hadronization of the QGP
remarks in memory of Jean Cleymans

- some historical comments: my 1st contact with Jean
- the early years: 1970 – 1990
- the beginning of work on the QCD phase diagram and hadron production 1991 - 1996
- the development of the statistical hadronization model
- transverse momentum distributions and the Tsallis approach
- system size dependence and canonical thermodynamics

pbm

remarks in honor of Jean Cleymans
Kruger 2022 – Discovery Physics at the LHC
Thursday, Dec. 8, 2022

ISOQUANT SFB1225
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
EMMI
GSI

Jean Cleymans
1944 born in Turnhout, Belgium
1970 doctorate in physics Louvain, Belgium
1970 – 1975 fellow positions in Aachen, SLAC, CERN
1975 – 1986 Bielefeld, Extraordinary Professor 1977
1986 - 2021 Cape Town Professor of Theoretical Physics

see also:
Satz, H. The Abundance of the Species Physics 2022, 4, 912–919. https://doi.org/10.3390/physics4030059

hadronization of the QGP
the title of one of Jean Cleymans' transformational papers
Z.Phys.C 58 (1993) 347-356
currently a core physics topic of
the CERN ALICE collaboration

- Jean Cleymans led South African physicists into the ALICE collaboration
- established the UCT-CERN research center
- established the South Africa-CERN program
- successfully supervised 17 PhD candidates
- played an important role in physics collaborations connected to CERN, JINR Dubna, GSI, iThemba LABS and a number of universities

Jean Cleymans
the theorist, the phenomenologist,
the organizer
the inspiring teacher

my first encounter with Jean Cleymans was more than 37 years ago:

an inspiring and influential review paper (more than 400 citations today)

QUARKS AND GLUONS AT HIGH TEMPERATURES AND DENSITIES

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Received May 1985

PHYSICS REPORTS (Review Section of Physics Letters) 130, No. 4 (1986) 217–292. North-Holland, Amsterdam

from 1975 on: focus on statistical QCD

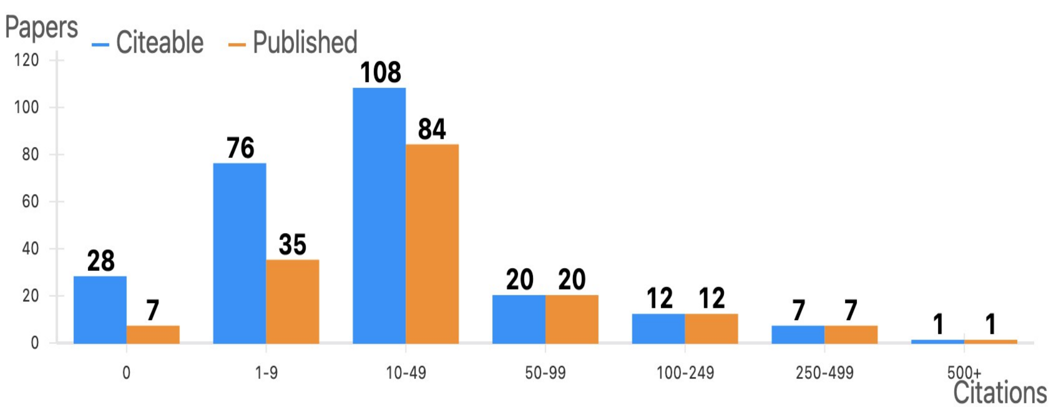
very impressive and unique publication record

without ALICE papers

Citation Summary

Exclude self-citations

	Citeable	Published
Papers	252	166
Citations	9,417	8,866
h-index	45	45
Citations/paper (avg)	37.4	53.4

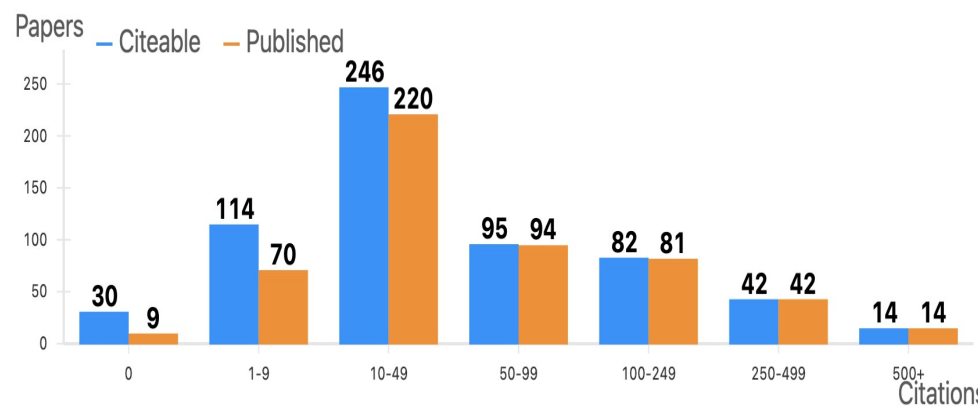


including ALICE papers

Citation Summary

Exclude self-citations

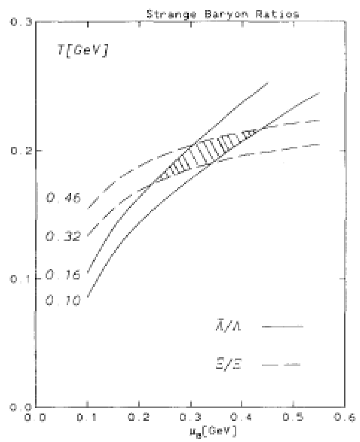
	Citeable	Published
Papers	623	530
Citations	53,230	52,429
h-index	119	119
Citations/paper (avg)	85.4	98.9

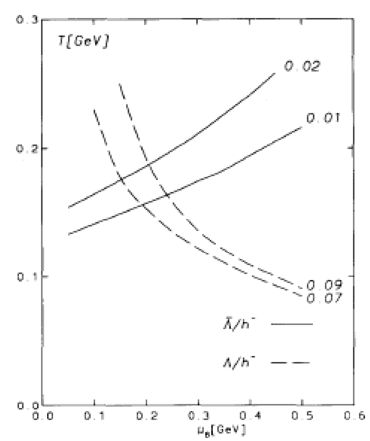


Thermal hadron production in high energy heavy ion collisions

J. Cleymans[1,2] and H. Satz[2,3] Z. Phys. C 57, 135–147 (1993)

the very beginnings; focus on strange particles; no consistent analysis possible because of data situation, experimental acceptances, and many difficulties with weak decays, protons left out,





data from WA85 collaboration
strange baryon ratios

data from NA35 collaboration
Λ/h- ratios

inconclusive results

next steps: analysis of all hadrons including protons and pions from AGS and SPS experiments

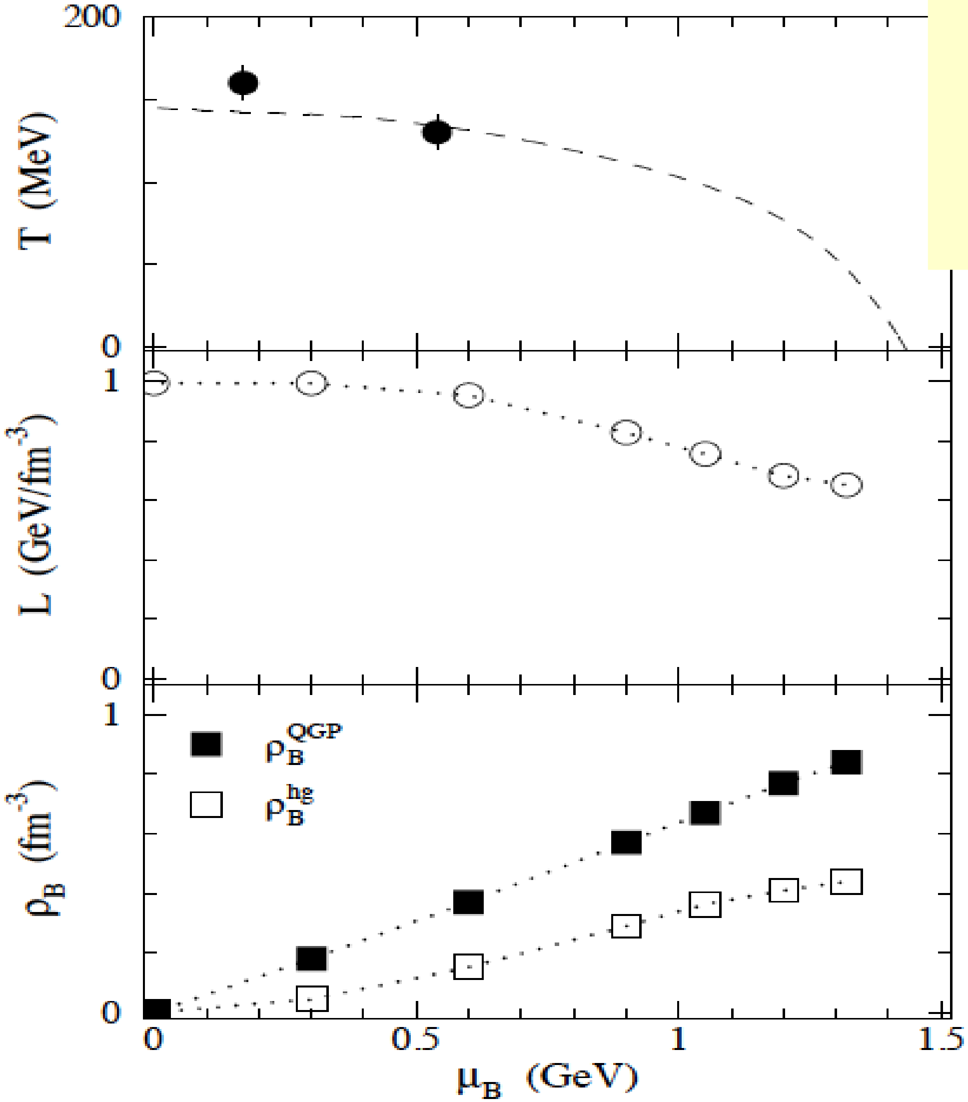
P. Braun-Munzinger, J. Stachel, J.P. Wessels, and N. Xu
Phys. Lett. B344 (1995) 43, B365 (1996) 1
first consistent results for T and μ_b = 540 MeV

for central collisions of 14.6 A GeV/c Si + Au(Pb).

Particles	Thermal Model		Data		
	T=.120 GeV	T=.140 GeV	exp. ratio	rapidity	ref.
$\pi/(p+n)$	1.29	1.34	1.05(5)	0.6 - 2.8	[4,3]
$d/(p+n)$	$4.3 \cdot 10^{-2}$	$5.8 \cdot 10^{-2}$	$3.0(3) \cdot 10^{-2}$	0.4 - 1.6	[4]
$\bar{p}/p$	$1.47 \cdot 10^{-4}$	$5.8 \cdot 10^{-4}$	$4.5(5) \cdot 10^{-4}$	0.8 - 2.2	[15]
K^+/π^+	0.23	0.27	0.19(2)	0.6 - 2.2	[4]
K^-/π^-	$5.0 \cdot 10^{-2}$	$6.2 \cdot 10^{-2}$	$3.5(5) \cdot 10^{-2}$	0.6 - 2.3	[4]
K^0_s/π^+	0.14	0.16	$9.7(15) \cdot 10^{-2}$	2.0 - 3.5	[16,4,21]
K^+/K^-	4.6	4.3	4.4(4)	0.7 - 2.3	[4]
$\Lambda/(p+n)$	$9.5 \cdot 10^{-2}$	0.11	$8.0(16) \cdot 10^{-2}$	1.4 - 2.9	[16,4,3]
$\bar{\Lambda}/\Lambda$	$8.8 \cdot 10^{-4}$	$3.7 \cdot 10^{-3}$	$2.0(8) \cdot 10^{-3}$	1.2 - 1.7	[15]
$\phi/(K^+ + K^-)$	$2.4 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$	$1.34(36) \cdot 10^{-2}$	1.2 - 2.0	[15]
Ξ^-/Λ	$6.4 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$	0.12(2)	1.4 - 2.9	[17]
$\bar{d}/\bar{p}$	$1.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$	$1.0(5) \cdot 10^{-5}$	2.0	[18]

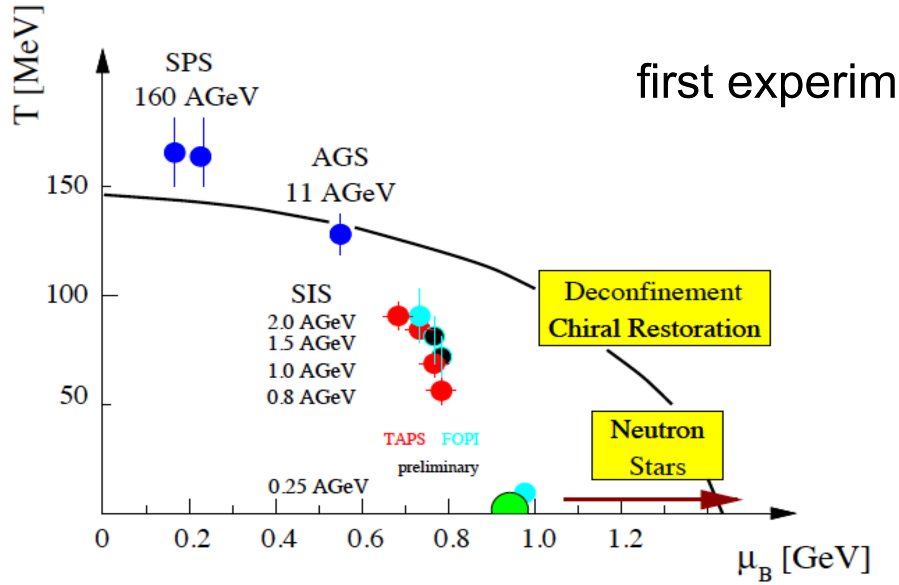
P. Braun-Munzinger, J. Stachel, J.P. Wessels, and N. Xu

Phys. Lett. B344 (1995) 43, B365 (1996) 1



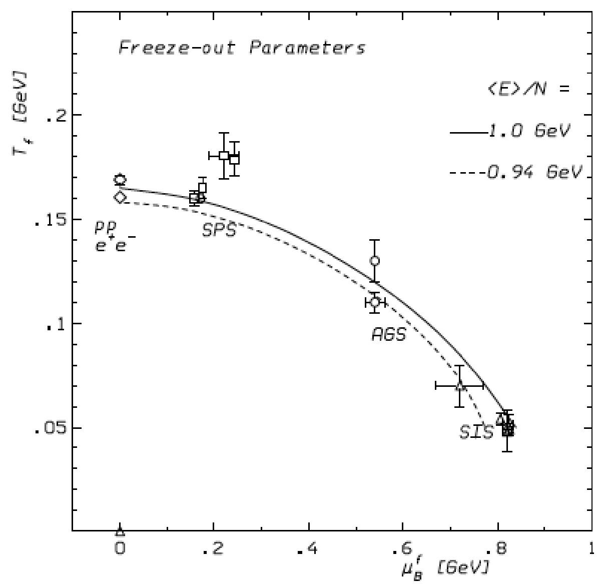
first connection between experimental data and QCD phase diagram

next steps:
P.Braun-Munzinger and J. Stachel, Nucl.Phys. A 638 (1998) 3-18, nucl-ex/9803015



first experimental 'freeze-out' curve

J. Cleymans and K. Redlich, Phys.Rev.Lett. 81 (1998) 5284-5286, nucl-th/9808030



first interpretation of freeze-out curve

peak structure in the energy dependence of particle ratios

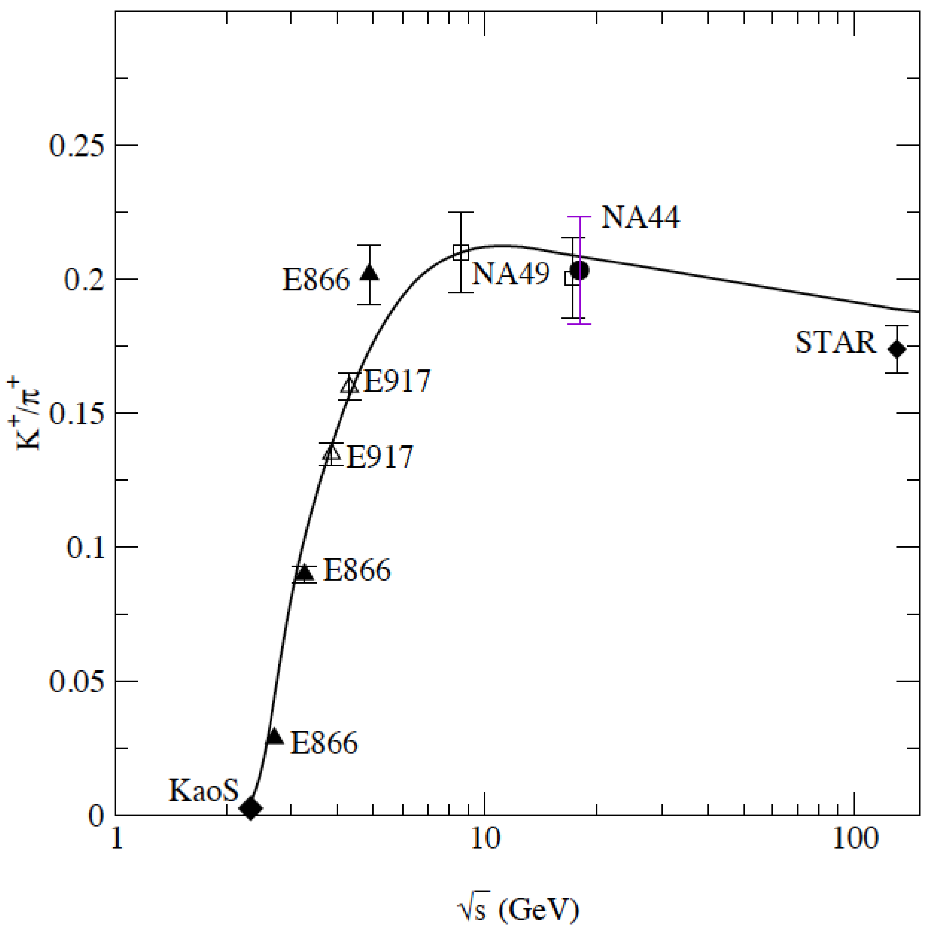
the 'NA49 horn' is a natural consequence of the transition from baryon dominated to meson dominated matter

see below

pbm, Cleymans, Oeschler, Redlich

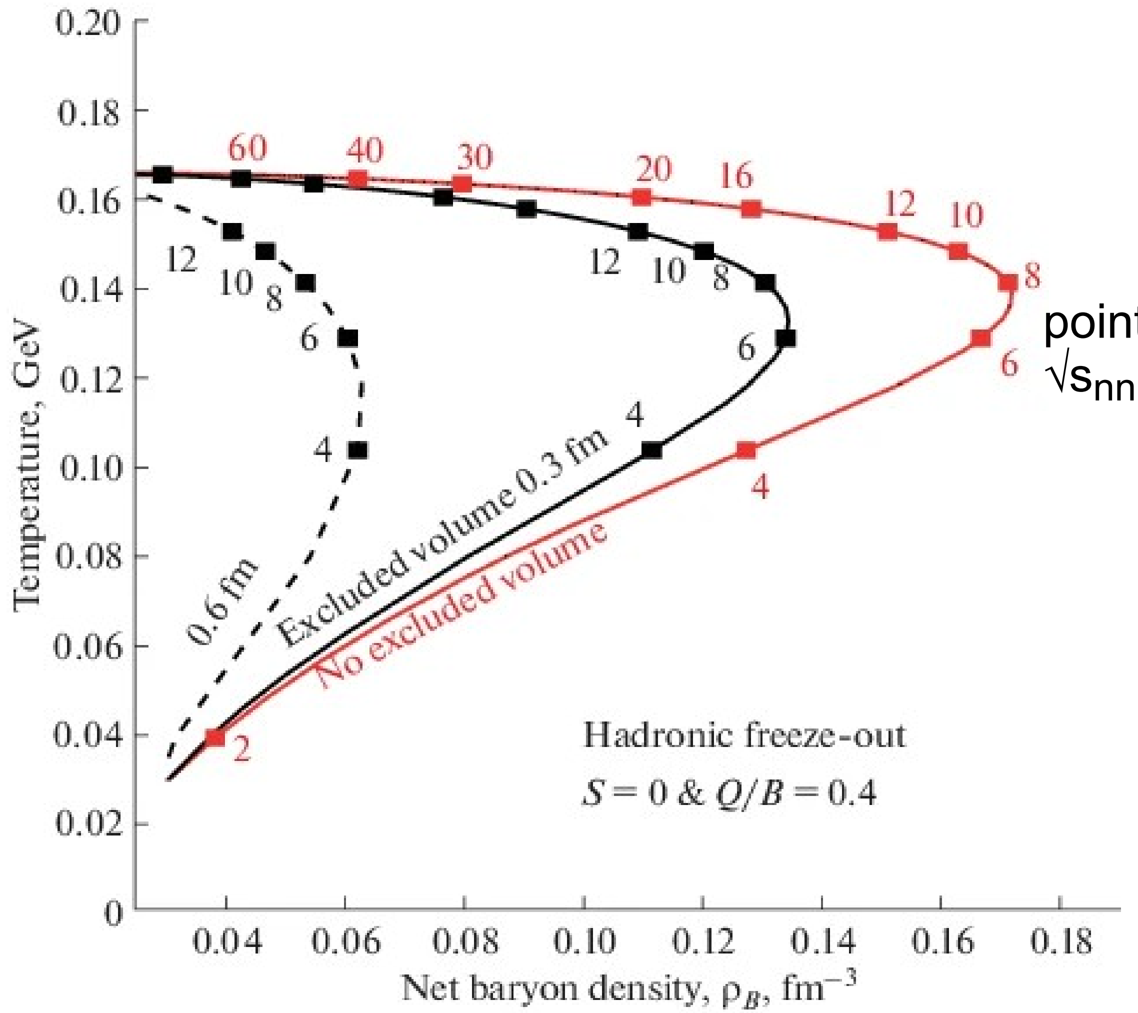
Nucl.Phys.A 697 (2002) 902-912
hep-ph/0106066 [hep-ph]

my first paper with Jean



net baryon densities along the chemical freeze-out curve in relativistic nuclear collisions

J. Randrup and J. Cleymans,
``Maximum freeze-out baryon density in nuclear collisions,''
Phys. Rev. C 74 (2006) 047901

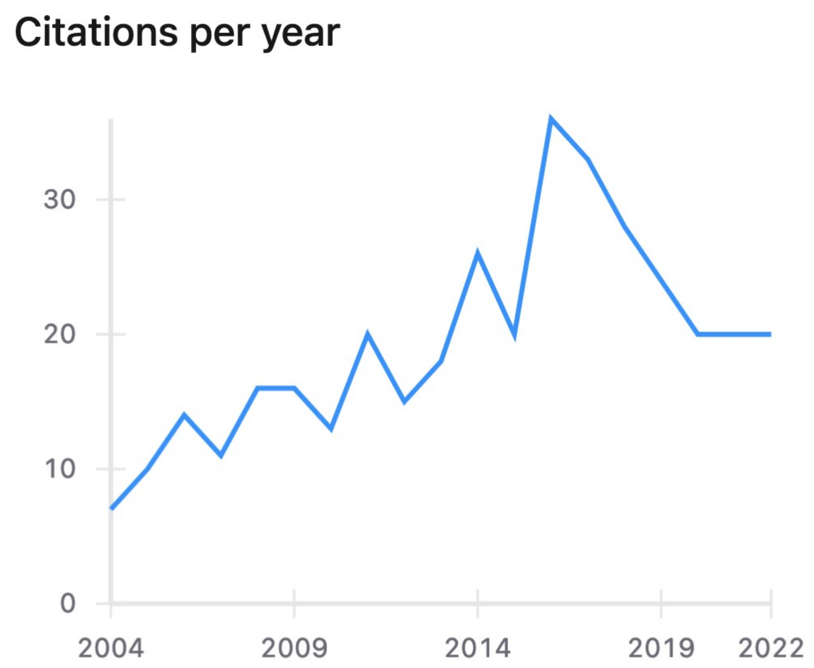


points indicate cm energies $\sqrt{s_{nn}}$ (GeV)

...and Jean developed a thermal model code

S. Wheaton and J. Cleymans,
``THERMUS: A Thermal model package for ROOT,''
Comput. Phys. Commun. 180 (2009), 84-106

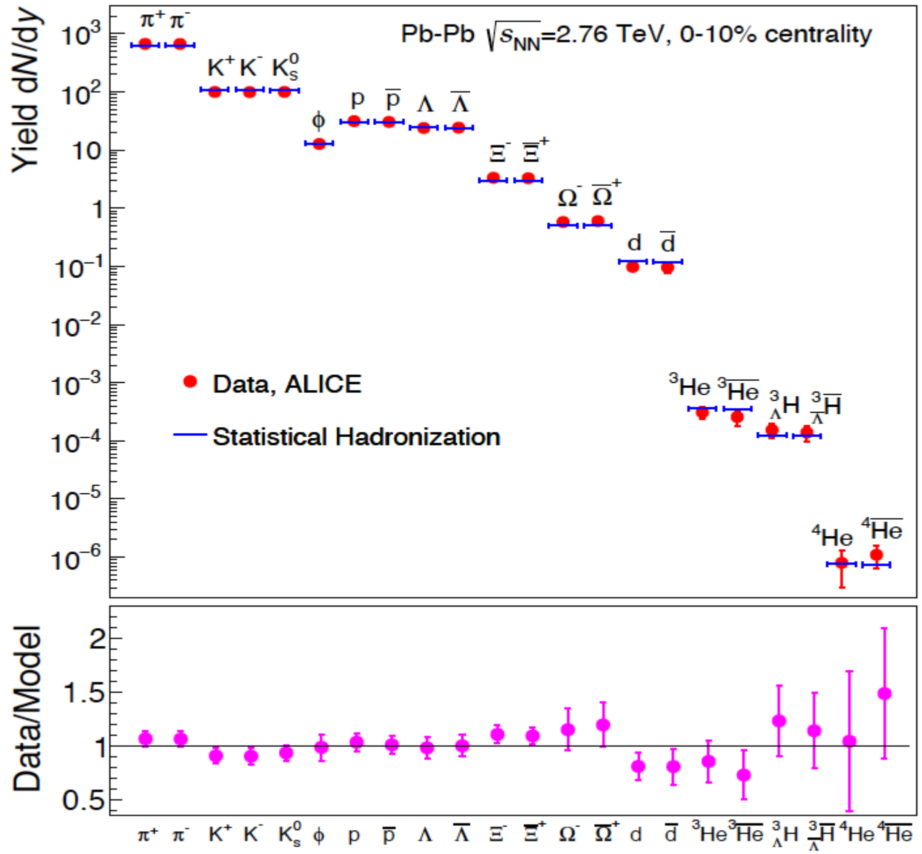
this code is in use throughout the community



(u,d,s) hadrons and the QGP phase boundary

statistical hadronization of (u,d,s) hadrons

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



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

Best fit:

$T_{CF} = 156.6 \pm 1.7$ MeV

$\mu_B = 0.7 \pm 3.8$ MeV

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

$\chi^2/N_{df} = 16.7/19$

S-matrix treatment of interactions (non-strange sect.)

"proton puzzle" solved

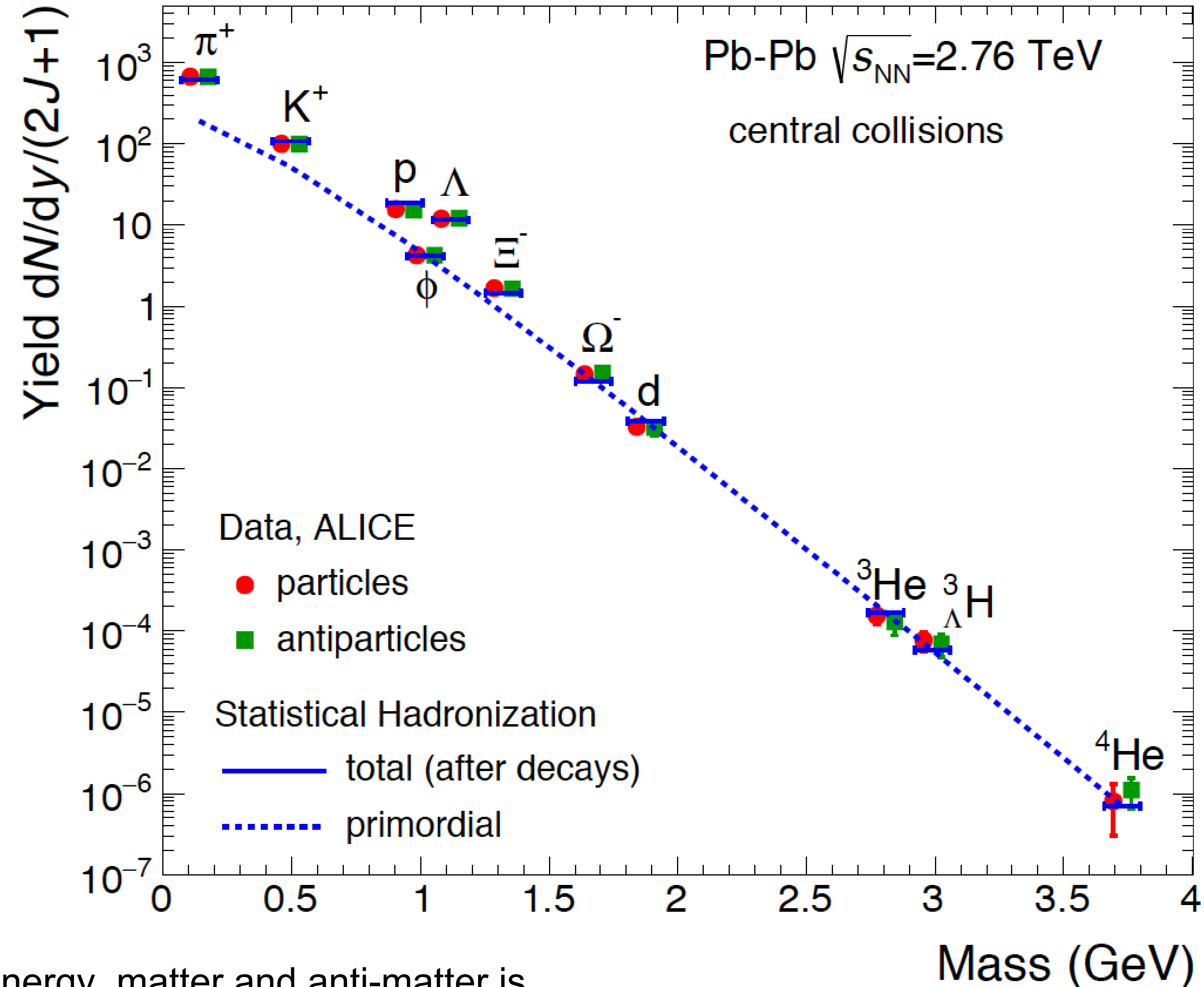
PLB 792 (2019) 304

data: ALICE coll.,
Nucl. Phys. A971 (2018) 1

similar results at lower energy, each new energy yields a pair of (T, μ_B) values

connection to QCD (QGP) phase diagram?

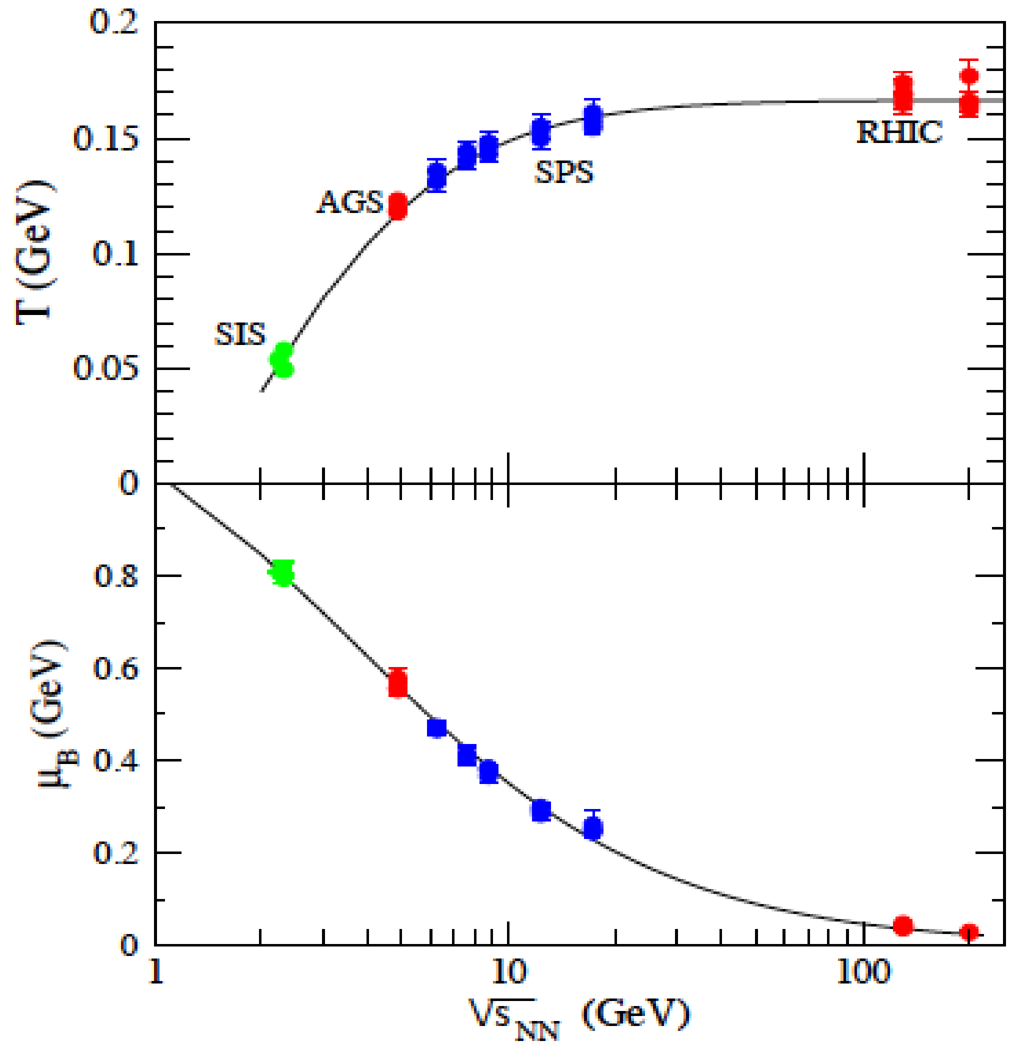
at LHC energy, production of (u,d,s) hadrons is governed
by mass and quantum numbers only
quark content does not matter



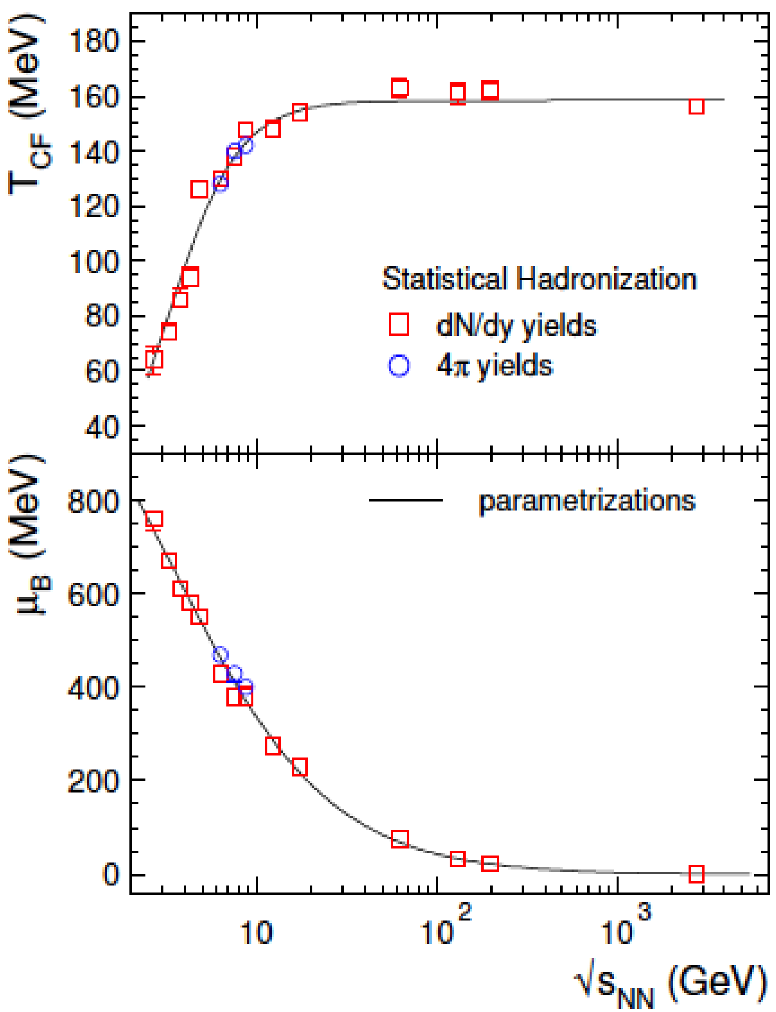
at LHC energy, matter and anti-matter is
produced with equal yields

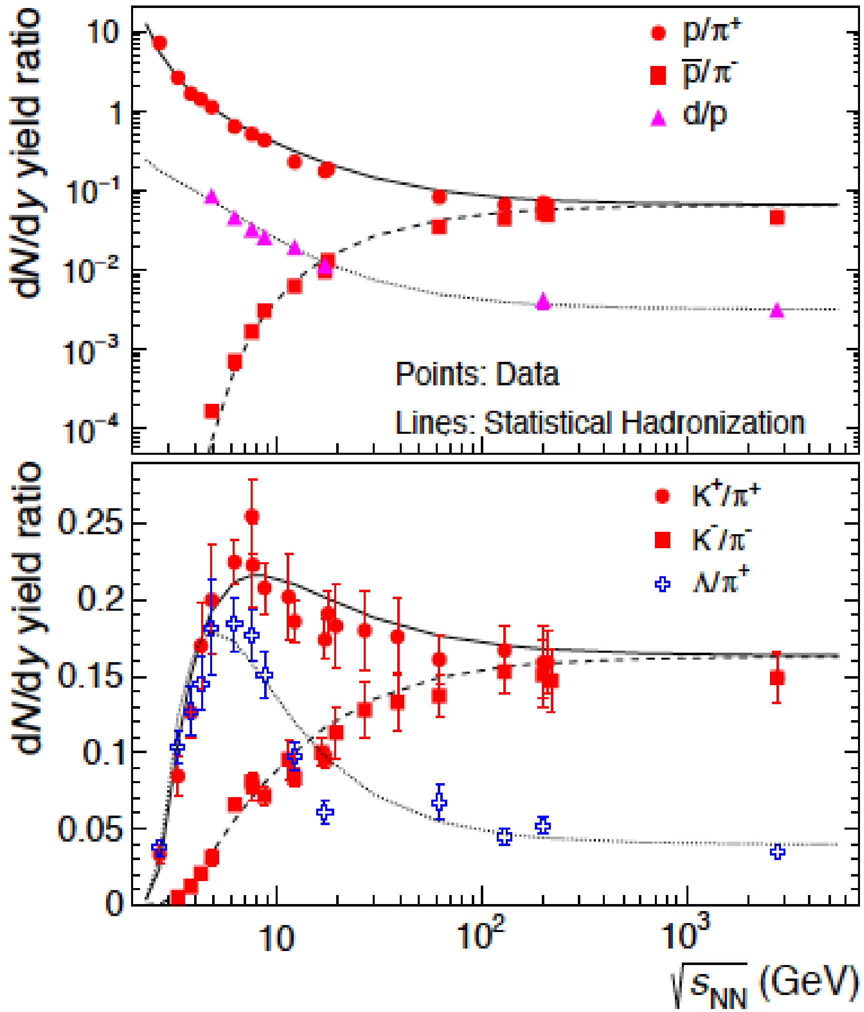
J. Cleymans, H. Oeschler, K. Redlich and S. Wheaton, ``Comparison of chemical freeze-out criteria in heavy-ion collisions,'' Phys. Rev. C{73}(2006),034905

energy dependence of T and μ_b



energy dependence of hadron production described quantitatively

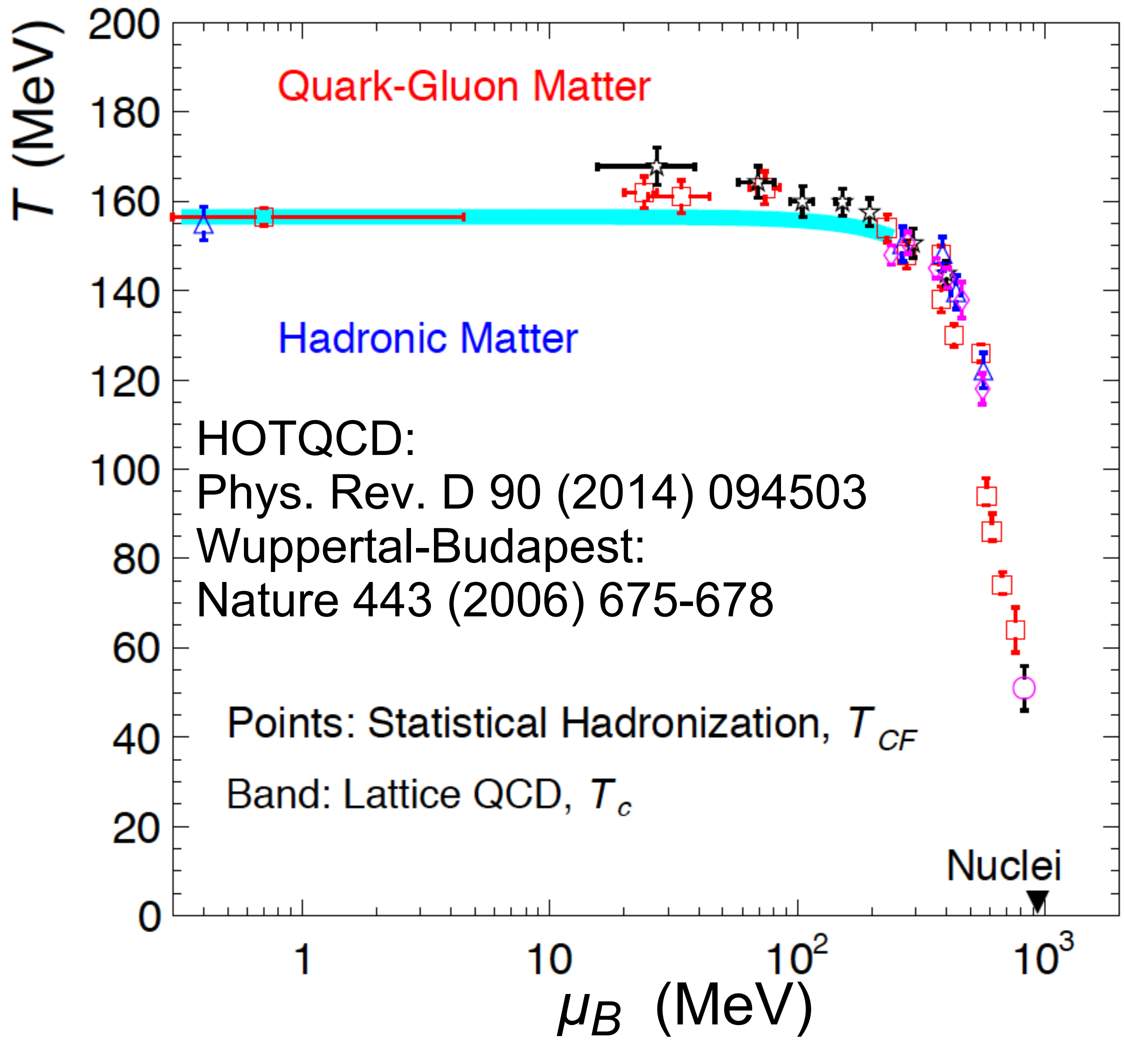




together with known energy dependence of
charged hadron production in Pb-Pb collisions we can predict
yield of all hadrons at all energies with < 10% accuracy

the QGP phase diagram, LatticeQCD, and hadron production data

note: all coll. at SIS, AGS, SPS, RHIC and LHC involved in data taking
each entry is result of several years of experiments, variation of μ_B via variation of cm energy



experimental determination of phase boundary at
T_C = 156.6 ± 1.7 (stat.) ± 3 (syst.) MeV and μ_B = 0 MeV
Nature 561 (2018) 321

quantitative agreement of chemical freeze-out parameters with most recent LQCD predictions for baryo-chemical potential < 300 MeV

cross over transition at μ_B = 0 MeV, no experimental confirmation

should the transition be 1st order for large μ_B (large net baryon density)?

then there must be a critical endpoint in the phase diagram

exploration of 'Tsallis' entropy formulation for particle production at the LHC

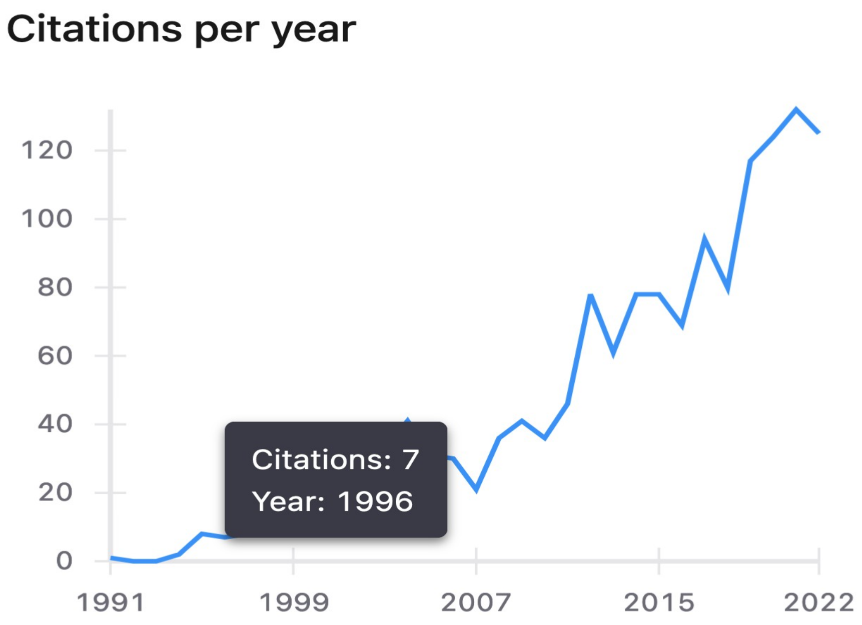
background: in 1988, Constantino Tsallis,Greek-born Brazilian physicist, published a seminal paper::

C. Tsallis,
``Possible Generalization of Boltzmann-Gibbs Statistics,''
J. Statist. Phys. {52} (1988), 479-487

this new concept was introduced by Tsallis to generalize the entropy concept in standard statistical mechanics by allowing entropy to be non-additive.

Tsallis statistics and entropy are applied to describe:

- cold atoms in optical traps
- velocity distributions in a dusty plasma
- spin glasses
- hadron transverse momentum distributions
- ...



Jean Cleymans developed and applied this concept successfully to describe LHC data

J. Cleymans, G. Lykasov, A. S. Parvan, A. S. Sorin, O. V. Teryaev and D. Worku,

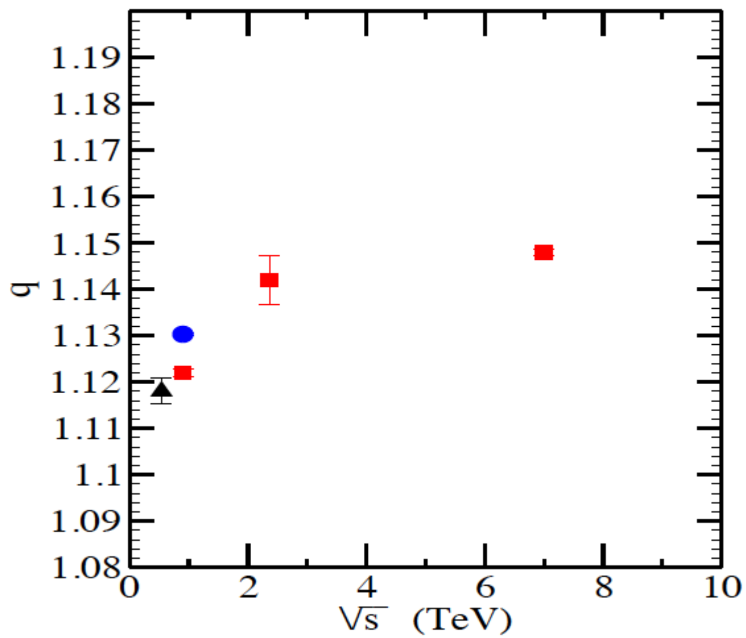
``Systematic properties of the Tsallis Distribution: Energy Dependence of Parameters in High-Energy p-p Collisions,''
Phys. Lett. B {723} (2013), 351-354

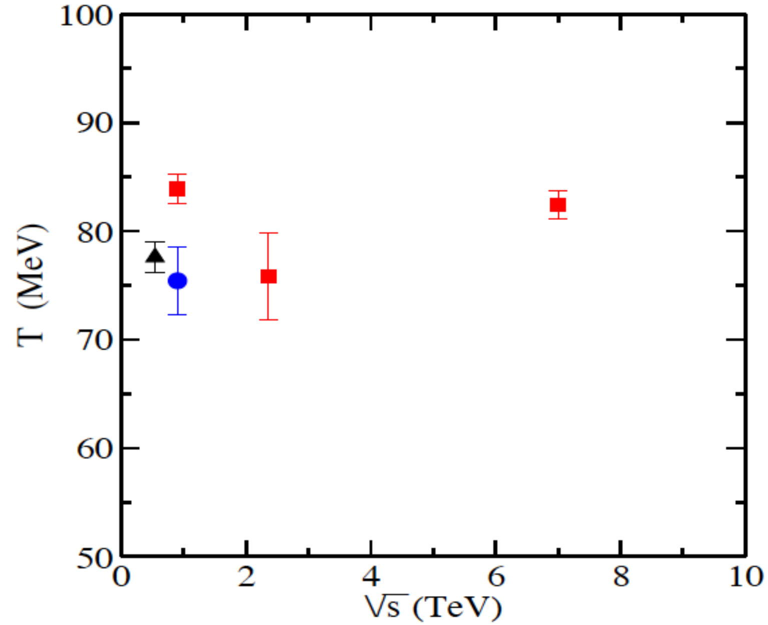
thermodynamics in the Tsallis approach with new parameter *q*

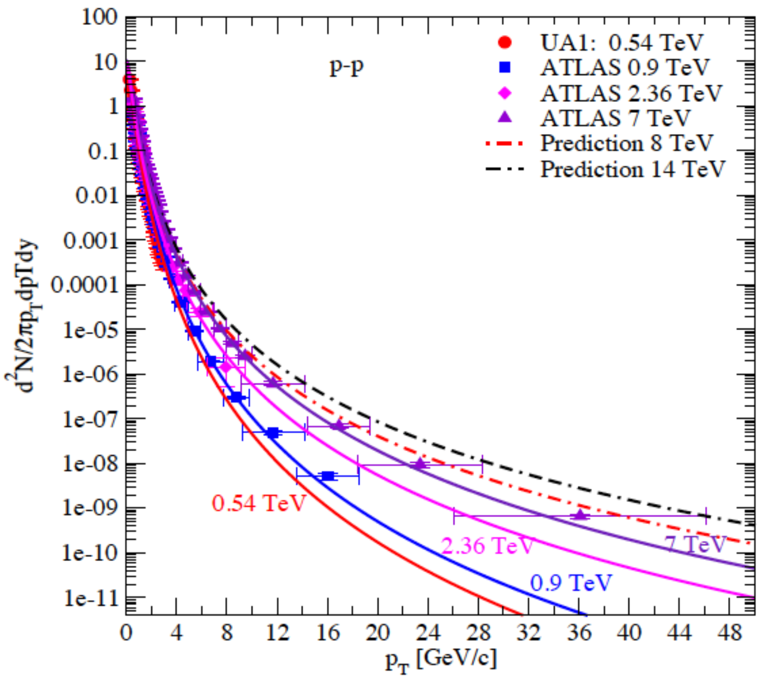
for *q* = 1 all distributions converge to Boltzmann-Gibbs thermodynamics

$$
\begin{aligned}
N &= gV \int \frac{d^3p}{(2\pi)^3} \left[1 + (q-1)\frac{E-\mu}{T}\right]^{-\frac{q}{q-1}}, \\
\epsilon &= g \int \frac{d^3p}{(2\pi)^3} E \left[1 + (q-1)\frac{E-\mu}{T}\right]^{-\frac{q}{q-1}}, \\
P &= g \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{3E} \left[1 + (q-1)\frac{E-\mu}{T}\right]^{-\frac{q}{q-1}} \\
\epsilon + P &= Ts + \mu n.
\end{aligned}
$$

Tsallis fits for charged hadron data from UA1, ALICE, ATLAS







description works for p_T up to 50 GeV, with q clearly exceeding 1 and slowly rising with energy

interpretation, in Jean's words:

The extremely large range of p_T described by Tsallis distribution makes it applicable in the region usually considered to be the domain of QCD hard scattering. This may be interpreted as a manifestation of the "duality" between the statistical and dynamical description of strong interactions In this sense Tsallis statistics may be considered as an effective theory allowing for an extension of the region of applicability of perturbative QCD from large to low p_T. It is not unnatural, as approximate scale invariance manifested in QCD both at large and small momentum scales is qualitatively similar to power law statistics. It remains to be understood whether anv further relations can be found, like the dynamical origins of thermal spectra

J. Cleymans, G.I. Lykasov, A.N. Sissakian, A.S. Sorin and O.V. Teryaev, arXiv:1004.2770[hep-ph].

J. Cleymans, G.I. Lykasov, A.S. Sorin and O.V. Teryaev, Phys. Atom. Nucl. **75**, 725 (2012) [arXiv:1104.0620 [hep-ph]].

statistical hadronization for small systems

ALICE data: J.~Adam et al. [ALICE],
``Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions,''
Nature Phys. {13} (2017), 535-539

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

arXiv:2009.04484, Phys.Rev.C 103 (2021) 1, 01490
arXiv:2010.02714, CPOD

It is shown that the number of charged hadrons is linearly proportional to the volume of the system. For small multiplicities the canonical ensemble with local strangeness conservation restricted to mid-rapidity leads to a stronger suppression of (multi-)strange baryons than seen in the data. This is compensated by introducing a global conservation of strangeness in the whole phase-space which is parameterized by the canonical correlation volume larger than the fireball volume at the mid-rapidity. The results on comparing the hadron resonance gas model with and without S-matrix corrections, are presented in detail. It is shown that the interactions introduced by the phase shift analysis via the S-matrix formalism are essential for a better description of the yields data.

very good agreement from pp to pPb to central Pb-Pb

arXiv:2009.04484

key new ingredient: strangeness conservation over the volume of the whole fireball, not in the slice at mid-rapidity
this is same as for baryons, see
pbm, Rustamov, Stachel, arXiv:1907.03032
ALICE coll., Phys.Lett.B 807 (2020) 135564

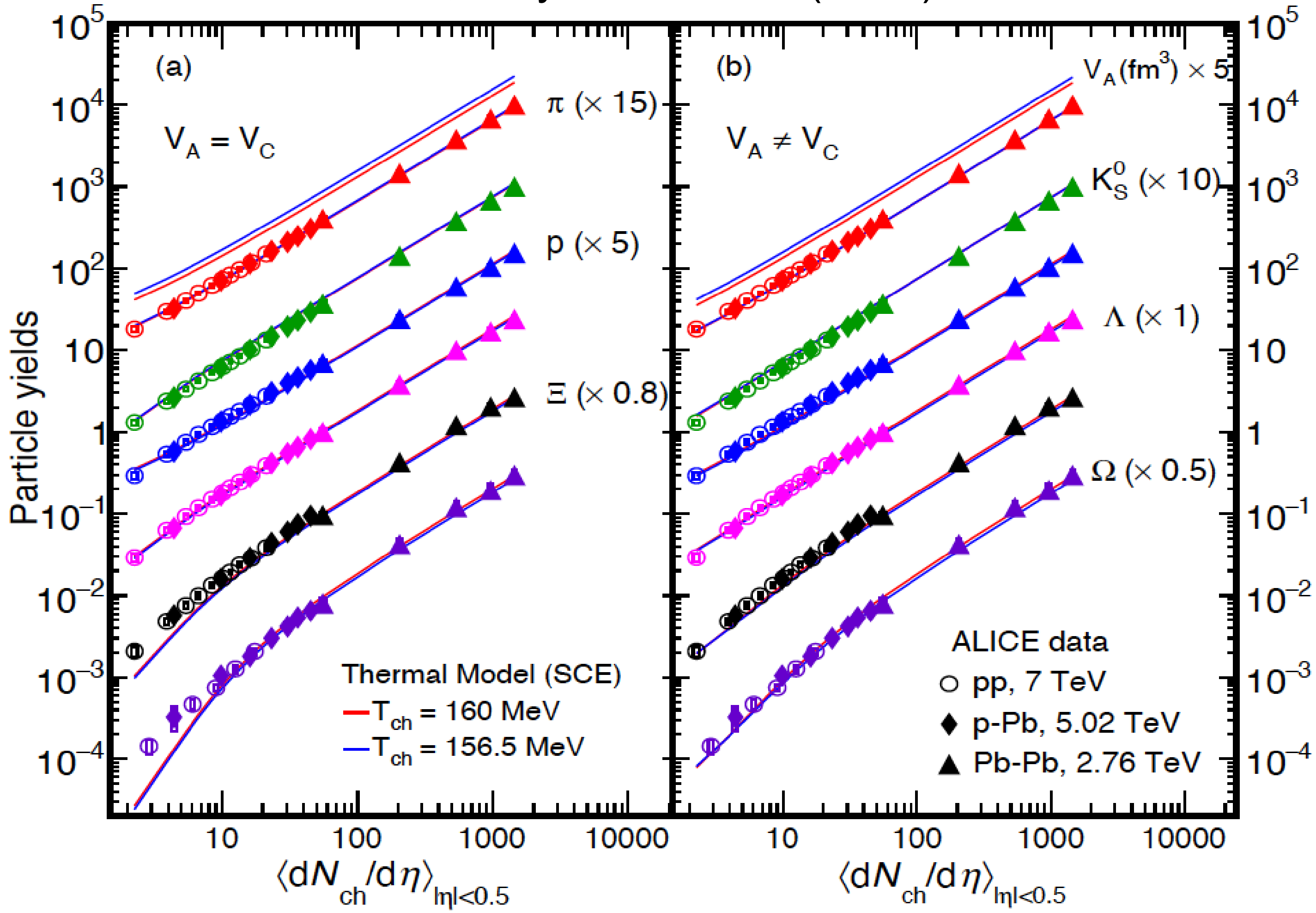


FIG. 5. Left-hand figure: Yields for $V_A = V_C$. Right-hand figure: Yields for $V_A \neq V_C$, Top line is the volume (x5) in fm^3. The particle yields are indicated in the right panel together with the multiplicative factor used to separate the yields. The solid blue lines have been calculated for $T = 156.5$ MeV while the solid red lines have been calculated for $T = 160$ MeV.

Jean Cleymans was a world-wide respected and influential scientist who steered South-African Nuclear and Particle Physics for more than two decades into the 'International Scientific Champions League'

It was a great joy and priviledge to work with him as friend and colleague. He is missed but remembered fondly.