Express analysis of hyperons and hypernuclei in BES-II and perspectives on hypernuclei physics with CBM

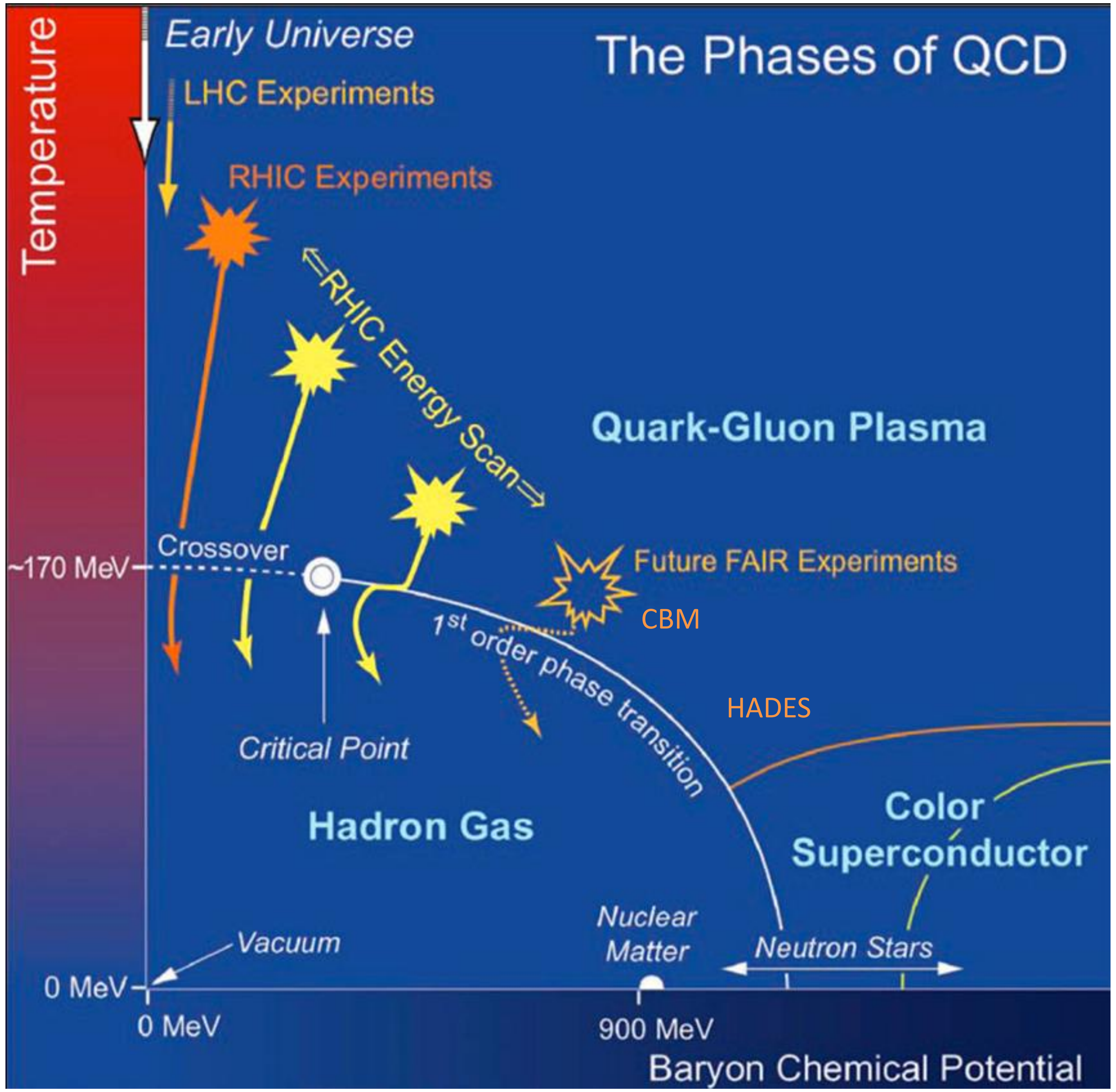
Iouri Vassiliev[4], Yuri Fisyak[1], Maksym Zyzak[3], Hongwei Ke[1], Ivan Kisel[2,3,4], Aihong Tang[1]
(for FLES CBM and TFG+HLT STAR groups)

1 – Brookhaven National Laboratory, Upton, USA
2 – Goethe-Universität Frankfurt, Frankfurt am Main, Germany
3 – FIAS Frankfurt Institute for Advanced Studies, Frankfurt am Main, Germany
4 – GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

3rd workshop on anti-matter, hyper-matter and exotica production at the LHC

2 Dec 2019 Wroclaw

Exploring the QCD phase diagram



Declared BES goals:

- **Deconfinement phase transition**
- **Phase boundary**
- **QCD critical endpoint**

Status:
BES-I completed,
Au+Au at 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4 and 62.4 GeV

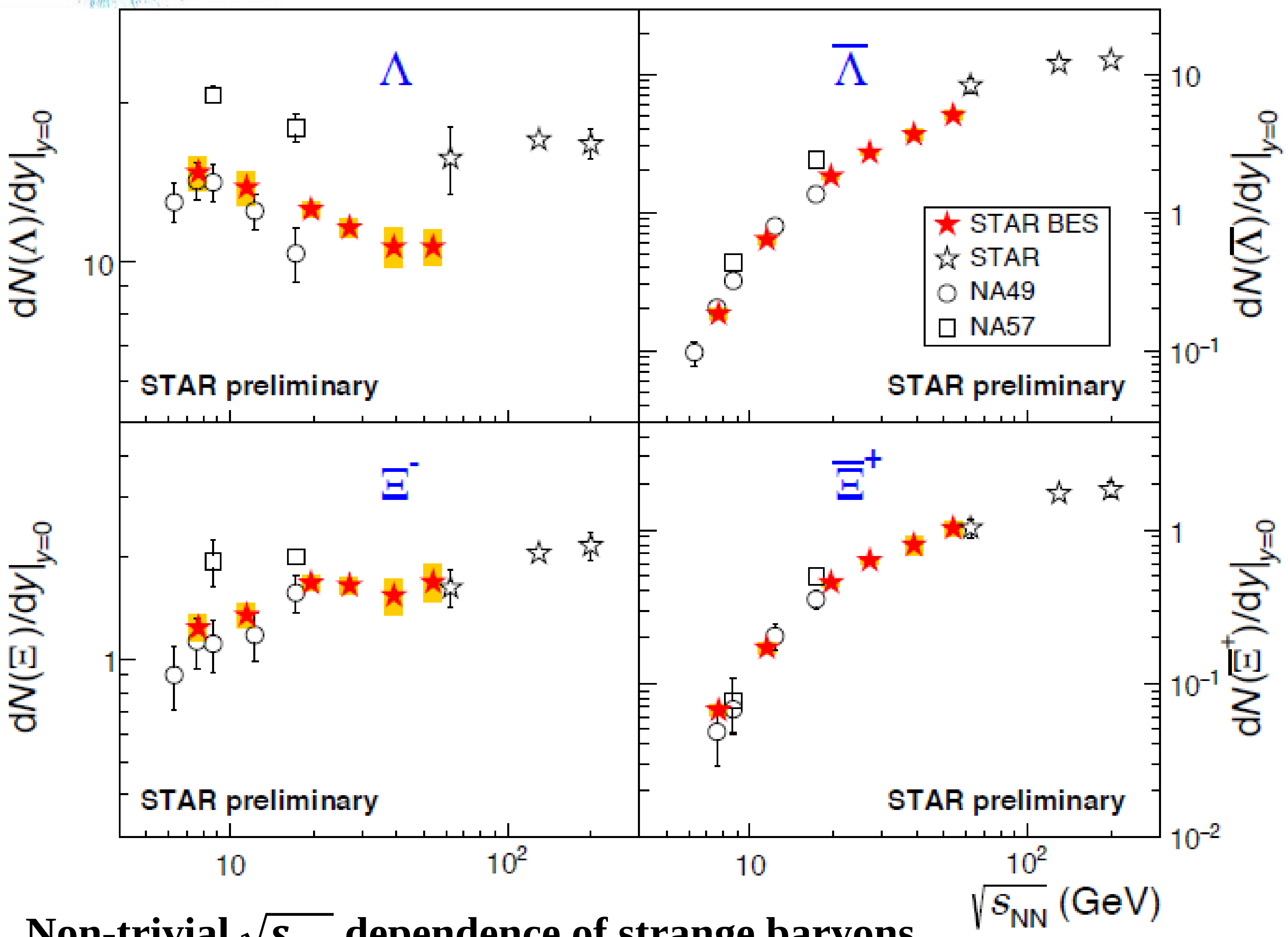
BES-II ongoing,
Au+Au $\sqrt{s_{NN}}$ = 7.7 – 19.6 GeV and

Fixed target $\sqrt{s_{NN}}$ = 3.0 – 7.7

Projects to explore the QCD phase diagram at large μ_B:
STAR@ RHIC, NA61@SPS,
CBM@FAIR, HADES@FAIR, MPD@NICA

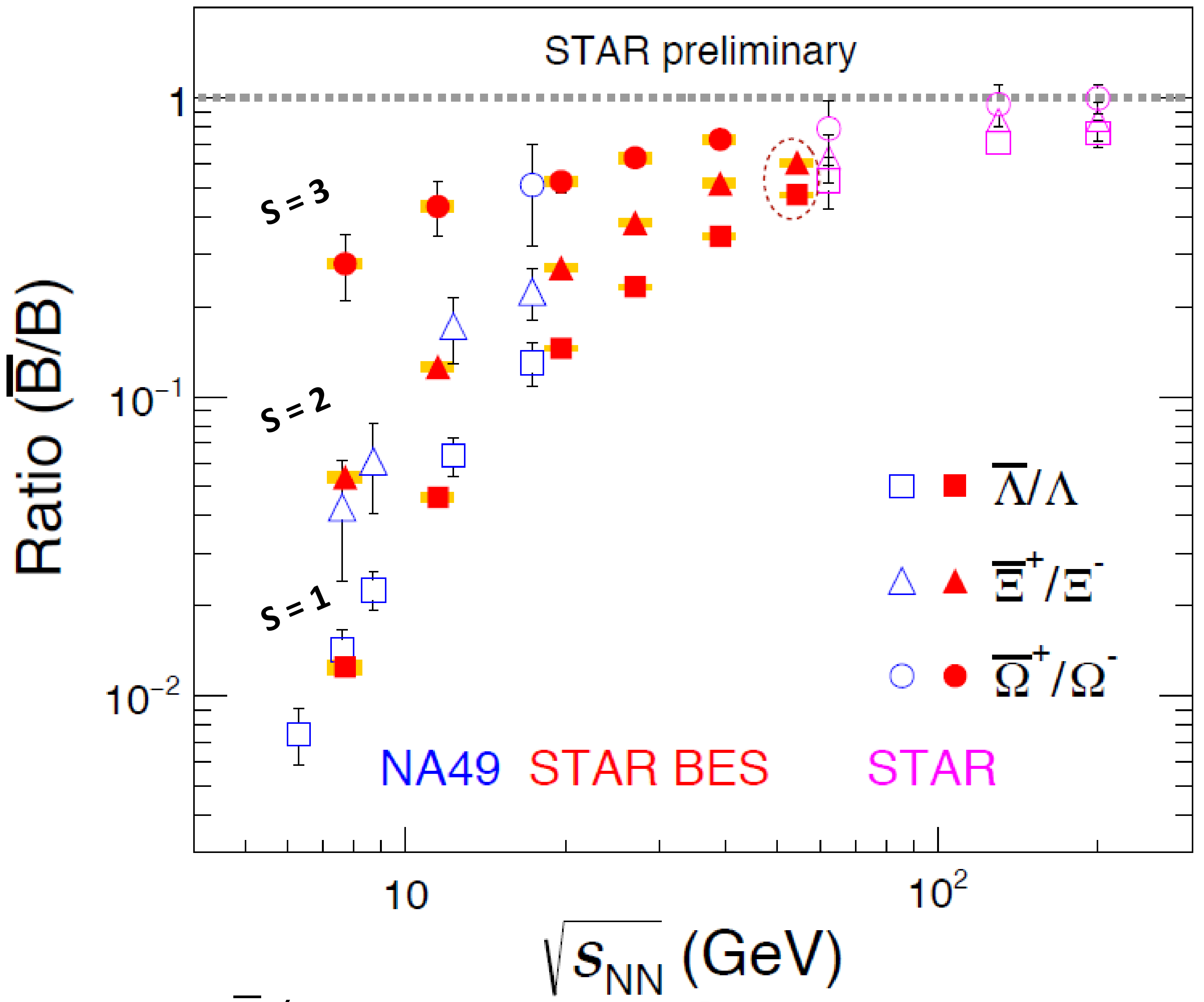
Selected results of BES-I (Strange Particle Yields)

M. Usman Ashraf, QM2019, Nov. 04-09 2019, Wuhan, China



Non-trivial $\sqrt{s_{NN}}$ dependence of strange baryons

This hierarchy is consistent with thermal models
A.Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A 772, 167 (2006)

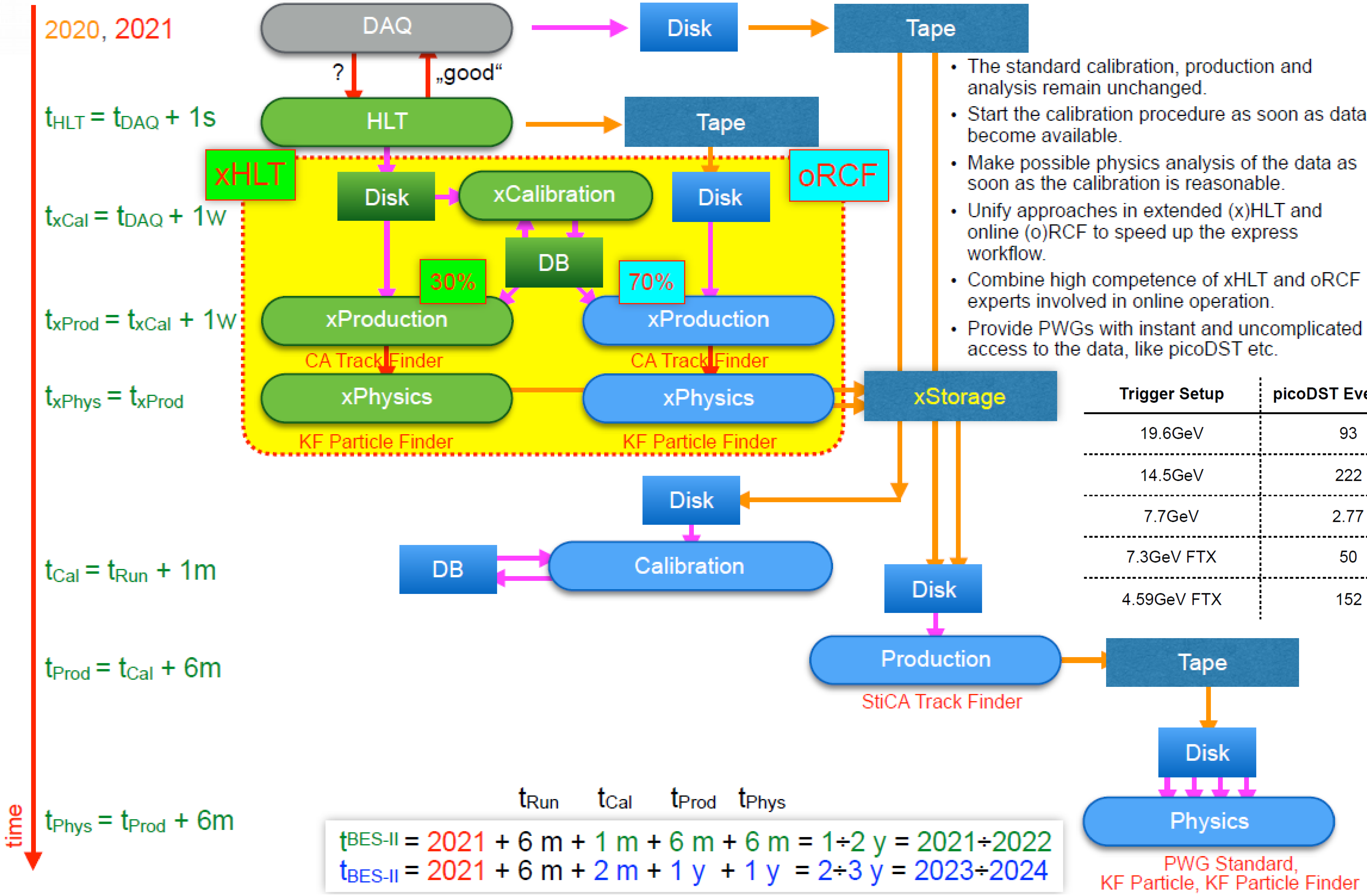


$\overline{B}/B$ ratio increase with strangeness

STAR Collaboration, arXiv:1906.03732
STAR Collaboration, PRC96, 044904, 2017
STAR Collaboration, Phys. Rev. C 83, 024901 (2011)
STAR Collaboration, Phys. Rev. Lett. 108, 072301 (2012)

Beam Energy (in GeV)	Baryon Chemical Potential (in MeV)	Year of Data Taking	Event Statistics (Millions)	Beam Time (weeks)
62.4	70	2010	67	1.5
39	115	2010	130	2.0
27	155	2011	70	1.0
19.6	205	2011	36	1.5
14.5	260	2014	20	3.0
11.5	315	2010	12	2.0
7.7	420	2010	4	4.0

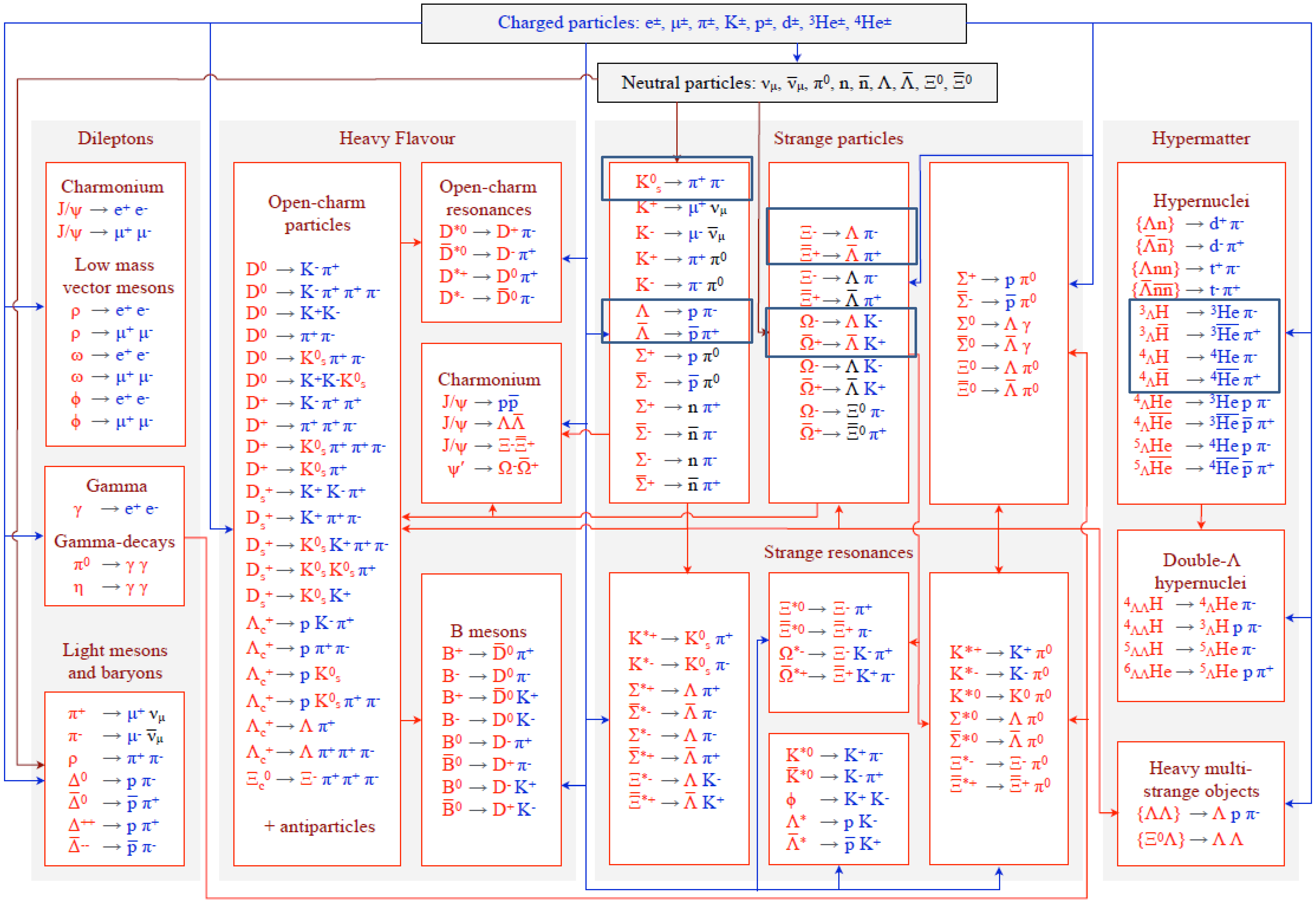
BES-II: eXpress+Standard Data Production and Analysis



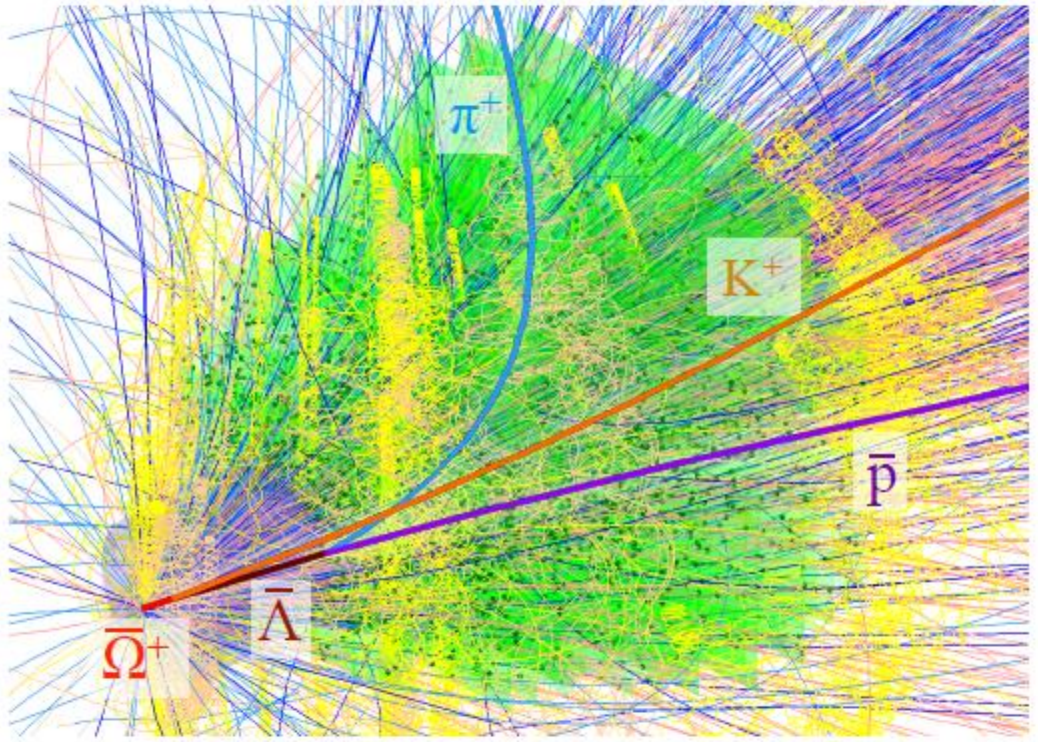
- The standard calibration, production and analysis remain unchanged.
- Start the calibration procedure as soon as data become available.
- Make possible physics analysis of the data as soon as the calibration is reasonable.
- Unify approaches in extended (x)HLT and online (o)RCF to speed up the express workflow.
- Combine high competence of xHLT and oRCF experts involved in online operation.
- Provide PWGs with instant and uncomplicated access to the data, like picoDST etc.

Trigger Setup	picoDST Events (M)	HLT Good Events (M)	Percentage
19.6GeV	93	582	16%
14.5GeV	222	325	68%
7.7GeV	2.77	2.86	97%
7.3GeV FTX	50	58	86%
4.59GeV FTX	152	200	76%

KF Particle Finder in BES-II



- More than 150 decays. All decays are reconstructed in one go.
- Covariance matrix contains essential information about tracking and detector performance.



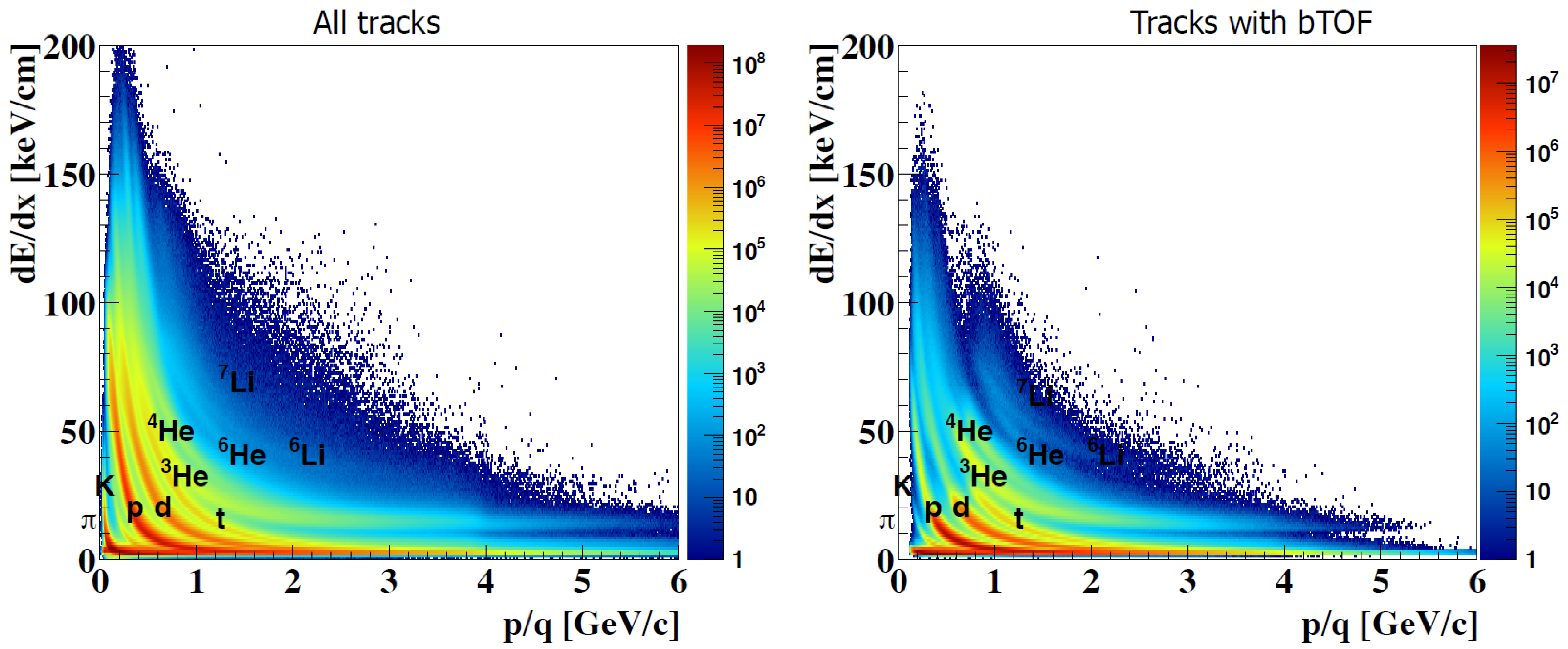
$\bar{\Omega}^+ \leftarrow \bar{\Lambda}\, K^+$

$\quad\quad\ \ \llcorner \bar{p}\, \pi^+$

```
KFParticle Lambda(P, Pi);
Lambda.SetMassConstraint(1.1157);
KFParticle Omega(K, Lambda);
PV -= (P; Pi; K); // clean the primary vertex
PV += Omega; // add Omega to the primary vertex
Omega.SetProductionVertex(PV);
(K; Lambda).SetProductionVertex(Omega);
(P; Pi).SetProductionVertex(Lambda);
```

1. 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

Particle identification with dE/dx (BES-II Fixed Target) (STAR performance express analysis)

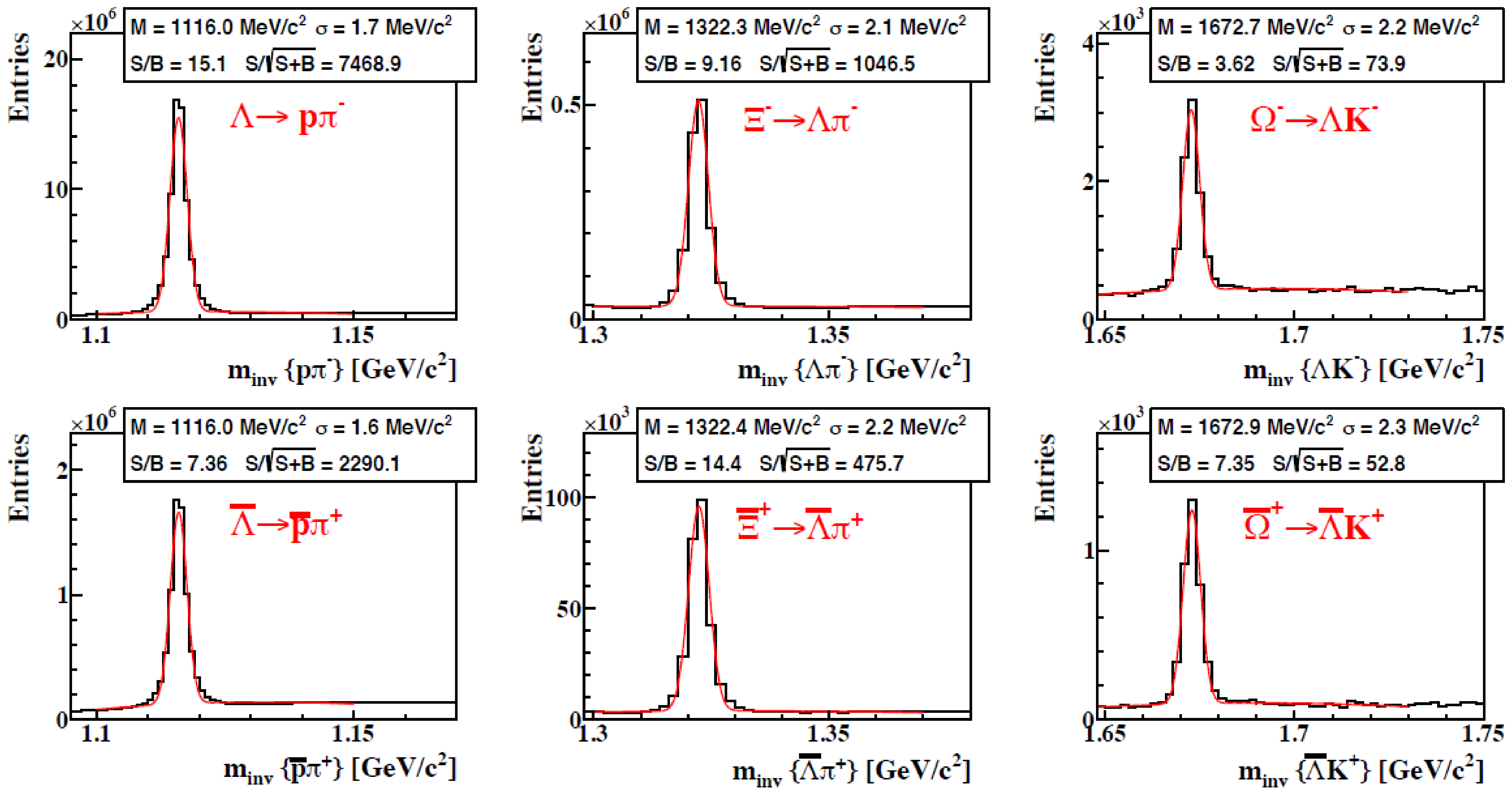


- Express production provides high quality of the dE/dx measurement.
- The cumulative spectra for fixed target mode (3, 3.2, 3.9 GeV) are presented.
- We clearly see particles up to ^{7}Li.

Excellent work of:
iTPC, oTPC, bTOF

Strange and multi-strange Hyperons (STAR performance express analysis)

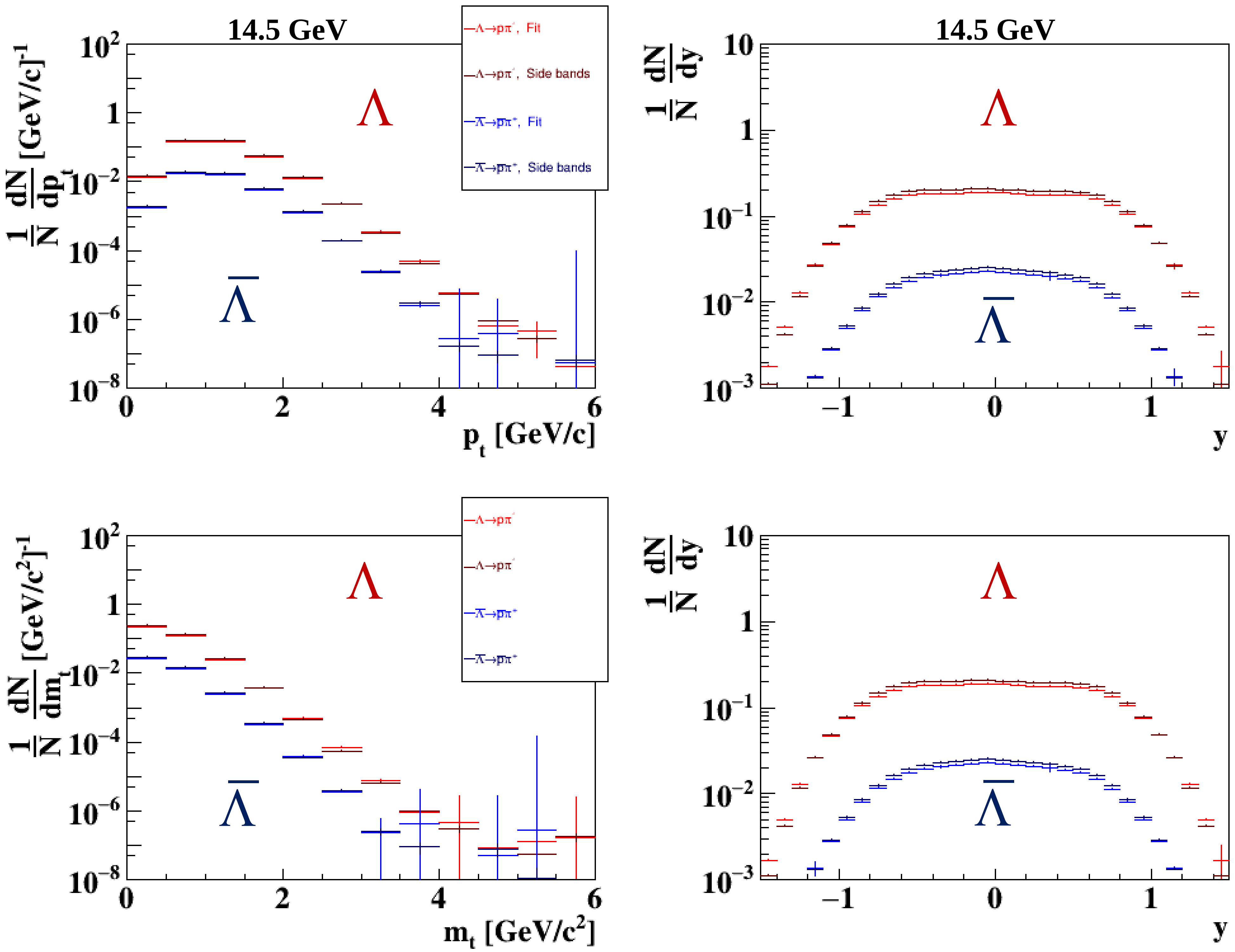
200M AuAu events at 14.5 GeV, 2019 BES II HLT express production



Excellent work of:
iTPC, oTPC, bTOF
CA tracking, KFParticle Finder

- Quality of the express production calibration and alignment is high enough to see hyperons with high significance and low level of background.
- Hyperons are clearly seen at all BES II energies: 3, 3.2, 3.9, 7.7, 9.1, 14.5, 19.6, 27 GeV.
- High significance allows extraction of spectra

Raw uncorrected spectra of hyperons
(STAR performance express analysis, BES-II)

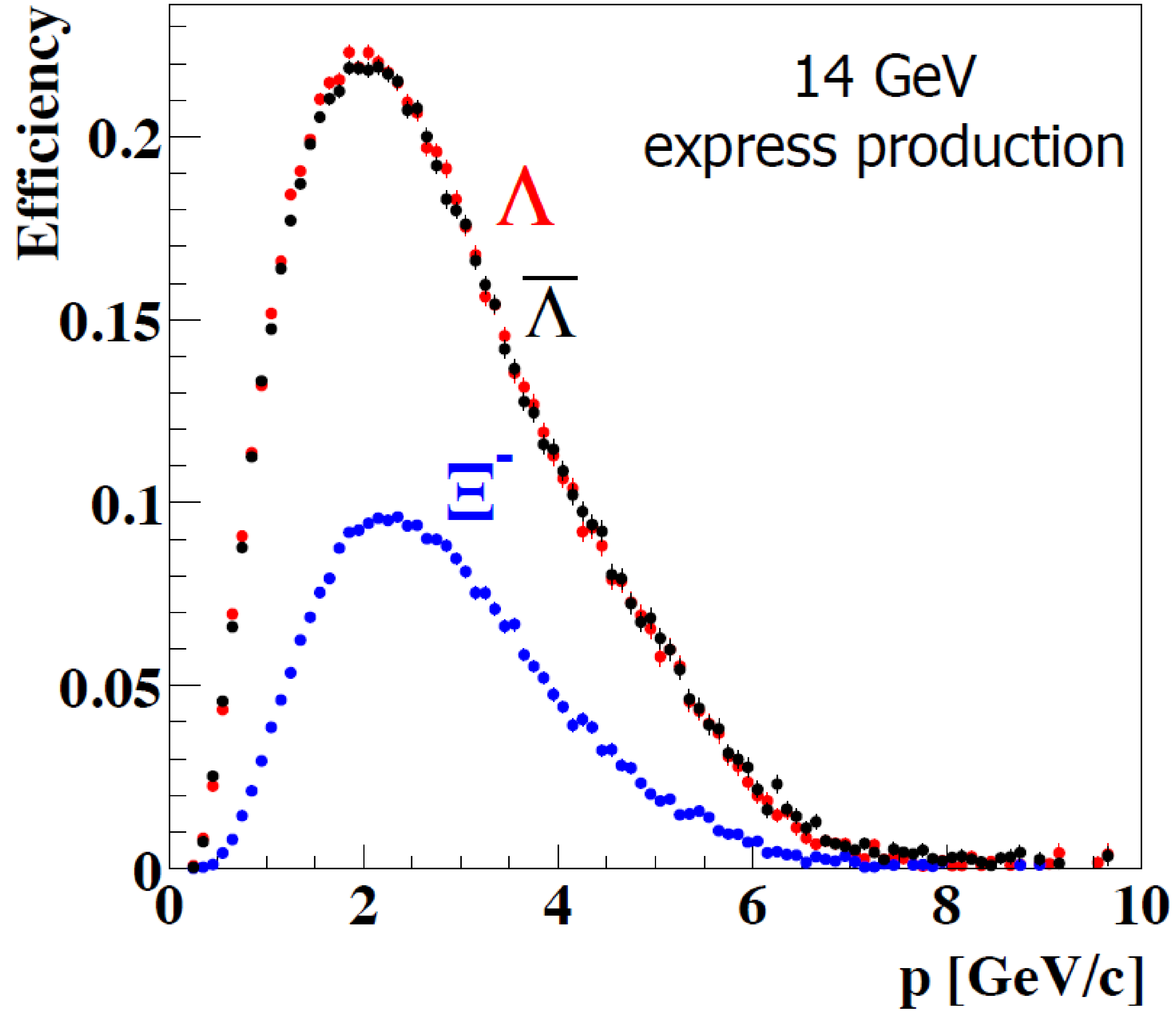


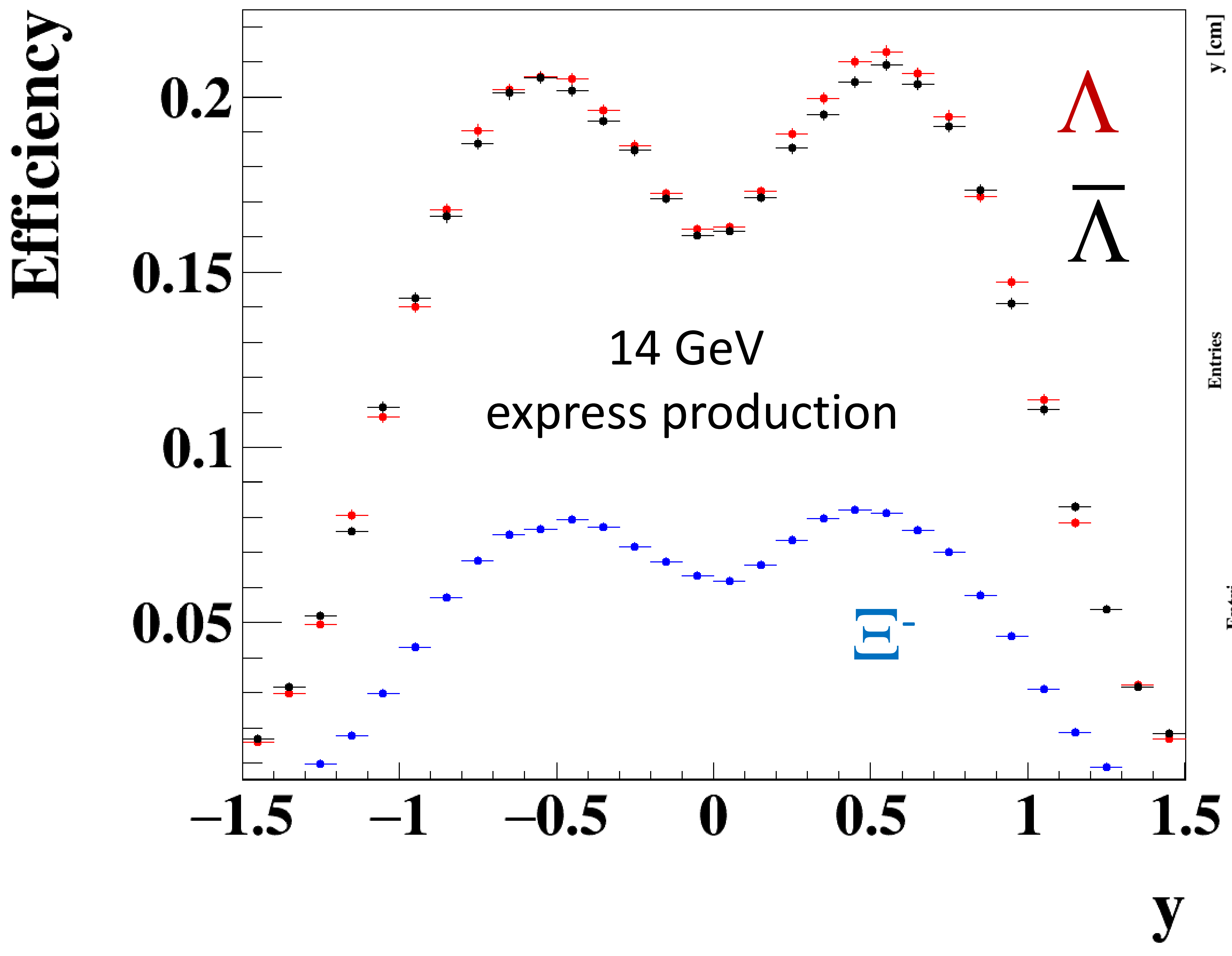
Spectra are shown at an example of Λ , 200M AuAu events at 14.5 GeV.
Two multi-differential methods are applied for extraction of spectra: side-bands and polynomial background fit. Moreover, rapidity spectra can be obtained from two independent distributions y-p_t and y-m_t, that can provide a tool for studies of systematics related to the acceptance effects.
Spectra in p_t and m_t are extracted within $-0.5 < y < 0.5$.

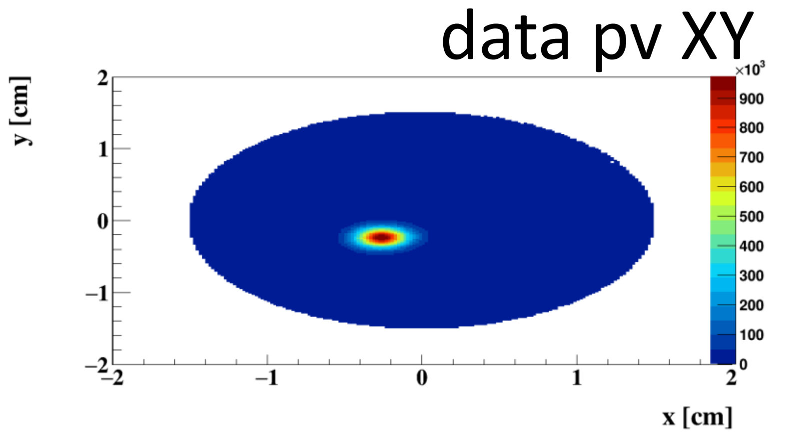
Efficiency calculation (STAR performance express analysis, BES-II)

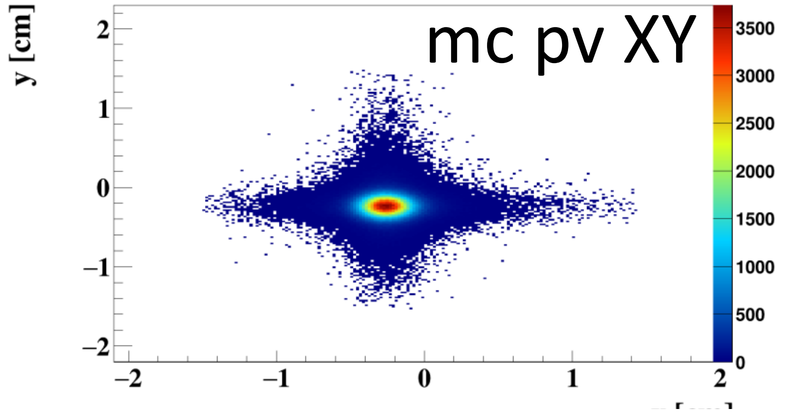
For efficiency calculation we use ROOT VMC approach, which provide tools to account detector misalignment in simulation.

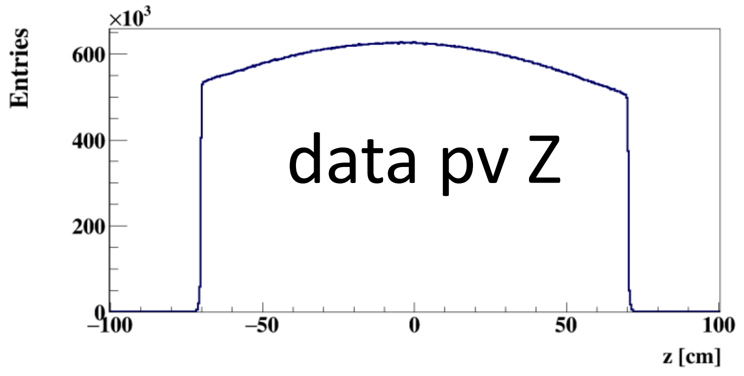
- The misalignment parameters are taken from the Database and are applied to the geometry used for VMC simulation.
- Currently, a simplified approach for efficiency calculation is applied: 20 signal particles are simulated per each event with primary vertex positions generated using real data distributions. Thermal spectrum is assumed.
- Currently, the TOF efficiency is not fully accounted.
- For accurate calculation of efficiency full embedding is required (work in progress).

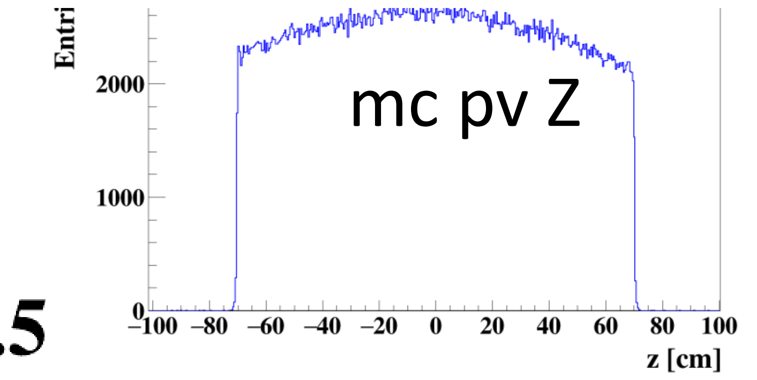




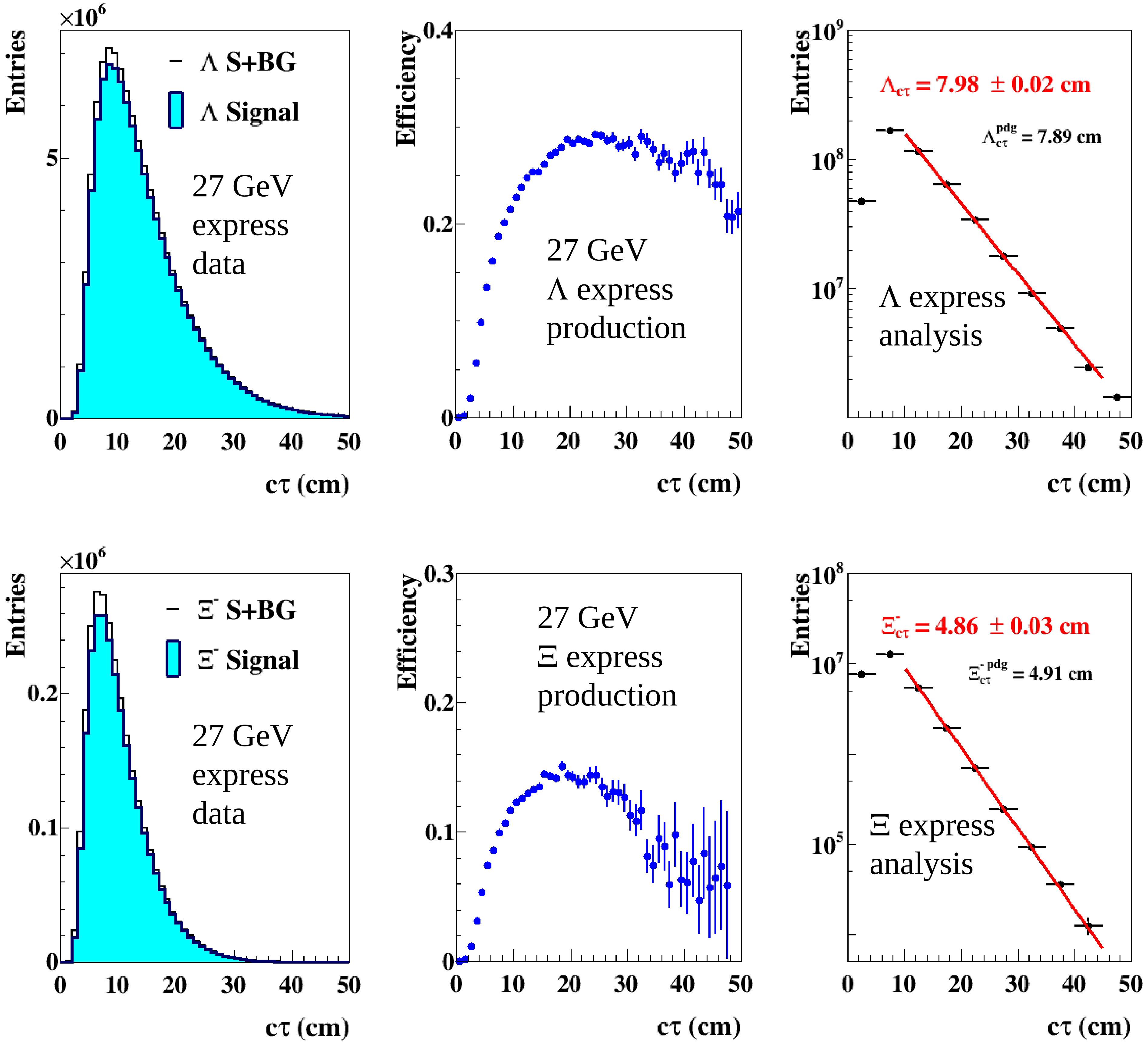


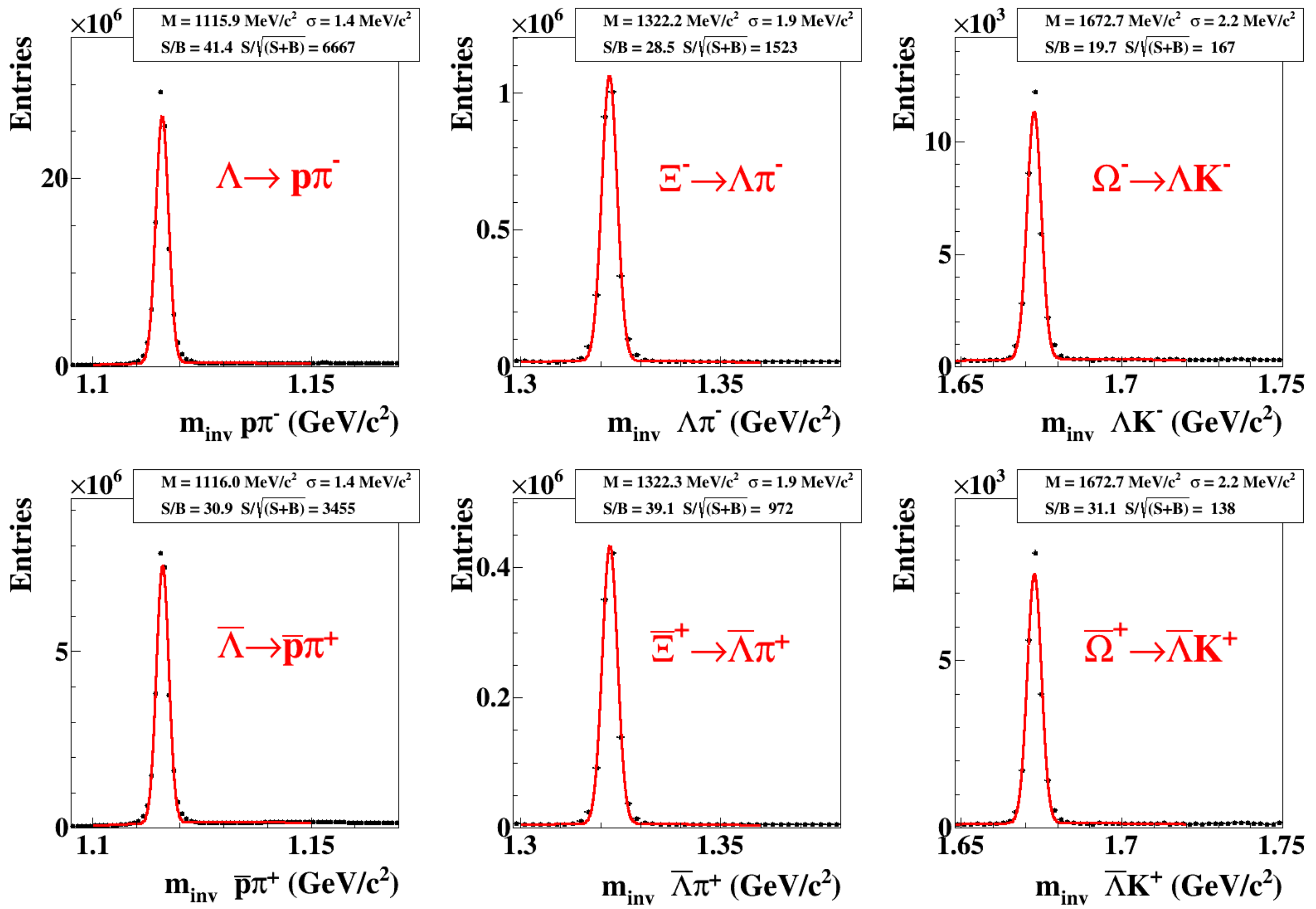






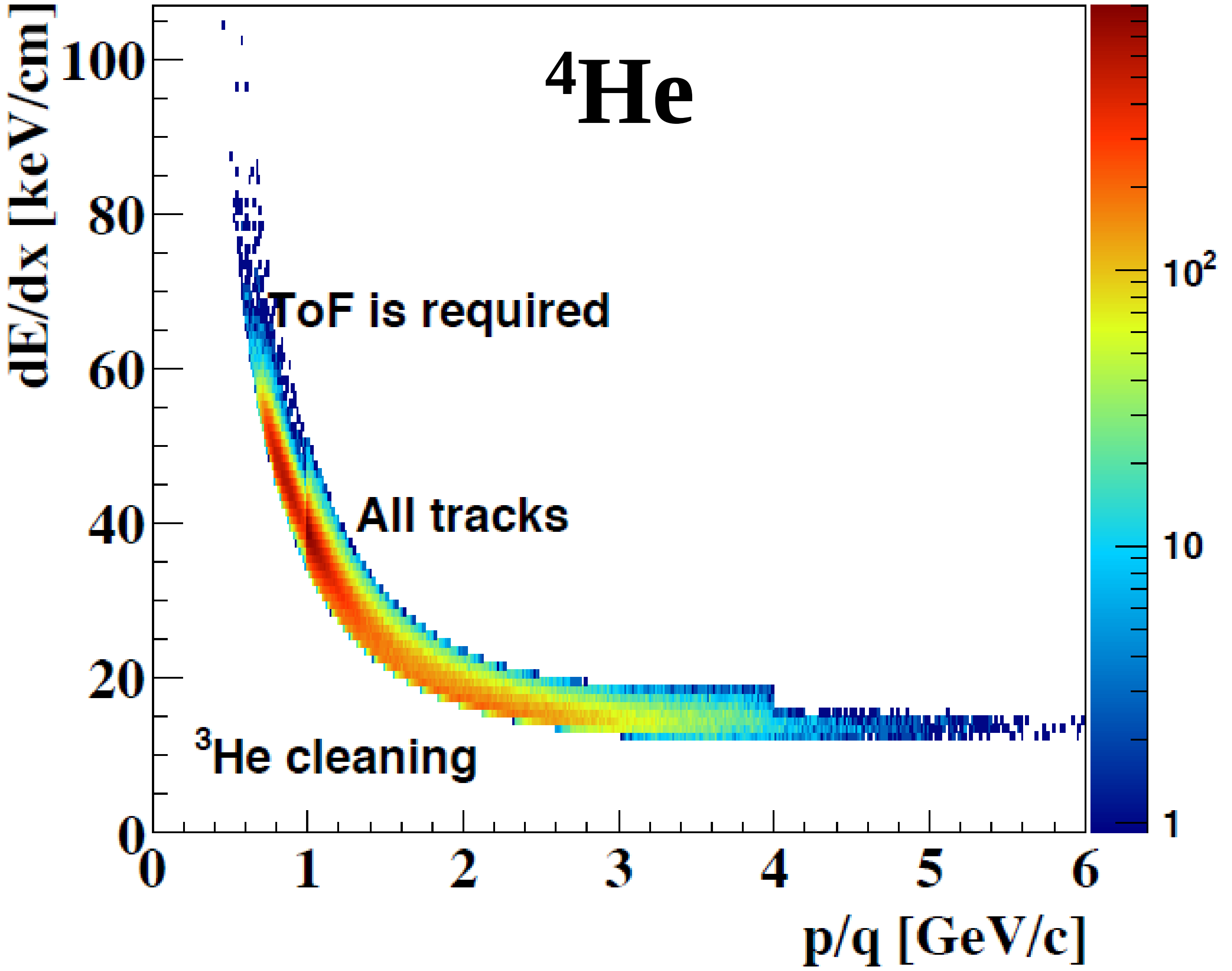
Λ and Ξ⁻ Hyperons lifetime
(STAR performance express analysis, BES-II)

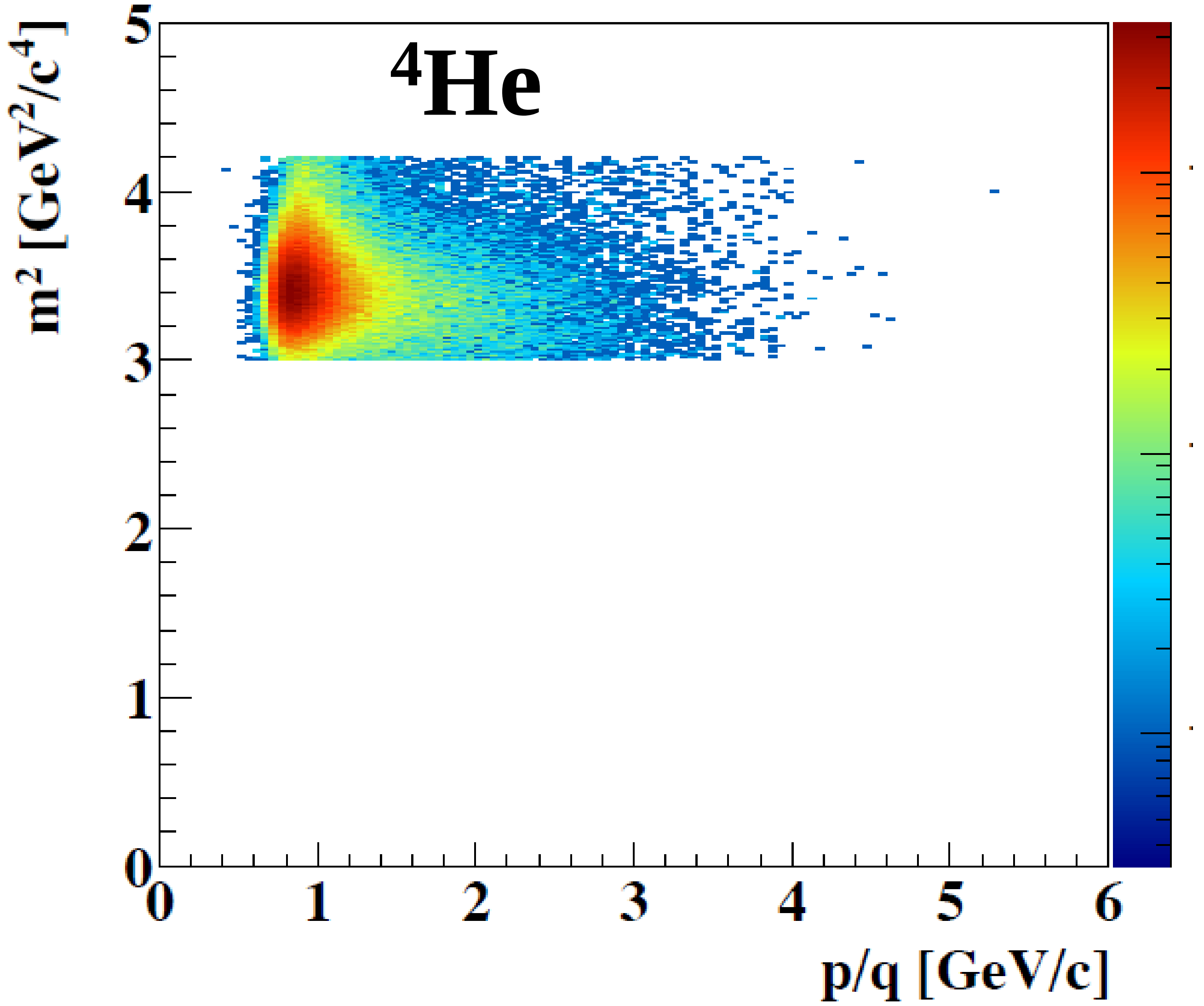


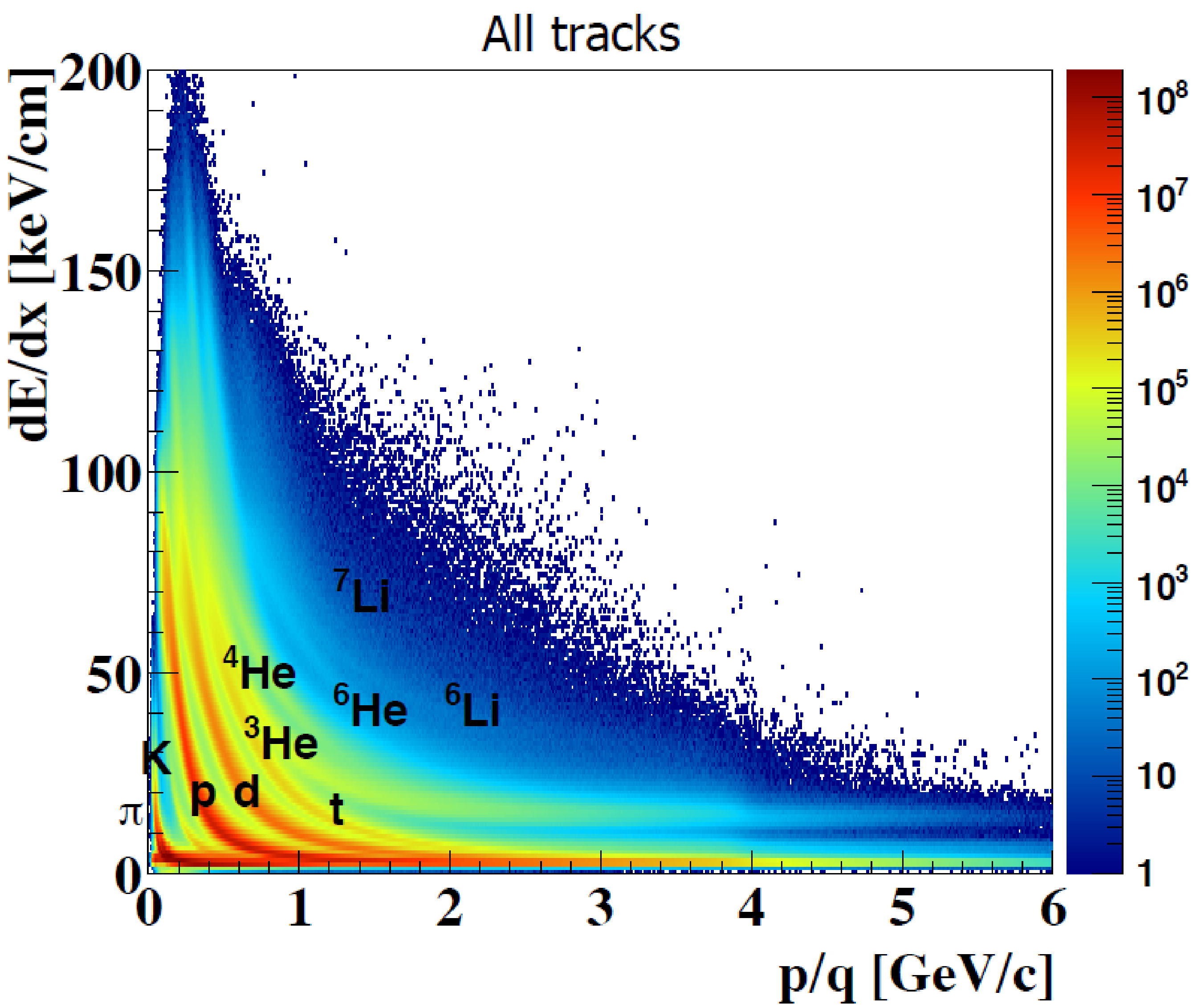


- 27 GeV data are used for extraction of the Λ and Ξ lifetime because of the extremely high significance.
- Lifetime of Λ and Ξ from the simulated data is extracted with high precision, while from the real data with (1-5)% systematic error - efficiency should be understood, embedding is needed.

Hypernuclei express analysis: ^{4}He PID

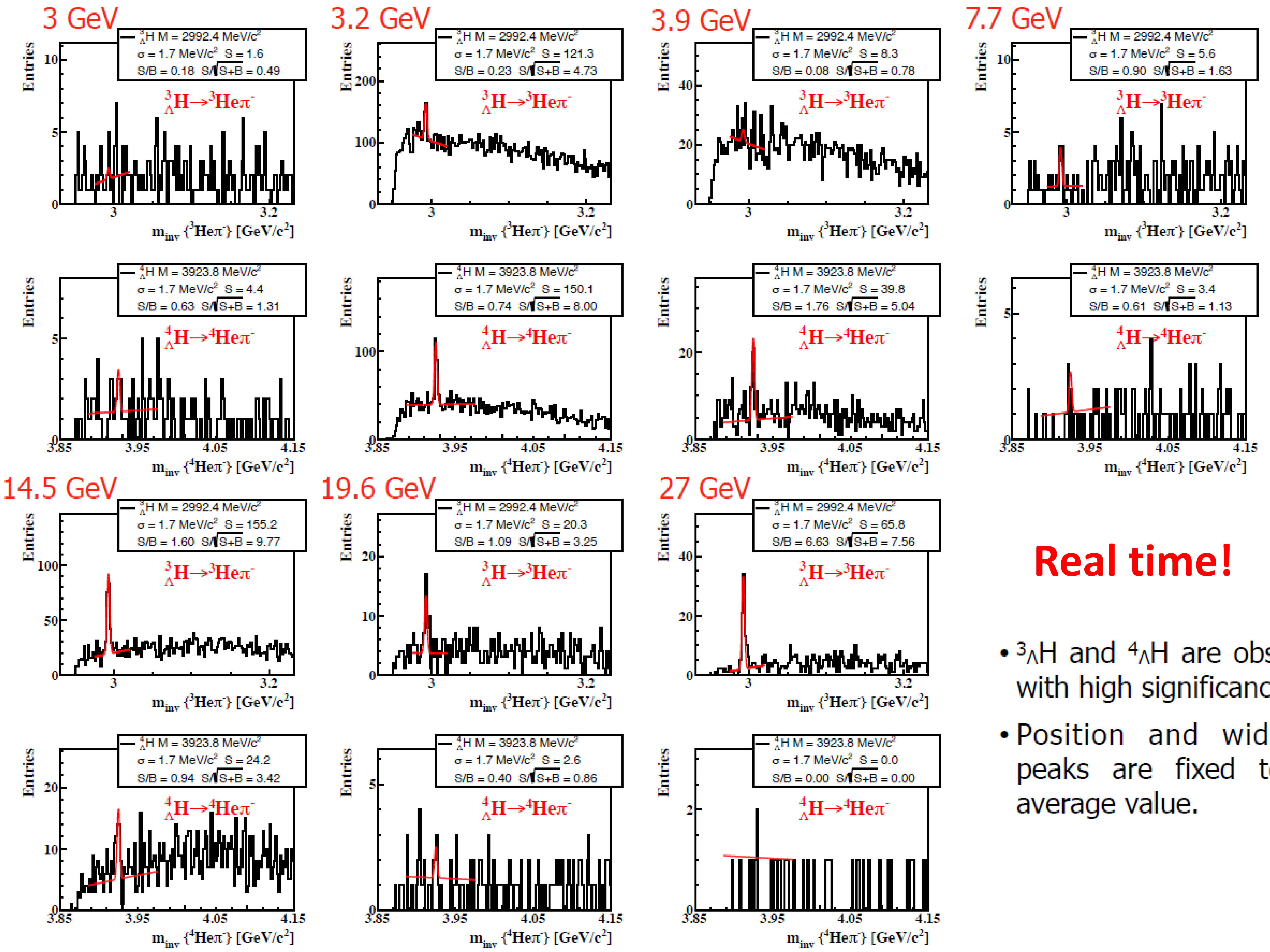






- PID is shown at an example of ^{4}He.
- Tracks with dE/dx within predefined region are selected.
- If track has a bTOF measurement it is checked to be within predefined range.
- For tracks with p/q < 1 GeV/c bTOF measurement is required.

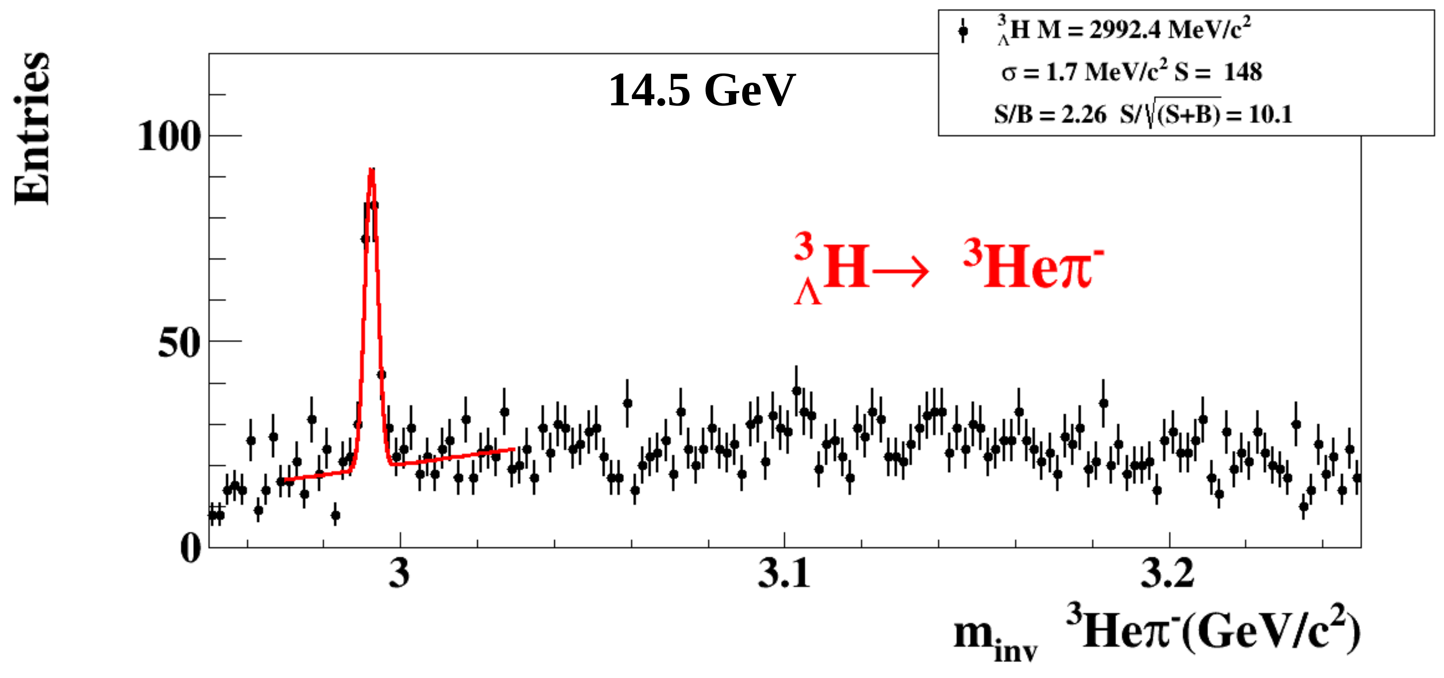
Hypernuclei in BES-II
(STAR performance express analysis)

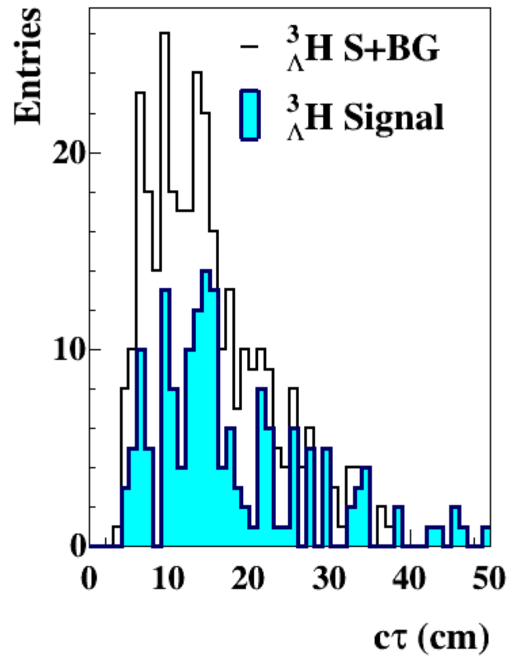


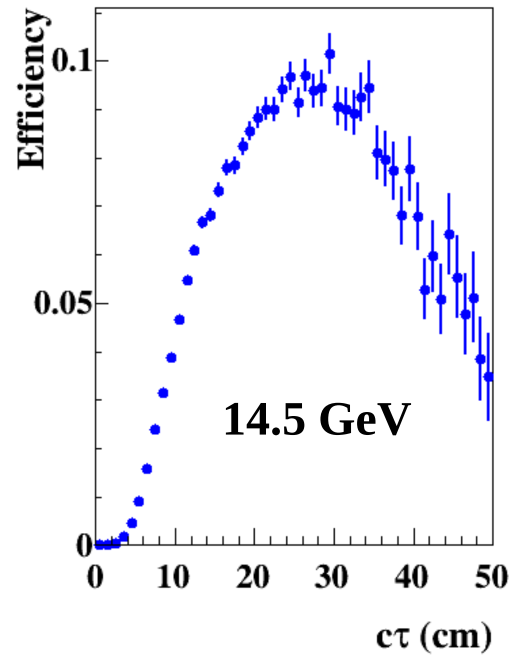
Real time!

- $^3{}_\Lambda H$ and $^4{}_\Lambda H$ are observed with high significance.
- Position and width of peaks are fixed to the average value.

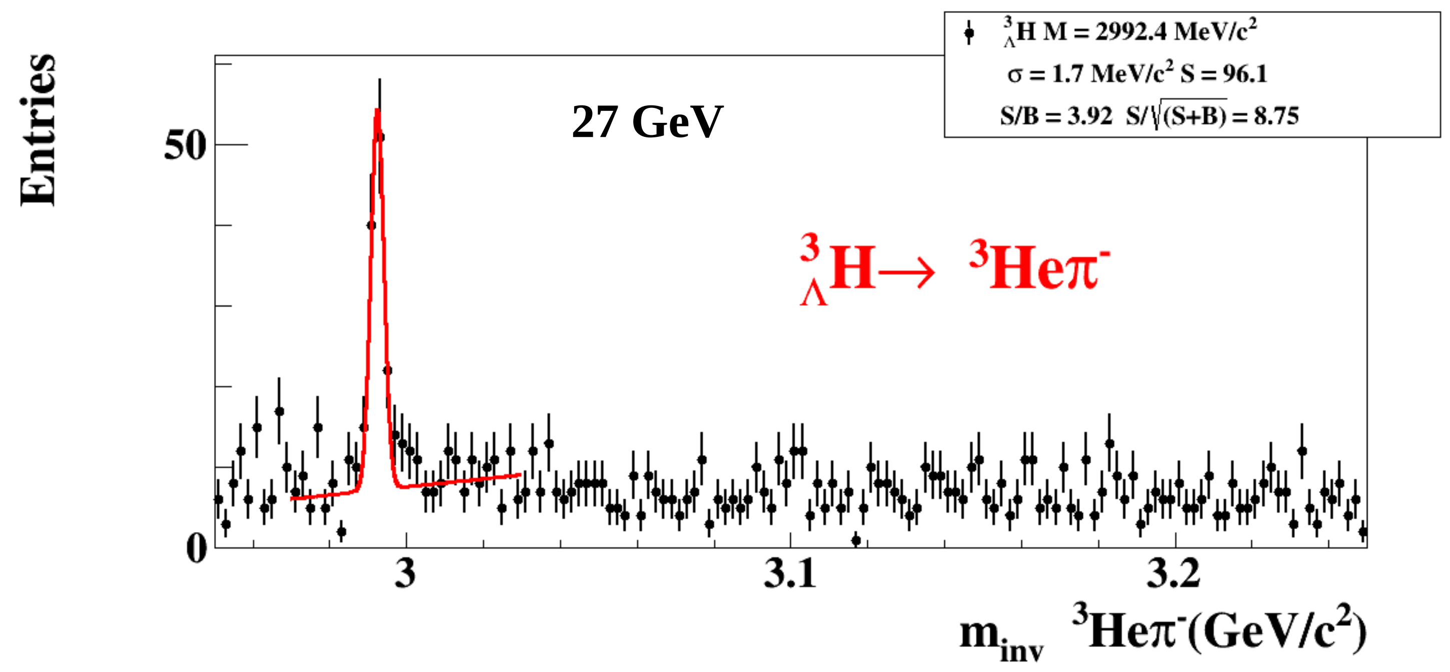
Hypernuclei in BES-II
($^{3}_{\Lambda}H$ STAR performance express analysis)

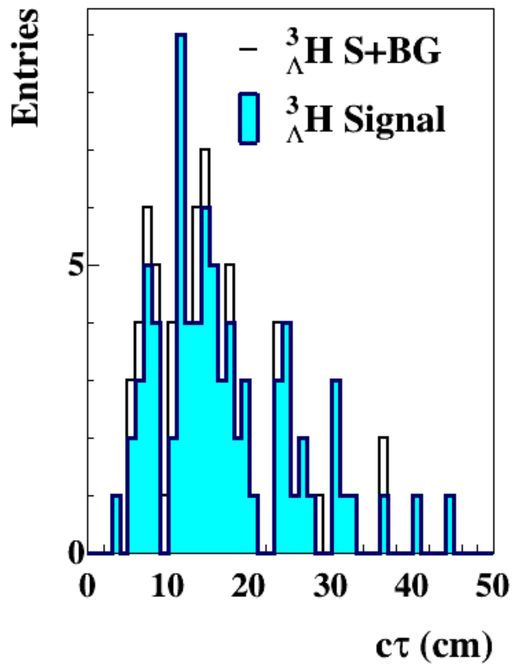


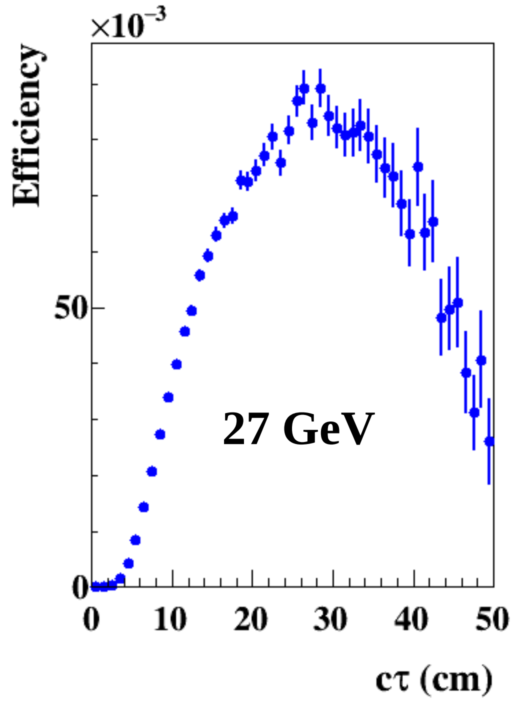




$^{3}_{\Lambda}H$ lifetime?





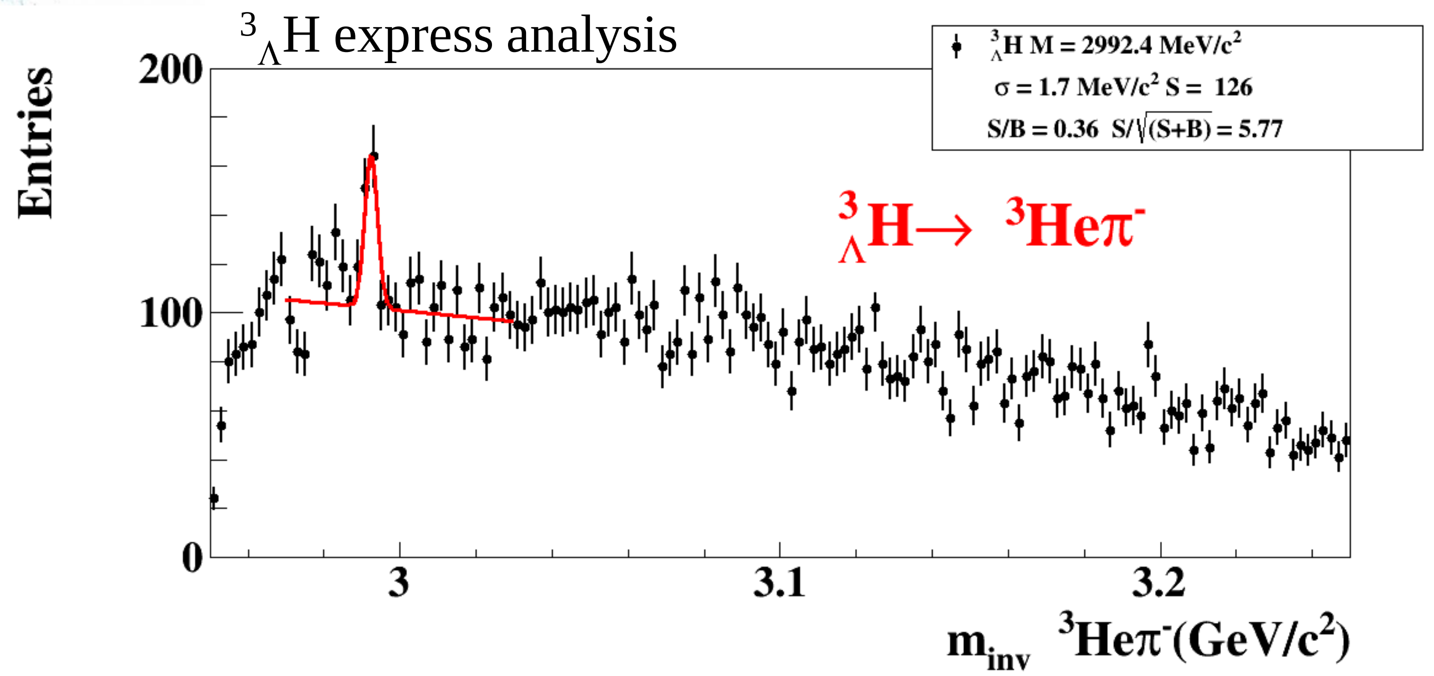


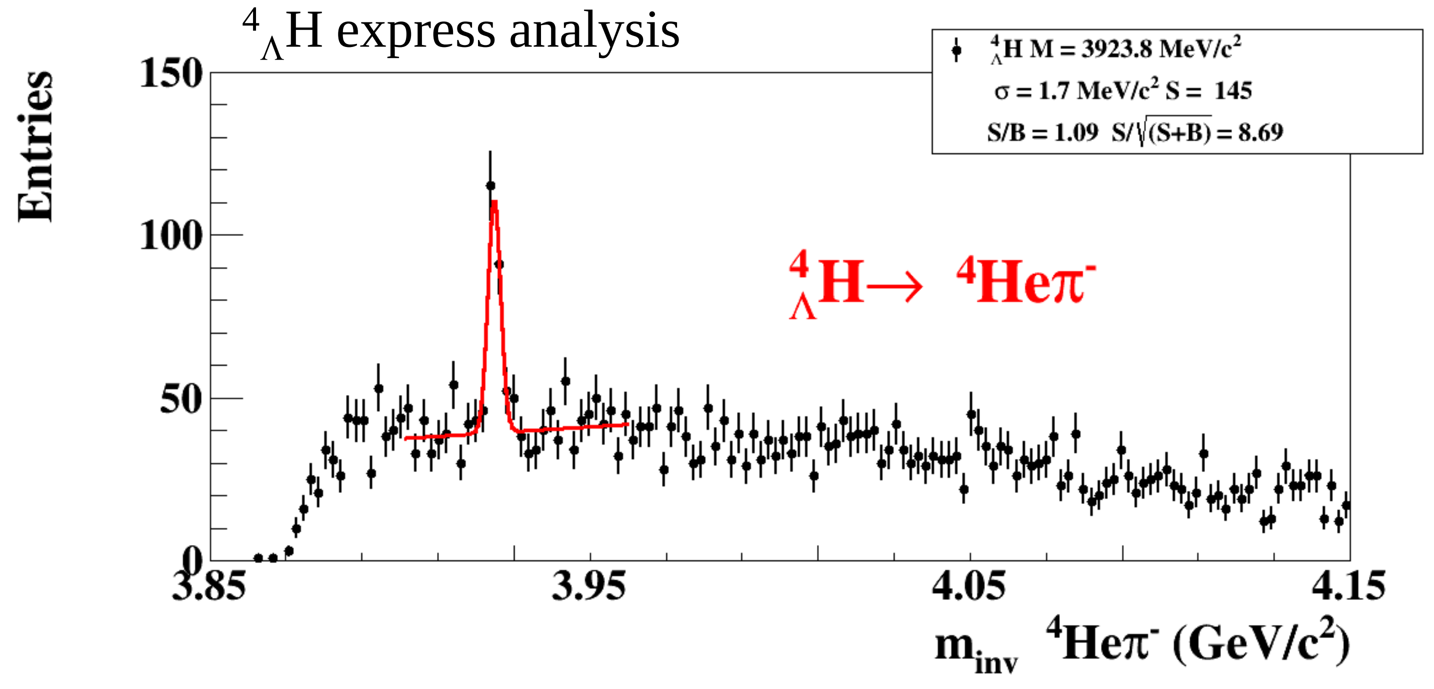
$^{3}_{\Lambda}H$ lifetime?

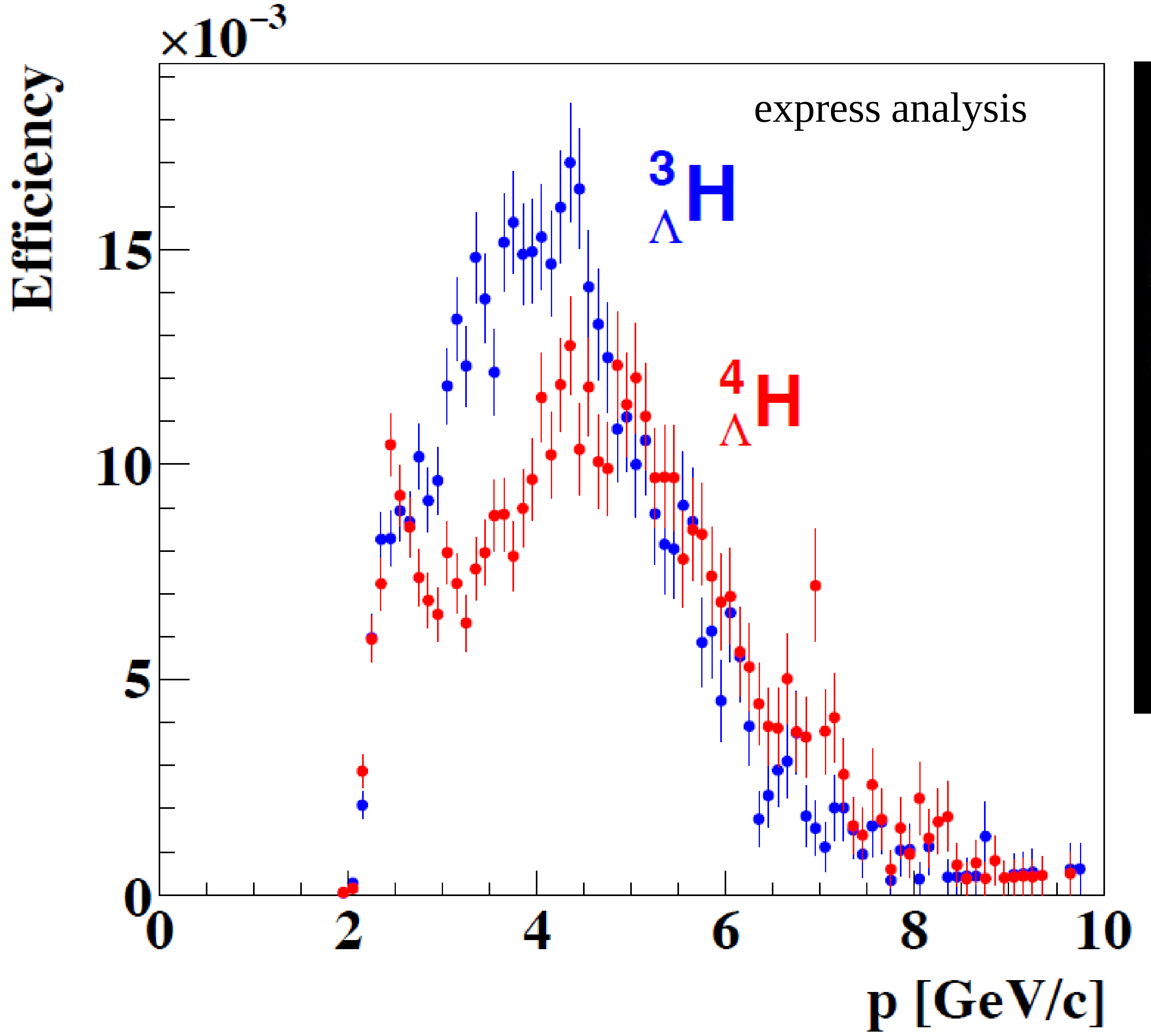
- Ready to extract yields for $^{3}_{\Lambda}H$
- Ready to extract lifetime for $^{3}_{\Lambda}H$
- Work in progress

Efficiency of hypernuclei for the Fixed Target 3.2 GeV

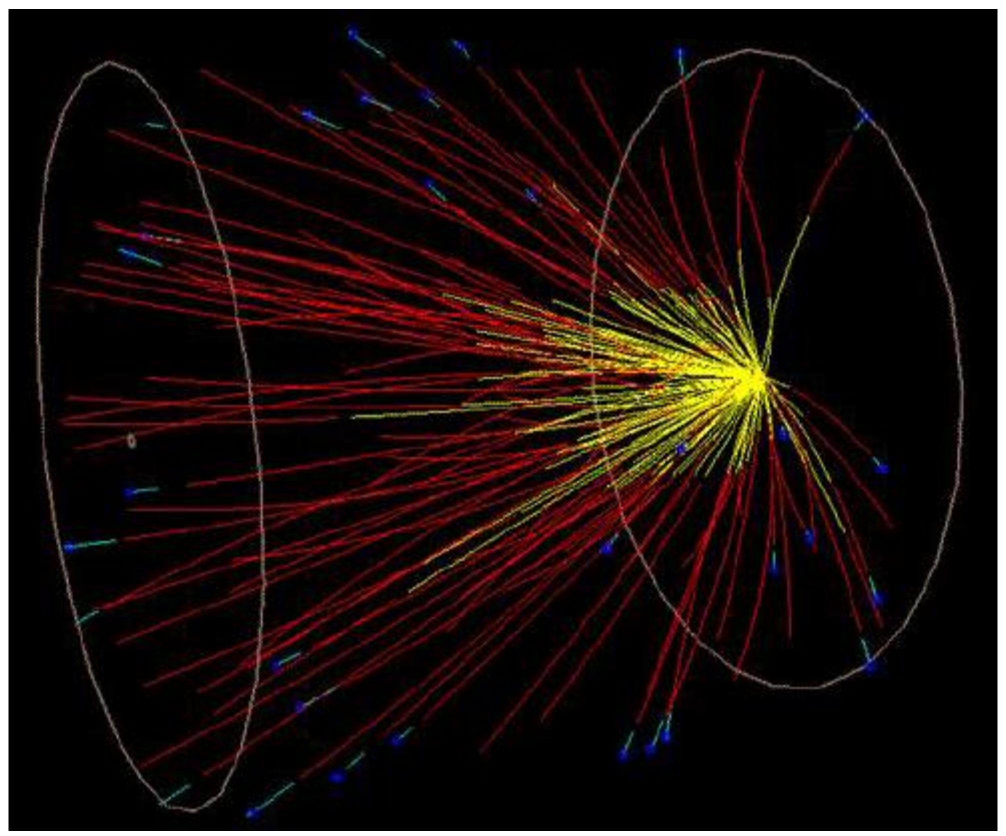
($^{3,4}_{\Lambda}H$ STAR performance express analysis)

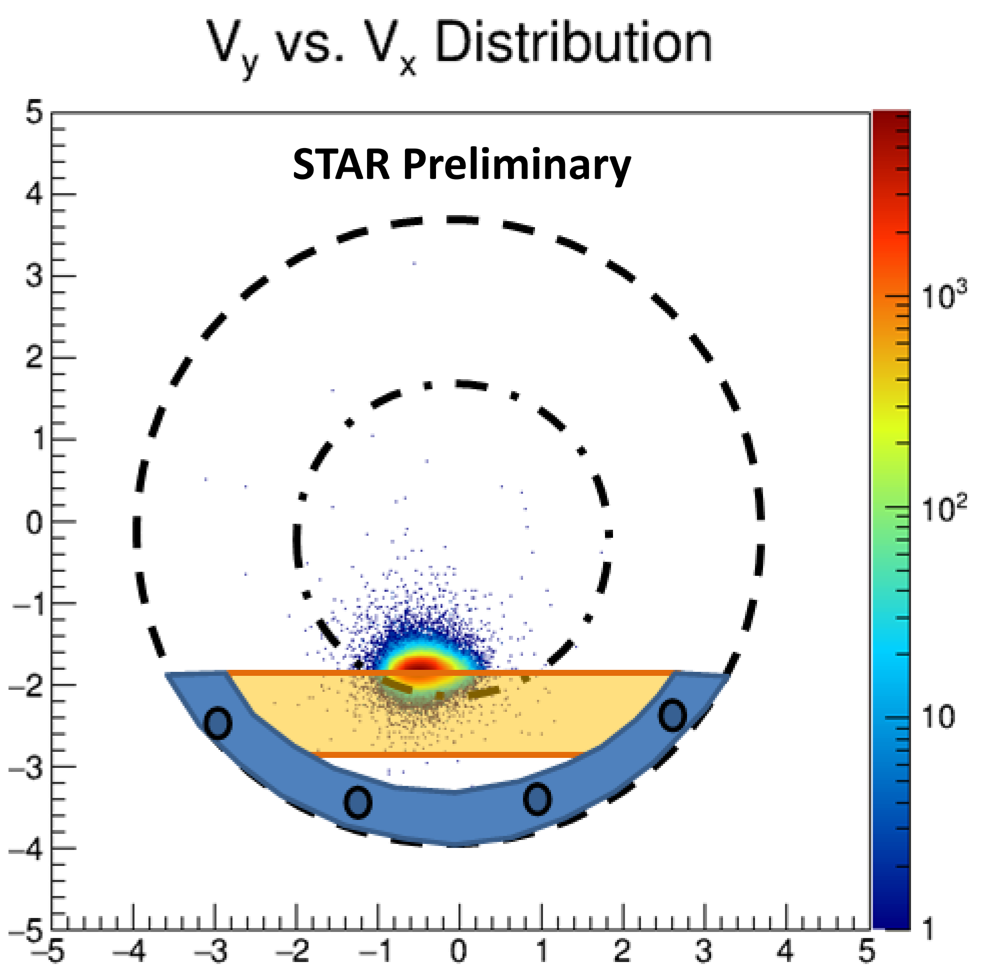






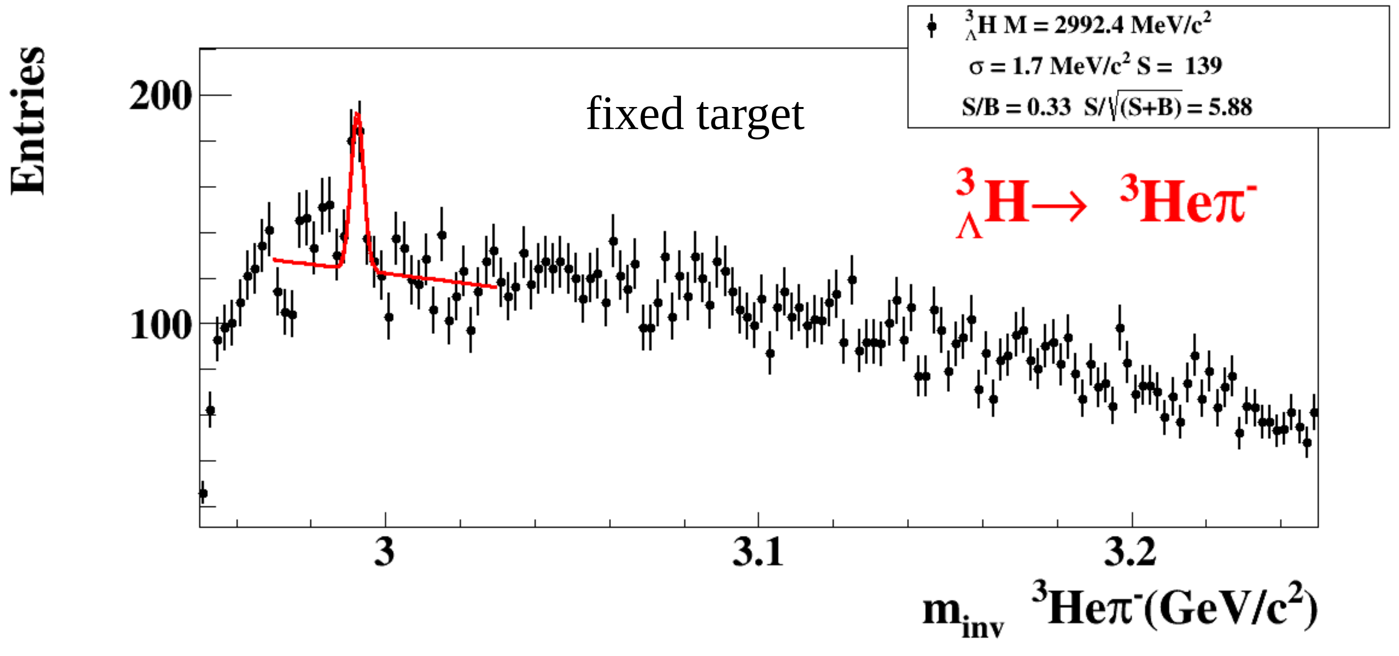
Reconstructed event 3.9 GeV

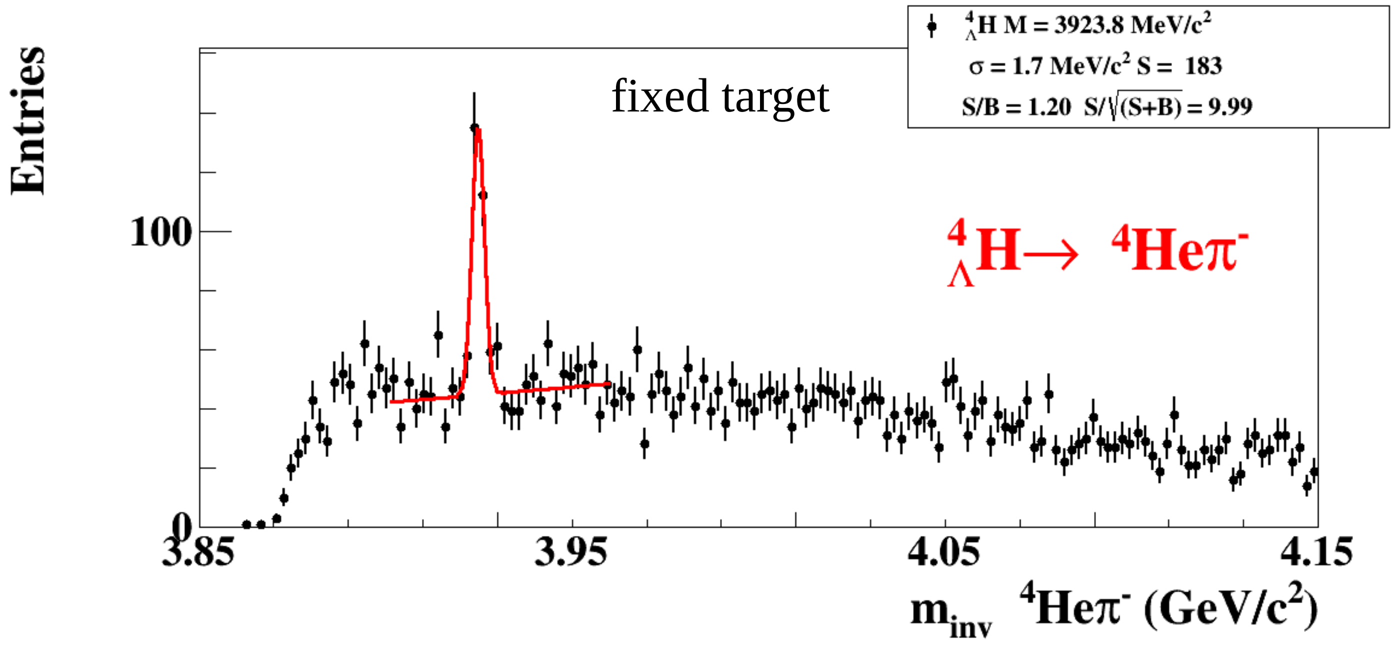


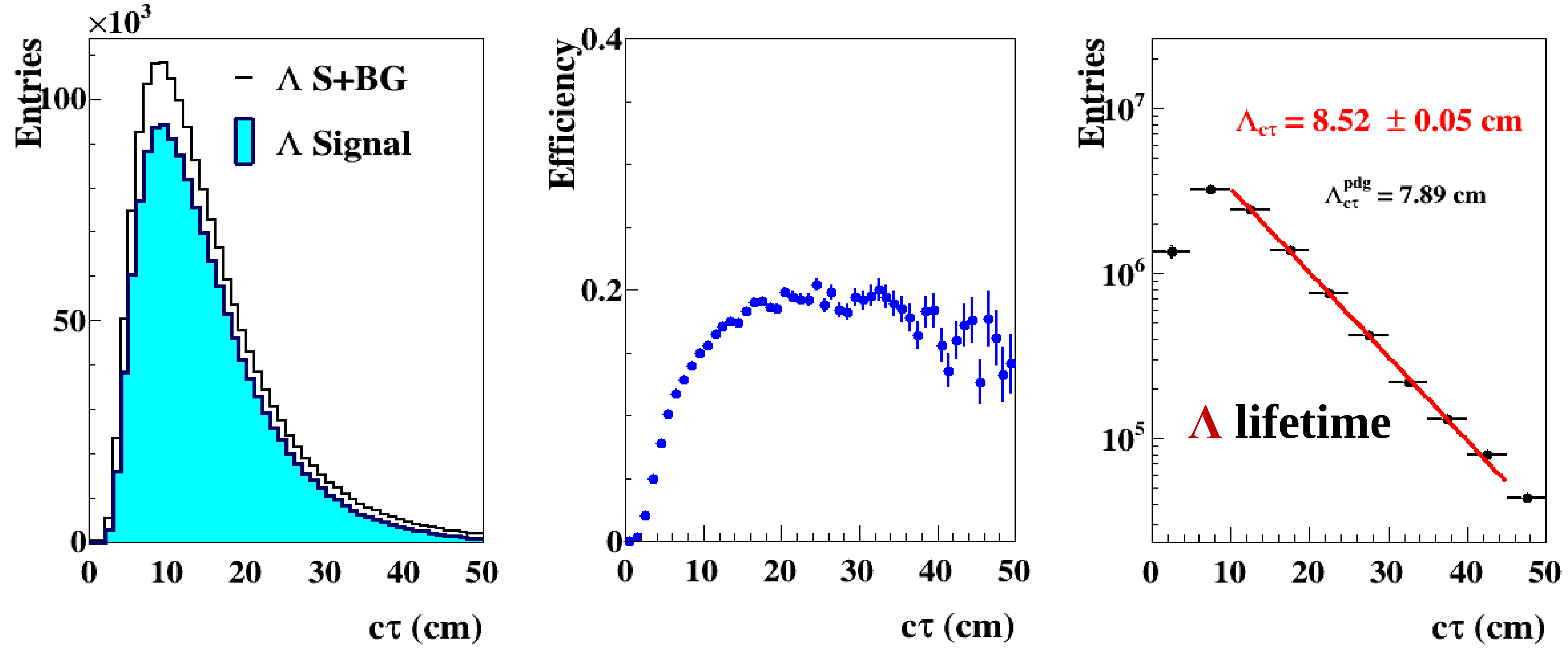


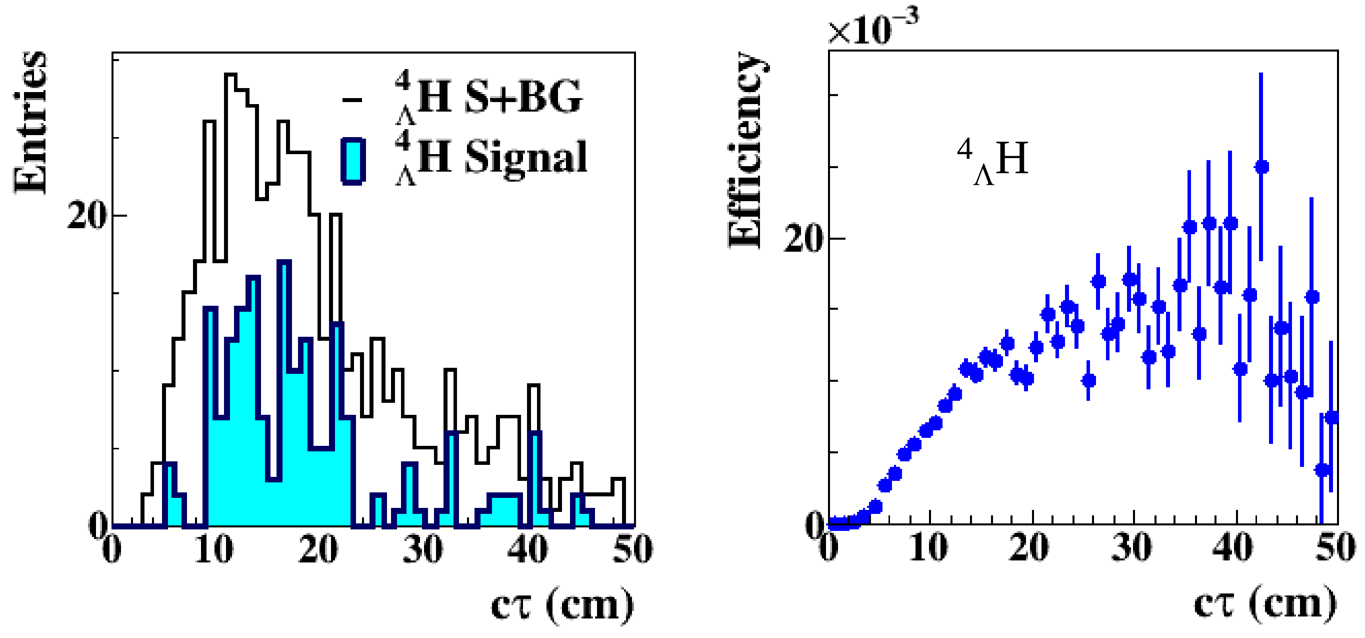
- Efficiency for the **fixed target** 3.2 GeV (4.55 in the lab frame) data is presented.
- Efficiency of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ are similar.
- Efficiency of $^{4}_{\Lambda}H$ is slightly smaller due to the tighter PID cuts and slightly different acceptance.

Hypernuclei in BES II ($^4_\Lambda H$ STAR performance express analysis)









$^4_\Lambda$**H lifetime?**

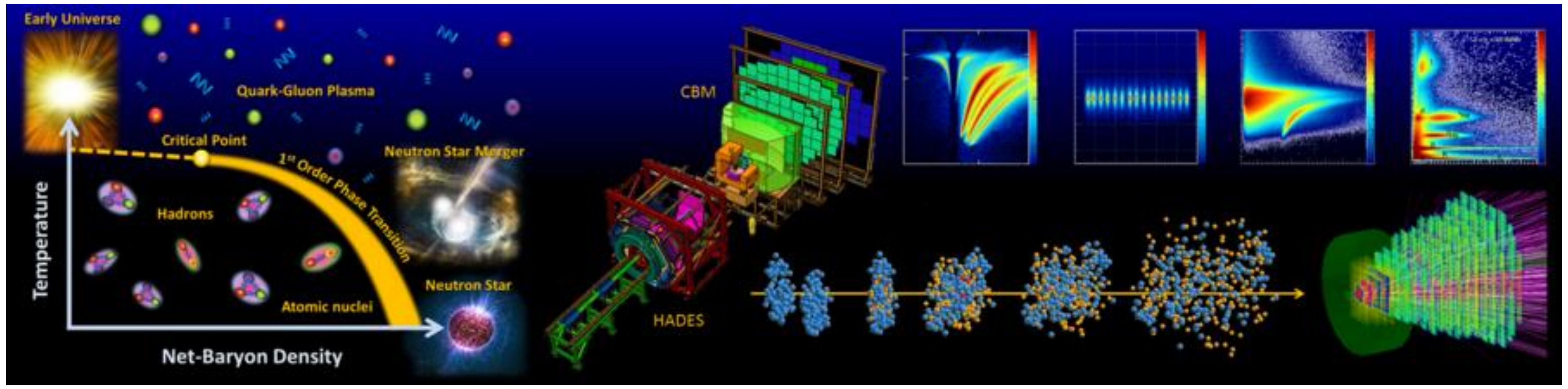
fixed target express data for $^3_\Lambda H$ and $^4_\Lambda H$

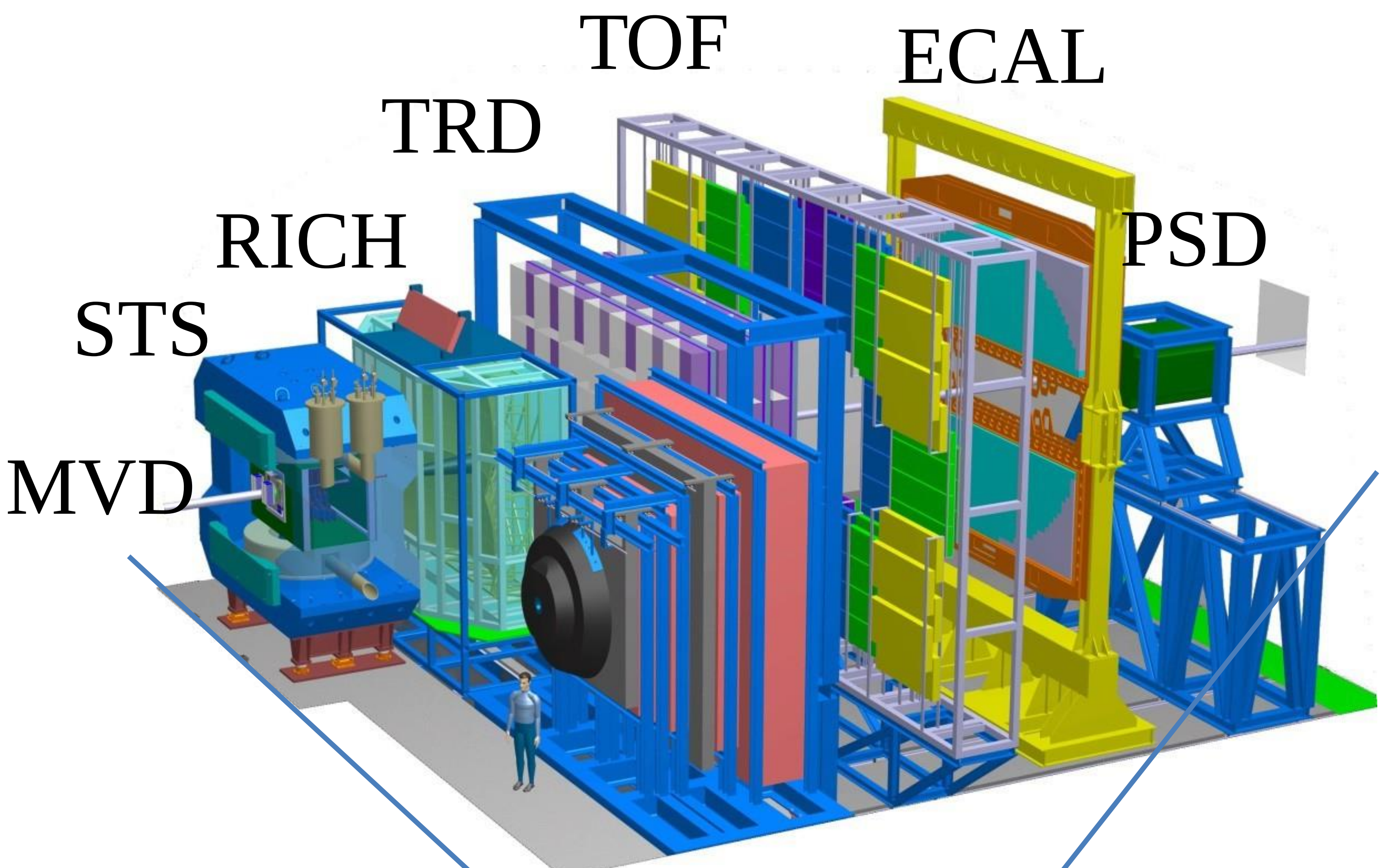
- 3.2 and 3.9 GeV (4.55 and 7.3 AGeV in the lab frame) data are used, since the efficiency is similar.
- Lifetime of Λ from the simulated data is extracted with high precision, while from the real data with 8% systematic error - efficiency should be understood, embedding is needed.
- Higher significance is required for the precise measurement.

Summary I

- KF Particle Finder was successfully applied for the express analysis of the HLT express production.
- The quality of the express production data allows to obtain clean spectra with high significance.
- Express analysis allows to monitor the quality of the collected data in real time.
- Analysing physics in real time we can observe unexpected effects and modify the run program if needed.
- Express production provides early access to the collected data, no need to wait for a couple of years to start your physics studies.
- With KF Particle Finder we are able to study wide range of physics including hyperons and hypernuclei in one go.

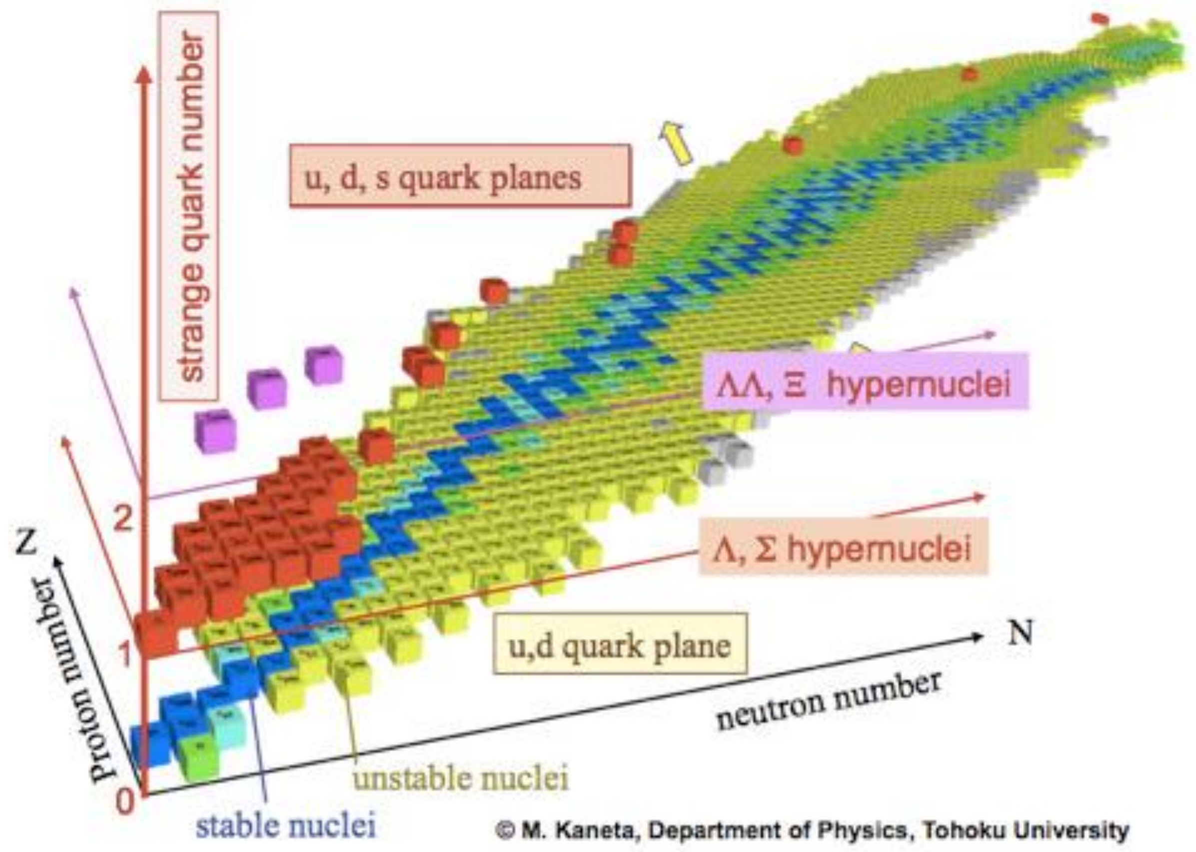
Perspectives on hypernuclei physics with CBM



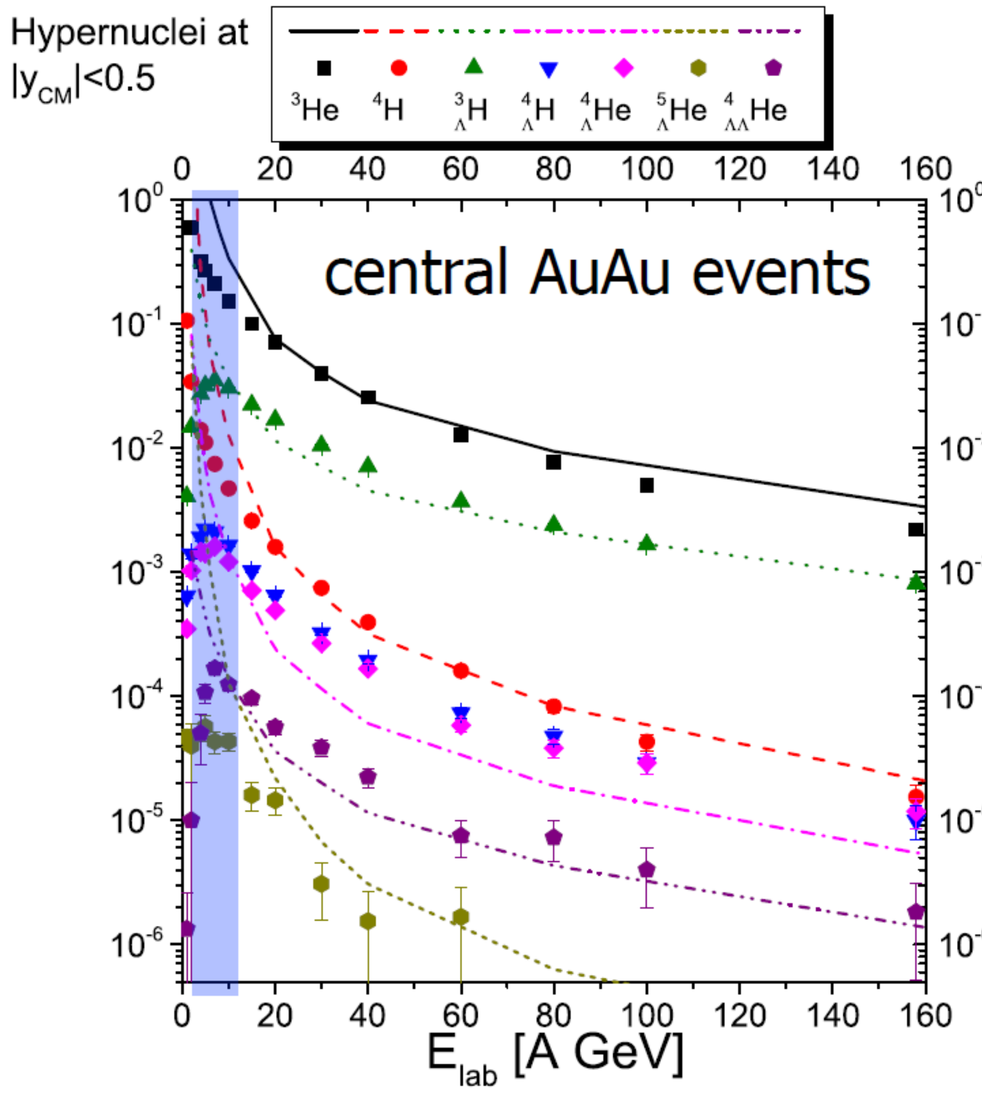


Motivation

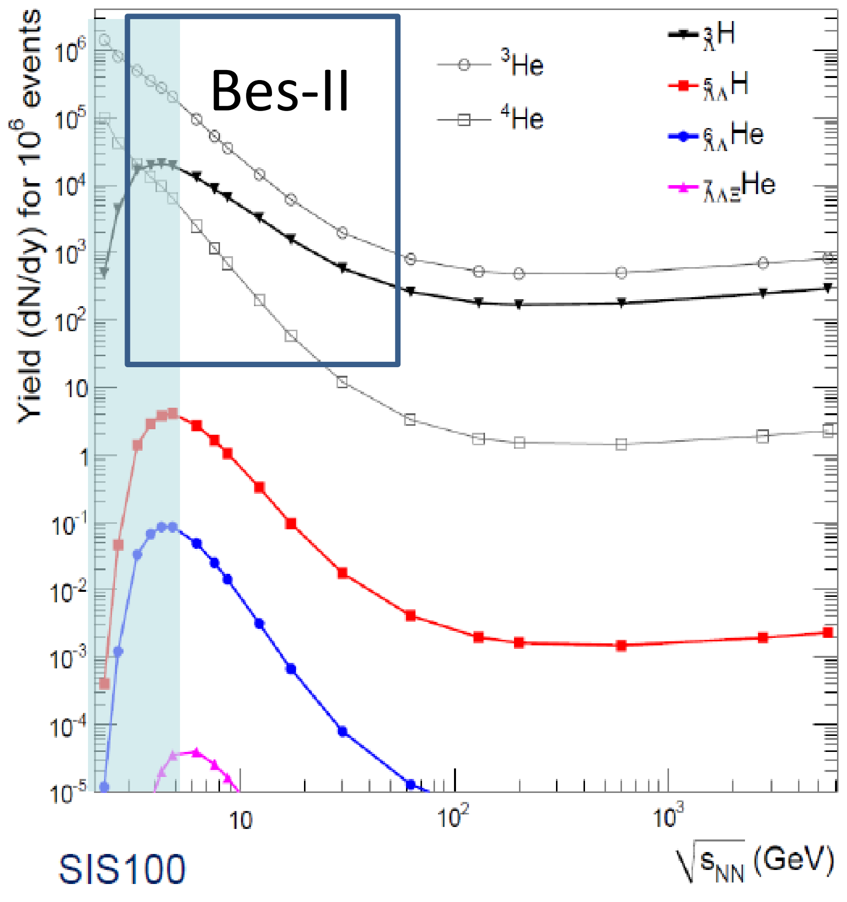
One of the physics cases of the CBM experiment is study of hypernuclei:
• Single and double hypernuclei.
• Precise measurements of hypernuclei lifetime.
• Measurement of branching ratios of hypernuclei.
• Direct access to the hyperon-nucleon (YN) interaction through measurements of B_{Λ} in a hypernucleus.
• "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. (BES-II express data!)
• 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.

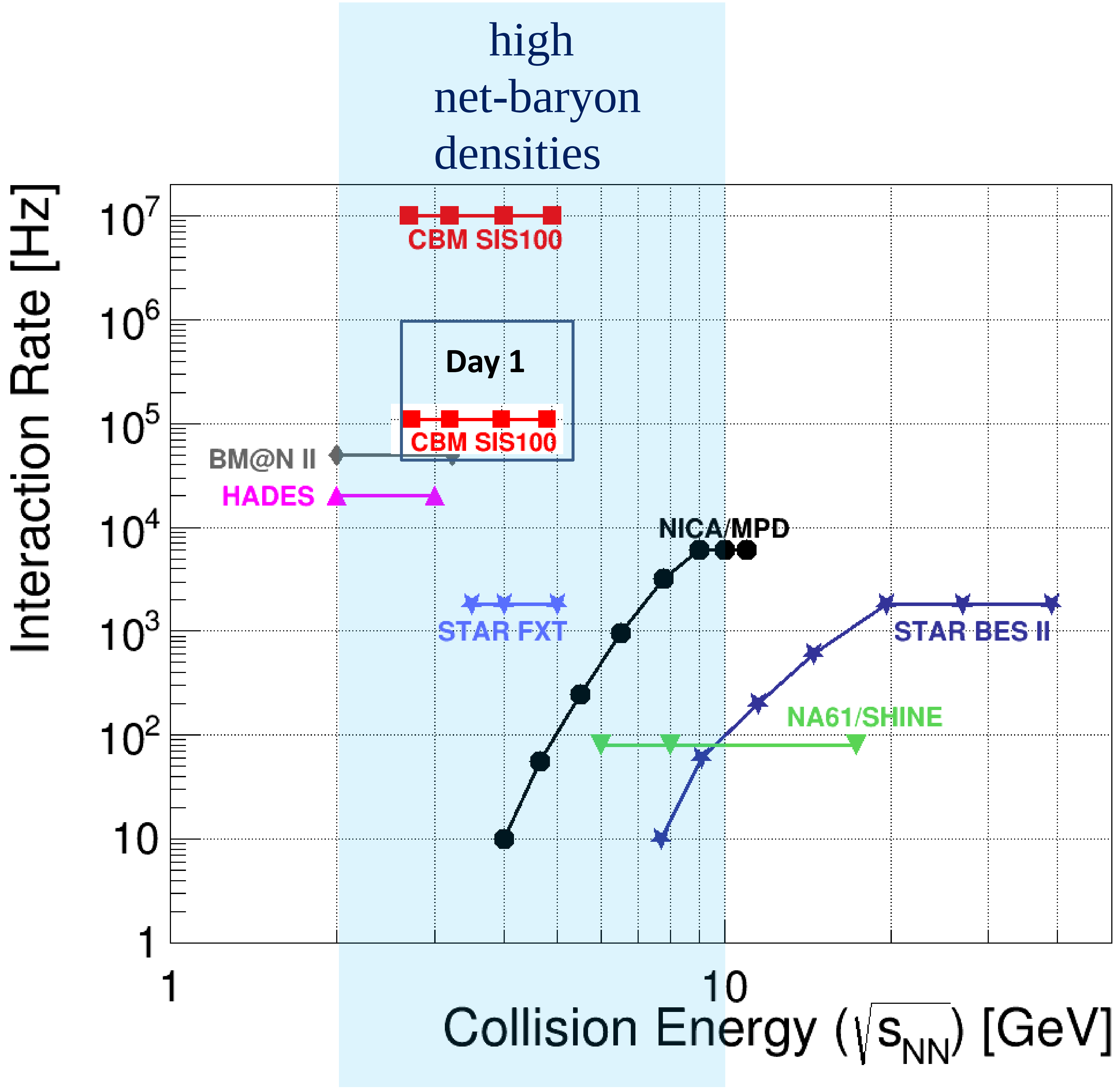


J. Steinheimer et al., Phys. Lett. B 714 (2012) 85



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

Experiments exploring dense QCD matter

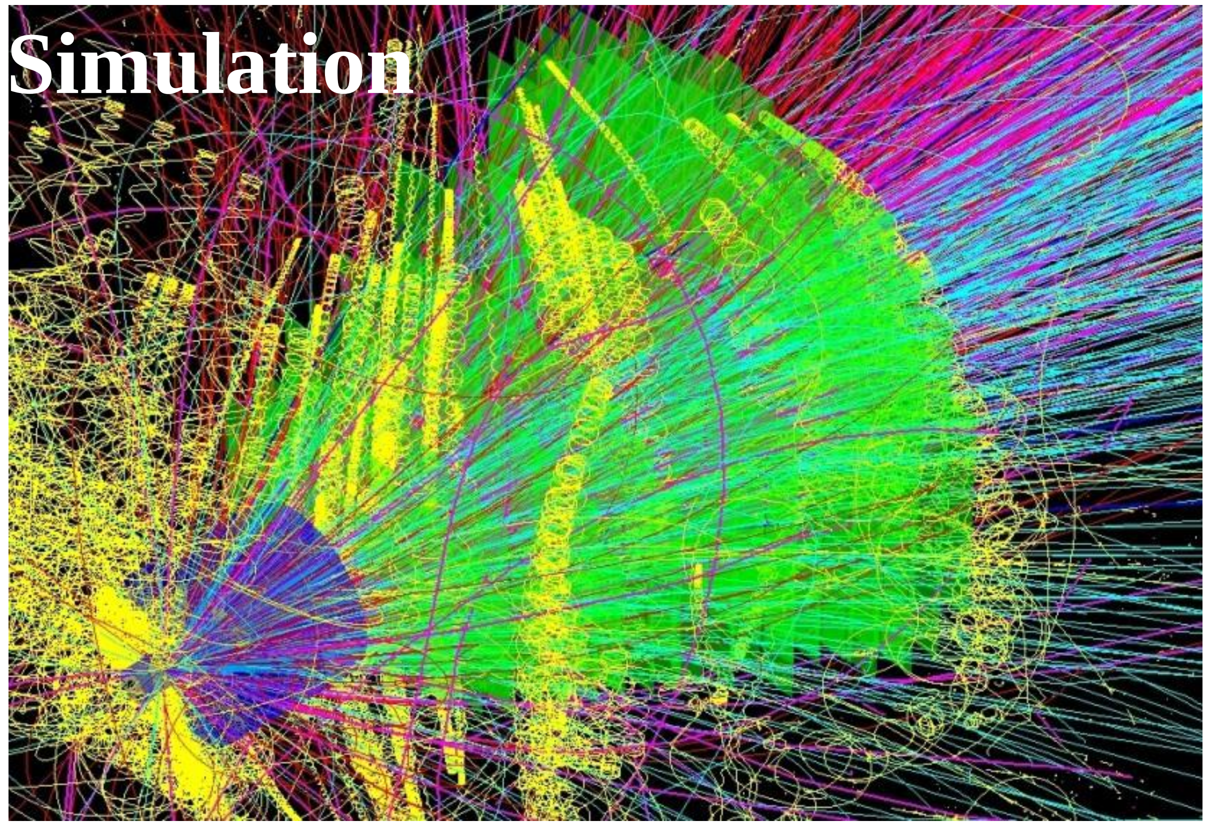


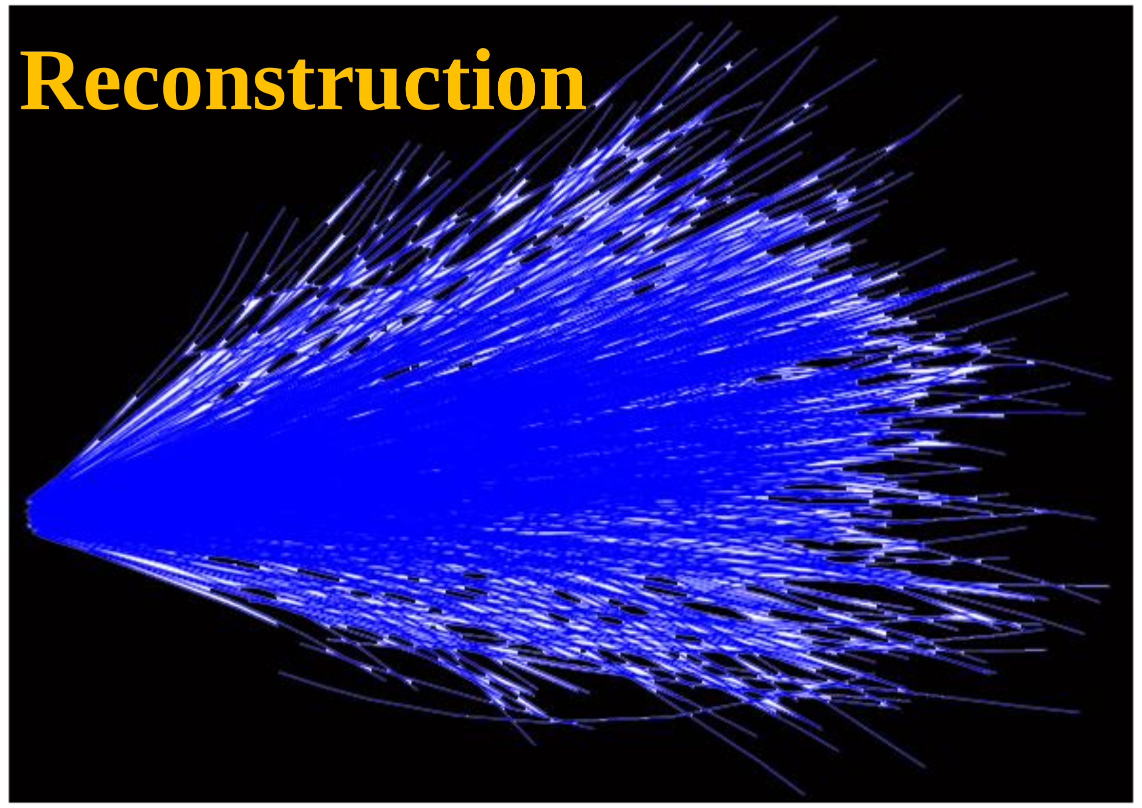
CBM:

***unprecedented* (high) rate capability**

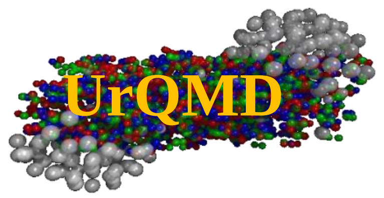
- determination of (displaced) vertices with high resolution (≈ 50 μm)
- identification of leptons and hadrons
- fast and radiation hard detectors
- self-triggered readout electronics
- high speed data acquisition and
- online event selection
- powerful computing farm *and 4D tracking*
- software triggers

Performance of the CBM track finder

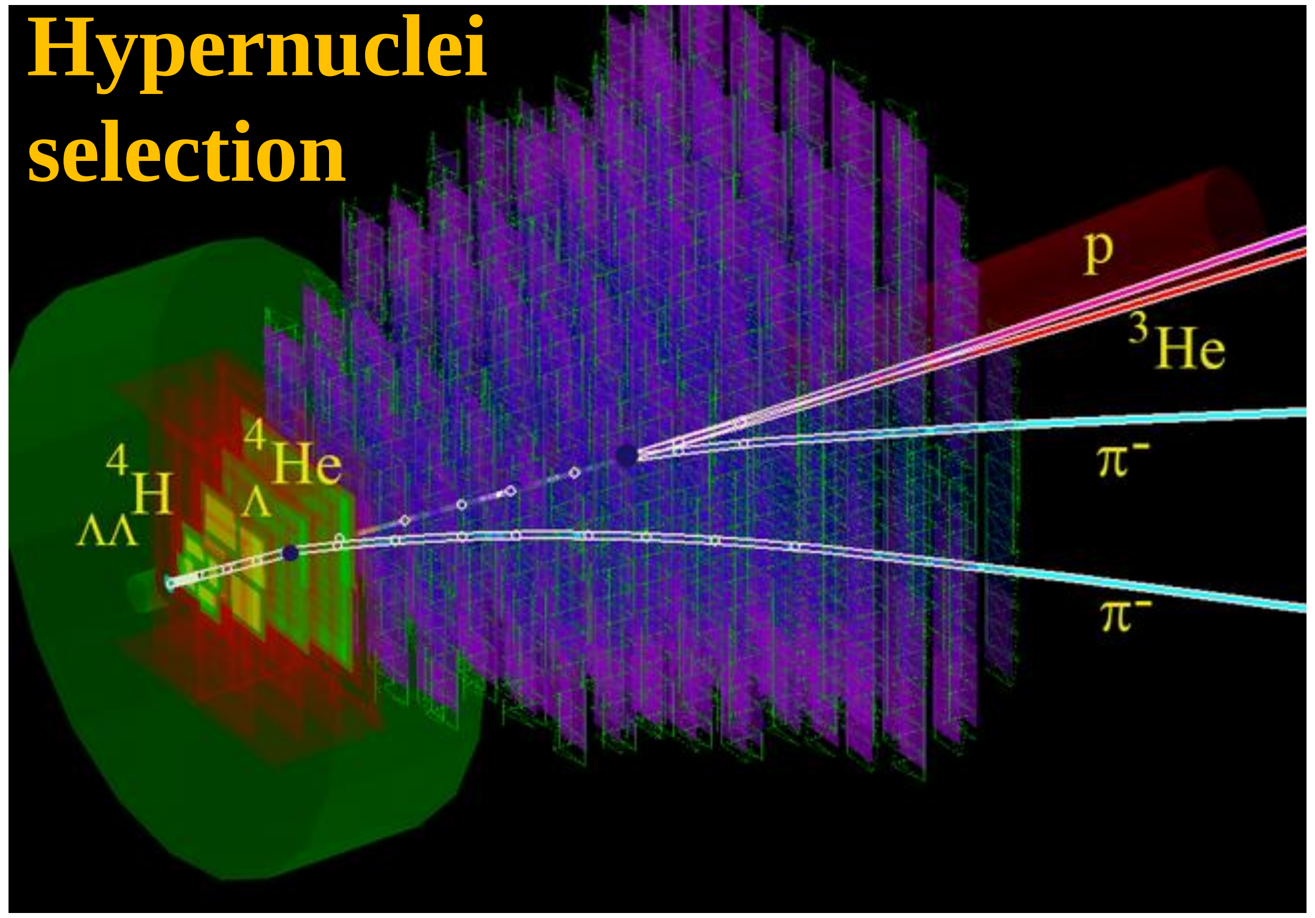




AuAu 10 AGeV/c
165 π
170 p
26 K
15 Λ
20 **K_S^0**
0.3 Ξ-



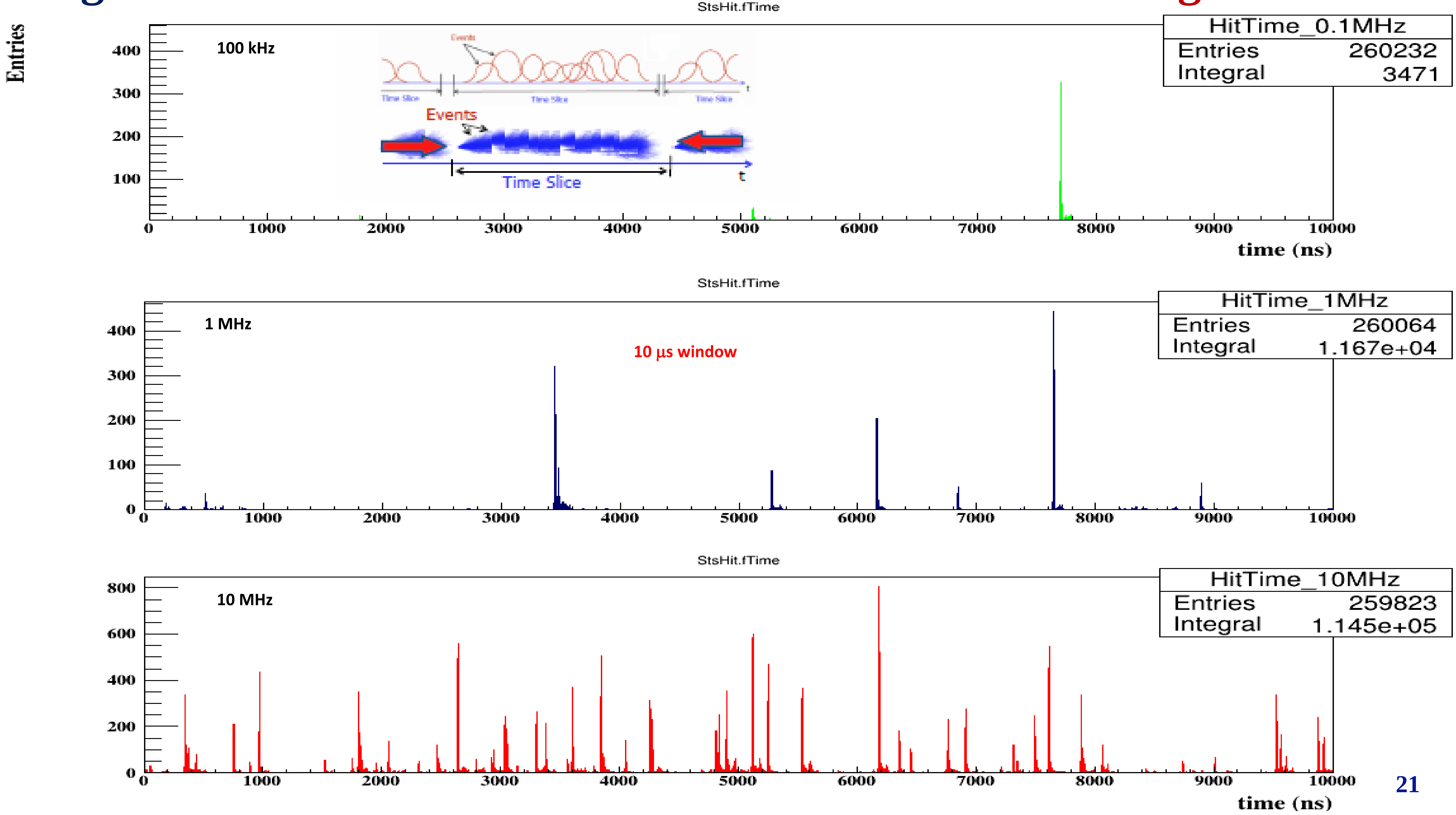
2 models



- For studies several theoretical models like UrQMD and PHSD are used.
- Track finder is based on the Cellular Automaton method.
- High efficiency for track reconstruction of more then **92%**, including fast (more then 90%) and slow (more then 65%) secondary tracks.
- Time-based track finder is developed, efficiency is stable with respect to the interaction rate.
- Low level of split and wrongly reconstructed (ghost) tracks.

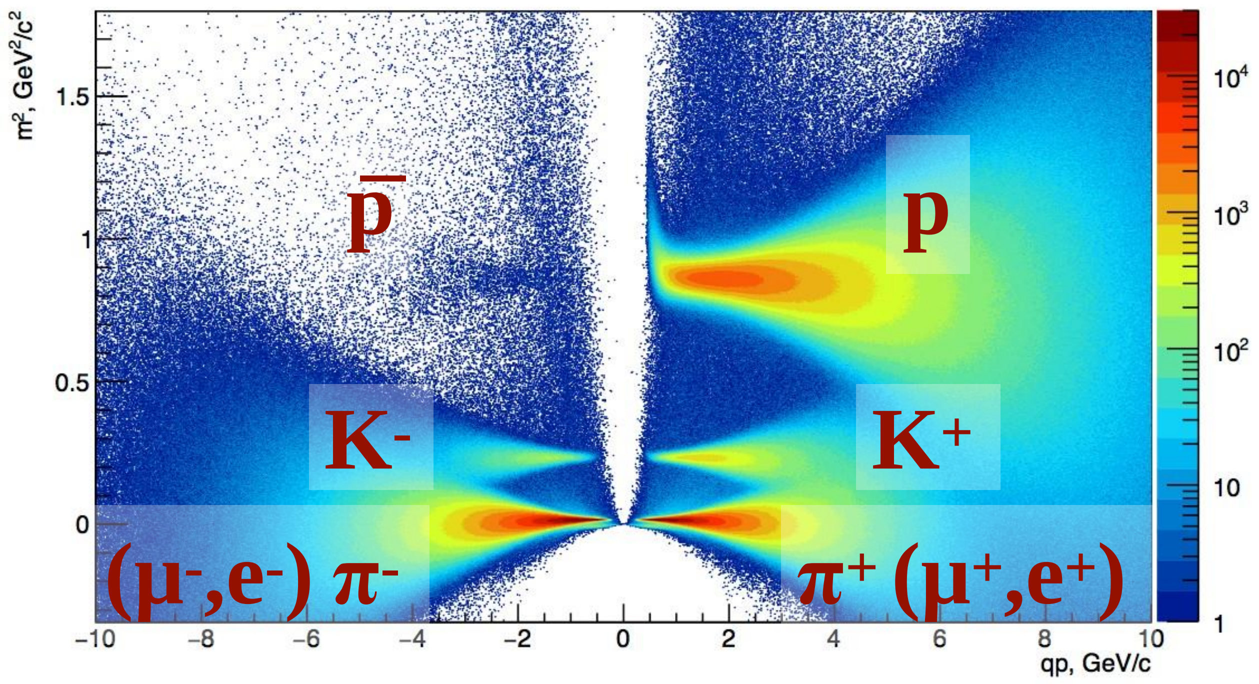
minimum bias : 6ms/core track finder, 1 ms/core particle finder

High rate scenario: event reconstruction with 4D tracking

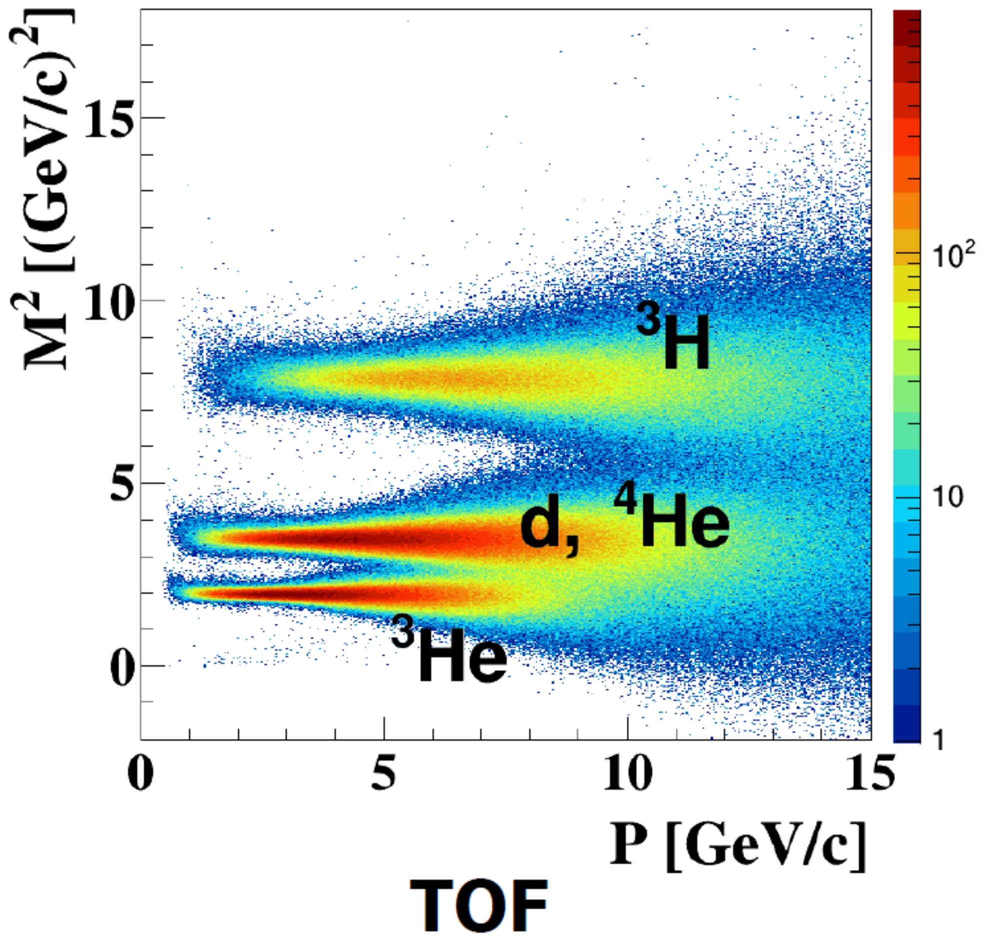


Particle identification with PID detectors

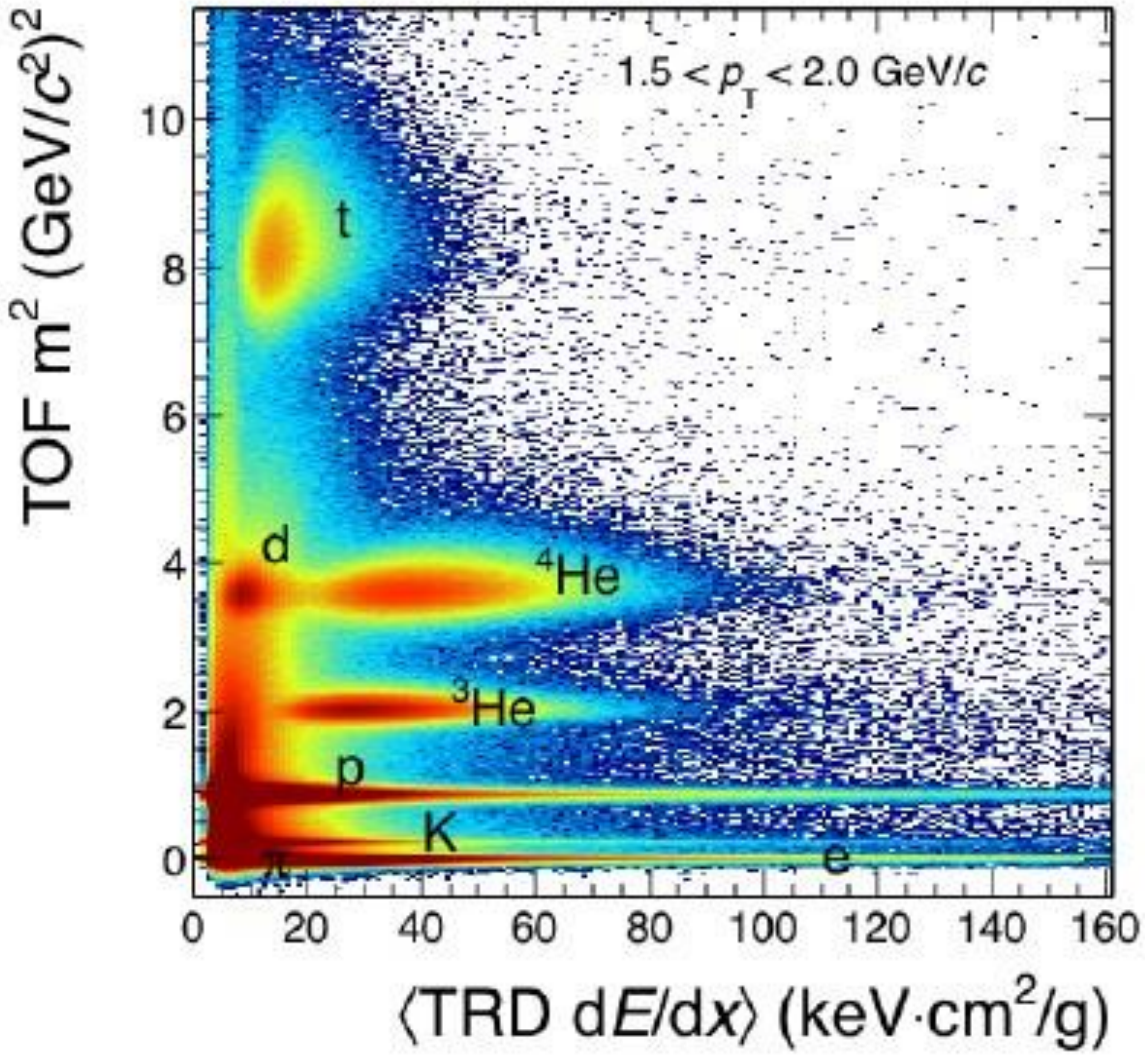
ToF: hadron identification



ToF: fragments identification



TRD: d-He separation



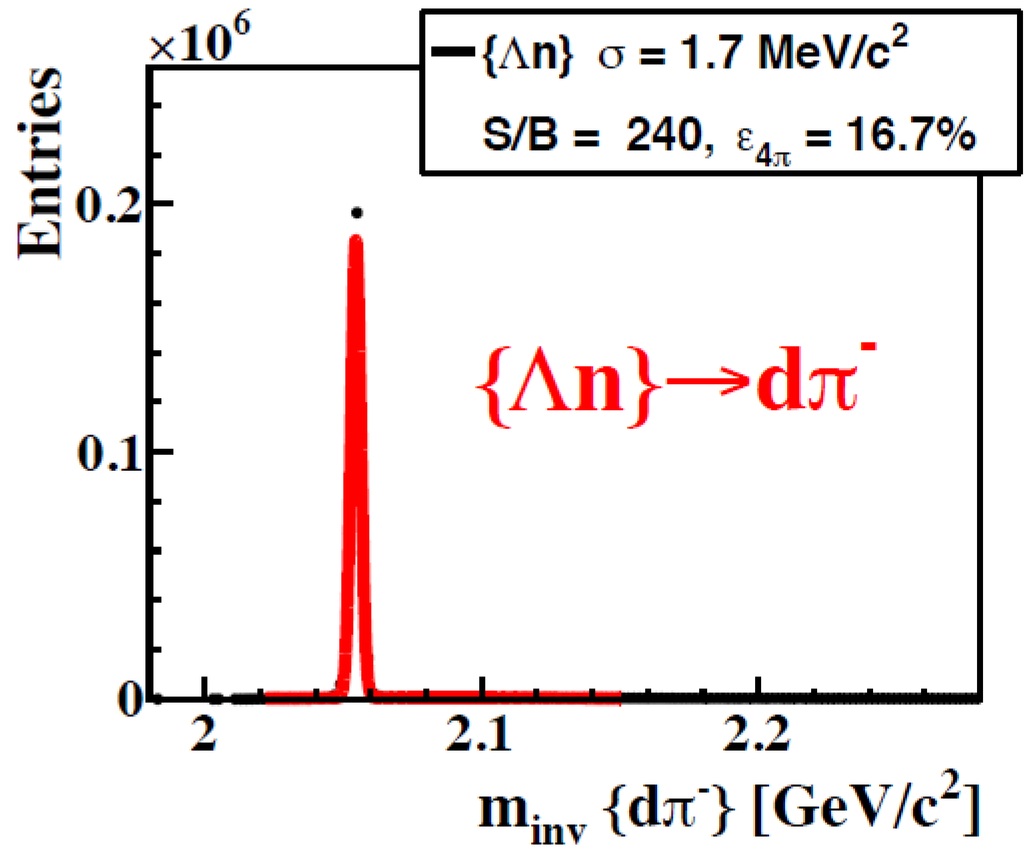
PID detectors:

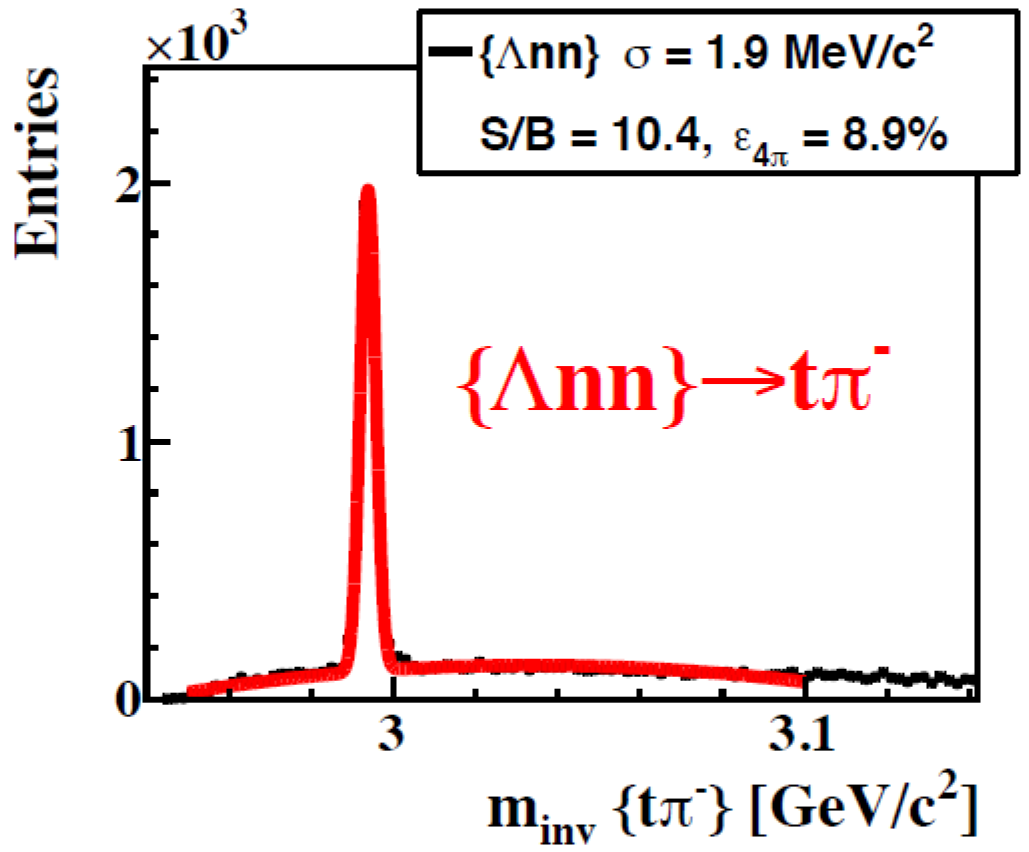
- ToF (Time of Filght) — hadron identification;
- TRD (Transition Radiation detector) — electron and heavy fragments identification.

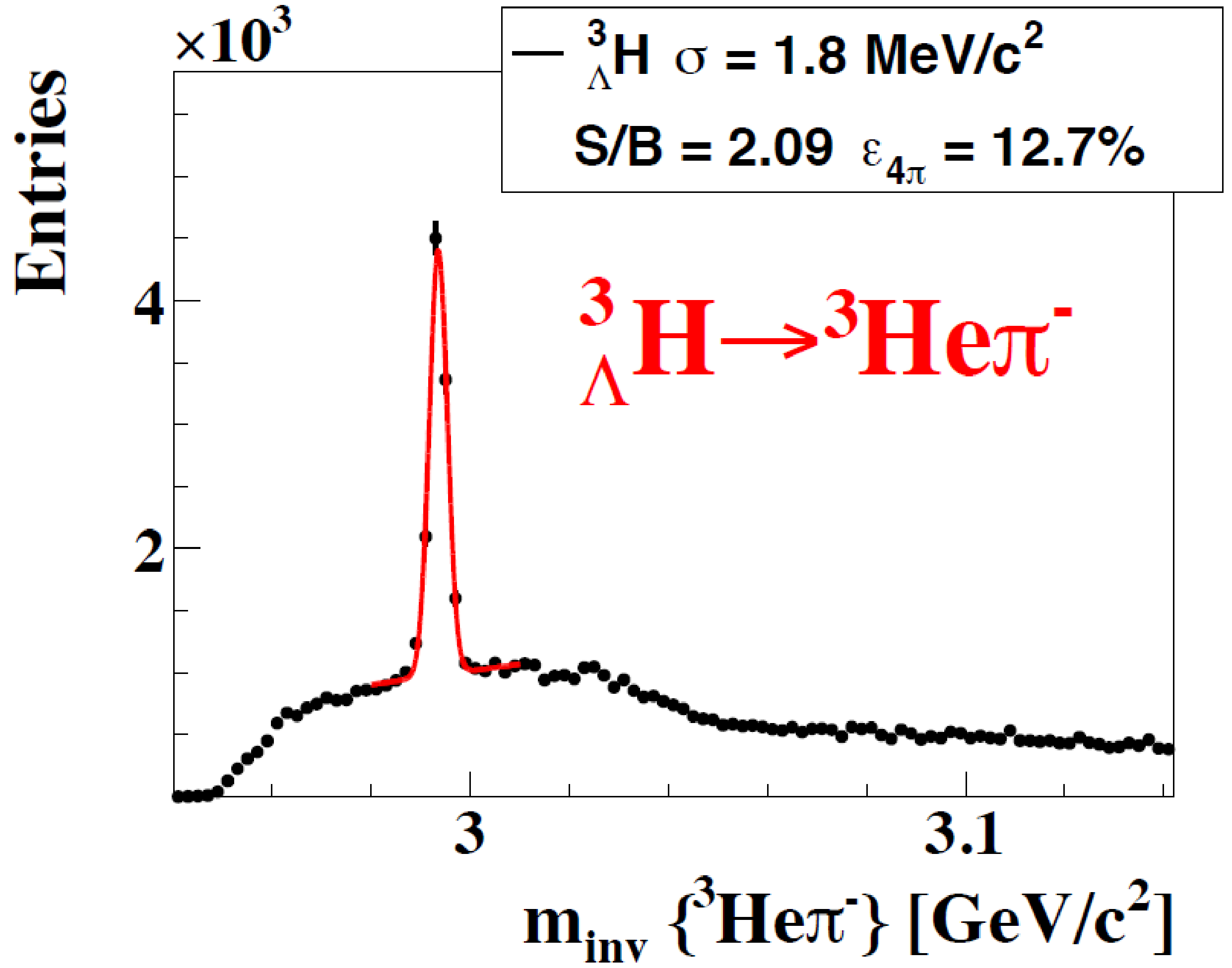
PID detectors of CBM will allow a clear identification of charged tracks.

Single-Λ hypernuclei

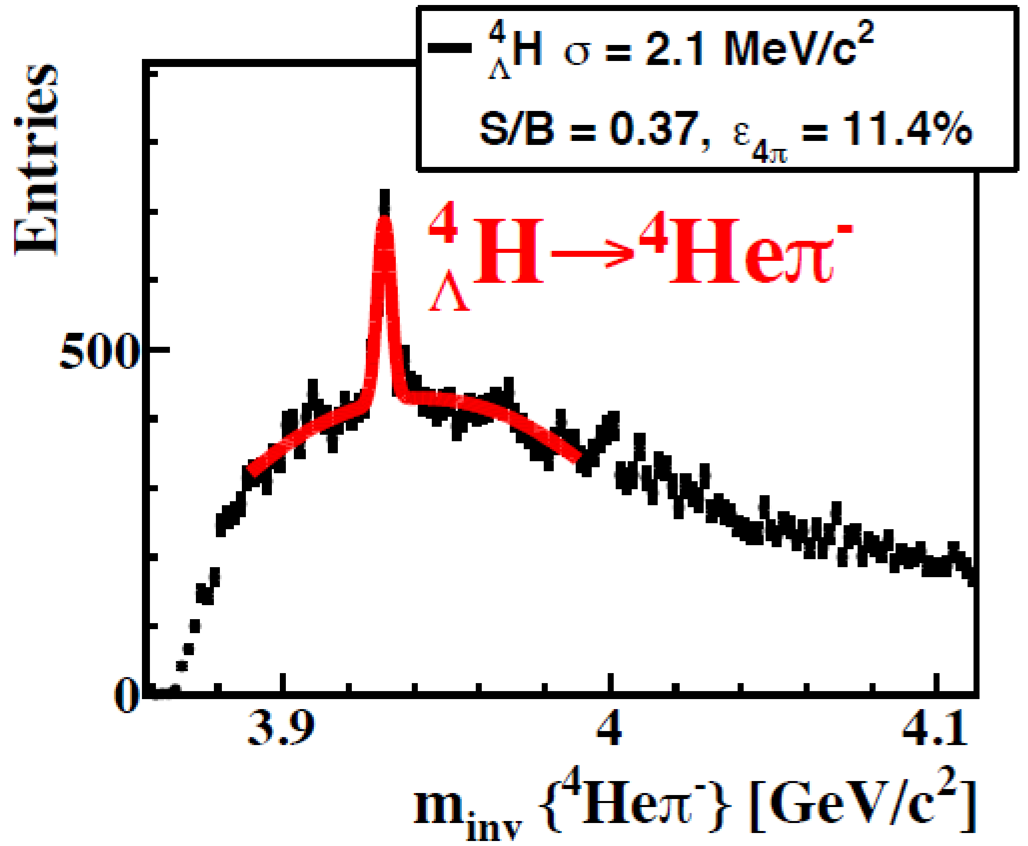
5M mbias events Au+Au at 10AGeV/c
50 sec at 0.1MHz IR (1.8 k/sec)

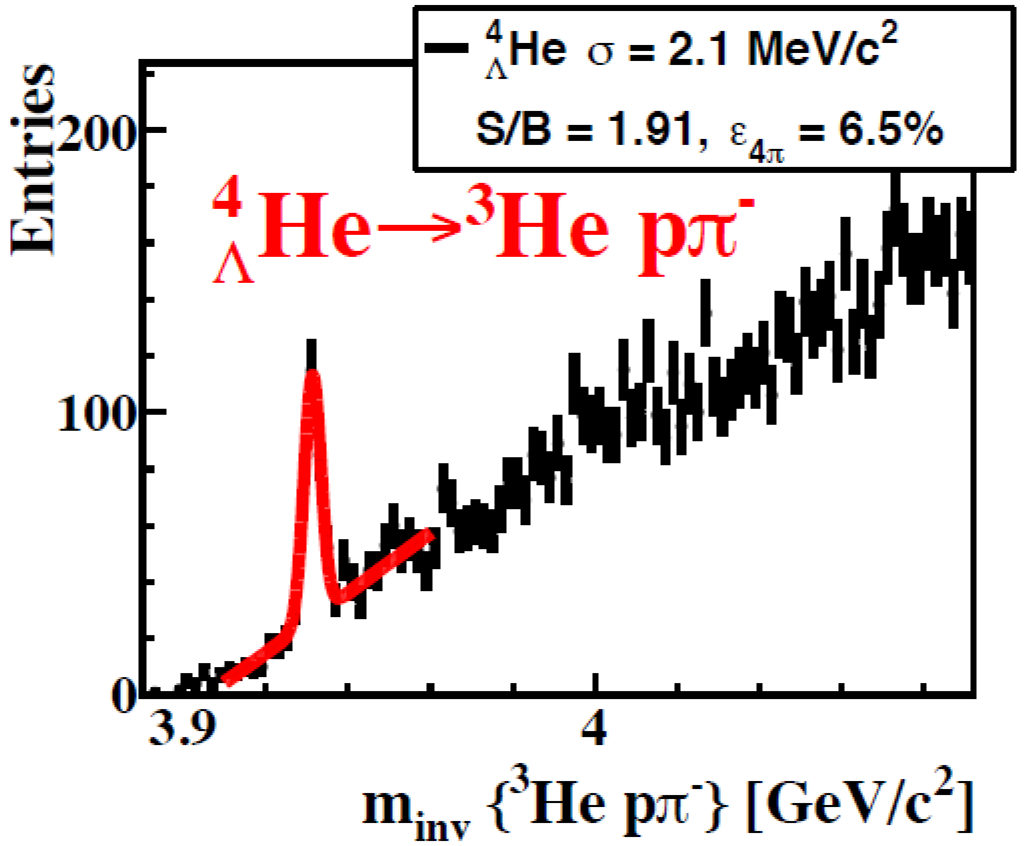






UrQMD





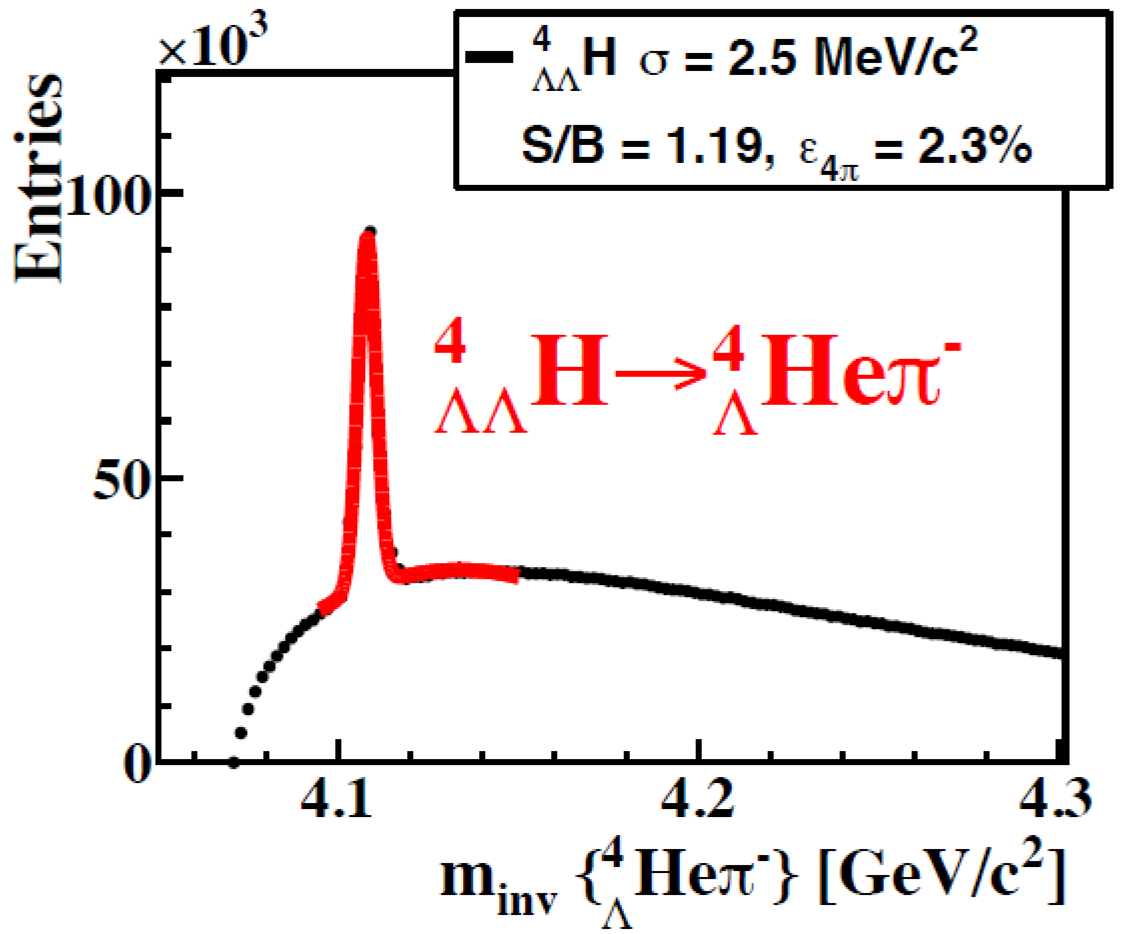
- AuAu, 10 AGeV, 5M central UrQMD events + thermal isotropic signal, TOF PID.
- Background can be further reduced with additional dE/dx PID.
- For $^{4}_{\Lambda}$He background can be reduced selecting only primary hypernuclei.

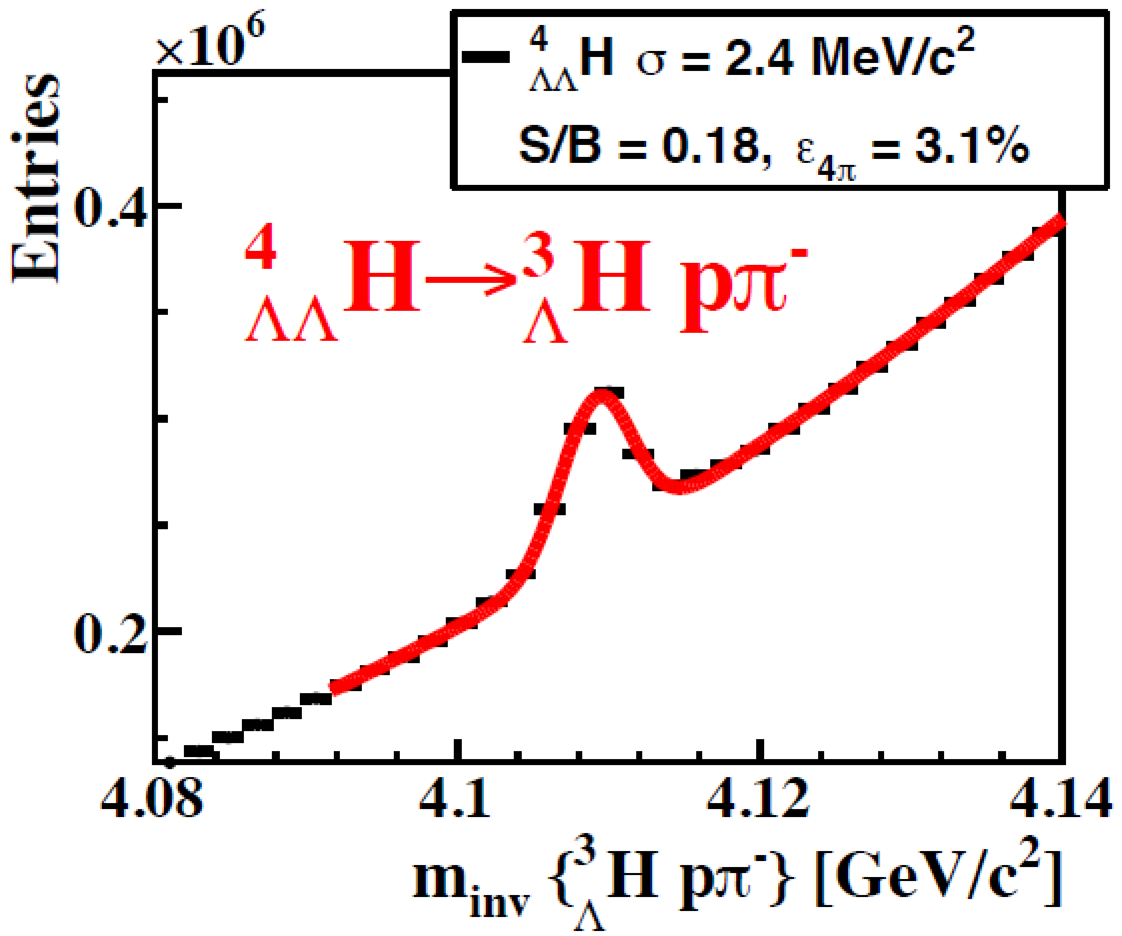
CBM is sensitive to light hypernuclei containing a single Λ within current predictions of their multiplicities

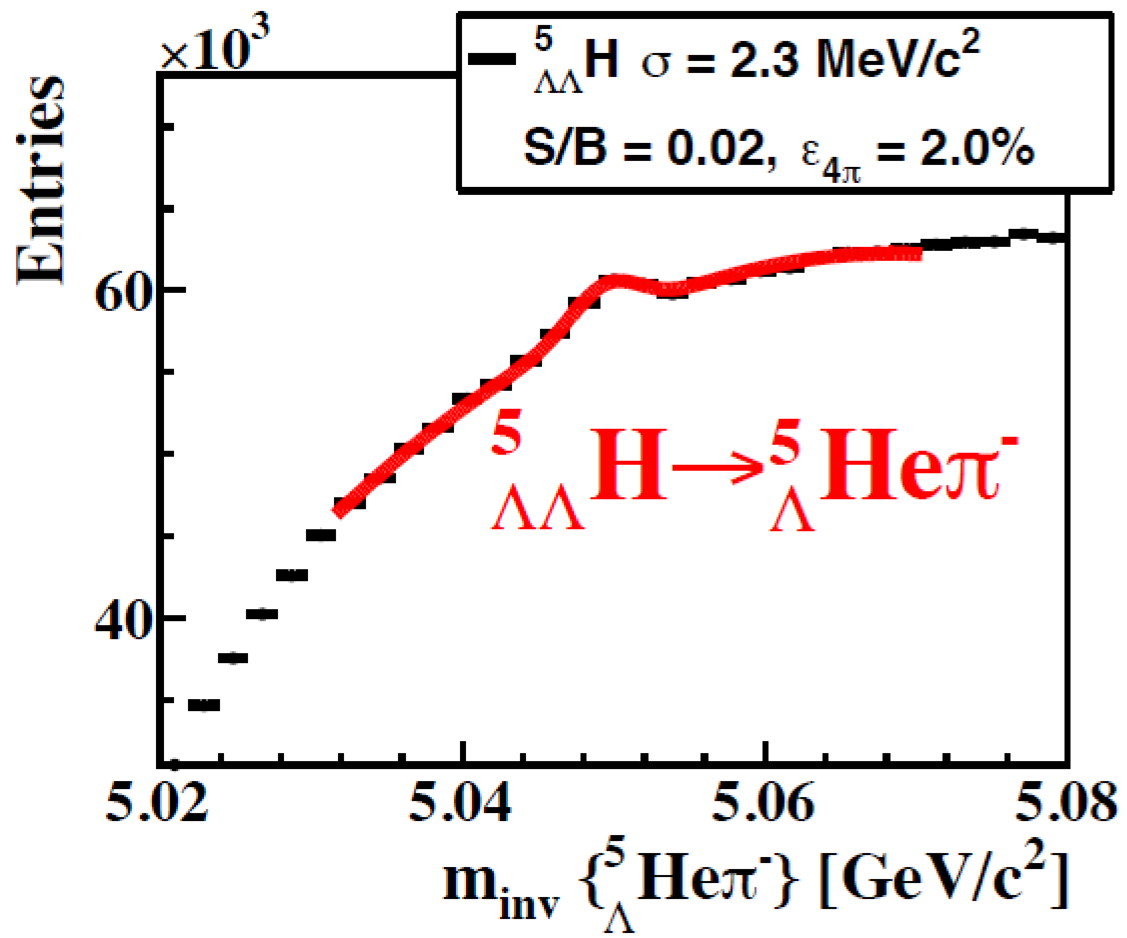
Multiplicities:

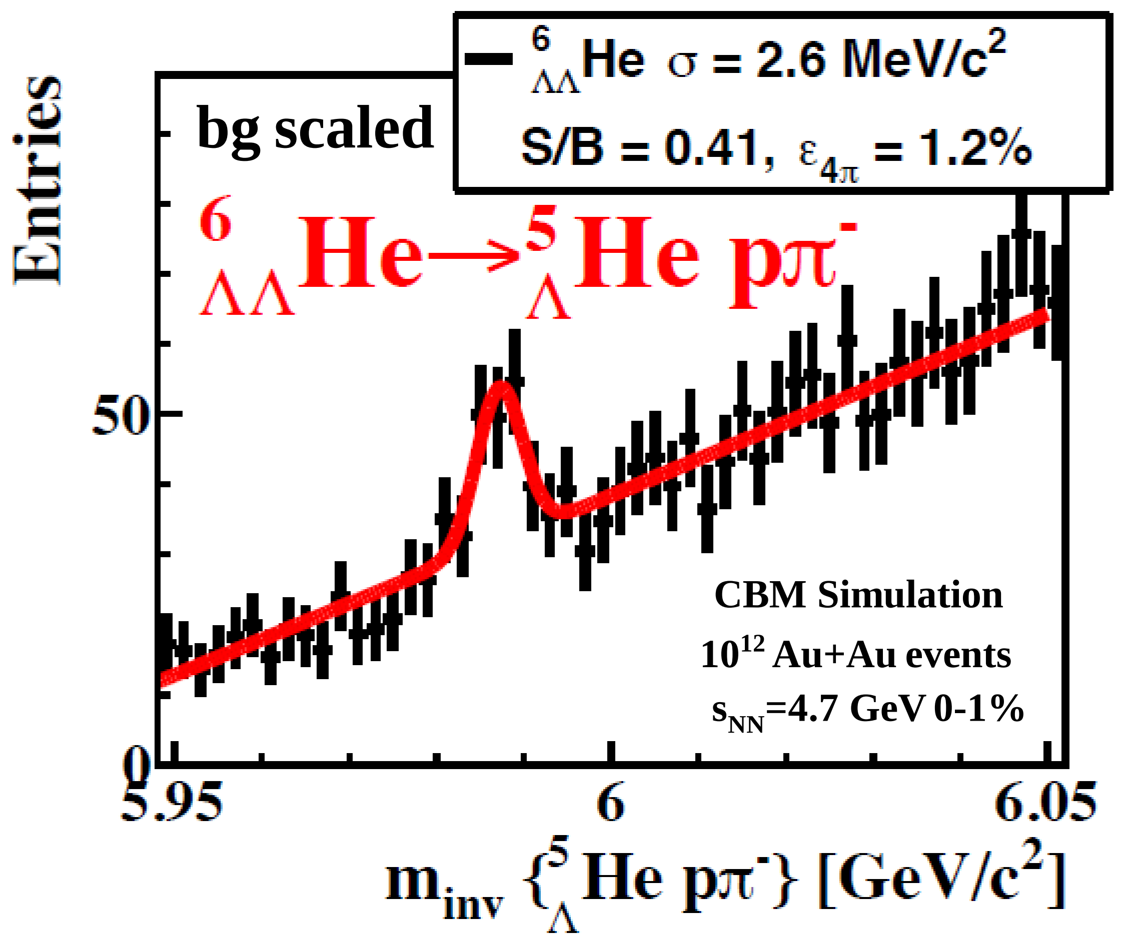
- A.Andronic, et. al, “Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions,” Phys. Lett. B, 697 (2011) 203
- J. Steinheimer et al., “Hypernuclei, dibaryon and antinuclei production in high energy heavy ion collisions: Thermal production versus Coalescence,”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

Double-Λ hypernuclei



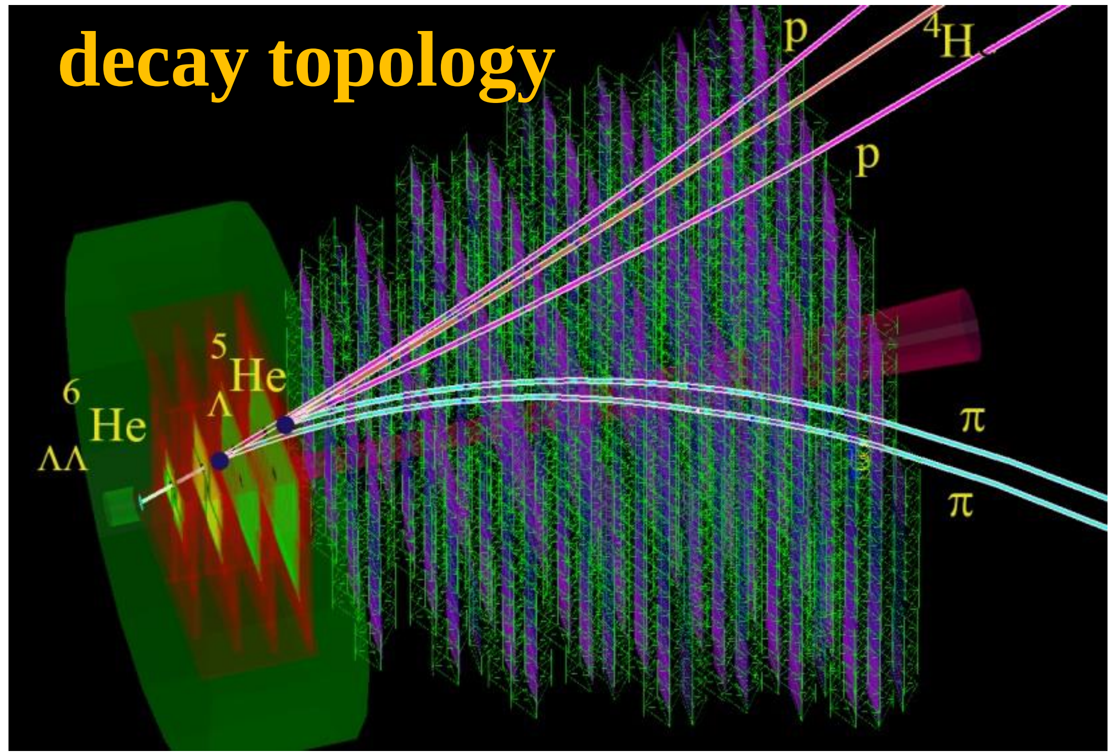






- AuAu, 10 AGeV, 10^{12} central UrQMD events equivalent
- thermal isotropic signal, TOF PID.
- Background can be further reduced with additional dE/dx PID.
- For ${}^{5}_{\Lambda\Lambda}$He background can be reduced selecting only primary hypernuclei.
- According to the current theoretical predictions CBM will be able to perform comprehensive study of hypernuclei, including:
  - precise measurements of lifetime;
  - excitation functions;
- It has a huge potential to register and investigate double Λ hypernuclei.

Expected collection rate: ~60 ${}^{6}_{\Lambda\Lambda}$He in 1 week at **10MHz IR** (not day-1)



Day-1: Expected particle yields
Au+Au @ 6, 10 AGeV

Particle (mass MeV/c^2)	Multiplicity central ev. 6 AGeV	Multiplicity central ev. 10 AGeV	decay mode	BR	ε (%)	yield in 90 days 6AGeV	yield in 90 days 10 AGeV	IR MHz
$\bar{\Lambda}$ (1115)	$5.1\cdot10^{-3}$	0.041	$\bar{p}\pi^+$	0.64	19.7	$1.2\cdot10^{8}$	$1.0\cdot10^{9}$	**0.1**
Ξ^- (1321)	0.11	0.36	$\Lambda\pi^-$	1	9.9	$2.0\cdot10^{9}$	$7.0\cdot10^{9}$	**0.1**
Ξ^+ (1321)	$1.8\cdot10^{-3}$	$1.5\cdot10^{-2}$	$\bar{\Lambda}\pi^+$	1	8.7	$3.0\cdot10^{7}$	$2.5\cdot10^{8}$	**0.1**
Ω^- (1672)	$6.8\cdot10^{-4}$	$4.4\cdot10^{-3}$	ΛK^-	0.68	4.4	$4.0\cdot10^{6}$	$2.6\cdot10^{7}$	**0.1**
Ω^+ (1672)	$1.4\cdot10^{-5}$	$2.6\cdot10^{-3}$	$\bar{\Lambda}K^+$	0.68	3.9	$7.0\cdot10^{4}$ (0 w/o QGP?)	$1.4\cdot10^{7}$	**0.1**
$^{3}_{\Lambda}H$ (2993)	$4.2\cdot10^{-2}$	$3.8\cdot10^{-2}$	$^{3}He\pi^-$	0.25	12.7	$2.7\cdot10^{8}$	$2.5\cdot10^{8}$	**0.1**
$^{4}_{\Lambda}He$ (3930)	$2.4\cdot10^{-3}$	$1.9\cdot10^{-3}$	$^{3}Hep\pi^-$	0.32	11.4	$1.7\cdot10^{7}$	$1.4\cdot10^{7}$	**0.1**
$^{4}_{\Lambda\Lambda}He$(4140)		$1.0\cdot10^{-4}$	$^{3}Hep2\pi$	0.01	2.3		$1.8\cdot10^{4}$	**0.1**
$^{6}_{\Lambda\Lambda}He$(5986)		$1.0\cdot10^{-7}$	$^{4}He2p2\pi$	0.01	1.2			**0.1**

Summary II

- CBM detector is an excellent device to measure not only bulk observables, but strangeness, hypernuclei and other rare probes with high statistic.

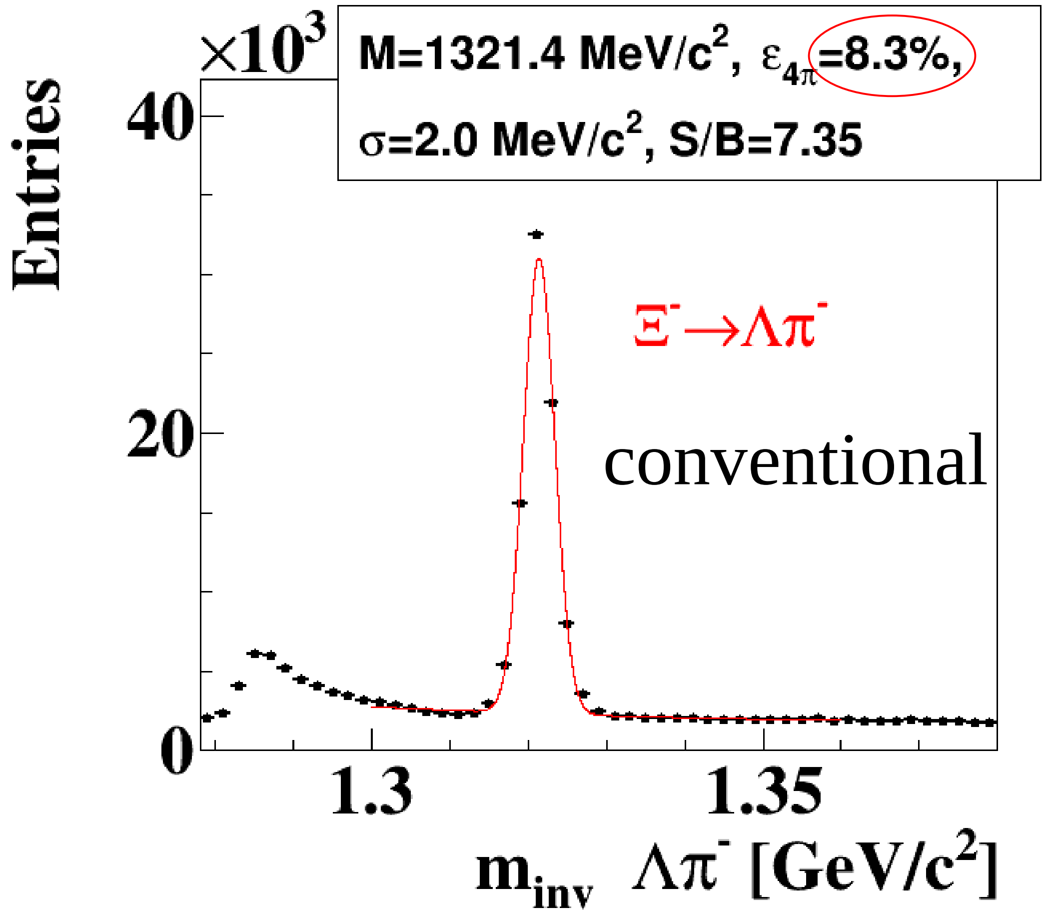
- The discovery of (double-) Λ hypernuclei and the determination of their lifetimes will provide information on the hyperon-nucleon and hyperon-hyperon interactions, which are essential ingredients for the understanding of the nuclear matter EoS at high densities, and, hence, of the structure of neutron stars.

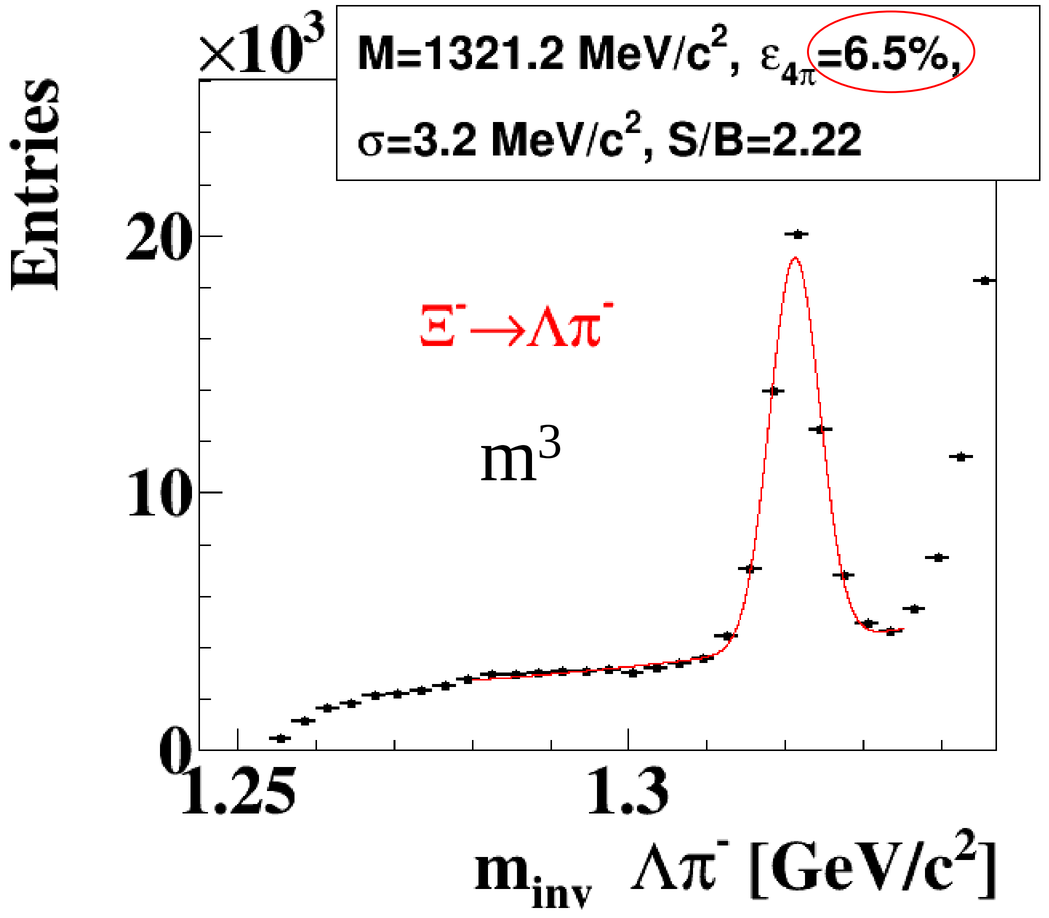
- Approbation with the real data (BES-II) allow to develop tools, which are complicate/impossible to develop with simulations.

Backup

Multi strange hyperons reconstruction with missing mass method

5M central AuAu collisions 10AGeV/c





- Comparable efficiencies, better control over the systematic errors
- Σ^+ and Σ^- physics: completes the picture of strangeness production

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

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

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