Study of Strange Matter in STAR with Express Analysis

Ivan Kisel

(for the STAR Collaboration)

Goethe University, Frankfurt am Main
FIAS, Frankfurt Institute for Advanced Studies, Frankfurt am Main
HFHF, Helmholtz Research Academy Hesse, Frankfurt am Main
GSI, Helmholtz Center for Heavy Ion Research, Darmstadt
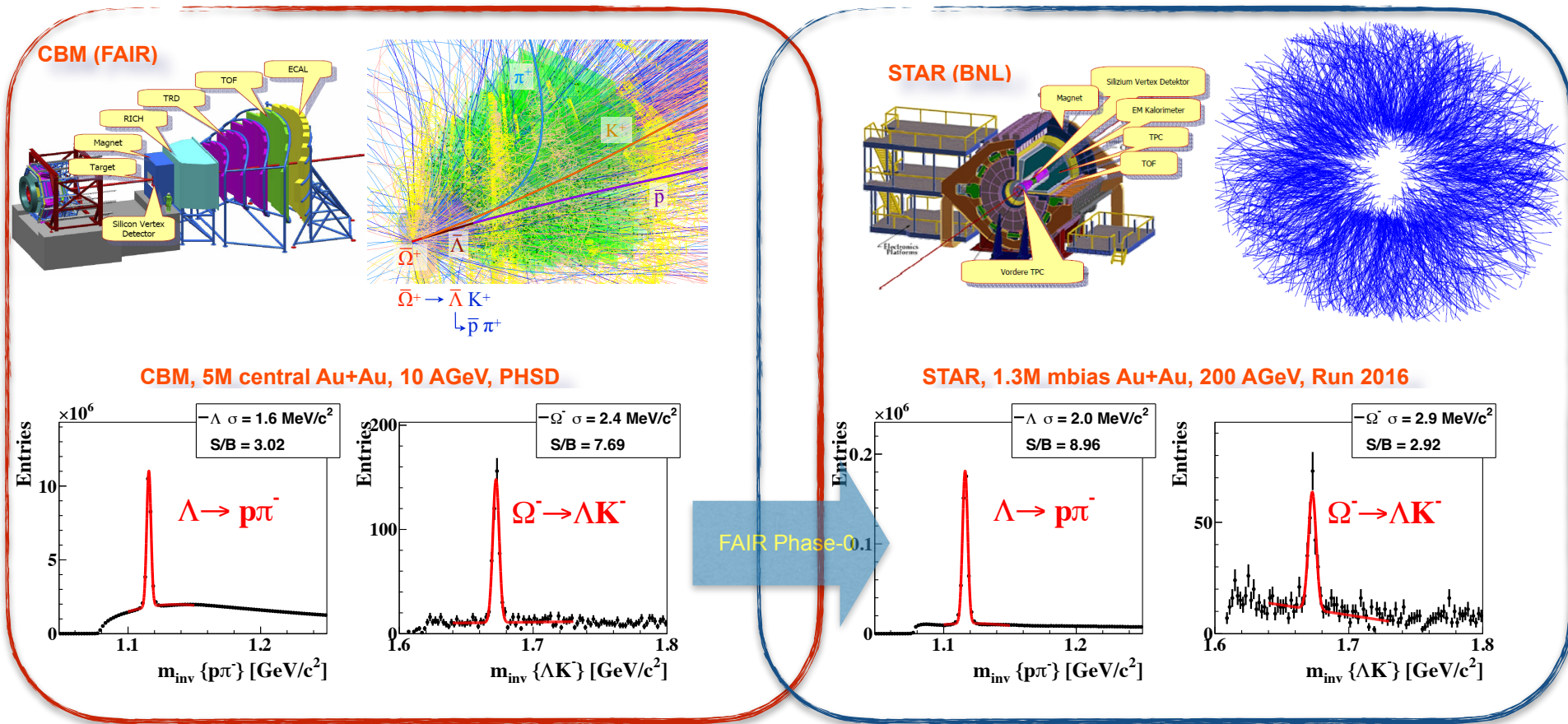
BES-II: HLT+xHLT

Extend the functionalities of STAR HLT farm with CBM FLES algorithms for express production (xHLT).
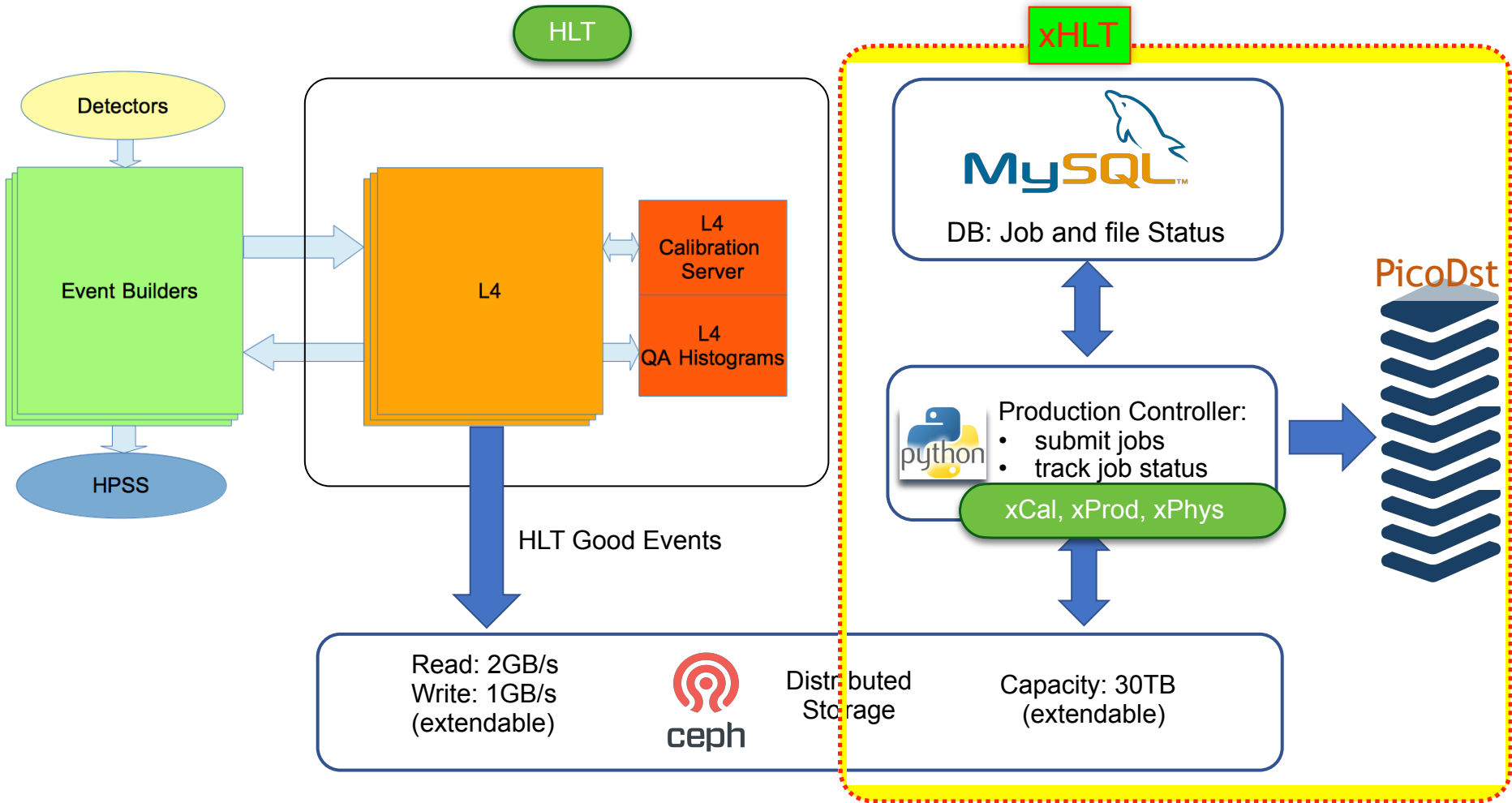
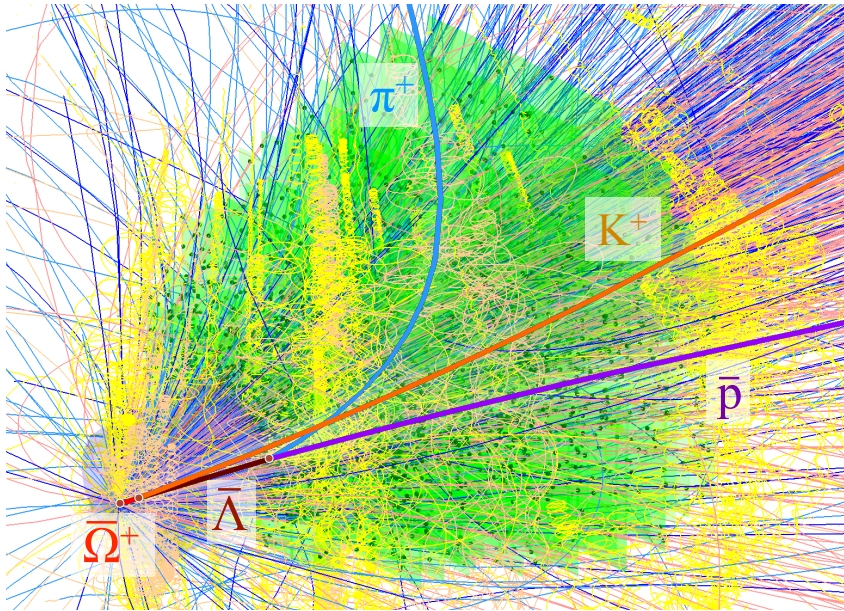Full chain of express production and analysis has been running since 2019

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.
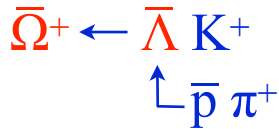

CBM, 5M central Au+Au, 30 AGeV, PHSD

$\Lambda \to p\pi^-$ — Λ σ = 1.6 MeV/c² S/B = 3.02

$\Omega^- \to \Lambda K^-$ — Ω^- σ = 2.4 MeV/c² S/B = 7.69

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

```
KFParticle Lambda(P, Pi);                // construct anti Lambda
KFParticle Omega(K, Lambda);             // construct anti Omega
PV -= (P; Pi; K);                        // clean 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
```

KFParticle provides uncomplicated approach to physics analysis (used ...)

FAIR Phase-0

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

$\Lambda \to p\pi^-$ — Λ σ = 2.0 MeV/c² S/B = 8.96

$\Omega^- \to \Lambda K^-$ — Ω^- σ = 2.9 MeV/c² S/B = 2.92

✓ Since 2016 the Cellular Automaton (CA) Track Finder is the default STAR track finder for data production. Use of CA provides 25% more D⁰ 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)

Concept of KF Particle in CBM

③ KFParticle: Reconstruction of Vertices and Decayed Particles

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

State vector

State vector — Position, direction, momentum and energy

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

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

Covariance matrix

Concept:
- Mother and daughter particles have the same state vector and are treated in the same way
- Reconstruction of decay chains ... by the state vector
- Kalman filter 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

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

Simulated AuAu collision at 25 AGeV

```
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
```
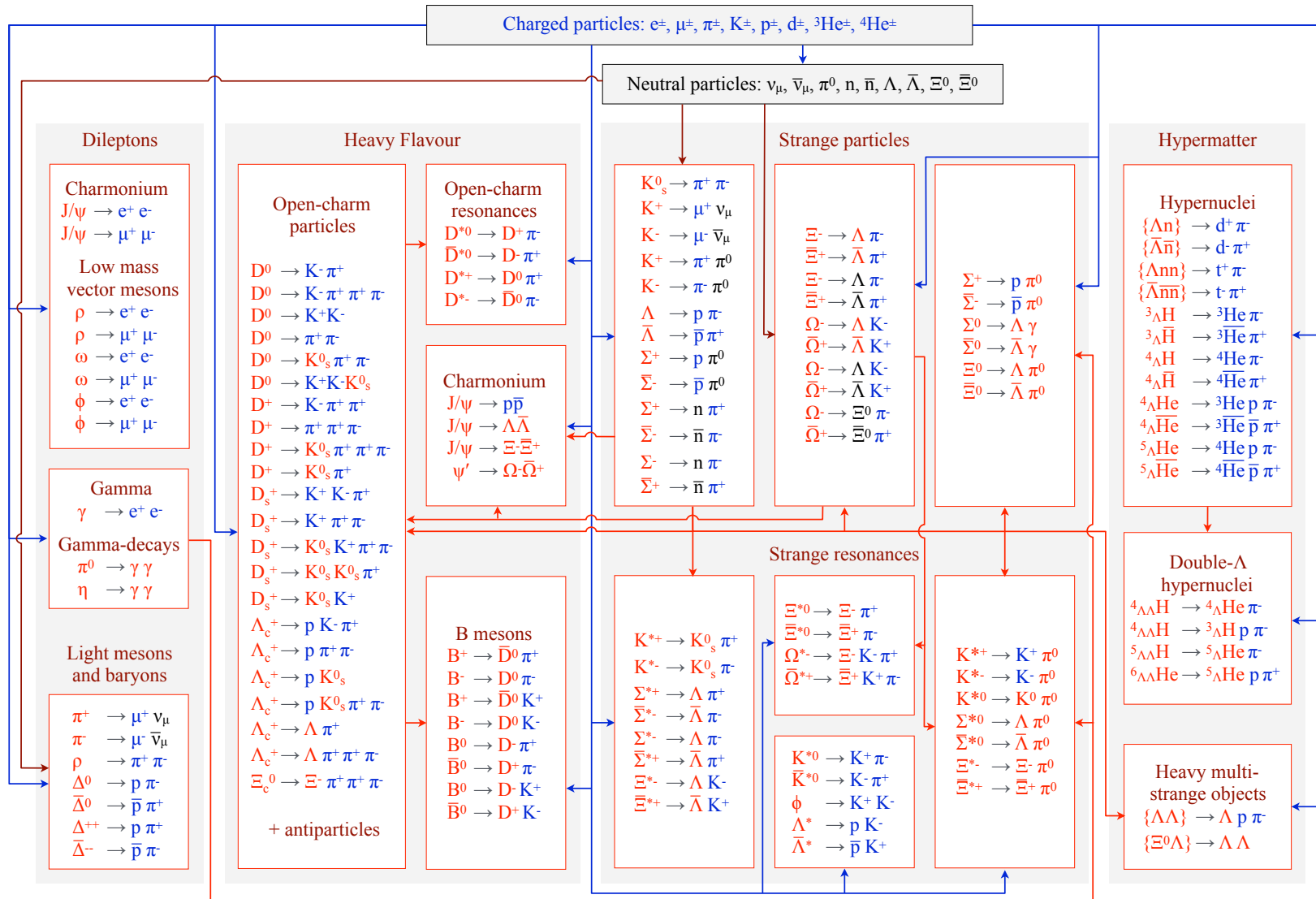
KFParticle provides uncomplicated approach to physics analysis (used in CBM, ALICE and STAR)

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

V. Akishina, I. Kisel, Uni-Frankfurt, FIAS   MMCP 2017, Dubna, 07.07.2017   11/16

correct usage of ... by the KF Particle (KF).

... fast and vectorised

... treated in the same

... allows to reconstruct

... dent and is used in different experiments (CBM, ALICE, STAR, sPHENIX).

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20 July 2018   STAR Collaboration Meeting

```
KFParticle Lambda(P, Pi);                    // construct anti Lambda
Lambda.SetMassConstraint(1.1157);            // improve momentum and mass
KFParticle Omega(K, Lambda);                 // construct anti Omega
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(P; Pi).SetProductionVertex(Lambda);         // p, pi are fully fitted
```

Reconstruction of decays with a neutral daughter by the Missing Mass Method:

Σ^- π^- n
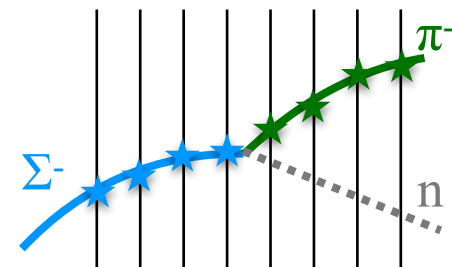
KF Particle provides a simple and very efficient approach to physics analysis

Charged particles: e±, μ±, π±, K±, p±, d±, ³He±, ⁴He±

Neutral particles: ν_μ, $\overline{\nu}_\mu$, π^0, n, $\overline{n}$, Λ, $\overline{\Lambda}$, Ξ^0, $\overline{\Xi}^0$

Dileptons

Charmonium
$J/\psi \to e^+ e^-$
$J/\psi \to \mu^+ \mu^-$

Low mass vector mesons
$\rho \to e^+ e^-$
$\rho \to \mu^+ \mu^-$
$\omega \to e^+ e^-$
$\omega \to \mu^+ \mu^-$
$\phi \to e^+ e^-$
$\phi \to \mu^+ \mu^-$

Gamma
$\gamma \to e^+ e^-$

Gamma-decays
$\pi^0 \to \gamma \gamma$
$\eta \to \gamma \gamma$

Light mesons and baryons
$\pi^+ \to \mu^+ \nu_\mu$
$\pi^- \to \mu^- \overline{\nu}_\mu$
$\rho \to \pi^+ \pi^-$
$\Delta^0 \to p \pi^-$
$\overline{\Delta}^0 \to \overline{p} \pi^+$
$\Delta^{++} \to p \pi^+$
$\overline{\Delta}^{--} \to \overline{p} \pi^-$

Heavy Flavour

Open-charm particles
$D^0 \to K^- \pi^+$
$D^0 \to K^- \pi^+ \pi^+ \pi^-$
$D^0 \to K^+ K^-$
$D^0 \to \pi^+ \pi^-$
$D^0 \to K^0_s \pi^+ \pi^-$
$D^0 \to K^+ K^- K^0_s$
$D^+ \to K^- \pi^+ \pi^+$
$D^+ \to \pi^+ \pi^+ \pi^-$
$D^+ \to K^0_s \pi^+ \pi^+ \pi^-$
$D^+ \to K^0_s \pi^+$
$D_s^+ \to K^+ K^- \pi^+$
$D_s^+ \to K^+ \pi^+ \pi^-$
$D_s^+ \to K^0_s K^+ \pi^+ \pi^-$
$D_s^+ \to K^0_s K^0_s \pi^+$
$D_s^+ \to K^0_s K^+$
$\Lambda_c^+ \to p K^- \pi^+$
$\Lambda_c^+ \to p \pi^+ \pi^-$
$\Lambda_c^+ \to p K^0_s$
$\Lambda_c^+ \to p K^0_s \pi^+ \pi^-$
$\Lambda_c^+ \to \Lambda \pi^+$
$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$
$\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-$

+ antiparticles

Open-charm resonances
$D^{*0} \to D^+ \pi^-$
$\overline{D}^{*0} \to D^- \pi^+$
$D^{*+} \to D^0 \pi^+$
$D^{*-} \to \overline{D}^0 \pi^-$

Charmonium
$J/\psi \to p\overline{p}$
$J/\psi \to \Lambda\overline{\Lambda}$
$J/\psi \to \Xi^-\overline{\Xi}^+$
$\psi' \to \Omega^-\overline{\Omega}^+$

B mesons
$B^+ \to \overline{D}^0 \pi^+$
$B^- \to D^0 \pi^-$
$B^+ \to \overline{D}^0 K^+$
$B^- \to D^0 K^-$
$B^0 \to D^- \pi^+$
$\overline{B}^0 \to D^+ \pi^-$
$B^0 \to D^- K^+$
$\overline{B}^0 \to D^+ K^-$

Strange particles

$K^0_s \to \pi^+ \pi^-$
$K^+ \to \mu^+ \nu_\mu$
$K^- \to \mu^- \overline{\nu}_\mu$
$K^+ \to \pi^+ \pi^0$
$K^- \to \pi^- \pi^0$
$\Lambda \to p \pi^-$
$\overline{\Lambda} \to \overline{p} \pi^+$
$\Sigma^+ \to p \pi^0$
$\overline{\Sigma}^- \to \overline{p} \pi^0$
$\Sigma^+ \to n \pi^+$
$\overline{\Sigma}^- \to \overline{n} \pi^-$
$\Sigma^- \to n \pi^-$
$\overline{\Sigma}^+ \to \overline{n} \pi^+$

$\Xi^- \to \Lambda \pi^-$
$\overline{\Xi}^+ \to \overline{\Lambda} \pi^+$
$\Xi^- \to \Lambda \pi^-$
$\overline{\Xi}^+ \to \overline{\Lambda} \pi^+$
$\Omega^- \to \Lambda K^-$
$\overline{\Omega}^+ \to \overline{\Lambda} K^+$
$\Omega^- \to \Lambda K^-$
$\overline{\Omega}^+ \to \overline{\Lambda} K^+$

$\Sigma^+ \to p \pi^0$
$\overline{\Sigma}^- \to \overline{p} \pi^0$
$\Sigma^0 \to \Lambda \gamma$
$\overline{\Sigma}^0 \to \overline{\Lambda} \gamma$
$\Xi^0 \to \Lambda \pi^0$
$\overline{\Xi}^0 \to \overline{\Lambda} \pi^0$

Strange resonances

$\Xi^{*0} \to \Xi^- \pi^+$
$\overline{\Xi}^{*0} \to \overline{\Xi}^+ \pi^-$
$\Omega^{*-} \to \Xi^- K^- \pi^+$
$\overline{\Omega}^{*+} \to \overline{\Xi}^+ K^+ \pi^-$

$K^{*+} \to K^0_s \pi^+$
$K^{*-} \to K^0_s \pi^-$
$\Sigma^{*+} \to \Lambda \pi^+$
$\overline{\Sigma}^{*-} \to \overline{\Lambda} \pi^-$
$\Sigma^{*-} \to \Lambda \pi^-$
$\overline{\Sigma}^{*+} \to \overline{\Lambda} \pi^+$
$\Xi^{*-} \to \Lambda K^-$
$\overline{\Xi}^{*+} \to \overline{\Lambda} K^+$

$K^{*+} \to K^+ \pi^0$
$K^{*-} \to K^- \pi^0$
$K^{*0} \to K^0 \pi^0$
$\Sigma^{*0} \to \Lambda \pi^0$
$\overline{\Sigma}^{*0} \to \overline{\Lambda} \pi^0$
$\Xi^{*-} \to \Xi^- \pi^0$
$\overline{\Xi}^{*+} \to \overline{\Xi}^+ \pi^0$

$K^{*0} \to K^+ \pi^-$
$\overline{K}^{*0} \to K^- \pi^+$
$\phi \to K^+ K^-$
$\Lambda^* \to p K^-$
$\overline{\Lambda}^* \to \overline{p} K^+$

Hypermatter

Hypernuclei
$\{\Lambda n\} \to d^+ \pi^-$
$\{\overline{\Lambda n}\} \to d^- \pi^+$
$\{\Lambda nn\} \to t^+ \pi^-$
$\{\overline{\Lambda nn}\} \to t^- \pi^+$
$^3_\Lambda H \to {}^3He \pi^-$
$^3_\Lambda \overline{H} \to {}^3\overline{He} \pi^+$
$^4_\Lambda H \to {}^4He \pi^-$
$^4_\Lambda \overline{H} \to {}^4\overline{He} \pi^+$
$^4_\Lambda He \to {}^3He p \pi^-$
$^4_\Lambda \overline{He} \to {}^3\overline{He} \overline{p} \pi^+$
$^5_\Lambda He \to {}^4He p \pi^-$
$^5_\Lambda \overline{He} \to {}^4\overline{He} \overline{p} \pi^+$

Double-Λ hypernuclei
$^4_{\Lambda\Lambda} H \to {}^4_\Lambda He \pi^-$
$^4_{\Lambda\Lambda} H \to {}^3_\Lambda H p \pi^-$
$^5_{\Lambda\Lambda} H \to {}^5_\Lambda He \pi^-$
$^6_{\Lambda\Lambda} He \to {}^5_\Lambda He p \pi^+$

Heavy multi-strange objects
$\{\Lambda\Lambda\} \to \Lambda p \pi^-$
$\{\Xi^0\Lambda\} \to \Lambda \Lambda$

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

xBES-II: Mesons

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

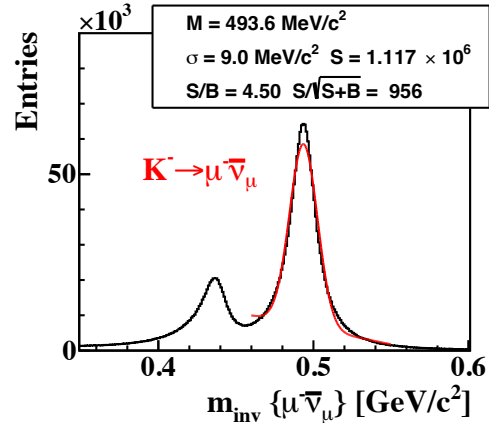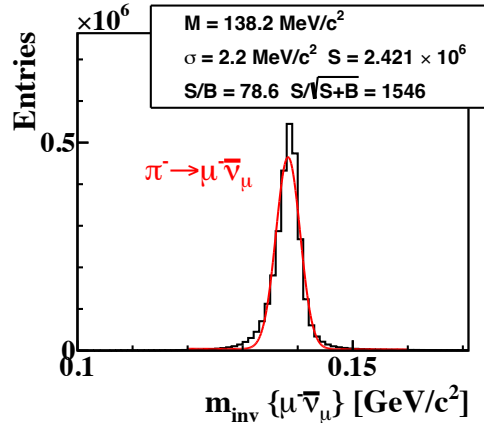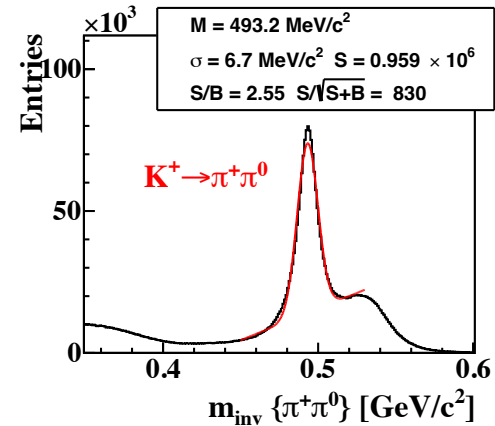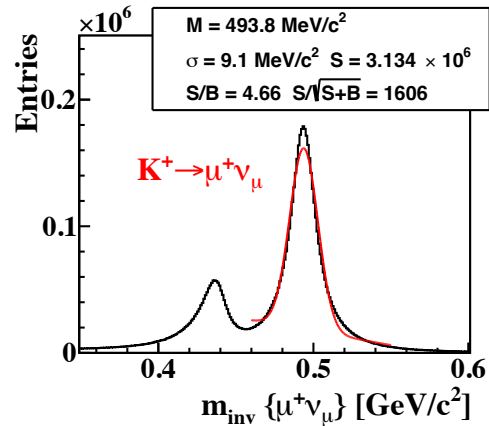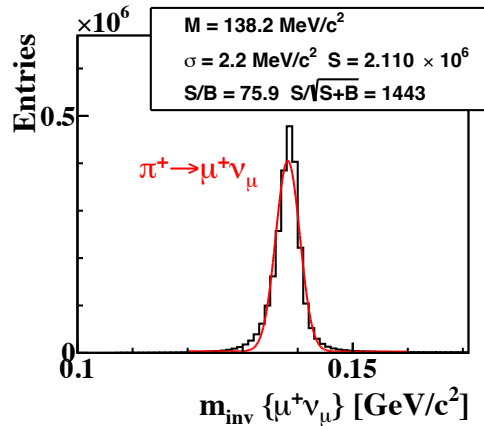Signal utilizing 32.5M AuAu events at 7.7 GeV, 2021 BES-II (x)production
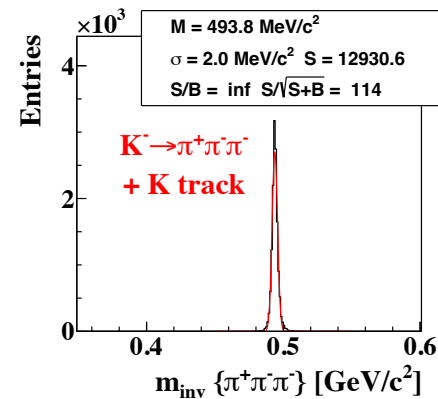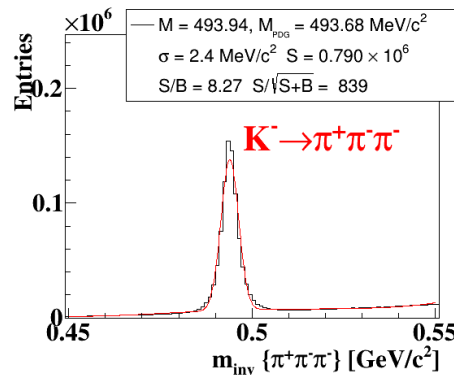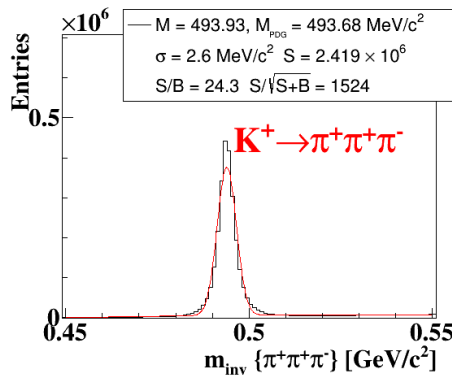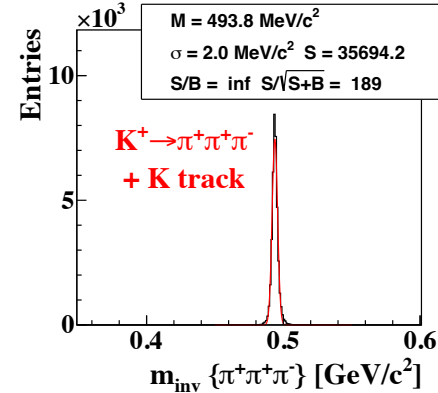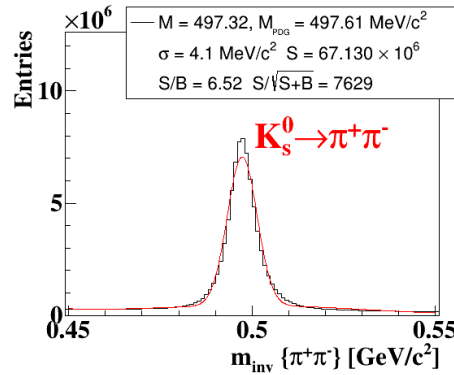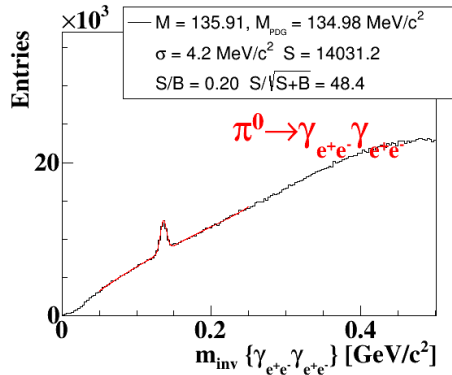
- Online (x)calibration and (x)reconstruction provide us with high quality data, thus allowing to observe even π^0 with 50 σ significance.
- Strange mesons are seen with a high significance and S/B ratio.
- STAR with its TPC allows background-free identification of charged kaons by full topological reconstruction with all 4 tracks.

Mesons are used as probes for the full reconstruction chain

xBES-II: Missing Mass Method

Signal utilizing 32.5M AuAu events at 7.7 GeV, 2021 BES-II (x)production
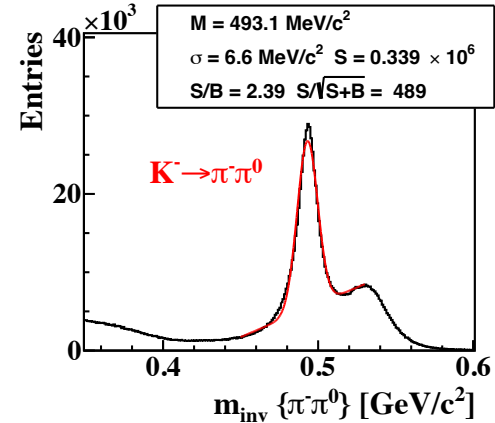
- · Kaons can also be found using the Missing Mass Method.
- · Second peak is due to the (μ/π) particle misidentification.

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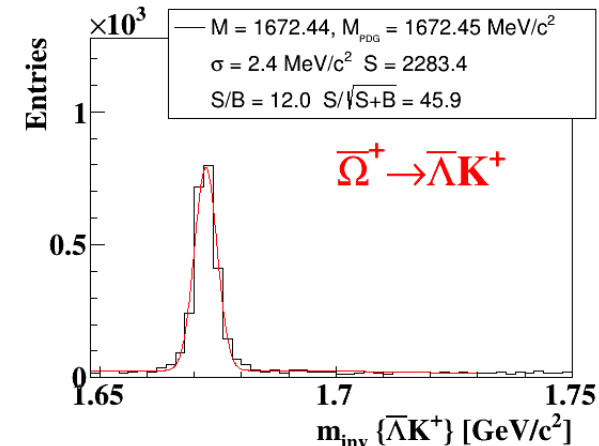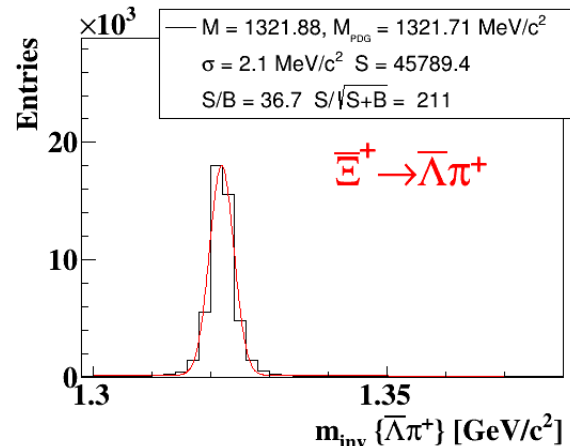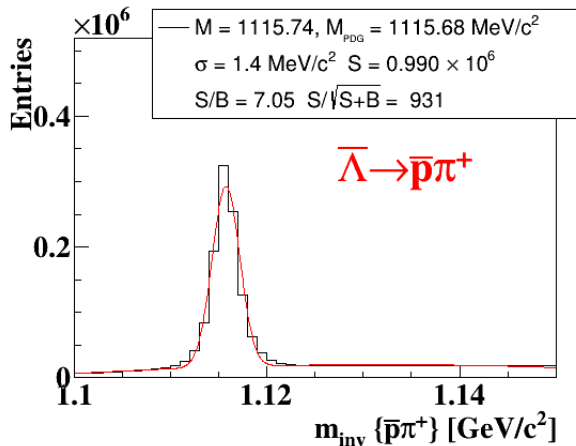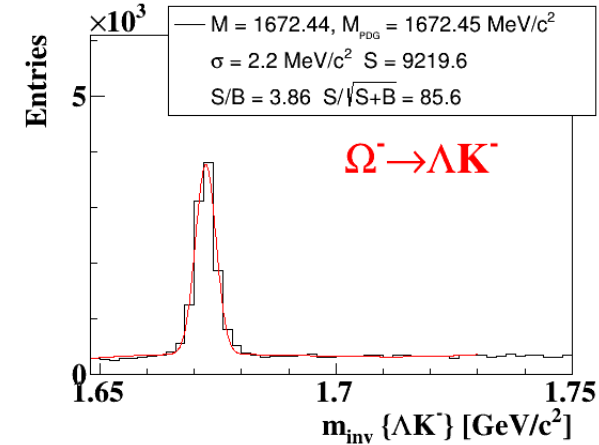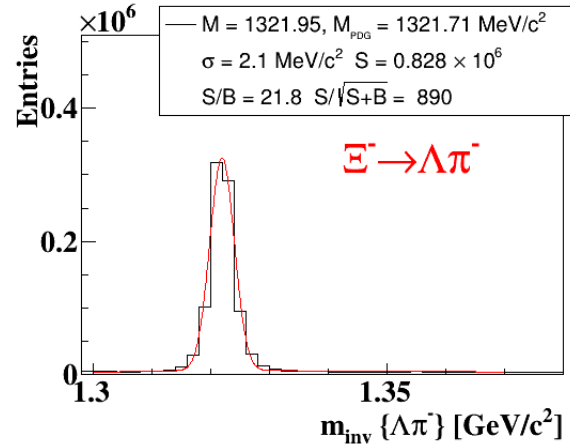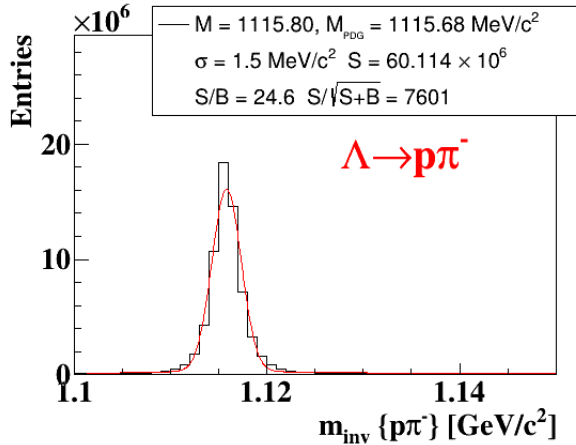
- Recently STAR has upgraded the inner part of TPC that together with an improved CA track finder have increased efficiency.
- New data give a possibility to study lower p_t region.

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

Fixed Target xBES-II: Pileup

ZR

XY
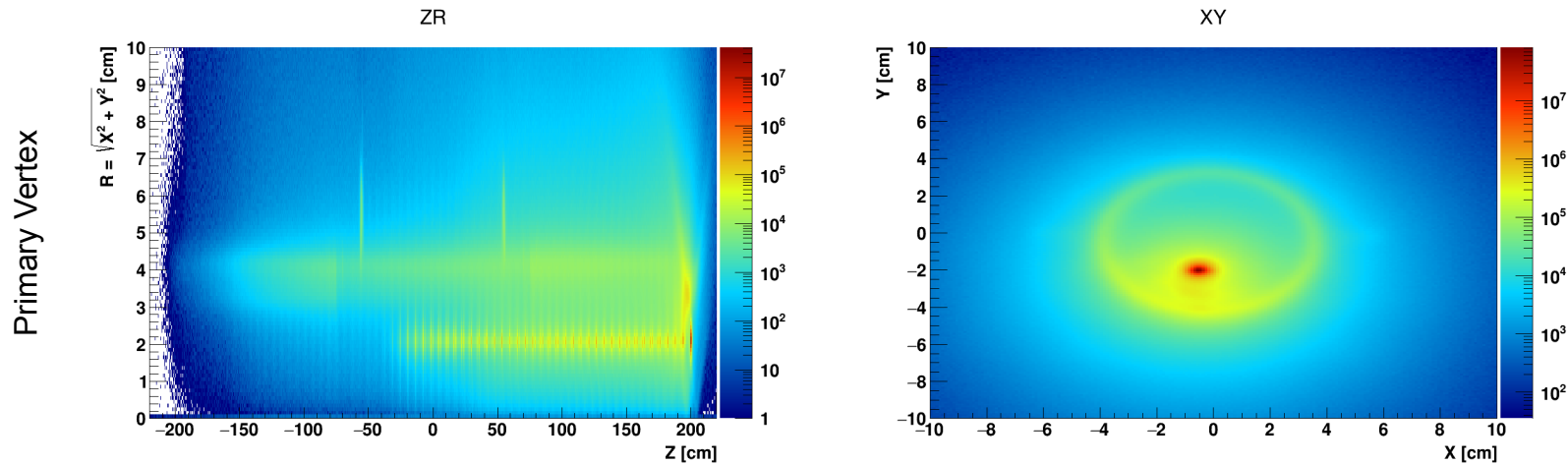
Primary Vertex

- 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 $^4_\Lambda He \to {}^3He + p + \pi^-$ candidates to the main primary vertex without and with the cleaning procedure.
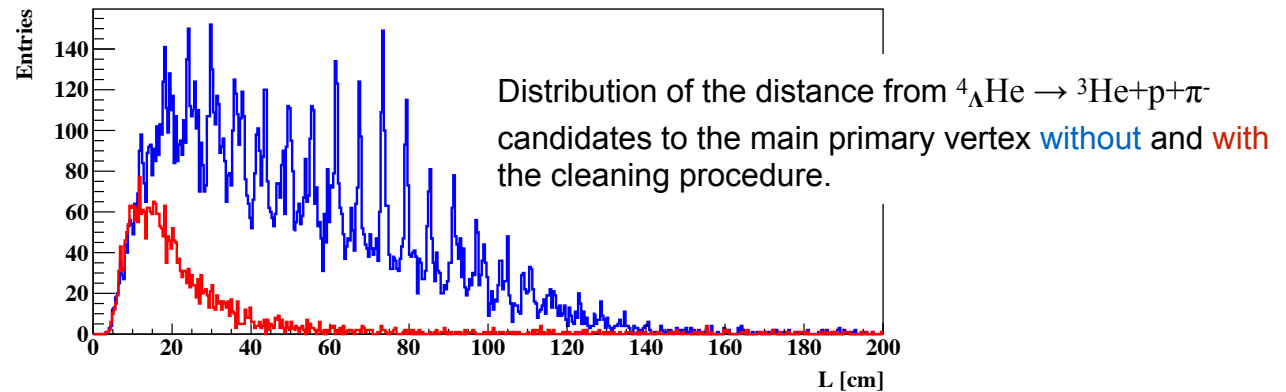
- The cleaning procedure: reconstruct primary vertices from pileup and interaction with the beam pipe, then discard these primary tracks.

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

Signal utilizing 437M AuAu HLT triggered events at √s$_{NN}$ = 3.0 GeV Fixed Target, 2021 BES-II (x)production
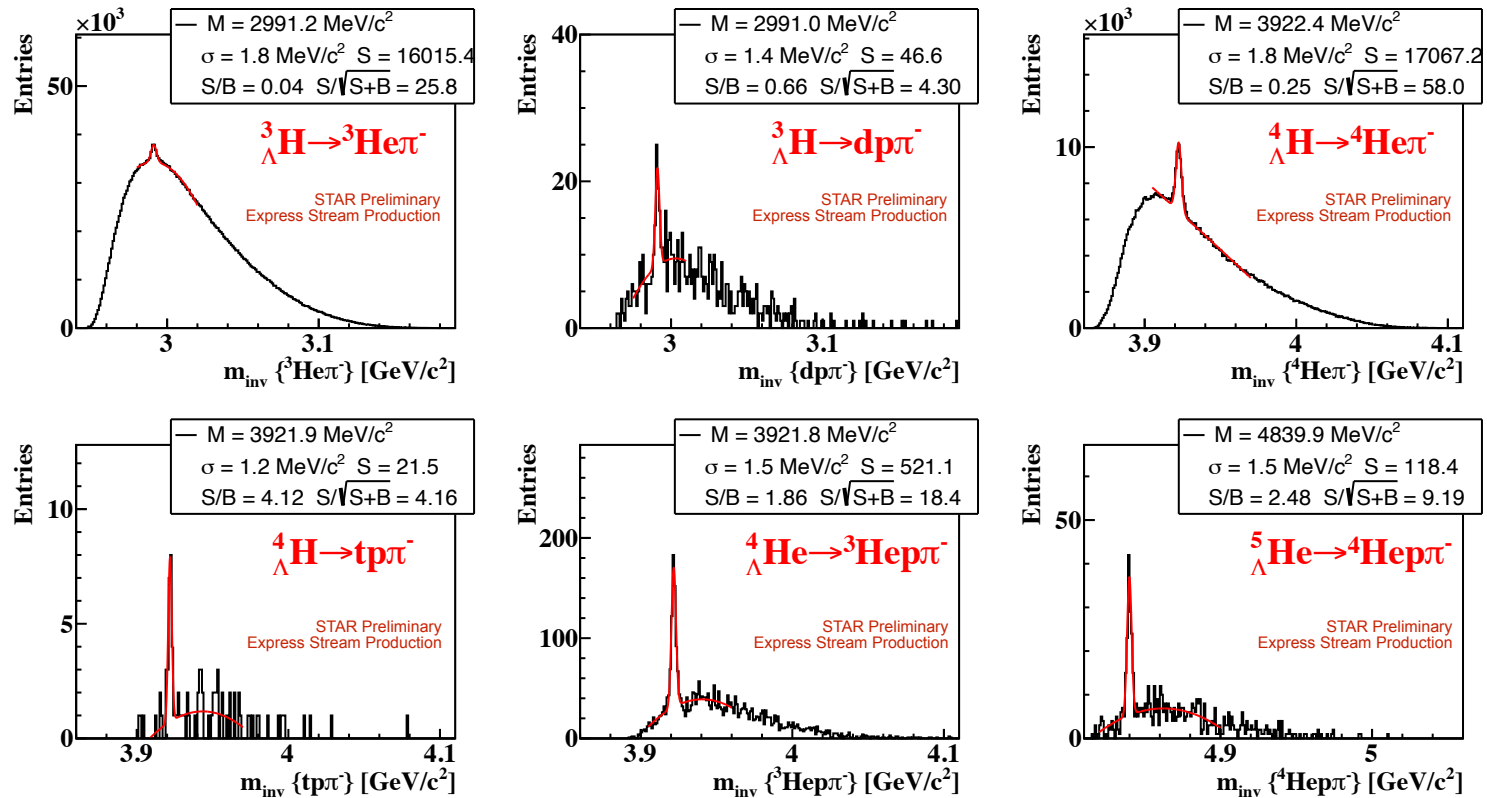
- With increased beam collision intensity in the Fixed Target mode HLT farm had not enough capacities to process all collected data online.
- Therefore a trigger on He has been introduced to enhance hypernuclei.

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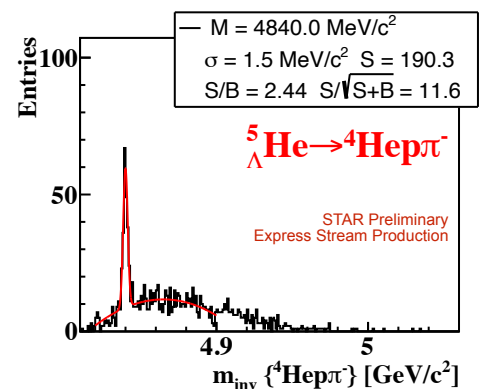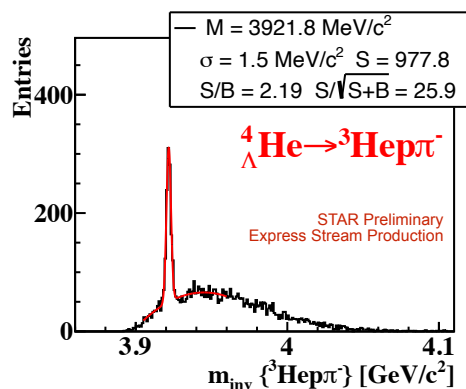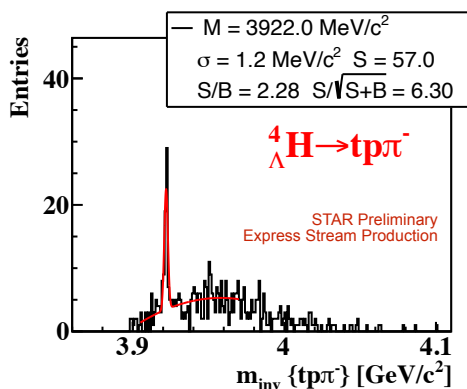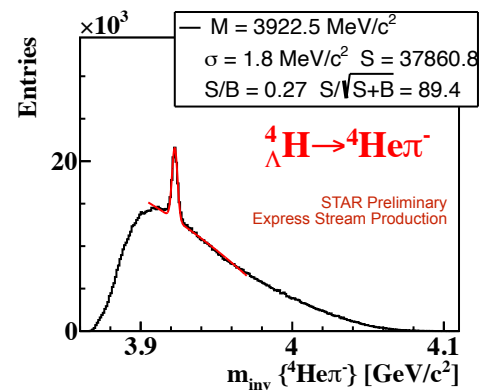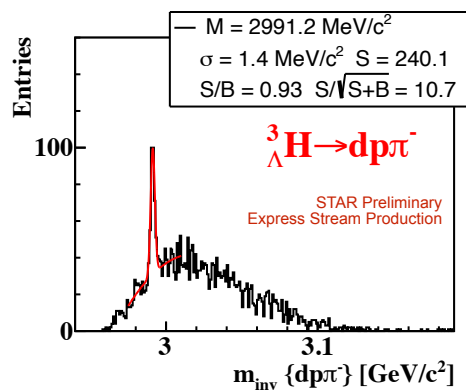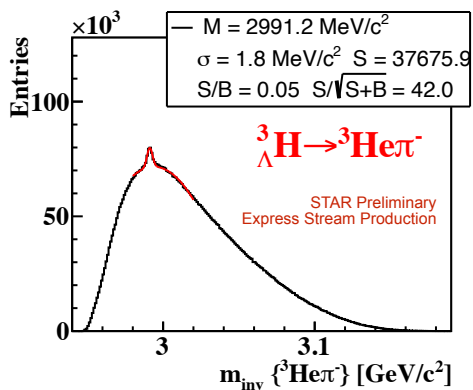
- With the same procedure all FXT data from 2018, 2019 and 2020 were analyzed.
- In all (standard and express) production data $^5_\Lambda$He is visible with significance **11.6 σ**.

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

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

Signal (978)
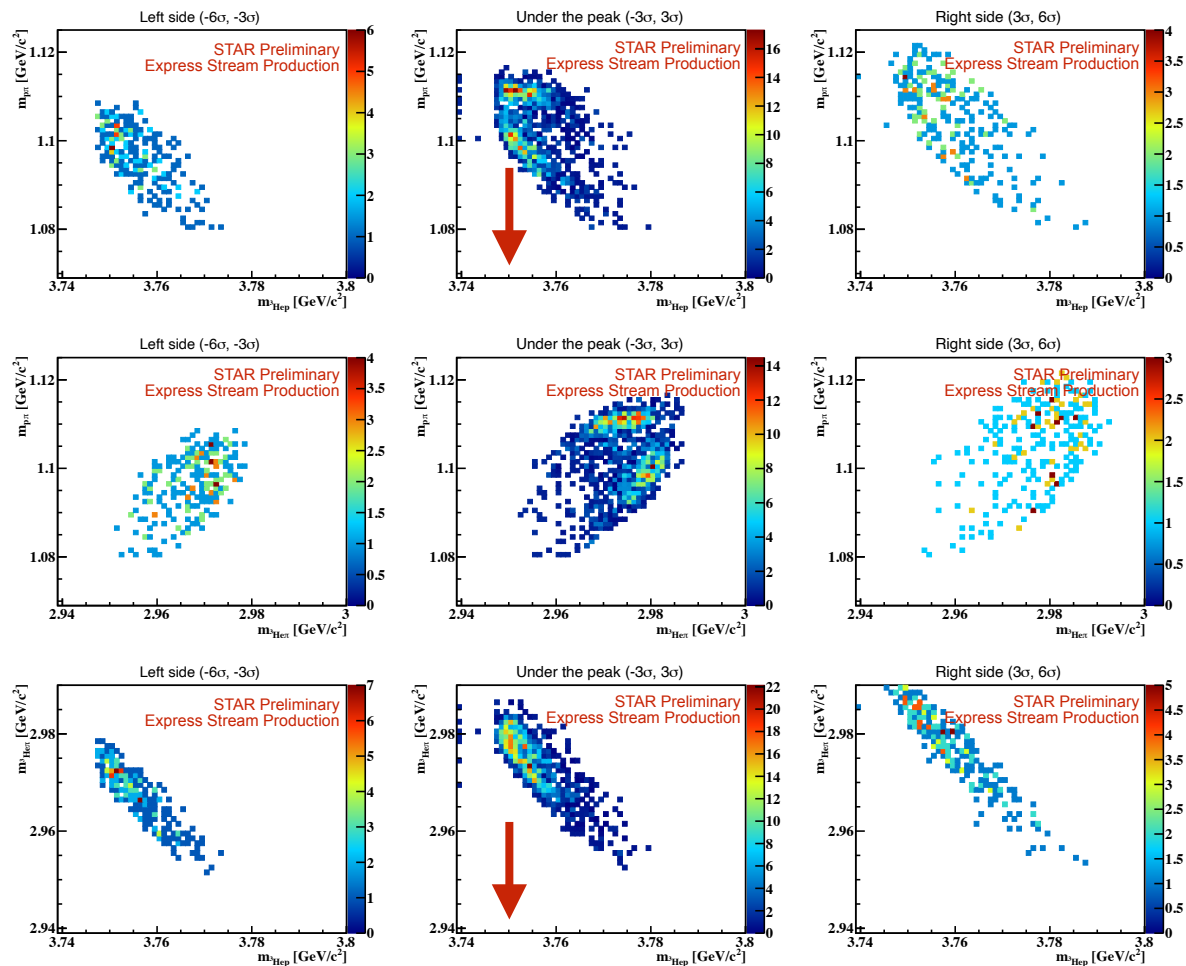
- The background was estimated with the side band method and subtracted under the peak.
- The background is smooth and no structures are observed.
- A complex structure in the signal can be explained as a possible spin effect.
- Hint of 2-body $^4\text{Li}\ \pi^-$ decay (^4Li ($J^P = 2^-$): M = 3.75 GeV/c^2, σ = 8.7 MeV/c^2).

BES-II: Dalitz Plots: $^4_\Lambda He \rightarrow \,^3He+p+\pi^-$
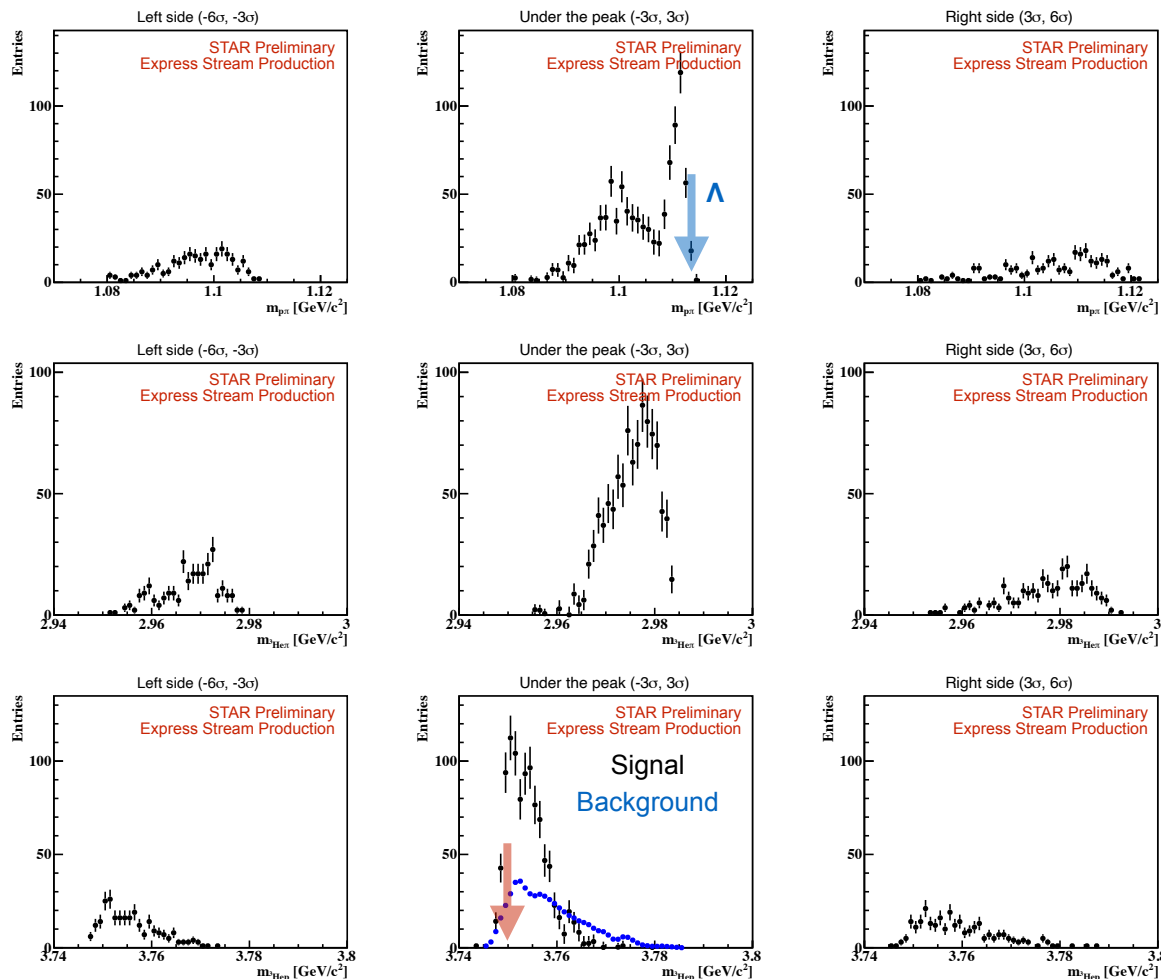
- These are projections of 2-body combinations.
- In the pπ projection the structure can be explained as a possible spin effect.
- In the nucleus-p combination the signal and background demonstrate different behavior.
- Hint of 2-body $^4Li\ \pi^-$ decay (^4Li (J^P = 2$^-$)): M = 3.75 GeV/c^2, σ = 8.7 MeV/c^2).

BES-II: Dalitz Plots: $^5_\Lambda\text{He} \rightarrow {}^4\text{He}+p+\pi^-$

Signal (190)
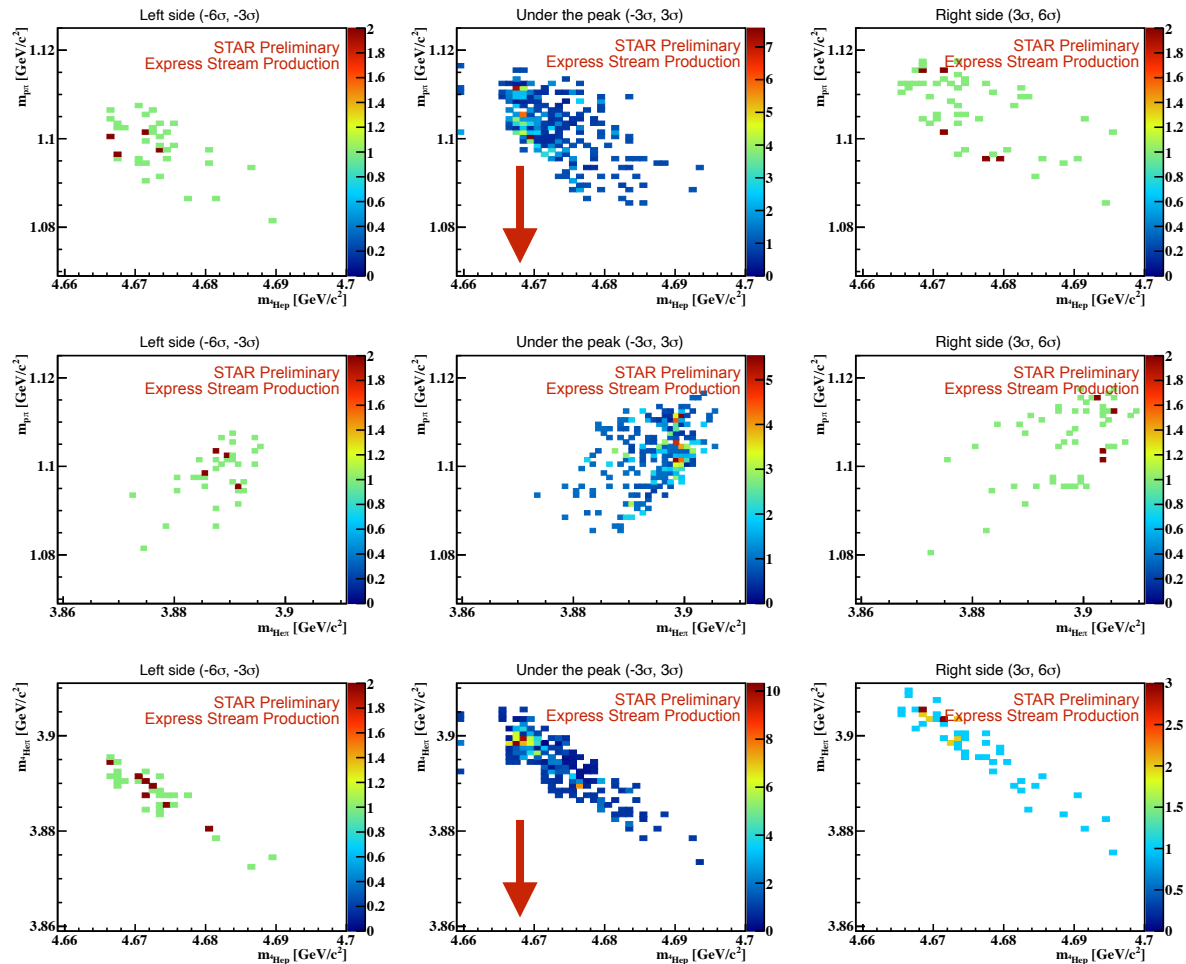
- We observe similar structures to $^4_\Lambda\text{He}$.
- Hint of 2-body $^5\text{Li}\,\pi^-$ decay (^5Li ($J^P = 3/2^-$): M = 4.665 GeV/c^2, σ = 2.2 MeV/c^2).
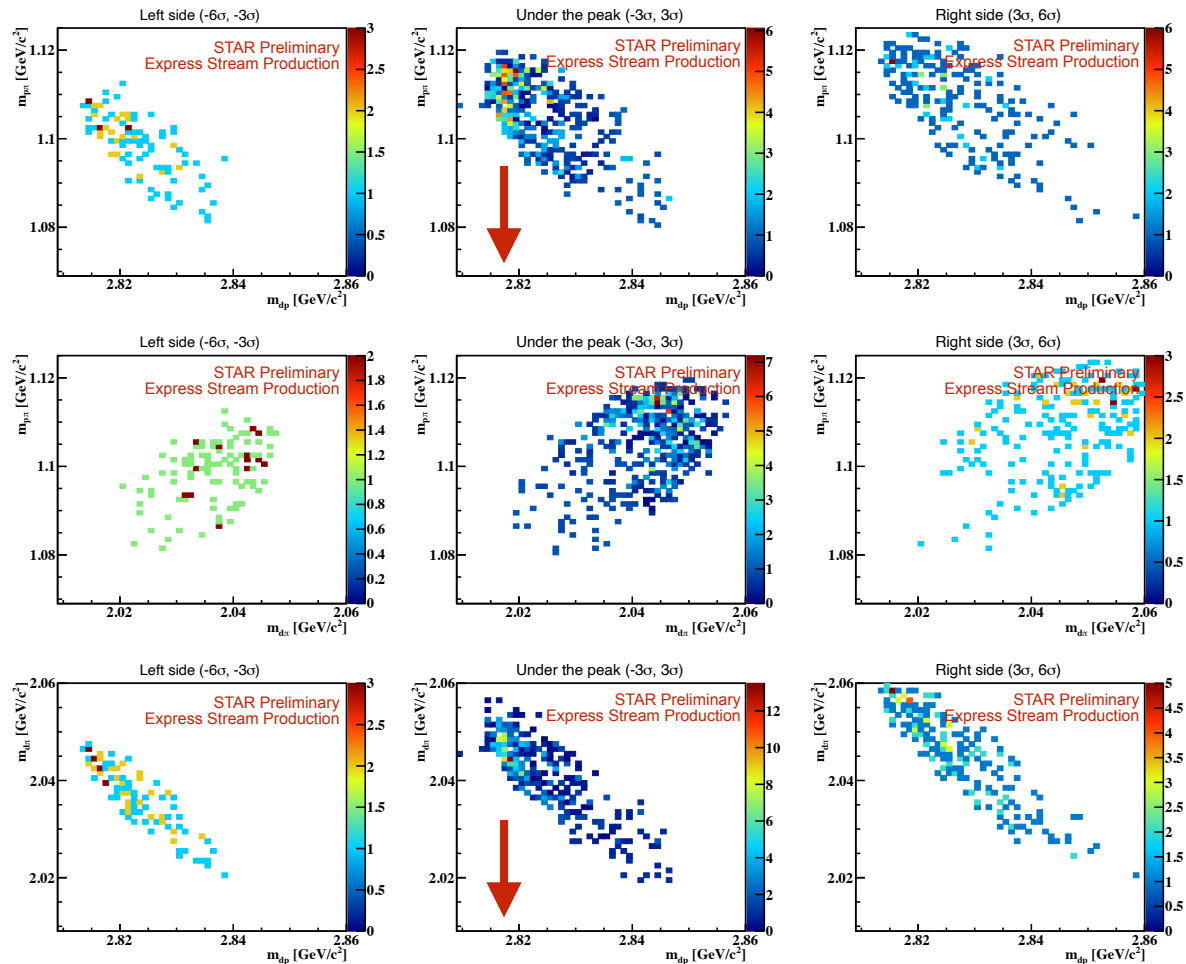
Signal (190)

- We observe similar structures to $^4_\Lambda$He.
- In the nucleus-p combination the signal and background demonstrate different behavior.
- Hint of 2-body ^{5}Li π^- decay (^{5}Li (J^P = 3/2$^-$): M = 4.665 GeV/c^2, σ = 2.2 MeV/c^2).

Signal (240)

- Because of use of the He based trigger in HLT, we expect higher statistics with offline production.
- Hint of 2-body resonance ^{3}He* ($\sim$2.818 GeV/c^2) decay, ^{3}He M = 2.808 GeV/c^2.

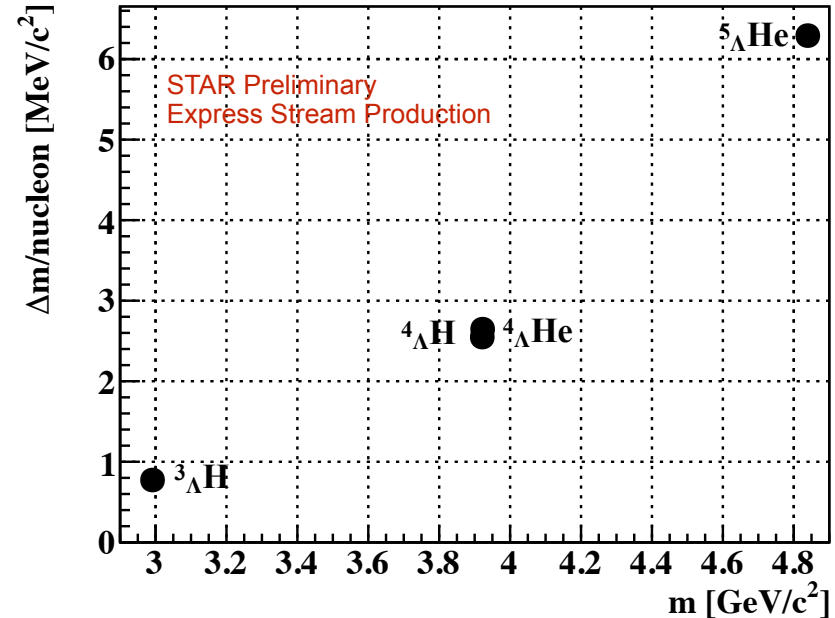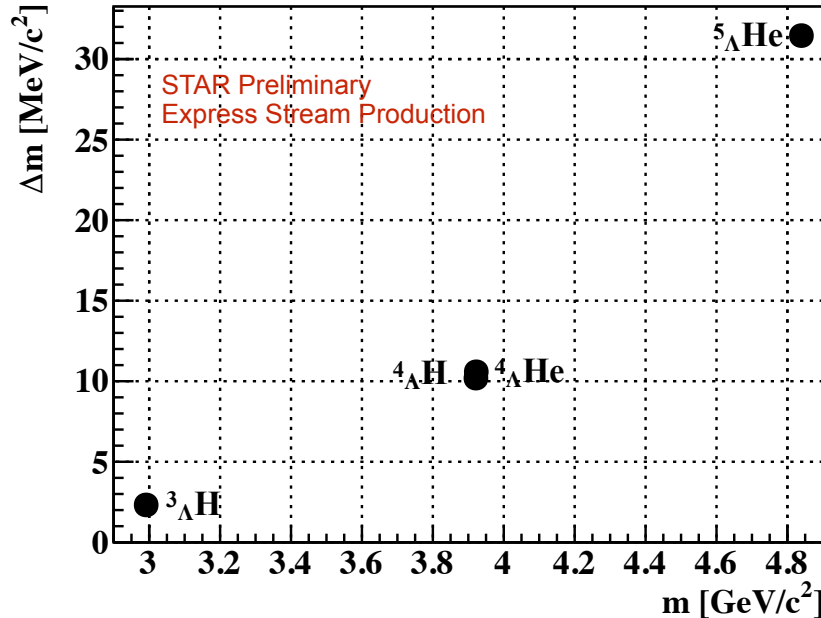# BES-II: Dalitz Plots: $^3_\Lambda H \rightarrow d+p+\pi^-$
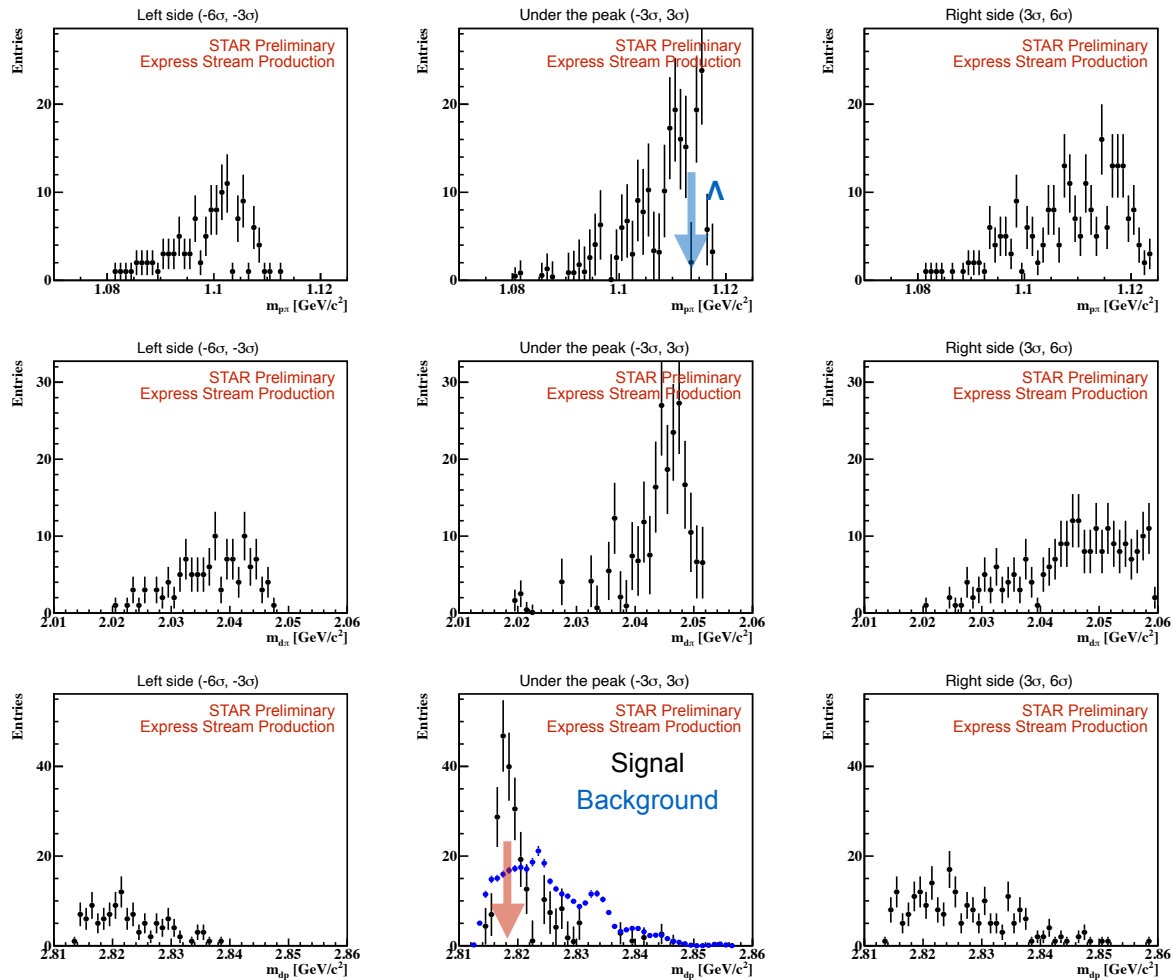
- Because of use of the He based trigger in HLT, we expect higher statistics with offline production.
- In the $p\pi$ projection we observe a smooth behavior.
- Hint of 2-body resonance ^{3}He* (~2.818 GeV/c^2) decay, ^{3}He M = 2.808 GeV/c^2.

xBES-II: Hypernuclei Binding Energy

- We observe that binding energy is increasing up to $^5_\Lambda$He.
- When comparing binding energies per nucleon, hypernuclei behave similar:
  - $^5_\Lambda$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 markers.

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

- 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 channels show complex structures: possibly, spin effect.

- Hints that a significant part of 3-body decays happen via nuclei 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.