Reconstruction of hypernuclei in CBM

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(for the CBM collaboration)

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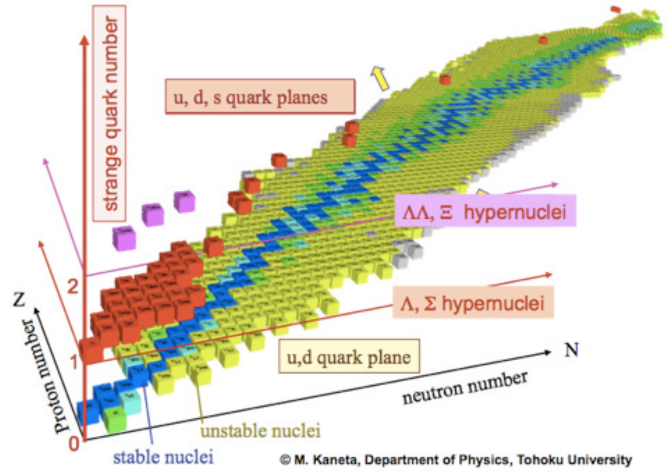
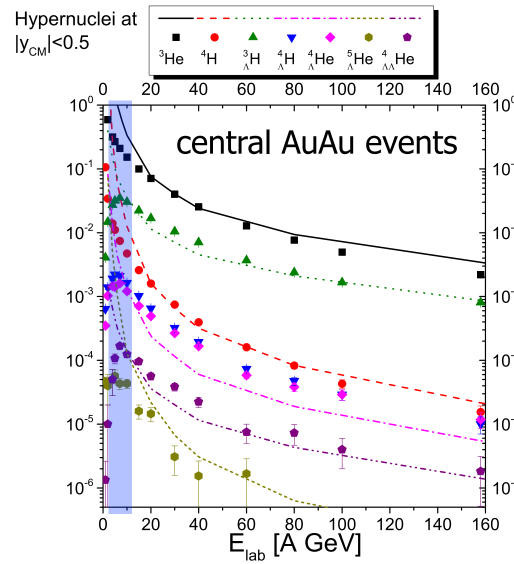
One of the physics cases of the CBM experiment is study of hypernuclei:

- Single and double hypernuclei.
- Precise measurements of hypernuclei lifetime.
- Measurement of branching ratios of hypernuclei.
- Direct access to the hyperon-nucleon (YN) interaction through measurements of B_Λ in a hypernucleus.
- "Hyperon puzzle" in the astrophysics: understanding of YN interaction is crucial for neutron star physics.
- Search for strange matter in the form of heavy multi-strange objects.



Advantages of CBM:

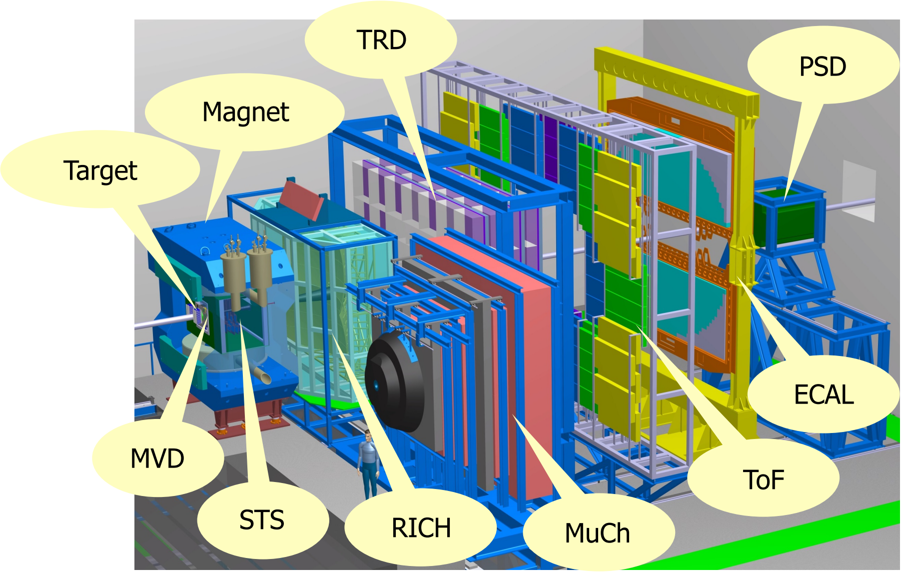
- According to theoretical predictions energy region of CBM is preferable for production of hypernuclei.
- Complex topology of decays can be easily identified in CBM with a low background.
- The detector system is well suited for identification of produced hypersystems.
- High interaction rates, optimal collision energies and clean identification will allow to search for ΛΛ-hypernuclei.



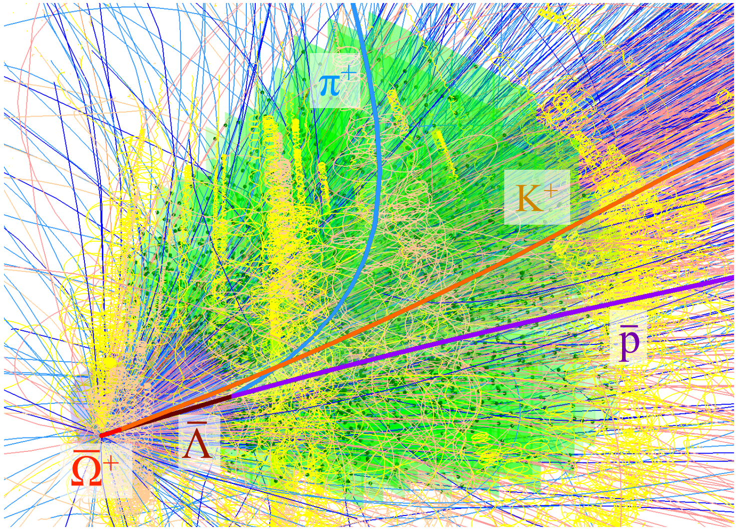
J. Steinheimer et al., "Hypernuclei, dibaryon and antinuclei production in high energy heavy ion collisions: Thermal production versus Coalescence," Phys. Lett. B 714 (2012) 85

Challenges in CBM

CBM experimental setup



Central AuAu UrQMD event with $\bar{\Omega}^+$ decay highlighted

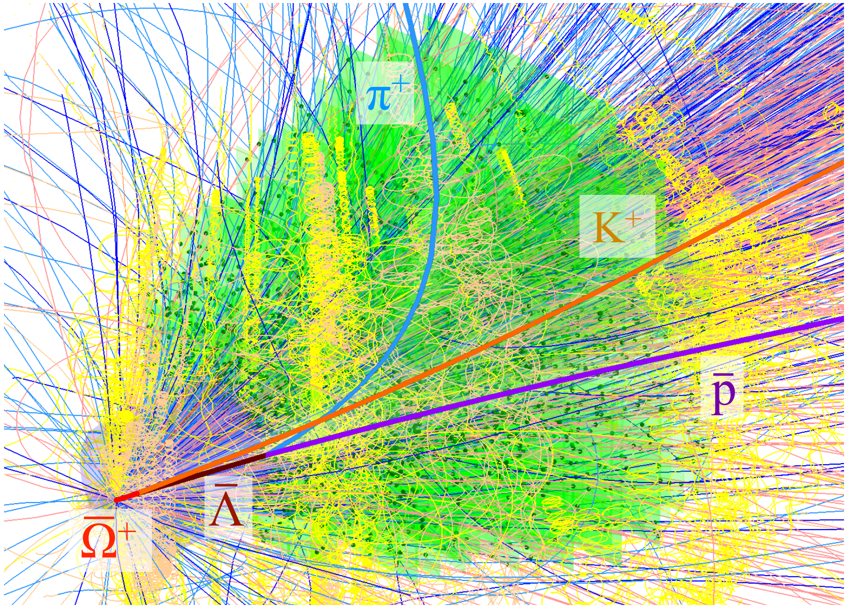


No hardware trigger possible

- A fixed-target experiment with a forward geometry — high track density.
- Up to 1000 charged particles/collision.
- 10^5-10^7 collisions per second.
- No hardware triggers — free streaming data.
- On-line time-based event reconstruction is required with selection of extremely rare probes (like one $\bar{\Omega}^+$ per 10^6 collisions).

- On-line reconstruction at the dedicated high performance computing farm (GSI Green IT Cube).
- High speed and efficiency of the reconstruction algorithms are required.
- The algorithms have to be highly parallelised and scalable.
- CBM event reconstruction: Kalman Filter and Cellular Automaton.

Concept of KF Particle



$$\bar{\Omega}^+ \leftarrow \bar{\Lambda}\, K^+$$
$$\bar{\Lambda} \rightarrow \bar{p}\, \pi^+$$

```
KFParticle Lambda(P, Pi);                    // construct anti Lambda
Lambda.SetMassConstraint(1.1157);            // improve momentum and mass
KFParticle Omega(K, Lambda);                 // construct anti Omega
PV -= (P; Pi; K);                            // clean the primary vertex
PV += Omega;                                 // add Omega to the primary vertex
Omega.SetProductionVertex(PV);               // Omega is fully fitted
(K; Lambda).SetProductionVertex(Omega);      // K, Lambda are fully fitted
(P; Pi).SetProductionVertex(Lambda);         // p, pi are fully fitted
```

1. KFParticle class describes particles by:

$$\mathbf{r} = \{\, x, y, z, p_x, p_y, p_z, E \,\}$$

State vector

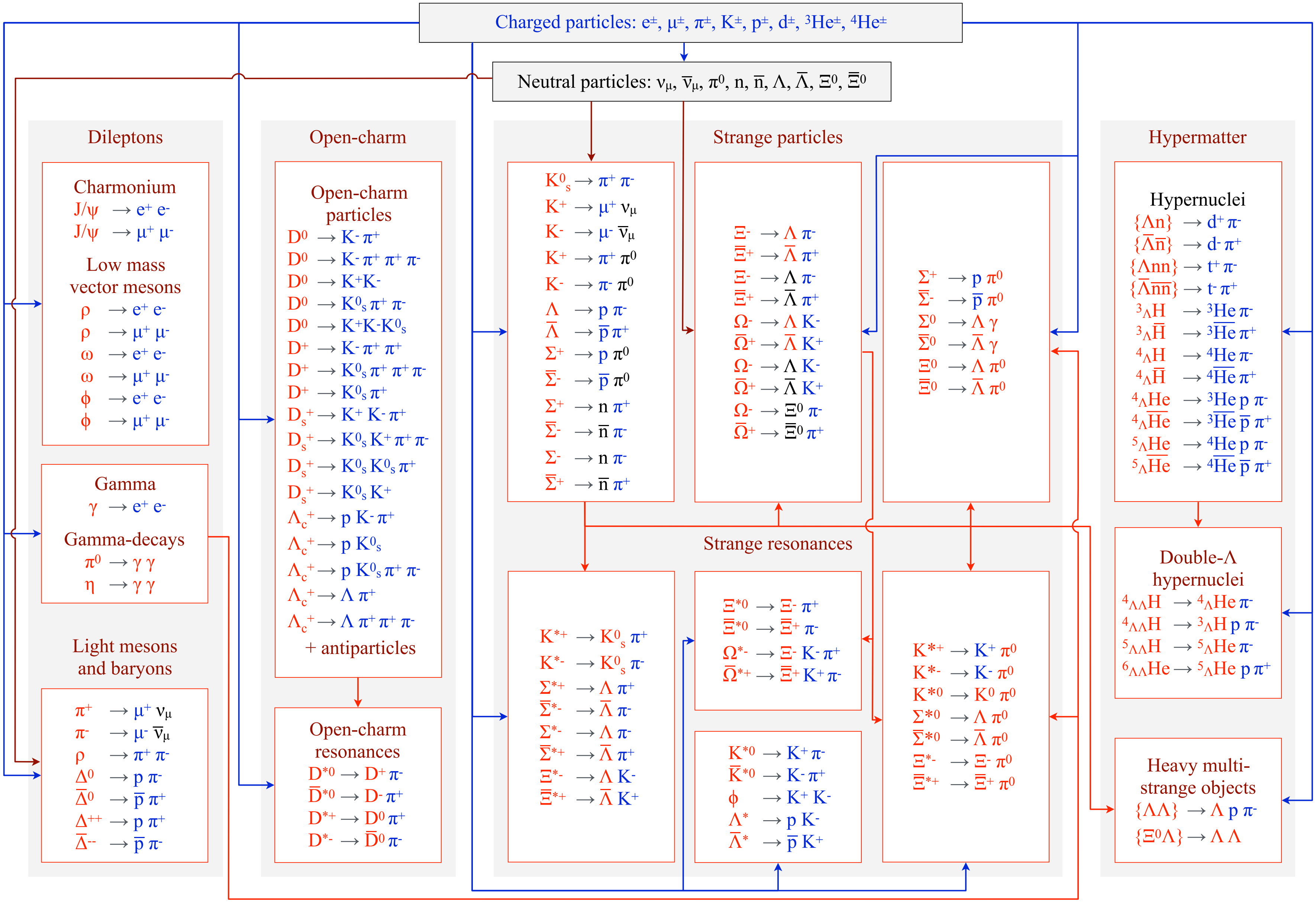
$$C = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\ C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\ C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\ C_{xp_x} & C_{yp_x} & C_{zp_x} & \sigma_{p_x}^2 & C_{p_xp_y} & C_{p_xp_z} & C_{p_xE} \\ C_{xp_y} & C_{yp_y} & C_{zp_y} & C_{p_xp_y} & \sigma_{p_y}^2 & C_{p_yp_z} & C_{p_yE} \\ C_{xp_z} & C_{yp_z} & C_{zp_z} & C_{p_xp_z} & C_{p_yp_z} & \sigma_{p_z}^2 & C_{p_yE} \\ C_{xE} & C_{yE} & C_{zE} & C_{p_xE} & C_{p_yE} & C_{p_zE} & \sigma_E^2 \end{bmatrix}$$

Covariance matrix

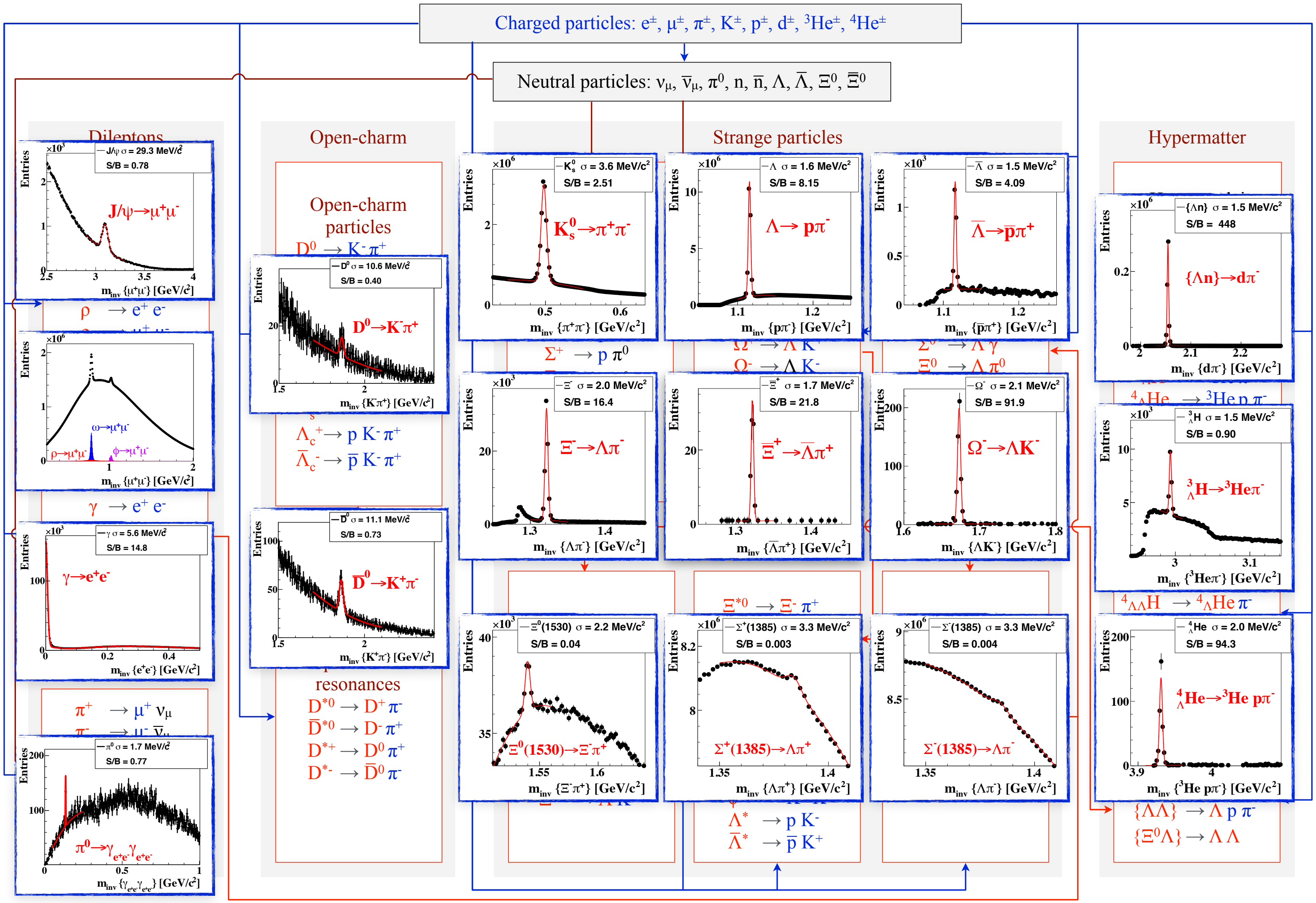
2. Covariance matrix contains essential information about tracking and detector performance.
3. The method for mathematically correct usage of covariance matrices is provided by the KF Particle package based on the Kalman filter (KF) developed by FIAS group[1,2] primarily for CBM and ALICE.
4. Heavy mathematics requires fast and vectorised algorithms.
5. Mother and daughter particles are KFParticle and are treated in the same way.
6. The natural and simple interface allows to reconstruct easily rather complicated decay chains.
7. The package is geometry independent and can be easily adapted to different experiments.

1. KF Particle — S. Gorbunov, "On-line reconstruction algorithms for the CBM and ALICE experiments," Dissertation thesis, Goethe University of Frankfurt, 2012, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/29538
2. KF Particle Finder — M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/41428

KF Particle Finder: more than 150 decay channels

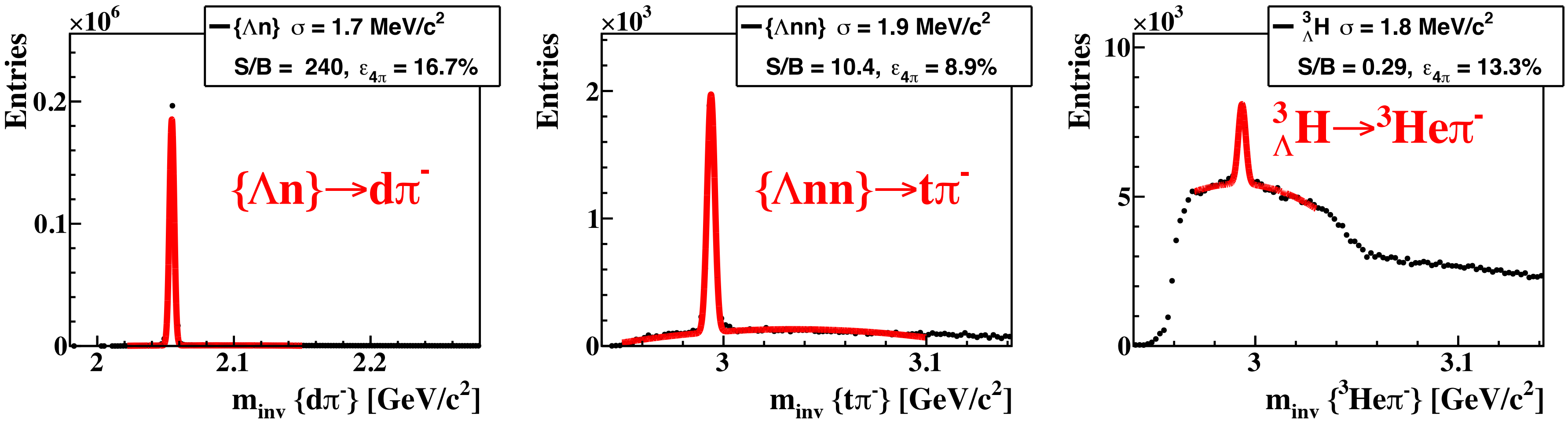


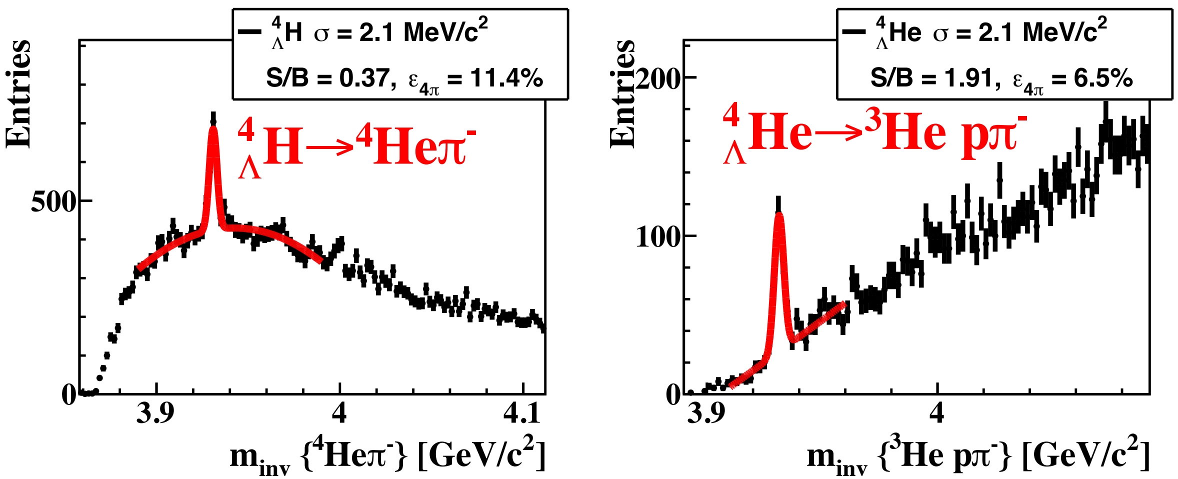
Physics coverage



All main CBM decays are covered

Single-Λ hypernuclei



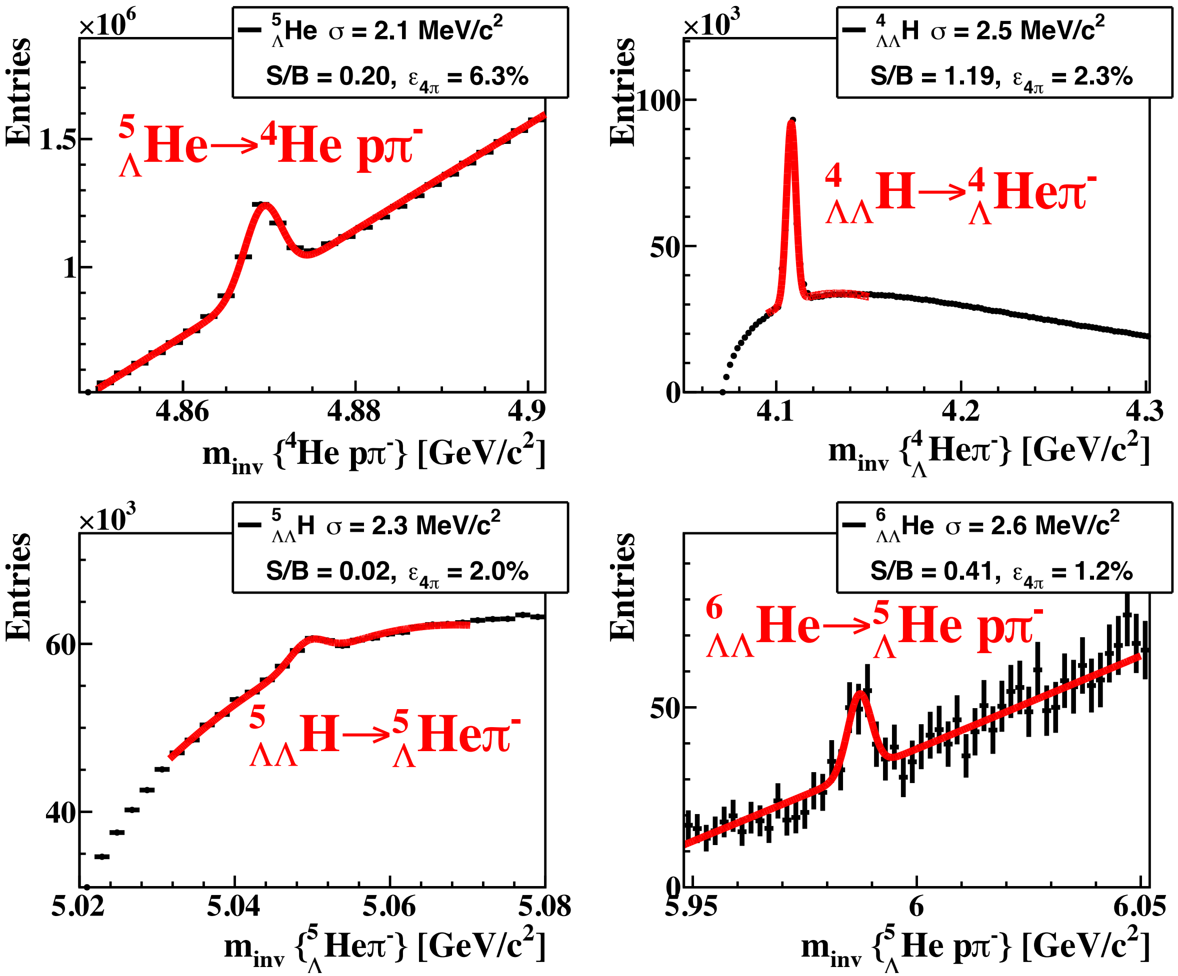


- AuAu, 10 AGeV, 5M central UrQMD events + thermal isotropic signal, TOF PID.
- Background can be further reduced with additional dE/dx PID.
- For $^4_\Lambda$He background can be reduced selecting only primary hypernuclei.

Multiplicities:

- A.Andronic, et. al, "Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions," Phys. Lett. B, 697 (2011) 203
- J. Steinheimer et al., "Hypernuclei, dibaryon and antinuclei production in high energy heavy ion collisions: Thermal production versus Coalescence," Phys. Lett. B 714 (2012) 85

CBM is sensitive to light hypernuclei containing a single Λ within current predictions of their multiplicities

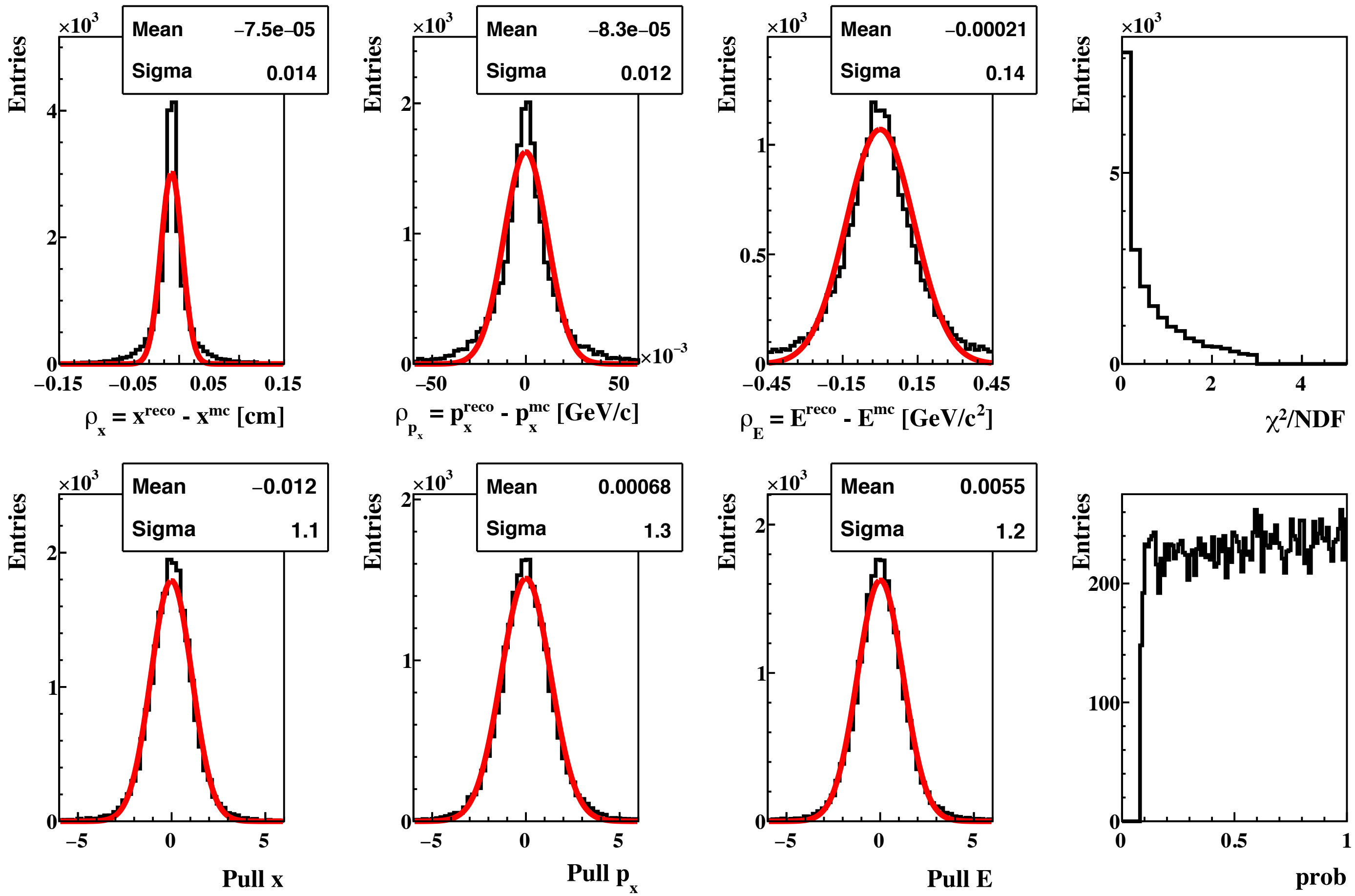


- Background can be further reduced with additional dE/dx PID.
- For $^{5}_{\Lambda}$He and $^{5}_{\Lambda\Lambda}$H background will be reduced selecting only primary hypernuclei.

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

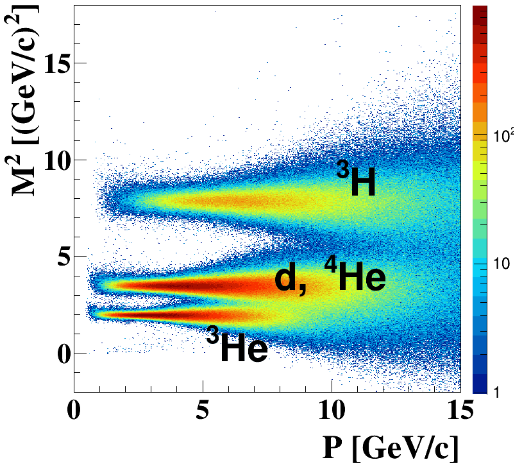
High statistic measurements at 10^7 interaction rates will allow to measure double-Λ hypernuclei

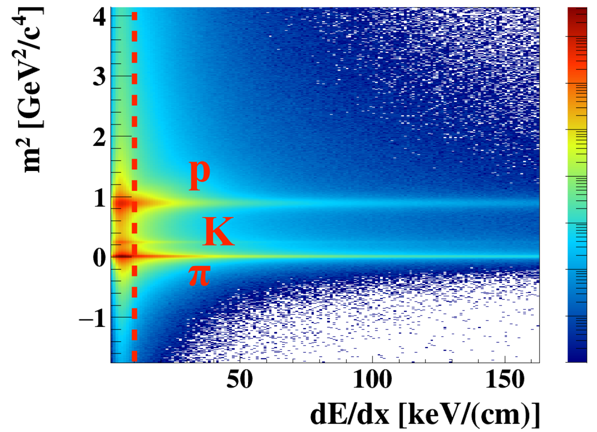
Fit quality of hypernuclei

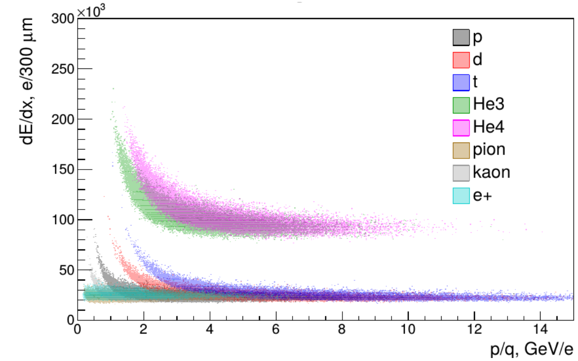


- The fit quality is demonstrated, for example, at $^{3}_{\Lambda}H$ hyperon.
- Y and Z components have similar distribution to X.
- Residual - difference between simulated and reconstructed parameters, pull - residual normalised by the error.
- The KF Particle mathematics allow to obtain correct errors and, as a result, correct pulls (unbiased, width about 1), χ^2 and flat prob (p-value) distributions.

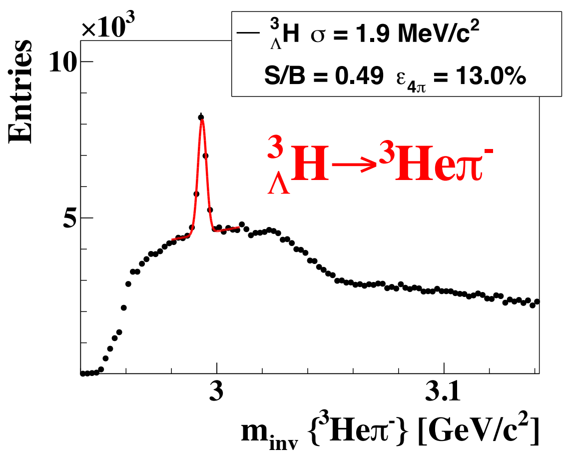
Further improvements: dE/dx in STS and TRD



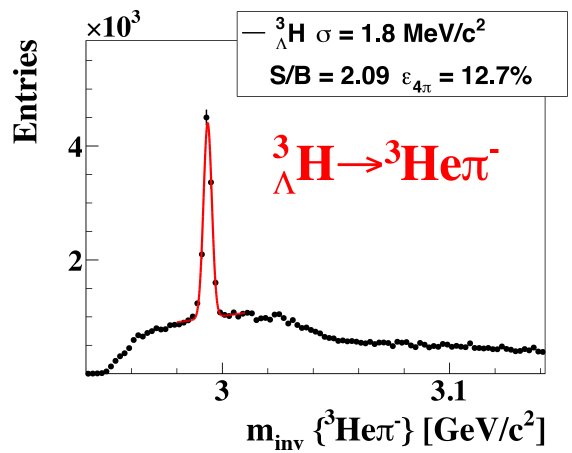




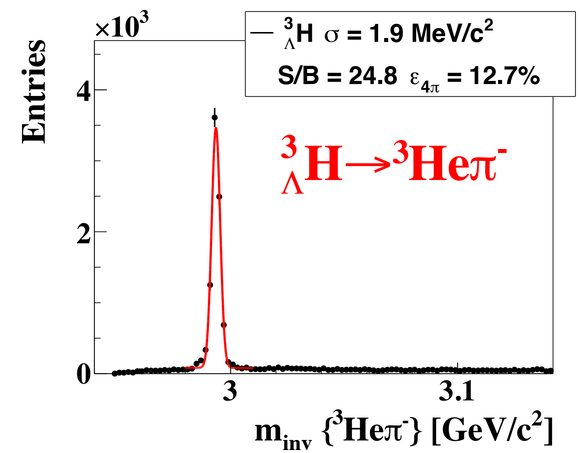
TOF



TOF + TRD

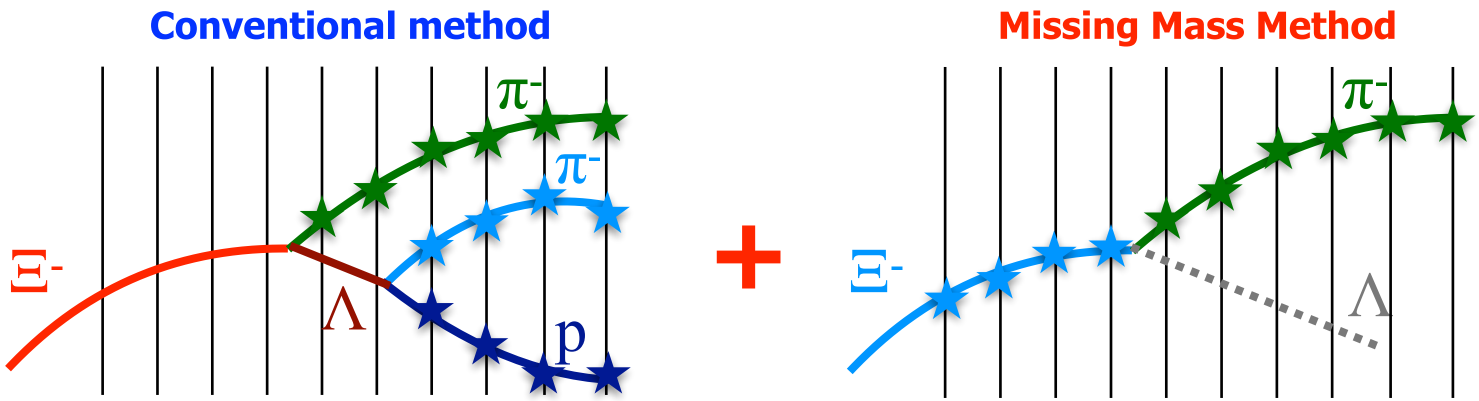


TOF + STS



- CBM can perform dE/dx PID in two detectors: STS built from silicon strip detectors and TRD built from gaseous detectors.
- The expected resolution should be enough to separate 1 and 2-charged particles and clean up ^{3}He from proton contamination and ^{4}He spectra from protons and deuterons.
- The studies of including dE/dx are ongoing.

Further improvements: add more channels



- For better control over the systematic errors all possible channels should be studied.
- The missing mass method for reconstruction of short-lived particles with a neutral daughter particle was developed and added to the KF Particle Finder package.
- It was successfully applied to reconstruction of Σ, Ξ, Ω hyperons (see next talk HK 20.5 by Pavel Kisel) and can be applied to the hypernuclei.
- Possible decays of single-Λ hypernuclei that can be studied:

$^{3}_{\Lambda}H \rightarrow$ $^3He\ \pi^-$
$d\ p\ \pi^-$
$p\ p\ n\ \pi^-$
$t\ \pi^0$

$^{4}_{\Lambda}H \rightarrow$ $^4He\ \pi^-$
$t\ p\ \pi^-$
$d\ d\ \pi^-$
$^3He\ n\ \pi^-$
$p\ p\ n\ \pi^-$

$^{4}_{\Lambda}He \rightarrow$ $^3He\ p\ \pi^-$
$d\ p\ p\ \pi^-$
$p\ p\ p\ n\ \pi^-$
$^4He\ \pi^0$
$d\ d\ \pi^0$
$t\ p\ \pi^0$

Summary and plans

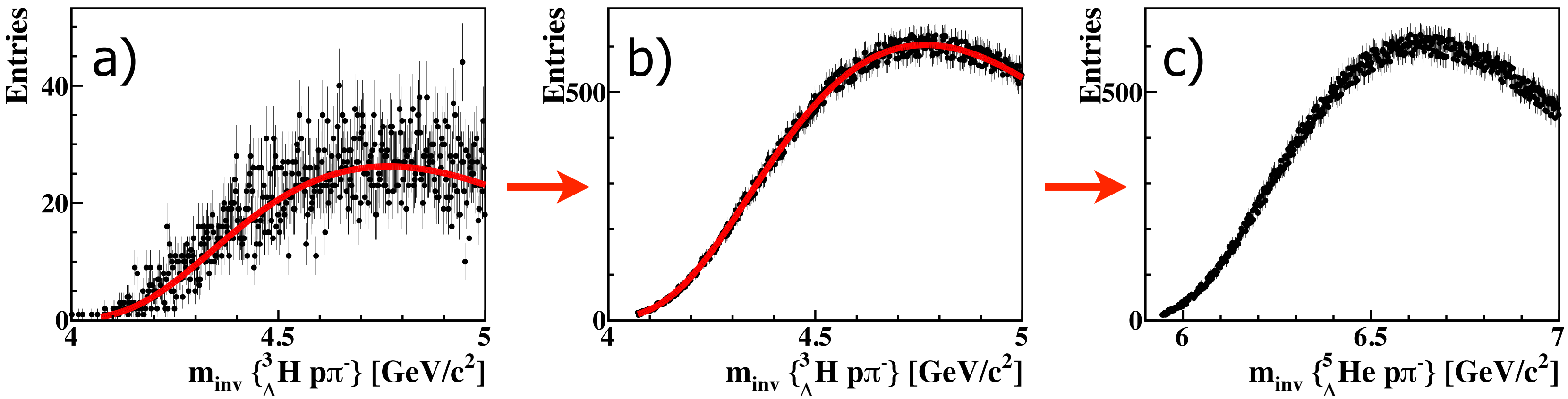
Summary

- CBM is perfectly suited for registration of hypernuclei.
- The mathematically correct algorithms of KF Particle Finder allow precise reconstruction with high efficiency and significance.
- With the optimal collision energies, data rates up to 10^7 Hz, precise reconstruction algorithms CBM provides great opportunities to study ΛΛ-hypernuclei.
- The developed missing mass method opens access to a large fraction of possible decay channels of hypernuclei, thus, allowing direct measurements of branching ratios and providing tools for the control over systematic errors.

Plans

- Improve PID of daughter particles by adding dE/dx information.
- Add more decay channels to the reconstruction scheme.
- Studies of systematic errors.

Background estimation for double-Λ hypernuclei



- Due to the low multiplicities, spectra for double-Λ hypernuclei can not be simulated on the event-by-event level with a statistics of 5M events.
- As the first approximation the background was
  - a) fitted with a function $f(x) = A \cdot e^{a_1x^2+b_1x} \cdot (B - e^{a_2x^2+b_2x})^p$;
  - b) normalized to 10^{12} events;
  - c) for $^{4}_{\Lambda\Lambda}$H, $^{5}_{\Lambda\Lambda}$H and $^{6}_{\Lambda\Lambda}$He the shape was taken from similar decay topologies and shifted according to the mass difference.
- In case of $^{6}_{\Lambda\Lambda}$He no entries were found for 5M events. As the upper limit one entry per 5M events was assumed.