Multi-strange Hyperons and Hypernuclei reconstruction at the CBM experiment

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Physics case
Developed methods & tasks
High rate scenario
Conclusions & plans

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Physics case: Exploring the QCD phase diagram

The equation-of-state at high $\rho_B$
- collective flow of hadrons
- particle production at threshold energies: open charm, multi-strange hyperons

Deconfinement phase transition at high $\rho_B$
- excitation function and flow of strangeness ($K, \Lambda, \Sigma, \Xi, \Omega$) and charm ($J/\psi, \psi', D^0, D_s, D^{\pm}, \Lambda_c$)

- Charmonium suppression, for $J/\psi$ and $\psi$

QCD critical endpoint
- excitation function of event-by-event fluctuations ($K/\pi, \ldots, \Xi/\pi, \Omega/\pi$)

Onset of chiral symmetry restoration at high $\rho_B$
- in-medium modifications of hadrons ($\rho, \omega, \phi$)
- excitation function of multi-strange (anti)hyperons (PHSD 4.0)

Projects to explore the QCD phase diagram at large $\mu_B$:
- RHIC energy-scan, NA61@SPS, MPD@NICA: bulk observables
- CBM: bulk and rare observables, high statistic!

Net Baryon Density

Temperature $T$ [MeV]
Experiments exploring dense QCD matter

CBM: world record rate capability

- determination of (displaced) vertices with high resolution ($\approx 50 \, \mu m$)
- identification of leptons and hadrons
- fast and radiation hard detectors
- self-triggered readout electronics
- high speed data acquisition and online event selection
- powerful computing farm 4-d tracking
- software triggers
Particle identification with PID detectors

Ni+Ni 15 AGeV
123 \pi
53 p
6 K^+
1.6 K^-
4 \Lambda
7.5 K_S^0
0.4 \Xi^-

Central event: 40 (TF) + 7 (PF) ms/core with MVD!
(\sim 2 faster w/o MVD)
SIS-300: central Au + Au (UrQMD or PHSD) events
Simulation and reconstruction

Simulation

reconstruction

CA track finder

low p tracks!

Simulation

648 reconstructed tracks
Ref. prim. eff = 96%
All set eff = 87%
dp/p = 1.2%

central: 82 (TF) + 16 (PF) ms/core
mbias: 10 (TF) + 2 (PF) ms/core
up to 80 cores/CPU
KF Particle Finder for the CBM Experiment

Charged particles: $e^+$, $e^-$, $\pi^+$, $\pi^-$, $K^+$, $K^-$, $\delta^+$, $\delta^0$, $\delta^-$, $\Lambda$, $\bar{\Lambda}$, $\Xi^0$, $\Xi^-$

Neutral particles: $\nu$, $\bar{\nu}$, $\pi^0$, $\eta$, $\Lambda_c$, $\Xi_c$, $\Xi_c^0$, $\Xi_c^-$

Dileptons
- Charmonium: $J/\psi \rightarrow e^+e^-$, $\Upsilon \rightarrow \mu^+\mu^-$
- Low mass vector mesons: $\rho \rightarrow e^+e^-$, $\rho \rightarrow \mu^+\mu^-$, $\omega \rightarrow e^+e^-$, $\omega \rightarrow \mu^+\mu^-$, $\phi \rightarrow e^+e^-$, $\phi \rightarrow \mu^+\mu^-$
- Gamma: $\gamma \rightarrow e^+e^-$, $\gamma \rightarrow \mu^+\mu^-$
- Gamma-decays: $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$
- Light mesons and baryons:
  - $\pi^+ \rightarrow \mu^+\nu$, $\pi^- \rightarrow \mu^-\bar{\nu}$, $\rho \rightarrow \pi^+\pi^-$, $\Delta^0 \rightarrow p\pi^0$, $\Delta^+ \rightarrow p\pi^+$, $\Delta^- \rightarrow p\pi^-$

Open-charm
- Open-charm particles:
  - $D^0 \rightarrow K^-\pi^+$
  - $D^\mp \rightarrow K^\mp\pi^\pm$
  - $D^0 \rightarrow K^+\pi^0$
  - $D^- \rightarrow K^-\pi^0$
  - $D_s^\pm \rightarrow K^\pm\pi^\mp$
  - $D_s^0 \rightarrow K^0\pi^0$
  - $\Lambda_c^- \rightarrow pK^-\pi^+$
  - $\Lambda_c^0 \rightarrow \bar{p}K^-\pi^+

Strange resonances
- Strange resonances:
  - $K^+ \rightarrow \Sigma^+\pi^+$
  - $K^- \rightarrow \Sigma^-\pi^-$
  - $\Sigma^+ \rightarrow \Lambda\pi^+$
  - $\Sigma^- \rightarrow \Lambda\pi^0$
  - $\Xi^0 \rightarrow \Xi^-\pi^0$

Strange particles
- Strange particles:
  - $\Xi^0 \rightarrow \Lambda\pi^0$
  - $\Xi^- \rightarrow \Lambda\pi^0$
  - $\Sigma^0 \rightarrow \Lambda\pi^0$
  - $\Sigma^- \rightarrow \Lambda\pi^0$
  - $\Omega^- \rightarrow \Lambda\pi^0$

Hypermatter
- Hypernuclei:
  - $\{\Lambda\eta\} \rightarrow d^*\pi^0$
  - $\{\Lambda\eta\} \rightarrow d^*\pi^+$
  - $\{\Lambda\eta\} \rightarrow t^*\pi^0$
  - $\{\Lambda\eta\} \rightarrow t^*\pi^+$
  - $\{\Lambda\eta\} \rightarrow t^*\eta$
  - $\{\Lambda\eta\} \rightarrow t^*\Delta$
  - $\{\Lambda\eta\} \rightarrow t^*\Lambda$

Double-$\Lambda$ hypernuclei:
- $\{\Lambda\Lambda\} \rightarrow \Lambda\Lambda$
- $\{\Xi\Xi\} \rightarrow \Lambda\Lambda$

Heavy multi-strange objects:
- $\{\Xi\Xi\} \rightarrow \Lambda\Lambda$
- $\{\Xi\Xi\} \rightarrow \Lambda\Lambda$
All physics observables are covered by the CBM reconstruction.
The signal distribution are nicely described by the BG subtraction method.

Due to the limited statistics in the outer regions multi-differential analysis can not be applied there, the integral distributions are describing the central region.
KF Particle Finder with ToF track ID: Au+Au @ 10AGeV SIS100

165 π
170 p
26 K
15 Λ
20 K_{S}^{0}
0.3 Ξ^{-}

QGP
QGP and CSR signatures at FAIR energies: Multi-strange baryons and antibaryons

• Most of the $\Omega^+$ produced by QGP @ FAIR energy
• CSR increase yield of MS Baryons & Antibaryons !?
Motivation: CBM physics program (P. Senger)

Strange matter
Hypernuclei, strange dibaryons and massive strange objects

Production of hypernuclei via coalescence of hyperons and light nuclei

Au+Au 10 AGeV 5M central events

Extended KFPParticle Finder $^3_\Lambda H$

5 seconds of data taking!

$^3_\Lambda H \rightarrow ^3\text{He} + \pi^-$

$\text{eff} = 19.2\%$

$\sigma = 1.7 \text{ MeV}$

$S/B \sim 1.5$

Double-$\Lambda$ hypernuclei

- Background can be further reduced with additional dE/dx PID.
- For $^5_\Lambda$He and $^5_{\Lambda\Lambda}$H background will be reduced selecting only primary hypernuclei.

AuAu, 10 AGeV, $10^{12}$ central events, TOF PID

High statistic measurements at $10^7$ interaction rates will allow to measure double-$\Lambda$ hypernuclei
Au+Au 10 AGeV 5M central events

Extended KFParticle Finder $^4_\Lambda$He

$^4_\Lambda$He $\rightarrow$ $^3$He+p+π$^-$

eff = 14.7%
σ = 1.6 MeV
S/B ~ 50
BR ~ 0.2

~ 1 min. of data taking!

3 prong detached vertex is good signature of $^4_\Lambda$He decay

Mass Spectra of Reconstructed Particles

New visit card of CBM

$\Sigma^- \rightarrow \pi^- n$

$\Sigma^+ \rightarrow \pi^+ n$

$\Sigma^+ \rightarrow p \pi^0$

$\Sigma^+ \rightarrow p \pi^0$

$K^+ \rightarrow \pi^+ \pi^0$

$K^- \rightarrow \pi^- \pi^0$

$\Xi^- \rightarrow \pi^- \Lambda$

$\Omega^- \rightarrow K^- \Lambda$

5M Au+Au central events, 10 AGeV, TOF PID
## Expected particle yields Au+Au @ 6, 10 AGeV

<table>
<thead>
<tr>
<th>Particle (mass MeV/c²)</th>
<th>Multi-plicity 6 AGeV</th>
<th>Multi-plicity 10 AGeV</th>
<th>decay mode</th>
<th>BR</th>
<th>ε (%)</th>
<th>yield (s⁻¹) 6AGeV</th>
<th>yield (s⁻¹) 10AGeV</th>
<th>yield in 10 weeks 6AGeV</th>
<th>yield in 10 weeks 10 AGeV</th>
<th>IR MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Λ⁻ (1115)</td>
<td>4.6·10⁻⁴</td>
<td>0.034</td>
<td>ππ⁺</td>
<td>0.64</td>
<td>11</td>
<td>1.1</td>
<td>81.3</td>
<td>6.6·10⁶</td>
<td>2.2·10⁸</td>
<td>10</td>
</tr>
<tr>
<td>Ξ⁻ (1321)</td>
<td>0.054</td>
<td>0.222</td>
<td>Λπ⁻</td>
<td>1</td>
<td>6</td>
<td>3.2·10³</td>
<td>1.3·10⁴</td>
<td>1.9·10¹⁰</td>
<td>7.8·10¹⁰</td>
<td>10</td>
</tr>
<tr>
<td>Ξ⁺ (1321)</td>
<td>3.0·10⁻⁵</td>
<td>5.4·10⁻⁴</td>
<td>Λπ⁺</td>
<td>1</td>
<td>3.3</td>
<td>9.9·10⁻¹</td>
<td>17.8</td>
<td>5.9·10⁶</td>
<td>1.1·10⁸</td>
<td>10</td>
</tr>
<tr>
<td>Ω⁻ (1672)</td>
<td>5.8·10⁻⁴</td>
<td>5.6·10⁻³</td>
<td>ΛK⁻</td>
<td>0.68</td>
<td>5</td>
<td>17</td>
<td>164</td>
<td>1.0·10⁸</td>
<td>9.6·10⁸</td>
<td>10</td>
</tr>
<tr>
<td>Ω⁺ (1672)</td>
<td></td>
<td>7·10⁻⁵</td>
<td>ΛK⁺</td>
<td>0.68</td>
<td>3</td>
<td>-</td>
<td>0.86</td>
<td>-</td>
<td>5.2·10⁶</td>
<td>10</td>
</tr>
<tr>
<td>³ΛH (2993)</td>
<td>4.2·10⁻²</td>
<td>3.8·10⁻²</td>
<td>³Heπ⁻</td>
<td>0.25</td>
<td>19.2</td>
<td>2·10³</td>
<td>1.8·10³</td>
<td>1.2·10¹⁰</td>
<td>1.1·10¹⁰</td>
<td>10</td>
</tr>
<tr>
<td>⁴ΛHe (3930)</td>
<td>2.4·10⁻³</td>
<td>1.9·10⁻³</td>
<td>³Heπ⁻</td>
<td>0.32</td>
<td>14.7</td>
<td>110</td>
<td>87</td>
<td>6.6·10⁸</td>
<td>5.2·10⁸</td>
<td>10</td>
</tr>
<tr>
<td>⁴ΛΛH (4108)</td>
<td></td>
<td>3.7·10⁻⁵</td>
<td>⁴ΛHeπ⁻</td>
<td>0.2</td>
<td>2.6</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
<td>3.8·10⁶</td>
<td>10</td>
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<tr>
<td>⁶ΛΛHe (5986)</td>
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<td>2.5·10⁻⁸</td>
<td>⁵ΛHeπ⁻</td>
<td>0.2</td>
<td>1.3</td>
<td>-</td>
<td>2.6·10⁻⁴</td>
<td>-</td>
<td>1.6·10³</td>
<td>10</td>
</tr>
</tbody>
</table>

4D time based analysis!
New tools;
A lot to learn;
10 mks window

100 kHz

1 MHz

10 MHz

Entries

HitTime_0.1MHz
Entries  260232
Integral  3471

HitTime_1MHz
Entries  260064
Integral  1.167e+04

HitTime_10MHz
Entries  260064
Integral  1.167e+04
# 4D Track Finder in CBMROOT

100 AuAu 10 AGeV mbias events

<table>
<thead>
<tr>
<th>Efficiency, %</th>
<th>3D</th>
<th>0.1 MHz</th>
<th>1 MHz</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>All tracks</td>
<td>92.5%</td>
<td>93.8%</td>
<td>93.5%</td>
<td>91.7%</td>
</tr>
<tr>
<td>Primary high-p</td>
<td>98.3%</td>
<td>98.1%</td>
<td>97.9%</td>
<td>96.2%</td>
</tr>
<tr>
<td>Primary low-p</td>
<td>93.9%</td>
<td>95.4%</td>
<td>95.5%</td>
<td>94.3%</td>
</tr>
<tr>
<td>Secondary high-p</td>
<td>90.8%</td>
<td>94.6%</td>
<td>93.5%</td>
<td>90.2%</td>
</tr>
<tr>
<td>Secondary low-p</td>
<td>62.2%</td>
<td>68.5%</td>
<td>67.6%</td>
<td>64.3%</td>
</tr>
<tr>
<td>Clone level</td>
<td>0.6%</td>
<td>0.6%</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Ghost level</td>
<td>1.8%</td>
<td>0.6%</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>True hits per track</td>
<td>92%</td>
<td>93%</td>
<td>93%</td>
<td>93%</td>
</tr>
<tr>
<td>Hits per MC track</td>
<td>7.0</td>
<td>7.0</td>
<td>6.97</td>
<td>6.70</td>
</tr>
</tbody>
</table>

*Timeslices from CBMROOT*

*Timebased digitisation, cluster and hit finder*
High rate scenario: MSH reconstruction with 4D tracking
High rate scenario: **MSH reconstruction with 4D tracking**

![Graph showing distribution of entries vs. mass [GeV/c^2]](image-url)
High rate scenario: MSH reconstruction with 4D tracking

<table>
<thead>
<tr>
<th>Frequency</th>
<th>K0s</th>
<th>Λ</th>
<th>Ā</th>
<th>Ξ−</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>εmethod. %</td>
<td>68.6</td>
<td>61.2</td>
<td>67</td>
<td>46.7</td>
</tr>
<tr>
<td>ε4π, %</td>
<td>20.7</td>
<td>19.4</td>
<td>28</td>
<td>10.5</td>
</tr>
<tr>
<td>S/B</td>
<td>10.6</td>
<td>23.7</td>
<td>12.7</td>
<td>21.8</td>
</tr>
<tr>
<td><strong>0.1 MHz</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>εmethod. %</td>
<td>68.5</td>
<td>62.0</td>
<td>62</td>
<td>45.2</td>
</tr>
<tr>
<td>ε4π, %</td>
<td>21.1</td>
<td>20.6</td>
<td>32</td>
<td>11.7</td>
</tr>
<tr>
<td>S/B</td>
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<td>10</td>
<td>14.2</td>
</tr>
<tr>
<td><strong>1 MHz</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>εmethod. %</td>
<td>67.5</td>
<td>60.9</td>
<td>59</td>
<td>46.0</td>
</tr>
<tr>
<td>ε4π, %</td>
<td>19.4</td>
<td>18.7</td>
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<td>12.5</td>
<td>10</td>
<td>12.3</td>
</tr>
<tr>
<td><strong>10 MHz</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>εmethod. %</td>
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<td>60.0</td>
<td>64</td>
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<td>8.2</td>
</tr>
<tr>
<td>S/B</td>
<td>9.2</td>
<td>12.2</td>
<td>8</td>
<td>11.7</td>
</tr>
</tbody>
</table>

3D
4D 100 kHz
4D 1 MHz
4D 10 MHz

Entries

m [GeV/c²]
Summary:
CBM detector is an excellent device to measure not only bulk observables, but **strangeness**, **hypernuclei** and other rare probes with high statistic.
Baryon densities in central Au+Au collisions


5 A GeV

10 A GeV

5 $\rho_0$

8 $\rho_0$

5 A GeV

10 A GeV

Phase coexistence
CBM First Level Event Selection (FLES)

The FLES package is **vectorized, parallelized, portable and scalable** up to 3 200 cores

**Example:**
Full track reconstruction including KF particle analysis of multi-strange (anti) hyperons for min. bias Au+Au collisions at 25 A GeV.

Single node with up to 80 cores

100 nodes with 32 cores each

[Graph showing event rate vs. number of logical cores for different processors and configurations]

220 k events/s!

HPC cluster at ITEP Moscow
Extraction of the signal: background subtraction

- Collect spectra ($M$, $p$, $p_T$, $y$, $Z$...) for the signal+BG (particles within the mass peak) and BG (particles near the peak).
- Calculate the correction factor using the fitted BG.
- Subtract the corrected BG.