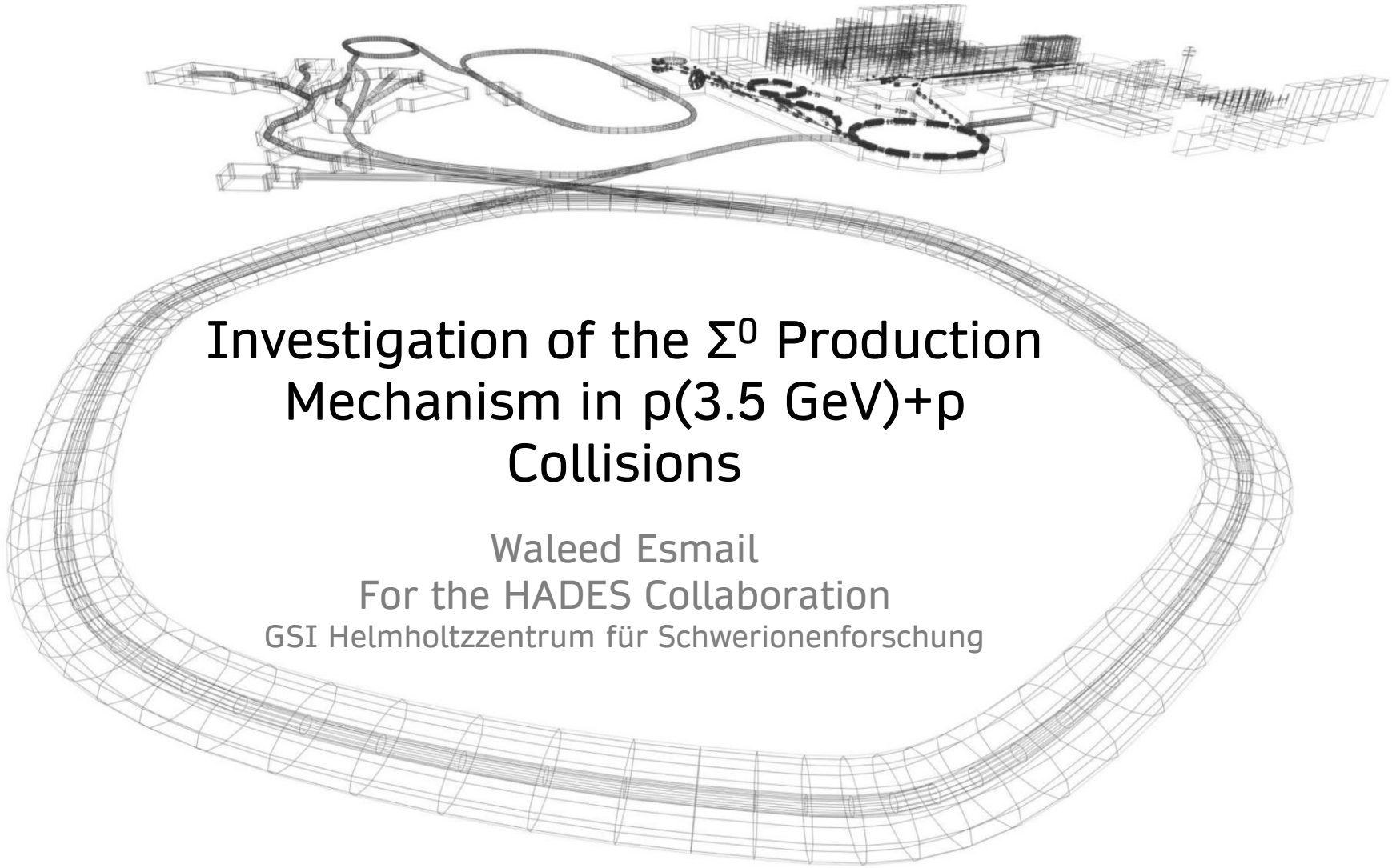


Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p Collisions

Waleed Esmail
For the HADES Collaboration
GSI Helmholtzzentrum für Schwerionenforschung

An Overview

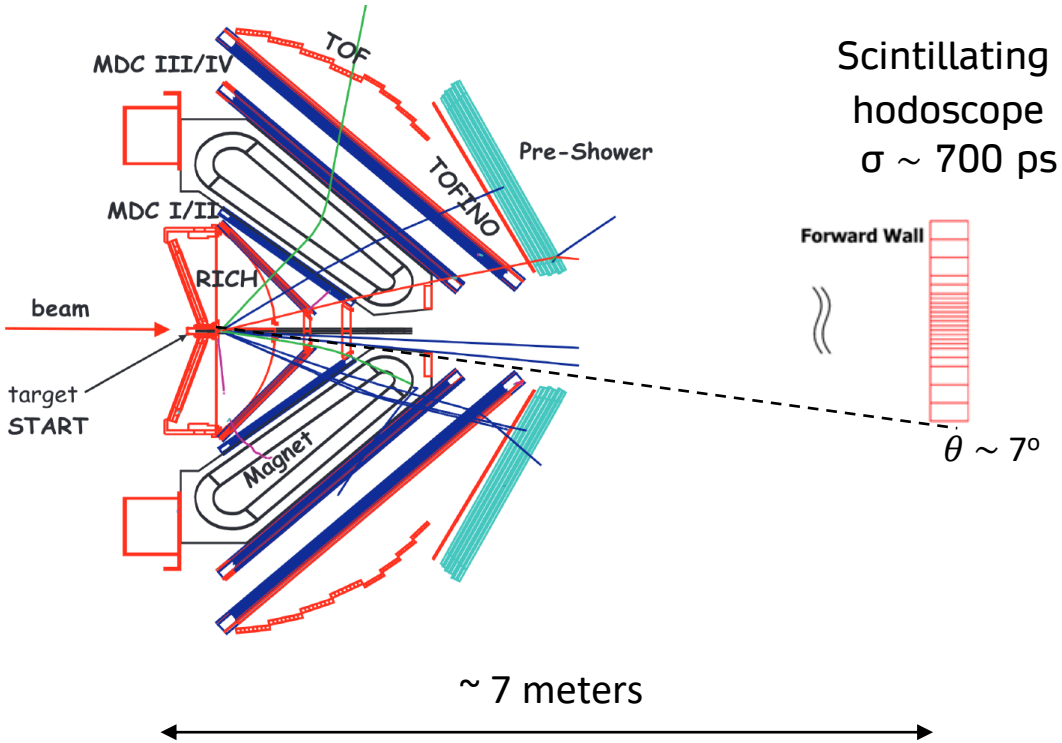
Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p collisions at HADES experiment

- Study of hyperon production serves as a tool to study QCD at the confinement scale
- Crucial for model calculations of heavy-ion collisions
- There are few measurements for Σ^0 compared to Λ hyperon production
- Focus on the **exclusive reaction**
  $p(3.5GeV)+p \rightarrow p + K^+ + \Sigma^0$

  $\Sigma^0 \rightarrow \Lambda\gamma$ (BR~100%) and $\Lambda \rightarrow p\pi^-$ (BR~64%)

$$pp \rightarrow pK^+ p\pi^- \gamma$$

High **A**cceptance **D**i-**E**lectron **S**pectrometer
HADES



Scintillating hodoscope
σ ~ 700 ps

Procedure

Analysis strategy:

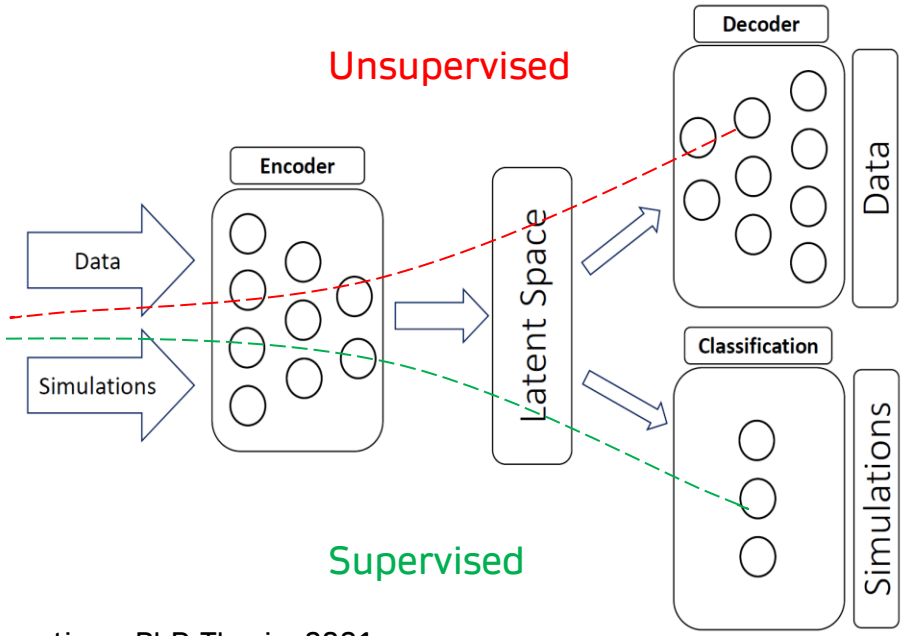
1. Signal Reconstruction
   - Particle Identification (PID)
   - Intermediate Λ reconstruction
   - Kinematic Refit

2. Physics of the Σ^0 hyperon production
   - Study of final state particles in various reference frames
     CMS, Gottfried-Jackson and helicity frames
   - Partial Wave Analysis (PWA)

PID

- Statement of the problem: identify the type of the charged tracks (**p**, K^+, π^+)
- PID was performed based on **D**eep **L**earning (**DL**) techniques
- Potential solution is **semi-supervised** training on *simulations* and *data* using an **autoencoder**
- Training features**: momentum components, energy loss and time of flight.**
- Inspired by the **M2 model*** Dropout were used to quantify the **network uncertainty**§

Particle	Accuracy %
p	98 %
K^+	76 %
π^+	92 %



* Durk P Kingma et al. "Semi-supervised Learning with Deep Generative Models"

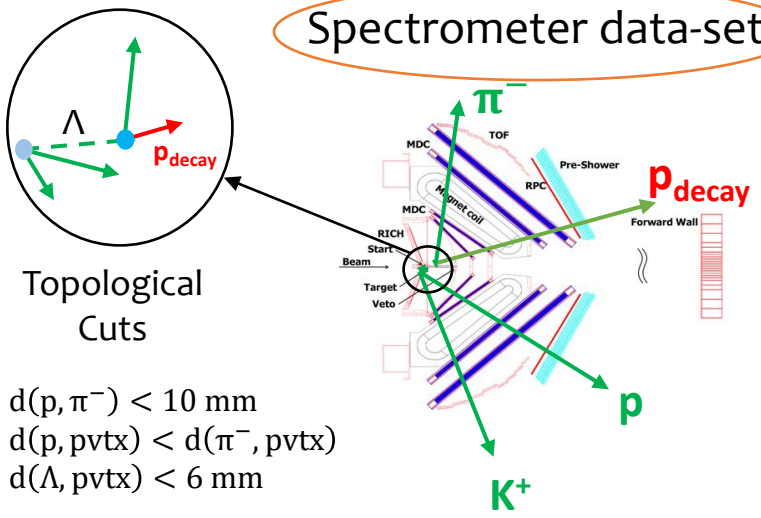
§ W. Esmail, Deep learning for track finding and the reconstruction of excited hyperons in proton induced reactions, PhD Thesis, 2021

Λ Reconstruction

Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p collisions at HADES experiment

$$pp \rightarrow p(\Lambda)K^+\gamma \rightarrow p(\mathbf{p_{decay}}\pi^-)K^+\gamma$$

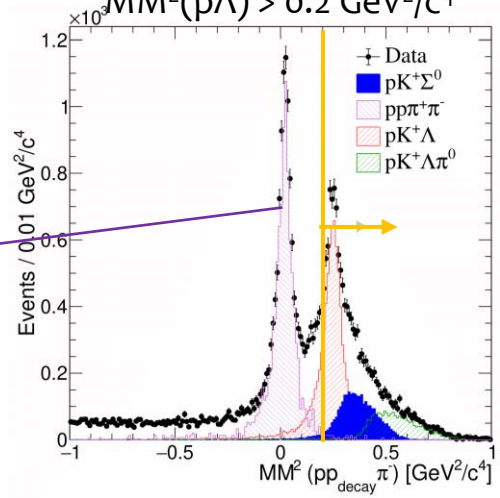
Spectrometer data-set



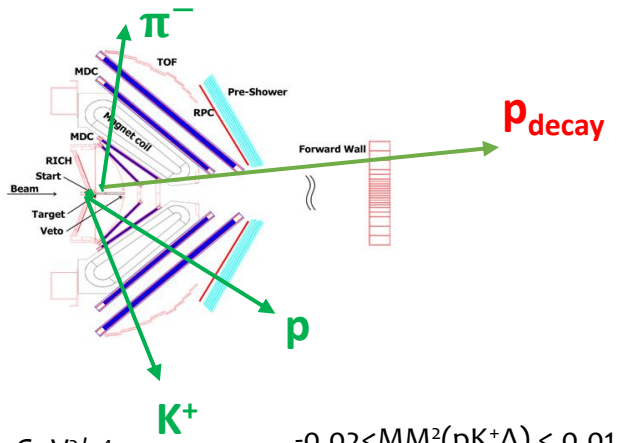
1. $d(p, \pi^-) < 10$ mm
2. $d(p, pvtx) < d(\pi^-, pvtx)$
3. $d(\Lambda, pvtx) < 6$ mm

$MM^2(p\Lambda) > 0.2$ GeV²/c⁴

pp π^- π^+

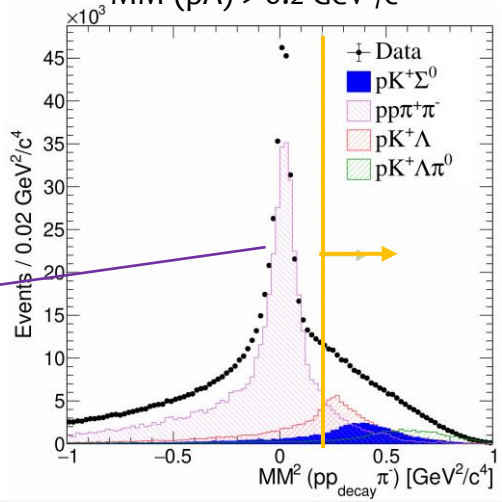


Wall data-set

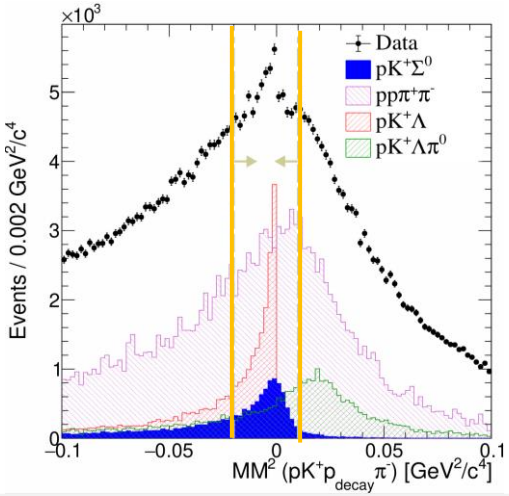


$MM^2(p\Lambda) > 0.2$ GeV²/c⁴

pp π^- π^+



$-0.02 < MM^2(pK^+\Lambda) < 0.01$



Λ Reconstruction

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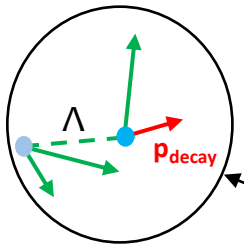
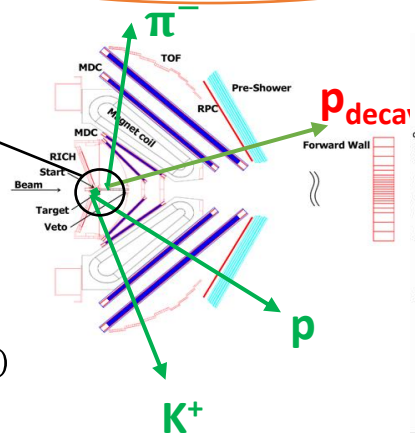
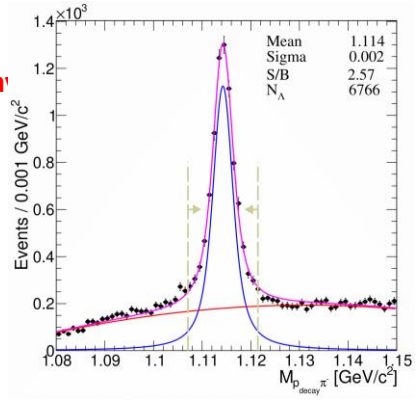


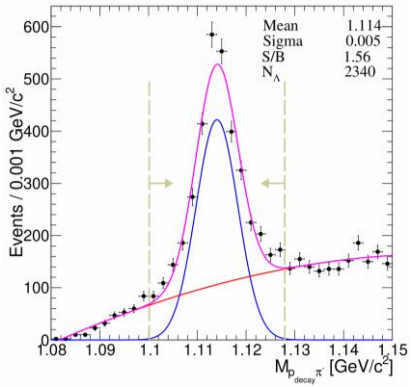
Topological Cuts

1. $d(p,\pi^-) < 10$ mm
2. $d(p,pvtx) < d(\pi^-,pvtx)$
3. $d(\Lambda,pvtx) < 6$ mm

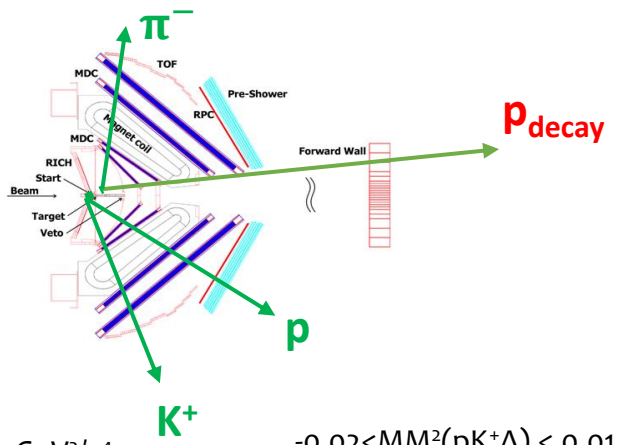
Spectrometer data-set



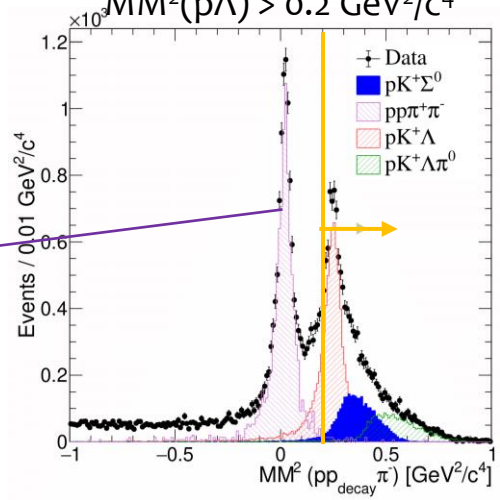




Wall data-set

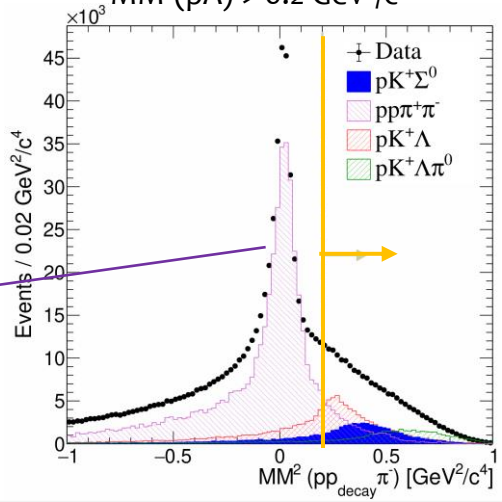


$MM^2(p\Lambda) > 0.2$ GeV²/c⁴



pp π⁻ π⁺

$MM^2(p\Lambda) > 0.2$ GeV²/c⁴



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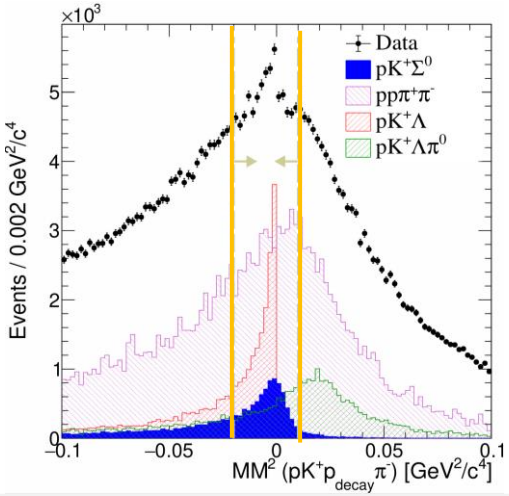


Kinematic Refit

1. $pp \rightarrow pK^+\Lambda\,\gamma \rightarrow pK^+\,p\pi^-\,\gamma$
2. $pp \rightarrow pK^+\Lambda\,\gamma \rightarrow pK^+\,p\pi^-\,\gamma$

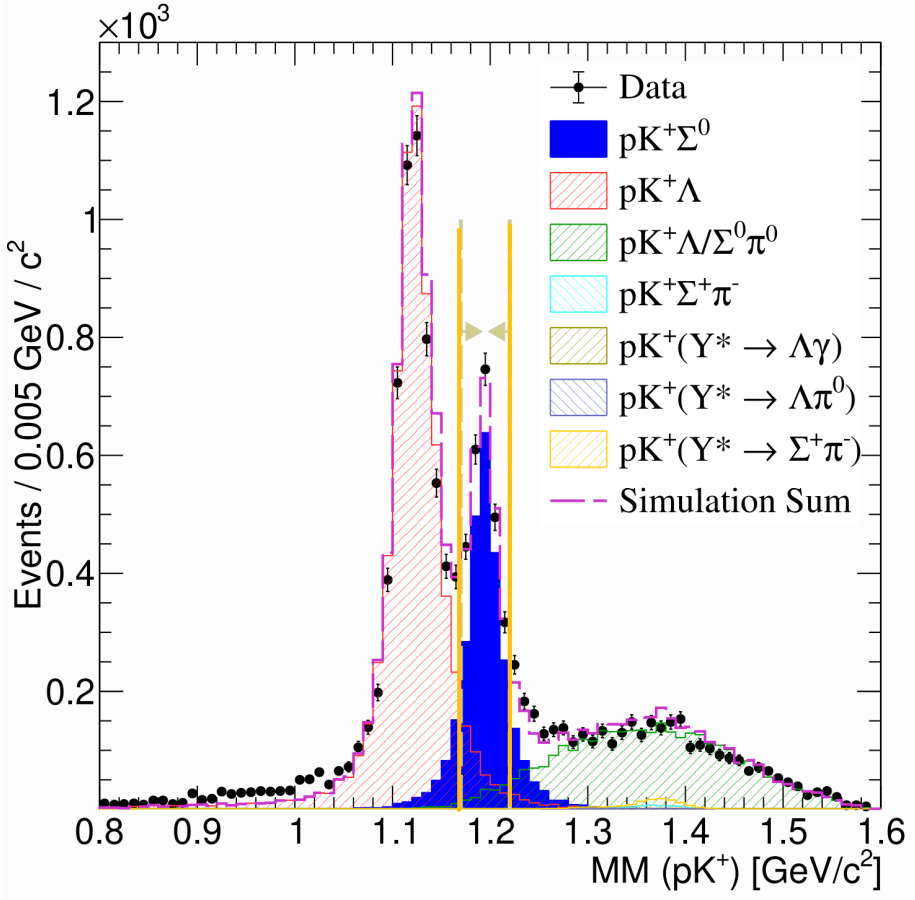
$$M_\Lambda = 1.115683\ GeV/c^2$$
$$M_\gamma = 0\ GeV/c^2$$

$$\chi^2 = (y-\eta)^T V^{-1}(y-\eta) \approx minimum$$
$$f(\eta,\xi) = 0$$

- Events with **P(χ^2) > 0.01** were selected

$$1.170 < MM(pK^+)[GeV/c^2] < 1.220$$

- **2613** Σs: **58% HADES**
  42% Wall
- The signal purity ~ 81%
- Background: $pK^+\Lambda$ ~ 14%
  $pK^+\Lambda\pi^0$ ~ 5%



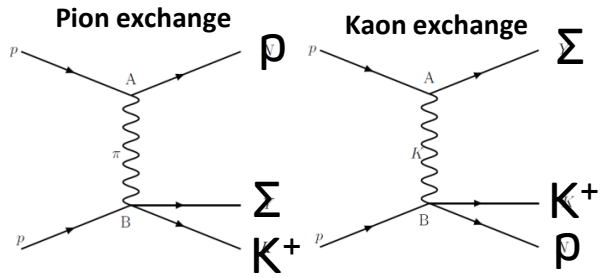
Physics Results

Physics Results

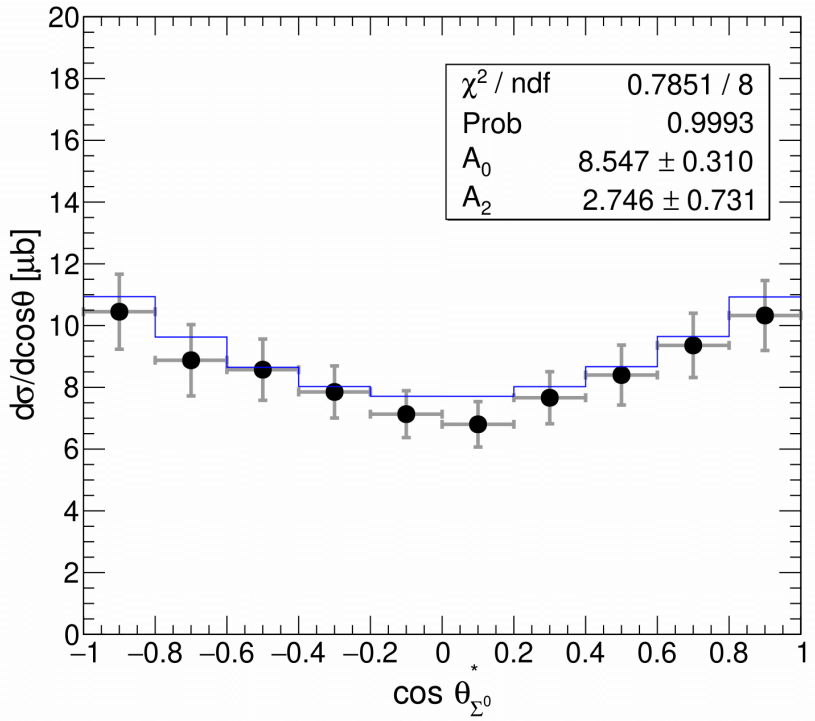
Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p collisions at HADES experiment

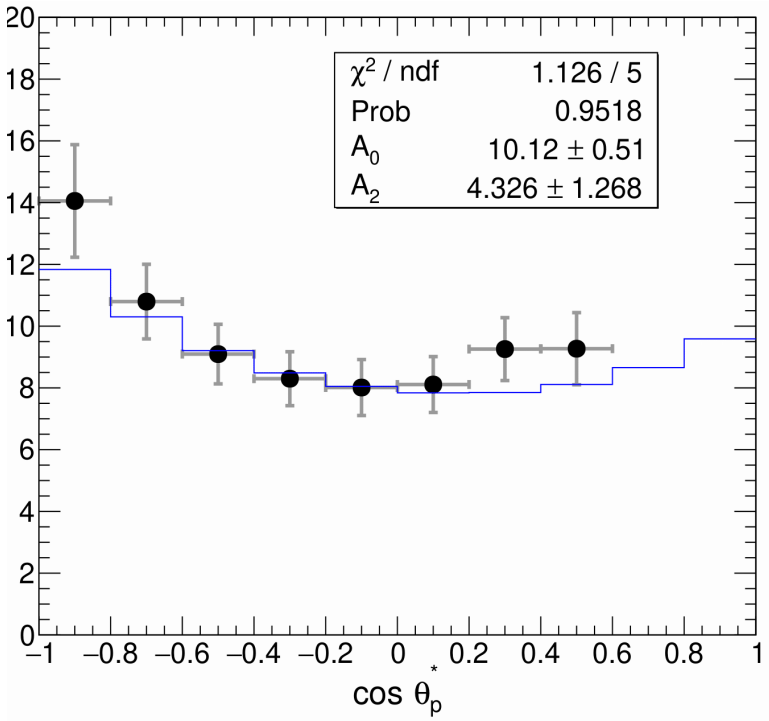
- Data were investigated in three reference frames $pK^+\Sigma^0$

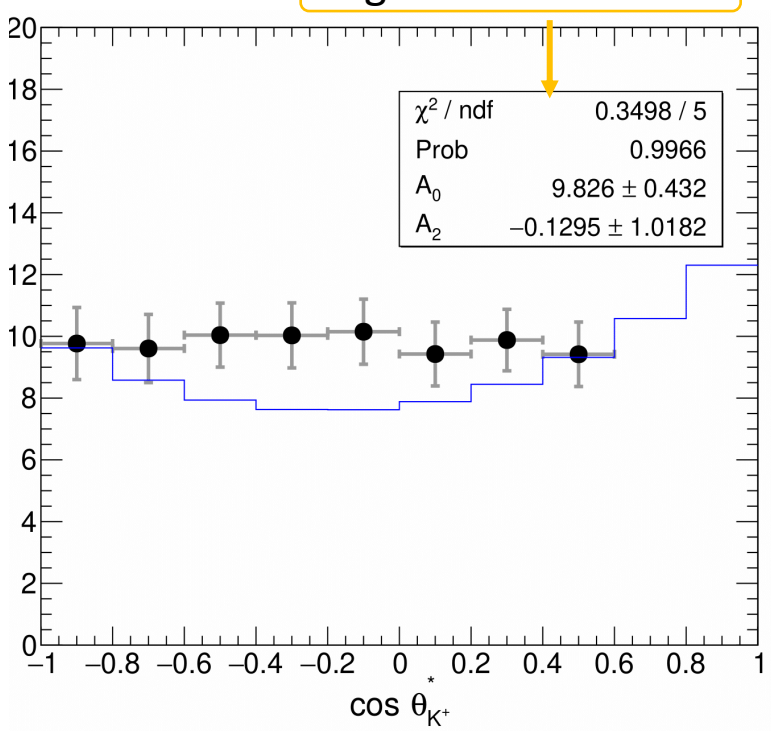
1. Center of Mass Frames → exchange boson properties
2. Gottfried-Jackson Frames → exchange boson properties & intermediate resonances
3. Helicity Frames → "projection" of the Dalitz plot



Legendre Parameters







Phase space simulations are weighted by $cos\theta^{cms}_{\Sigma^0}$ and $cos\theta^{RFp\Sigma}_{p_{b,t},p}$ obtained from data

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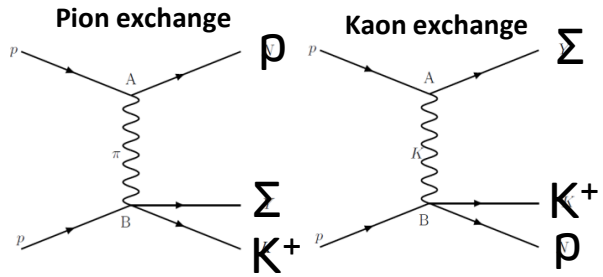

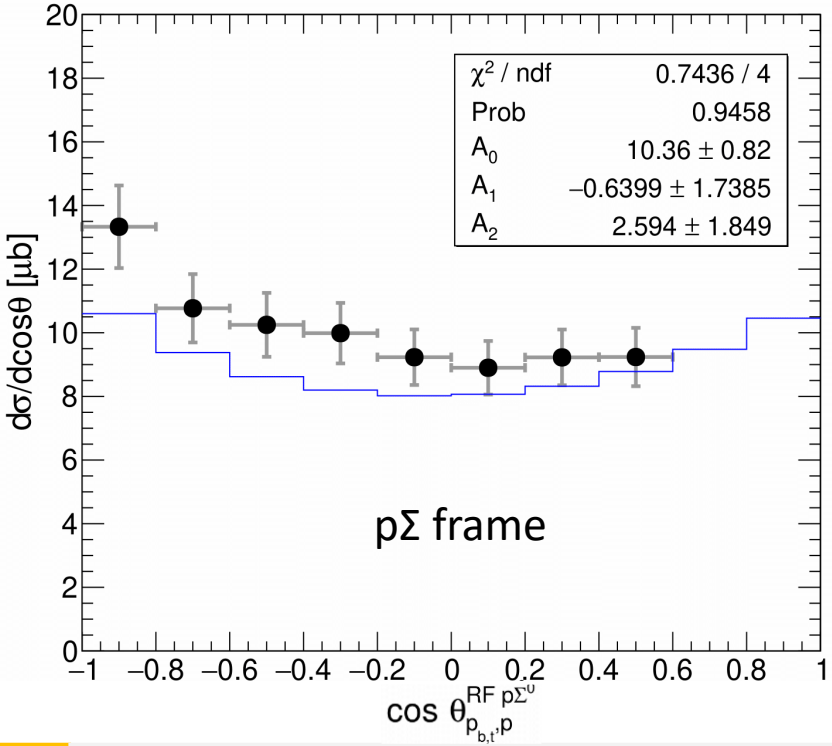

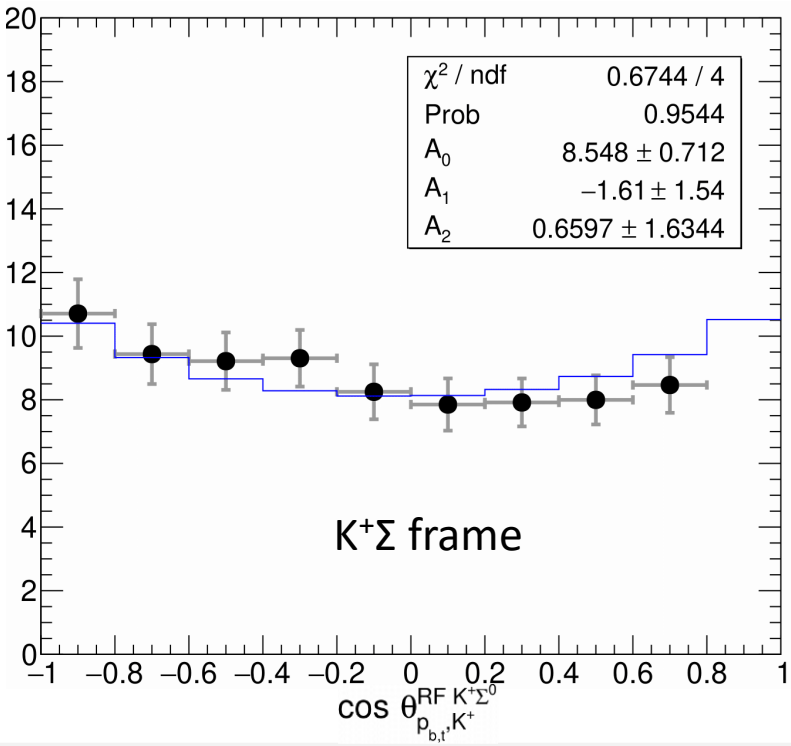

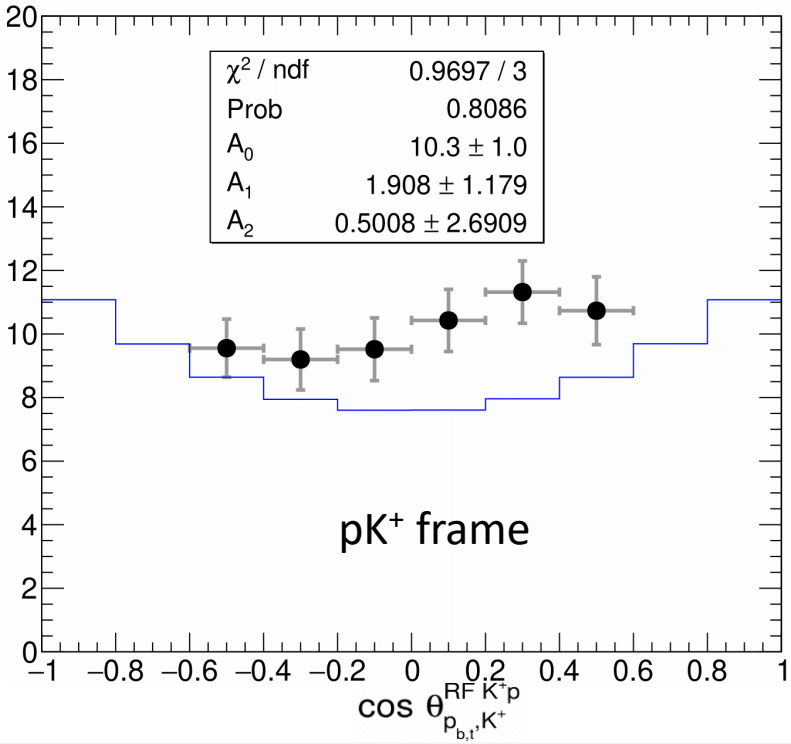

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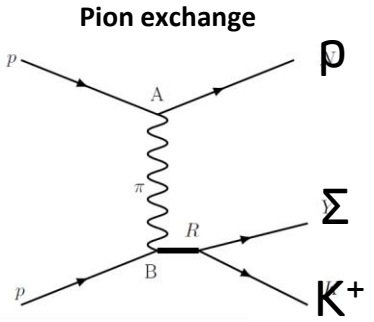

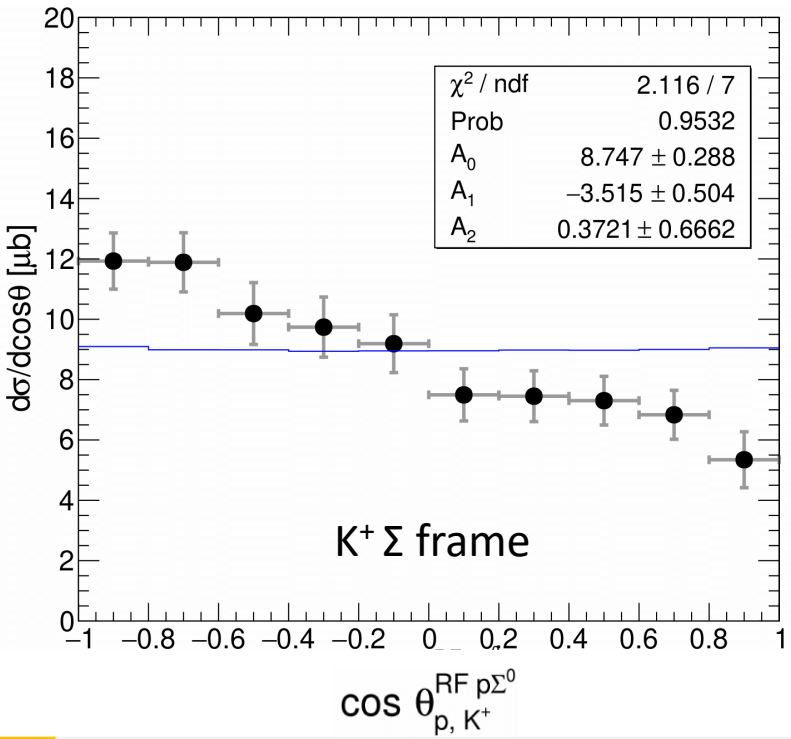

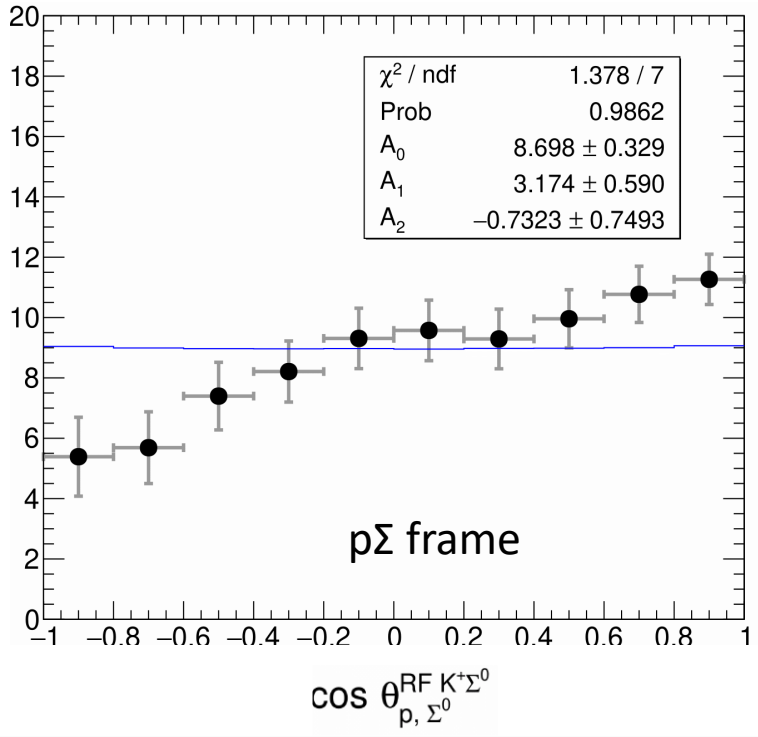

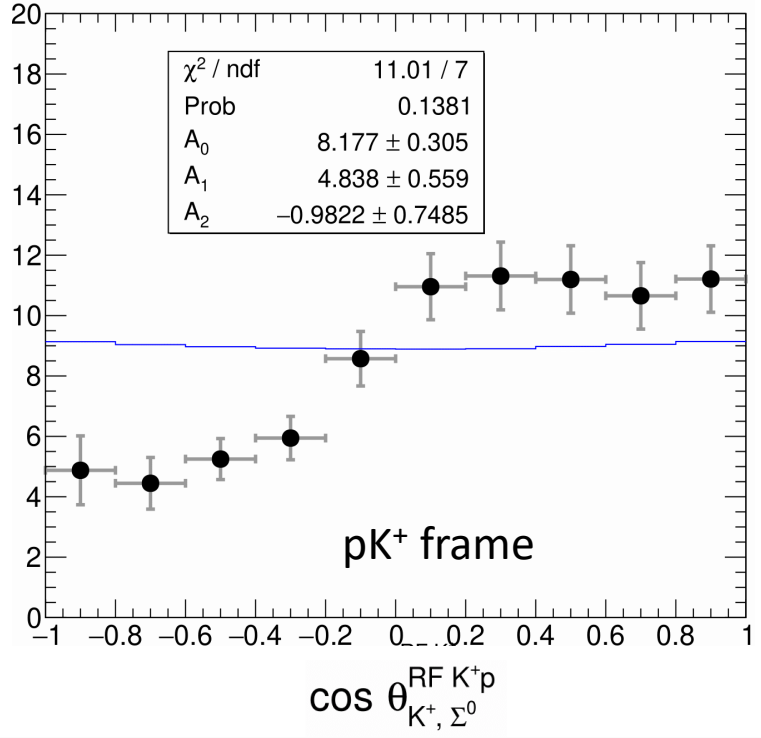

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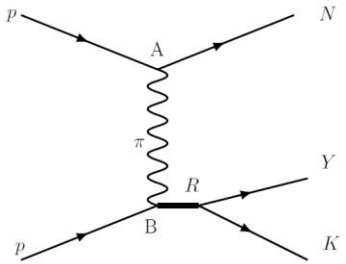
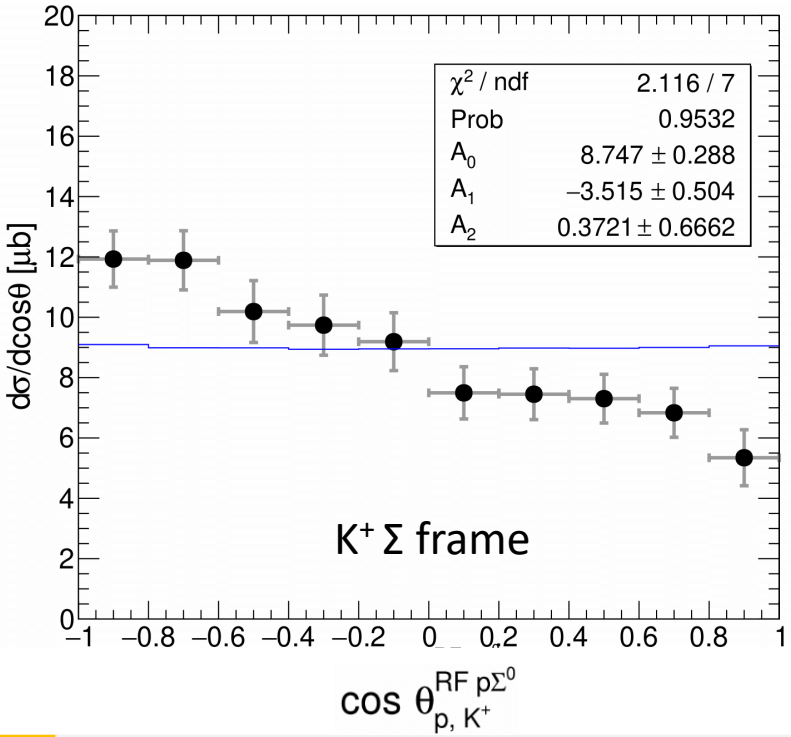
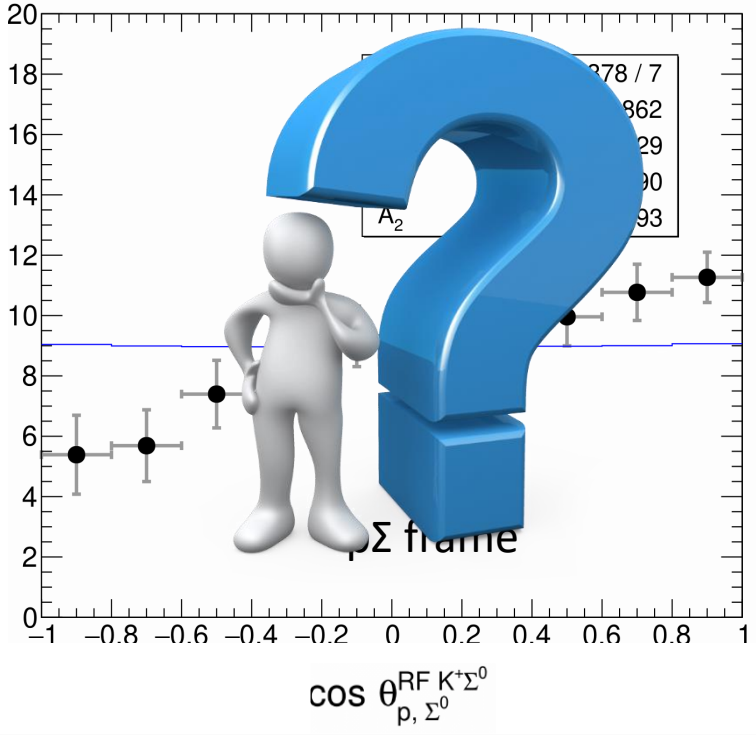
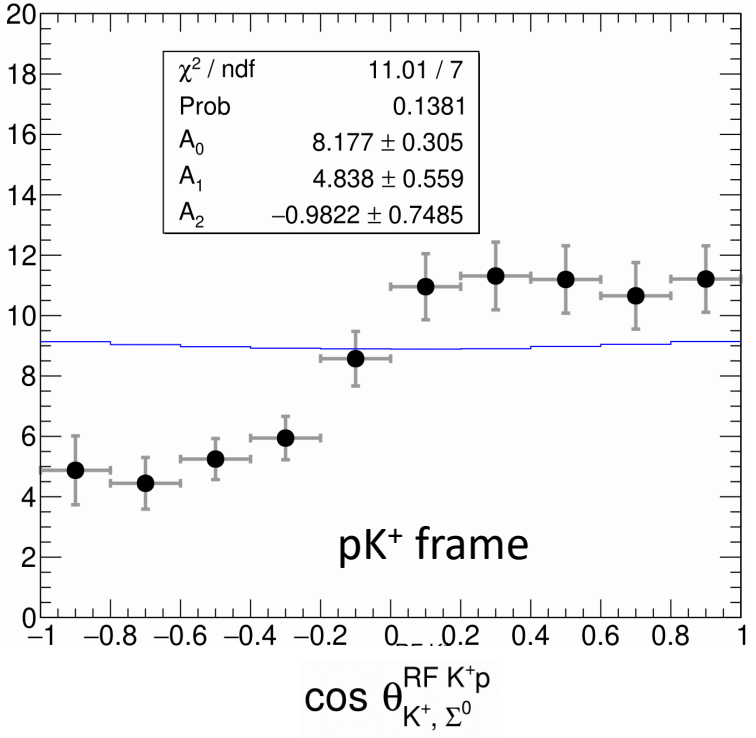
Pion exchange









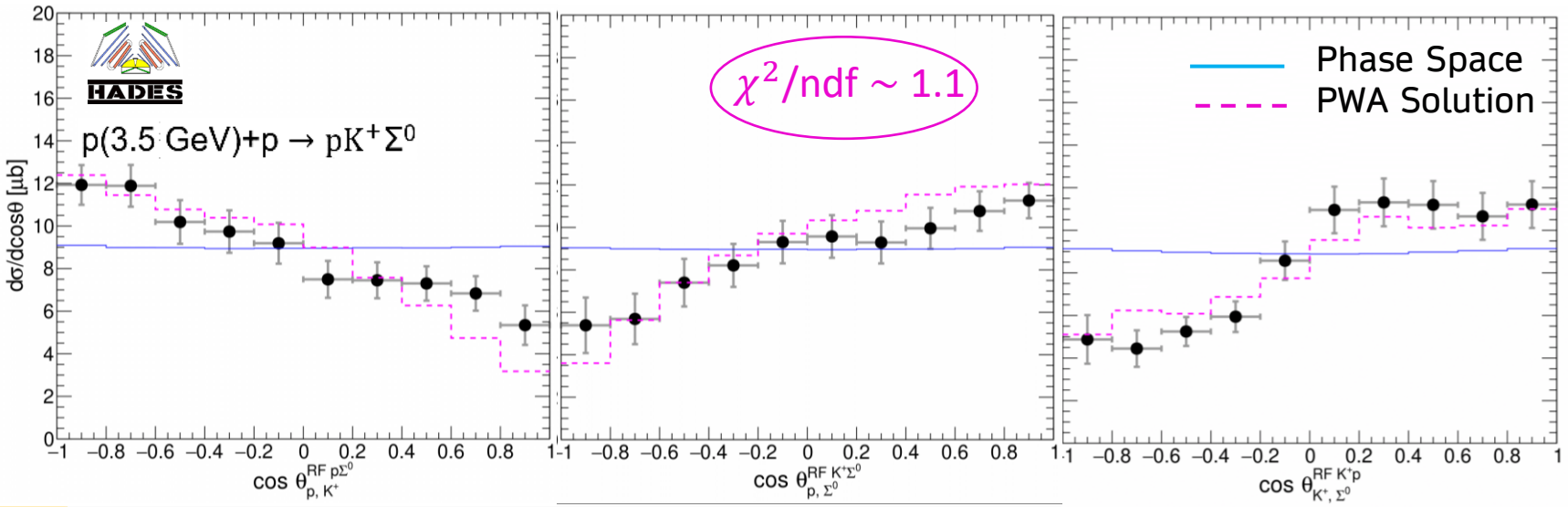
Partial Wave Analysis

- **P**artial **W**ave **A**nalysis (**PWA**) was performed in order to estimate resonant contributions
- PWA aims to determine the transition amplitude
- Tool used: **Bonn-Gatchina PWA** (log-likelihood minimization)

Helicity Frames Revisited: PWA solution provides a good description of angular distributions

- Nucleon resonances involved are:

  $N^*(1710)$ ($J^P = 1/2^+$), $N^*(1900)$ ($J^P = 3/2^+$) and $\Delta^*(1900)$ ($J^P = 1/2^-$)



$$pp \rightarrow pR \rightarrow pK^+\Sigma^0$$

- Eight resonances:

$N^*(1710)$, $N^*(1875)$, $N^*(1880)$, $N^*(1895)$, $N^*(1900)$, $\Delta^*(1900)$, $\Delta^*(1910)$ and $\Delta^*(1920)$

- Eight non-resonant contributions:

$^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^3F_2$, $^3F_3$ and $^3F_4$

Production Cross Section

Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p collisions at HADES experiment

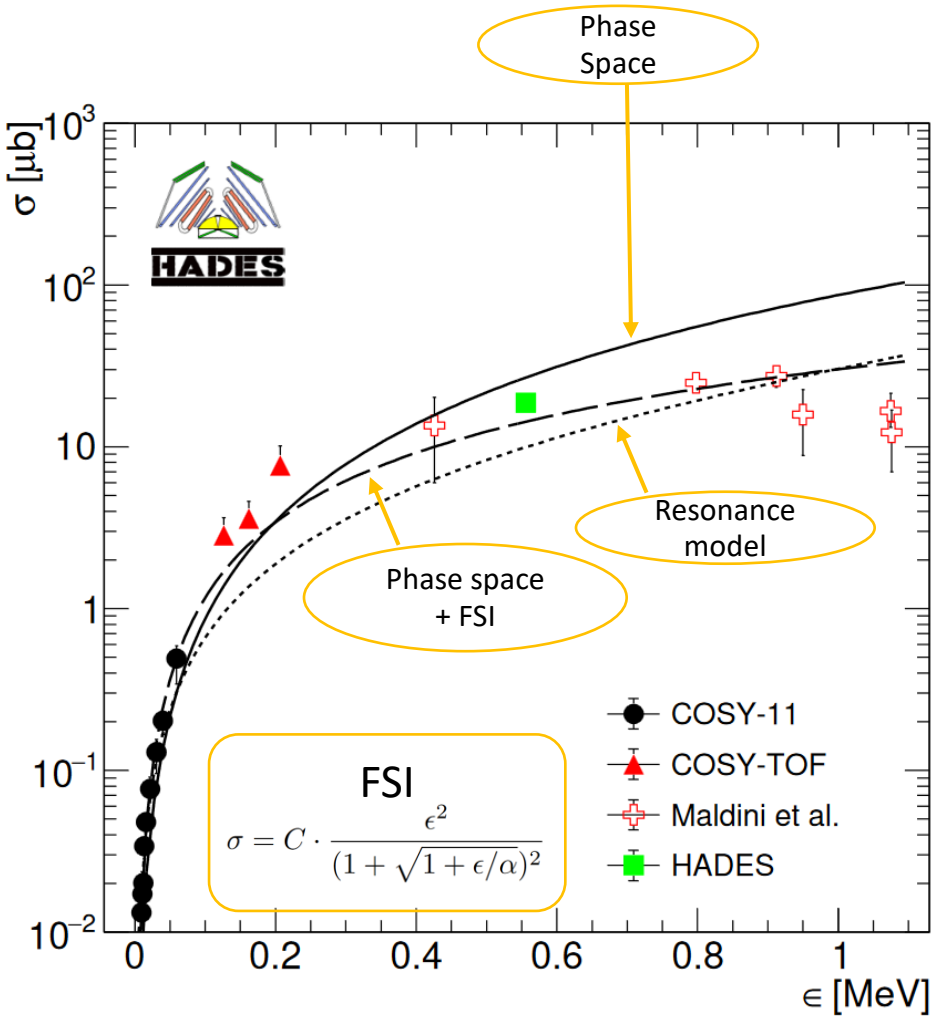
- The cross section is obtained by integrating the yield of the angular distributions

$$\sigma(pK^+\Sigma^0)[\mu b] = 18.74 \pm 1.01(stat) \pm 1.71(syst)$$

$$\sigma(pK^+\Lambda)/\sigma(pK^+\Sigma^0) = 1.90 \pm 0.41$$

- Systematic error sources:

1. PID: $\pm$ 5% error
2. Analysis Cuts: $\pm$ 2% error
3. Normalization: $\pm$ 7% error

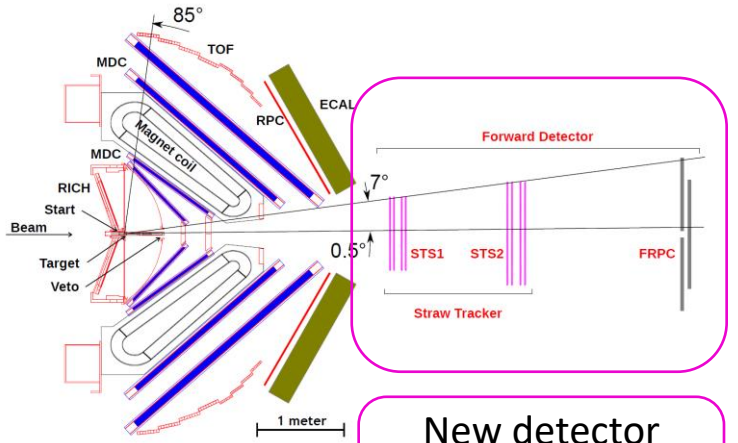


- Resonance model study of kaon production in baryon-baryon reactions for heavy-ion collisions, K. Tsushima, **Phys. Rev. C 59** (1999)
- Comparison of the near-threshold production of η- and K-mesons in proton-proton collisions, G. Fäldt ***Zeitschrift für Physik A Hadrons and Nuclei*** **357**, (1997)
- **Partial Wave Analysis of the Reaction $p(3.5GeV) + p \rightarrow pK^+\Lambda$ to Search for the "ppK^-" Bound State** HADES Collaboration *Phys.Lett.B* 742 (2015)

Summary

- Investigation of the Σ^0 production mechanism in p(3.5GeV)+p collisions
- Phase space description is not sufficient
- Dominance of pion exchange mechanism
- Resonances with mass around **1.710** GeV/c^2 and **1.900** GeV/c^2 are preferred by the PWA fit
- Due to limited statistics, there is a significant uncertainty to the relative contributions of the different resonances

- **Upgraded HADES setup (Recent data p(4.5GeV)+p)**



New detector based on PANDA FTS

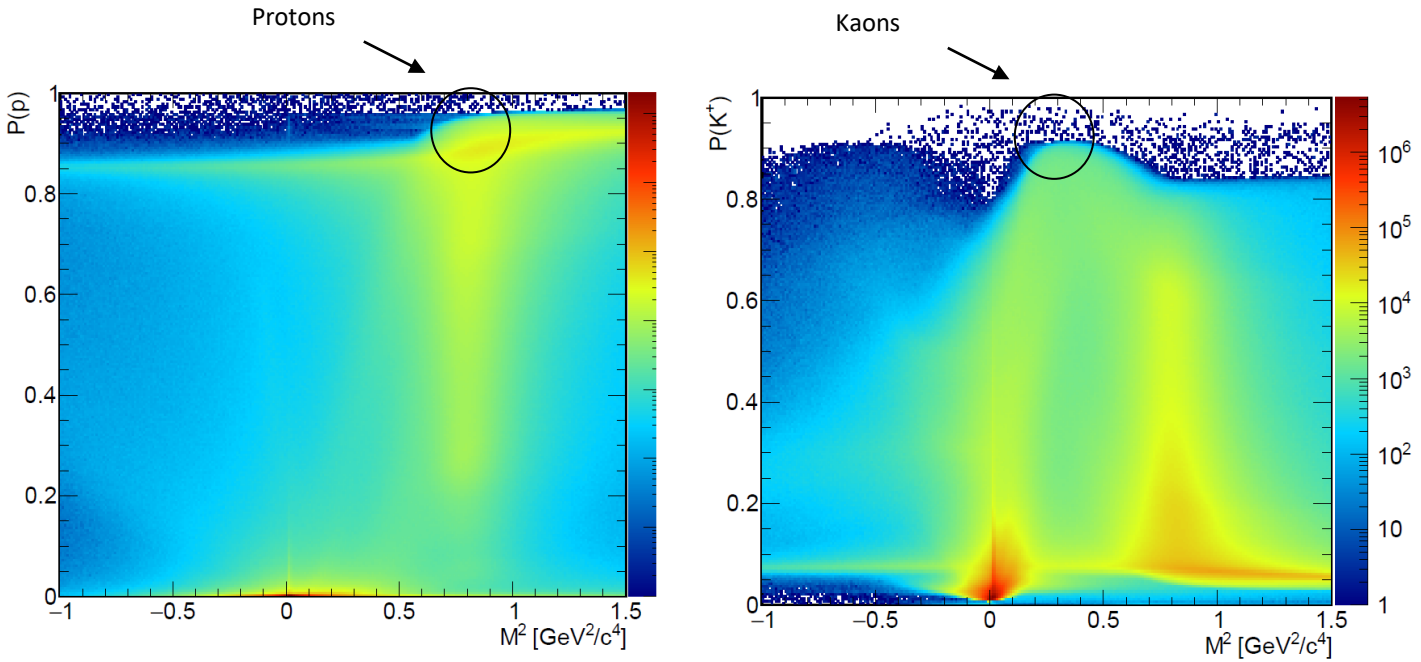
HADES Collaboration, Production and electromagnetic decay of hyperons: a feasibility study with HADES as a phase-0 experiment at FAIR, EPJA **57**, (2021)

Thank You

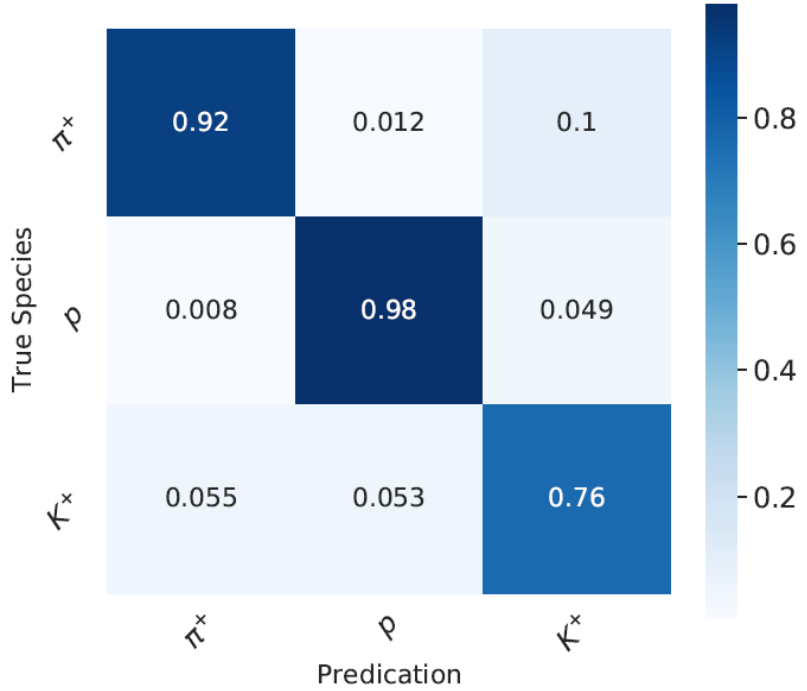
Backups: PID

- Training Features: p_i(GeV/c), dE/dx(a.u.), TOF(ns), d_{META} (m)

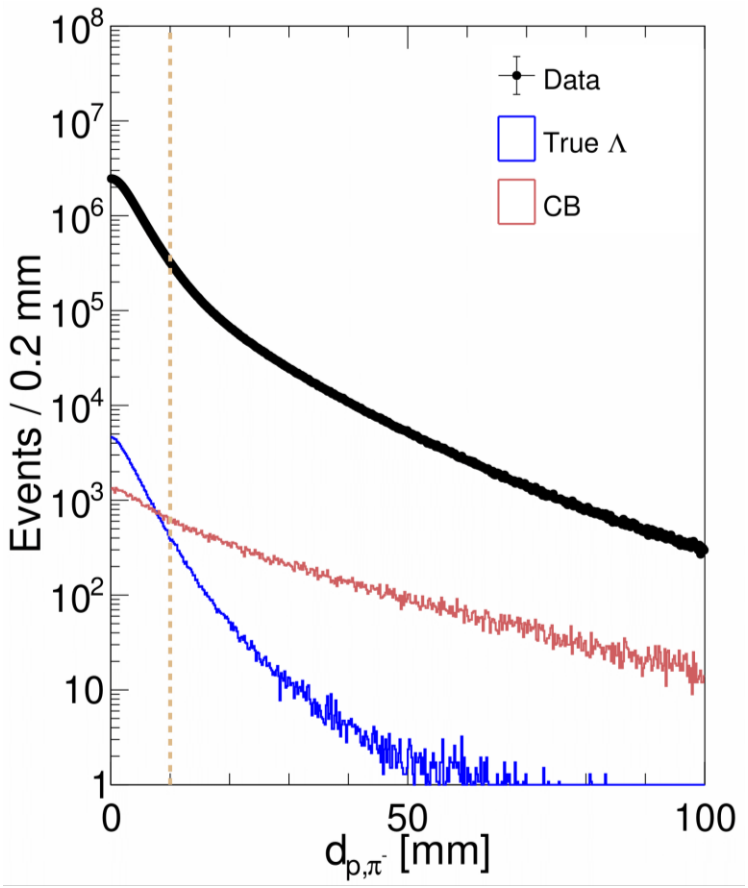
Performance evaluated on real data

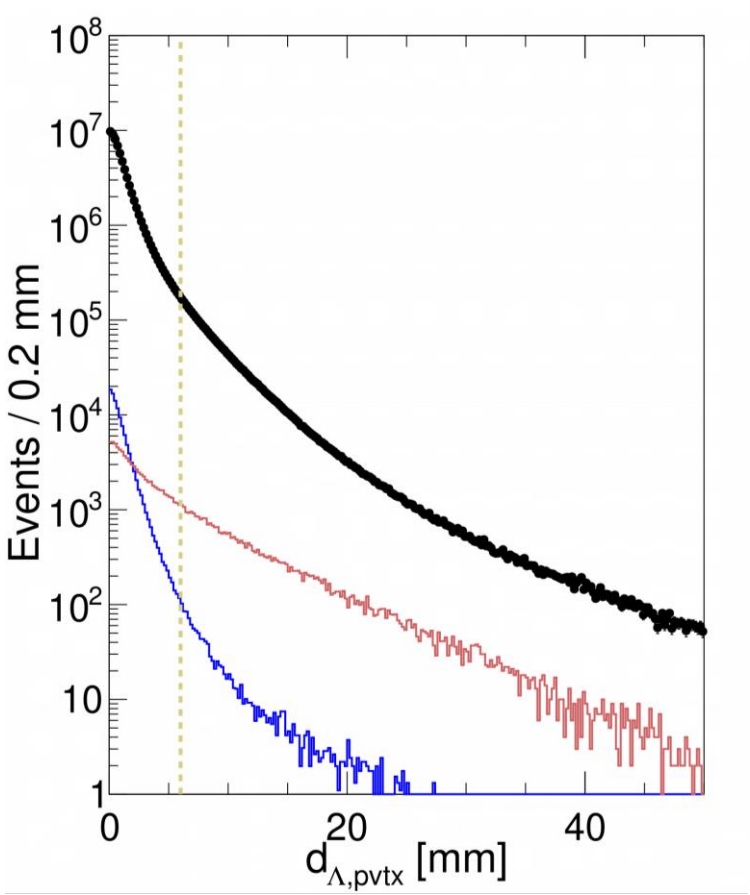


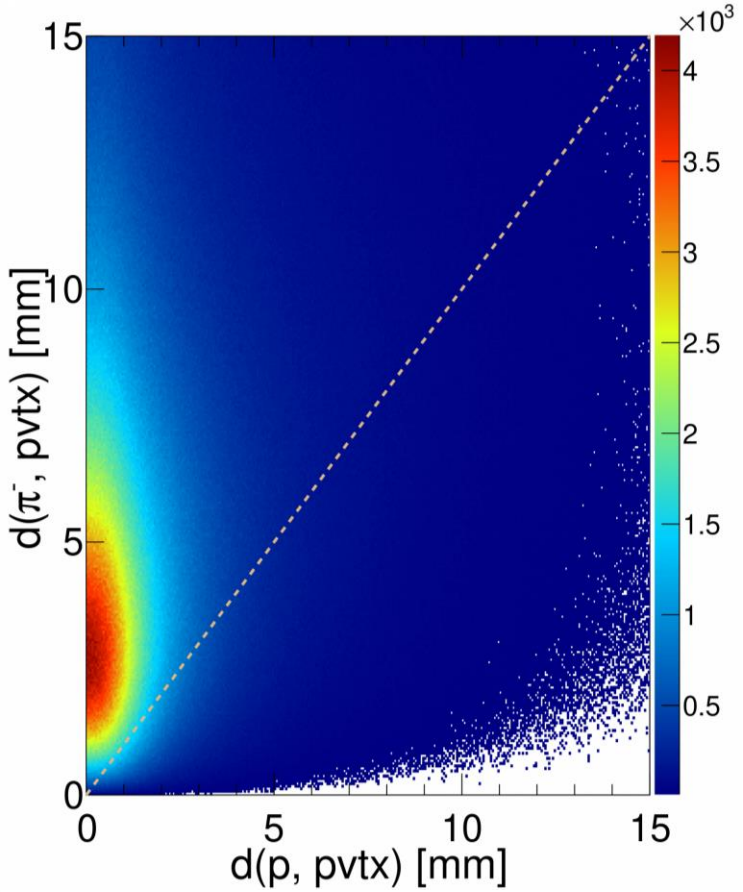
Confusion Matrix (Simulations)



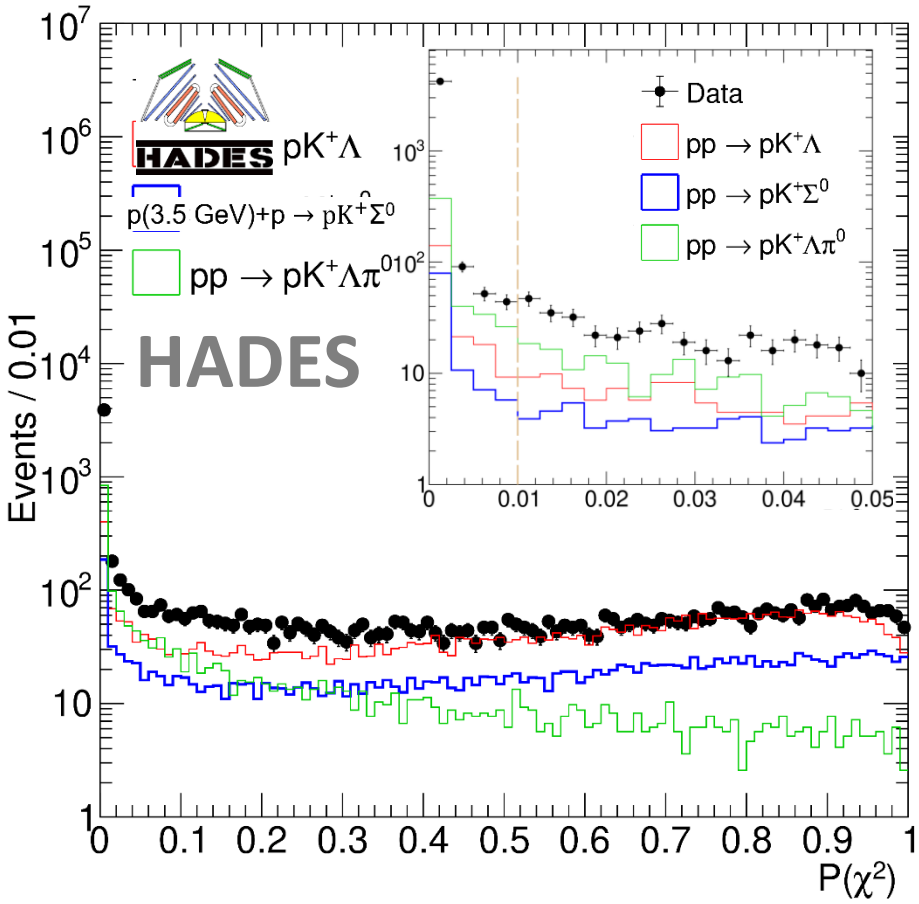
Backups: Lambda Selection

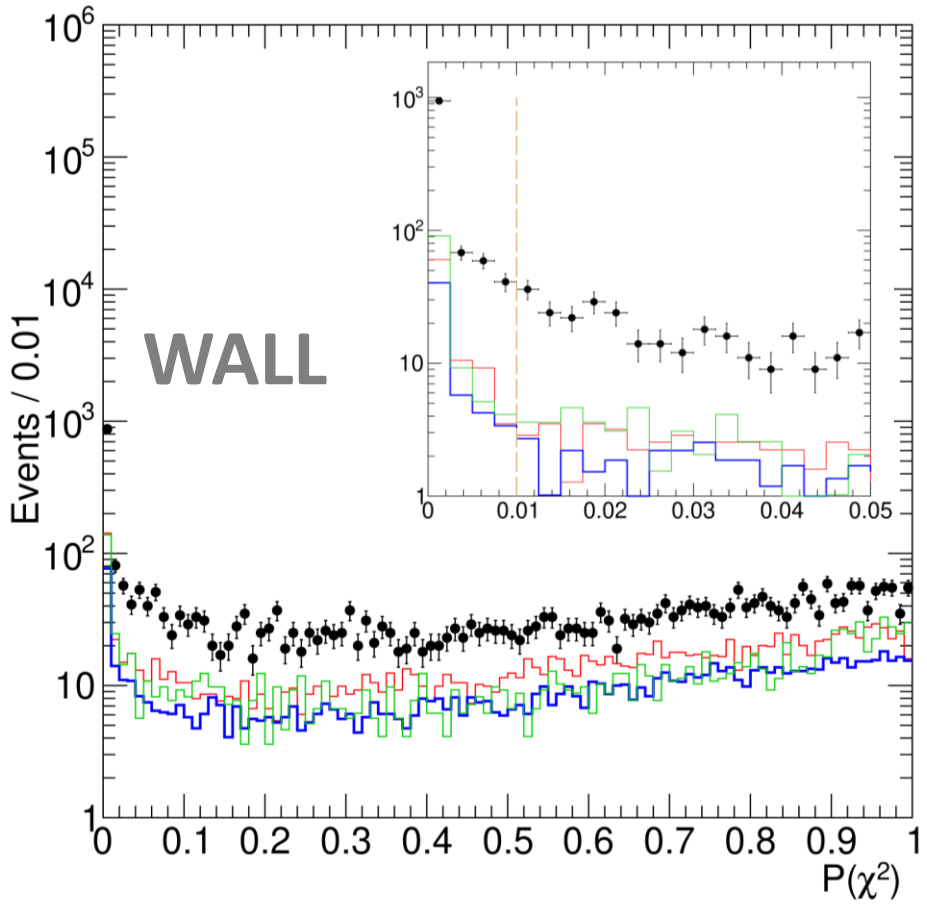






Backups: Kinematic Refit





Backups: Reference Frames

1. Center of Mass CMS Frame:

- The beam and target proton have identical momenta in opposite directions

2. Gottfried Jackson G-F Frame:

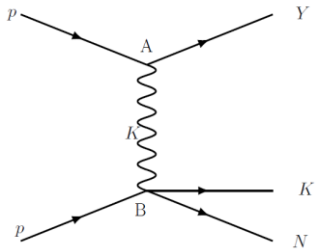
- is the polar angle between the final state particle B and the initial proton

as measured in the rest frame of particles A and B

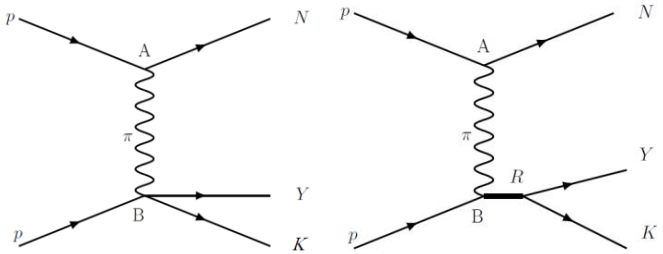
3. Helicity Frame:

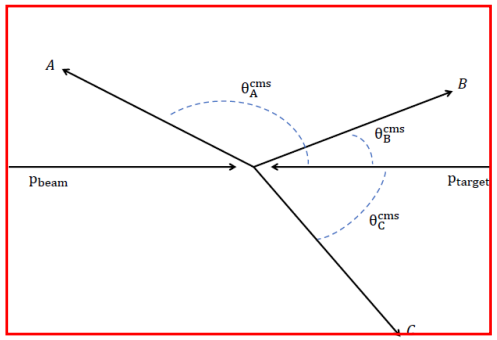
- Defined similar to the G-F angle, but the angle with respect to the third produced particle is used

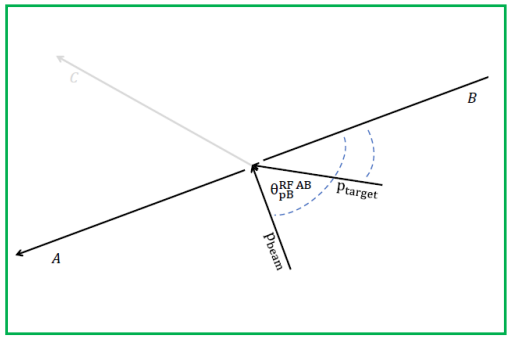
Kaon exchange

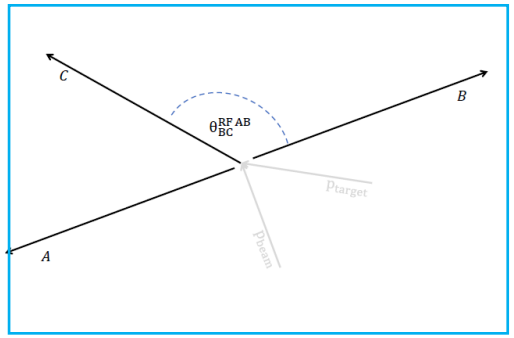


Pion exchange









Backups: Efficiency Corrections

- Experimental distributions are represented by binned histograms

$$M = RT$$

- **R** is the **detector response** and **T** is the **true distribution**
- **R** now is represented as a *matrix*

$$R_{ij} = P(\text{reconstructed in bin i} \mid \text{generated in bin j})$$

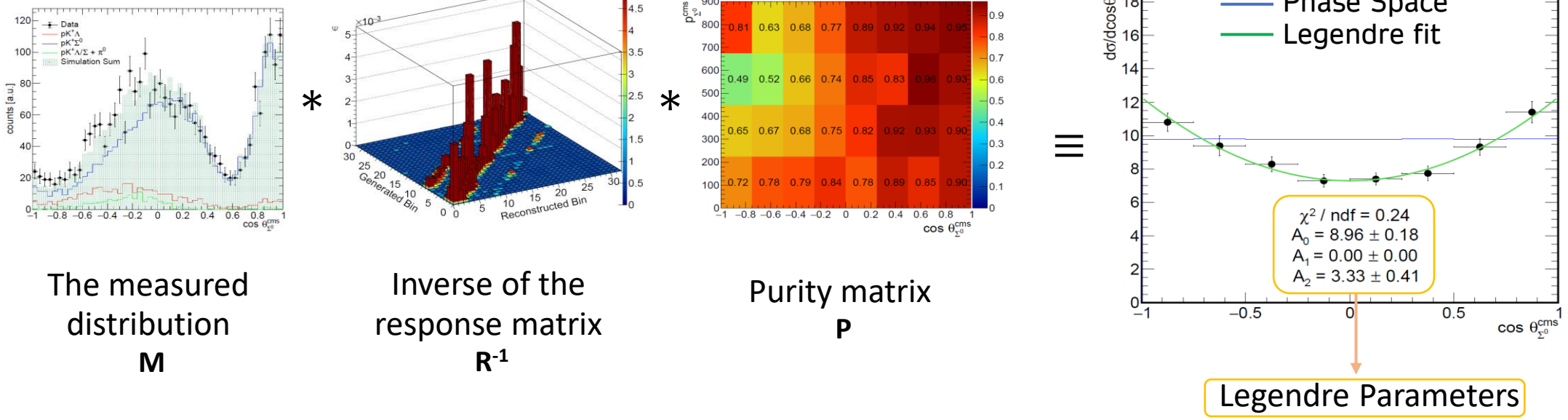
- **Correction** or data unfolding means to **invert** the **response matrix**
- **Inversion** is done via the Singular Value Decomposition **SVD** implemented using **RooUnfold framework**
- Since there are background events, a **purity matrix** is defined as

$$P_{bin} = \frac{n(pK^+\Sigma^0)}{n(pK^+\Lambda) + n(pK^+\Sigma^0) + n(pK^+\Lambda\pi^0)}$$

Backups: Efficiency Corrections

- Example: Correction of the Σ^0 CMS angular distribution
- 2D correction in $cos\theta^{cms}_{\Sigma^0}$ and $p^{cms}_{\Sigma^0}$
- The corrected number of Σ^0 events are transformed into a cross section by normalizing to elastic collisions at the same beam energy

$R_{ij} = P(\text{reconstructed in bin i} \mid \text{generated in bin j})$



The measured distribution **M**

*

Inverse of the response matrix **R^{-1}**

*

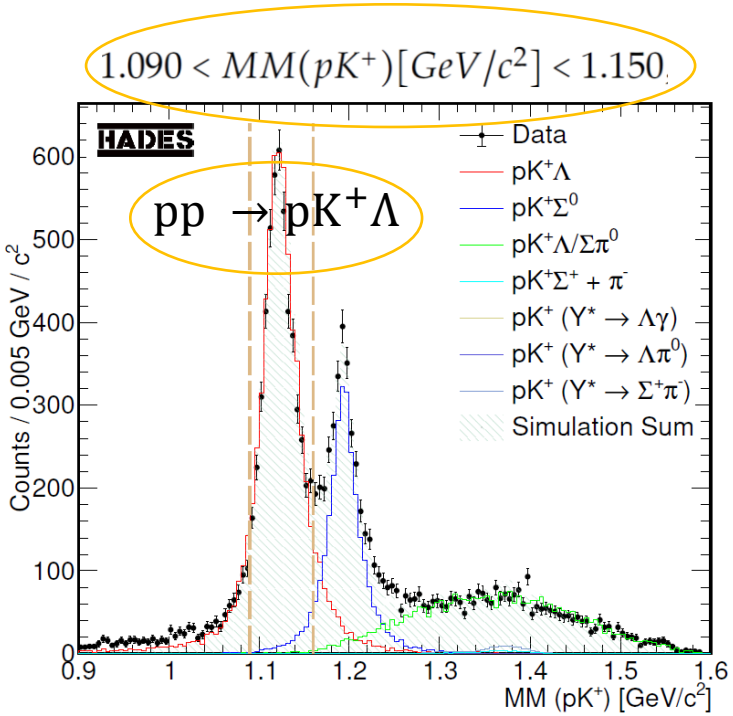
Purity matrix **P**

≡

Backups: Partial Wave Analysis

- **P**artial **W**ave **A**nalysis (**PWA**) was performed in order to estimate resonant contributions
- PWA aims to determine the transition amplitude $A_{tr}^{\alpha}(s) = (\alpha_1 + \alpha_3\sqrt{s})e^{i\alpha_2}$
- Tool used: Bonn-Gatchina PWA (log-likelihood minimization)
- Eight resonances + eight non-resonant contributions ($^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^3F_2$, $^3F_3$ and $^3F_4$)
- Resonance masses and widths were fixed to the PDG values

- PWA is first applied to $\mathbf{pp \rightarrow pK^+\Lambda}$
- Solution No. 8/1 from * including :
  (N*(1650), N*(1710), N*(1720) and N*(1900))
- An estimate of $\mathbf{pp \rightarrow pK^+\Lambda}$ within the signal region is ~ 290 events



* **Partial Wave Analysis of the Reaction $p(3.5GeV) + p \rightarrow pK^+\Lambda$ to Search for the "ppK^-" Bound State**
HADES Collaboration *Phys.Lett.B* 742 (2015)

Backups: Partial Wave Analysis

Resonance	Mass [GeV/c^2]	Width [GeV/c^2]	J^P
$N^*(1710)$	1.710	0.140	$\frac{1}{2}^+$
$N^*(1875)$	1.875	0.200	$\frac{3}{2}^-$
$N^*(1880)$	1.880	0.300	$\frac{1}{2}^+$
$N^*(1895)$	1.895	0.120	$\frac{1}{2}^-$
$N^*(1900)$	1.920	0.200	$\frac{3}{2}^+$
$\Delta^*(1900)$	1.860	0.250	$\frac{1}{2}^-$
$\Delta^*(1910)$	1.900	0.300	$\frac{1}{2}^+$
$\Delta^*(1920)$	1.920	0.300	$\frac{3}{2}^+$

Solution No.	Initial State	Partial Wave Contributions	$\mathcal{L}$
1	$^1S_0, ^1D_2, ^3P_0, ^3P_1, ^3P_2, ^3F_2$	$pK^+\Sigma^0 \approx 41\%$ $N^*(1710) \approx 23\%$ $N^*(1900) \approx 17\%$ $\Delta^*(1900) \approx 19\%$	-333
2	$^1S_0, ^1D_2$	$pK^+\Sigma^0 \approx 27\%$ $N^*(1710) \approx 22\%$ $N^*(1900) \approx 9\%$ $\Delta^*(1900) \approx 42\%$	-184
3	$^1S_0, ^1D_2, ^3P_0, ^3P_1, ^3P_2$	$pK^+\Sigma^0 \approx 63\%$ $N^*(1710) \approx 18\%$ $N^*(1900) \approx 18\%$ $\Delta^*(1900) \approx 2\%$	-182
4	$^1S_0, ^1D_2, ^3P_0, ^3P_1, ^3P_2, ^3F_2$	$pK^+\Sigma^0 \approx 33\%$ $N^*(1710) \approx 27\%$ $N^*(1880) \approx 40\%$	-151
5	$^1S_0$	$pK^+\Sigma^0 \approx 17\%$ $N^*(1710) \approx 79\%$ $\Delta^*(1900) \approx 5\%$	-123

Backups: Treiman-Yang Angle

For a **pure pion exchange**
the Treiman-Yang angle measured in the
$K^+\Sigma^0$ rest frame
is expected to be an **isotropic distribution**