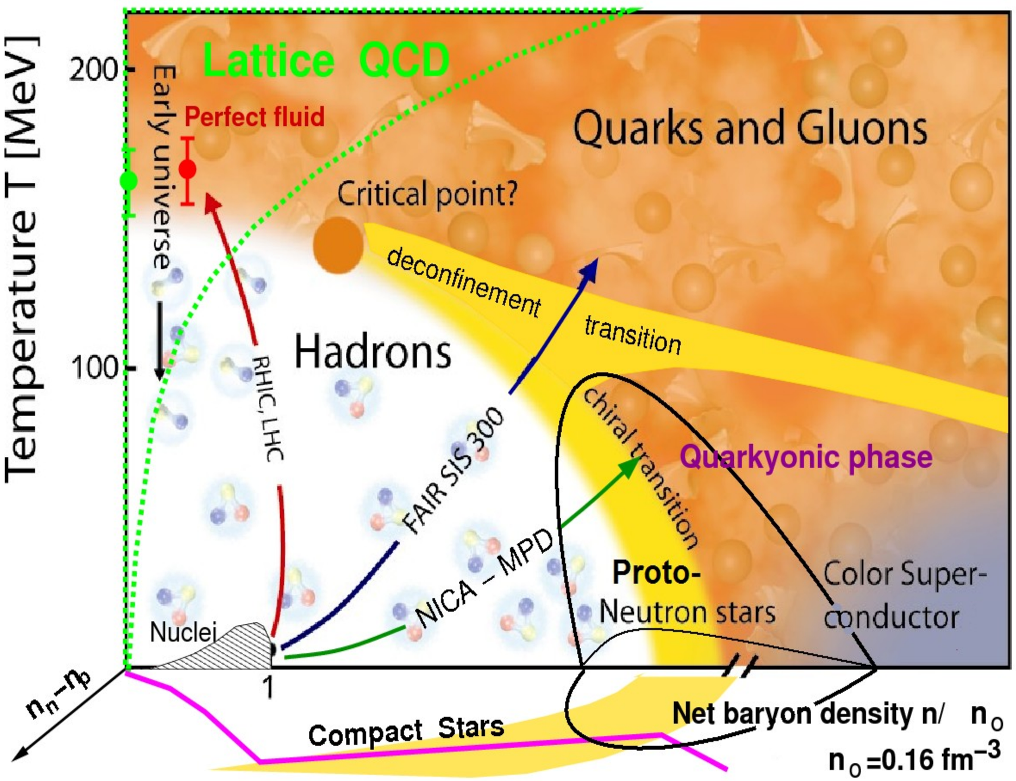
Experimental Exploration of the QCD Phase Diagram

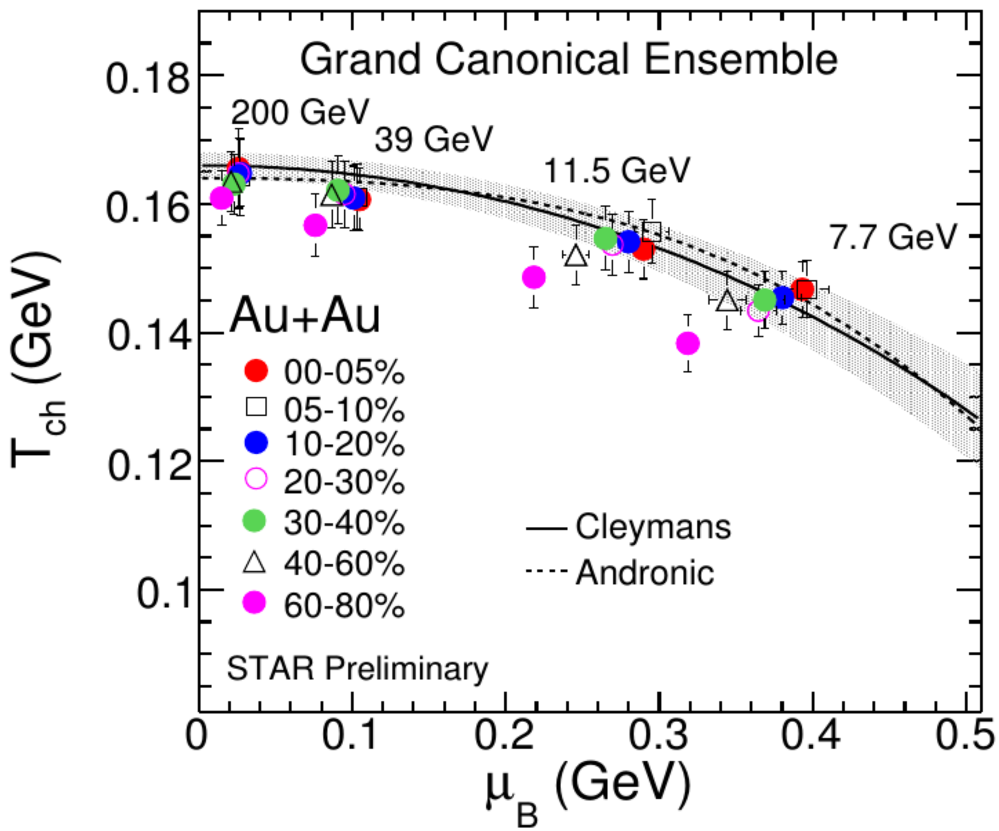
Rogachevsky Oleg
for MPD collaboration

Hadronic matter
under Extreme Conditions
Oct ,31 2016
Dubna

QCD Phase diagram

Grazyna Odyniec
Journal of Physics: Conference Series
455 (2013) 012037



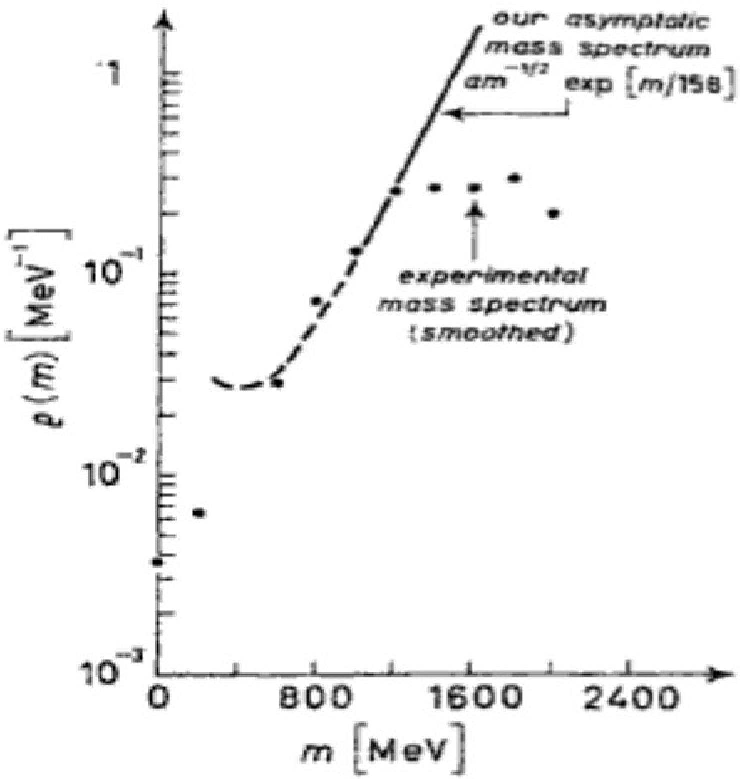


The dependence of T_{ch} on μ_B , fitted with the Grand Canonical approach in THERMUS Model

Hagedorn temperature

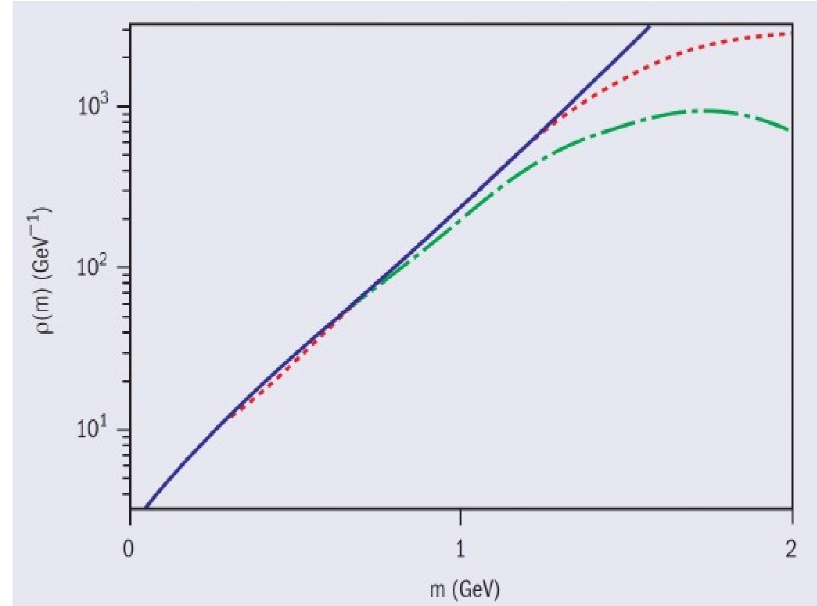
Statistical Thermodynamics of Strong Interactions at High Energies.

R. HAGEDORN
CERN - Geneva



$$\bar{\varrho}_{exp}(m) = \frac{1}{\sqrt{2\pi\tau^2}} \sum_{i=1}^{N} \nu_i \exp\left[-\frac{(m-m_i)^2}{2\tau^2}\right],$$

where the sum goes from the pion mass to the highest known resonances.



The smoothed mass spectrum of hadronic states as a function of mass. Experimental data: long-dashed green line with the

1411 states known in 1967; short-dashed red line with the 4627 states of mid '90s.

The solid blue line represents the exponential fit yielding T_H = 158 MeV.

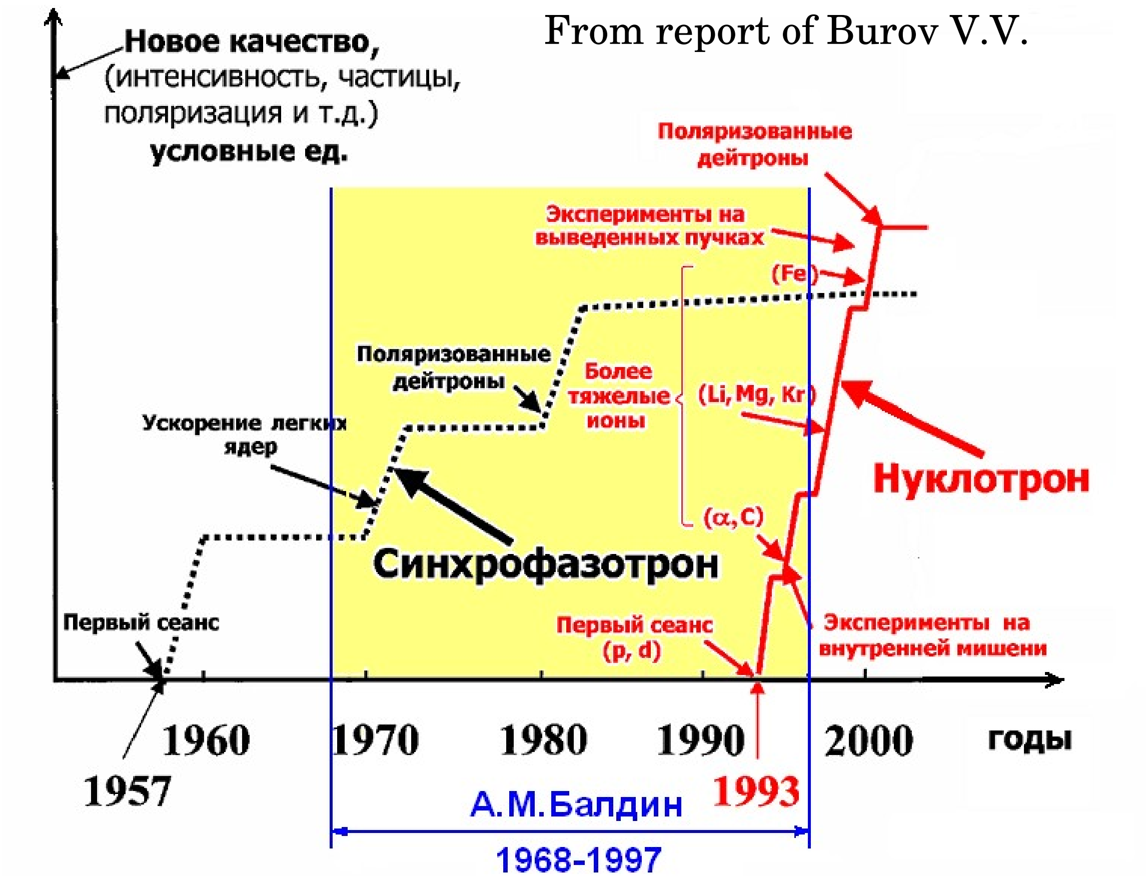
Depending on the preexponential factor, a range T_H = 150 ± 15 MeV is possible.

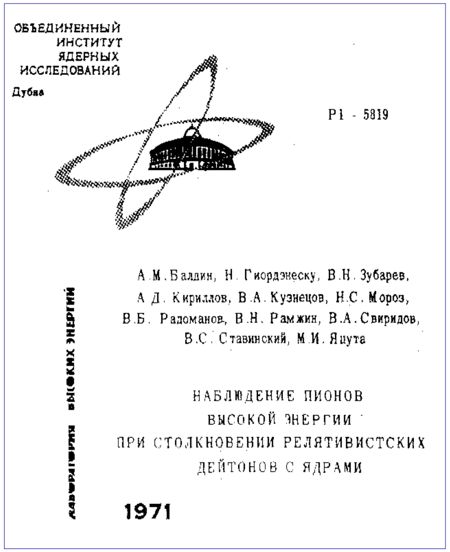
Accelerators for Relativistic Nuclear Physics

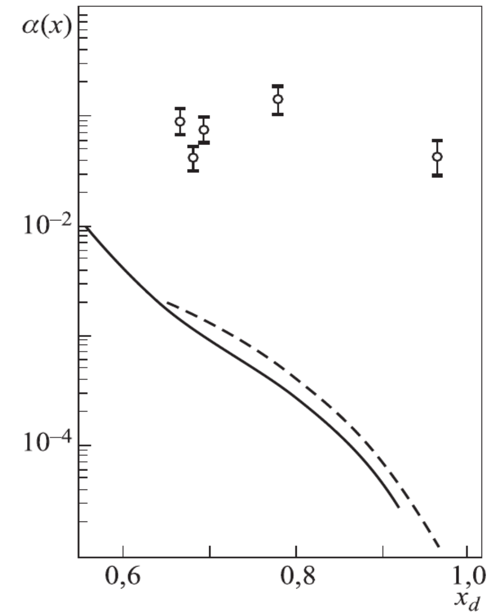
Accelerator	Place	Ion periods	Energy	Projectiles
Synchro-Phasatron	JINR Dubna	1971 - 1985	3.6 AGeV	d, He, C
Bevalac	LBNL Berkeley	1984 - 1993	< 2AGeV	C,Ca,Nb, Ni,Au,...
AGS	BNL, Brookhaven	1986 - 1994	14,5/11,5 AGeV	Si, Au
SPS	CERN, Geneva	1986 - 2002	200/158 AGeV	O,S,In,Pb
SIS 18	GSI,Darmstadt	1992 - today	2 AGeV	Kr,Au
Nuclotronn	JINR Dubna	1993 - today	< 4.5 AGeV	p, d, He,C,Li, Mg, Kr
RHIC	BNL, Brookhaven	2000 - today	$\sqrt{S_{NN}}$ = 200 GeV	Cu, Au
LHC	CERN, Geneva	2010	$\sqrt{S_{NN}}$ = 5.5 TeV	Pb
NICA	JINR Dubna	2019	$\sqrt{S_{NN}}$ = 4 -11 GeV	p - Au
SIS 100	GSI,Darmstadt	2025	2 – 11 AGeV	Au

Relativistic nuclear physics in JINR LHE

From report of Burov V.V.







$$\alpha(x_d) = \frac{d^2\sigma(d + \mathrm{Cu} \to \pi^- + \ldots)}{d^2\sigma(p + \mathrm{Cu} \to \pi^- + \ldots)}$$

Fixed Target Experiments at Relativistic Energies

Beam energies: 100A MeV – 2A GeV

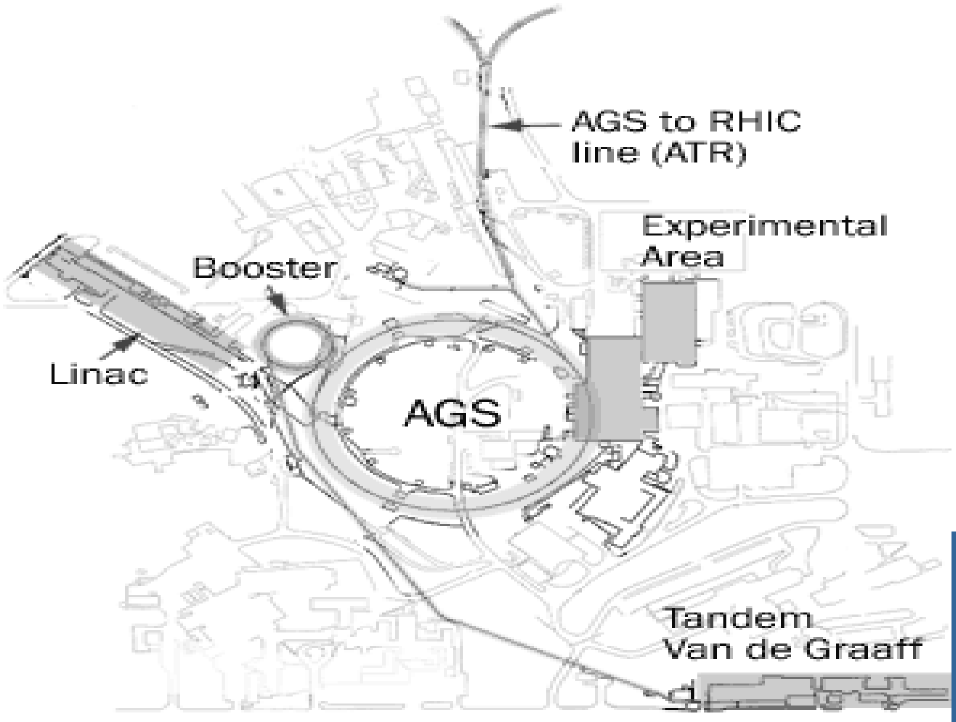
Pioneering experiments
Synchrophasotron – Dubna (1975 – 1985) DISK, 2-m B.C.
BEVALAC: Plastic Ball and Streamer Chamber (1984 - 1986)

2-nd generation experiments
SIS-100 GSI: FOPI, KAOS (finished),
HADES (1990 – today)
BEVALAC: EOS-TPC, DLS (1990 – 1992)

Physics:
Collective effects => Discovery and investigation of flow effects
Equation of state (EOS) => Study of compressibility of dense nuclear matter
In-medium modifications => Kaons, low mass di-leptons

Basic result:
Nuclear matter can be compressed and high energy densities can be achieved

Alternating Gradient Synchrotron



BNL-AGS (1986 – 2002)

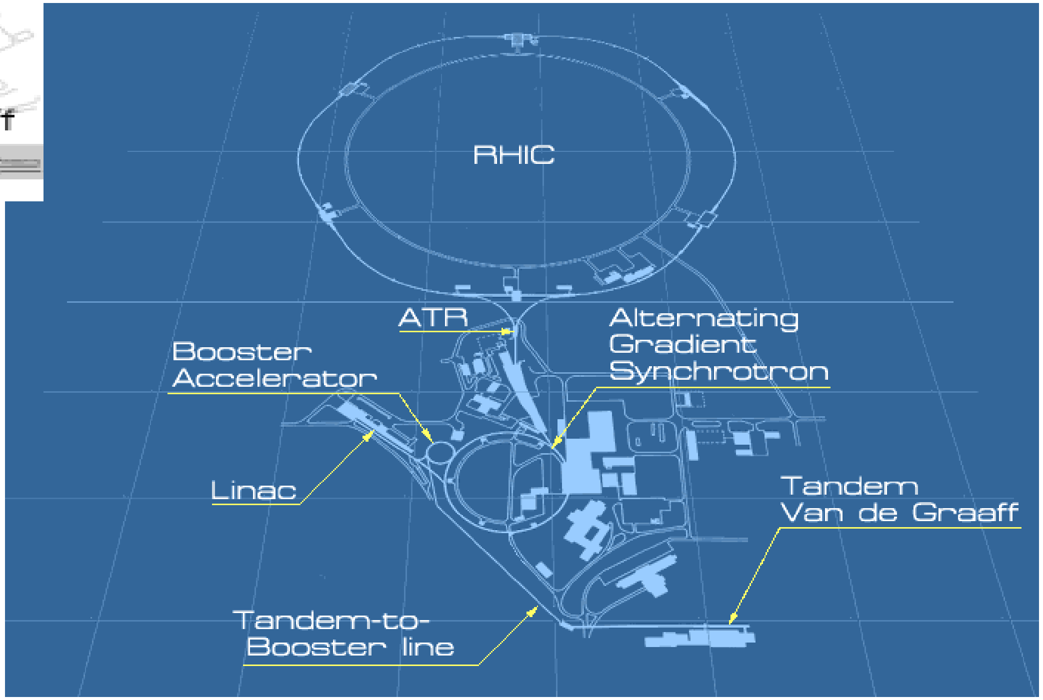
(1986 – 1991):

^{16}O & ^{28}Si, E_{lab}^{max} = 14.5 A GeV

1991: AGS Booster, to have more intense proton beams and heavy ions at the AGS

(1992 – 1994): "heavy" Au ions

^{197}Au, $E_{lab}^{max} = 11.5A$ GeV



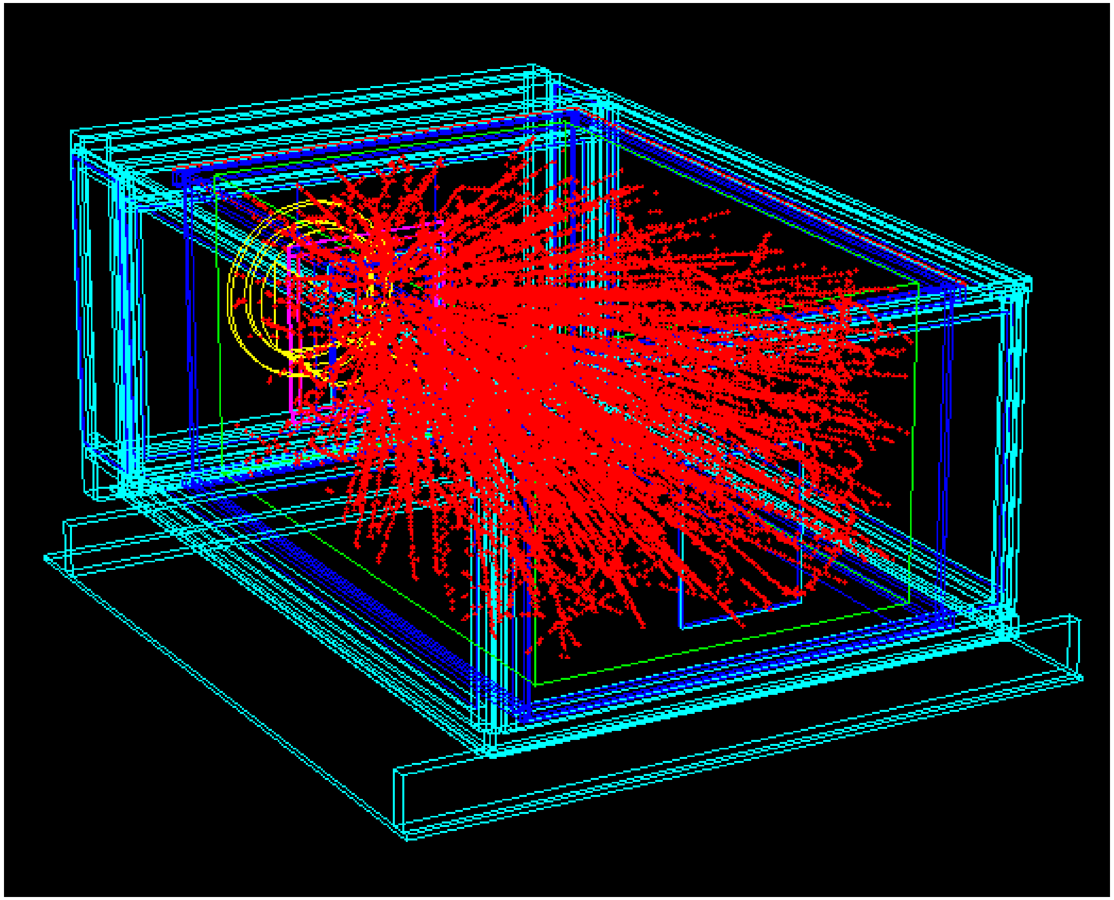
Heavy Ion Experiments at the AGS

5 large experiments: E802/866/917, E810, E814/877, E864,E895.

Experiment	Beam	Technology	Observables
E802	Si	Single arm magnetic spectrometer	Spectra (π, p, $K^{\pm}$), HBT
E810		TPCs in magnetic field	Strangeness (K^0_s, Λ)
E814		Magnetic spectrometer + calorimeters	Spectra (p) + E_t
E859		E802 + 2^{nd} level PID trigger	Strangeness (Λ)
E866	Au	2 magnetic spectrometers (TPC, TOF)	Strangeness (Kaons)
E877		Upgrade of E814	
E891		Upgrade of E810	
E895		EOS TPC	Spectra (π, p, $K^{\pm}$), HBT
E896		Drift chamber + neutron detector	H^0 Di-baryon, Λ
E910		EOS TPC + TOF	p+A Collisions
E917		Upgrade of E866	

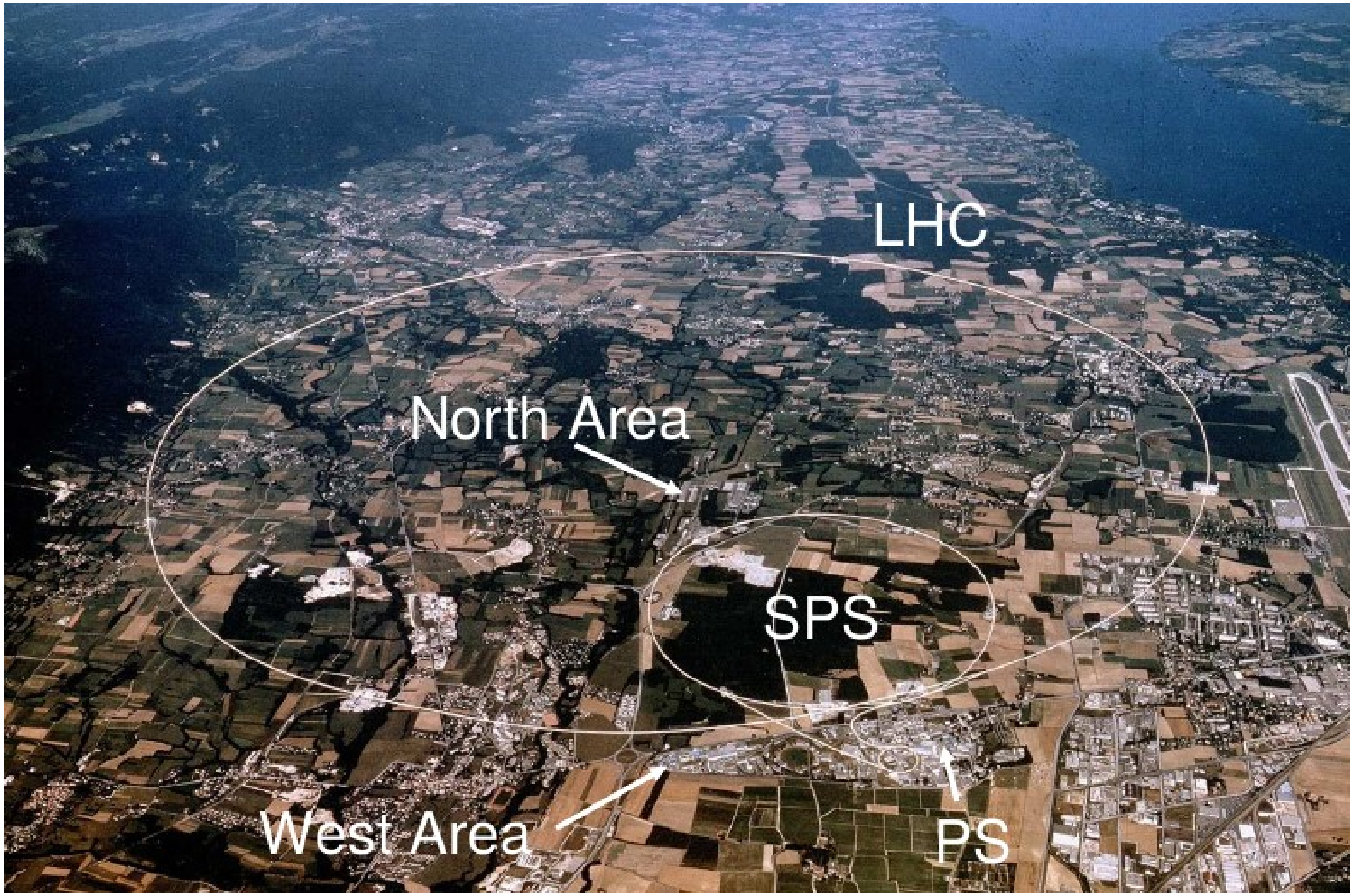
E895/910 experiment

- EOS TPC; developed for Bevalac experiment
- Spectra ($\pi^{\pm}$, p, $K^{\pm}$), particle correlation, HBT



CERN accelerator complex

CERN-SPS (1986 – 2004): $\sqrt{s}$ = 17 GeV, Pb + Pb collisions
7 large experiments: WA80/98, NA35/49/61, NA38/50/60,
NA44, NA45/CERES, WA97/NA57, NA52.

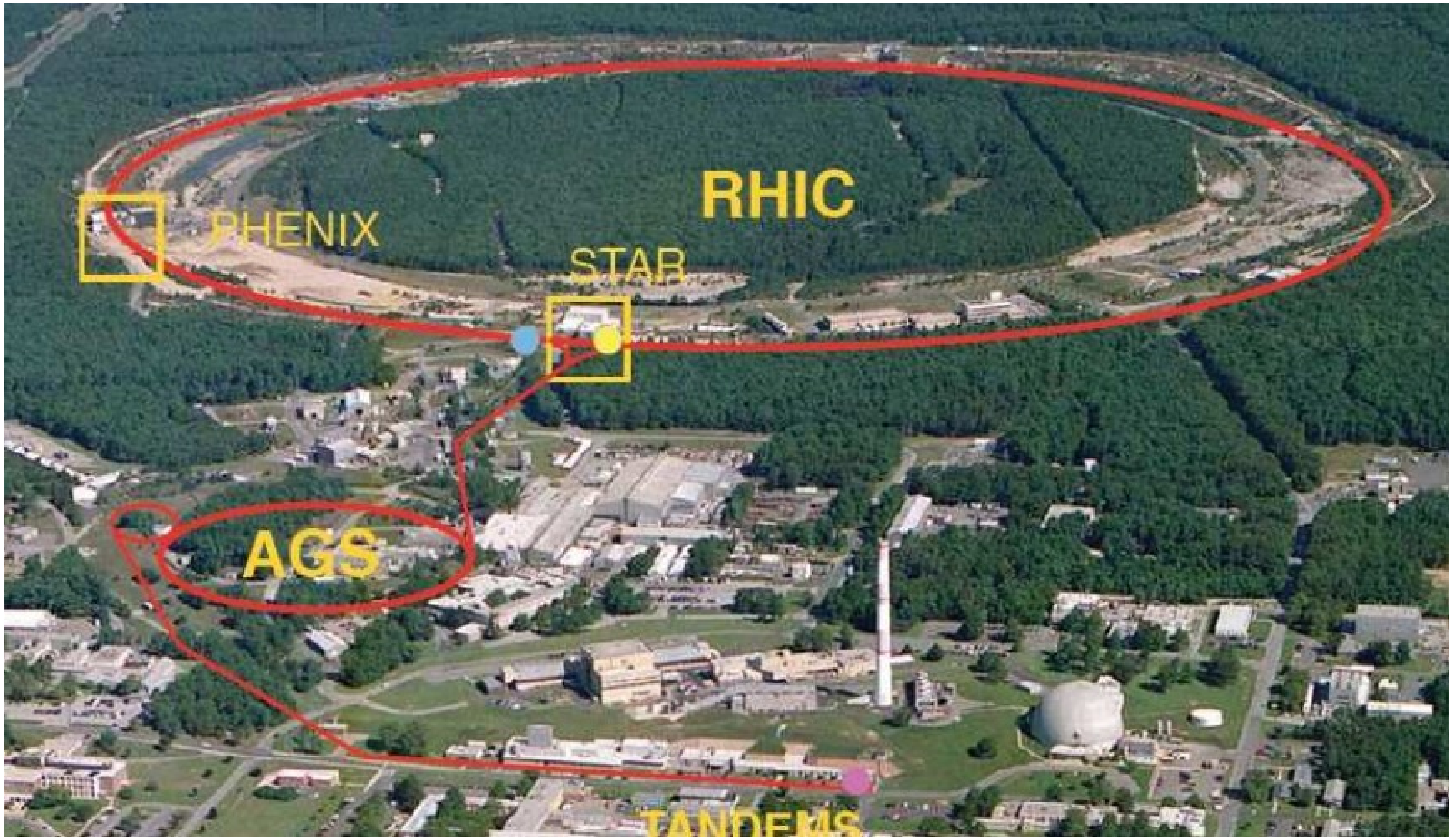


Heavy Ion Experiments at the SPS

Experiment	Beam	Technology	Observables
NA34	^{16}O, ^{32}S	Muon spectrometer + calorimeter	Di-leptons, p, π, K, γ
NA35		Streamer chamber	π^-, K^0_s, Λ, HBT
NA36		TPC	K^0_s, Λ
NA38		Di-muon spectrometer (NA10)	Di-leptons, J/ψ
WA80/WA93		Calorimeter + Plastic Ball	γ, π^0, η
WA85		Mag. spectrometer with MWPCs	K^0_s, Λ, Ξ
WA94		WA85 + Si strip detectors	K^0_s, Λ, Ξ
NA44	^{16}O, ^{32}S, ^{208}Pb	Single arm magnetic spectrometer	π, $K^\pm$, p
NA45		Cherenkov + TPC	Di-leptons (low mass)
NA49	^{208}Pb	Large volume TPCs	π, $K^\pm$, p, K^0_s, Λ, Ξ, Ω, ...
NA50		NA38 upgrade	Di-leptons, J/ψ
NA52		Beamline spectrometer	Strangelets
WA97		Mag. spectrometer with Si tracker	h^-, K^0_s, Λ, Ξ, Ω
WA98		Pb-glass calorimeter + mag. spectrom.	γ, π^0, η
NA57		WA97 upgrade	h^-, K^0_s, Λ, Ξ, Ω
NA60	^{114}In	NA50 + Si vertex tracker	Di-leptons, J/ψ

RHIC

BNL-RHIC (from 2000):
$\sqrt{s}$ = 200 GeV, Au + Au collisions
4 large experiments: BRAHMS, PHENIX, PHOBOS, STAR.



Heavy Ion Experiments at RHIC

Experiment	Technology	Observables
STAR	TPC and Si vertex tracker (+ EMCAL, TOF)	π, $K^{\pm}$, p, K^0_s, Λ, Ξ, Ω, …
PHENIX	Drift chambers, calorimeter, RICH, TOF, muon spectrometer	γ, π^0, η, J/ψ, $K^{\pm}$, p, …
BRAHMS	2 arm magnetic spectrometer	π, $K^{\pm}$, p (large acceptance)
PHOBOS	Magnetic spectrometer with Si tracker	charged particles (large acceptance)

The Quark-Gluon-Plasma is Found at RHIC

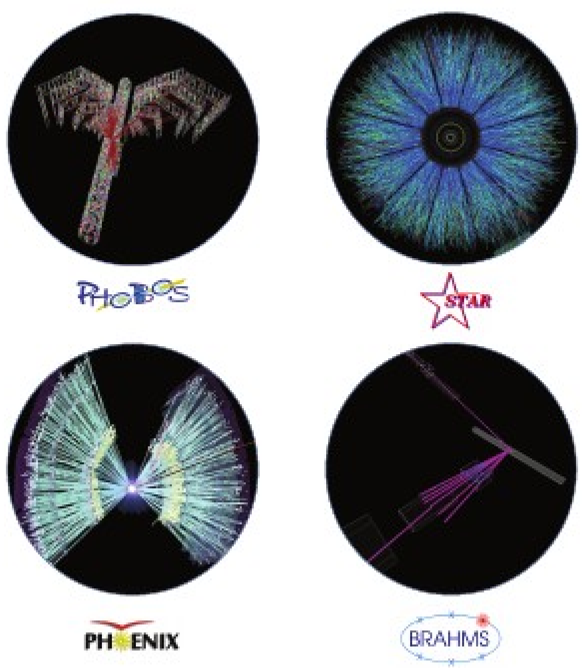
BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005



Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. DEPARTMENT OF ENERGY

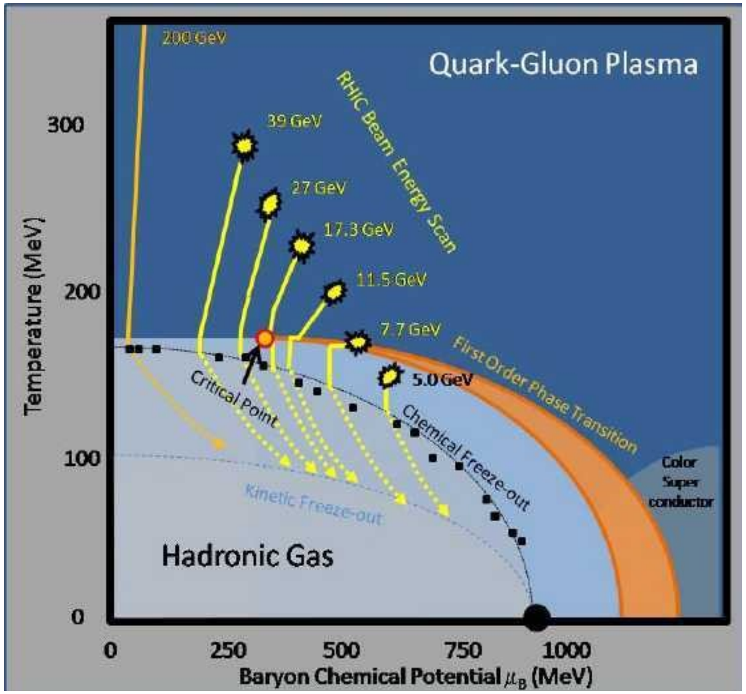
BROOKHAVEN NATIONAL LABORATORY

CONTENTS

The early measurements have revealed compelling evidence for the existence of a new form of nuclear matter at extremely high density and temperature – a medium in which the predictions of QCD can be tested, and new phenomena explored, under conditions where the relevant degrees of freedom, over nuclear volumes, are expected to be those of quarks and gluons, rather than of hadrons. This is the realm of the quark gluon plasma, the predicted state of matter whose existence and properties are now being explored by the RHIC experiments.

STAR BES program (2005)

BES-Short-v8.3_0



Experimental Study of the QCD Phase Diagram and Search for the Critical Point:
Selected Arguments for the Run-10 Beam Energy Scan at RHIC

The STAR Collaboration (B. I. Abelev et al.)

Introduction & Summary

We present an overview of the main ideas that have emerged from discussions within STAR for the Beam Energy Scan (BES). The formulation of this concise and abridged document is facilitated by the existence of a much longer and more comprehensive companion document entitled Experimental Exploration of the QCD Phase Diagram: Search for the Critical Point [1].:

A. A search for turn-off of new phenomena already established at higher RHIC energies; QGP signatures are the most obvious example, but we define this category more broadly. If our current understanding of RHIC physics and these signatures is correct, **a turn-off must be observed in several signatures, and such corroboration is an essential part of the "unfinished business" of QGP discovery [2].**

STAR BES QGP signatures

The particular observables that STAR has identified as the essential drivers of our run plan are:

(A-1) Constituent-quark-number scaling of v_2 , indicating partonic degrees of freedom;
(A-2) Hadron suppression in central collisions as characterized by the ratio R_{CP} ;
(A-3) Untriggered pair correlations in the space of pair separation in azimuth and pseudorapidity, which elucidate the ridge phenomenon;
(A-4) Local parity violation in strong interactions, an emerging and important RHIC discovery in its own right, is generally believed to require deconfinement, and thus also is expected to turn-off at lower energies.

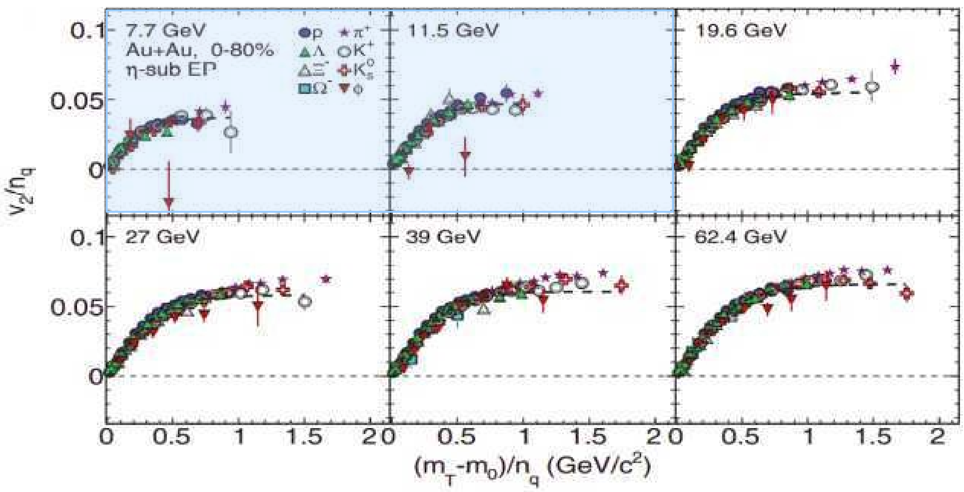
A search for signatures of a phase transition and a critical point. The particular observables that we have identified as the essential drivers of our run plan are:

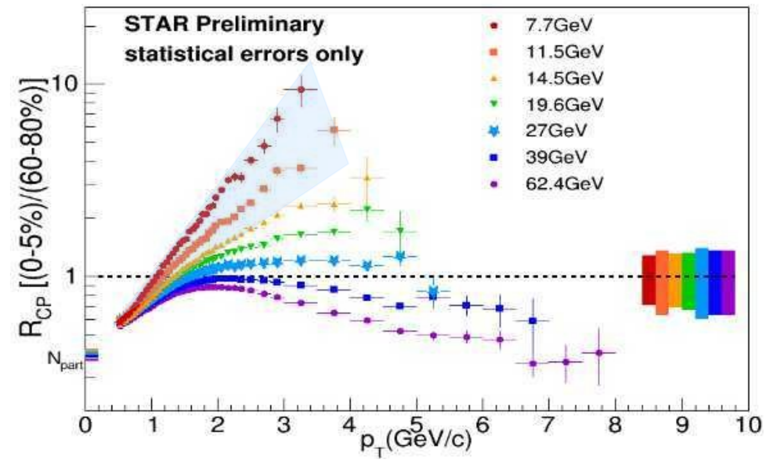
(B-1) Elliptic & directed flow for charged particles and for identified protons and pions, which have been identified by many theorists as highly promising indicators of a “softest point” in the nuclear equation of state;
(B-2) Azimuthally-sensitive femtoscopy, which adds to the standard HBT observables by allowing the tilt angle of the ellipsoid-like particle source in coordinate space to be measured; these measurements hold promise for identifying a softest point, and complements the momentum-space information revealed by flow measurements, and
(B-3) Fluctuation measures, indicated by large jumps in the baryon, charge and strangeness susceptibilities, as a function of system temperature – the most obvious expected manifestation of critical phenomena.

STAR BES I results

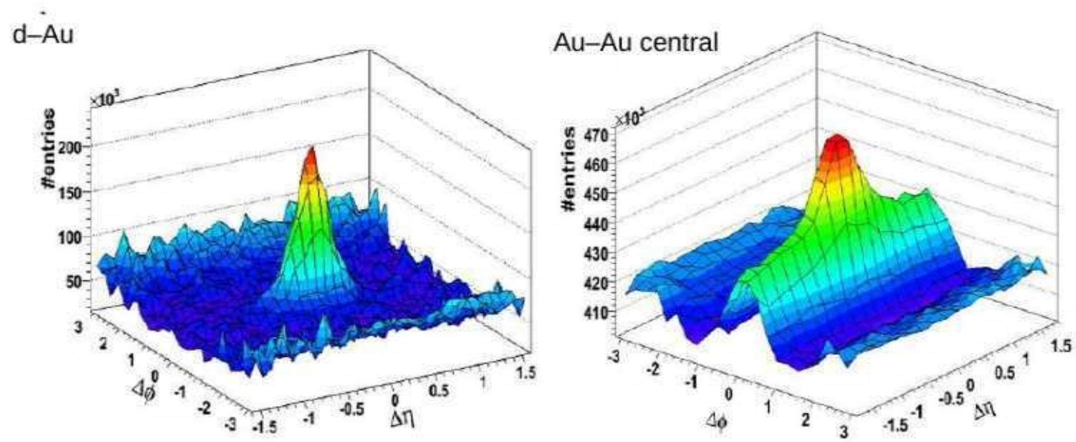
Stephen Horvat Quark Matter 2015,

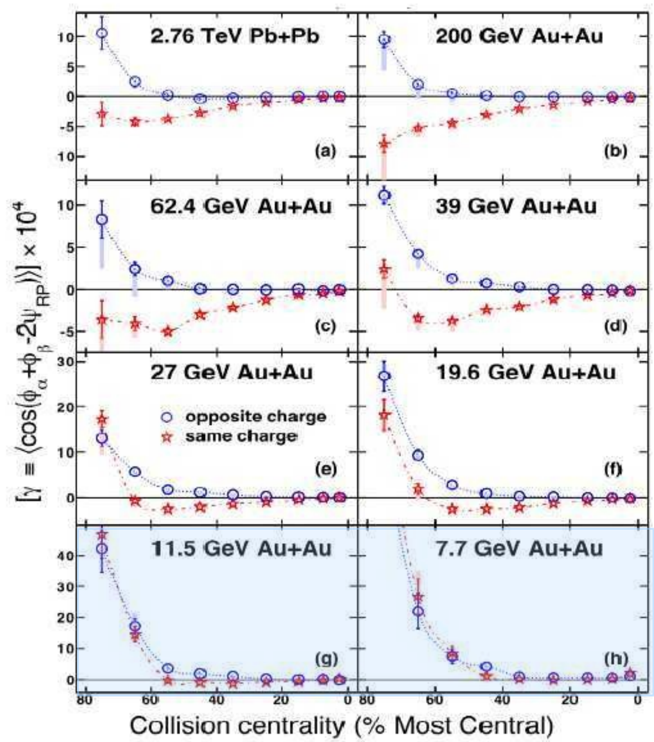
Phys Rev C 88 (2013) 014902





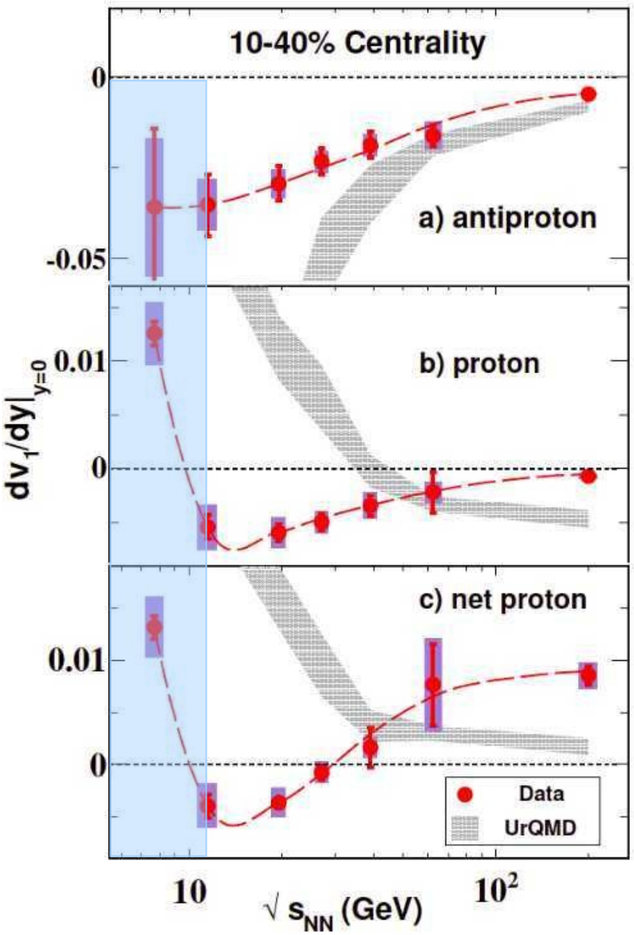
B. Abelev et al., Phys. Rev. C80, 064912 (2009).



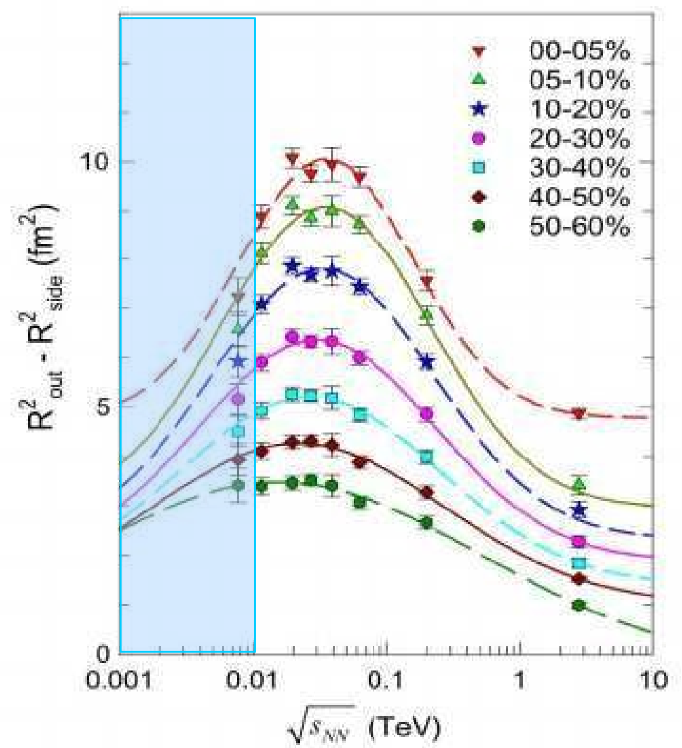


STAR BES I results

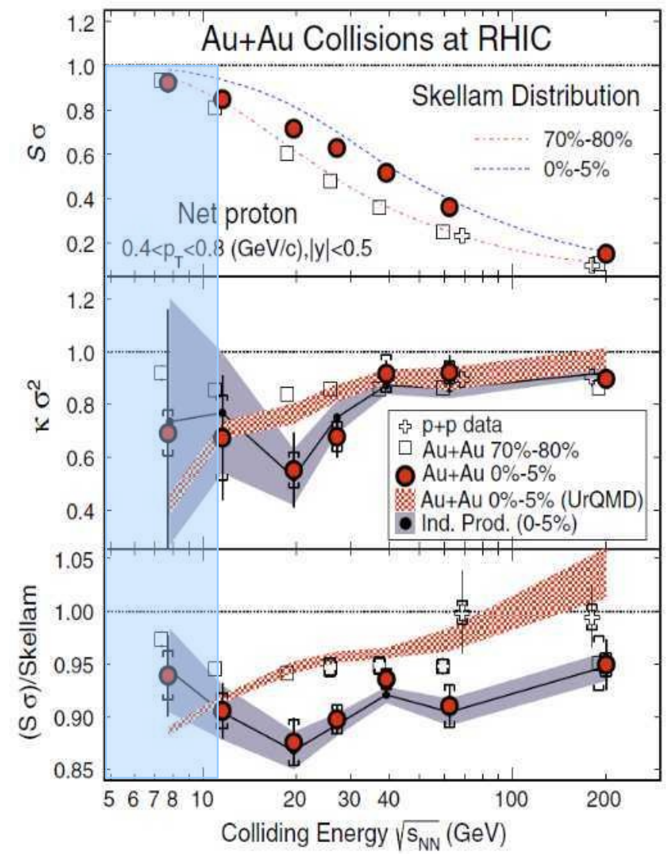
PRL 112 (2014) 162301



R. Lacey, PRL 114, 142301 (2015)



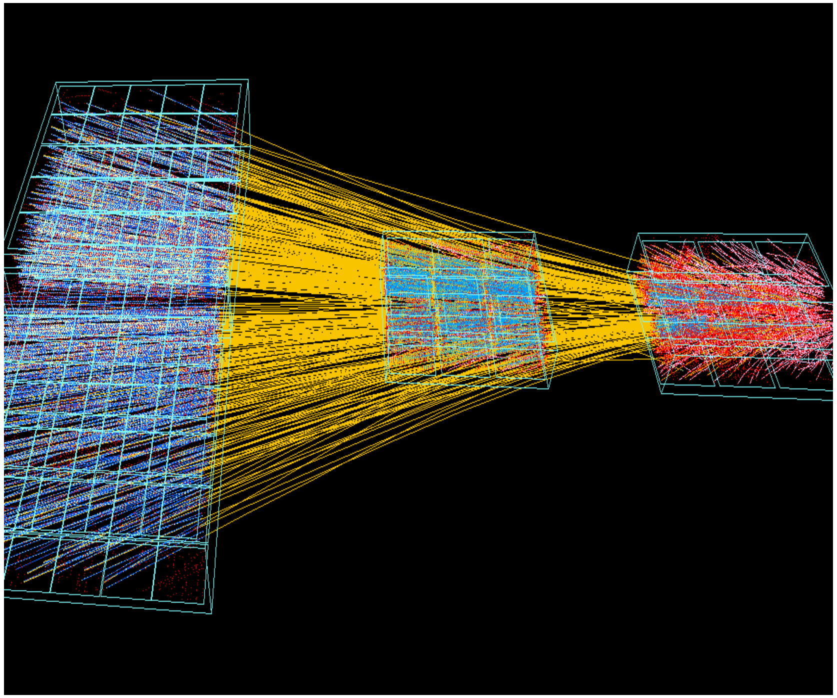
STAR, PRL 112, 032302 (2014)

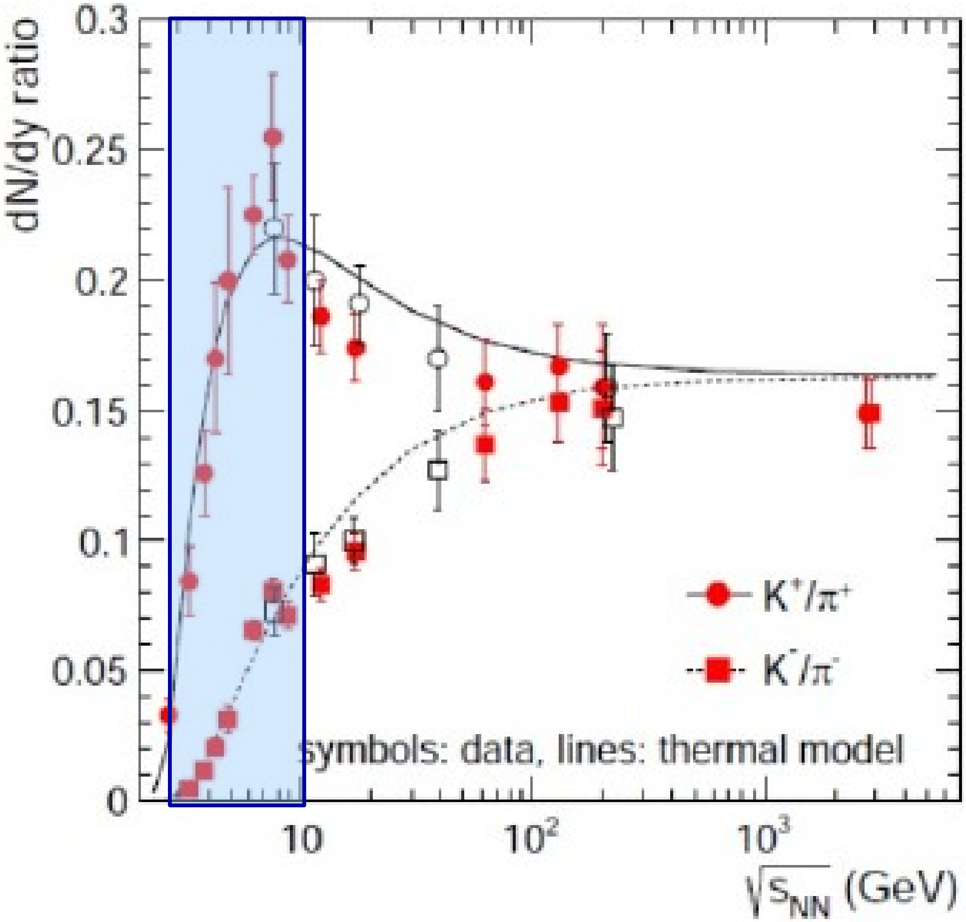


Onset of deconfinement (NA49/61)

Statistical Model of the Early Stage

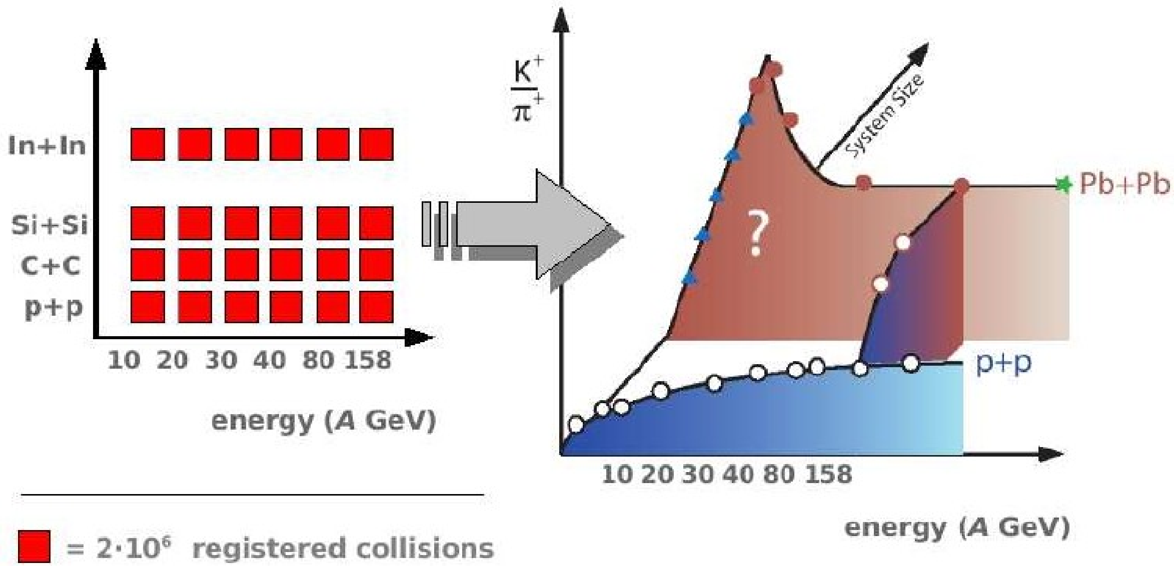
Gazdzicki M. Gorenstein M.
Acta. Phys. Pol., B30: 2705 1999



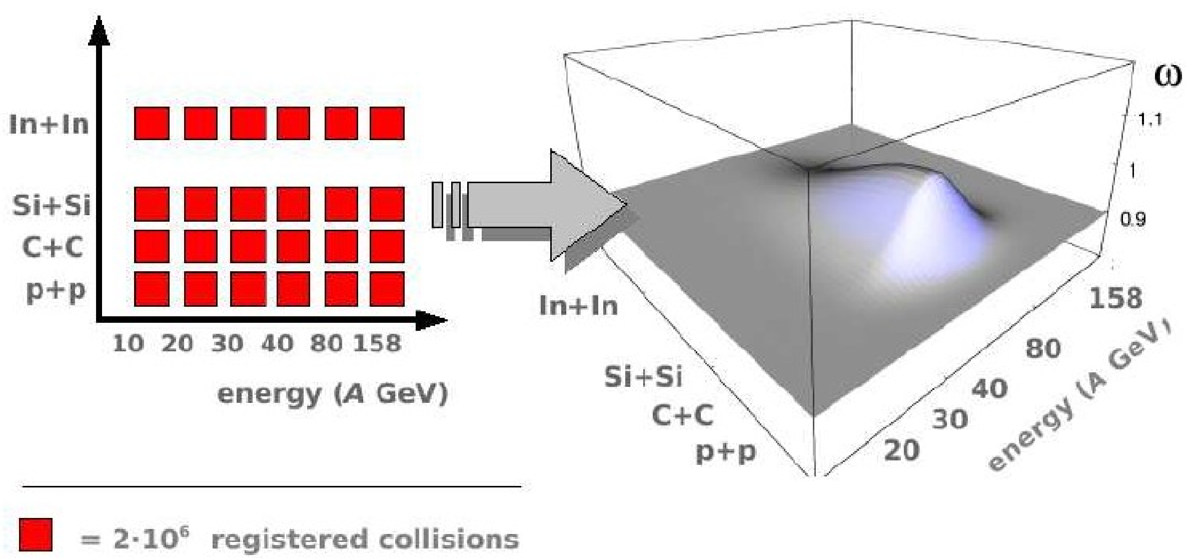


NA49 scan

arXiv:nucl-ex/0612007

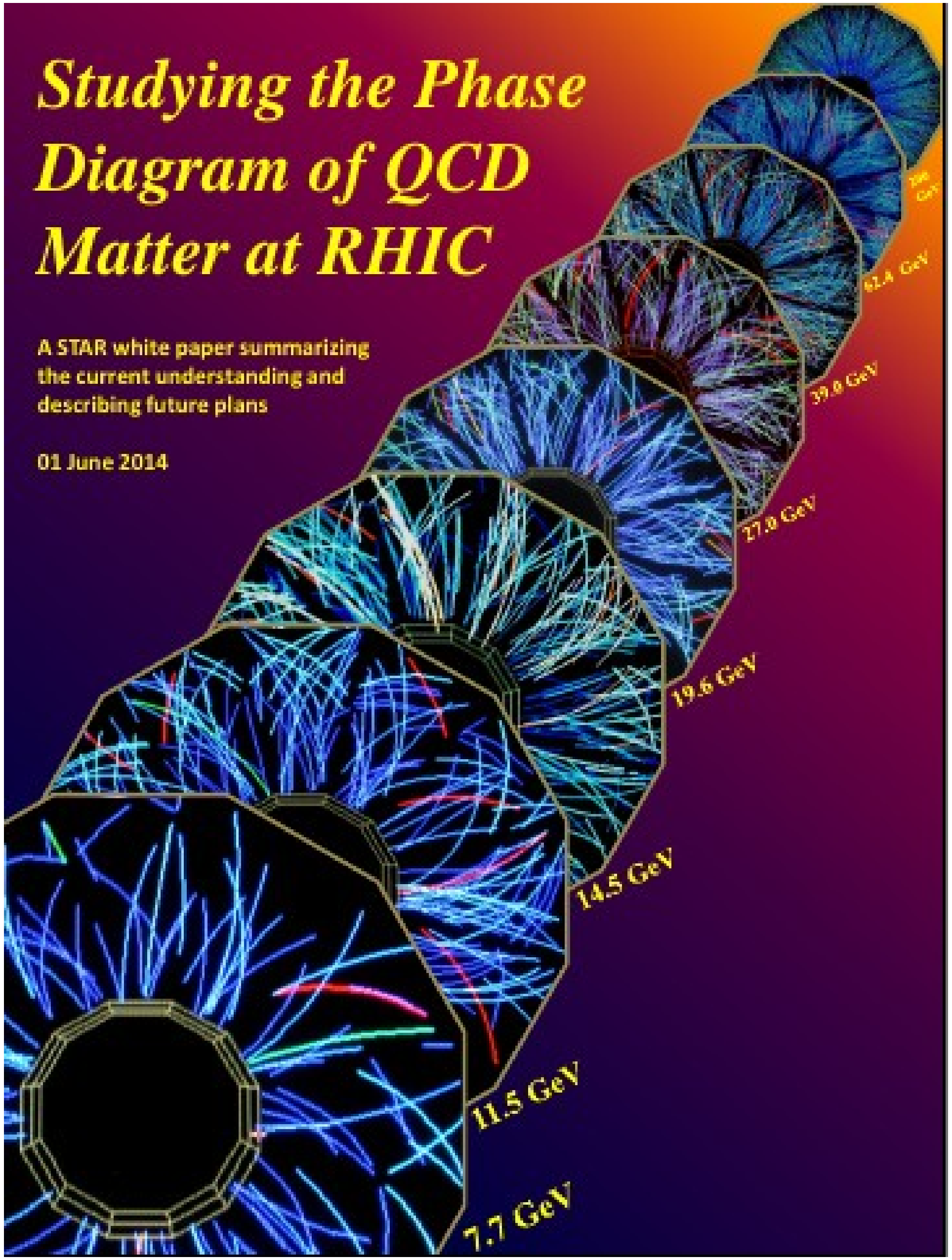


Horn vanishing



The scaled variance of the multiplicity distribution of negatively charged hadrons in the projectile hemi-sphere

SN0598 : Studying the Phase Diagram of QCD Matter at RHIC

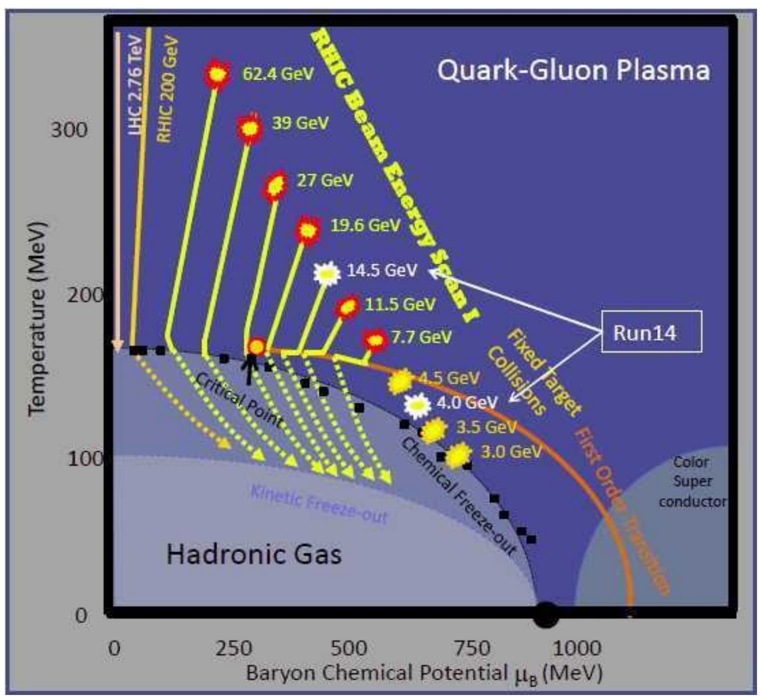


Contents

STAR BES II program

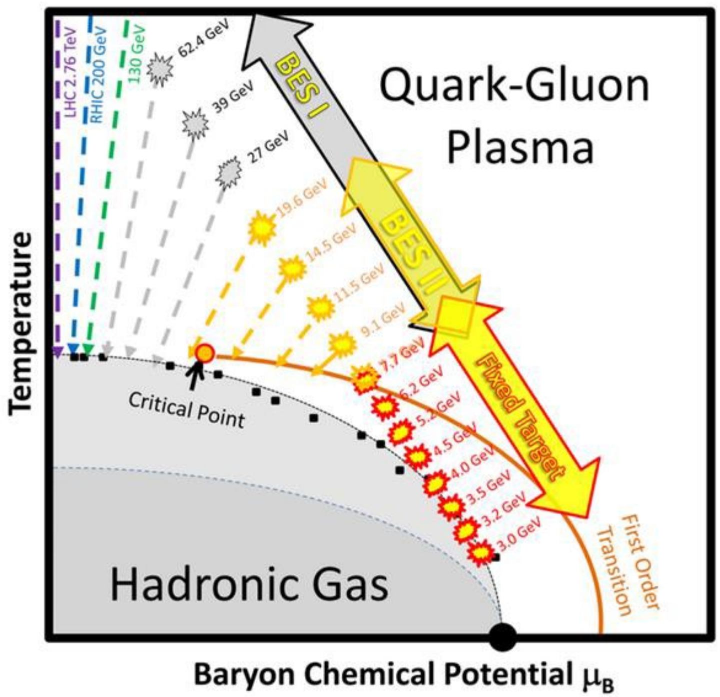
$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	MinBias Events (10^6)	Time (weeks)	Year
7.7	420	4.3	4	2010
11.5	315	11.7	2	2010
14.5	**260**	**24.0**	**3**	**2014**
19.6	205	35.8	1.5	2011
27.0	155	70.4	1	2011
39.0	115	130.4	2	2010
62.4	70	67.3	1.5	2010

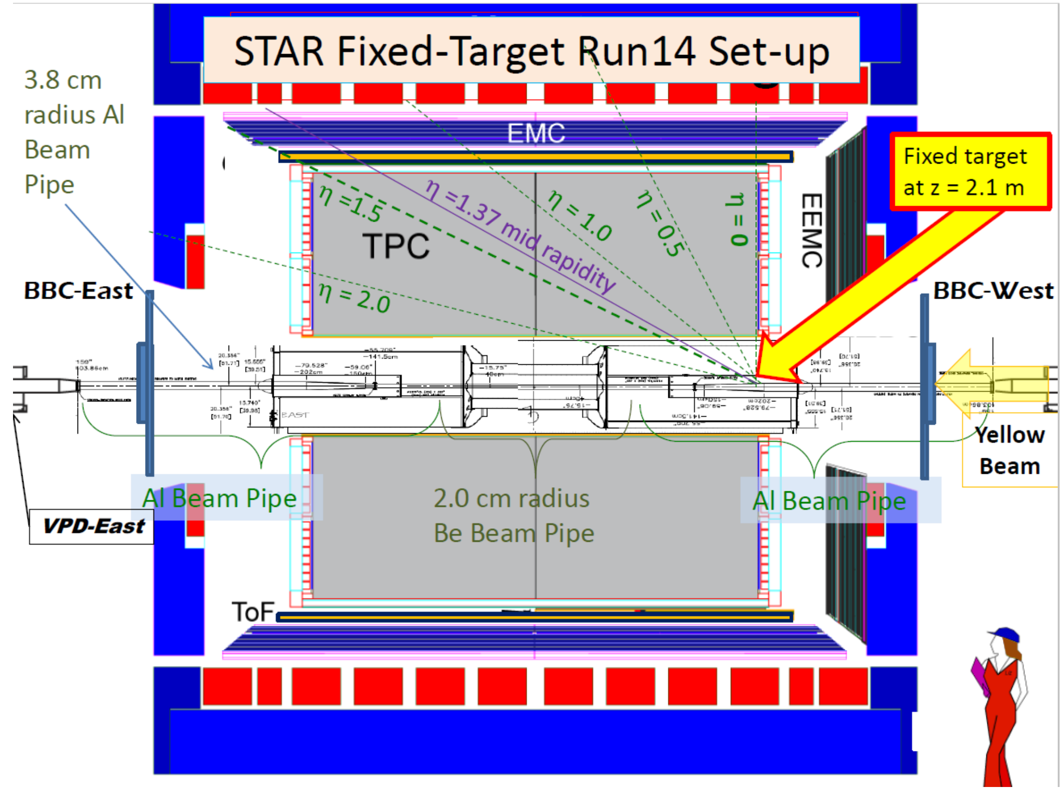
$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Needed Events (10^6)
7.7	420	100
9.1	370	160
11.5	315	230
14.5	**260**	**300**
19.6	205	400



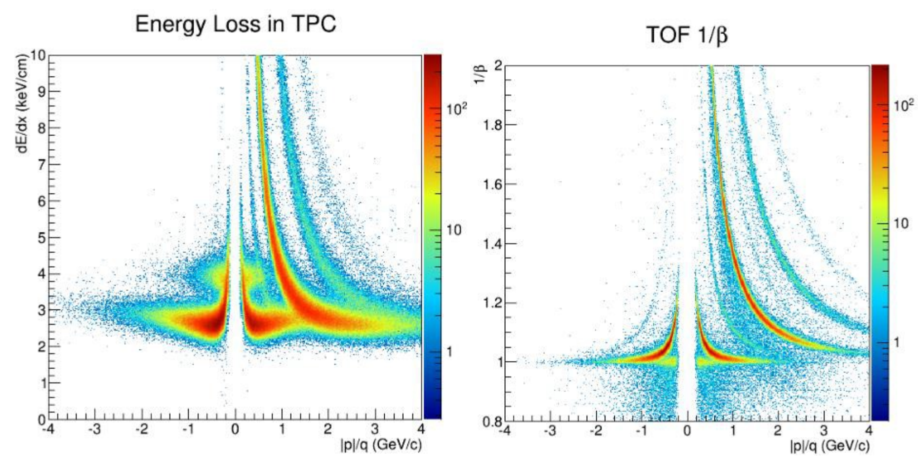
Year	System and Energy	Physics/Observables	Upgrade
2017	• p+p @ 500 GeV • Au+Au @ 62.4 GeV	• Spin sign change diffractive • Jets	FMS post-shower, EPD (1/8th), eTOF prototype
2018	• Zr+Zr, Ru+Ru @ 200 GeV • Au+Au @ 27 GeV	• CME, di-leptons • CVE	Full EPD? eTOF prototype
2019	Au+Au @ 14.5-20 GeV + fixed target	• QCD critical point • Phase transition • CME, CVE,…	Full iTPC, eTOF, and EPD
2020	Au+Au @ 7-11 GeV + fixed target	• QCD critical point • Phase transition • CME, CVE,…	
2020+	• Au+Au @ 200 GeV • p+A/p+p @ 200 GeV	• Unbiased jets, open beauty • PID FF, Drell-Yan, longitudinal correlations	• HFT+ • FCS, FTS

Fixed Target Program with STAR



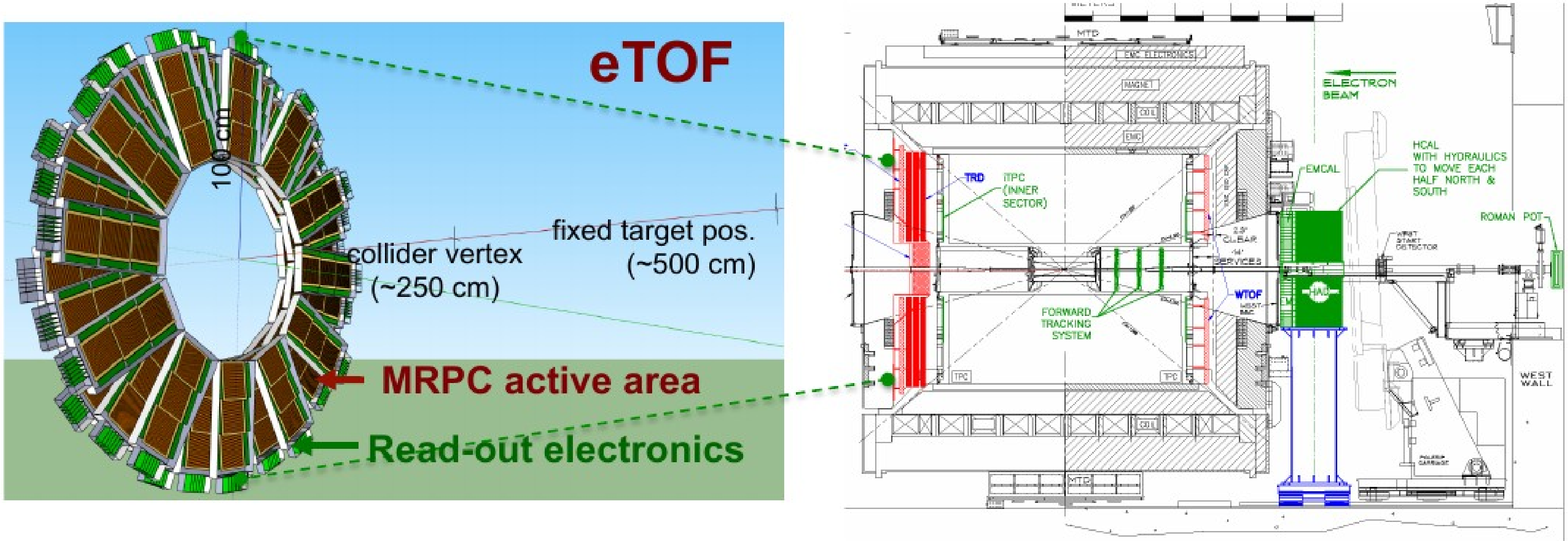


Au+Au FXT at 3.9GeV



- Extend energy reach to overlap/complementary AGS/FAIR/JPARC
- Real collisions taken in run 14 and results (K. Meehan @ QM15 & WWND16)
- Upgrades (iTPC+eTOF+EPD) crucial
- Unprecedented coverage and PID for Critical Point search in BES-II
- Spectra, flow, fluctuations and correlations

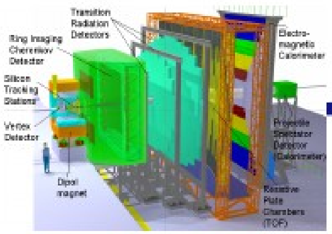
CBM Phase-0 Exp: eTOF at STAR



Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, starting in 2019

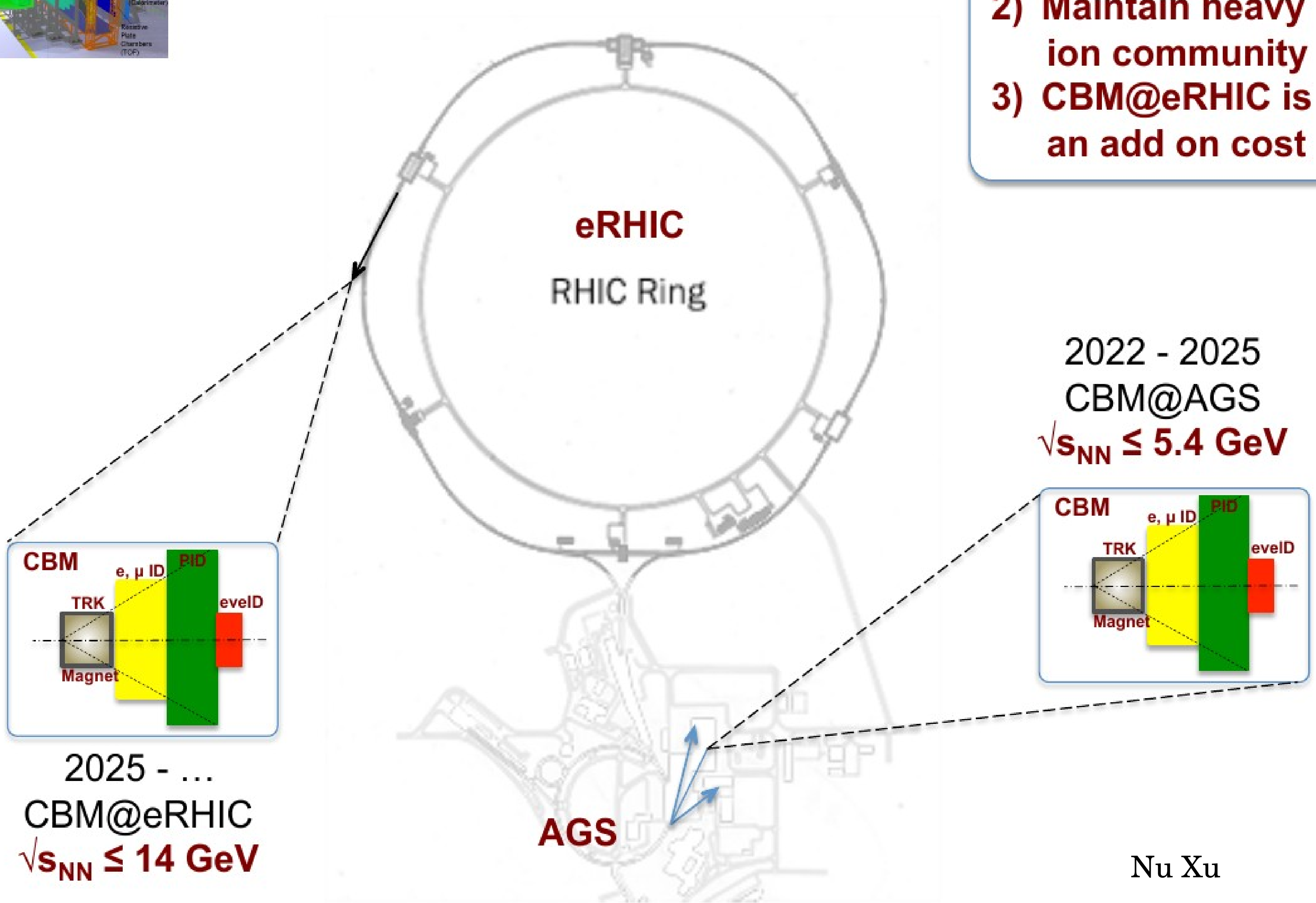
CBM participating in RHIC Beam Energy BES-II in 2019-2020:

- Complementary to part of CBM's physics program: $\sqrt{s_{NN}}$ = **3**, **3.6**, **3.9**, **4,5**, 7.7 GeV especially for the physics of ***B-*** & ***s-***production and fluctuations
- Operating of ~30 CBM TOF modules and electronics (~10 m^2, 10k channels)
- Experiencing with detector system, online calibration and monitoring tools
- Developing analysis strategies for particle identification and efficiency extraction



BES-III: CBM@BNL

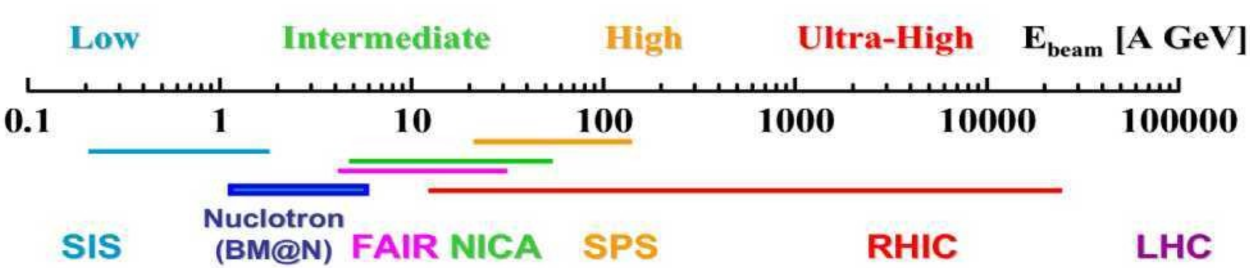
1) Study QCD phase structure
2) Maintain heavy ion community
3) CBM@eRHIC is an add on cost



Nu Xu

Resent & future experiments for HIC

Facility	SPS	RHIC BES II	Nuclotron M	NICA	SIS/100 (300)	J-PARK HI
Laboratory	CERN Geneva	BNL Brookhaven	JINR Dubna	JINR Dubna	FAIR GSI Darmstadt	J-PARK
Experiment	NA61 SHINE	STAR PHENIX	BM@N	MPD	HADES CBM	JHITS
Start of data taking	2011	2017	2015	2019	2020/25	2025
$\sqrt{s_{NN}}$ (GeV)	4.9 – 17.3	7.7 – 200	< 3.5	4 - 11	2.7 – 8.2	2.0 – 6.2
Physics	CP & OD	CP & OD	HDM	OD & HDM	OD & CP	OD& HDM

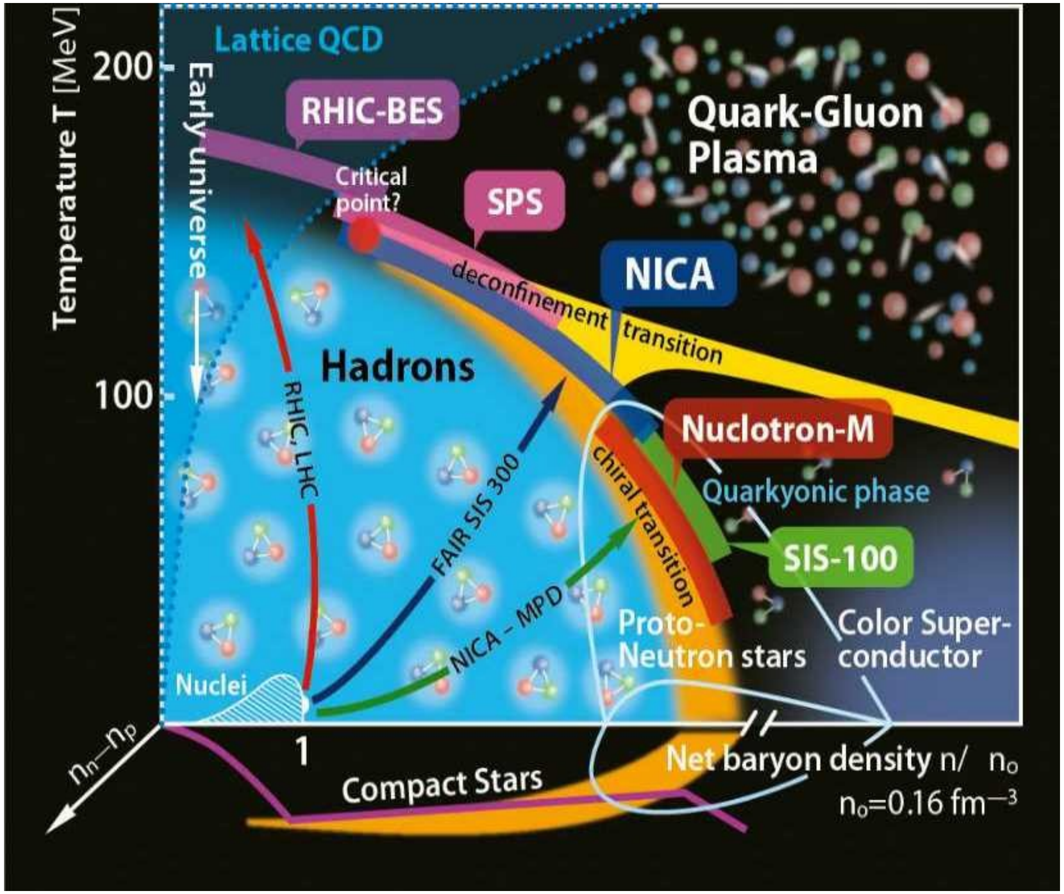


CP — critical point
OD — onset of deconfinement, mixed phase, 1st order phase transition
HDM — hadrons in dense matter
PDM — properties of deconfined matter

NICA goal

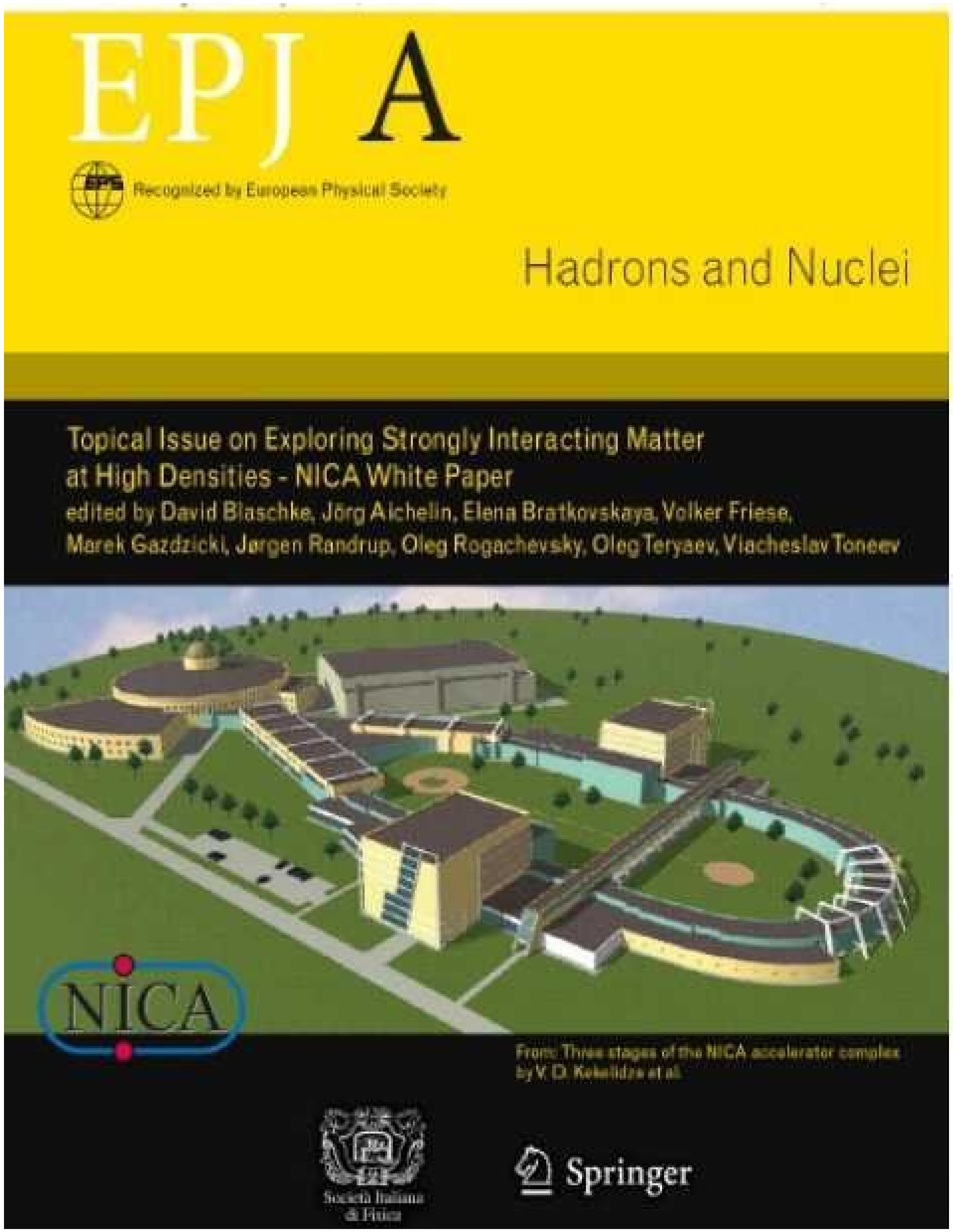
twiki-cgi/view/ NICA/WebHomehttp://theor0.jinr.ru/

The collision of two heavy nuclei which approach and smash against each other with almost the speed of light creates in the laboratory the primordial state of matter, called Quark-Gluon Plasma (QGP). The QGP expands like a fireball, cools and finally turns into ordinary matter.



NICA priorities

- Corroborate NA49, STAR and other experiments results at NICA energy range
- Looking for the more comprehensive physics analysis methods for searching mixed phase (QGP).



Thank you for attention