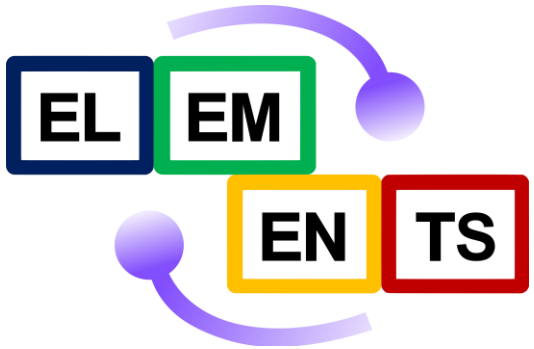
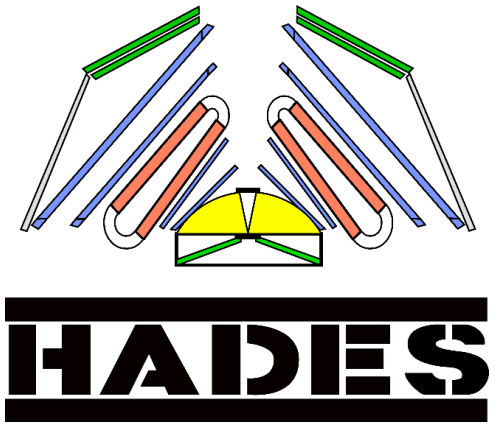
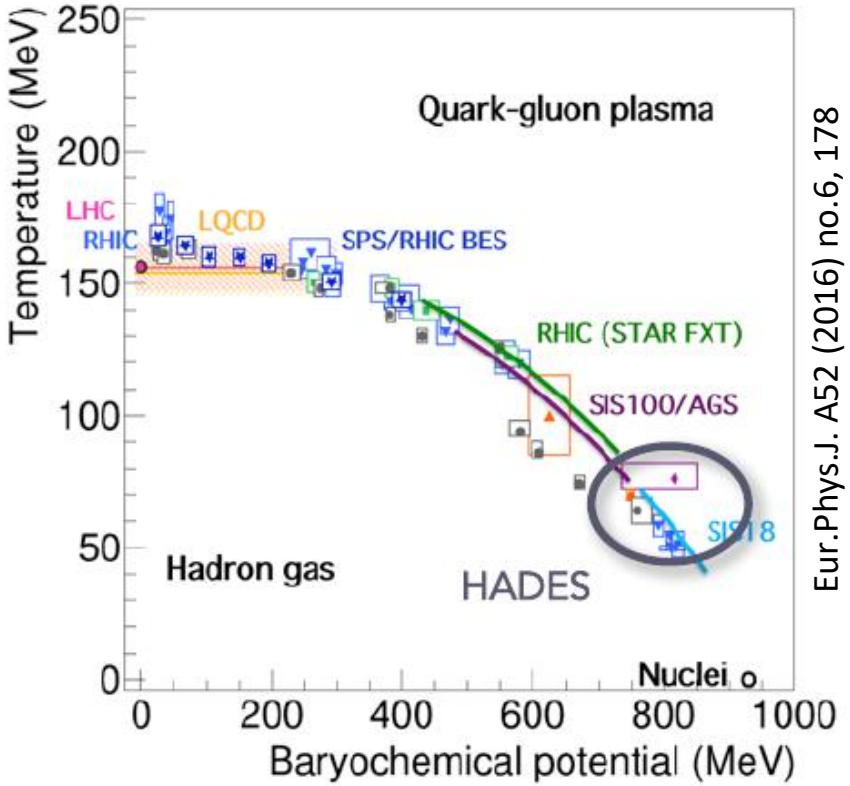
Hypernuclei at HADES

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





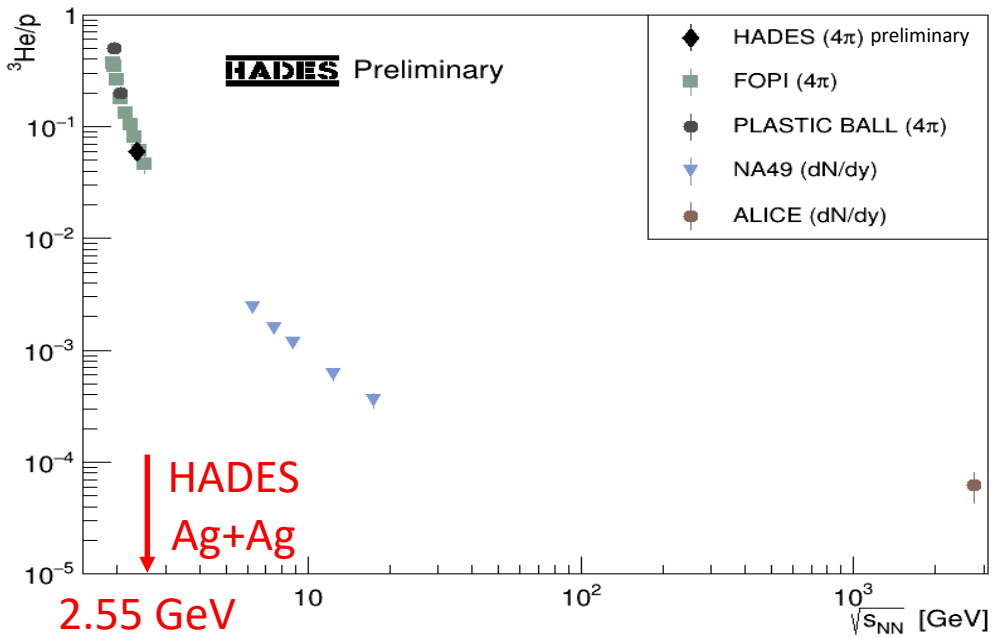
Nuclear collisions at few GeV



Eur.Phys.J. A52 (2016) no.6, 178

- 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)

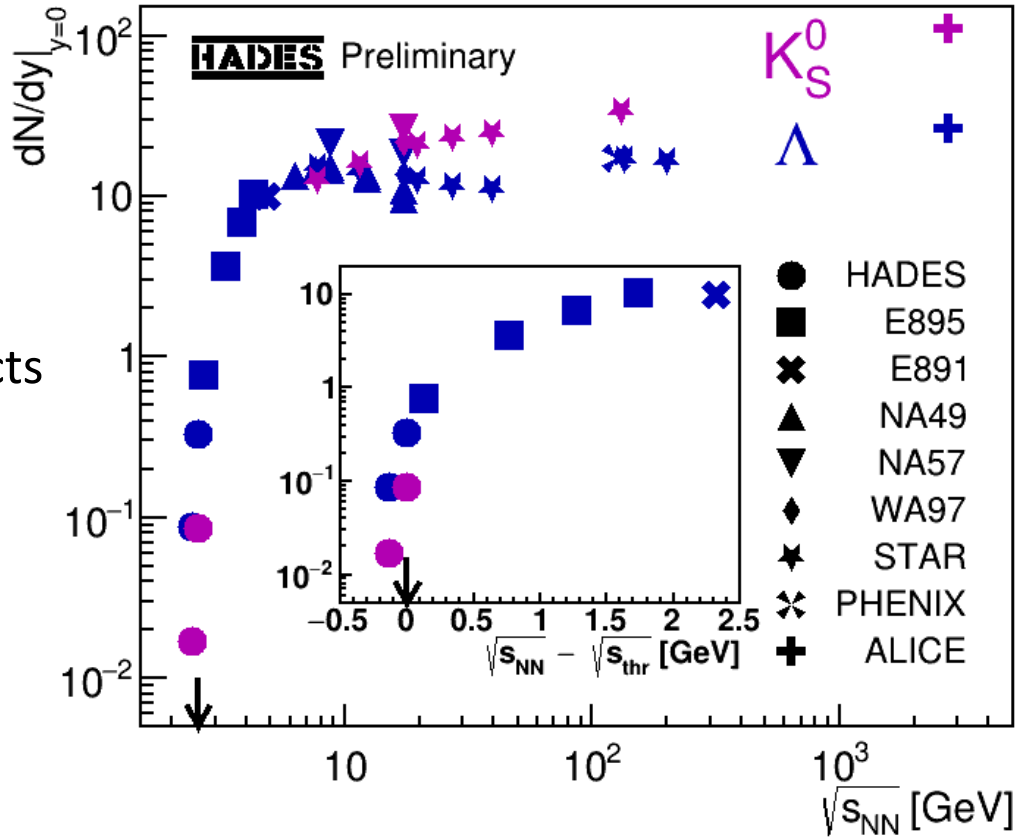
- Nucleons stopped in collision zone
  - Baryon dominated fireball N(B) ≈ 10 N(π)
- Large proportion of baryons clustered in light nuclei (About 50% of protons)



Data Collection: Phys.Lett.B 809 (2020) 135746

Nuclear collisions at few GeV

- 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 + $\overline{K}$

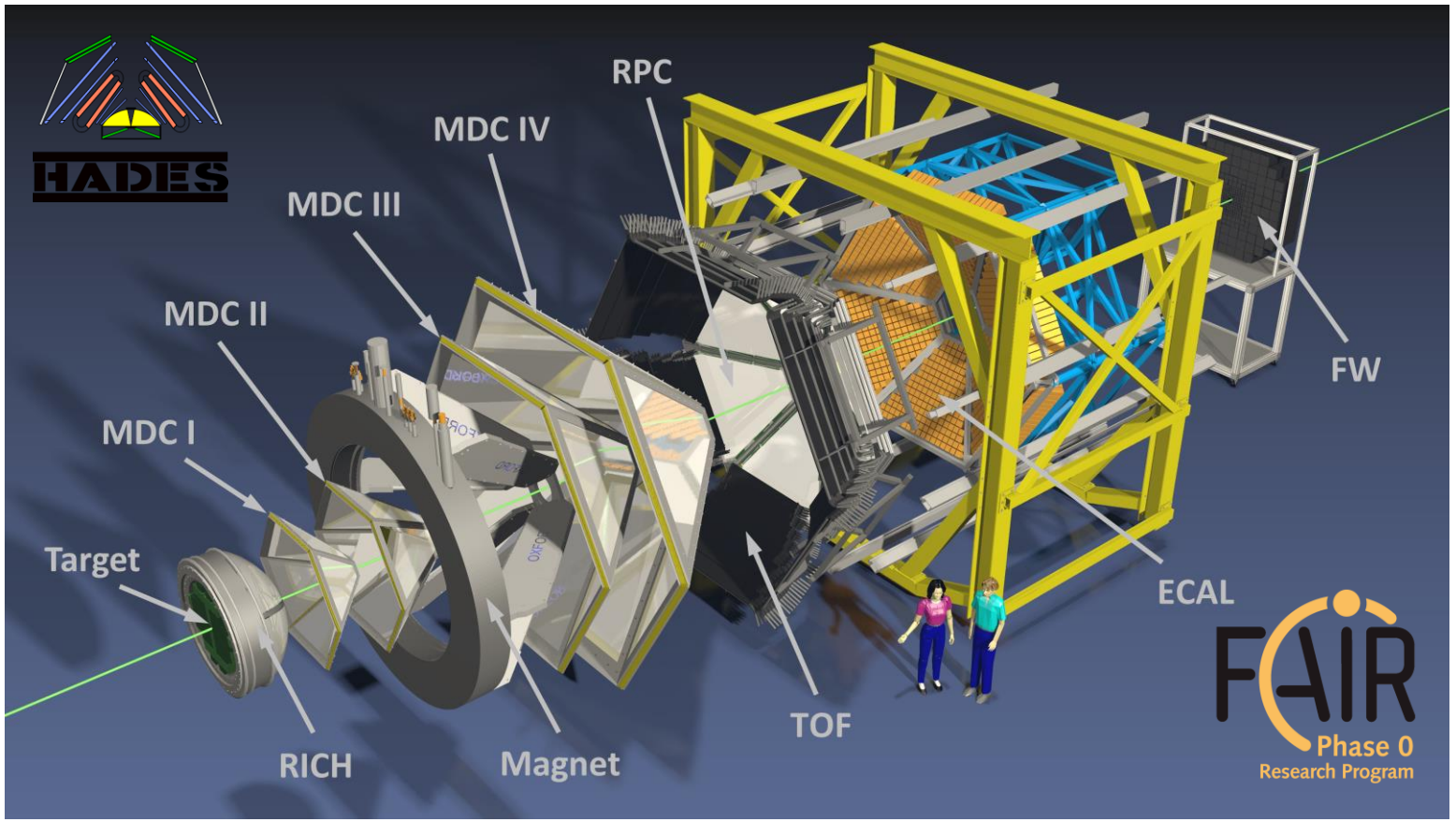


Data: Phys.Lett.B 793 (2019) 457-463

- 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

The HADES Experiment

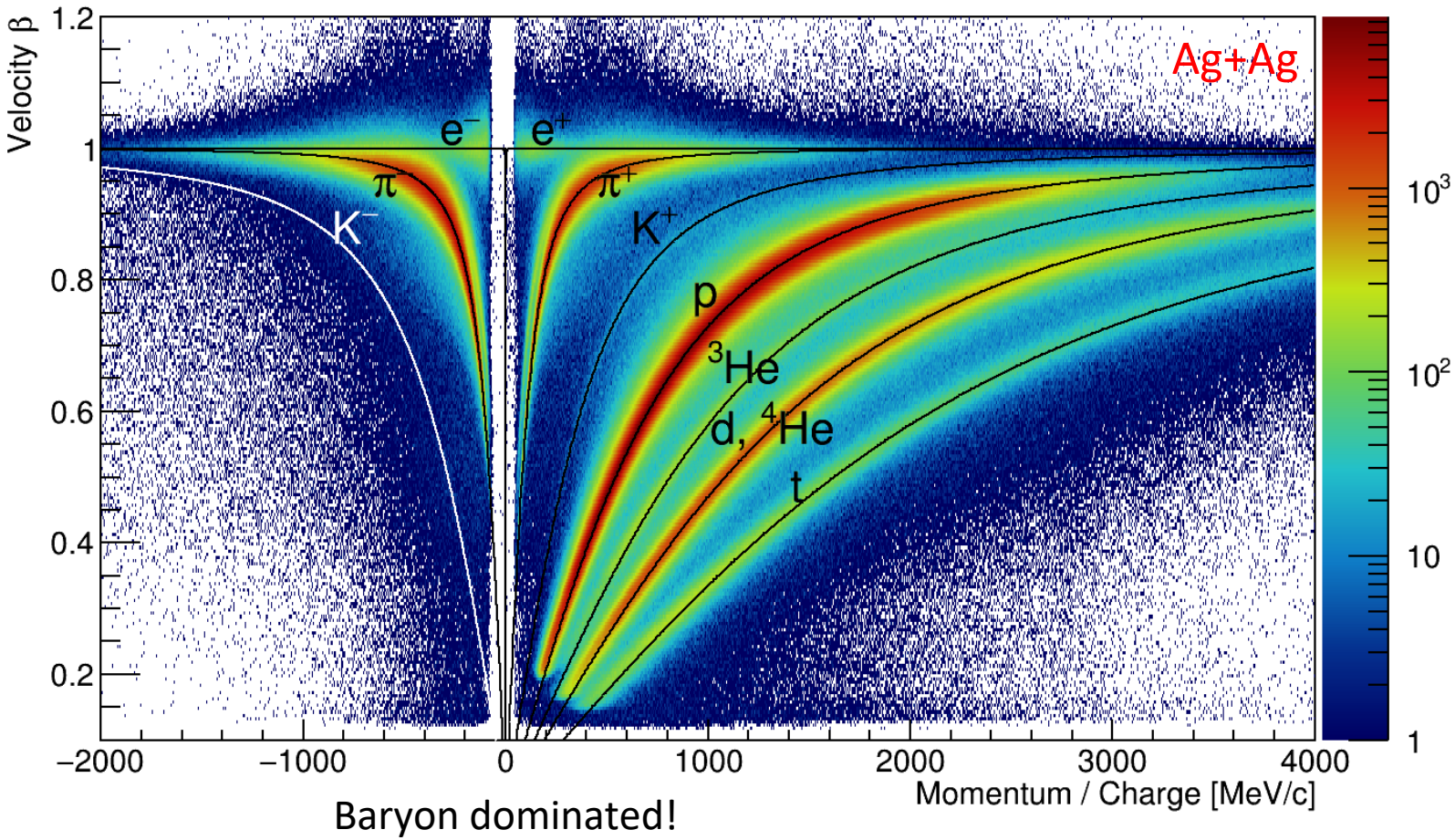
- Fixed target experiment at SIS18 (GSI, Germany)
- Magnet spectrometer
- Low mass Mini-Drift-Chambers (MDCs)
- Time of flight walls RPC and ToF
- RICH and ECAL for e^+e^- and photon identification
- Forward hodoscope for spectators detection



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

The HADES Experiment

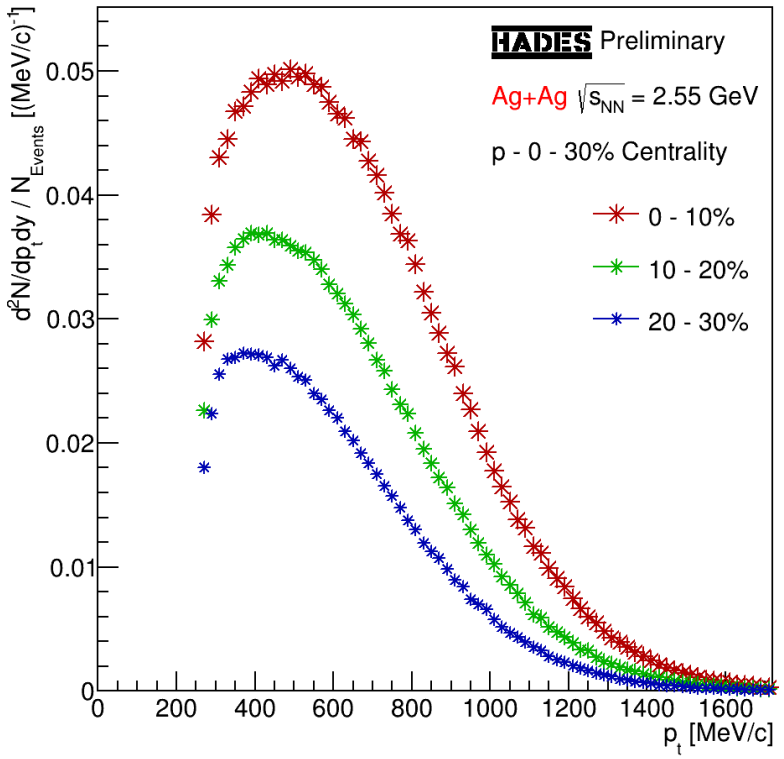
- PID primarily via. momentum and velocity
  - Separation of multiple charged particles via. specific energy loss
- Heavy-ion beamtimes:
  - 2012: Au(1.23A GeV)+Au
    $\sqrt{s_{NN}}$ = 2.42 GeV
    7 billion events
  - 2019: Ag(1.58A GeV)+Ag
    $\sqrt{s_{NN}}$ = 2.55 GeV
    14 billion events

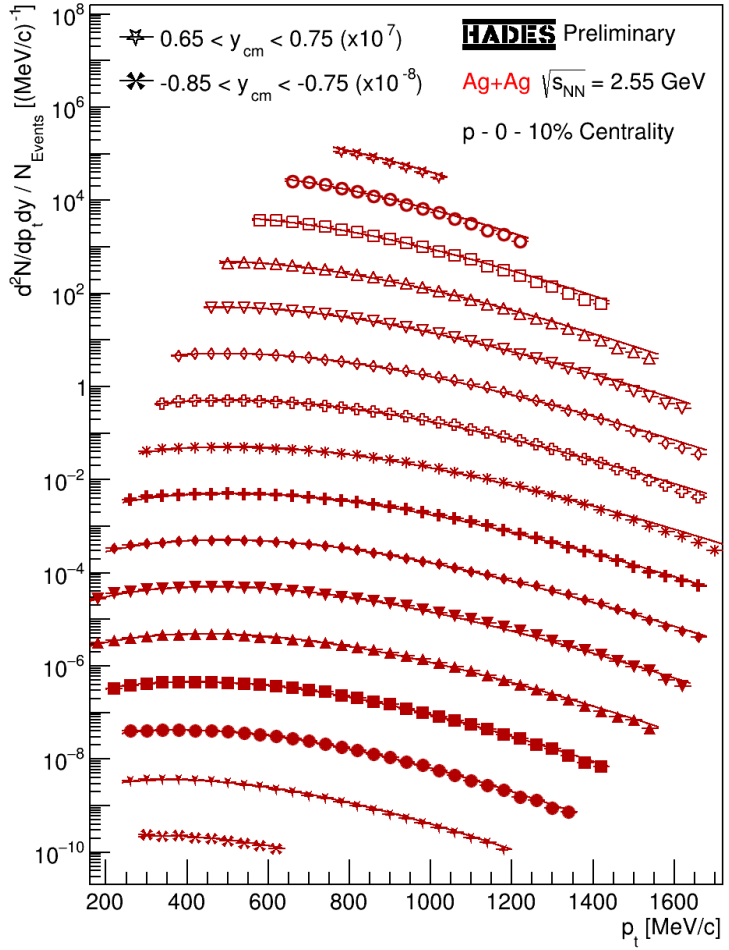


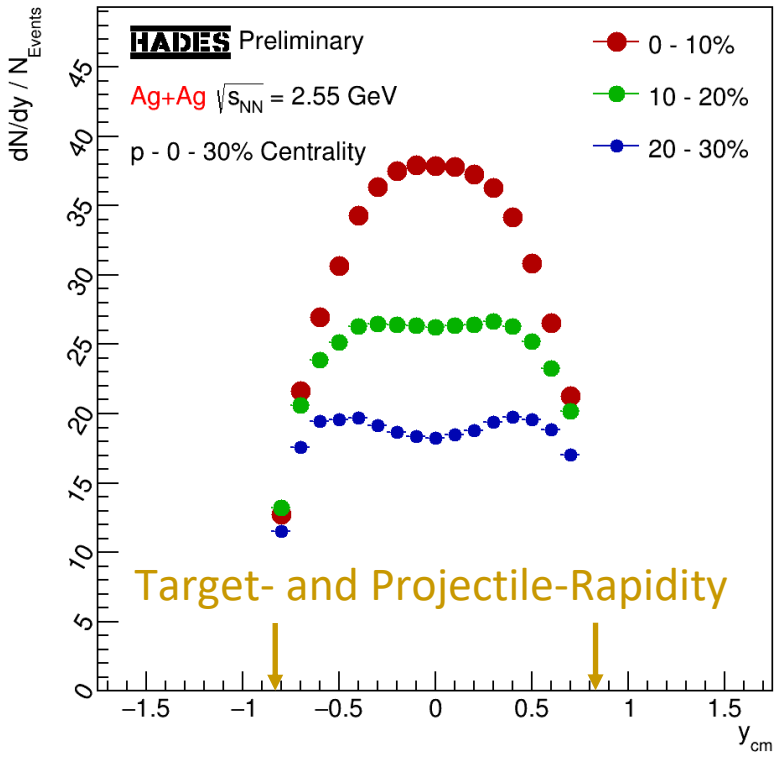
Charged Particles

Analysis of Protons, Light Nuclei and Pions

Protons: Yield and Kinematic Distributions







- Large phase space coverage with small statistical and systematic errors

- 0-10%: Nucleons almost stopped
- 10-30%: Nucleons not stopped and contaminated with spectators

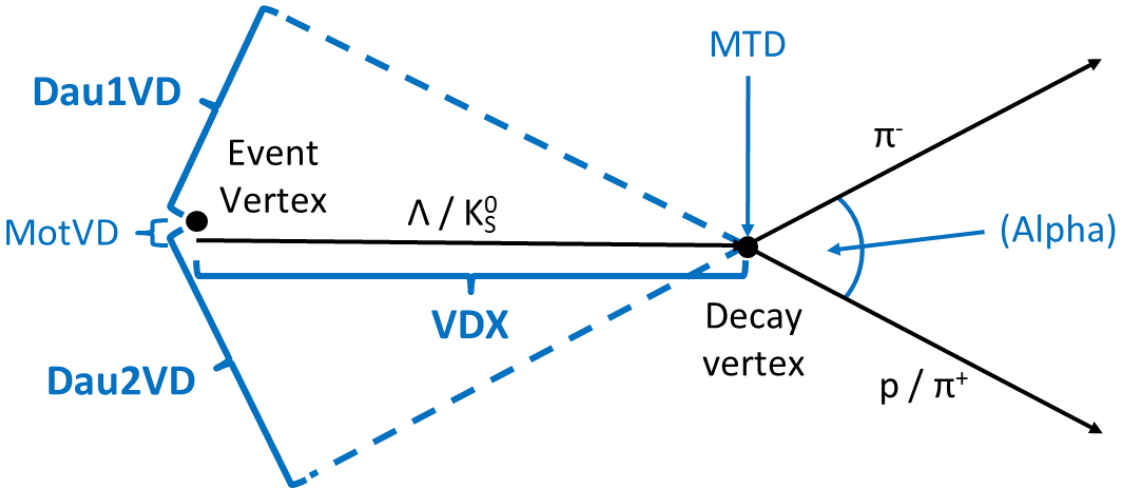
Weak Decays

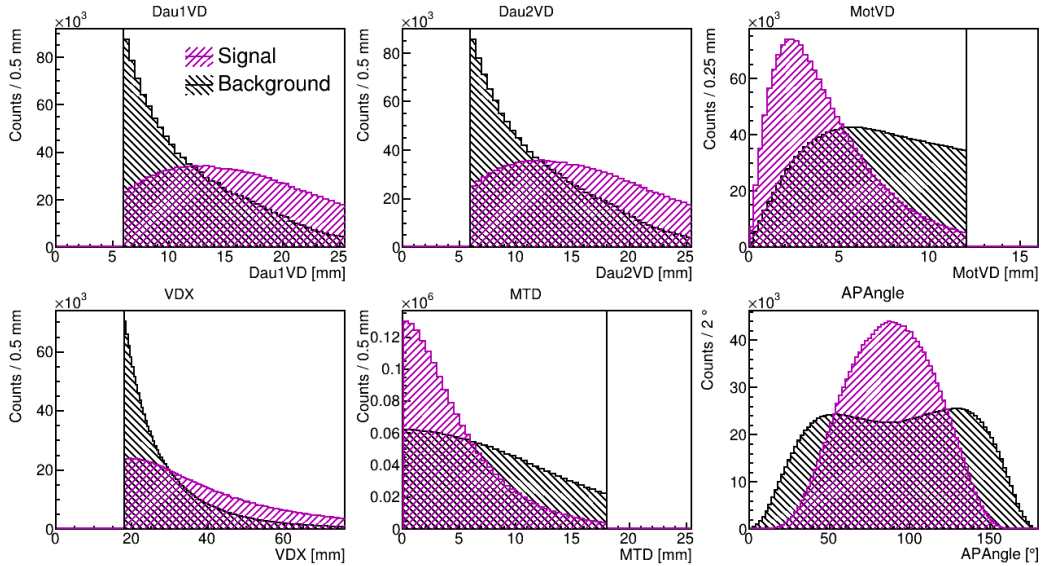
Reconstruction and Analysis of weakly decaying Hadrons

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

- Combinatorial background about factor 10,000 above signals
- Long lifetimes → Off-vertex-topology
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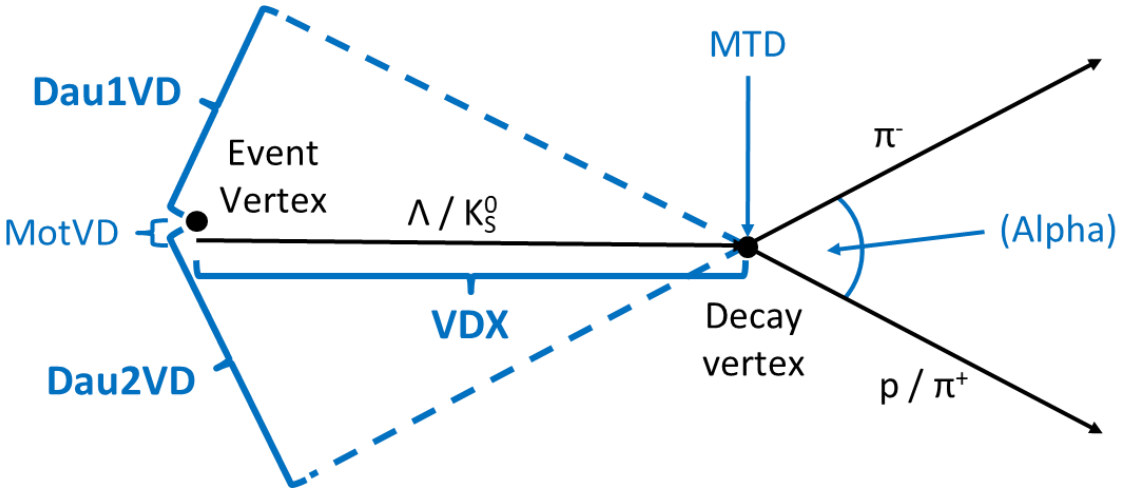
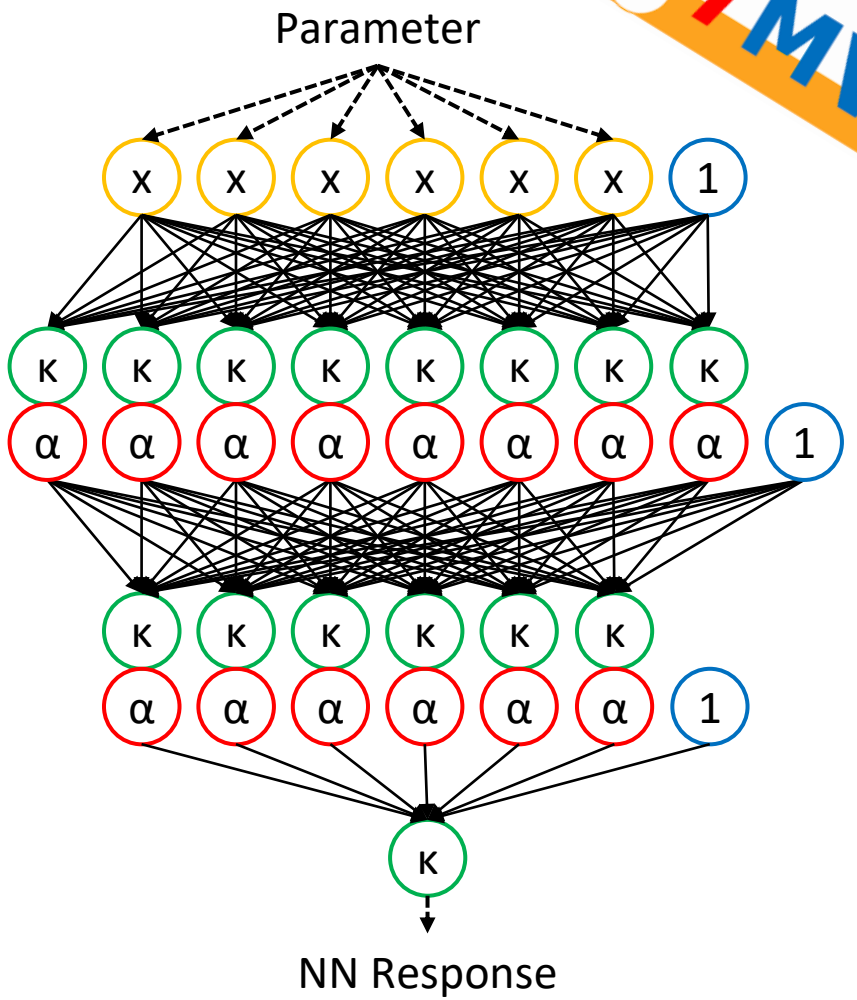
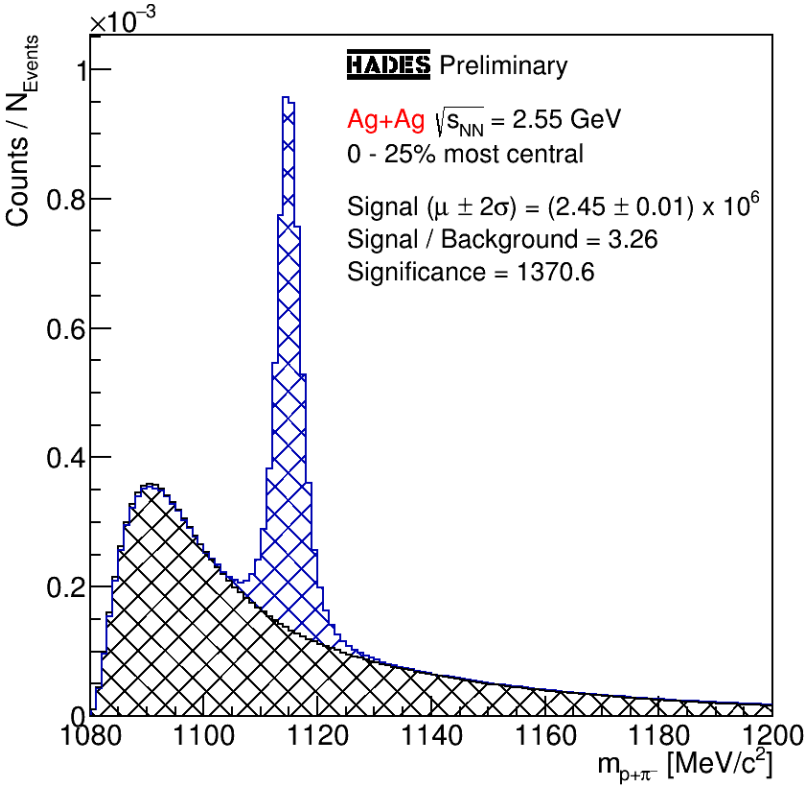
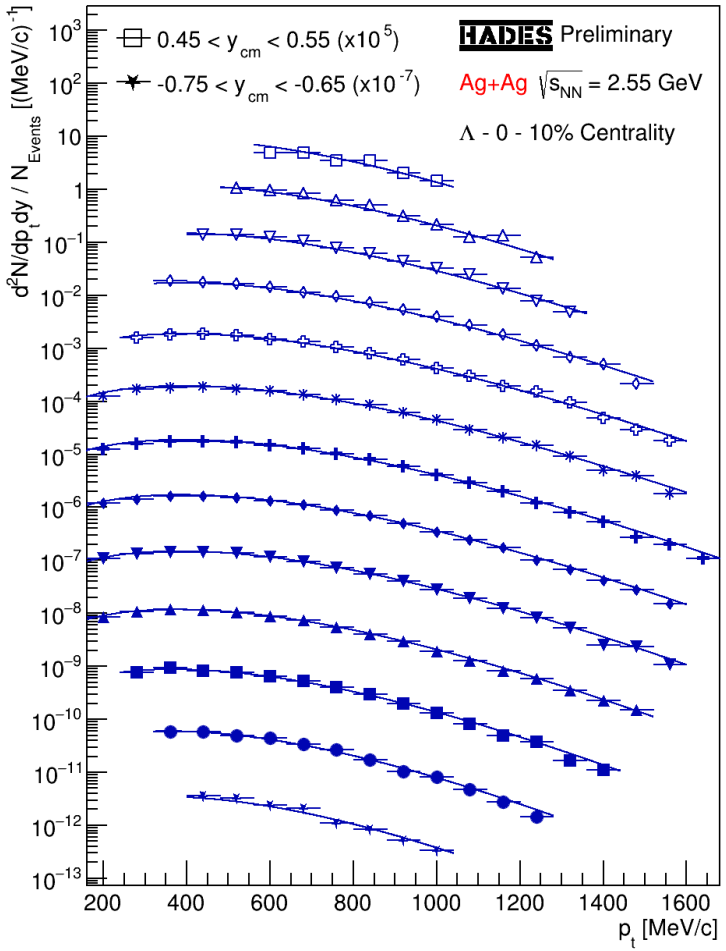
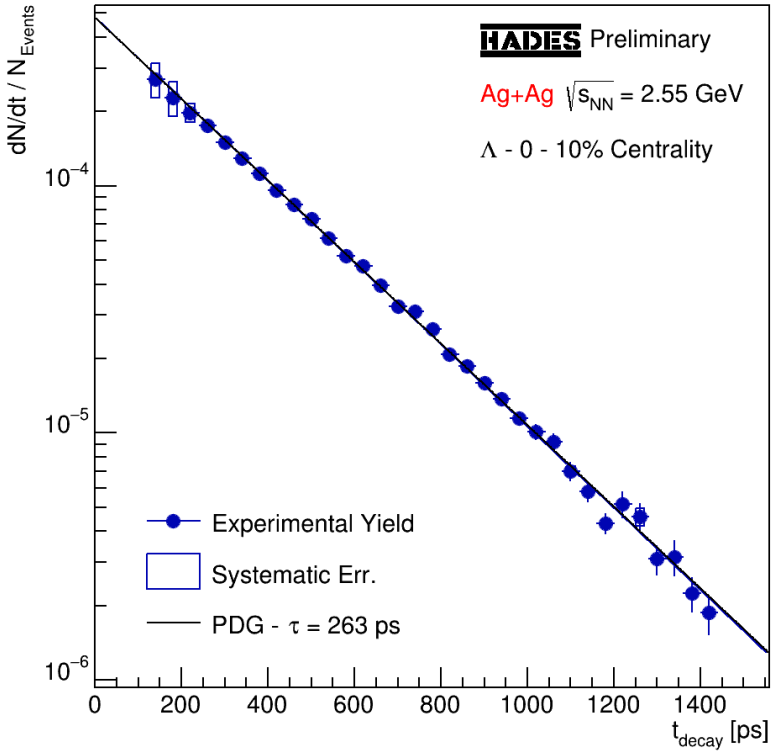




Reconstruction and Analysis of Λ Hyperons



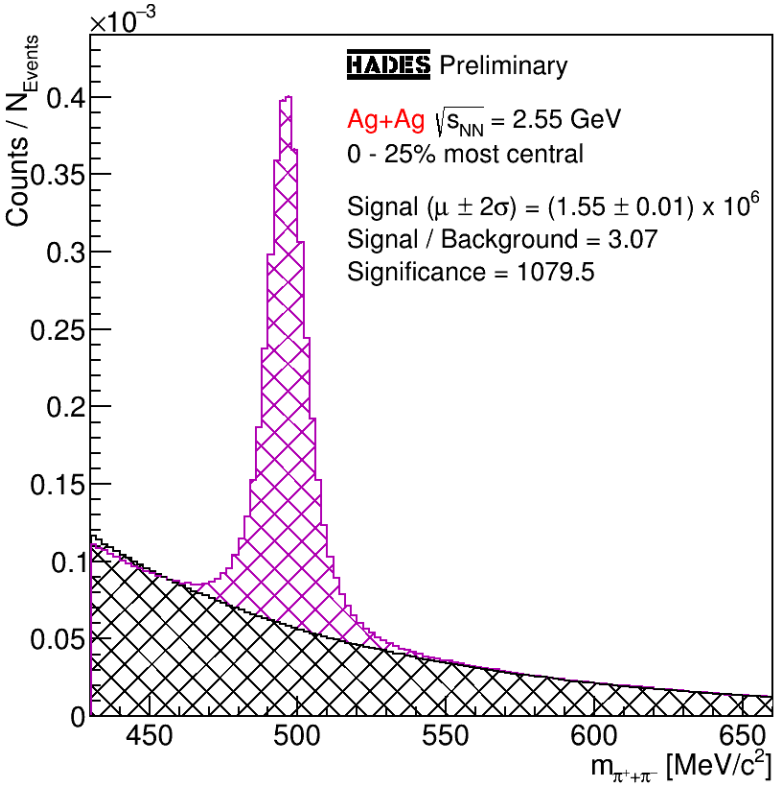




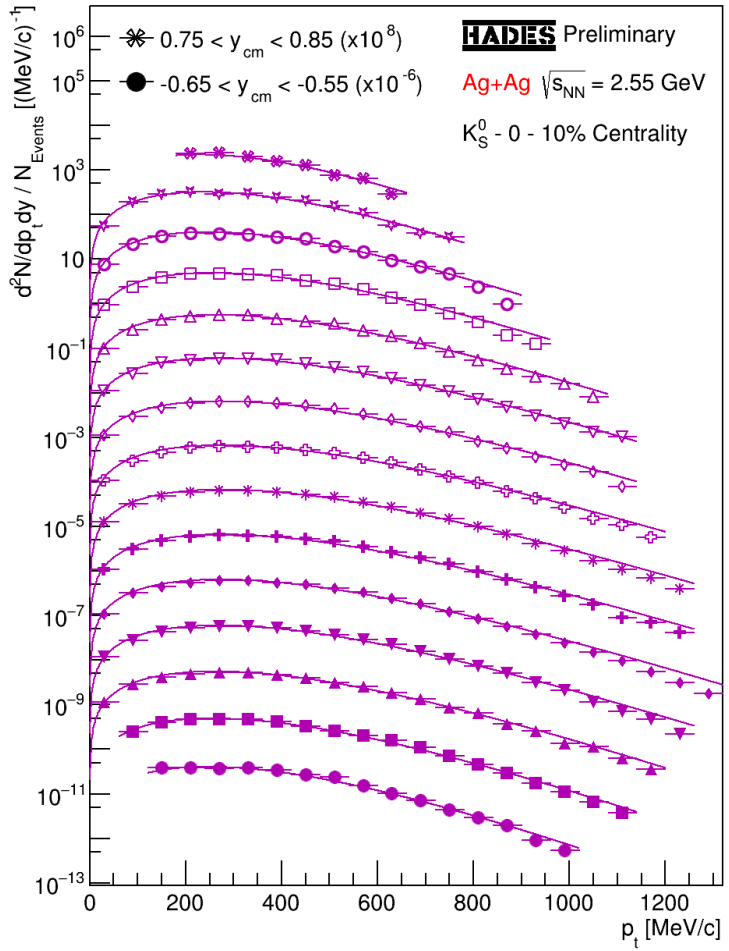
- Very significant signal
- Detailed analyses of hyperon production possible

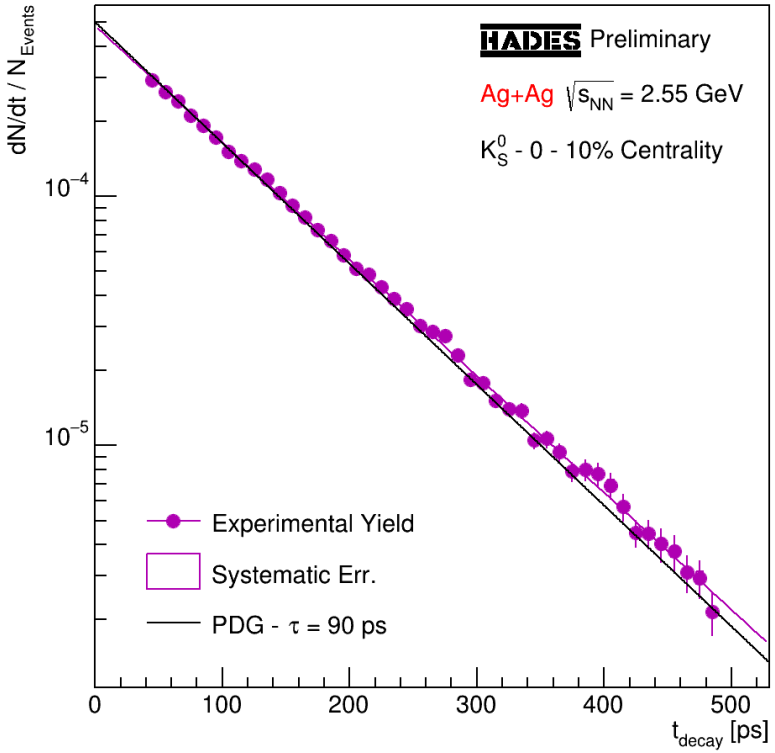
- Lifetime measurement as test-case
- Result of (262 ± 2 ± 3) ps compatible with PDG value

Reconstruction and Analysis of K^0_S Mesons



- Very significant signal
- Detailed analyses of strange meson production possible





- Lifetime measurement as test-case
- Result of (92 ± 1 ± 1) ps compatible with PDG value

Hypernuclei

Reconstruction and Analysis of Hypernuclei

Hypernuclear Properties

The Hypertriton – ${}^{3}_{\Lambda}$H

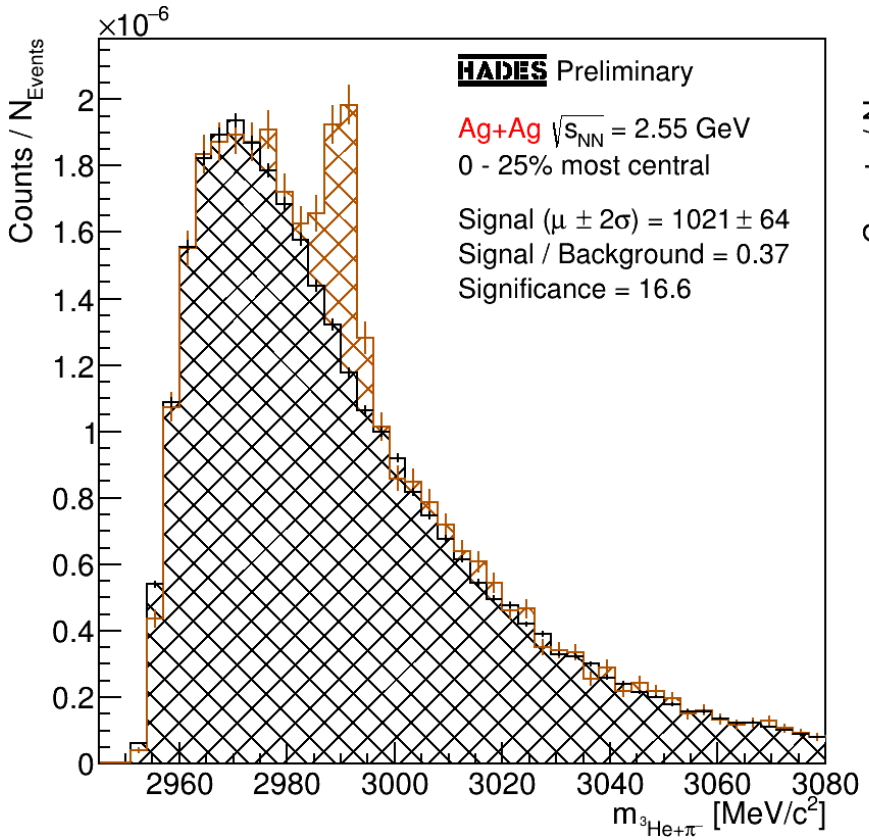
- Mass of ≈ 2991 MeV/c^2
  - Binding energy B(${}^{3}_{\Lambda}$H) ≈ 0.79 MeV/A
- Primarily four mesonic decay channels:
  - **${}^{3}_{\Lambda}$H → ^{3}He + π^- (BR ≈ 27%)**
  - ${}^{3}_{\Lambda}$H → t + π^0 (BR ≈ 13%)
  - ${}^{3}_{\Lambda}$H → d + p + π^- (BR ≈ 40%)
  - ${}^{3}_{\Lambda}$H → d + n + π^0 (BR ≈ 20%)
- Lightest known hypernucleus
- Current World-Average Lifetime: (211 ± 9) ps

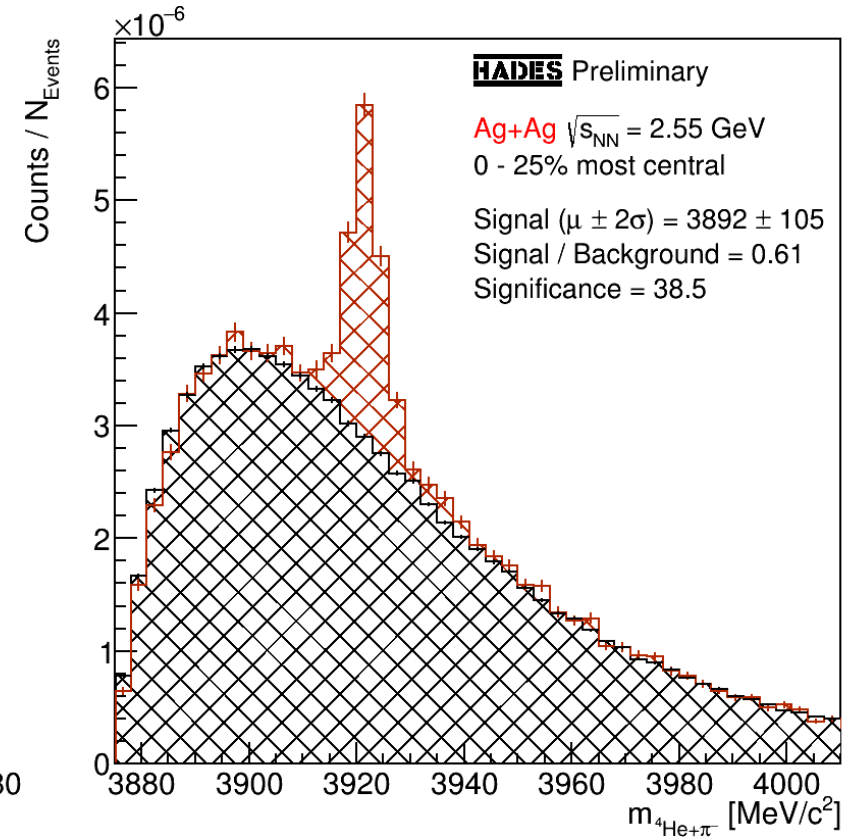
The Hyperhydrogen4 – ${}^{4}_{\Lambda}$H

- Mass of ≈ 3923 MeV/c^2
  - Binding energy B(${}^{4}_{\Lambda}$H) ≈ 2.63 MeV/A
    → ≈ 3.3 B(${}^{3}_{\Lambda}$H)
- Primarily three mesonic decay channels:
  - **${}^{4}_{\Lambda}$H → ^{4}He + π^- (BR ≈ 50%)**
  - ${}^{4}_{\Lambda}$H → t + p + π^- (BR ≈ 33%)
  - ${}^{4}_{\Lambda}$H → t + n + π^0 (BR ≈ 17%)
- Compared to the ${}^{3}_{\Lambda}$H higher binding energy and BR of the two-body decay channel
- Current World-Average Lifetime: (218 ± 5) ps

Hypernuclei from Ag(1.58A GeV)+Ag

- Reconstruction method developed for Λ and K^0_S applied conversely
- Significant signals in the two-body-decay channels
- Three-body-decay channels more challenging due to increased combinatoric background

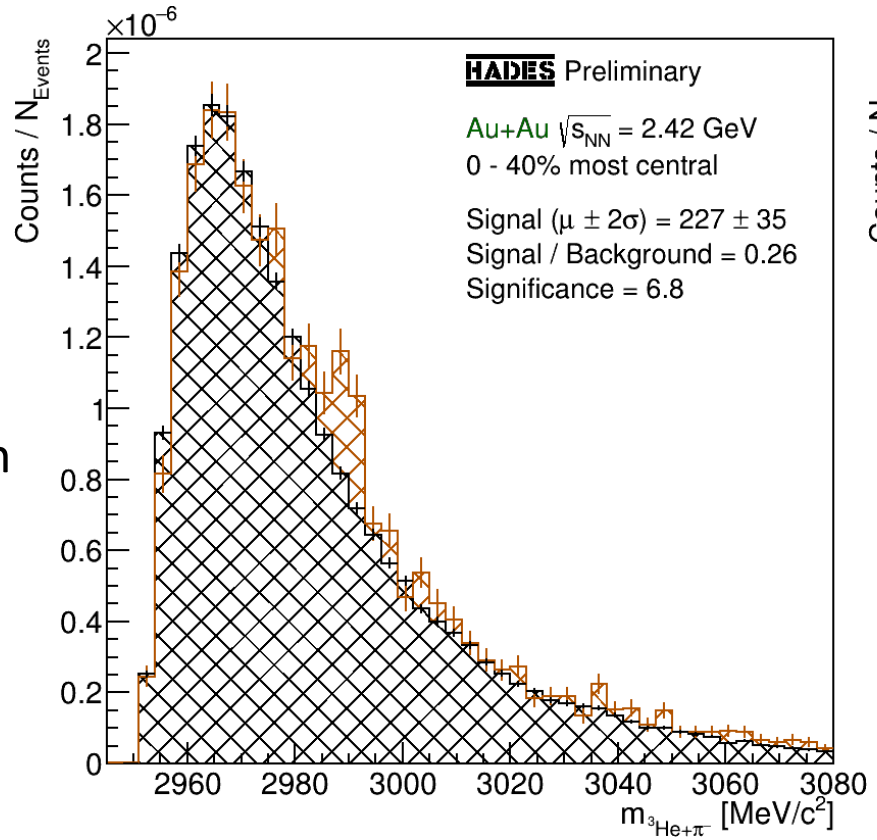


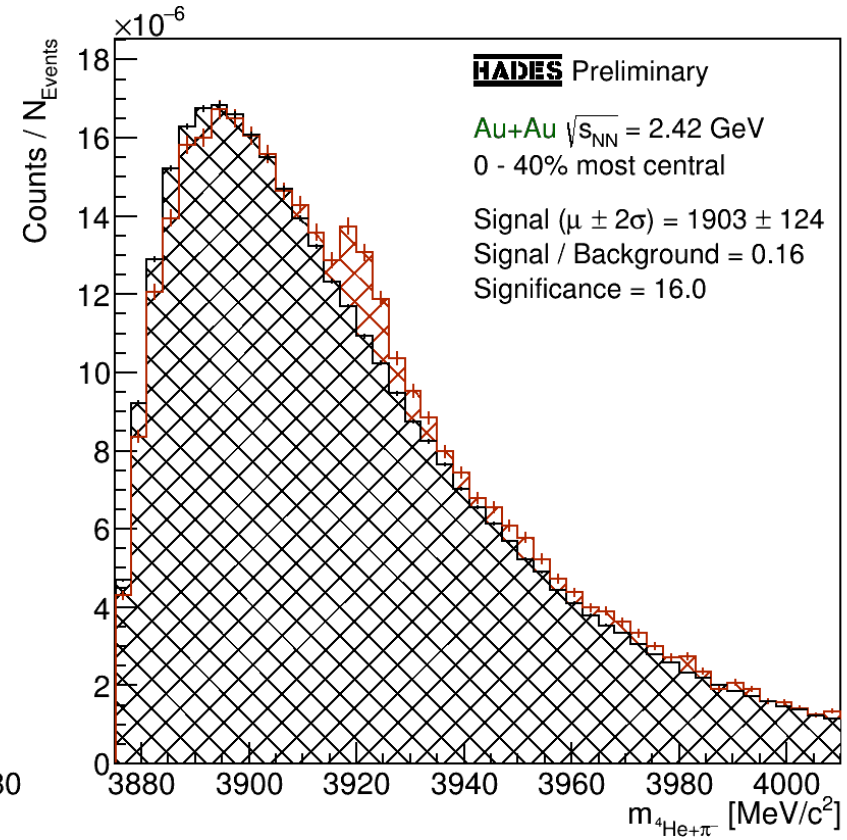


- Multi-differential analysis of Hypernuclei production possible

New: Hypernuclei from Au(1.23A GeV)+Au

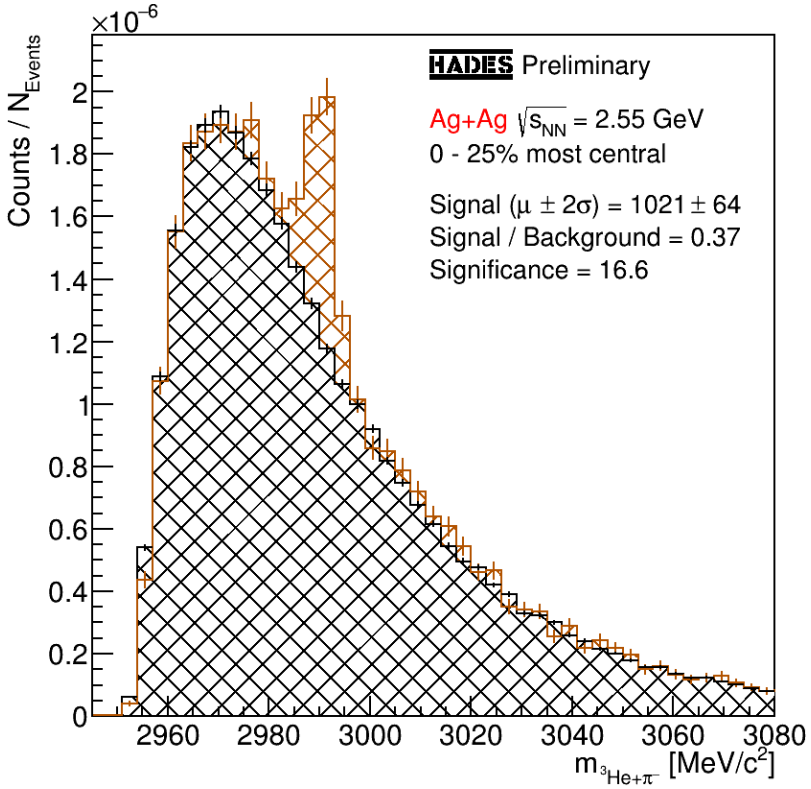
- Au(1.23A GeV)+Au data reanalyzed
- Prior only estimation of upper production rate limit possible
- Improved reconstruction method applied
- Lowest energy at which Hypernuclei were ever reconstructed in Heavy-ion collisions

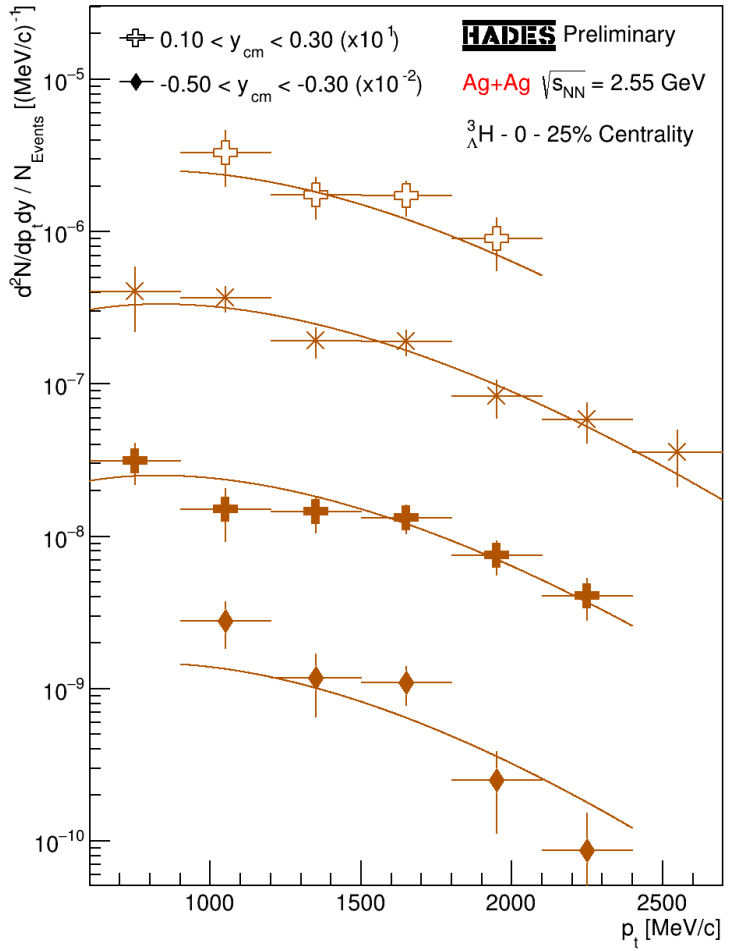


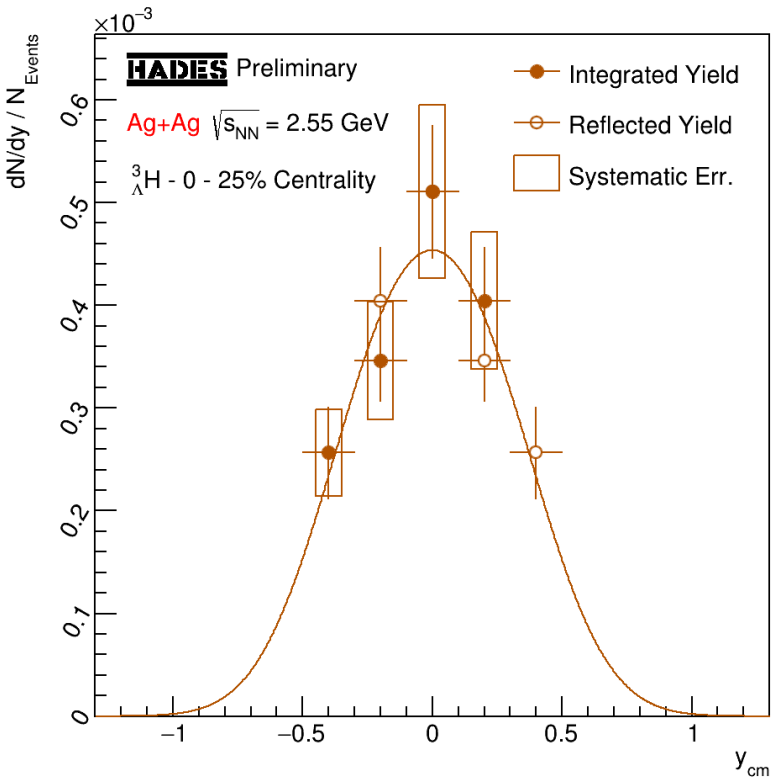


- In case of the ${}^{4}_{\Lambda}$H sufficient statistics to analyze the production differentially

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



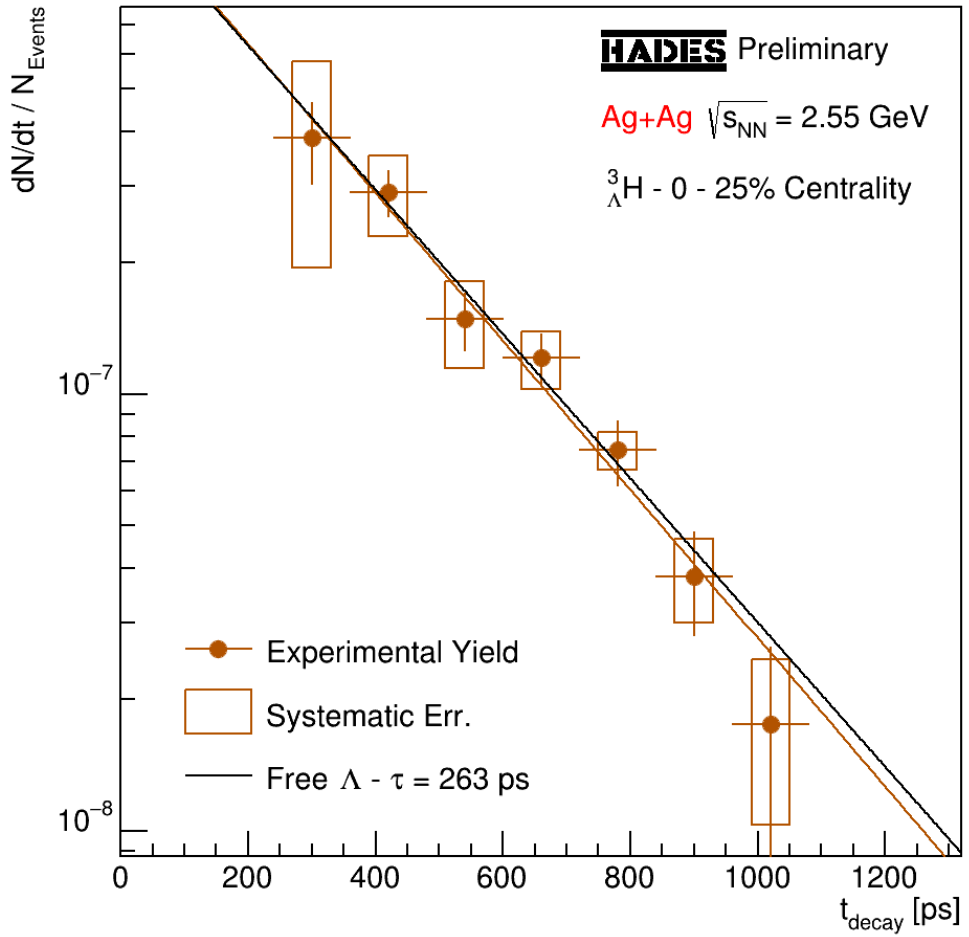




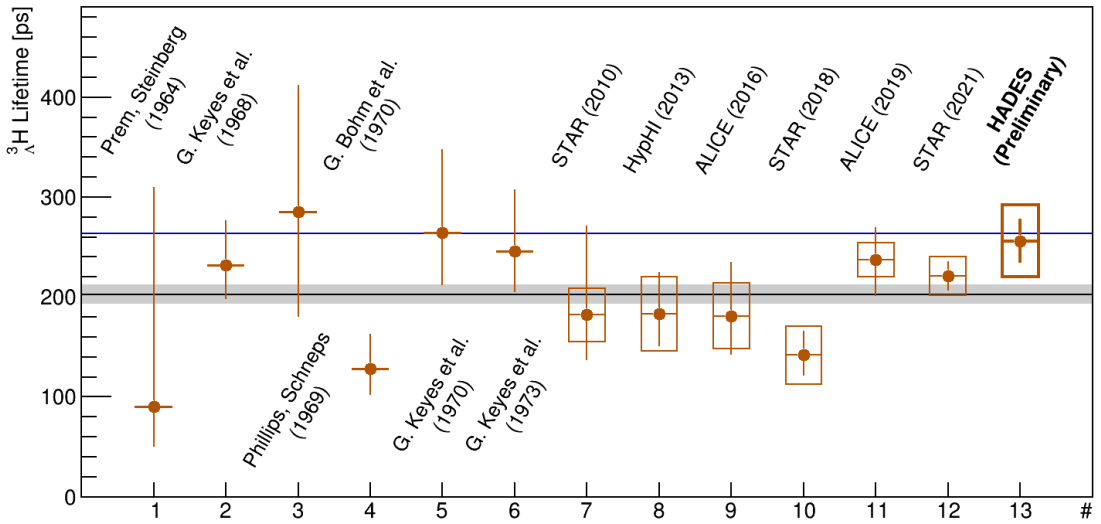
- Significant signal
- Multi-differential analysis of ${}^{3}_{\Lambda}\mathrm{H}$ production possible

- **First measurement at mid-rapidity at this energy**
- Systematic studies ongoing

${}^{3}_{\Lambda}$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 (256 ± 22 ± 36) ps compatible with free Λ lifetime measured
- Further uncertainty analyses required



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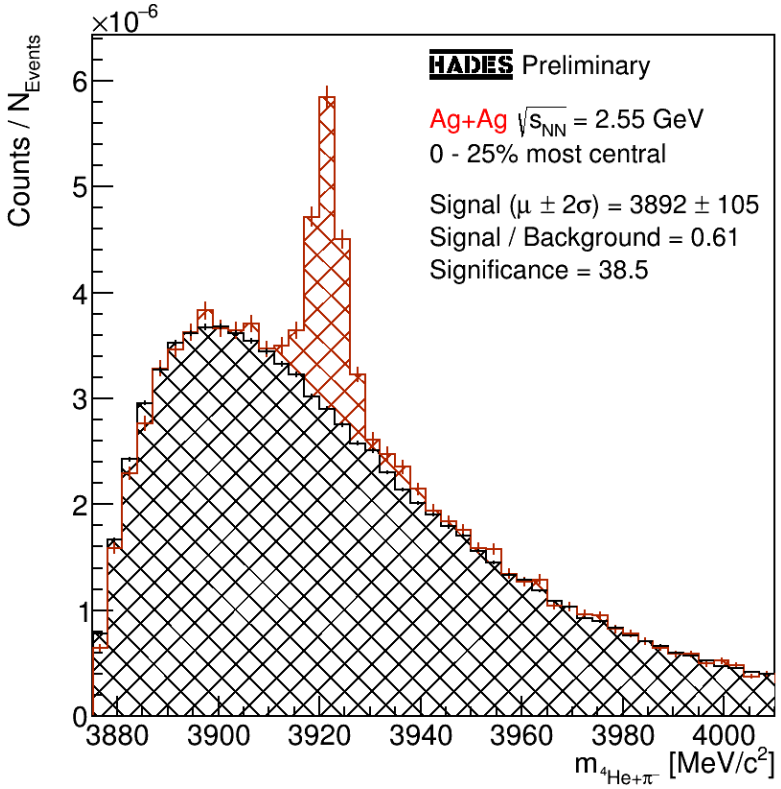

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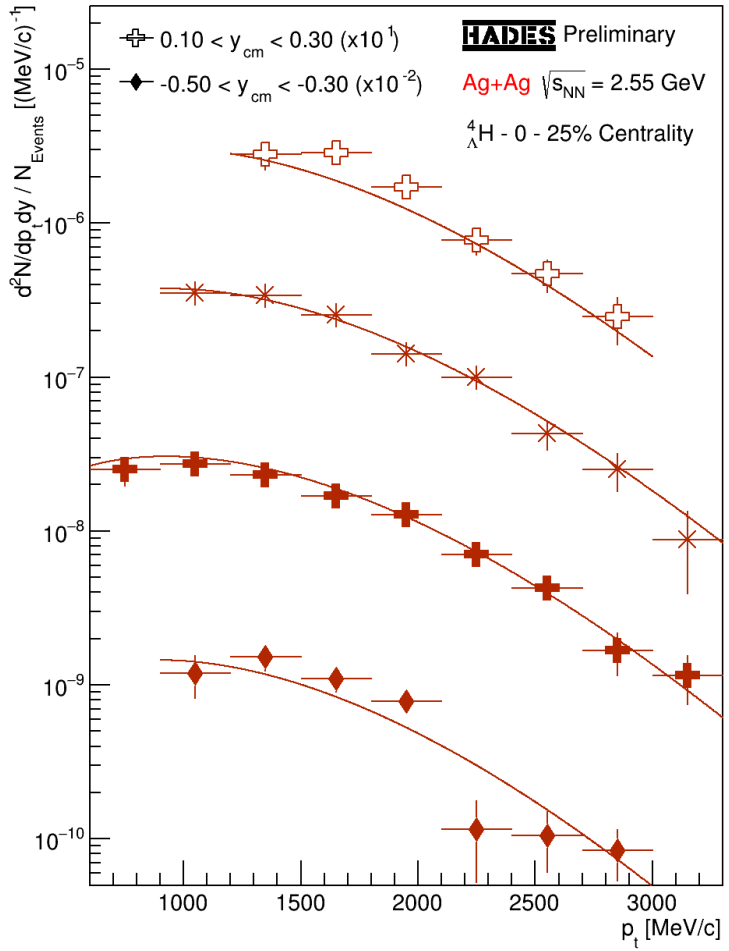

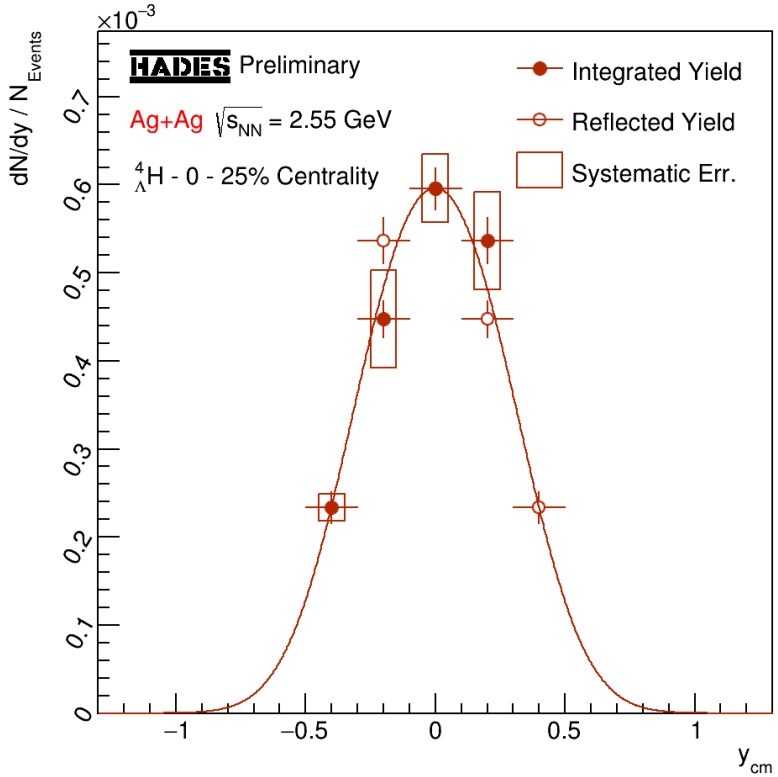

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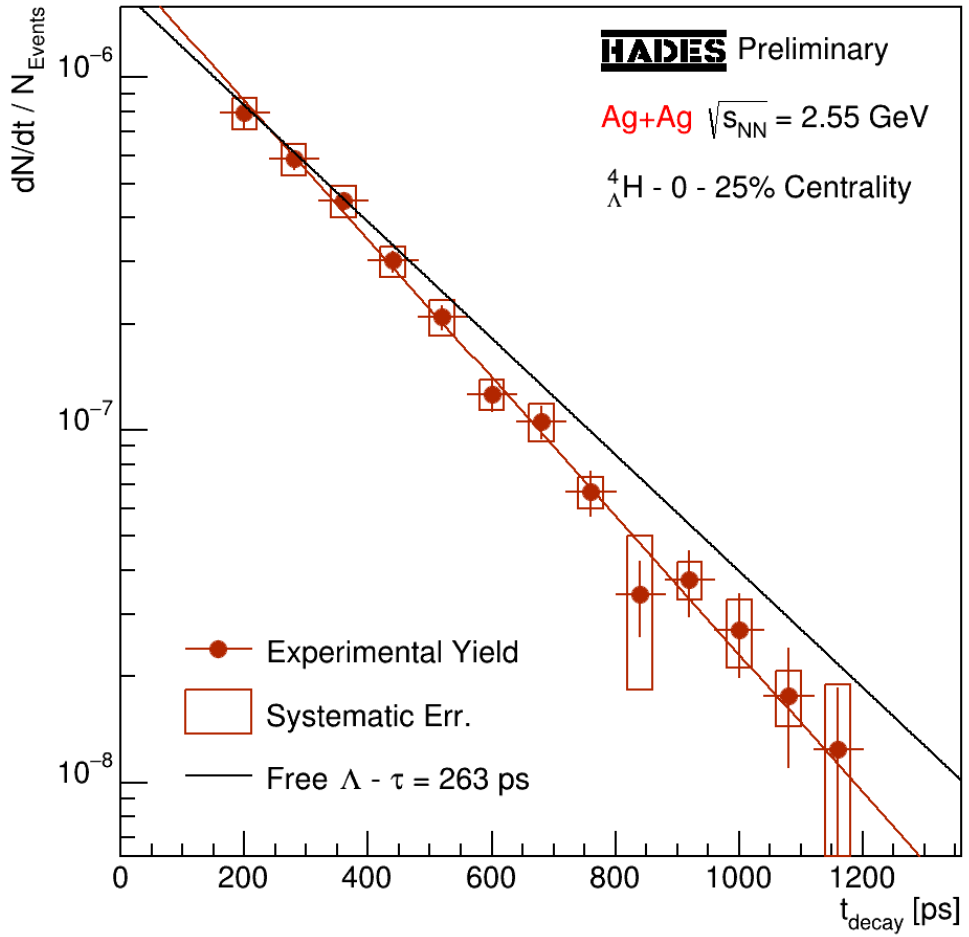
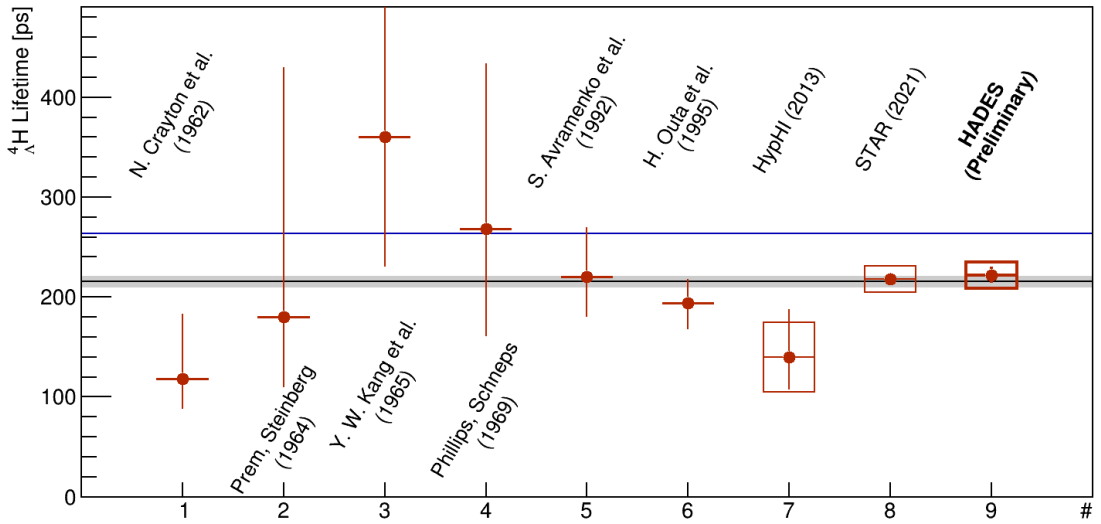
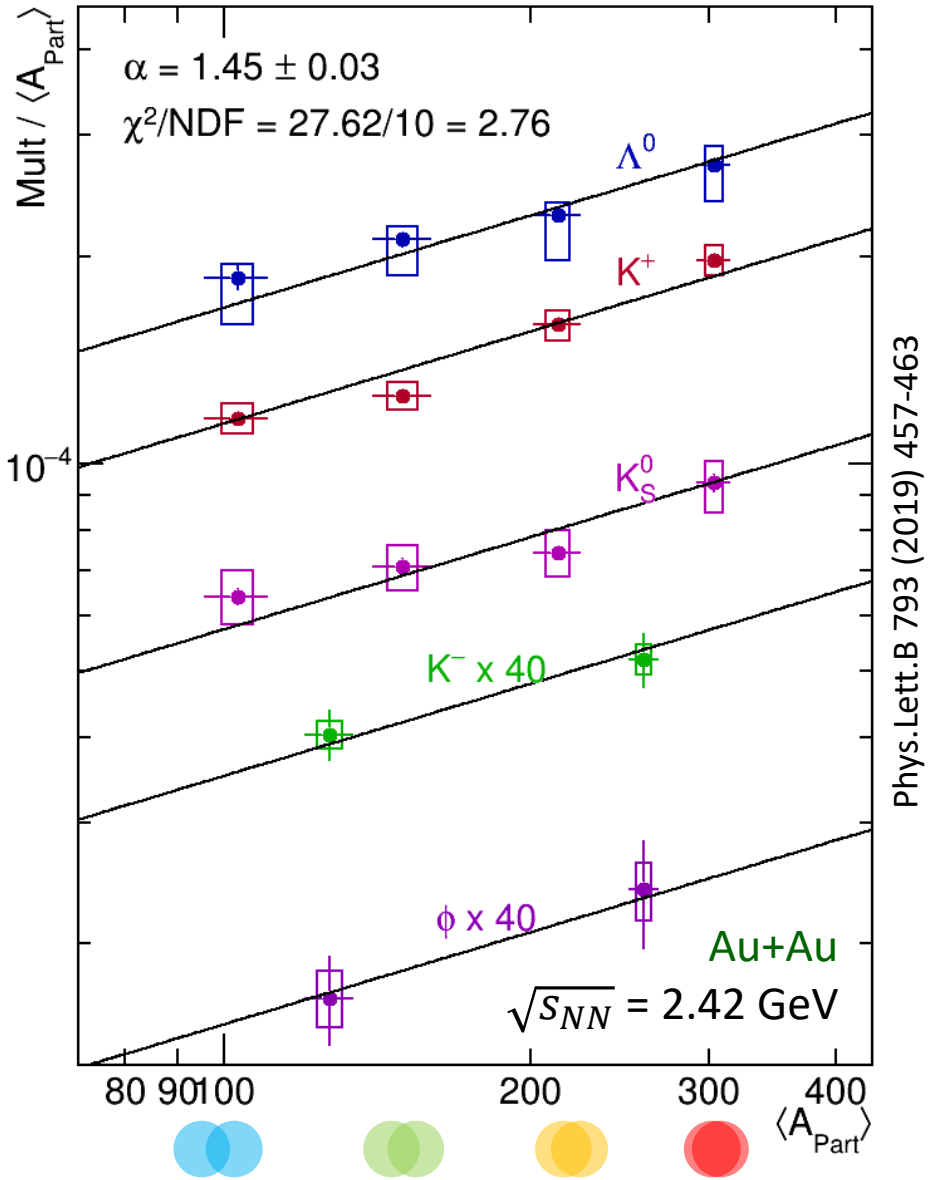


- ${}^{4}_{\Lambda}$H Lifetime measurement to contribute to world data on Hypernuclei lifetimes
- Lifetime of (222 ± 8 ± 13) ps compatible with earlier measurements measured
- Further uncertainty analyses required



Strange Yields vs. $\langle A_{Part} \rangle$

- Production below (at) free NN-threshold:
  N + N → Y + K + N: $\sqrt{s}$ = 2.55 GeV
  N + N → K + $\overline{K}$ + N + N: $\sqrt{s}$ = 2.86 GeV
  - Energy provided by the system
- Strange hadron yields scale similar with $\langle A_{Part} \rangle$:
  Mult ~ $\langle A_{Part} \rangle^{\alpha}$ with α_{Au+Au} = 1.45 ± 0.06
  - Hierarchy in production thresholds not reflected
- Scaling with absolute amount of $s\bar{s}$



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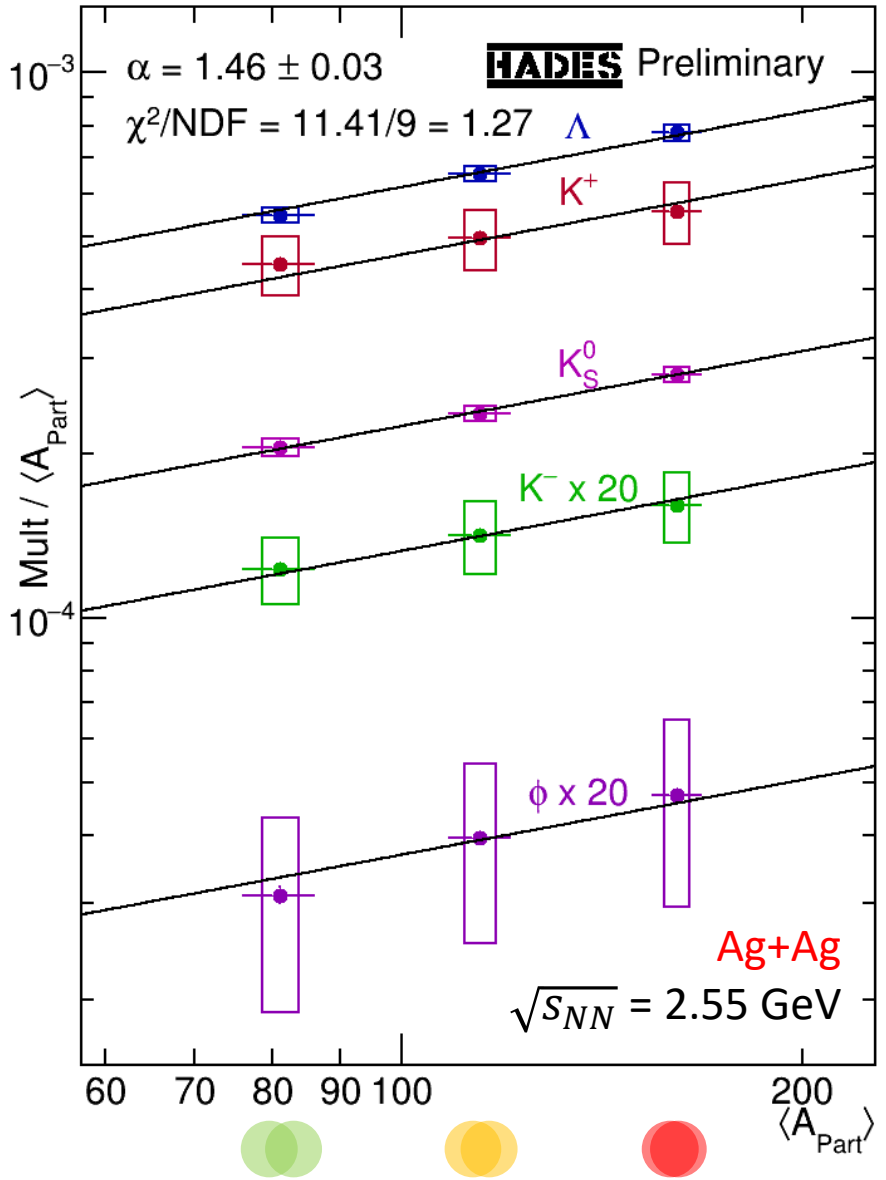
- Ag+Ag slope equal within errors α_{Ag+Ag} = 1.46 ± 0.03
- Further reduction of systematic uncertainties ongoing



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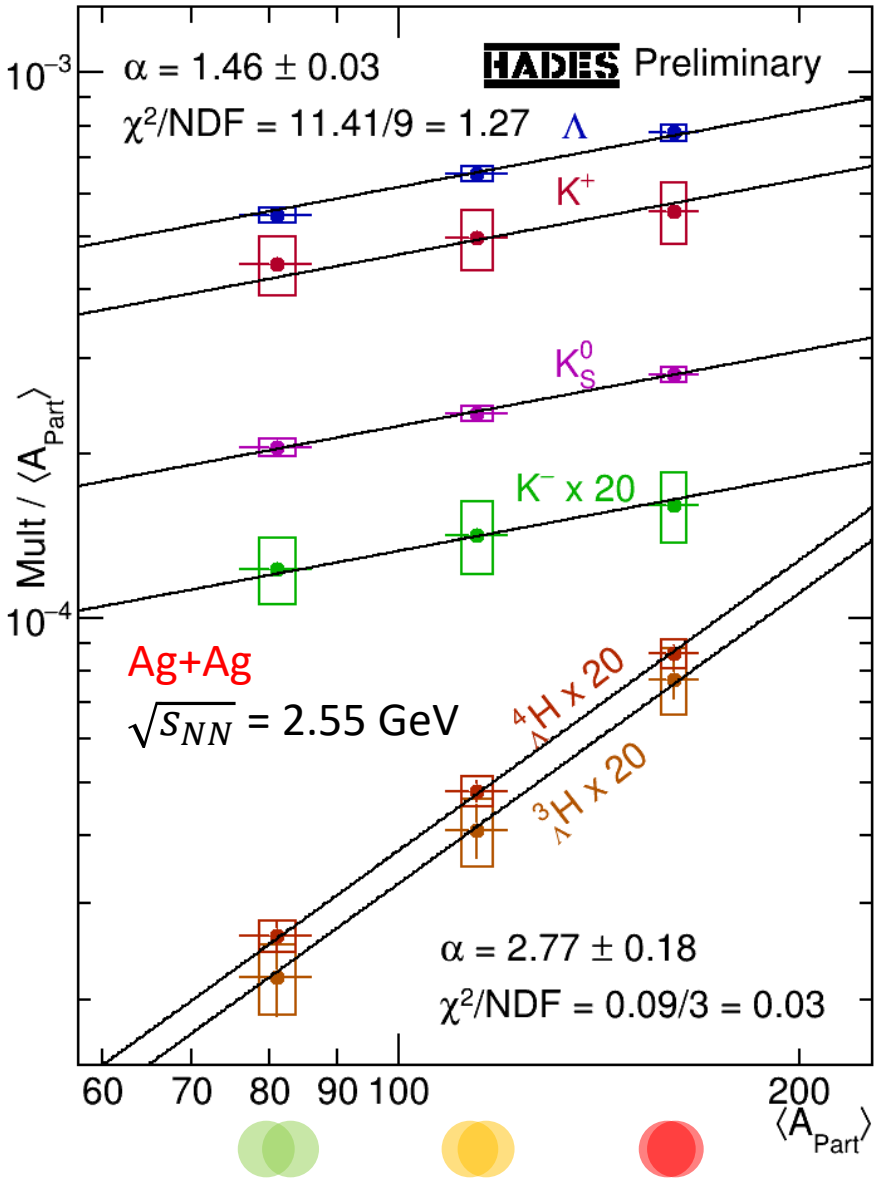
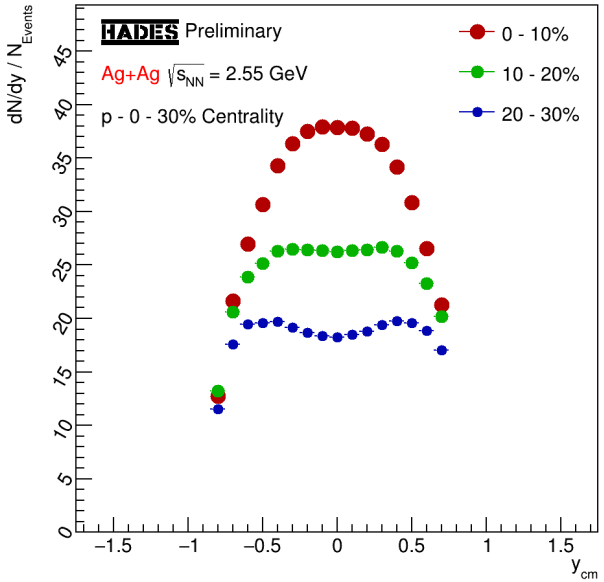
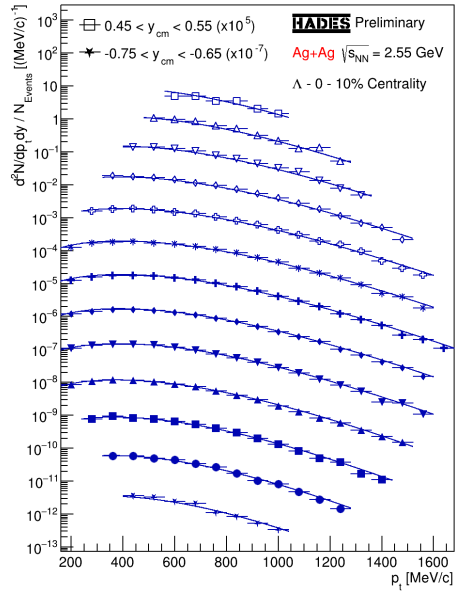
  - Energy provided by the system
- Strange hadron yields scale similar with $\langle A_{Part} \rangle$:
  Mult ~ $\langle A_{Part} \rangle^{\alpha}$ with α_{Au+Au} = 1.45 ± 0.06
- Ag+Ag slope equal within errors α_{Ag+Ag} = 1.46 ± 0.03
- ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Hypernuclei scale also with similar but significantly steeper slope of α_{Hyp} = 2.77 ± 0.18
  - Reflects the increased availability of nucleons in more central collisions

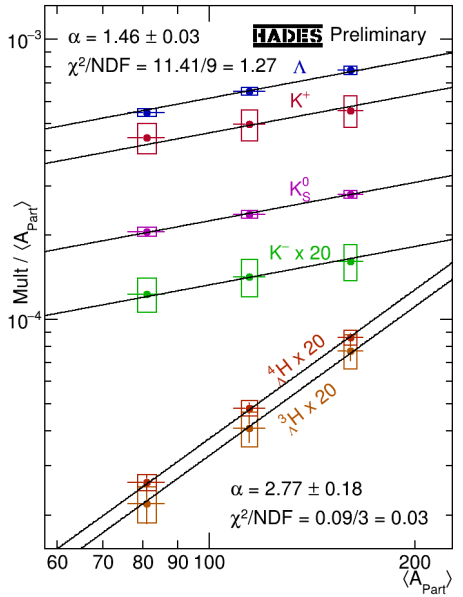


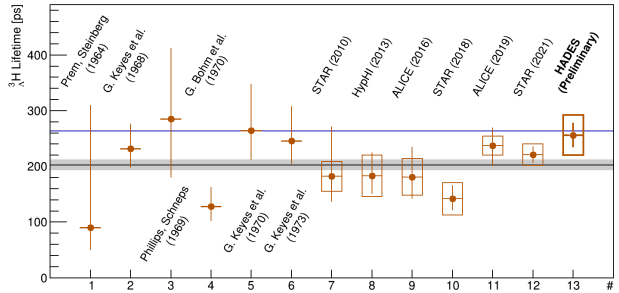
Summary

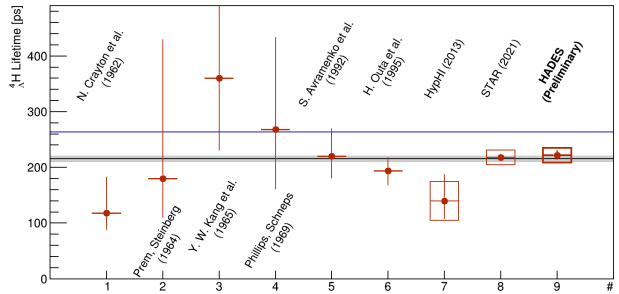
- HADES detector upgraded with FAIR technology (ECAL, RICH, STS1,2 and fRPC)
- 14 billion Ag(1.58A GeV)+Ag events collected in 2019 run
- Very detailed analyses of bulk particles (Protons, Light Nuclei and Pions)
- High quality analysis of weak decays with an artificial neural network
  - First multi-differential analysis of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H production around mid-rapidity at SIS18 energies
  - Contribution to $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H lifetime measurements





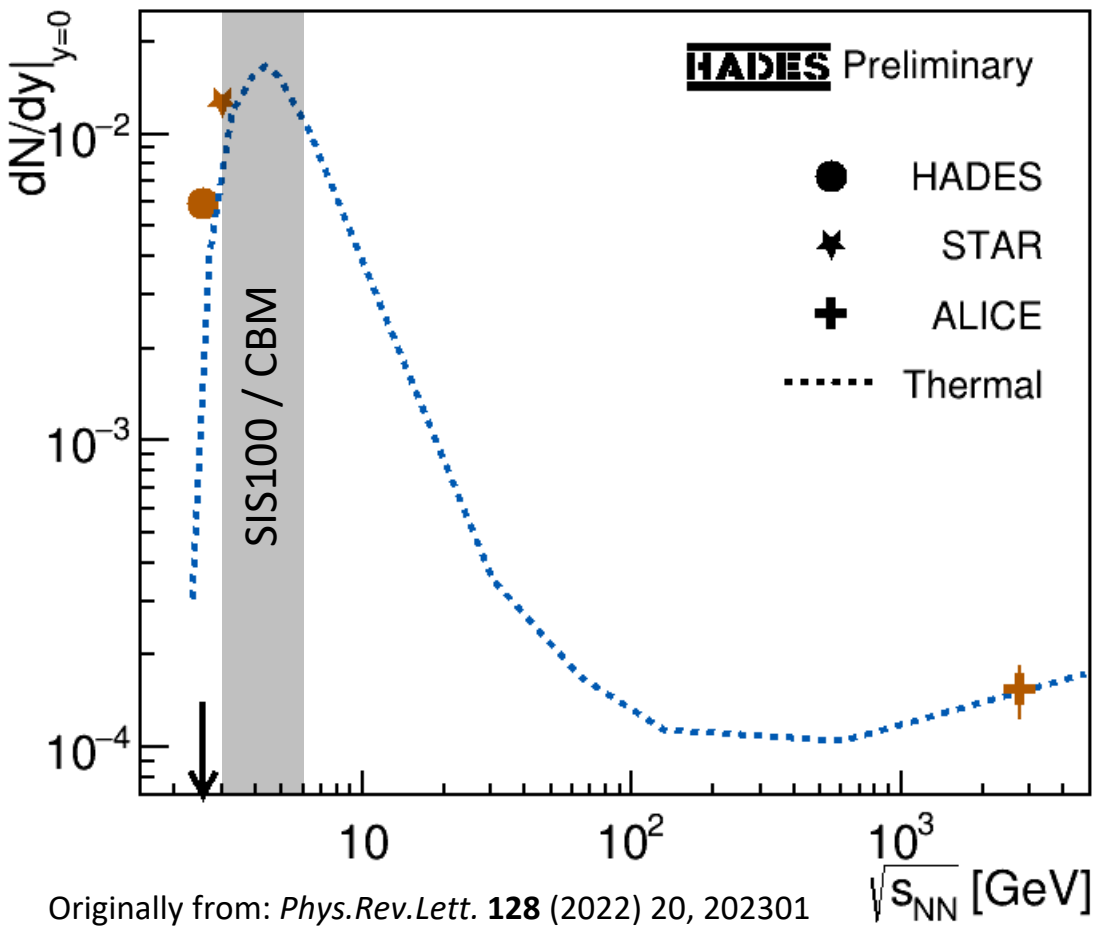






Outlook: Hypernuclei at SIS100 / CBM

- 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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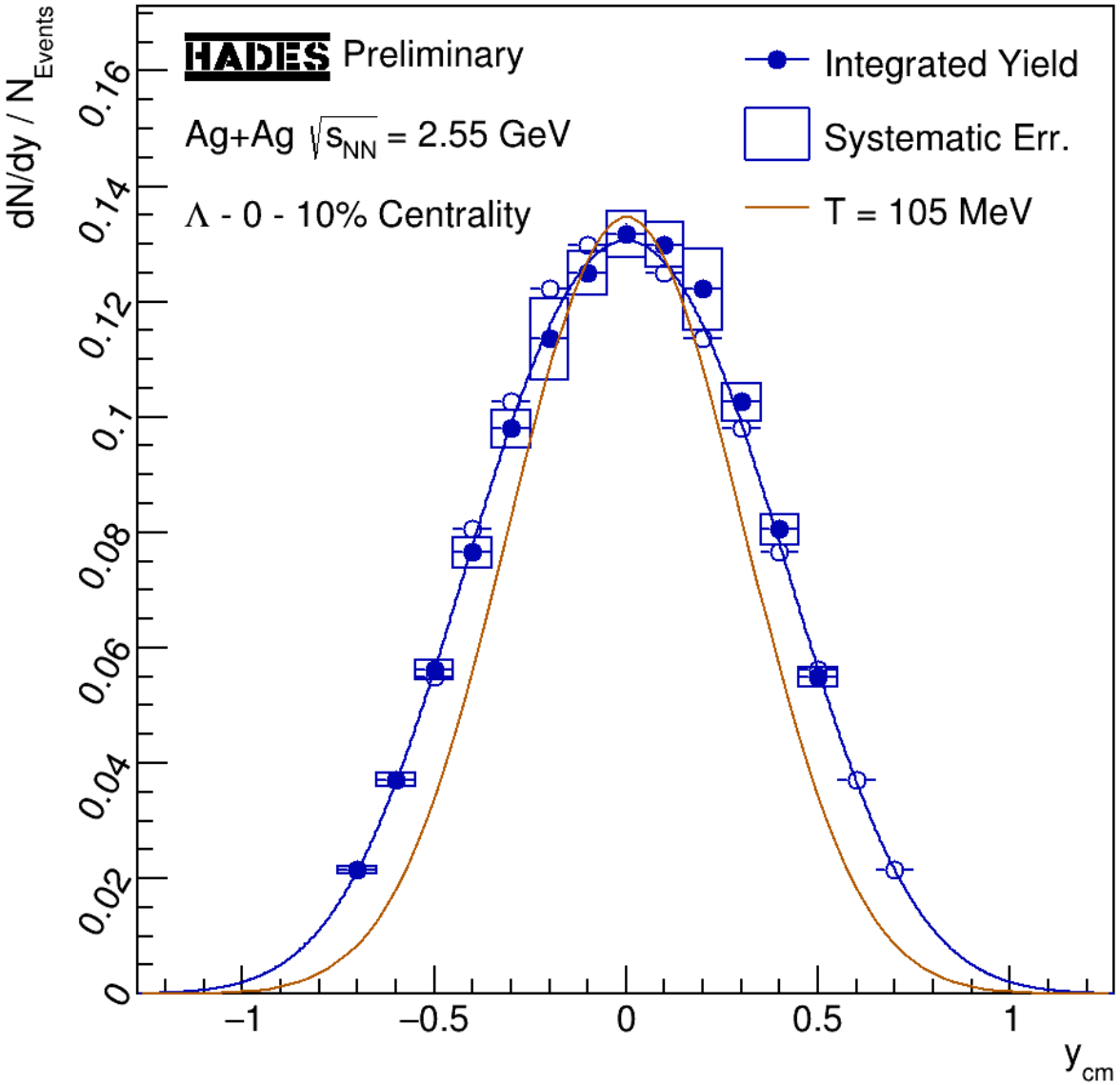
The HADES Collaboration


Thank you
for your
Attention!
1500
1000
500
0
−500
−1000
−1500
−2000
−1500
−1000
−500
0
500
1000
1500
2000

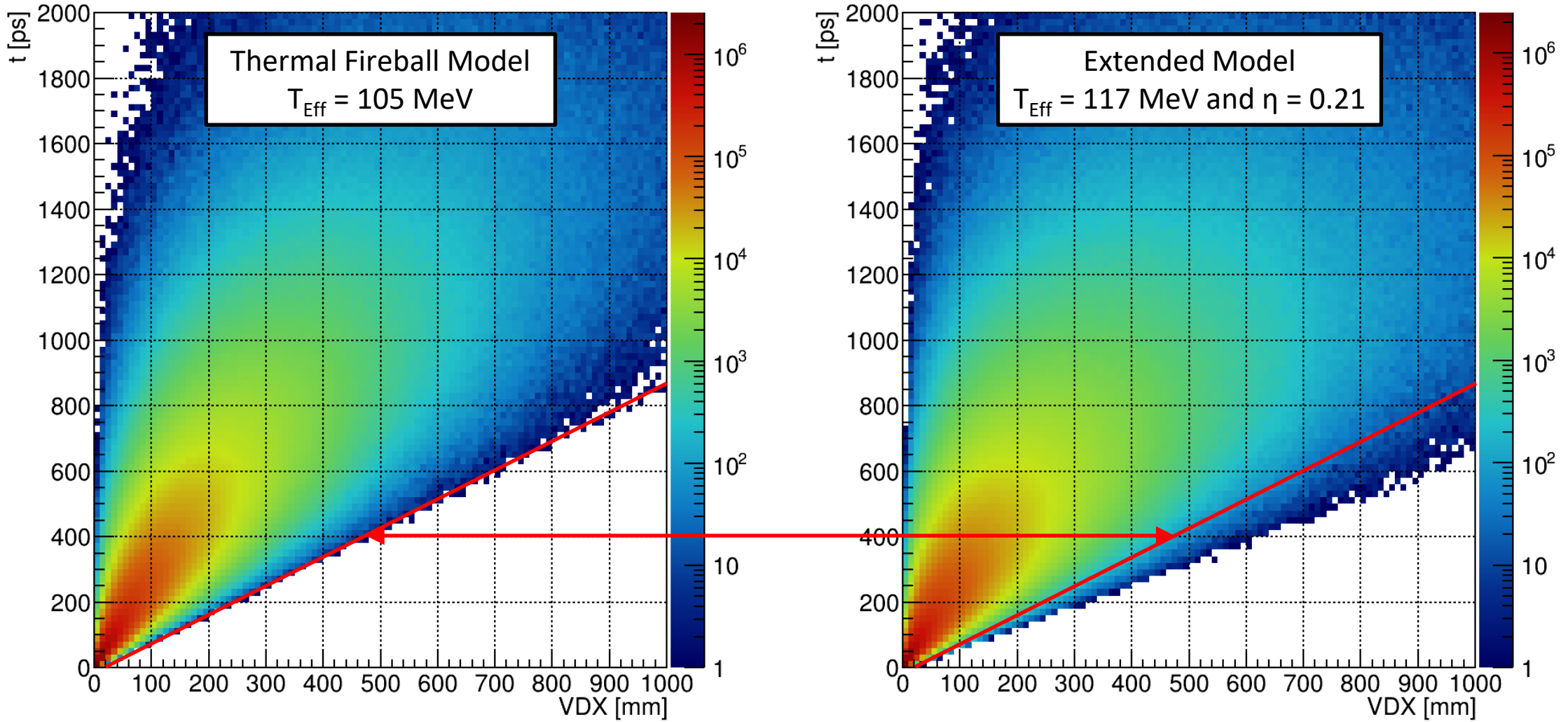
BACKUP

Λ dN/dy Spectrum

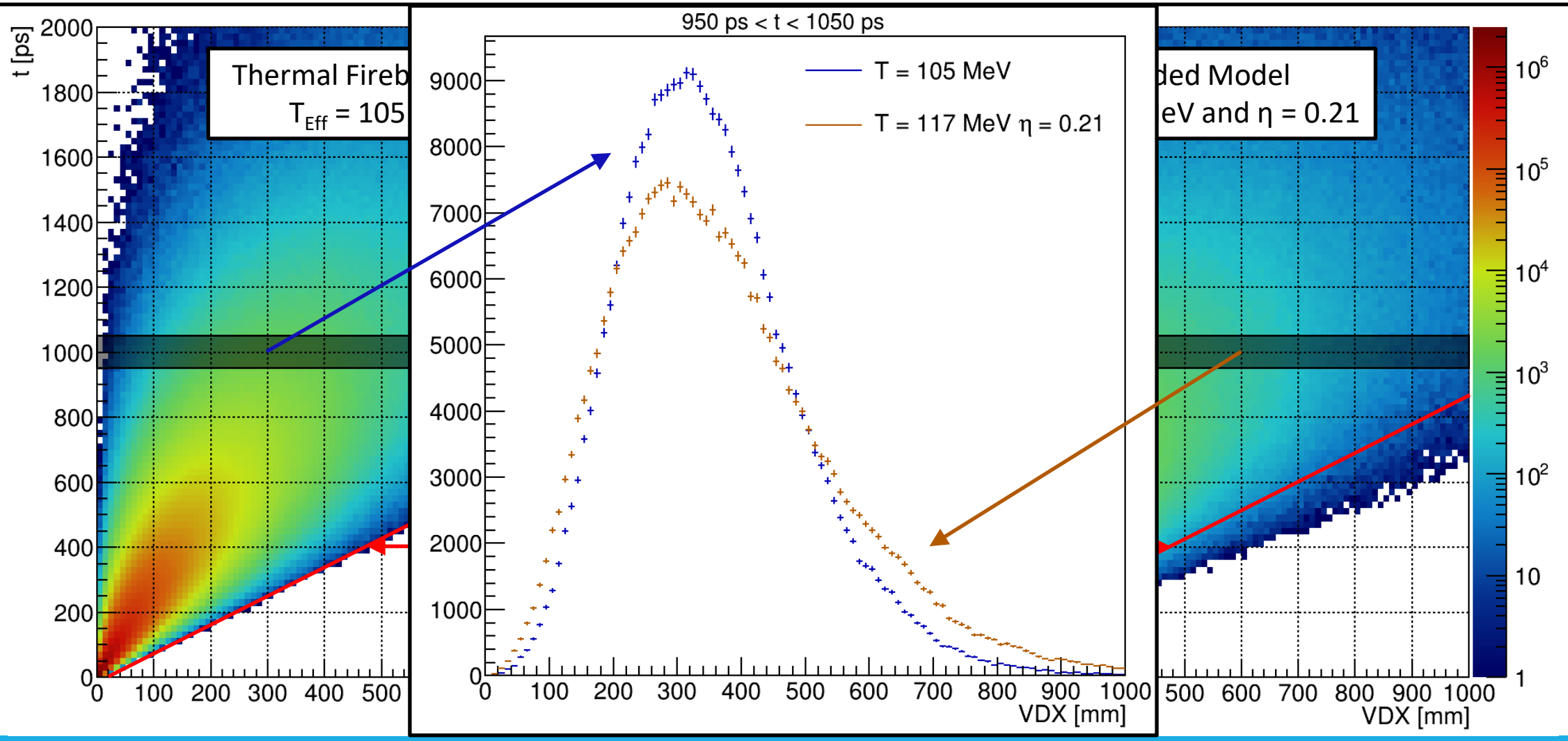
- Longitudinal anisotropy of particle emission due to only partial stopping of nucleons in the collision zone
- Longitudinal and transverse kinetic spectra cannot be described by statistical model with single effective temperature
- Effective Temperature of 105 MeV describes transverse spectra but results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



Strange Yields vs. $\langle A_{Part} \rangle$

- Production below (at) free NN-threshold:
  N + N
  N + N
  - Ene
- Strang
  Mult
- Ag+Ag
- $^{3}_{\Lambda}$H and
  signifi
  - Reflects the increased availability of nucleons in more central collisions

Side remark: Why are the production rates of $^{4}_{\Lambda}$H above the ones of $^{3}_{\Lambda}$H?

Unlike the $^{3}_{\Lambda}$H, the $^{4}_{\Lambda}$H (and the $^{4}_{\Lambda}$He) have bound excited states which are populated in addition to the ground states