$\Lambda(1520)$ and $\Sigma^*(1385)$ in p+p and p+Nb reactions measured with HADES

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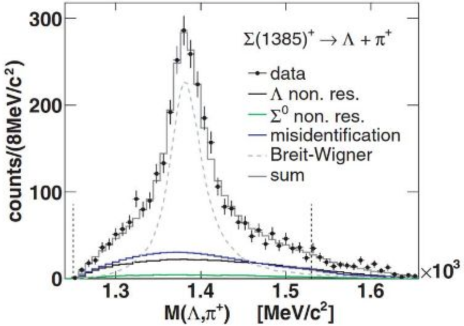
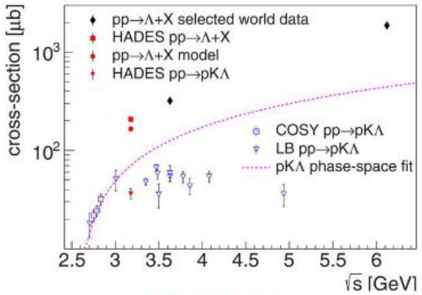
Hyperon production in HADES in p+p/A collisions

- Strangeness production in pp and pA collisions is a significant part of HADES Physics Program:
  - ***Inclusive Λ(1116) production, polarization and p-Λ correlations in pp/pNb*** Phys.Rev.C 95 (2017) 1, 015207, Eur.Phys.J. A50 (2014) 81, Phys.Rev.C 94 (2016) 2, 025201
  - ***Inclusive Λ(1116) and Σ0 production in pNb@3.5 GeV*** Phys.Lett. B781 (2018) 735-740
  - ***Exclusive Σ(1385)+ production in pp@3.5 GeV*** Phys.Rev. C85 (2012) 035203
  - ***Exclusive Λ(1405) production and line shape measurement in pp*** Phys.Rev. C87 (2013) 025201
  - ***A Ξ production in pA Phys.Rev.Lett.*** 114 (2015) 212301, Phys. Rev. Lett.103, 132301 (2009)
  - ***Inclusive Λ(1520) production in pp and pNb at 3.5 GeV and 4,5 GeV***

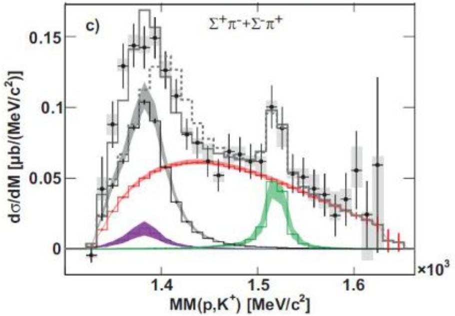
New p+p run at 4,5 GeV → ~60 times greater integrated accepted luminosity.

Σ(1385)



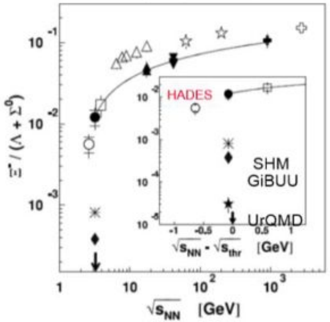


Λ(1405)



Ξ(1321)

Strong enhacement above models (Statistical Hadron Model (SHM), UrQMD, GiBUU



Case of Λ(1520) and Σ*(1385)

- **Λ(1520)** structure is controversially discussed:
  - Excited quark state
  - Baryon – meson molecule : Λ(1520) is a dynamically generated state resulting from decouplet baryon x meson interaction (S.Sarkar, E. Oset, J. Vacas *“Baryonic resonances from baryon decuplet-meson octet interaction”*)
- Modification of **Σ*(1385) - π** loop in medium (p+A) → Important implication for properties of **Λ(1520)**
  - **M**↓(1500-1490 MeV)
  - **Γ**↑(40-70 MeV)
  - **BR(Λ ππ)** ↑(~25%)
  - Changes for **Σ*(1385)** even stronger
- Hadronic decays of **Λ(1520)** → **$\Lambda\pi^+\pi^-$** in p+p and p+A, particularly interesting:
  - Currently poorly studied
  - Complementary channel to Dalitz decay: Λ(1520) → $\Lambda(1116)e^-e^+$
  - High branching ratio compared to Dalitz decay, BR = $6.6{\cdot}10^{-2}$

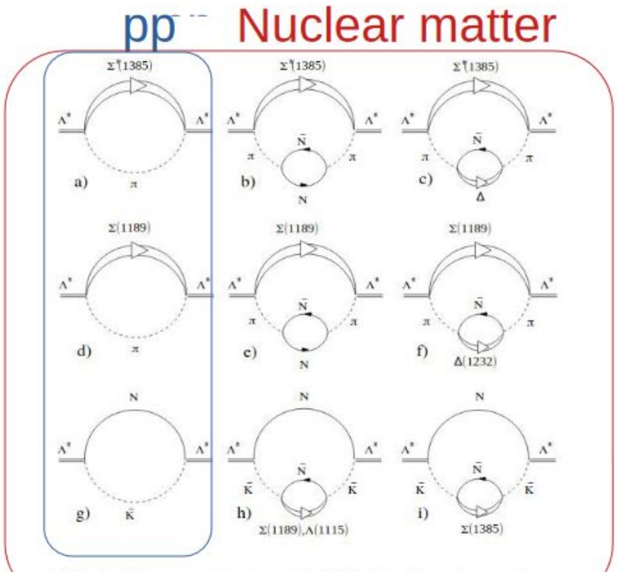
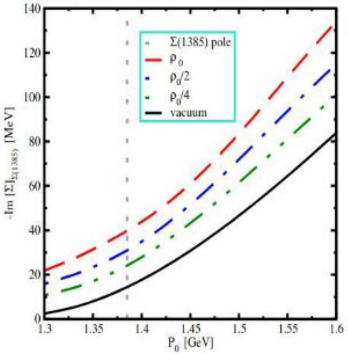


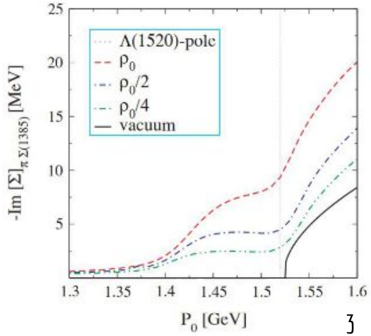
FIG. 1: The renormalization of the Λ(1520) in the nuclear medium.

“Λ(1520)and Σ(1385)in the nuclear medium”
Murat M. Kaskulov and E. Oset

Σ*(1385) width

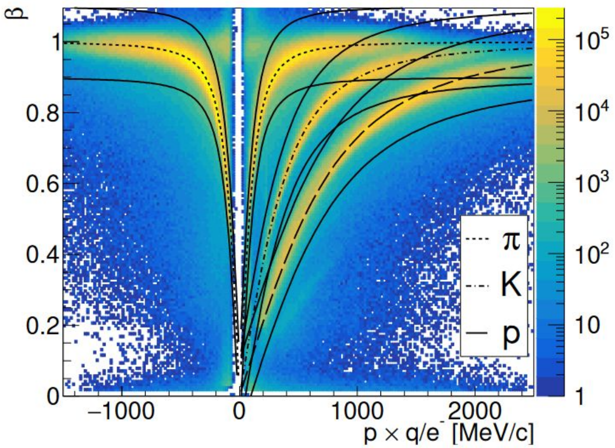


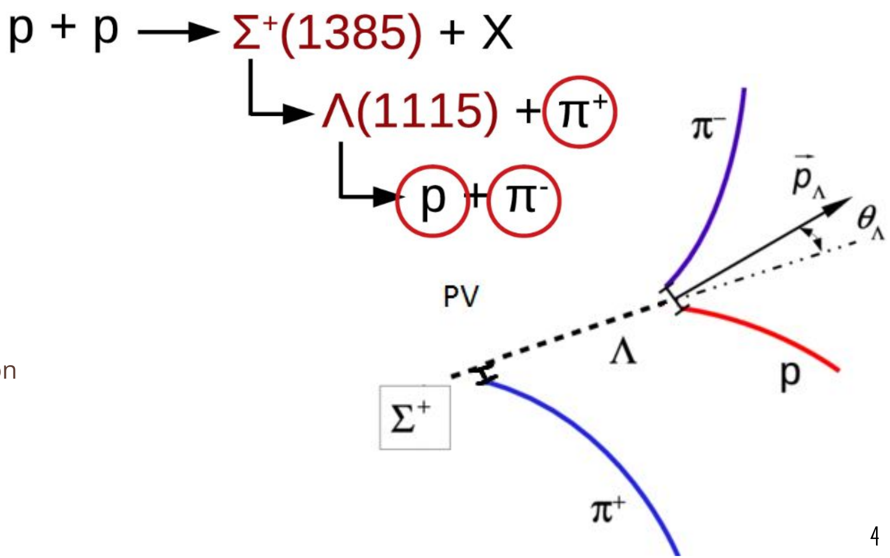
Σ*(1385) - π width



Event selection

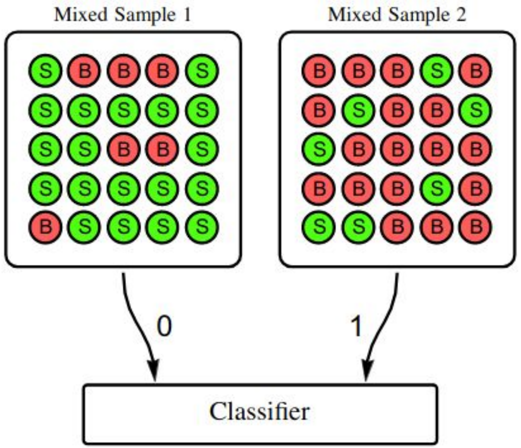
- Track reconstruction and Particle Identification (PID) → based on β vs mom or dE/dx vs mom distributions.
- Track combinations for **Λ(1520)** (p,π^-,π^+,π^-) and **Σ^*(1385)** (p,π^-,π^+) reconstruction.
- Minimal bias conditions for **Λ(1115)** background reduction use cuts on:
  - Minimal Track Distance: MTD(p,π^-)
  - Vertexes Positions and Distance
  - In p+p Missing Mass ($MM_{p\pi-}$) > $M_{nucleon}$ + M_{kaon}



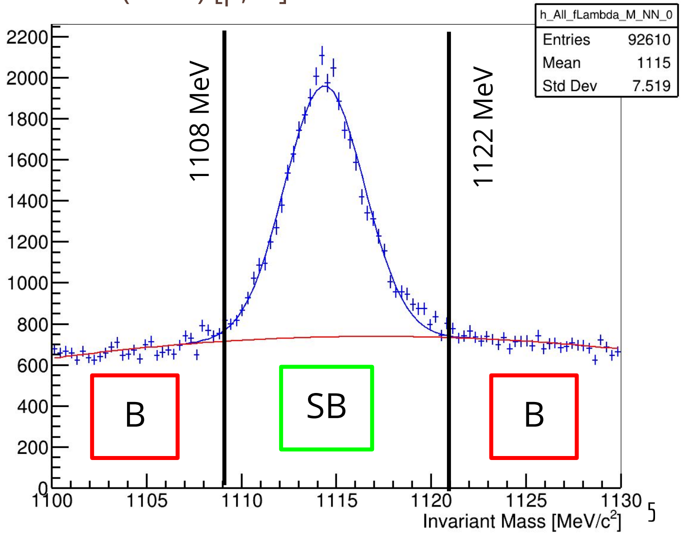


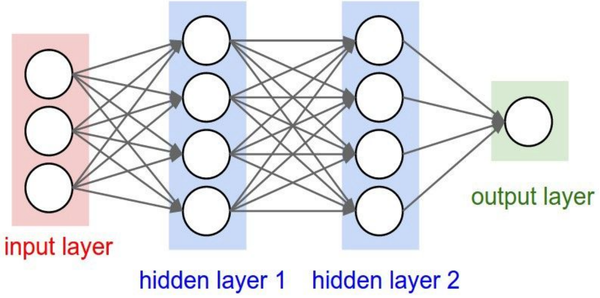
Λ(1115) identification with Neural Networks

- Background reduction performed using **TMVA** based, **Multilayer Perceptron** type **Neural Network** approach utilizing data driven so-called **Classification without Labels (*"CWoLa"*)** method (no simulations needed).
- Optimal classifier for distinguishing between M1 and M2 ($L_{M1/M2}$) is a monotonically related to classifier $L_{S/B}$ and as such **$L_{S/B}$ and $L_{M1/M2}$ can be used interchangeably.**



Λ(1115) [p,π⁻] Invariant Mass





$\Sigma^{*+}(1385)$ in p+p @ 4,5 GeV

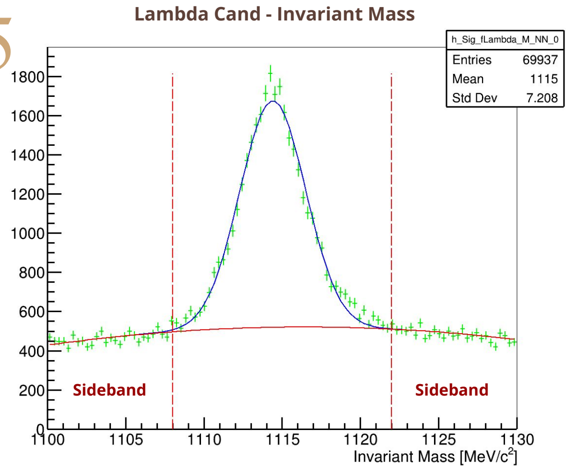
- Sideband subtraction for **Σ*(1385)** reconstruction.
- Breit-Wigner distribution fitting to **Σ*(1385)** invariant mass.

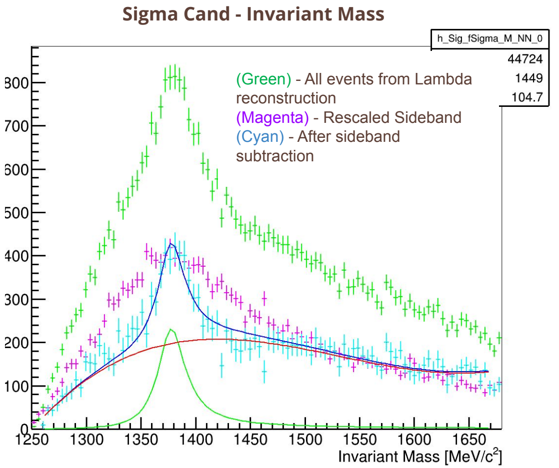
$$\text{Breit-Wigner} \propto \frac{q^2}{q_0^2}\frac{m_0^2\Gamma_0^2}{(m_0^2-m^2)^2+m_0^2\Gamma^2},$$

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

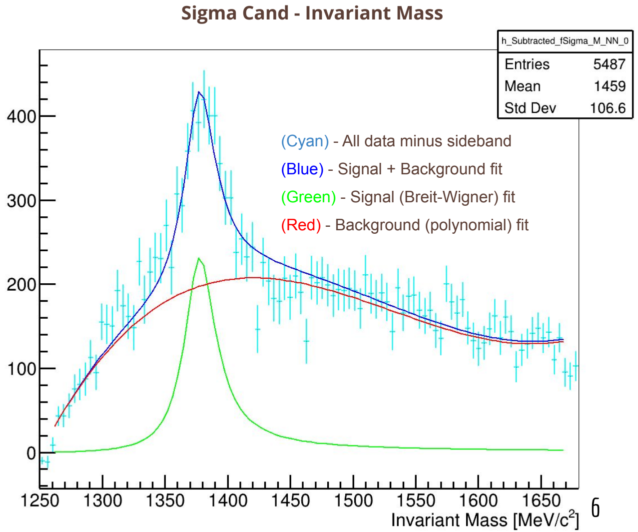
$$F_1(q) = \frac{1+(q_0R)^2}{1+(qR)^2},$$

- ***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.





~4% total statistics



Breit-Wigner:

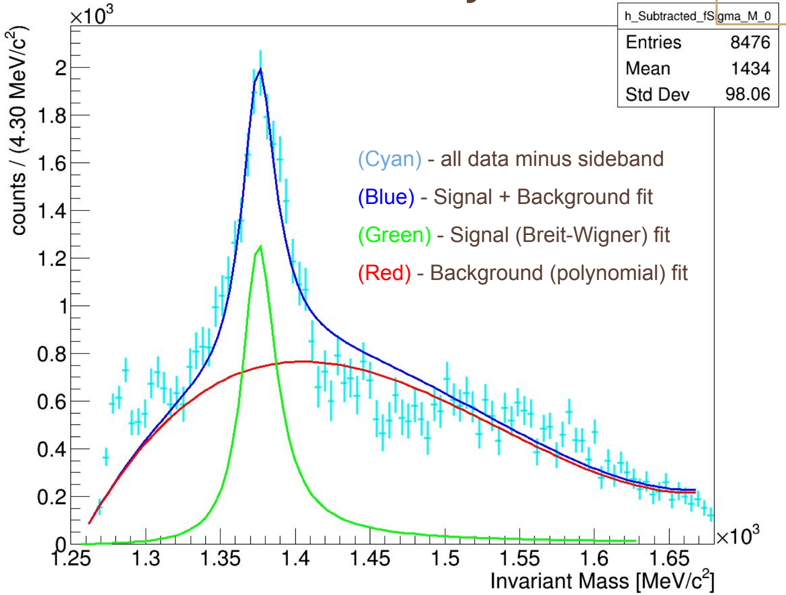
- M_0 = 1378.7 +/- 1.4 MeV/c^2
- Γ_0 = 32.2 +/- 4.1MeV/c^2

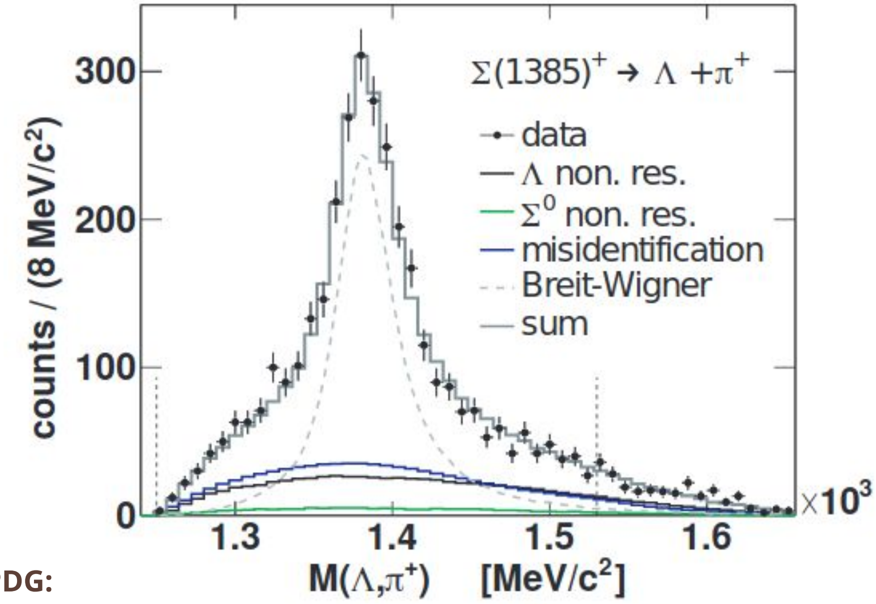
$\Sigma^{*+}(1385)$ in p+p @ 3,5 GeV

Inclusive analysis

Entire run statistics

Exclusive analysis ($pK^{+}\Sigma^{*+}$)





$$M_0 = 1382.65 \pm 0.59\ \mathrm{MeV/c^2}$$

$$\Gamma_0 = 32.9 \pm 1.6\ \mathrm{MeV/c^2}$$

PDG:

$M_0 = 1382.80 \pm 0.35$ MeV/c^2

$\Gamma_0 = 36.0 \pm 0.7$ MeV/c^2

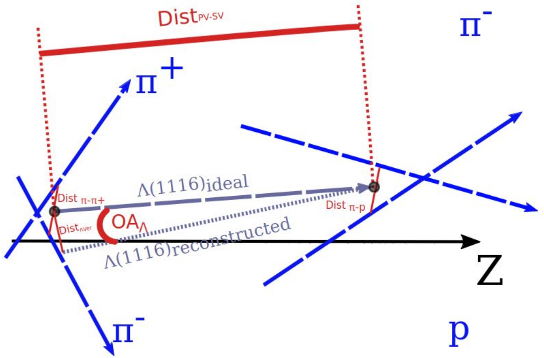
$m_0 = 1383.2 \pm 0.9\ ^{+0.1}_{-1.5}$ MeV/c^2

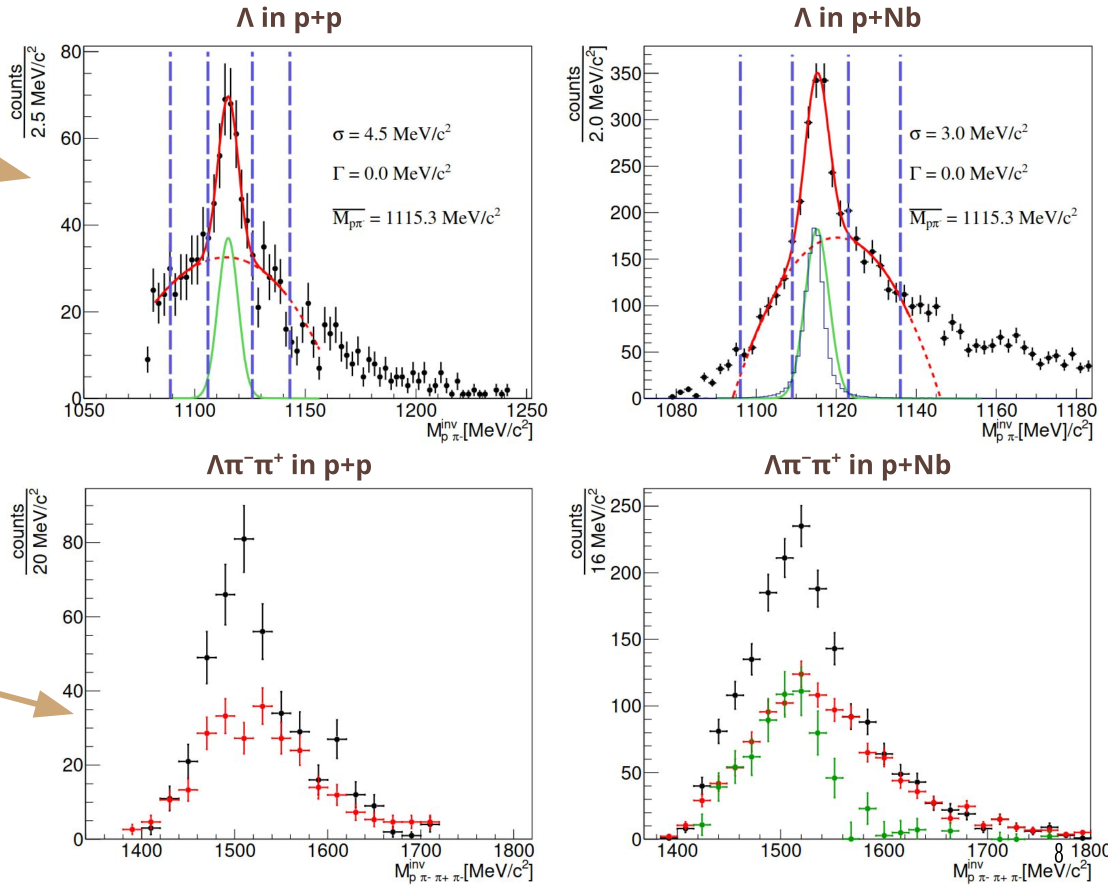
$\Gamma_0 = 40.2 \pm 2.1\ ^{+1.2}_{-2.8}$ MeV/c^2

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

Λ(1520) in p+p and p+Nb @ 3,5 GeV

- **Λ(1115) selection** based on topological cuts produced by Neural Network training:





- **Λ(1520) signal extraction** based on sideband.

> - Main background contributions in p+p:
>   - $\Delta^{++}\pi^{-}\Delta^{++}\pi^{-}$ channel
>   - $p+p \rightarrow \Lambda[p\pi^{-}]K^{0}[\pi^{+}\pi^{-}]p\pi^{+}$

Λ(1520) in p+p and p+Nb @ 3,5 GeV

- Λ(1520) invariant mass reconstruction results:

	$M_{\Lambda 0\pi+\pi-}$ [MeV]	σ [MeV]	Γ [MeV]
pNb	1519 ± 4.2	14.7	24 ± 10
pp	1509 ± 4.7	14.7	15.6 ± 1

- Peak position in p+p smaller than PDG (interferences, systematics? → To be checked in p+p @ 4,5 GeV).
- Calculated cross section values for inclusive channels:

$$\sigma_{p+p\to\Lambda(1520)X} = 7.1 \pm 1.1 \pm {}^{0.0}_{2.14}\ \mu b$$

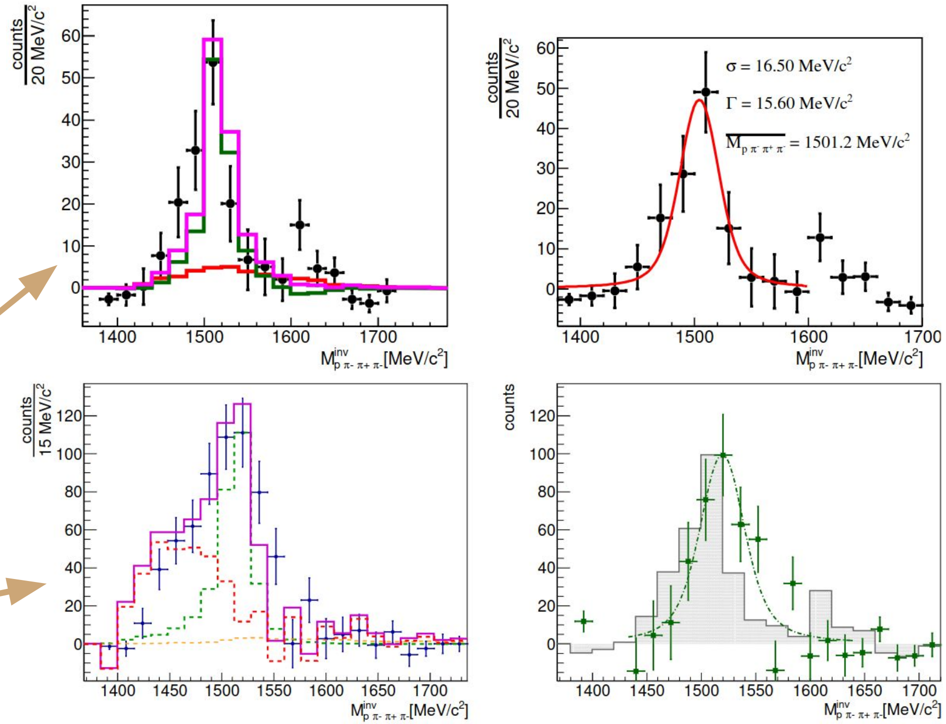
$$\sigma_{p+Nb\to\Lambda(1520)X} = 4.97 \pm 0.45 \pm {}^{3.58}_{2.53}\ mb$$

- **Λ(1520) Invariant mass decomposition:**
  - points - experimental data
  - green – Λ(1520) simulated signal
  - red – simulated non-resonant background (UrQMD for pNb)
  - magenta - sum of simulated channels (fit)

PRELIMINARY

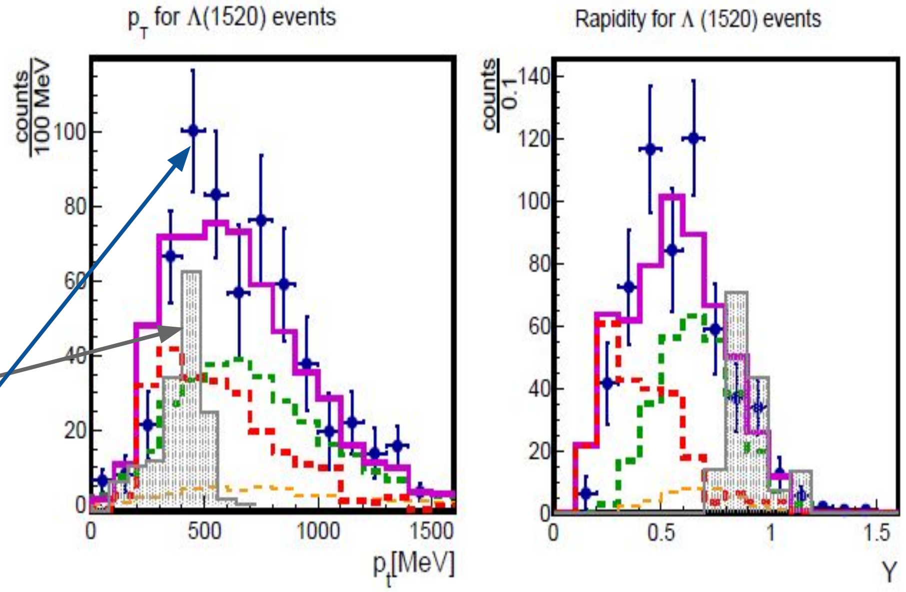
p+p

p+Nb



Λ(1520) in p+p and p+Nb @ 3,5 GeV

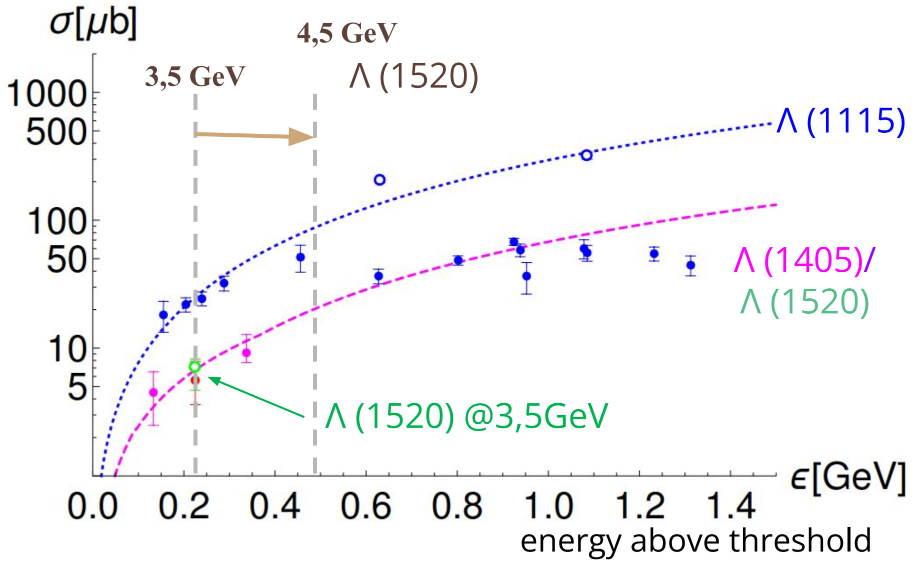
- In **p+Nb** case, compared to **p+p** case:
  - transverse momentum broader and shifted to higher values
  - rapidity distribution shifted to lower values
- **Conclusion** → Λ(1520) events from **p+Nb** are emitted from a slower source, as compared to **p+p** reaction, as expected for re-scattering in the medium.



- **Λ(1520) transverse momentum and rapidity → p+p**
- **Λ(1520) transverse momentum and rapidity → p+Nb**
  - blue - experimental data
  - green – Λ(1520) resonant contribution (sim)
  - orange – Σ(1385) resonant contribution
  - red – simulated non-resonant background (URQMD)
  - magenta - fit of simulated channels

Summary & outlook

- Λ (1520) measured for the first time in pp and pA collisions close to threshold (@ 3.5 GeV)
- New high statistics data from pp @ 4.5 GeV will provide:
  - Cross sections for $\Sigma^*(1385)$ (all isospin states) and Λ (1520)
  - Dalitz plot Λππ to analyse $\Sigma^*(1385)$-π decay branch
  - Reference for Dalitz Λ(1520), $\Sigma^*(1385) \rightarrow \Lambda\, e^+e^-$ decays (branching ratio)



~100x (Lumi x cross section) increase in statistics for Λ (1520) expected in 4,5 GeV in comparison to 3,5 GeV.

BACKUP

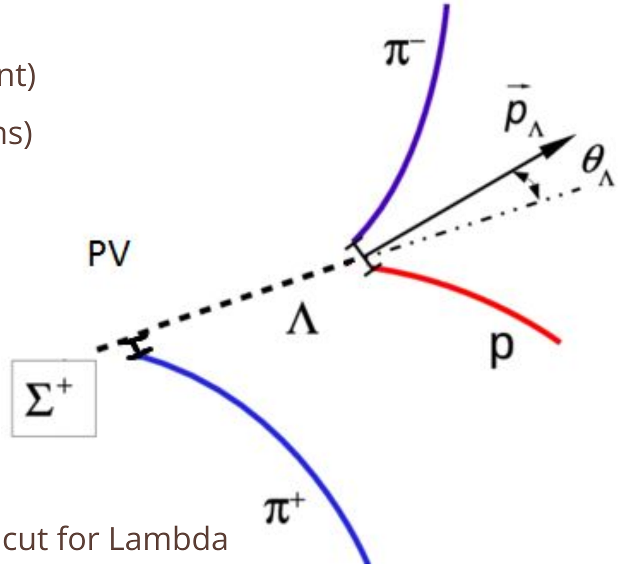
$\Sigma^+(1385)$ in p+p at 4,5 GeV

$p + p \longrightarrow \Sigma^+(1385) + X$

$\quad \hookrightarrow \Lambda(1115) + \pi^+$

$\quad\quad \hookrightarrow p + \pi^-$

- Two cases:
    - **HHH** - All three particles (p,π^-,π^+) in HADES
    - **HHF** - π^- and π^+ in HADES + p in FwDet (no PID in FwDet - assumption of a proton)
- **Lambda (1115)** candidates reconstruction - Minimum bias conditions:
    - At least 3 tracks in event (considering combinations of all tracks in event)
    - Particle Identification (PID) $(p+\pi^-) + \pi^+$ (based on β vs mom distributions)
    - $InvMass_{Lambda(p\,\pi-)} \in$ (1080 MeV;1150 MeV) - Relevance window
    - Minimal Track Distance: $MTD(p,\pi^-) < 20$ mm
    - $Vertex\_Z_{Primary} < Vertex\_Z_{Lambda}$
    - $Dist(Vertex_{Primary}; Vertex_{Lambda}) > 10$ mm
    - $MissMass_{Lambda} > Mass_{nucleon} + Mass_{kaon}$
- **Sigma (1385)** candidates reconstruction - conditions:
    - $MissMass_{Sigma(p\,\pi-\pi+)} > Mass_{nucleon} + Mass_{kaon}$ (more restrictive than MM cut for Lambda Cand)



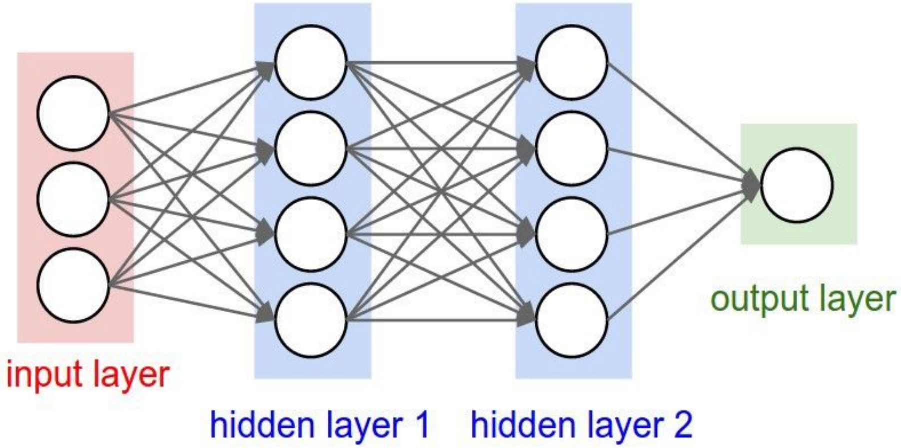
Strange baryonic resonances in p+p 3.5 GeV

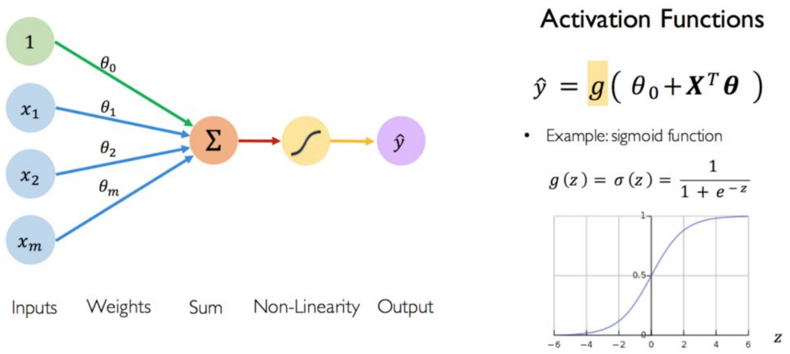
Channels included in the analysis

id	pp→ reaction	$\sigma_0^{(id)}$ cross section [μb]	∡ var.	∡(a_2, a_4)		H	notes	fit result	
			3-body channels						
1	$\Lambda p K^+$	$35.26 \pm 0.43\ ^{+3.55}_{-2.83}$	θ^{cms}_{Λ}	0.798	0.134	✓	[16]	38.835 ± 0.026	$\top$
2	$\Sigma^0 p K^+$	$16.5 \pm 20\,\%$	$\theta^{cms}_{\Sigma^0}$	0.034 ± 0.241	—		[21]+calc.	19.800 ± 0.094	$\top$
3	$\Lambda \Delta^{++} K^0$	$29.45 \pm 0.08\ ^{+1.67}_{-1.46} \pm 2.06$	$\theta^{cms}_{\Delta^{++}}$	1.49 ± 0.3	—	✓	[13]	32.10 ± 0.11	$\top$
4	$\Sigma^0 \Delta^{++} K^0$	$9.26 \pm 0.05\ ^{+1.41}_{-0.31} \pm 0.65$	$\theta^{cms}_{\Delta^{++}}$	0.08 ± 0.02	—	✓	[13]	8.5 ± 2.1	$\perp$
5	$\Lambda \Delta^{+} K^+$	$9.82 \pm 20\,\%$	$\theta^{cms}_{\Delta^{+}}$	from $\Lambda \Delta^{++} K^0$			res. mod.	11.78 ± 0.15	$\top$
6	$\Sigma^0 \Delta^{+} K^+$	$3.27 \pm 20\,\%$	$\theta^{cms}_{\Delta^{+}}$	from $\Sigma^0 \Delta^{++} K^0$			res. mod.	2.6 ± 1.3	$\perp$
7	$\Sigma(1385)^+ n K^+$	$22.42 \pm 0.99 \pm 1.57\ ^{+3.04}_{-2.23}$	$\theta^{cms}_{\Sigma^{+*}}$	1.427 ± 0.3	0.407 ± 0.108	✓	[17]	17.905 ± 0.075	$\perp$
8	$\Delta(2050)^{++} n$	33 % feeding for $\Sigma^* n K^+$	θ^{cms}_{n}	1.27	0.35	✓	[17]	8.82 ± 0.13	$\top$
9	$\Sigma(1385)^+ p K^0$	$14.05 \pm 0.05\ ^{+1.79}_{-2.14} \pm 1.00$	$\theta^{cms}_{\Sigma^{+*}}$	1.42 ± 0.3	—	✓	[13]	16.101 ± 0.072	$\top$
10	$\Sigma(1385)^0 p K^+$	$6.0 \pm 0.48\ ^{+1.94}_{-1.06}$	$\theta^{cms}_{\Sigma^{0*}}$	from $\Sigma(1385)^+ n K^+$		✓	[17]	7.998 ± 0.069	$\top$
11	$\Lambda(1405) p K^+$	$9.2 \pm 0.9 \pm 0.7\ ^{+3.3}_{-1.0}$	—	—	—	✓	[18]	7.7 ± 3.0	$\perp$
12	$\Lambda(1520) p K^+$	$5.6 \pm 1.1 \pm 0.4\ ^{+1.1}_{-1.6}$	—	—	—	✓	[18]	7.2 ± 3.6	$\top$
13	$\Delta^{++} \Lambda(1405) K^0$	$5.0 \pm 20\,\%$	—	—	—		[23]	6.0 ± 1.6	$\top$
14	$\Delta^{++} \Sigma(1385)^0 K^0$	$3.5 \pm 20\,\%$	—	—	—		[23]	4.90 ± 0.46	$\top$
15	$\Delta^{+} \Sigma(1385)^+ K^0$	$2.3 \pm 20\,\%$	—	—	—		[23]	3.2 ± 1.1	$\top$
16	$\Delta^{+} \Lambda(1405) K^+$	$3.0 \pm 20\,\%$	—	—	—		compl. to above	4.2 ± 1.9	$\top$
17	$\Delta^{+} \Sigma(1385)^0 K^+$	$2.3 \pm 20\,\%$	—	—	—		compl. to above	3.2 ± 1.1	$\top$
			4-body channels						
18	$\Lambda p \pi^+ K^0$	$2.57 \pm 0.02\ ^{+0.21}_{-1.98} \pm 0.18$		—		✓	[13]	2.8 ± 1.5	$\top$
19	$\Lambda n \pi^+ K^+$	from $\Lambda p \pi^+ K^0$		—				2.8 ± 1.5	$\top$
20	$\Lambda p \pi^0 K^+$	from $\Lambda p \pi^+ K^0$		—				2.8 ± 1.4	$\top$
21	$\Sigma^0 p \pi^+ K^0$	$1.35 \pm 0.02\ ^{+0.10}_{-1.35} \pm 0.09$		—		✓	[13]	1.48 ± 0.76	$\top$
22	$\Sigma^0 n \pi^+ K^+$	from $\Sigma^0 p \pi^+ K^0$		—				1.48 ± 0.84	$\top$
23	$\Sigma^0 p \pi^0 K^+$	from $\Sigma^0 p \pi^+ K^0$		—				1.48 ± 0.75	$\top$

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.





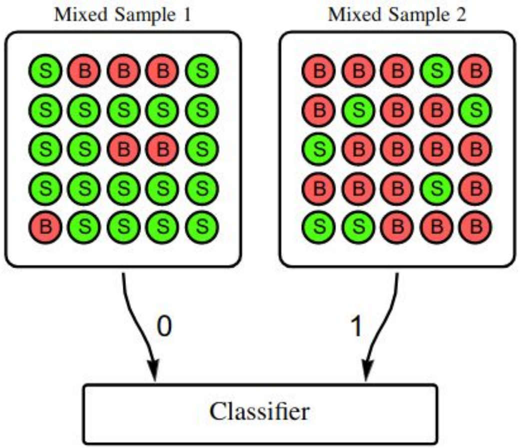
MIT: Alexander Amini, 2018 introtodeeplearning.com

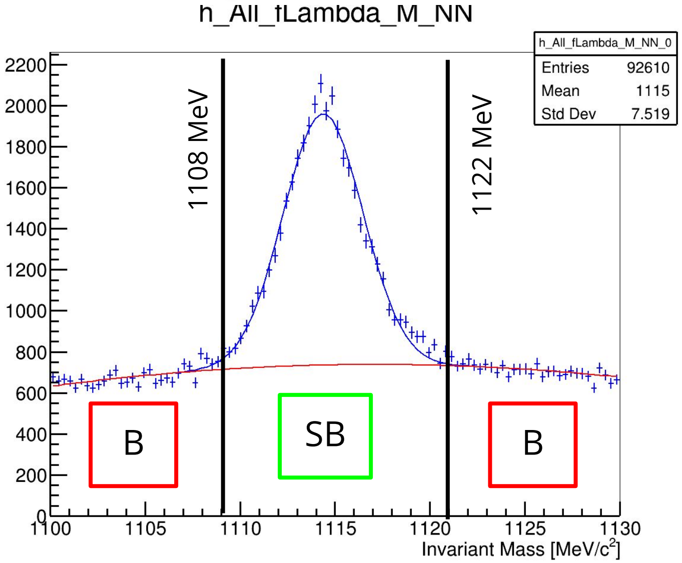
Λ(1115) classification with Neural Networks

- **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 $L_{S/B}$:

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

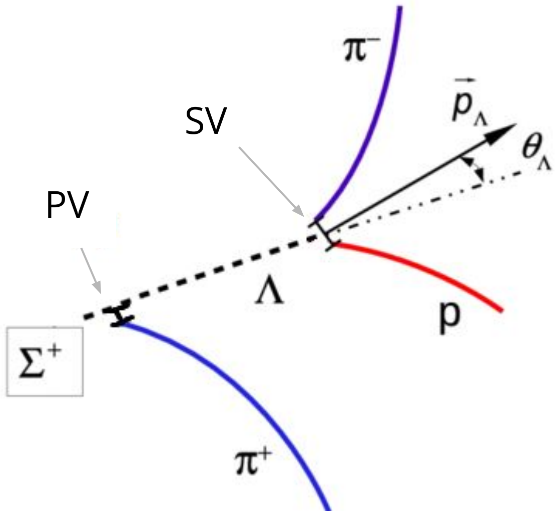
- Which is a monotonically increasing rescaling of the likelihood $L_{S/B}$ as long as f1 > f2.
- **Therefore, $L_{S/B}$ and $L_{M1/M2}$ define the same classifier.**





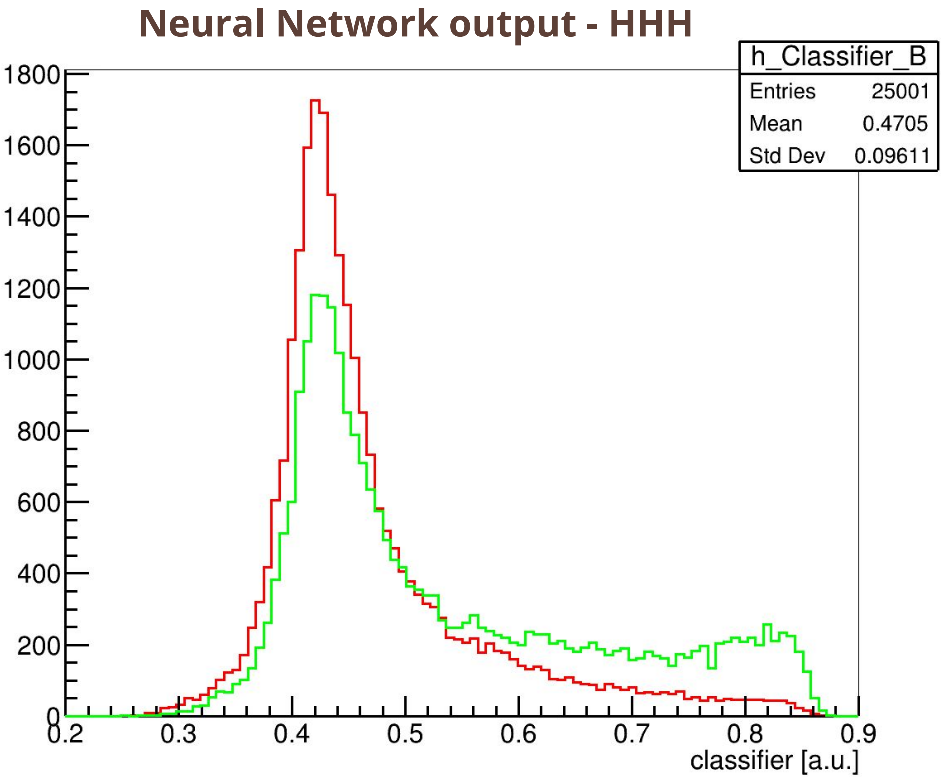
Neural Network training details

- Neural Network Parameters:
  - Type: Multi Layer Perceptron
  - Activation function: Sigmoid
  - Number of Hidden Layers: 4
  - Number of neurons in layer: 23



- List of variables utilized for neural network training:
  - **Lambda 1115 candidate (p π^-)**:
    - Minimal Track Distance (MTD)
    - Opening Angle (OA)
    - Momentum Theta
    - Momentum Phi
    - Decay Vertex coordinates (X, Y, Z)
    - Distance Z from Primary Vertex
    - Absolute Distance from Primary Vertex
  - **Sigma 1385**: **candidate (Λ π^+ = (p π^-) π^+)**:
    - Minimal Track Distance (MTD)
    - Opening Angle (OA)
    - Momentum Theta
    - Momentum Phi
    - Decay Vertex coordinates (X, Y, Z)
  - **Primary Vertex coordinates (X, Y, Z)**

Classifier



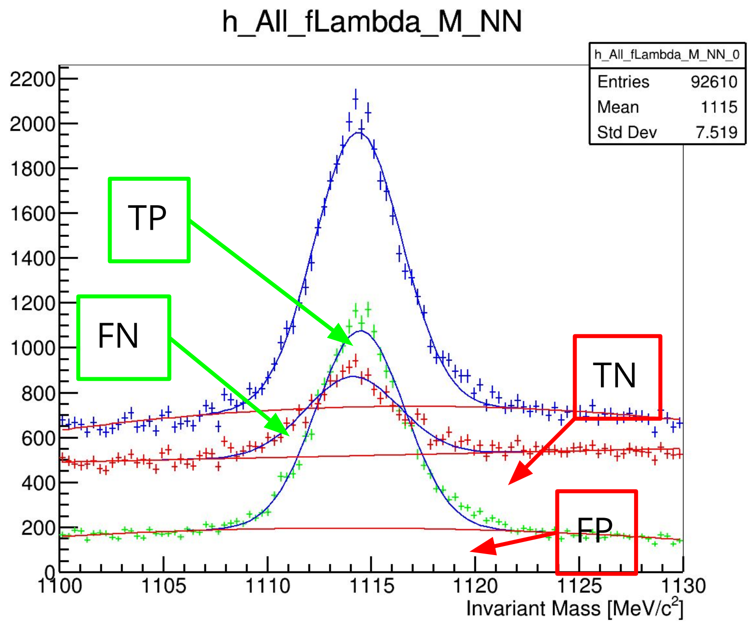
Classifier produced by training a Multilayer Perceptron type network on two sets of data, each containing 50000 events (currently only for HHH case):

- (Green) - Data in range of Lambda InvMass (1108 MeV - 1122 Mev) - Signal + Background
- (Red) - Data outside of range of Lambda InvMass (1108 MeV - 1122 Mev) - Just Background

Confusion matrix

- **Confusion matrix**, also known as an error matrix, is a specific table layout that allows visualization of the performance of an algorithm.
- Each **row of the matrix** represents the instances in a predicted class, while **each column** represents the instances in an actual class (or vice versa).
- The name stems from the fact that it makes it easy to see whether the system is confusing two classes (i.e. commonly mislabeling one as another).
- Possible combinations in binary classification:
    - **True Positive (TP)** - eqv. with hit
    - **True Negative (TN)** - eqv. with correct rejection
    - **False Positive (FP)** - eqv. with false alarm, type I error
    - **False Negative (FN)** - eqv. with miss, type II error

		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



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:

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

- False Positive Rate:

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