Hypernuclei and Ξ^- at HADES

Recent results from measurements of Hypernuclei and Ξ^- Hyperons in the high μ_B / high net-baryon density region of the QCD phase diagram

Simon Spies for the HADES Collaboration

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

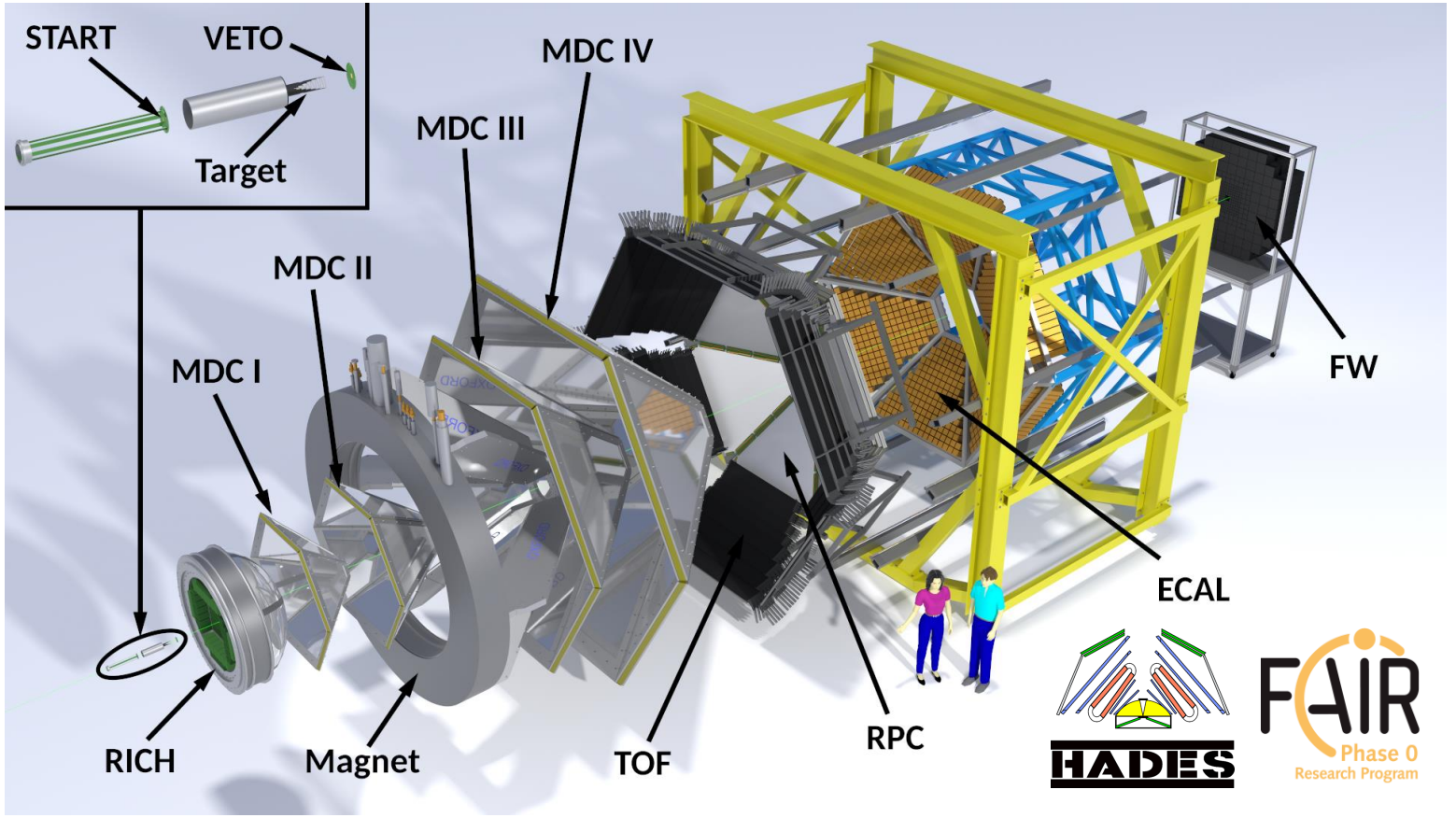
FAIR Phase 0 Research Program

EL EM EN TS

HADES

The HADES Experiment (Heavy-Ion Setup)

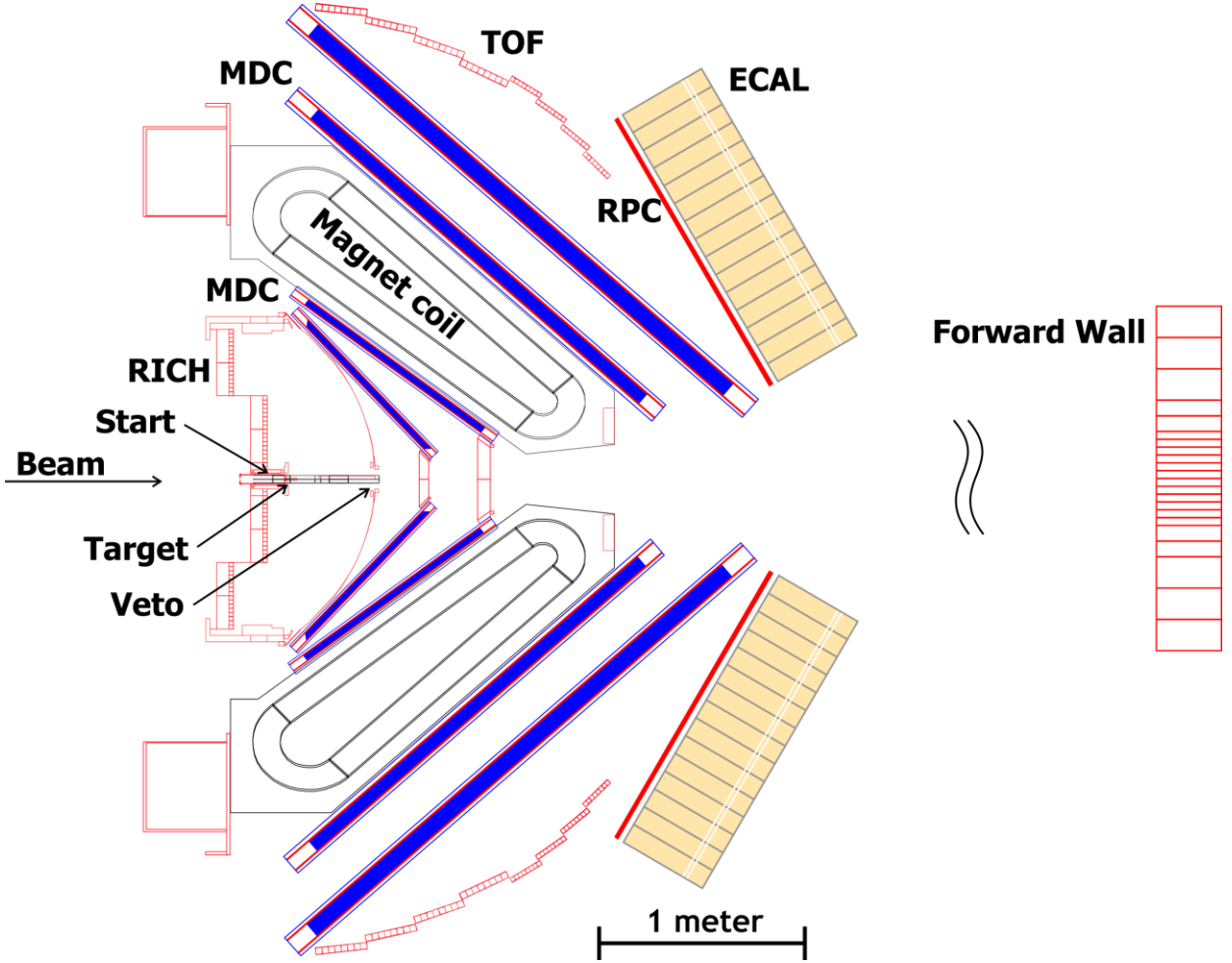
- Fixed target experiment at SIS18 (GSI, Germany)
- Magnet spectrometer
- Low mass Mini-Drift-Chambers (MDCs)
- Time of flight walls RPC and TOF
- RICH and ECAL for e^+/e^- and photon identification
- Forward hodoscope (FW) for spectator detection



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

The HADES Experiment (Heavy-Ion Setup)

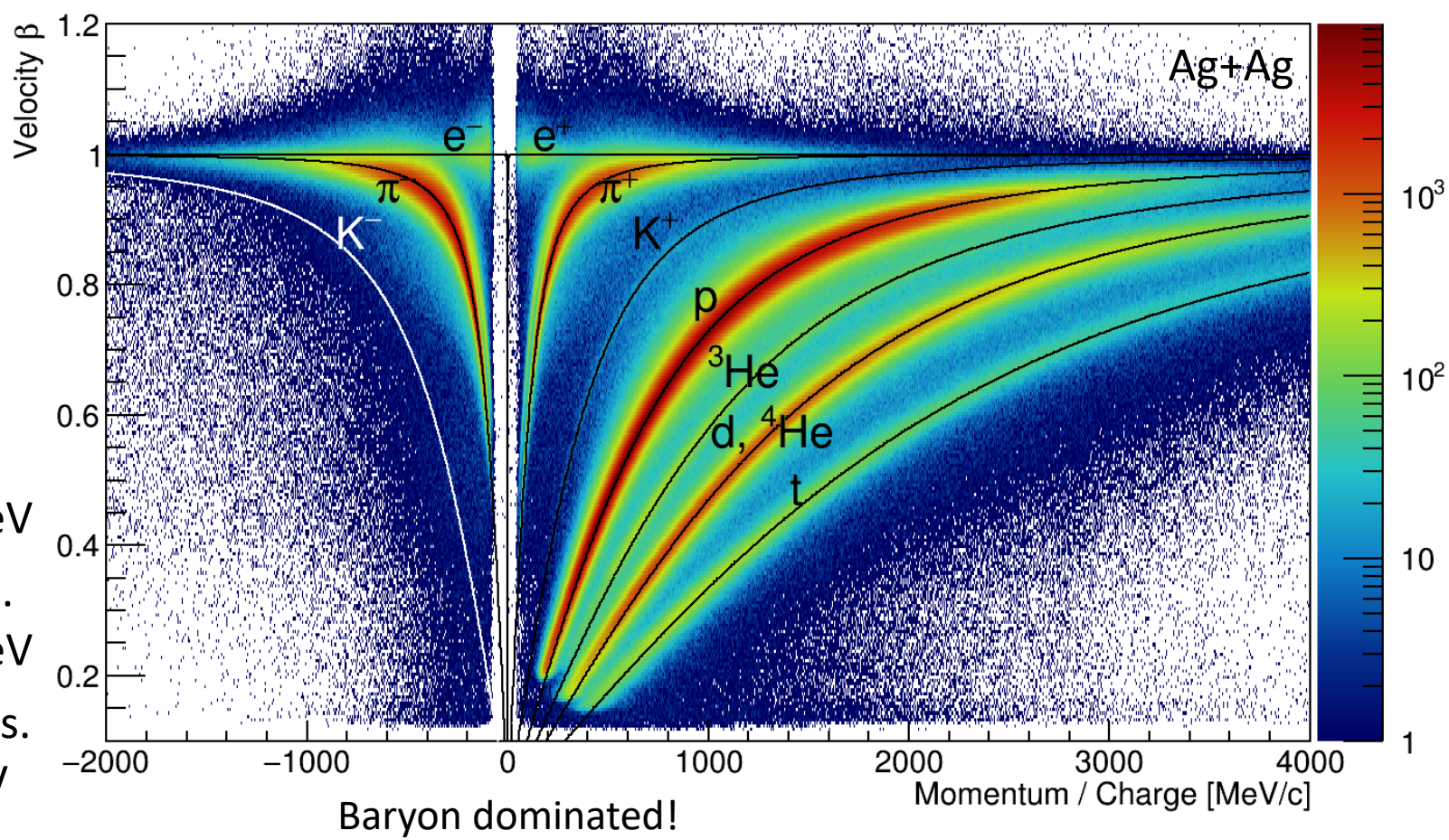
- Setup optimized for low material budget around target region to reduce γ conversion probability
  - ➢ Advantageous for Hypernuclei measurements as they have large in-medium absorption cross-sections (Phys. Rev. Lett. 131 (2023) 102302)
- Produced particles leave beampipe and enter RICH radiator gas after ≈ 2.5cm
  - ➢ Due to minimum decay length criterion all analyzed Hypernuclei decay within the RICH radiator gas



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



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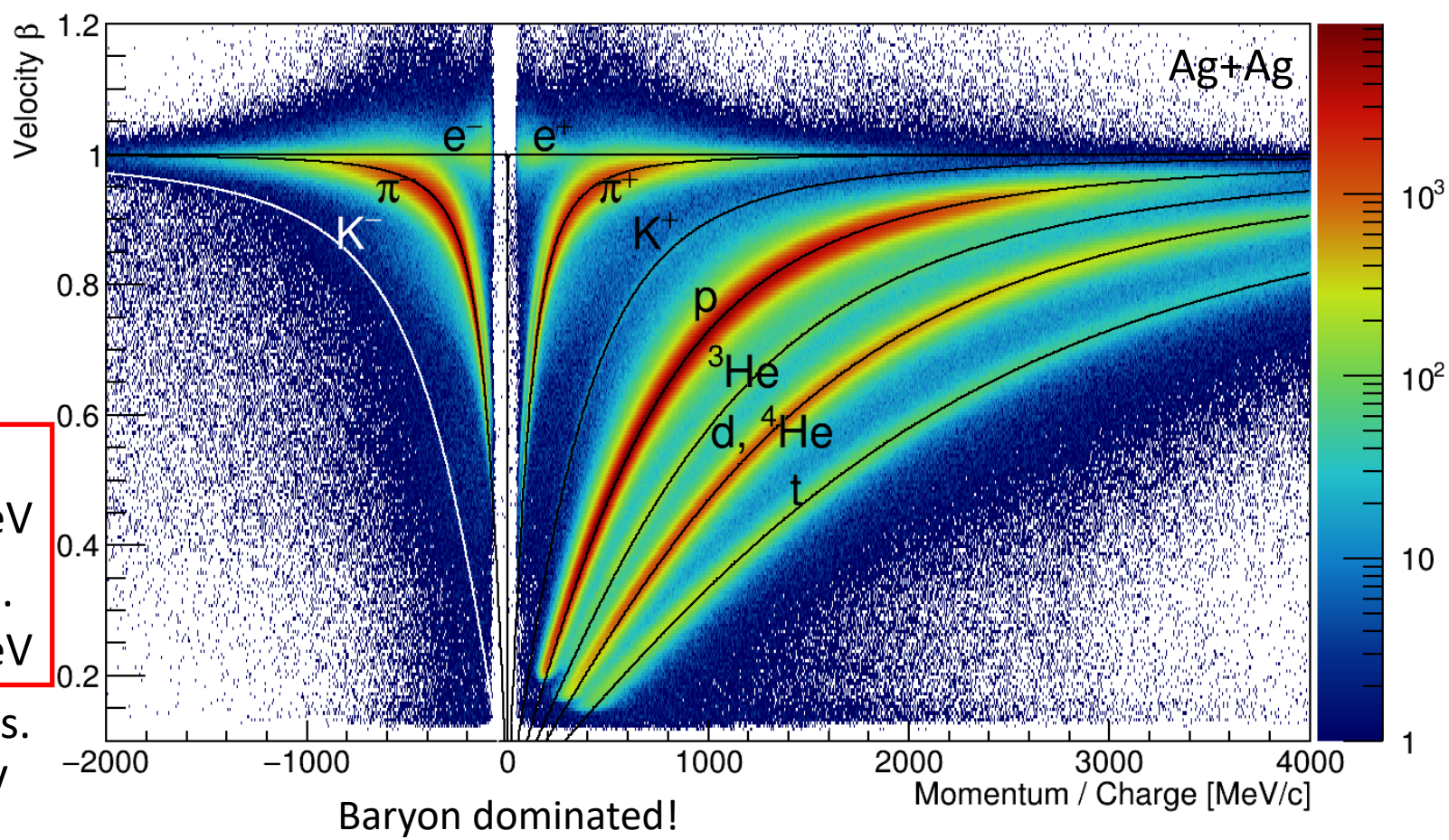
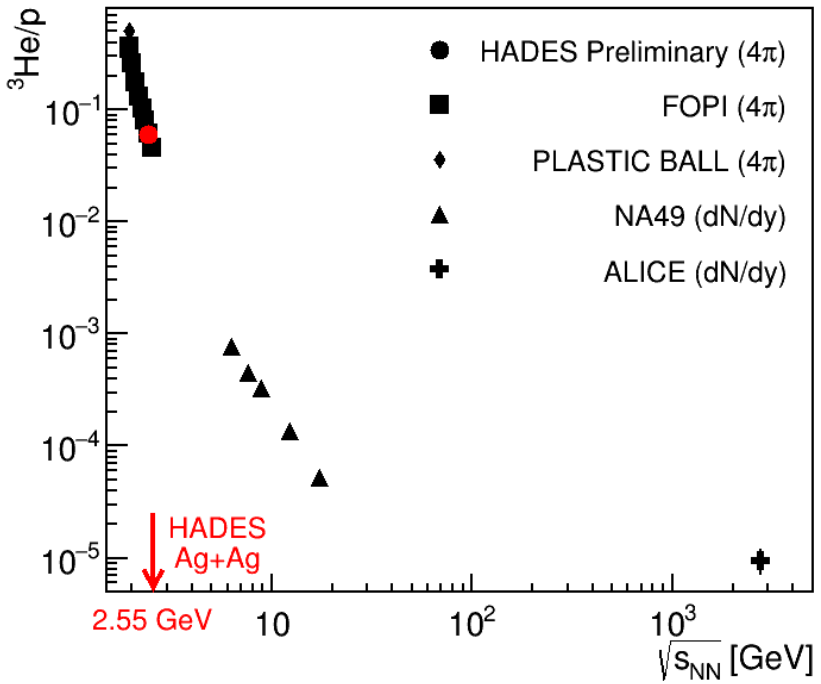


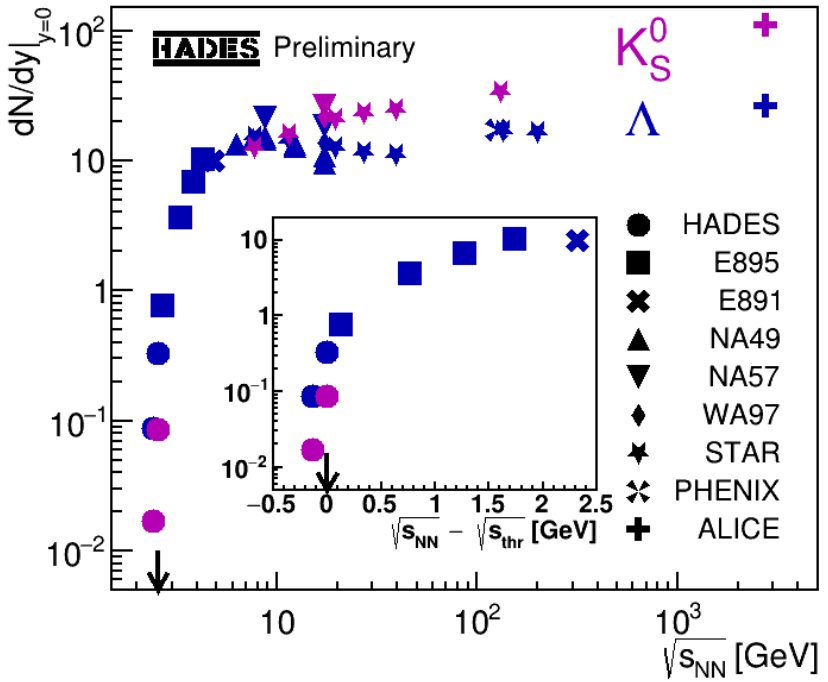
Nuclear Collisions at SIS18/HADES Energies



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

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

- Λ Hyperon production close to free NN threshold energy, Ξ Hyperons far below free NN threshold:
  N + N → Y + K + N: $\sqrt{s}$ = 2.55 GeV
  N + N → Ξ + K + K + N: $\sqrt{s}$ = 3.25 GeV

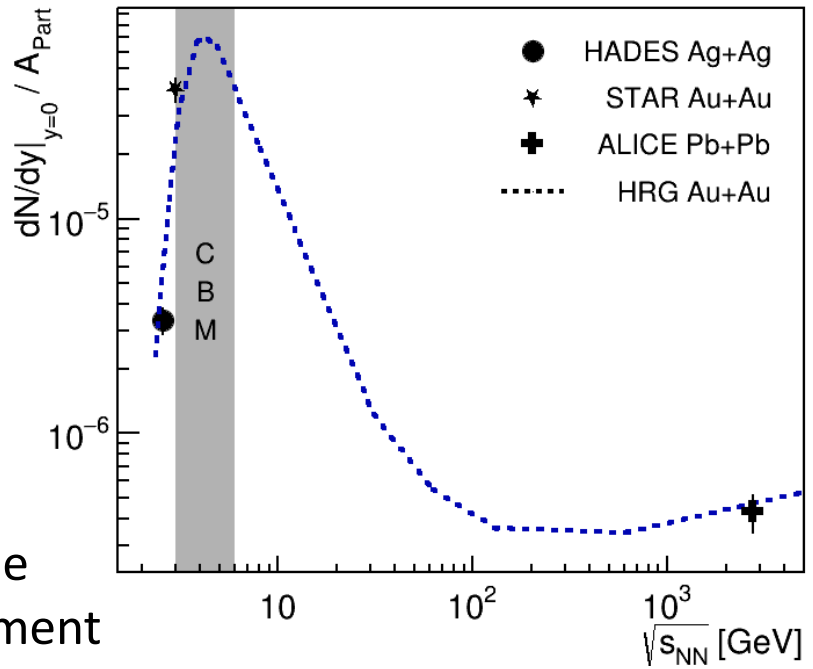


Data: Phys.Lett.B 793 (2019) 457-463

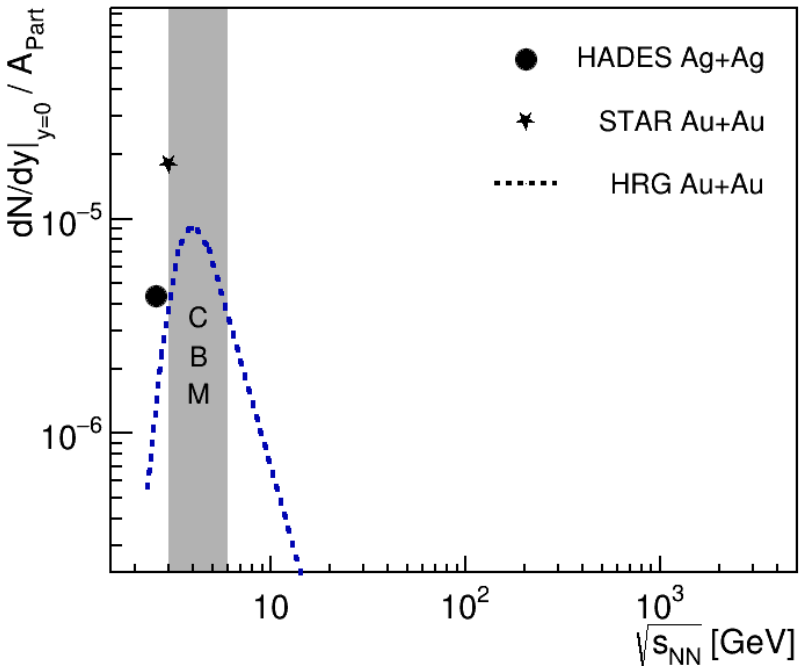
Hypernuclei at SIS18/HADES Energies

- Production of Hypernuclei favored by baryon dominance of the fireball
- Production of Hypernuclei limited by the amount of produced Λ Hyperons
- "Sweet Spot" for the production of Hypernuclei expected in the energy regime of the upcoming CBM experiment
  (Lect.Notes Phys. **814** (2011) pp.1-980)

Hypertriton ${}^{3}_{\Lambda}H$



Hyperhydrogen4 ${}^{4}_{\Lambda}H$



Original Plots from: Phys.Rev.Lett. 128 (2022) 20, 202301

- Hypernuclei might allow deductions on their underlying Y-N interactions relevant for the nuclear EOS at high densities

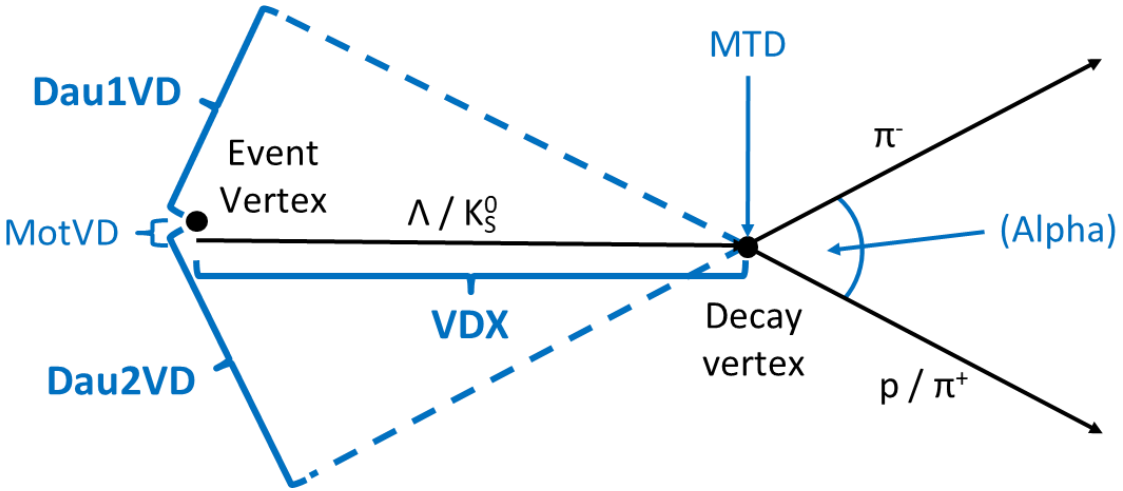
Weak Decays

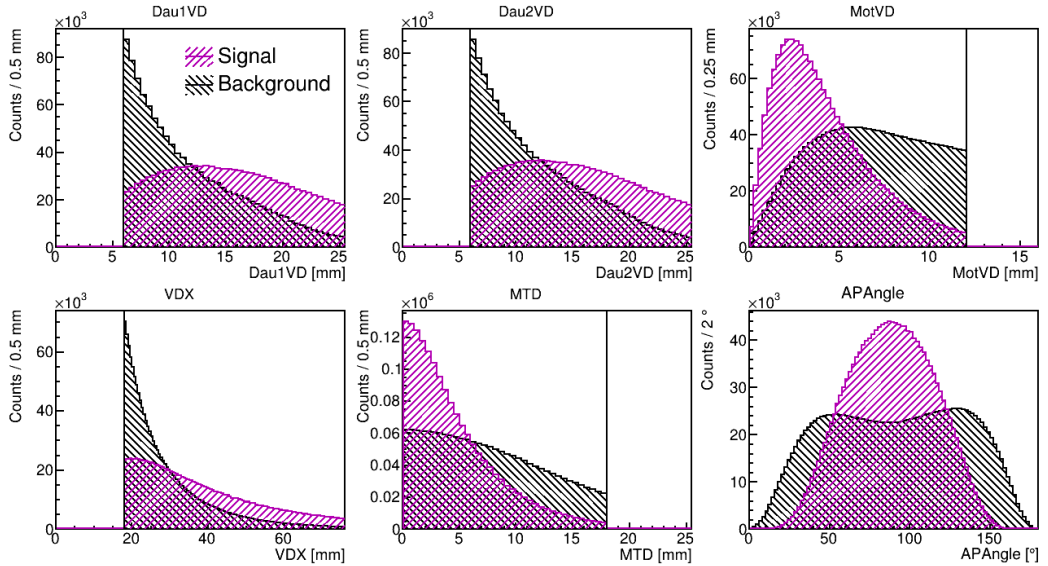
Reconstruction and Analysis of weakly decaying Hadrons

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]





TMVA

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

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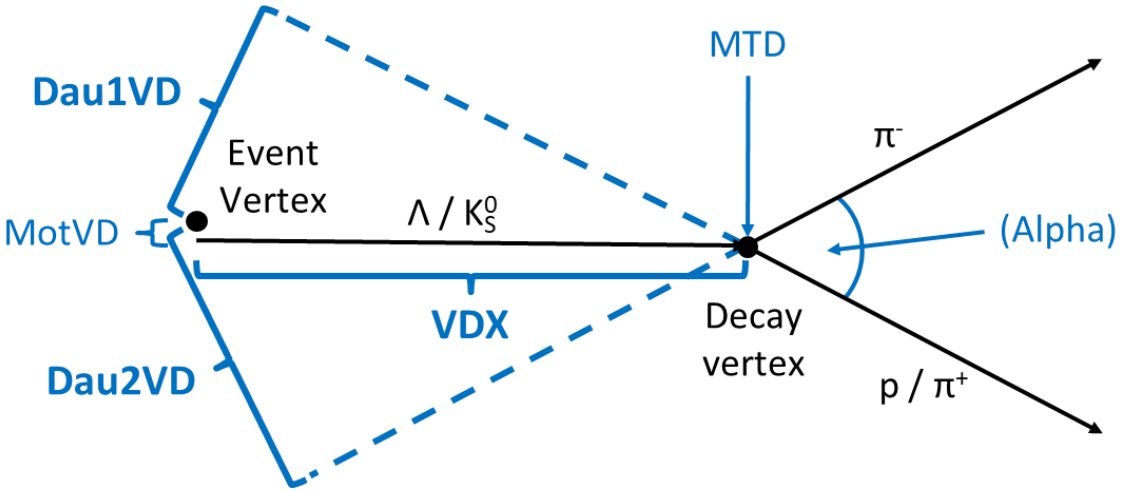

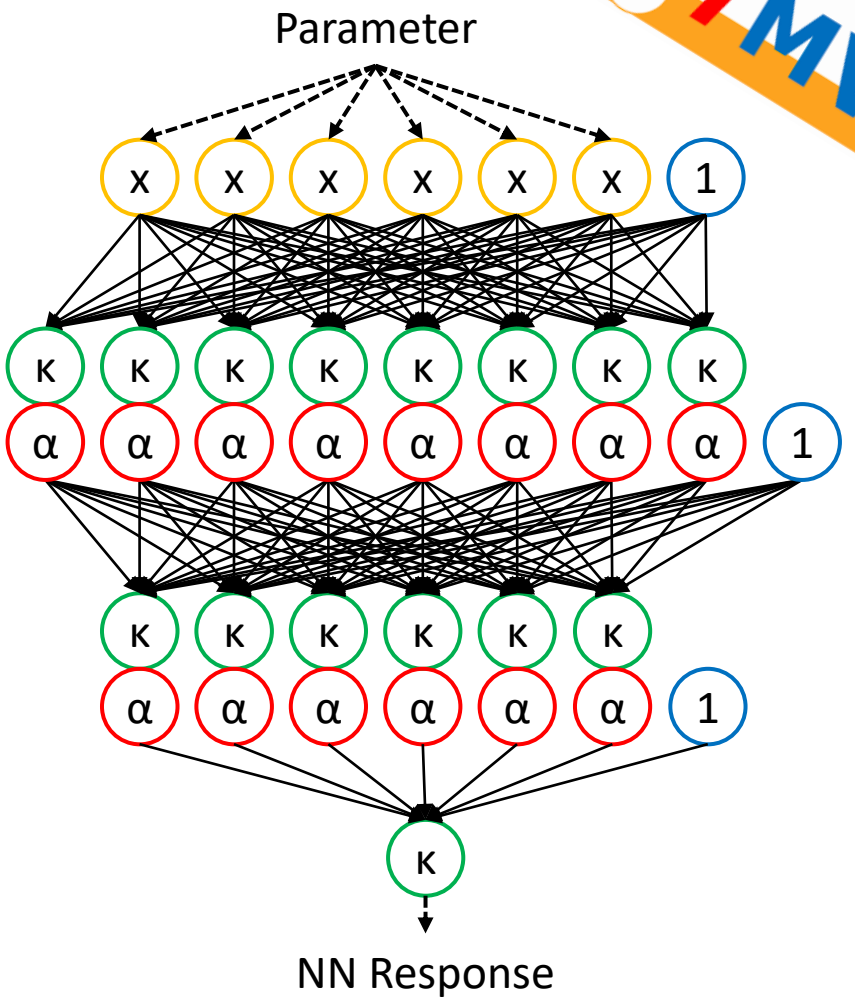

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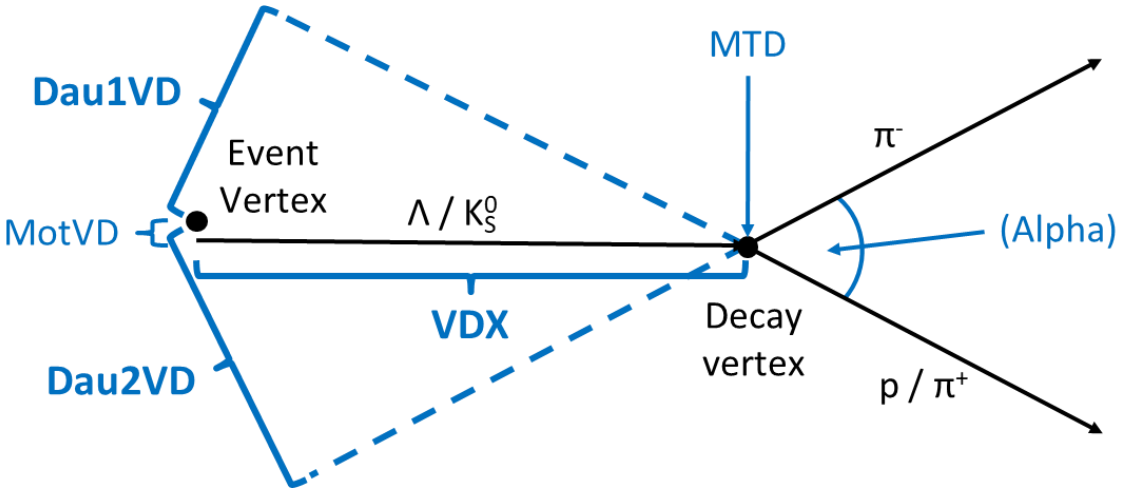
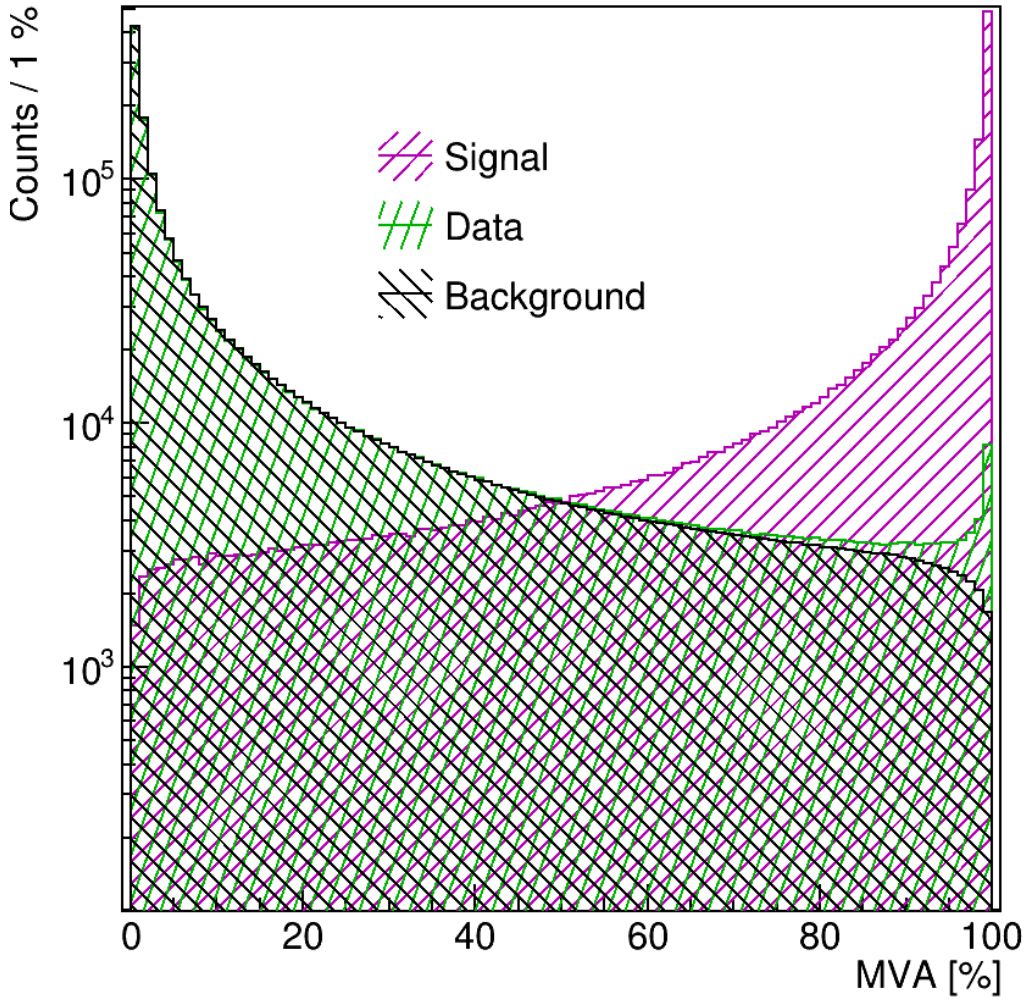
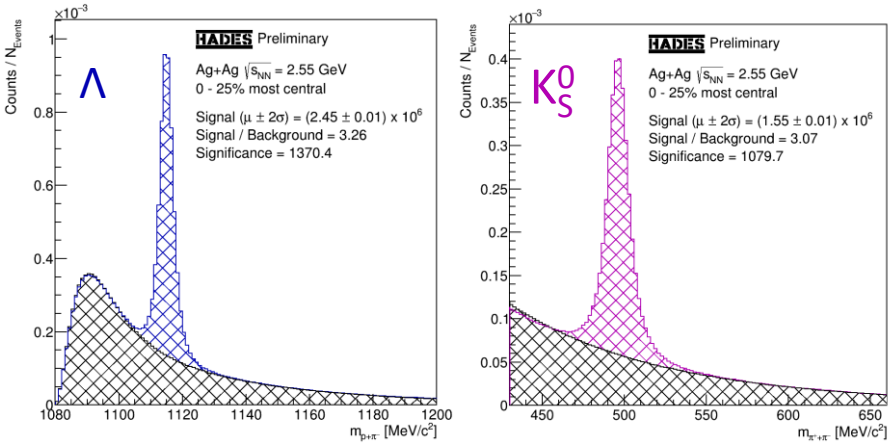
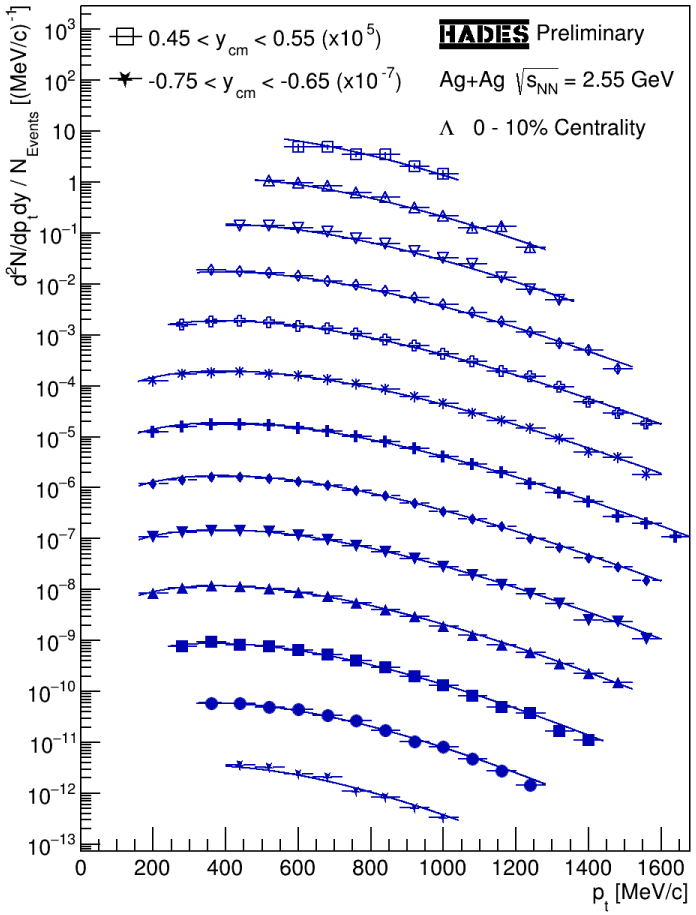


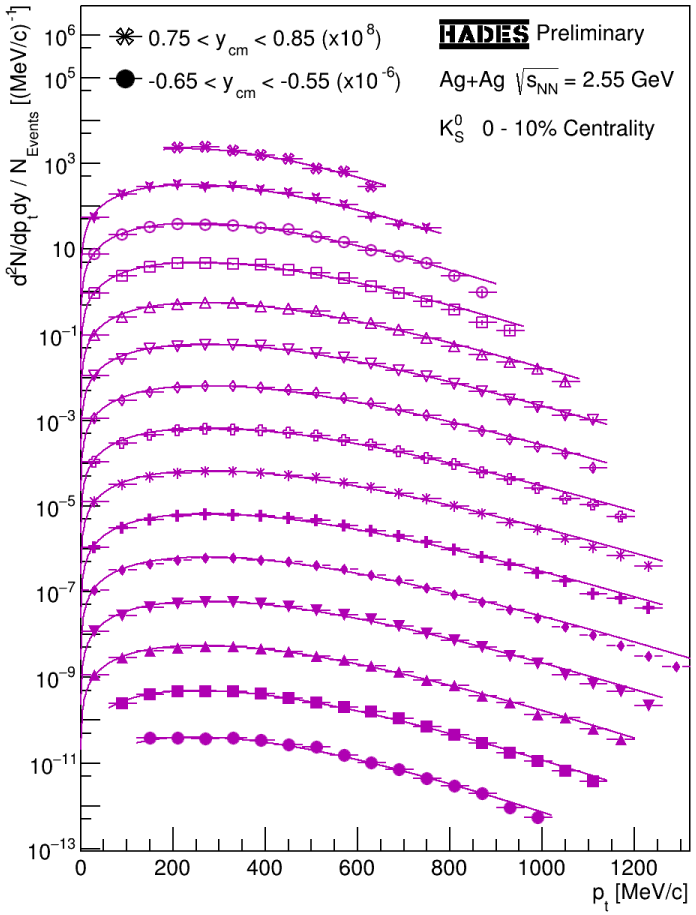


Weak Decay Reconstruction Performance



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



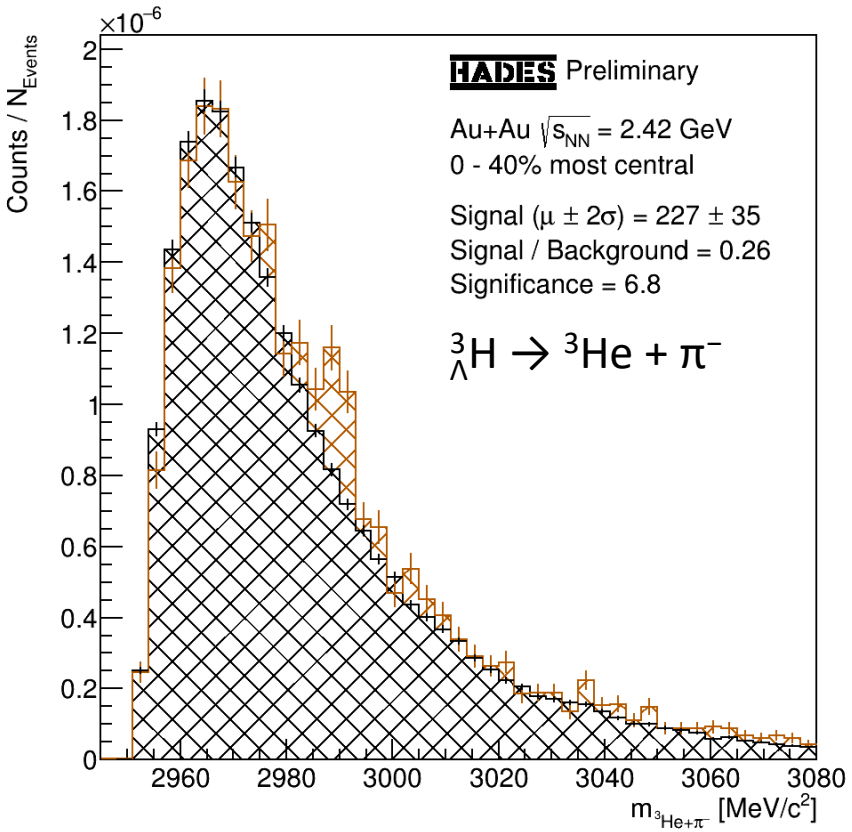


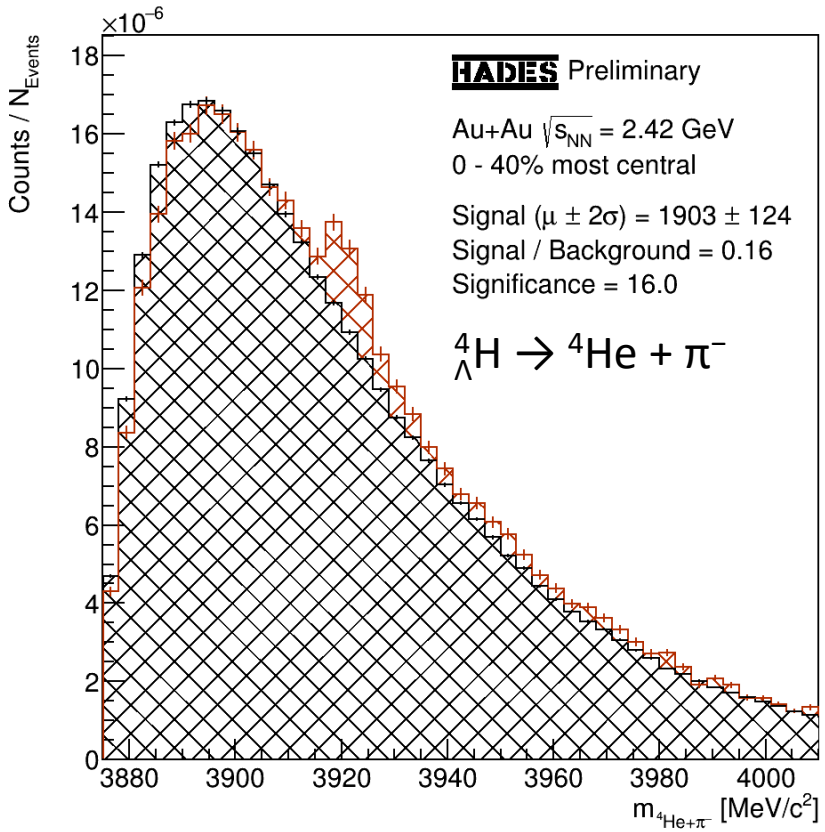
Hypernuclei

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

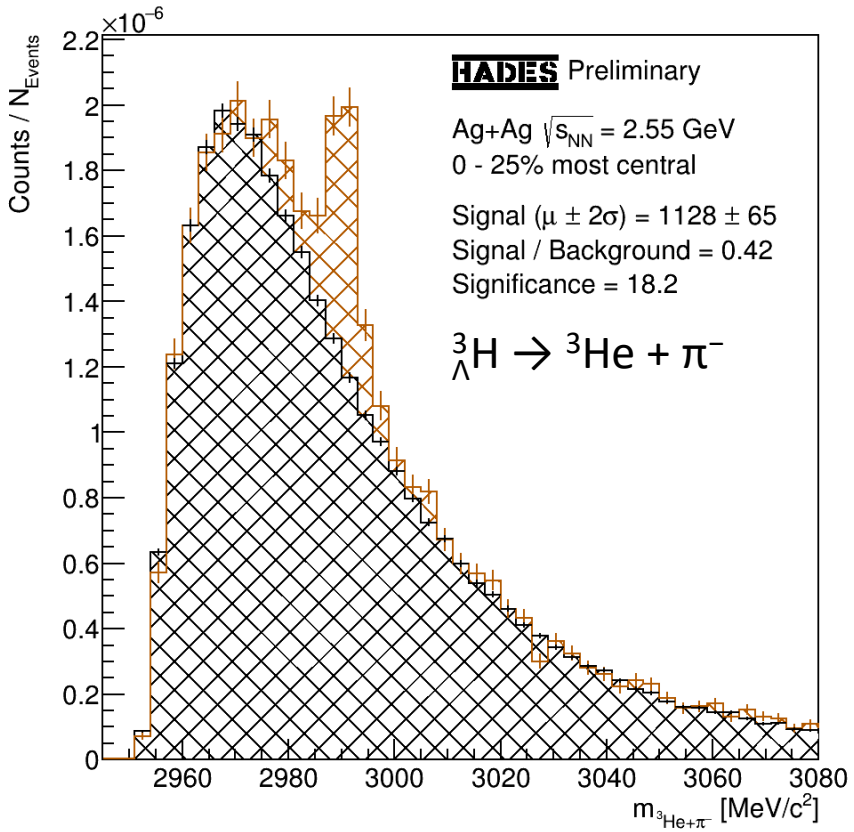


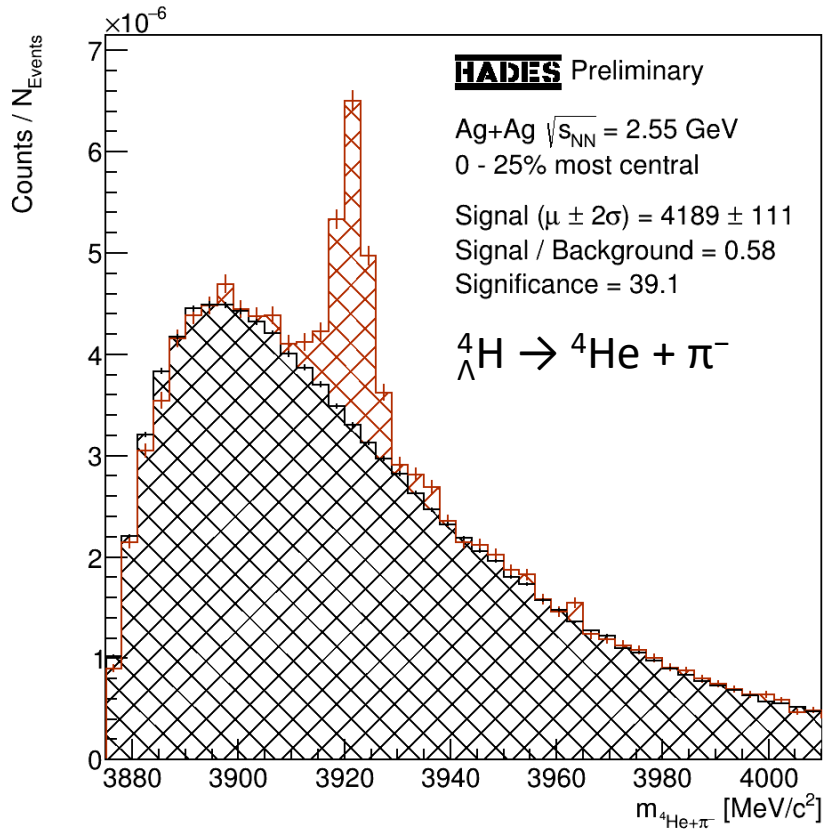


- In case of the $^4_\Lambda H$ sufficient statistics to analyze the production differentially

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

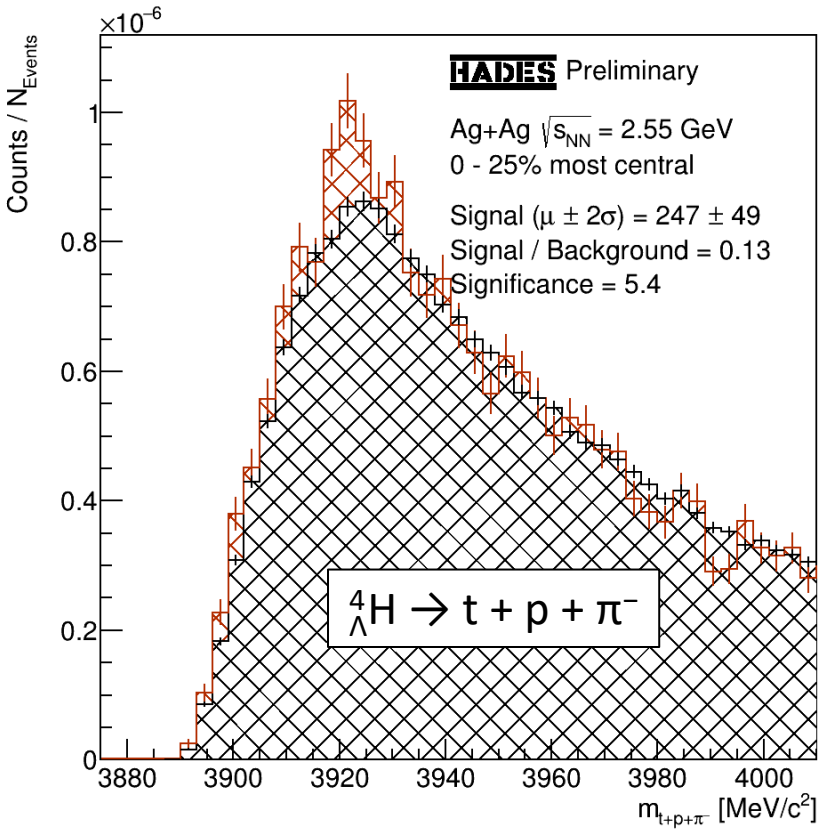


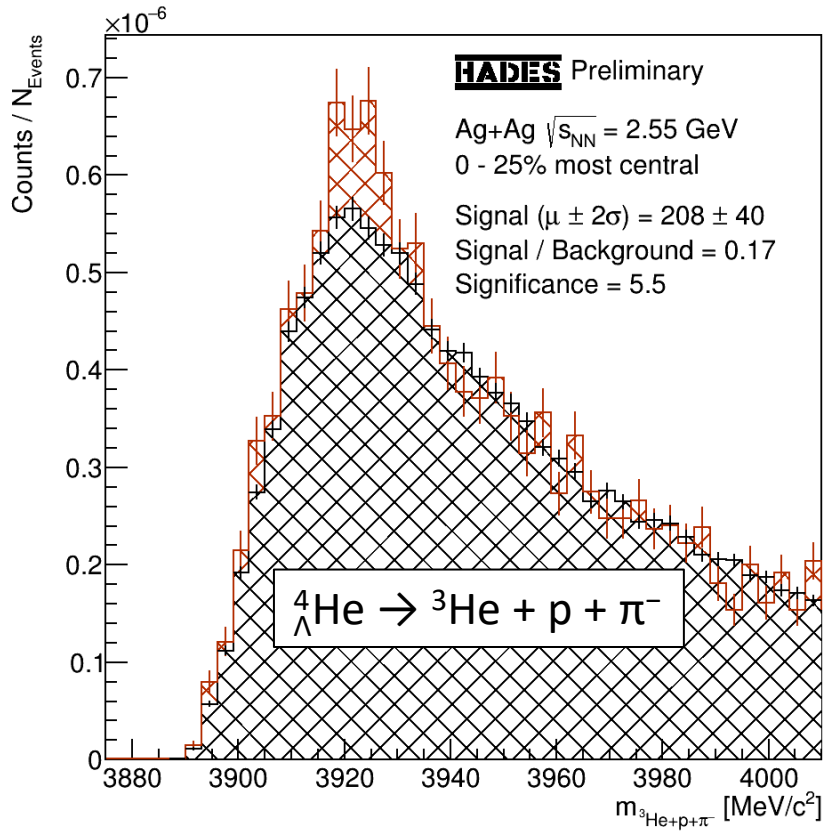


- More significant signals → Focus on this dataset to reduce uncertainties

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

- Hints for signals in the three-body-decay channels for $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He
- Strong combinatoric background suppression using strong selection on aNN response
- Contamination by $\Lambda \rightarrow p + \pi^-$ decays removed by $m_{p+\pi-} < 1110$ MeV/c^2
- Further attempts to improve the signals ongoıng





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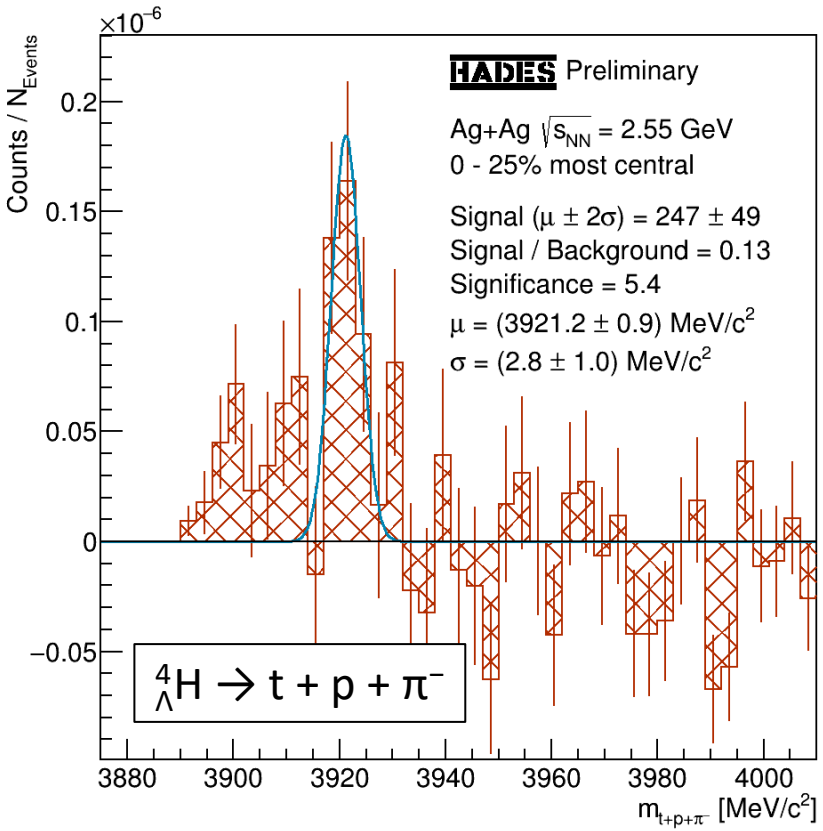

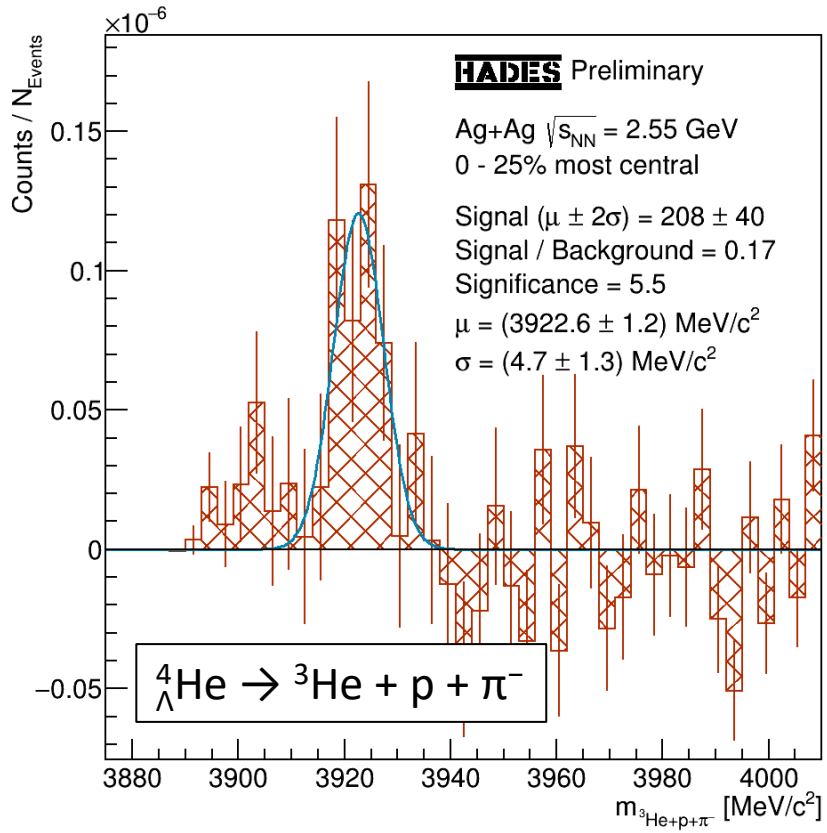

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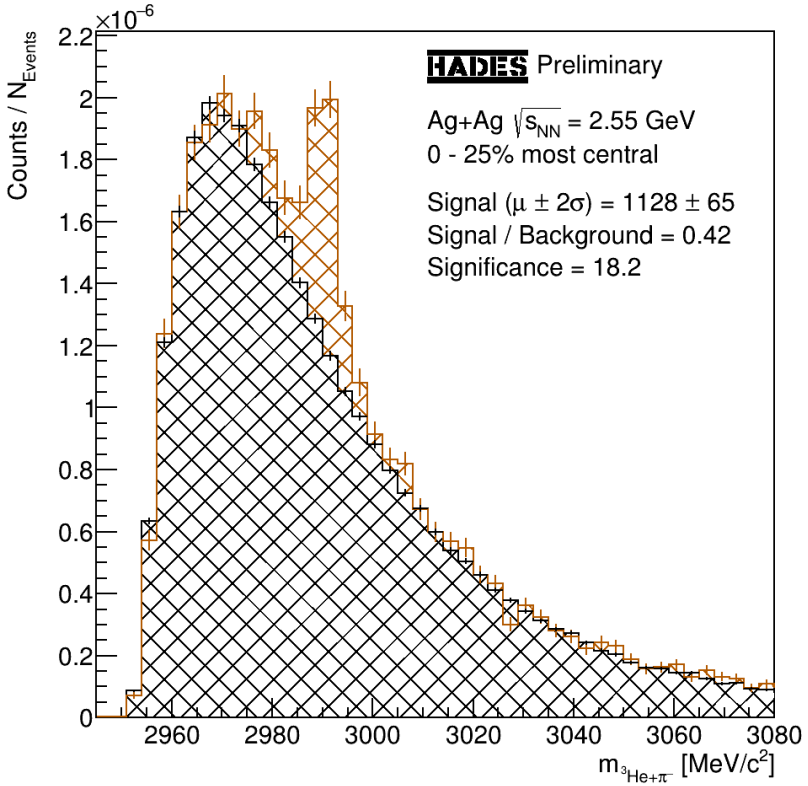
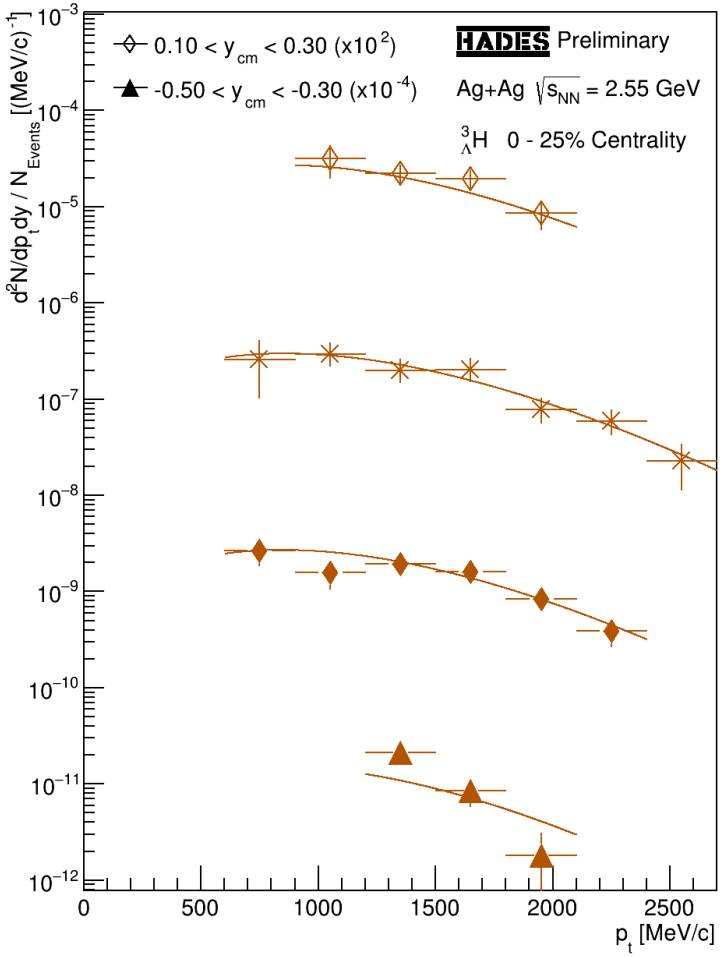
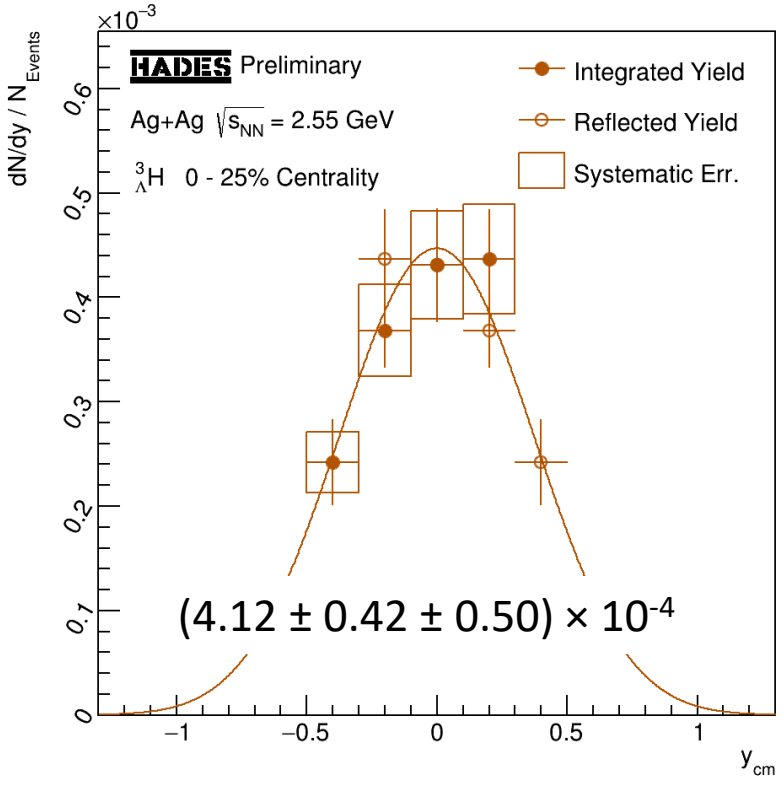
${}^{3}_{\Lambda}$H Two-Body Decay: ${}^{3}_{\Lambda}$H → ^{3}He + π⁻



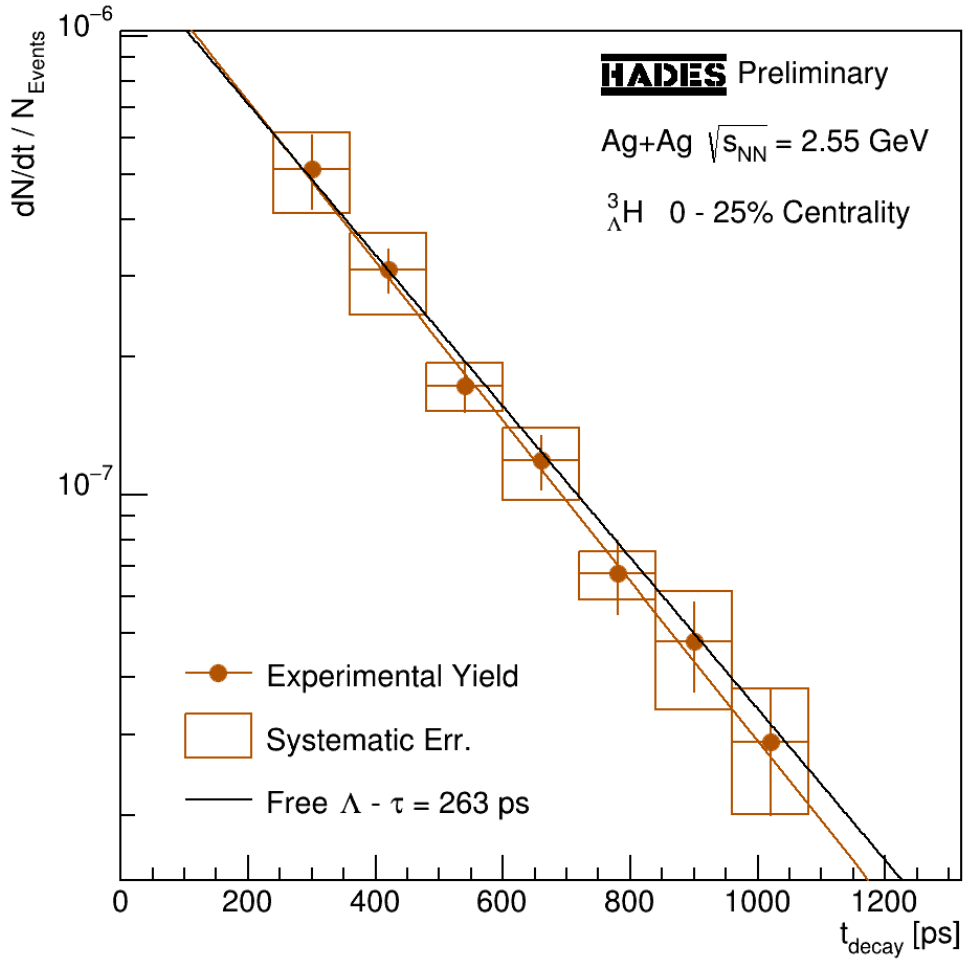




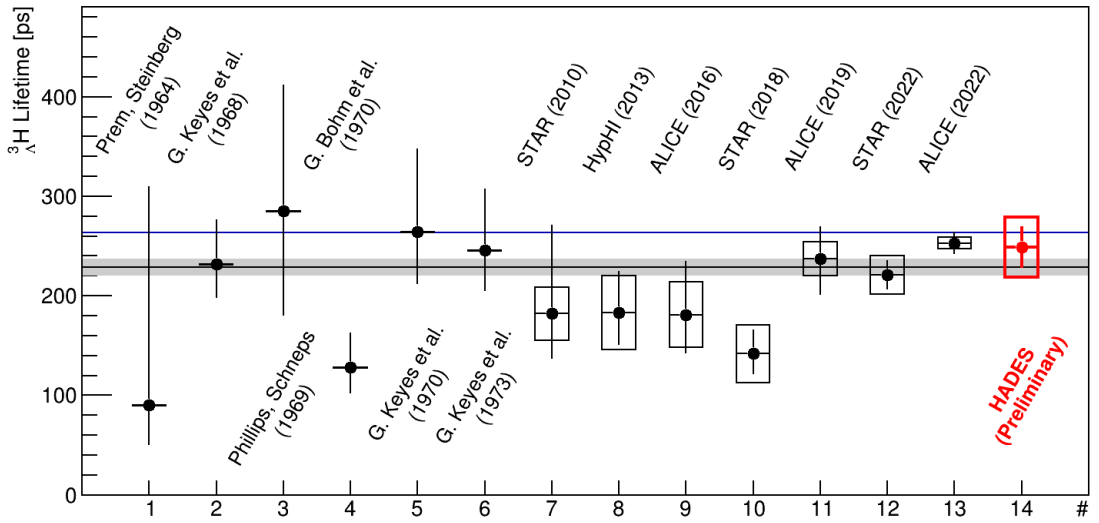
- Multi-differential analysis of ${}^{3}_{\Lambda}$H production as a function of transverse momentum and rapidity

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

${}^{3}_{\Lambda}$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



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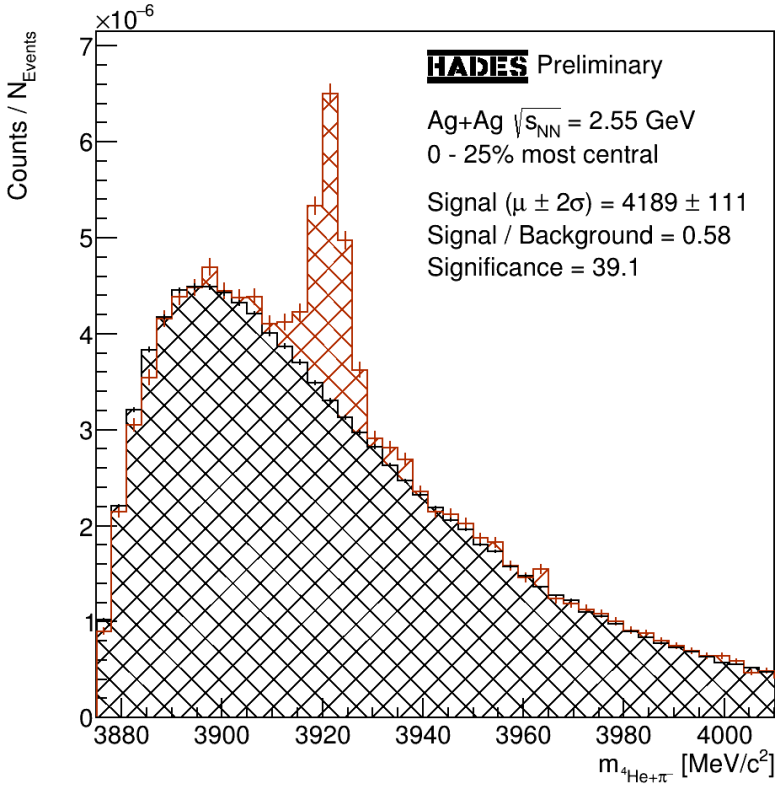

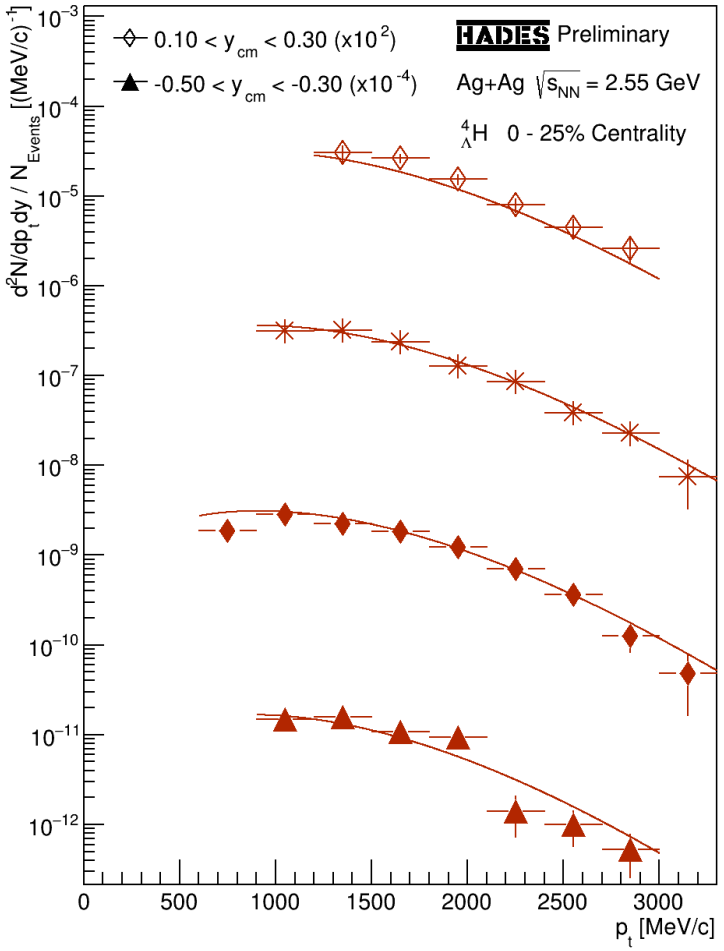

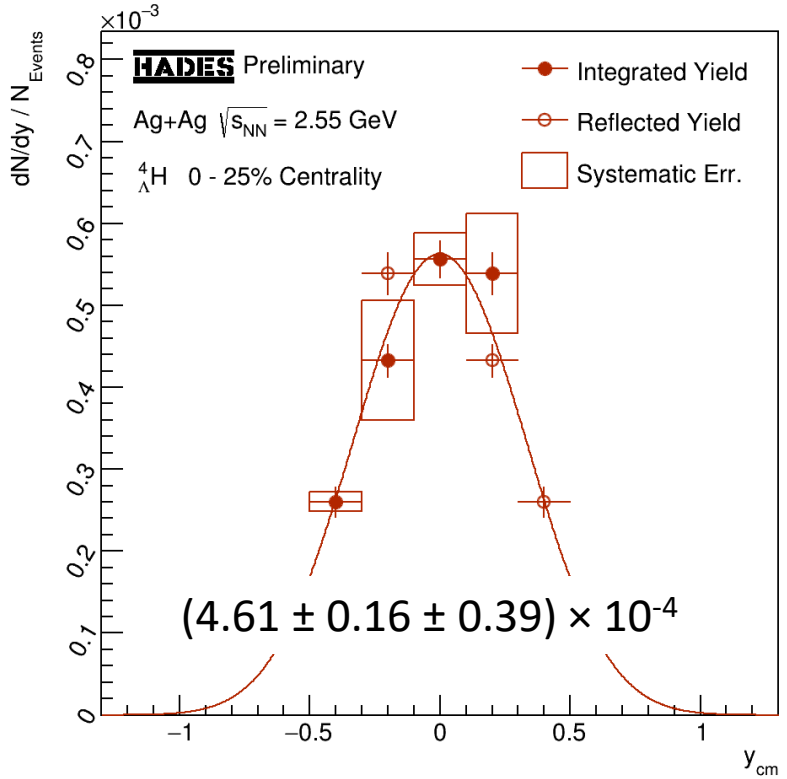

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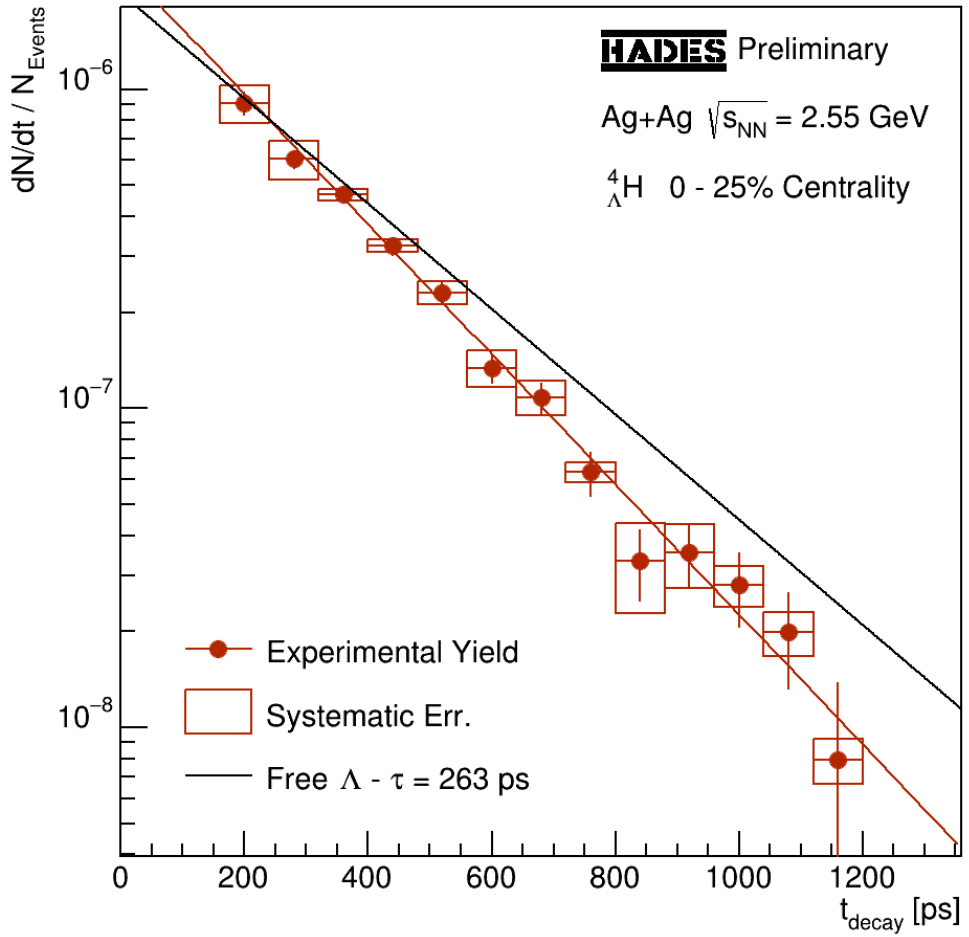
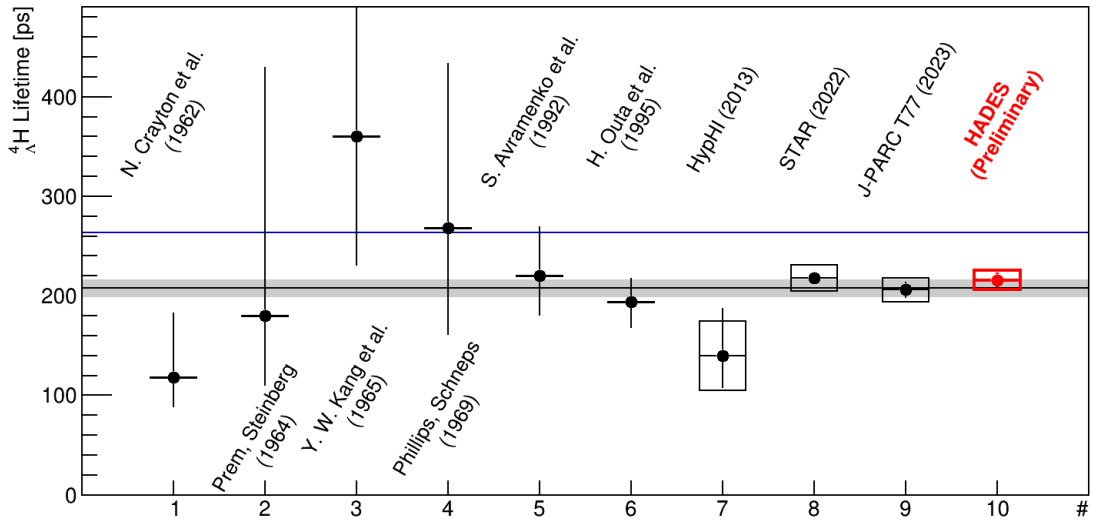
${}^{4}_{\Lambda}$H Two-Body Decay: ${}^{4}_{\Lambda}$H → ^{4}He + π^-



- ${}^{4}_{\Lambda}$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

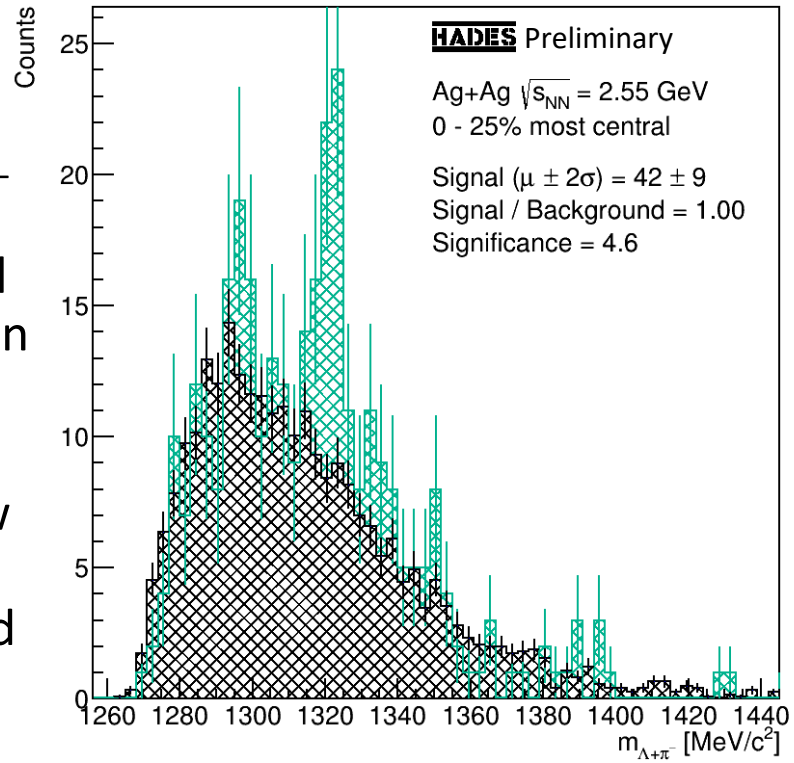


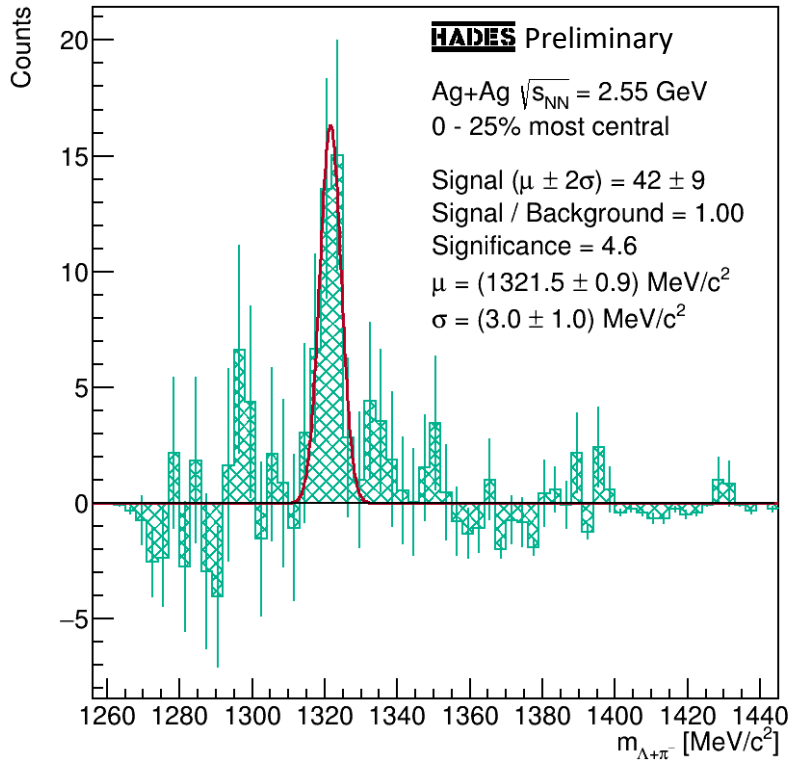
Ξ^- Hyperons

Reconstruction and analysis of Ξ^- Hyperons

Reconstruction of double-strange Ξ^- Hyperons

- Ξ^- Hyperons measured via their double-weak decay chain:
  $\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^- + \pi^-$
  - ➢ Excellent combinatorial background suppression enabled by two aNN
- Significance slightly below 5σ yet clear signal above combinatorial background observable



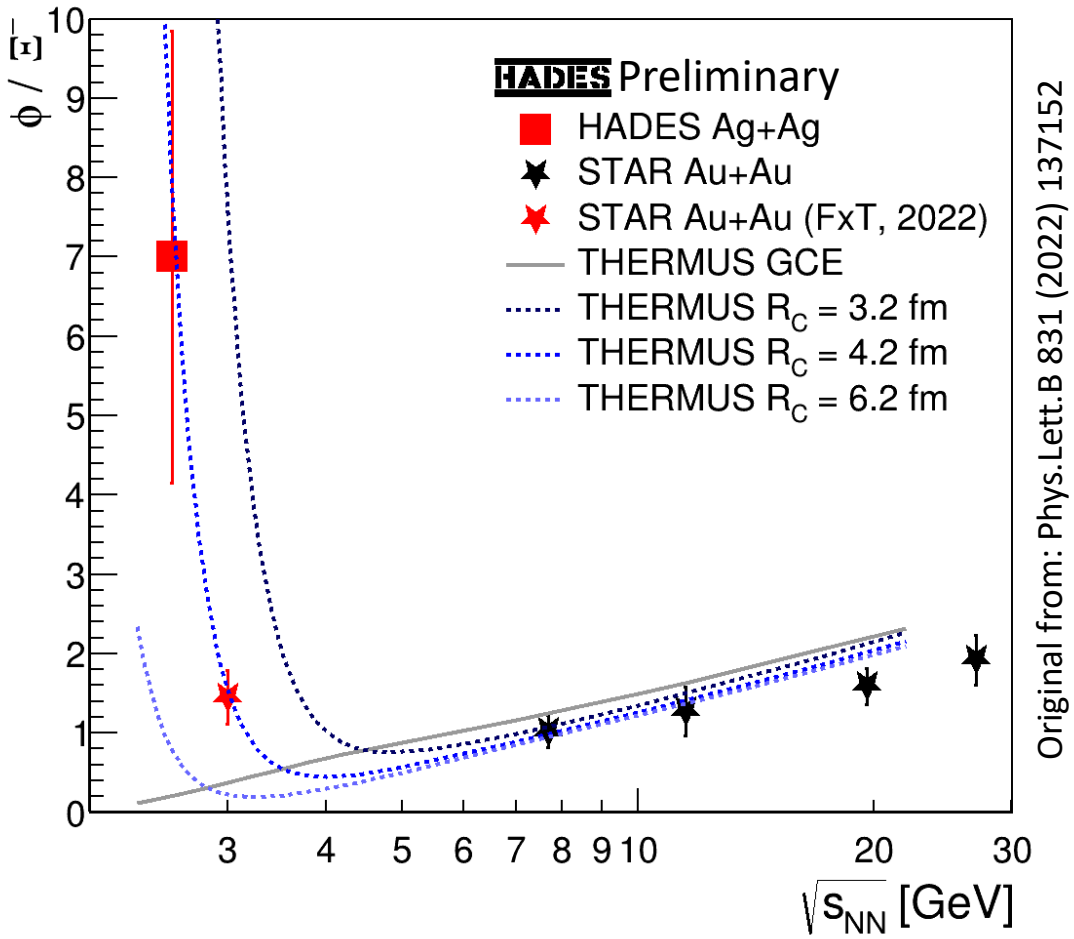


- First measurement of double-strange Ξ^- Hyperons in few GeV Ag+Ag collisions
- Outlook: Improved reconstruction efficiencies using KFParticle package

Analysis of double-strange Ξ^- Hyperons

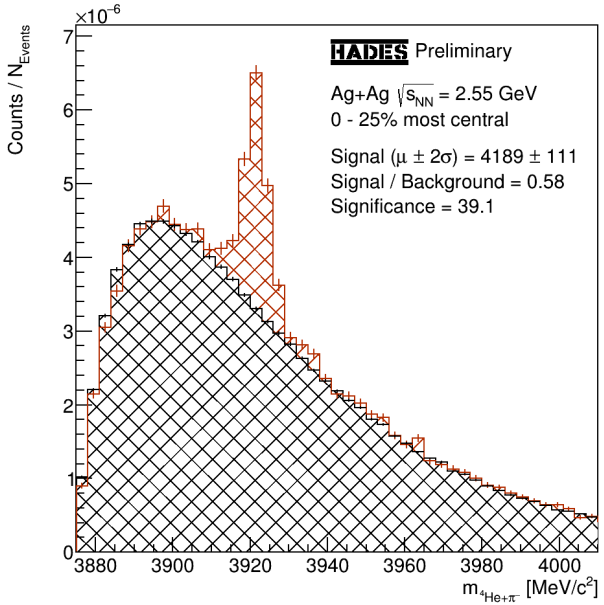
- Statistics not sufficient for multi-differential analysis of production and extrapolation to 4π
  - ➢ 4π yield determined by an educated guess of the Ξ^- emission pattern based on multi-differential analysis of Λ hyperons
  - ➢ Large systematic uncertainties!
- Canonically extended SHM model predicts strong dependence of canonical radius R_C and ϕ/Ξ^- ratio
  - ➢ Measurement is of high importance for the SHM fit despite its large uncertainties

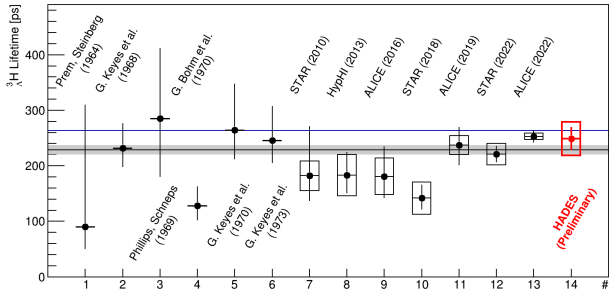
Poster by Marvin Kohls
"Systematics of Hidden and Open Strangeness Production in Few GeV HICs"

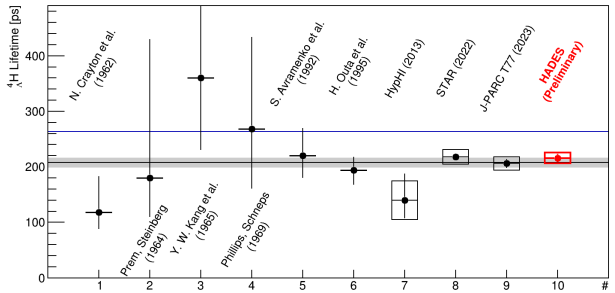


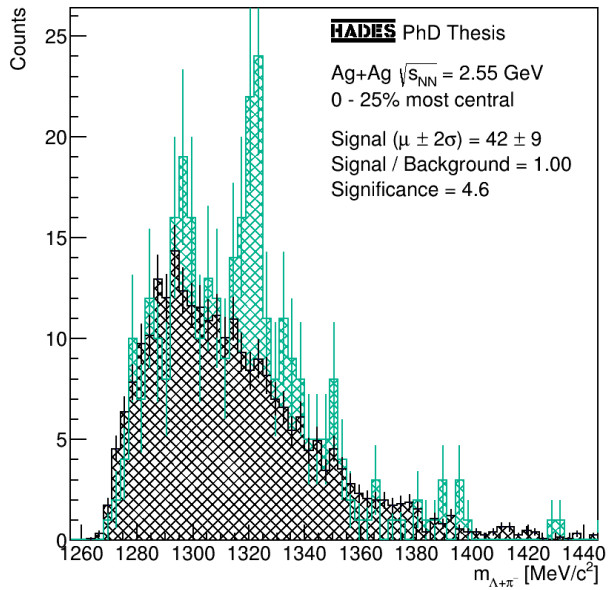
Summary

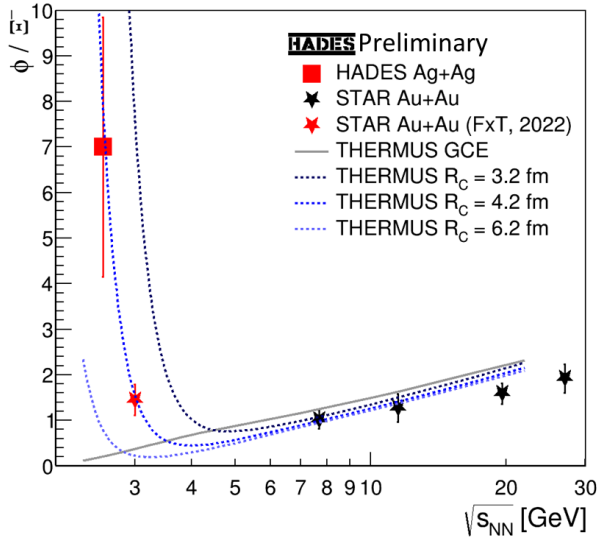
- First multi-differential analysis of Hypernuclei around mid-rapidity at SIS18 energies
- Bell-shaped rapidity distributions
- Lifetime measurements compatible with recent measurements by STAR and ALICE
- Extensive uncertainty evaluation performed
- Paper on Hypernuclei in preparation
- First measurement of double-strange Ξ^- Hyperons in few GeV Ag+Ag collisions
- Ξ^- may help to constrain canonical SHM fit



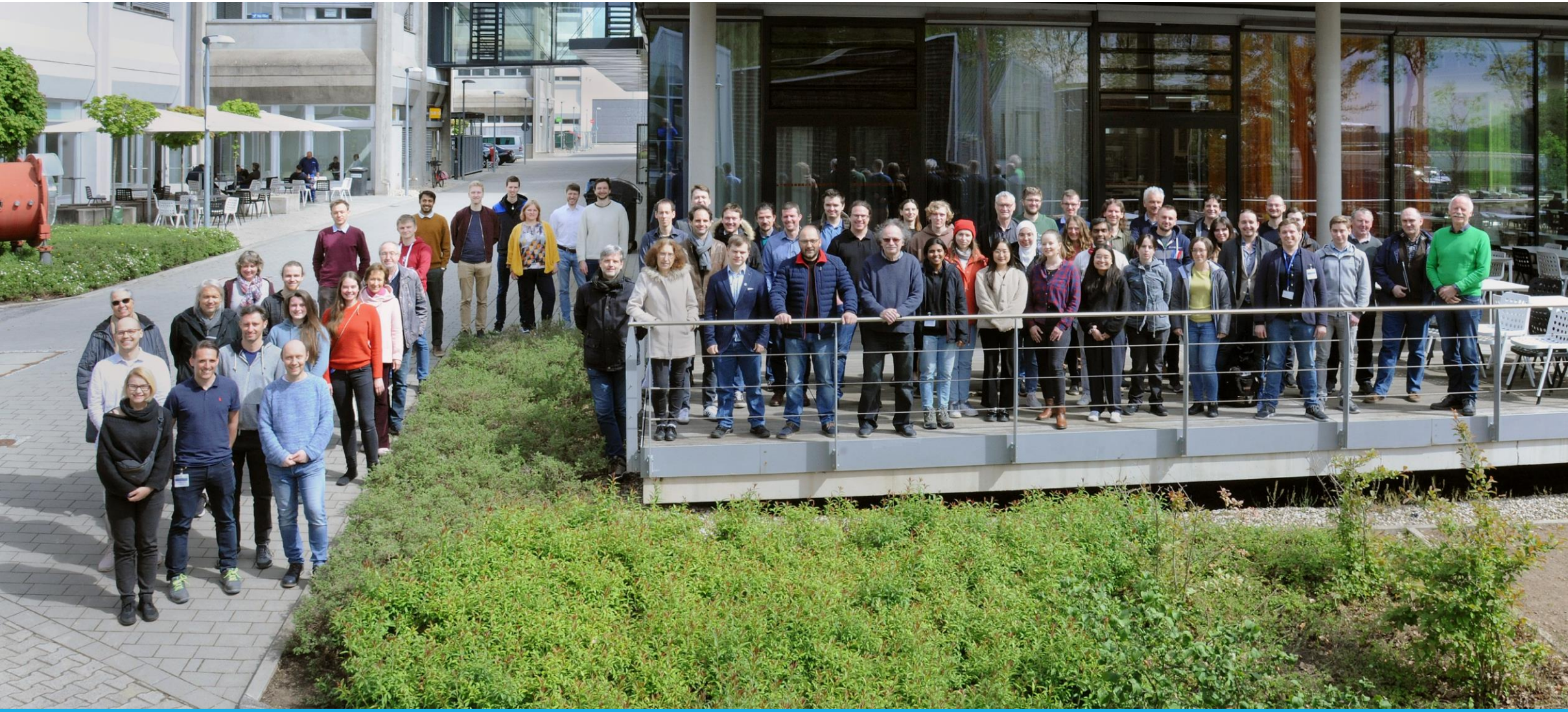






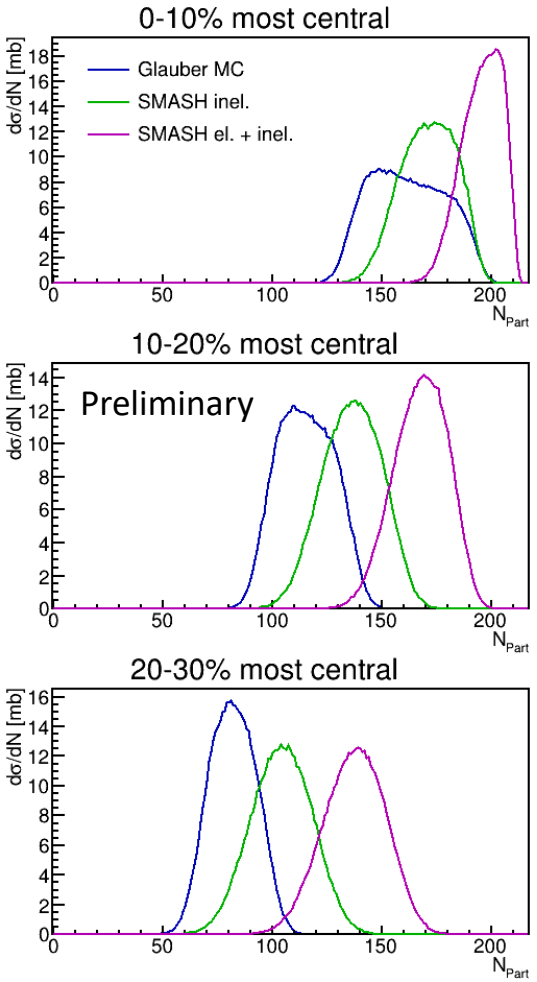


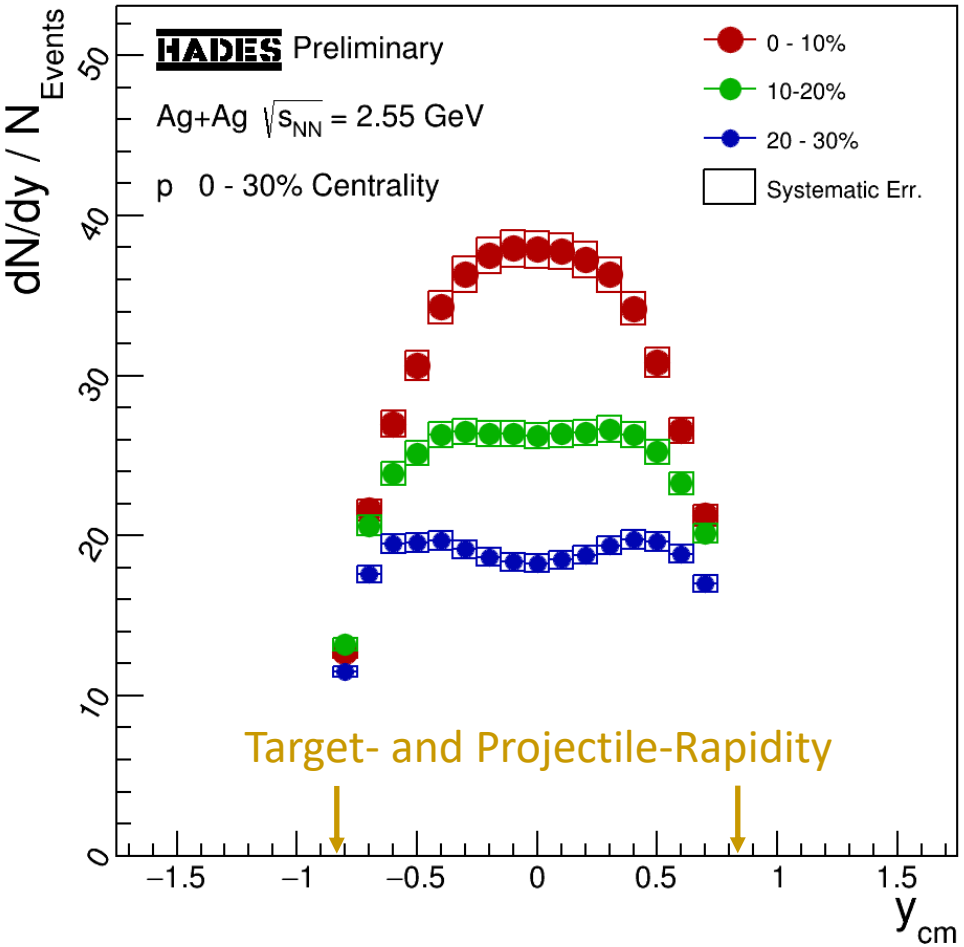
The HADES Collaboration



Nuclear Collisions at SIS18/HADES Energies

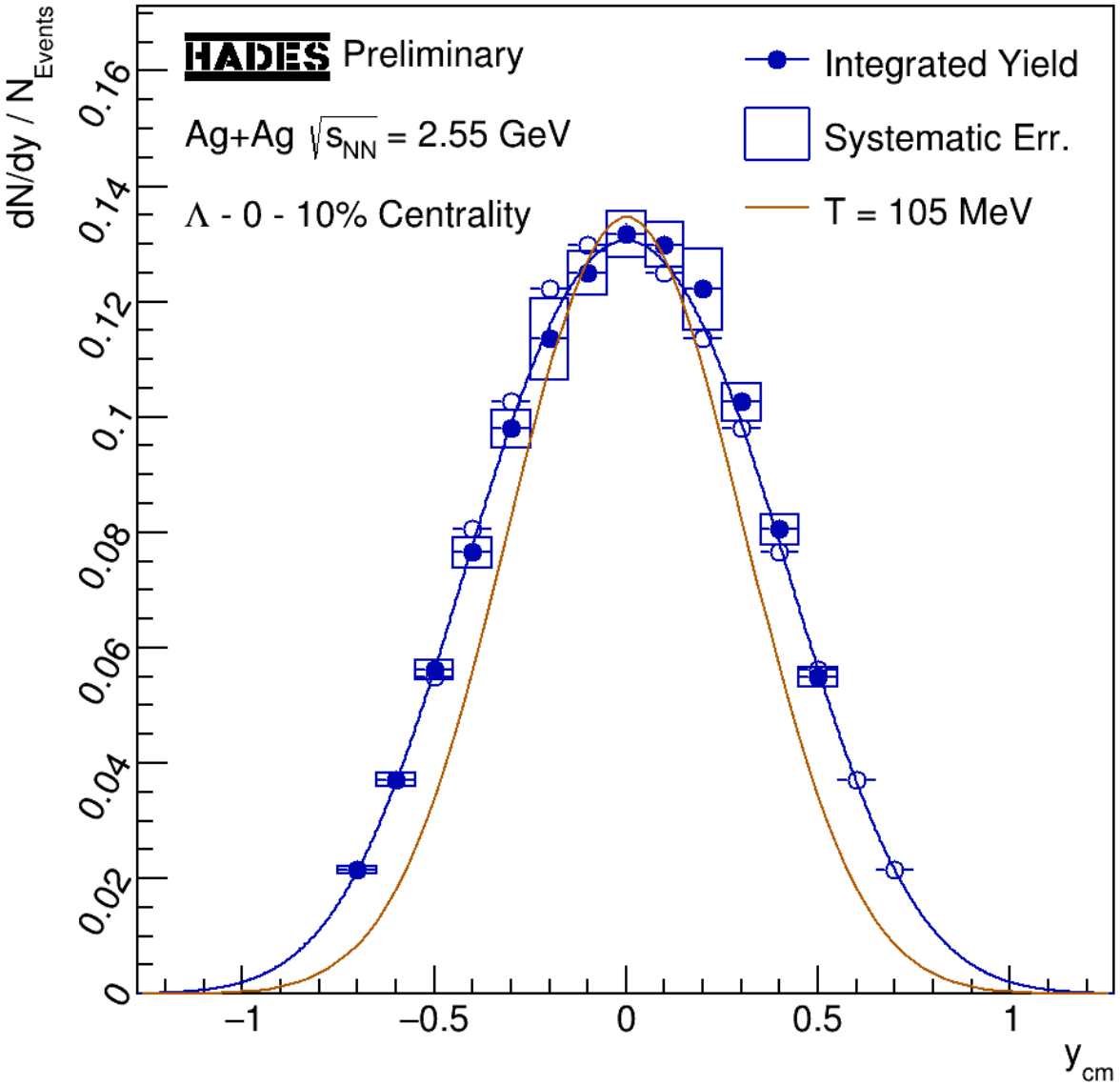
- Nucleons essentially stopped in collision zone
  - ➢ Detected particles pre-dominantly rescattered nucleons
- Slow spectators – $\beta_{CM} \approx 2/3c$
  - ➢ Secondary interactions in spectator regions (pole caps)
- Centrality estimation more challenging than at high collision energies



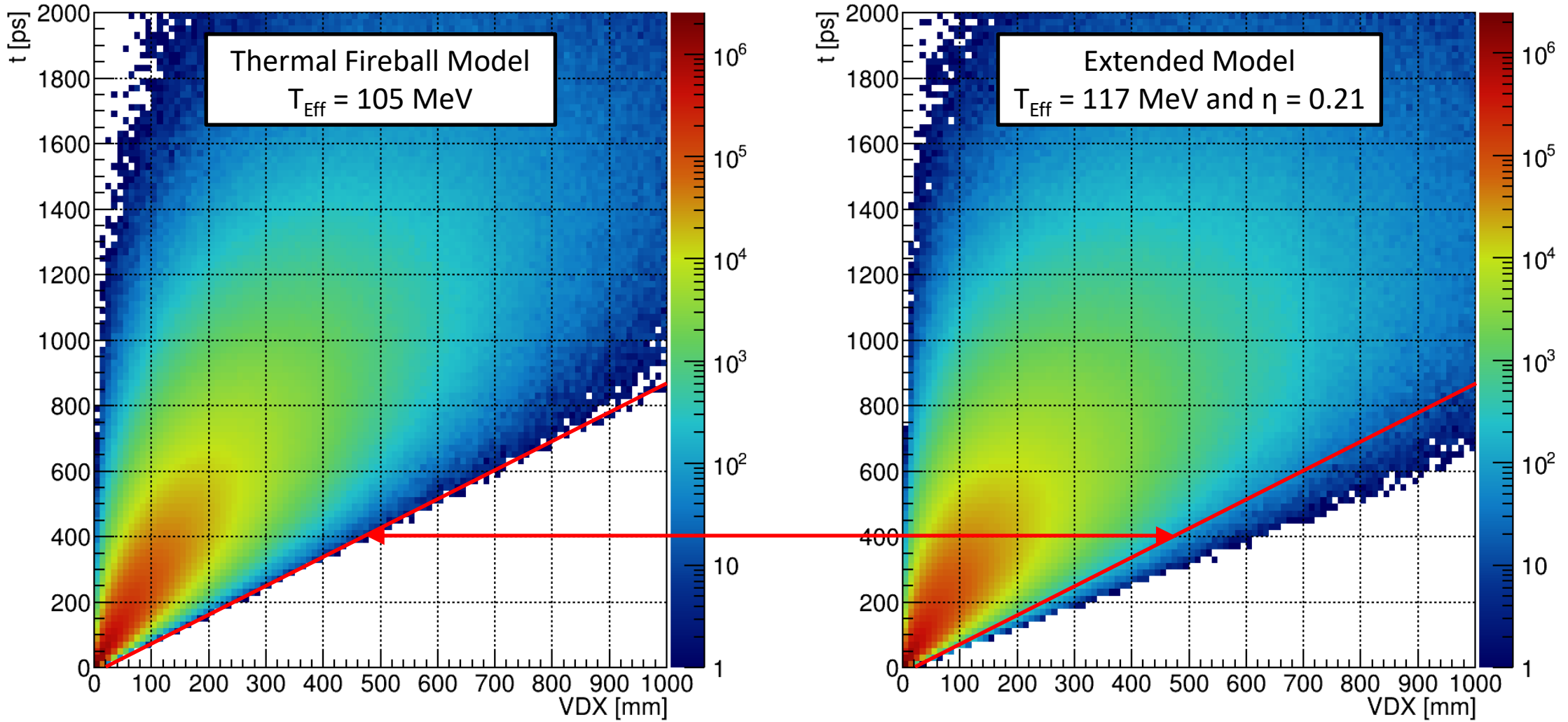


Λ dN/dy Spectrum

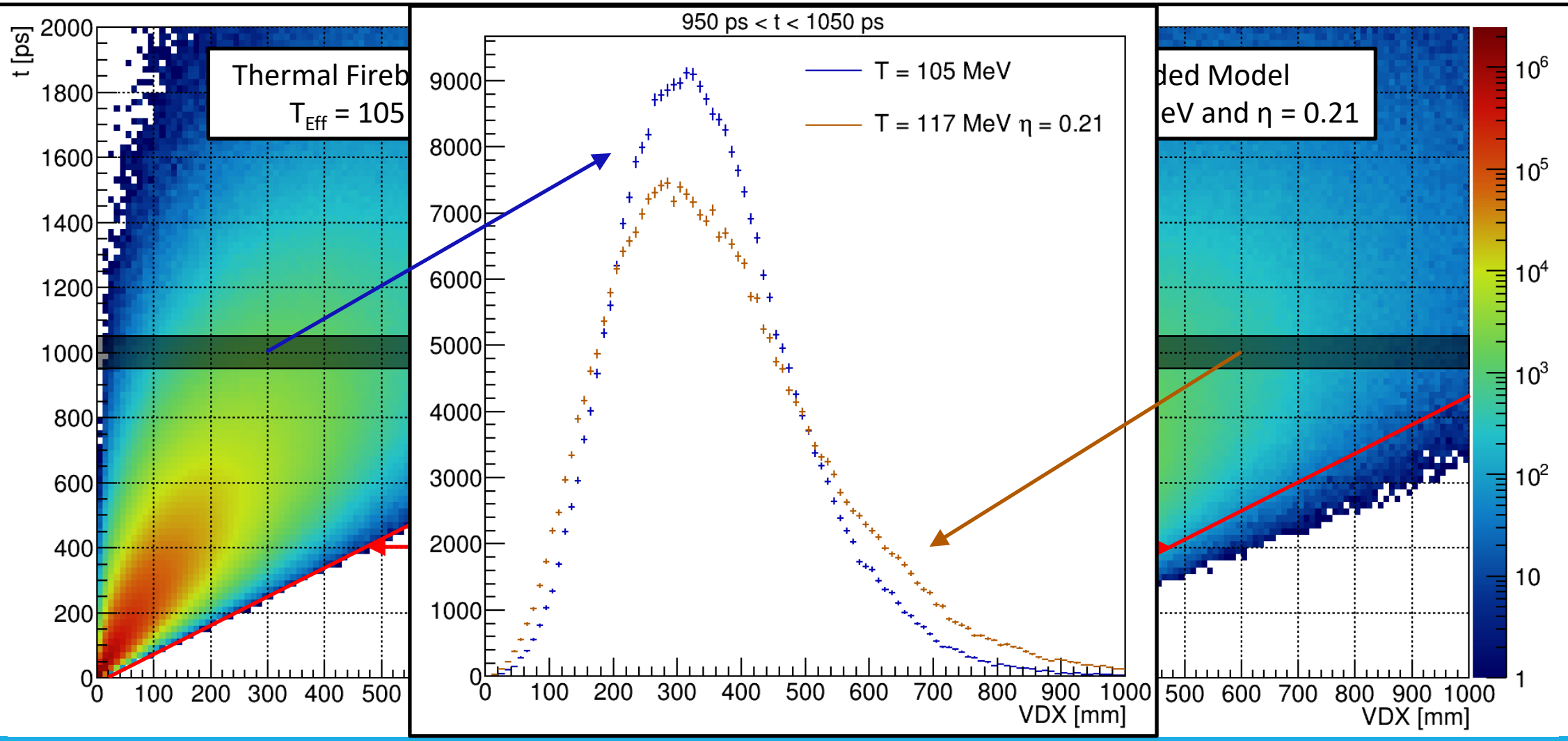
- Longitudinal anisotropy of particle emission due to only partial stopping of nucleons in the collision zone
- Longitudinal and transverse kinetic spectra cannot be described by statistical model with single effective temperature
- Effective Temperature of 105 MeV describes transverse spectra but results 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

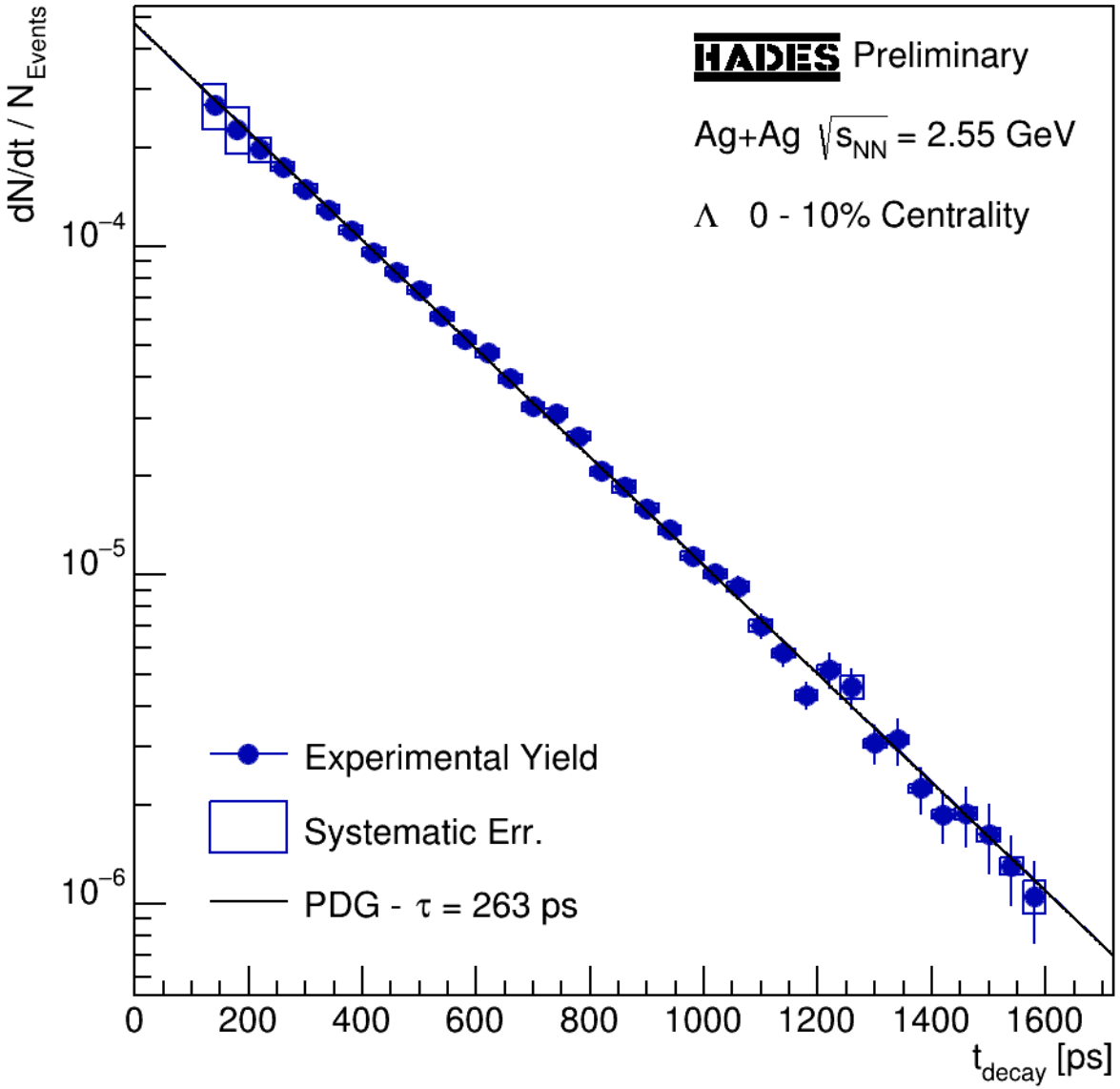


Λ Lifetime t vs. Decay Length VDX

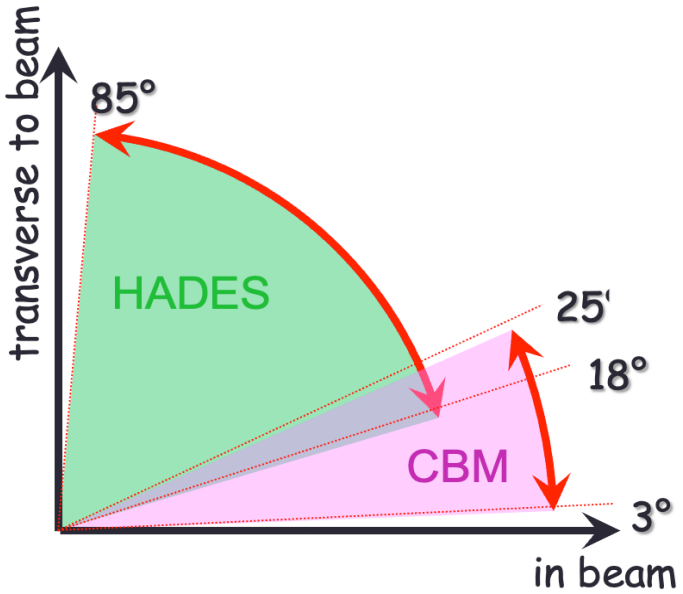


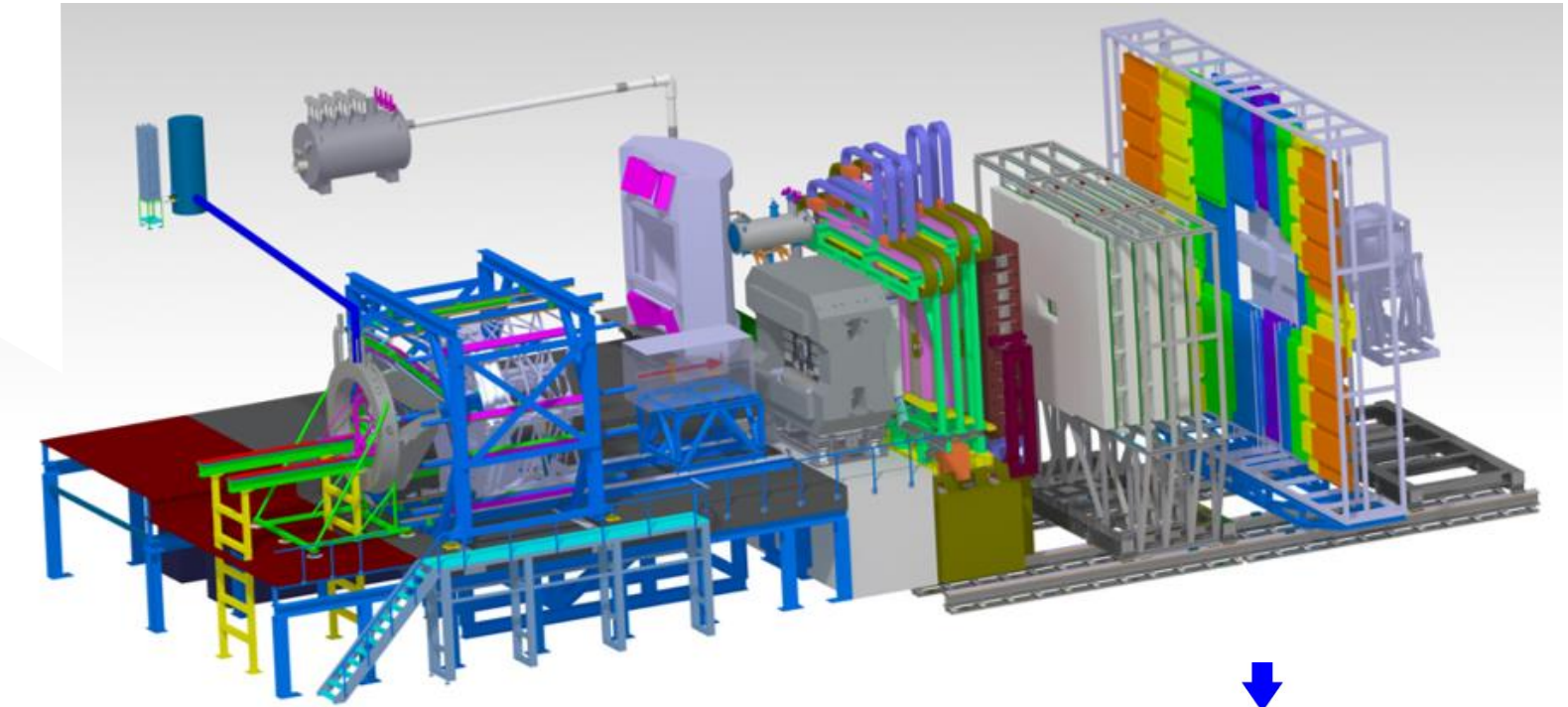
Test case: Λ Lifetime

- 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 ${}^{4}_{\Lambda}H$!



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