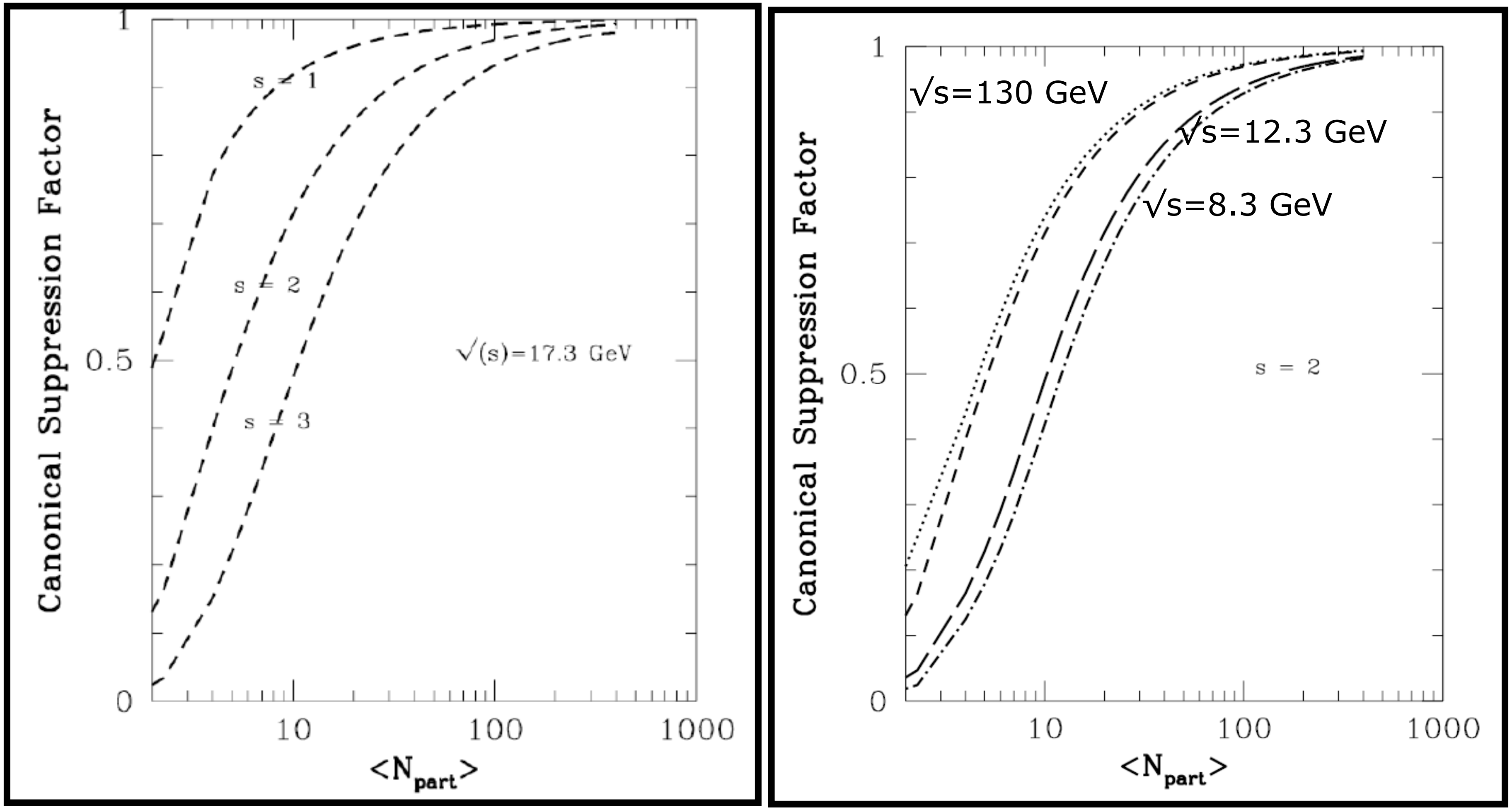
here 'K' stands generically for all hadrons with S = -1

$$\langle N_K \rangle^C = \langle N_K \rangle^{GC} \frac{I_1(2\langle N_K \rangle^{GC})}{I_0(2\langle N_K \rangle^{GC})}$$

and analogously for S = -2 (S = -3): $I_1 \rightarrow I_2$(I_3)

Canonical Suppression

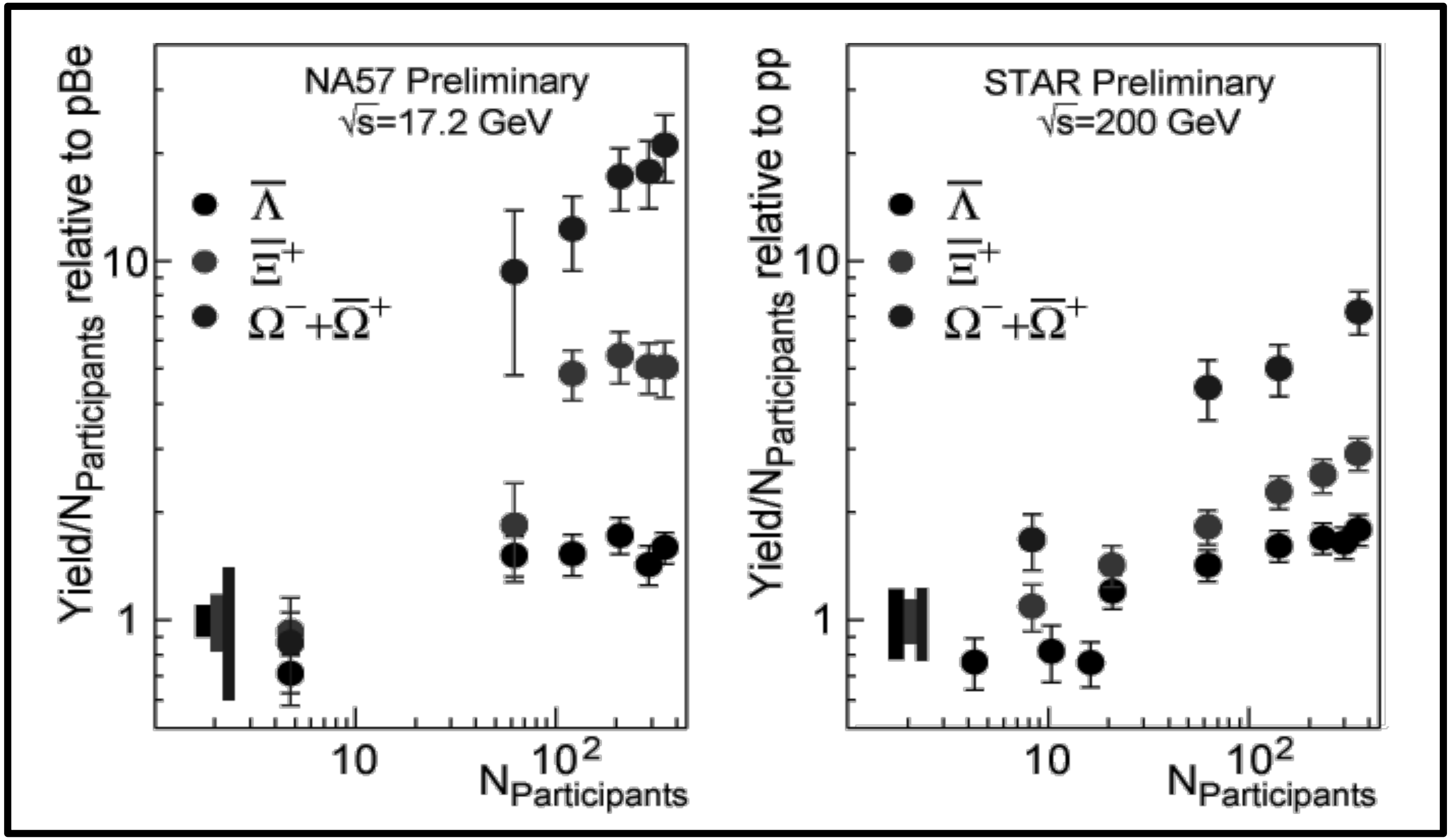
A. Tounsi and K. Redlich, arXiV:0111159[hep-ph].



In central Pb-Pb collisions (100 of 416 nucleons in overlap zone) deviations already small (< 10%)at SPS energies

Deviation gets even smaller with higher collision energy

Lifting of strangeness suppression



Relative effect (compared to pp collisions) larger for increasing strangeness and larger at lower energies

Statistical hadronization model

Partition function

$$ln\,Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2\,dp\,ln(1 \pm exp(-(E-\mu_i)/T))$$

Particle density

$$\rho_i = N/V = -\frac{T}{V}\frac{\partial ln\,Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{exp((E_i-\mu_i)/T) \pm 1}$$

For every conserved quantum number there is a chemical potential

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$$

Use conservation laws to constrain: V, μ_S, μ_{I_3}

$$V\sum_i n_i B_i = Z + N$$

$$V\sum_i n_i S_i = 0$$

$$V\sum_i n_i I_{3,i} = \frac{Z-N}{2}$$

→ only 2 parameters left to fit to data:

$$T, \mu_B$$

Chemical Freeze-out Model

P. Braun-Munzinger et al., nucl-th/0304013.

Density of particle *i*

$$\rho_i = \square \frac{g_i}{2\pi^2} {T_{ch}}^3 \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ {\lambda_q}^{Q_i}\ {\lambda_s}^{s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

Q_i : 1 for u and d, -1 for $\bar{u}$ and $\bar{d}$
s_i : 1 for s, -1 for $\bar{s}$
g_i : spin-isospin freedom
m_i : particle mass

T_{ch} : Chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strange-quark chemical potential
V : volume term, drops out for ratios!

$\mu_B = 3\mu_q$

*Compare particle **ratios** to **experimental data***

Example

A. Proton to anti-proton ratio

All terms drop, except fugacity $\Lambda^{Qi} = \exp(\mu_q/T_{ch})^{Qi}$

For proton, $Q_i = 3$ (3 quarks, uud)

For anti-proton, $Q_i = -3$

At RHIC: T_{ch} = 160 MeV, μ_q = 7 MeV

Proton to anti-proton ratio =

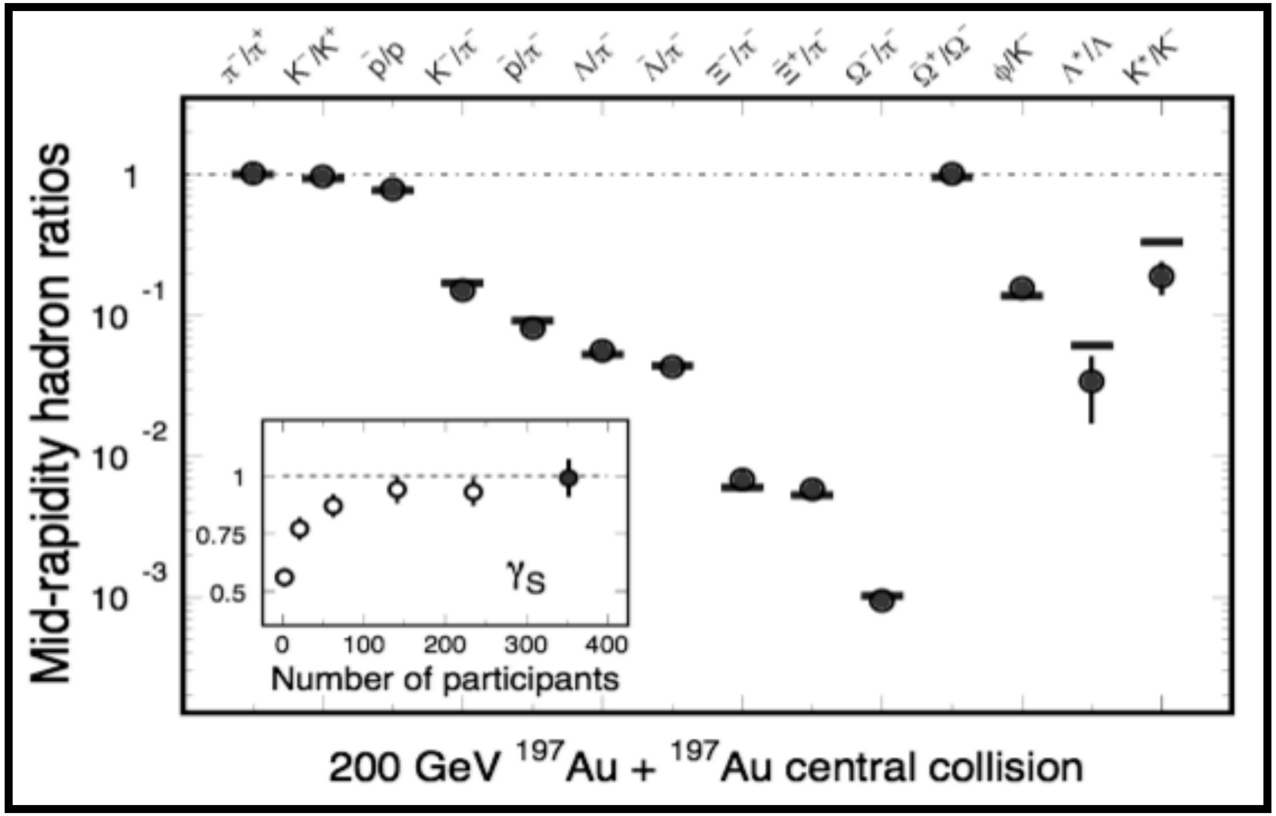
exp[(3*7 - (-3*7))/160] = 0.77

B. J/ψ to ψ' ratio

$m_{J/\psi}$ = 3.1 GeV, $m_{\psi'}$ = 3.6 GeV, look up $K_2(m/T_{ch})$

Ratio = 3%

Hadron Yields – Ratios

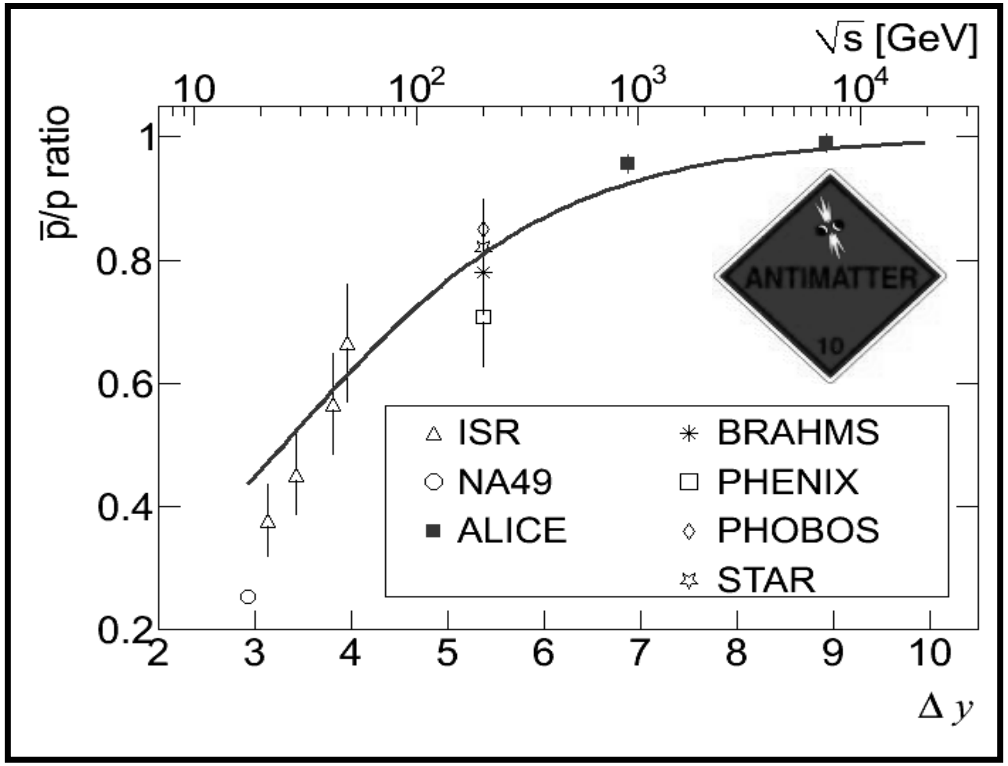


RHIC white papers - 2005, Nucl. Phys. A757, STAR: p102; PHENIX: p184;
Statistical Model calculations: P. Braun-Munzinger *et al.* nucl-th/0304013.

1) At RHIC:
   T_{ch} = 160 ± 10 MeV
   μ_B = 25 ± 5 MeV
2) γ_S = 1.
   ⇒ The hadronic system is thermalized at RHIC.
3) Short-lived resonances show deviations.

⇒ There is life after chemical freeze-out.

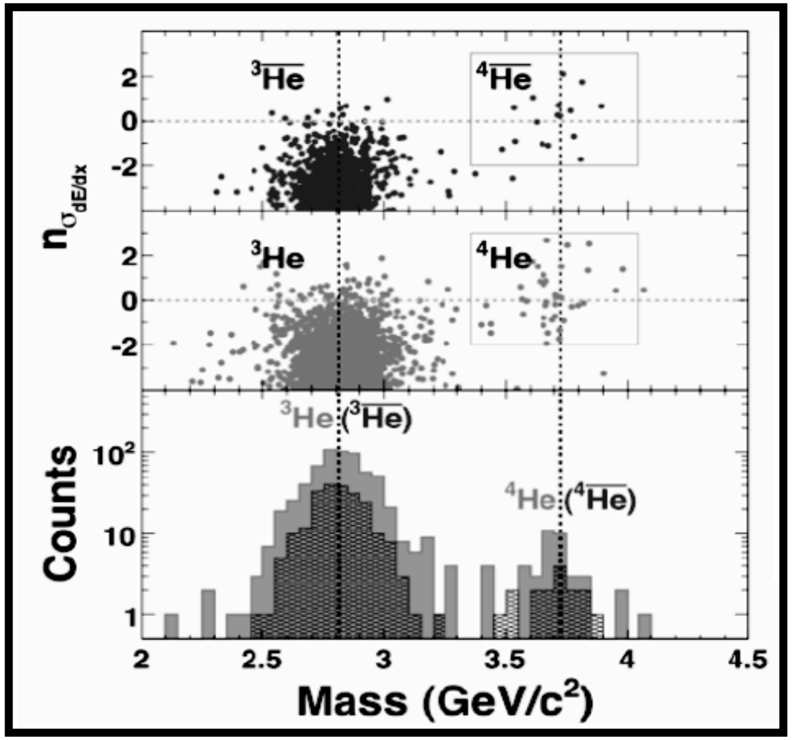
(Anti)-Proton Production at LHC

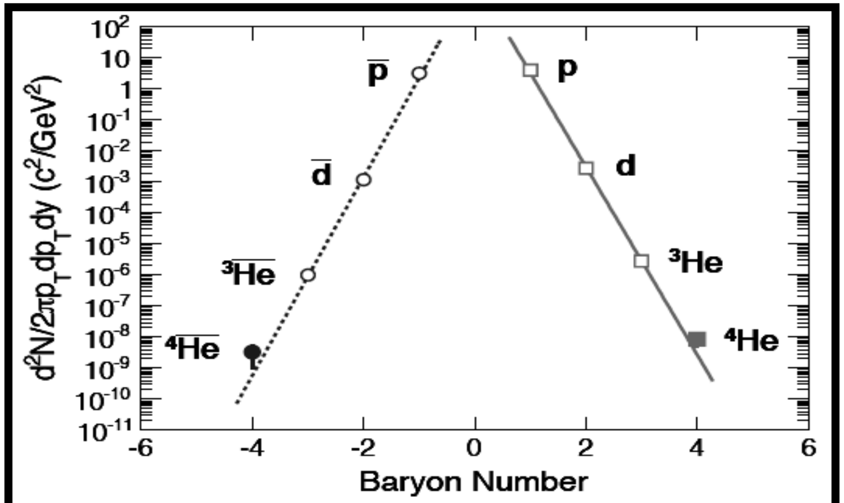


ALICE, Phys. Rev. Lett. 105, 072002 (2010).

- At LHC energies:
  Ratio of anti-p/p ≈ 1
- No need for exotic baryon transport mechanism
- Address hadro-chemistry in PbPb within 1 day

Anti-nuclei production

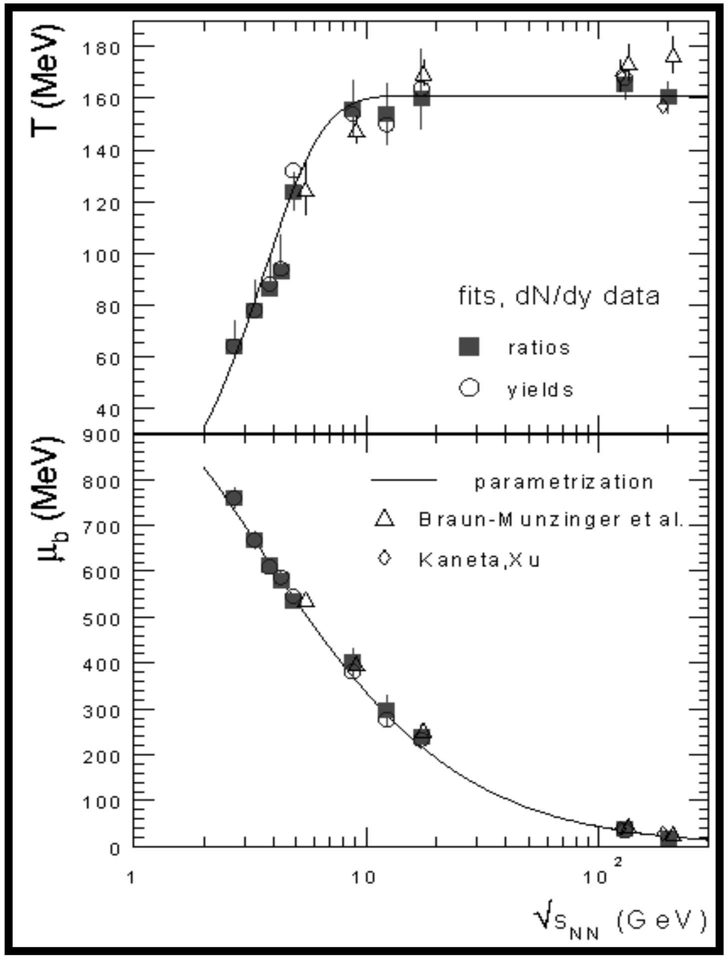




Nature 473, 353-356, (19 May 2011)
doi:10.1038/nature10079

- **Anti-alpha** particle **discovered**
- **Penalty factor** of **~1000** per added nucleon
  → anti-alpha / anti-proton ~ 10^{-9}

Beam Energy Dependence



A. Andronic et al., NPA 772 (2006) 167.

With increasing energy:

• T_{ch} **increases** and **saturates**

at T_{ch} = 160 MeV

• Coincides with Hagedorn temperature

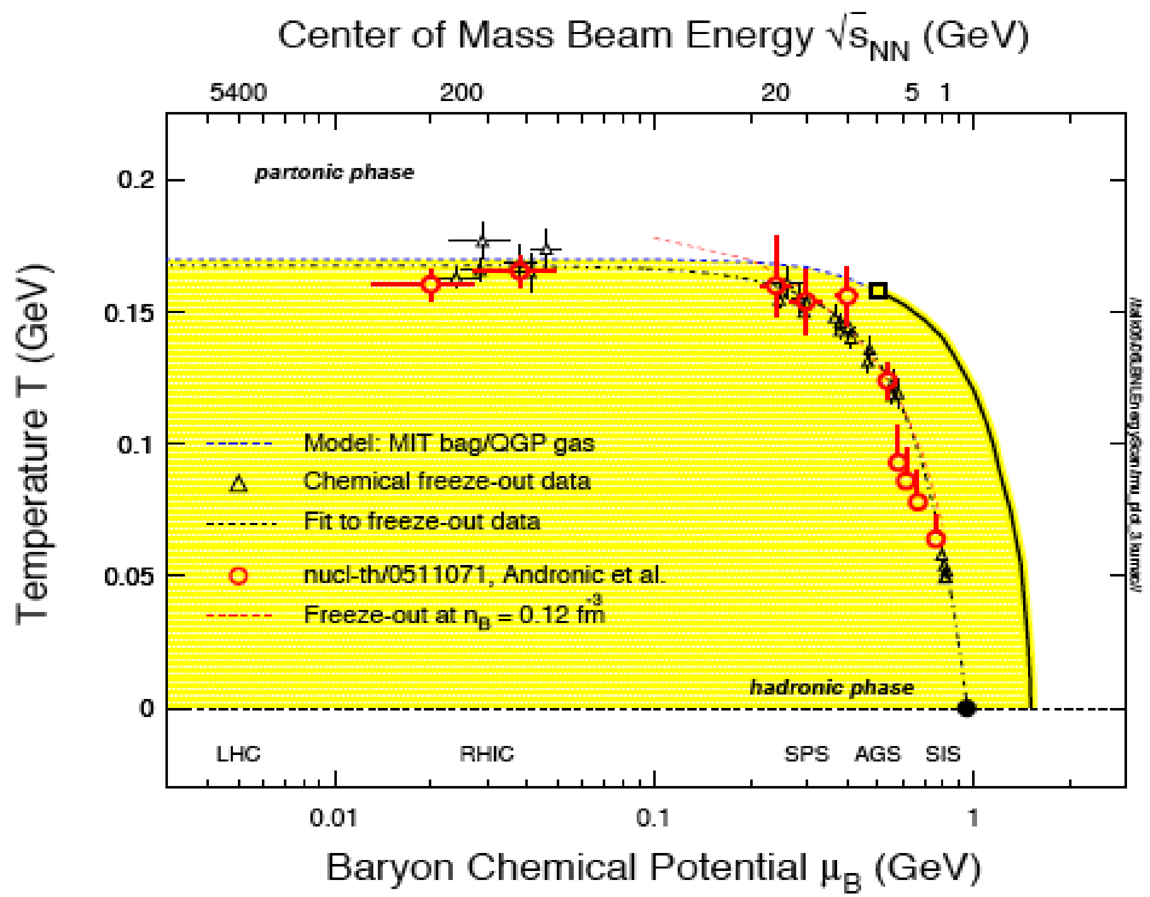
• Coincides with early lattice results

⇒ **limiting temperature** for hadrons, $T_{ch} \approx$ 160 MeV !

• μ_B decreases, μ_B = 1MeV at LHC

⇒ Nearly **net-baryon free** !

QCD phase diagram



Lesson learnt

- From **measured** particle **abundances** and description within the **Statistical Model**, determine **T_{ch} = 160 MeV** at **highest** collider **energies**
- canonical **suppression** of **strangeness** production **lifted** in nucleus-nucleus collisions
- **Limiting temperature** - where **hadrons** can exist
- Study phase **QCD diagram** by dialing μ_B **and T_{ch}** via **beam energy**