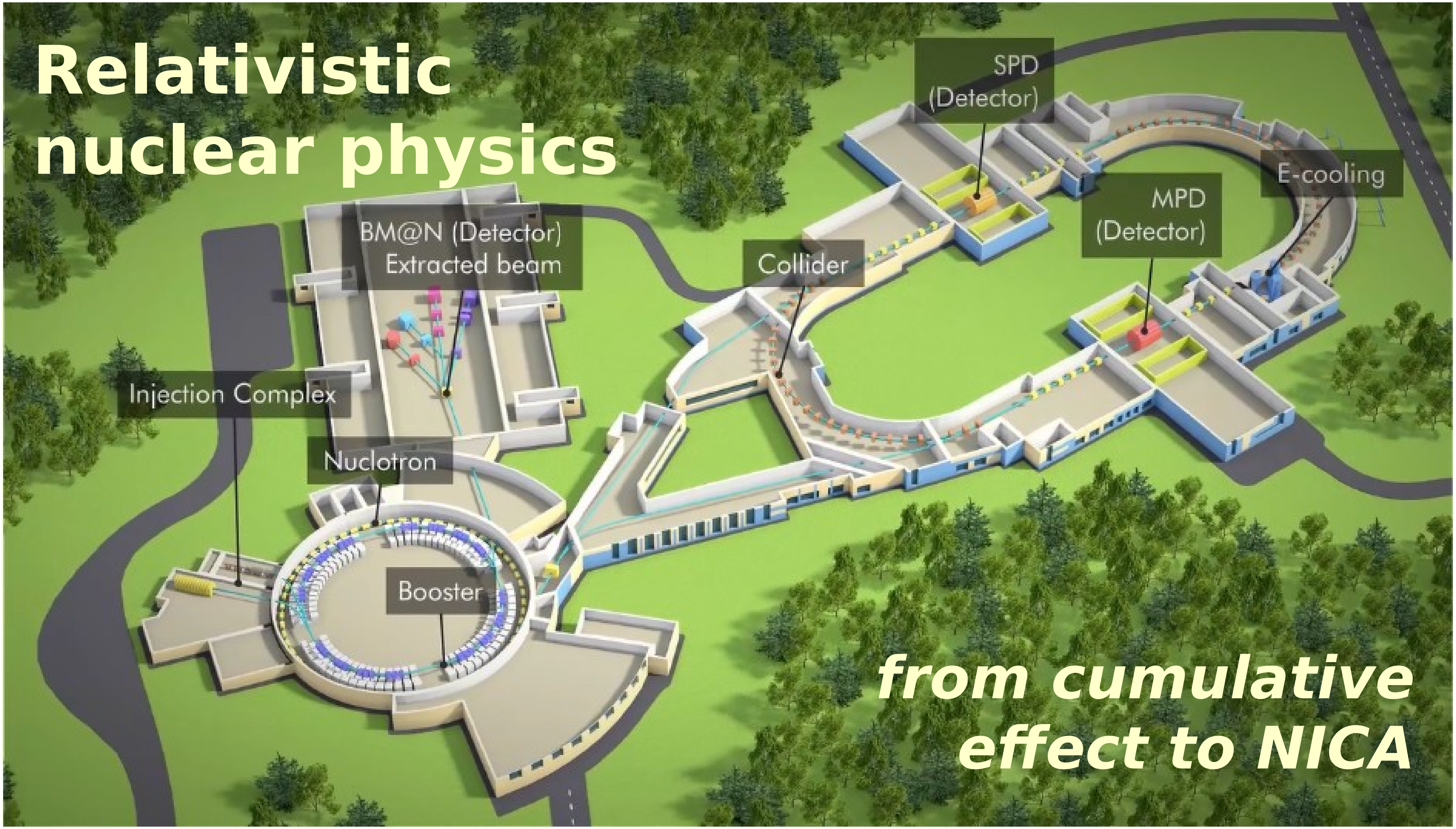
Relativistic nuclear physics



from cumulative effect to NICA

ROGACHEVSKY Oleg

- ***for MPD collaboration***

AYSS school
April 24 2018
Dubna

Hagedorn temperature

Statistical Thermodynamics of Strong Interactions at High Energies.

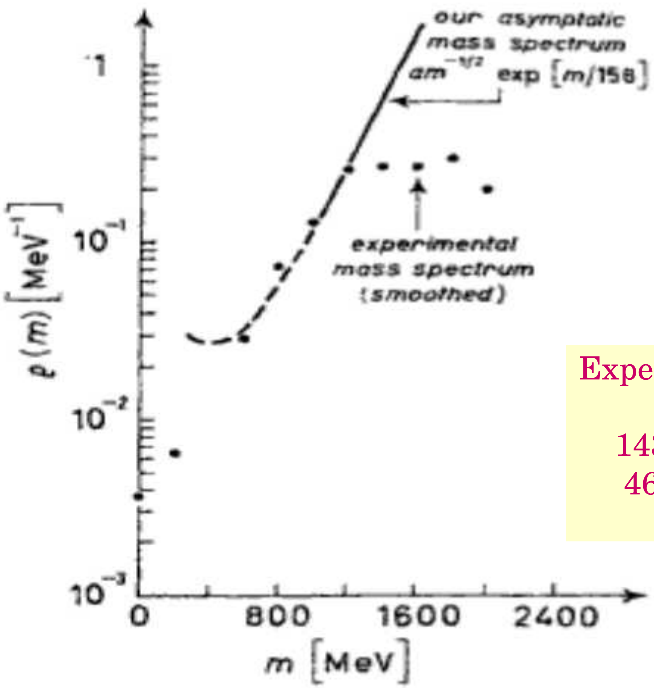
R. HAGEDORN

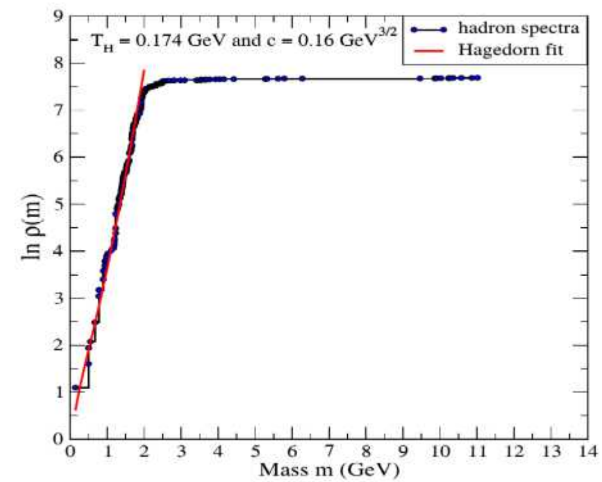
CERN - Geneva

(ricevuto il 12 Marzo 1965)

J. Cleymans and D. Worku

Modern Physics Letters A
Vol. 26, No. 16 (2011) 1197–1209





Experimental data:

1432 states known in 1967;
4627 states of mid '90s.

$$\rho_h(m) = \frac{c}{(m^2 + m_0^2)^{5/4}} \exp\left(\frac{m}{T_{\rm H}}\right)$$

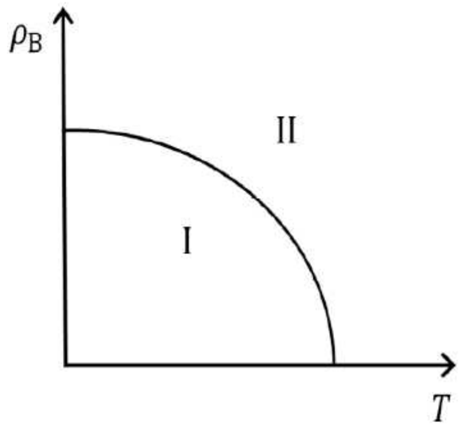
Parameter	
c (GeV)$^{3/2}$	0.16 ± 0.02
m_0 (GeV)	0.5
$T_{\rm H}$ (GeV)	0.174 ± 0.011

$$\bar{\varrho}_{\rm exp}(m) = \frac{1}{\sqrt{2\pi\tau^2}} \sum_{i=1}^{N} \nu_i \exp\left[-\frac{(m-m_i)^2}{2\tau^2}\right], \qquad \tau = 200\ \text{MeV},$$

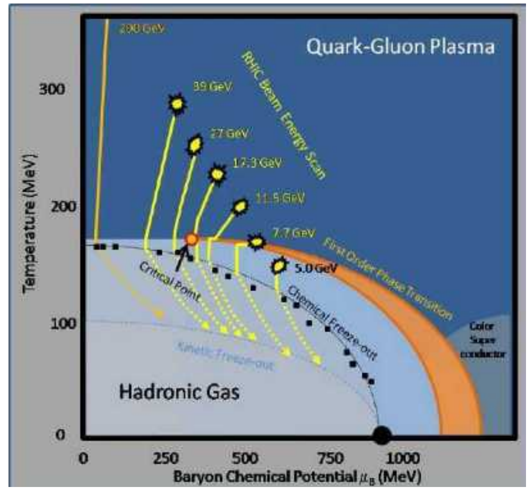
where the sum goes from the pion mass to the highest known resonances.

QCD Phase diagram

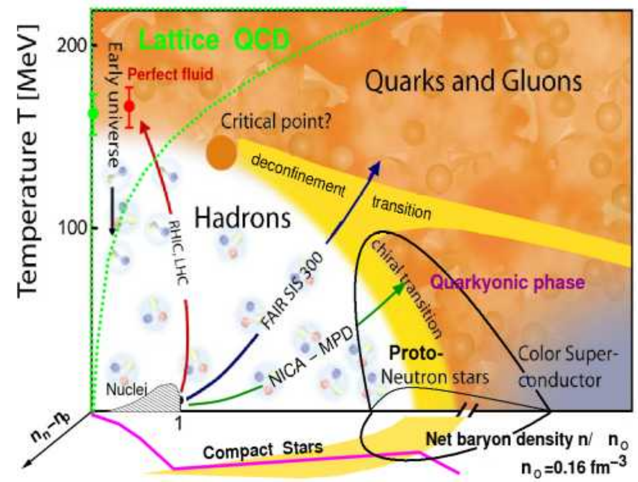
N. Cabibbo and G. Parisi,
Phys. Lett. B59 (1975) 6769



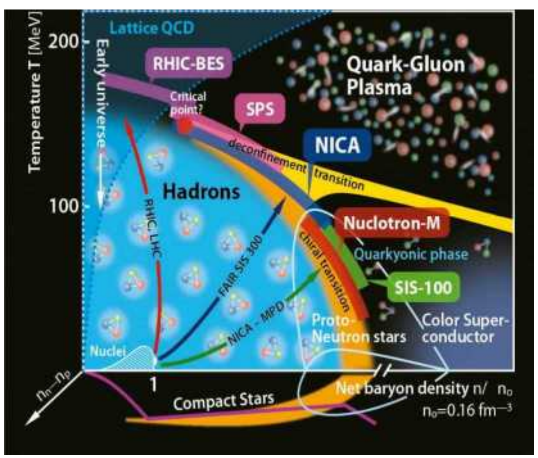
STAR BES program



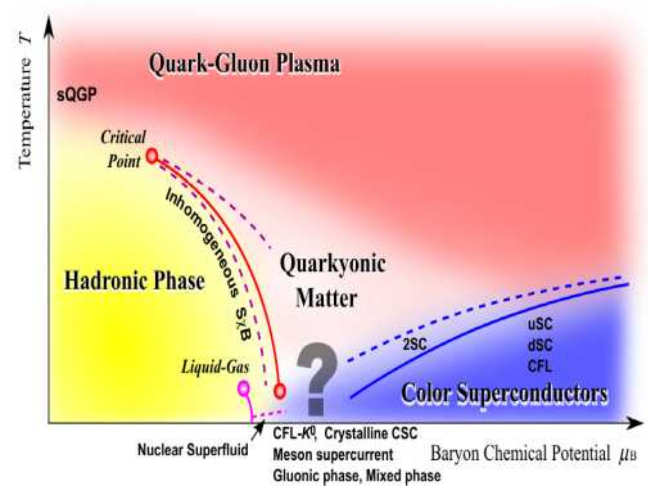
FAIR - CBM



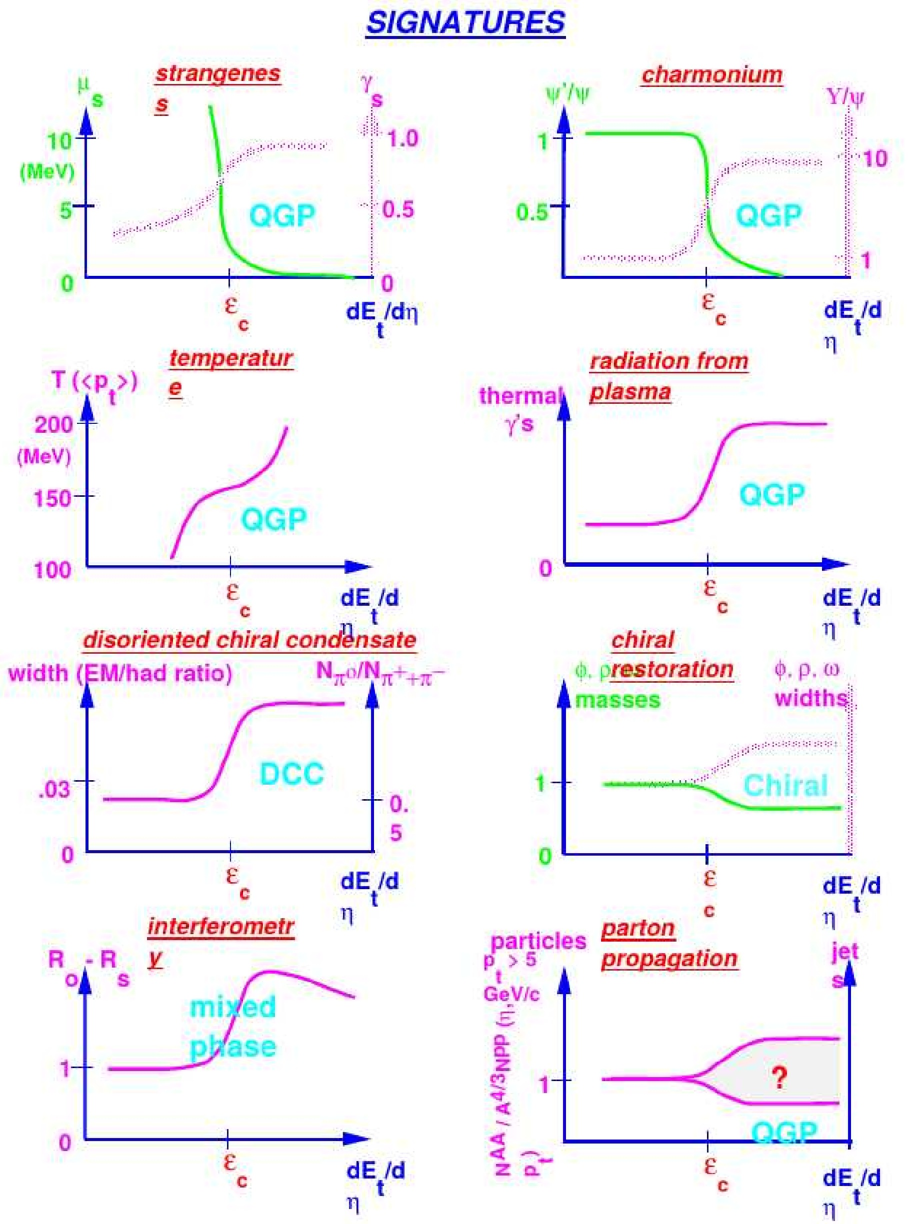
NICA – MPD - BM@N



Fukushima, Hatsuda
Rep. Prog. Phys. 74 (2011) 014001



Theoretical predictions



The Search for the Quark-Gluon Plasma

arXiv:hep-ph/9602235

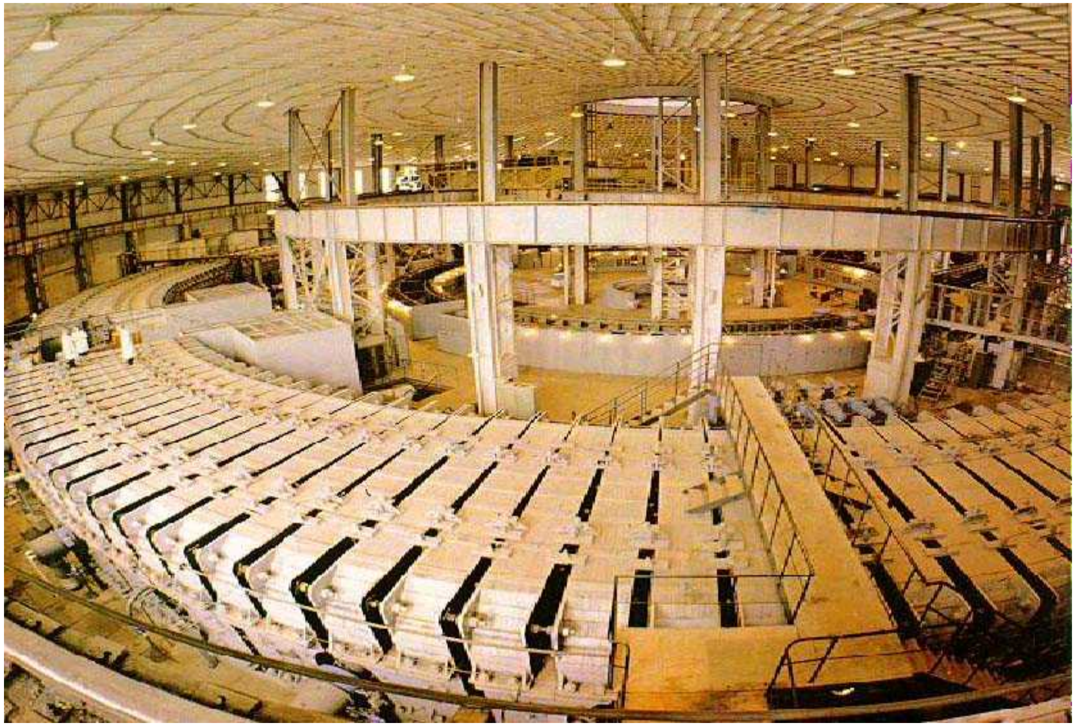
John W. Harris, Berndt Müller

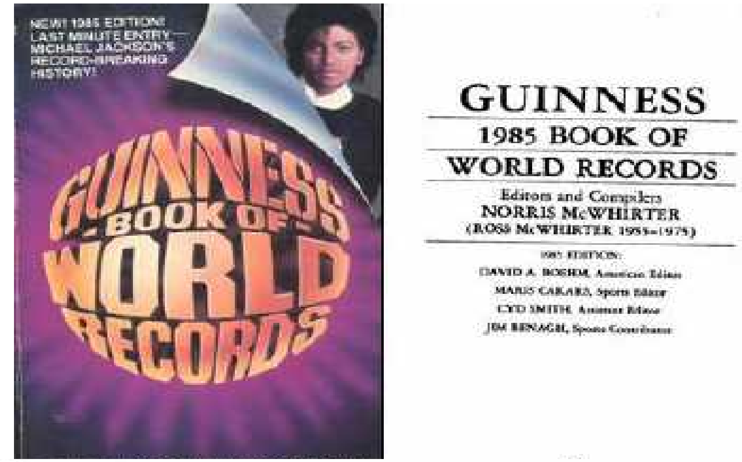
Signatures of quark-gluon plasma formation and the chiral phase transition. The expected behavior of the various signatures is plotted as a function of the measured transverse energy, which is a measure of the energy density, in the region around the critical energy density ε_c of the transition. When two curves are drawn, the hatched curve corresponds to the variable described by the hatched ordinate on the right. See text of review for details

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	1972 - 1984	< 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
Nuclotron	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	2020	$\sqrt{S_{NN}}$ = 4 -11 GeV	p - Au
SIS 100	GSI,Darmstadt	2025	2 – 11 AGeV	Au

Synchrophasotron & Nuclotron



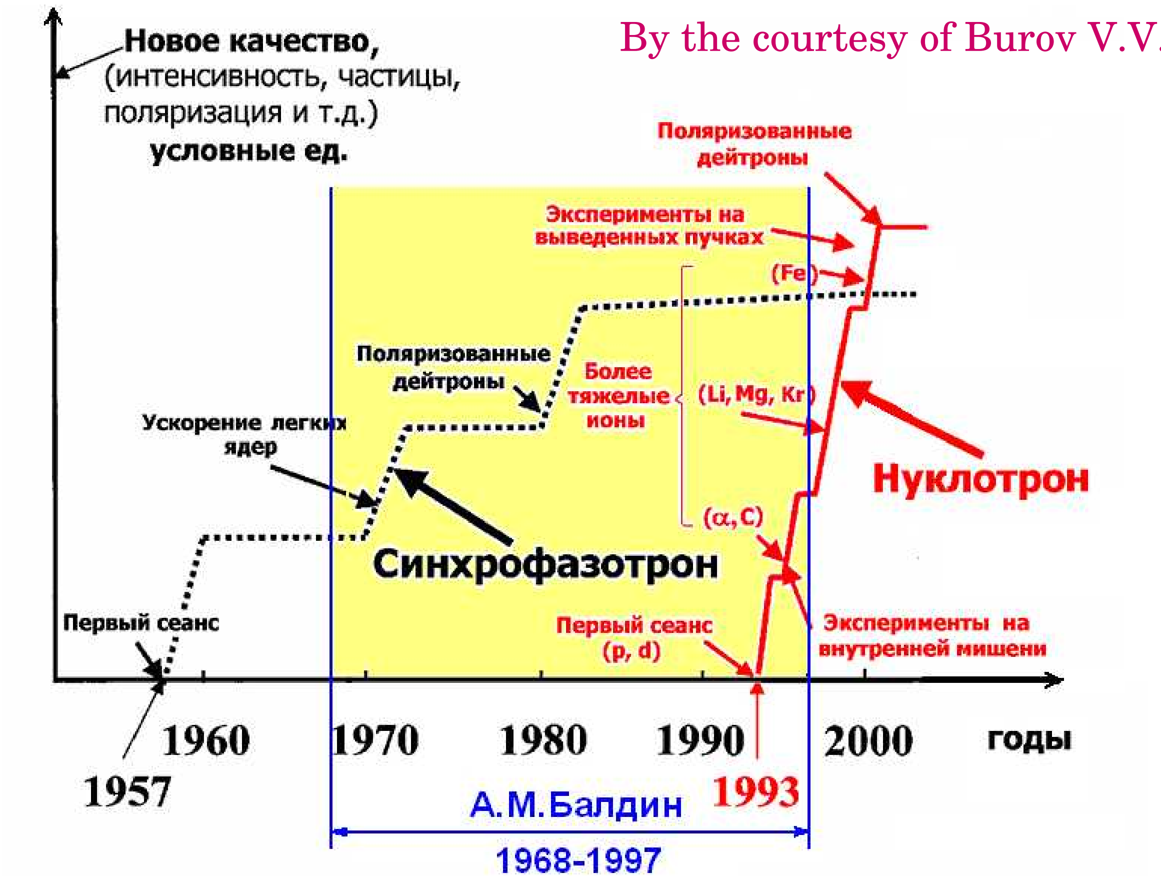


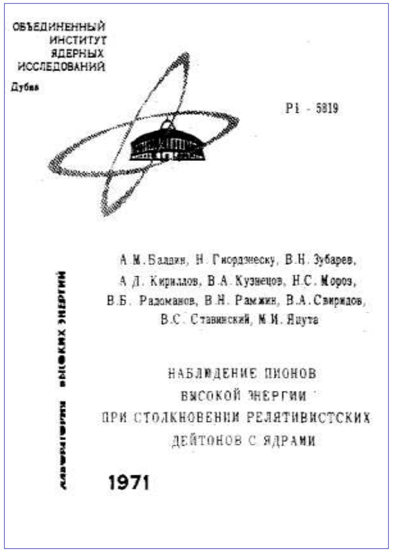
Heaviest Magnet

The heaviest magnet is one measuring 196 ft in diameter, with a weight of 40,000 tons, for the 10 GeV synchrophasotron in the Joint Institute for Nuclear Research at Dubna, near Moscow.

Relativistic nuclear physics: cumulative effect

By the courtesy of Burov V.V.




ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

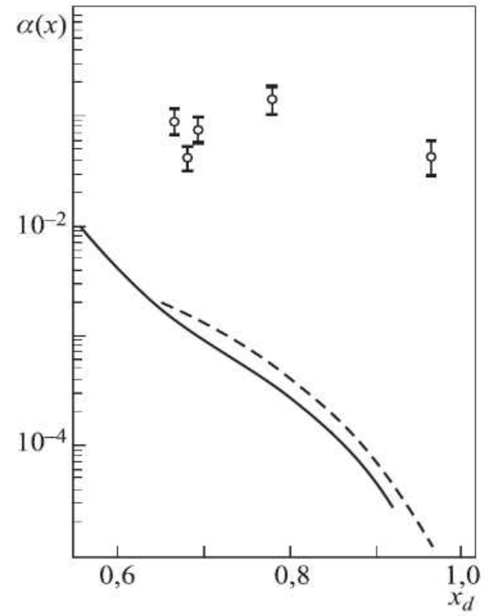
Дубна

P1 - 5819

А.М. Балдин, Н. Гиордэнеску, В.Н. Зубарев, А.Д. Кириллов, В.А. Кузнецов, Н.С. Мороз, В.Б. Радоманов, В.Н. Рамжин, В.А. Свиридов, В.С. Ставинский, М.И. Яцута

НАБЛЮДЕНИЕ ПИОНОВ ВЫСОКОЙ ЭНЕРГИИ ПРИ СТОЛКНОВЕНИИ РЕЛЯТИВИСТСКИХ ДЕЙТОНОВ С ЯДРАМИ

1971



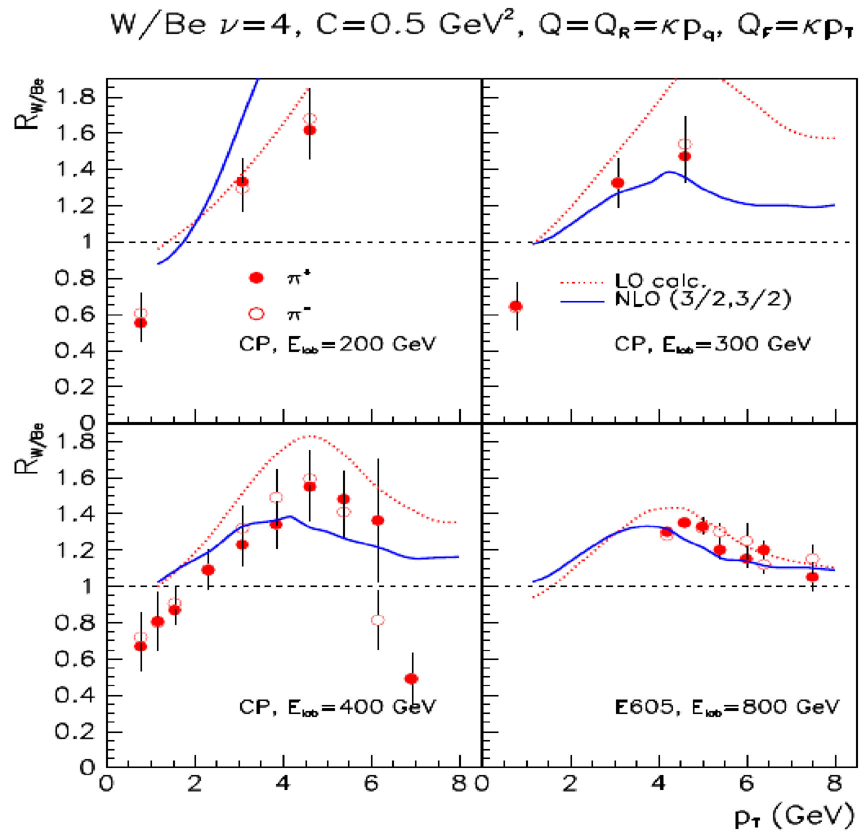
$$\alpha(x_d) = \frac{d^2\sigma(d + \mathrm{Cu} \to \pi^- + \ldots)}{d^2\sigma(p + \mathrm{Cu} \to \pi^- + \ldots)}$$

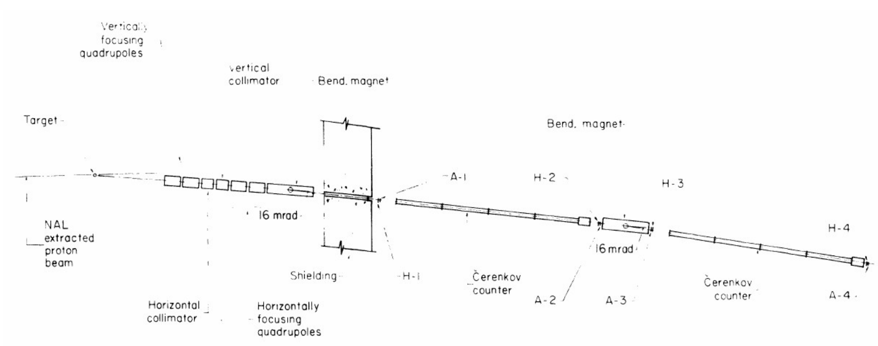
Relativistic nuclear physics: Cronin effect

Increased particle production in
3 GeV < p T < 6 GeV range (1975)

More particles are produced in
pA than expected from N_{bin}
scaled pp collisions

J.W.Cronin et al. Phys. Rev. D11, 3105 (1975)
D. Antreasyan et al. Phys. Rev. D19, 764 (1979)

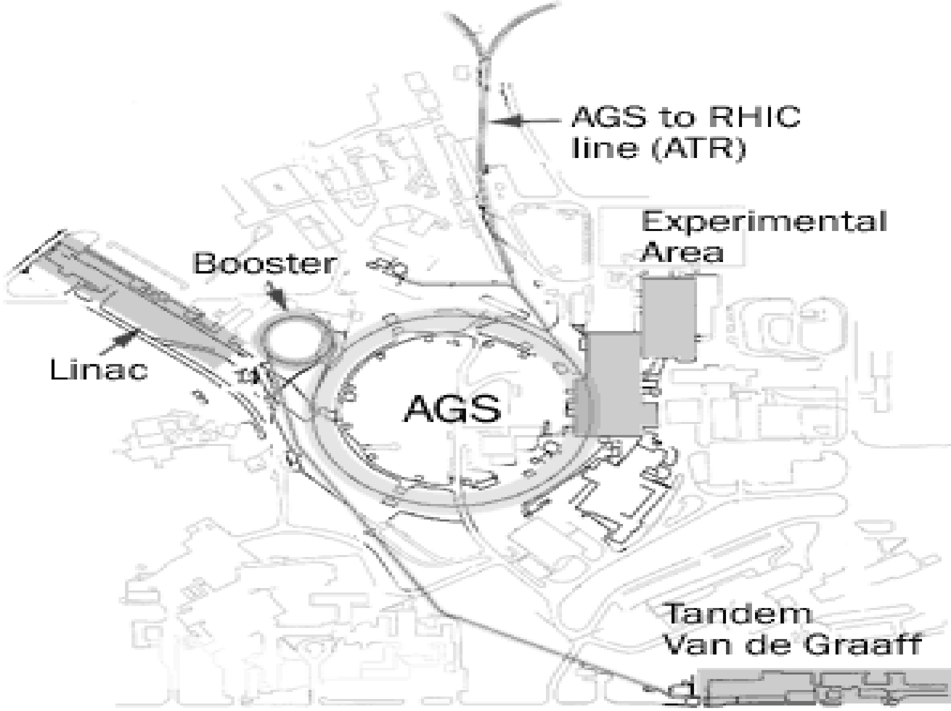




Nuclear modification factor

$$R_{AA} = \frac{1}{N_{bin}} \frac{\mathrm{d}N_{AA}/\mathrm{d}y\, \mathrm{d}^2 p_T}{\mathrm{d}N_{pp}/\mathrm{d}y\, \mathrm{d}^2 p_T}$$

Alternating Gradient Synchrotron



BNL-AGS (1986 – 2002)

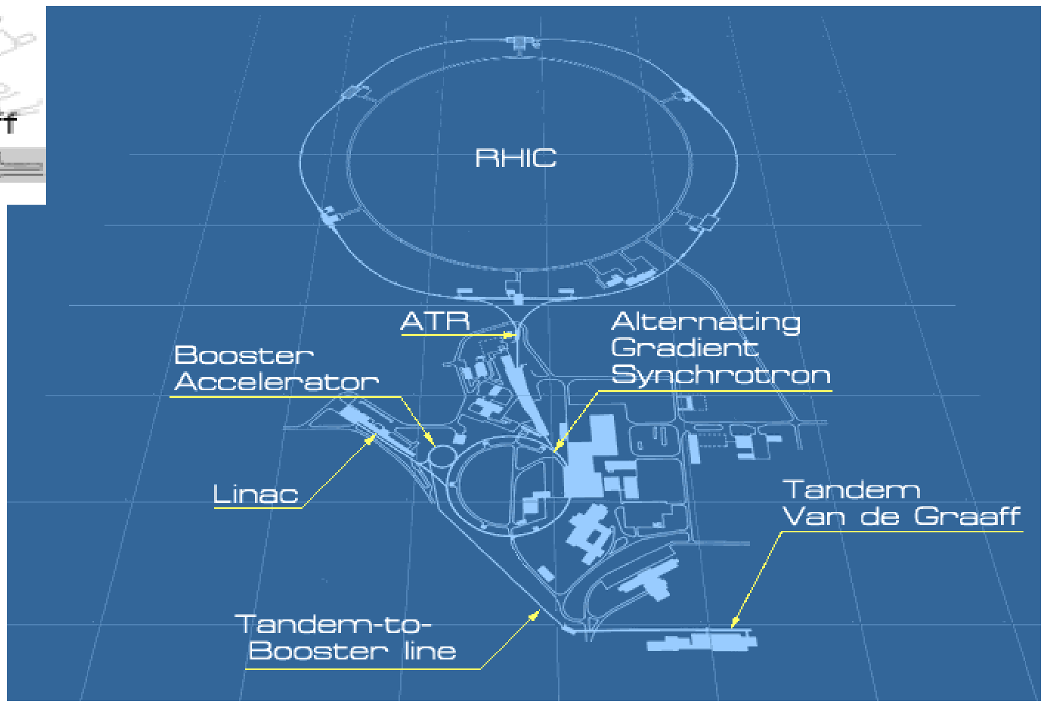
(1986 – 1991):

^{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



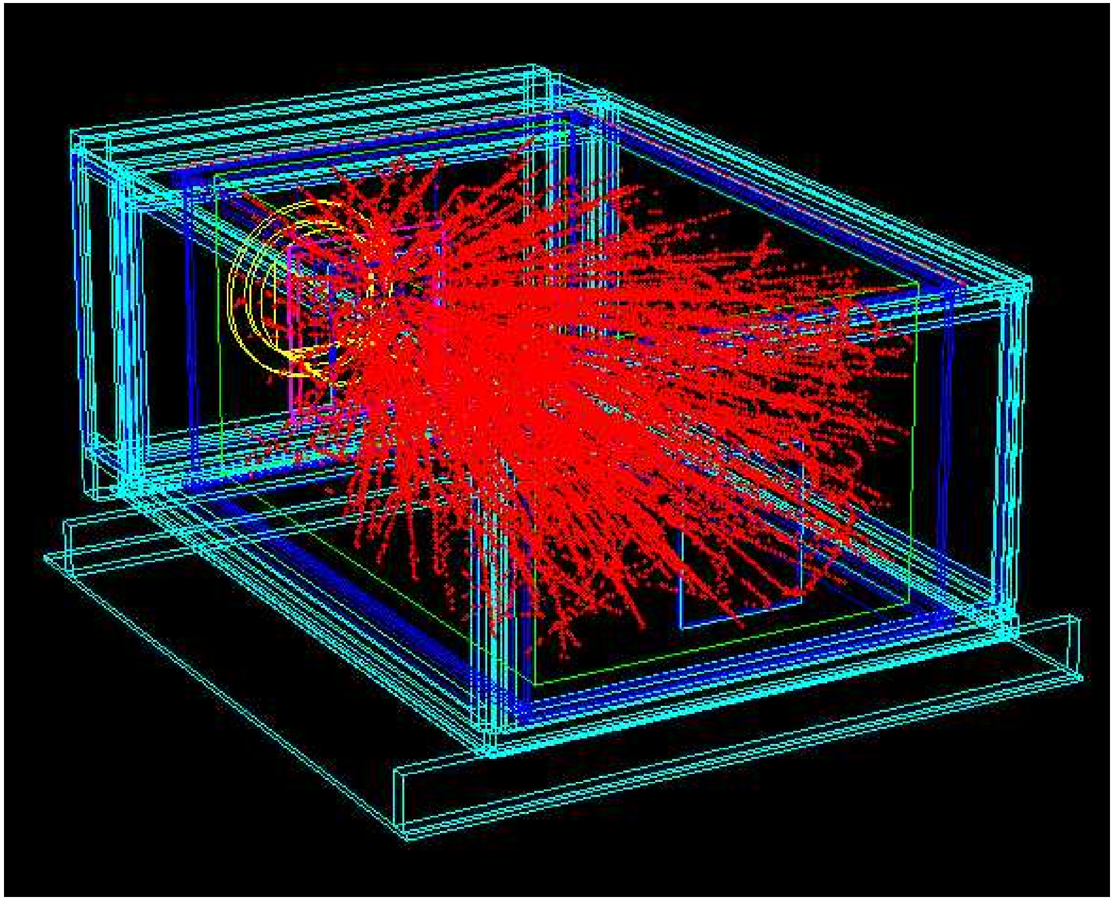
Heavy Ion Experiments at the AGS

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 + 2nd 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



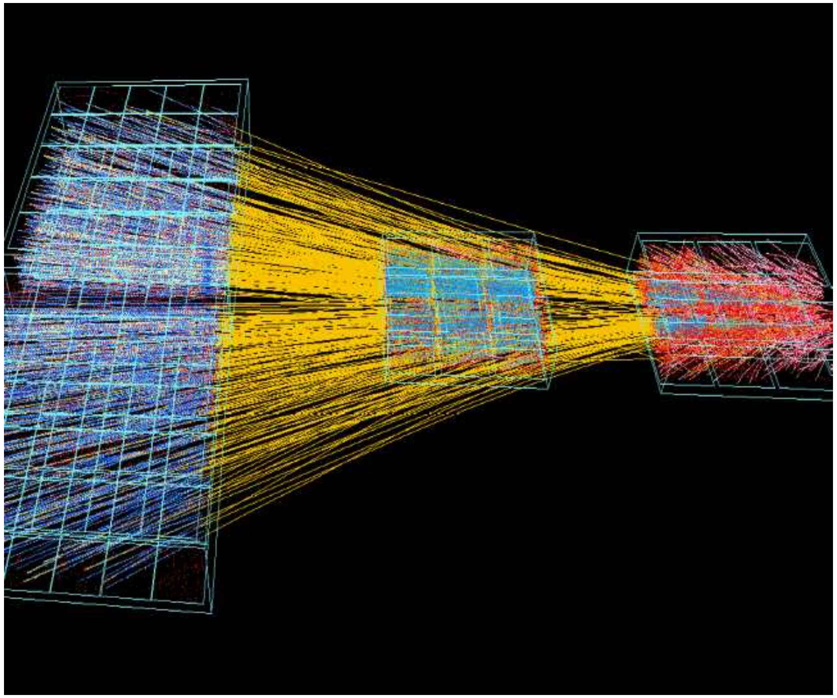
Heavy Ion Experiments at the SPS

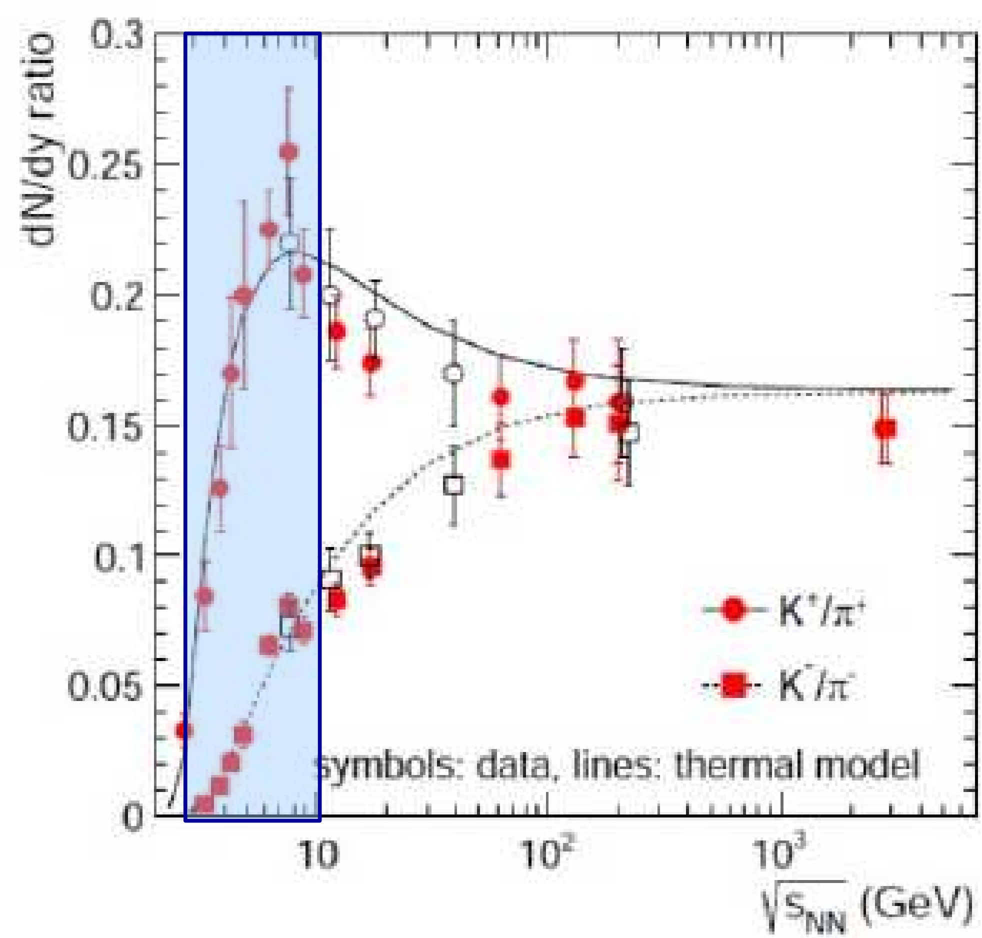
Experiment	Beam	Technology	Observables
NA34	^{16}O, ^{32}S	Muon spectrometer + calorimeter	Di-leptons, p, π, K, γ
NA35		Streamer chamber	π^-, K^0_s, Λ, HBT
NA36		TPC	K^0_s, Λ
NA38		Di-muon spectrometer (NA10)	Di-leptons, J/ψ
WA80/WA93		Calorimeter + Plastic Ball	γ, π^0, η
WA85		Mag. spectrometer with 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

Onset of deconfinement (NA49/61)

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

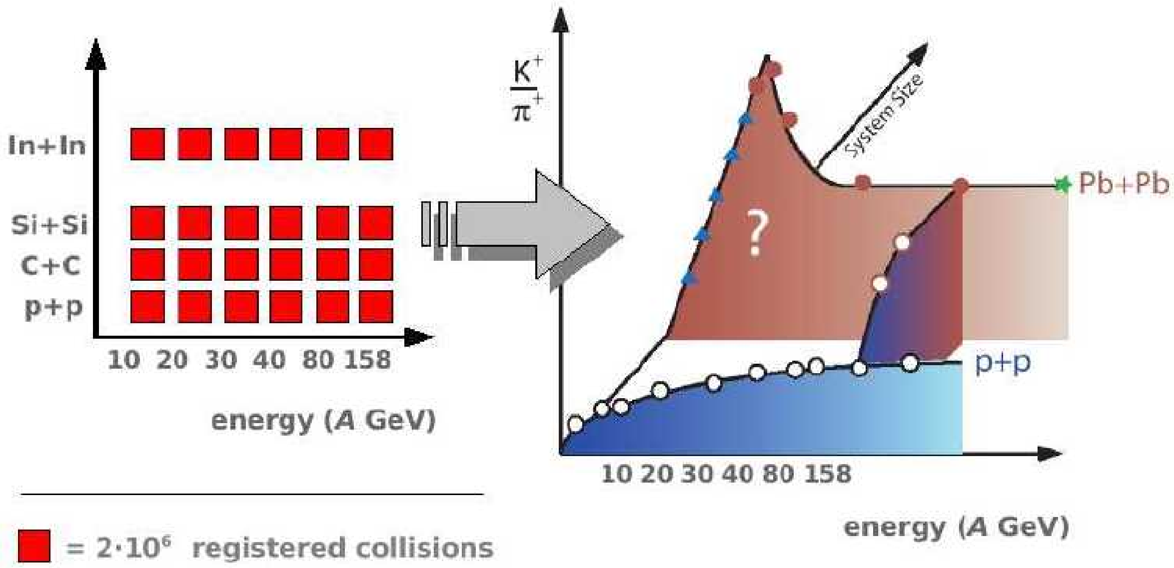
Statistical Model of the Early Stage



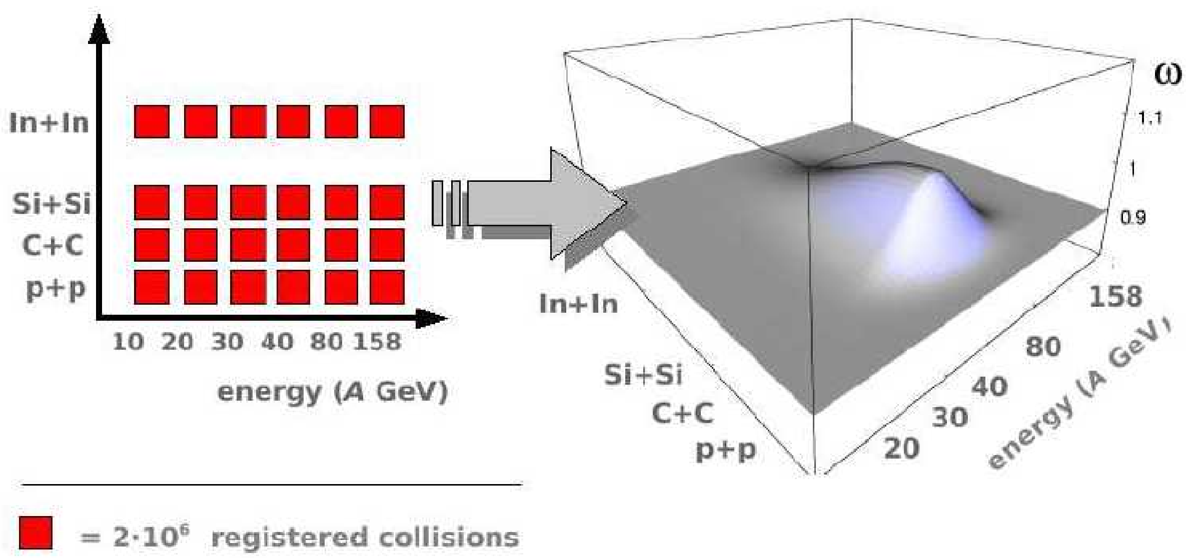


NA49 scan

arXiv:nucl-ex/0612007



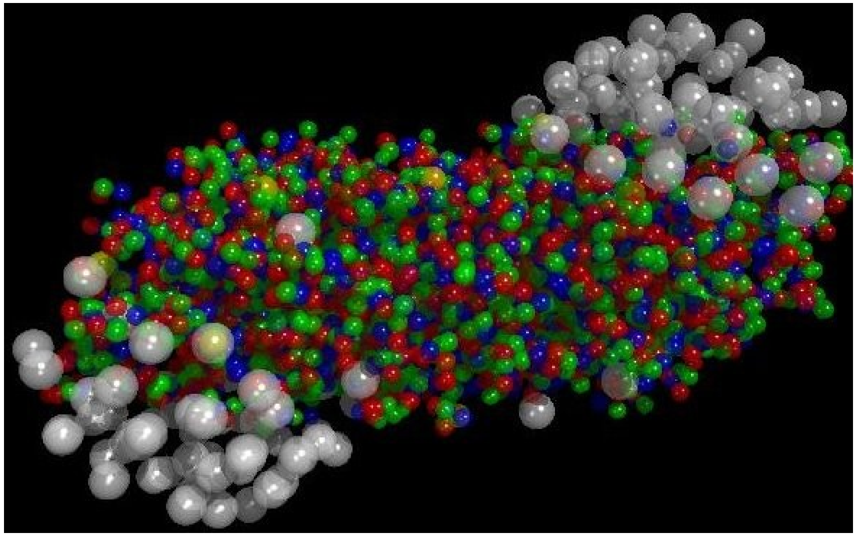
Horn vanishing



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

New State of Matter created at CERN

Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN1'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.



Professor Luciano Maiani, CERN 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."

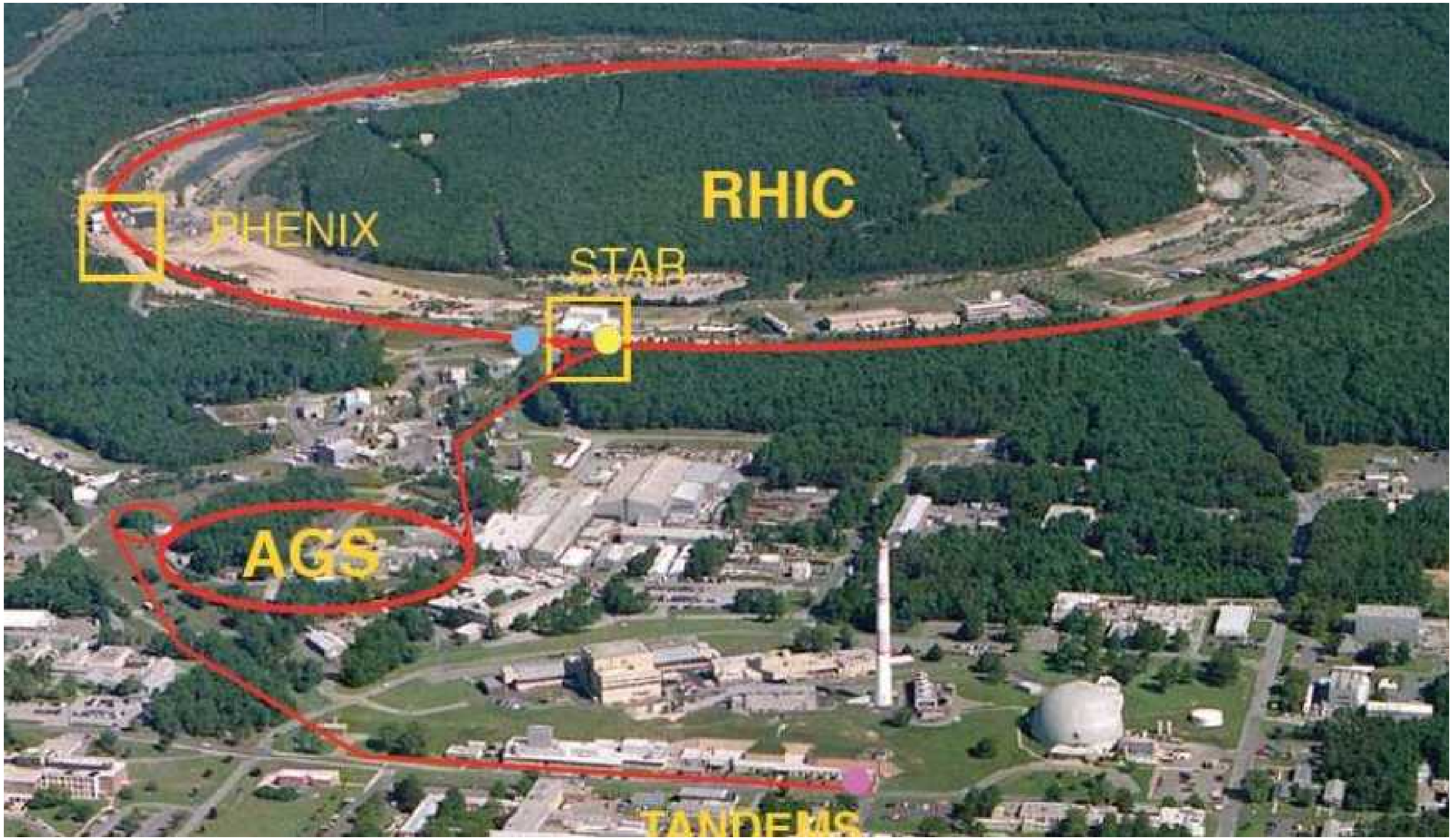
The lead beam programme started in 1994, after the CERN accelerators has been upgraded by a collaboration between CERN and institutes in the Czech Republic, France, India, Italy, Germany, Sweden and Switzerland. A new lead ion source was linked to pre-existing, interconnected accelerators, at CERN, the Proton Synchrotron (PS) and the SPS. The seven large experiments involved measured different aspects of lead-lead and lead-gold collisions. They were named NA44(link is external),NA45(link is external), NA49, NA50, NA52(link is external), WA97 / NA57and WA98. Some of these experiments use multipurpose detectors to measure and correlate several of the more abundant observable phenomena. Others are dedicated experiments to detect rare signatures with high statistics. This co-ordinated effort using several complementing experiments has proven very successful.

RHIC

BNL-RHIC (from 2000):

$\sqrt{s}$ = 200 GeV, Au + Au collisions

4 large experiments: BRAHMS, PHENIX, PHOBOS, STAR.

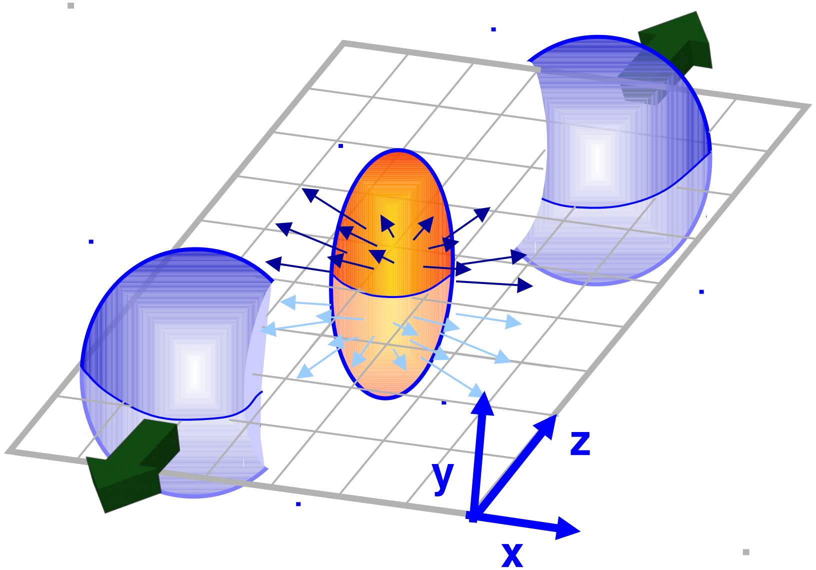


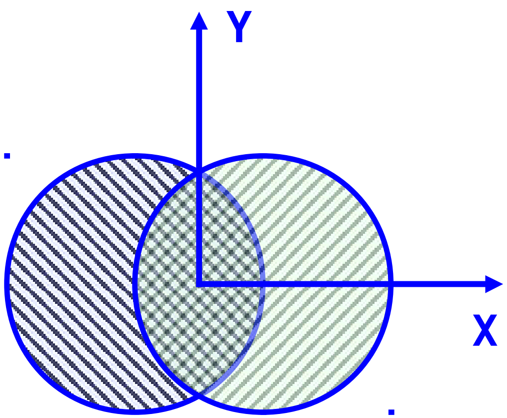
Heavy Ion Experiments at RHIC

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)

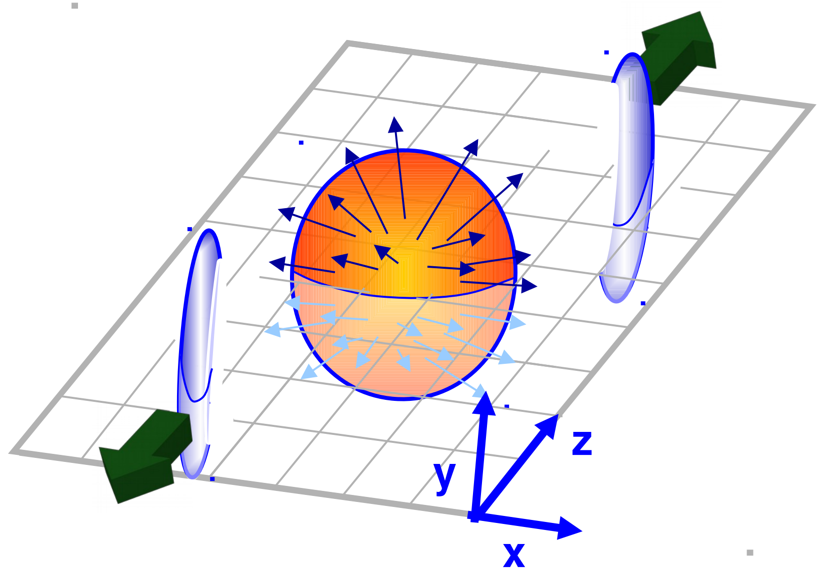
Nucleus collisions

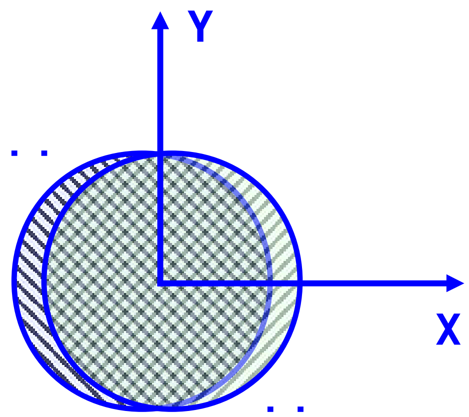
Peripheral Collision



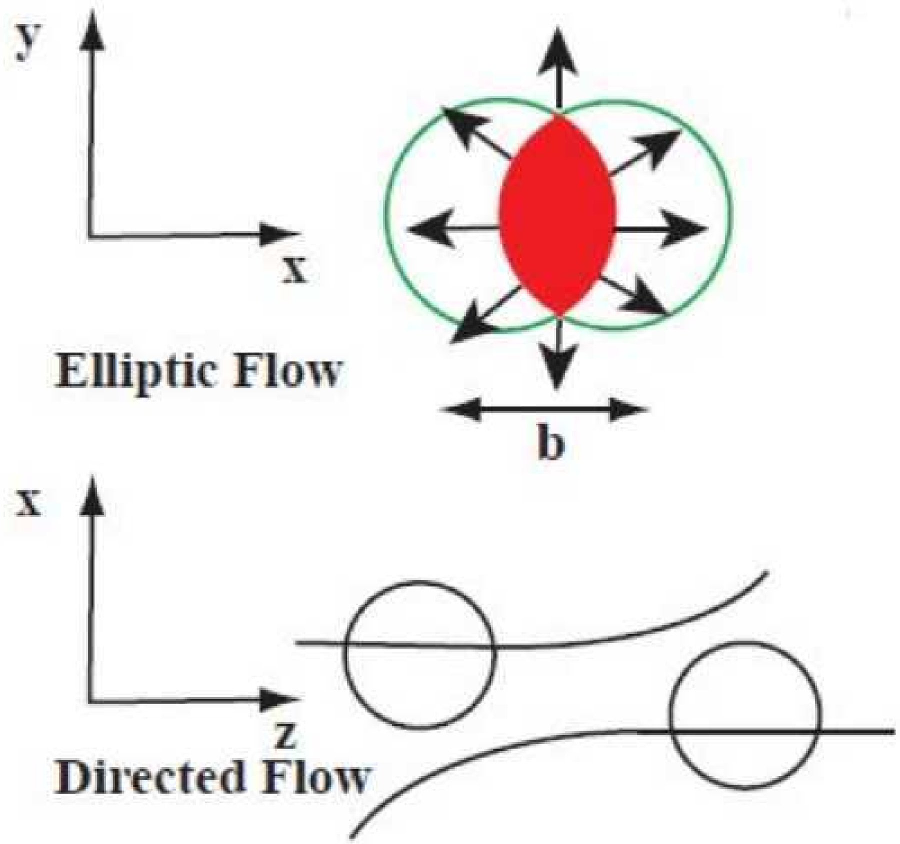


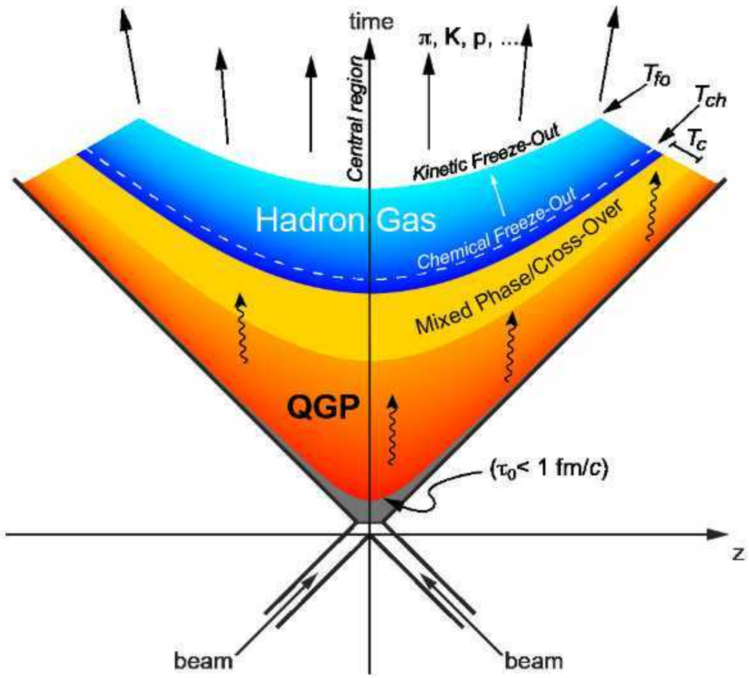
(near) Central Collision





Nucleus collisions





The Quark-Gluon-Plasma is Found at RHIC

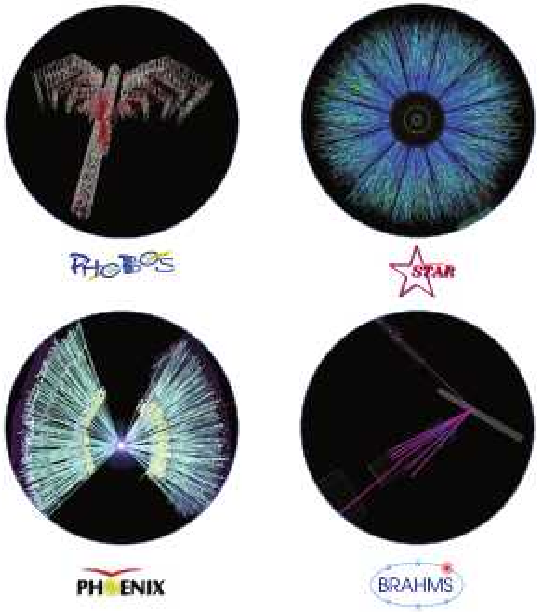
BNL -73847-2005
Formal Report

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

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Forward.. i

Quark Gluon Plasma and Color Glass Condensate at RHIC? The Perspective from the BRAHMS Experiment.. 1

Formation of Dense Partonic Matter in Relativistic Nucleus-Nucleus Collisions at RHIC: Experimental Evaluation by the PHENIX Collaboration 33

The PHOBOS Perspective on Discoveries at RHIC 159

Experimental and Theoretical Challenges in the Search for the Quark Gluon Plasma: The STAR Collaboration's Critical Assessment of the Evidence from RHIC Collisions 253

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 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.

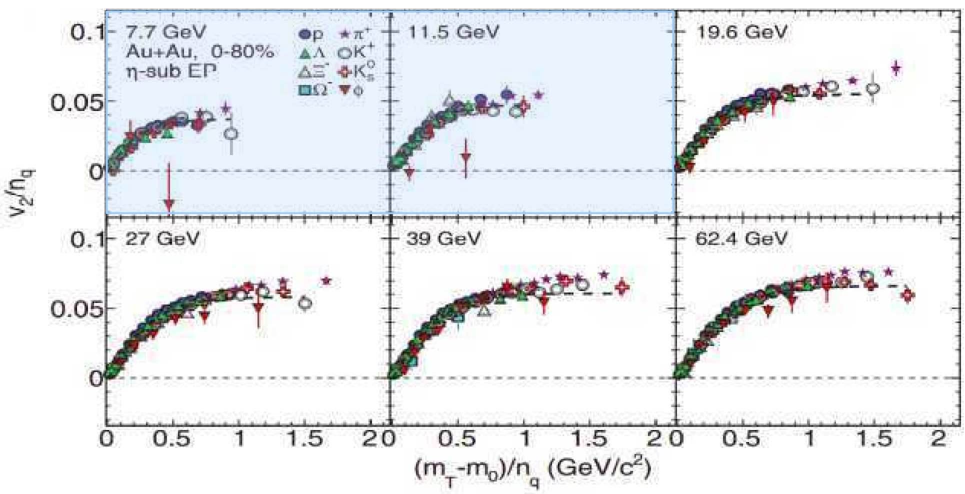
A search for signatures of a phase transition and a critical point. The particular observables that we have identified as the essential drivers of our run plan are:

(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

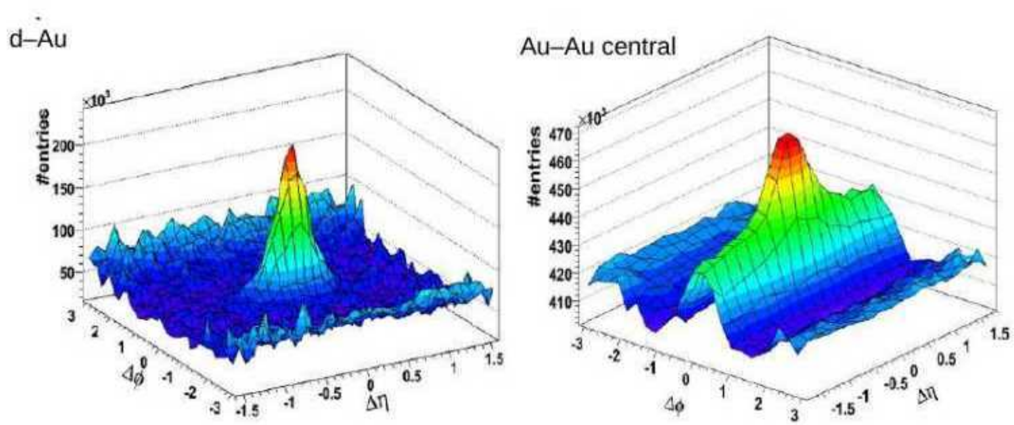
Number of constituent quarks scaling

Phys. Rev. C88, (2013), 014902



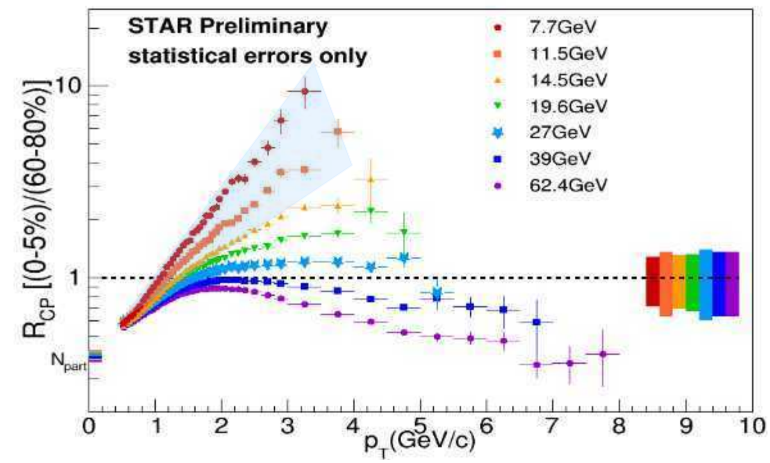
Ridge effect

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

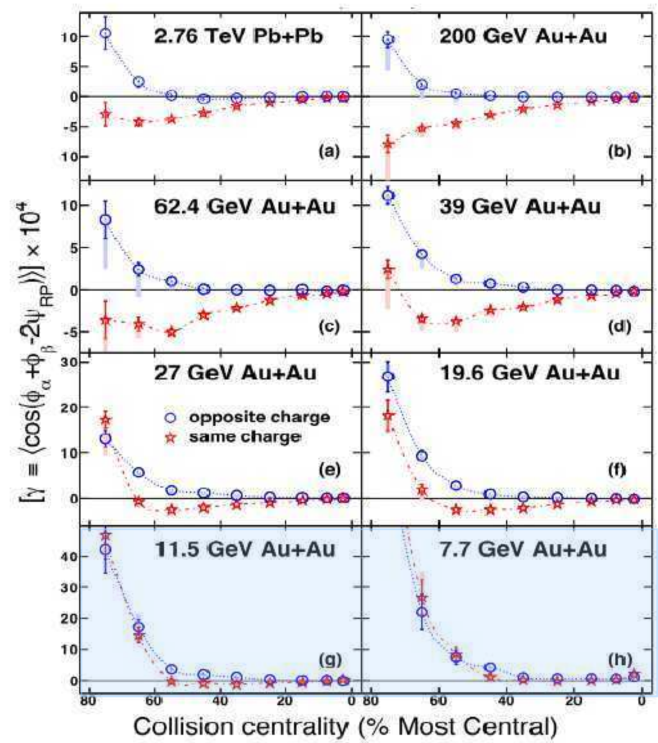


High P_T suppression

Stephen Horvat Quark Matter 2015

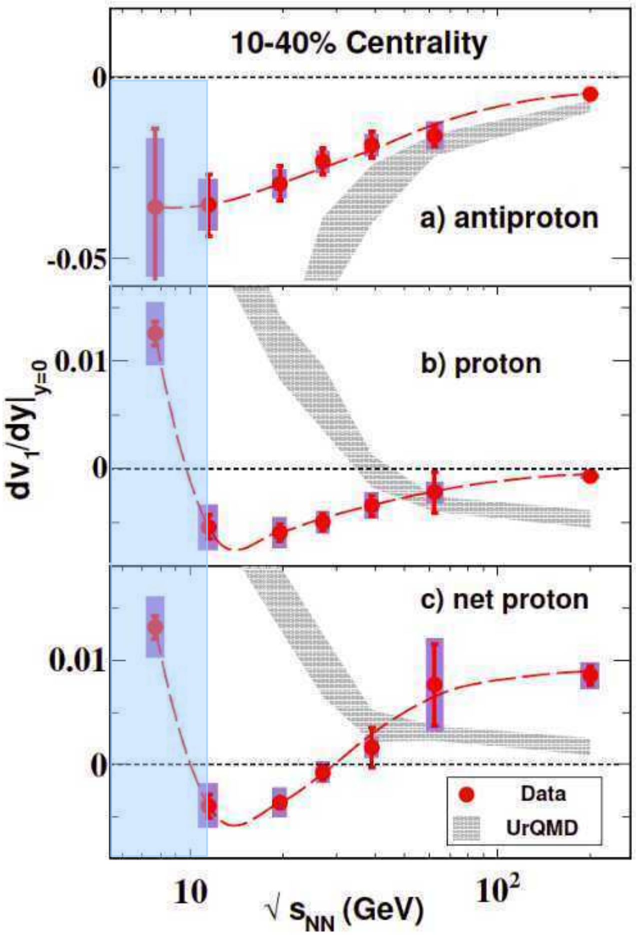


Chiral Magnetic Effect



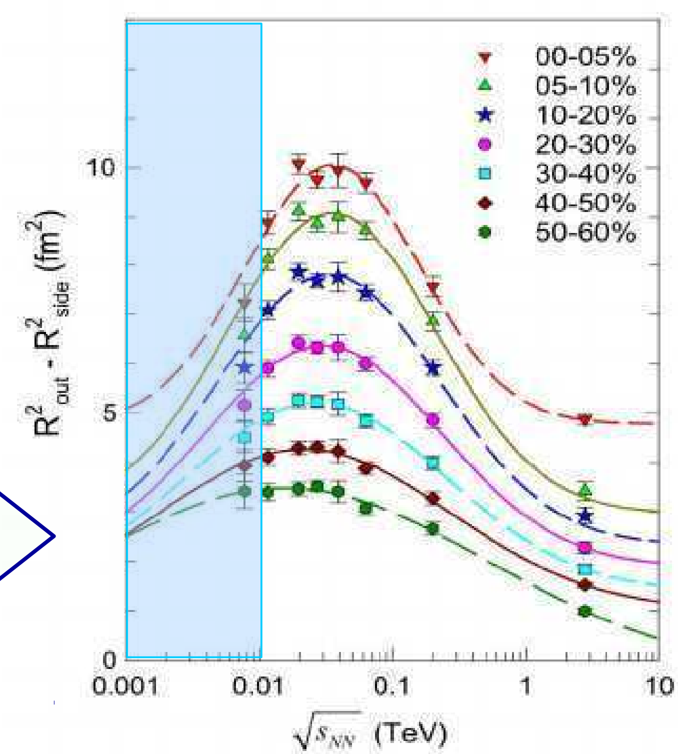
STAR BES I results

PRL 112 (2014) 162301



The rapidity-slope of the net proton directed flow v_1 , dv_1/dy. This quantity is sensitive to early pressure gradients in the medium.

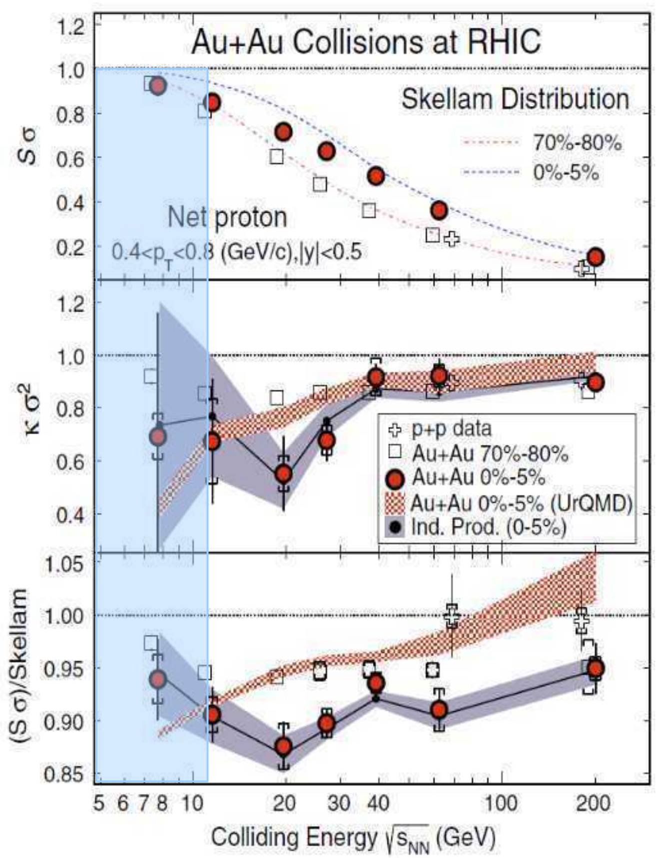
R. Lacey, PRL 114, 142301 (2015)



R^2_{out} - R^2_{side} – reflects the lifetime of the collision fireball and was predicted to reach a maximum for collisions in which a hydrodynamic fluid forms at temperatures where the equation of state is softest.

STAR BES I results

STAR, PRL 112, 032302 (2014)



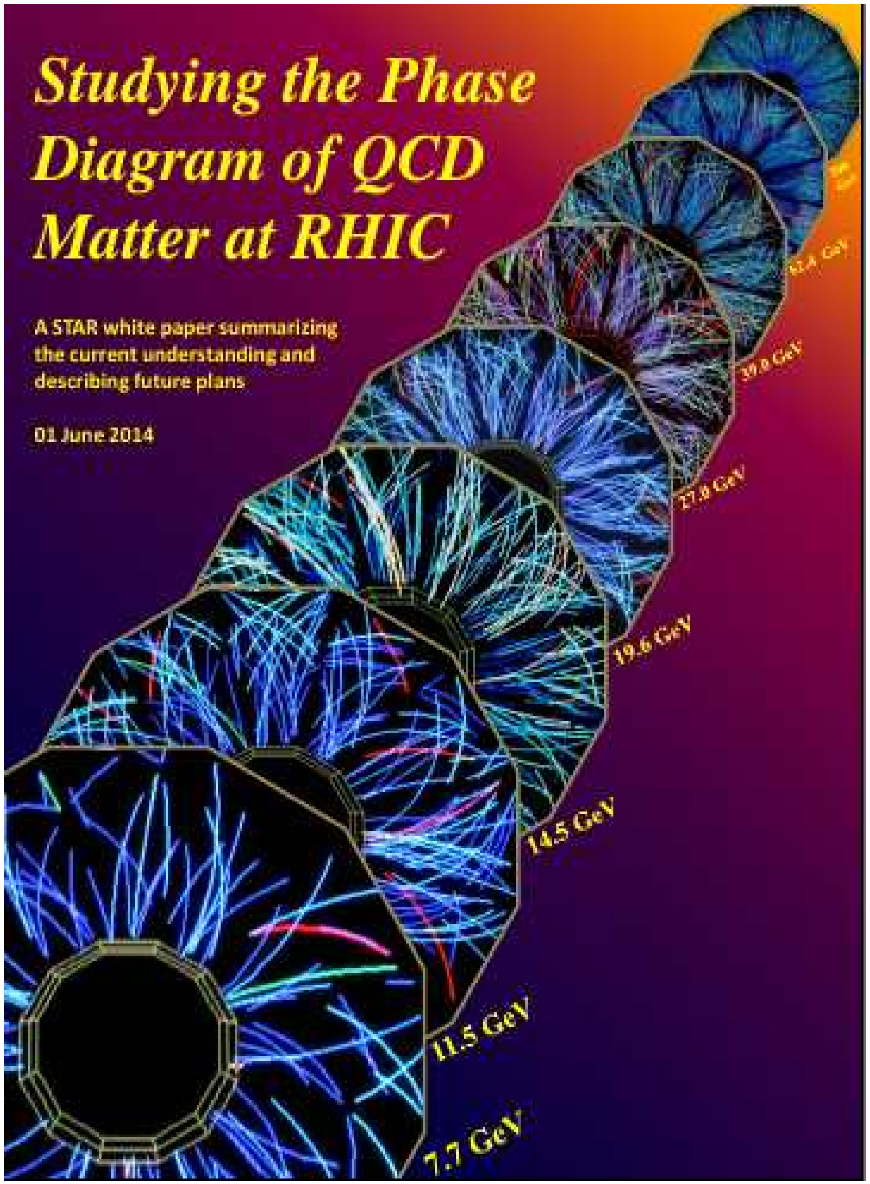
The kurtosis of the event-by-event distribution of the net proton (i.e. proton minus antiproton) number per unit of rapidity, normalized such that Poisson fluctuations give a value of 1.

In central collisions, published results in a limited kinematic range show a drop below the Poisson baseline around $\sqrt{s_{NN}}$ =27 and 19.6 GeV.

New preliminary data over a larger p_T range, although at present still with substantial error bars, hint that the normalized kurtosis may, in fact, rise above 1 at lower $\sqrt{s_{NN}}$, as expected from critical fluctuations..

The grey band shows the much reduced uncertainties anticipated from BES-II in 2018-2019, for the 0-5% most central collisions.

Studying the Phase Diagram of QCD Matter at RHIC



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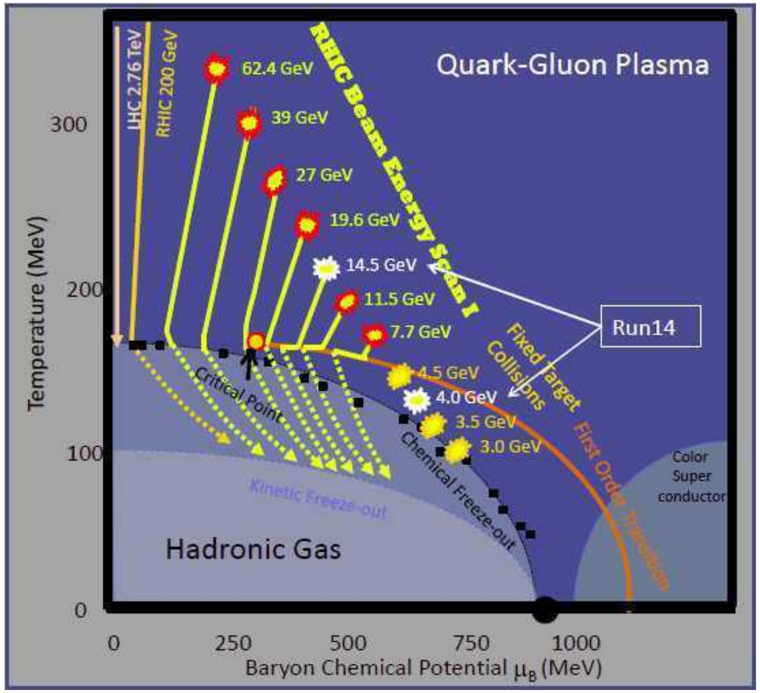
STAR BES program

I

$\sqrt{s_{NN}}$ (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

II

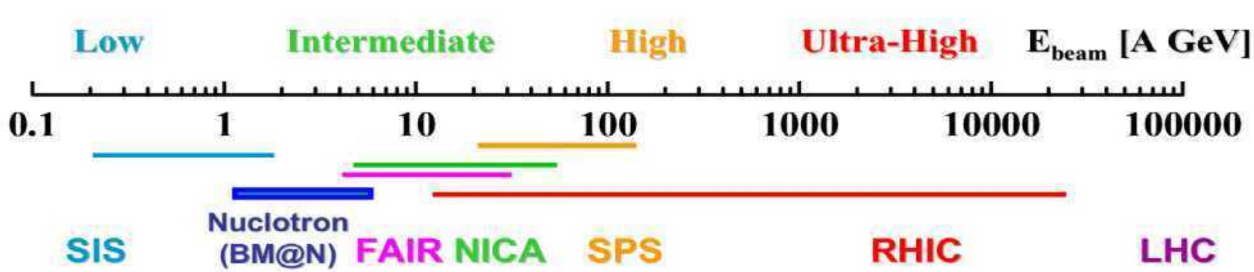
$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Needed Events (10^6)
7.7	420	100
9.1	370	160
11.5	315	230
14.5	**260**	**300**
19.6	205	400



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

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 advantagies

J. Cleymans
MPD collaboration
Meeting April, 2018

- Maximum in K^+/π^+ ratio is in the NICA energy region,
- Maximum in Λ/π ratio is in the NICA energy region,
- Maximum in the net baryon density is in the NICA energy region,
- Transition from a baryon dominated system to a meson dominated one happens in the NICA energy region.

Nuclotron based Ion Collider fAcility

Beams – p,d(h)..$^{197}Au^{79+}$

Collision energy $\sqrt{s}$= **4-11** GeV/u (Au), **12-27** (p)

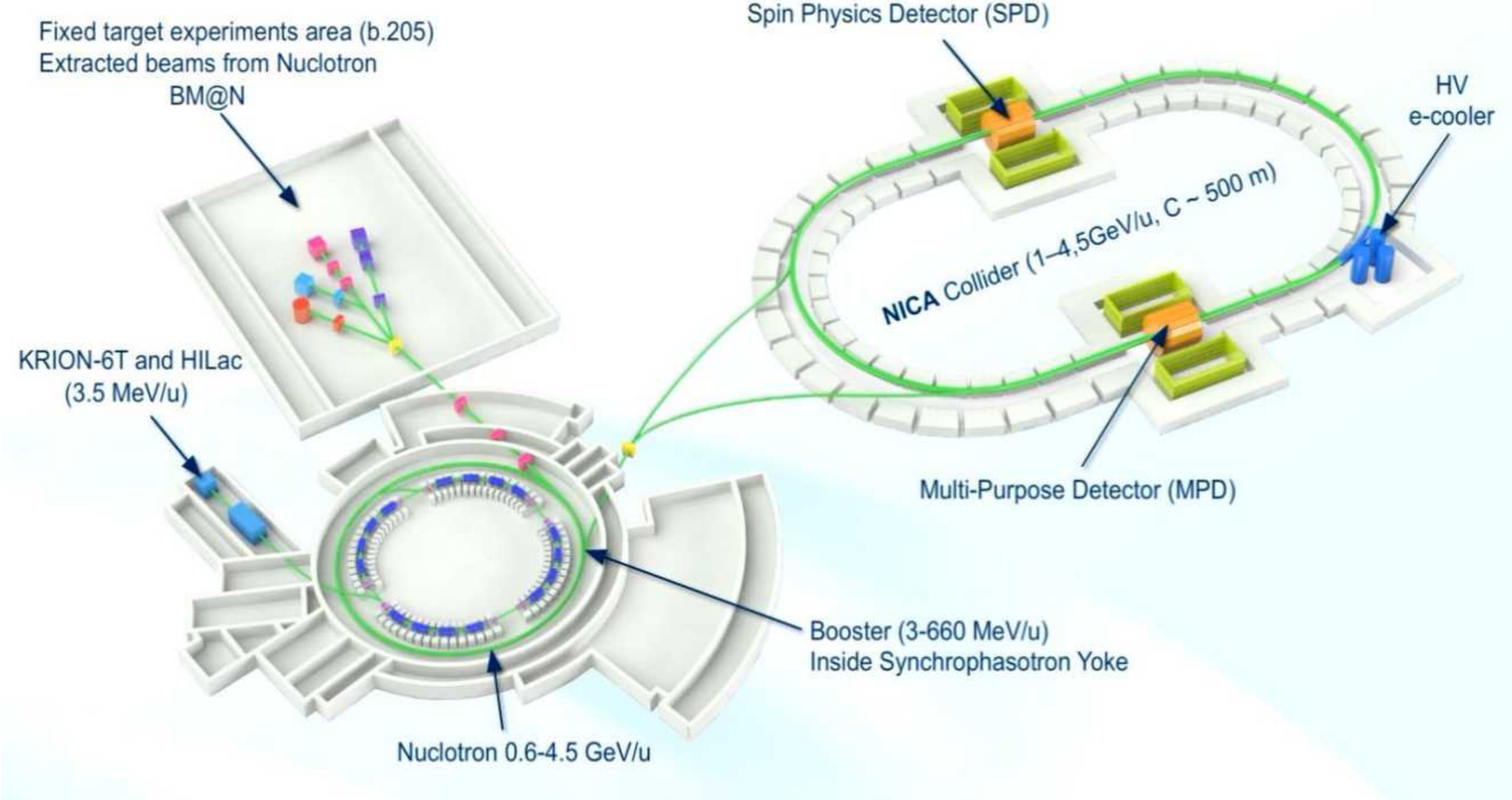
Beam energy (fixed target) - **1-6** GeV/u

Luminosity: **10^{27}** $cm^{-2}s^{-1}$(Au), **10^{32}** (p)

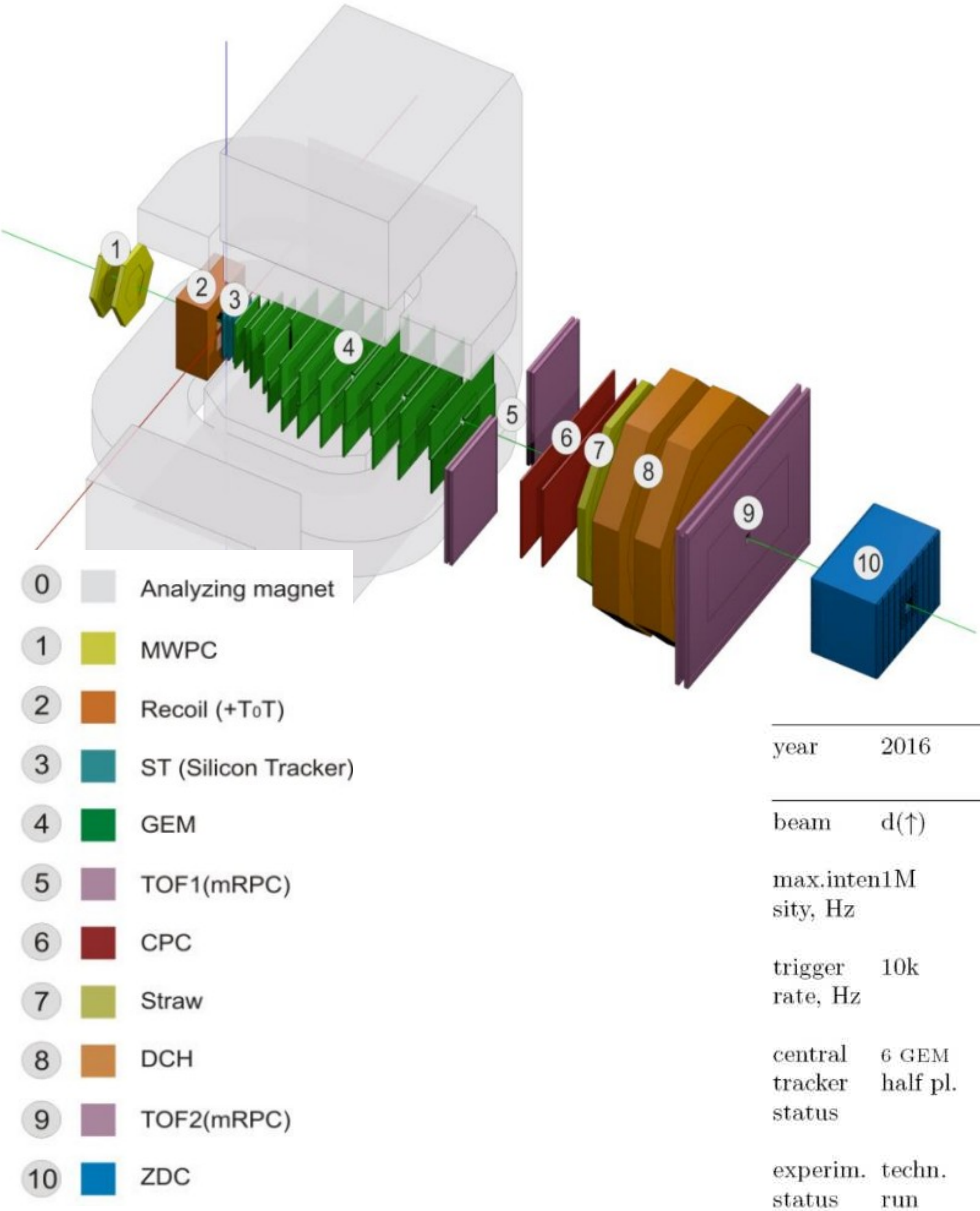
Experiments:

2 Interaction points – **MPD** and SPD

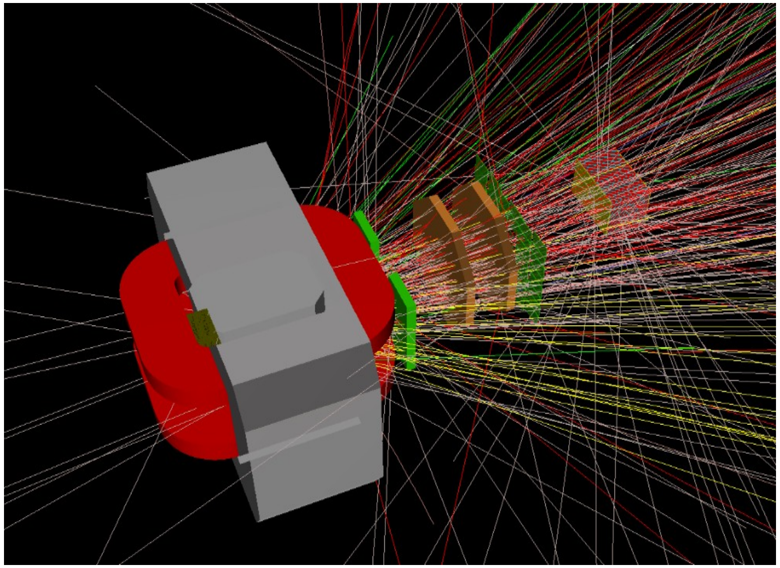
Fixed target experiment **BM@N**



BM@N experiment at NICA

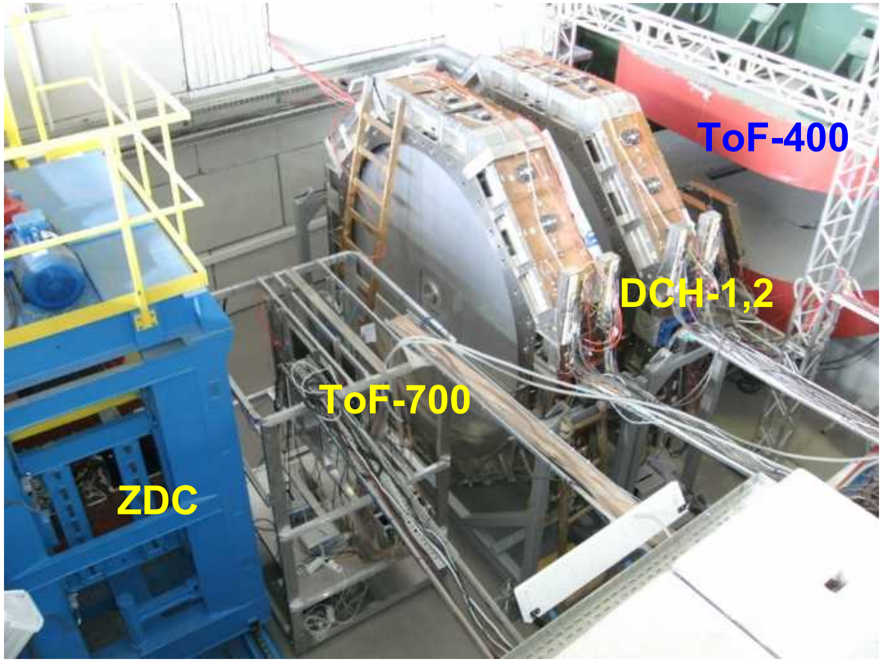


AuAu $E_{beam} = 4$ GeV

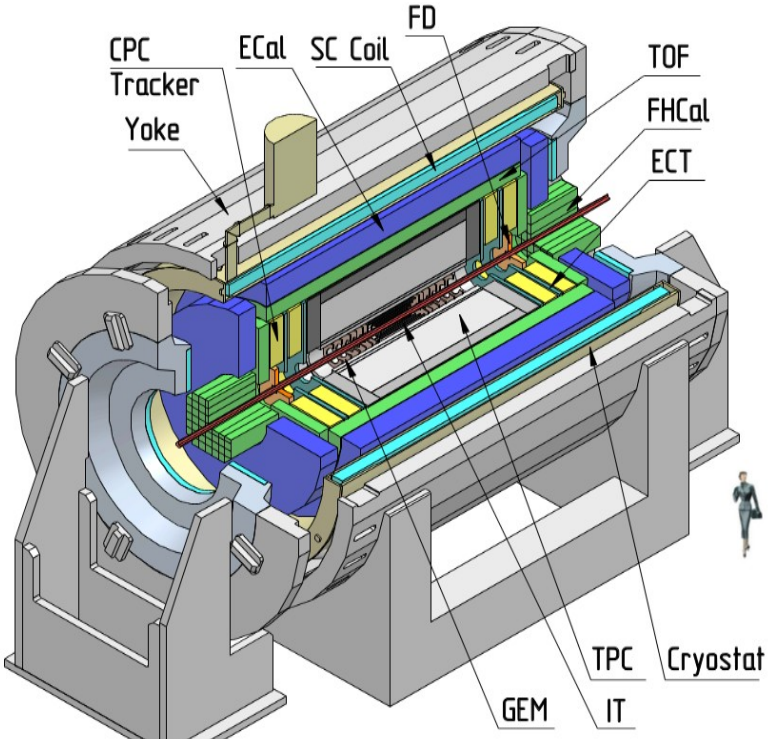


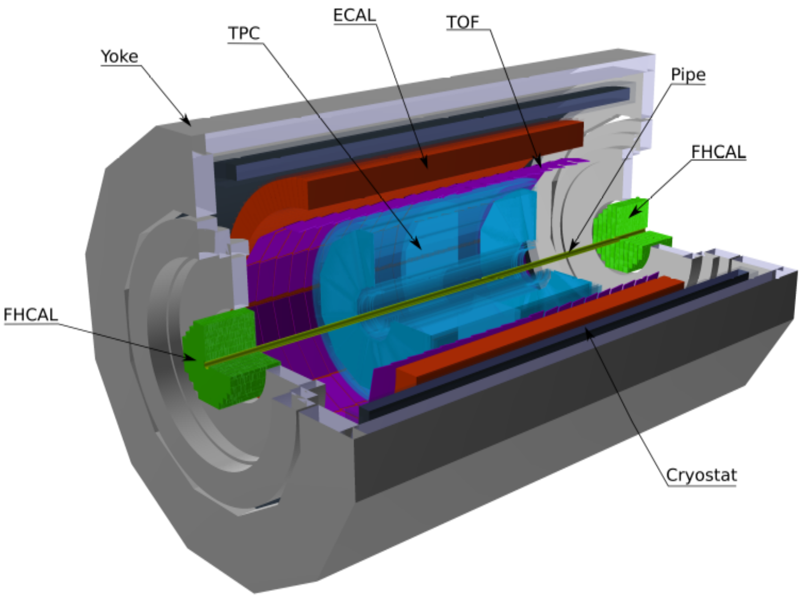
year	2016	2017 spring	2017 autumn	2019	2020 and later
beam	d(↑)	C, Ar	Kr	Au	Au, p
max.intensity, Hz	1M	1M	1M	1M	10M
trigger rate, Hz	10k	10k	20k	20k	50k
central tracker status	6 GEM half pl.	8 GEM half pl.	10 GEM half pl.	8 GEM full pl.	12 GEMs or 8 GEMs + Si planes
experim. status	techn. run	techn. run	physics run	stage 1 physics	stage 2 physics

BM@N experiment at NICA

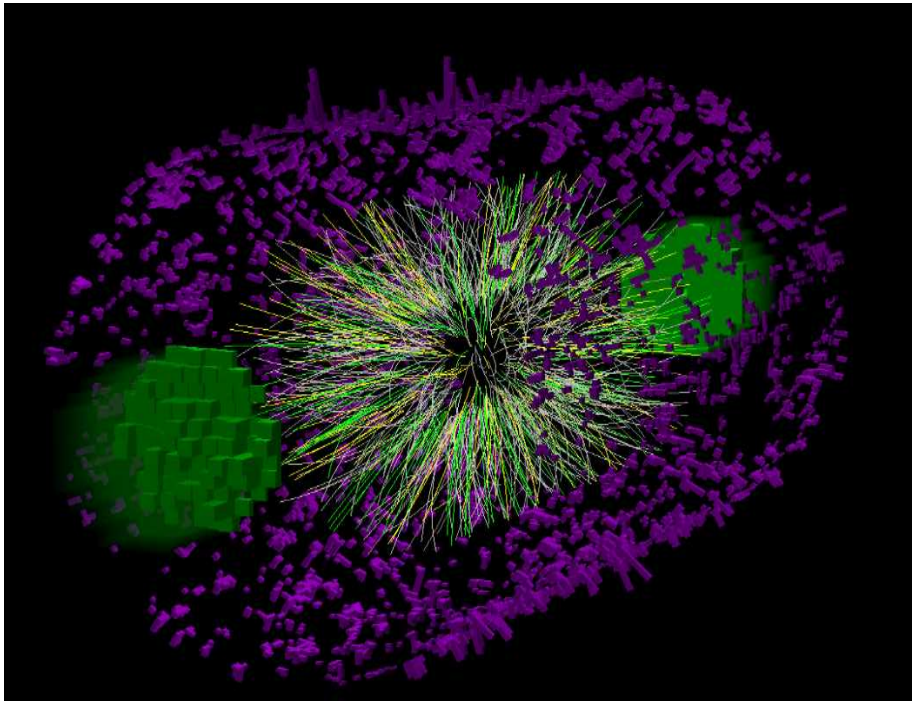


MPD experiment at NICA





MPD event display
AuAu √s = 11 GeV



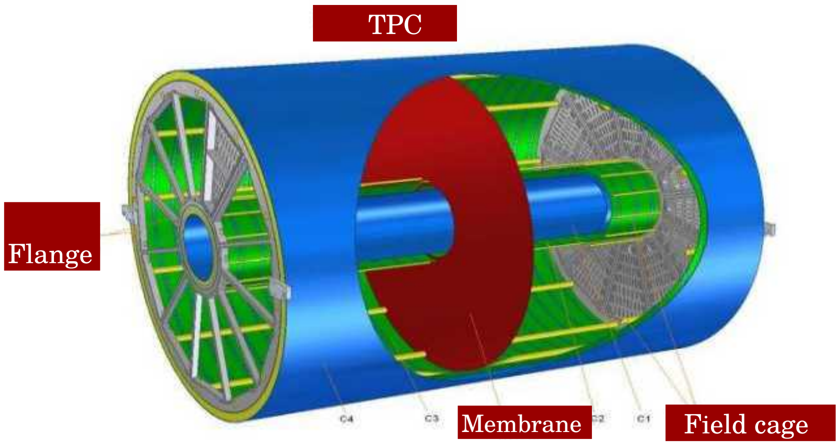
MPD magnet yoke

- **Iron Yoke**

Outer diameter 6583 mm
Length 9010 mm
Dist. In between poles 7390 mm
Weight 727 ton

28 plates 16 T each
2 support rings 42.5 T each
2 poles 50 T each

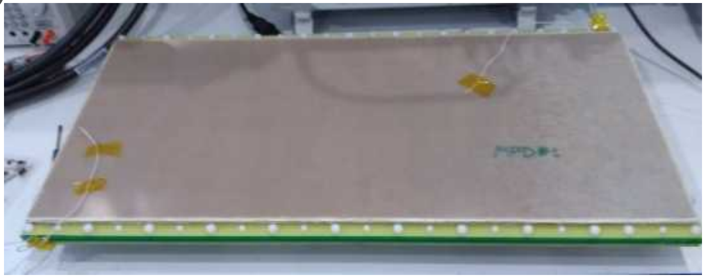
MPD Time Projection Chamber

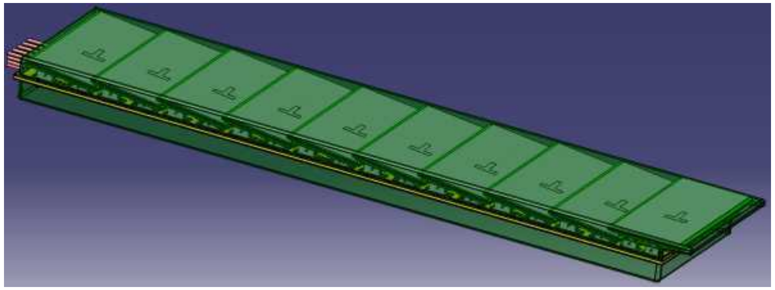


Item	Dimension
Length of the TPC	340cm
Outer radius of vessel	140cm
Inner radius of vessel	27 cm
Outer radius of the drift volume	133cm
Inner radius of the drift volume	34cm
Length of the drift volume	170cm (of each half)
HV electrode	Membrane at the center of the TPC
Electric field strength	~140V/cm;
Magnetic field strength	0.5 Tesla
Drift gas	90% Ar+10% Methane, Atmospheric pres. + 2 mbar
Gas amplification factor	~ 10^4
Drift velocity	5.45 cm/μs;
Drift time	< 30μs;
Temperature stability	< 0.5°C
Number of readout chambers	24 (12 per each end-plate)
Segmentation in φ	30°
Pad size	5x12mm^2 and 5x18mm^2
Number of pads	95232
Pad raw numbers	53
Pad numbers after zero suppression	< 10%
Maximal event rate	< 7 kHz (Lum. 10^{27})
Electronics shaping time	~180 ns (FWHM)
Signal-to-noise ratio	30:1
Signal dynamical range	10 bits
Sampling rate	10 MHz
Sampling depth	310 time buckets

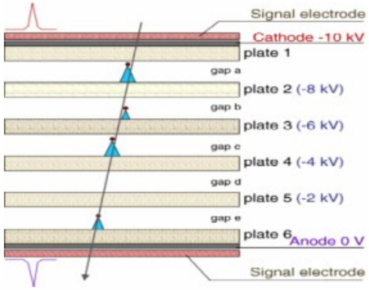
Time Of Flight detector

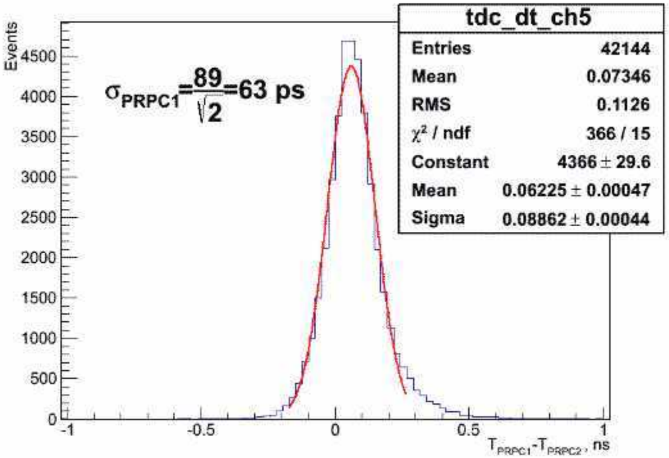
mRPC prototype with a strip





multigap resistive plate chamber

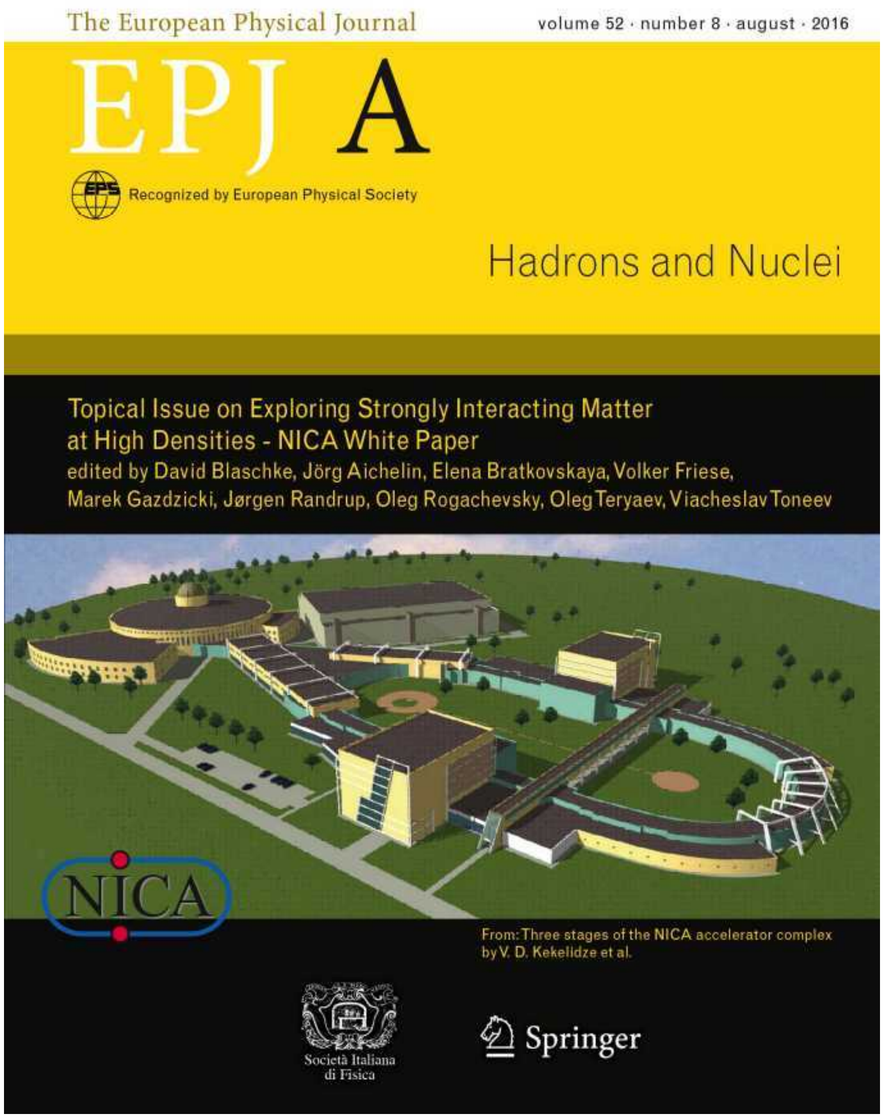




(T1 - T2) for two mRPCs

Full scale mRPC prototype with a strip

NICA White Paper



ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2016. Т. 47. ВЫП. 4

FEASIBILITY STUDY OF HEAVY ION PHYSICS PROGRAM AT NICA

P. N. Batyuk [1,*], *V. D. Kekelidze* [1], *V. I. Kolesnikov* [1], *O. V. Rogachevsky* [1], *A. S. Sorin* [1,2], *V. V. Voronyuk* [1]
on behalf of the BM@N and MPD collaborations

[1] Joint Institute for Nuclear Research, Dubna
[2] National Research Nuclear University "Moscow Engineering Physics Institute" (MEPhI), Moscow

There is strong experimental and theoretical evidence that in collisions of heavy ions at relativistic energies the nuclear matter undergoes a phase transition to the deconfined state — Quark–Gluon Plasma. The caused energy region of such a transition was not found at high energy at SPS and RHIC, and search for this energy is shifted to lower energies, which will be covered by the future NICA (Dubna), FAIR (Darmstadt) facilities and BES II at RHIC. Fixed target and collider experiments at the NICA facility will work in the energy range from a few A GeV up to $\sqrt{s_{NN}} = 11$ GeV and will study the most interesting area on the nuclear matter phase diagram.

The most remarkable results were observed in the study of collective phenomena occurring in the early stage of nuclear collisions. Investigation of the collective flow will provide information on Equation of State (EoS) for nuclear matter. Study of the event-by-event fluctuations and correlations can give us signals of critical behavior of the system. Femtoscopy analysis provides the space-time history of the collisions. Also, it was found that baryon stopping power revealing itself as a "wiggle" in the excitation function of curvature of the (net) proton rapidity spectrum relates to the order of the phase transition.

The available observations of an enhancement of dilepton rates at low invariant masses may serve as a signal of the chiral symmetry restoration in hot and dense matter. Due to this fact, measurements of the dilepton spectra are considered to be an important part of the NICA physics program. The study of strange particles and hypernuclei production gives additional information on the EoS and "strange" axis of the QCD phase diagram.

In this paper a feasibility of the considered investigations is shown by the detailed Monte Carlo simulations applied to the planned experiments (BM@N, MPD) at NICA.

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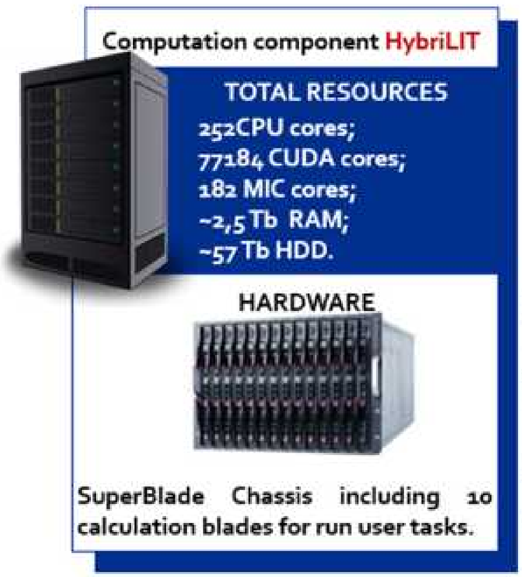
NICA Computing resources

GOVORUN



OS: **Scientific Linux 6**
distributed file system: **EOS**
batch system: **SLURM**

HybriLIT

Thank you for attention