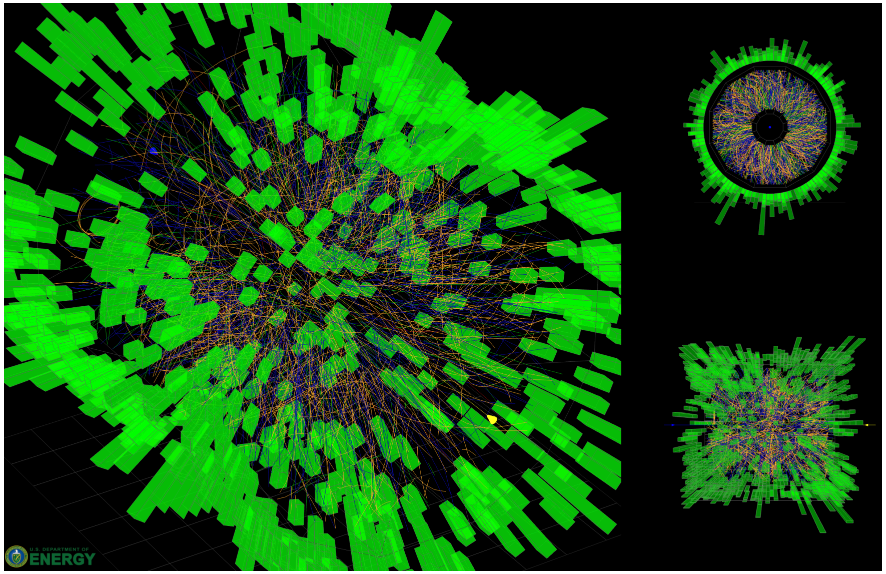
Pavel Kisel

KF Particle Finder: Reconstruction of Short-Lived Particles in STAR (BNL) and CBM (FAIR) Experiments

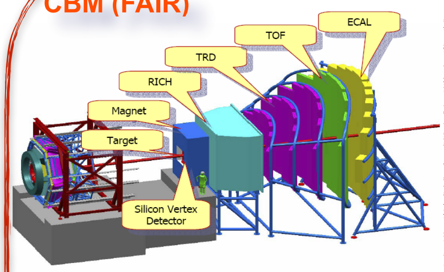


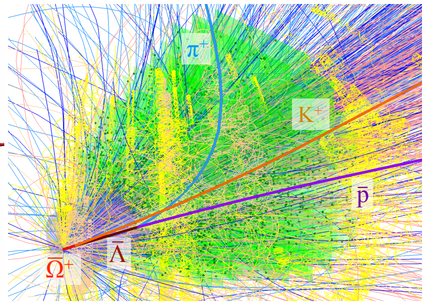
Brookhaven, NY   ePIC Group Meeting   16 July 2024

CBM → STAR: Beam Energy Scan (BES) program

Within the FAIR Phase-0 program the CBM KF Particle Finder has been adapted to STAR and applied to Au+Au collisions recorded during 2014, 2016 and BES-I.

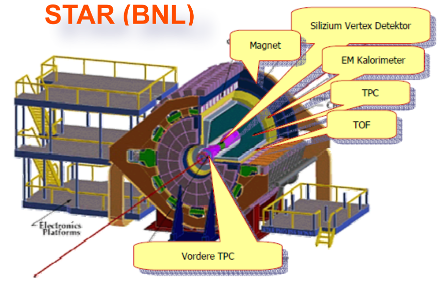
CBM (FAIR)

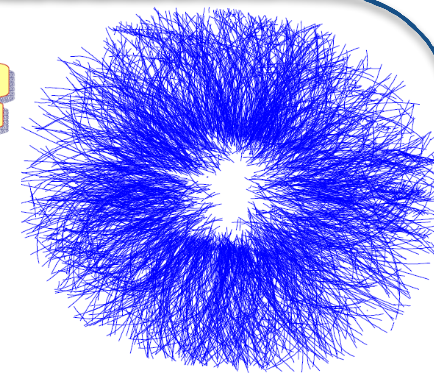




$\bar{\Omega}^+ \to \bar{\Lambda}\, K^+$
$\quad \hookrightarrow \bar{p}\, \pi^+$

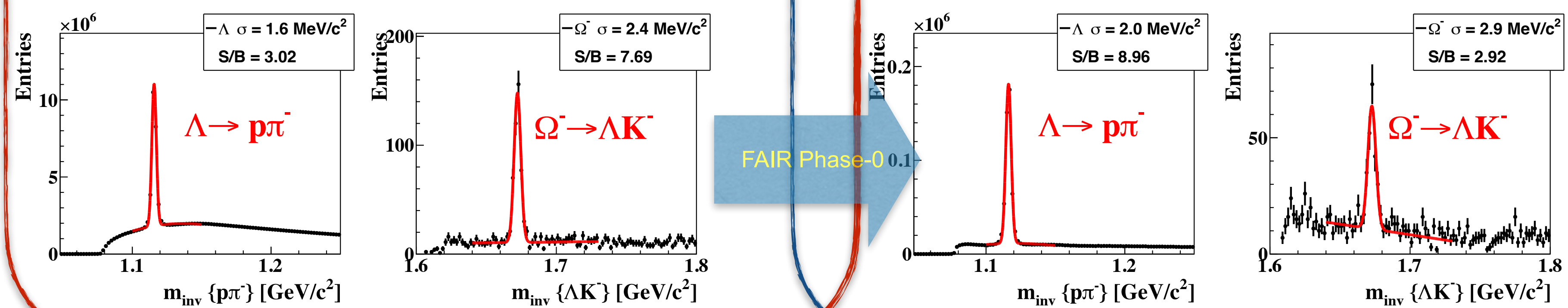
STAR (BNL)





CBM, 5M central Au+Au, 10 AGeV, PHSD

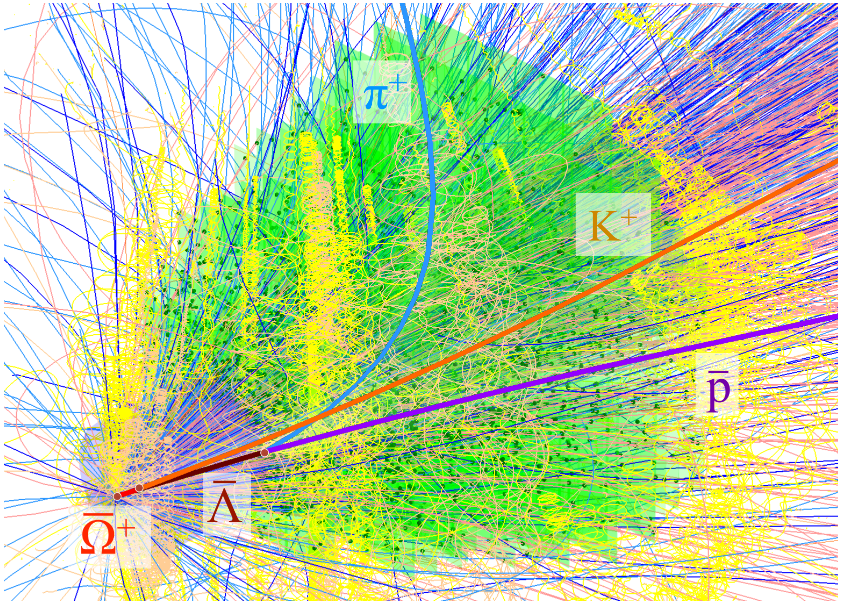
STAR, 1.3M mbias Au+Au, 200 AGeV, Run 2016



- Cellular Automaton (CA) Track Finder is the default STAR track finder for data production. Use of CA provides 25% more D^0 and 20% more W by reprocessing of 2013 pp510 data sample.
- The KF Particle Finder provides a factor 2 more signal particles than the standard approach in STAR. The integration of the KF Particle Finder into the official STAR repository for use in physics analysis is currently in progress.

Used for the real-time express physics analysis during the BES-II runs (2018-2021)

KF Particle Library



Simulated AuAu collision at 25 GeV/n, PHSD+GEANT3

$\bar{\Omega}^+ \longleftarrow \bar{\Lambda}\ K^+$

$\quad\quad\quad\ \ \lfloor \bar{p}\ \pi^+$

State vector of particle parameters:

$$\mathbf{r} = [x, y, z, p_x, p_y, p_z, E, 1/p]$$

Covariance matrix of their errors:

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

The **KF Particle** library is an essential part of the **FLES** package for efficient physics analysis in **CBM**, but is also used in **ALICE** and **STAR**.

Extended concept:

- Kalman Filter (KF) based mathematics
- mother and daughter particles have the same form of the state vector and the covariance matrix
- works in 3D space, therefore geometry independent
- vectorized to use SIMD of modern computer architectures

Rich in functionality:

- construction of short-lived particles
- transport of a particle state vector to any point
- calculation of an angle between particles
- constraints on mass, production point and decay length
- and many other important features used in physics analysis

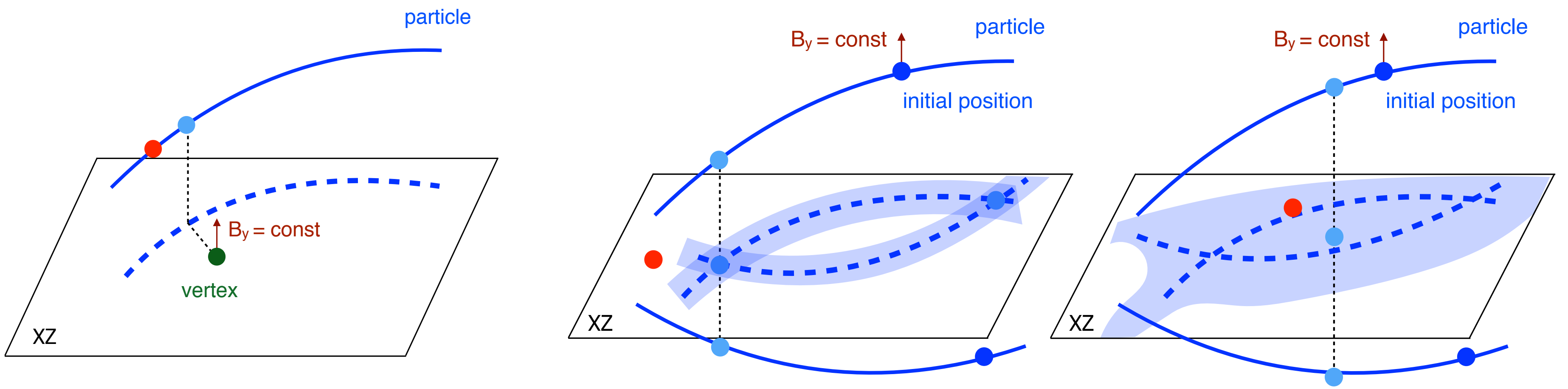
The KF Particle library is the software foundation for comprehensive reconstruction and analysis of collisions in online and offline modes

Assumptions:

- distance between the point of closest approach and particle is short;
- constant one-component field B_y — works well for short distances.

Point of closest approach between a particle and a vertex:

Point of closest approach between two particles:



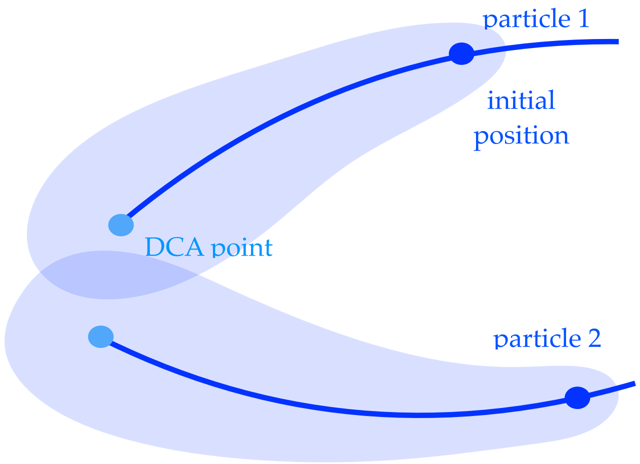
- find points in 2D (solved analytically) and select the closest approximation taking into account errors and distance in 3D;
- transport particles to that point;
- assuming a small distance between the 2D and 3D point, find point in 3D using a Taylor expansion.

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

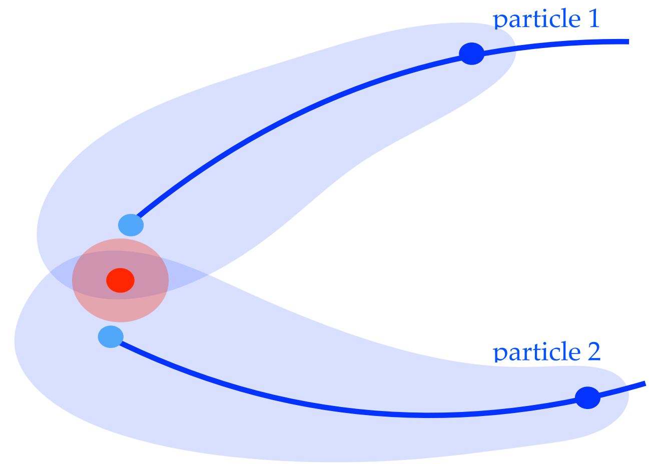
Point of closest approach calculation is used as an initialization for the Kalman filter

Point of Closest Approach Calculation

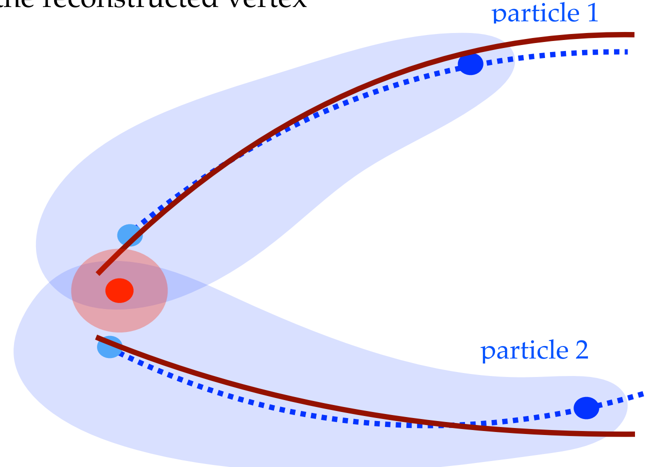
1) Find the point of the closest approach and transport particles there



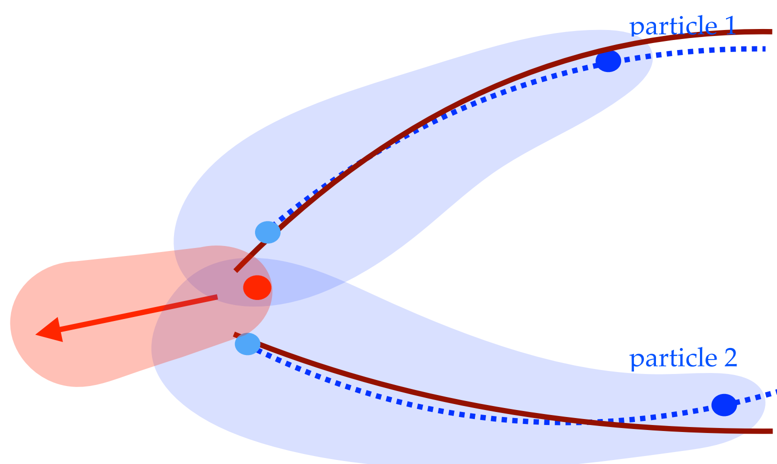
2) Fit the vertex by the Kalman filter method



3) Improve momenta of daughters with respect to the reconstructed vertex



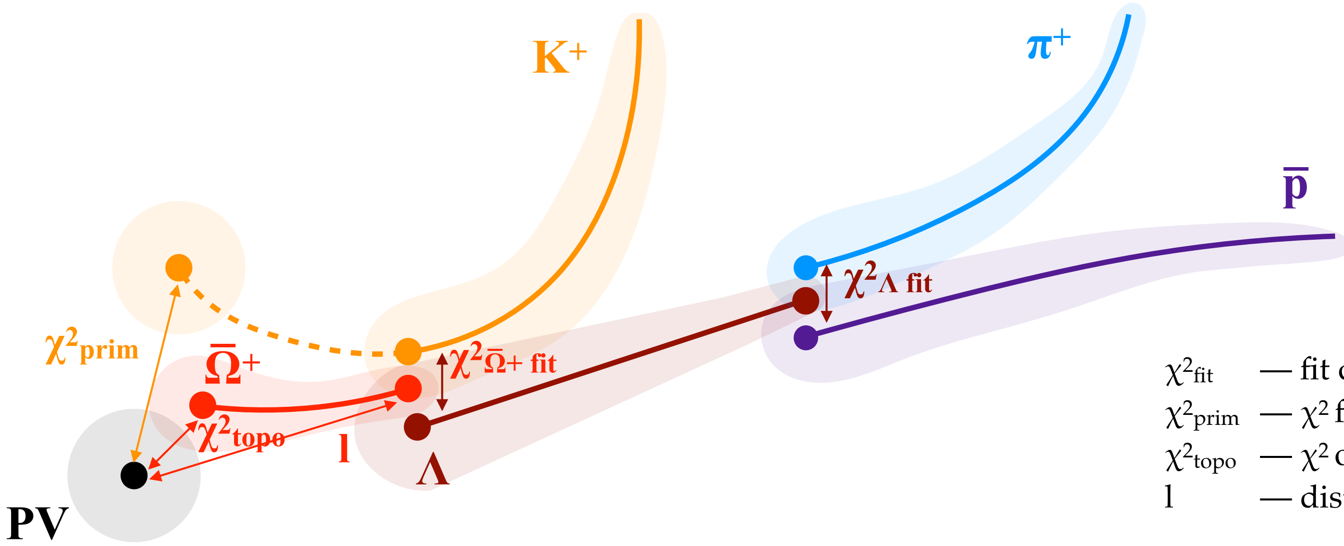
4) Add the corrected momenta



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

Point of closest approach calculation is used as an initialization for the Kalman filter

Selection of short-lived particle candidates



χ^2_{fit}	— fit quality
χ^2_{prim}	— χ^2 from primary vertex (PV)
χ^2_{topo}	— χ^2 of a particle fitted to PV
l	— distance to PV

* Simplified scheme of the complex topology reconstruction (shown at the example of $\bar{\Omega}^+$):

  select secondary tracks that are far from the primary vertex (χ^2_{prim});

  add them, construct a Λ candidate of two of two of them, check that these two tracks are close to each other (χ^2_{fit}), otherwise reject the candidate;

  check, that the Λ candidate is secondary, i.e. far from the primary vertex (χ^2_{topo});

  check that the obtained mass is the mass of Λ within the errors;

  add the Λ candidate with the K^+ track check that they are close to each other (χ^2_{fit});

  check that the decay point of the constructed $\bar{\Omega}^+$ candidate is far from the primary vertex (l) and that the candidate originates from the primary vertex.

* In case of the resonance reconstruction tracks are checked to be primary and added together. Additional checks on p_t, number of hits in the tracks, PID criteria, etc. can be applied

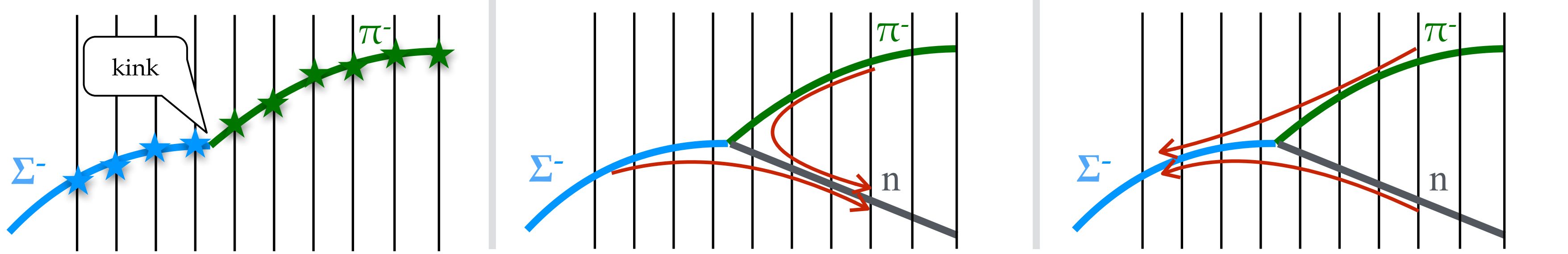
KF Particle Finder is able to reconstruct even the most complicated decay chains

Introduction to the Missing Mass Method

Consider the Missing Mass Method using the decay $\Sigma^- \to n\pi^-$.

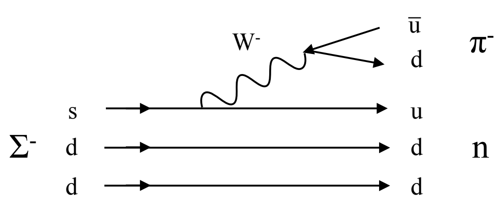
The Missing Mass Method is based on the laws of conservation of energy and momentum:

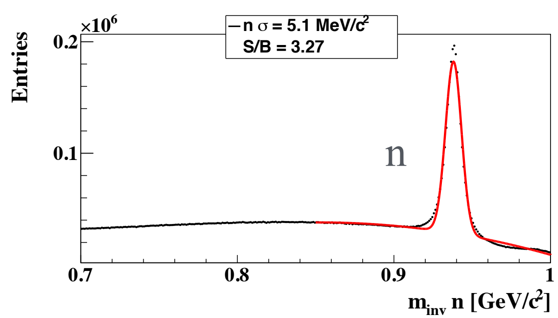
$$E_\Sigma = E_\pi + E_n \qquad \vec{p}_\Sigma = \vec{p}_\pi + \vec{p}_n$$

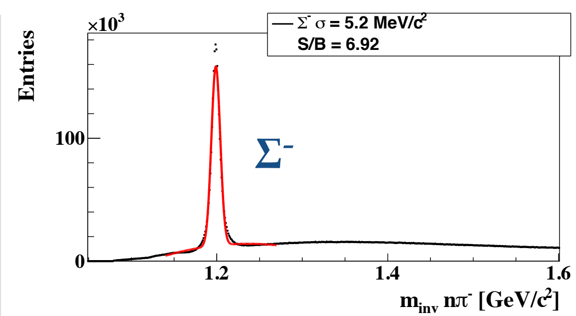


The implementation of the method for $\Sigma^- \to n\pi^-$ (BR = 99.8%) decay has three steps:

1. Find the tracks of Σ^- and its charged daughter particle π^- in the tracking system.
2. Reconstruct the parameters of the neutral daughter particle **n** using the parameters of the mother particle and the charged daughter.
3. Reconstruct the mother particle Σ^- from the charged π^- and obtained neutral **n** daughter particles.



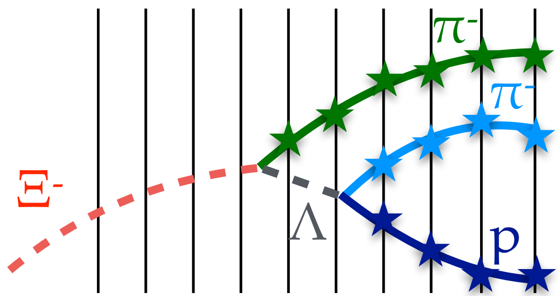




The Missing Mass Method significantly extends the possibilities of studying strange particles in the CBM experiment

Standard Approach vs Missing Mass Method

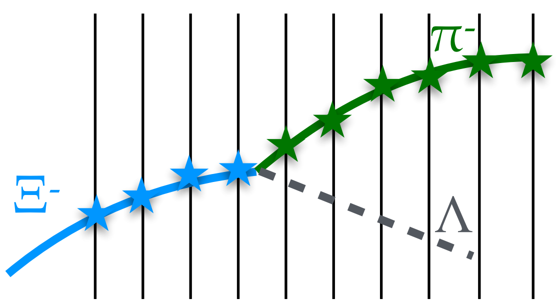
Standard Approach in KF Particle



1. Find in the tracking system the tracks of the charged daughter particle π^- from Ξ^- and both charged daughter particles π^- and $\mathbf{p}$ from the neutral particle Λ.
2. Reconstruct the neutral daughter particle Λ from its charged daughter particles π^- and $\mathbf{p}$.
3. Reconstruct the mother particle Ξ^- from the charged π^- and obtained neutral Λ daughter particles.

In **36%** of cases $\Lambda \to n\pi^0$, such that Ξ^- decays cannot be reconstructed by the standard approach

Missing Mass Method in KF Particle



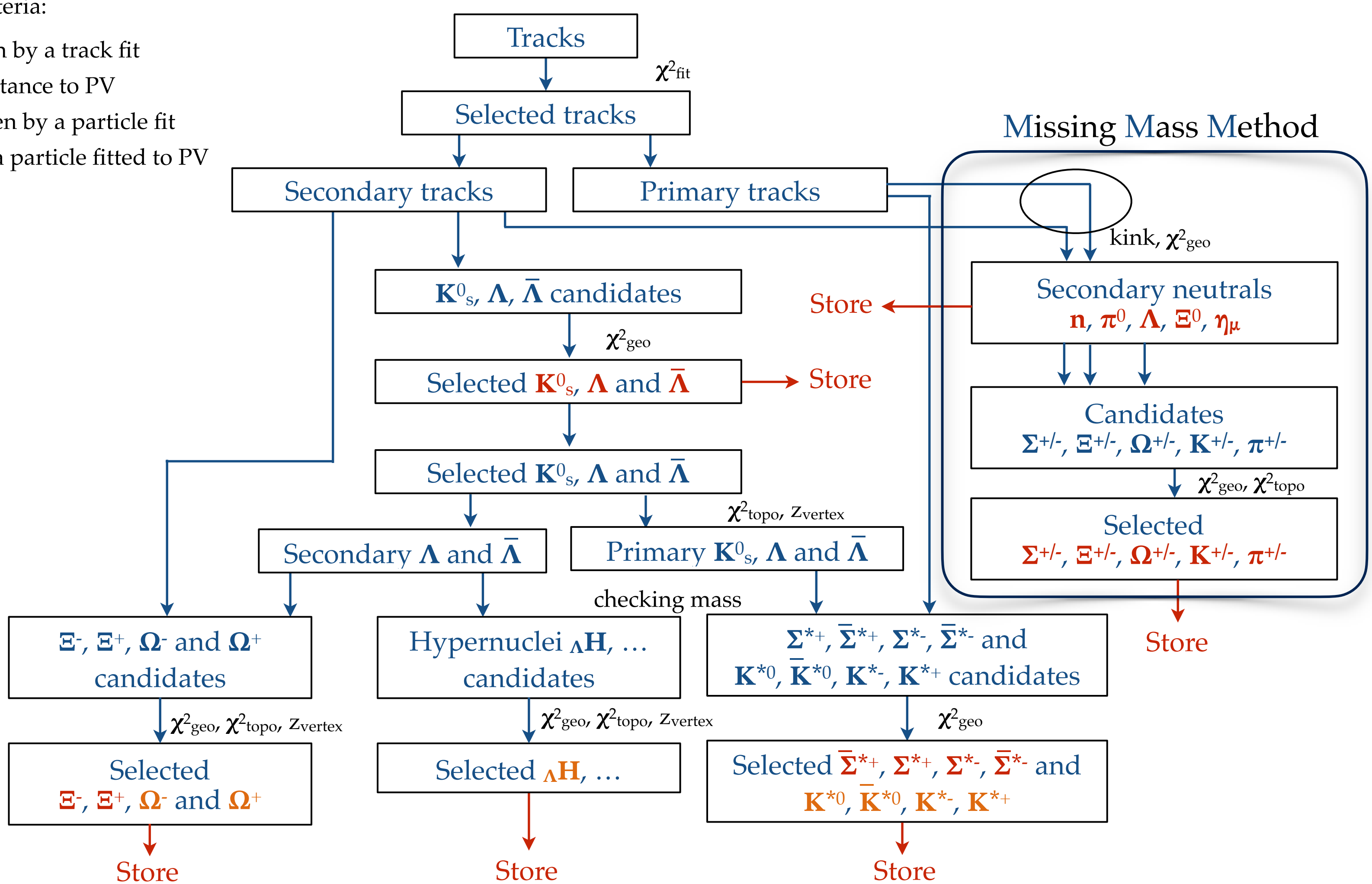
1. Find in the tracking system the tracks of Ξ^- and its charged daughter particle π^-.
2. Reconstruct the parameters of the neutral daughter particle Λ using the parameters of the mother particle Ξ^- and the charged daughter π^-.
3. Reconstruct the mother particle Ξ^- from the charged π^- and the obtained neutral daughter particle Λ.

The Missing Mass Method not only provides a significant addition to the picture of created strange particles, but also allows to investigate systematic errors, using both methods independently of each other

A Simplified Block Diagram of the KF Particle Finder

Selection criteria:

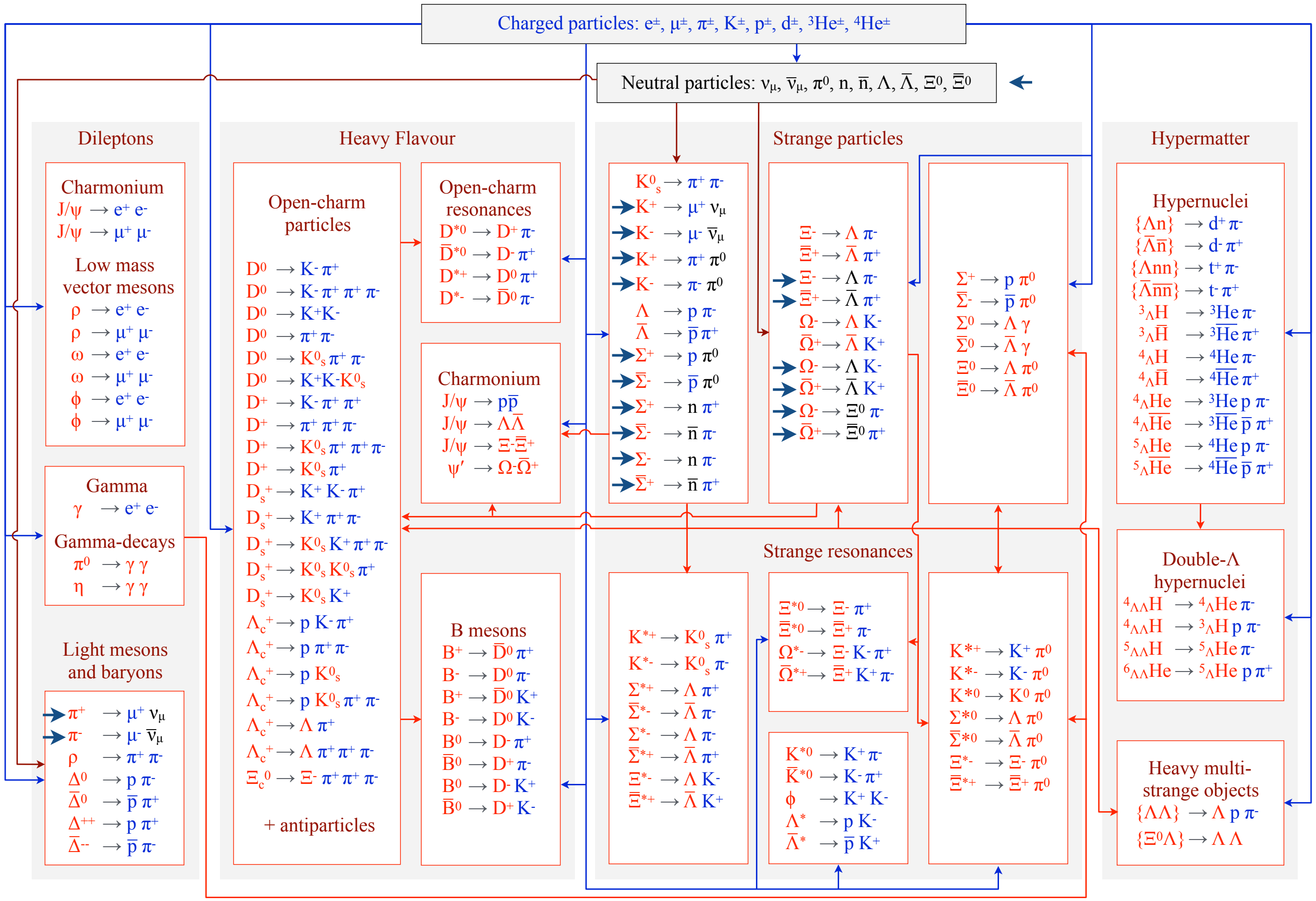
χ^2_{fit} - χ^2 given by a track fit
χ^2_{prim} - χ^2 distance to PV
χ^2_{geo} - χ^2 given by a particle fit
χ^2_{topo} - χ^2 of a particle fitted to PV



- The KF Particle Finder package is a complex set of procedures for combinatorial choice of primary and secondary particles, calculation of parameters, selection of mother particles, and search for decay chains.
- Sorting of data is actively used to create parallel data streams at each stage in order to achieve efficient use of SIMD.

The Missing Mass Method is implemented as a part of the KF Particle Finder package

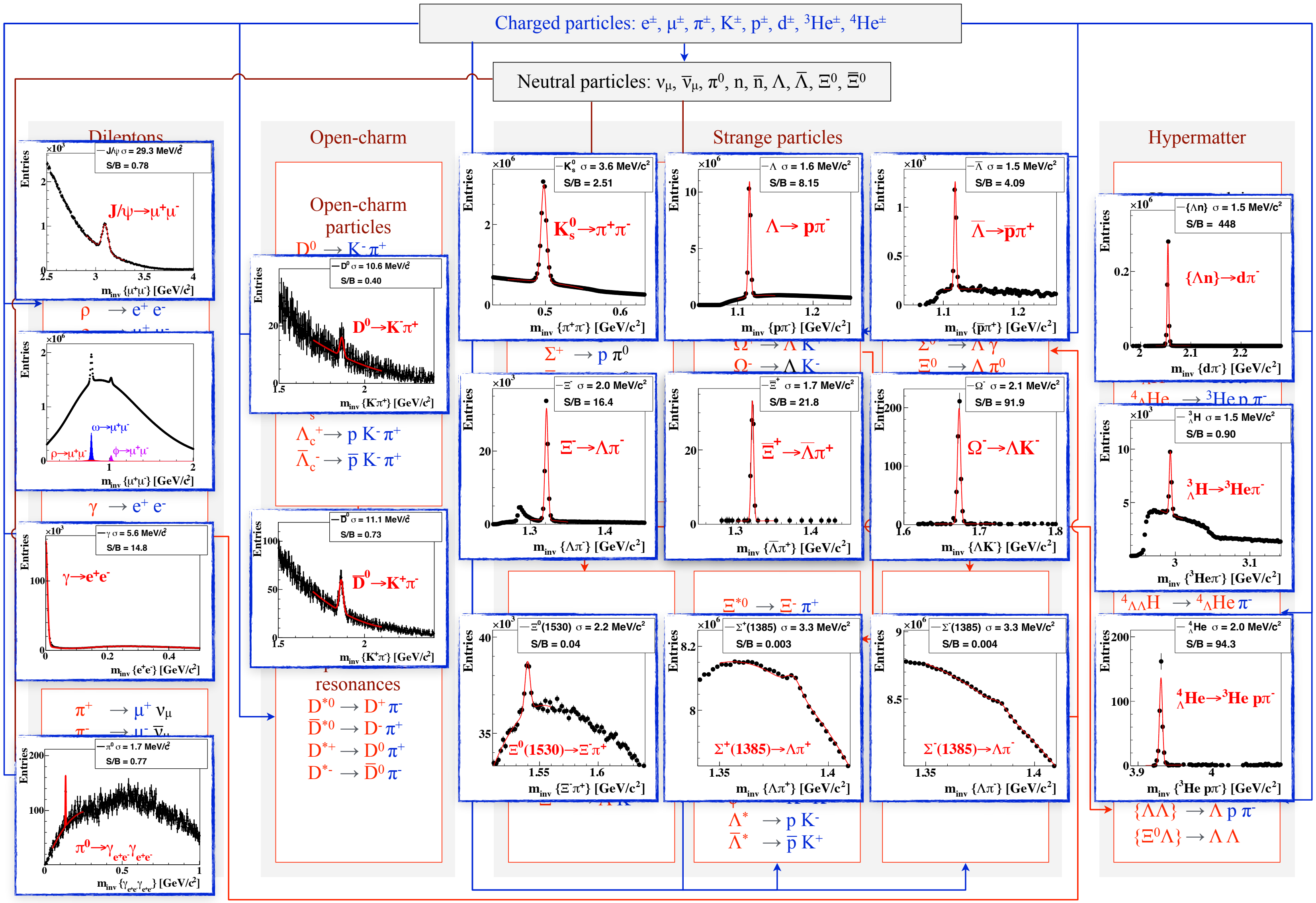
KF Particle Finder



- The task of the KF Particle Finder package is to search in real time for all short-lived particles of interest for the CBM experiment.
- All procedures of the package are vectorized and parallelized, and its running time is on average 1.4 ms/event/core.
- Currently the package contains procedures for searching up to 200 decays of short-lived particles of different types.
- Based on the Missing Mass Method, the procedures for searching 9 neutral particles, 2 decays of light mesons, and 16 decays of strange particles have been created.

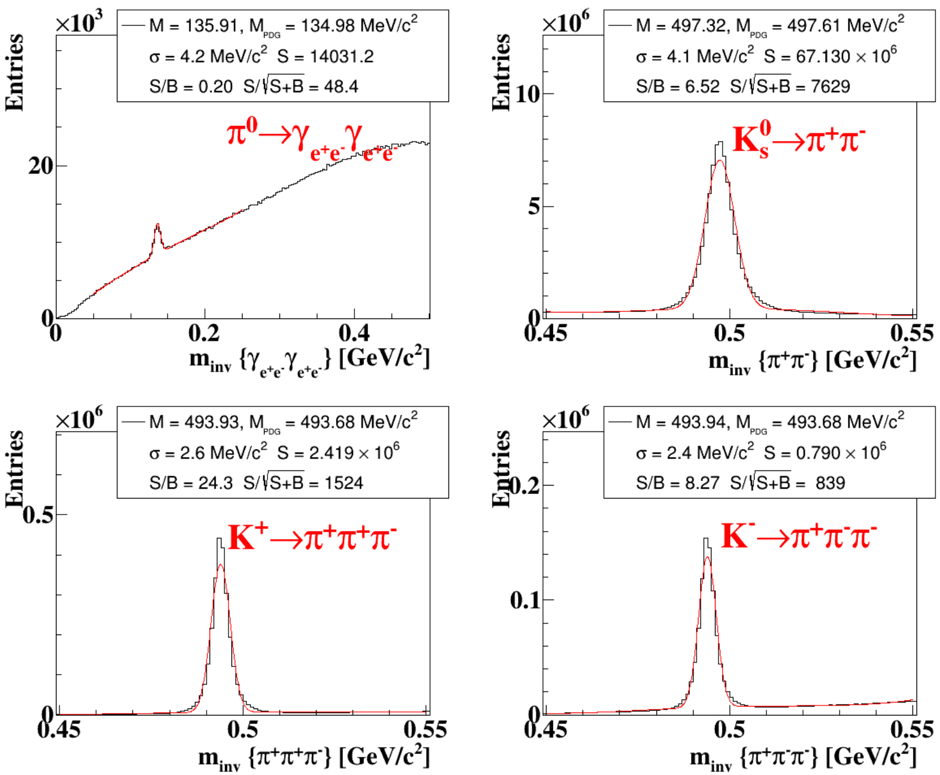
The search for up to 200 decay channels is implemented in the KF Particle Finder

Physics Coverage

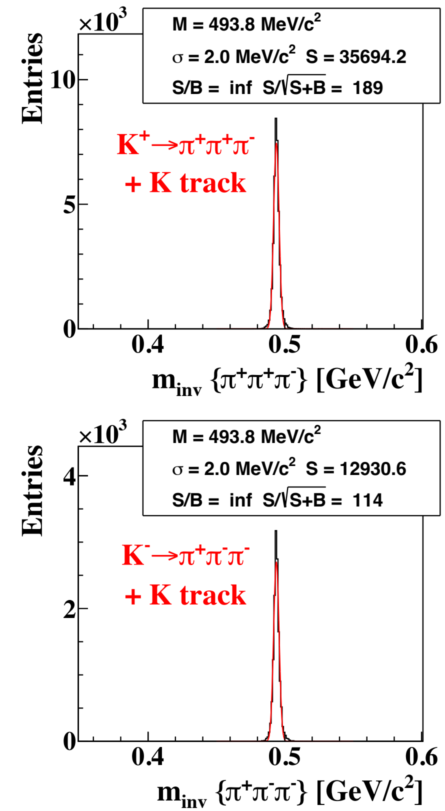


All main CBM and STAR decays are currently covered and checked

Signal utilizing 140M AuAu xEvents at 7.7 GeV,
2021 BES-II (x)production



Signal utilizing 32.5M AuAu events at 7.7 GeV,
2021 BES-II (x)production

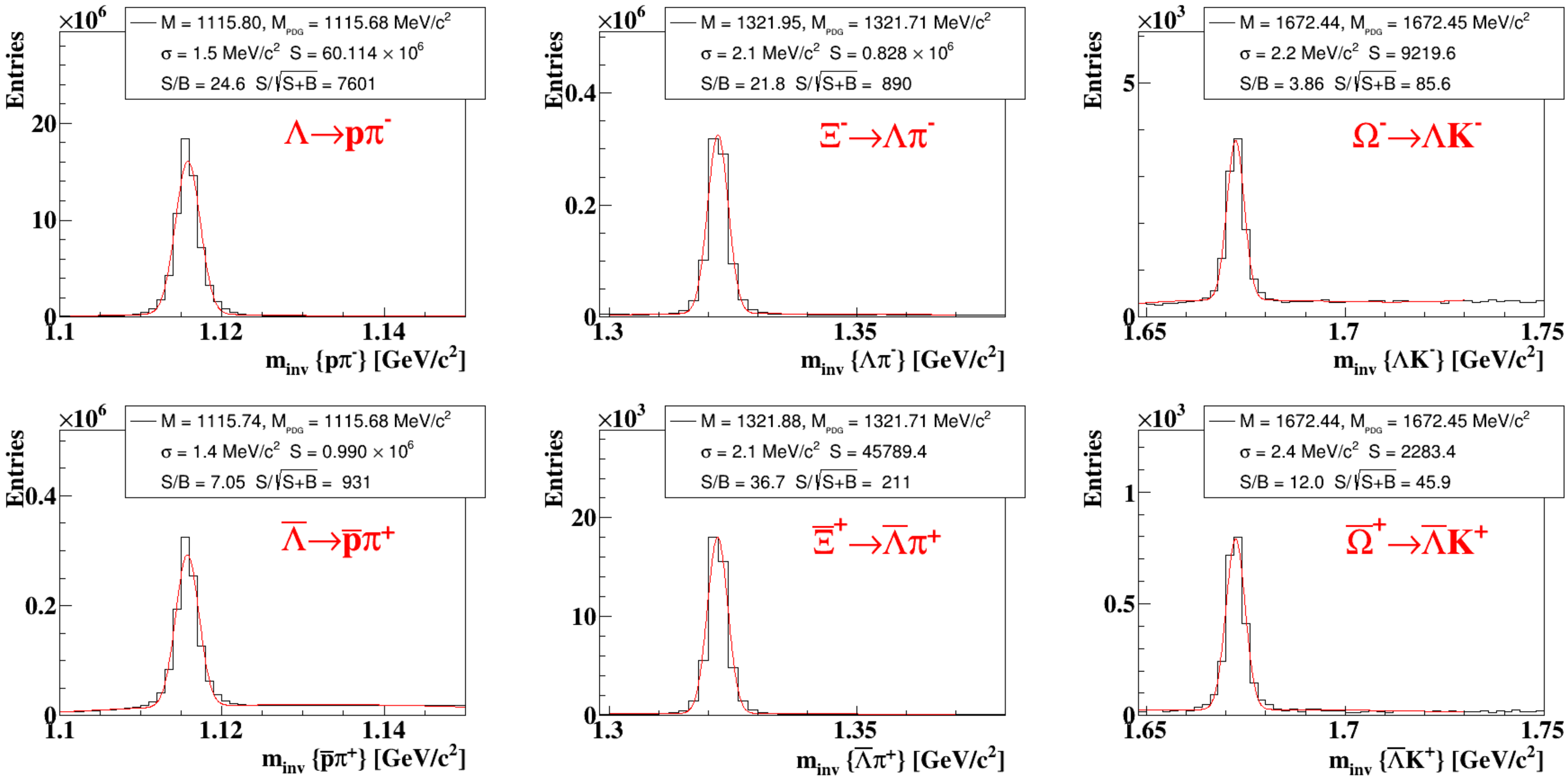


- Online (x)calibration and (x)reconstruction provide us with high quality data, thus allowing to observe even π^0 with 50 σ significance.
- Strange mesons are seen with a high significance and S/B ratio.
- STAR with its TPC allows background-free identification of charged kaons by full topological reconstruction with all 4 tracks.

Mesons are used as probes for the full reconstruction chain

xBES-II: Hyperons

Signal utilizing 140M AuAu events at 7.7 GeV, 2021 BES-II (x)production

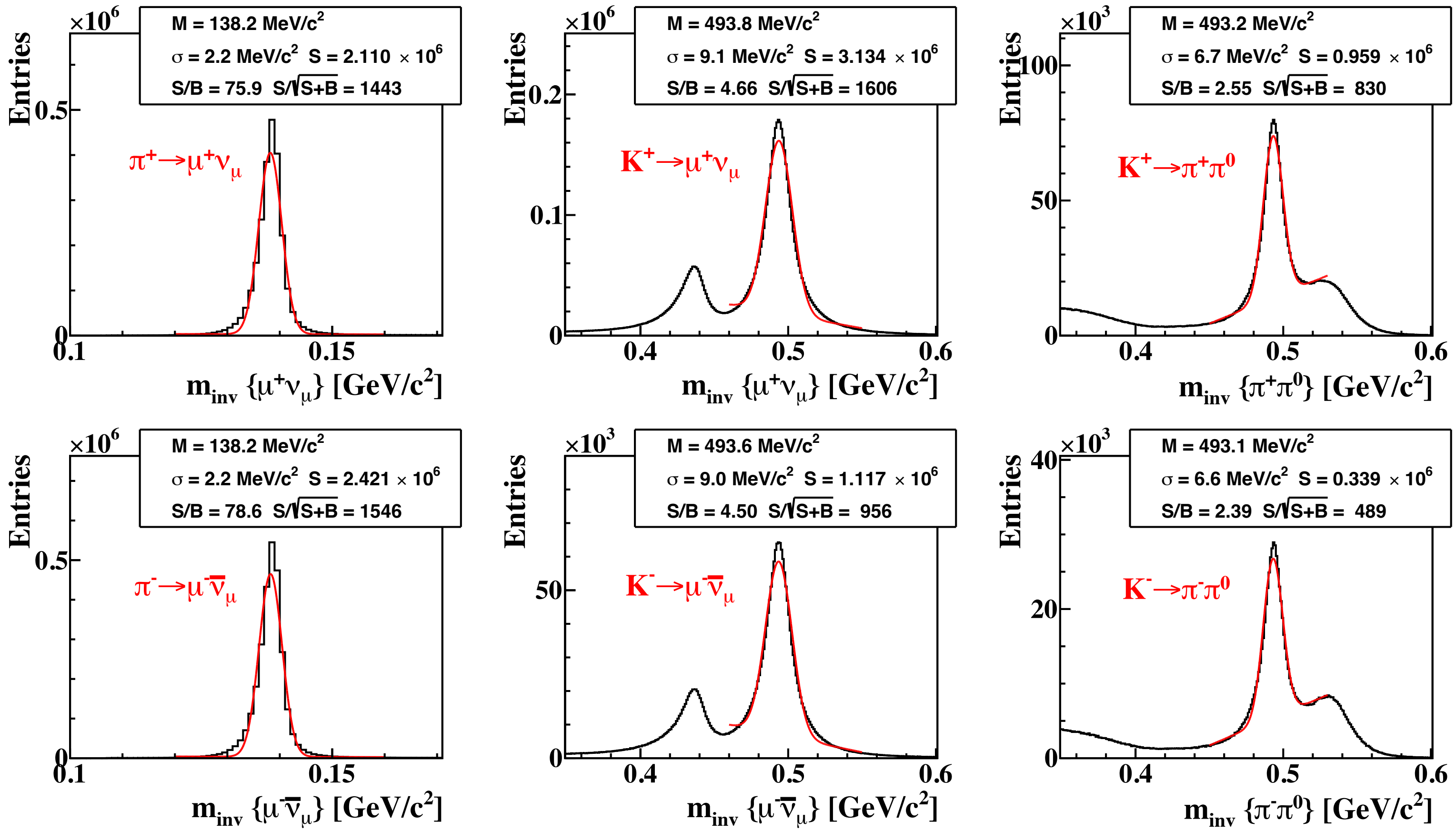


- STAR has upgraded the inner part of TPC that together with an improved CA track finder have increased efficiency.
- New data give a possibility to study lower p_t region.

With express calibration and production we observe all hyperons with high significance and S/B ratio

xBES-II: Missing Mass Method

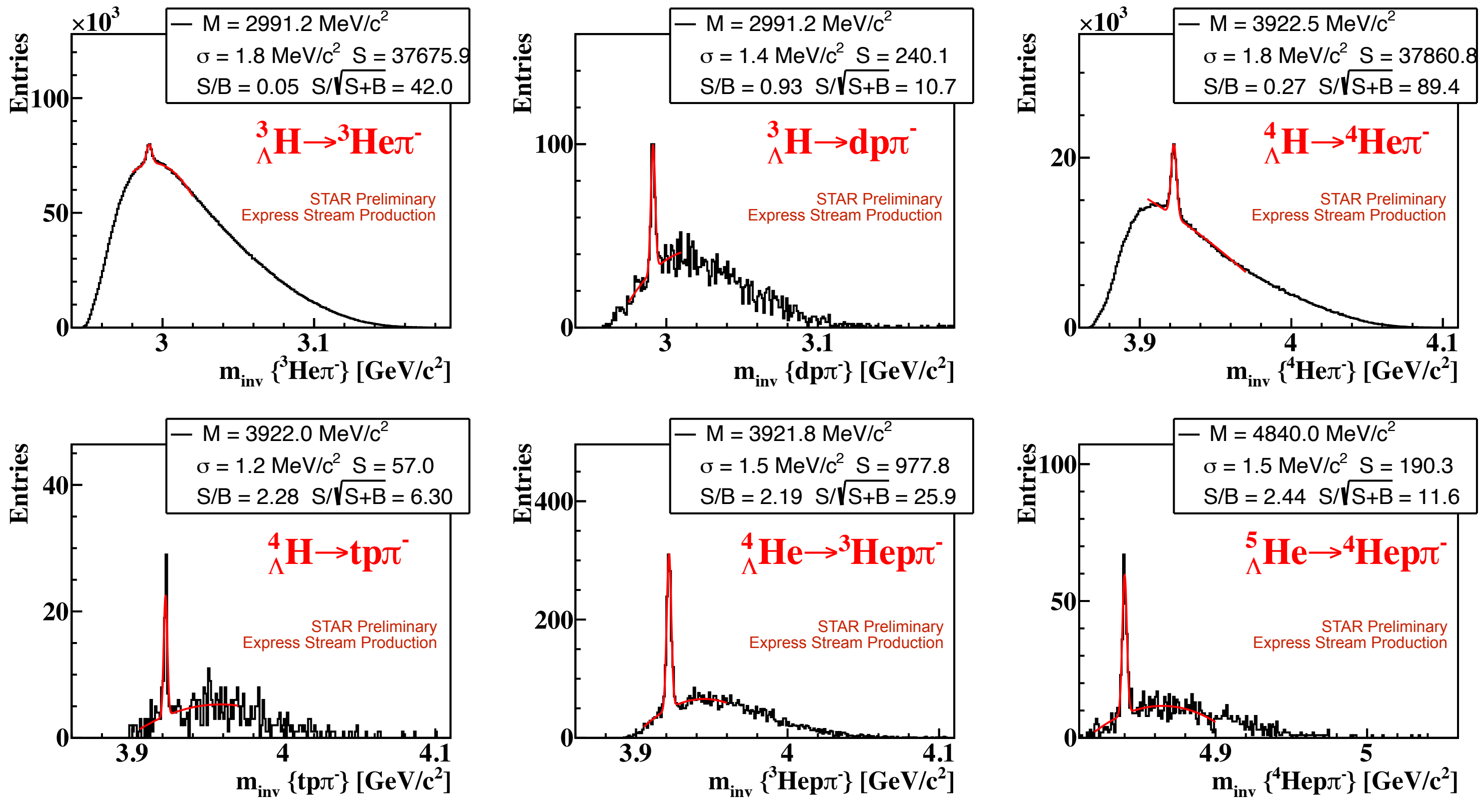
Signal utilizing 32.5M AuAu events at 7.7 GeV, 2021 BES-II (x)production



- Kaons can also be found using the Missing Mass Method.
- Second peak is due to the (μ/π) particle misidentification.

The missing mass method provides additional opportunities in the study of decay channels

2018, 2019, 2020, 2021x FXT and 2021x collider at 7.7 GeV

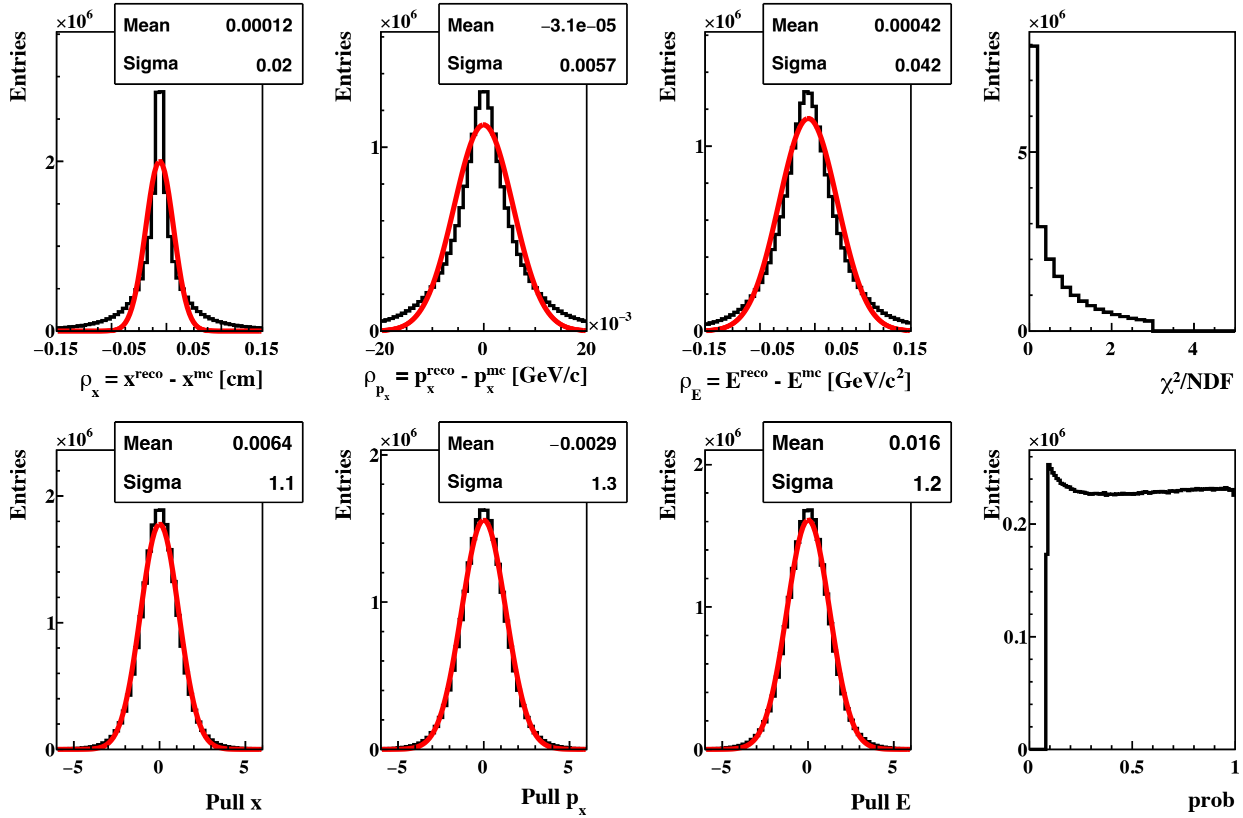


- With the same procedure all FXT data from 2018, 2019 and 2020 were analyzed.
- In all (standard and express) production data $^{5}_{\Lambda}$**He** is visible with significance **11.6 σ**.

The collected statistics is enough to study Dalitz plots of 3-body channels

KF Particle: Fit Quality

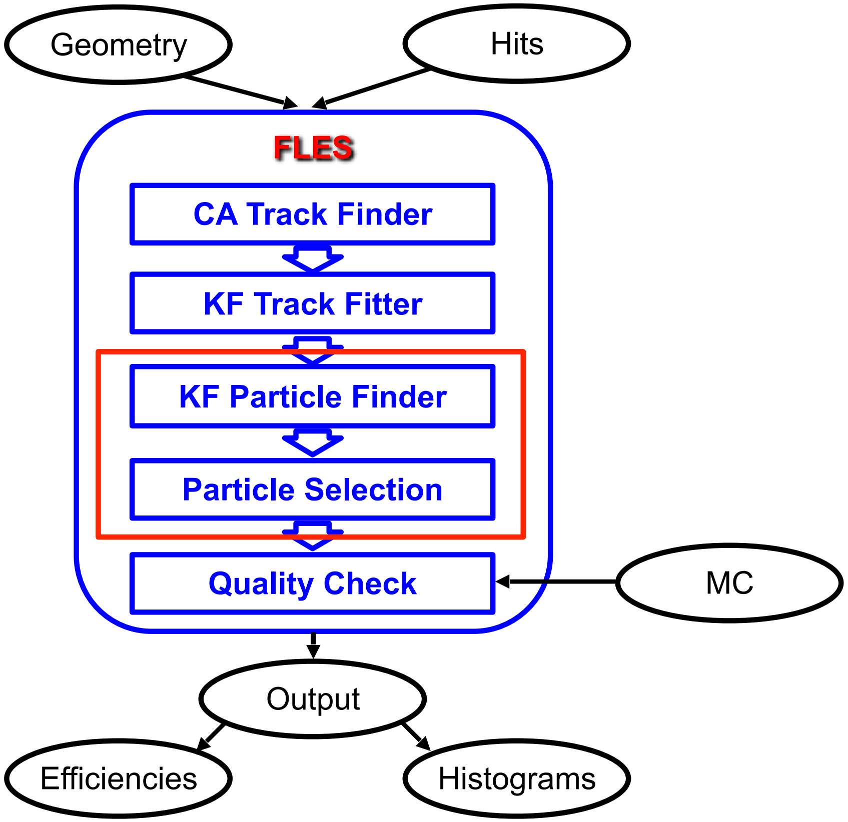
AuAu, 10 AGeV, 5M central UrQMD events, realistic PID

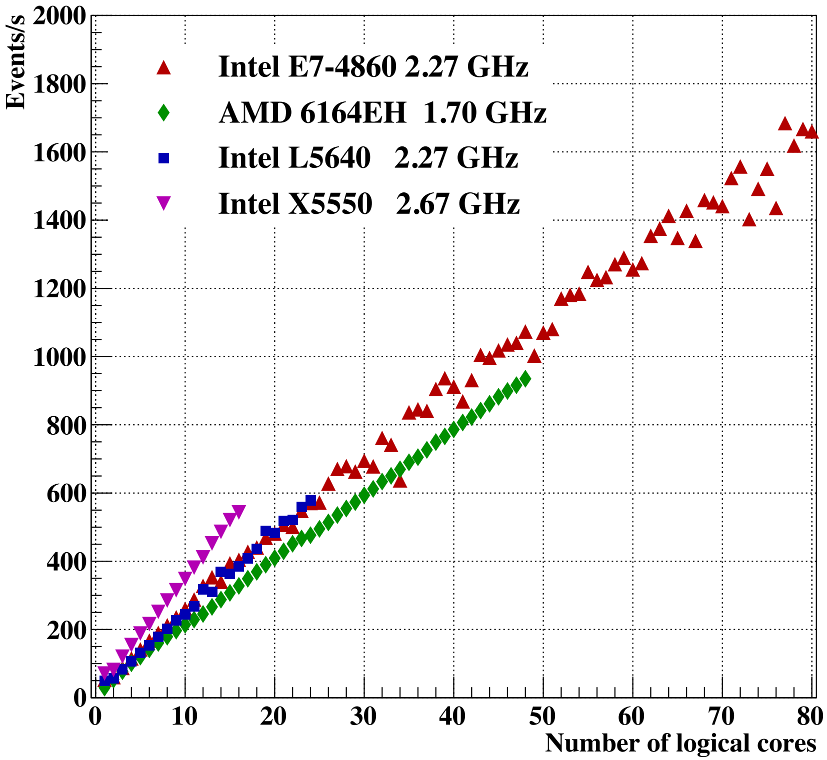


- The fit quality demonstrated at the example of Λ particle:
- Pull: $P(x) = (x_{reco} - x_{true})/\sigma_x$. Pulls should be gaussians with a unit standard deviation.
- Prob (p-value) distribution reflects quality of the χ^2-criterion. Probability distribution should be flat.
- Correctness of the mathematics should be always checked. Correct mathematics allow to obtain predictable results, better understand selection criteria and as a result improve reconstruction scheme.

The KF Particle Finder produces mathematically accurate results,
with the residual, pull, and prob distributions having the correct shapes

KF Particle Finder with modern CPUs

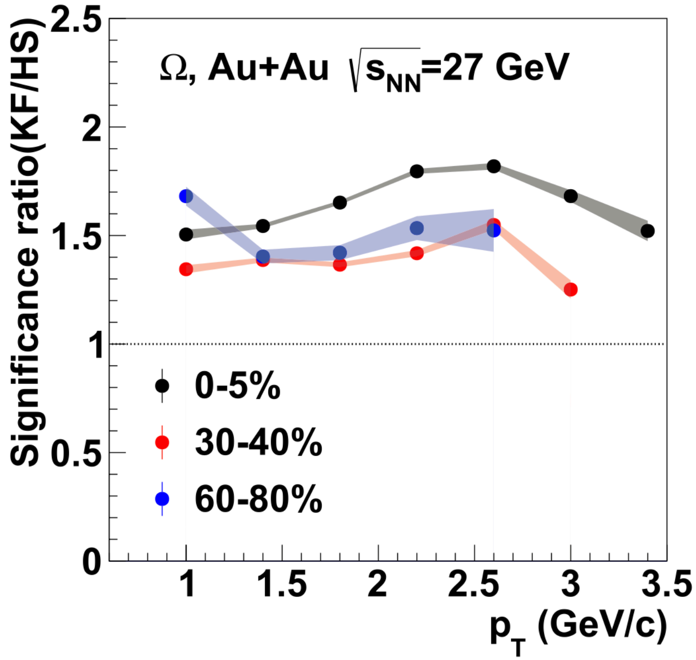


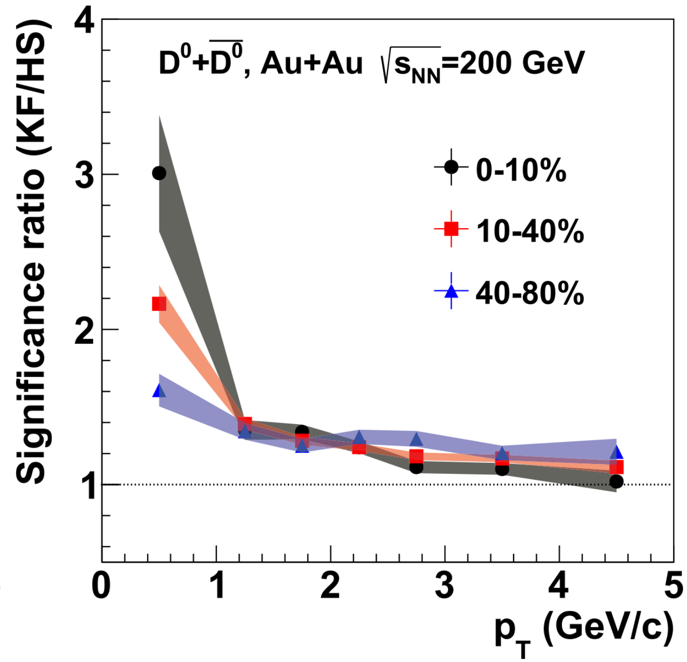


- CBM will require online reconstruction of short-lived particles.
- KF Particle Finder is tested in the first version of the First Level Event Selection (FLES) package.
- The FLES package shows strong scalability on many-core computers.

The KF Particle Finder exhibits linear scalability with most modern computer architectures

Comparison with the Standard Approach





Decay	year	Signal	Significance	p_t
$D^0 \to K\pi$	2014	10393	70	0-10 GeV/c
		5774	45	
$D^\pm \to K\pi\pi$	2014	1357	30	1-10 GeV/c
		774	25	
$\Lambda_c^\pm \to pK\pi$	2014	261	11.0	3-10 GeV/c
		122	8.3	
	2016	459	9.6	
		337	7.6	

- Results obtained with KF Particle Finder are compared with the standard reconstruction approach by **Sooraj** and **Xinyue**. Mother and daughter particles have the same form of the state vector and the covariance matrix

Applying the Kalman filter particle method to strange and open charm hadron reconstruction in the STAR experiment

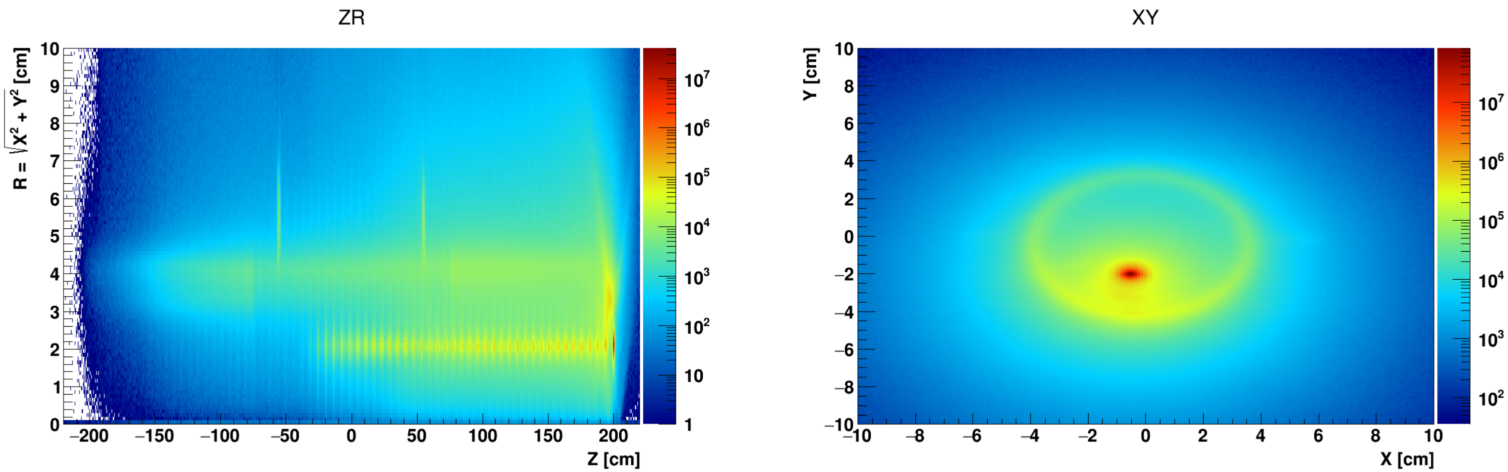
Xin-Yue Ju[1,2] · Yue-Hang Leung[2,3] · Sooraj Radhakrishnann[2,4] · Petr Chaloupka[5] · Xin Dong[2] · Yury Fisyak[6] · Pavol Federic[7] · Ivan Kisel[8,9,10] · Hong-Wei Ke[6] · Michal Kocan[5] · Spyridon Margetis[4] · Ai-Hong Tang[6] · Iouri Vassiliev[10] · Yi-Fei Zhang[1] · Xiang-Lei Zhu[11] · Maksym Zyzak[10]

Received: 24 March 2023 / Revised: 5 July 2023 / Accepted: 11 July 2023 / Published online: 30 October 2023
© The Author(s), under exclusive licence to China Science Publishing & Media Ltd. (Science Press), Shanghai Institute of Applied Physics, the Chinese Academy of Sciences, Chinese Nuclear Society 2023

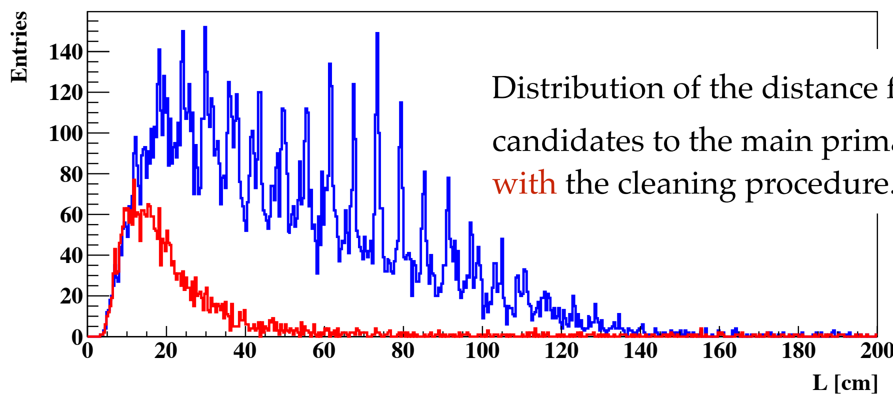
KF Particle Finder allows to get 1.5-2 times more signal with 1.2-1.5 times better significance reconstructed in all compared channels due to better utilization of the data.

Fixed Target xBES-II: Pileup

Primary Vertex



- To increase statistics the beam interaction intensity was increased.
- This resulted in more than a half of events with at least two reconstructed primary vertices.
- A structure at R = 2 cm is formed by pileup.
- Interactions with the beam pipe material and support structures are also visible.



Distribution of the distance from ${}^{4}_{\Lambda}He \to {}^{3}He + p + \pi^{-}$ candidates to the main primary vertex without and with the cleaning procedure.

- The cleaning procedure: reconstruct primary vertices from pileup and interaction with the beam pipe, then discard these primary tracks.

The cleaning procedure significantly reduces background, especially in 3-body channels

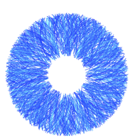
Conclusion

- The KF Particle package enables us to construct particles together with their state vectors and covariance matrices, thus accumulating all information from experimental measurements. This approach has allowed us to outperform traditional approaches without covariance matrices by a factor of two when comparing the number of signal particles found and their significance on the same real data.

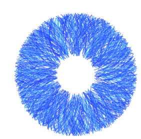
- The KF Particle Finder package of algorithms includes a search for about 200 decays of short-lived particles and resonances. The package can be used to operate in real time on-line with an experiment, or as an example for developing algorithms to find other decays or decay chains.

- The KF Particle and KF Particle Finder packages are used in the experiments **CBM** and **HADES** (FAIR/GSI), **ALICE** (CERN), **STAR** and s**PHENIX** (BNL).

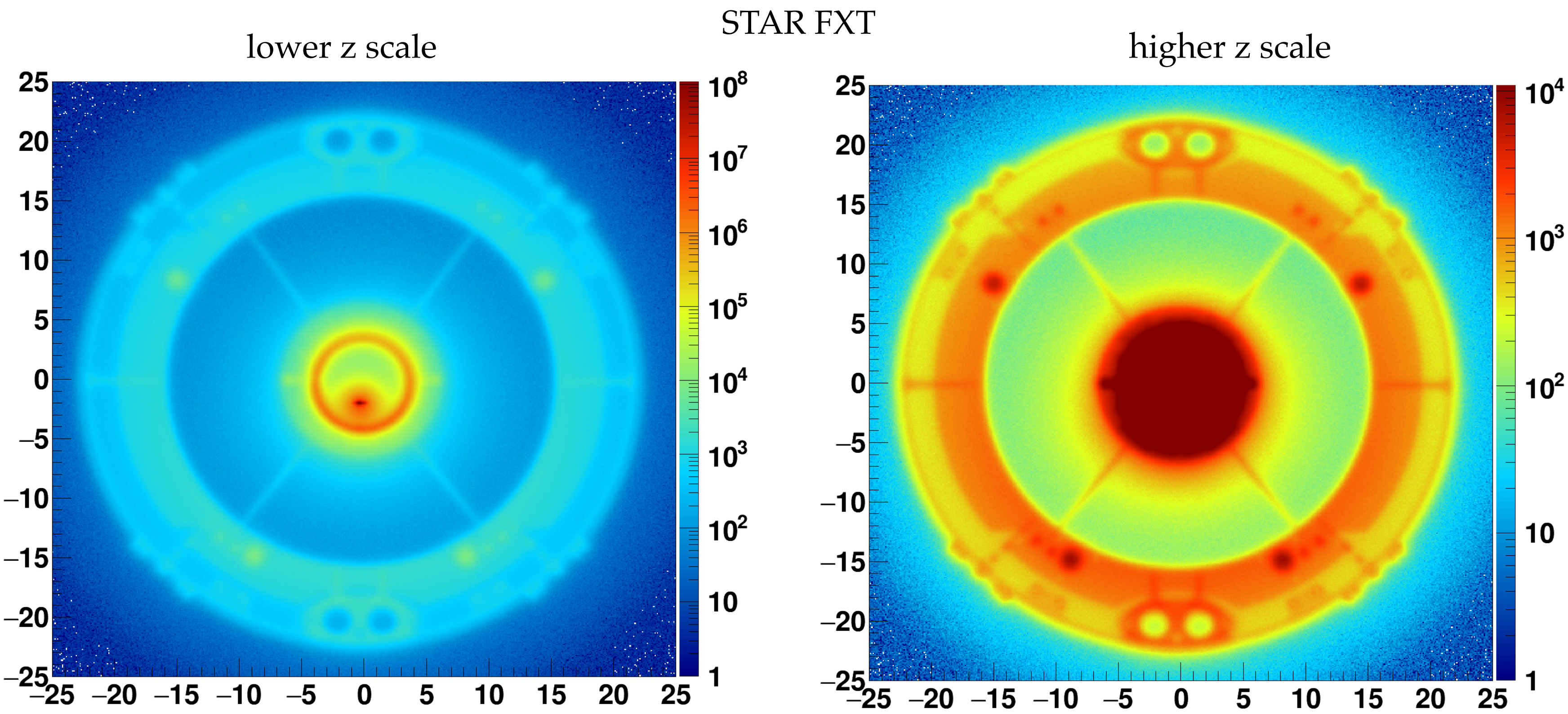
- The KF Particle and KF Particle Finder packages are maintained and developed by the research teams at FIAS (the original developer of the packages) and the CBM, ALICE and STAR experiments.



Thank you!

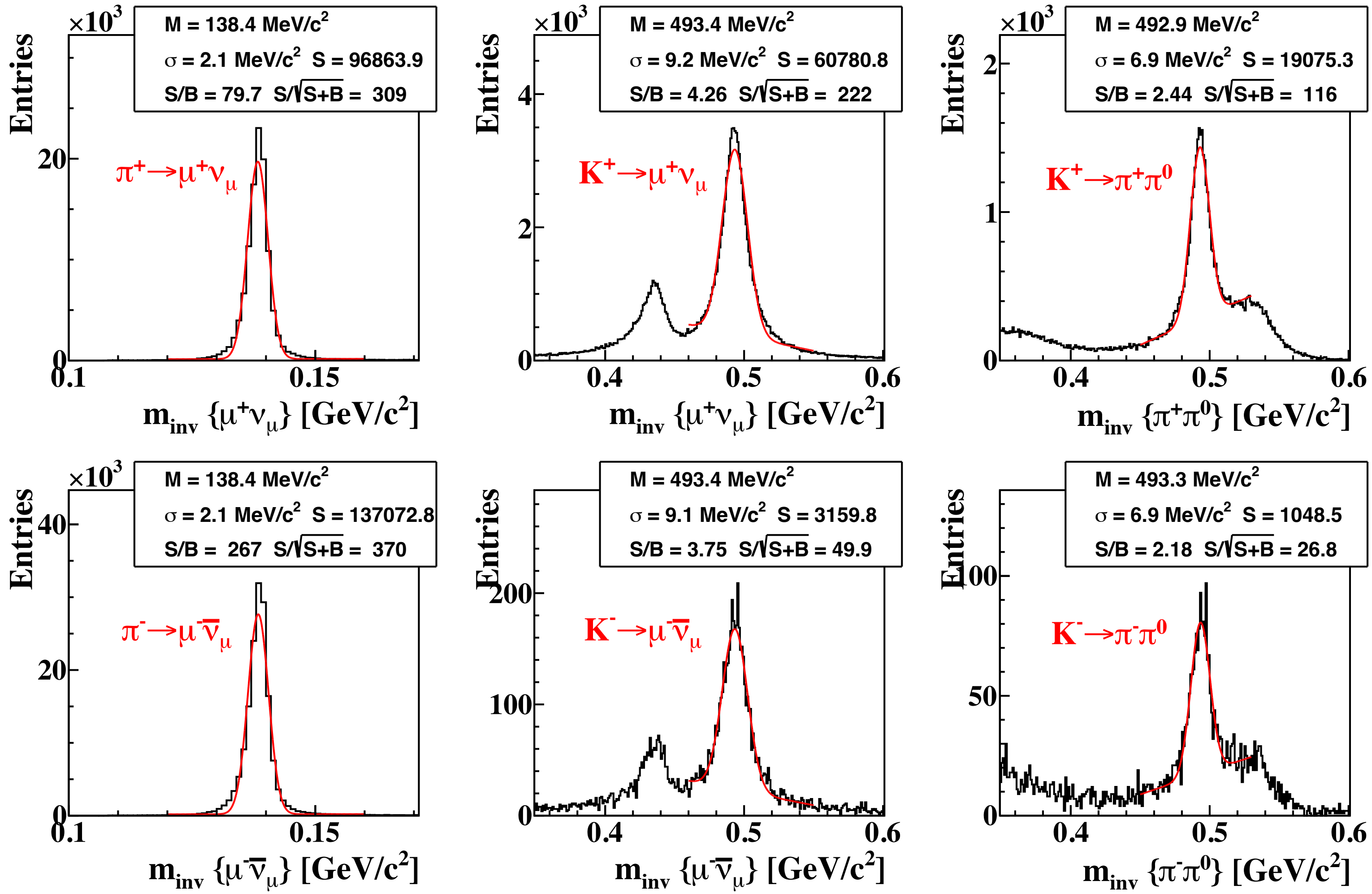


Backup Slides



New bonus pictures from Maksym Zyzak (FIAS, Germany)

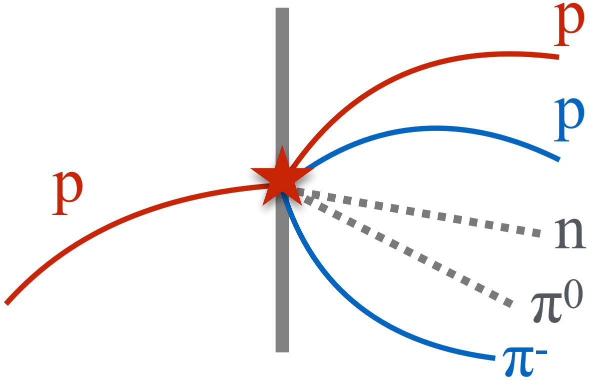
The KF Particle detector enables detailed imaging,
revealing even the smallest details of a tracking detector



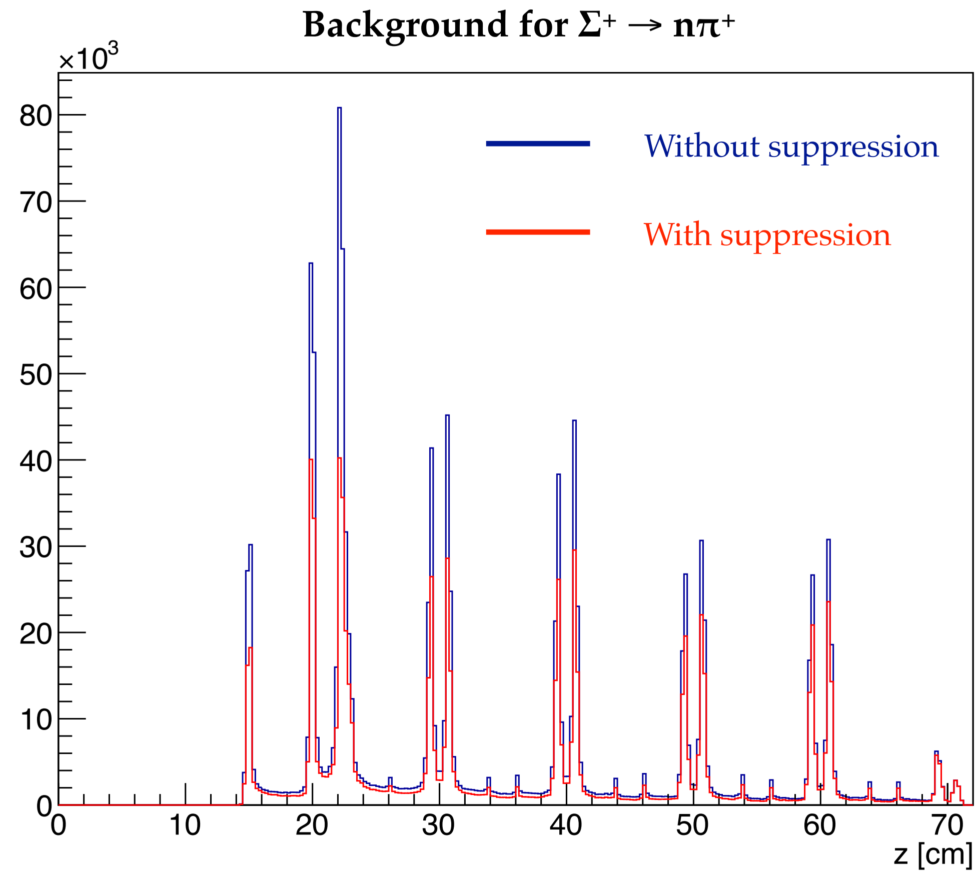
9M AuAu collisions with 3.85 GeV/n, May 1-2, 2021

- Here are the results of the Missing Mass Method obtained on May 1 and 2, 2021 on the HLT computer cluster at the lowest collision energy in the STAR BES-II program with a fixed target, which is most interesting for the CBM experiment.

The Missing Mass Method has successfully demonstrated its robustness and high efficiency on real STAR data

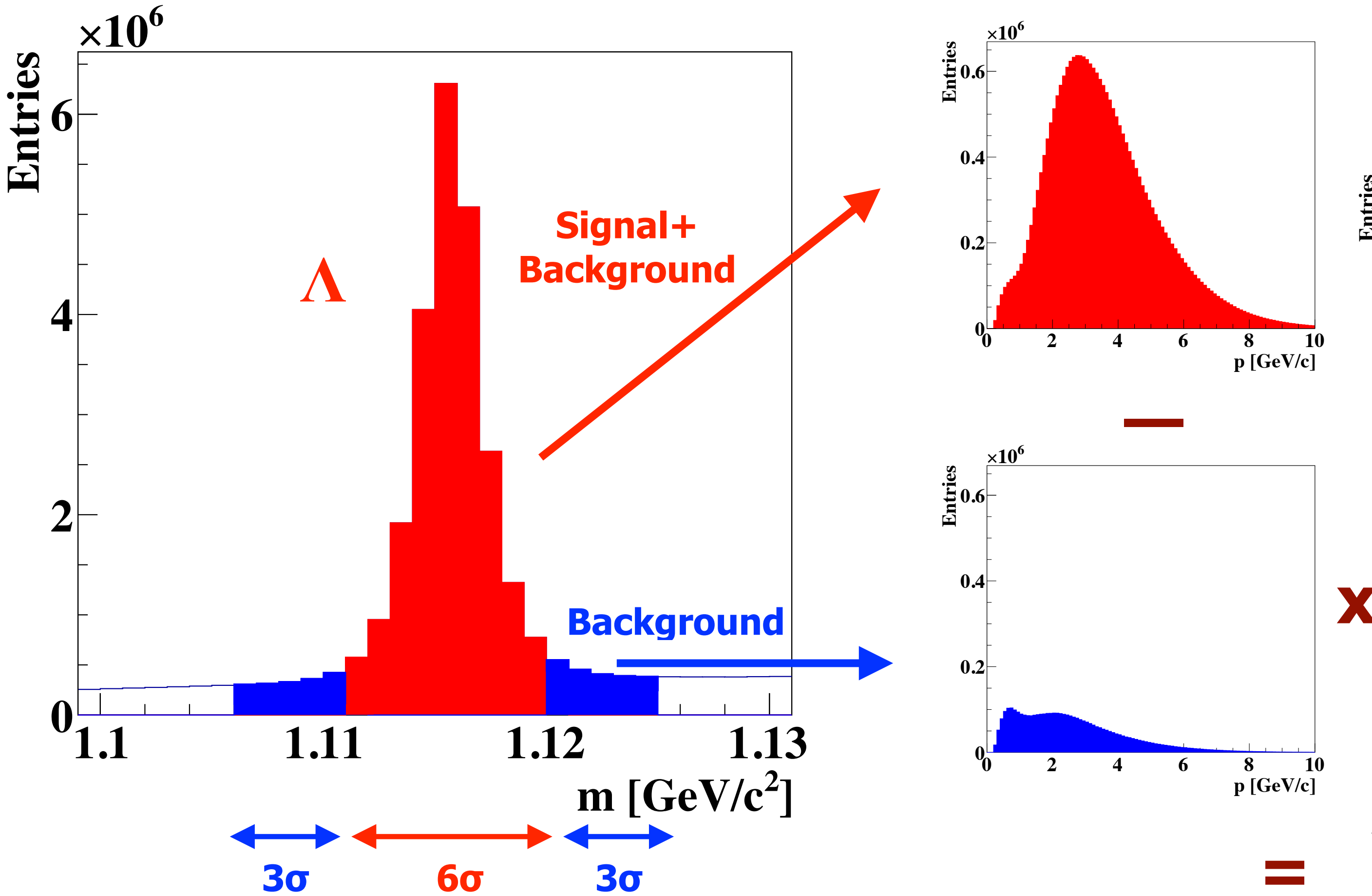


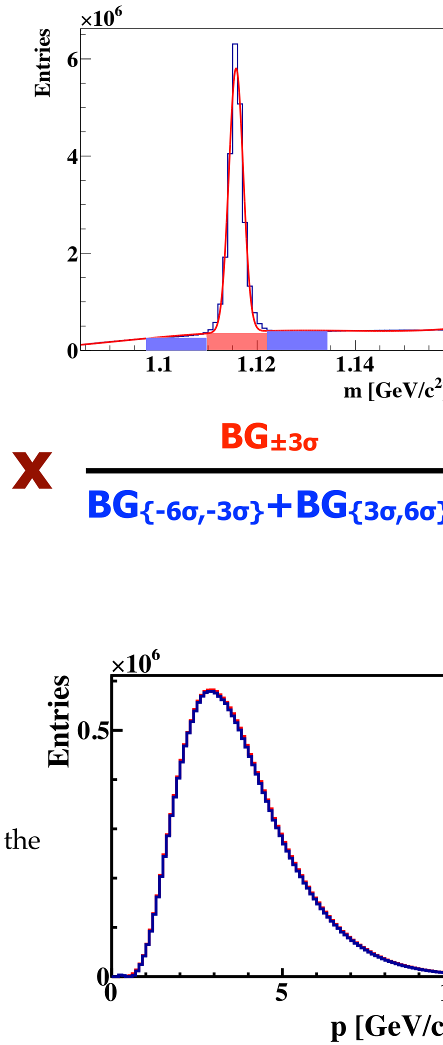
Track-candidate is removed if similar „star“ is detected



- The main background for missing mass method is due to:
  (1) the interaction with the detector material and
  (2) misidentification of daughter particles
- To suppress background from interaction with the material one more track (p, π, …) is added to the reconstructed candidate (p). If it fits — the candidate is considered as background and removed

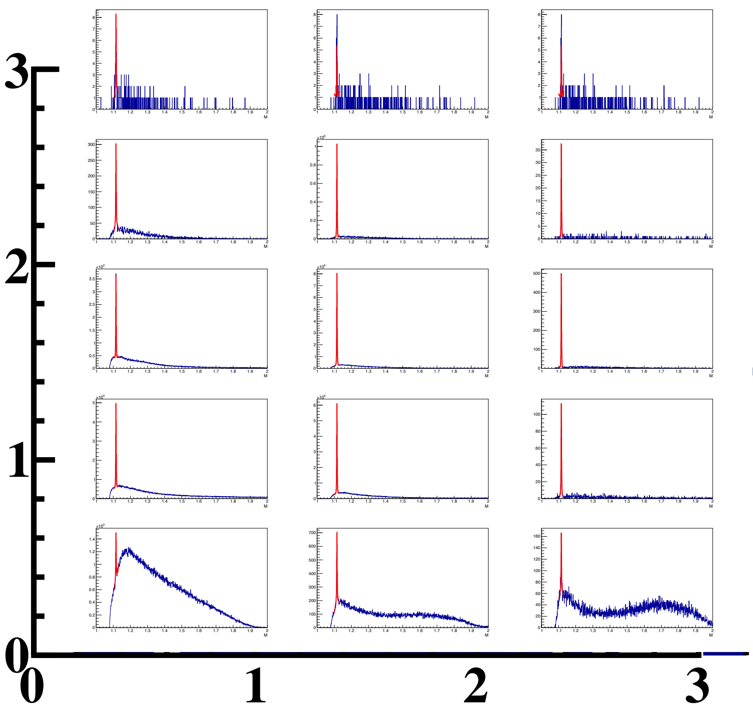
For $\Sigma^+ \to n\pi^+$ background is reduced by 33%, while signal is slightly dropped by 1.5%



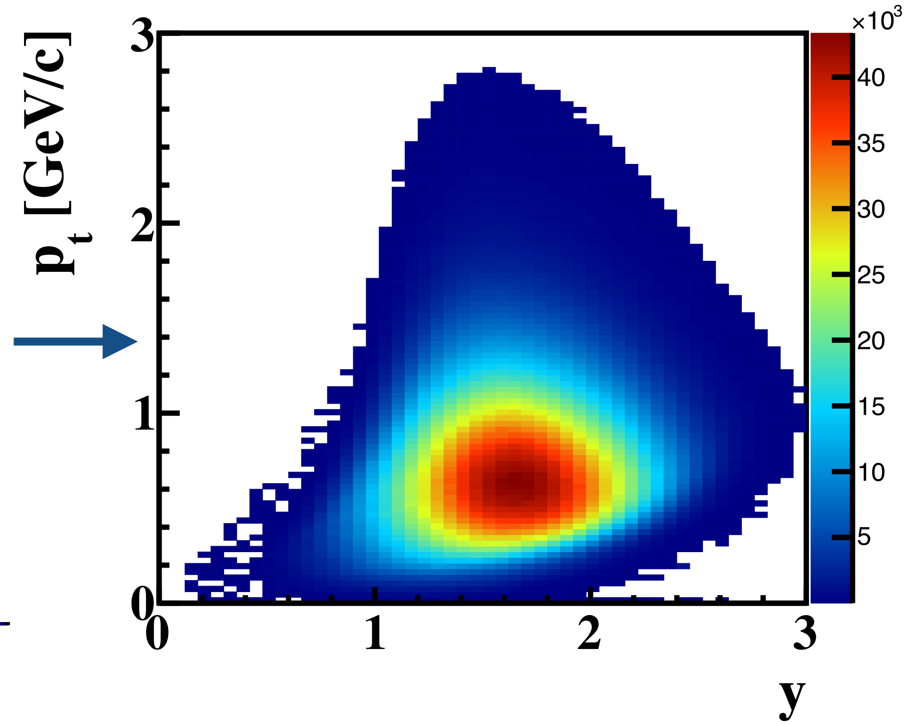


1. Spectra of particles by mass, momentum, transverse momentum, rapidity, z are produced.
2. The mass spectrum is approximated in the peak region to estimate the signal along with the background, and in the side-bands around it to estimate the background.
3. A correction factor is calculated to determine the background in the area of the signal peak.
4. The corrected background of the side-bands is subtracted from the signal peak area.
5. The spectra of particles by mass, momentum, transverse momentum, and rapidity, as well as the distribution of decay vertices along the z-axis, are produced cleaned from the background contribution.

Side bands method is very suitable for fast analysis of particle spectra



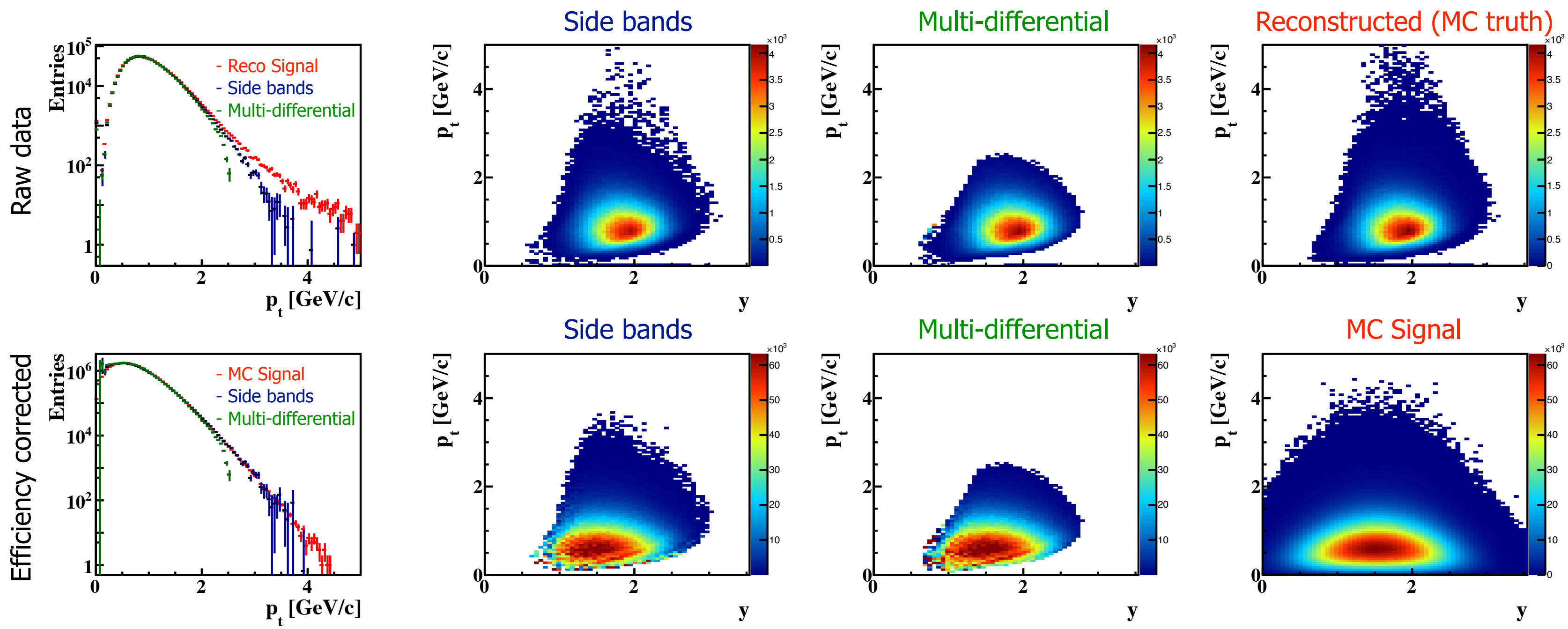
Mass spectra for each individual y-p_t bin



1. The entire phase space (y, p_t) is partitioned into sufficiently small bins.
2. Individual mass spectra are produced in each of the bin.
3. In each individual bin, the mass spectrum is approximated by a function of the form „signal + background“.
4. From the approximation parameters an estimate of the number of signal inputs in each bin is taken.
5. The whole region (y, pt) is filled in each bin with the obtained corresponding number of signal inputs.

Multi-differential analysis takes into account local features of the spectrum, but requires significantly more statistics

Side Bands vs Multi-Differential

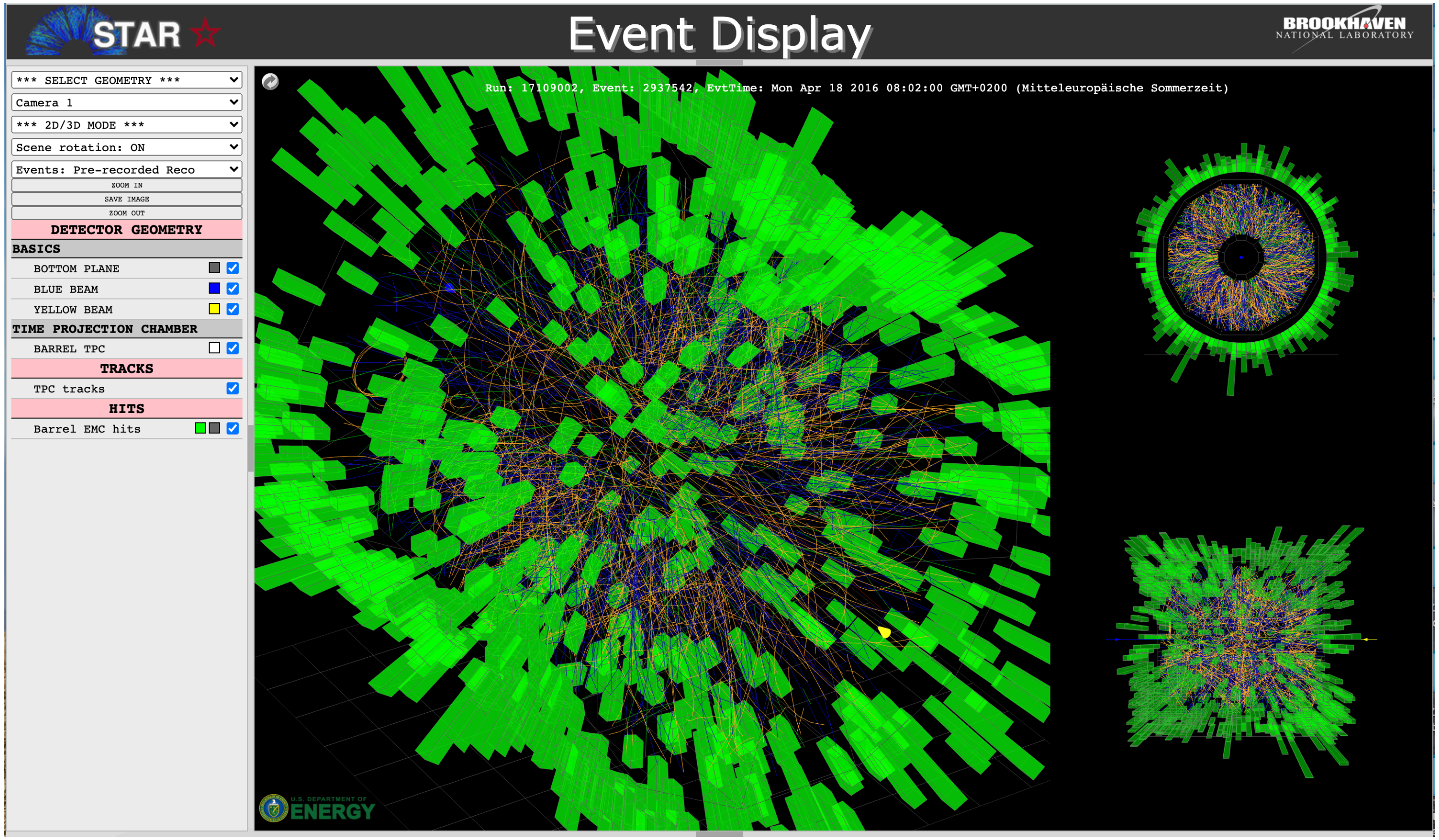


5M central AuAu events UrQMD 10 AGeV

- Comparison of the results of applying the side-bands method and the multi-differential analysis method in the reconstruction of spectra for decay $\Sigma^- \to n\pi^-$.
- The bottom row shows histograms corrected for 4π efficiency, which when compared to the top row gives an idea of the CBM experiment's detector system acceptance.

Both implemented methods reconstruct the particle spectra very well within the statistical errors, and since the methods are completely independent, this allows to accurately study the systematic errors of the collected particle spectra

Reconstruction Challenge in STAR

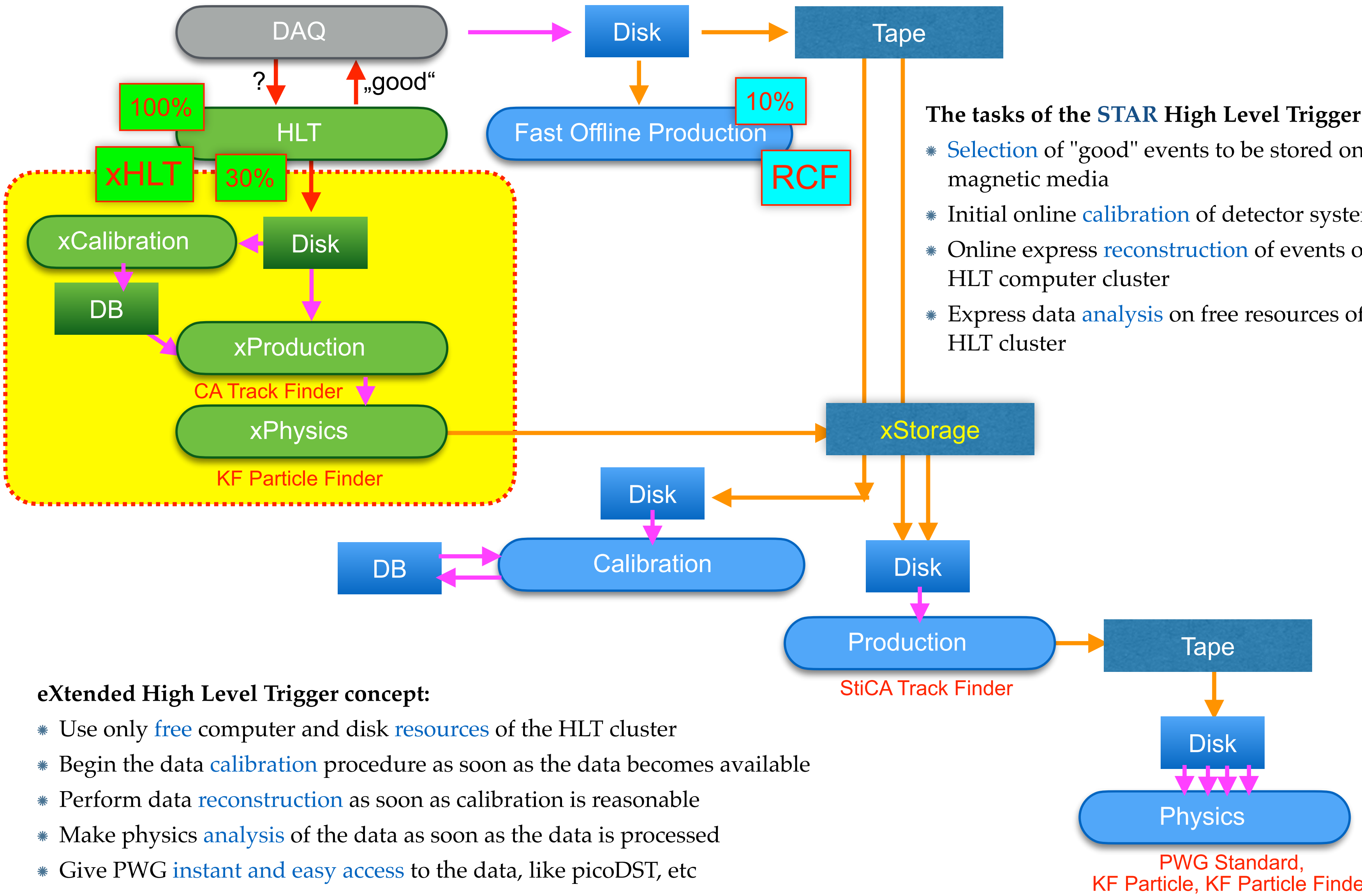


Event display of a heavy ion collision in STAR with particle trajectories reconstructed in TPC and their energy measurements in EMC.

- The collisions of heavy ions in the STAR experiment have a complicated topology with a large multiplicity of trajectories of charged particles.
- Since all algorithms of the KF Particle Finder package work with trajectories in 3D space, they do not depend on the detector geometry.
- Therefore, the migration of the KF Particle Finder package from the CBM experiment to the STAR experiment was not too complicated.
- Only some procedures had to be adapted, such as the suppression of the background from the interaction of particles with material of the STAR detector.

The KF Particle Finder package is a universal platform for operation in the most complicated heavy ion experiments

eXpress Data Production and Analysis on STAR HLT



The tasks of the STAR High Level Trigger:

- Selection of "good" events to be stored on magnetic media
- Initial online calibration of detector systems
- Online express reconstruction of events on HLT computer cluster
- Express data analysis on free resources of the HLT cluster

eXtended High Level Trigger concept:

- Use only free computer and disk resources of the HLT cluster
- Begin the data calibration procedure as soon as the data becomes available
- Perform data reconstruction as soon as calibration is reasonable
- Make physics analysis of the data as soon as the data is processed
- Give PWG instant and easy access to the data, like picoDST, etc

The results of data analysis in the express chain can serve as a reliable evaluation of the final analysis, which will be obtained after the final calibration and standard offline data processing is performed