Hyperon and Hypernuclei production in Ag+Ag collisions at 1.58 AGeV beam energy ($\sqrt{s_{NN}} = 2.55\,\mathrm{GeV}$) with the HADES experiment

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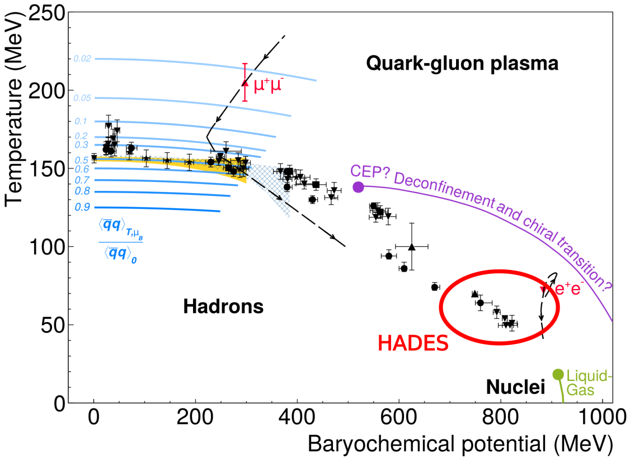
Outline

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 medium effects on strangeness production close to threshold?
- Are hadrons produced in a thermal system?
- How is strangeness produced at high μ_B and moderate temperatures?

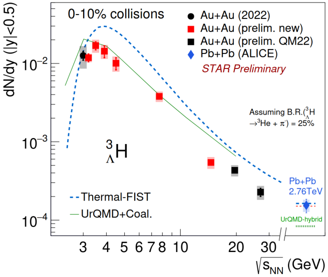


Nature Physics volume 15, pages 1040–1045 (2019)

Motivation - Hyperons and Hypernuclei

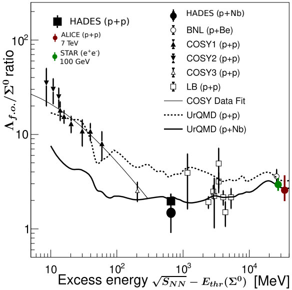
Strangeness production at threshold energy and high baryon density is sensitive to medium effects:

- High baryon density at SIS18 energies leads large cross sections of Hypernuclei production
- CBM will cover the energy range of maximum production rate around $\sqrt{s_{NN}} \approx 5$ GeV.

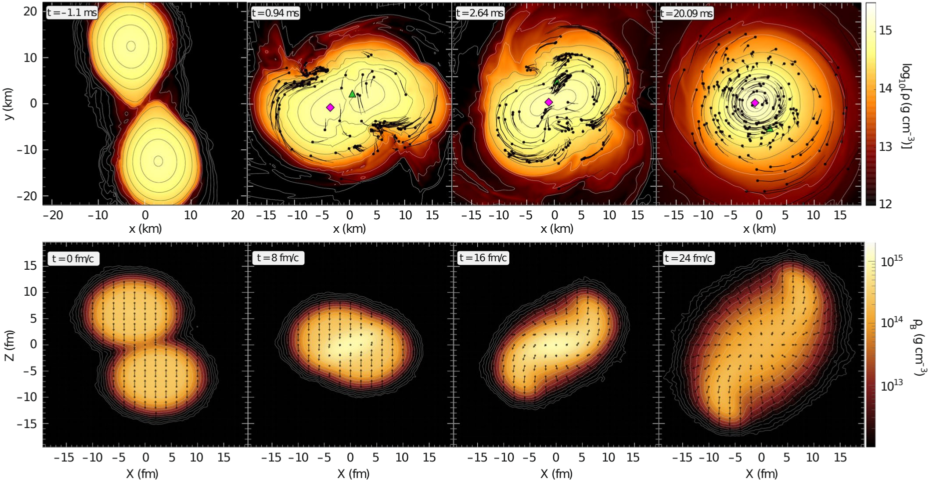


Yuanjing Ji for the STAR collaboration (2024), arXiv:2312.15768v2

- No experimental measurements of Σ^0 baryon production in AA collisions near threshold due to its difficult reconstruction.
- In p+p collisions, $\Lambda_{f.o.}/\Sigma^0$ strongly increasing towards threshold



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

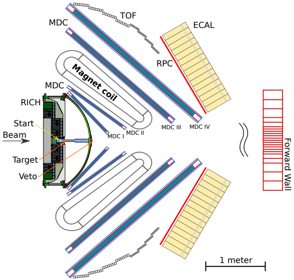


Similar conditions for neutron star merger events and heavy ion collisions at SIS18 energies: $T < 70\,\mathrm{MeV}$ with a nuclear density of $\rho \approx 2 - 3\rho_0$, impact of YN interactions

The HADES experiment and PID

HADES - High Acceptance Dielectron Spectrometer

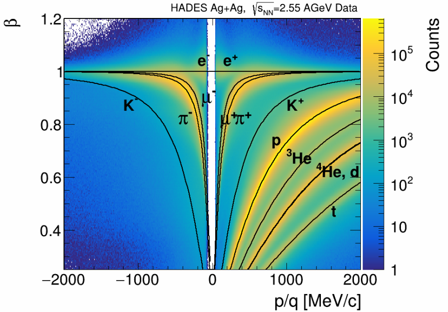
- Located at GSI in Darmstadt
- Successful operation for more than 20 years
- Upgraded RICH for lepton identification
- New ECal especially for photon reconstruction



Schematic view of the setup during data taking

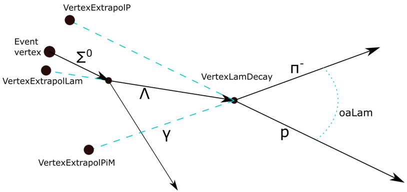
High resolution in β-momentum for PID

- 4 layers of Multiwire Drift Chambers for tracking & momentum reconstruction
- Magnet coil inbetween MDC layers 2 and 3
- RPC and TOF for velocity information

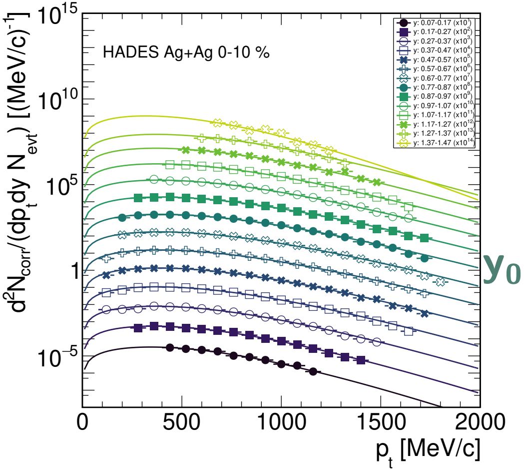


Ag+Ag at $\sqrt{s_{NN}} = 2.55\,\mathrm{GeV} = \Lambda_{NN}$ threshold

- Weak decays result in a lifetime of $\approx 10^{-10}$ s, which allows a secondary vertex reconstruction
- Highly correlated decay topology parameters are evaluated by artificial neural networks
  TMVA: arXiv:physics/0703039v5 [physics.data-an]
- Background suppression factor 10^4 allows high precision multi-differential analysis for the most common hadrons with strangeness.



Schematic weak decay topology (not to scale)

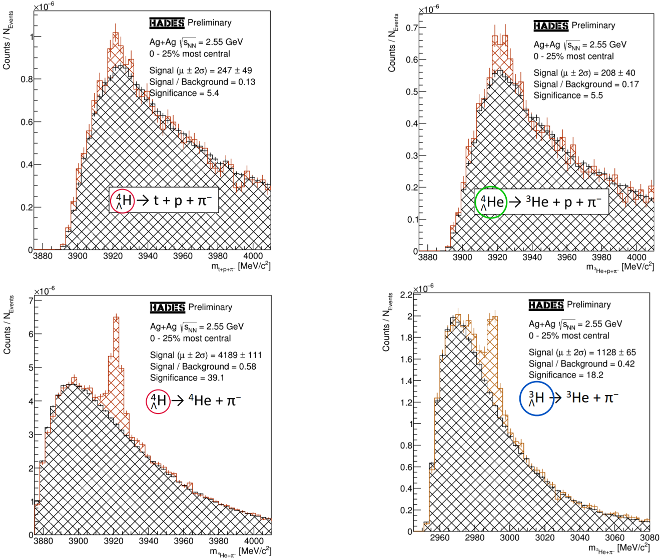


Large phase space coverage of Λ allowing for model independent extrapolation.

Hypernuclei - Reconstruction

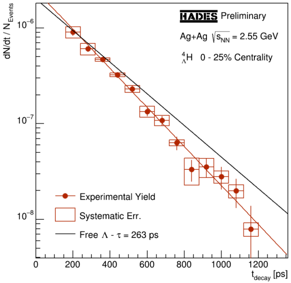
- Hypertriton - ${}^{3}_{\Lambda}H$:
  binding energy of 0.79 MeV/A, as lightest known hypernucleus
- Hyperhydrogen4 - ${}^{4}_{\Lambda}H$:
  binding energy of 2.63 MeV/A, more stable than ${}^{3}_{\Lambda}H$:
  $B({}^{4}_{\Lambda}H) \approx 3.3B({}^{3}_{\Lambda}H)$
- HADES can measure 2 or 3 body decays of Hypernuclei

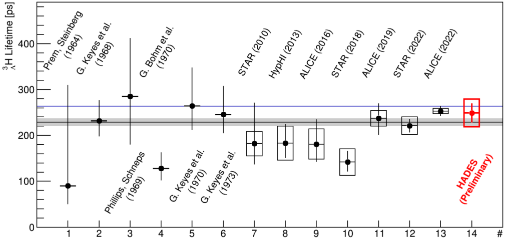
First Hypernuclei reconstruction in Heavy-ion collisions at such low energies in the participant region!

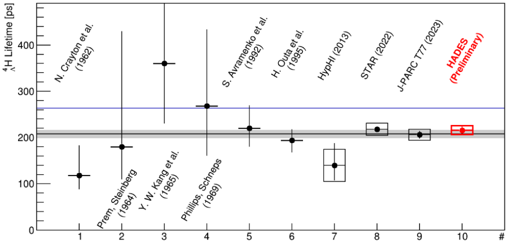


Hypernuclei - Lifetime measurement

- Use 2-body decays for lifetime measurements
- Competitive lifetime extraction compared to previously measured Hypernuclei lifetimes
- Methodology tested on well known Λ and K_s^0 hadrons



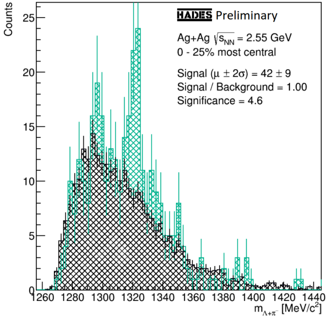


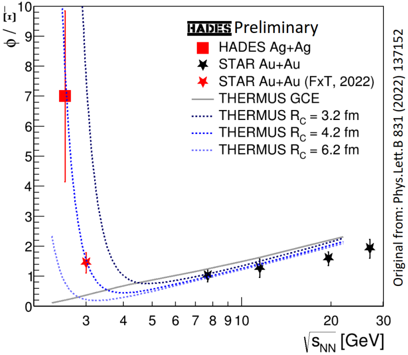


Blue line: free Λ lifetime, Black line: world average

The double strange Ξ^- hyperon

- Measurement via double weak decay chain
- Both decays selected by the neural network for weak decay recognition
- First measurement in sub-threshold AA collisions

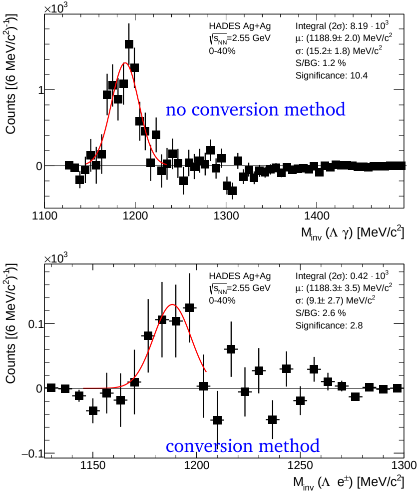




- First data at low energies of particular interest for model constrains and understanding of (multi)strange hadron production at low energies

Σ^0 reconstruction

- The new ECal allows the reconstruction of $\Sigma^0 \rightarrow \Lambda\gamma$ for the first time in AA collision
- Especially close to the production threshold only pp data is available
- Achieved significance of ≈ 10 with a S/BG on the order of 1%
- Signal also extracted in the $\Lambda e^{\pm}$ conversion channel by pairing only one of the conversion leptons with the Λ, but only a significance of ≈ 3 can be achieved.
- Feasibility study in p+p collisions at 4.5 GeV, ongoing attempts to extract Σ^0 electromagnetic form factor

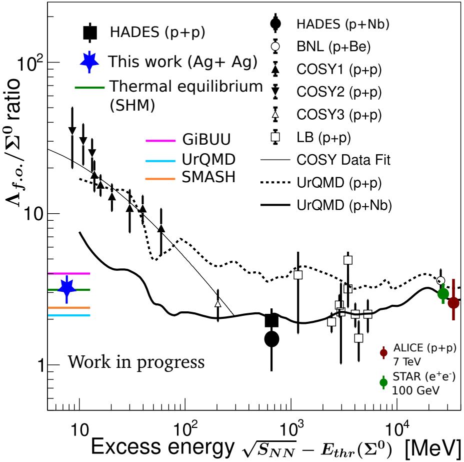


Clear reconstructed Σ^0 signal in a subthreshold AA collision!

Λ/Σ^0 ratio

- $R_{\Lambda/\Sigma^0} = N_{\Lambda_{rec}} / N_{\Sigma^0_{rec}} \cdot \epsilon_\gamma$
- Dedicated efficiency correction accounting for differences in simulation and data
- Systematic error estimation by variation of cut sets, choice of side bands and splitting in subsets; ECal timing resolution dominant
- $R_{\Lambda/\Sigma^0} = 4.2 \pm 0.9$
- $M(\Sigma^0, 0-40\,\%) = (15.7 \pm 3.2) \cdot 10^{-3}/\mathrm{evt}$

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

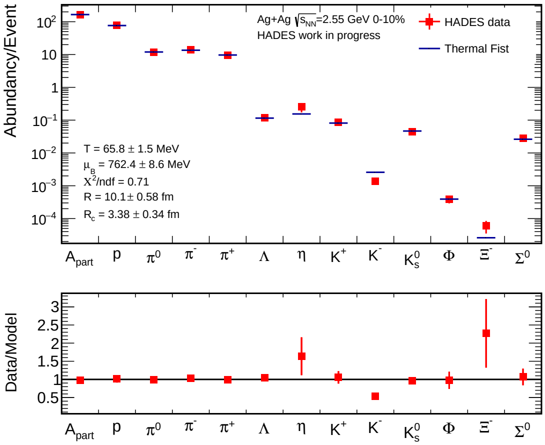


Freeze out ratio : $R'_{\Lambda/\Sigma^0} = \frac{\Lambda_{all} - \Sigma^0}{\Sigma^0} = \frac{\Lambda_{f.o.}}{\Sigma^0} = 3.2$

Statistical model collision parametrization

- Extracted freeze out ratio $R'_{\Lambda/\Sigma^0} = 3.2 \pm 0.7$ delivers estimation of the temperature: $T = \Delta m / ln(R') \approx 66\,\mathrm{MeV}$
- Thermal-FIST
  1. No strangeness: $T = 74 \pm 6\,\mathrm{MeV}$
  2. With strangeness: $T = 66 \pm 2\,\mathrm{MeV}$
- Transport models (R'_{Λ/Σ^0})
  1. GiBUU (4.0)
  2. SMASH (2.3)
  3. UrQMD (2.1)

  differ slightly
- Fit independent of Σ^0 due to nice agreement and Ξ^- due to large uncertainties

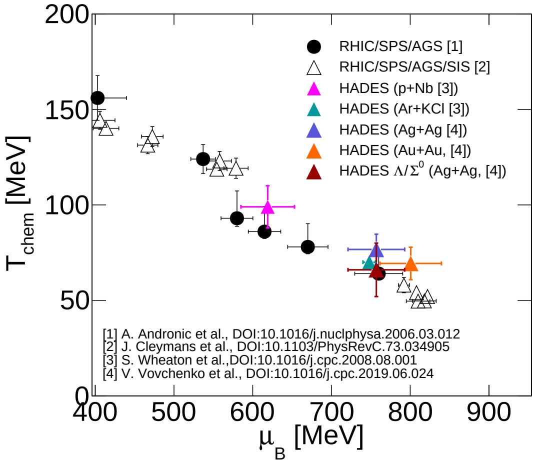


Conclusion: Σ^0 production in good agreement to thermal model!

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)

Summary

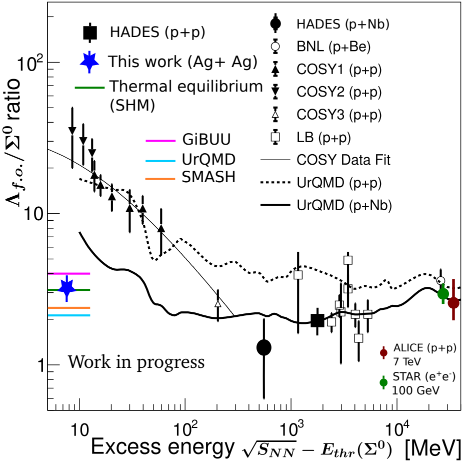
- Successful usage of aNN for weak decay reconstruction
- Various light Hypernuclei can be measured and analysed
- Lifetime estimation of the Hypernuclei are competitive with the world data
- High precision measurement of Λ; Ξ^- and Σ^0 measured for the first time in this energy regime
- Ξ^- yield important for model constrains
- Freeze-out ratio: $R'_{\Lambda/\Sigma^0} = 3.2$ can be directly translated in a temperature estimation $T = \Delta m / ln(R') \approx 66\,\text{MeV}$ independent of any additional measurement
- Σ^0 production rate agrees to thermal fits with while transport models differ



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.
- ϵ_β estimated from data (leptons)
- Systematic error estimation by variation of cut sets, choice of side bands and splitting in subsets; ECal timing resolution dominant
- $R_{\Lambda/\Sigma^0} = 4.2 \pm 0.9$
- $M(\Sigma^0, 0-40\,\%) = (15.7 \pm 3.2) \cdot 10^{-3}$/evt



Freeze out ratio :

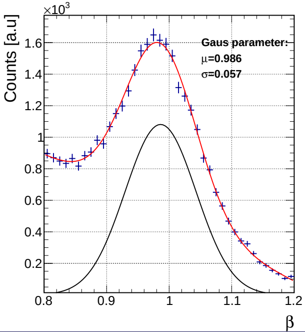
$$R'_{\Lambda/\Sigma^0} = \frac{\Lambda_{all} - \Sigma^0}{\Sigma^0} = \frac{\Lambda_{f.o.}}{\Sigma^0} = 3.2$$

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

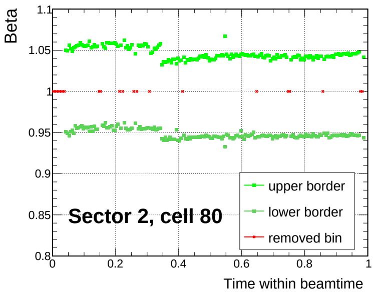
Backup - Data driven efficiency correction

- $e^{\pm}$ 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.

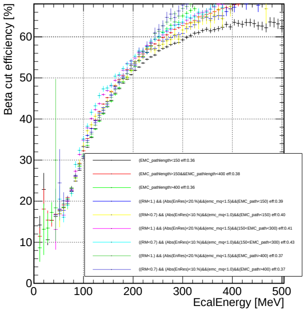
Time dependent scan



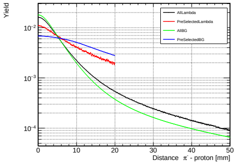
Extract cut values

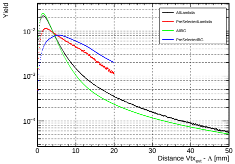


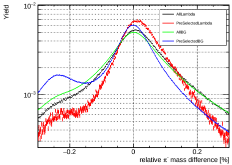
Efficiency measurable for leptons

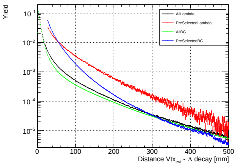


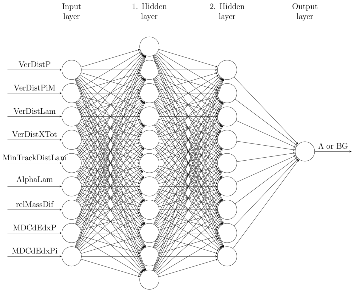
Backup - Lambda MLP parameter

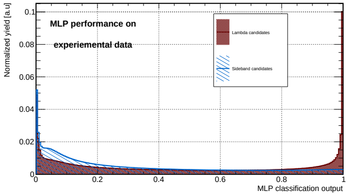












- Weak deacays as rare probe of the HIC
- Off-Vertex topology parameters highly dependent
- Ideal conditions for a multivariate analysis
- Pre-selection highly improves the performance

Backup - Strangeness balance

$$M(\Lambda) + M(\Sigma^-) + M(\Sigma^0) + M(\Sigma^+) = M(K^+) + M(K^0_S) + M(K^0_L)$$

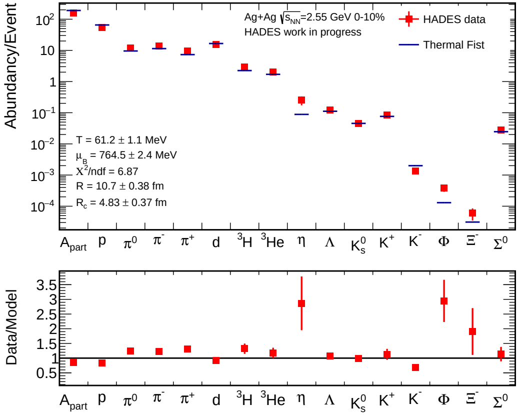
Centrality	Production rate $[10^{-2}/\text{event}]$				Σ^0/Λ
	Lambda	Σ^+	Σ^0	Σ^-	
0-10%	10.09	2.20	2.39	2.60	0.24
10-20%	6.00	1.36	1.48	1.61	0.25
20-30%	3.47	0.90	0.98	1.06	0.28

- 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 $K^+/2K^0_s = 0.92 - 1.02$
- Measured value $\Lambda/\Sigma^0 = 3.2 \pm 0.7$ slightly below the calculated value of 4.0

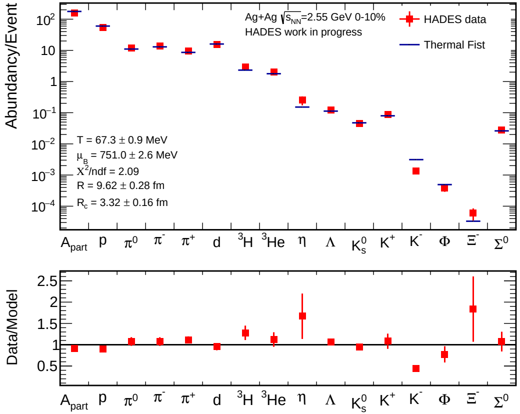
Backup - Thermal Fist - with excited nuclei

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

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

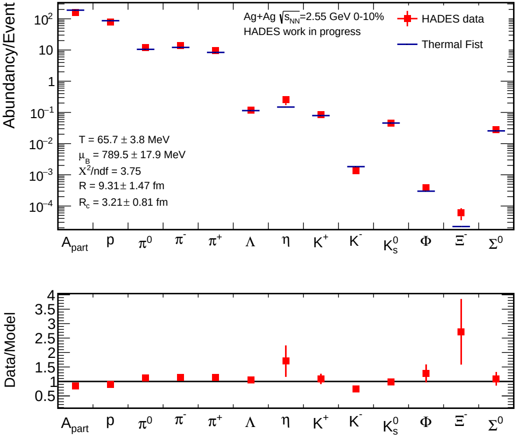


K^- from fit excluded: $\chi^2/Ndf = 2.09$



Backup - Thermal Fist - without nuclei

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



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