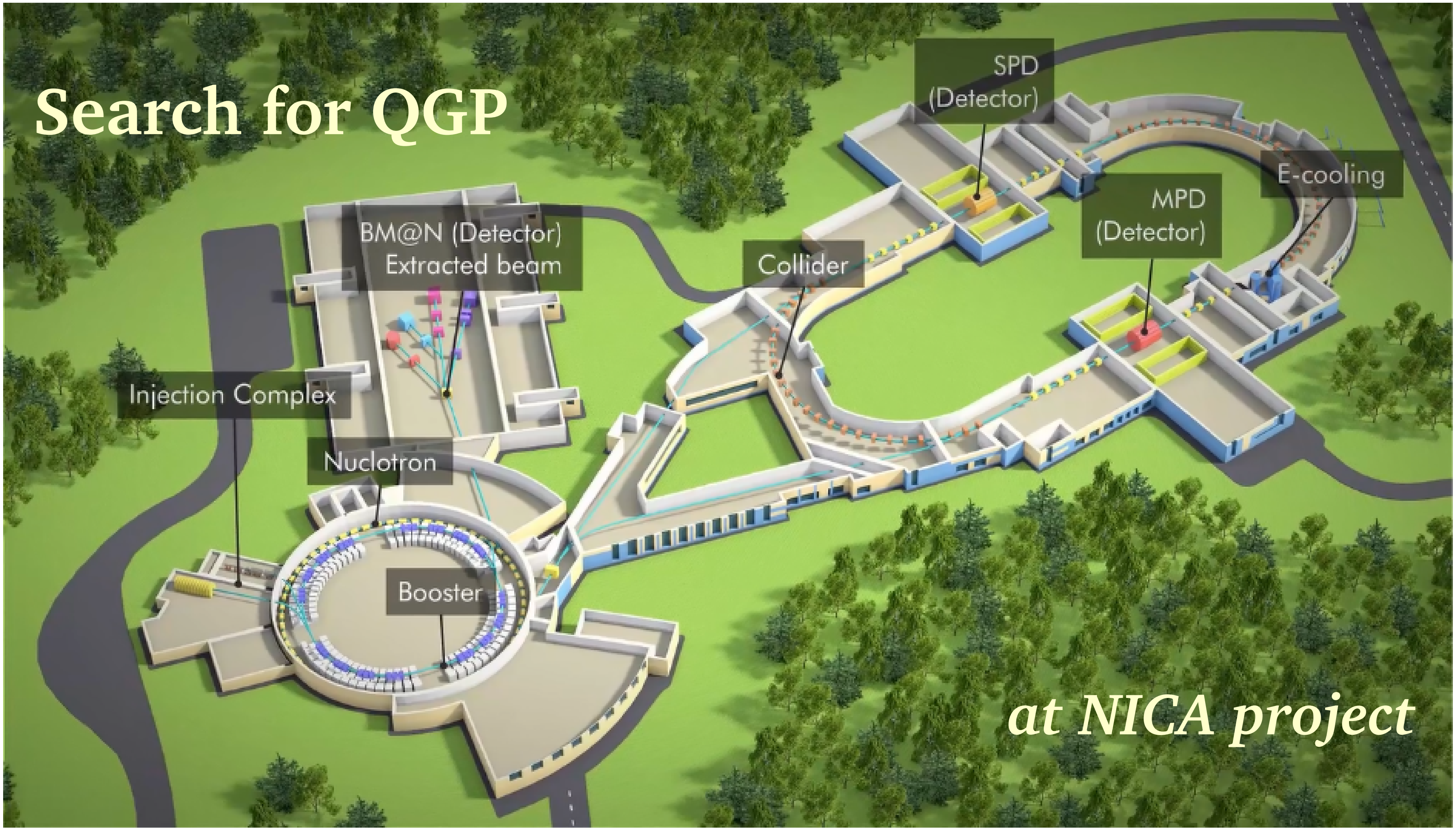
Search for QGP at NICA project



ROGACHEVSKY Oleg

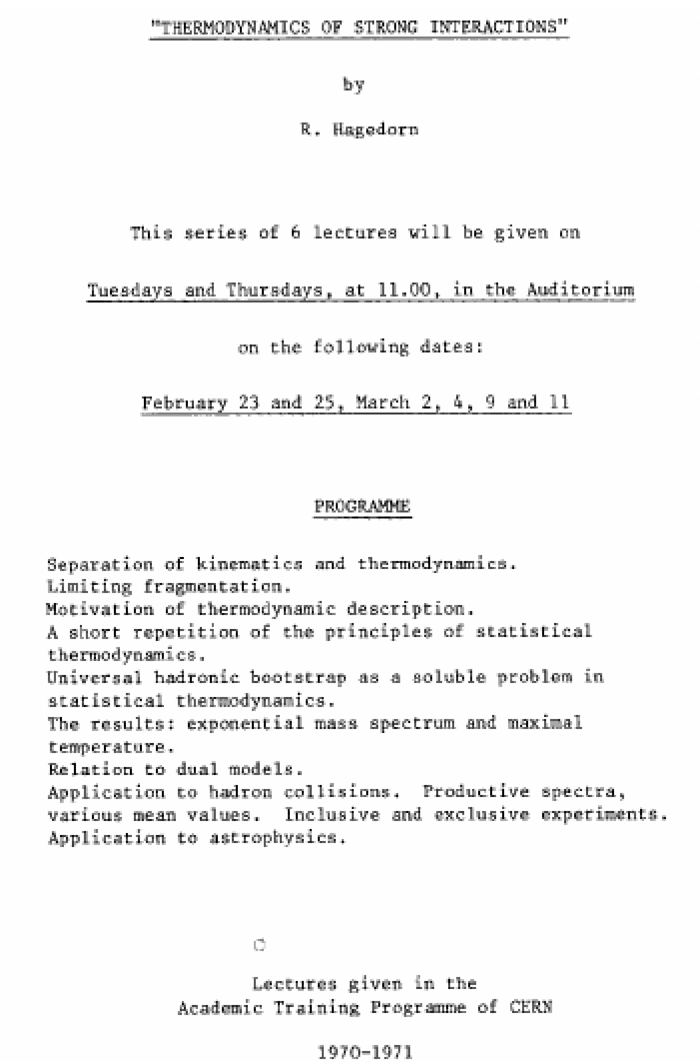
- *for MPD collaboration*

The Actual Problems of Microworld Physics

August 15 2018

Grodno

Phase transition



"THERMODYNAMICS OF STRONG INTERACTIONS"

by

R. Hagedorn

This series of 6 lectures will be given on

Tuesdays and Thursdays, at 11.00, in the Auditorium

on the following dates:

February 23 and 25, March 2, 4, 9 and 11

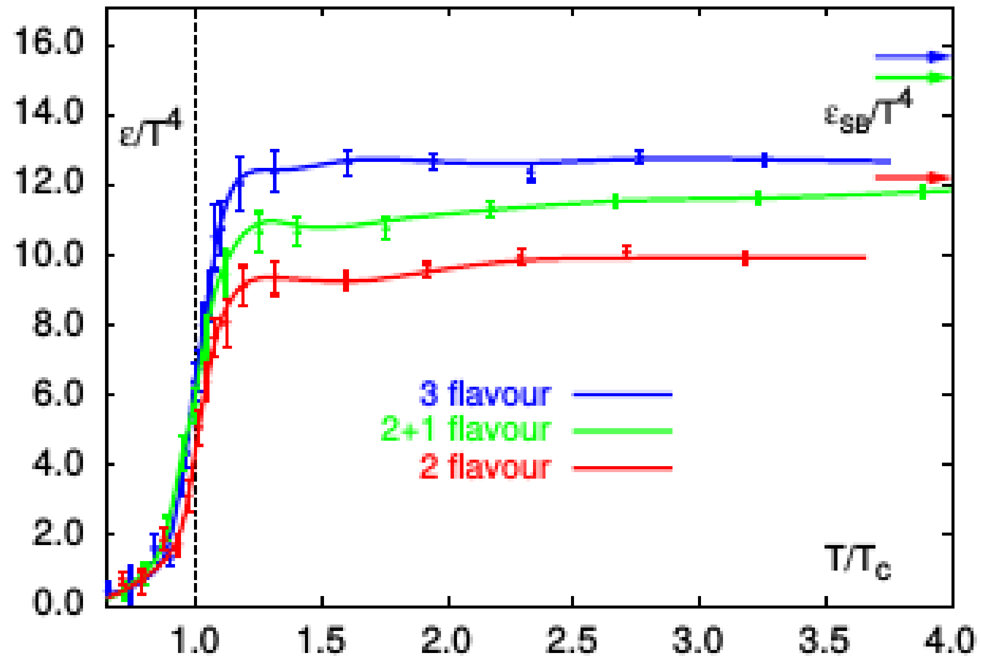
PROGRAMME

Separation of kinematics and thermodynamics.
Limiting fragmentation.
Motivation of thermodynamic description.
A short repetition of the principles of statistical thermodynamics.
Universal hadronic bootstrap as a soluble problem in statistical thermodynamics.
The results: exponential mass spectrum and maximal temperature.
Relation to dual models.
Application to hadron collisions. Productive spectra, various mean values. Inclusive and exclusive experiments.
Application to astrophysics.

Lectures given in the
Academic Training Programme of CERN

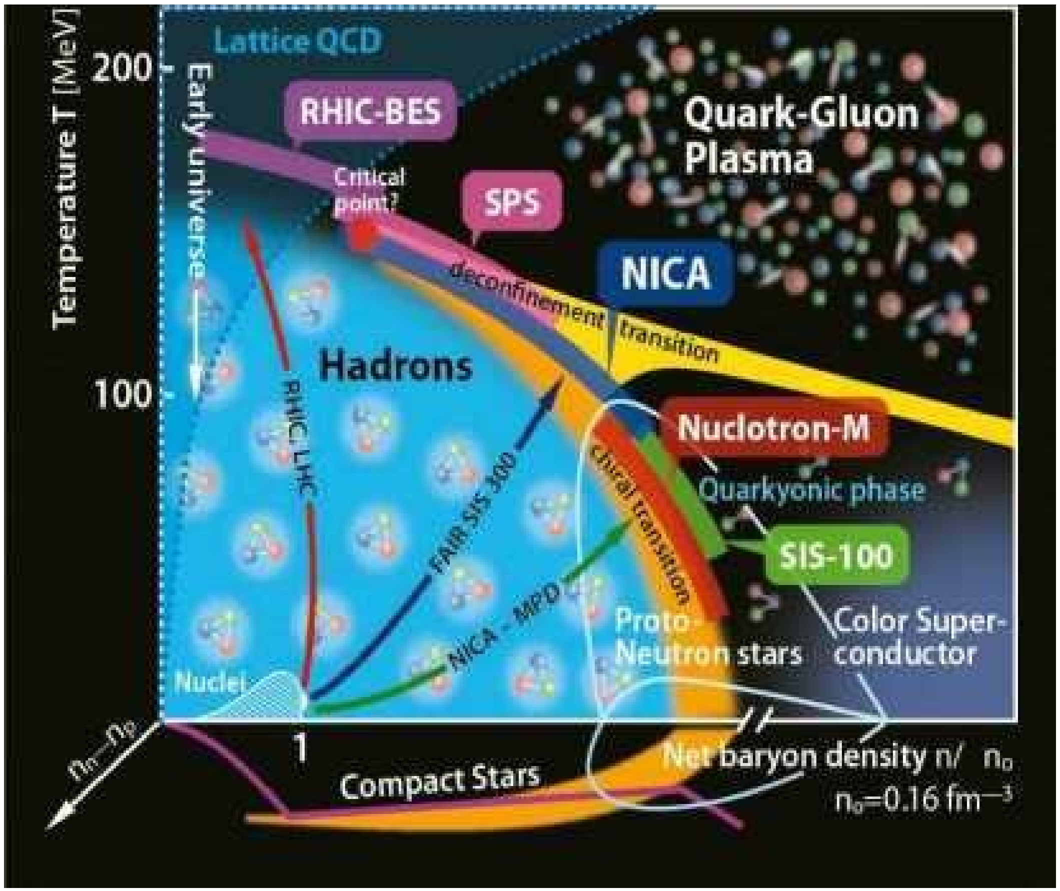
1970-1971

Lattice calculations, under a variety of assumptions (e.g. number of quark flavors or ms), make therobust prediction that the degrees of freedom available to the system rise rapidly.



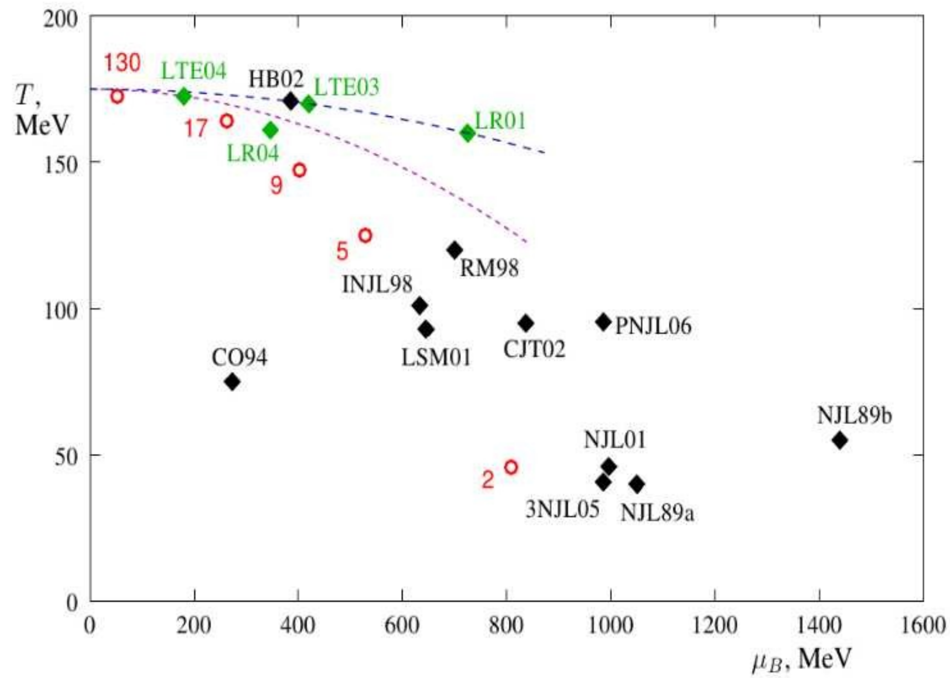
F. Karsch, Lect. Notes Phys. 583, 209 (2002)

QCD phase diagram

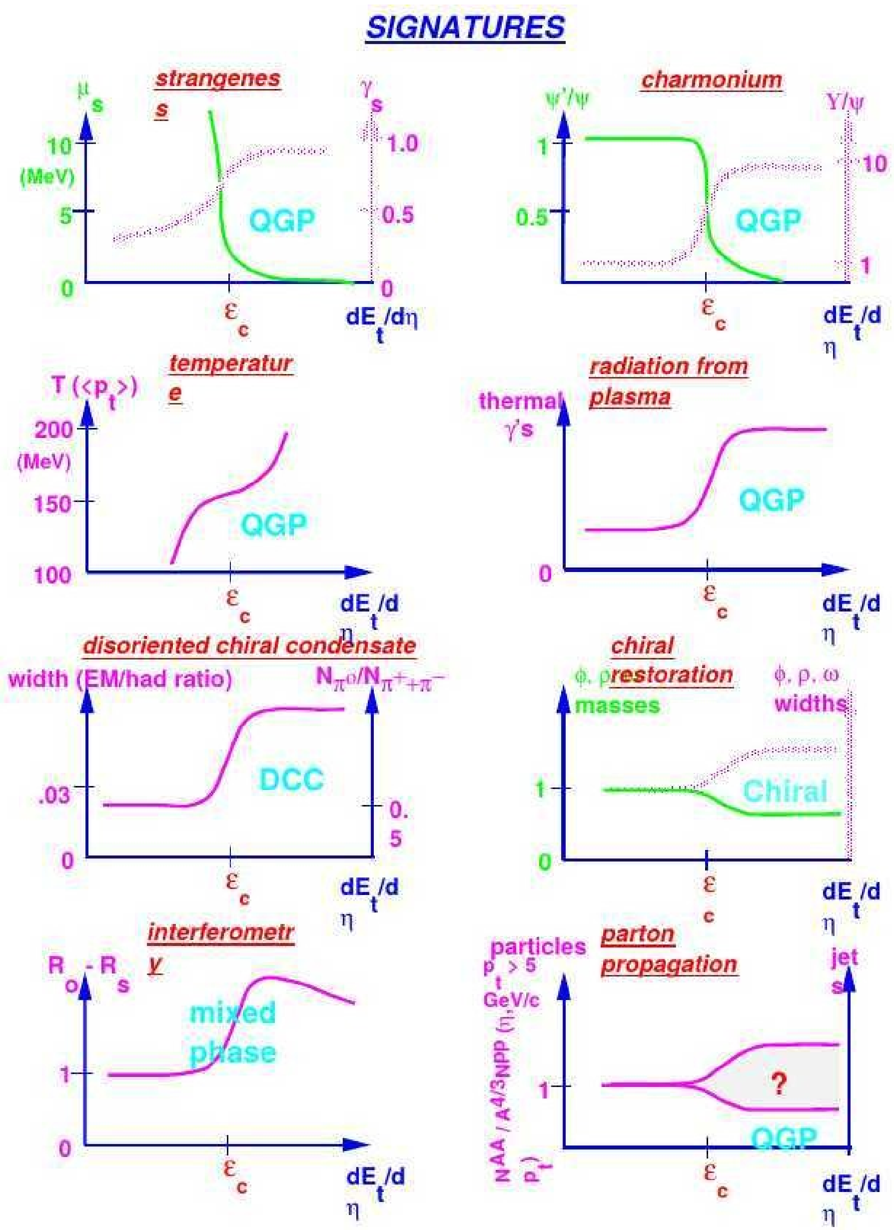


M. Stephanov

arXiv:hep-lat/0701002v1



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

Strangeness in QGP

In 1982 J. Rafelski and B. Müller predicted that enhancement of strangeness production is a signal of QGP
"Strangeness Production in the Quark-Gluon Plasma"
Phys. Rev. Lett. 48(1982)

" A substantial enhancement of production rates of multi-strange anti-baryons in nuclear collisions in particular at central rapidity and at highest transverse masses has therefore been proposed as a characteristic signature of QGP."
Phys. Lett. 62(1991)

Idea: if s-(anti)quarks are created at QGP stage, then their number should not be changed during further evolution since s-(anti)quarks number is small and since density decreases => there is no chance for their annihilation! Hence, we should observe chemical enhancement of strangeness

Heavy Ion Experiments at the AGS

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	

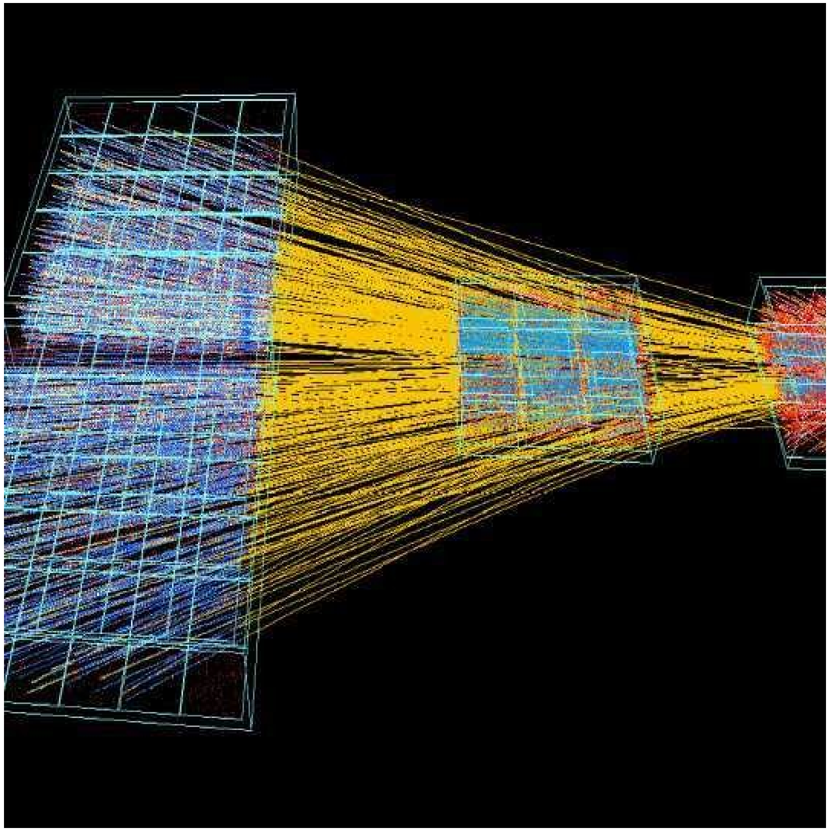
Heavy Ion Experiments at the SPS

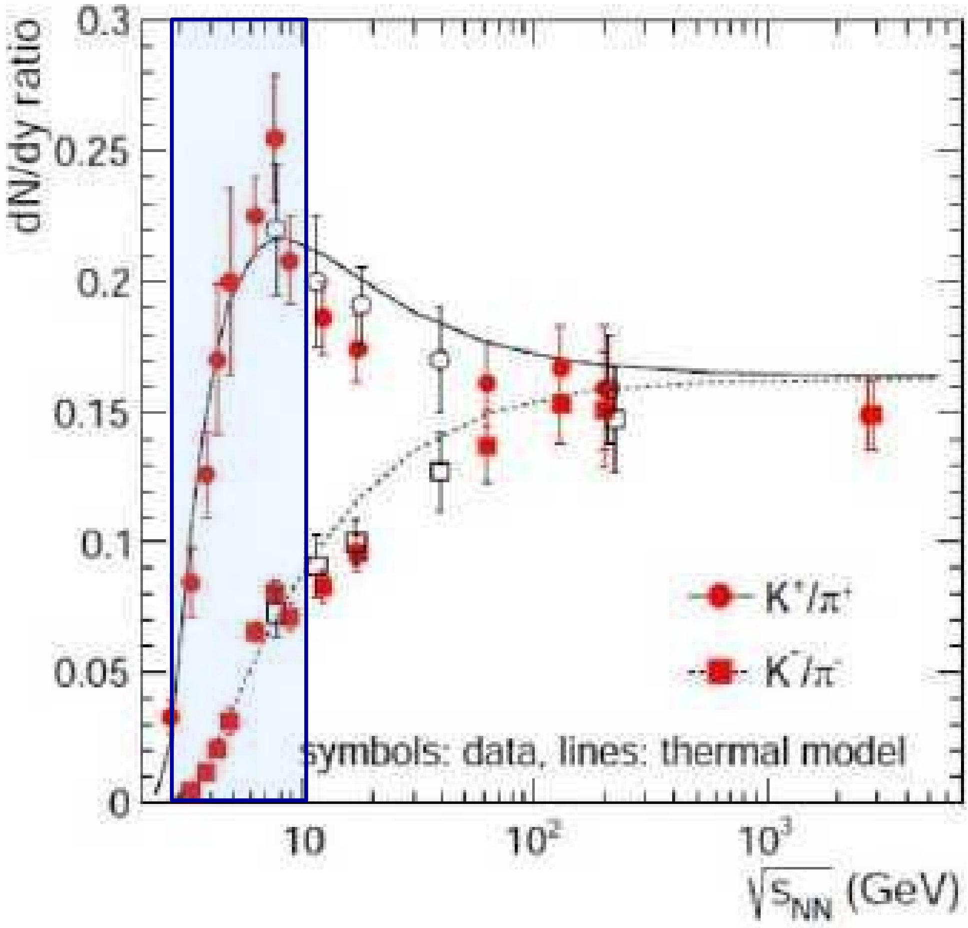
Experiment	Beam	Technology	Observables
NA34	^{16}O, ^{32}S	Muon spectrometer + calorimeter	Di-leptons, p, π, K, γ
NA35		Streamer chamber	π^-, K^0_s, Λ, HBT
NA36		TPC	K^0_s, Λ
NA38		Di-muon spectrometer (NA10)	Di-leptons, J/ψ
WA80/WA93		Calorimeter + Plastic Ball	γ, π^0, η
WA85		Mag. spectrometer with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

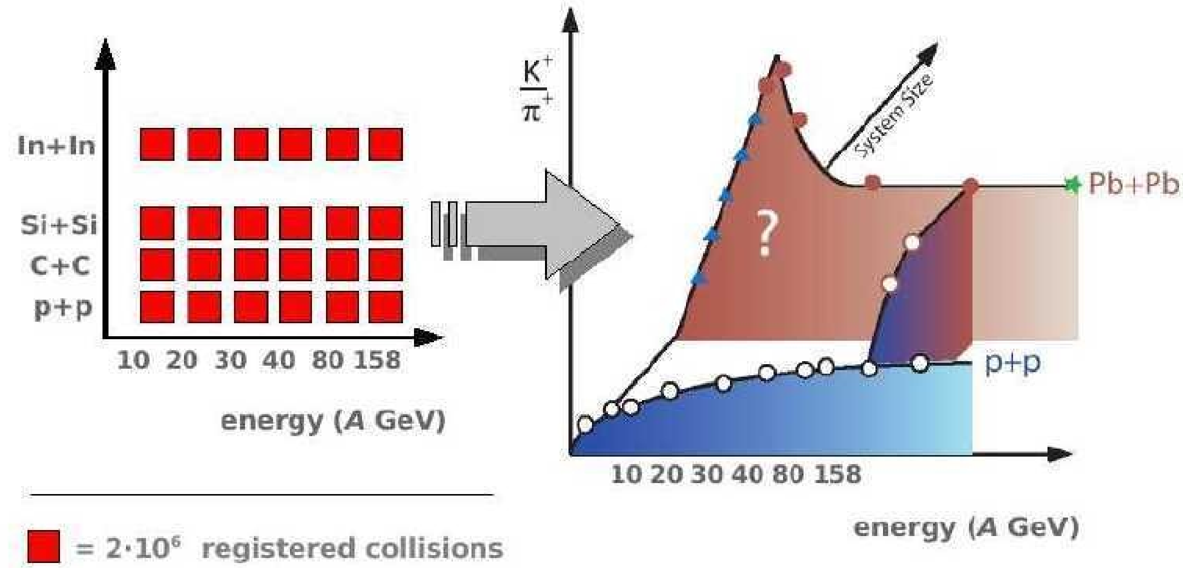
Statistical Model of the Early Stage



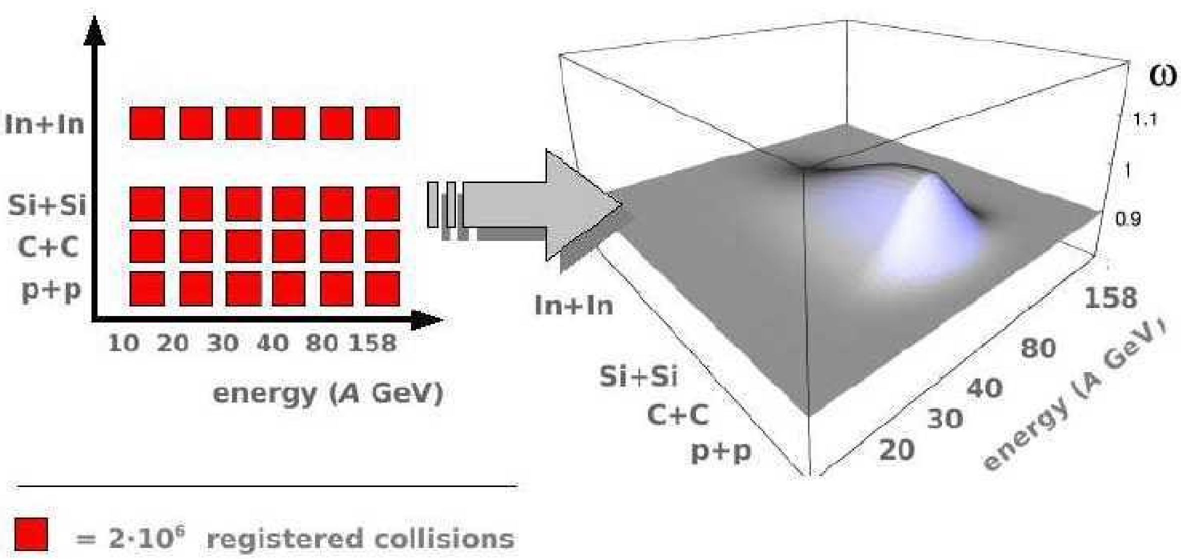


NA49 scan

arXiv:nucl-ex/0612007

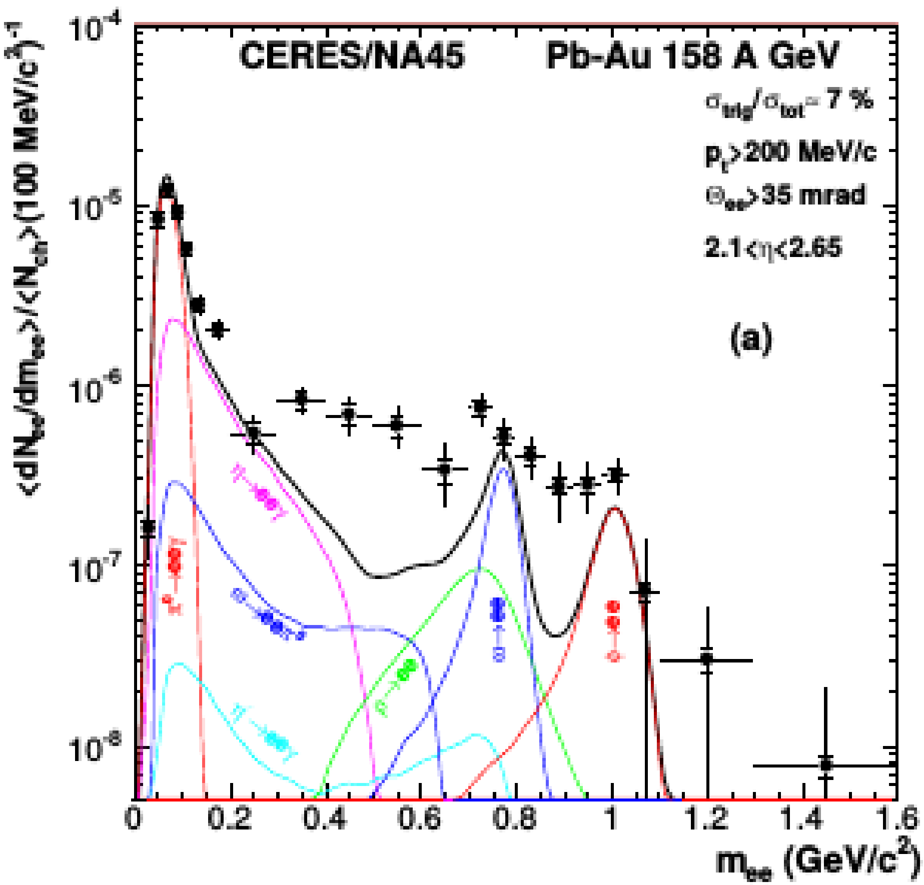


Horn vanishing

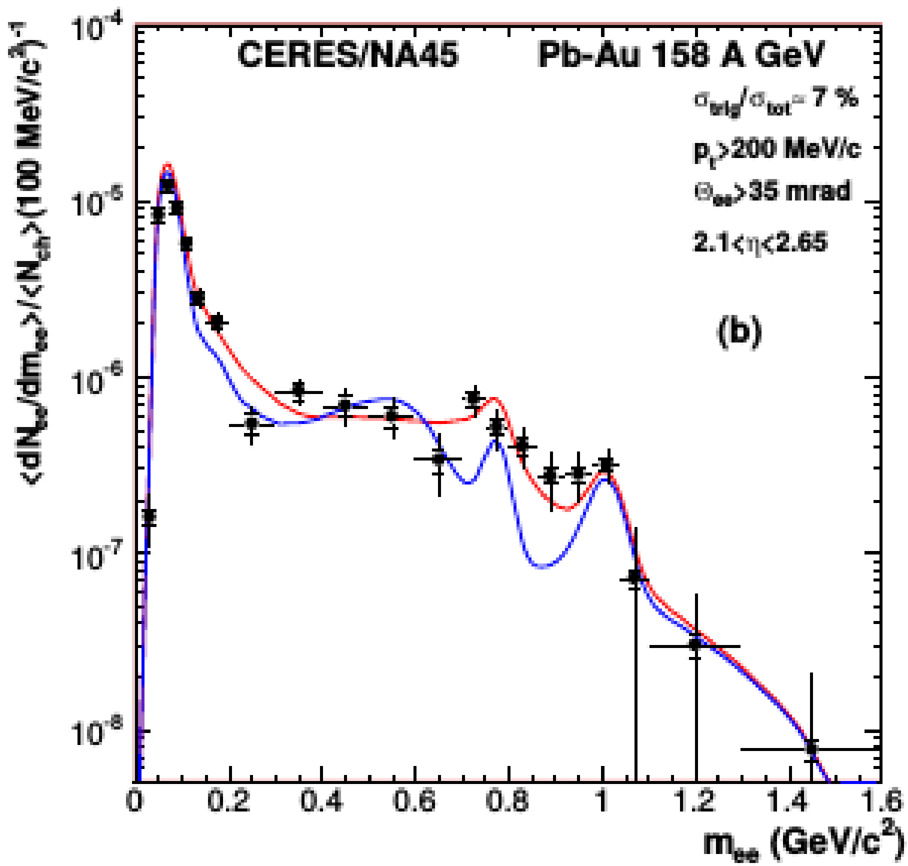


The scaled variance of the multiplicity distribution of negatively charged hadrons in the projectile hemi-sphere

NA 45



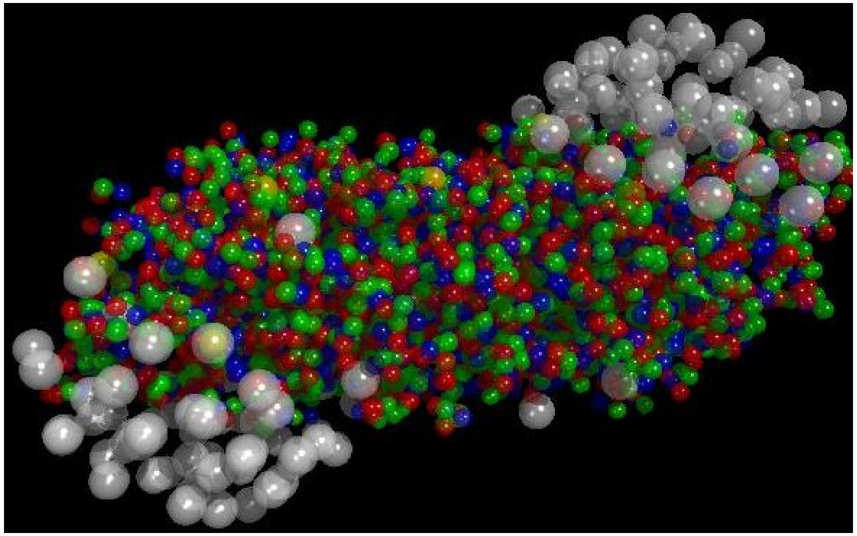
Invariant-mass spectrum of $e^+ e^-$ -pairs compared to the expectation from the hadron decay cocktail.



The expectations from model calculations assuming a dropping of the ρ meson mass (blue) or a spread of the ρ width in the medium (red) are also shown.

New State of Matter created at CERN in 2000

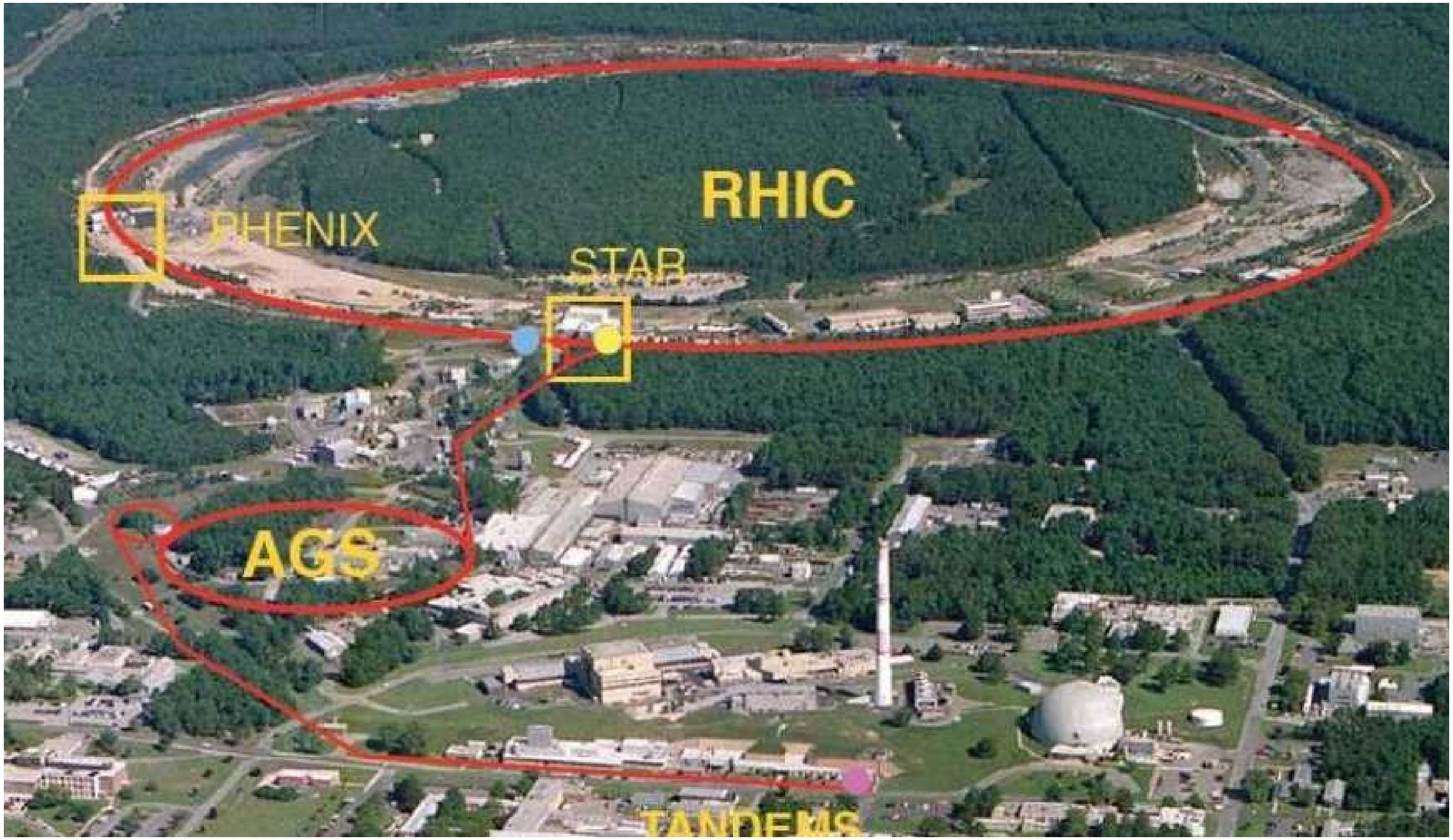
Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN1's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, 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.

BNL-RHIC from 2000

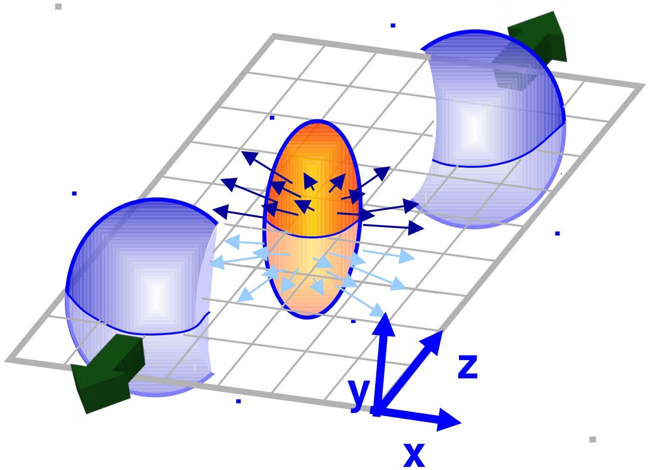


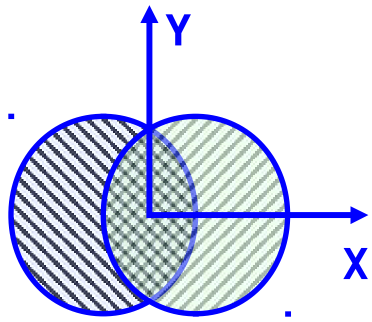
Heavy Ion Experiments at RHIC

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)

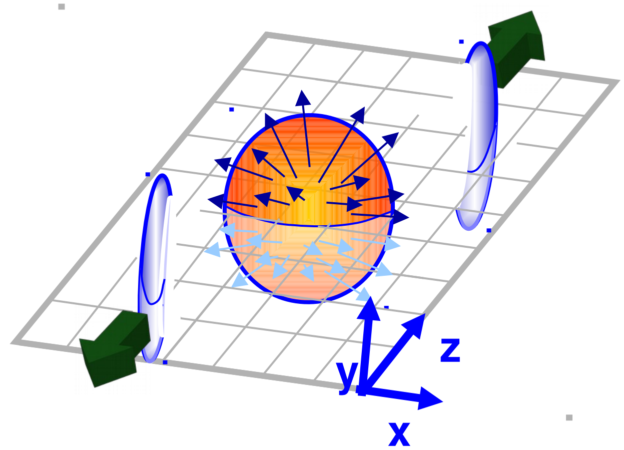
Nucleus collisions - flow

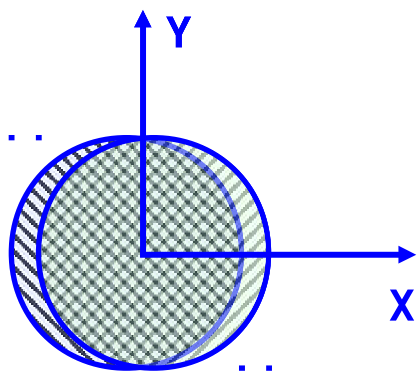
Peripheral Collision

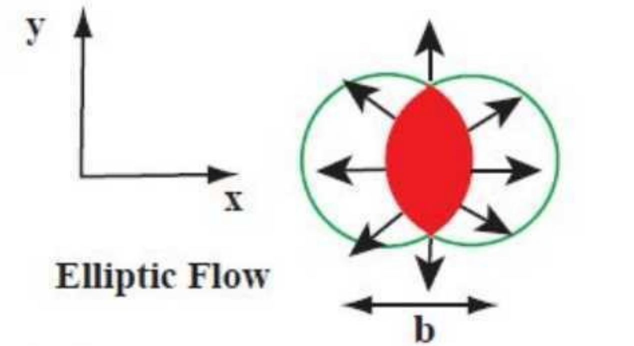


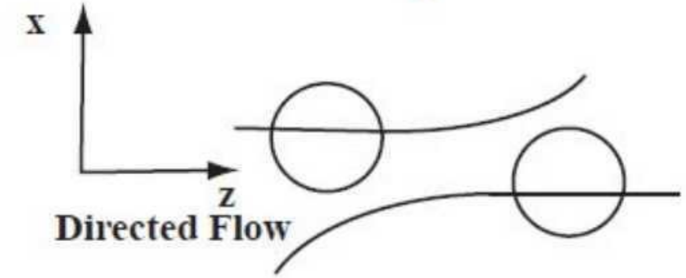


(near) Central Collision

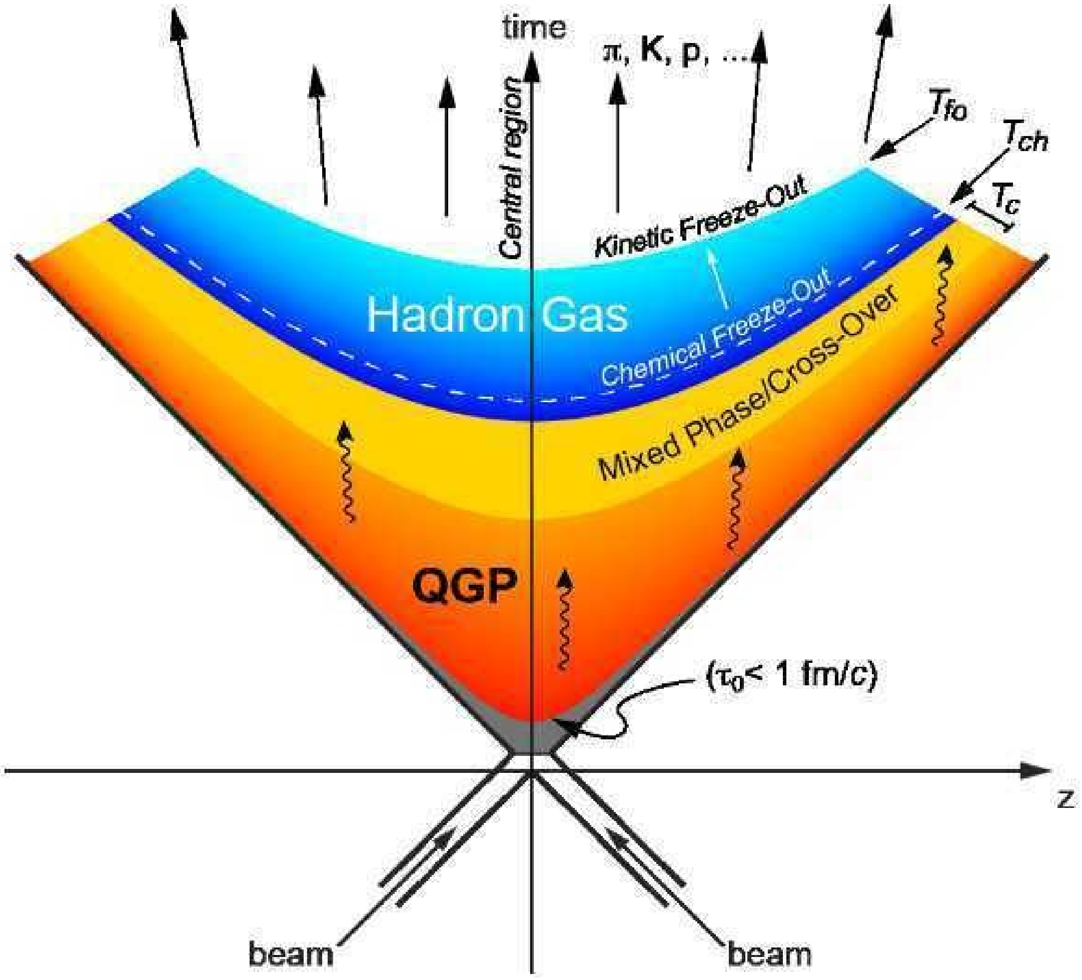








QGP in nucleus collisions



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

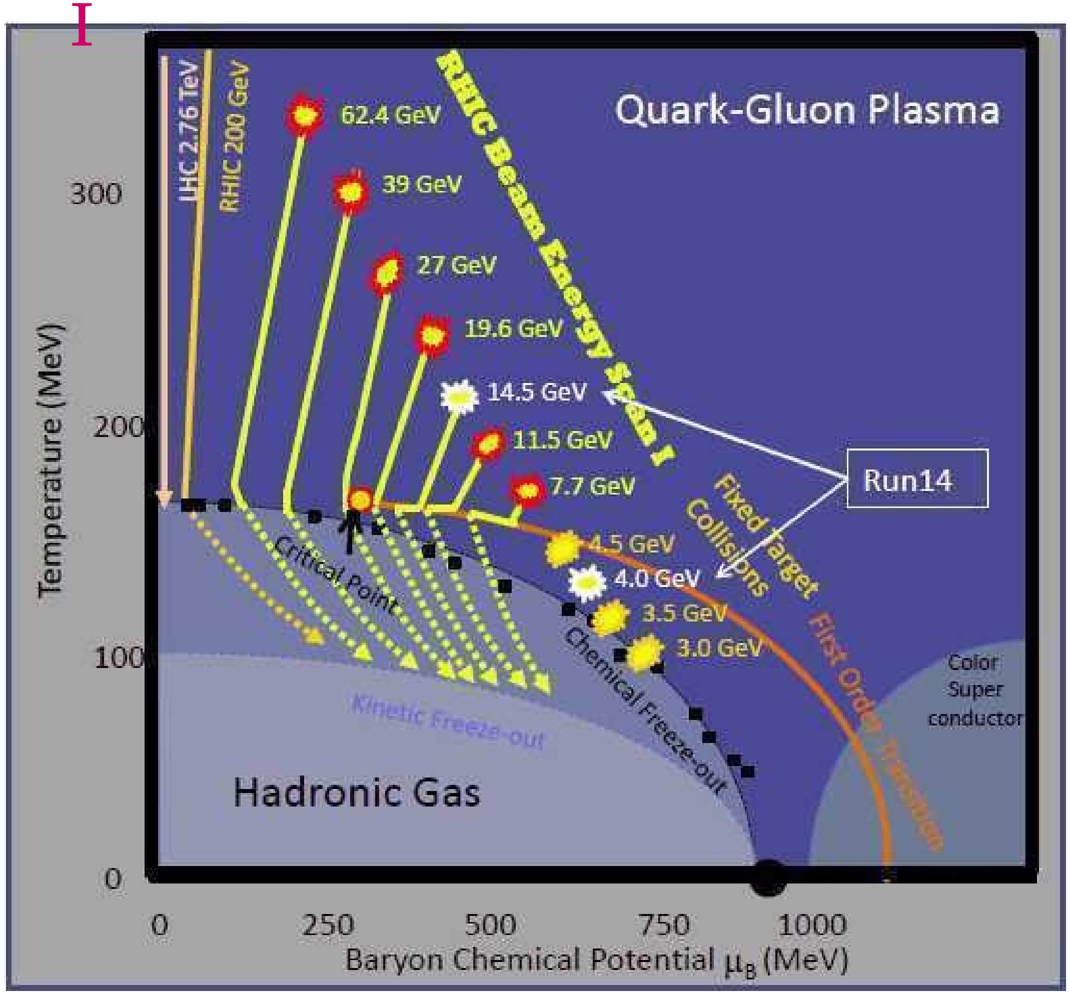
Office of Science U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

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 Beam Energy Scan 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

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.

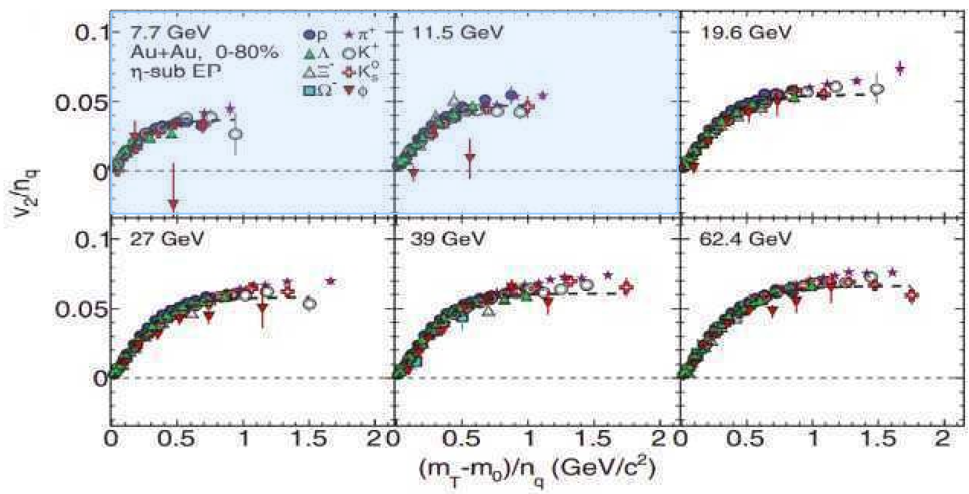
A search for signatures of a phase transition and a critical point. The particular observables that we have identified as the essential drivers of our run plan are:

(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

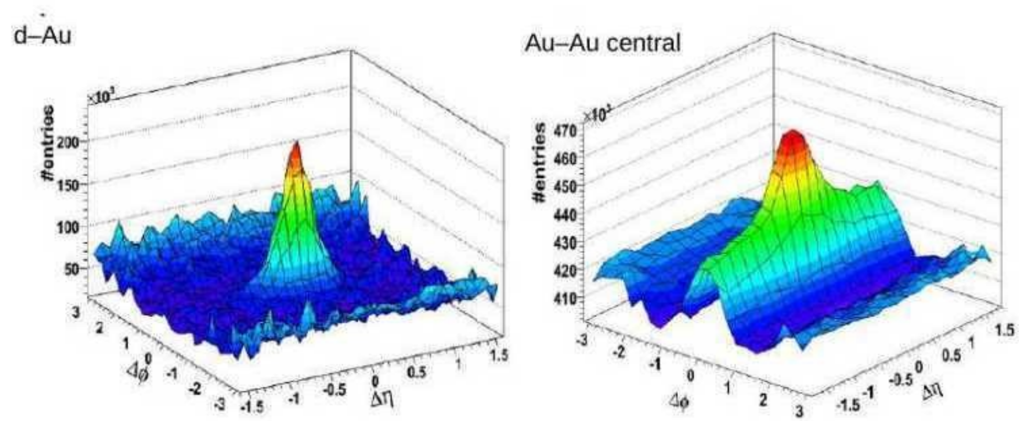
Number of constituent quarks scaling

Phys. Rev. C88, (2013), 014902



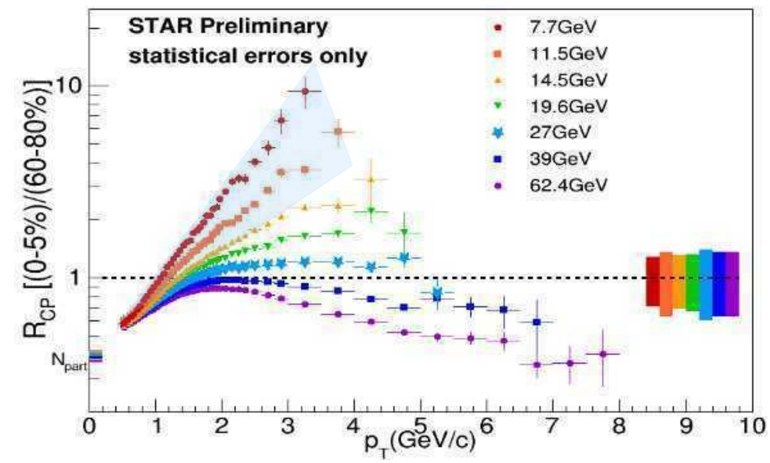
Ridge effect

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

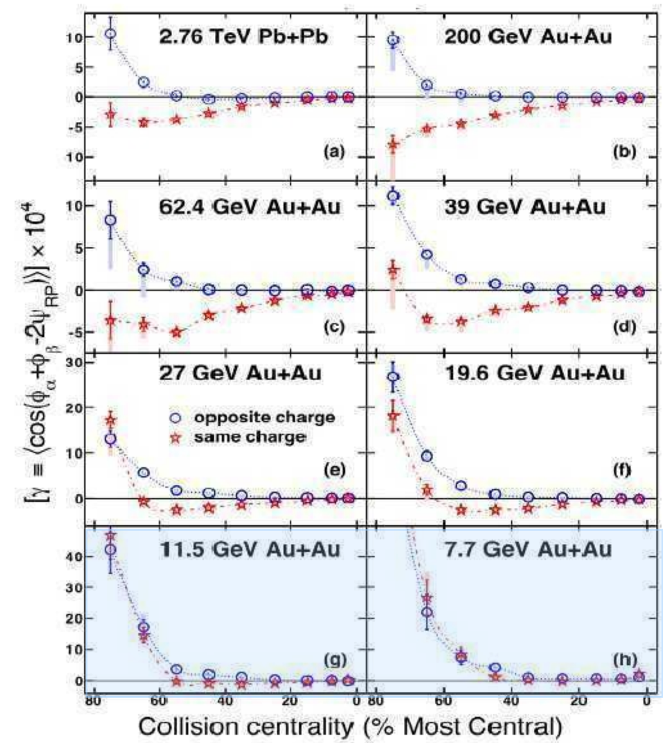


High P_T suppression

Stephen Horvat   Quark Matter 2015

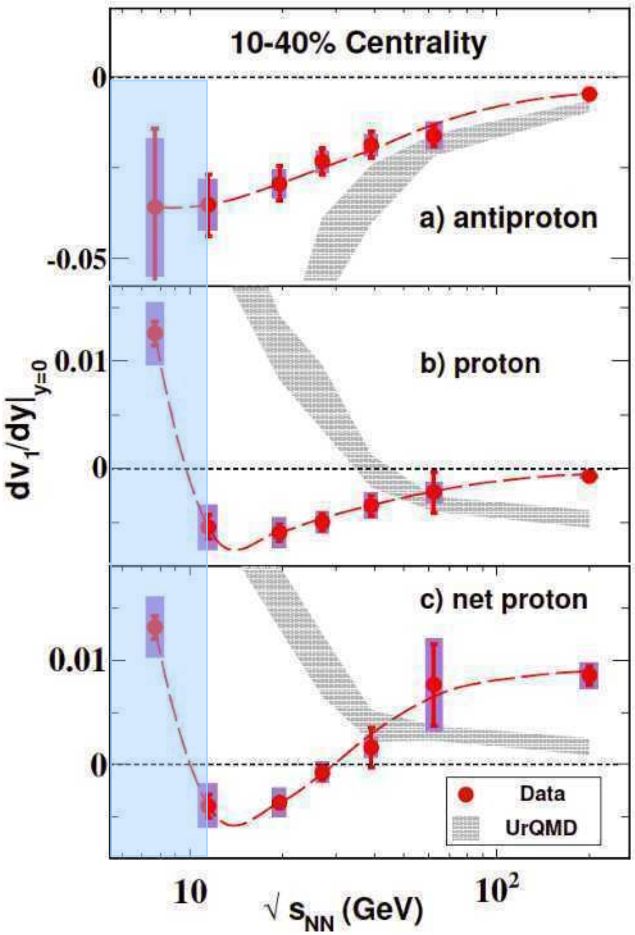


Chiral Magnetic Effect



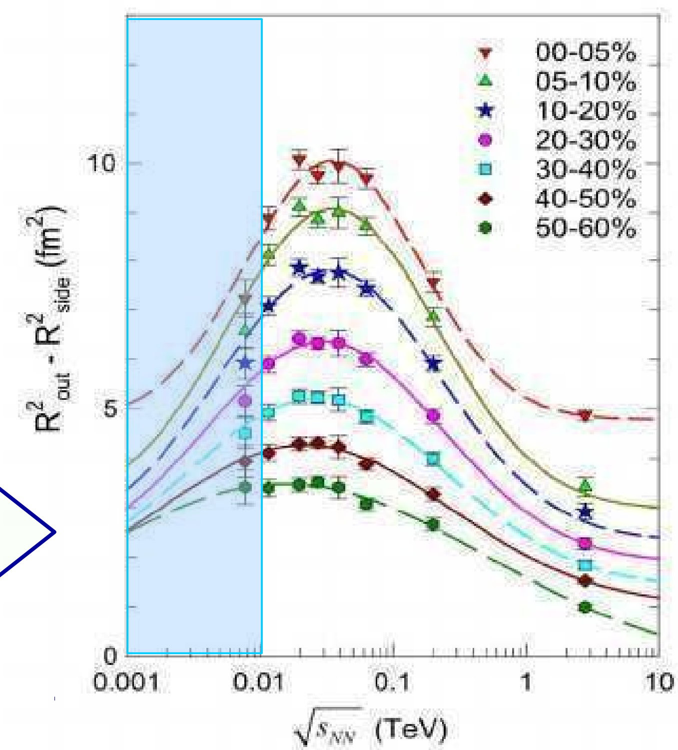
STAR BES I results

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.

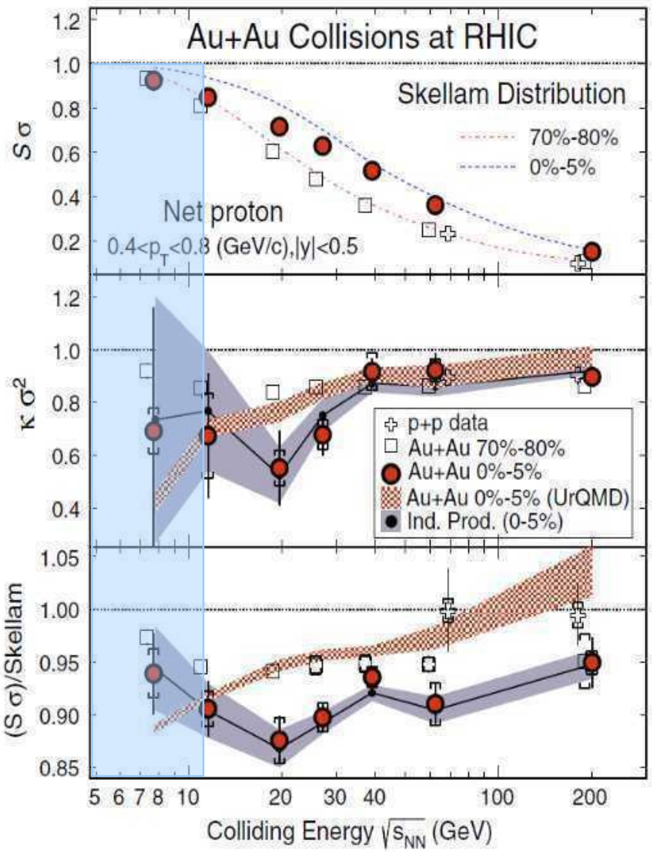
R. Lacey, PRL 114, 142301 (2015)



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)



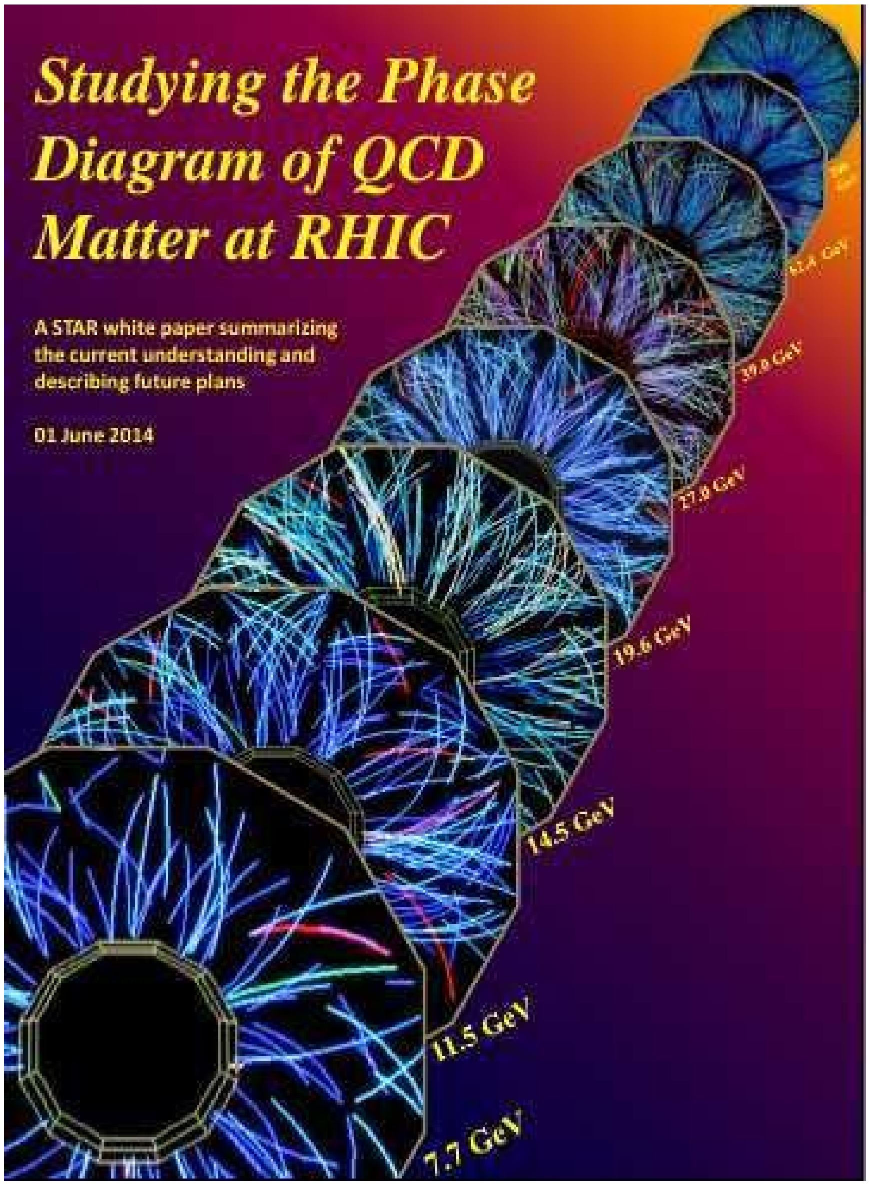
The kurtosis of the event-by-event distribution of the net proton (i.e. proton minus antiproton) number per unit of rapidity, normalized such that Poisson fluctuations give a value of 1.

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



Contents

STAR BES II program

I

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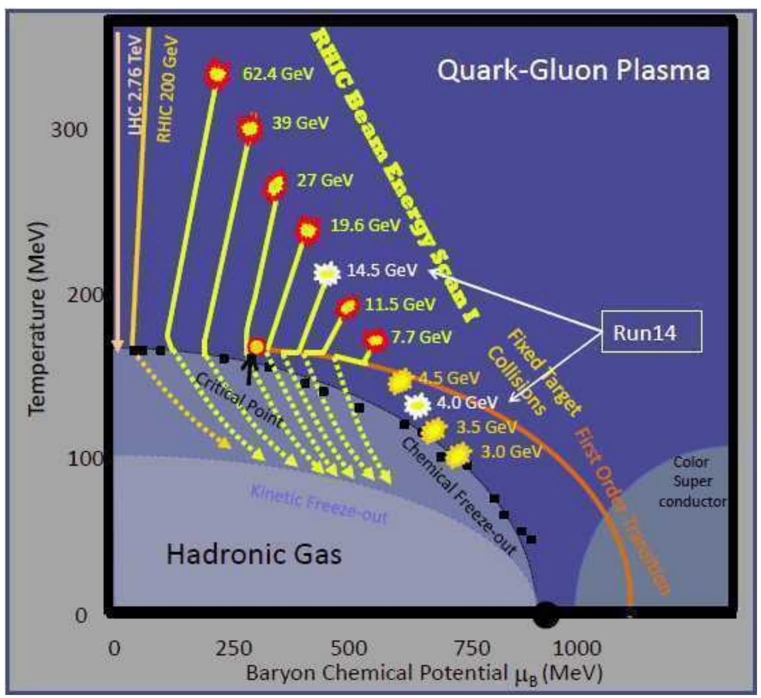
19.6	205	35.8	1.5	2011
27.0	155	70.4	1	2011
39.0	115	130.4	2	2010
62.4	70	67.3	1.5	2010

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 (1/8[th]), 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

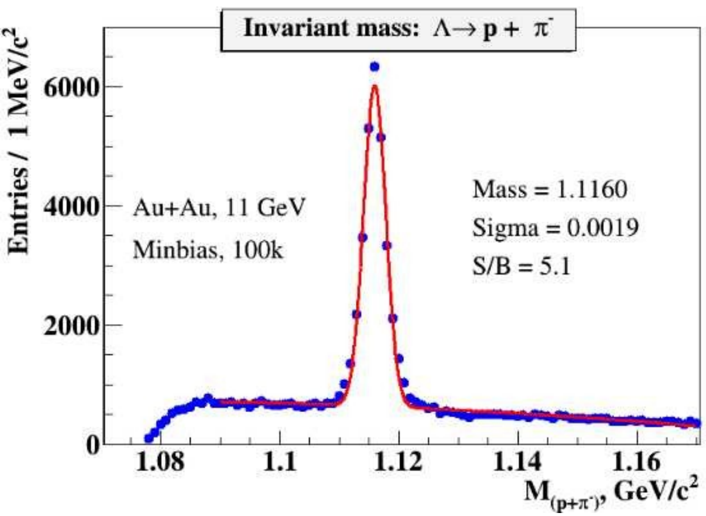
Feasibility study for heavy Ion collision at NICA

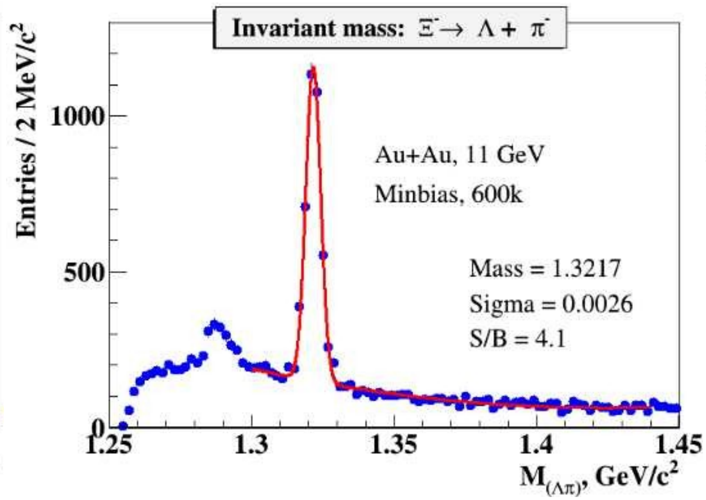
- UrQMD
- QGSM
- Hybrid UrQMD
- VHLLE
- THESEUS
- pHSD

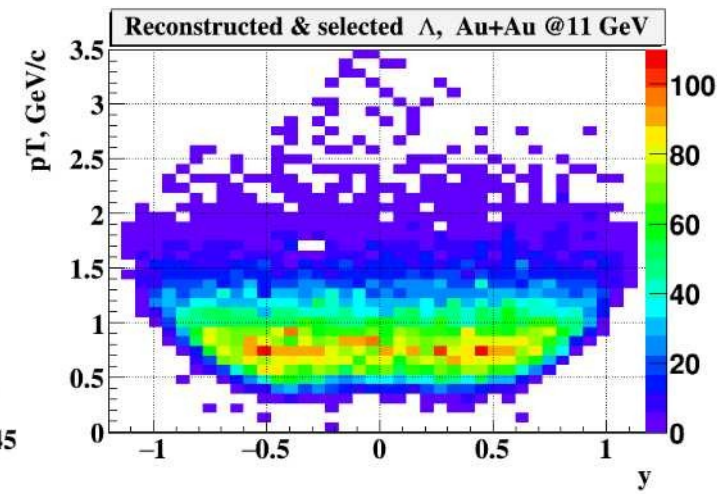
Strange and multi-strange baryons

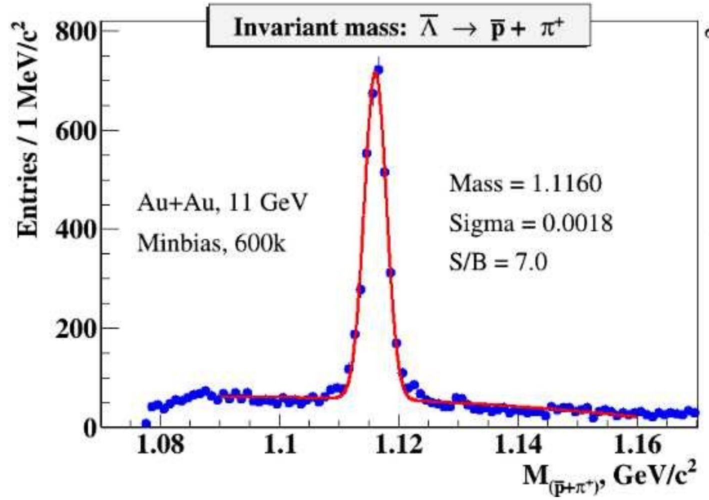
Stage'1 (TPC+TOF): Au+Au @ 11 GeV, UrQMD

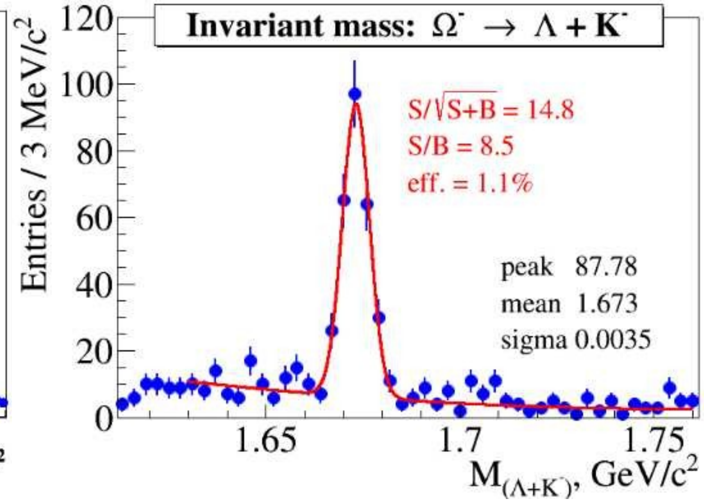
large phase-space

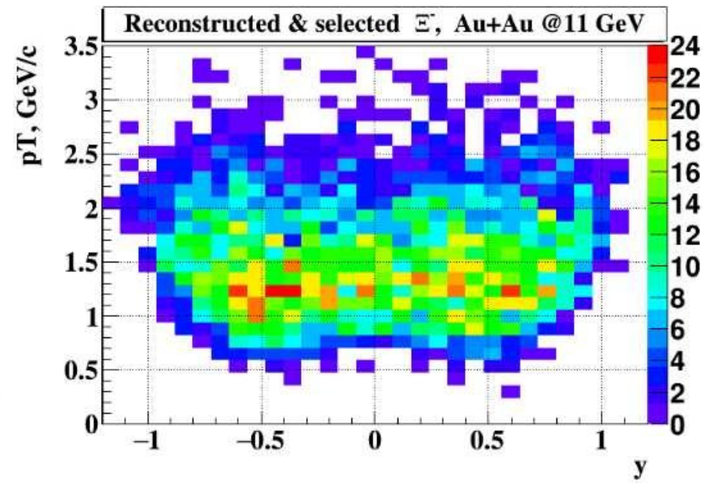








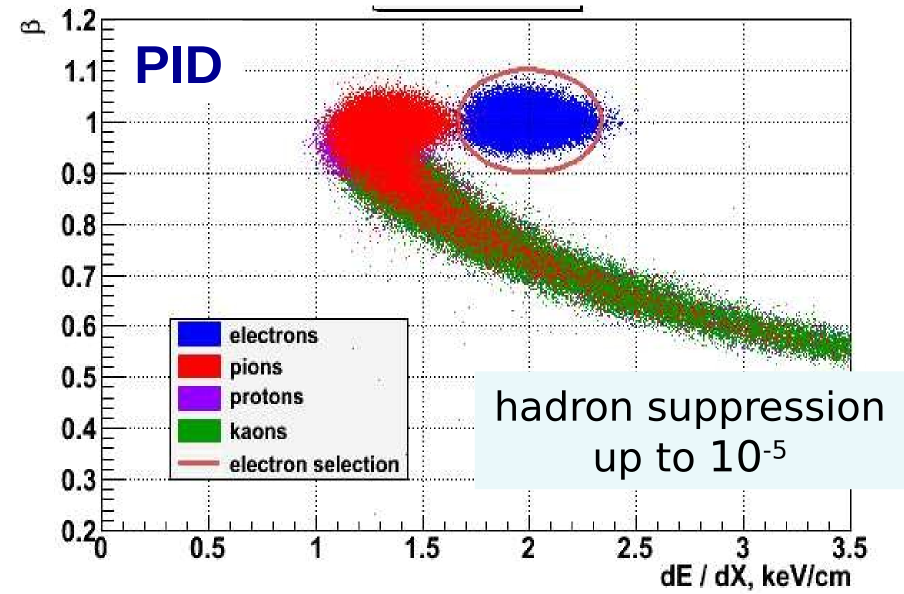


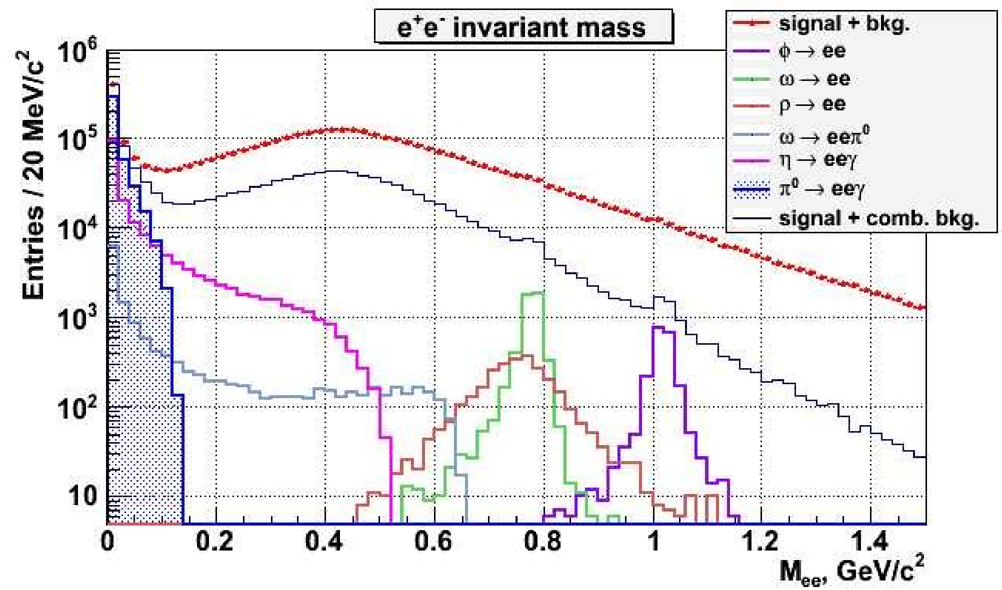


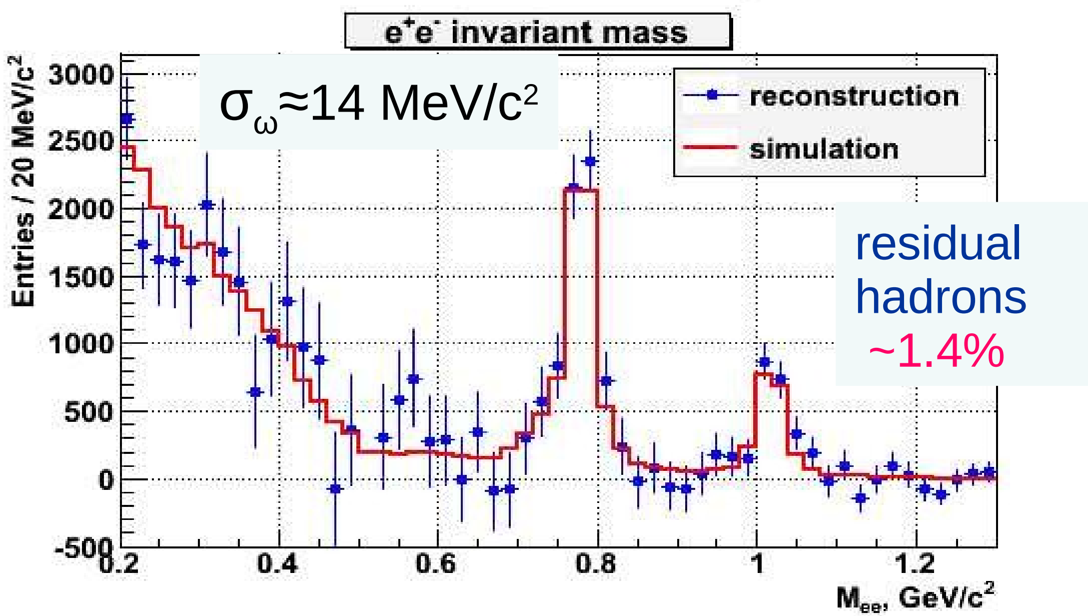
particle	Λ	anti-Λ	Ξ^-	anti-Ξ^+	Ω^-	anti–Ω^+
yield in 10 weeks	$3 \cdot 10^8$	$3.5 \cdot 10^6$	$1.5 \cdot 10^6$	$8.0 \cdot 10^4$	$7 \cdot 10^4$	$1.5 \cdot 10^4$

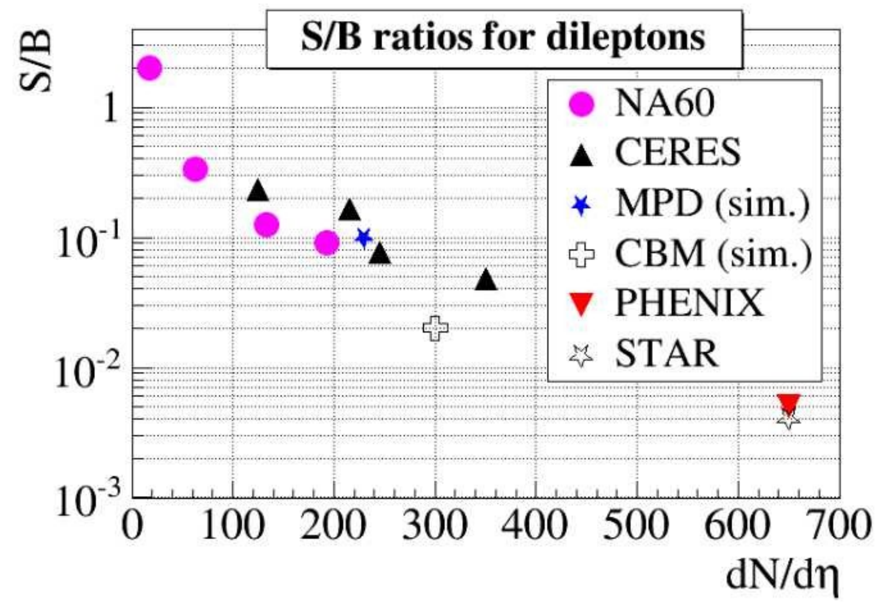
Prospects for study of dileptons

- **Event generator:** *UrQMD+Pluto (for the cocktail) central Au+Au @ 8 GeV*
- **PID**: *dE/dx (from TPC) + TOF (s ~100 ps) + ECAL*









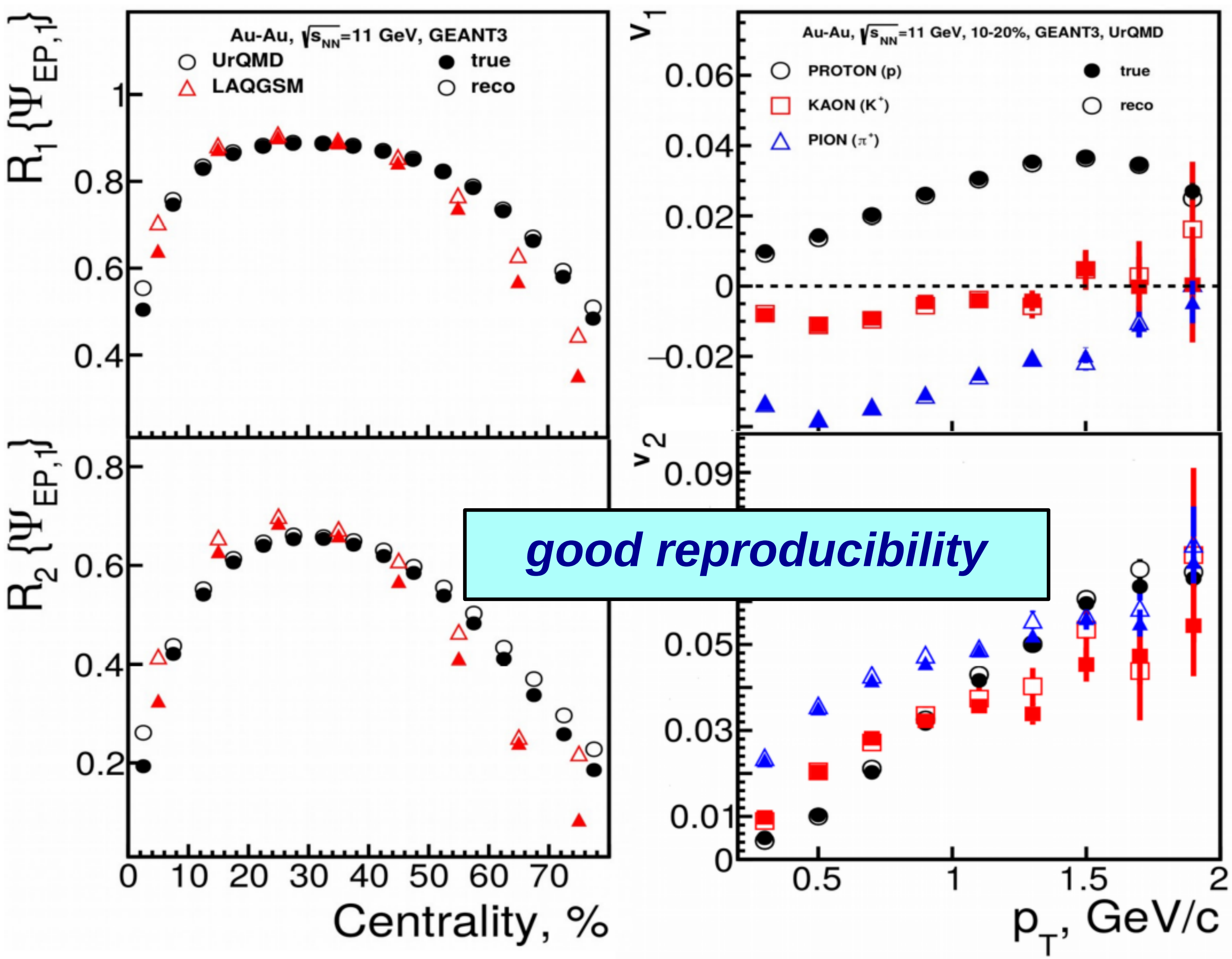
Flow performance

Au+Au@11 A GeV;   GEANT3;
UrQMD (LAQGSM), 4M events

***$v_n = \{\cos[n(\phi - \Psi_{EP,1})]\} / R_n(\Psi_{EP,1})$** - azimuthal flow coefficients*

event plane resolution

flow harmonics (v_1 / v_2)



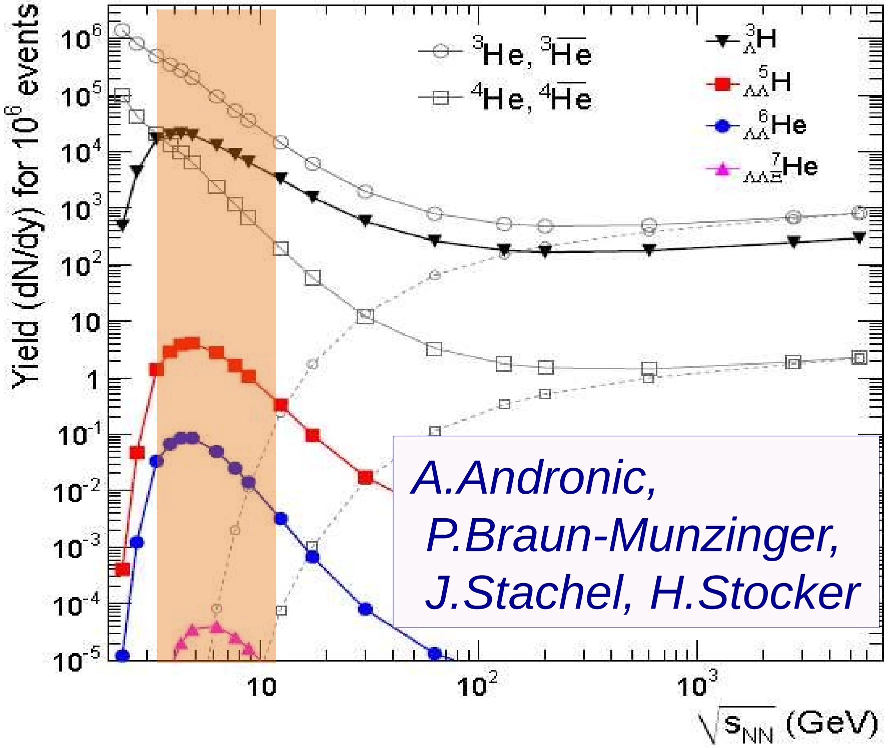
good reproducibility

***$R_n(\Psi_{EP,1})$** – resolution correction factor*

ϕ – azimuthal angle of produced particle
$\Psi_{EP,1}$ – event plane angle

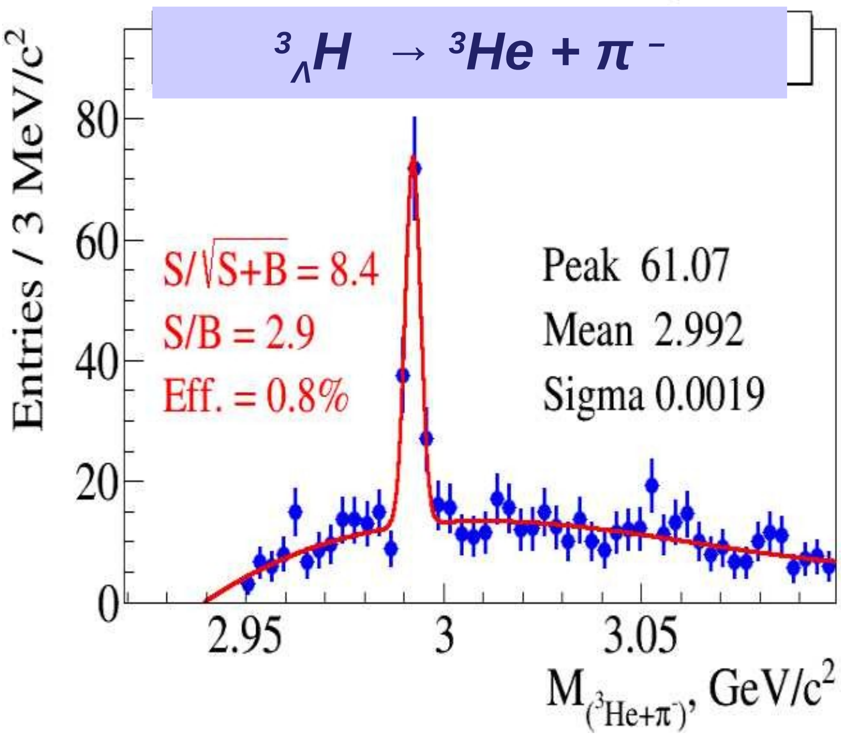
event plane: **FHCal**
centrality: **TPC**
PID: **TOF+TPC**

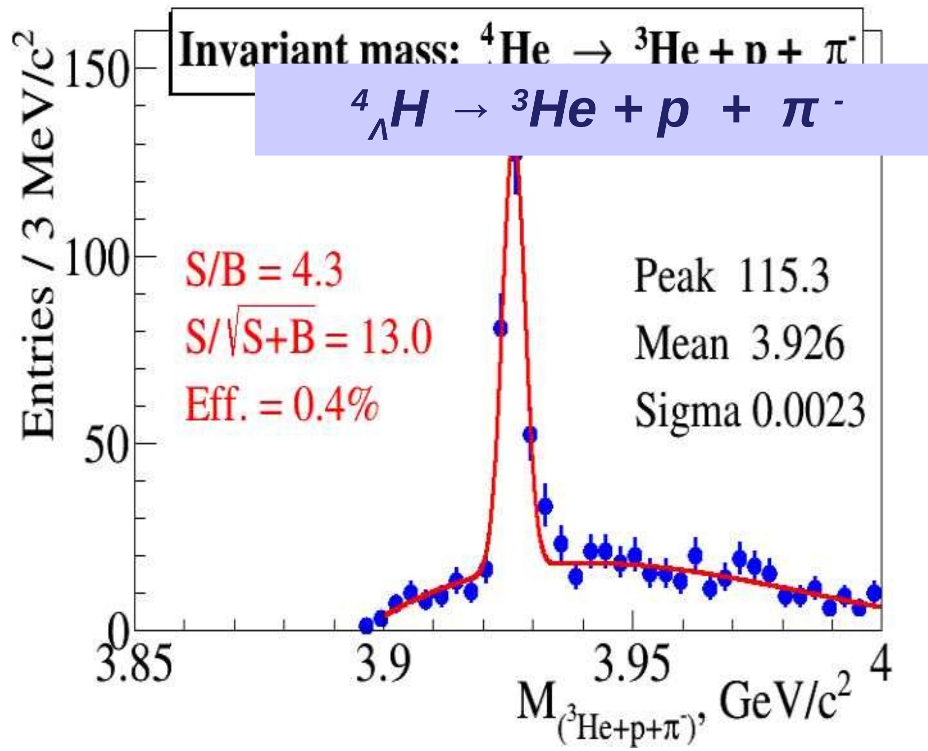
Hyper nuclei



Stage 2: *central* ***Au+Au @ 5*** *AGeV;*
DCM-QGSM

hyper nucleus	yield in 10 weeks
$^3_\Lambda$He	$9 \cdot 10^5$
$^4_\Lambda$He	$1 \cdot 10^5$



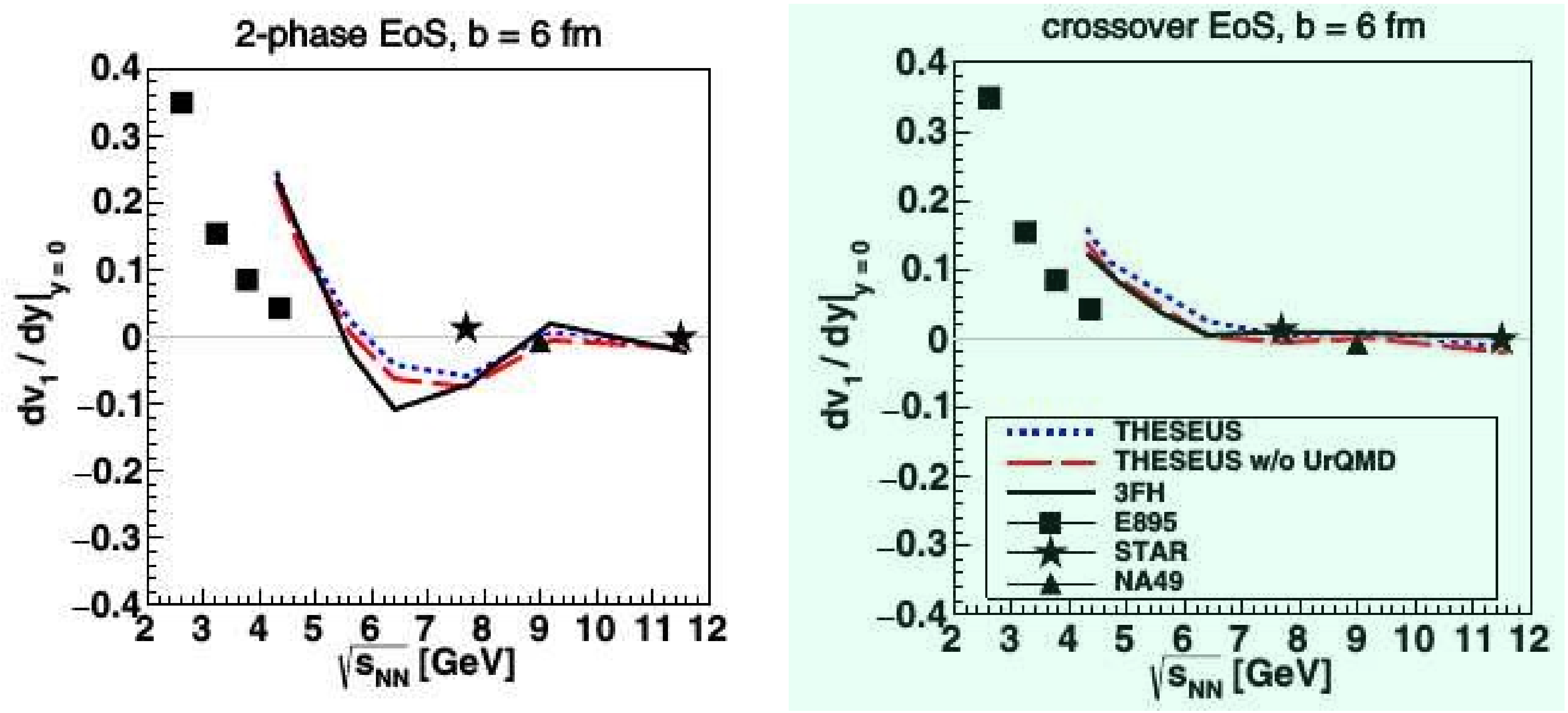


Directed flow slope

P. Batyuk et al. Phys. Rev. C 94, 044917 (2016)

THESEUS

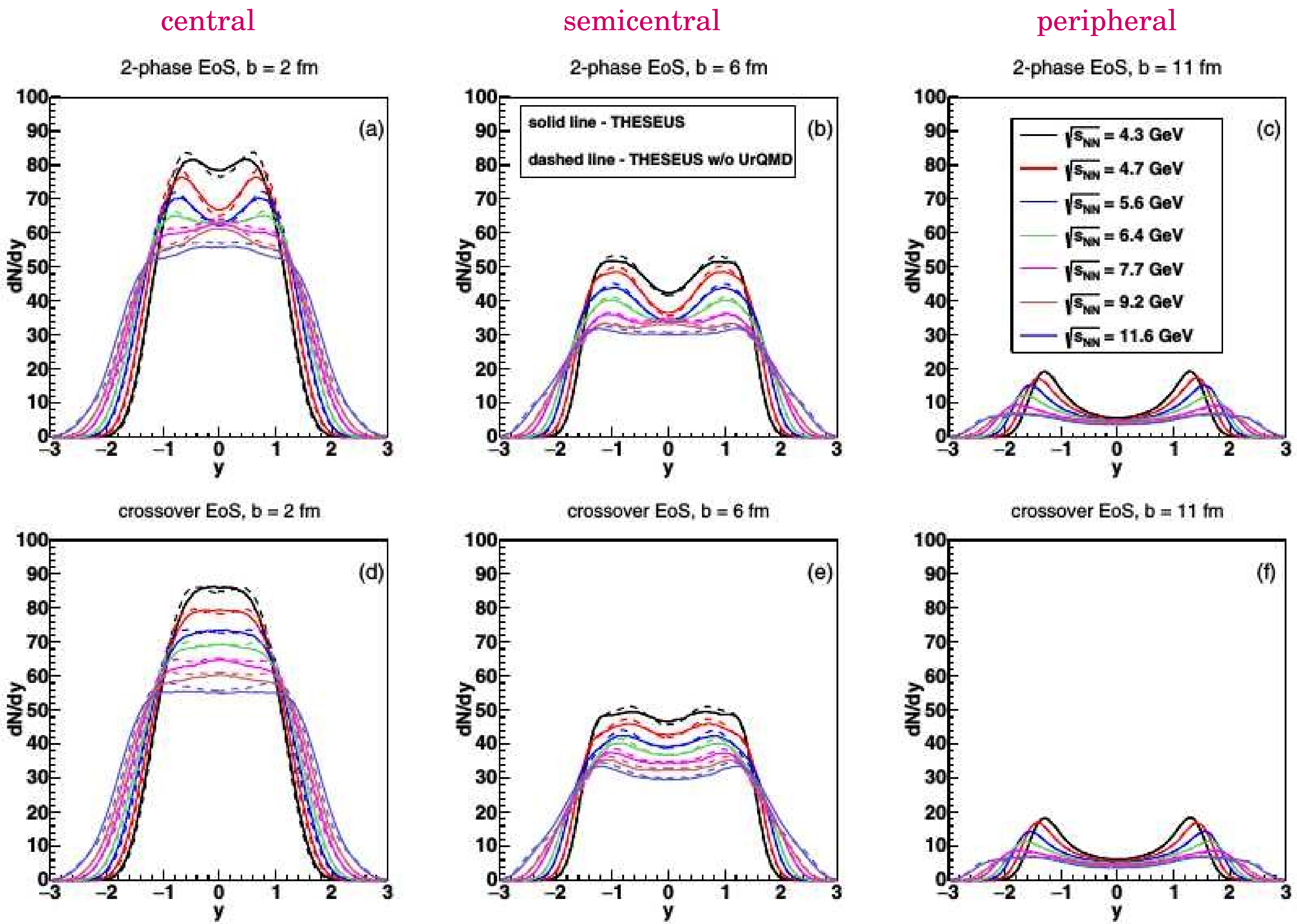
$$v_1(y) = \langle \cos(\phi - \Psi_{RP}) \rangle = \left\langle p_x / \sqrt{p_x^2 + p_y^2} \right\rangle,$$



Energy scan of the slope of the directed flow (dv_1/dy) of protons for semicentral (b = 6 fm) Au+Au collisions

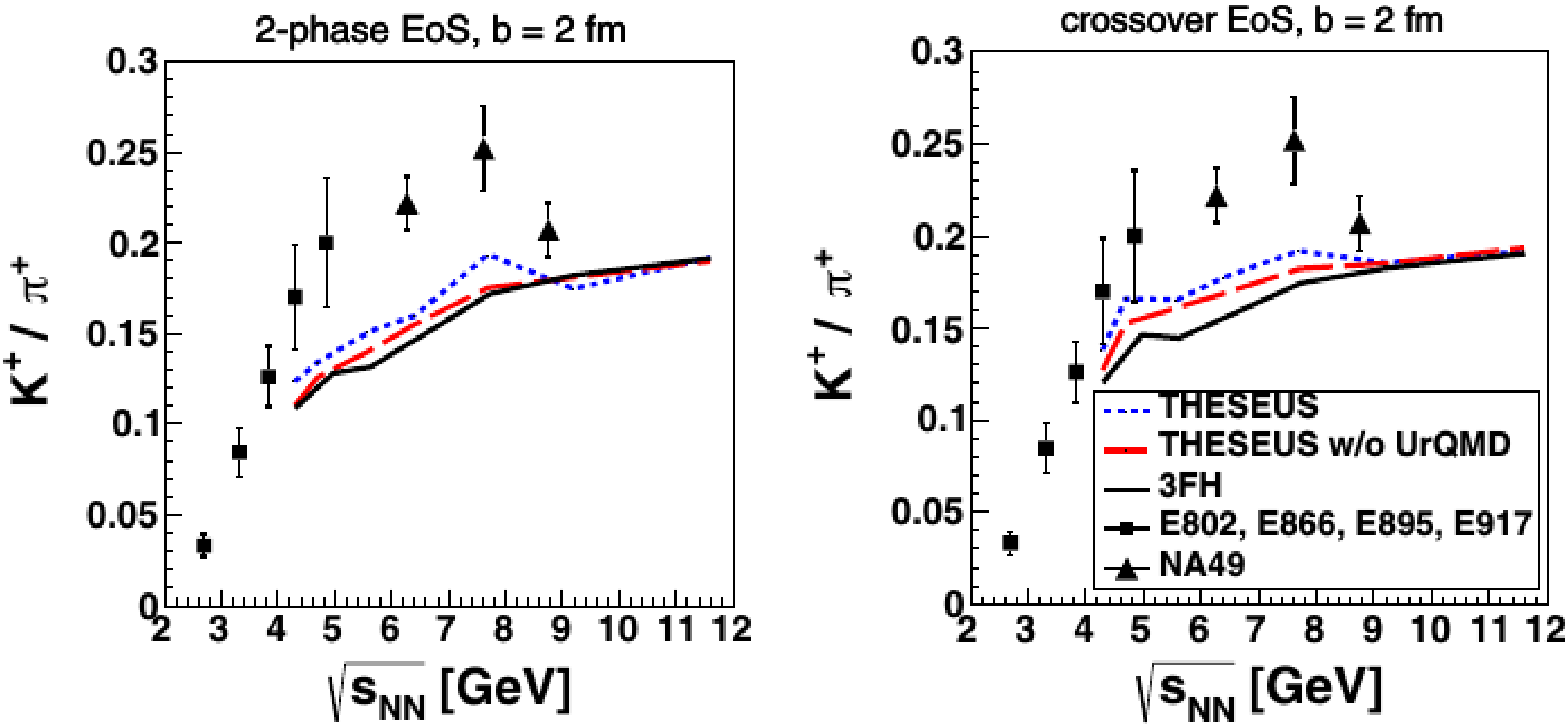
Proton rapidity in Theseus

THESEUS



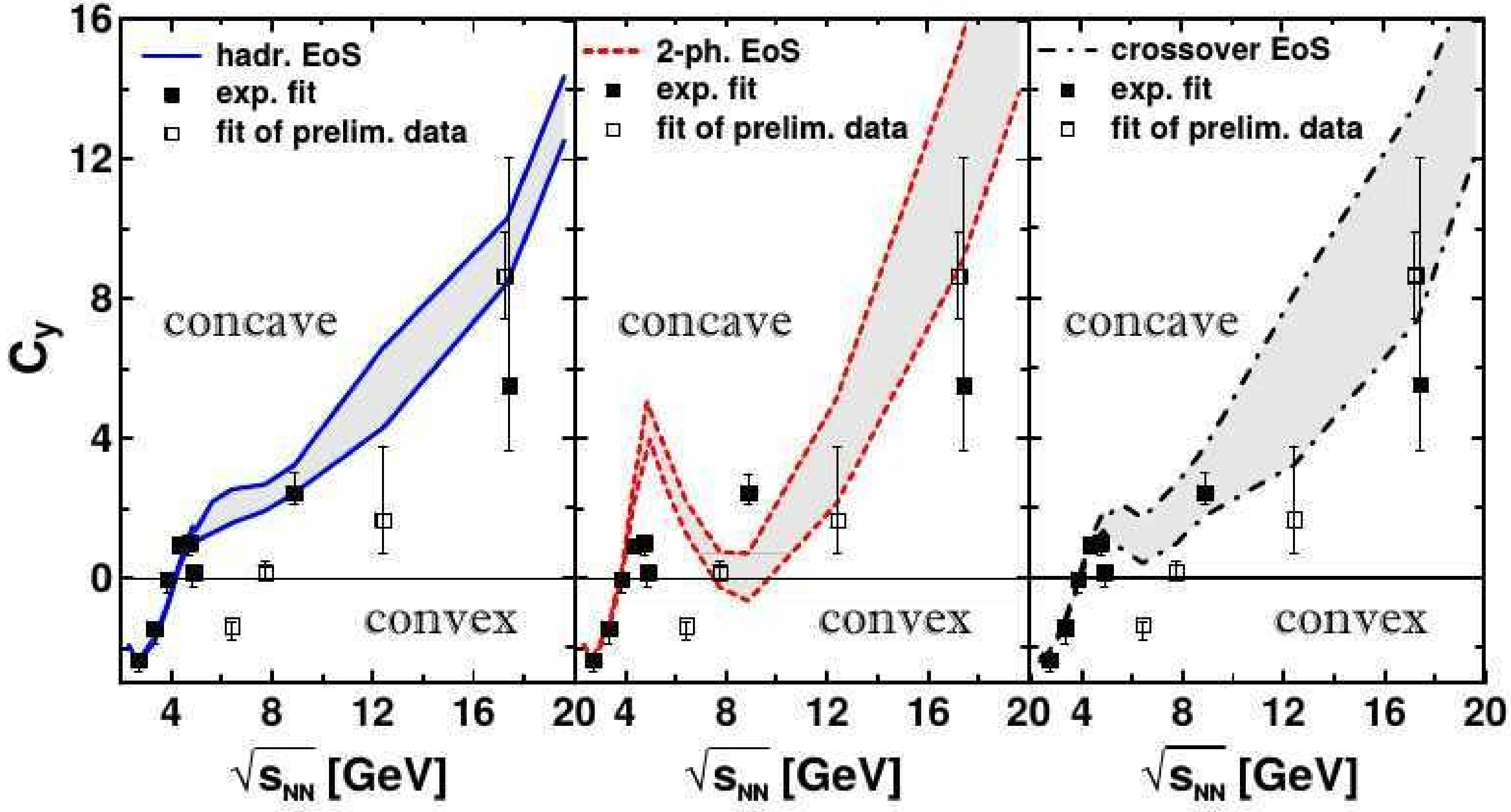
K^+/π^+ ratio

THESEUS



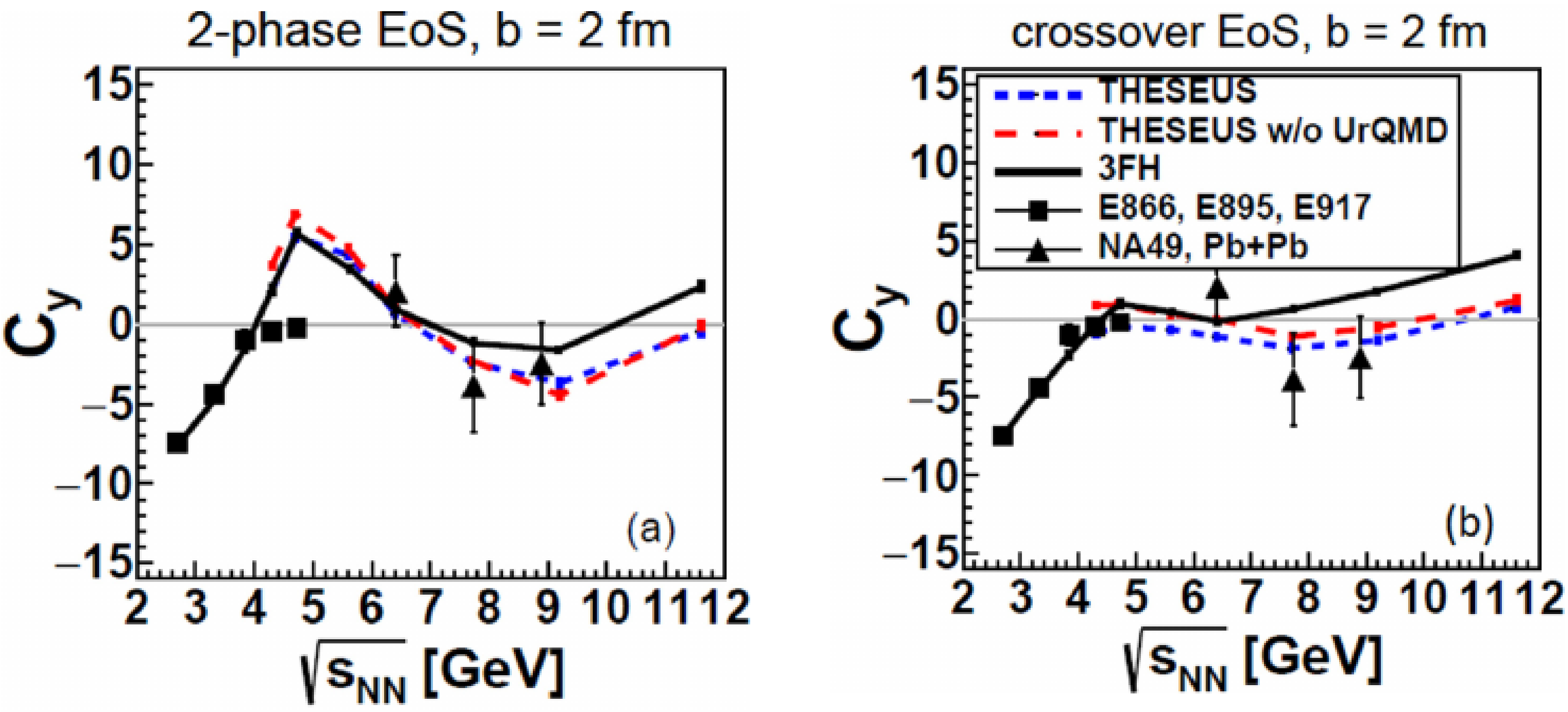
Net-proton mid rapidity Curvature

Yu.B. Ivanov, Phys. Lett. B721 123 (2013)



$$C_y = \left(y_{\rm beam}^3 \frac{d^3N}{dy^3} \right)_{y=0} \Big/ \left(y_{\rm beam} \frac{dN}{dy} \right)_{y=0} = (y_{\rm beam}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s \right)$$

THESEUS

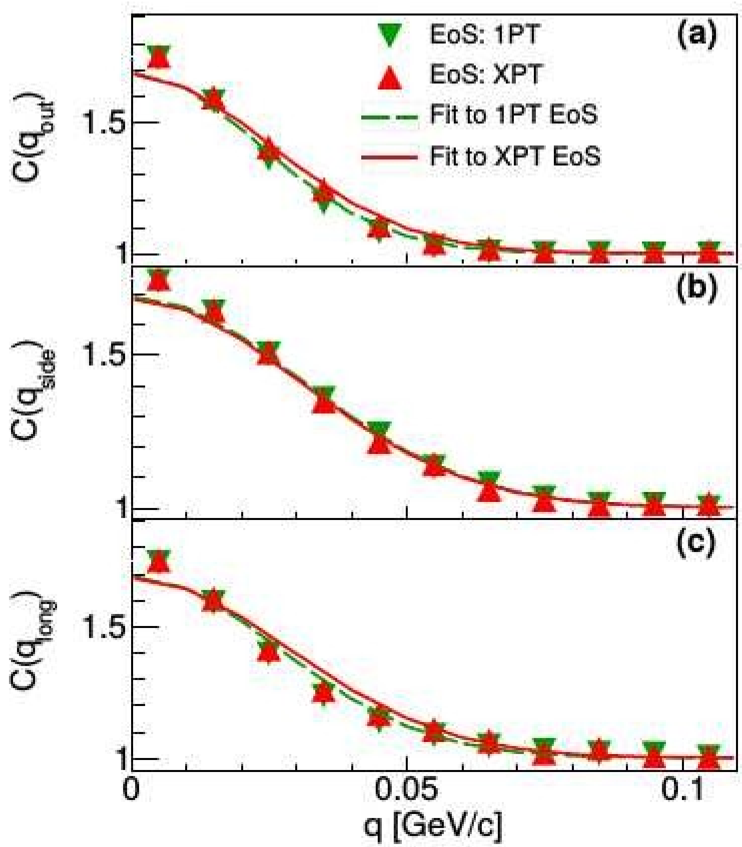


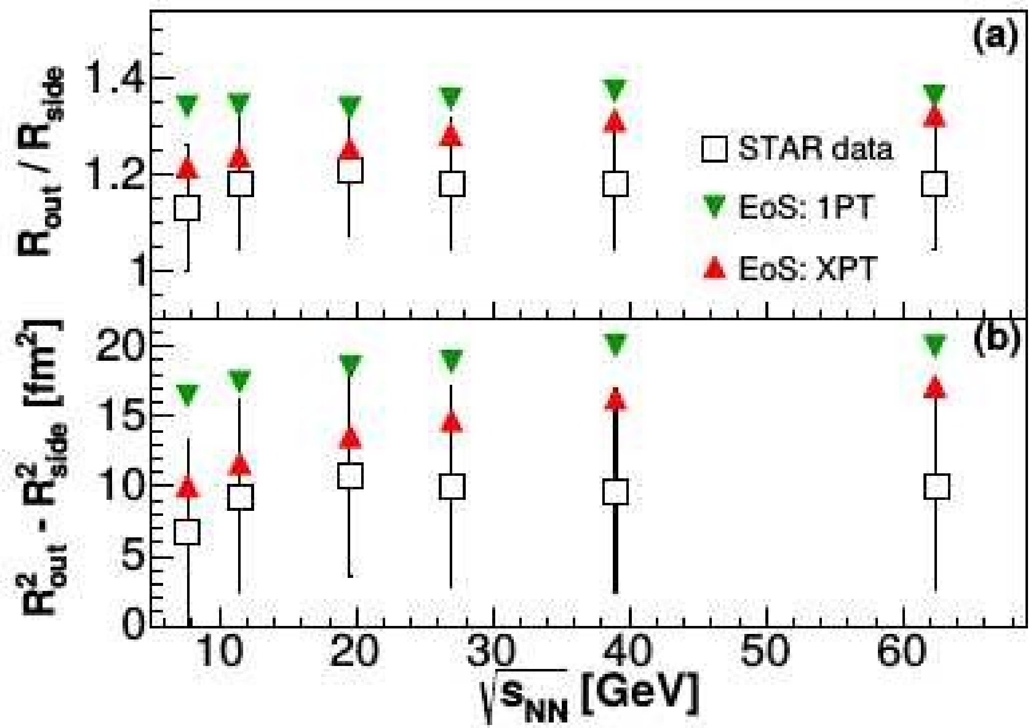
2-phase EoS, b = 2 fm
15
10
5
0
−5
−10
−15
C_y
(a)
2 3 4 5 6 7 8 9 10 11 12
$\sqrt{s_{NN}}$ [GeV]
crossover EoS, b = 2 fm
THESEUS
THESEUS w/o UrQMD
3FH
E866, E895, E917
NA49, Pb+Pb
(b)

Femtoscopy @ NICA

VHLLE+URQMD MODEL
Phys. Rev. C 91, 064901 (2015)

$$C(\mathbf{q}) = N\left(1 + \lambda \exp(-R_{\rm out}^2 q_{\rm out}^2 - R_{\rm side}^2 q_{\rm side}^2 - R_{\rm long}^2 q_{\rm long}^2)\right)$$

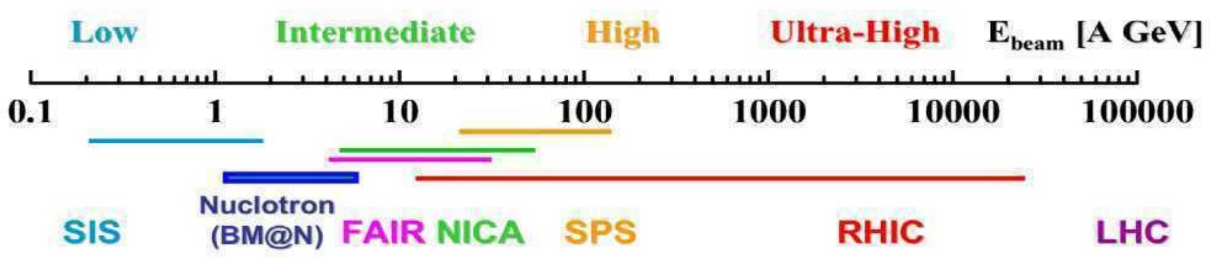




STAR data (0.15 < k_T < 0.25 GeV/c, 0-5% centrality)

Resent & future experiments for HIC

Facility	SPS	RHIC BES II	Nuclotron-M	NICA	SIS/100 (300)	LHC
Laboratory	CERN Geneva	BNL Brookhaven	JINR Dubna	JINR Dubna	FAIR GSI Darmstadt	CERN Geneva
Experiment	NA61 SHINE	STAR PHENIX	BM@N	MPD	HADES CBM	ALICE ATLAS CMS
Start of data taking	2011	2010	2015	2020	2025	2009
$\sqrt{s_{NN}}$ GeV	4.9 – 17.3	7.7 – 200	< 3.5	4 - 11	2.3 – 4.5	up to 5500
Physics	CP & OD	CP & OD	HDM	OD & HDM	OD & CP	PDM



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

Nuclotron based Ion Collider fAcility

Beams – p,d(h)..$^{197}Au^{79+}$

Collision energy √s= **4-11** GeV/u (Au), **12-27** (p)

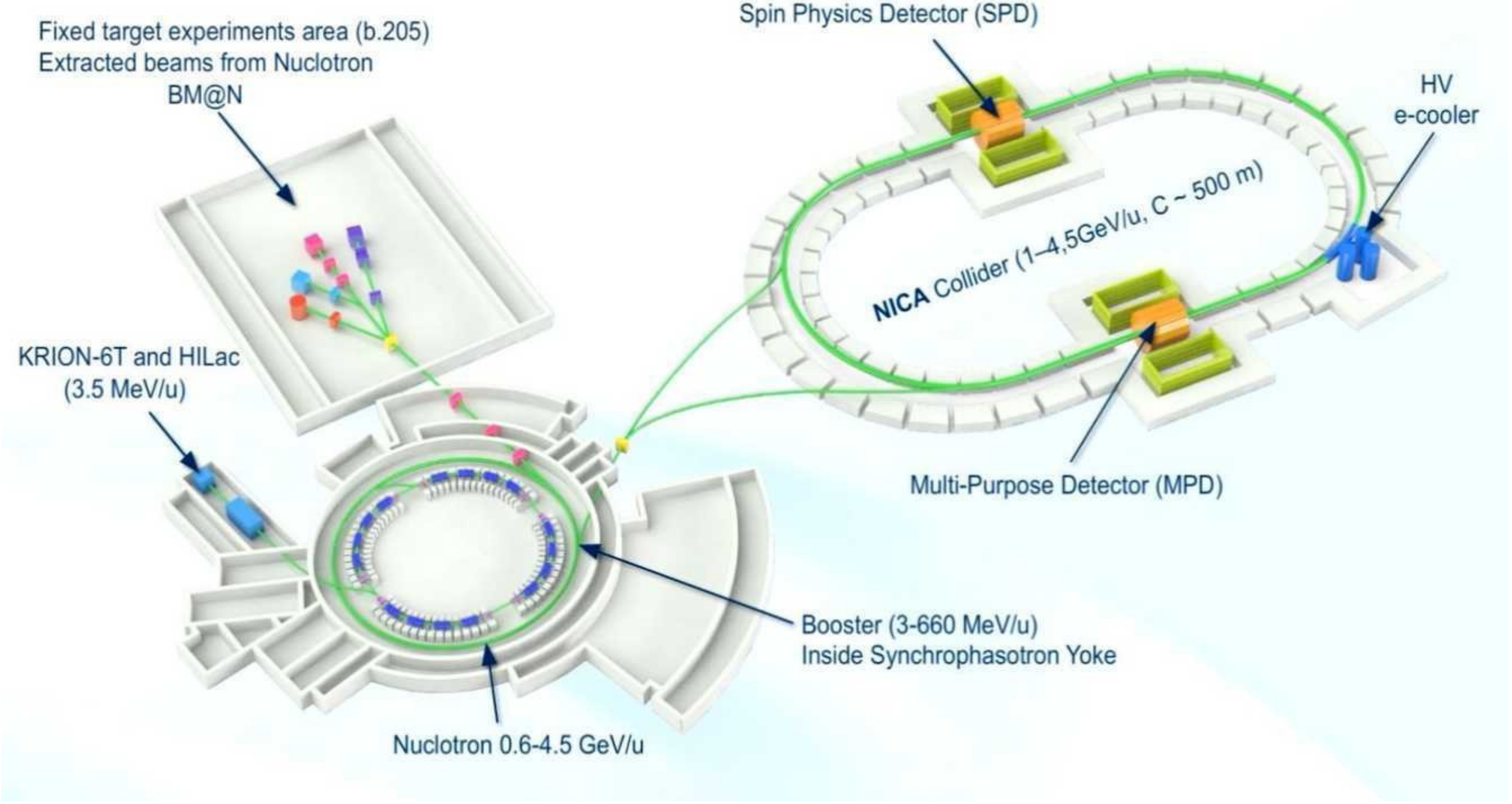
Beam energy (fixed target) - **1-6** GeV/u

Luminosity: 1**0**^{27} cm^{-2}s^{-1}(Au), **10**^{32} (p)

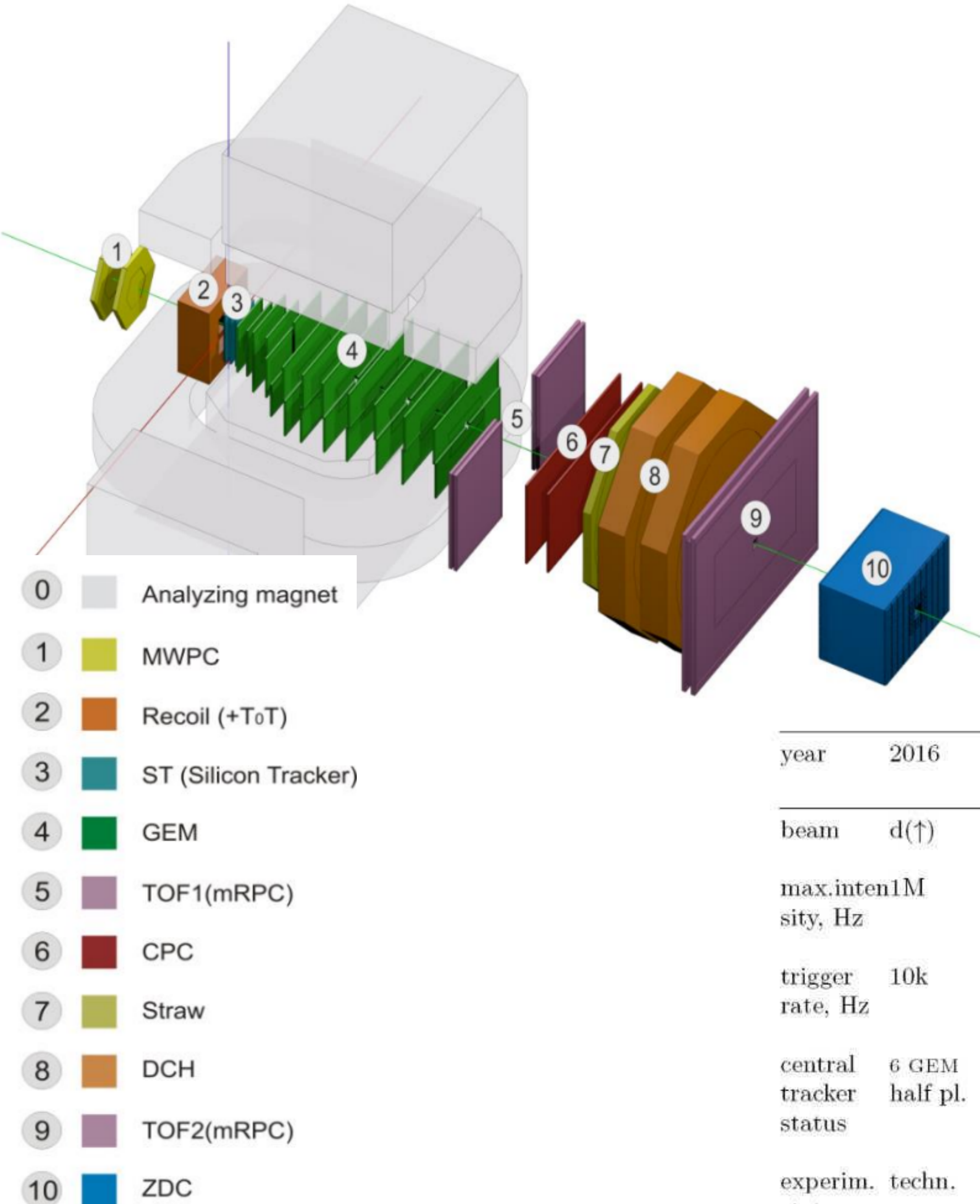
Experiments:

2 Interaction points – **MPD** and SPD

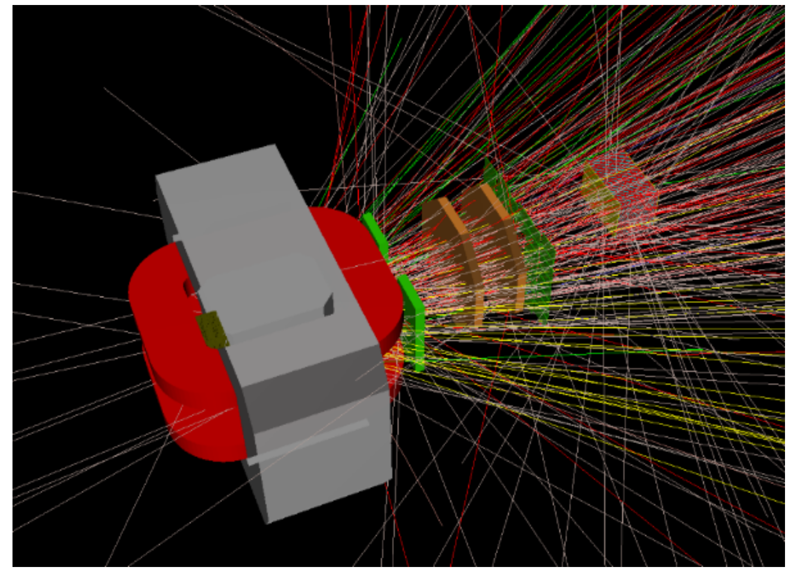
Fixed target experiment **BM@N**



BM@N experiment at NICA

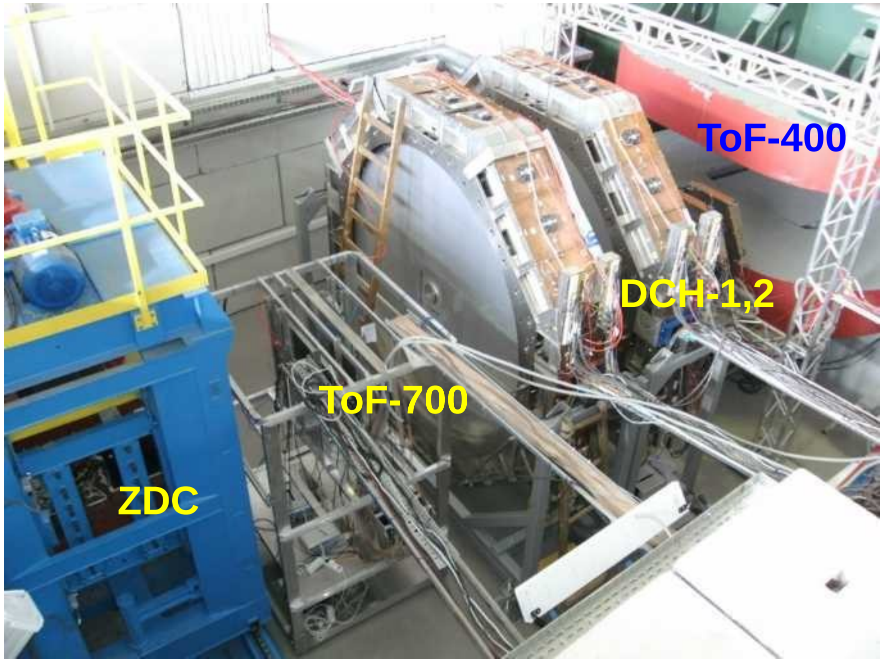


AuAu E_{beam} = 4 GeV

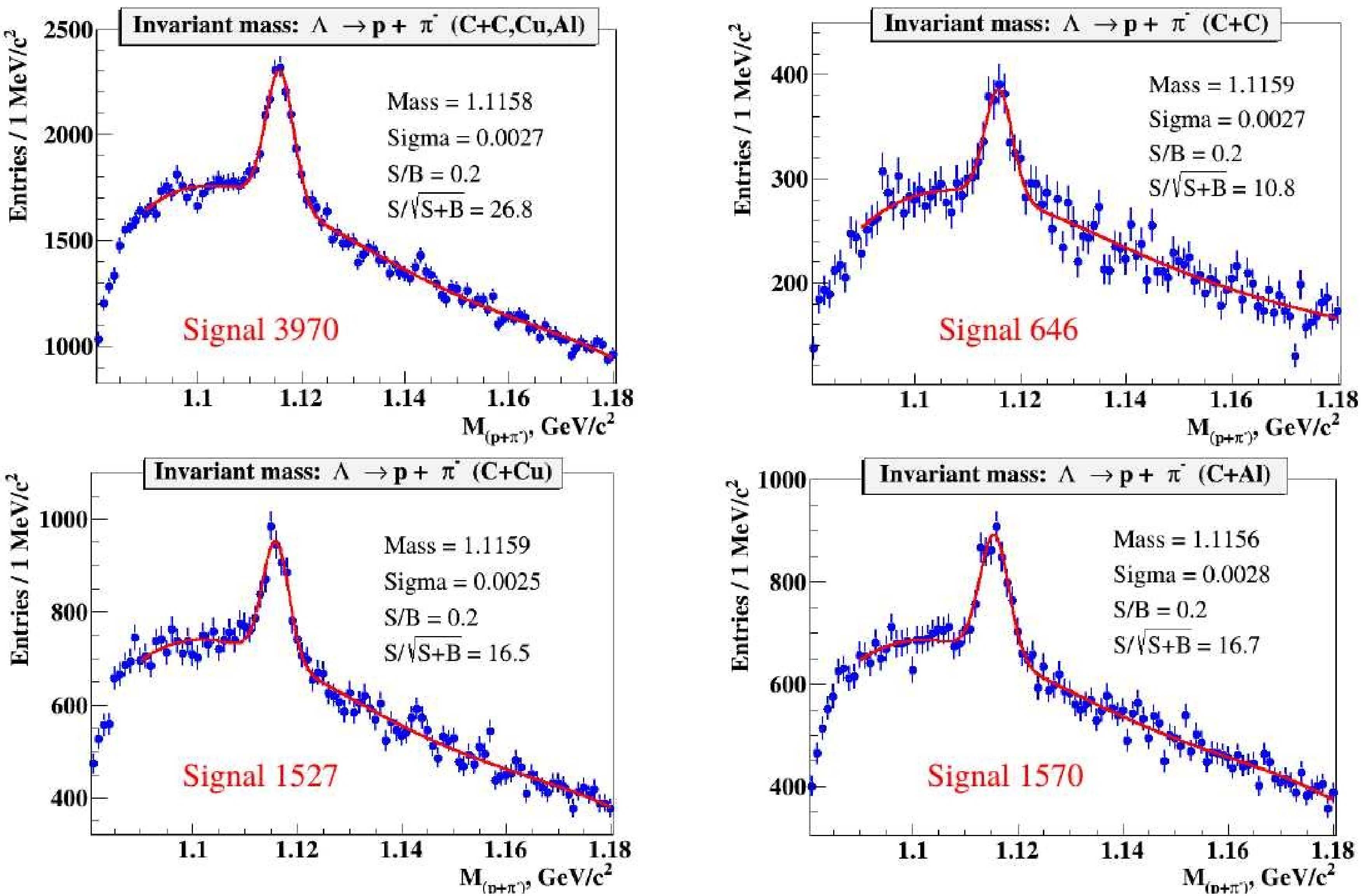


year	2016	2017 spring	2017 autumn	2019	2020 and later
beam	d(↑)	C, Ar	Kr	Au	Au, p
max.intensity, Hz	1M	1M	1M	1M	10M
trigger rate, Hz	10k	10k	20k	20k	50k
central tracker status	6 GEM half pl.	8 GEM half pl.	10 GEM half pl.	8 GEM full pl.	12 GEMs or 8 GEMs + Si planes
experim. status	techn. run	techn.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

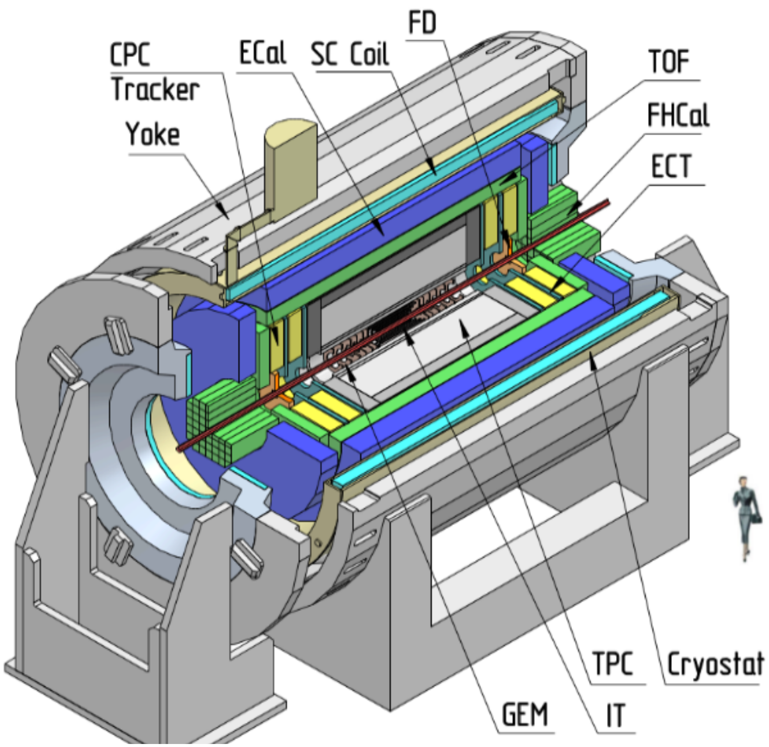
BM@N experiment at NICA

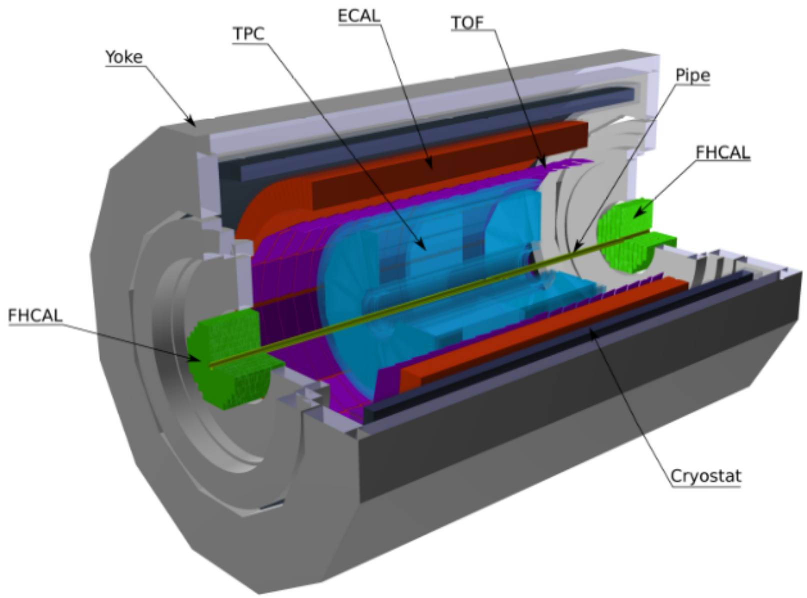


BM@N Λ^0 reconstruction ($E_{kin}^{beam} = 4.0$ AGeV)

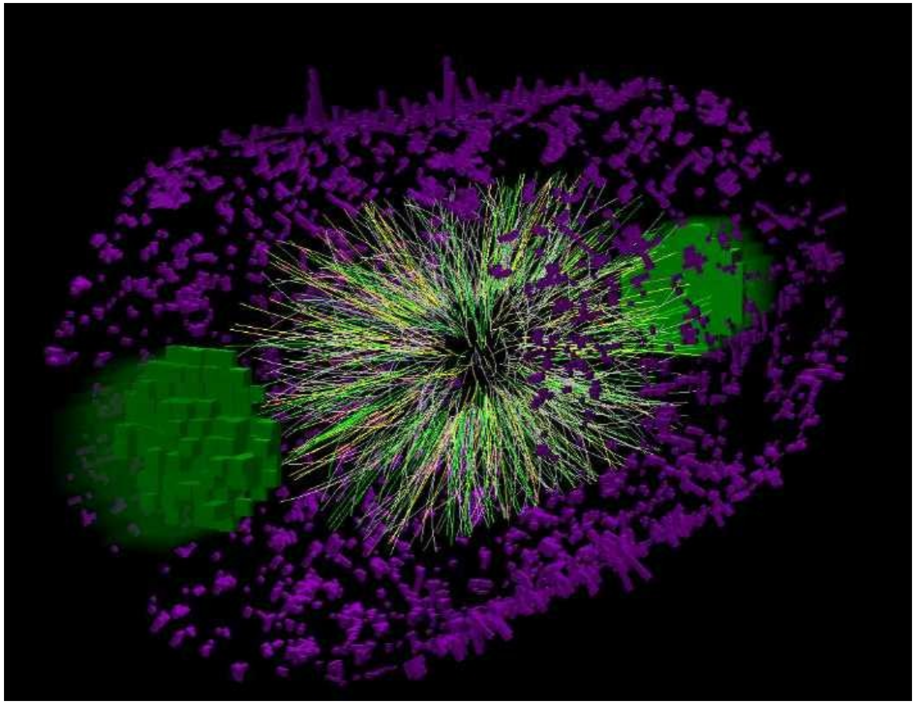


MPD experiment at NICA

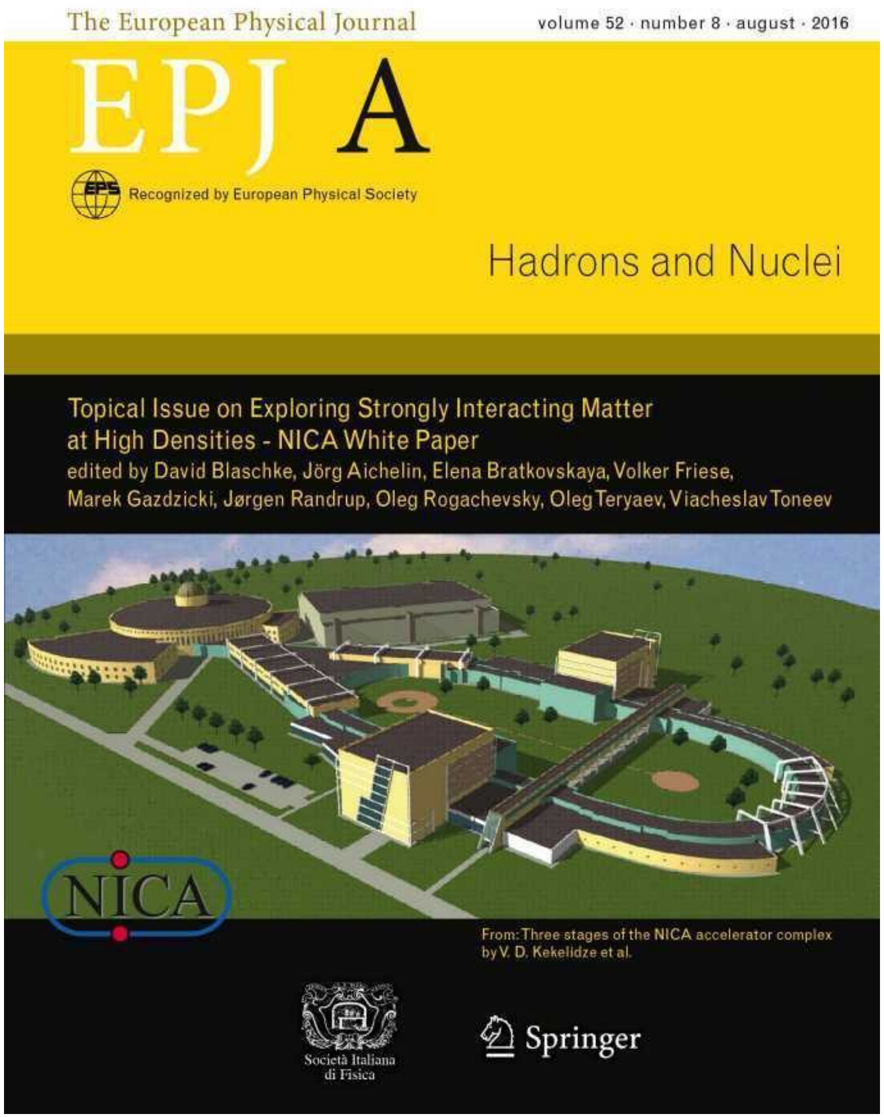




MPD event display
AuAu $\sqrt{s}$ *= 11 GeV*



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 AGeV 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.

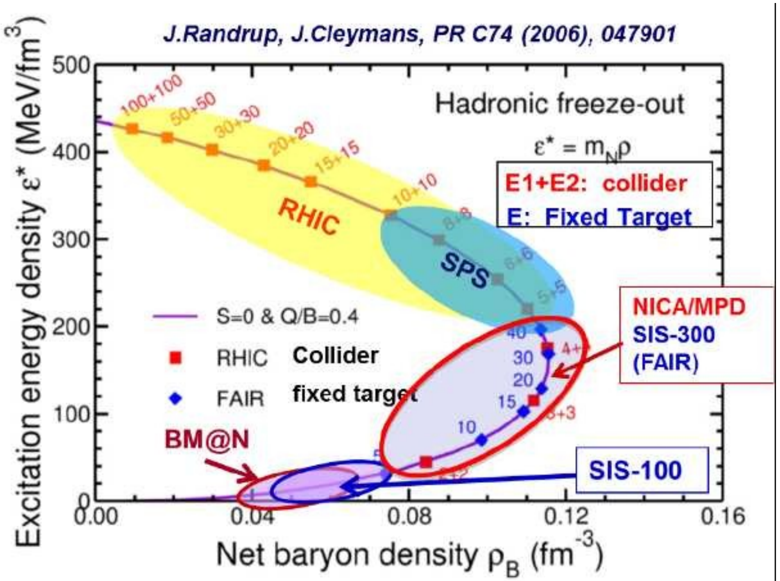
The available observations of an enhancement of dilepton rates at low invariant masses may serve as a signal of the chiral symmetry restoration in hot and dense matter. Due to this fact, measurements of the dilepton spectra are considered to be an important part of the NICA physics program. The study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

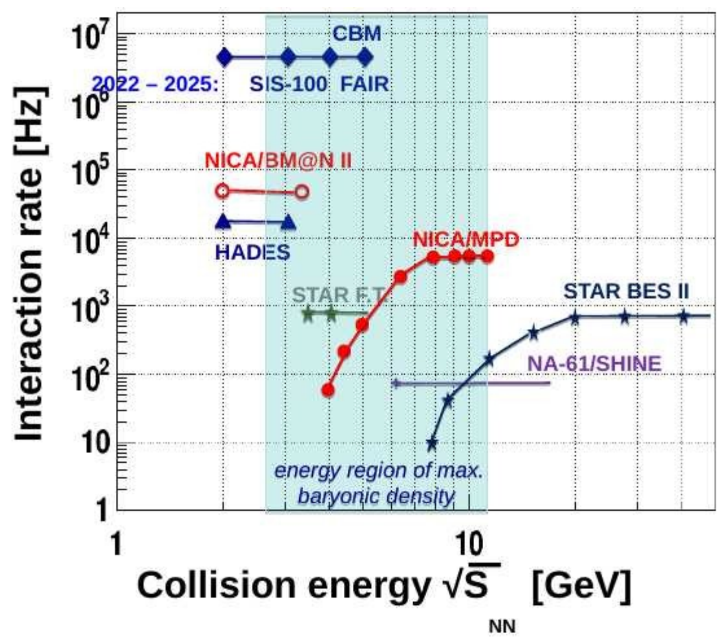
In this paper a feasibility of the considered investigations is shown by the detailed Monte Carlo simulations applied to the planned experiments (BM@N, MPD) at NICA.

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.





Basic NICA milestones

- *2018 – start of **BM@N** experiment*
- ***2018** – start of **Booster** commissioning*
- ***2020** – completion of civil constructions **(b. 17)***
- ***2019** – **MPD** magnet commissioning*
- ***2019** – start of **MPD** detectors assembly*
- ***2020** – start of **Collider assembly***
- ***2020** – start of **Collider** commissioning*
- ***2020** – start of **MPD** commissioning*
- ***2020** – completion of **«Center NICA»** construction*
- ***2020 –** start of assembly of **Computer center** elements*

Thank you for attention

Welcome
to NICA physics