Exact strangeness conservation in HIC

Krzysztof Redlich, University of Wroclaw

- Professor Jean Cleymans and his scientific path
- Multiplicity dependence of (multi)strange baryons
  in the canonical ensemble with phase shift corrections

Jean Cleymans, Pok Man Lo, Natasha Sharma & Krzysztof Redlich

Phys. Rev.C 103 (2021) 1, 014904

Jean Willy André Cleymans (1944 – 1921)
22 February 2021

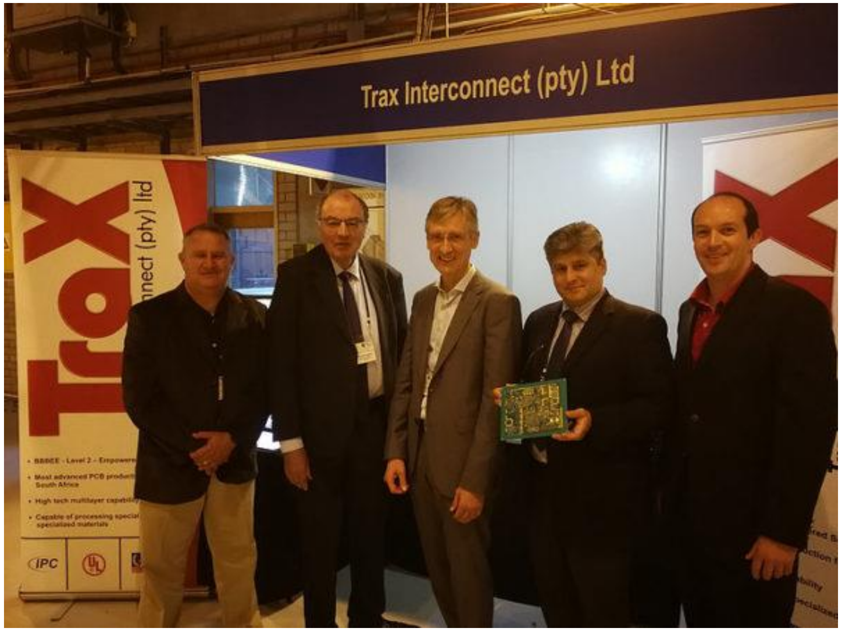
Jean Cleymans, one of the pioneers in the study of ultra-relativistic heavy-ion collisions and a leader of the South Africa – CERN Collaboration.

He passed away on 22 February 2021 in a tragic accident in his hometown, Turnhout in Belgium.

Jean was not only a most distinguished theorist in the field of high energy nuclear collisions; he also played a crucial role in establishing and operating several large international collaborations, bringing together CERN, Dubna, GSI, iThemba labs, and a number of universities.

He had initiated and played a leading role in establishing the South Africa - CERN and South Africa – JINR Dubna program, and the participation of South Africa in the ALICE collaboration.

Jean was a member of the Program Advisory Committee for Particle Physics at JINR Dubna.



Jean was born on August 5, 1944, in Turnhout. He studied physics at the University of Louvain, where he received his doctorate in 1970. Subsequently, he worked as Humboldt-Fellow in Aachen (Germany), as NATO Fellow at SLAC (California), and as TH-CERN Fellow.

From 1975 to 1986, he was at the University of Bielefeld (Germany), where he carried out his Habilitation in 1977 and subsequently became Extraordinary Professor.

In 1986 he moved to Cape Town, where in 1988 he was appointed as Full Professor of Theoretical Physics.

The development of theoretical physics there, the training of young students in high energy physics, and the connection of South Africa to international research is to a very large extent the work of Jean.

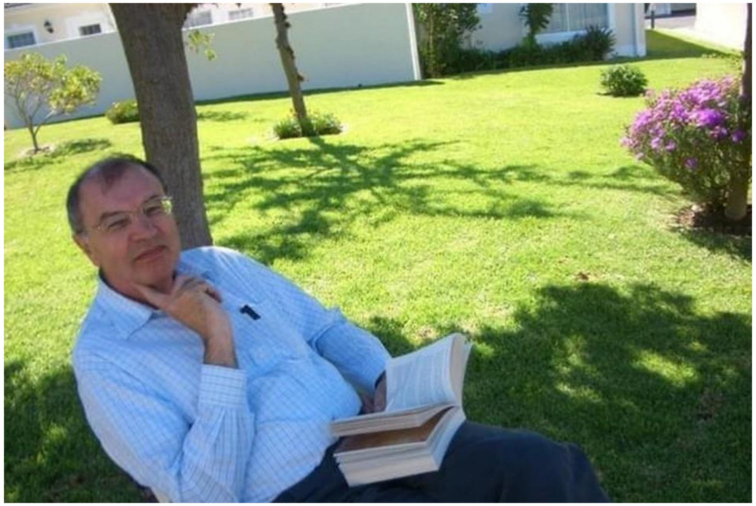
Jean made seminal contributions to numerous areas in heavy ion physics. Of particular impact was his work on the statistical description of hadron production in nuclear collisions; his pioneering work effectively started the approach.
His numerical code for the analysis of hadron multiplicities remains an essential tool for experimental studies, and in recent years has opened_-up new perspectives with the availability of high precision experimental data at RHIC and LHC.
He published more than 300 papers in leading physics journals.

Jean has been instrumental in organizing numerous conferences and workshops in the field e.g. SQM 2004 in Cape Town. He was acting as a member of a number of important international advisory committees, e.g. SQM and former Hard Probes Collaboration which provided the foundation for future collaborative work in that area.

Jean has organized well-received meetings in South Africa, bringing experts from throughout the world there and establishing connections with South African researchers.

Jean has done much to make the field attractive to students and young scientists. He was an inspiring and passionate teacher and supervised 24 M.Sc. and 17. Ph.D. candidates. “One of his former postgraduates and long-time collaborators, Azwinndini Muronga, now the dean of Science at Nelson Mandela University, remembers Jean as having *“qualities of excellence and humanising pedagogy – excellence with purpose”*.”

By joining the ALICE Collaboration and establishing first the UCT-CERN Research Centre and then the national South Africa–CERN program, he reached even more students, researchers, and academics. Even after becoming Professor Emeritus of the University of Cape Town in 2010, Jean continued to lead these initiatives and saw them grow into a vibrant high-energy physics community in South Africa with strong links to CERN.



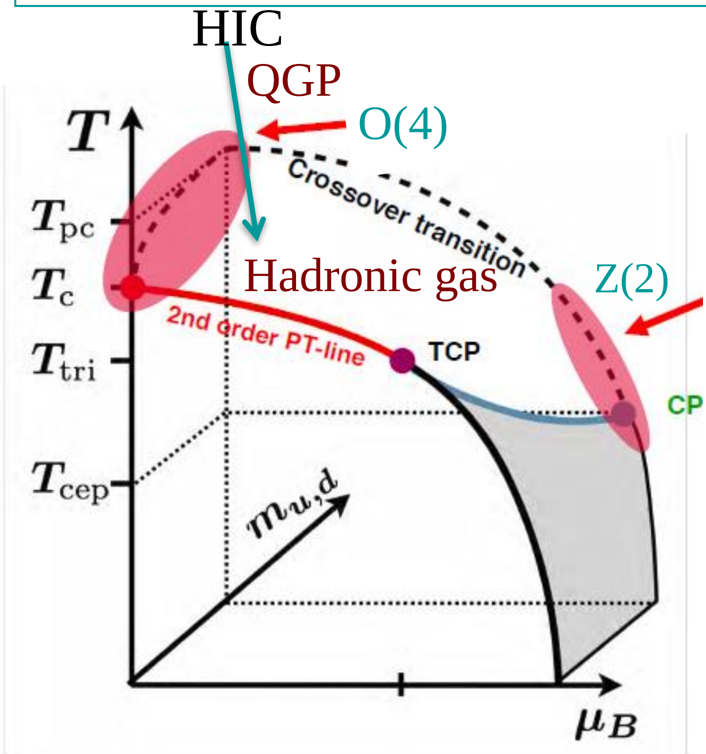
For his achievements, Jean has received numerous honors –
in 1993 he was elected Fellow of the Royal Society of South Africa,
in 1999 he received the prestigious Alexander-von-Humboldt Research Prize,
in 2000 the Prize of the Polish Ministry of Education for Research Excellence,
to cite just three here.

Jean was always receptive to new ideas and willing to enter joint work with others. His attitude was inspirational and creative. In this process, he had close friends and collaborators in many parts of the world.

On 22 February, the field has certainly lost one of its great and inspiring leaders,
just as we have lost a Great Friend.

K. Redlich, H. Satz & ALICE Collaboration: https://home.cern/news/obituary/cern/jean-willy-andre-cleymans-1944-2021
Andy Buffler: https://www.news.uct.ac.za/article/-2021-02-22-emeritus-professor-jean-cleymans-19442021

QCD phase diagram and HIC



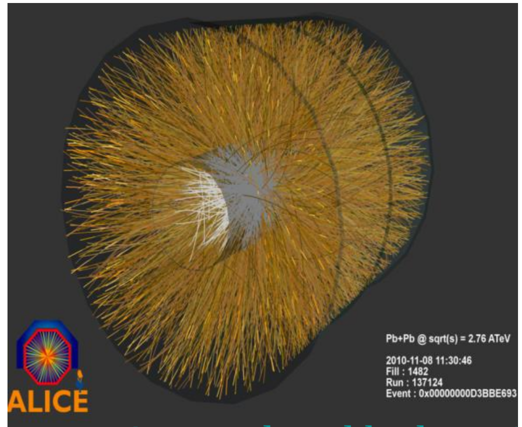
F. Karsch

- Direct delineation of QCD phase diagram in HIC via particle production and fluctuations

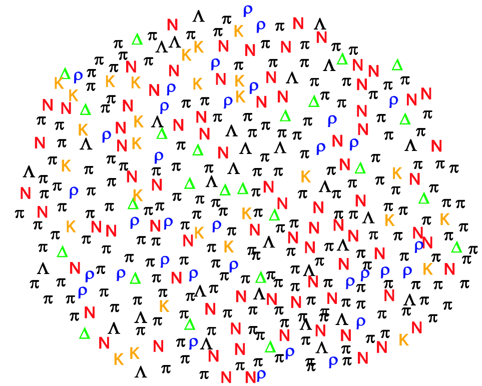
M. A. Stephanov, K. Rajagopal, E. V. Shuryak Phys.Rev.Lett. 81 (1998) 4816, Phys.Rev.D 60 (1999)
S. Ejiri, F. Karsch and K.Redlich PLB 633 (2006)
M. Asakawa, K. Yazaki Nucl.Phys.A 504 (1989)
S. Ejiri et al., PRD 80 (2009):
O. Kaczmarek, F. Karsch et al., 2010.15593 [hep-lat
A. Andronic, P. Braun-Munzinger et al, Nature 561 (2018)

Jean Cleymans

Pb-Pb Collisions



Hadronic gas



- Are produced hadrons in HIC thermal in nature
- What is the statistical operator of matter produced in HIC: how it is connected to QCD thermodynamic potential
- How to include conservation laws: canonical or grand-canonical and their phenomenology. How they influence particle multiplicities and their fluctuations and correlations
- Hadron yields systematics for different collision energies: differences between hadron production in pp, pA and AA
- what are characteristic thermal properties of collision fireball
- What is the link between QCD phase boundary and chemical freezeout in HIC
- Collective flow and particle production, Tsallis statistics, hard probes and thermal field theory …..

Modelling QCD thermodynamic and particle production in HIC

Pressure of an interacting, a+b ⇔ a+b, hadron gas in equilibrium

$$P(T,\vec{\mu}) \approx P_a^{id} + P_b^{id} + P_{ab}^{\text{int}}$$

The leading order interactions, determined by the two-body scattering phase shift, which is equivalent to the second virial coefficient

$$P^{\text{int}} = \sum_{I,j} \int_{m_{th}}^{\infty} dM \; B_j^I(M) P^{id}(T,M)$$

$$B_j^I(M) = \frac{1}{\pi} \frac{d}{dM} \delta_j^I(M)$$

↓ ↓

Effective weight function *Scattering phase shift*

R. Dashen, S. K. Ma and H. J. Bernstein, Phys. Rev. 187, 345 (1969)

R.Venugopalan, and M. Prakash, Nucl. Phys. A 546 (1992) 718.

W. Weinhold,, and B. Friman, Phys. Lett. B 433, 236 (1998).

Pok Man Lo, Eur. Phys.J. C77 (2017) no.8, 533

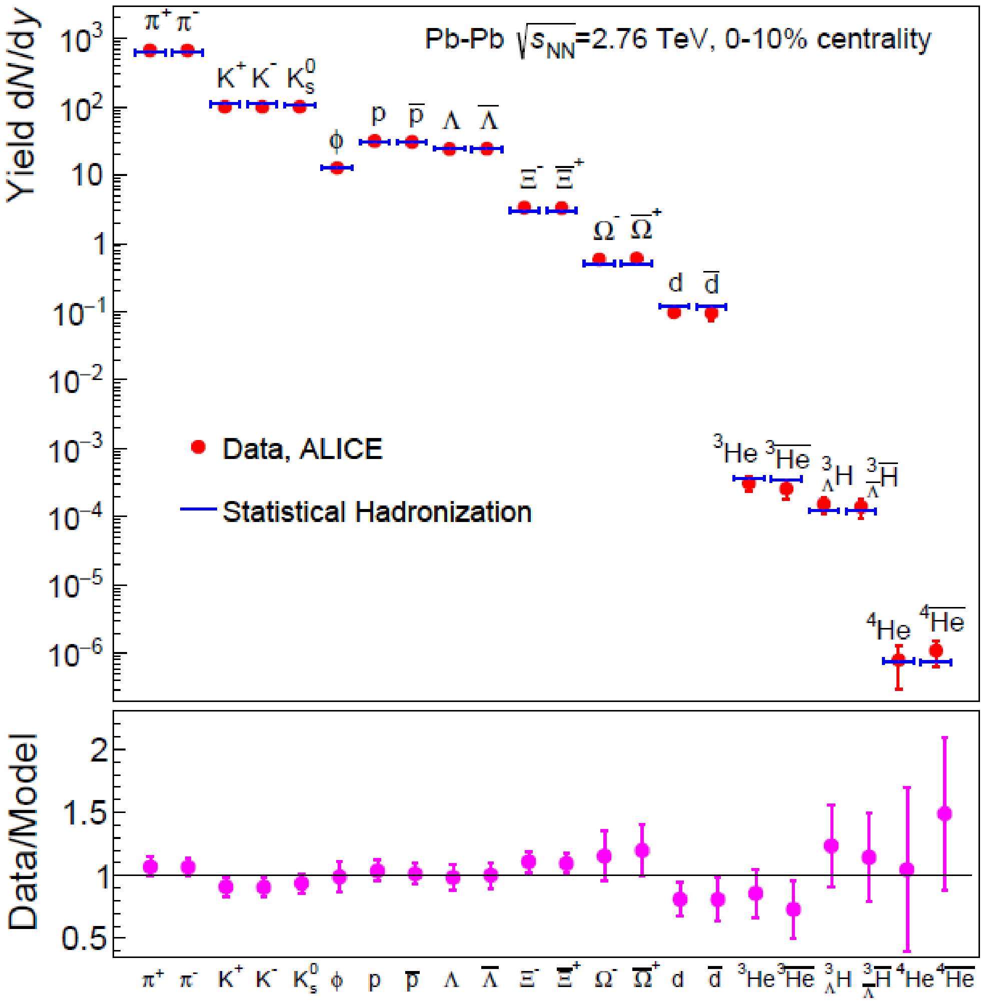
- Interactions driven by narrow resonance of mass M_R

$$B(M) \sim \delta(M^2 - M_R^2) \quad \Rightarrow \quad P^{\text{int}} = P^{id}(T, M_R) \Rightarrow HRG$$

For finite and small width of resonance, B(M) => Breit-Wigner form

- For non-resonance interactions or for broad resonances $P_{ab}^{\text{int}}(T)$ should be linked to the phase shifts

S-matrix HRG and particle yields in Pb-Pb collisions at the LHC



The S-matrix HRG model formulated in GC ensemble that incudes empirical information on pion-nucleon interactions provides a very good description of LHC yields data

- Measured yields reproduced at

$$T = 156.6 \pm 1.7 \text{MeV}$$

$$\mu = 0.7 \pm 3.8 \ \text{MeV}$$

$$V_{\Delta y=1} = 4175 \pm 380 \ \text{fm}^3$$

$$\chi^2 / dof = 16.7 / 19$$

- A fireball in central Pb-Pb collisions is matter at the QCD phase boundary

A. Andronic, P. Braun-Munzinger, Pok Man Lo, B. Friman, J. Stachel & K.R Phys. Lett. B 792, 304 (2019)

A. Andronic, P. Braun-Munzinger, J. Stachel & K.R., Nature 561, 302 (2018)

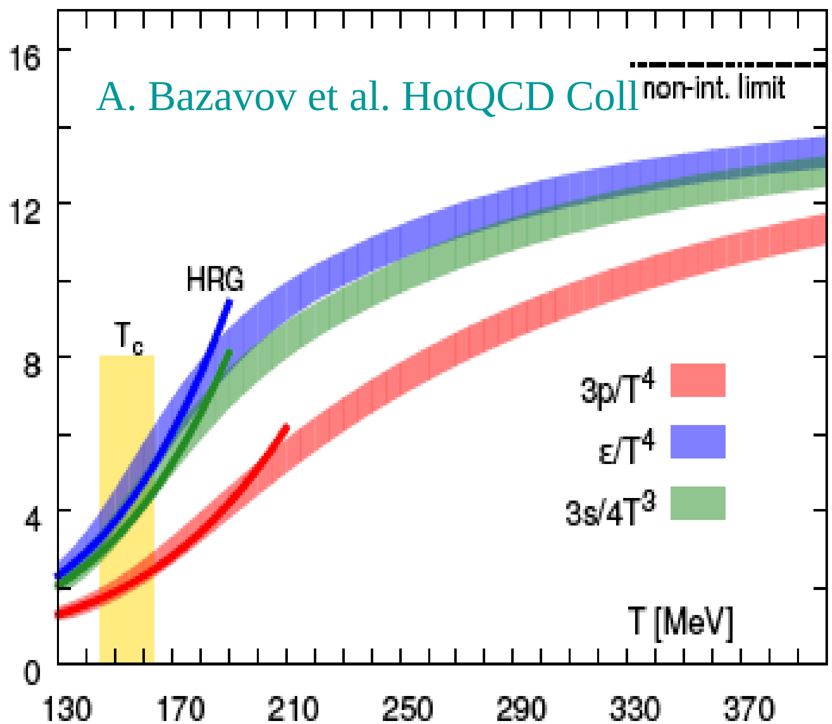
Quark-Hadron duality near the QCD phase boundary

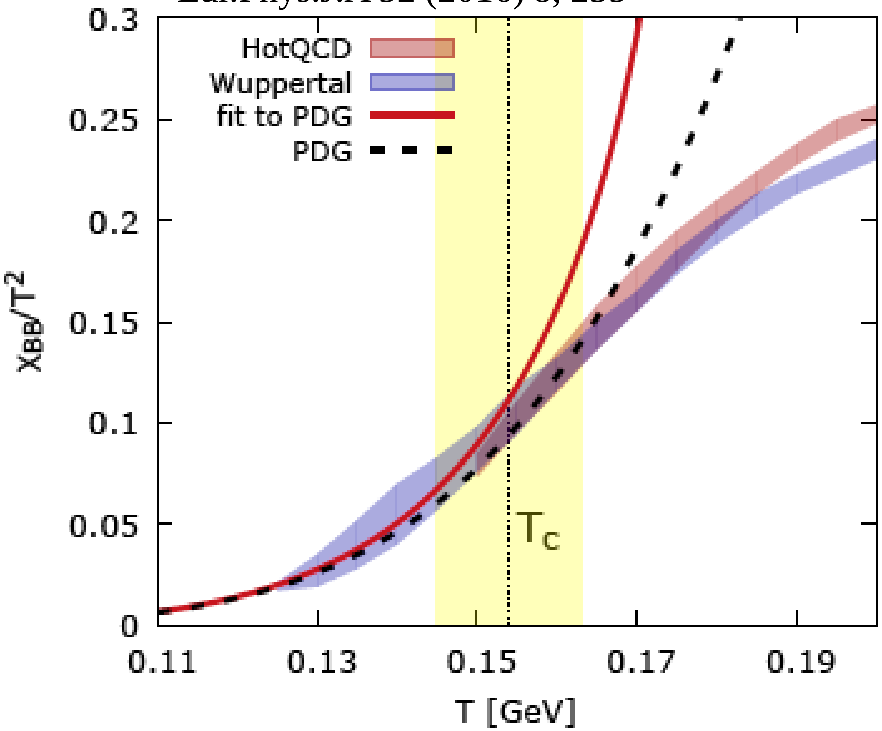
$$P(T,\vec{\mu}) \approx \sum_H P_H^{id} + \sum_R P_R^i$$

see also: J. Goswami, et al., 2011.02812 [hep-lat]
R. Bellwied, et al. 2102.06625 [hep-lat]
S. Borsányi, et. al 2102.06660 [hep-lat]

$$P_R^{\,i} = \pm \frac{Tg_i}{2\pi^2} \int p^2 dp \int dM \ln(1 \pm e^{-\beta(E_i - \vec{q}_i \vec{\mu}_i)}) F_R^{BW}(M)$$

SQM talks: Pok Man Lo, Paolo Parotto, P. Dennis
Pok Man Lo, M. Marczenko et. al.
Eur.Phys.J.A 52 (2016) 8, 235





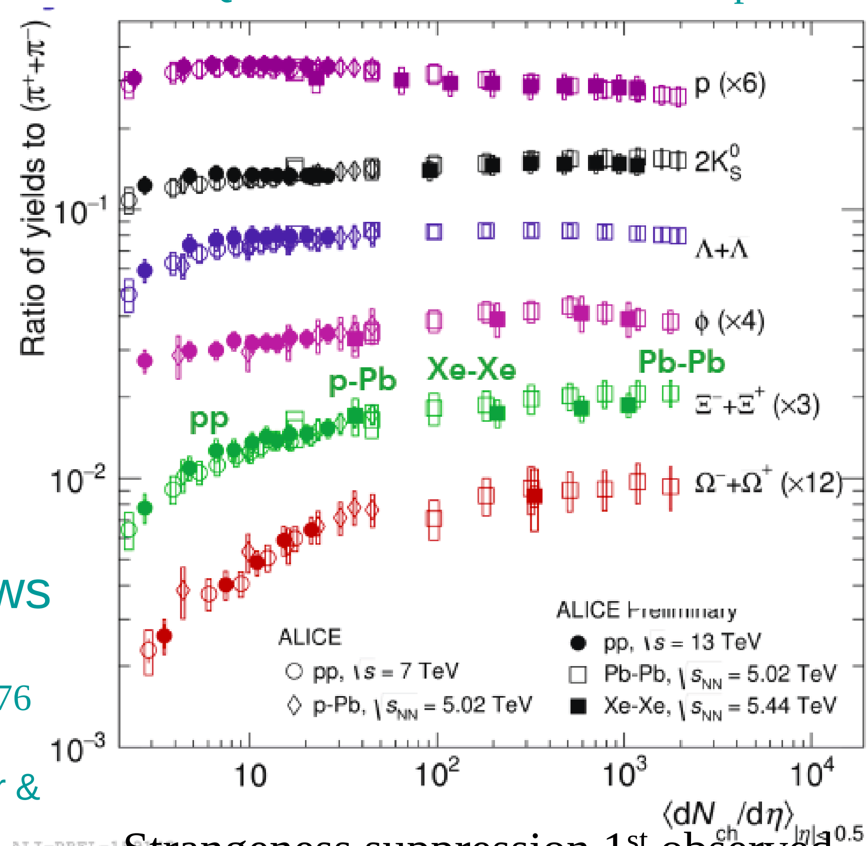
- SM Hadron Resonance Gas thermodynamic potential provides good approximation of the QCD equation of states in confined phase
- Consistent description of the net- baryon number fluctuations and in further sectors of hadronic quantum numbers

Particle yields linked to $dN_{ch}/d\eta$: from pp, pA to AA

- Increase of strangeness production with increasing multiplicity until saturation,
  as well as,
  its dependence on strange quantum number of hadrons can be
  linked to "canonical suppression effect"
  i.e.
  constraints imposed on thermal particle yields due to exact strangeness conservation which requires canonical ensemble formulation of conservation laws

Smooth evolution of particle yields as function of charged particle multiplicity, and strangeness suppression

See SQM talk: Anders Garritt Knospe



Strangeness suppression 1st observed at CERN SPS by WA97, NA57 Coll.

J. Cleymans, E. Suhonen & K.R. Z.Phys.C 51 (1991) 137, Z.Phys.C 76 (1997) 269. S. Hamieh, A. Tounsi & K.R. Phys. Lett. B486 (2000), Eur.Phys.J. C24 (2002) , J. Cleymans, H. Oeschler & K.R. Phys. Rev. C59 (1999) 1663. P. Braun-Munzinger, J. Cleymans, et al. Nucl.Phys.A 697 (2002), 902

Strangeness canonical suppression with yields of charged particles

- If the number of s-particles is small then strangeness conservation must be exact

$$Z^{GC}(\mu) = Tr[e^{-\beta(H-\mu S)}] \Rightarrow Z_S^C = Tr[e^{-\beta H}\delta_S]$$

$$Z^{GC}(\lambda) = \sum_{S=-\infty}^{\infty} \lambda^S Z_S^C \Rightarrow Z_S^C \sim \int_{-\pi}^{\pi} d\varphi e^{i\phi S} e^{\mathrm{Ln}(Z^{GC}(\mu\to i\varphi))}$$

$$\ln Z^{GC} = \sum_{S=-3}^{S=+3} z_S e^{S\mu_S/T}$$

- This implies strangeness suppression effect

$$< N_s >_A^C \approx V_A n^{GC} \sim \frac{I_s(2V_C n_{s=1}(T))}{I_0(2V_C n_{s=1}(T))}$$

where volume parameters $V_{A(C)} \sim dN_{ch}/d\eta$

V_C - full phase-space volume where S is exactly conserved

V_A - effective fireball volume in the acceptance

The suppression factor $I_S(x)/I_0(x) \le 1$, decreases with decreasing x, and increasing strange s-quantum number of hadron.

J. Cleymans, E. Suhonen & K.R. Z.Phys.C 51 (1991) 137; Z.Phys.C 76 (1997) 269

J. Cleymans, P. Koch Z. Phys. C52 (1991)

J. Cleymans, H. Oeschler and K.R. *Phys. Rev. C* 59 (1999) 1663; *Phys.Lett.B* 485 (2000); *Phys.Lett.B* 603 (2004) 146; *Phys.Lett.B* 615 (2005) 50 (with S. Wheaton)

P. Braun-Munzinger, J. Cleymans, H. Oeschler, K. Redlich Nucl.Phys.A 697 (2002), 902

F. Becattini, J. Cleymans, A. Keranen, E Suhonen, K. R. Phys. Rev. C 64 (2001), 024901

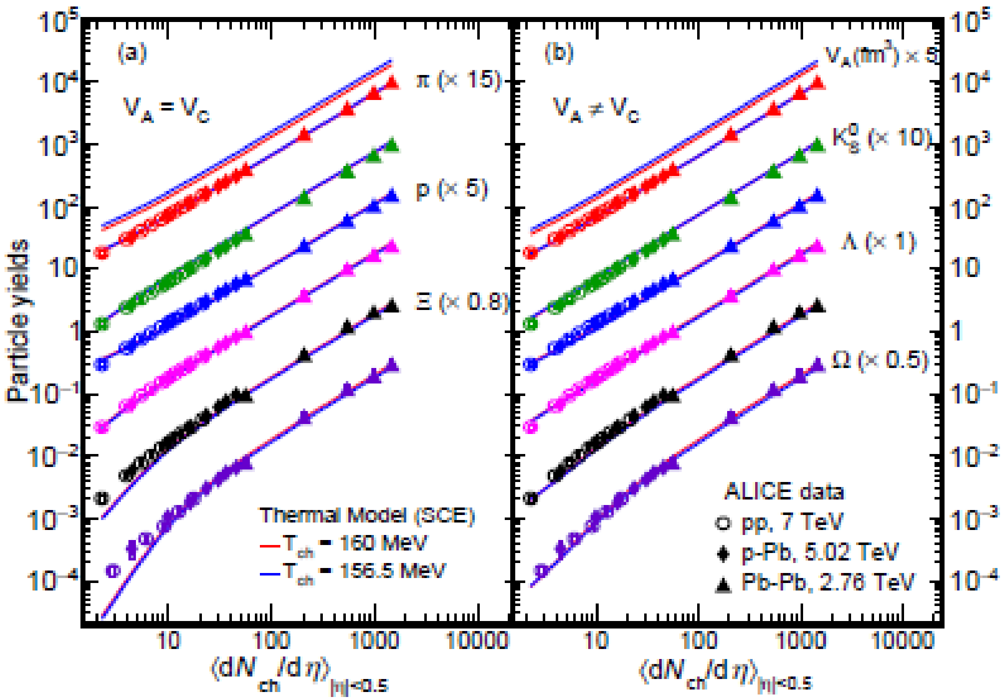
normalized to pion

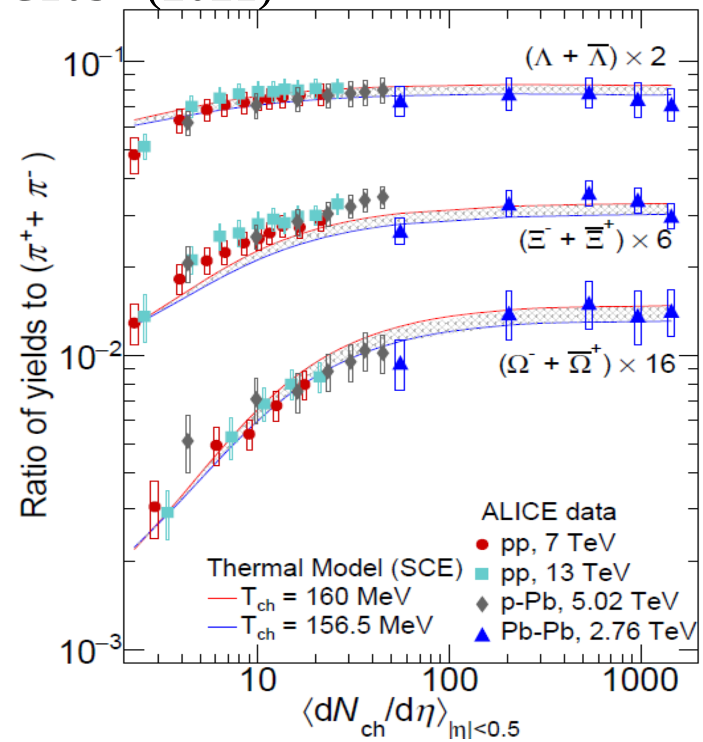
$$\frac{< N_s >_A^C}{< N_\pi >_A} \approx \frac{n_s(T)}{n_\pi(T)} \sim \frac{I_s(2V_C n_{s=1}(T))}{I_0(2V_C n_{s=1}(T))}$$

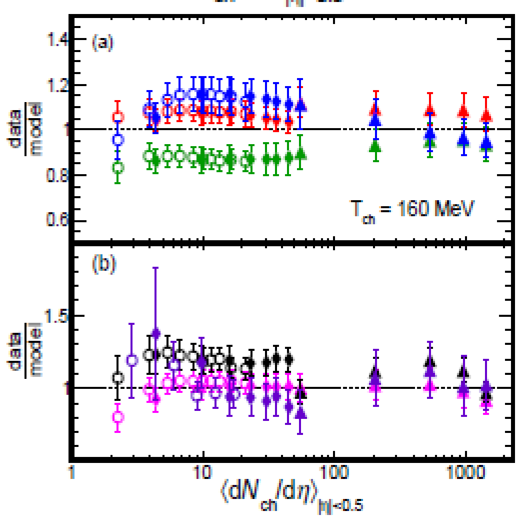
Only 1-papametr left $V_C = f(N_\pi)$, thus at LHC expected N_π – scaling of the ratios

Strangeness canonical ensemble and ALICE data

J. Cleymans, Pok Man Lo, N. Sharma & K.R. Phys. Rev. C103 (2021)







THERMUS: S. Wheaton and J. Cleymans Comput. Phys. Commun. 180 (2009)

B. Hippolyte and Y. Schutz; J. Cleymans, N. Sharma & Pok Man Lo

- Strangeness canonical HRG model consistent with data within 2σ
- Strangeness is globally conserved : strangeness correlation volume larger than fireball volume at acceptance
- S-matrix corrections to proton and lambda production are important to provide best description of data

see SQM talk: Pok Man Lo

Correlated strangeness production

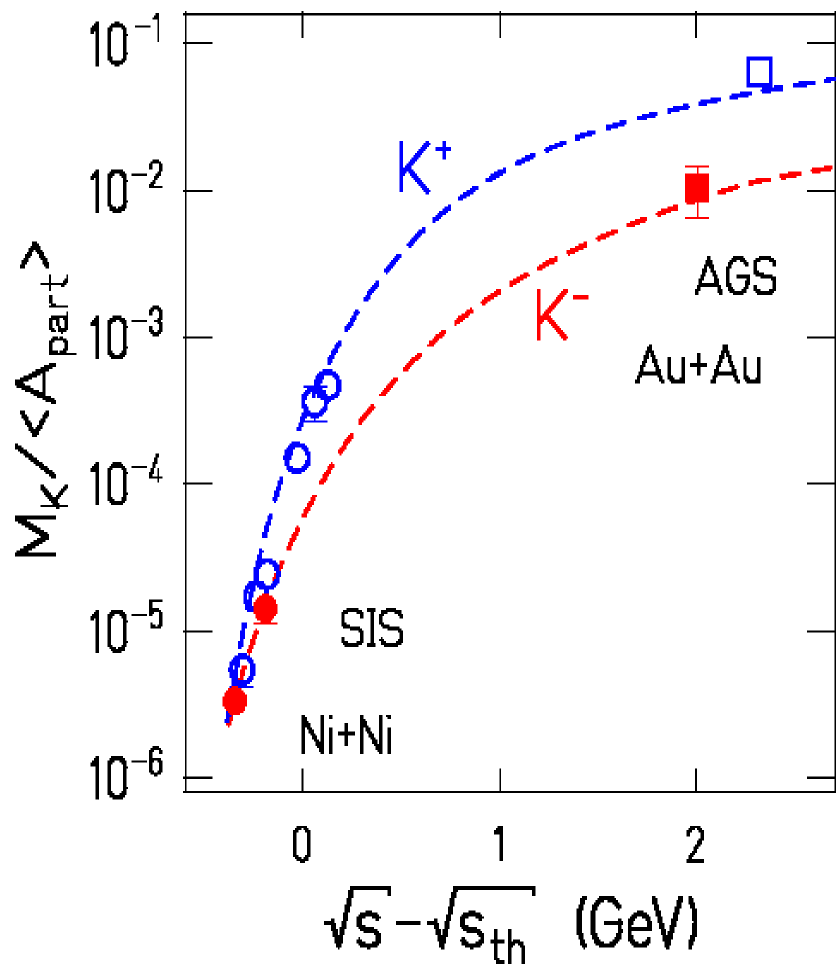
$N + N \rightarrow K^{+} + Y + N$ ⇒ $< K^{+} >^{C} \simeq V_A e^{-m_k/T} V_C e^{-(m_Y - \mu_B)/T}$

$\pi + Y \rightarrow K^{-} + N$

J. Cleymans, H. Oeschler, & K.R.

Phys.Rev.C 59 (1999), Phys.Lett.B 485 (2000)

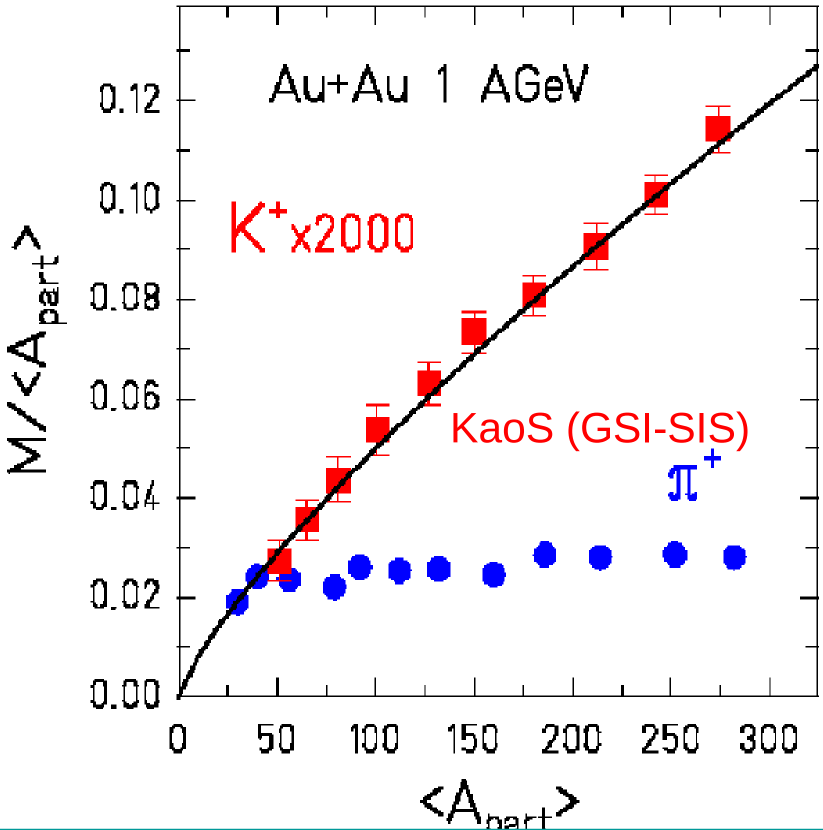
- If the number of produced particles carrying conserved charges is small, then it is essential to describe their thermodynamics in the canonical ensemble with respect to conservation laws

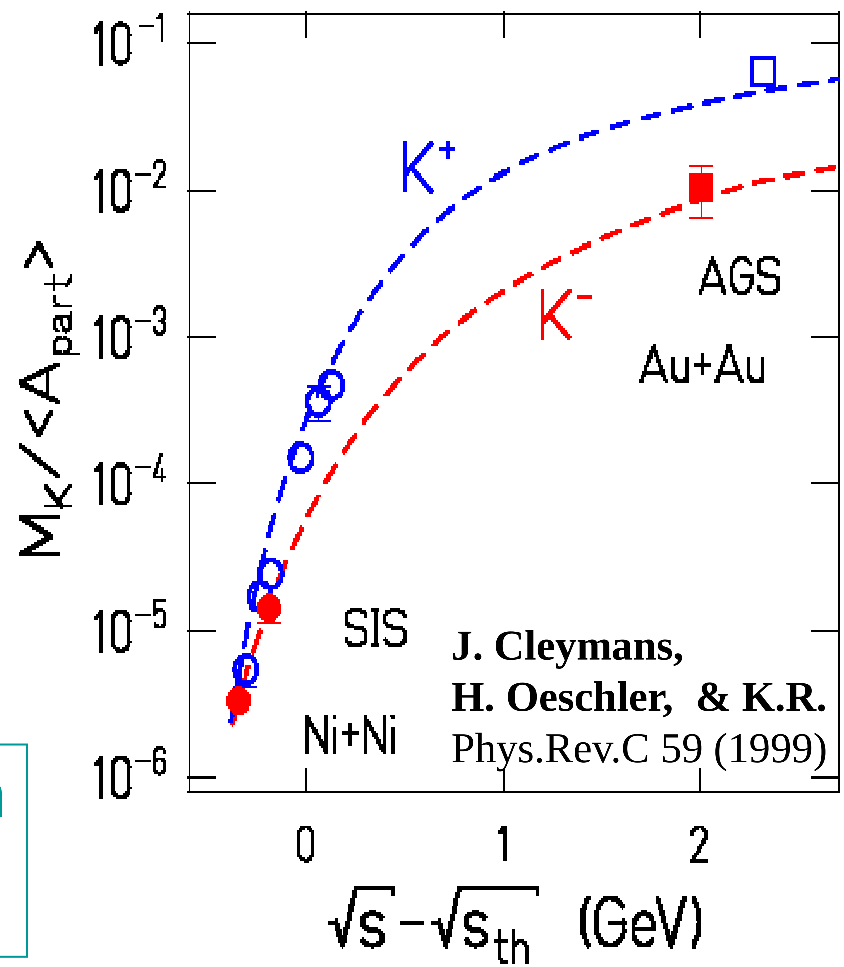


Correlated strangeness production

$\pi + N \rightarrow K^+ + Y$ ⇒ $\langle K^+ \rangle^C \propto A_{part}^2 e^{-m_k/T} e^{-(m_Y - \mu_B)/T}$

$\pi + Y \rightarrow K^- + N$





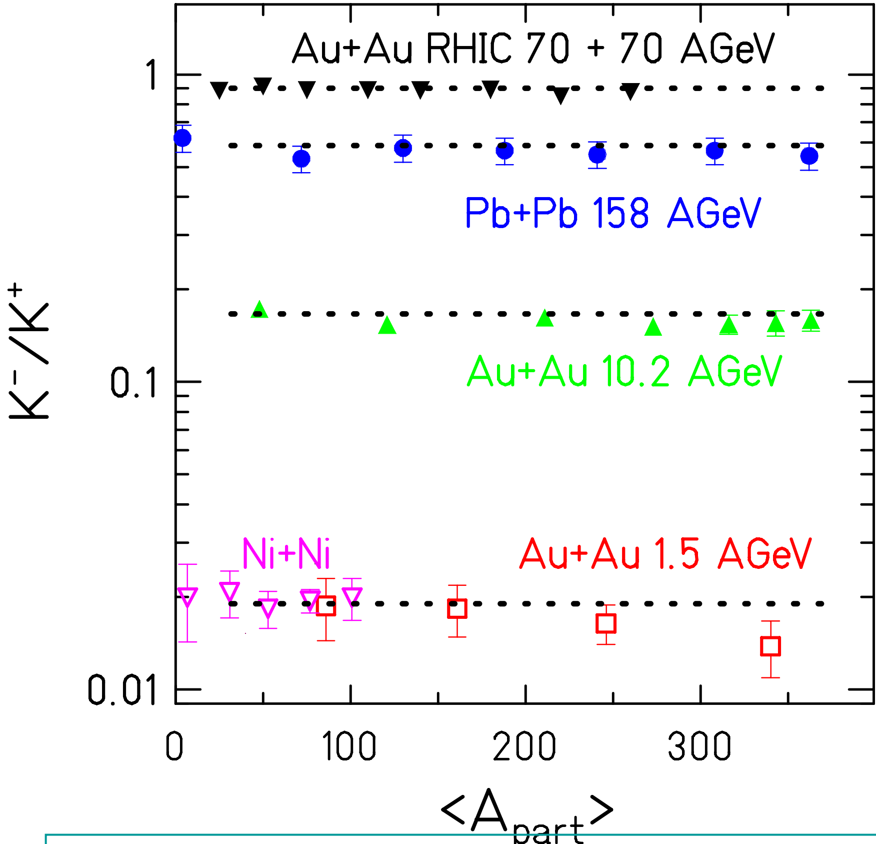
J. Cleymans, H. Oeschler, & K.R. Phys.Rev.C 59 (1999)

- Nearly quadratic increase of Kaon yield with a number of participant

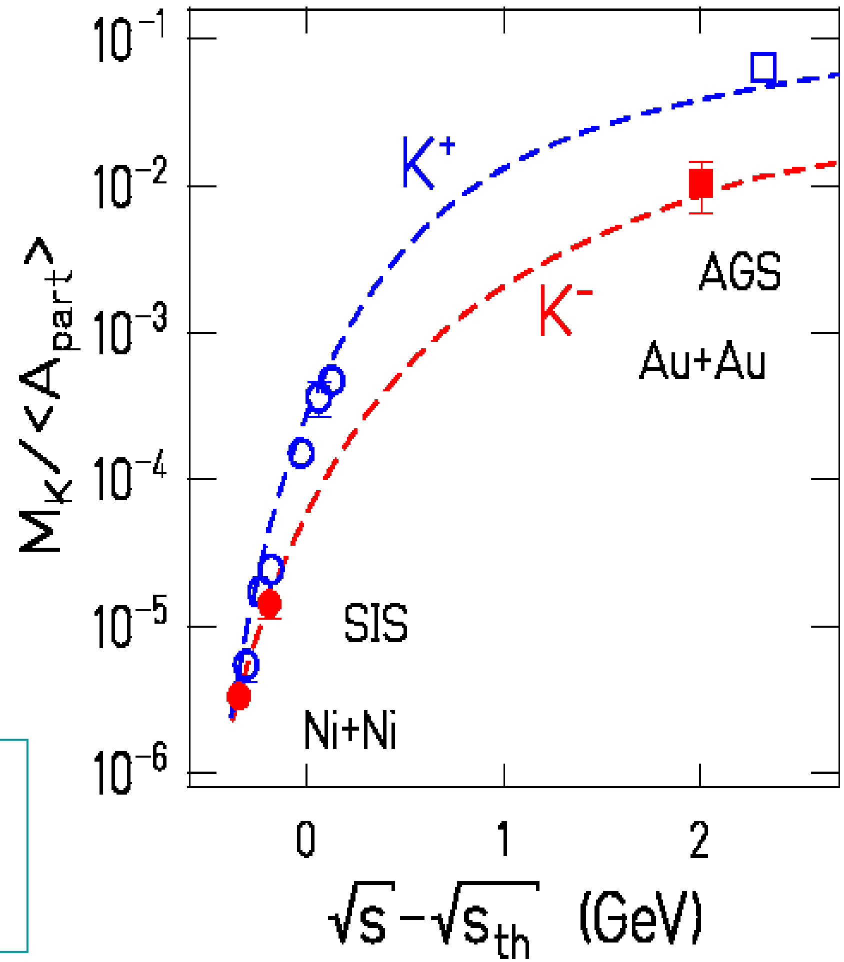
Correlated strangeness production

$\pi + N \square \quad K^+ + Y$

$< K^+ >^C \square \; A_{part}^2 e^{-m_k/T} e^{-(m_Y - \mu_B)/T}$

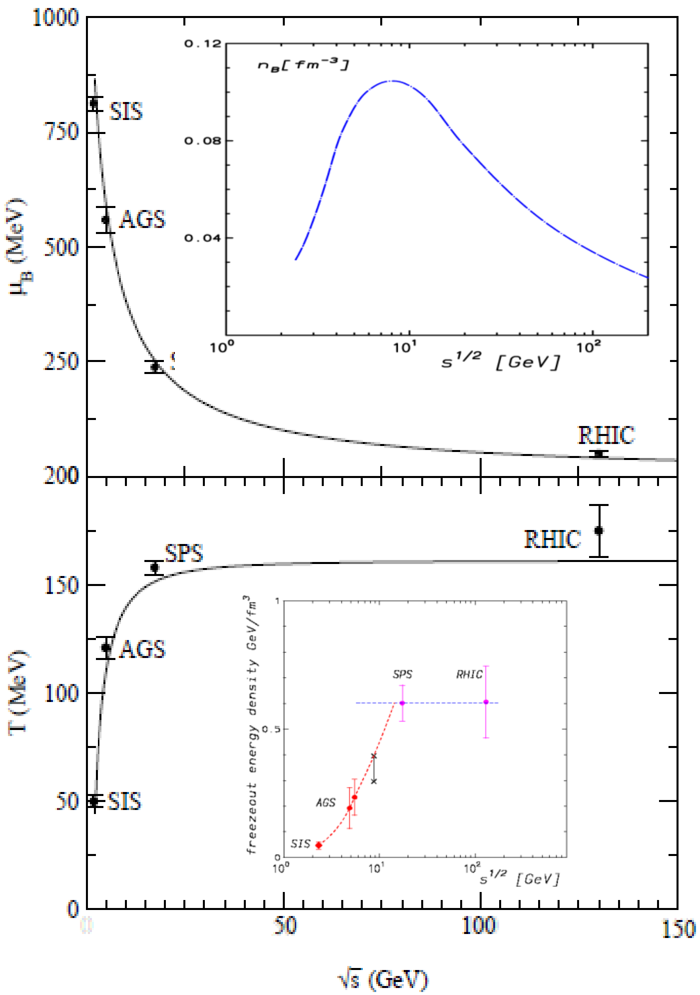


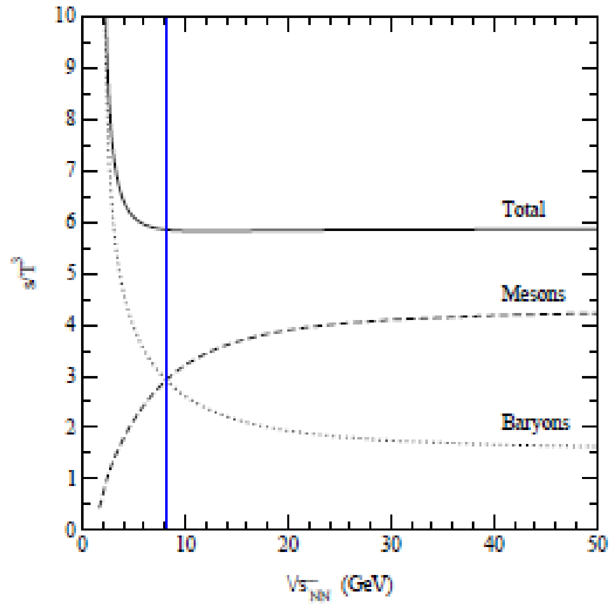
$\pi + Y \square \quad K^- + N$

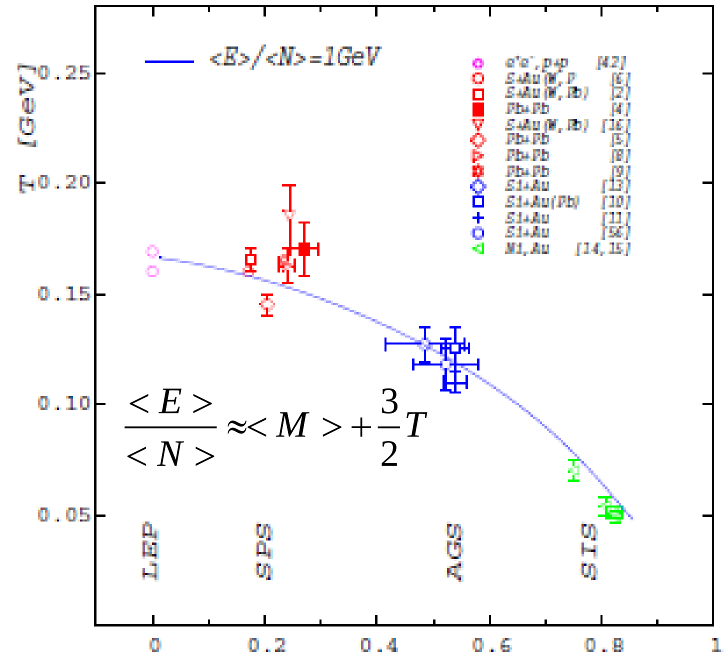


- Ratio independent of the number of participant

Unified description of freezeout parameters in HIC







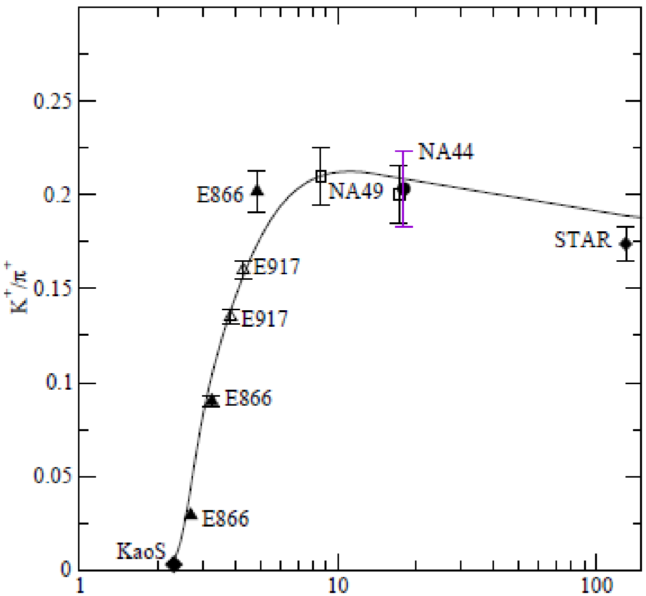
See SQM talk T. Reichert

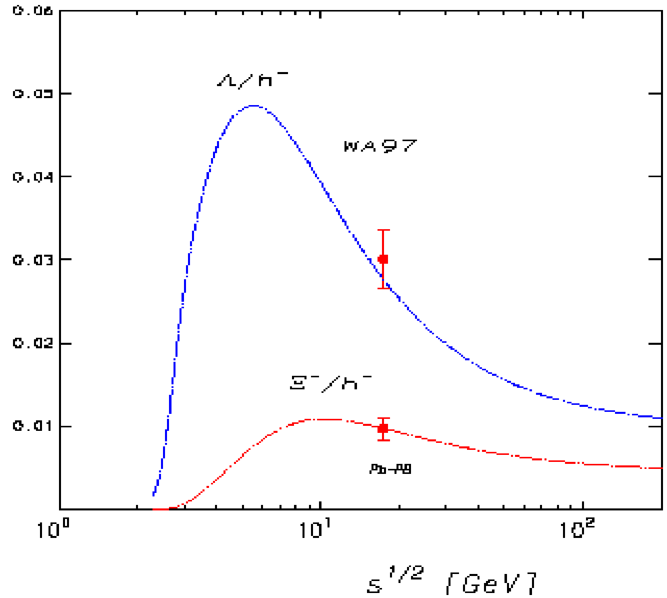
- Thermal properties of collision fireball at chemical freezeout and medium composition
- Provide predictions for different yields ratios and their energy excitation functions

J. Cleymans, K. Redlich Phys. Rev. Lett. 81 (1998), *Phys.Rev.C* 60 (1999) 054908

J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton Phys. Rev. C.73. (2006) 034905

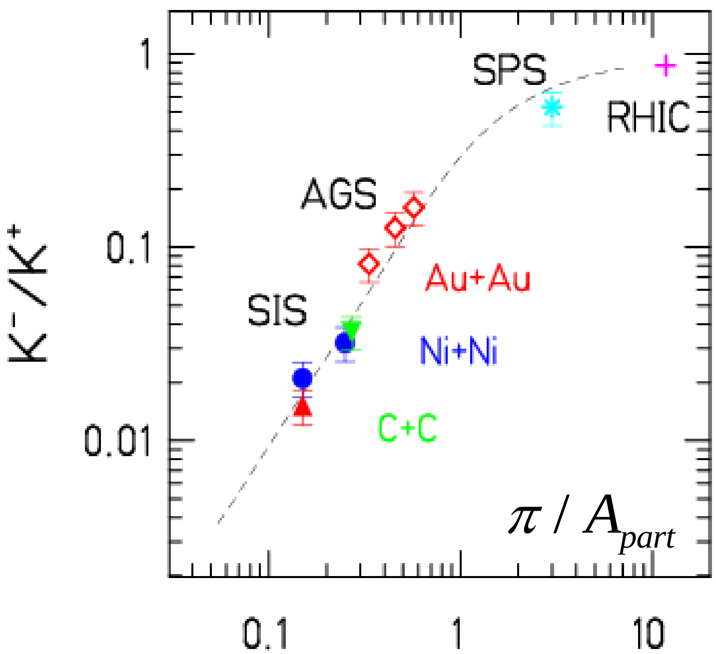
Particle production and energy dependence

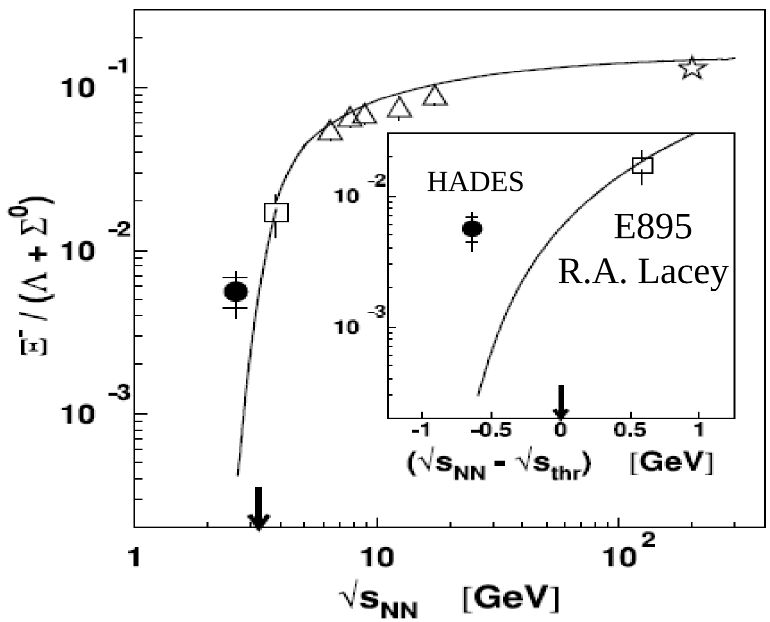




P. Braun-Munzinger, J. Cleymans, H. Oeschler, K. Redlich Nucl.Phys.A 697 (2002), 902

J. Cleymans, A. Forster, H. Oeschler, K. Redlich , F. Uhlig Phys.Lett.B 603 (2004) 146





J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton *Eur.Phys.J.A* 29 (2006) 119 *J.Phys.G* 32 (2006) S165

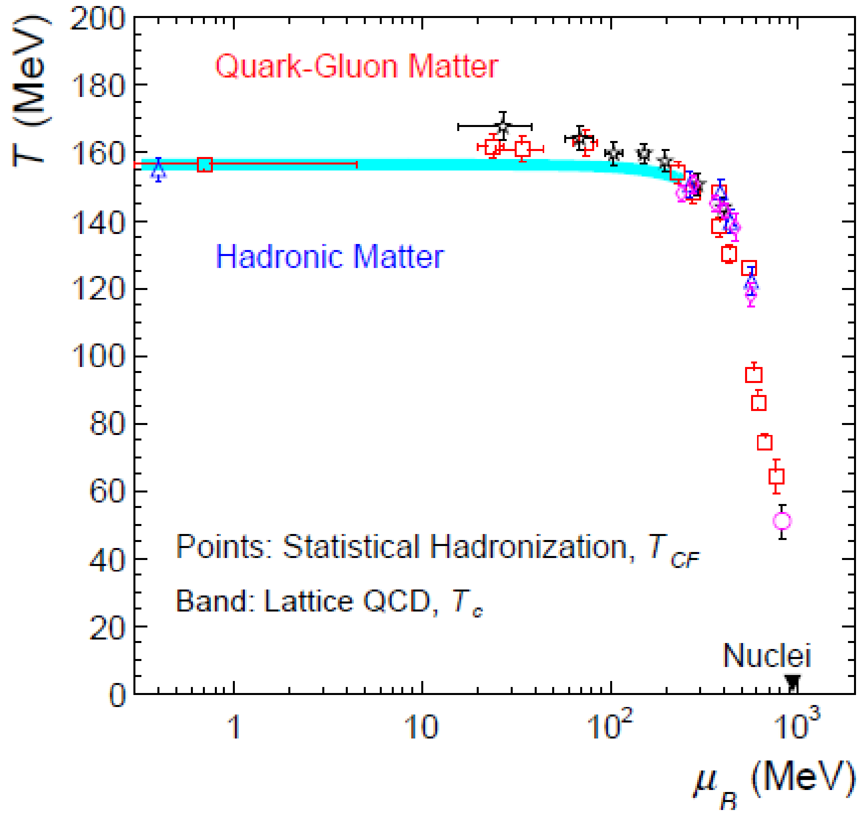
A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, et al., Nucl.Phys.A 837 (2010) 65

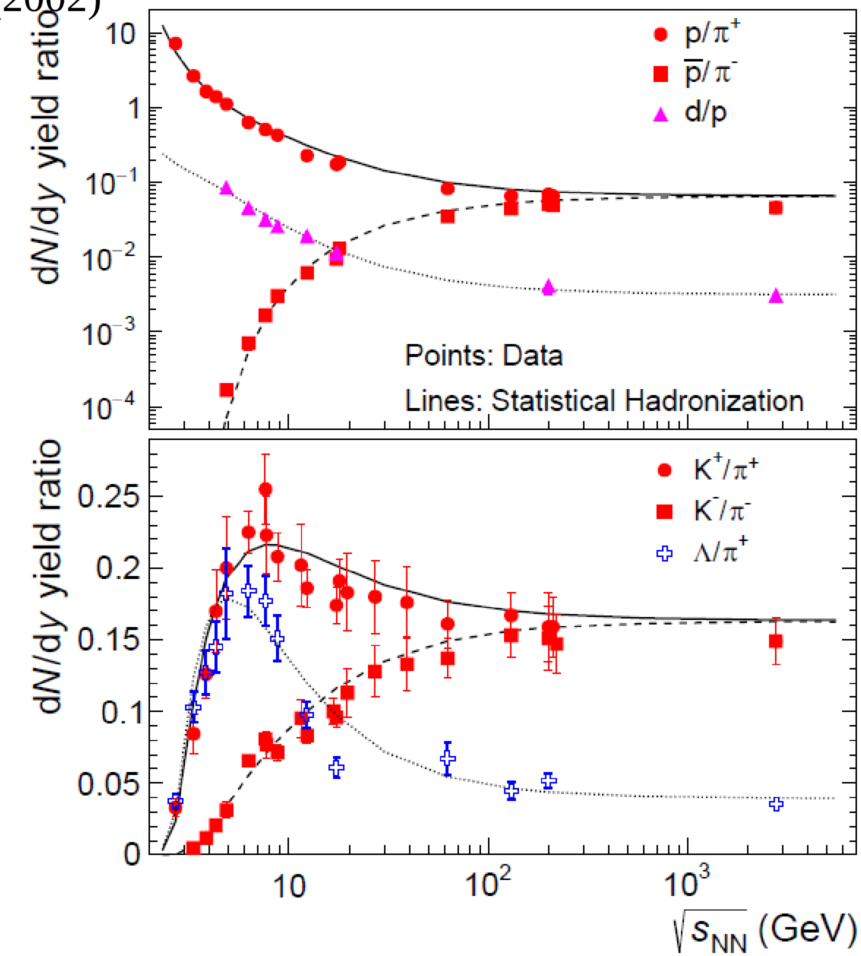
J. Cleymans, H. Oeschler, et al. *Phys.Lett.B* 485 (2000) 27

Thermal origin of light flavors in HIC consistent to predictions of Jean Cleymans et al.

P. Braun-Munzinger, J. Cleymans, et al. Nucl. Phys.A 697 (2002)

A. Andronic, et al, Nature 561 (2018) and references therein





- Hadron yields in heavy-ion collisions are consistent with predictions by the statistical thermal model formulated in the canonical ensemble. This can be also extended to charm production in HIC (see P. Braun-Munzinger and J. Stachel Phys. Lett. B490 (2000), SQM talk: Vytautas Vislavicius)

CONCLUSIONS:

The confirmed success of thermal description of particle production in heavy-ion collisions and their energy and system size dependence, which provide a baseline for a detailed understanding of high-density QCD matter and its phase diagram, can be attributed to a large extent to seminal works of Jean Cleymans