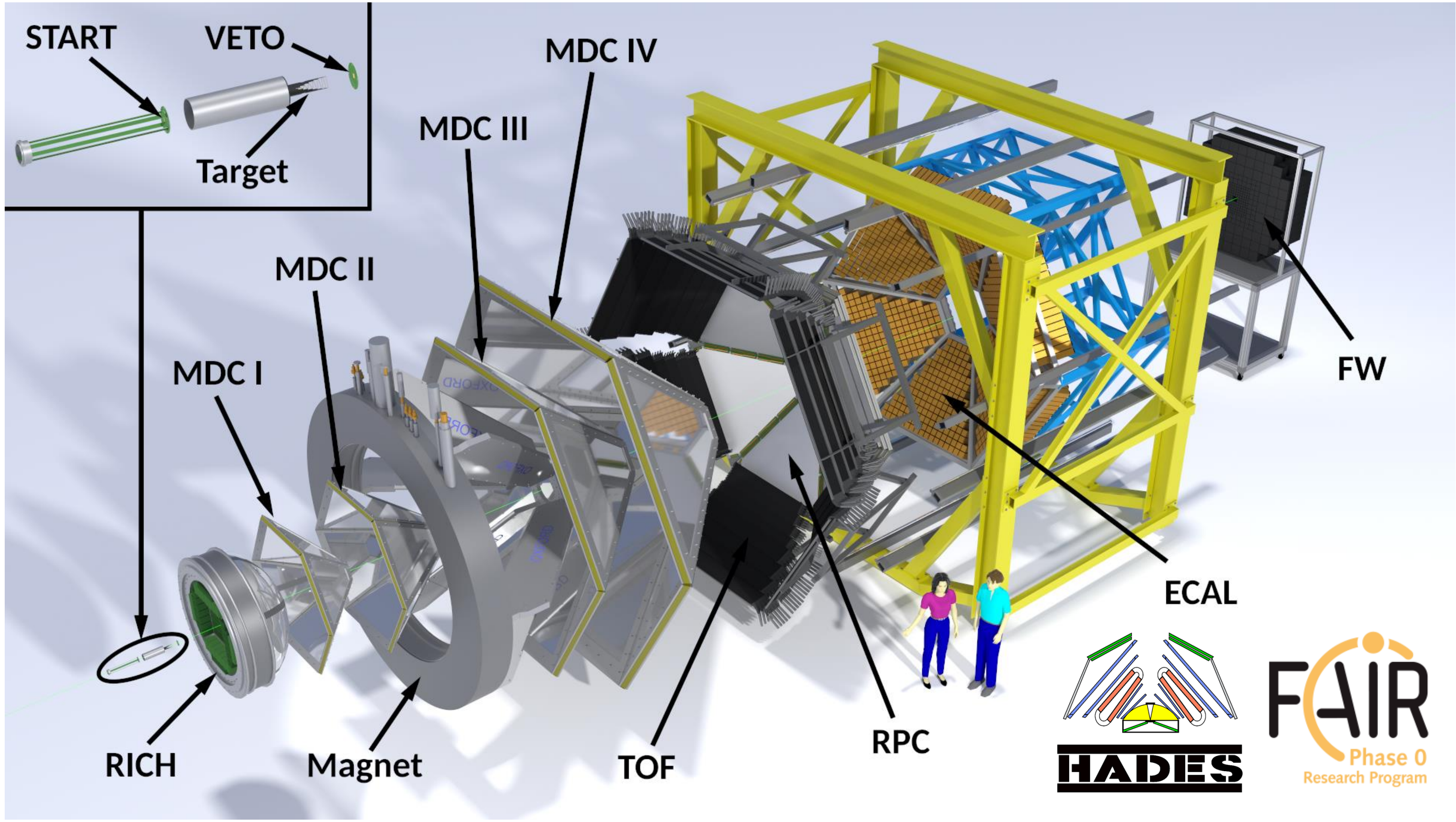
Weak Decays at HADES

Enhancing the reconstruction of weakly decaying particles using an artificial Neural Network at HADES

Simon Spies for the HADES Collaboration

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

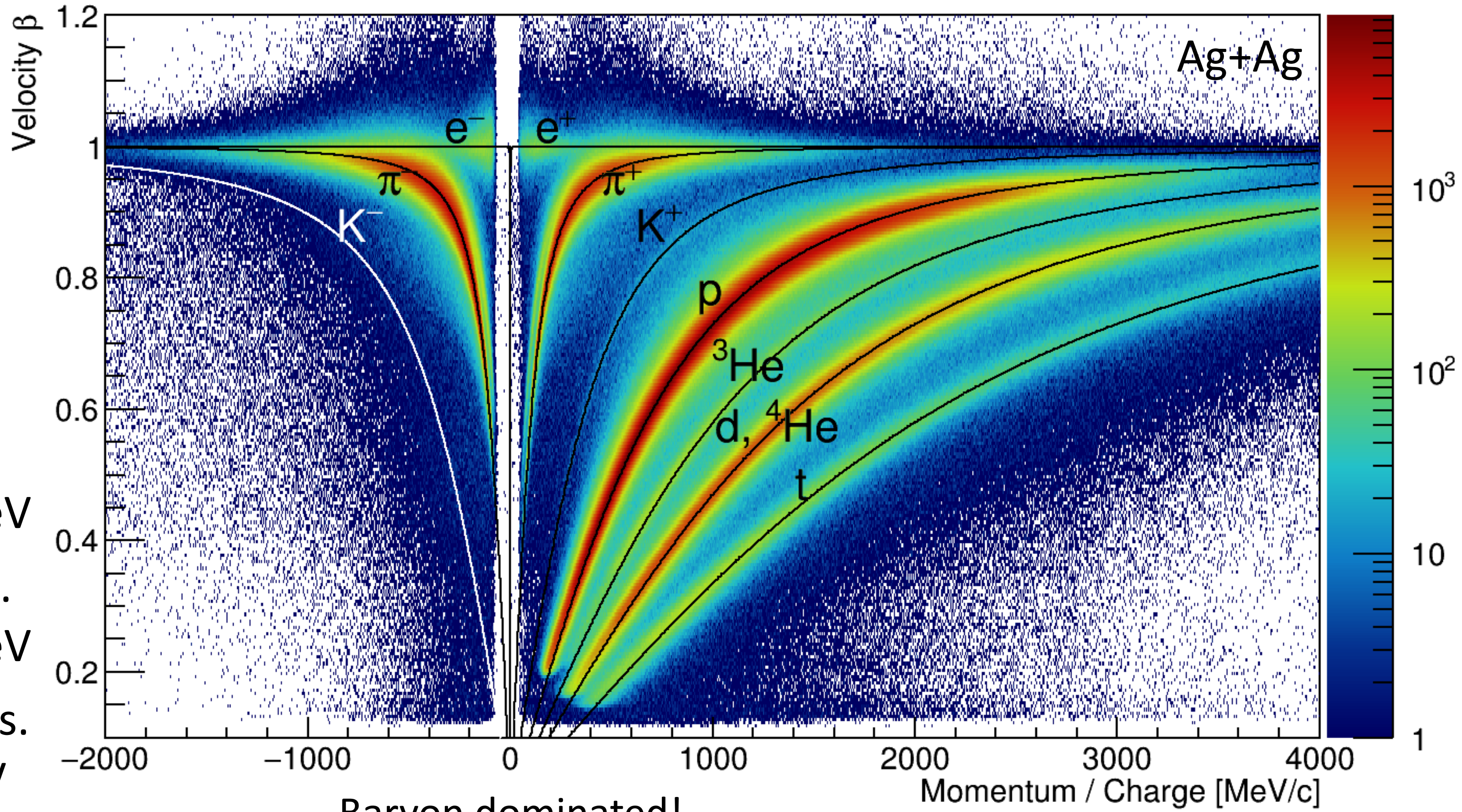


- Almost full azimuthal angle and polar angles between 18° and 85° covered

The HADES Experiment

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

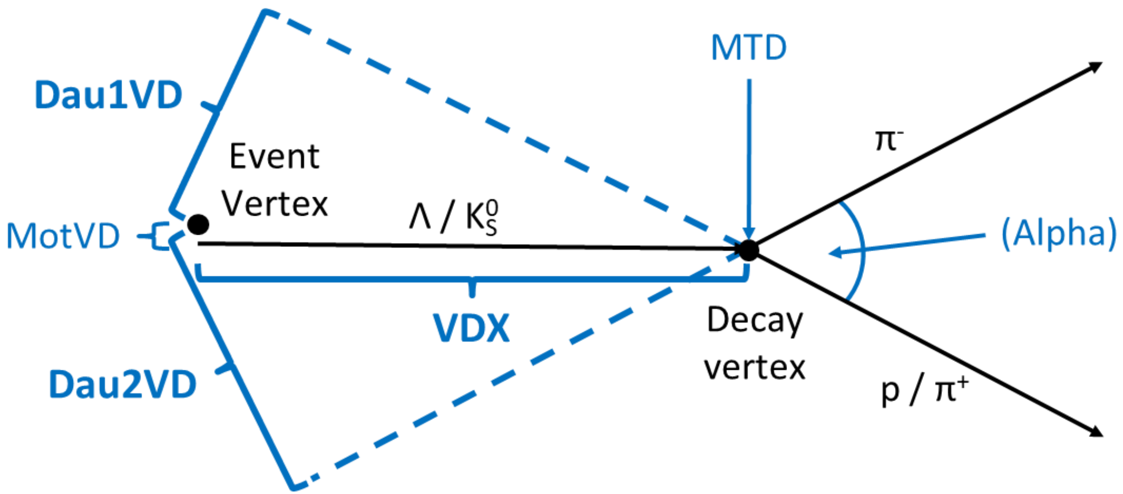
- Heavy-ion beamtimes:
  - 2012: 7 billion Au+Au evts. 1.23A GeV: $\sqrt{s_{NN}}$ = 2.42 GeV
  - 2019: 14 billion Ag+Ag evts. 1.58A GeV: $\sqrt{s_{NN}}$ = 2.55 GeV
  - 2024: 1.8 billion Au+Au evts. 0.8A GeV: $\sqrt{s_{NN}}$ = 2.24 GeV

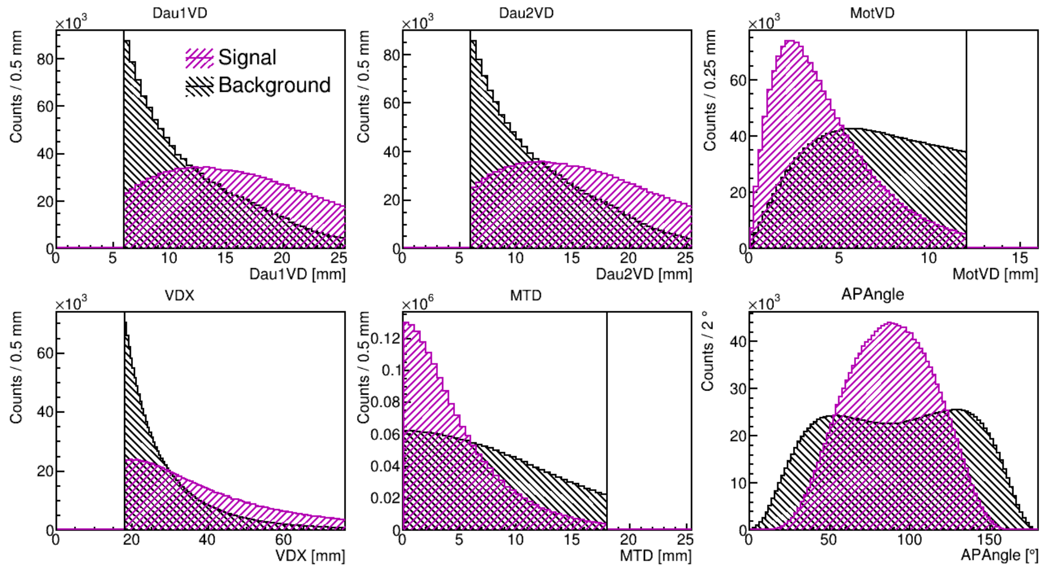


Baryon dominated!

Weak decay reconstruction

- Combinatorial background about factor 10,000 above signals
- Long lifetimes → Off-vertex-topology
- Evaluated by an artificial intelligence tool
  TMVA: arXiv:physics/0703039v5 [physics.data-an]





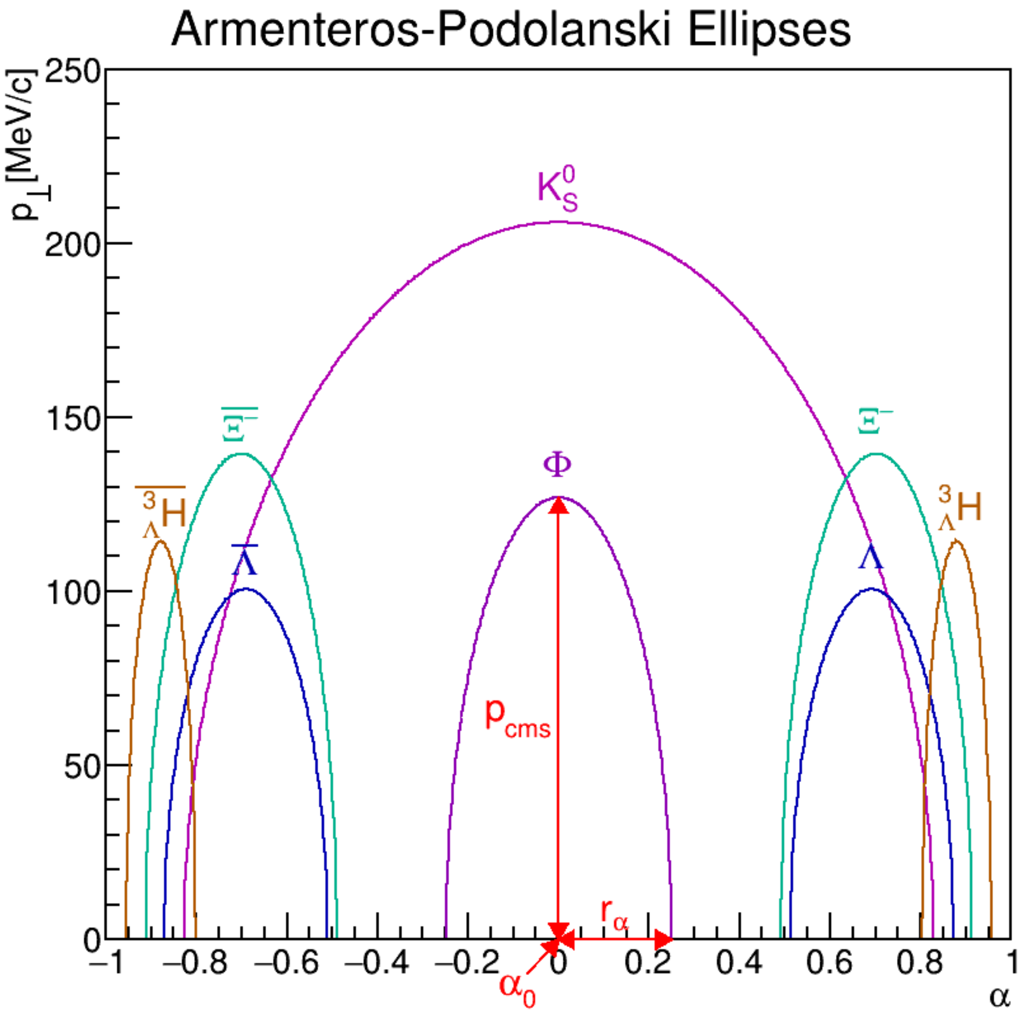
Toolkit for **M**ulti**V**ariate Data **A**nalysis with ROOT

Armenteros-Podolanski Method

- Ellipse equation: $\left(\frac{\alpha_{AP}-\alpha_0}{r_\alpha}\right)^2 + \left(\frac{p_\perp}{p_{cms}}\right)^2 = 1$

  - $p_{cms} = \sqrt{\left(\frac{m_M^2+m_\pm^2-m_\mp^2}{2m_M}\right)^2 - m_\pm^2}$
  - $\alpha_0 = \frac{m_+^2-m_-^2}{m_M^2}$ und $r_\alpha = 2\frac{p_{cms}}{m_M}$

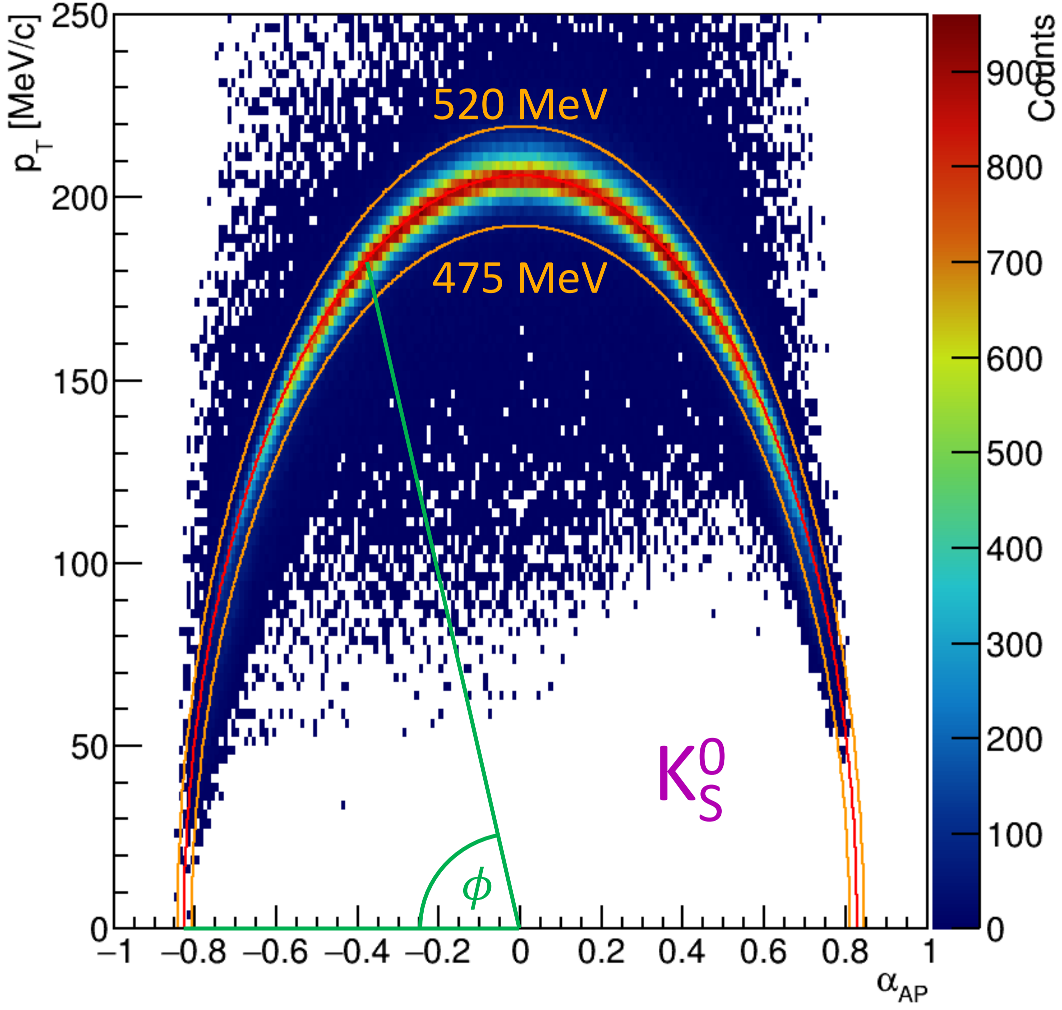
- Only works for ultra relativistic systems with $\beta_{coll} \rightarrow 1$
- For Ag+Ag @ 1.58A GeV: $\beta_{coll} = 0.676$
  - Additional artificial boost with β = 0.99 in longitudinal direction required



Armenteros-Podolanski Method Extended

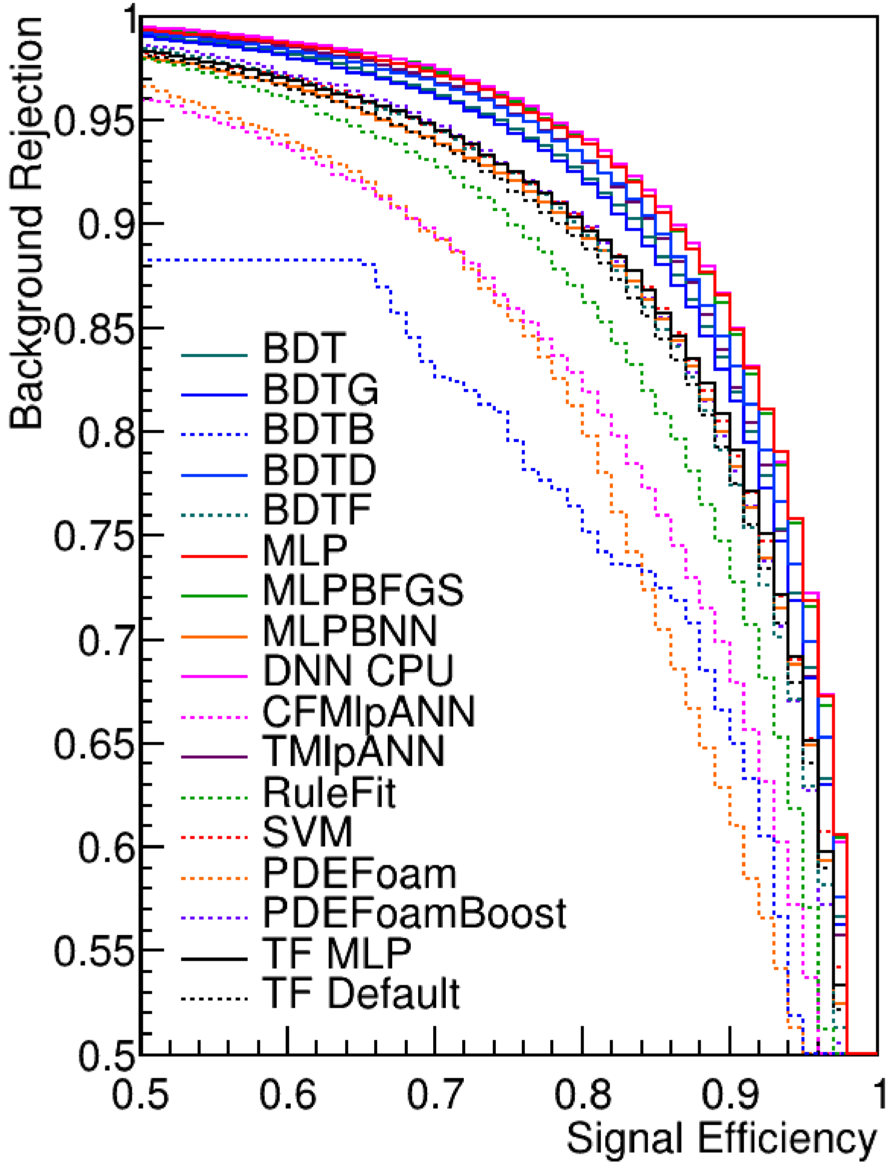
- Straight forward approach: Cut on ideal curve
  - Corresponds to a simple invariant mass cut
  - Estimation of residual background impossible
- Interpret ellipse in polar coordinates:
  - Radius corresponds to invariant mass
  - Angle ϕ completely independent from inv. mass
- Use polar angle ϕ as aNN input parameter:

$$\phi = arctan\left(\frac{p_\perp}{p_{cms}} * \frac{r_\alpha}{(\alpha_0 - \alpha_{AP})}\right)$$

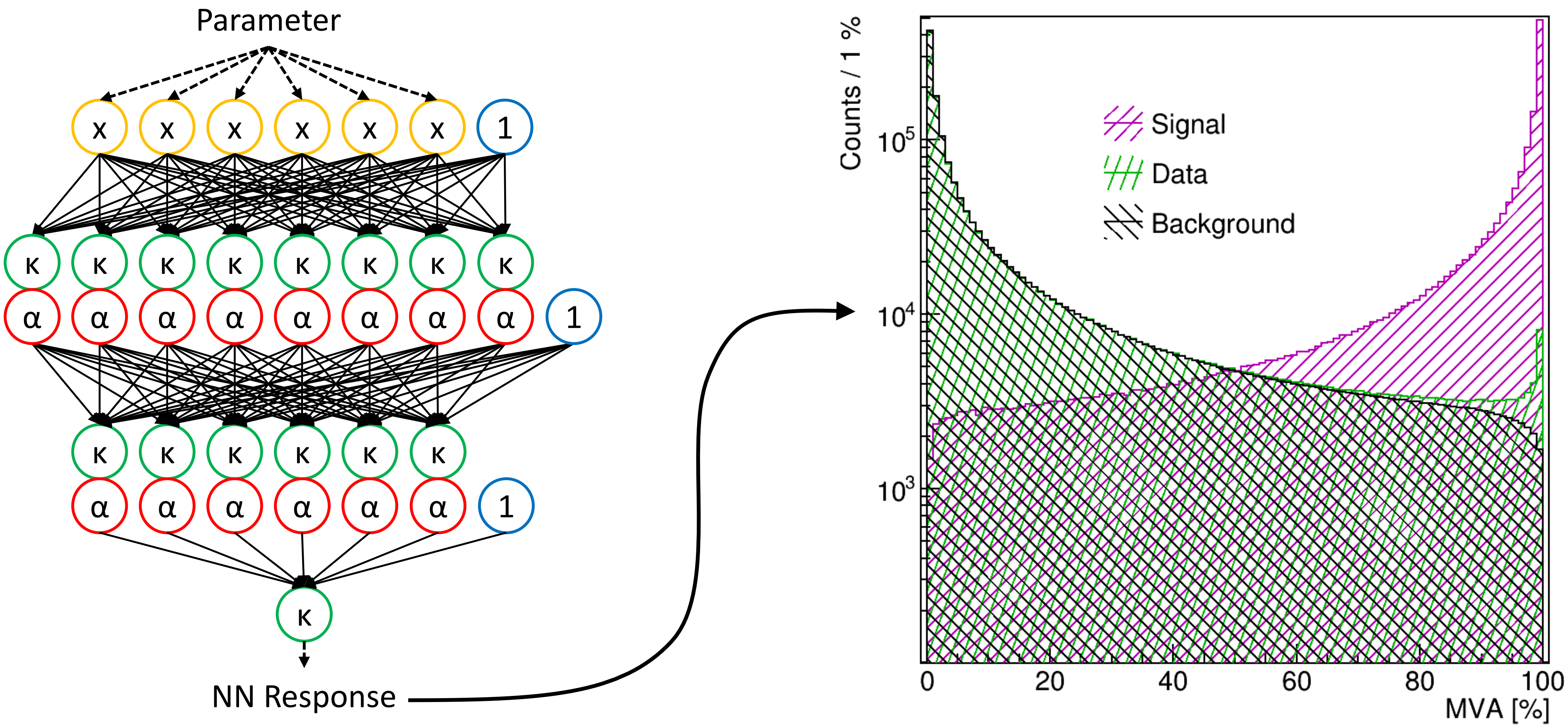


Different MVA approaches

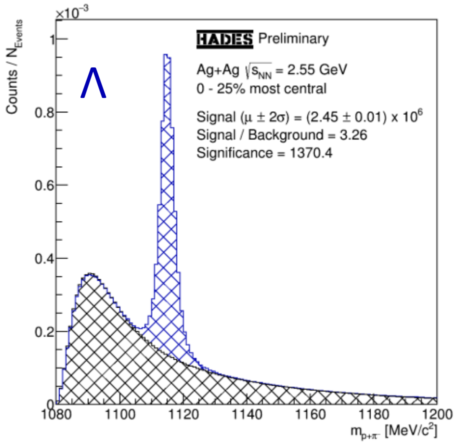
- All MVA methods rated “+” for non-linear correlations performance and at least “0” for response speed in the TMVA manual taken into consideration
  - ➢ All variants of these methods predefined in the TMVA examples tested with default settings
- Fully supervised training using simulated particle decays as signal- and mixed-event pairs as background-sample
- Multi-Layer-Perceptron aNN among the best performing methods
  - ➢ Has already been used at HADES for e^+e^- identification

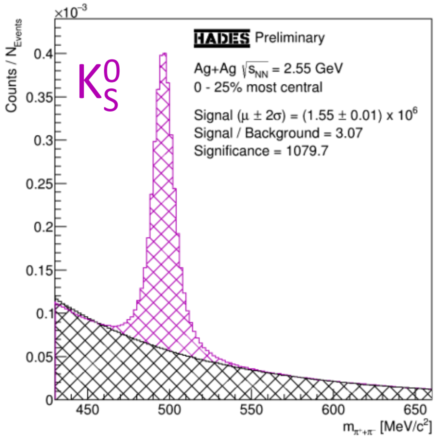


Artificial Neutral Network Response

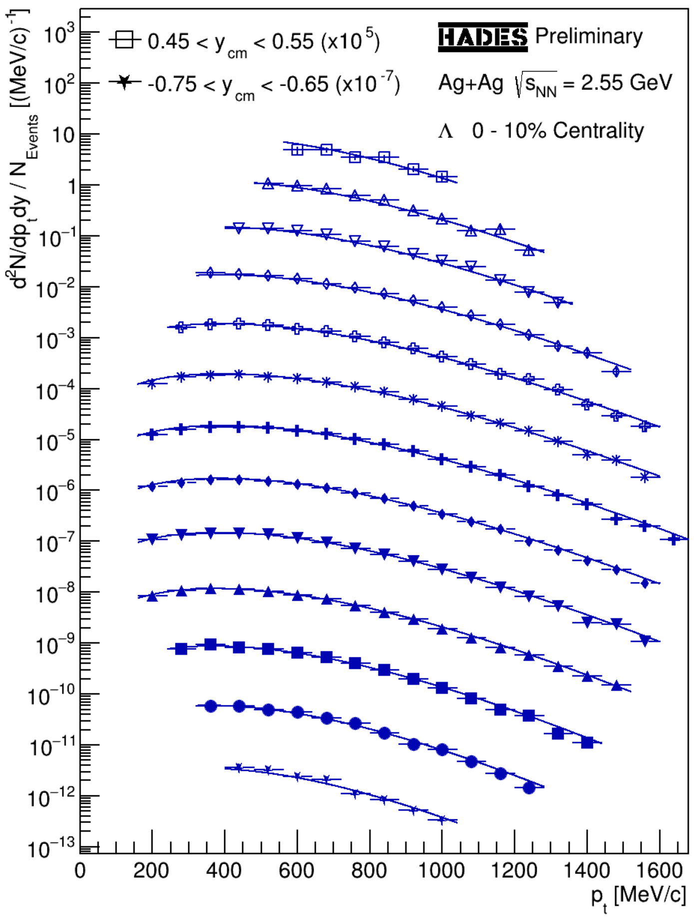


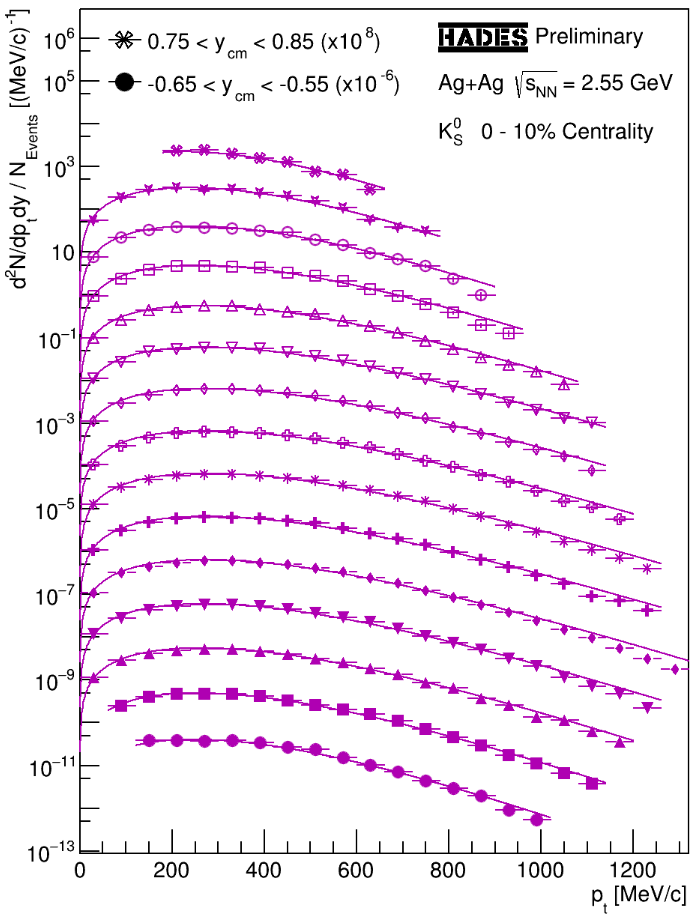
Weak Decay Reconstruction Performance





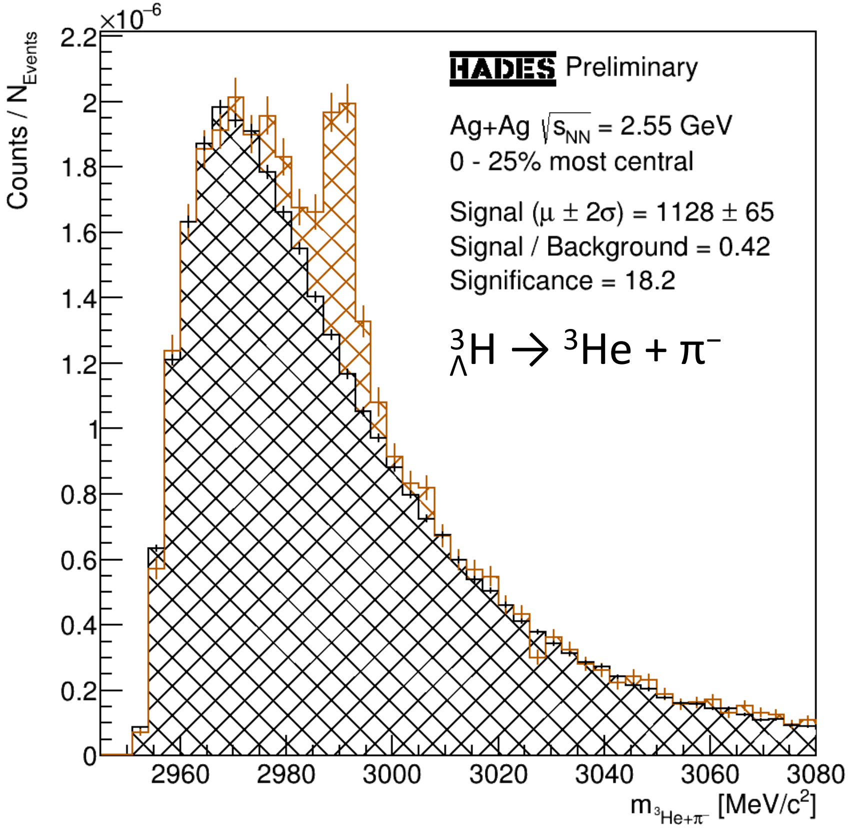
- Large phase space coverage with low statistical errors
- Data points well described by Boltzmann functions
  - ➢ Extrapolation to 4π

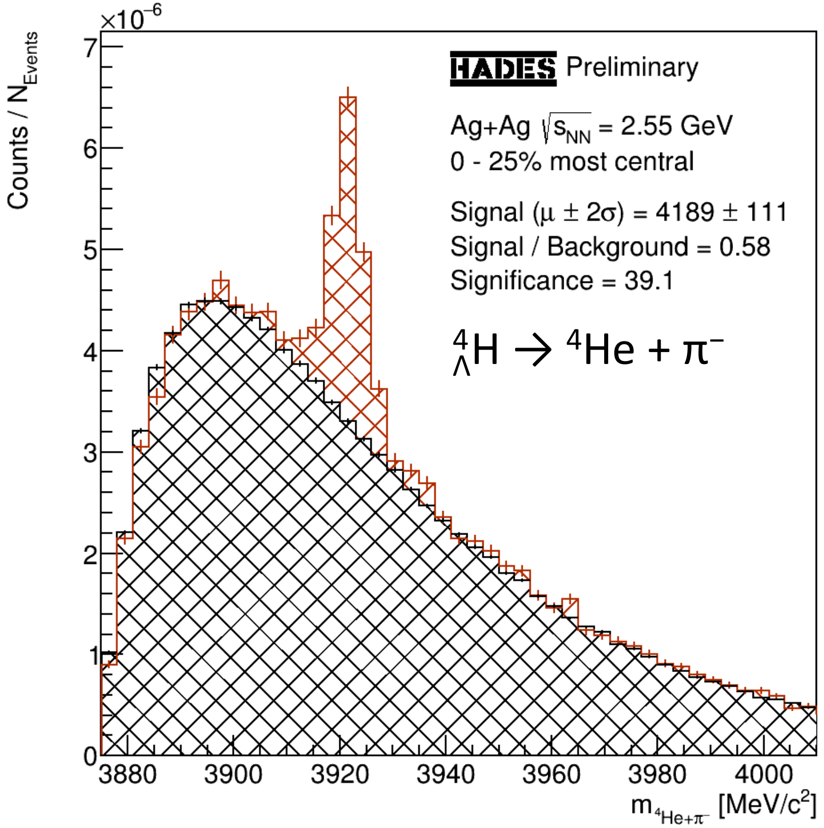




Hypernuclei from Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV

- 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

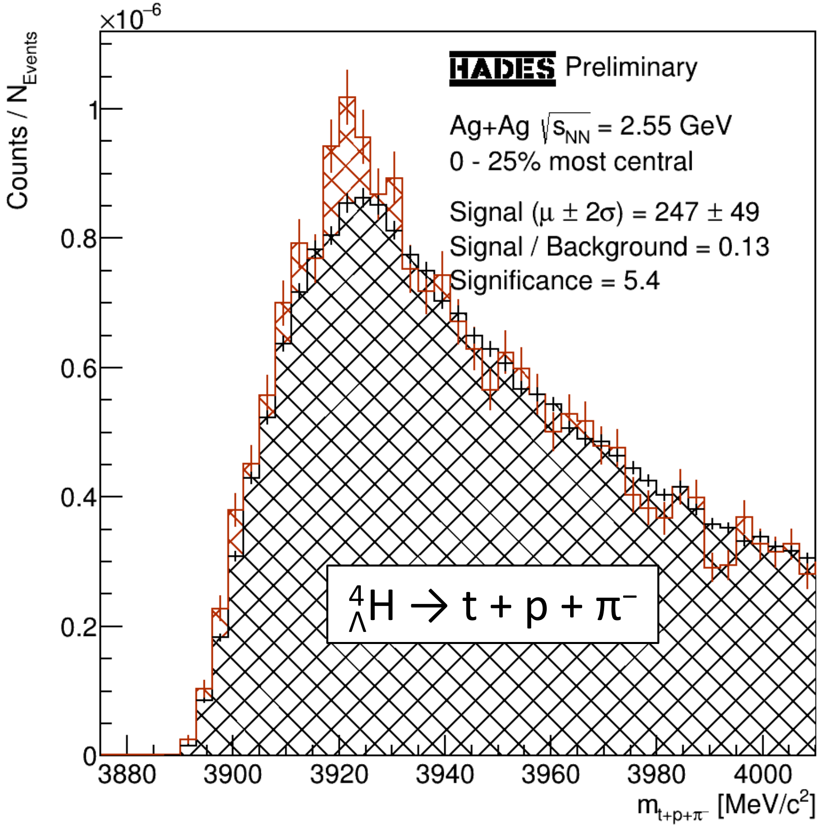


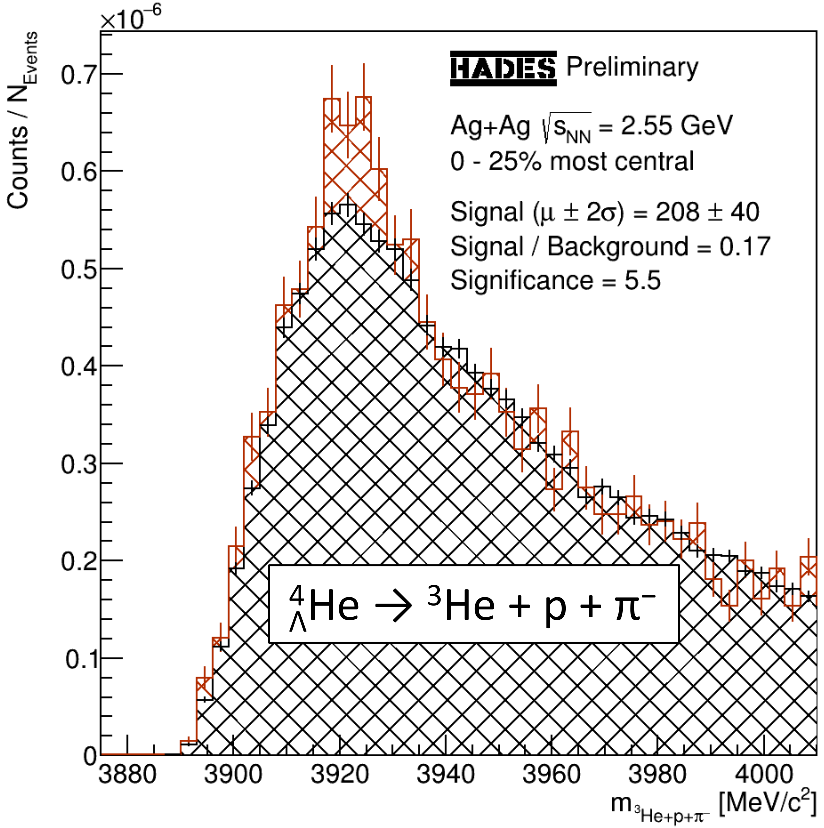


- More significant signals than in Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV data

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



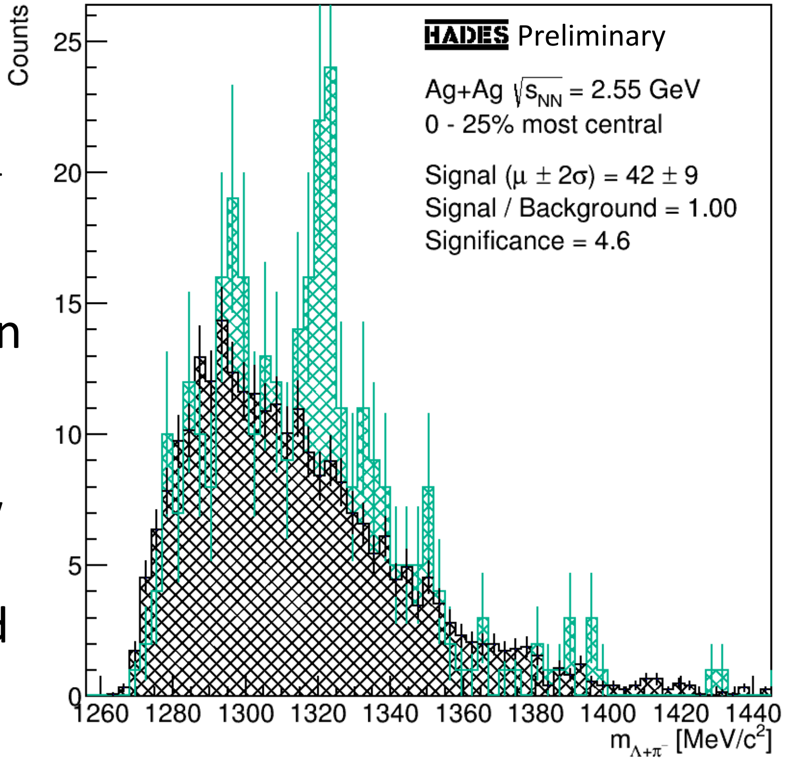


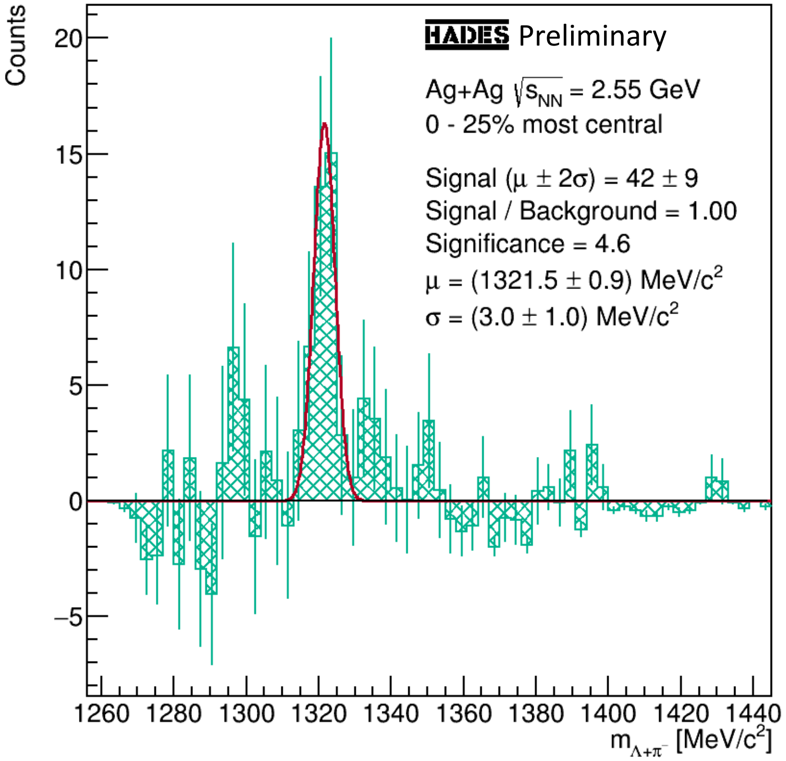
- For the moment not sufficient statistics to analyze the signals differentially

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

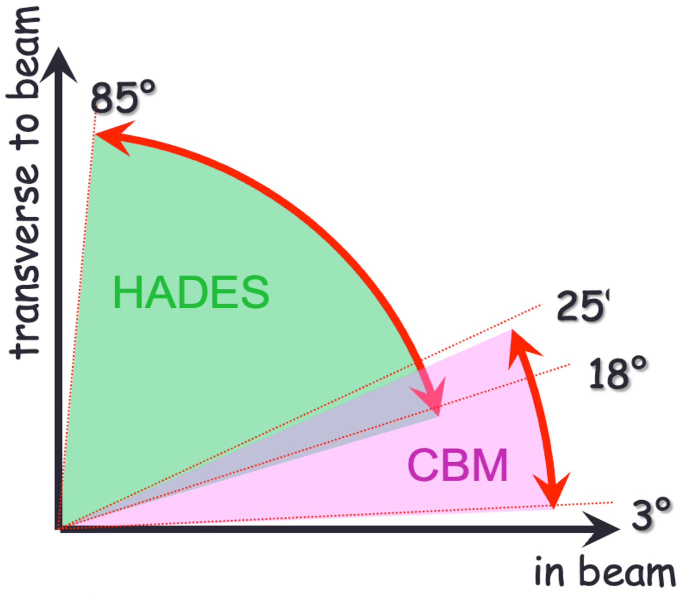


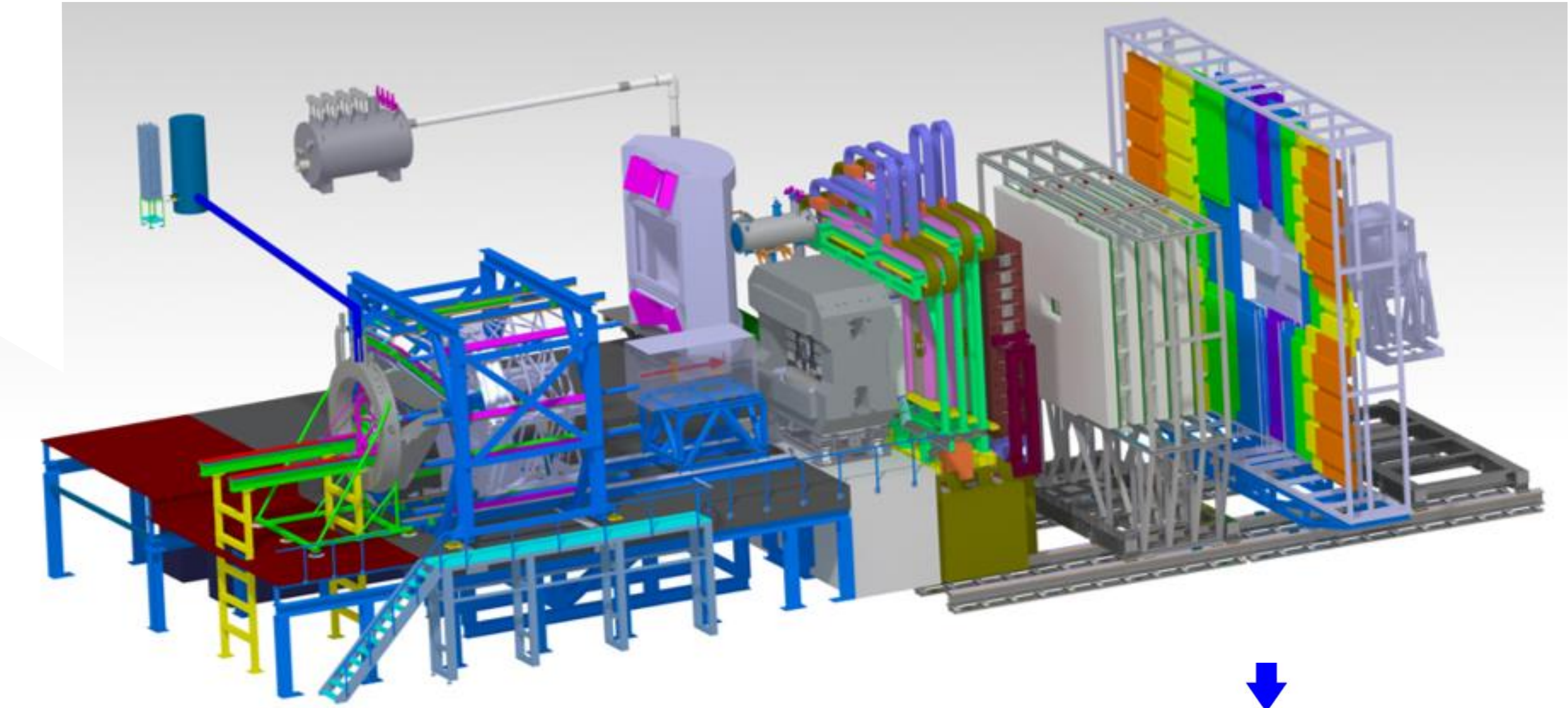


- First measurement of double-strange Ξ^- Hyperons in few GeV Ag+Ag collisions

- Outlook: Improved reconstruction efficiencies using KFParticle package

Outlook: HADES and CBM @ SIS100



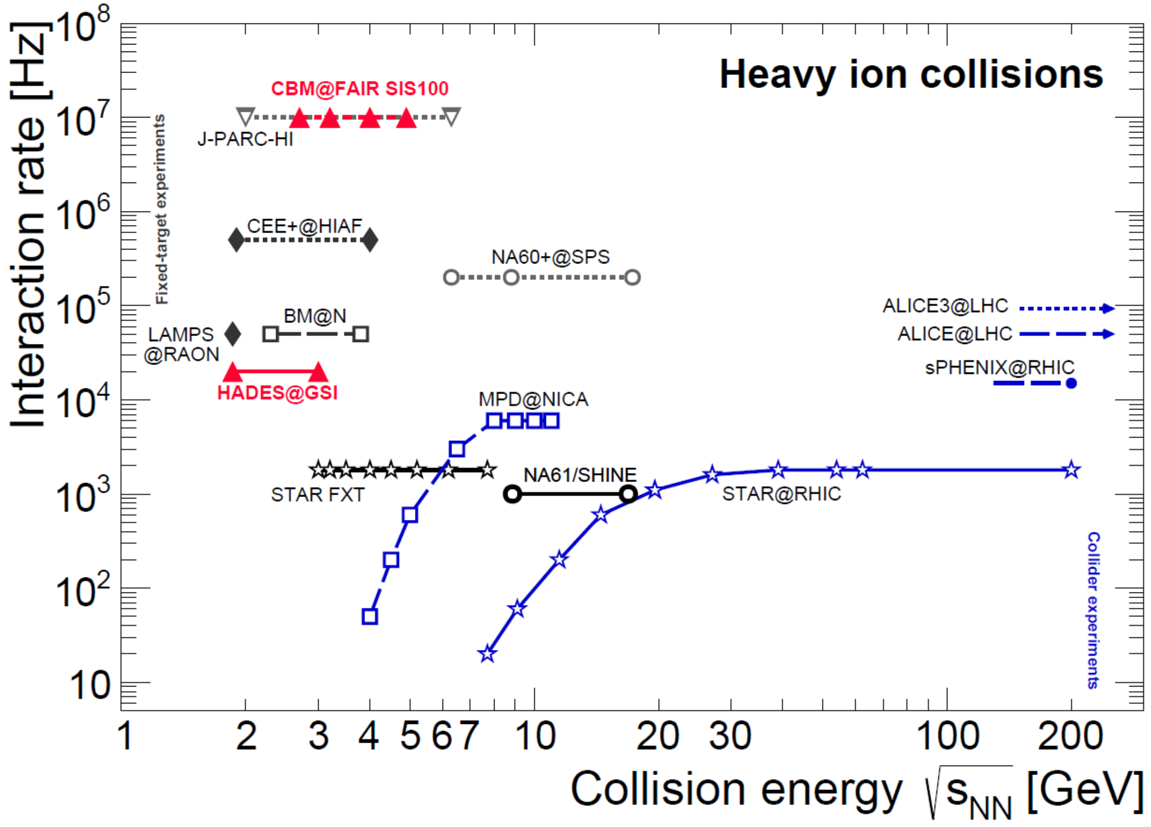


- HADES and CBM will be operated at the SIS100
- Angular coverage of both detectors complementary

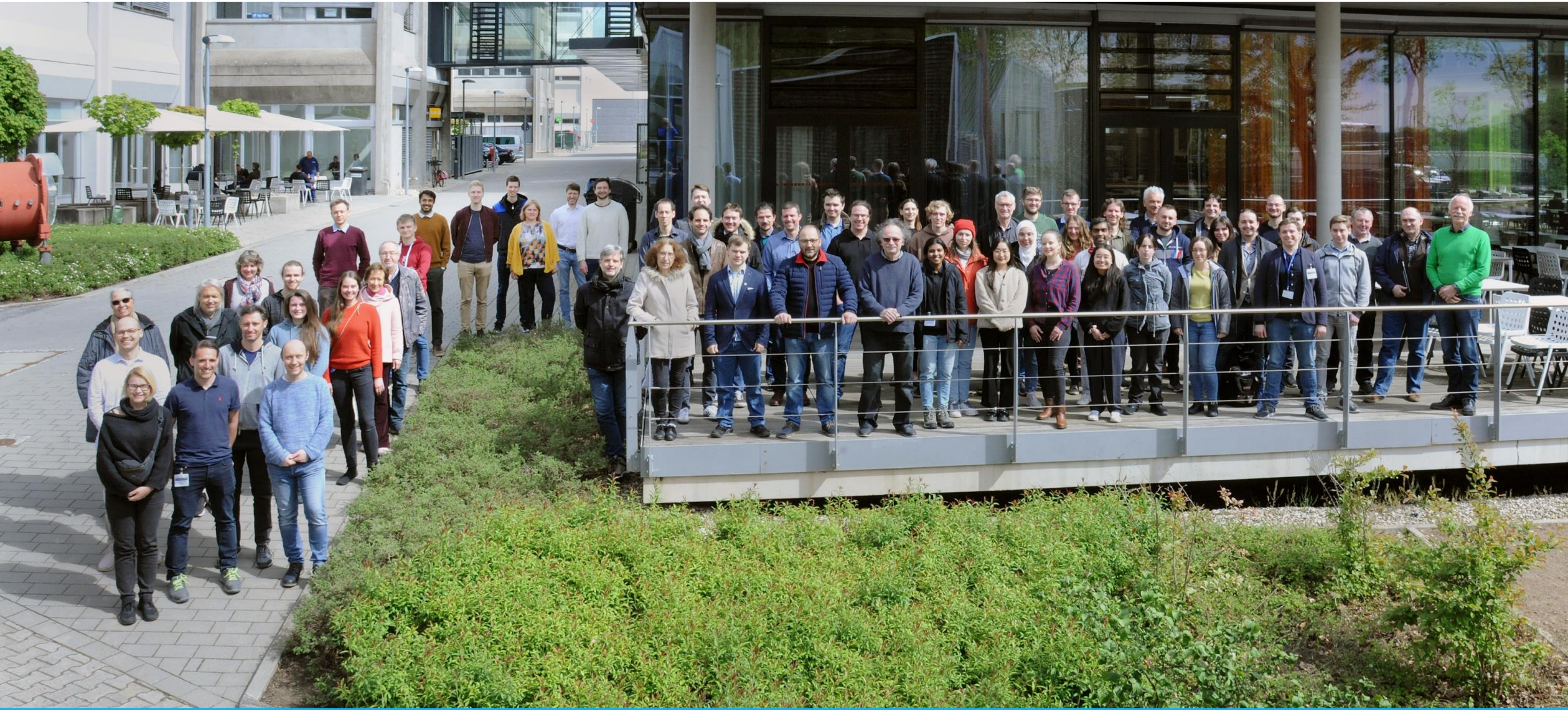
Outlook: HADES and CBM @ SIS100

- 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

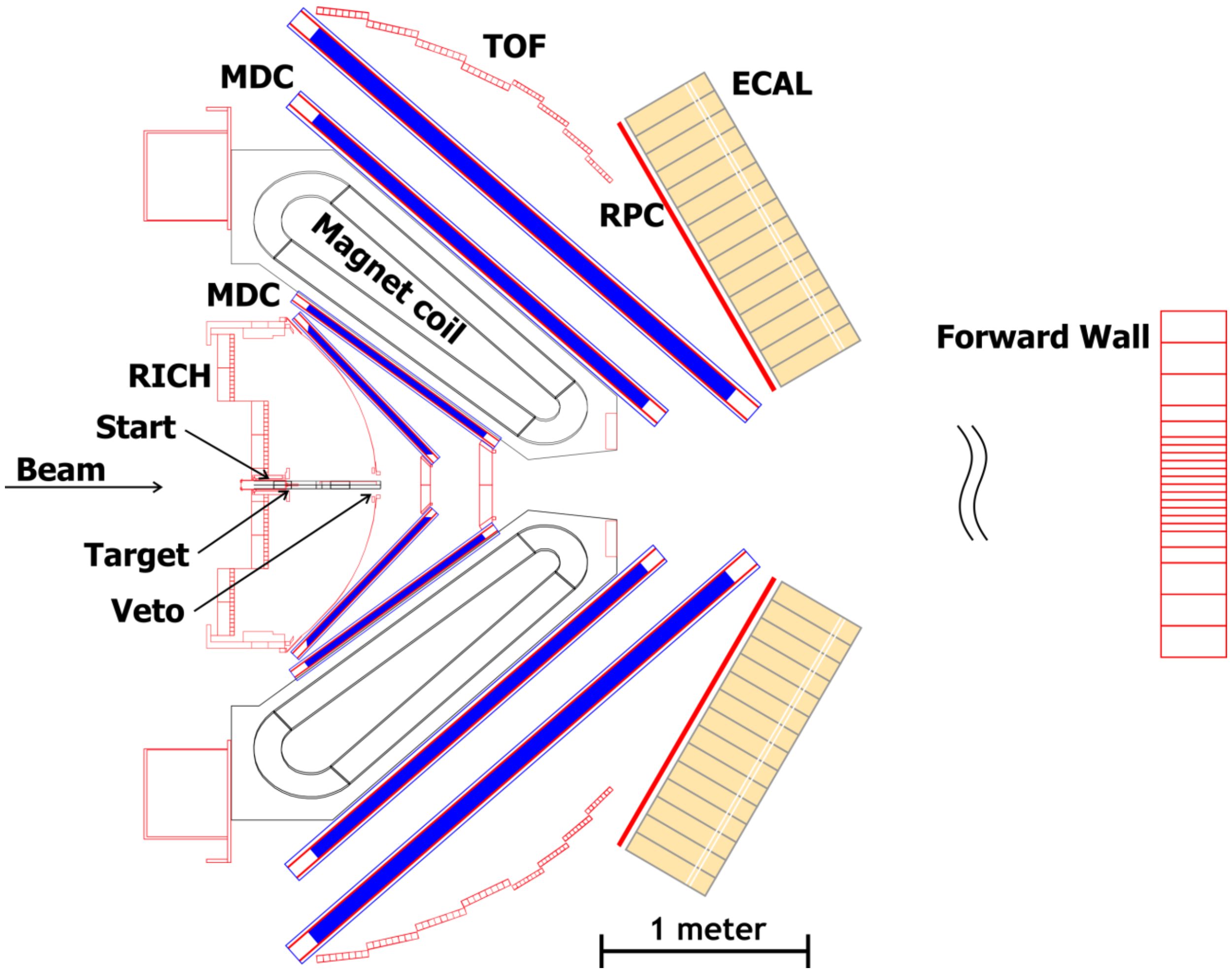


The HADES Collaboration

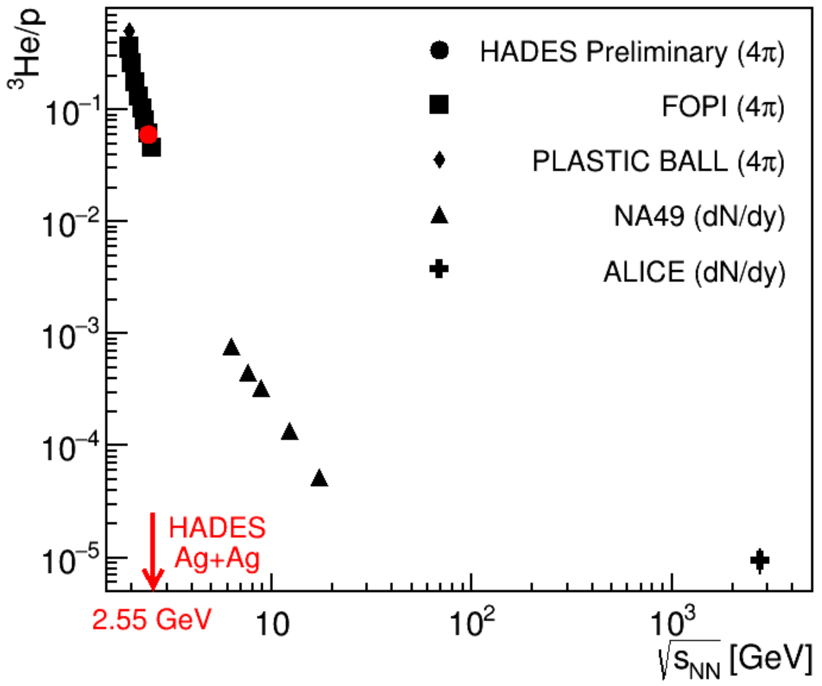


The HADES Experiment (Heavy-Ion Setup)

- 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



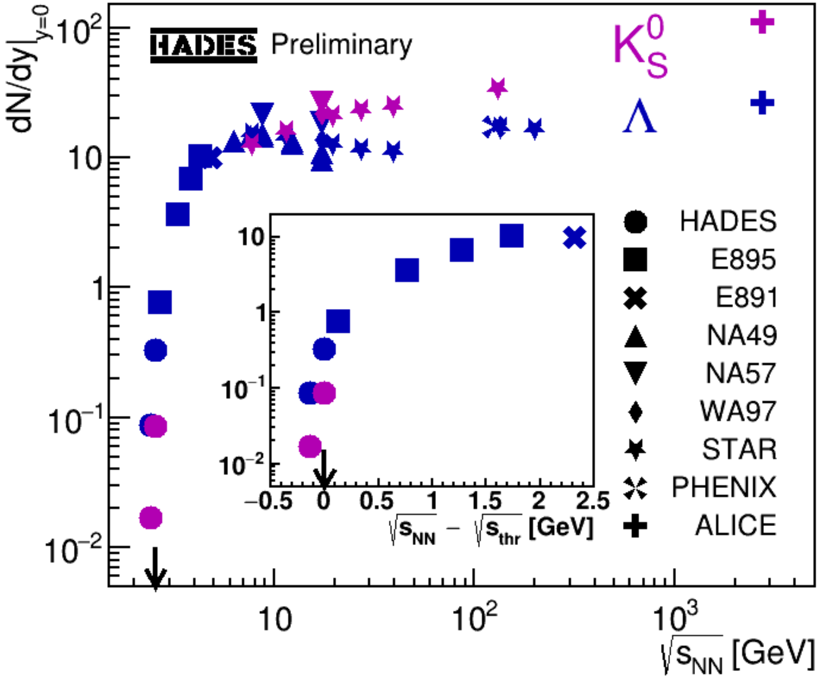
Nuclear Collisions at SIS18/HADES Energies



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

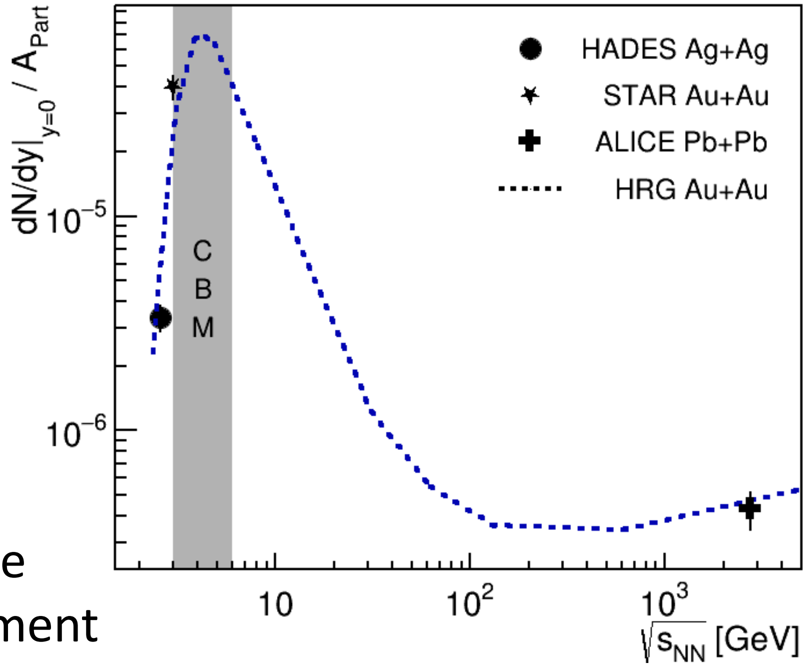


Data: Phys.Lett.B 793 (2019) 457-463

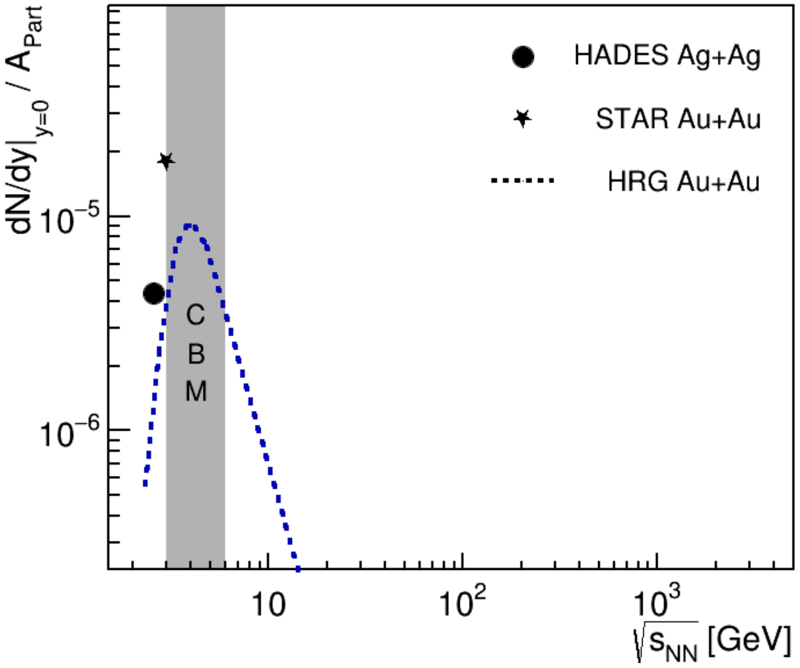
Hypernuclei at SIS18/HADES Energies

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

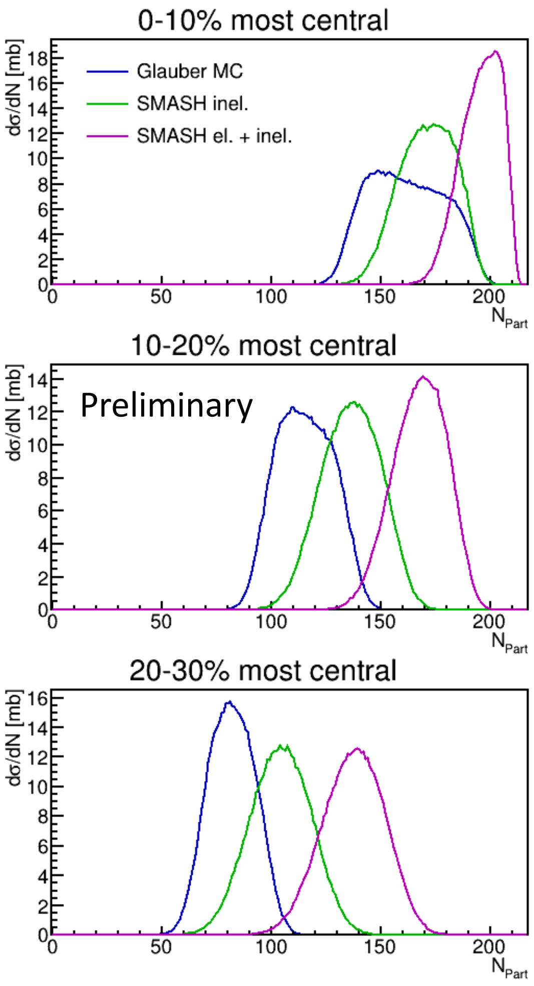


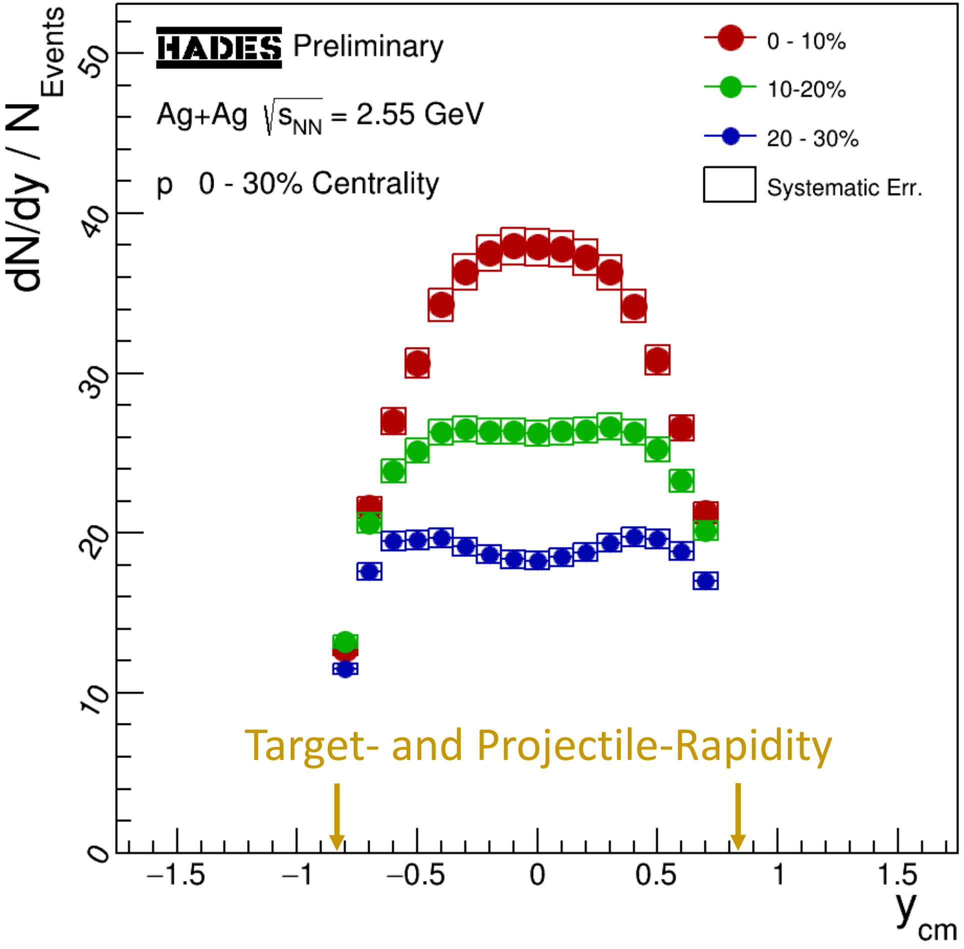
Original Plots from: Phys.Rev.Lett. 128 (2022) 20, 202301

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

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





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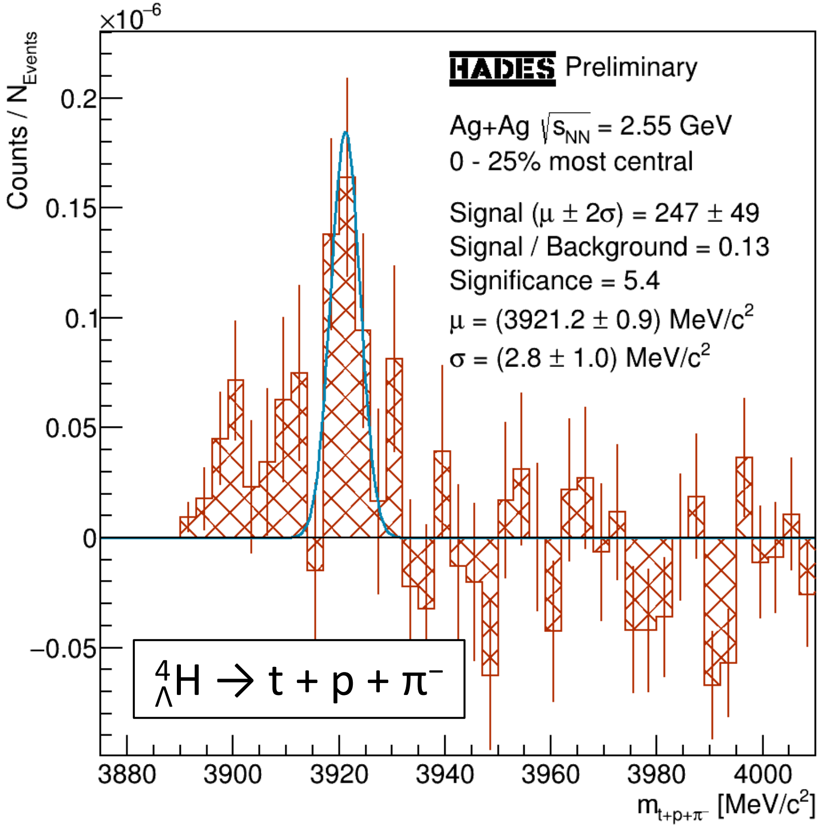

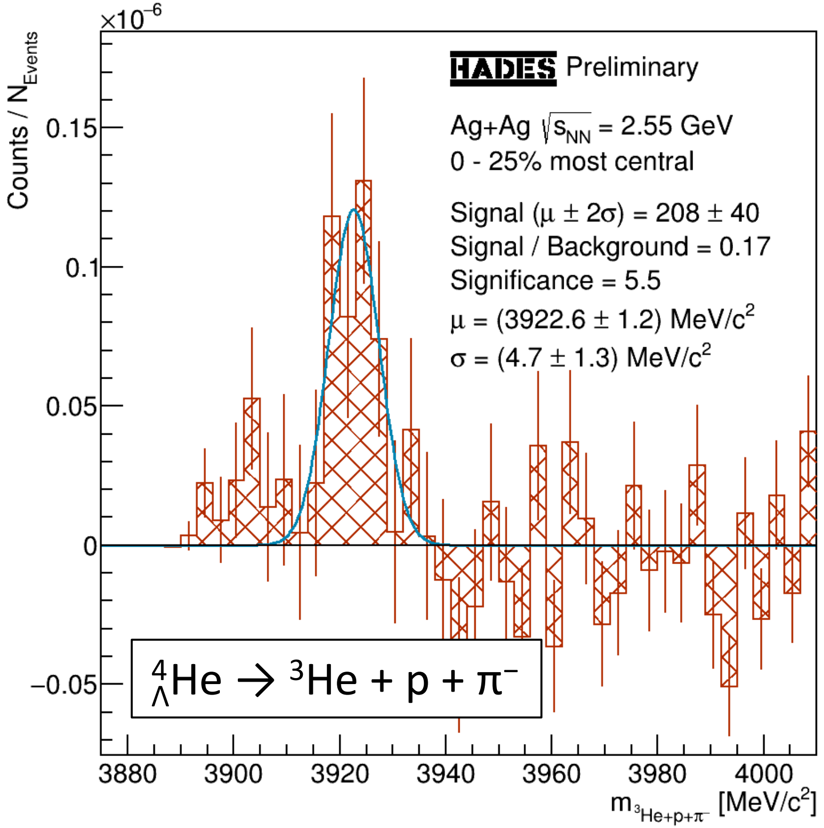

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