# *$\Lambda(1405)$ reconstruction in $\Sigma^0\pi^0$ decay channel with HADES detector*

FAIRNESS

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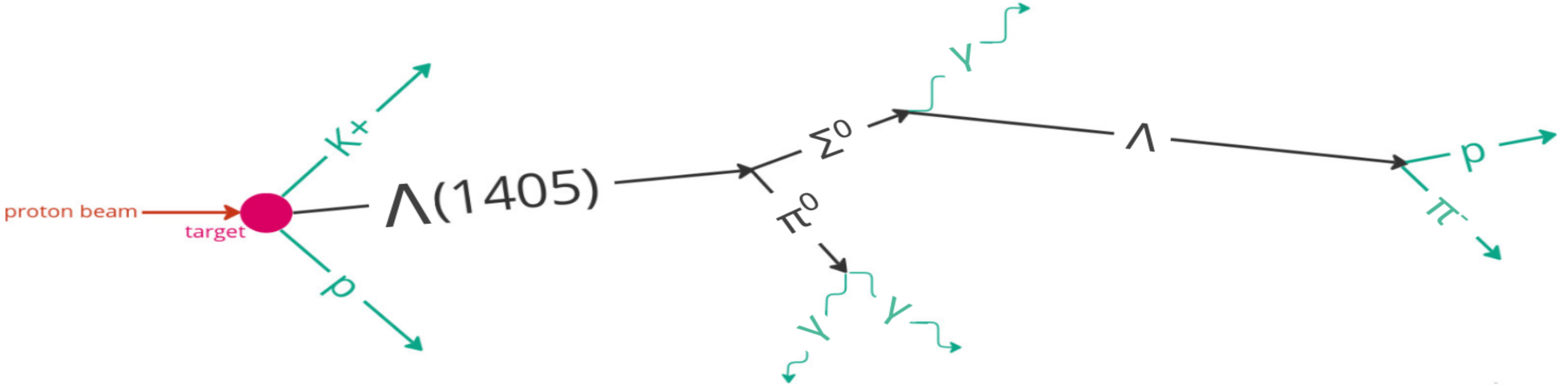



I. Introduction and motivations
- Hypotheses on the structure of Λ(1405)
- Results from other experiments
- HADES Detector

II. Inclusive analysis **Λ(1405)->$\Sigma^0$(Λ+γ)+$\pi^0$**
- **Λ->p$\pi^-$** (topology & mass cuts)
- **$\Sigma^0$->Λγ** (sideband method)
- comparison with estimates from cross sections

III. Exclusive analysis

**p+$K^+$+Λ(1405)->$\Sigma^0$(Λ+γ)+$\pi^0$**
- $\pi^0$ identified via missing mass method
- **Λ(1405), $\Sigma^0$, Λ(1520)** signals
- Estimates from cross sections

IV. Summary & outlook

# Λ(1405) - hypotheses

1) Before the quark model: **anty-K N bound state**. First seen in: $K^- p \to \Sigma 3\pi$

Alston M. H. et al. Study of resonances of the Σ−π system. Phys. Rev. Lett., 6:698–702, 1961.

Serves well for deeply bound hypernuclei ppK$^-$ concept

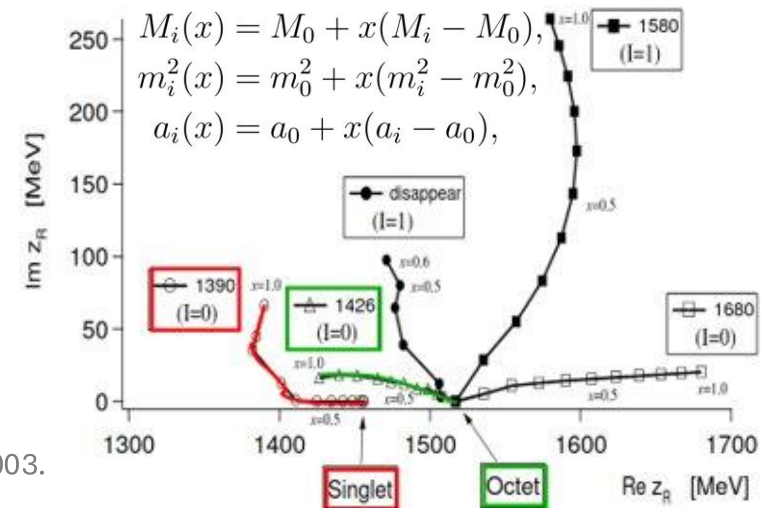
2) Dynamically generated **meson–baryon resonance molecule**: **Σπ**. <= From the leading order chiral SU(3) meson–baryon scattering Lagrangian.

An excellent description of the $K^- p$, $K^0 n$, $\pi^0\Lambda$, $\pi^\pm\Sigma^\mp$, $\pi^0\Sigma^0$ scattering data and the πΣ mass distribution

Kaiser N., Siegel P.B., Weise W. Chiral dynamics and the low-energy kaon - nucleon interaction. Nucl. Phys. A, 594: 325–345, 1995.

3) With next-to-leading order: **$\bar{K}$N - Σπ interference decaying into the $(\Sigma\pi)^0$**

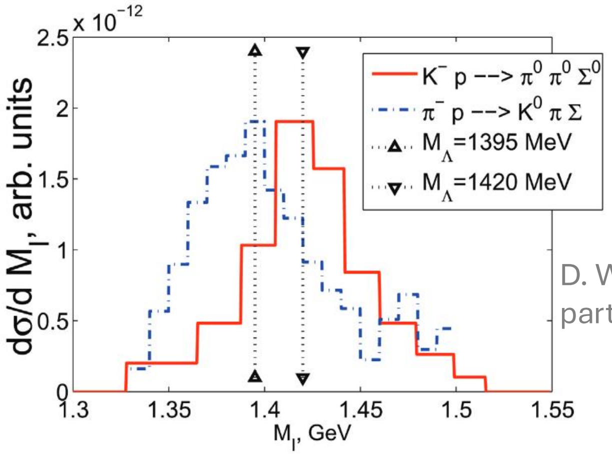
$m_i$- meson mass, Mi – barion mass, $a_i$ _const.
$0 \le x \le 1$
$x = 0$ <= SU(3) symmetry
$x = 1$ <= physical masses



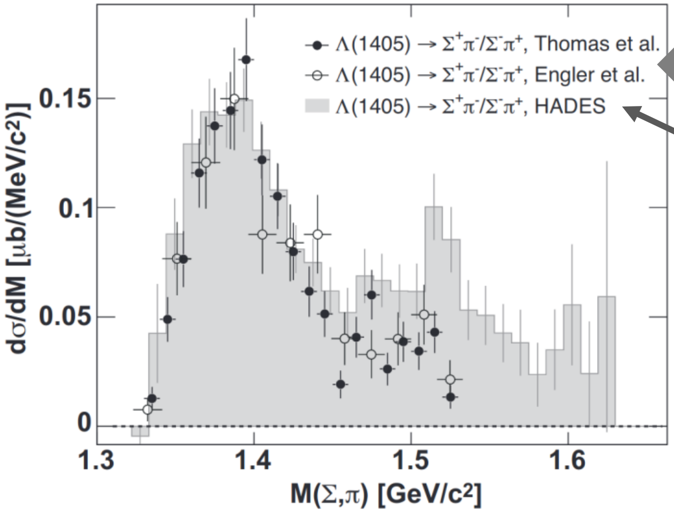

Jido D. et al. Chiral dynamics of the two Λ(1405) states. Nucl. Phys., A725:181–200, 2003.

# Previous results

- **Peak position** for **different-sign $(\Sigma\pi)^0$** channels:




S. Prakhov et al K−p → π0π0Σ0 at p(K−) = 514 MeV/c to 750 MeV/c and with other π0π0 production (2004)



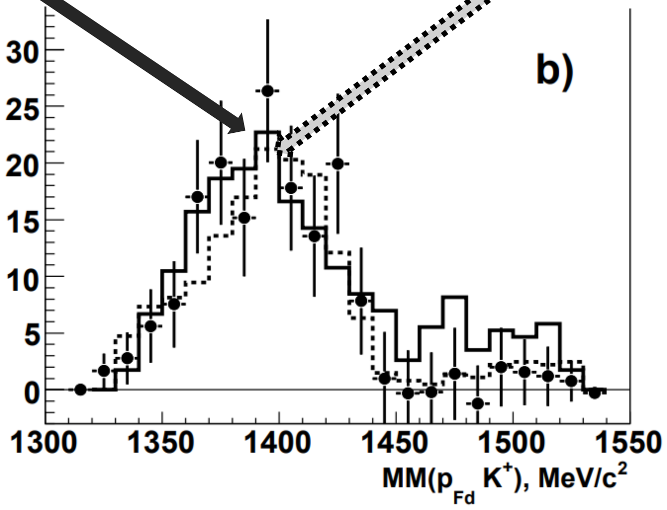

π⁻p collisions

pp collisions

J.Siebenson and L. Fabbietti Investigation of the Λ(1405) line shape in pp collisions (2013)

D. W. Thomas, A. Engler, H. E. Fisk and R. W. Kraemer Strange particle production from π− p interactions at 1.69 GeV/c (1973) $\pi^- p \to K^0(\Sigma\pi)^0$

R.J. Hemingway, Nucl. Phys. B 253 (1984) $K^- p \to \pi^+\pi^-\Sigma^+\pi^-$




Points:

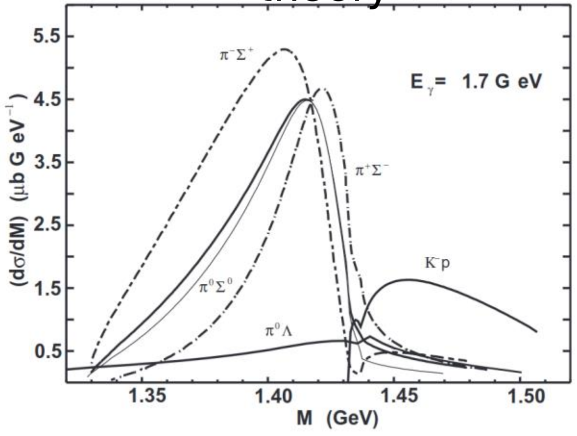
$pp \to pK^+\Lambda(1405) \to pK^+\Sigma^0\pi^0$

I. Zychor et al Lineshape of the Λ(1405) Hyperon Measured Through its Σ 0π 0 Decay (2008)

- **Peak position** for different **entrance channels**:

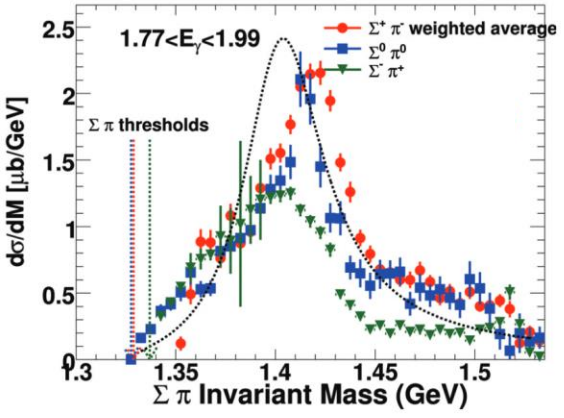
$\gamma p \to \Lambda(1405)K^+$

theory




(a)

experiment




(b)

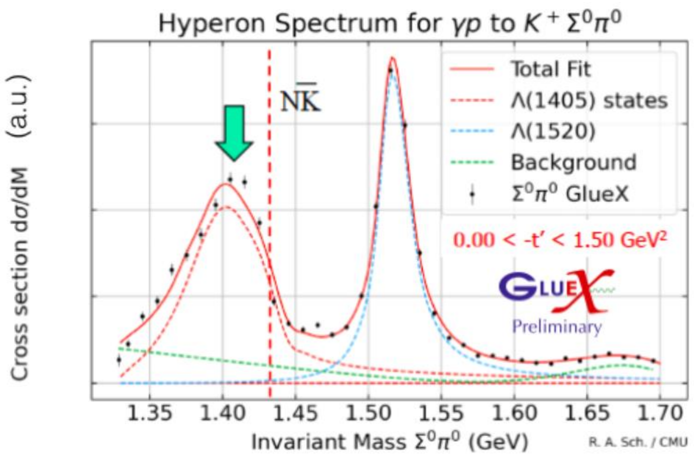
J. C. Nacher, E. Oset, H. Toki and A. Ramos *Photoproduction of the Λ(1405) on the proton and nuclei* (1999)

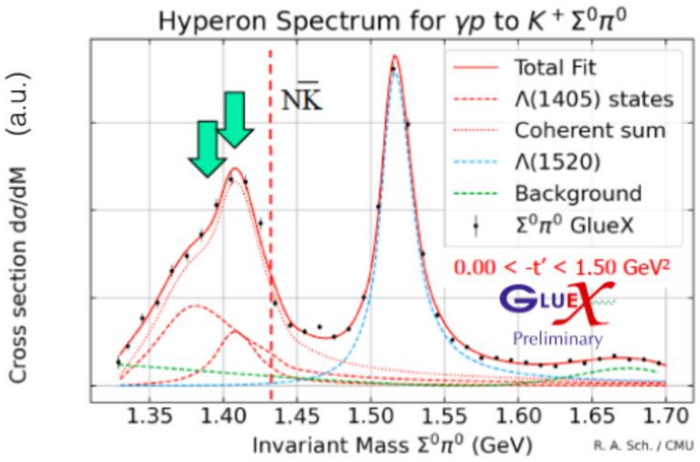
K. Moriya and R. Schumacher *Properties of the Λ(1405) measured at CLAS* (2010)

# Previous results

$$\gamma p \rightarrow K^+\Sigma^0\pi^0$$

N. Wickramaarachchi, R. A.Schumacher, G. Kalicy, Decay of the Λ(1405) Hyperon to Σ0π0 Measured at GlueX, 2022

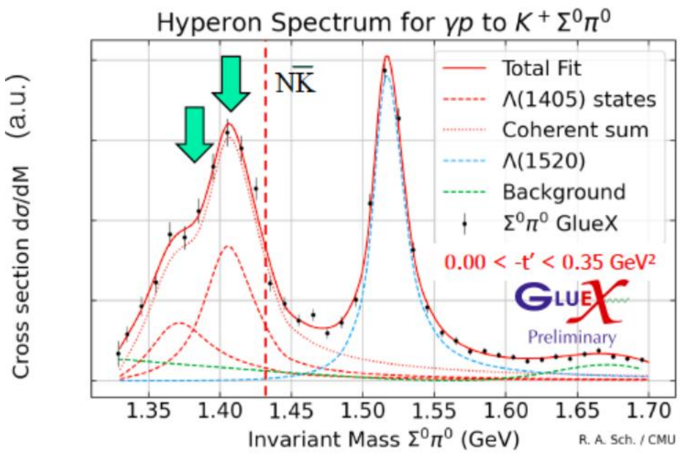


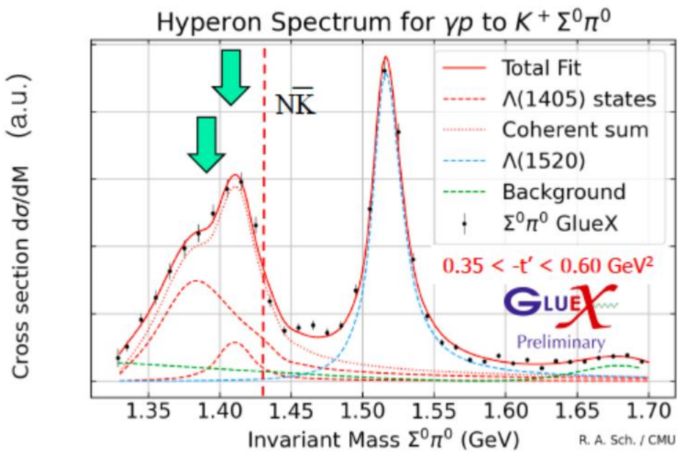

**Line shape analysis**

**Mandelstam term:**

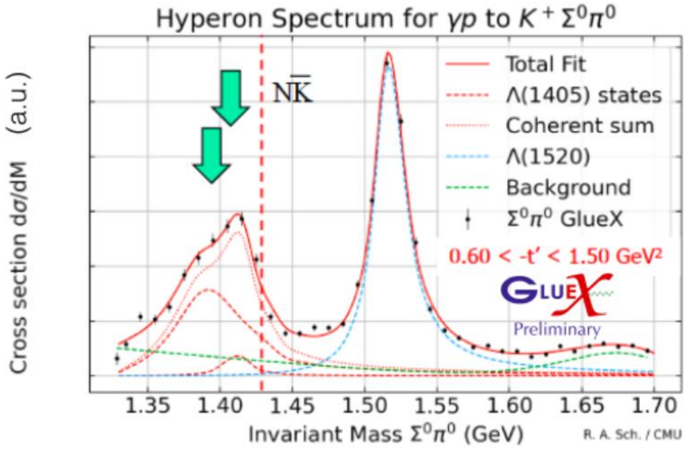
$$t = (p_{beam} - p_{K^+})^2$$




$$0 < -(t - t_{min}) < 0.35$$



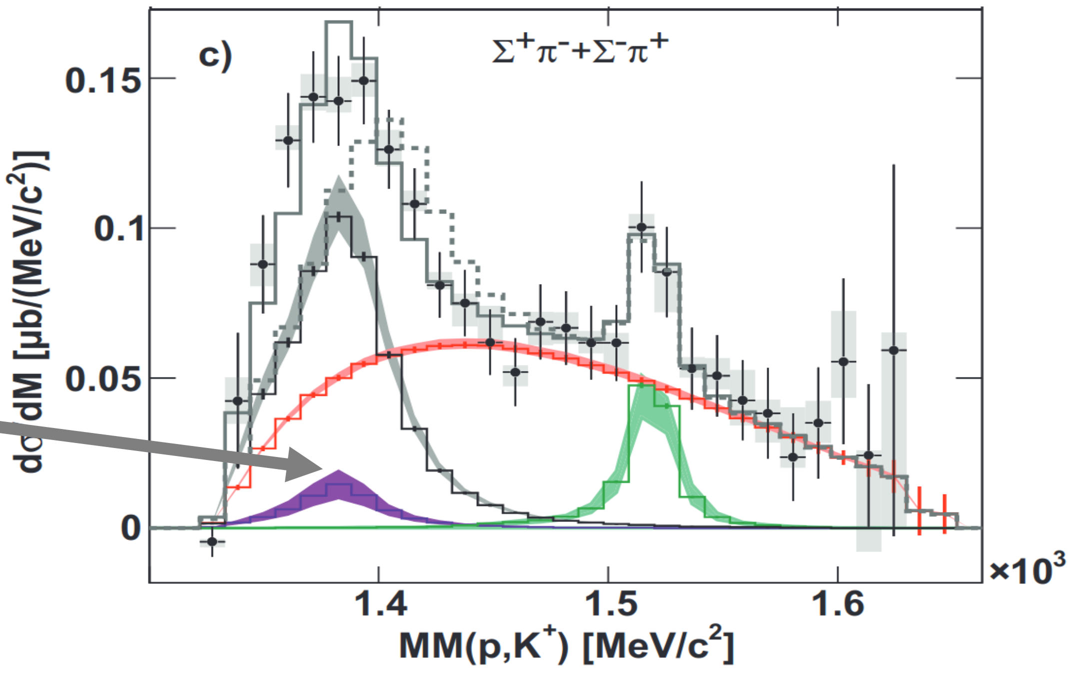

$$0.35 < -(t - t_{min}) < 0.6$$



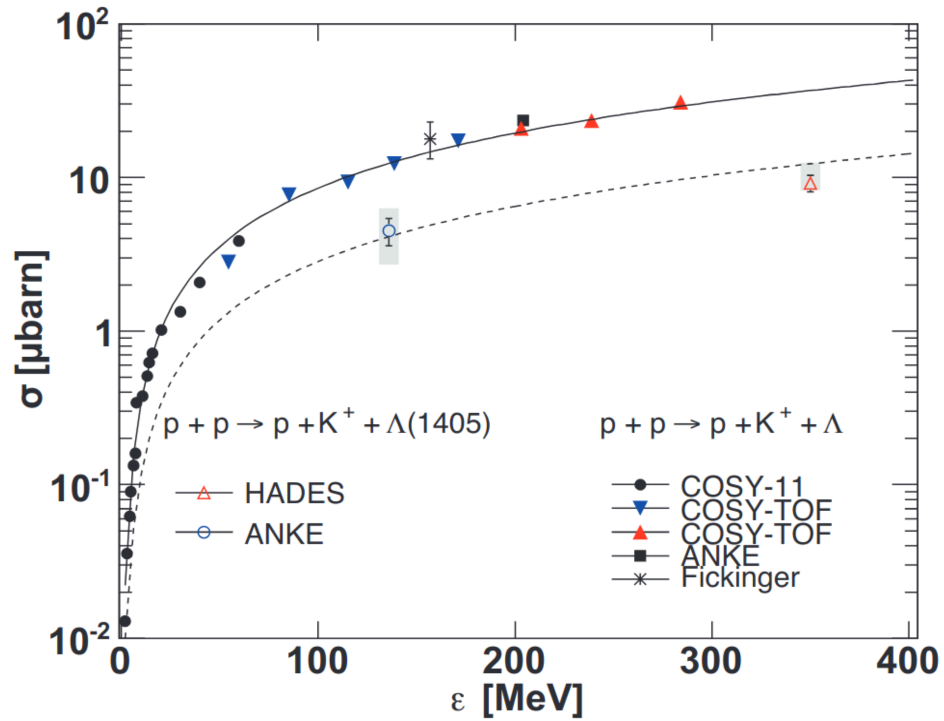

$$0.6 < -(t - t_{min}) < 1.5$$

# Previous results: HADES
# decay channels: $\Sigma^{\pm}\pi^{\mp}$ @(3.5GeV)p+p

**Λ(1405)** shift with maximum around 1385 MeV - overlap with **Σ(1385)**




**$\sigma_{\Lambda X}/\sigma_{\Lambda(1405)X}$** ratio assumed to be around **3**:




$$p + p \xrightarrow{3.5GeV} \Lambda(1405) + K^+ + p$$
$$\hookrightarrow \Sigma^{\pm} + \pi^{\mp}$$
$$\hookrightarrow \pi^{\pm} + n$$

$$\Sigma(1385)^0 + p + K^+ \overset{12\%}{\to} \Sigma^{\pm} + \pi^{\mp} + p + K^+,$$

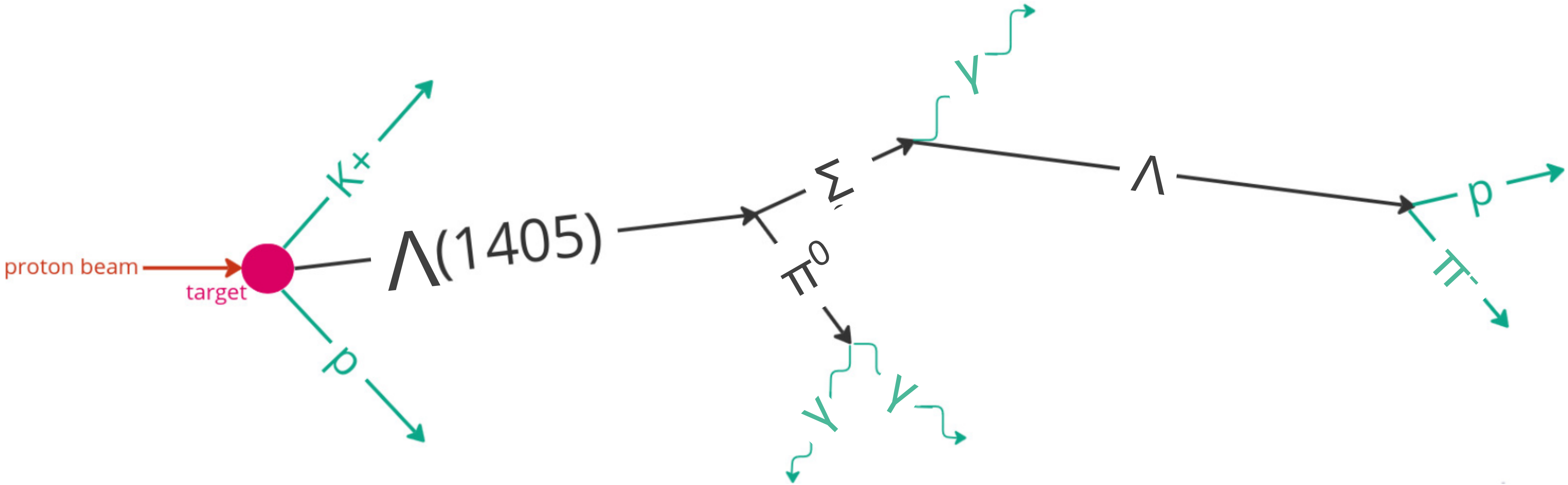
$$\Lambda(1520) + p + K^+ \overset{28\%}{\to} \Sigma^{\pm} + \pi^{\mp} + p + K^+,$$

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

Dotted line – sim sum if Λ(1405) simulated with mass 1405 MeV/c²

G. Agakishiev et al. *Baryonic resonances close to the K̄N threshold: the case of Λ(1405) in pp collisions* (2013)

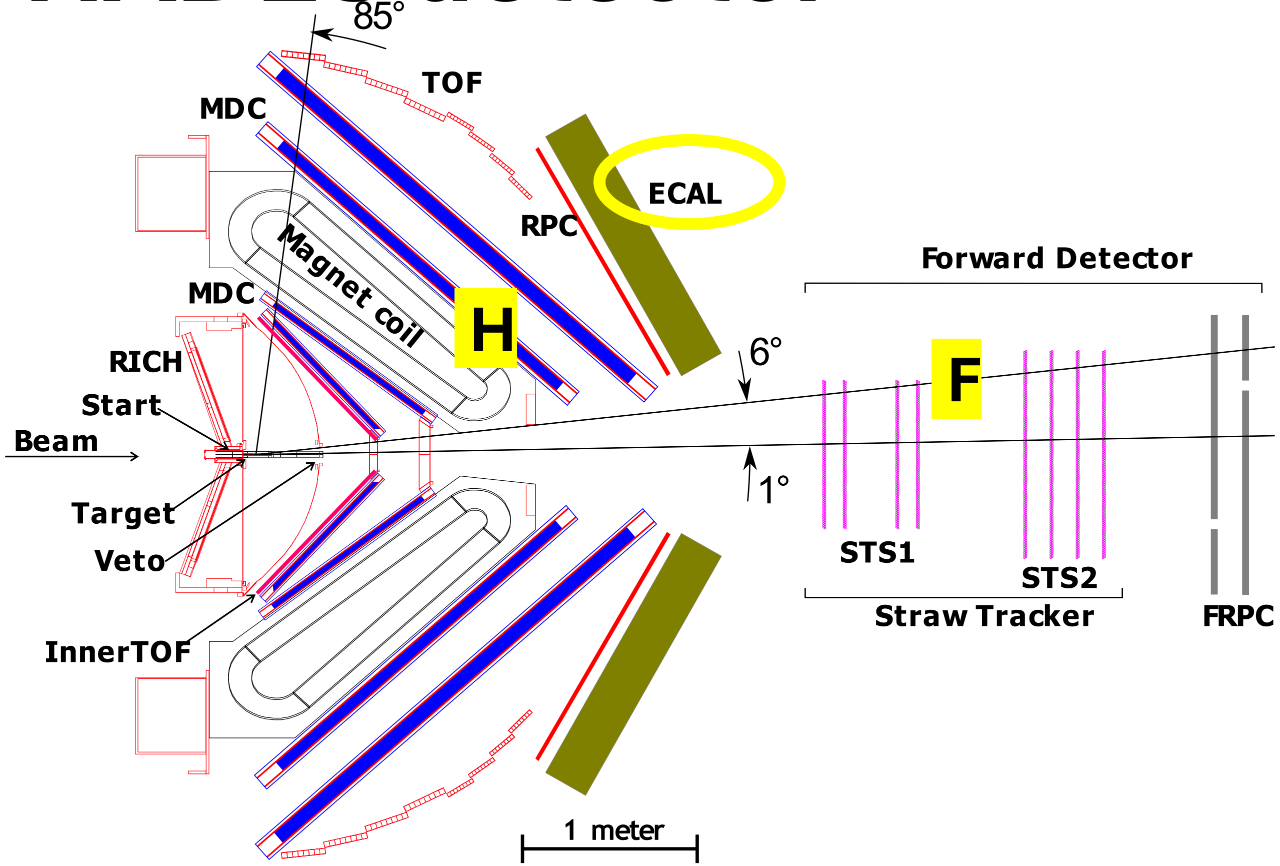
# Channel of interest – with $\Sigma^0\pi^0$




With γ-s - not available for Σ(1385)
**Possibility to disentangle Λ(1405) from Σ(1385) with ECAL**

# HADES detector

High Acceptance DiElectron Spectrometer




- Fixed target
- proton **4.5 GeV** beam from SIS18
- Azymutal acceptance: 85%

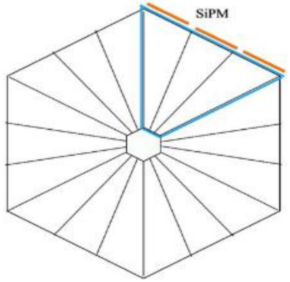
Magnetic spetrometer (HADES): z Mini Drift Chambers (MDC-s), polar acceptance 18°-85°, **charged products**: momenta, production vertexes, energy losses

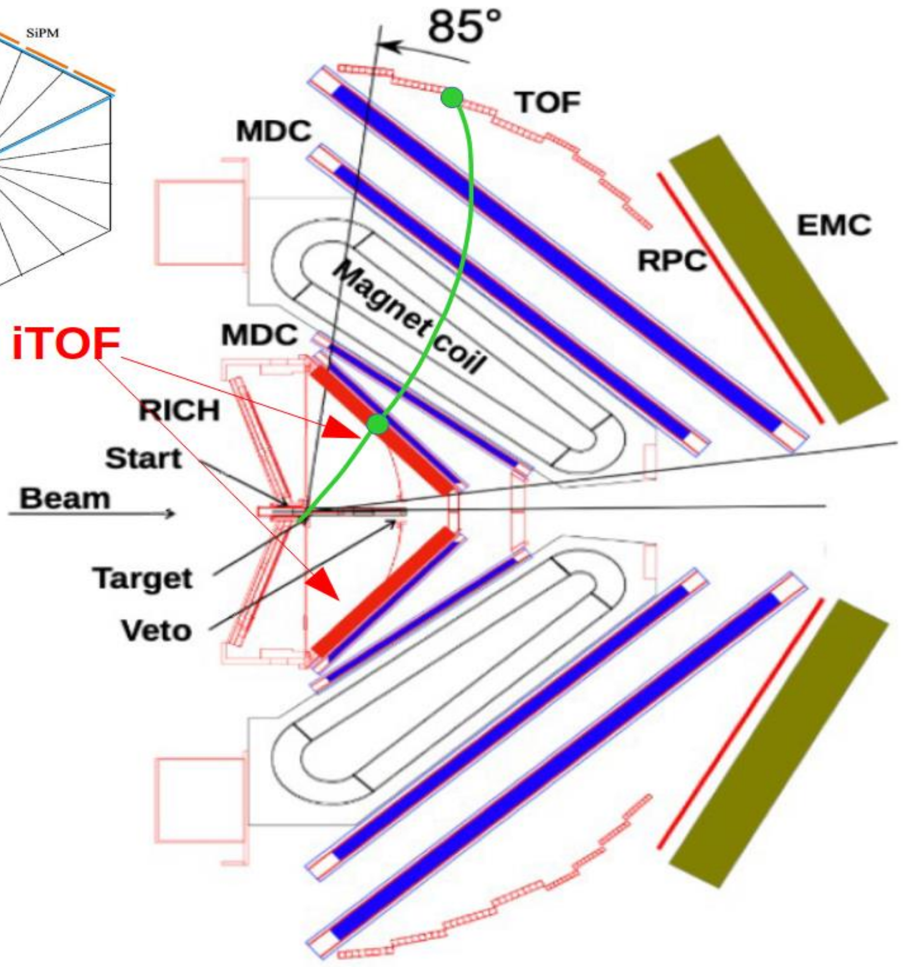
Forward Detector - straw detectors (tracks and energy losses), Resistive Plate Chambers (time-of-flight measurements), 0.5°-6.5°, **protons**

**ECAL** calorimeter, resolution ~ 6%/$E^{1/2}$, lead glass, 16°-45°: photons

# Trigger systems – events selection

- Inner Time of Flight detector (**iTOF**) - few **SiPM**-s z from the same scintilator have to fire
- Multiplicity and Electron Trigger Array (**META)**: Resistive Plate Chambers **RPC** (18°-44°) and scintilating detector **TOF** (44°-88°)



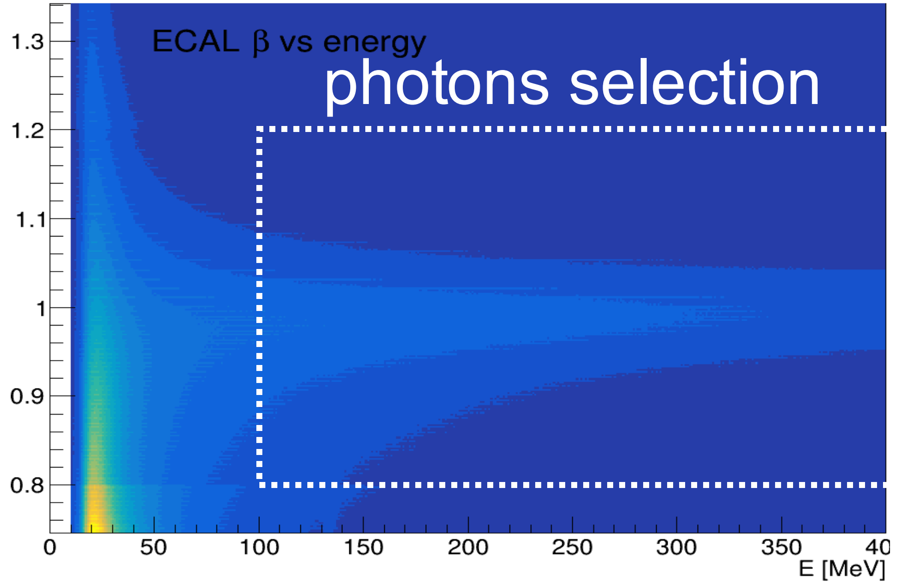




Two systems:

- **PT2 – minimum bias:** min. 1 signal in iTOF + 1 signa in META in corresponding sectors (1 coincidence)
- **PT3:** min. 3 signals in iTOF + 2 in META (2 coincidences + 1signal in iTOF without coincidence)

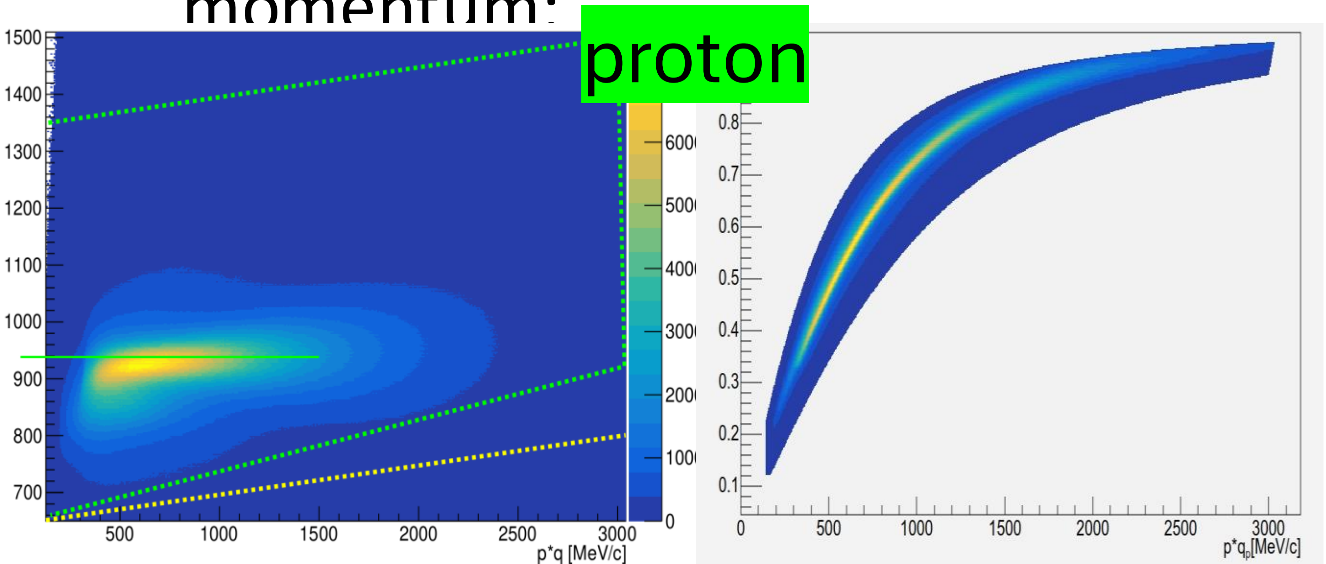
# Starting conditions – inclusive analysis

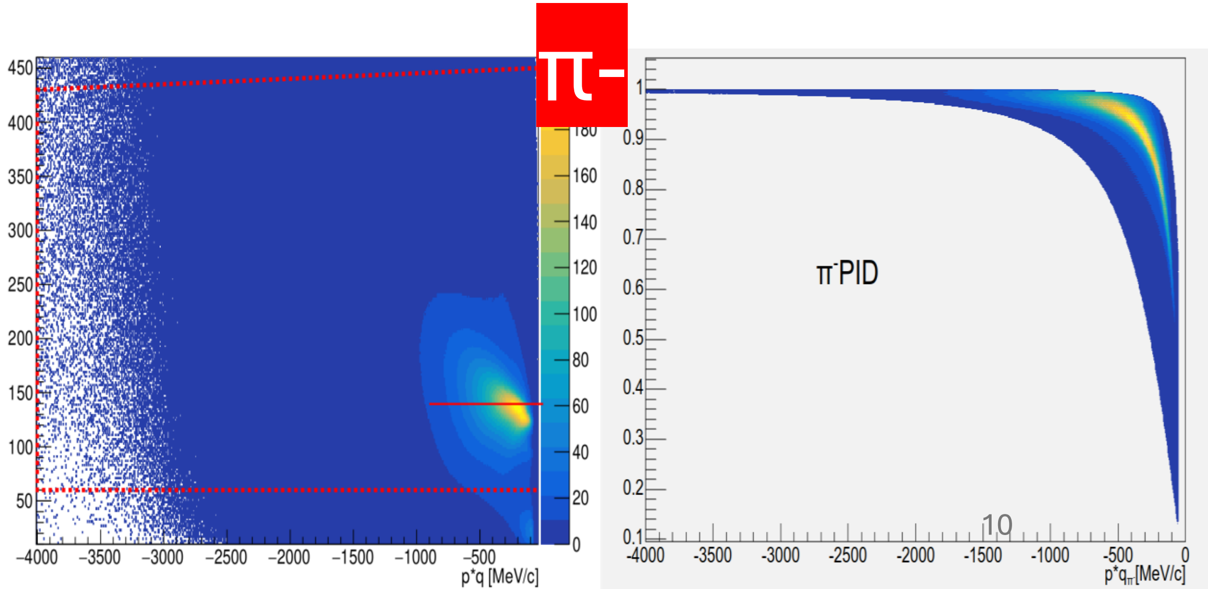
- PT3/PT2 trigger



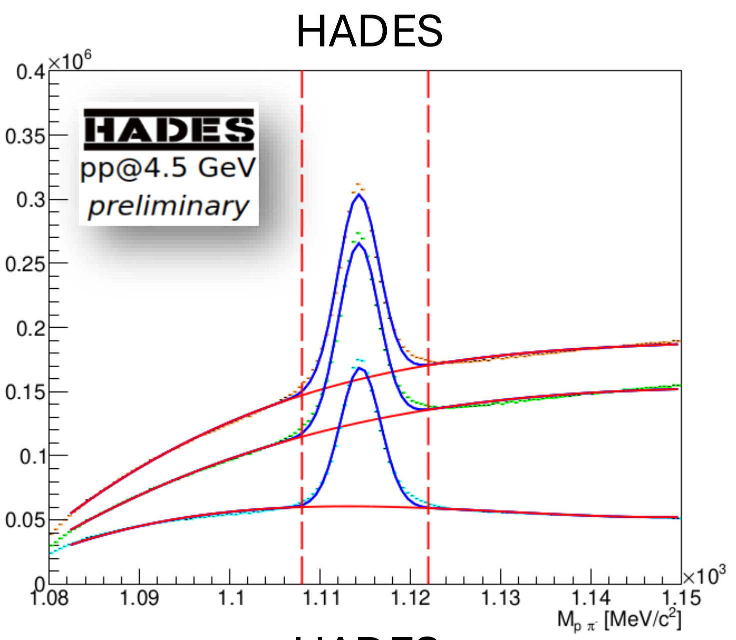

- $energy_{\gamma} > 100$ MeV
- $0.8 > Beta_{\gamma} > 1.2$

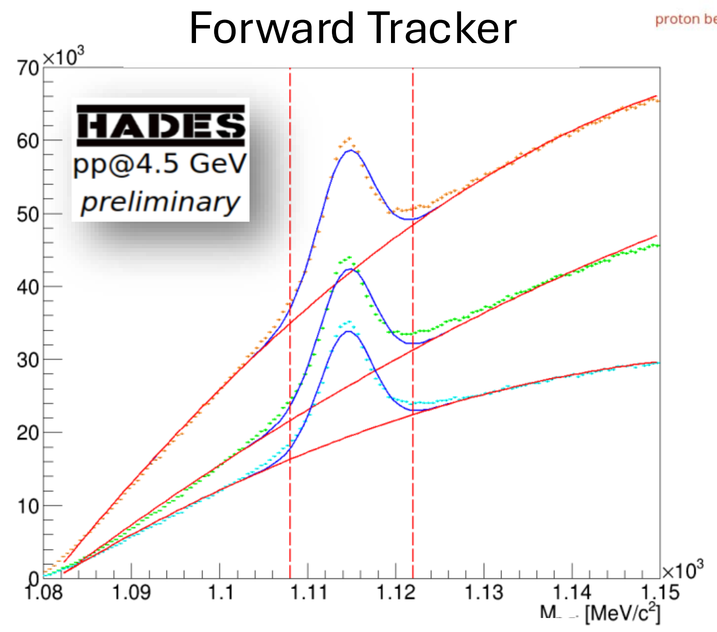
- graphical cuts on mass vs. momentum:

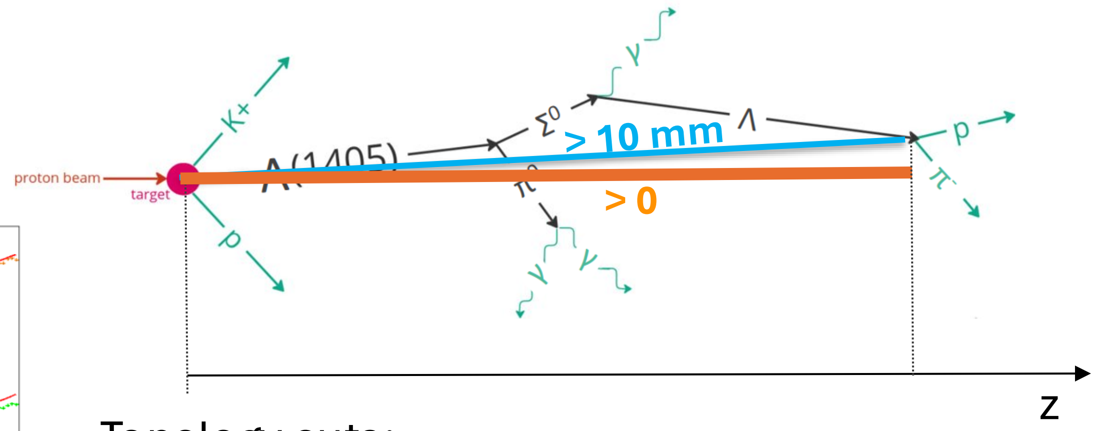


# Λ=>pπ⁻ inclusive analysis

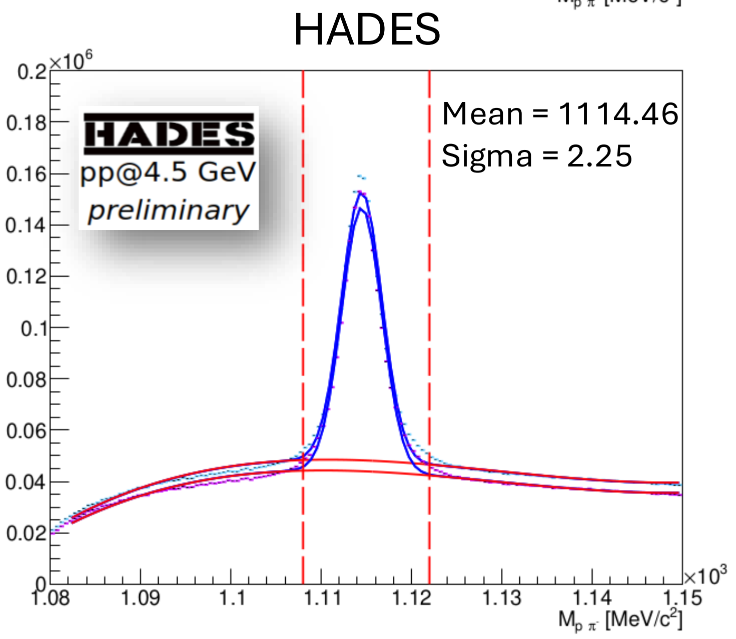


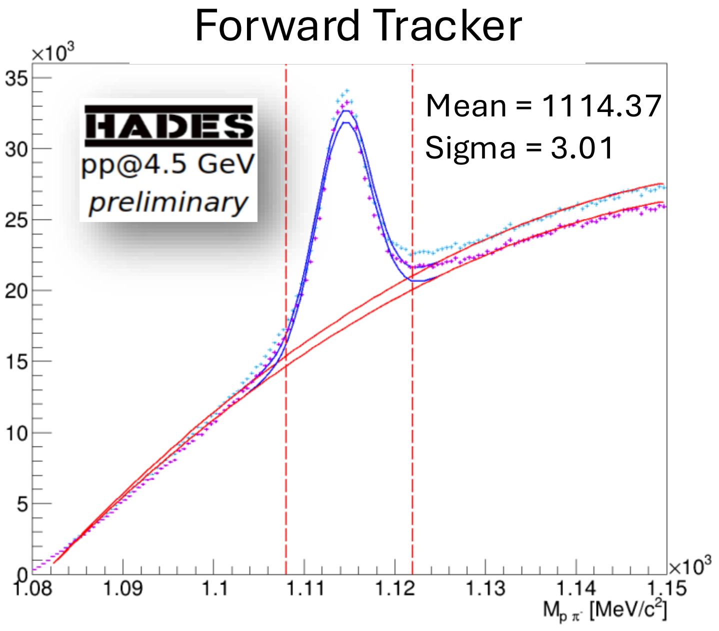




Topology cuts:

- Λ vertex *z* coordinate with respect to the target > 0
- above + minimal distance between p and π- tracks < 20 mm
- above + Λ decay length > 10 mm



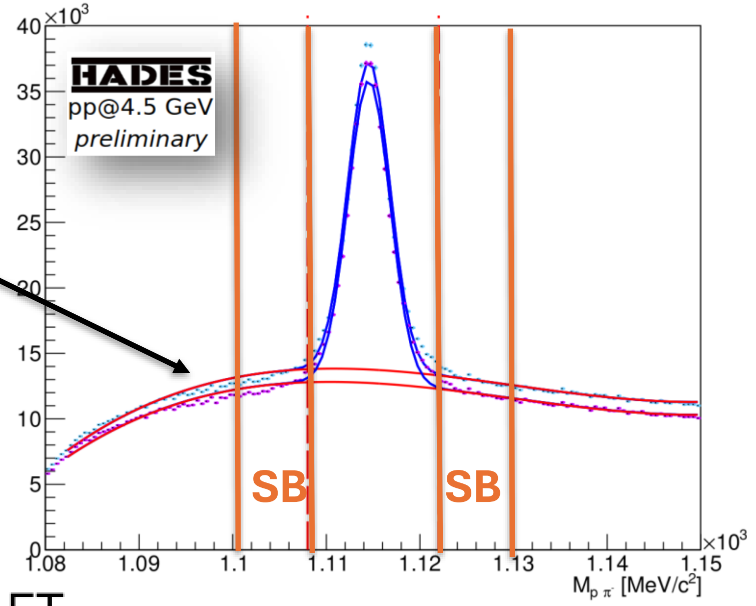




Missing mass cuts:

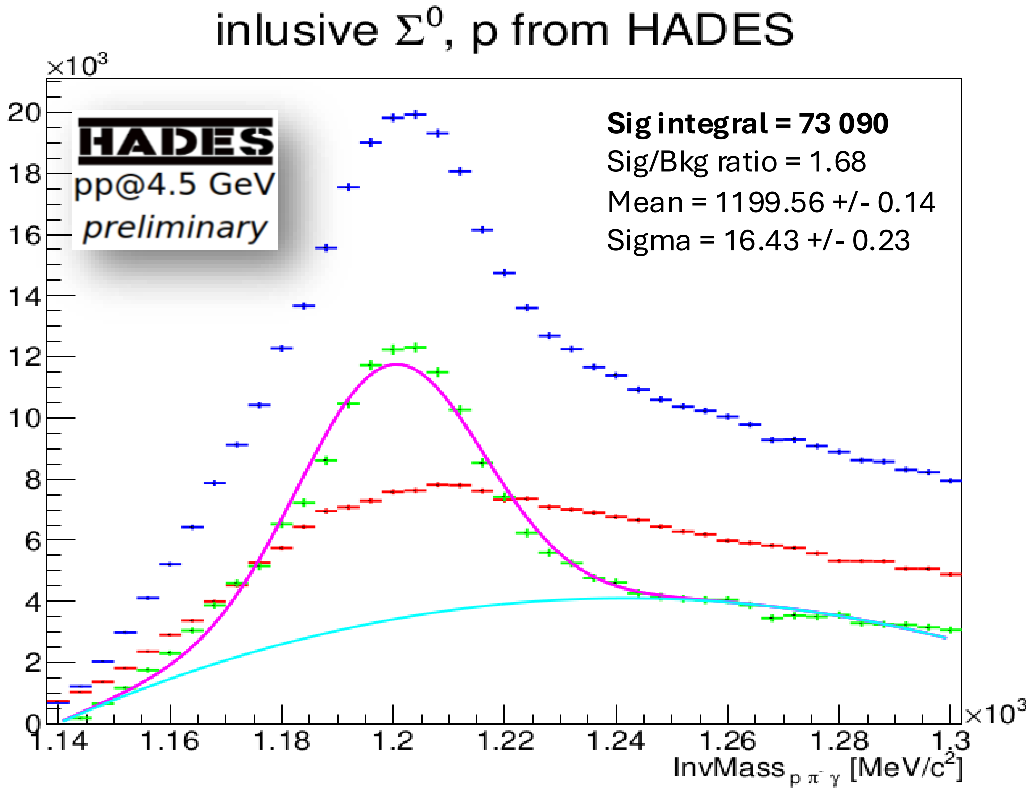
- above + $MM_{p\,\pi-} > M_{p\,K+}$ (for charge and strangeness to be conserved in hyperon production)
- above + $MM_{p\,\pi-} > M_{p\,K+\,\pi 0}$ ($\pi^0$ production condition)

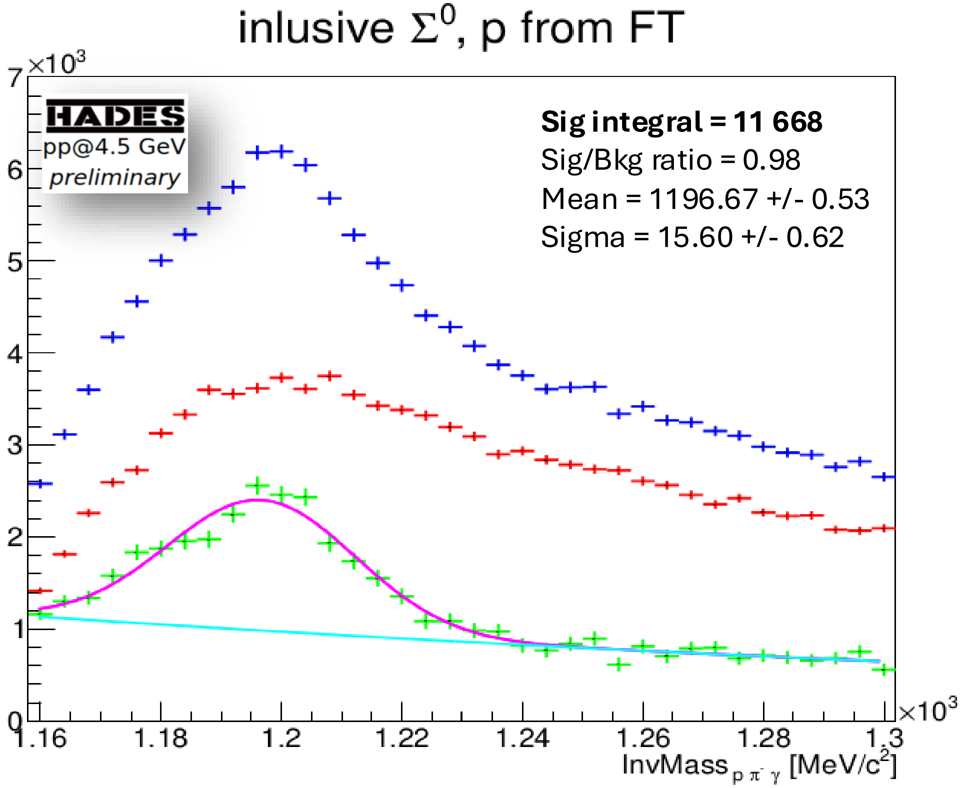
# $\Sigma^0$->$\Lambda$(->$p\pi^-$)$\gamma$ inclusive analysis

Background substraction with sideband method:




**RED histogram**: Pseudo-signal of $\Sigma^0$ created with **SB** scalled to the same integral as bkg under Lambda peak
**BLUE**: $\Sigma$0 signal created with Lambda peak
**GREEN**: BLUE minus RED



# $\Lambda(1115) \Rightarrow p\pi^-$ and **Sigma0->$\Lambda(\to p\pi^-)\gamma$ - inlusive σ-s estimations**

Threshold for Lambda production: $\sqrt{s_{th}} = 2.55$ GeV

Excess energy: $\epsilon = \sqrt{s} - \sqrt{s_{th}}$ = 3.46 GeV - 2.55 GeV = 0.91 GeV

$\sigma_{pp\to\Lambda X} = 47.97\epsilon + 292.6\epsilon^2 - 45.36\epsilon^3 \mu b$ = **258 μb**

$\mathcal{L}_{day:\,61}$~ **250 /*nb***  **$\varepsilon_{\Lambda X}$ = 4.52%**  **$BR_{\Lambda\to p\pi^-}$ = 64%**

$N_\Lambda$ = 2.5e11 x 2.58e-4 x 4.52e-2 x 0.64 = 1.87 mln (prediction)

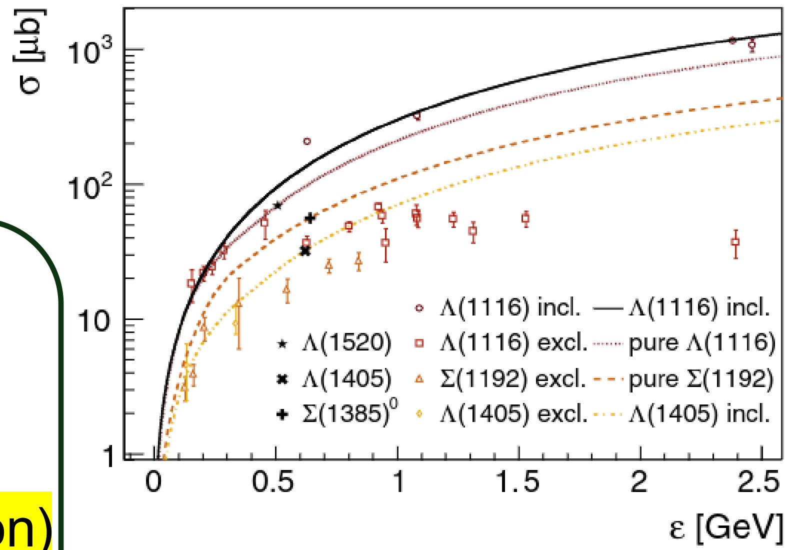
Found in analysis: PT3 - $N_\Lambda$ = 1.32 mln, PT2 - $N_\Lambda$ = 1.78 mln

$\frac{\sigma_{\Lambda X}}{\sigma_{\Sigma^0 X}}(\epsilon) = 2.215 - 0.027\epsilon$  **$\varepsilon_{\Sigma 0\, X}$= 0.9%**

$N_{\Sigma 0}$ = 2.5e11 x 1.18e-4 x 9e-3 x 0.64 =169 920 (prediction)

Found in analysis: PT3 - $N_{\Sigma 0}$ = 84 758, PT2 - $N_{\Sigma 0}$ = 96 512

Trigger bias

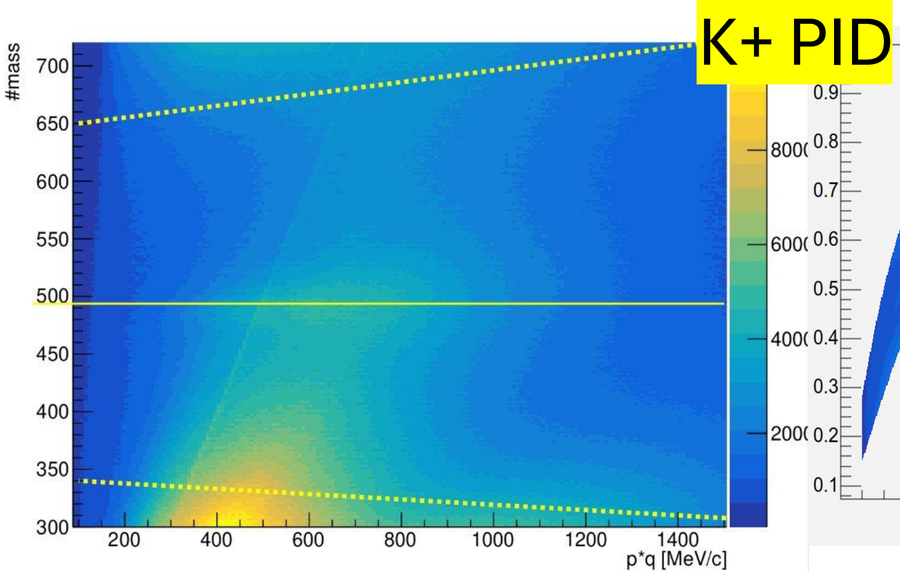


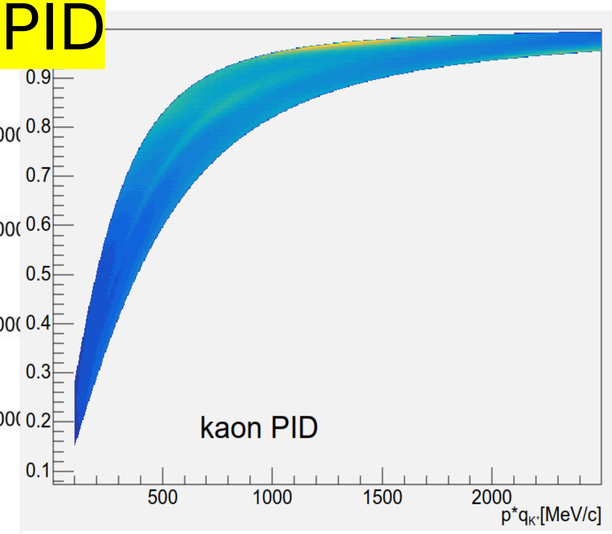

*Production and electromagnetic decay of hyperons: a feasibility study with HADES as a phase-0 experiment at FAIR*

Efficiencies **(ε)** here are specified only for production channels with p nad K+ (from PLUTO & GEANT sim), while more channels could be taken into account with different generators (Smash, GiBBU).

# Exclusive analysis for **Λ(1405)** reconstruction

- PT3 trigger
- All already mentioned cuts and selection criterias
- Cut around Sigma$^0$ mass peak ~ ± 2.5 σ
- $K^+$ PID: graphical cut on m vs. p

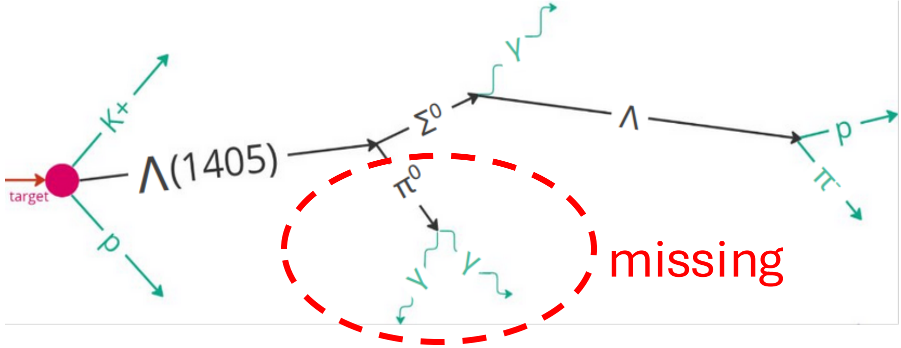



**>=1 π-, >=1 K+, >=1 foton, >=2 p**

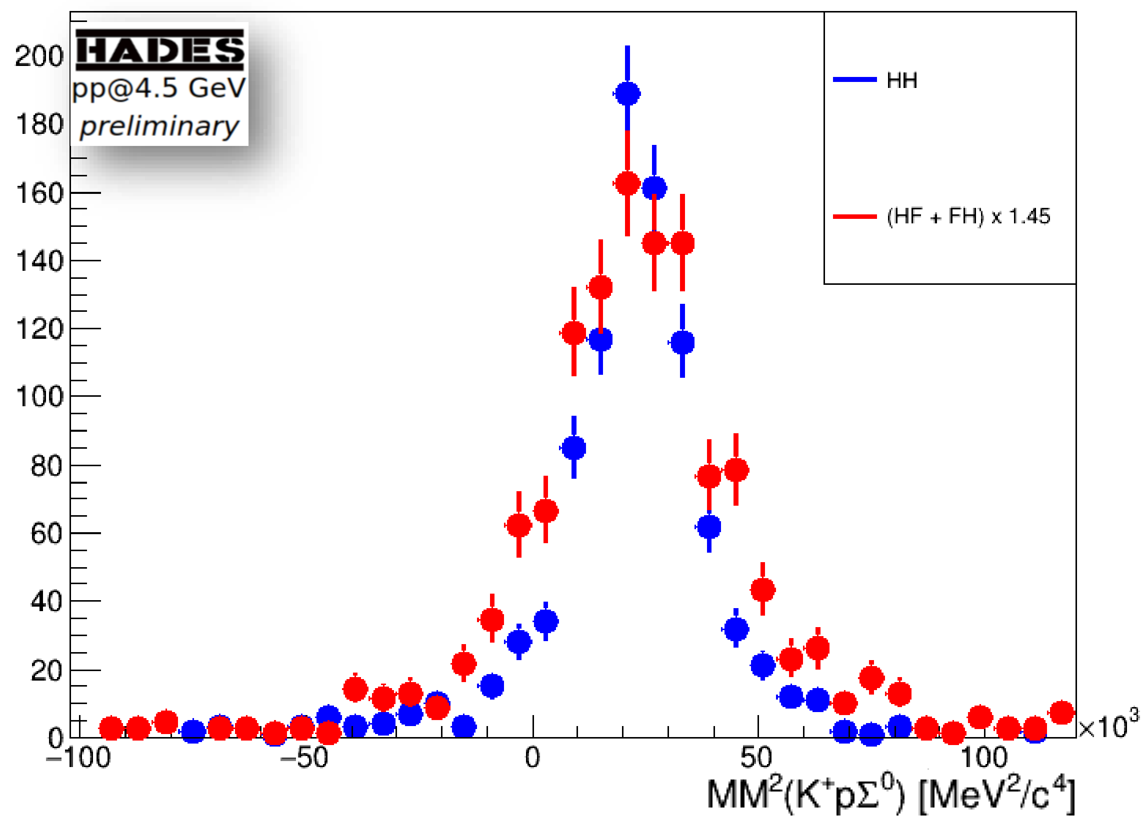
Tagging protons:

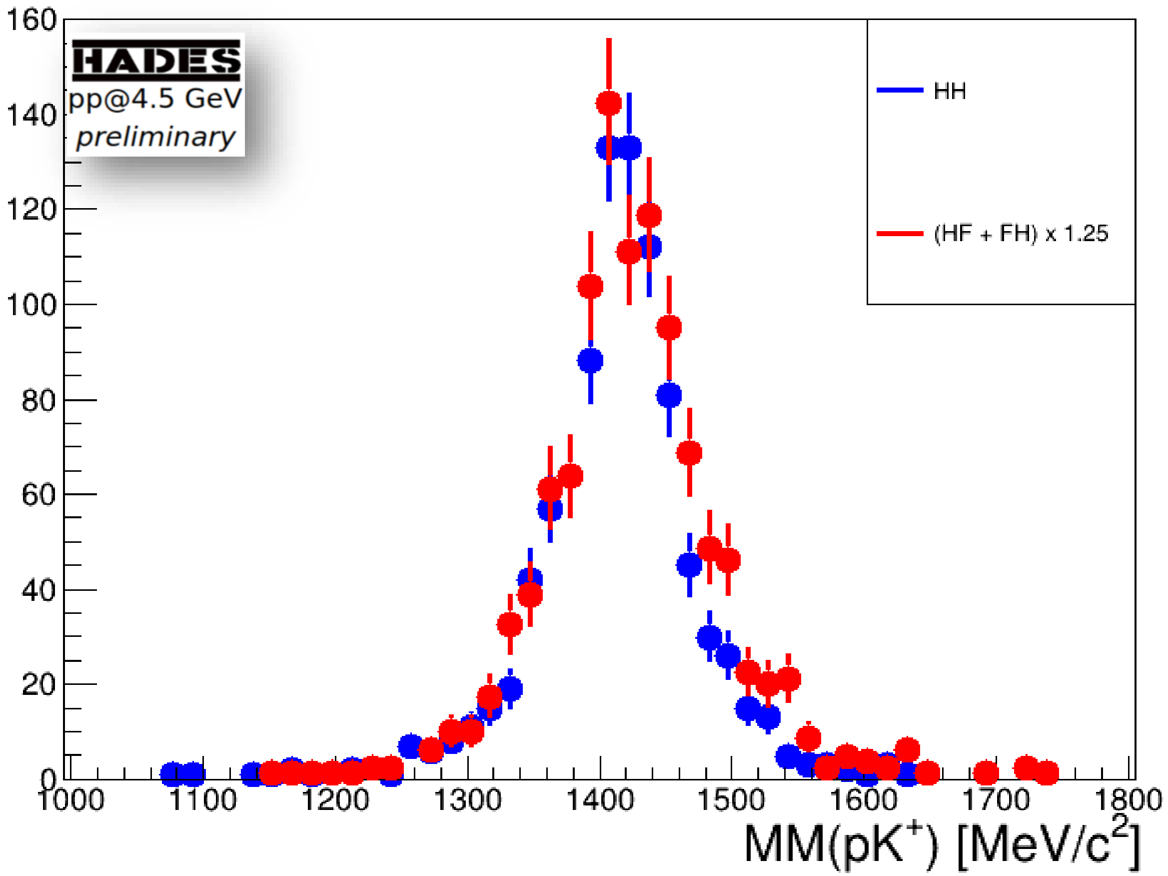
- either in HADES (full PID) or track in FD (assumed to be proton-momentum calculated from TOF)
- used for Λ reco / not used for Λ reco




=> HH, FH, HF, FF cases – separately and combined while non of the proton used for Λ reco is used as the proton coming from the event vertex

# Shape check between different $p_{H/F}\,p_{H/F}$ cases with PLUTO&GEANT simulation



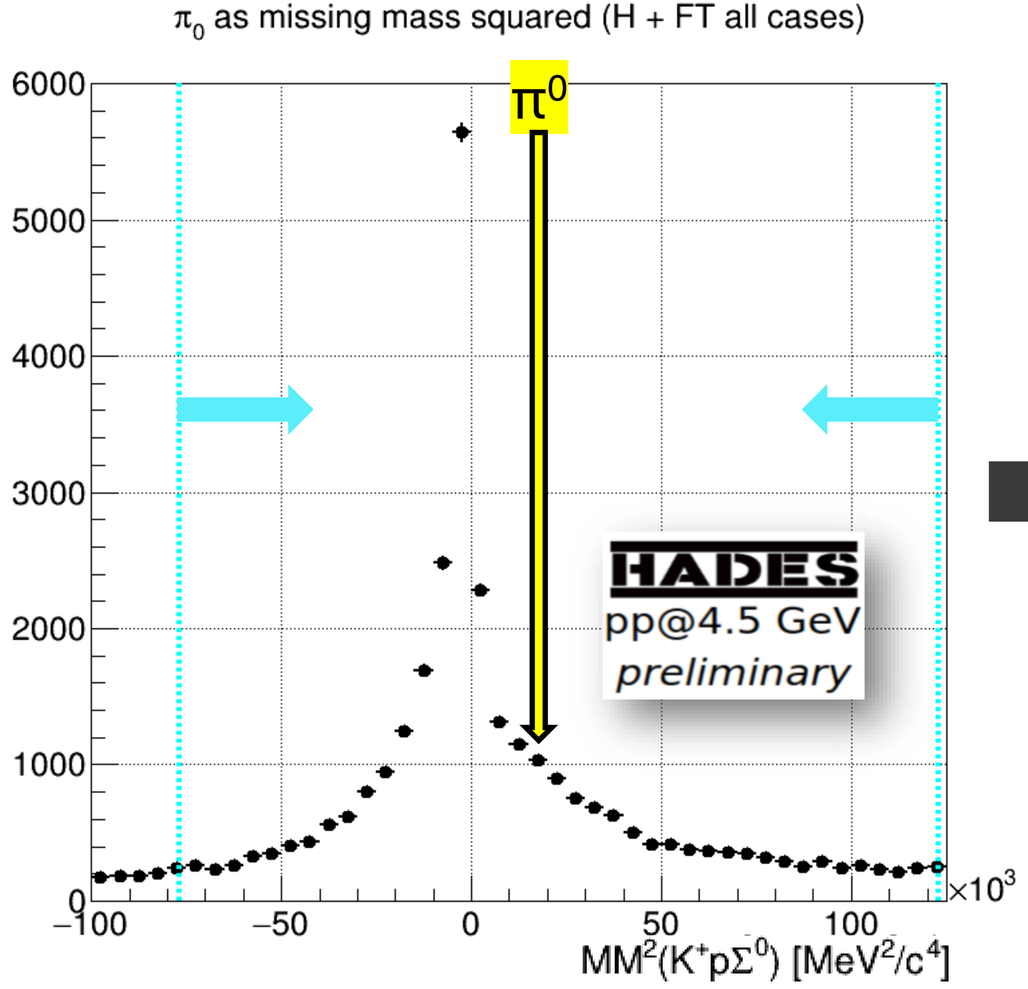



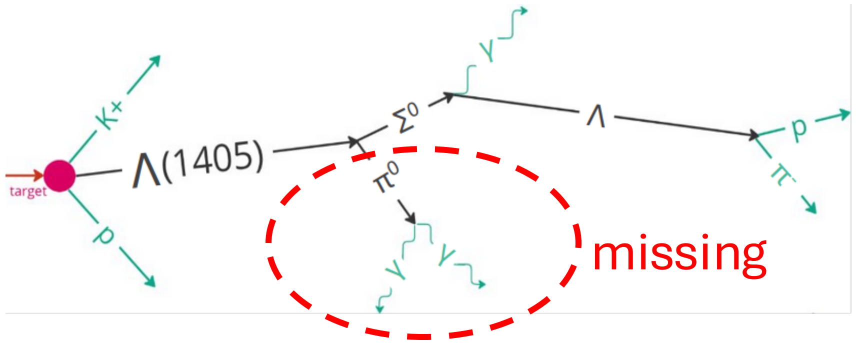

Different acceptances of FD (forward production detection) and HADES lead to the detection of heavy hyperons emitted in different directions, depending on *t*

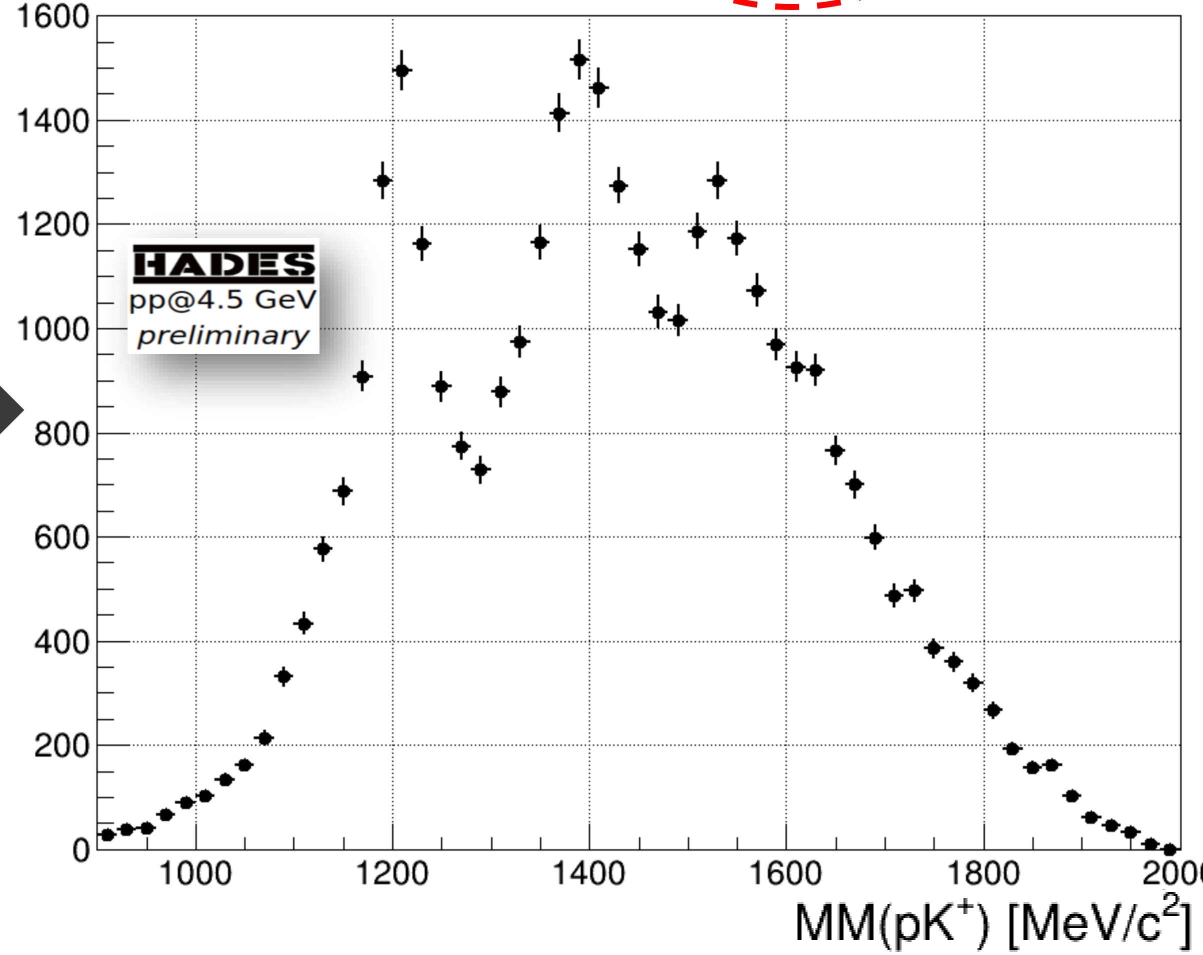
Similar spectrum shapes for both H & F cases suggest that we can add results from different cases and maybe even discuss the line shapes differences between them when those seen in data

# Method with missing $\pi^0$ for $\Lambda(1405)$ signal reconstruction

At first wide cut around $\pi^0$ mass was performed:

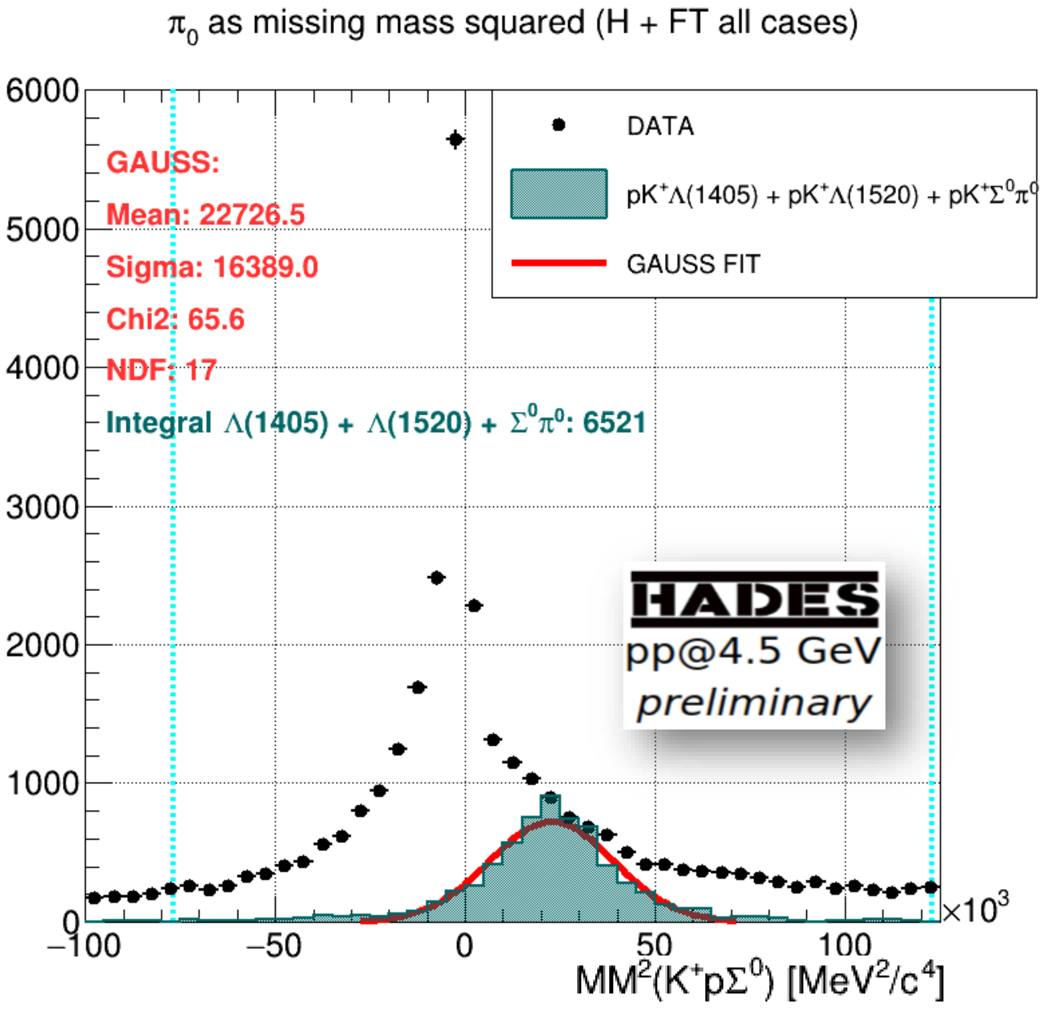


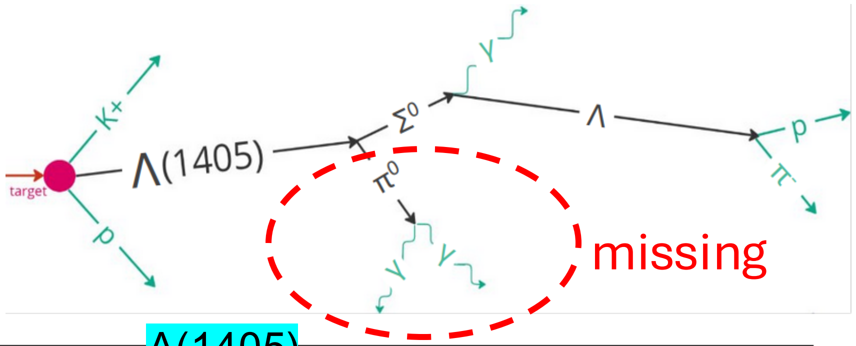



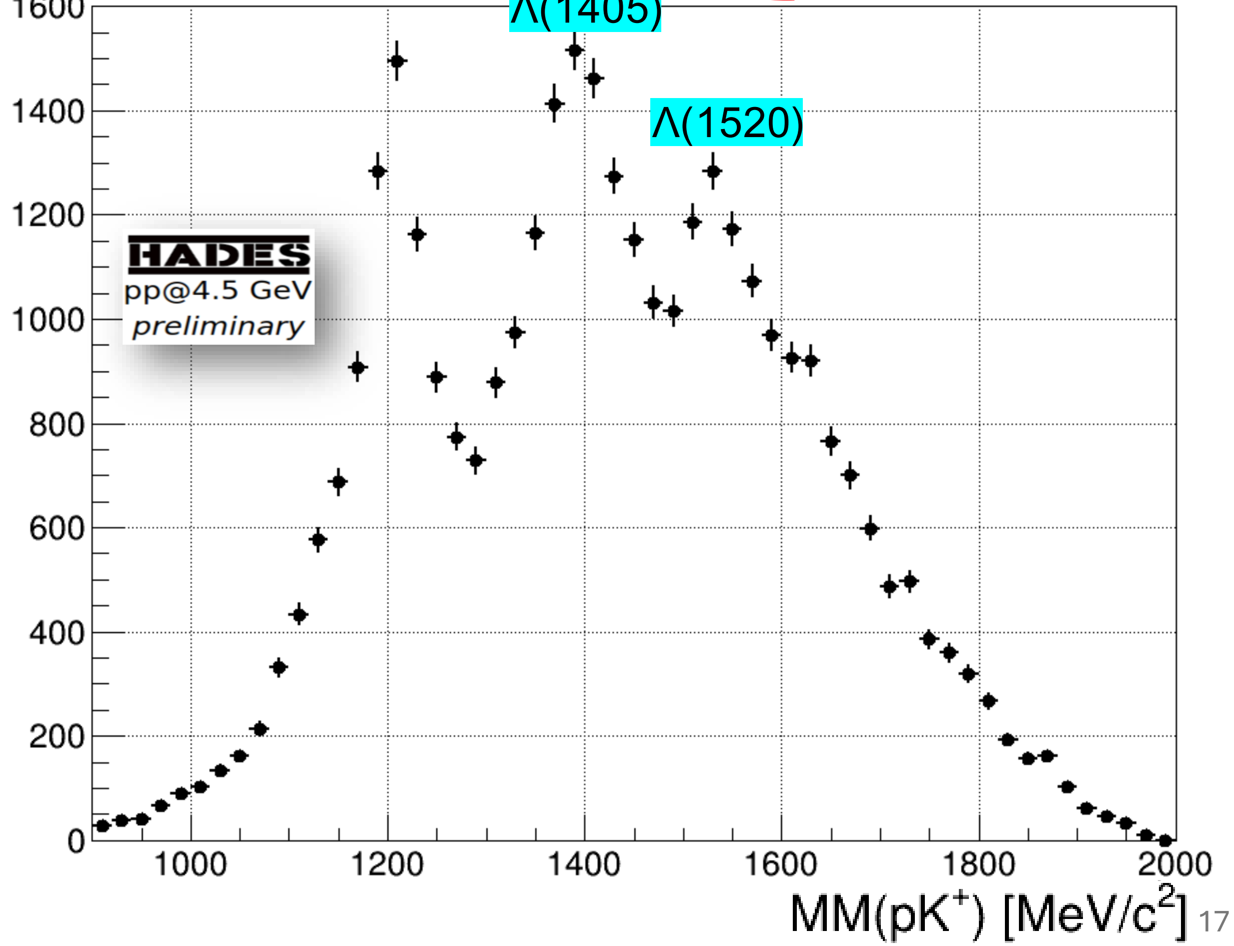



# Method with missing $\pi^0$ for $\Lambda(1405)$ signal reconstruction

Main contributions in $\pi^0$ signal are $\Lambda(1405)$, $\Lambda(1520)$ and unresonant $\Sigma^0\pi^0$

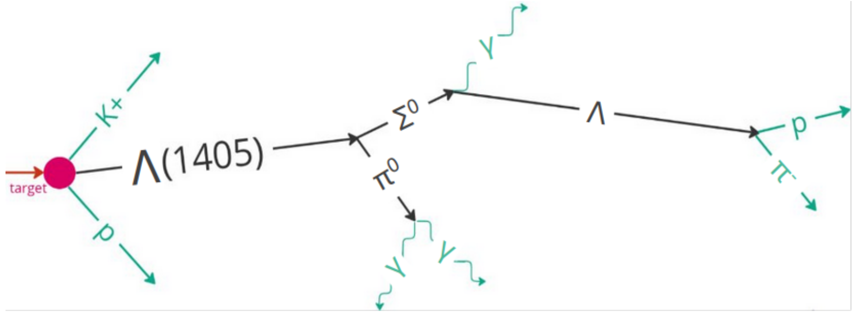


# Estimations of Λ(1405) signal from cross sections

$\mathcal{L}_{days:\,37,\,50,\,61\text{-}67} \sim 2/pb$ (Available $\mathcal{L} \sim 6/pb$ )




**Λ(1405)** threshold: 2.84 GeV

Excess energy: 3.46 GeV - 2.84 GeV = 0.62 GeV

$$\sigma_{pp\rightarrow\Lambda X} = 47.97\epsilon + 292.6\epsilon^2 - 45.36\epsilon^3 \mu b$$ = 131 $\mu b$

Taking into account feed-down of Λ from $\Sigma^0$ decay:

$$\frac{\sigma_{\Lambda X}}{\sigma_{\Sigma^0 X}}(\epsilon) = 2.215 - 0.027\epsilon$$ = 2.198

$\sigma_{\Lambda X}$ = 131 $\mu b$ - (131 $\mu b$ / 2.198) = 71 $\mu b$

Considering assumed* $\sigma_{\Lambda X}/\sigma_{\Lambda(1405)X}$ ratio:

$\sigma_{\Lambda(1405)X} \sim 24\ \mu b$ *

$\epsilon_{\Lambda(1405)}$ = 0.1%, $BR_{\Lambda(1405)\rightarrow\Sigma 0\pi 0}$ = 33%

$N_{\Lambda(1405)X}$ = 2e12 x 2.4e-5 x 1e-3 x 0.64 x 0.33 = 10 000

Measured for p(3.5 GeV)+p:

$\sigma_{pK+\Lambda(1405)} \sim 9\ \mu b$ *

$N_{\Lambda(1405)}$ = 2e12 x 9e-6 x 1e-3 x 0.64 x 0.33 = 3 800

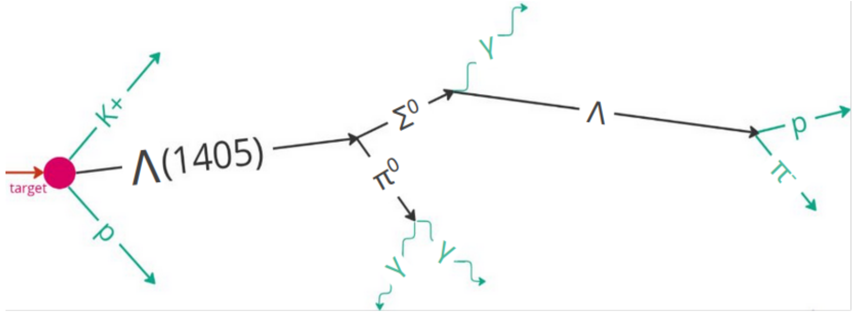
At 4.5 GeV one could expect:

**3 800 > $N_{pK+\Lambda(1405)}$ > 10 000**

* G. Agakishiev et al. *Baryonic resonances close to the ¯KN threshold: the case of Λ(1405) in pp collisions (2013)*

# Estimations of Λ(1520) signal from cross sections

$\mathcal{L}_{days:\ 37,\ 50,\ 61\text{-}67} \sim 2/pb$ (Available $\mathcal{L} \sim 6/pb$ )




**Λ(1520)** threshold: 2.95 GeV

Excess energy: 3.46 GeV - 2.84 GeV = 0.51 GeV

$$\sigma_{pp\rightarrow\Lambda X} = 47.97\epsilon + 292.6\epsilon^2 - 45.36\epsilon^3 \mu b = 94\ \mu b$$

Taking into account feed-down of Λ from $\Sigma^0$ decay:

$$\frac{\sigma_{\Lambda X}}{\sigma_{\Sigma^0 X}}(\epsilon) = 2.215 - 0.027\epsilon = 2.2$$

$\sigma_{\Lambda X} = 94\ \mu b - (94\ \mu b / 2.2) = 51\ \mu b$

$\sigma_{\Lambda(1520)X} \sim 51\ \mu b$ *, $\epsilon_{\Lambda(1520)} = 0.1\%$, $BR_{\Lambda(1520)\rightarrow\Sigma0\pi0} = 14\%$

$N_{\Lambda(1520)} = 2e12 \times 1e\text{-}3 \times 5.1e\text{-}5 \times 0.64 \times 0.14 = 3\,000$

Measured for p(3.5 GeV)+p:

$\sigma_{pK+\Lambda(1520)} \sim 5.6\ \mu b$ *

$N_{\Lambda(1520)} = 2e12 \times 5.6e\text{-}6 \times 1e\text{-}3 \times 0.64 \times 0.14$

$= 1\,000$

At 4.5 GeV one could expect:

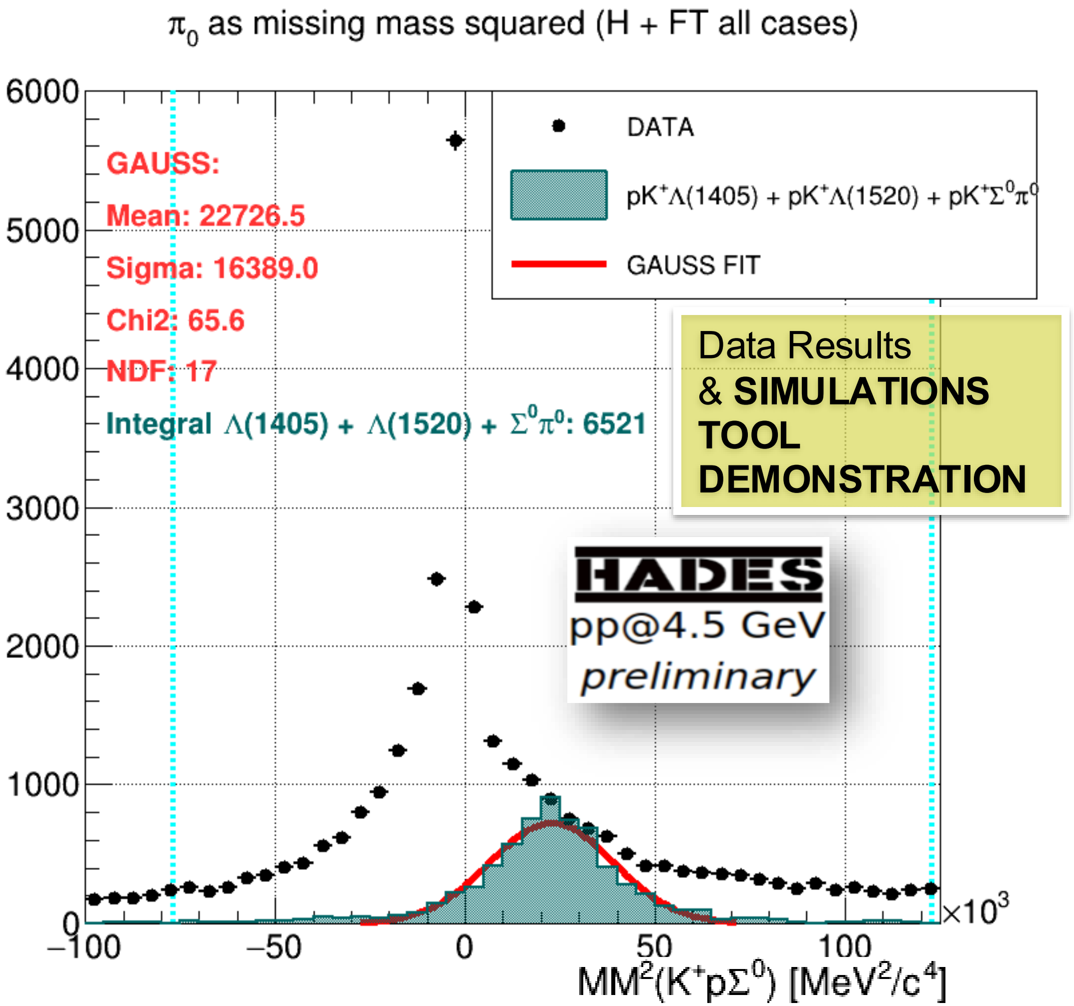
**$1\,000 > N_{pK+\Lambda(1520)} > 9\,100$**

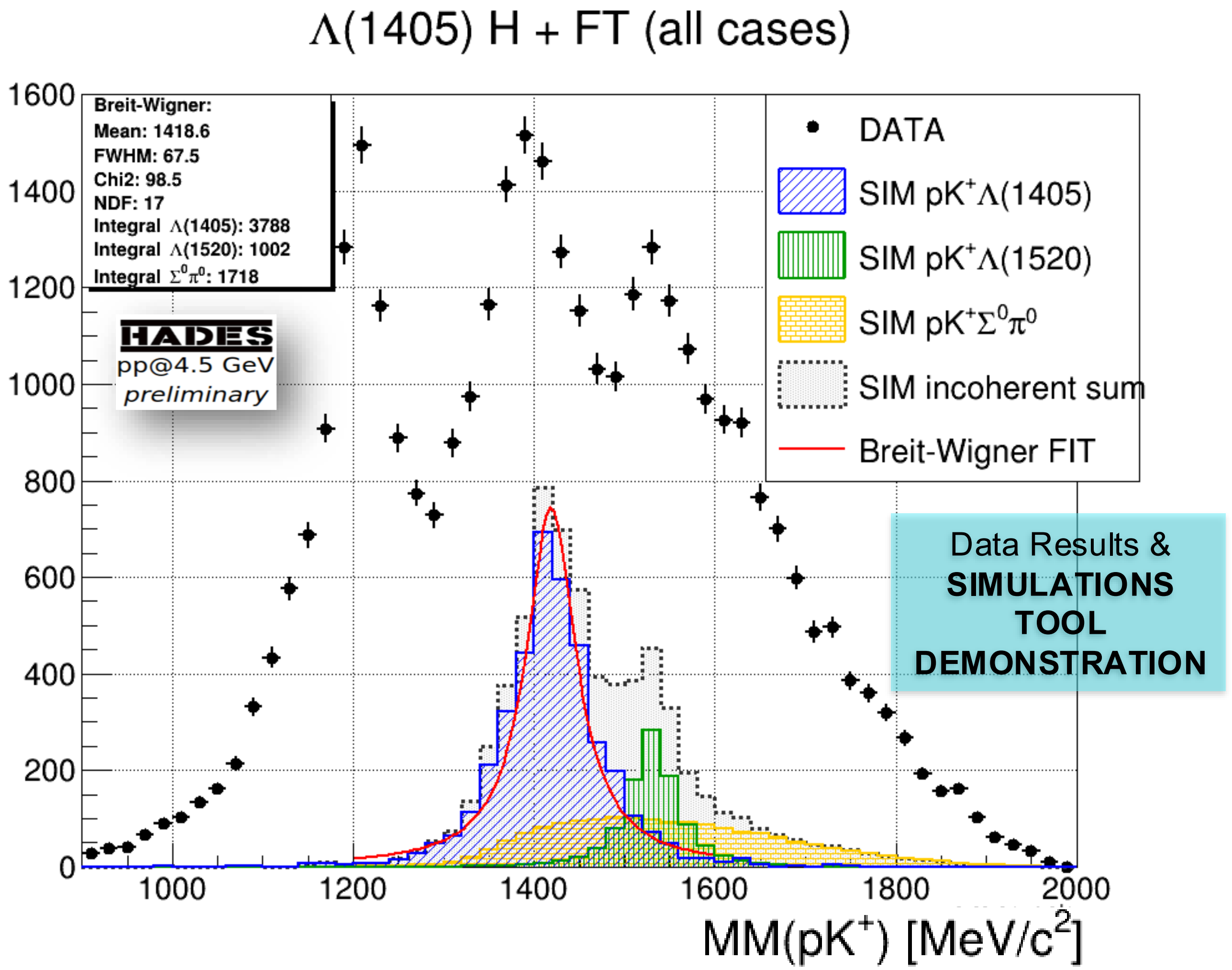
* G. Agakishiev et al. *Baryonic resonances close to the ̄KN threshold: the case of Λ(1405) in pp collisions (2013)*

# Method with missing $\pi^0$ for $\Lambda(1405)$ signal reconstruction

Simulation histograms of $\Lambda(1405)$, $\Lambda(1520)$ are scalled to the down limit integrals (previous slides) while the rest of $\pi^0$ signal is assigned to $\Sigma^0\pi^0$

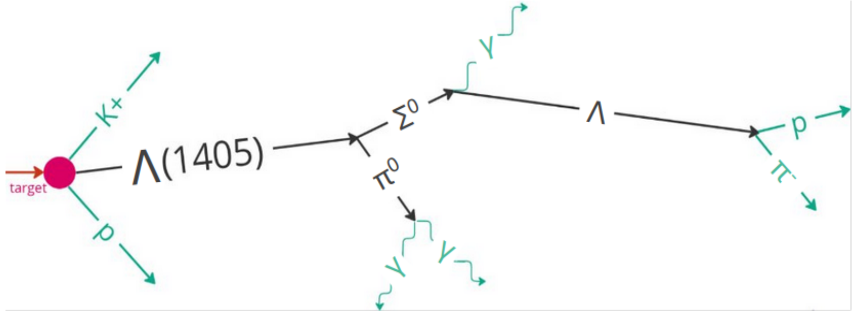
Huge peak in 0 corresponds to $pK^+\Sigma^0$ channel

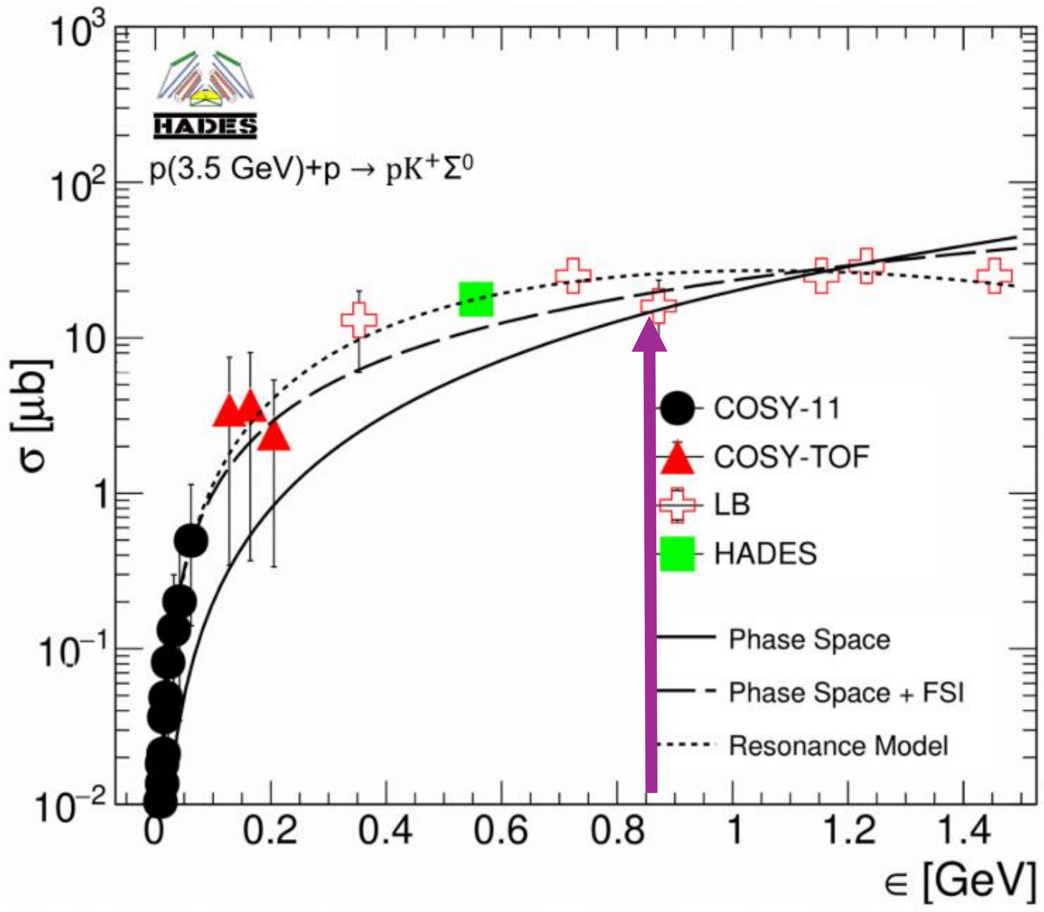


# Estimations of $\Sigma^0$ signal from cross sections

$\mathcal{L}_{days:\ 37,\ 50,\ 61\text{-}67} \sim 2/pb$ (Available $\mathcal{L} \sim 6/pb$ )



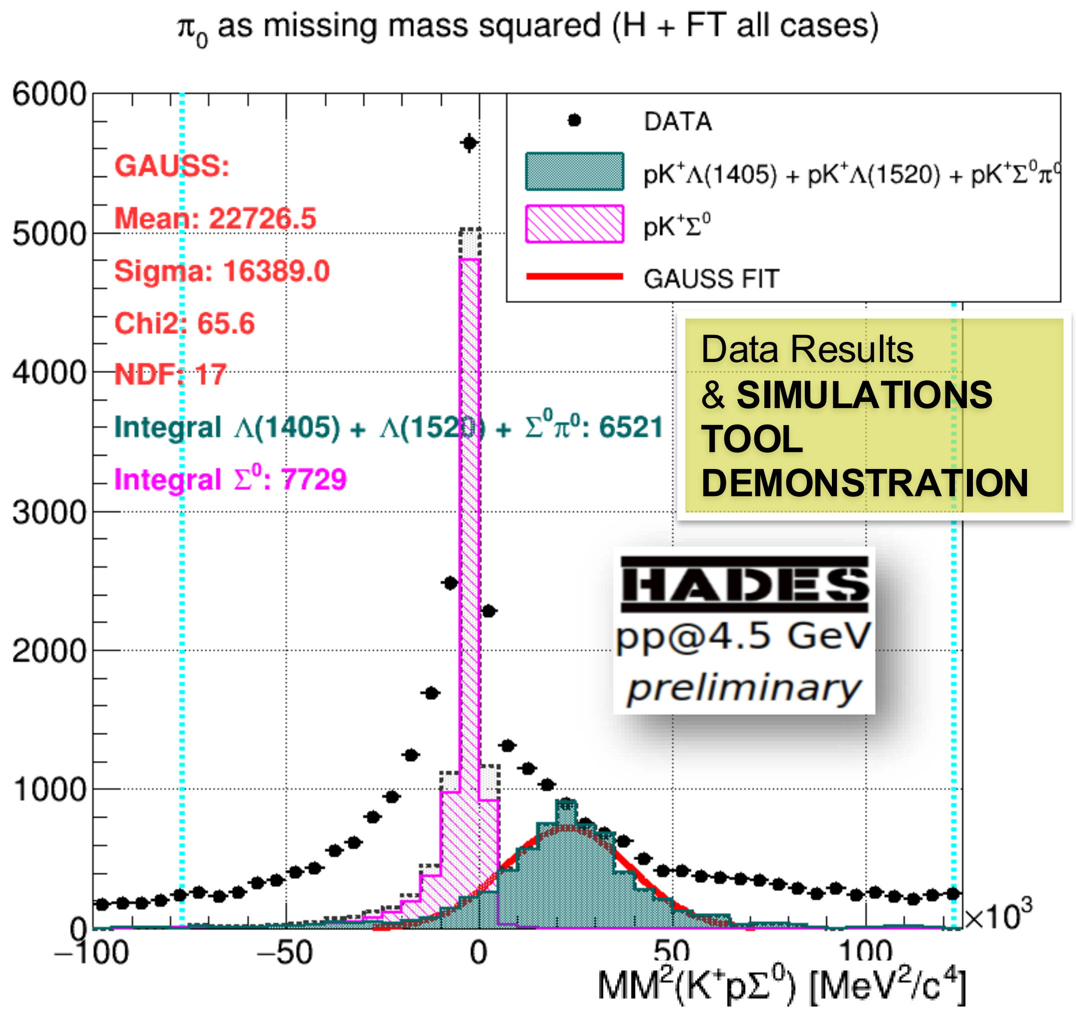

$\sigma_{pK+\Sigma0} \sim 15\ \mu b$ **, $\epsilon_{\Sigma0}$ = 0.16%

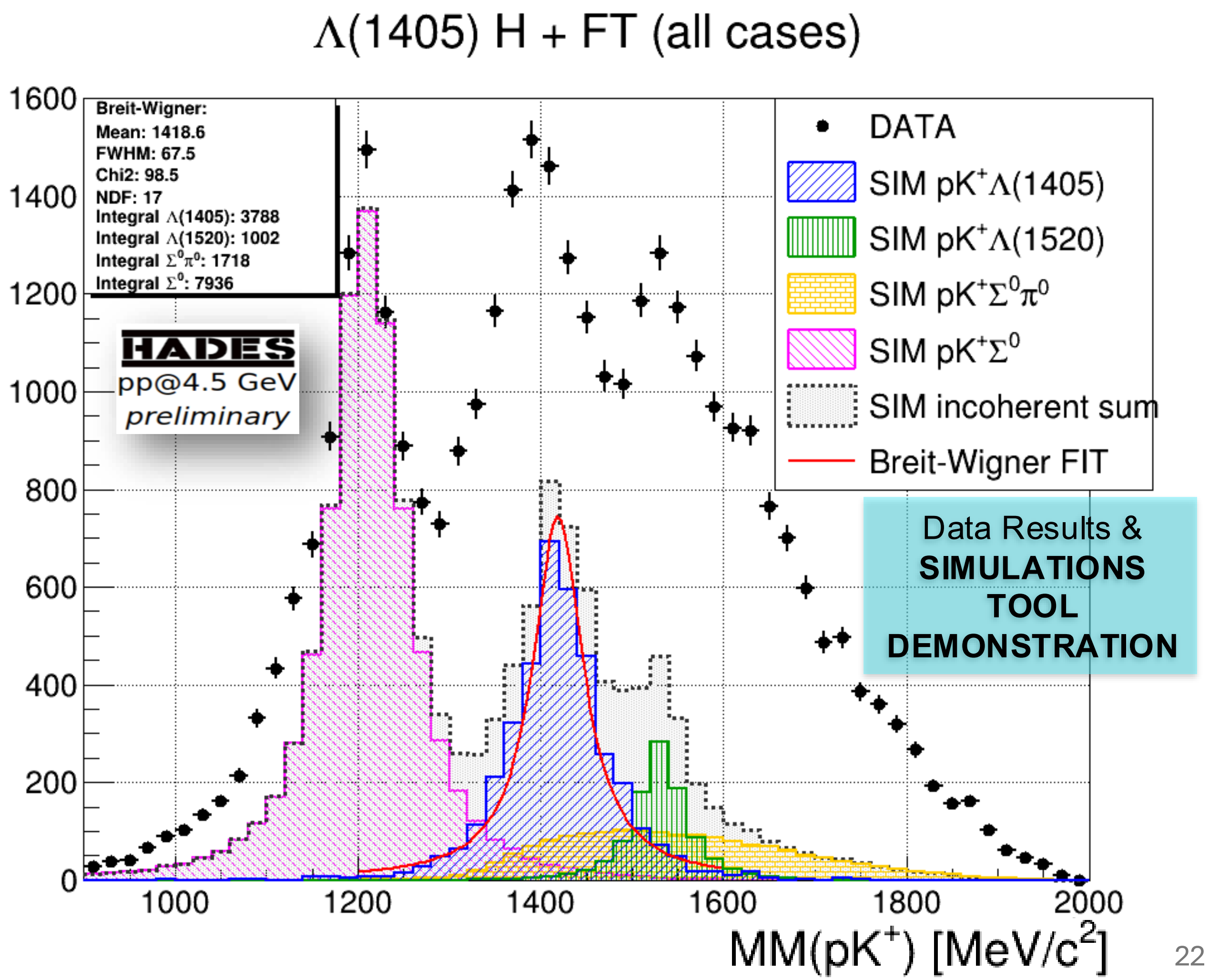
$\mathbf{N_{pK+\Sigma0}}$ = 2e12 x 1.5e-5 x 1.6e-3 x 0.64 = **30 000**

** R. Abou Yassine et al. *Investigation of the Σ0 Production Mechanism in p(3.5 GeV)+p Collisions (2024)*

# Method with missing $\pi^0$ for $\Lambda(1405)$ signal reconstruction

Estimated for 4.5 GeV: **$N_{\Sigma 0}$ ~ 30 000**, while in data:



# Method with missing $\pi^0$ for $\Lambda(1405)$ signal reconstruction

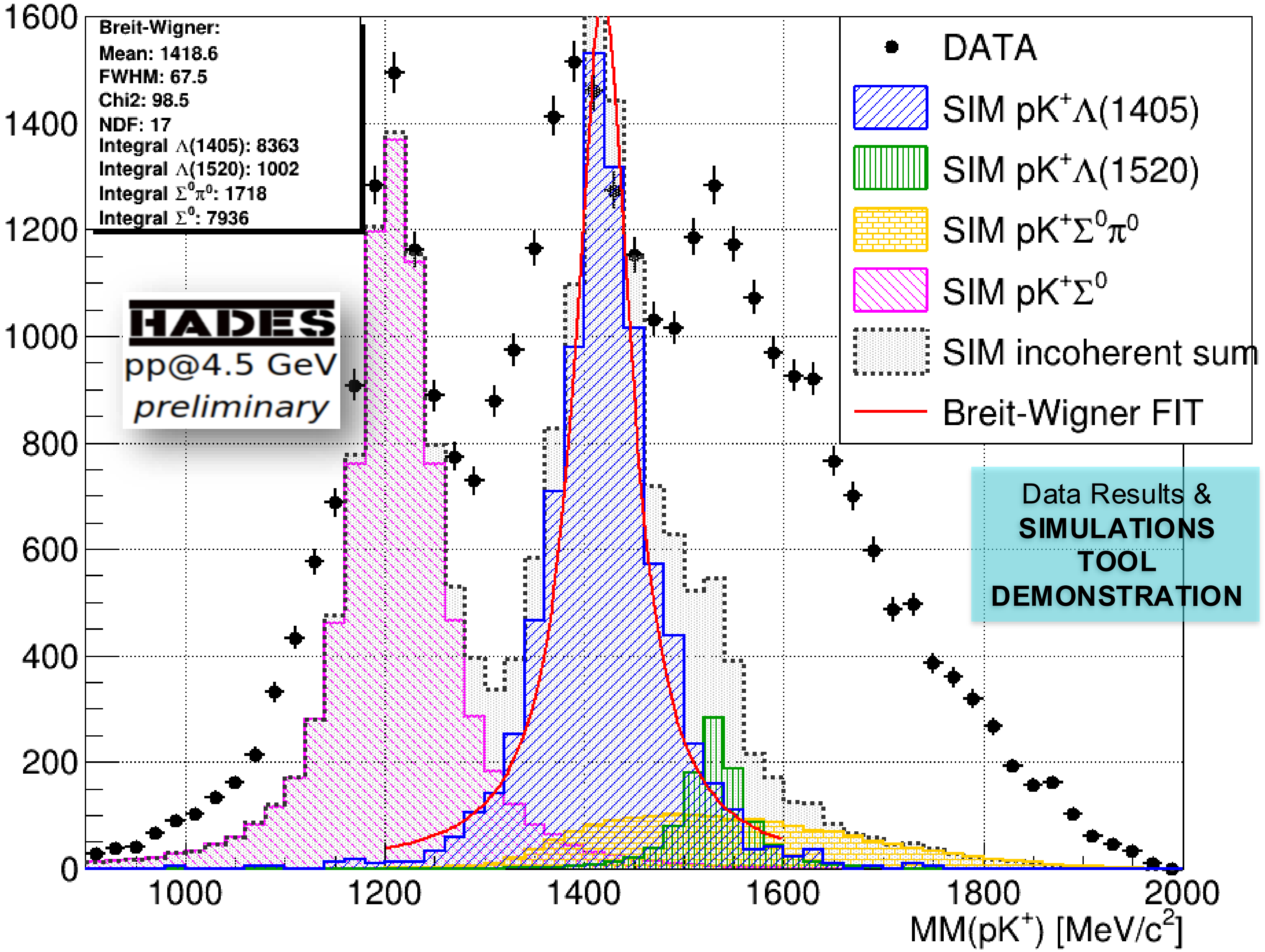
Different magnitudes of contributions from different channels needs to be considered.

**$N_{pK+\Lambda(1405)}$ ~ 8 000** - when scalling to the maximum value in data

Visible shift of $\Lambda(1405)$ to the lower values

Potential higher mass resonances visible

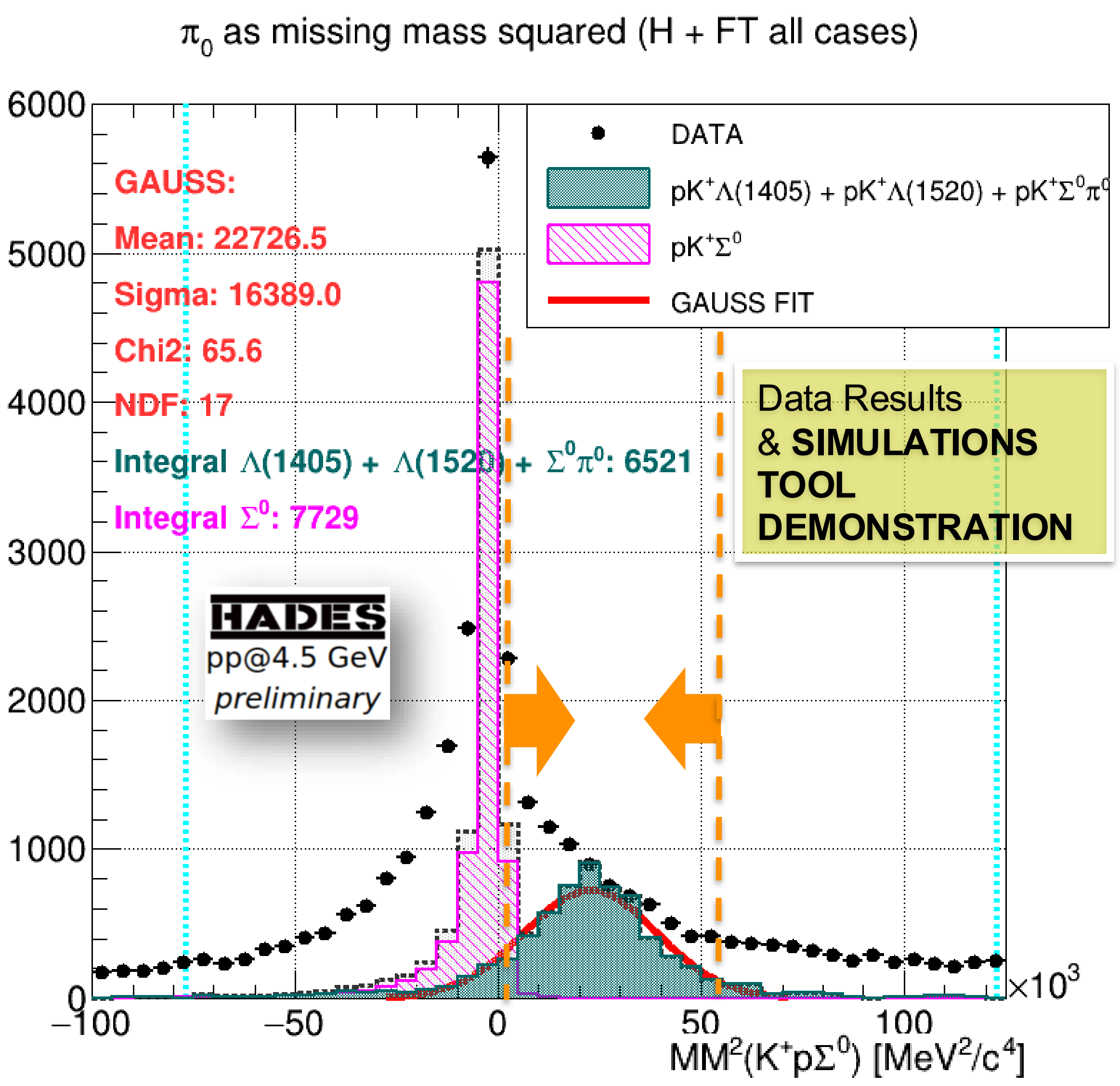
1/3 of the collected data (1/3 luminosity) was analysed as for now

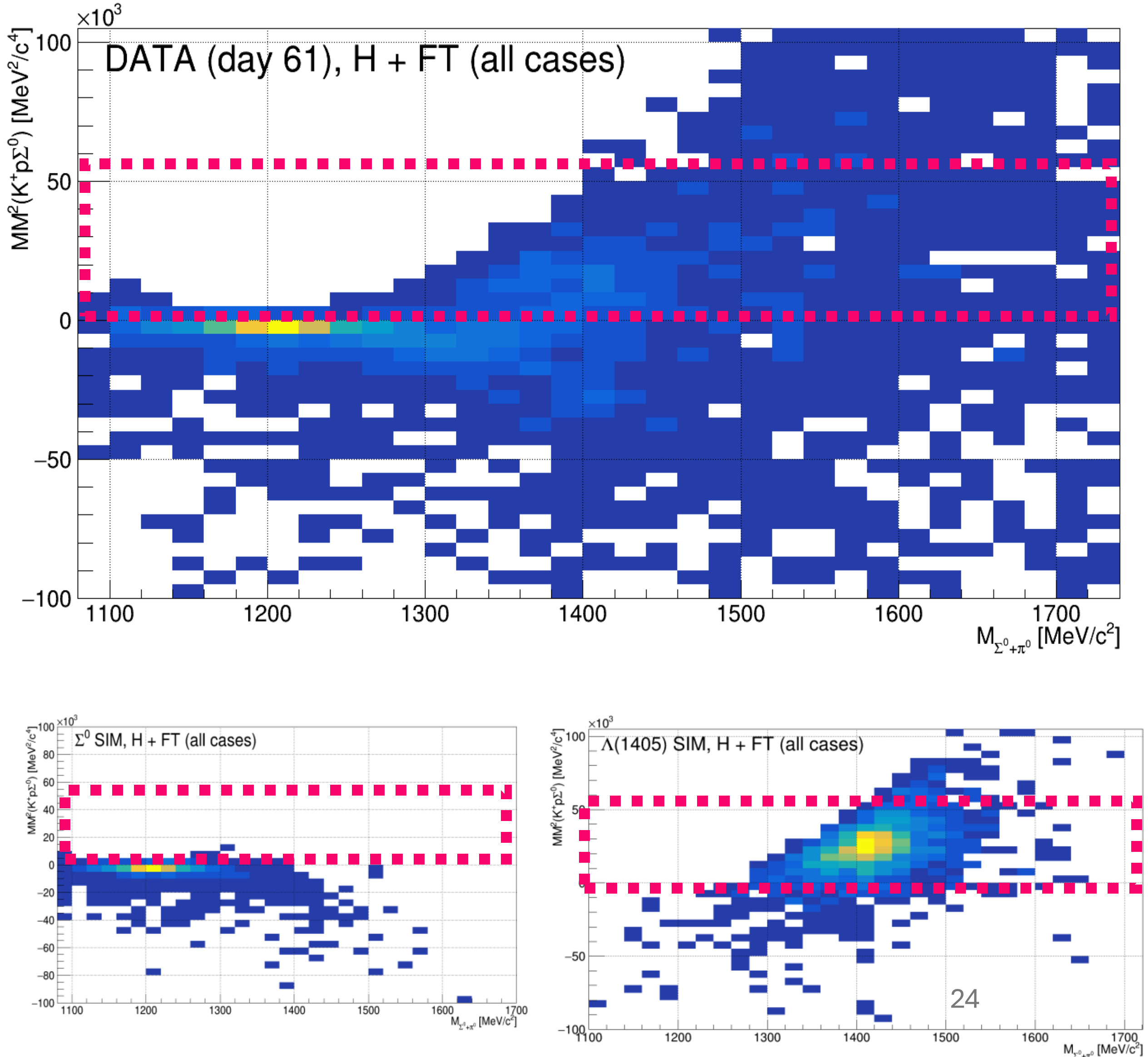



Data Results & **SIMULATIONS TOOL DEMONSTRATION**

**3 800 > $N_{pK+\Lambda(1405)}$ > 10 000** **1 000 > $N_{pK+\Lambda(1520)}$ > 9 100**

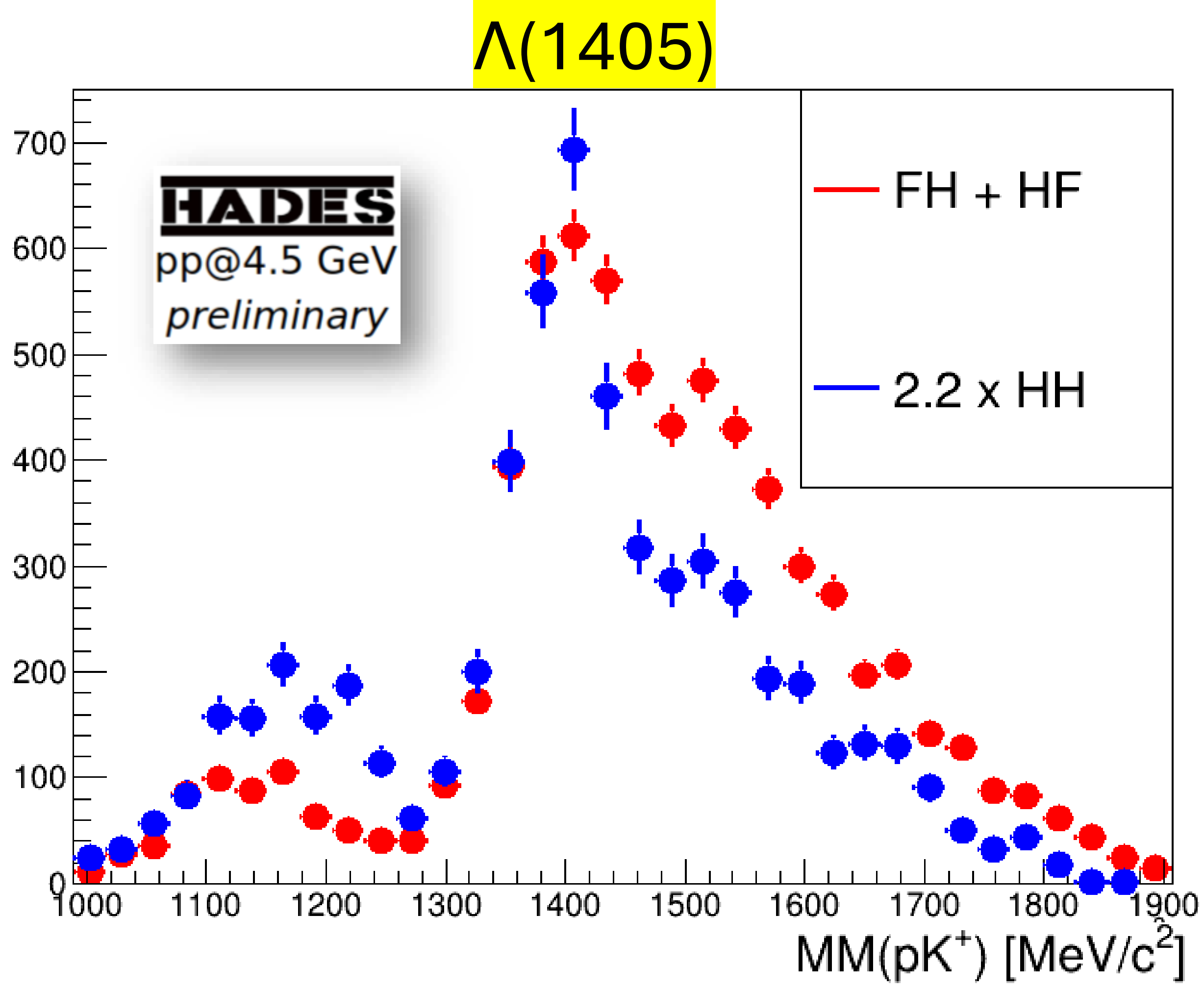
# Method with missing $\pi^0$ for $\Lambda(1405)$ signal reconstruction

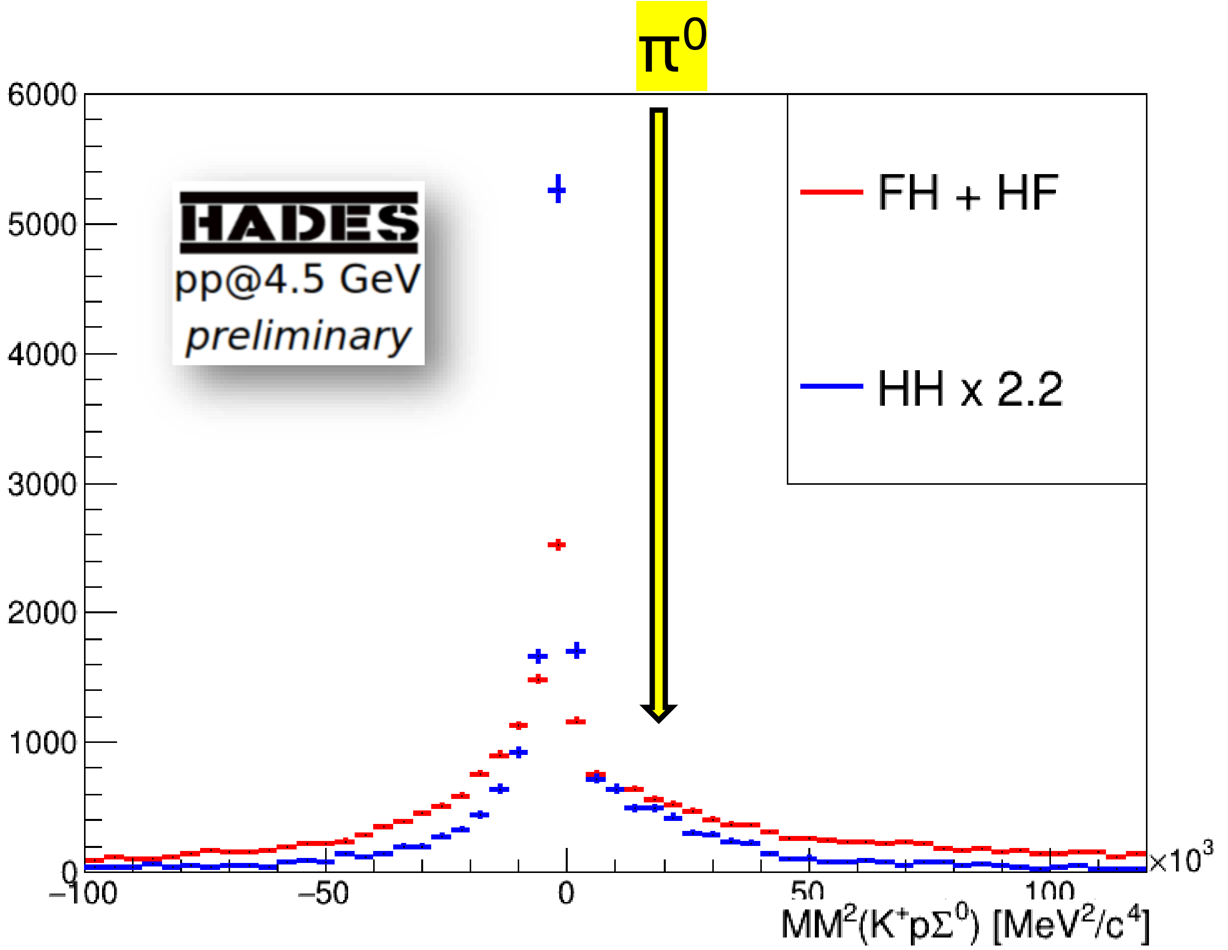


# Comparison between different $p_{H/F}\,p_{H/F}$ cases **DATA**

With narrower cut around π0:




Contributions from different resonant and unresonant channels seem to be different between the HH and FH/HF cases

# SUMMARY

Inclusive analysis $\Sigma^0 \to \Lambda(\to \pi^- p) + \gamma$)

- Relatively good agreemnet between cross section and number of Λ-s seen in data for PT2
- But factor down 2 for $\Sigma^0$-s

To do:

- Consider the usage of different simulation generators (Smash, GiBUU) -> better efficiency prediction
- Systematic study of photons selection cuts and their influence od sig/bkg of $\Sigma^0$

Exclusive analysis $p+K^+ + \Lambda(1405) \to \Sigma^0(\Lambda+\gamma)+\pi^0$

- Λ(1405) is found in $\Sigma^0\pi^0$ decay channel for the first time in p+p colisions in HADES!
- Mass peak shifted towards lower masses from 1405 MeV/$c^2$
- Potentialy seen line shape difference between HH case and FH/HF (for different proton acceptances)

To do:

- Kinematic refit
- Analysis of $p+K^+ + \Lambda(1405)(\to \Sigma^\pm \pi^\mp)$