Study of the $\Lambda(1405)$ ‘golden channel’ measured in p+p at HADES

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HADES

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FAIR

GSI

Plan

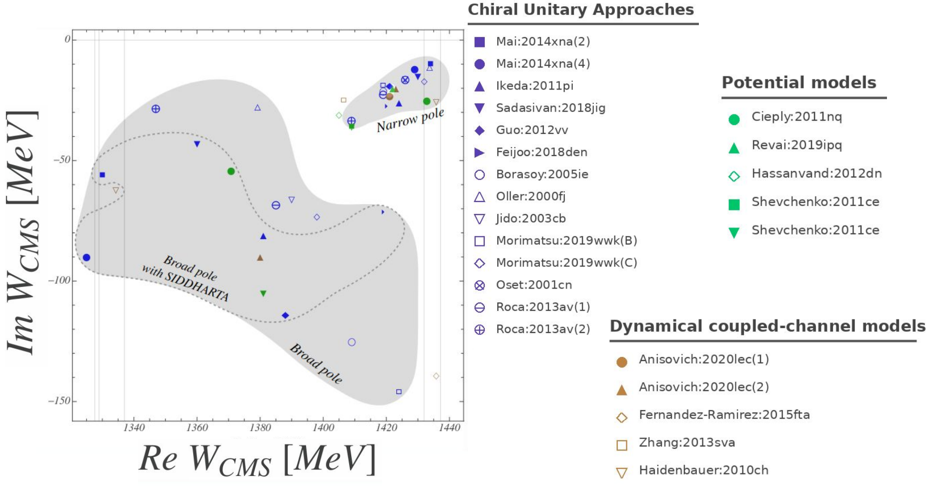
- Motivation

- Analysis of exclusive channel **p(4.5 GeV)+p → $pK^+\Lambda(1405)$ → $(\Sigma^0(\Lambda(\to p\pi^-)\gamma)\pi^0(\to \gamma\gamma))$**
  - final states selection
  - kinematic refit of $\Sigma^0\pi^0$ mass
  - side-band analysis

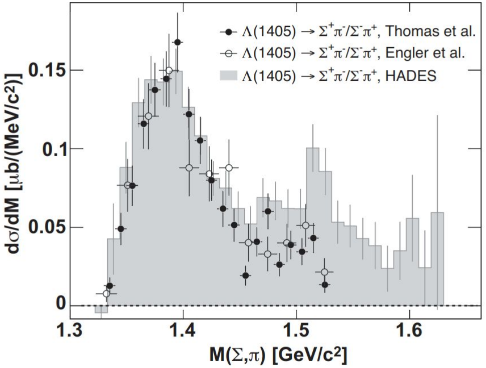
- Preliminary results
  - *t* dependence
  - comparison to theoretical prediction
  - lineshape analysis: empirical fit with a two-pole model

Λ(1405) poles studies

- ongoing debate on one- / two-pole structure hypotheses
- most data from low-energy NK scattering, kaonic atoms – not very sensitive to lower (Σπ) pole position
- previous HADES measurements in pp@3.5 GeV with charged final states indicate stronger coupling to the lower pole (similarly to π^-p production)
- two-pole picture complemented by results from lattice QCD calculations

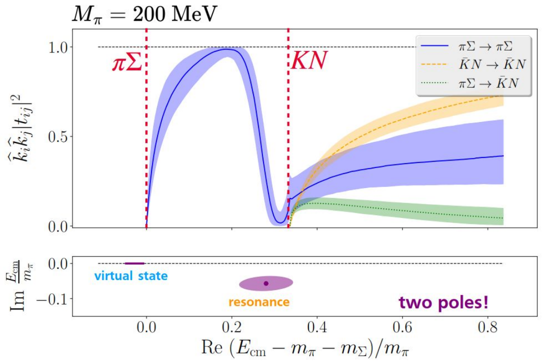


M. Mai, Eur. Phys. J. ST 230, 1593 (2021)



J. Siebenson and L. Fabbietti, Phys. Rev. C 88, 055201 (2013)

lattice QCD results:

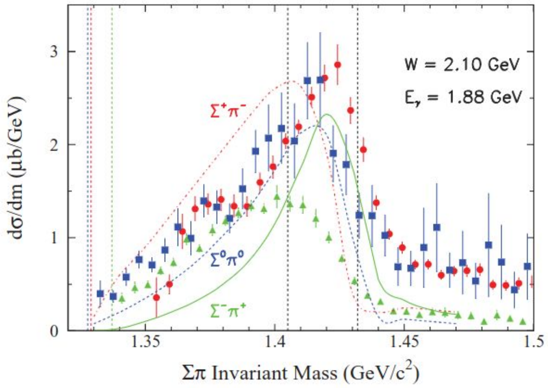


Bulava et al., arXiv:2307.13471 (2023); arXiv:2307.10413 (2023)

Isospin decomposition of $\Sigma\pi$ channels

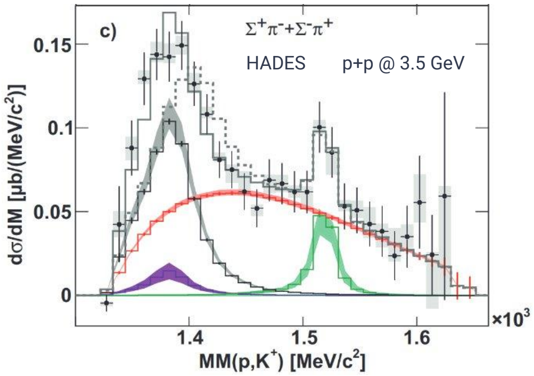
- lineshape differs for 3 final states
- I = 1 amplitude: significant contribution in charged final states from $\Sigma(1385)^0$ and new $J=1/2^-$ states 1394 ± 20 MeV/c^2 and 1413 ± 10 MeV/c^2 (CLAS)
- **neutral final state (BLUE) - pure I = 0 !!**

Photoproduction:



CLAS Collaboration, Phys. Rev. C 87, 035206 (2013)

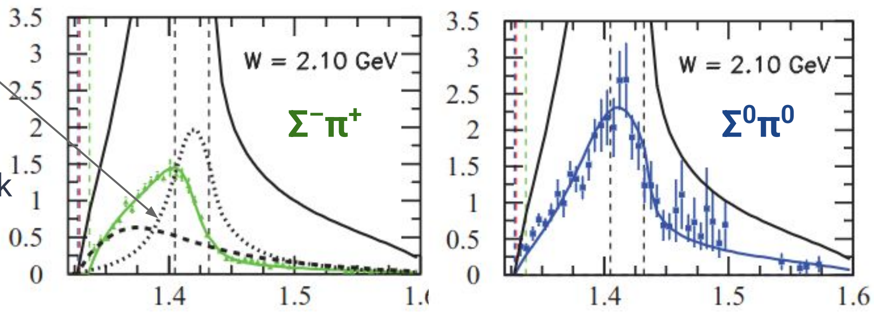
Dashed colored lines from theoretical model:
J. C. Nacher, E. Oset, H. Toki, and A. Ramos, Phys. Lett. B 455, 55 (1999)



HADES Collab., Phys. Rev. C 87, 025201 (2013)

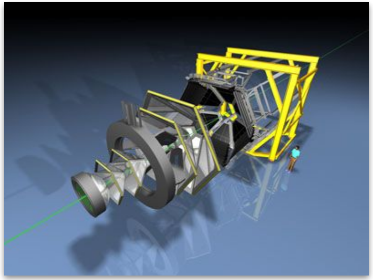
I =1: dashed black lines

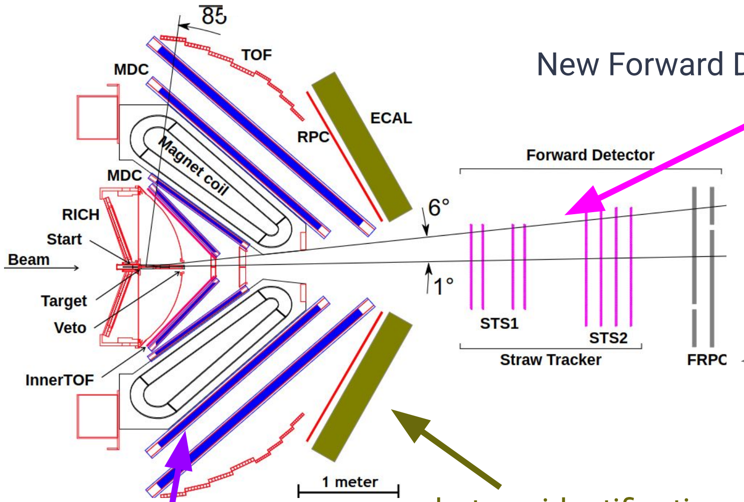
I =0: solid black line



CLAS Collaboration, Phys. Rev. C 87, 035206 (2013)

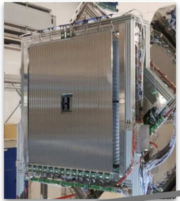
High Acceptance DiEectron Spectrometer



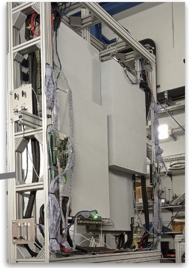


New Forward Detector: increased hyperons acceptance!

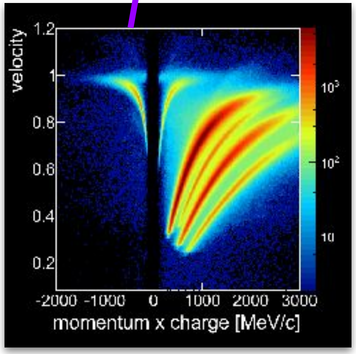
track reconstruction



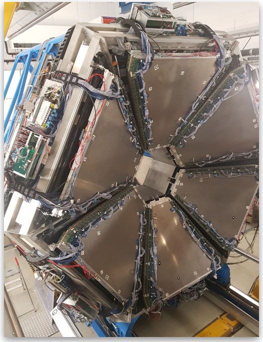
ToF measurements



No magnetic field: particle hypothesis, momentum estimated from TOF



photons identification



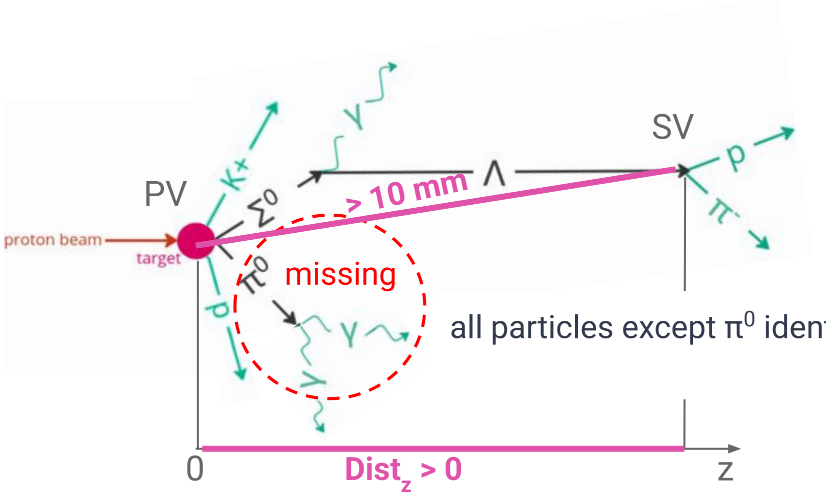
now available with significant statistics:

$\Sigma^0 \rightarrow \Lambda\gamma$

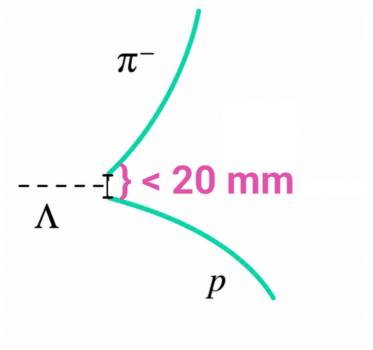
$\pi^0 \rightarrow \gamma\gamma$

$\Lambda(1405) \rightarrow \Sigma^0\pi^0$

$pK^{+}\Sigma^{0}\pi^{0}$ reaction channel reconstruction



all particles except π^0 identified → 1C fit applied



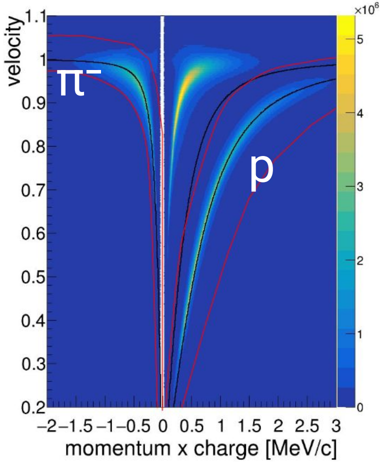
PID in HADES (magnetic spectrometer):

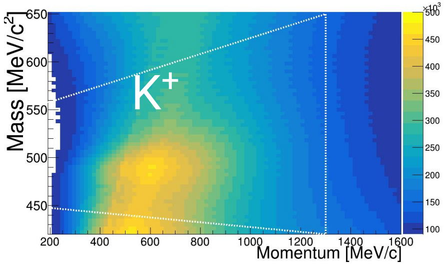
cuts on β vs. momentum, mass vs momentum, $\Lambda \to p\pi^-$

decay topology and MM cuts: $MM_{exp}(p\pi^-) > m_p + m_{K+} + m_{\pi 0}$

photon in ECAL: β vs. energy cut

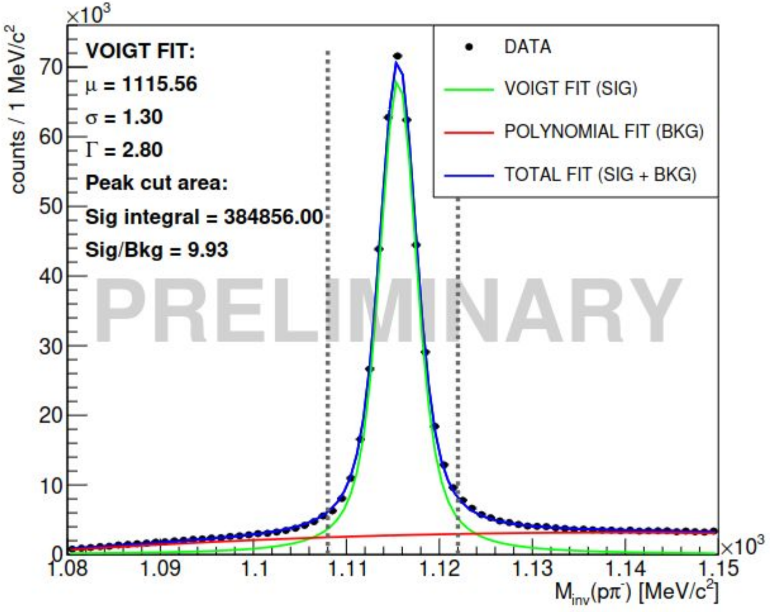
Tracks in Forward Tracker assumed to be protons: particles in FD are mainly protons (known from MC)





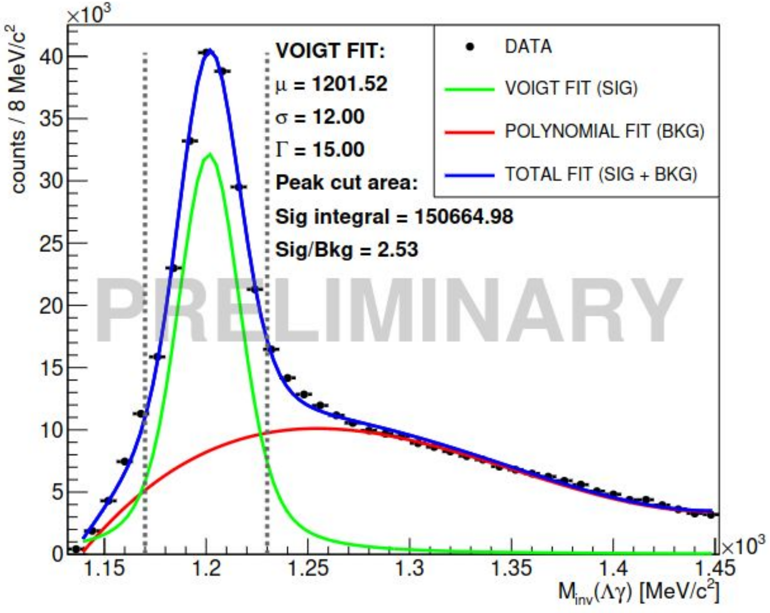
Λ and Σ^0 identification and selection

PDG: 1115.683 ± 0.006 MeV



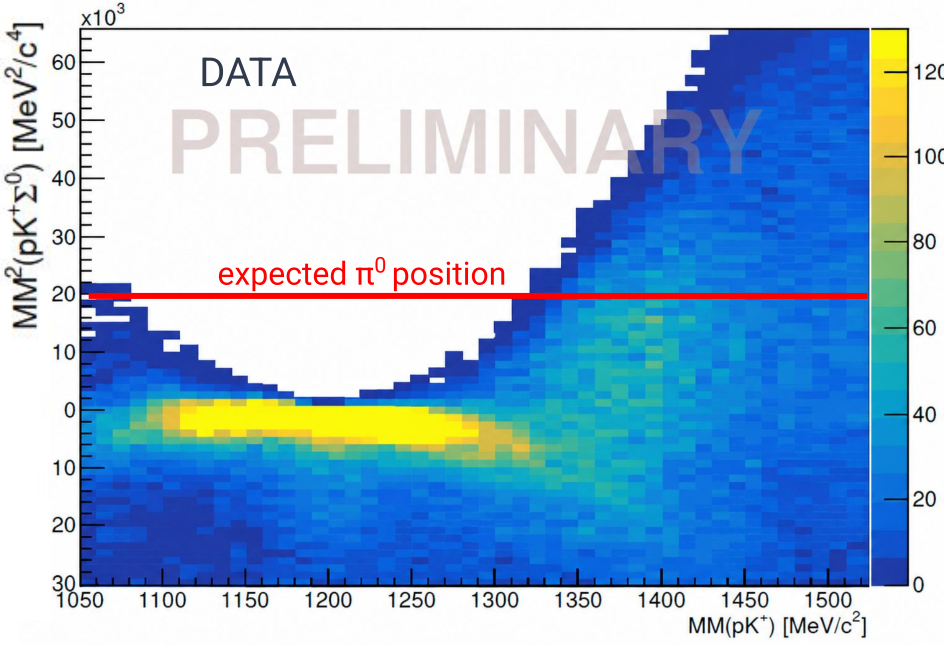
protons that did not fall into the Λ mass window are from now on marked as protons coming from event vertex (spectators)

PDG: 1192.662 ± 0.024 MeV



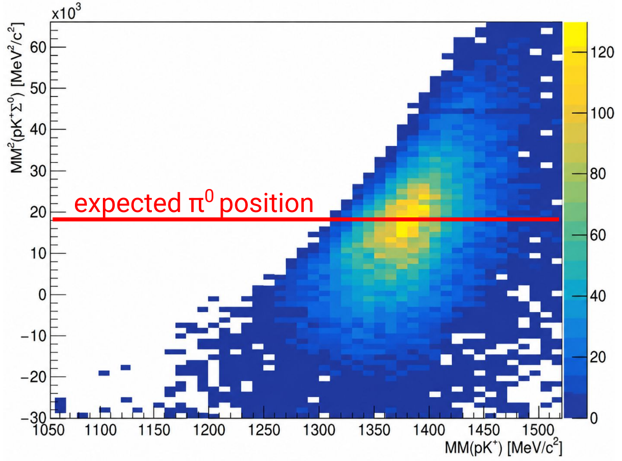
systematic shift due to ECAL calibration (work in progress)

π^0 identification



Simulation

p+p → pK⁺Λ(1405) → (Σ⁰(Λ(→ pπ⁻)γ)π⁰(→ γγ))



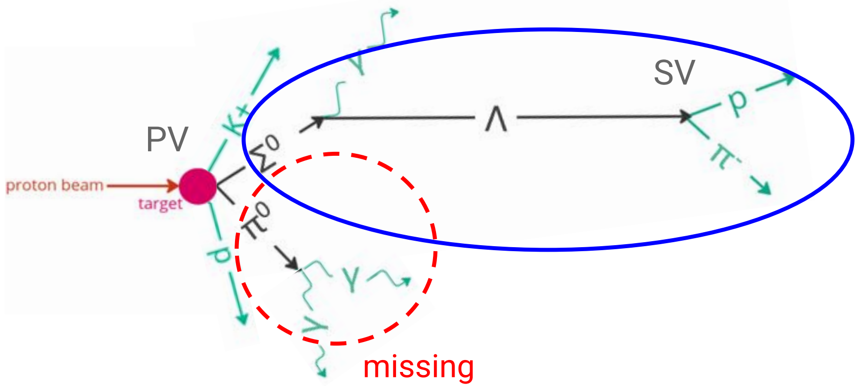
Kinematical refit

- 1C: Σ^0 mass constraint

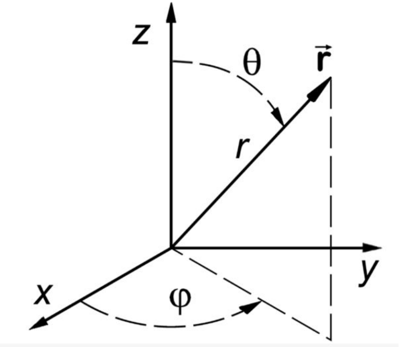
$$\boxed{f = \sqrt{\left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{p}_i\right)^2} - m_{\text{mother}} = 0}$$

- 1C: π^0 missing mass constraint

$$\boxed{f = \sqrt{\left(E_{\text{ini}} - \sum_{i=1}^{N} E_i\right)^2 - \left(\vec{p}_{\text{ini}} - \sum_{i=1}^{N} \vec{p}_i\right)^2} - m_{\text{miss}} = 0}$$

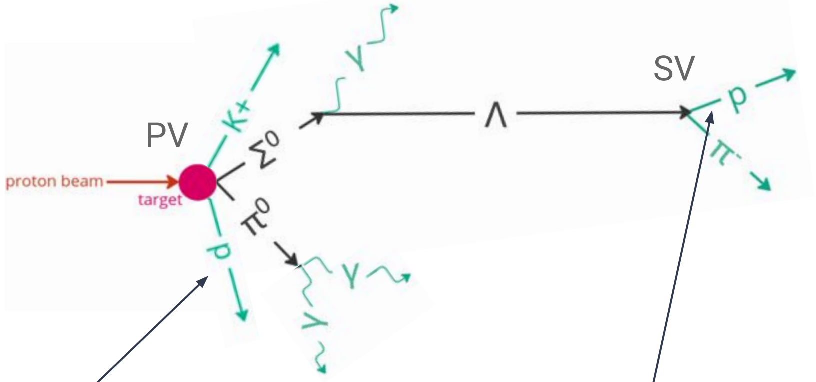


- measured track parameters:
  - inverse momentum 1/p [MeV^{-1}/c]
  - polar angle θ [radians] defined from 0 to π
  - azimuthal angle ϕ [radians] defined from $-\pi$ to π relative to the beam (z) axis



W. Esmail et al., Comput. Softw. Big Sci. 8, 3 (2024)

Verification of the method



- should be centered around 0 with σ = 1:

$$pull_i = \frac{y_i - x_i}{\sqrt{\sigma^2(y_i) - \sigma^2(x_i)}}$$

- overestimation / underestimation of errors → *p*-distribution pulled to higher / lower values

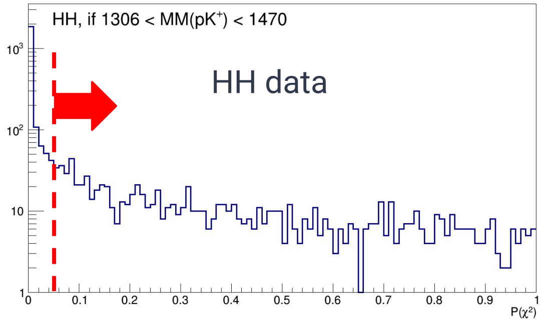
$$p = \int_{\chi^2}^{\infty} f_{\mathrm{NDF}}(z)\, dz$$

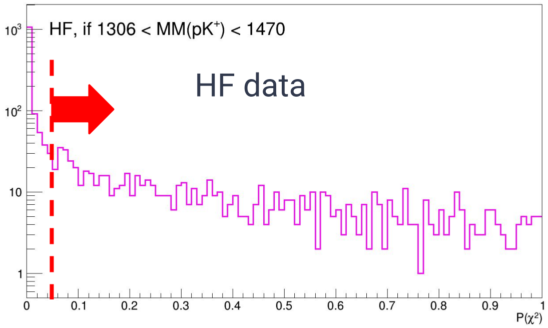
proton spectator (first letter)

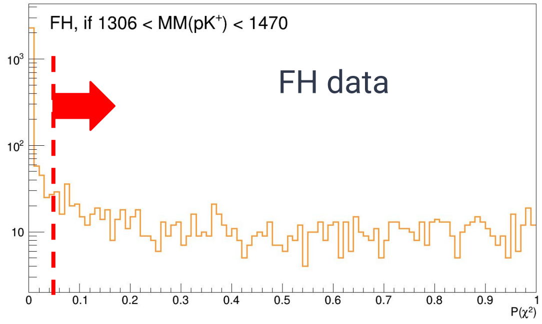
p from Λ decay (second letter)

H – detected in HADES

F – detected in Forward Tracker

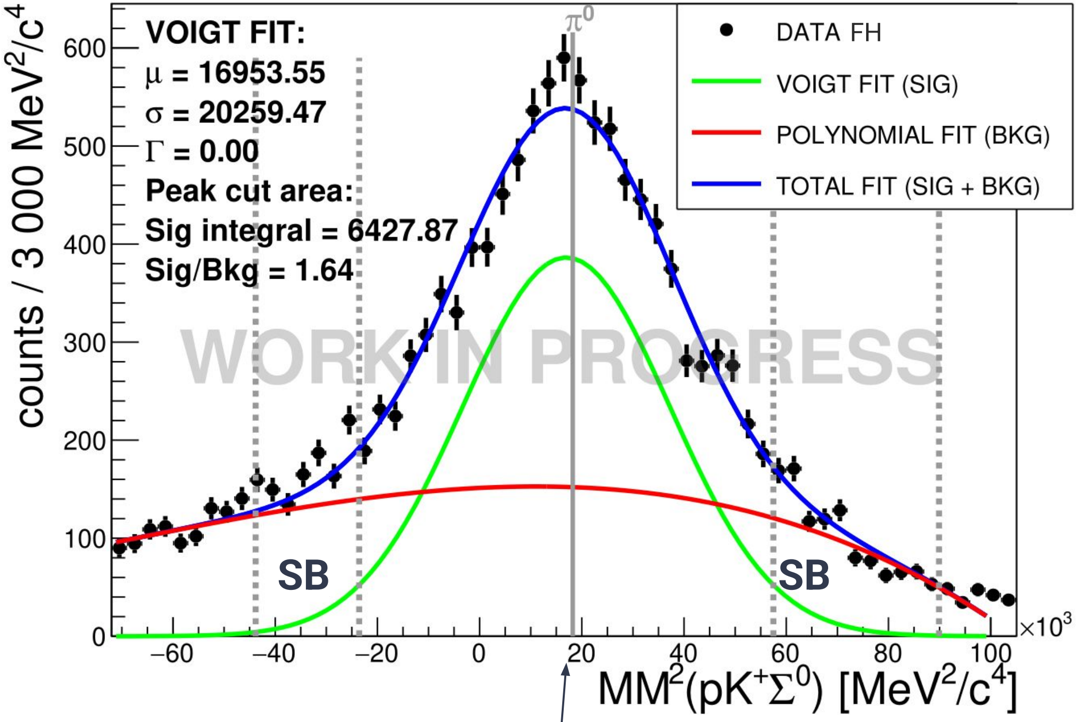






- $p(\chi^2) > 0.05$ cut is performed

Missing π^0 mass squared after refit

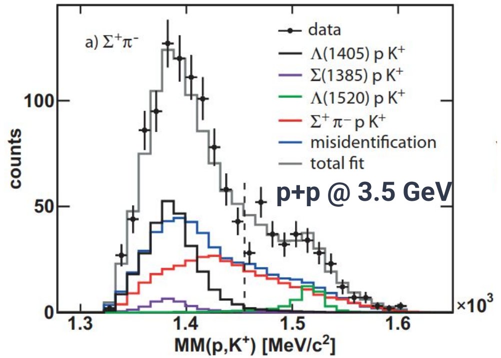


expected π^0 position

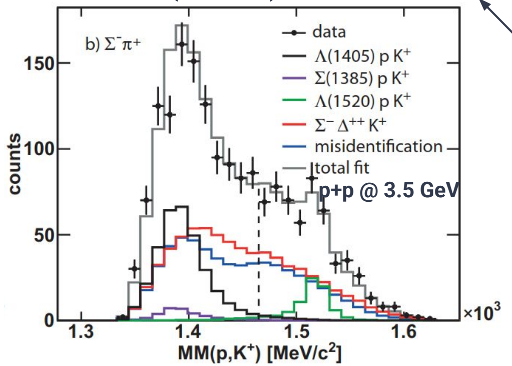
- π^0 signal reconstructed with events selected by the refit procedure and $p(\chi^2)$ cut
- reconstructed with uncorrected (by refit) four-vectors
- p $K^+ \Sigma^0 \pi^0$ events reconstructed from events inside the peak
- sideband subtraction to account for background

Comparison with previous HADES results at 3.5 GeV

$\Lambda(1405) \to \Sigma^+\pi^-$

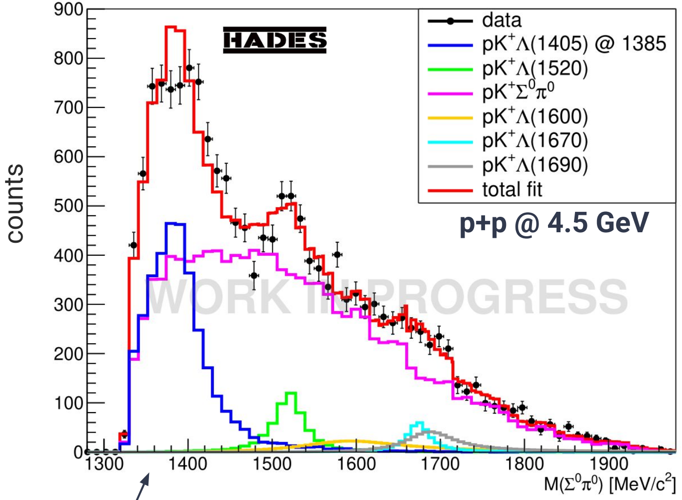


$\Lambda(1405) \to \Sigma^-\pi^+$



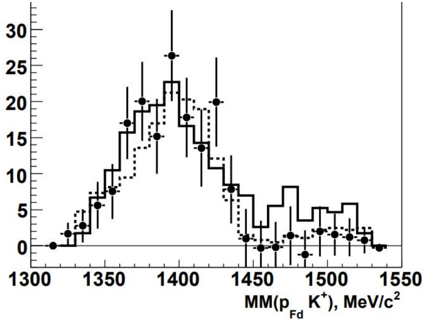
J. S. Siebenson, Diploma thesis, Technische Universität München (2010)

$\Lambda(1405) \to \Sigma^0\pi^0$



same binnig and same ansatz: incoherent sum, Λ (1405) as BW with m = 1385 MeV/c^2, Γ = 50 MeV/c^2

order-of-magnitude improvement in statistics!



points (ANKE-COSY):

$$pp \to pK^+\Lambda(1405) \to pK^+\Sigma^0\pi^0$$

I. Zychor et al., Phys. Lett. B 660, 167 (2008)

solid line:

$$\pi^-p \to K^0(\Sigma\pi)^0$$

D. W. Thomas et al., Nucl. Phys. B 56, 15 (1973)

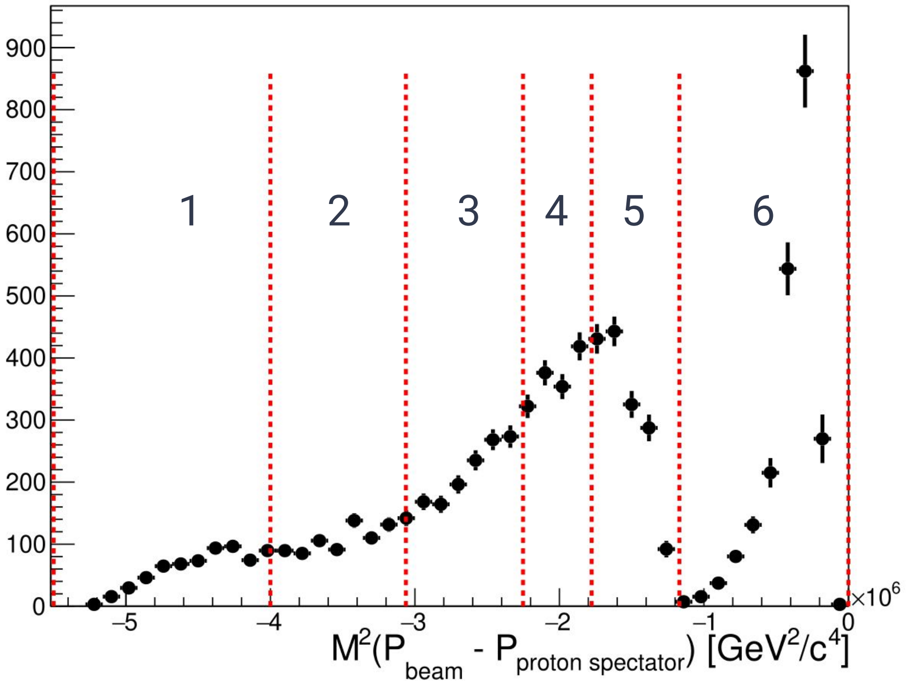
dotted line:

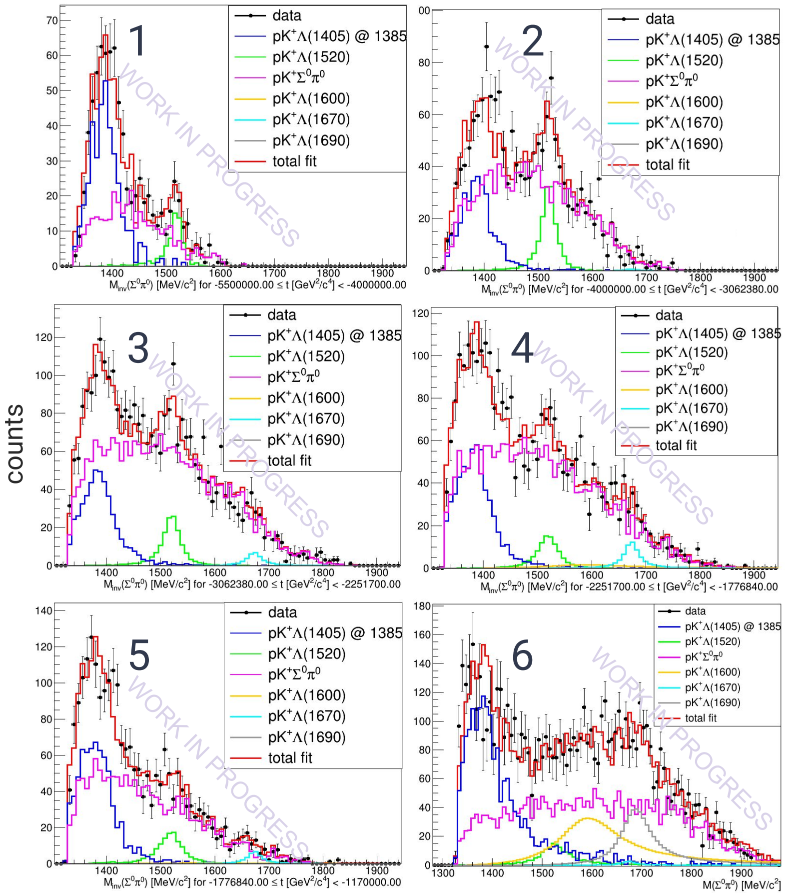
$$K^-p \to \pi^+\pi^-\Sigma^+\pi^-$$

R. J. Hemingway, Nucl. Phys. B 253, 742 (1985)

Differential distributions in function of four-momentum transfer *t*

Inside HADES acceptance:





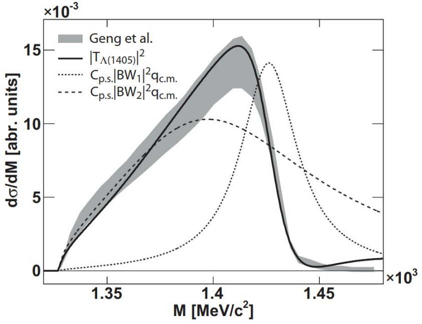
Acceptance and efficiency 2D corrections done on *t* vs. invariant mass based on simulation model

$M_{inv}(\Sigma^0\pi^0)$ – corrected spectra

- **Λ(1405)** - modeled as a coherent sum of two Breit-Wigner functions fitted to the theoretical prediction based on UChPT two-pole approach
- non-resonant bkg added incoherently
- amplitudes of six contributions are free parameters

$$\frac{d\sigma}{dm} = \left|T_{\Lambda(1405)}\right|^2 = C_{\rm p.s.}(m)\left|BW_1(m)e^{i\varphi_1} + BW_2(m)\right|^2 q_{\rm c.m.}$$

$$BW_i = A_i \frac{1}{m - m_{0,i} + i\Gamma_{0,i}/2}$$



J. Siebenson, Ph.D. Thesis, Technische Universitat Munchen (2013)

L. S. Geng and E. Oset, Eur. Phys. J. A 34, 405 (2007)

m_1 = 1426 MeV/c²

Γ_1 = 32 MeV/c²

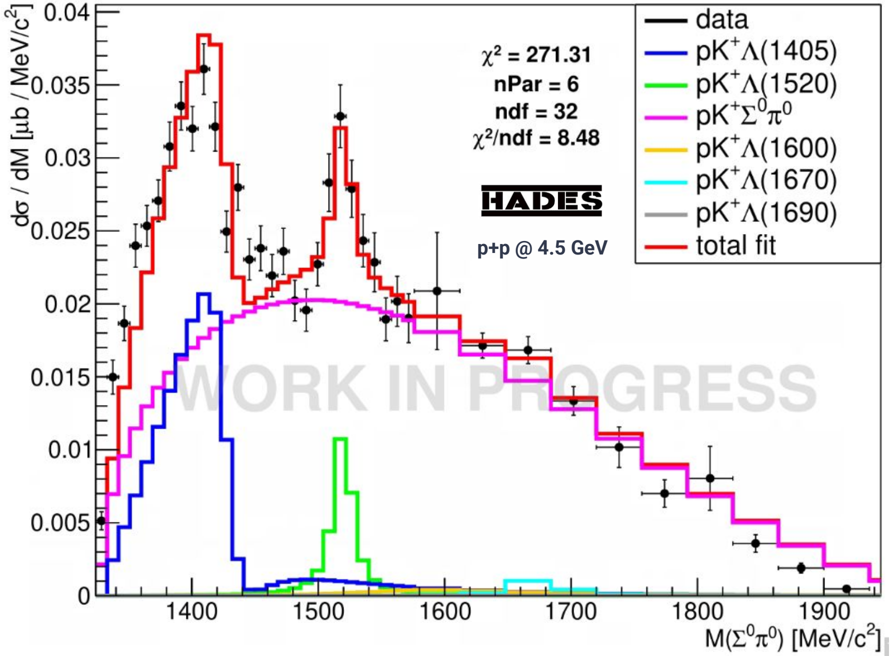
m_2 = 1390 MeV/c²

Γ_2 = 132 MeV/c²

D. Jido, et. al, arXiv:nucl-th/0303062

A_1/A_2 = 0.28

φ = 157 deg



data not well described by the model

$M_{inv}(\Sigma^0\pi^0)$ – corrected spectra

- **Λ(1405)** - modeled as a coherent sum of two Breit-Wigner functions
- parameters of two poles now varied within theoretical prediction constrained with SIDDHARTA measurements:

$$z_1 = 1424^{+7}_{-23} - i\,26^{+3}_{-14}\ \text{MeV}\ , \qquad z_2 = 1381^{+18}_{-6} - i\,81^{+19}_{-8}\ \text{MeV}$$

Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A 881, 71 (2012)

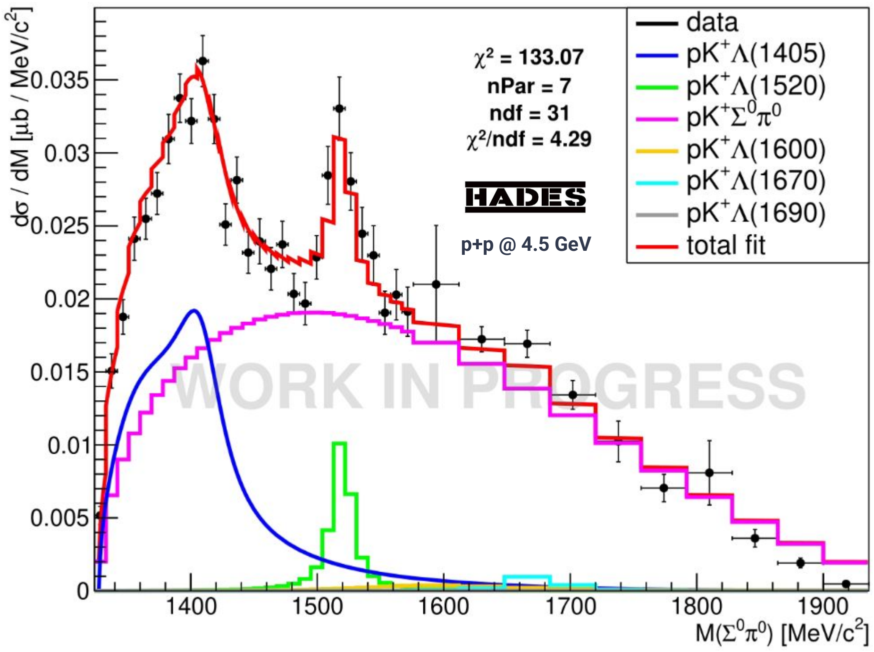
- non-resonant bkg added incoherently

$$\frac{d\sigma}{dm} = \left|T_{\Lambda(1405)}\right|^2 = C_{\text{p.s.}}(m)\left|BW_1(m)e^{i\varphi_1} + BW_2(m)\right|^2 q_{\text{c.m.}}$$

$$BW_i(m) = A_i \frac{1}{m_{0,i}^2 - m^2 - i\,m_{0,i}\Gamma_i(m)}$$

- free parameters:

m_1 = 1410 ± 16 MeV/c^2
Γ_1 = 51 ± 19 MeV/c^2
m_2 = 1387 ± 13 MeV/c^2
Γ_2 = 164 ± 35 MeV/c^2
A_1/A_2 = 0.51 ± 0.19
φ = 173 ± 29 deg
*only statistical errors



Better description of data

Summary

- Λ(1405) pole/poles positions - the subject of ongoing debate
- Line-shape of Λ(1405) depends strongly on reaction and decay (I=0, I=1) type → calls for the input from different channels
- Λ(1405) signal has been identified in the 'golden channel' Λ(1405) → $\Sigma^0\pi^0$ in new HADES data in pp collisions at 4.5 GeV with an order of magnitude improvement in statistics with respect to previous result at 3.5 GeV
- Clear contribution from the Λ(1520) resonance, as well as an enhancement near the masses of Λ(1600), Λ(1670), Λ(1690) identified
- The order of magnitude of the statistics enables differential analysis in a function of *t*
- Tested model with the two-pole approach reproduces the main features of the spectrum
- Only statistical uncertainties are currently included
- More advanced fitting: *K*-matrix approach simultaneously for the invariant mass distributions of Σπ and pK^- (→ talk by Valentin Kladov, Thu) and JüBo DCC model (→ talk by A. M. Foda, Mon)

Outlook: studies of shapes in function of *t*, studies of interference effects and opening of KN channel (via Flatte mechanism)

BACKUP

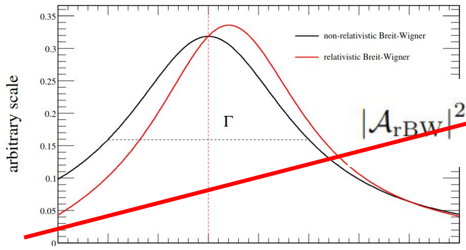
Λ(1405) essentials

- S = −1
- observed in decay to:

  $\Sigma^+\pi^-$

  $\Sigma^-\pi^+$

  $\Sigma^0\pi^0$
- decays right below $N\bar{K}$ threshold (1433 MeV)
- observed line shape is not a Breit-Wigner



$$|\mathcal{A}_{\mathrm{rBW}}|^2 = \frac{1}{2\pi}\frac{4\Gamma M M_0}{(M^2 - M_0^2)^2 + M_0^2\Gamma^2},$$

K. Moriya, Ph.D. Thesis, Indiana University / Jefferson Lab (2010)

- recently introduced in PDG Λ(1380)

Properties of Λ(1405) from PDG:

Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024) and 2025 update

$\boxed{\Lambda(1405)\ 1/2^-}$ $I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

Λ(1405) MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$1405.1^{+1.3}_{-1.0}$ OUR AVERAGE				

Λ(1405) WIDTH

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
50.5± 2.0 OUR AVERAGE				

Λ(1405) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Sigma\pi$	100 %
Γ_2	$\Lambda\gamma$	
Γ_3	$\Sigma^0\gamma$	
Γ_4	$N\bar{K}$	

$\boxed{\Lambda(1380)\ 1/2^-}$ $J^P = \frac{1}{2}^-$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

See the related review on "Pole Structure of the Λ(1405) Region."

Λ(1405) as a 3-quark orbital excitation of Λ(1115)

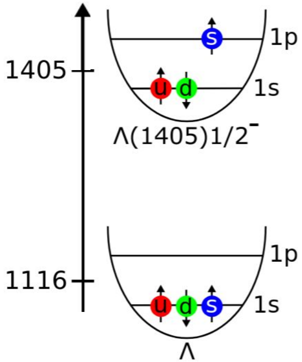
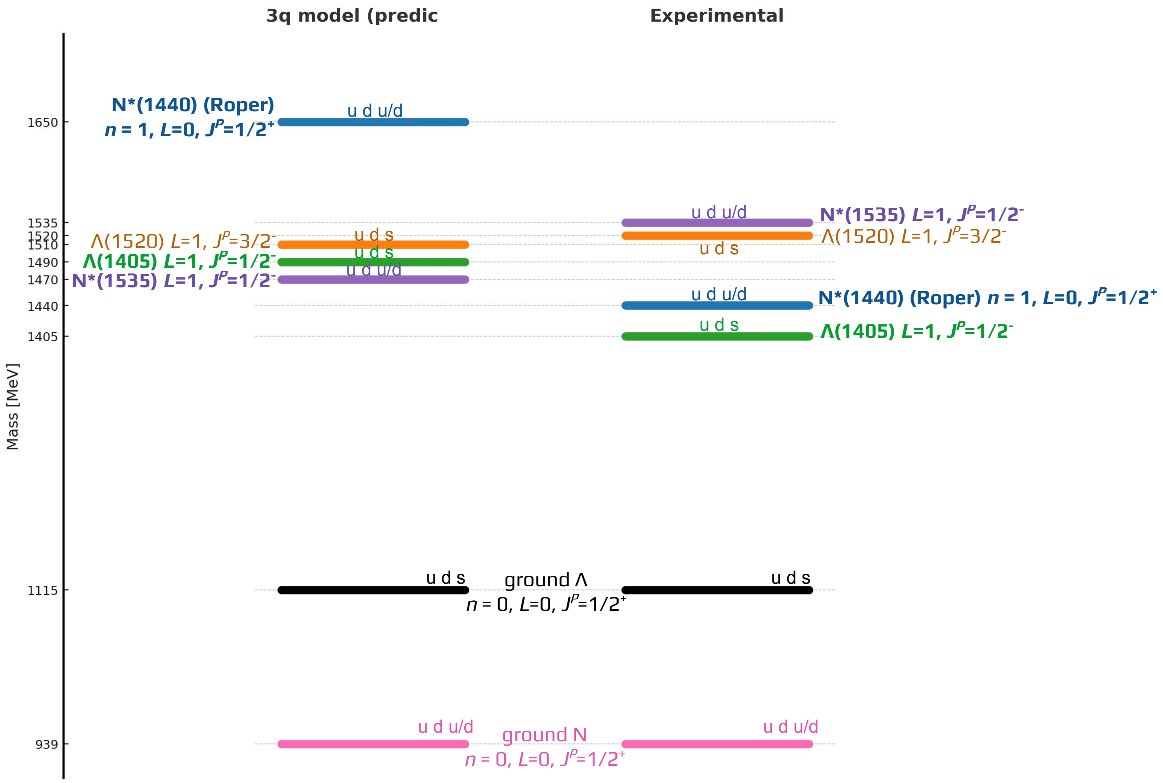


Figure adapted from: D. Werthmüller and R. A. Schumacher, arXiv:1802.01720 [nucl-ex] (2018)

- lighter than the S11(1535) and P11(1440) nucleon resonances
- its splitting from the spin-orbit partner Λ(1520) is unusually large compared to the nucleon sector



Burkert and Roberts, Rev. Mod. Phys. 91, 011003 (2019)
Y. Zhong et al., arXiv:2409.07998 (2024)
N. Isgur and G. Karl, Phys. Rev. D 18, 4187 (1978)

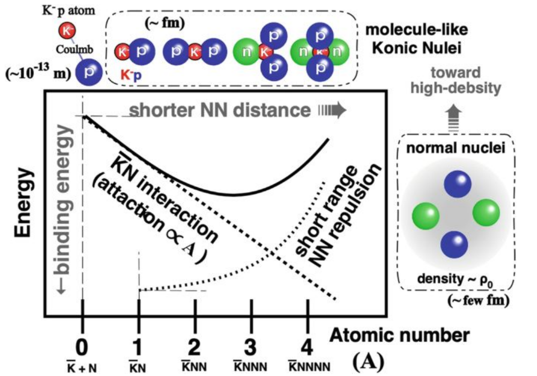
Λ(1405) not compatible with quark model predictions

$\Lambda(1405)$ as a $N\bar{K}$ quasi-bound state

- Predicted by Dalitz & Tuan (1960s) examining low energy reaction of $K^- + p$
- No data on the final $\Sigma\pi$ state available back then
- From analysis of above-threshold behaviour of $K^- + p$ in unphysical region below $p_{K^-} = 0$ the below threshold $\Sigma\pi$ could be predicted
- Resonance that happens in $\Sigma\pi$ system explained as a result of an unstable bound state
- $\Lambda(1405)$ as a potential doorway state for forming $N\bar{K}$ bound systems $K^-pp \sim \Lambda(1405)\ p$

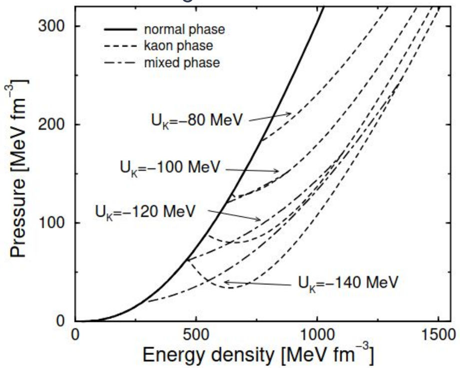
NK channel plays an important role in the nature of the Λ (1405)

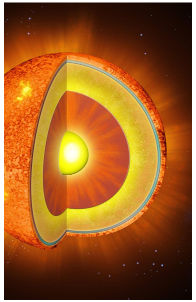
kaonic nuclei



T. Yamazaki and Y. Akaishi, Phys. Lett. B 535, 70 (2002)

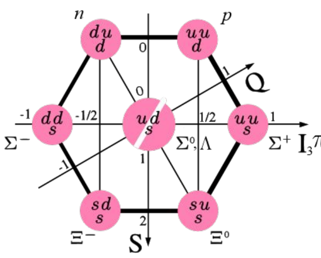
softening of the EoS of the neutron star

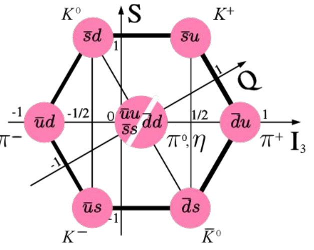




A. Ramos et al., Lect. Notes Phys. 578, 175 (2001)

Λ(1405) as a two-pole structure

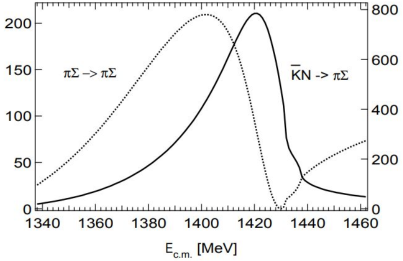




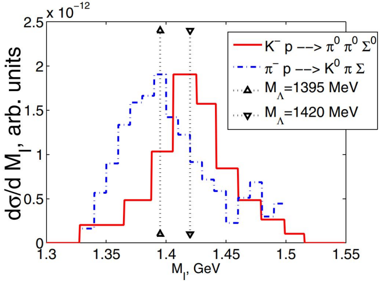
Chiral unitary approach - A.Ramos, E. Oset (2003)

- interaction of the baryon ground-state octet with the pseudoscalar meson octet
- unitarity and analyticity of scattering amplitudes implemented in coupled-channel dynamics
- SU(3) baryons irreps 1+8s+8a combine with 0- Goldstone bosons to generate two octets and a singlet of ½- baryons dynamically generated in the SU(3) limit
- SU(3) breaking leads to two S = -1, I = 0 poles near 1405 MeV, lower one, strongly coupled to Σπ and higher one, dominantly coupled to NK̅
- possible weak I=1 pole also predicted

Λ(1405) line-shape depend on the decay and production channel

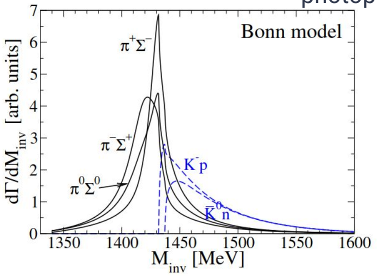


A. Ramos et al., Nucl. Phys. A 754, 202 (2005)

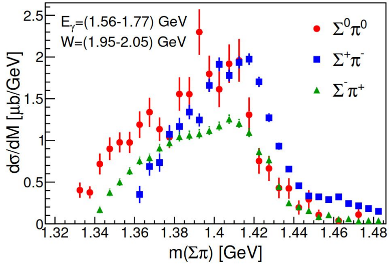


V. K. Magas, E. Oset, and A. Ramos, Phys. Rev. Lett. 95, 052301 (2005)

photoproduction:



L. Roca et al., Eur. Phys. J. C 75, 218 (2015)



D. Werthmüller and R. A. Schumacher, arXiv:1802.01720 (2018)

Similar structures predictions

- S = - 2 sector:

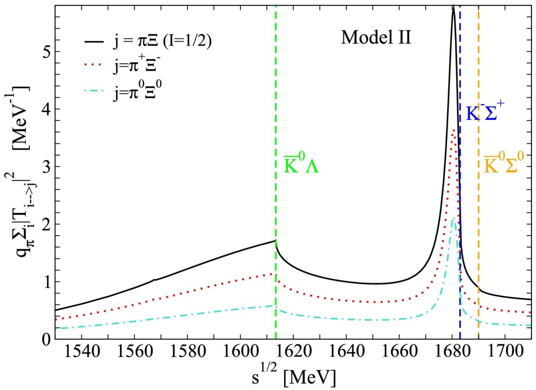
  Ξ(1620), Ξ(1690) in coupled channels πΞ, Λ /Σ $\bar{K}$

  (decays to πΞ, Λ$\bar{K}$ planned to be measured in the future CBM experiment)

  Ξ(1620) molecular state?

  Ξ(1690) quasi-bound Σ$\bar{K}$ state?

  Thresholds close to Ω mass



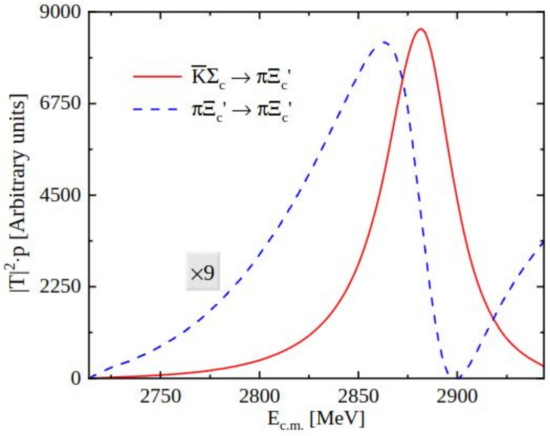
A. Feijoo et al., Phys. Lett. B 841, 137927 (2023)

- pseudoscalar meson – vector meson interactions: two-pole structure predicted for $K_1(1270)$

  poles below the ρK and above the $K^*π$

- charmed baryon sector:

  two-pole structure predicted for channels $\bar{K}Σ_c(2949)$ and $πΞ'_c(2714)$



Xie et al., Phys. Rev. D 108, L111502 (2023)

$\Lambda(1405)$ in p+(@ 3.5 GeV)p – HADES measurements

- single pole approach

  incoherent MC sim sum

  dotted line – sim sum if $\Lambda(1405)$ simulated with

  mass 1405 MeV/c^2

  m = 1385 MeV/c^2, Γ = 50 MeV/c^2

- two-pole UχPT approach

  poles added coherently

  - considering interference with the

    non–resonant background

    m_1 = 1426 MeV/c^2, Γ_1 = 28 MeV/c^2

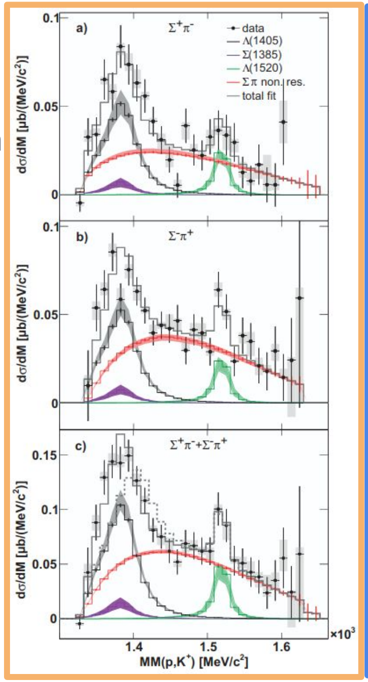
    m_2 = 1375 MeV/c^2, Γ_2 = 147 MeV/c^2

  - neglecting interference with the

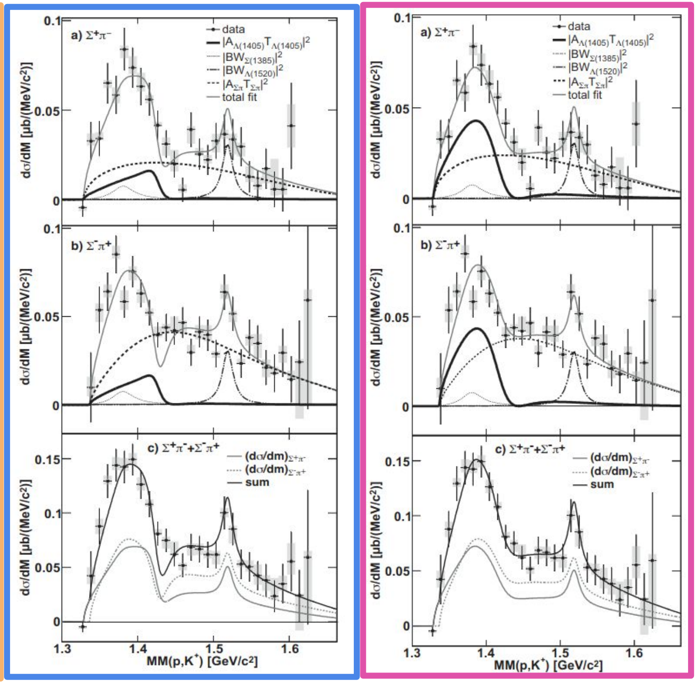
    non–resonant background

    m_1 = 1418/1431 MeV/c^2, Γ_1 = 58 MeV/c^2

    m_2 = 1375 MeV/c^2, Γ_2 = 146 MeV/c^2

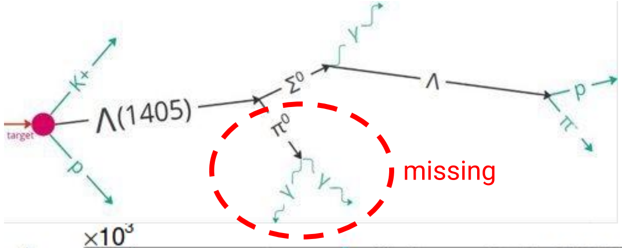


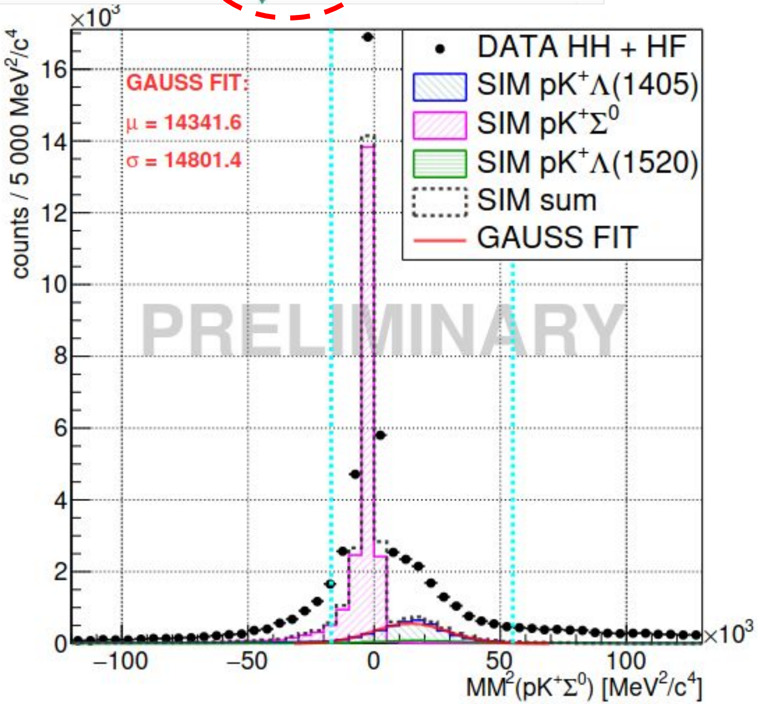
HADES Collab., Phys. Rev. C 87, 025201 (2013)

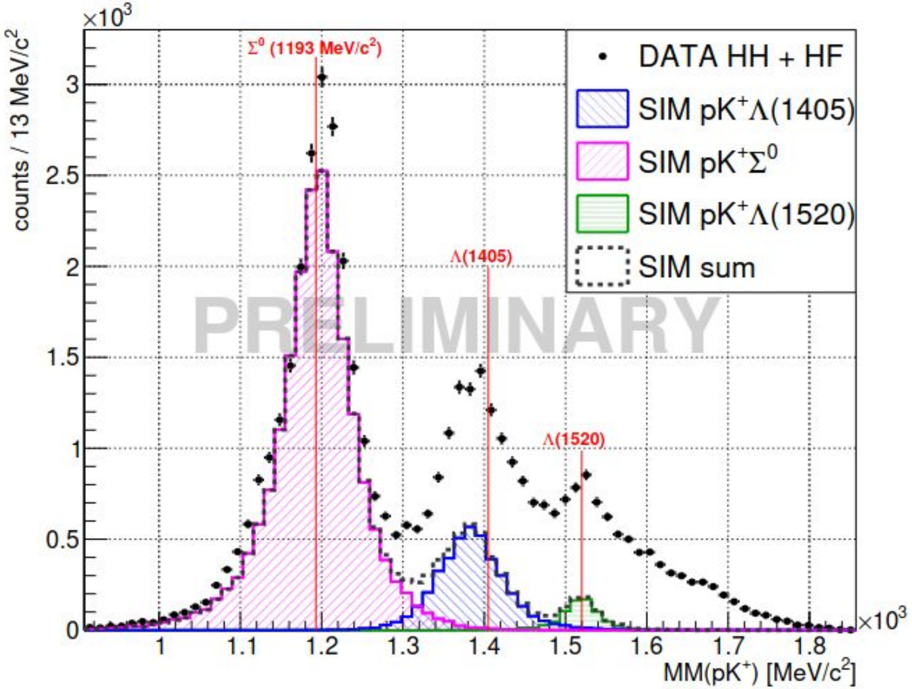


J. Siebenson and L. Fabbietti, Phys. Rev. C 88, 055201 (2013)

$MM^2(pK^+\Sigma^0)$ and $M_{inv}(\Sigma^0\pi^0)$ before the refit







Kinematical refit

$$\chi^2 = (\vec{y} - \vec{x})^T V^{-1}(\vec{x})(\vec{y} - \vec{x})$$

x – measured

y – estimated

V – covariance matrix

$$f\left(\overrightarrow{x}, \overrightarrow{\xi}\right) = 0$$

$$\mathcal{L} = \chi^2(\vec{x}, \vec{\xi}, \vec{\lambda}) = (\vec{y} - \vec{x})^T V^{-1}(\vec{x})(\vec{y} - \vec{x}) + 2\vec{\lambda}^T \cdot \vec{f}(\vec{x}, \vec{\xi})$$

Minimization:

$$\nabla_x \chi^2 = -2V^{-1}\left(\overrightarrow{y} - \overrightarrow{x}\right) + 2D_x^T \overrightarrow{\lambda} = 0$$

$$\nabla_\xi \chi^2 = 2D_\chi^T \overrightarrow{\lambda} = 0,$$

$$\nabla_\lambda \chi^2 = 2\overrightarrow{f}^T = 0.$$

λ - Lagrange multiplier

D - derivative matrix of constraint equation

- the iterative procedure is obtained changing the parameters and errors values.
- stopped when convergence is reached based on one of criteria: change in χ^2, constraint equation norm, or change in track parameters

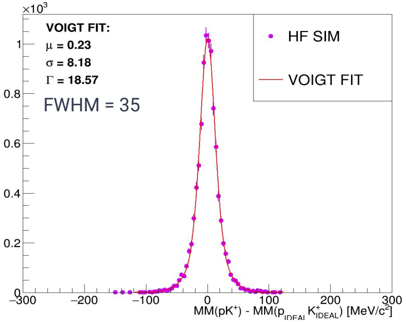
  (default threshold: 10^{-4}, with a maximum of 20 iterations)

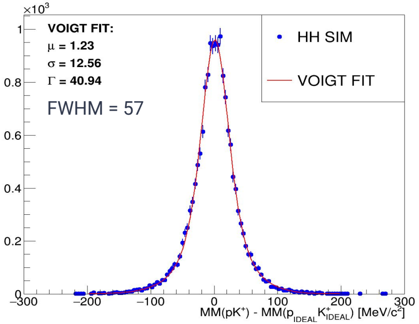
Λ(1405) mass resolution from simulation

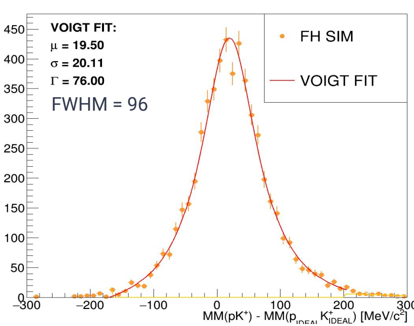
- Λ(1405) natural width (PDG): 50.5 ± 2.0
- obtained sensitivity to the line shape and peak position by improvement of the mass resolution with kinematic fitting:

  $MM(p_{RECO}K^{+}_{RECO}) - MM(p_{TRUE}K^{+}_{TRUE})$

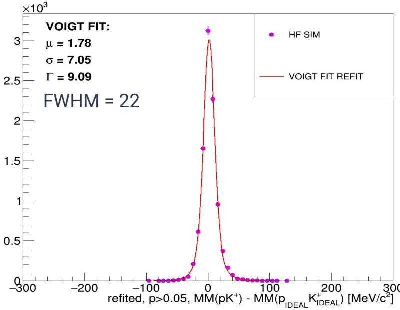
  - before refit

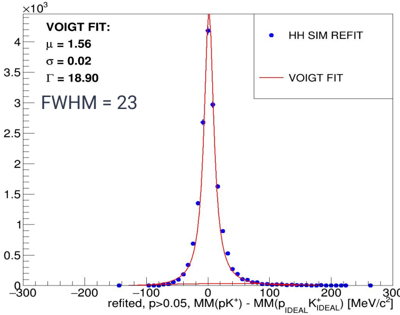


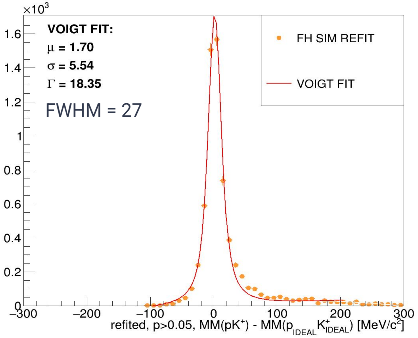




  - after refit

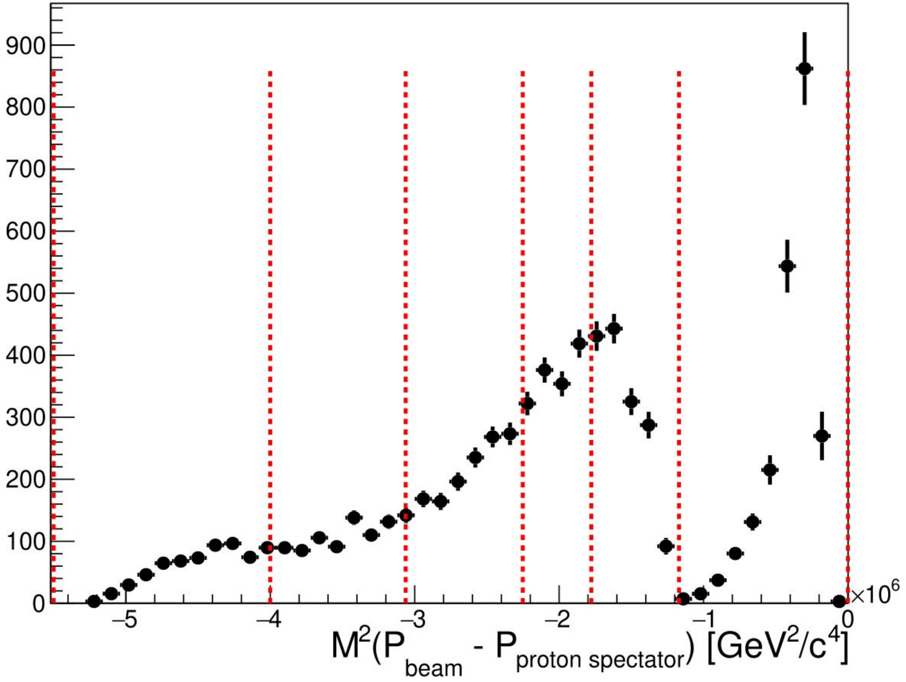


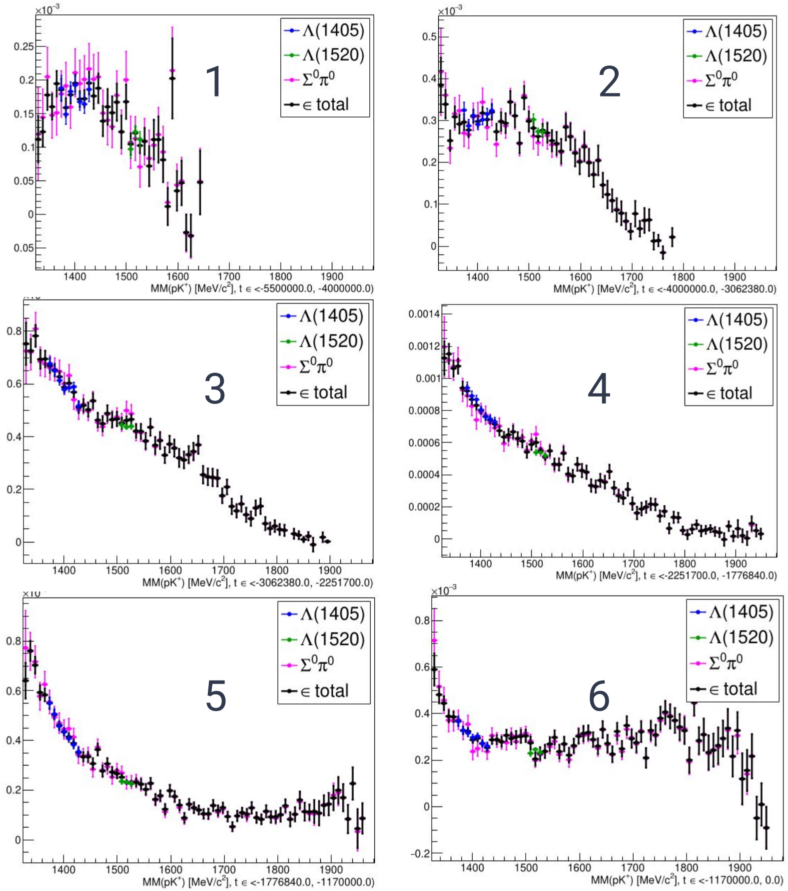




Acceptance and reconstruction 2D corrections

t vs. invariant mass





$M_{inv}(\Sigma^0\pi^0)$ – corrected spectra

- **Λ(1405)** - modeled as a coherent sum of two Breit-Wigner functions
- parameters of two poles now varied within theoretical prediction constrained with SIDDHARTA measurements:

$$z_1 = 1424^{+7}_{-23} - i\,26^{+3}_{-14}\ \mathrm{MeV}\quad,\qquad z_2 = 1381^{+18}_{-6} - i\,81^{+19}_{-8}\ \mathrm{MeV}$$

Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A 881, 71 (2012)

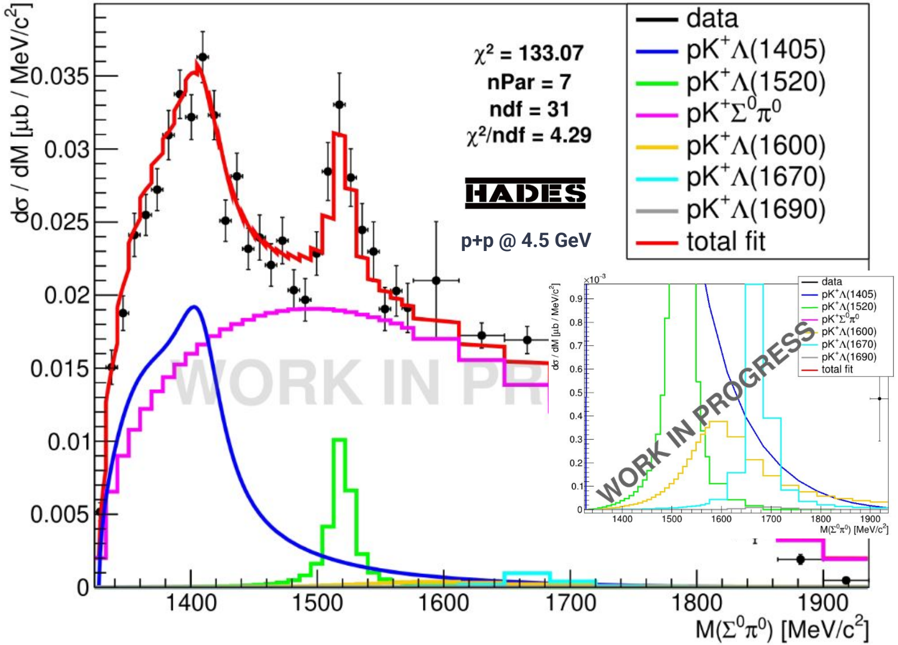
- non-resonant bkg added incoherently

$$\frac{d\sigma}{dm} = \left|T_{\Lambda(1405)}\right|^2 = C_{\mathrm{p.s.}}(m)\left|BW_1(m)e^{i\varphi_1} + BW_2(m)\right|^2 q_{\mathrm{c.m.}}$$

$$BW_i(m) = A_i\frac{1}{m_{0,i}^2 - m^2 - i\,m_{0,i}\Gamma_i(m)}$$

- free parameters:

m_1 = 1410 ± 16 MeV/c^2
Γ_1 = 51 ± 19 MeV/c^2
m_2 = 1387 ± 13 MeV/c^2
Γ_2 = 164 ± 35 MeV/c^2
A_1/A_2 = 0.51 ± 0.19
φ = 173 ± 29 deg
*only statistical errors



Better description of data