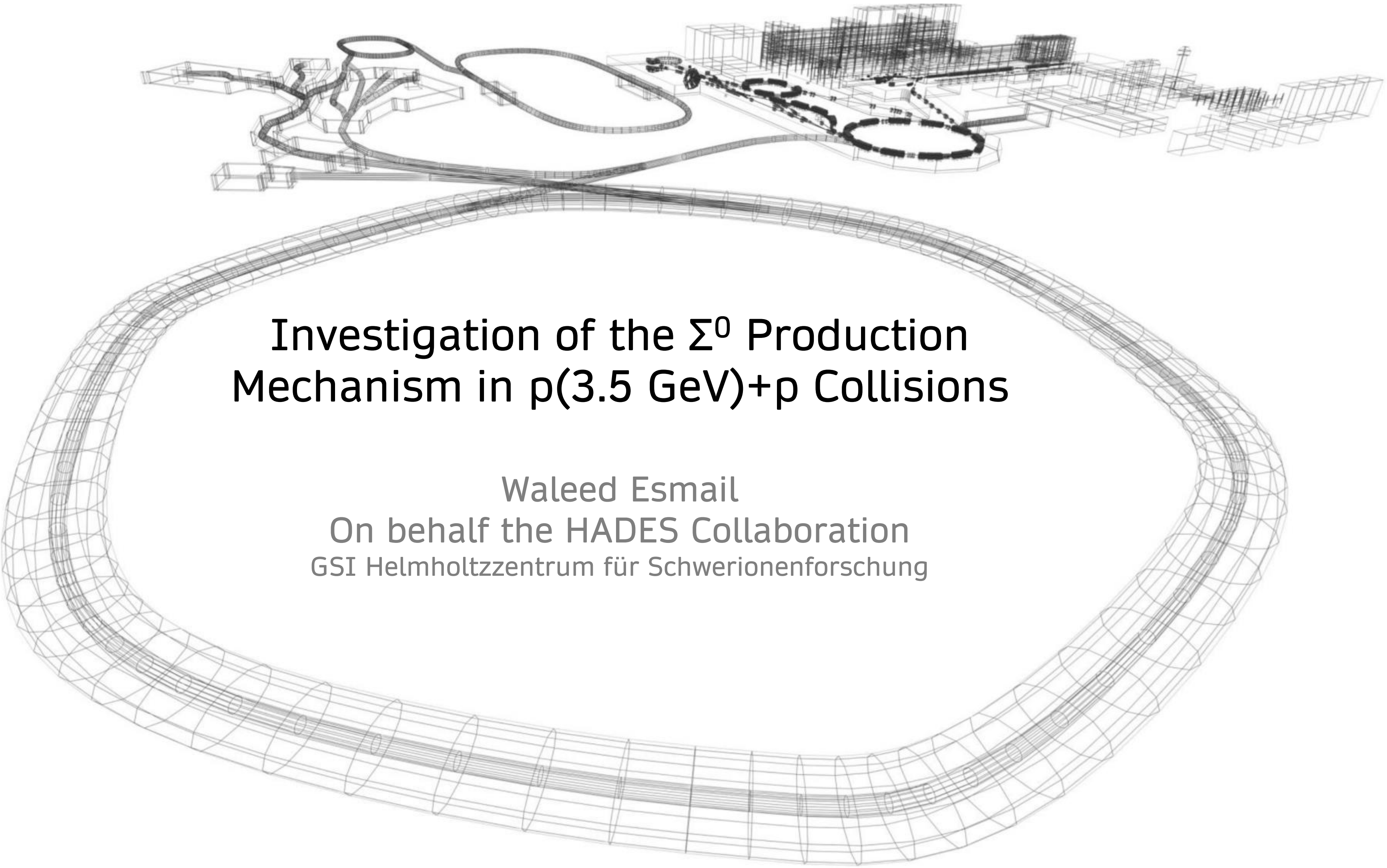


Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p Collisions

Waleed Esmail
On behalf the HADES Collaboration
GSI Helmholtzzentrum für Schwerionenforschung

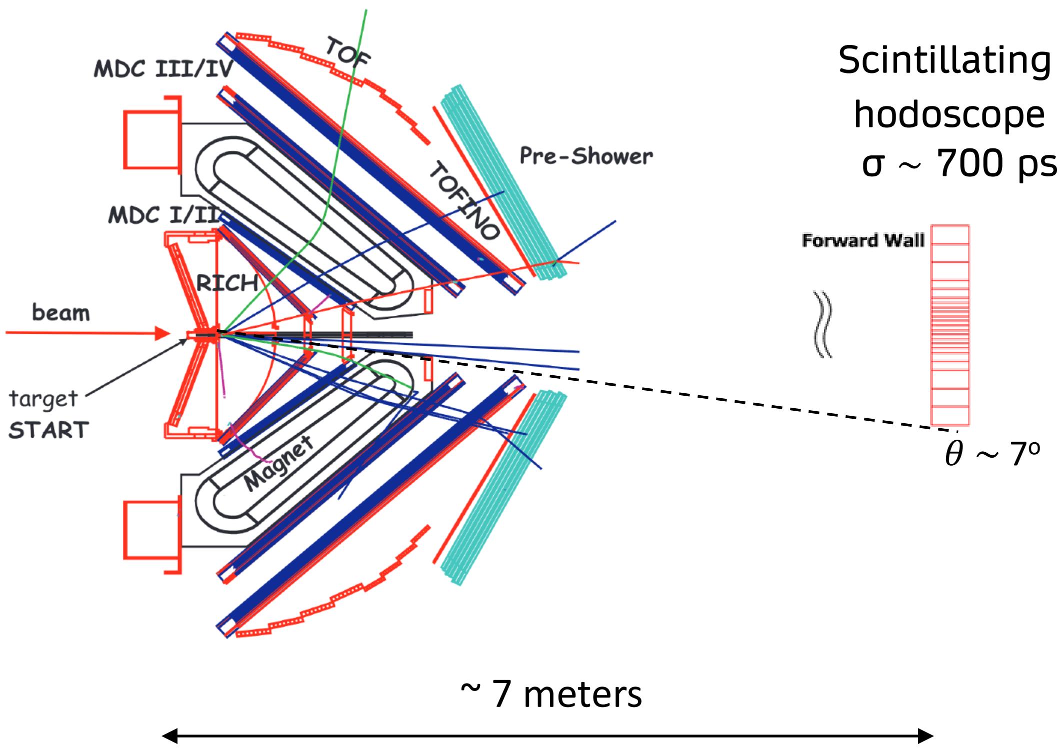
A Motivation

- Study of hyperon production serves as a tool to study QCD at the confinement scale
- Hyperon production mechanism is poorly understood near threshold
- 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%)

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

<u>H</u>igh <u>A</u>cceptance <u>D</u>i-<u>E</u>lectron <u>S</u>pectrometer HADES

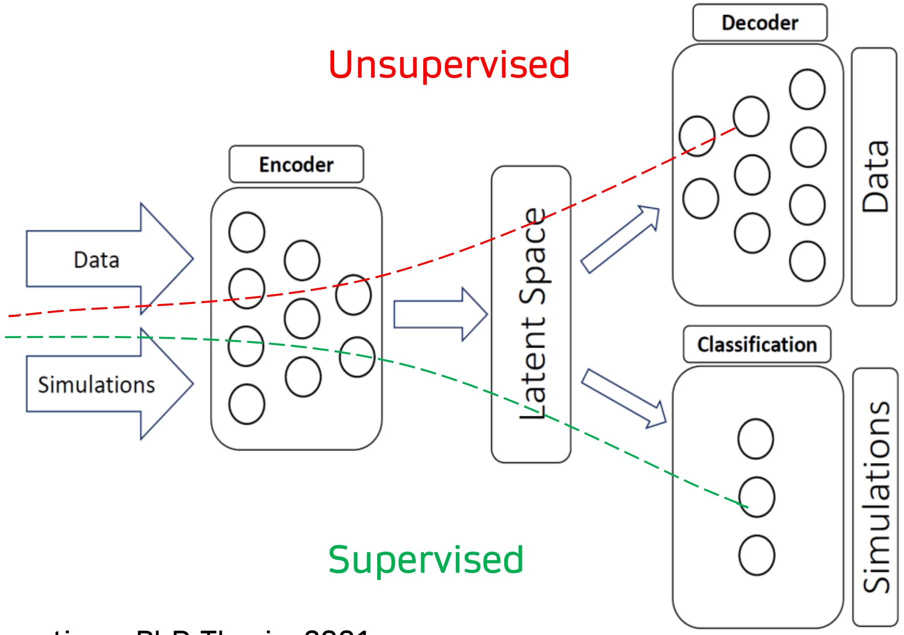


Particle Identification (PID)

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

- π^- is identified as any **negative** charged track that is **uncorrelated** to a ring in RICH
- Statement of the task: identify the type of the charged tracks (**p**, **K^+**, **π^+**)
- PID was performed based on **D**eep **L**earning (**DL**) techniques
- A neural network is trained using a **semi-supervised** technique on *simulations* and *data*
- 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 %



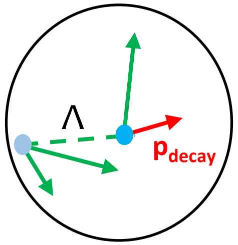
* Durk P Kingma et al. “Semi-supervised Learning with Deep Generative Models”

[§] 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

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



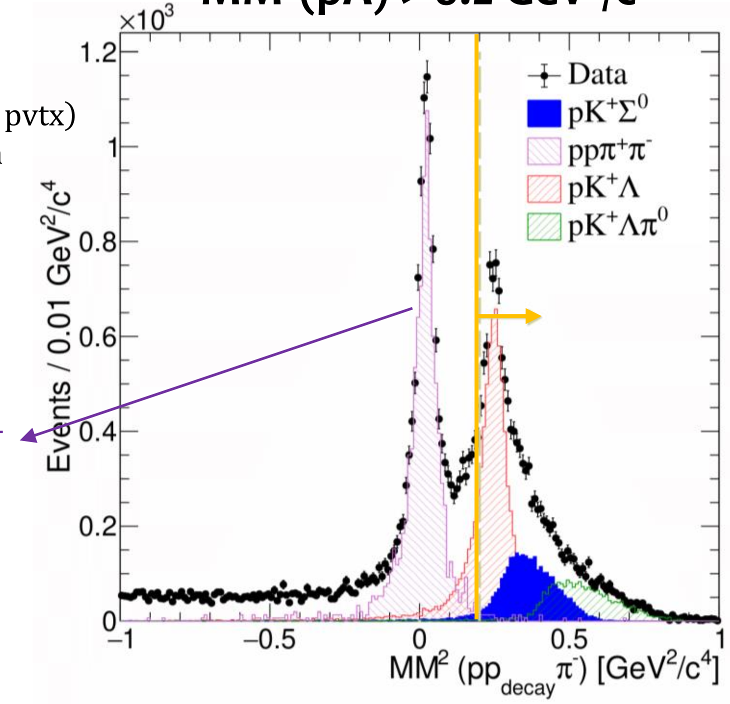
Topological Cuts

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

Spectrometer data-set

All particles within HADES acceptance

MM²(pΛ) > 0.2 GeV²/c⁴



pp π^- π^+

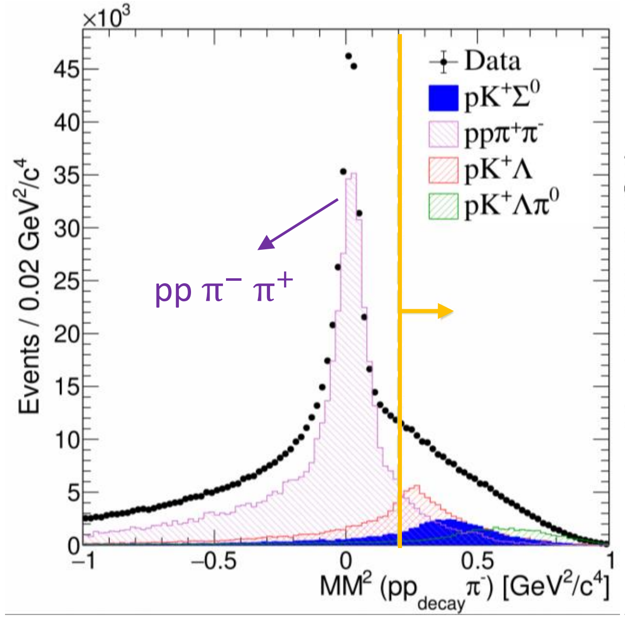
Wall data-set

3 particles within HADES acceptance ($p\ K^+\ \pi^-$)

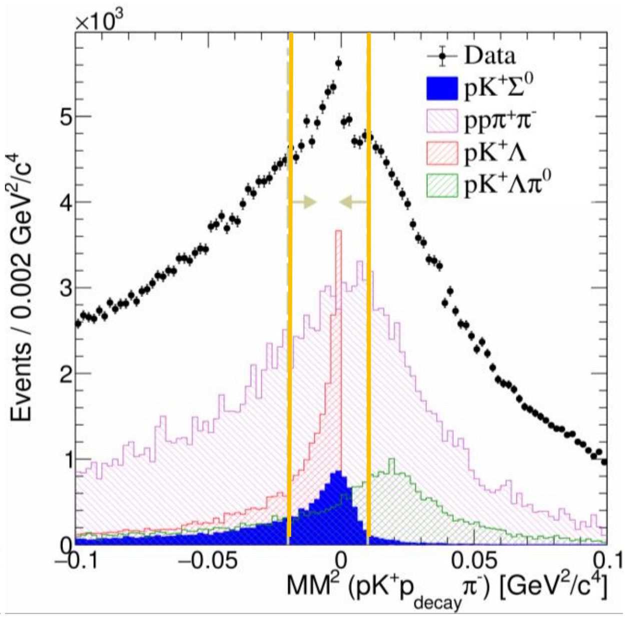
&

1 hit in the Forward Wall (p_{decay})

MM²(pΛ) > 0.2 GeV²/c⁴



-0.02<MM2(pK+Λ) < 0.01



Λ Reconstruction

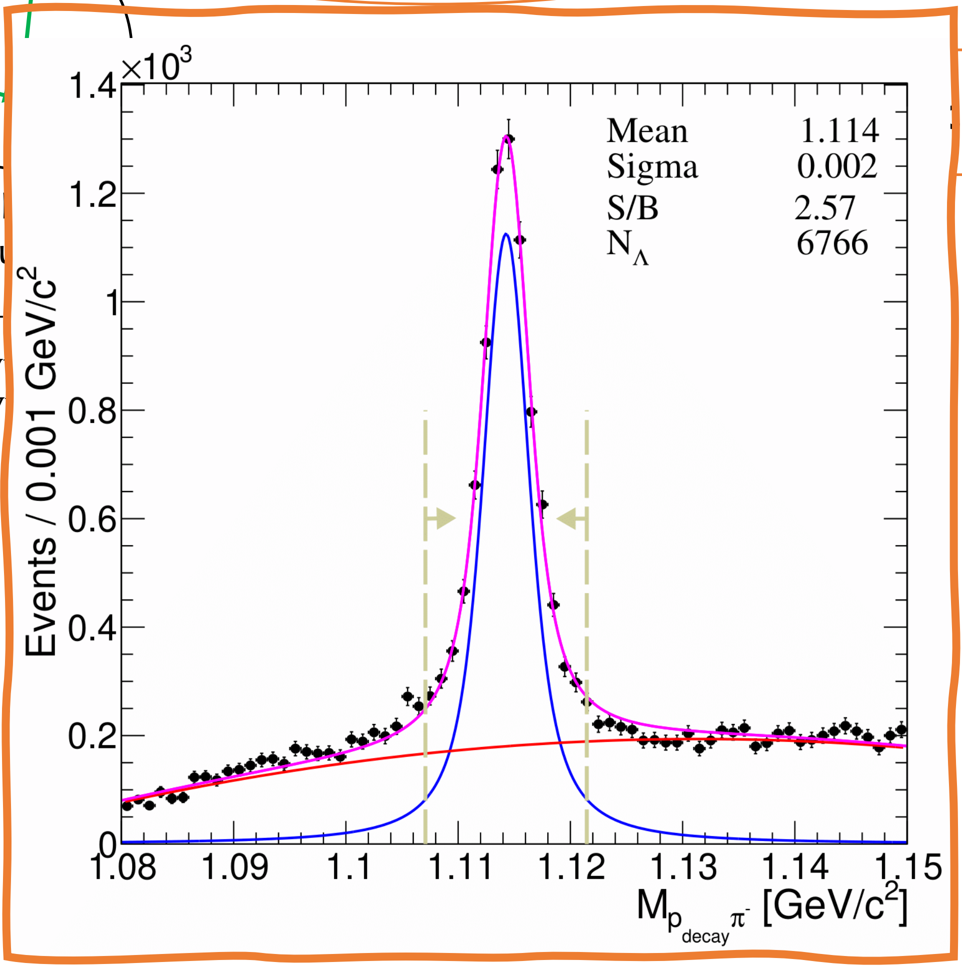
Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p collisions at HADES experiment

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

Spectrometer data-set

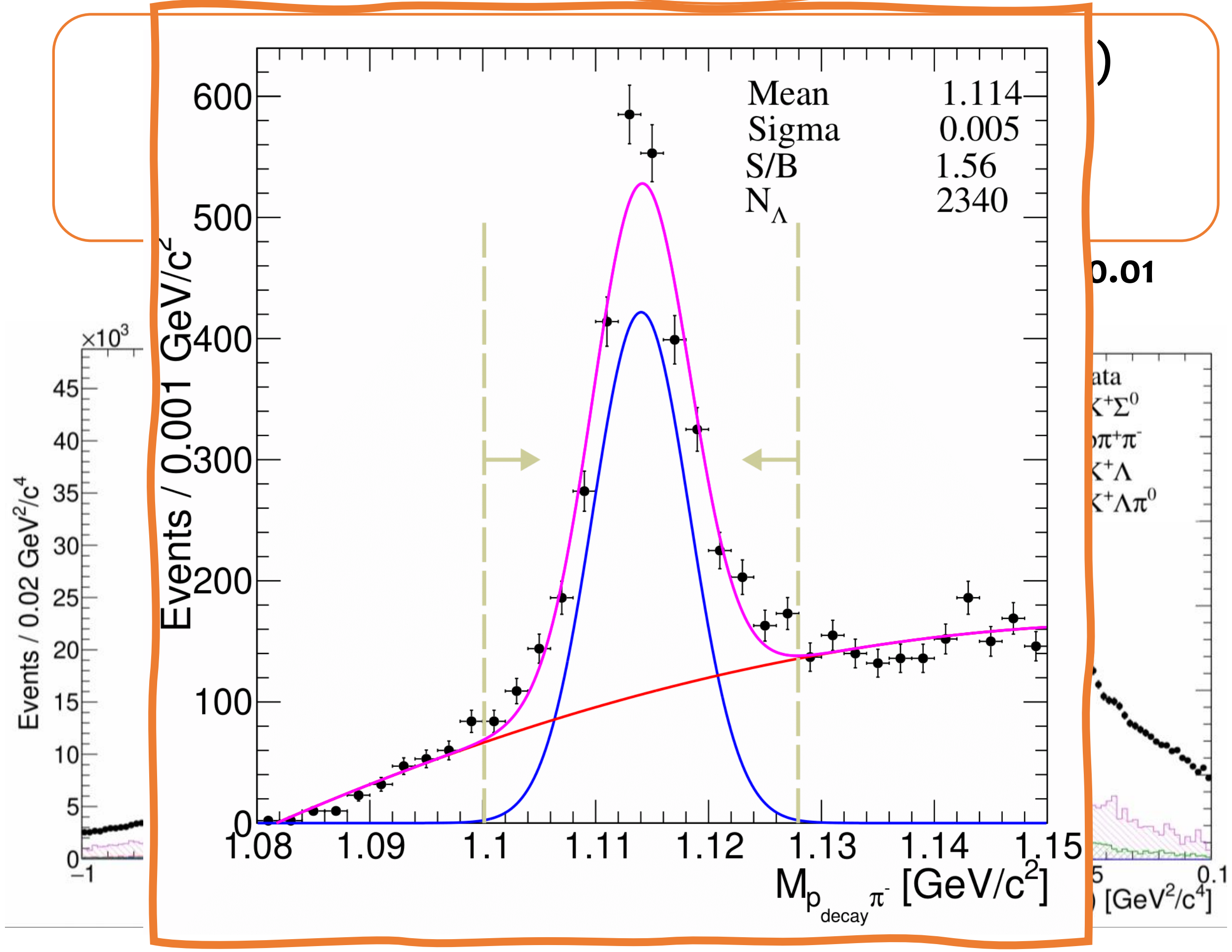
Topol
Cu

1. $d(p, \pi^-$
2. $d(p, pv$
3. $d(\Lambda, pv$



Wall data-set

0.01



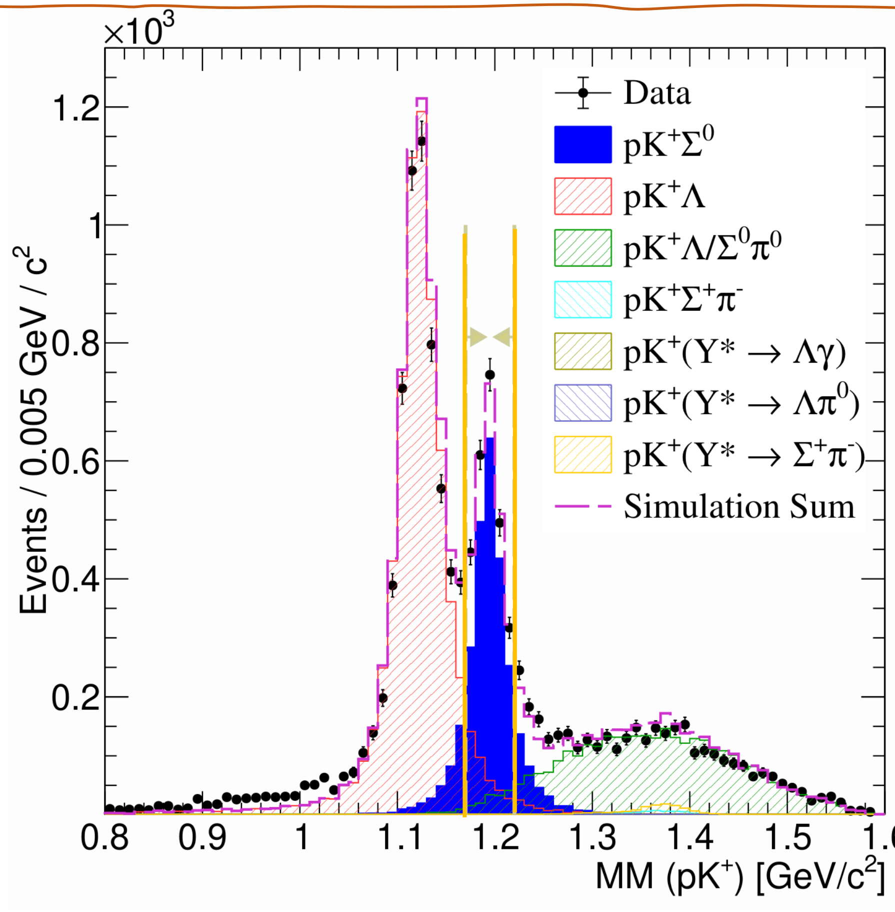
Kinematic Refit

1. **IM** $pp \rightarrow pK^+\Lambda\gamma \rightarrow pK^+ p\pi^- \gamma$ $M_\Lambda = 1.115683\ GeV/c^2$ $\chi^2 = (y-\eta)^T V^{-1}(y-\eta) \approx minimum$
2. **MM** $pp \rightarrow pK^+\Lambda\gamma \rightarrow pK^+ p\pi^- \gamma$ $M_\gamma = 0\ GeV/c^2$ $f(\eta,\xi) = 0$

- Events with **$P(\chi^2) > 0.01$** 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%



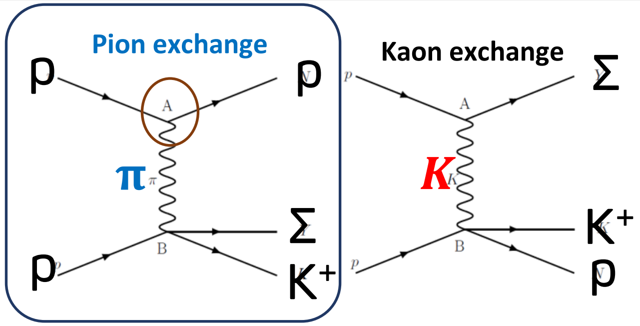
Physics Results

Angular Distributions: **CMS Frame**

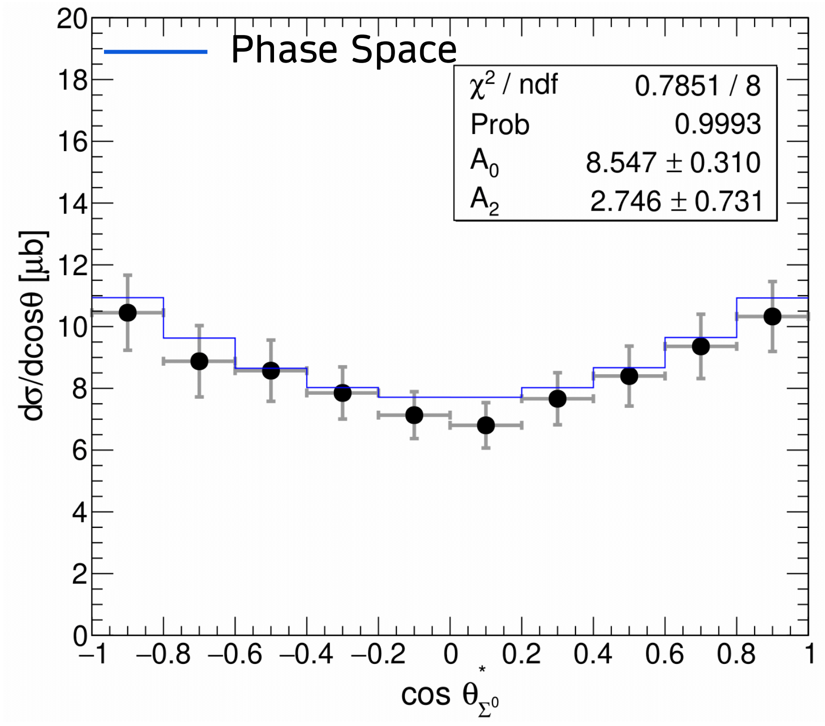
Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p collisions at HADES experiment

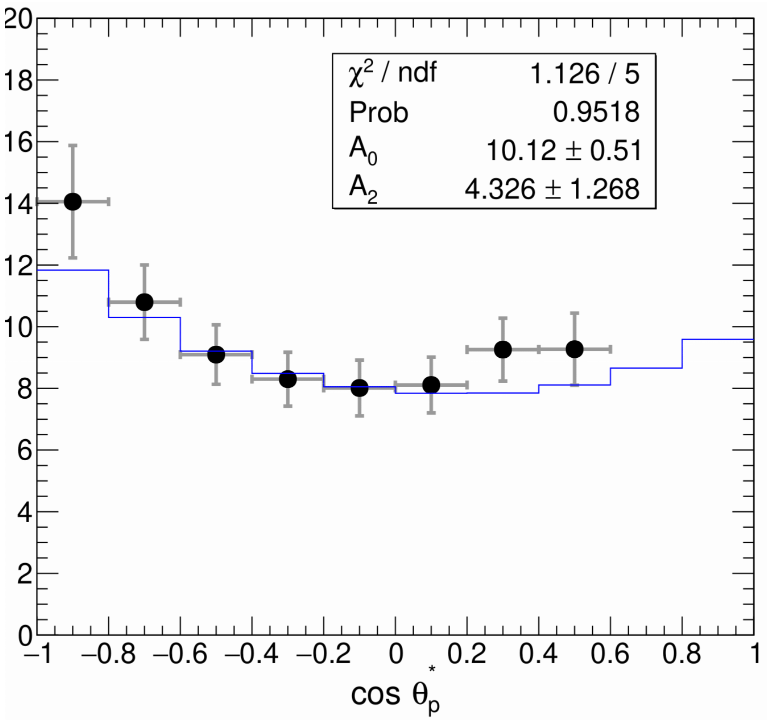
- CMS provides information on the exchange boson properties
- An anisotropy observed in the **Σ^0** and **p** distributions
- An indication of a **pion exchange** mechanism

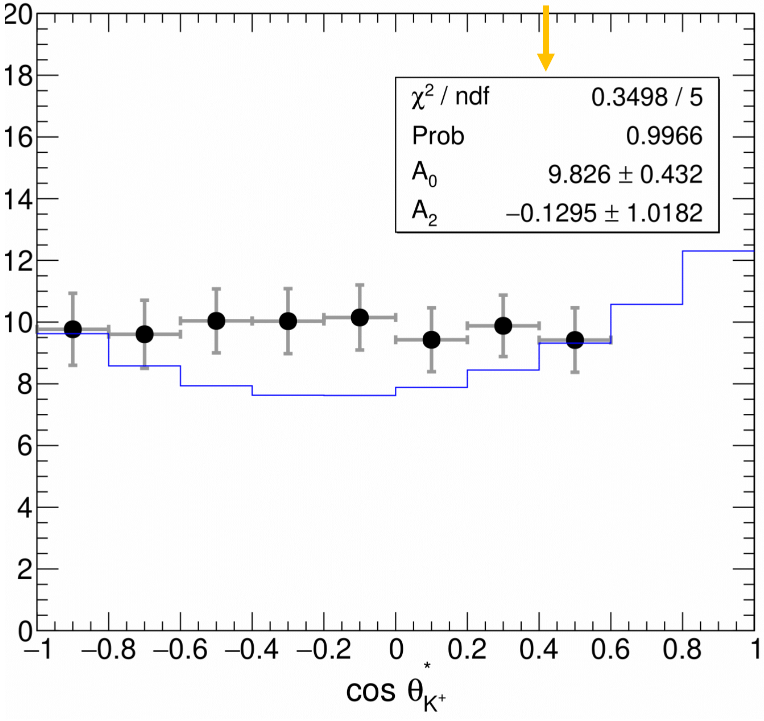
$pK^+\Sigma^0$



Legendre Parameters





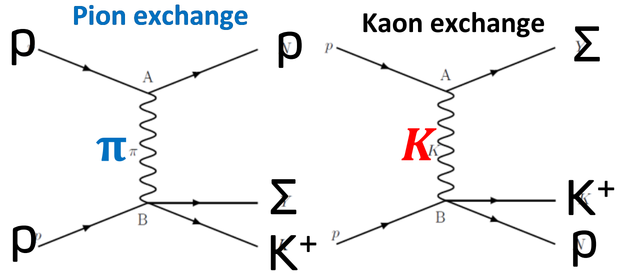


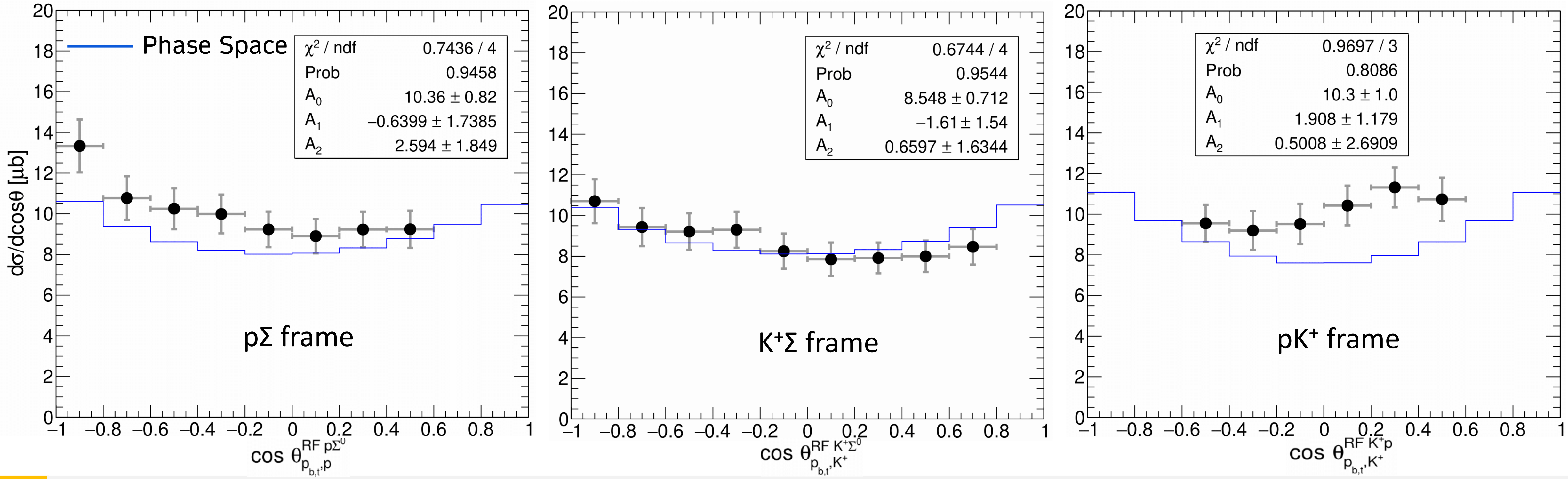
Phase space simulations are weighted by $cos\theta^{cms}_{\Sigma^0}$ **and** $cos\theta^{RFp\Sigma}_{p_{b,t},p}$ **obtained from data**

Angular Distributions: **Gottfried-Jackson Frames**

- Gottfried-Jackson frames provides information on the exchange boson properties and intermediate resonances
- An anisotropy observed in the **Σ^0p** distribution
- Asymmetry in the **$K^+\Sigma$** distribution (resonances)

$pK^+\Sigma^0$

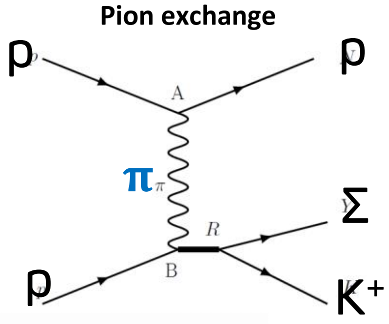


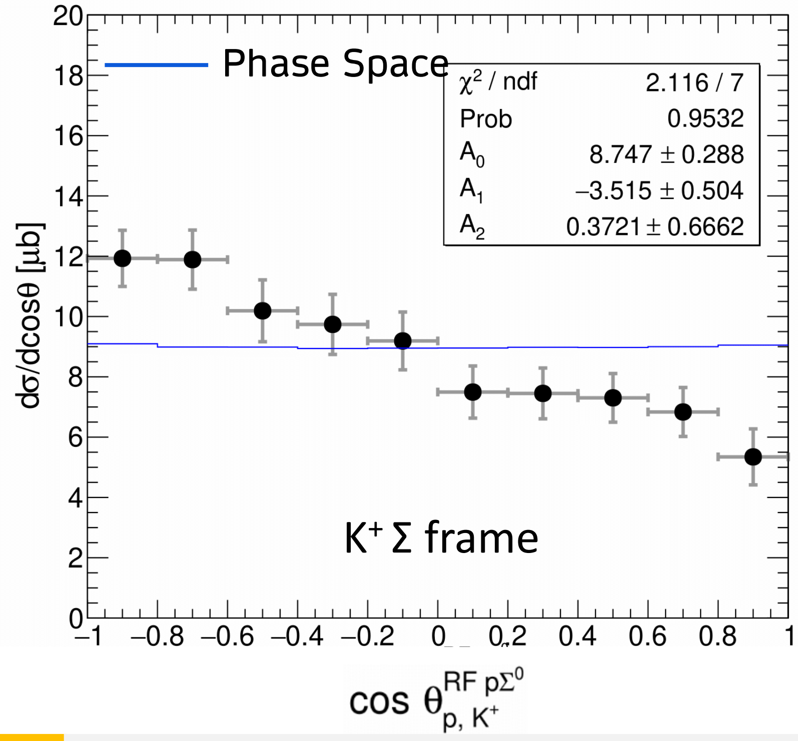


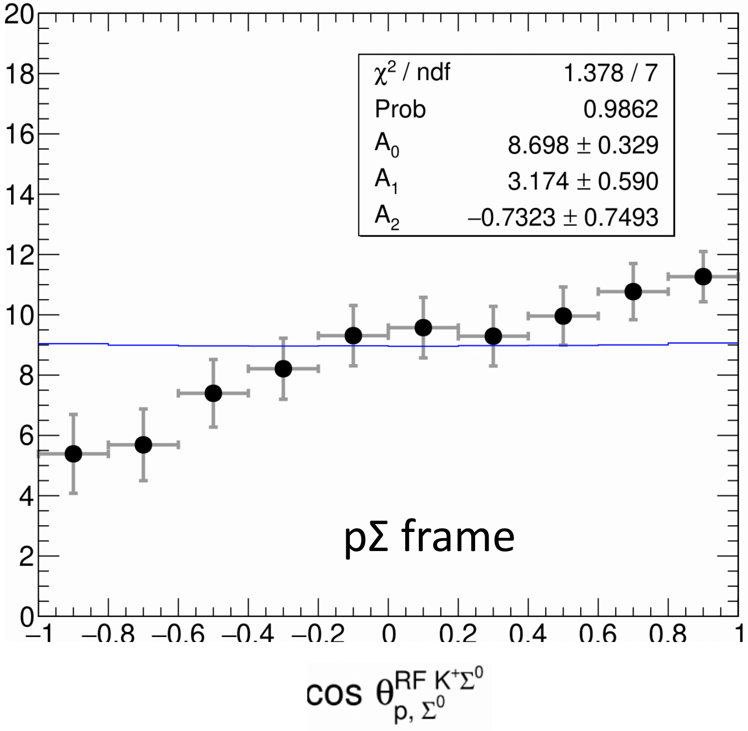
Angular Distributions: **Helicity Frames**

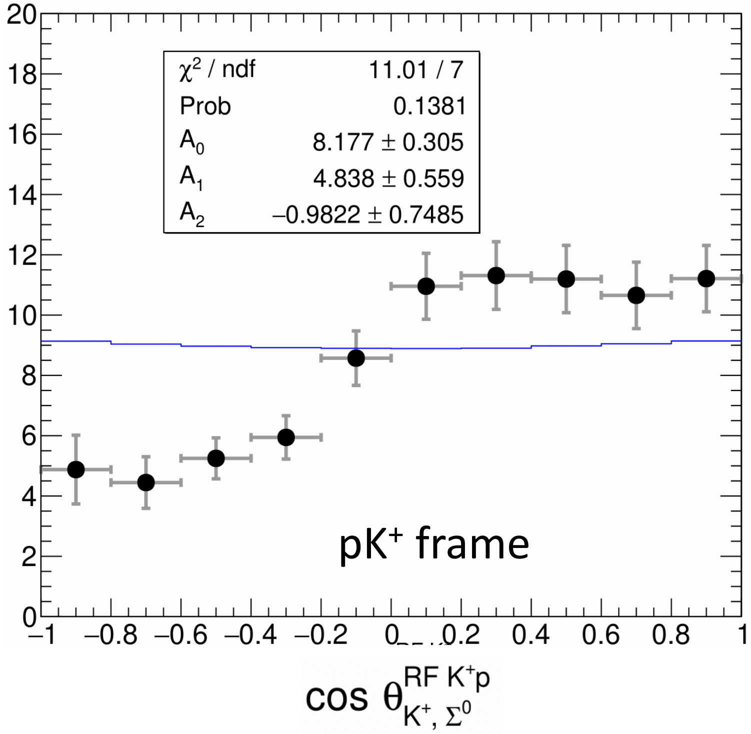
- Helicity frames are “projections” of the Dalitz plot
- Isotropic distribution is an indication of phase space production

$pK^+\Sigma^0$



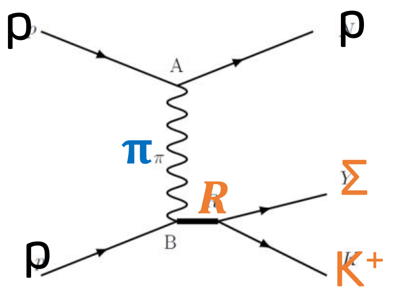






Partial Wave Analysis

- **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)

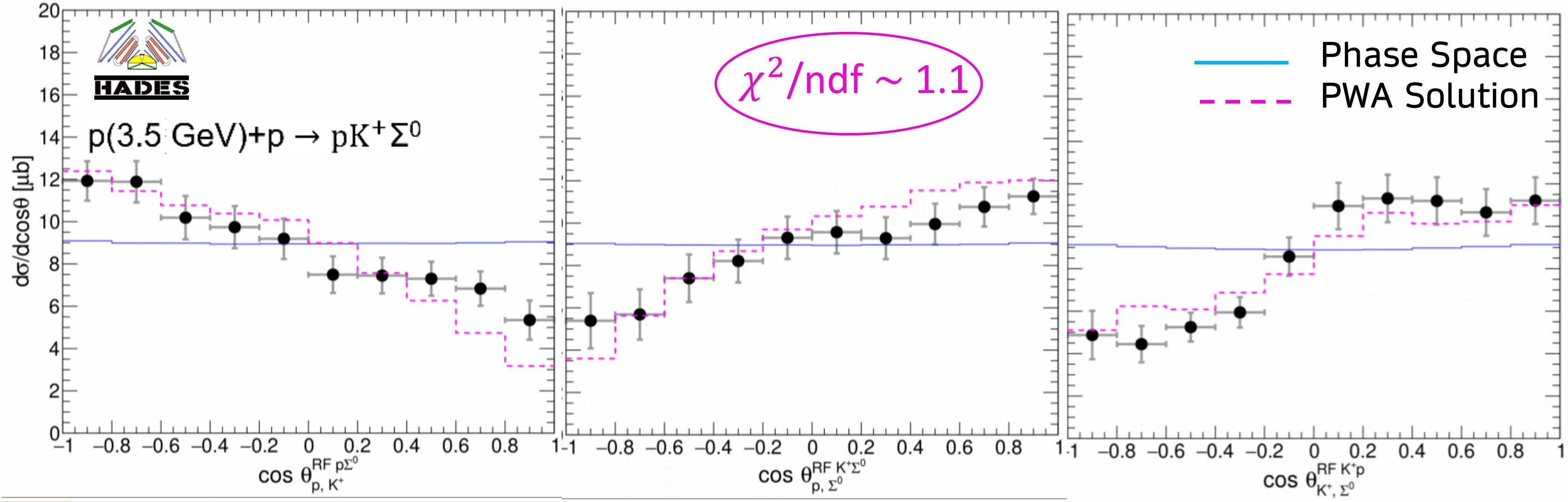


Helicity Frames Revisited: PWA solution provides a good description of angular distributions

- Nucleon resonances involved are:

  $N^*(1710)$ (J^P = ½+), $N^*(1900)$ (J^P = 3/2+) and $\Delta^*(1900)$ (J^P = ½-)

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



- Eight resonances:

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

- Eight non-resonant contributions:

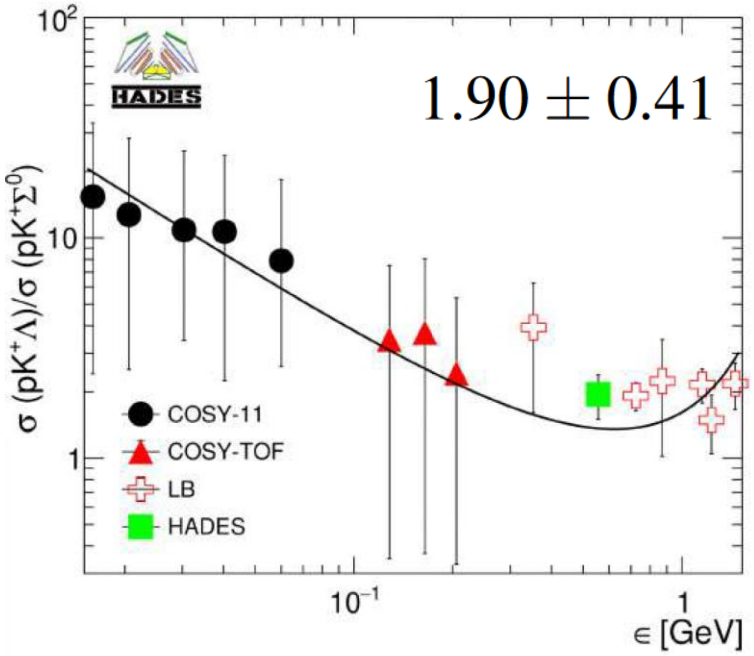
$^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^3F_2$, $^3F_3$ and $^3F_4$

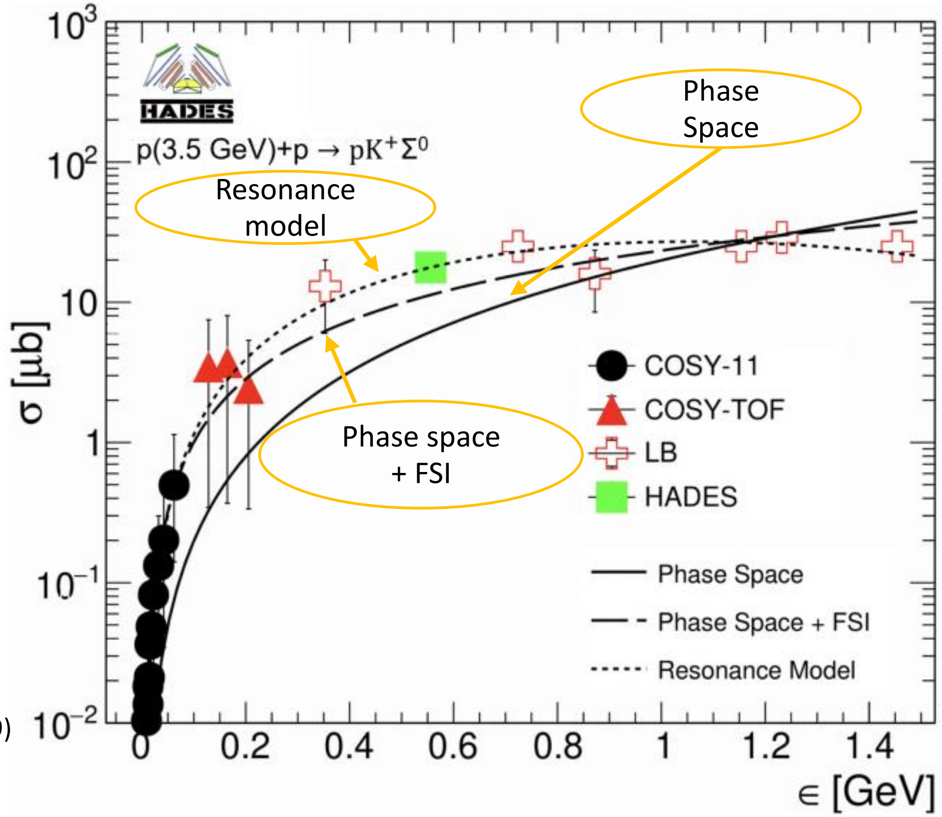
Production Cross Section

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 Σ^0 CMS angular distribution

$$\sigma(\mathrm{pK}^+\Sigma^0) = 17.7 \pm 1.7(\mathrm{stat}) \pm 1.6(\mathrm{syst})\ \mu\mathrm{b}$$





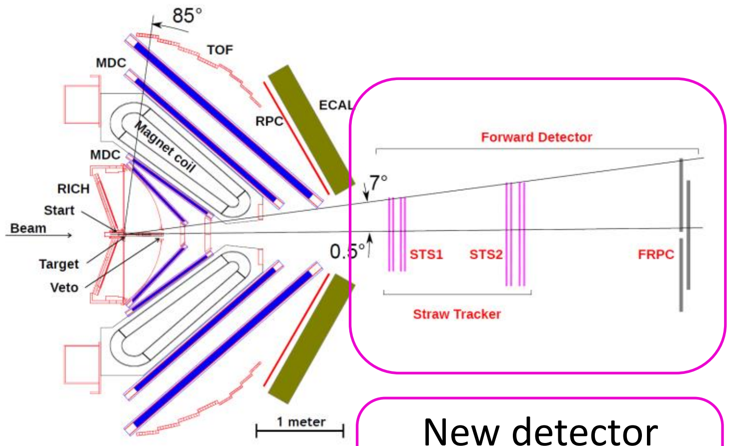
- Resonance model study of kaon production in baryon-baryon reactions for heavy-ion collisions, K. Tsushima**, Phys. Rev. C 59** (1999)
- Comparison of the near-threshold production of η- and K-mesons in proton-proton collisions, G. Fäldt *Zeitschrift für Physik A Hadrons and Nuclei* **357**, (1997)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

Summary

HADES Collaboration, Investigation of the Σ^0 Production Mechanism in p(3.5 GeV)+p collisions, *arXiv:2301.11766 [nucl-ex]*

- 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 (p(4.5GeV)+p Feb 2022 beam time)**
- **The photon is measured in ECAL**
- **Analysis of real and virtual photon decays is in progress**



New detector based on PANDA FTS

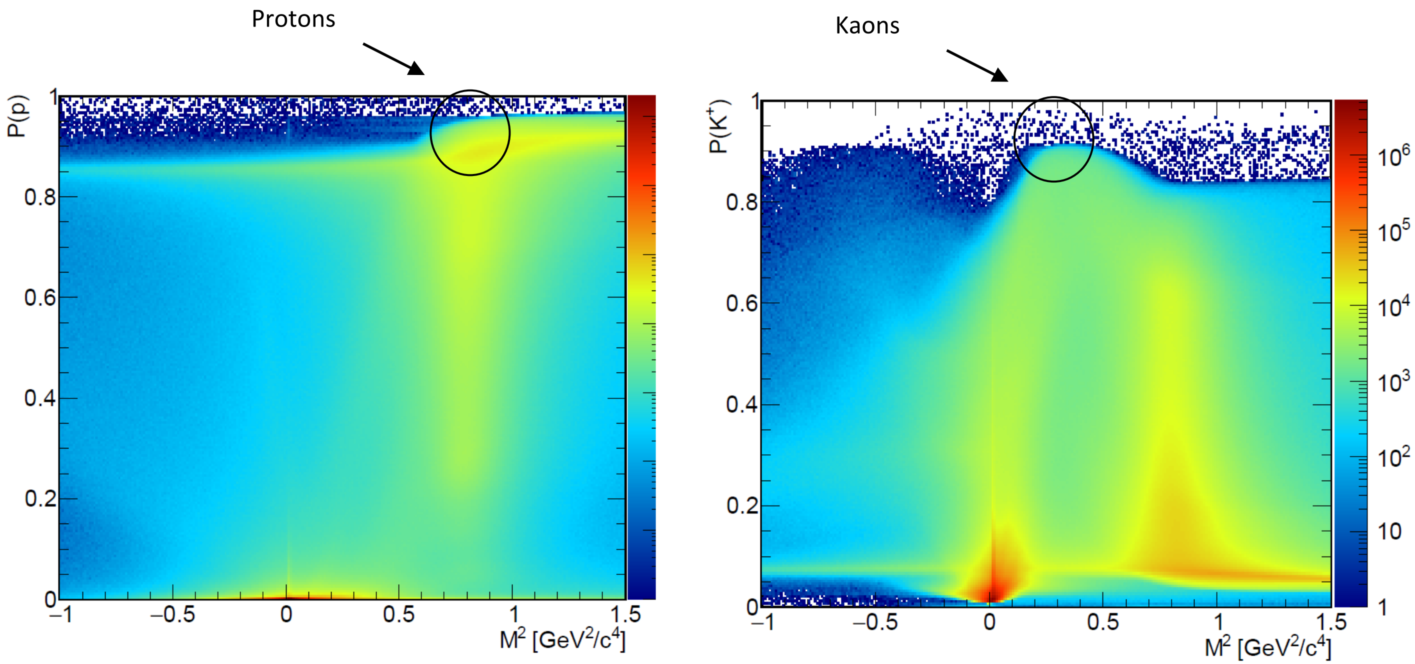
Thank You

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

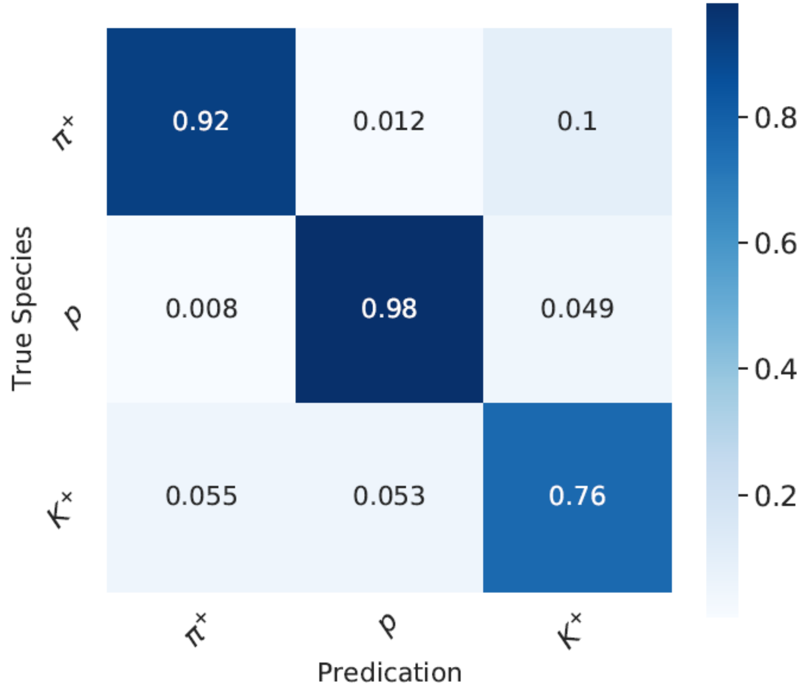
Backups: PID

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

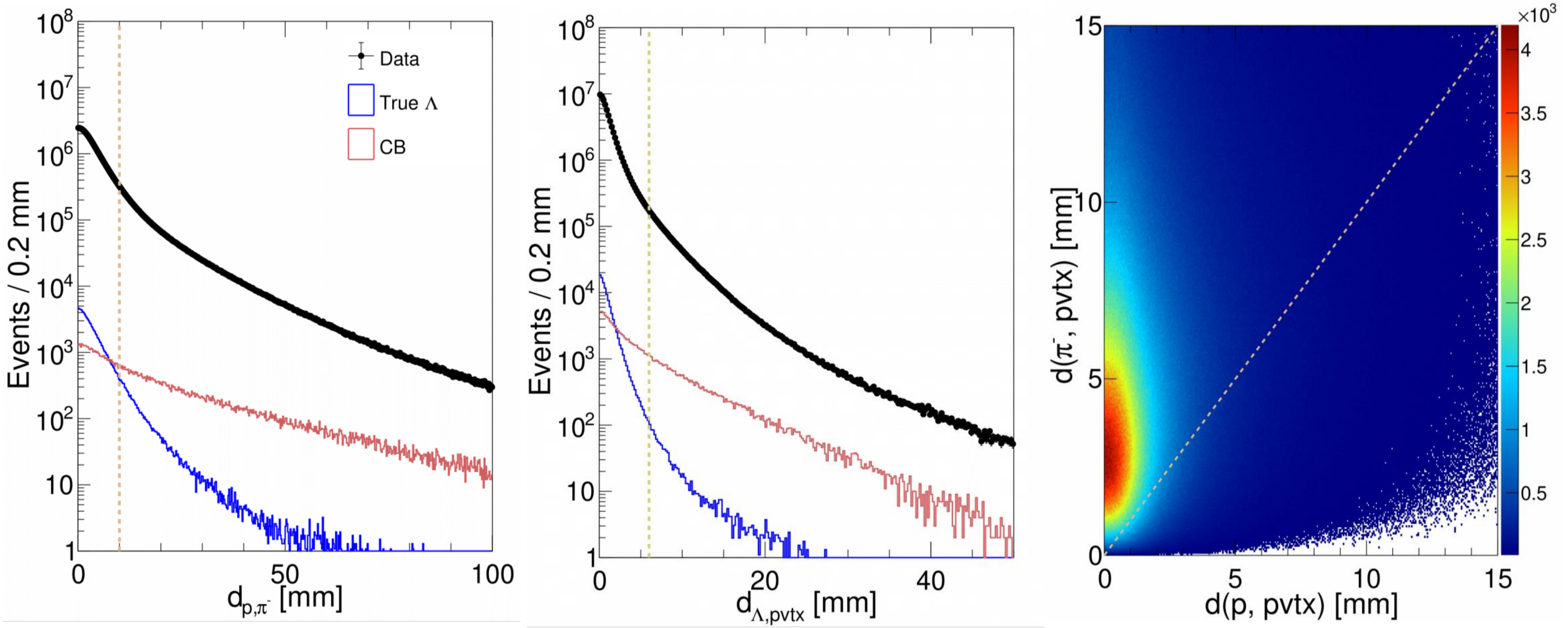
Performance evaluated on real data



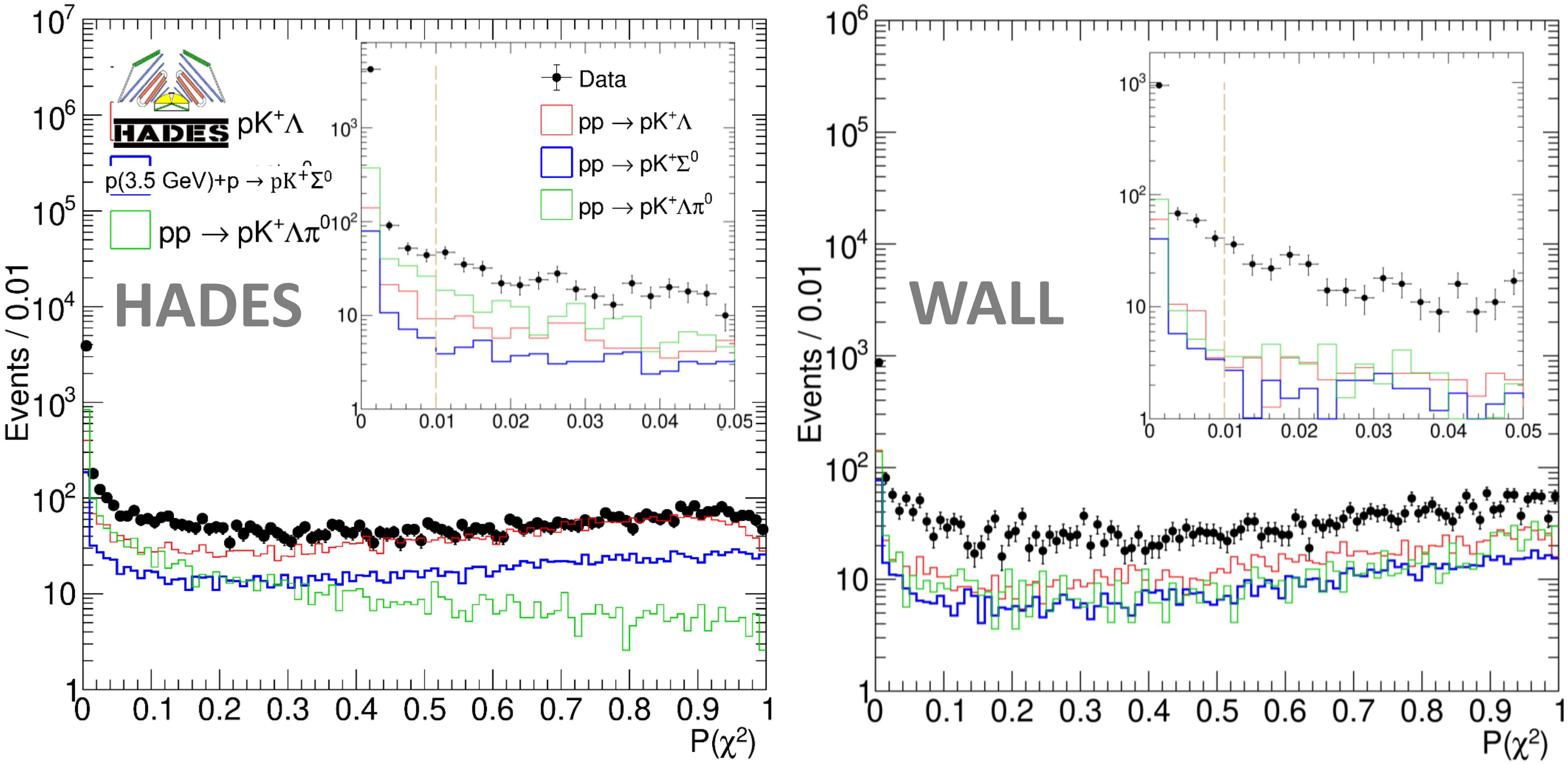
Confusion Matrix (Simulations)



Backups: Lambda Selection



Backups: Kinematic Refit



Backups: Reference Frames

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

1. Center of Mass CMS Frame:

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

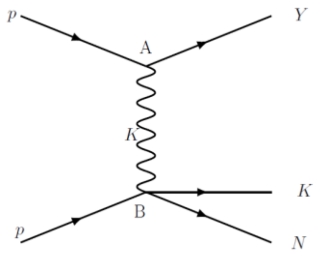
2. Gottfried Jackson G-F Frame:

- 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

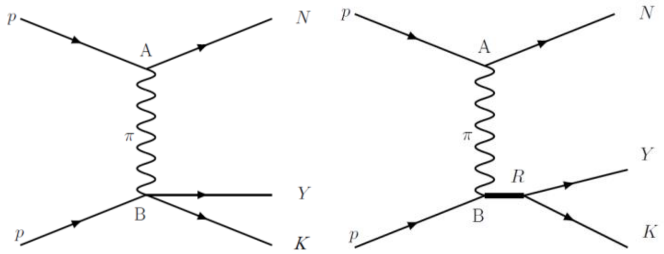
3. Helicity Frame:

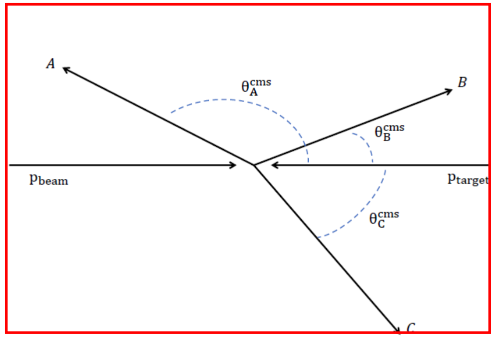
- Defined similar to the G-F angle, but the angle with respect to the third produced particle is used

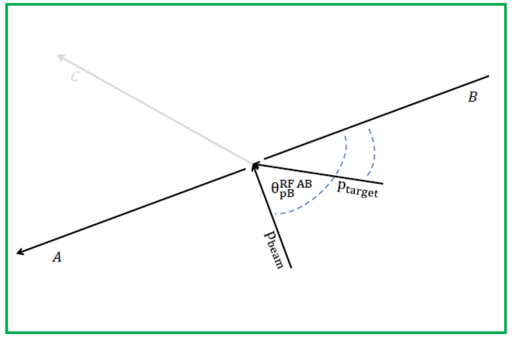
Kaon exchange

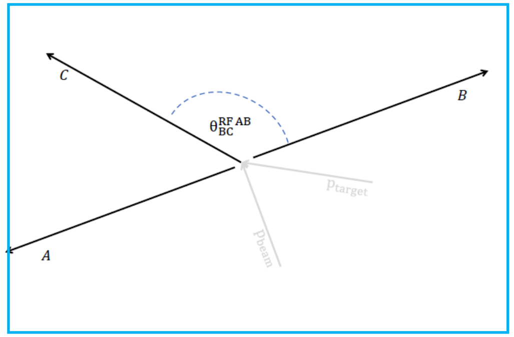


Pion exchange









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*

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

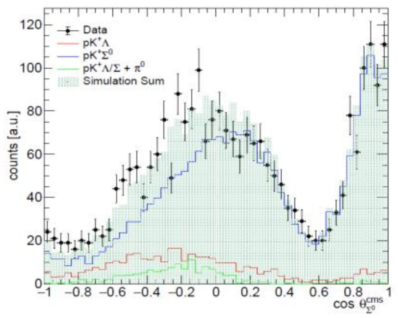
- **Correction** or data unfolding means to **invert** the **response matrix**
- **Inversion** is done via the Singular Value Decomposition **SVD** implemented using **RooUnfold framework**
- Since there are background events, a **purity matrix** is defined as

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

Backups: Efficiency Corrections

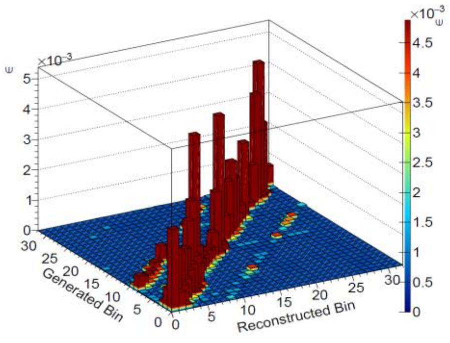
- Example: Correction of the Σ^0 CMS angular distribution
- 2D correction in $cos\theta^{cms}_{\Sigma^0}$ and $p^{cms}_{\Sigma^0}$
- The corrected number of Σ^0 events are transformed into a cross section by normalizing to elastic collisions at the same beam energy

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



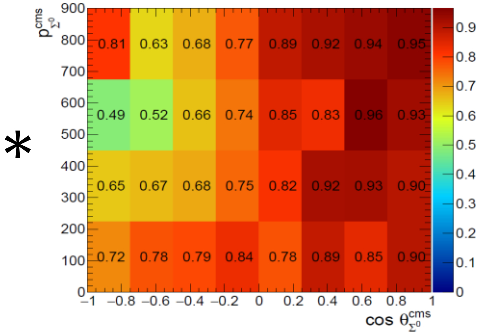
The measured distribution
M

*



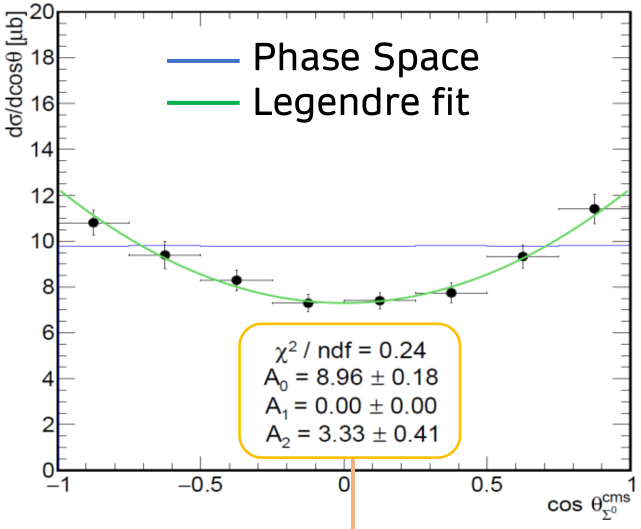
Inverse of the response matrix
R^{-1}

*



Purity matrix
P

≡



Legendre Parameters

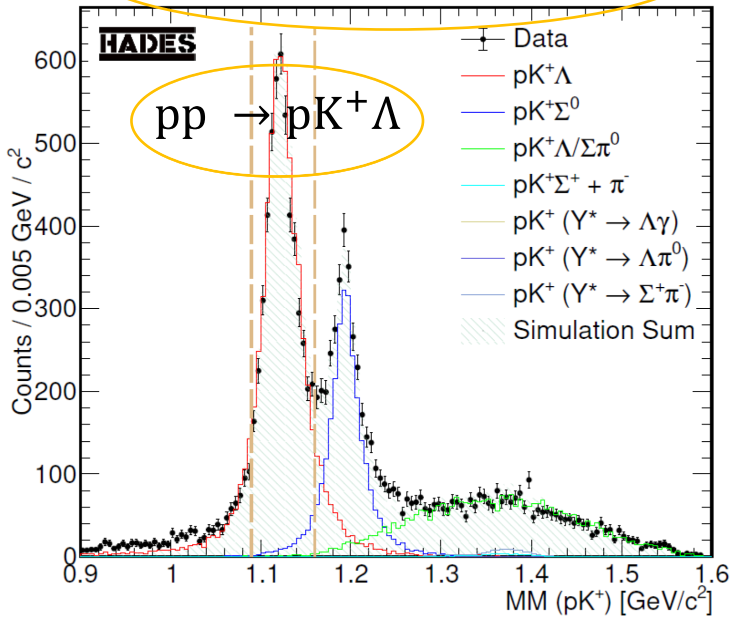
Backups: Partial Wave Analysis

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

- **P**artial **W**ave **A**nalysis (**PWA**) was performed in order to estimate resonant contributions
- PWA aims to determine the transition amplitude $A^{\alpha}_{tr}(s) = (\alpha_1 + \alpha_3\sqrt{s})e^{i\alpha_2}$
- 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

$1.090 < MM(pK^+)[GeV/c^2] < 1.150$



*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**