Simulations for heavy-ion program

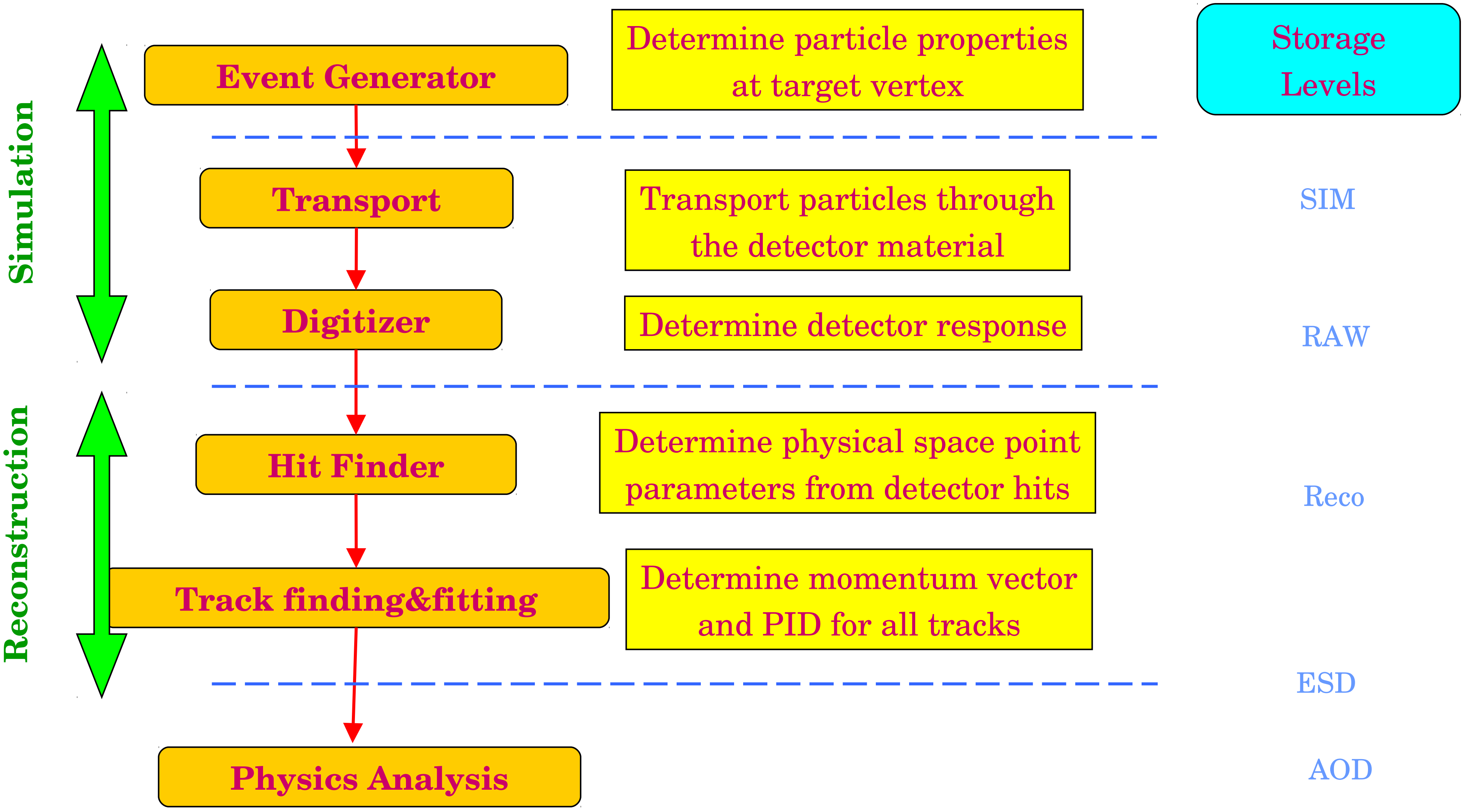
at NICA collider

ROGACHEVSKY Oleg

- *for MPD collaboration*

Helmholtz International Summer School
August 28 2018
Dubna

HEP experiments data flow

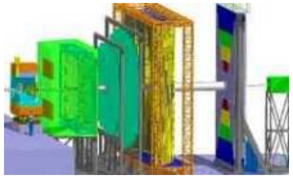


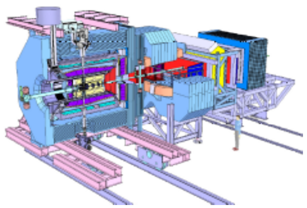
FairRoot

Start testing the VMC concept for CBM

2004

First Release of CbmRoot

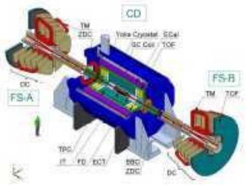




Panda decided to join-> FairRoot: same Base package for different experiments

2006

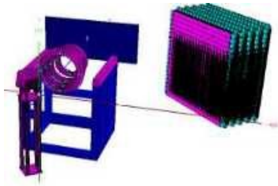
MPD (NICA) start also using FairRoot

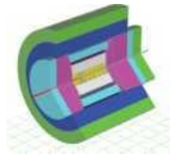


R3B joined

2010

ASYEOS joined (ASYEOSRoot)



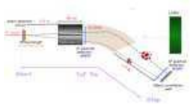


EIC (Electron Ion Collider BNL)

EICRoot

2011

GEM-TPC seperated from PANDA branch (FOPIRoot)

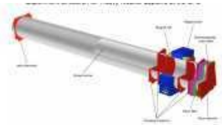


SOFIA (Studies On Fission with Aladin)

2012

2013

ENSAR-ROOT Collection of modules used by structural nuclear phsyics exp.



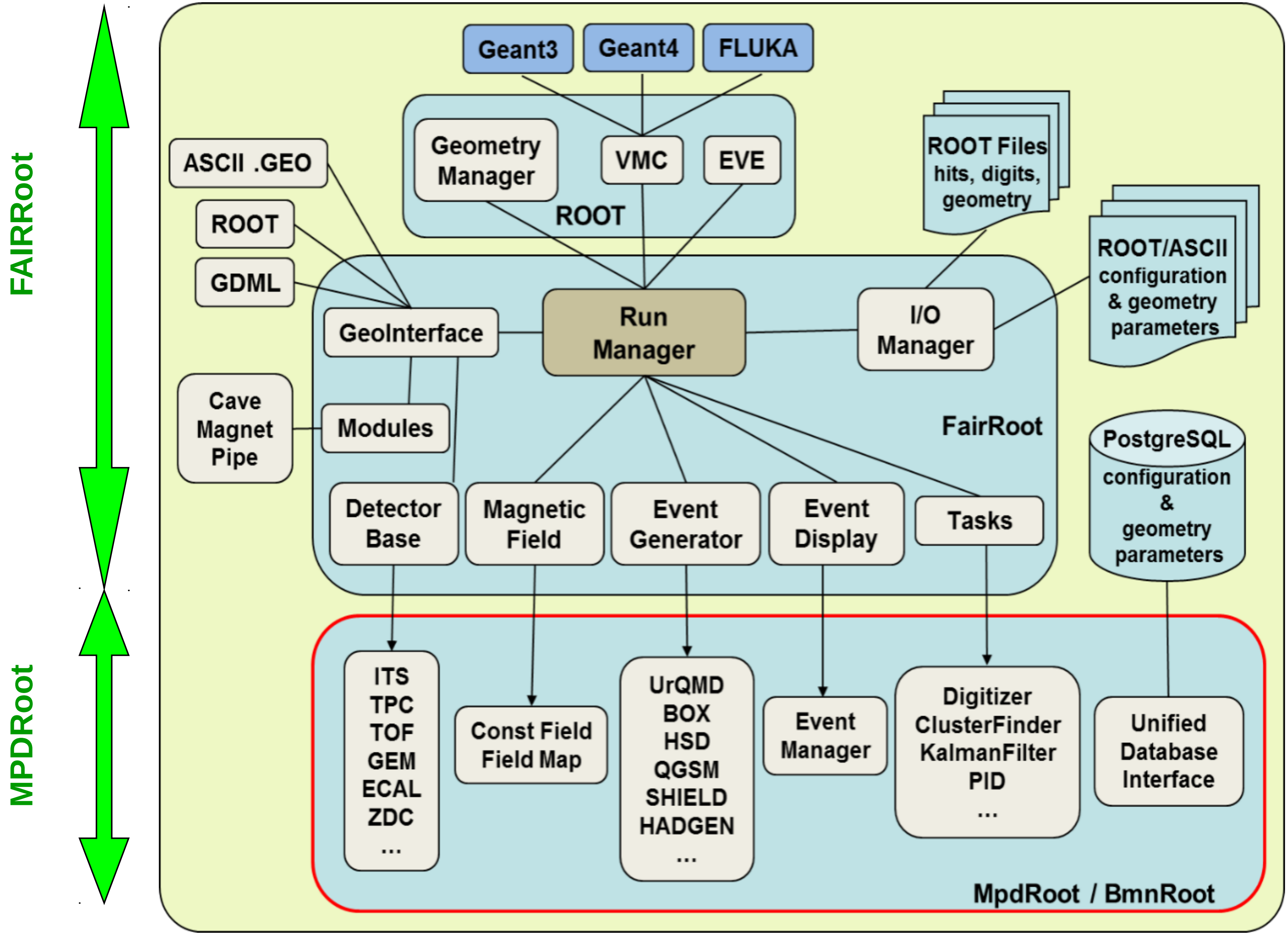
SHIP - Search for HIdden Particles

2014

2015

ALICE
FAIR

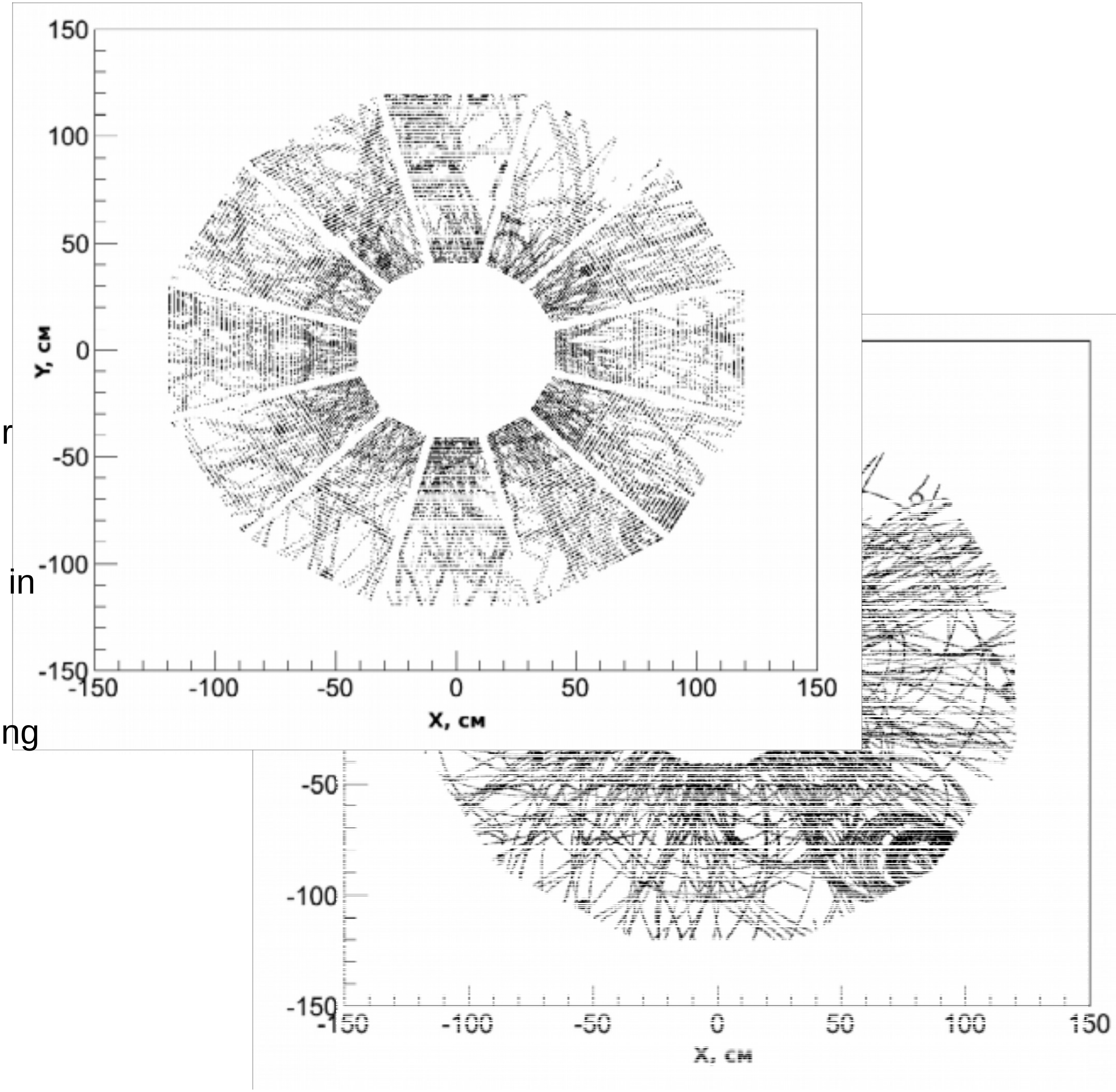
MPD/BM@N/SPDRoot design



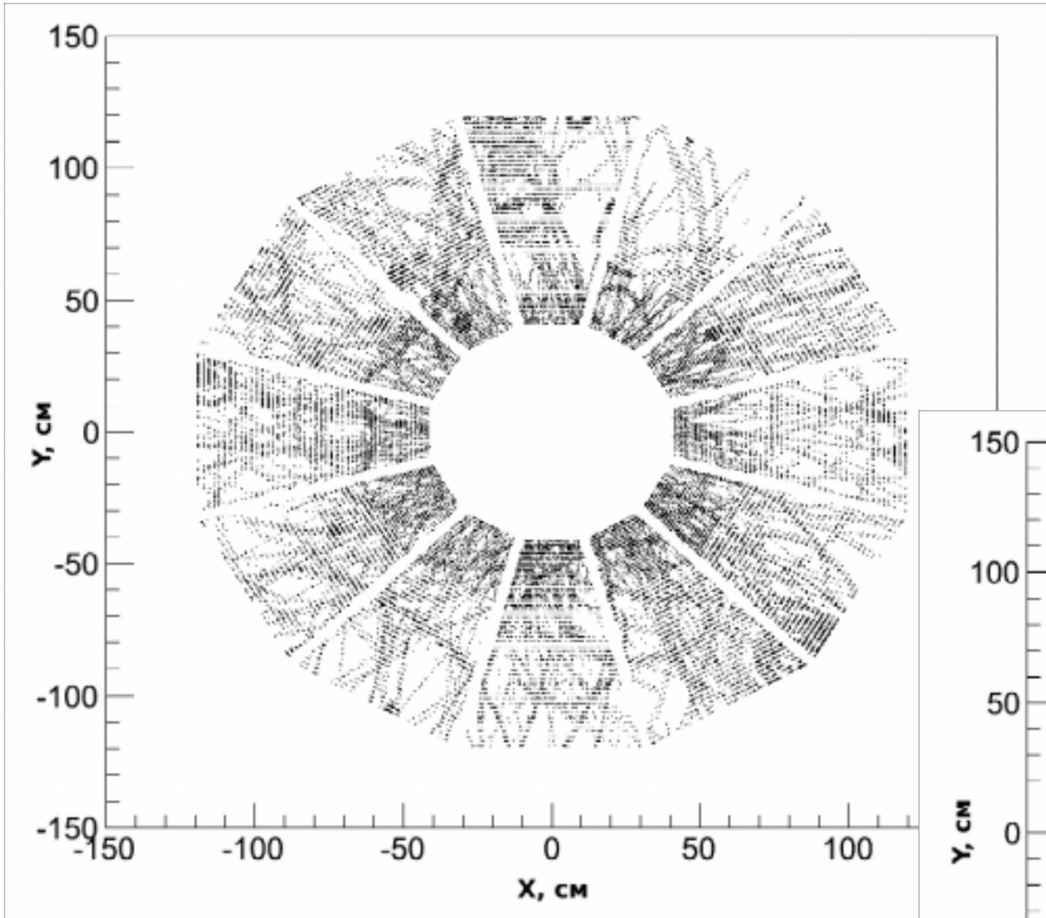
Realistic clustering in MPD TPC

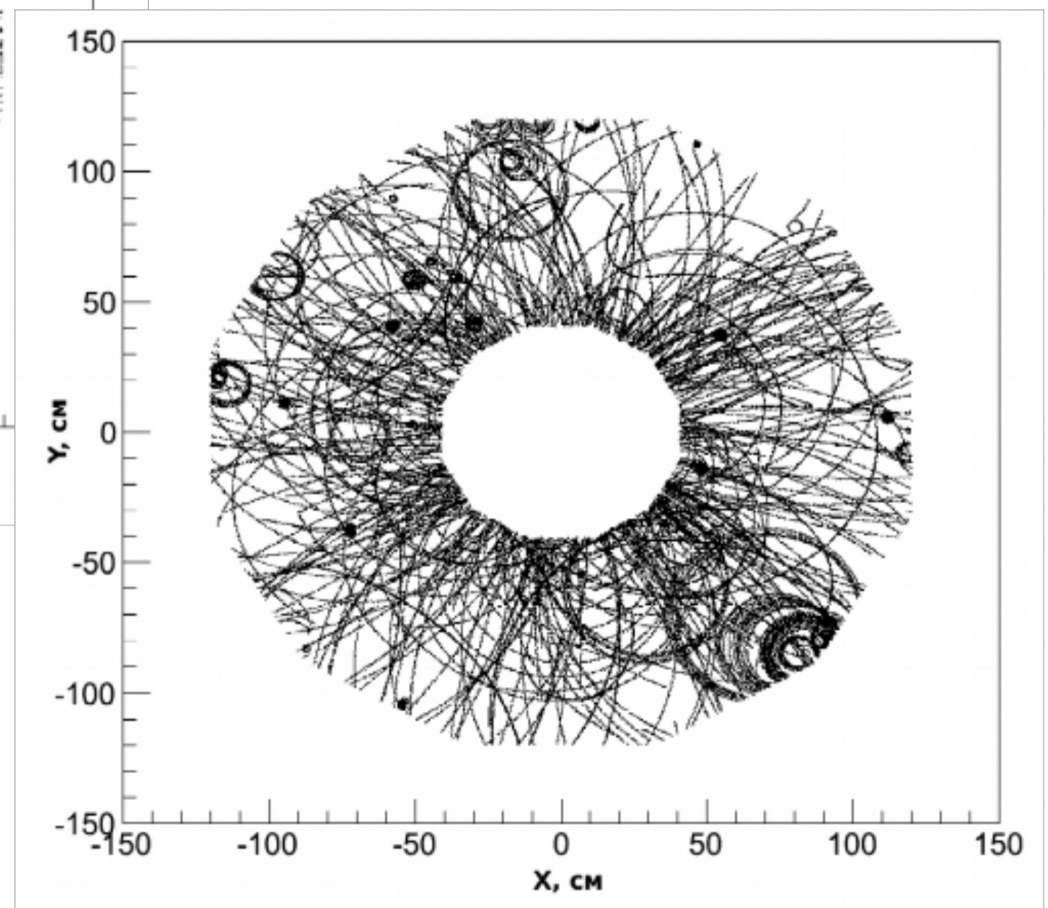
The hit reconstruction algorithm contains the following main steps:

1) Searching for extended clusters in (Pad-Time) for each pad raw.
2) Searching for peaks in time-profile for each pad in the found extended cluster.
3) Combining the neighboring peaks into resulting hits.



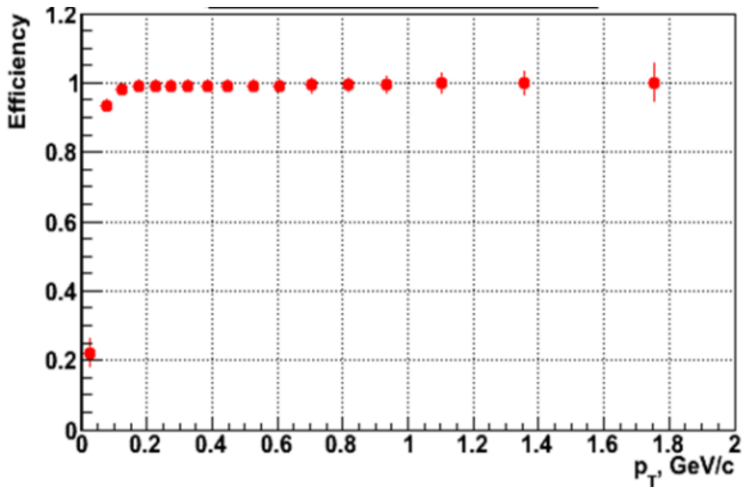
Tracking in MPD TPC



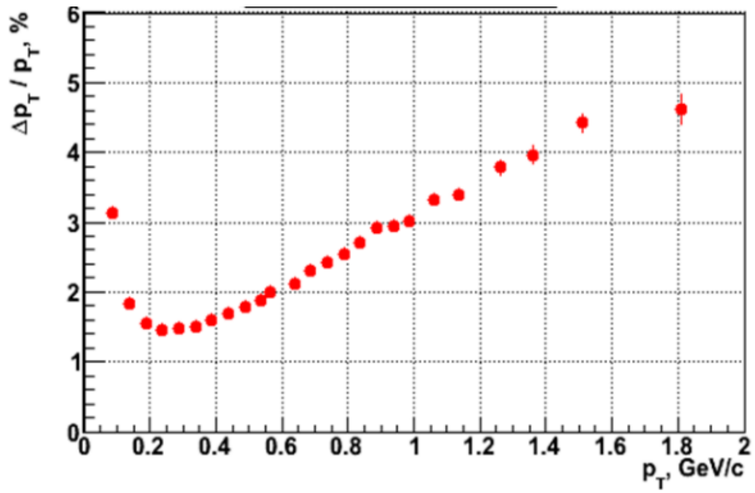


Tracking in MPD TPC

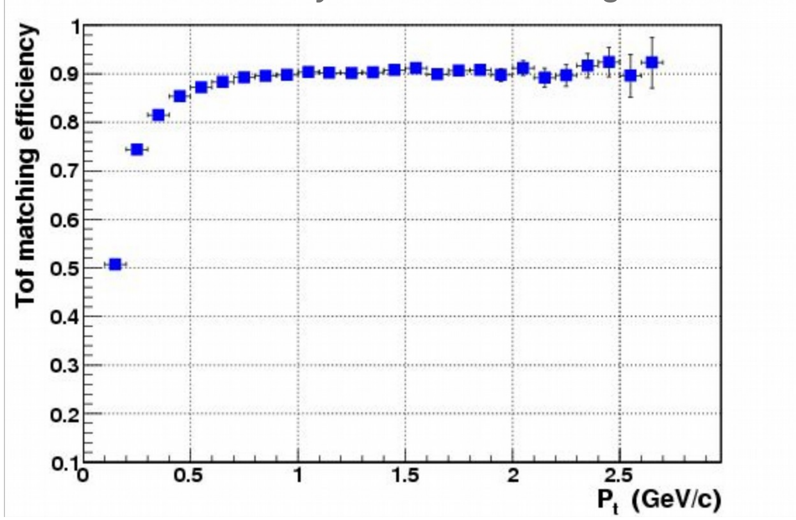
TPC tracking efficiency



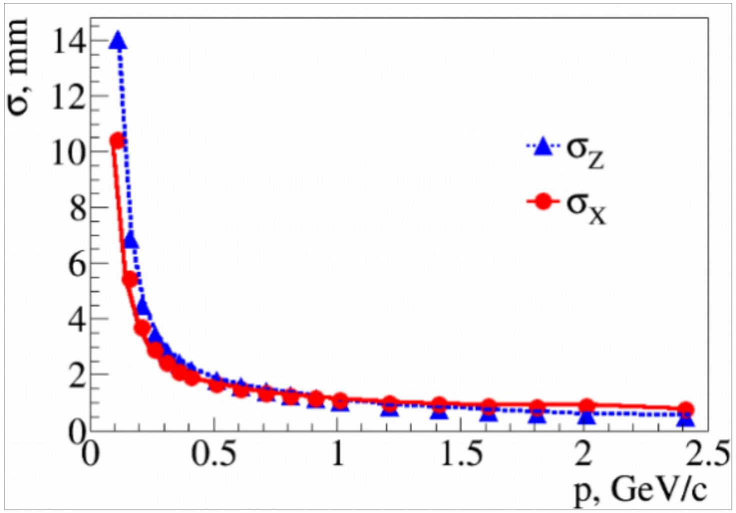
Momentum resolution



Efficiency of TOF matching

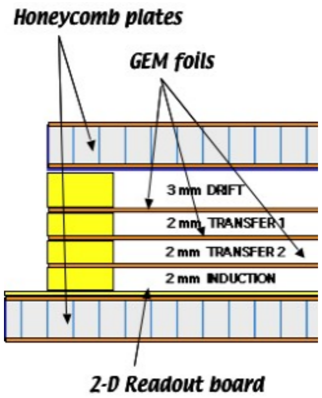


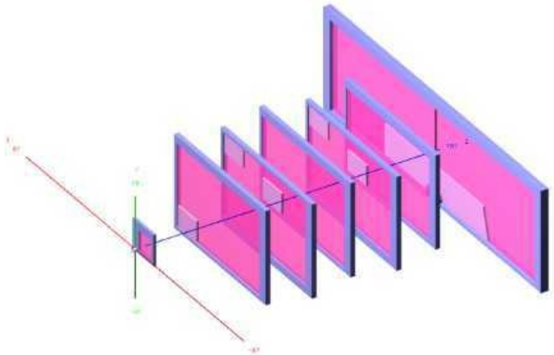
Primary vertex resolution



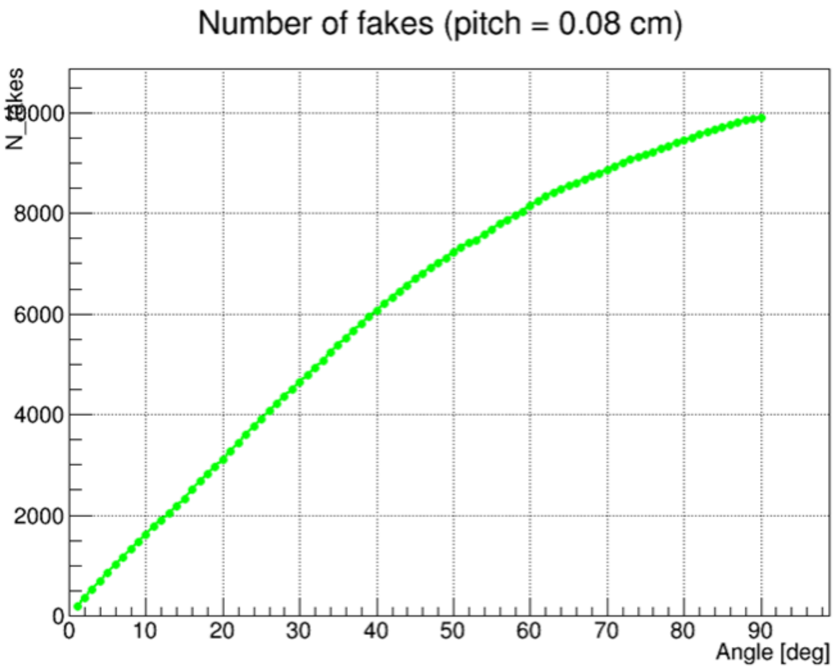
Clustering in GEM

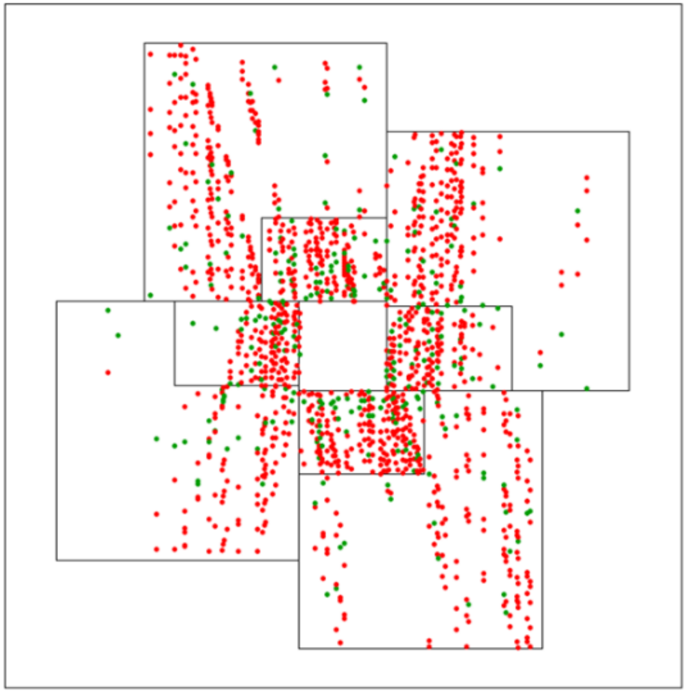
- There are realistic hit finder in GEMs
- For the GEM stations procedure of the fake hits production is implemented





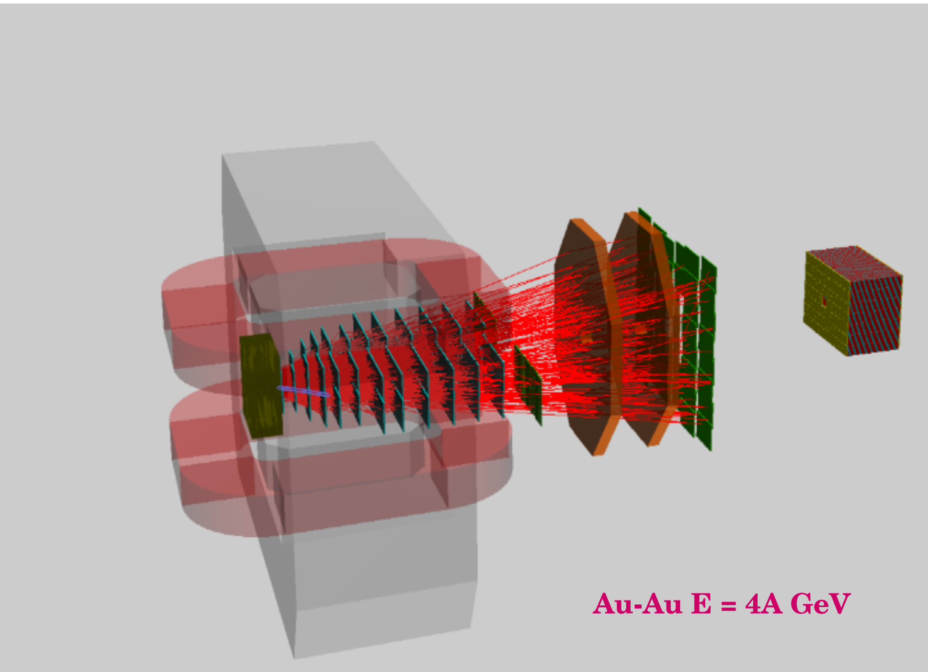
Station 0 (what is it)





Event Display for the NICA experiments

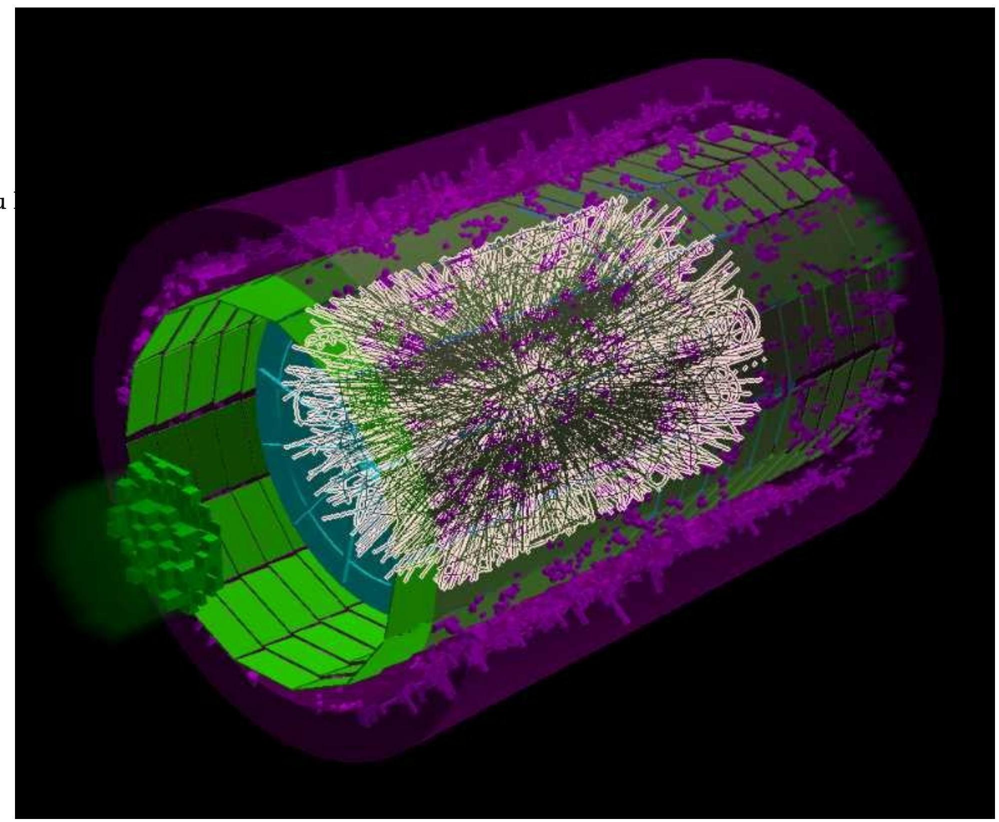
based on EVE package



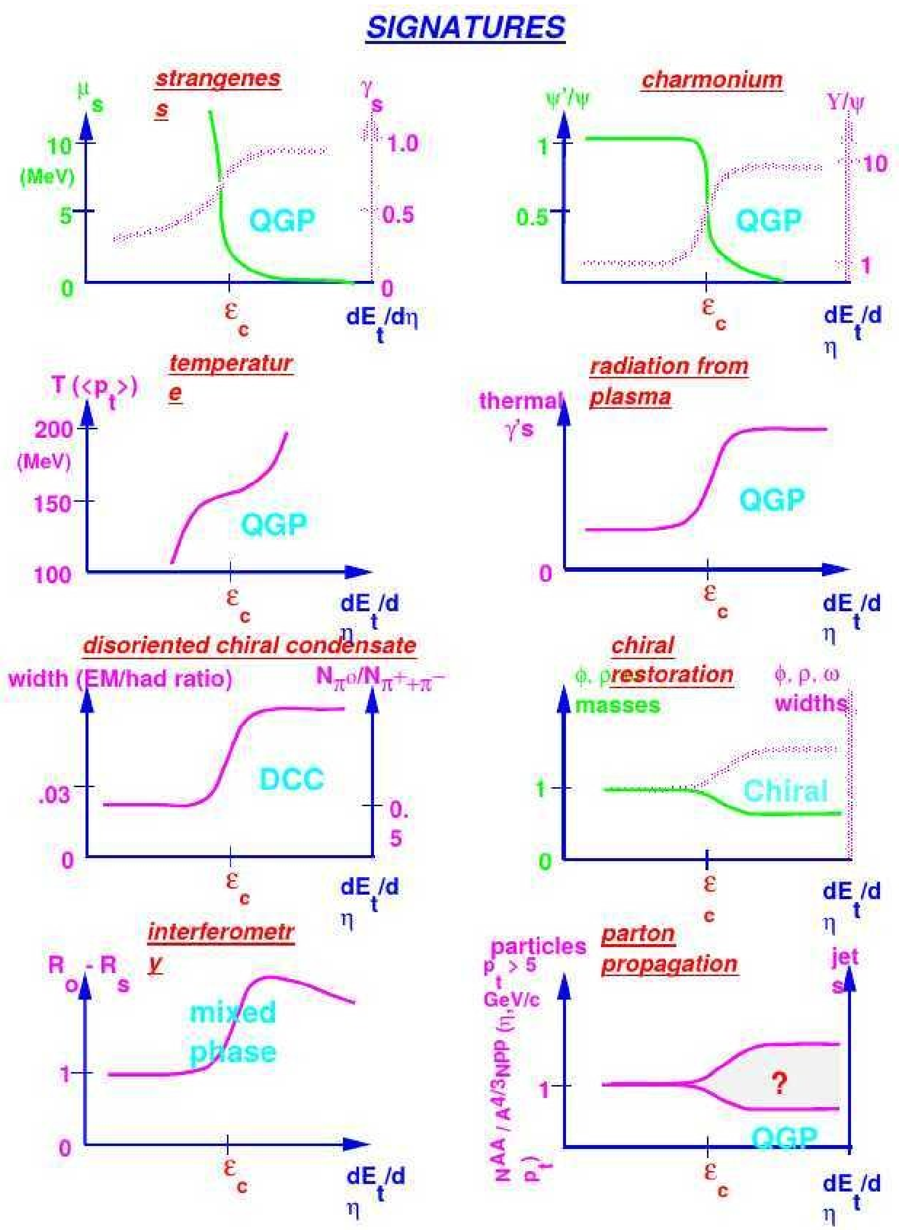
BM@N event data:
GEM points and reconstructed tracks

MPD event data:
TPC hits and EMC towers

Au-Au



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

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	

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

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)

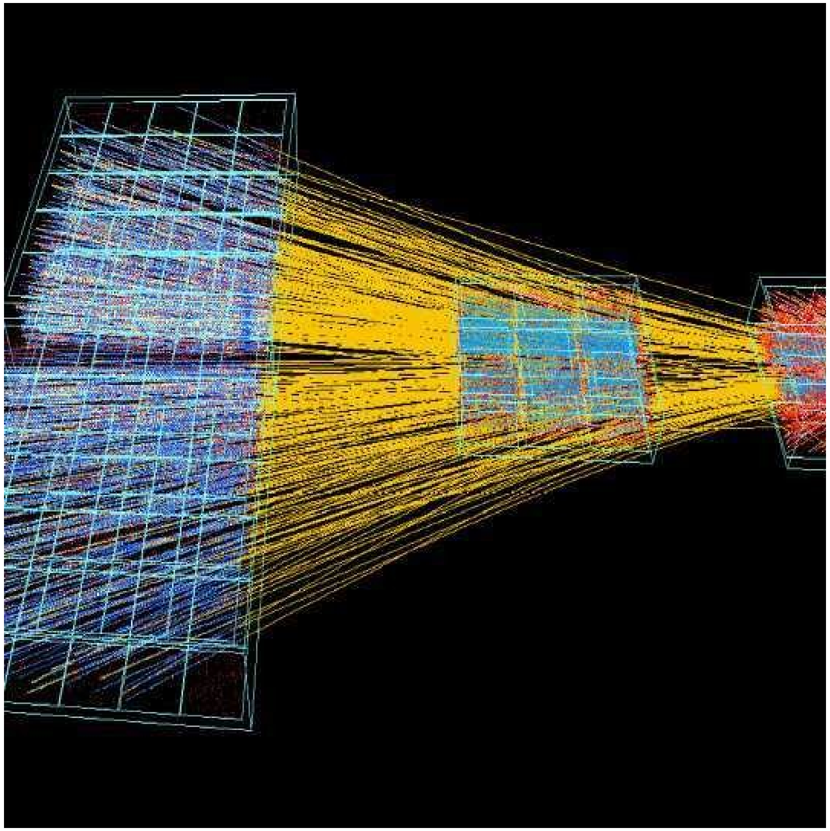
" A substantial enhancement of production rates of multi-strange anti-baryons in nuclear collisions in particular at central rapidity and at highest transverse masses has therefore been proposed as a characteristic signature of QGP."
Phys. Lett. 62(1991)

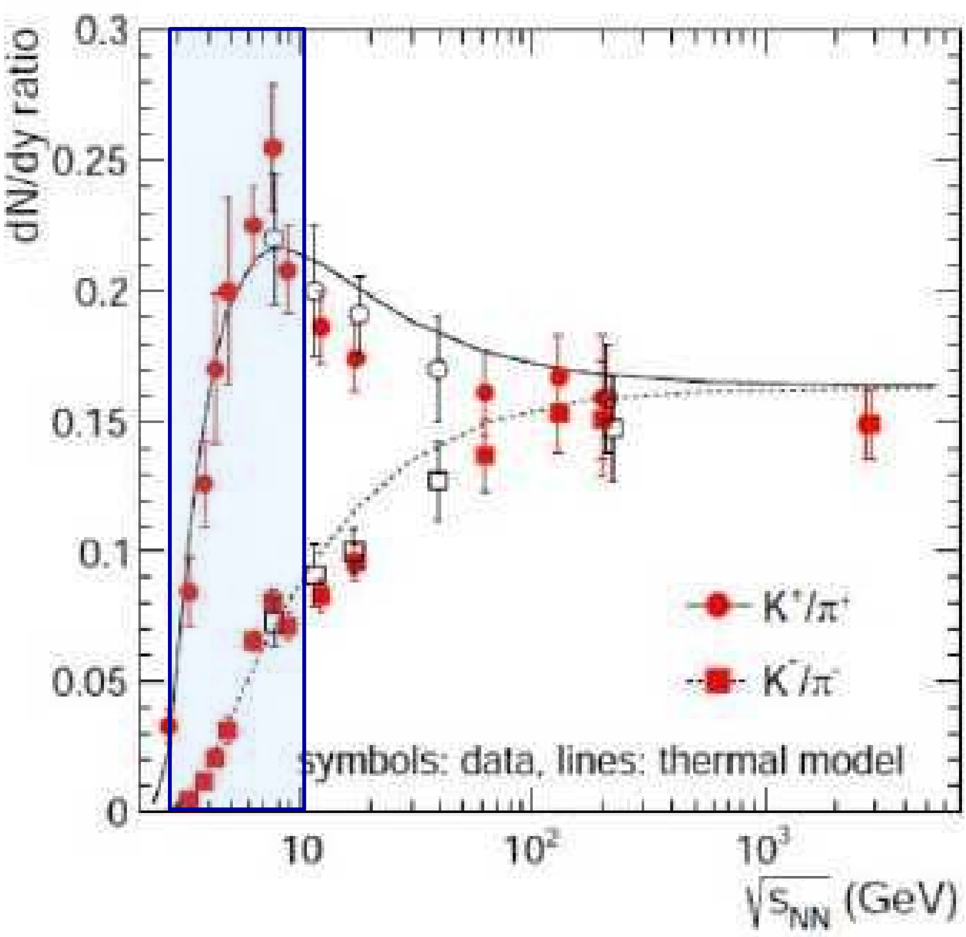
Idea: if s-(anti)quarks are created at QGP stage, then their number should not be changed during further evolution since s-(anti)quarks number is small and since density decreases => there is no chance for their annihilation! Hence, we should observe chemical enhancement of strangeness

Onset of deconfinement (NA49/61)

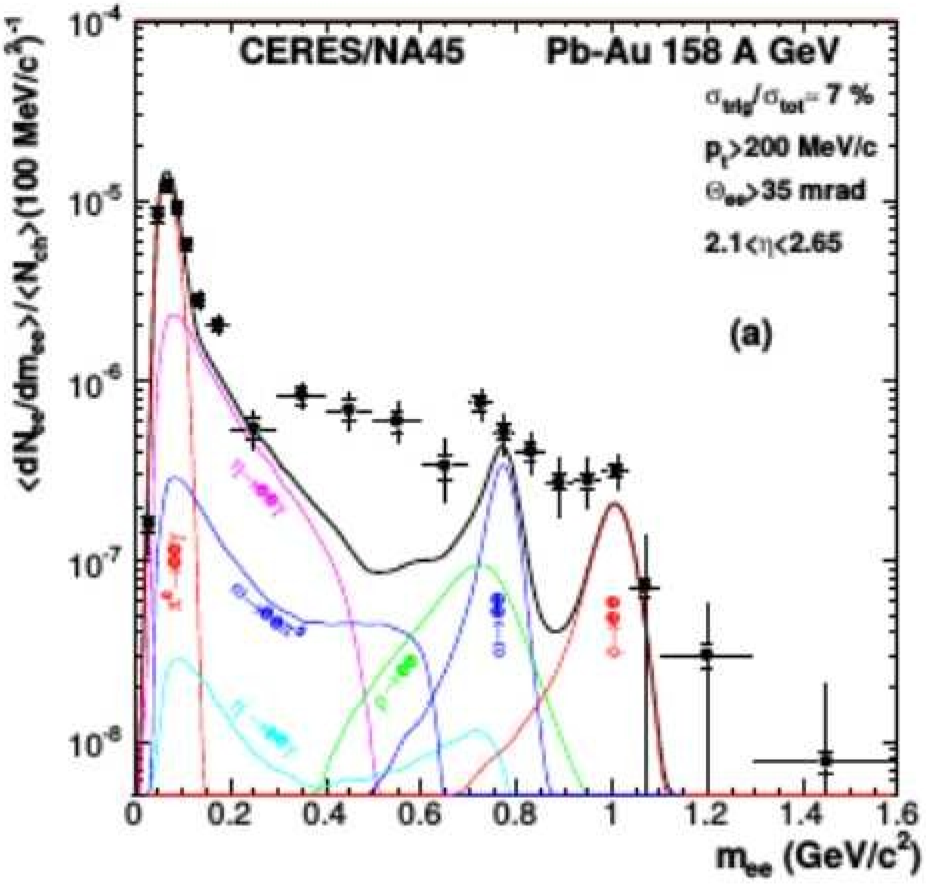
Gazdzicki M. Gorenstein M.
Acta. Phys. Pol., B30: 2705 1999

Statistical Model of the Early Stage

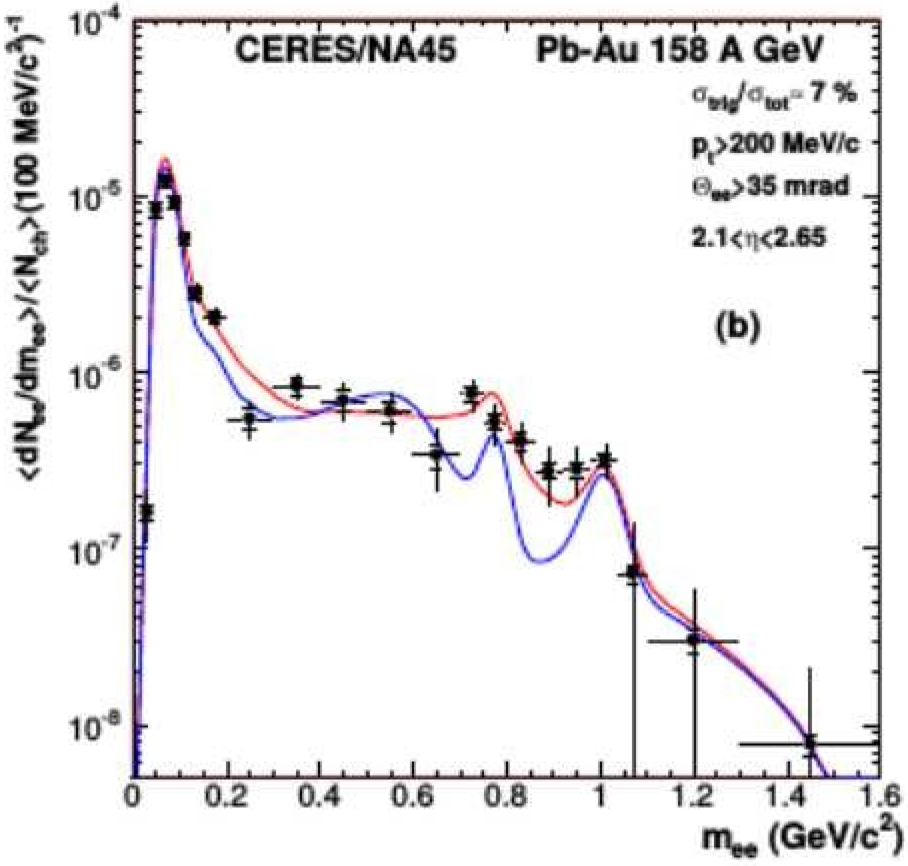




NA 45



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

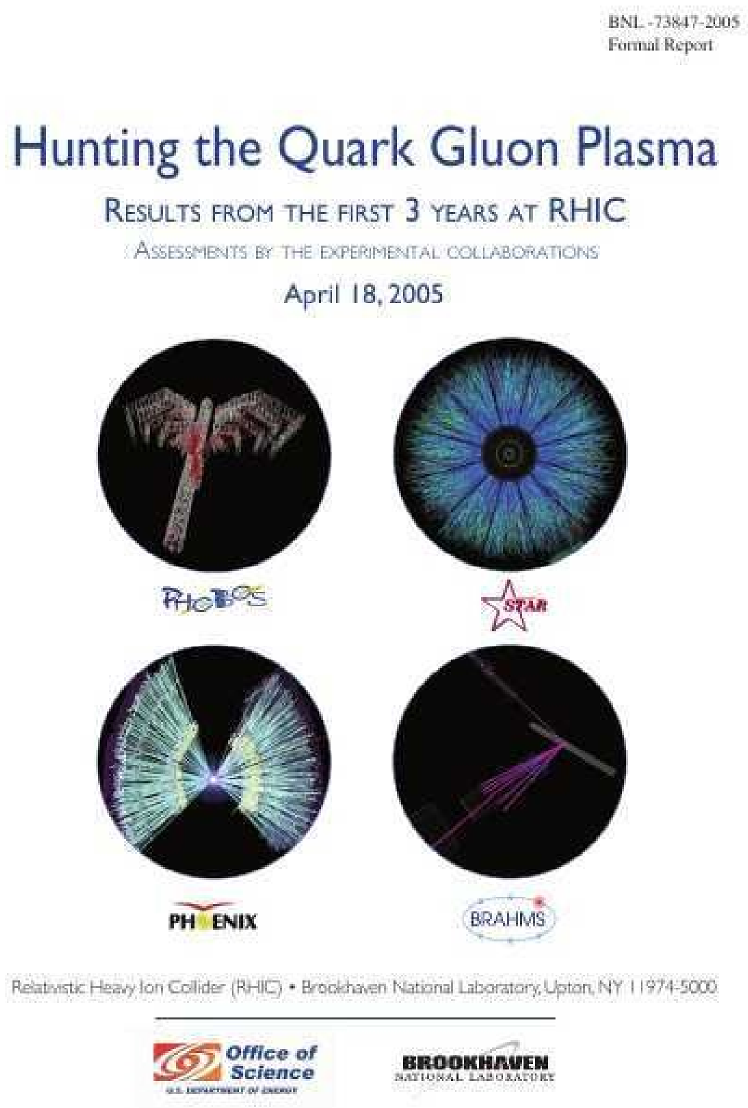


The expectations from model calculations assuming a dropping of the ρ meson mass (blue) or a spread of the ρ width in the medium (red) are also shown.

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

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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.

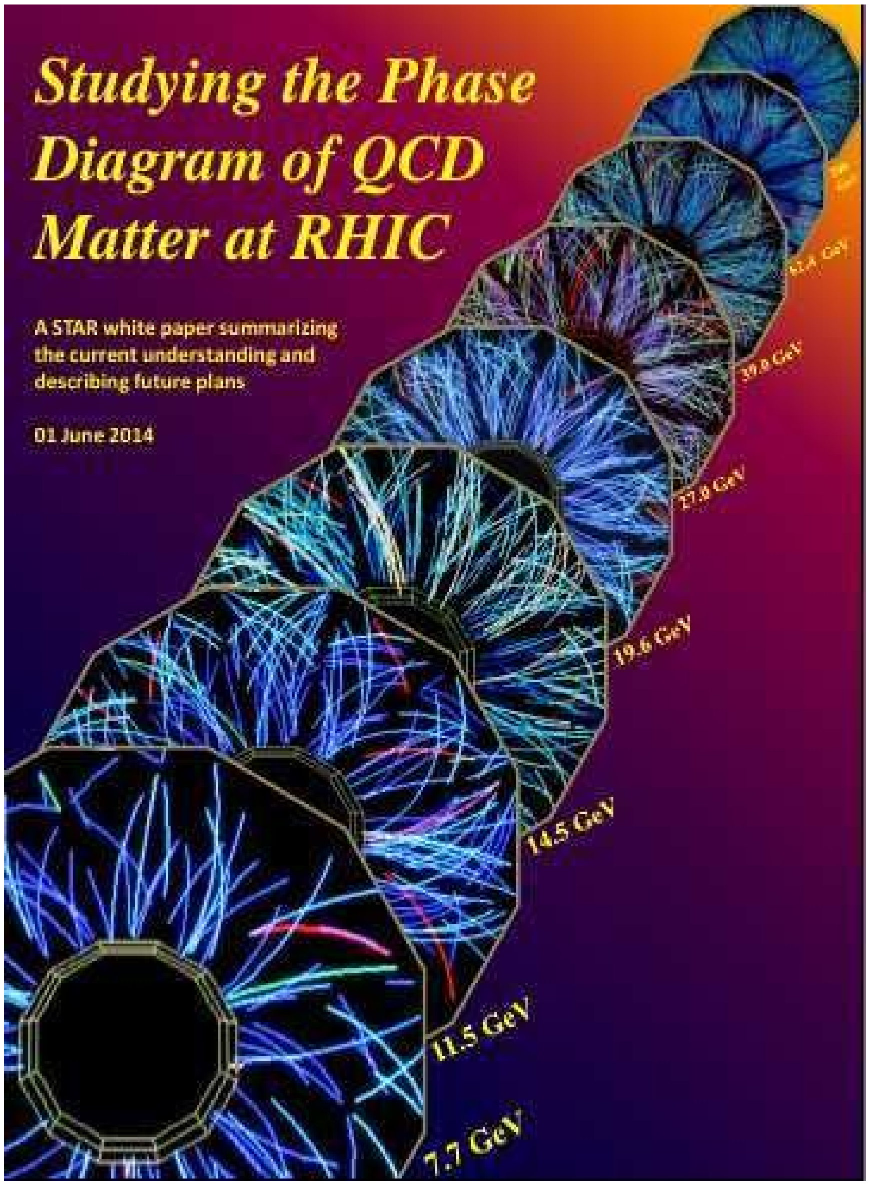
A search for signatures of a phase transition and a critical point. The particular observables that we have identified as the essential drivers of our run plan are:

(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.

Studying the Phase Diagram of QCD Matter at RHIC



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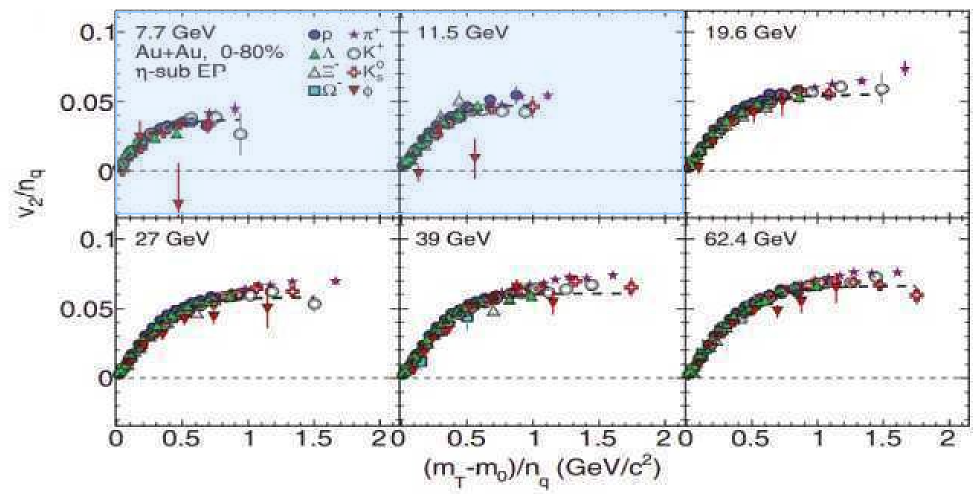
4 Summary **50**

STAR BES I results

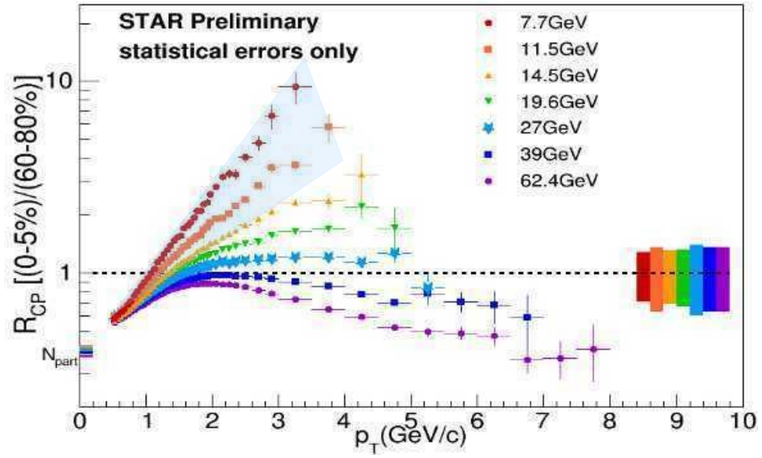
Number of constituent quarks scaling

Phys. Rev. C88, (2013), 014902



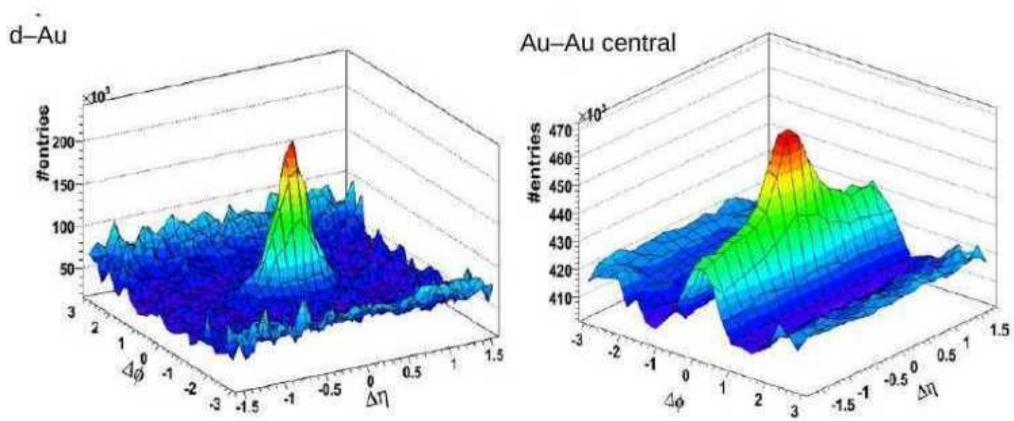
High P_T suppression

Stephen Horvat Quark Matter 2015

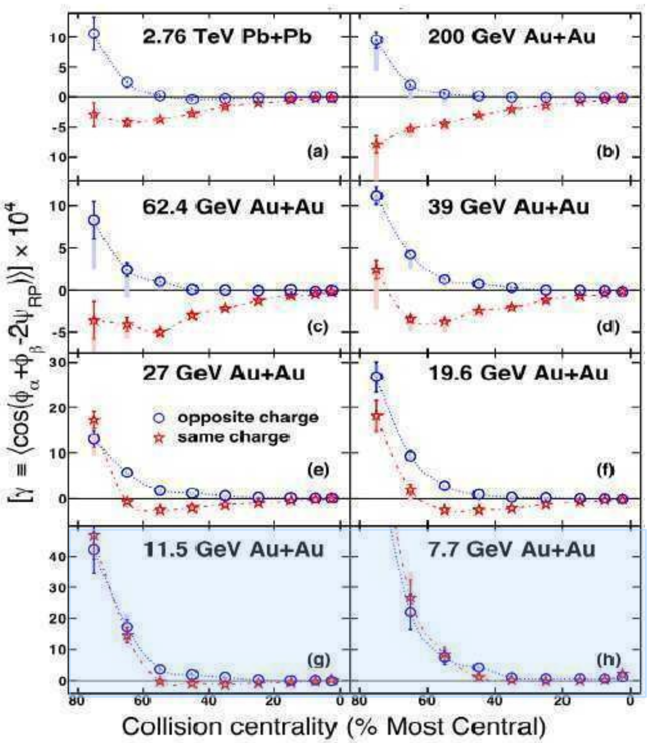


Ridge effect

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

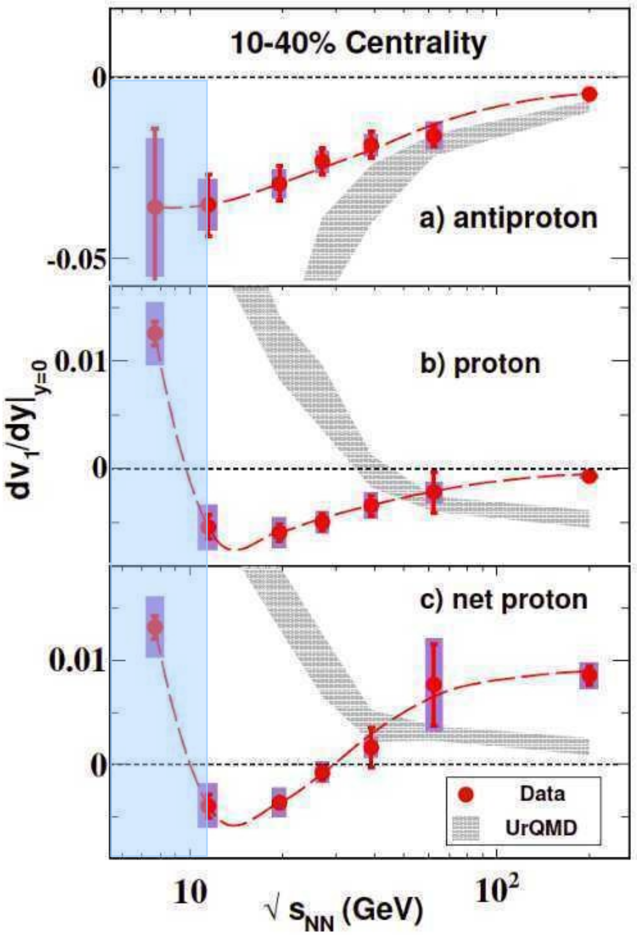


Chiral Magnetic Effect



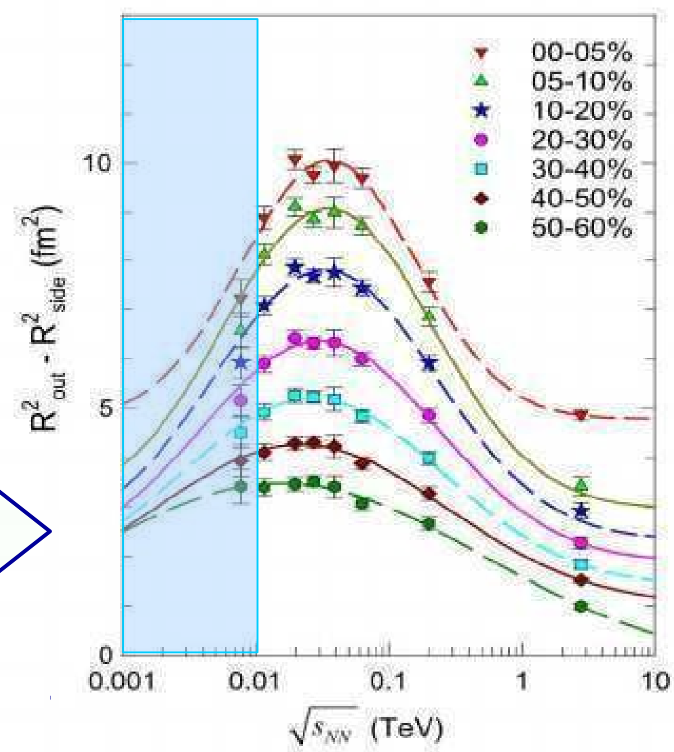
STAR BES I results

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.

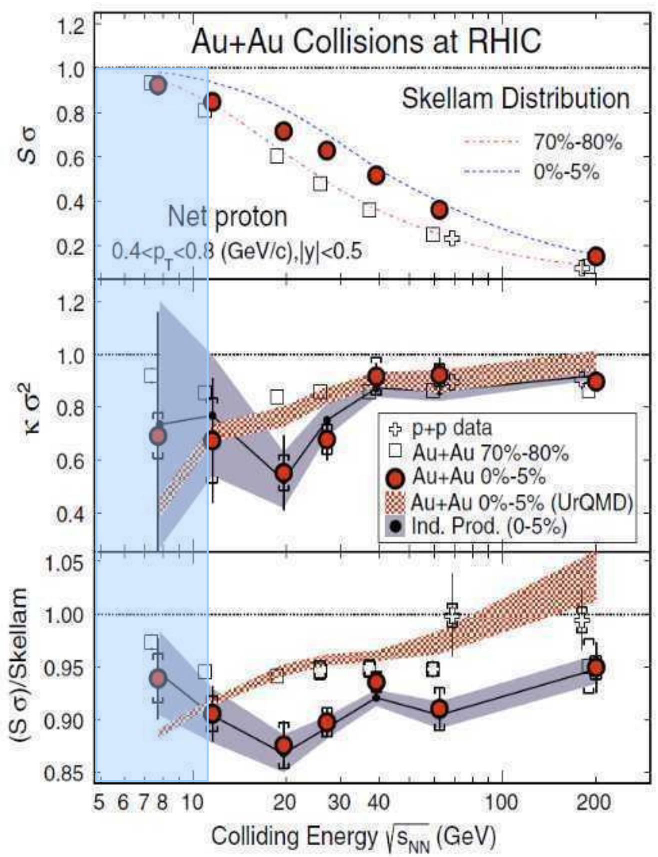
R. Lacey, PRL 114, 142301 (2015)



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.

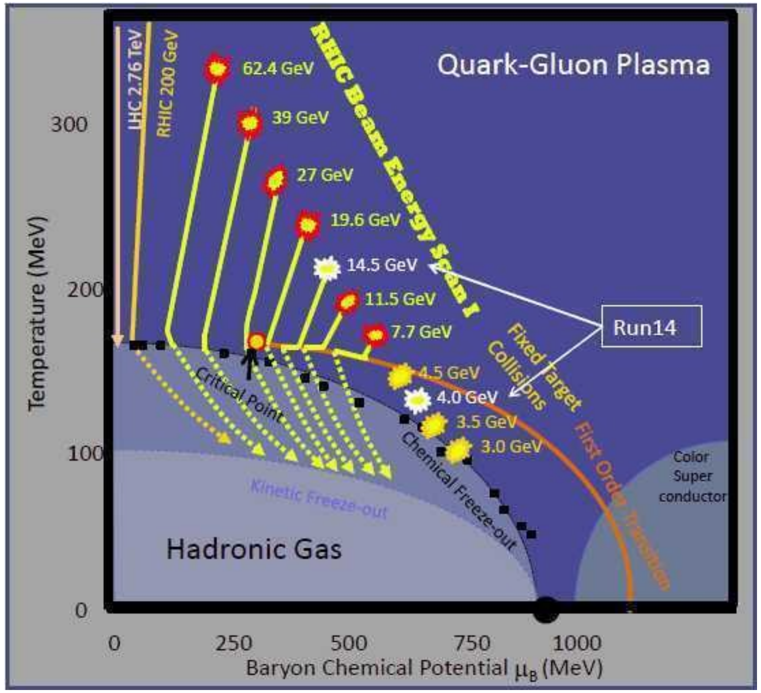
STAR BES program

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

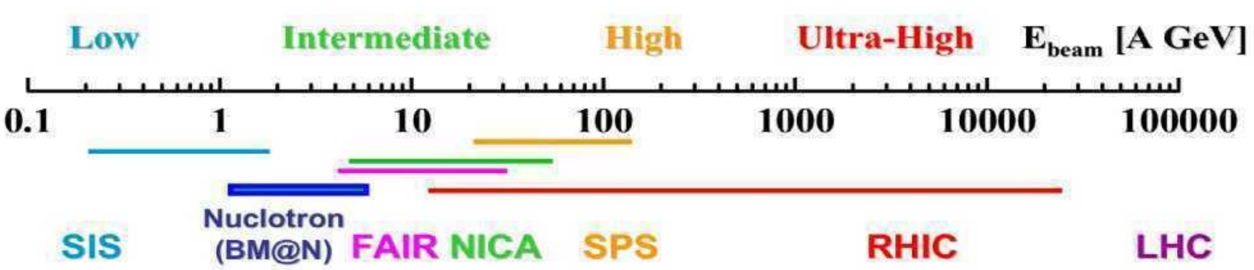
$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Needed Events (10^6)
7.7	420	100
9.1	370	160
11.5	315	230
14.5	**260**	**300**
19.6	205	400



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

Nuclotron based Ion Collider fAcility

Beams – p,d(h)..$^{197}Au^{79+}$

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

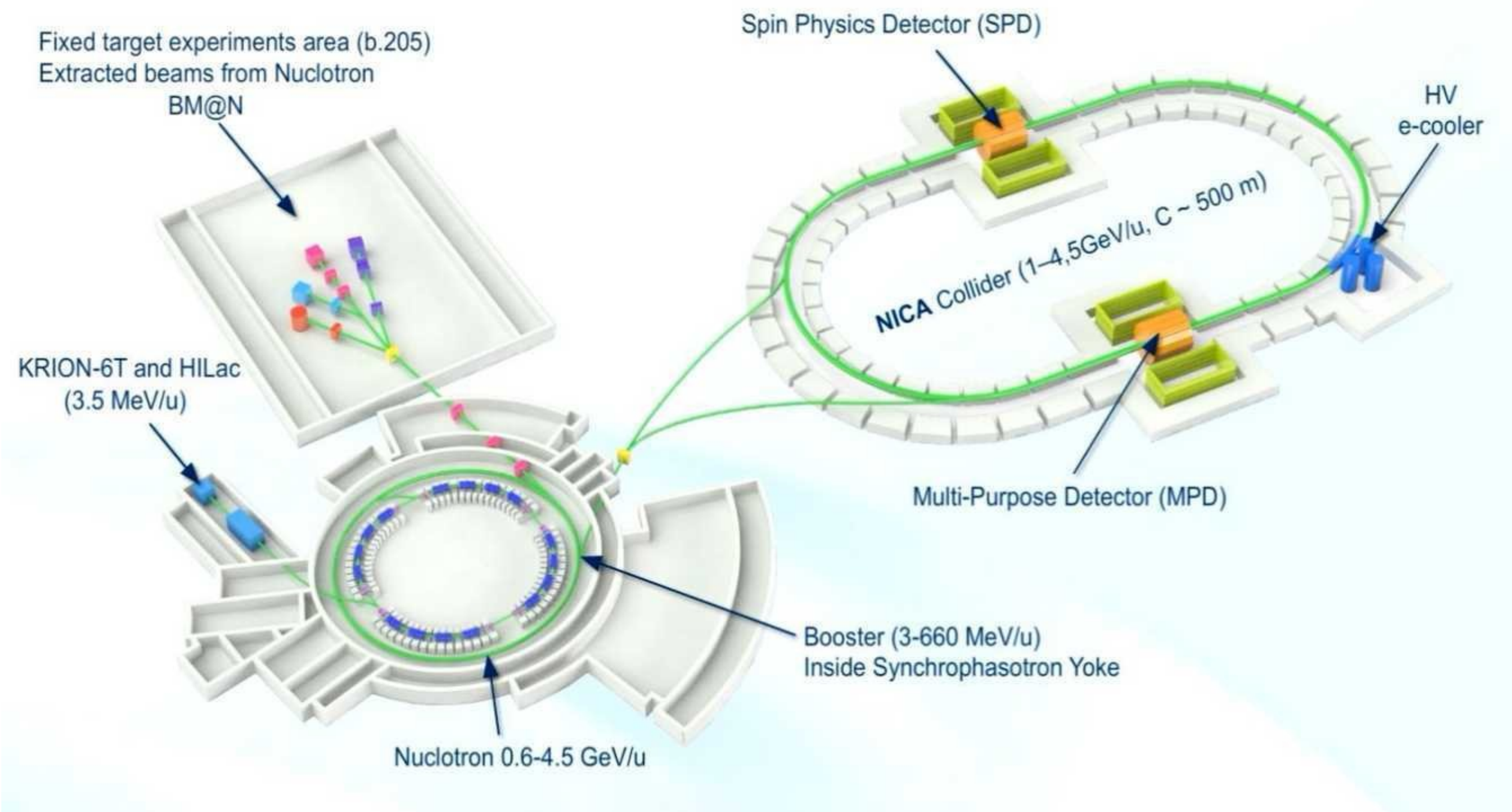
Beam energy (fixed target) - **1-6** GeV/u

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

Experiments:

2 Interaction points – **MPD** and SPD

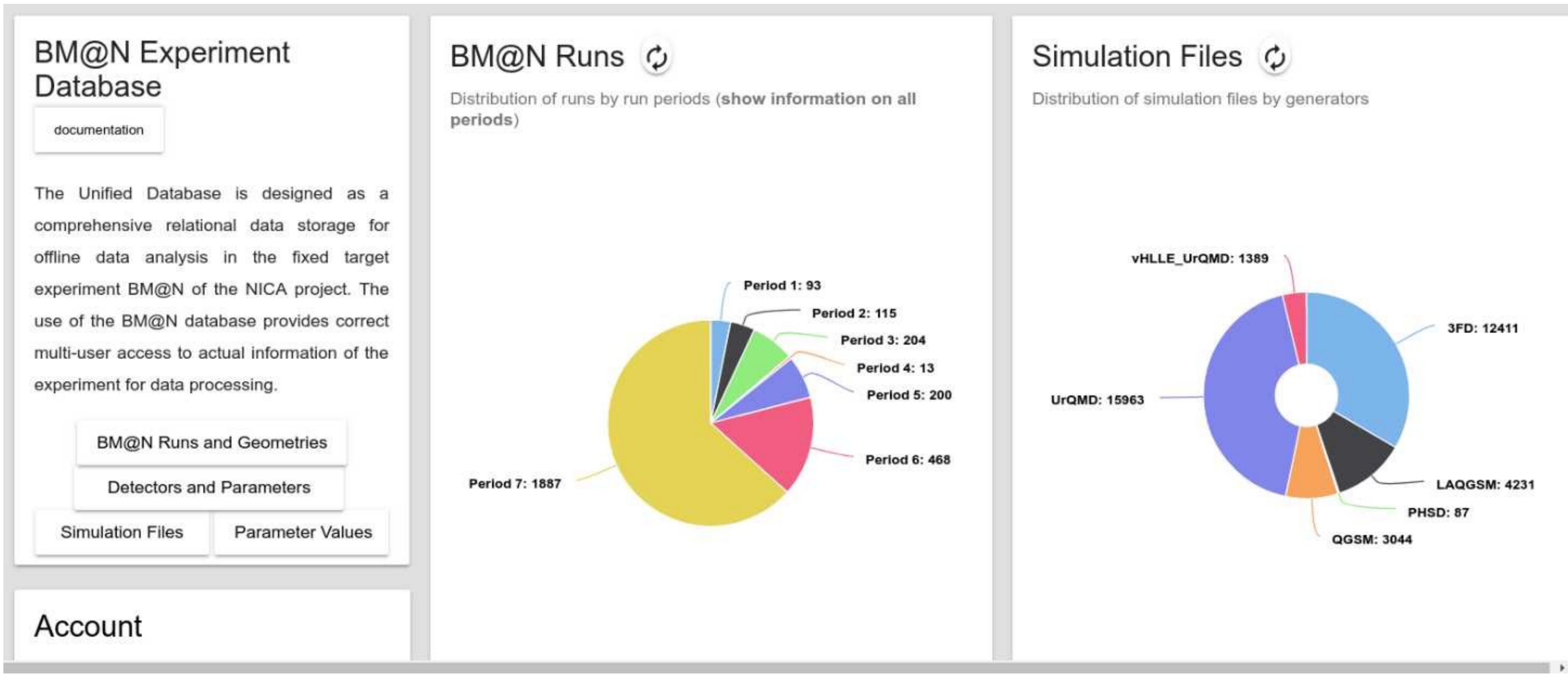
Fixed target experiment **BM@N**



Feasibility study for heavy Ion collision at NICA

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

Event generators + exp. data databases



- ✔ UrQMD
- ✔ QGSM
- ✔ PHSD

- ✔ Hybrid UrQMD
- ✔ vHLLE_UrQMD
- ✔ 3FD(Theseus)

Interactions
AuAu MC
pC MC+exp
CC

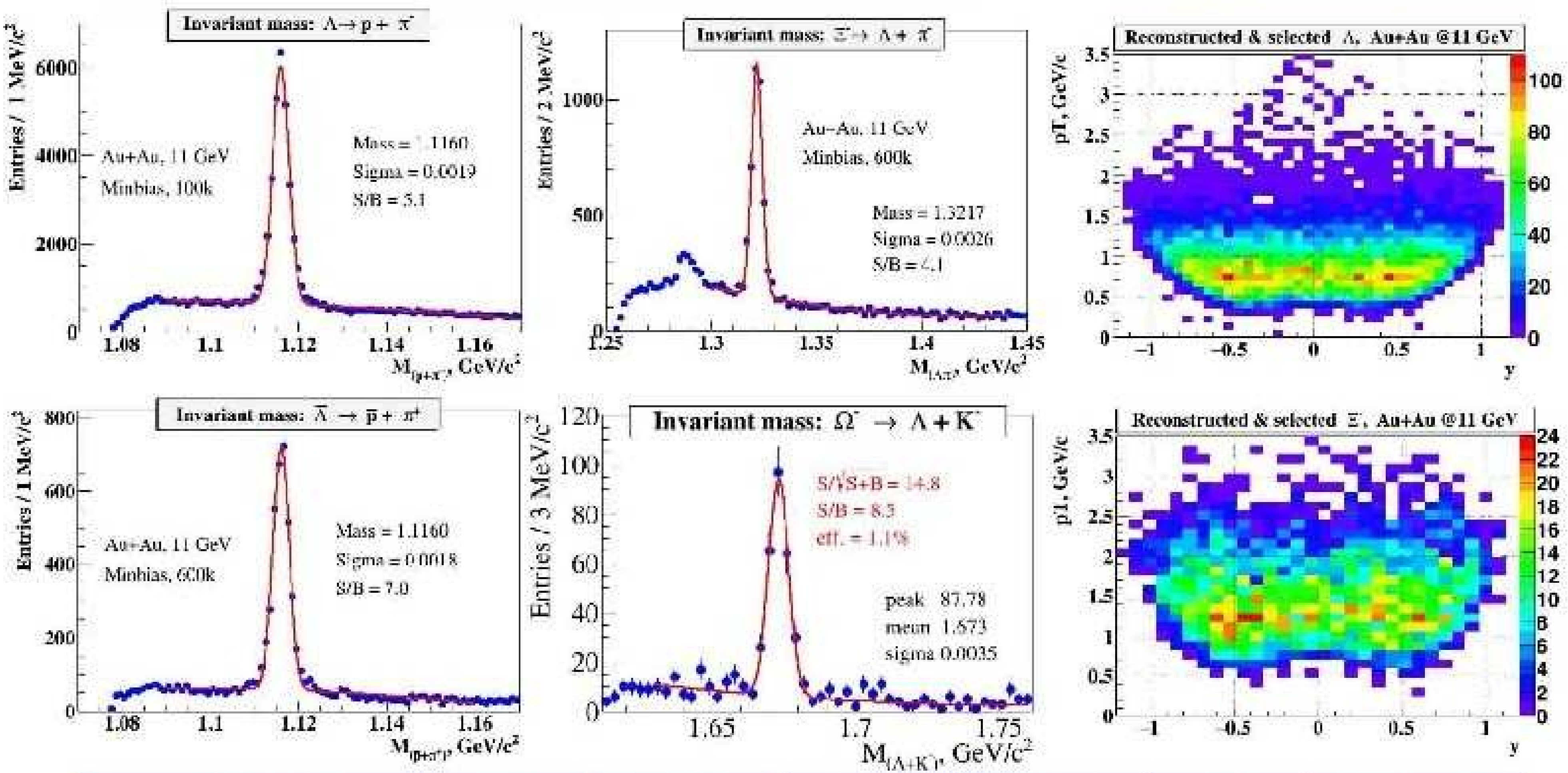
Energy s
2, 4, 7, 9, 11

32902 files
~ 10^6 events
for each
interaction

Strange and multi-strange baryons

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

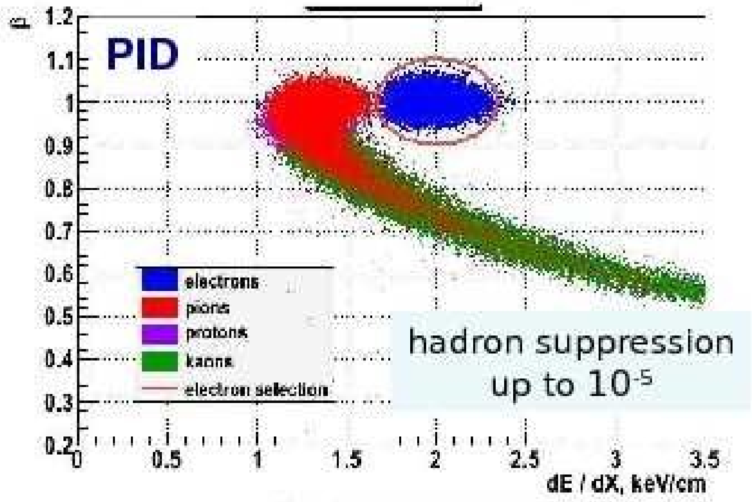
large phase-space

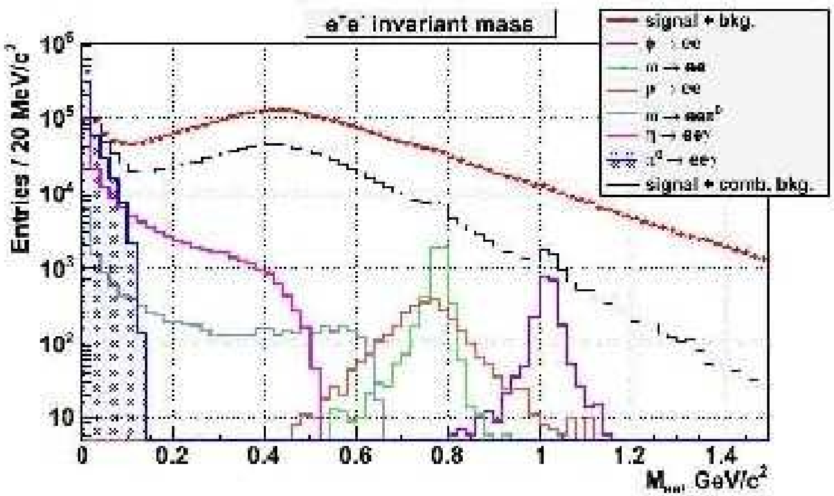


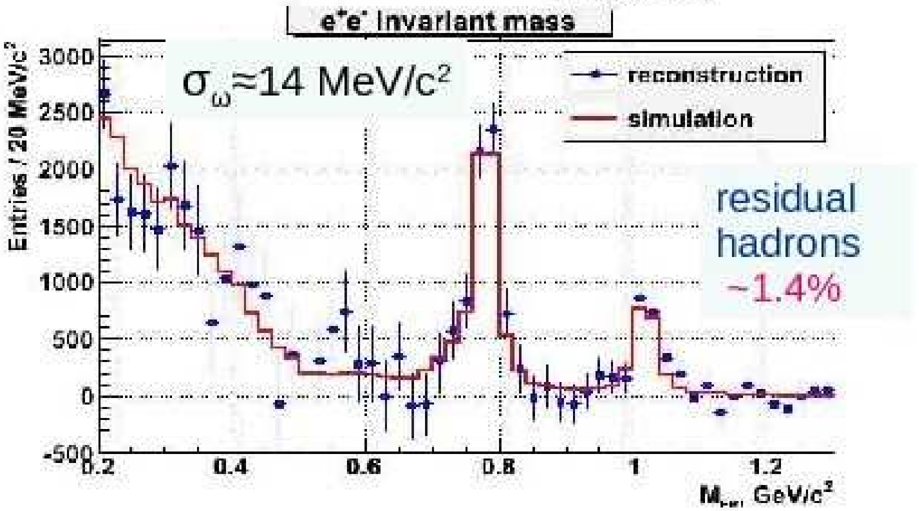
particle	Λ	anti-Λ	Ξ^-	anti-Ξ^+	Ω^-	anti-Ω^+
yield in 10 weeks	$3 \cdot 10^8$	$3.5 \cdot 10^6$	$1.5 \cdot 10^6$	$8.0 \cdot 10^4$	$7 \cdot 10^4$	$1.5 \cdot 10^4$

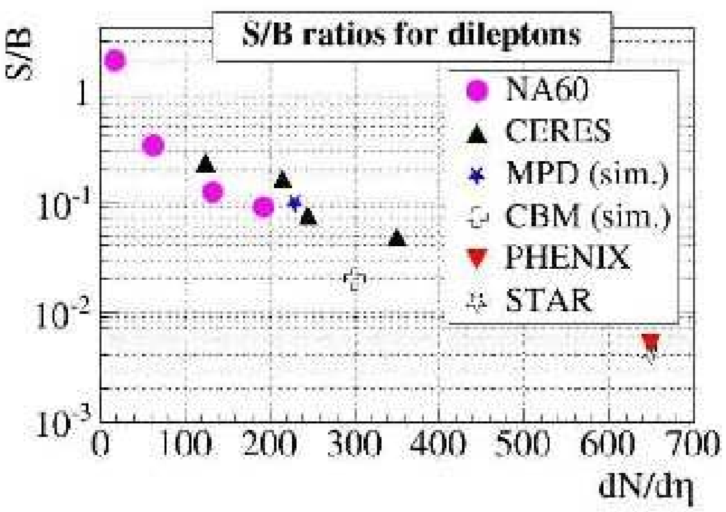
Prospects for study of dileptons

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









Prospects for study of dileptons

- **Event generator:** *UrQMD+Pluto (for the cocktail) central Au+Au @ 8 GeV*
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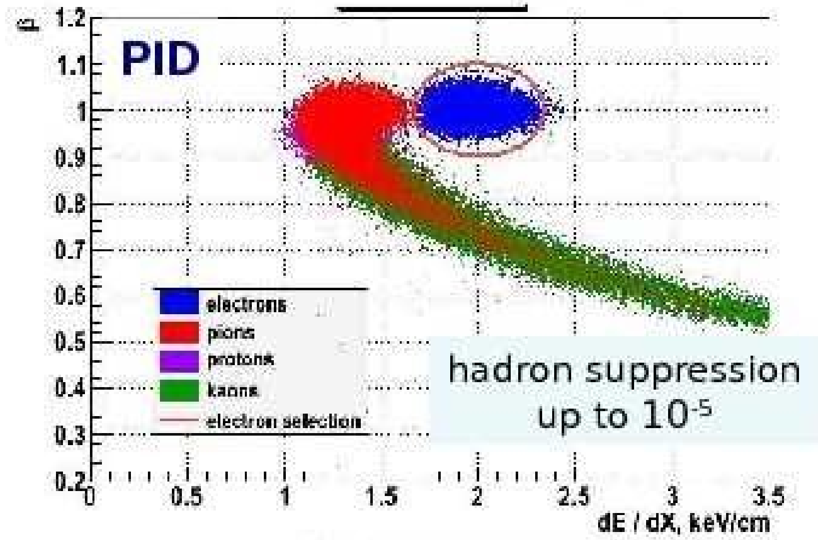
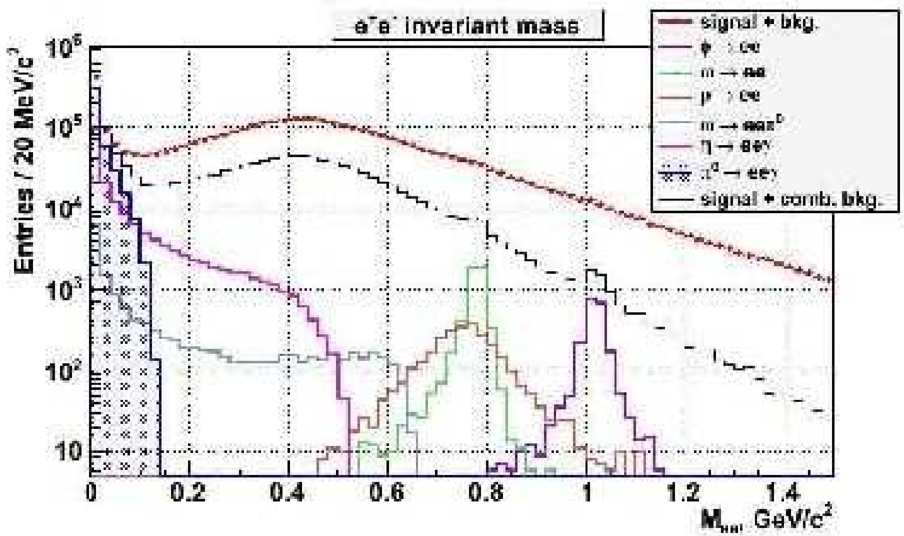
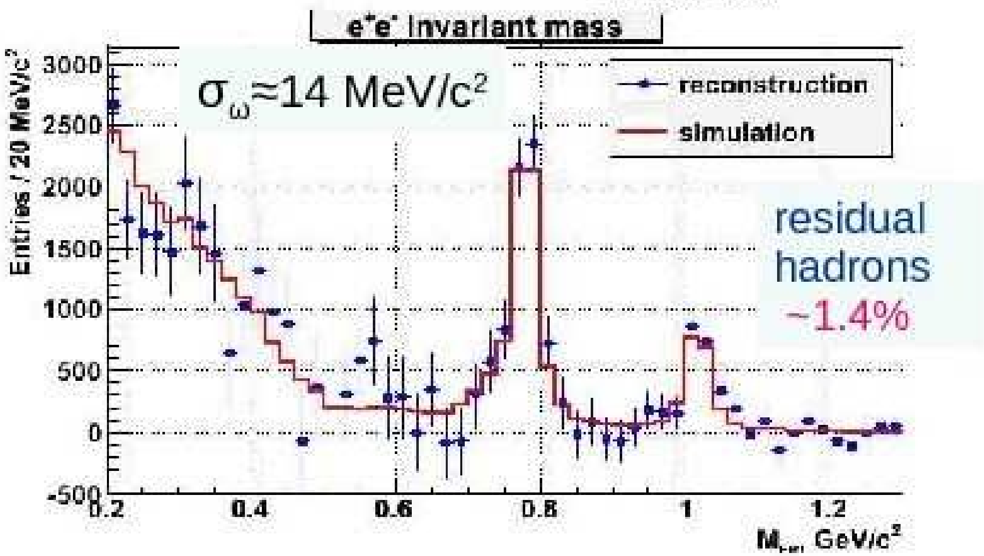
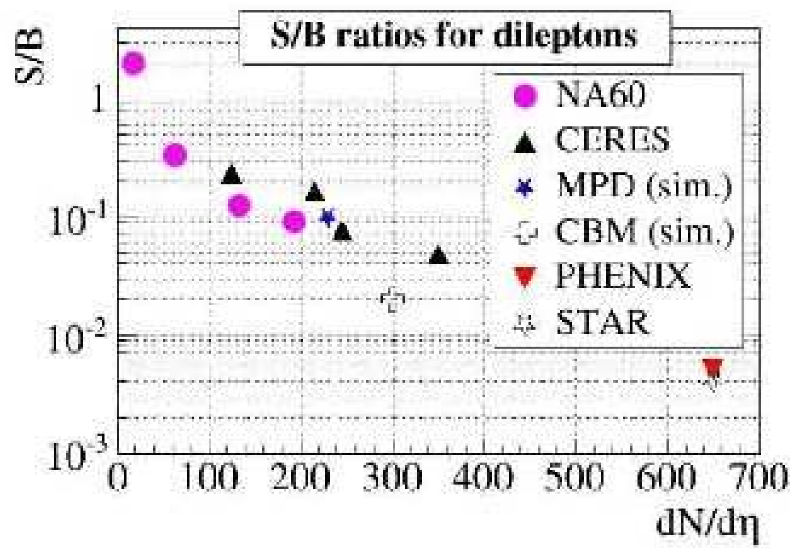








Flow performance

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

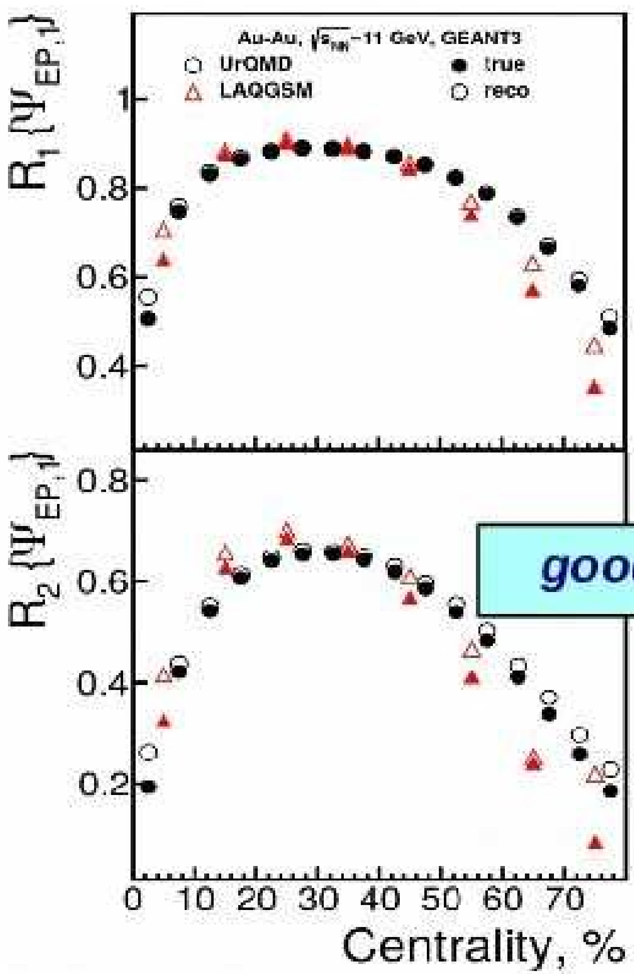
***$v_n = \{\cos[n(\phi - \Psi_{EP,1})]\} / R_n(\Psi_{EP,1})$** - azimuthal flow coefficients*

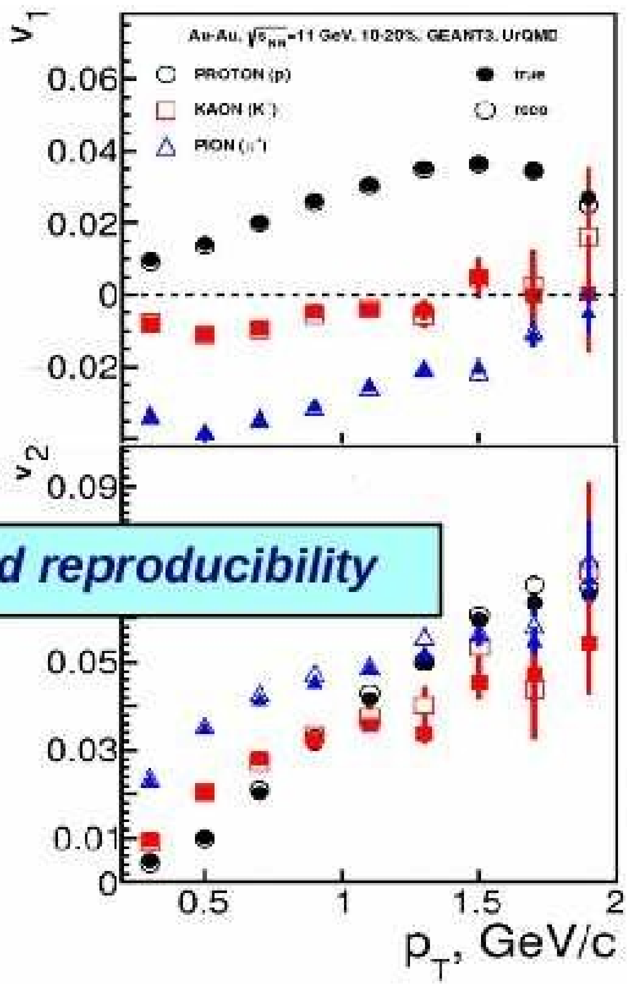
event plane resolution

flow harmonics (v_1 / v_2)

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

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





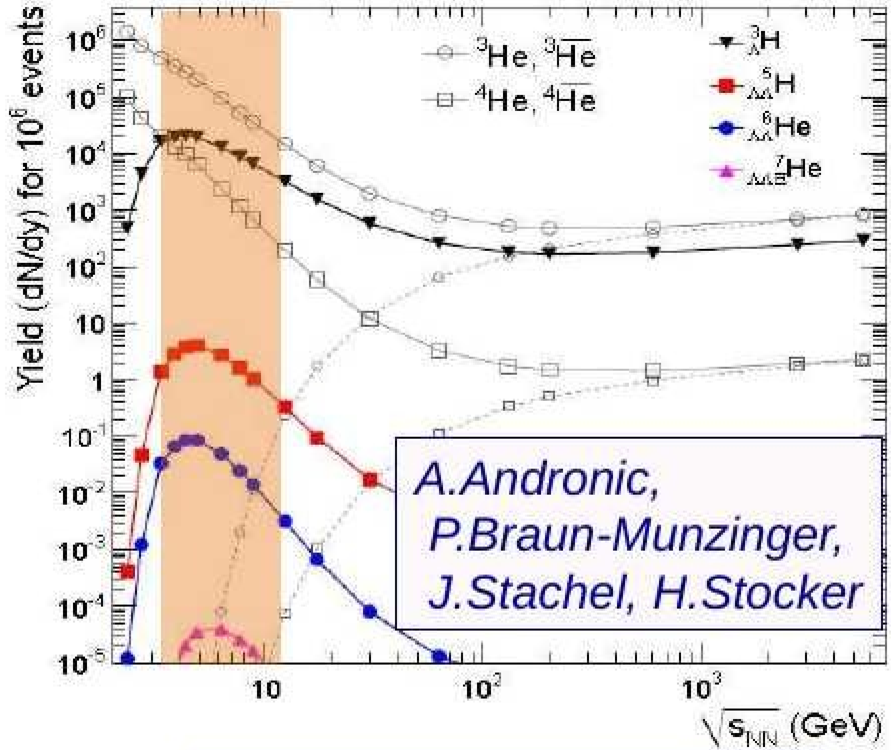
good reproducibility

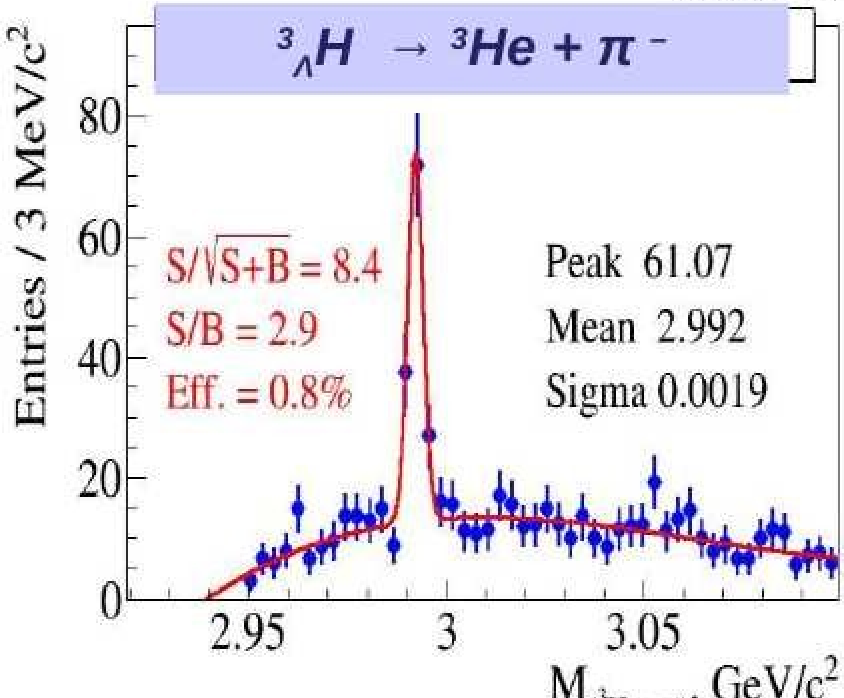
event plane: **FHCal**
centrality: **TPC**
PID: **TOF+TPC**

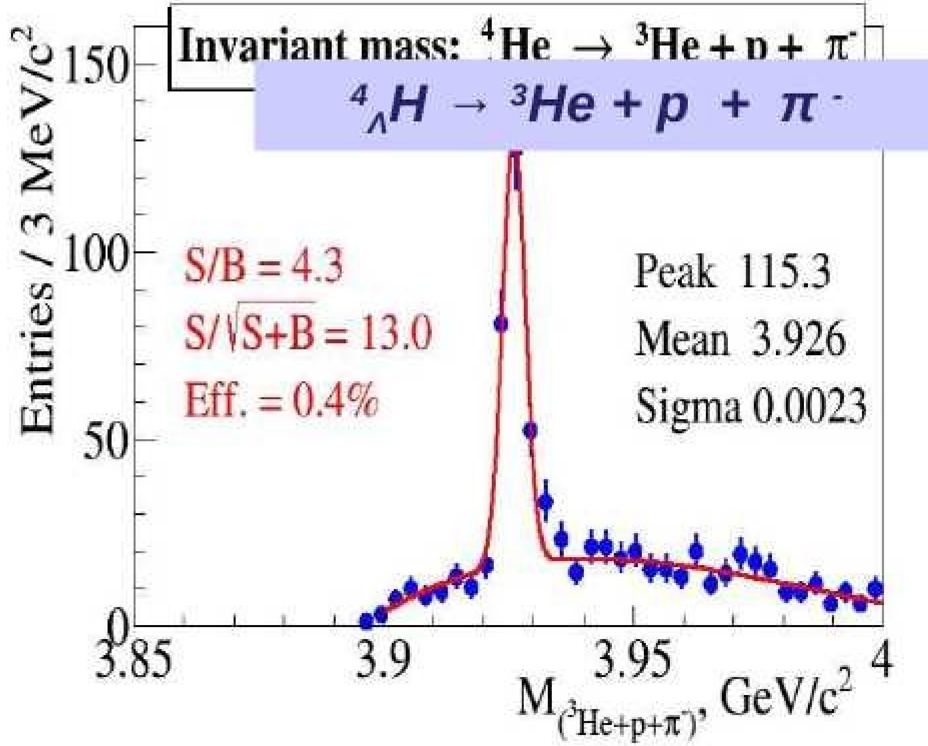
Hyper nuclei

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

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





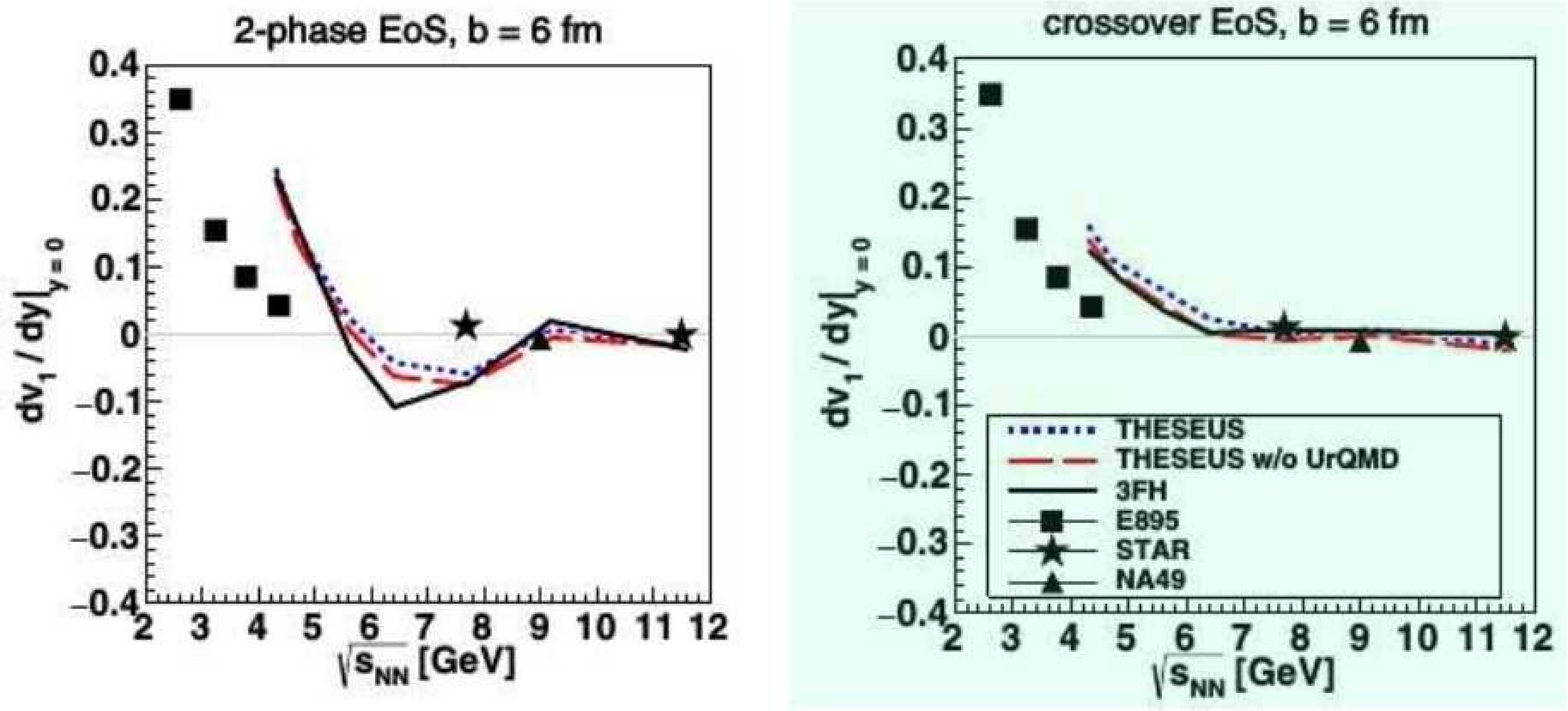


Directed flow slope

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

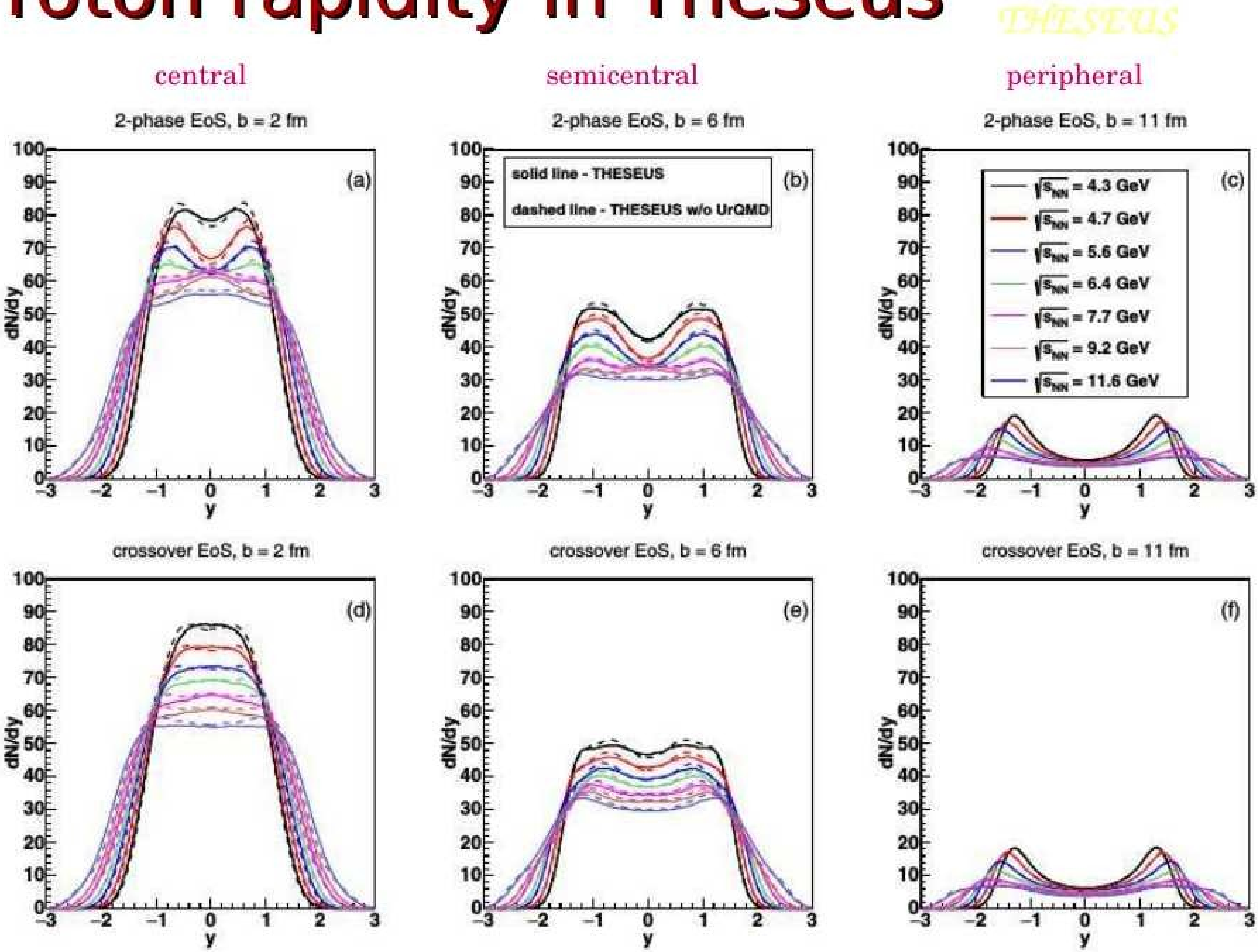
THESEUS

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



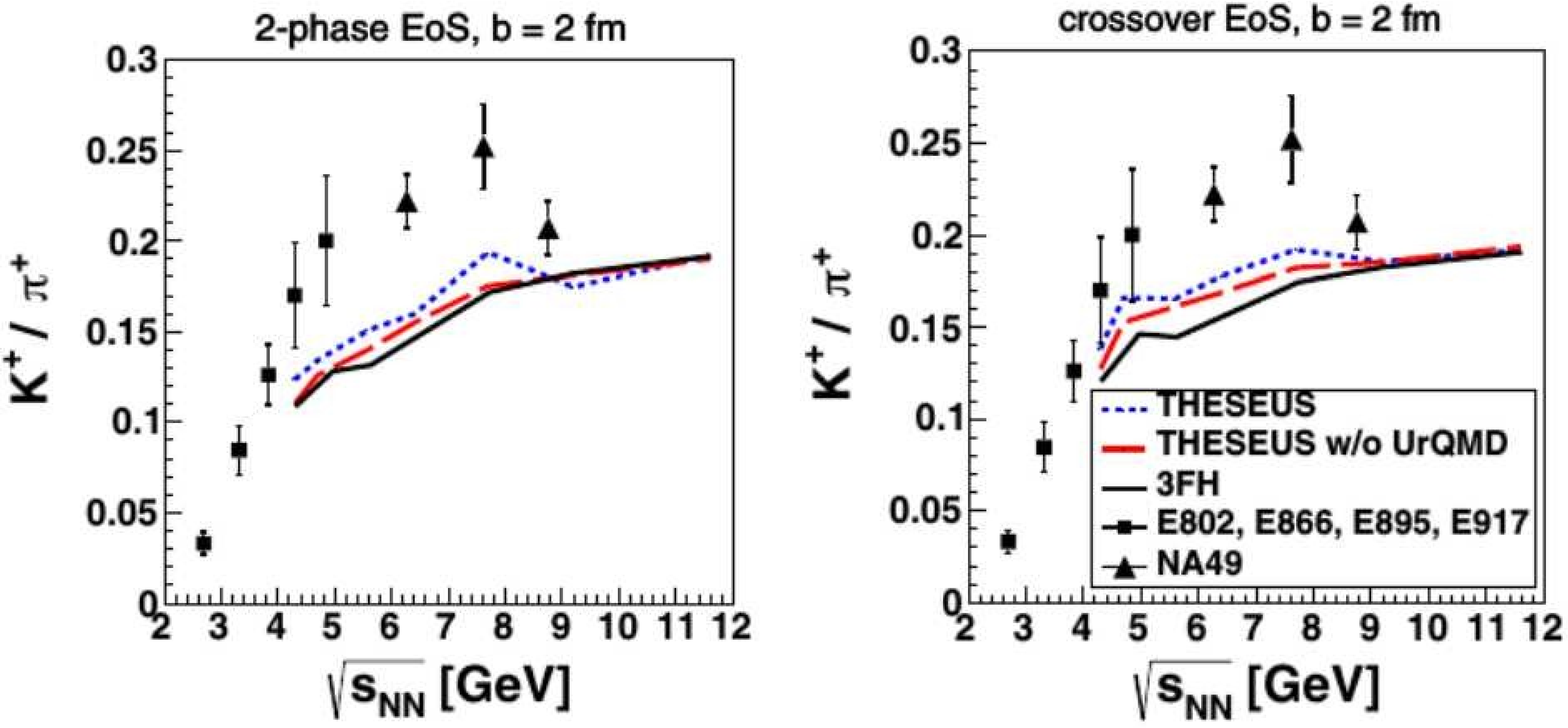
Energy scan of the slope of the directed flow (dv_1/dy) of protons for semicentral (b = 6 fm) Au+Au collisions

Proton rapidity in Theseus



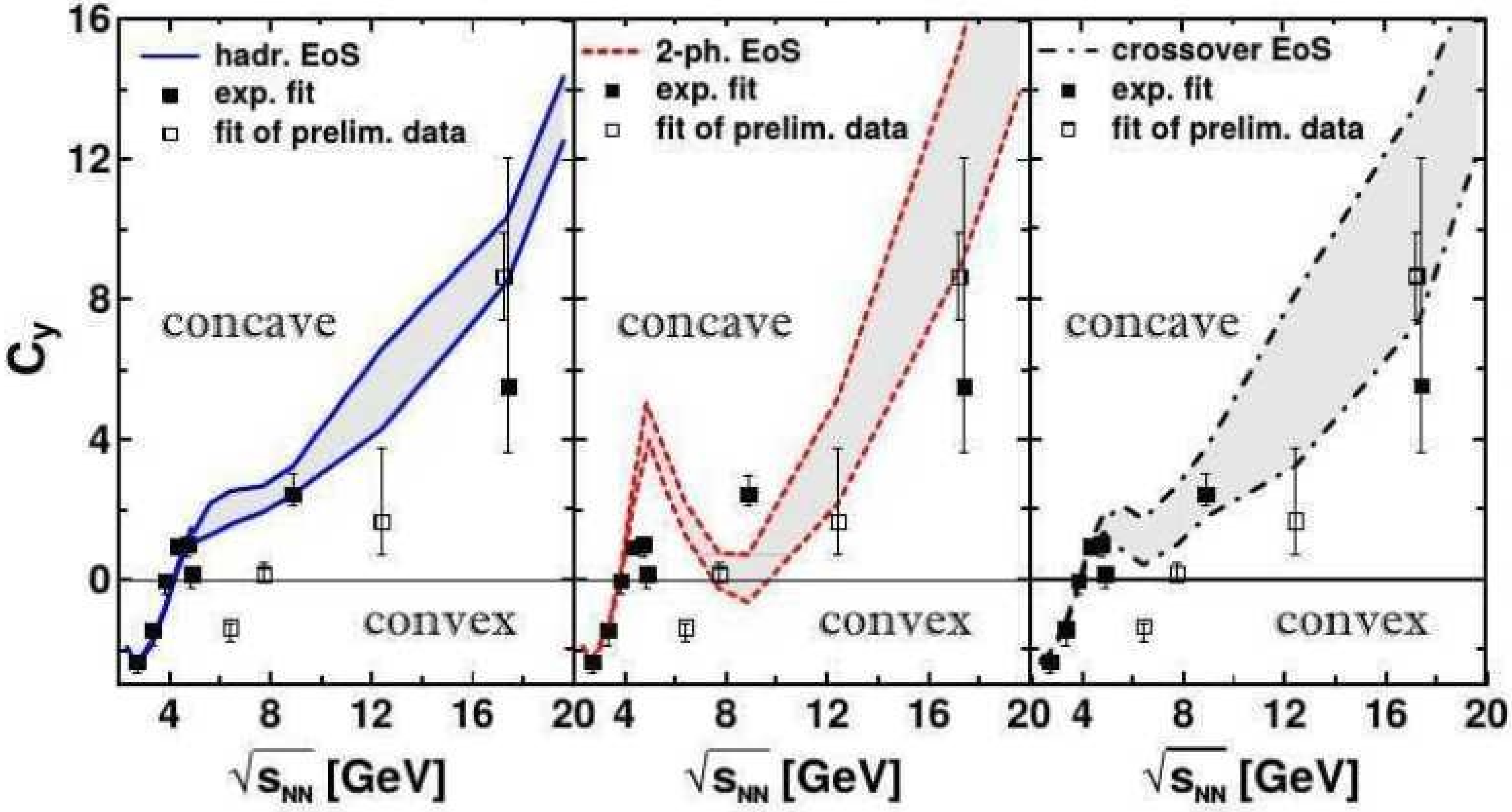
K^+/π^+ ratio

THESEUS



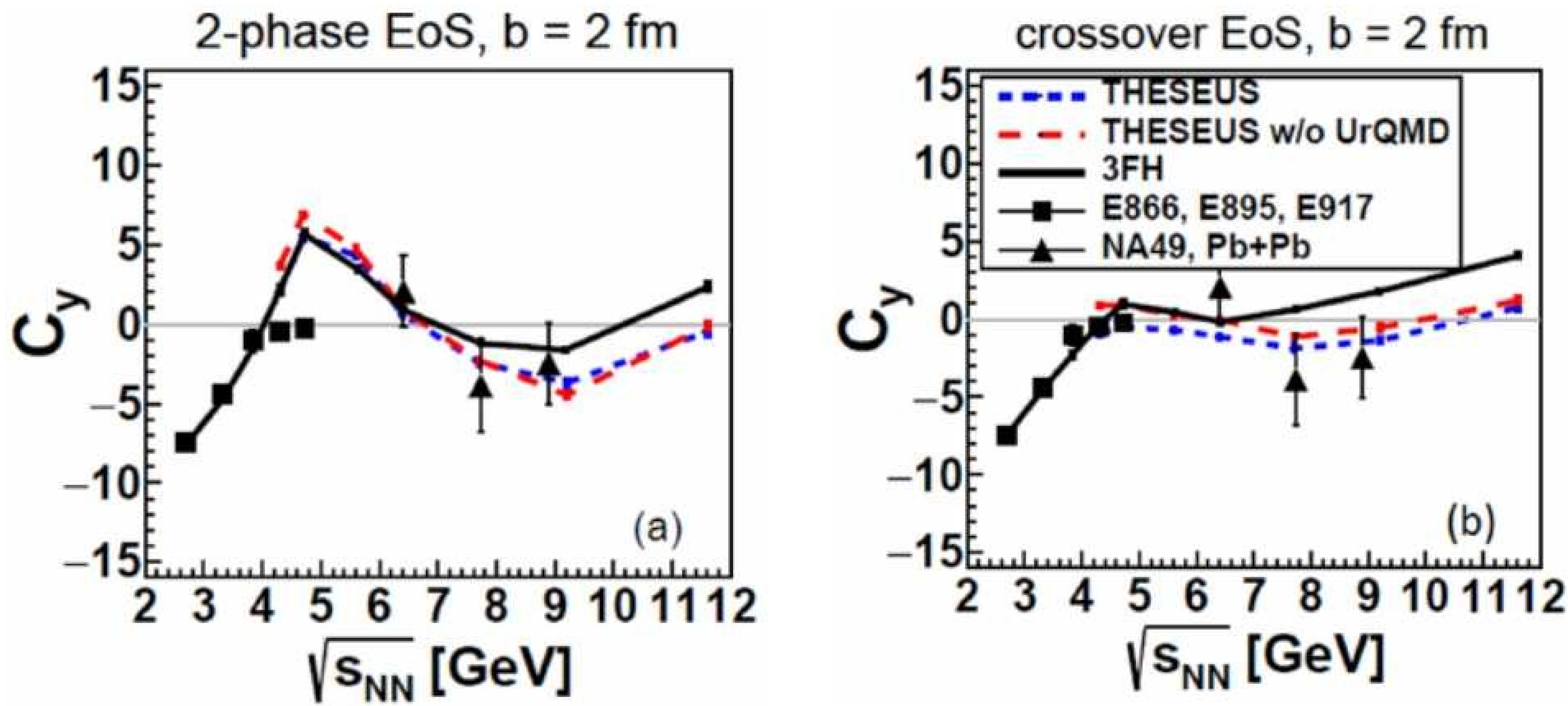
Net-proton mid rapidity Curvature

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



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

THESEUS

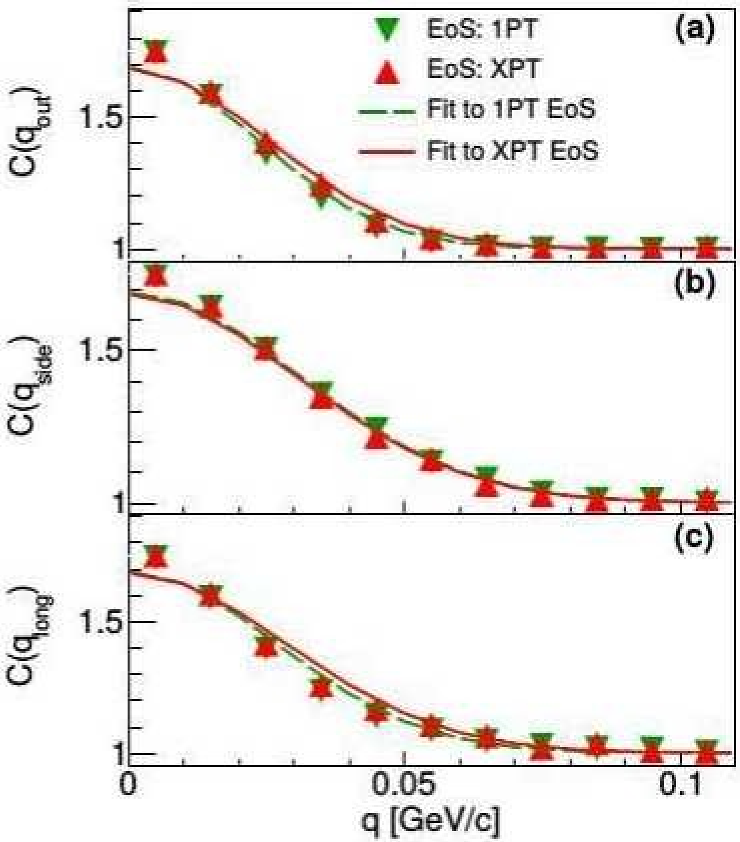


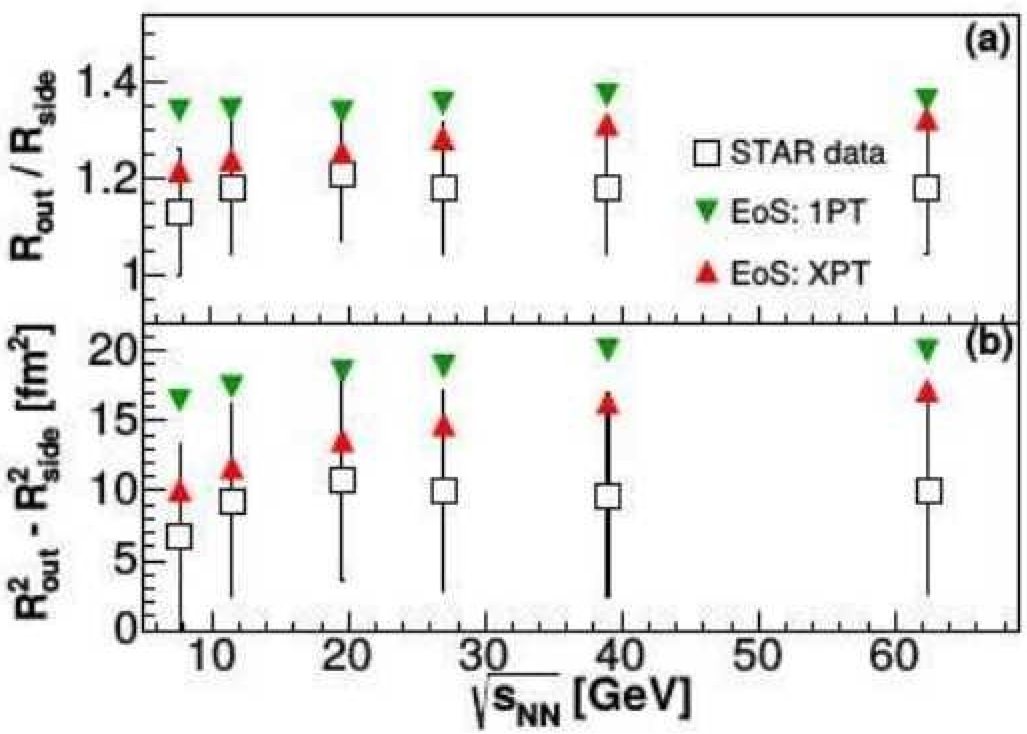
2-phase EoS, b = 2 fm
crossover EoS, b = 2 fm
THESEUS
THESEUS w/o UrQMD
3FH
E866, E895, E917
NA49, Pb+Pb
C_y
$\sqrt{s_{NN}}$ [GeV]
(a)
(b)

Femtoscopy @ NICA

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

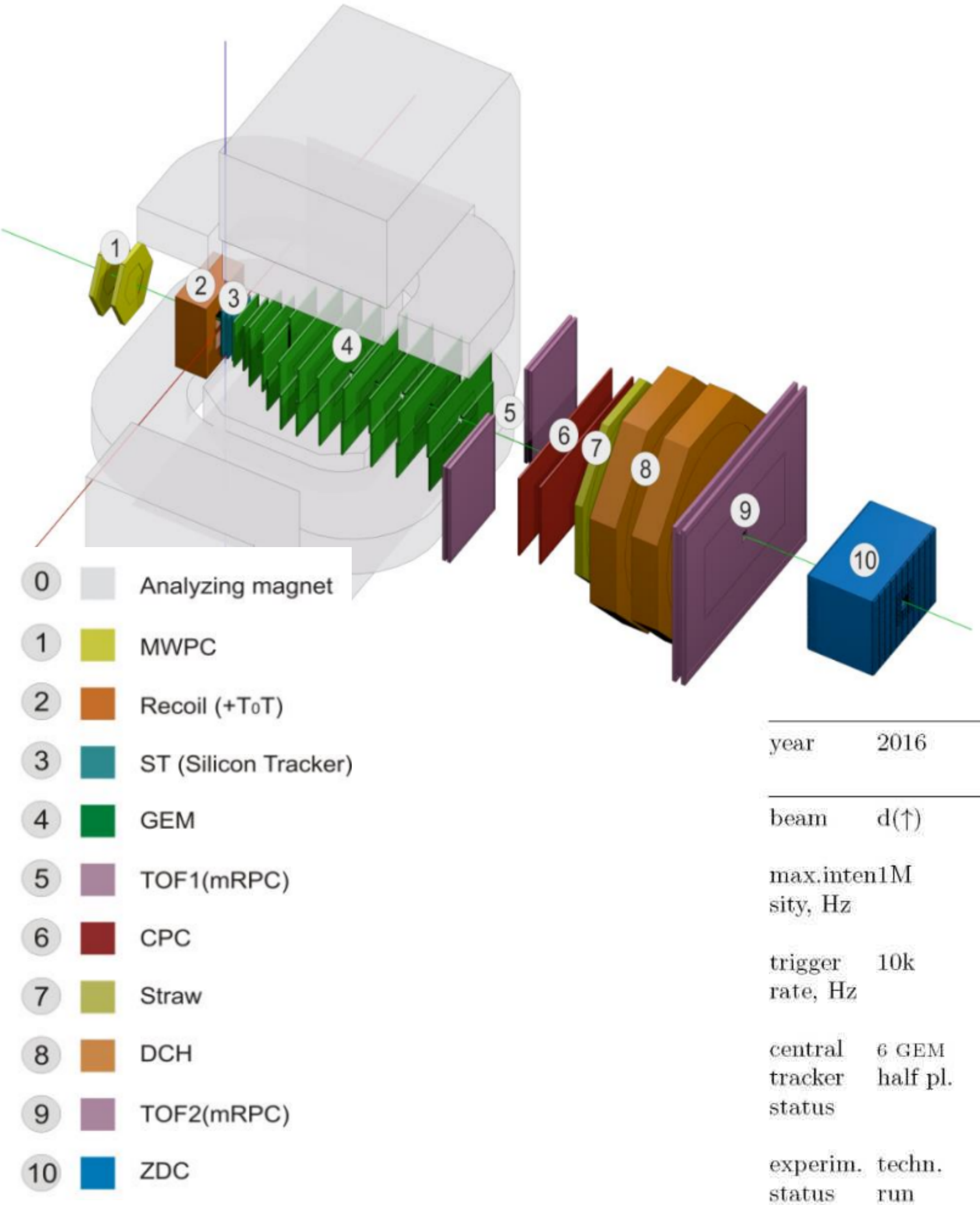
$$C(\mathbf{q}) = N\left(1 + \lambda \exp(-R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 - R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 - R_{\mathrm{long}}^2 q_{\mathrm{long}}^2)\right)$$



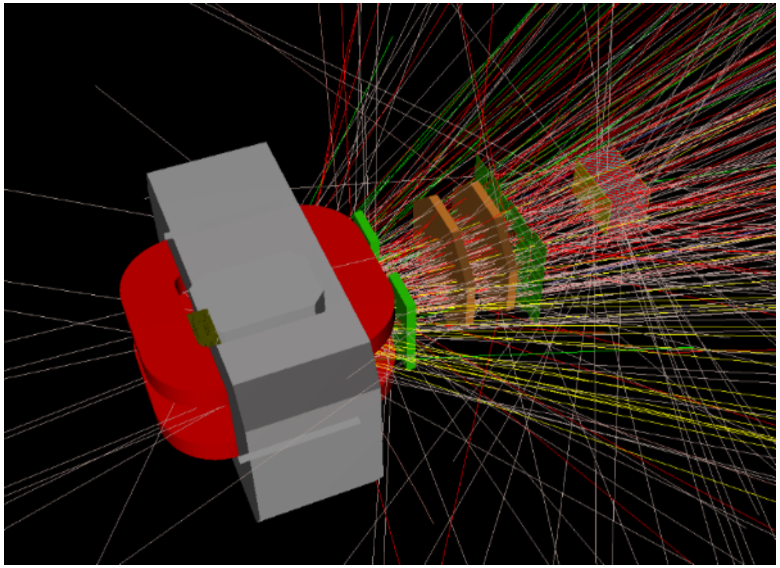


STAR data ($0.15 < k_T < 0.25$ GeV/c, 0-5% centrality)

BM@N experiment at NICA

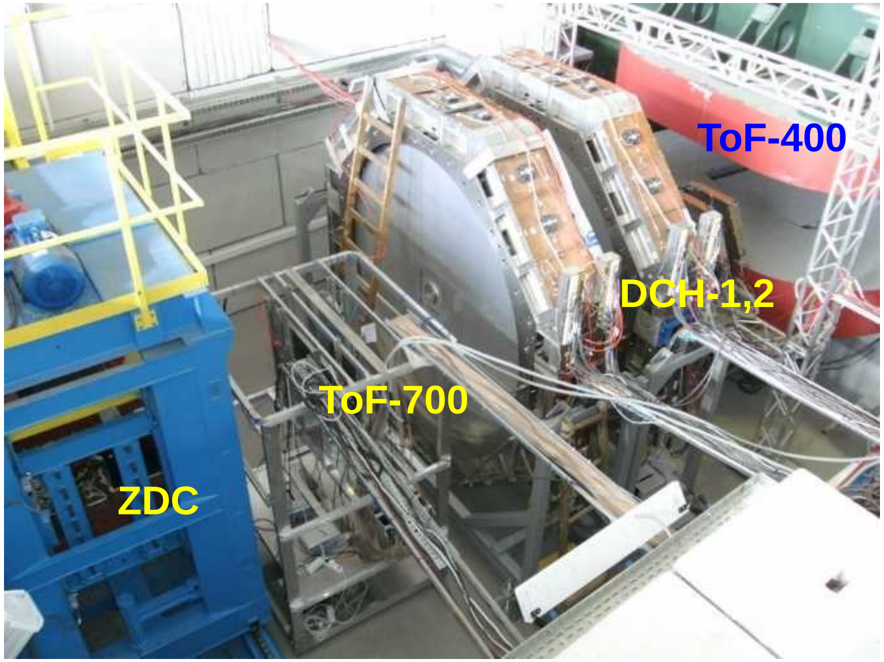


AuAu E_{beam} = 4 GeV

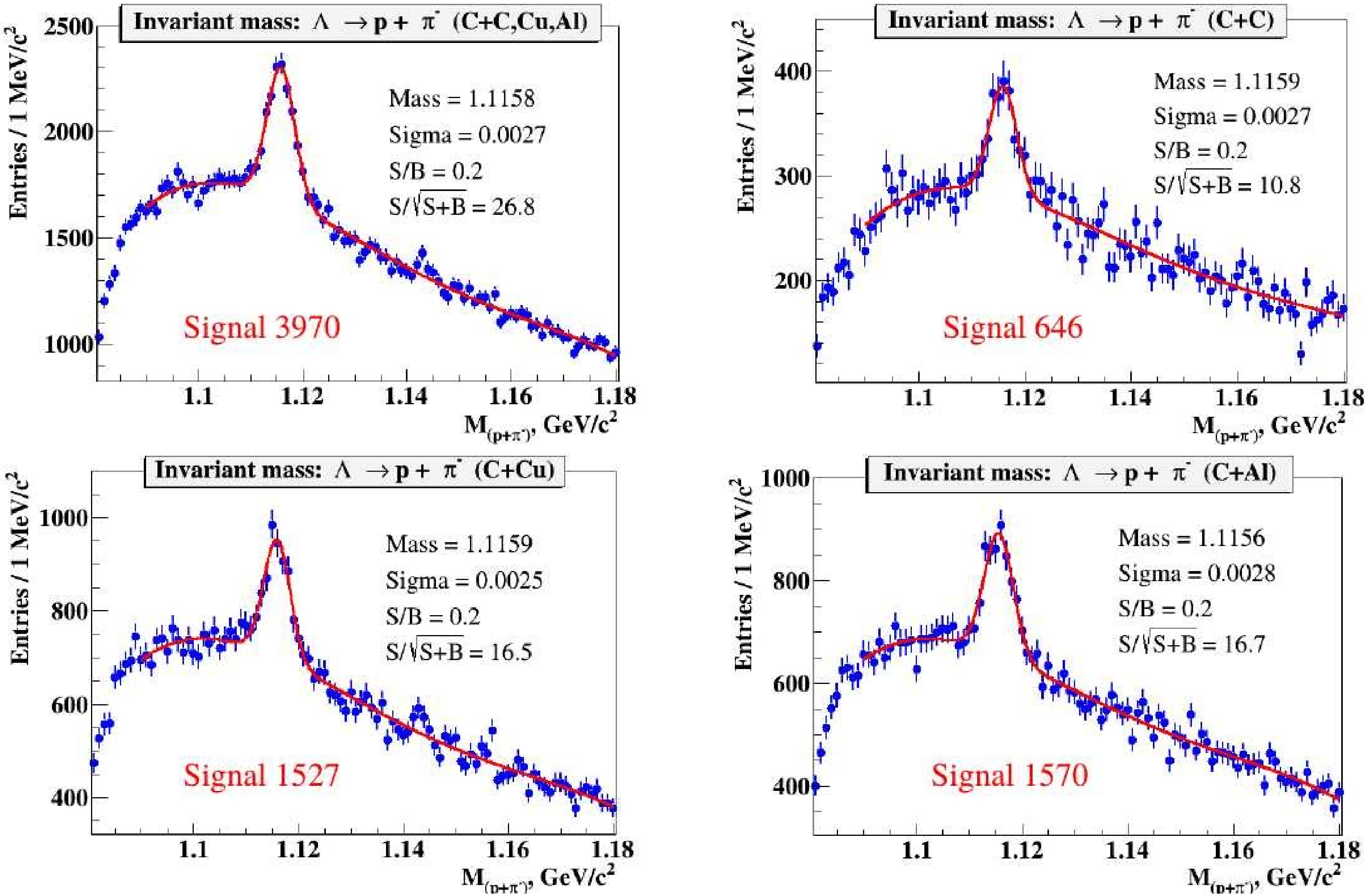


year	2016	2017 spring	2017 autumn	2019	2020 and later
beam	d(↑)	C, Ar	Kr	Au	Au, p
max.intensity, Hz	1M	1M	1M	1M	10M
trigger rate, Hz	10k	10k	20k	20k	50k
central tracker status	6 GEM half pl.	8 GEM half pl.	10 GEM half pl.	8 GEM full pl.	12 GEMs or 8 GEMs + Si planes
experim. status	techn. run	techn.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

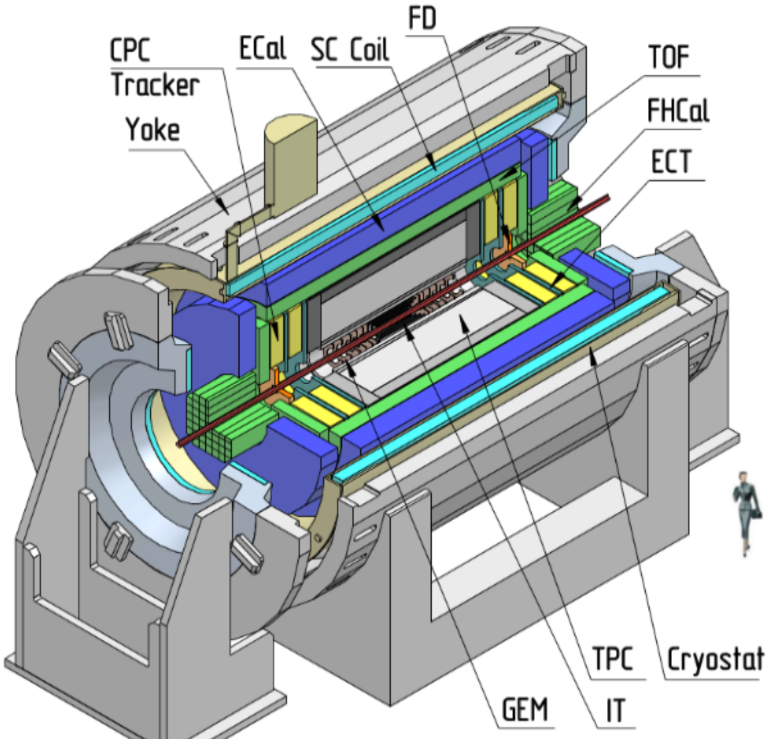
BM@N experiment at NICA

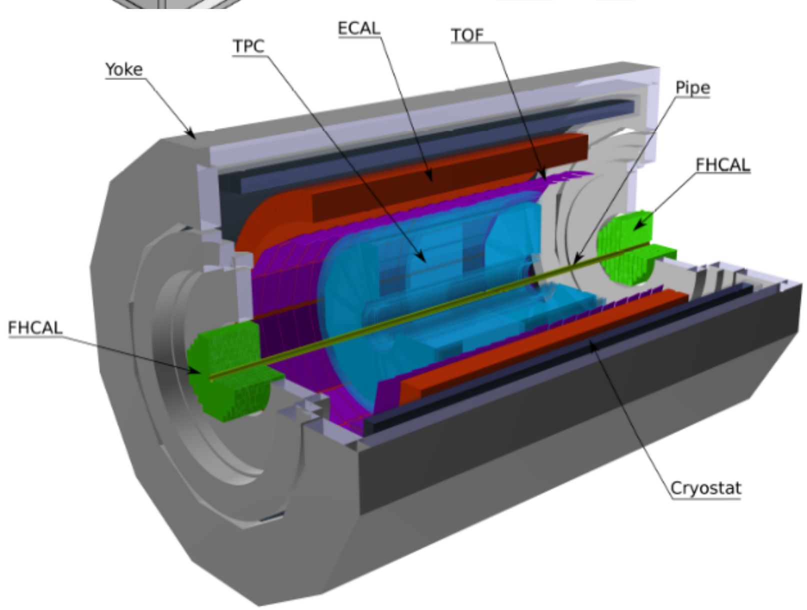


BM@N Λ^0 reconstruction (E_{kin}^{beam} = 4.0 AGeV)

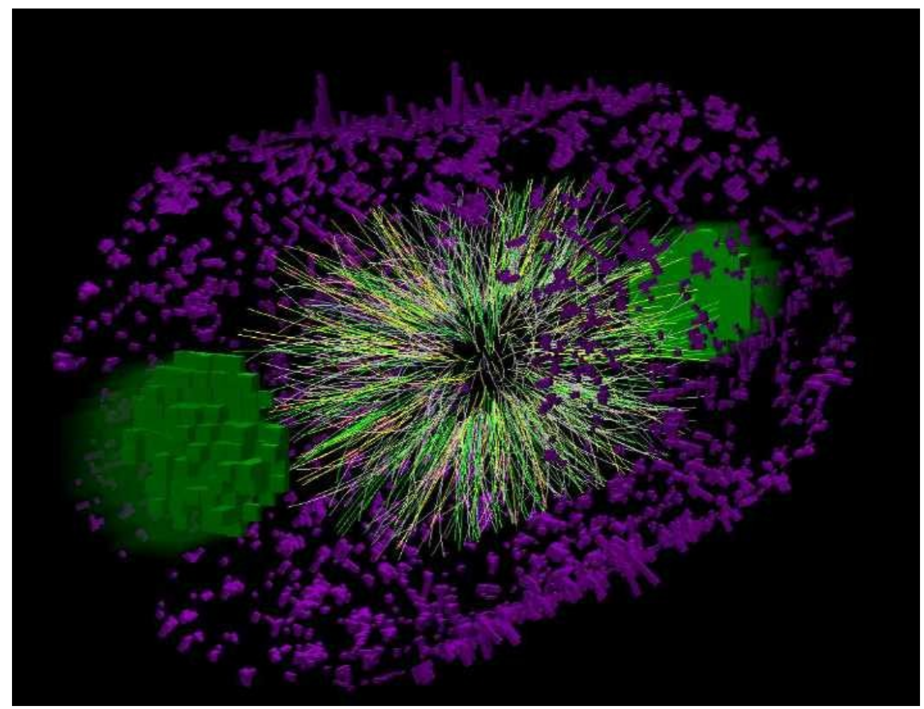


MPD experiment at NICA

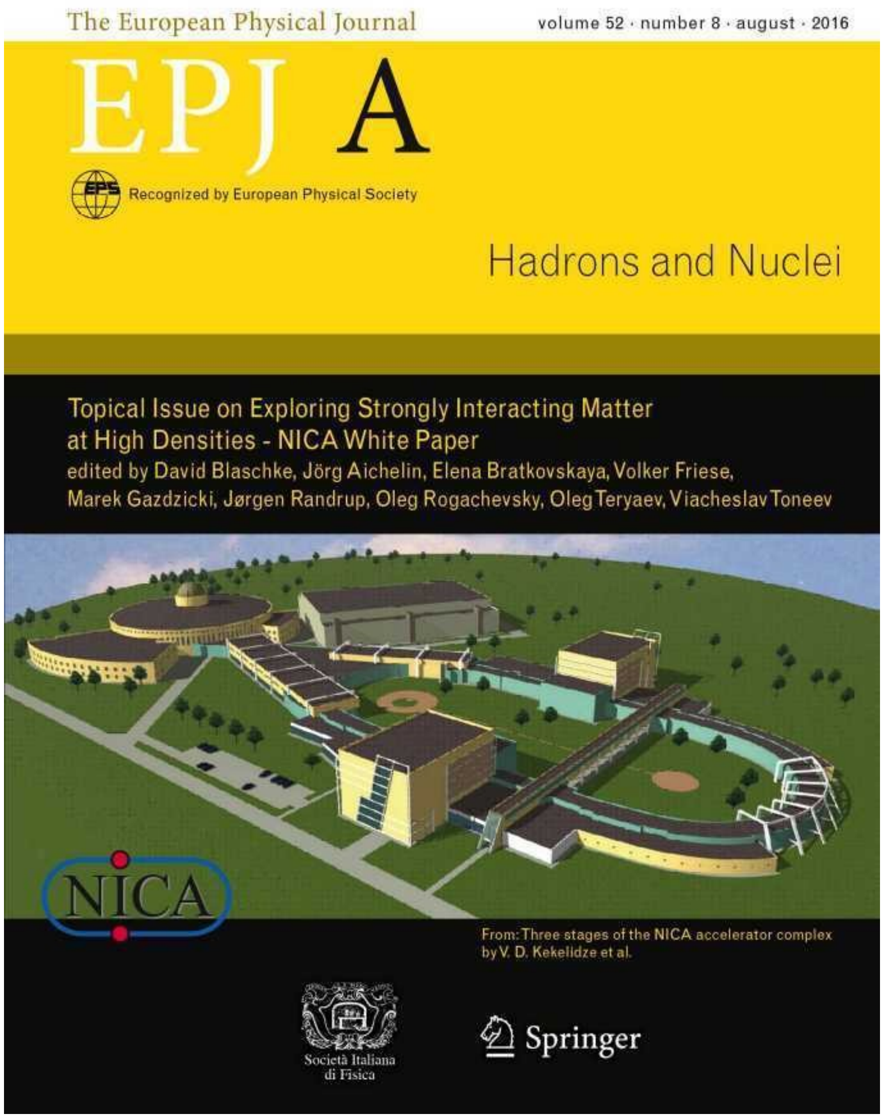




MPD event display
AuAu $\sqrt{s}$ = *11 GeV*



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 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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PHYSICS STUDIES AT THE NUCLOTORON ENERGIES	1041
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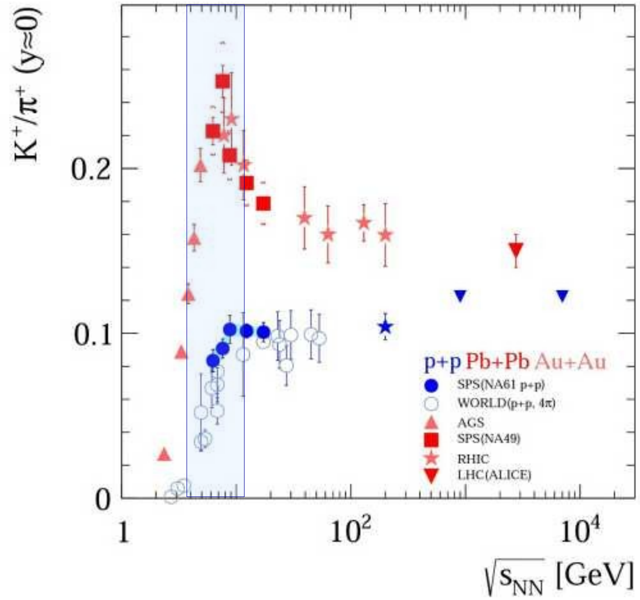
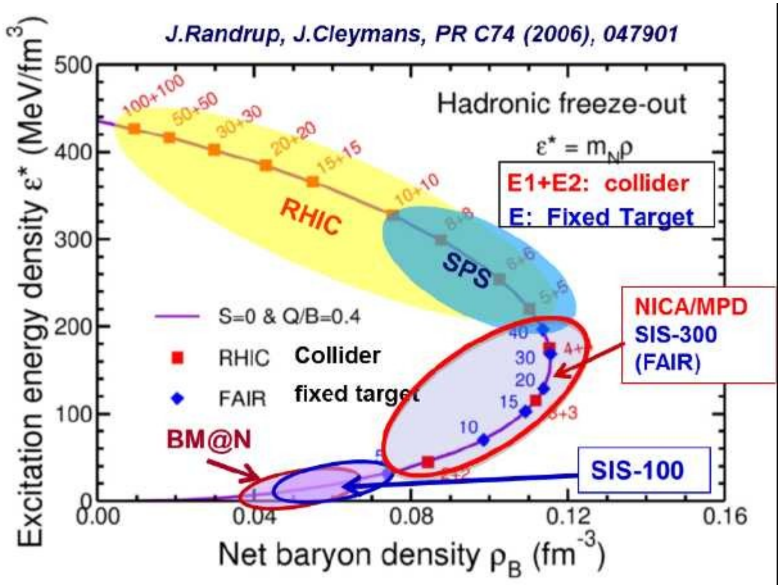
NICA advantagies

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.





Thank you for attention

Welcome
to NICA physics