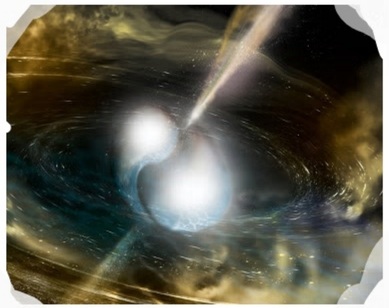
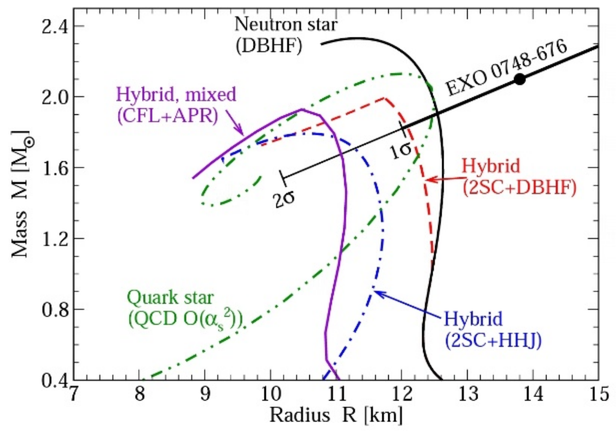
HAPPY BIRTHDAY TO DAVID!

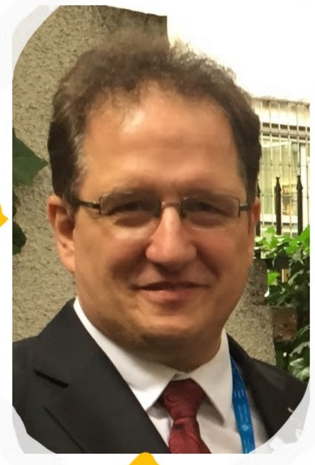


UNIVERSE OF DAVID

STARS

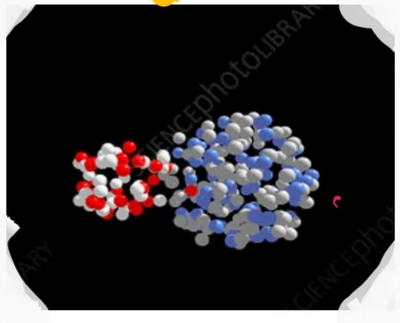


THEORY



EXPERIMENT

NUCLEI



... AND CONTINUE RUNNING YOUR UNIVERSE FOR MANY YEARS TO COME!

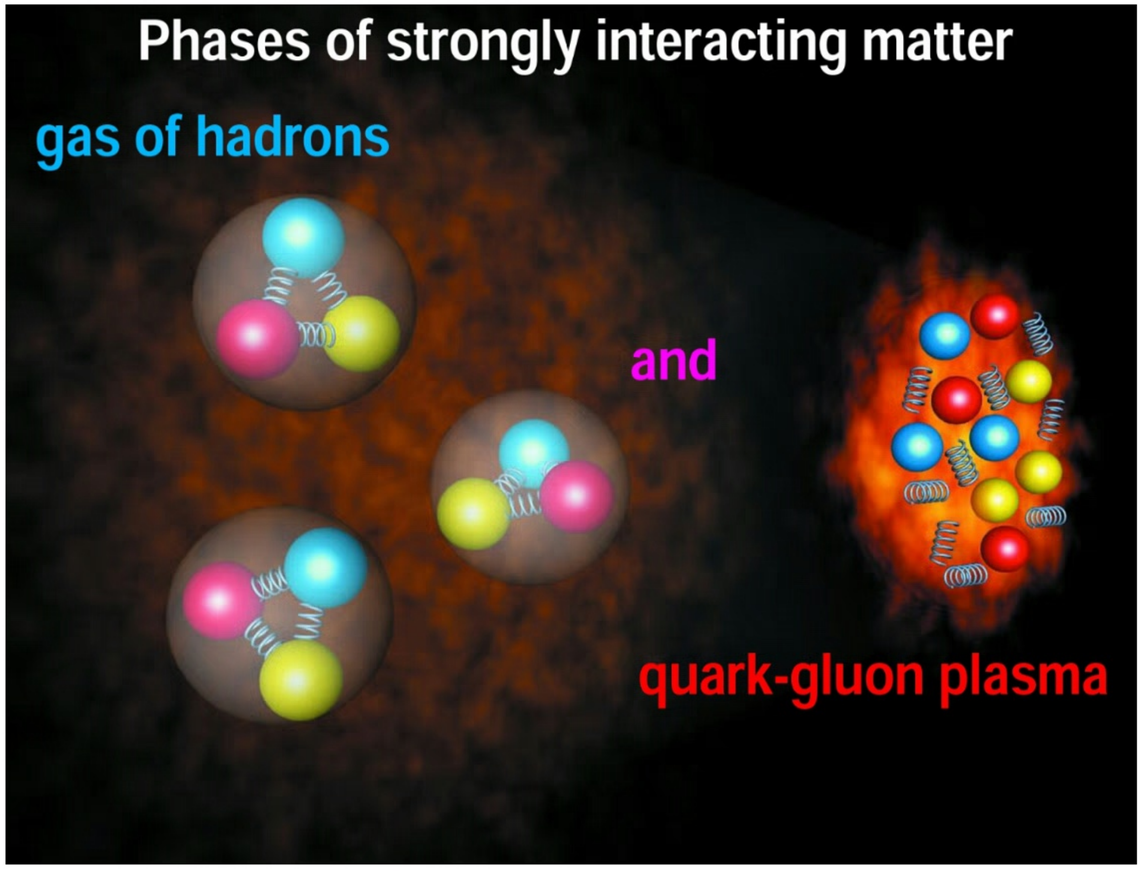
UNCOVERING CRITICAL STRUCTURES IN STRONG INTERACTIONS

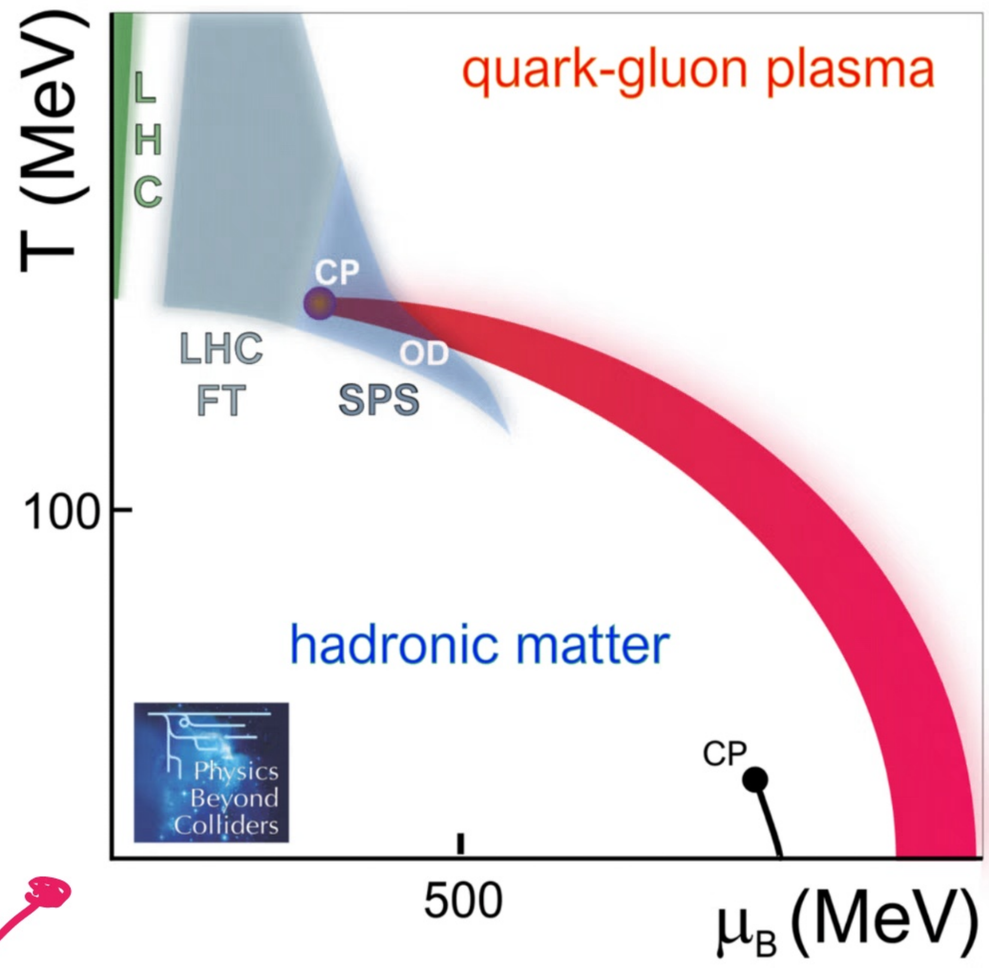
M. GAZDZICKI, KIELCE, FRANKFURT

- VOCABULARY
- STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS (< 1986)
- QUARK-GLUON PLASMA (1986 – 2003)
- CRITICAL STRUCTURES (1997 - 2025 ?)
- FUTURE

VOCABULARY

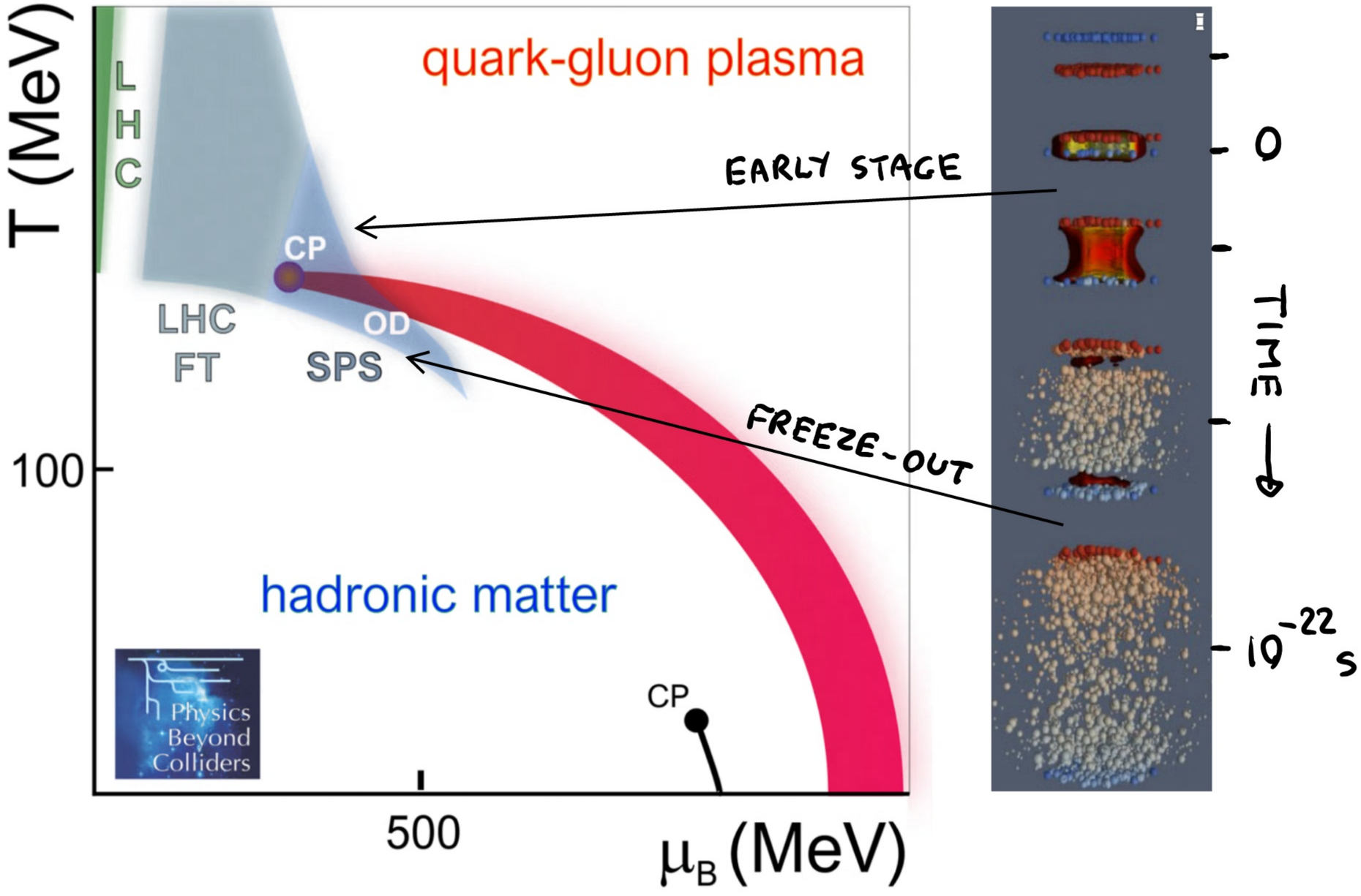
THE QUARK-GLUON PLASMA HYPOTHESIS (1965 - 1975)



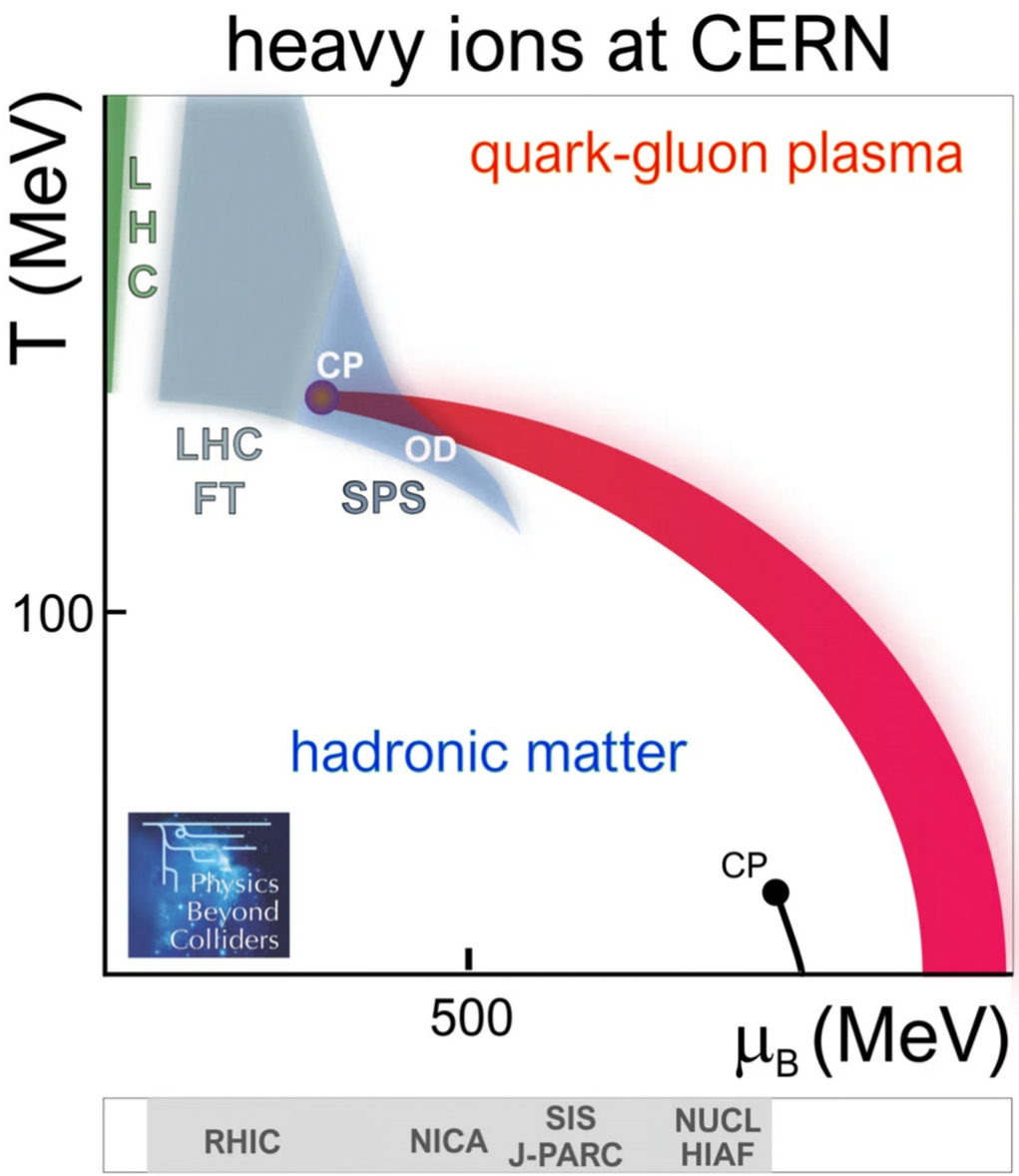


EARLY UNIVERSE
NEUTRON STARS
HEAVY ION COLLISIONS

VOCABULARY


T (MeV)
quark-gluon plasma
LHC
CP
LHC
FT
OD
SPS
EARLY STAGE
FREEZE-OUT
hadronic matter
Physics Beyond Colliders
CP
100
500
μ_B (MeV)
0
TIME
10^{-22} s

VOCABULARY



CRITICAL STRUCTURES:

- ONSET OF FIREBALL - BEGINING OF CREATION OF STRONGLY INTERACTING MATTER WITH INCREASING NUCLEAR MASS NUMBER.
  TRANSITION FROM NON-EQULIBRIUM STRINGS AND RESONACES TO EQULIBRIUM HADRON GAS OR QGP

- ONSET OF DECONFINEMENT (OD) - BEGINING OF QGP CREATION WITH INCREASING COLLISION ENERGY

- CRITICAL POINT (CP) - END POINT OF FIRST ORDER TRANSITION LINE THAT HAS PROPERTIES OF SECOND ORDER PHASE TRANSITION

STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS

QUARK-GLUON PLASMA HYPOTHESIS

DISCOVERIES OF HADRONS (CR, BNL, LBL, CERN PS)

1964: QUARK MODEL OF HADRON CLASSIFICATION
GELL-MANN, ZWEIG

1965- QUARK MATTER IN SUPERDENSE STAR CORES

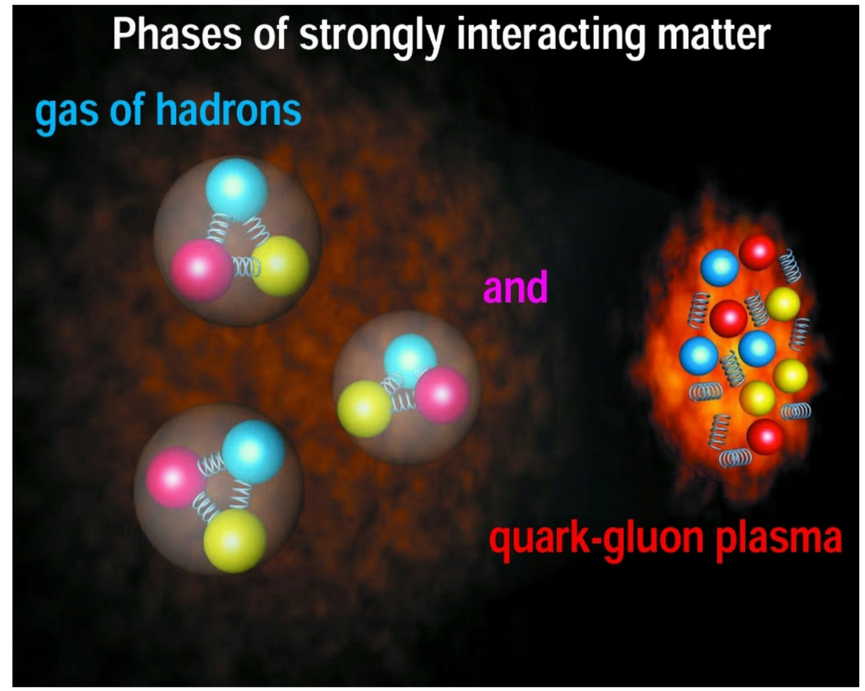
1975: IVANENKO, KURDGELAIDZE, ITOH, COLLINS, PERRY

1968: DISCOVERY OF PARTONS (SLAC)

1972: QCD AS THEORY OF STRONG INTERACTIONS
GELL-MANN, FRITZSCH, GROSS, WILCZEK, POLITZER

1975: QCD QUARK-GLUON PLASMA
SHURYAK

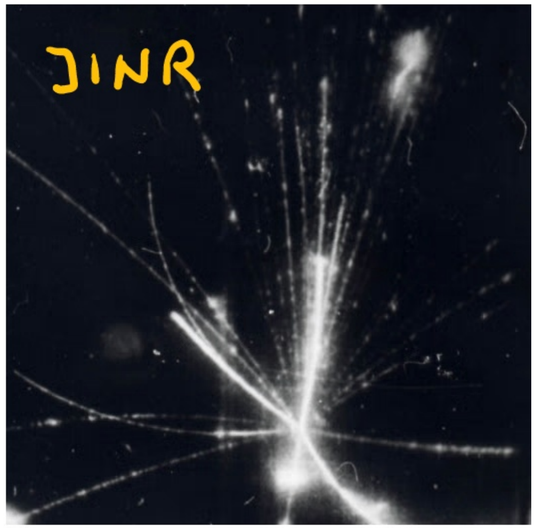
1979: DISCOVERY OF GLUONS (DESY)



STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS

FIRST RELATIVISTIC HEAVY ION EXPERIMENTS:

- SINCE 1970: AT SYNCHROPHASOTRON IN DUBNA (UP TO ≈5A GEV)
- SINCE 1975: AT BEVELAC IN BERKELEY (UP TO ≈2A GEV)

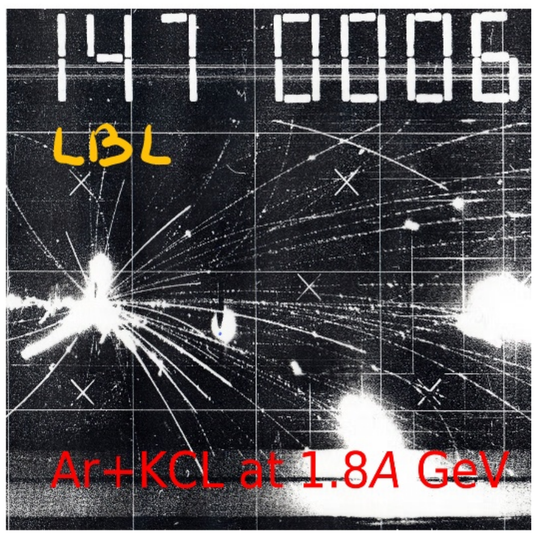


⇓

OBSERVATION OF COLLECTIVE EFFECTS (FLOW, STRANGENESS ENHANCEMENT, ...)

⇓

STRONGLY INTERACTING MATTER (SIM) IS PRODUCED IN HEAVY ION COLLISIONS



STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS

TOWARDS QUARK-GLUON PLASMA

THEORY:
SIM AT HIGH ENERGY DENSITY IS IN A STATE OF QUARK-GLUON PLASMA

EXPERIMENT:
SIM IS PRODUCED IN RELATIVISTIC HEAVY ION COLLISIONS

↓

COLLIDE HEAVY IONS AT THE MAXIMUM POSSIBLE ENERGY AND DISCOVER QGP

BEGINNING OF QUARK MATTER CONFERENCE

→ HIC AT THE CERN SPS

EDITORS: BOCK AND STOCK
OPENING TALK: WILLIS
SUMMARY: SPECHT

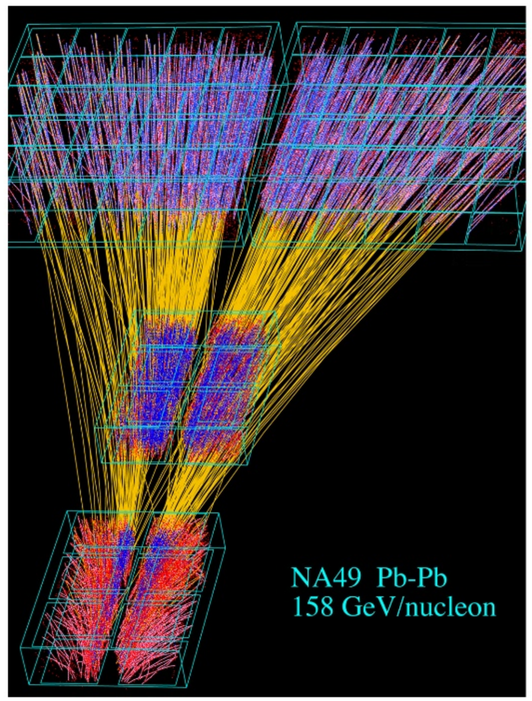
QUARK-GLUON PLASMA

PREDICTED QGP SIGNALS:

- DILEPTON/PHOTON QGP RADIATION (SHURYAK, 1980)
- STRANGENESS AND MULTI-STRANGE HYPERON ENHANCEMENT (RAFELSKI, MULLER, 1982)
- J/ψ SUPPRESSION (MATSUI, SATZ, 1986)

MEASURMENTS:

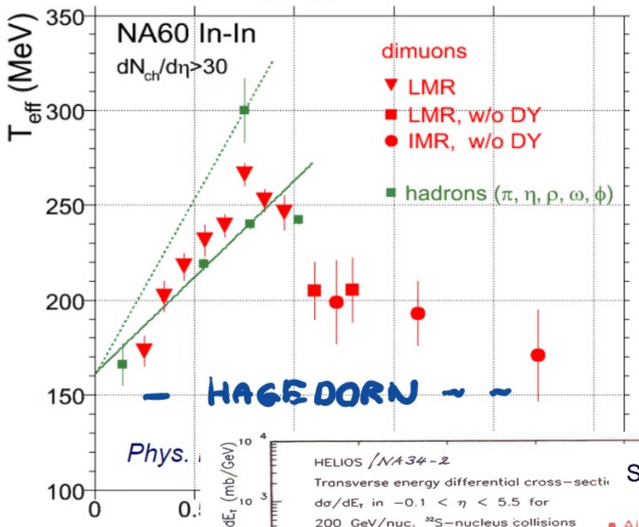
- 1986-1987: OXYGEN AND SULPHUR AT 200A GEV
  (NA34-2, 35, 36, 38, WA80, 85, 94)
- 1996-2003: LEAD AND INDIUM AT 158A GEV
  (NA44, 45, 49, 50, 52, 57, 60, WA97, 98)

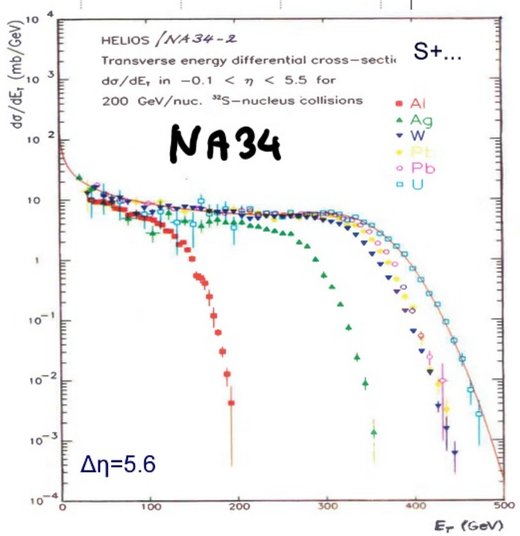


QUARK-GLUON PLASMA

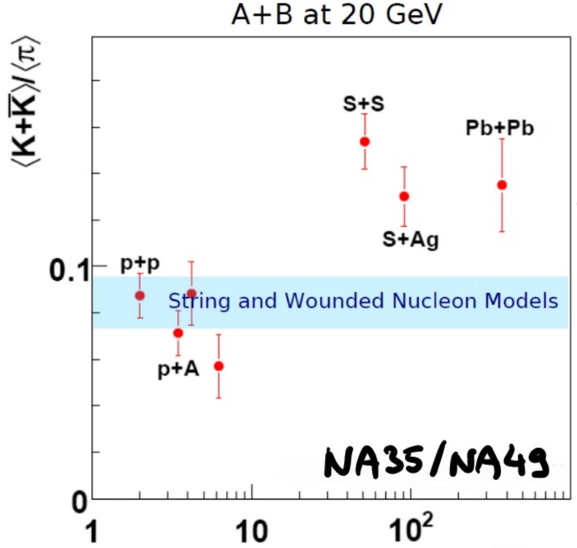
RESULTS ARE CONSISTENT WITH A QGP BEING CREATED ...

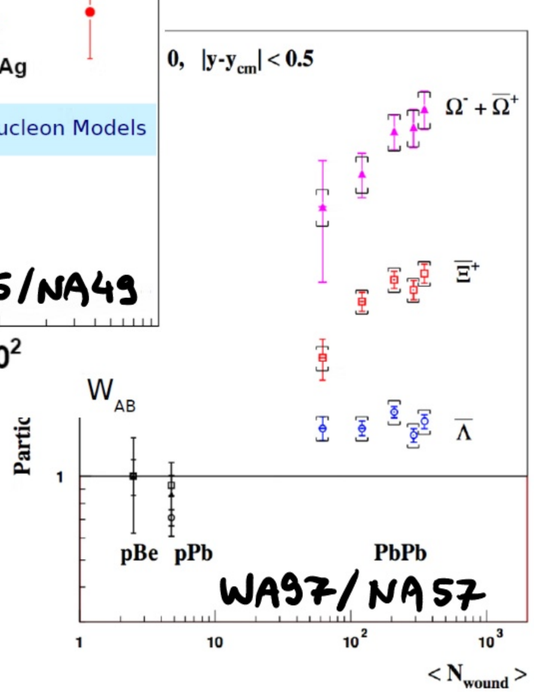
QGP TEMPERATURE T ≈ 200 MEV





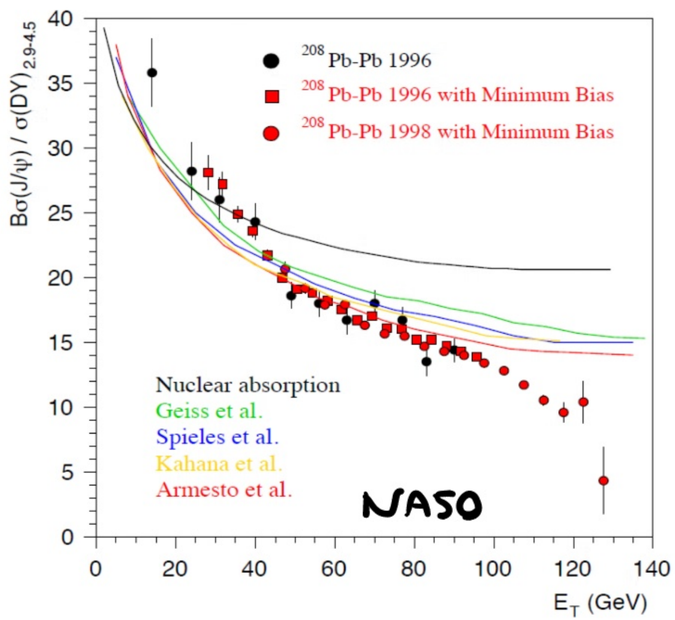
STRANGENESS AND MULTI-STRANGE HYPERON ENHANCEMENT IN QGP





AND ENERGY DENSITY $\varepsilon \gtrsim 1$ GeV/fm^3

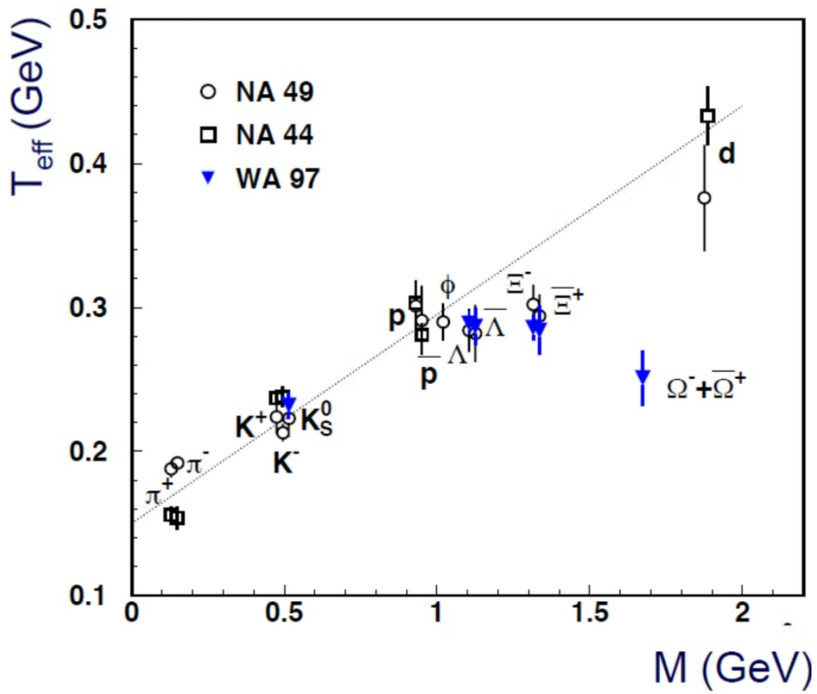
J/ψ MELTING IN QGP



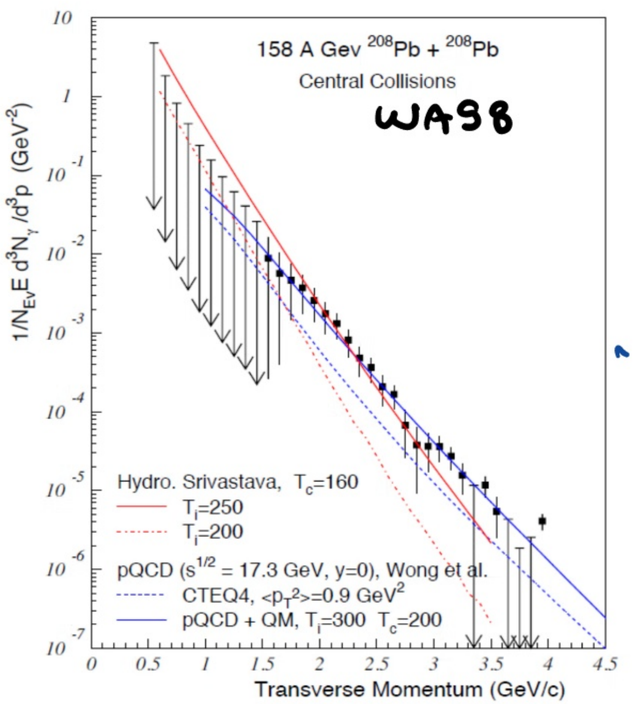
QUARK-GLUON PLASMA

... MATTER EXPANDS, RADIATES PHOTONS AND DILEPTONS ...

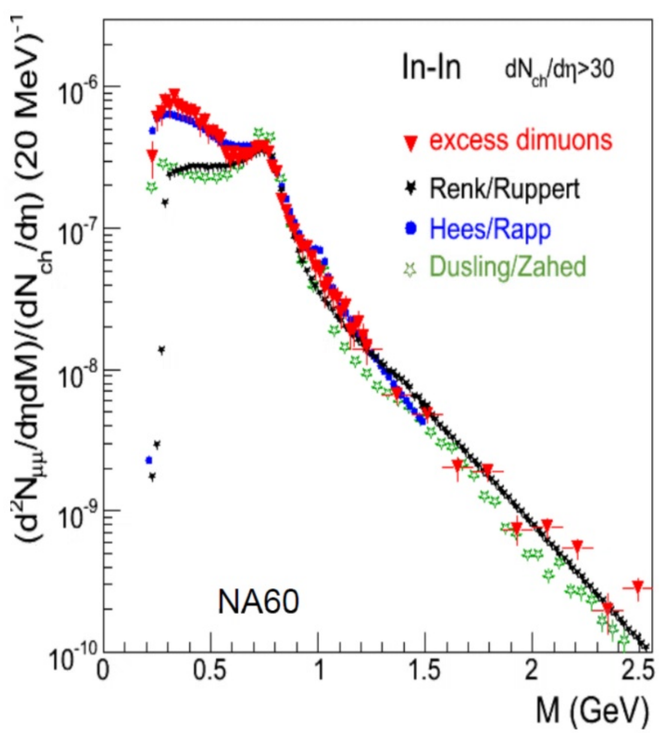
TRANSVERSE EXPANSION



PHOTON RADIATION



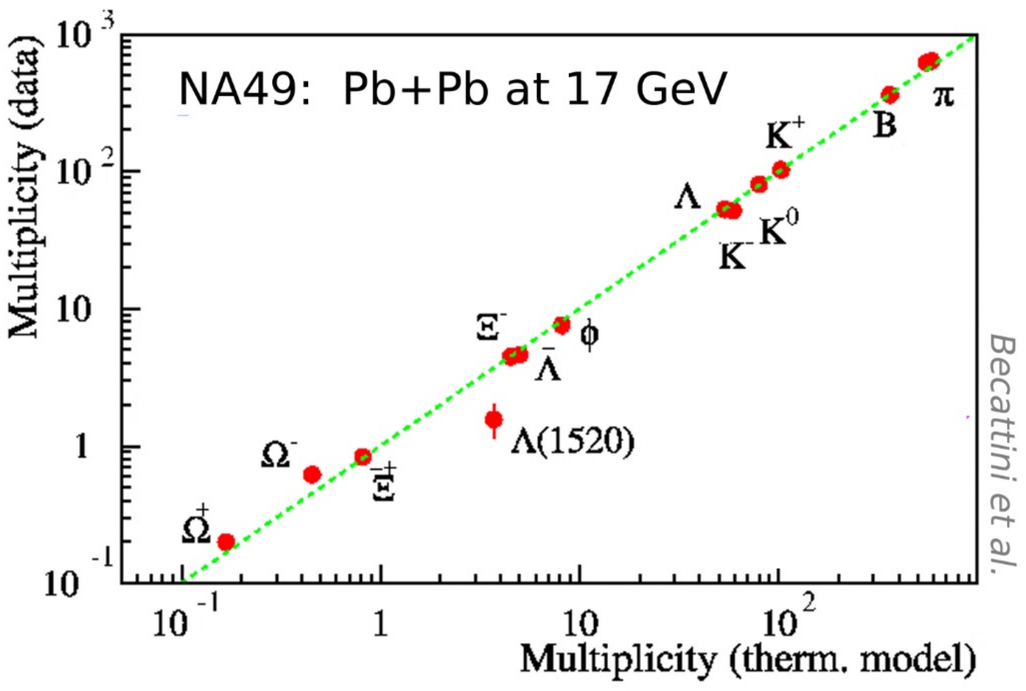
DIMUON RADIATION



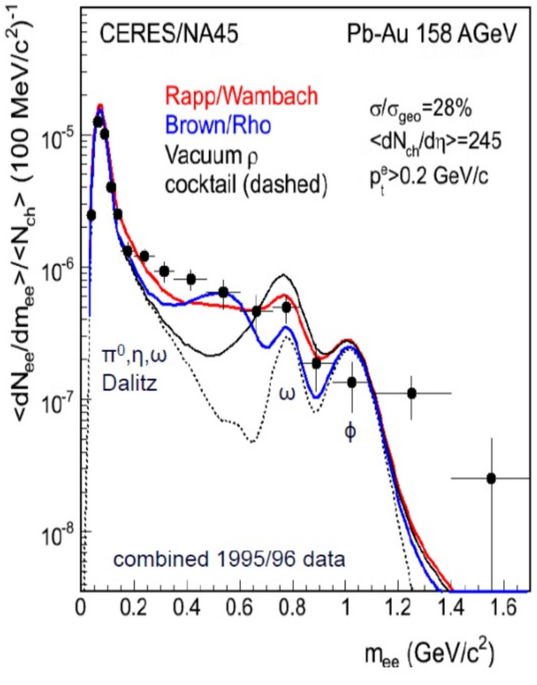
QUARK-GLUON PLASMA

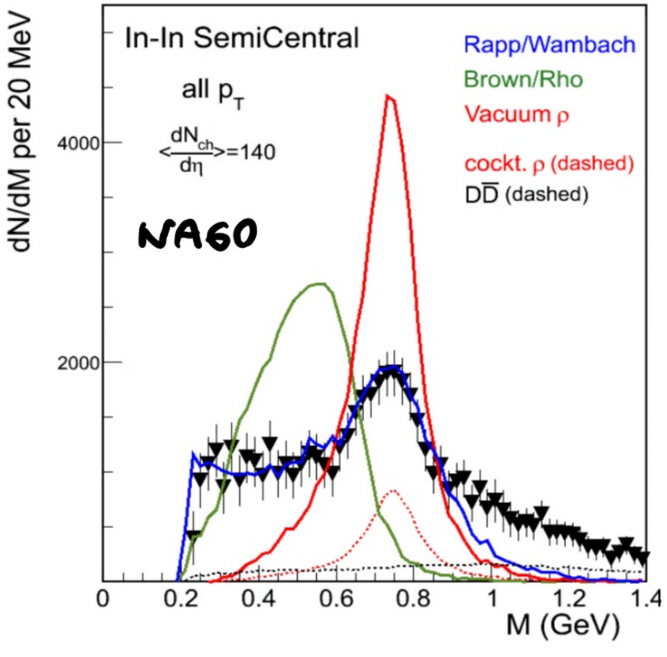
... AND AFTER STATISTICAL HADRONIZATION, THE MATTER IS STILL DENSE ENOUGH TO MODIFY HADRON PROPERTIES

STATISTICAL HADRONIZATION



MODIFICATION OF VECTOR MESON PROPERTIES





QUARK-GLUON PLASMA

CERN PRESS RELEASE (FEB 2000)

CERN

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

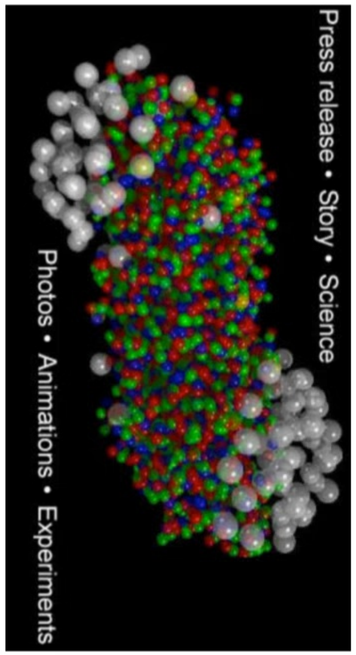
PR01.00
10.02.00

New State of Matter created at CERN

At a special seminar on 10 February, spokespersons from the experiments on CERN's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Professor Luciano Maiani, CERN[1] Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*



HEAVY ION COMMUNITY SPLITS:

→ PROPERTIES OF HIGH TEMPERATURE QGP → VERY HIGH ENERGIES AT RHIC, LHC

→ SEARCH FOR THE ONSET OF QGP CREATION → COLLISION ENERGY SCAN AT SPS

CRITICAL STRUCTURES

PHASE I: SEARCHING FOR ONSET OF QGP CREATION

PREDICTED SIGNALS:

- PION YIELD ENHANCEMENT AND STRANGENESS TO PION YIELD SUPPRESSION (M.G., GORENSTEIN 1998)

- SOFTENING OF COLLECTIVE FLOW (GORENSTEIN, M.G., BUGAEV 2003, STOECKER 2004, BLEICHER 2005)

MEASUREMENTS:

- 1999 - 2002: Pb BEAMS AT 20A, 30A, 40A, 80A, 158A GEV ← CERN SPS (NA49, NA45, NA57, NA60) →

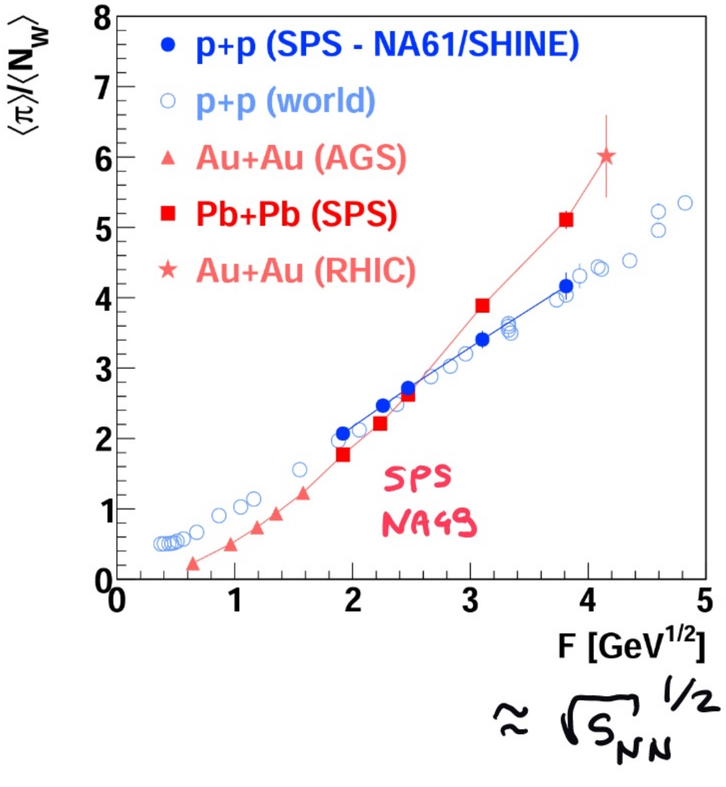
  → 2010 - 2014: Au BEAMS AT EQUIV. 30A - 200A GEV ← BNL RHIC (STAR, PHENIX : BESI)

CRITICAL STRUCTURES

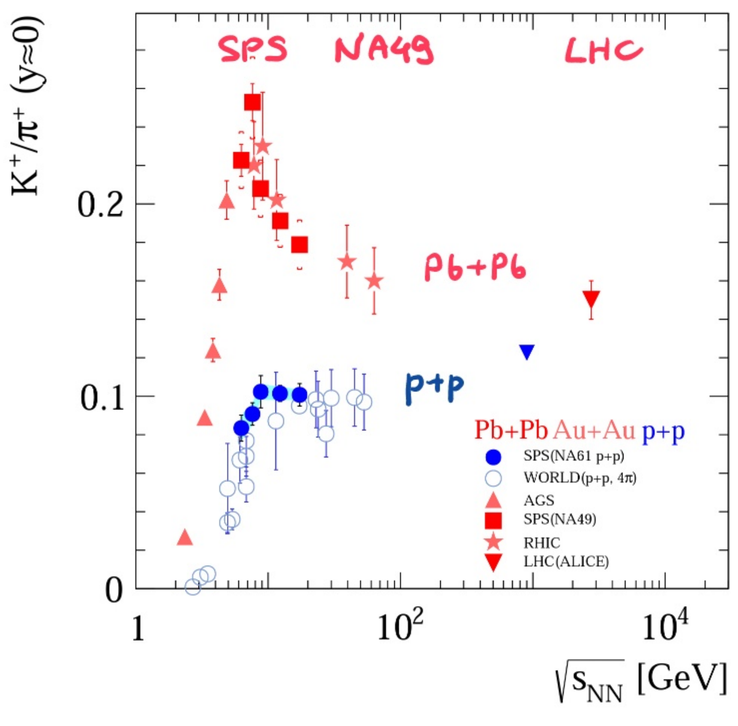
PHASE I: SEARCHING FOR ONSET OF QGP CREATION

OBSERVED ANOMALIES IN COLLISION ENERGY DEPENDENCE ARE CONSISTENT WITH THE QGP ONSET AT LOW SPS ENERGIES

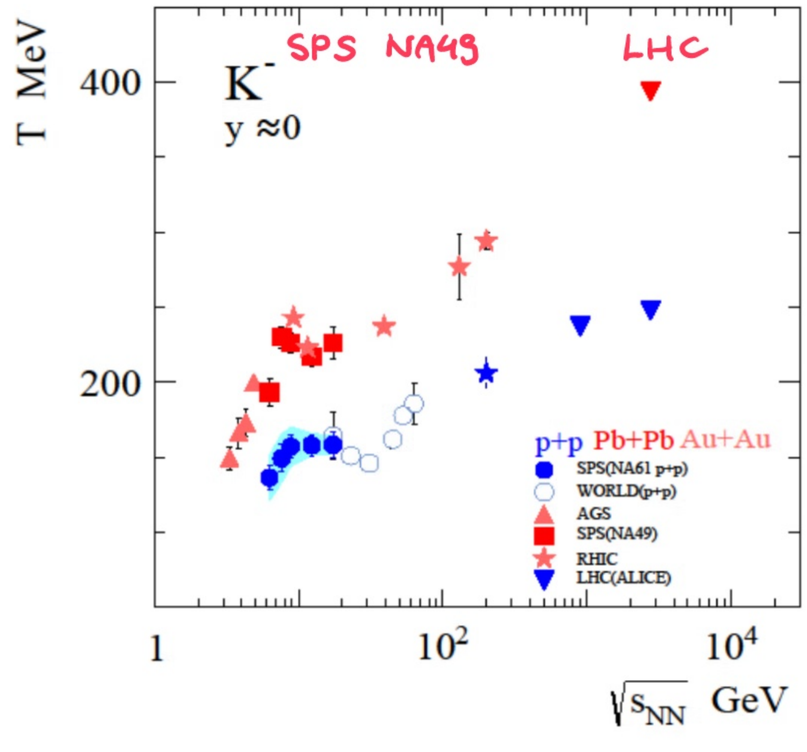
PION YIELD ENHACEMENT



STRNGENESS/PION SUPPRESSION



SOFTENING OF COLLECTIVE FLOW

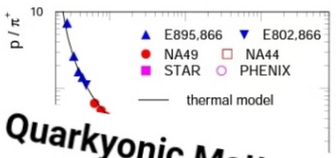


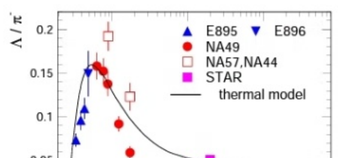
DAVID AND "HORN"

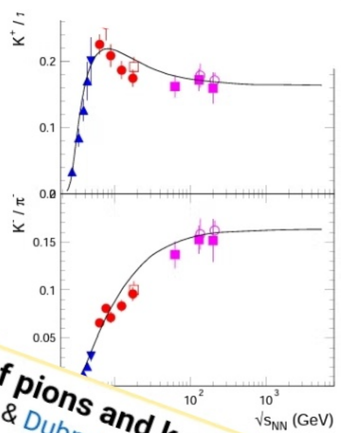
Hadron Production in Ultra-relativistic Nuclear Collisions: Quarkyonic Matter and a Triple Point in the Phase Diagram of QCD

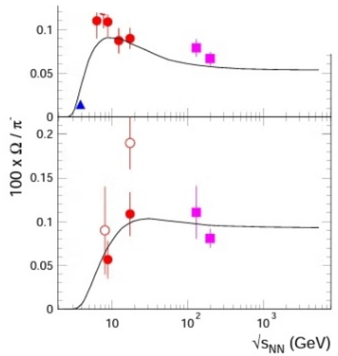
A. Andronic (Darmstadt, GSI) *et al.*. Nov 2009. 28 pp.

Published in **Nucl.Phys. A837 (2010) 65-86**





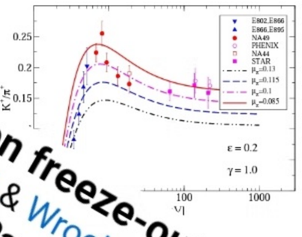


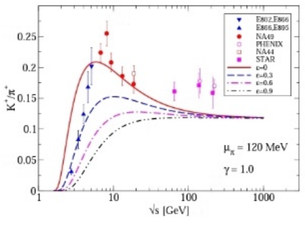


Mott-Anderson freeze-out and the strange matter "horn"

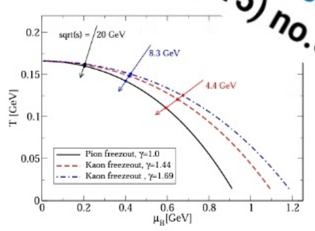
M. Naskret (CERN & Wroclaw U.), D. Blaschke (Wroclaw U. & Dubna, JINR), A. Dubinin (Wroclaw U.). Jan 7, 2015. 5 pp.

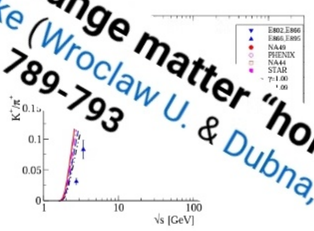
Published in **Phys.Part.Nucl. 46 (2015) no.5, 789-793**





n_{K^+}/n_{π^+} according to Eqs. (8)-(9) compared with e… nonequilibrium parameter μ_π (left) and varying str… (right).



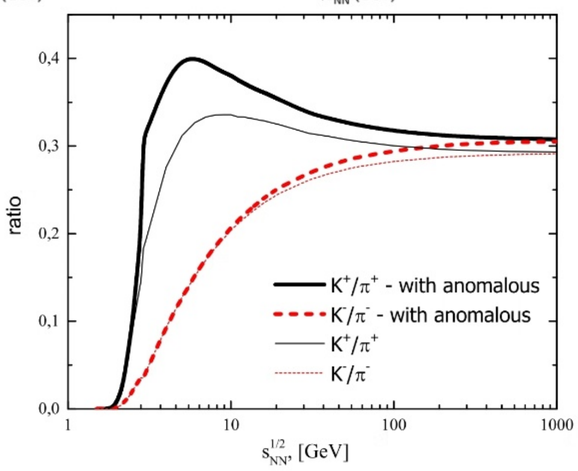


Mott dissociation of pions and kaons in

D. Blaschke (Wroclaw U. & Dubna, JINR & Moscow

14 pp.

Published in **Phys.Rev. D96 (2017) no.9, 094008**



Wroclaw U.), A. Radzhabov (

CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT

APRIL 2004: WORKSHOP IN ECT TRENTO:

→ RESULTS ARE CONSISTENT WITH QGP ONSET IN Pb+Pb AT LOW SPS ENERGIES →

→ SEARCH FOR CRITICAL POINT

→ SCAN IN ENERGY AND NUCLEAR MASS NUMBER

CERN COURIER SEPT. 2004

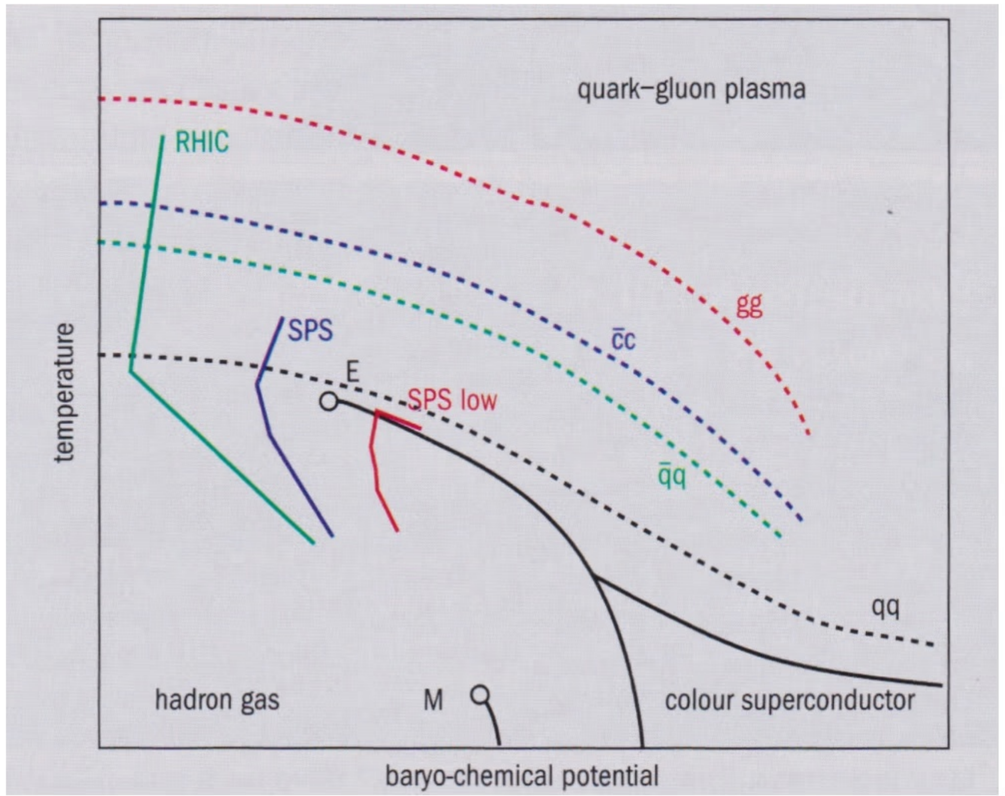
HEAVY IONS

When quarks and gluons become free

Recent results and future experiments were the topics in a workshop to look into exactly what happens as strongly interacting matter becomes deconfined.

MG SEYBOTH SHURYAK

BEGINING OF CRITICAL POINT AND ONSET OF DECONFINEMENT WORKSHOPS



DAVID AND CPOD

6th International Workshop on Critical Point and Onset of Deconfinement

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- A.S. Sorin - Vice-chairman
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Critical Point and Onset of Deconfinement 2016 (17)

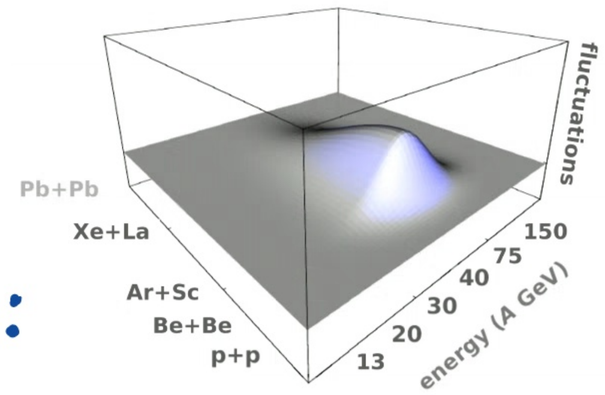
and

Working Group Meeting of COST Action MP1304

Wrocław, Poland
May 30th - June 4th, 2016

CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT



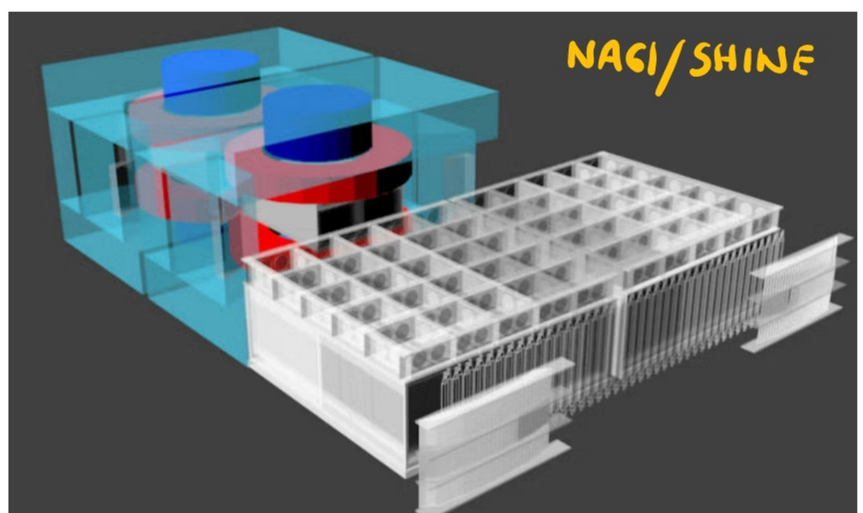
PREDICTED SIGNALS:

- MAXIMUM OF FLUCTUATIONS IN (COLLISION ENERGY) - (NUCLEAR MASS NUMBER) PLANE:
  - INTERMITTENCY AND PROTON FLUCTUATIONS
    (BIALAS, HWA 1991, ANTONIOU, DIAKONOS, KAPOYANIS 2006, STEPHANOV 2011)
  - PION p_T-N FLUCTUATIONS
    (STEPHANOV, RAJAGOPAL, SHURYAK 1998)

MEASUREMENTS:

- 2009 - 2018: SCAN IN $\sqrt{s_{NN}}$ - A
  (NA61/SHINE AT CERN SPS)

- 2019 - 2020: SCAN IN $\sqrt{s_{NN}}$ WITH Au
  (STAR, PHENIX AT BNL RHIC; BES I/II)

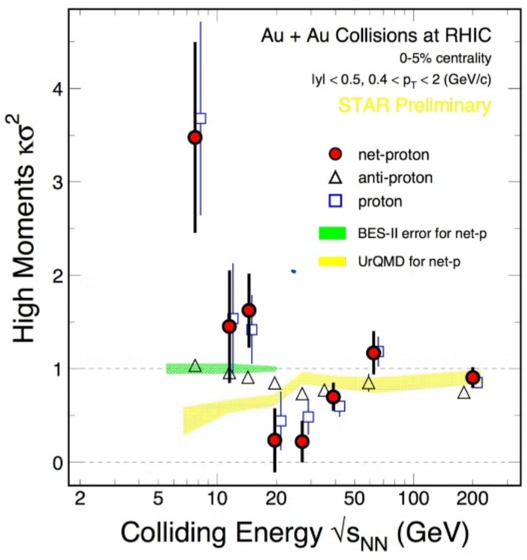


CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT

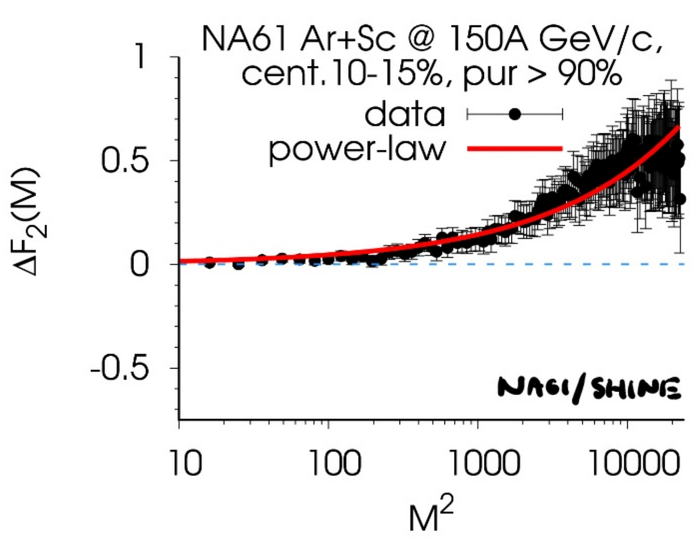
CP INDICATIONS → DIFFERENT ENERGIES/REACTIONS

HIGHER ORDER MOMENTS



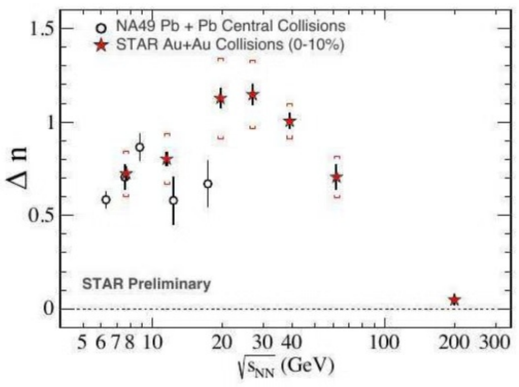
≈ 7 GeV

PROTON INTERMITTENCY



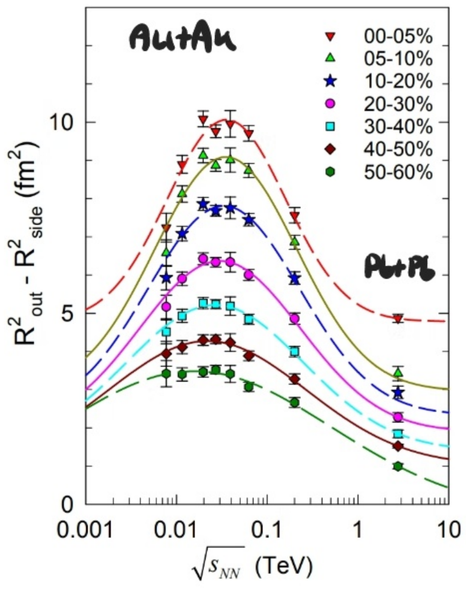
≈ 17 GeV

LIGHT IONS



≈ 20 GeV

SHORT-RANGE CORRELATIONS



≈ 50 GeV

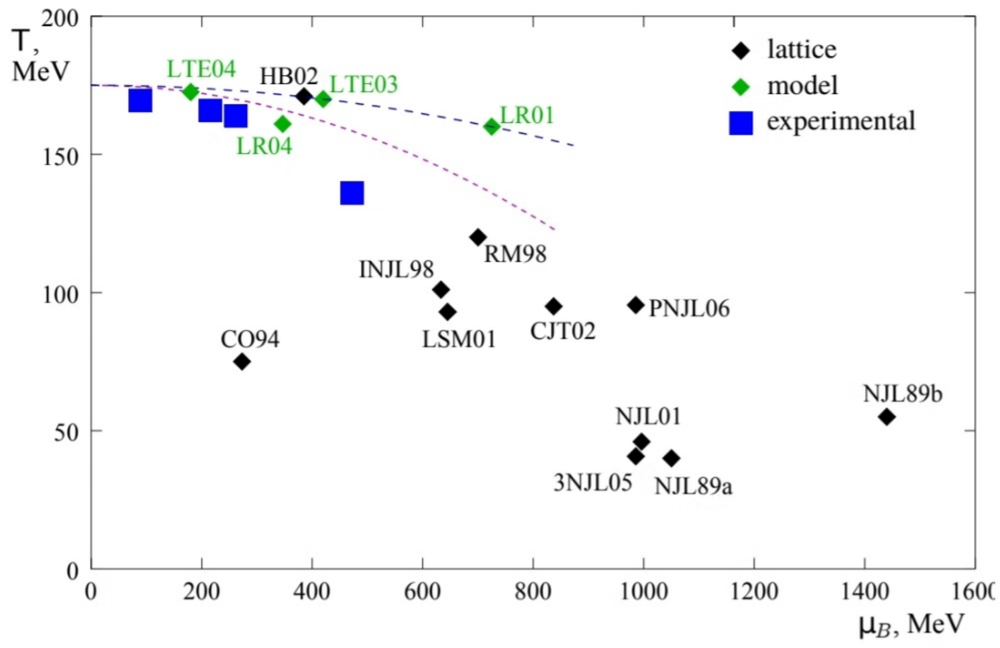
CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT

AS FOR NOW EXPERIMENTAL AND THEORETICAL RESULTS ARE INCONCLUSIVE / CONFUSING

CZAPLWICZ SQM 2019

- 4^{th} moment of net-proton dist.: ≈ 7 GeV (Au+Au)
- Proton intermittency: ≈ 17 GeV (Si+Si and Ar+Sc)
- Light ion production: ≈ 20 GeV (Au+Au)
- Pion interferometry: ≈ 47 GeV (Au+Au)

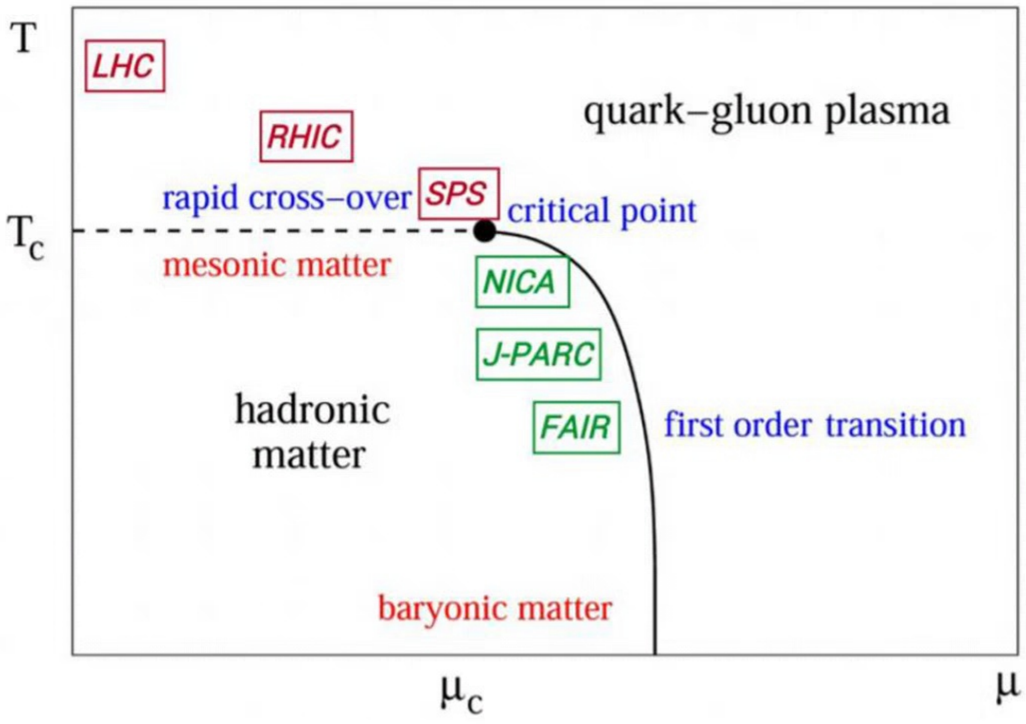


NEW RESULTS EXPECTED SOON FROM NA61/SHINE AND STAR BES II

FUTURE (OF UNCOVERING CRITICAL STRUCTURES)

QGP ONSET AND CHARM QUARKS

LANDSCAPE OF PRESENT AND FUTURE HEAVY ION EXPERIMENTS



POTENTIAL FOR $\langle c\bar{c} \rangle$ MEASURMENTS

LHC and RHIC at high energies ($\sqrt{s_{NN}} \geq 200$ GeV):
measurements in limited phase space due to collider geometry and kinematics

RHIC BES ($3 - 39$ GeV):
measurement not under consideration

NICA (< 11 GeV):
under consideration during stage 2

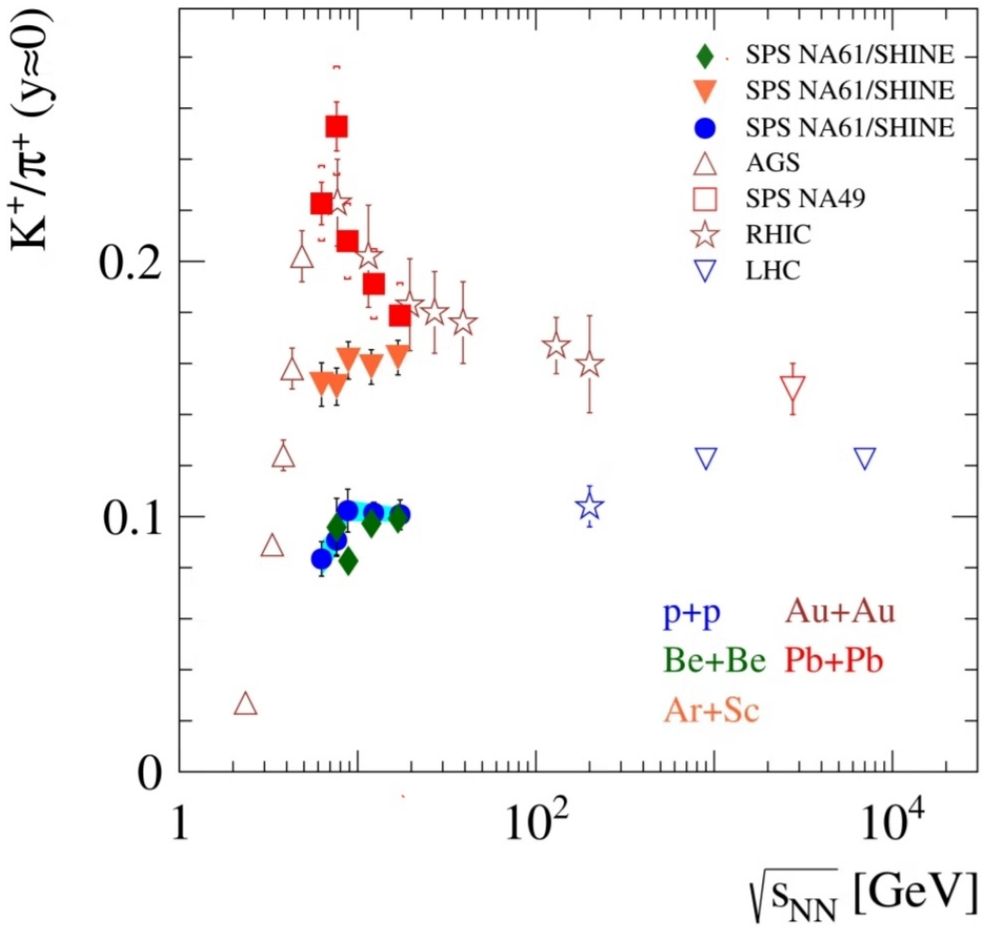
J-PARC (< 6 GeV) :
maybe possible after 2025

FAIR SIS-100 (< 5 GeV):
not possible at SIS-100,

NAGI/SHINE (8, 17 GeV)
PLANNED IN 2021-24

FUTURE (OF UNCOVERING CRITICAL STRUCTURES)

ONSET OF FIREBALL - RECENT NA61/SHINE DISCOVERY



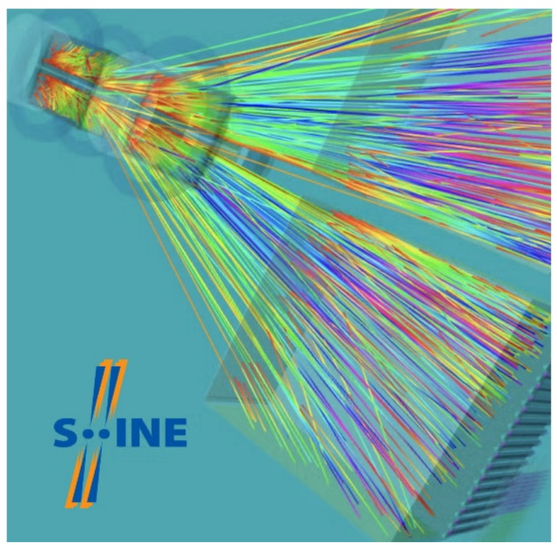
Ar+Sc ≈ Pb+Pb

Be+Be ≈ ≈ p+p

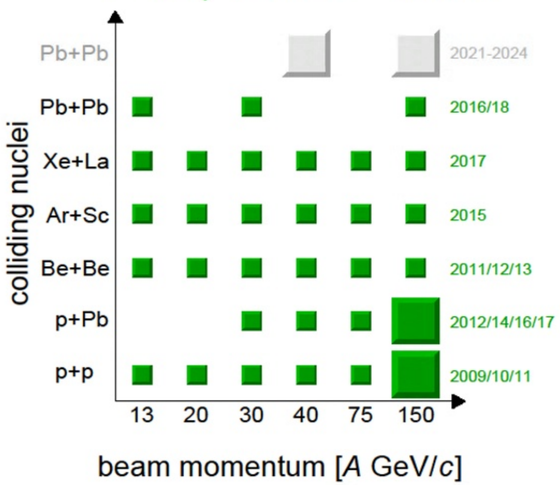
STATISTICAL MODELS

A ↑ ONSET OF FIREBAL

STRING - RESONANCE MODELS

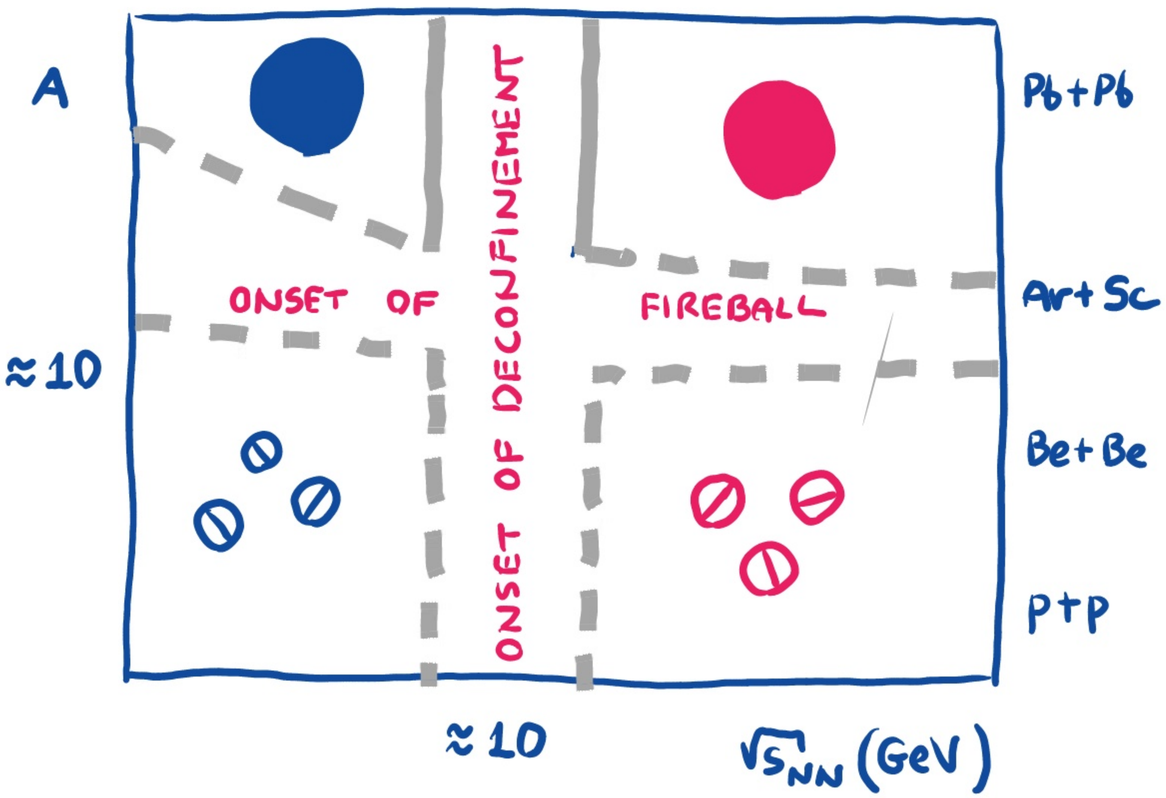


NA61/SHINE DATA



FUTURE (OF UNCOVERING CRITICAL STRUCTURES)

ONSET OF FIREBALL → DETAILED SCAN IN (NUCLEAR MASS NUMBER)-(COLLISION ENERGY) SHOULD BE POSSIBLE AT:



NICA (< 11 GeV): 2022+

FAIR (< 5 GeV): 2025+

SPS (5-17 GeV): 2025+

J-PARC (< 6 GeV): ?

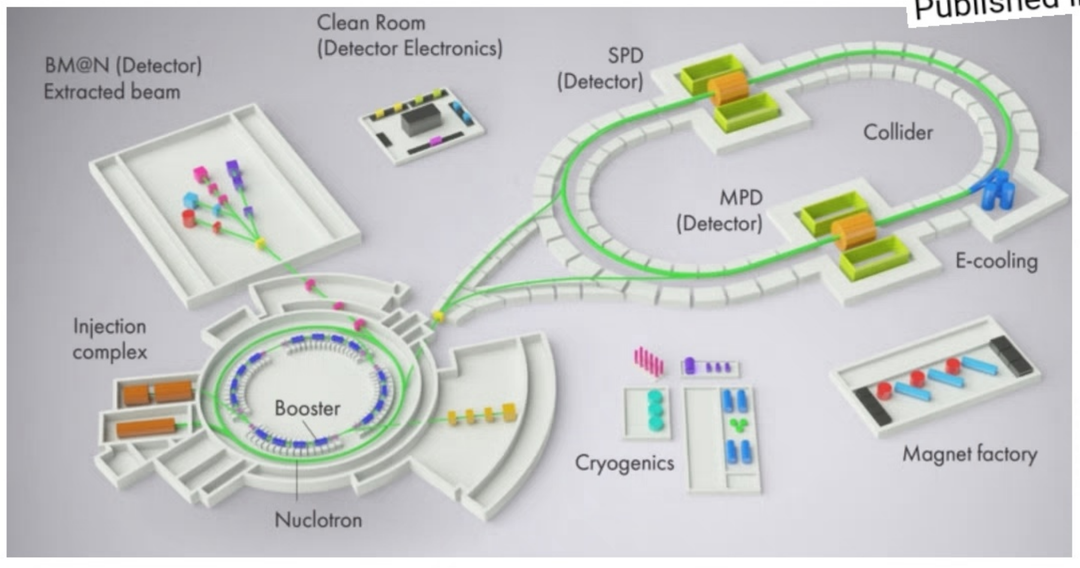
DAVID AND NICA

The European Physical Journal A
Exploring strongly interacting matter at high densities - NICA White Paper

David Blaschke, Jörg Aichelin, Elena Bratkovskaya, Volker Friese, Marek Gazdzicki, Jørgen Randrup, Oleg Rogachevsky, Oleg Teryaev and Viacheslav Toneev

Medium effects on freeze-out of light clusters at NICA energies
G. Röpke (Rostock U. & Moscow Phys. Eng. Inst.), D. Blaschke (Moscow Phys. Eng. Inst. & Dubna, JINR & Wroclaw U.), Kurchatov Inst., Moscow), Iu Karpenko (SUBATECH, Nantes), O.V. Rogachevsky (Dubna, JINR), H.H. Wolter (Munich U.)
Published in **Phys.Part.Nucl.Lett. 15 (2018) no.3, 225-229**

Recent selected theory developments for NICA
David Blaschke (Dubna, JINR & Moscow Phys. Eng. Inst. & Wroclaw U.).
Published in **EPJ Web Conf. 138 (2017) 01004**



Light cluster production at NICA
N. -U. Bastian (Wroclaw U.), P. Batyuk (Dubna, JINR), D. Blaschke (Dubna, JINR & Moscow Phys. Eng. Inst. & Wroclaw U.) Inst., Moscow & Moscow Phys. Eng. Inst.), Iu. Karpenko (BITP, Kiev & INFN, Florence), G. Röpke (Moscow Phys. Eng. Inst (LMU Munich (main)). Aug 9, 2016. 7 pp.
Published in **Eur.Phys.J. A52 (2016) no.8, 244**

The MPD detector at the NICA heavy-ion collider at JINR

Kh.U. Abraamyan [a], S.V. Afanasiev [a], V.S. Alfeev [a], N. Anfimov [a], D. Arkhipkin [a], P.Zh. Aslanyan [a], V.A. Babkin [a], M.I. Baznat [g], S.N. Bazylev [a], D. Blaschke [a], D.A. Bliznyuk [i], D.N. Bogoslovsky [a], I.V. Boguslavski [a], E.E. Boos [c], V.V. Borisov [a], V.N. Borshchov [j], K.A. Bugaev [f], A.V. Butenko [a] ... Yu.R. Zulkarneeva [a]

SUMMARY

ONSET OF QGP (DECONFINEMENT):

- OBSERVED IN PbtPb/AutAu AT ≈ 8 GEV (SPS, RHIC BES)
- RESULTS TO BE COMPLETED BY OPEN CHARM MEASURMENTS (SPS, NICA, J-PARC ?)

CRITICAL POINT:

- INCONCLUSIVE INDICATIONS FROM SPS AND RHIC
- COMING RESULTS FROM NA61/SHINE AND STAR BES II SHOULD (AT LEAST PARTLY) REMOVE THE TENSION AND ALLOW TO DEFINE NEXT STEPS

ONSET OF FIREBALL:

- INDICATIONS FROM 2D SCAN AT SPS (NA61/SHINE)
- DETAILED SCAN ($\sqrt{s_{NN}} \lesssim 20$ GEV, $A \lesssim 100$) IS NEEDED (NICA, SPS, SIS100, J-PARC ?)