Hypernuclei at HADES

Recent results from the measurement of Hypernuclei in Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.55 GeV with the HADES experiment

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

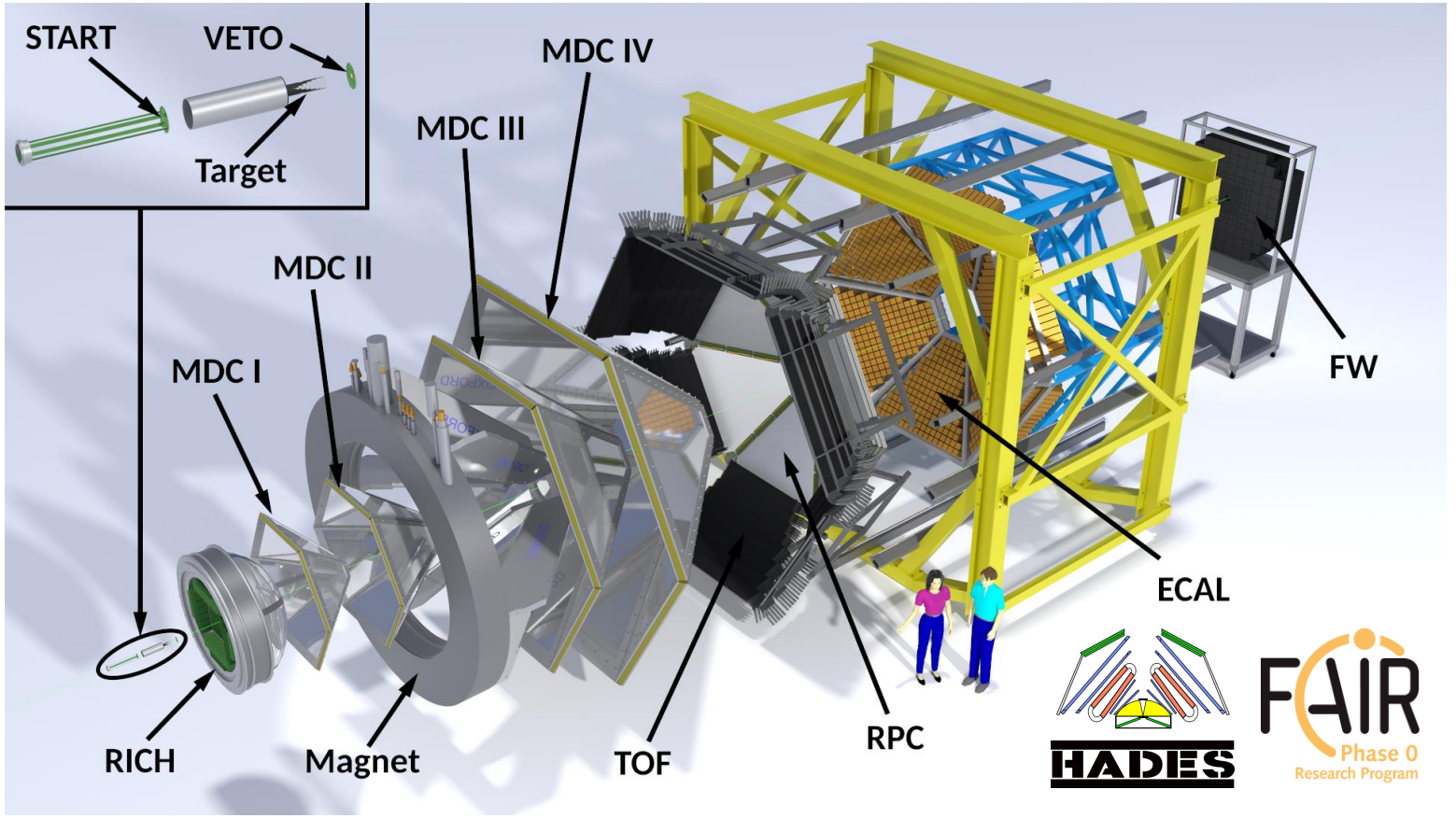
FAIR Phase 0 Research Program

EL EM EN TS

HADES

The HADES Experiment (Heavy-Ion Setup)

- Fixed target experiment at SIS18 (GSI, Germany)
- Magnet spectrometer
- Low mass Mini-Drift-Chambers (MDCs)
- Time of flight walls RPC and TOF
- RICH and ECAL for e^+/e^- and photon identification
- Forward hodoscope (FW) for spectator detection

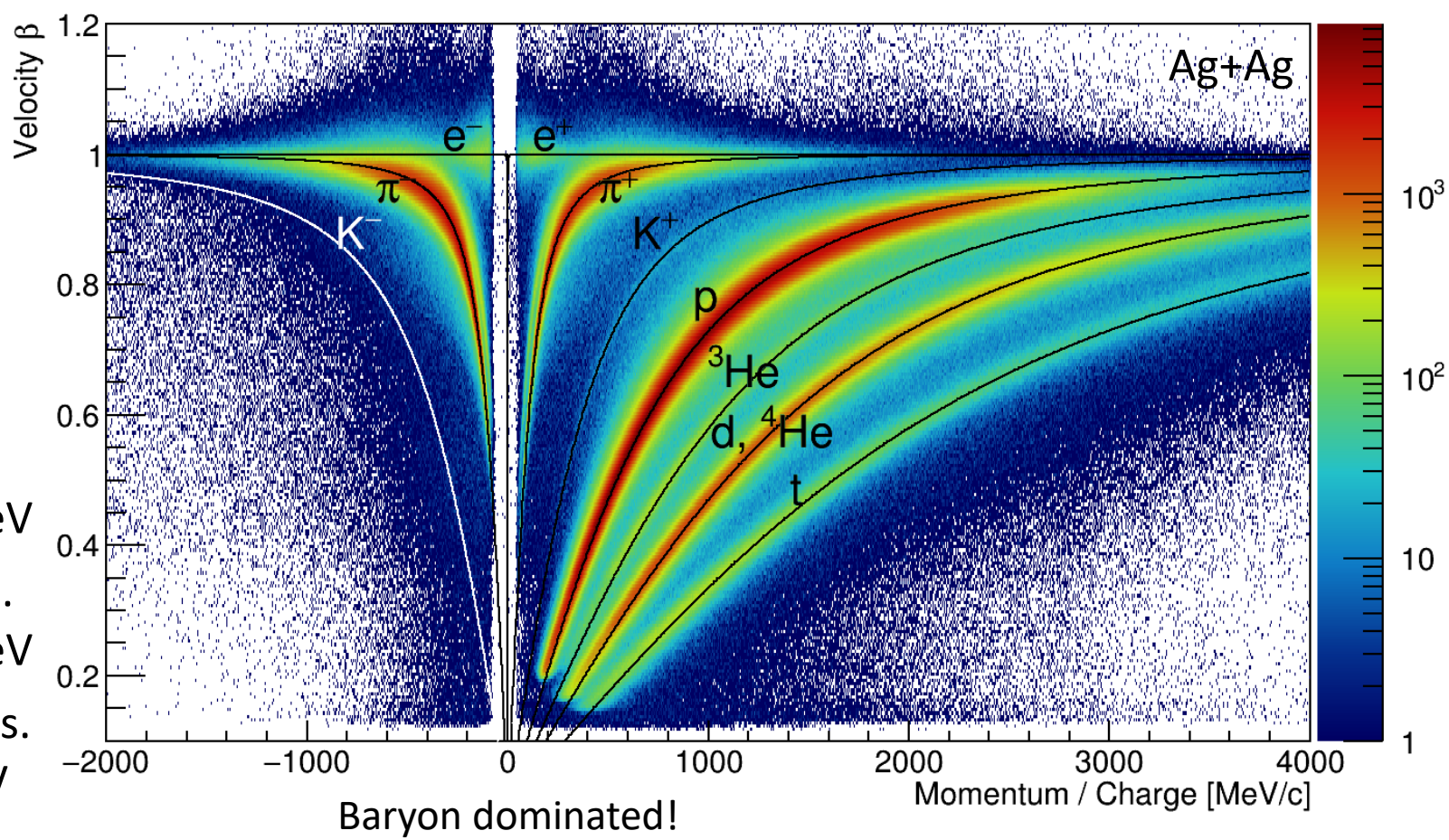


- Almost full azimuthal angle and polar angles between 18° and 85° covered

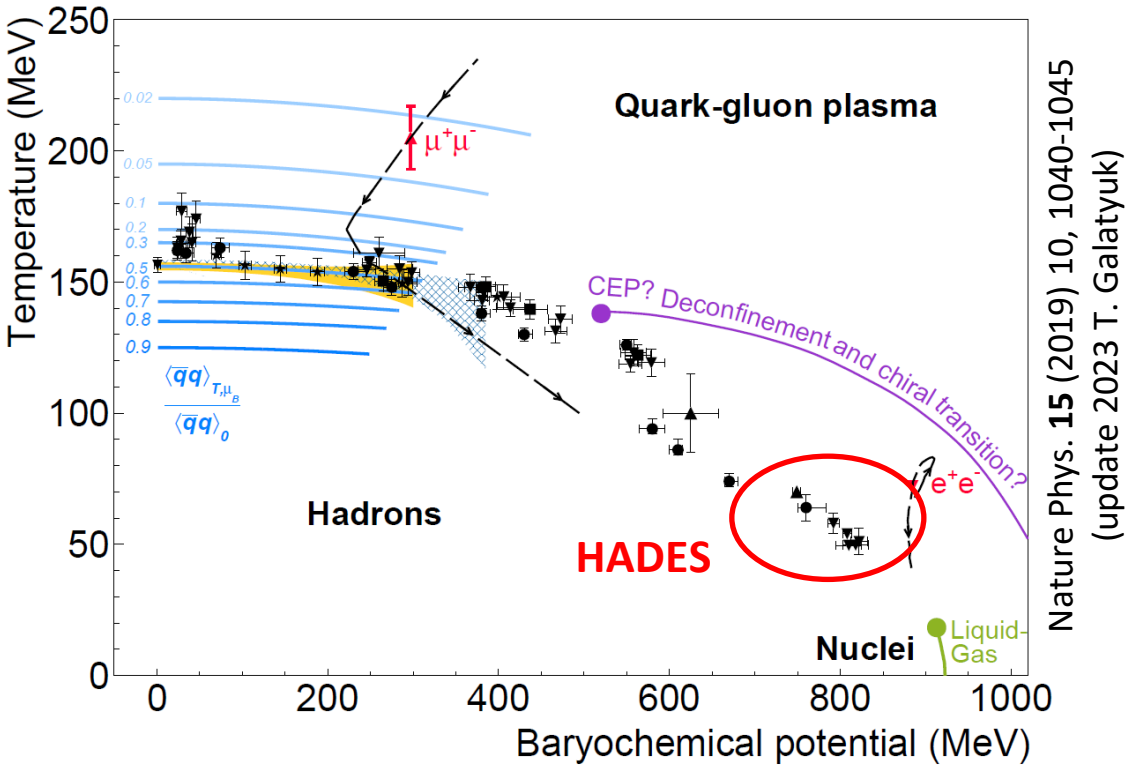
The HADES Experiment

- PID primarily via. momentum and velocity
  - Separation of multiple charged particles via. specific energy loss

- Heavy-ion beamtimes:
  - 2012: 7 billion Au+Au evts. 1.23A GeV: $\sqrt{s_{NN}}$ = 2.42 GeV
  - 2019: 14 billion Ag+Ag evts. 1.58A GeV: $\sqrt{s_{NN}}$ = 2.55 GeV
  - 2024: 1.8 billion Au+Au evts. 0.8A GeV: $\sqrt{s_{NN}}$ = 2.24 GeV



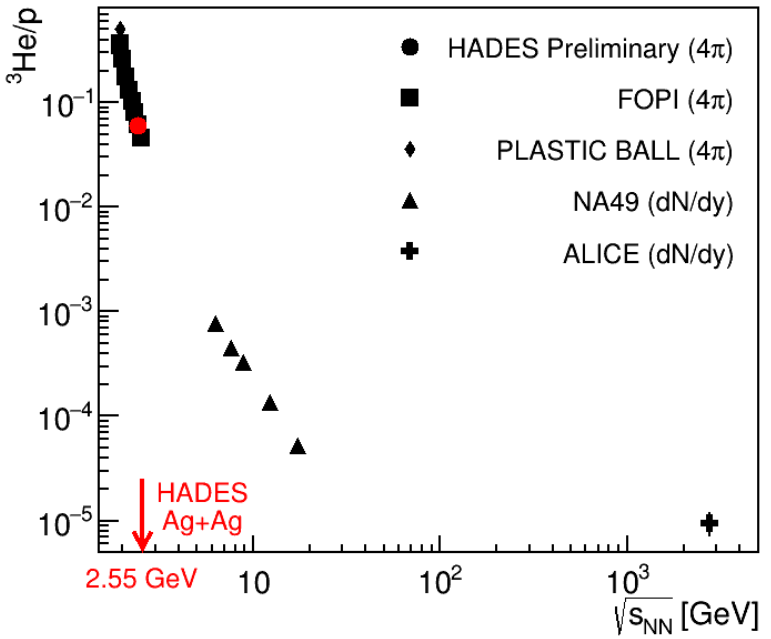
Nuclear Collisions at SIS18/HADES Energies



Nature Phys. **15** (2019) 10, 1040-1045
(update 2023 T. Galatyuk)

- Similar conditions as expected in merging neutron stars (Nature Physics **15**, 1040–1045 (2019), J. Phys.: Conf. Ser. **878** 012031, Phys. Rev. Lett. **122**, 061101)

- Nucleons essentially stopped in collision zone
  - ➢ Baryon dominated fireball N(B) ≈ 10 N(π)
- About 50% of protons clustered in light nuclei

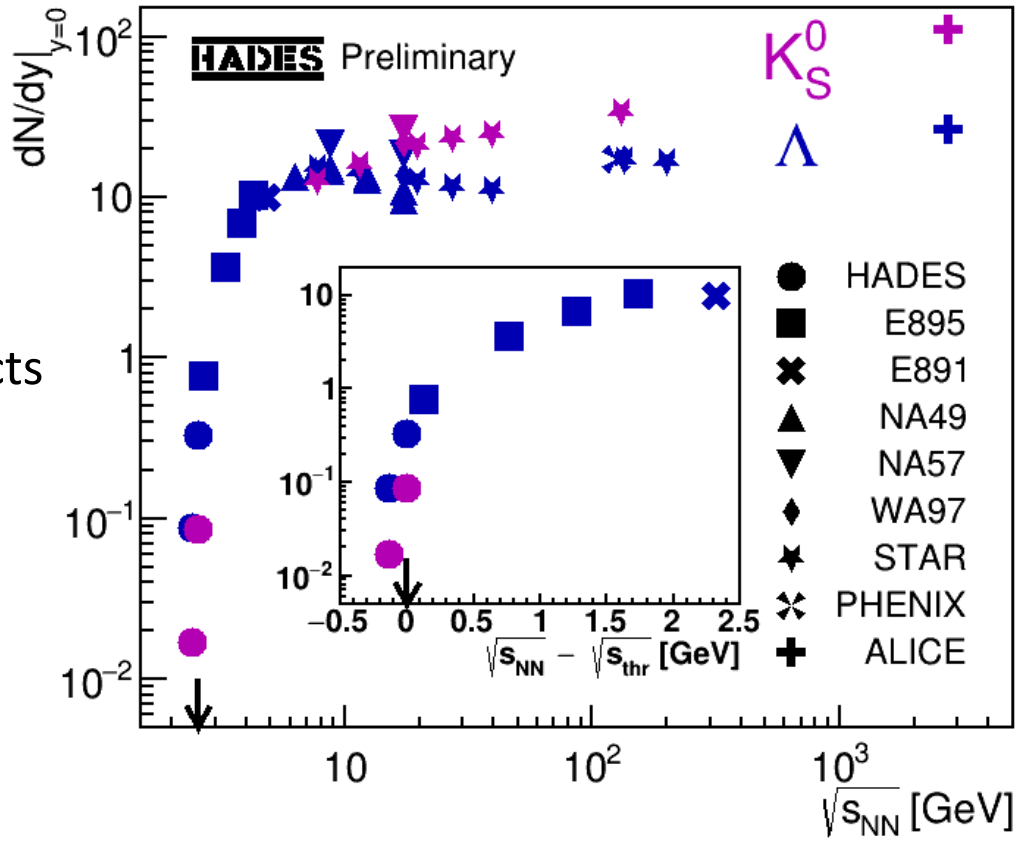


Data Collection:
Phys.Lett.B **809** (2020) 135746
STAR 3 GeV data upcoming

Strange Hadrons at SIS18/HADES Energies

- Strangeness production close to free NN threshold energy:
  N + N → Y + K + N: $\sqrt{s}$ = 2.55 GeV
  N + N → K + $\overline{K}$ + N + N: $\sqrt{s}$ = 2.86 GeV
  - ➢ Steep excitation function, sensitive to medium effects
  - ➢ Strangeness exchange reactions: Y + π → N + $\overline{K}$

- Production of Hypernuclei favored by baryon dominance of the fireball
  - ➢ Hypernuclei might allow deductions on their underlying Y-N interactions relevant for the nuclear EOS at high densities



Data: Phys.Lett.B 793 (2019) 457-463

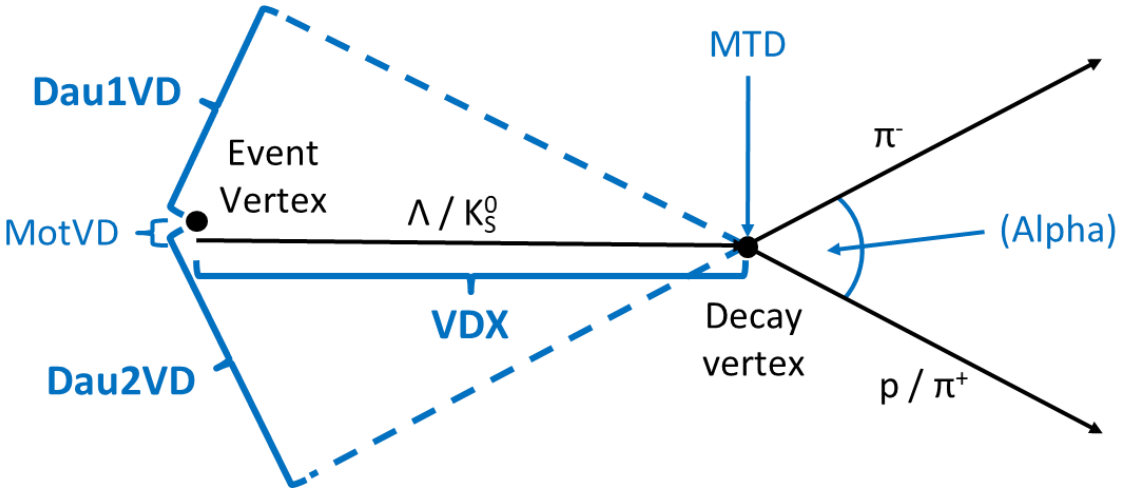
Weak Decays

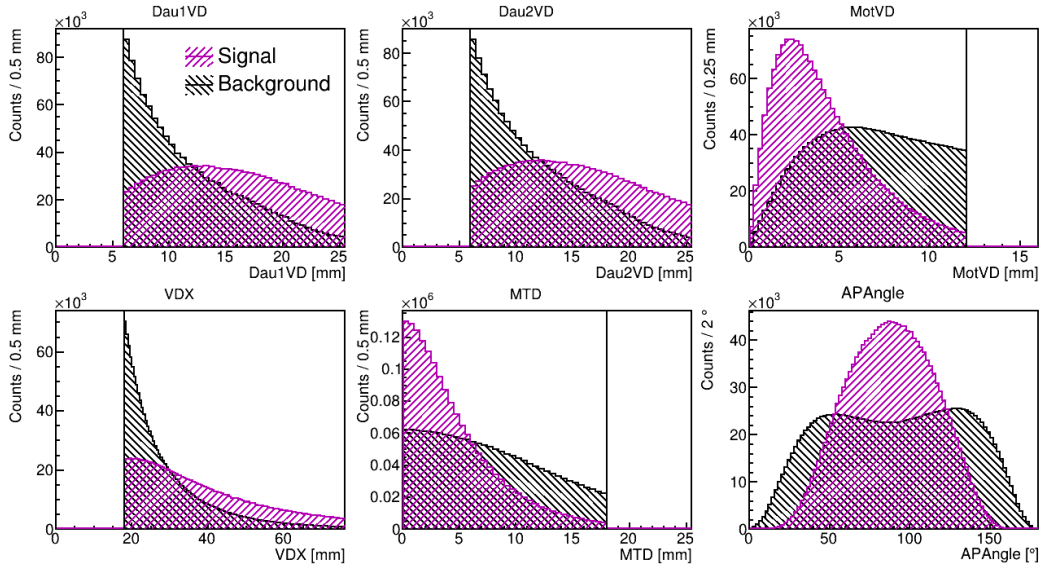
Reconstruction and Analysis of weakly decaying Hadrons

Weak decay reconstruction

- Combinatorial background about factor 10,000 above signals
- Long lifetimes → Off-vertex-topology
- Evaluated by an artificial neural network

  TMVA: arXiv:physics/0703039v5 [physics.data-an]





Toolkit for **M**ulti**V**ariate Data **A**nalysis with ROOT

Weak decay reconstruction

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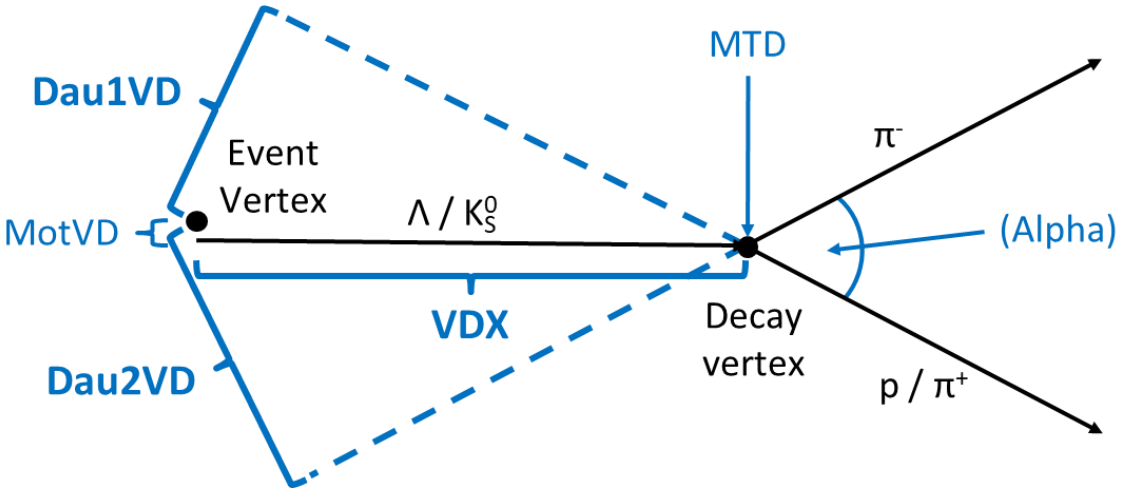
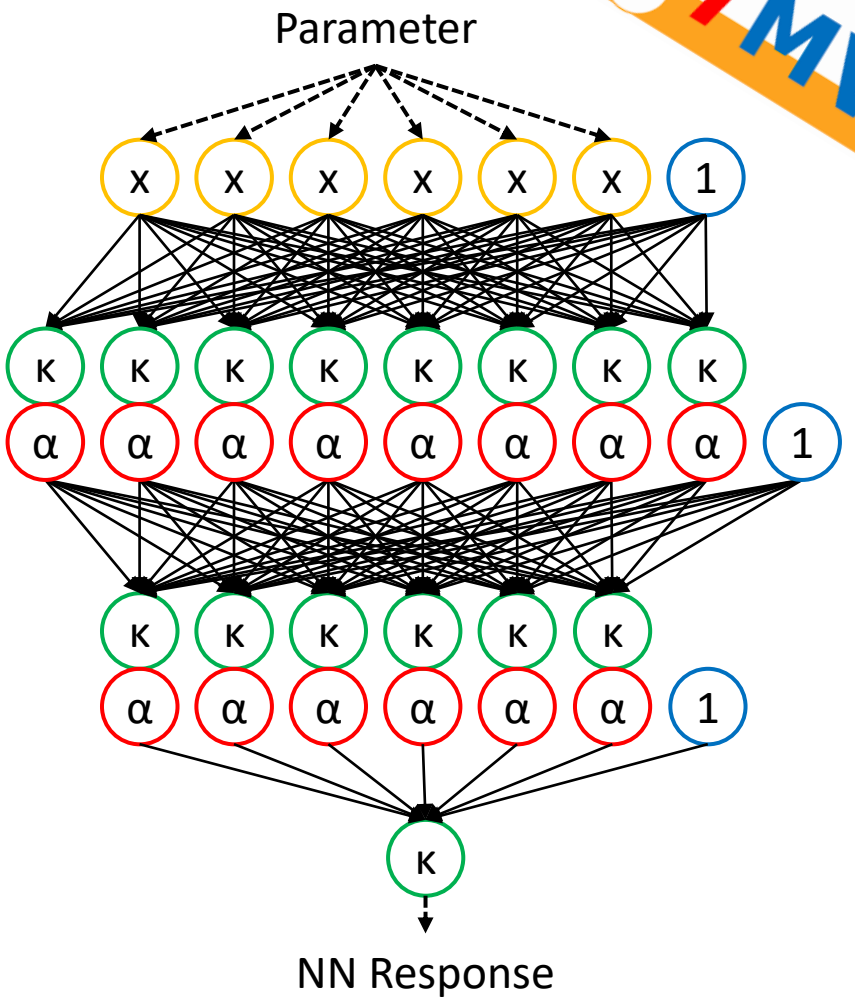
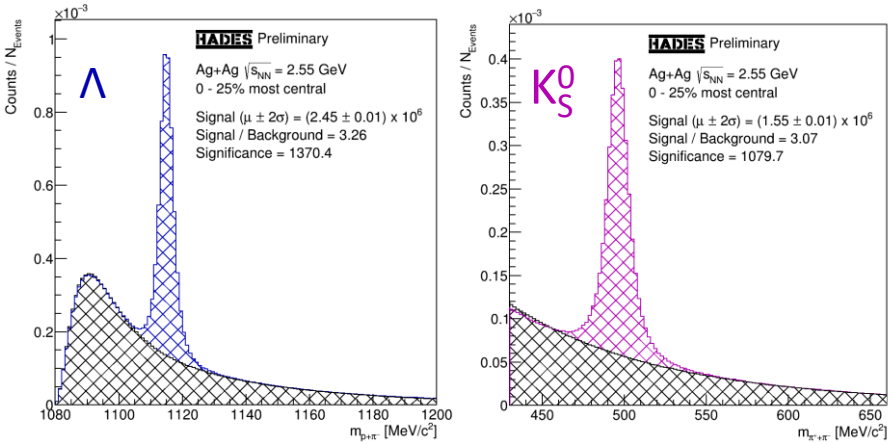
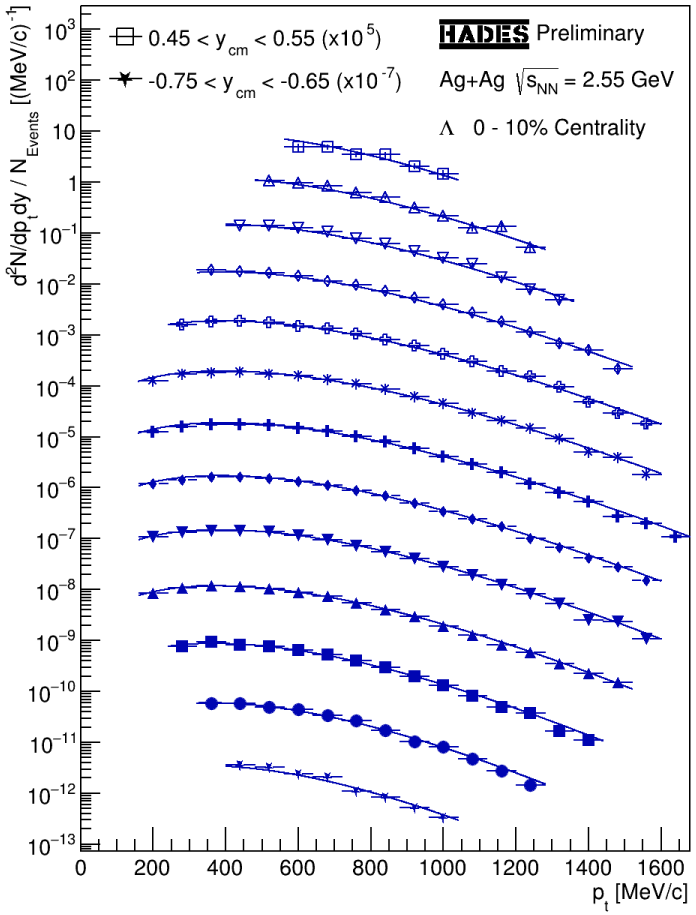


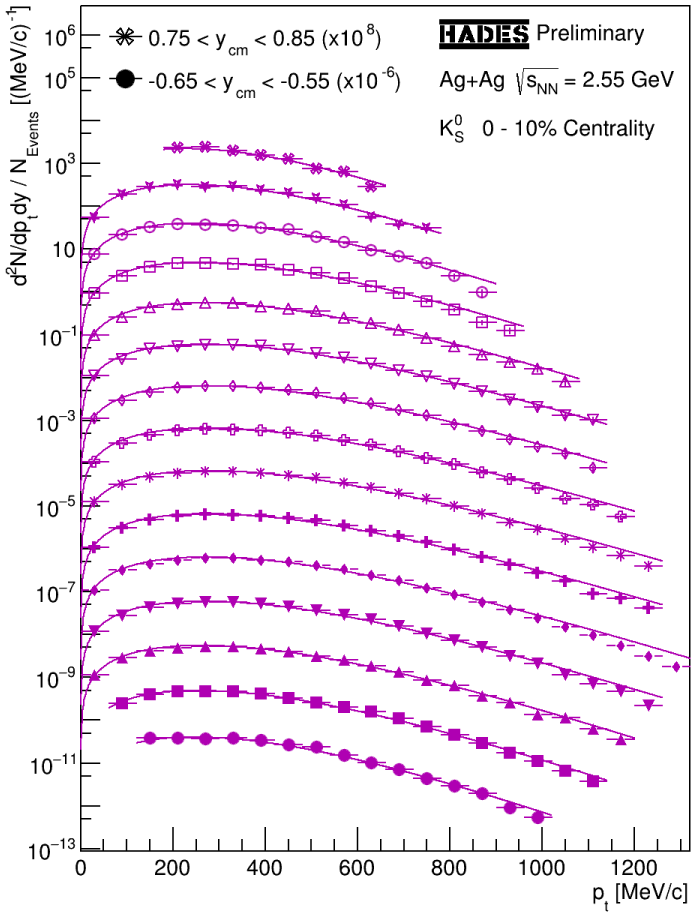


Weak Decay Reconstruction Performance



- Large phase space coverage with low statistical errors
- Data points well described by Boltzmann functions
  - ➢ Extrapolation to 4π



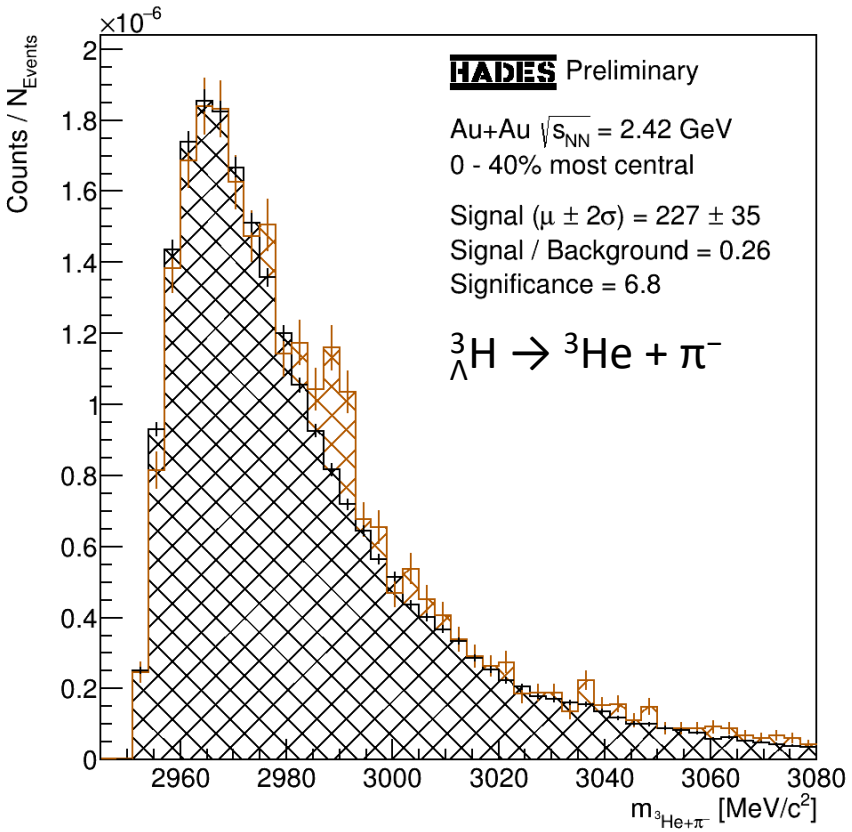


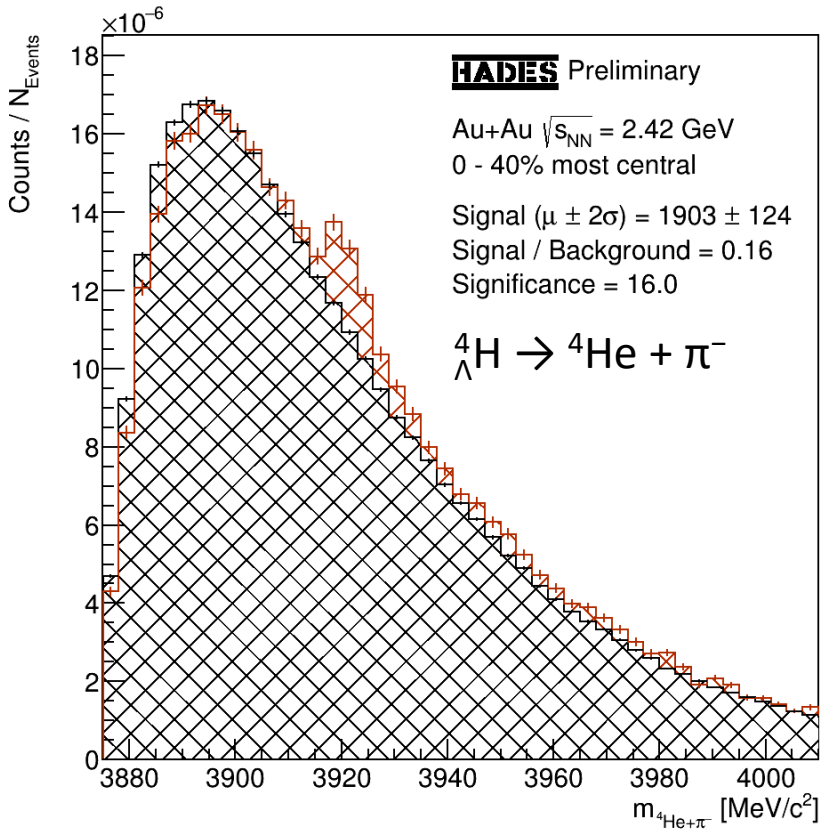
Hypernuclei

Reconstruction and Analysis of Hypernuclei

Hypernuclei from Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV

- Prior only estimation of upper production rate limit possible
- Same method as for Λ and K^0_S applied
- Significant signals in the two-body-decay channels
- Lowest energy at which Hypernuclei were ever reconstructed in Heavy-ion collisions

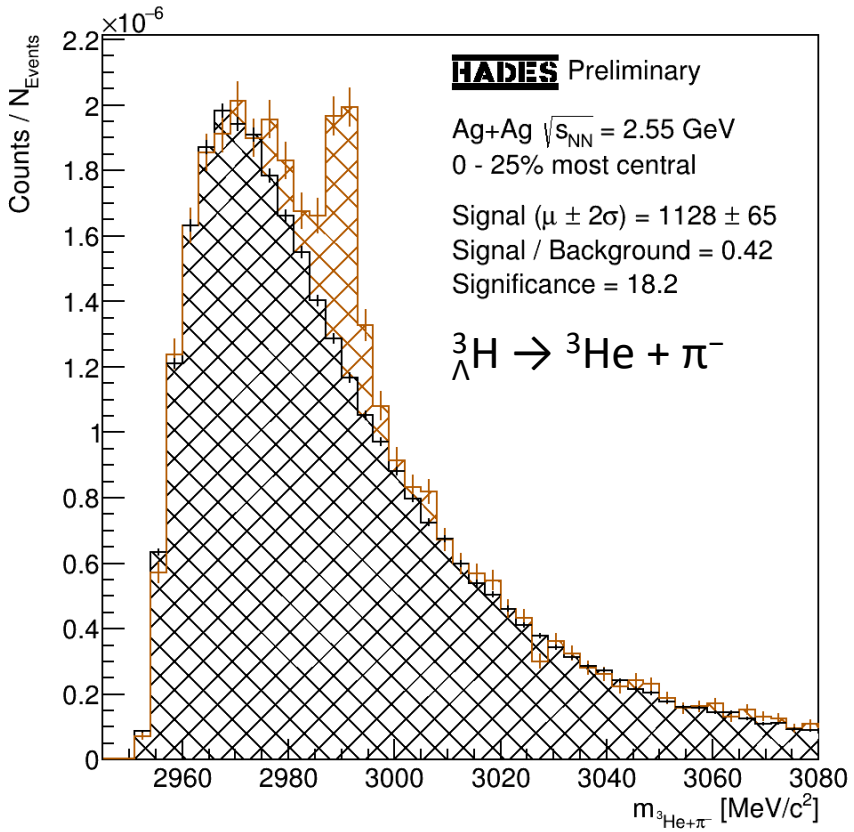


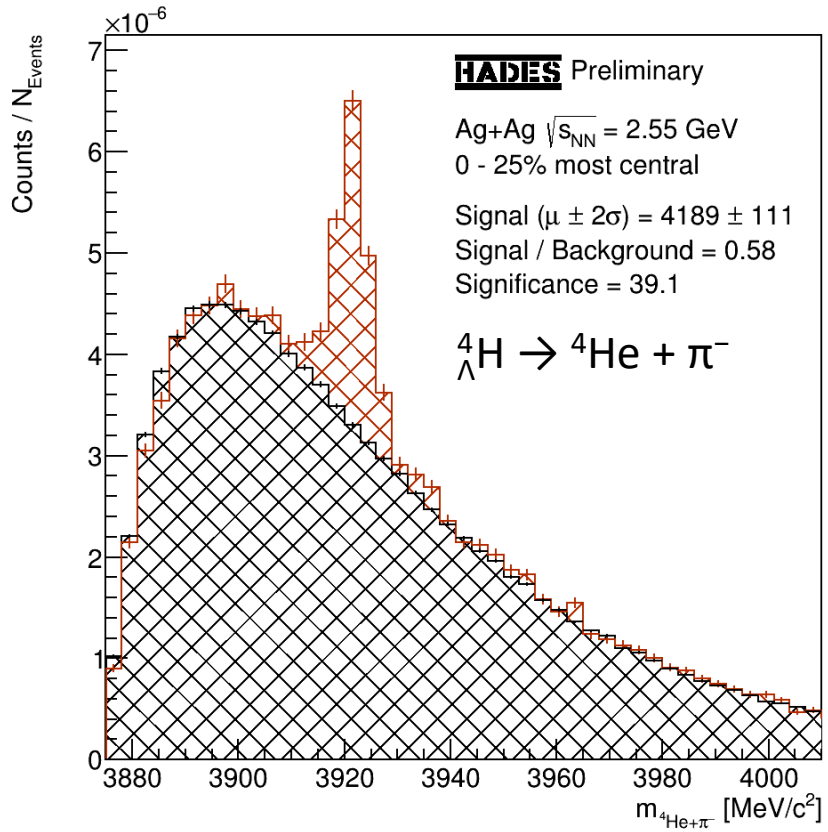


- In case of the $^4_\Lambda$H sufficient statistics to analyze the production differentially

Hypernuclei from Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV

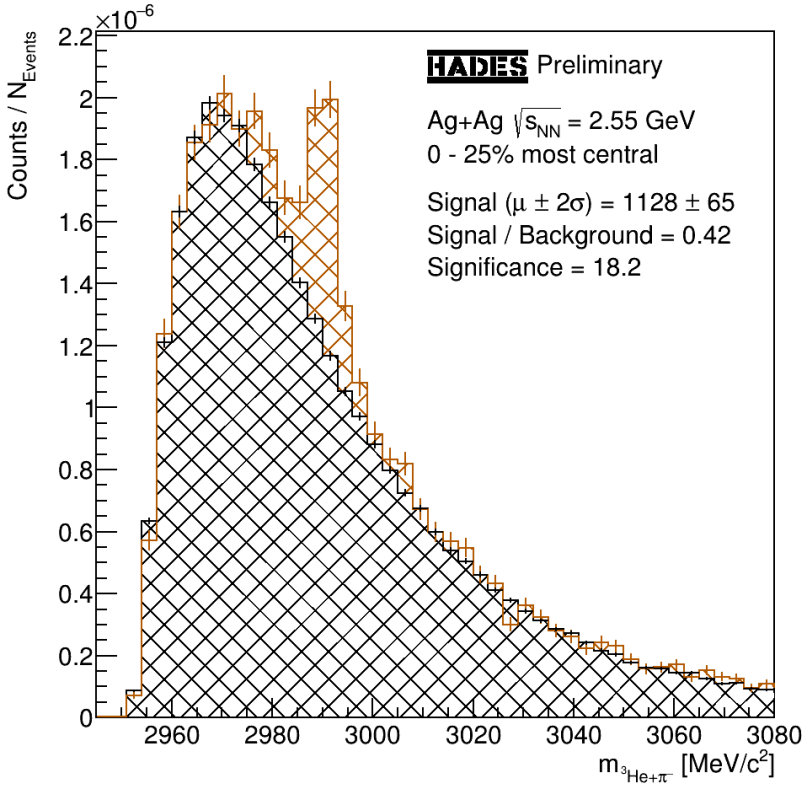
- Significant signals in the two-body-decay channels
- Three-body-decay channels more challenging due to increased combinatoric background
- Multi-differential analysis of Hypernuclei production possible

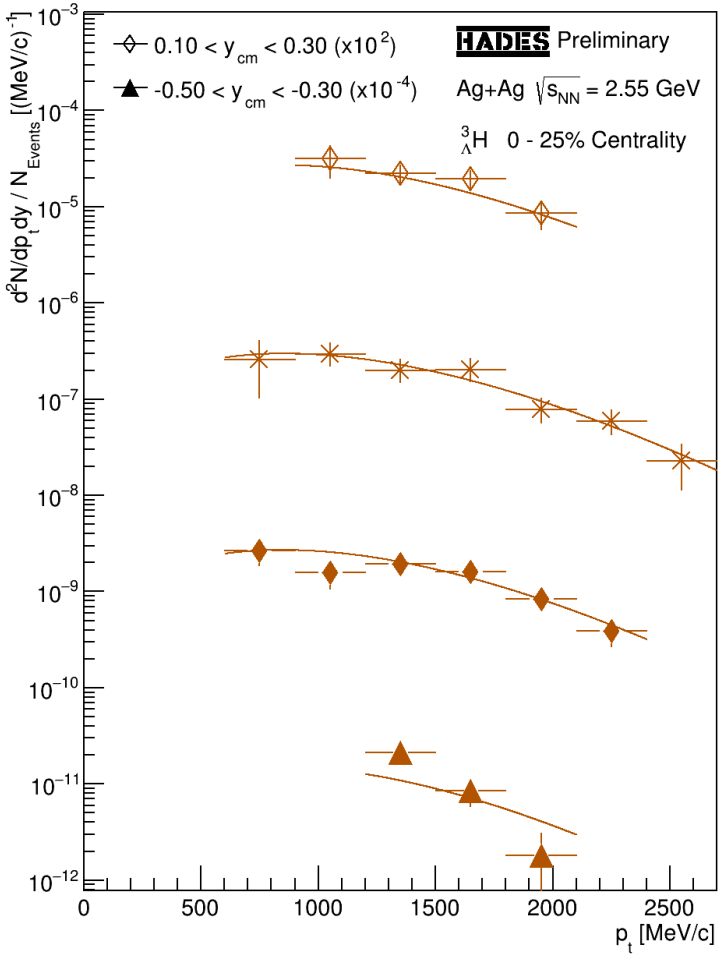


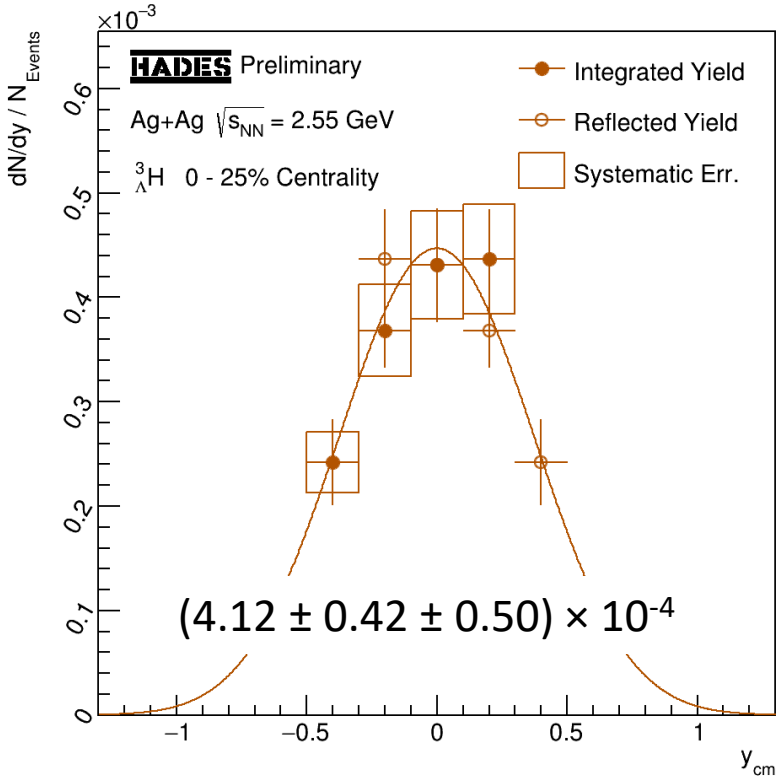


- More significant signals → Focus on this dataset to reduce uncertainties

${}^{3}_{\Lambda}\mathrm{H}$ Two-Body Decay: ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$



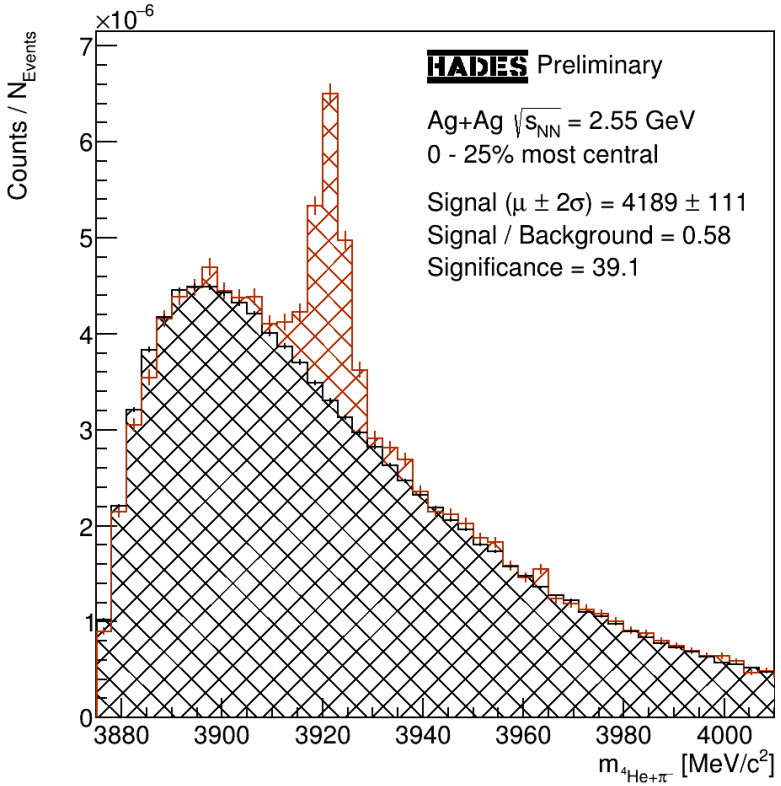


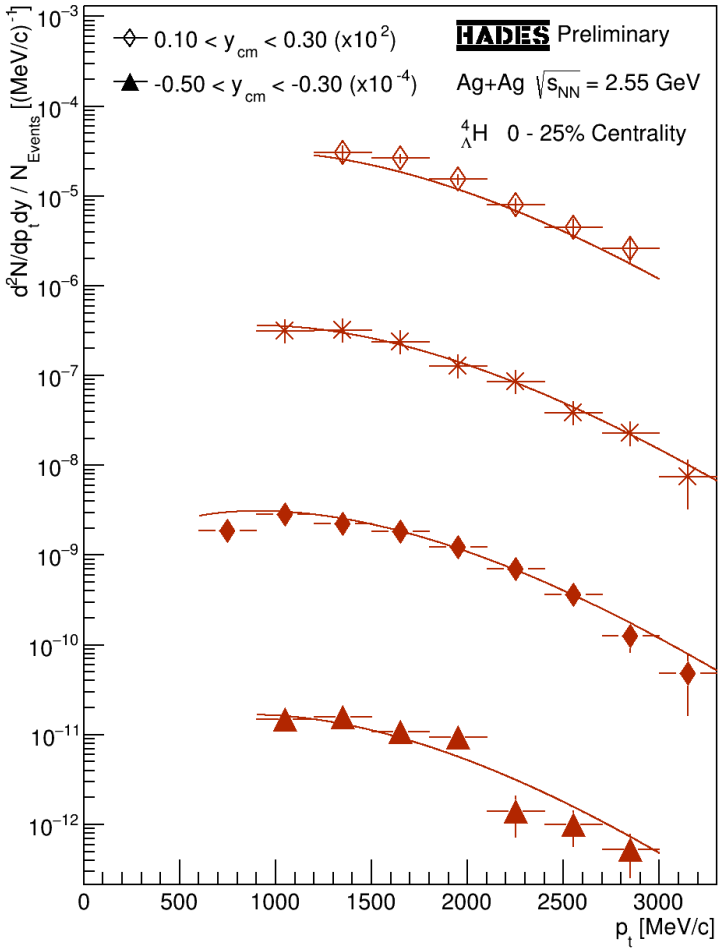


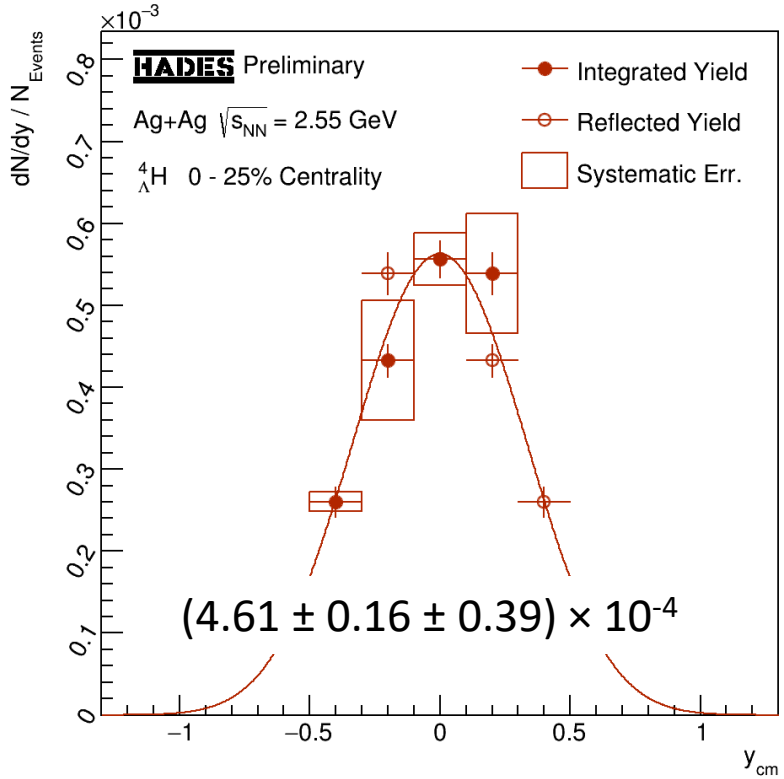
- Multi-differential analysis of ${}^{3}_{\Lambda}\mathrm{H}$ production as a function of transverse momentum and rapidity

- **First measurement at mid-rapidity at this energy**
- Bell-shape like observed for Λ

${}^{4}_{\Lambda}$H Two-Body Decay: ${}^{4}_{\Lambda}$H → ^{4}He + π⁻







- Multi-differential analysis of ${}^{4}_{\Lambda}$H production as a function of transverse momentum and rapidity

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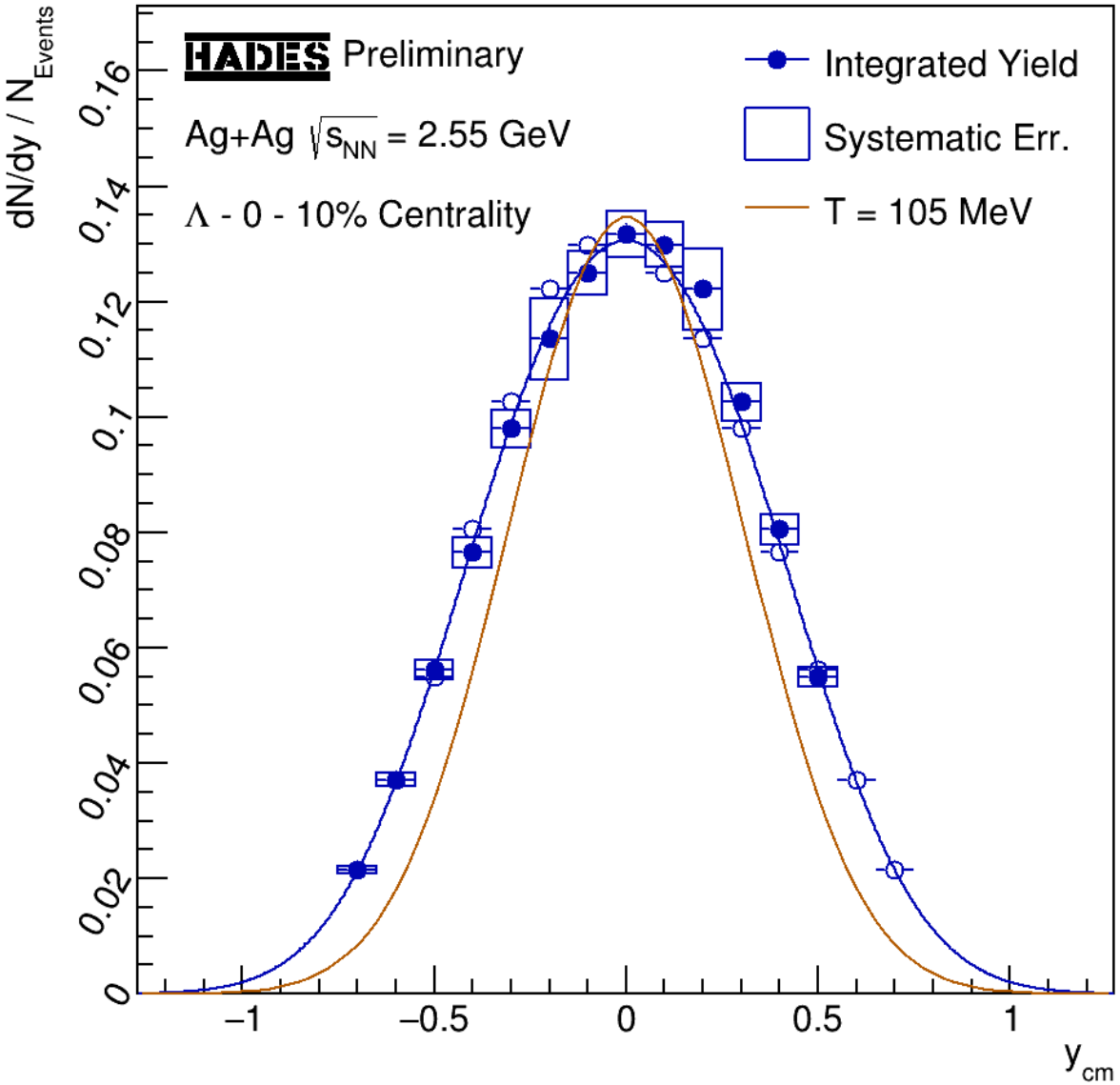
Lifetimes

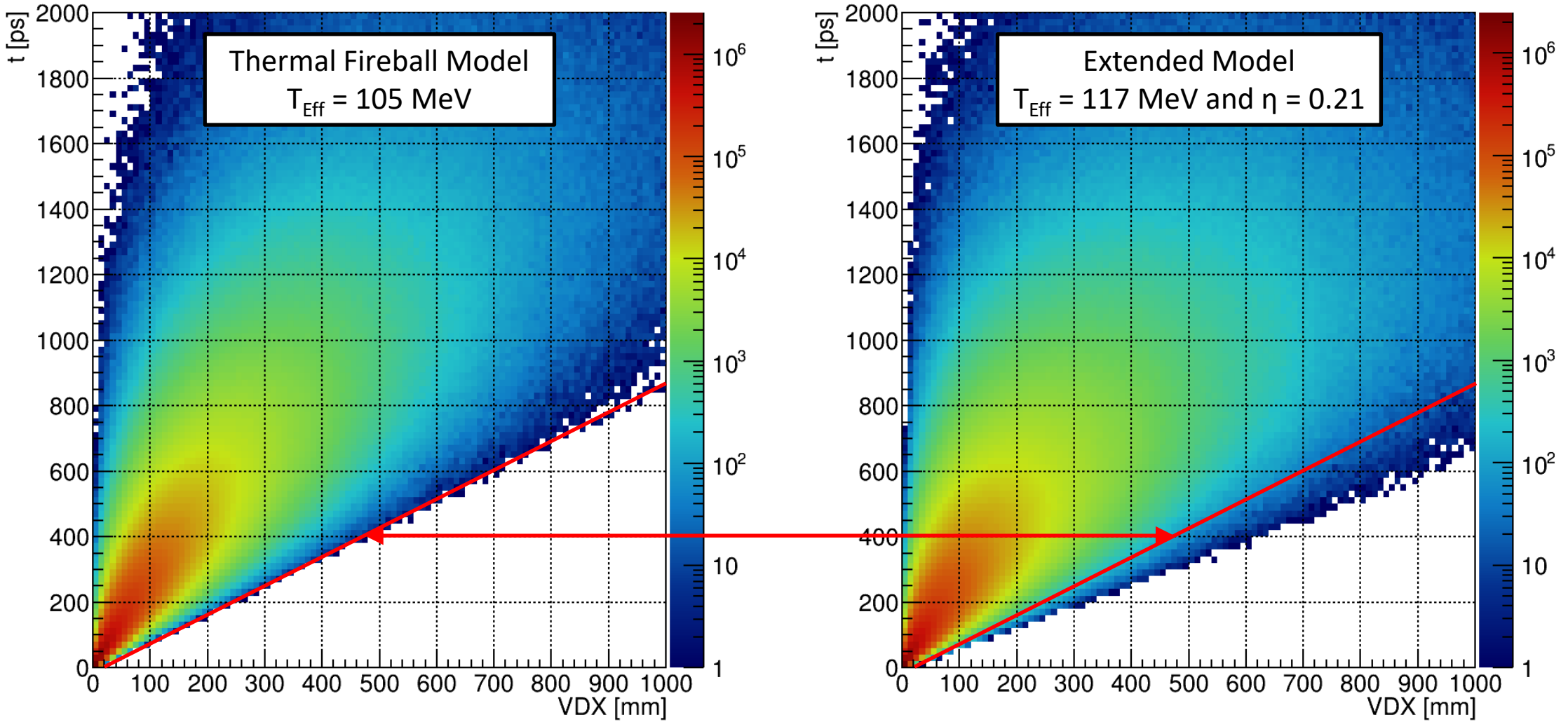
Measurement of Lifetimes of Weakly Decaying Hadrons

Λ dN/dy Spectrum

- Longitudinal anisotropy of particle emission due to only partial stopping of nucleons in the collision zone
- Longitudinal and transverse kinetic spectra cannot be described by statistical model with single effective temperature
- Effective Temperature of 105 MeV describes transverse spectra but results in too narrow longitudinal spectrum (Orange Function)
- An extended model with additional parameter η describing the longitudinal anisotropy allows precise description with T_{Eff} = 117 MeV and η = 0.21 (Blue Function)



Λ Lifetime t vs. Decay Length VDX



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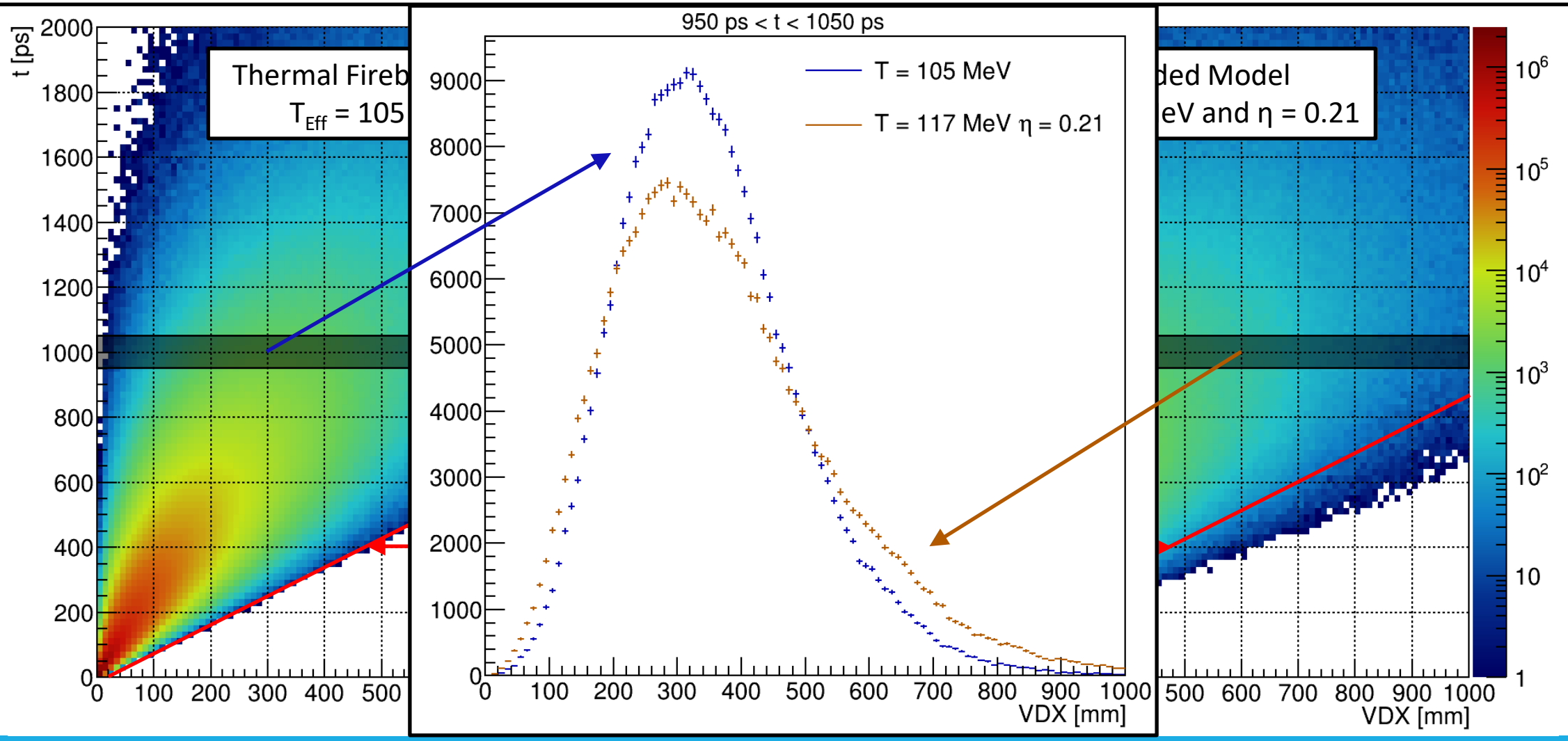
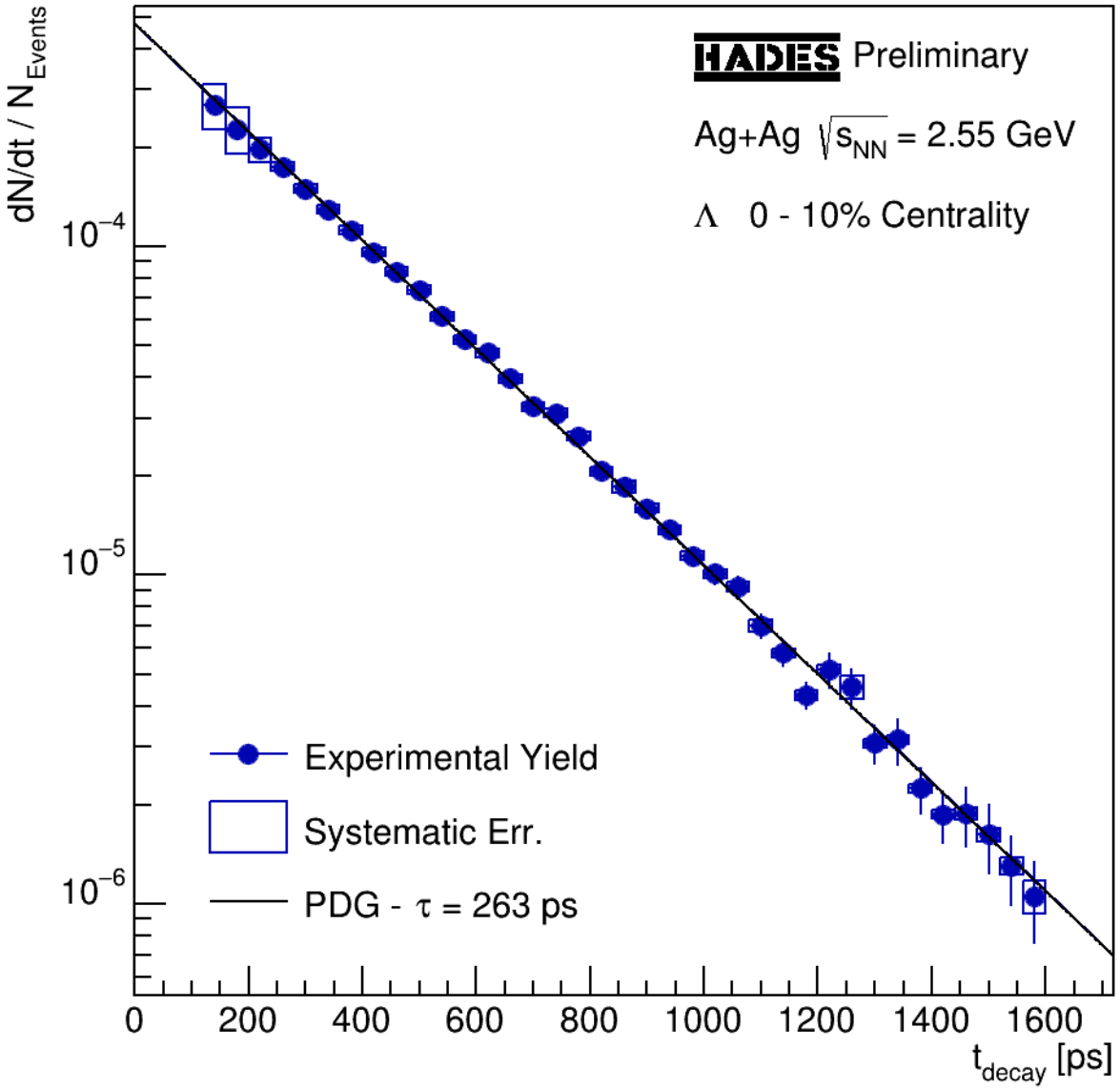
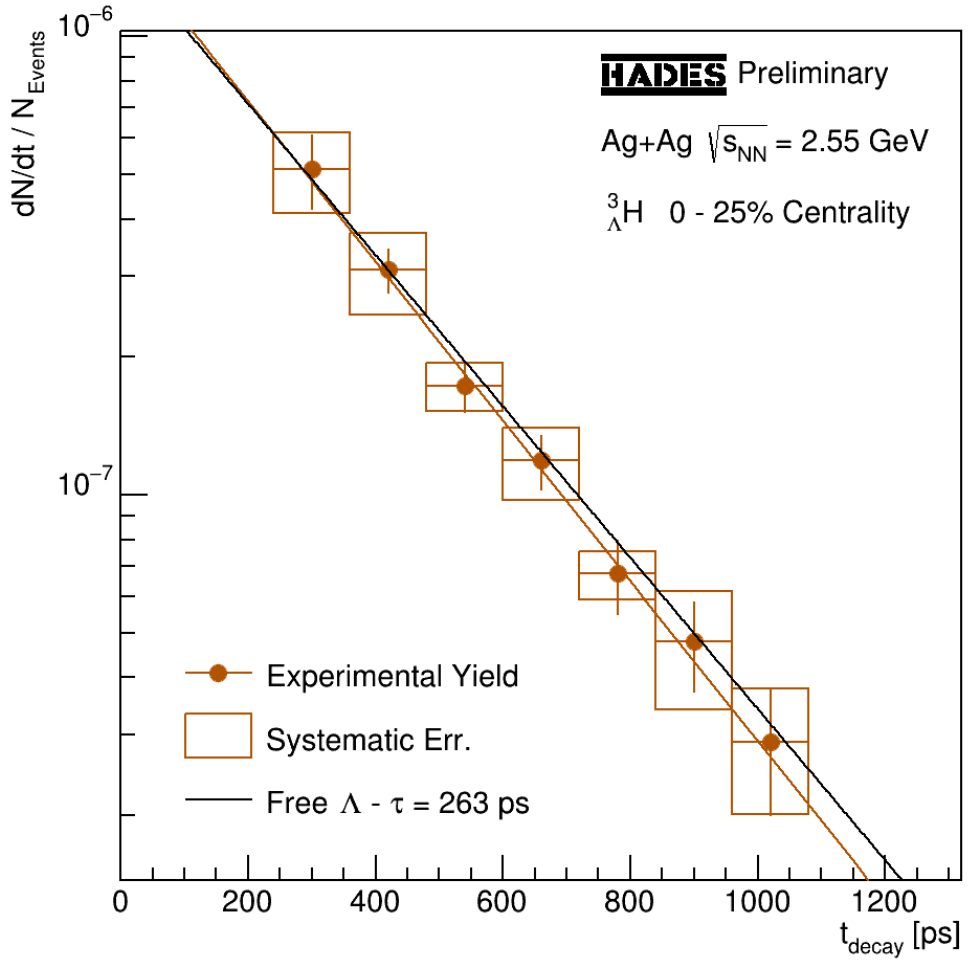


Test case: Λ Lifetime

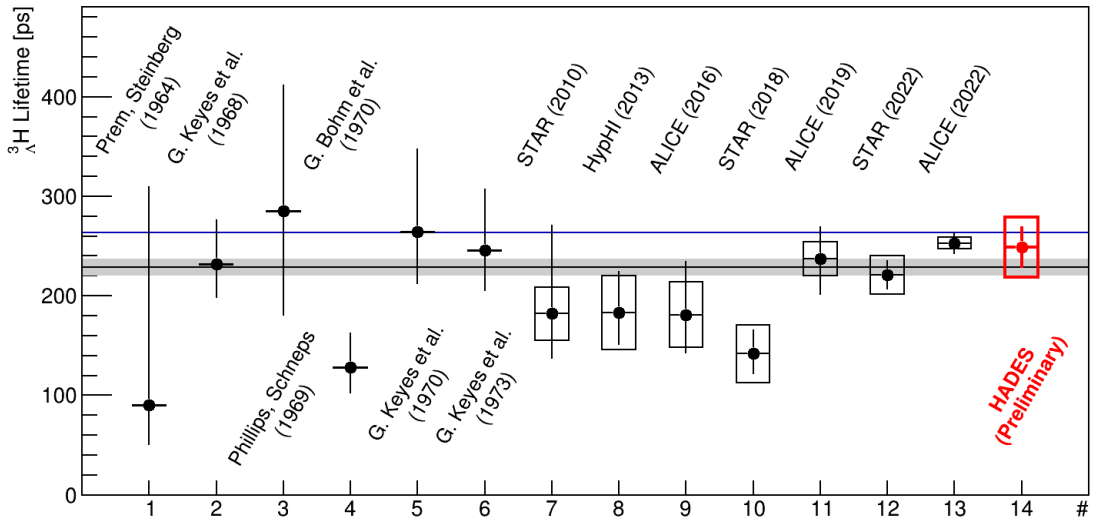
- Using the Extended Model with T_{Eff} = 117 MeV and η = 0.21 for acceptance and efficiency correction
- Exponential decay curve measured for Λ hyperons yields (262 ± 2) ps – In perfect agreement with PDG lifetime of ≈ 263 ps!
- Needs to be taken into account for the lifetime measurements of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$!



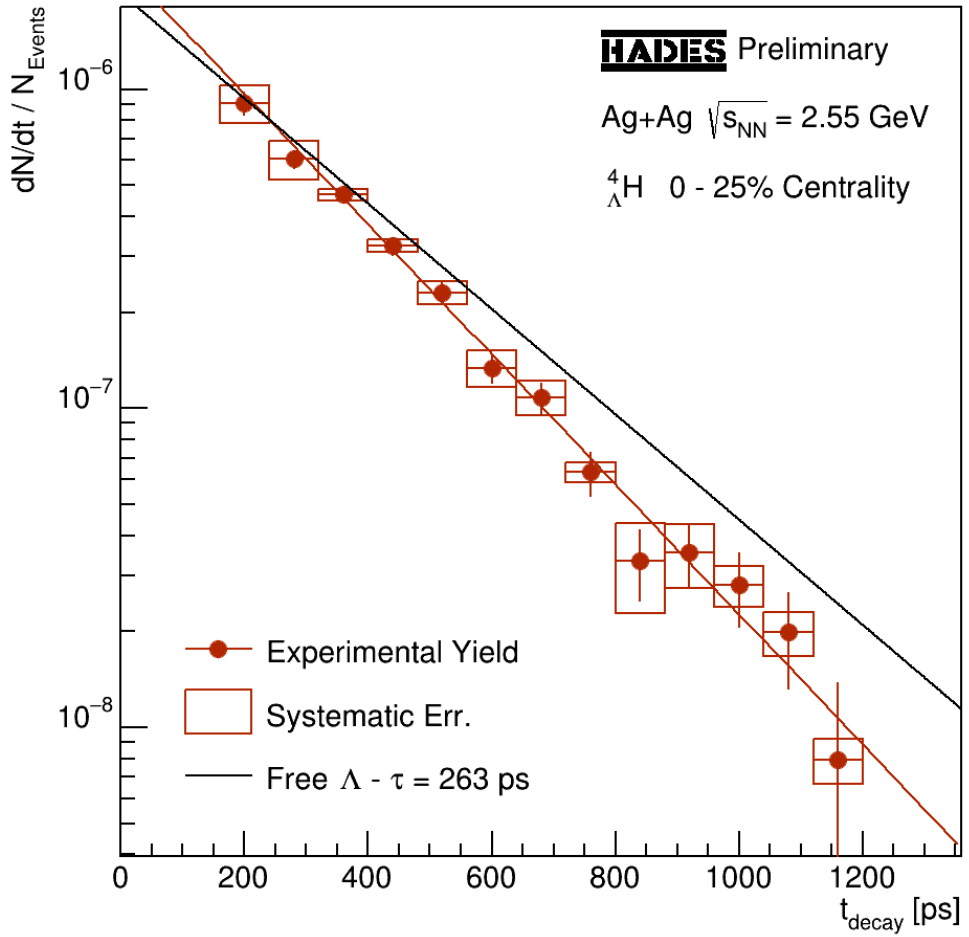
${}^{3}_{\Lambda}$H Two-Body Decay: ${}^{3}_{\Lambda}$H → ^{3}He + π⁻



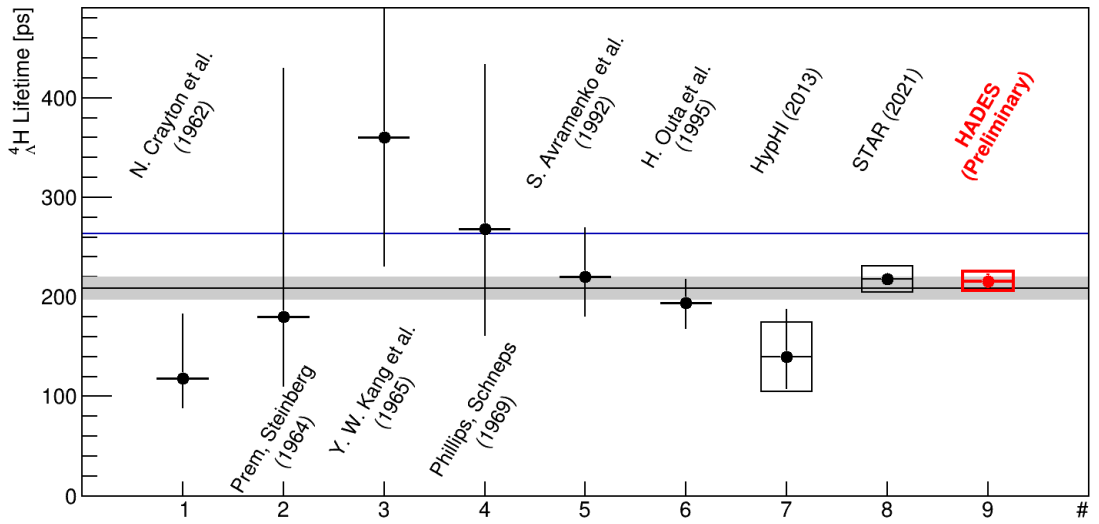
- ${}^{3}_{\Lambda}$H Lifetime measurement to contribute to resolving the ${}^{3}_{\Lambda}$H lifetime puzzle
- Lifetime of (249 ± 21 ± 30) ps compatible with free Λ lifetime measured
- Extensive uncertainty evaluation performed



${}^{4}_{\Lambda}$H Two-Body Decay: ${}^{4}_{\Lambda}$H → ^{4}He + π^-



- ${}^{4}_{\Lambda}$H Lifetime measurement to contribute to world data on Hypernuclei lifetimes
- Lifetime of (216 ± 7 ± 10) ps compatible with earlier measurements measured
- Extensive uncertainty evaluation performed

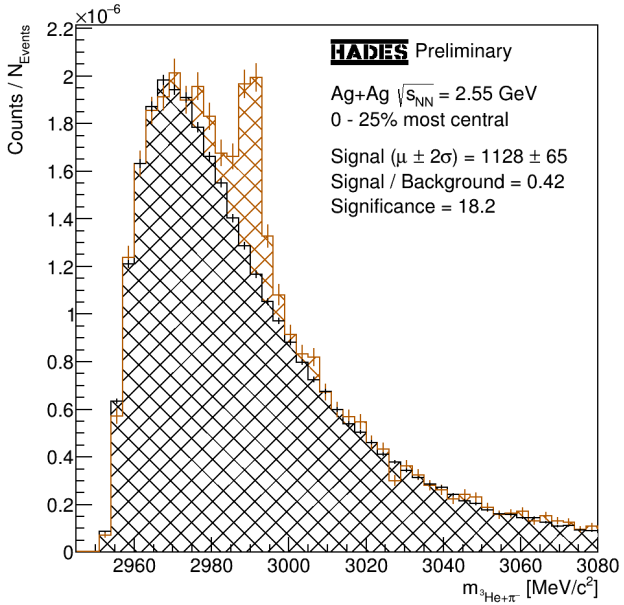


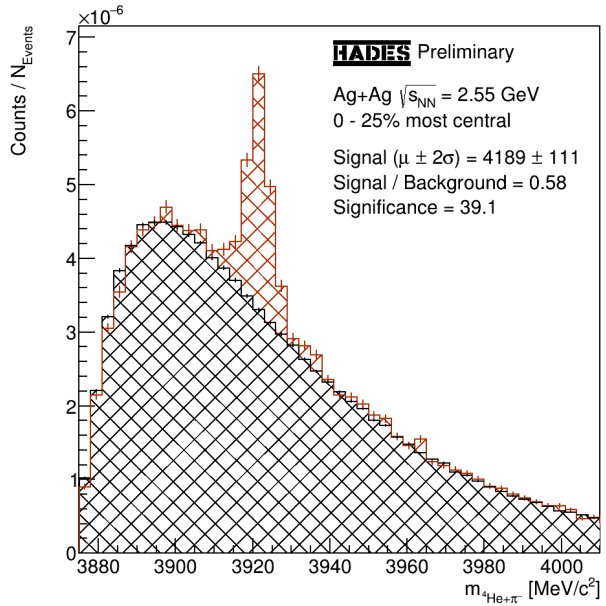
Hypernuclei Lifetimes Systematic Variations

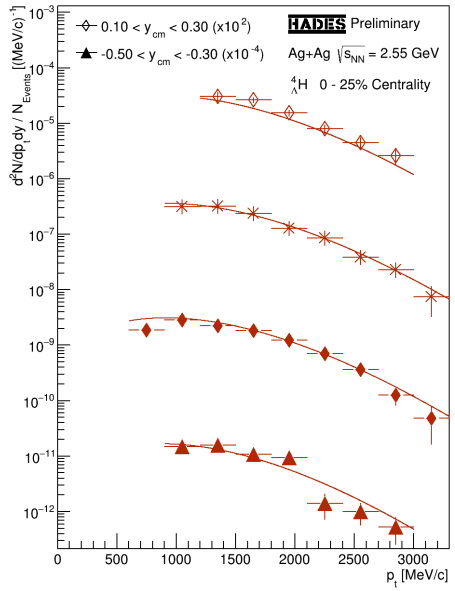
- Source variations: Parameters obtained by performing multi-differential p_t-y analysis using three different values for the longitudinal anisotropy parameter η
- Particle PID variations: In addition to the default 3σ p-β and 2σ p-dE/dx selection more open PID selection of 4σ p-β and 3σ p-dE/dx tested
- Decay Topology variations: In addition to the default analysis using the ANN, three hard-cut analyses with different strength tested
- Breakup cross-sections in matter: Tested No, 1x and 2x the breakup cross-sections in the HADES detector material estimated based on *Phys.Rev.Lett.* **131** (2023) 10, 102302 by ALICE
- Taking all the different variations into account the final systematic uncertainties of the yields and lifetimes are obtained

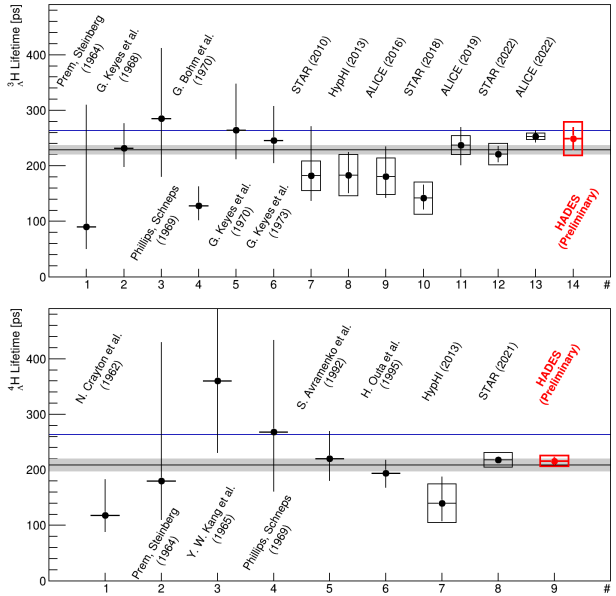
Summary

- First multi-differential analysis of Hypernuclei around mid-rapidity at SIS18 energies
- Bell-shaped rapidity distributions
- Lifetime measurements compatible with recent measurements by STAR and ALICE
- ${}^{3}_{\Lambda}\mathrm{H}$ lifetime compatible with free Λ lifetime
- ${}^{4}_{\Lambda}\mathrm{H}$ lifetime 4.8σ below free Λ lifetime
- Extensive uncertainty evaluation performed
- Paper in preparation

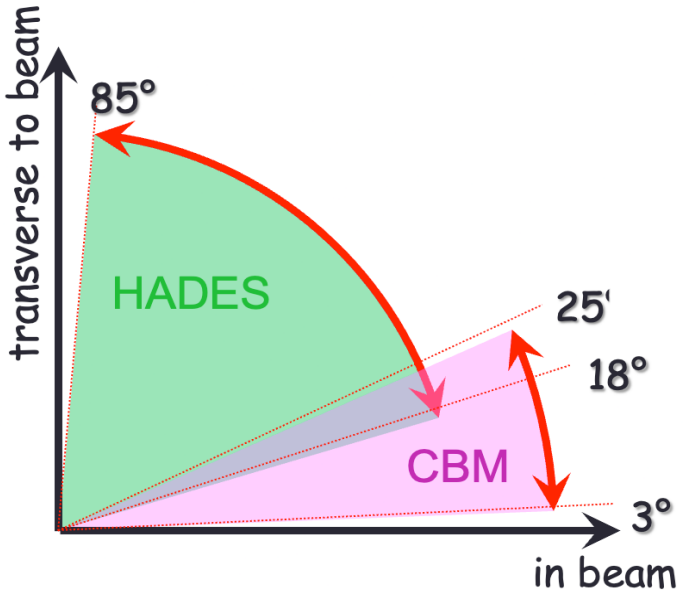


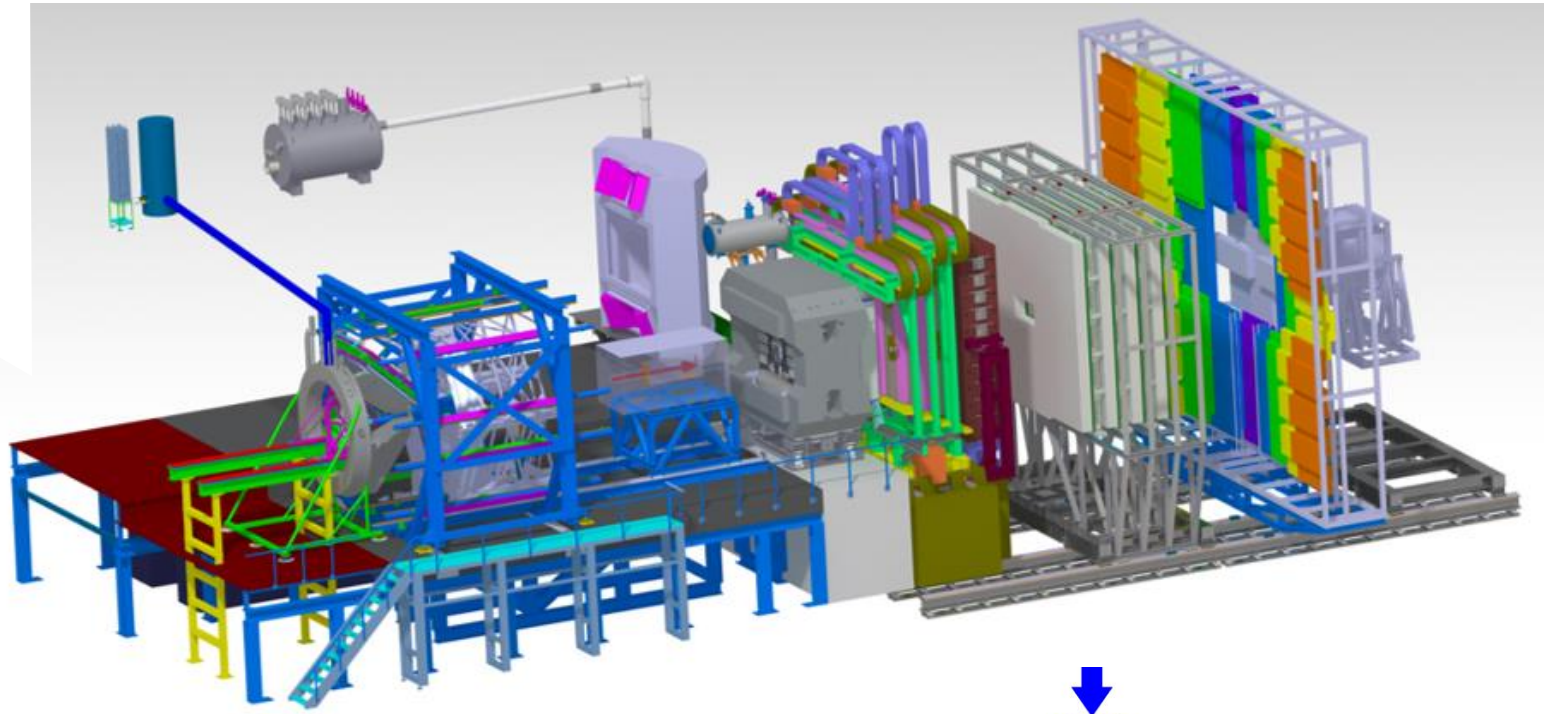






Outlook: HADES and CBM @ SIS100





- HADES and CBM will be operated at the SIS100
- Angular coverage of both detectors complementary

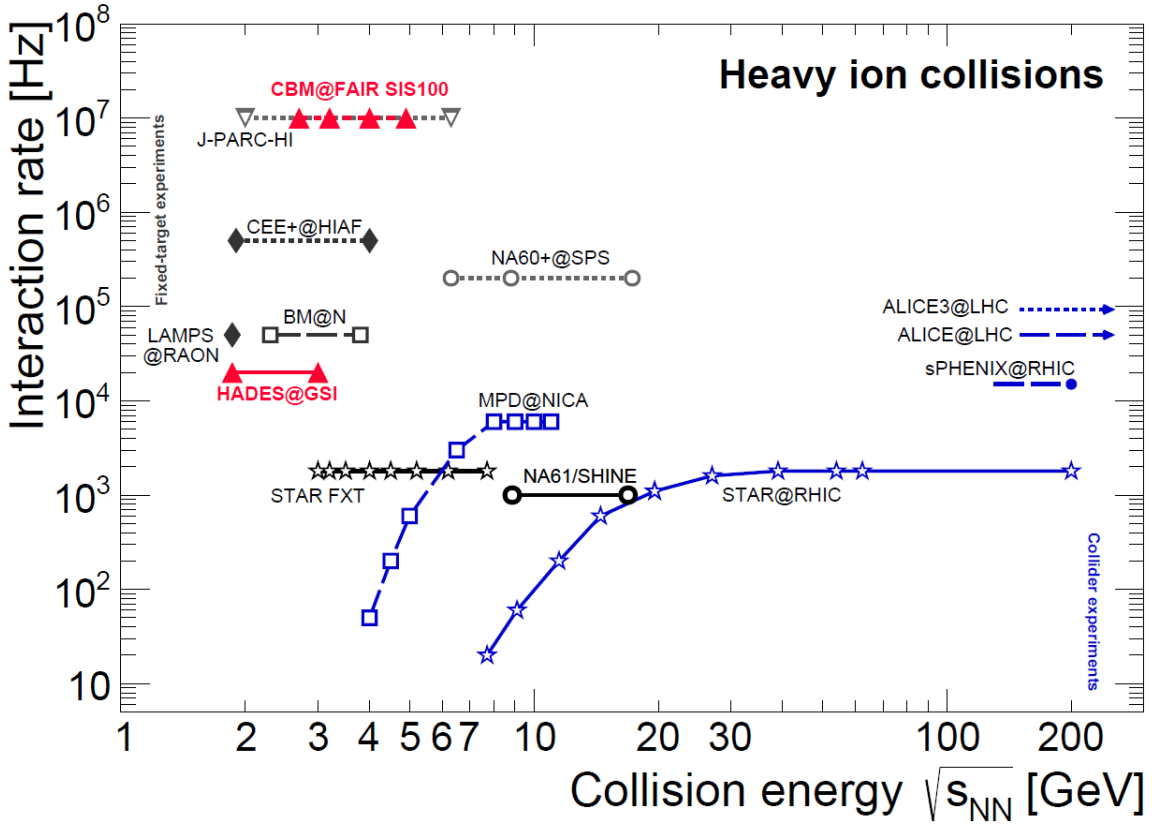
HADES

CBM

Outlook: HADES and CBM @ SIS100

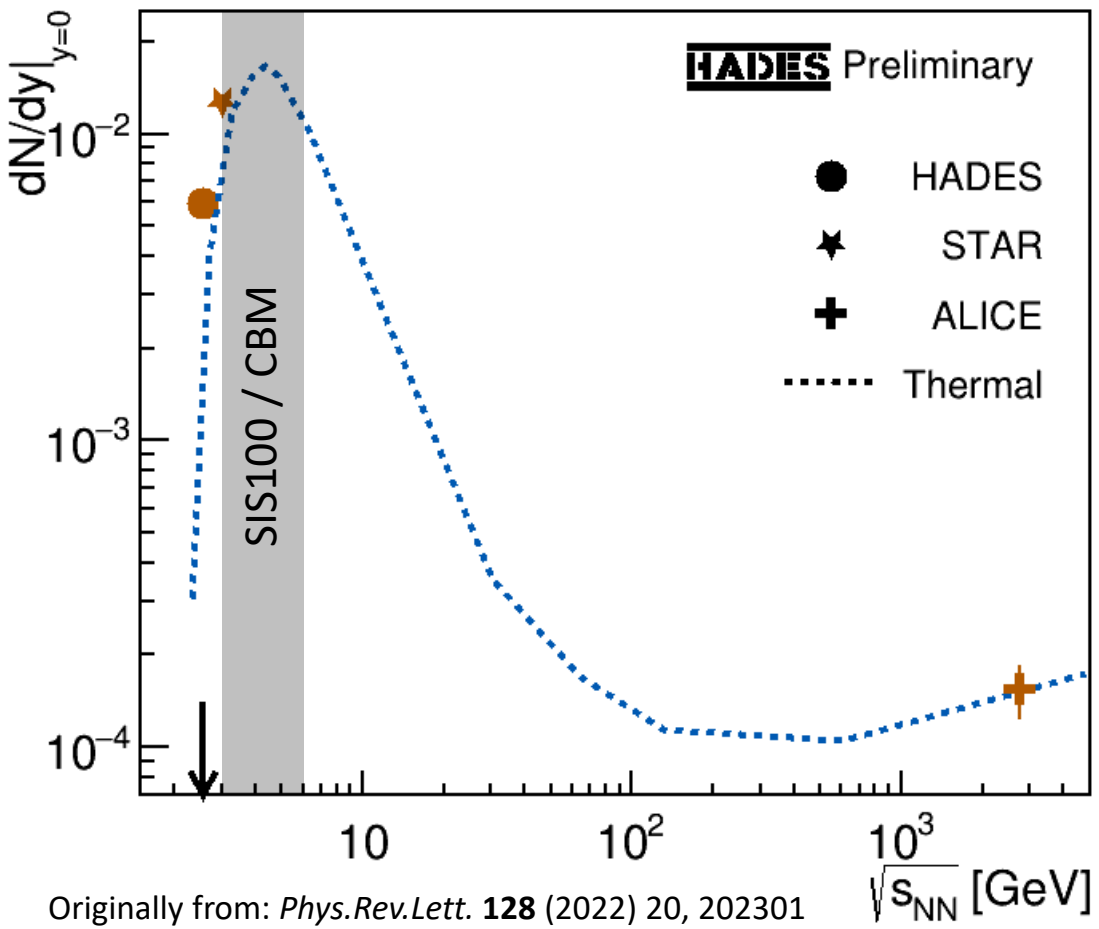
- Investigation of the QCD phase-diagram in the 2.7-4.9 GeV energy regime
- Interaction rates of up to 10 MHz with CBM using free streaming data collection
  - ➢ Rare probes can be studied in detail
- Di-electron and di-muon setup available
- Micro-Vertex-Detector / Tracker
  - ➢ Reconstruction of further particles possible e.g. $\Sigma^{\pm}$, $D^{\pm}$, etc.
- CBM physics program:
  Lect.Notes Phys. **814** (2011) pp.1-980

https://github.com/tgalatyuk/interaction_rate_facilities



Outlook: Hypernuclei at SIS100

- Energy Excitation functions of Hypernuclei
  - Steep rise at low energies due to strangeness production threshold
  - Drop at high energies due to vanishing baryon dominance
  - Maximum production rates around $\sqrt{s_{NN}}$ = 4 - 5 GeV (CBM physics program)
- Only sparse data on Hypernulcei production rates available
- Available data support expected trend



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The HADES Collaboration