Application of Kinematic Fitters to reconstruct the Σ^0 Dalitz Decay with HADES

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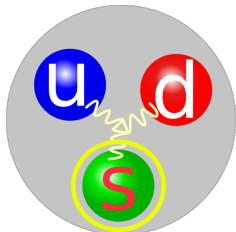Uppsala University

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Hyperon Session
$\bar{P}$ANDA Collaboration Meeting 2 – 2021

The Σ^0 Hyperon

Σ^0 $I(J^P) = 1(\frac{1}{2}^+)$

Mass: $1193\,\mathrm{MeV}$
Mean life: $7.4 \cdot 10^{-20}\,s$

Decay mode	Branching ratio
$\Lambda\gamma$	$100\,\%$
$\Lambda\gamma\gamma$	$< 3\,\%$
$\Lambda e^+ e^-$	$5 \cdot 10^{-3}$ unmeasured

P.A. Zylaet al.(Particle Data Group), Prog. Theor. Exp. Phys.2020, 083C01 (2020)

$\Sigma^0 \to \Lambda e^+ e^-$

- $m(\Sigma^0) - m(\Lambda) = $ 76.959 $\pm 0.023\,\mathrm{MeV}$
- First measurement
- Transition form factors accessible through Dalitz decay

The Reaction
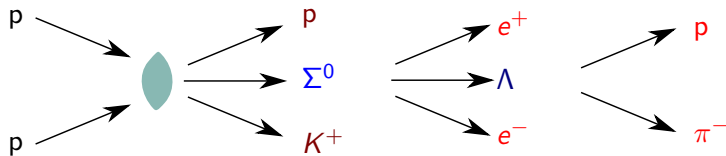
Challenges

- Low $\Sigma^0 - \Lambda$ mass difference $\rightarrow$ slow dileptons
- Displaced Λ decay vertex
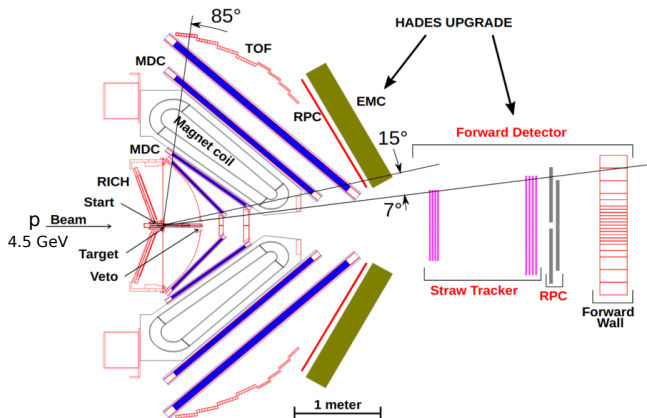- Low branching ratio compared to radiative Σ^0 decay

Solution: Kinematic fitting!

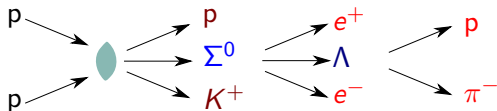Mathematical details: See my talk from last collaboration meeting

HADES Setup

Beamtime for approved Hyperon program: pp @ $4.5\,\mathrm{GeV}$
$\rightarrow$ 30 days in spring 2022!

Simulation

Pluto

- 950 000 events
- $pp \to pK^+\Sigma^0$, $\Sigma^0 \to \Lambda e^+ e^-$
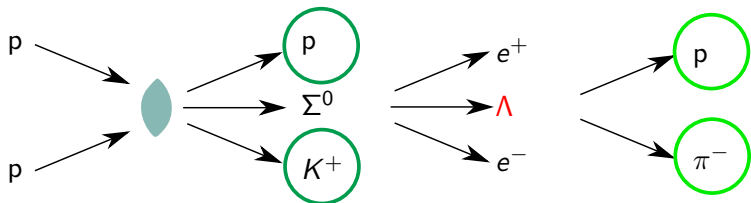- $4.5\,\mathrm{GeV}$ beam kinetic energy

HGeant/Hydra

- Use FwDet version
- Λ decay by HGeant ($\mathrm{BR} = 0.639$)

Analysis

- Ideal PID, combinatorial BG
- Select events with at least $1K$, $2p$, $1\pi^-$ and $1e^-$
- Combine HADES and FwDet

Λ Reconstruction

Vertex fit in secondary vertex

- Σ^0 decays in IP, Λ in secondary vertex
- Apply HVertexFinder to build a vertex from $p\pi^-$ and pK^+

  See Jenny's presentation for details

- Λ direction is given by vertex positions
- → Apply HNeutralCandFinder
- Do 3C fit in secondary vertex to reconstruct Λ momentum
- Choose best vertex pair from 3C fit probability

3C Fit

Four-momentum conservation in decay vertex of mother particle

Constraint equations:

$$f_1 = p_p \cdot \sin \vartheta_p \cos \varphi_p + p_\pi \cdot \sin \vartheta_\pi \cos \varphi_\pi - p_\Lambda \cdot \sin \vartheta_\Lambda \cos \varphi_\Lambda = 0$$

$$f_2 = p_p \cdot \sin \vartheta_p \sin \varphi_p + p_\pi \cdot \sin \vartheta_\pi \sin \varphi_\pi - p_\Lambda \cdot \sin \vartheta_\Lambda \sin \varphi_\Lambda = 0$$
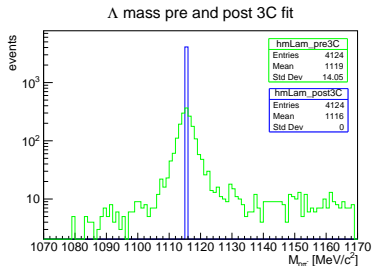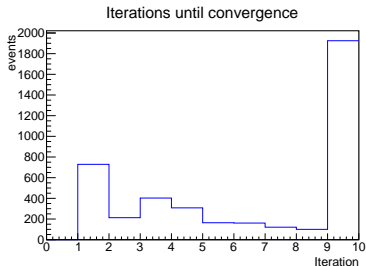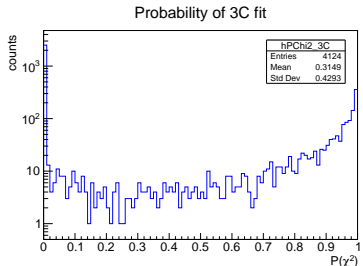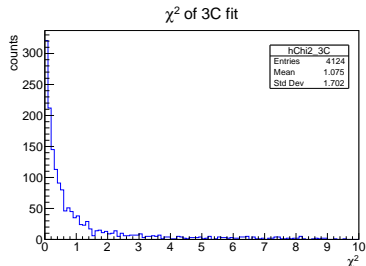
$$f_3 = p_p \cdot \cos \vartheta_p + p_\pi \cdot \cos \vartheta_\pi - p_\Lambda \cdot \cos \vartheta_\Lambda 0$$

$$f_4 = \sqrt{p_p^2 + m_p^2} + \sqrt{p_\pi^2 + m_\pi^2} - \sqrt{p_\Lambda^2 + m_\Lambda^2} = 0$$

Input: Four-momenta of daughter particles, direction of mother, fixed masses
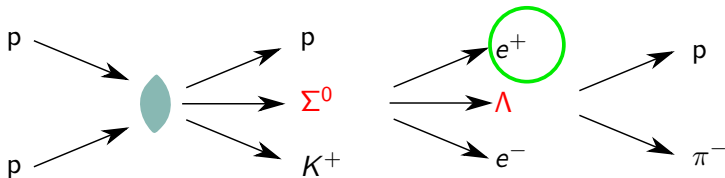
Unknown variable: Mother momentum

3C Fit – Output

Convergence: $\Delta\chi^2 < 1$ in consecutive iterations

e^+ Reconstruction

Get e^+ from $pK^+\Lambda e^-$ missing 4-momentum

- Initial 4-momentum is known
- Λ candidate from vertex fit
- Other final state particles measured
- Determine e^+ momentum by kinematic fit with fixed mass
- Select e^- by largest fit probability

Missing Particle Fit

Four-momentum conservation in primary vertex of mother particle

Constraint equations:

$$f_1 = \sum_{n \in p, K, \Lambda, e^-} p_n \cdot \sin \vartheta_n \cos \varphi_n + p_{e^+} \cdot \sin \vartheta_{e^+} \cos \varphi_{e^+} - p_x^{\text{ini}} = 0$$

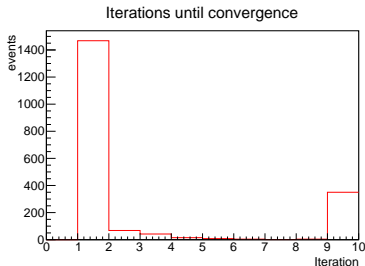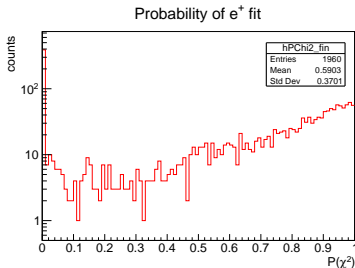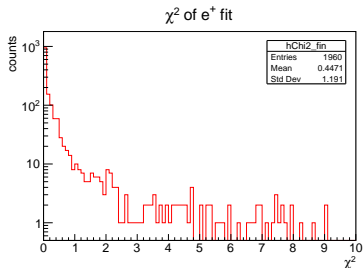$$f_2 = \sum_{n \in p, K, \Lambda, e^-} p_n \cdot \sin \vartheta_n \sin \varphi_n + p_{e^+} \cdot \sin \vartheta_{e^+} \sin \varphi_{e^+} - p_y^{\text{ini}} = 0$$

$$f_3 = \sum_{n \in p, K, \Lambda, e^-} p_n \cdot \cos \vartheta_n + p_{e^+} \cdot \cos \vartheta_{e^+} - p_z^{\text{ini}} = 0$$

$$f_4 = \sum_{n \in p, K, \Lambda, e^-} \sqrt{p_n^2 + m_n^2} + \sqrt{p_{e^+}^2 + m_{e^+}^2} - E^{\text{ini}} = 0$$

Input: Initial four-momentum, four-momenta of p, K, Λ and e^-, particle masses

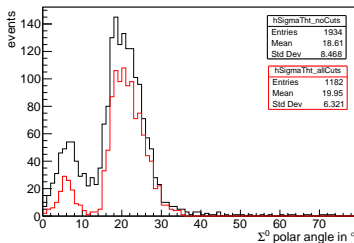Unknown variables: e^+ momentum and direction
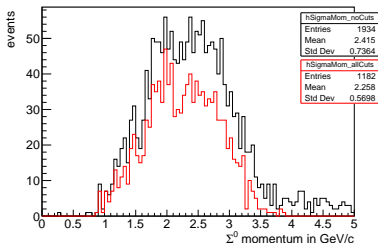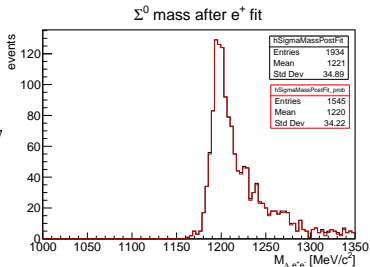
Missing Particle Fit – Output

Convergence: $\Delta\chi^2 < 1$ in consecutive iterations

Σ^0 Reconstruction

Finally: Build Σ^0 from $\Lambda e^+ e^-$

- $P(\chi^2) > 1\,\%$
- $1150\,\mathrm{MeV}/c^2 < m_\Sigma < 1250\,\mathrm{MeV}$

Σ^0 mass after e^+ fit

Efficiencies

- Total number of events with p, K^+, p, π^-, e^- Geant tracks in acceptance: 1631
- Events with reconstructed p, K^+, p, π^-, e^- combination: 1960
- Of which 721 contain at least one FwDet track (37 %)

	% of true tracks	% of reco candidates	% of FwDet
After 3C fit, $P(\chi^2 > 1\%)$	94	78	
After e^+ fit, $P(\chi^2 > 1\%)$	95	79	
$P(\chi^2 > 1\%)$, both fits	88	73	74
$1150\,\mathrm{MeV}/c^2 < m_\Sigma < 1250\,\mathrm{MeV}/c^2$	74	62	
All cuts	72	60	61

Conclusions

- Kinematic fitting makes reconstruction of Σ^0 Dalitz decay possible
- Correct assignment of protons to vertices by 3C fit
- Selection of correct e^- by missing particle fit
- Forward Detector increases acceptance significantly
- Quite high efficiency after fitting procedure

- Peaking probability – Overestimated uncertainties?
- Σ^0 has tail towards higher masses

Outlook

- Investigate tail towards higher masses of $\Lambda e^+ e^-$ invariant mass peak
- Fine-tune convergence criteria, probability cuts
- Improve uncertainty estimation of fitting variables
- Consider background channels (e.g. $\Sigma^0 \to \Lambda\gamma$)

- Do $\bar{\text{P}}$ANDA simulation of $\bar{p}p \to \bar{\Sigma}^0\Lambda$