

Σ^0 reconstruction in Ag+Ag collisions at 1.58 AGeV with HADES

Marten Becker

for the HADES collaboration,
Justus-Liebig-Universität Giessen

Quark Matter, Houston

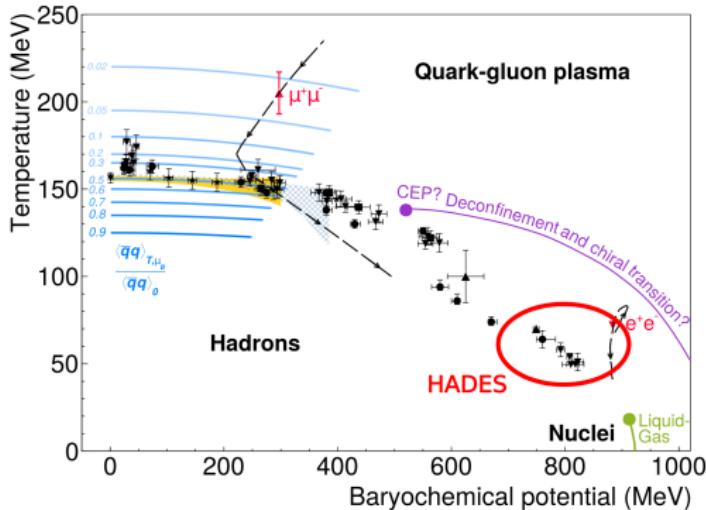
06.09.2023

Outline

- 1 Motivation
- 2 The HADES Experiment & Data Sample
- 3 Daughter Particle Reconstruction
- 4 Signal Extraction
- 5 Λ/Σ^0 Estimation

Motivation

- Investigation of the QCD phase diagram at high μ_B and moderate T.
- HADES provides various strategies for characterization of the collision:
 - ① Dilepton measurements
 - ② Hadron multiplicities
 - ③ Fluctuation & collectivity
- What is the impact of the medium effects on strangeness production close to threshold?
- Are hadrons produced in a thermal system?

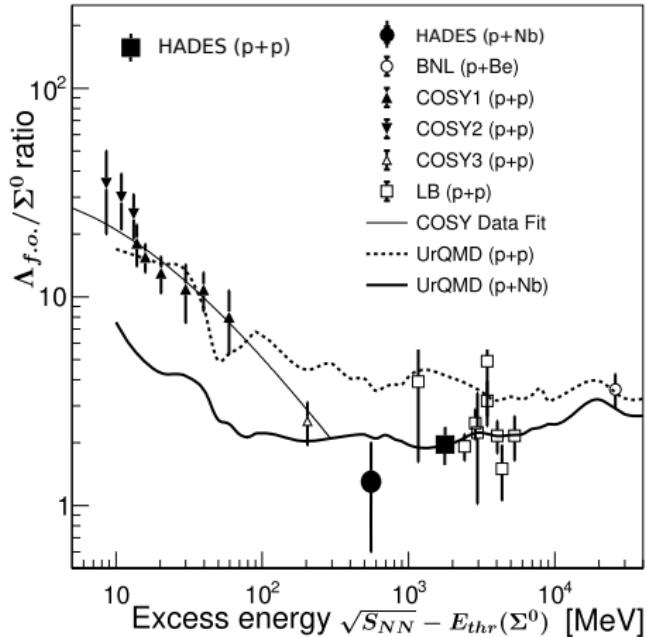


Nature Physics volume 15, pages 1040–1045 (2019)

How is strangeness produced at high μ_B and moderate temperatures?

Motivation

- Hadron production and particular strangeness production at threshold are sensitive to medium effects
- Λ well measured from many experiments, significantly harder to reconstruct the Σ^0
- No experimental measurements of Σ^0 baryon production in AA collisions near threshold
- In p+p collisions, $\Lambda_{f.o.}/\Sigma^0$ strongly increasing towards threshold
- Theoretical models profit from distinguishing Λ and $\Sigma^0 \rightarrow$ additional information on Σ^\pm

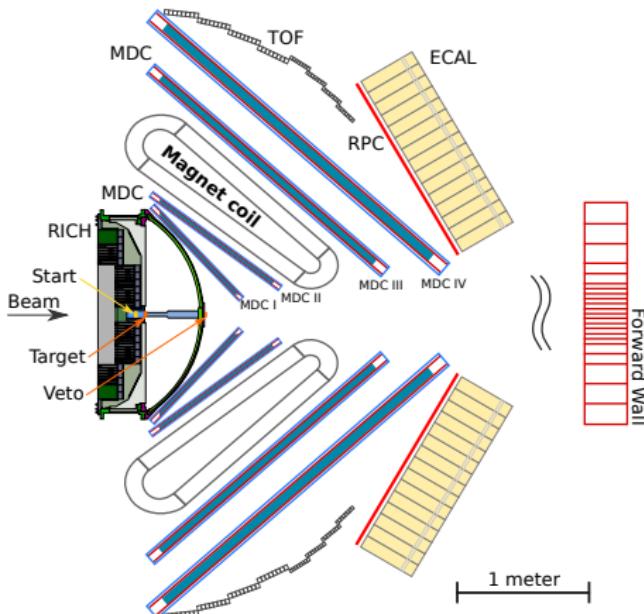


Phys.Lett.B 781 (2018) 735-740,
arXiv:2301.11766

The HADES experiment

High Acceptance Dielectron Spectrometer

- Operating for more than 20 years
- 4 layers of Multiwire Drift Chambers for tracking & momentum reconstruction
- Magnet coil inbetween MDC layers 2 and 3
- RPC and TOF for velocity information
- Upgraded RICH for lepton identification
- New ECal especially for photon reconstruction



Schematic view of the setup for the march 2019 beamtime

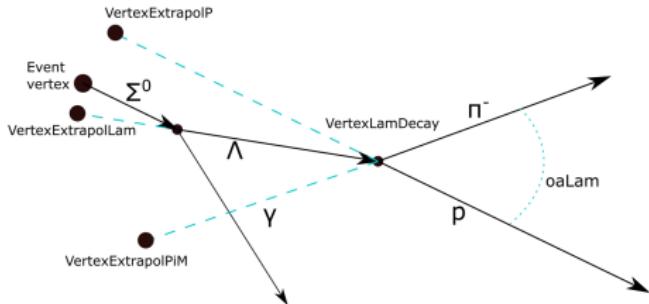
The Σ^0 baryon

- $\tau(\Sigma^0) \approx 7.4 \cdot 10^{-20} s$
- $\tau(\Lambda) \approx 2.6 \cdot 10^{-10} s$
- $m_\Sigma - m_\Lambda \approx 77 \text{ MeV}/c^2$
- γ conversion probability in the RICH is in the order of a few percent
- Sub threshold:

$$\sqrt{s_{NN}}_{Ag+Ag} = 2.55 \text{ GeV}$$

$$E_{thr}(\Lambda) = 2.55 \text{ GeV}$$

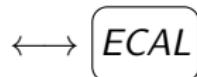
$$E_{thr}(\Sigma^0) = 2.63 \text{ GeV}$$



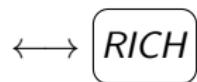
Schematic view of the decay topology of the Σ^0 and the following decay of the Λ (not to scale).

Different decay channels are of interest:

- $\Sigma^0 \rightarrow \Lambda + \gamma \rightarrow p + \pi^- + \gamma$

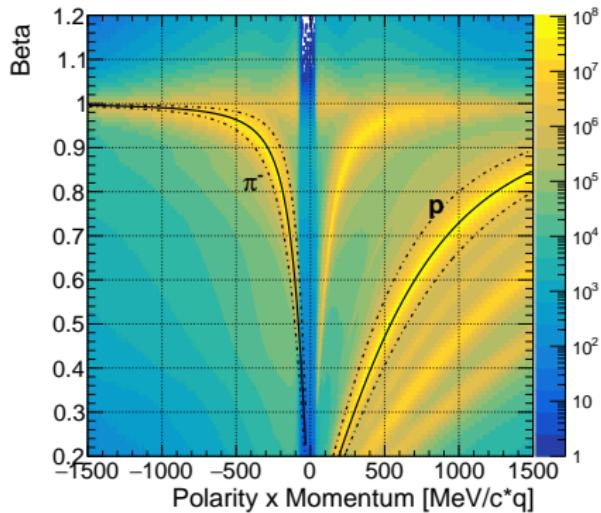
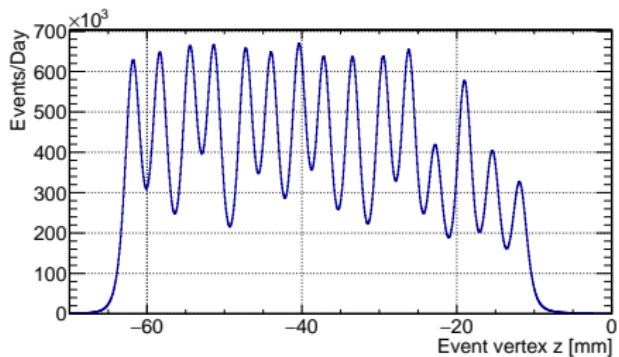


- $\Sigma^0 \rightarrow \Lambda + (\gamma/\gamma^*) \rightarrow p + \pi^- + e^+e^-$



Data sample

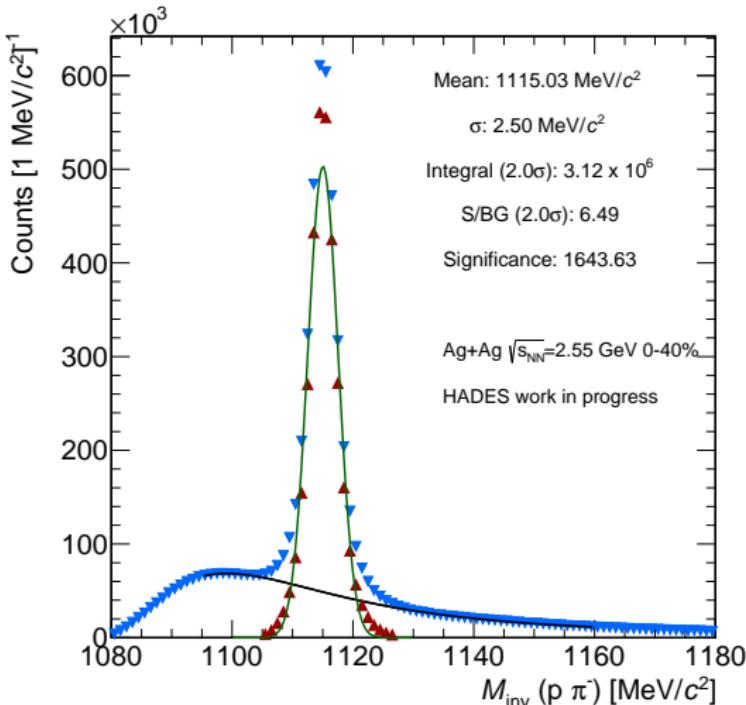
- Ag+Ag collisions at 1.58 AGeV collected in march 2019
- 0-40 % most central collisions corresponds to $b_{max} = 8 \text{ fm}$
- $4.75 \cdot 10^9$ events available after quality selection



High momentum and time of flight resolution allows pre selection based on calculated effective mass

Lambda reconstruction

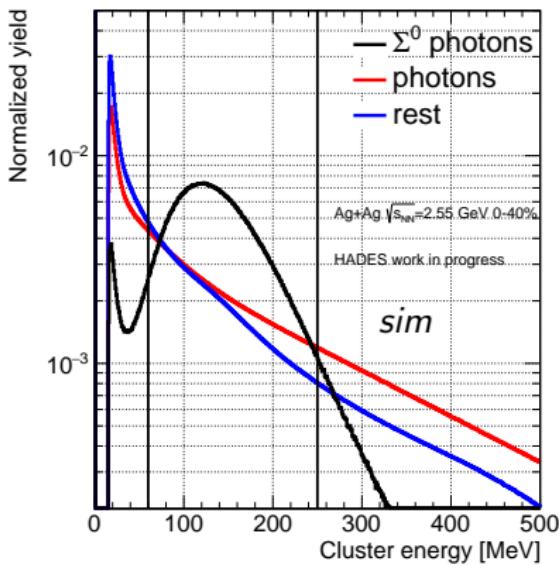
- Reconstructed mass:
 $\pi : m_{pdg}(\pi) \pm 20\%$ and
 $p : m_{pdg}(p) \pm 30\%$
- Selection via Off-Vertex topology
- Energy loss & π velocity as additional parameters
- Including MLP from TMVA for enhanced statistics and improved background suppression
(arXiv:physics/0703039)
- $3.1 \cdot 10^6$ reconstructed Λ with $S/B(2\sigma) > 6$
- Multiplicity extraction in full phase space consistent
 $M(\Lambda, 0 - 40\%) = 0.066/\text{evt}$



Challenging: RICH around target \Leftrightarrow no tracking available near interaction vertex

Photon reconstruction

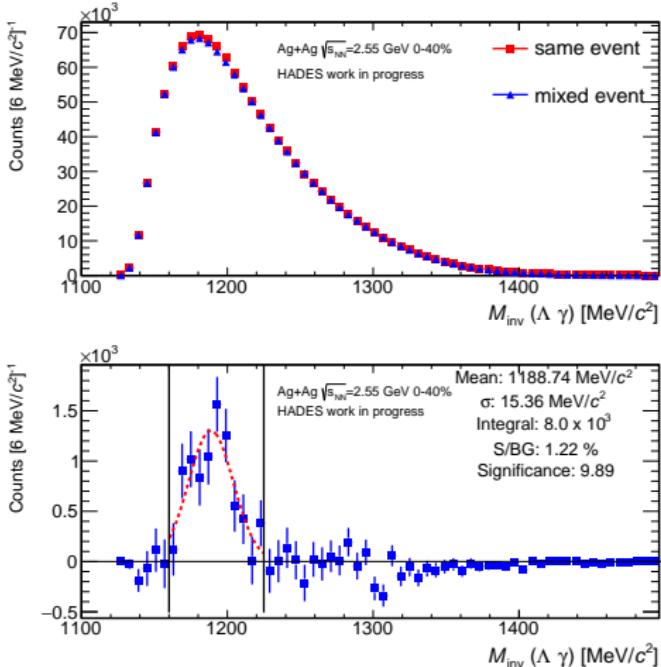
- Newly installed lead glass electromagnetic calorimeter provides opportunity for the first time in HADES
- Challenging: polar angle coverage from $\approx 16\text{--}45^\circ$ with the first 2/6 sectors almost fully equipped
- No tracking available for photons
→ only ECal information can be used
- No matched charged track
- Cluster energy
 $60 < E \text{ [MeV]}^{-1} < 250$
- Cluster size 1 which avoids additional energy spread
- Calculated velocity $0.8 < \beta < 1.3$
- Difficult calibration for low energy photons
- Individual β cut for each cell



Signal extraction

Describing the combinatorial background by event mixing technique

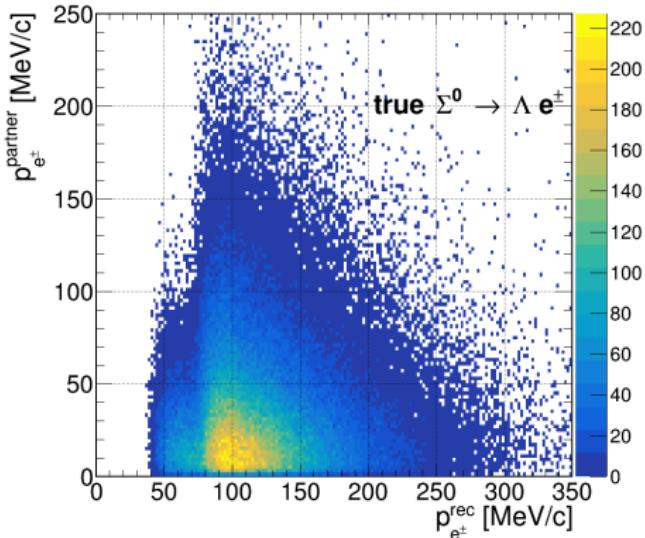
- Classification of events concerning track multiplicity and target layer
- Normalizing background to sidebands
- Experimentally measured width is expected by simulations
- Systematic error estimation from sideband choice and selection criteria $\approx 10\%$
- Large amount of photon background sources lead to $S/BG \approx 1\%$



Clear reconstructed Σ^0 signal in a subthreshold AA collision!

Feasibility studies $\Sigma^0 \rightarrow \Lambda e^\pm$ in simulation

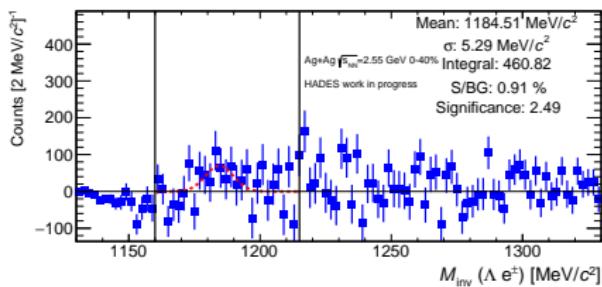
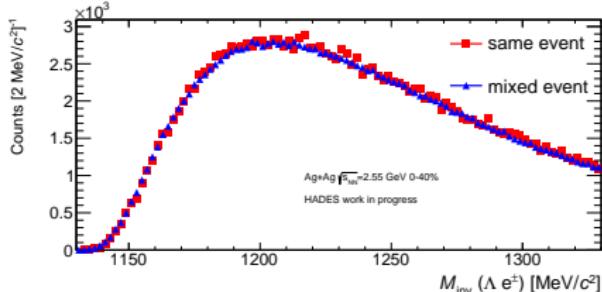
- HADES was developed for lepton reconstruction with high precision and acceptance.
- Low material budget to reduce conversion probability
- The magnetic field restricts lepton momentum reconstruction $p < 70 \text{ MeV}/c$
- In the RICH, each lepton $p > 10 \text{ MeV}/c$ produces Cherenkov photons.
- Neglecting the conversion partner with low momentum allows to reconstruct the Σ^0
- Successfully tested on $p(4.5\text{GeV})+p$ dataset



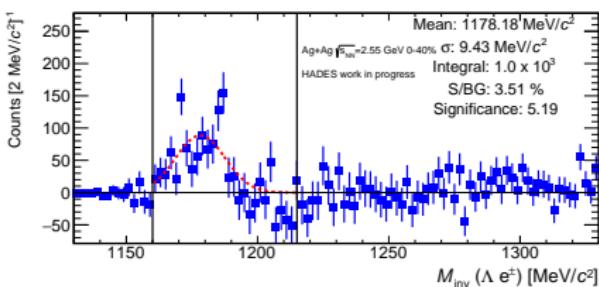
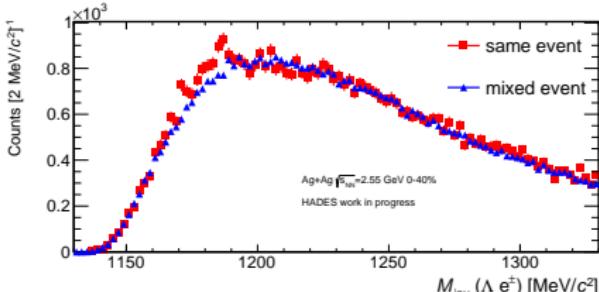
Reconstructed e^\pm momenta using thermal Σ^0 embedded in data: We are only capable to reconstruct a Σ^0 - e^\pm when the conversion partner has low energy.

Feasibility studies $\Sigma^0 \rightarrow \Lambda e^\pm$

Experimental data



Thermal Σ^0 embedded in data



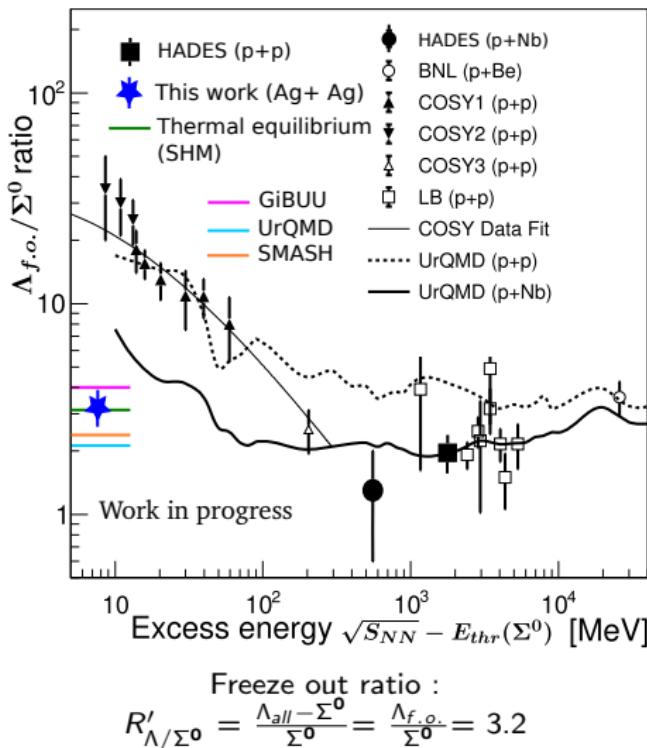
- No signal in experimental data

Expected amount of Σ^0 : $14.1 \cdot 10^6$ in data from $\Lambda\gamma$ which would correspond to a few 100 reconstructed counts in $\Lambda + \text{Lepton}$.

- Enhancement seen in simulation

Λ/Σ^0 ratio

- $R_{\Lambda/\Sigma^0} = N_{\Lambda_{rec}}/N_{\Sigma^0_{rec}} \cdot \epsilon_\gamma \cdot \epsilon_\beta$,
 $\epsilon_\gamma = 0.028$ & $\epsilon_\beta = 0.40$
- ϵ_γ extracted from PLUTO generated Σ^0 in experimental data
- ϵ_β correction due to missing energy dependent resolution in ECal simulation & detector cell instabilities.
- ϵ_β determined from data (leptons)
- Systematic error estimation by variation of cut sets, choice of side bands and splitting in subsets; ECal timing resolution dominant
- $R_{\Lambda/\Sigma^0} = 4.2 \pm 0.9$
- $M(\Sigma^0, 0-40\%) = (15.7 \pm 3.2) \cdot 10^{-3}/\text{evt}$



Λ/Σ^0 ratio in pp collisions highly dependent on available phase space: Obvious deviation of AA from pp collisions.

Comparison to theory

- Extracted freeze out ratio

$R'_{\Lambda/\Sigma^0} = 3.2 \pm 0.7$ delivers estimation of the temperature:

$$T = \Delta m / \ln(R') \approx 66 \text{ MeV}$$

- Thermal-FIST

① No strangeness: $T = 74 \pm 6 \text{ MeV}$

② With strangeness: $T = 66 \pm 2 \text{ MeV}$

- Transport models (R'_{Λ/Σ^0})

① GiBUU (4.0)

② SMASH (2.3)

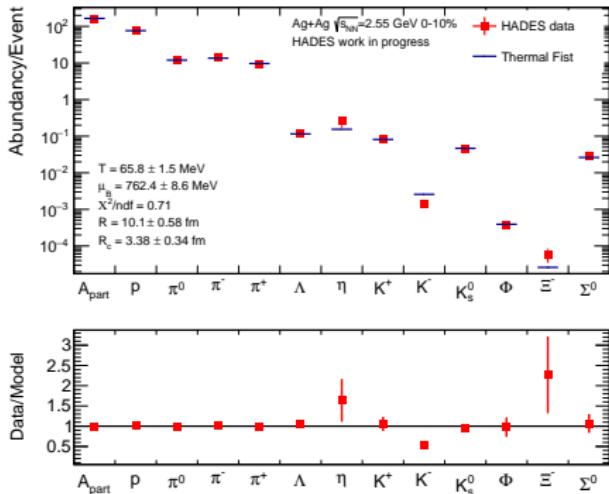
③ UrQMD (2.1)

differ slightly

Conclusion: Σ^0 production in good agreement to thermal model!

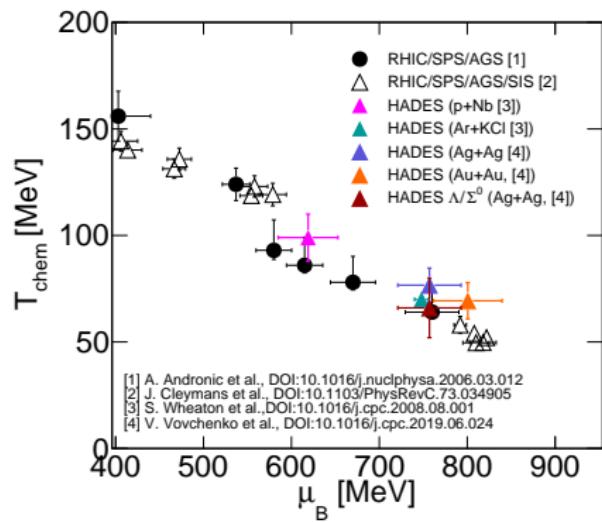
GiBUU (Phys. Rept. 512 (2012) 1-124), UrQMD (Nucl. Phys. 41 (1998) 225-370),
SMASH (10.1103/PhysRevC.94.054905), Thermal-FIST (arXiv:1901.05249)

Poster by Marvin Kohls, contribution 622



Summary

- The new ECal which was used in march 2019 for the first time allows to reconstruct the Σ^0 baryon for the first time in A+A collisions below threshold
- Full efficiency correction in the $\Lambda\gamma$ channel delivers Λ/Σ^0 ratio
 $R_{\Lambda/\Sigma^0} = 4.2 \pm 0.9$
- Freeze-out ratio: $R'_{\Lambda/\Sigma^0} = 3.2$
- Extracted ratio delivers estimation of the temperature:
 $T = \Delta m / \ln(R') \approx 66 \text{ MeV}$
- Agrees to thermal fits



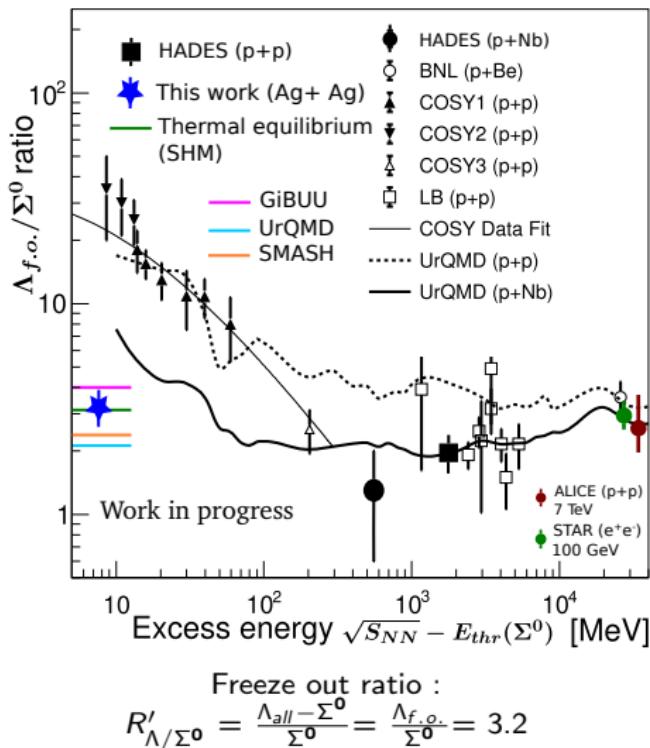
R'_{Λ/Σ^0} well described by a purely thermal approach!

The HADES collaboration



Backup - Comparison to world data

- $R_{\Lambda/\Sigma^0} = N_{\Lambda_{rec}} / N_{\Sigma^0_{rec}} \cdot \epsilon_\gamma \cdot \epsilon_\beta$,
 $\epsilon_\gamma = 0.028$ & $\epsilon_\beta = 0.40$
- ϵ_γ extracted from PLUTO generated Σ^0 in experimental data
- ϵ_β correction due to missing energy dependent resolution in ECal simulation & detector cell instabilities.
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- Systematic error estimation by variation of cut sets, choice of side bands and splitting in subsets; ECal timing resolution dominant
- $R_{\Lambda/\Sigma^0} = 4.2 \pm 0.9$
- $M(\Sigma^0, 0-40\%) = (15.7 \pm 3.2) \cdot 10^{-3} / \text{evt}$



Freeze out ratio :

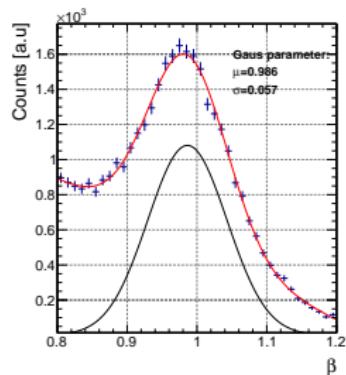
$$R'_{\Lambda/\Sigma^0} = \frac{\Lambda_{all} - \Sigma^0}{\Sigma^0} = \frac{\Lambda_{f.o.}}{\Sigma^0} = 3.2$$

Λ/Σ^0 ratio in pp collisions highly dependent on available phase space: Obvious deviation of AA from pp collisions.

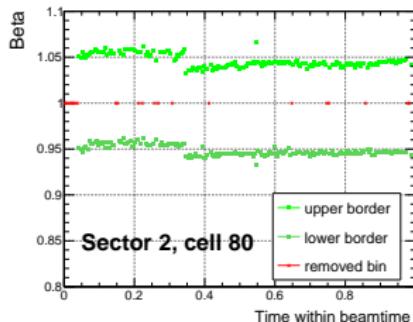
Backup - Data driven efficiency correction

- e^\pm and γ behave the same in the electromagnetic calorimeter.
- Instabilities during the beamtime lead to time dependent timing information.
- Energy dependent efficiency correction adjusted by leptons measured in data.

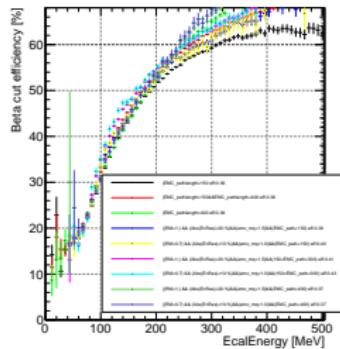
Time dependent scan



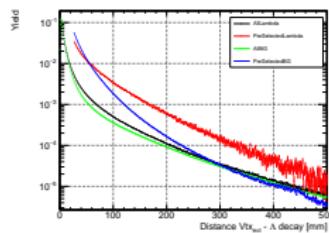
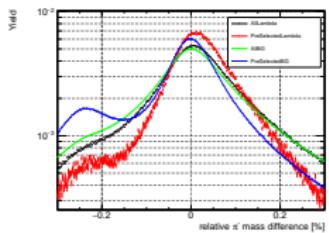
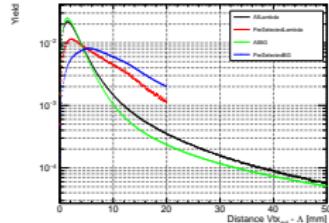
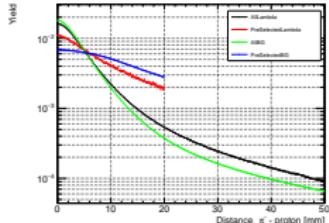
Extract cut values



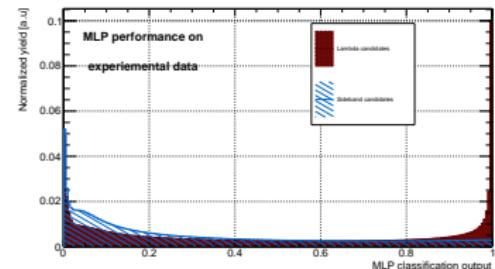
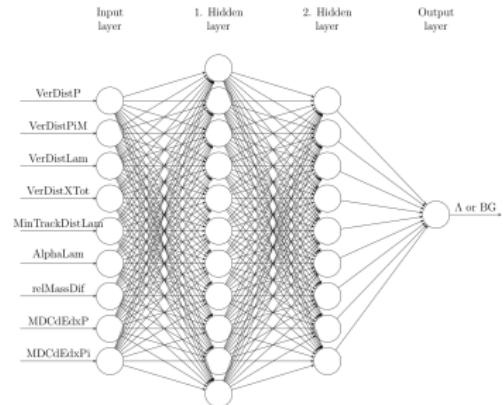
Efficiency measurable for leptons



Backup - Lambda MLP parameter



- Weak decays as rare probe of the HIC
- Off-Vertex topology parameters highly dependent
- Ideal conditions for a multivariate analysis
- Preselection highly improves the performance



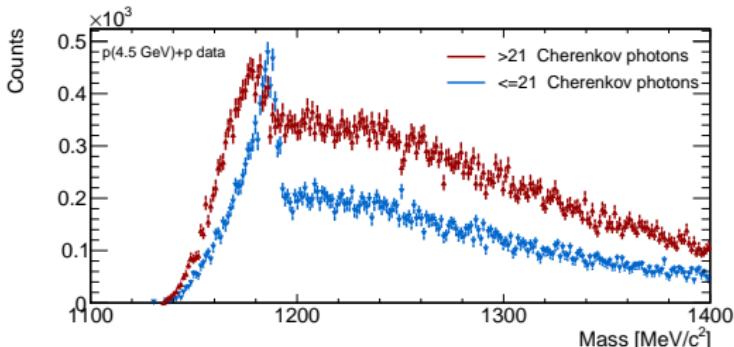
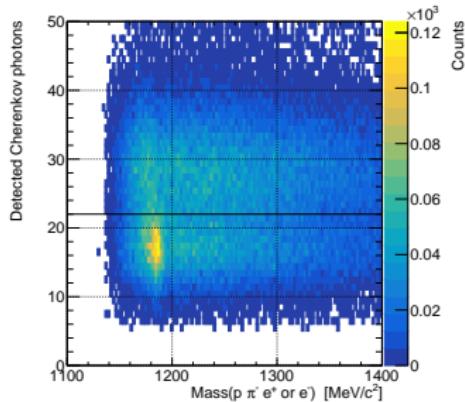
Backup - Strangeness balance

$$M(\Lambda) + M(\Sigma^-) + M(\Sigma^0) + M(\Sigma^+) = M(K^+) + M(K_S^0) + M(K_L^0)$$

Centrality	Production rate [$10^{-2}/\text{event}$]				Σ^0/Λ
	Lambda	Σ^+	Σ^0	Σ^-	
0-10%	10.09	2.20	2.39	2.60	0.24
10-20%	6.00	1.36	1.48	1.61	0.25
20-30%	3.47	0.90	0.98	1.06	0.28

- Calculations performed by S.Spies,
PhD Thesis: Strange Hadron
Production in Ag+Ag Collisions at
1.58A GeV, 2022
- Consideration of strangeness
conservation in strong interaction and
isospin asymmetry
- Tested on Kaons $N_u/N_d = 0.92$ and
 $K^+/2K_s^0 = 0.92 - 1.02$
- Measured value $\Lambda/\Sigma^0 = 3.2 \pm 0.7$
slightly below the calculated value
of 4.0

Backup - Feasibility studies $\Sigma^0 \rightarrow \Lambda e^\pm$ in p(4.5 GeV)+p

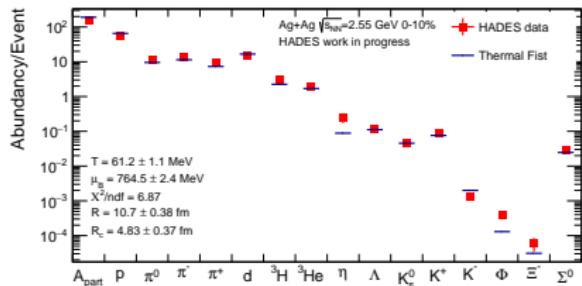


- Method successfully applied on p(4.5 GeV)+p data set.
- Sharp peak in case of few Cherenkov photons, which corresponds to a partner lepton sub Cherenkov threshold ($p_e < 10 \text{ MeV}/c$)
- RICH Cherenkov photon reconstruction precision will allow further decay property analysis

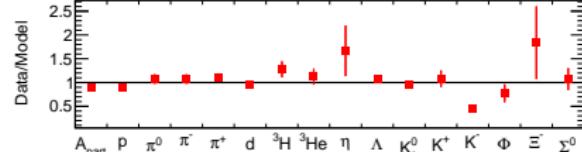
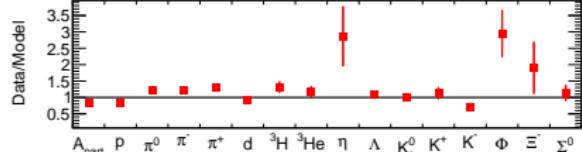
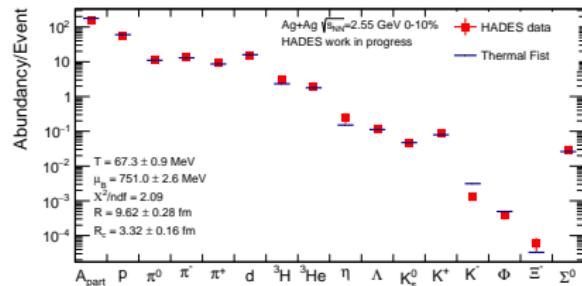
Backup - Thermal Fist - with excited nuclei

- Ideal hadron gas model, strangeness-canonical ensemble
- Energy dependent Breit Wigner with constant branching ratio
- K⁻ can not be described in thermal equilibrium

K^- in fit included: $\chi^2/Ndf = 6.87$

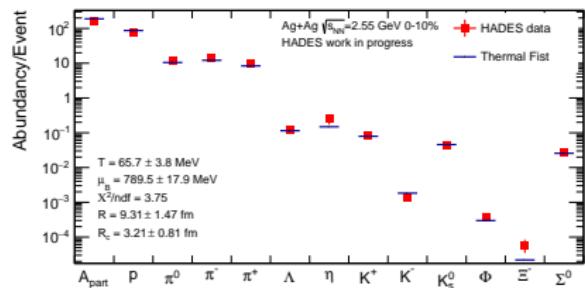


K^- from fit excluded: $\chi^2/Ndf = 2.09$



Backup - Thermal Fist - without nuclei

K^- in fit included: $\chi^2/Ndf = 3.75$



K^- from fit excluded: $\chi^2/Ndf = 0.71$

