Quark-Gluon Plasma Physics

5. Statistical Model and Strangeness

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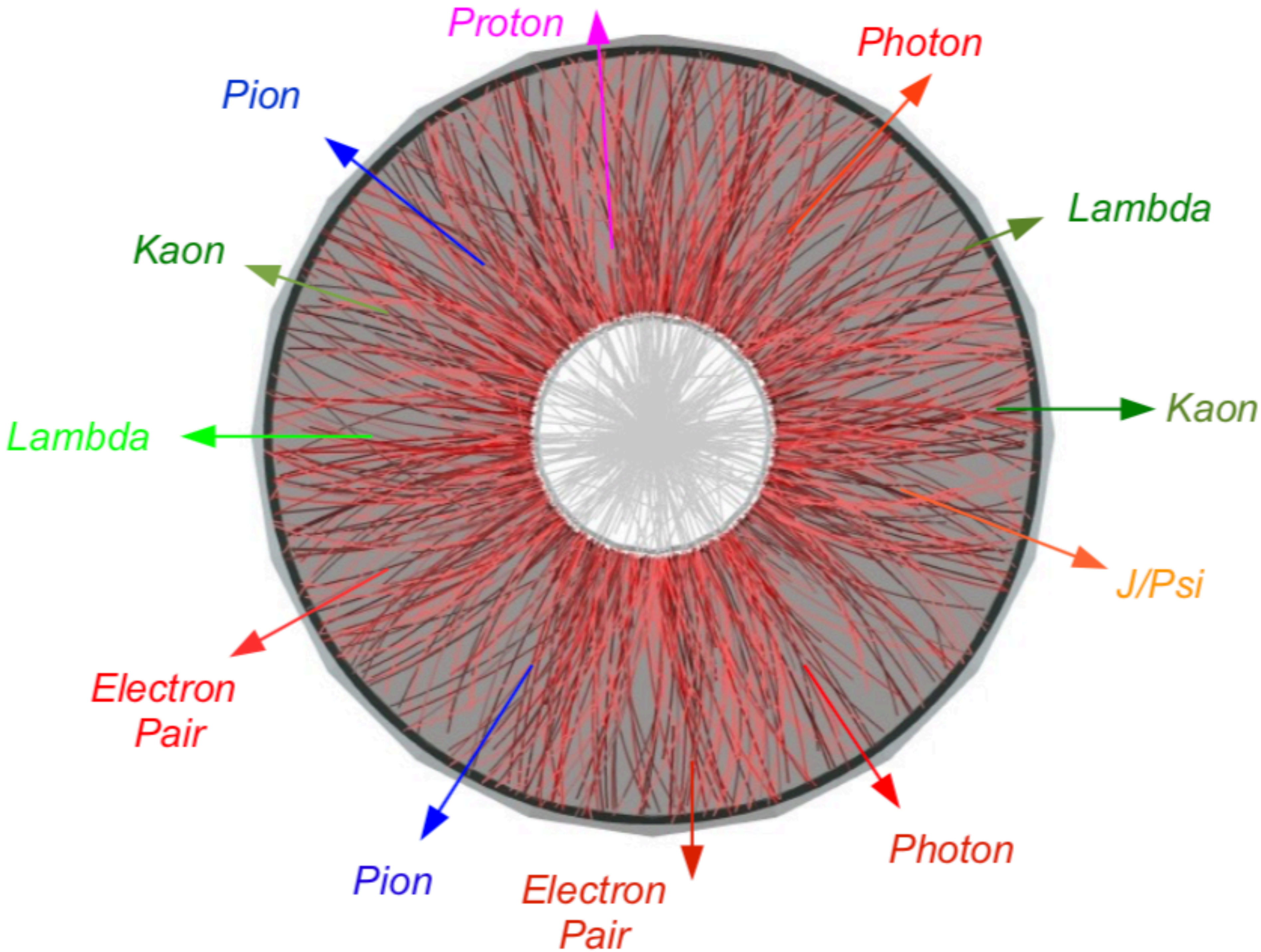
Hadronization of the nuclear fireball



the fireball properties can be determined by measurement of the emitted particles
In this chapter as first species: hadrons with up,down,strange constituent quarks

Strangeness production in hadronic interactions

Particles with strange quarks:

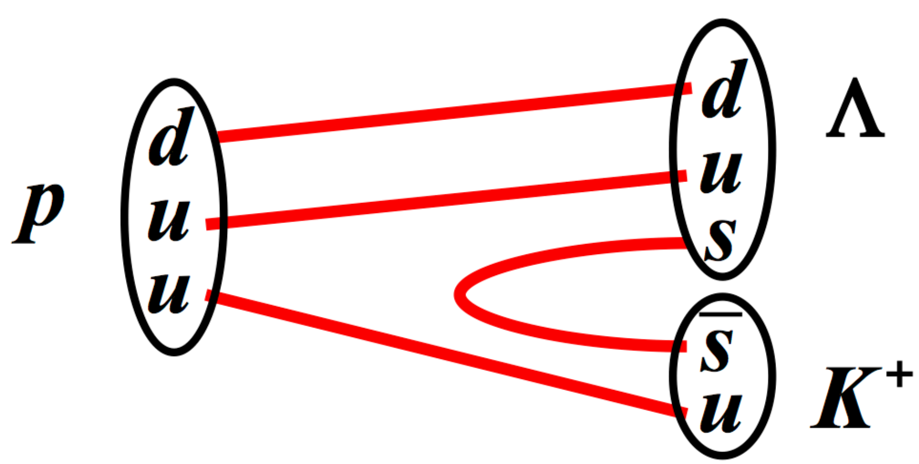
"hidden strangeness"

$$K^+ = (u\bar{s}),\ K^- = (\bar{u}s),\ K^0 = (d\bar{s}),\ \bar{K}^0 = (\bar{d}s),\ \phi = (s\bar{s}),$$

$$\Lambda = (uds),\ \Sigma = (qqs),\ \Xi = (qss),\ \Omega^- = (sss)$$

Creation in collisions of hadrons:

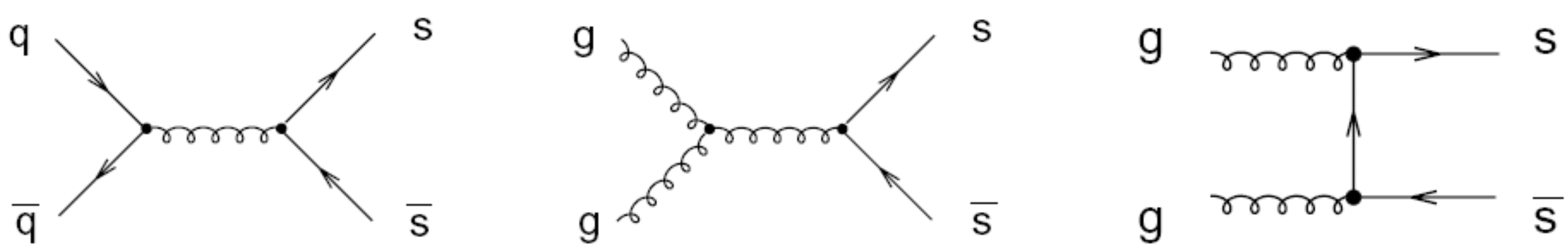
Example 1: $p + p \to p + K^+ + \Lambda, \quad Q = m_\Lambda + m_{K^+} - m_p \approx 670\,\text{MeV}$



associated production
of strangeness

Example 2: $p + p \to p + p + \Lambda + \bar{\Lambda}, \quad Q = 2m_\Lambda \approx 2230\,\text{MeV}$

Strangeness production in the QGP

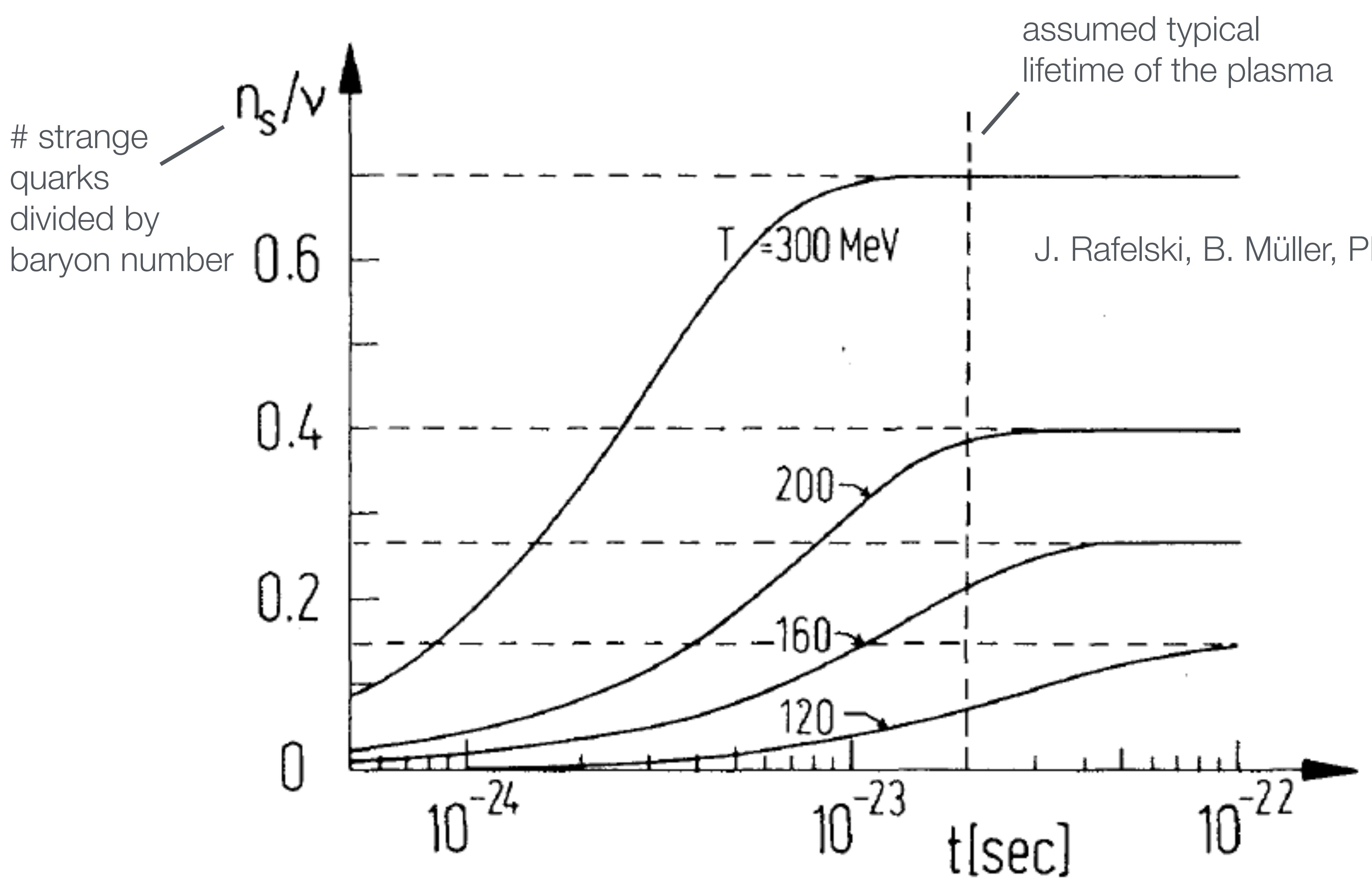


$$Q_{\mathrm{QGP}} \approx 2m_s \approx 200\,\mathrm{MeV}$$

Q value in the QGP significantly lower than in hadronic interactions

This reflects the difference between the current quarks mass (QGP) and the constituent quark mass (chiral symmetry breaking)

Strangeness enhancement: One of the earliest proposed QGP signals



J. Rafelski, B. Müller, PRL 48 (1982) 1066

Strangeness equilibration was expected to be sufficiently fast

Quark composition of the ideal QGP

Particle densities for a non-interacting massive gas of fermions (upper sign)/ bosons (lower sign):

"Boltzmann approximation" (neglect "±1"): first term of the sum

$$n_i = g_i \frac{4\pi}{(2\pi)^3} \int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) \pm 1} = \frac{g_i}{2\pi^2} m^2 T \sum_{k=1}^{\infty} \frac{(\mp 1)^{k+1}}{k} \lambda^k K_2\left(\frac{km}{T}\right)$$

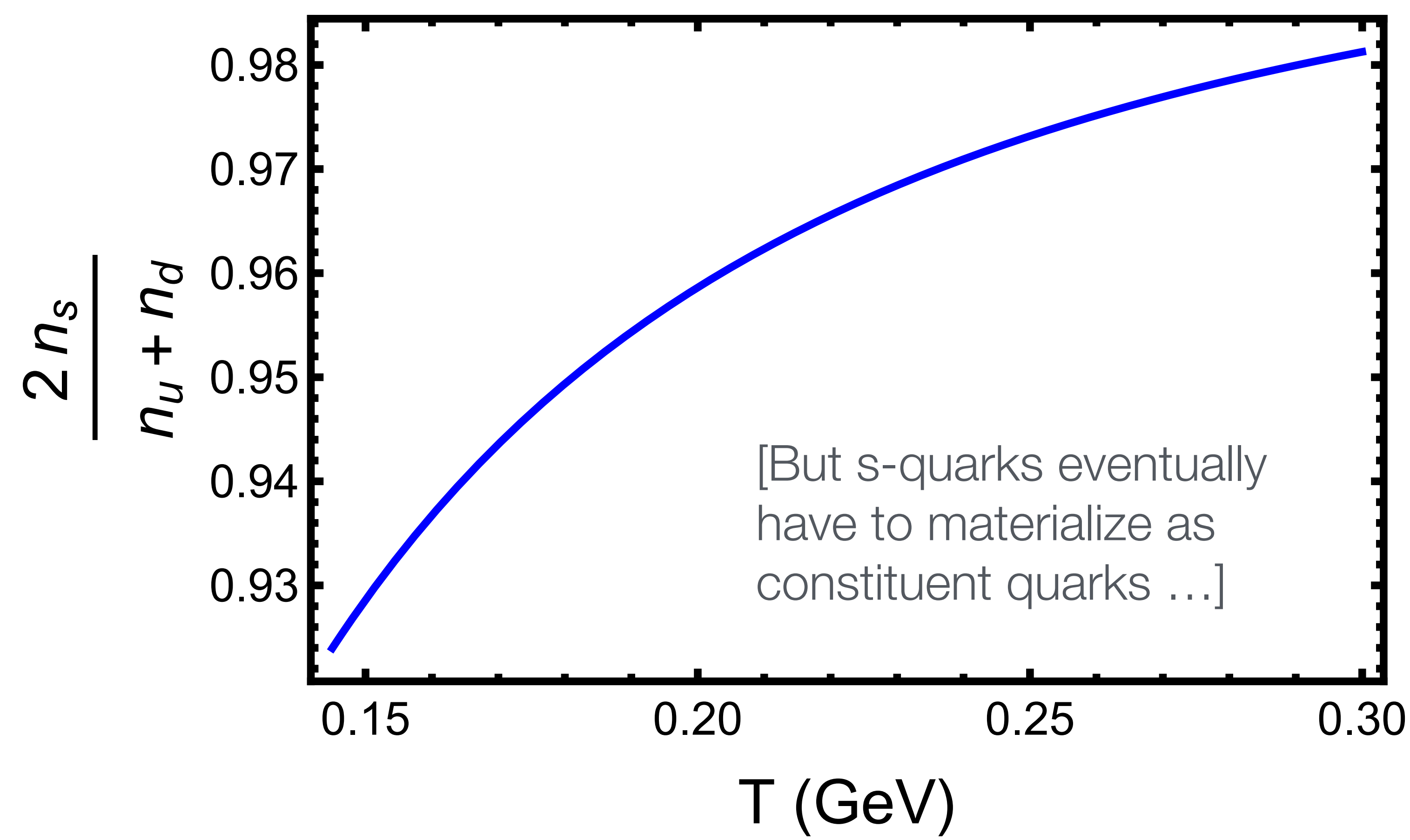
$$\lambda = e^{\mu/T}$$

upper sign: fermions, lower sign: bosons

Quarks: fermions ("upper sign"), m_u = 2.2 MeV, m_d = 4.7 MeV, m_s = 96 MeV,

In a QGP with μ = 0 and 150 < T < 300 MeV:

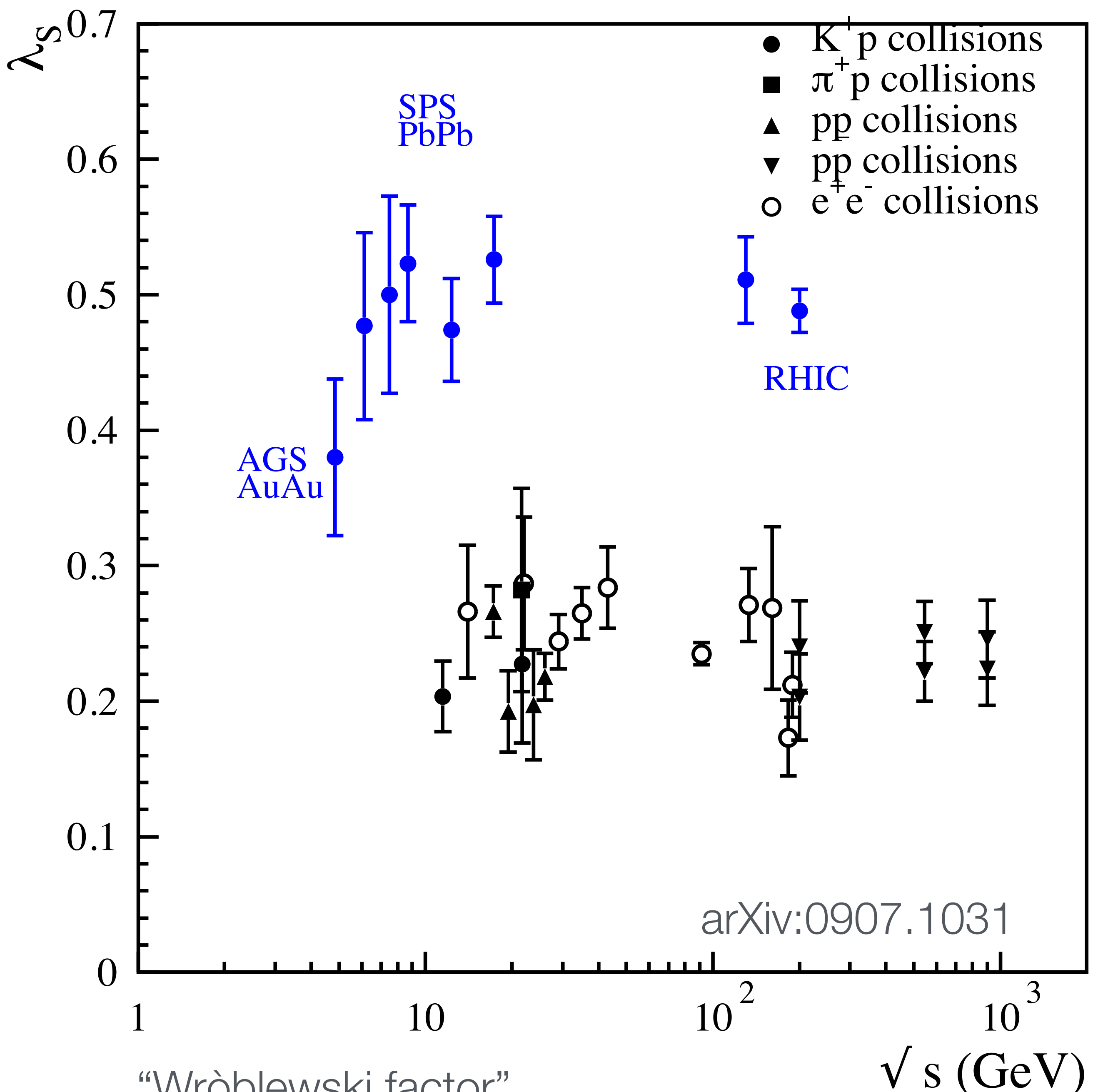
$$\frac{2(n_s + n_{\bar{s}})}{n_u + n_{\bar{u}} + n_d + n_{\bar{d}}} \approx 0.92\text{–}0.98$$



Fraction of strange quarks: A+A vs. e⁺e⁻, πp, and pp

$$\lambda_s = \frac{2\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

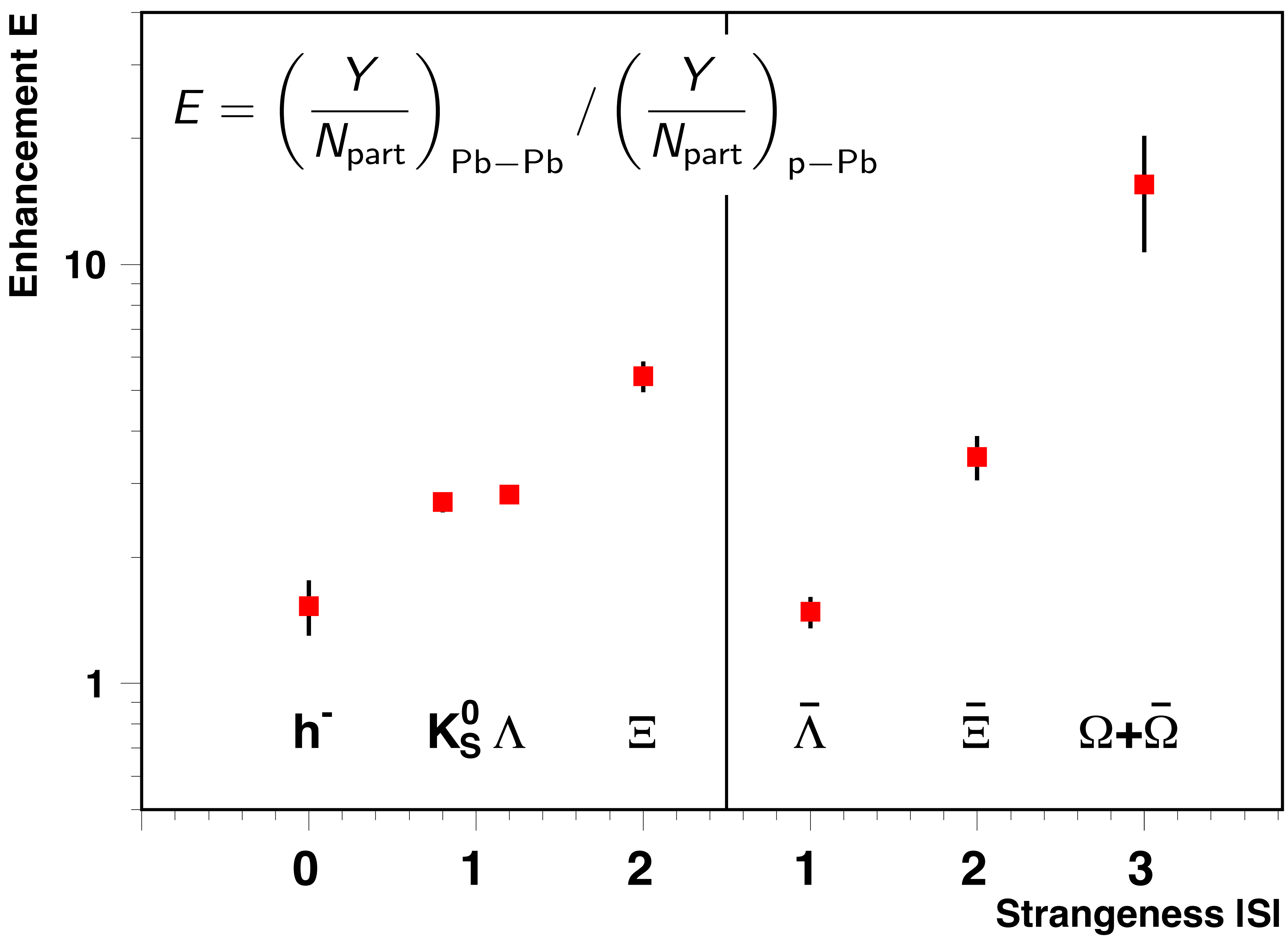
ratio of newly created valence quark pairs before strong decays (ρ, Δ, …)



"Wròblewski factor",
Acta Phys. Pol. B16 (1985) 379

Strangeness indeed enhanced in nucleus-nucleus collisions relative to e^+e^-, πp, and pp collisions

Strangeness Enhancement in Pb-Pb relative to p-Pb at $\sqrt{s_{NN}}$ = 17.3 GeV



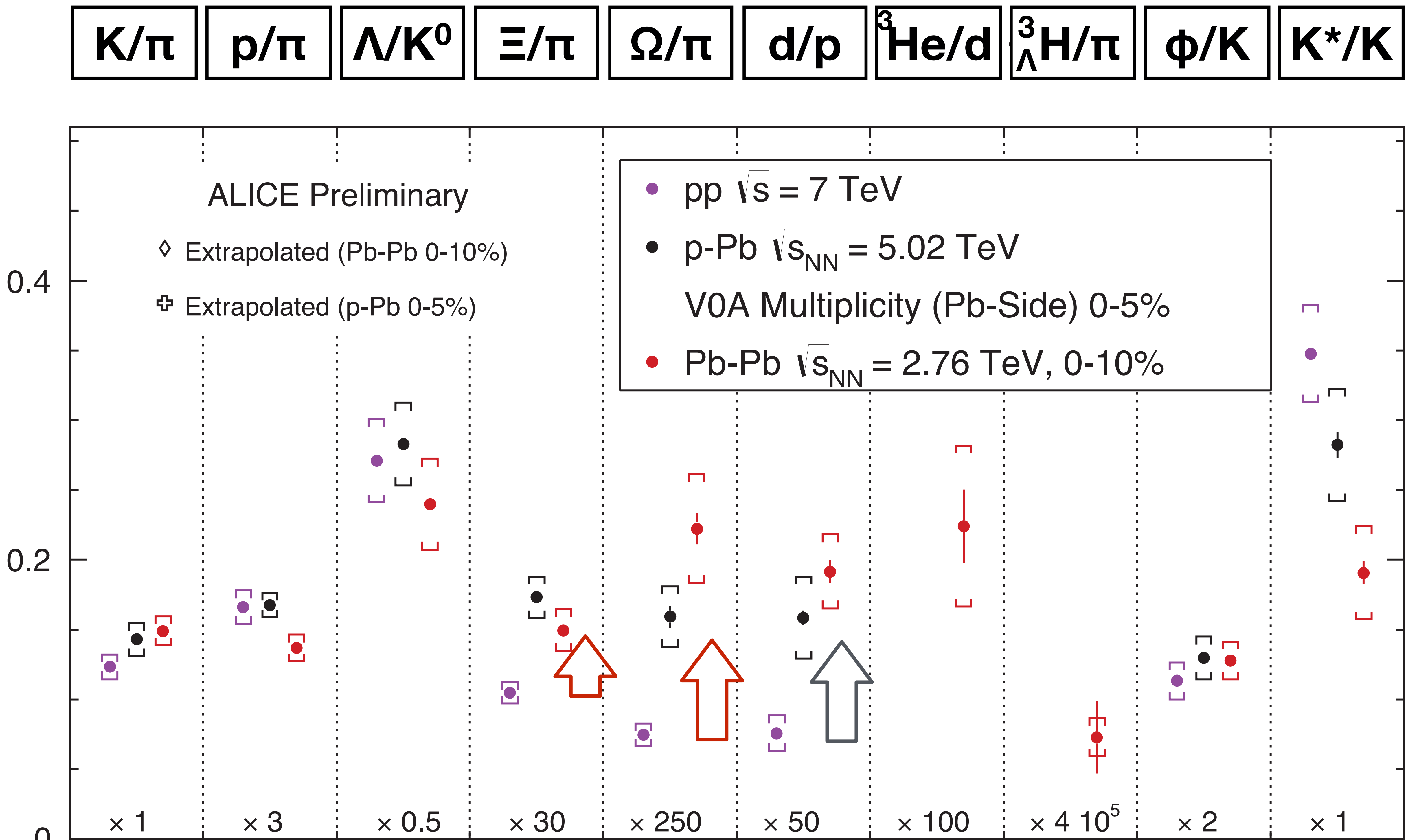
0-40% Pb-Pb
at $\sqrt{s_{NN}}$ = 17.3 GeV

WA97,
PLB 449 (1999) 401,
CERN-EP/99-29

p-Be reference instead of p-Pb: similar behavior (NA57)

Strangeness enhancement increases with s quark contents (up to factor 17 for the Ω baryon)

Ξ/π and Ω/π enhancement in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

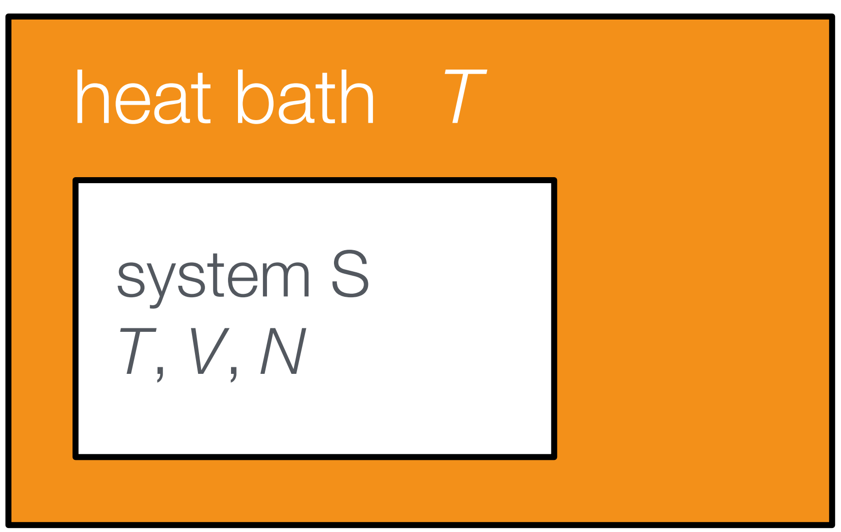


Interestingly, ϕ/π very similar in pp, p-Pb, and Pb-Pb

Particle yields from the hadron resonance gas

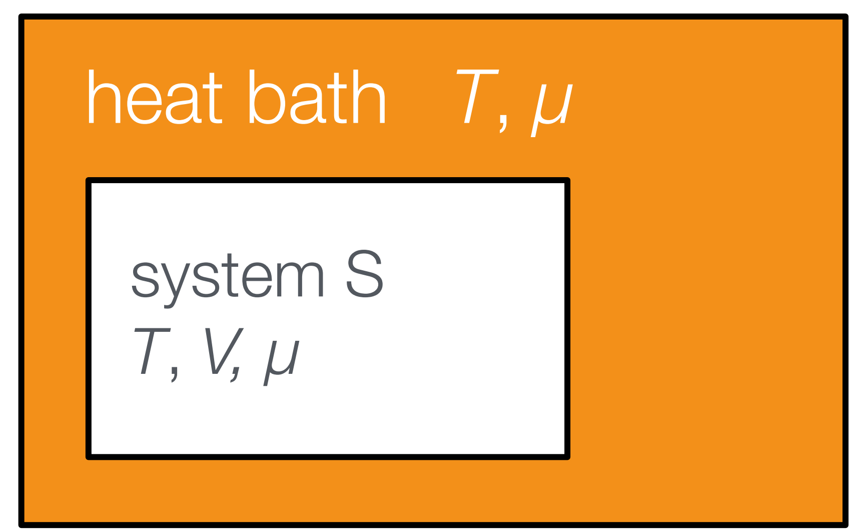
- Idea: Freeze-out of the QGP creates an equilibrated hadron resonance gas
- The HRG then freezes out with a characteristic temperature T_{ch} close to T_c which determines the yields of different particle species
- What is the appropriate statistical ensemble for the theoretical treatment?

canonical ensemble:
N and *V* fixed, energy *E* of the system fluctuates
($E_s + E_b = E$, *T* is given)



pp collisions, strangeness locally conserved

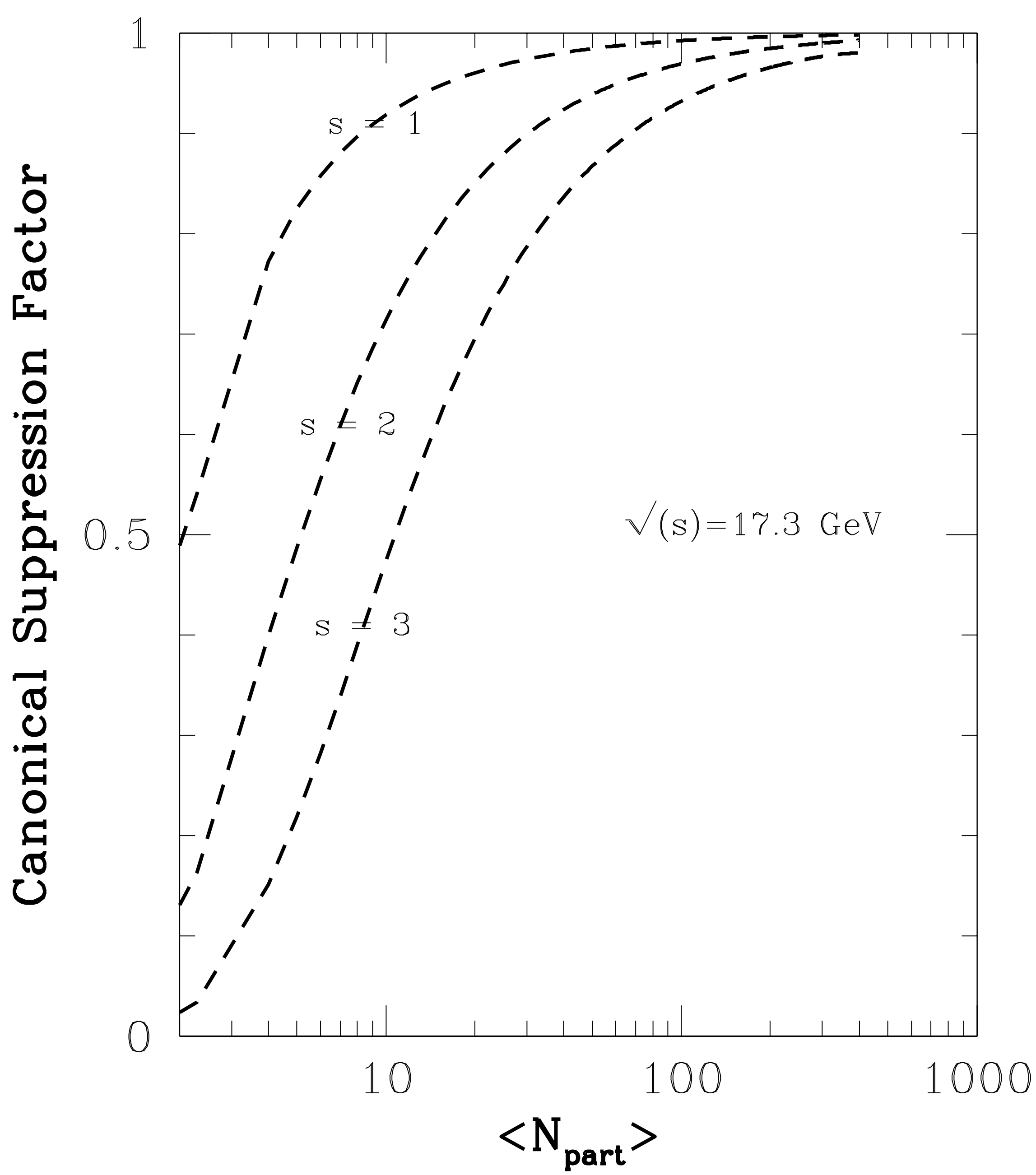
grand-canonical ensemble:
V fixed, energy *E* and particle number *N* fluctuate
(T, μ given)



central A-A collisions, local strangeness fluctuations possible,“there is a medium”

Braun-Munzinger, Redlich, Stachel, nucl-th/0304013v1

Grand canonical ensemble: Large volume limit of the canonical treatment



A. Tounsi, K. Redlich, hep-ph/0111159

Canonical suppression factor F_S:

$$n_K^C = n_K^{GC} \cdot F_S$$

$$F_S = \frac{I_K(2n_K^{GC} V)}{I_0(2n_K^{GC} V)}$$

n_K : Density of particles with strangeness K = |S|, S =-1, -2, -3

I_n : Modified Bessel function of the first kind

Already at moderately central Pb-Pb collisions the grand canonical ansatz is justified

Statistical model (hadron gas, grand canonical ensemble)

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

$E_i^2 = p_i^2 + m_i^2$

Partition function (particle species *i*):

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

"-" for bosons, "+" for fermions

Particle densities:

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

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}

strangeness: $\sum_i n_i S_i = 0 \quad \rightarrow \quad \mu_S$

charge: $V \sum_i n_i I_{3,i} = \frac{Z - N}{2} \quad \rightarrow \quad \mu_{I_3}$

baryon number: $V \sum_i n_i B_i = Z + N \quad \rightarrow \quad \mu_B$

Only two parameters left (T, μ_B)

Example: **Boltzmann approximation**

$$n(\bar{p})/n(p) = \exp(-2\mu_B/T)$$

→ determine (T, μ_B) for different $\sqrt{s_{NN}}$ from fits to data

Production of hadrons and (anti-)nuclei at LHC described quantitatively by GC statistical model

1 free parameter: temperature T

T = 156.5 ± 1.5 MeV

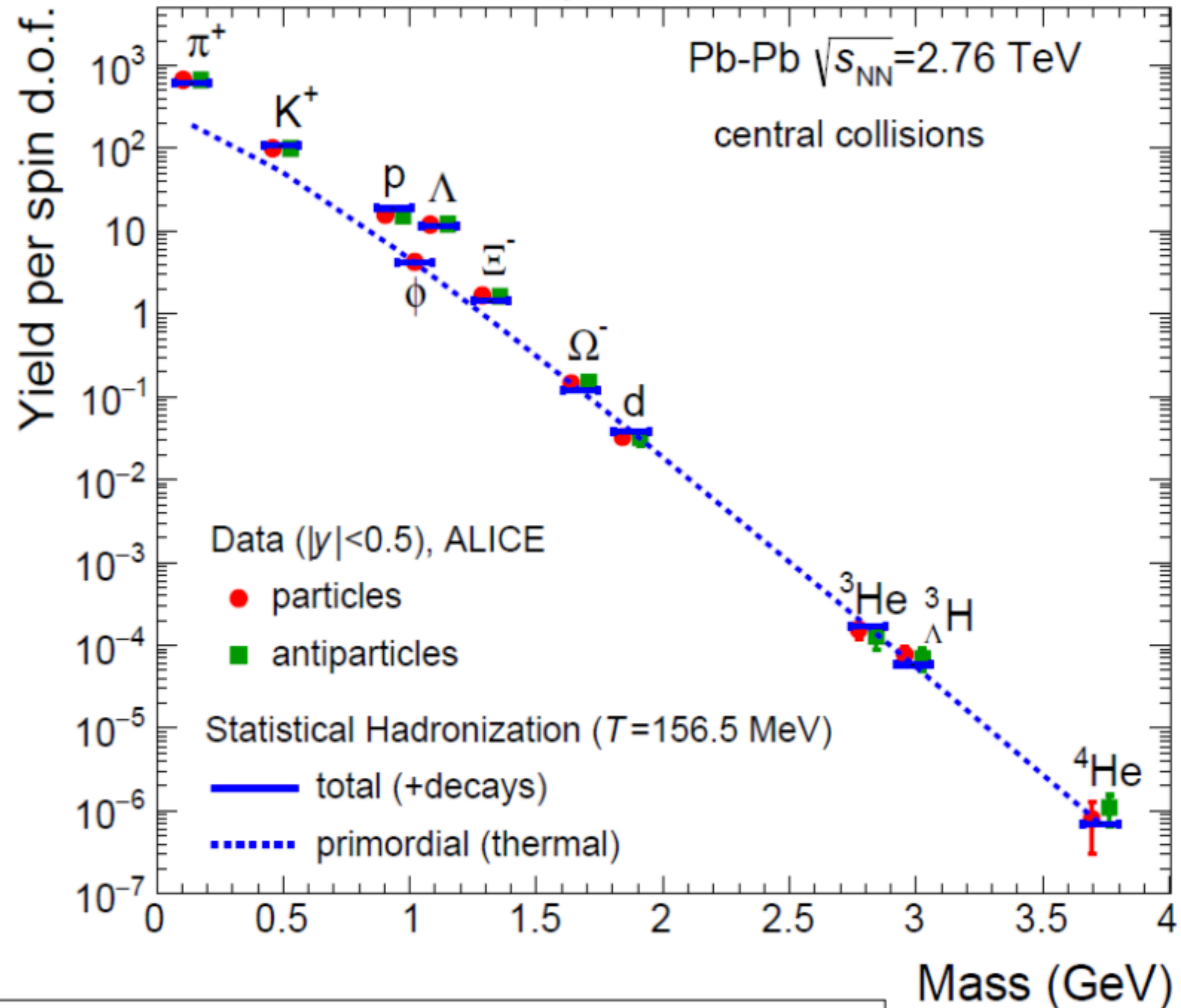
agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

- matter and antimatter formed in equal portions
- even large very fragile (hyper) nuclei follow the systematics

suggestion: they are formed as compact multiquark states at hadronization and evolve into their wavefunctions

needs testing in Run3/4

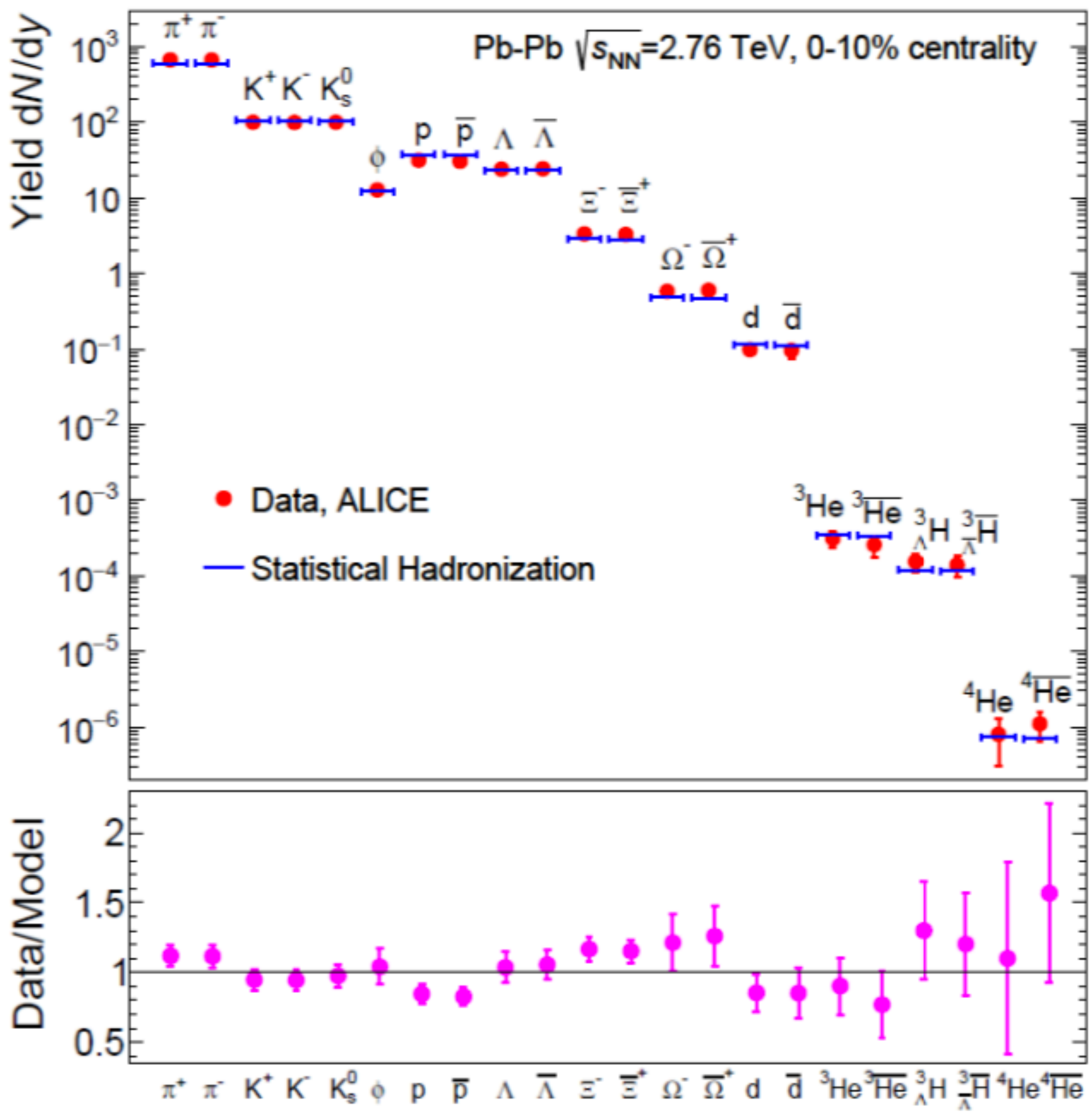
A. Andronic, P. Braun-Munzinger, K. Redlich, JS Nature 561 (2018) 321



smooth evolution of yields from pp, pPb to PbPb
apparent scaling with multiplicity → backup

χ^2 fit of the statistical models to LHC data

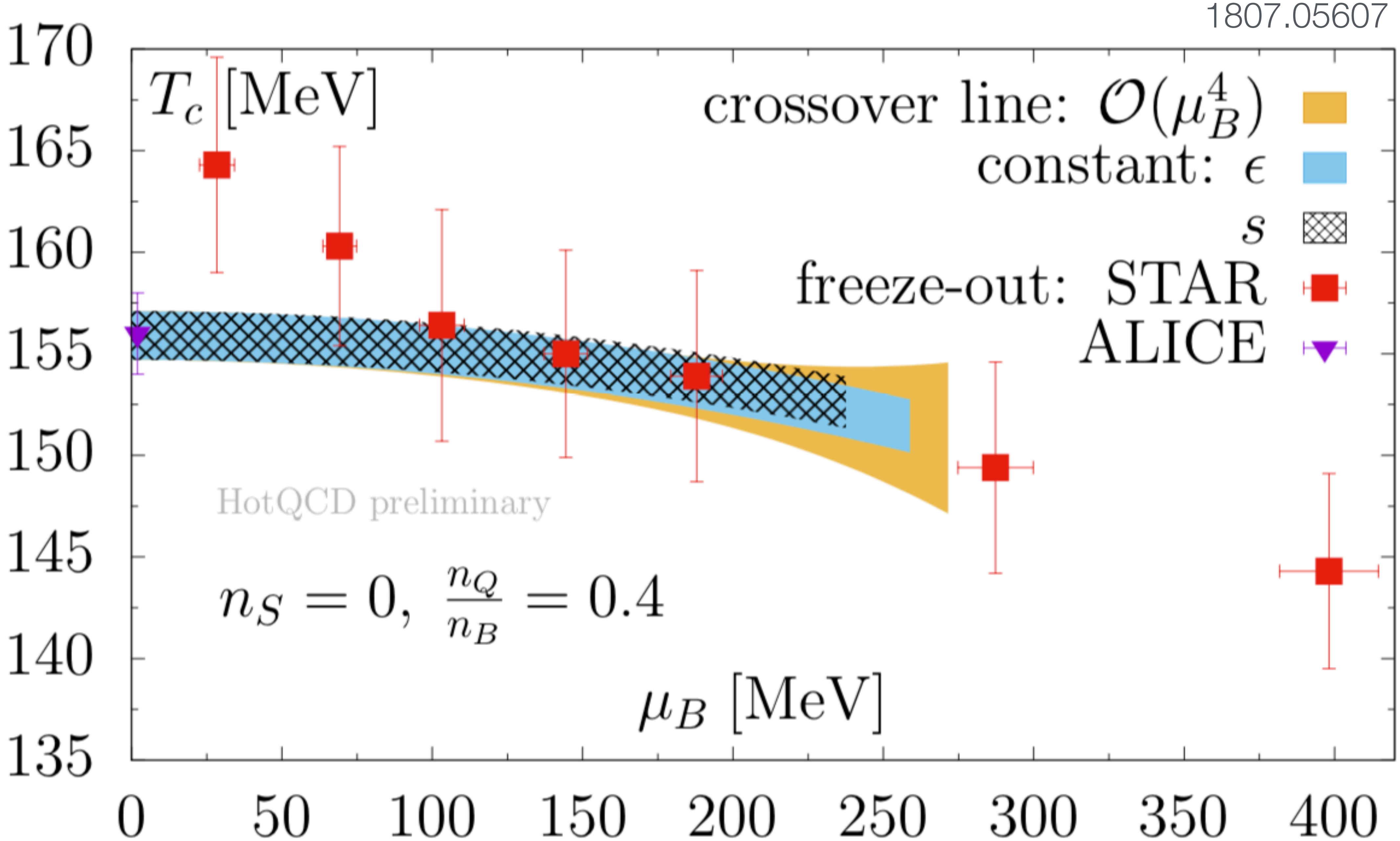
A. Andronic, P. Braun-Munzinger, K. Redlich, JS
Nature (in print) arXiv: 1710.09425



- Very good agreement with data
- T = 156.5 ± 1.5 MeV, μ_B = 0 ± 2 MeV, V = 5330 ± 400 fm^3

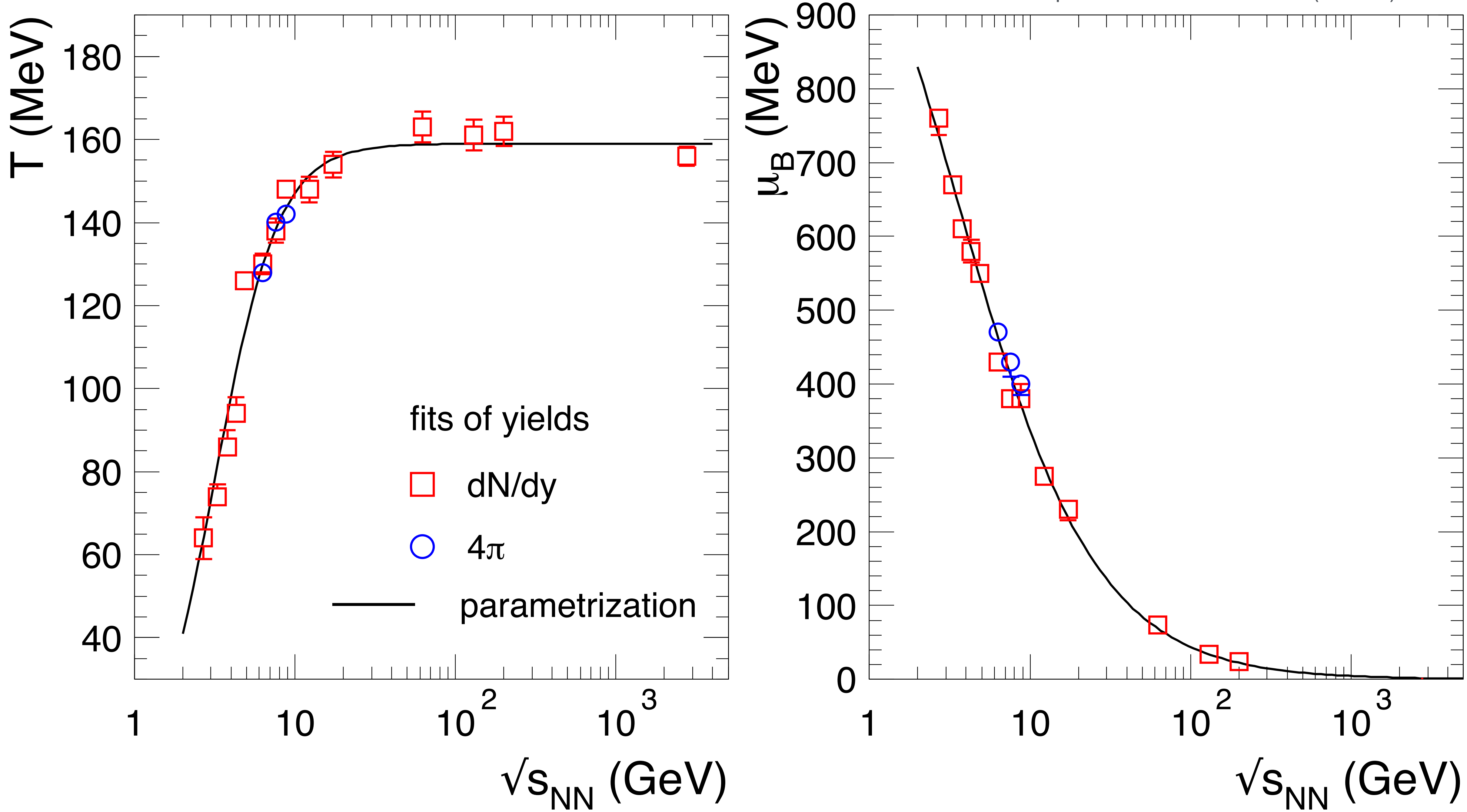
Comparison to Lattice QCD

1807.05607



$\sqrt{s_{NN}}$ dependence of T and μ_B

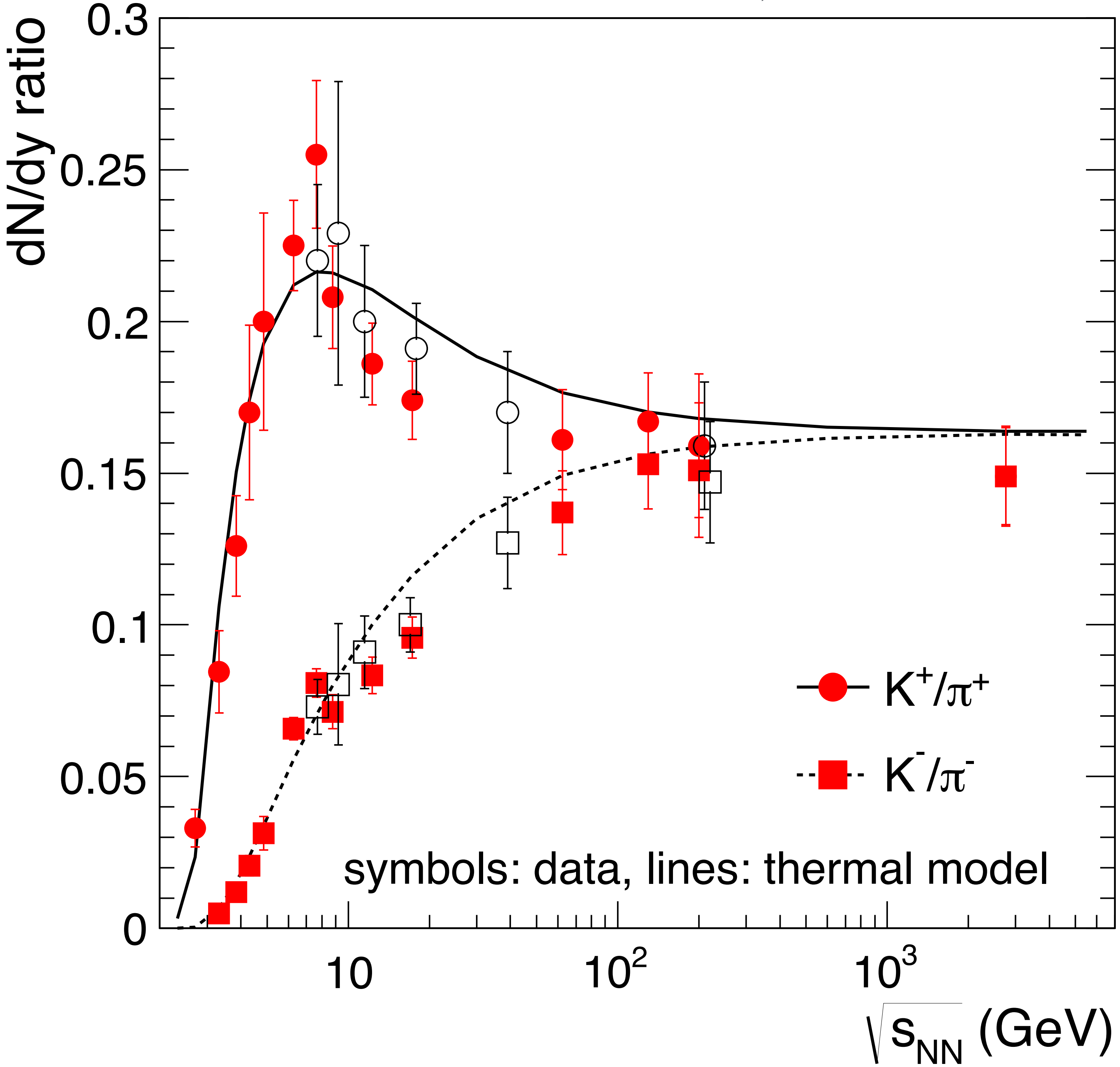
update of PLB 673 (2009) 142



- Smooth evolution of T and μ_B with $\sqrt{s_{NN}}$
- T reaches limiting value of T_{lim} = 159 ± 2 MeV

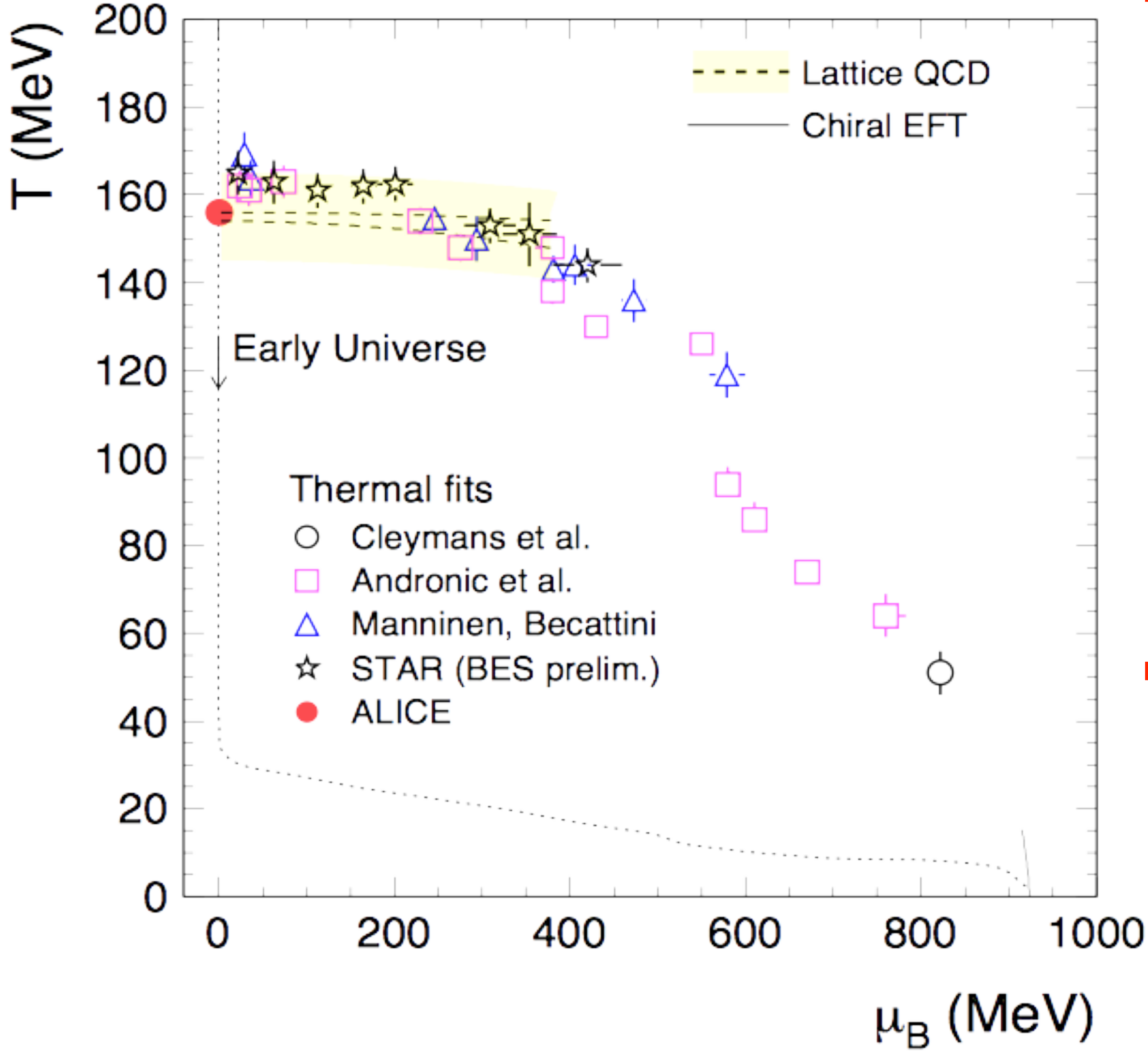
K/π ratio vs. $\sqrt{s_{NN}}$

A. Andronic, arXiv:1407.5003v1



- Maximum in K^+/π^+ ("the horn") was discussed as a signal for the onset of deconfinement at $\sqrt{s_{NN}}$ ≈ a few GeV
- However, in the GC statistical model the structure can be reproduced with T, μ_B that vary smoothly with $\sqrt{s_{NN}}$

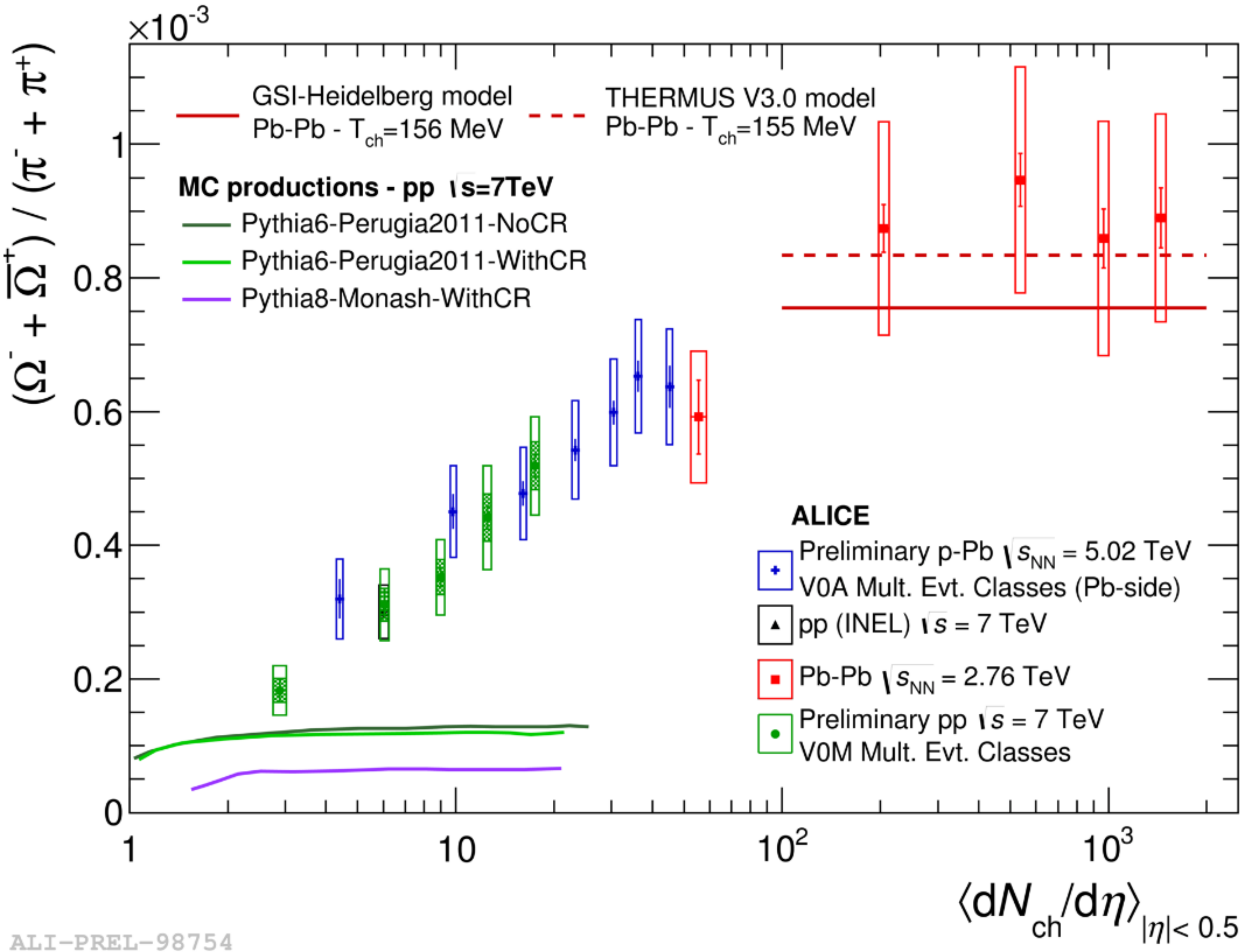
Freeze-out points for $\sqrt{s_{NN}} \gtrsim 10$ GeV from thermal model fits coincide with T_c from lattice calculations



- What is the origin of equilibrium particle yields?
  - General property of the QCD hadronization process ("particle born into equilibrium")
  - Or does the hadron gas thermalizes via particle scattering after the transition?
- Possible mechanism for fast thermalization after the transition: multi-hadron scattering resulting from high particle densities

Braun-Munzinger, Stachel, Wetterich, PLB 596 (2004) 61

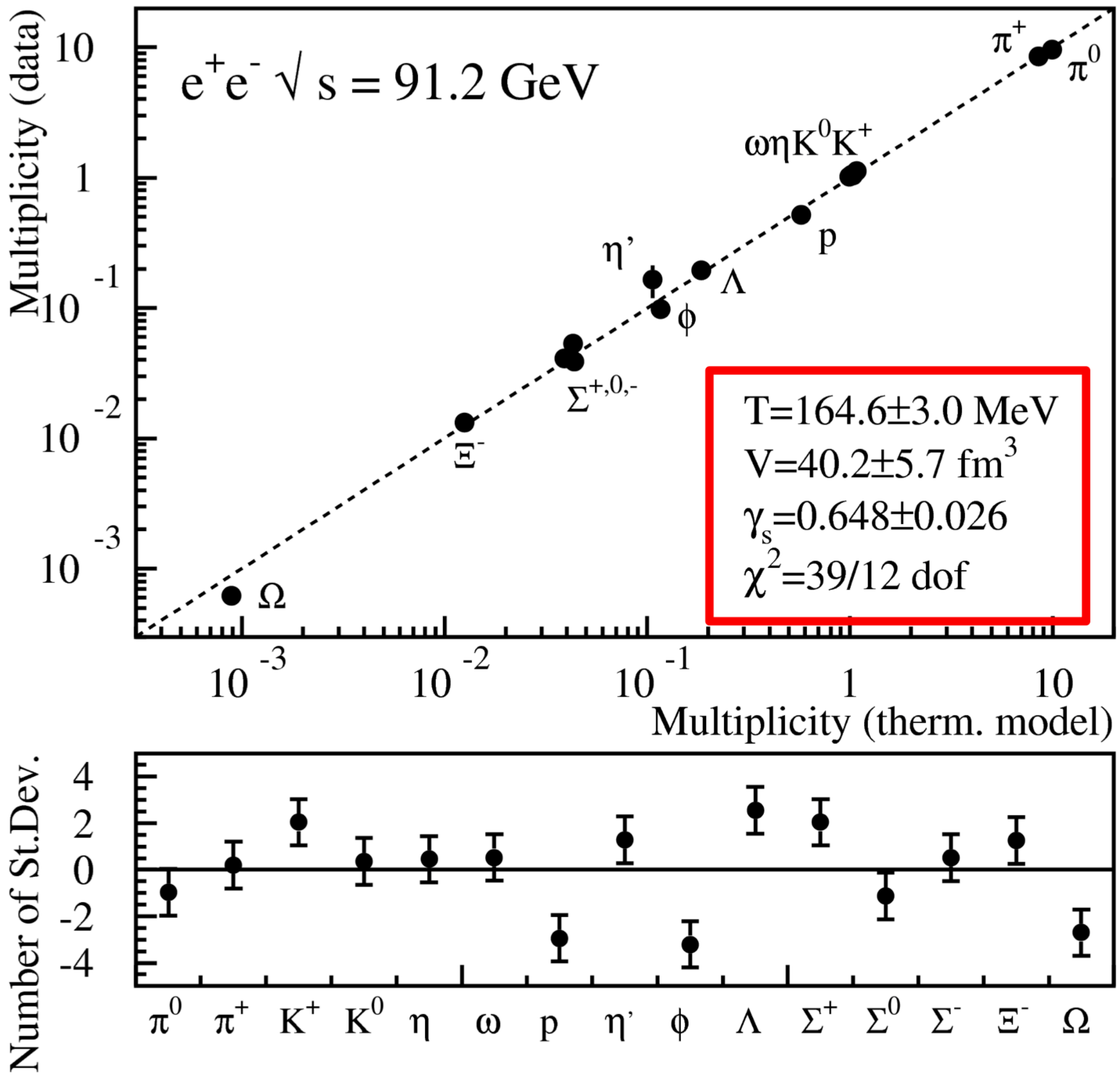
Strangeness enhancement already in small systems: Multiplicity dependence of Ω/π in pp, p-Pb, and Pb-Pb



Significant increase in Ω/π with $dN_{ch}/d\eta$ already in pp and p-Pb

Even yields in e^+e^- are not so far from chemical equilibrium

Becattini, Castorina, Manninen, Satz, 0805.0964



Statistical model + phenomenological factor $\gamma_s < 1$, reducing hadron yields by γ_s^N where N is the number of strange quarks (or antiquarks)

T not so different from the one in central A+A

Summary/questions strangeness

- Strangeness is enhanced in A-A collisions relative to e^+e^- and pp
- LHC: Strangeness enhancement in high-multiplicity pp collisions approaches the enhancement in Pb-Pb
- Origin of the strangeness enhancement?
  - Collisional equilibration?
  - Or "born into equilibrium"?
  - Strange quark coalescence ("recombination")?
  - Or something else?
- Strangeness provides important information and probably points to QGP formation
  - But why does the statistical approach also work to some degree in e^+e^- where no QGP is expected?
  - Better understanding of the mechanisms of strangeness enhancement is needed