Search for Hypernuclei in STAR Express Stream with KF Particle Package

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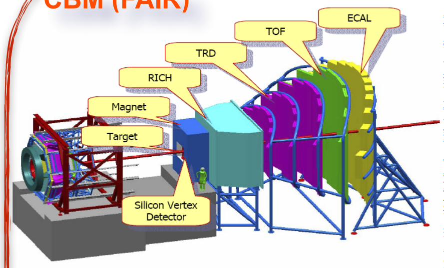
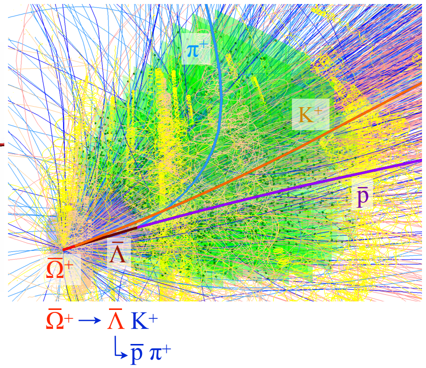
CBM → STAR: Reconstruction and Analysis Software

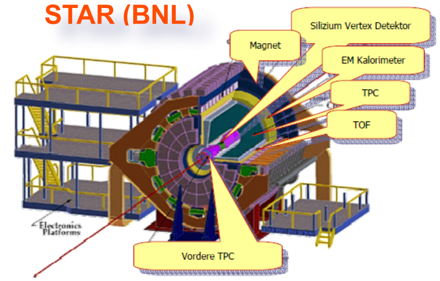
Within the FAIR Phase-0 program the CBM KF Particle Finder has been adapted to STAR and applied to Au+Au collisions recorded during 2014, 2016 and BES-I.

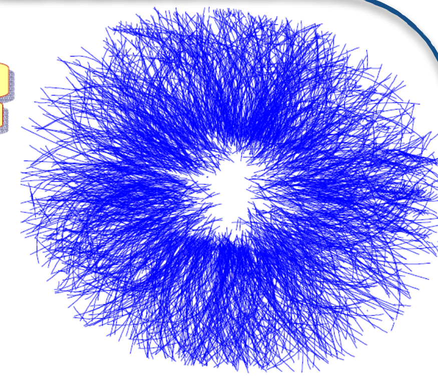
CBM (FAIR)





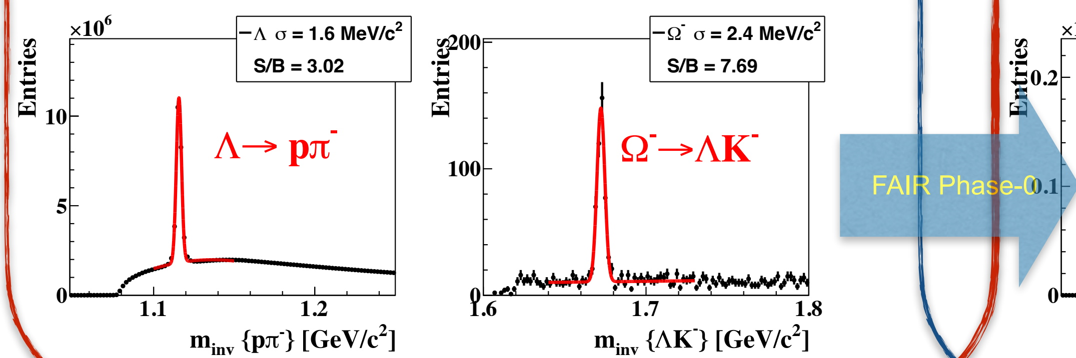
STAR (BNL)

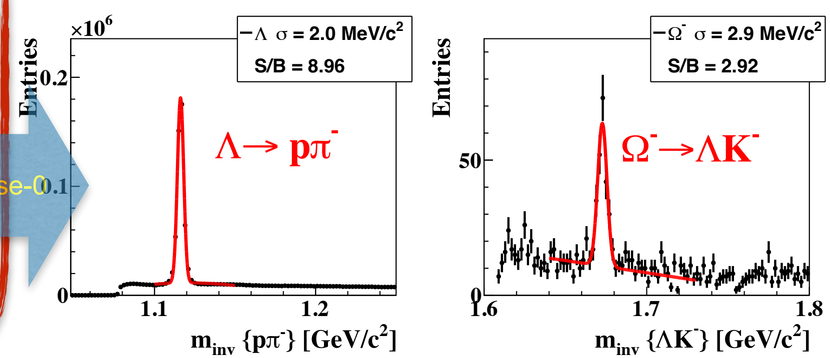




CBM, simulated data, 5M central Au+Au, 10 AGeV, PHSD

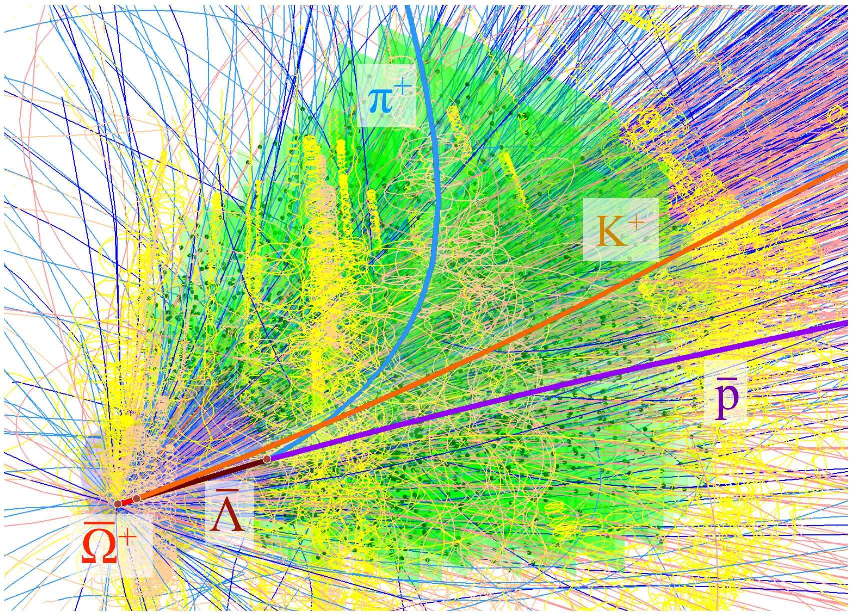
STAR, real data, 1.3M mbias Au+Au, 200 AGeV, Run 2016





- ✓ Since 2016 the 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 2013 pp 510 GeV 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)



Simulated AuAu collision at 25 AGeV

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

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

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

State vector

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

Covariance matrix

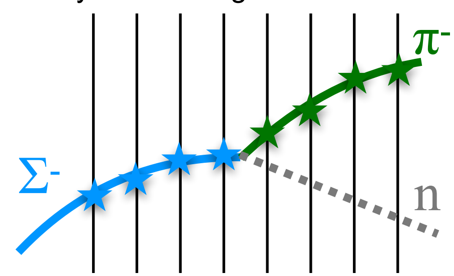
Features:

- KF Particle class describes particles by the state vector and the covariance matrix.
- The method for mathematically correct usage of covariance matrices is provided by the KF Particle package based on the Kalman Filter (KF).
- Heavy mathematics of KF requires fast and vectorised algorithms.
- Mother and daughter particles are treated in the same way.
- The natural and simple interface allows to reconstruct easily complicated decay chains.
- The package is geometry independent and is used in different experiments (CBM, ALICE, STAR, sPHENIX).

```
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
```

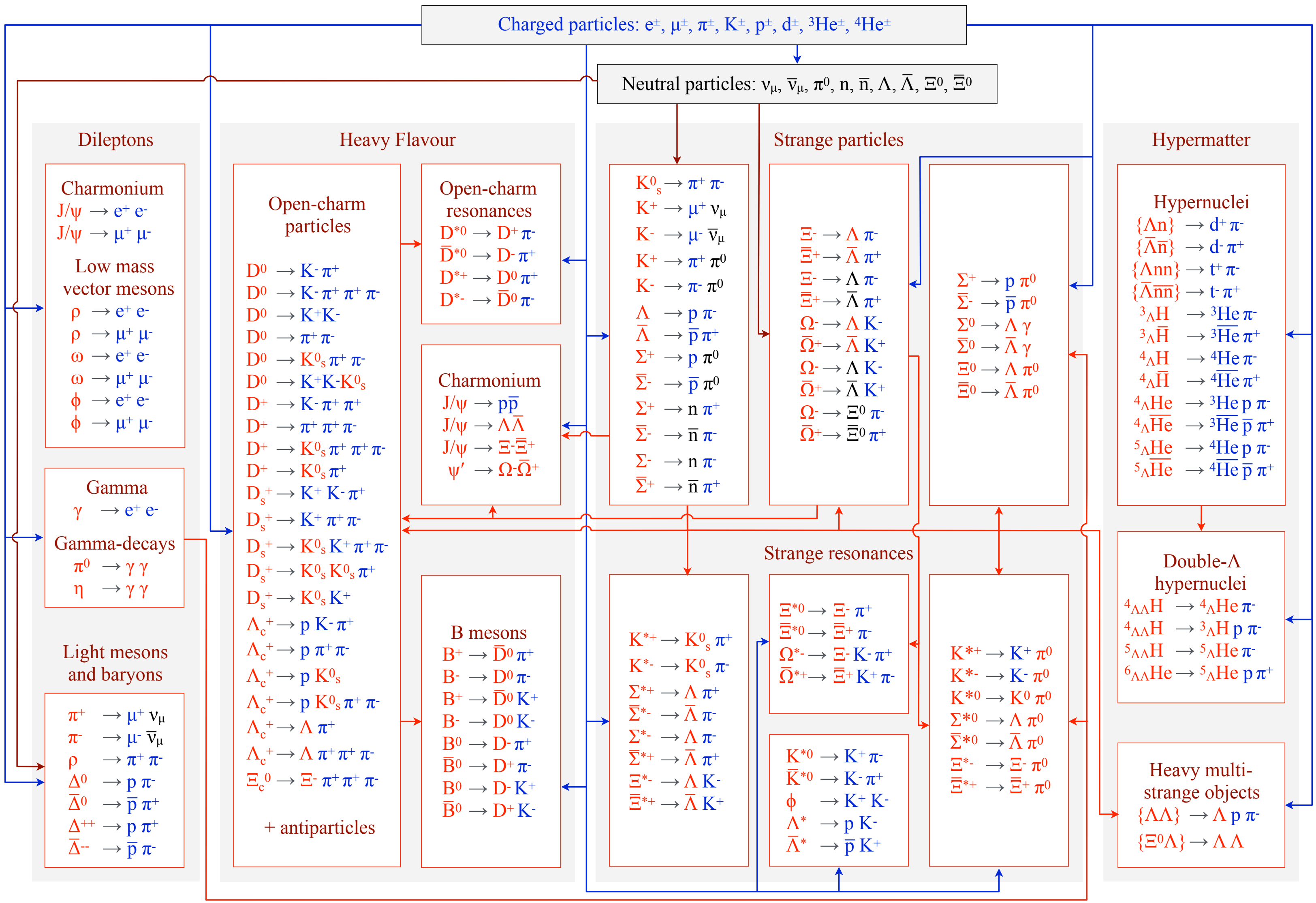
Reconstruction of decays with a neutral daughter

by the Missing Mass Method:



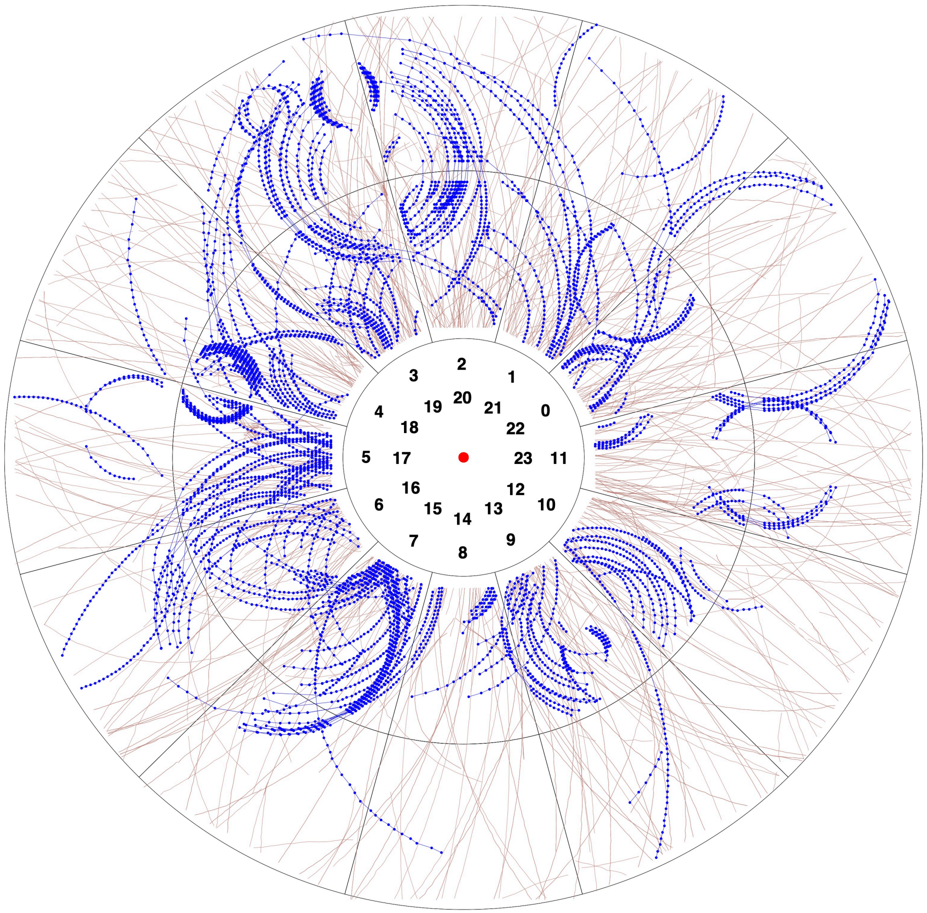
KF Particle provides a simple and very efficient approach to physics analysis

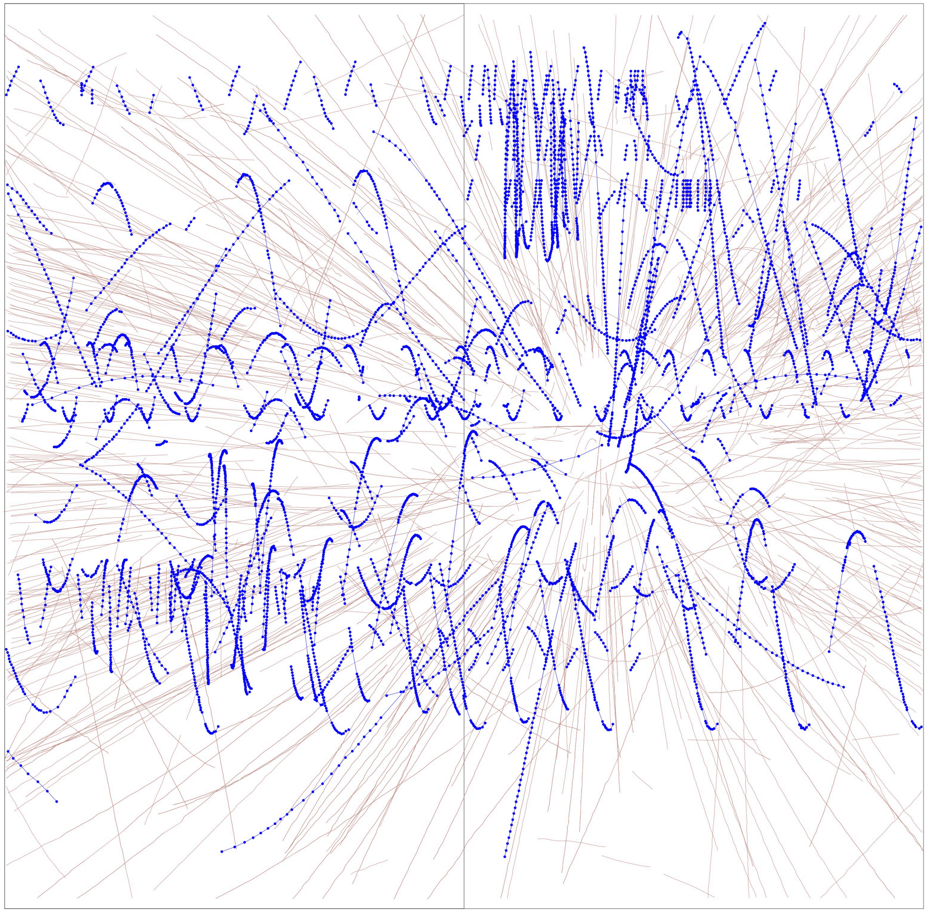
CBM → STAR: KF Particle Finder



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

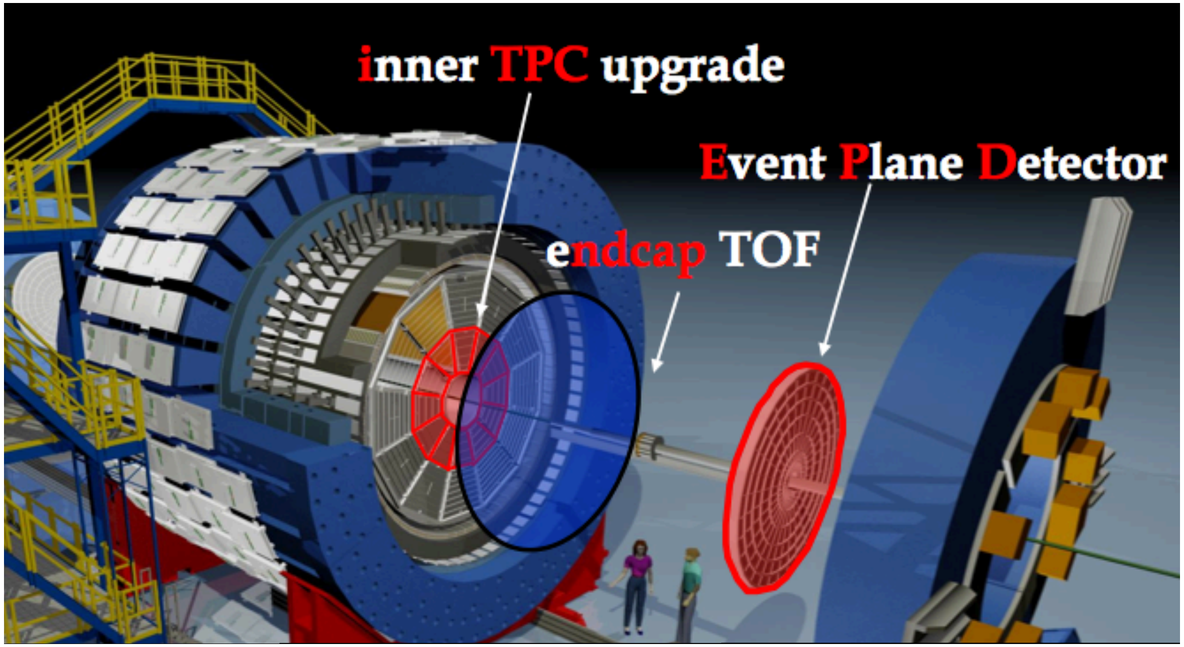
Cellular Automaton Track Finder

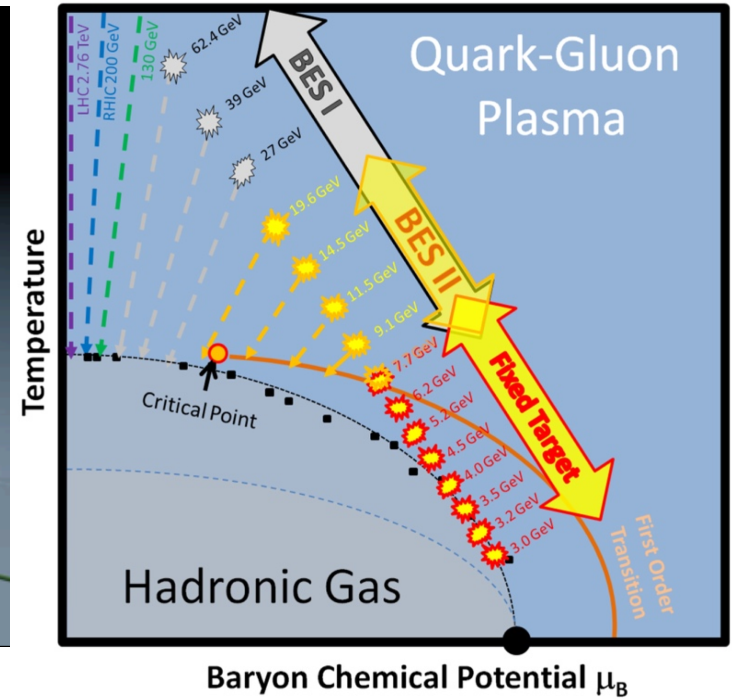


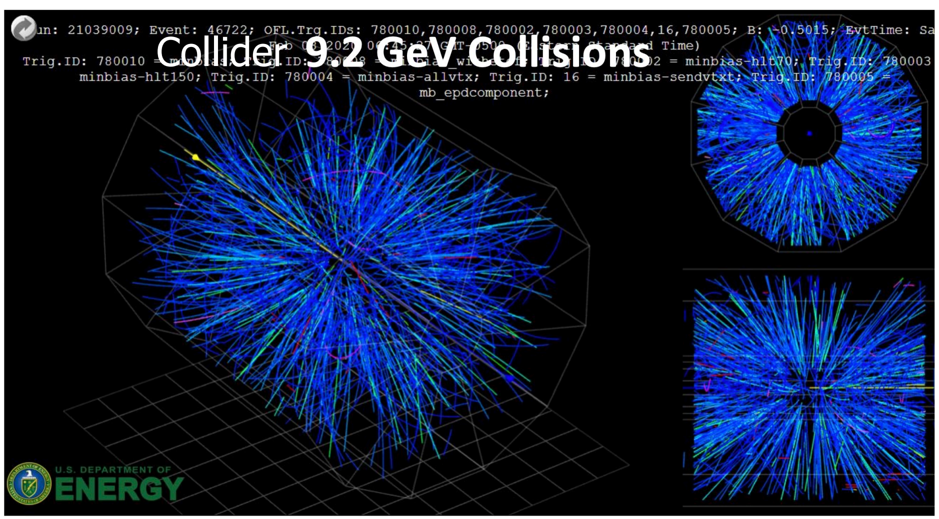


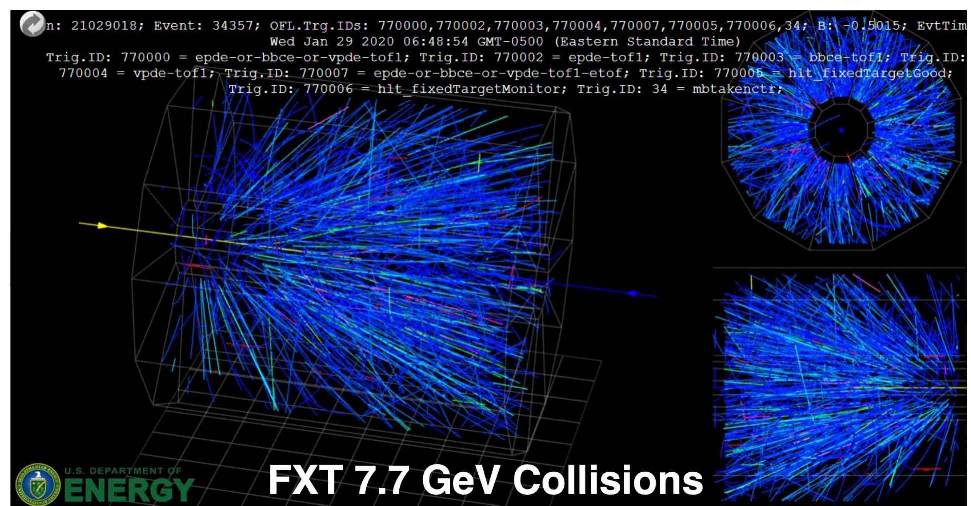
- The CA track finder has been extended to find loopers of low-momentum particles to increase pseudorapidity acceptance for tracks with $p_T < 0.4$ GeV/c.

BES-II: 2018-2021



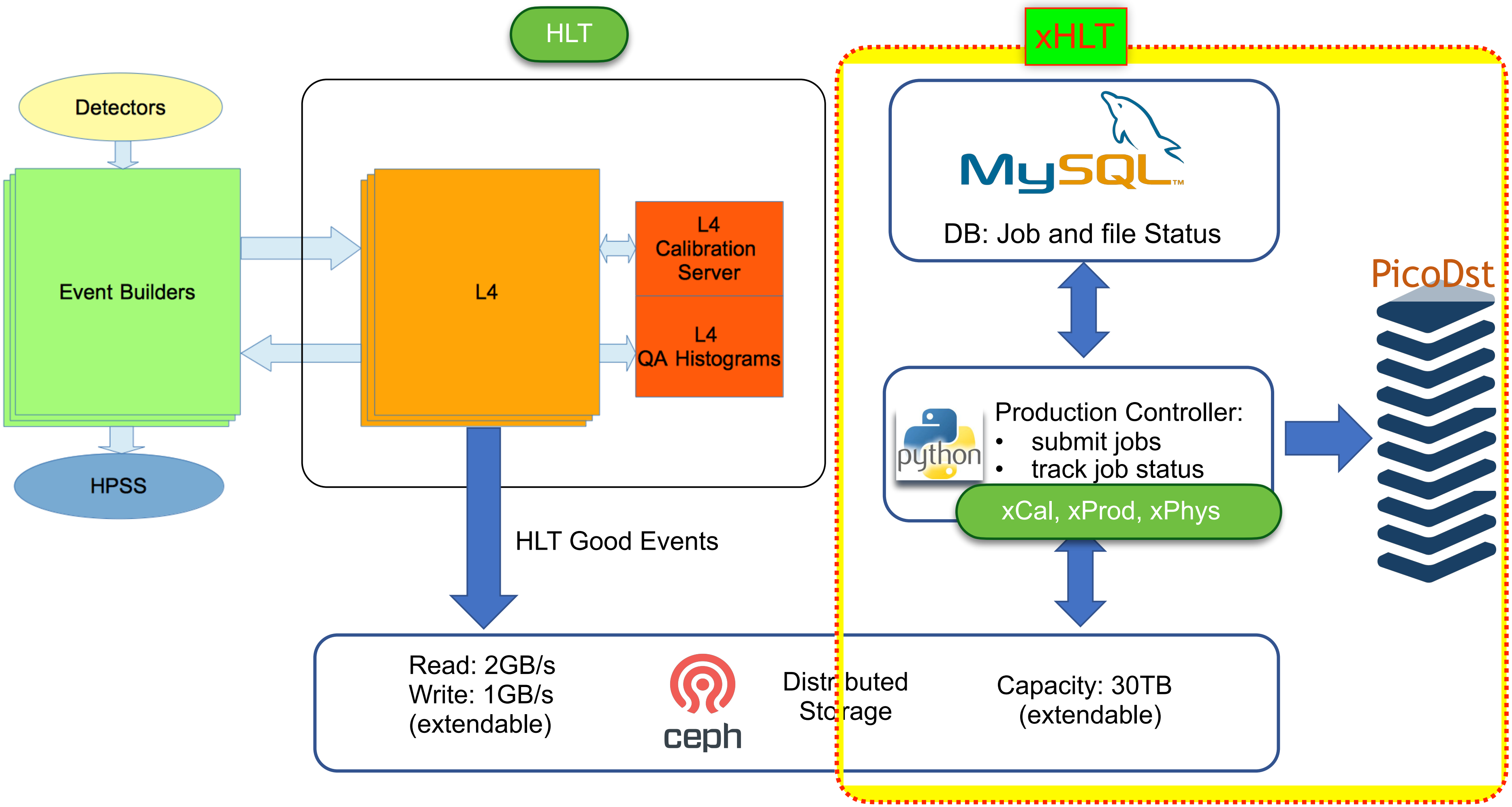






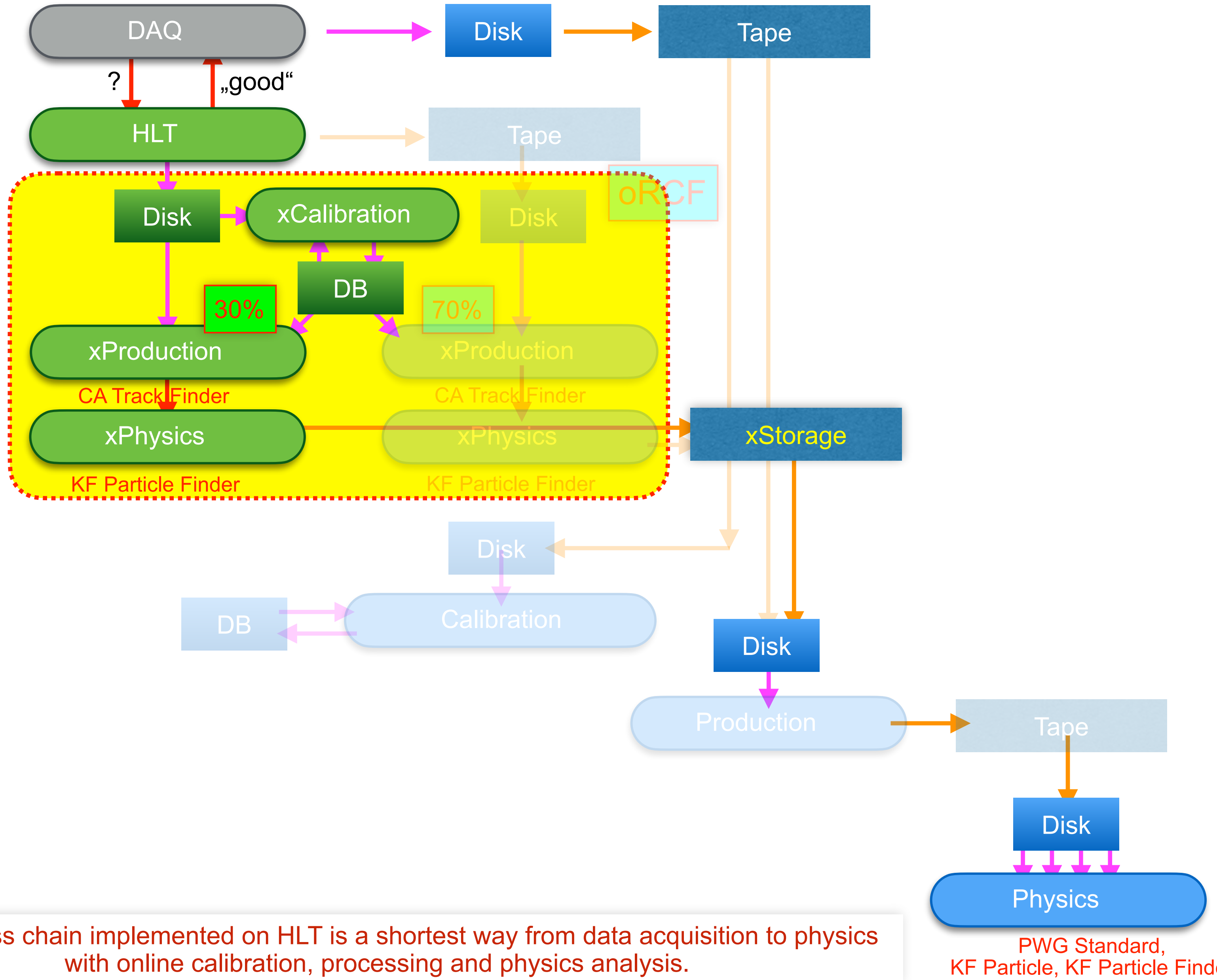
BES-II: HLT+xHLT

Extend the functionalities of STAR HLT farm with CBM FLES algorithms for express production (xHLT).



Full chain of express production and analysis has been running since 2019

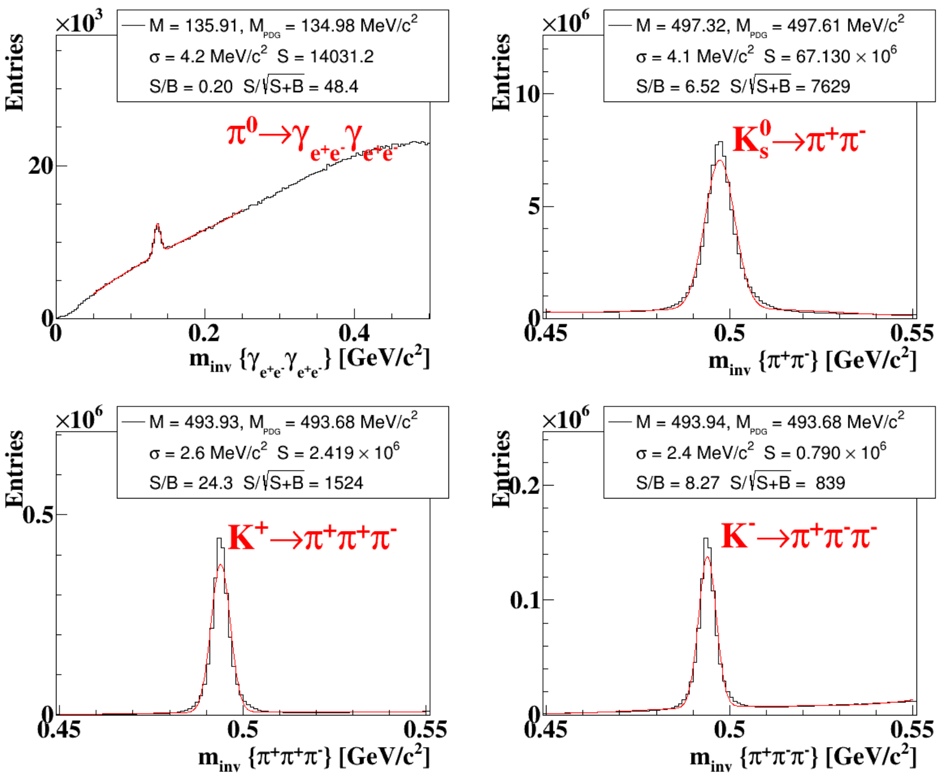
BES-II: Express Production Data Stream



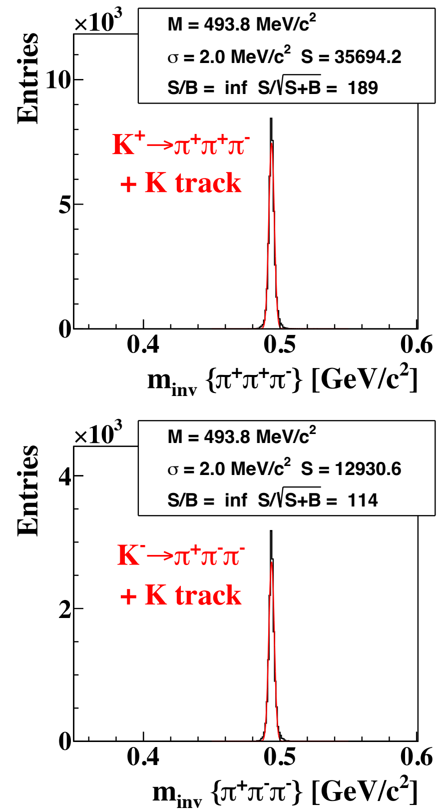
The express chain implemented on HLT is a shortest way from data acquisition to physics with online calibration, processing and physics analysis.

xBES-II: Mesons

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

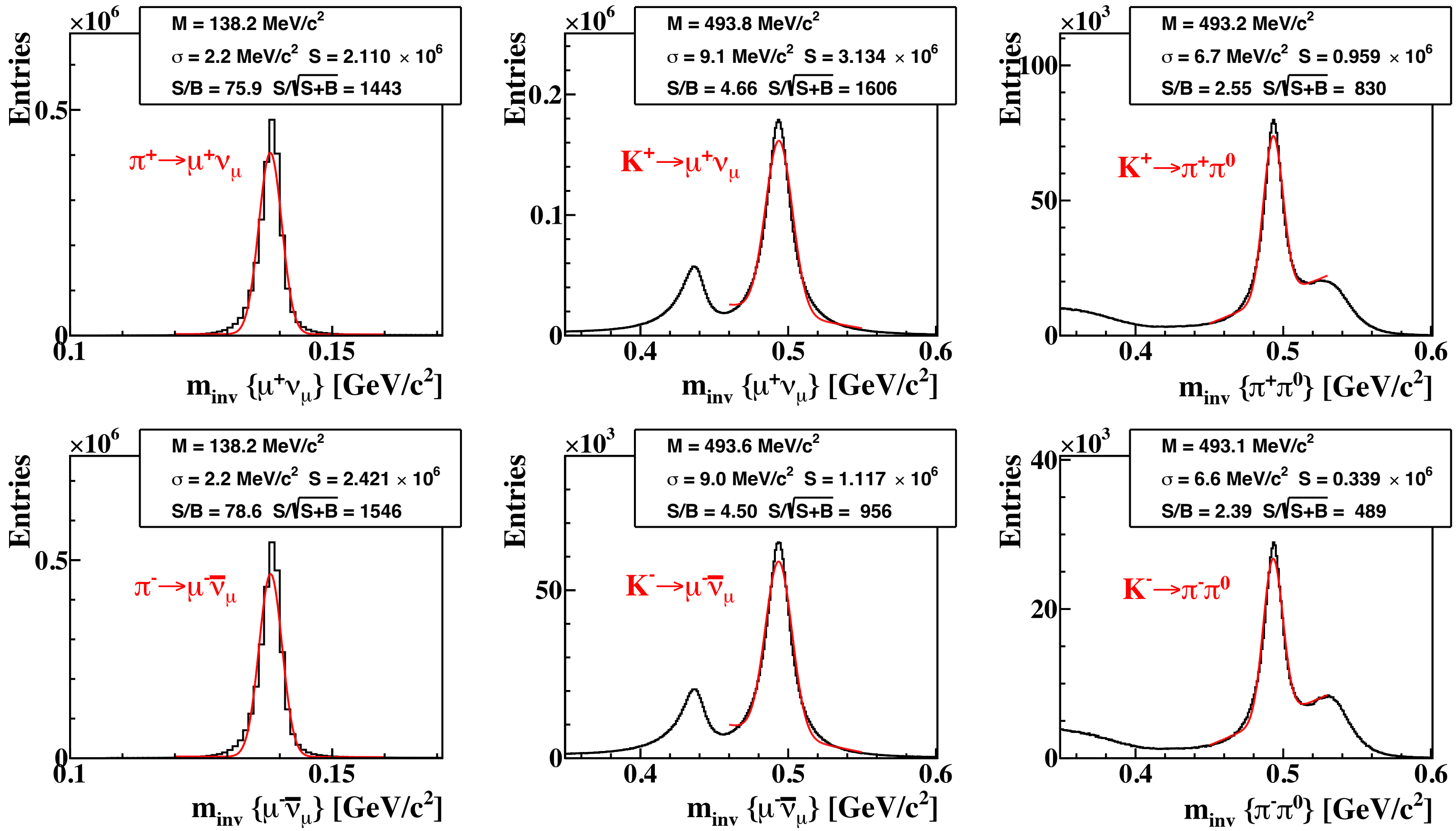


- Online (x)calibration and (x)reconstruction provide us with high quality data, thus allowing to observe even π^0 with 48 σ significance.
- Strange mesons are seen with a high significance and S/B ratio.
- STAR with its TPC allows background-free identification of charged kaons by full topological reconstruction with all 4 tracks.

Mesons are used as testbeds for the full reconstruction chain

xBES-II: Missing Mass Method

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

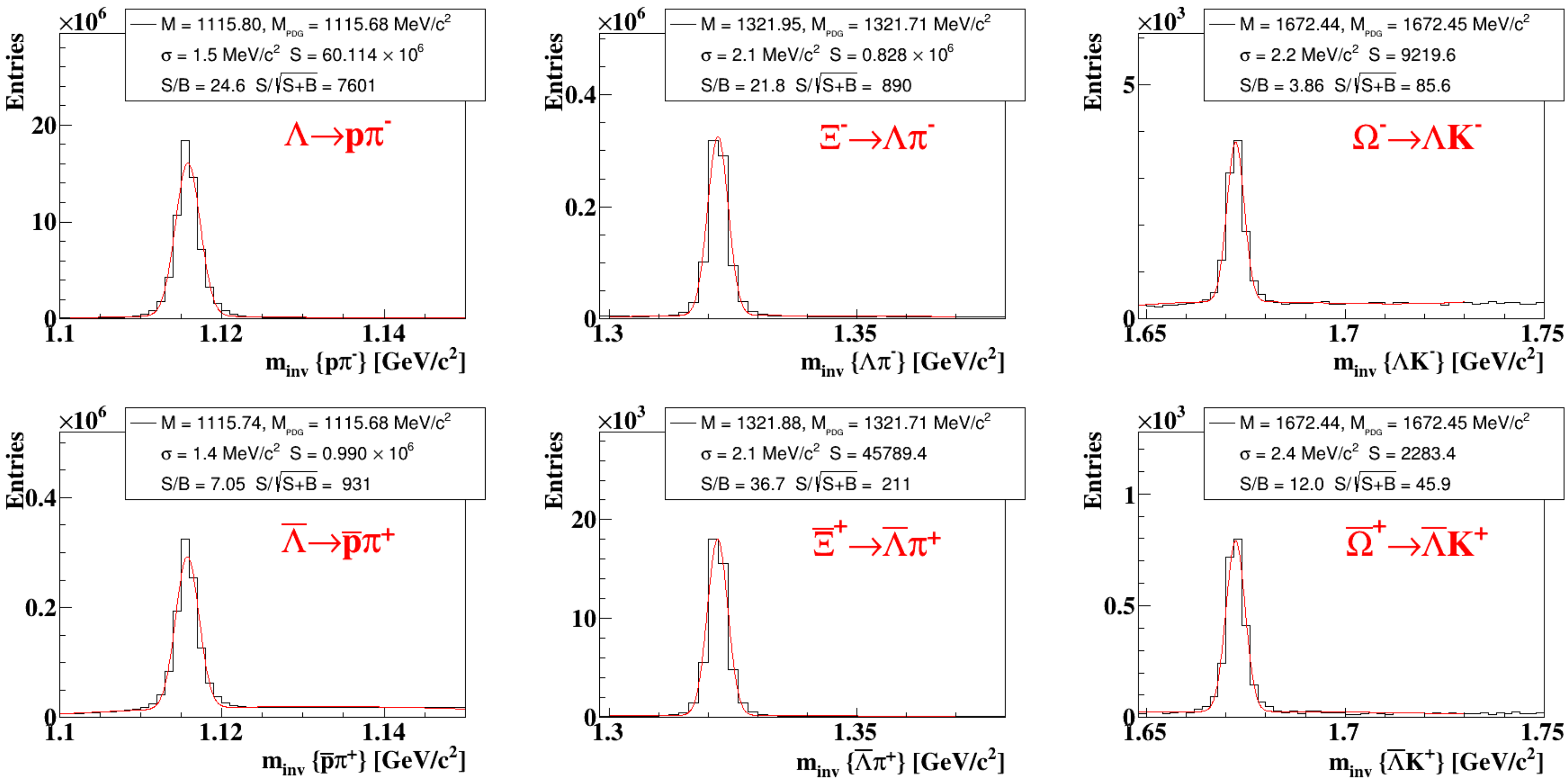


- Kaons can also be found using the Missing Mass Method.
- Second peak is due to the (μ/π) particle misidentification.

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

xBES-II: Hyperons

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

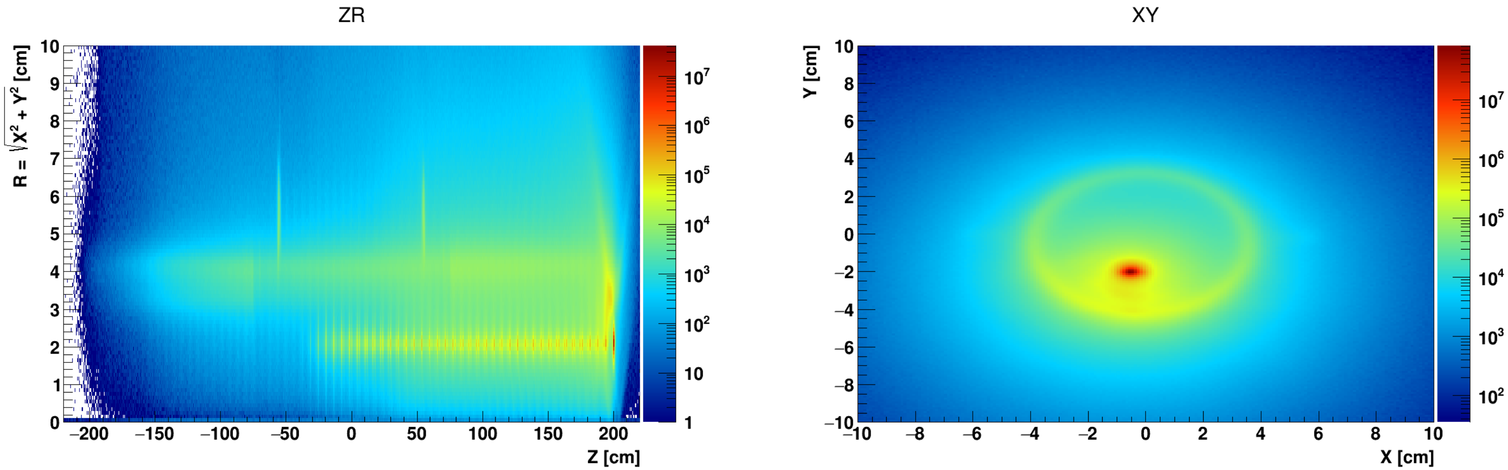


- Recently STAR has upgraded the inner part of TPC that together with an improved CA track finder have increased efficiency.
- New data give a possibility to study lower p_T region.

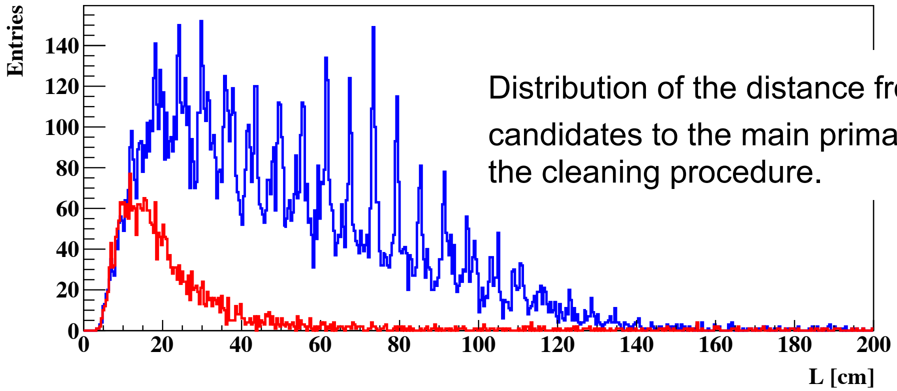
With express calibration and production we observe all hyperons with high significance and S/B ratio

Fixed Target xBES-II: Pileup

Primary Vertex



- To increase statistics the beam 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.



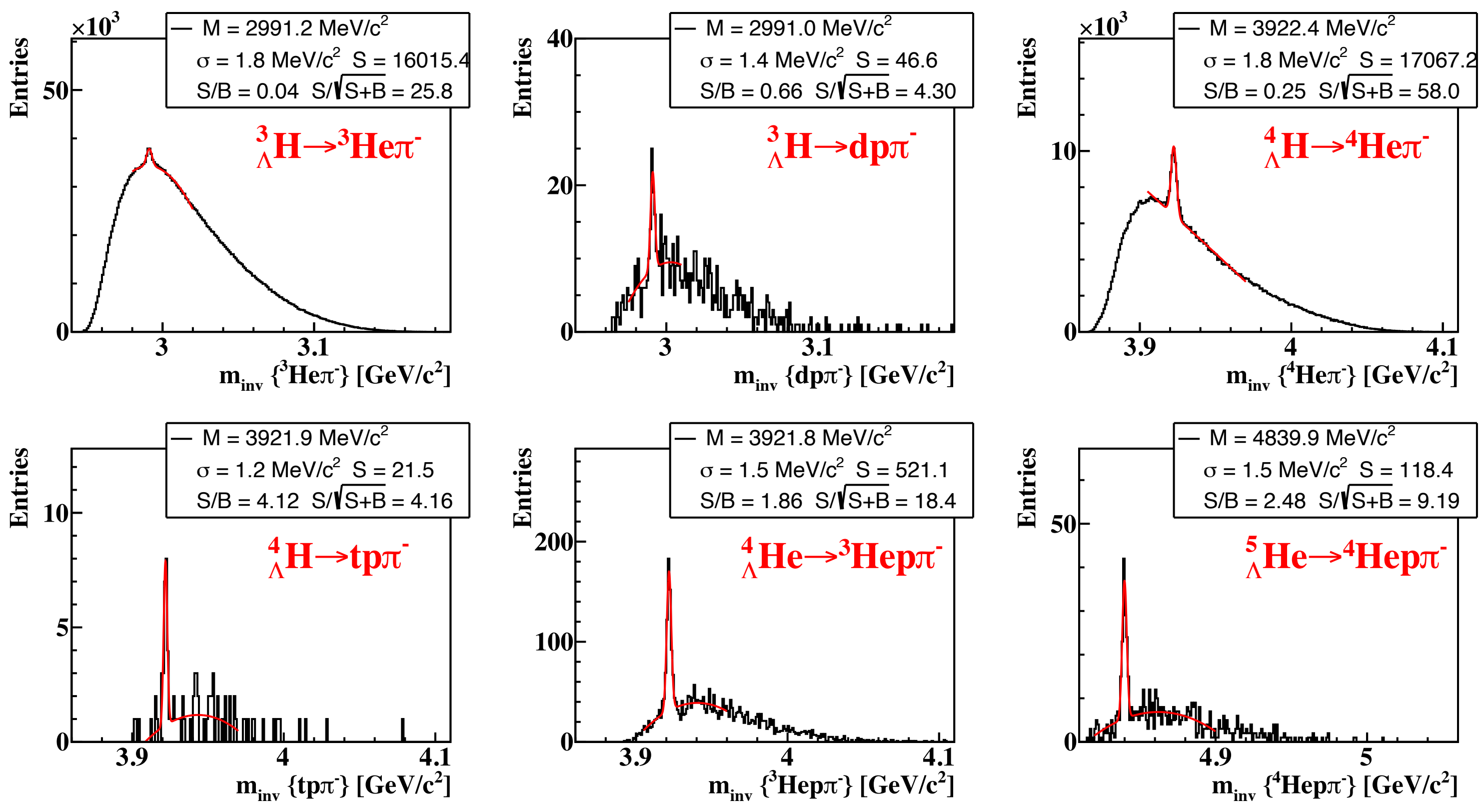
Distribution of the distance from ${}^{4}_{\Lambda}He \rightarrow {}^{3}He+p+\pi^-$ candidates to the main primary vertex without and with the cleaning procedure.

- 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 decay channels

xBES-II: Hypernuclei

Signal utilizing 437M AuAu HLT triggered events at $\sqrt{s_{NN}}$ = 3.0 GeV Fixed Target, 2021 BES-II (x)production

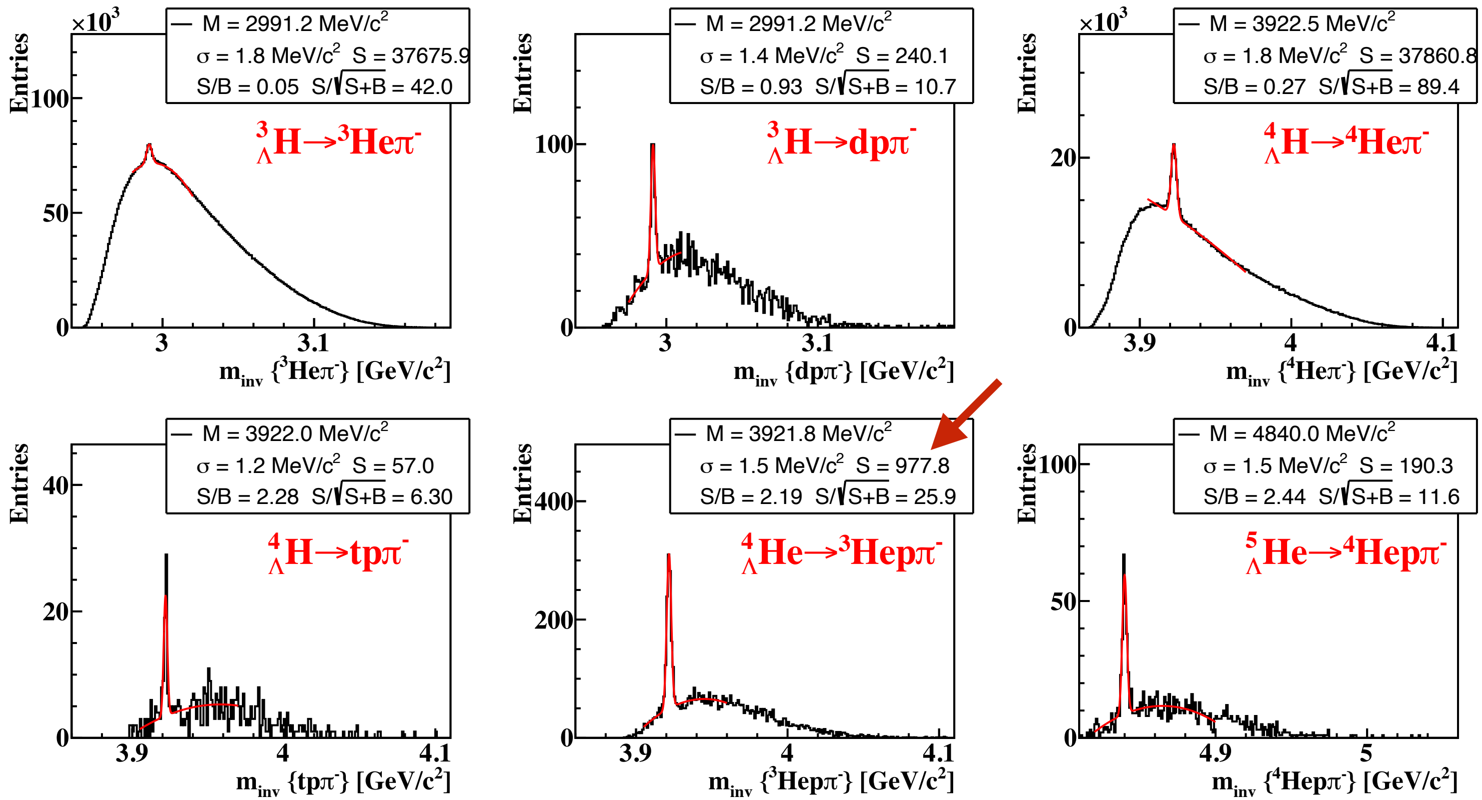


- With increased beam intensity in the Fixed Target mode HLT farm does not have enough capacities to process all collected data online.
- Therefore a trigger on He has been introduced to enhance hypernuclei.

The collected statistics is enough to measure yields, lifetimes and spectra of these hypernuclei

BES-II: Hypernuclei

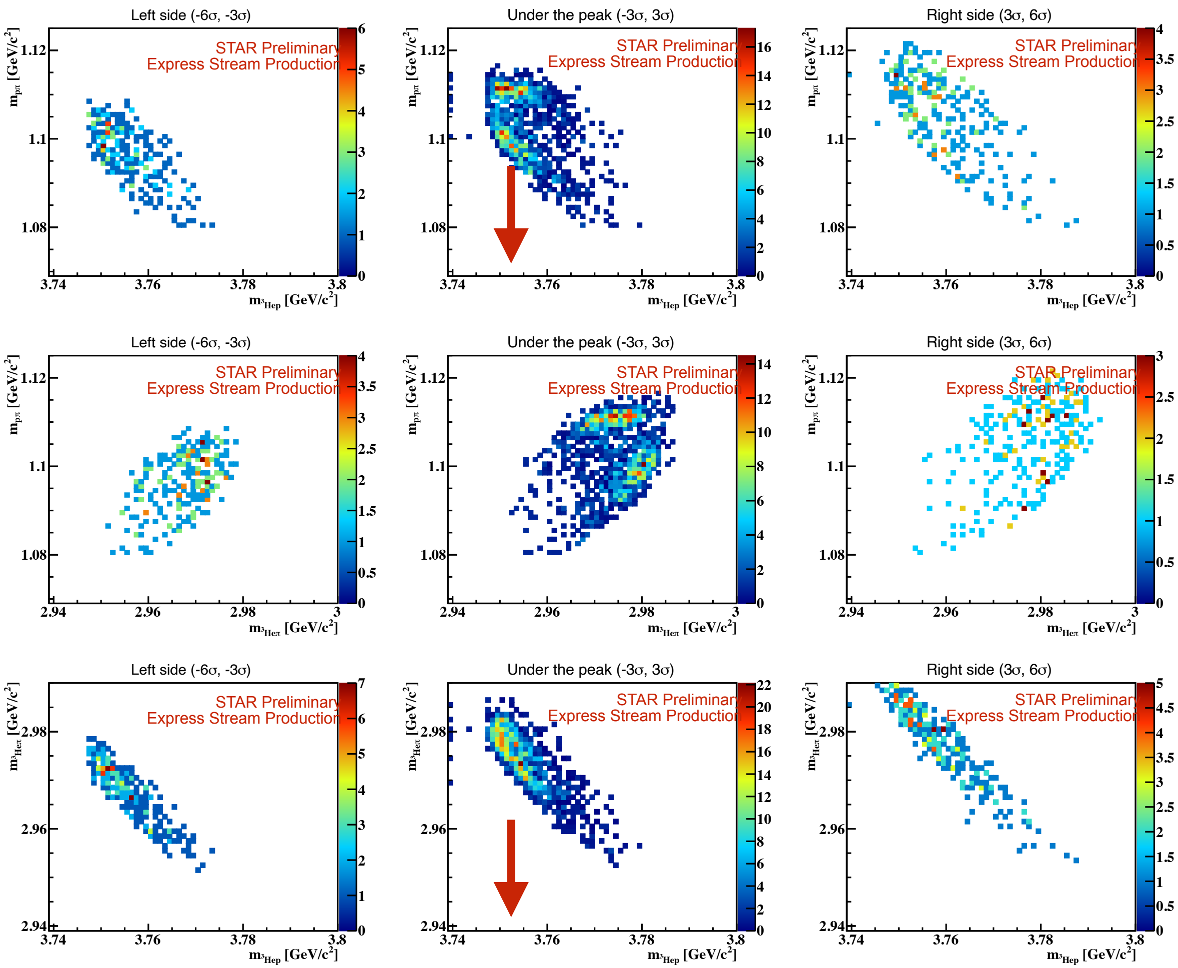
2018, 2019, 2020, 2021x FXT and 2021x collider at 7.7 GeV



- 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**.

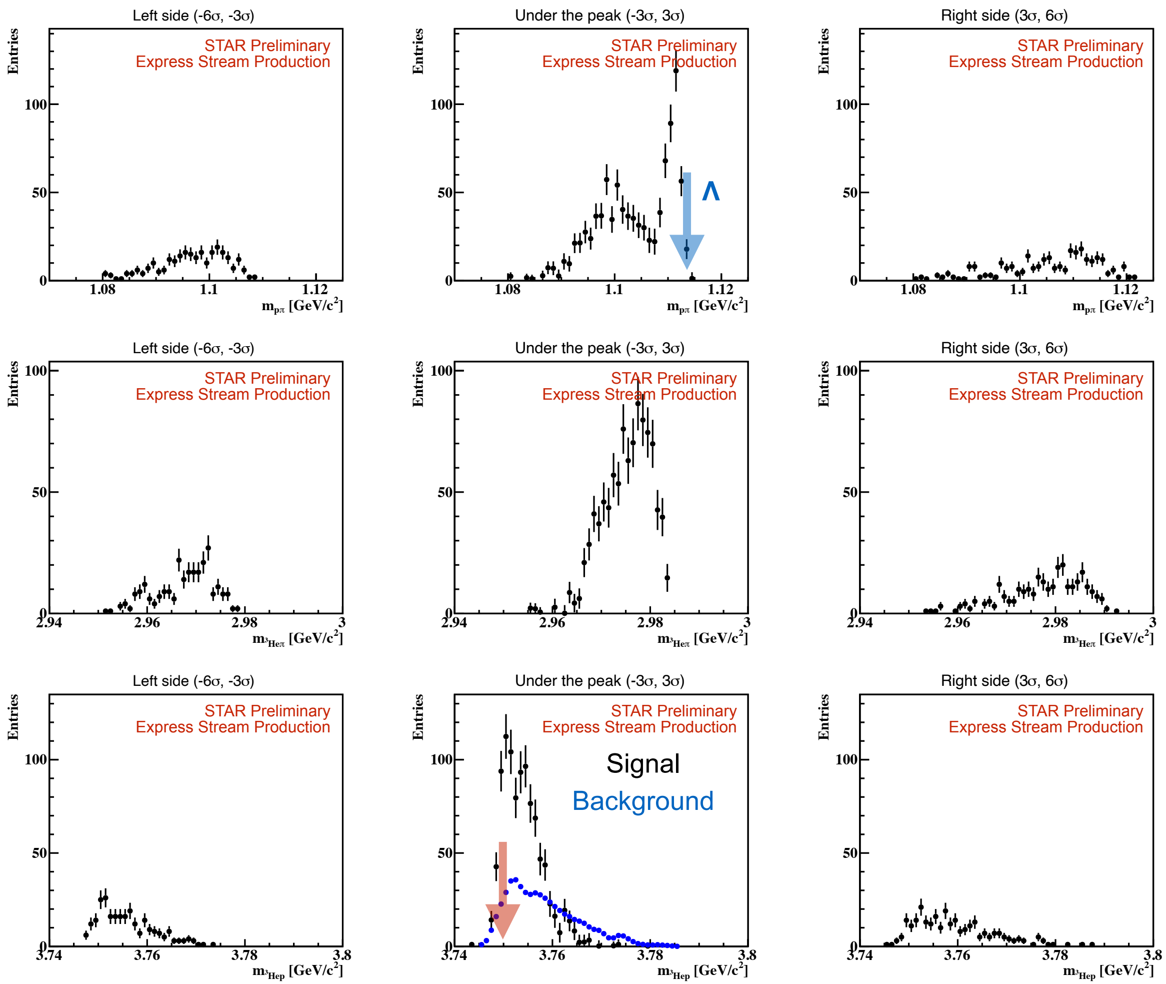
The collected statistics is enough to study Dalitz plots of 3-body channels

BES-II: Dalitz Plots: ${}^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$

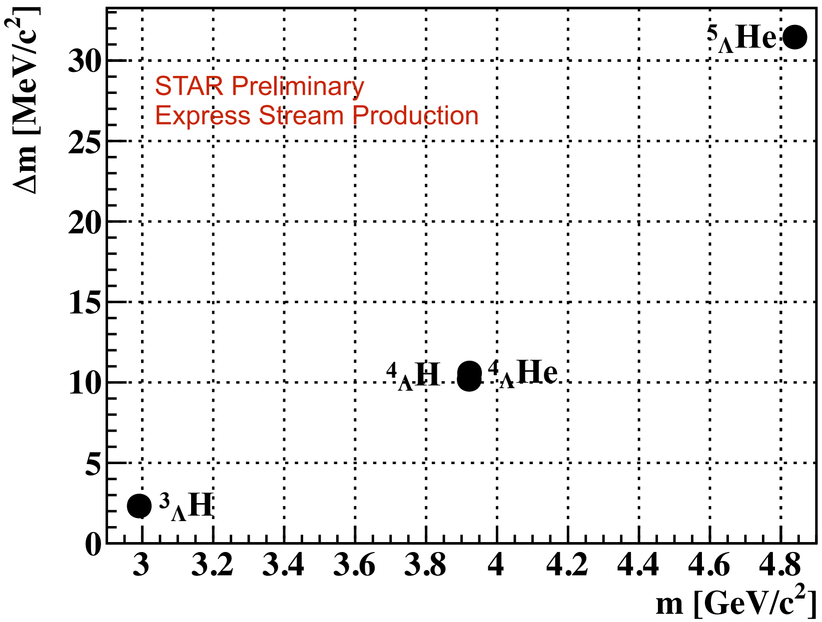


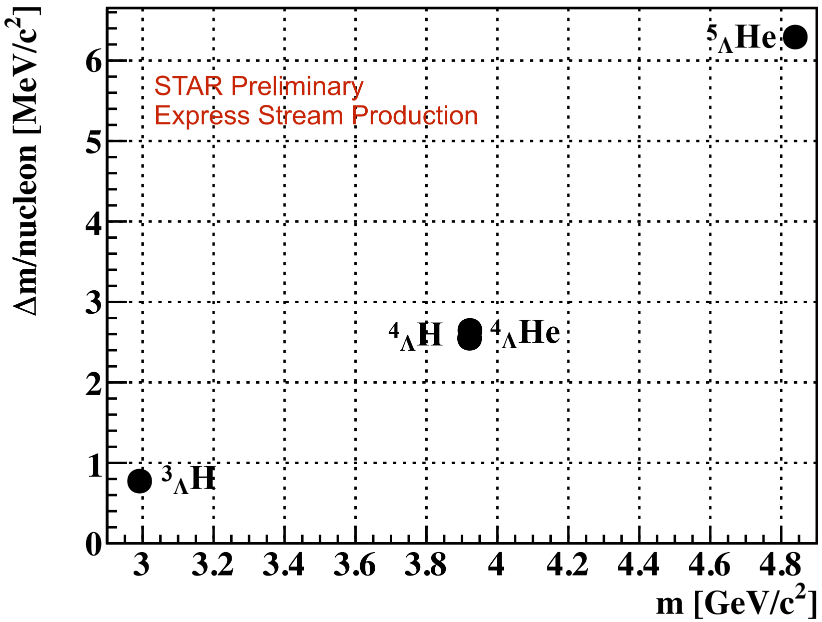
- The background was estimated with the side band method and subtracted under the peak.
- The background is smooth and no structures are observed.
- A complex structure in the signal can be explained as a possible spin effect.
- Hint of 2-body **${}^{4}Li\ \pi^{-}$** decay (${}^{4}Li$ ($J^{P} = 2^{-}$): M = 3.75 GeV/c^2, σ = 8.7 MeV/c^2).
- We observe similar structures for **${}^{3}_{\Lambda}H$** and **${}^{5}_{\Lambda}He$.**

BES-II: Dalitz Plots: ${}^{4}_{\Lambda}He \rightarrow {}^{3}He+p+\pi^{-}$



- These are projections of 2-body combinations.
- In the pπ projection the structure can be explained as a possible spin effect.
- In the nucleus-p combination the signal and background demonstrate different behavior.
- Hint of 2-body ^{4}**Li** π^{-} decay (^{4}Li ($J^{P} = 2^{-}$): M = 3.75 GeV/c^2, σ = 8.7 MeV/c^2).
- We observe similar structures for ${}^{3}_{\Lambda}$**H** and ${}^{5}_{\Lambda}$**He.**





- We observe that binding energy is increasing up to $^{5}_{\Lambda}$He.
- When comparing binding energies per nucleon, hypernuclei behave similarly as light nuclei:
  - $^{5}_{\Lambda}$He - 6.30 MeV/c², ^{4}He - 7.07 MeV/c², ^{5}He - 5.48 MeV/c², ^{5}Li - 5.27 MeV/c²;
  - $^{4}_{\Lambda}$He - 2.55 MeV/c², ^{3}He - 2.57 MeV/c², ^{4}He - 7.07 MeV/c², ^{4}Li - 1.15 MeV/c²;
  - $^{4}_{\Lambda}$H - 2.65 MeV/c², ^{3}H - 2.83 MeV/c², ^{4}H - 1.40 MeV/c²;
  - $^{3}_{\Lambda}$H - 0.8-0.9 MeV/c², ^{2}H - 1.11 MeV/c², ^{3}H - 2.83 MeV/c².
- Statistical errors are 40 - 200 keV/c², and smaller than the marker size.

Binding energy of hypernuclei together with hints on their 2-body resonance decays can be an indication that Λ behaves similarly to other nucleons (n and p) in hypernuclei

Summary

- In the express production data stream we see all signals starting from mesons and up to hypernuclei using KF Particle Finder on HLT.
- We observe ${}^{5}_{\Lambda}\mathrm{He}$ with significance of $11.6\ \sigma$.
- Dalitz plots of 3-body hypernuclei decay channels show complex structures: possibly, spin effect.
- Hints that a significant part of 3-body hypernuclei decay channels happen via nuclear resonances.
- Hypernuclei binding energy per nucleon is increasing with A up to ${}^{5}_{\Lambda}\mathrm{He}$.
- There are indications that Λ behaves similarly to other nucleons (n and p) in hypernuclei.
- Decay models are needed for efficiency estimation of 3-body channels and branching ratios.