Heavy Ion Collisions - Density Frontier

V. Kekelidze,
Joint Institute for Nuclear Research

50 years of
Baksan Neutrino Observatory

June 6, 2017
Exploring the QCD phase diagram

The Phases of QCD

Quark-Gluon Plasma

FAIR and NICA

Hadron Gas

Critical Point

Vacuum

Baryon Chemical Potential

0 MeV

900 MeV

0 MeV

Temperature

~170 MeV

Early Universe

Future LHC Experiments

Current RHIC Experiments

Crossover

1st order phase transition

Vacuum
The regime of "asymptotic freedom" is reached in hard processes at sufficiently high energies, however this regime could be available already at rather low energies in super dense nuclear matter (the distance between particles \( \sim 1/T \)). Typical size \( R_0 \sim 1 \text{ fm} \approx 10^{-13} \text{ cm} \).
Synchrophasotron; SC synchrotron - Nuclotron (1993) based on superconducting fast cycling magnets developed at LHE JINR

Nuclotron ring (c=251,5 m)
CERN LH Collider, experiments with fixed target at SPS

CMS

~ 27 km

ALICE

NA49/61

SPS

ATLAS

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BNL: ASG, Relativistic Heavy Ion Collider

Designed Energy $\sqrt{s_{NN}} = 200$ GeV

BNL 2000: RHIC

~ 4 km

PHENIX

STAR

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Phase Transition

transvers energy & energy density

\begin{align*}
\eta &= \frac{1}{2} \log \left( \frac{\sqrt{\mathbf{p}^2 + p_z^2}}{\sqrt{\mathbf{p}^2} - p_z} \right) = -\ln(\tan \frac{\Theta}{2}) \\
\langle m_T \rangle &= \sqrt{m^2 + \mathbf{p}_T^2}
\end{align*}
What we have learned of > 30 years of HIC study

- Strangeness Enhancement
- Triumph of Thermal Model
- Onset of deconfinement
  - Quarkonia suppression
  - $\rho$ melting
- Femtoscopy – Crossover in PT
- Collective motion (Hydrodynamics)
  - Chiral Magnetic Effect (CME)
  - Ridge Effect (puzzle?)
  - Vorticity – $\Lambda$ polarization
Strangeness Enhancement: \textit{SPS CERN, RHIC}

Hyperon production

Indication to chiral symmetry restoration

Energy region of NICA

"Horn" effect onset of deconfinement requires more detailed study

Pb+Pb:
- NA49
- AGS
- RHIC


\textit{STAR}: QM2011 proceedings
Thermal / Statistical model

thermal particle production; predicted for equilibrated matter/QGP

Dozens of particle yields with very few parameters: $T_{ch}$, $\mu_B$, $\gamma_s$ ($V$ – for abs. scale)

in $e^+e^-$, pp, pA, AA:

$$n_i = \frac{g_i}{2N_{BW}} \frac{1}{M_{thr}} \int_{m_i - \mu_B}^{m_i + \mu_B} \frac{p^2 dp}{(m - m_i)^2 + \frac{p^2}{4} \exp[\frac{(E_i - m_i)}{T}] \pm 1}$$

ALICE: Pb+Pb

Thermal model
- a “snapshot” of AA collision at chemical freeze-out
Chemical equilibrium is a very good approximation in heavy-ion collisions. Only one volume! Only one temperature!

\[ T = T_{\text{lim}} \frac{1}{1 + \exp(2.60 \ln(\sqrt{S_{NN}(\text{GeV})}) / 0.45)} \]

\[ b[\text{MeV}] = \frac{1303}{1 + 0.286(\sqrt{S_{NN}(\text{GeV})})} \]

\[ T_{\text{lim}} = 164 \pm 4 \text{ MeV} \]
Onset of deconfinement: Quarkonium suppression

‘Anomalous’ $J/\Psi$ Suppression

predicted as deconfinement signal – color screening

Charm Recombination: parton or hadron coalescence

$(D+D \rightarrow J/\Psi + X)$

$R_{AA}$ $J/\Psi$: LHC > RHIC

ALICE PRL 109 (2012) 072301
Onset of deconfinement: Leptons

Low Mass Lepton Pair Enhancement 'rho melting', sign of chiral symmetry restoration?
continuum -> thermal radiation
$<T> = 230 \pm 10$ MeV

$\mu^+\mu^-$ pair yield

Planck-like spectrum
$dN/dM \sim M^{3/2} \times \exp(-M/T)$

$\rho$ broadens $\rightarrow$ hadrons 'melt' close to $T_c$
Approach to Chiral Symmetry restoration

P.M. Hohler and R. Rapp, PLB 731 (2014) 103
Study phase transition with femtoscopy

\[ C(\vec{q}) - 1 \equiv R(\vec{q}) = \int (|\phi(\vec{q}, \vec{r})|^2 - 1) S(\vec{r}) d\vec{r} \]

\[ S(\vec{x}) \sim \exp \left( -\frac{x_o^2}{2R_o^2} - \frac{x_s^2}{2R_s^2} - \frac{x_l^2}{2R_l^2} \right) \]

3D Femtoscopy radii


\[ R_l \text{ - long} \]
\[ R_o \text{ - out} \]
\[ R_s \text{ - side} \]

Green triangles - 1\text{st} order EoS,

Red triangle - crossover EoS,

A.Kisiel, WUT
Collective effects; Hydrodynamics

Elliptic flow of central fireball matter (collective motion)

\[ \frac{\langle y^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \]

initial coordinate-space anisotropy

\[ v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \]

final momentum-space anisotropy

\[ \frac{dN}{d\mu} \left[ 1 + 2 v_1 \cos[(R)] + 2 v_2 \cos[2(R)] + ... \right] \]

equation

Elliptic flow establishes there is strongly interacting matter at t \sim 0

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Hydro-Dynamics (Exp+Th):

**LO:** radial ($v_0$) & directed ($v_1$) & elliptic ($v_2$)  
**NLO:** higher harmonics $v_n$, $n = 1, \ldots, 6$  
**NNLO:** non-linear mode mixing, $v_n \neq \varepsilon_n$, mode coupling in viscous fluid  

Factorization violation $\nu(p_{T1}, p_{T2}) \neq \nu(p_{T1})^* \nu(p_{T2})$

**Strong Elliptic Flow** $\sim$ max possible  
i.e. 'ideal liquid' ($\eta/s \approx 0$)

<table>
<thead>
<tr>
<th>$v_2/\varepsilon$ (scaled) Flow</th>
<th>Reaction plane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HYDRO limits</strong></td>
<td></td>
</tr>
<tr>
<td><strong>RHIC</strong></td>
<td></td>
</tr>
</tbody>
</table>

**AGS**  
**SPS**  
**RHIC**  
**NICA**
Strongly Interacting Matter

High $p_T$ Suppression - ’jet-quenching’
– very strongly interacting matter (large energy loss)

Jet Fragmentation $D(z)$
central/peripheral

$D(z) = \frac{1}{N_{jet}} \frac{dN_h}{dz}$
$Z = \frac{P_T^h \times P_T^{jet}}{P_T^{jet}} \mid \frac{P_T^{jet}}{2}$

$D(z)$ - softens
in strongly interacting matter


**Azimuthal correlations; Ridge Effect**

\[
S(\eta, \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{same}}}{d\eta d\phi} \\
B(\eta, \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{mix}}}{d\eta d\phi}
\]

\[
\Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}} \\
\Delta \phi = \phi^{\text{assoc}} - \phi^{\text{trig}}
\]

---

**Hydrodynamic origin?**

A matter created in central AuAu collisions (volume of the order of 5000 fm\(^3\)) behaves as a macroscopic ideal fluid.

**Than pPb and pp ridge is a real puzzle!**

How come such a tiny hydrodynamical object (few fm\(^3\))?

**Projection of nucleon-nucleon scattering (flux tubes) to the transverse plane?**

---

**Au Au: 0 – 12%**

**pp: N>110, 1<P_T<3GeV/c**
charge asymmetry w.r.t. reaction plane – local Parity Violation

electric current induced by chirality anomaly in high $\vec{B}$

Electric dipole moment of QCD matter!
**Chiral anomaly:** *chirality imbalance + chiral charge non conservation*


- Generate strong magnetic fields: \( e\vec{B} \approx O(10m_\pi^2) \approx 10^{15} T \)
- Light quarks \( \rightarrow \) Chiral fermions

**CME:** *Charge Dependent Correlations*

**Electric current could be generated in strong magnetic field** \( \vec{B} \)

\[
\vec{J} = \sigma_5 \vec{B} \quad \text{and} \quad 5 = \frac{Q_e}{2} \quad 5
\]

\[
\vec{J} \rightarrow Q_e \vec{J} = \frac{Q_e}{2\pi^2} \mu_5 \vec{B}
\]

Chiral Magnetic Effect' signals (CME, CMW, ..)

Fundamental QCD relation (chiral anomaly, ..) ?
Vorticity & $\Lambda$ Polarization

\[ \vec{J} = \frac{1}{\pi^2} \mu_s \mu \vec{\omega} \quad \vec{\omega} = \frac{1}{2} \nabla \times \vec{v} \]

$\Lambda$ polarization $\sim$ anomalously induced axial current: \[ J_A \sim \frac{2}{3(1 + P)} \]

\[ \left< \frac{1}{\Pi_0} \right> \]

\[ \begin{array}{c}
\text{Data STAR} \\
\text{Au + Au, } \kappa = 0.0 \\
\text{b = 8.0 fm} \\
\text{b = 6.4 fm} \\
\text{b = 4.8 fm}
\end{array} \]

\[ \text{NICA} \]

O. Rogachevsky, A. Sorin, O. Teryaev, Phys. Rev. C 82, 054910, 2010;
M. Baznat, K. Gudima A. Sorin, O. Teryaev arXiv:1701.00923

STAR Coll., arXiv:1701.06657

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The freeze-out condition (of phase transition)

Hadronic freeze-out

J. Randrup & J. Cleymans
Present and future HI experiments

Interaction rate [Hz] vs. Collision energy $\sqrt{S_{NN}}$ [GeV]

- CBM
- HADES
- NICA/BM@N II
- STAR F.T.
- NICA/MPD
- STAR BES II
- NA-61/SHINE

2022 – 2025: SIS-100 FAIR

Energy region of max. baryonic density
Net Baryonic density to be reached in Au + Au collisions

FAIR SIS-100

5 A GeV

5 A GeV Au + Au (b=0): $\rho(0,0,0,t)$

NICA

10 A GeV

10 A GeV Au + Au (b=0): $\rho(0,0,0,t)$

Complex FAIR: experiments with fixed target

Darmstadt, Germany
HADES

p+p, p+A
A+A (low mult.)

Experimental requirements

Dipol Magnet
Silicon Tracking System
Ring Imaging Cherenkov
Muon Detector

Transition Radiation Detector
Time of Flight Detector

DAQ/FLES HPC cluster

Projectile Spectator Detector
QCD matter at the **NICA energies**:

- maximum in the net baryon density – *density frontier*;
- maximum in $K^+/\pi^+$ ratio;
- maximum in $\Lambda/\pi$ ratio;
- transition from a Baryon dominated system to a Meson dominated one;
- maximum of the $\Lambda$ polarization;
- 1-st order transition & mixed phase creation;
- **Critical Endpoint ?**
NICA major facility

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NICA accelerator complex
### Machines: Nuclotron

*In operation since 1993*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nuclotron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>type</strong></td>
<td>SC synchrotron</td>
</tr>
<tr>
<td><strong>particles</strong></td>
<td>↑ p, ↑ d, nuclei</td>
</tr>
<tr>
<td><strong>injection energy, MeV/u</strong></td>
<td>5 (↑p, ↑d) 570-685 (Au)</td>
</tr>
<tr>
<td><strong>max. kin. energy, GeV/u</strong></td>
<td>12.07 (↑p); 5.62 (↑d) 4.38 (Au)</td>
</tr>
<tr>
<td><strong>magnetic rigidity, T m</strong></td>
<td>25 – 43.25</td>
</tr>
<tr>
<td><strong>circumference, m</strong></td>
<td>251.52</td>
</tr>
<tr>
<td><strong>cycle for collider mode, s</strong></td>
<td>1.5-4.2 (active); 5.0 (total)</td>
</tr>
<tr>
<td><strong>vacuum, Torr</strong></td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td><strong>intensity, Au ions/pulse</strong></td>
<td>$1 \times 10^9$</td>
</tr>
<tr>
<td><strong>transition energy, GeV/u</strong></td>
<td>7.0</td>
</tr>
<tr>
<td><strong>RF range, MHz</strong></td>
<td>0.6 -6.9 (↑p, ↑d) 0.947 – 1.147 (nuclei)</td>
</tr>
<tr>
<td><strong>spill of slow extraction, s</strong></td>
<td>up to 10</td>
</tr>
</tbody>
</table>

Modernized in **2010-2015**

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The Collider

45 T*m, 4.5 GeV/u for Au$^{79+}$

**Double aperture magnets:** dipole & quadrupole prototypes

**Ring circumference, m** | 503.04
---|---
**Number of bunches** | 22
**r.m.s. bunch length, m** | 0.6
**$\beta$, m** | 0.35
**max. int. Energy, GeV/u** | 11.0
**r.m.s. $\Delta p/p$, $10^{-3}$** | 1.6
**IBS growth time, s** | 1800
**Luminosity, cm$^{-2}$ s$^{-1}$** | $1 \times 10^{27}$

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Civil Construction

- 3600 piles are already pressed in
- concrete works are in progress
Production of SC magnets (Dubna type technology) for (Booster, Collider) / NICA & SIS-100/FAIR

serial tests of Booster magnets have started

fabrication of magnet parts is on schedule
Finally the cooling power should be doubled from 4 kW to 8 kW @ 4.5K
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 Tech.Uni.  
Israel: Tel Aviv Uni., Weitzman Inst.  
Germany: Frankfurt Uni.; eoi GSI  
USA: MIT

Nuclotron

Physics:
✓ strange / multi-strange hyperon and hypernuclei production at the threshold  
✓ hadron femtoscopy  
✓ short range correlations  
✓ event-by-event fluctuations  
✓ in-medium modifications of strange & vector mesons in dense nuclear matter  
✓ electromagnetic probes, states decaying into γ, e (with ECAL)
**BM@N status and milestones**

**BM@N schematic view**

- **DAQ**
- **GEM (CERN)**
- **ST**
- **TOF**
- **Outer tracker**

- **2016, IV:**
  - Basic config.
  - 6 half planes
  - 1 small plane
  - Half config.
  - DCH

- **2017, III:**
  - Complete
  - 10 h/pl.
  - 2 s/pl.
  - Basic
  - DCH

- **2019, I:**
  - 8-10 full pl.
  - 2 s., 2 large pl.
  - Complete
  - Straw + DCH

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BM@N feasibility study

A. Zinchenko, V. Vasendina

Simulation: *UrQMD & DCM-QGSM, Au+Au 4.5 AGeV*

900k central events
7.5M $\Xi^-$ in 1 m, 20 kHz trigger

2.6M central events
8.5M $^3H_\Lambda$ in 1 m, 20 kHz trigger

---

**Invariant mass: $\Xi^- \rightarrow \Lambda + \pi^-$**

- S/B = 3.6
- S/\sqrt{S+B} = 14.0
- Eff. = 0.8%
- Peak 77.53
- Mean 1.321
- Sigma 0.0027

---

**Invariant mass: $^3H_\Lambda \rightarrow ^3He + \pi^-$**

- S/B = 1.6
- S/\sqrt{S+B} = 22.4
- Eff. = 1.0%
- Peak 271.8
- Mean 2.991
- Sigma 0.0025
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;

• CERN;
• DF, US, Mexico;
• ICN UNA; Mexico;
• DF, CIEA del I.P.N, Mexico;
• FCF-M UAS, Sinaloa, Mexico;
• FCF-MB UAP, Puebla, Mexico;
• 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
• CCTVVal, Univ. Téch. Federico SantaMaría, Chile.
MPD detector for Heavy-Ion Collisions @ NICA

Tracking: up to $|\eta|<1.8$ (TPC)
PID: hadrons, $e, \gamma$ (TOF, TPC, ECAL)
Event characterization:
  centrality & event plane (ZDC)

$B_0=0.66$ T
weight
~ 900 t

Stage 1:
  TPC, TOF, ECAL, ZDC, FD

Stage 2:
  IT + Endcaps (tracker, TOF, ECAL)

Status: technical design – completed / close to completion; preparation for the mass production

General contractor:
ASG Superconductors, Genova, Italy

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Magnet production: at ASG (Genova) & Vitkovice HM

VITKOVICE Heavy Machinery, Sept. 2016

from Forgital (Northern France) to the SIMIC Genova (Italy), June 2017
**TPC: assembly stage**

**Sketch of TPC**
- 12 Readout chamber
- HV-electrode ~ 28 kV
- ~ 98 000 RO channels
- production of RO Chambers

assembly workshop (clean room) & tooling

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**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

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**Yields for 10 weeks of running**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Expected yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>$5.8 \cdot 10^9$</td>
</tr>
<tr>
<td>$\bar{\Lambda}$</td>
<td>$7.3 \cdot 10^7$</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>$2.9 \cdot 10^7$</td>
</tr>
<tr>
<td>$\bar{\Xi}^+$</td>
<td>$1.6 \cdot 10^6$</td>
</tr>
<tr>
<td>$\Omega^-$</td>
<td>$1.4 \cdot 10^6$</td>
</tr>
<tr>
<td>$\bar{\Omega}^+$</td>
<td>$2.9 \cdot 10^5$</td>
</tr>
</tbody>
</table>
**Inner Tracking System**

**ALICE/CERN & JINR** – joint efforts for:
- manufacturing the **ITS** carbon fiber space frames for **NICA (BM@N & MPD)& FAIR**;
- construction of **MAPS based ITS for MPD & ALICE**

**ITS MPD layout**

<table>
<thead>
<tr>
<th># layer</th>
<th>R0 mm</th>
<th>Active l, mm</th>
<th>N of staves</th>
<th>N of chips / layer</th>
<th>active area, cm²</th>
<th>number of pixel cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24,4</td>
<td>542,4</td>
<td>12</td>
<td>216</td>
<td>889,9</td>
<td>113 246 208</td>
</tr>
<tr>
<td>2</td>
<td>42,0</td>
<td>542,4</td>
<td>22</td>
<td>264</td>
<td>1 087,7</td>
<td>138 412 032</td>
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<tr>
<td>3</td>
<td>60,0</td>
<td>542,4</td>
<td>32</td>
<td>384</td>
<td>1 582,1</td>
<td>201 326 592</td>
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<tr>
<td>4</td>
<td>107</td>
<td>1477,5</td>
<td>12</td>
<td>1176</td>
<td>4 845,1</td>
<td>616 562 688</td>
</tr>
<tr>
<td>5</td>
<td>156,5</td>
<td>1477,5</td>
<td>18</td>
<td>1764</td>
<td>7 267,7</td>
<td>924 844 032</td>
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<tr>
<td>6</td>
<td>206,5</td>
<td>1477,5</td>
<td>24</td>
<td>2352</td>
<td>9 690,2</td>
<td>1 233 125 376</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
<td></td>
<td>6156</td>
<td>25 362,7</td>
<td></td>
<td><strong>3 227 516 928</strong></td>
</tr>
</tbody>
</table>

**workshop for detector assembly & test was put in operation in 2015**

**D. Gross in the workshop**

**stand for beam tests of boards with sensors – in operation**
• **TDR – OK!** Production close to completion
• **Tests of the trigger electronics & software at BM@N**
• **Progress in FE electronics and LV system for FFD**

![Diagram](image1)

*FFD*$_E$  

*FFD*$_W$  

L = 140 cm

![Diagram](image2)

**The time resolution < 50 ps was obtained in technical run (Dec. 2016)**
TOF Barrel: MRPC ready for mass production

module housing box was developed in close cooperation with NC PHEP BSU and “Artmash” (Minsk, Belarus)

workshop for the MRPC mass-production

basic elements - NINO & HPTDC chips have been purchased sufficient to produce read-out electronics for the TOF + reserve (~24000 channels).
Electromagnetic calorimeter: ECAL

common project with Tsinghua University, China

- Pb+Sc “Shashlyk”
- read-out: WLS fibers + MAPD
- $L \sim 35 \text{ cm} (\sim 14 X_0)$
- Segmentation (4x4 cm$^2$),
- $\sigma(E)$ better than 5% @ 1 GeV;
- time resolution $\sim 500$ ps

Barrel ECAL $\sim 43\,000$ modules

Projective geometry

Prototype of a module
MPD performance for dileptons

Good probes to indicate medium modifications of spectral functions due to chiral symmetry restoration in A+A collisions; effect is proportional to baryon density

\[ \sigma_\omega \approx 14 \text{ MeV/c}^2 \]

Hadron suppression up to \(10^{-5}\)

Yields, central Au+Au at \(\sqrt{s_{NN}} = 8.8\) GeV/u

<table>
<thead>
<tr>
<th>meson</th>
<th>Yields</th>
<th>Yield/1 w</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4\pi)</td>
<td>(\gamma=0)</td>
<td></td>
</tr>
<tr>
<td>(\rho)</td>
<td>31</td>
<td>17</td>
</tr>
<tr>
<td>(\omega)</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>(\phi)</td>
<td>2.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

S/B ratios for dileptons

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Hypernuclei production enhanced at high baryon densities (NICA)

Hypertritons

(central Au+Au @ 5A GeV (DCM-QGSM))

\[ {}_3^\Lambda H \rightarrow {}^3\text{He} + \pi^- \]

\[ \frac{S}{S+B} = 8.4 \]

\[ S/B = 2.9 \]

\[ \text{eff.} = 0.8\% \]

\[ \sim 10^6 {}_3^\Lambda H \text{ are expected in 10 weeks} \]

\[ \frac{S}{S+B} = 10.9 \]

\[ S/B = 11.8 \]

\[ \text{eff.} = 1.0\% \]
**FHCAL: for determination of reaction plane and centrality**

- 2-arm (left/right) calorimeter (at ~3.2 m from the IP)
- each arm consists of 45 modules.

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

Transverse granularity allows to measure:
- *the reaction plane with the accuracy* $\sim 20^0$-$30^0$
- *the centrality with accuracy below* 10%

**FHCal provides required resolution**

**modules production – in progress**

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Flow performance: \( v_n \) of charged hadrons (FHCAl event plane)

**Event plane resolution**

*Simulated* \( v_n \) (true) and *reconstructed* \( v_n \) (reco) are in a good agreement.

**Flow harmonics** \( (v_1/v_2) \)

MEPhI/GSI:
P. Parfenov, I. Svintsov
I. Selyuzhenkov, A. Taranenko

Azimuthal flow coefficients:
\[ vln = \langle \cos[n(\phi - \Psi_{\downarrow EP,1})] \rangle / R_{ln} \{\Psi_{\downarrow EP,1}\} \]

- \( R_{ln} \{\Psi_{\downarrow EP,1}\} \) - resolution correction factor
- \( \phi \) – azimuthal angle of the produced particles
- \( \Psi_{\downarrow EP,1} \) - event plane angle

Good event plane resolution with FHCAl

Centrality with TPC estimator

June 6, 2017
V. Kekelidze, BNO-50
### NICA schedule

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**running time**
Concluding remarks

- Despite of > 30 years study of HI collisions and various discoveries in this field, still many issues should be clarified.
- Density frontier is less explored area the study of which promises many discoveries.
- NICA complex has a potential for competitive research in dense baryonic matter.
- The construction of accelerator complex and both detectors BM@N & MPD is going close to the schedule.
- NICA is open for new participants.

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Thank you