Investigating the Σ^0 Production In p(3.5GeV)+p Collisions

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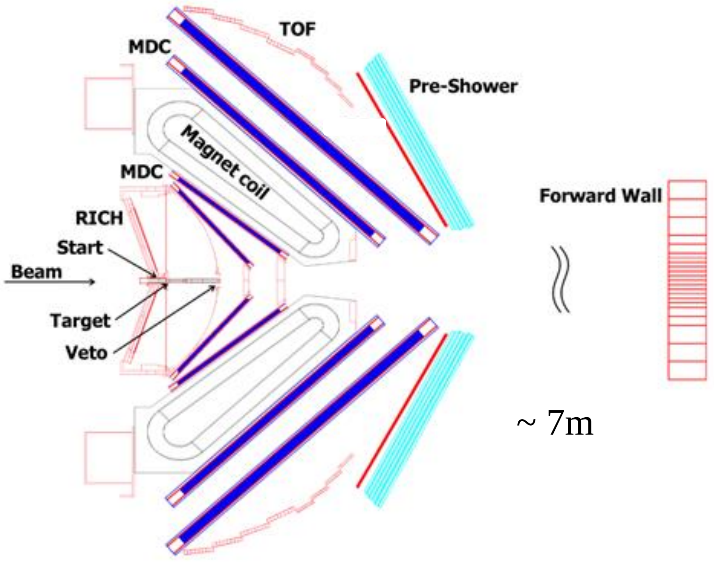
An Overview

Motivation:

- The study of hyperon production in p+p collisions at **energies of a few GeV** is important for a better **understanding of the strong interaction**
- Is crucial as a baseline for in-depth **studies** of the **heavy ion collisions**
- Hyperon **radiative decay** provides a **clean probe** of the hyperon **wave function**
- There **are few measurements** for Σ^0 hyperon



Dataset:

- Proton beam (3.5 GeV) incident on LH2 target with 50 mm thickness collected in 2007
- In total there were 1.14×10^9 LVL1 events

Reaction:

- Exclusive reconstruction of

$$p + p \rightarrow p + K^+ + \Sigma^0, \text{ BR } (\Sigma^0 \rightarrow \Lambda\gamma) \sim 100\%$$

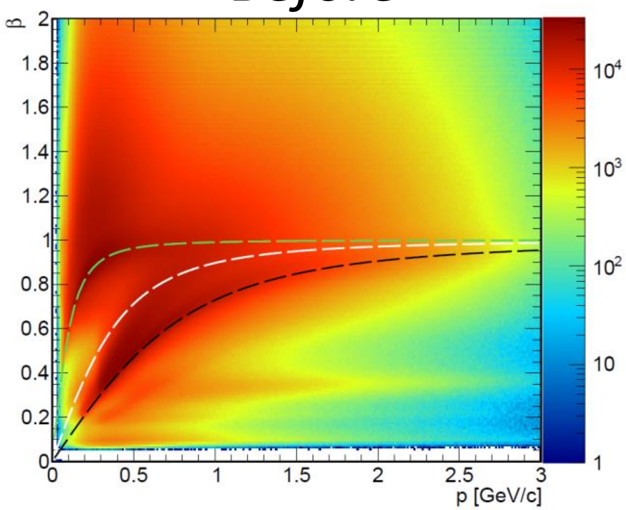
Reconstrcution Strategy

1. Time of flight reconstruction
2. Charged Particle Identification PID
3. Lambda Reconstruction
   i. HADES data-set
   ii. The Forward Wall data-set
4. Kinematic Refit
5. Sigma Reconstruction
6. Efficiency Correction
7. Physics Conclusions

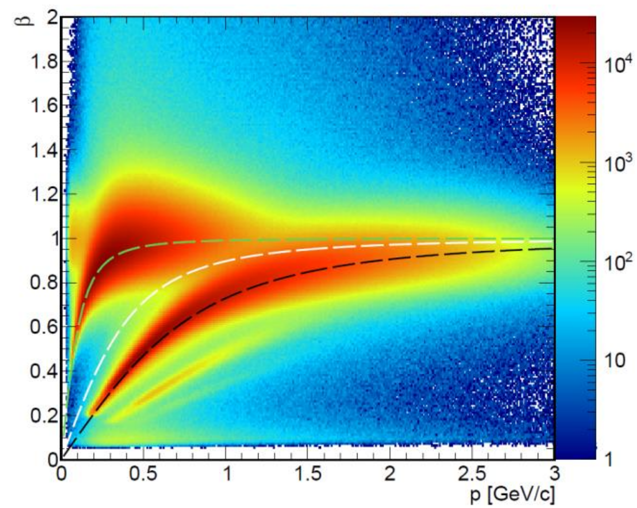
Time of Flight Reconstruction

- Important **variable** for the **PID** algorithm
- At *least one particle must be identified*, π^- were identified (no correlation with RICH)
- $$tof = \frac{L}{c} \cdot \frac{\sqrt{p^2 + m^2}}{p}, \quad \text{with} \quad tof = t_s - t_0$$
- An average **common start time** $\bar{t}_0 = \frac{\sum_i w_i t_{0,i}}{\sum_i w_i}$

Before



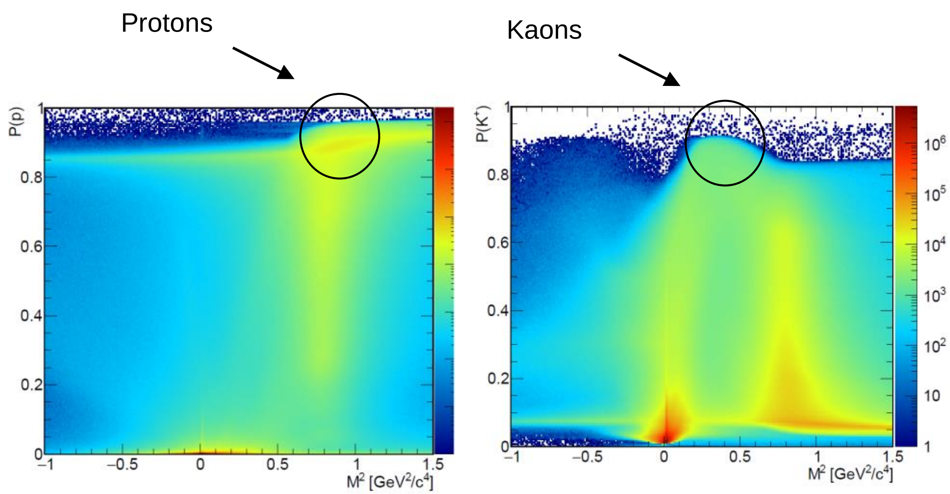
After

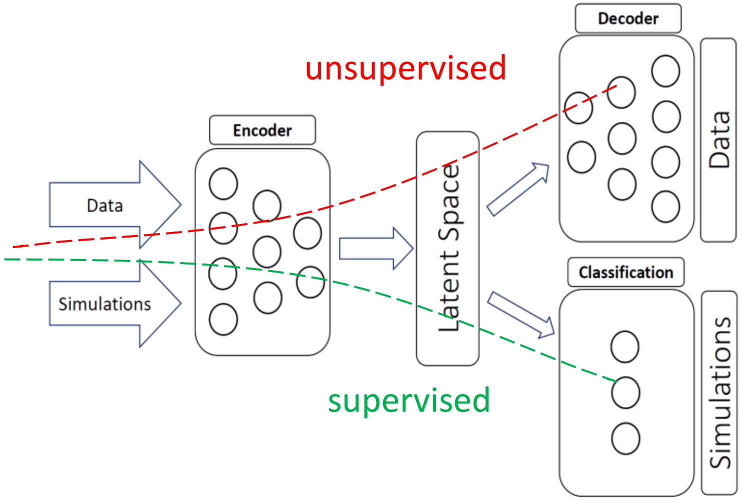


Particle Identification PID

- Identification of **3 types** of particles: **p, K^+, π^+**
- Deep Learning based PID: A **multi-class classification** problem
- But simulation does not model real data perfectly well (**domain shift**)
- Potential solution: **Autoencoders**
- Classification Accuracy: π^+ ~ 92%, p ~ 98%, K^+ ~ 76%

Performance evaluated on real data



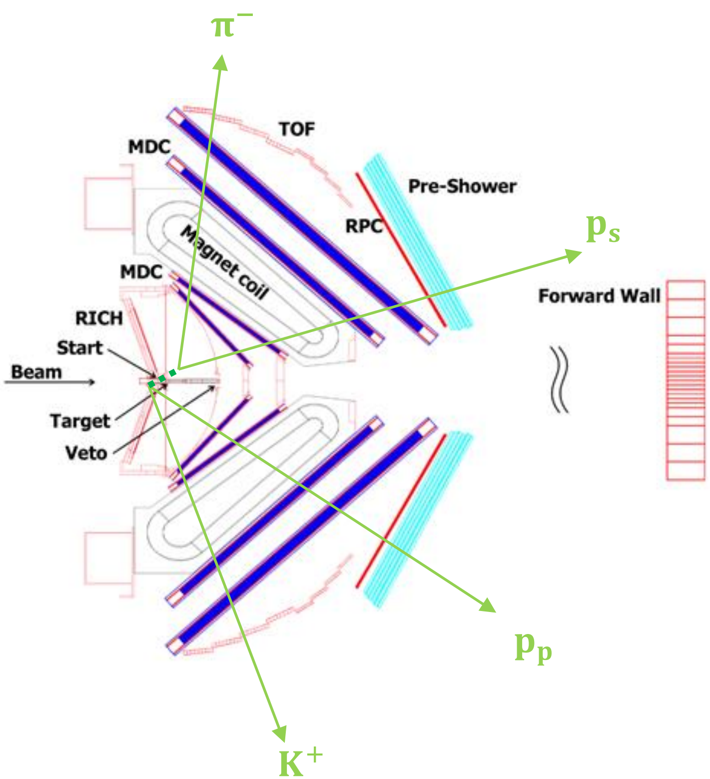


Lambda Reconstruction

$$p + p \rightarrow p + K^{+} + \Sigma^{0} \rightarrow p + K^{+} + p + \pi^{-} + \gamma$$

HADES data-set

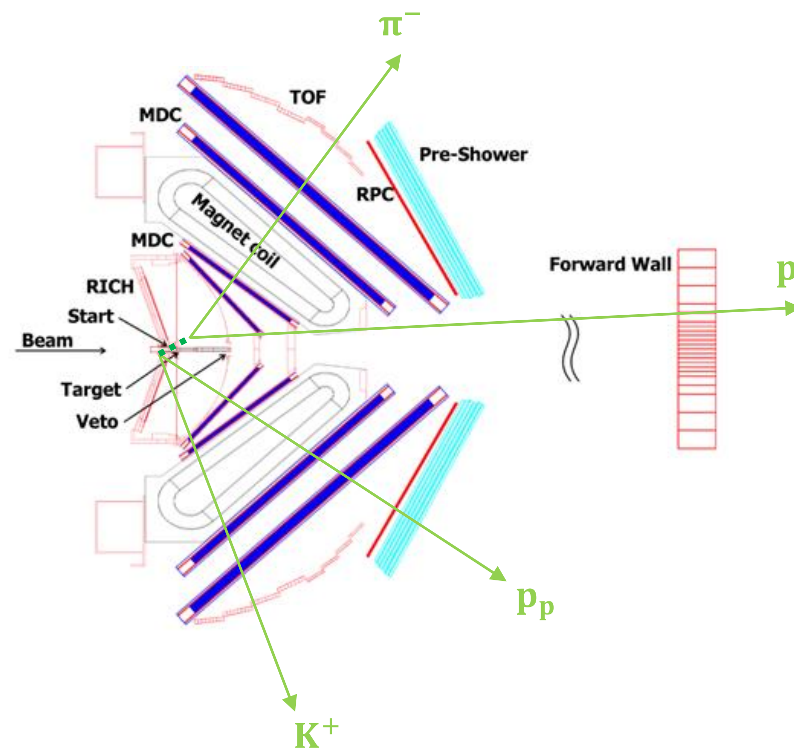
✓ All particles in HADES acceptance



Wall data-set

✓ p, K^{+}, π^{-} in HADES acceptance

✓ One hit in the FW



Lambda Reconstruction

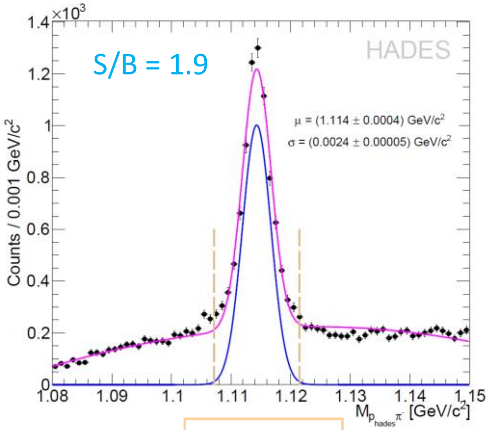
- **Primary vertex**: Intersection point or the PCA of **pK⁺**

➢ $-65 < z[mm] < -5$

➢ $r[mm] < 5$

HADES data-set

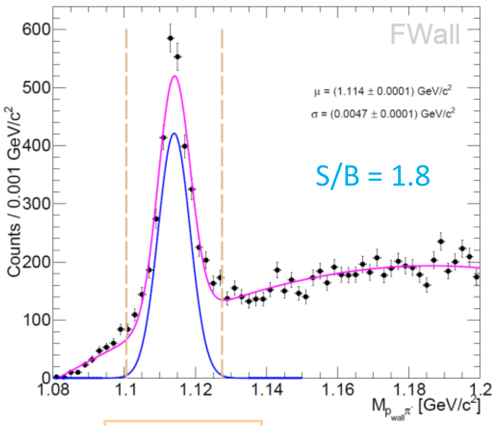
1. $d(p, \pi^-) < 10$ mm
2. $d(p, pvtx) < d(\pi^-, pvtx)$
3. $d(\Lambda, pvtx) < 6$ mm
4. $MM^2(pp_{hades}\pi^-)[GeV^2/c^4] > 0.2$



$\mu \pm 3\sigma$

Wall data-set

1. $-0.02 < MM^2(pK^+p_{wall}\pi^-)[GeV^2/c^4] < 0.01$
2. $MM^2(pp_{wall}\pi^-)[GeV^2/c^4] > 0.2$



$\mu \pm 3\sigma$

Kinematic Refit

- A **constrained fit** to provide better estimation of **track parameters**
- Suppression of background + better mass resolution
- Based on Lagrange Multipliers*

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

- Track parametrization 1/p, θ, φ
- **Covariance matrix** is estimated from the simulation and **tuned** via the pull **distributions**

Invariant mass constraint

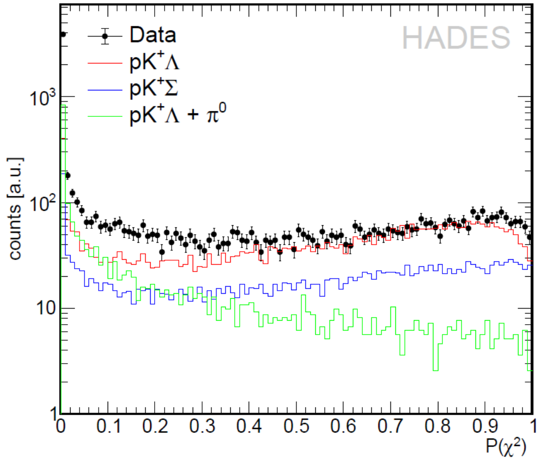
$$f = \begin{pmatrix} (E_{p_s}+E_{\pi^-})^2 - (\vec{p}_{p_s}+\vec{p}_{\pi^-})_x^2 - (\vec{p}_{p_s}+\vec{p}_{\pi^-})_y^2 - (\vec{p}_{p_s}+\vec{p}_{\pi^-})_z^2 - M_\Lambda^2 \\ (E_t + E_b - \sum_{i=1}^{4} E_i)^2 - (\vec{p}_t + \vec{p}_b - \sum_{i=1}^{4n} \vec{p}_i)^2 - M_\gamma^2 \end{pmatrix} = 0$$

Missing mass constraint

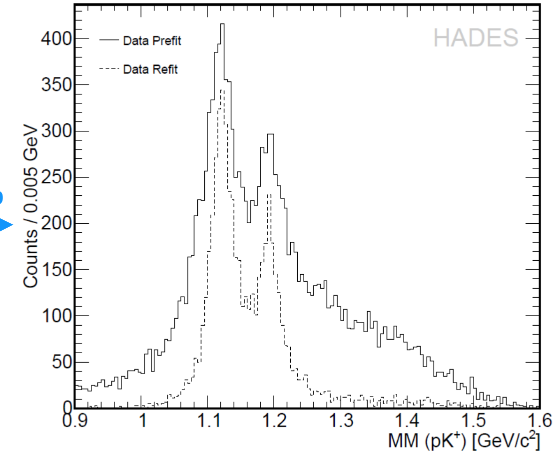
*In cooperation with Jenny Regina and Jana Rieger

Kinematic Refit

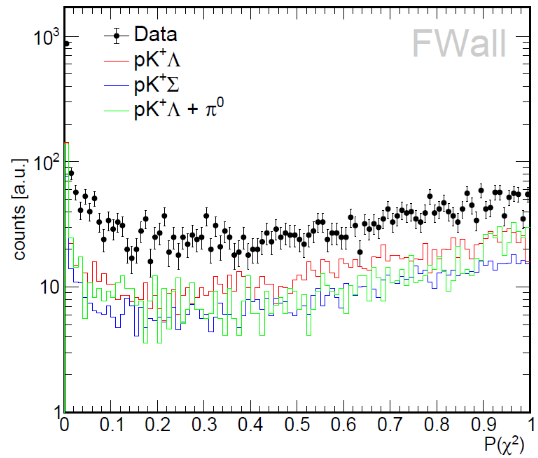
HADES data-set



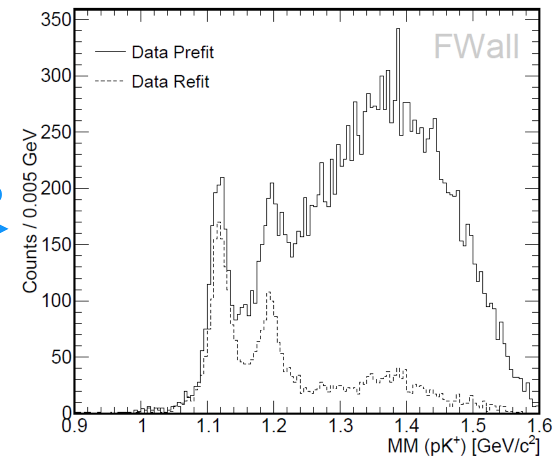
P-value > 1%



Wall data-set



P-value > 1%



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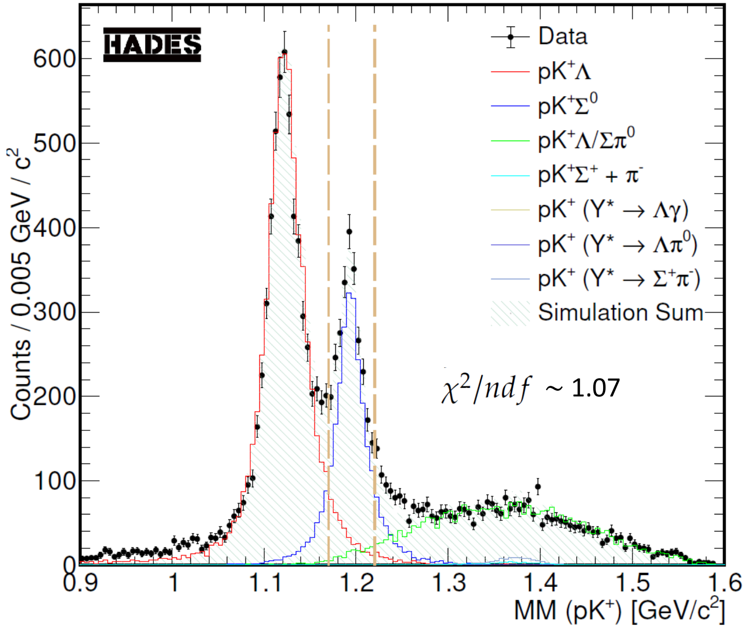
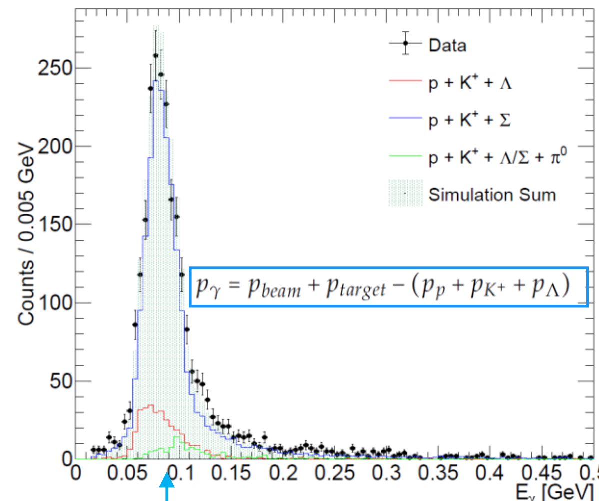
Sigma Reconstruction



$$\chi^2 = \sum_i^{n_{bins}} \frac{(n_{data} - \sum_{ch}(f^{ch} \times n^{ch}_{simulation}))^2}{\sigma^2_{data} + \sigma^2_{simulation}}$$

	Channel
1	$p + p \to p + K^+ + \Lambda$
2	$p + p \to p + K^+ + \Sigma(1385)$
3	$p + p \to p + K^+ + \Lambda(1405)$
4	$p + p \to p + p + \pi^+ + \pi^-$
5	$p + p \to p + p + \pi^+ + \pi^- + \pi^0$
6	$p + p \to p + K^+ + \Sigma^0$
7	$p + p \to p + K^+ + \Lambda + \pi^0$
8	$p + p \to p + K^+ + \Sigma^0 + \pi^0$
9	$p + p \to p + K^+ + \Sigma^+ + \pi^-$



~ 77 MeV

- $1.170 < MM(pK^+)[GeV/c^2] < 1.220$
- 2613 Σ^0s: 58% HADES + 42% Wall (purity 81%)
- Background: $pK^+\Lambda$ ~ 14%

  $pK^+\Lambda/\Sigma^0\pi^0$ ~ 5%

Reference Frames

1. Center of Mass CMS Frame:

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

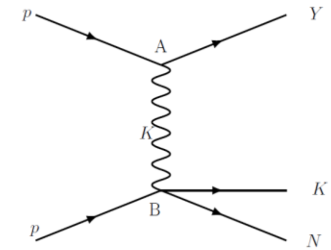
2. Gottfried Jackson G-F Frame:

- $cos\theta_{p,B}^{RF\ AB}$ 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

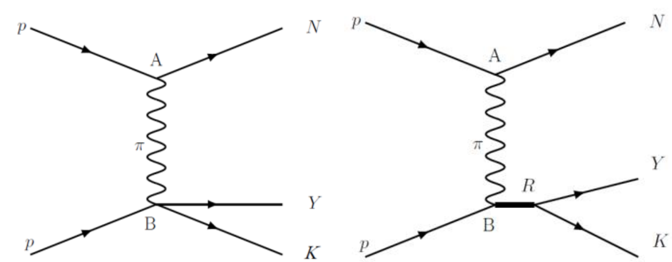
3. Helicity Frame:

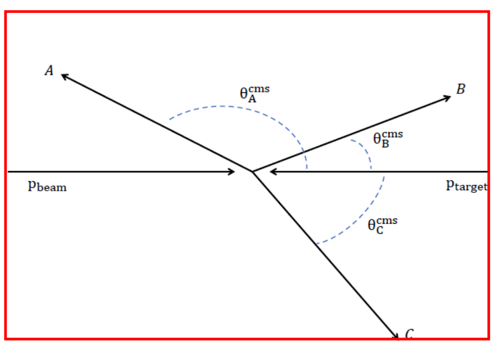
- Defined similar to the G-F angle, but the angle with respect to the third produced particle is used

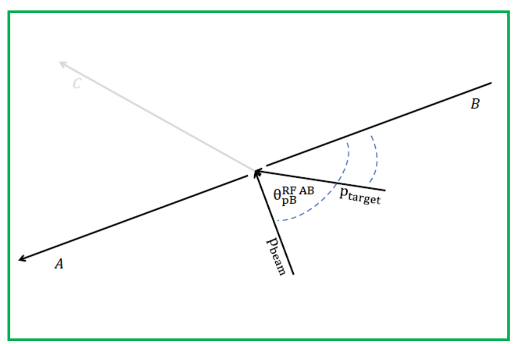
Kaon exchange

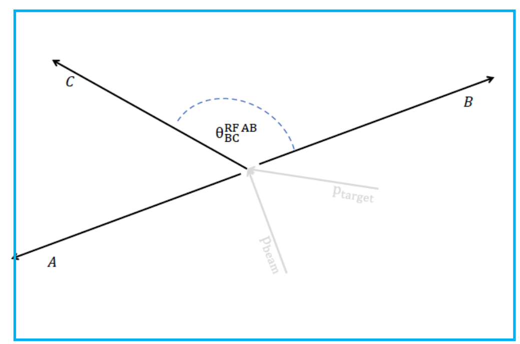


Pion exchange









Acceptance and Efficiency Correction

- 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

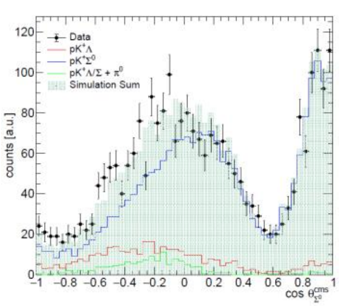
$$P_{bin} = \frac{n(pK^+\Sigma^0)}{n(pK^+\Lambda) + n(pK^+\Sigma^0) + n(pK^+\Lambda\pi^0)}$$

- True distribution is then given by: **$T = R^{-1}MP$**

Acceptance and Efficiency Correction

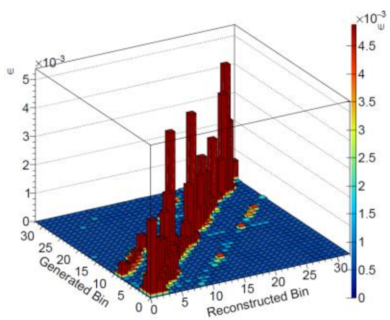
- Correction of **Σ^0 CMS angular distribution**
- **2D correction** in $cos\theta^{cms}_{\Sigma^0}$ and $p^{cms}_{\Sigma^0}$
- The corrected number of Σ^0 events is transformed into a cross section:

$$\sigma_{\Sigma^0}[\mu b] = \frac{1}{N_{files}} \cdot \frac{\sigma^{elastic}_{pp}}{N^{elastic}_{pp}} \cdot N_{\Sigma^0} \cdot f_{downscale} \cdot 10^3$$



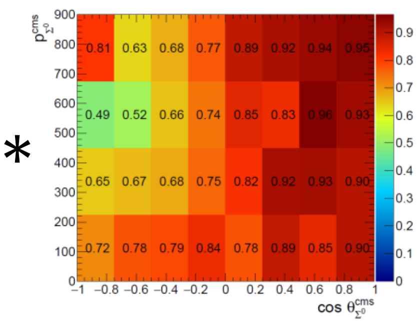
The measured distribution
M

*



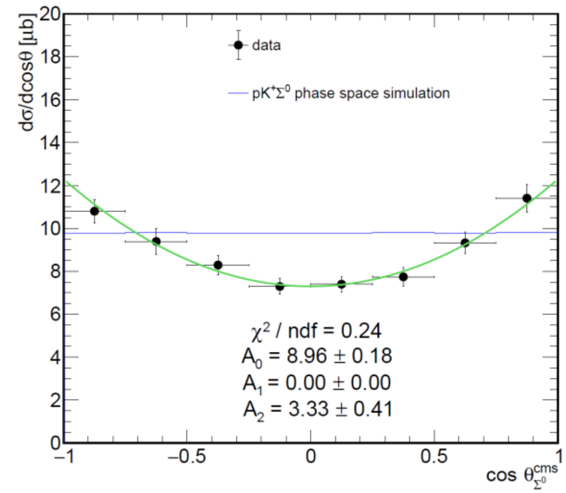
The inverse of the response matrix
R⁻¹

*



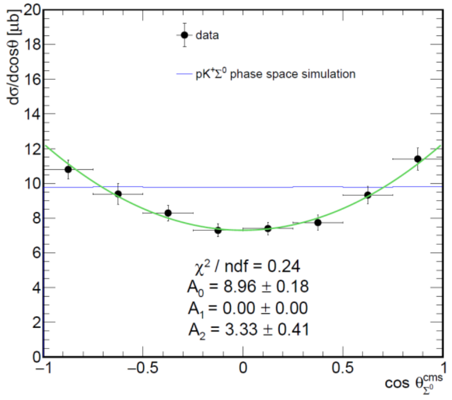
The purity matrix
P

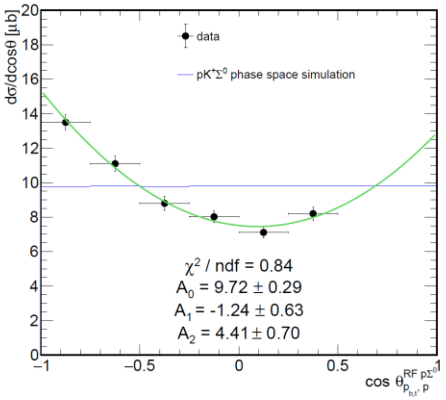
≡



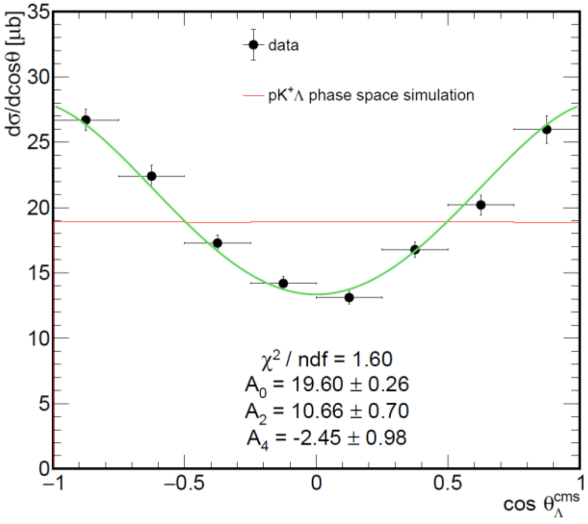
Tunning the Simulation Model

- Phase space simulations are weighted by $cos\theta_{\Sigma^0}^{cms}$ and $cos\theta_{p_{b,t},p}^{RFp\Sigma}$ obtained from data
- The helicity angular distributions are not affected by this weighting
- The **purity matrix depends** on the $pp \rightarrow pK^+\Lambda$ **kinematics**
- $pp \rightarrow pK^+\Lambda$ *phase space simulation is folded by* $cos\theta_{\Lambda}^{cms}$ *obtained from data*





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

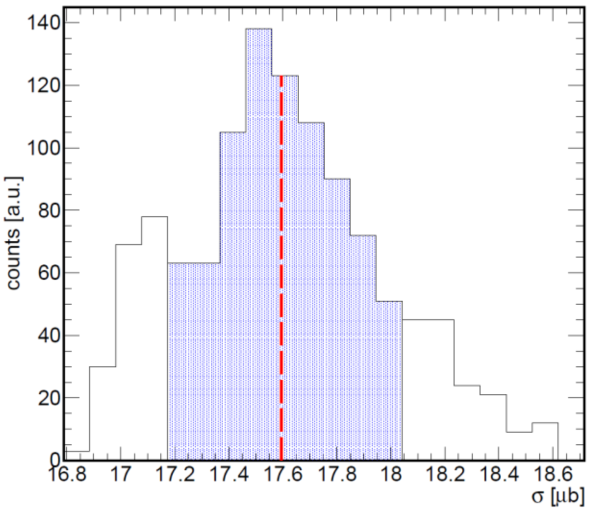


same correction procedure

Systematic Errors

Possible sources:

1. **PID (neural network uncertainty)**
   - *Implemented dropout layers are activated during inference (a Bayesian Approximation [§])*
   - *Introduces ± 5% error*
2. **Analysis cuts (topological and missing mass cuts)**
   - *Each cut is varied in two steps in either direction, the cross section is calculated for every cut combination*
   - *The systematic uncertainty is defined as the 68% confidence central interval of this distribution*
   - *Introduces ± 2% systematic error*



3. ***Normalization to elastic scattering***
   - *Introduces ± 7% systematic error*

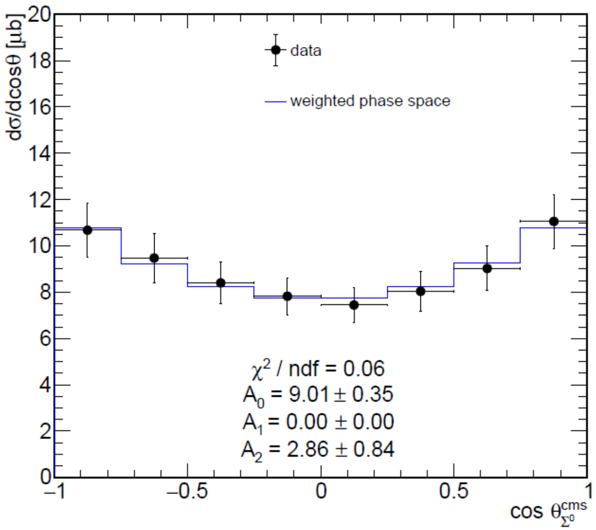
same correction procedure

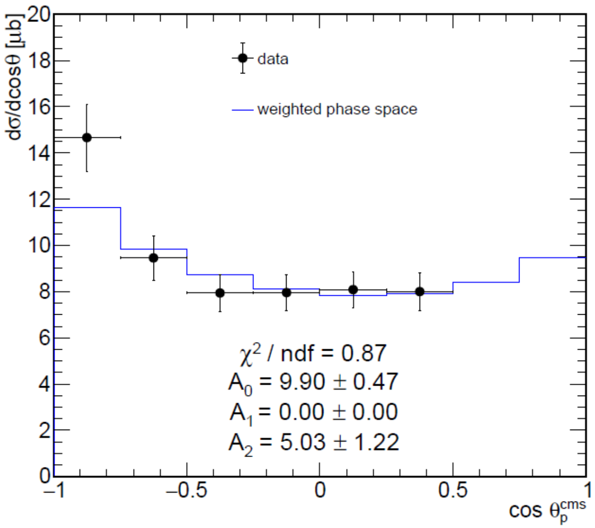
[§] *Yarin Gal "Dropout as a Bayesian Approximation: Representing Model Uncertainty in Deep Learning" 2015*

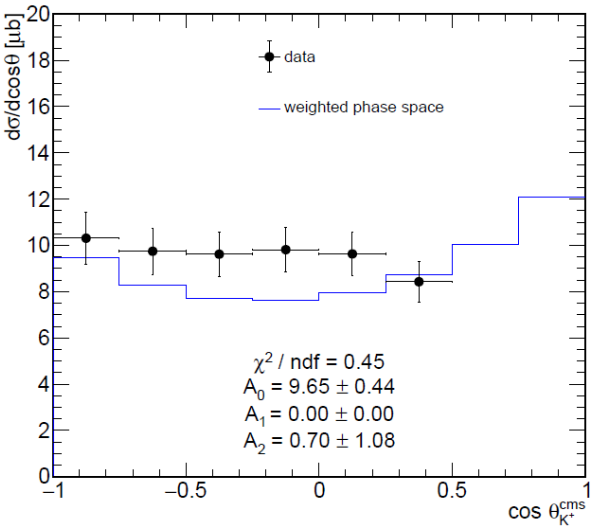
Angular Distributions

CMS frame

- *An indication of dominantly **pion exchange** production mechanism*



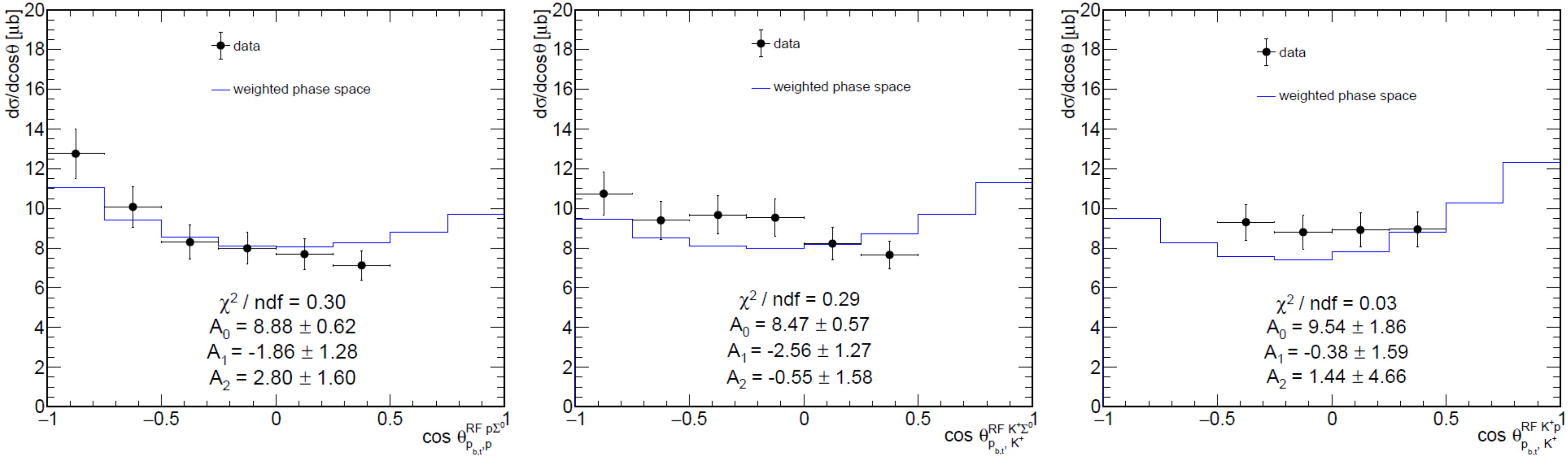




Angular Distributions

G-J Frame

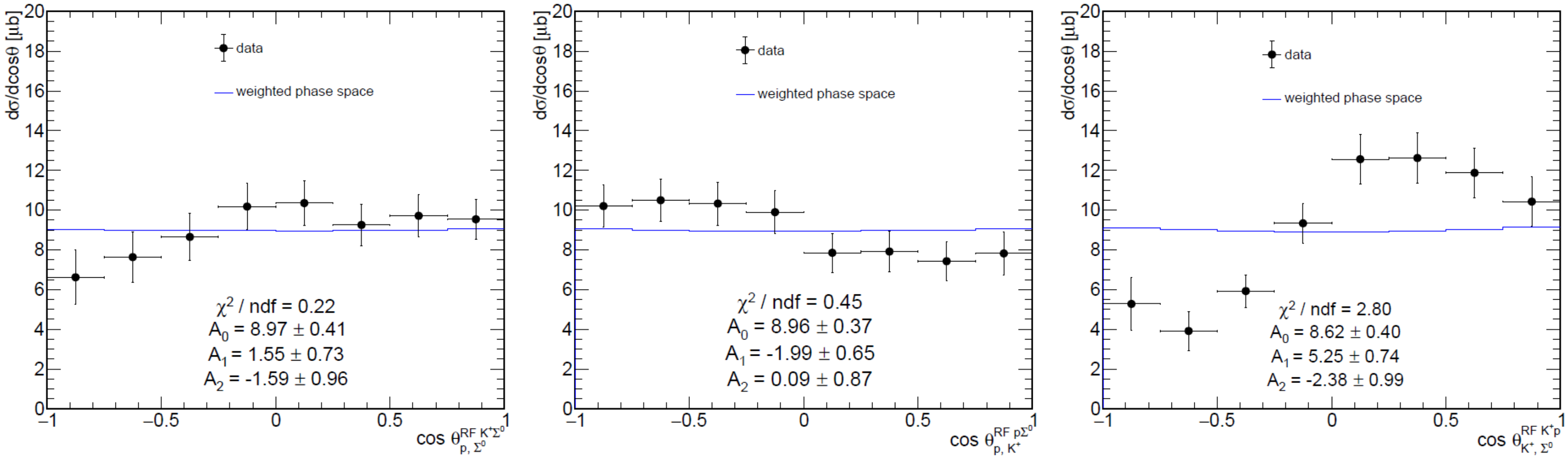
- *An indication that **more than one nucleon resonance** participates in the production process **N*/Δ****



Angular Distributions

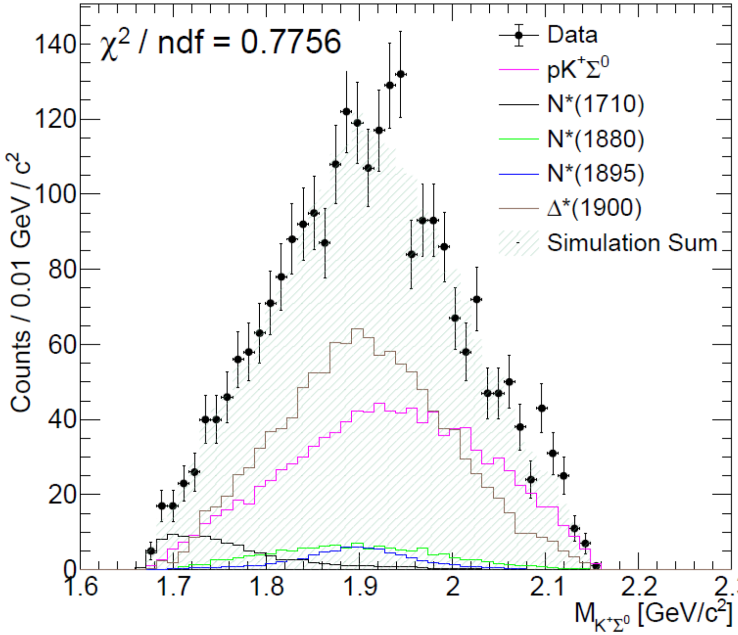
Helicity Frame

- ***Strongly non-isotropic***, *dominated by intermediate* ***resonant*** *production*



Angular Distributions

- **The Incoherent Sum**
- *Isospin 1/2 N* or isospin 3/2 Δ^* could contribute to the production*
- The **incoherent sum** of **resonances** and **phase space** have been scaled to match the experimental data
- A fit of phase space alone **result in** $\chi^2/ndf \sim 4.1$
- The **cocktail fit result in** $\chi^2/ndf \sim 0.8$

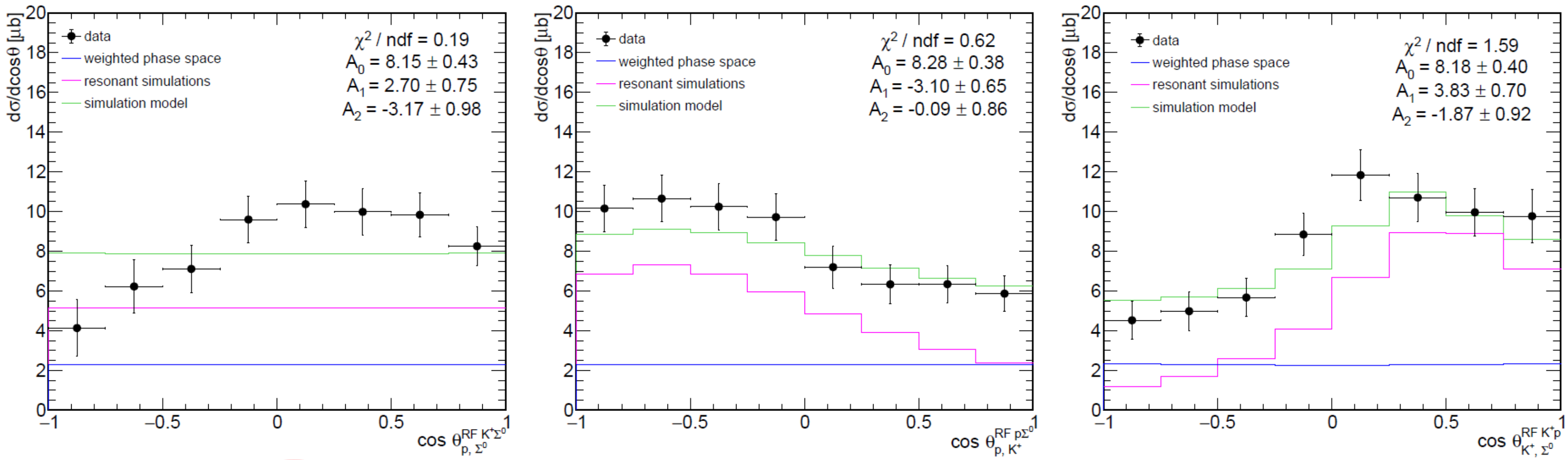


Resonance	Mass $[GeV/c^2]$	Width $[GeV/c^2]$	J^P	BR $(K^+\Sigma^0)$	ϵ [MeV]
$N^*(1710)$	1.710	0.140	$\frac{1}{2}^+$	seen	528
$N^*(1875)$	1.875	0.200	$\frac{3}{2}$	seen	363
$N^*(1880)$	1.880	0.300	$\frac{1}{2}^+$	10-24%	358
$N^*(1895)$	1.895	0.120	$\frac{1}{2}$	6-20%	343
$N^*(1900)$	1.920	0.200	$\frac{3}{2}^+$	3-7%	338
$\Delta^*(1900)$	1.860	0.250	$\frac{1}{2}$	seen	338
$\Delta^*(1910)$	1.900	0.300	$\frac{1}{2}^-$	4-14%	328
$\Delta^*(1920)$	1.920	0.300	$\frac{3}{2}^+$	2-6%	318

Angular Distributions

Helicity Frame Revisited

The simulation model used to correct the experimental data is the incoherent cocktail of 31% phase space, 6.7% N(1710), 4.3% N(1880), 3.0% N(1895) and 55% Δ(1900)



Interference Effects ?!

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Partial Wave Analysis PWA

Motivation:

- PWA is needed for better description of experimental distributions
- Tool used is the **Bonn-Gatchina PWA framework**
- Works on an event-by-event basis

- PWA is first applied to $pp \rightarrow pK^+\Lambda$ (mass window $1.090 < MM(pK^+)[GeV/c^2] < 1.150$)
- *Solution No. 8/1 from * including N(1650), N(1710), N(1720) and N(1900)*
- The obtained solution is applied to the $pp \rightarrow pK^+\Lambda$ 4π phase space simulation and processed through the full simulation and analysis chain.
- An estimate of $pp \rightarrow pK^+\Lambda$ within the signal region is 292 events
- Those events are subtracted

*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)

Partial Wave Analysis PWA

PWA applied to $p + p \rightarrow \Sigma^0 + K^+ + p$

Best Solution

Solution	Initial State	non-resonant contributions	resonant contributions	$\mathcal{L}$
solution 1	$^1S_0,\ ^1D_2$ $^3P_0,\ ^3P_1$ $^3P_2,\ ^3F_2$	61.77 %	$N^*(1710) \approx 17.40$ % $N^*(1900) \approx 18.51$ % $\Delta^*(1900) \approx 02.31$ %	-333.65
solution 2	$^1S_0,\ ^1D_2$	25.79 %	$N^*(1710) \approx 22.25$ % $N^*(1900) \approx 09.82$ % $\Delta^*(1900) \approx 42.15$ %	-184.40
solution 3	$^1S_0,\ ^1D_2$ $^3P_0,\ ^3P_1$ $^3P_2$	45.06 %	$N^*(1710) \approx 21.40$ % $N^*(1895) \approx 16.17$ % $N^*(1900) \approx 15.88$ % $\Delta^*(1900) \approx 01.49$ %	-181.80
solution 4	$^1S_0,\ ^1D_2$ $^3P_0,\ ^3P_1$ $^3P_2,\ ^3F_2$	33.10 %	$N^*(1710) \approx 26.8$ % $N^*(1880) \approx 40.1$ %	-151.34
solution 5	$^1S_0$	16.75 %	$N^*(1710) \approx 78.55$ % $\Delta^*(1900) \approx 04.62$ %	-122.71

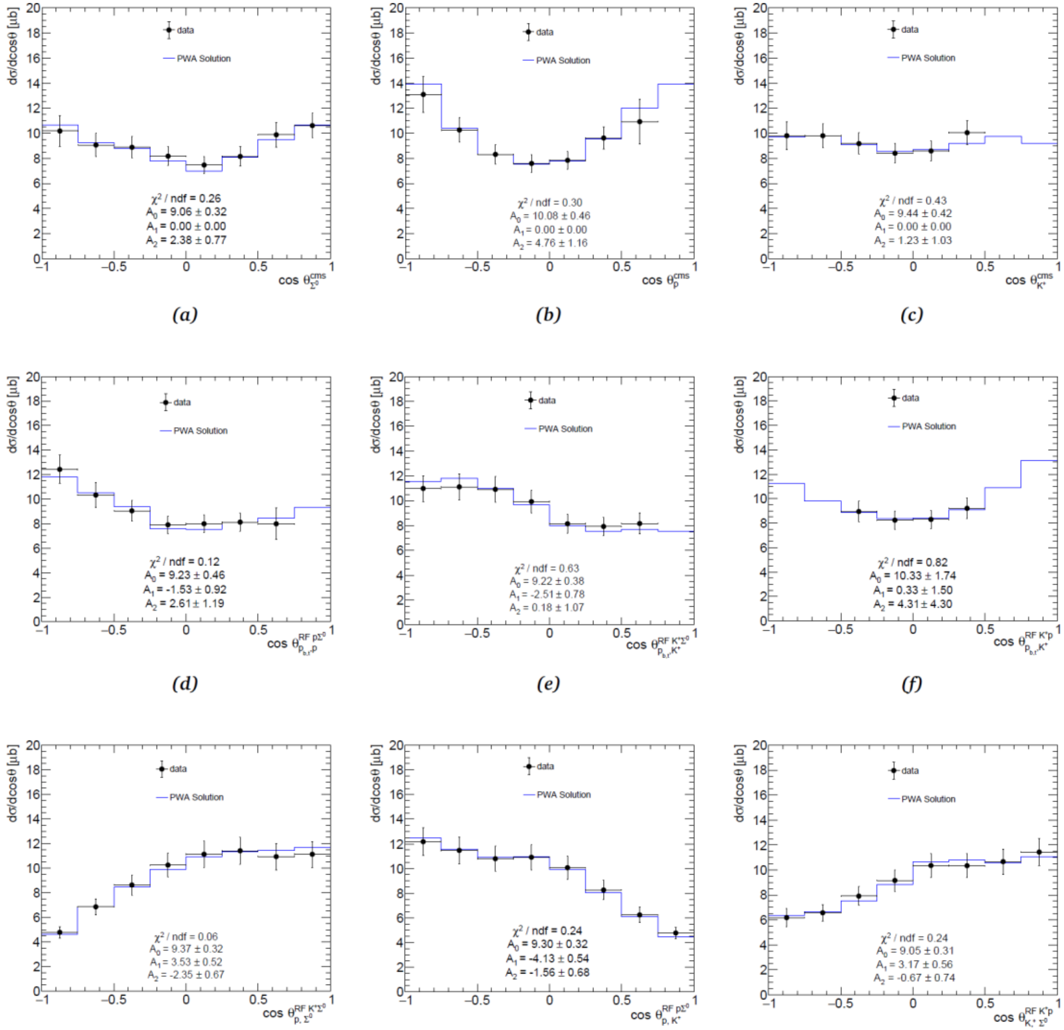
Partial Wave Analysis PWA

Angular Distributions Revisited

CMS Frame

G-J Frame

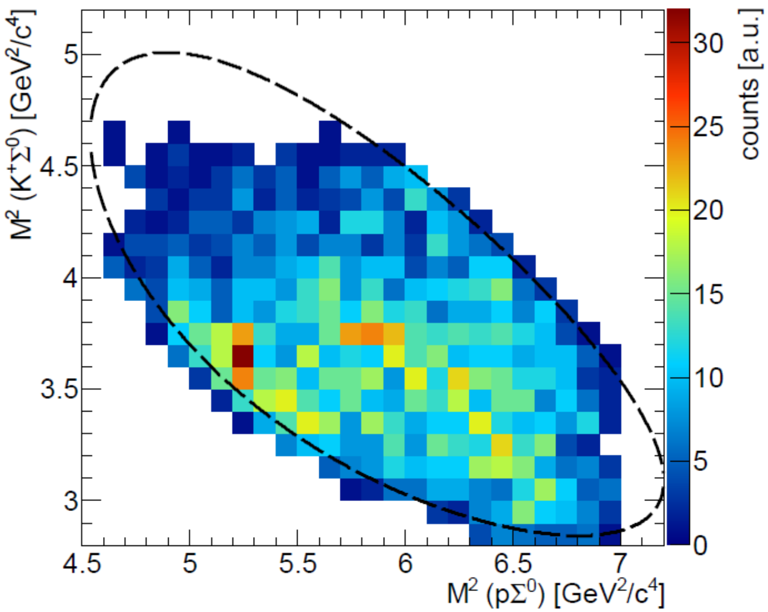
Helicity Frame



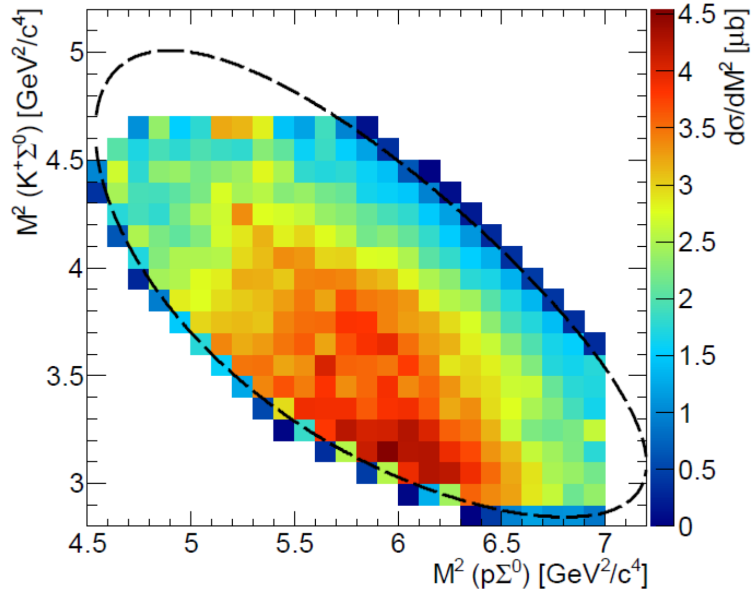
Partial Wave Analysis PWA

The Dalitz Plot

Uncorrected



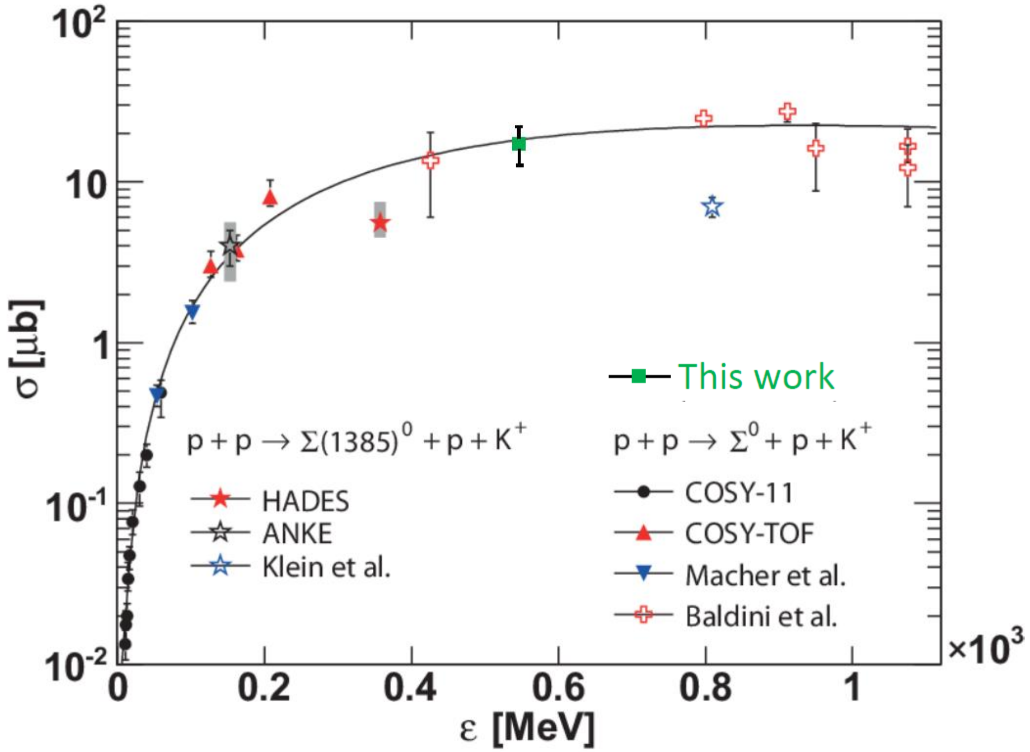
Corrected



Total Production Cross Section

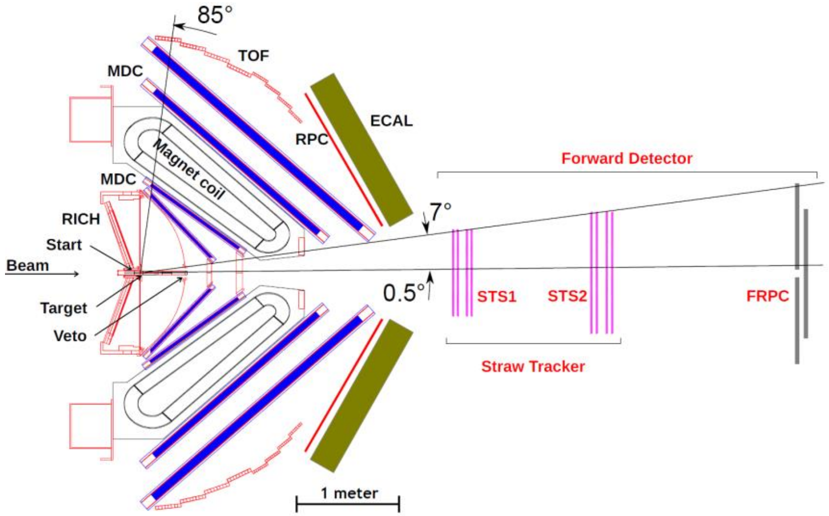
- The cross section is obtained by integrating the yield for different differential distributions

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



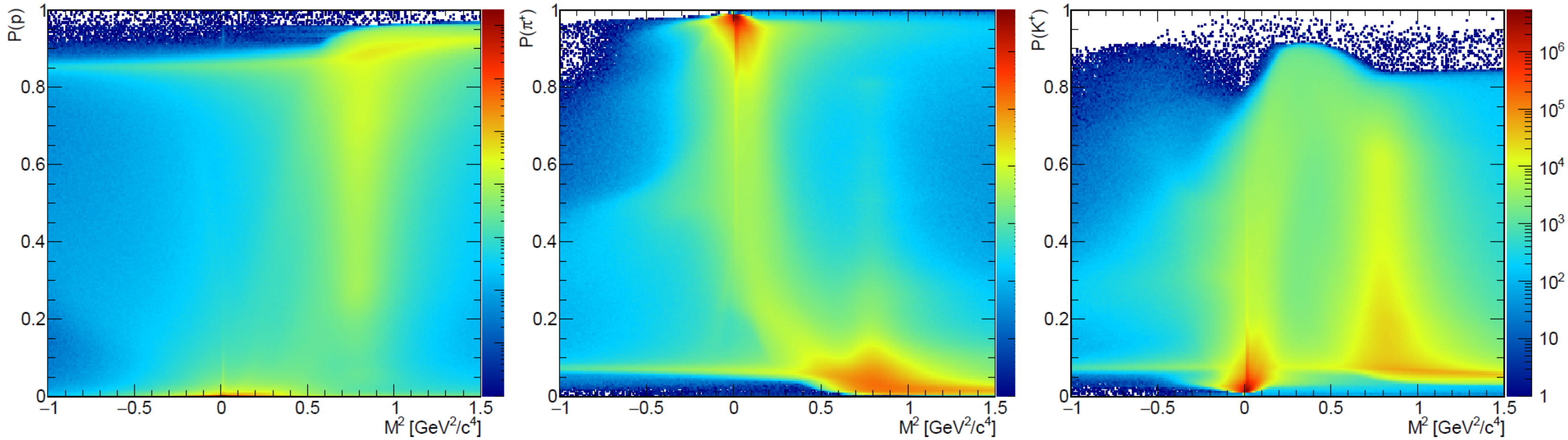
Summary

- An Investigation of the Σ^0 production mechanism in p+p collisions
- Data supports pion exchange mechanism
- The Σ^0 hyperon is produced by resonant and non-resonant reactions
- Due to limited statistics, there is a significant uncertainty to the relative contributions
- Resonances with mass around 1.710 GeV/c^2 and 1.900 GeV/c^2 are preferred by the PWA fit.
- A first step towards the measurement of the radiative decays of excited hyperons $Y^* \rightarrow \Lambda\gamma$ (Feb 2022)

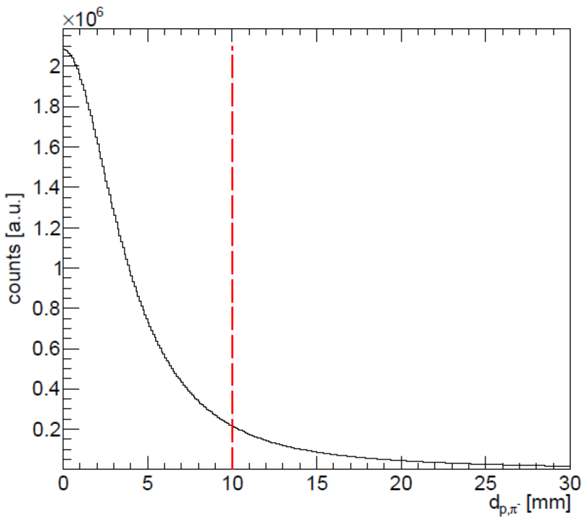


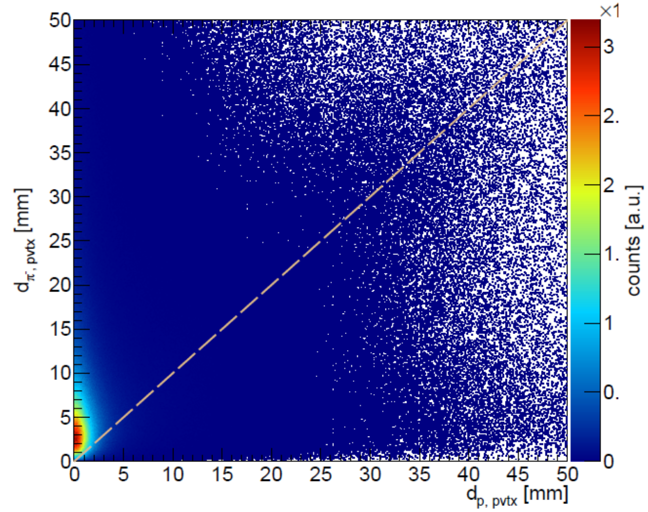
THANK YOU
QUESTIONS?

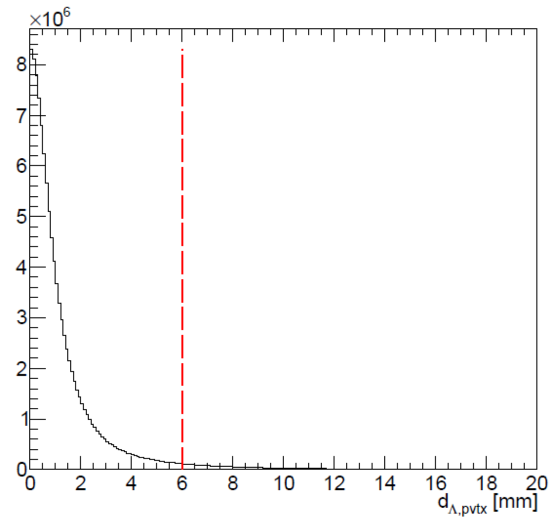
PID Algorithm Performance on data:



Lambda Toplogical Cuts Distributions:

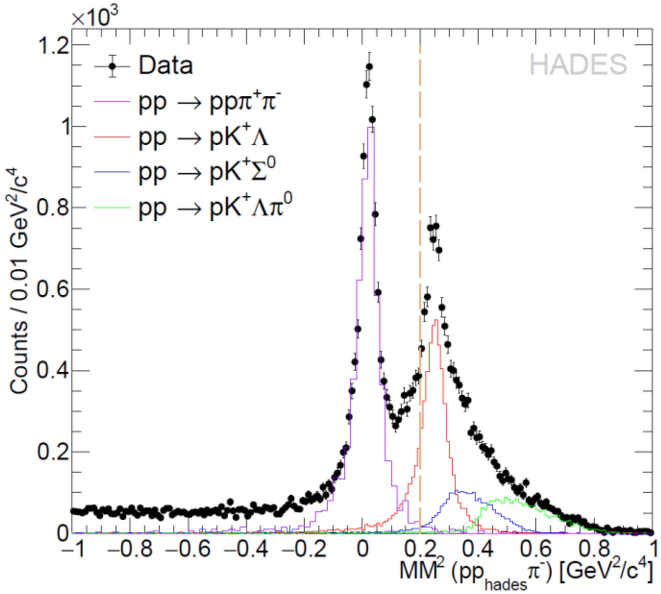






Missing Mass Distributions:

HADES



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