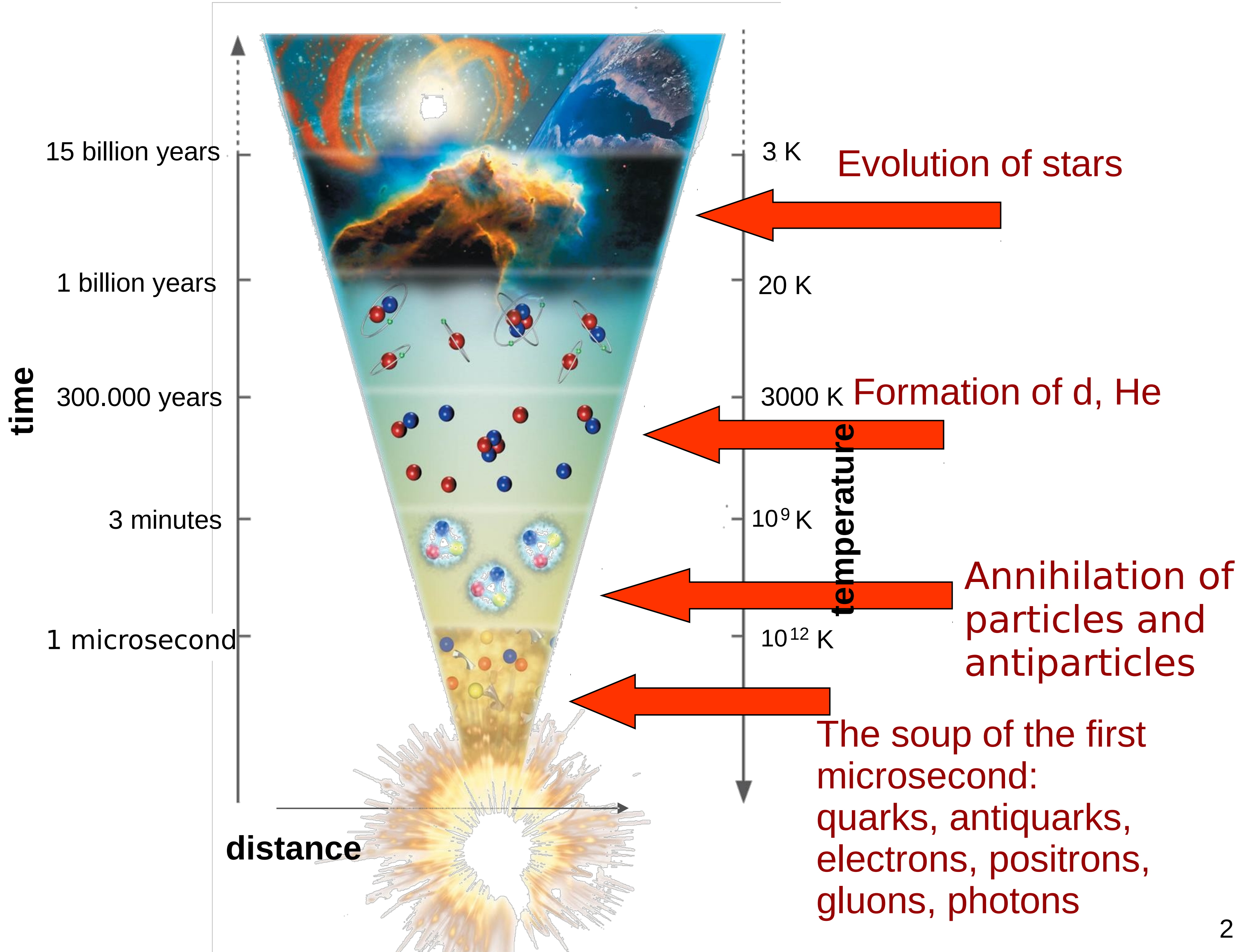
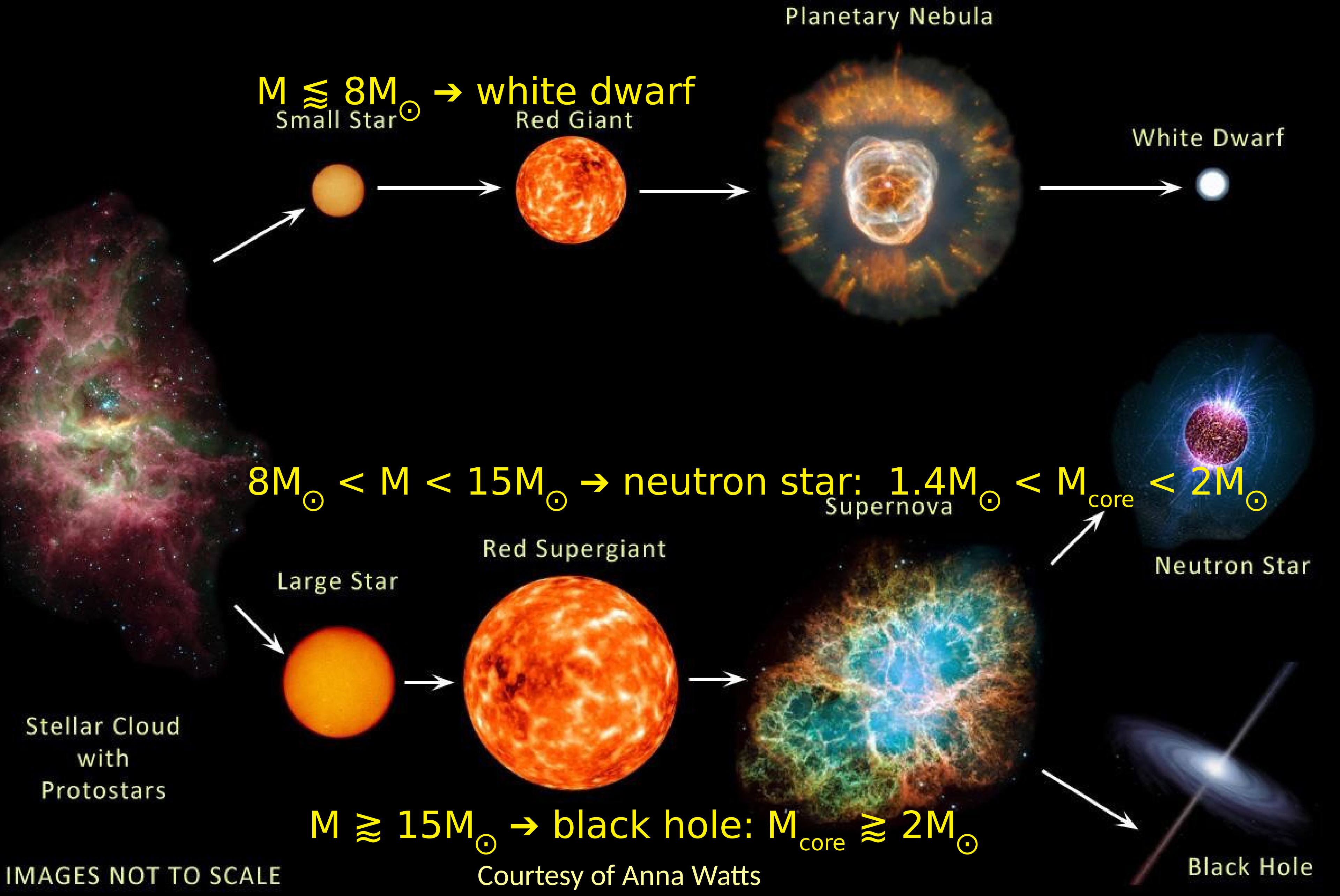
V. Kireyeu
VBLHEP, JINR

The evolution of matter in the universe

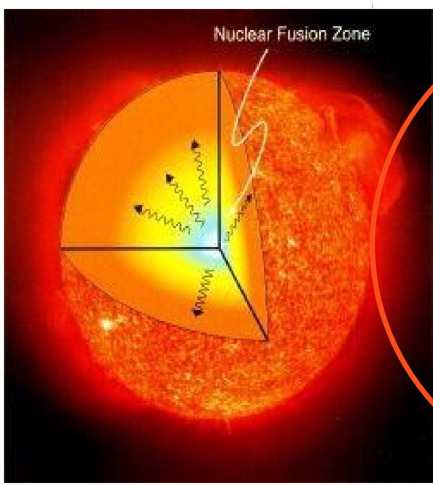


The evolution of stars

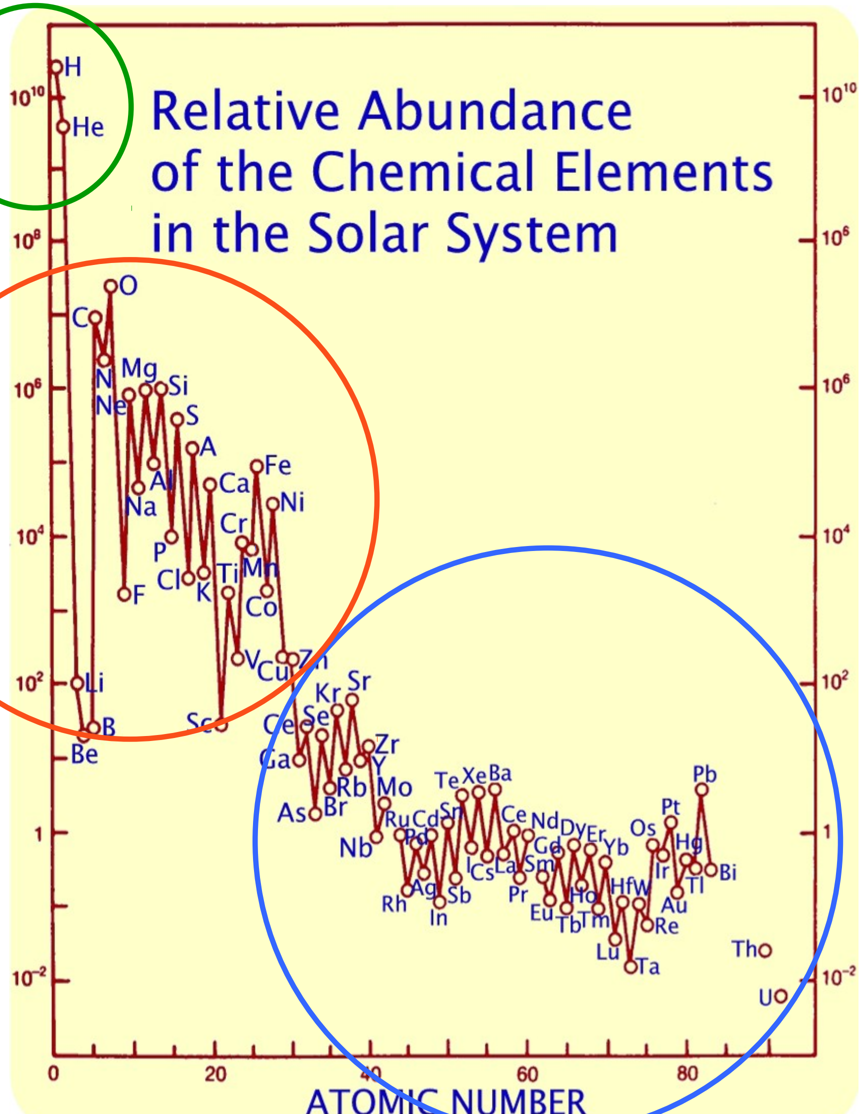


The Origin of Elements

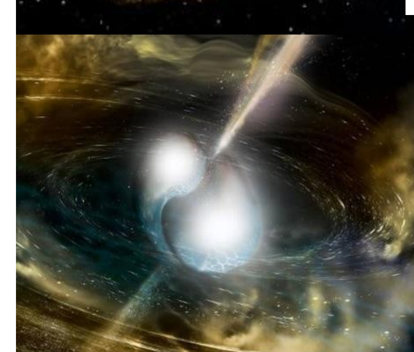
Nucleosynthesis after the Big Bang



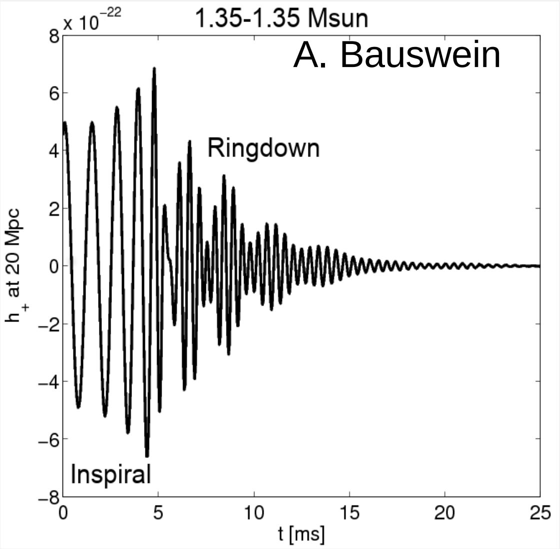
Nuclear fusion in stars



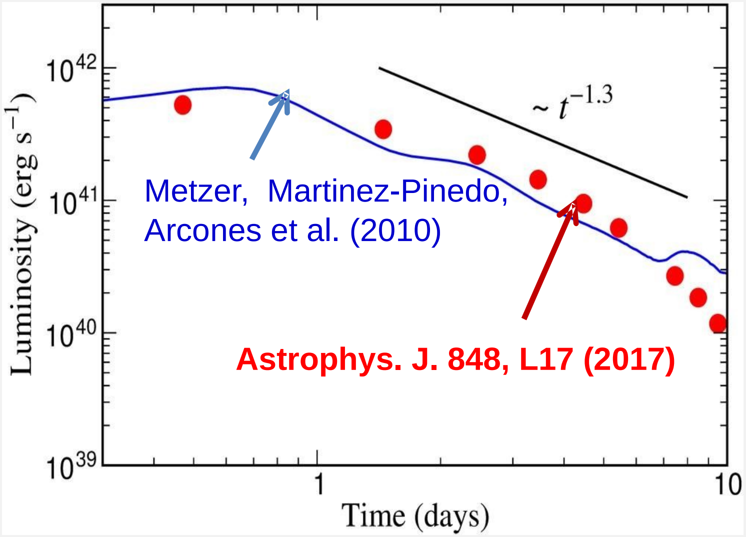
Neutron capture in Red Giants (s-process) or in supernovae or neutron star mergers (r-process)



Astrophysical site of heavy element production (r process) in the universe: Neutron star merger !



Gravitational Wave Signal

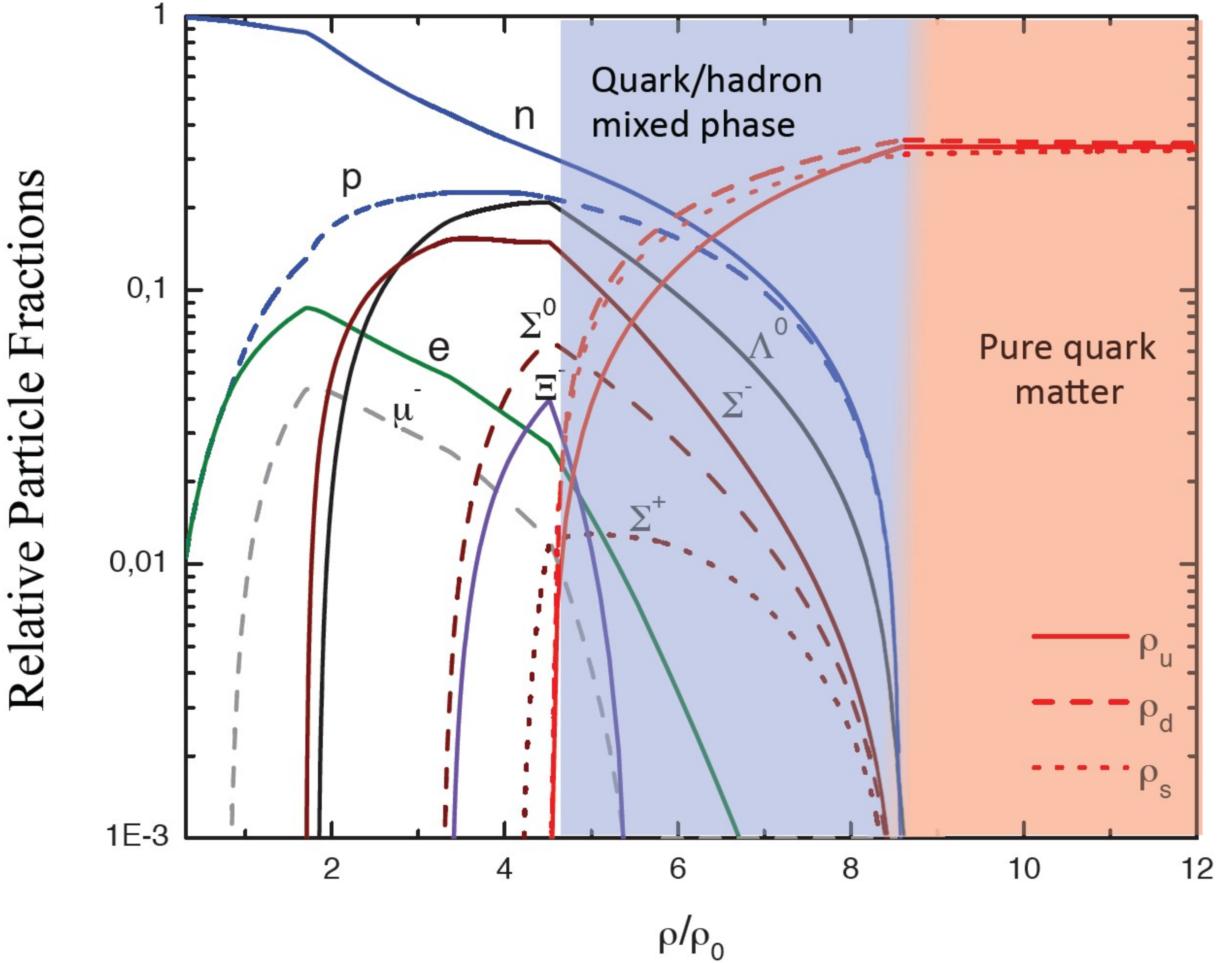


Electromagnetic "Kilonova" Signal

- Electromagnetic "Kilonova" signal due to "r process" in neutron star merger theoretically predicted by GSI scientists in 2010.
- Confirmation by recent astronomical observations after gravitational wave detection from GW170817 (August 2017).
- Source of heavy elements including gold, platinum and uranium.

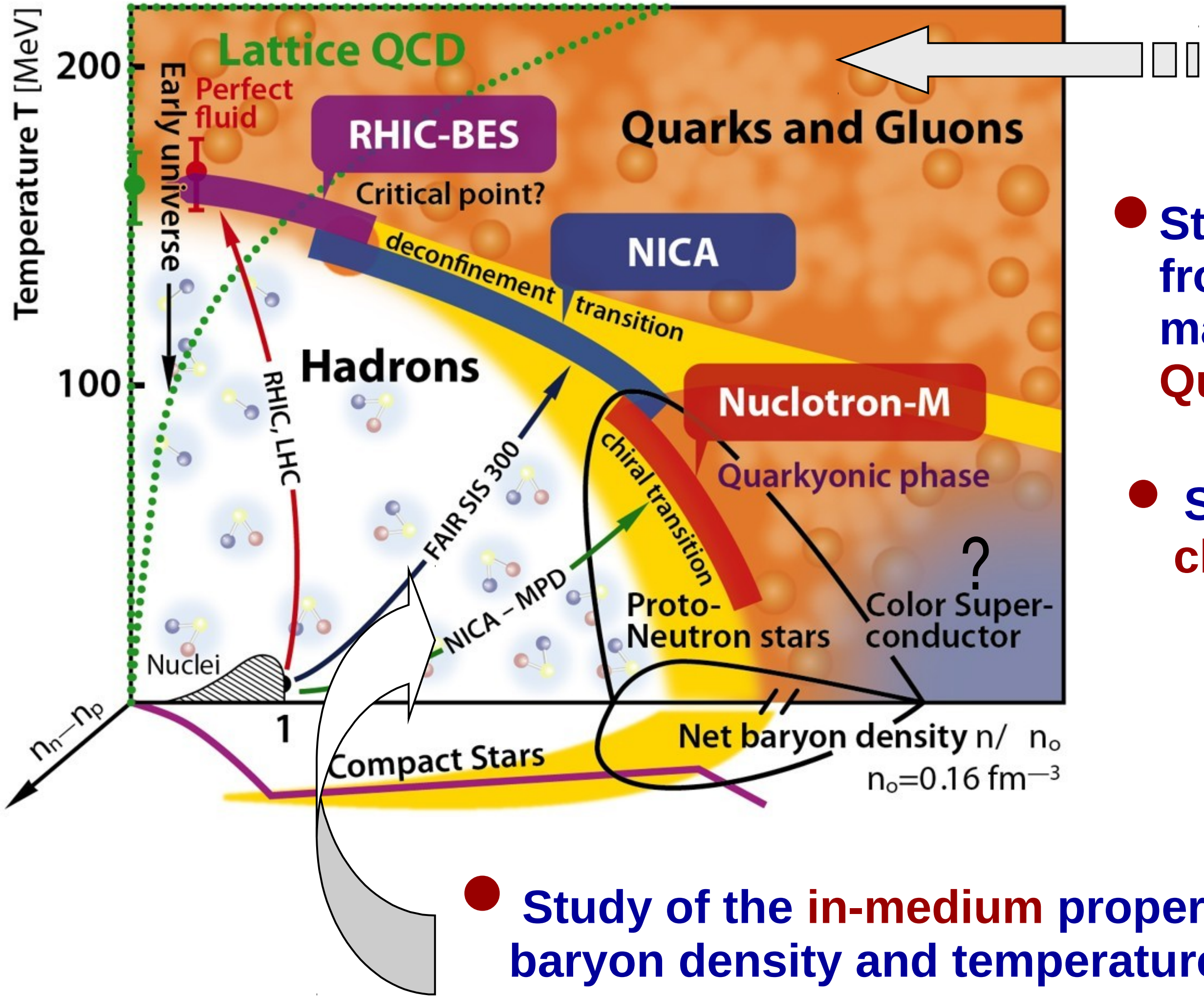
Quark matter in massive neutron stars?

M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657
Phys. Rev. C 89, 015806, 2014



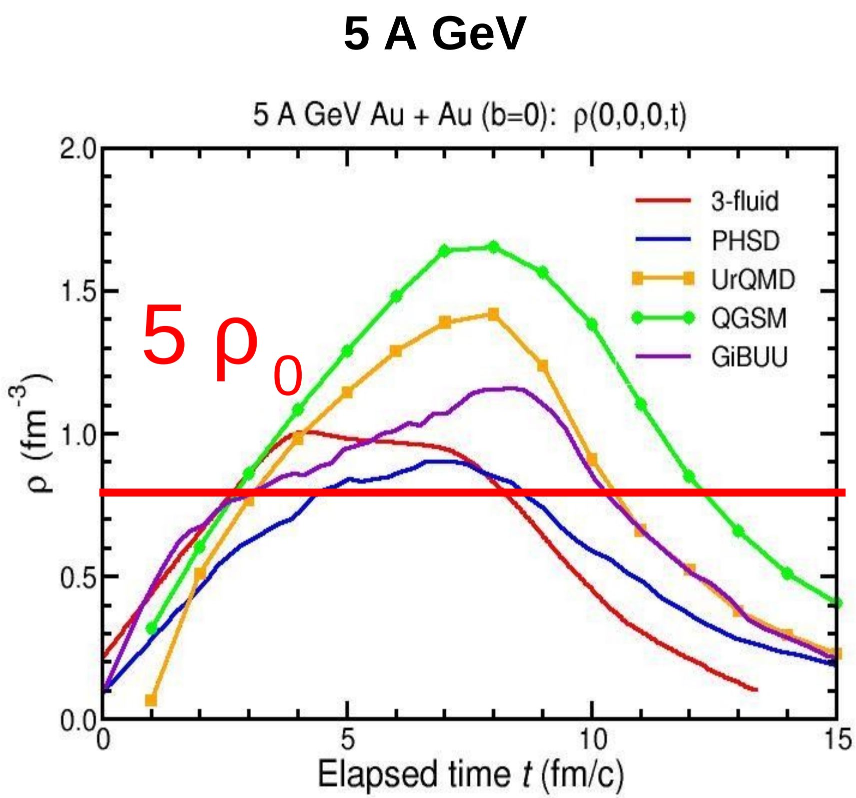
Heavy ion collisions

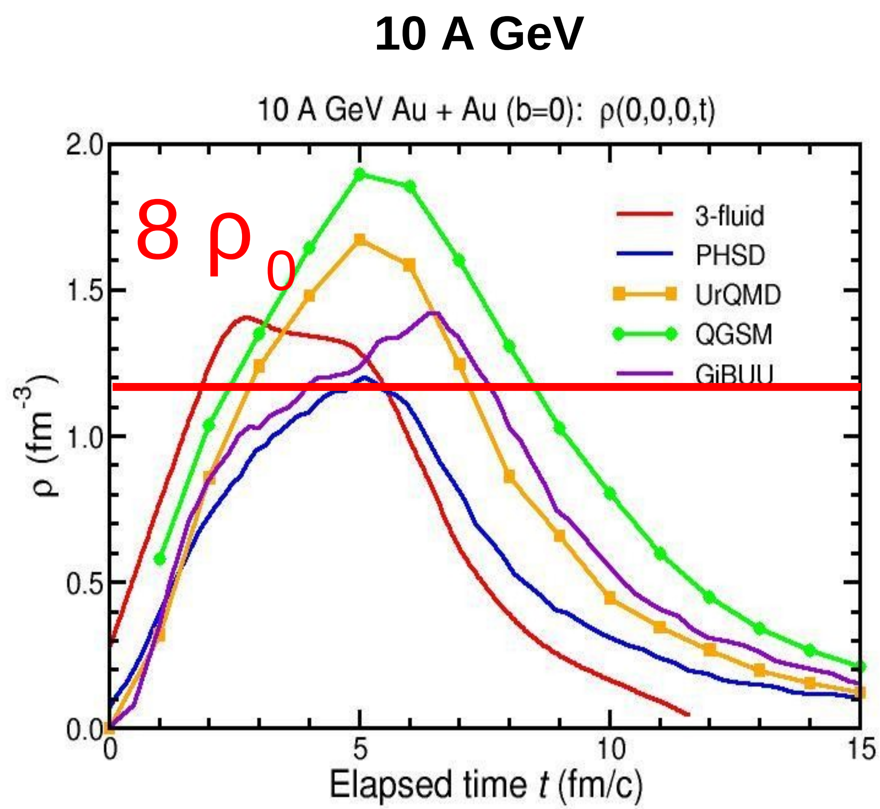
The phase diagram of QCD



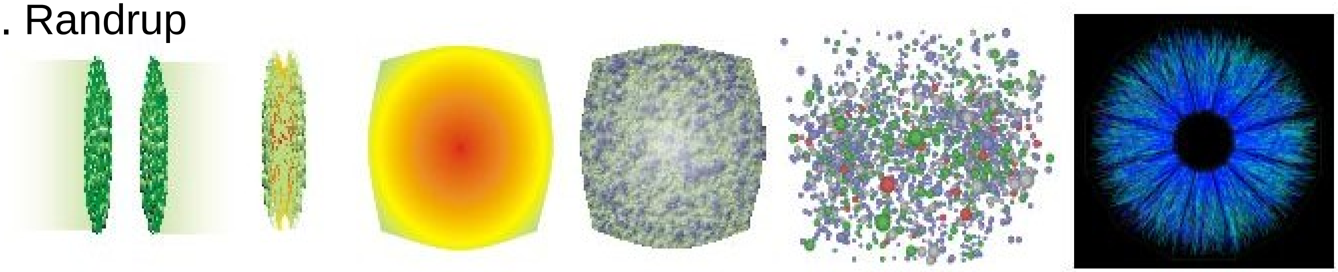
- **Search for the critical point**
- **Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma**
- **Search for the signatures of chiral symmetry restoration**
- **Study of the in-medium properties of hadrons at high baryon density and temperature**

Baryon densities in central Au+Au collisions

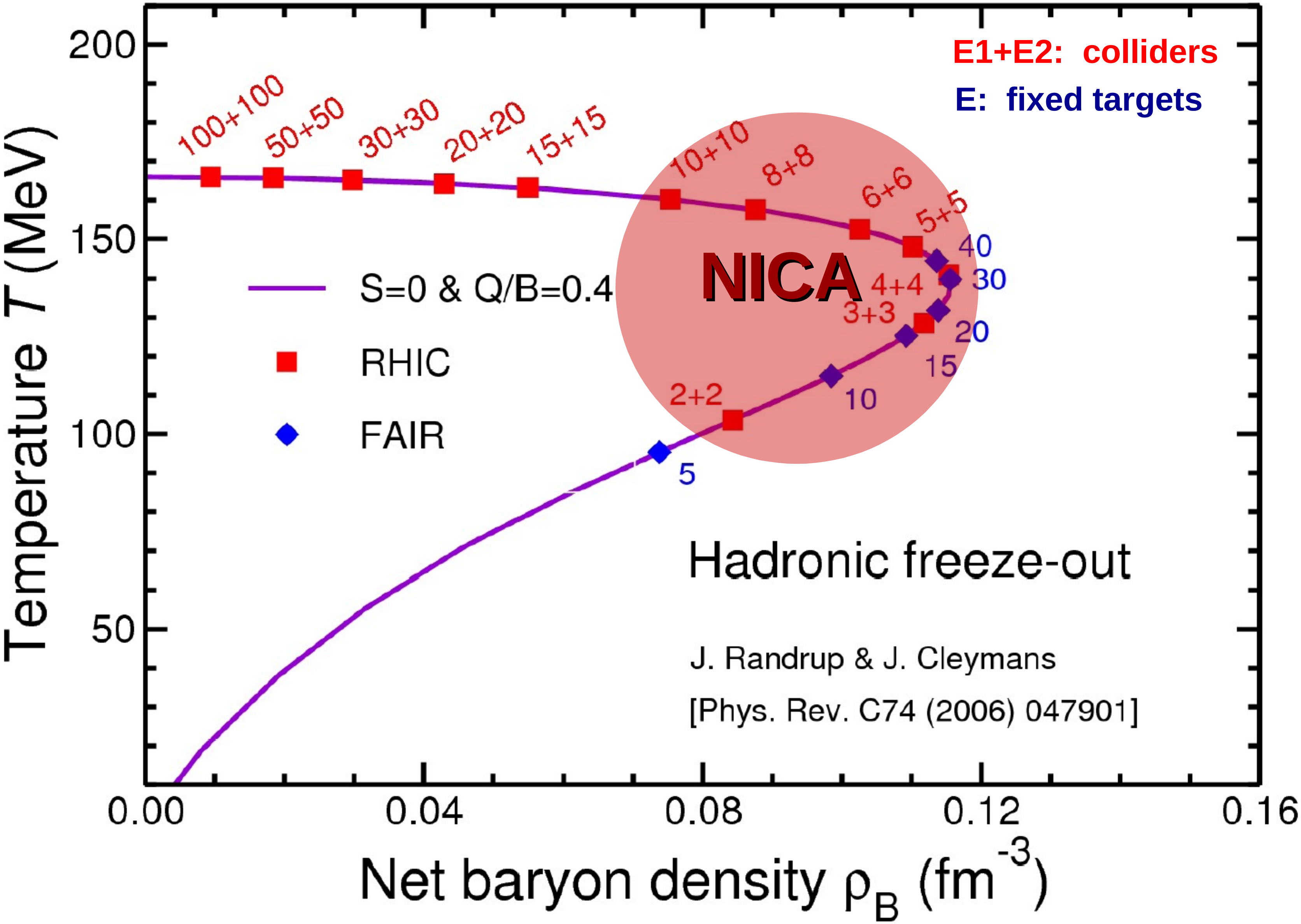




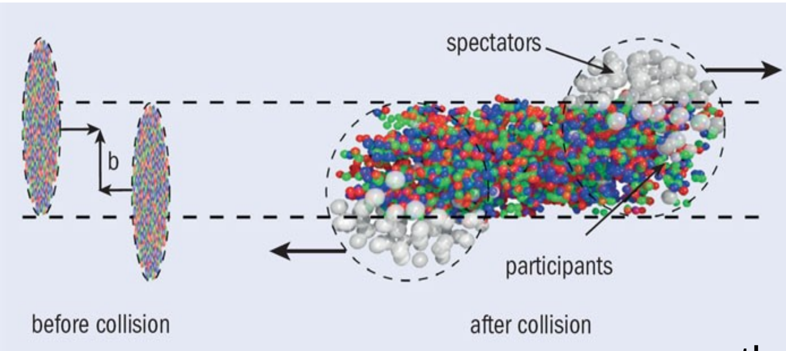
Courtesy of J. Randrup



The «freeze-out» condition



NICA observables: Flow



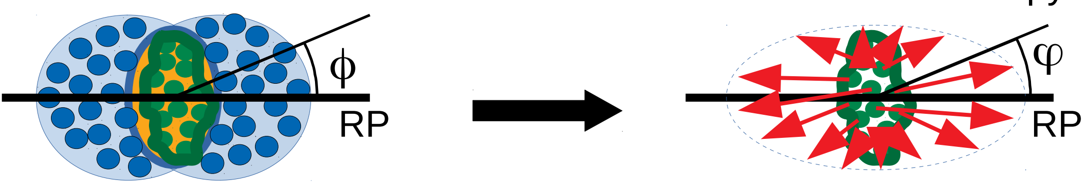
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n cos[n(\varphi - \Psi_n)]\right)$$

$$v_n = \langle cos[n(\varphi - \Psi_n)]\rangle \qquad \phi = \text{atan}\frac{p_y}{p_x}$$

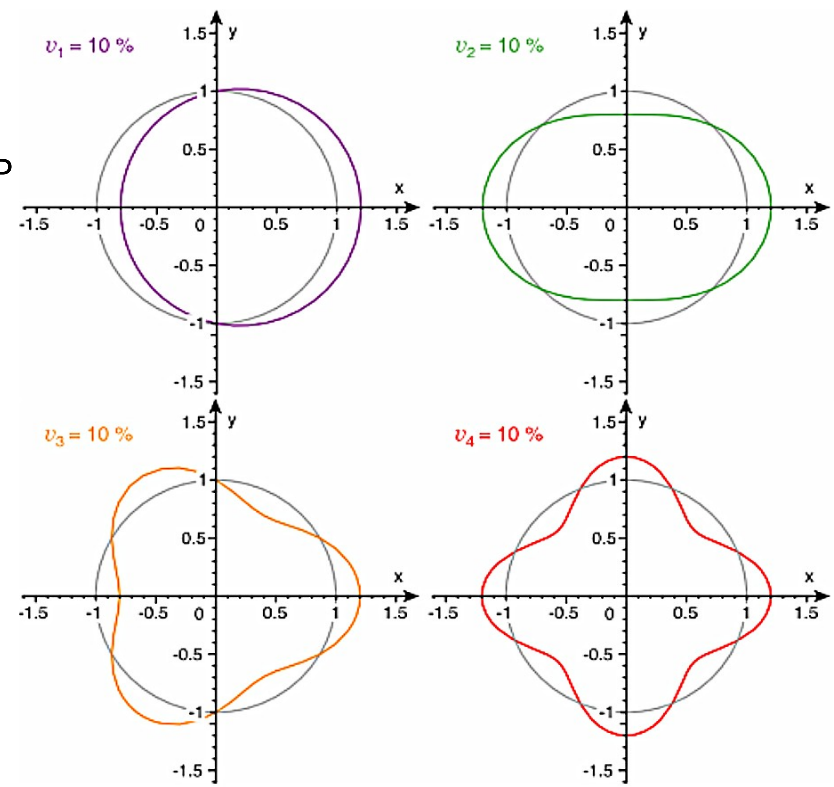
n−th flow harmonic with respect to n−th order symmetry plane.

Spatial anisotropy

Momentum anisotropy



Initial eccentricity ε_n leads to momentum anisotropy v_n

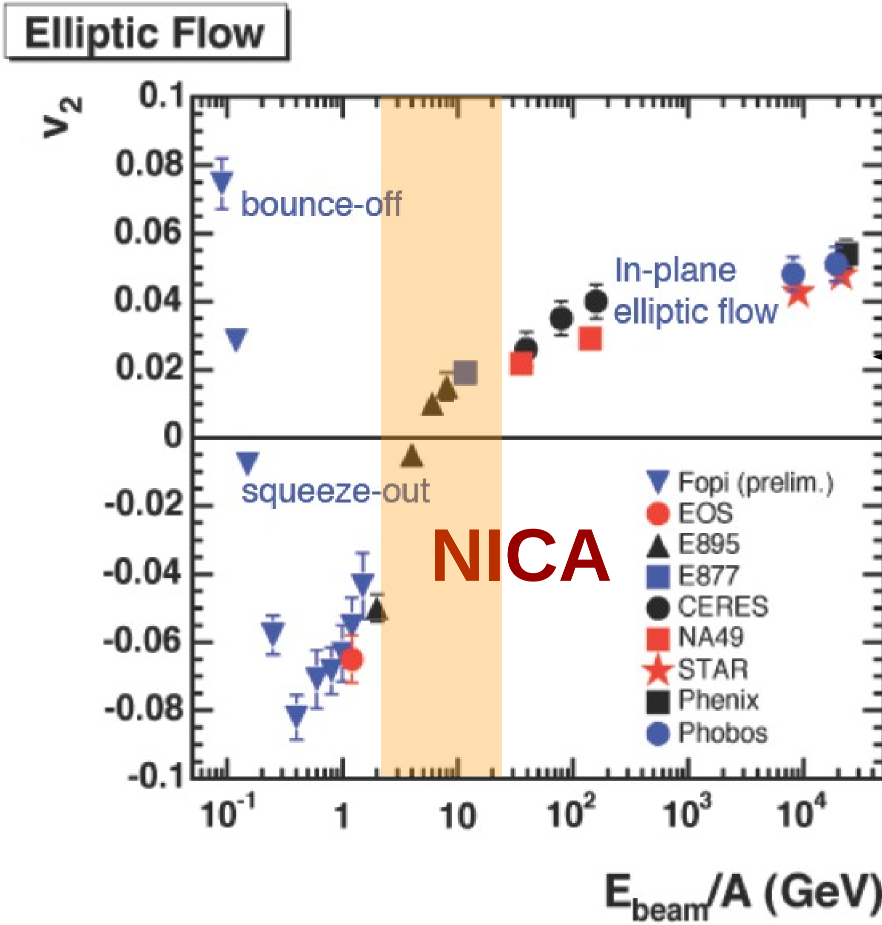


v_1 – directed flow,

v_2 – elliptic flow,

v_n – higher-order harmonics

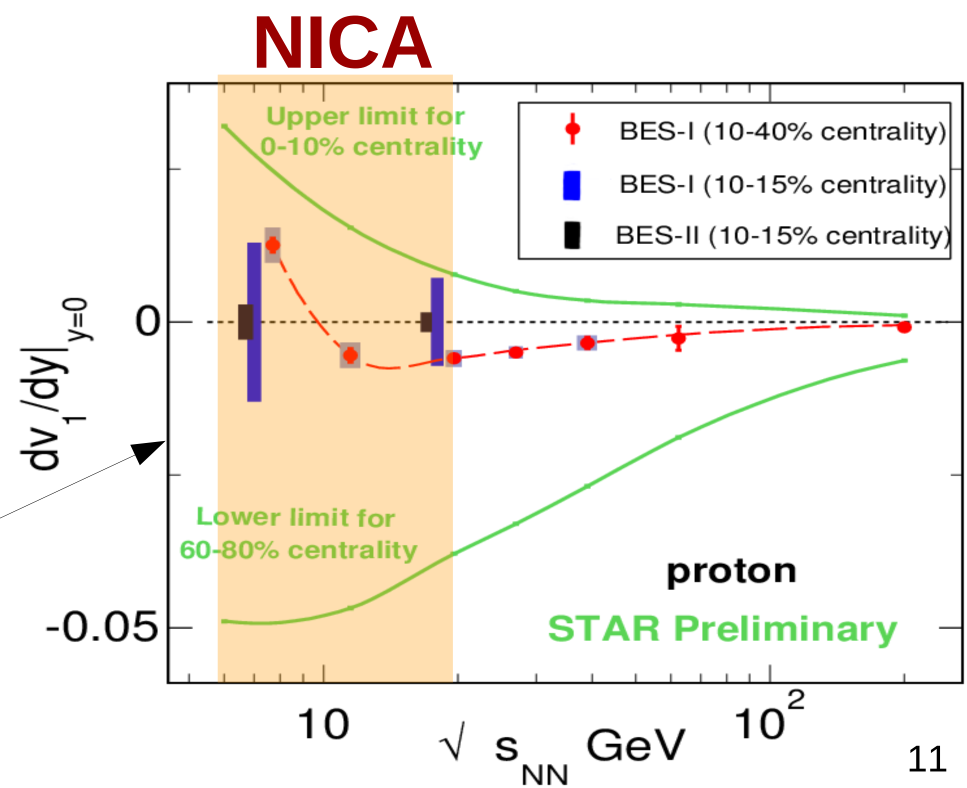
NICA observables: Flow



NICA energy region contains:

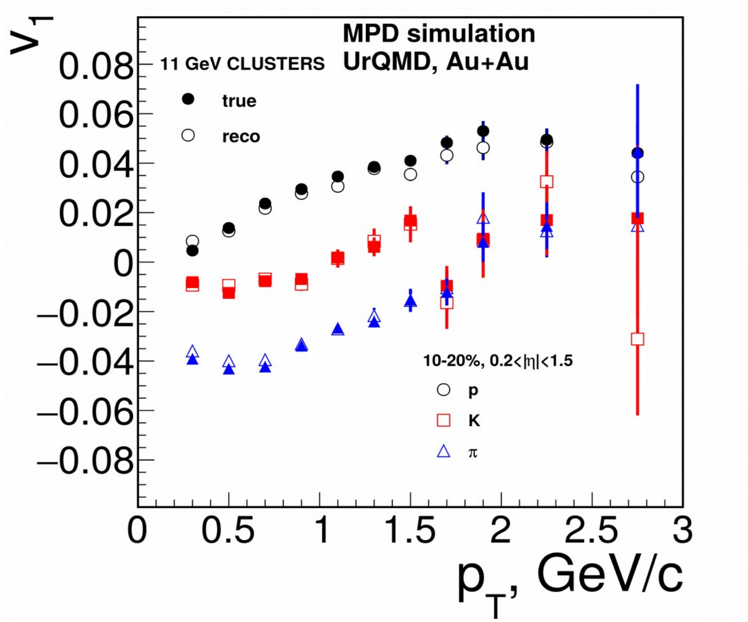
- $v_2 < 0$ (E_A= 2A GeV)
- $v_2 \approx 0$ (E_A= 4A GeV)
- $v_2 > 0$ (E_A= 6A GeV)

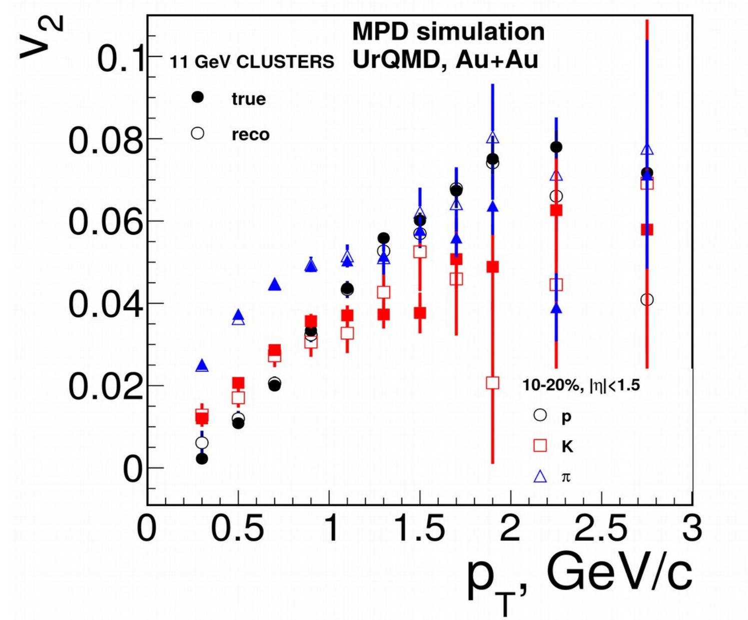
v_2 is very sensitive to the equation of state

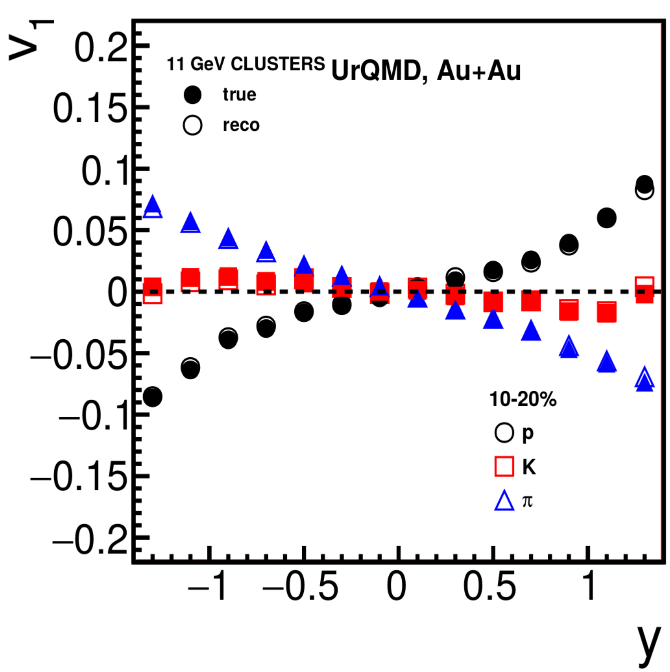


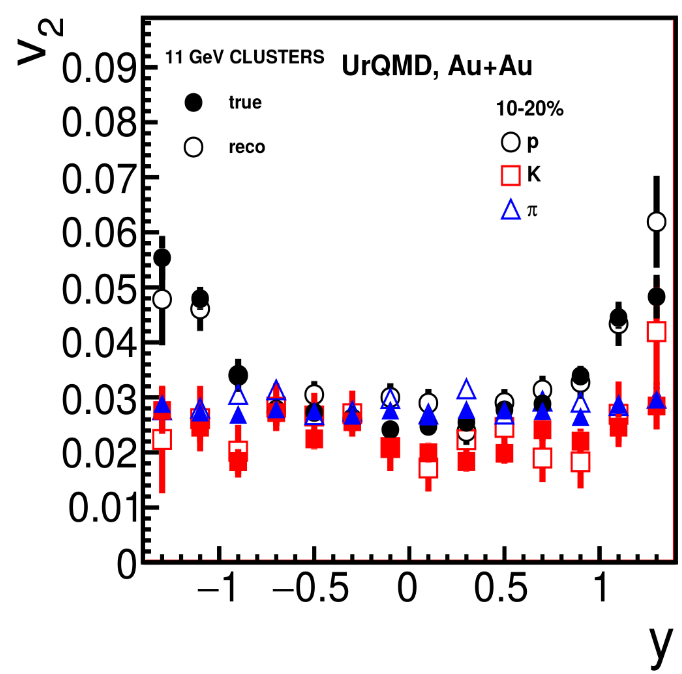
- Large uncertainty in the existing experimental data at NICA energy range
- Non-monotonic v_1 slope behavior can be a signature of a phase transition
- More differential (centrality classes) measurements required

NICA observables: Flow

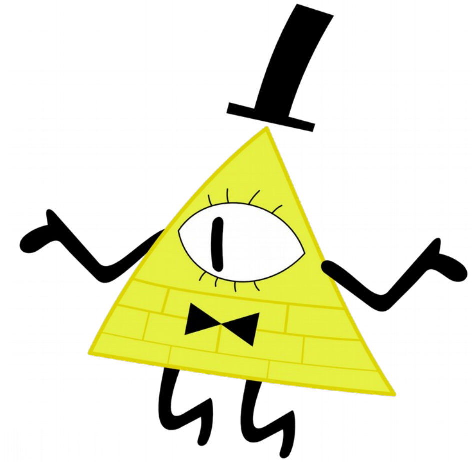








NICA observables: Strangeness

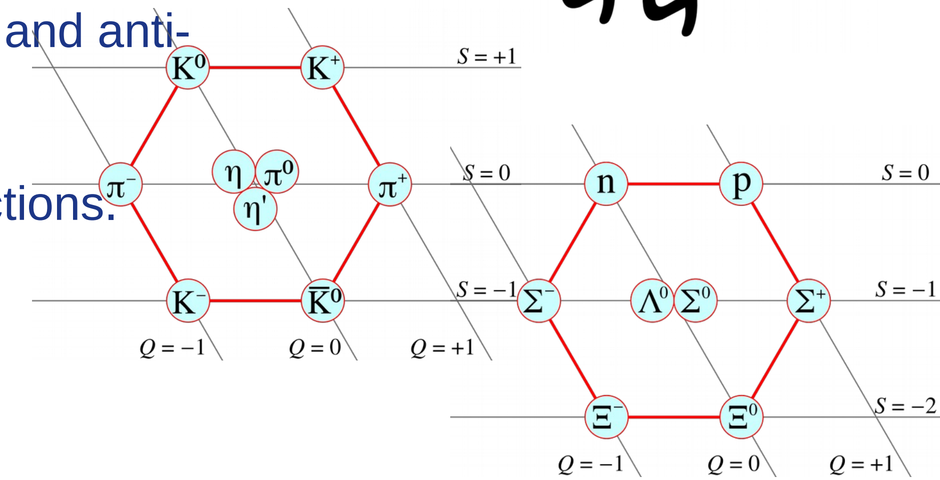


In particle physics:

- Strangeness ("**S**") is a property of particles, expressed as a quantum number

- Strangeness of a particle is defined as $S = (n_s - n_{\bar{s}})$, where n_s and $n_{\bar{s}}$ are the numbers of strange and anti-strange quarks, respectively.

- Strangeness is conserved in strong interactions.



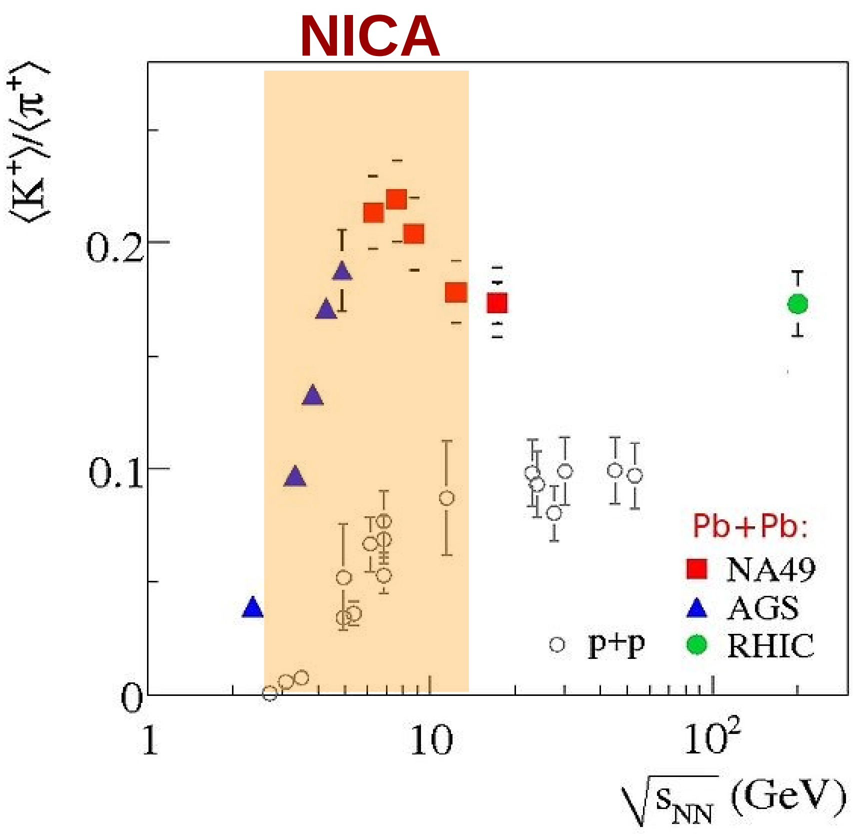
In heavy ion physics:

- Produced strangeness means a number of pairs of strange and anti-strange particles, $N_{s\bar{s}}$

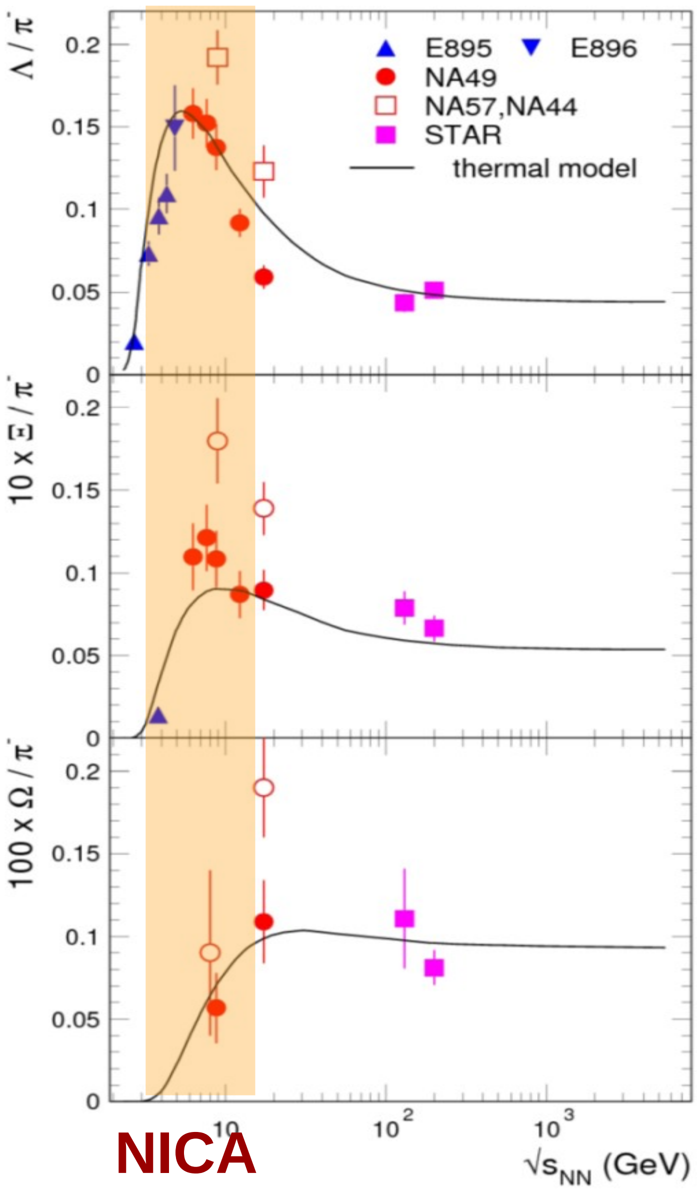
- The most popular hadrons which carry strangeness are:
  * the lightest (anti-)strange mesons (M ≈ 0.5 GeV): $K^+(u\bar{s})$, K^- $(\bar{u}s)$, K^0 $(d\bar{s})$, $\bar{K}^0$ $(\bar{d}s)$
  * the lightest strange baryon (M ≈ 1.1 GeV): Λ (uds), $\bar{\Lambda}$ $(\bar{u}\bar{d}\bar{s})$

- Strange and anti-strange quarks can also be hidden in strangeness neutral φ $(s\bar{s})$ meson.

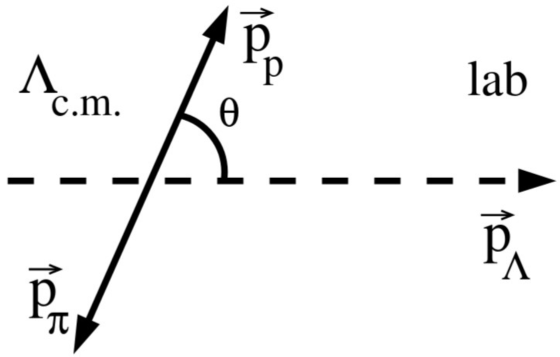
NICA observables: Strangeness



NA49 : Phys. Rev. C 77, (2008)



NICA observables: Λ polarization

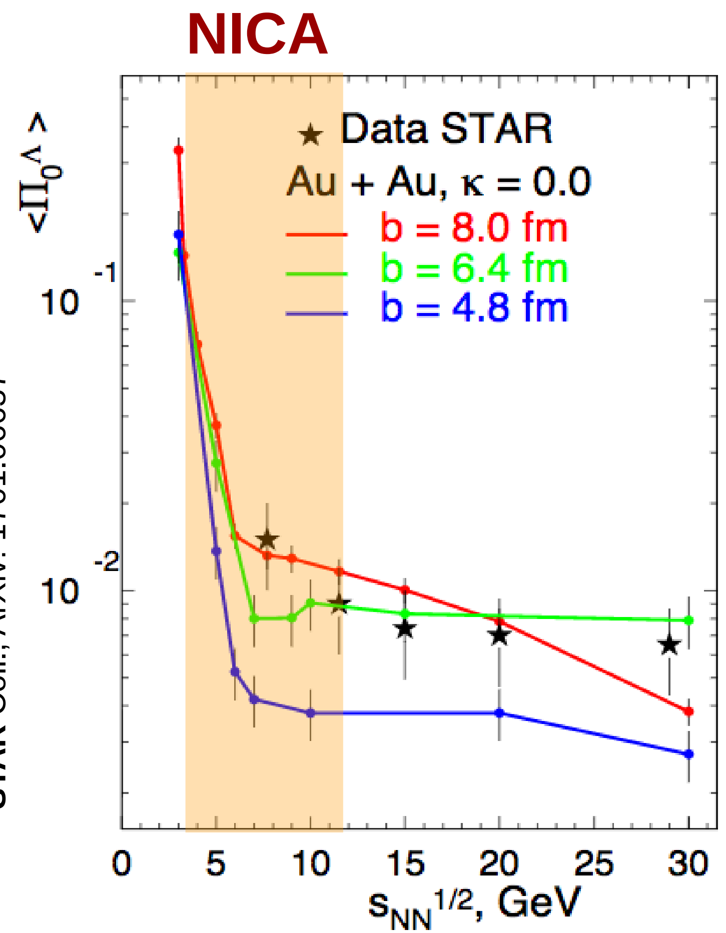


$\Lambda^0 \rightarrow + \pi^-$

$$P_\Lambda = \frac{1}{\alpha}\frac{\langle \cos(\theta_{cm})\rangle}{\langle \cos^2(\theta_{cm})\rangle}$$

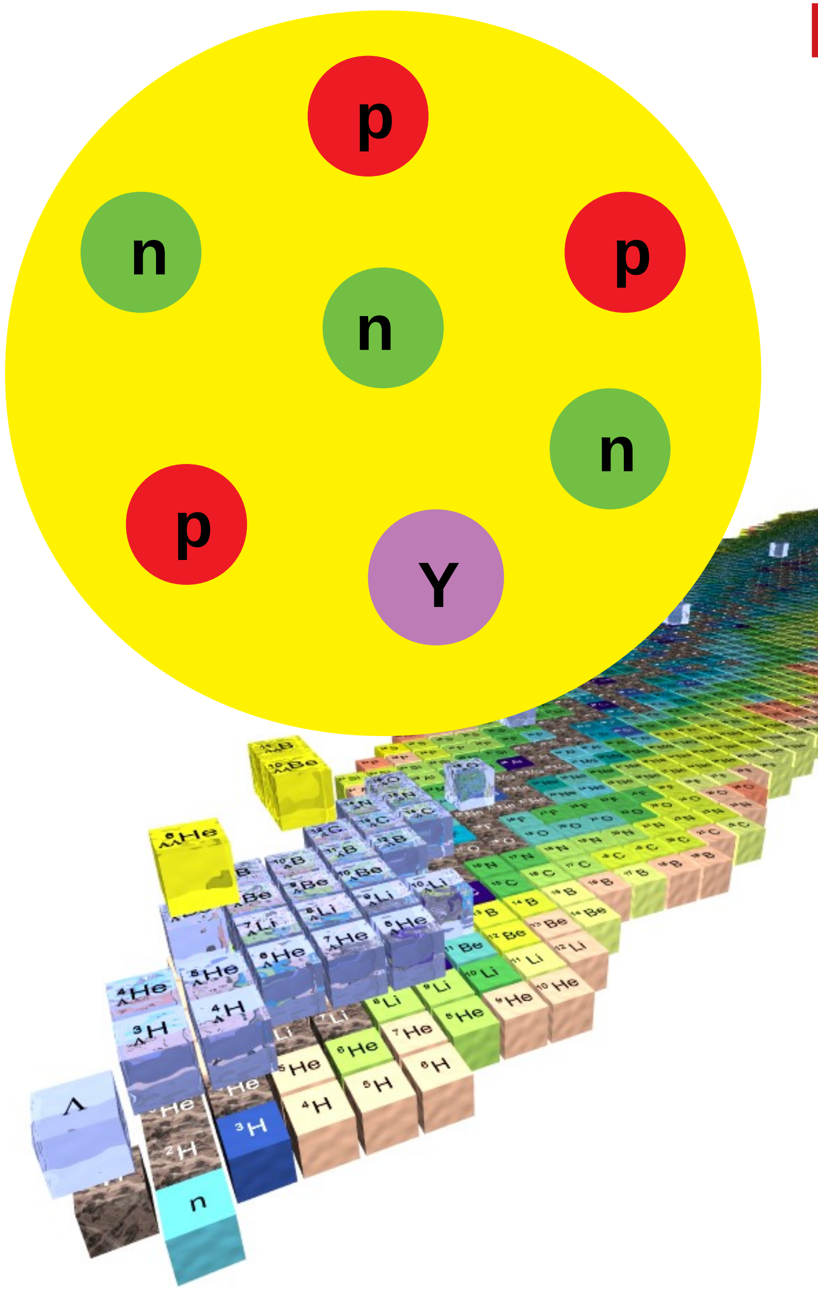
θ = angle between proton momentum and Λ polarization plane in Λ rest frame

α = 0.642 - Λ^0 decay assymetry parameter



STAR Coll., ArXiv: 1701.06657

NICA observables: Hypernuclei – hyperons bound in nucleons

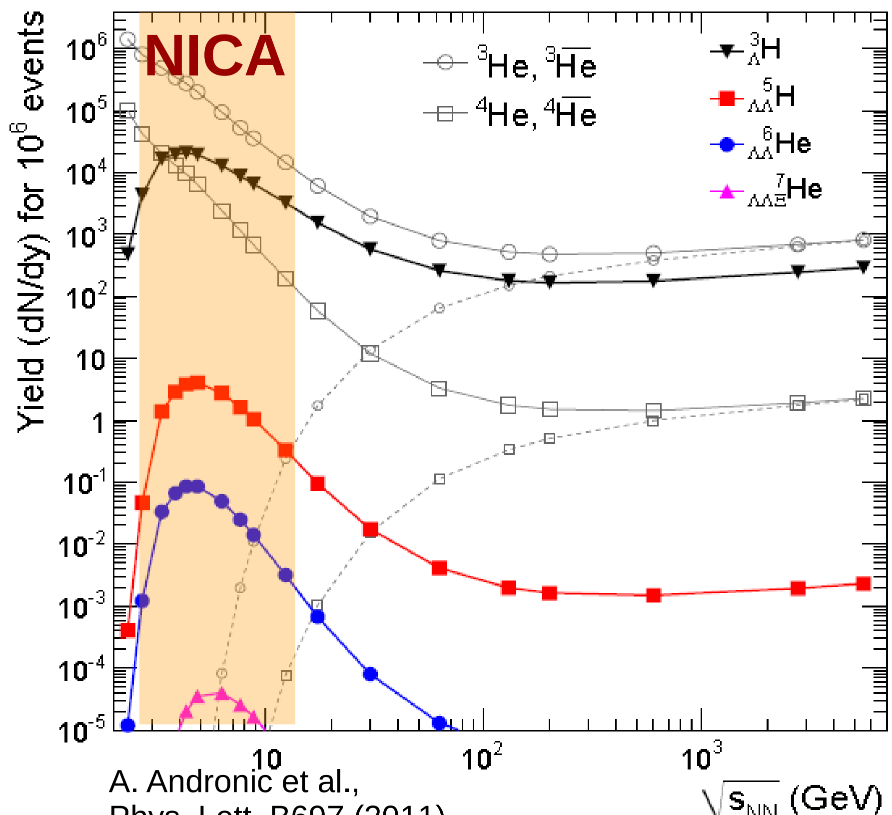


$${}^{A}_{Y}Z$$

Y = Hyperon

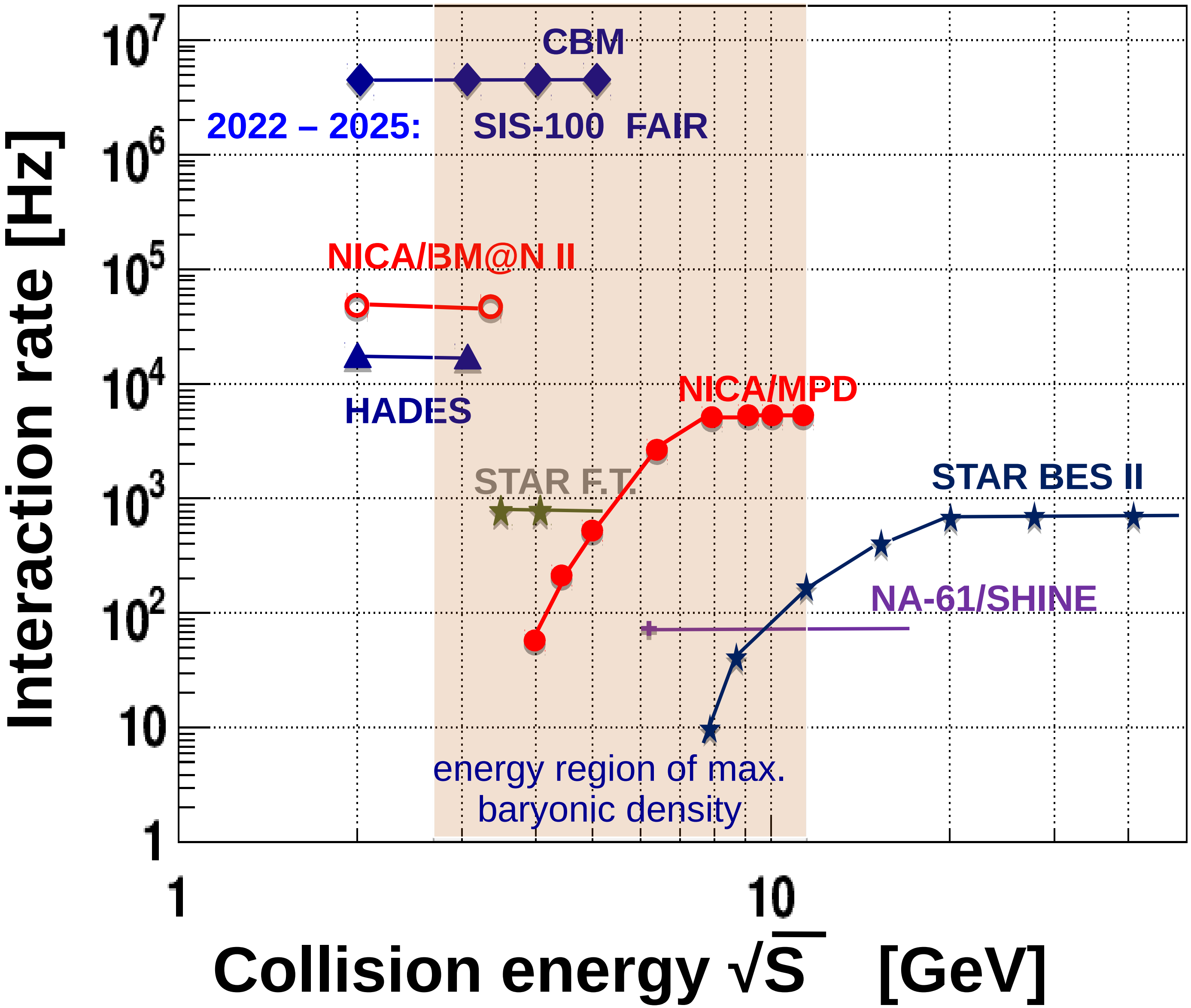
$Z = Z_p + (N_y * q_y)$

$A = N_n + N_p + N_y$



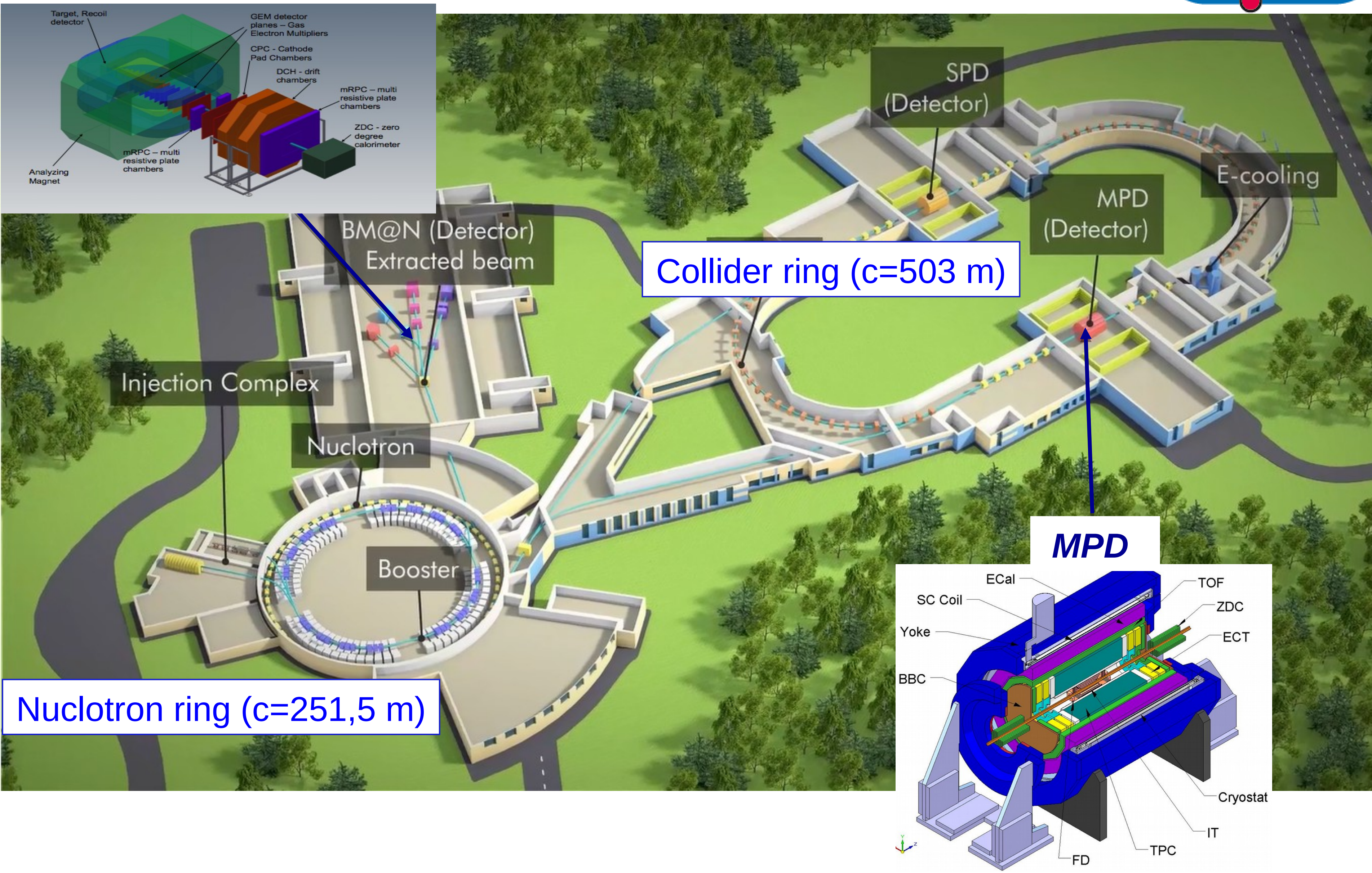
A. Andronic et al., Phys. Lett. B697 (2011) 203

Present and future HI experiments



BM@N

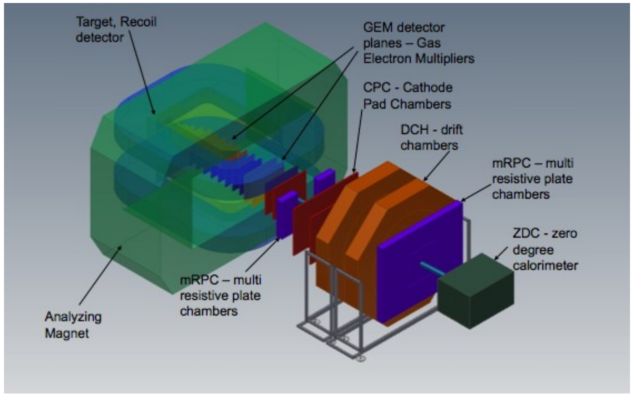
NICA basic facility



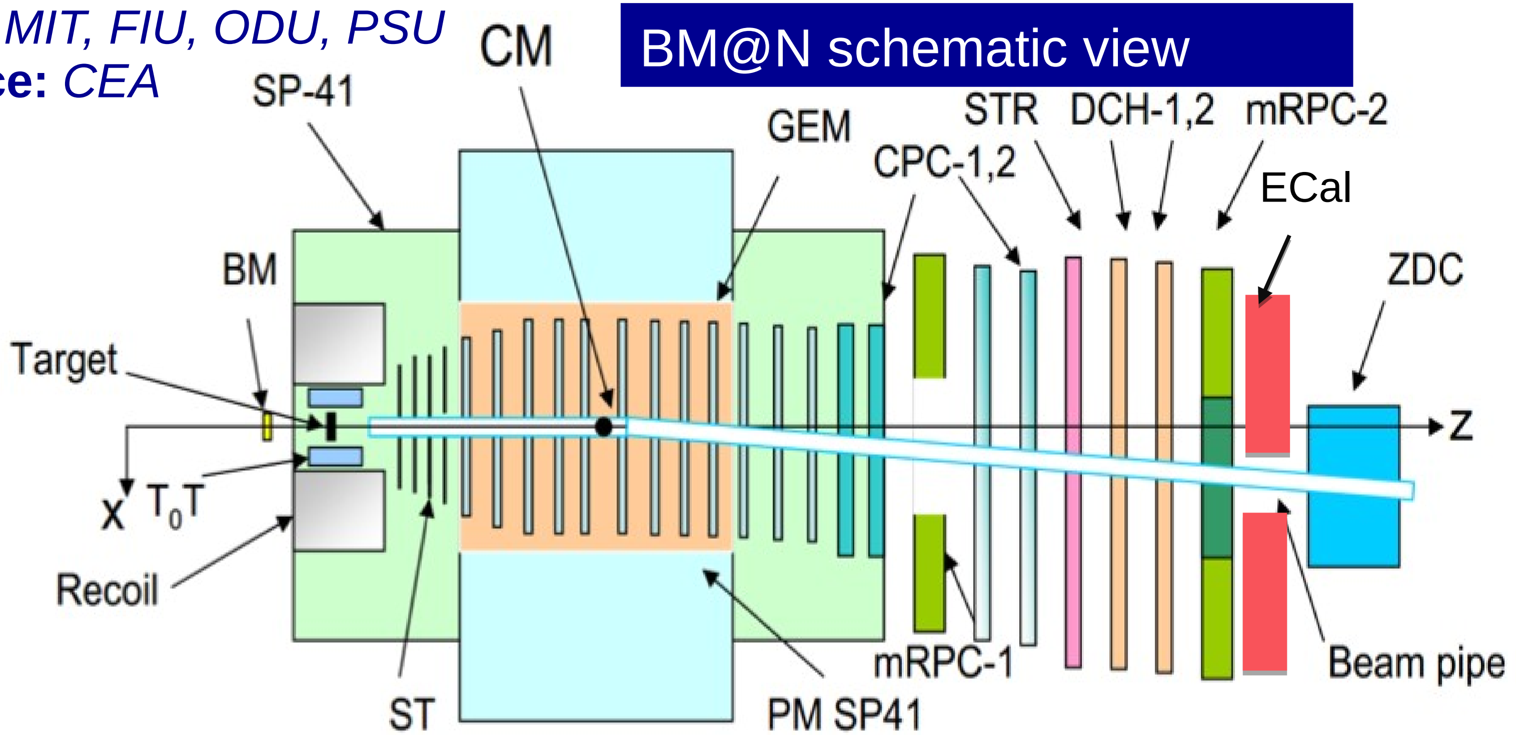
Baryonic Matter at Nuclotron (BM@N)

experiment at Nuclotron extracted beams

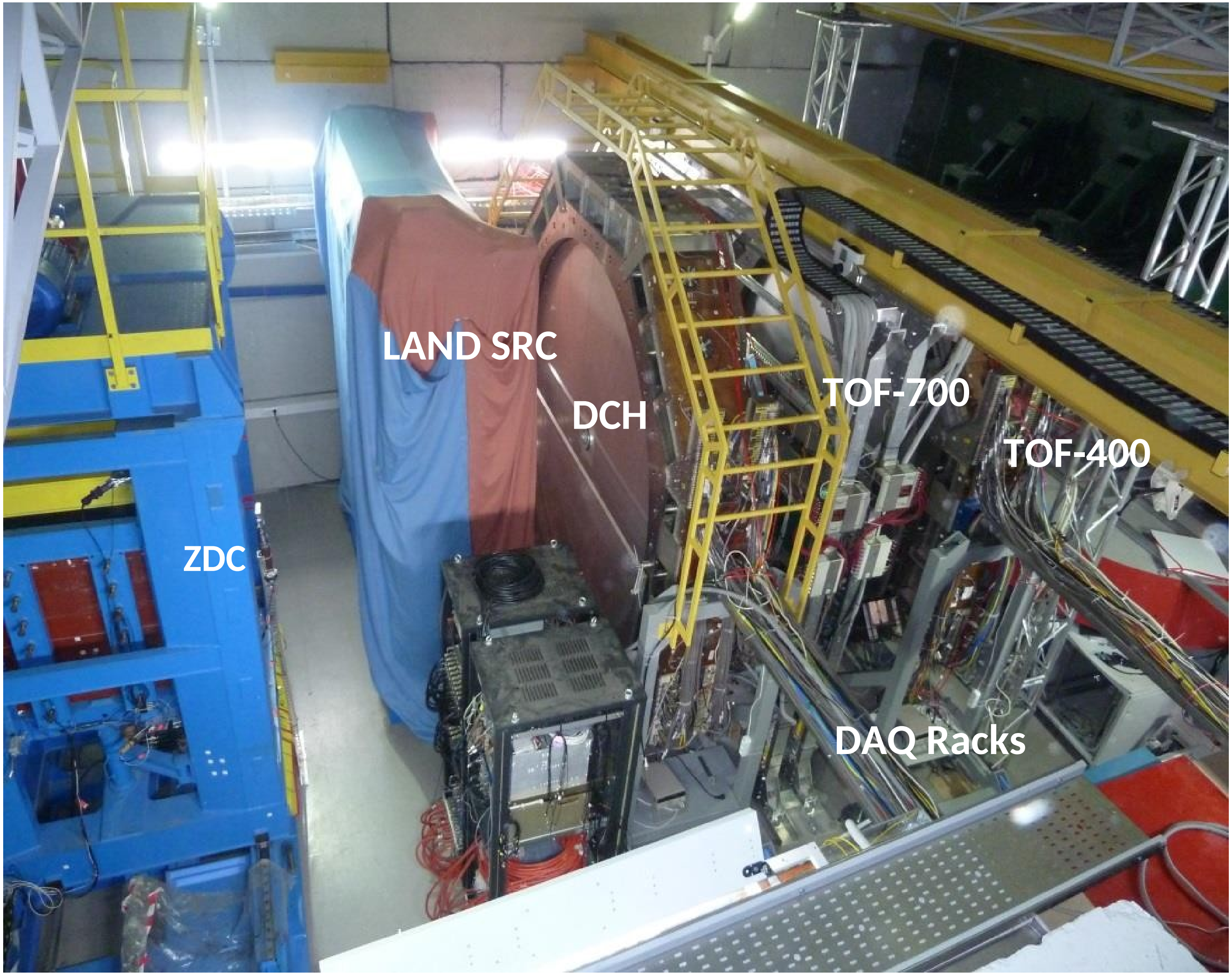
BM@N Collaboration:
Russia: *INR, MEPhi, SINP, MSU, IHEP, S-Ptr Radium Inst.*
Bulgaria: *Plovdiv University;*
China: *Tsinghua University, Beijin;*
Poland: *Warsaw University of Technology;*
Israel: *Tel Aviv Uni., Weitzman Inst.*
Germany: *Frankfurt Uni.; GSI*
USA: *MIT, FIU, ODU, PSU*
France: *CEA*



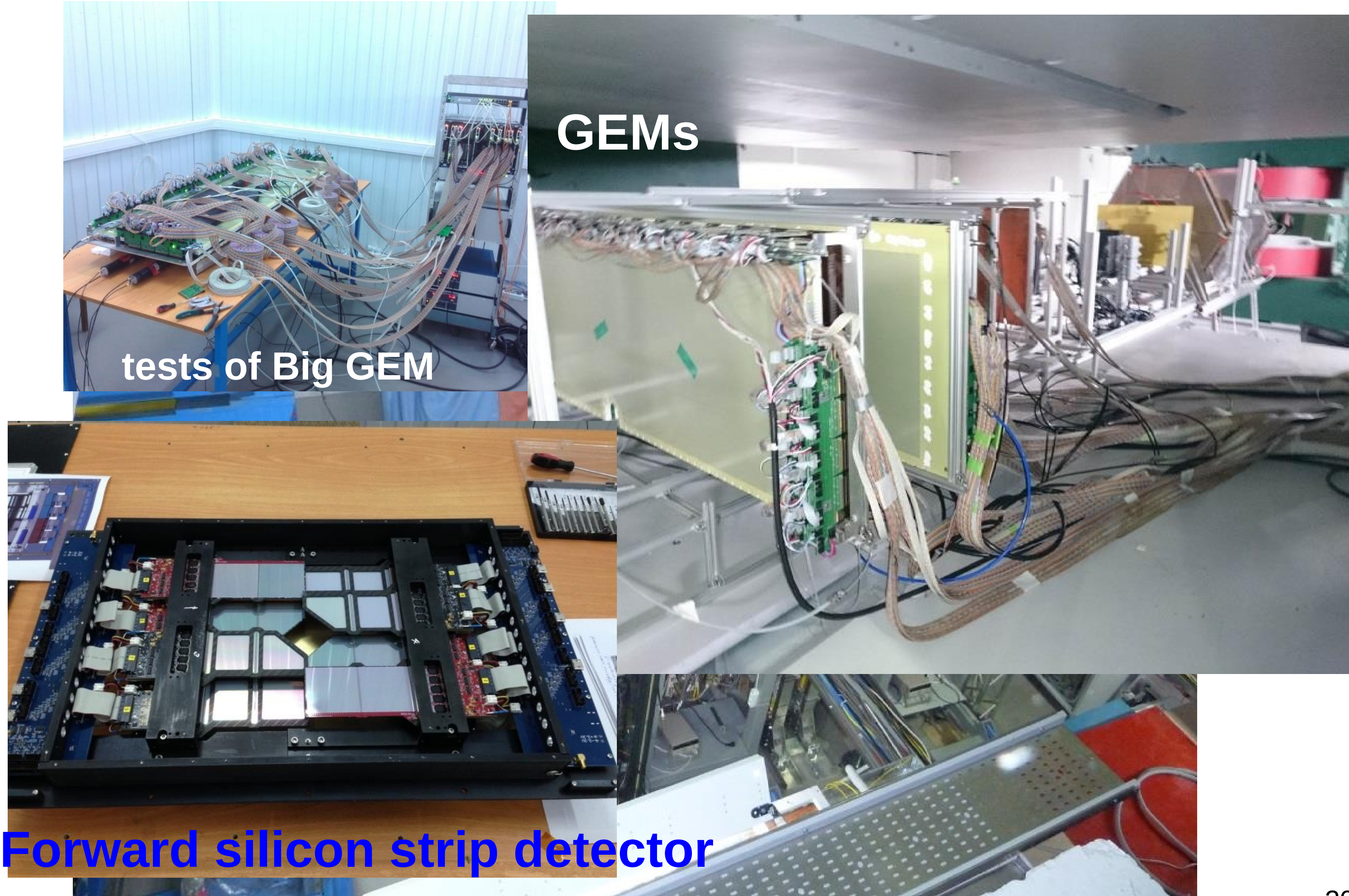
BM@N schematic view



BM@N setup



BM@N setup



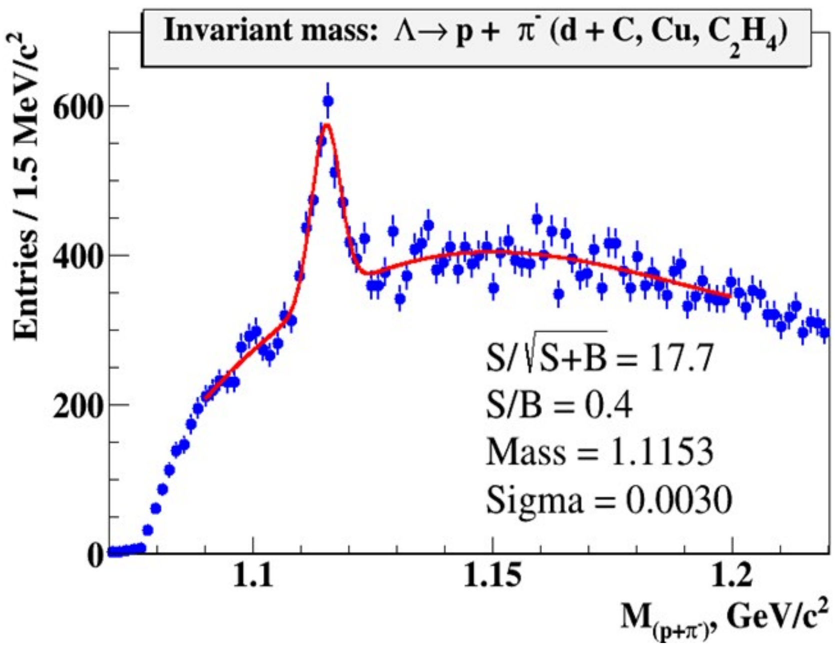
Λ in deuteron and carbon beams

d (C) + A → X

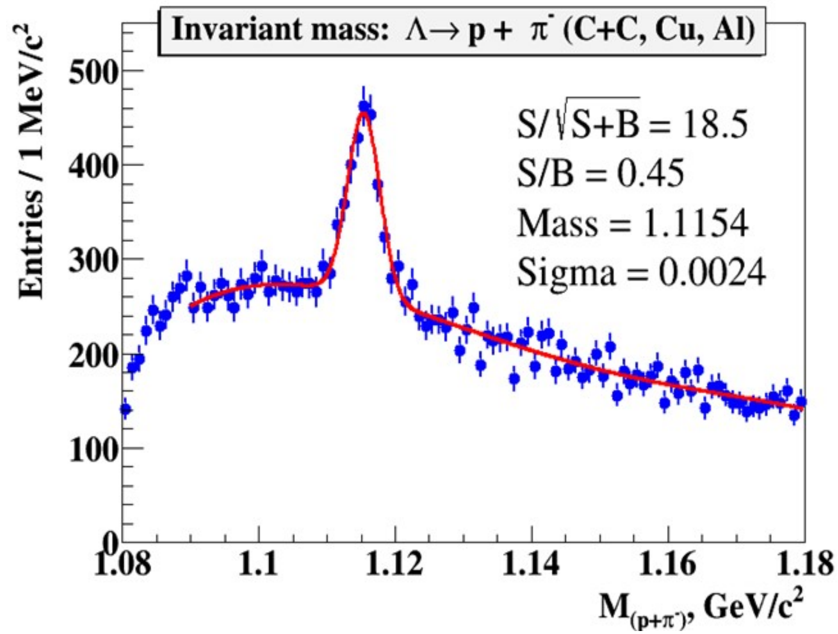
Λ signal width of 2.4 - 3 MeV

G.Pokatashkin, I.Rufanov, V.Vasendina and A.Zinchenko

Deuteron Data



Carbon beam run, 4 AGeV



To improve vertex and momentum resolution and reduce background under Λ:

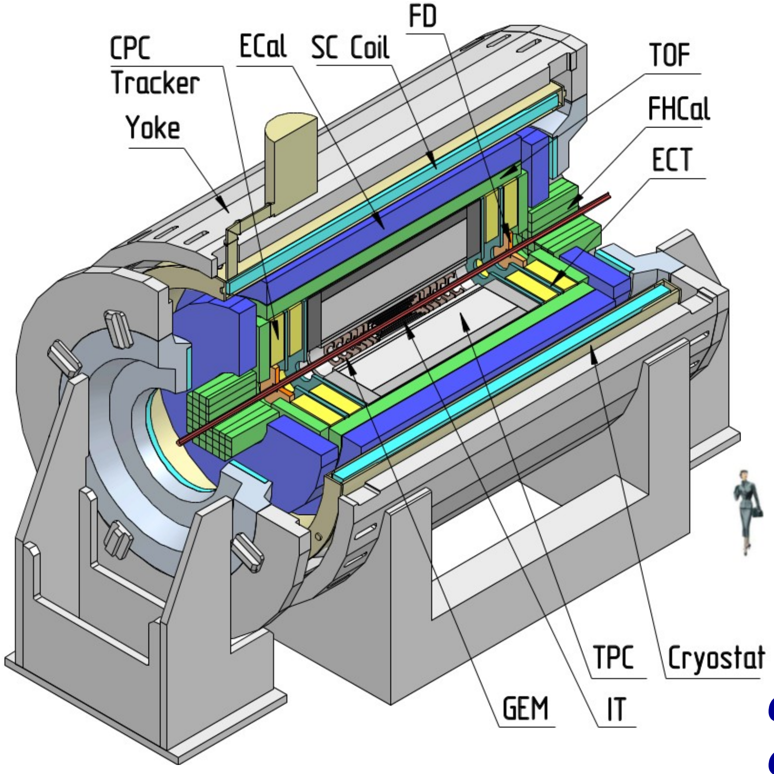
- **Need few planes of forward Silicon detectors → 3 planes in next run**
- **Need more GEM planes to improve track momentum reconstruction**

https://doi.org/10.1134/S1547477118020036

MultiPurpose Detector (MPD)

Main target:

- *study of hot and dense baryonic matter at the energy range of max net baryonic density*



MPD Collaboration:

- *JINR, Dubna;*
- *Tsinghua University, Beijing, China;*
- *MEPhI, Moscow, Russia.*
- *INR, RAS, Russia;*
- *PPC BSU, Minsk, Belarus;*
- *WUT, Warsaw, Poland;*

expression of interest by:

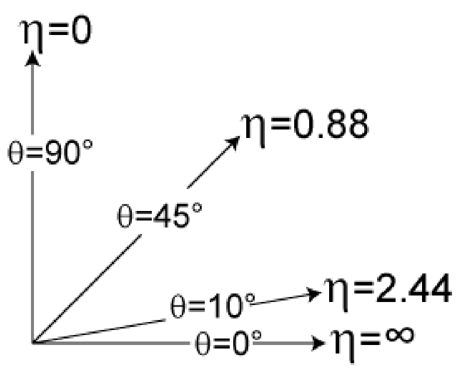
CERN;
Mexico Institutions;
PI Az.AS, Baku, Azerbaijan;
ITEP, NC KI, Moscow, Russia;
PNPI NC KI, Saint Petersburg, Russia;
CPPT USTC, Hefei, China;
SS, HU, Huzhou, Republic of South Africa.

MultiPurpose Detector @ NICA

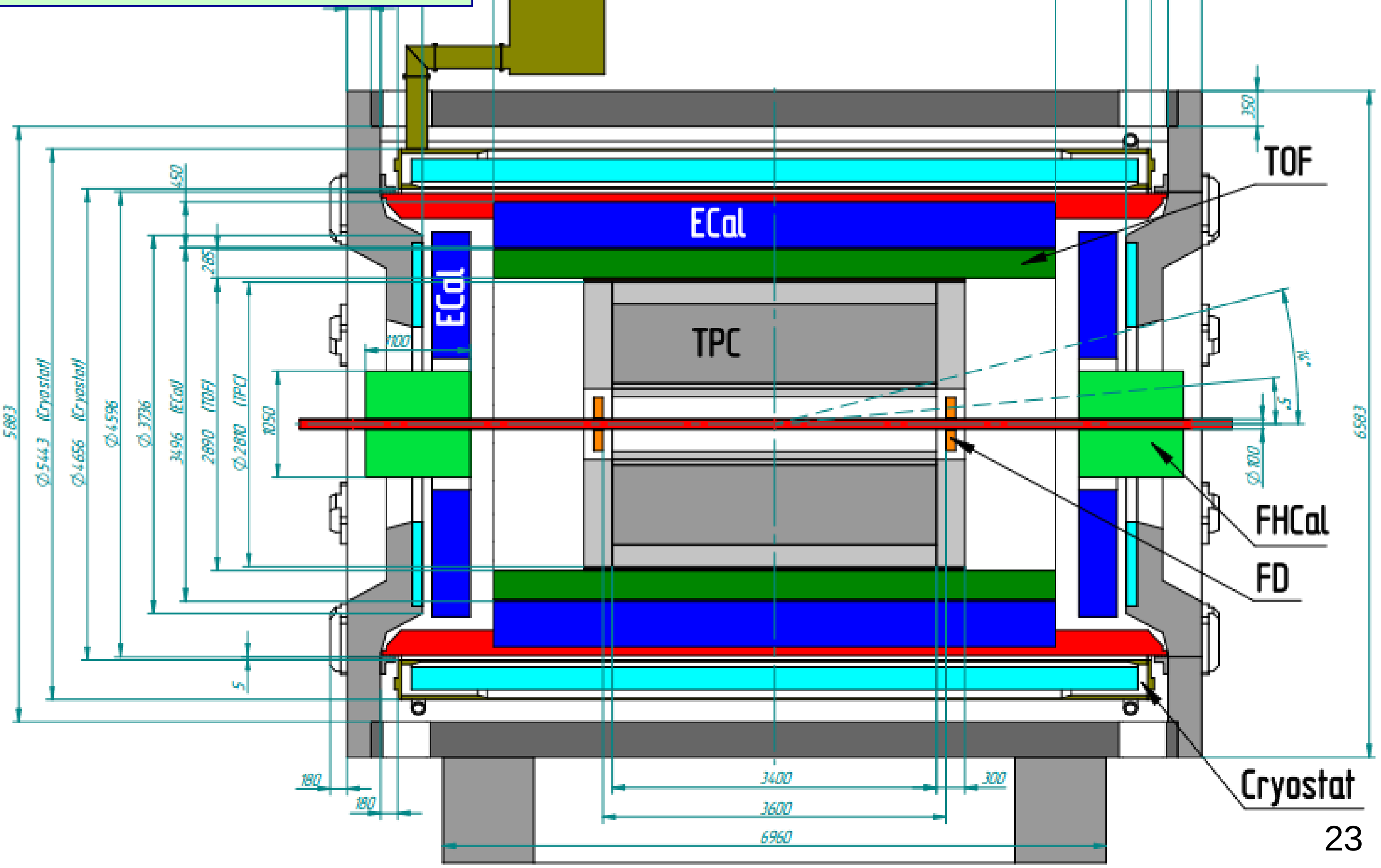
Tracking: up to |η|<1.8 (TPC)
PID: hadrons, e, γ (TOF, TPC, ECAL)
Event characterization:
centrality & event plane (FHCal)

Stage 1 *(2020)*: **TPC**, **FHCal, FFD, Barrel** (TOF, Ecal)

Stage 2 *(2023)*: **ITS** (JINR+ **CERN**), **EndCaps** (tracker, TOF, Ecal)

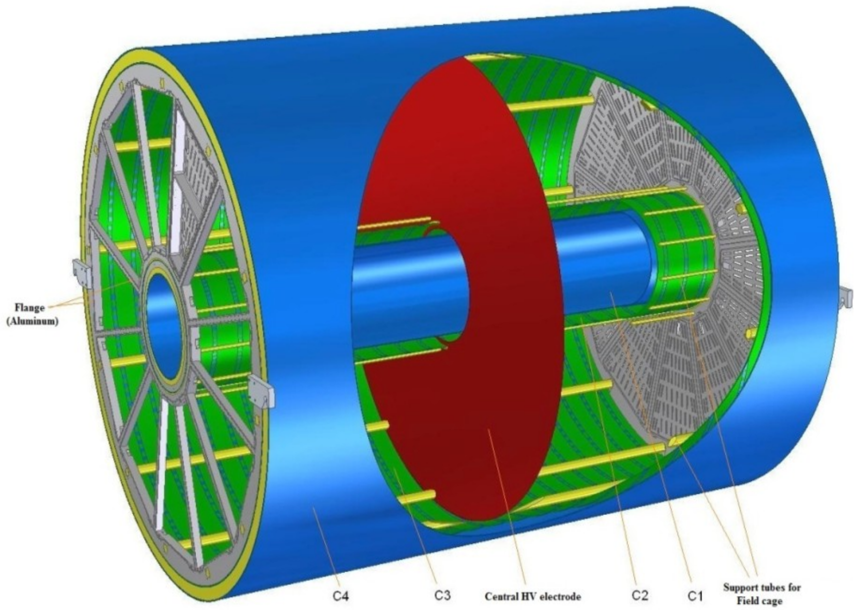


$$\eta = -\ln\left[\operatorname{tg}\left(\frac{\theta}{2}\right)\right]$$



Time Projection Chamber (TPC)

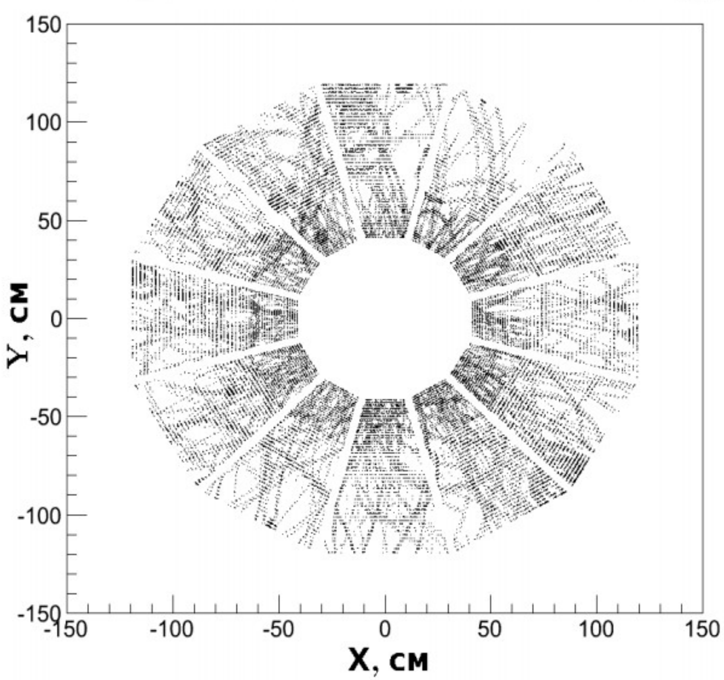
NICA

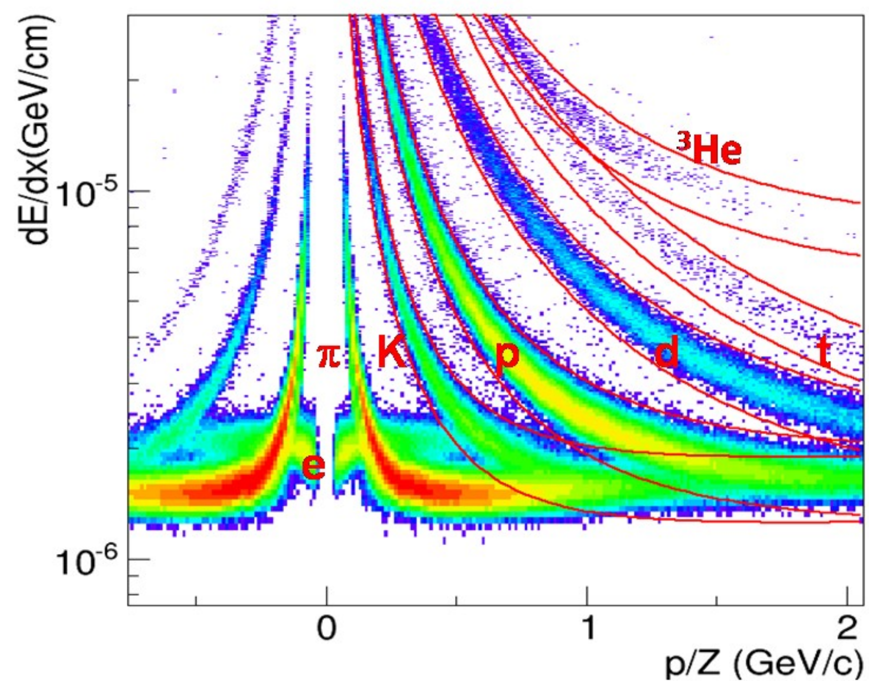


The main tracking detector of the central barrel.

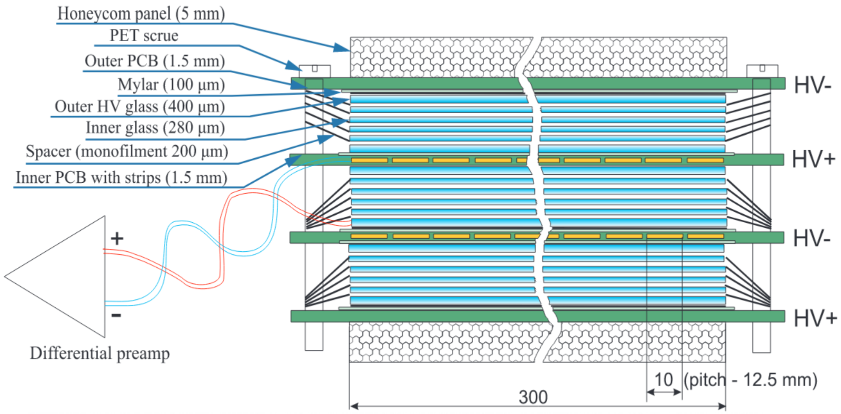
3-d tracking and PID for high multiplicity events.

- The overall acceptance of $|\eta| < 1.2$
- The momentum resolution for charge particles under 3% in $0.1 < pt < 1$ GeV/c.
- Two-track resolution of about 1 cm.
- Hadron and lepton identification by dE/dx measurements with a resolution better than 8%.



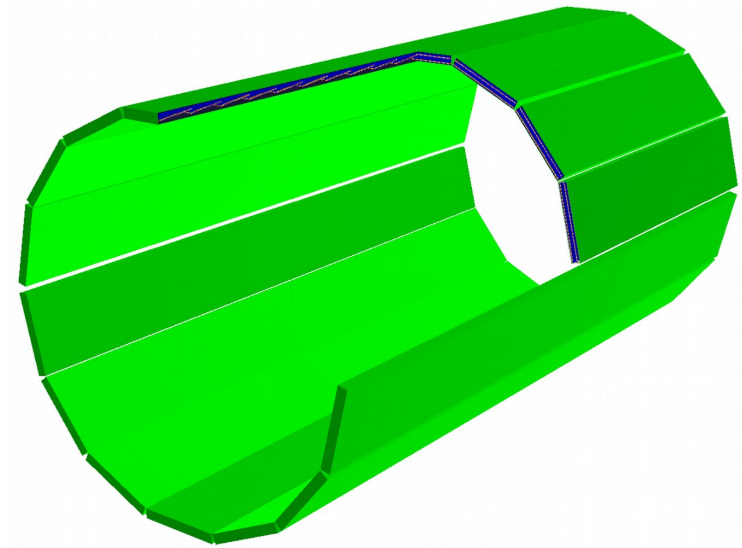


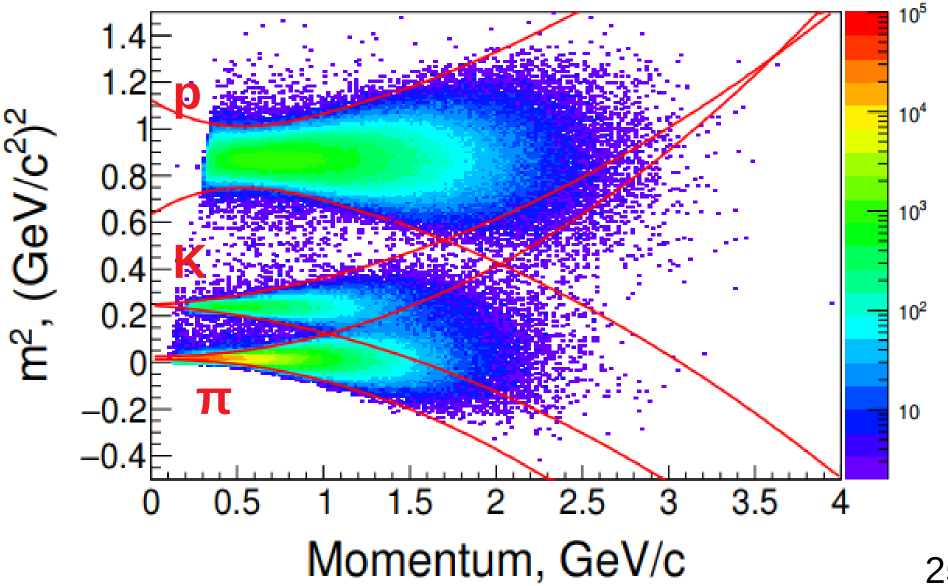
Time Of Flight system (ToF)



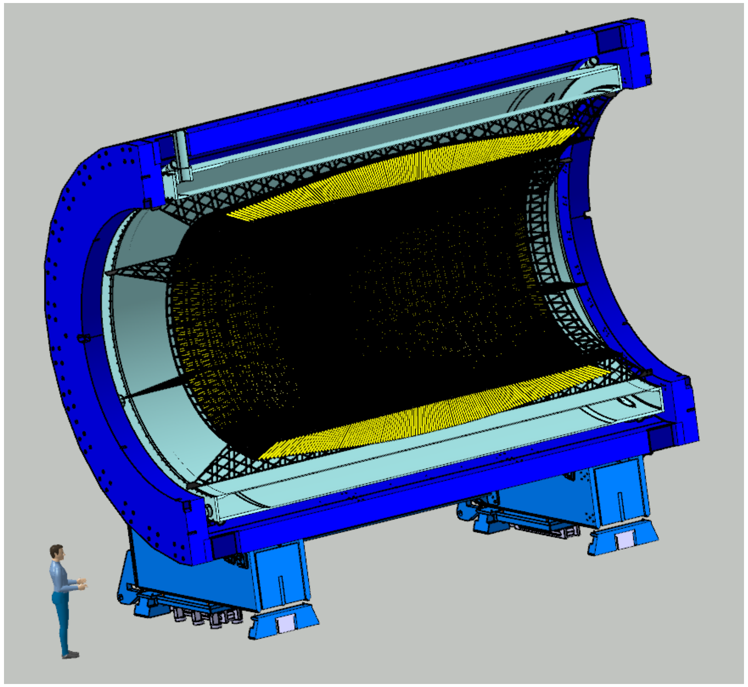
Identification of charged hadrons (PID) at intermediate momenta (0.1 – 2 GeV/c).
Based on Multigap Resistive Plate Chambers
Maximum occupancy does not exceed 15% per channel.
Geometrical efficiency ~95%
Time resolution of MRPC prototype ~60 ps

$$M^2 = (p/q)^2 \left(\frac{c^2 t^2}{l^2} - 1 \right)$$

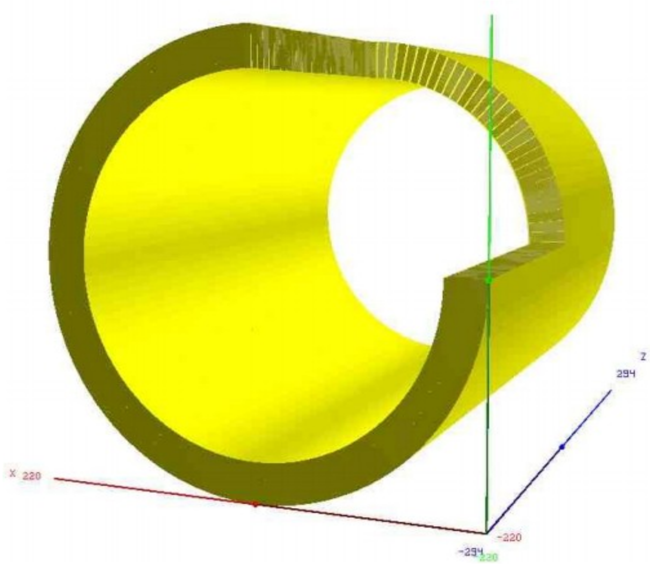


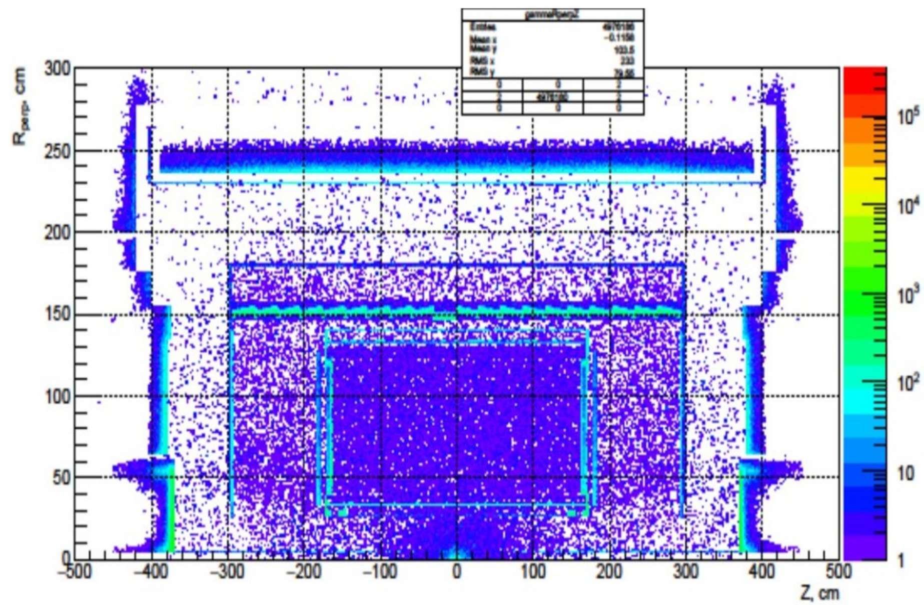


Electromagnetic Calorimeter (ECal)

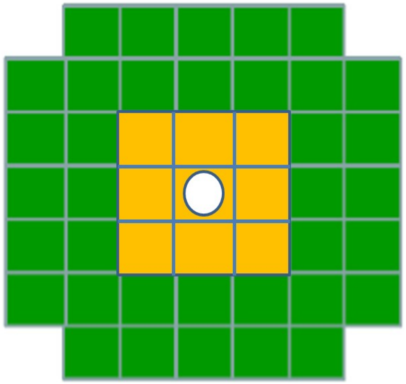


* ECal will provide measurements for electromagnetic and hadronic showers caused by particle interaction.
* Modules are a shashlyk type alternating lead-scintilator, light is carried by Wave Length Shifting Fibers to HAMAMATSU MAPD photon counters
* Trapezoidal projective geometry



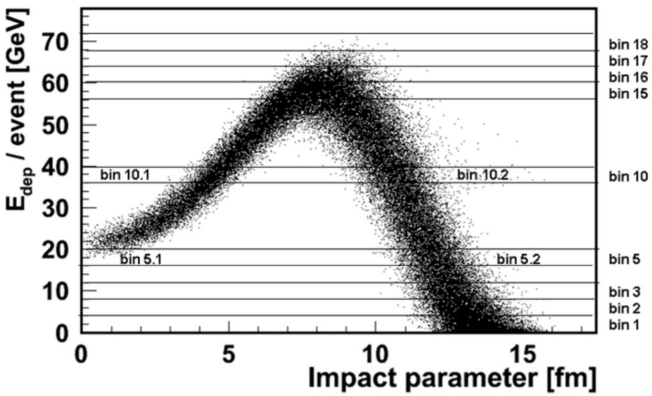


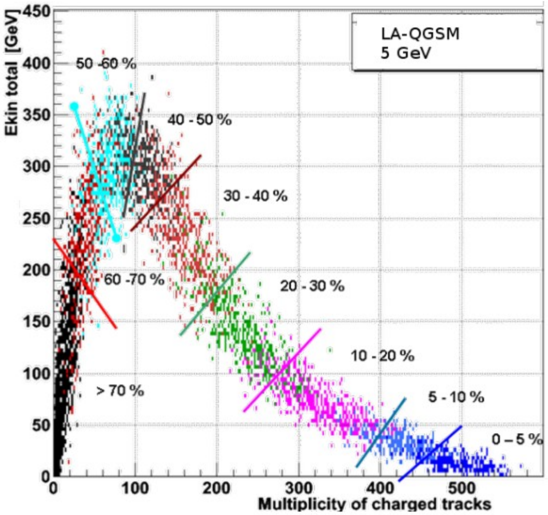
Forward Hadron Calorimeter (FHCal)

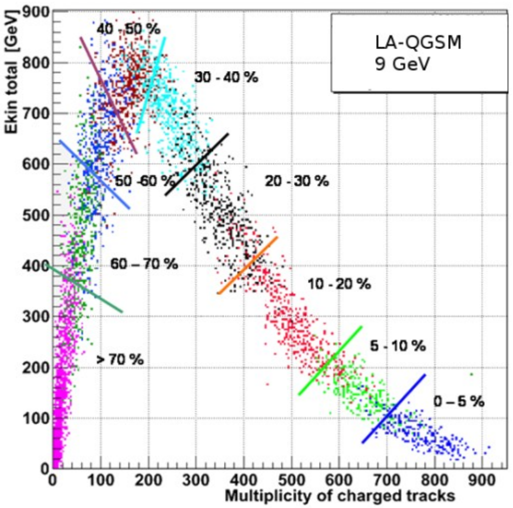


Measures the energy of non-interacting nucleons and fragments (spectators) in AA collisions.
Determination of reaction plane and centrality
- the reaction plane with the accuracy ~ 20^0-30^0
- the centrality with accuracy below 10%

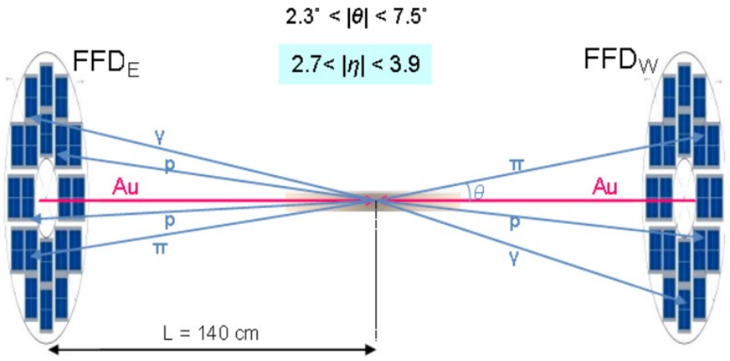
FHCal coverage: $2.2<|\eta|< 4.8$



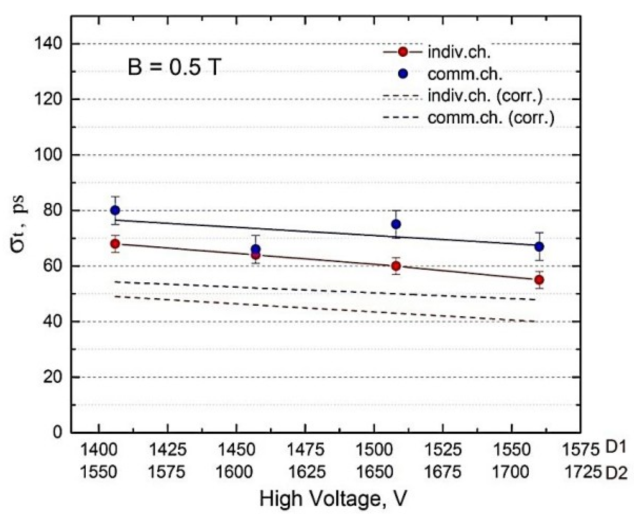




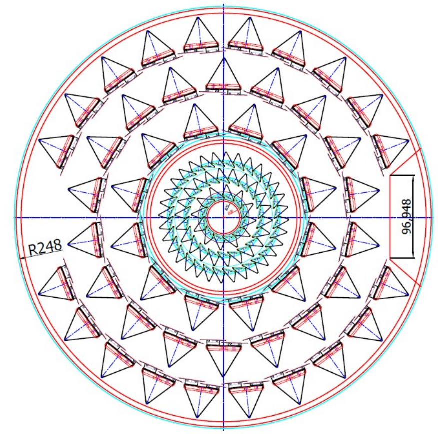
Fast Forward Detector (FFD)

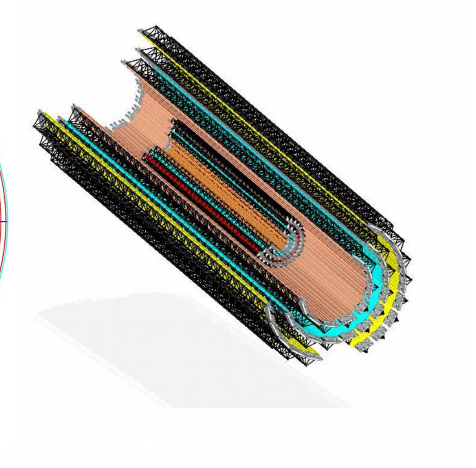


Detects high-energy photons by conversion to electrons in a 10 mm Pb plate The electrons pass through a quartz radiator generating Cherenkov light, collected by photo cathode
Main aims of the FFD:
* Fast and effective triggering of collisions
* Generation of the start pulse for the TOF



Inner Tracking System (ITS)

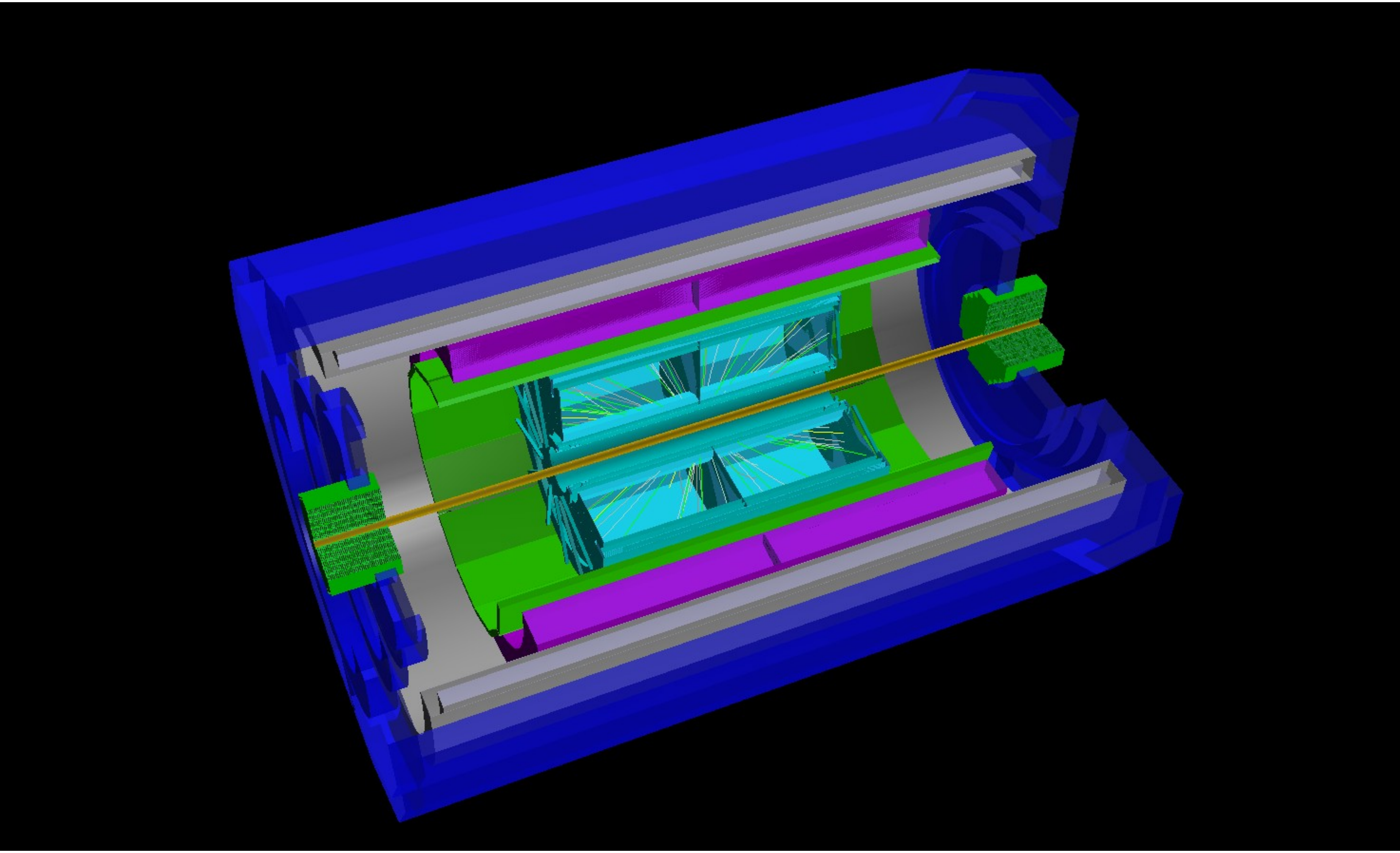




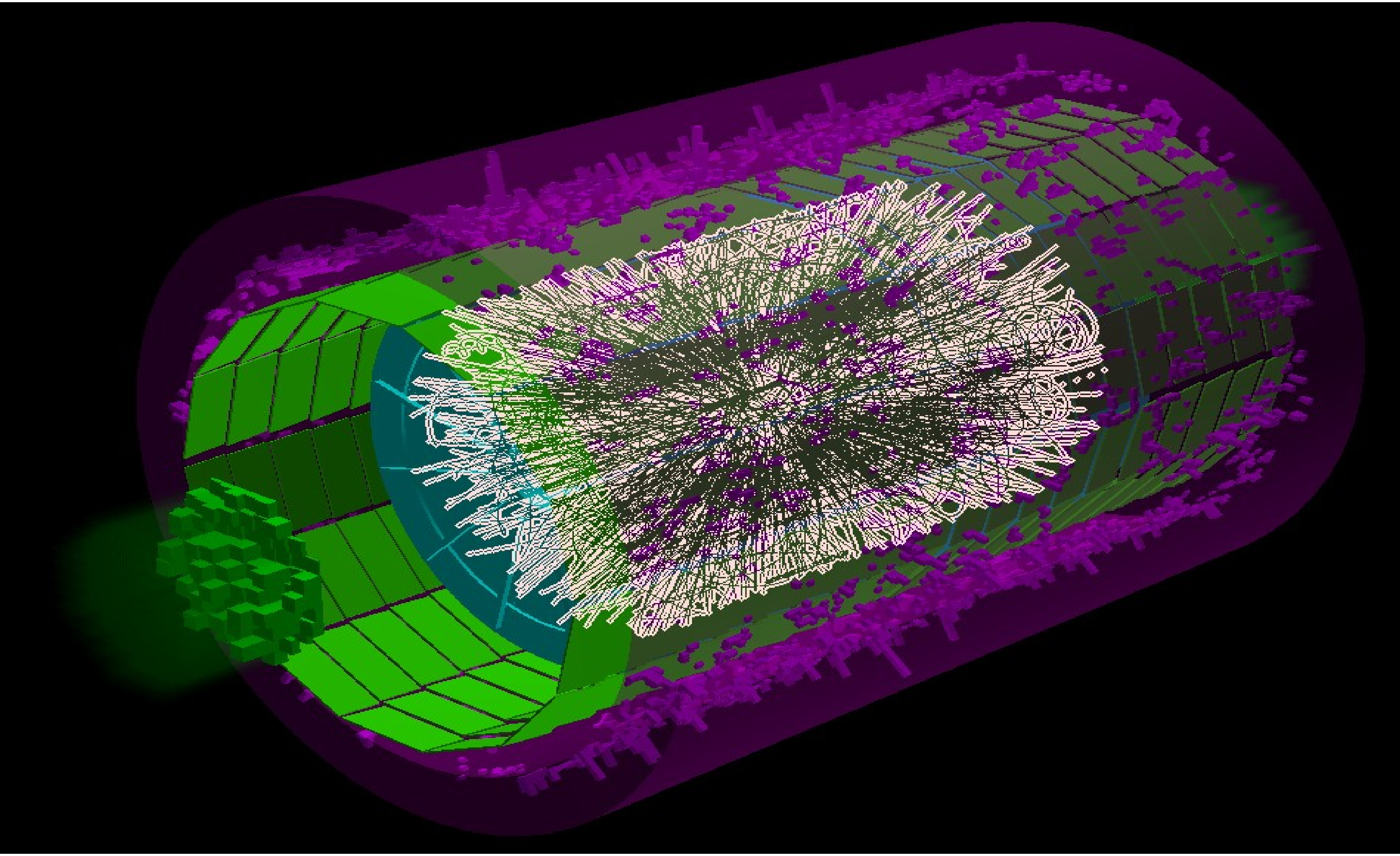
Track reconstruction enhancement and identification of relatively rare events with (multistrange) hyperons.

Cooperation with **CBM/FAIR, ALICE/CERN**:
- manufacturing the **ITS** carbon fiber space frames for **NICA** (BM@N & MPD)& **FAIR;**
- construction of **ALICE type** (MAPS) **ITS**

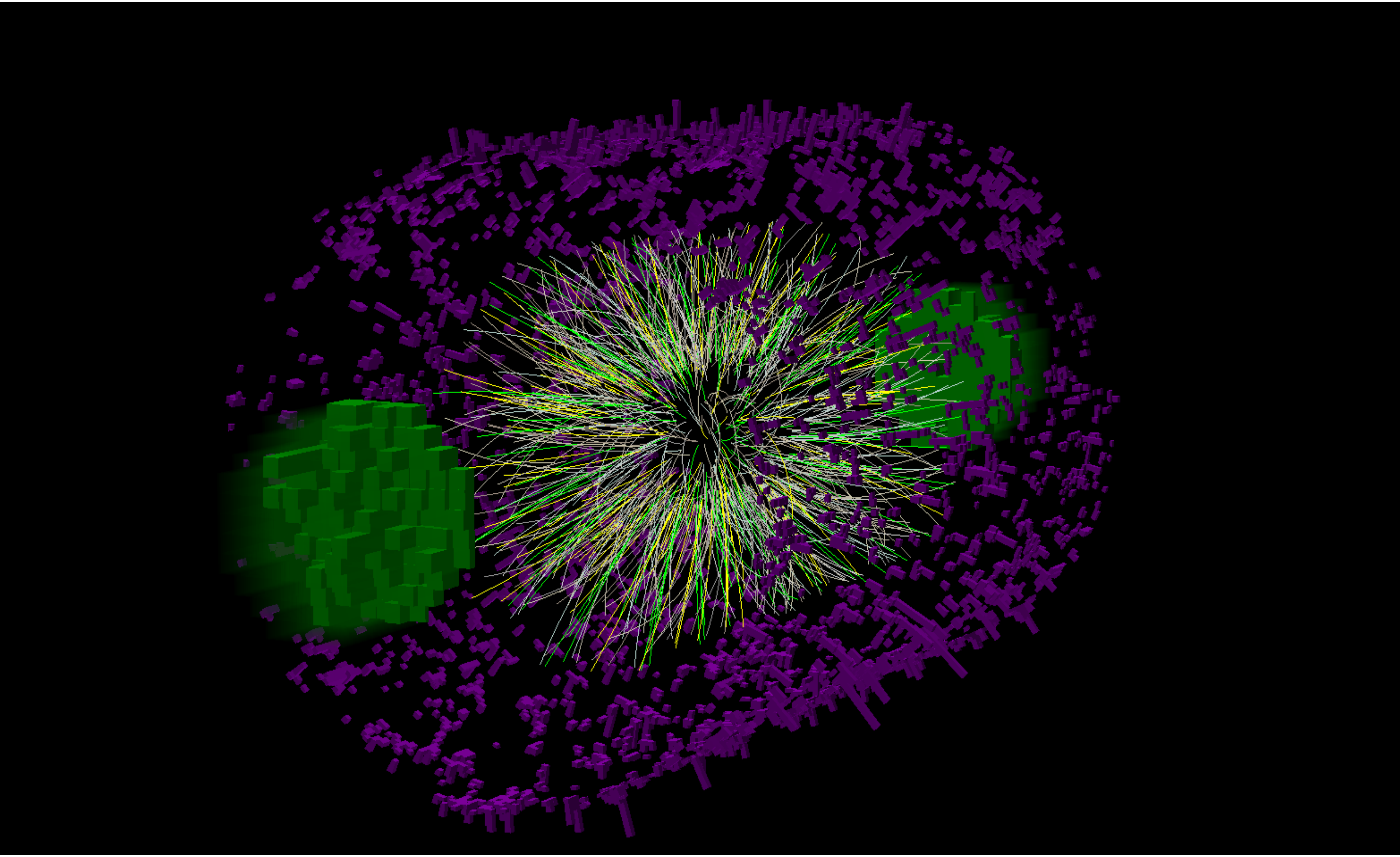
MPD performance



MPD performance



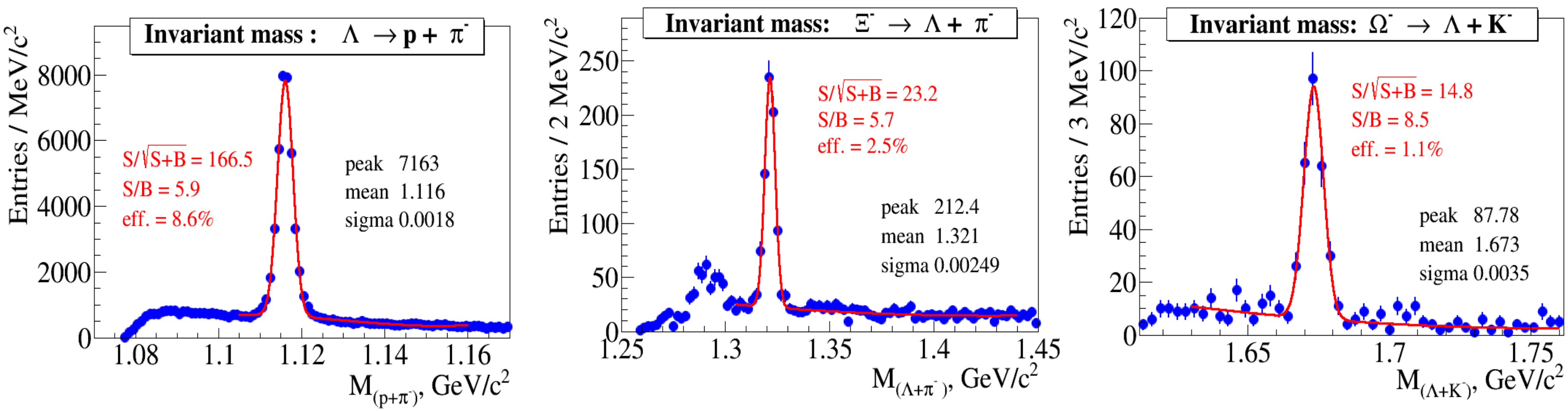
MPD performance



MPD performance: hyperons

production of multi-strange hyperons to study the properties of the strongly interacting system and signal for QGP

- *Central Au+Au @ 9A GeV (UrQMD) , TPC+TOF barrel*
- *Realistic tracking and PID, secondary vertex reconstruction*



Yields for 10 weeks of running

hyperon	Λ	$\bar{\Lambda}$	Ξ^-	$\bar{\Xi}^+$	Ω^-	$\bar{\Omega}^+$
statistics	$6\ 10^9$	$7.3\ 10^7$	$3\ 10^7$	$1.6\ 10^6$	$1.4\ 10^6$	$3\ 10^5$

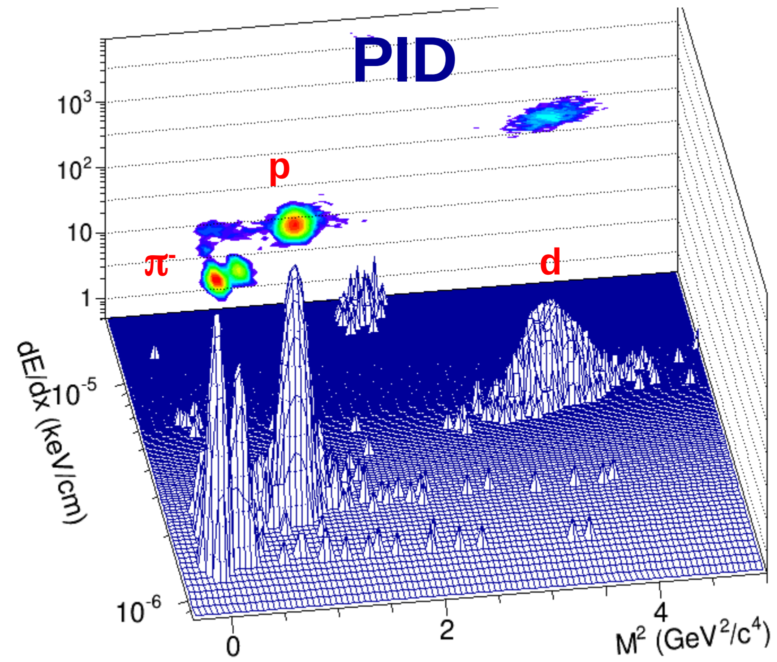
Hypernuclei @ MPD

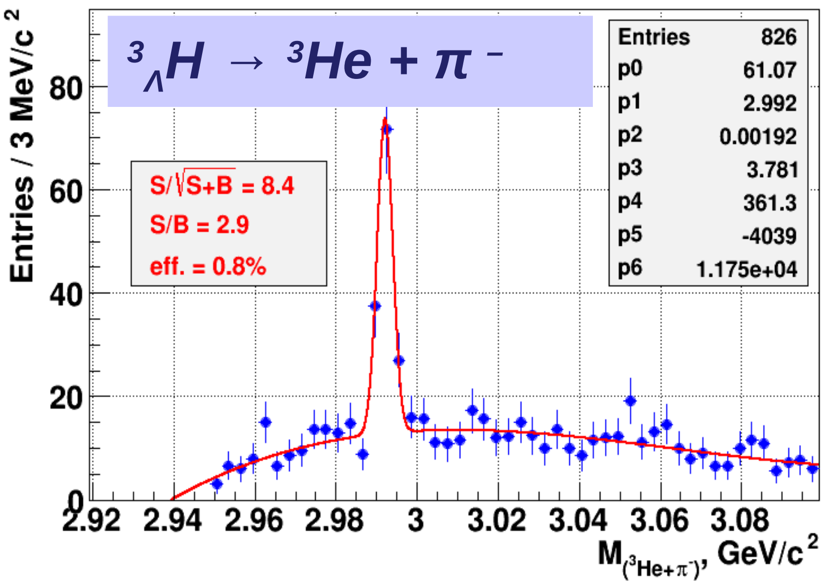
Hypertritons

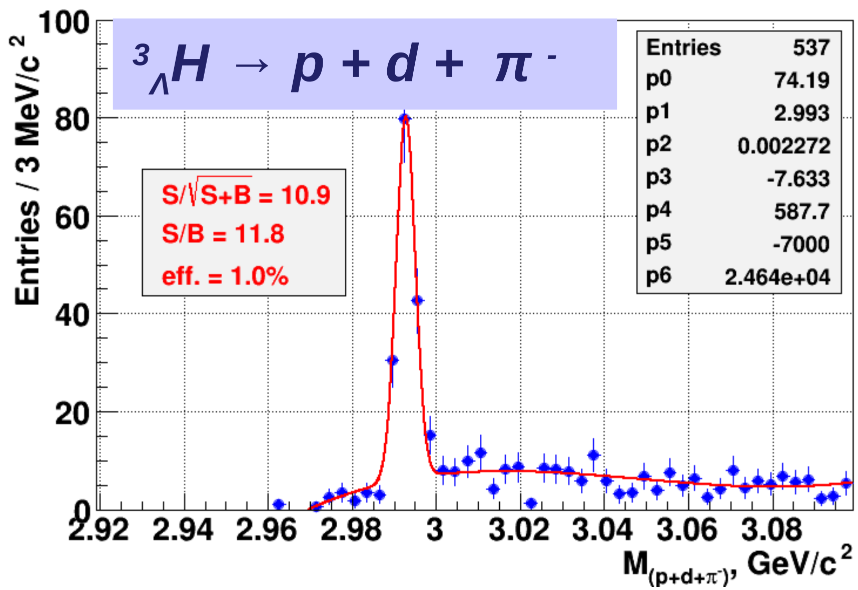
central Au+Au @ 5A GeV

(DCM-QGSM)

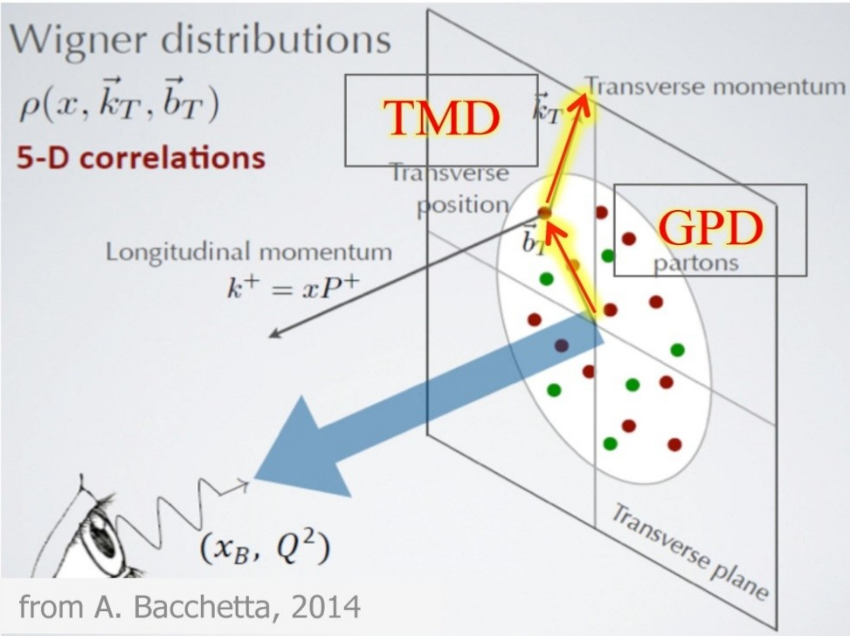
~ 10^6 $^{3}_{\Lambda}H$ *are expected in 10 weeks*



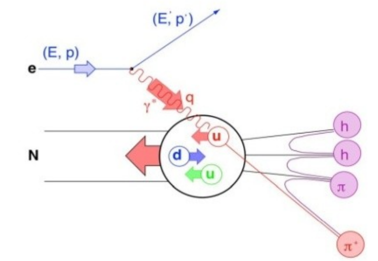




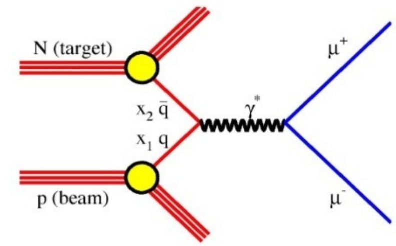
Spin Physics Detector (SPD)



Semi-Inclusive DIS



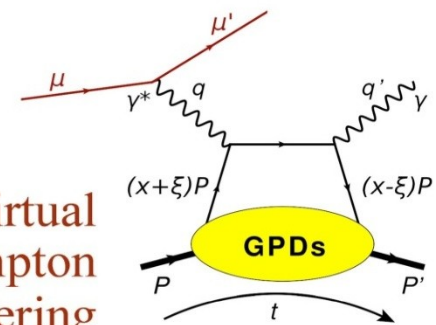
Drell-Yan process



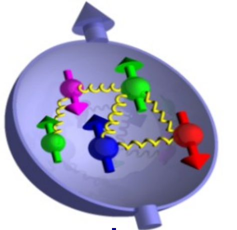
Transversity Momentum Distributions: TMD (x,k_T):
probe the transverse parton momentum dependence

Generalized Parton Distributions : GPD (x,b_T):
probe the transverse parton distance dependence

Deeply Virtual Compton Scattering



Experiments studying the Drell-Yan pair production



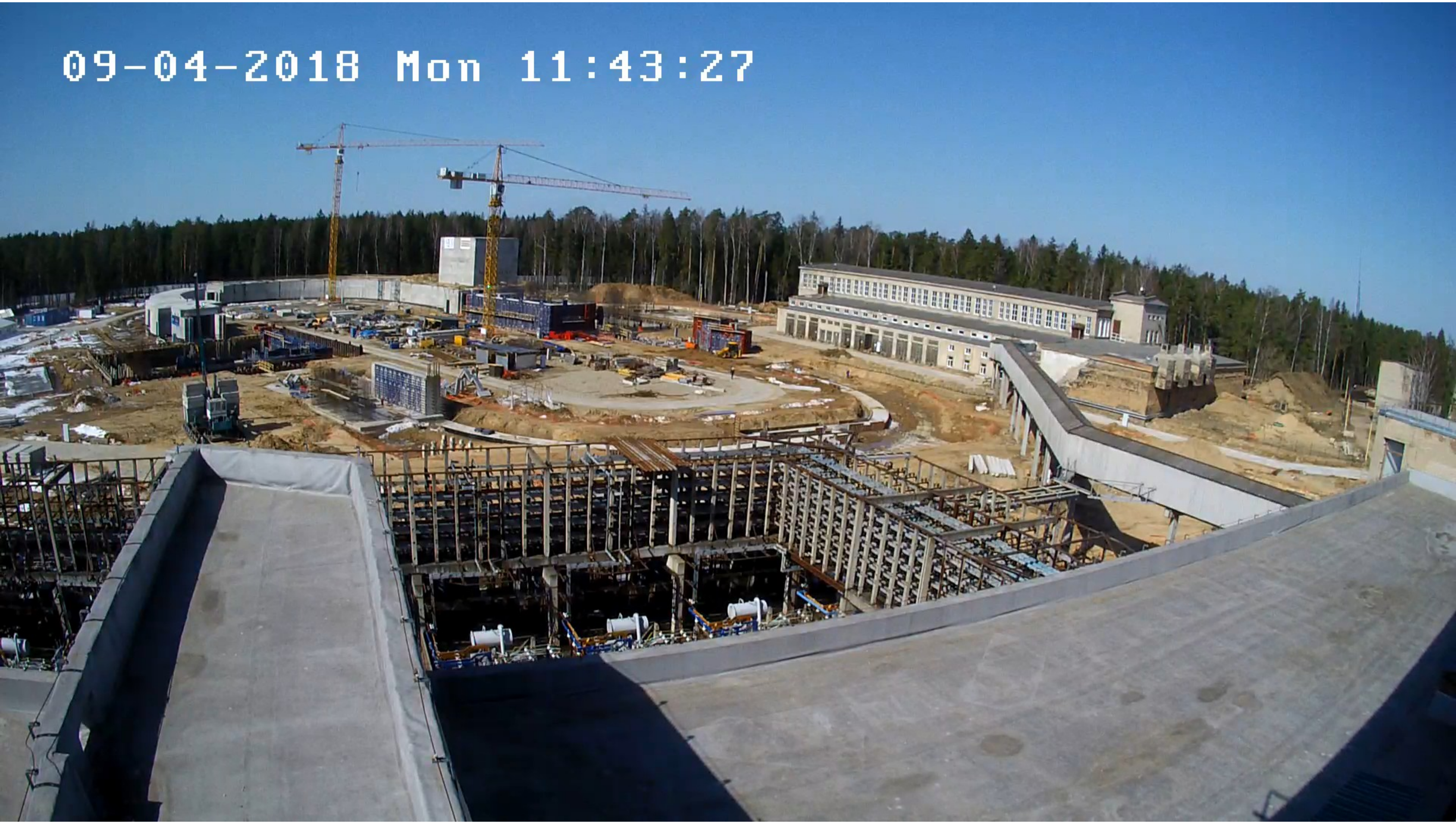
The SPD experiments will have a number of advantages for DY measurements related to nucleon structure studies. These advantages include:

- running with pp, pd and dd beams,
- scan of the effects over a range of beam energies,
- measurement of effects via muon and electron-positron pairs simultaneously,
- running with non-polarized, transverse and longitudinally polarized beams or their combinations.

Experiment	CERN, COMPASS-II	FAIR, PANDA	FNAL, E-906	RHIC, STAR	RHIC-PHENIX	NICA, SPD
mode	*fixed target*	*fixed target*	*fixed target*	*collider*	*collider*	*collider*
Beam/target	*π-, p*	*anti-p, p*	*π-, p*	*pp*	*pp*	*pp, pd,dd*
Polarization:b/t	*0; 0.8*	*0; 0*	*0; 0*	*0.5*	*0.5*	*0.9*
Luminosity	$2{\cdot}10^{33}$	$2{\cdot}10^{32}$	$3.5{\cdot}10^{35}$	$5{\cdot}10^{32}$	$5{\cdot}10^{32}$	10^{32}
√s, GeV	*14*	*6*	*16*	*200, 500*	*200, 500*	*10-26*
$x_{1(beam)}$ *range*	*0.1-0.9*	*0.1-0.6*	*0.1-0.5*	*0.03-1.0*	*0.03-1.0*	*0.1-0.8*
q_T, *GeV*	*0.5 -4.0*	*0.5 -1.5*	*0.5 -3.0*	*1.0 -10.0*	*1.0 -10.0*	*0.5 -6.0*
Lepton pairs,	*μ-μ+*	*μ-μ+*	*μ-μ+*	*μ-μ+*	*μ-μ+*	*μ-μ+, e+e-*
Data taking	*2014*	*>2018*	*2013*	*>2016*	*>2016*	*>2018*
Transversity	NO	NO	NO	YES	YES	YES
Boer-Mulders	YES	YES	YES	YES	YES	YES
Sivers	YES	YES	YES	YES	YES	YES
Pretzelosity	YES (?)	NO	NO	NO	YES	YES
Worm Gear	YES (?)	NO	NO	NO	NO	YES
J/Ψ	YES	YES	NO	NO	NO	YES
Flavour separ	NO	NO	YES	NO	NO	YES
Direct γ	NO	NO	NO	YES	YES	YES

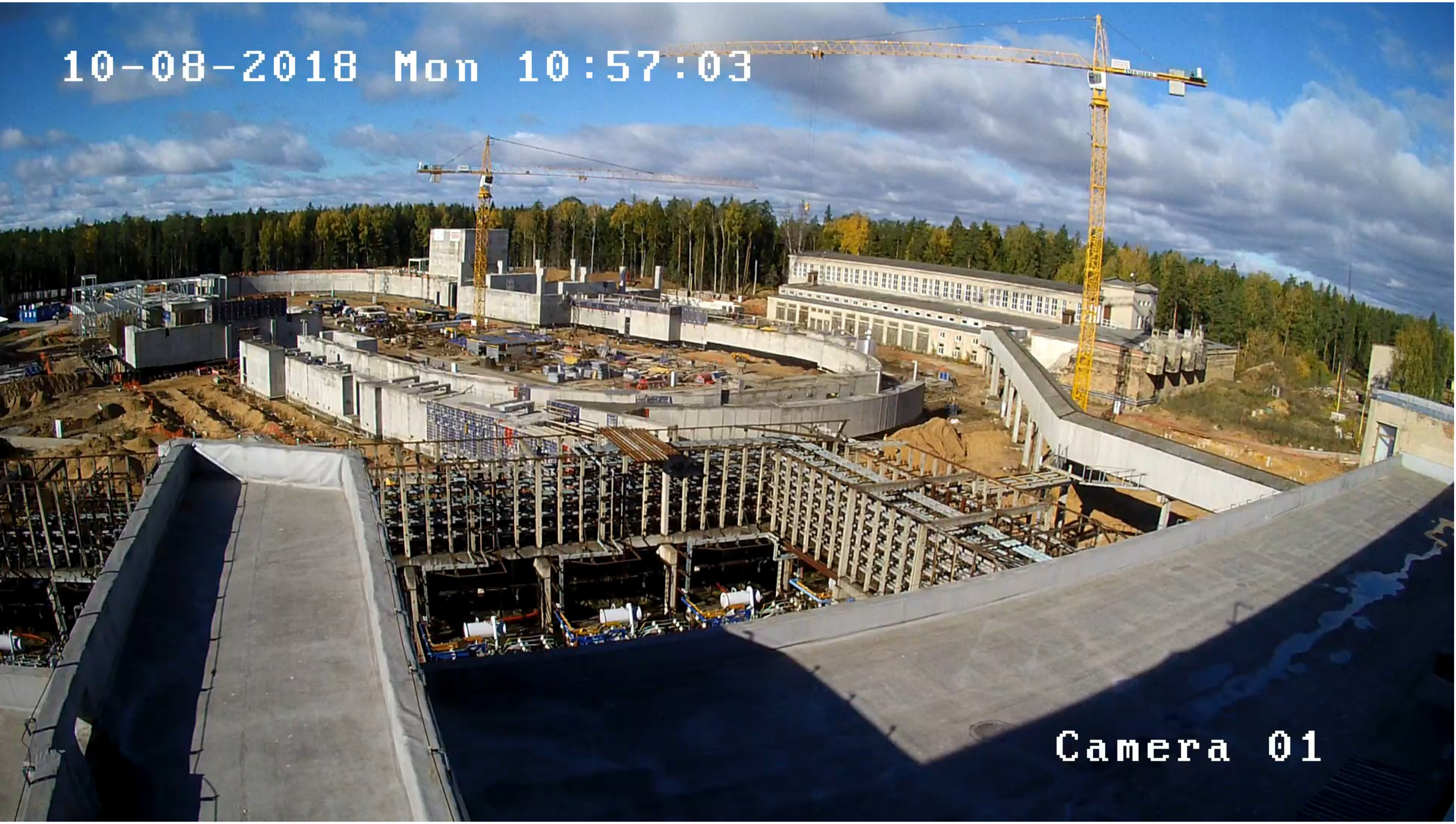
The above advantages permit for the first time to perform comprehensive studies of all leading twist PDFs of nucleons in a single experiment with minimum systematic errors.

Construction live view



http://nucloweb.jinr.ru/nucloserv/205corp.htm

Construction live view



http://nucloweb.jinr.ru/nucloserv/205corp.htm

Summary

- **Density frontier is less explored area of the QCD phase diagram and its study could lead to interesting discoveries**

- **In the medium-term prospect the NICA complex will be the only facility in Europe providing high intensity ion beams from p to Au in the energy range from 2 – 27 GeV (c.m.s.), which could be used for both fundamental and applied researches.**

- **NICA complex will provide unique polarized p↑ and d↑ beams for the spin physics studies.**

- **The construction of accelerator complex and both detectors BM@N & MPD is going close to the schedule**

Acknowledgments

I would like to express my gratitude and appreciation to all my colleagues who helps me with this presentation

P. Senger *(GSI)*
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V. Kolesnikov *(JINR)*
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N. Geraksiev *(JINR)*
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P. Parfenov *(MEPHI)*
V. Kekelidze *(JINR)*
R. Tsenov *(JINR)*
O. Rogachevsky *(JINR)*
M. Kapishin *(JINR)*
A. Taranenko *(MEPHI)*
A. Rustamov *(GSI)*
K. Gertsenberger *(JINR)*

And your for your attention and patience

Thank you!

EXTRA

Basic models for heavy-ion collisions

Statistical models:
basic assumption: system is described by a (grand-) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium

[- : no dynamics]

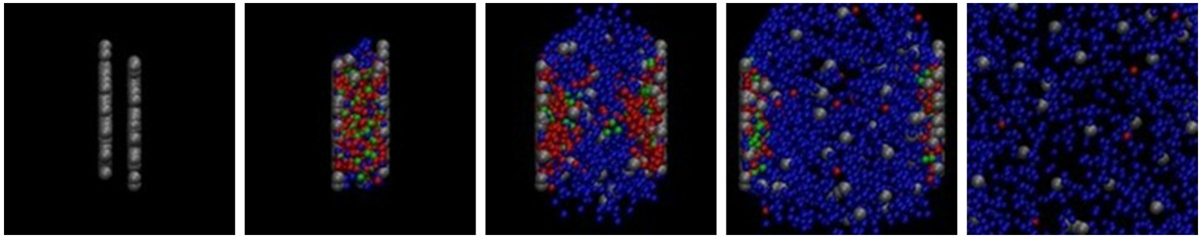
(Ideal) hydrodynamical models:
basic assumption: conservation laws + equation of state; assumption of local thermal and chemical equilibrium

[- : simplified dynamics]

Transport models:
based on transport theory of relativistic quantum many-body systems -
Actual solutions: Monte Carlo simulations

[+ : full dynamics | - : very complicated]

Microscopic transport models provide a unique **dynamical** description of **nonequilibrium** effects in heavy-ion collisions



Experimental modes

Collider (MPD)

Fixed target (BM@N)

Pros:

Collider (MPD):

- ***coverage of max. phase space***
- *free of target parasitic effects*
- *energy and particle independent phase space coverage*

Fixed target (BM@N):

- *rate is limited just by detector capability*
- *easy upgradable*
- *wide rapidity coverage*

Cons:

Collider (MPD):

- *limited combinations "beam"/"target"*
- *Measurements only at mid-rapidity*
- *...*

Fixed target (BM@N):

- *Energy and particle dependent phase space coverage*
- *momentum dependent corrections*
- *...*

NICA - Nuclotron based Ion Collider fAcility

ПРАВИТЕЛЬСТВО РОССИЙСКОЙ ФЕДЕРАЦИИ

РАСПОРЯЖЕНИЕ

от 27 апреля 2016 г. № 783-р

МОСКВА

О подписании Соглашения между Правительством Российской Федерации и международной межправительственной научно-исследовательской организацией Объединенным институтом ядерных исследований о создании и эксплуатации комплекса сверхпроводящих колец на встречных пучках тяжелых ионов NICA

1. В соответствии с пунктом 1 статьи 11 Федерального закона "О международных договорах Российской Федерации" одобрить представленный Минобрнауки России согласованный с МИДом России, Минфином России, Минэкономразвития России и международной межправительственной научно-исследовательской организацией Объединенным институтом ядерных исследований проект Соглашения между Правительством Российской Федерации и международной межправительственной научно-исследовательской организацией Объединенным институтом ядерных исследований о создании и эксплуатации комплекса сверхпроводящих колец на встречных пучках тяжелых ионов NICA (прилагается).

2. Поручить Минобрнауки России провести переговоры с международной межправительственной научно-исследовательской организацией Объединенным институтом ядерных исследований и по достижении договоренности подписать от имени Правительства Российской Федерации указанное в пункте 1 настоящего распоряжения Соглашение, разрешив вносить в прилагаемый проект изменения,

During 2013-2016 NICA successfully passed several stages of International expertise, had assembled a wide collaboration (95 participants from 25 countries). An important step – **inclusion of NICA into ESFRI Strategy Report** on Research Infrastructures and ESFRI Roadmap 2016 Update **as complimentary project to ESFRI landmark** project FAIR

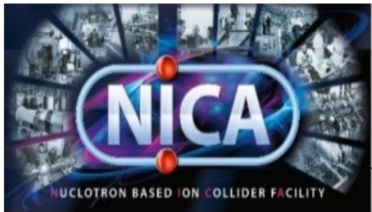
On 27th April 2016 the RF Prime-minister issued the Governmental Decree about establishment of the NICA mega-science on Russian territory at JINR.

Agreement between RF Government and JINR (signed on 2nd June 2016) in the frame of Decree formulates basic principles of the setting and development of the International collaboration "Complex NICA".

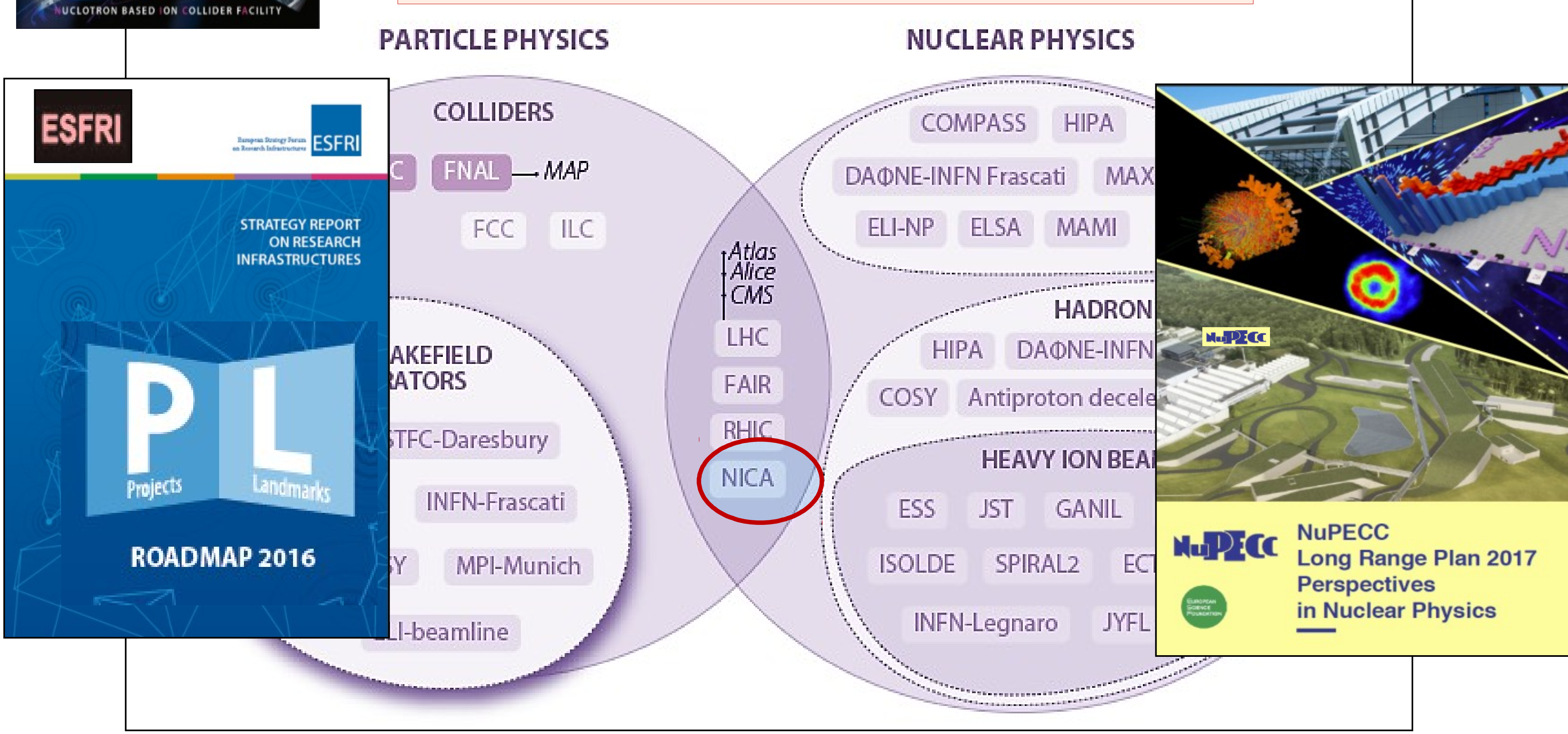
We assume that in coming years similar Agreements will be prepared, agreed and signed with other countries and International Scientific centers, expressed their interest to participate and contribute to NICA.

NICA - Nuclotron based Ion Collider fAcility

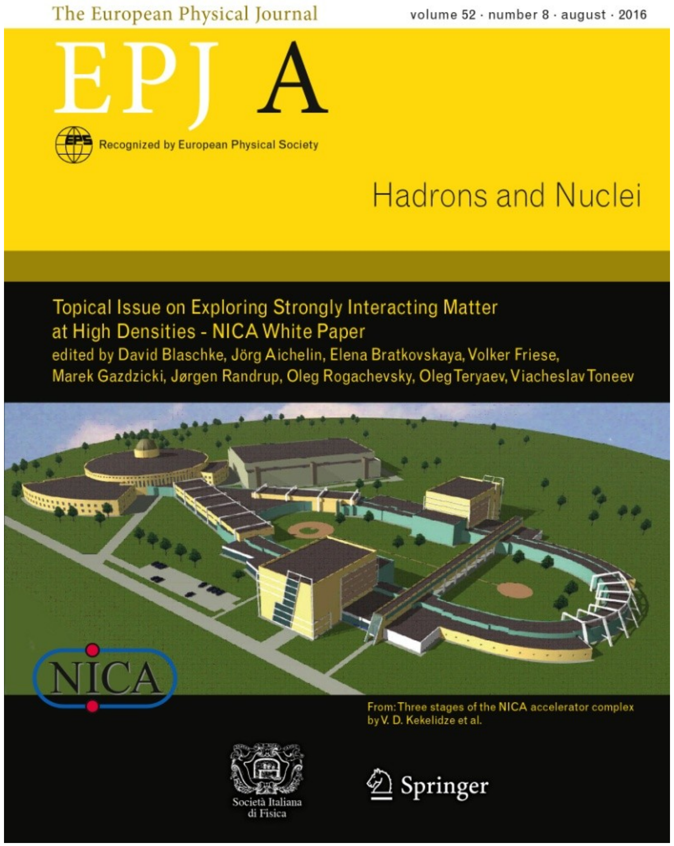
NICA is included in the ESFRI ROADMAP-2016 and in the NuPECC Long Range Plan 2017 - Perspectives in Nuclear Physics



Main Research Infrastructures in Particle and Nuclear Physics



NICA - Nuclotron based Ion Collider fAcility

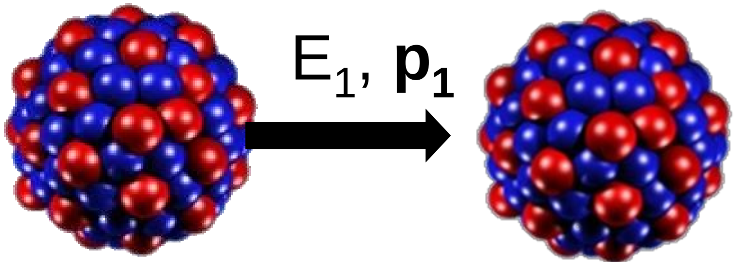


- The White paper of the NICA scientific program is continuously updated

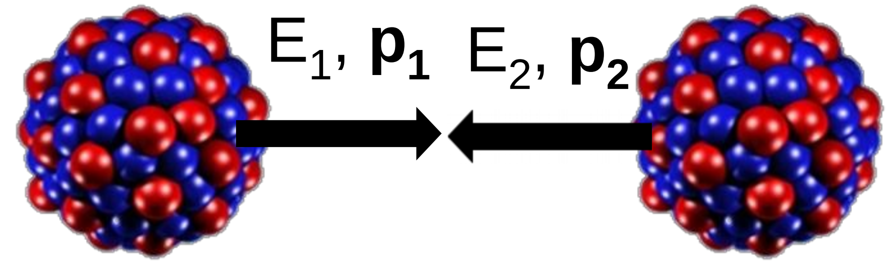
- The collected contributions on signatures of the 1st order phase transition and the mixed phase in the NICA energy region culminated in the release of the "NICA White Paper" as a Topical Issue of the **EPJ A** (July 2016).

111 *contributions,*
188 *authors*
from **24** *countries*

Fixed target vs collider mode



$E_2 = m$, $\mathbf{p_2} = 0$



$$(E_1 + E_2)^2 = (\mathbf{p_1} + \mathbf{p_2})^2 + (m + m)^2 \quad \text{with } E = E_{kin} + m$$

$$(m + m)^2 = s_{NN} = (E_1 + E_2)^2 - (\mathbf{p_1} + \mathbf{p_2})^2$$

$\sqrt{s_{NN}}$: Available energy per nucleon in the center-of mass system

Fixed target: $E_2 = m$, $\mathbf{p_2} = 0$

$$S_{NN} = (E_{kin} + 2m)^2 - \mathbf{p_1}^2$$

$$S_{NN} = 2 \cdot m \cdot (E_{kin} + 2m)$$

For $E_{kin} >> m$: $\sqrt{S_{NN}} \approx 1.4 \sqrt{E_{kin}}$

Example SIS100:

$E_{kin} = 11$ GeV $\rightarrow$: $\sqrt{S_{NN}} = 4.9$ GeV

Collider: $\mathbf{p_1} + \mathbf{p_2} = 0$

$$\sqrt{S_{NN}} = E_1 + E_2$$

Example NICA:

$E_{kin} = 4.5$ GeV $\rightarrow$: $\sqrt{S_{NN}} = 11$ GeV

Reaction rates: Collider

Collider Luminosity: $L = N_1 \cdot N_2 \cdot B / F$ [$cm^{-2}s^{-1}$]

N_1, N_2 = beam particles per bunch

B = number of bunch crossing per second

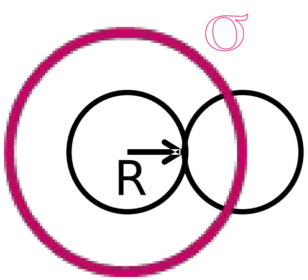
F = beam size in cm^2

Typical numbers:

$N_1 = N_2 = 10^9$

$B = 10^4$ $\rightarrow L = 10^{27}$ $cm^{-2}s^{-1}$

$F = 10^{-5}$ cm^2



Reaction rate: $R = L \cdot \sigma$

σ = reaction cross section

$\sigma = \pi \cdot (2 \cdot R)^2 = 4\pi \cdot (r_0 \cdot A^{1/3})^2$ with r_0=1.2 fm

Au+Au collisions: A = 197 → σ = 6 barn, 1 barn = 10^{-24} cm^2

Collider reaction rates for Au+Au:

$R = 10^{27}$ $cm^{-2}s^{-1} \cdot 6 \cdot 10^{-24} cm^2 = 6000$ s^{-1}

Reaction rates: Fixed target

Fixed target Luminosity: $L = N_B \cdot N_T / F$ [$cm^{-2}s^{-1}$]

N_B = beam particles / second

N_T/F = target atoms/cm^2 = $N_A \cdot \rho \cdot d/A$

with Avogadros Number $N_A = 6.02 \cdot 10^{23}$ mol^{-1}

material density ρ [g/cm^3]

target thickness d [cm]

atomic number A [g/mol]

Typical numbers:

$N_B = 10^9 s^{-1}$

Au target $\rho = 19.3$ g/cm^3, A = 197

d = 0.3 mm (1% interaction rate)

$L = 1.8 \cdot 10^{30}$ $cm^{-2}s^{-1}$

Fixed target reaction rates for Au+Au:

$R = L \cdot \sigma = 1.8 \cdot 10^{30}$ $cm^{-2}s^{-1} \cdot 6 \cdot 10^{-24}$ $cm^2 = 10^7$ s^{-1}