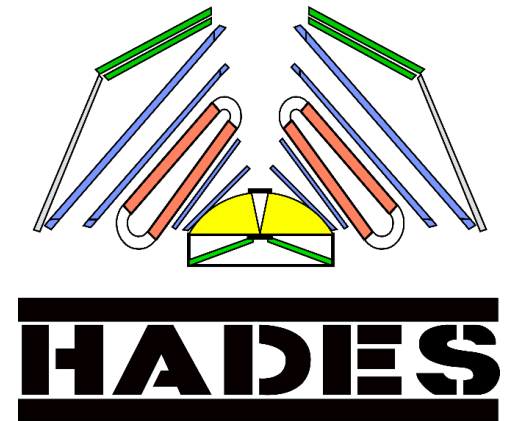
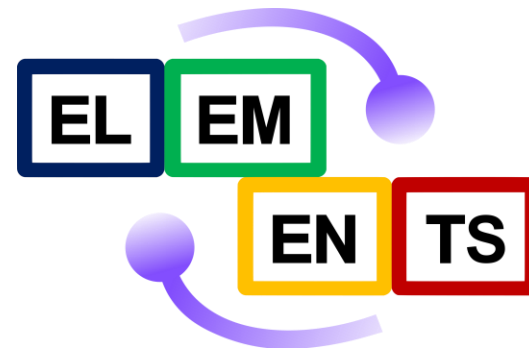


# HADES Overview

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Recent results from the measurement heavy-ion and elementary collisions in the few GeV energy regime

Simon Spies for the HADES Collaboration



# The HADES Physics Program

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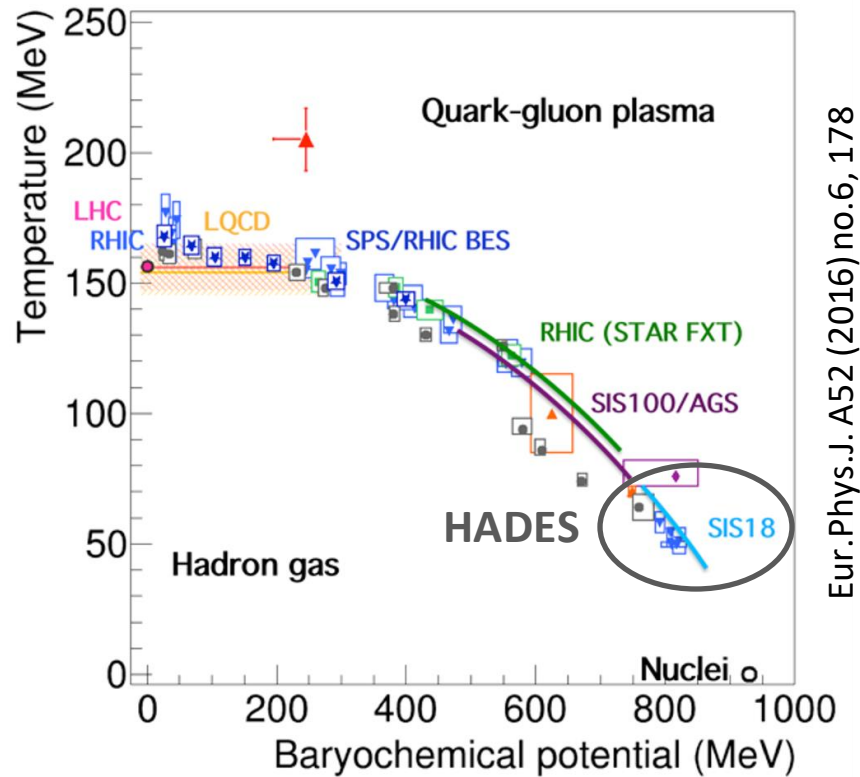
## Heavy-Ion Collisions

- Three most recent beamtimes:
  - Ar+KCl @ 1.76A GeV (2005)
  - Au+Au @ 1.23A GeV (2012)
  - Ag+Ag @ 1.58 / 1.23A GeV (2019)
- Properties of nuclear matter at highest baryochemical potential / nuclear density
- Event-by-event correlations and fluctuations
- Strangeness production close to or below the free NN threshold energy
- Di-Lepton signals from various sources

## Elementary Collisions

- Three most recent beamtimes:
  - p+Nb @ 3.5 GeV (2008)
  - $\pi$ +W /  $\pi$ +C /  $\pi$ +PE @ 1.7 GeV (2014)
  - p+p @ 4.5 GeV (2022)
- Electromagnetic structure of Baryons and Hyperons
- Reference measurements to separate in-medium effects in heavy-ion collisions
- (Rare) electromagnetic hadron decays
- Di-Lepton signals from various sources

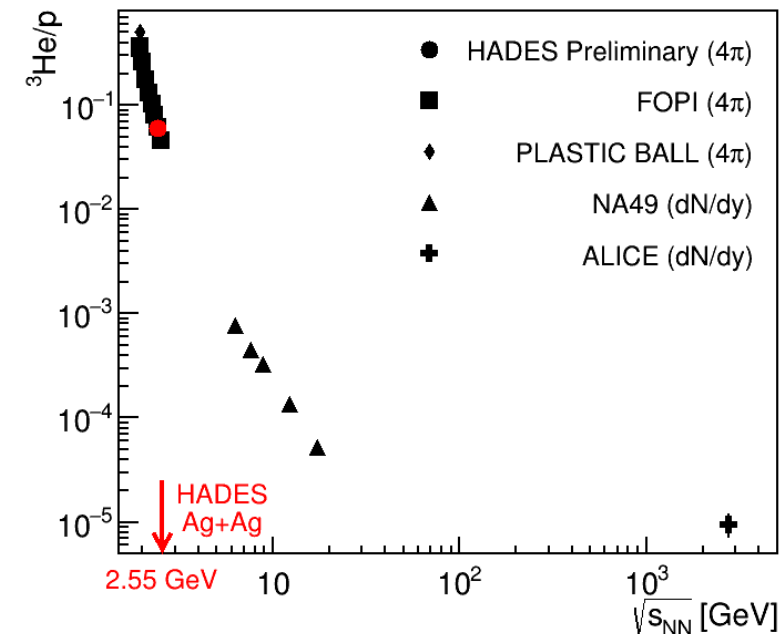
# Nuclear Collisions at SIS18/HADES Energies



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 essentially stopped in collision zone
  - Baryon dominated fireball  $N(B) \approx 10 N(\pi)$
- About 50% of protons clustered in light nuclei



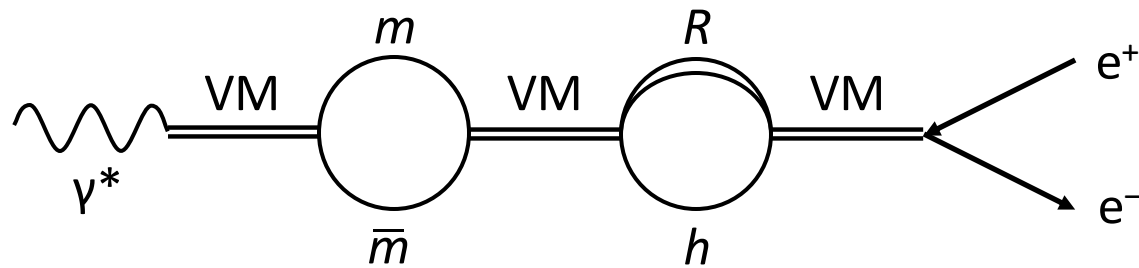
Data Collection:

Phys.Lett.B809 (2020) 135746

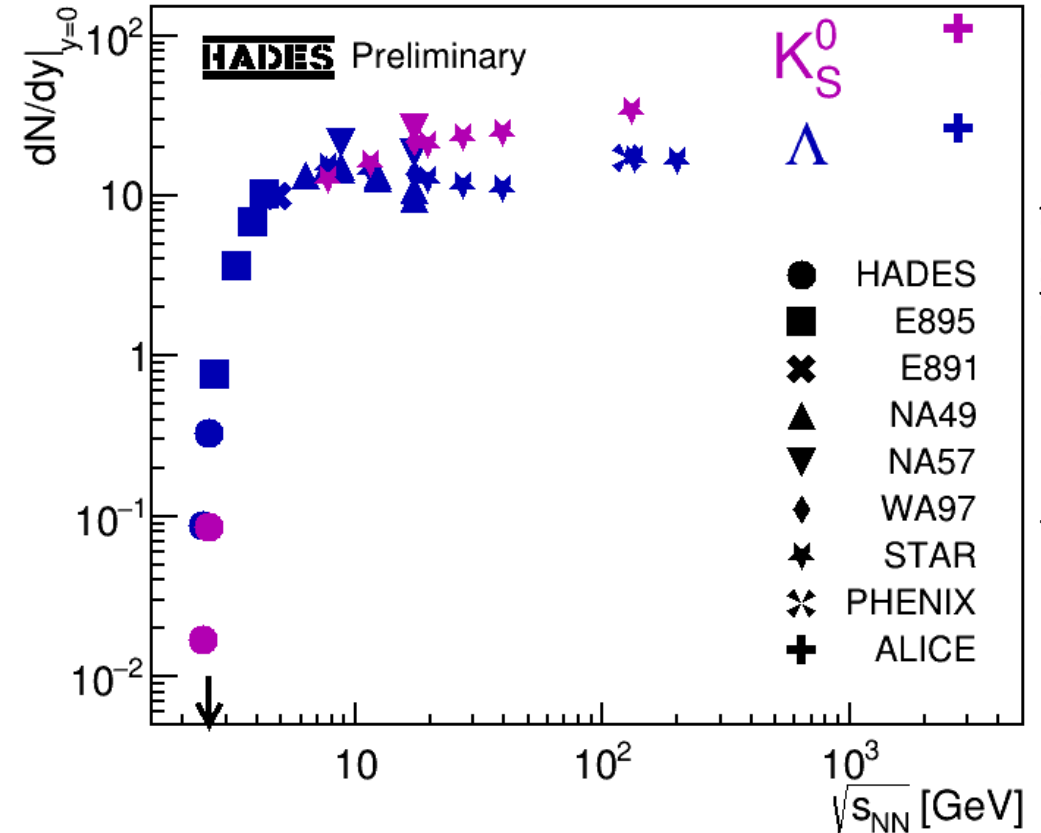
STAR 3 GeV data upcoming

# Rare Probes at SIS18/HADES Energies

- Strangeness production close to or below free NN threshold energy
- Steep excitation function, sensitive to medium effects



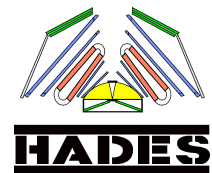
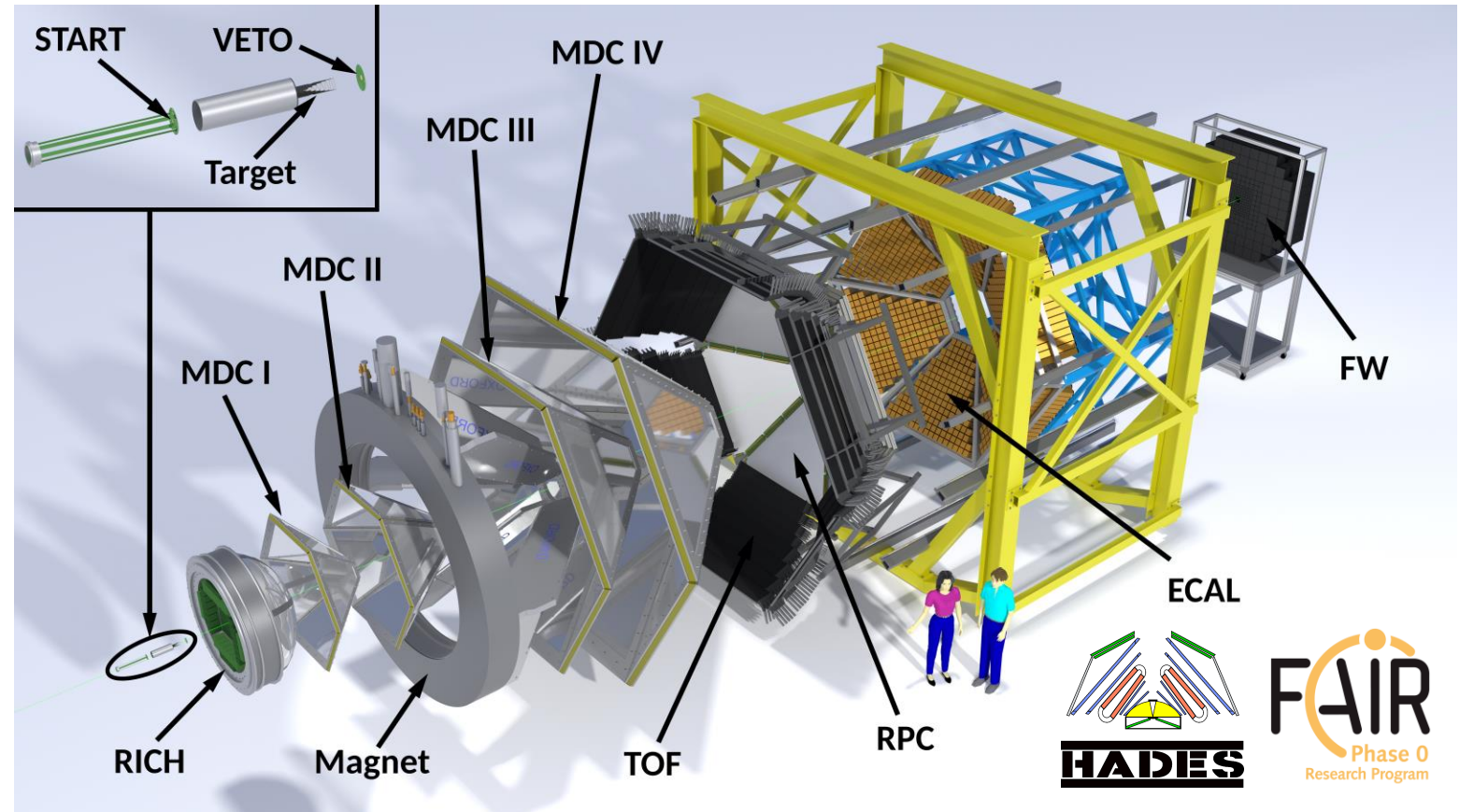
- Spectral functions of mesons modified by interactions with baryons and mesons
- Leptonic decay products decouple from the fireball → Direct access to medium properties



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

# 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 spectators detection
- Almost full azimuthal angle and polar angles between  $18^\circ$  and  $85^\circ$  covered

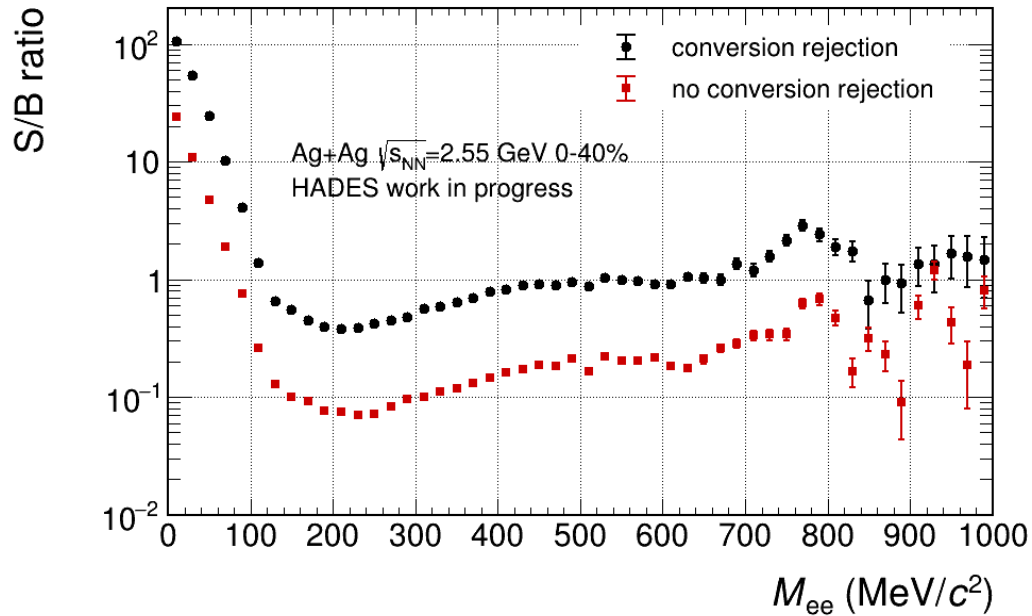


# Electromagnetic Probes

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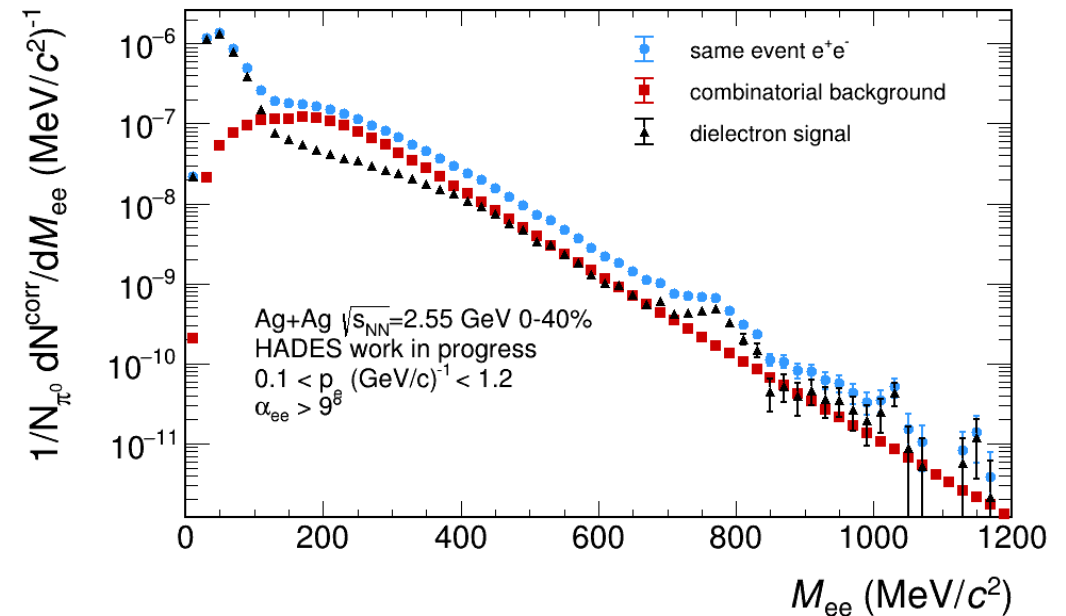
Reconstruction and Analysis of Virtual and Real Photons

# Dilepton Reconstruction Performance



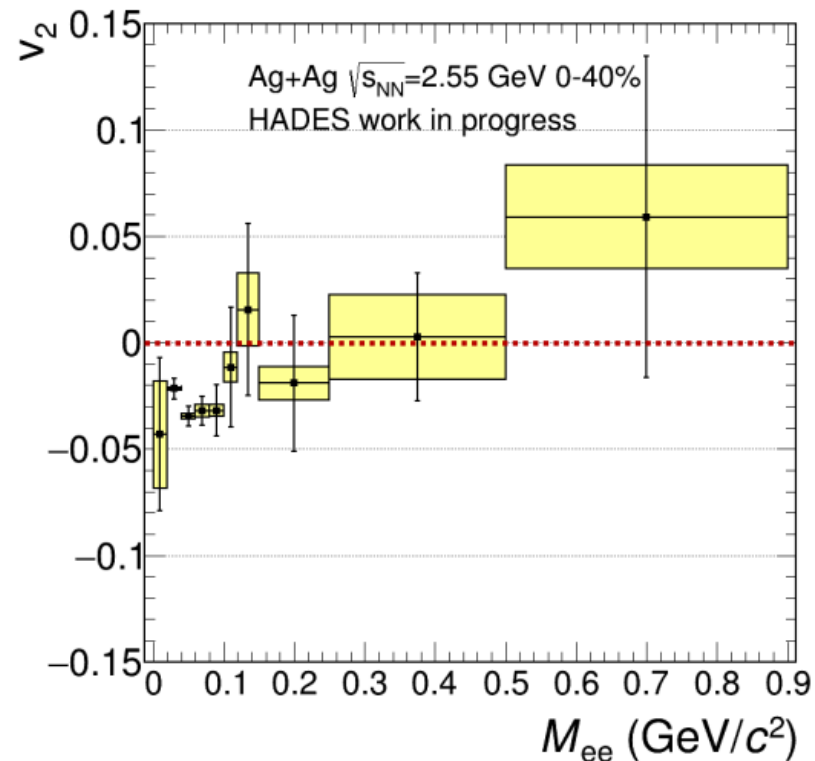
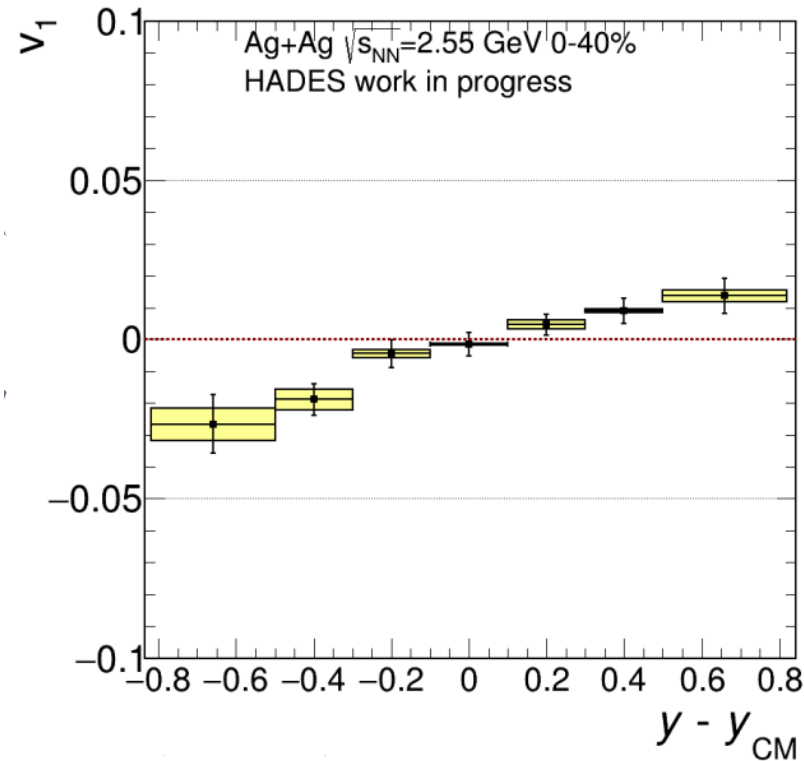
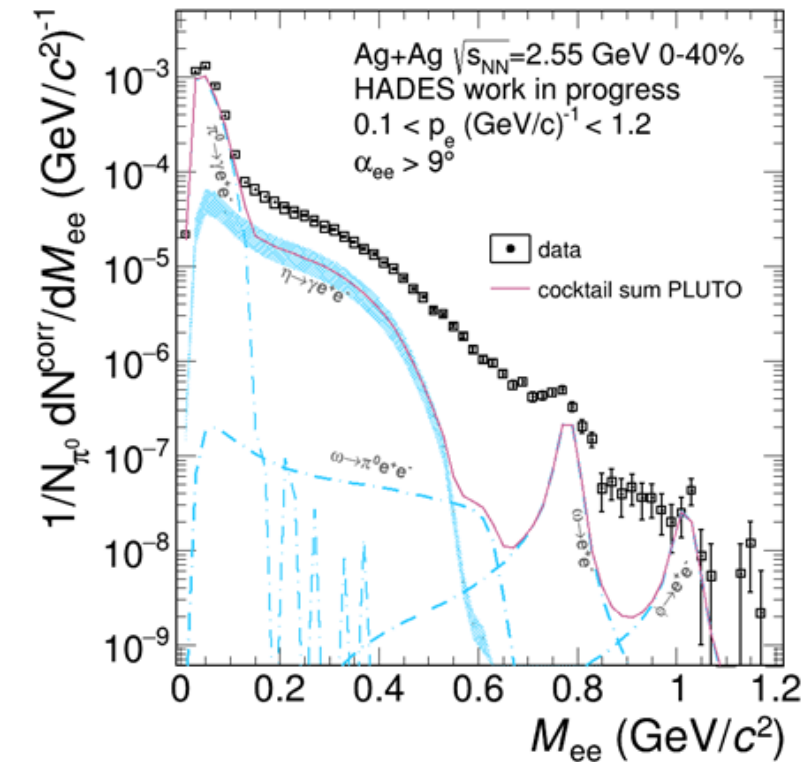
- Significantly improved lepton identification and double-ring detection by RICH upgrade
  - Strong suppression of lepton pairs from  $\gamma$  conversion

- Significant statistics up to high invariant mass  $\approx 1000 \text{ MeV}/c^2$
- $\omega(782)$  and  $\phi(1020)$  signals clearly visible





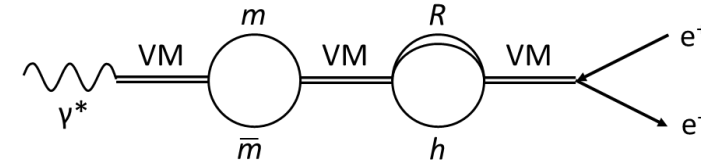
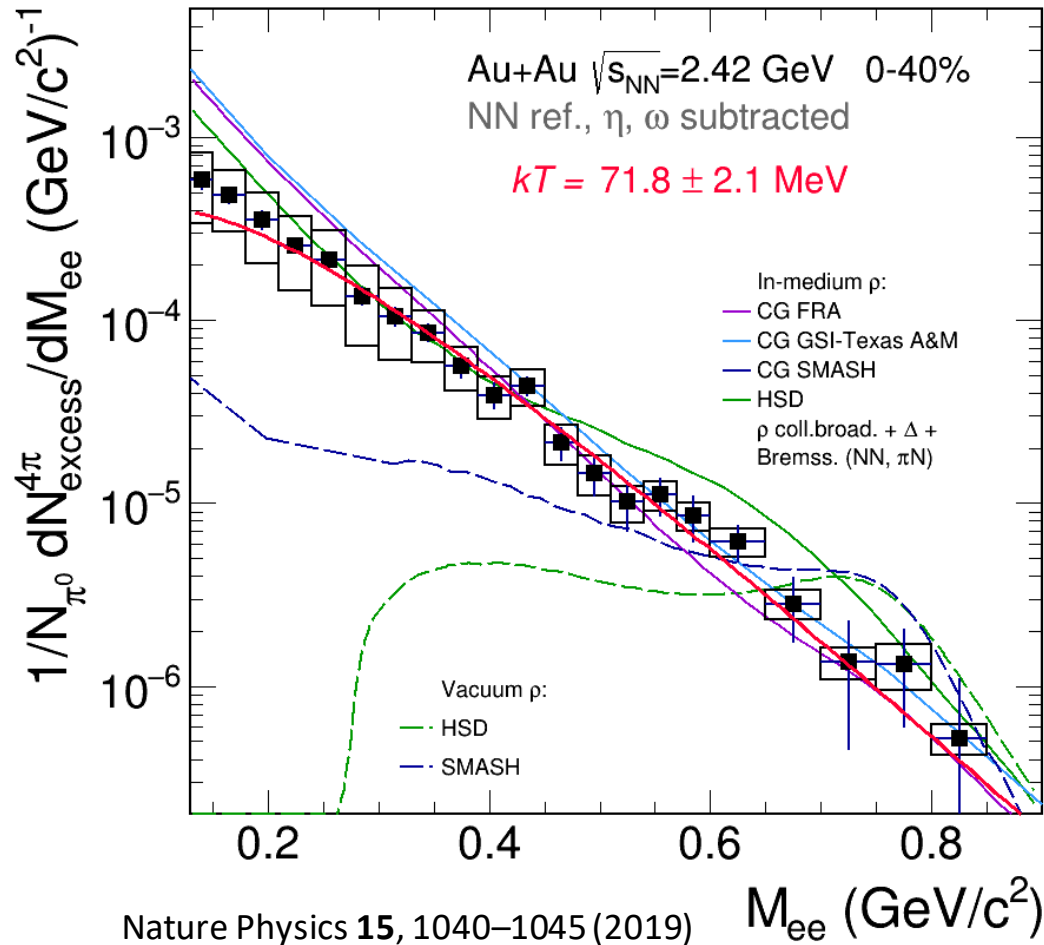
# Dilepton Spectra and Flow from Ag+Ag



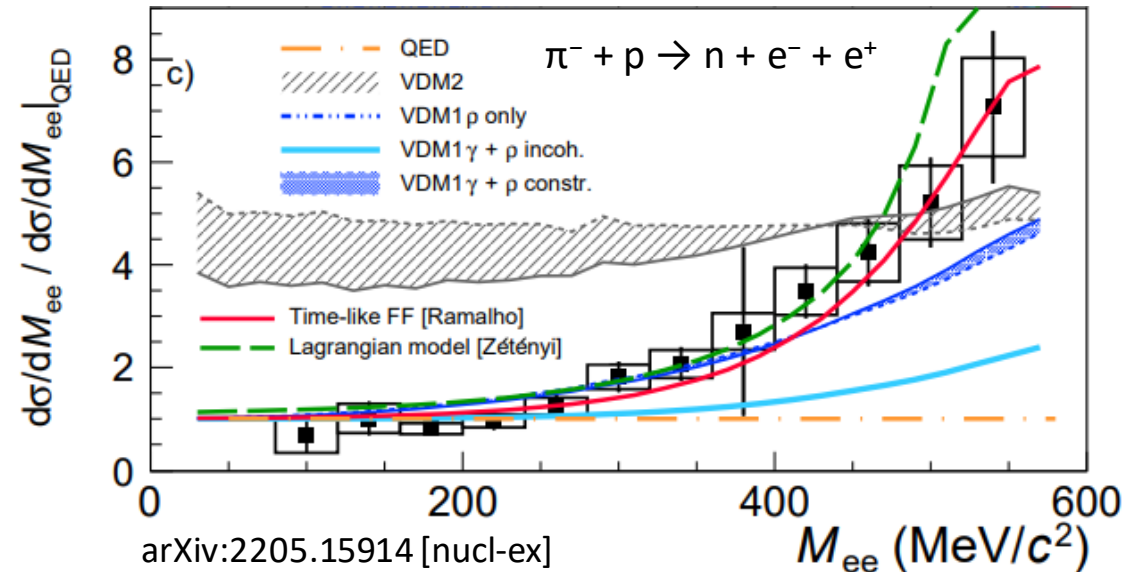
- Up to now no (elementary) reference measurement for Ag+Ag data available → Using simulations
- $v_2$  becomes 0 at  $M_{ee} > 120$  MeV → Dileptons are penetrating probes



# Dilepton Excess Radiation from Au+Au



- Excess Radiation in heavy-ion reactions properly described by Coarse Graining approach – VDM justified!



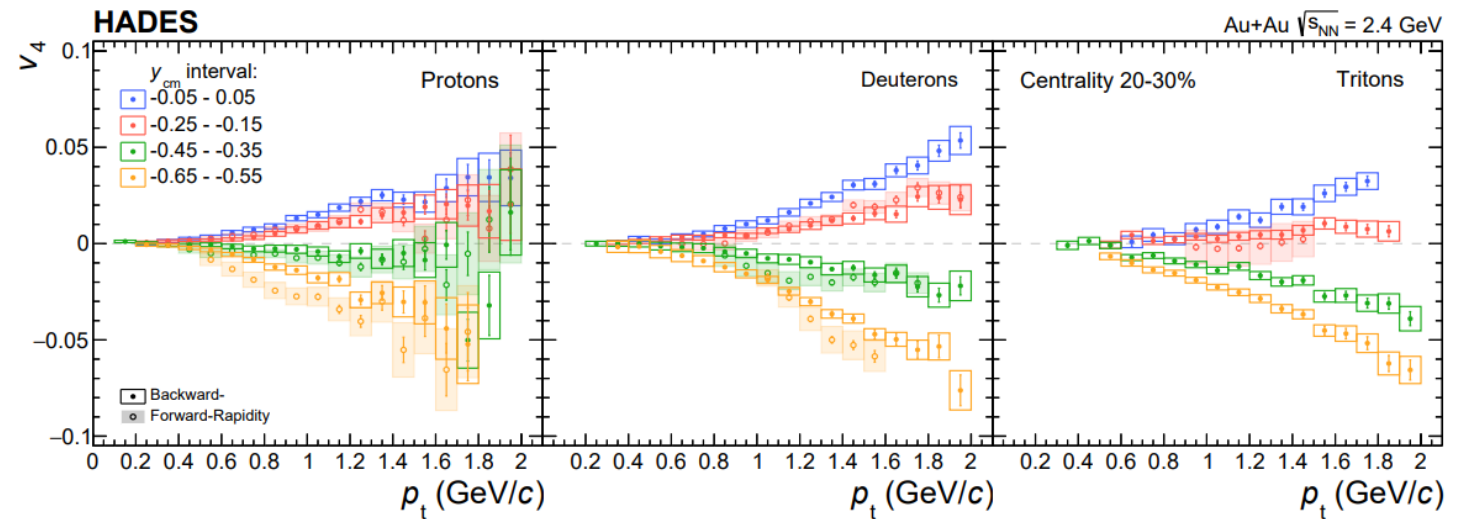
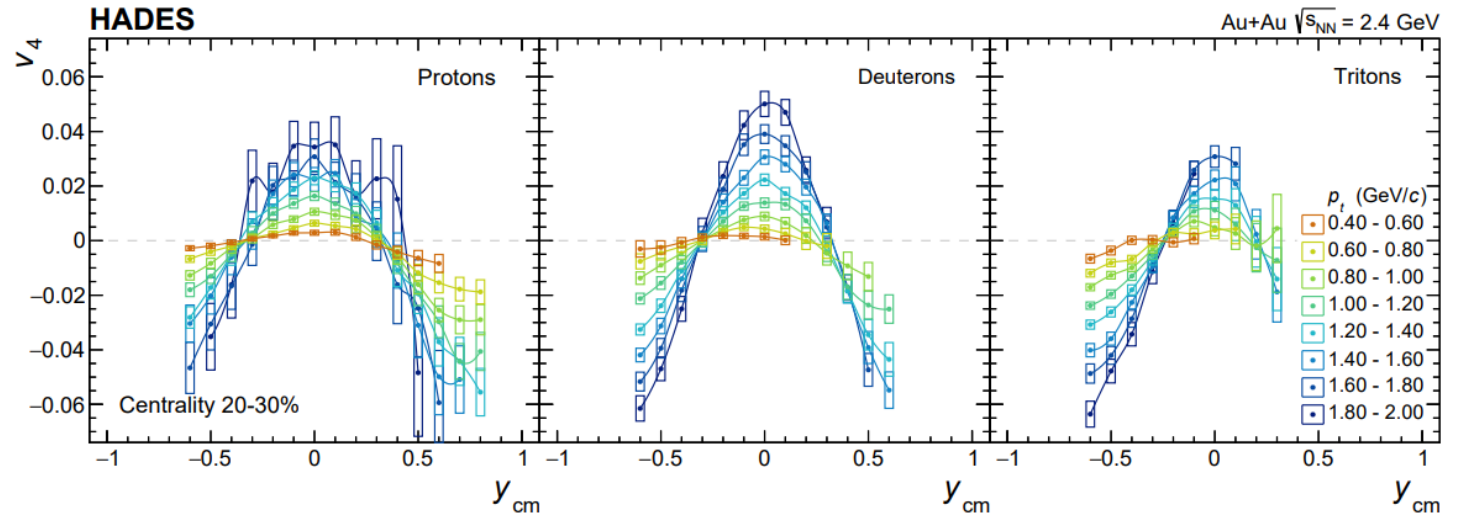
# Collective Phenomena

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Flow, Correlations, Fluctuations of (abundant) particles

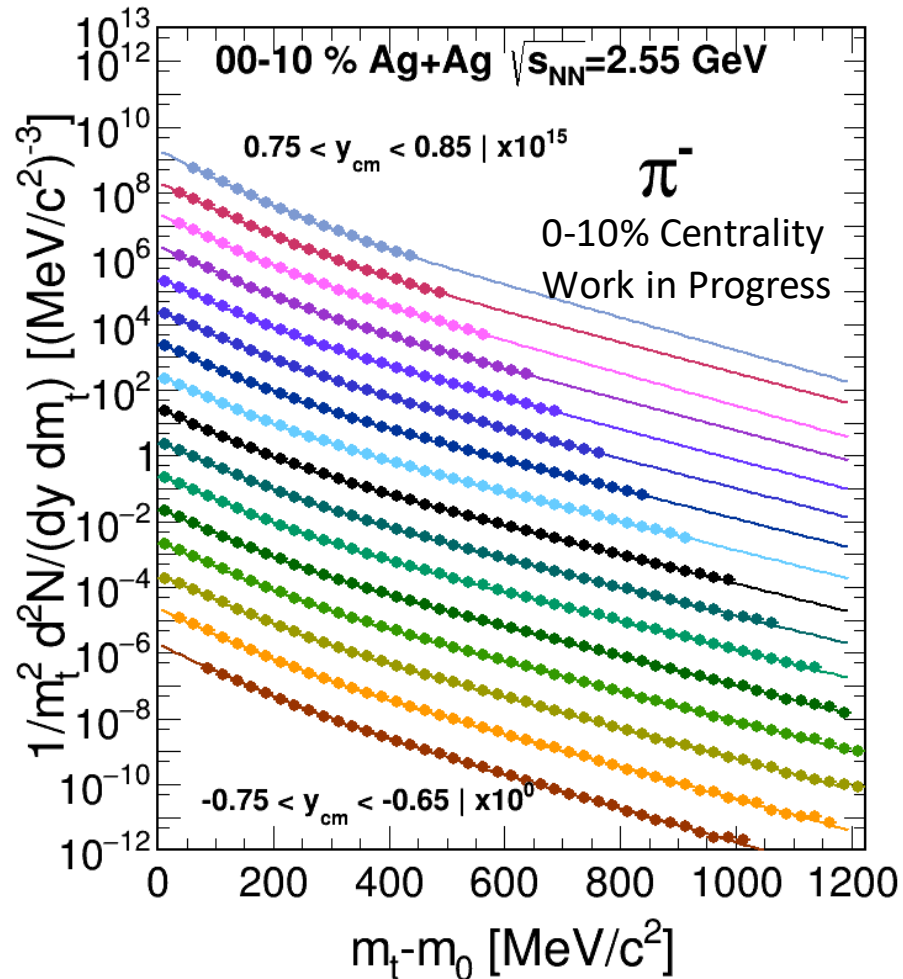
# Flow (Au+Au)

- High precision measurement of Proton, Deuteron and Triton flow coefficients up to  $v_4$   
*Eur.Phys.J.A* **59** (2023) 4, 80
- Wide ranges in rapidity and transverse momentum covered
- Important input to model calculations to constrain of EoS of compressed baryonic matter
- Ag+Ag data under analysis

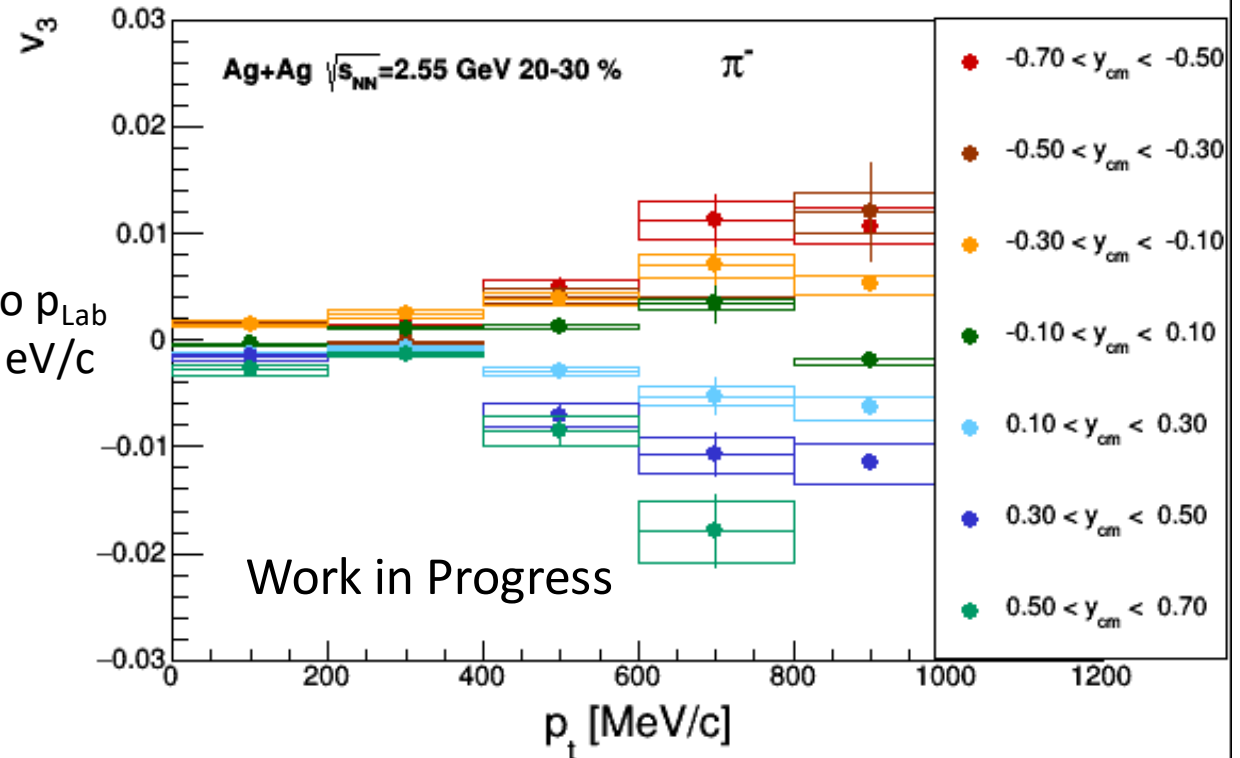


*Eur.Phys.J.A* **59** (2023) 4, 80

# Charged Pions



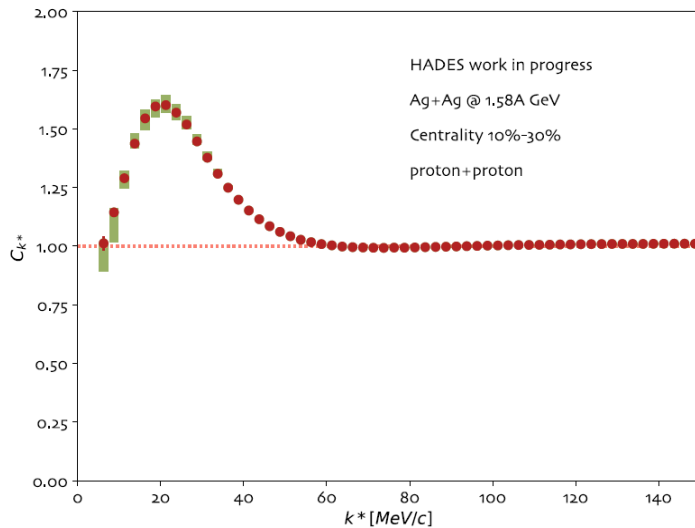
Down to  $p_{Lab}$   
= 60 MeV/c



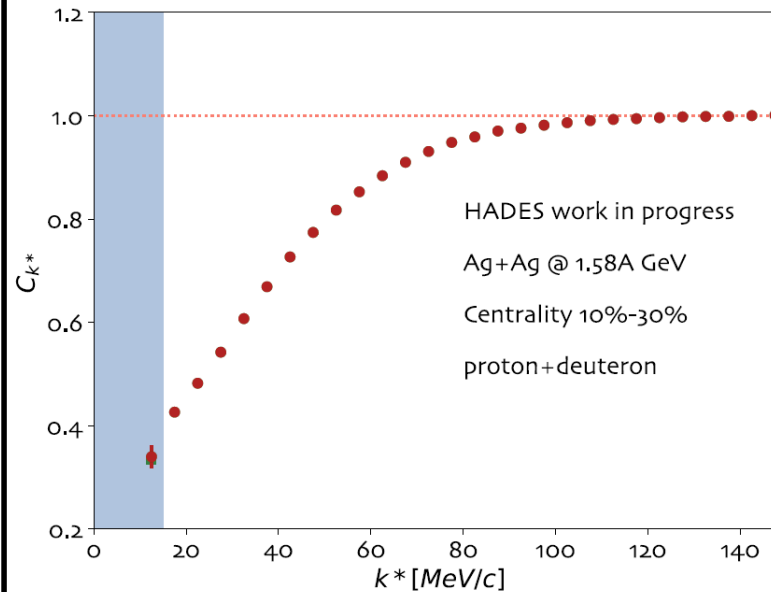
- High statistics enable multi-differential analyses (spectra, angular distributions, azimuthal anisotropy, coulumb force, etc.)
- First observation of Pion- $v_3$  at this energy

# Two-Particle Femtoscropy Correlations

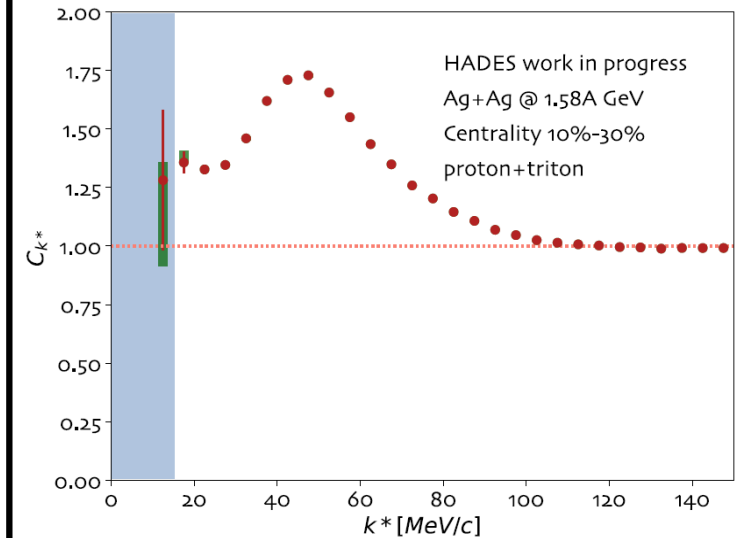
Proton + Proton



Proton + Deuteron



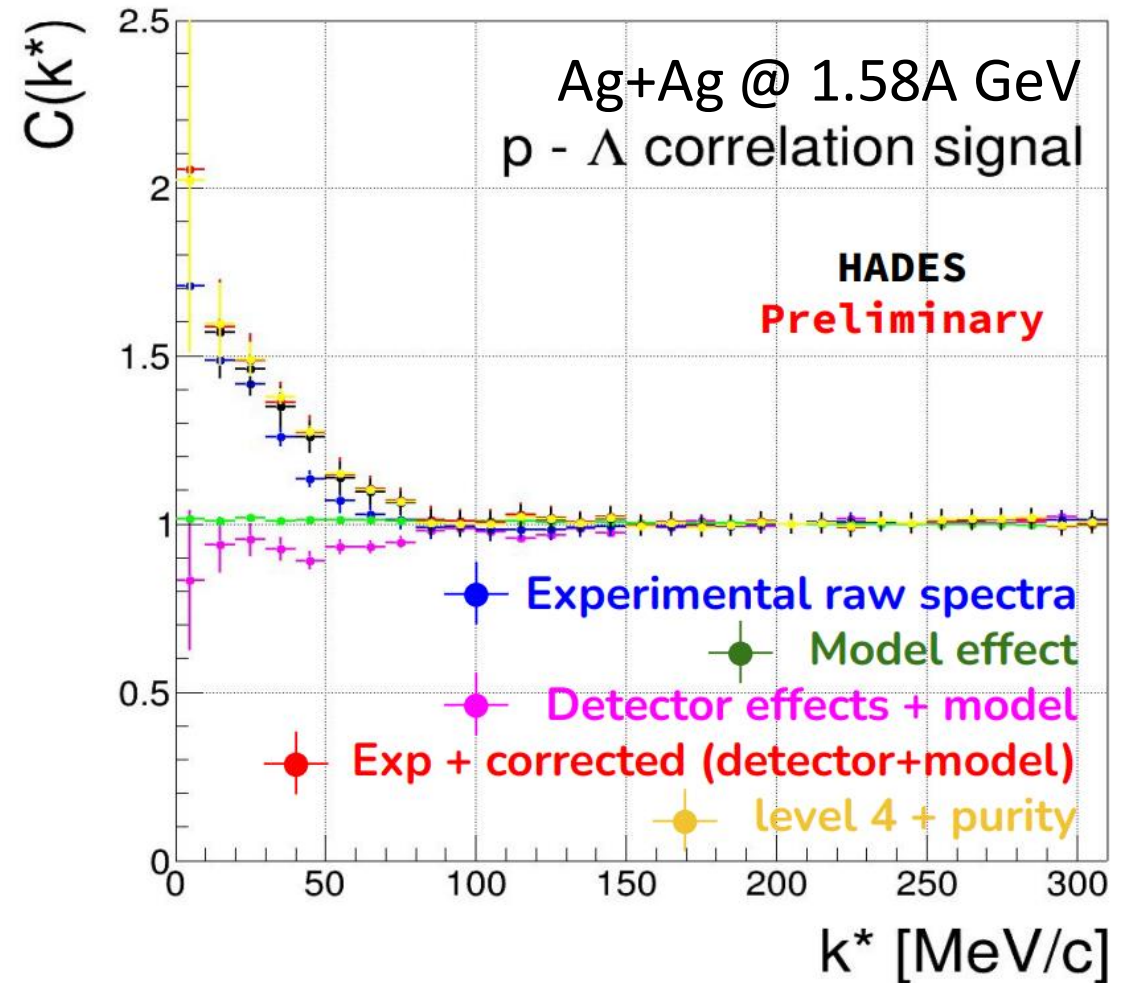
Proton + Triton



- Proton + Proton, Proton + Cluster and Cluster + Cluster Correlation Functions measured down to  $k^*$  of few MeV/c with high precision and low statistic and systematic uncertainties
- Important input to constrain the EoS of dense nuclear matter

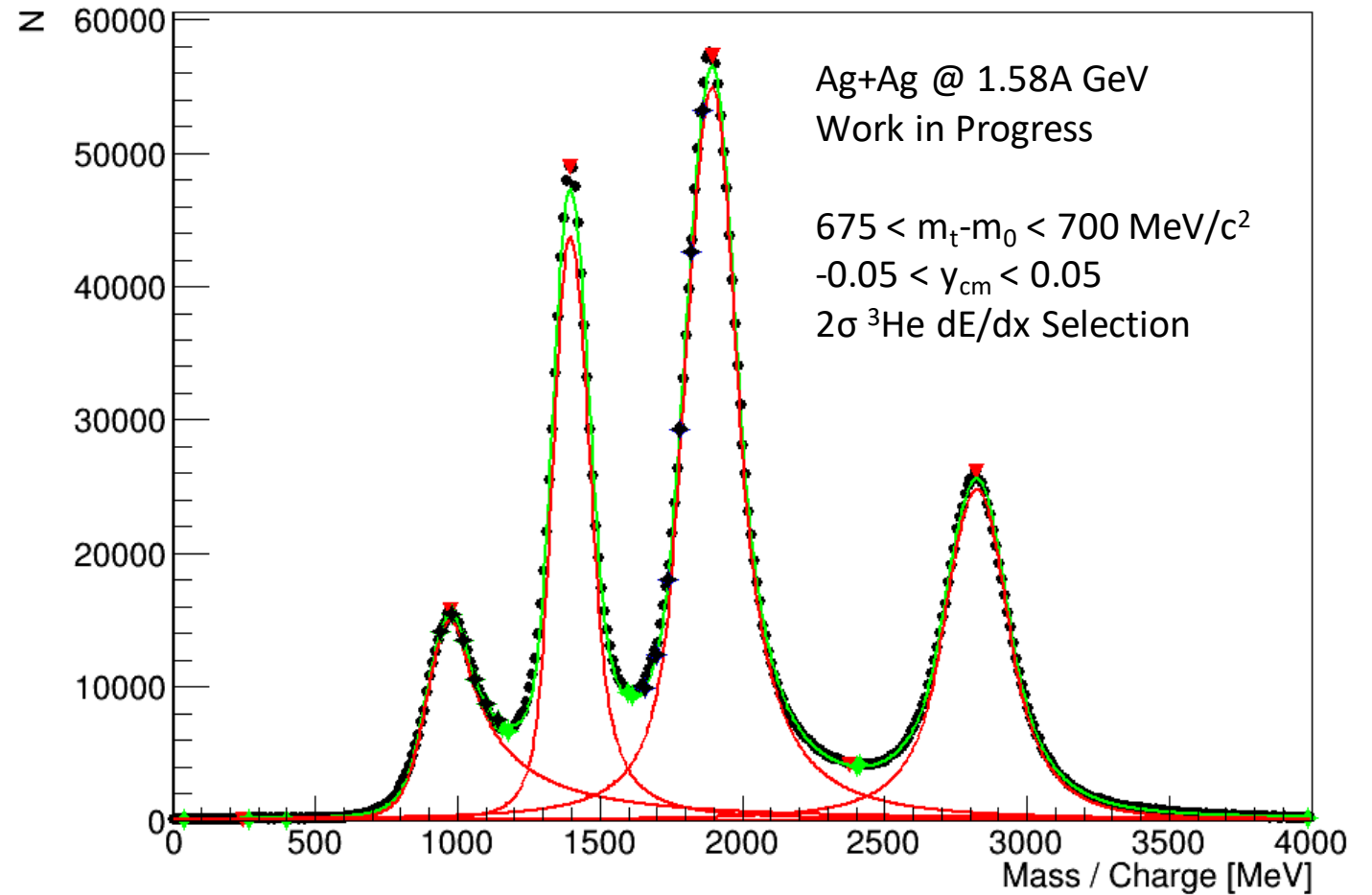
# Two-Particle Femtoscopy Correlations

- Proton +  $\Lambda$  Correlation Functions measured down to  $k^*$  of few MeV/c
- Low statistic and systematic uncertainties
- Important input to constrain the EoS of dense nuclear matter
  - Particularly relevant to further understand Hyperon-Nucleon interactions
  - Closely connected to Hypernuclei
- Further studies ongoing



# Outlook: Event-by-Event Fluctuations

- Net-Particle Event-by-Event fluctuations sensitive to phase transitions of nuclear matter
- Mass spectrum fitted with individual functions for each particles species
- Application of Identity method to separate particle species
  - Also applied at ALICE
- First results on Event-by-Event fluctuations from Ag+Ag data expected soon



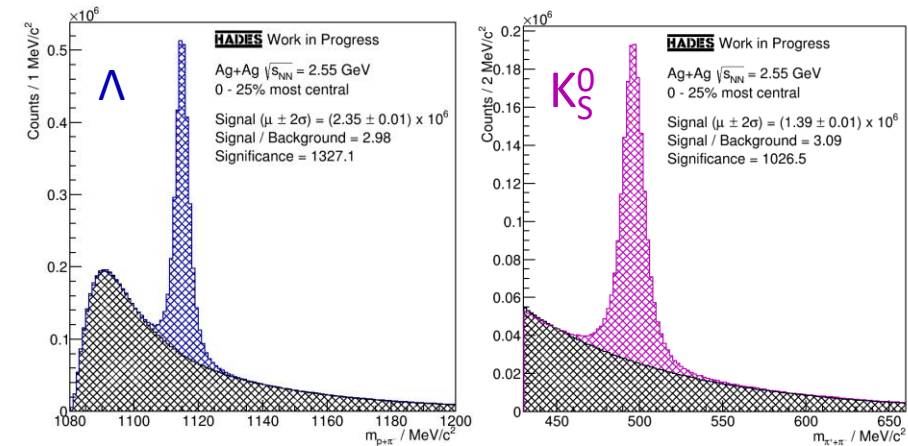


# Strange Hadrons

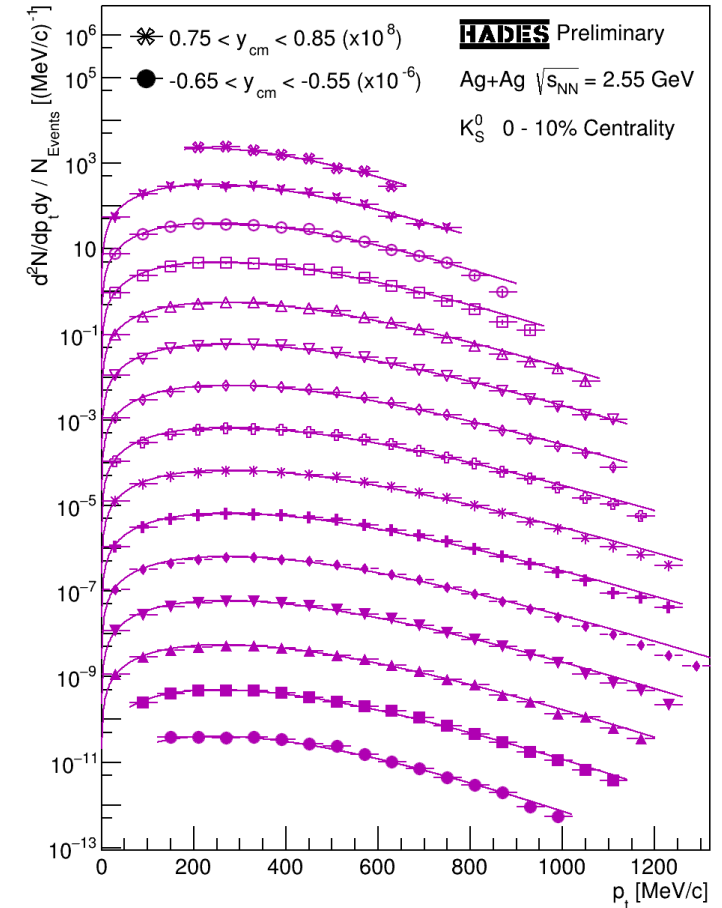
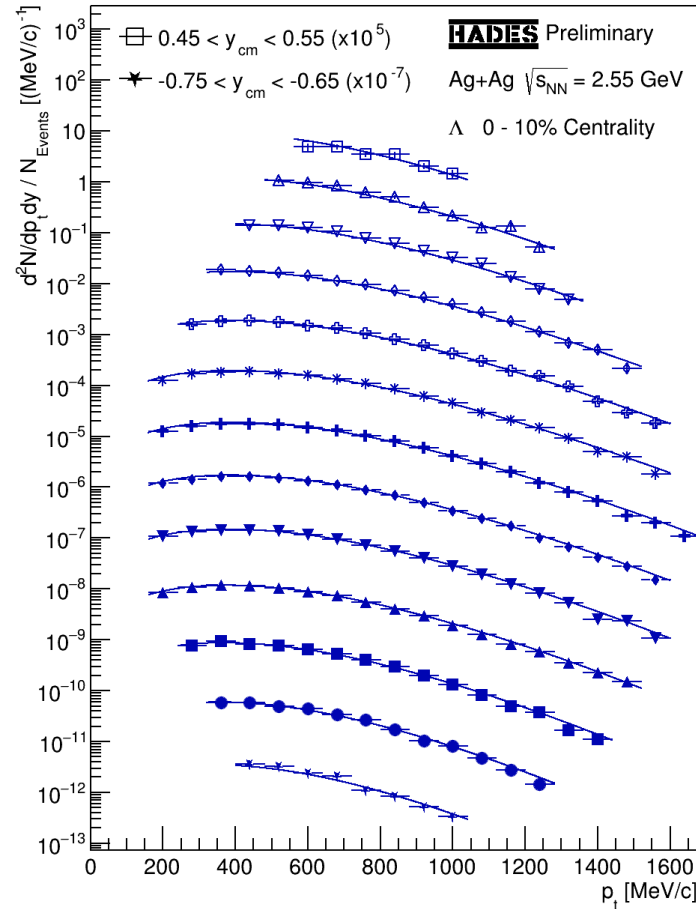
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Reconstruction and Analysis of Hadrons containing Strangeness

# Weak Decay Reconstruction

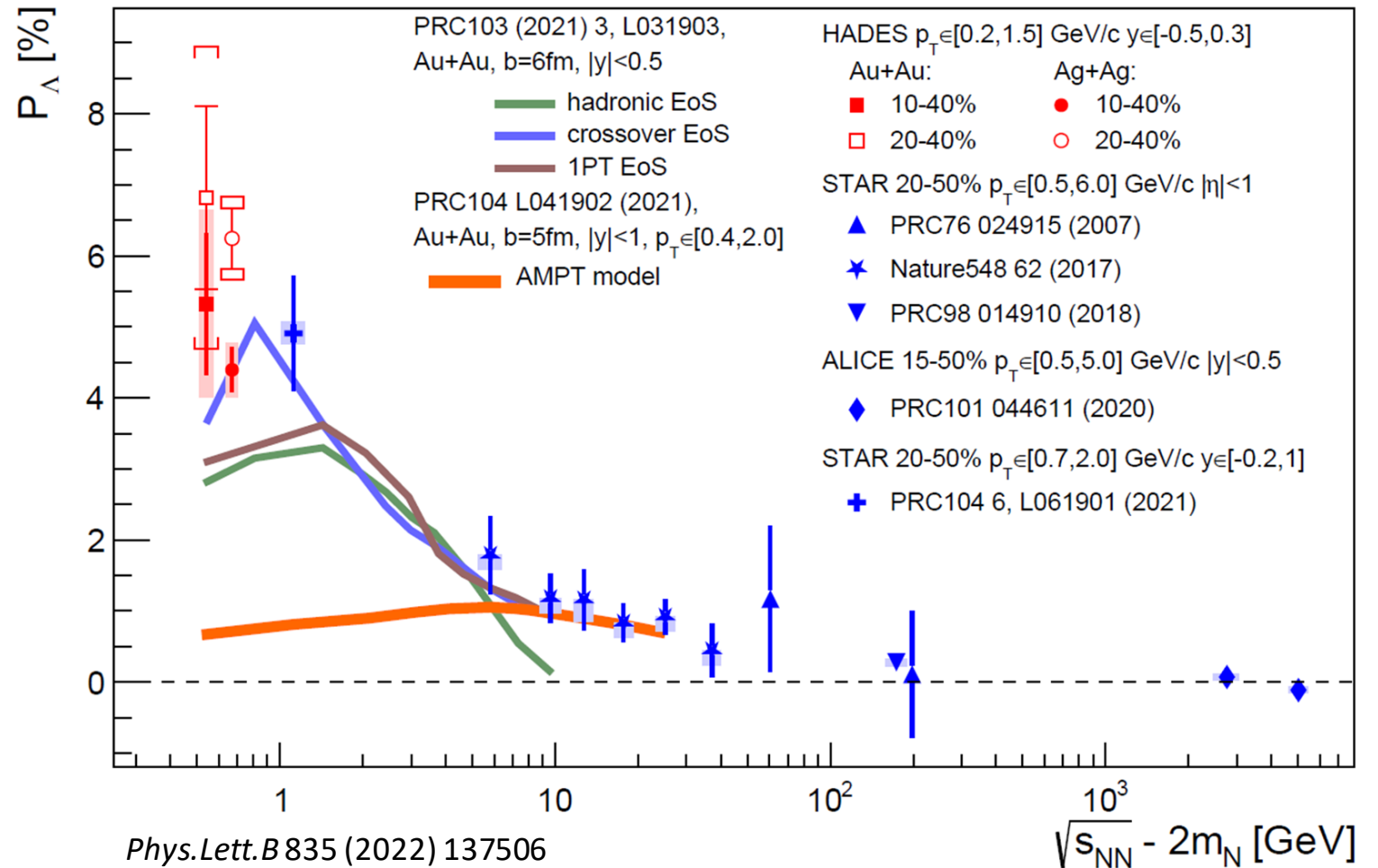


- Large phase space coverage with low statistical errors
  - Data points well described by Boltzmann functions
- Extrapolation to  $4\pi$



# $\Lambda$ Polarization / Vorticity

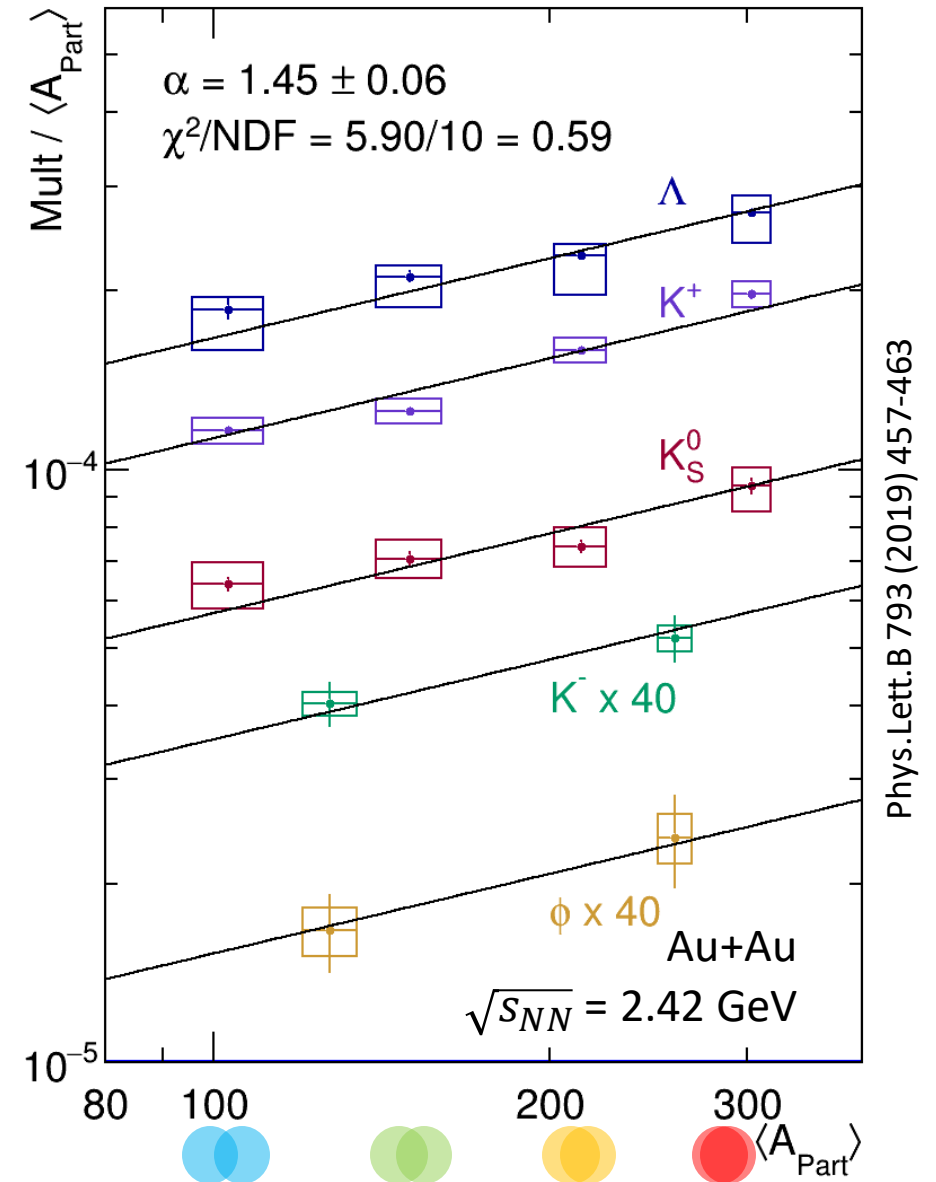
- Measurement of the global spin polarization using self-analyzing  $\Lambda$  decays
  - Performed multi-differentially in transverse momentum, rapidity and centrality
- Strongest polarization observed at low energies
- Further constraints for the EoS of compressed baryonic matter



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

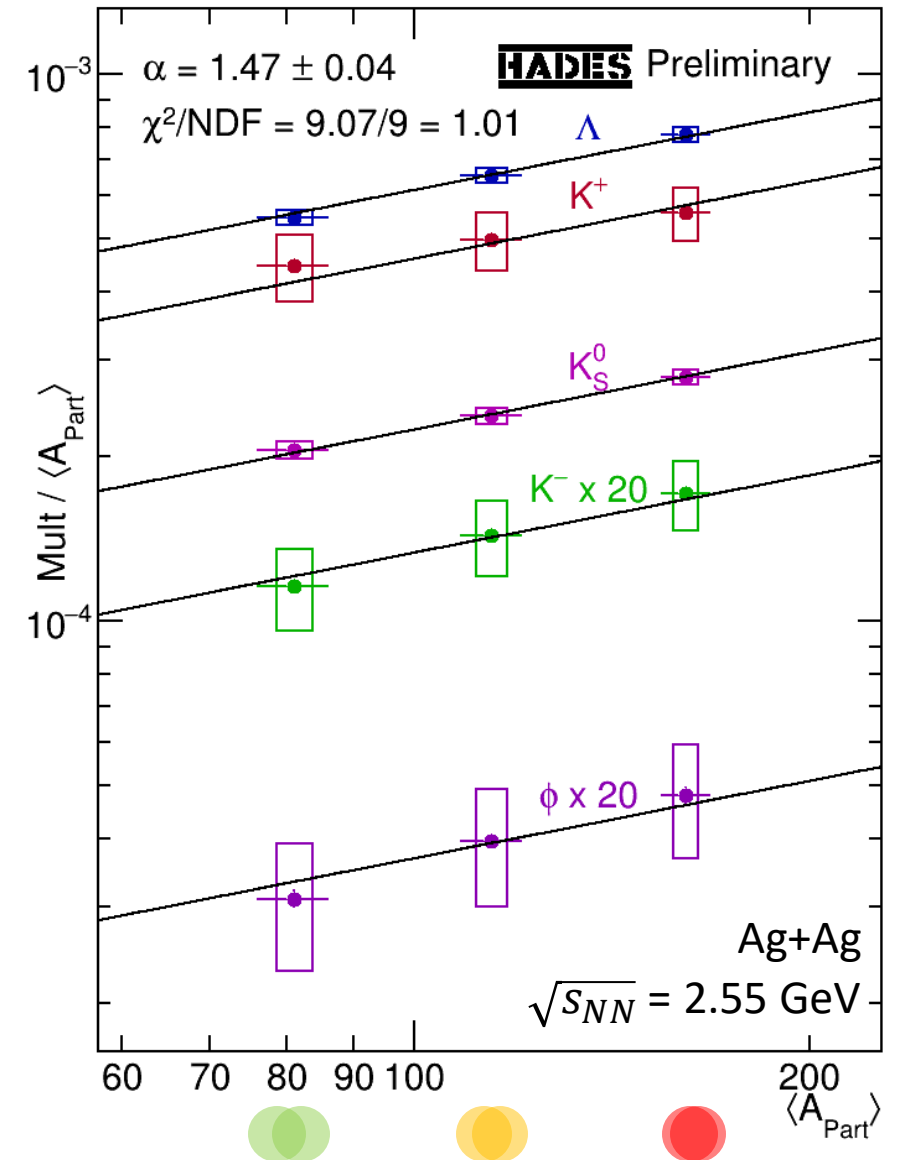
- Production below (at) free NN-threshold
  - Missing energy provided by the system
- Centrality dependence compatible with universal scaling assumption:  
 $\text{Mult} \propto \langle A_{\text{Part}} \rangle^\alpha$  with  $\alpha_{\text{Au+Au}} = 1.45 \pm 0.06$ 
  - Hierarchy in production thresholds not reflected
  - Suggests scaling of primary  $s\bar{s}$  creation
  - Hint for quark percolation

K. Fukushima, T. Kojo, W. Weise, PRD 102, 096017 (2020)



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  - Hint for quark percolation  
K. Fukushima, T. Kojo, W. Weise, PRD **102**, 096017 (2020)
- Ag+Ag: identical slope within errors  $\alpha_{\text{Ag+Ag}} = 1.47 \pm 0.04$
- Further investigation to reduce systematic uncertainties ongoing

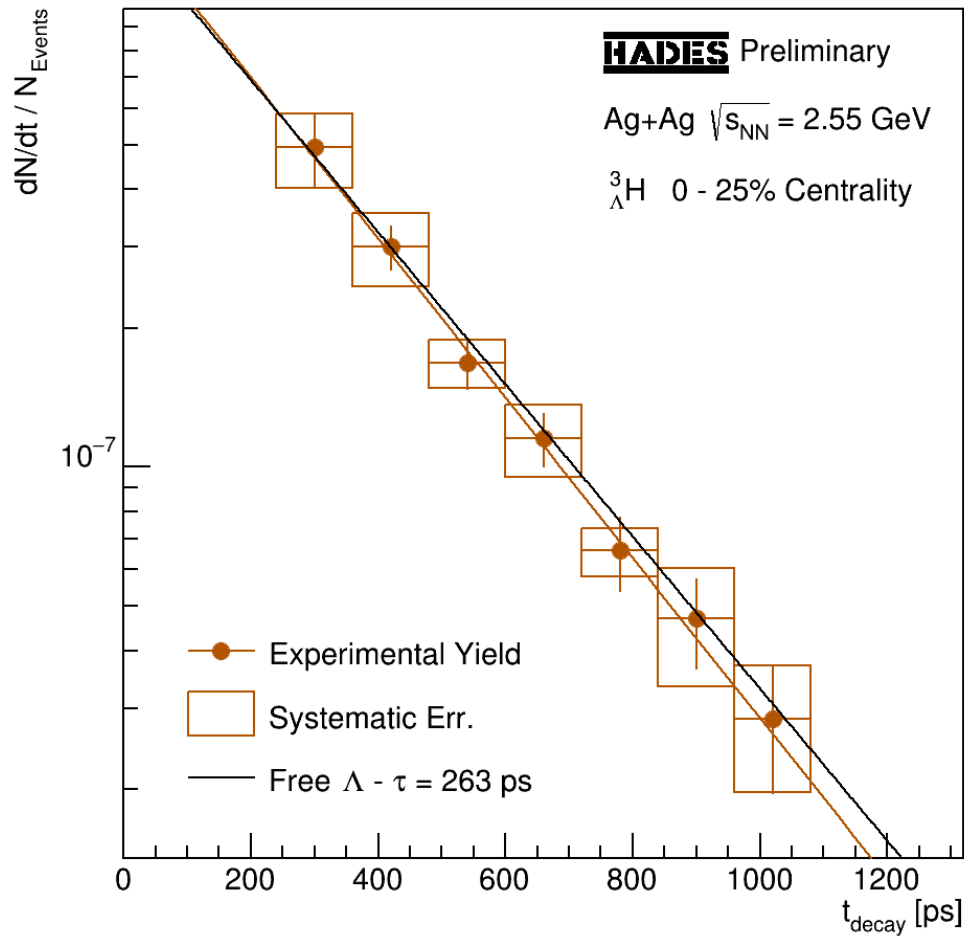


# Hypernuclei

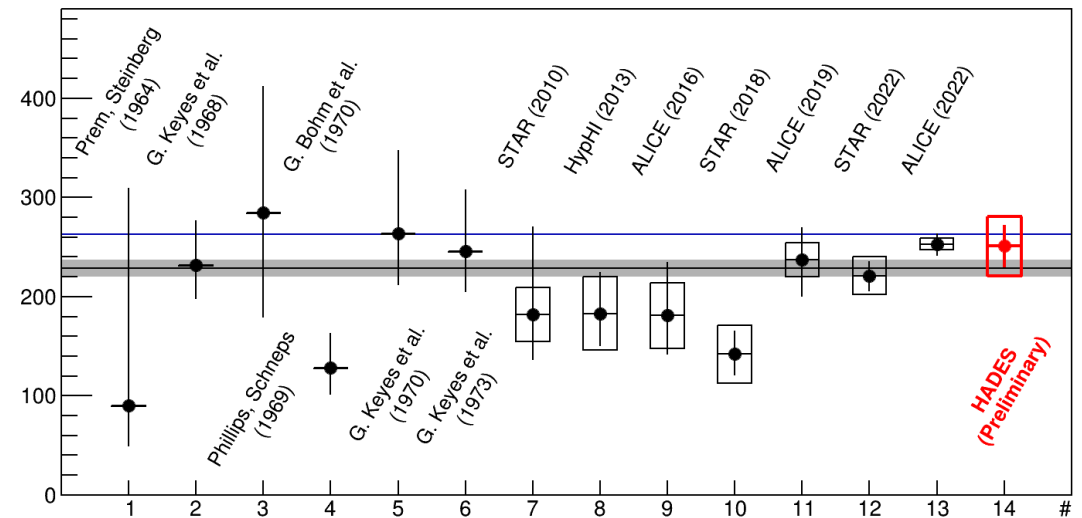
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Reconstruction and Analysis of Hypernuclei

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

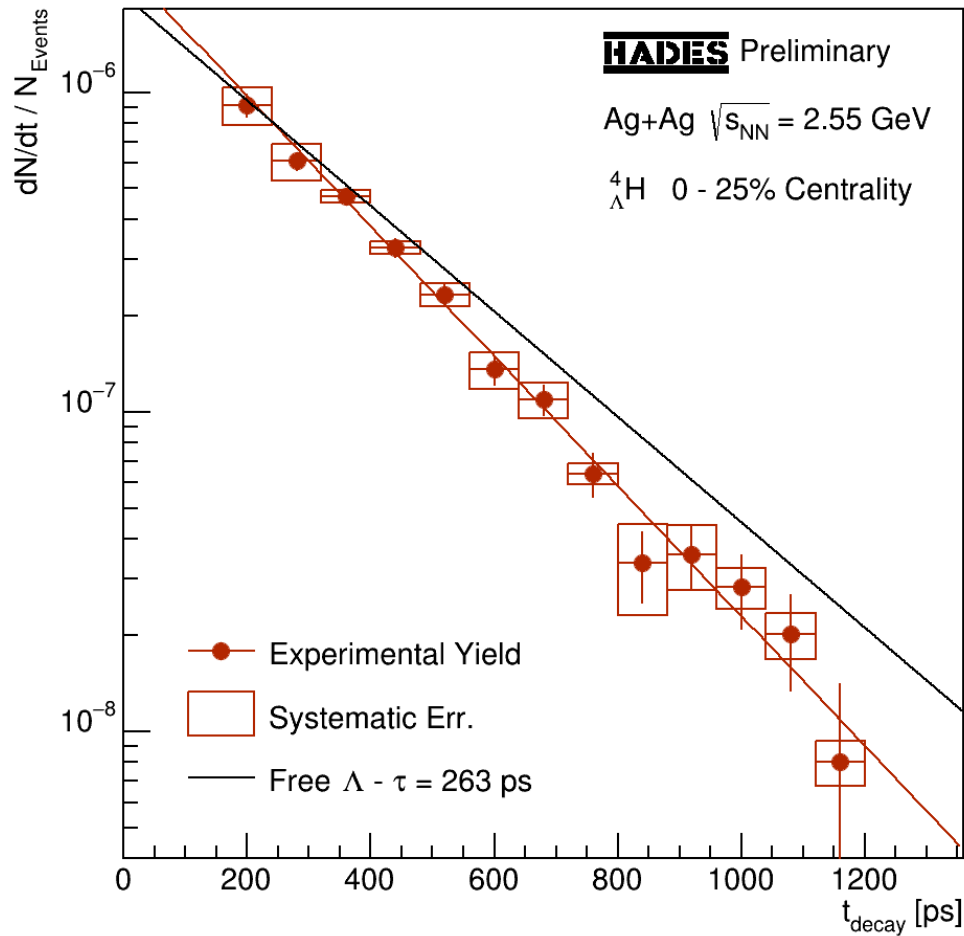


- ${}^3_{\Lambda}\text{H}$  lifetime measurement contributing to resolving the  ${}^3_{\Lambda}\text{H}$  lifetime puzzle
- Lifetime of  $(251 \pm 21_{\text{stat}} \pm 30_{\text{sys}})$  ps compatible with free  $\Lambda$  lifetime measured
- Further systematic uncertainty analyses ongoing

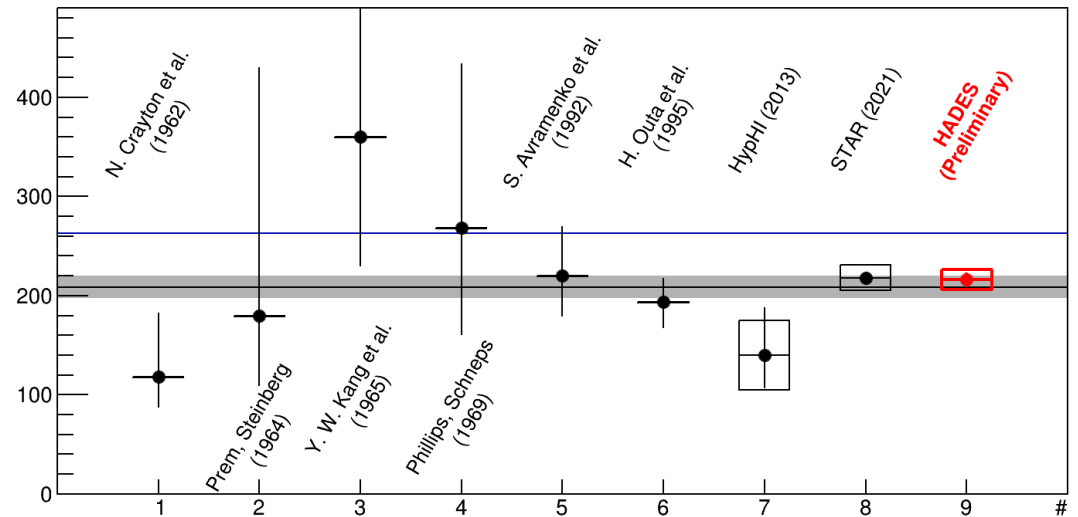




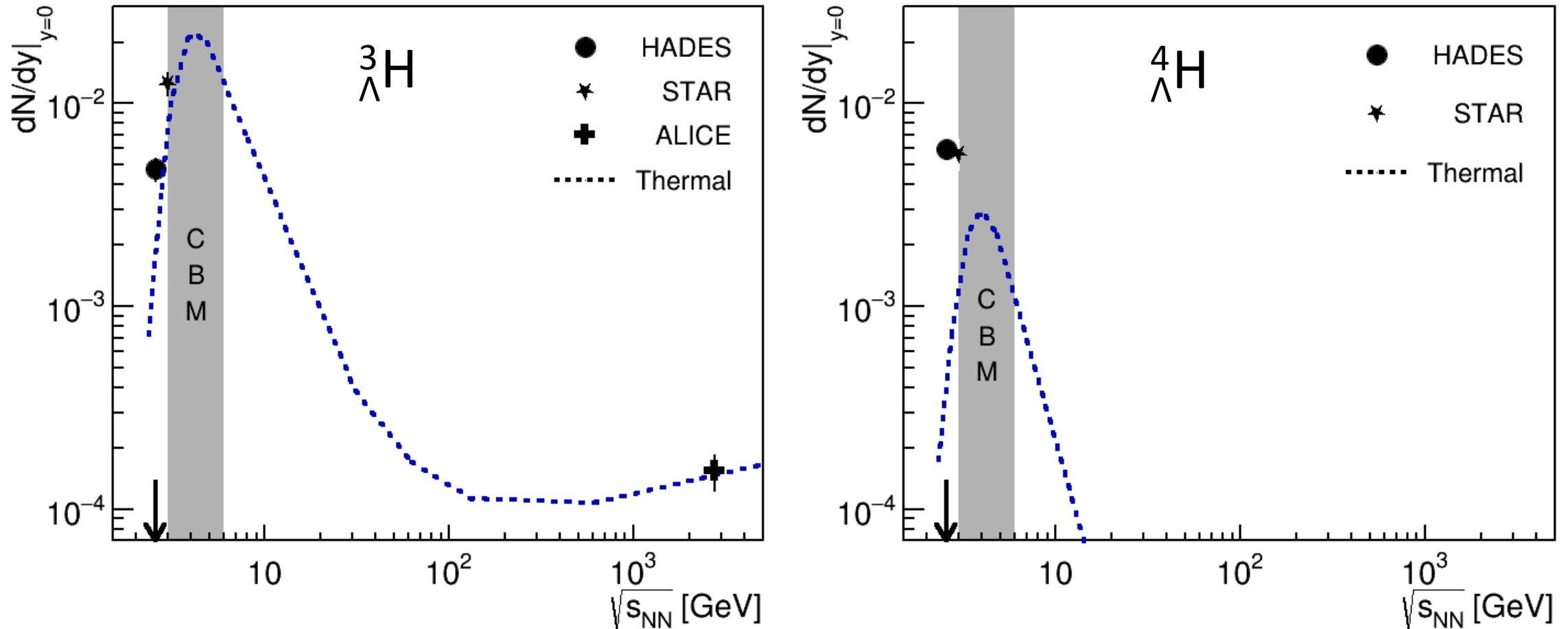
# ${}^4_{\Lambda}\text{H}$ Two-Body Decay: ${}^4_{\Lambda}\text{H} \rightarrow {}^4\text{He} + \pi^-$



- ${}^4_{\Lambda}\text{H}$  lifetime measurement contribution to world data
- Lifetime of  $(216 \pm 7_{\text{stat}} \pm 10_{\text{sys}})$  ps compatible with earlier measurements measured
  - $4.85\sigma$  deviation to free  $\Lambda$  lifetime
- Further systematic uncertainty analyses ongoing



# Hypernuclear Excitation Functions

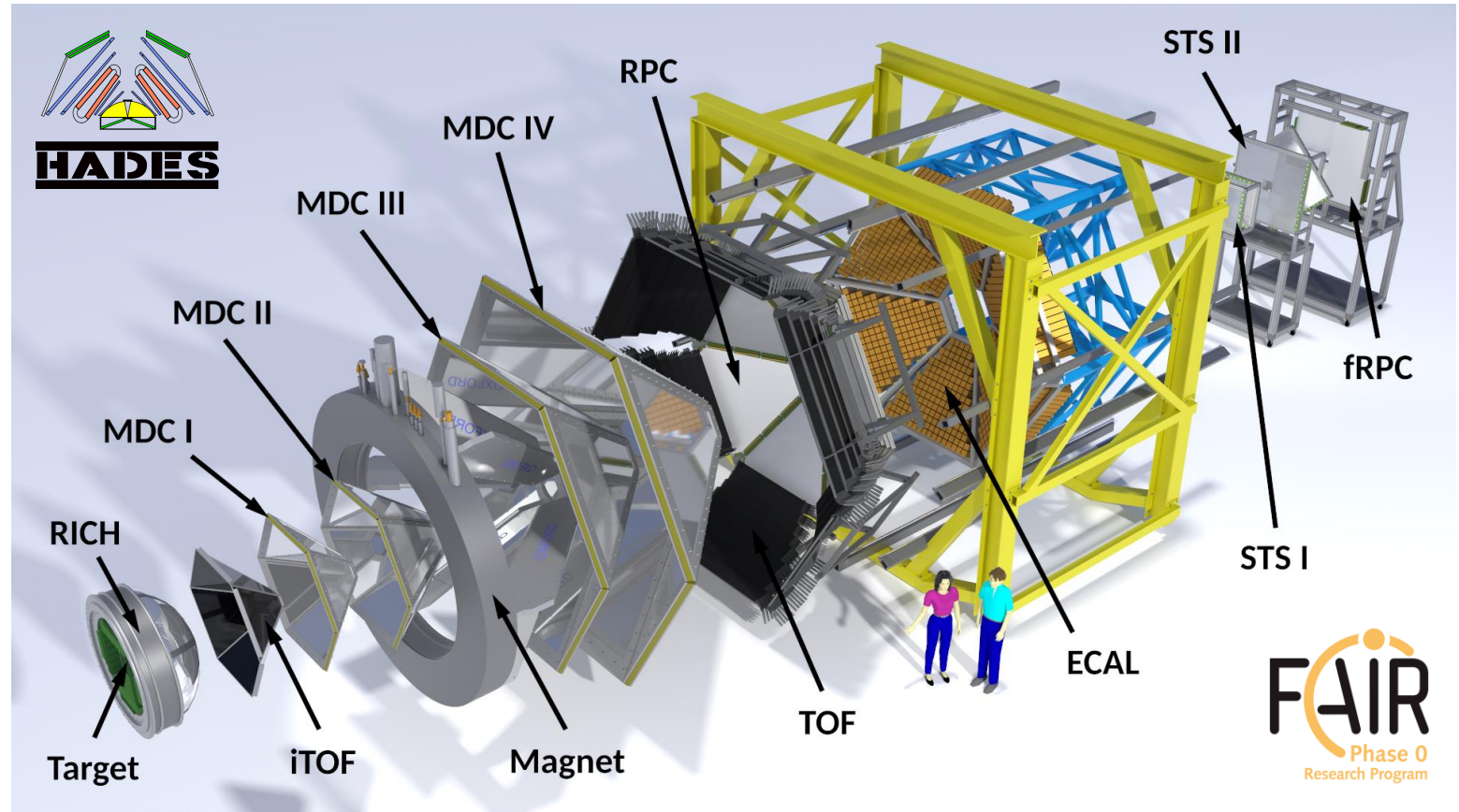


Plots based on Phys.Rev.Lett. 128 (2022) 20, 202301

Only few measurements available → Interesting prospects for upcoming FAIR experiments (e.g. CBM)

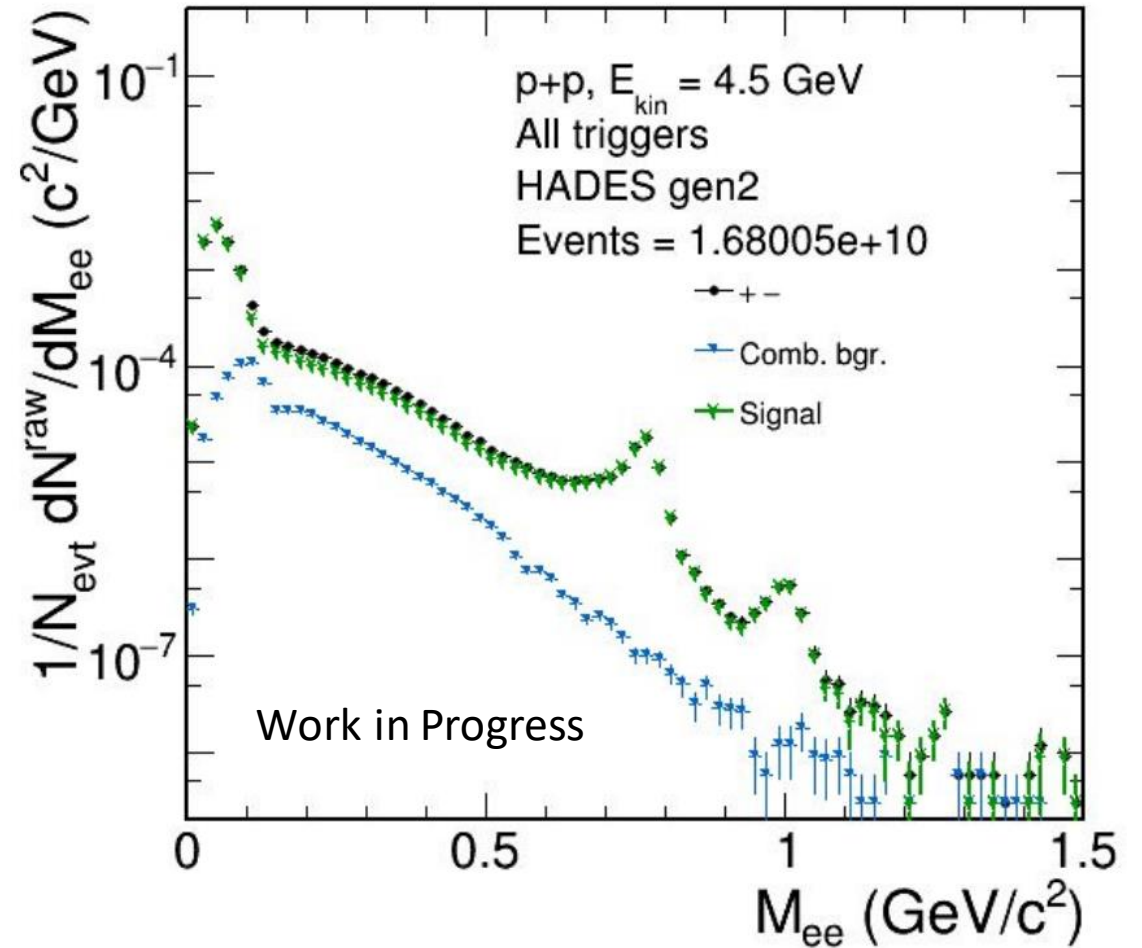
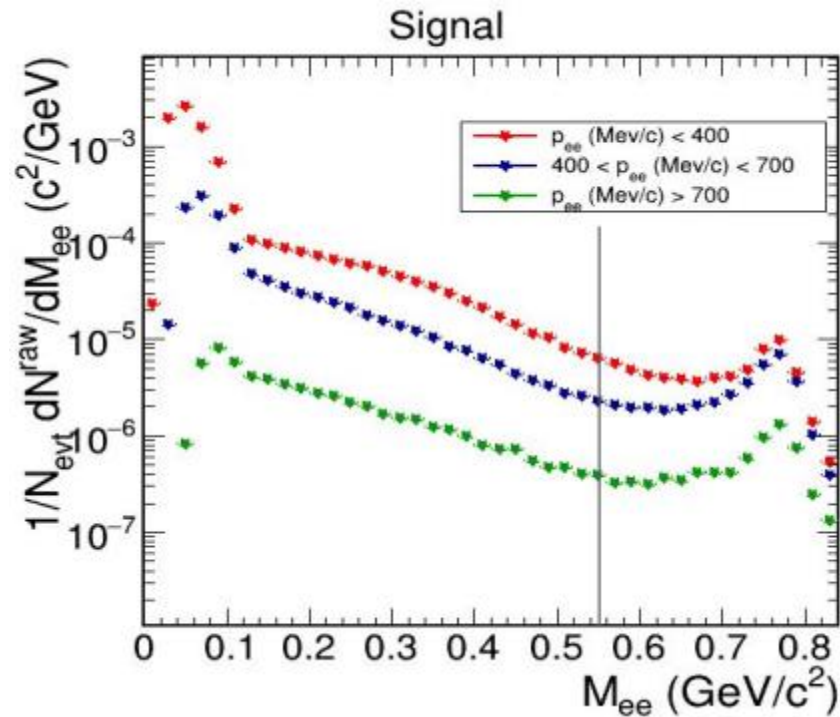
# The HADES Experiment (p+p Setup)

- iTOF plastic szintillator for event triggering
- Two straw-tube-tracking-stations (STS I and II) in forward direction
  - Four layers in two orientations per station
  - Built in collaboration with PANDA
- Forward time-of-flight detector (fRPC)
- Extends the polar coverage to the region between  $7^\circ$  and down to almost  $0^\circ$

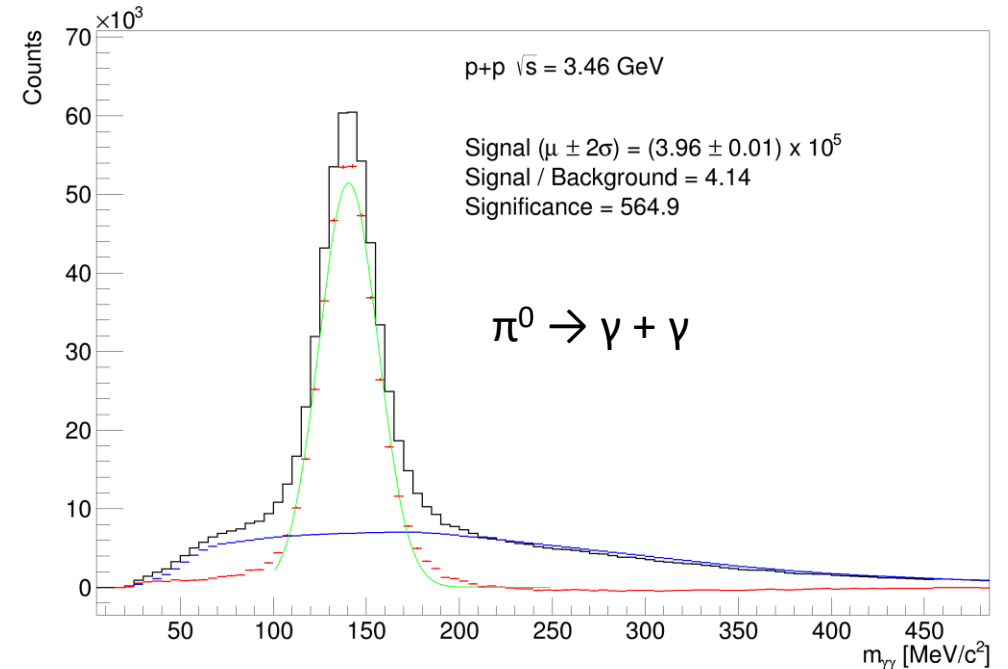
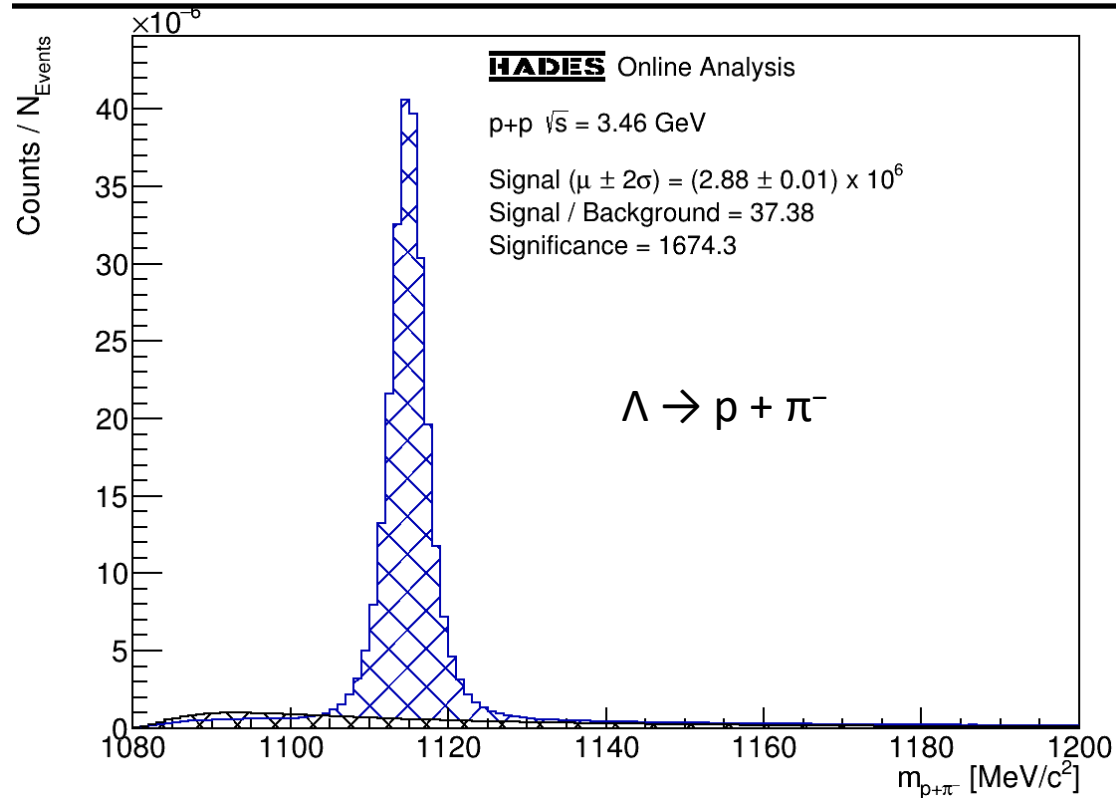


# Dilepton Reconstruction Performance

- High statistics in the  $\phi(1020)$  invariant mass region and above
- $\omega(782)$  and  $\phi(1020)$  signals clearly visible



# Hadron Reconstruction Performance

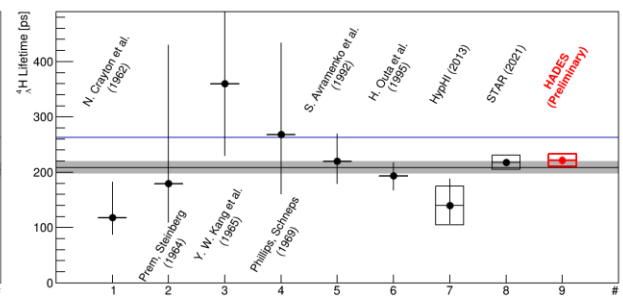
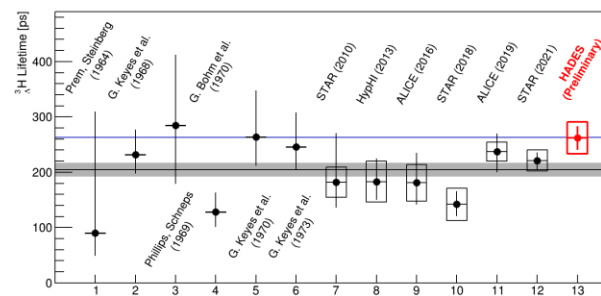
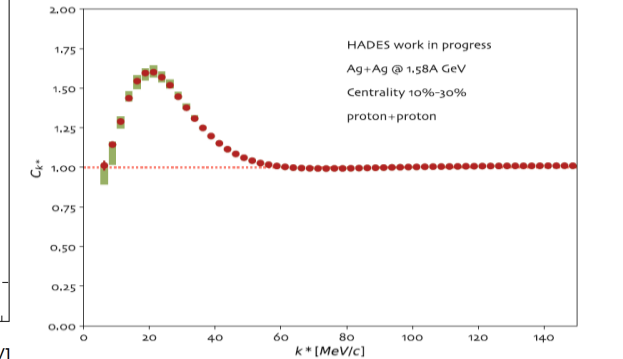
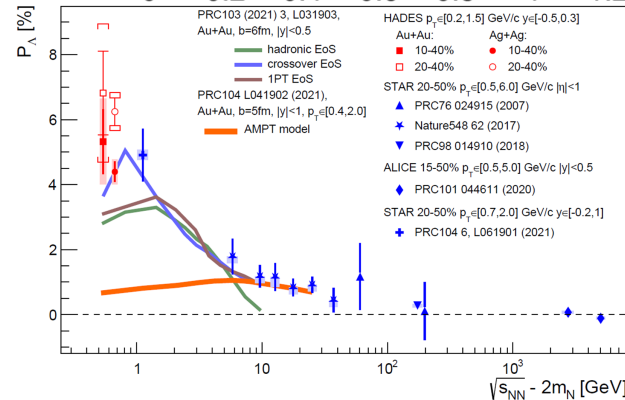
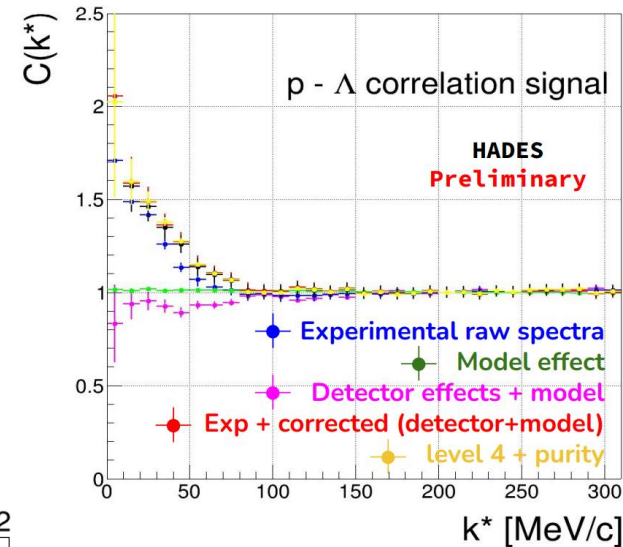
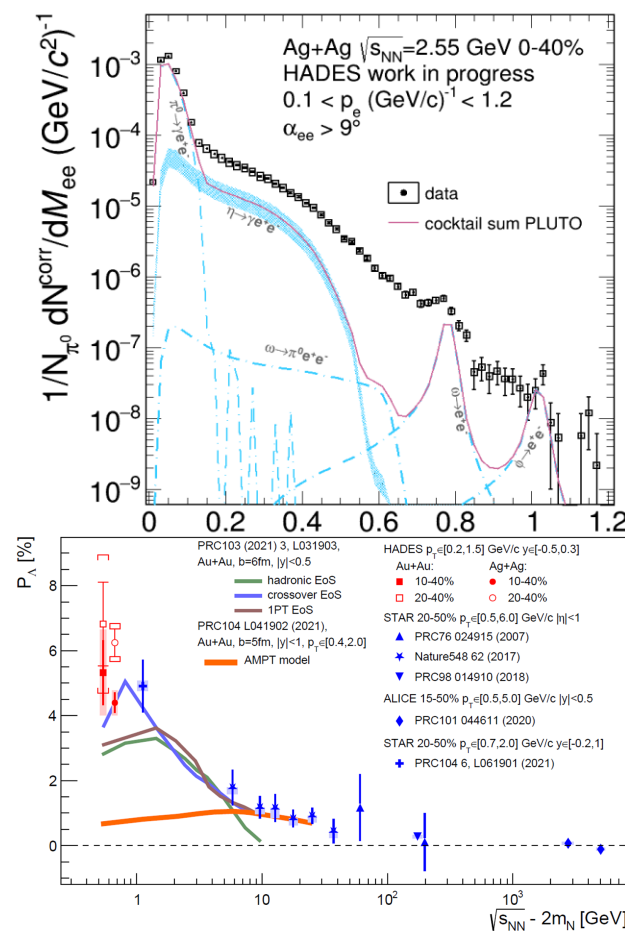


- High statistic signals from  $\Lambda$  and  $\pi^0$  decays  $\rightarrow$  Detailed studies of (rare) hadron properties possible
- NN reference measurements for CBM and STAR Fixed-Target data

# Summary



- HADES detector is upgraded with FAIR technology (ECAL, RICH, iTOF, STS1,2 and fRPC)
- High statistics in dilepton invariant mass spectrum → observed  $\phi(1020)$  signal
- Detailed analyses of bulk particles (Protons, Light Nuclei and Pions)
  - p+p, p+A, A+A, p+ $\Lambda$  Femtoscopy
- Universal strangeness scaling holds in Ag+Ag
- High quality analysis of weak decays with an artificial neural network
  - $4.85\sigma$  deviation of  $^4_\Lambda\text{H}$  lifetime to free  $\Lambda$
- Data from most recent p+p beamtime





# The HADES Collaboration

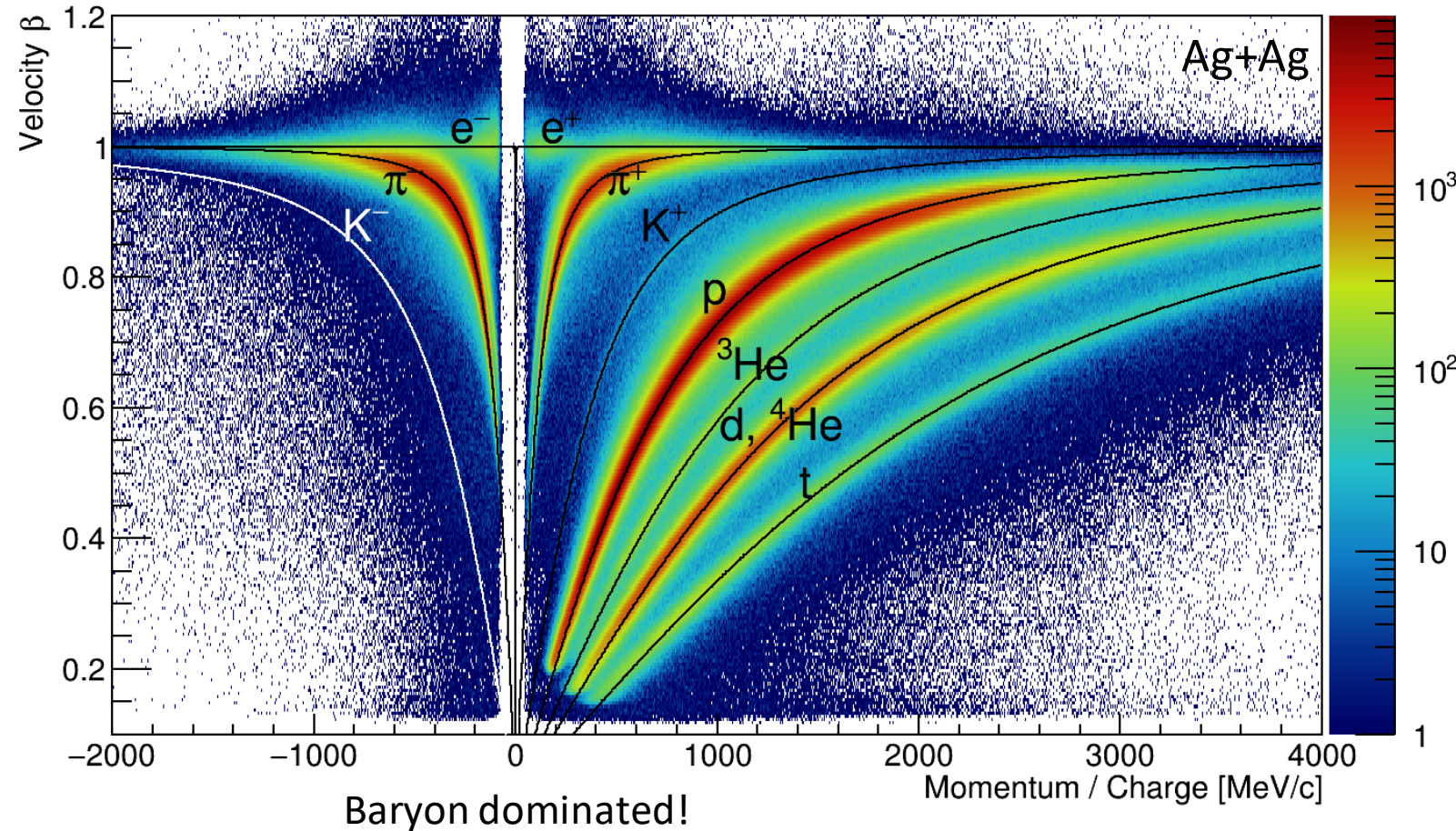




# BACKUP

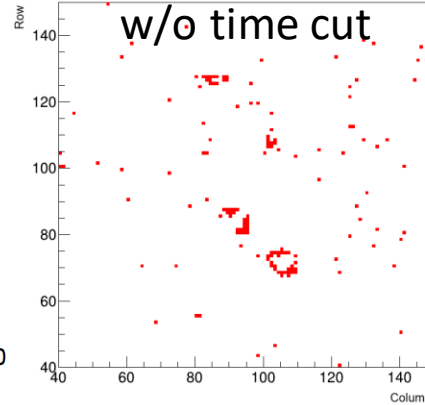
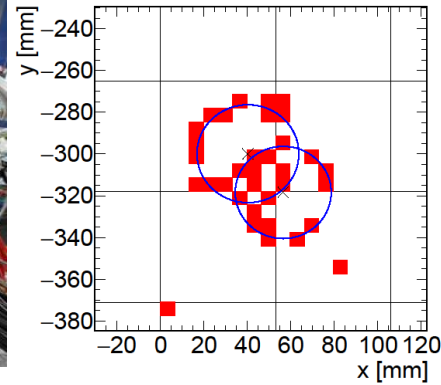
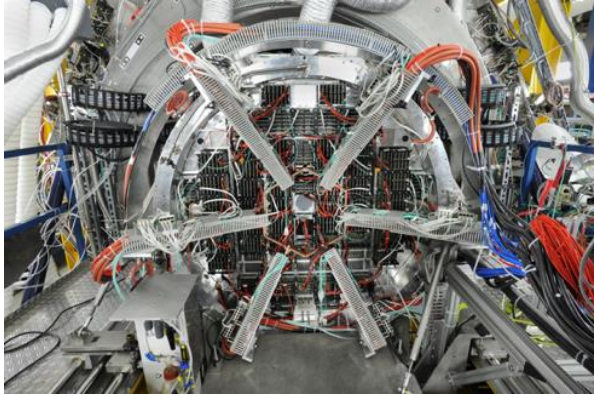
# Hadron Identification with HADES

- Heavy-ion runs:
  - 2012: Au+Au  
 $\sqrt{s_{NN}} = 2.42$  GeV  
7 billion collected events
  - 2019: Ag+Ag  
 $\sqrt{s_{NN}} = 2.55$  and 2.42 GeV  
14 billion collected events
- Hadron PID primarily via momentum and velocity
  - Separation of multiple-charged particles via specific energy loss

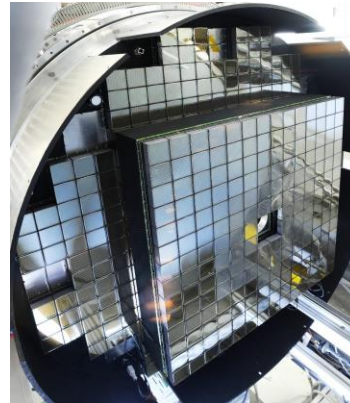


# Lepton Identification with HADES

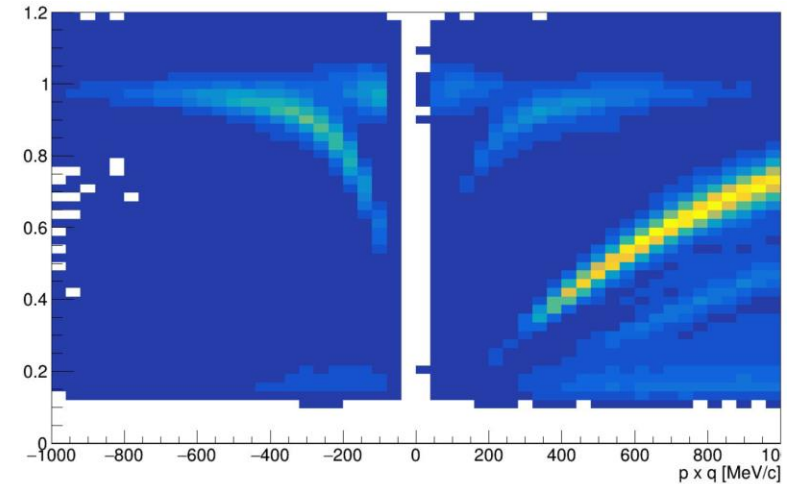
Ag+Ag



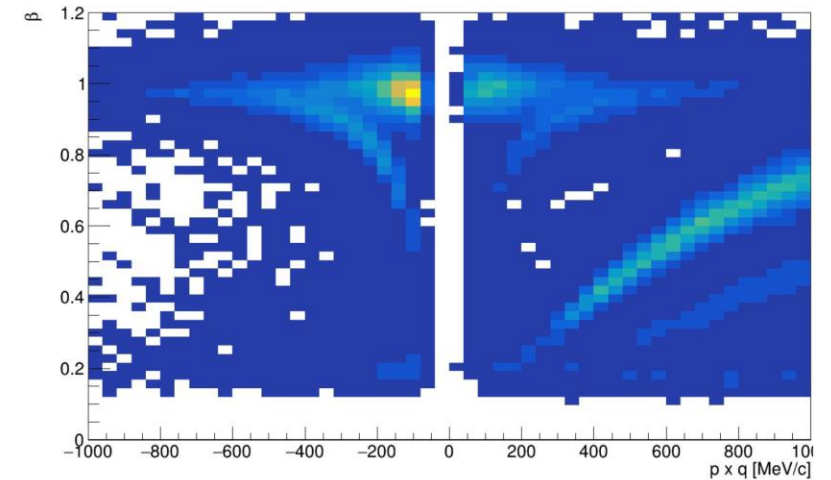
- Upgraded RICH photodetection plane involving future CBM @ FAIR technology
- Good time resolution and increased sensitivity → Allows for time cuts to enhance lepton purity
- Significantly improved lepton identification and double-ring detection → On average 16 hits per ring detected



w/o time cut



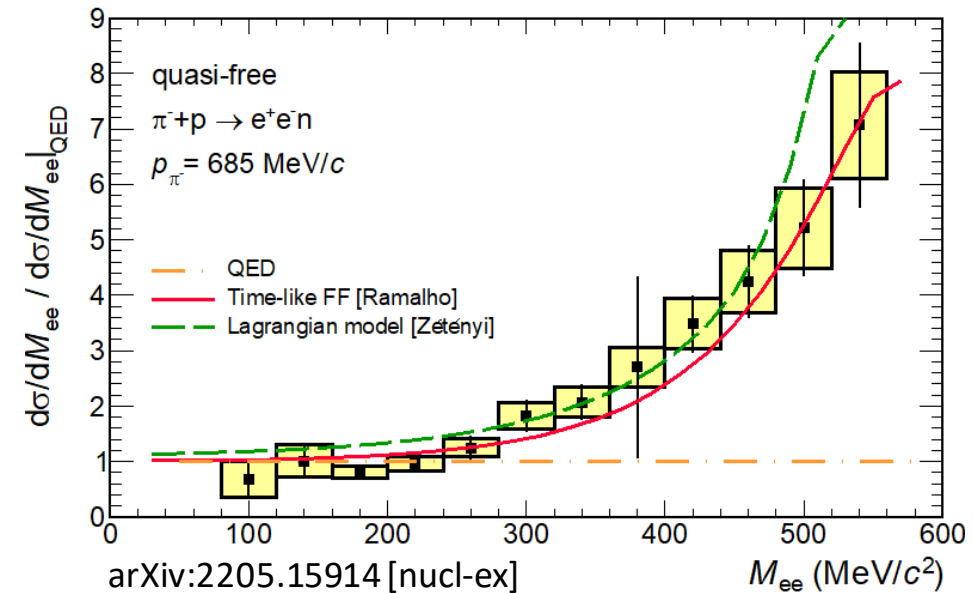
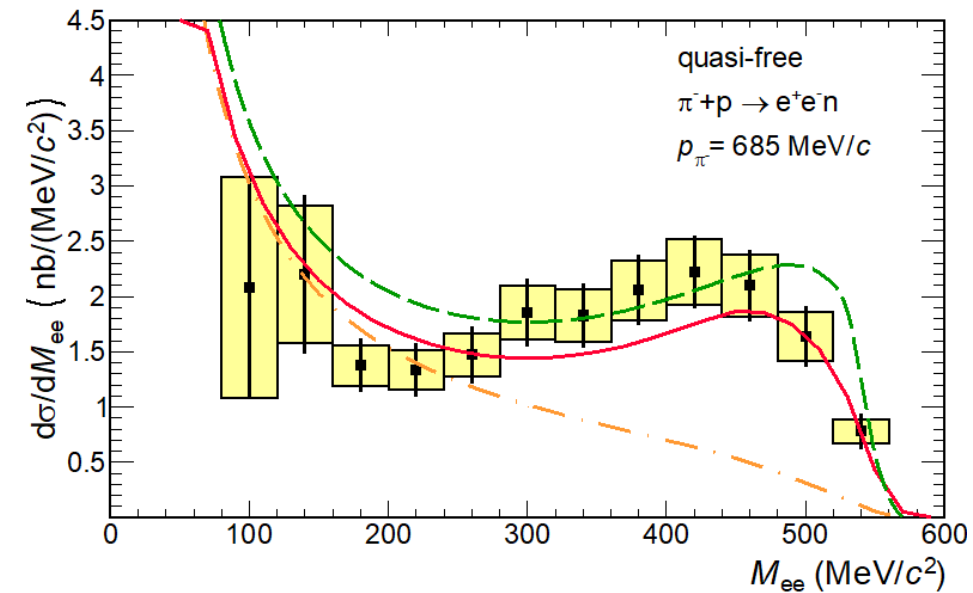
w/ time cut



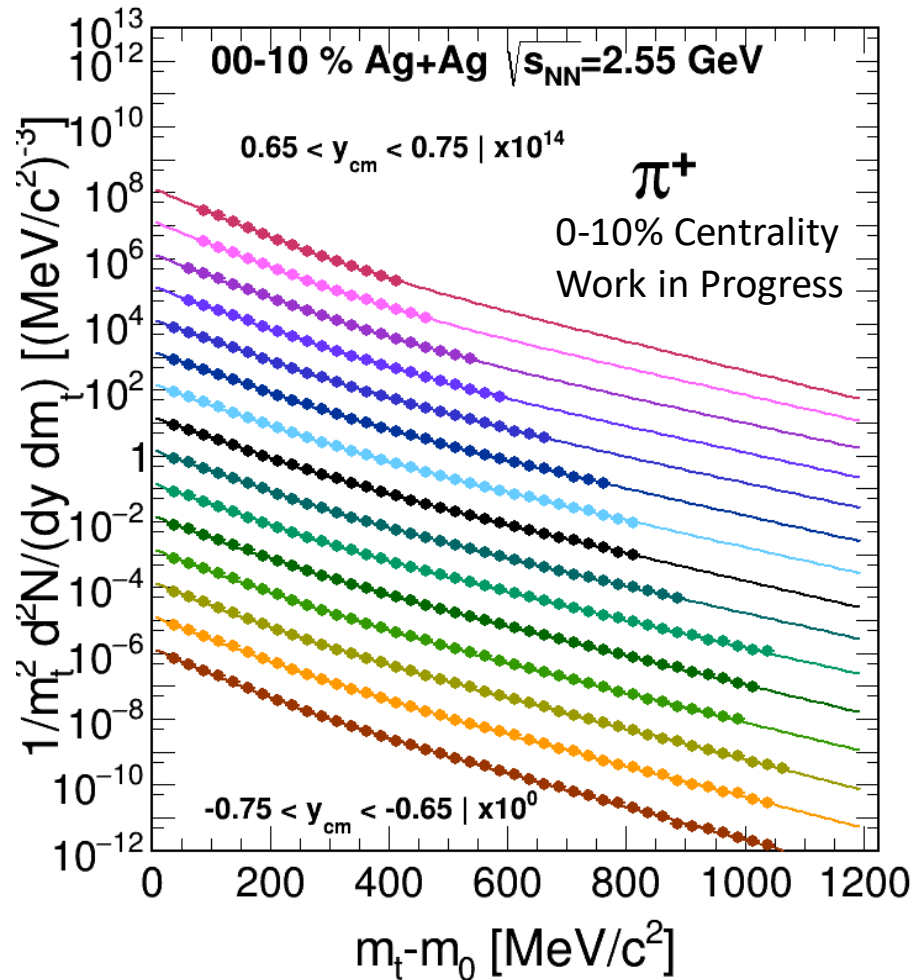
# First measurement of massive $\gamma^*$ emission from $N^*$ baryon resonances

- $\pi^- + p \rightarrow n + \pi^- + \pi^+$ 
  - included in PWA (Bonn-Gatchina) to provide partial wave decomposition
- $\pi^- + p \rightarrow n + e^- + e^+$ 
  - probe baryon resonance – nucleon transition
- Dominance of the  $N^*(1520)$  resonance at  $\sqrt{s_{NN}} = 1.49$  GeV
  - $\rho$  meson as “excitation” of the meson cloud
  - **Vector Meson Dominance – foundation of the emissivity calculations for QCD matter**

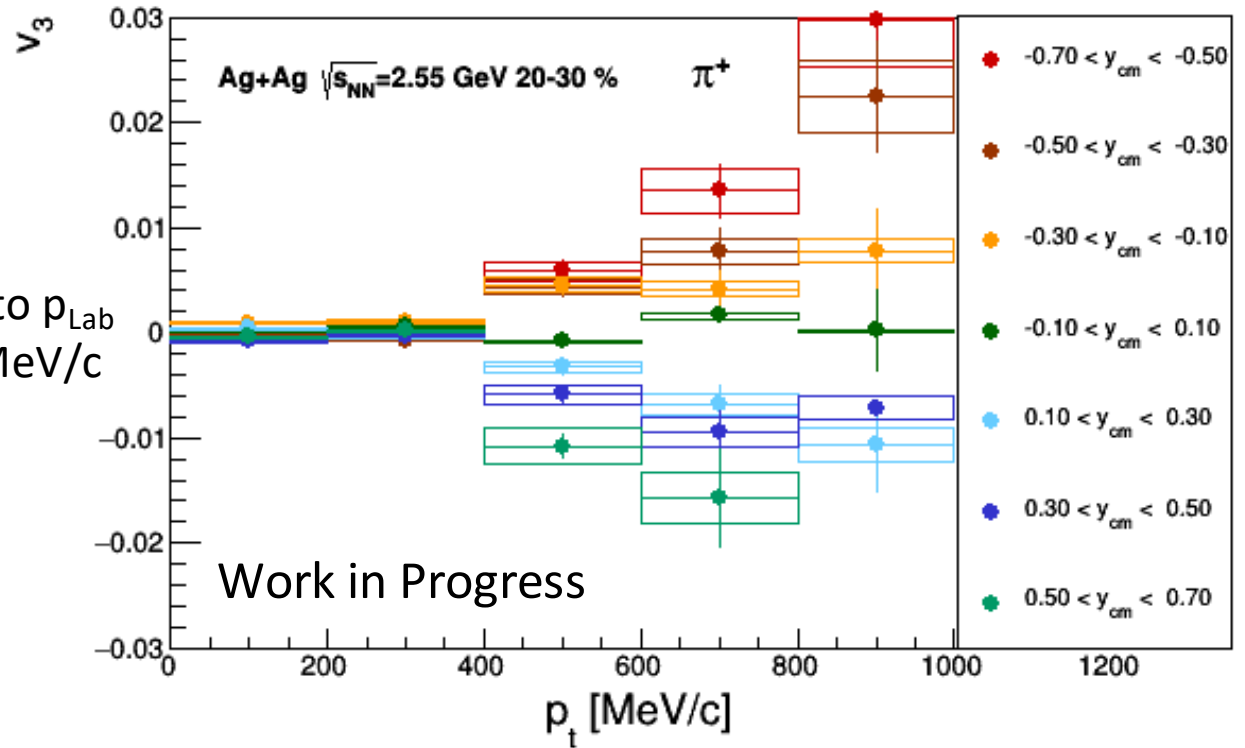
HADES, PRC 102 (2020) 2, 024001  
HADES, PRC 95 (2017) 065205  
 4 first entries ( $N\rho$ )  
4 additional entries



# Charged Pions



Down to  $p_{Lab}$   
= 60 MeV/c

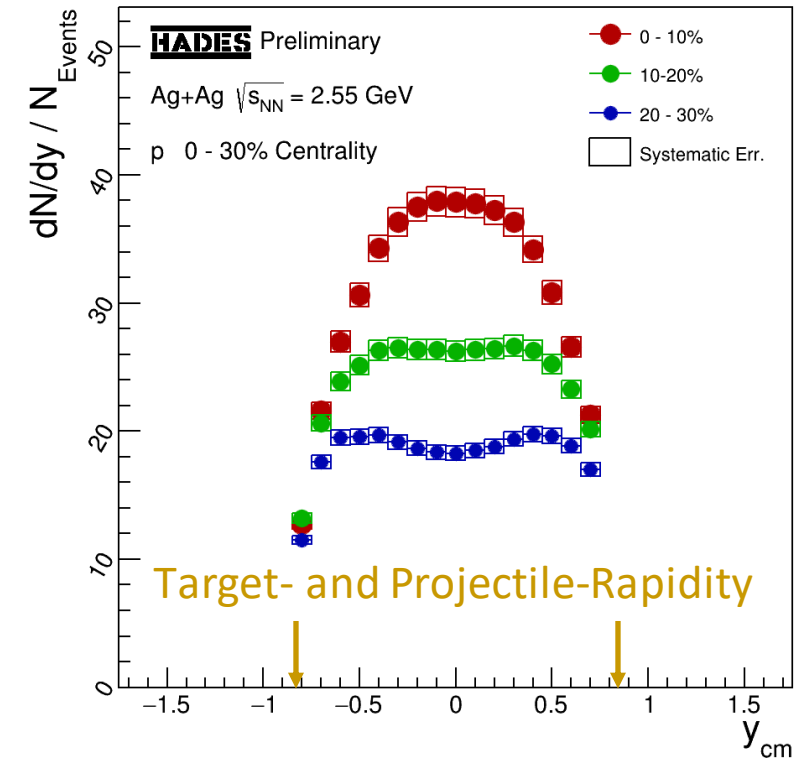
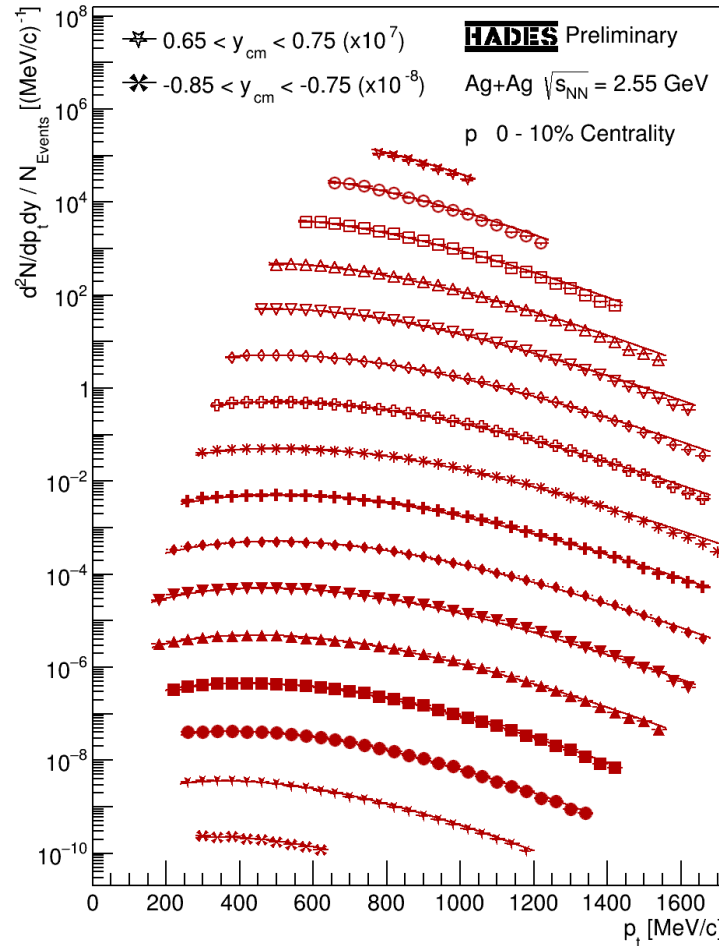


- High statistics allow for multi-differential analyses (spectra, angular distributions, azimuthal anisotropy, coulumb force, etc.)
- First observation of Pion- $v_3$  at this energy



# Protons: Yield and Kinematic Distributions

- Large phase space coverage with small statistical and systematic errors
- Influence of spectator matter clearly visible in peripheral collisions
- Various multi-differential analyses (spectra, angular distributions, azimuthal anisotropy, etc.) possible
- Light Nuclei (d, t,  $^3\text{He}$ ) under analysis

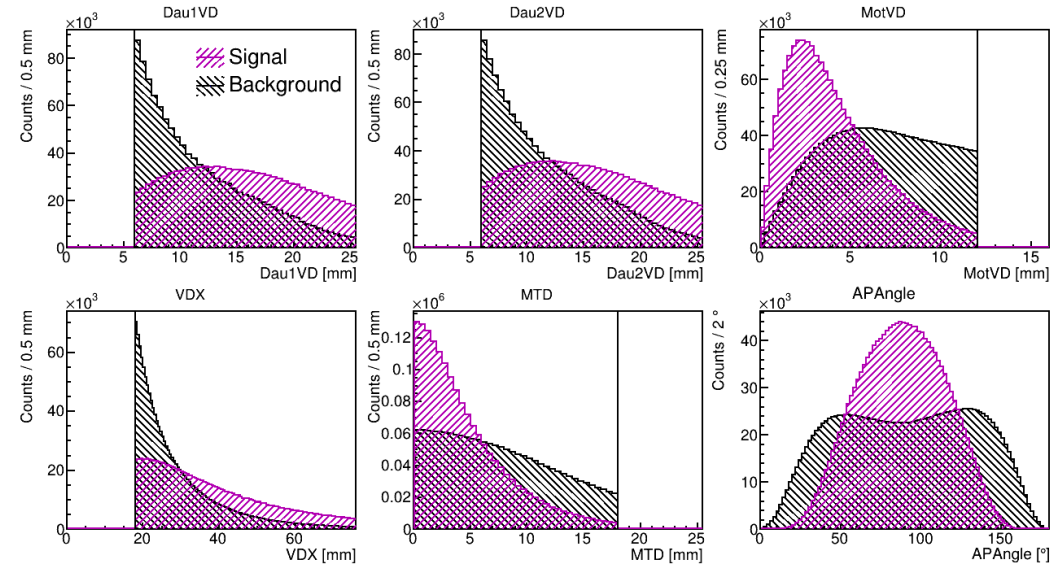
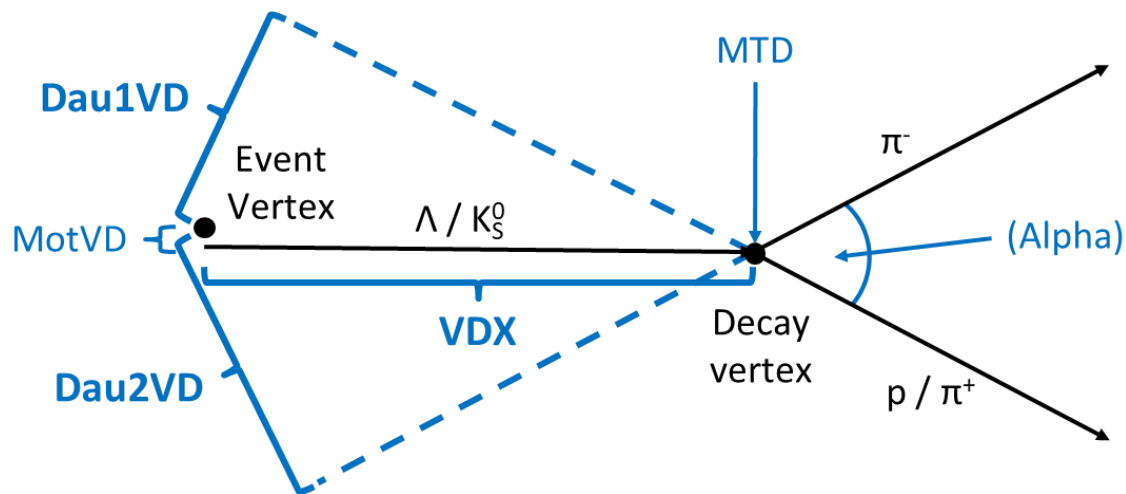


- 0-10%: Nucleons almost stopped
- 10-30%: Participant region contaminated with spectators



# Weak decay reconstruction

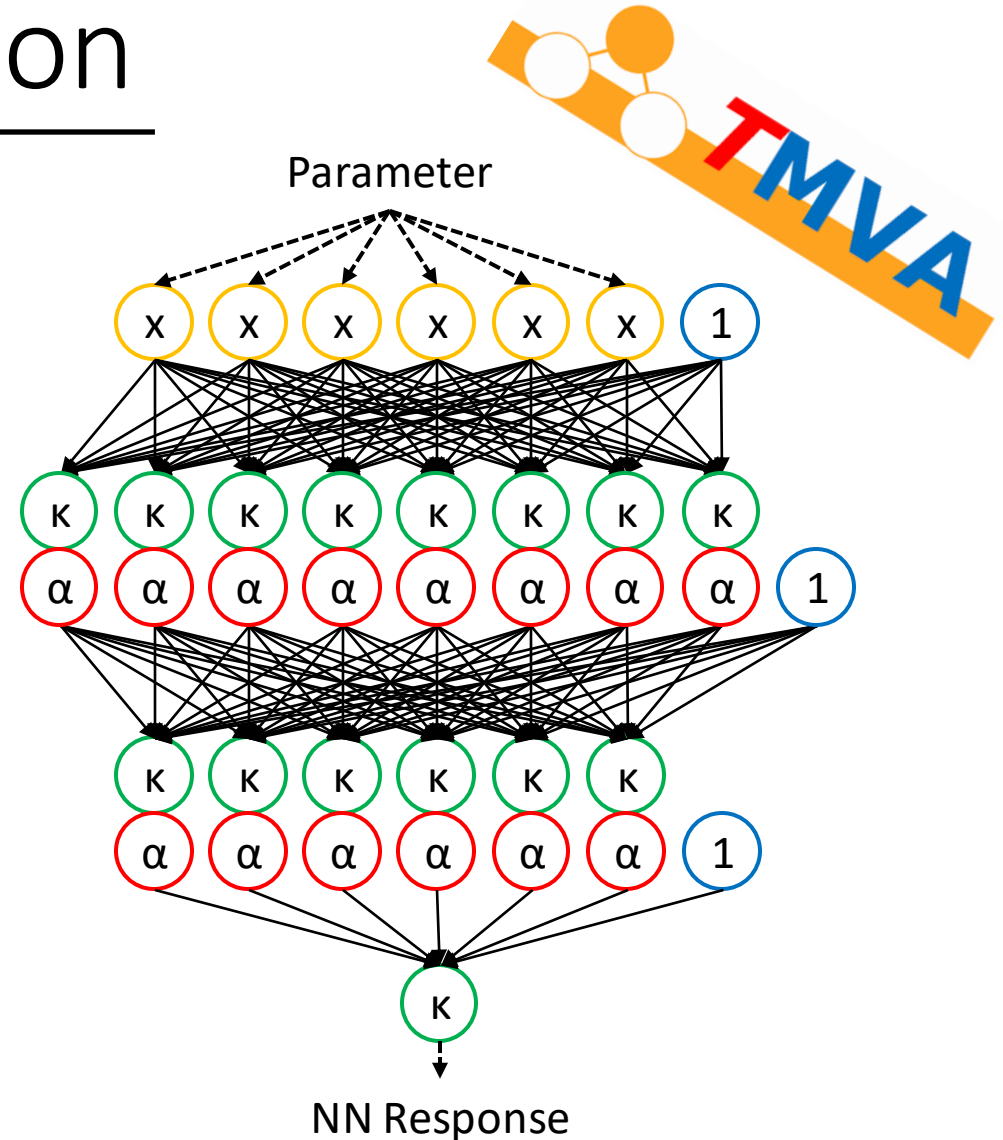
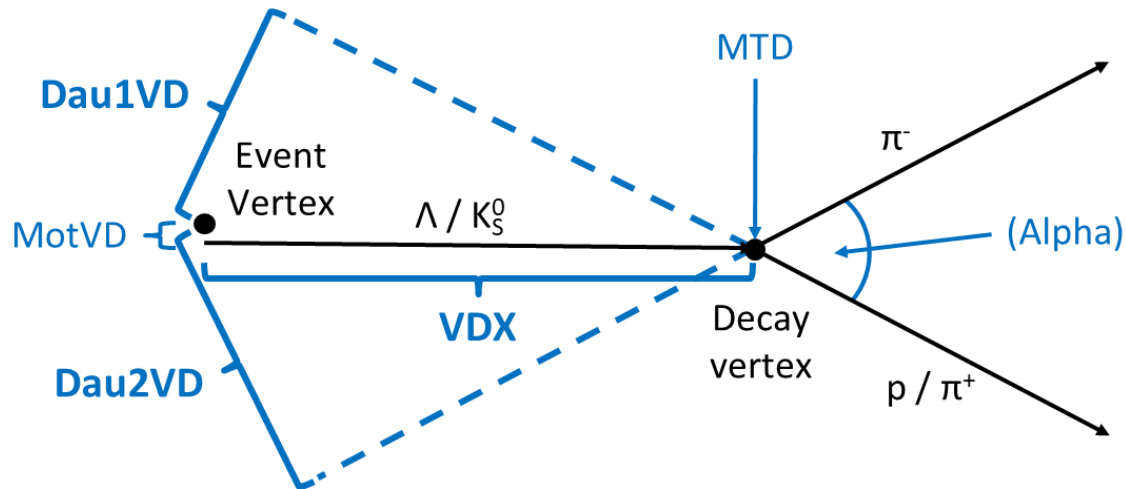
- Combinatorial background about factor 10,000 above signals
- Long lifetimes  $\rightarrow$  Off-vertex-topology
- Evaluated by an artificial neural network  
TMVA: arXiv:physics/0703039v5 [physics.data-an]



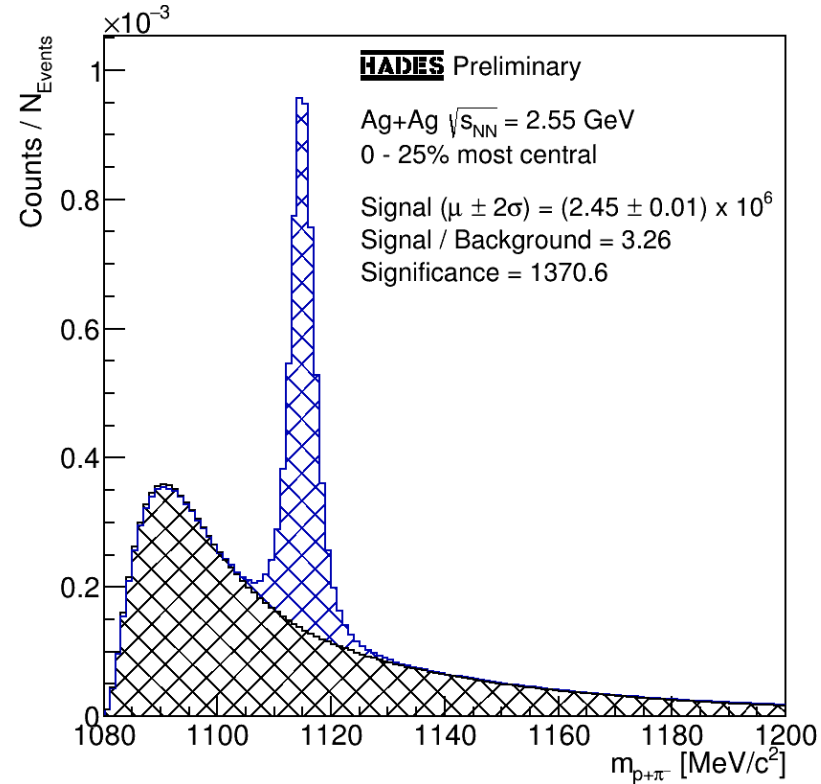
Toolkit for **M**ulti**V**ariate Data **A**nalysis with **R**OOT

# Weak decay reconstruction

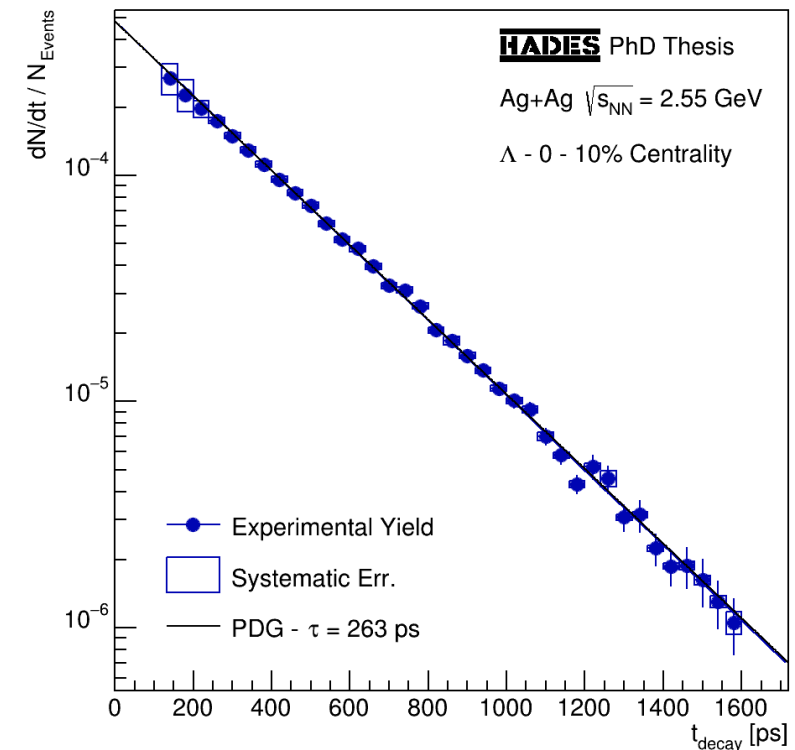
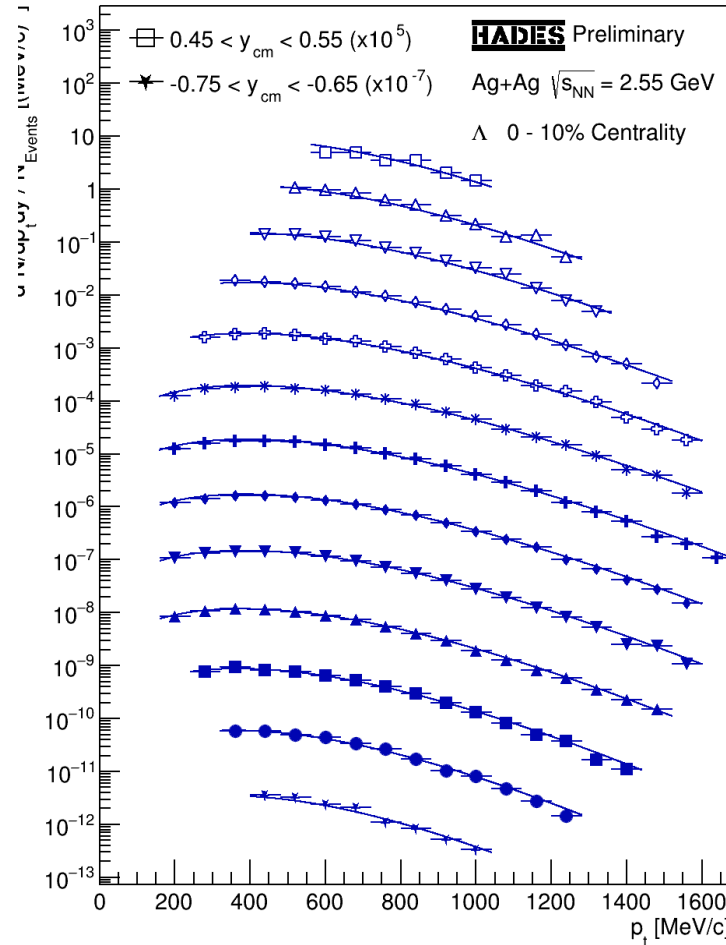
- Combinatorial background about factor 10,000 above signals
- Long lifetimes  $\rightarrow$  Off-vertex-topology
- Evaluated by an artificial neural network  
TMVA: arXiv:physics/0703039v5 [physics.data-an]



# Reconstruction and Analysis of $\Lambda$ Hyperons

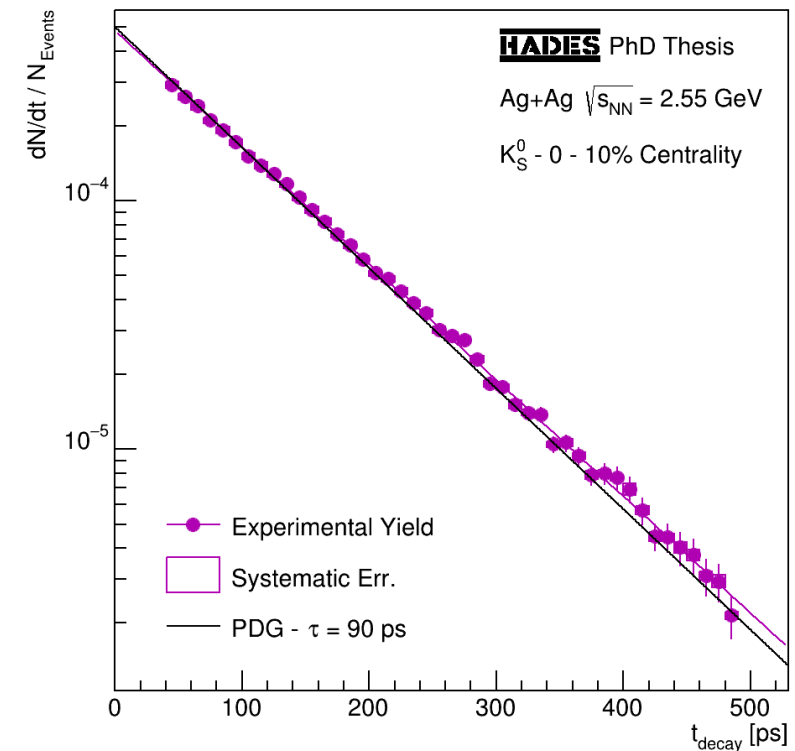
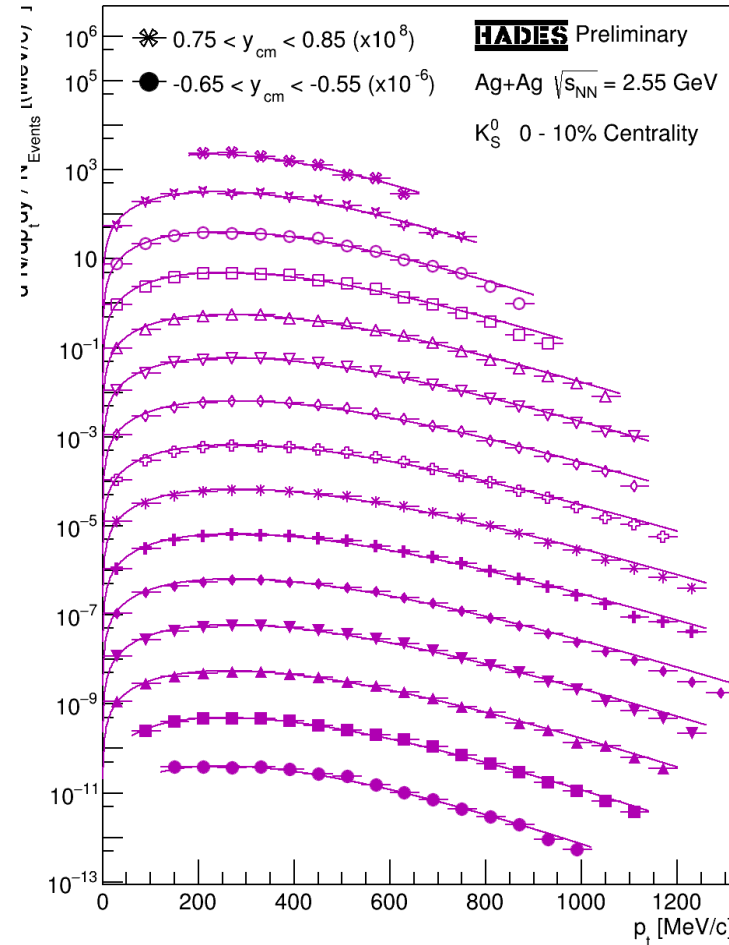
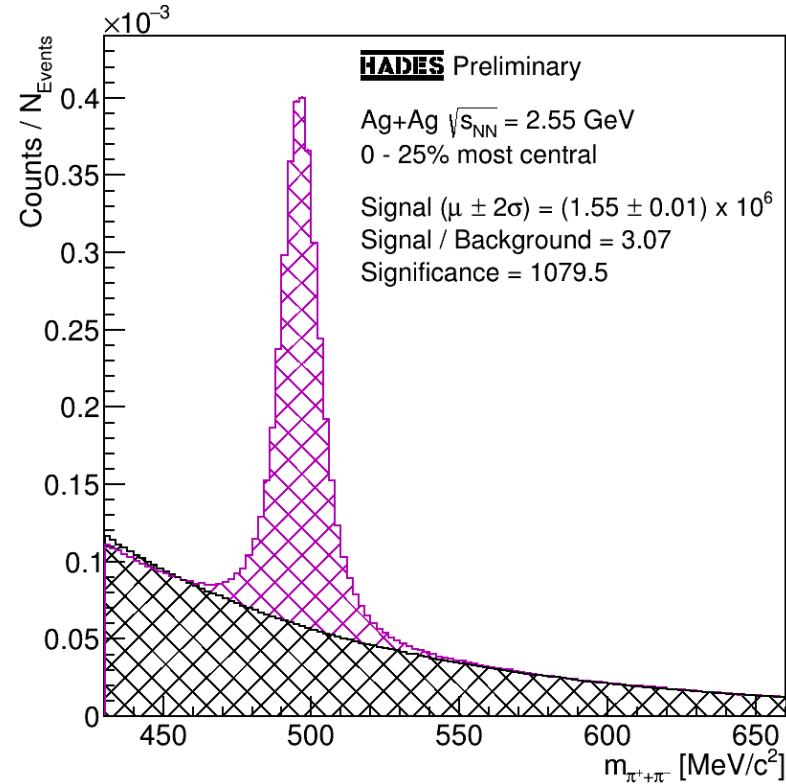


- Very significant signal
- Detailed analyses of hyperon production possible



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

# Reconstruction and Analysis of $K_S^0$ Mesons

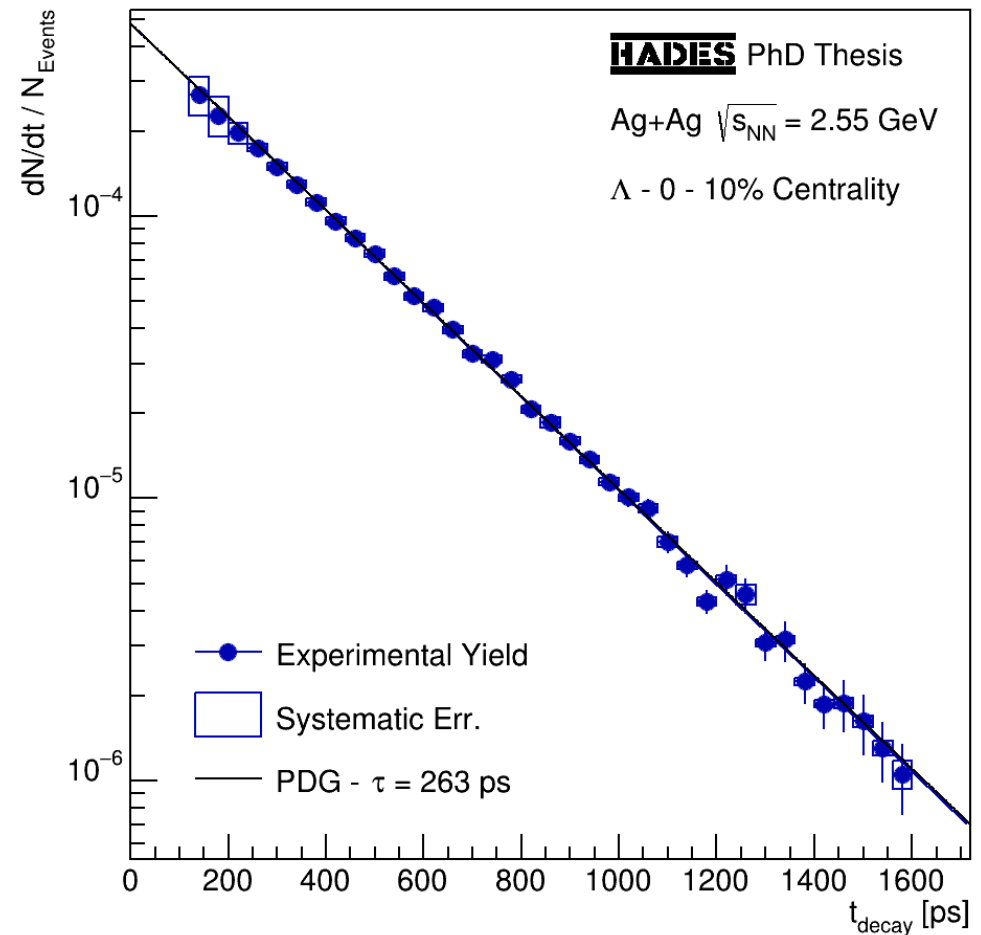


- Very significant signal
- Detailed analyses of strange meson production possible

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

# $\Lambda$ Lifetime Measurement

- Test case for measurements of hypernuclei lifetimes
- Efficiency correction very sensitive to momentum distribution of simulated  $\Lambda$ s
  - Multi-differential efficiency correction – Challenging for rare particles
  - Measured phase-space distribution as simulation input – Distribution must be known
- Obtained lifetime of  $(262 \pm 2 \pm 3)$  ps in good agreement with PDG lifetime



# Hypernuclear Properties

## The Hypertriton – ${}^3_{\Lambda}\text{H}$

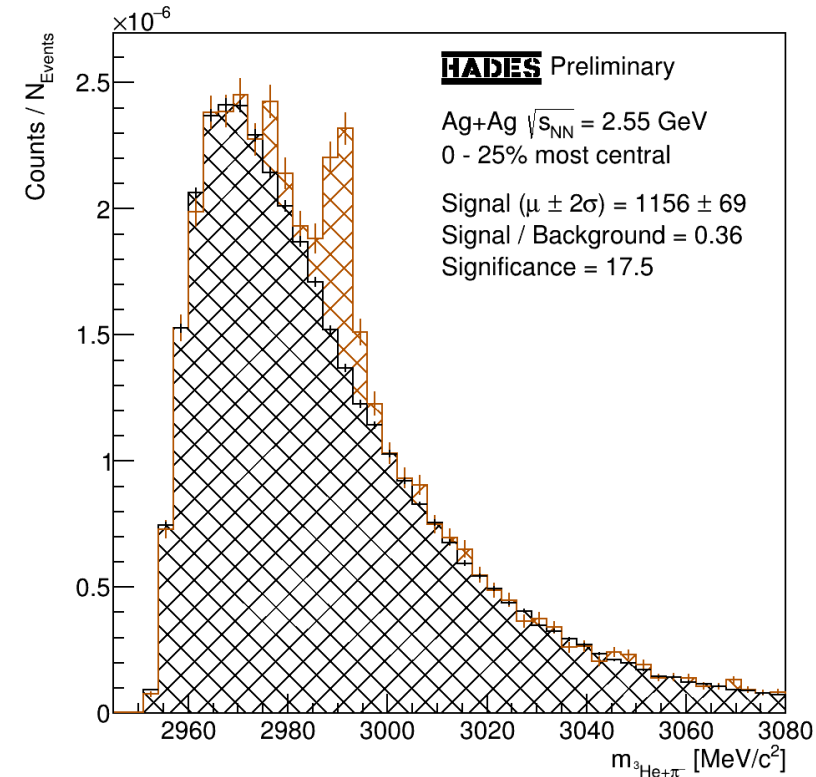
- Mass of  $\approx 2991 \text{ MeV}/c^2$ 
  - Binding energy  $B({}^3_{\Lambda}\text{H}) \approx 0.79 \text{ MeV}/A$
- Primarily four mesonic decay channels:
  - ${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He} + \pi^-$  (BR  $\approx 27\%$ )
  - ${}^3_{\Lambda}\text{H} \rightarrow t + \pi^0$  (BR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

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

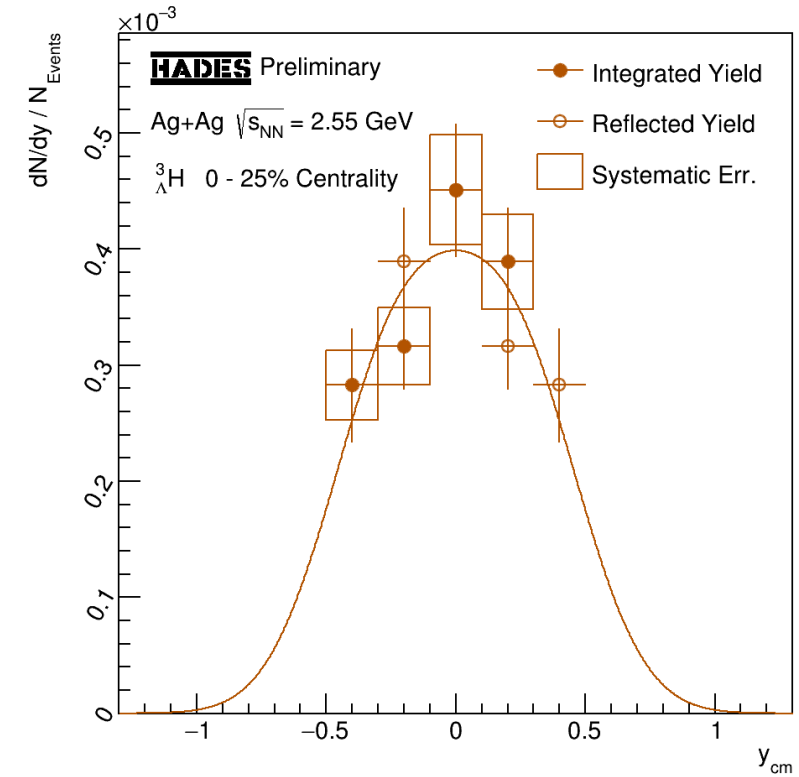
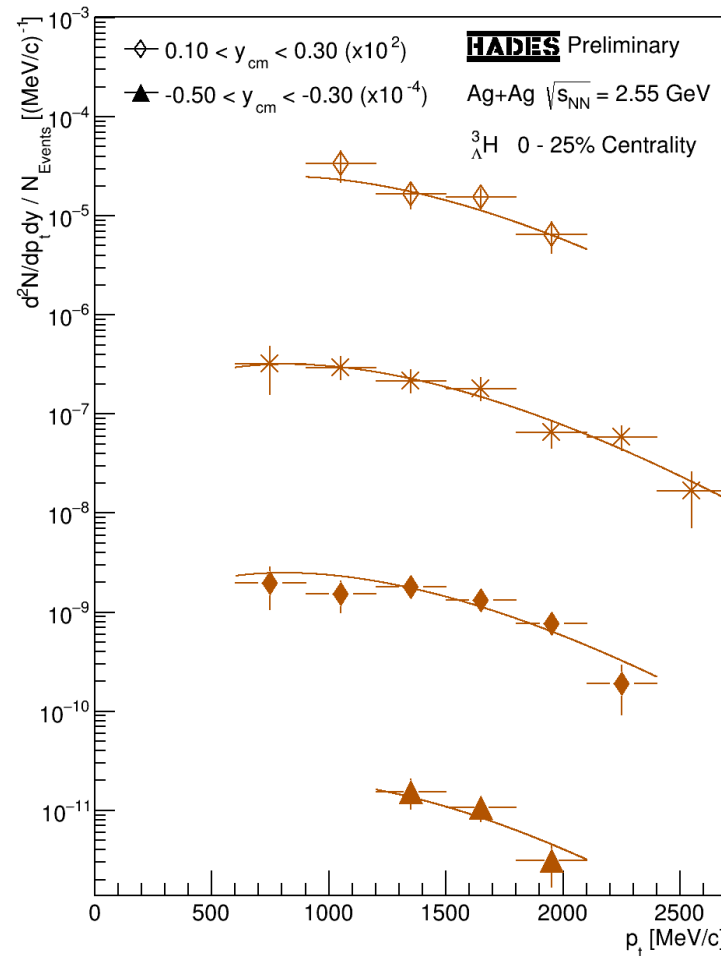
- Mass of  $\approx 3923 \text{ MeV}/c^2$ 
  - Binding energy  $B({}^4_{\Lambda}\text{H}) \approx 2.63 \text{ MeV}/A$   
 $\rightarrow \approx 3.3 B({}^3_{\Lambda}\text{H})$
- Primarily three mesonic decay channels:
  - ${}^4_{\Lambda}\text{H} \rightarrow {}^4\text{He} + \pi^-$  (BR  $\approx 50\%$ )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



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

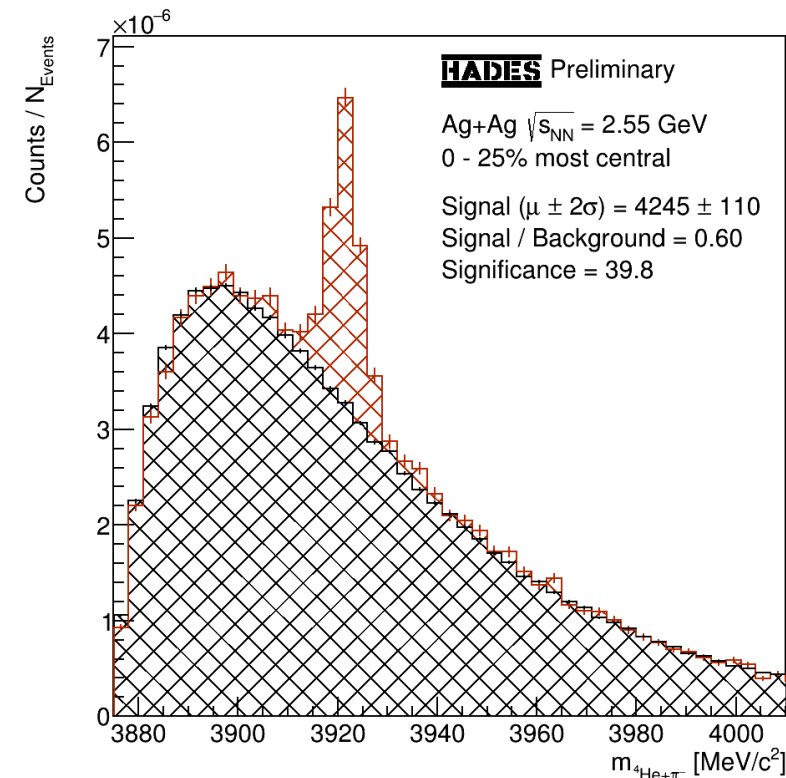


- Significant signal
- Multi-differential analysis of  ${}^3_{\Lambda}\text{H}$  production possible

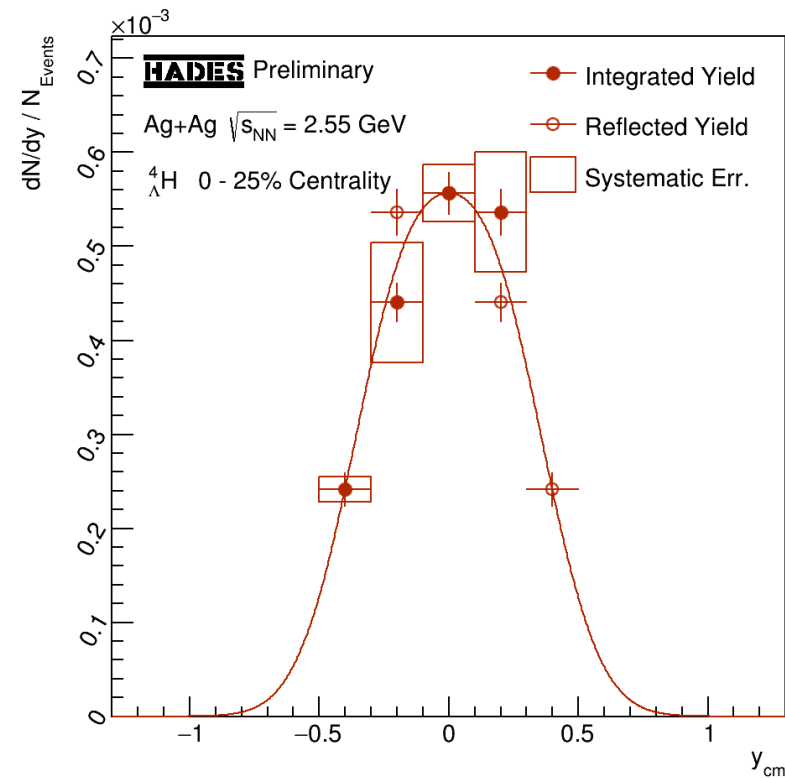
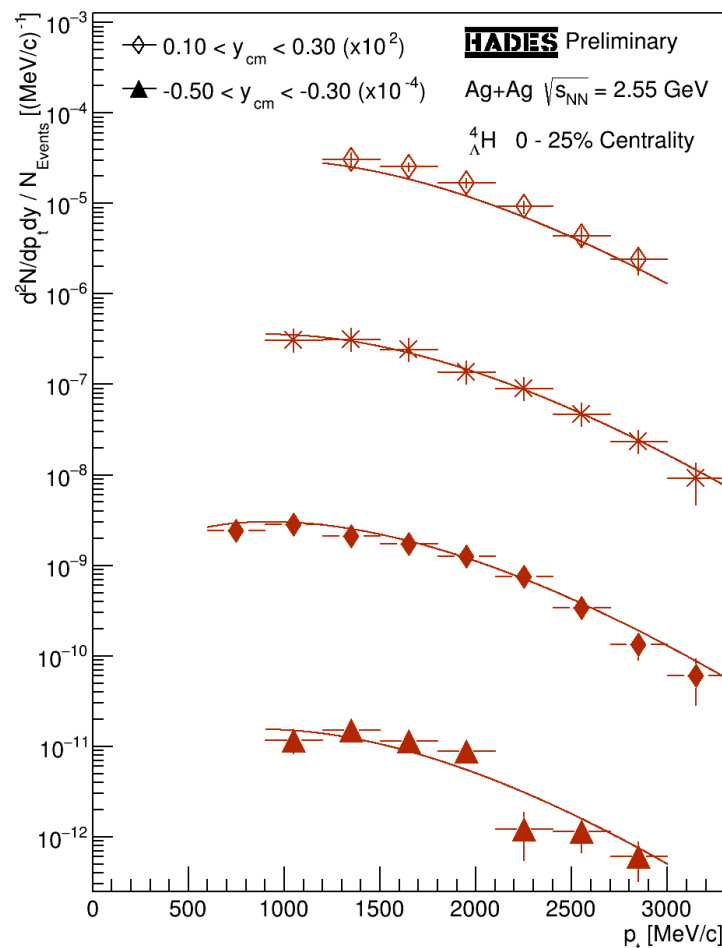


- **First measurement at mid-rapidity at this energy**
- Systematic studies ongoing

# ${}^4_{\Lambda}\text{H}$ Two-Body Decay: ${}^4_{\Lambda}\text{H} \rightarrow {}^4\text{He} + \pi^-$

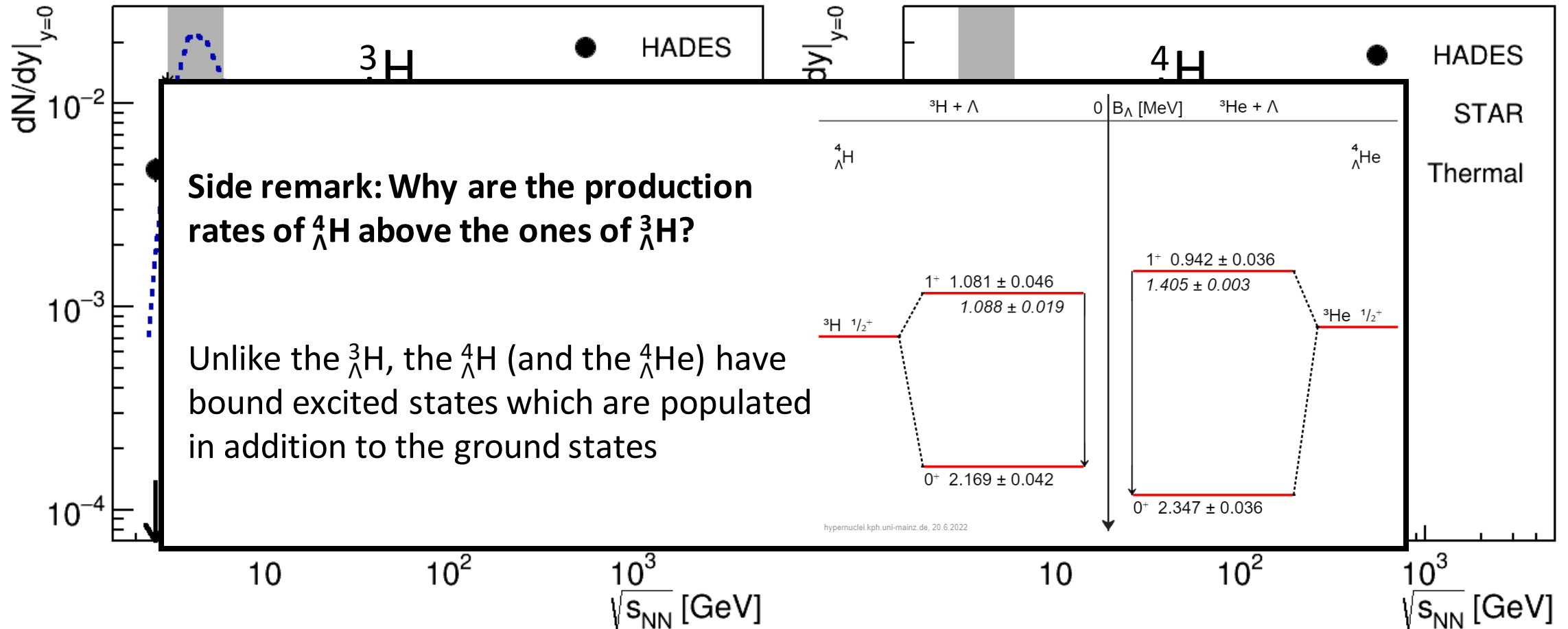


- Significant signal
- Multi-differential analysis of  ${}^4_{\Lambda}\text{H}$  production possible



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

# Hypernuclear Energy Excitation Functions



Only few measurements available → Interesting prospects for upcoming FAIR experiments (e.g. CBM)