



Hyperon *production, interaction* and *structure* studies in proton-proton data with HADES

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On Behalf of the HADES Collaboration

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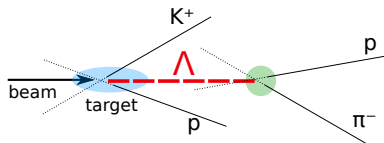
Hyperon Physics

Particles containing s quarks in addition to u/d quarks

Much is well understood about hyperons but still a lot left to investigate!

Want to understand coupling of baryons to virtual (massive) photons

- Radiative and Dalitz decays of hyperons
 - Gives information about the structure of hyperons
- Measure Dalitz decays of baryonic resonances
- Production of $\Sigma^0(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$
- Experimental results on electromagnetic hyperon decays sparse or has not been measured



Double strange systems

- $\Lambda\Lambda$ - Measuring interactions important for understanding the cores of neutron stars
- Ξ^- - production in $p+p$ reactions important for understanding production in heavy ion reactions and presence of excited resonances in the medium

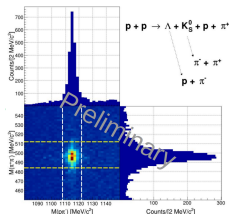
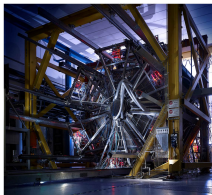
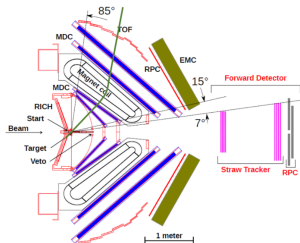
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The HADES Spectrometer

High-Acceptance Di-Electron Spectrometer

Versatile detector operating at GSI at SIS18 since 2001 allowing to study both hadron and heavy-ion physics

- Precision spectroscopy of e^+e^- pairs and charged hadrons and calorimetry
 - Perfect for hyperon structure studies
- pp, heavy ion (e.g. Ag-Ag, Au-Au) and pion induced reactions
 - Hyperons are produced and used as probes for in-medium properties
- Acceptance of detector: $\sim 15\text{-}85^\circ$ + extended with a forward detector at lower angles for pp data @ $T_{beam} = 4.5$ GeV
 - Important for detection of hyperon decay products



ΛK_S^0 analysis by S. Pattnaik (GSI)



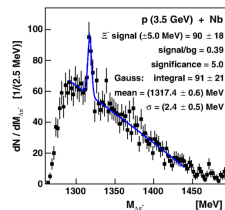
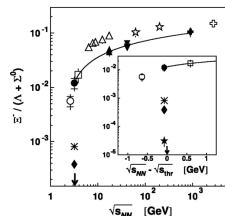
Ξ^- Puzzle

- Production of hyperons important to determine cross sections and investigate the baryon spectrum
- Excess of sub-threshold Ξ^- production measured at HADES in Ar+KCl Reactions at 1.76A GeV [*] and p(3.5 GeV)+Nb collisions [**]
- Could be explained by resonances with significant branching fractions into the Ξ^- channel [***]
- Need experimental observation of $N^* \rightarrow \Xi^- K^+ K^+$ in p+p reactions

[*] PRL 103, 132301 (2009)

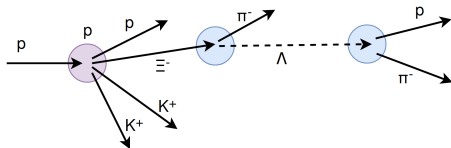
[**] Phys. Rev. Lett. 114, 212301 (2015)

[***] J. Steinheimer et al., J.Phys. G43 (2016) 015104

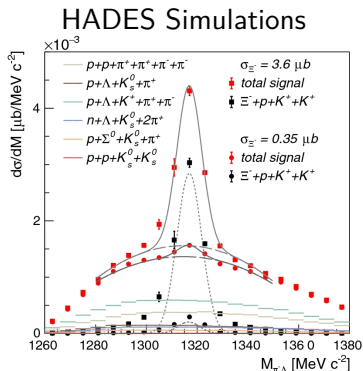


Figs. from [**]

Ξ^- Production @ 4.5 GeV



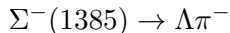
- **Cross section estimates:** $0.35 \mu\text{b} - 3.6 \mu\text{b}$
- **Main backgrounds**
 - $pp \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ with $\sigma = 227 \mu\text{b}$
 - Various Λ and K_S^0 production channels
- **Goal of Analysis**
 - Total and differential cross section determination
- **Long term physics goals**
 - Spectroscopy
 - Interaction studies: $\Xi^- p$ -potential



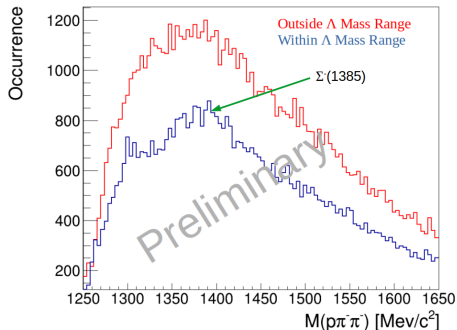
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Ξ^- Production

$\Sigma^-(1385)$ as reference particle

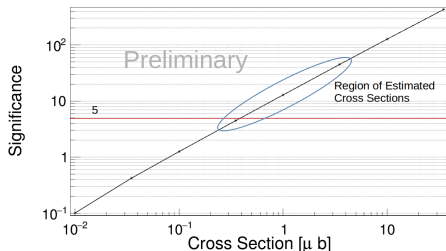


- Same inclusive final state as Ξ^-
- Protons and pions measured in main HADES
- Missing mass cut applied, $>$
 $M(p) + M(K^+) + M(\pi^-) - 20 \text{ MeV}/c^2$
 $= 1551.5 \text{ MeV}/c^2$
- $\Sigma^-(1385)$ structure appear when applying a cut on the Λ mass range



Sensitivity

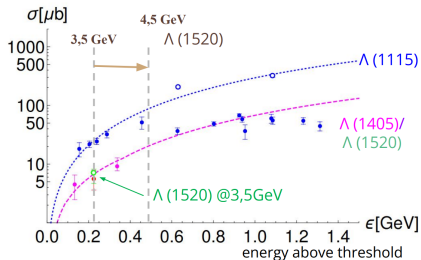
- Pions measured in main HADES and protons in the forward detector
- Missing mass cut applied
- Treat MC simulation as signal and data as background
- Scale the MC simulation to the expected number of counts for a given cross section
- Select range 1280 - 1350 MeV/c²
 - **Signal entries** = entries in scaled simulation within range
 - **Background entries** = entries in data within range



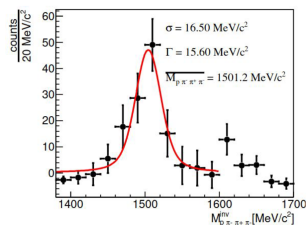
- Can reach a significance of 5 sigma for cross sections within the expected range

Production and Nature of $\Lambda(1520)$ and $\Sigma^+(1385)$

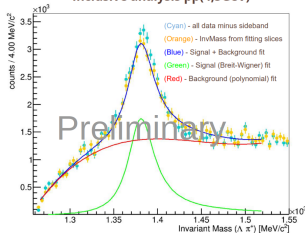
- $\Lambda(1520)$ structure
 - Excited quark state or baryon - meson molecule?
- In-medium modification of $\Sigma^*(1385) - \pi$ loop
- 60 times higher integrated luminosity at 4.5 GeV than pp run at 3.5 GeV
- Analysis by K. Sumara (Jagiellonian University)



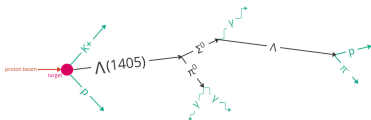
$\Lambda(1520)$ @ $T_{beam} = 3.5$ GeV



Inclusive analysis pp(4,5GeV)



Production and Nature of $\Lambda(1405)$

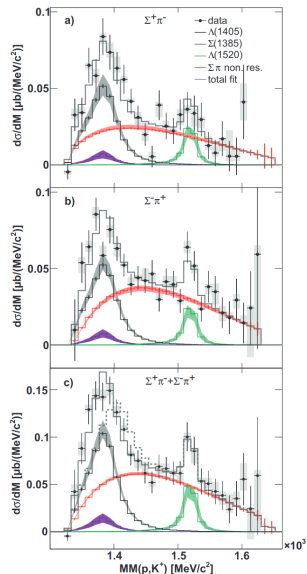


- $\Lambda(1405)$: KN bound state?
- Line shape measurement
- Has previously been measured at HADES with Σ^+/π^- final state (right Fig.) [*]
- In 4.5 GeV pp data
 - Exclude contribution from $\Sigma(1385)$ by selecting neutral decay channel with photons
 - 3 charged tracks and one neutral measurement
 - Allow for missing π^0 to increase statistics
 - Future plans to use KinFit [**] for reconstructing missing π^0
 - Analysis by A. Władyszewska (Jagiellonian University)

[*] Phys. Rev. C 87, 025201

[**] CSBS (2024) 8:3

<https://doi.org/10.1007/s41781-023-00112-x>



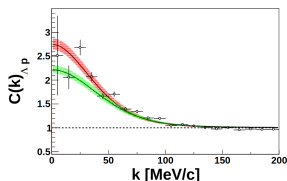
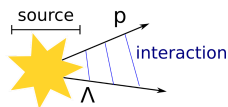
Hyperon Correlations

Important for understanding the strangeness content of neutron stars

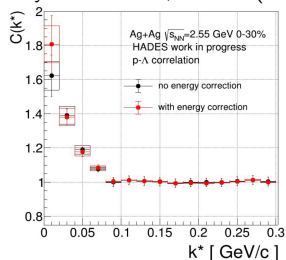
Femtoscopy studies via correlation function

$$C(p_1, p_2) \equiv \frac{P(p_1, p_2)}{P(p_1) \cdot P(p_2)}$$

- Λp potential inferred from correlation function at HADES in $p+\text{Nb}$ @ $\sqrt{s_{NN}} = 3.18$ GeV [*] (right upper plot)
- Need further studies in $p+p$ and $p+\text{Ag}$ reactions with HADES
- HADES operates at energy range close to production threshold which is beneficial for interaction studies
- Current work by N. Rathod (Warsaw University of Technology) to extract $p-\Lambda$ correlations at HADES (lower plot)

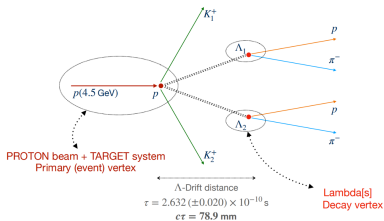


[*] Phys. Rev. C 94, 025201 (2016)

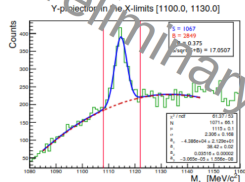
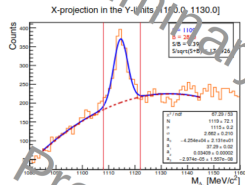
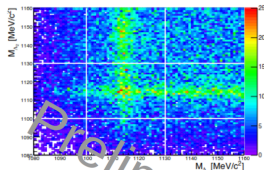


$\Lambda\Lambda$ Interactions

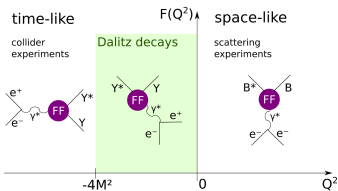
- Interaction studies to determine YY -potential for single strange hyperons
- $\Lambda\Lambda$ potential previously inferred from correlation function at ALICE in p+p collisions at $\sqrt{s}=13$ GeV [*]
 - Extend to lower energies
- Protons and pions are combined into Λ
- Two Λ in the same event
- Background analysis in progress
- Work by G. Appagere (Stockholm University)



[*] Phys. Lett. B 797:134822 (2019)

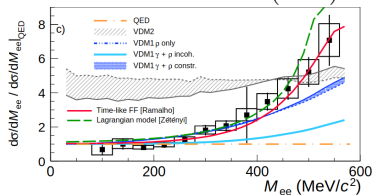


Hyperon Structure

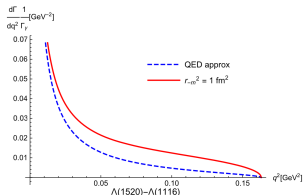


- Electromagnetic structure of strange resonances, such as $\Sigma^0 \rightarrow \Lambda \gamma^* \rightarrow \Lambda e^+ e^-$
- Structure described in terms of electric and magnetic transition form factors
- Time-Like FF of $N^*(1520) \rightarrow ne^+e^-$ has been measured at HADES
 - Test of Vector Meson Dominance (ρ)
 - Dominance of pion cloud effects
 - Want to extend this to the $\Lambda(1520)$ $\Sigma^*(1385)$
- Decay rates at low q^2 sensitive to electromagnetic structure

$\pi^- p \rightarrow ne^+e^-$
Red curve: eTFF of $N^*(1520)$

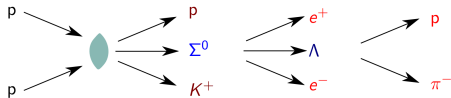


DOI:10.48550/arXiv.2205.15914

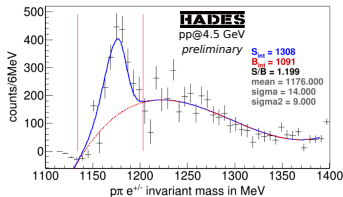
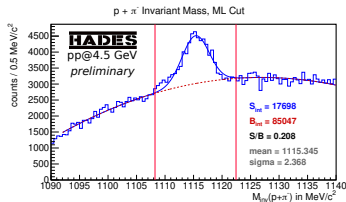


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Dalitz Decay of Σ^0



- Decay not yet observed
- Challenging analysis due to small branching fraction ($< 5 \times 10^{-3}$)
- HADES excellent for identifying e^+e^-
- Need to reject conversion electrons
- Future activities to identify $\Sigma^0(1385)$ and $\Lambda(1520)$ via lepton decay channels
- Analysis by J. Rieger (Uppsala University)



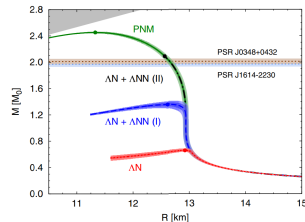
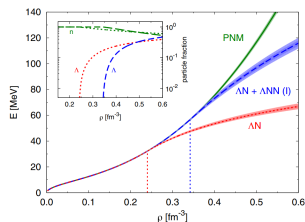
Summary

- Hyperons important for understanding interior of neutron stars and give insight to the production and structure of baryons
- HADES had a successful pp run @ 4.5 GeV in February 2022
- Hyperon- production, interaction and structure studies are a large part of the program
- Analysis of $\Lambda\Lambda$, $\Xi^-(1321)$, Σ^0 , $\Lambda(1405)$, $\Lambda(1520)$, $\Sigma^+(1385)$ ongoing
 - Stay tuned!

Thank you! Questions?

Hyperon Interactions

- Neutron Stars – a very hot and interesting topic
- Hyperon Puzzle
 - Strangeness production favorable
 - Reduction of Fermi pressure
 - Softer EOS
 - Lower allowed mass compared to observed mass
- Could solve the Puzzle
 - Three-body hyperon interactions or strong repulsion in YN or YNN interactions
- Need to determine the potentials



Phys. Rev. Lett. 14, 092301 (2015)