Proton-Proton Scattering from Standard to the Unknown with P̄ANDA @ HADES

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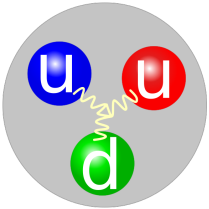
Uppsala University

June 1st
PANDA Collaboration Meeting 1/2022

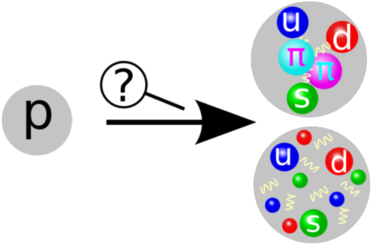
Knut and Alice Wallenberg Foundation
Swedish Research Council

Outline

Hyperons vs. Nucleons

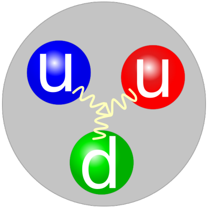


proton



Hyperons vs. Nucleons

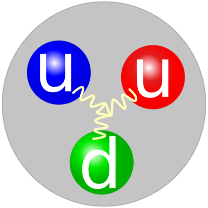
What if we add strangeness?



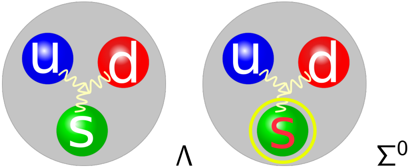
proton

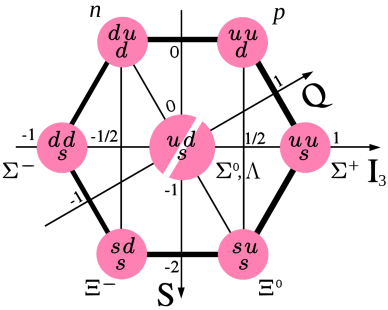
Hyperons vs. Nucleons

What if we add strangeness?

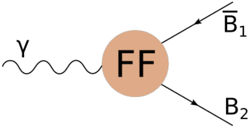


proton





Form Factors

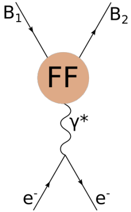


Describe non-point-like character of particles, dependent on four-momentum transfer q

→ Coupling of photon to hadron

Nucleon: Electron scattering

- Space-like ($q^2 < 0$) region
- Fixed target experiment

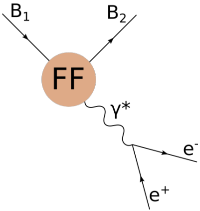


Challenge of hyperons: They are unstable!

→ Study **Dalitz decay**

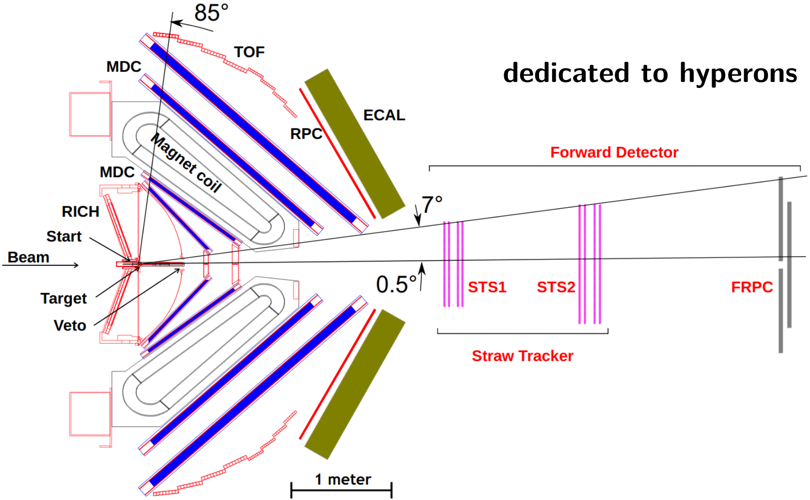
- Makes hyperon-hyperon TFF accessible
- Time-like ($q^2 > 0$) region

This has never been measured before!



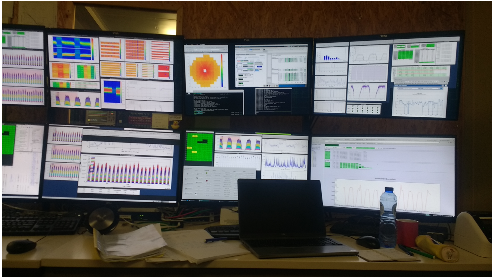
$\bar{\text{P}}$ANDA @HADES – Setup for *pp* @ 4.5 GeV Beam Time in Spring 2022

dedicated to hyperons

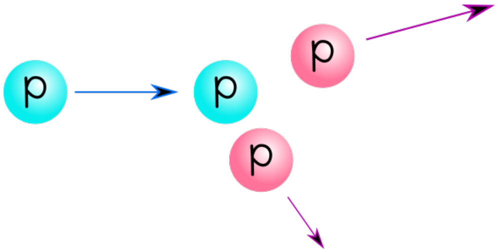


The HADES Feb22 Beam Time

- *pp* collisions at 4.5 GeV beam kinetic energy
- Hyperon campaign
  see also talk by Konrad Sumara:
  "Production and decays of hyperons in p+p reactions measured with HADES", Tuesday
- Total of 488.25 hours of data taking
- Total amount of data collected:
  41 G Events (all triggers)
  683973.7 GB

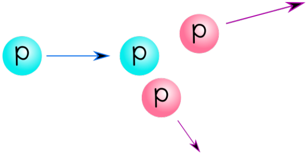


The Standard
– *pp* Elastic Scattering –



Many exeriment parameters are still unknown but we know the physics...

pp Elastic Scattering



A well defined reaction

Kinematic relations

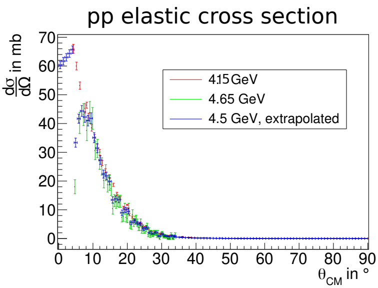
$$p = \frac{p_{\mathrm{beam}}}{\cos\theta \cdot (1 + \tan\theta^2 \gamma_{\mathrm{CM}}^2)}$$

$$\tan\theta_1 \cdot \tan\theta_2 = \frac{1}{\gamma_{\mathrm{CM}}^2} = 0.29429$$

$$\varphi_2 = |180^\circ - \varphi_1|$$

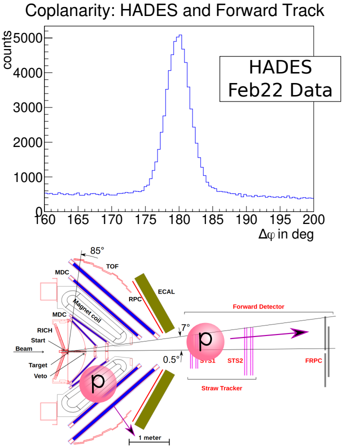
With a lot of existing data

from SAID database



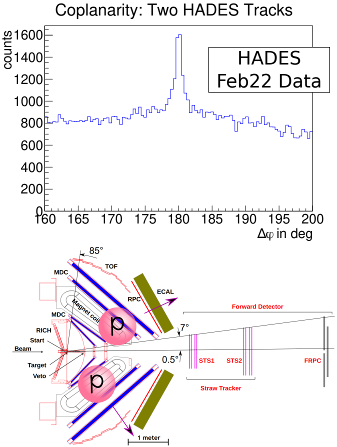
What can we learn from it?

- Online monitoring



Selection:

$\tan\theta_1 \cdot \tan\theta_2 = 0.294 \pm 0.1$

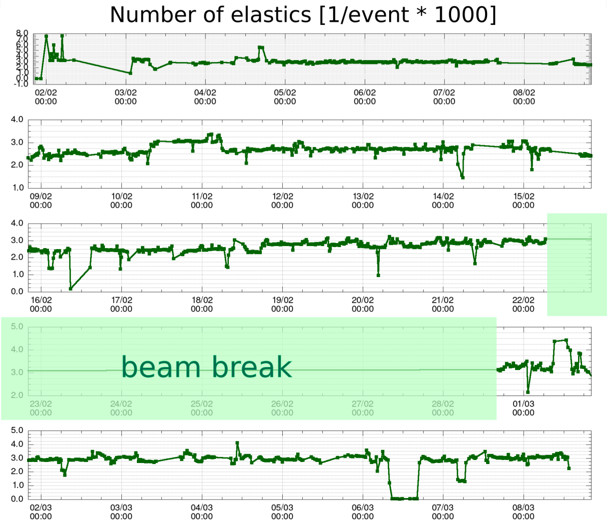


Selection:

$\tan\theta_1 \cdot \tan\theta_2 = 0.294 \pm 0.015$

What can we learn from it?

- Online monitoring



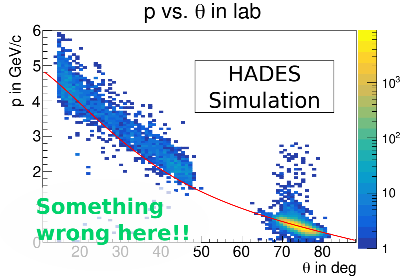
Selection on $\Delta\varphi$ and $\tan\theta_1 \cdot \tan\theta_2$

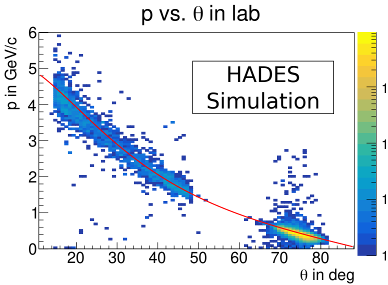
Credits to Rafał Lalik and Konrad Sumara

What can we learn from it?

- Online monitoring
- Calibration and quality assurance
  see also talk by Gabriela Perez:
  The new Forward Tracker System for the HADES FAIR Phase-0 experiment", Wednesday

From elastic scattering kinematics: $p = \frac{p_{\text{beam}}}{\cos\theta \cdot (1+\tan\theta^2 \gamma_{\text{CM}}^2)}$

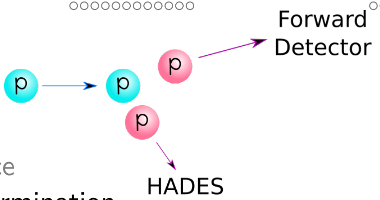




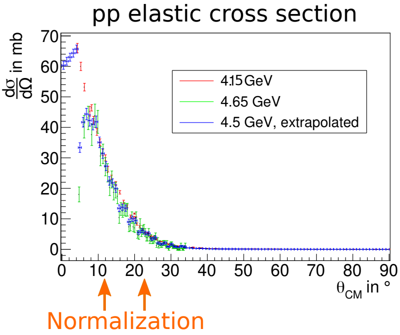
Corrected geometry

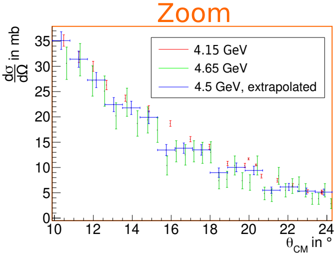
Elastic scattering, both protons detected

What can we learn from it?



- Online monitoring
- Calibration and quality assurance
- Normalization – luminosity determination

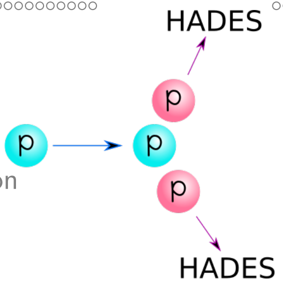


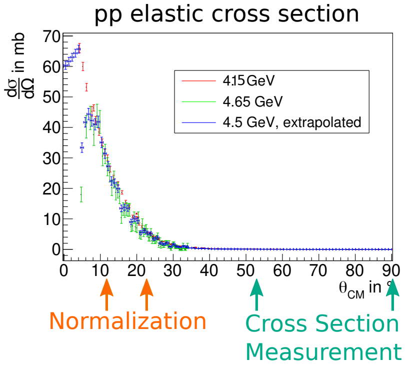


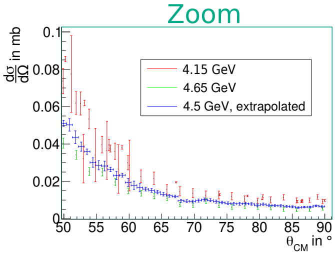
Integrated cross section from $\theta_{\mathrm{CM}} = 13^\circ - 22^\circ = 3.7^{+0.7}_{-0.3}\,\mathrm{mb}$

What can we learn from it?

- Online monitoring
- Calibration and quality assurance
- Normalization – luminosity determination
- *pp* elastic cross section measurement

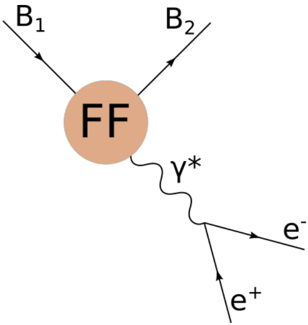






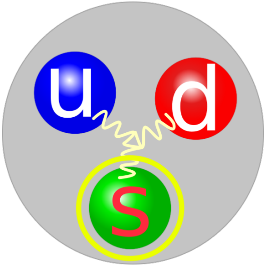
Integrated cross section from $\theta_{\mathrm{CM}} = 55^\circ - 90^\circ = 0.04^{+0.02}_{-0.01}\,\mathrm{mb}$

The Unknown
– Hyperon Form Factors –



Now the experiment is known and we can explore unknown physics ...

The Σ^0 Hyperon



Σ^0 $I(J^P) = 1(\frac{1}{2}^+)$

Mass: $1193 \pm 0.024\,\mathrm{MeV}$
Mean life: $(7.4 \pm 0.7) \cdot 10^{-20}\,s$

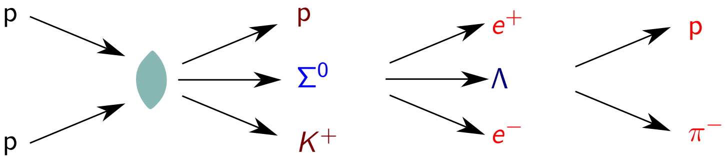
Decay mode	Branching ratio
$\Lambda\gamma$	$100\,\%$
$\Lambda\gamma\gamma$	$< 3\,\%$
$\Lambda e^+ e^-$	$5 \cdot 10^{-3}{}_{\text{unmeasured}}$

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

Dalitz Decay – Challenges

- $\Sigma^0 - \Lambda$ mass difference (only $77\,\mathrm{MeV}$)
  $\Rightarrow$ low dielectron (e^+e^-) mass
- Large background from $\Sigma^0 \to \Lambda\gamma$

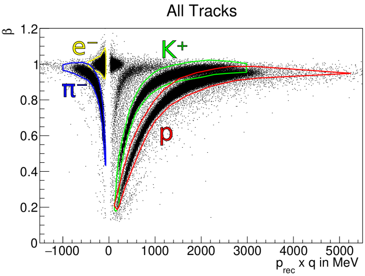
Simulation



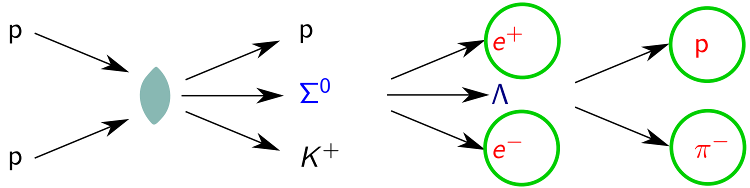
Simulated signal

- 1 000 000 events
- 4.5 GeV beam kinetic energy
- Uniform phase-space population

Particle identification



Reconstruction Strategy I



Simulated signal

- 1 000 000 events
- 4.5 GeV beam kinetic energy $\widehat{=}$ $\sqrt{s} = 3.5\,\mathrm{GeV}$

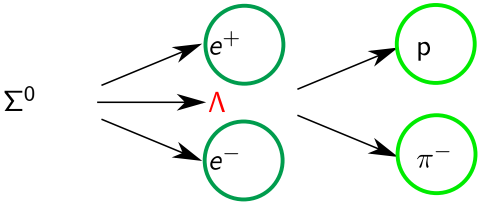
Analysis Strategy I

Inclusive reconstruction of $\Sigma^0 \to \Lambda e^+ e^-$

○ Reconstructed particles

Strategy I: Λ Reconstruction

Vertex fit in secondary vertex



- Λ production vertex from e^+ and e^-
- Λ decay vertex from p and π^-
- Λ direction is given by vertex positions
- Kinematic fit ensures 4-momentum conservation in secondary vertex to reconstruct Λ momentum

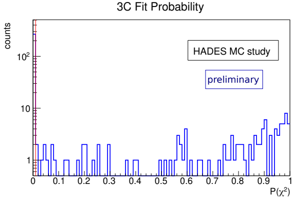
Kinematic fitting software developed in Uppsala

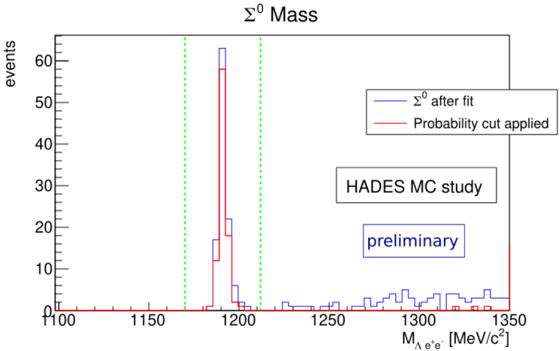
Strategy I: Σ^0 Reconstruction

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

Selection:

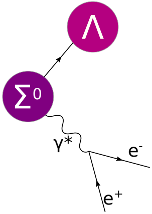
- $P(\chi^2) > 1\,\%$
- $1170\,\mathrm{MeV}/c^2 < m_\Sigma < 1216\,\mathrm{MeV}/c^2$



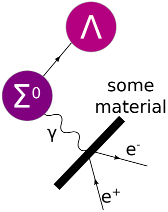


Strategy I: Σ^0 Radiative Decay as Background Source

Dalitz decay:



Photon conversion:



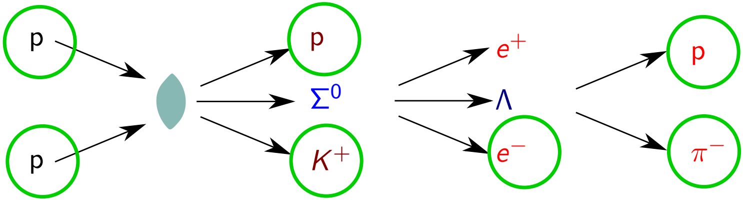
$\boldsymbol{pp \to pK^+\Sigma^0[\Lambda\gamma]}$

- Cross section $pp \to pK^+\Sigma^0$: $23.5\,\mu b$

  V. Flaminio, et al., (1984), eprint: CERN-HERA-84-01
- Fraction that passes the Σ^0 Dalitz selection criteria: $5 \cdot 10^{-8}$ (1 of 20 million)
- Corresponding $S/\sqrt{S+B}$: 9.1

Very good background suppression by kinematic fit

Reconstruction Strategy II



Simulated signal

- 1 000 000 events
- 4.5 GeV beam kinetic energy $\hat{=}$ $\sqrt{s} = 3.5$ GeV

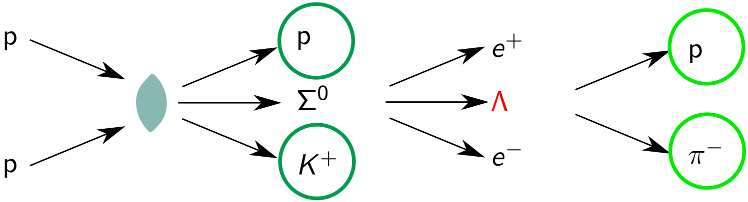
Analysis Strategy II

(almost) Exclusive reconstruction of $pp \to pK^+\Sigma^0[\Lambda e^+ e^-]$,
e^+ constructed by kinematic fitting

○ Reconstructed particles

Strategy II: Λ Reconstruction

Vertex fit in secondary vertex

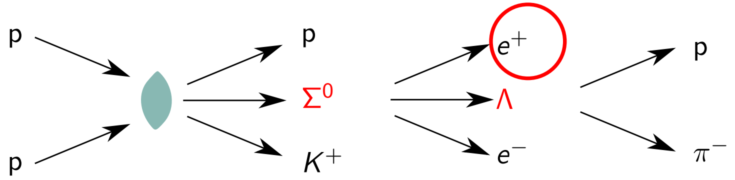


- Σ^0 decays in interaction point, Λ in secondary vertex
- Find two vertices from $p\pi^-$ and pK^+
- Λ direction is given by vertex positions
- Kinematic fit in secondary vertex to reconstruct Λ momentum

Kinematic fitting software developed in Uppsala

Strategy II: e^+ Reconstruction

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



- Initial 4-momentum is known
- Λ candidate from vertex fit
- p, K^+ and e^- measured
- Determine e^+ momentum by kinematic fit

○ Missing particle

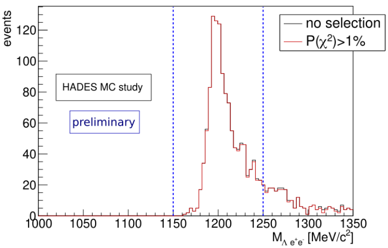
Kinematic fitting software developed in Uppsala

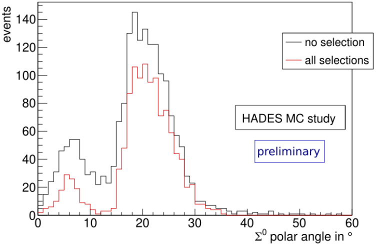
Strategy II: Σ^0 Reconstruction

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

Selection criteria:

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





Strategy II: Most Prominent BG: Σ^0 Radiative Decay

$\boldsymbol{pp \to pK^+\Sigma^0}[\Lambda\gamma]$

- Cross section $pp \to pK^+\Sigma^0$: $23.5\,\mu b$

  V. Flaminio, et al., (1984), eprint: CERN-HERA-84-01
- Fraction that passes the Σ^0 Dalitz selection criteria: $4.5 \cdot 10^{-5}$ (886 of 20 million)
- Corresponding $S/\sqrt{S+B}$: 11.5
- Phase space largely overlapping

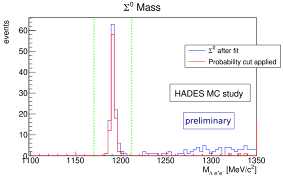
Apply additional background suppression selections

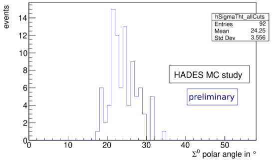
- Electron production vertex and hit structure
- **Signal:** -18 %; **BG:** -76 %
- New $S/\sqrt{S+B}$: 17

Strategy I and II

Strategy I

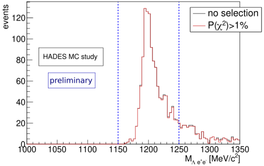
- Detected particles: e^-, e^+, p, π^-
- Very good background supp.: $\frac{S}{\sqrt{S+B}} = 9.1$, $\frac{S}{B} = 92$
- Counts/day: 15

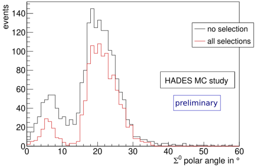




Strategy II

- Detected particles: p, K^+, e^-, p, π^-
- More signal, more background: $\frac{S}{\sqrt{S+B}} = 17$, $\frac{S}{B} = 0.48$
- Counts/day: 152





Conclusion

At First: The standard, elastic scattering

- Understand the data
- Calibrate the data
- Normalize the data
- Analyze the data

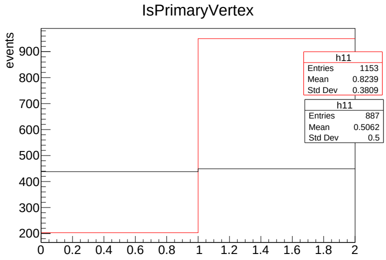
Then: The unknown, Σ^0 Dalitz decay

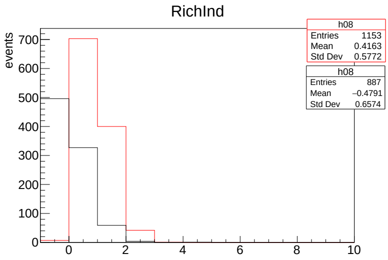
- Do analysis on Feb22 beam time data
- Measure the Σ^0 Dalitz decay!

BACKUP

Strategy I: Most Prominent BG: Σ^0 Radiative Decay

Find background suppression criteria





Cut on RICH index ≥ 0 and isPrimaryVertex $==1$

Signal: 1153→947; **BG:** 886→209

New S/B: 0.477

Expected Count Rates

- Luminosity $\mathcal{L} = 1.5 \cdot 10^{31}\,\mathrm{cm}^{-2} s{-}1$ (beam time proposal)
- Cross section $\sigma(pp \to pK^+\Sigma^0) = 23.5\,\mu\mathrm{b}$
- Branching ratio $\mathrm{BR}(\Sigma^0 \to \Lambda e^+ e^-) = 5 \cdot 10^{-3}$
- Efficiency and Acceptance $(\epsilon \cdot A \cdot \mathrm{BR}(\Lambda \to p\pi^-))$
  $= 9.968 \cdot 10^{-4}$ (exclusive $pp \to pK^+\Sigma^0[\to \Lambda e^+ e^-]$)
  $= 9.684 \cdot 10^{-5}$ (inclusive $\Sigma^0 \to \Lambda e^+ e^-$)

$pp \to pK^+\Sigma^0[\to \Lambda(e^+)e^-]$/day

$N_{\mathrm{LH}} = \mathcal{L} \cdot \sigma \cdot \mathrm{BR} \cdot (\epsilon A) \cdot t \approx 152$

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

$N_{\mathrm{LH}} = \mathcal{L} \cdot \sigma \cdot \mathrm{BR} \cdot (\epsilon A) \cdot t \approx 15$

Kinematic Fitter for HADES Software

Suppose there are N measured and M unmeasured variables related by K constraints

$$f_k(\eta_1, \eta_2, ...\eta_N, \xi_1, \xi_2, ...\xi_M) = 0. \quad (1)$$

Goal: Minimize $\chi^2(\eta) = (y - \eta)^T V(y)(y - \eta)$ under those K constraints
Procedure: Introduce Lagrangian Multiplliers λ

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

y: Measurements, $V(y)$: Covariance matrix of y

4C Fitter

Constraint equations for N particles:

$$f_1 = \sum_{n=1}^{N} p_n \cdot \sin\vartheta_n \cos\varphi_n - p_{x_{\mathrm{ini}}} = 0$$

$$f_2 = \sum_{n=1}^{N} p_n \cdot \sin\vartheta_n \sin\varphi_n - p_{y_{\mathrm{ini}}} = 0$$

$$f_3 = \sum_{n=1}^{N} p_n \cdot \cos\vartheta_n - p_{z_{\mathrm{ini}}} = 0$$

$$f_4 = \sum_{n=1}^{N} \sqrt{p_n^2 + m_n^2} - E_{\mathrm{ini}} = 0$$

The Fitting Procedure – Minimization

χ^2 minimization will result in $N + M + K$ equations:

$$\nabla_\eta \chi^2 = -2V^{-1}(y - \eta) + 2F_\eta^T \lambda = 0$$
$$\nabla_\xi \chi^2 = 2F_\xi^T \lambda = 0$$
$$\nabla_\lambda \chi^2 = 2f(\eta, \xi) = 0$$

where F_η and F_ξ are defined by

$$(F_\eta)_{ij} = \frac{\partial f_i}{\partial \eta_j}, \qquad (F_\xi)_{ij} = \frac{\partial f_i}{\partial \xi_j} \tag{3}$$

$\rightarrow$Solve in iterative procedure