four decades of experiments with relativistic heavy ions
past, present, and future

- the very beginnings – Bear Mountain 1974
- the long way toward SPS heavy ions
- the AGS ion program
- towards RHIC and LHC
- selected highlights of the program up to now
- looking into the crystal ball – future opportunities

pbm

ICPPA 2020 conference

Zoom presentation

Wed. Oct. 7, 2020

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

EMMI

GSI

HUAZHONG UNIVERSITY

BNL 50445
(Physics, Nuclear – TID-4500)

Report of the Workshop on BEV/NUCLEON COLLISIONS OF HEAVY IONS – HOW AND WHY

November 29–December 1, 1974

Bear Mountain, New York

Supported by
NATIONAL SCIENCE FOUNDATION
and
NEVIS LABORATORIES, COLUMBIA UNIVERSITY

Organizing Committee
A. KERMAN, L. LEDERMAN, T.D. LEE, M. RUDERMAN, J. WENESER

Scientific Reporters
LAWRENCE E. PRICE, JAMES P. VARY

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Workshop on BeV Collisions of Heavy Ions: How and Why

Nov 29 - Dec 1 1974

Bear Mountain New York

Introduction and Summary:

The history of physics teaches us that profound revolutions arise from a gradual perception that certain observations can be accommodated only by radical departures from current thinking. The workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable.

Leon Lederman and Joseph Weneser

It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.

T. D. Lee

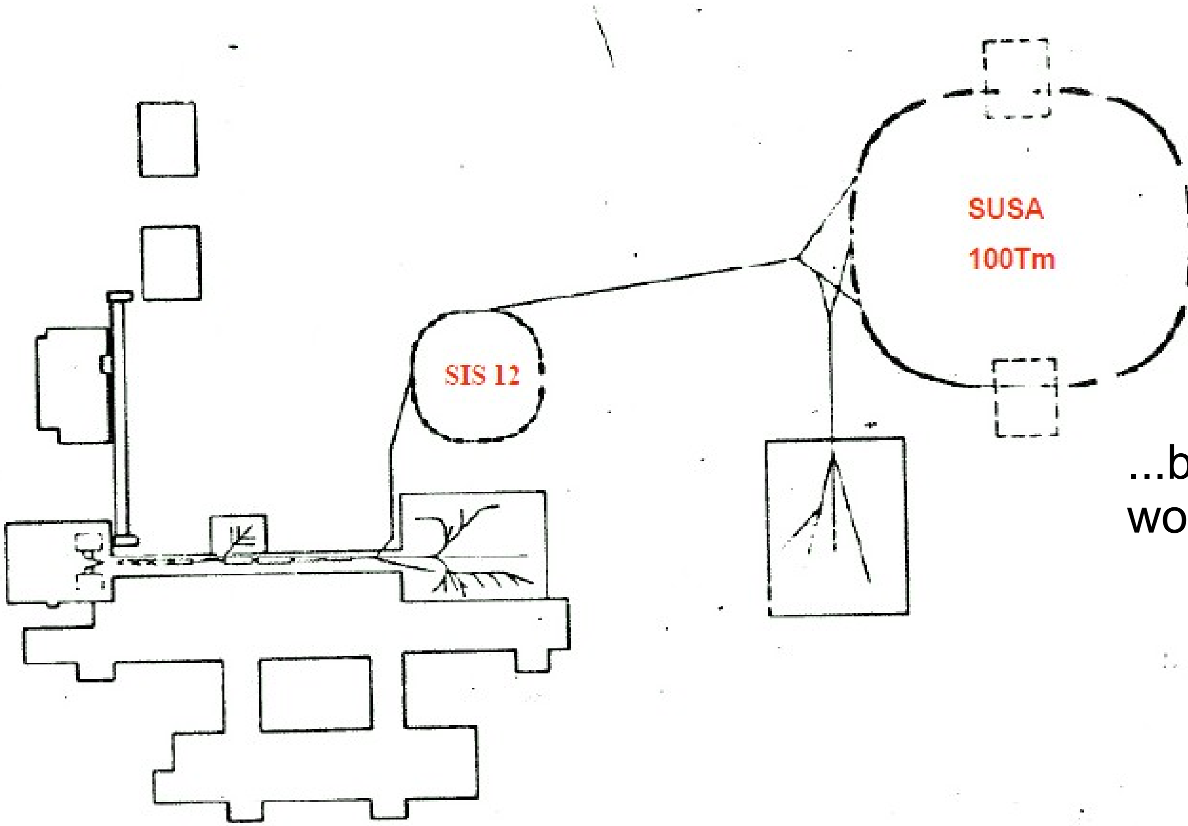
GSI-P-2-77
JANUAR 1977

shortly thereafter, in 1977, big accelerator plans were contemplated at GSI

ÜBERLEGUNGEN
ZUR PHYSIK DER KERNMATERIE
UNTER EXTREMEN BEDINGUNGEN
UND
ZU EINEM BESCHLEUNIGER
FÜR RELATIVISTISCHE SCHWERE IONEN

GSI - BERICHT P-2-77
GESELLSCHAFT FÜR SCHWERIONENFORSCHUNG MBH, DARMSTADT

An dieser Studie wirkten mit:
K. Blasche, R. Bock, B. Franzke, W. Greiner,
H.H. Gutbrod, B. Povh, Ch. Schmelzer und R. Stock



...but a 100 Tm ring is now the work horse for FAIR at GSI

16.10.1978
SIS 12 plus Superconducting Storage Ring (SUSA) with possibility for a collider mode

RHIC at GSI in the 1980ties? This was too big a step for the German and European communities and 'only' SIS18 was realized in the 1990ties, also ISR at CERN had started in 1971, with α-α collisions at $\sqrt{s}$ = up to 64 GeV/nucleon pair running in the 80ties Many interesting but no spectacular results came out as 'new physics' was expected at large rapidities, not near y = 0...

the origin of the Quark Matter conferences

First workshop on ultra-relativistic nuclear collisions,
Berkeley, May 1979 (w. GSI) (L. Schroeder) = QM 0

High-energy nuclear interactions and the properties of dense nuclear matter,
Hakone, Japan, July 1980, K. Nakai & A. Goldhaber

Workshop on 'Statistical mechanics of quarks and hadrons',
Bielefeld, Aug. 1980, H. Satz, QM 1A, focussed on theory

Workshop on 'Future relativistic heavy ion experiments'
GSI, Oct. 1980, R. Bock, R. Stock, QM 1B, focussed on experiments

Quark matter formation and heavy ion collisions
Bielefeld, May 1982, M. Jacob, H.Satz, QM 2

Quark Matter 1983
Brookhaven National Laboratory, Sep. 1983, T. Ludlam and H. Wegner, QM 3

a defining moment for me,
I joined the field

the origin of the Quark Matter conferences continued

Quark Matter 1984
June 1984, Helsinki, K. Kajantie, QM 4

Quark Matter 1986
April 1986, Pacific Grove (Ca), L.S. Schroeder, M. Gyulassy, QM5

Quark Matter 1987
Aug. 1987, Nordkirchen (Germany), H. Satz, H. Specht, R. Stock, QM 6

a defining moment for me, Johanna and I joined the field

Quark Matter 1988
Sep. 1988, Lenox (MA), G. Baym, P. Braun-Munzinger, S. Nagamiya, QM7

the Kandinsky for the poster was spotted in the Guggenheim museum (NYC) by Johanna and myself

… the rest you find on the web, Quark Matter 2021 will be in Oct. 2021 in Krakow, as QM 29

A. B. Migdal　G. Baym　T. D. Lee　Mayor of Bielefeld　H. Satz

International Symposium

Statistical Mechanics of Quarks and Hadrons

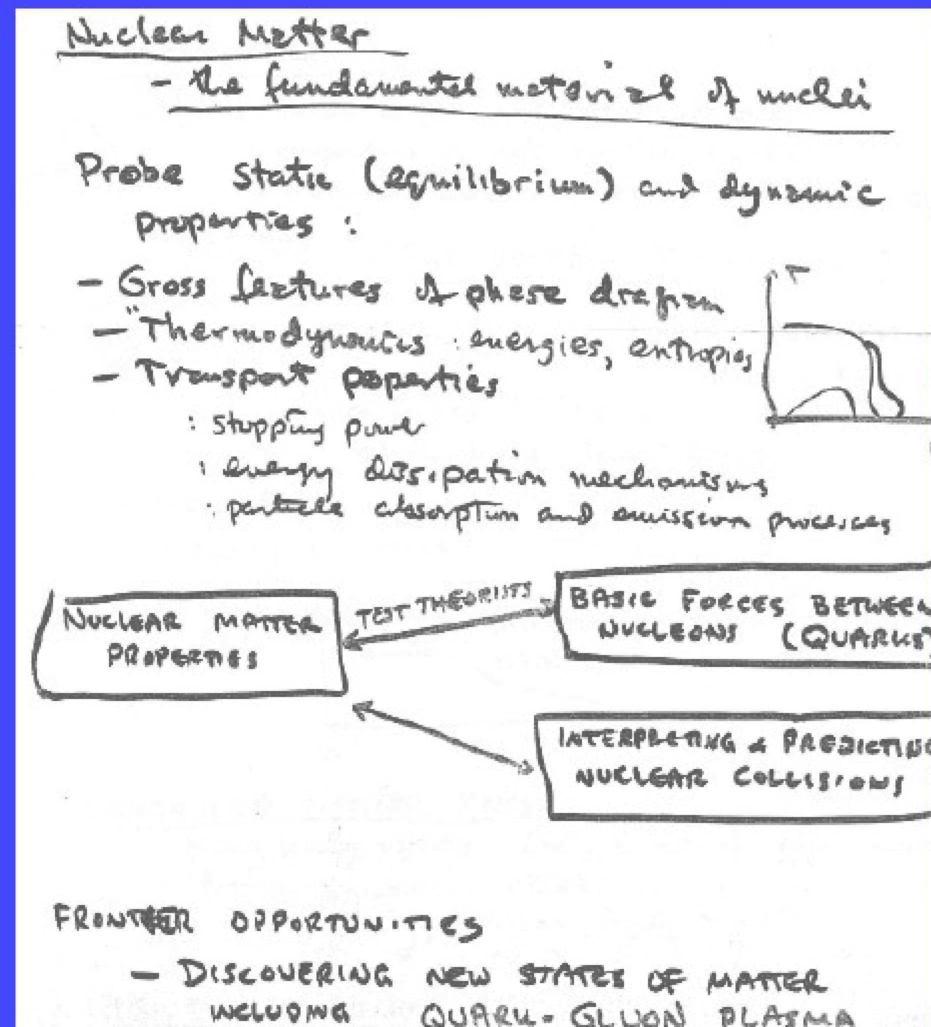
Bielefeld, August 24-31, 1980

enjoying a moment during a QM 1 reception

just before QM 3 an important US Nuclear Science Advisory Committee meeting (NSAC) took place, slide courtesy Gordon Baym

NSAC Meeting at Wells College, Aurora, N.Y. July 11-15, 1983

Subgroup on nuclear matter under extreme conditions: *Arthur Kerman, Arthur Schwarzschild, & GB (chair) (NSAC); Miklos Gyulassy, Tom Ludlam, Larry McLerran, Lee Schroeder, Steve Vigdor, & Steve Koonin*



Nuclear Matter
- the fundamental material of nuclei

Probe static (equilibrium) and dynamic properties:
- Gross features of phase diagram
- "Thermodynamics: energies, entropies
- Transport properties
  : stopping power
  : energy dissipation mechanisms
  : particle absorption and emission processes

NUCLEAR MATTER PROPERTIES

TEST THEORISTS

BASIC FORCES BETWEEN NUCLEONS (QUARKS)

INTERPRETING & PREDICTING NUCLEAR COLLISIONS

FRONTIER OPPORTUNITIES
- DISCOVERING NEW STATES OF MATTER INCLUDING QUARK-GLUON PLASMA

a consequence of QM 3: 1983 International RHIC task force

B. Baym, J. Bjorken, C.K. Gelbke, H.H. Gutbrod, A. Kerman, C. Leeman, L. Madansky, A. Mueller, I. Otterlund, A. Ruggiero, L. Schroeder, G. Young, W.I. Willis

Report of Task Force for relativistic heavy ion physics, Nucl. Phys. **A418** (1984) 657c. As the plans for RHIC came more into focus, the Task Force was succeeded by an *ad hoc* panel which met in December 1983, the RHIC Technical Committee, chaired by Bill Willis, which met in April 1984, the RHIC Review Board, chaired by Allan Bromley, which met in May 1984, and eventually by the RHIC Policy Committee, chaired by Herman Feshbach, which met regularly from 1991 through 1995.

in 1995, timeline for completion of RHIC shifted to1999
first RHIC run in 2000

RHIC Advisory Committee

1991 RHIC Policy Committee. Front row: J Ball, J Sandweiss, T D Lee, J Symons, E Henley, S Hayakawa, W Willis, H Feshbach; back row: S Ozaki, R Bock, N P Samios, J Schiffer, G Baym, P Darriulat, M Schwartz, A Kerman.

...and during QM 3, the ideas for a fixed target program at the BNL AGS and at the CERN SPS were planted and bore fruit very quickly

first Si beams at BNL in 1986 at 14.5 GeV/nucleon, first O and S beams at CERN in 1986 200 GeV/nucleon

… and the more ambitious collider plans for RHIC took shape

for a detailed account of the history of the RHIC facility,
see G. Baym, talk at QM2015 and Nucl.Phys.A 956 (2016) 1-10, arXiv:1701.03972

Panel discussion at Quark Matter 1983

The Panel: From left to right, J. D. Bjorken, M. Gyulassy, D. A. Bromley (Chairman), R. Stock, A. Schwarzschild and K. Nakai

ideas about BNL fixed target and collider program

Arthur Schwarzschild, then chair of BNL physics

Arthur Schwarzschild described an intermedite program for heavy ion physics at Brookhaven; nuclear beam accelerated to 15 GeV/nucleon in the AGS for fixed target experiments. An early program, possible within two years, would have beams of ^{32}S injected directly from the Tandem Van de Graaff accelerator. The later addition of a cyclotron or small synchrotron booster would extend the range of ion masses, and these beams could ultimately be injected into collider rings in the CBA tunnel, as described by Mark Barton (Sec.). The fixed target program would take advantage of a large number of developed beam lines and extensive experimental support infrastructure which exists at the AGS. It would also address in a natural and timely way some of the manpower and sociology issues raised by the prospect of a heavy ion collider program:

- Building a constituency for collider experiments
- Effecting collaborative efforts between nuclear and particle physicists.
- Providing an appropriate arena and stimulus for detector development necessary for collider experiments.

As Schwarzschild put it, "The new physics calls for a marriage between nuclear and high energy experimenters, and this conference looks like an engagement party to me."

Reinhard Stock as the driving force behind the CERN fixed target and collider program

Reinhardt Stock described the applications and requirements of detection equipment for nucleus-nucleus experiments in both fixed target and collider experiments. Noting the technical challenges implied by the extraordinary complexity of the interesting final states, he reminded the audience that even the most straightforward measurements require "equipment at the limit of our present state of the art." Nonetheless, he described the experiments presently approved for nuclear beams at CERN, which meet this criterion but make use of existing equipment from particle physics experiments and from the Bevalac program. He concluded that the development of new detector technology would be required for collider experiments by the end of the decade, but that "the research is really on a solid path, with the fixed target experiments as a preparatory stage."

INSTITUT FÜR KERNPHYSIK

DER JOHANN WOLFGANG GOETHE-UNIVERSITÄT FRANKFURT AM MAIN

Prof. Dr. H. Schopper
Prof. Dr. R. Klapisch
C.E.R.N.
1211 GENEVA 23

D-6000 FRANKFURT (M) 90
AUGUST-EULER-STRASSE 6
TELEFON (069) 798-42 40
ODER (069) 798-42 38

September 1st, 1986

Dear Professor Schopper and Professor Klapisch,

Enclosed please find a draft paper with thoughts on a possible future extension of the heavy ion SPS program to the acceleration of all nuclei up to lead. It briefly discusses the physics arguments in favour of heavy nuclear projectiles as part of a long-term CERN nuclear beam program. It also outlines the required accelerator construction, chiefly a new ECR source, an RFQ and a Linac at the site of the old Linac 1.

A preliminary version of the paper has been widely discussed among accelerator groups at CERN, GSI and Grenoble. The conclusion is that the proposed scheme should be close enough to any final solution in order to serve as a trigger and guideline for an initial discussion. A first presentation within the CERN "heavy ion community", convened on 1 August 1986 by N. McCubbin and G. London at the initiative of the SPSC, has received enthusiastic support of such plans by all experimental groups. It was decided to further discuss future experiments and to work out a more detailed accelerator design. This is expected to lead to a more formal proposal early next year, to be submitted by a wider and more international group. The experiences made in the first heavy ion runs will, of course, also guide the further approach. However, we consider it justified already now to point out to CERN the possibilities to further develop this attractive field of basic research.

The purpose of this letter is to bring these thoughts to your attention at the occasion of the first internal CERN discussion, taking place on September 2 in the joint SPSC/PSCC meeting. We would very much appreciate if you could support this idea, introduce it into the discussion and decision-making process, and, if possible, give an early indication of CERN's basic backing and support for an extended nuclear beam program.

Yours sincerely,

R. Bock (GSI)
W. Geist (LBL)
H.H. Gutbrod (GSI)
L. Kluberg (Ec.Poly.Palaiseau)
F. Pühlhofer (U. Marburg)
R. Santo (U. Münster)
N. Schmitz (MPI München)
H.J. Specht (U. Heidelberg)
R. Stock (U. Frankfurt)

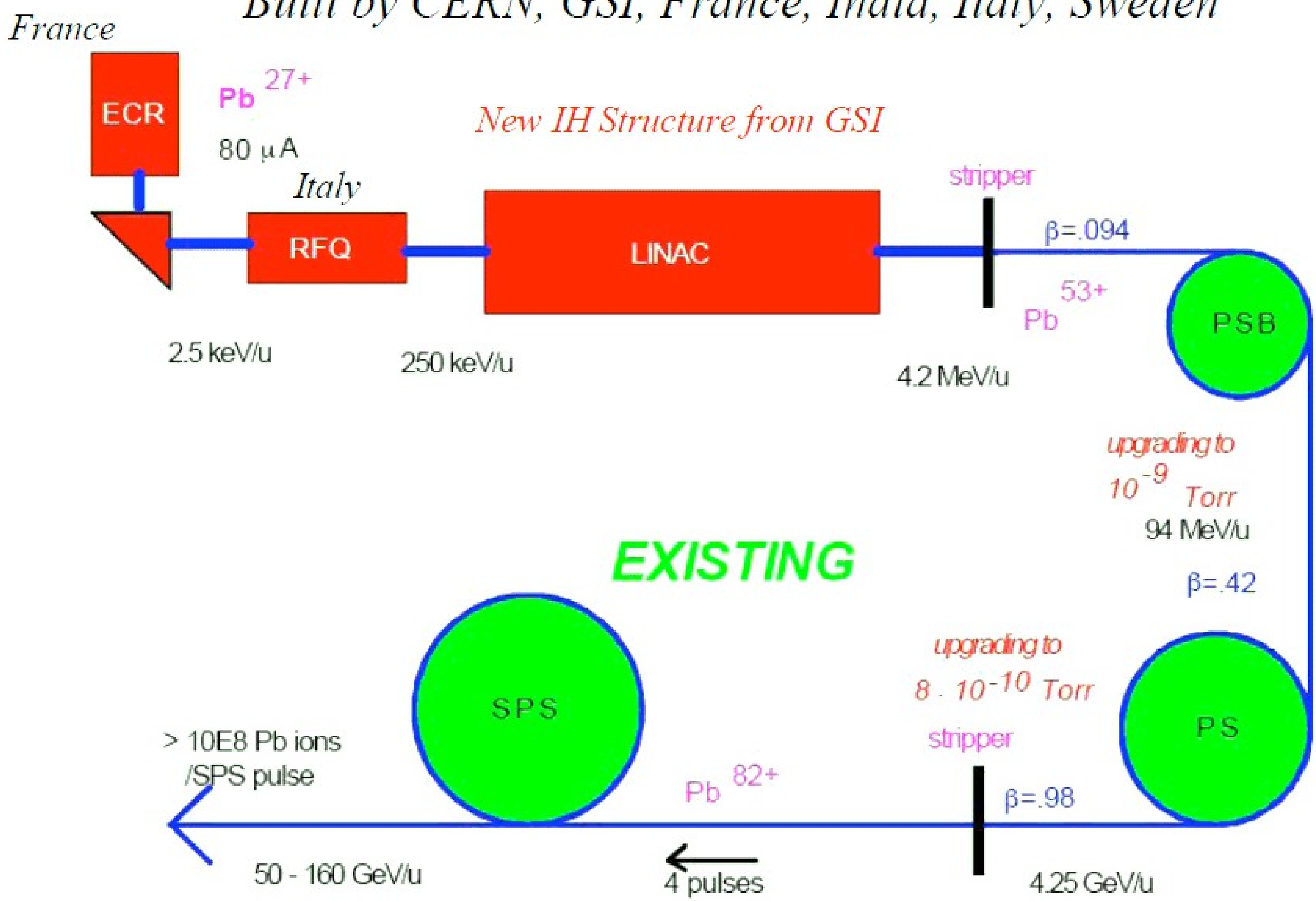
c.c Prof. L. Foà,
Prof. G. Brianti,
Dr. N. McCubbin,
Dr. G. W. London

begin of the program
with ultra-relativistic nuclear
beams at CERN

first SPS S and Pb beams

The new CERN Lead Injector

Built by CERN, GSI, France, India, Italy, Sweden



also LBNL contribution to RFQ development

impressive experimental data base from the fixed target program and from RHIC

- fixed target data from AGS (2 – 14.6 A GeV) from 1986 – 2002 and SPS (20 – 200 A GeV) from 1986 till now
- this culminated in the CERN press release of Jan. 31, 2000 'evidence for a new state of matter' with nuclear collisions at the CERN SPS
- collider data from RHIC ($\sqrt{s_{nn}}$ = 7.7 – 200 GeV) from 2000 on
- at all energies, production yields have been measured for (nearly) all stable or weakly decaying hadrons over a substantial part of the available phase space.

ideal fluid scenario and jet quenching discovered at RHIC
interdisciplinary connections to string theories, cold quantum gases, black holes, ...

most important physics results

- the fireball produces particles near T_c in chem. equilibrium
- strong collective expansion flowing like a liquid is observed
- jet suppression: the fireball is opaque to fast partons
- low mass lepton pairs enhanced
- 'anomalous' charmonium production (now seen in a completely new light)

CERN Press Release January 31, 2000

Evidence for a New State of Matter: An Assessment of the Results from the CERN Lead Beam Programme

Ulrich Heinz and Maurice Jacob
Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland

A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.

arXiv:nucl-th/0002042

and now on to physics – a few remarks only

tremendous progress of the past decade

for highlights from the past 5 years, see:

pbm, Koch, Stachel, Schaefer,
Phys. Rept. 621 (2016) 76-126

Busza, Rajagopal, van der Schee,
Ann. Rev. Nucl. Part. Sci. 68 (2018) 339-376

here, I will concentrate only on 2 examples:

1. statistical hadronization of (u,d,s,c) quarks at the QGP phase boundary and the fate of J/ψ in the fireball

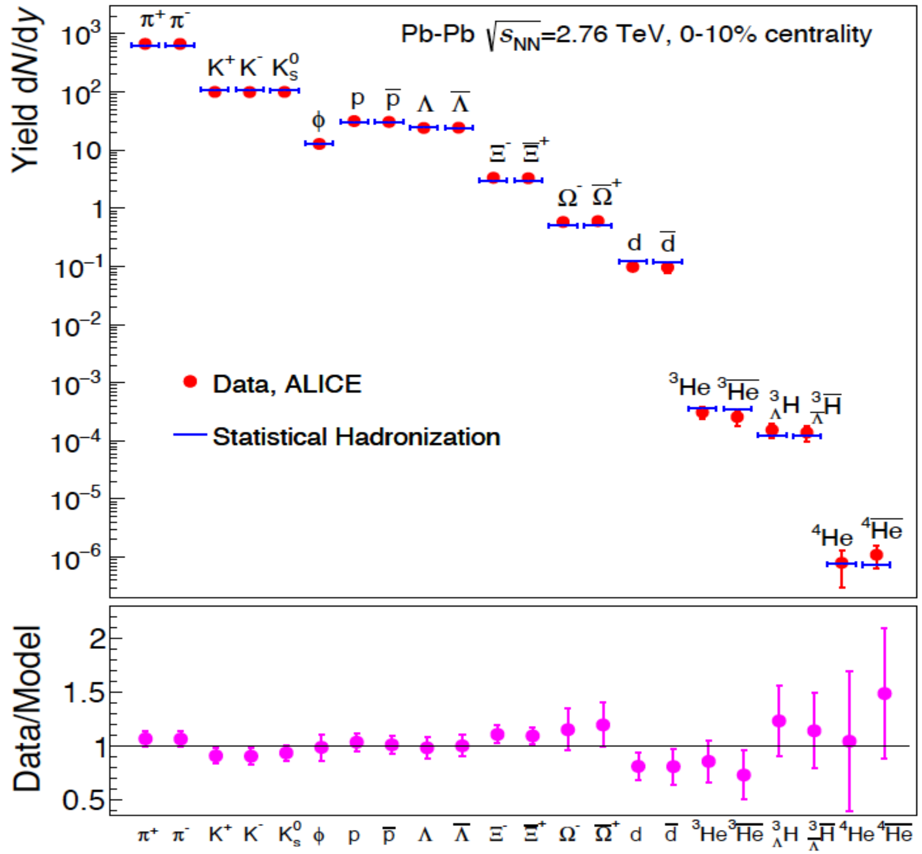
2. the search for a possible critical end point in the QCD phase diagram

see also the talks by M. Lisa , M. van Leeuwen, and J. Steinheimer at this conference

(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



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

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

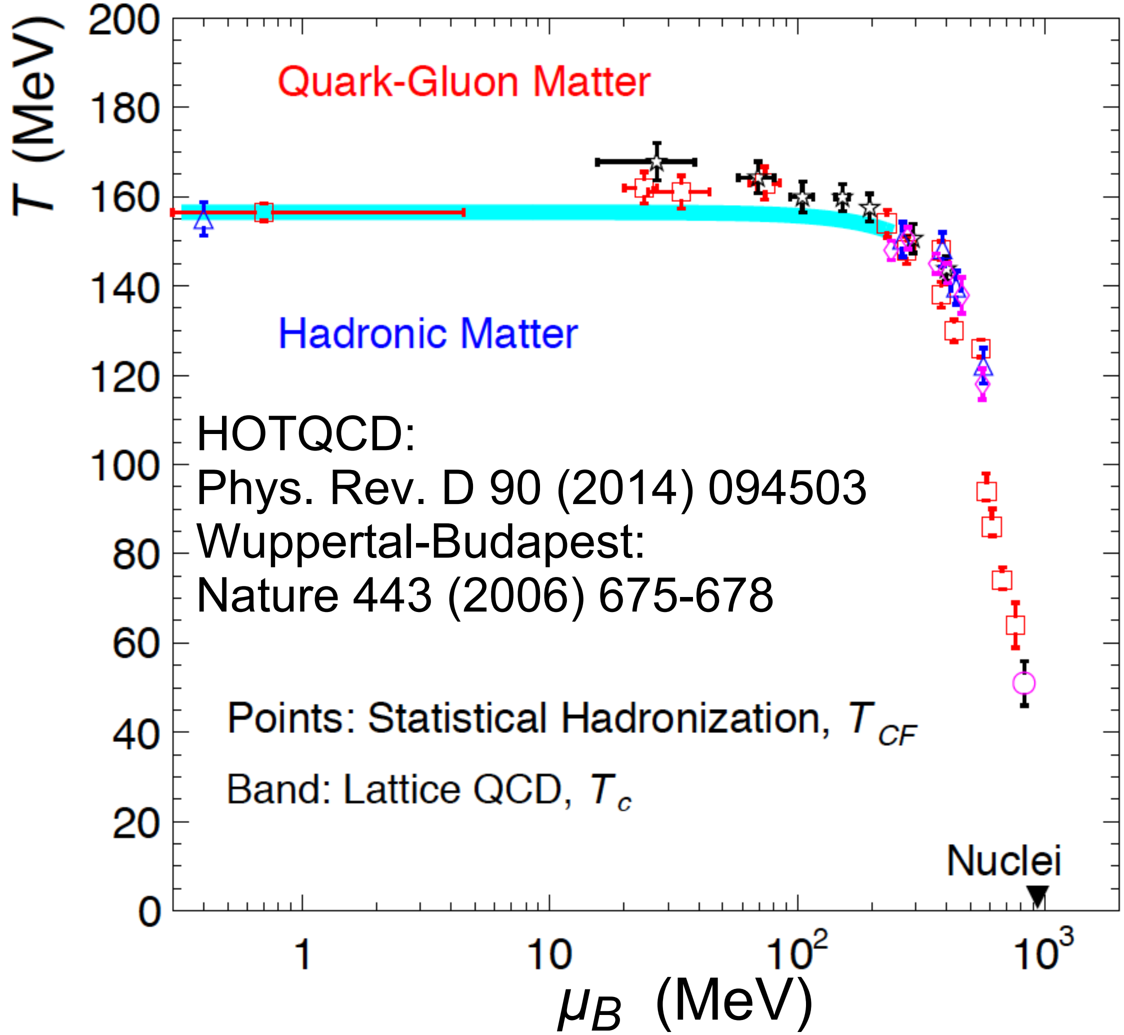
similar results at lower energy, each new energy yields a pair of (T, μ_B) values

connection to QCD (QGP) phase diagram?

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



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 μ_B (large net baryon density)?

then there must be a critical endpoint in the phase diagram, see below

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

how about charm and statistical hadronization?

charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting (suppression)

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks production probability scales with $N(_{ccbar})^2$

reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

nearly simultaneous: Thews, Schroeder, Rafelski 2001

formation and destruction of charmonia inside the QGP

n.b. at collider energies there is a complete separation of time scales

$t_{coll} << t_{QGP} < t_{Jpsi}$

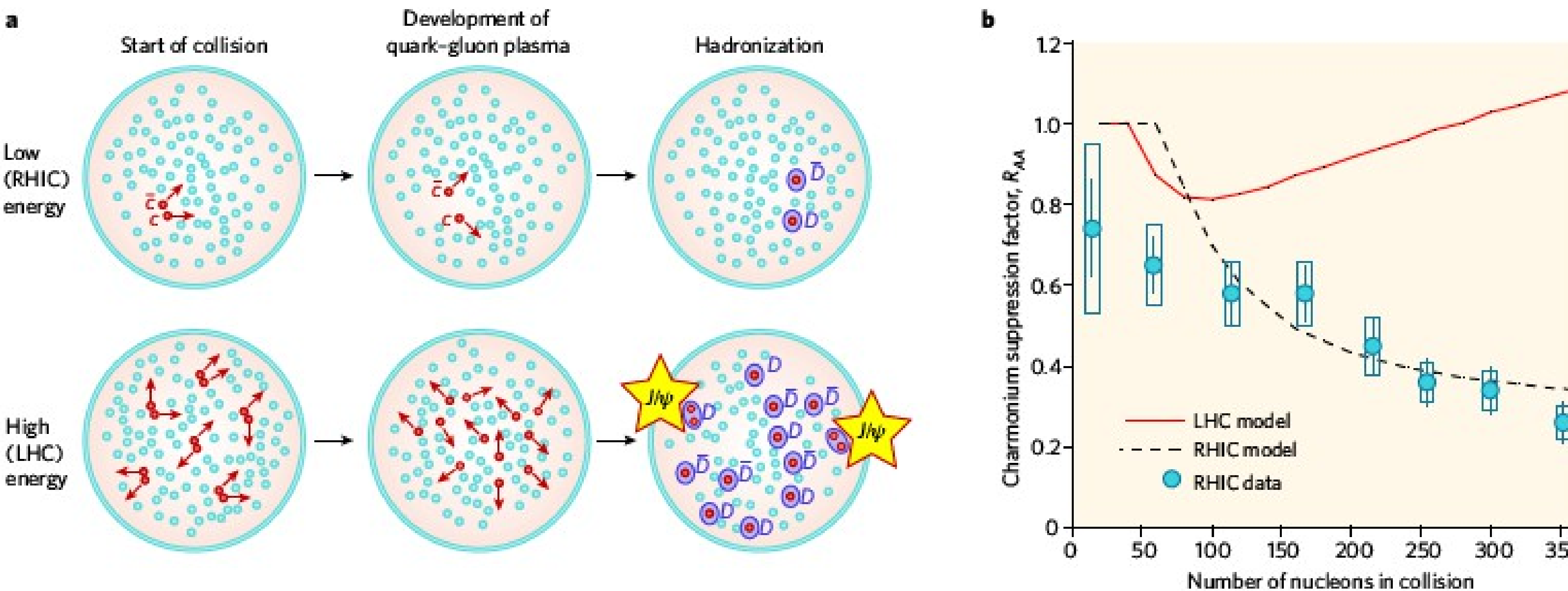
implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

also charm quark production increases strongly with collision energy

charmonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture

P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma, Nature **448** Issue 7151, (2007) 302-309.



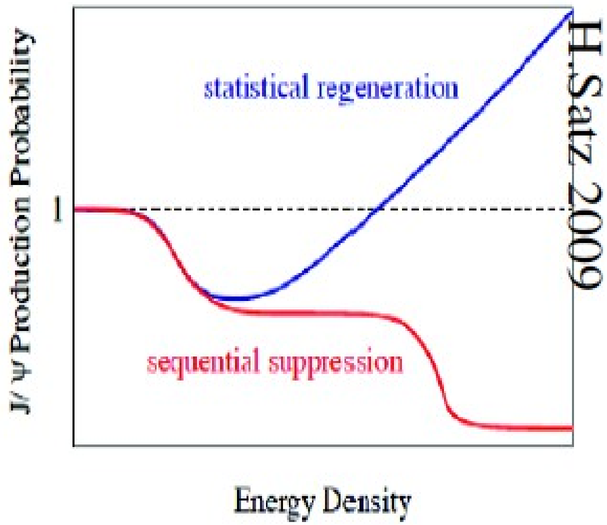
charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

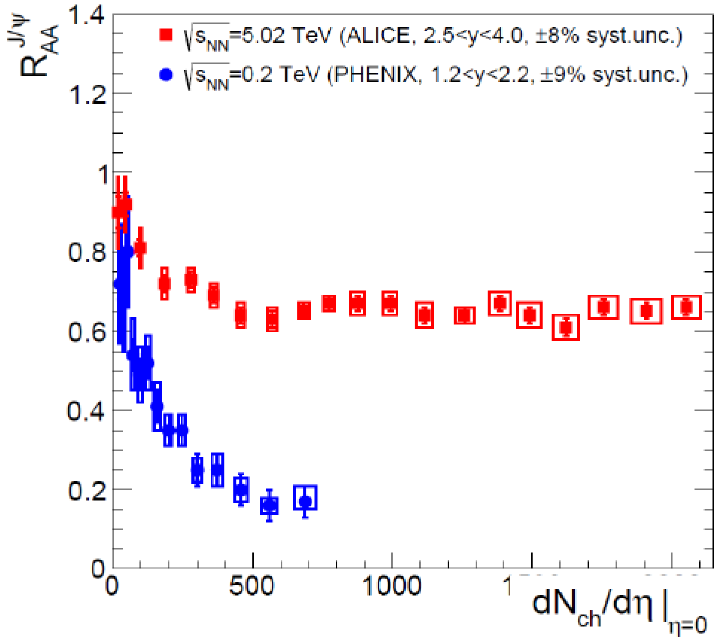
prediction long before the LHC started data taking

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

sequential suppression vs statistical hadronization

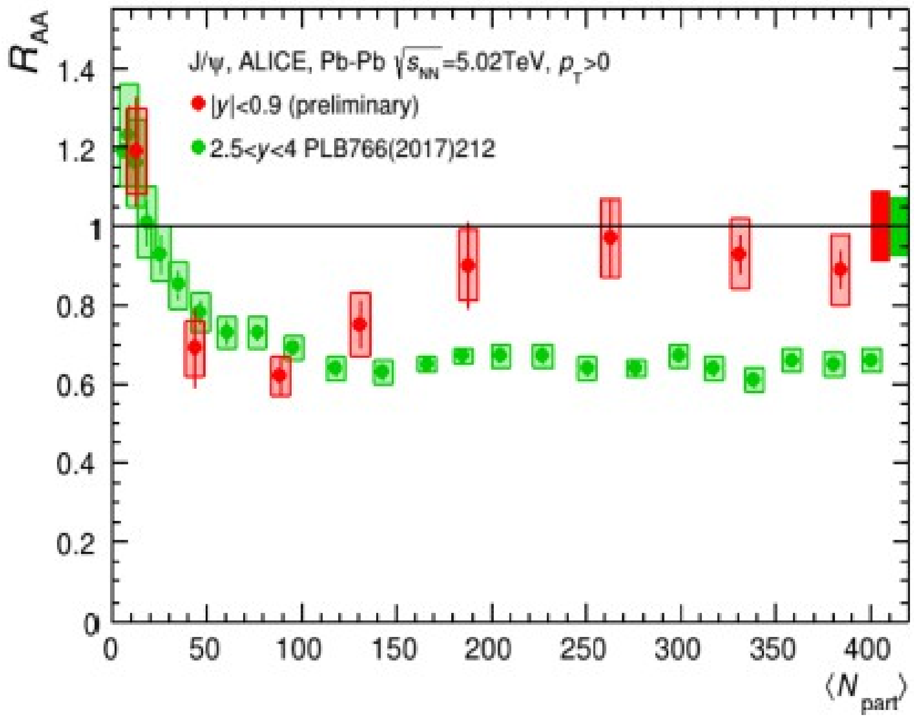
LHC data settle the issue in favor of statistical hadronization/generation at the phase boundary

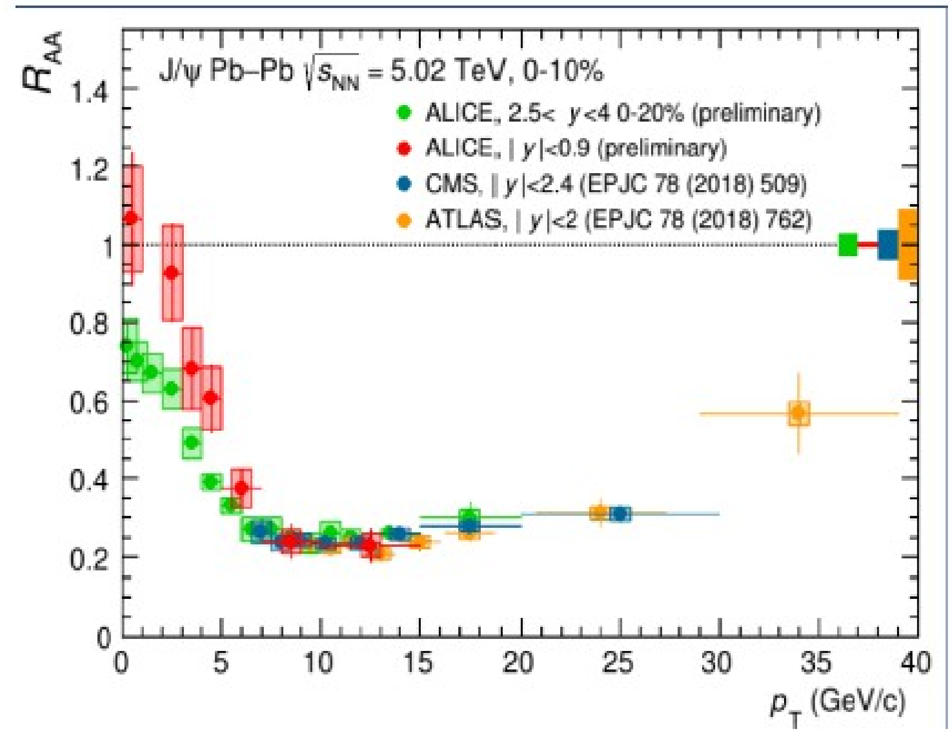




charmonium formation from uncorrelated c quarks at the phase boundary ⟶ direct proof of deconfinement for charm quarks, see Nature 561 (2018) 321

enhancement is at low (transverse) momentum and at angles perpendicular to the beam direction, as expected for a thermal, nearly isotropic source



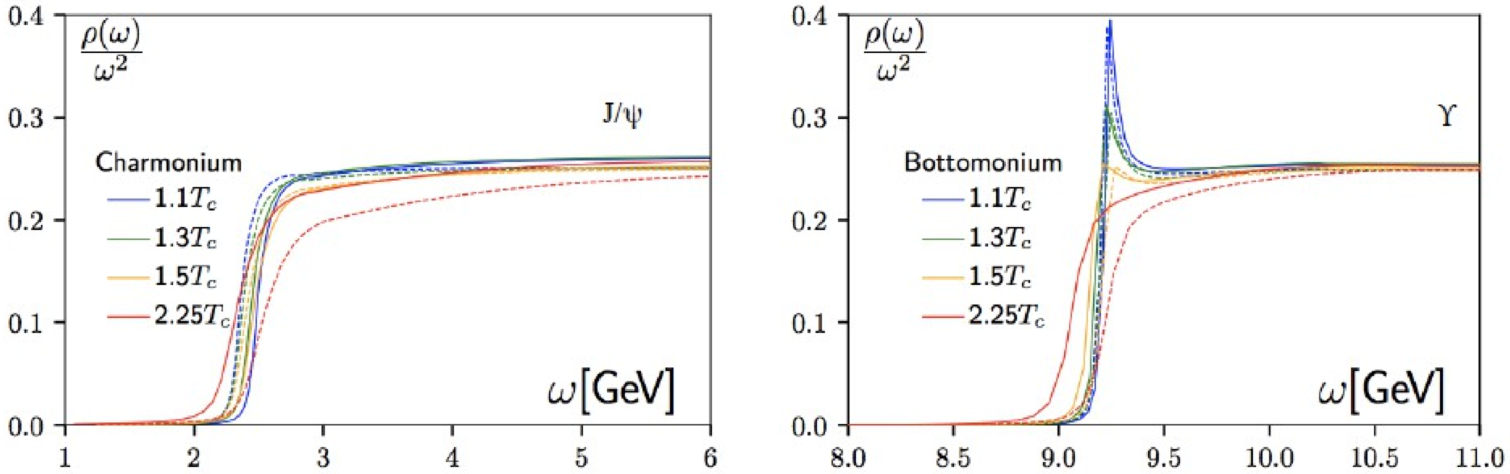


enhancement is due to statistical combination of charm- and anti-charm quarks these heavy quarks have masses O(1 GeV) and are not produced thermally since T_{cf} = 156 MeV << 1 GeV. Interactions in the hot fireball bring the charm quarks close to equilibrium → production probability scales with N_{ccbar}^2

newest result from the Bielefeld/BNL/Wuhan lattice group arXiv:2002.00681

little modification of quarkonia in QGP:
charmonium melts at T_c
bottomonium melts at < 1.5 T_c

Thermal modification of spectral functions for charmonium and bottomonium at high temperature



A.L. Lorenz, H.T. Ding, O. Kacmarek et al., arXiv:2002.00681

No evidence of survival of charmonium bound states above T_c

Survival of bottomonium significantly above T_c

-> Consistent with picture of statistical (re-)generation of J/ψ at freeze-out

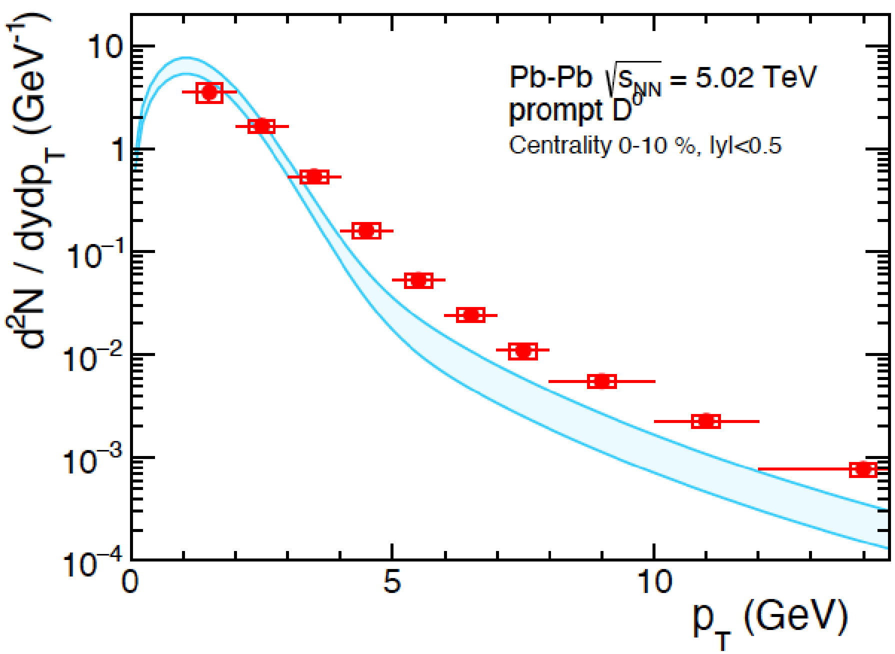
statistical hadronization for hidden and open charm

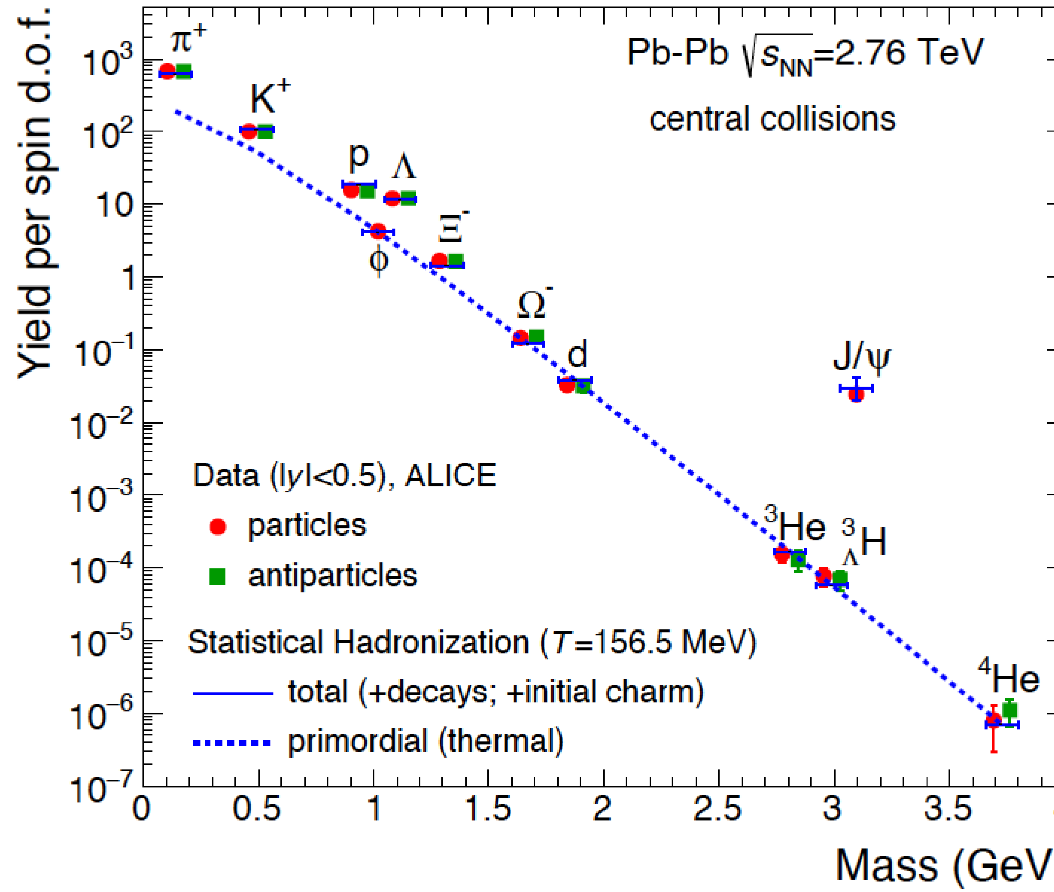
J/ψ enhanced compared to other M = 3 GeV hadrons since number of c-quarks is about 30 times larger than expected for pure thermal production at T = 156 MeV due to production in initial hard collisions and subsequent thermalization in the fireball.

production probability scales with N_{ccbar}^2

enhancement factor is 900 for J/ψ

enhancement factor is 30 for D^0





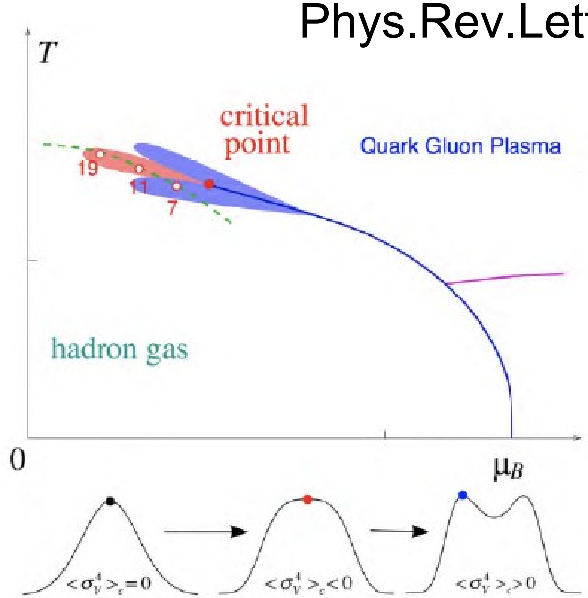
Andronic et al, PLB 792 (2019) 304
and in preparation

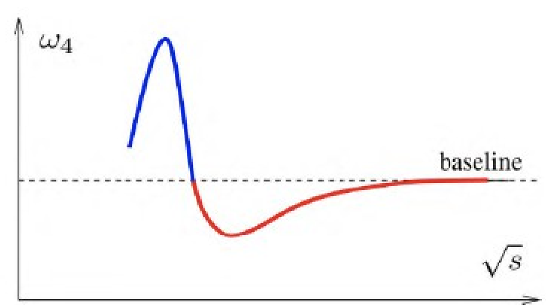
quantitative agreement for open and hidden charm hadrons, same mechanism should work for all open and hidden charm hadrons,
even for exotica such as Ω_{ccc} where enhancement factor is nearly 30000
quantitative tests in LHC Run3/Run4

search for a possible critical endpoint in the QCD phase diagram

If the QCD phase transition is of cross-over type at vanishing net-baryon density, and of 1st order at large baryon density (large μ_B) then there must be a critical endpoint at the end of the 1st oder line (Asakawa and Yazaki, Nucl. Phys. A 504 (1989) 668-684, Stephanov, Rajagopal, Shuryak, Phys.Rev.Lett. 81 (1998) 4816-4819). This leads to critical fluctuations which could be observed by studying fluctuations of net baryons along the chemical freeze-out line, i.e. through their variation with √s.

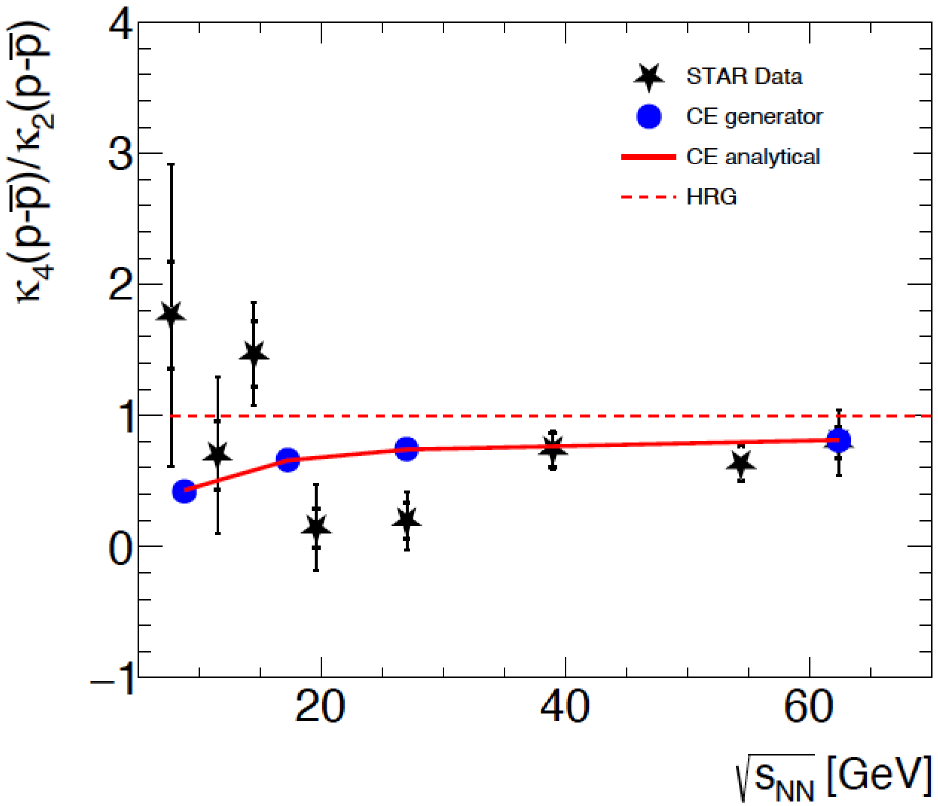
variation with √s of 4th moment ω_4 of net baryons near a hypothetical critical endpoint (Stephanov, Phys.Rev.Lett. 102 (2009) 032301





experimental search for the critical endpoint

the STAR collaboration has pioneered this search, by measuring at RHIC net proton fluctuations in central Au-Au collisions up to the 6th moment (arXiv:2001.02852 and refs. there) over a wide range of √s. the most recent results are shown below and compared to a non-critical baseline evaluated in (arXiv:2007.02463, pbm, Friman, Redlich, Rustamov, Stachel)



comparison of baseline prediction with data on the energy dependence of moment ratios. statistical analysis implies a 1.5 σ significance for non-monotonic behavior in the data, no evidence yet for a critical point

we all look forward to much improved data from the RHIC beam energy scan 2

future programs with relativistic nuclear collisions in the high baryon density region

a variety of facilities for the baryon-rich region promises a rich physics program centered around critical endpoint and exotica for the coming decade and beyond

RUNNING AND PLANNED HIGH μ_B FACILITIES

Compilation TG, Nucl.Phys. A982 (2019)

Facility	SIS18	HIAF	Nuclotron	J-PARC-HI	SIS100	NICA	RHIC	SPS	SPS
Experiment	HADES /mCBM	CEE	BM@N	DHS, D2S	CBM / HADES	MPD	STAR	NA61/SHINE	NA60+
Start	2012, 2018	2023	2022 (Au)	>2025(?)	2025	2022	2010,2019	2009 - 2022	>2025(?)
$\sqrt{s_{NN}}$, GeV	2.4 – 2.6	2 – 2.7	2 – 3.5	2 – 6.2	2.7 – 5	4 – 11	3 – 19.6	4.9 – 17.3	4.9 – 17.3
μ_B, MeV	880 – 670	880 – 750	850 – 670	850 – 490	780 – 400	750 – 330	720 – 210	560 – 230	560 – 230
Hadrons	+	+	+	+	+	+	+	+	(+)
Dileptons	+		(+)	+	+	+	+		+
Charm				(+)	(+)	+	+	+	+

Allows overlap and independent confirmation of results

Figure courtesy Tetyana Galatyuk

LHC overall timeline and future prospects

1982 first discussion on LHC in LEP tunnel

1987: La Thuile WS: first discussion of Pb ions in LHC

1985-90 4 workshops on physics and detectors

1990: Aachen: first ideas for HI expt.

1992: Evian: Expression of Interest EoI

1994/6: approval of LHC

1997: approval of ALICE

1998-2008: Technical Design Reports

Sep. 2008	**LHC start and stop**
Nov. 2009	**pp physics program starts at 0.9 and 2.36 TeV**
March 2010	**pp physics at 7 TeV**
Nov. 2010	**Start LHC Run 1, Pb beams, 2.76 TeV**
Nov. 2015	**Start LHC Run2, Pb beams, 5.0 (5.46) TeV**
Nov. 2021	**Start LHC Run3, from pp to pPb to Pb-Pb**
2027	**Start LHC Run4**
2032 -	**LHC Run5/6 with full pp, pA, ion program**

LHC Run3 and Run4 will feature for ALICE a factor 100 increase in 'effective' luminosity, with upgraded TPC and entirely new inner tracking system plus many other upgades:

physics focus will be on:

- light flavor hadrons including light nuclei
- heavy flavor hadrons including quarkonia and exotica
- jets with particle ID
- low mass lepton pairs and real photons from 100 MeV to 100 GeV
- ultra-peripheral collisions
- correlations and hadron-hadron interactions

all LHC collision systems

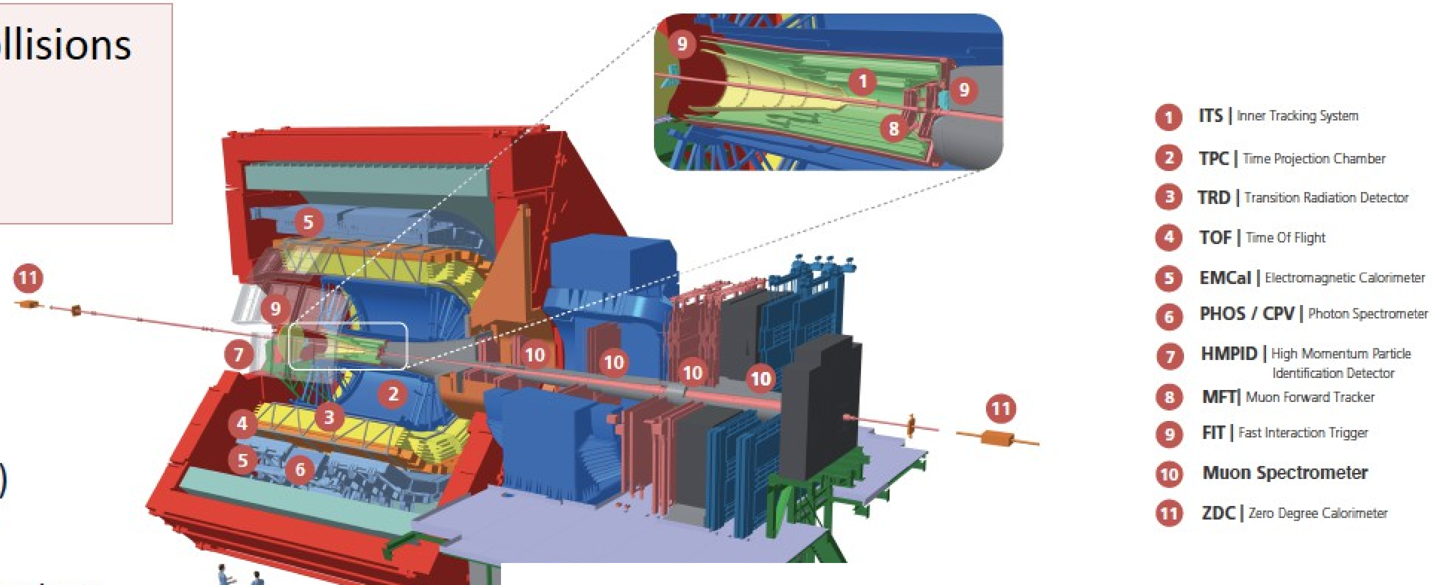
Runs 1 and 2: 1 nb^{-1} of Pb-Pb collisions

Interaction rate ~8 kHz

readout rate ≈ 1 kHz

LS2 upgrade

- New TPC R/O planes
- New silicon tracker (ITS & MFT)
- New Fast Interaction Trigger (FIT)
- New Online/Offline system (**O2**)
- Upgrade readout of all other detectors



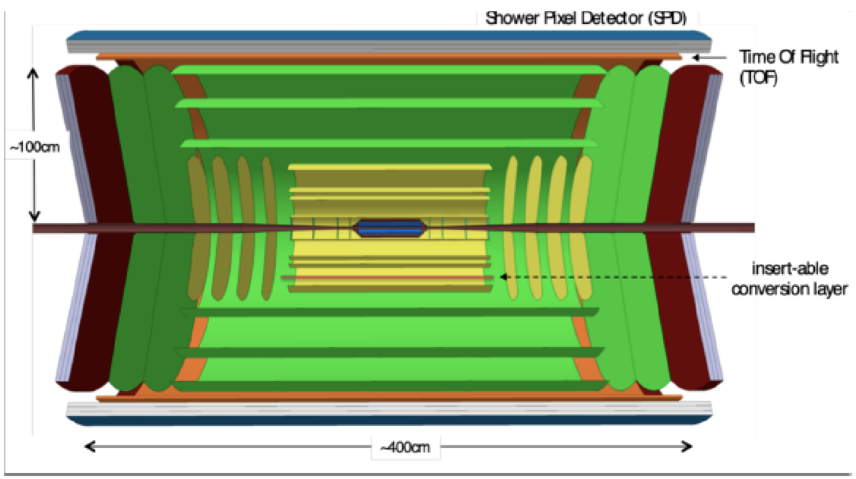
Run 3+Run 4: **13 nb^{-1} of Pb-Pb collisions**

readout rate ≈ 50 kHz (Pb-Pb), ≈ 1 MHz (pp)

online reconstruction : all events to storage!

ALICE Future: ALICE3

ALICE 3: a next generation HI detector for LHC Run5 and 6



Fast and ultra-thin detector with precise tracking and timing

- Another **factor 50x** in luminosity
- Exploit higher LHC lumi with nuclei lighter than Pb
- **Ultra-lightweight** tracker based on CMOS pixels (MAPS)
- Si-based Time Of Flight determination: ~20ps time resolution
- **Fast** to sample large luminosity: 50-100x Run 3/4
- **Large** acceptance barrel + end caps $\Delta\eta = 8$
- arXiv: 1902.01211

Ultimate performance for heavy flavor hadrons, thermal radiation and soft hadrons (p_T < 50 MeV/c)

- Multiply heavy flavor hadron production, multi-quark states
- Chiral symmetry restoration (e.m. probes)
- Beyond HI (phase space complementary to other experiments):
  - Test of fundamental properties of quantum field theories (emission of soft photons)
  - New physics in soft sector, e.g. dark photons

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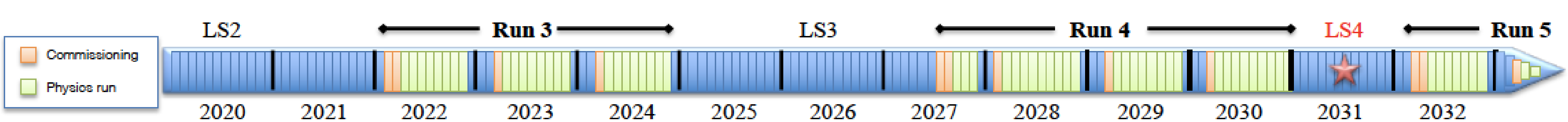
European Strategy for Particle Physics



Slide courtesy Luciano Musa