Missing Mass Method for reconstruction of short-lived particles in the CBM and STAR experiments

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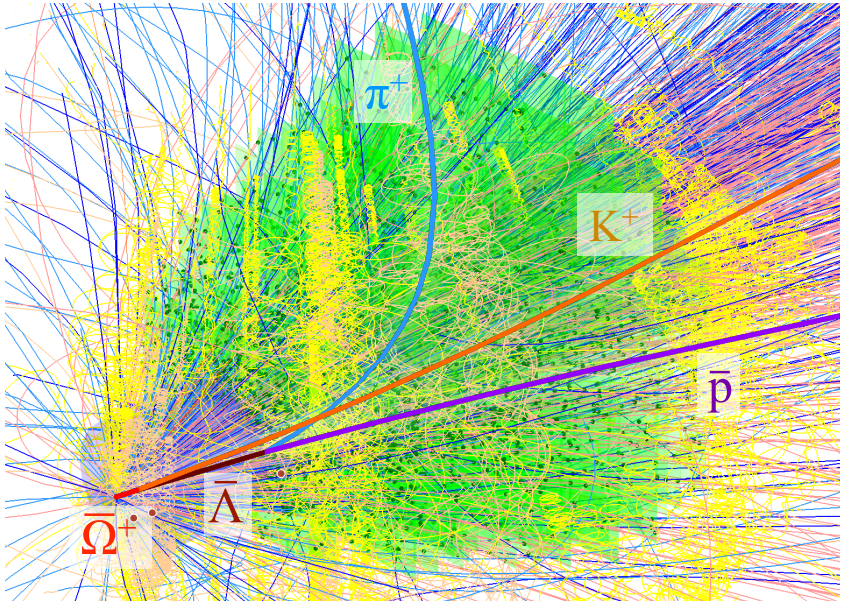
KF Particle: reconstruction of short-lived particles



Simulated AuAu collision at 25 AGeV

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

(r,C)

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

$C = \langle \mathbf{r}\mathbf{r}^T \rangle =$ — Covariance matrix

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

```
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
```

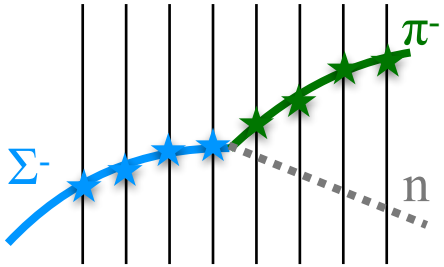
Concept:

- Mother and daughter particles have the same state vector and are treated in the same way
- Reconstruction of decay chains
- Kalman Filter (KF) based
- Geometry independent
- Vectorized
- Uncomplicated usage

Functionality:

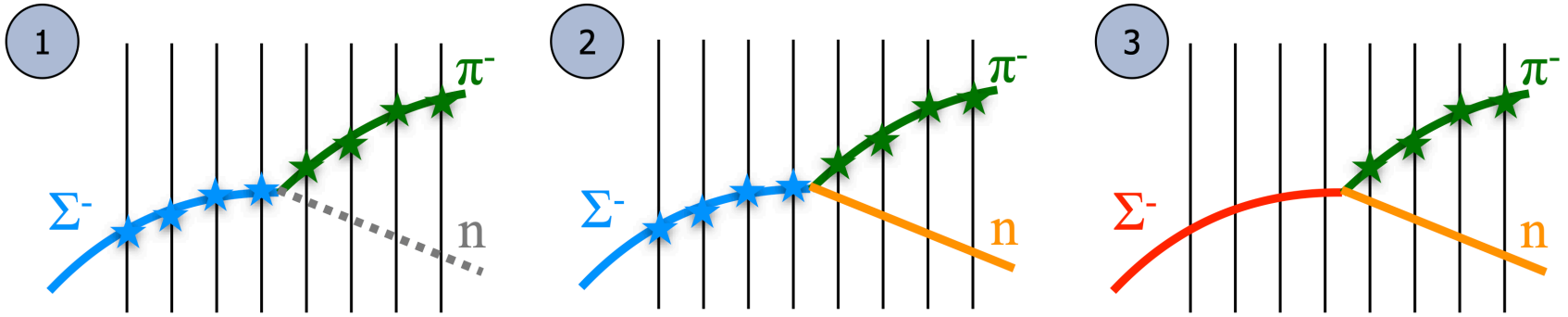
- Construction of short-lived particles
- Addition and subtraction of particles
- Transport
- Calculation of an angle between particles
- Calculation of distances and deviations
- Constraints on mass, production point and decay length
- KF Particle Finder

Reconstruction of decays with neutral daughter
by the **m**issing **m**ass **m**ethod:



KF Particle package provides a simple and direct approach to physics analysis. Now is used in CBM, ALICE and STAR.

Missing Mass Method: an illustrative sketch

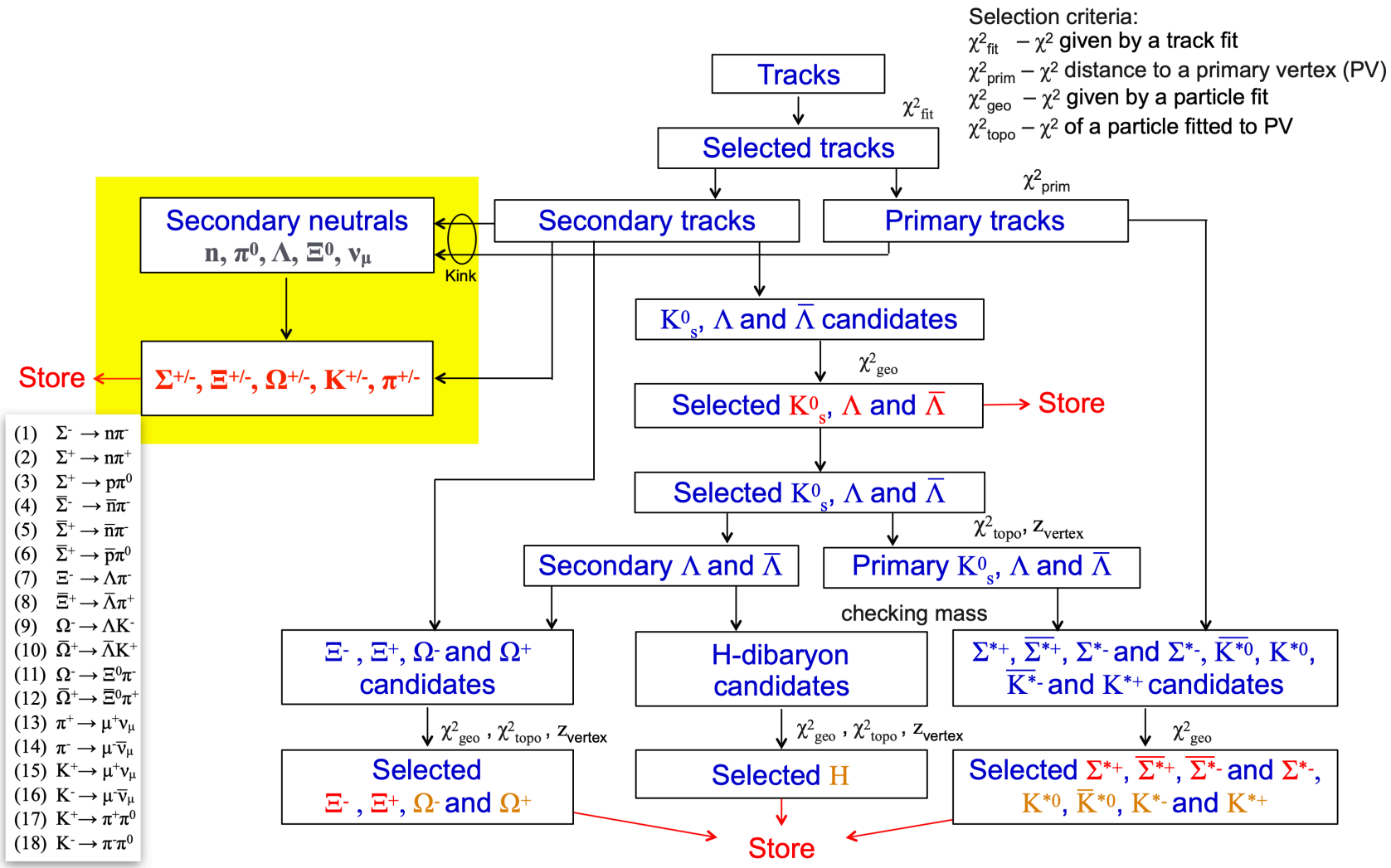


Implementation of the method for $\Sigma^- \rightarrow n\pi^-$ decay has three steps:

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

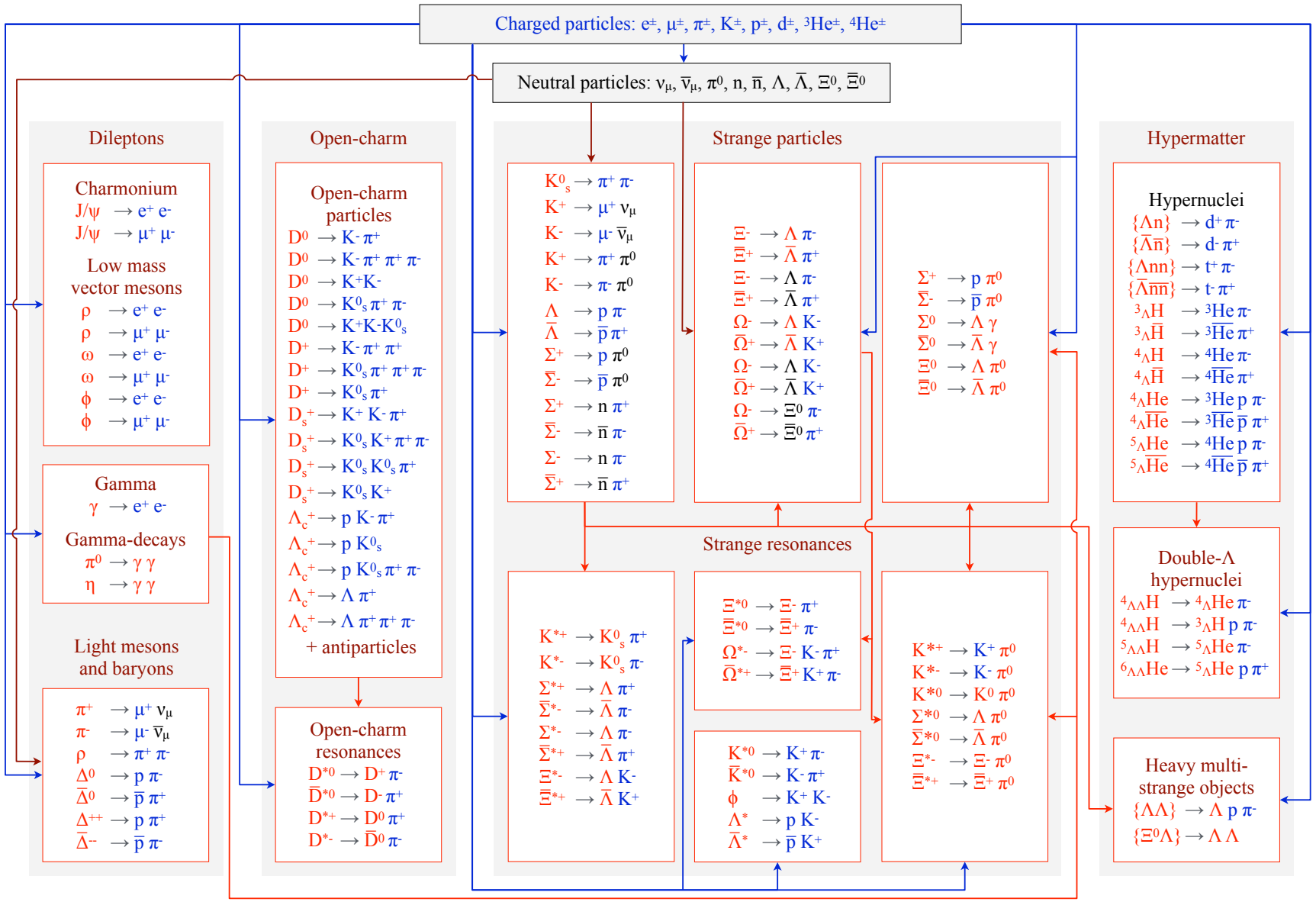
The Missing Mass Method allows a significant expansion of the physics programs of HEP and HI experiments.

A simplified block diagram of the Missing Mass Method



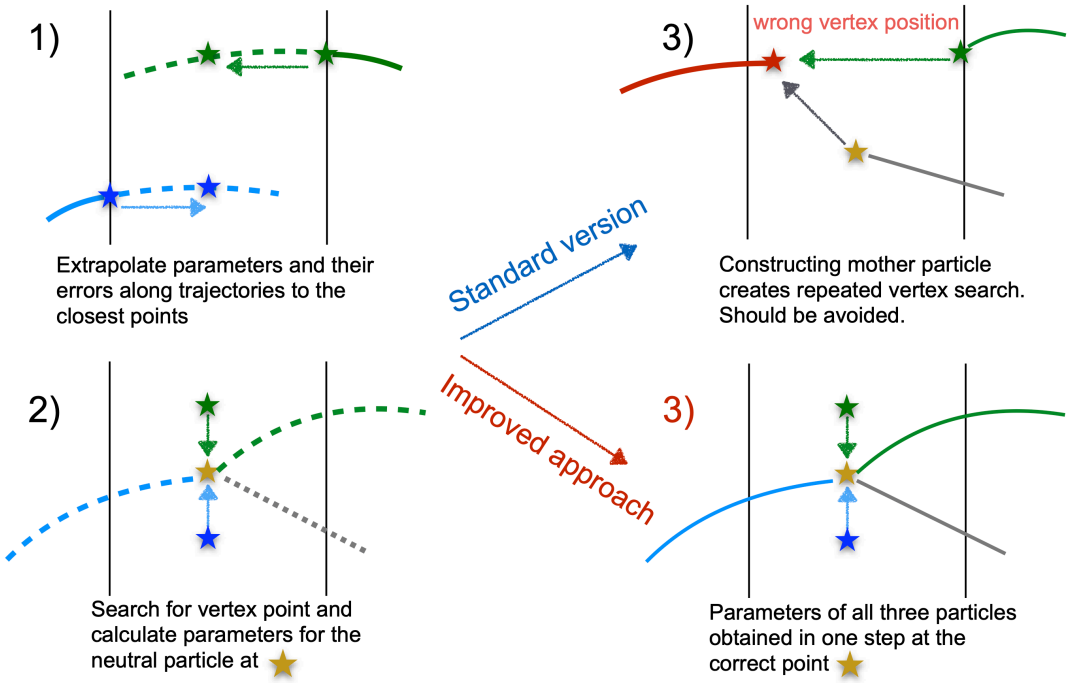
The Missing Mass Method is implemented as a part of the KF Particle Finder package.

KF Particle Finder: a package for online physics analysis and selection



(mbias: 1.4 ms; central: 10.5 ms)/event/core

Improved mathematics and optimised decay vertex search



The decay point of the charged particle, or its secondary vertex, is found in two steps at once at the initial stage and does not require refinement and recalculation later, which is mathematically more accurate, whereas previously the coordinates of the charged daughter particle participated in the calculation of the vertex position twice, which improperly overestimated their weight, that is significant especially for low-momentum particles.

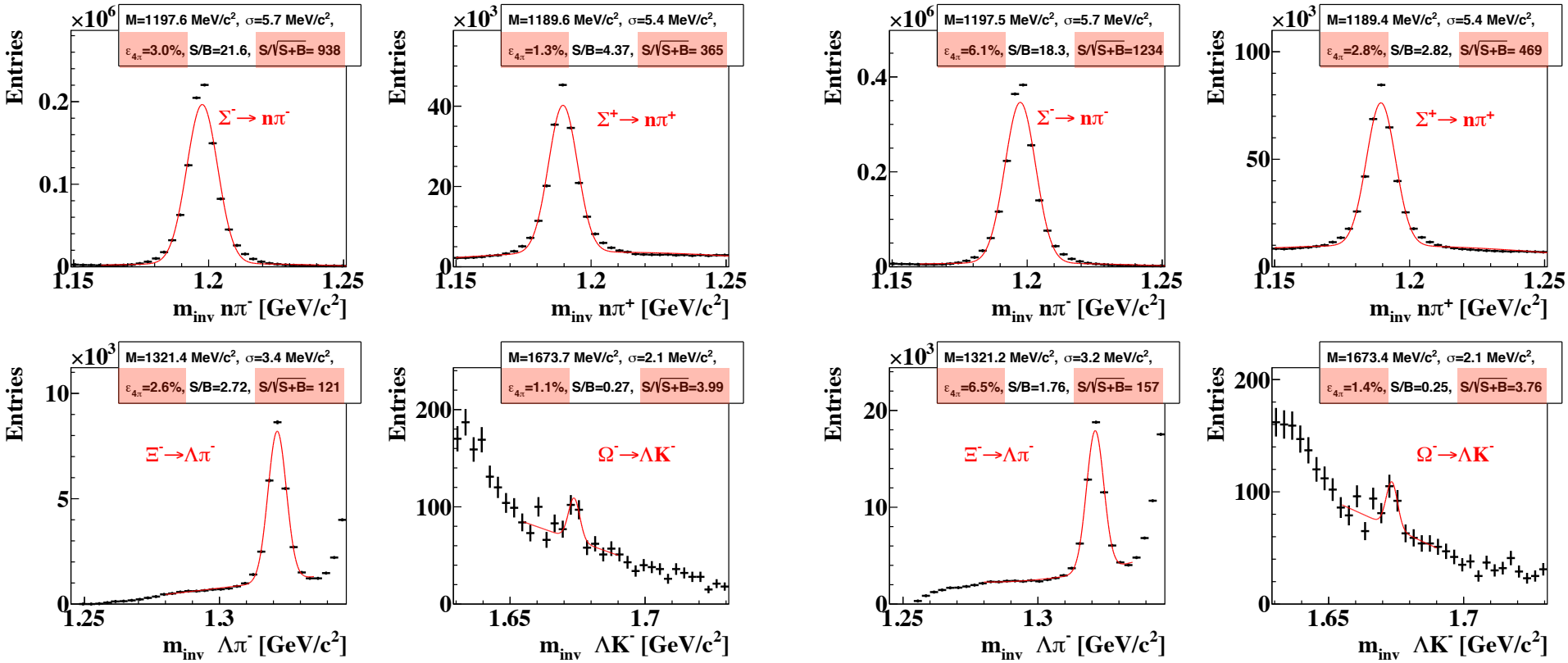
Improved mathematics:

- A more accurate and faster mathematical apparatus is implemented.
- All main calculations are done with 6x6 matrices instead of the former 7x7.
- The energy is removed from the state vector and the covariance matrix.
- Calculation of the energy and mass is done separately at the final stage.
- The parameters of all decay particles are found in one iteration of the Kalman filter instead of the former two.
- This allows to abandon the very resource-intensive mass-constrained method, which balanced the parameters of the particles in some parts of the calculations.

Performance of the Missing Mass Method in CBM

5M central AuAu UrQMD events at 10 AGeV

Standard Version → **Improved Version**



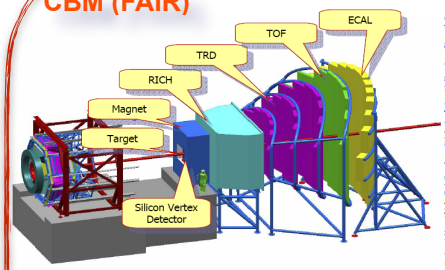
- Correct mathematics and decay vertex search.
- Double-step extrapolation.
- Reduction of background from interaction with material.
- Tracks without PID are considered as pions.

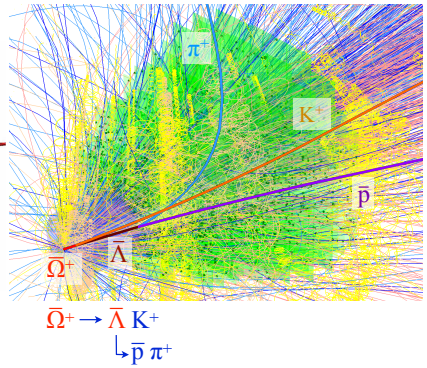
Efficiency increased by factor 2, significance by 25-30%

CBM → STAR: reconstruction and analysis software

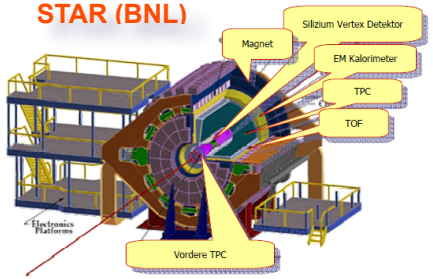
Within the FAIR Phase-0 program the CBM KF Particle Finder has been adapted to STAR and applied to real data of 2014, 2016 and BES-I.

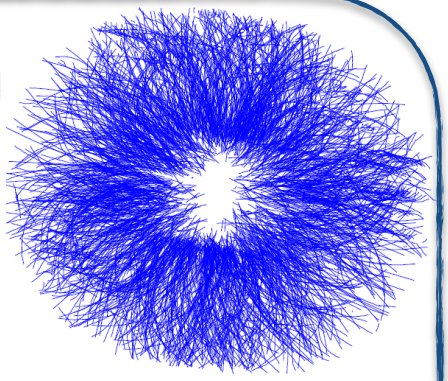
CBM (FAIR)



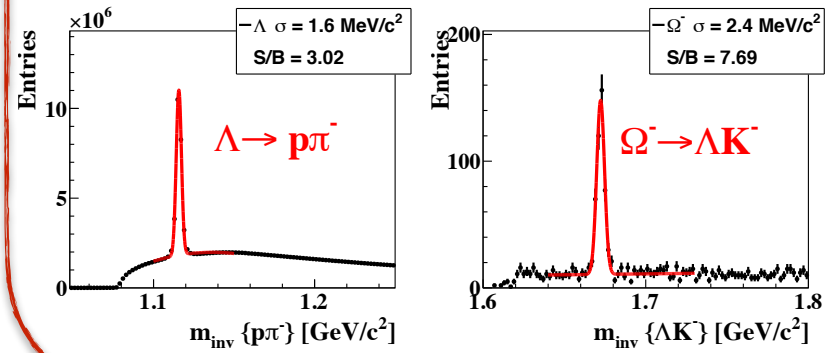


STAR (BNL)

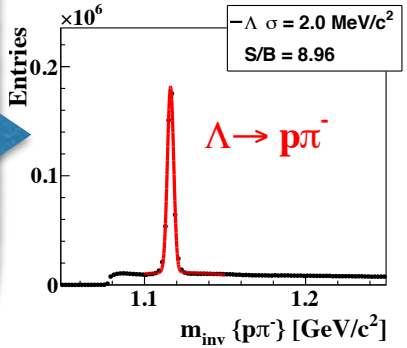


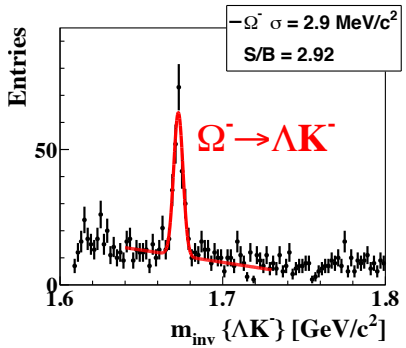


CBM, 5M central Au+Au, 10 AGeV, PHSD



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

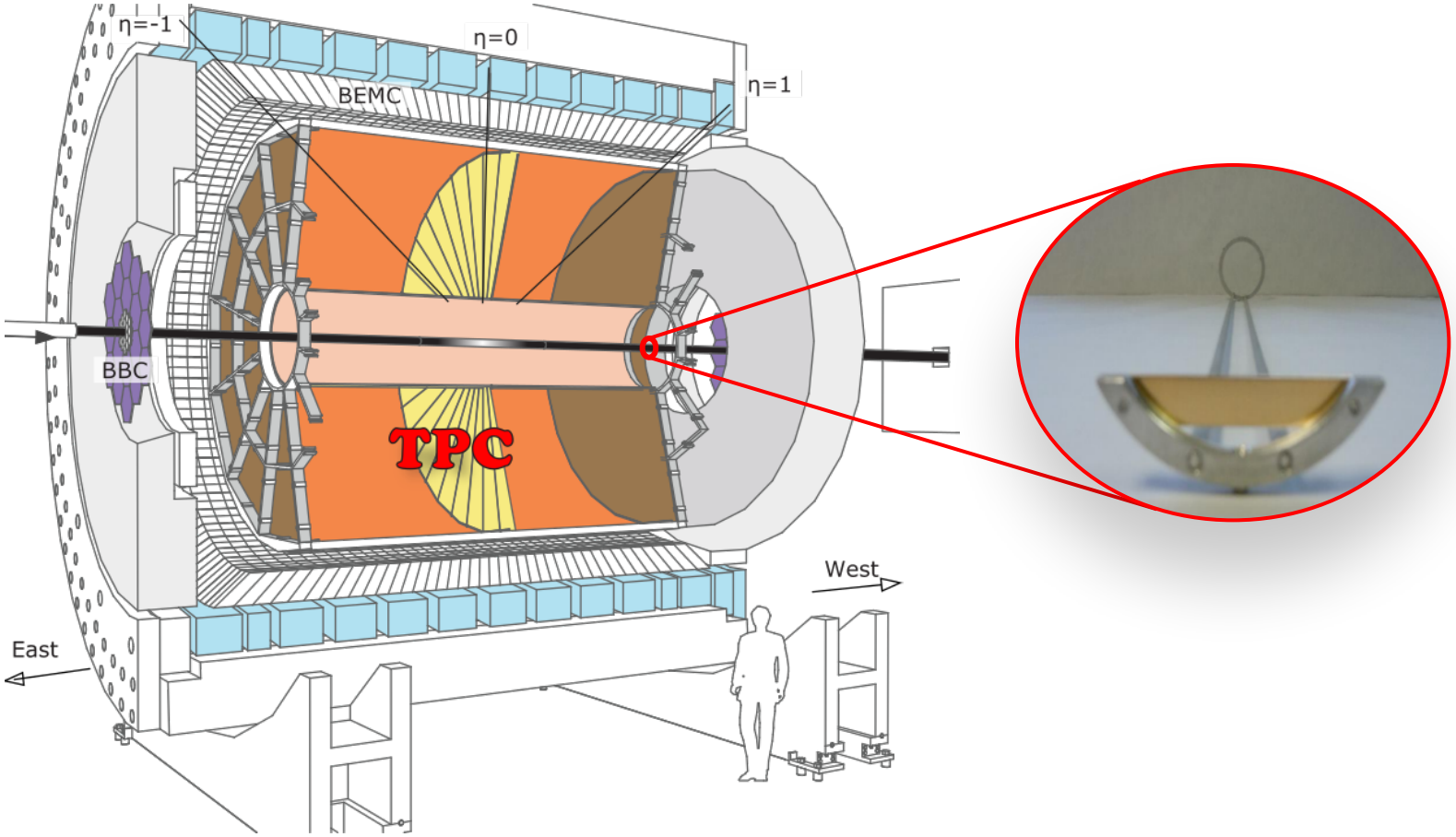




The KF particle finder provides better signal significance than the standard approach in STAR.
The integration of the KF particle finder into the official STAR repository for use in physics analysis is currently in progress.

Use for real-time express physics analysis during the BES-II runs (2019-2021)

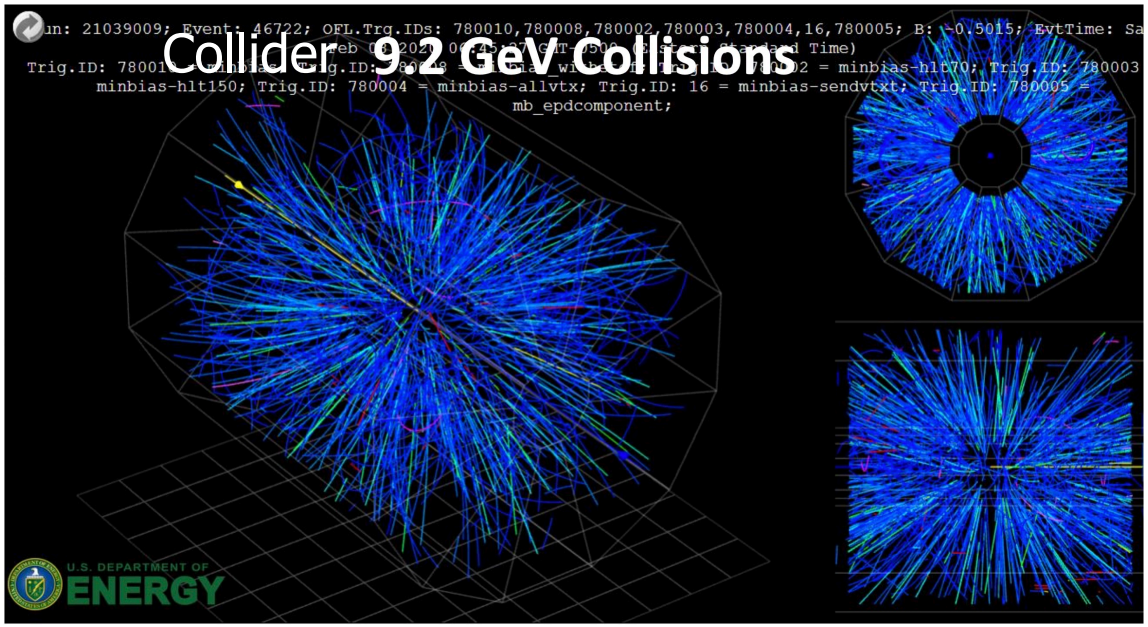
STAR Fixed Target (FXT) BES-II Program

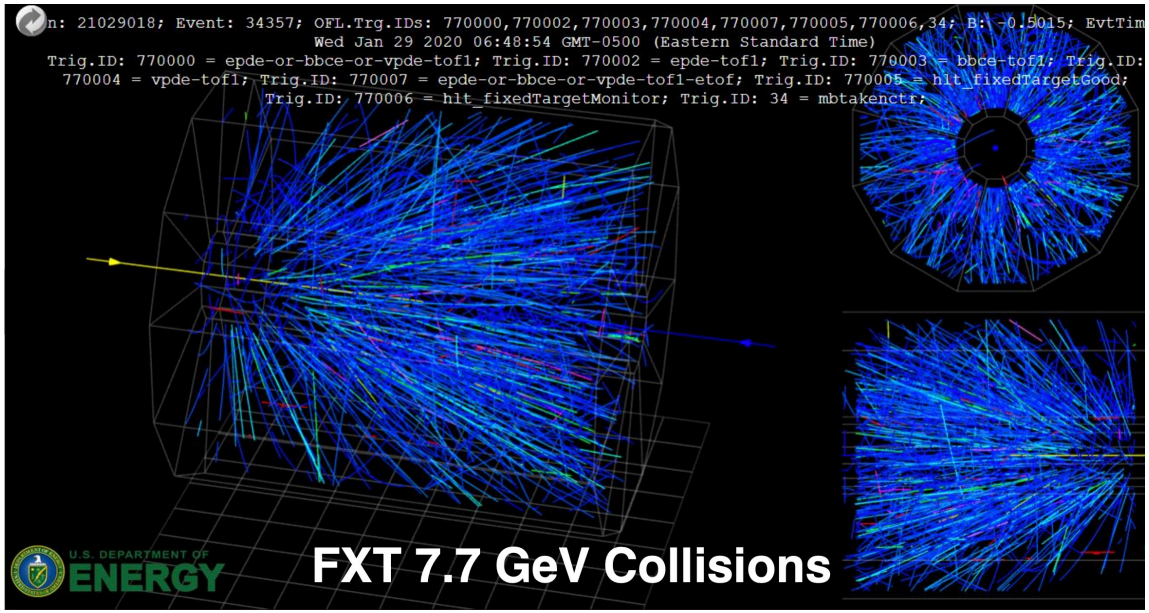


Fixed target is located at the west side of TPC where it is hit by a single beam

The idea of the Beam Energy Scan (BES) program is to experiment with a set of beam energies (single and colliding) from low to very low.

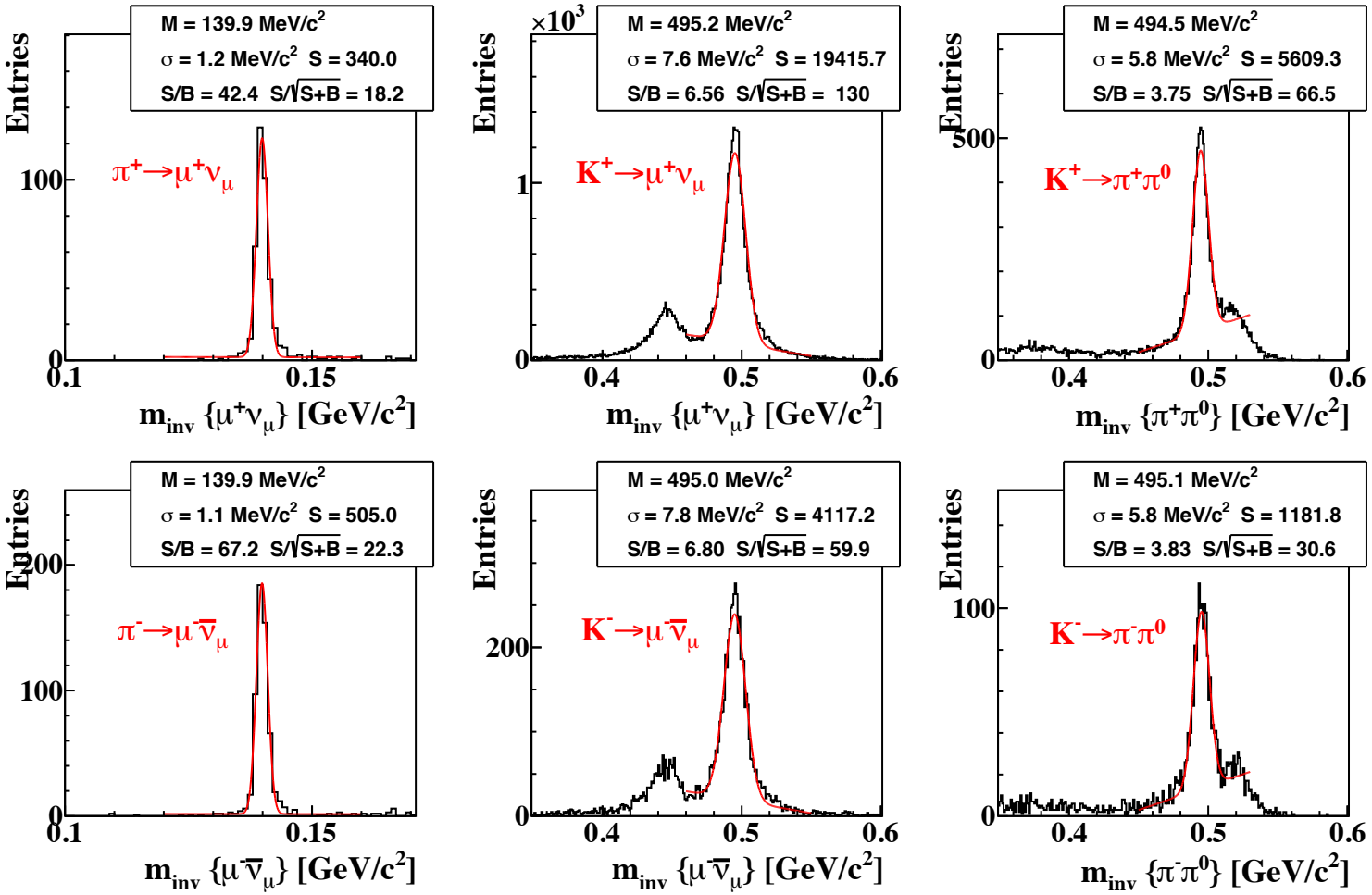
STAR BES-II: 2018-2021





STAR FXT, run 20, HLT online express production (standard version)

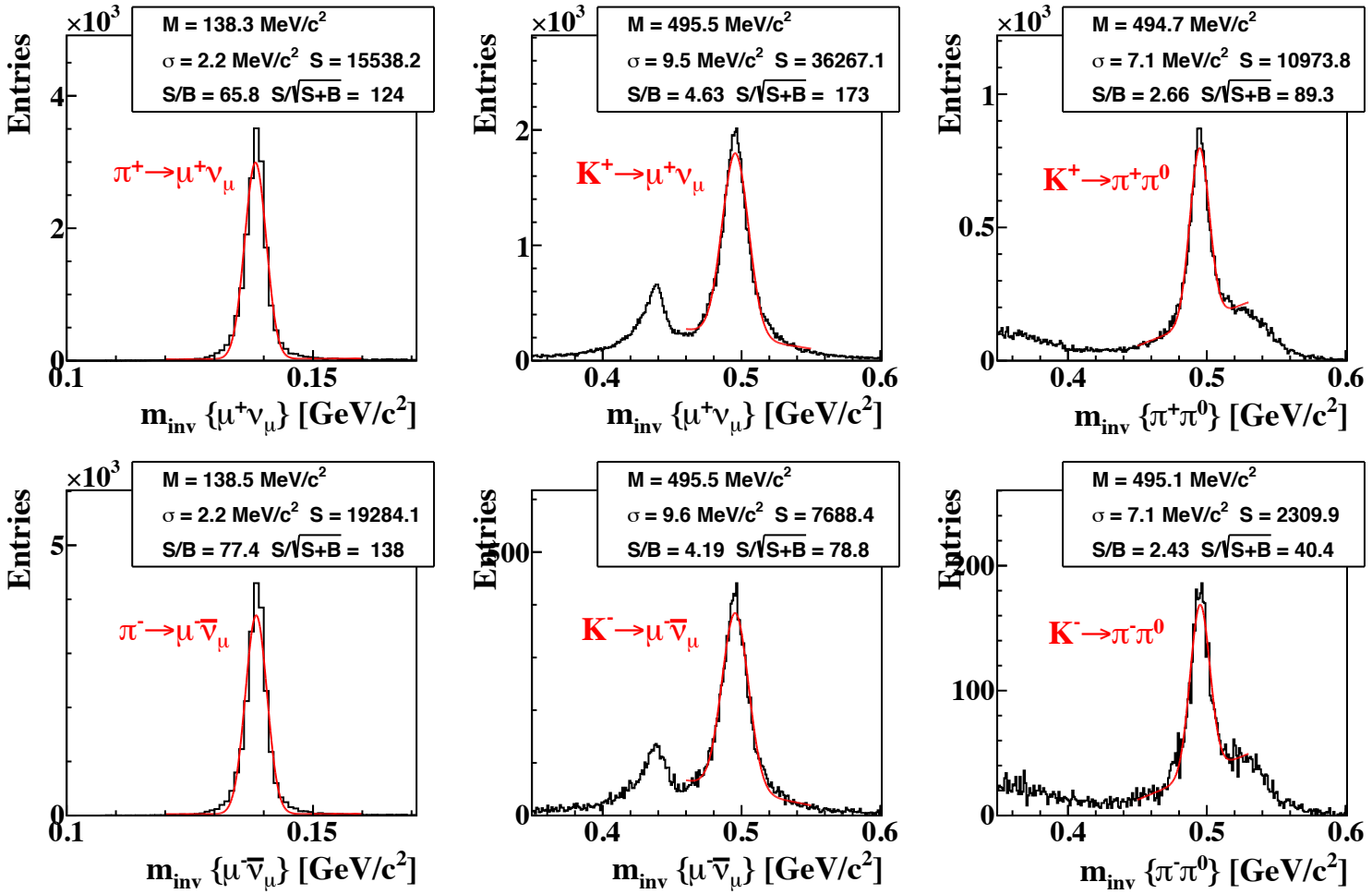
2M AuAu events at 5.75+7.3+9.8+26.5 AGeV



The standard version of the missing mass method provides online reconstruction of short-lived particles of the 2020 year data with high signal to background ratio and significance.

STAR FXT, run 20, HLT online express production (improved version)

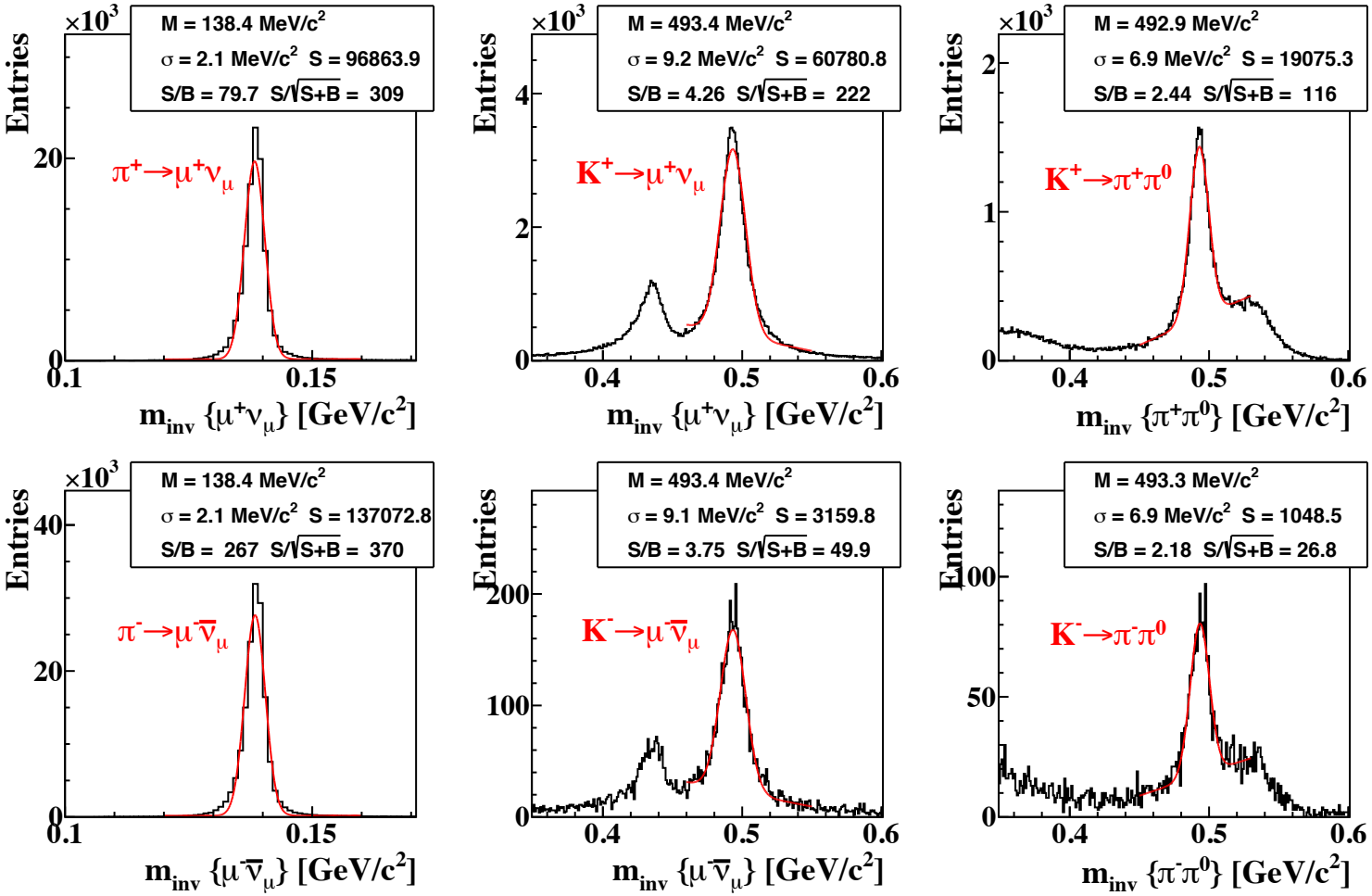
2M AuAu events at 5.75+7.3+9.8+26.5 AGeV



In the improved version in $\pi^{\pm} \rightarrow \mu^{\pm}\nu$ channels the signal increased by a factor of 40, and the significance - by a factor of 7.
In $K^{\pm} \rightarrow \mu^{\pm}\nu$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ channels, the signal increased by a factor of 2, and the significance - by a factor of 1.5.

STAR FXT, run 21, HLT online express production (May 1-2, 2021)

9M AuAu events at 3.85 AGeV



Results of the missing mass method application to real data collected in May 2021 and processed on HLT within the online express production chain.

*Second peak in $K^{\pm}$ decays resulted by misidentification of π as μ with online calibration.

Summary

- ✓ KF Particle package provides a simple and direct approach to physics analysis and is now used in CBM (FAIR/GSI), ALICE (CERN) and STAR (BNL) experiments.
- ✓ KF Particle Finder package is developed for fast online reconstruction and selection of short-lived particles.
- ✓ The Missing Mass Method is implemented as a part of the KF Particle Finder package for reconstruction of short-lived particles with neutral daughter.
- ✓ The Missing Mass Method allows a significant expansion of the physics programs of HEP and HI experiments.
- ✓ Within the FAIR Phase-0 program the KF Particle Finder package, initially developed for the CBM experiment, has been adapted to the STAR experiment and applied to real data of BES-II.
- ✓ The Missing Mass Method provides online reconstruction of real data with high signal to background ratio and significance.
- ✓ In the improved version the signal in $\pi^{\pm} \rightarrow \mu^{\pm}\nu$ channels increased by a factor of 40, and the significance - by a factor of 7. In $K^{\pm} \rightarrow \mu^{\pm}\nu$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ channels, the signal increased by a factor of 2, and the significance - by a factor of 1.5.
- ✓ Work is currently underway by the STAR collaboration to incorporate the KF Particle Finder into the StRoot framework for analysis also in the standard offline mode.