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

- $\Lambda(1520)$ structure is controversially discussed:
  - Excited quark state
  - Baryon – meson molecule: $\Lambda(1520)$ 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 $\Sigma^*(1385) - \pi$ loop in medium (p+A) → Important implication for properties of $\Lambda(1520)$
  - $M\downarrow(1500-1490\text{ MeV})$
  - $\Gamma\uparrow(40-70\text{ MeV})$
  - BR($\Lambda\pi\pi\pi$) $\uparrow(\sim25\%)$
  - Changes for $\Sigma^*(1385)$ even stronger

- Hadronic decays of $\Lambda(1520) \rightarrow \Lambda\pi^+\pi^-$ in p+p and p+A, particularly interesting:
  - Currently poorly studied
  - Complementary channel to Dalitz decay: $\Lambda(1520) \rightarrow \Lambda(1116)e^-e^+$
  - High branching ratio compared to Dalitz decay, BR = 6.6·10^{-2}
Event selection

- Track reconstruction and Particle Identification (PID) → based on $\beta$ vs mom or dE/dx vs mom distributions.
- Track combinations for $\Lambda(1520)$ ($p,\pi^-,\pi^+,\pi^-$) and $\Sigma^*(1385)$ ($p,\pi^-,\pi^+$) reconstruction.
- Minimal bias conditions for $\Lambda(1115)$ background reduction use cuts on:
  - Minimal Track Distance: $\text{MTD}(p,\pi^-)$
  - Vertexes Positions and Distance
  - In $p+p$ Missing Mass ($\text{MM}_{p\pi^-} > M_{\text{nucleon}} + M_{\text{kaon}}$)
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.
**Σ⁺(1385) in p+p @ 4.5 GeV**

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

**Breit-Wigner**

\[
\text{Breit-Wigner} \propto \frac{q^2}{q_0^2} \frac{m^2_0 \Gamma_0^2}{(m_0^2 - m^2)^2 + m_0^2 \Gamma^2},
\]

\[
\Gamma = \Gamma_0 \frac{m_0 q^3}{m_0^3} F_1(q),
\]

\[
F_1(q) = \frac{1 + (q R_0)^2}{1 + (qR)^2},
\]

- **q** - momentum
- **q₀** - momentum that corresponds to the mass m₀
- **m** - mass variable
- **Γₐ₀** - resonance width
- **Γ** - mass-dependent resonance width
- **F₁(q)** - Blatt-Weisskopf parameter
- **R = 1/197.327 MeV⁻¹** - centrifugal barrier parameter.

**Breit-Wigner**:

- **M₀ = 1378.7 +/- 1.4 MeV/c²**
- **Γ₀ = 32.2 +/- 4.1 MeV/c²**

~4% total statistics
$\Sigma^+(1385)$ in $p+p \@ 3.5\text{ GeV}$

**Inclusive analysis**
- (Cyan) - all data minus sideband
- (Blue) - Signal + Background fit
- (Green) - Signal (Breit-Wigner) fit
- (Red) - Background (polynomial) fit

**Exclusive analysis**

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

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

**Entire run statistics**

- Entries: 8476
- Mean: 1434
- Std Dev: 98.06

**PDG:**
- $M_0 = 1382.80 \pm 0.35 \text{ MeV/c}^2$
- $\Gamma_0 = 36.0 \pm 0.7 \text{ MeV/c}^2$

Agakishiev, Geydar et al. (2012). Baryonic resonances close to the $K^0N$ threshold: The case of $\Sigma(1385)^+$ 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:

  - Main background contributions in p+p:
    - Δ⁺⁺π⁻Δ⁺⁺π⁻ channel
    - p+p→Λ[π⁺π⁻][K⁰][π⁺π⁻]π⁺π⁺

- **Λ(1520) signal extraction** based on sideband.
Λ(1520) in p+p and p+Nb @ 3.5 GeV

- Λ(1520) invariant mass reconstruction results:

<table>
<thead>
<tr>
<th></th>
<th>(M_{Λ0ππ^-} ) [MeV]</th>
<th>(σ) [MeV]</th>
<th>(Γ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>pNb</td>
<td>1519 ± 4.2</td>
<td>14.7</td>
<td>24 ± 10</td>
</tr>
<tr>
<td>pp</td>
<td>1509 ± 4.7</td>
<td>14.7</td>
<td>15.6 ± 1</td>
</tr>
</tbody>
</table>

- 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:

\[\sigma_{p+p→Λ(1520)X} = 7.1 ± 1.1 ± \frac{0.0}{2.14} \ \mu b\]
\[\sigma_{p+Nb→Λ(1520)X} = 4.97 ± 0.45 ± \frac{3.58}{2.53} \ \text{mb}\]

- 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)
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

- $\Lambda (1520)$ 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 $\Lambda (1520)$
  - Dalitz plot $\Lambda \pi \pi$ to analyse $\Sigma^*(1385)-\pi$ decay branch
  - Reference for Dalitz $\Lambda (1520)$, $\Sigma^*(1385) \to \Lambda e^+e^-$ decays (branching ratio)

~100x (Lumi x cross section) increase in statistics for $\Lambda (1520)$ expected in 4,5 GeV in comparison to 3,5 GeV.
BACKUP
**Σ⁺(1385) in p+p at 4.5 GeV**

- 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) \((p+π^-) + π^+\) (based on \(β\) vs mom distributions)
  - \(\text{InvMass}_{\Lambda(p\,π^-)} \in (1080\,\text{MeV};1150\,\text{MeV})\) - Relevance window
  - Minimal Track Distance: \(\text{MTD}(p, π^-) < 20\,\text{mm}\)
  - \(\text{Vertex}_Z_{\text{Primary}} < \text{Vertex}_Z_{\Lambda}\)
  - \(\text{Dist}(\text{Vertex}_{\text{Primary}}; \text{Vertex}_{\Lambda}) > 10\,\text{mm}\)
  - \(\text{MissMass}_{\Lambda} > \text{Mass}_{\text{nucleon}} + \text{Mass}_{\text{kaon}}\)

- **Sigma (1385)** candidates reconstruction - conditions:
  - \(\text{MissMass}_{\Sigma(p\,π^-π^+)} > \text{Mass}_{\text{nucleon}} + \text{Mass}_{\text{kaon}}\) (more restrictive than MM cut for Lambda Cand)
### 3-body channels

<table>
<thead>
<tr>
<th>id</th>
<th>reaction</th>
<th>$\sigma_0^{(id)}$ cross section [nb]</th>
<th>$\varphi_{\ell}$</th>
<th>$\varphi_{\ell}^{\text{ms}}$</th>
<th>$\ell(a_2, a_4)$</th>
<th>H</th>
<th>notes</th>
<th>fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\Lambda p K^+$</td>
<td>35.26 ± 0.43 $^{+3.55}_{-2.83}$</td>
<td>0.798</td>
<td>0.134</td>
<td>✓</td>
<td>[16]</td>
<td>$38.835 ± 0.026$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$\Sigma^0 p K^+$</td>
<td>16.5 ± 20 %</td>
<td>0.034 ± 0.241</td>
<td>—</td>
<td>—</td>
<td>[21] + calc.</td>
<td>$19.800 ± 0.004$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$\Lambda \Delta^{++} K^0$</td>
<td>29.45 ± 0.08 $^{+1.67}_{-1.41}$ $\pm 2.06$</td>
<td>1.49 ± 0.3</td>
<td>—</td>
<td>✓</td>
<td>[13]</td>
<td>$32.10 ± 0.11$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$\Sigma^0 \Delta^{++} K^0$</td>
<td>9.26 ± 0.05 $^{+1.41}_{-0.31}$ $\pm 0.65$</td>
<td>0.08 ± 0.02</td>
<td>—</td>
<td>✓</td>
<td>[13]</td>
<td>8.5 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$\Lambda \Delta^{++} K^+$</td>
<td>9.82 ± 20 %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>res. mod.</td>
<td>$11.78 ± 0.15$</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$\Sigma^0 \Delta^{++} K^+$</td>
<td>3.27 ± 20 %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>res. mod.</td>
<td>2.6 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$\Sigma(1385)^+ n K^+$</td>
<td>22.42 ± 0.99 $^{+1.57}_{-2.23}$ $\pm 3.04$</td>
<td>1.427 ± 0.3 $\pm 4.07 ± 0.108$</td>
<td>✓</td>
<td>[17]</td>
<td>$17.965 ± 0.075$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$\Delta (2050)^++ n$</td>
<td>33 % feeding for $\Sigma^* n K^+$</td>
<td>1.27</td>
<td>0.35</td>
<td>✓</td>
<td>[17]</td>
<td>$8.82 ± 0.13$</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$\Sigma(1385)^0 n K^+$</td>
<td>14.05 ± 0.05 $^{+1.79}_{-1.06}$ $\pm 1.00$</td>
<td>1.42 ± 0.3</td>
<td>—</td>
<td>✓</td>
<td>[13]</td>
<td>$16.101 ± 0.072$</td>
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<tr>
<td>10</td>
<td>$\Sigma(1385)^0 p K^+$</td>
<td>6.0 ± 0.48 $^{+1.34}_{-1.06}$ $\pm 1.33$</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>[17]</td>
<td>$7.998 ± 0.069$</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>$\Lambda (1405) p K^+$</td>
<td>9.2 ± 0.9 ± 0.7 $^{+1.3}_{-1.0}$</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>[18]</td>
<td>$7.7 ± 3.0$</td>
<td></td>
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<tr>
<td>12</td>
<td>$\Lambda (1520) p K^+$</td>
<td>5.6 ± 1.1 ± 0.4 $^{+1.1}_{-1.6}$</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>[18]</td>
<td>$7.2 ± 3.6$</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>$\Delta^{++} \Lambda (1405) K^0$</td>
<td>5.0 ± 20 %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>[23]</td>
<td>$6.0 ± 1.6$</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>$\Delta^{++} \Sigma (1385) K^0$</td>
<td>3.5 ± 20 %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>[23]</td>
<td>$4.90 ± 0.46$</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>$\Delta^{++} \Sigma (1385)^0 K^0$</td>
<td>2.3 ± 20 %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>[23]</td>
<td>$3.2 ± 1.1$</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>$\Delta^{++} \Sigma (1385)^0 K^+$</td>
<td>3.0 ± 20 %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>compl. to above</td>
<td>$4.2 ± 1.9$</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>$\Delta^{++} \Sigma (1385)^0 K^+$</td>
<td>2.3 ± 20 %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>compl. to above</td>
<td>$3.2 ± 1.1$</td>
<td></td>
</tr>
</tbody>
</table>

### 4-body channels

<table>
<thead>
<tr>
<th>id</th>
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<th>H</th>
<th>notes</th>
<th>fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>$\Lambda p \pi^+ K^0$</td>
<td>2.57 ± 0.02 $^{+0.21}_{-0.18}$ $\pm 0.18$</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>[13]</td>
<td>$2.8 ± 1.5$</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>$\Lambda n \pi^+ K^+$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$2.8 ± 1.5$</td>
</tr>
<tr>
<td>20</td>
<td>$\Lambda \pi^0 K^+$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$2.8 ± 1.4$</td>
</tr>
<tr>
<td>21</td>
<td>$\Sigma^0 p \pi^+ K^+$</td>
<td>1.35 ± 0.02 $^{+0.10}_{-0.35}$ $\pm 0.09$</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>[13]</td>
<td>$1.48 ± 0.76$</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>$\Sigma^0 n \pi^+ K^+$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$1.48 ± 0.84$</td>
</tr>
<tr>
<td>23</td>
<td>$\Sigma^0 p \pi^0 K^+$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$1.48 ± 0.75$</td>
</tr>
</tbody>
</table>
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.

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**Activation Functions**

\[ y = g(\theta_0 + \mathbf{x}^T \mathbf{\theta}) \]

- Example: sigmoid function
  \[ g(x) = \sigma(x) = \frac{1}{1 + e^{-x}} \]

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 $L_{S/B}$:
  \[
  L_{M1/M2} = \frac{p_{M1}}{p_{M2}} = \frac{f_1 p_S + (1 - f_1) p_B}{f_2 p_S + (1 - f_2) p_B} = \frac{f_1 L_{S/B}}{f_2 L_{S/B}} + \frac{(1 - f_1)}{(1 - f_2)},
  \]

- Which is a monotonically increasing rescaling of the likelihood $L_{S/B}$ as long as $f_1 > f_2$.

- 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** ($p \pi^-$):
    - 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 ($\Lambda \pi^+ = (p \pi^-) \pi^+$):
    - 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
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:
\[
TPR = \frac{TP}{P} = \frac{TP}{TP + FN} = 1 - FNR
\]

False Positive Rate:
\[
FPR = \frac{FP}{N} = \frac{FP}{FP + TN} = 1 - TNR
\]