Inclusive $\Sigma^+(1385)$ production in p+p 3.5 GeV

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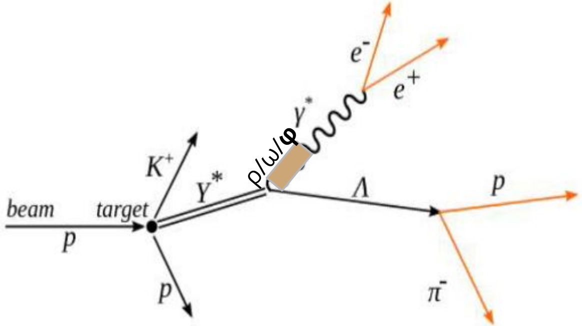
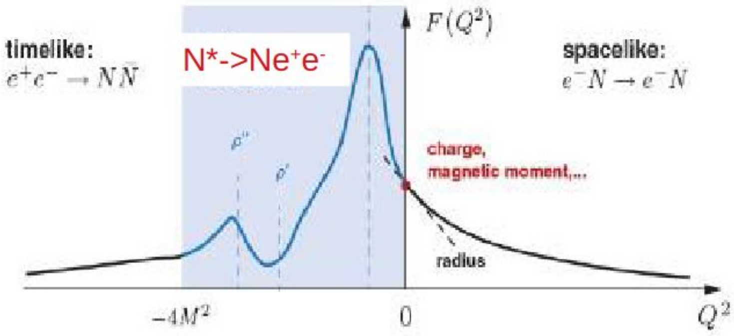
Agenda

1. Motivation
2. Introduction to **Σ^+(1385)** analysis
3. HADES Experiment
4. Machine Learning methods and metrics introduction
5. **Λ(1115)** distribution reconstruction and background reduction
6. Reconstruction of **Σ^+(1385)** and background subtraction
7. Analysis of **Σ^+(1385)** signal distributions
8. Short presentation of **Λ(1520)** decay analysis by Krzysztof Nowakowski
9. Conclusions and outlook

Hyperon radiative and Dalitz decay

- One of physics goals of pp 4.5 GeV proposal:
  - Provide insight into photon-hyperon coupling, including applicability of Vector Meson Dominance model.
  - Dalitz decays of Λ(1520)/Σ(1385) → Λe^+e^- allow for first measurement of hyperon Form Factors in time-like region.
  - Production cross-sections of Λ(1520)/Σ(1385) are not yet measured in pp and pA reactions at HADES energies.
  - Hadronic decays of Λ(1520) → $\Lambda\pi^+\pi^-$ and Σ(1385) → $\Lambda\pi^+\pi^-$ (large branching ratios) can be used for normalization for Dalitz decay studies.



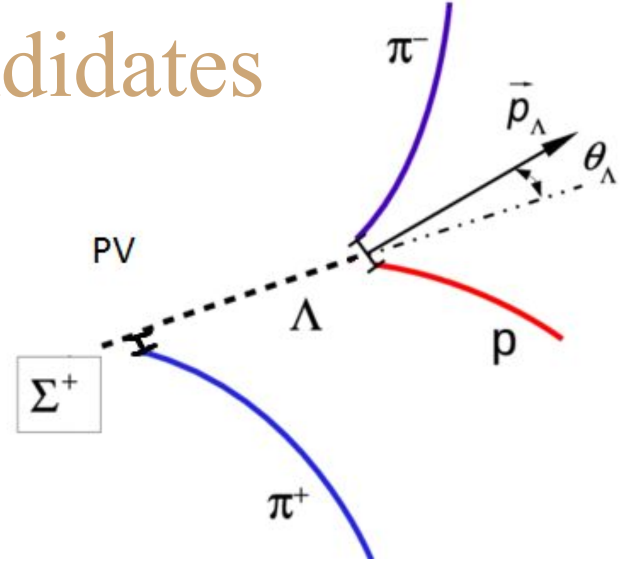


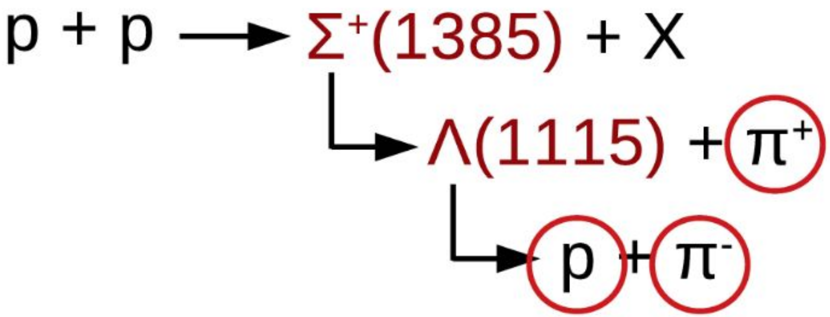
Expected dependence of FF for nucleon resonances (N*)

Physical Review D73, 114001 (2006)

Selection of $\Sigma^+(1385)$ candidates

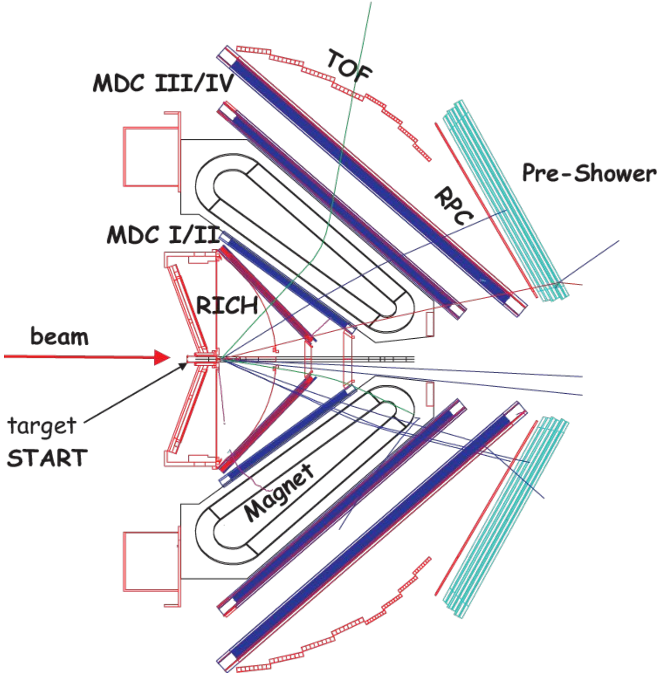
- Reconstruction of **Λ(1115)** and reduction of background utilizing neural networks.
- Reconstruction of **$\Lambda\pi^+$** signal
- Search for **$\Sigma^+(1385)$** and background subtraction.
- Analysis of **$\Sigma^+(1385)$** signal distributions:
  - Invariant mass
  - Transverse momentum
  - Rapidity





HADES experiment in pp 3.5 GeV

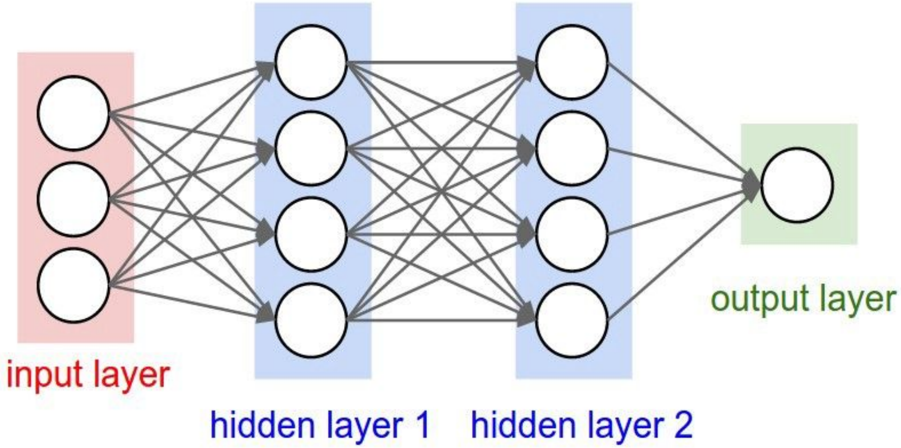
- **High Acceptance Di-Electron Spectrometer (HADES)** operating on a beam from the SIS18 synchrotron at the GSI research facility.
- The experiment uses a stationary target.
- Specialized in the detection of dileptons (e.g. electron-positron pair) and hadrons during heavy-ion collisions in the 1-4 GeV energy range.
- High angular acceptance: 18º - 80º (now upgraded + 3º - 7º with Forward Detector → details in Gabriela Perez talk) in polar angle and almost complete in azimuthal angle.

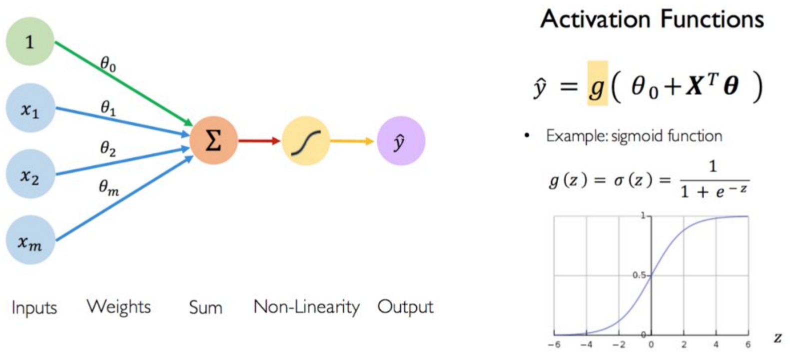


https://www-hades.gsi.de/

Artificial Neural Networks

- **Artificial Neural Networks -** machine learning methods inspired by structure of biological neural networks present in human and animal brains.:
  - Training information presented in the form of examples.
  - Information gathered during **training** stores in the form of **strength (weights) of connection between neurons** in the network.
- **Multilayer Perceptron (MLP)** - most commonly used class of feedforward artificial neural networks.





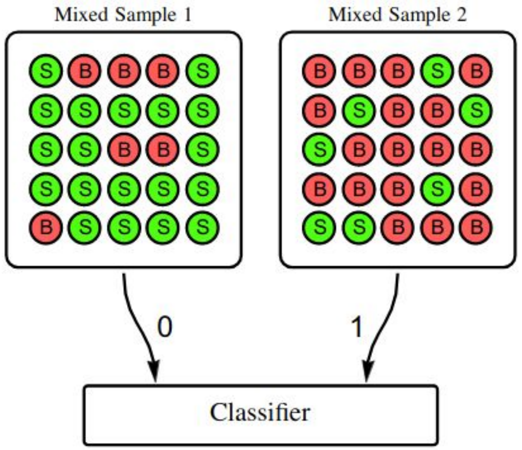
MIT: Alexander Amini, 2018 introtodeeplearning.com

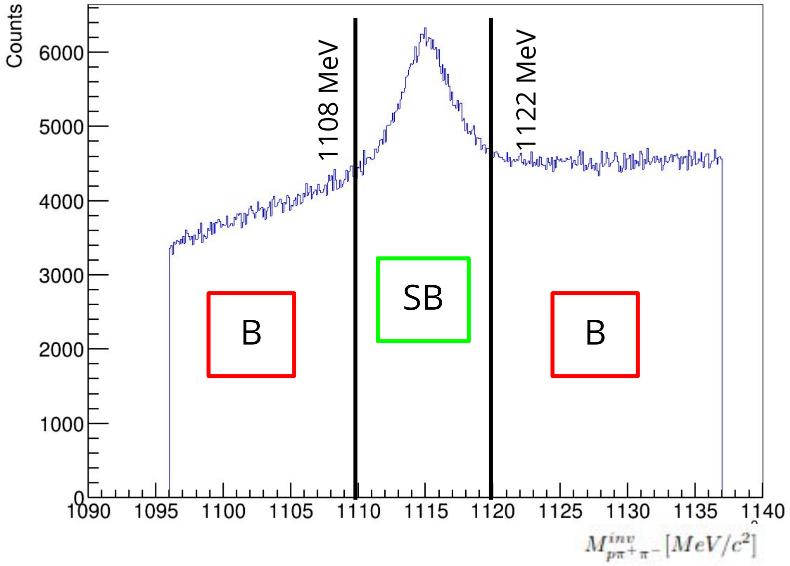
Classification without labels

- **Neymann-Pearson Lemma**: the optimal classifier is the ratio of probabilities of the event being signal and background respectively, or any classifier that is monotonically related to it.
- Optimal classifier for distinguishing between M1 and M2 ($L_{M1/M2}$) can be expressed through classifier $L_{S/B}$:

$$L_{M_1/M_2} = \frac{p_{M_1}}{p_{M_2}} = \frac{f_1\, p_S + (1-f_1)\, p_B}{f_2\, p_S + (1-f_2)\, p_B} = \frac{f_1\, L_{S/B} + (1-f_1)}{f_2\, L_{S/B} + (1-f_2)},$$

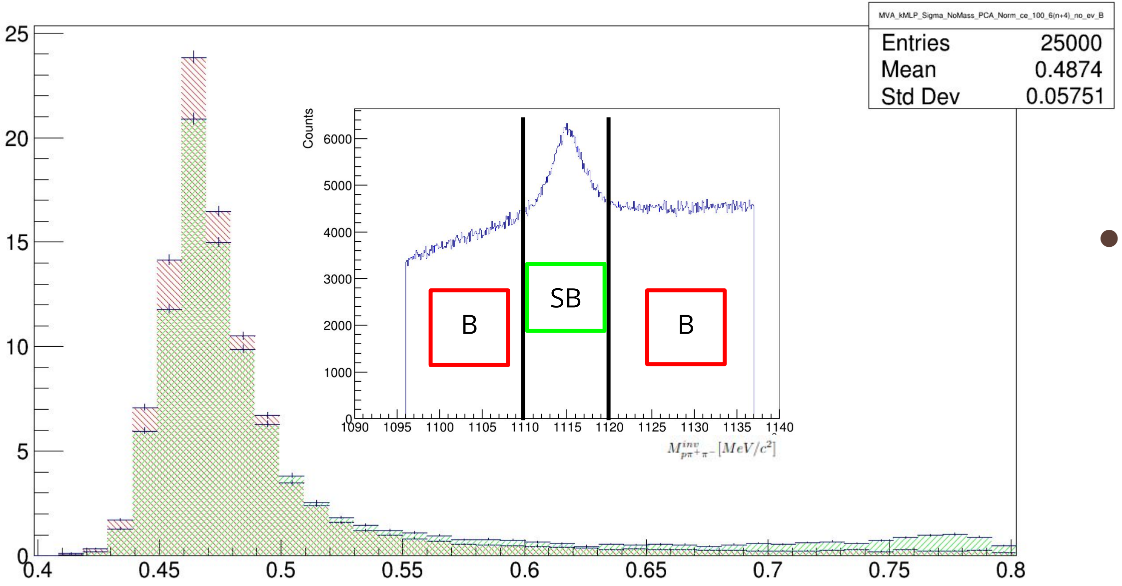
- Which is a monotonically increasing rescaling of the likelihood $L_{S/B}$ as long as f1 > f2.
- **Therefore, $L_{S/B}$ and $L_{M1/M2}$ define the same classifier.**





Classification

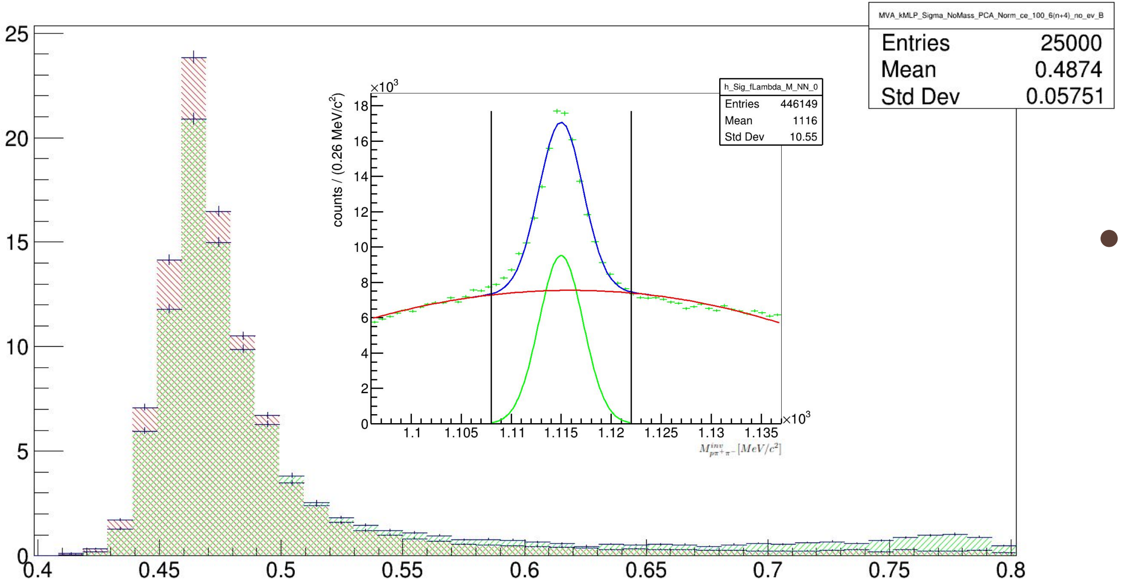
Neural Network output



- Classifier produced by training a Multilayer Perceptron type network on two sets of data, each containing 50 000 events:
  - (Green) - Signal + Background Dataset
  - (Red) - Background Dataset
- Training of Neural Network and classification performed sequentially in 4 steps → Improved Signal/Background ratio improves classification efficiency in each subsequent iteration

Classification

Neural Network output



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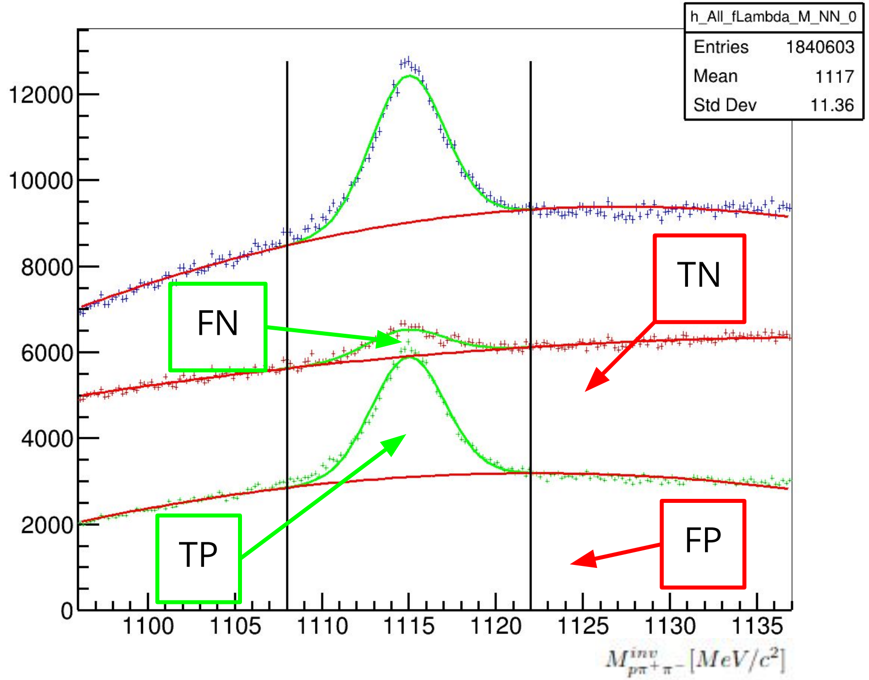
Confusion matrix

- **Confusion matrix**, also known as an error matrix, is a specific table layout that allows visualization of the performance of an algorithm.
- Possible combinations in binary classification:

		Actual Value (as confirmed by experiment)	
		positives	negatives
Predicted Value (predicted by the test)	positives	**TP** True Positive	**FP** False Positive
	negatives	**FN** False Negative	**TN** True Negative

Lambda invariant mass (example cut on NN output)



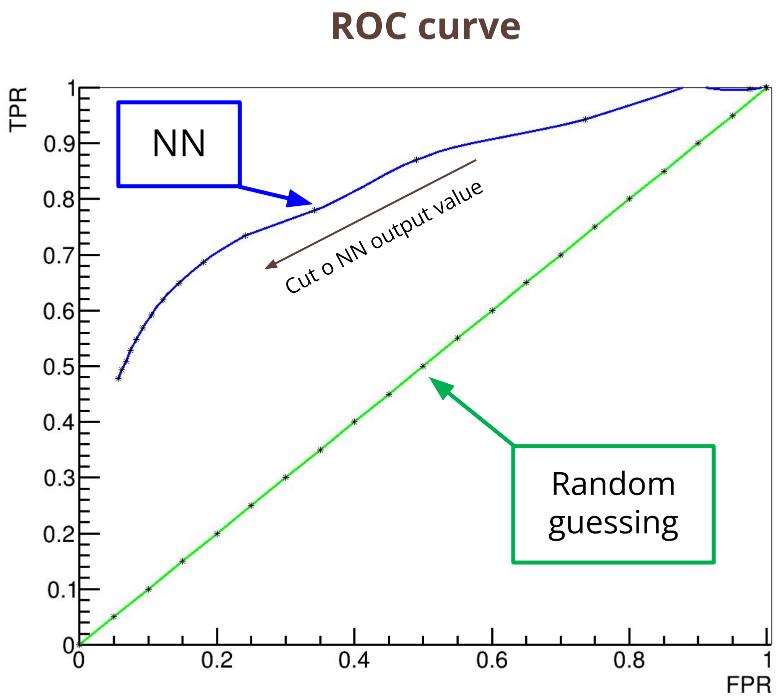
ROC curve

- A **Receiver Operating Characteristic curve**, or **ROC curve**, is a graphical plot that illustrates the diagnostic ability of a binary classifier system as its discrimination threshold is varied.
- The ROC curve is created by plotting the **true positive rate (TPR)** against the **false positive rate (FPR)** at various threshold settings.
- True Positive Rate (signal efficiency):

$$\mathrm{TPR} = \frac{\mathrm{TP}}{\mathrm{P}} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FN}} = 1 - \mathrm{FNR}$$

- False Positive Rate (misidentified background):

$$\mathrm{FPR} = \frac{\mathrm{FP}}{\mathrm{N}} = \frac{\mathrm{FP}}{\mathrm{FP} + \mathrm{TN}} = 1 - \mathrm{TNR}$$



How to find best operating point?

- In statistical analysis of binary classification, the **F-score** or **F-measure** is a measure of a test's accuracy. It is calculated from the precision and recall of the test.
- **Precision** is the number of correctly identified positive results divided by the number of all positive results, including those not identified correctly.

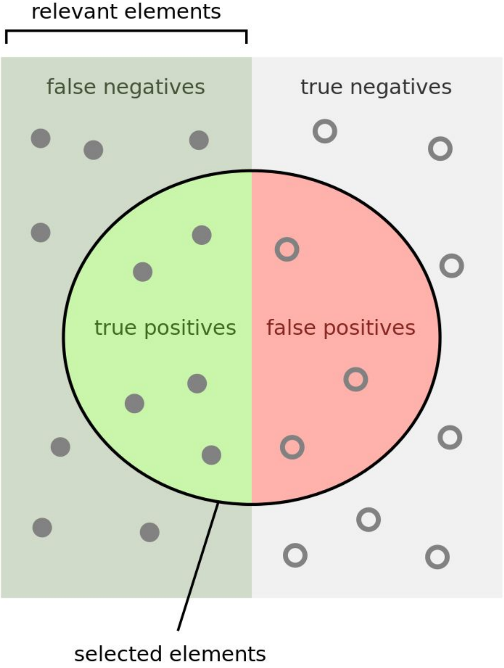
$$\text{Precision} = \frac{True\ Positive}{True\ Positive + False\ Positive}$$

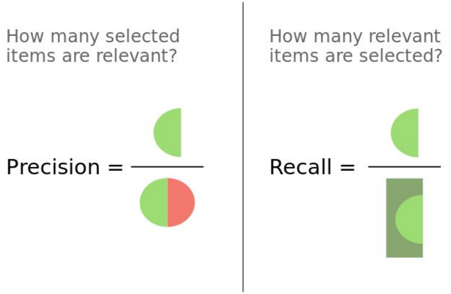
- **Recall** is the number of correctly identified positive results divided by the number of all samples that should have been identified as positive.

$$\text{Recall} = \frac{True\ Positive}{True\ Positive + False\ Negative}$$

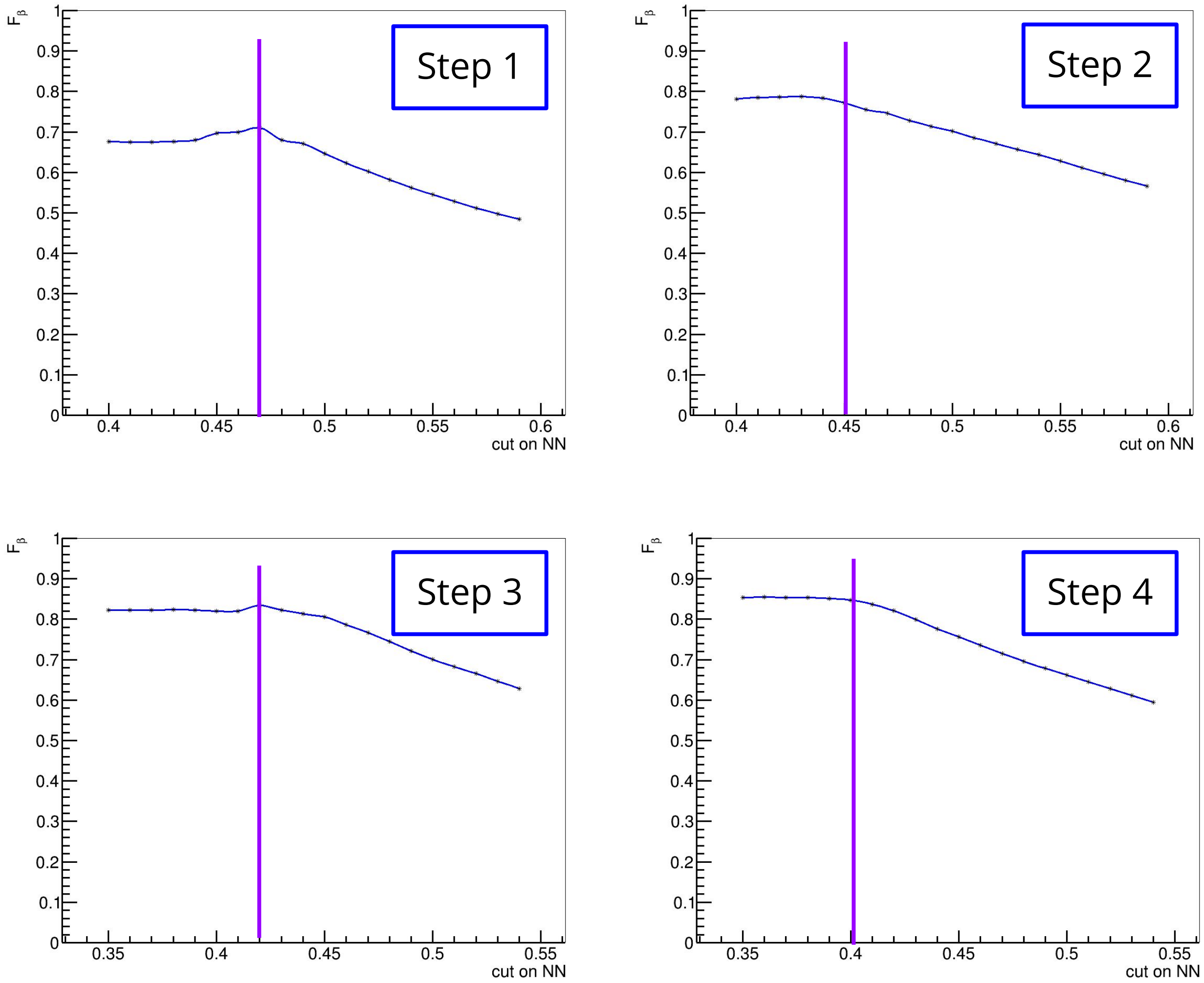
- The $\mathbf{F_1}$ score is the harmonic mean of the **precision** and **recall**. The more generic $\mathbf{F_\beta}$ score applies additional weights, valuing recall **β** times more than precision.

$$F_\beta = (1 + \beta^2) \cdot \frac{\text{precision} \cdot \text{recall}}{(\beta^2 \cdot \text{precision}) + \text{recall}}$$





https://en.wikipedia.org/wiki/Precision_and_recall

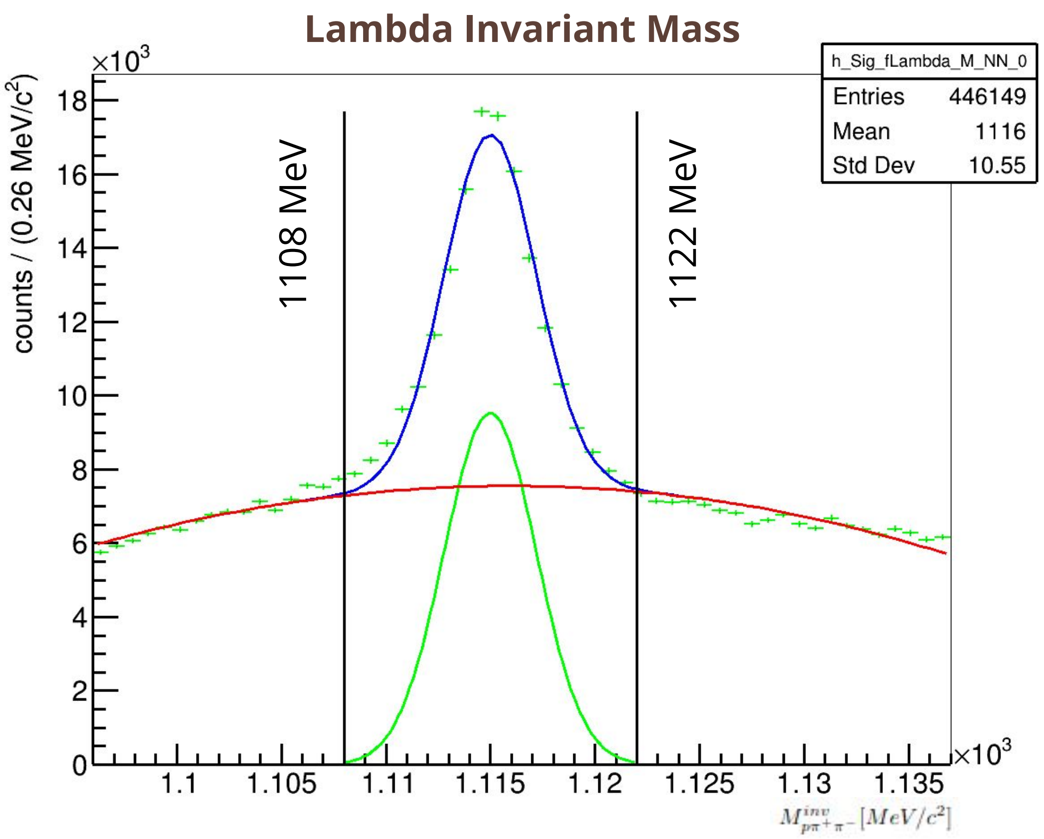


$F_{3.5}$ score

$$F_\beta = (1+\beta^2)\cdot\frac{\text{precision}\cdot\text{recall}}{(\beta^2\cdot\text{precision})+\text{recall}}$$

- $F_{3.5}$ score plots for each step of the analysis.
- In each step $F_{3.5}$ score at selected cut value has a bit higher value than in previous step → in each step classification is a bit more efficient than in previous one.

Background subtraction



- Events from outside signal range were used as sideband to approximate background underneath the Gaussian signal distribution.
- Rescaling was applied based on integrals from a polynomial function fitted to data (red line).

Sigma Invariant Mass - Fitting

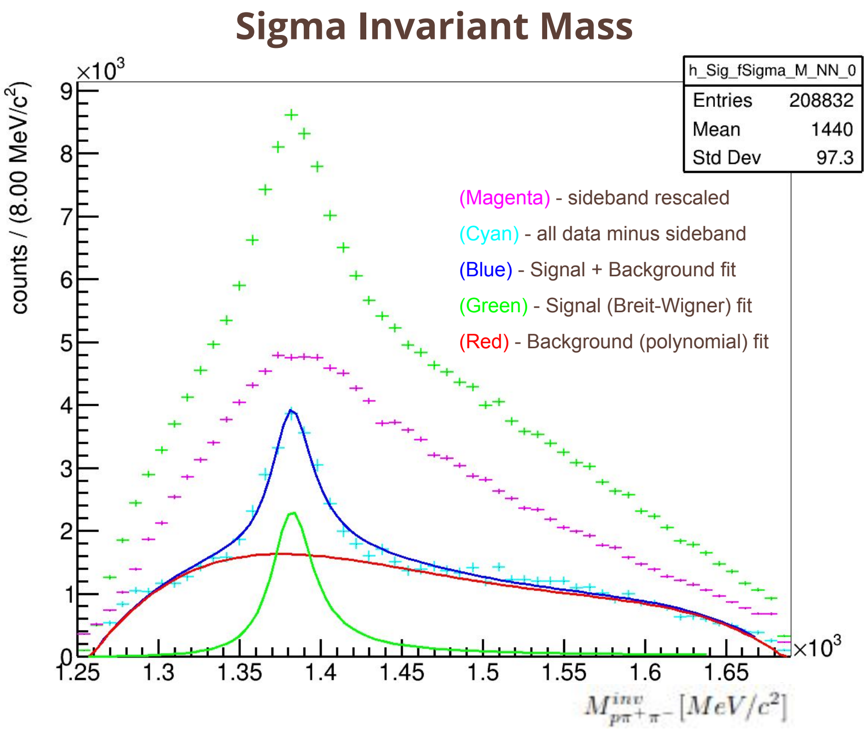
- Fitting of relativistic Breit-Wigner distribution on top of background (fifth degree polynomial), to the spectrum achieved by sideband subtraction (cyan spectrum in histogram), was performed.

$$\text{Breit-Wigner} \propto \frac{q^2}{q_0^2}\frac{m_0^2\Gamma_0^2}{(m_0^2 - m^2)^2 + m_0^2\Gamma^2},$$

$$\Gamma = \Gamma_0 \frac{m_0 q^3}{m q_0^3} F_1(q),$$

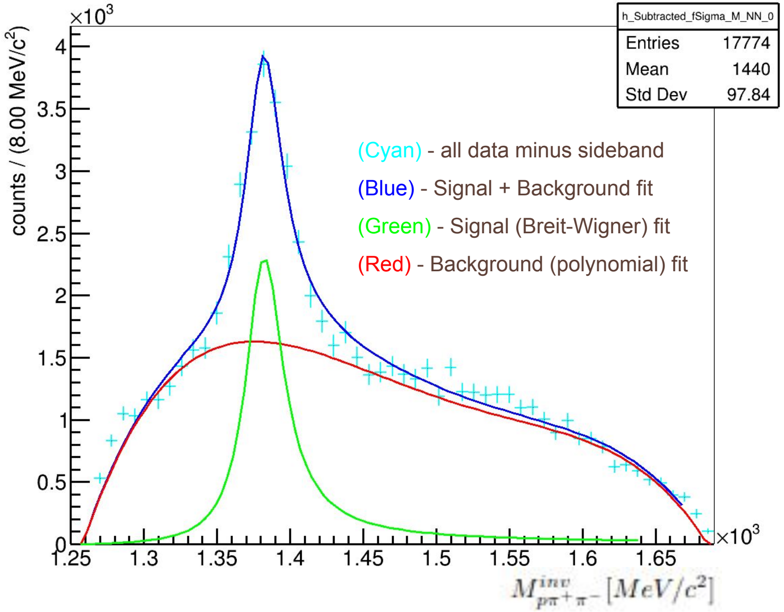
$$F_1(q) = \frac{1 + (q_0 R)^2}{1 + (qR)^2},$$

- ***q*** - momentum
- q_0 - momentum that corresponds to the mass m_0,
- ***m*** - mass variable,
- Γ_0 - resonance width,
- Γ - mass-dependent resonance width,
- $F_1(q)$ - Blatt-Weisskopf parameter
- ***R*** = 1/197.327 MeV^{-1} - centrifugal barrier parameter.



Inclusive and exclusive comparizon

Inclusive analysis

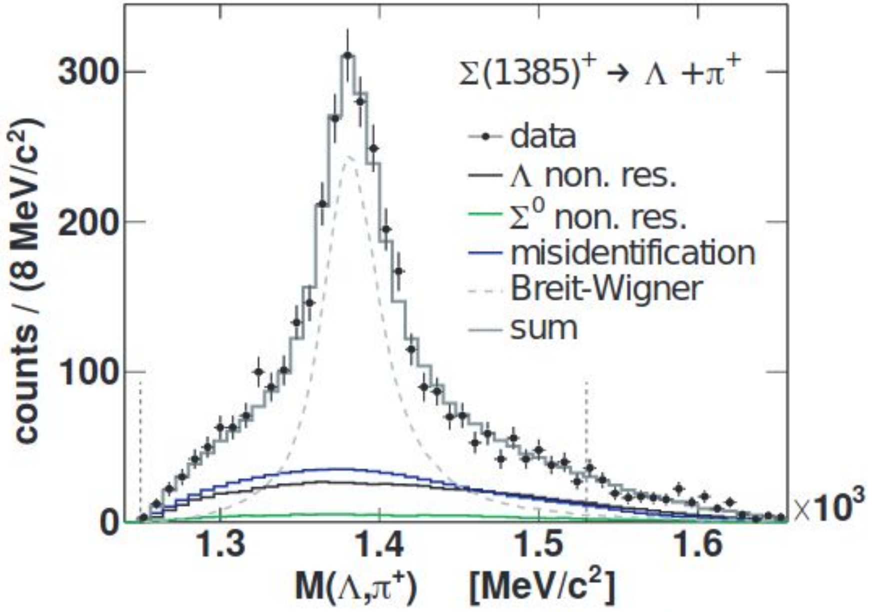


$M_0 = 1382.96 \pm 0.59$ MeV/c^2

$\Gamma_0 = 32.7 \pm 1.9$ MeV/c^2

Yield = 15010 ± 540 counts

Exclusive analysis



$m_0 = 1383.2 \pm 0.9 ^{+0.1}_{-1.5}$ MeV/c^2

$\Gamma_0 = 40.2 \pm 2.1 ^{+1.2}_{-2.8}$ MeV/c^2

PDG (Particle Data Group):

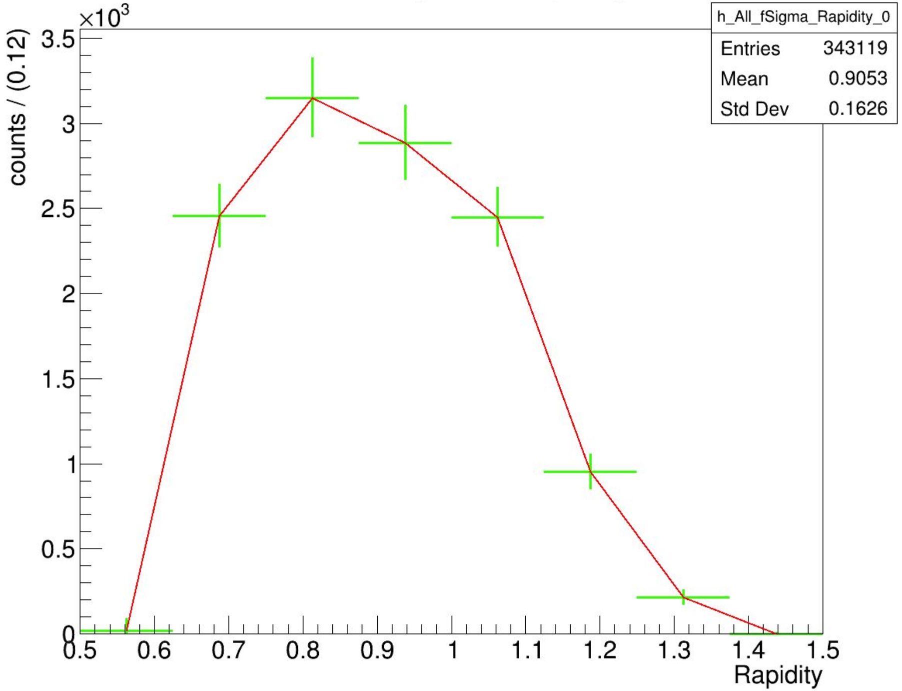
M_0 = 1382.80 ± 0.35 MeV/c^2

Γ_0 = 36.0 ± 0.7 MeV/c^2

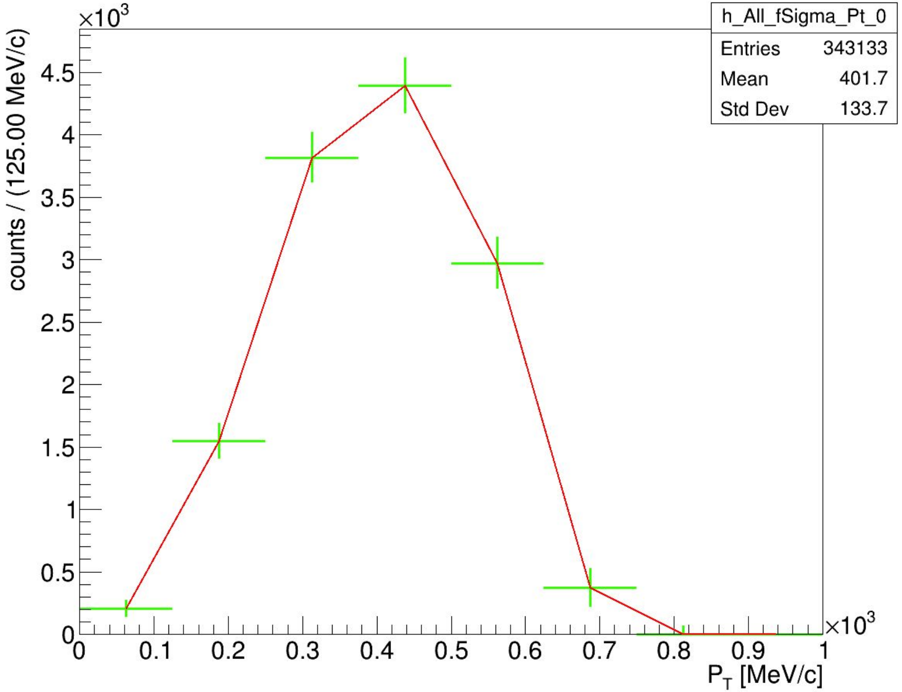
Agakishiev, Geydar et al. (2012). Baryonic resonances close to the K⁻N threshold: The case of Σ (1385)+ in pp collisions. Physical Review C. 85. 10.1103

Rapidity and Transverse Momentum

Sigma 1385 Rapidity

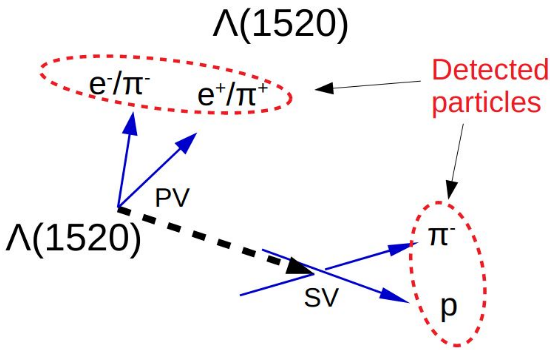


Sigma 1385 Transverse Momentum



Not yet acceptance and efficiency corrected!

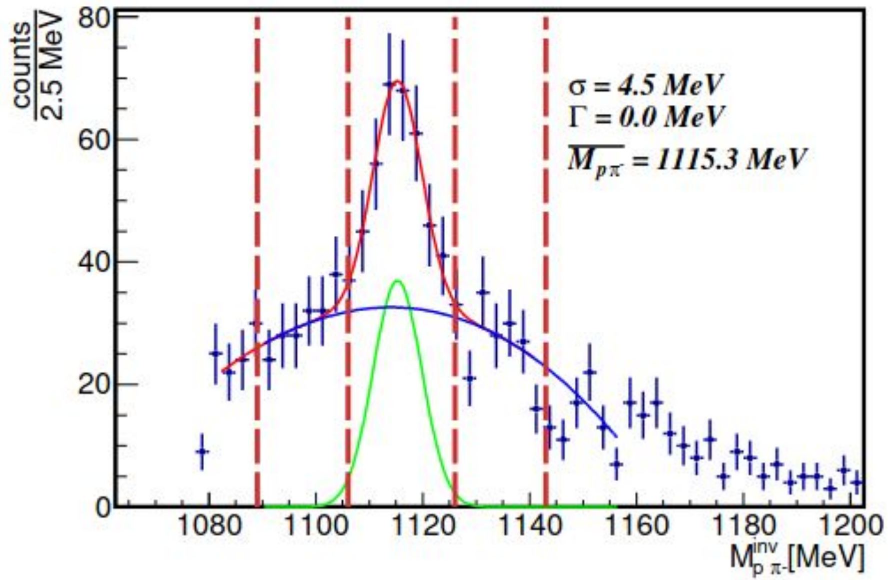
Λ(1520) decay analysis



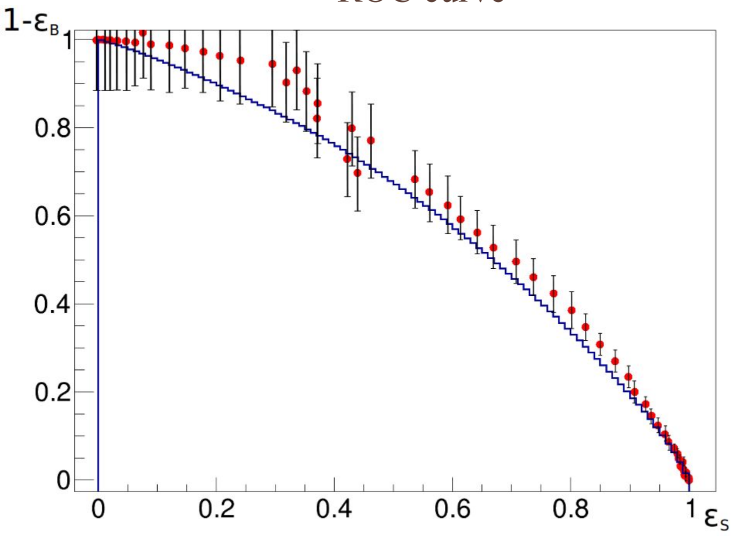
- Λ(1520) decay analysis has been performed by Krzysztof Nowakowski in his PhD thesis:

$pp \to pK^{+}\Lambda(1520) \to pK^{+}\Lambda(1116)\pi^{+}\pi^{-} \to pK^{+}p\pi^{-}\pi^{+}\pi^{-}$

Λ(1116) reconstruction invariant mass

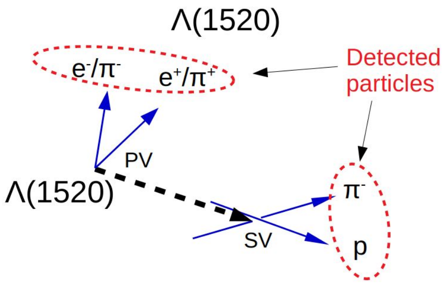


ROC curve



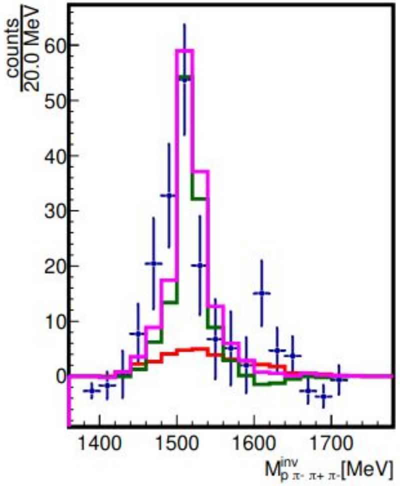
Krzystof Nowakowski, PhD Thesis, *"Measuring Λ(1520) production in proton-proton and proton-nucleus collisions with HADES detector"*, 2022

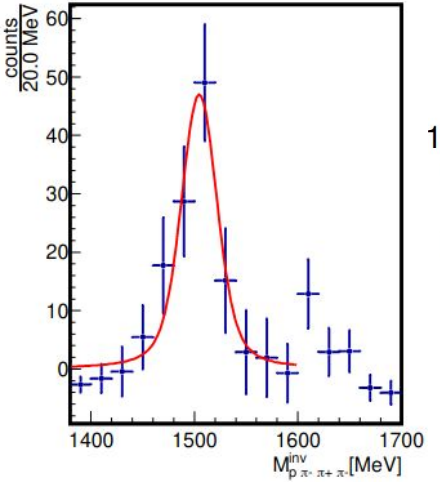
Λ(1520) decay analysis



$pp \rightarrow pK^+\Lambda(1520) \rightarrow pK^+\,\Lambda(1116)\pi^+\pi^- \rightarrow pK^+p\pi^-\pi^+\pi^-$

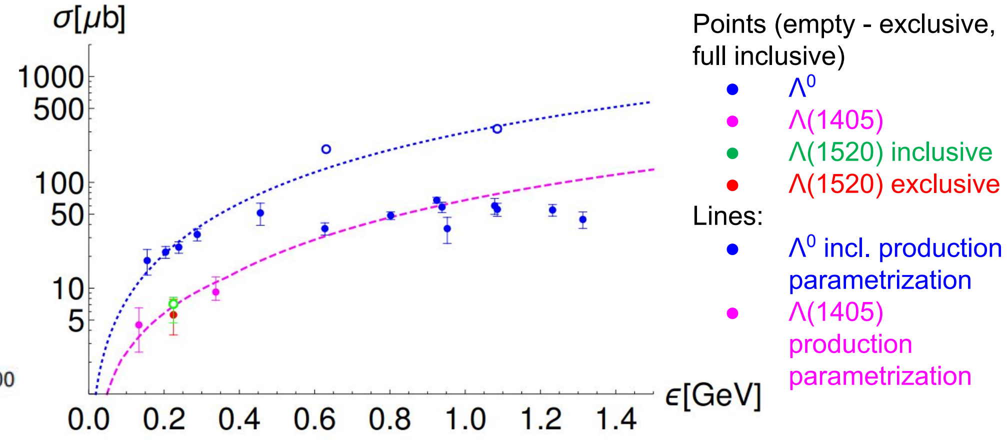
Λ(1520) reconstruction invariant mass





	$M_{\Lambda(1520)}$[MeV]	$\sigma_{\Lambda(1520)}$[MeV]
PDG	$1519,5 \pm 1$	not applicable
experiment	1504.5 ± 4.7	14.7 ± 6.7
simulation	1515.6 ± 2.1	11.3 ± 3.6

Cross section vs excess energy



$$\sigma_{pp \rightarrow \Lambda(1520)X} = 7.1 \pm 1.1^{+0.0}_{-2.14}\,\mu b.$$

Krzystof Nowakowski, PhD Thesis, *"Measuring Λ(1520) production in proton-proton and proton-nucleus collisions with HADES detector"*, 2022

Conclusions

- **Σ^+(1385)** channel has been reconstructed and parameters of the distribution have been calculated:

$$\mathbf{M_0 = 1382.96 \pm 0.59\ MeV/c^2}$$
$$\mathbf{\Gamma_0 = 32.7 \pm 1.9\ MeV/c^2}$$

- Analysis technique utilizing machine learning methods has been developed and verified as effective for **Σ^+(1385)** and **Λ(1520)** analysis.

Outlook

- Calculating value of cross-section for this channel.
- Performing analogous analysis for **Σ^+(1385)** and **Λ(1520)** channel reconstruction in **proton - proton 4.5 GeV** scattering.
- Expected increase of statistics by ~2 orders of magnitude due to larger luminosity and cross-section in 4.5 GeV.