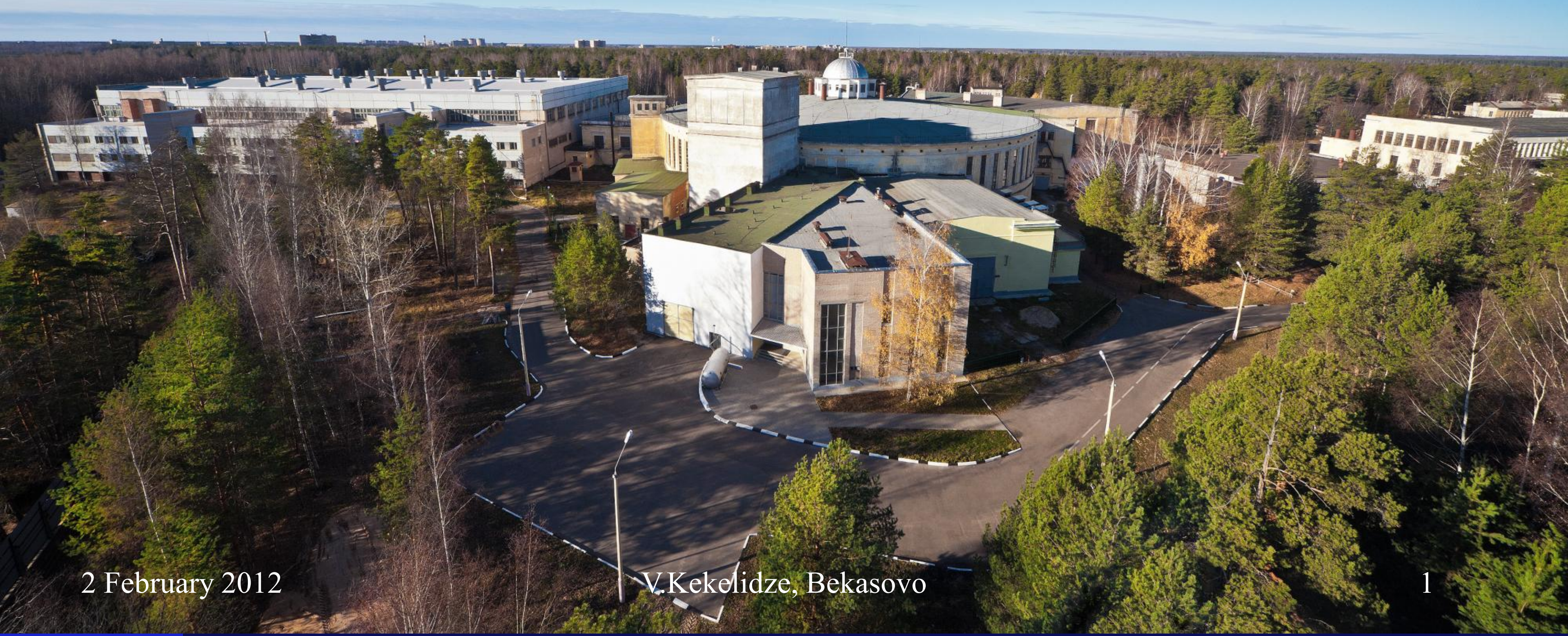
Experiments with Relativistic Heavy Ions at JINR: MultiPurpose Detector (MPD) & Baryonic Matter at Nuclotron (BM@N)

"Second Joint Helmholtz – Rosatom School devoted to Fair Accelerators and Scientific Program" & ITEP Winter School of Physics "Extreme State of Matter"

V. Kekelidze, JINR, Dubna



Research in Relativistic Heavy Ions

is one of intensively developing fields in the last few decades

many discoveries have been made,
interesting processes have been observed
and precisely measured in the series of experiments
at RHIC (BNL), SPS (CERN) and GSI (SIS18)

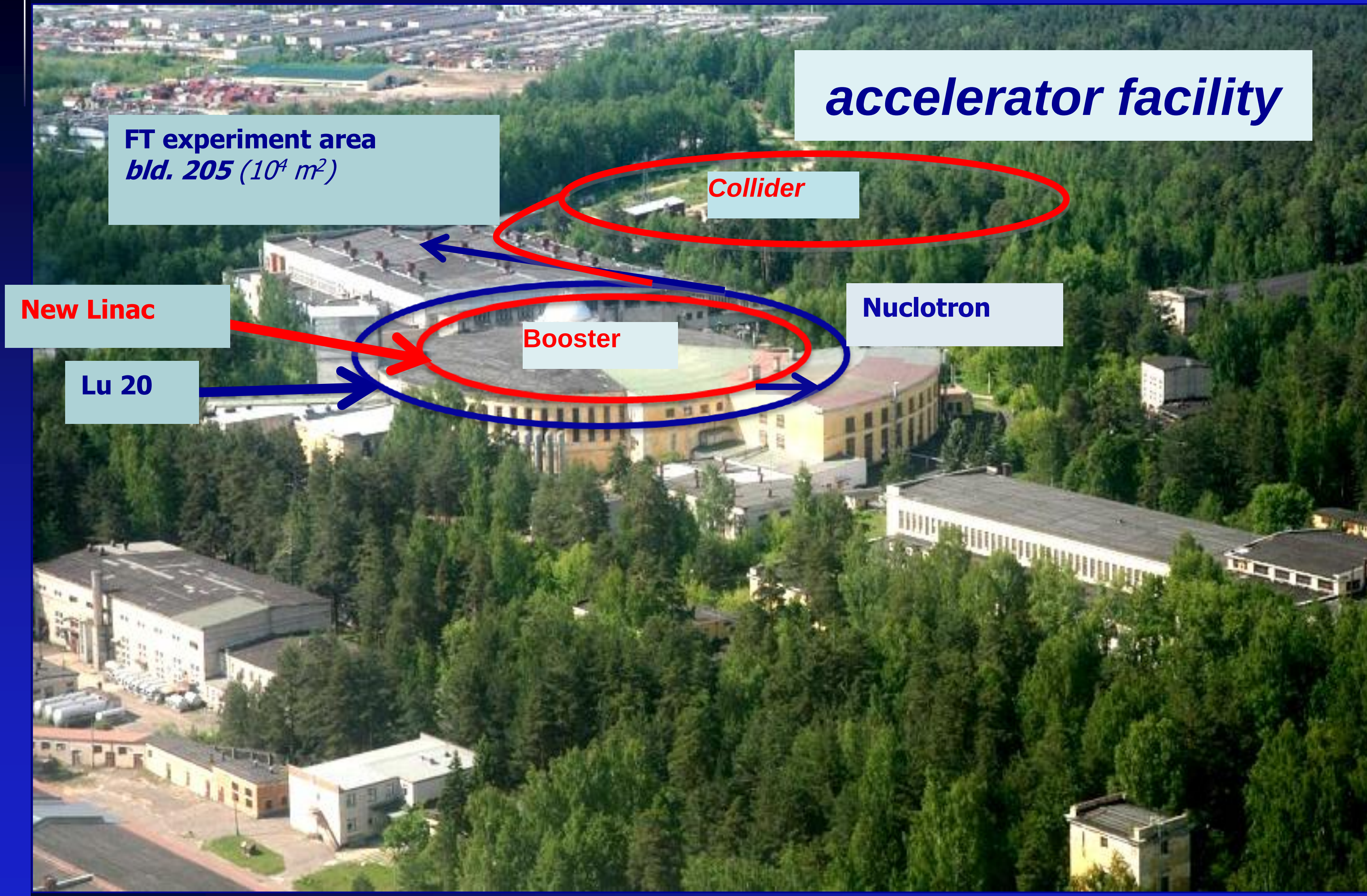
The researches are carried out at LHC,
in preparation at SIS100 (FAIR)

However the most interesting phenomena *as*
the mixed phase, critical endpoint, max. of baryonic density etc.
are not observed yet

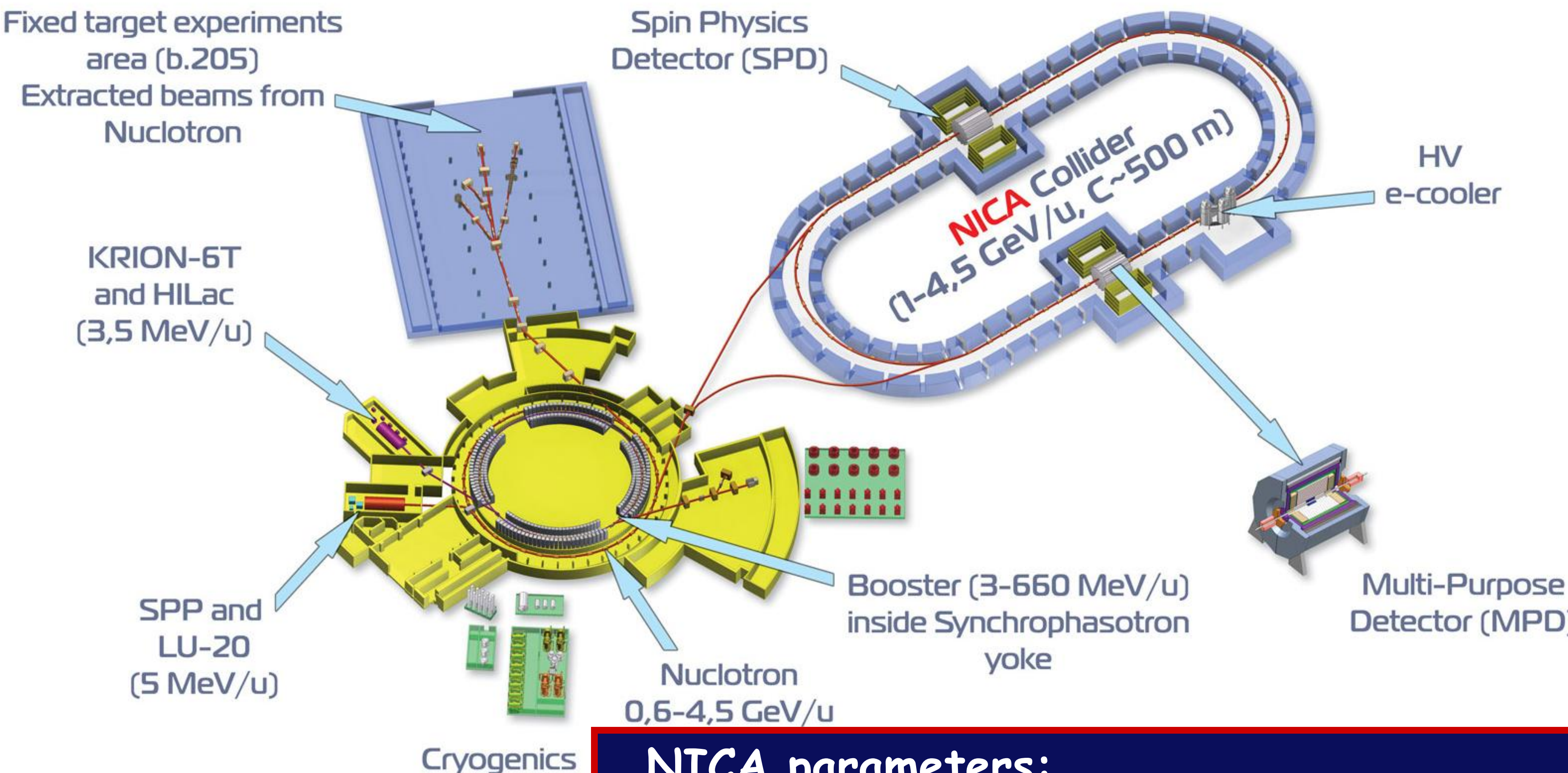
in this view the energy scan in wide region
- is the high priority task

this report presents such a possibility at ***LHEP JINR***

Veksler & Baldin Laboratory of HEP, JINR



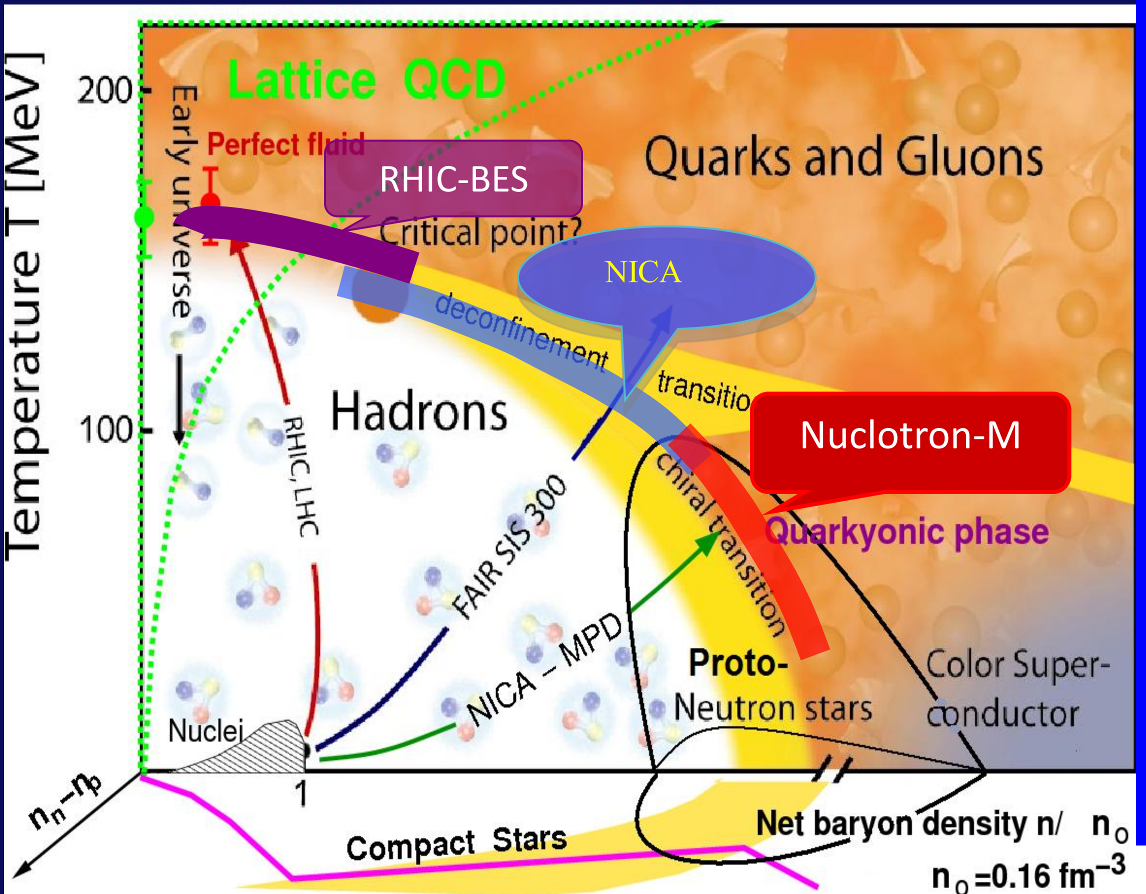
Superconducting accelerator complex NICA
(Nuclotron based Ion Collider fAcility)



NICA parameters:

- Energy range: $\sqrt{s_{NN}}$ = 4-11 GeV
- Beams: from p to Au
- Luminosity: L~10^{27} (Au), 10^{32} (p)
- Detectors: MPD (ions), SPD (spin physics)

QCD phase diagram. Prospects for NICA

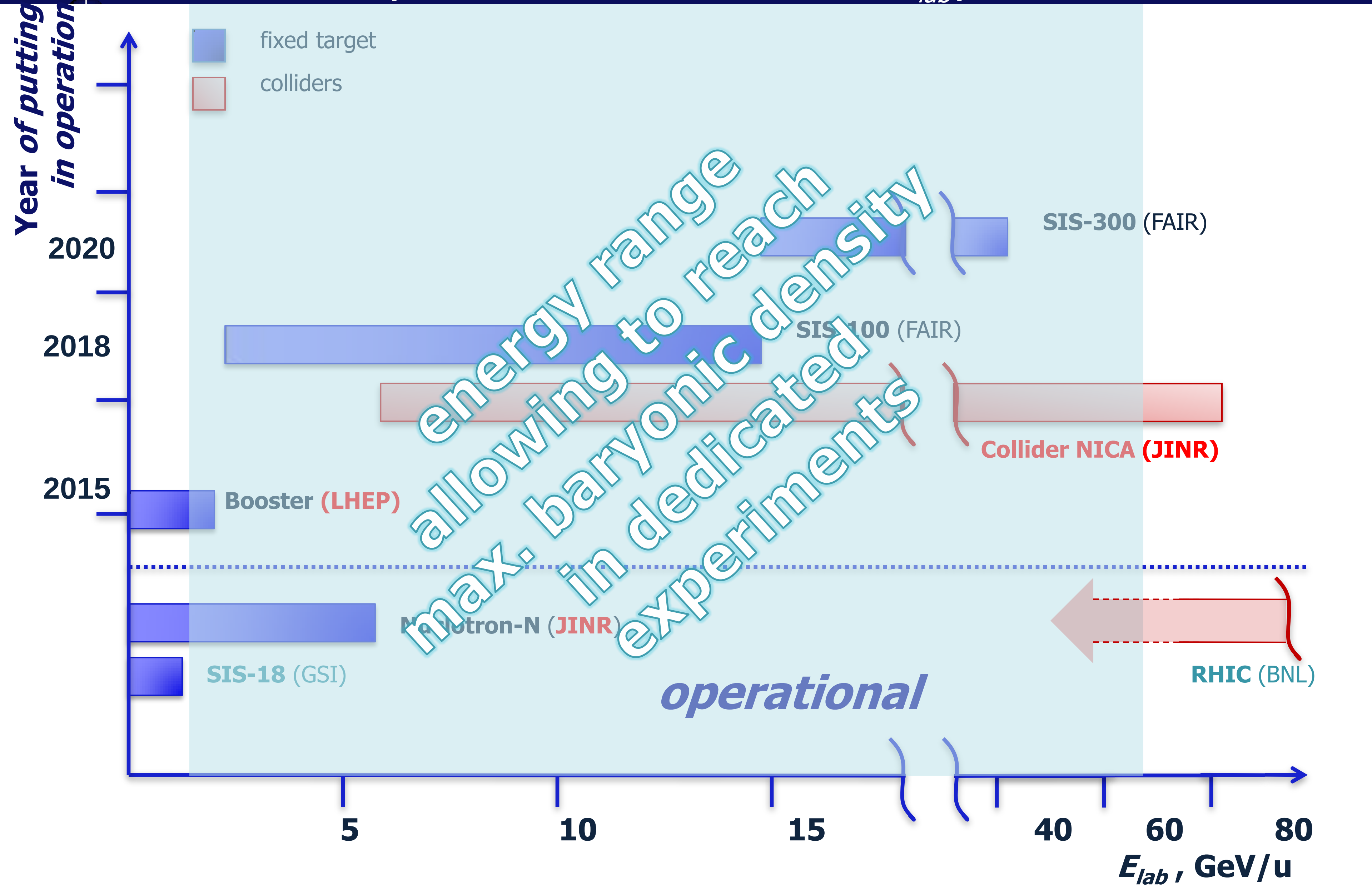


Energy Range of NICA
unexplored region of
the QCD phase diagram:

- Highest net baryon density
- Onset of deconfinement phase transition
- Strong discovery potential:
  a) Critical End Point (CEP)
  b) Chiral Symmetry Restoration
- Complementary to the RHIC/BES, FAIR & CERN experimental programs

NICA facilities provide capabilities for studying a variety of phenomena in a large region of the phase diagram

Energy regions covered by the LHEP and GSI facilities
(for Z/A=1/2, recalculated for E_{lab})



Baryonic Matter at Nuclotron (**BM@N**)

Nuclotron-M/NICA

- **JINR HEP** basic facility (*in operation since* **'93)** *based on the unique technology of* ***super-conducting fast cycling magnets*** *developed in JINR*
- provides proton, **polarized** deuteron *& multi charged ion beams*

The goal:

- *acceleration of heavy ions -> $^{197}Au^{79+}$*
- *energy ~ 4.5 GeV/u*
- *beam intensity ~ 10^9 A/cycle*

Nuclotron development:

- **Nuclotron-M** *(vacuum, PS, orbit corr. +…)* *completed in* **2010**
- **Nuclotron-NICA** *(Krion-6T, SPI, RF, new Linac +…)* *to be fulfilled in* ***2015***

Beam	Nuclotron beam intensity (particle per cycle)		
	Current	Ion source type	New ion source + booster
p	$3{\cdot}10^{10}$	Duoplasmotron	$5{\cdot}10^{12}$
d	$3{\cdot}10^{10}$	--- „ ---	$5{\cdot}10^{12}$
^{4}He	$8{\cdot}10^{8}$	--- „ ---	$1{\cdot}10^{12}$
d↑	$2{\cdot}10^{8}$	SPI	$1{\cdot}10^{10}$
^{7}Li	$8{\cdot}10^{8}$	Laser	$5{\cdot}10^{11}$
^{11,10}B	$1{\cdot}10^{9,8}$	--- „ ---	
^{12}C	$1{\cdot}10^{9}$	--- „ ---	$2{\cdot}10^{11}$
^{24}Mg	$2{\cdot}10^{7}$	--- „ ---	
^{14}N	$1{\cdot}10^{7}$	ESIS (“Krion-6T”)	$5{\cdot}10^{10}$
^{24}Ar	$1{\cdot}10^{9}$	--- „ ---	$2{\cdot}10^{11}$
^{56}Fe	$2{\cdot}10^{6}$	--- „ ---	$5{\cdot}10^{10}$
^{84}Kr	$1{\cdot}10^{4}$	--- „ ---	$1{\cdot}10^{9}$
^{124}Xe	$1{\cdot}10^{4}$	--- „ ---	$1{\cdot}10^{9}$
^{197}Au	-	--- „ ---	$1{\cdot}10^{9}$

energy of beams extracted from Nuclotron

covers the gap between SIS-18 and AGS *(with some overlaps)*

	Z/A	***max*** $\sqrt{s_{NN}}$ *(GeV/n)*	***max.*** T_{kin} *(GeV/n)*
p	***1***	≈ ***5.2***	≈ ***12***
d	***1/2***	≈ ***3.8***	≈ ***5.7***
			(including polarized deuterons)
Au	***0.4***	≈ ***3.5***	≈ ***4.5***
			*(at **2T** in dipoles)*

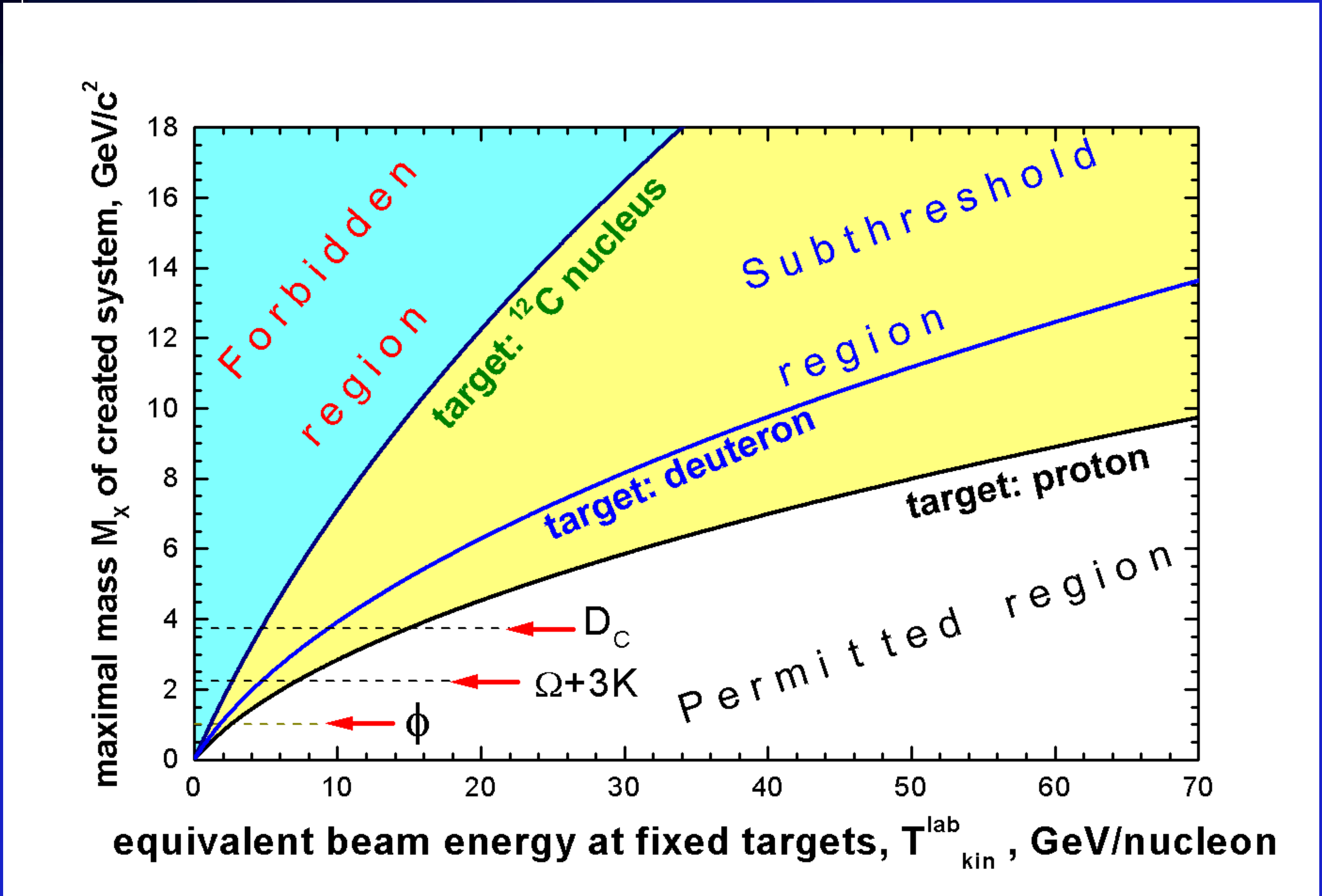
These allow:

- *study of dense baryonic matter at temperatures up to **100** MeV,*
- *(multi)-strangeness (open & hidden) production in dense baryonic matter,*
- *modification of particle properties in dense nuclear matter*

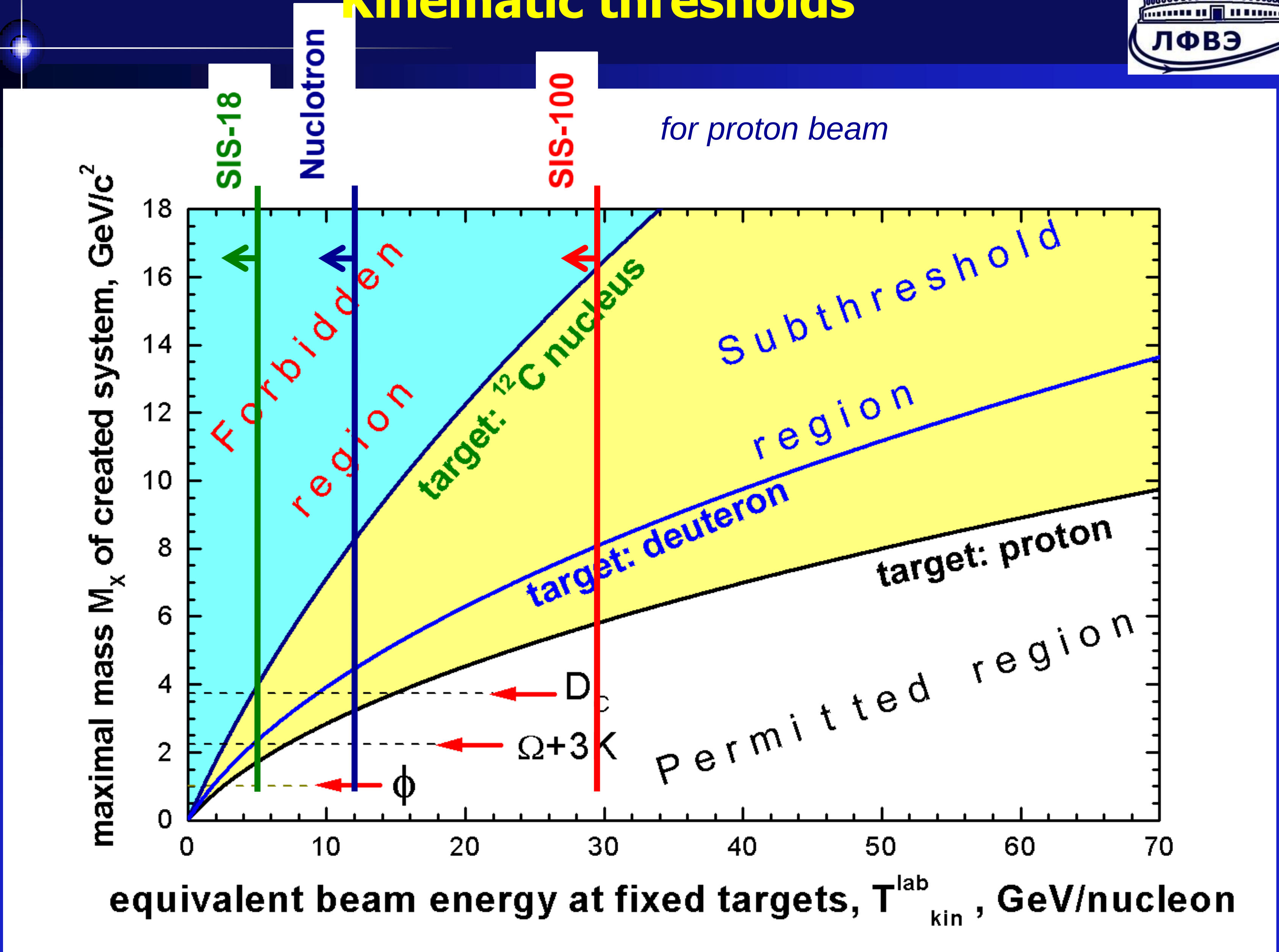
The corresponding multi-purpose setup

Baryonic Matter at Nuclotron (BM@N)

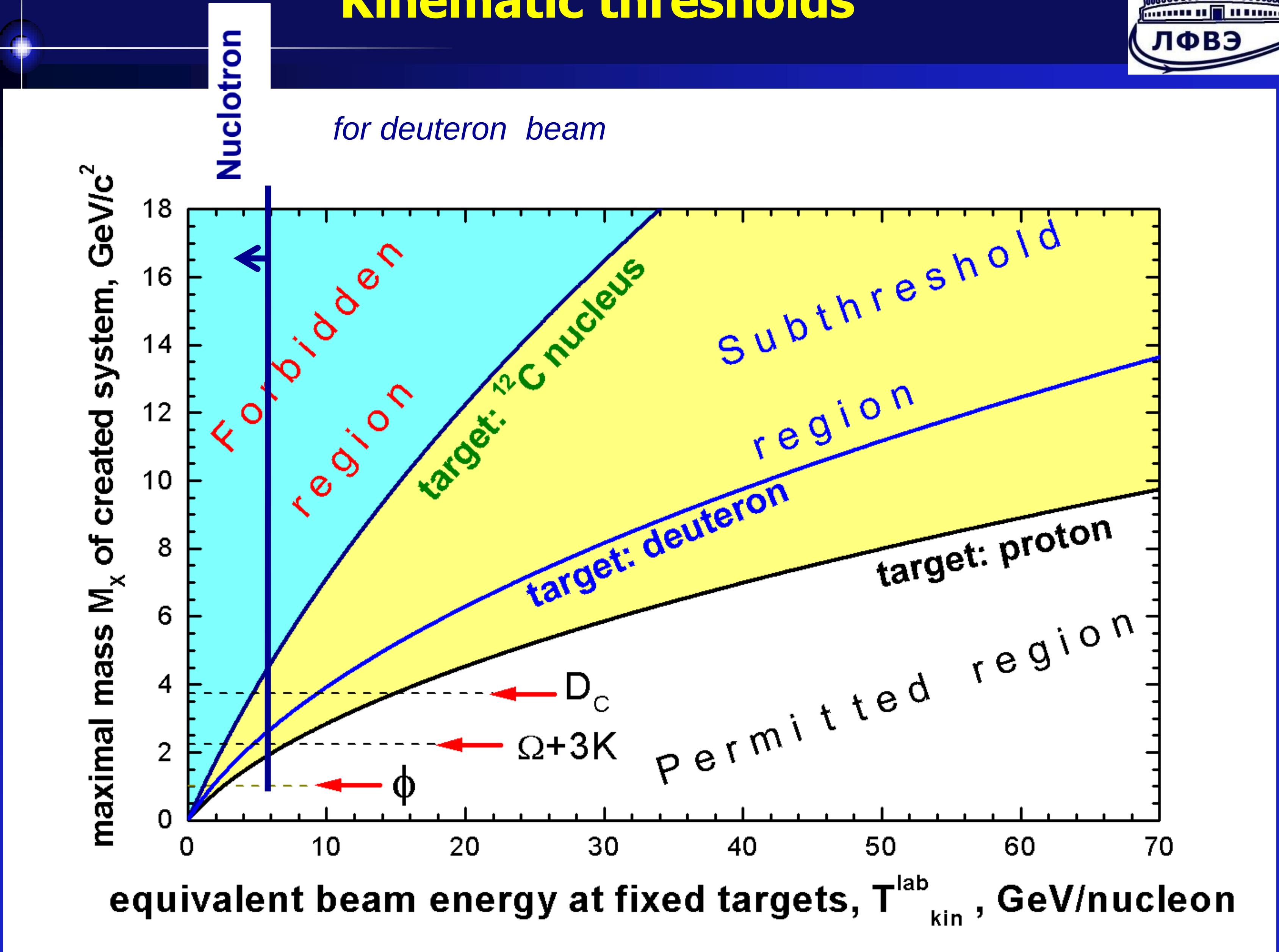
Kinematic thresholds



Kinematic thresholds



Kinematic thresholds



Yield of (multi-s) hypernuclei in A+A collisions

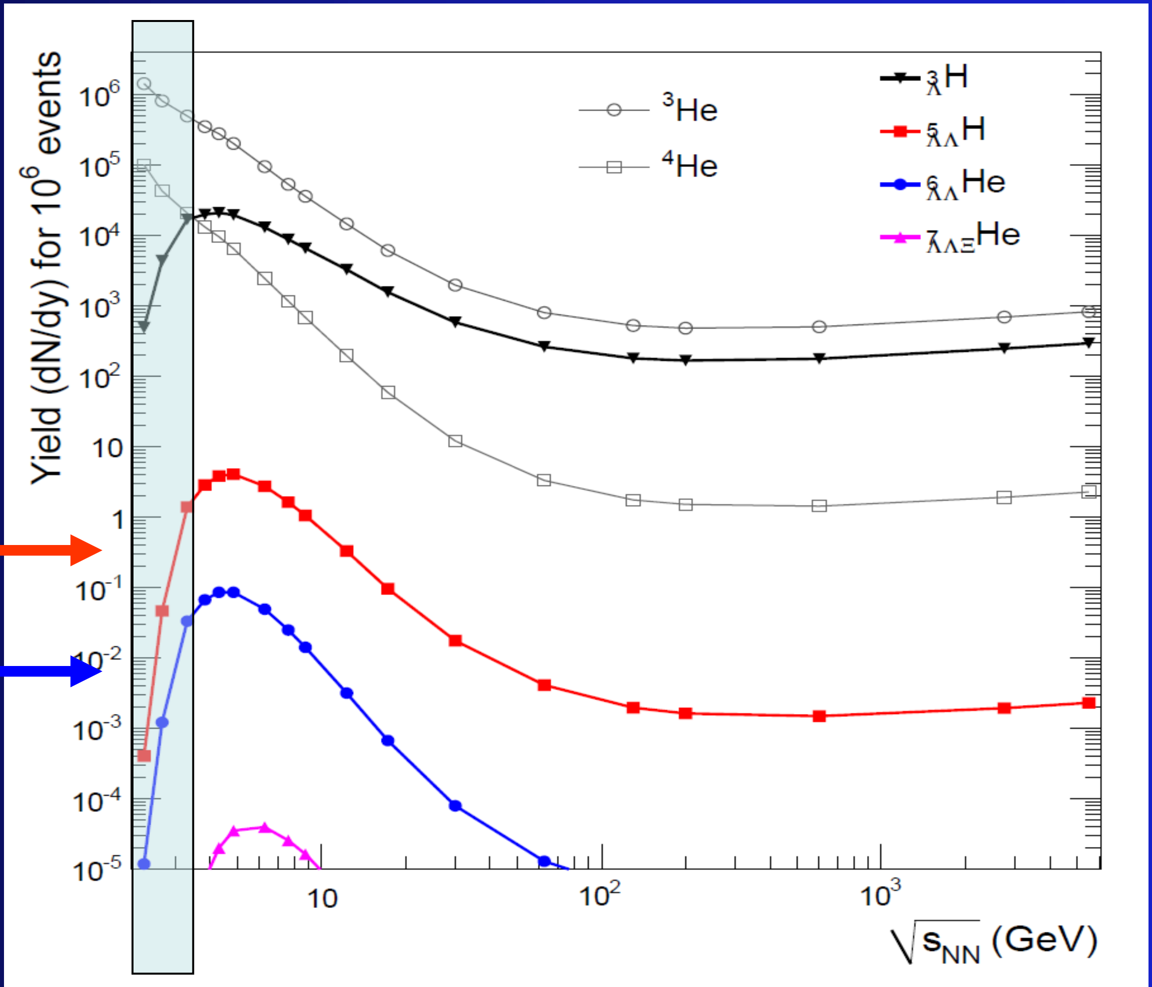
Thermal model:

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, arXiv:1010.2995v1 [nucl-th]

Nuclotron ($\sqrt{s_{NN}}$ = 3.3 GeV)

Yield of $_{\Lambda\Lambda}{}^{5}H \approx 10^{-6}$

Yield of $_{\Lambda\Lambda}{}^{6}He \approx 4 \cdot 10^{-8}$



Study of dense baryonic matter at < 6 GeV/n

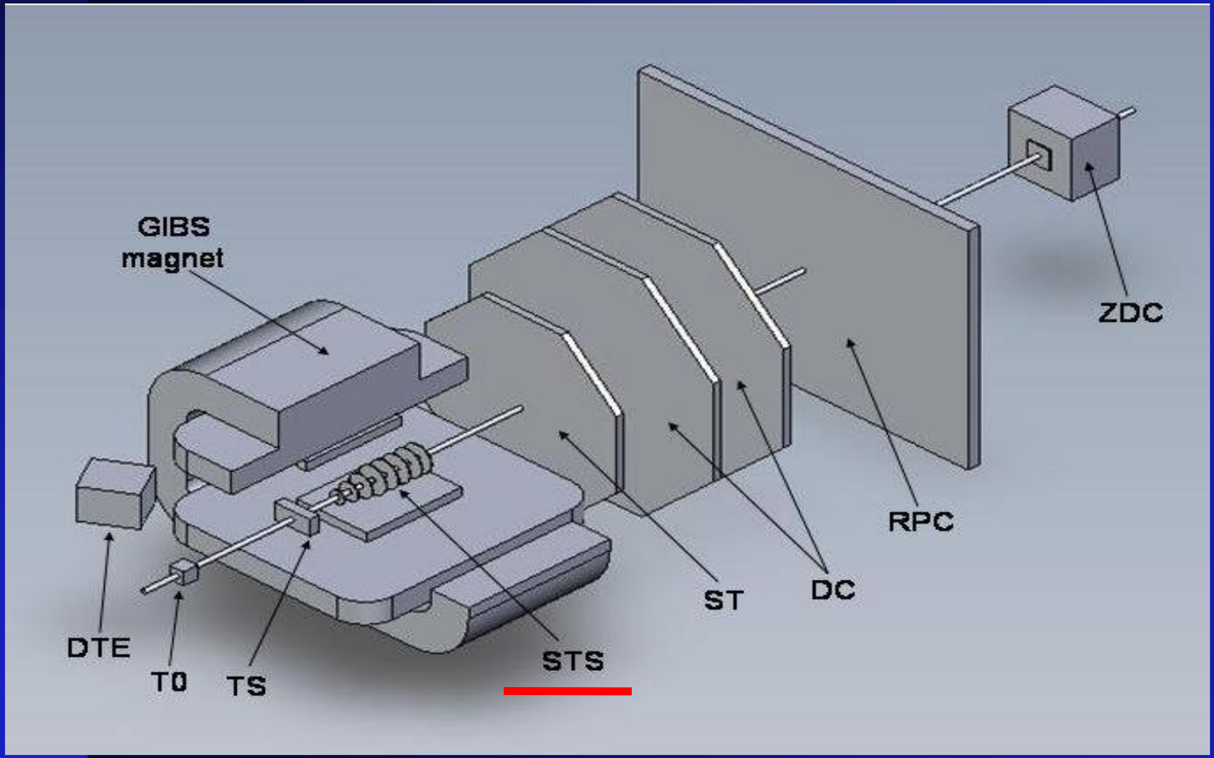
Physics is complementary to the MPD program
& will be actual even after start of the MPD runs:

- **AA interactions:**
  - particle production, incl. subthreshold one;
  - particle(collective) flows, event-by-event fluctuations, correlations;
  - multiplicities, phase space distributions of p, n, π, K, hyperons,
    light nuclear fragments, vector mesons, hadronic resonances,
    direct light hypernuclei production in central AA collisions.
  - ratios of yields (π/K etc) in different kinematical regions.

- **pA, nA, dA interactions in direct & inverse** (Ap, Ad) **kinematics:**
  - to get a "reference" data set for comparison with AA interactions,
  - to investigate particle modifications in hadronic matter
    advantages of the inverse kinematics (Ap, Ad collisions)
    may play significant role
  - to look for polarization effects in particle production
    off nuclear targets by polarized d, p, n.

Goal of the BM@N experiment

- measurements of the mult-istrange objects (Ξ, Ω, exotics) & hypernuclei in HI collisions
- close to the threshold production in the region of high sensitivity to the models prediction



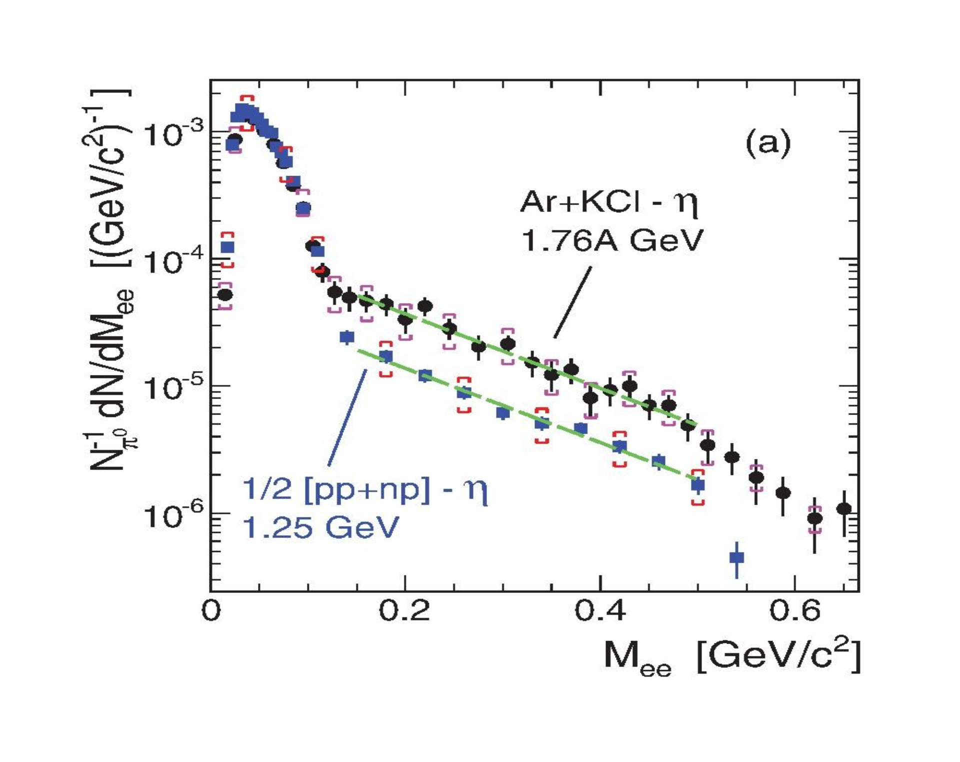
GIBS magnet (SP-41)

TS-target station,
T0- start diamond detector,
STS - silicon tracker,
ST- straw tracker,
DC- drift chambers,
RPC- resistive plate chambers,
ZDC- zero degree calorimeter,
DTE – detector of tr. energy.

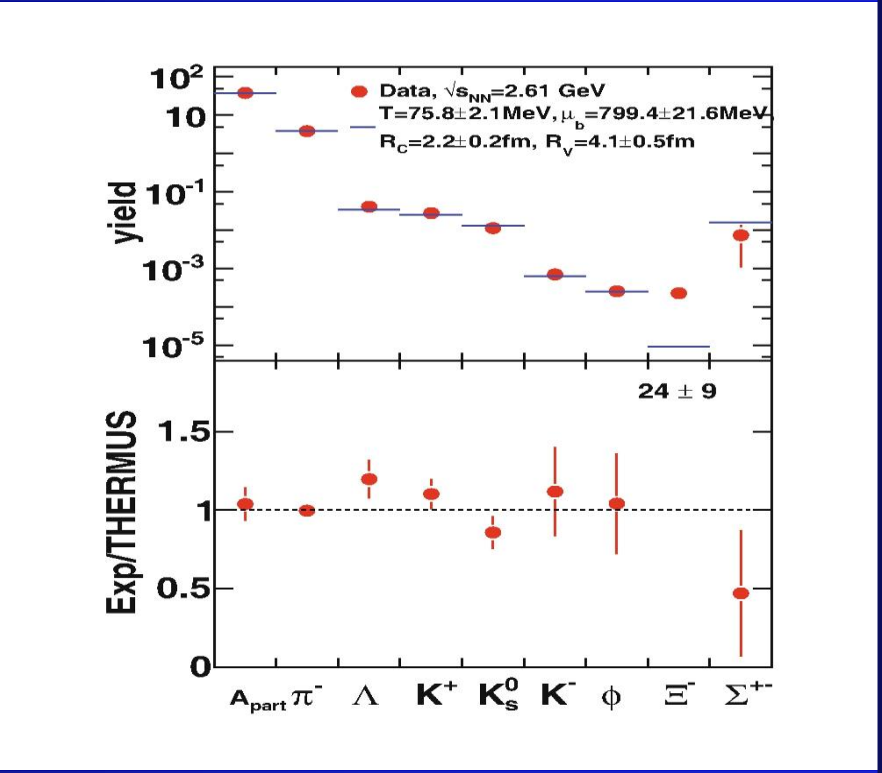
- the detector based on the sub-detectors developed for CBM, MPD & SPD

Recent exciting results from HADES

Enhancement of the dilepton yield in Ar+KCl at 1.76 A GeV



Large excess of Ξ hyperons production (20 times)



Strong impact to the physics program at BM@N and MPD

Counting rate and beam time estimation

Hyperons production in Au+Au @ 4 GeV

Particle	$E_{thr}NN$ GeV	M central	M m.bias	ε %	Yield/s m. bias	Yield/week m. bias
Ξ^-	3.7	$1\cdot10^{-1}$	$2.5\cdot10^{-2}$	3	75	$4.5\cdot10^{7}$
Ω^-	6.9	$2\cdot10^{-3}$	$5\cdot10^{-4}$	3	1.5	$9\cdot10^{5}$
Anti-Λ	7.1	$2\cdot10^{-4}$	$5\cdot10^{-5}$	15	0.15	$9\cdot10^{4}$
Ξ^+	9.0	$6\cdot10^{-5}$	$1.5\cdot10^{-5}$	3	$4.5\cdot10^{-2}$	$2.7\cdot10^{4}$
Ω^+	12.7	$1\cdot10^{-5}$	$2.5\cdot10^{-6}$	3	$7.5\cdot10^{-3}$	$4.5\cdot10^{3}$

Hyper nuclei production in Au+Au @ 4 GeV

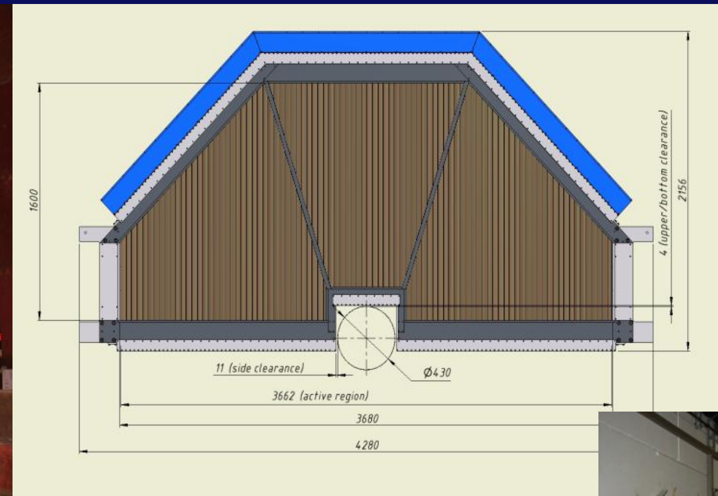
Hyper nuclei	M central	ε %	Yield/s central	Yield/week central
${}_{\Lambda}^{3}H$	$2\cdot10^{-2}$	8	16	10^{7}
${}_{\Lambda\Lambda}^{5}H$	$1\cdot10^{-6}$	1	$1\cdot10^{-4}$	60
${}_{\Lambda\Lambda}^{6}He$	$3\cdot10^{-8}$	1	$3\cdot10^{-6}$	1.8

0.1 MHz min.bias interactions

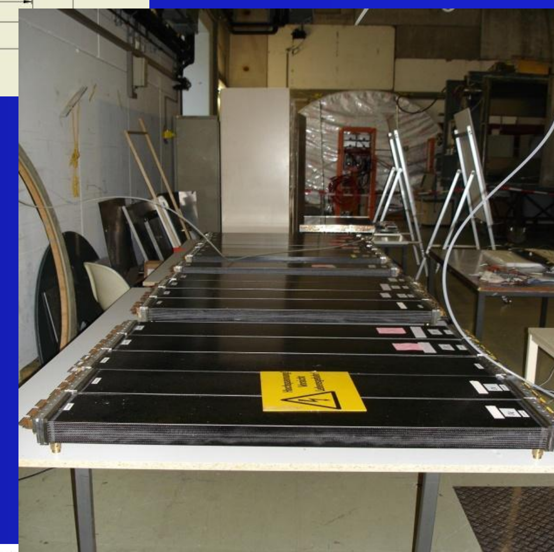
(beam is 10^{7} Au/sec and thin - 1% Au target)

Tracking, particle ID & centrality measurements

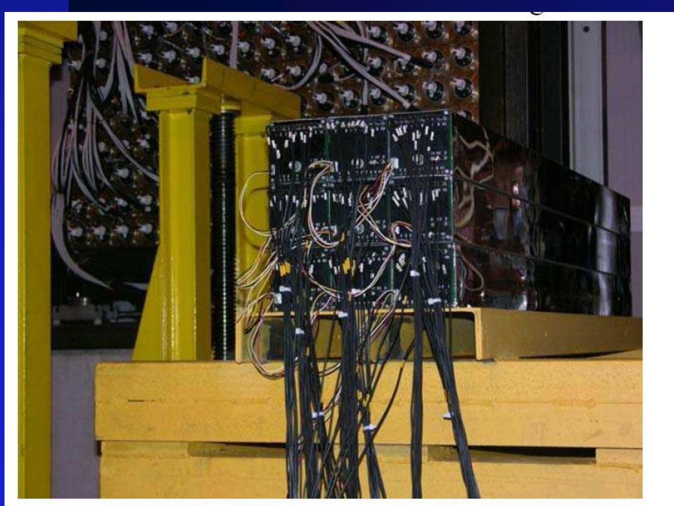
NA48 drift chambers
(NA48 – CERN/JINR)



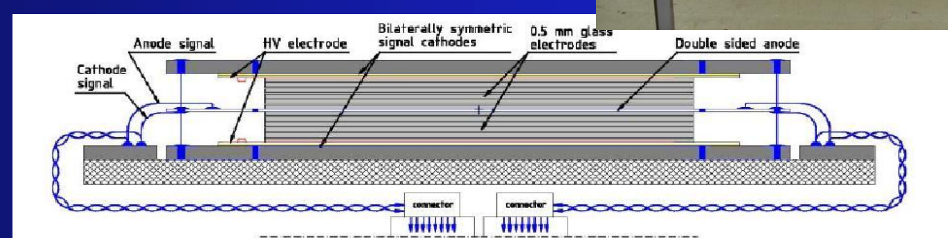
Straw tracker
(CBM/MPD)



RPC TOF

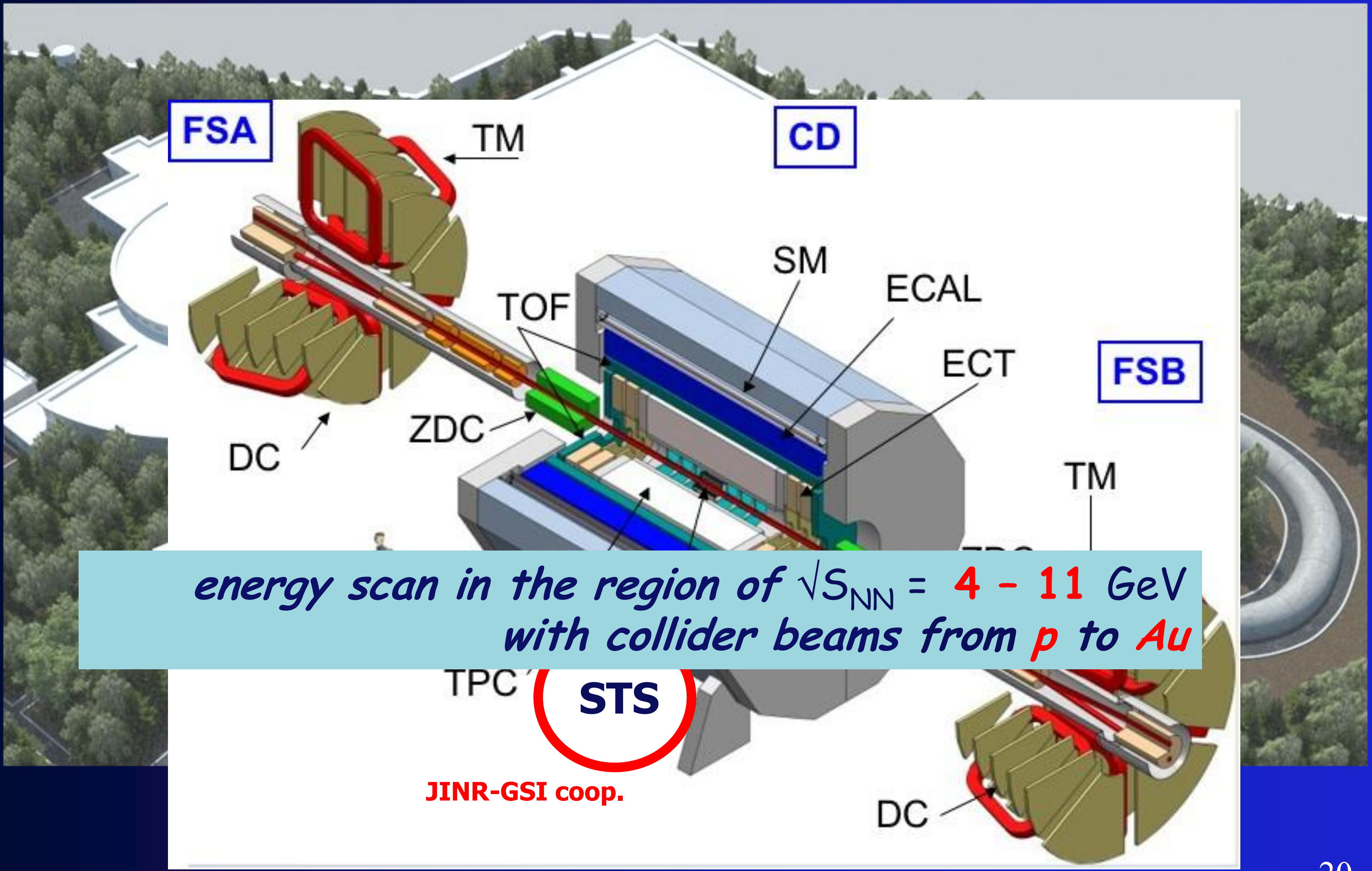


ZDC (CBM/MPD -INR,JINR)



Symmetrical structure, differential readout

MPD



energy scan in the region of $\sqrt{S_{NN}}$ = **4 – 11** GeV
with collider beams from p to Au

MPD Observables

- *Particle yields and spectra (π,K,p,clusters,Λ, Ξ ,Ω)*
- *Event-by-event fluctuations* ***(high statistics, 4pi)***
- *Femtoscopy involving π, K, p, Λ* ***(high statistics, 4pi)***
- *Collective flow for identified hadron species*
- *Electromagnetic probes (electrons, gammas)*
- *Di-Lepton* ***precise*** *study* (high performance Ecal)
- *Asymmetries study* (reaction plane determination)

Measurements regarded as complementary to RHIC/BES and CERN/NA61,
However, higher statistics & (close to) the total yields for rare probes at MPD
No boost invariance at NICA
– more accurate source parameters fit without rapidity cut
Rapidity dependence of the fireball thermal parameters will be possible at NICA

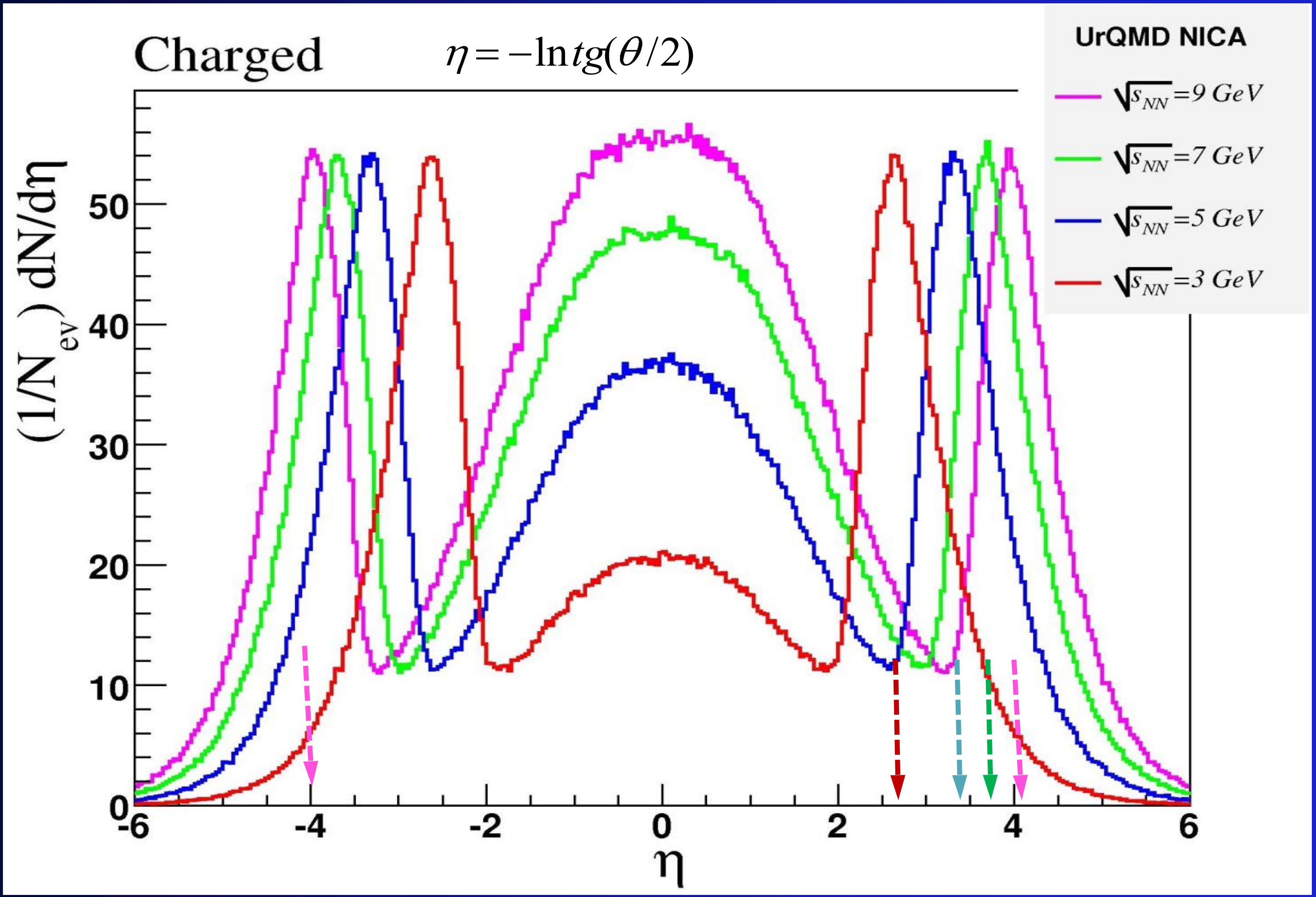
Particle yields, Au+Au @ $\sqrt{s_{NN}}$ = 8 GeV *(central collisions)*

Expectations for 10 weeks of running at $L = 10^{27} cm^{-2}s^{-1}$ *(duty factor = 0.5)*

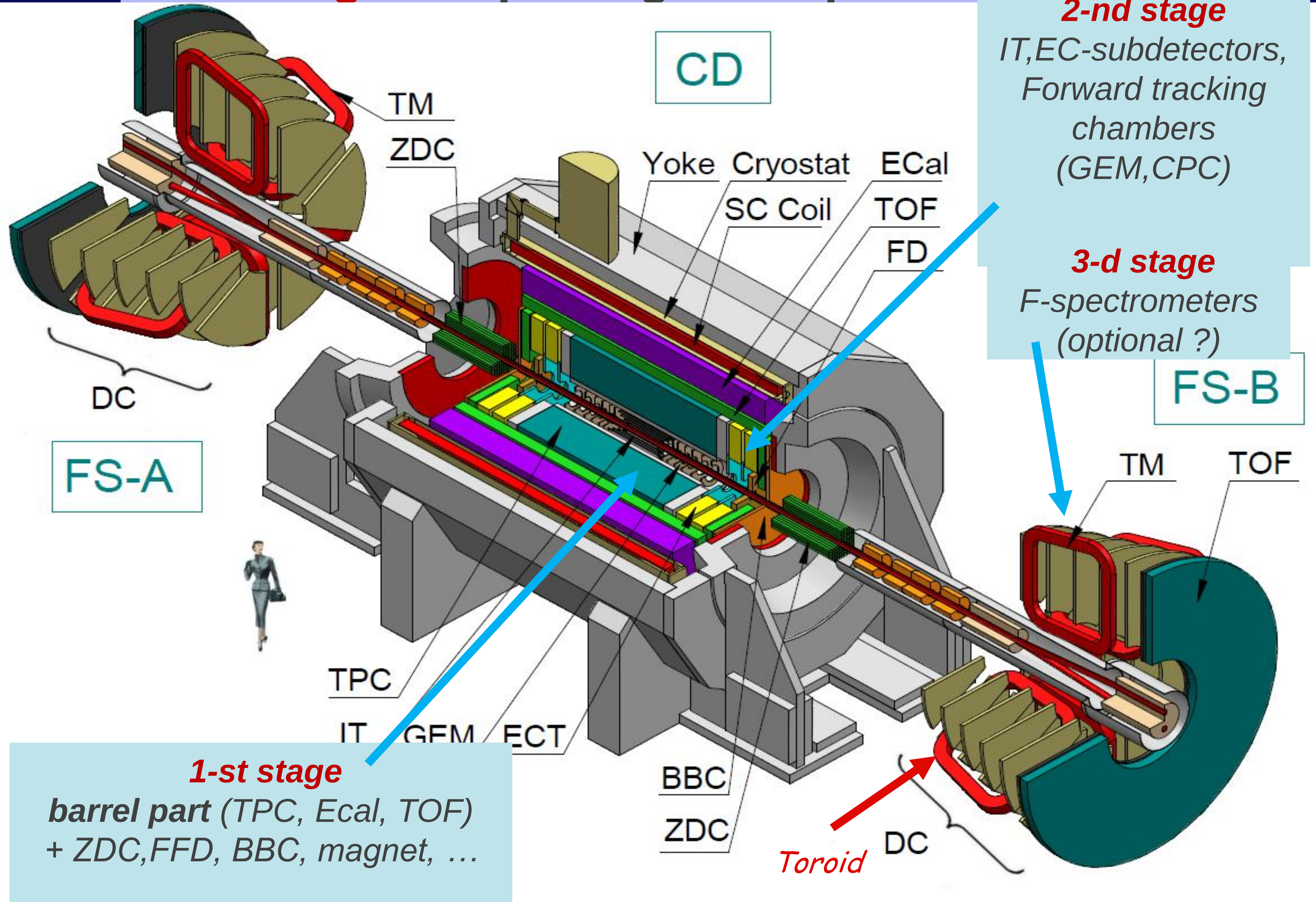
Particle	Yields 4π	Yields y=0	Decay mode	BR	*Effic. %	Yield/10 w
π^+	293	97	----	---	61	$2.6 \cdot 10^{11}$
K^+	59	20	---	----	50	$4.3 \cdot 10^{10}$
p	140	41	---	----	60	$1.2 \cdot 10^{11}$
ρ	31	17	e+e-	$4.7 \cdot 10^{-5}$	35	$7.3 \cdot 10^{5}$
ω	20	11	e+e-	$7.1 \cdot 10^{-5}$	35	$7.2 \cdot 10^{5}$
φ	2.6	1.2	e+e-	$3 \cdot 10^{-4}$	35	$1.7 \cdot 10^{5}$
Ω	0.14	0.1	ΛK	0.68	2	$2.7 \cdot 10^{6}$
D^0	$2 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$K^+\pi^-$	0.038	20	$2.2 \cdot 10^{4}$
J/ψ	$8 \cdot 10^{-5}$	$6 \cdot 10^{-5}$	e+e-	0.06	15	10^{3}

*Efficiency includes the MPD acceptance, realistic tracking and particle ID.
Particle Yields from experimental data (NA49), statistical and HSD models.
Efficiency from MPD simulations. Typical efficiency from published data (STAR)

Pseudorapidity distributions in Au-Au minimum bias events



3 stages of putting into operation

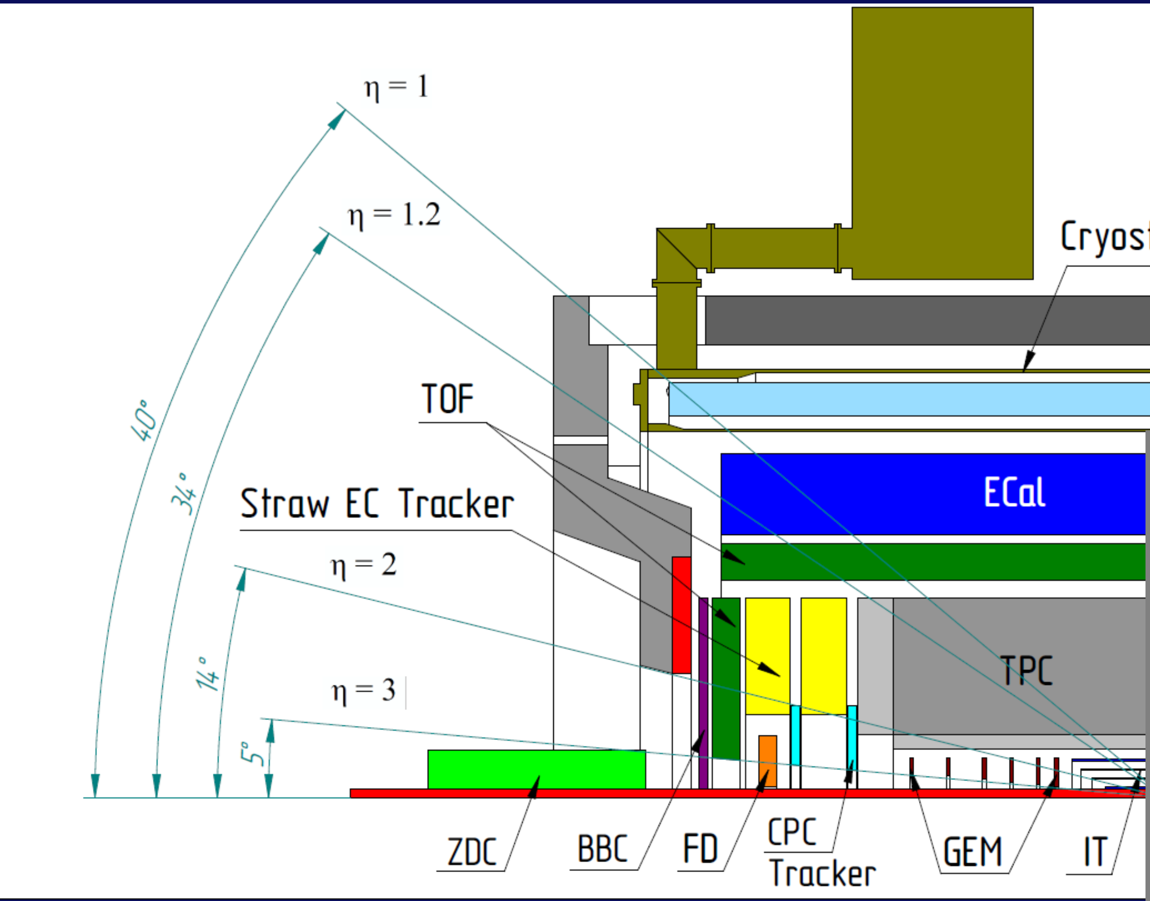


2-nd stage
IT,EC-subdetectors, Forward tracking chambers (GEM,CPC)

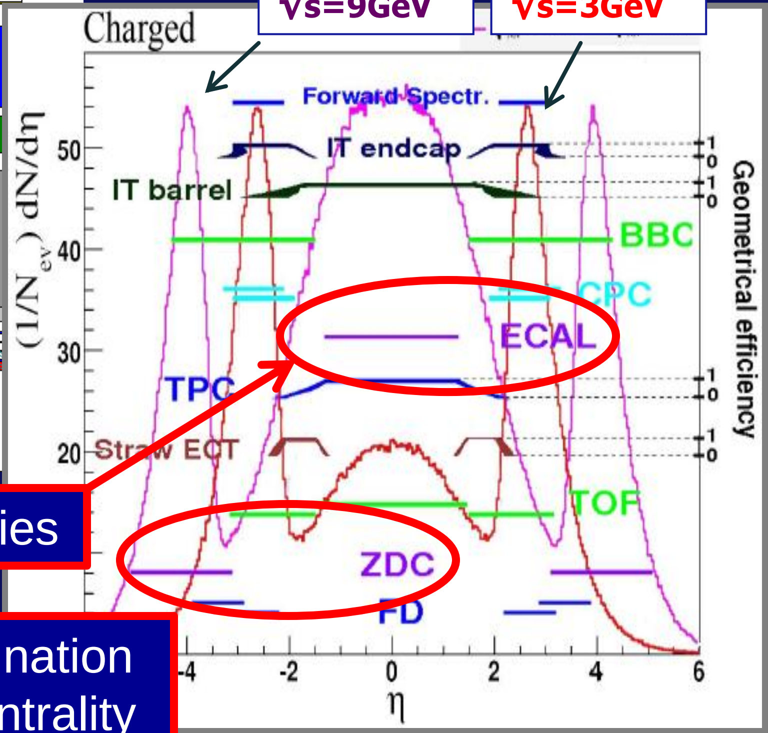
3-d stage
F-spectrometers (optional ?)

1-st stage
***barrel part** (TPC, Ecal, TOF) + ZDC,FFD, BBC, magnet, …*

Coverage of angles



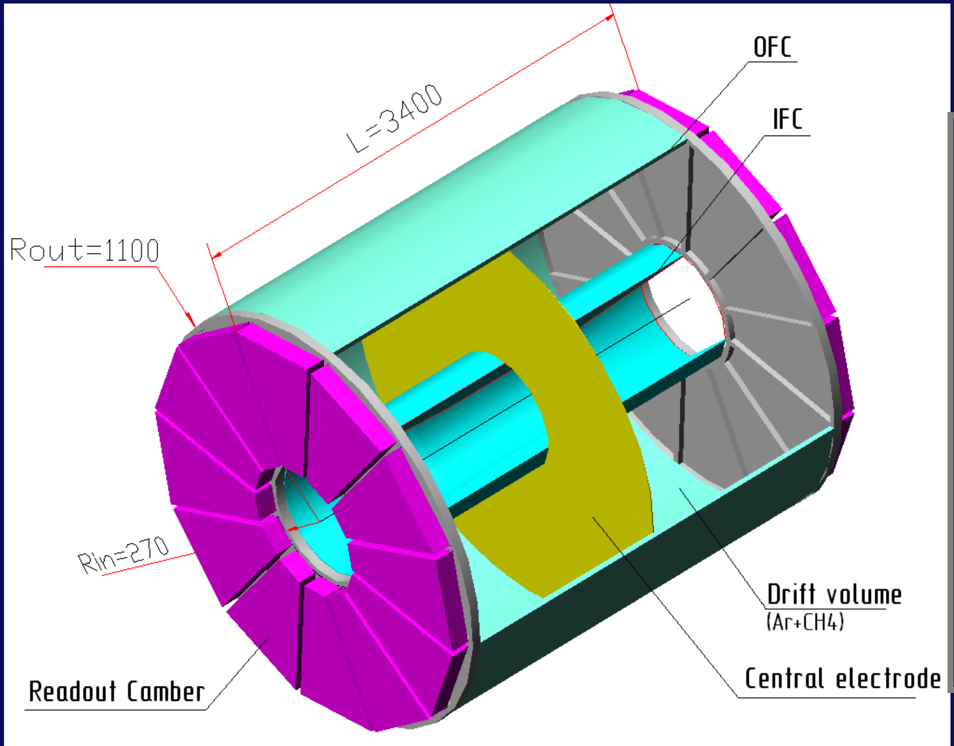
Acceptance (B=0.5 T):
Full azimuthal
IT (|h|<2.5)
TPC (|h|<2)
ECAL (|h|<1.2)
FD (2<|h|<4)
TOF (|h|<3)
ZDC (|h|>3)



ECal coverage for Di-Lepton studies

ZDC coverage for determination of the reaction plane & centrality

Time Projection Chamber (TPC)



TPC is a heart of MPD

Main Parameters

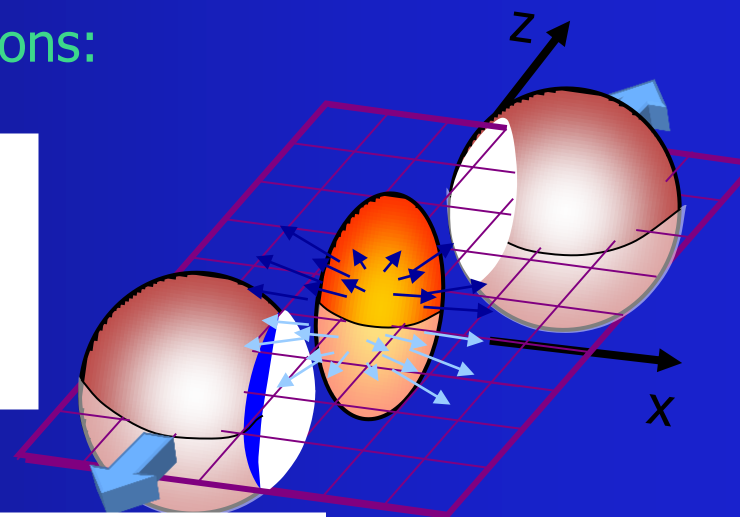
Size: 3.4 m (length) x 2.2 m (diameter)
Drift Length: 150cm
Electric field: 140V/cm
Magnetic field: 0.5 T (max.)
Gas: 90% Argon + 10% Methane
Readout: 2x12 sectors (MWPC+ pads or GEM)
Pad size – 5x12 mm in all sector area
Total # of pads: ~80 000
Rate capability: ~ 7 kHz

Performance required

Spatial resolution: $\sigma_{r\phi}$~300 μm, σ_z~ 2 mm
Two track resolution: < 1 cm
Momentum resolution: $\Delta p/p$ < 3% (0.2<p<1 GeV/c)
dE/dx resolution: < 8%
Max. multiplicity: ~ 1000 (central collision)

Directed flow v_1 & elliptic flow v_2

Non-central Au+Au collisions:



Interactions between constituents leads to a pressure gradients => spartial asymmetry is converted in asymmetry in momentum space => collective flows

$$\frac{dN}{dy\,dp_T\,d\varphi} = \frac{dN}{dy\,dp_T}\frac{1}{2\pi}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$ - directed flow

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$ - elliptic flow

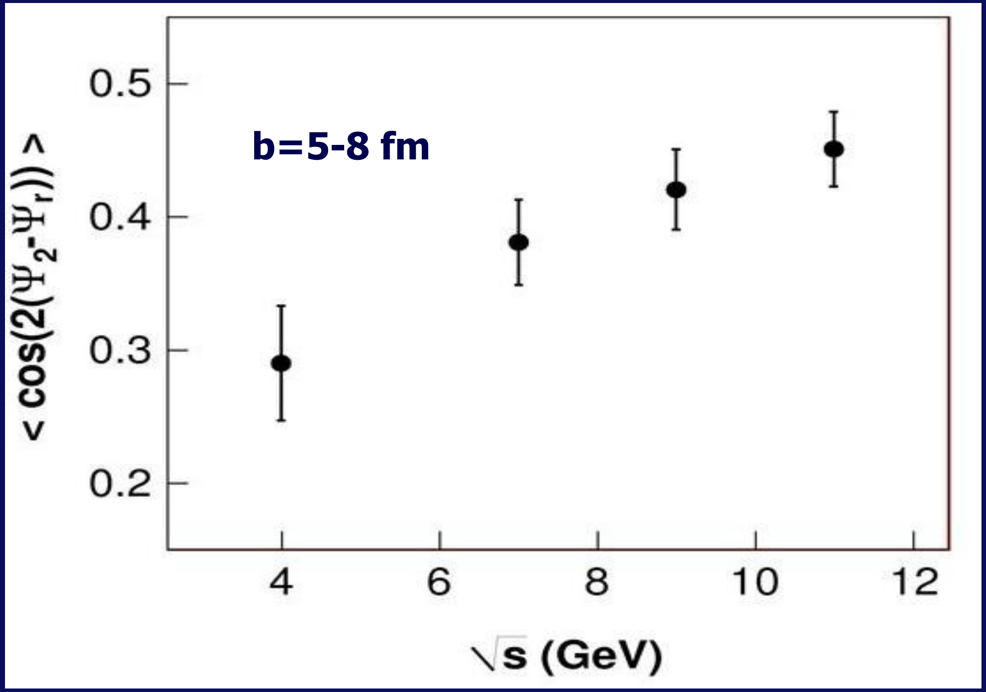
$V_2>0$ indicates in-plane emission of particles

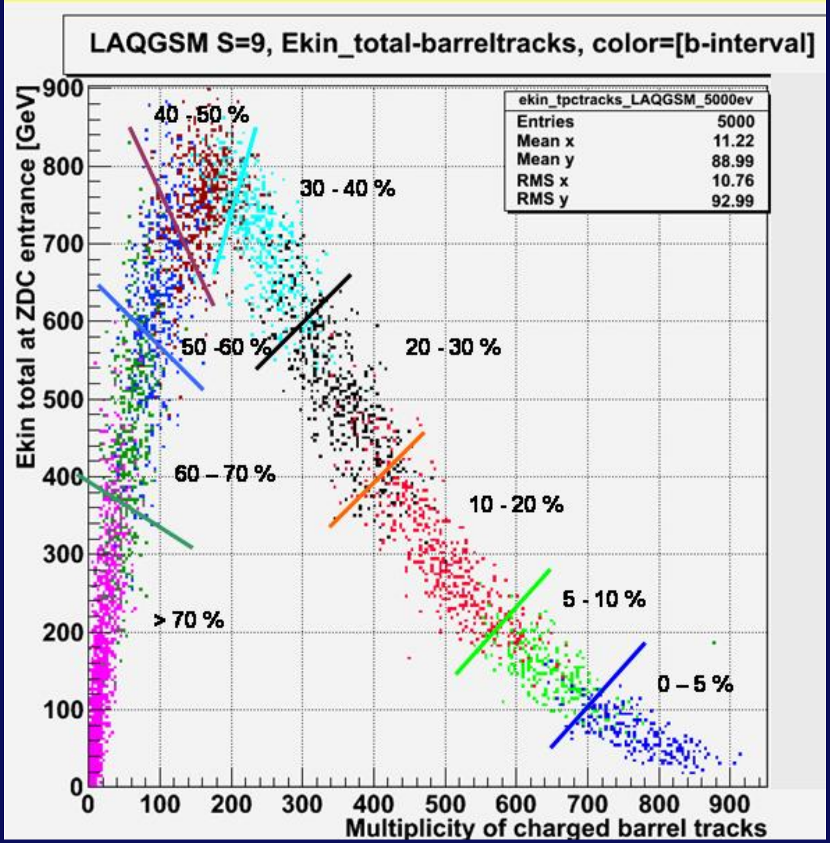
$V_2<0$ corresponds to out-of-plane emission (squeeze-out perpendicular to the reaction plane)

NICA/MPD. Flow.

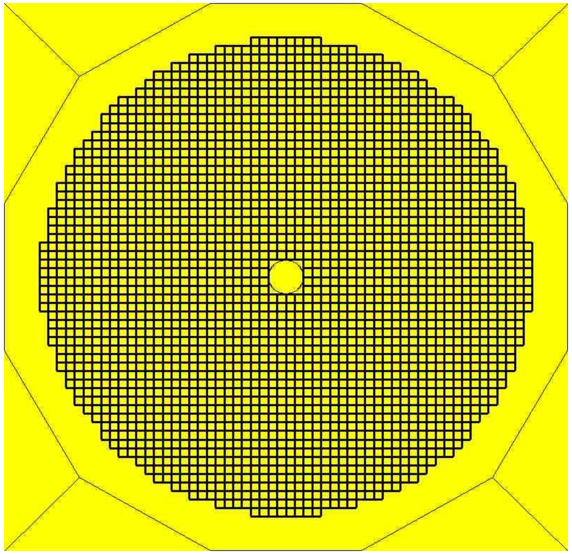
- ✓ MPD capability for event plane determination: v2 in TPC and v1 at high rapidities **(potential for improvements up to a factor of 2)**
- ✓ v2 in TPC by a ‘two sub-events method’ to avoid autocorrelations
- ✓ Measurement of spectators of both colliding nuclei; centrality determination by track multiplicity and spectator energy deposit

Event plane resolution for “central events”



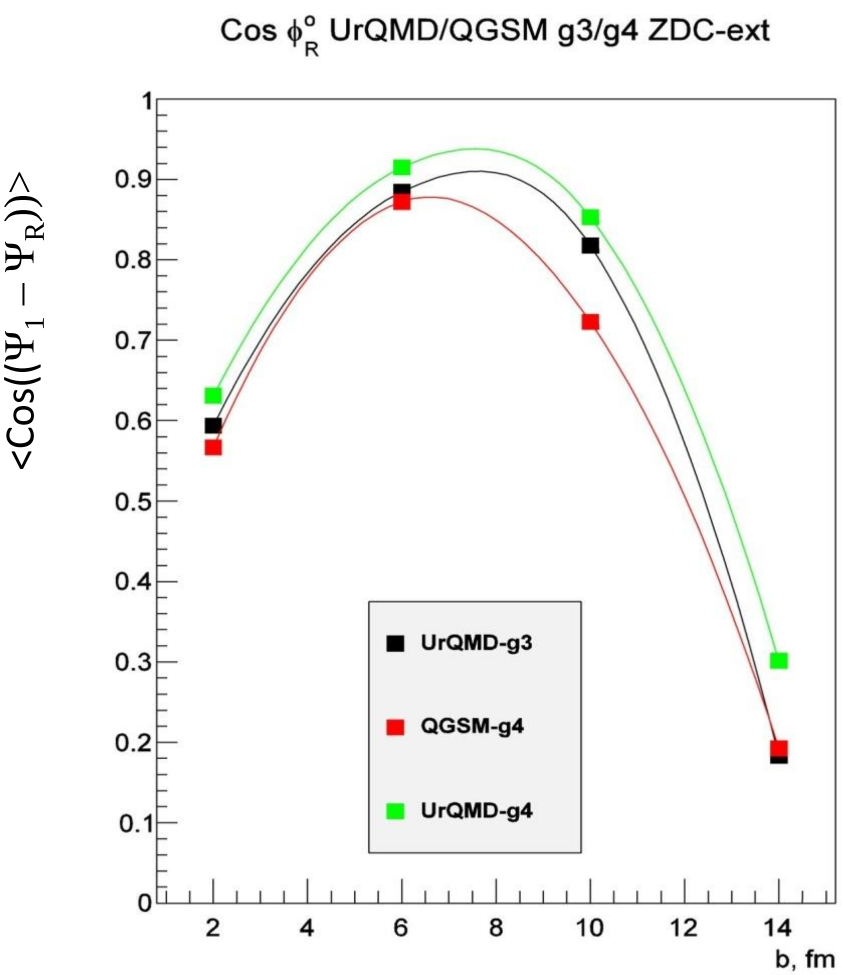


Extended ZDC detector (2<η<5) improves RP resolution at low and medium b



V.Kapishin

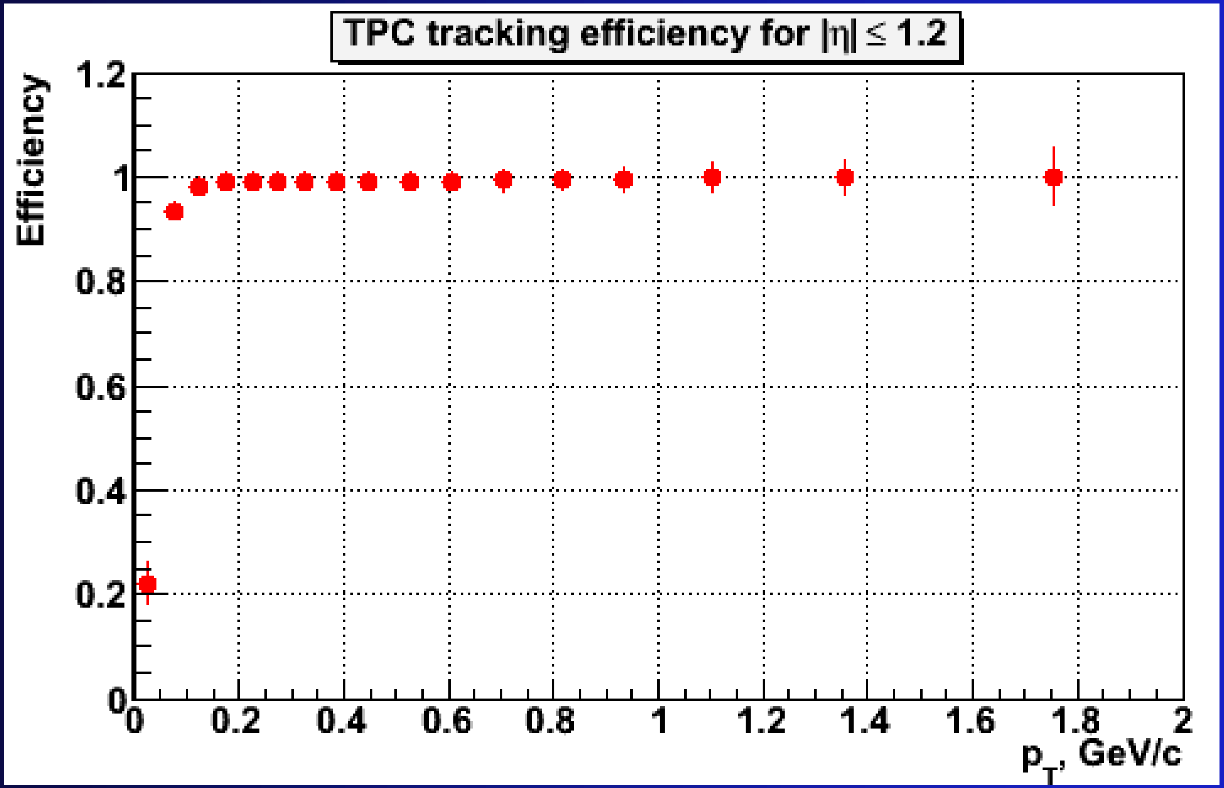
Event plane resolution (ext-ZDC)



Simulation of extended ZDC (ext-ZDC) as a detector for event plane determination:

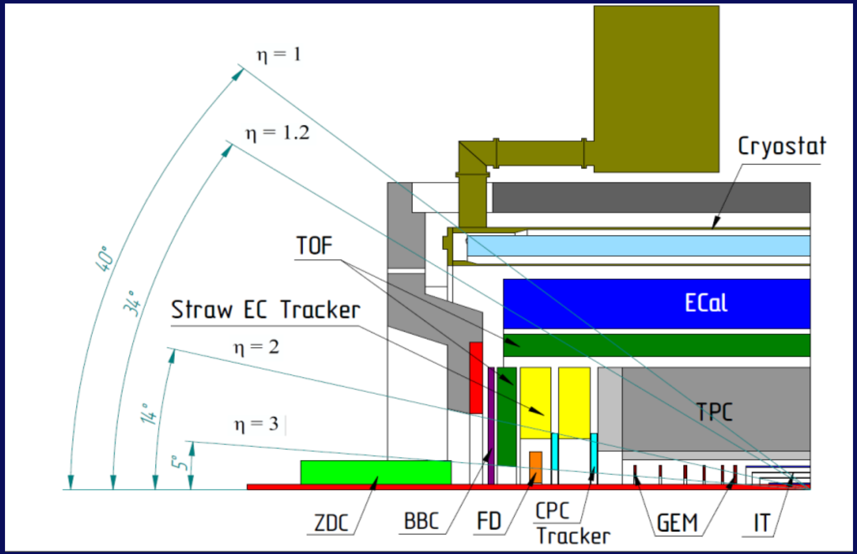
- L = 120 (60) cm
- 5 < R < 71 cm, 1<θ<14° (2<η<5)
- Cell dimensions= 2.5x2.5 (5x5,10x10) cm
- $w_i = \Sigma\ E_{loss}$ in active layers as weights
- No π/p identification
- Geant 3 vs Geant 4

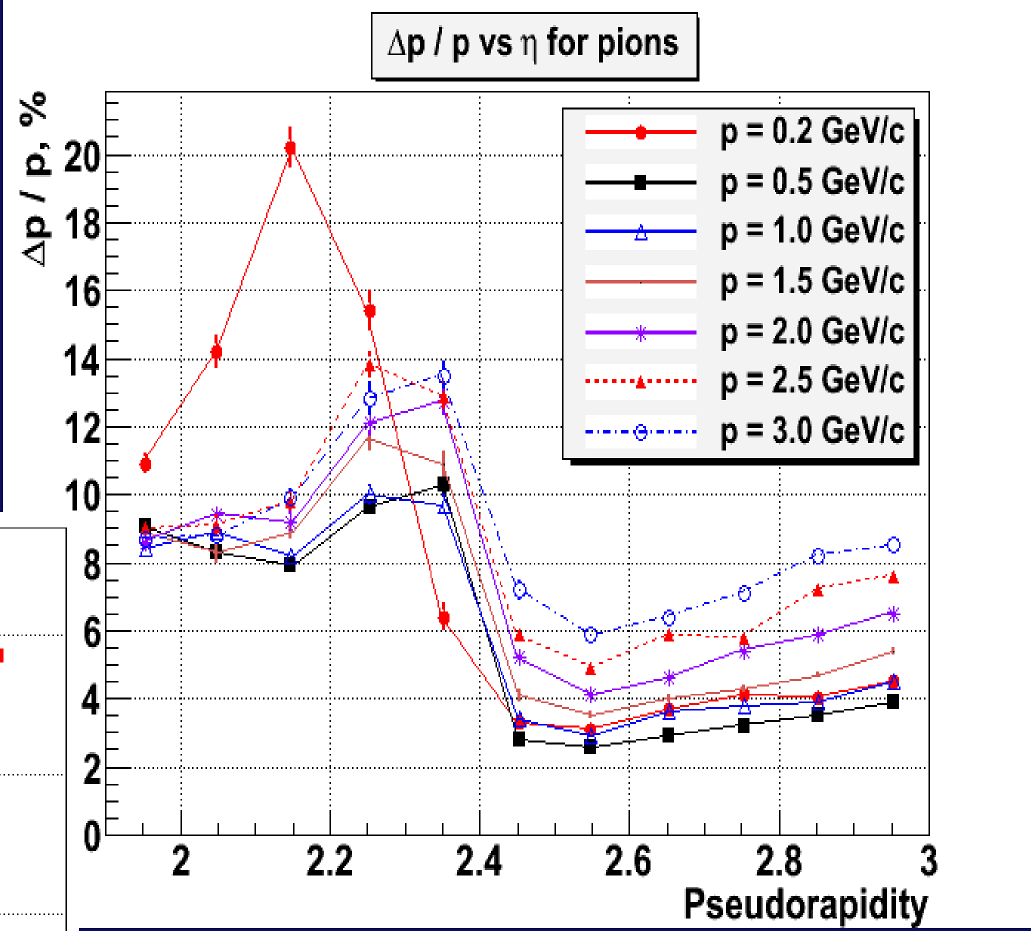
MPD performance: *tracking, PIID*

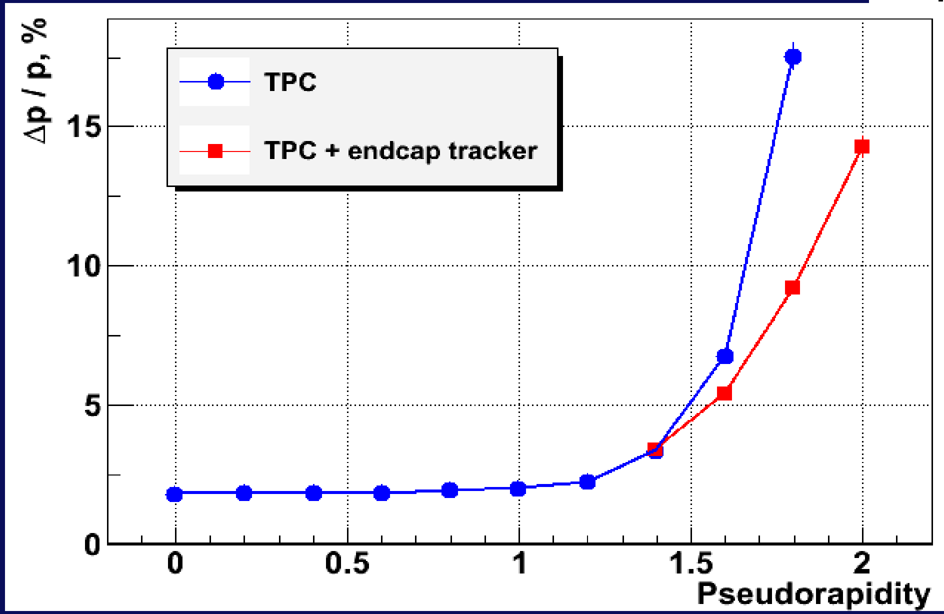


Low-p cutoff ~ **100 MeV** for a **0.5 T** magnetic field

Tracking capability in the Forward direction
(momentum resolution)

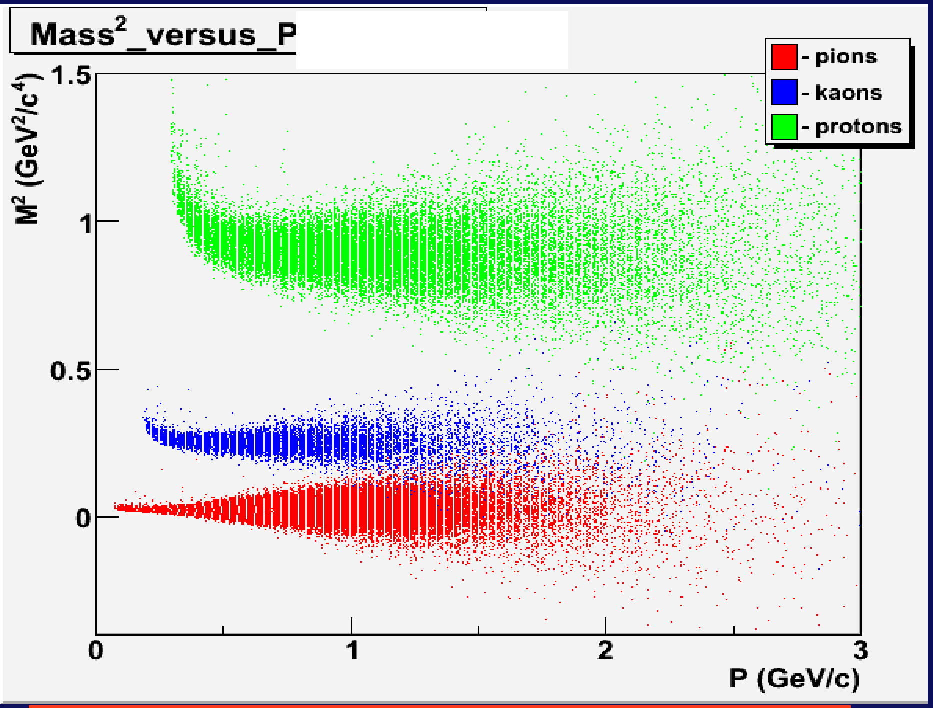


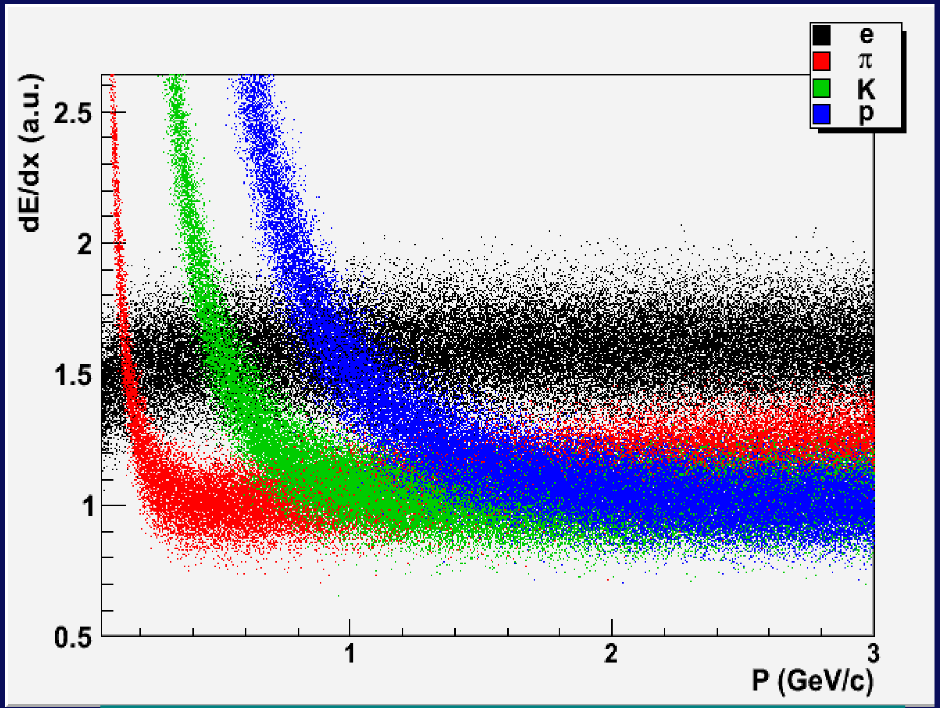




Particle IDentification in MPD

(realistic detector simulation)





PID: *Time Of Flight*
Separation: e/h – 0.1..0.35 GeV/c
π/K – 0.1..1.5 GeV/c
K/p – 0.1..2.5 GeV/c

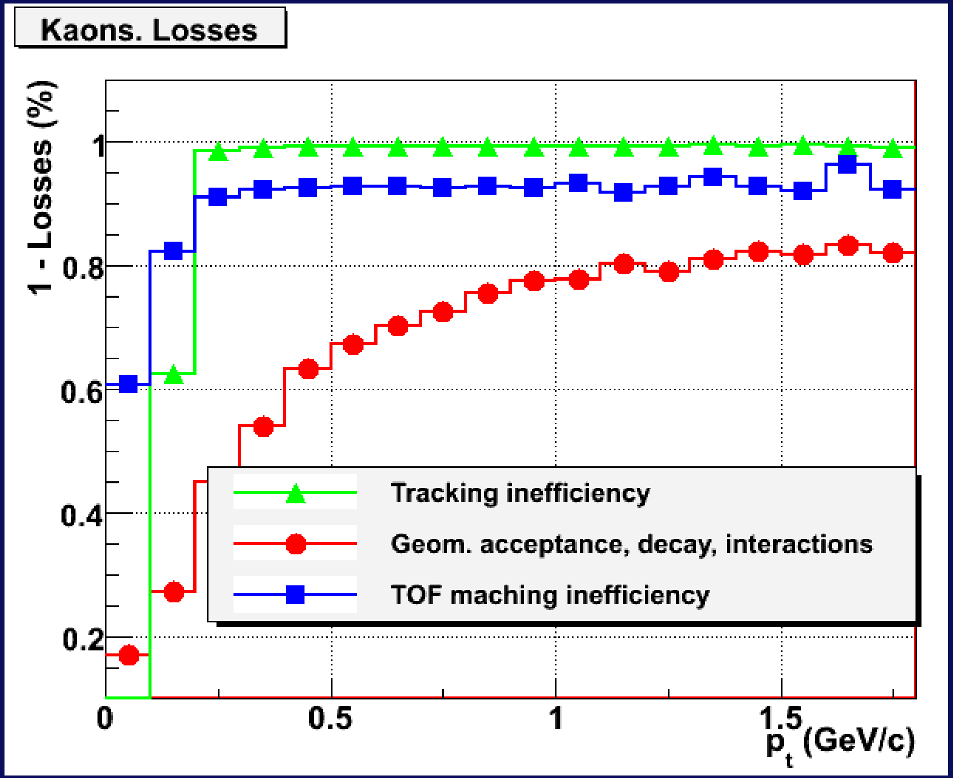
PID: *Ionization loss (dE/dx)*
Separation: e/h – 1.3..3 GeV/c
π/K – 0.1..0.6 GeV/c
K/p – 0.1..1.2 GeV/c

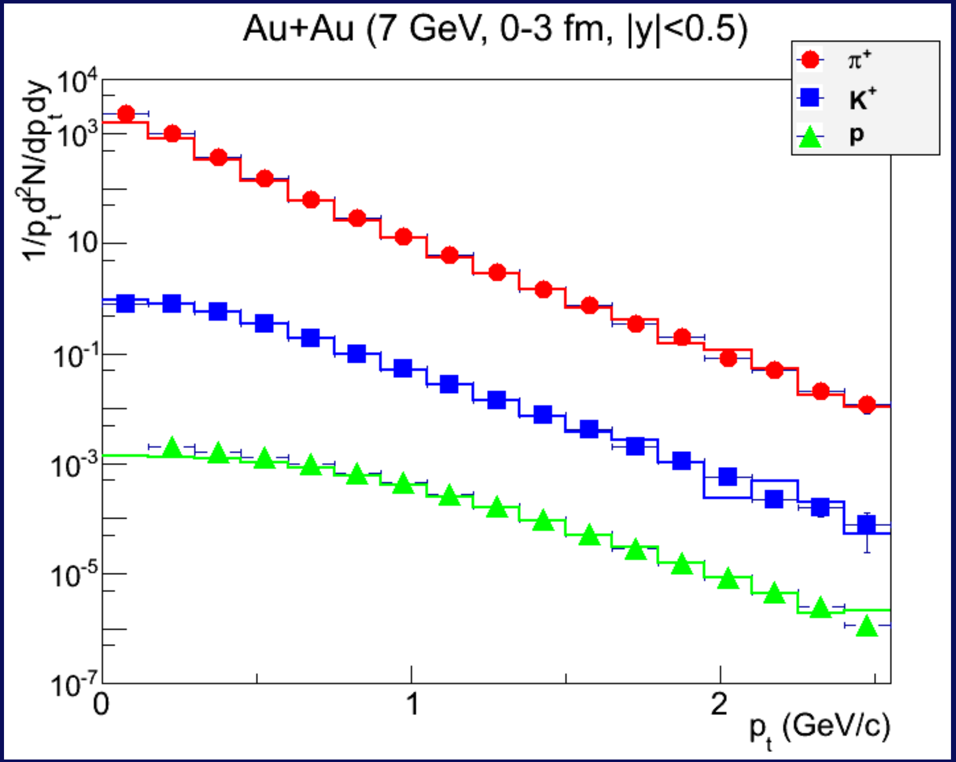
- **Coverage**: *$|\eta| < 1.4$, p_t=0.1-2 GeVc barrel $|\eta| < 2.6$, pt=0.1-2 GeVc barrel+EC*
- **Matching eff.**: *> 85% at p_t > 0.5 GeV/c*
- **PID:** *2σ π/K ~ 1.7 GeV/c, (π,K)/p ~ 2,5 GeV/c*

Hadron spectra and yields in MPD

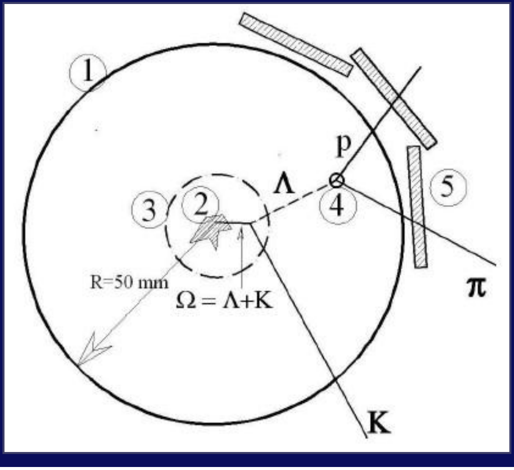
1st Stage (Simulation)

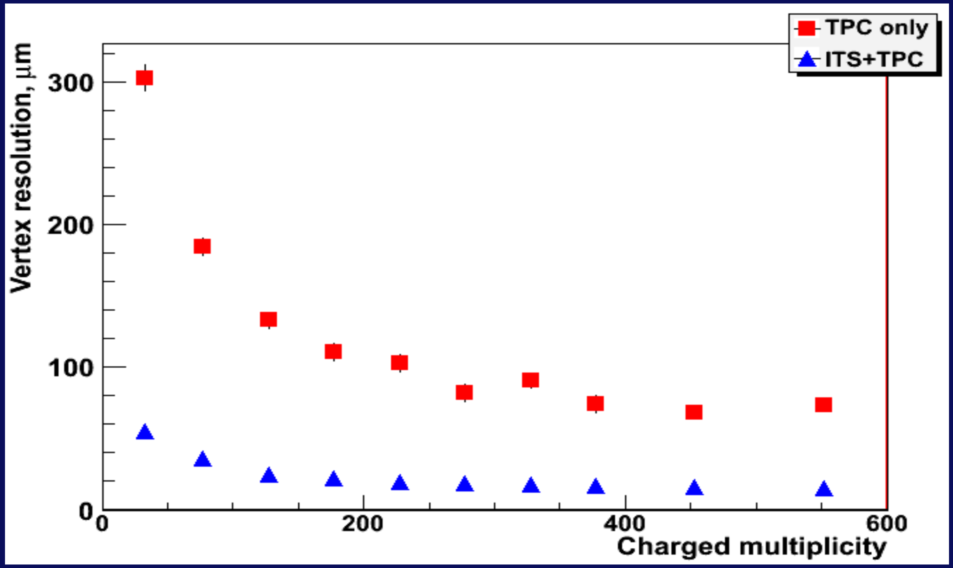
- *Full reconstruction chain, realistic PID, corrections from simulations*
- *Hadron spectra at midrapidity: large pT-coverage*
- *Forward rapidities: extrapolations to unmeasured regions under development*

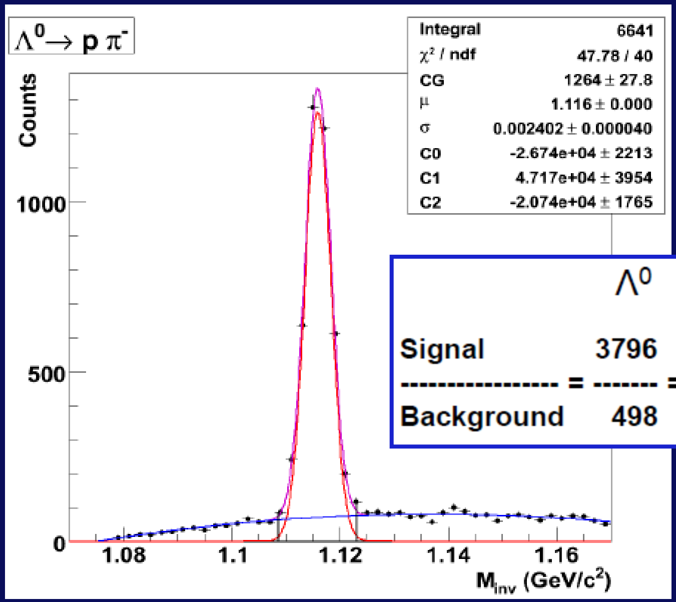




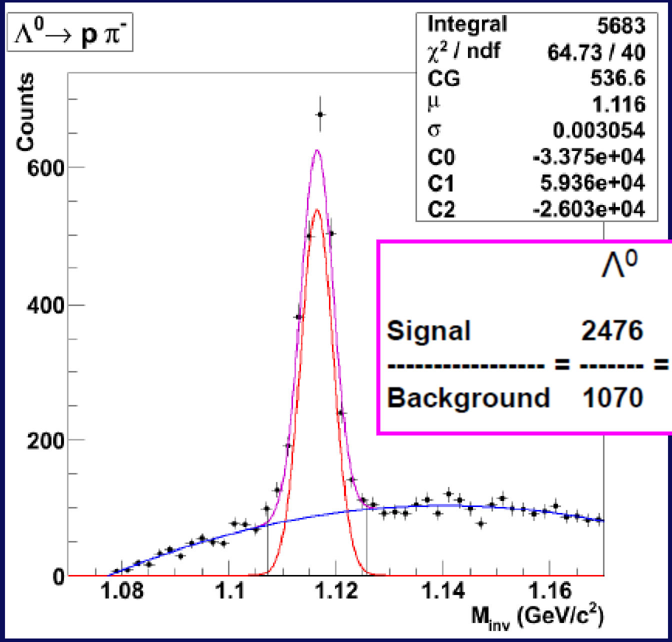
V0 performance (TPC+IT)







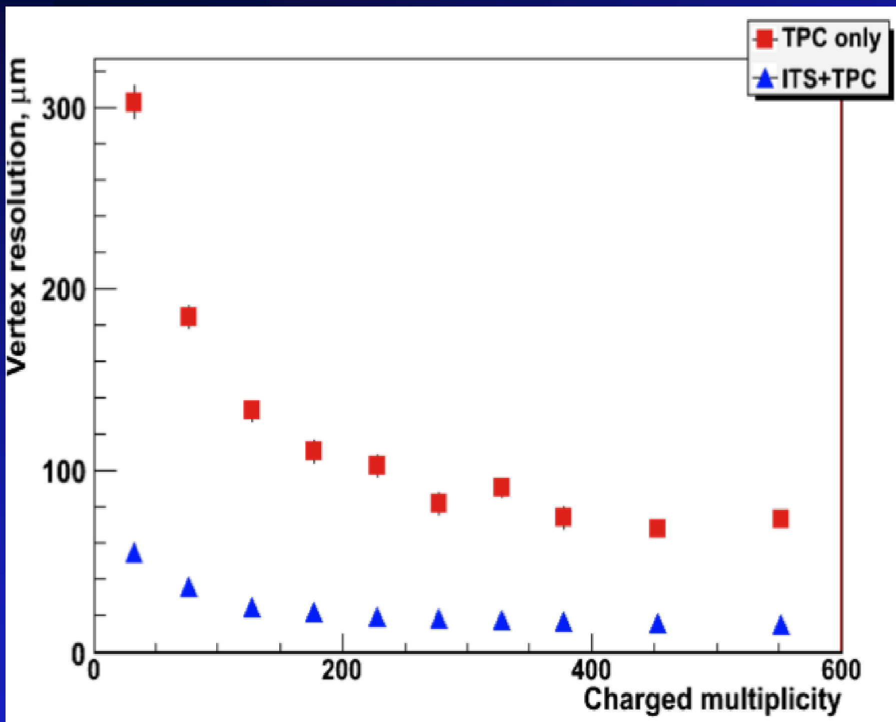
	Λ^0	K_s^0
Signal / Background	3796 / 498 = 7.6;	4845 / 962 = 5

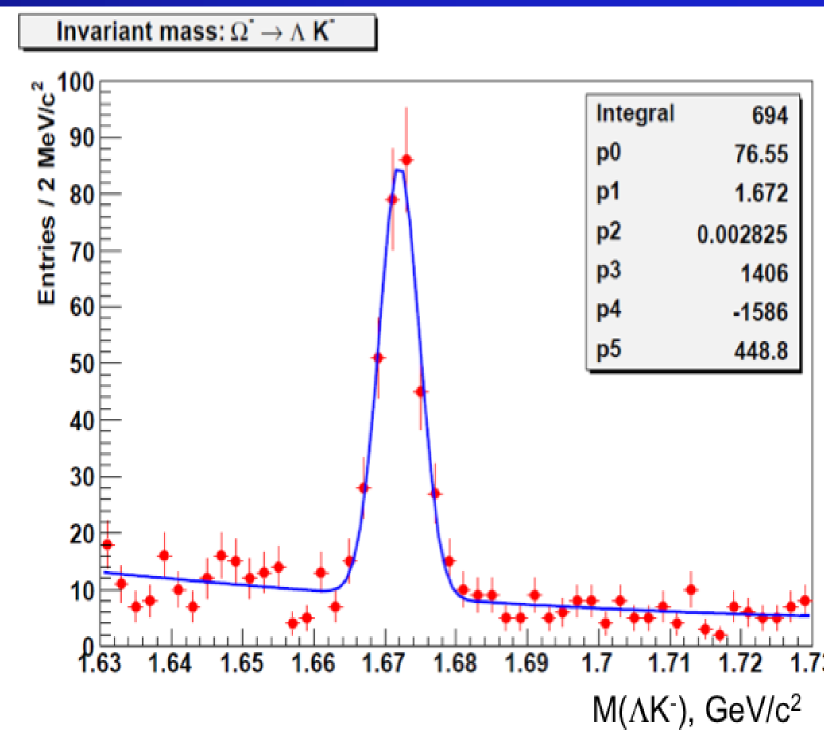


	Λ^0	K_s^0
Signal / Background	2476 / 1070 = 2.3;	3155 / 2362 = 1.3

- **Improved Signal-to-Background ratio (S/B) with the vertex IT detector**

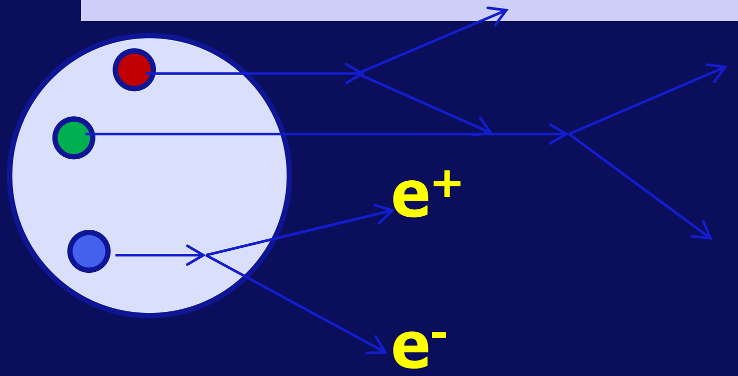
Ω^- -> ΛK^- *decay reconstruction* *(vertex + particle ID)*





Study of lepton pair production

- *In-medium modification of vector meson properties may signal on partial chiral symmetry restoration in heavy ion collisions*
- *Dileptons as penetrating probes of the fireball interior – no FSI*
- *Existing experimental data underestimated by the vacuum spectral functions for 0.3 GeV < Mee < 0.7 GeV*



Required experimental mass resolution ~ 10 MeV

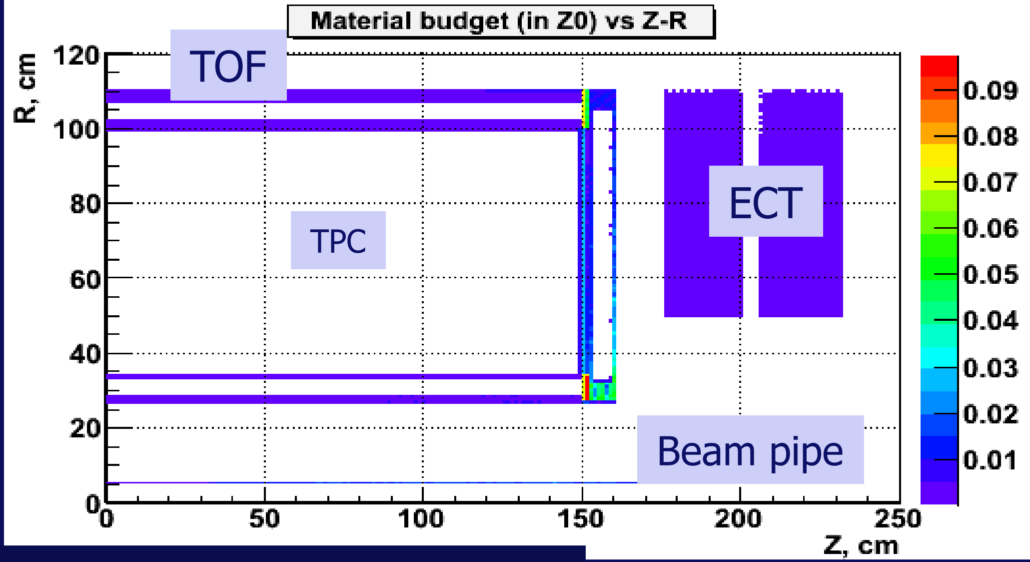
ω : $c\tau$ = **23 fm** M=783 MeV, Γ=8 MeV

φ : $c\tau$ = **44 fm** M=1019 MeV, Γ=4 MeV

ρ : $c\tau$ = **1.3 fm** M=768 MeV Γ=149 MeV

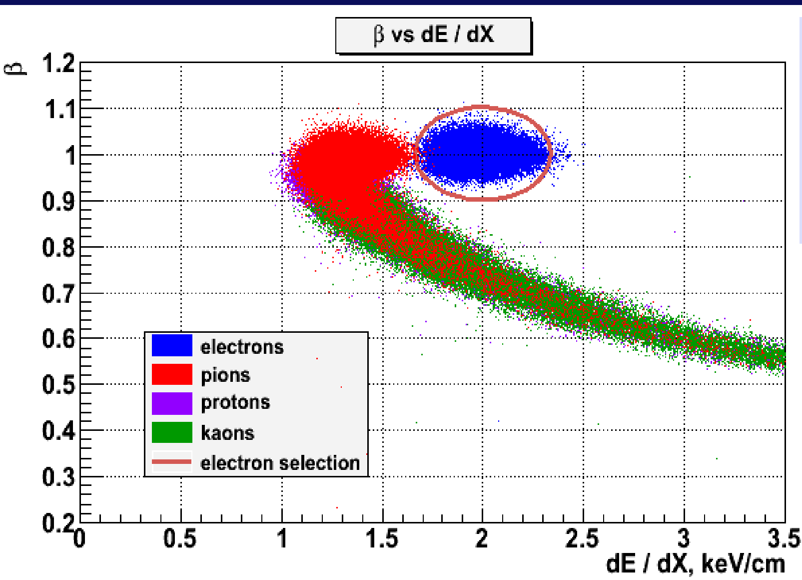
MPD detector relevant features:

- Low material budget
- Electron ID via combined dE/dx & TOF
- Extra hadron suppression by ECAL
- High event rate allowing studying of dielectron continuum up to a large pT



TPC Endcap material total budget including electronics ~ 17% !

Dileptons

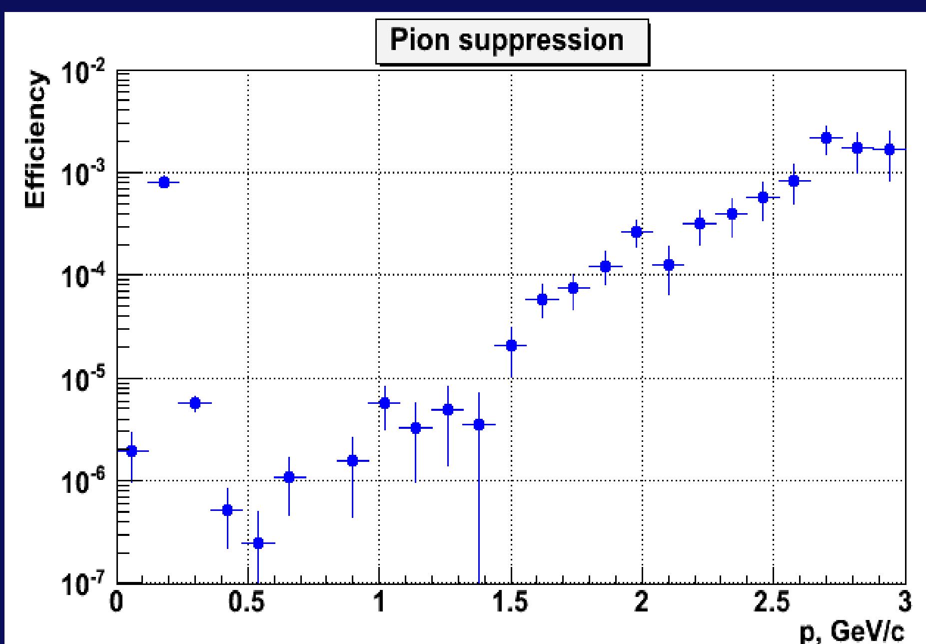


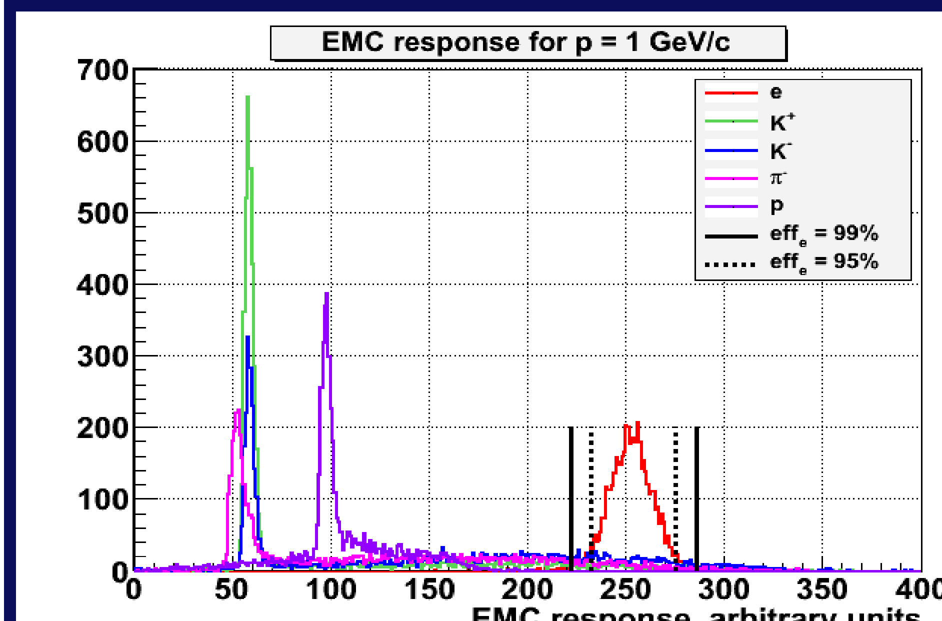
- Input : central Au+Au at 7 GeV, Pluto + RQMD model
- track selection and e-conversion suppression
- PID by dE/dx and TOF, hadron suppression ~ 10^{-5}
- Extra suppression by ECAL

Selection: $|\eta| < 1.2$, # of TPC points ≥ 20
0.2 p<2 GeV/c

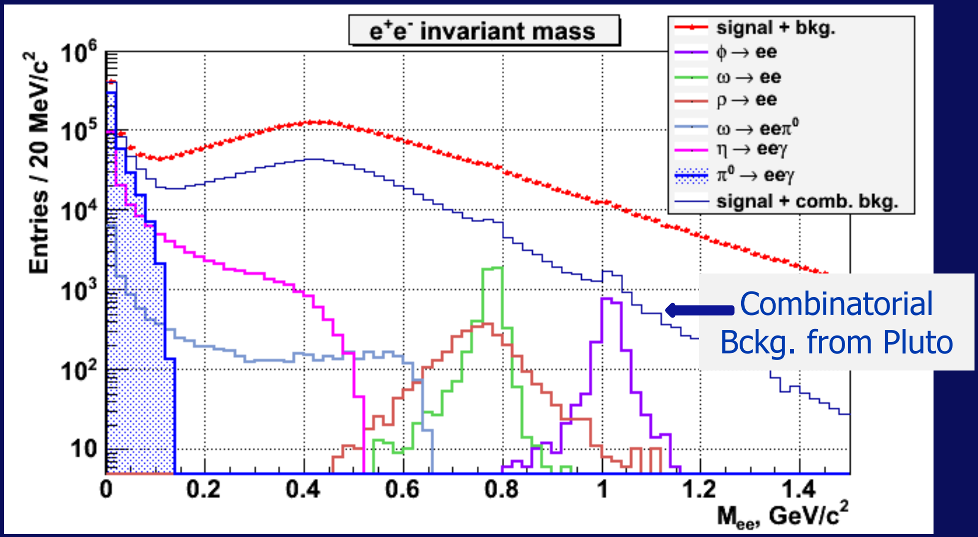
Efficiency **35%**

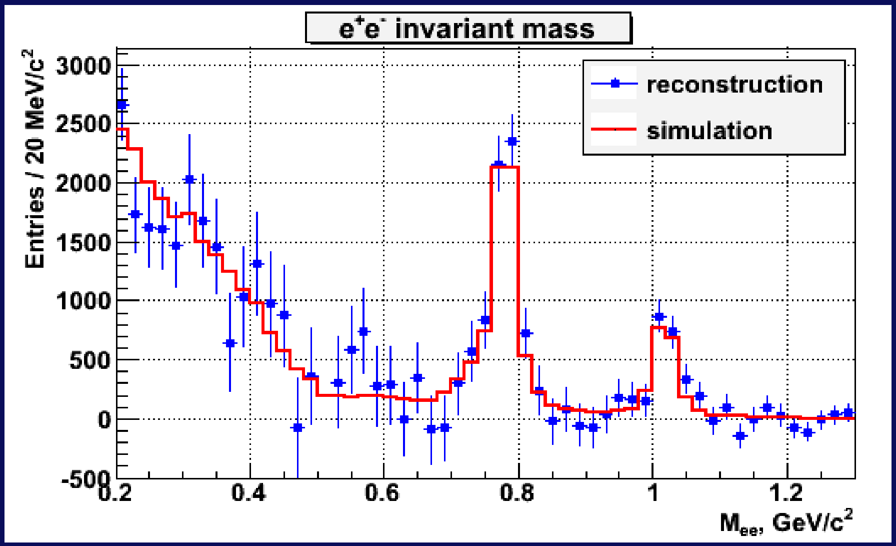
misID contamination -**19.0**% *(w/o cut on **ECAL** signal)*
- **1.4**% *(w cut on **ECAL** signal)*





Dilepton invariant spectra *(simulation -> reconstruction)*





NICA-MPD:
σ_φ = 17 MeV, S/B = 0.045
σ_ω = 14 MeV, S/B = 0.047

NA49 (φ) S/B = 2%
STAR (ω,φ) S/B = 4-6%
CERES (0.2<Mee<1.2 GeV/c^2) S/B = 17% (!)

Source of a large background so far: conversion electrons and misidentified hadrons

Progress in R&D

MPD systems status

Magnet	technical project – close to completion
TPC	the first prototype - ready for tests
ECal	several prototypes are tested
TOF	-"-
Straw wheels	full scale prototype – in preparation
ZCal	design optimization
CPC	*design – in progress*
FFD	first prototypes are tested
VD	*elements protyping, general desigh in progress*
DAQ	*archetecture design – in progress*
Analysis	*going on*
SoftWare	*well developed*
Integration	*design – in progess*

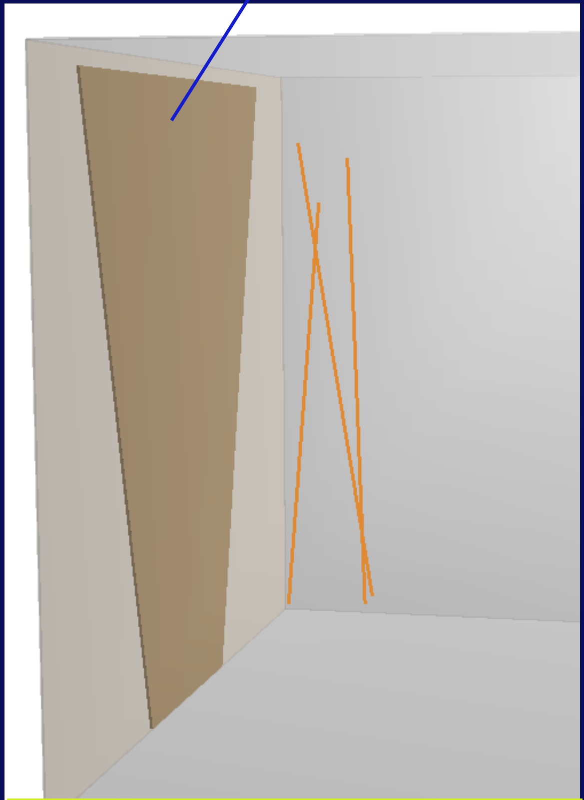
Assembling and Testing of Prototype ‘0’

Two prototypes are constructed:
- Prototype ‘0’
- Technological prototype (constructed with INDUSTRY)

Testing of Prototype ‘0’

The **Prototype ‘0’** is tested with UV laser and cosmic rays.

Pad Plane



Reconstructed tracks of cosmic ray in Prototype ‘0’

- *Drift length = 40 cm, E drift = 140 v/cm*
- *Pad Plane in readout chamber ; Pad size - 6 x 12 mm*
- *256 channels of FEE*
- *2 quartz windows for laser beam*
- *Obtained Spatial resolution*
  - *for UV Lase beam – 0,3 mm*
  - *for cosmic rays - 0,4 mm*

Technological Prototype of TPC / MPD

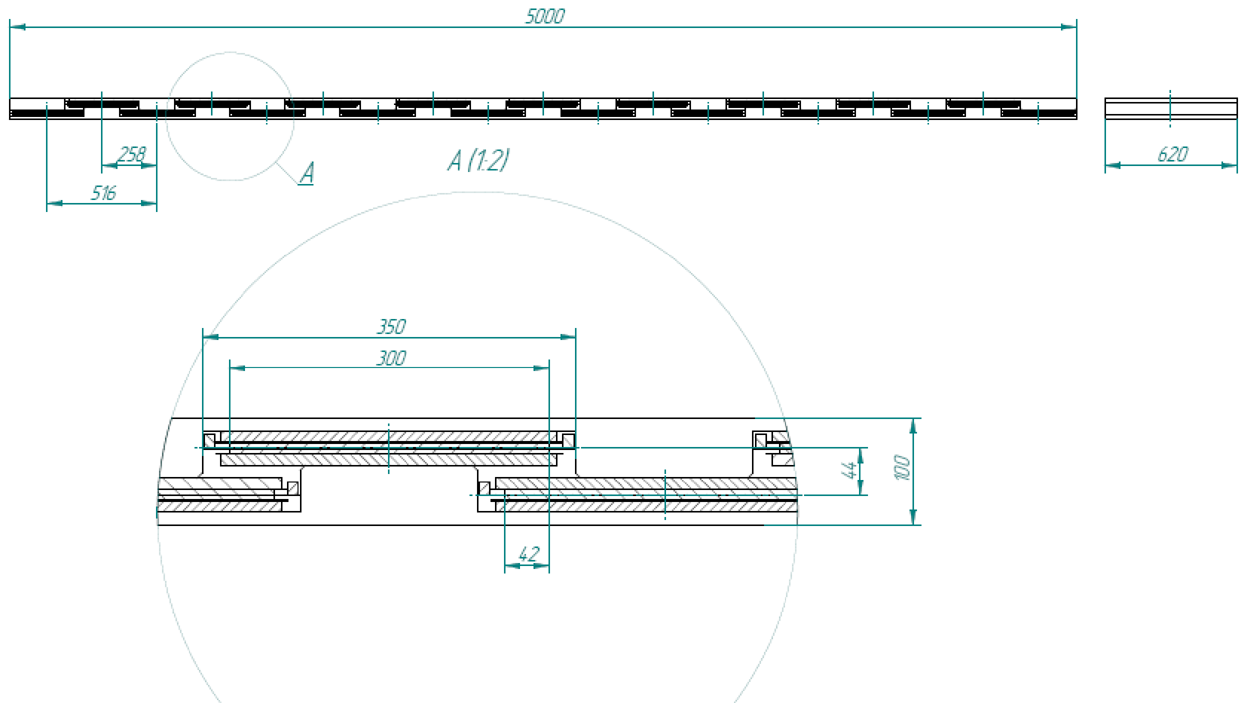
Preliminary assembling of Technological Prototype TPC in November 2011.
Start of the Prototype testing is planning on February 2012.

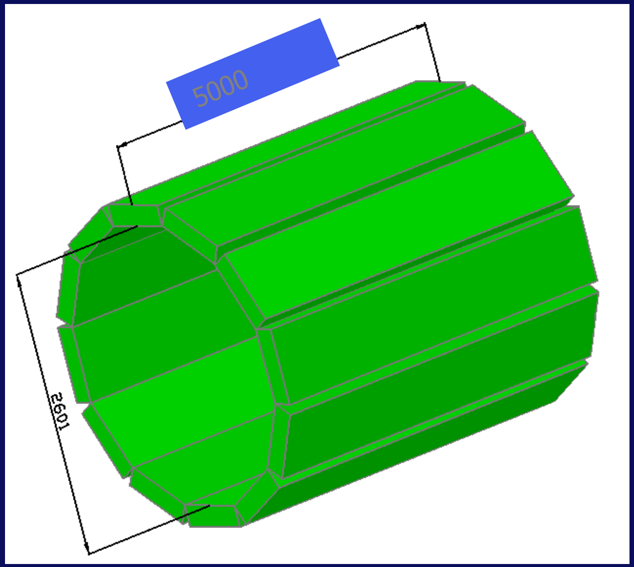
Technological prototype of TPC's inner tube

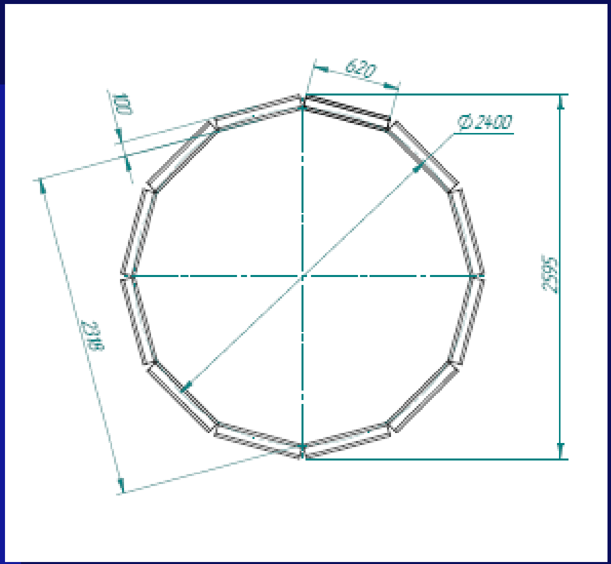
Diameter = 0.57 m,
Length = 3.0 m

Material:
Kevlar laminated by Tedlar film

Diameter - 950 mm
Length - 900 mm
Wall thickness - 2 mm
Weight ~ **10 kg**







In sector → 19 mRPCs; 1 mRPC has 24 strips (60x2) cm^2

In sector → 19 mRPC x 24 strips =456 channels

In barrel → 12 sectors;

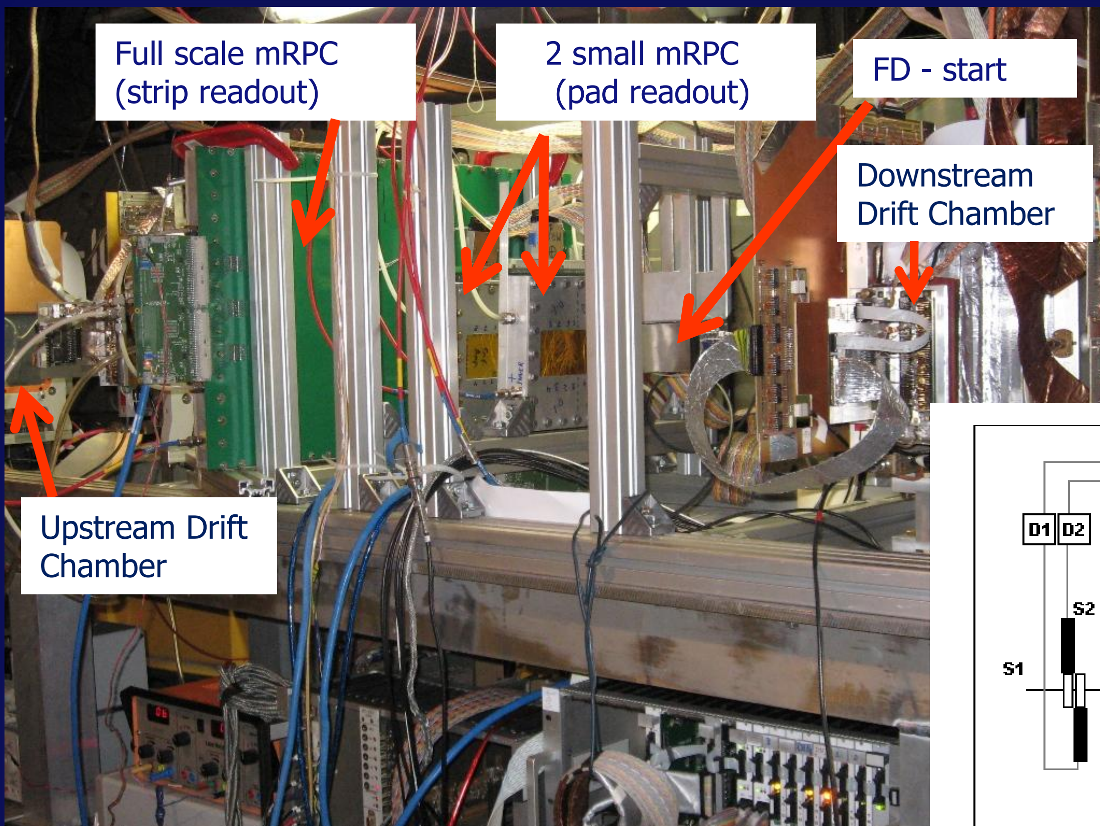
In barrel → 19 mRPC x 12 sectors =228 mRPC

In barrel → 228 mRPC x 24 strips = 5472 channels;

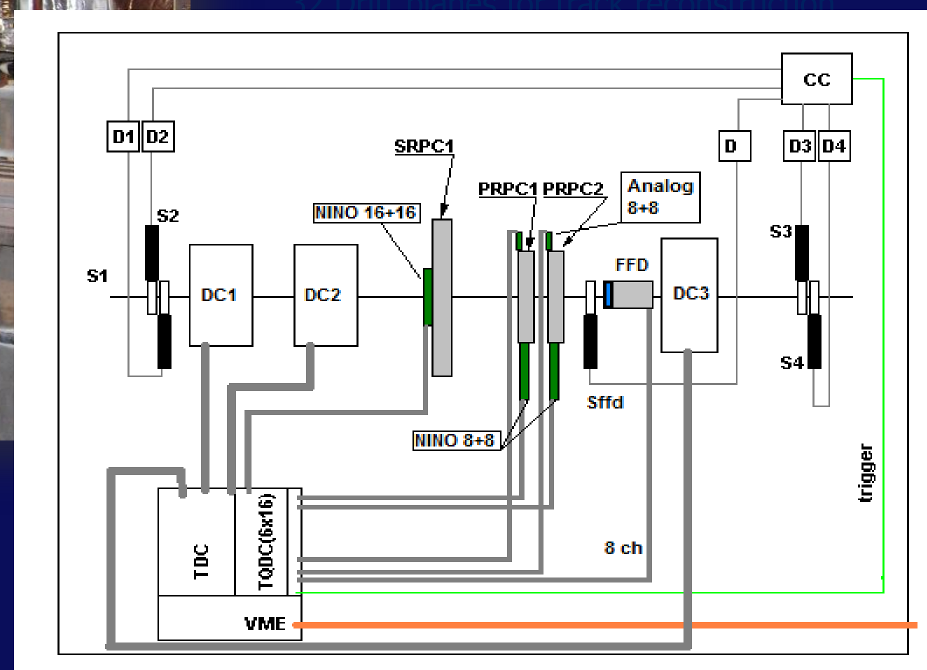
In case if readout from both sides = 10944 channels=1368 chips NINO(8ch)

We have enough electronics for barrel TOF

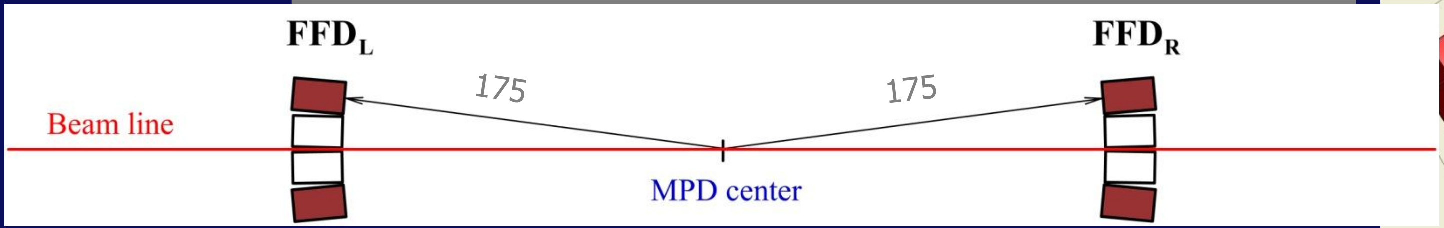
Experimental Setup for TOF prototypes test in the NUCLOTRON beam line *(Run 44, December 2011)*

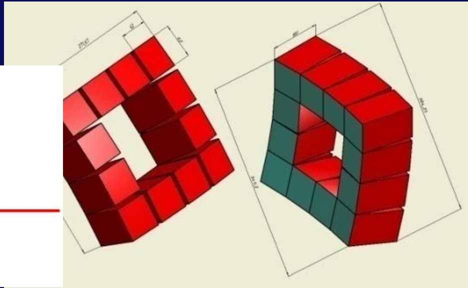


16 strips were readout from both sides
2 mRPC with 8 readout pads each

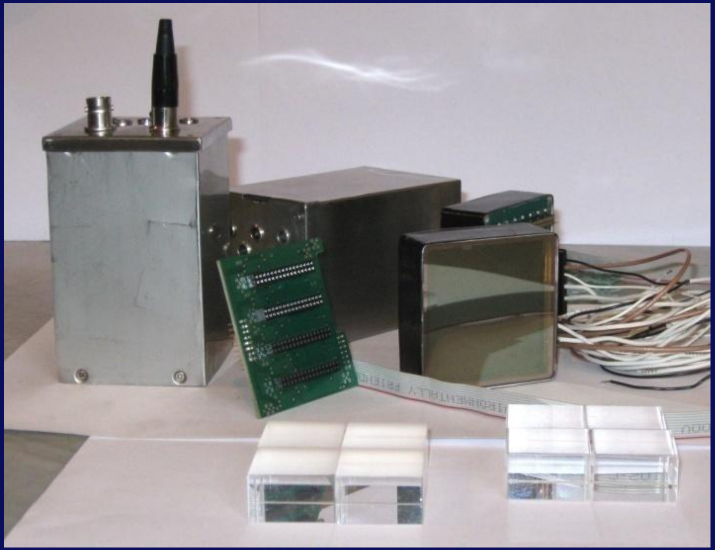


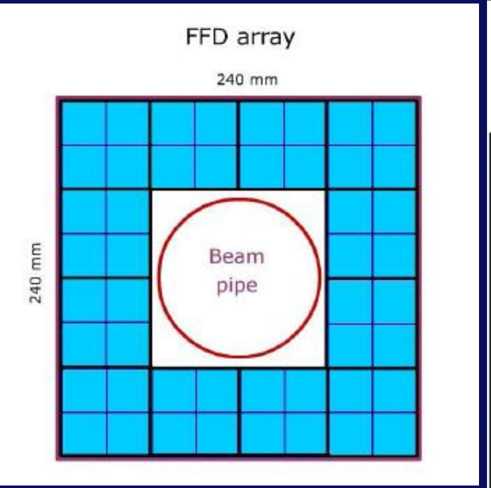
Fast Forward Detector (FFD)

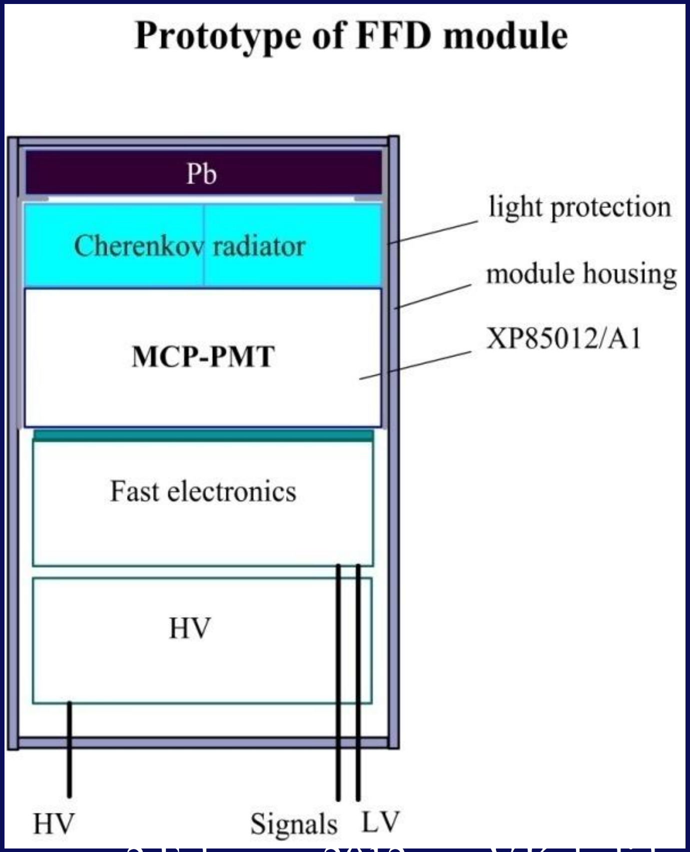


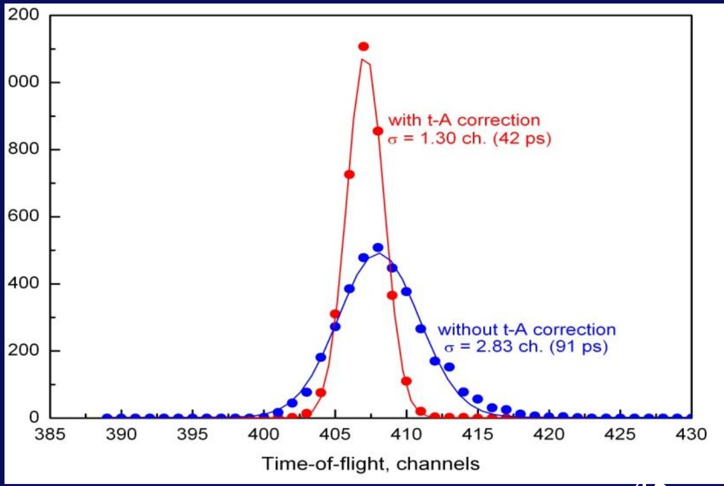


FFD: quartz Cherenkov radiator with micro-channel plate PMT



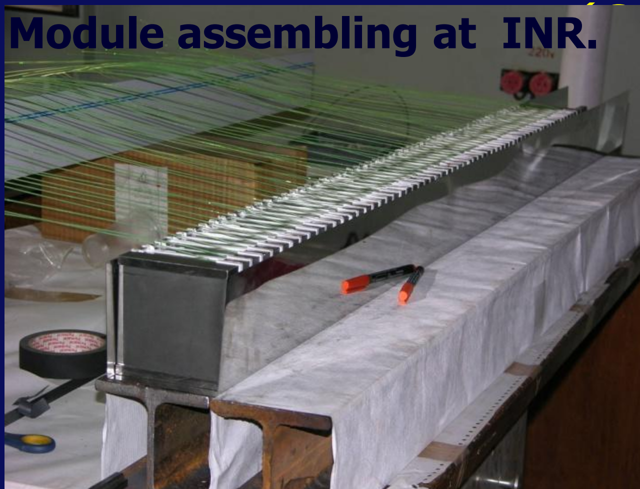


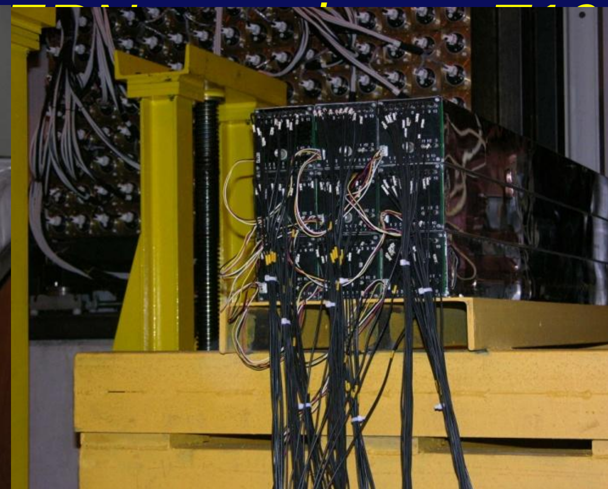




Beam test of 3x3 supermodule at low energies

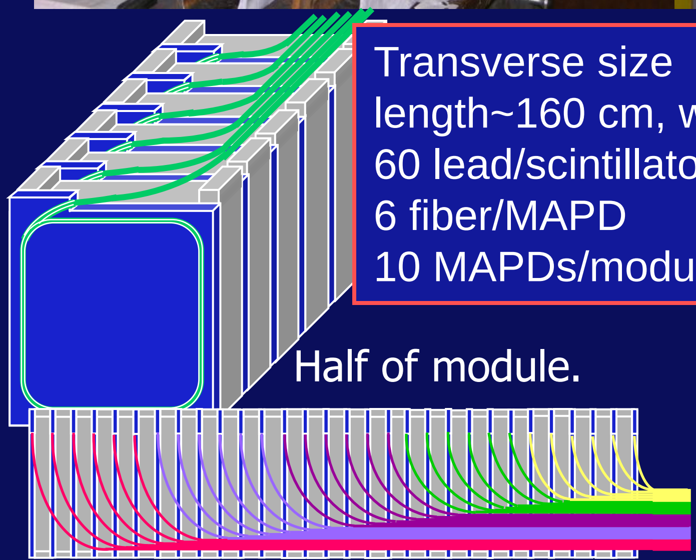
(CERN test beam T10)



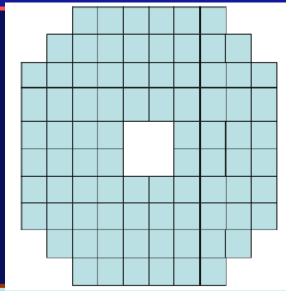


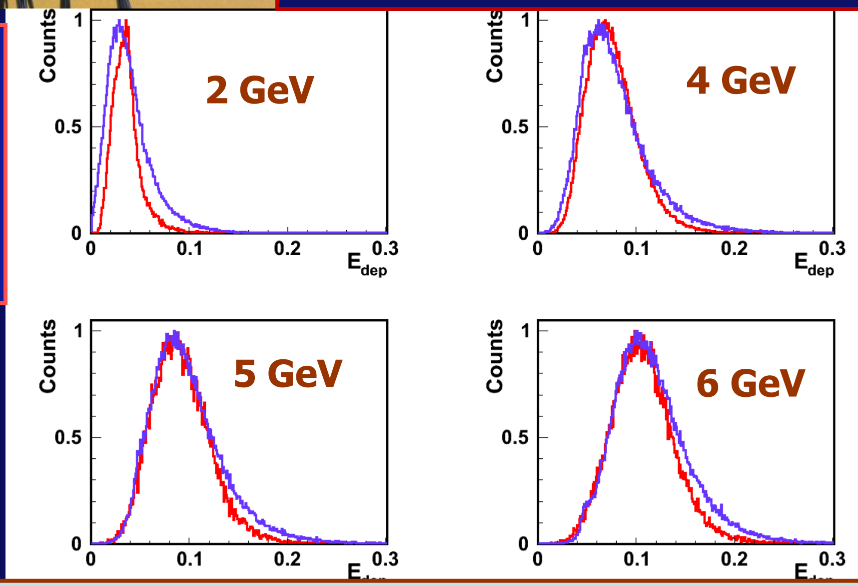
Tasks of beam test:

- *E resolution at 1-6 GeV*
- *detector performance at NICA energies*
- *performance of new MAPDs with high dynamical range (Sadygov-Dubna-Zecotek)*
- *feasibility of calibration of individual sections with μ*



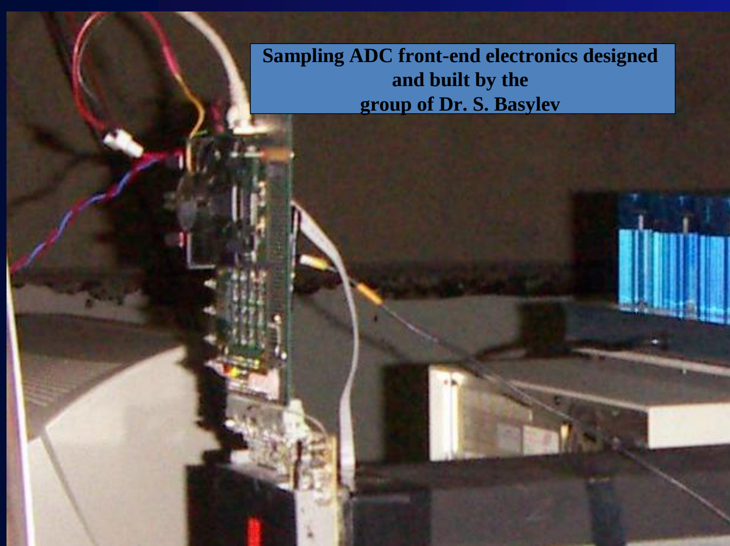
Transverse size 10x10 cm^2, length~160 cm, weight ~120 kg.
60 lead/scintillator sandwiches.
6 fiber/MAPD
10 MAPDs/module



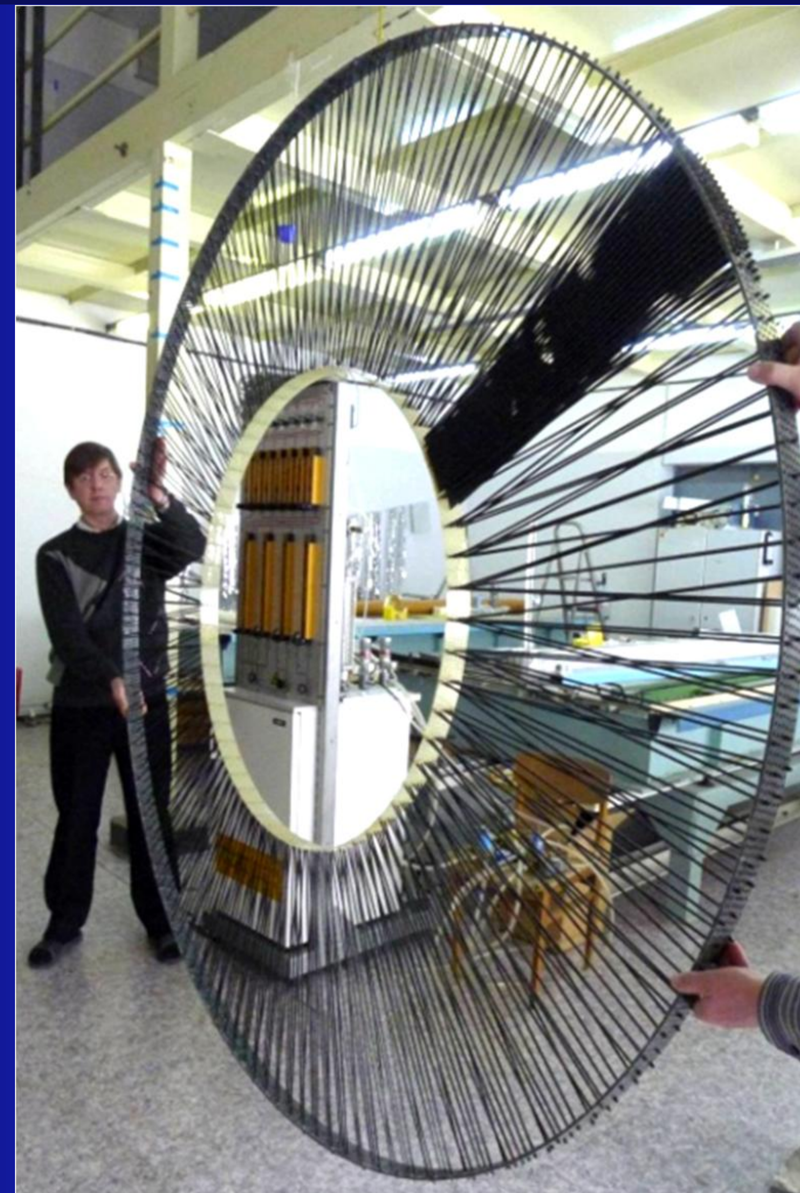


- *Experimental and MC spectra (good agreement at > 2 GeV); studies are required at 2 GeV*
- *The energy resolution of 3x3 supermodule: ~56% (stochastic term) + 3.7% (constant term).*

ECAL-ReadOut

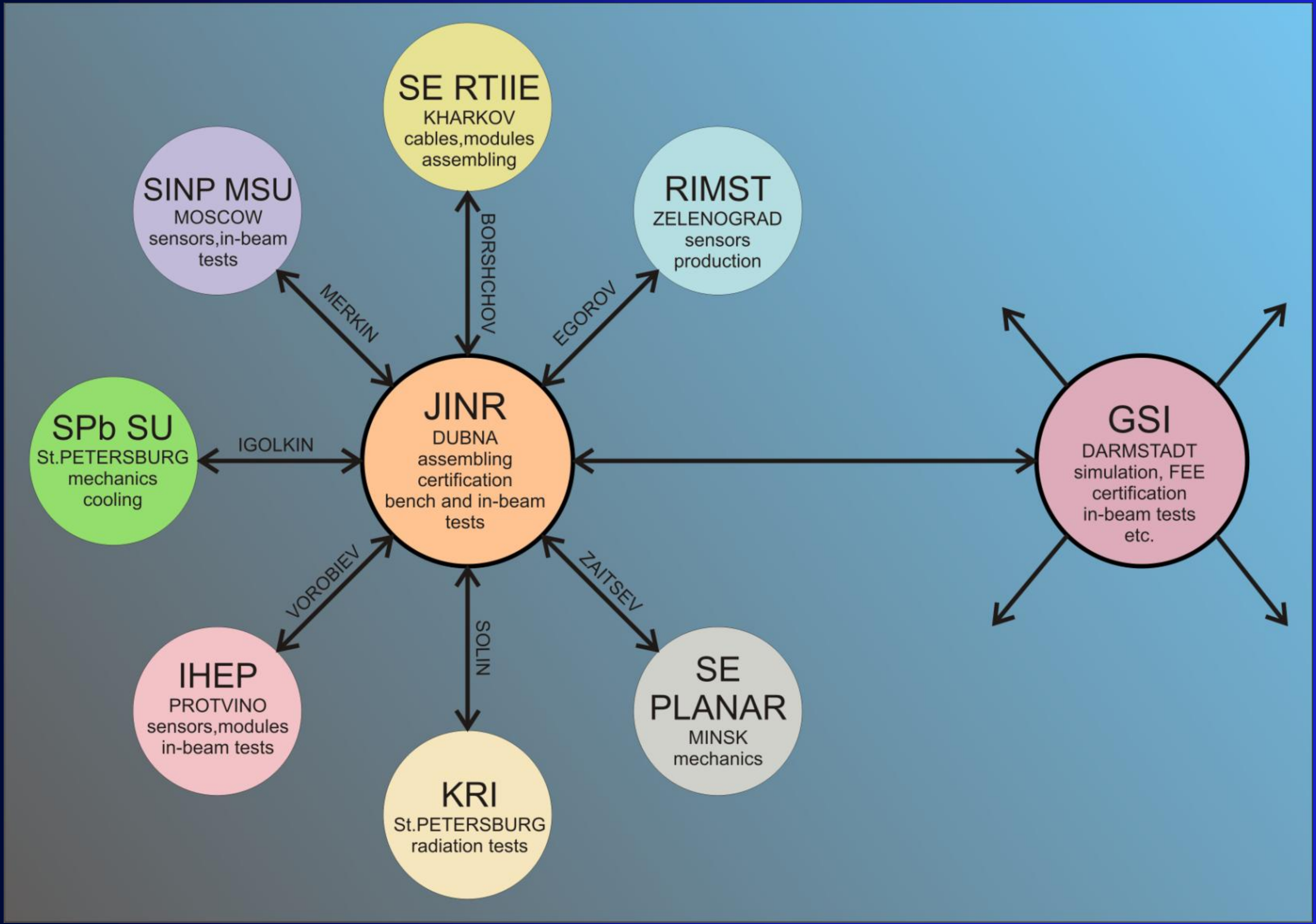


Straw f.s. prototype



CBM-MPD consortium structure

(for VD module development)



Inner Tracker (IT)

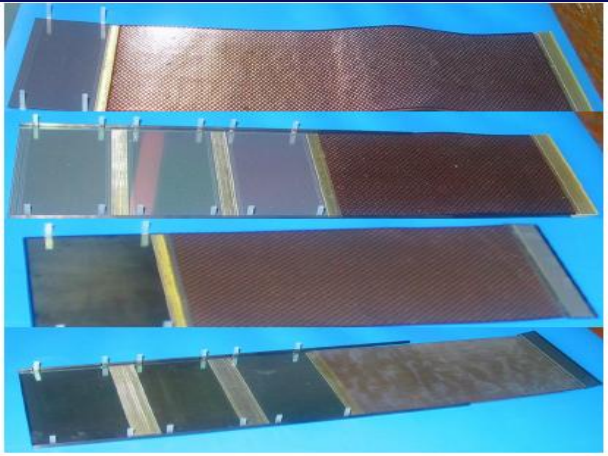


Figure 1: Prototypes of CBM STS sensitive modules.

- 4 cylindrical & disk layers
- 300 μm double-sided silicon microstrip detectors, pitch - 100 μm
- Thickness/layer ~ 0.8% X_0
- Barrel: R=1-4 cm, coverage $|\eta|<2.5$ 806 sensors of 62x62 mm^2
- Disks: under optimization
- resolution: σ_z = 120 μm, $\sigma_{r\phi}$ = 23 μm

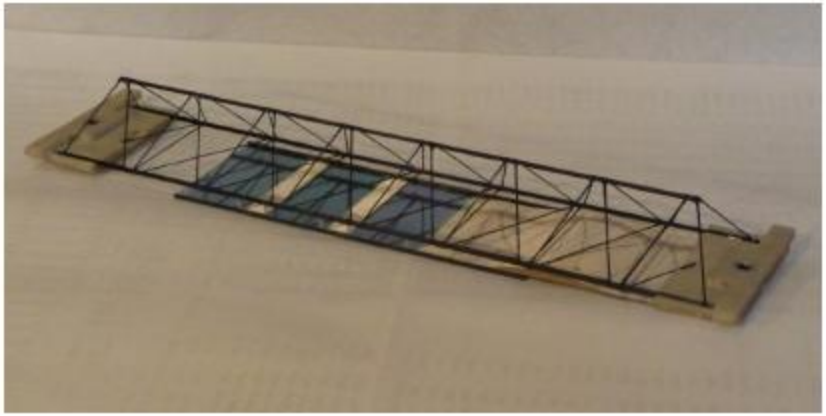
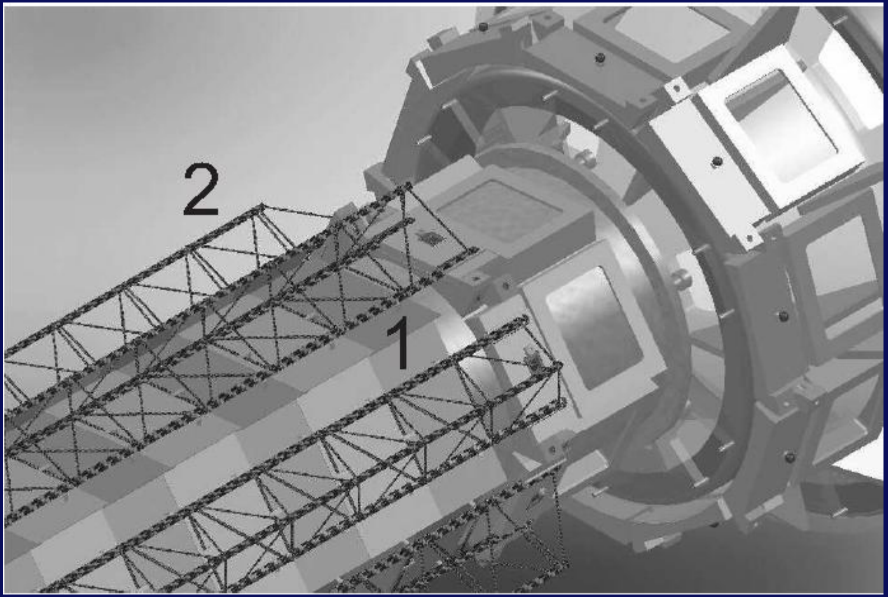
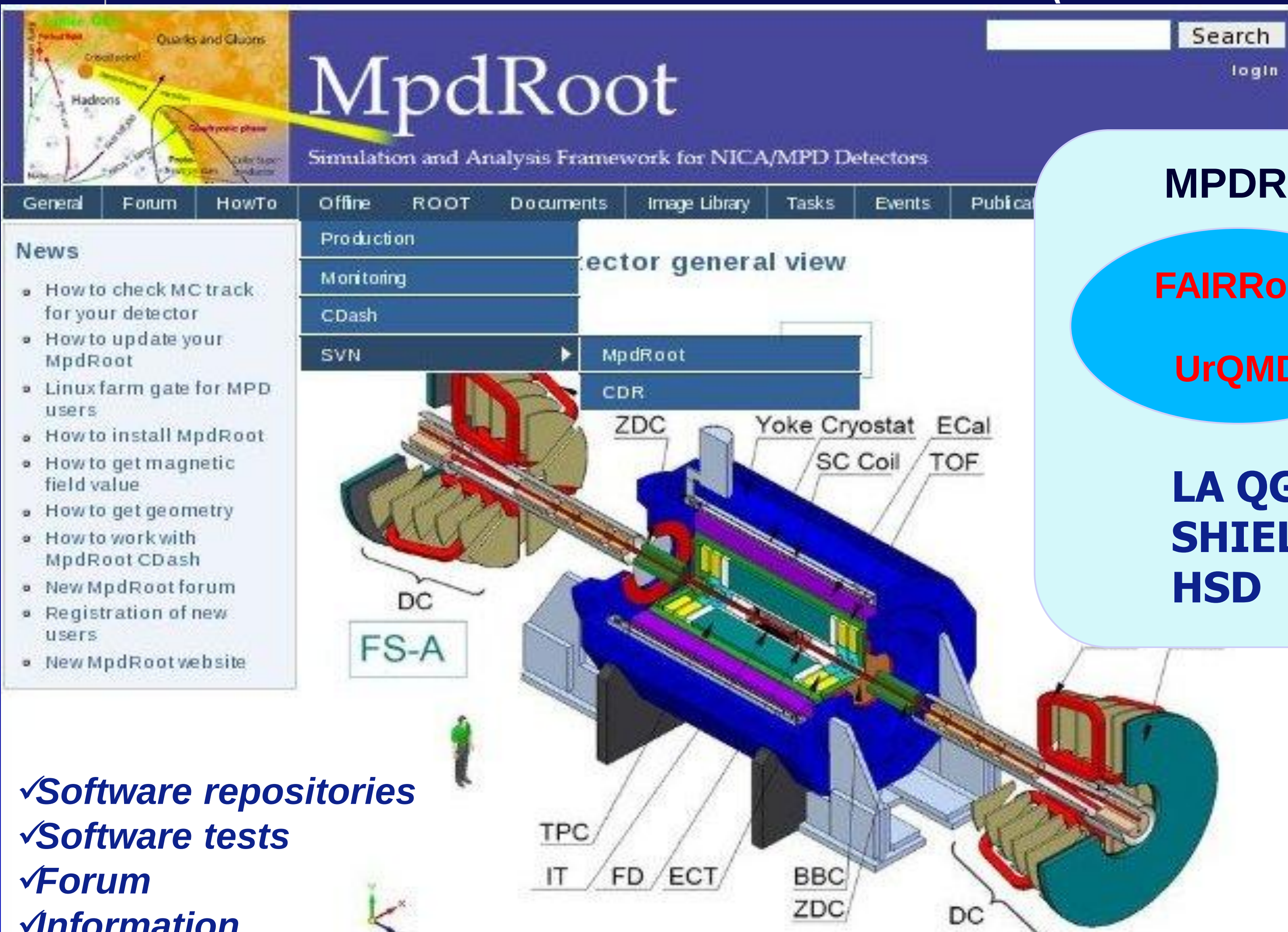


Figure 2: Prototype of the ladder of the CBM STS (super-module) with one sensitive detector module built of three sensors



Framework for MPD (…+ models)



MPDRoot

FAIRRoot

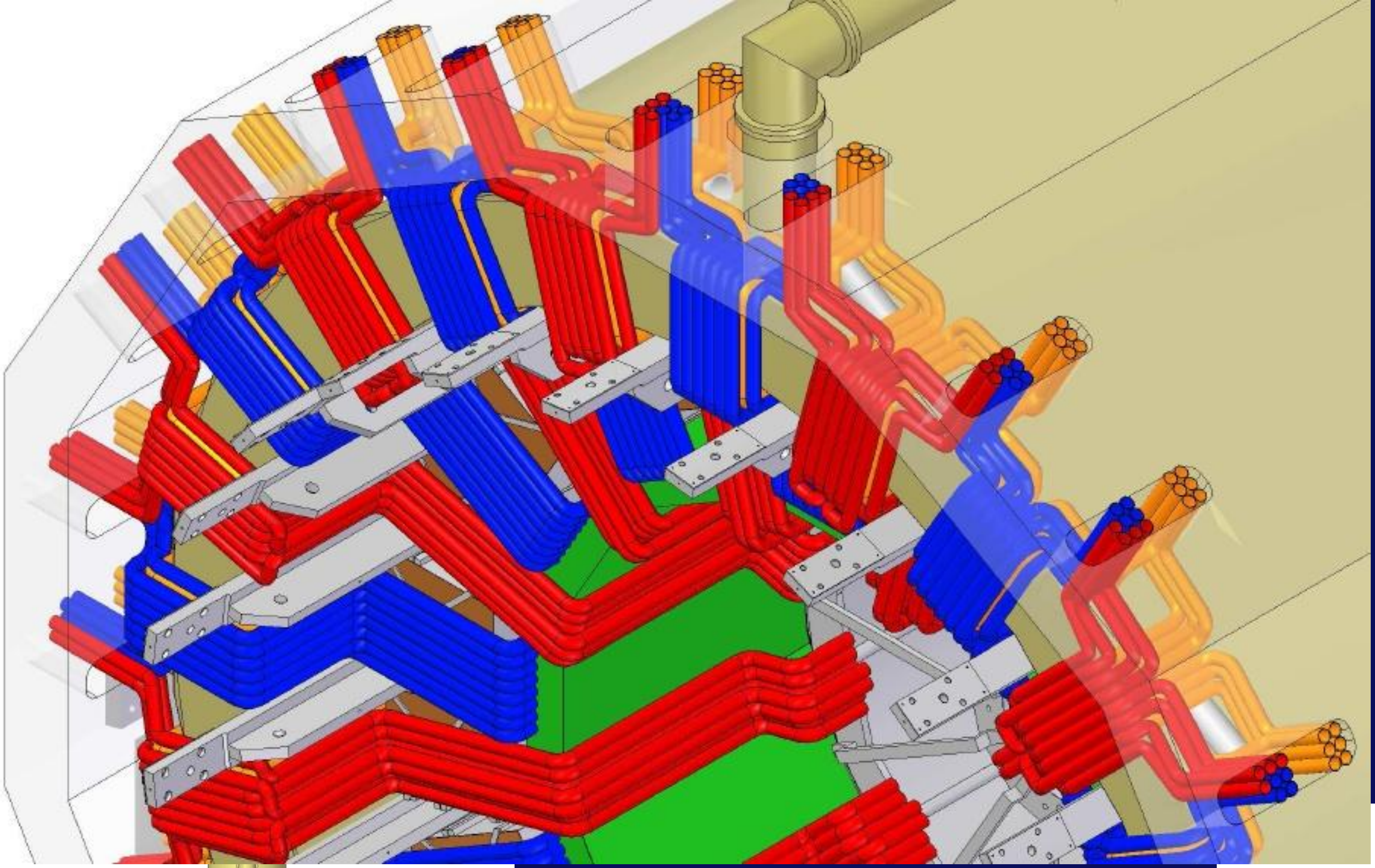
UrQMD

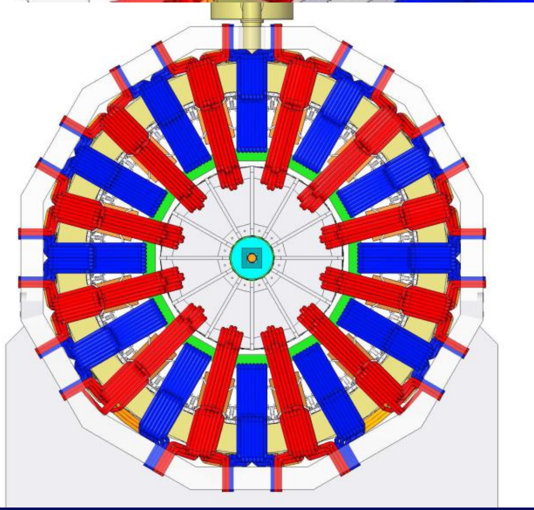
LA QGSM
SHIELD
HSD

nucleus-nucleus models

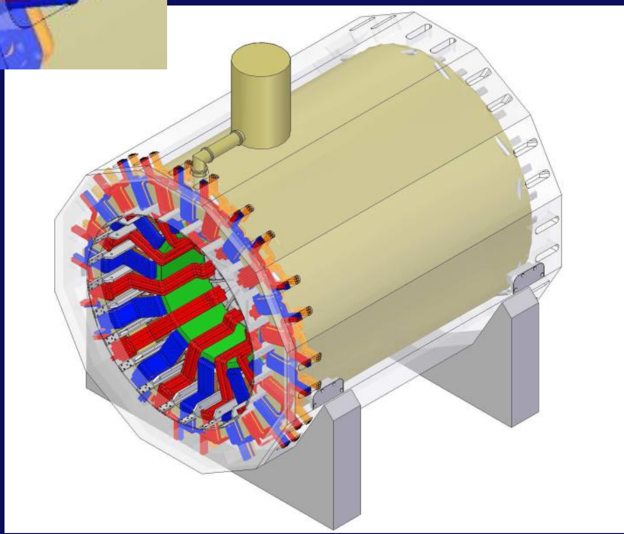
✓Software repositories
✓Software tests
✓Forum
✓Information
etc.

- Inherits basic properties from FairRoot (developed at GSI), C++ classes
- Extended set of event generators for heavy ion collisions
- Detector composition and geometry; particle propagation by GEANT3/4
- Advanced detector response functions, realistic tracking and PID included

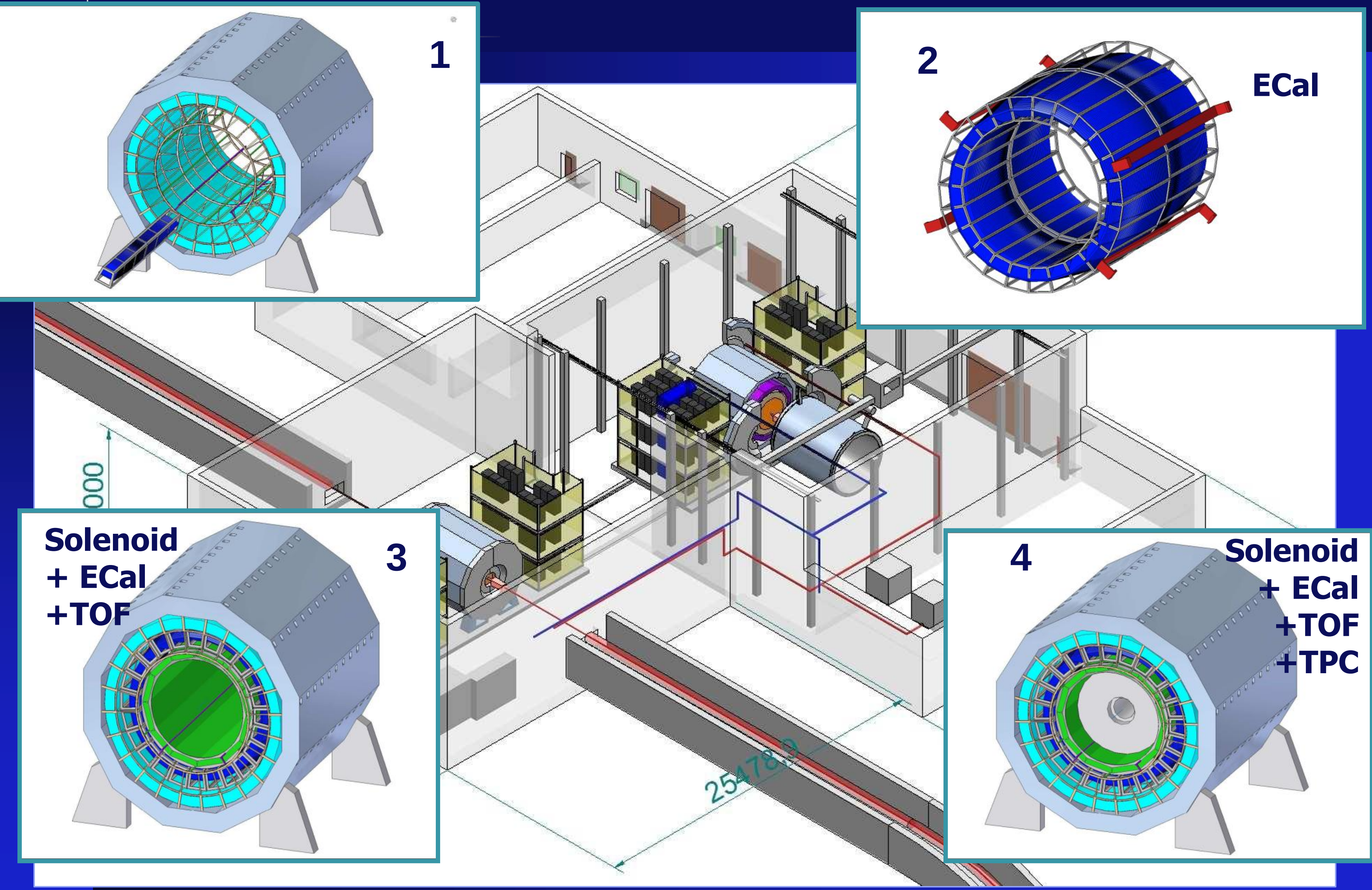




Cabling and cooling lines scheme

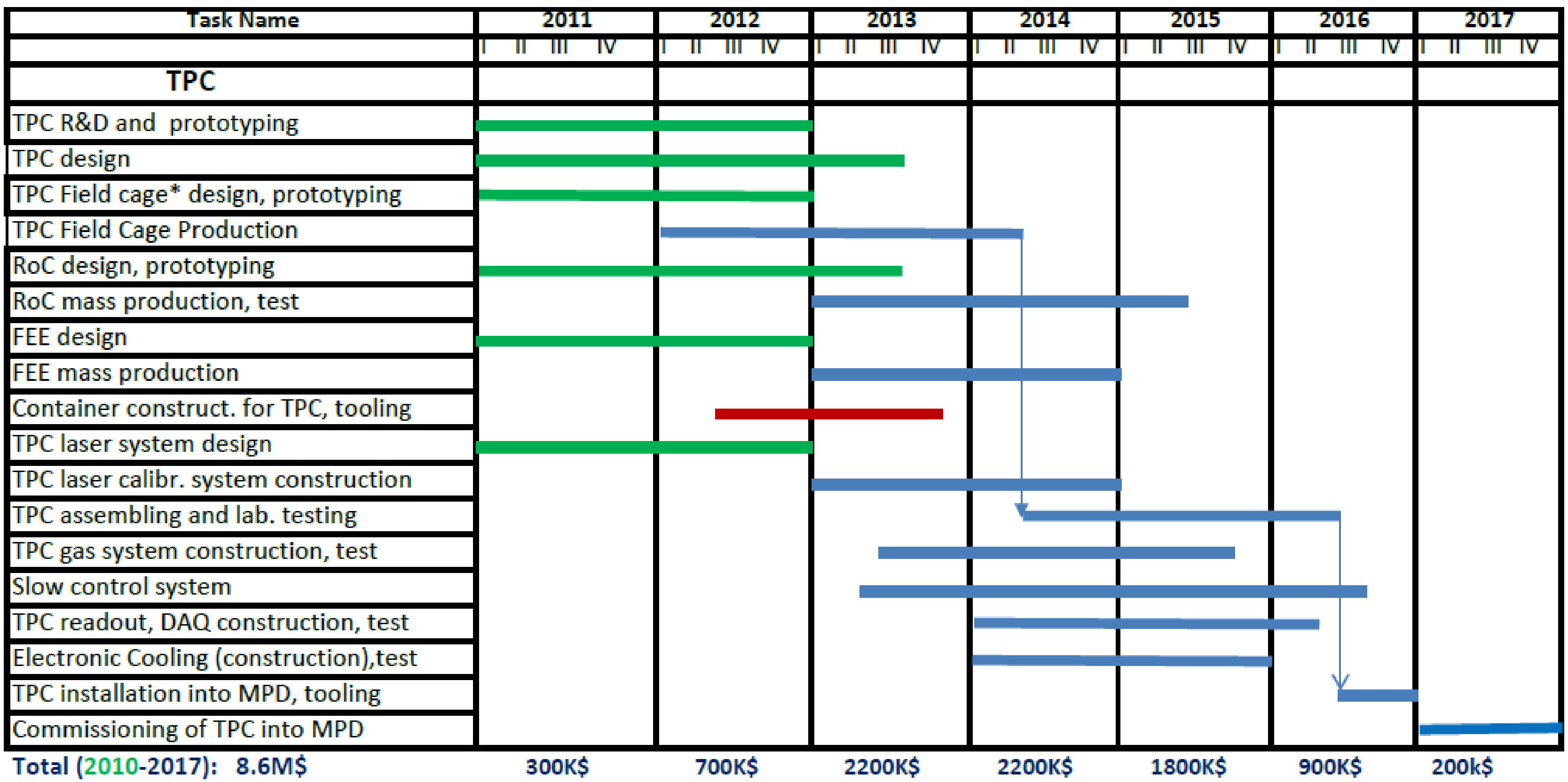


Assembly and maintenance



Time schedule of TPC design and construction

Time Schedule of R&D, Desing, and Production of TPC/MPD (including Infrustructure)



R&D, Design, Prototyping Cost - 1,5 M$ (2010-2013) — **R&D, Design, Prototyping**

Productin Cost - 6,85 M$ (2012-2017) — **Production**

Infrustructure Cost - 0,25 M$ (2012-2013) — **Inftrustructure**

Timetable of MPD construction and commissioning

	Stage/Year	1	2	3	4	5	Total
	Budget profile for MPD ----→	1080	12500	15500	9300	2560	**40940**
1	**Experimental Hall**						
	NICA Hall Construction						
	Electricity,water & infrastructure						
	Crane(construction & certification)						
2	**Superconducting Magnet**						
	Magnet TDR and Tender						
	Call for Tender-Yoke,SC,trim coils						
	Contracts signing						
	Construction of Iron York & SC						
	Transportation						
	Cryogenics for Solenoid						
	Assembling & Commiss. of Solenoid						
	Field measurements						
3	**TPC**						
	TPC Assembling workshop						
	TPC Construction						
	TPC tests						
	TPC installation and Commissioning						
4	**TOF**						
	TOF Assembling area						
	Test area of TOF mRPC						
	TOF Mass Production and test						
	TOF installation & Commissioning						
5	**ECal modules production**						
	ECal Assembling in sectors						
	ECal installation & Commissioning						
6	**ZDC construction and installation**						
7	**Electronics, Network and**						
	DAQ production &implementation						
	Control Room construction						
	Slow Control system implementation						
	Computing for Data taking & network						
8	**Detector Assembling**						
9	**Commissioning and Cosmic Tests**						

Start up minimum

Conclusion

- essential progress is achieved in the development of HEP basic facility – Nuclotron-M -> NICA

- the proper preparation of FT area is going well

- that allow to start up a challenging research program already at the Nuclotron *attractive for wide international collaborations*

- the corresponding project - **BM@N** has been initiated for preparation

Conclusion

- The MPD design - close to completion
- The MPD technical project preparation is under progress
- The key milestones should be defined/corr. asap
- The major element production/construction should start-up in 2012

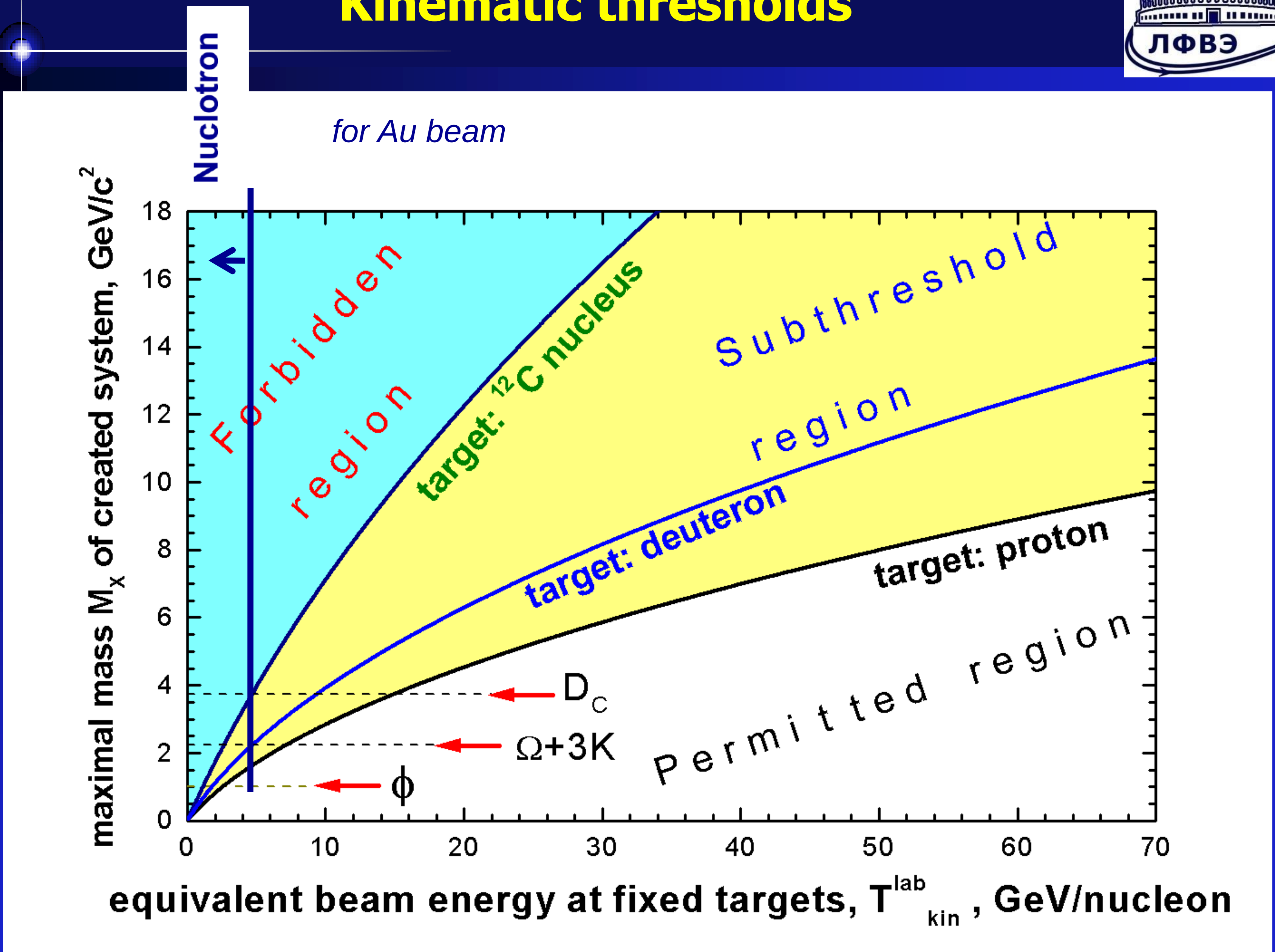
Possible tasks

- to obtain overall picture of available energy regions for Au + Au in the c.m.s. *(s. # 6)*

- to evaluate kinematic thresholds for different Mx production in Au + Au interactions in f.t. experiment

- to upgrade the MPD design in order to reach max yields / efficiencies for vector mesons (s. # 38)

Kinematic thresholds




Thank you

spare

MPD construction staging

is driven

- on one hand, by the goal

to start energy scan as soon as the first beams are available

(simultaneously with detector & machine final commissioning)

- on the other hand,

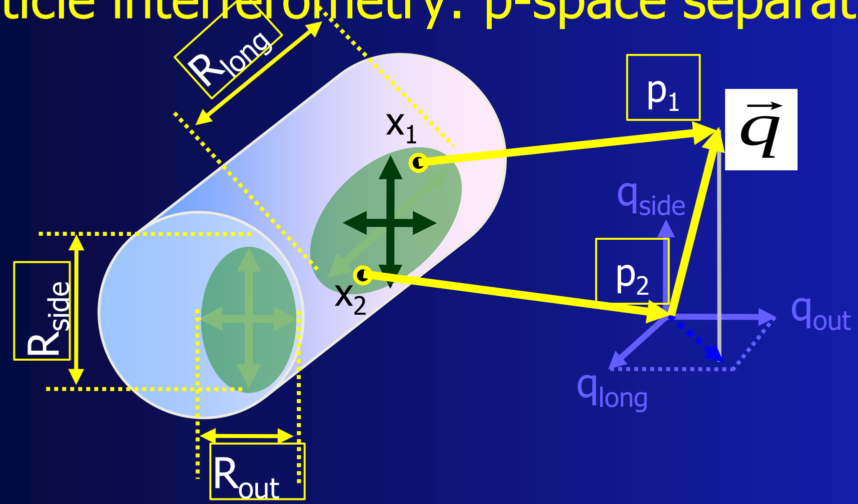
by the present constrains in resources & manpower

the conditions to be fulfilled:

- ***keeping flexibility for upgrading towards interesting physics***
- ***foreseeing possibility of new technology implementations***
- ***foreseeing fields of activities for new potential collaborators***

HBT interferometry

- Two-particle interferometry: p-space separation ↔ space-time separation



$$\vec{q} = \vec{p}_1 - \vec{p}_2$$

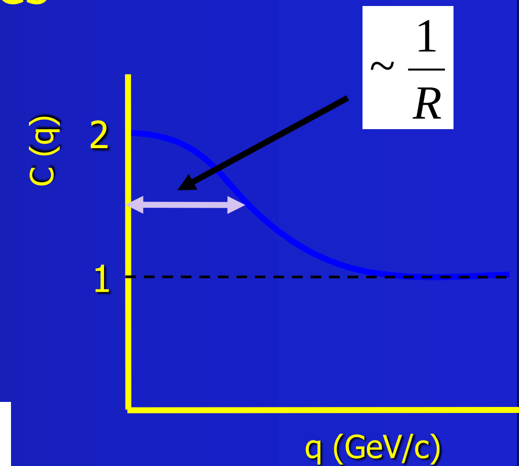
$$\vec{k} = \frac{1}{2}\left(\vec{p}_2 + \vec{p}_1\right)$$

- HBT: Quantum interference between identical particles

$$C(\vec{q},\vec{k}) = \frac{P(\vec{p}_1,\vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} = \frac{\text{real}}{\text{mixed}}$$

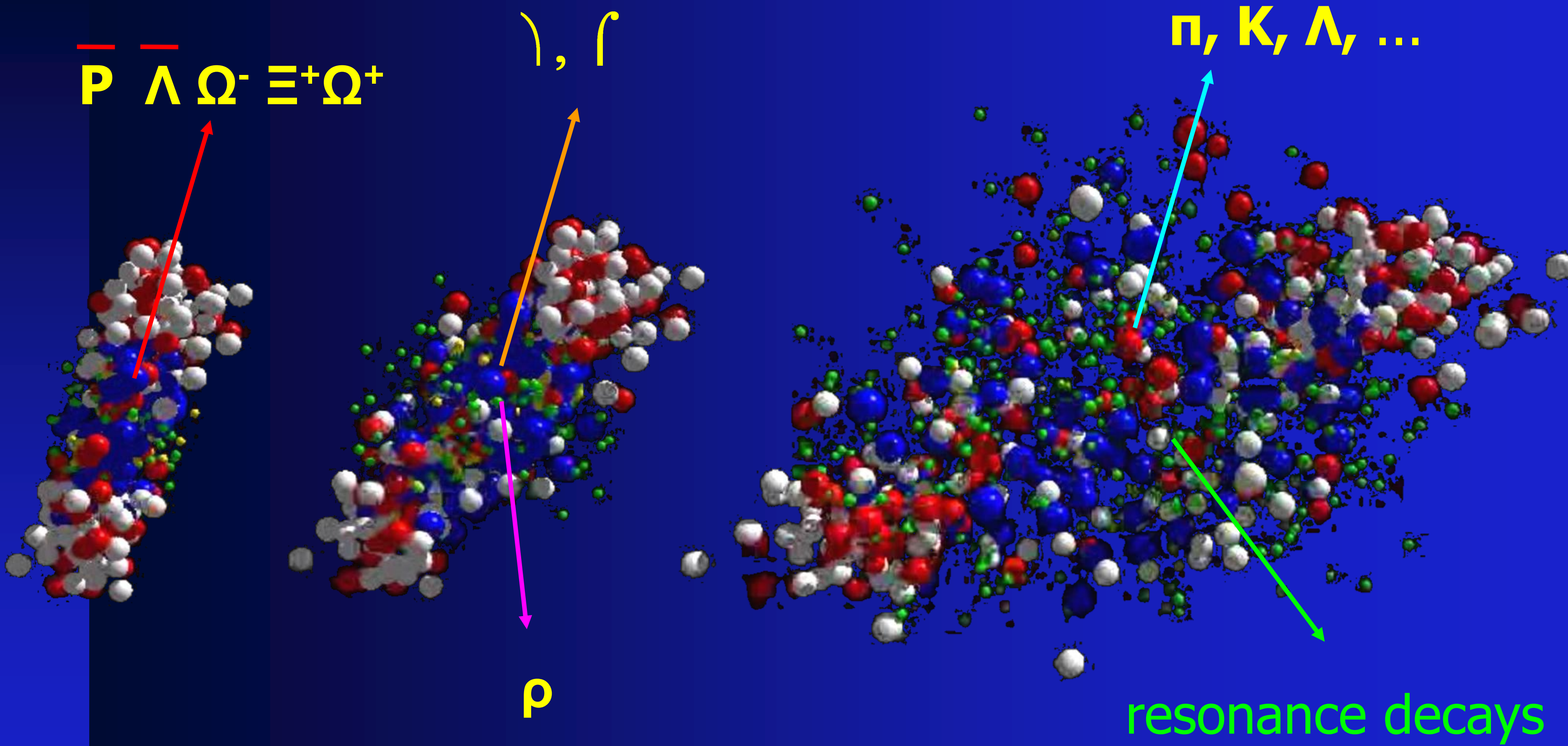
Gaussian model (3-d):

$$C(\vec{q},\vec{k}) = 1 + \lambda(\vec{k})\, e^{-q_{\text{out}}^2 R_{\text{out}}^2 - q_{\text{side}}^2 R_{\text{side}}^2 - q_{\text{long}}^2 R_{\text{long}}^2}$$



– Final-state effects (Coulomb, strong) also can cause correlations, need to be accounted for

Messengers from the dense fireball at Nuclotron beam energies

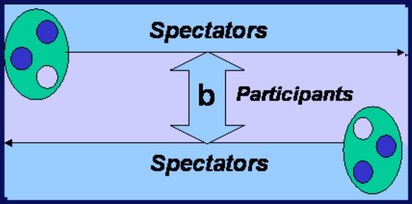


JINR contribution -Transition Radiation Detectors

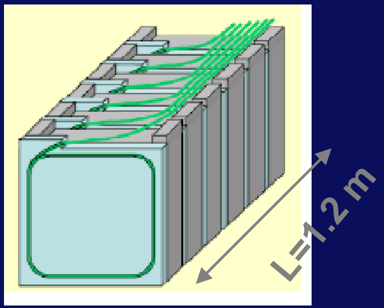
- The TRD is the part of the electron-positron ID system
- Large experience at LHEP JINR for ALICE@CERN


Visits of Prof. H. Stoeker (GSI) , and Prof. R. Hoyer (CERN)

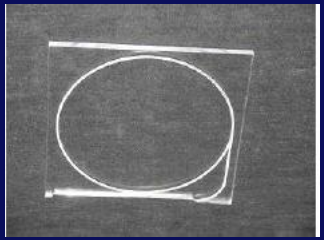
Zero Degree Calorimeter

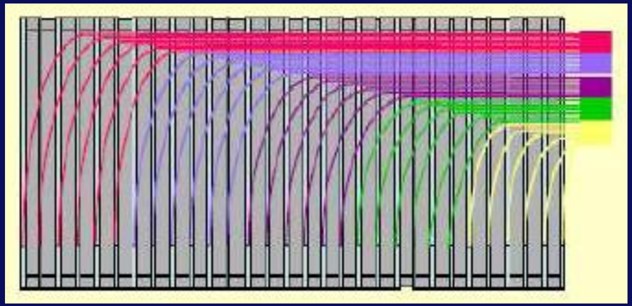


. measures the energy deposited by spectators.
▪ event centrality determination (offline b-selection)



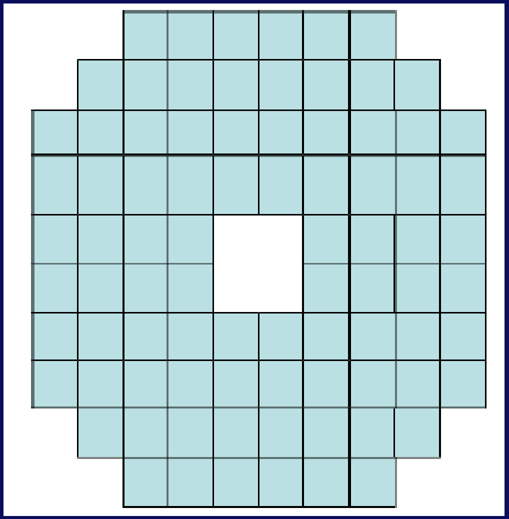
80 modules 5x5 cm^2

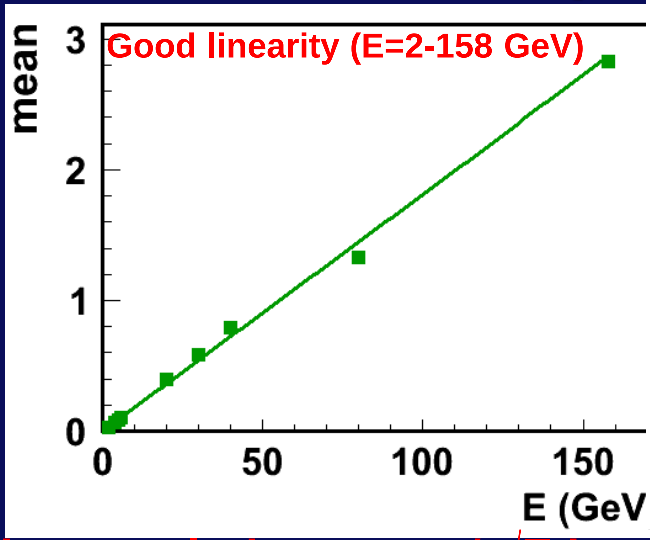


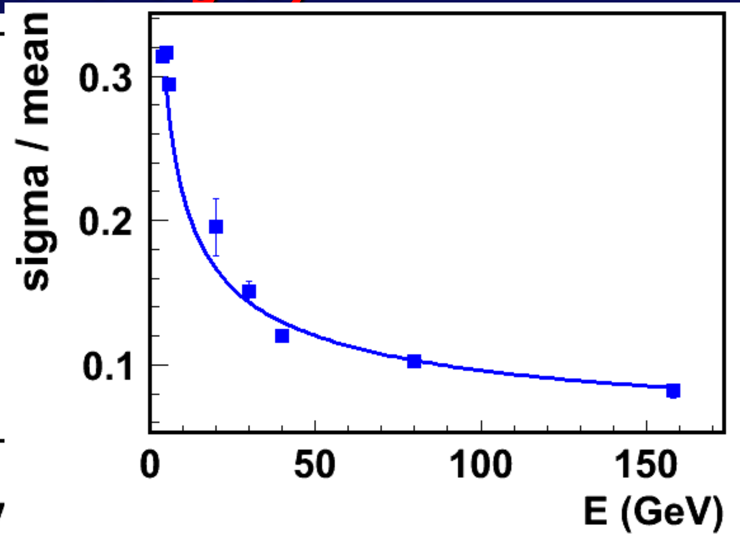


▪ Pb(16mm)+Scint.(4mm) sandwich
▪ 60 layers of lead-scintillator (1.2m, 5λ)
▪ 1mm WLS fibers + micropixel APD

------ Beam test of ZDC at SPS/CERN (NICA energies) -------

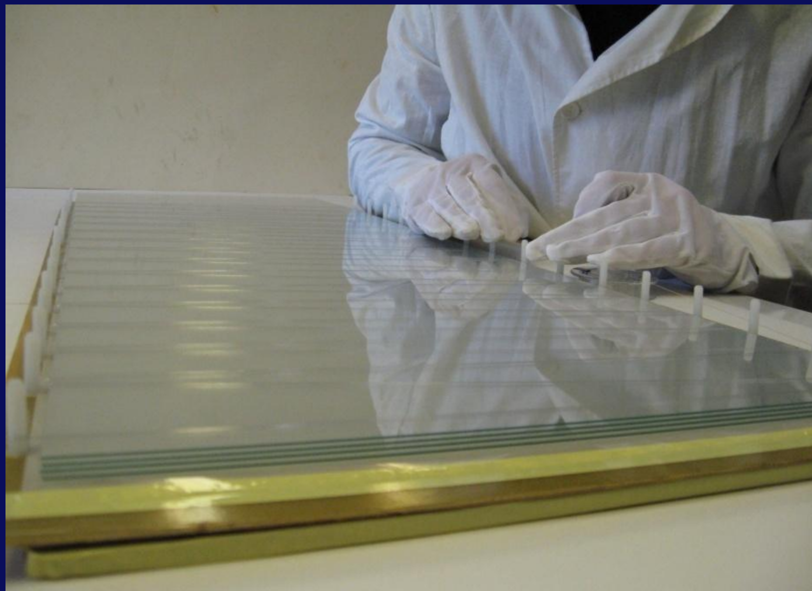




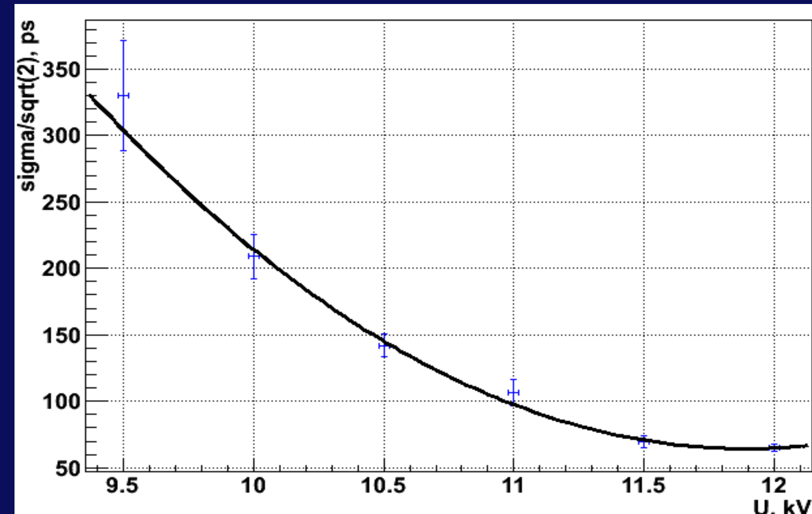


Design resolution ~ 60%/ $\sqrt{E}$ is proven

Full scale prototype tests



Assembling of a full-scale
RPC prototype with strip readout



Time resolution of the first RPC prototype with active area 7 x 14 cm^2 . Time resolution < 100 ps.

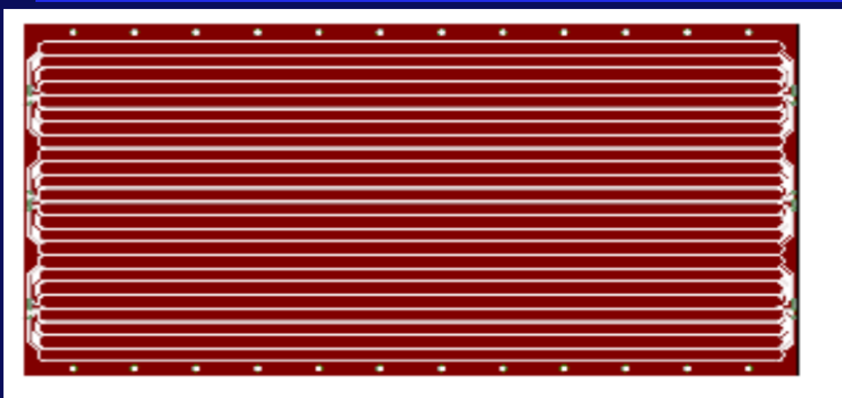
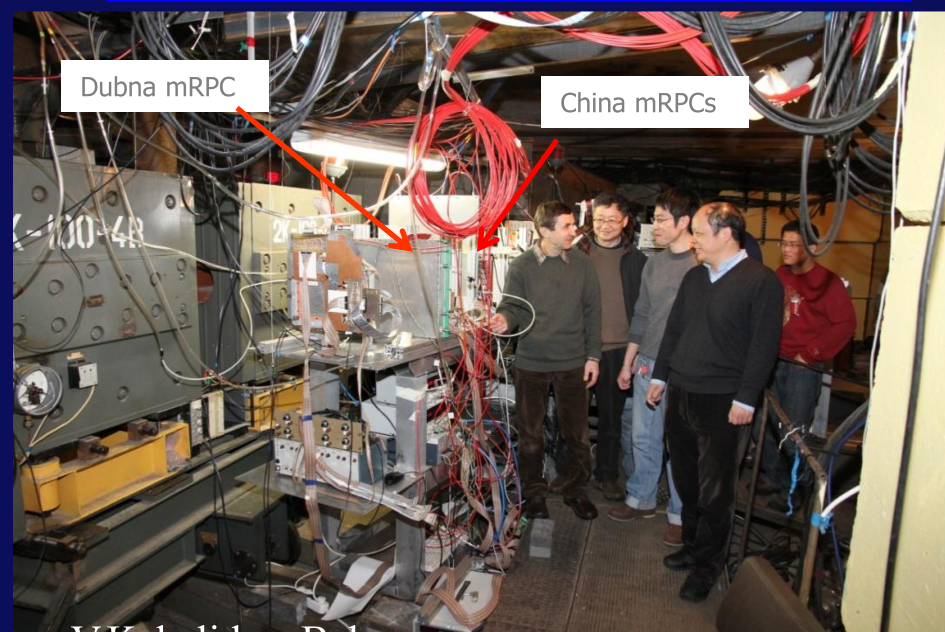


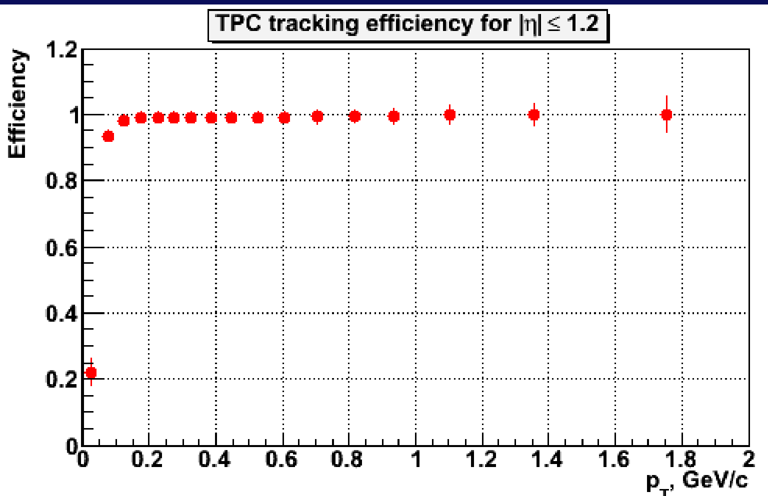
Fig. 2.78: A prototype mRPC plate with the read-out strips.

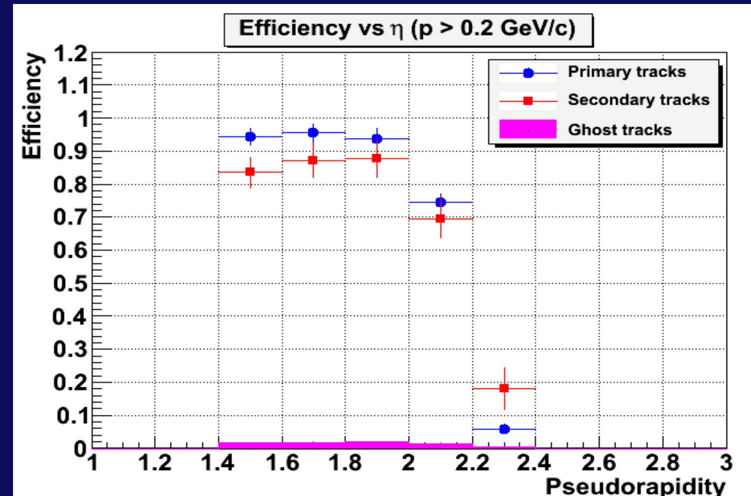


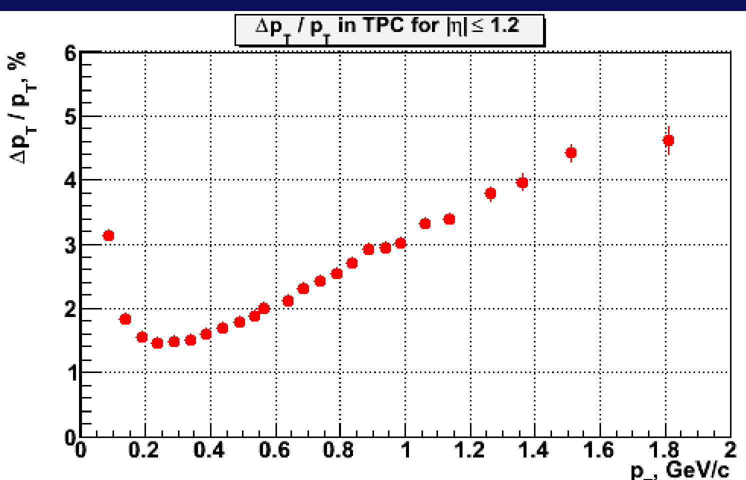
Beam tests for MPD at Nuclotron
Dubna (Russia), Beijing and Hefei (China)

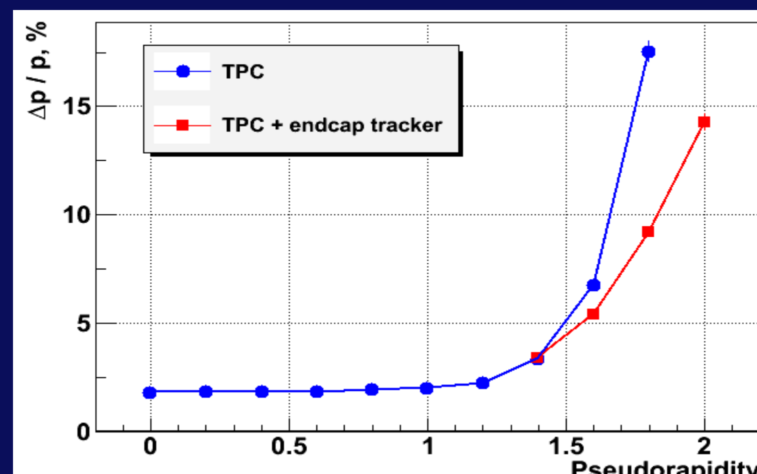
MPD performance

Tracking, PID



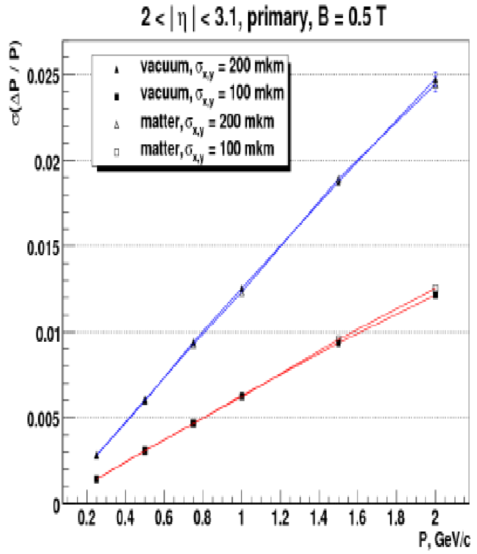




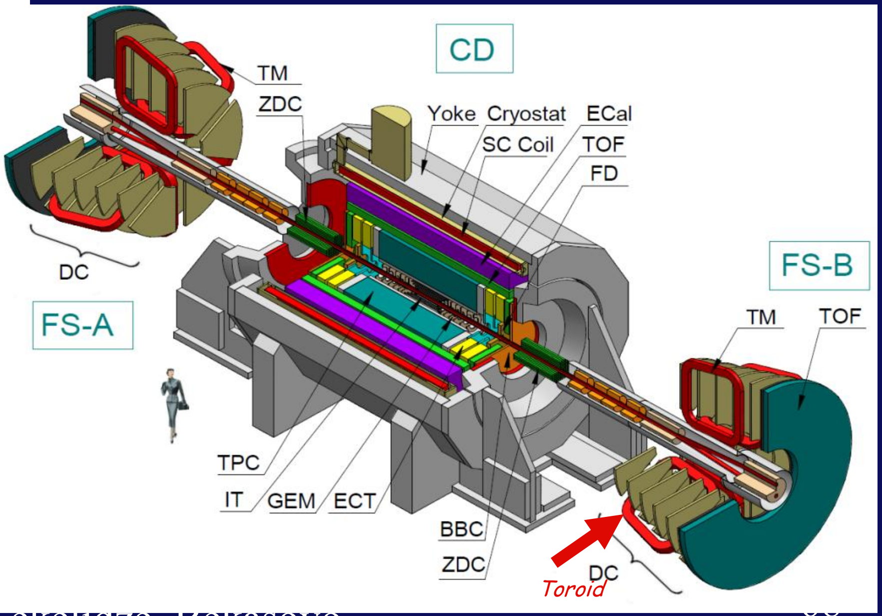


- $\Delta p/p < 3\%$ at $p_t < 1$ GeV/c (barrel)
- $\Delta p/p < 15\%$ for the endcap region
- TPC+IT tracking : $s_{r\varphi}, s_Z \sim 40$ mm

Forward Spectrometer

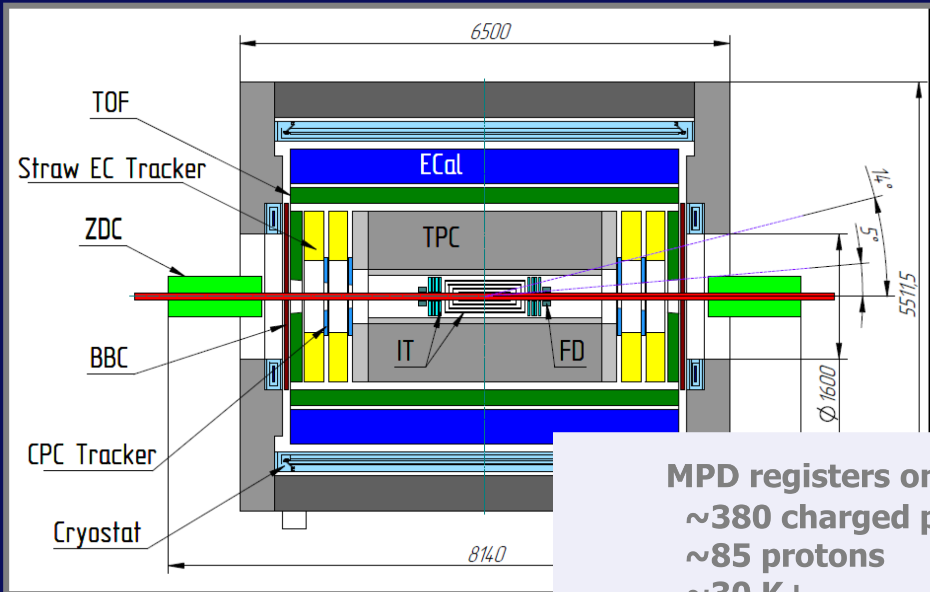


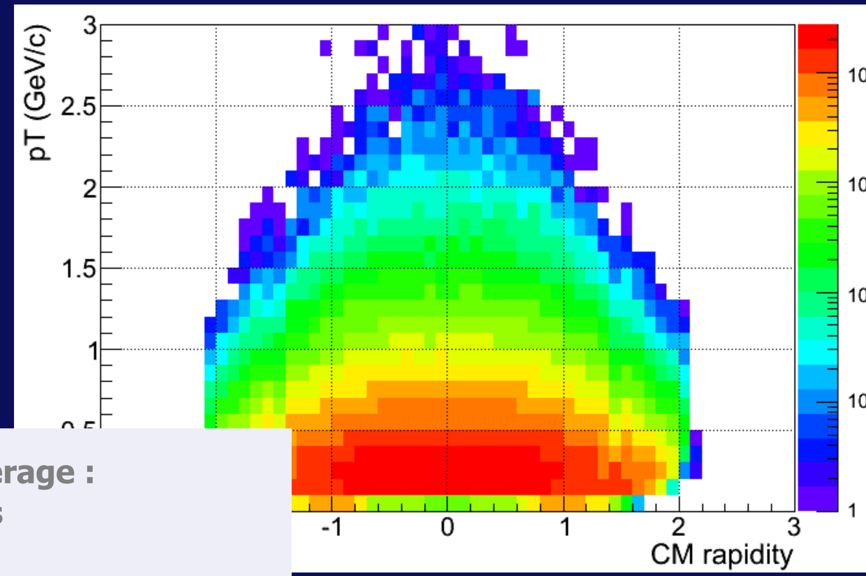
Momentum resolution of Forward Spectrometer as a function of particle momentum. Two lines represent coordinate resolution of tracker 200 µm (top line) and 100 µm (bottom line).



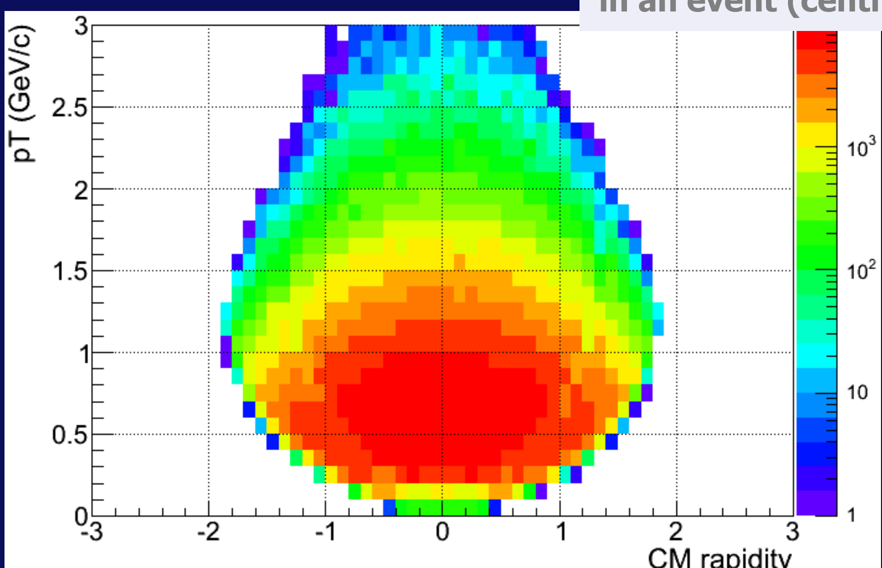
MPD phase-space coverage

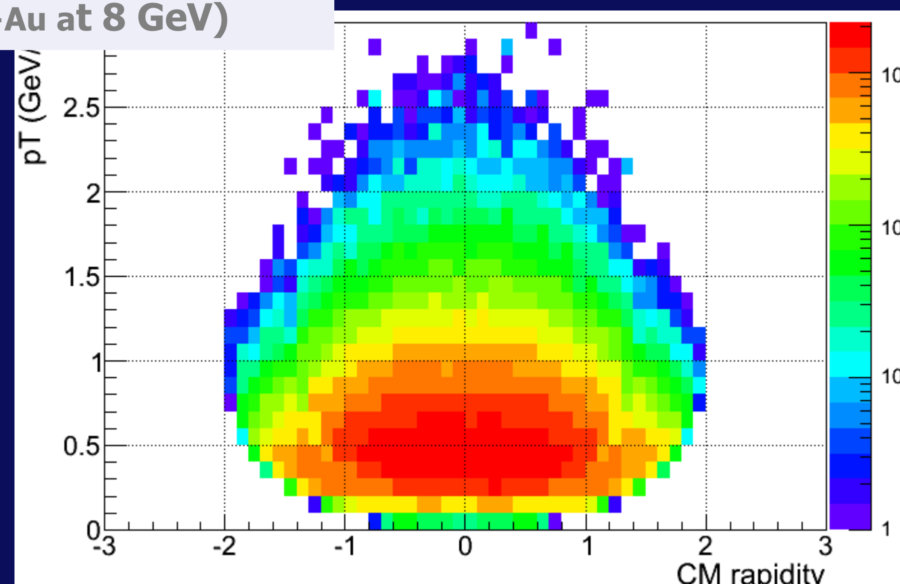
(barrel+endcap, **no IT,** identified hadrons)



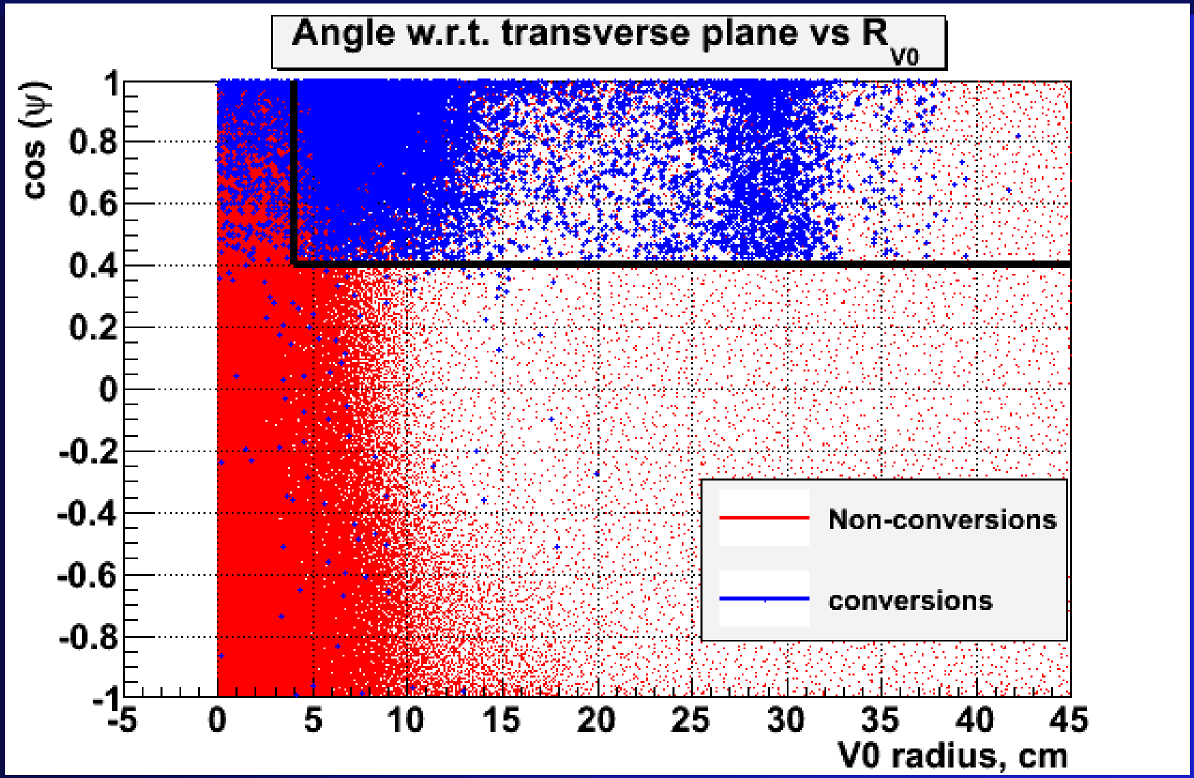


MPD registers on average :
~380 charged pions
~85 protons
~30 K+
in an event (central Au+Au at 8 GeV)





Rejection of conversion electrons in MPD



$\cos(\psi) = ([\mathbf{p}_1 \times \mathbf{p}_2],\mathbf{B}) / |[\mathbf{p}_1 \times \mathbf{p}_2]| / |\mathbf{B}|$

Selection: V0 > 4cm && cos(ψ) > 0.4

NICA/MPD. Bulk observables (1st Stage)

Particle spectra, yields, ratios:

- ❖ Basic information about the fireball properties:
  thMapping the QCD phase diagram in the (T-μ_B) plane
  termodynamics, chemistry, expansion
- ❖ Underlying dynamics, signal of deconfinement:
  non-monotonic behavior in hadron production
- ❖ Search for the Critical Point: particle number fluctuations, etc.

MPD detector relevant features:

- ❑ Large phase-space coverage
- ❑ Tracking and PID up to high pseudorapidities
- ❑ Precise event characterization