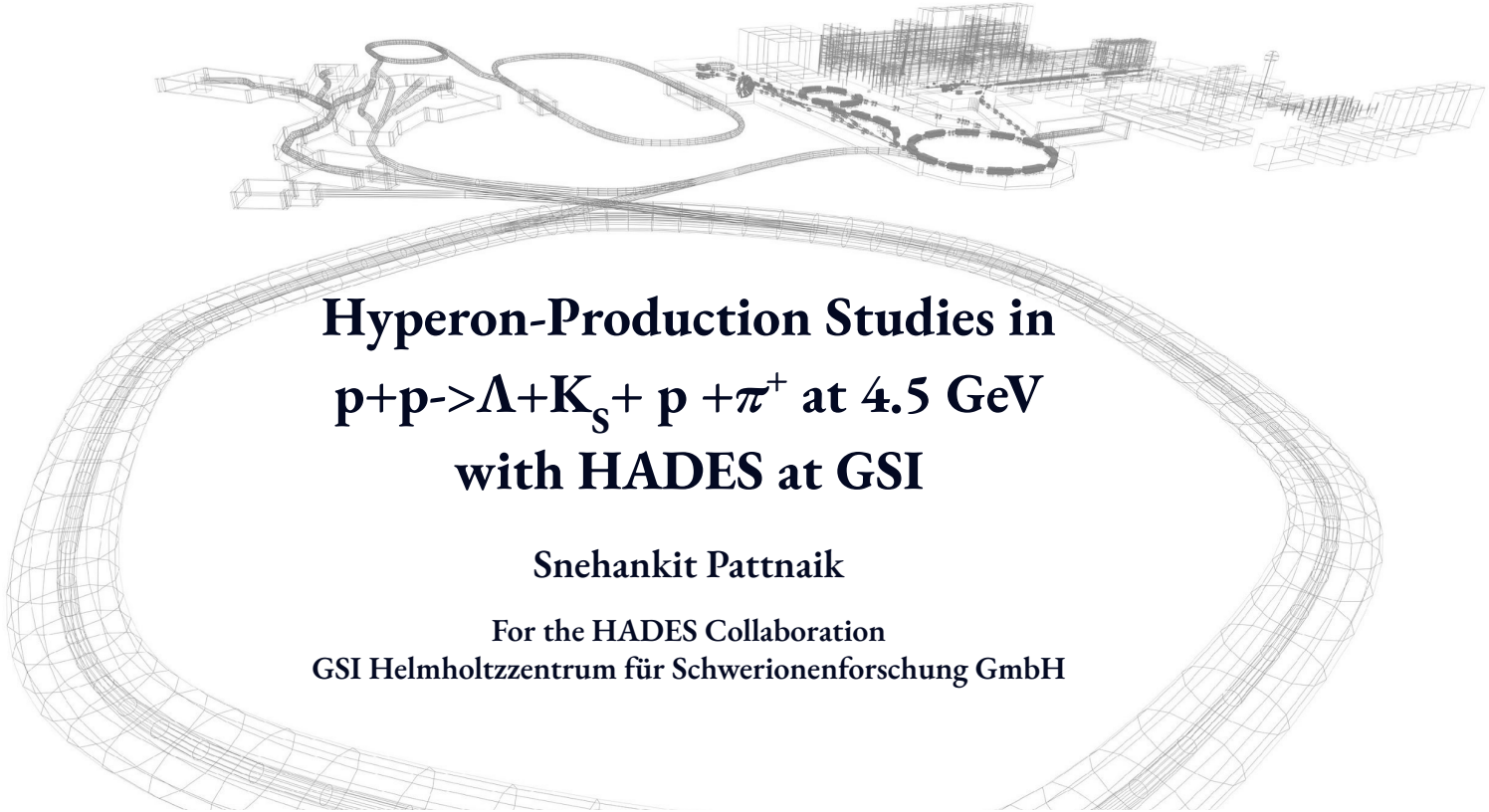


# Hyperon-Production Studies in $p+p->\Lambda+K_s+p+\pi^+$ at 4.5 GeV with HADES at GSI

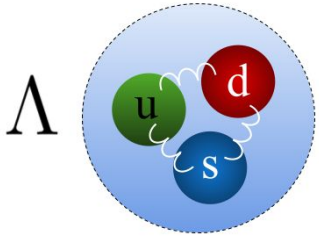

**Snehankit Pattnaik**

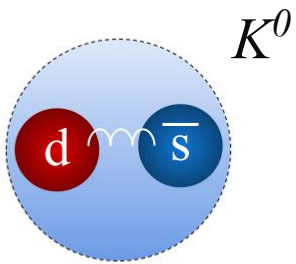
For the HADES Collaboration
GSI Helmholtzzentrum für Schwerionenforschung GmbH

# Introduction

## Outline

- **Motivation**
- **HADES experiment**
- **Analysis techniques**
- **Results**
- **Outlook**



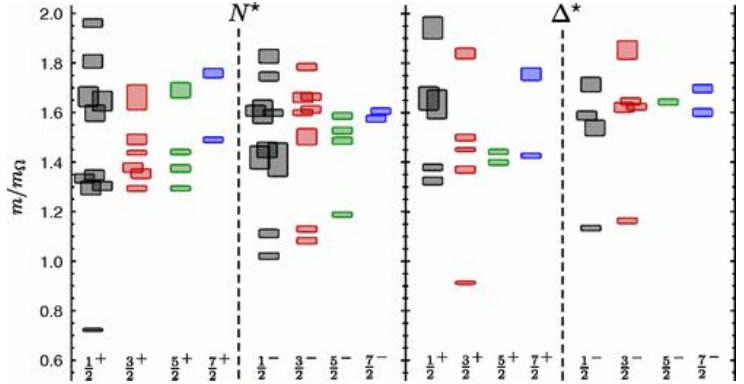

## Strangeness Studies

- Baryons containing at least a strange/charm quark.
- Probe to study the strong interaction, via spectroscopy and structure studies.
- Formation of hyperons of interest to understand dense QCD matter, such as the core of neutron stars [1].
- Microscopic study of the hyperon-nucleon interaction necessary to describe the Equation Of State and resolve the hyperon puzzle [1].

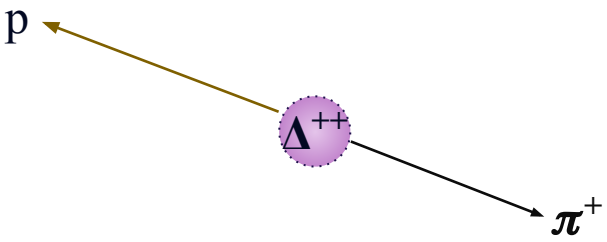
[1] Diego Lonardoni *et al* 2015, Phys. Rev. Lett. 114, 092301

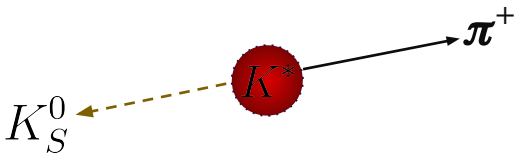
# Hyperon Resonances

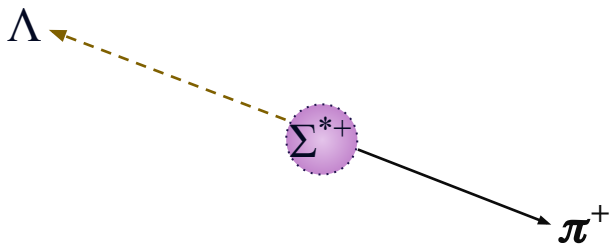
- Non-perturbative QCD isn't well understood at low energies:
  - The study of hyperon resonances can provide insights into hyperon production and final state interactions.
- Hyperon spectrum :
  - Lattice QCD predict many states not yet discovered [1].
  - Hints of exotic states e.g. pentaquarks and dibaryon structures [2].
- Multiple Decay Channels with intermediate resonances:
  - *N** often couple strongly to meson-baryon channels.




Nucleons and Deltas spectrum from lattice calculations [1].





[1] R. G. Edwards *et al.* 2011 Phys Rev D 84.7.
[2] M Nekipelov *et al* 2007 *J. Phys. G: Nucl. Part. Phys.* 34 627

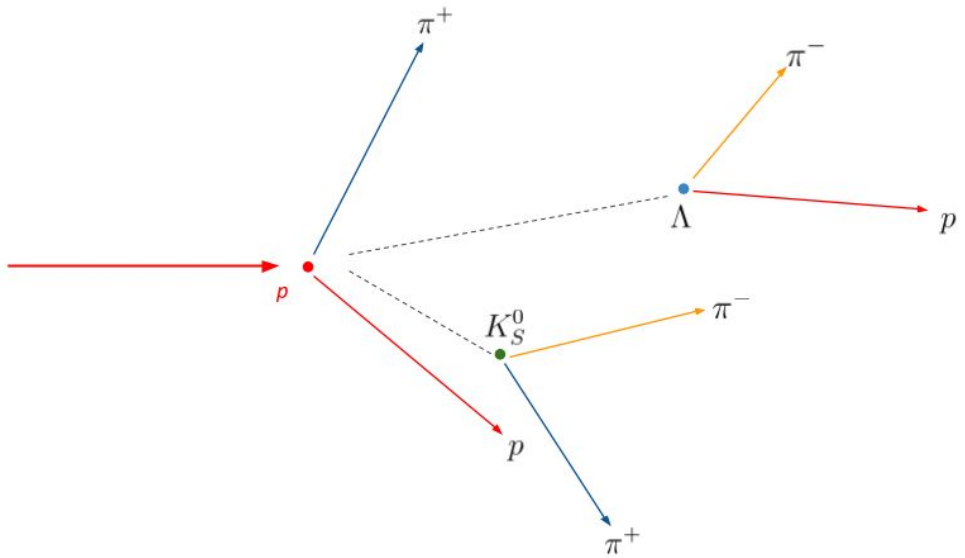
# Methodology

This work at kinetic energy of 4.5 GeV

$$pp \rightarrow \Lambda + K_S^0 + p + \pi^+$$

$$\begin{cases} pp \rightarrow \Lambda + K_S^0 + \Delta^{++}[p\pi^+] \\ pp \rightarrow K^+(892)[K_S^0\pi^+] + \Lambda + p \\ pp \rightarrow \Sigma^+(1385)[\Lambda\pi^+] + K_S^0 + p \end{cases}$$

- $pp \rightarrow \mathbf{\Lambda}+K^+ + p$, previously analyzed at T = 3.5 GeV.
- Hints of hyperon resonances within mass range of 1.6 GeV/c² to 2.0 GeV/c² at 3.5 GeV [1-2].
- Search for $N^*$ resonance decays to strangeness with $K_S$ and $\mathbf{\Lambda}$ as final state particles [1-2].
- Total and differential cross section measurements for this channel at 4.5 GeV with proton-proton reaction.
- Extract spin degrees of freedom via measurements of spin density matrix elements of $K^*$ and self-polarization of $\mathbf{\Lambda}$.





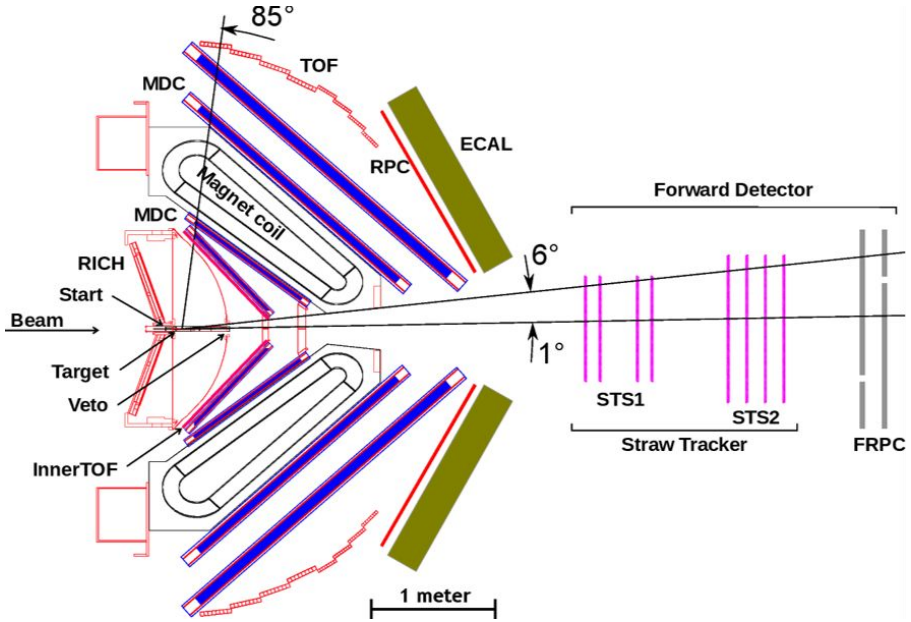
[1] G. Agakishiev *et al.* 2015 Phys.Lett. B 742 242-248.
[2] R. Munzer *et al.* 2018 Phys. Lett. B 785, 574–580.

# The High-Acceptance Di-Electron Spectrometer - HADES

- HADES is a fixed target experiment.
- The detector operates at the SIS18 accelerator providing heavy-ion and proton beams up to 4.5 GeV.
- Good charged particle tracking with the MDC.
- Particle Identification sub detectors:
  - RICH
  - MDC
  - TOF & RPC

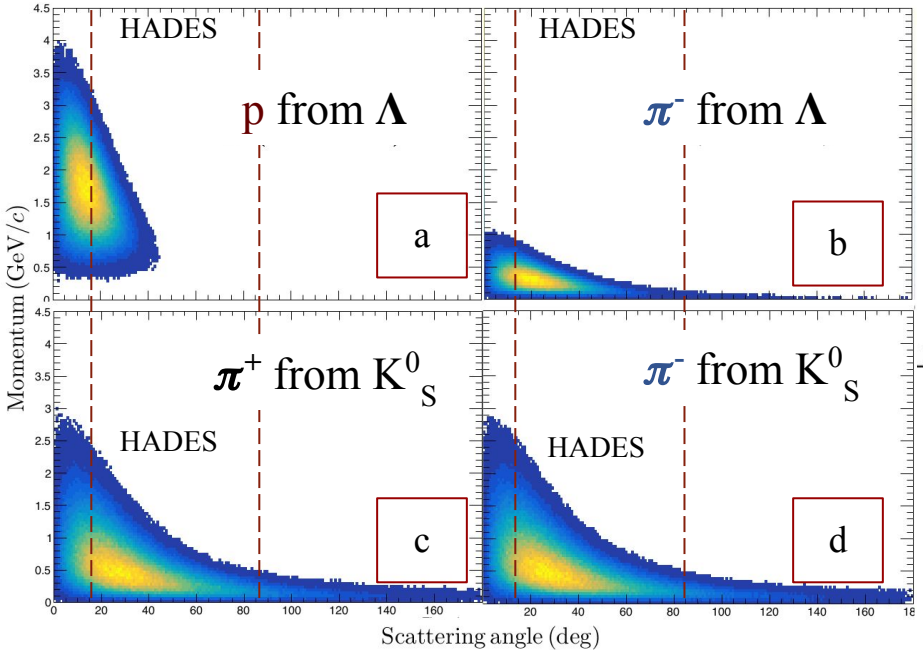
Large acceptance - it can detect particles that are emitted at a wide range of angles and energies.

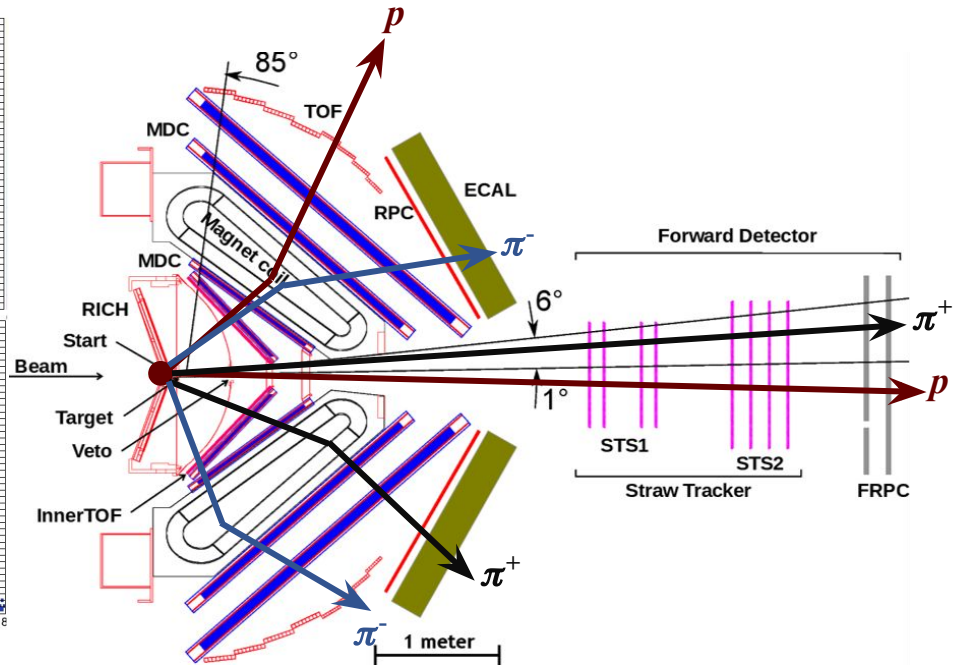
Track reconstruction allows for a clean signal selection by using displaced vertices.




J. Adamczewski-Musch *et al.* 2021 Eur. Phys. J. A 57 :138

# Exclusive Reaction at HADES




- An acceptance of about 50% for the exclusive reaction.
- The forward detector can enhance signal reconstruction for the high momentum protons.

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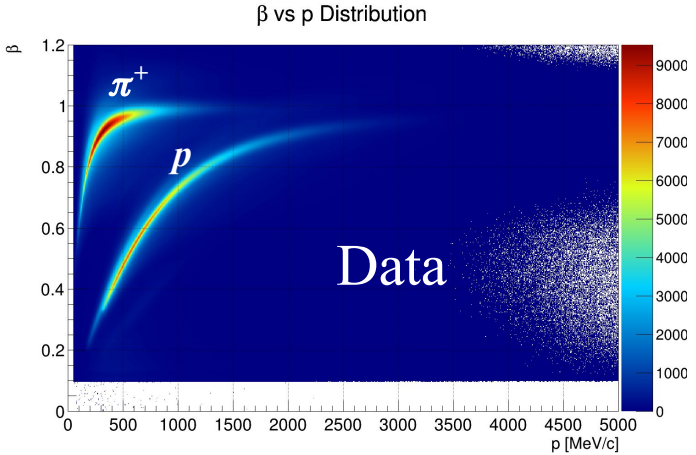
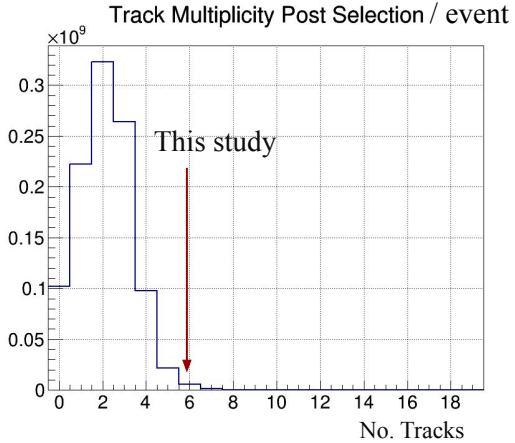
$$pp \rightarrow \Lambda + K_S^0 + p + \pi^+$$

# Particle Identification and Event Selection

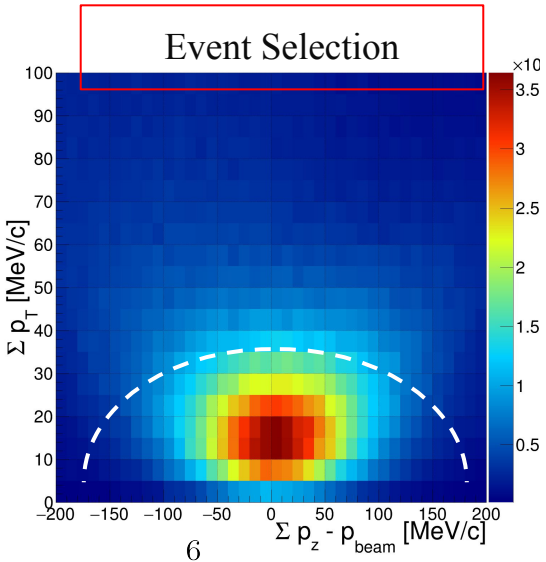
- A total of **39 x $10^9$** events stored from 2022 beamtime.
- A good particle identification for separating pions and protons.
- This reaction requires events with at least 6 tracks.
- Selected 6-track events ~ **1.8 x $10^7$** events.
- Total luminosity (5.86 ±0.09 $pb^{-1}$ ) at 4.5 GeV is 60 times higher than the previous proton beam at 3.5 GeV!

$$pp \rightarrow \Lambda + K_S^0 + p + \pi^+$$
$$\Lambda \rightarrow p + \pi^-$$
$$K_S^0 \rightarrow \pi^- + \pi^+$$



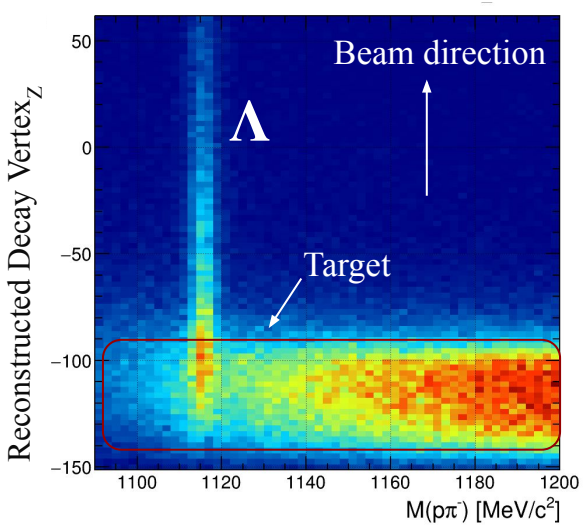



# Momentum Constraints for Exclusive Channel Selection




$\sum_{n=1}^{6} \vec{p_{\mathrm{T}}}$ and $\left(\sum_{n=1}^{6} \vec{p_{\mathrm{z}}}\right) - p_{\mathrm{beam}}$ close to 0.

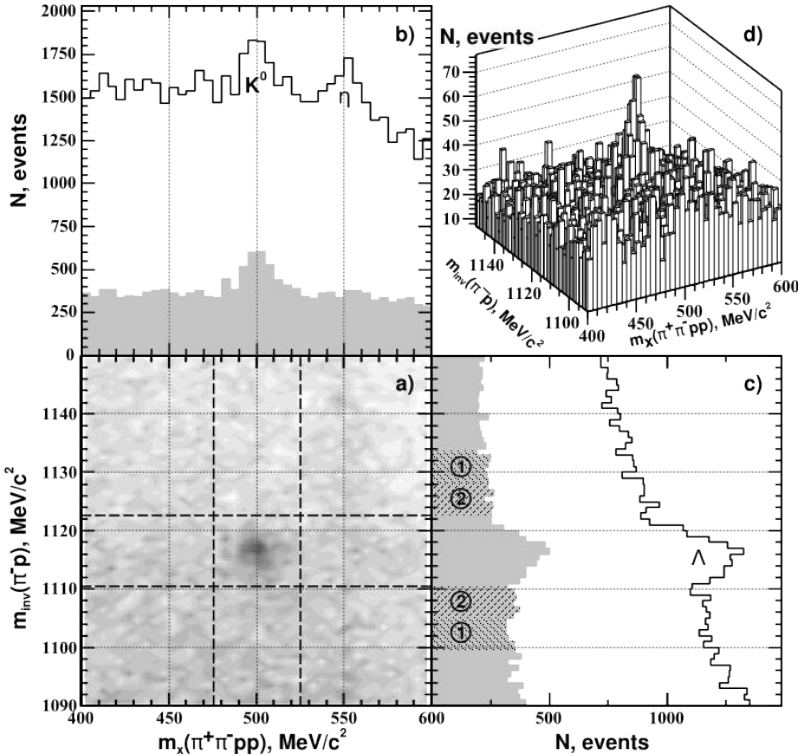
- A good parameter for exclusive channel selection.
- An ellipse cut which reduces the background and only exclusive events are remaining.



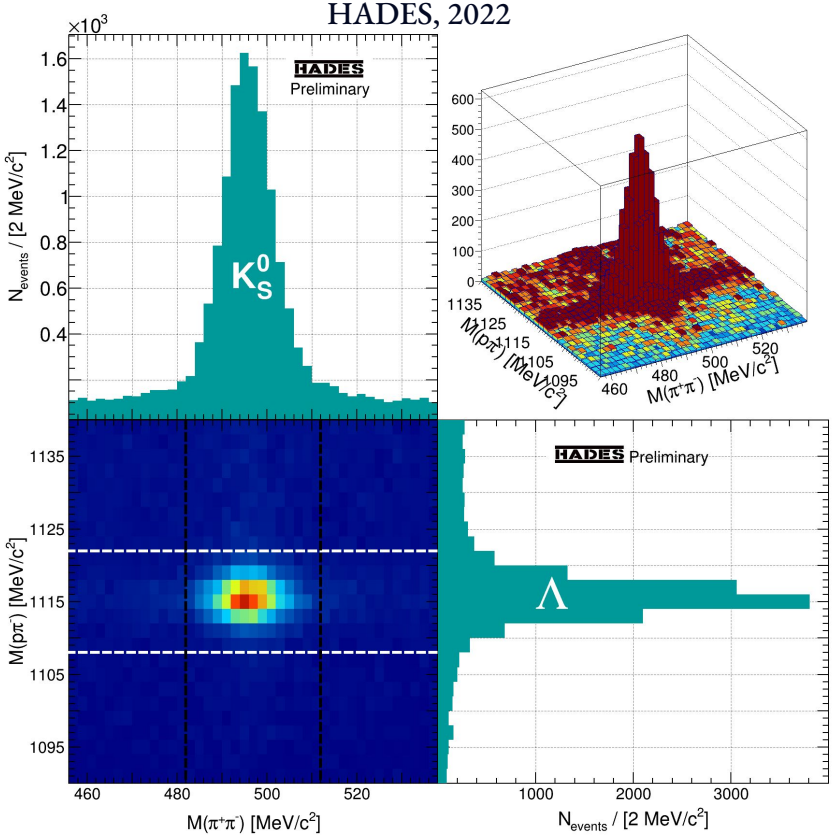

- Displaced vertex from decay candidates outside the target region.
- Additionally distance of closest approach between decay tracks is used for signal selection.

# $M(\pi^- p)$ vs $M(\pi^+\pi^-)$

ANKE Experiment, 2007



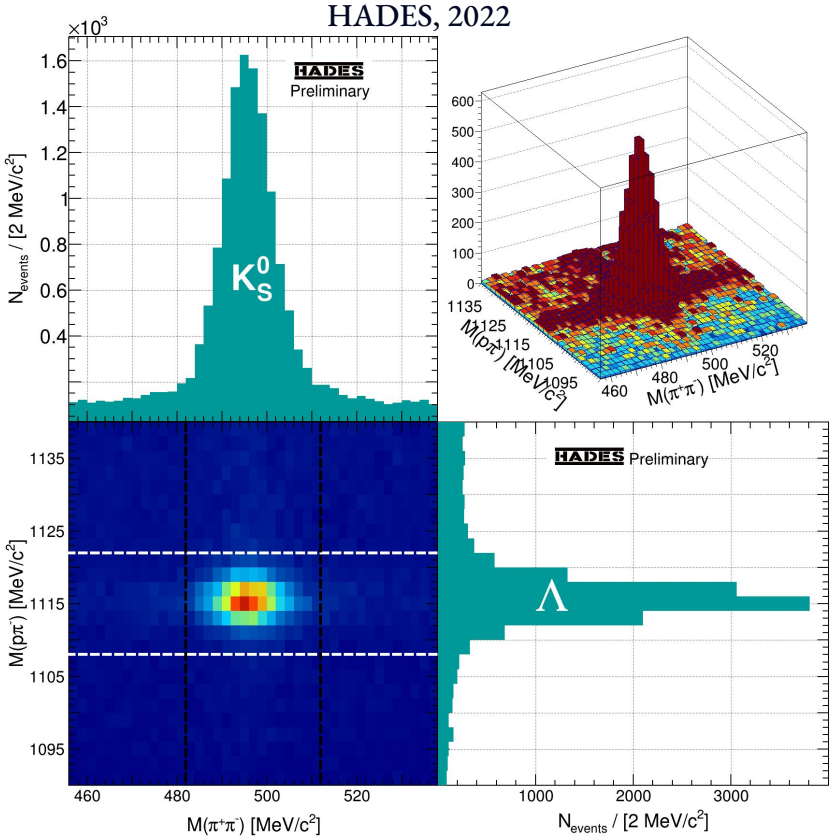

HADES, 2022



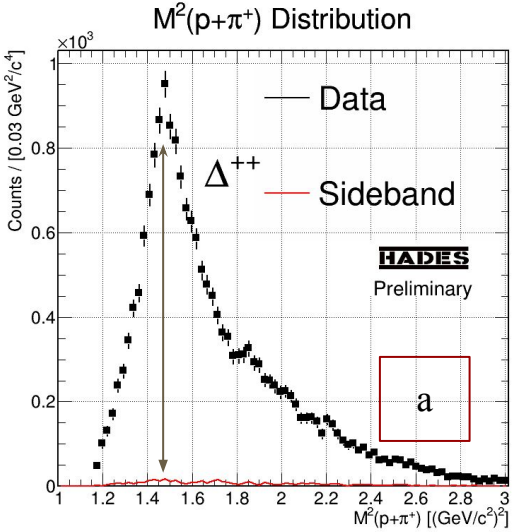

[1] M Nekipelov *et al* 2007 *J. Phys. G: Nucl. Part. Phys.* 34 627

# $M(\pi^- p)$ vs $M(\pi^+\pi^-)$

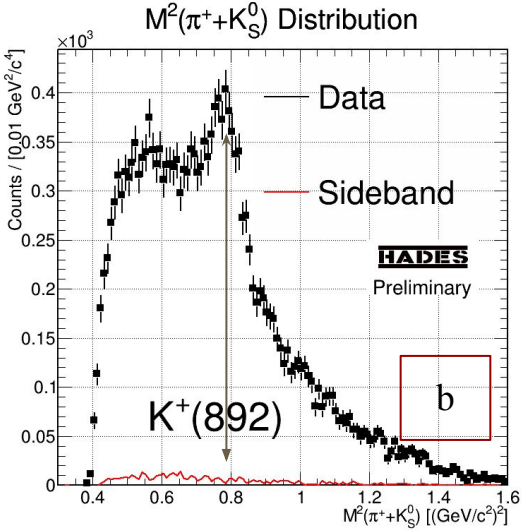
| 4.5 GeV | Λ | $K^0_S$ |
|---|---|---|
| Mass [MeV/$c^2$] | 1115.6 ± 0.1 | 495.8 ± 0.3 |
| Width [MeV/$c^2$] | 2.2 ± 0.1 | 5.4 ± 0.1 |
| # Signal events | 15560 | 15020 |
| Background | 4036 | 4763 |
| S/B | 3.9 | 3.1 |
| Significance | 109.9 | 103.5 |



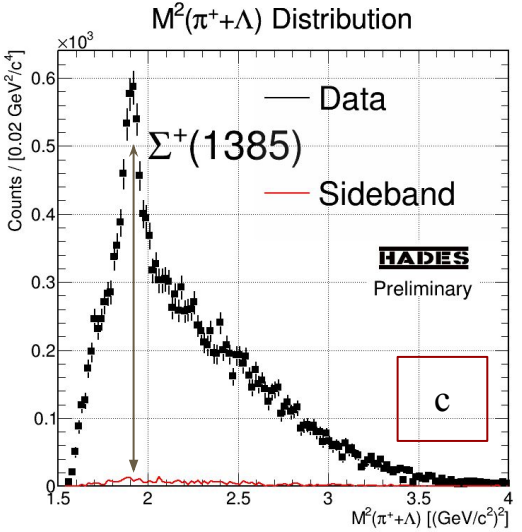
# Intermediate Resonances




- A clear signature of the decay of the $\Delta^{++} \rightarrow p\pi^+$ observed.

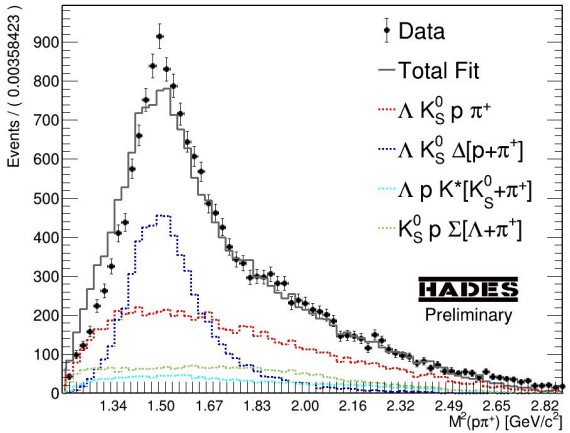


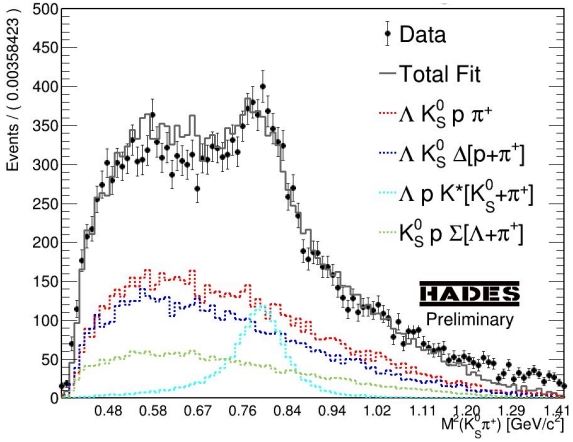

- The process $K^* \rightarrow K^0_S\pi^+$ clearly observed by the peak at 0.8 $GeV^2/c^4$ .

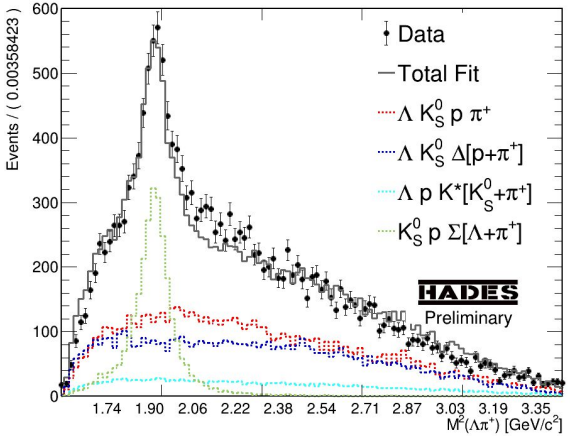



- The process $\Sigma^{*+} \rightarrow \Lambda\pi^+$ clearly observed by the peak at 1.9 $GeV^2/c^4$ .

# Simultaneous Fit for Intermediate Resonances



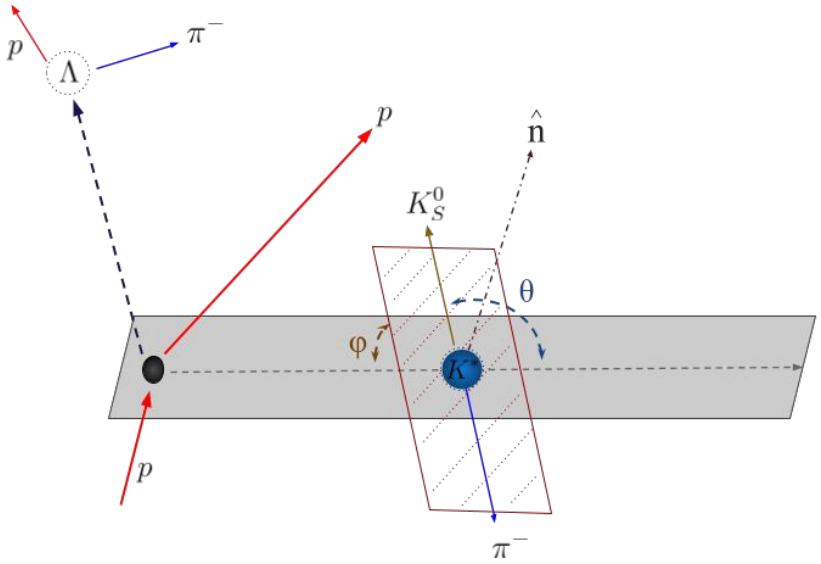



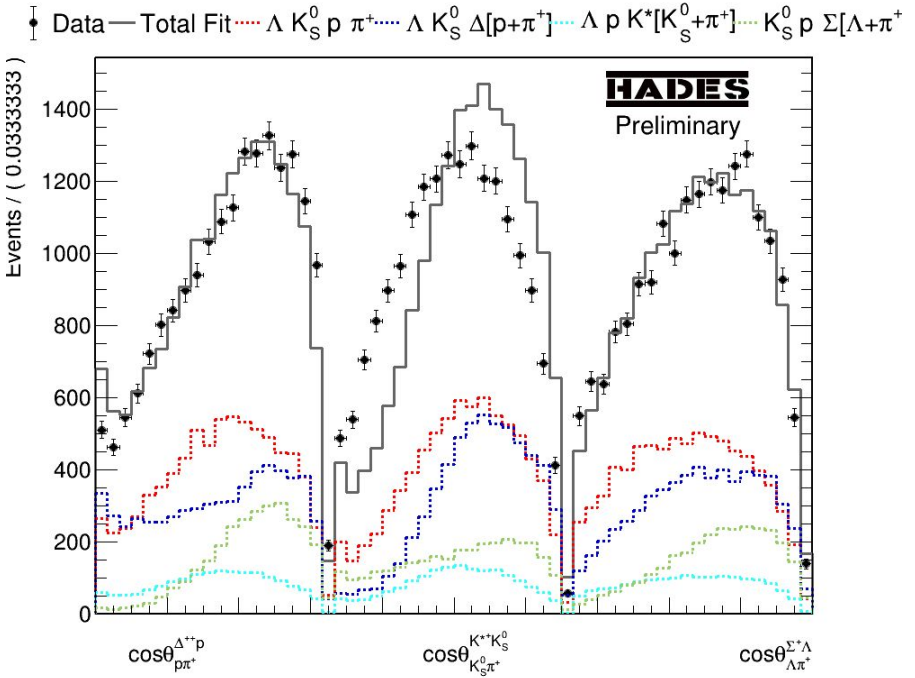

$pp \rightarrow \Lambda + K_S^0 + \Delta^{++}[p\pi^+]$ $pp \rightarrow K^+(892)[K_S^0\pi^+] + \Lambda + p$ $pp \rightarrow \Sigma(1385)[\Lambda\pi^+] + K_S^0 + p$

- Monte Carlo approach to understand our data to simulate different intermediate resonance.
  - Pluto event generator,
  - Geant3 to replicate the detector response.
- Acceptance x reconstruction efficiency
  - $\varepsilon_{\text{acc x rec}}$ = **2‰.**

- A simultaneous incoherent fit is performed for the three different invariant mass distributions.
- The dataset is well described by the combined fit.
- To extract *N** resonance parameters, a partial wave analysis is needed.

# Angular Distributions



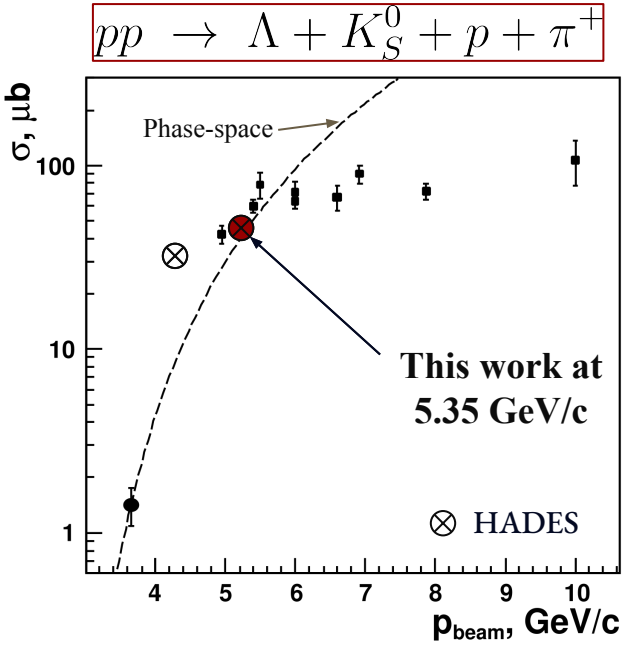

To extract spin degrees of freedom for the $K^*$ production [1].

- The fractions from the combined invariant mass fit results are used for describing the angular distribution.
- The combined fit is able to describe the $\Delta^{++}$ and the $\Sigma^+(1385)$ angular distributions but deviates for the $K^*$.
- The observed angular distributions show deviations from an isotropic behaviour as used by the simulations.

[1] G. Agakishiev *et al.* 2015 Phys. Rev. C 92, 024903.

# Preliminary Cross Sections and Comparison with Earlier Work

| $p_p$ (GeV/$c$) | $\sigma_{tot}$ ($\mu$b) | NR (%) | $\Delta^{++}$ (%) | $\Sigma^{*+}$ (%) | $K^{+*}$ (%) | $N^*$ (%) |
|---|---|---|---|---|---|---|
| 3.65 [1] | 1.41 | 65 | 35 | *seen* | - | - |
| This work 5.35 | 50 | 45 | 33 | 18 | 9 | **?** |
| 6.70 [2] | 64 | 36 | 36 | 18 | 10 | *seen* |
| 7.87 [3] | 72.4 | 5.7 | 34.2 | 29.1 | 15.5 | 15.6 |




Cross section as a function of proton beam momentum, adapted from [1].

- Observables from earlier experiments extracted using a one-pion-exchange model assumption [2-3].
- Previous experiments hampered by limited statistics.
- Preliminary cross sections (total and individual contributions) extracted from this work compatible with earlier results [1-3].
- Partial wave analysis necessary to extract couplings and intermediate resonances.


[1] M Nekipelov *et al* 2007 J. Phys. G: Nucl. Part. Phys. 34 627.
[2] Klein S *et al.* 1970 Phys. Rev. D 1 3019.
[3] Firebaugh M *et al.* 1968 Phys. Rev. 172 1354.
[4] K. Tsushima et al 1999, Phys. Rev. C 59, 369.

# Summary

- Current analysis improves our signal extraction and significance.
- Clear observation of $\Delta^{++}$, $\Sigma^{*+}$ (1385) and $K^{*+}$ (892) production in this channel.
- Cross section estimate for $\Lambda+K_S+p+\pi^+$ at 4.5 GeV is extracted as 50 μb.
- Slight discrepancy between data and simulations.

# Outlook

➔ Improve the statistics and resolutions by missing-particle analysis and further exploit kinematic fitters.

➔ Short term: Extract polarization observables via spin-density matrix elements studies of $K^*$ and self-polarization of $\Lambda$ weak decay.

➔ Long term: partial wave analysis.

Thank you