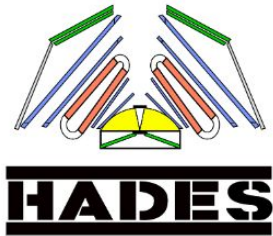


$\Lambda(1405)$ 'golden channel' measured in p+p at HADES

MESON

2026

Anna Koperwas-Władyszewska

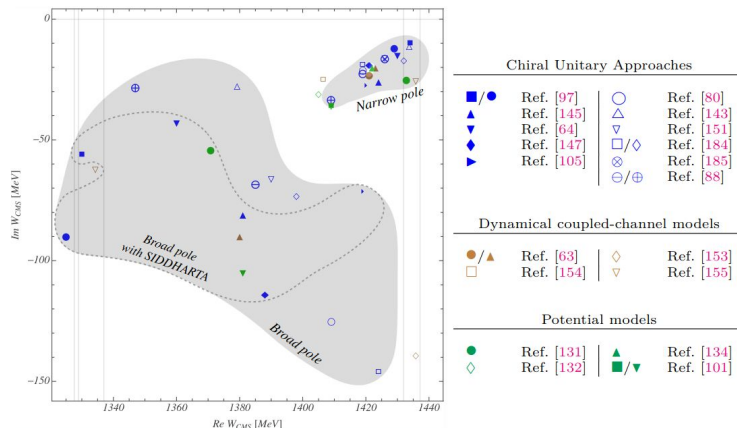


Plan

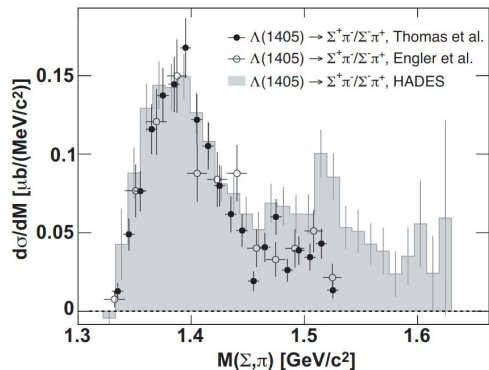
- Motivation
- Previous HADES measurements @ p(3.5 GeV)+p
 $pK^+\Lambda(1405) \rightarrow (\Sigma^{+/-}(\rightarrow n\pi^{+/-})\pi^{-/+})$
- Analysis of exclusive channel @ p(4.5 GeV)+p
 $pK^+\Lambda(1405) \rightarrow (\Sigma^0(\Lambda(\rightarrow p\pi^-)\gamma)\pi^0(\rightarrow \gamma\gamma))$
 - particles selection
 - kinematic fitting (M_{inv} , MM constraints)
 - side-band analysis
 - preliminary results of invariant mass analysis in Mandelstam term bins
- Perspectives
 - Joint analysis of $\Lambda(1405) \rightarrow \Sigma^0\pi^0$ and $\Lambda(1520) \rightarrow pK^-$ invariant mass spectra with K -matrix

$\Lambda(1405)$ poles studies

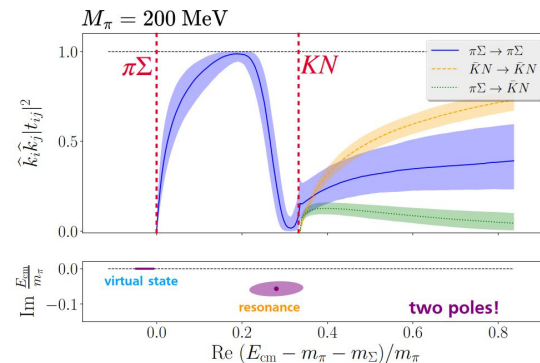
- ongoing debate on one- / two-pole structure hypotheses
- most data from low-energy NK scattering, kaonic atoms – not very sensitive to lower ($\Sigma\pi$) pole position
- previous HADES measurements in pp show a shift to lower masses (similarly to π -p production), indicating stronger coupling to the lower pole for pp initial channel
- 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)



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

Of interest - 'golden' channel with decay to $\Sigma^0\pi^0$

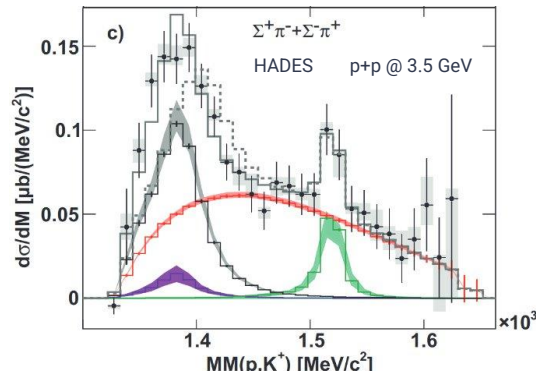
- $\Lambda(1405)$ overlap with $\Sigma(1385)$ for $\Sigma^{\pm}\pi^{\mp}$ -channels

$$I = 1 \quad \Sigma(1385)^0 \rightarrow \Lambda\pi^0$$

- no contribution from $\Sigma(1385)$ for $\Sigma^0\pi^0$ channel

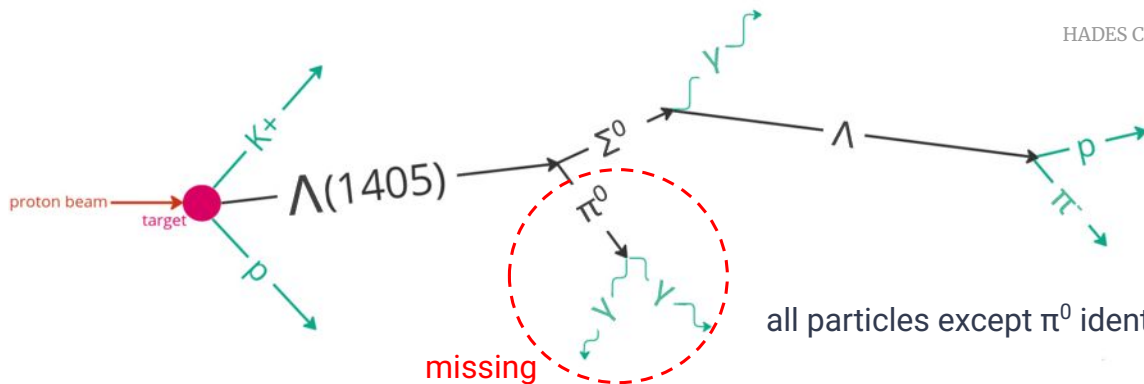
$$I = 0 \quad \Lambda(1405) \rightarrow \Sigma^0\pi^0 \rightarrow \Lambda\gamma\pi^0$$

HADES results from $p(@ 3.5 \text{ GeV})+p$

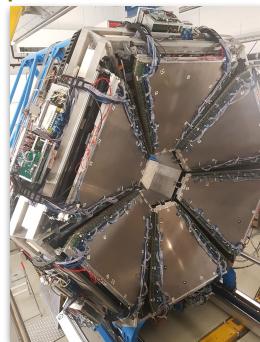
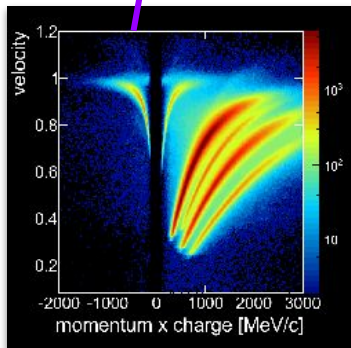
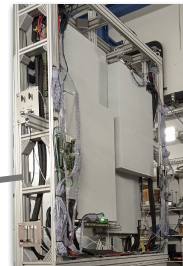
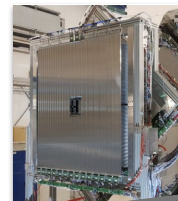
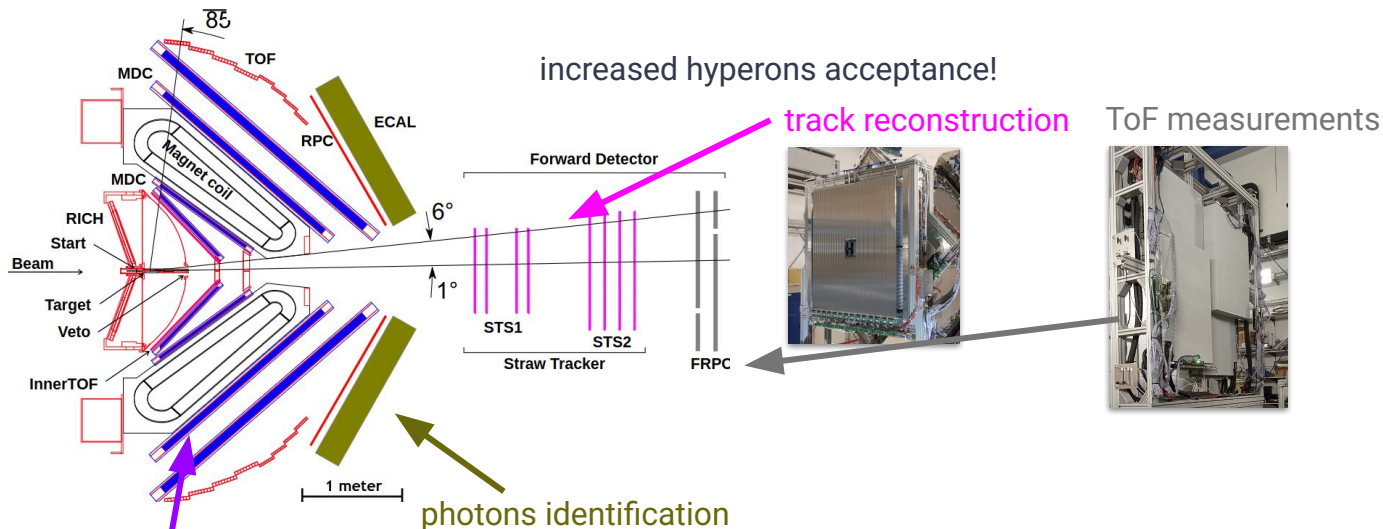
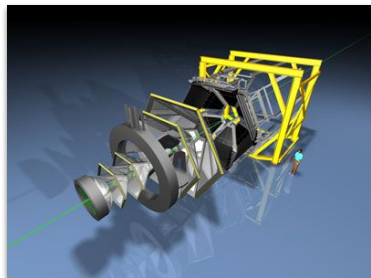
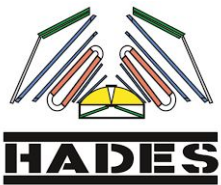


single-pole
approach
with BW:
 $m = 1385 \text{ MeV}/c^2$
 $\Gamma = 50 \text{ MeV}/c^2$

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



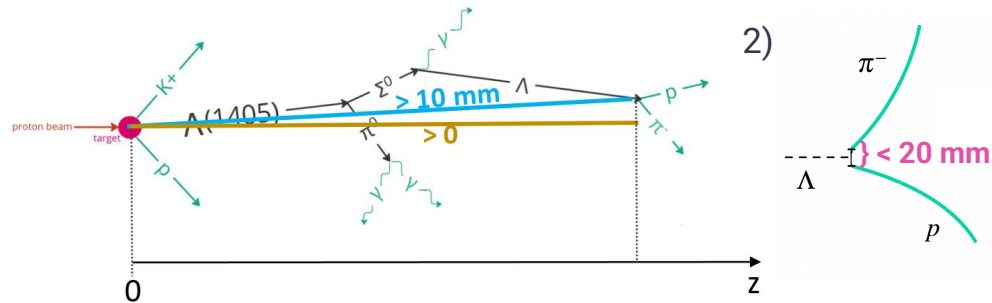
High Acceptance DiElectron Spectrometer



now available with significant statistics:

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

Particles identification



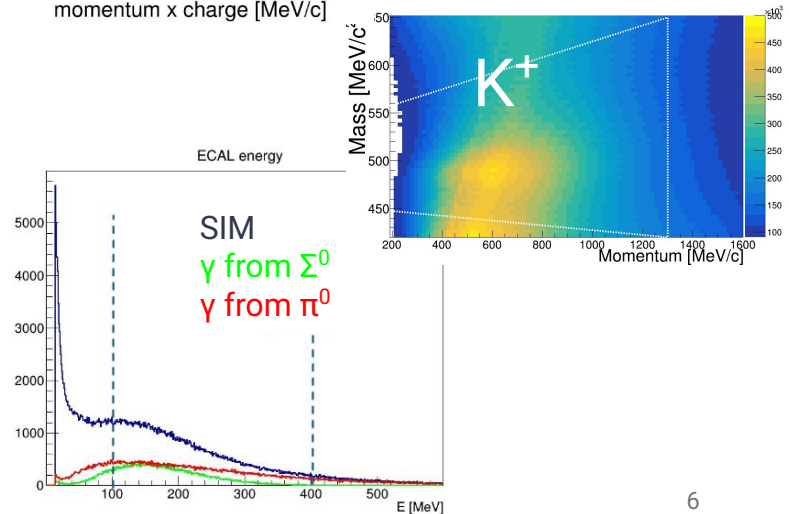
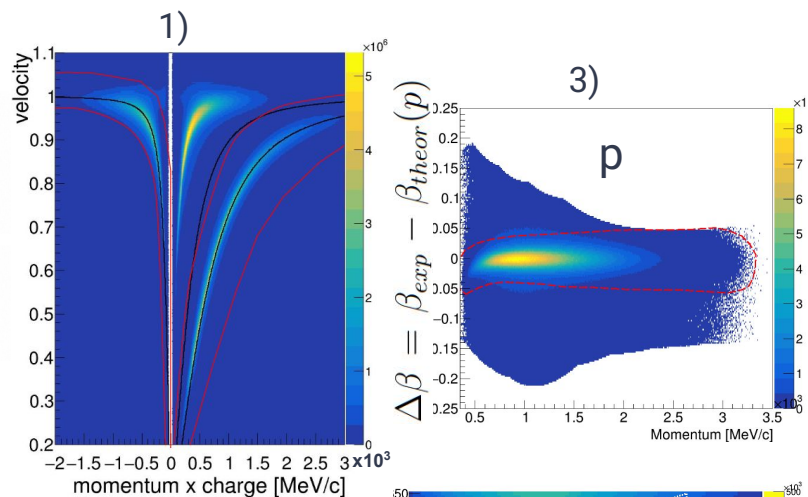
p and π^- in HADES (magnetic spectrometer)

- 1) preselection: broad graphical cuts on velocity (β) vs. momentum
- 2) $\Lambda \rightarrow p\pi^-$ preselection - topology and MM cut: $MM_{p\pi^-} > M_{pK+\pi^0}$
- 3) 3.5σ criteria in $\beta - \beta_{th}$ vs. momentum slices

K^+ in HADES: cut on mass vs. momentum

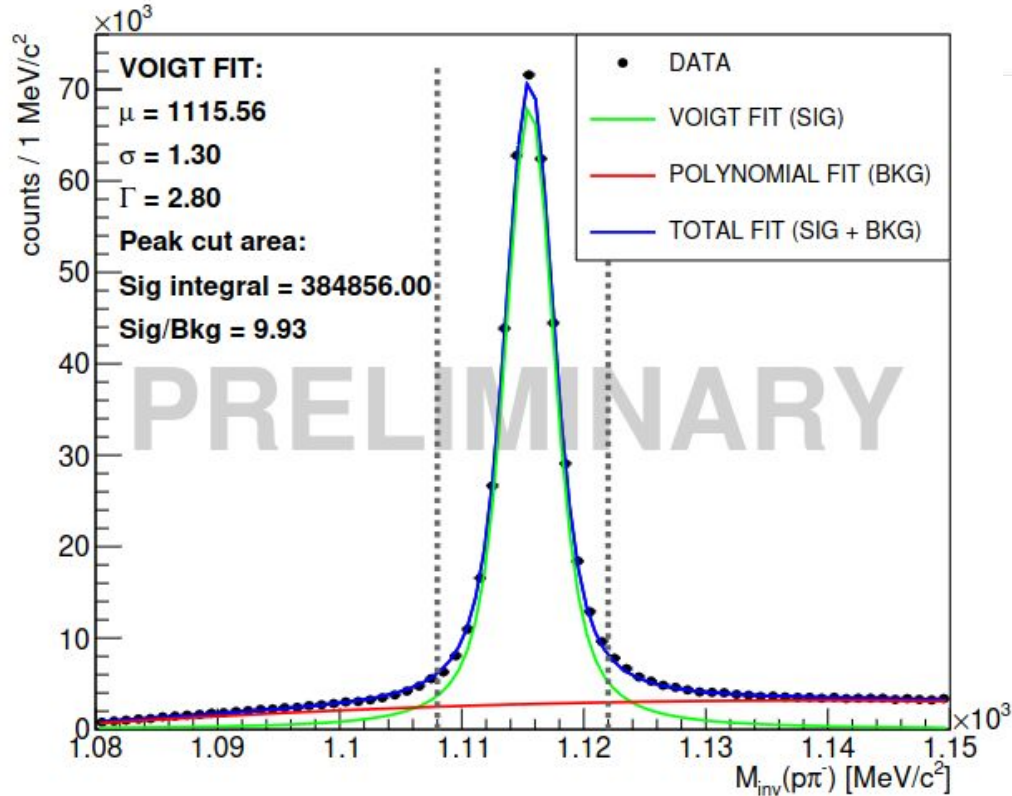
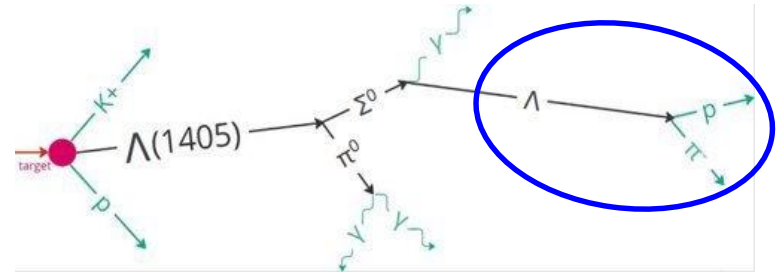
tracks in Forward Tracker assumed to be protons: majority are protons based on MC SIM

γ in ECAL: $100 \text{ MeV} < \text{energy}_\gamma < 400 \text{ MeV}$, $0.8 < \beta_\gamma < 1.2$



Λ selection

for Λ reconstruction only events with $\geq 1 \pi^-$, $\geq 1 K^+$, $\geq 1 \gamma$, $\geq 2 p$ are taken into account

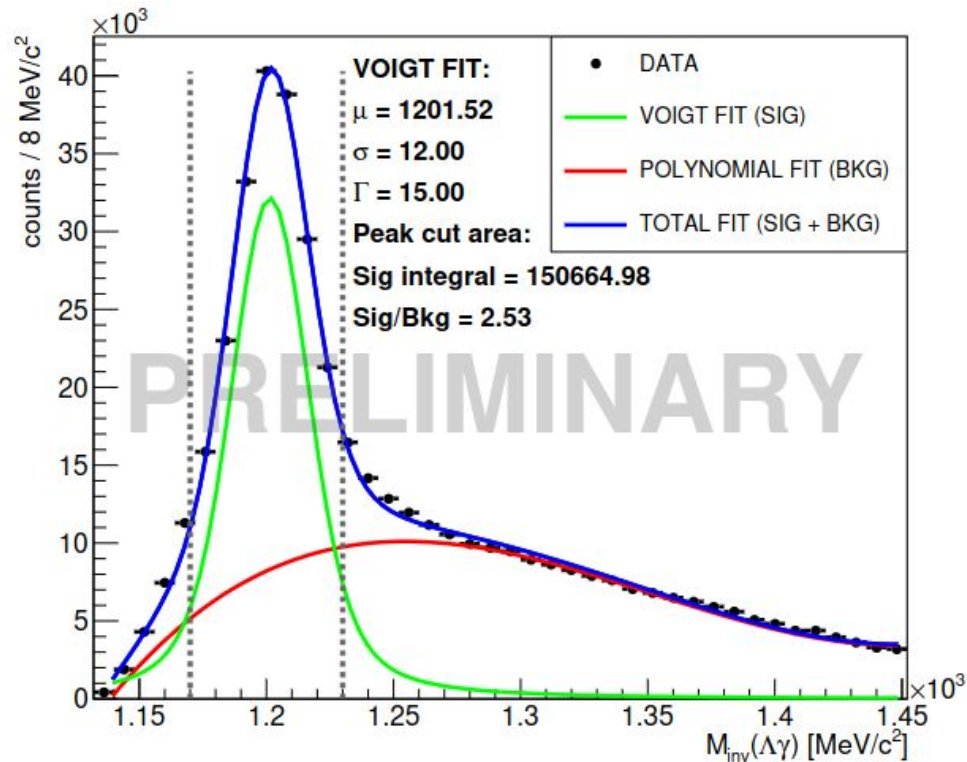


PDG: 1115.683 ± 0.006 MeV

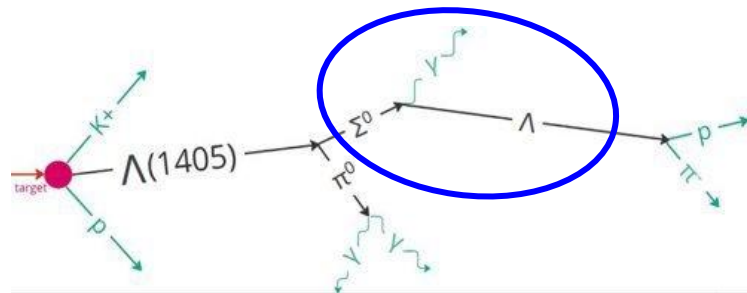
Protons that did not fall into the Λ mass window are from now on marked as protons coming from event vertex (spectators)

Σ^0 selection

$\geq 1 \Lambda$, ≥ 1 proton spectator



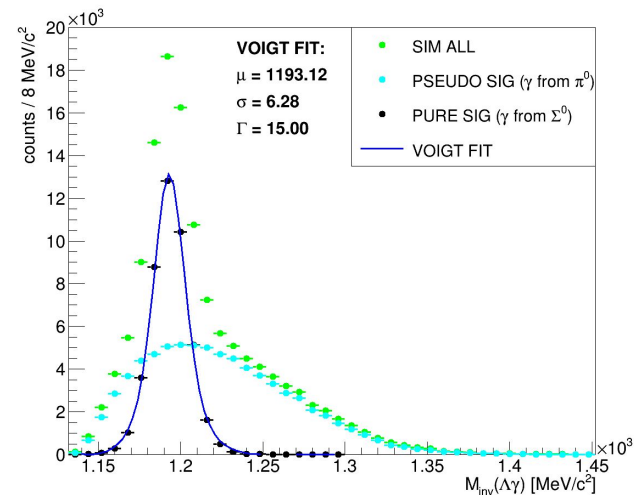
systematic shift due to ECAL calibration (work in progress)



PDG: 1192.662 ± 0.024 MeV

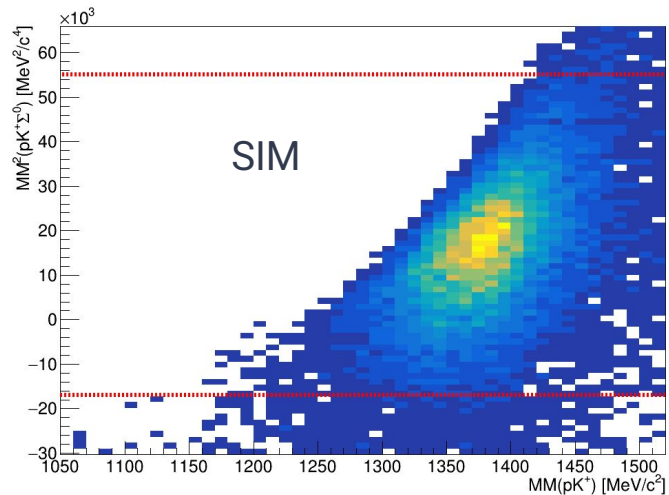
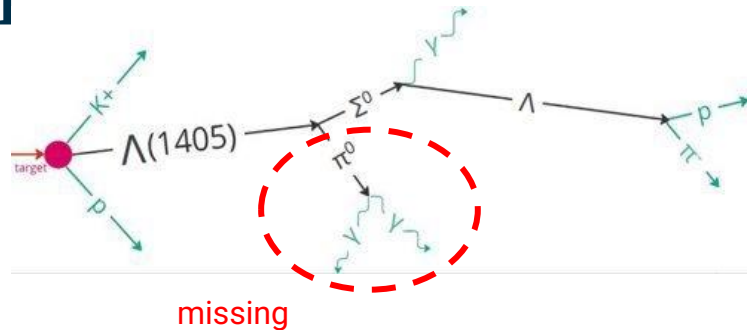
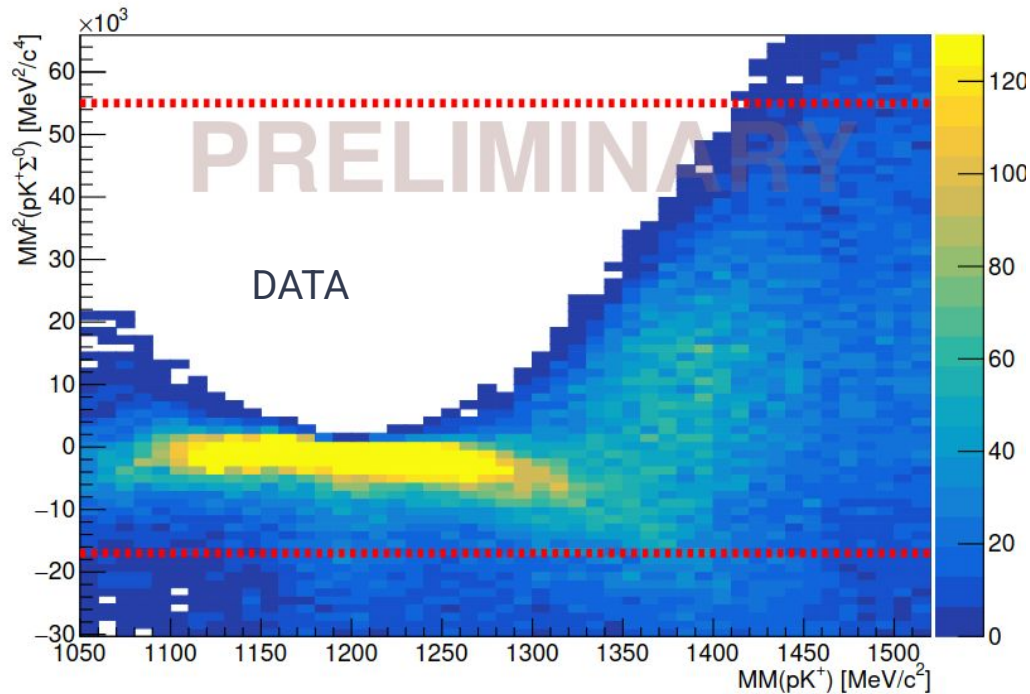
SIMULATION

$pK^+\Lambda(1405) [\rightarrow \pi^0(\rightarrow \gamma\gamma)\Sigma^0(\rightarrow \Lambda\gamma)]$



π^0 vs. $\Lambda(1405)$ expected signal

$\geq 1 \Sigma^0$



Kinematical refit

- 1C: Σ^0 mass constraint

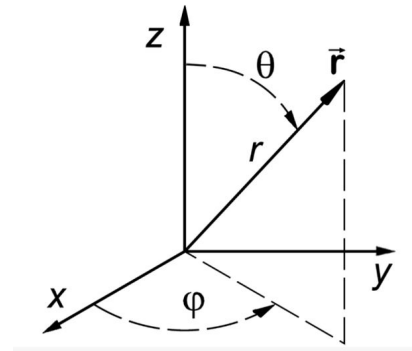
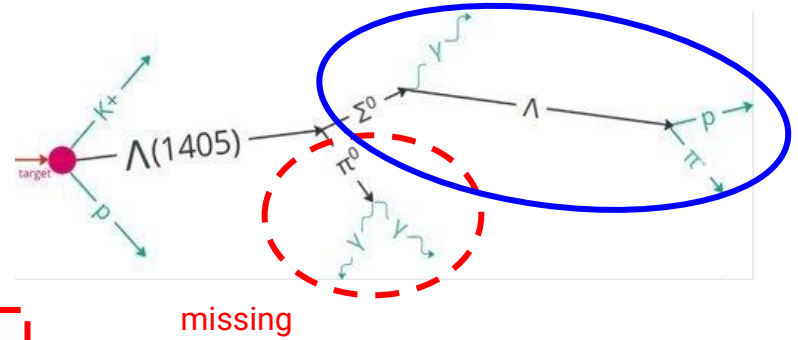
$$f = \sqrt{\left(\sum_{i=1}^N E_i\right)^2 - \left(\sum_{i=1}^N \vec{p}_i\right)^2} - m_{\text{mother}} = 0$$

- 1C: π^0 missing mass constraint

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

- 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



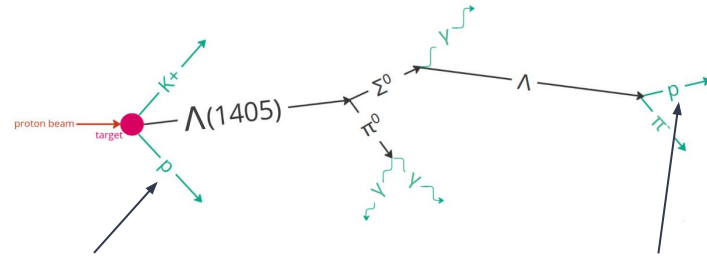
Verification of the method

- should be centered around 0 with $\sigma = 1$:

$$\text{pull}_i = \frac{y_i - \eta_i}{\sqrt{\sigma^2(y_i) - \sigma^2(\eta_i)}}$$

- overestimation / underestimation of errors \rightarrow p -distribution pulled to higher / lower values

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

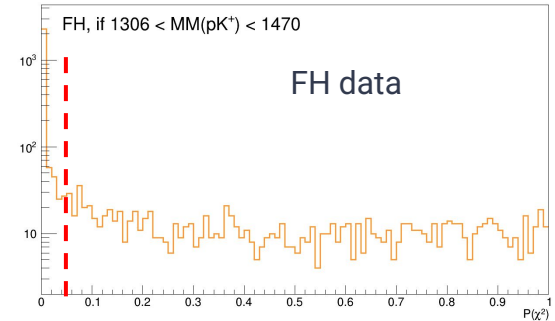
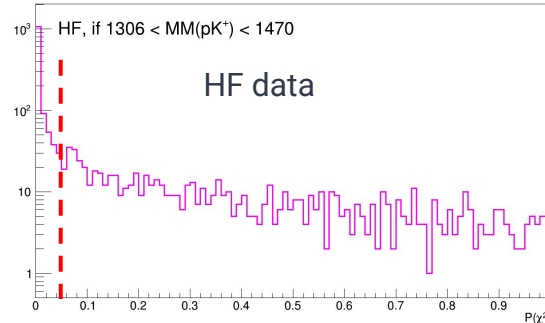
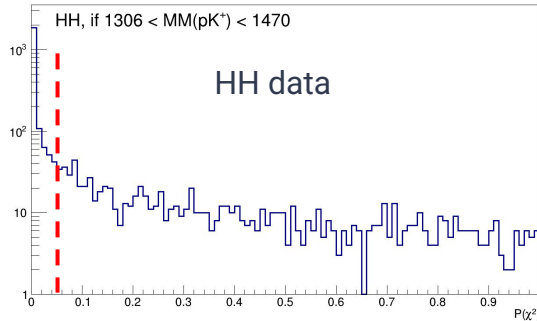


proton spectator (first letter)

p from Λ decay (second letter)

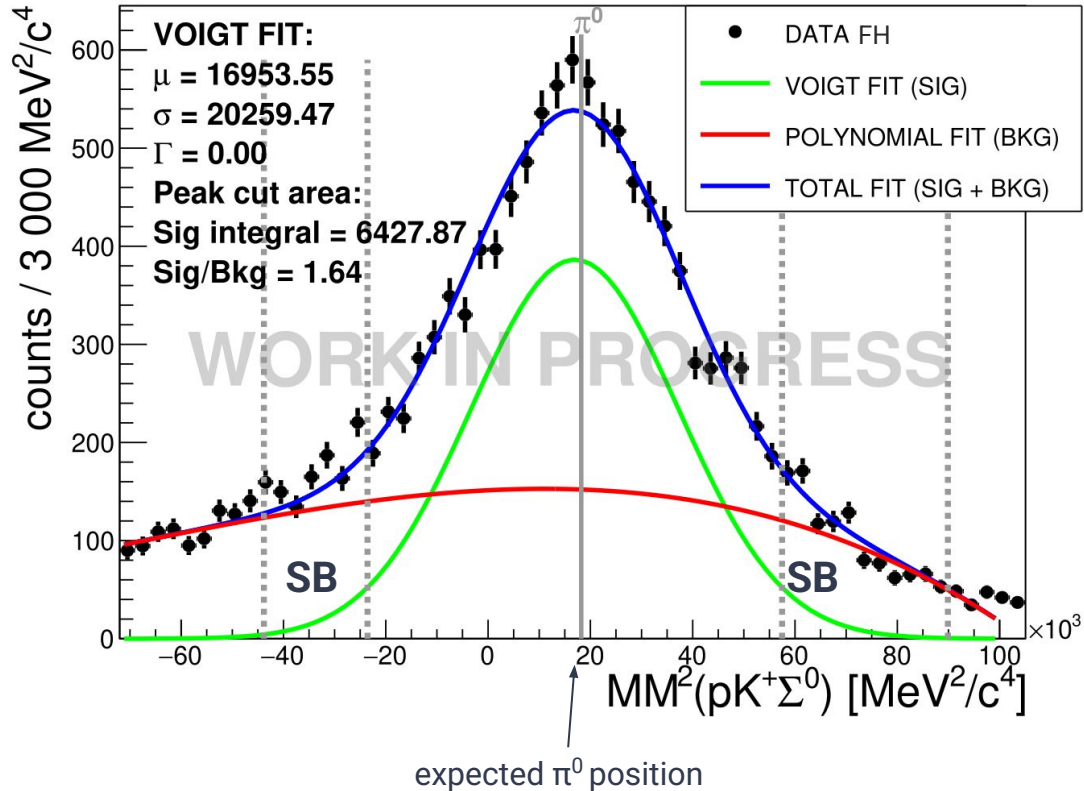
H – detected in HADES

F – detected in Forward Tracker



- $p > 0.05$ cut is performed

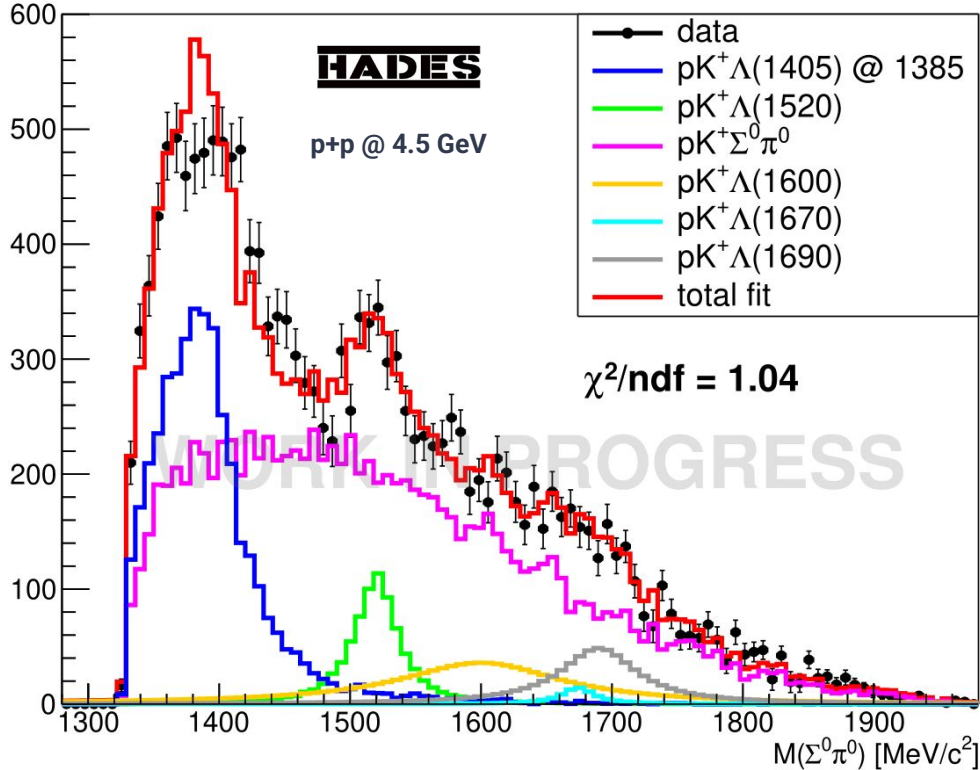
Missing π^0 mass squared after refit



- $\text{p K}^+ \Sigma^0 \pi^0$ events reconstructed from events inside the peak
- sideband subtraction to account for background

$M_{inv}(\Sigma^0\pi^0)$ in HADES acceptance

incoherent sum fitted to experimental distribution



Λ(1405) - modeled as a Breit-Wigner (single-pole approach), $m = 1385$ MeV/c², $\Gamma = 50$ MeV/c² -
- ansatz used in former HADES analysis at 3.5 GeV

Λ(1520) - BW: $m = 1519$, $\Gamma = 16$

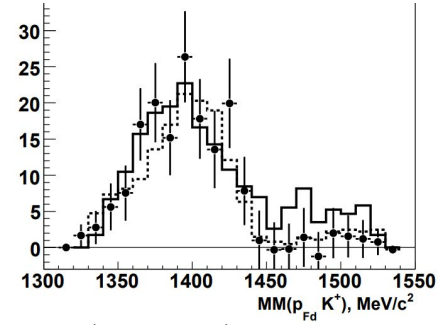
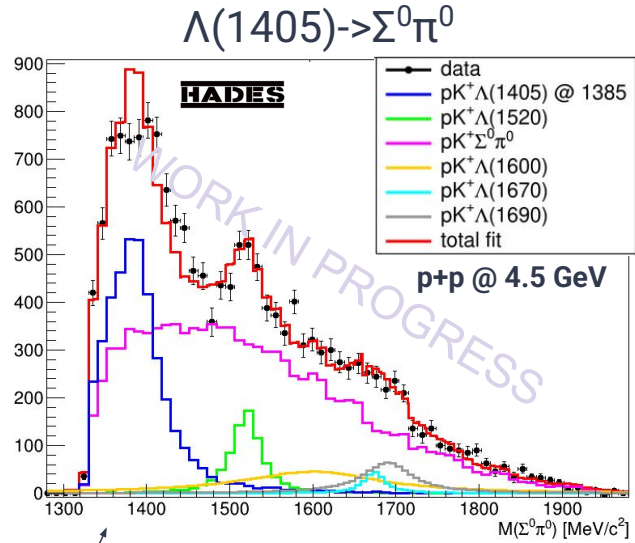
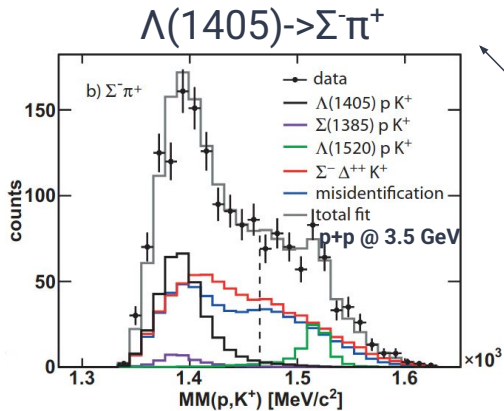
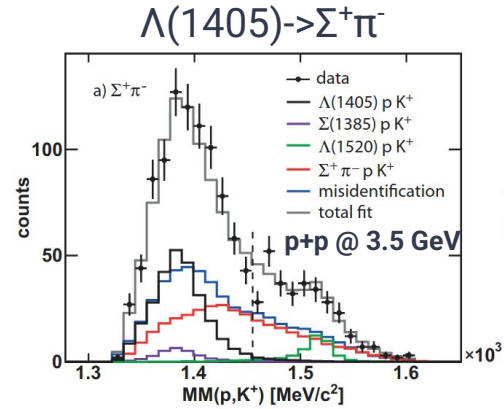
Σ⁰π⁰ - non-resonant contribution

Λ(1600) - BW: $m = 1600$, $\Gamma = 150$

Λ(1670) - BW: $m = 1674$, $\Gamma = 30$

Λ(1690) - BW: $m = 1690$, $\Gamma = 70$

Comparison with previous HADES results at 3.5 GeV



same binnig and same ansatz: incoherent sum, $\Lambda(1405)$ as BW with $m = 1385 \text{ MeV}/c^2$, $\Gamma = 50 \text{ MeV}/c^2$

order-of-magnitude improvement in statistics!

points (ANKE-COSY):

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

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

solid line:

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

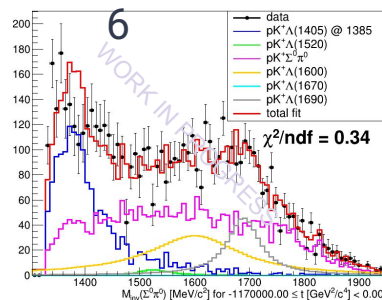
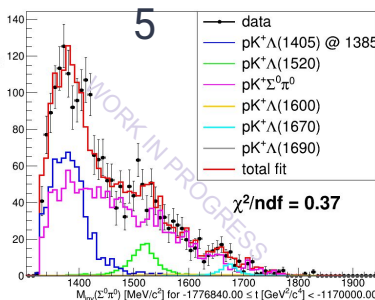
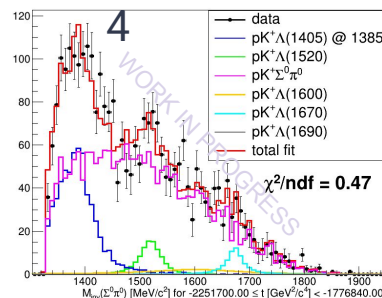
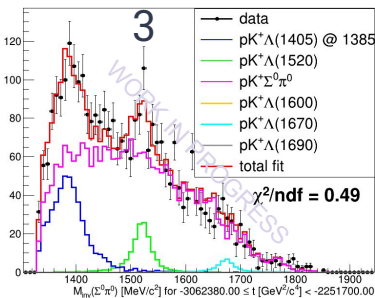
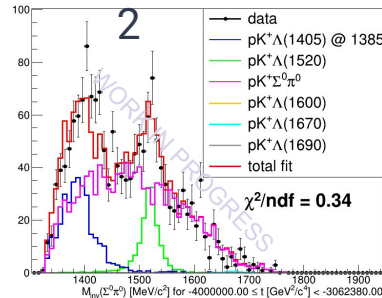
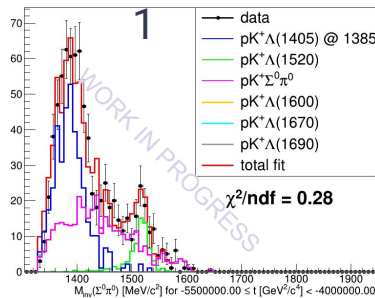
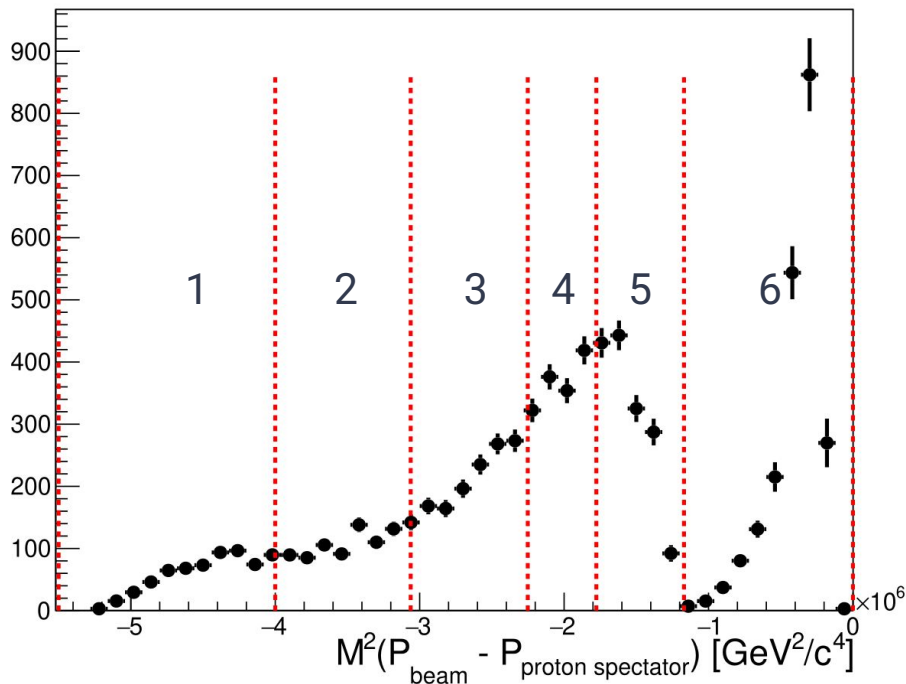
D. W. Thomas et al, Nucl. Phys. B 56, 15 (1973)

dotted line:

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

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

Differential distributions in function of four-momentum transfer t



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

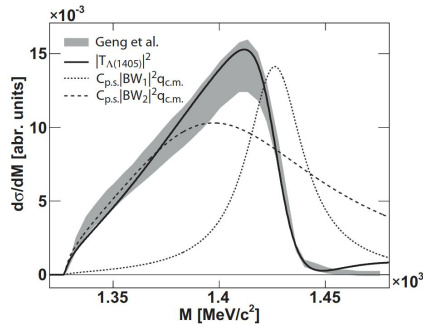
- acceptance and reconstruction 2D corrections: t vs. invariant mass
- $\Lambda(1405)$ - modeled as a coherent sum of two Breit-Wigner functions (based on UChPT two-pole approach)

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

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

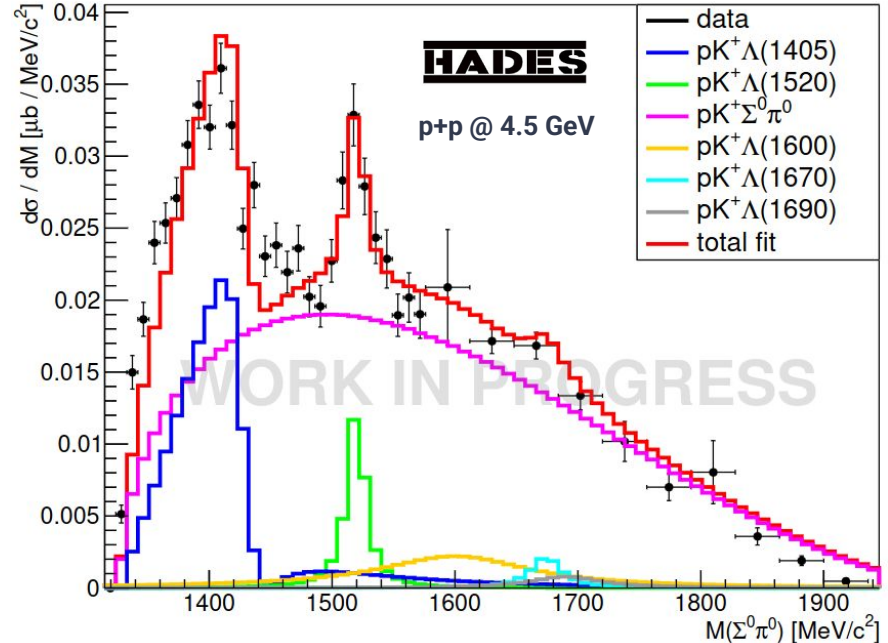
- non-resonant bkg added incoherently
- parameters fixed to values obtained from fit

the theoretical prediction:



$$\begin{aligned} m_1 &= 1426 \text{ MeV}/c^2 \\ \Gamma_1 &= 32 \text{ MeV}/c^2 \\ m_2 &= 1390 \text{ MeV}/c^2 \\ \Gamma_2 &= 132 \text{ MeV}/c^2 \\ A_1/A_2 &= 0.28 \\ \varphi &= 157 \text{ deg} \end{aligned}$$

J. Siebenson, Ph.D. Thesis, Technische Universität München (2013)
L. S. Geng and E. Oset, Eur. Phys. J. A 34, 405 (2007)



data not well described by the model

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

- acceptance and reconstruction 2D corrections: t vs. invariant mass
- **$\Lambda(1405)$** - modeled as a coherent sum of two Breit-Wigner functions (based on UChPT two-pole approach)

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

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

- non-resonant bkg added incoherently
- parameters fixed to values obtained from fit

the p(3.5 GeV)+p HADES data

$$m_1 = 1431 \text{ MeV}/c^2$$

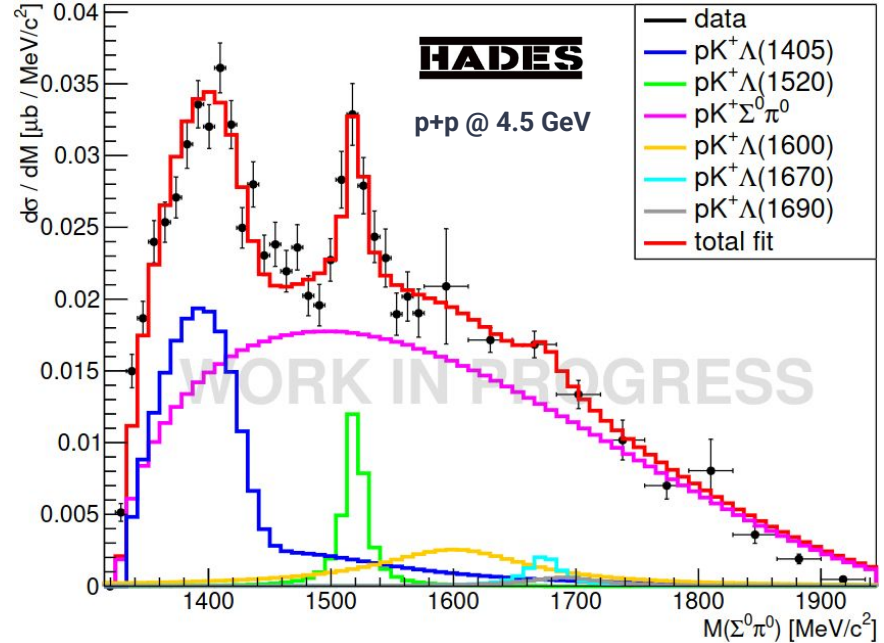
$$\Gamma_1 = 58 \text{ MeV}/c^2$$

$$m_2 = 1375 \text{ MeV}/c^2$$

$$\Gamma_2 = 146 \text{ MeV}/c^2$$

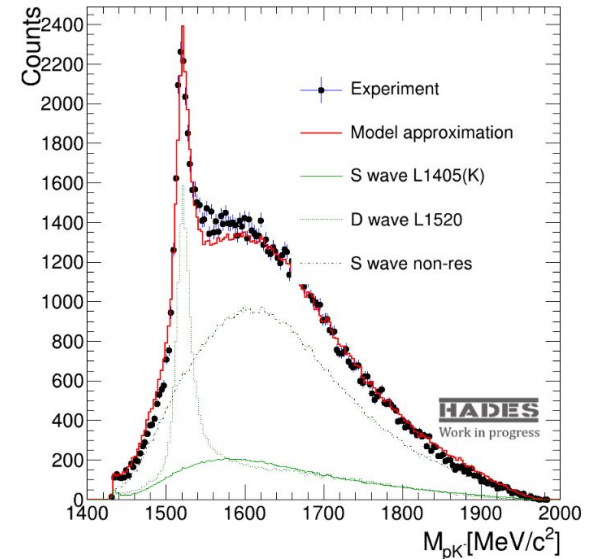
$$A_1/A_2 = 0.204$$

$$\varphi = 164 \text{ deg}$$



Summary

- $\Lambda(1405)$ pole/poles positions - the subject of ongoing debate
- line-shape and peak position varies between different result \rightarrow calls for the input from different initial channels
- $\Lambda(1405)$ signal has been identified in the 'golden channel' $\Lambda(1405) \rightarrow \Sigma^0 \pi^0$ 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 contributions from the $\Lambda(1520)$ resonance, as well as an enhancement near the masses of $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$
- the order of magnitude of the statistics enables differential analysis in a function of t
- UChPT approach used to describe the data in this neutral mode channel; poles position and widths as well as interference with non-resonant background will be studied
- more advanced fitting using K -matrix approach simultaneously for the invariant mass distributions of $\Sigma\pi$ and pK^- (\rightarrow see next talk by V. Kladov)



BACKUP

$\Lambda(1405)$ essentials

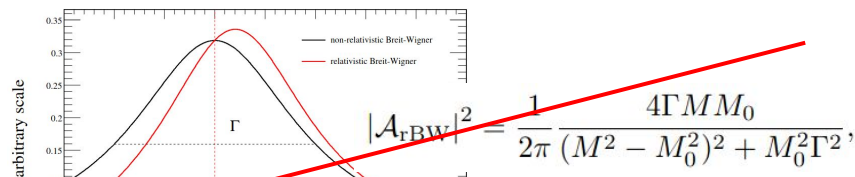
- $S = -1$
- observed in decay to:

$$\Sigma^+\pi^-$$

$$\Sigma^-\pi^+$$

$$\Sigma^0\pi^0$$

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



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

- recently introduced in PDG $\Lambda(1380)$

Properties of $\Lambda(1405)$ from PDG:

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

$$\Lambda(1405) \ 1/2^-$$

$$I(J^P) = 0(\frac{1}{2}^-) \ \text{Status: } ***$$

$\Lambda(1405)$ MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
-------------	------	-------------	------	---------

1405.1^{+1.3}_{-1.0} OUR AVERAGE

$\Lambda(1405)$ WIDTH

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
-------------	------	-------------	------	---------

50.5 \pm 2.0 OUR AVERAGE

$\Lambda(1405)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$\Gamma_1 \ \Sigma\pi$	100 %
$\Gamma_2 \ \Lambda\gamma$	
$\Gamma_3 \ \Sigma^0\gamma$	
$\Gamma_4 \ N\bar{K}$	

$$\Lambda(1380) \ 1/2^-$$

$$J^P = \frac{1}{2}^- \ \text{Status: } **$$

OMITTED FROM SUMMARY TABLE

See the related review on "Pole Structure of the $\Lambda(1405)$ Region."

$\Lambda(1405)$ as a 3-quark orbital excitation of $\Lambda(1115)$

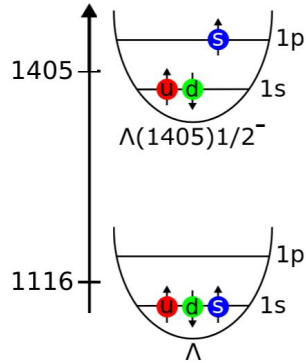
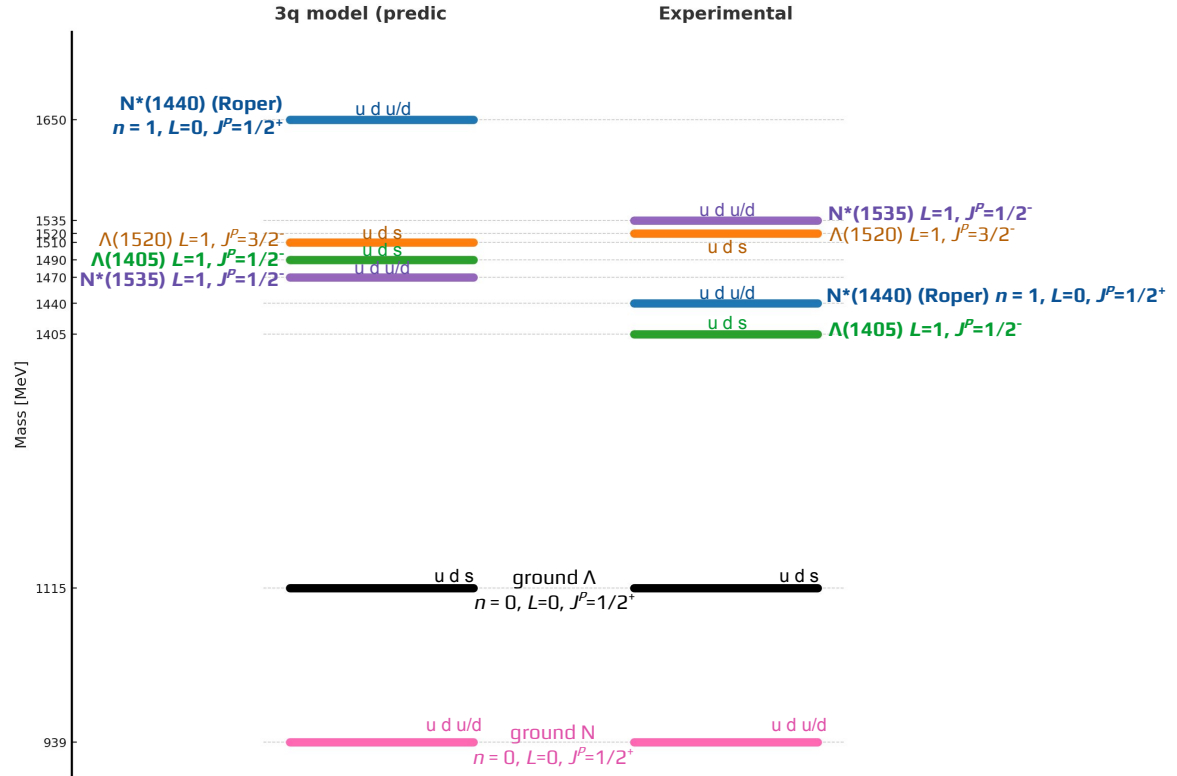


Figure adapted from:
D. Werthmüller and R. A. Schumacher, arXiv:1802.01720 [nucl-ex] (2018)

- lighter than the $S_{11}(1535)$ and $P_{11}(1440)$ nucleon resonances
- its splitting from the spin-orbit partner $\Lambda(1520)$ is unusually large compared to the nucleon sector

$\Lambda(1405)$ not compatible with quark model predictions

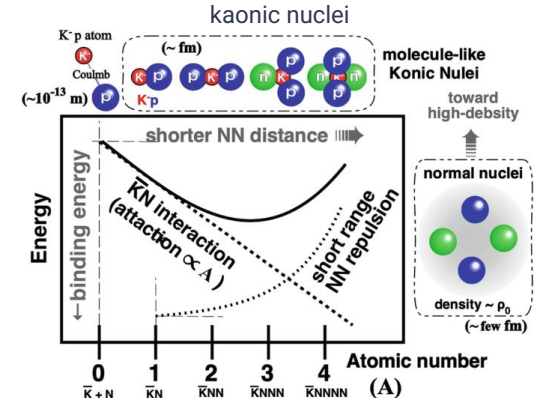


Burkert and Roberts, Rev. Mod. Phys. 91, 011003 (2019)
Y. Zhong et al., arXiv:2409.07998 (2024)
N. Isgur and G. Karl, Phys. Rev. D 18, 4187 (1978)

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

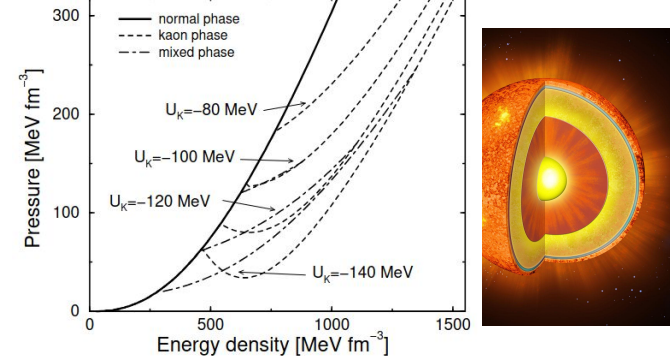
- Predicted by Dalitz & Tuan (1960s) examining low energy reaction of $K^- + p$
- No data on the final $\Sigma\pi$ state available back then
- From analysis of above-threshold behaviour of $K^- + p$ in unphysical region below $p_{K^-} = 0$ the below threshold $\Sigma\pi$ could be predicted
- Resonance 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 $\Lambda(1405)$



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

softening of the EoS of the neutron star



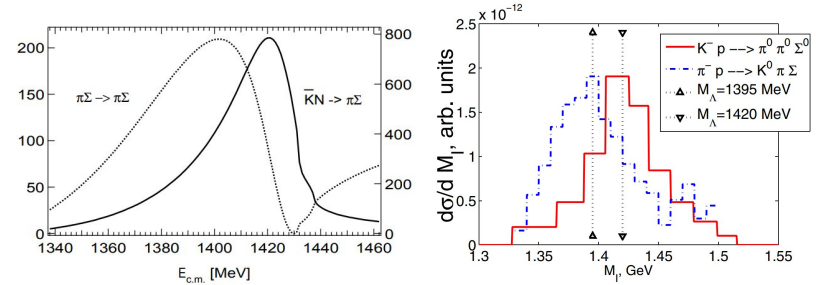
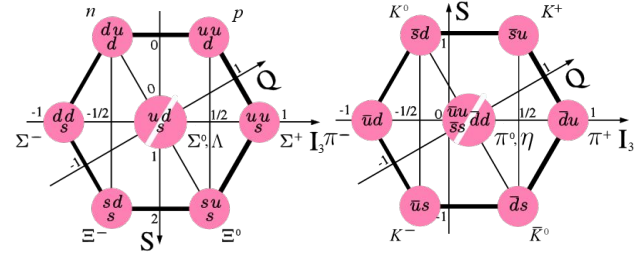
A. Ramos et al., Lect. Notes Phys. 578, 175 (2001)

$\Lambda(1405)$ as a two-pole structure

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

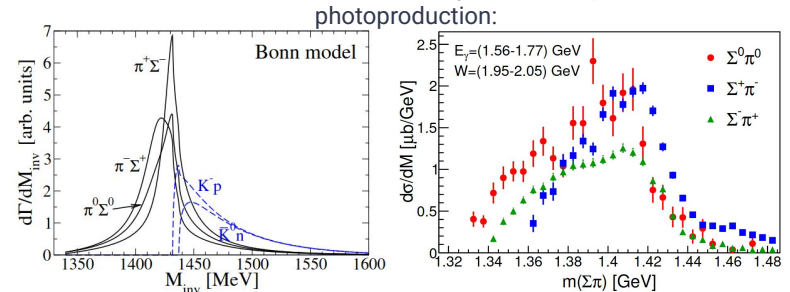
- interaction of the baryon ground-state octet with the pseudoscalar meson octet
- unitarity and analyticity of scattering amplitudes implemented in coupled-channel dynamics
- SU(3) baryons irreps $1+8_s+8_a$ combine with 0- Goldstone bosons to generate two octets and a singlet of $\frac{1}{2}^-$ baryons 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 $\Sigma\pi$ and higher one, dominantly coupled to $N\bar{K}$
- possible weak $I=1$ pole also predicted

$\Lambda(1405)$ 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)



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

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

Isospin decomposition of $\Sigma\pi$ channels

$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 + \frac{2}{\sqrt{6}}\text{Re}(T^{(0)}T^{(1)*}),$$

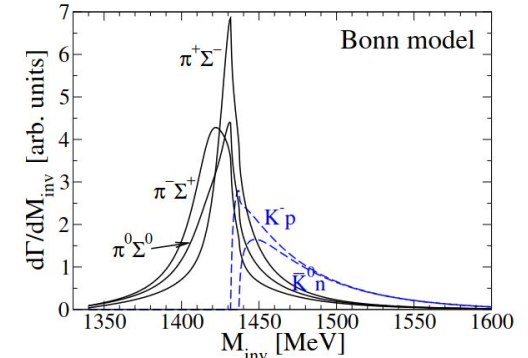
$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 - \frac{2}{\sqrt{6}}\text{Re}(T^{(0)}T^{(1)*}),$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2,$$

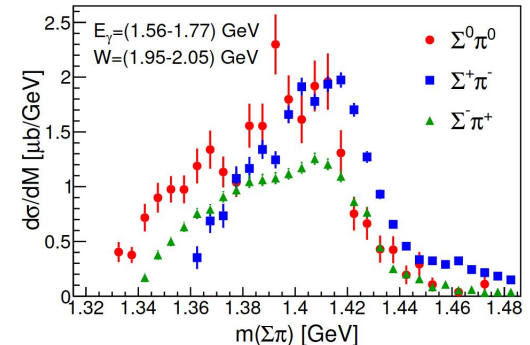
$I = 1$ amplitude might not be negligible and influence the distribution differently in each decay mode

Studies of $\Lambda(1405)$ photoproduction suggest a dependence of peak position and line shape on the decay channel

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:

$\Xi(1620), \Xi(1690)$ in coupled channels $\pi\Xi, \Lambda/\Sigma \bar{K}$

(decays to $\pi\Xi, \Lambda\bar{K}$ planned to be measured in the future CBM experiment)

$\Xi(1620)$ molecular state?

$\Xi(1690)$ quasi-bound $\Sigma\bar{K}$ state?

Thresholds close to Ω mass

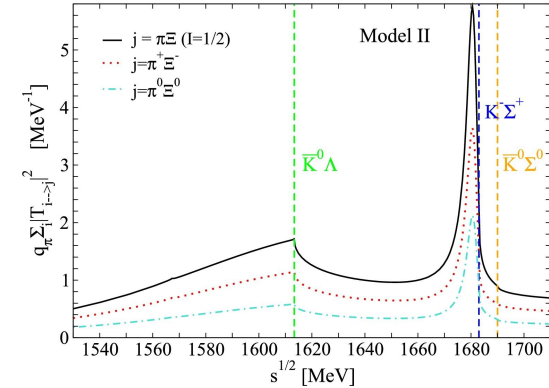
- pseudoscalar meson – vector meson interactions: two-pole structure predicted for $K_1(1270)$

poles below the pK and above the $K^*\pi$

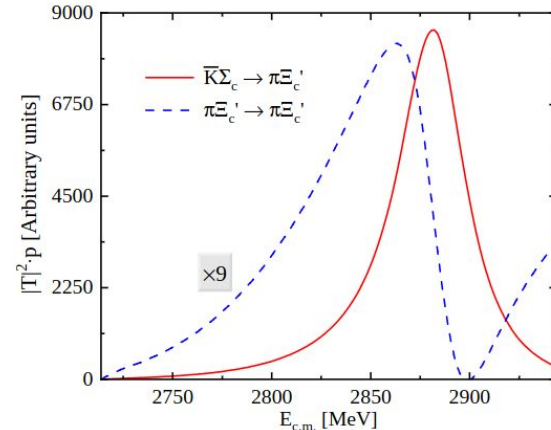
- charmed baryon sector:

two-pole structure predicted for channels $\bar{K}\Sigma_c(2949)$ and

$\pi\Xi'_c(2714)$



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



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

$\Lambda(1405)$ in $p+(\text{@ } 3.5 \text{ GeV})p$ - HADES measurements

- single pole approach
incoherent MC sim sum
dotted line – sim sum if $\Lambda(1405)$ simulated with mass $1405 \text{ MeV}/c^2$

$$m = 1385 \text{ MeV}/c^2, \Gamma = 50 \text{ MeV}/c^2$$

- two-pole U χ PT approach
poles added coherently
 - considering interference with the non-resonant background

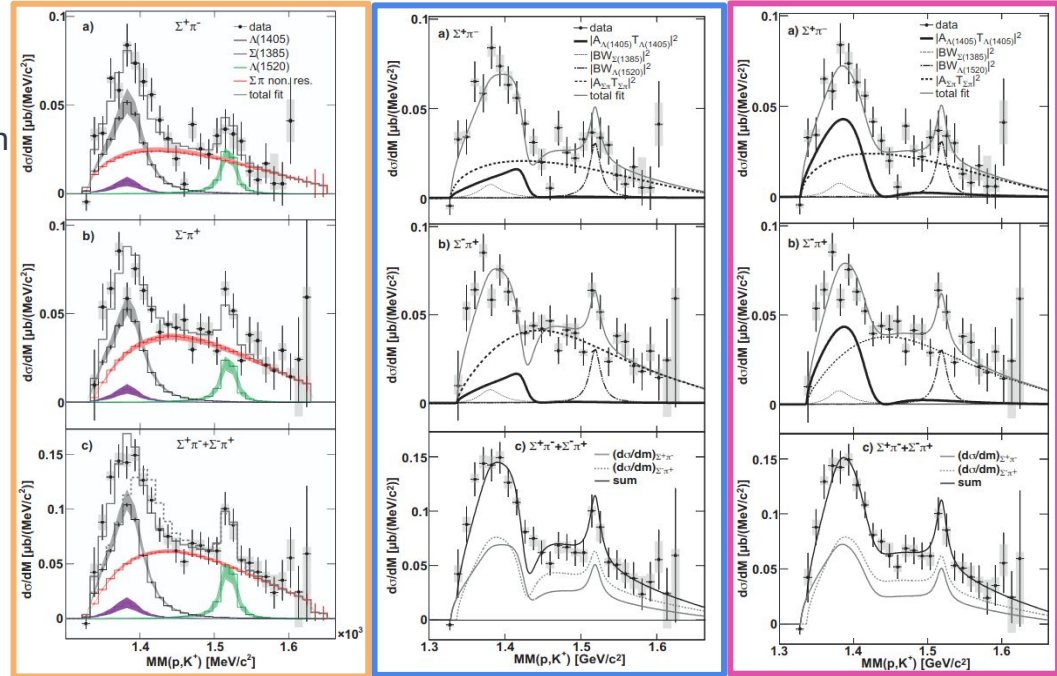
$$m_1 = 1426 \text{ MeV}/c^2, \Gamma_1 = 28 \text{ MeV}/c^2$$

$$m_2 = 1375 \text{ MeV}/c^2, \Gamma_2 = 147 \text{ MeV}/c^2$$

- neglecting interference with the non-resonant background

$$m_1 = 1418/1431 \text{ MeV}/c^2, \Gamma_1 = 58 \text{ MeV}/c^2$$

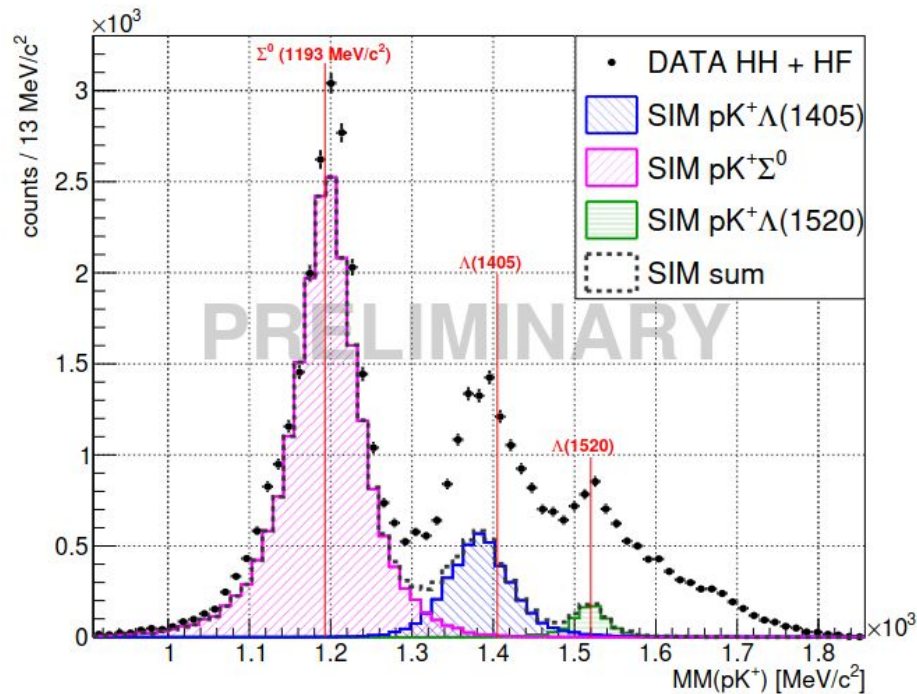
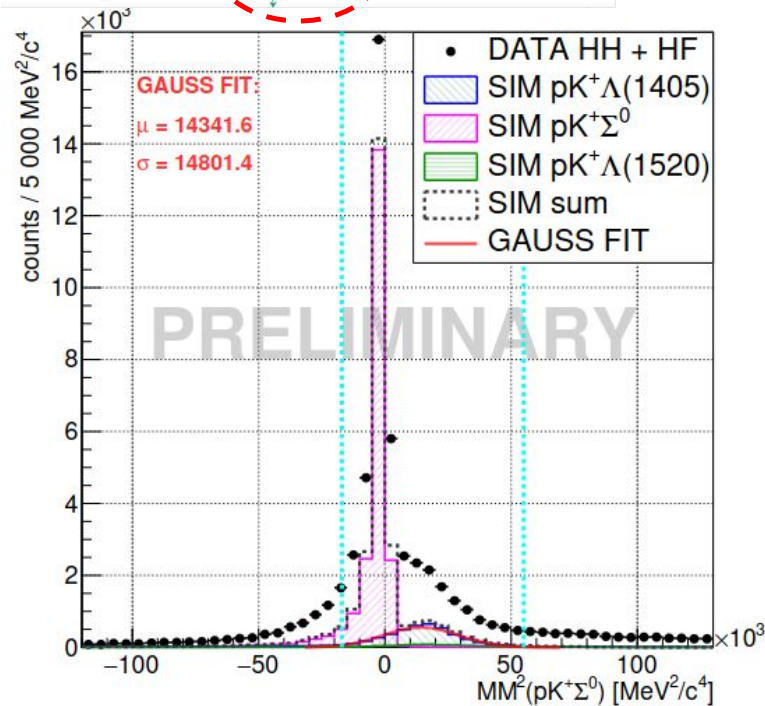
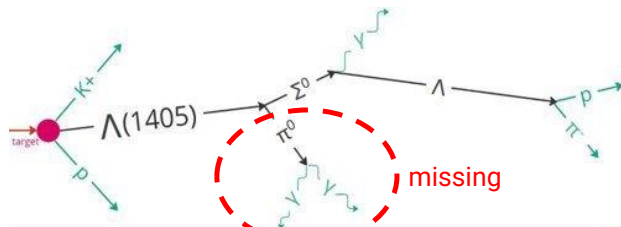
$$m_2 = 1375 \text{ MeV}/c^2, \Gamma_2 = 146 \text{ MeV}/c^2$$



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

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

x - measured

y - estimated

V - covariance matrix

$$f(\vec{x}, \vec{\xi}) = 0$$

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

Minimization:

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

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

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

λ - Lagrange parameters

D - derivative matrix of constraint equation

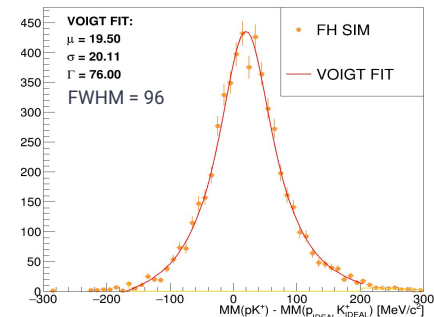
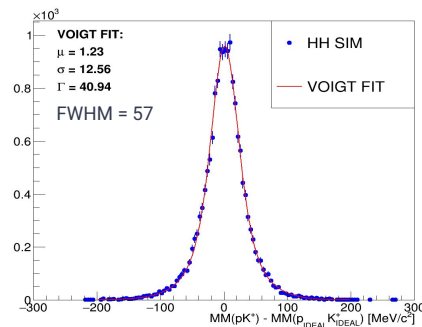
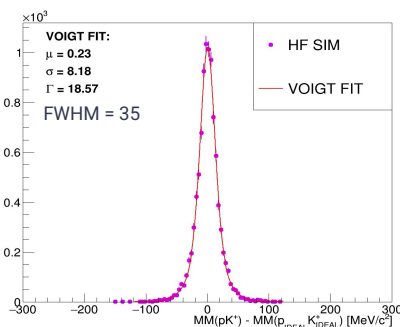
- the iterative procedure is obtained changing the parameters and errors values.
- stopped when convergence is reached based on one of criteria: change in χ^2 , constraint equation norm, or change in track parameters
(default threshold: 10^{-4} , with a maximum of 20 iterations)

$\Lambda(1405)$ mass resolution from simulation

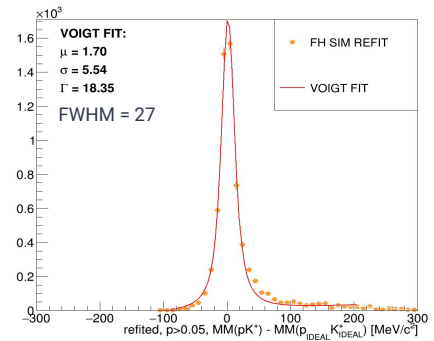
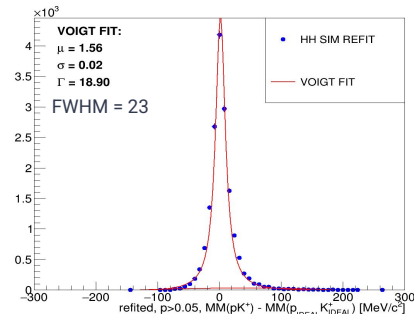
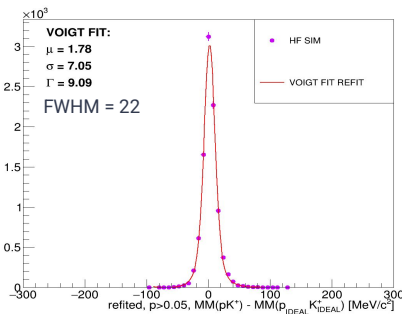
- $\Lambda(1405)$ natural width (PDG): 50.5 ± 2.0
- obtained sensitivity to the line shape and peak position by improvement of the mass resolution with kinematic fitting:

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

○ before refit

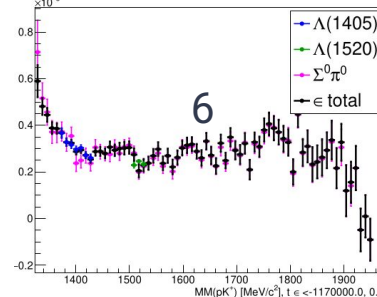
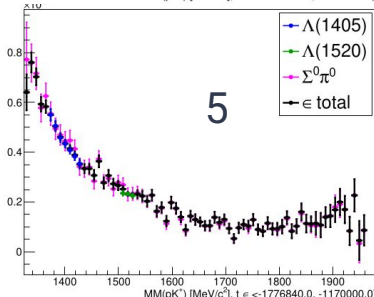
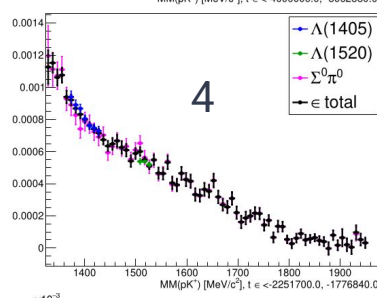
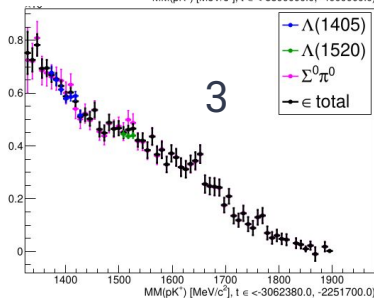
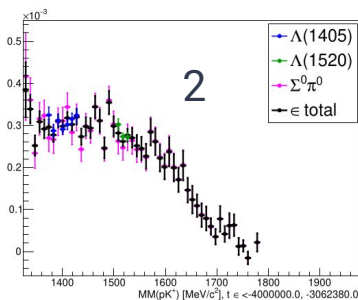
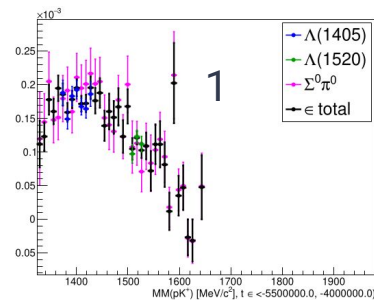
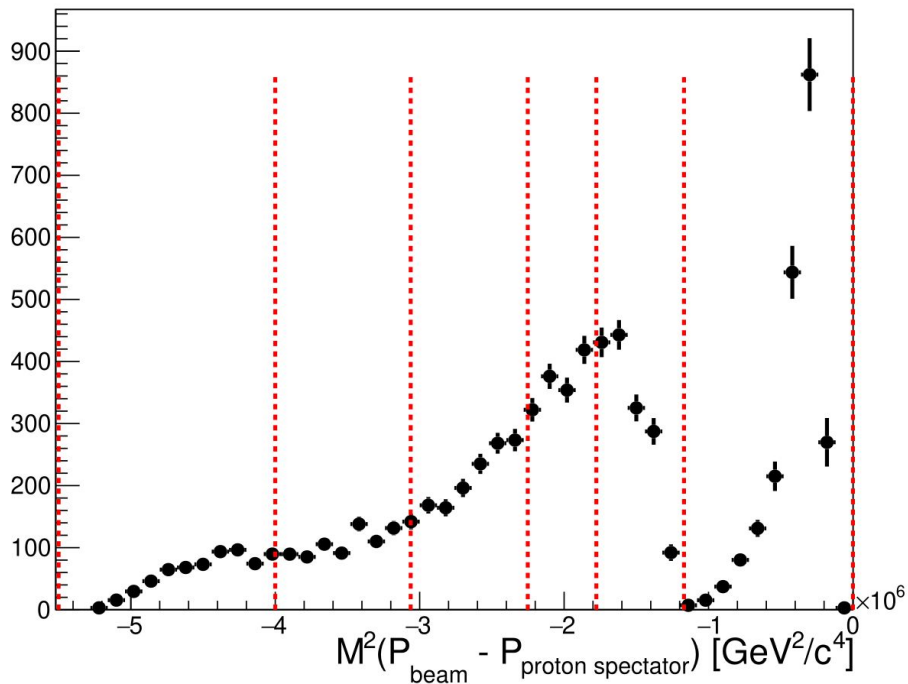


○ after refit



Acceptance and reconstruction 2D corrections

t vs. invariant mass



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

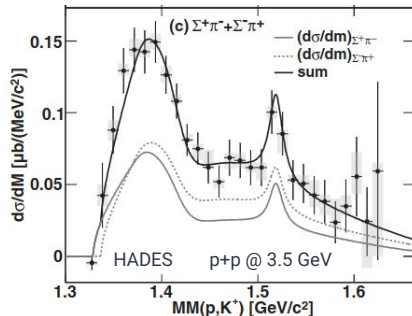
- acceptance and reconstruction 2D corrections: t vs. invariant mass
- $\Lambda(1405)$ - modeled as a coherent sum of two Breit-Wigner functions (based on UChPT two-pole approach)

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

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

- non-resonant bkg added incoherently
- parameters fixed to values obtained from fit

the $p(3.5 \text{ GeV})+p$ HADES (case with $A_{\Sigma^+\pi^-}$ and $A_{\Sigma^-\pi^+}$ being fixed parameters)



$$m_1 = 1418 \text{ MeV}/c^2$$

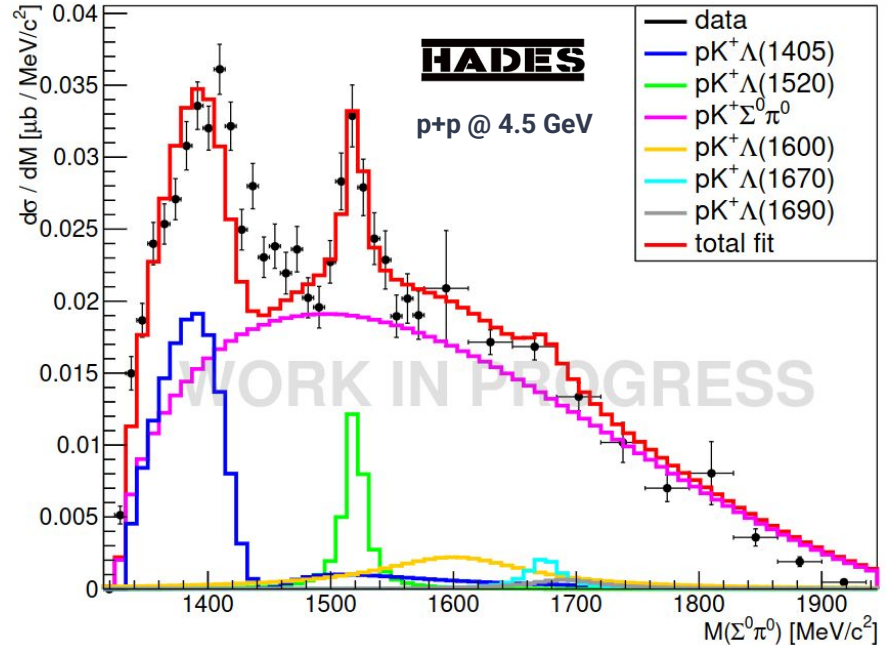
$$\Gamma_1 = 58 \text{ MeV}/c^2$$

$$m_2 = 1375 \text{ MeV}/c^2$$

$$\Gamma_2 = 146 \text{ MeV}/c^2$$

$$A_1/A_2 = 0.395$$

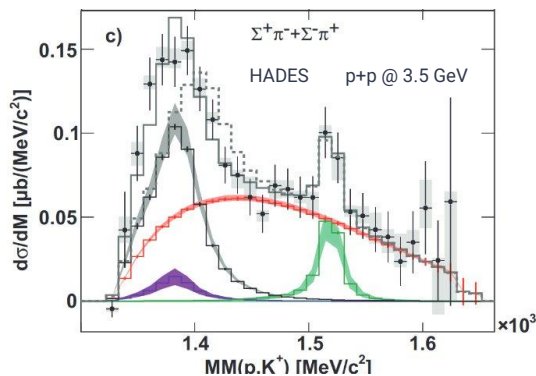
$$\varphi = 178 \text{ deg}$$



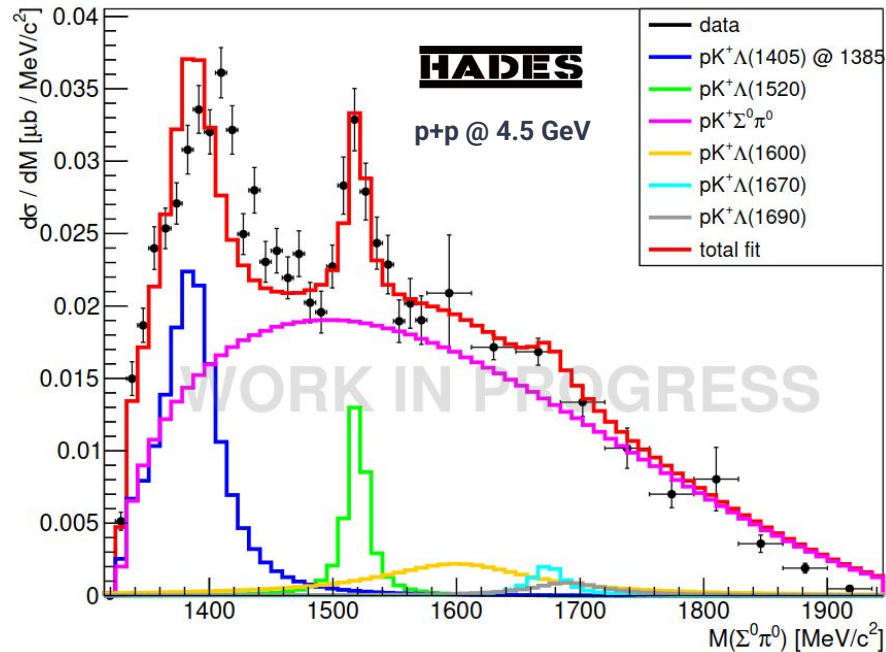
data not well described by the model

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

- acceptance and reconstruction 2D corrections:
t vs. invariant mass
- $\Lambda(1405)$ - modeled as a Breit-Wigner
(single-pole approach)
 $m = 1385 \text{ MeV}/c^2$, $\Gamma = 50 \text{ MeV}/c^2$
- components added incoherently
- ansatz used in former HADES analysis at 3.5 GeV:



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



data not well described by the model