JOINT INSTITUTE FOR NUCLEAR RESEARCH

NUCLOTRON BASED ION COLLIDER FACILITY

2nd China-Russia Joint Workshop on NICA Facility
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Study of hyperon and hypernuclei production at NICA

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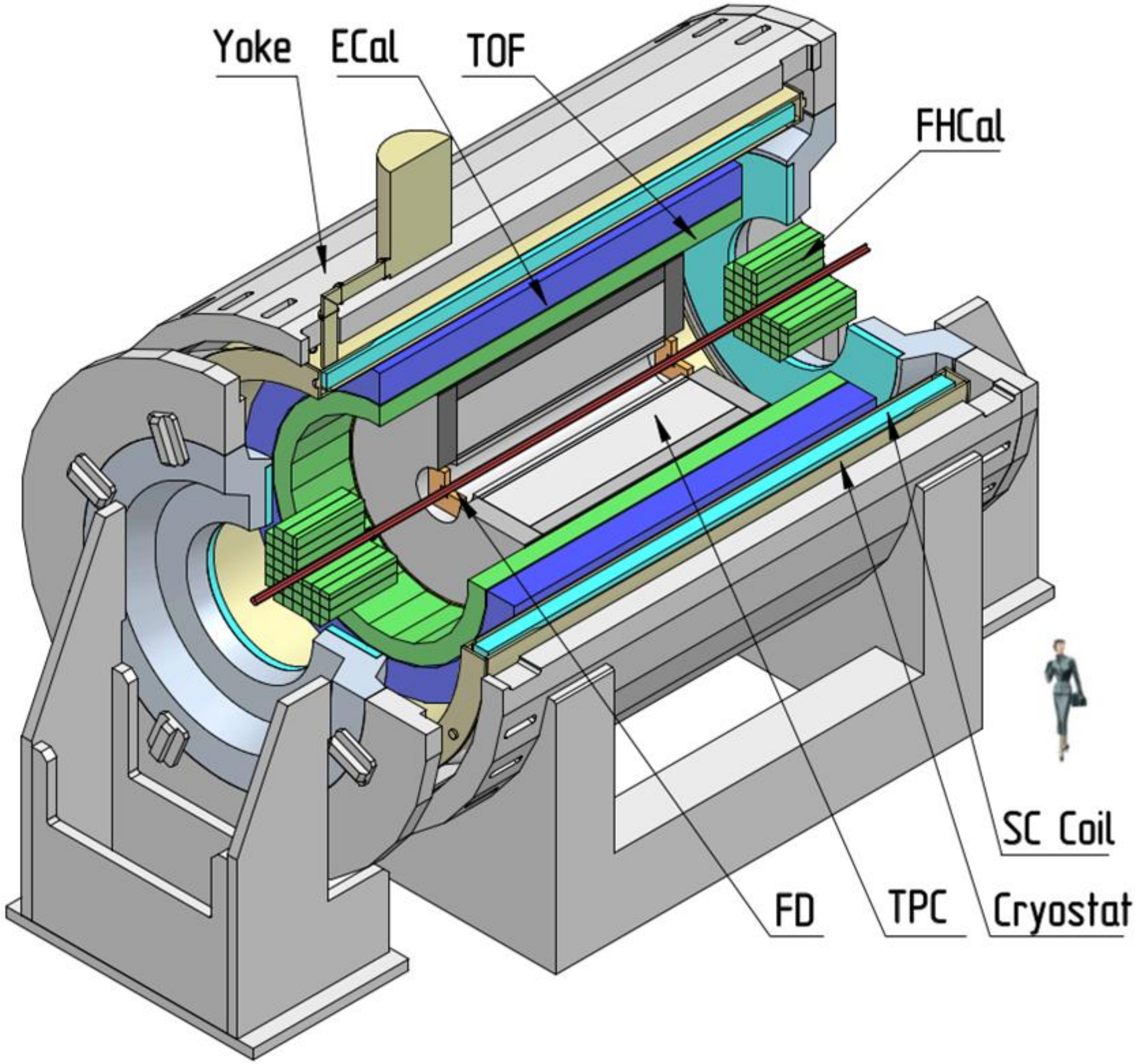
Outline

- MPD detector performance
- Realistic simulation / reconstruction of hyperons (Λ, Λ_{bar}, $\Xi^{\pm}$, $\Omega^{\pm}$)
- Machine Learning Method for hyperon selection
- Realistic simulation / reconstruction of hypernuclei:
  - ${}_{\Lambda}^{3}H \rightarrow {}^{3}He + \pi^{-}$
  - ${}_{\Lambda}^{3}H \rightarrow d + p + \pi^{-}$
  - ${}_{\Lambda}^{4}H \rightarrow {}^{4}He + \pi^{-}$
  - ${}_{\Lambda}^{4}He \rightarrow {}^{3}He + p + \pi^{-}$
- Strangeness analysis at BM@N experiment
- Summary and Plans

Multi-Purpose Detector @ NICA



MPD at Stage 1

Magnet: 0.5 T superconductor
Tracking: TPC
Particle ID: TOF, ECal, TPC
T0, Triggering: FD
Centrality, Event plane: FHCal

- ✓ **TPC tracking:** $|\eta| < 1.6$ ($N_{hits} > 15$)
- ✓ **TOF coverage:** $|\eta| < 1.4$
- ✓ **PID:** combined $|\eta| < 1.4$, $0.1 < p < 3$ GeV/c
  limited in $1.4 < |\eta| < 1.6$ (*dE/dx* only)

Realistic MPD tracking

Simulation procedure (digitization):

- Primary ionization (ionization clusters)
- Drift and diffusion of ionization electrons
- Gas gain fluctuations (Polya distribution)
- Pad response (charge distribution on pad plane)
- Electronics shaping
- Signal digitization (ADC overflow)

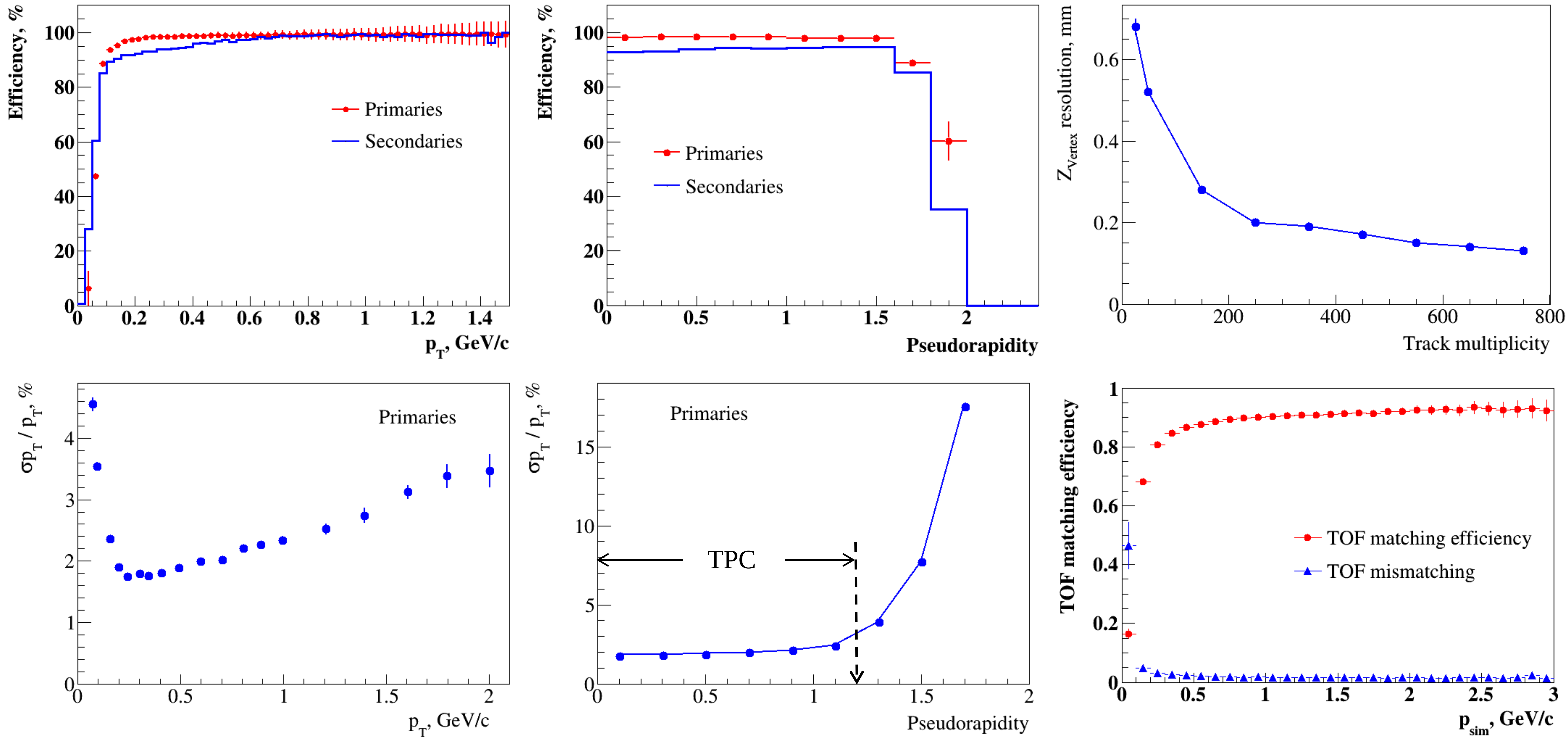
Cluster / hit reconstruction

- Precluster finder (group of adjacent pixels in time bin – pad space)
- Hit finder (“peak-and-valley” algorithm either in time bin – pad space (for simple topologies) or in time-transverse coordinate pixel space after Bayesian unfolding (for more complicated topologies)) → COG around local maxima

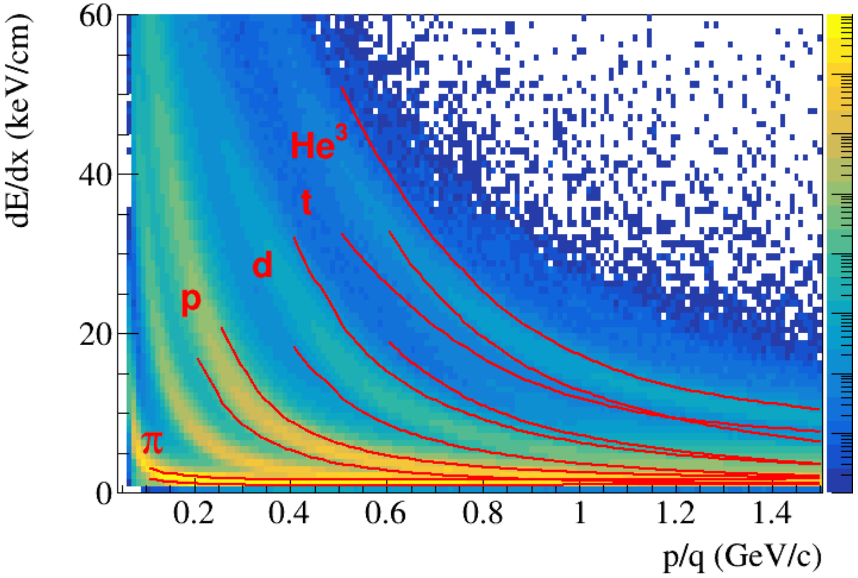
TPC parameters

Parameter	Value
Magnetic field	0.5 T
Drift gas	P10 (90% Ar + 10% CH_4)
Drift velocity	5.45 cm/μs
Transverse diffusion at 0.5 T	185 μm/√cm
Longitudinal diffusion	320 μm/√cm
Pad size	5x12 mm^2 (27 rows) + 5x18 mm^2 (26 rows)
Charge spread σ	0.196 mm
Electronics shaping time	180 ns (FWHM)
ADC dynamic range	10 bits
ADC sampling frequency	10 MHz

Track reconstruction performance



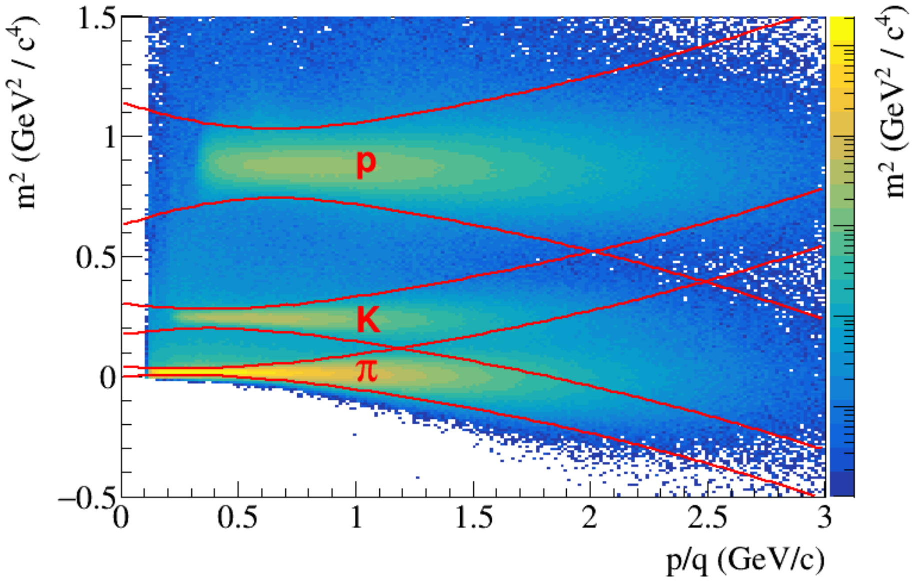
PID performance in TPC & TOF

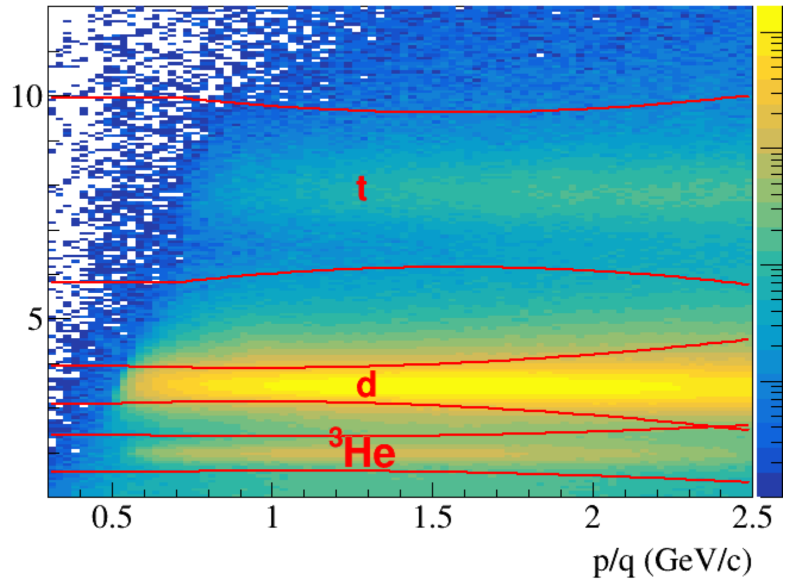


dE/dx vs momentum in TPC and
m^2 vs momentum in TOF
(Red lines $\pm 3\sigma$)

Mass square calculated using the measurements of magnetic rigidity (*p/q*), time-of-flight (*T*) and trajectory length (*L*):

$$m^2 = p^2\left(\frac{c^2T^2}{L^2} - 1\right)$$

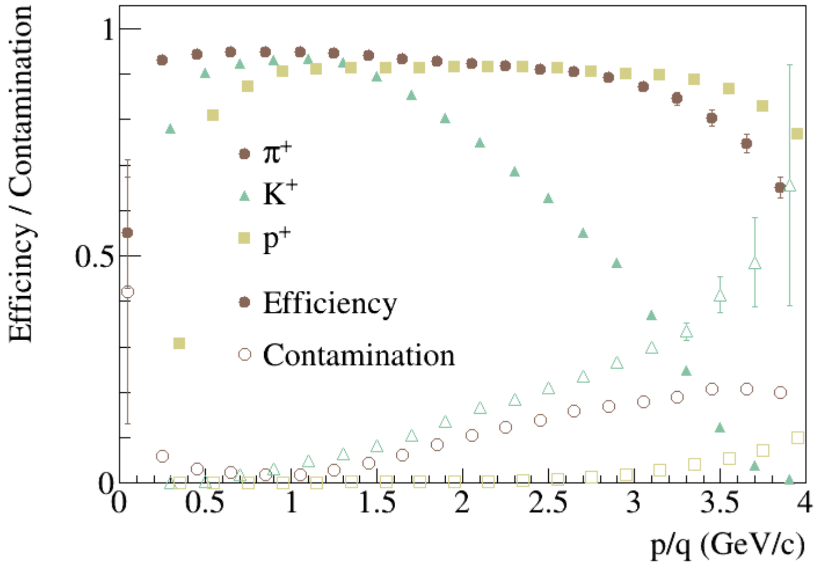




Selection criteria for events and identified tracks:

1. $|Z_{PV}| < 50$ cm
2. Primary particles
3. $N_{TPC\_hits} \geq 27$
4. $|\eta| < 1.3$

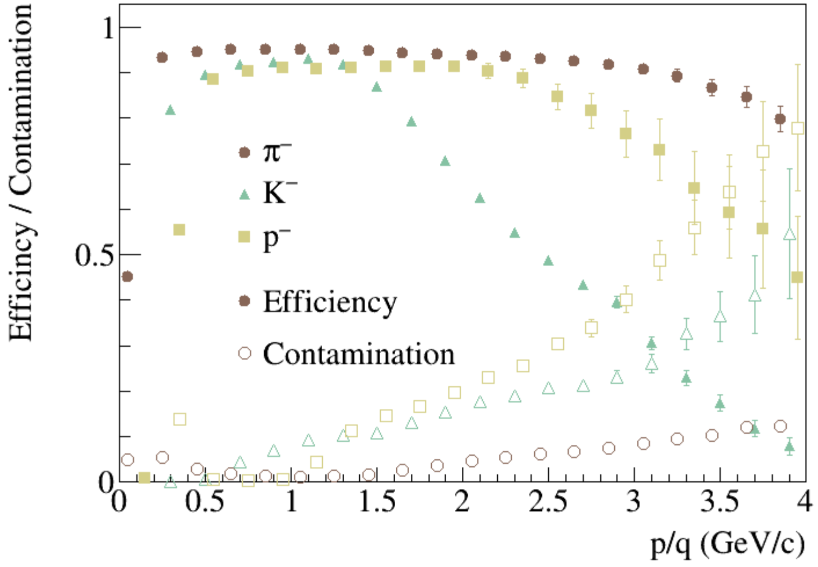
PID: Efficiency and Contamination

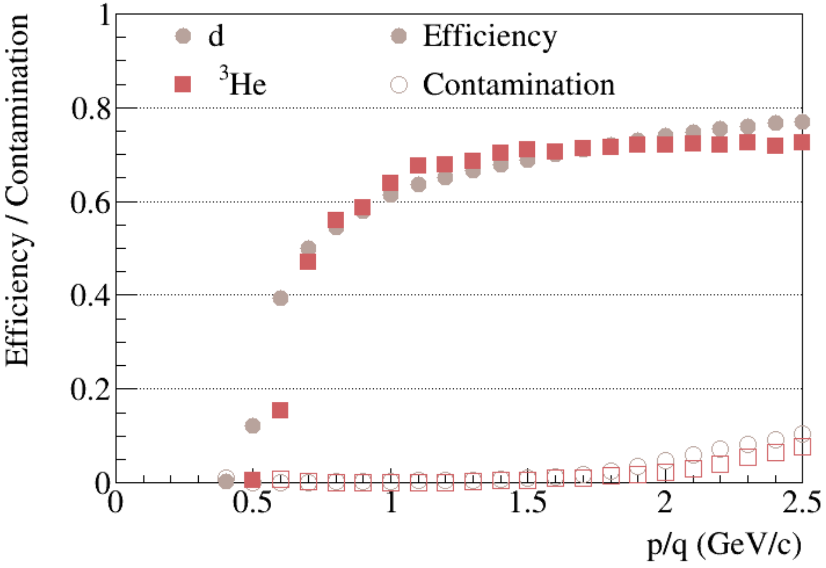


Primaries + secondaries (after GEANT) particles

$$\text{Eff.} = \frac{\text{particles which are correctly identified}}{\text{all particles of a given species (PDG)}}$$

$$\text{Cont.} = \frac{\text{particles which are falsely identified}}{\text{all identified particles of a given species}}$$





Hyperon reconstruction

Data set

- **Generators:** PHSD, Au+Au @ 11 GeV, 8M min. bias events
  PHQMD, Bi+Bi @ 9.2 GeV, 40M min. bias events
  UrQMD, Bi+Bi @ 9.2 GeV, 50M min. bias events
- **Detectors:** start version of MPD with up-to-date TPC & TOF
- **Track reconstruction:** two-pass Kalman filter with track seeding using outer hits (*1st pass*) or leftover inner hits (*2nd pass*)
- **Track acceptance criterion:** $|\eta| < 1.3$, $N_{TPC\_hits} \geq 10$ (for reconstructed tracks)
- **Particle Identification:** *dE/dx* in TPC & m^2 in TOF, $N_{TPC\_hits} \geq 20$ (for identified tracks)
- **Vertex reconstruction:** Kalman filter - based formalism working on MpdParticle objects

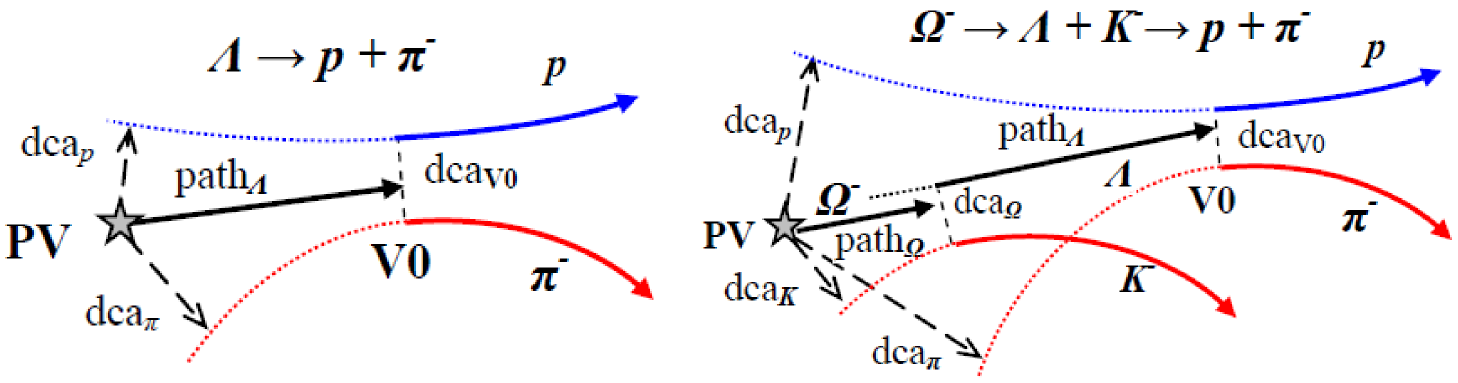
Analysis goals and Event topology

Goals:

- ✓ Hyperons – convenient tool for simulation and reconstruction testing
- ✓ Secondary Vertex Reconstruction algorithms development for multistrangeness analysis
- ✓ Optimization of selection criteria in p_T and centrality; hyperon reconstruction efficiency at high p_T
- ✓ Analysis macros for invariant spectra reconstruction
- ✓ Estimates of MPD efficiency and expected event rates
- ✓ Phase space coverage evaluation
- ✓ Determination of efficiency and production of invariant p_T spectra

Analysis method:

Secondary Vertex Finding Technique

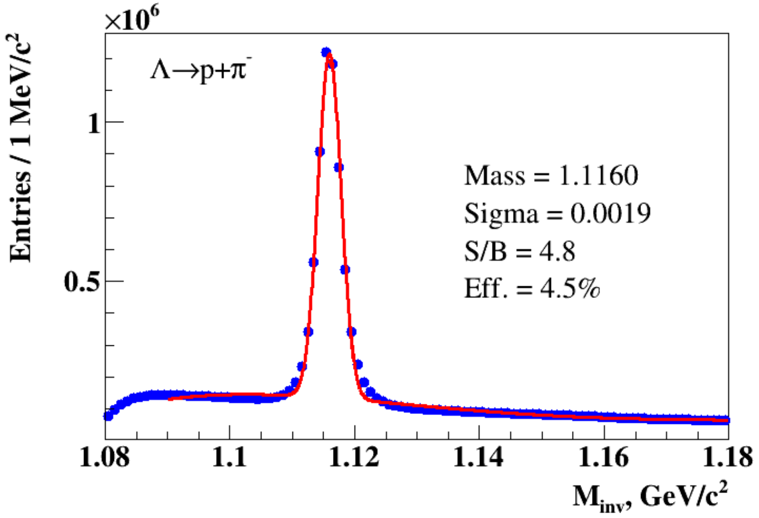


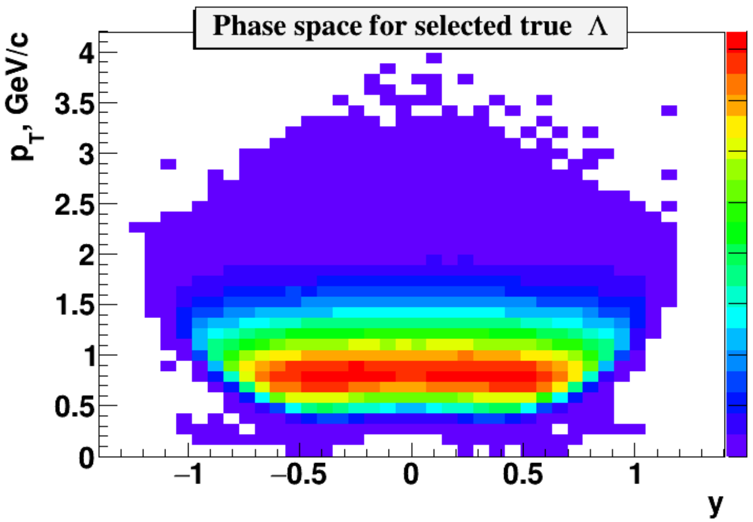
Event topology:

- PV – primary vertex
- V_0 – vertex of hyperon decay
- dca – distance of the closest approach
- path – decay length

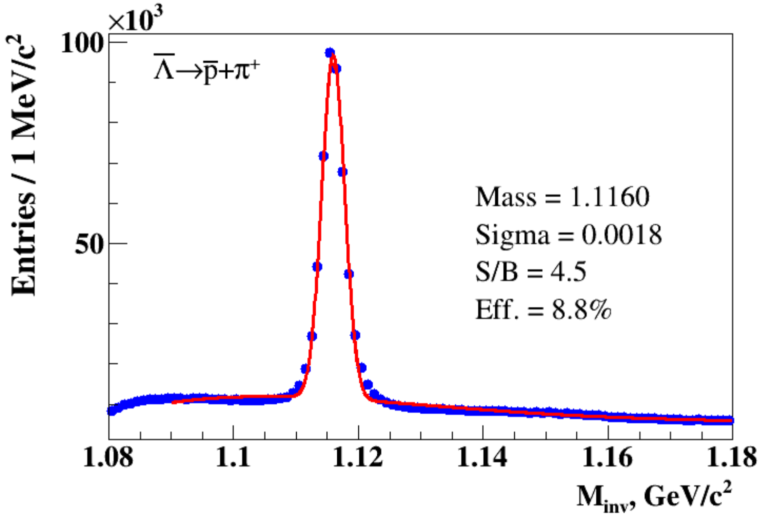
Λ, $\bar{\Lambda}$, Ξ^- reconstruction (PHSD, 11 GeV, 8M)

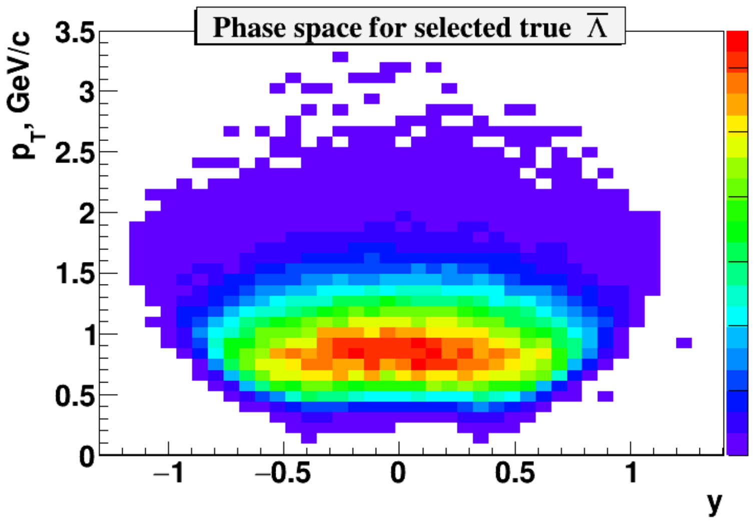
Eff. (for |*y*|<0.5) =10.4%



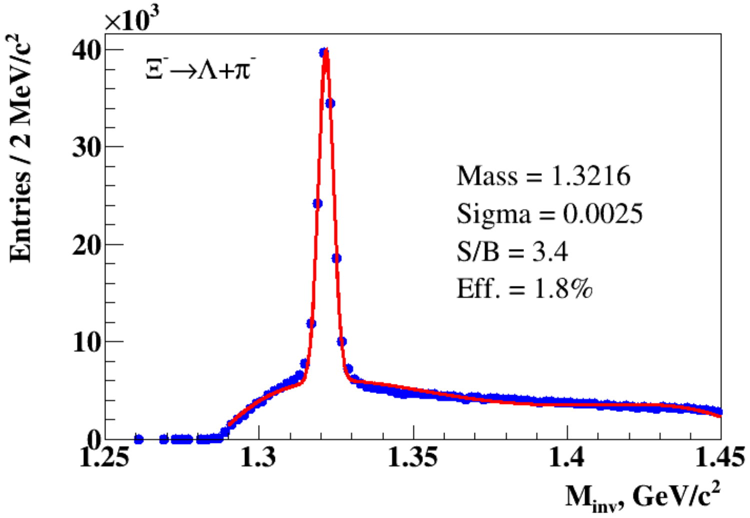


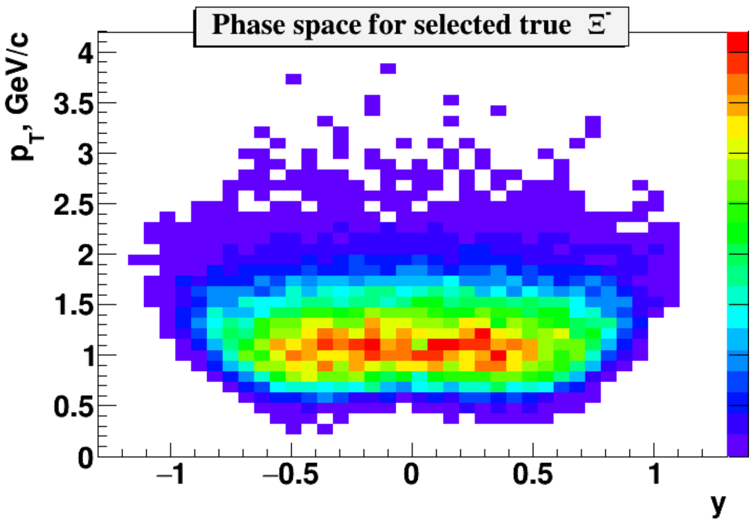
Eff. (for |*y*|<0.5) =14.1%





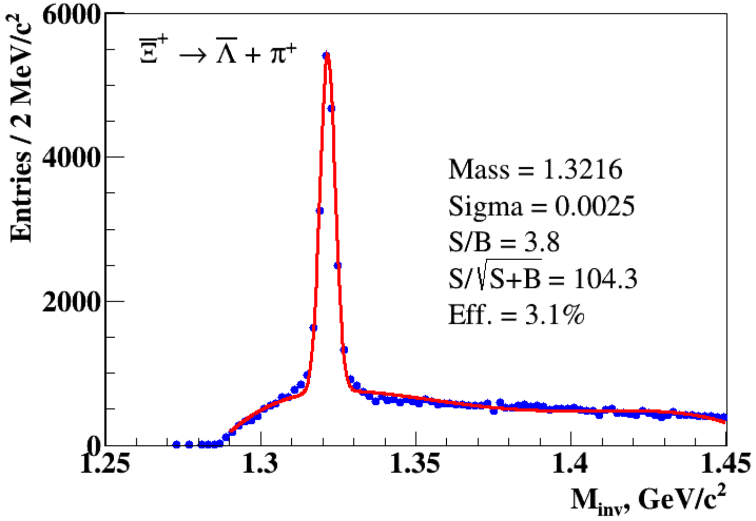
Eff. (for |*y*|<0.5) =3.6%

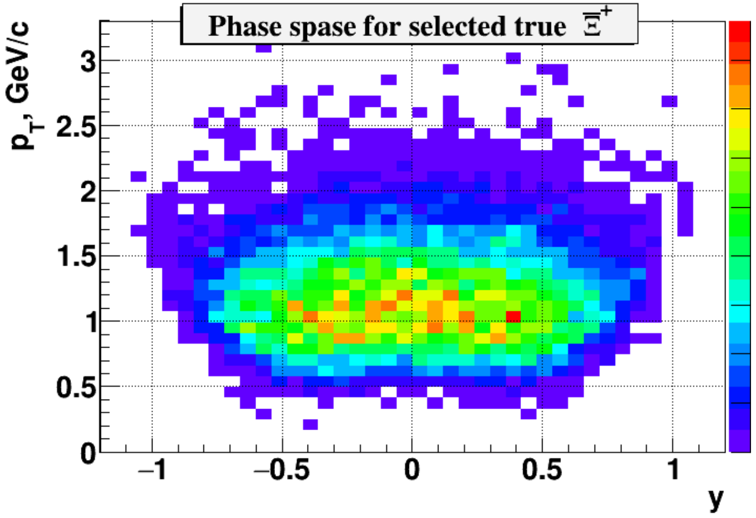




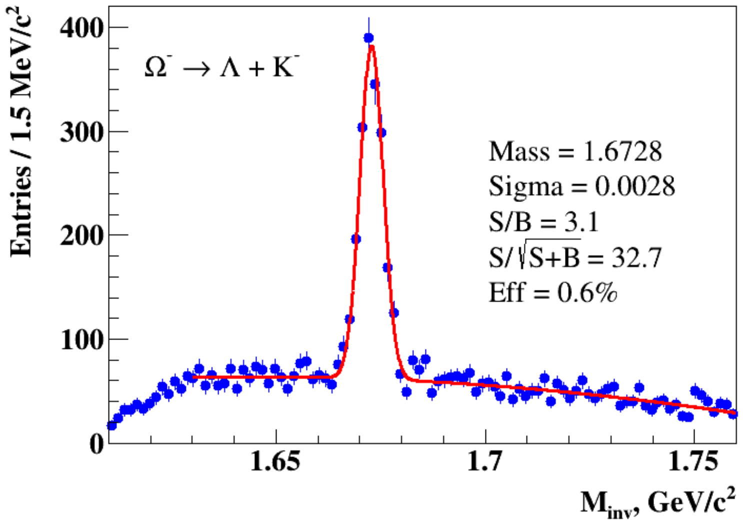
$\bar{\Xi}^+$, Ω^-, $\bar{\Omega}^+$ reconstruction (PHSD, 11 GeV, 8M)

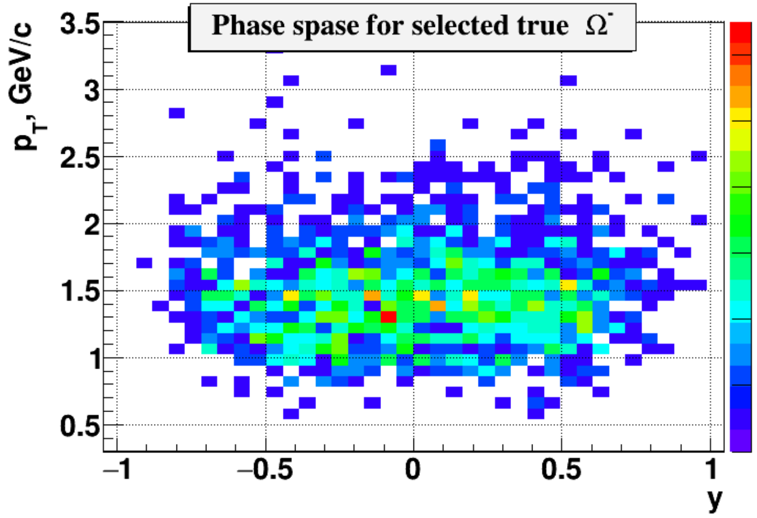
Eff. (for |y|<0.5) =4.7%



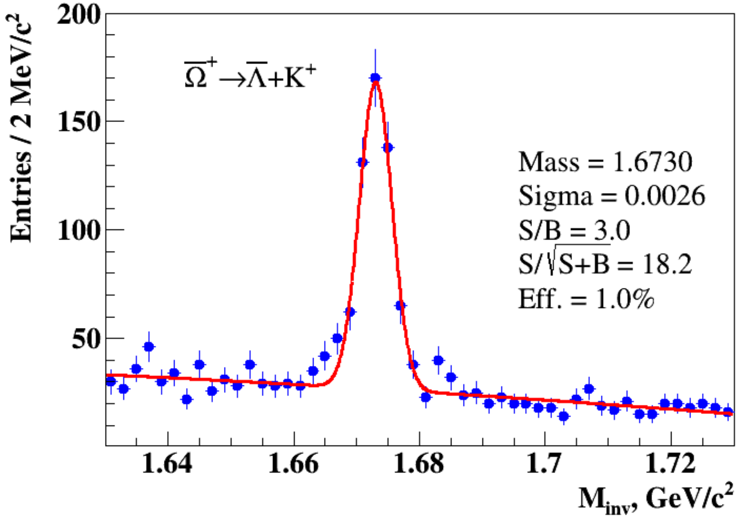


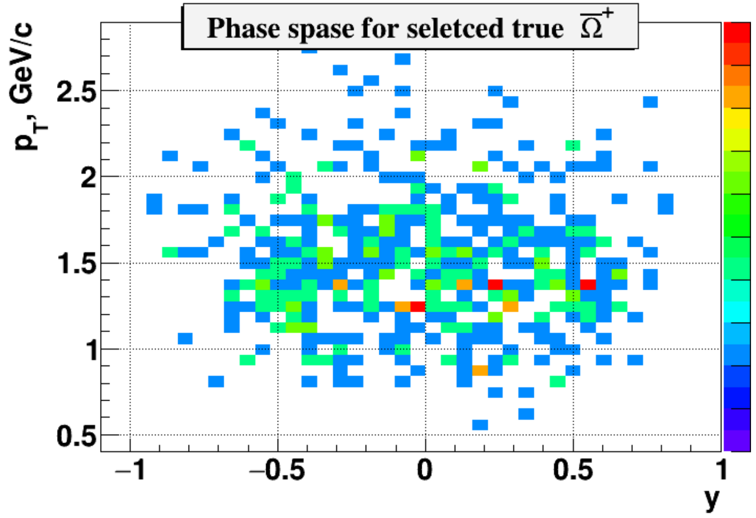
Eff. (for |y|<0.5) =1.1%





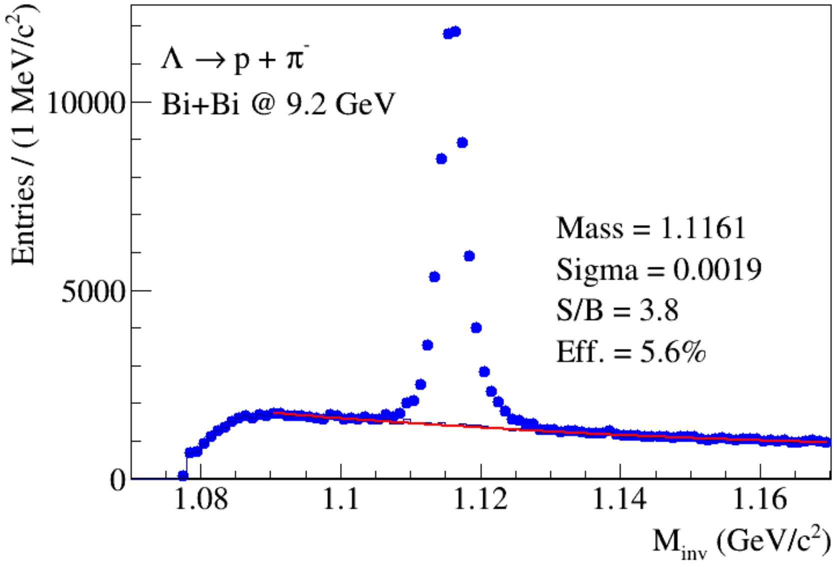
Eff. (for |y|<0.5) =1.5%



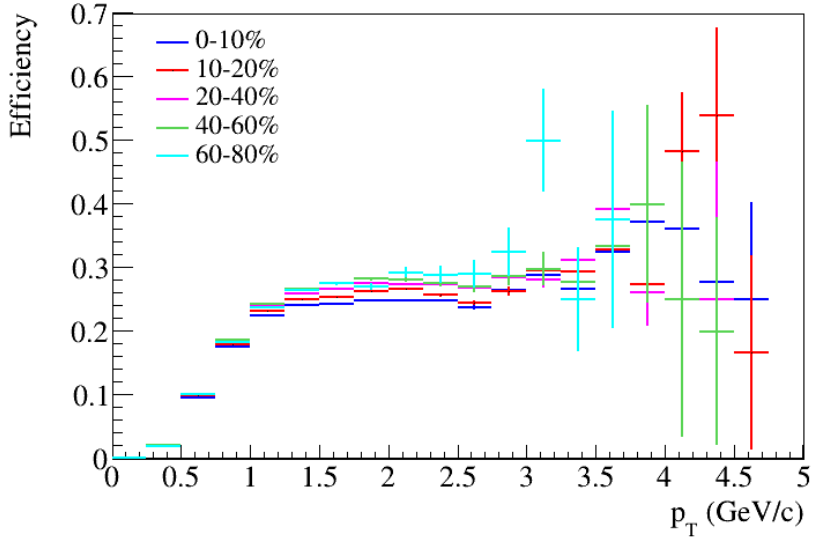


Analysis of Λ

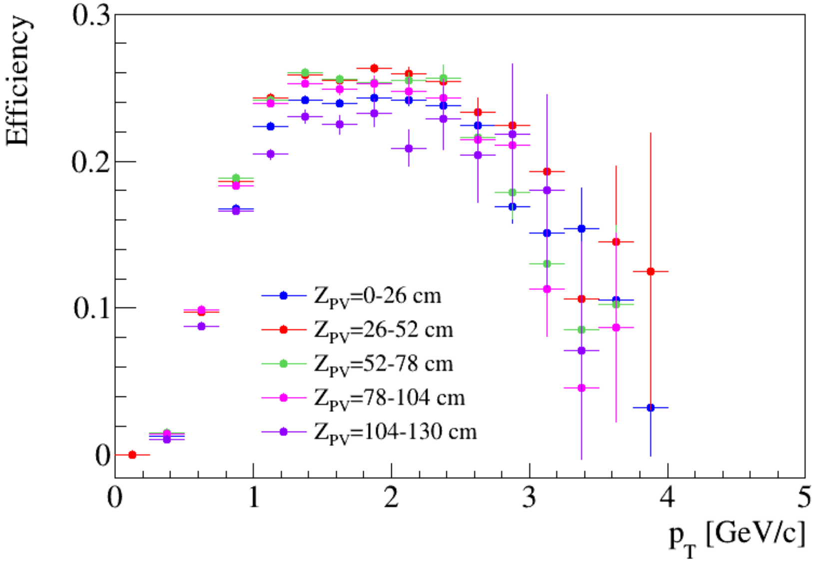
UrQMD, Bi+Bi @ 9.2 GeV, 50M

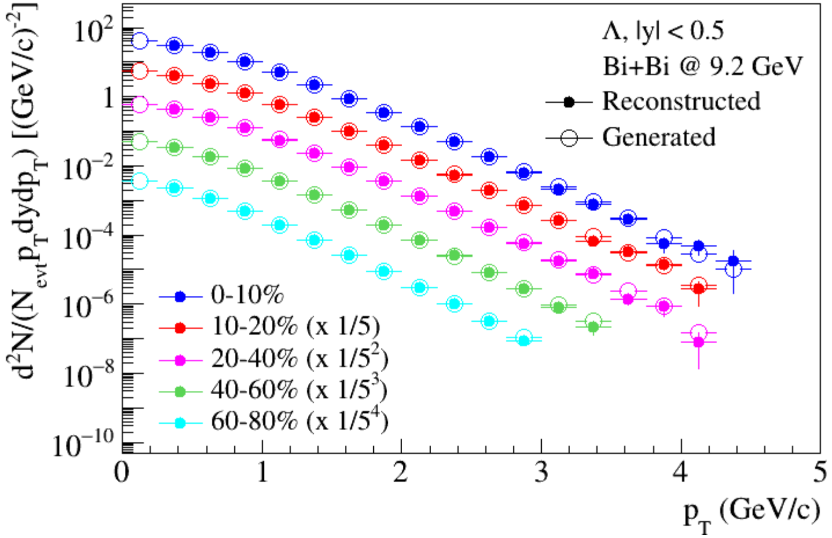


Efficiency of Λ in centrality bins



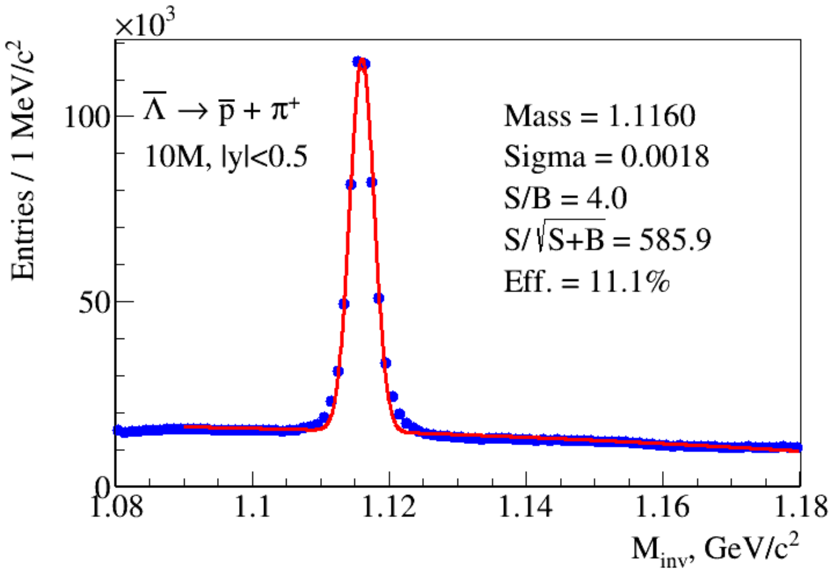
Efficiency of Λ in Z_{PV} bins

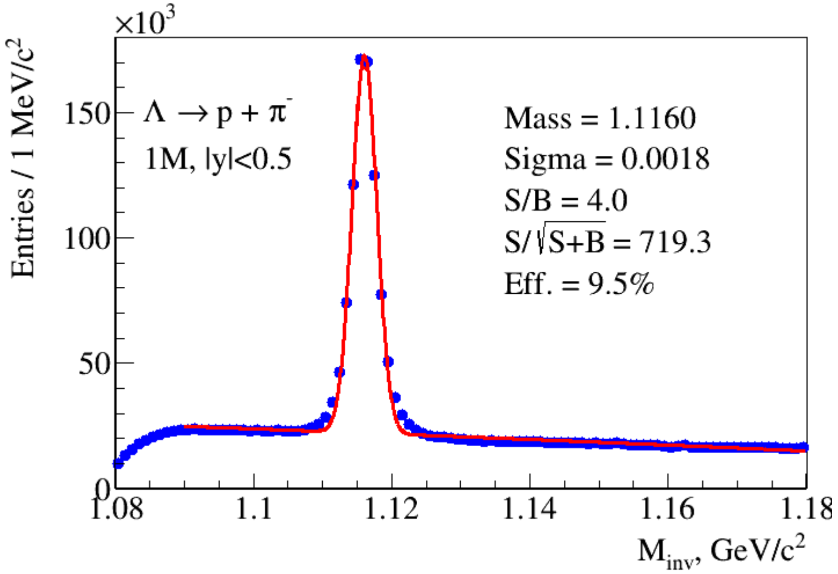




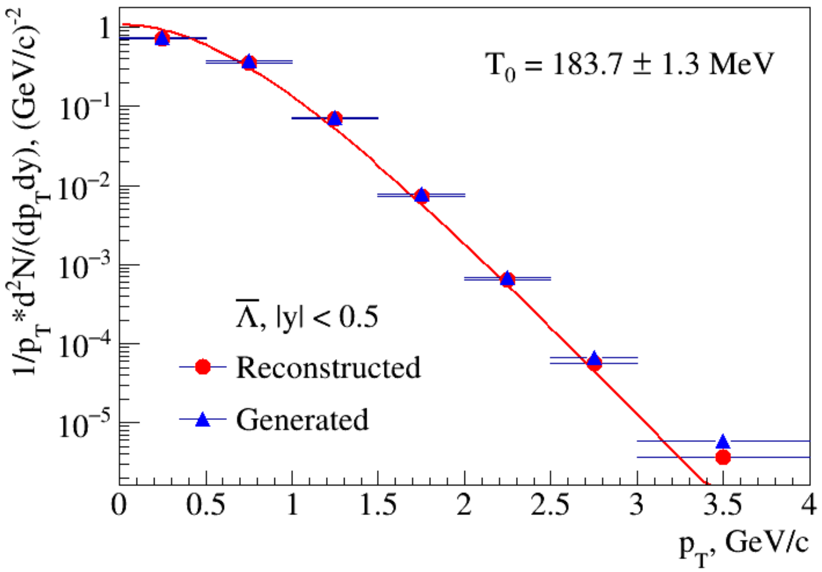
Invariant p_T -spectra of Λ in centrality bins

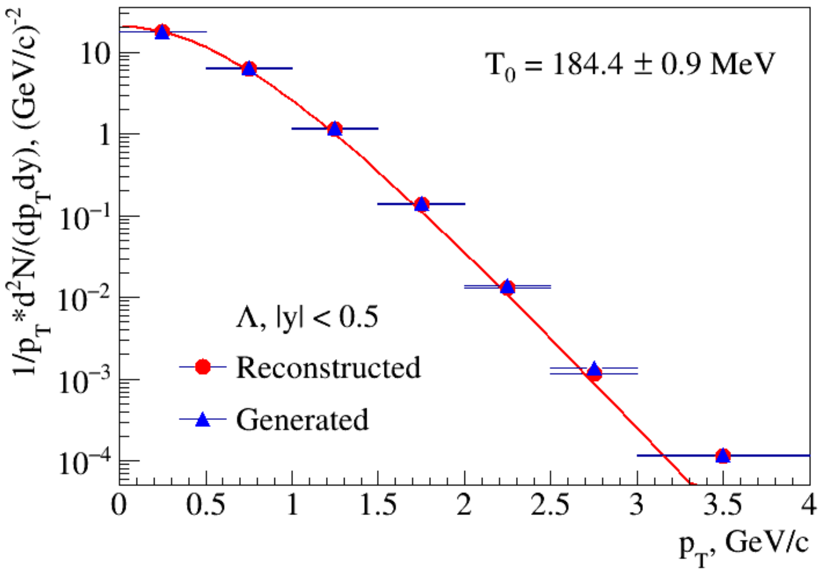
$\bar{\Lambda}$ / Λ ratio

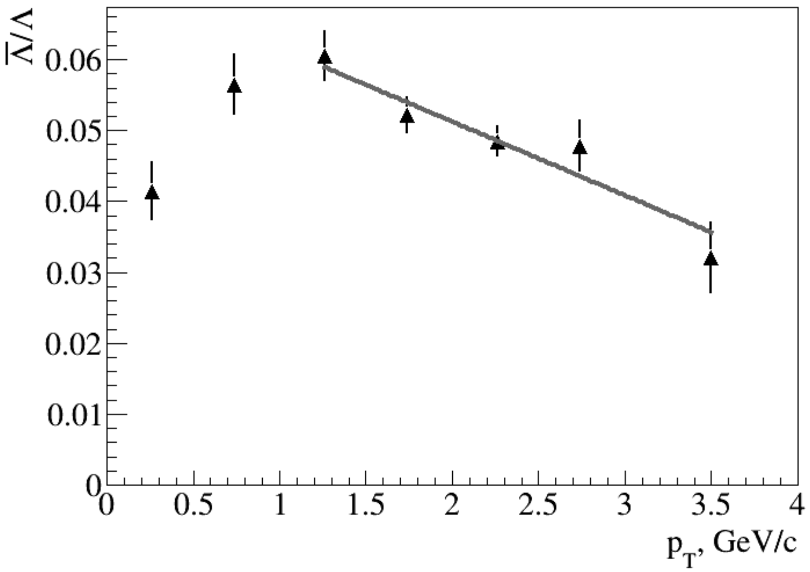




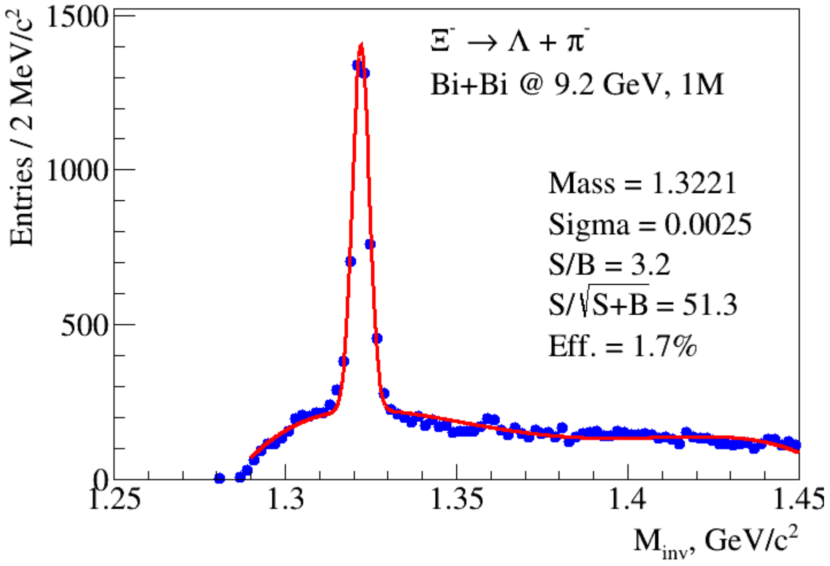
PHQMD, Bi+Bi @ 9.2 GeV,
40M events, |y|<0.5

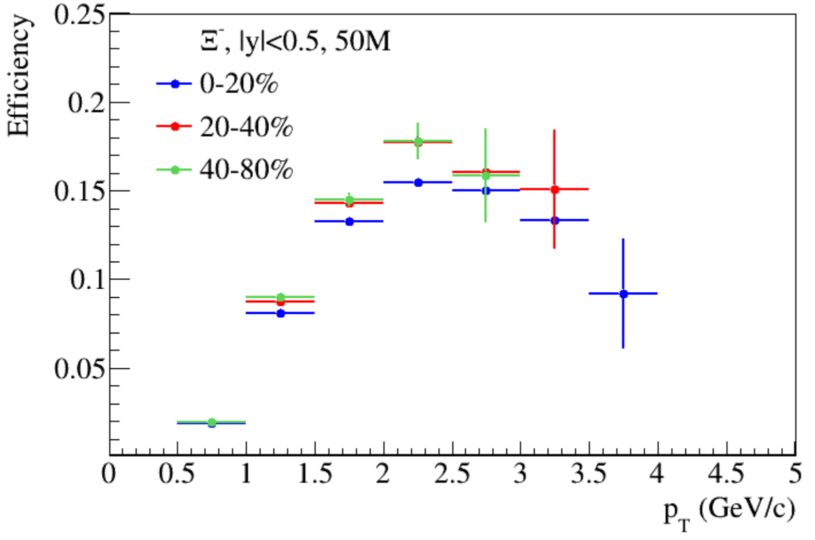


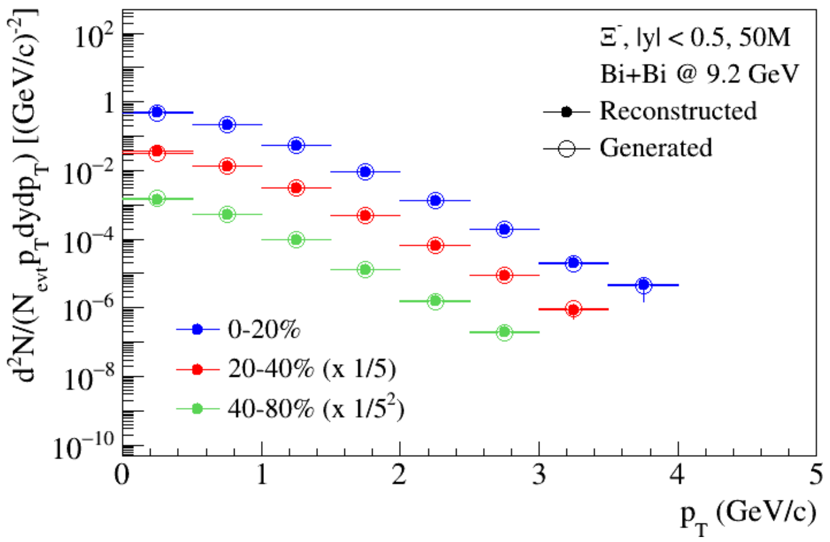


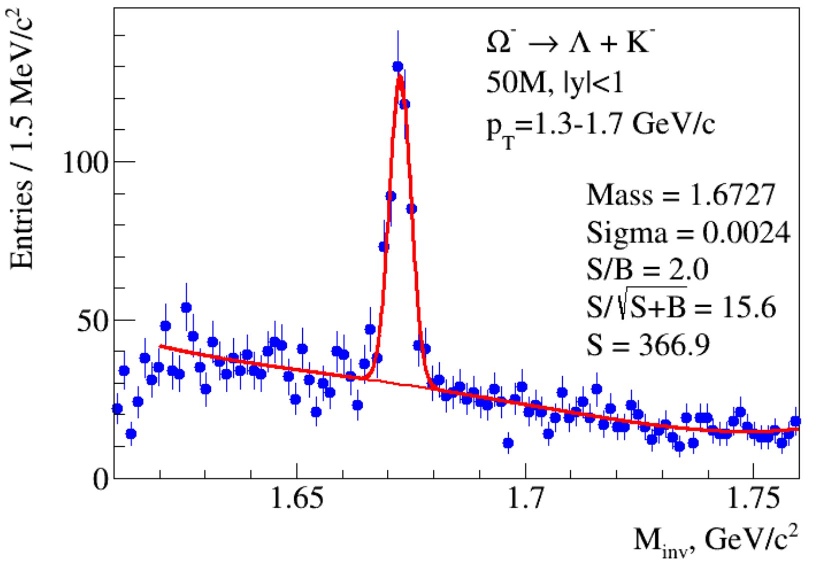


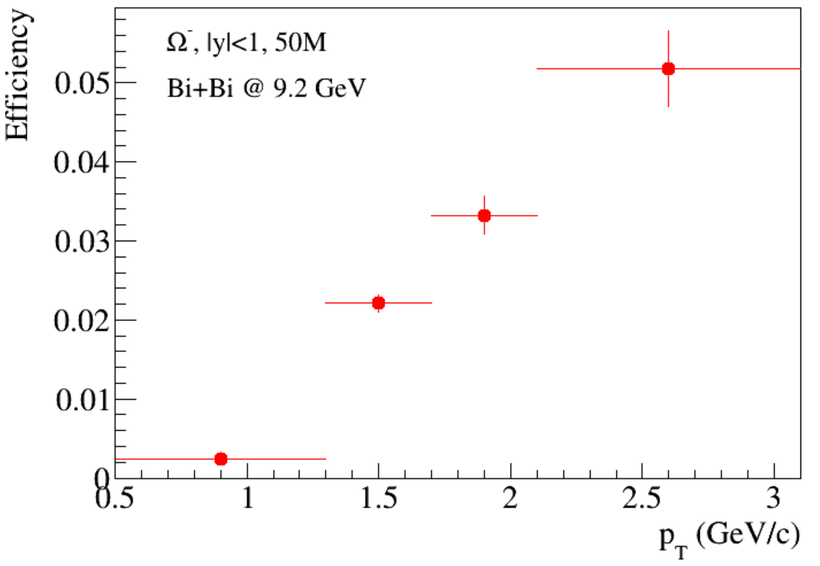
Analysis of Ξ^- and Ω^- hyperons

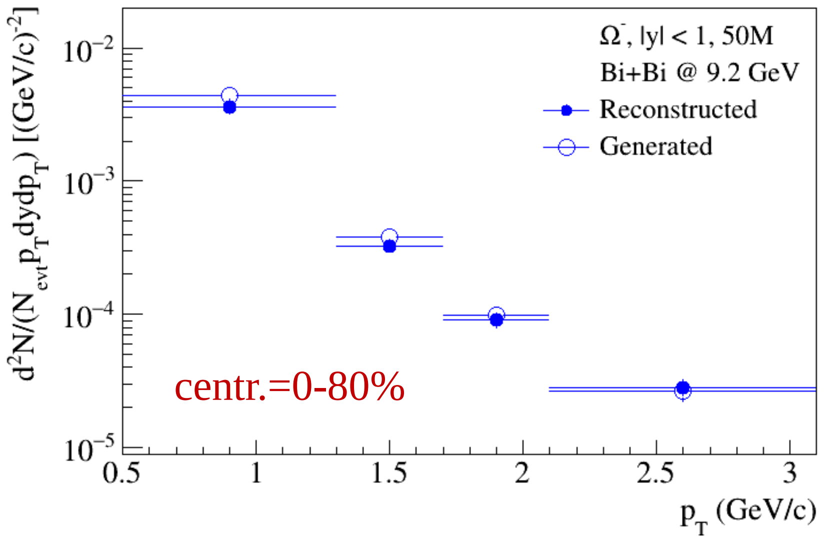




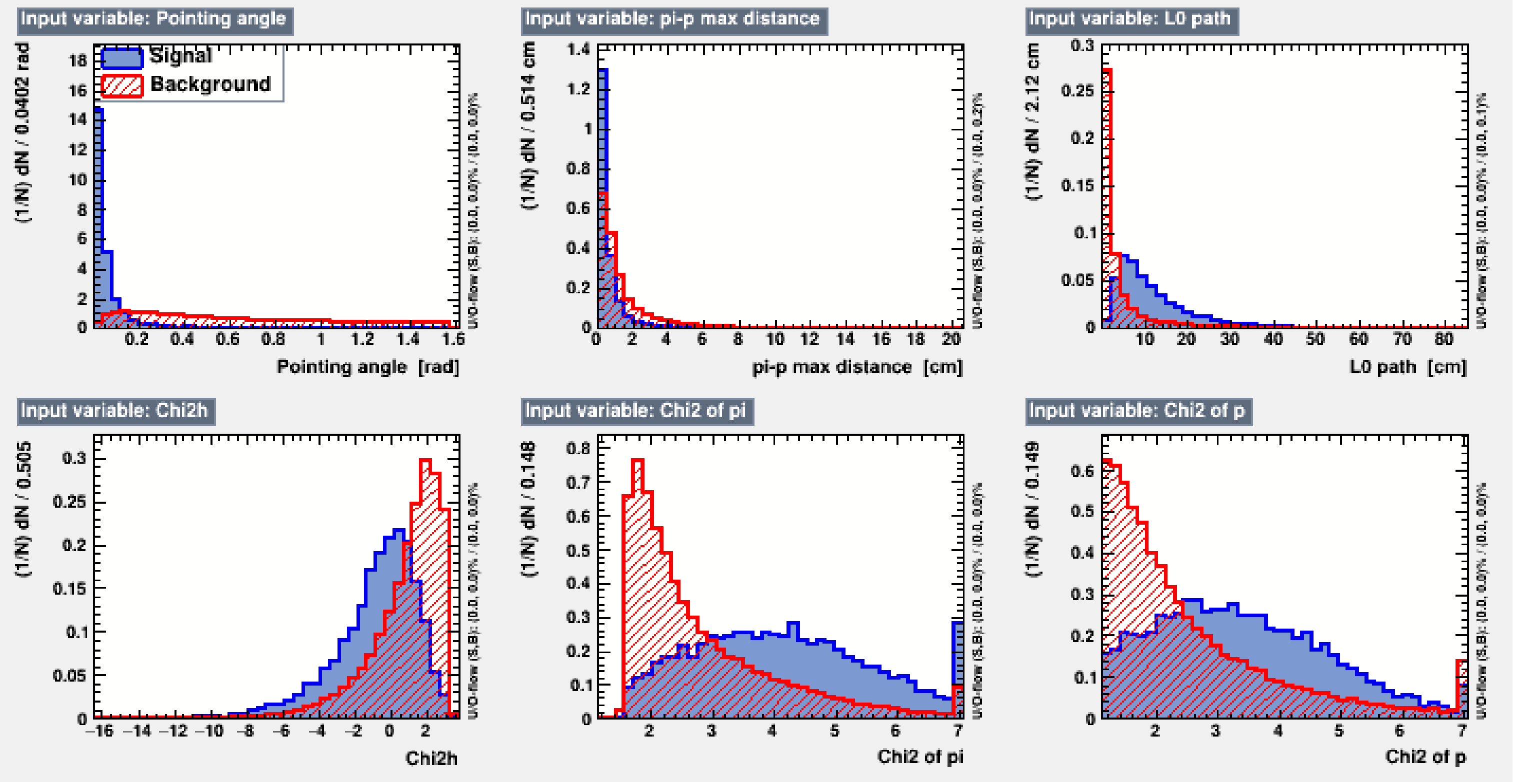


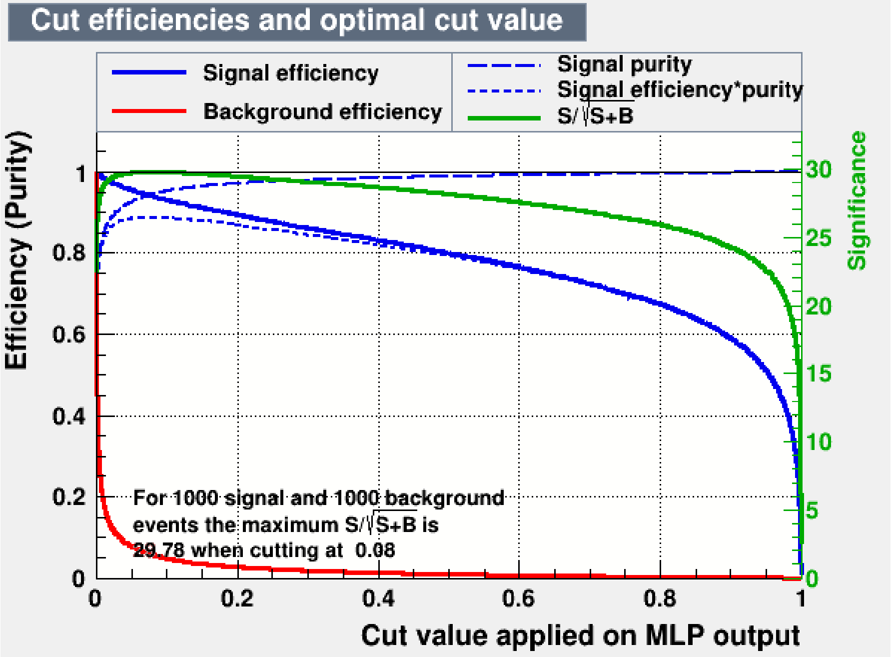




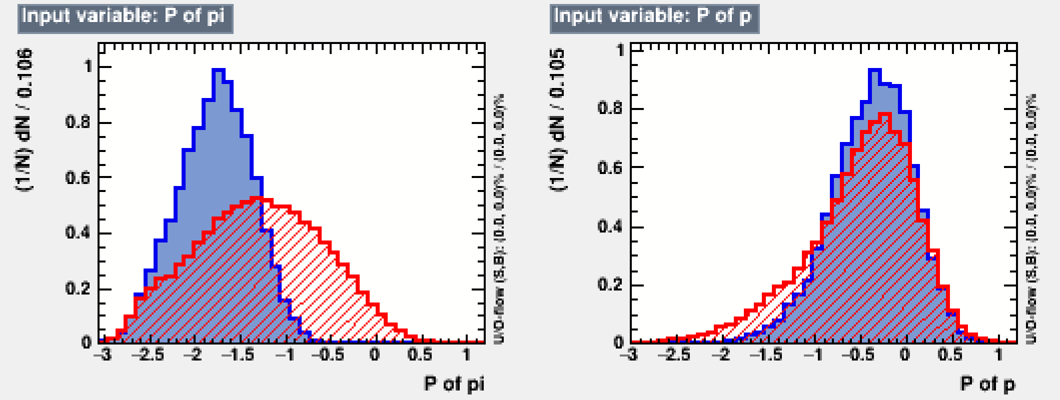


Λ reconstruction: Machine Learning Method

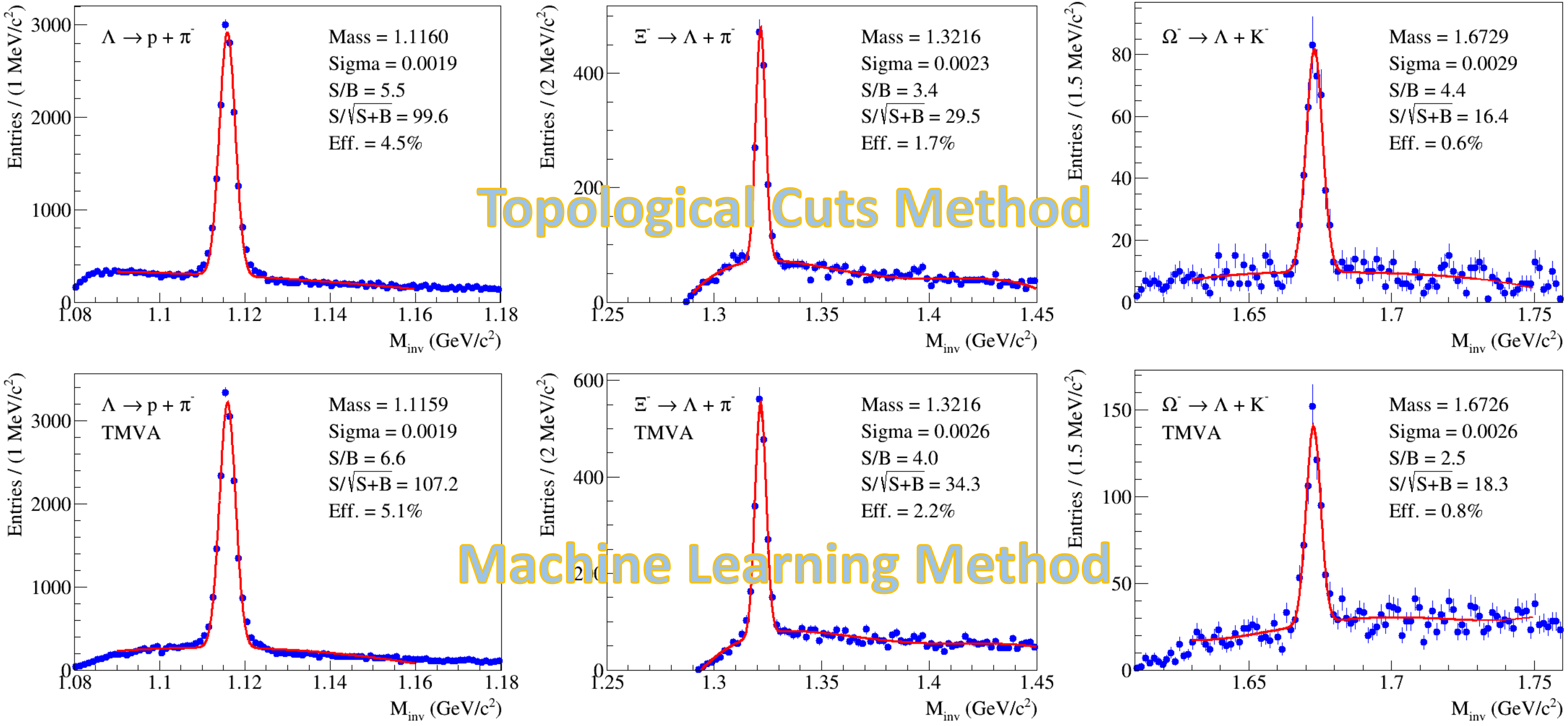




TMVA method



Hyperon reconstruction: TC vs TMVA



Hypernuclei reconstruction

Main objectives:

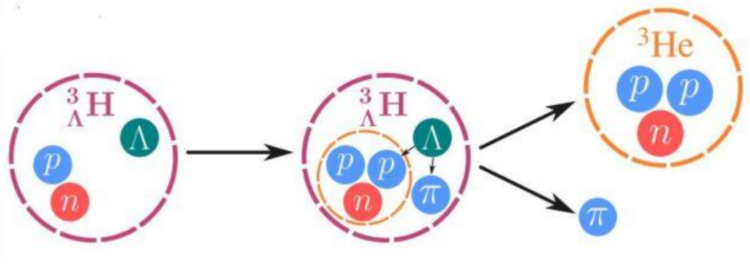
Realistic hypernuclei reconstruction with realistic MPD performance

Software development: Towards a realistic simulation of the MPD / NICA

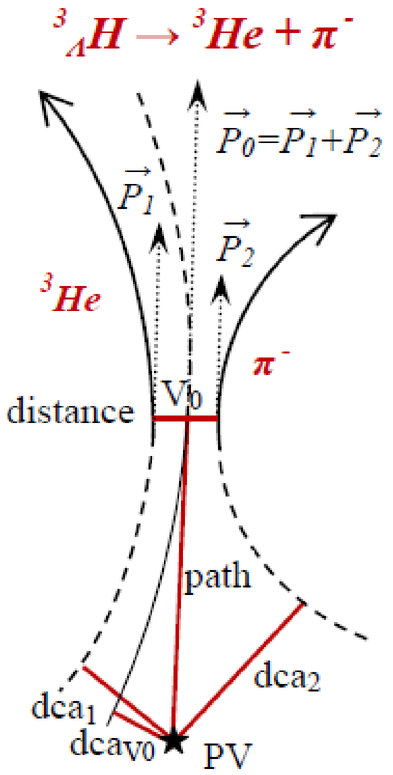
- Realistic description of the response of detectors, development, implementation and optimization of algorithms for reconstruction of signals in detectors
- Realistic track reconstruction procedure in TPC
- Description of ionization losses in TPC gas based on Garfield ++ simulations that are consistent with STAR data
- Realistic identification of electrons, hadrons and light nuclei in TPC and TOF software

Software requirements for hypernuclei reconstruction:

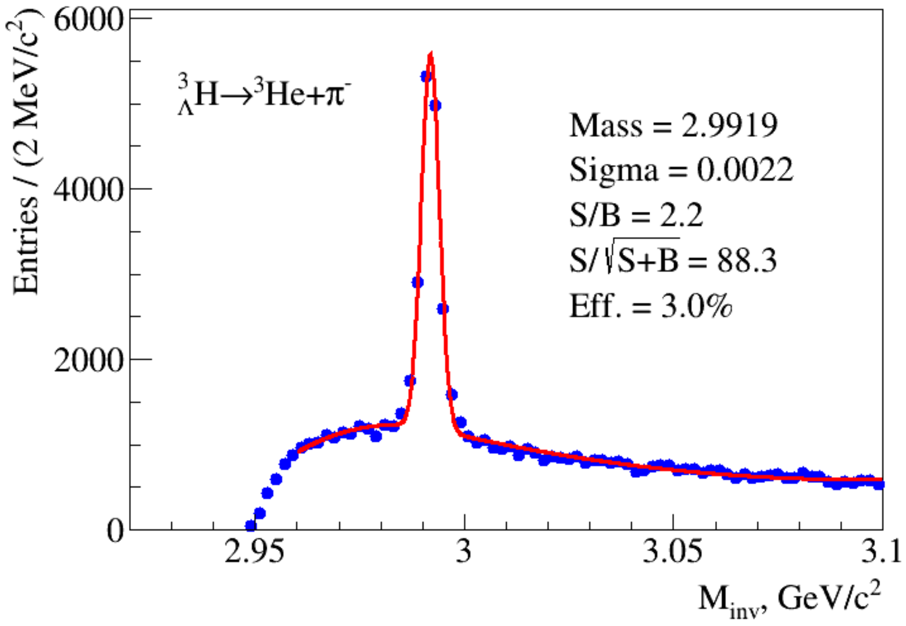
- High-quality reconstruction of the tracks of hadrons and light nuclei
- Good reconstruction of primary and secondary vertices
- High efficiency of identification of both hadrons and light nuclei

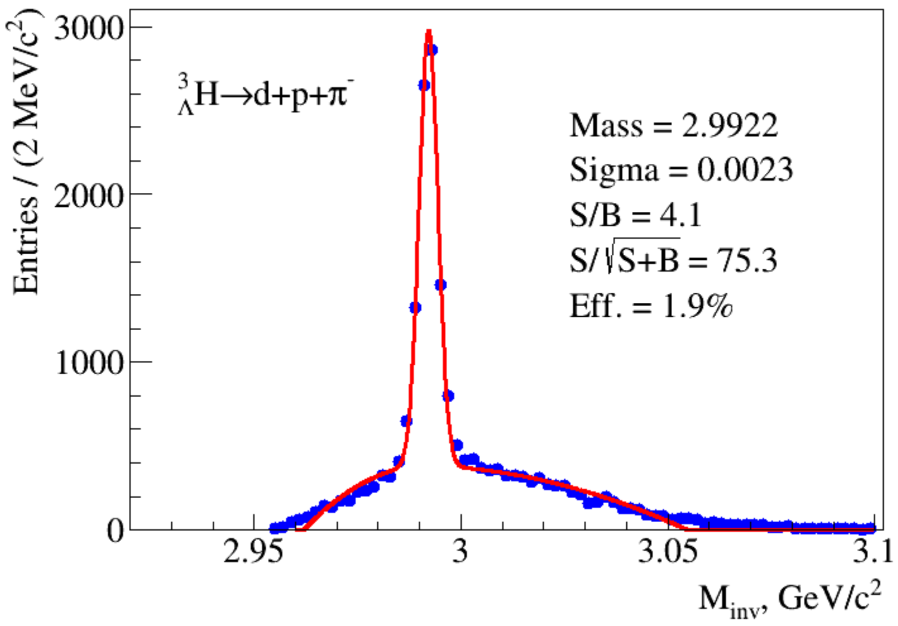


Hypertriton reconstruction



PHQMD, Bi+Bi @ 9.2 GeV, min. bias, 40M



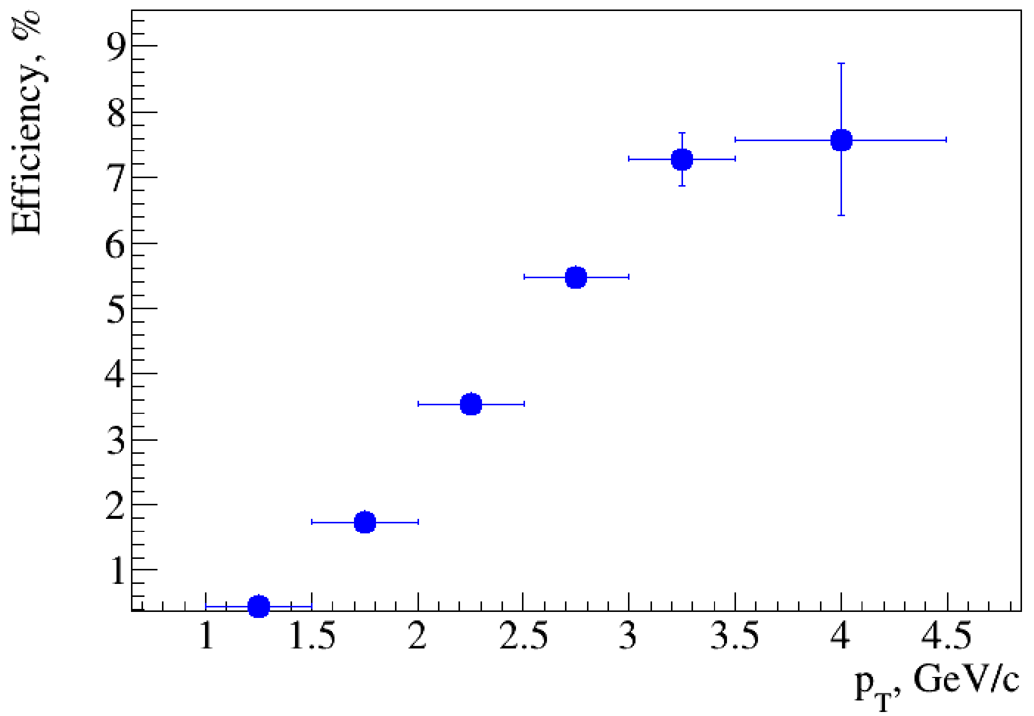


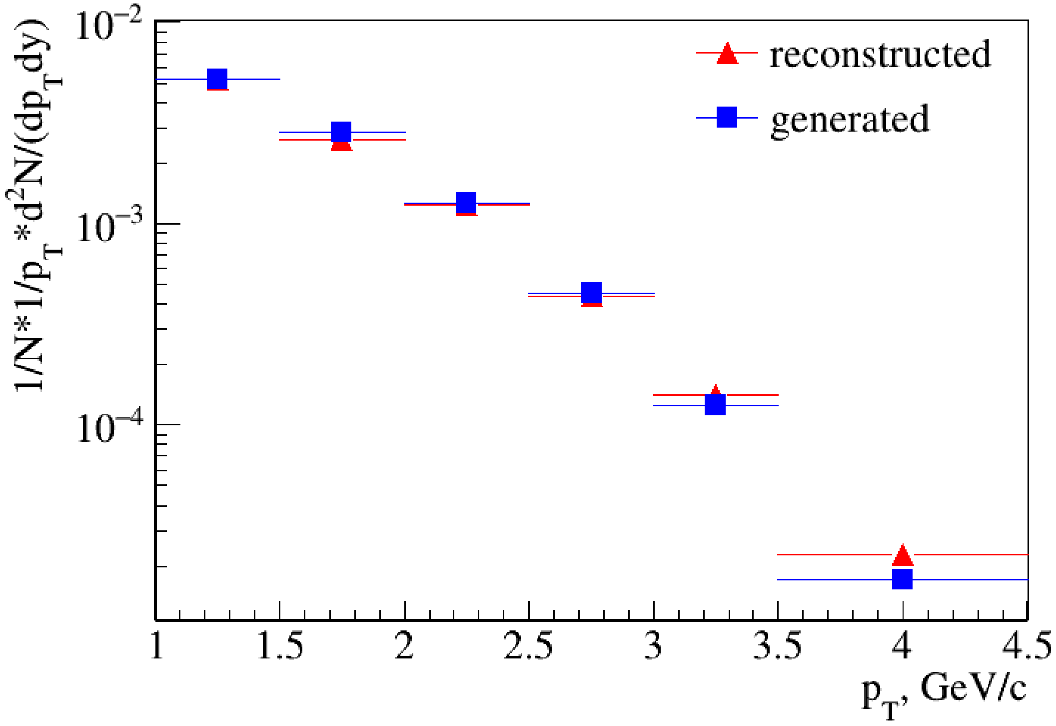
Mesonic decay of $_{\Lambda}{}^{3}H$: event topology

- PV – primary vertex
- V_0 – vertex of hyperon decay
- dca – distance of the closest approach
- path – decay length

Decay channel	Branching ratio	Decay channel	Branching ratio
$\pi^- + {}^3He$	**24.7%**	$\pi^- + p + p + n$	1.5%
$\pi^0 + {}^3H$	12.4%	$\pi^0 + n + n + p$	0.8%
$\pi^- + p + d$	**36.7%**	$d + n$	0.2%
$\pi^0 + n + d$	18.4%	$p + n + n$	1.5%

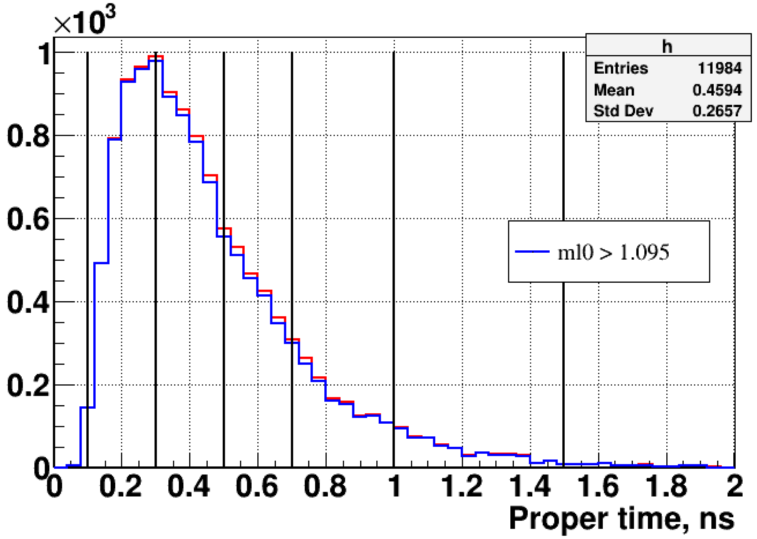
p_T -spectrum of hypertritons





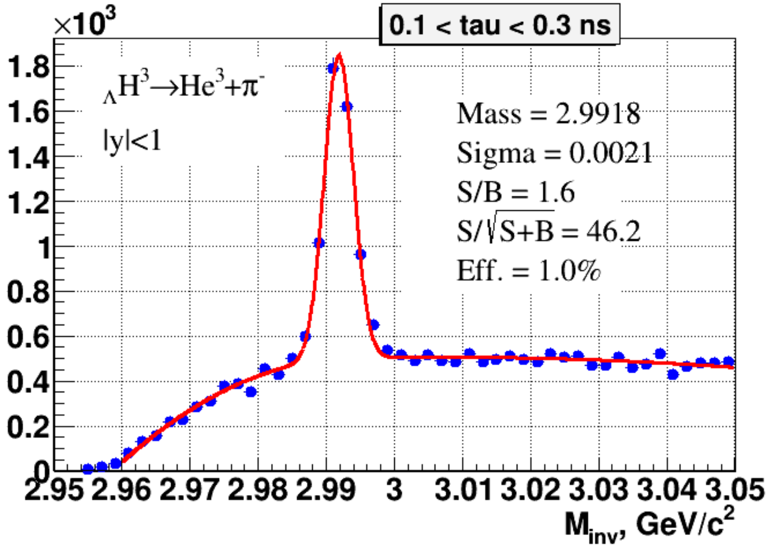
- Invariant spectrum is reconstructed up to $p_T = 4.5$ GeV/c
- Rapidity density can be obtained in min. bias Bi+Bi collisions (with a proper fit function)

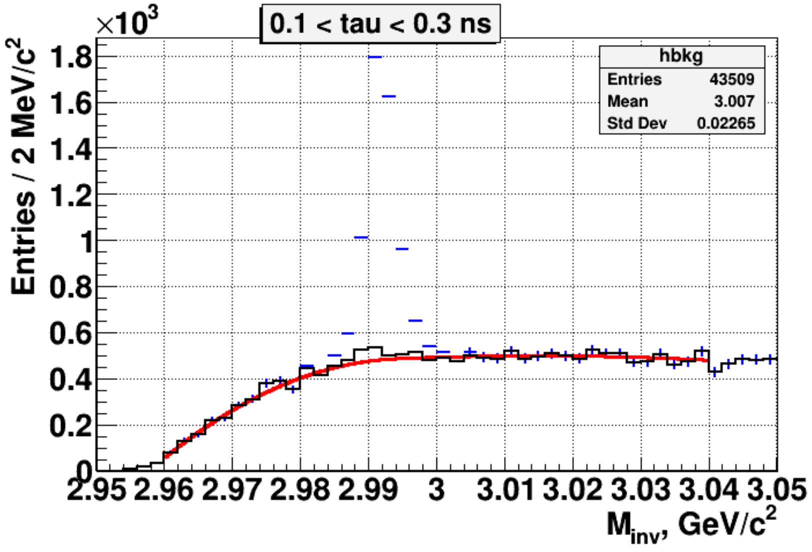
Hypertriton lifetime analysis

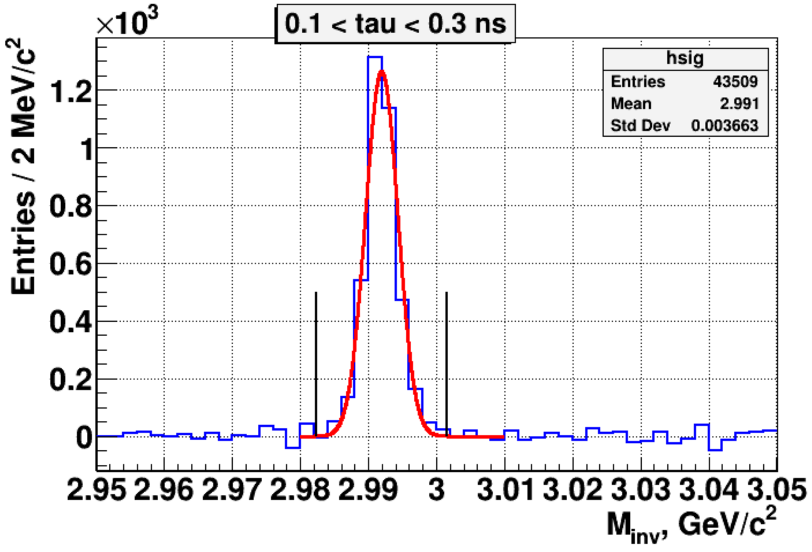


- Large event statistics allows extraction of the lifetime
- Hypertritons are reconstructed in several $c\tau$ bins
- The yields are extracted similarly

$c\tau = cML / p$ (c – speed of light, M – hypertriton mass, L – track length)



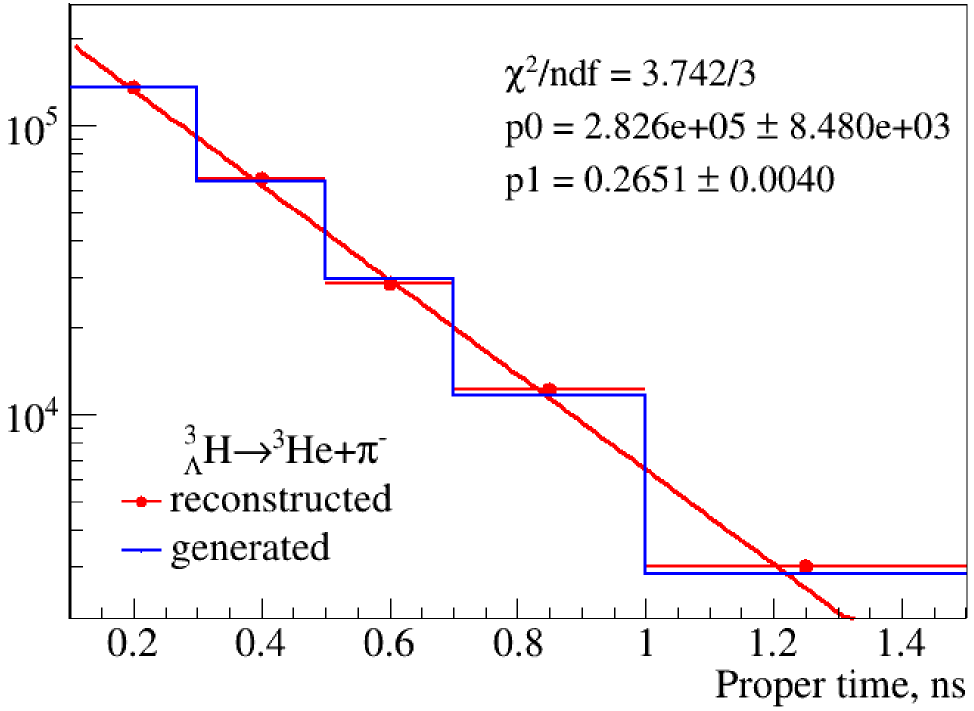


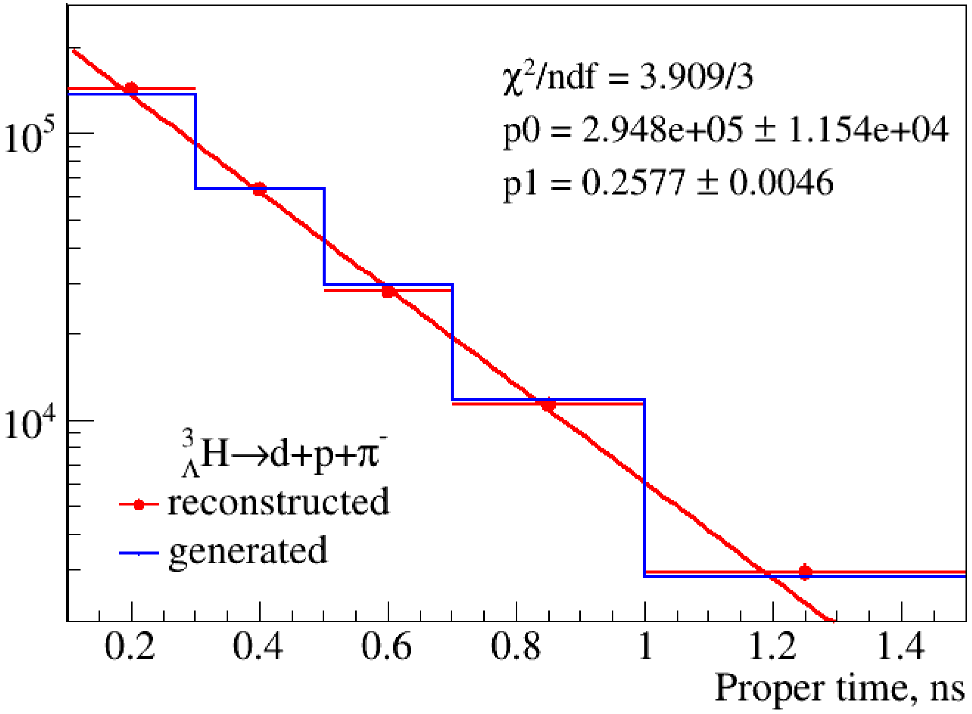


Hypertriton lifetime

Bi+Bi @ 9.2 GeV, min. bias, 40M
b0 < 12 fm, τ = [0.1–1.5] ns

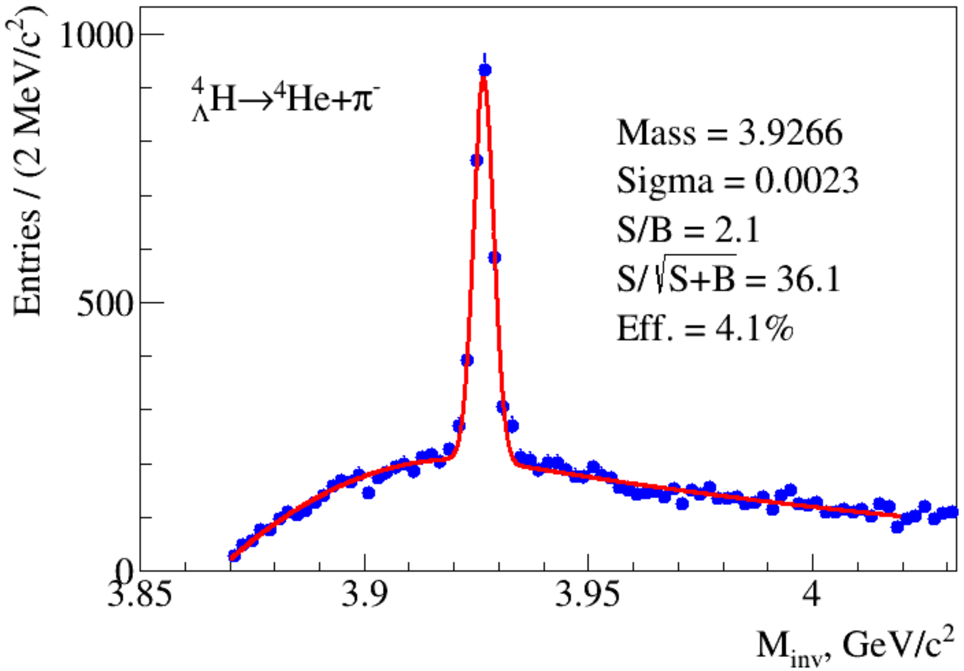
$$N(\tau) = N(0)\exp\left(-\frac{\tau}{\tau_0}\right) = N(0)\exp\left(-\frac{ML}{cp\tau_0}\right),$$

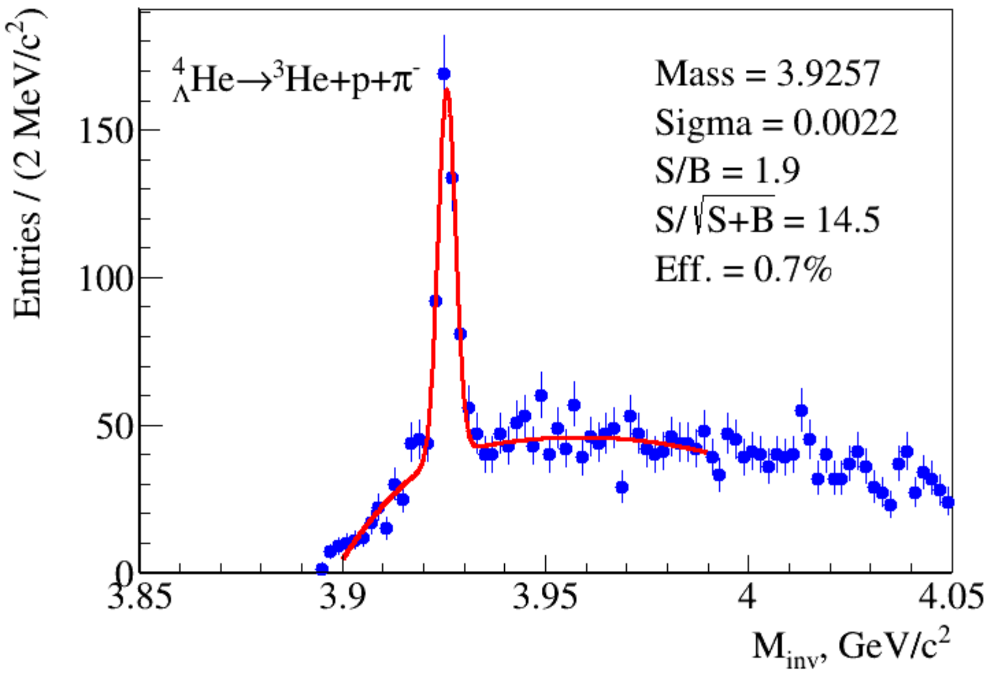




Results for different decay modes are consistent

$^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ reconstruction





Branching ratio: 75%

Branching ratio: 32%

Signal embedding technique: The Monte Carlo event sample was enriched by signal particles (hypernuclei), distributed according to the η-p_T phase space given by the PHQMD generator

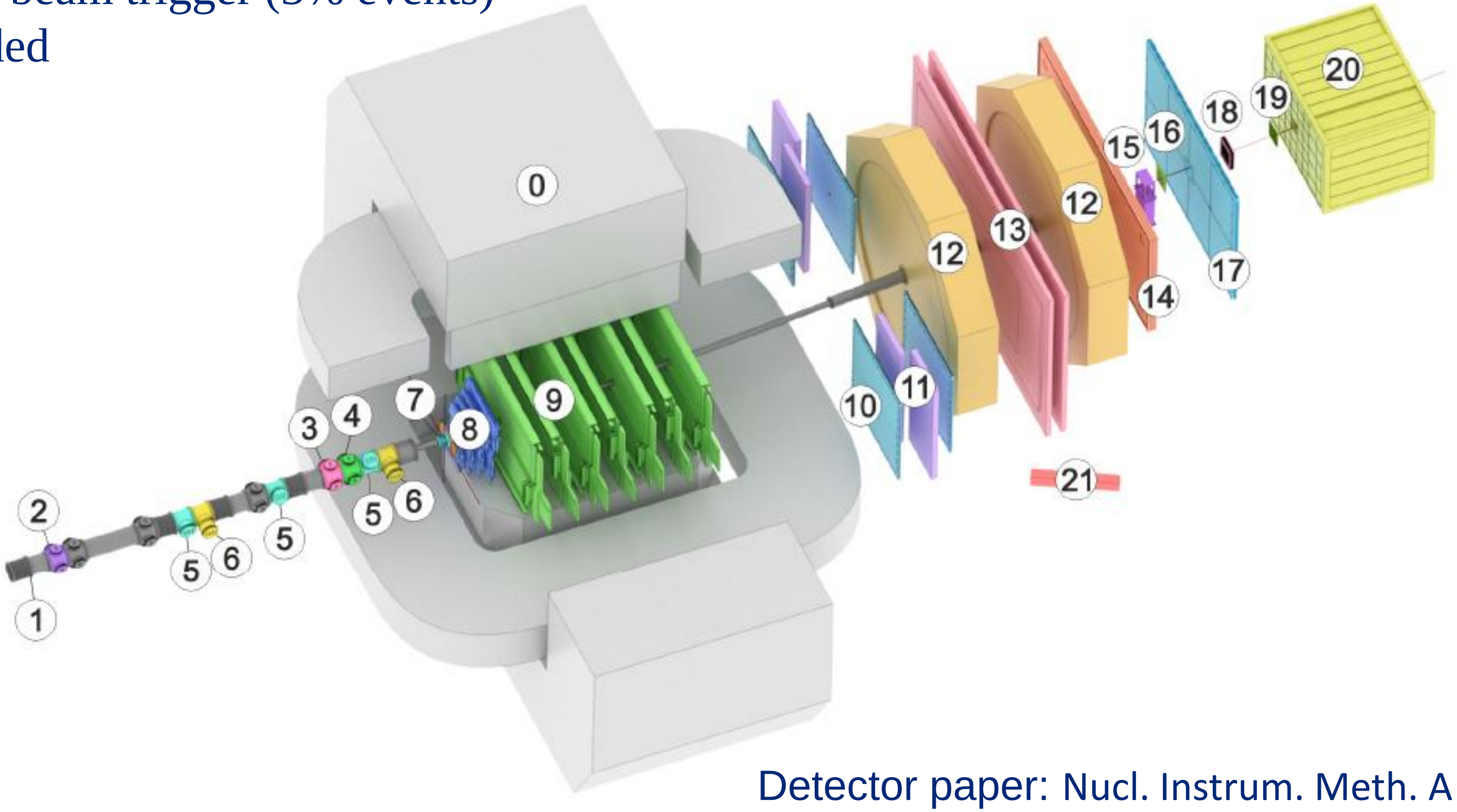
Equivalent statistics: ~140 M events for $_{\Lambda}^{4}H$ and for $_{\Lambda}^{4}He$

Strangeness analysis at BM@N experiment

Configuration of BM@N detector in Xe+CsI run

First physics run with full configuration Dec. 2022 – Jan. 2023
Xe^{124} + CsI interactions, beam kinetic energy 3.8A GeV:

main trigger covers centrality < 70-75% (85% events), min bias trigger (7% events), beam trigger (3% events)
~500M triggers recorded

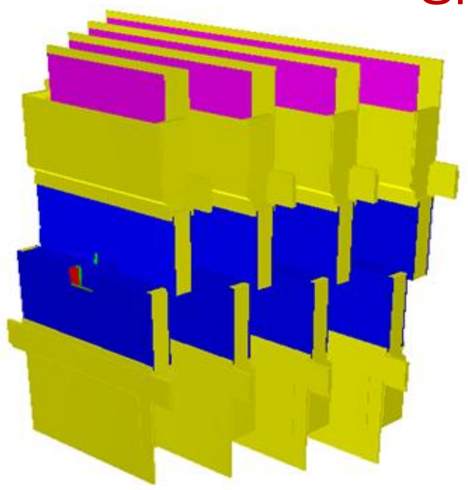


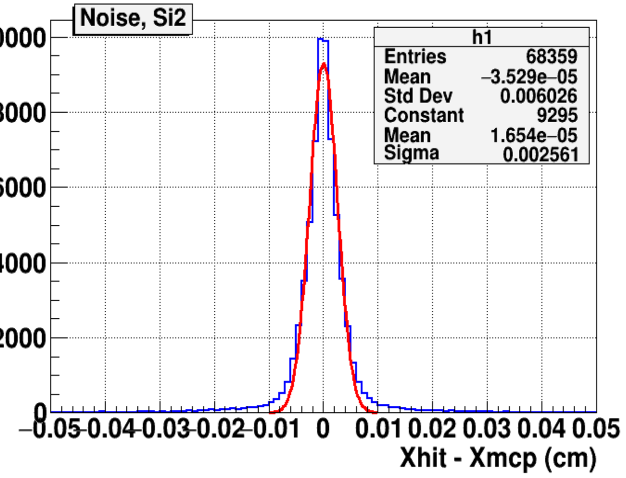
- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- Triggers: BD + SiMD (7)
- FSD, GEM (8, 9)
- CSC 1x1 m^2 (10)
- TOF 400 (11)
- DCH (12)
- TOF 700 (13)
- ScWall (14)
- FD (15)
- Small GEM (16)
- CSC 2x1.5 m^2 (17)
- Beam Profilometer (18)
- FQH (19)
- FHCal (20)
- HGN (21)

Detector paper: Nucl. Instrum. Meth. A **1065**, 169532 (2024)

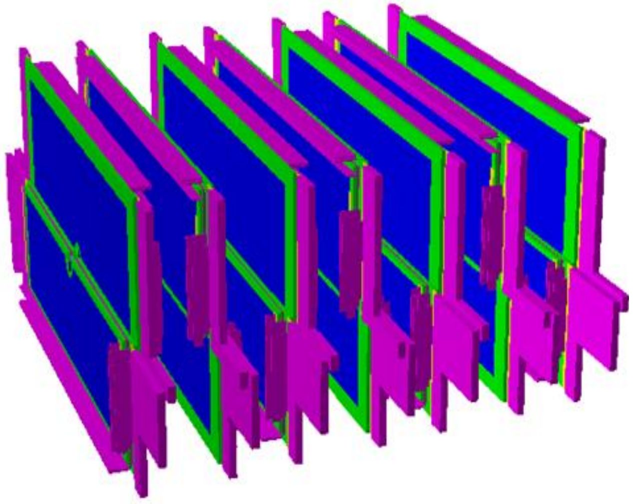
Central tracker performance

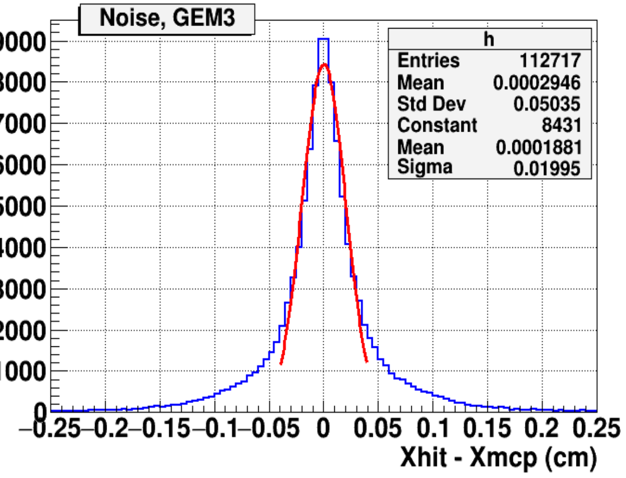
Si tracker

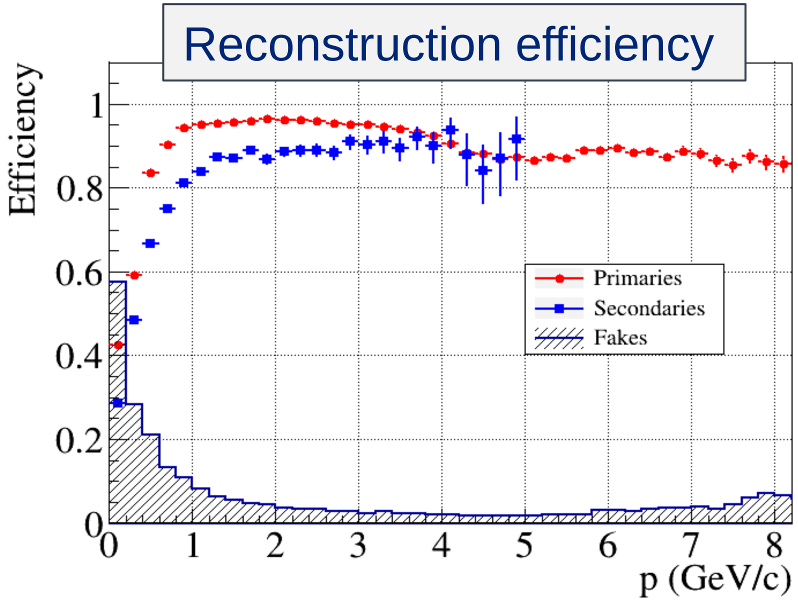


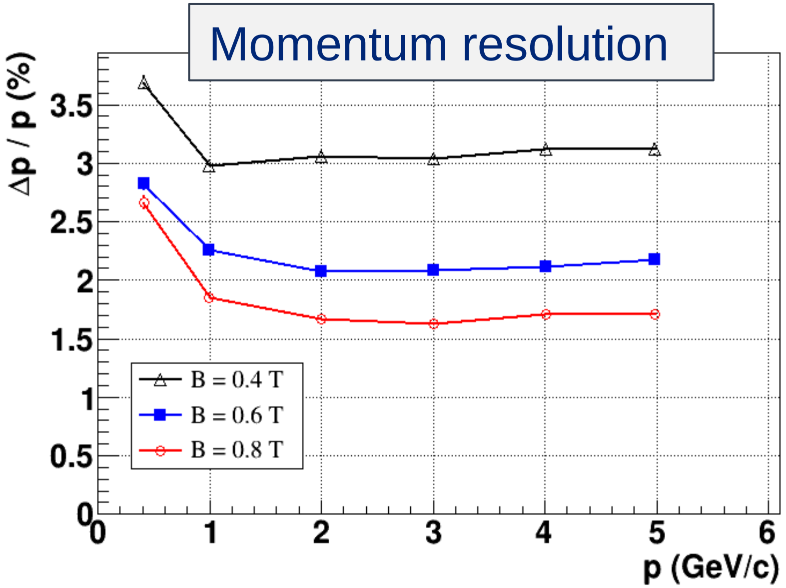


GEMs





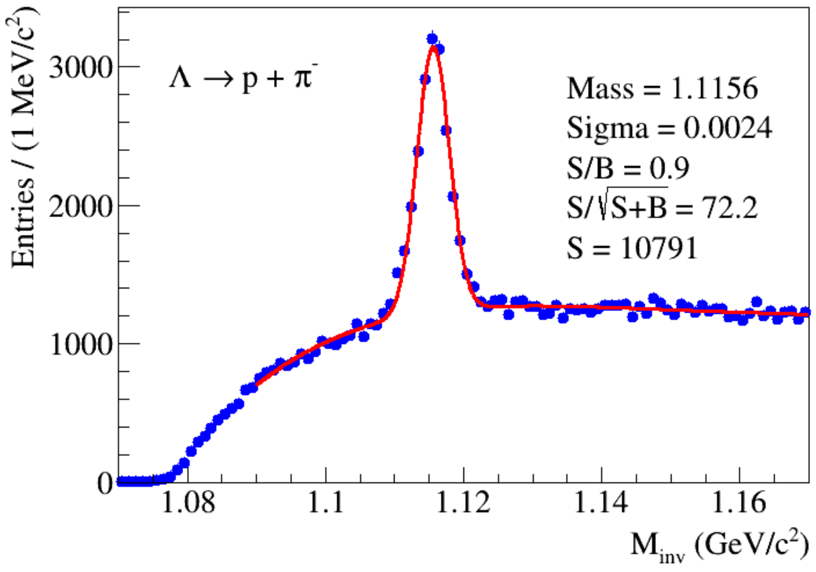


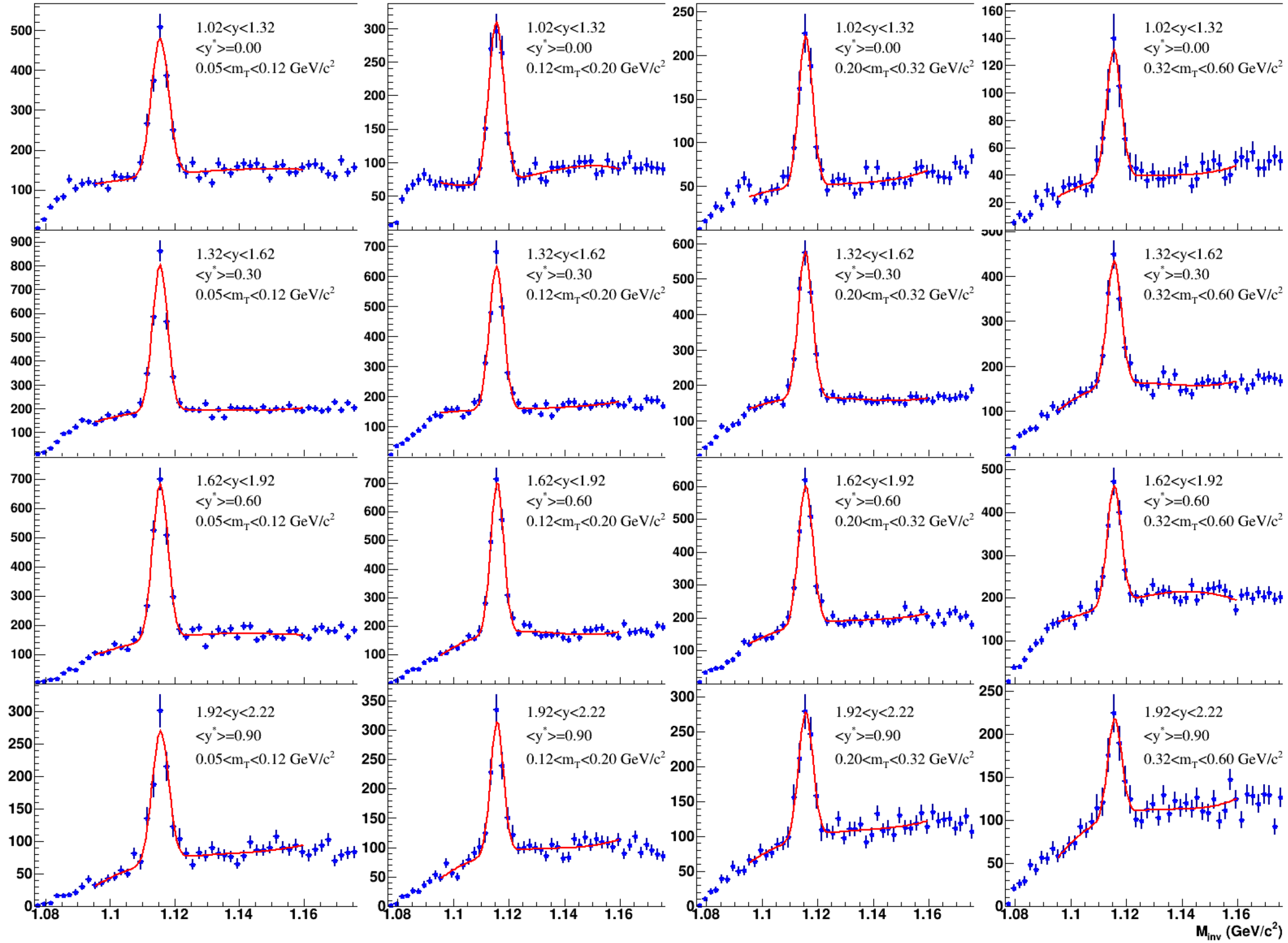


Track reconstruction:

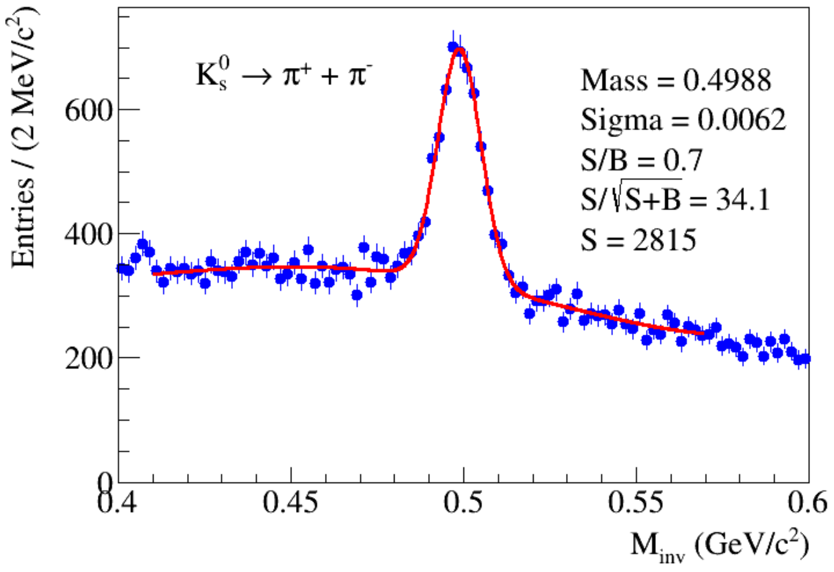
Vector Finder (VF) – homemade package

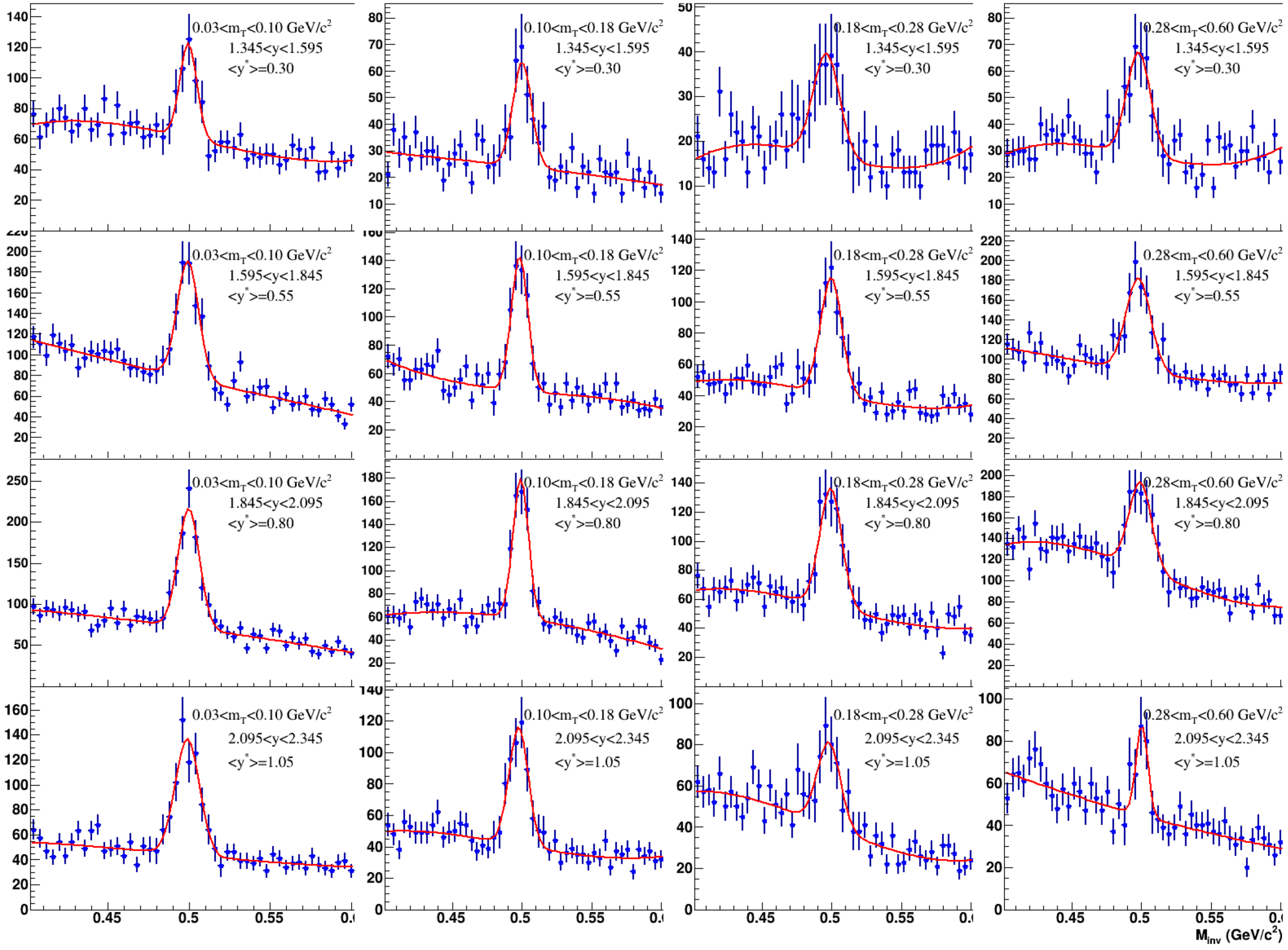
Λ selection: bins y vs m_T



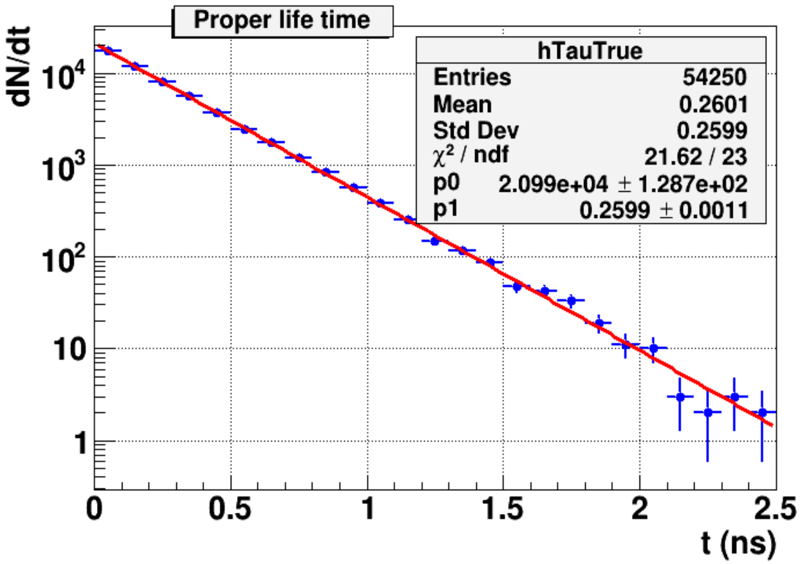


K^0_s selection: bins y vs m_T





Lifetime of Λ: MC vs Data



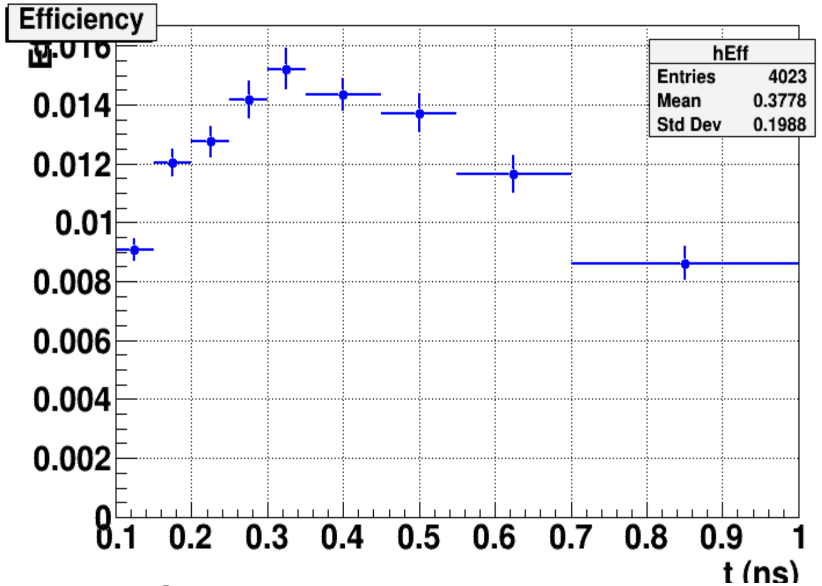
Decay formula:

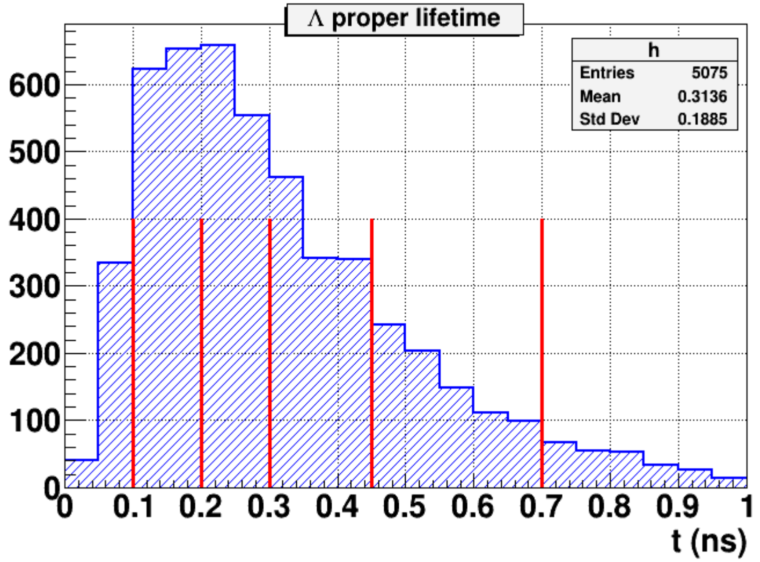
$dN / dt = N_0 / \tau * exp(-t/\tau),$

$N_0 = p0 * p1 = 54574$

Proper life time:

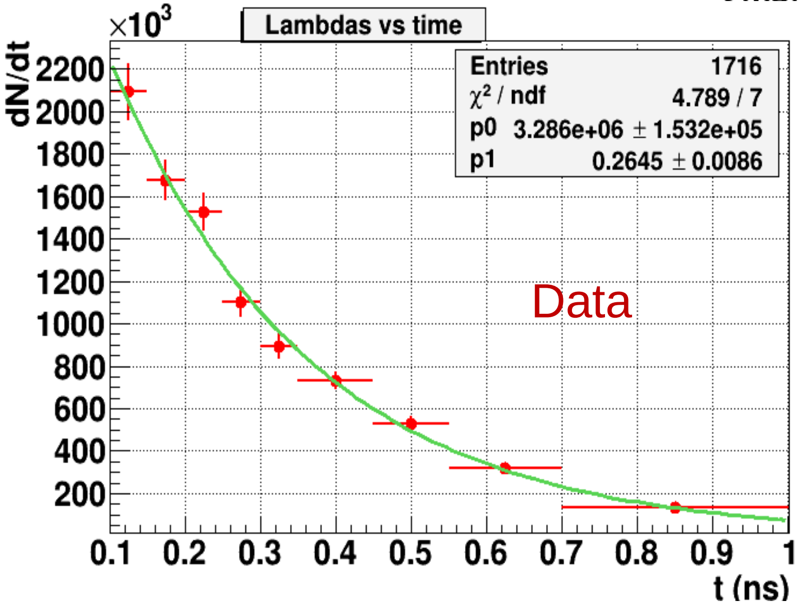
$\tau = lm / (pc)$



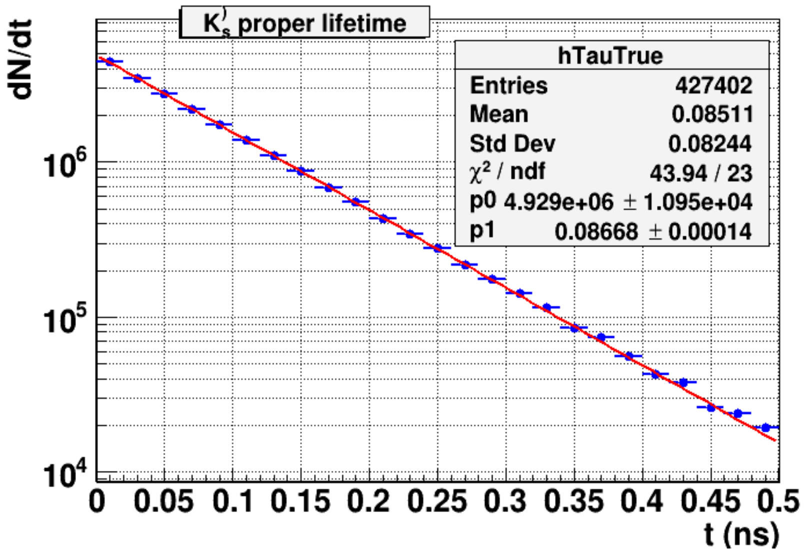


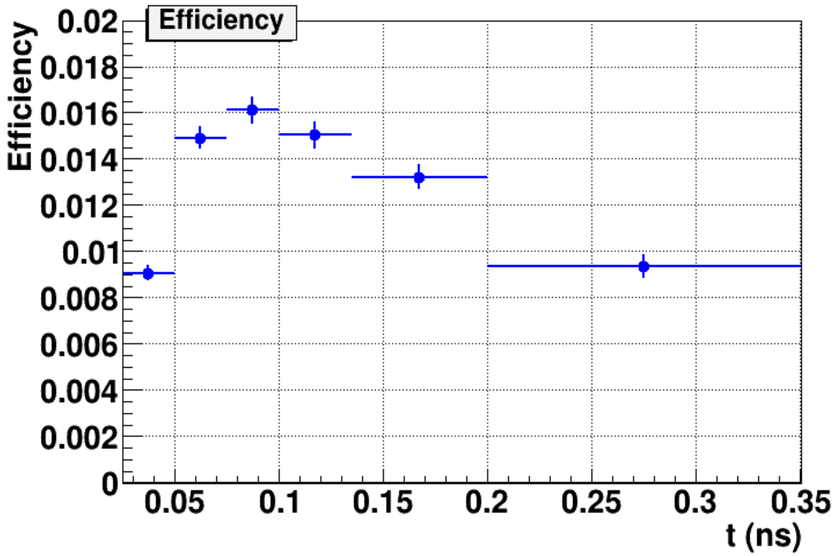
MC (1M events): 0.270 ± 0.011 ns

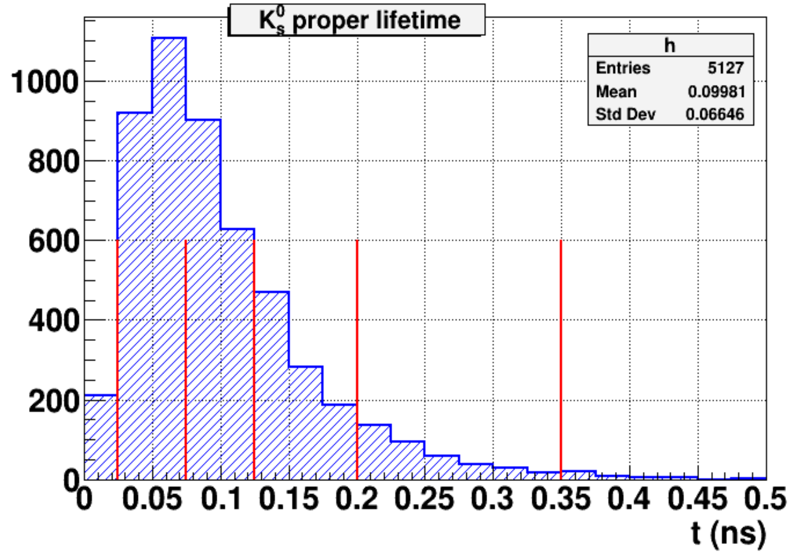
Data (1M events): 0.265 ± 0.009 ns



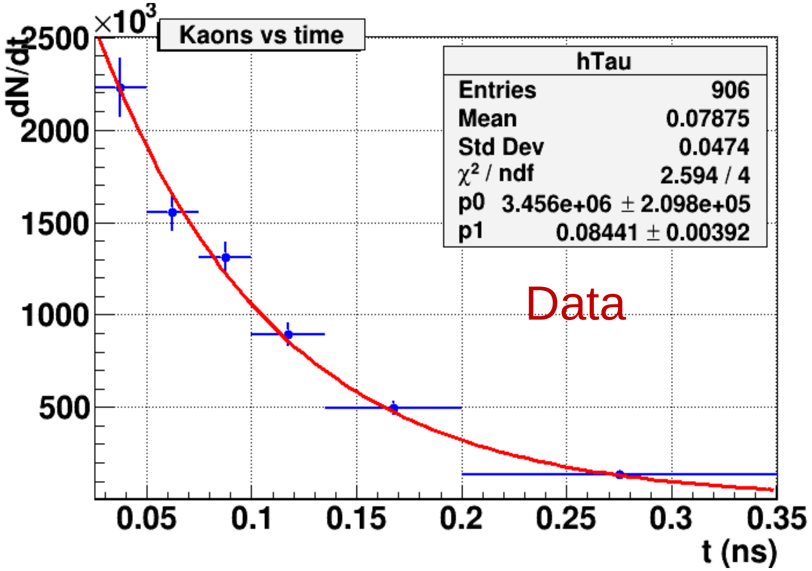
Lifetime of K^0_s: MC vs Data







MC (1M events): 0.082 ± 0.004 ns
Data (1M events): 0.084 ± 0.004 ns



Summary

- The MPD reconstruction and identification packages have been tested using hyperons and hypernuclei as a testing tool
- Clear peaks of different hyperons and hypernuclei ${}_{\Lambda}^{3}H$, ${}_{\Lambda}^{4}H$ and ${}_{\Lambda}^{4}He$ in invariant mass spectra have been obtained
- p_T-spectra of hyperons and ${}_{\Lambda}^{3}H$ have been obtained
- ${}_{\Lambda}^{3}H$ decay time has been extracted
- Collected events of Xe+CsI interactions from the BM@N spectrometer are being processed and analyzed

Look into the future

- Test of Machine Learning Methods for particle identification and hypernuclei selection at NICA/MPD
- Data analysis at BM@N (synergy with fixed target program of MPD)
- Performance evaluation of the MPD setup with the 1st stage ITS (3 layers) for strangeness studies