Finding the Σ^0's Dalitz Decay with $\bar{\text{P}}$ANDA @ HADES

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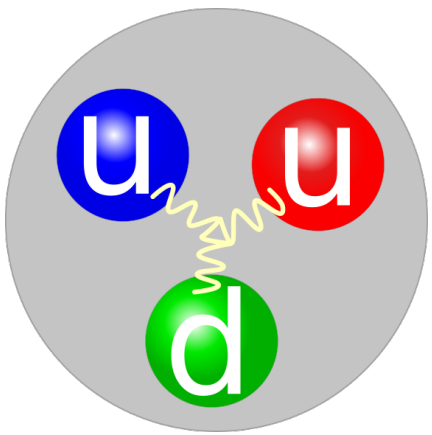
Swedish Research Council
Knut and Alice Wallenberg Foundation

Outline

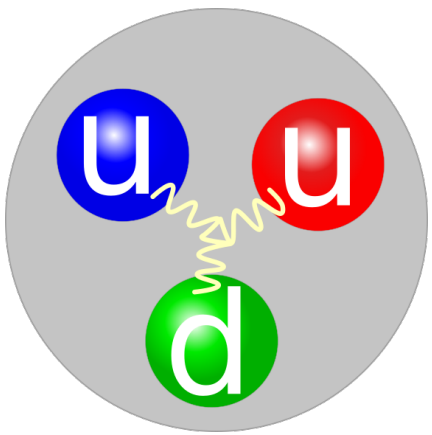
Hyperons



proton

Hyperons

What if we add strangeness?



proton

Hyperons

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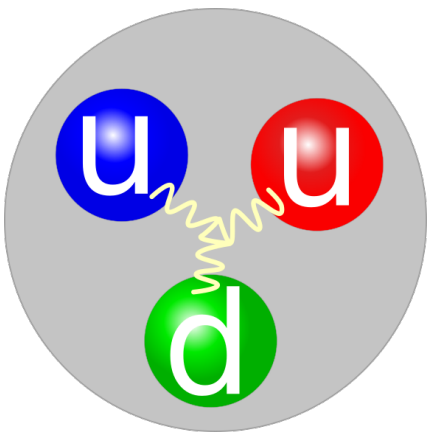
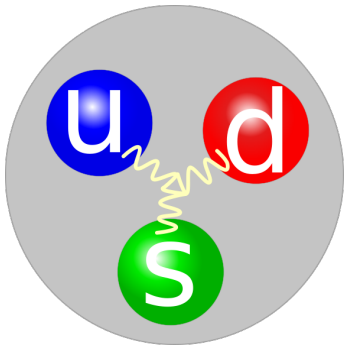
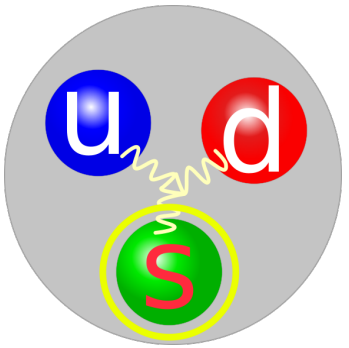


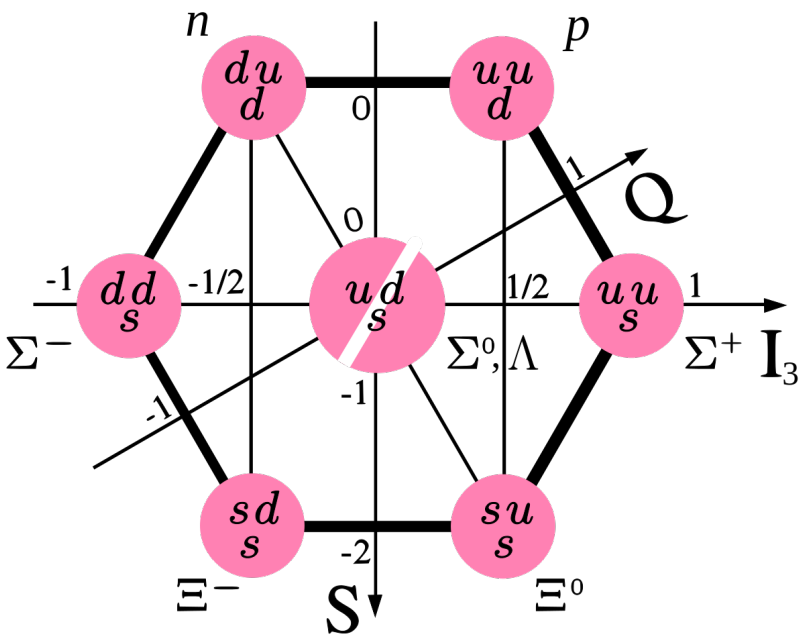
proton



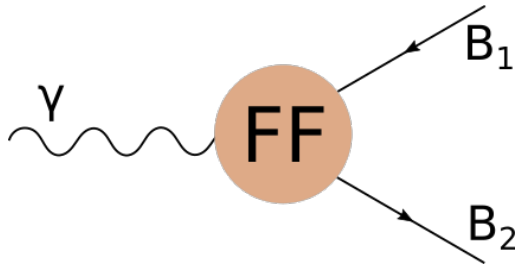
Λ



Σ^0

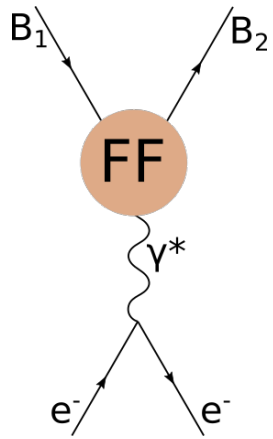


Form Factors



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

$\rightarrow$ Coupling of photon to hadron



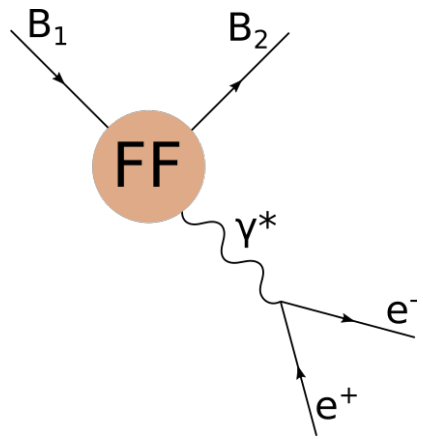
Nucleon: Electron scattering

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

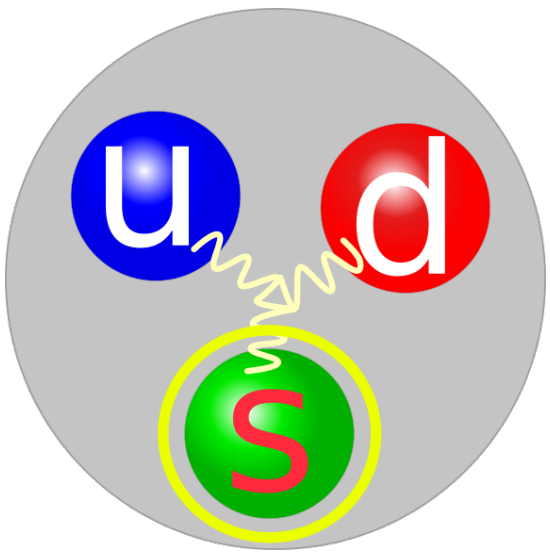
Challenge of hyperons: They are unstable!

$\rightarrow$ Study **Dalitz decay**

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



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

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

Σ^0 Dalitz Decay

Motivation

- Large branching ratio
- Not measured before
- Transition form factors accessible

Challenges

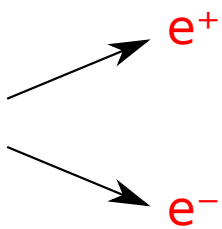
- $\Sigma^0 - \Lambda$ mass difference (only $77\,\mathrm{MeV}$)
  $\Rightarrow$ low dielectron (e^+e^-) mass
- Large background from $\Sigma^0 \to \Lambda\gamma$

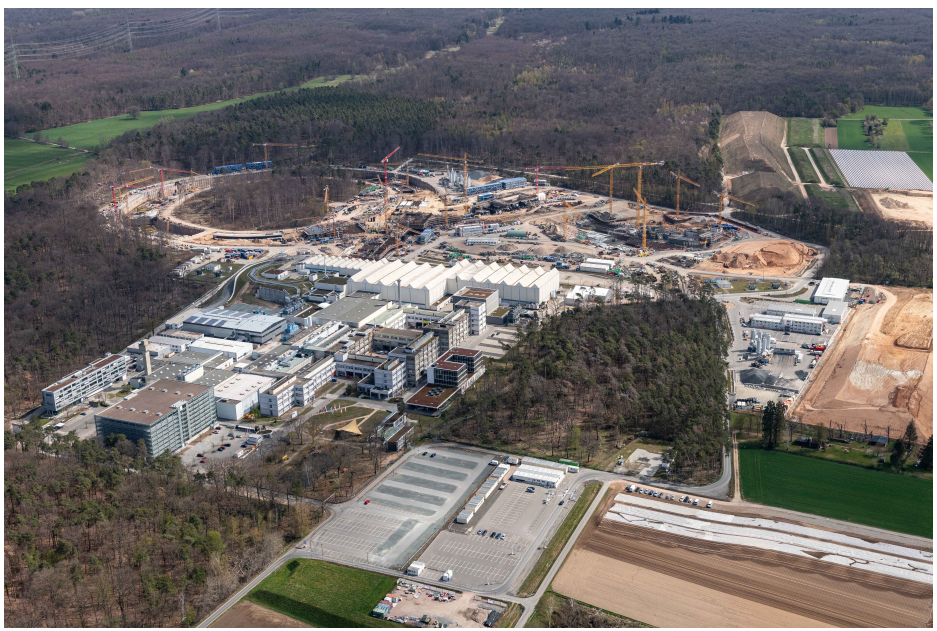
Great tool to attack those challenges: HADES/$\bar{\text{P}}$ANDA

GSI and FAIR

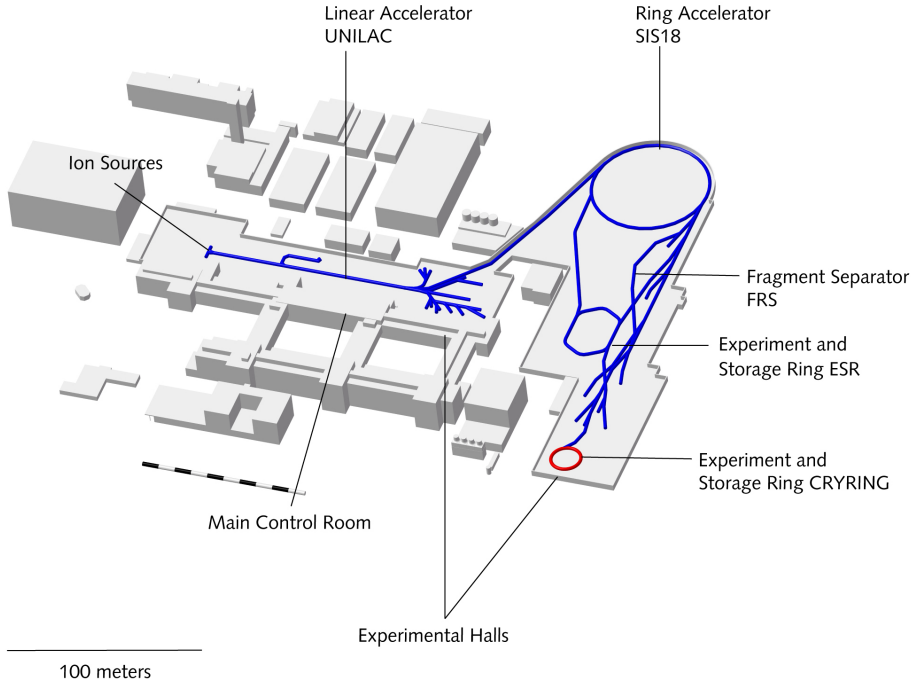
HADES @ GSI:

The dielectron expert $\longrightarrow$



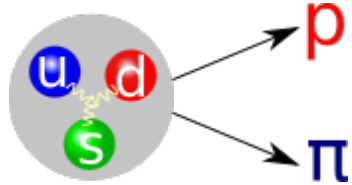


GSI Helmholtzzentrum für Schwerionenforschung,
D. Fehrenz, April 2021



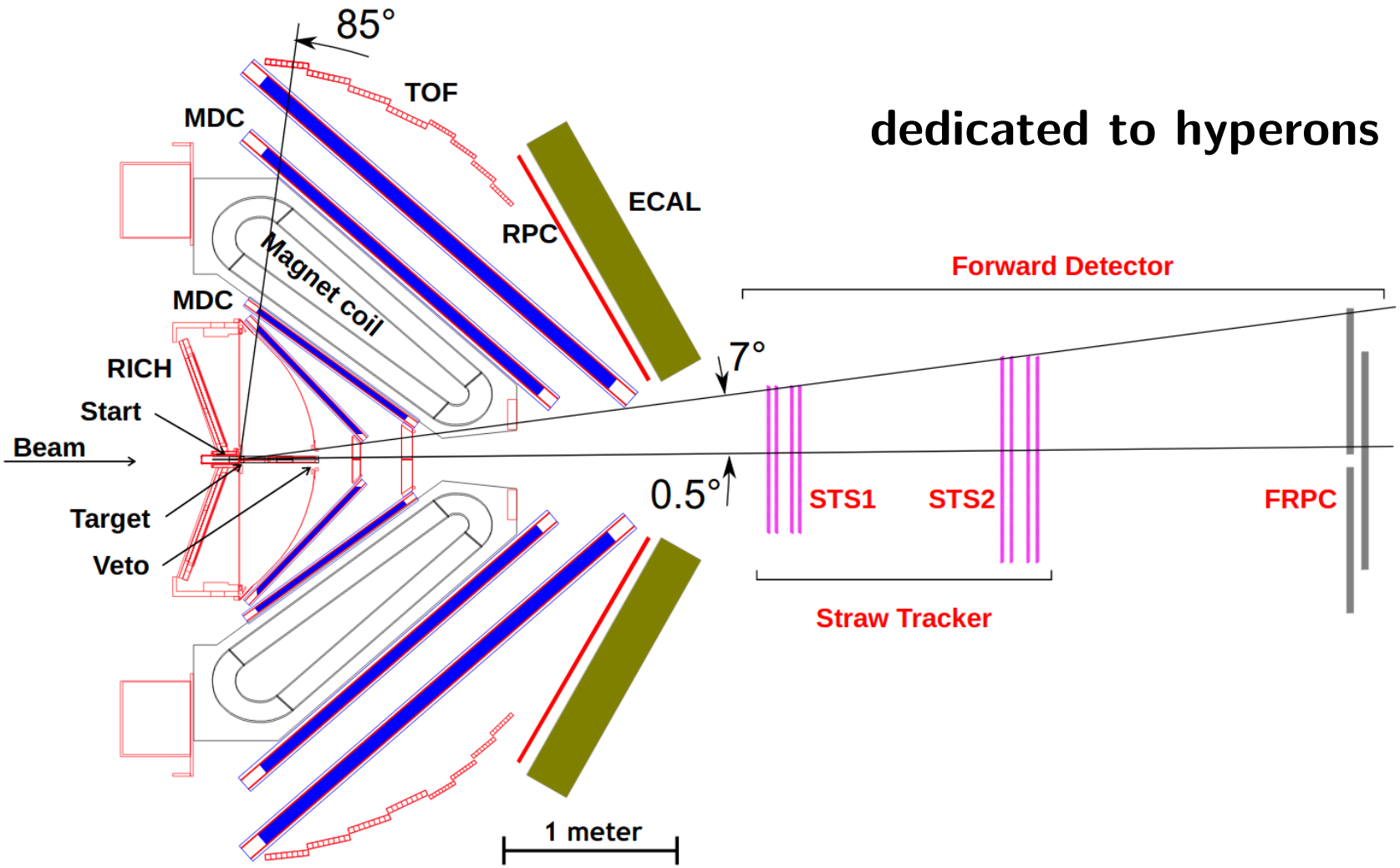
$\bar{\text{P}}$ANDA @ FAIR:

$\longleftarrow$ The fast proton expert

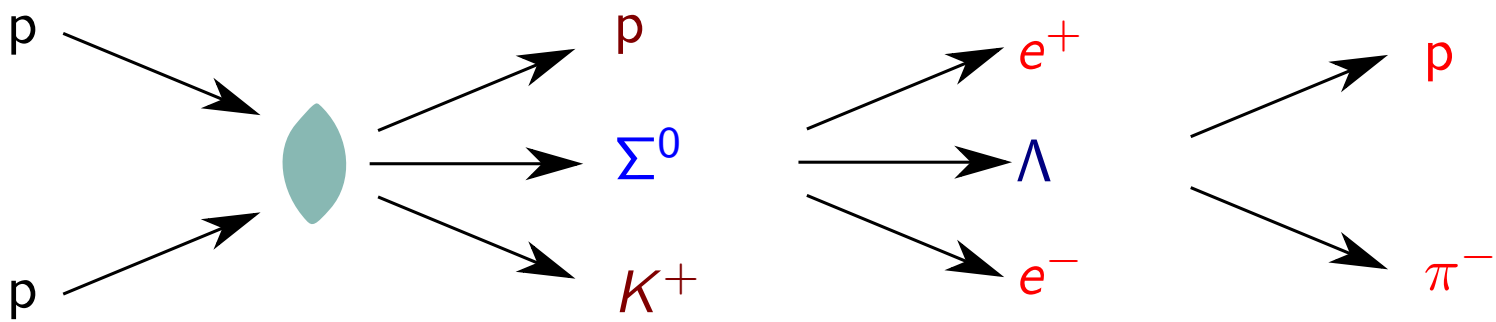


- Located in Darmstadt, DE

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



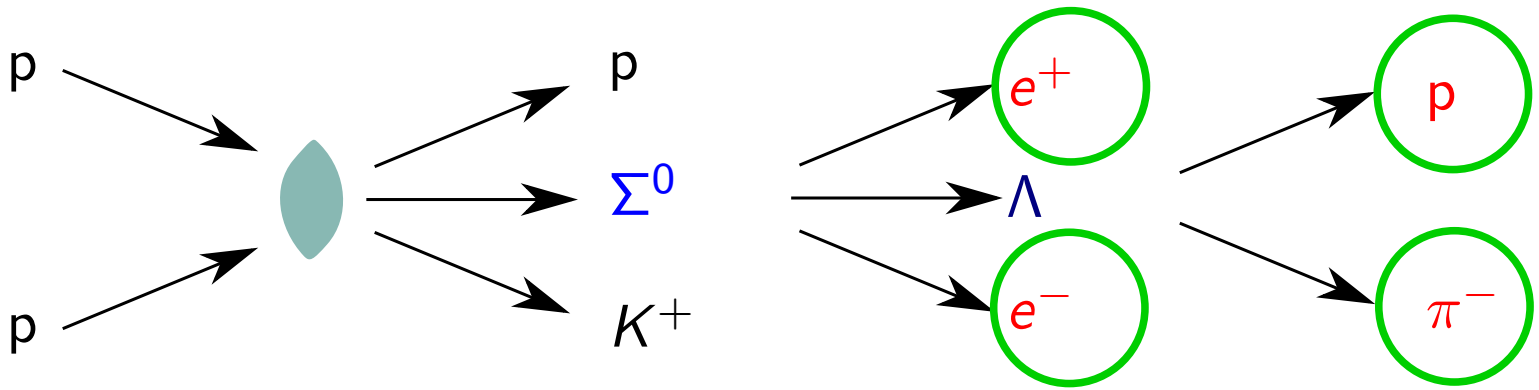
Simulation



Simulated signal

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

Simulation



Simulated signal

- 1 000 000 events
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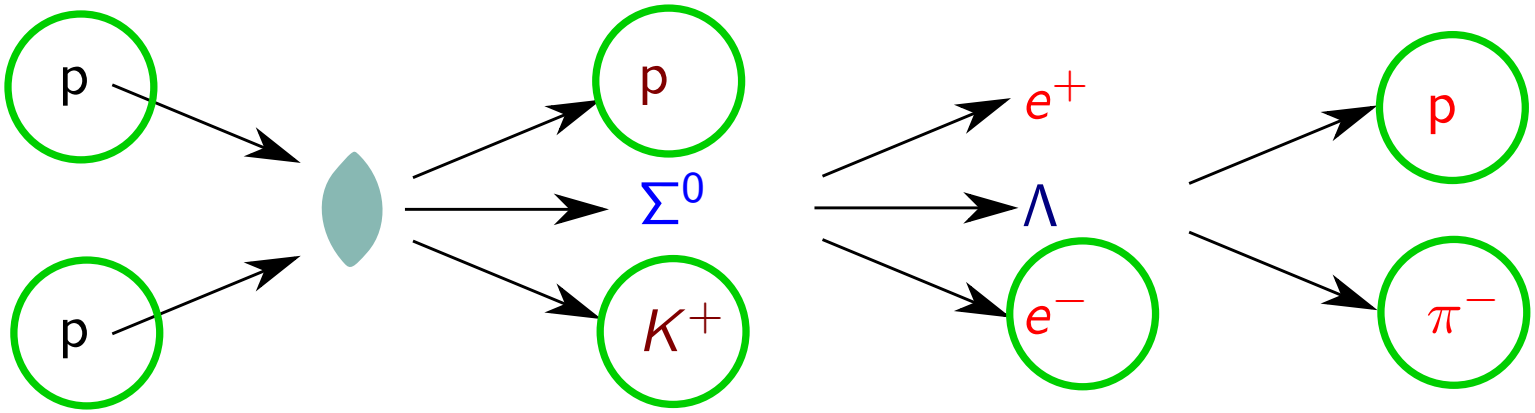
Analysis Strategy I

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

Simulation



Simulated signal

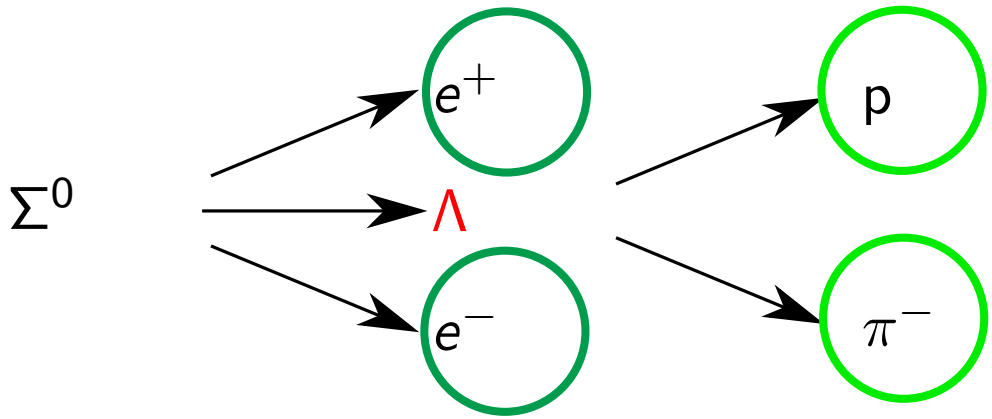
- 1 000 000 events
- 4.5 GeV beam kinetic energy $\widehat{=}$ $\sqrt{s} = 3.5\,\mathrm{GeV}$

Analysis Strategy II

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

Strategy I: Λ Reconstruction

Vertex fit in secondary vertex



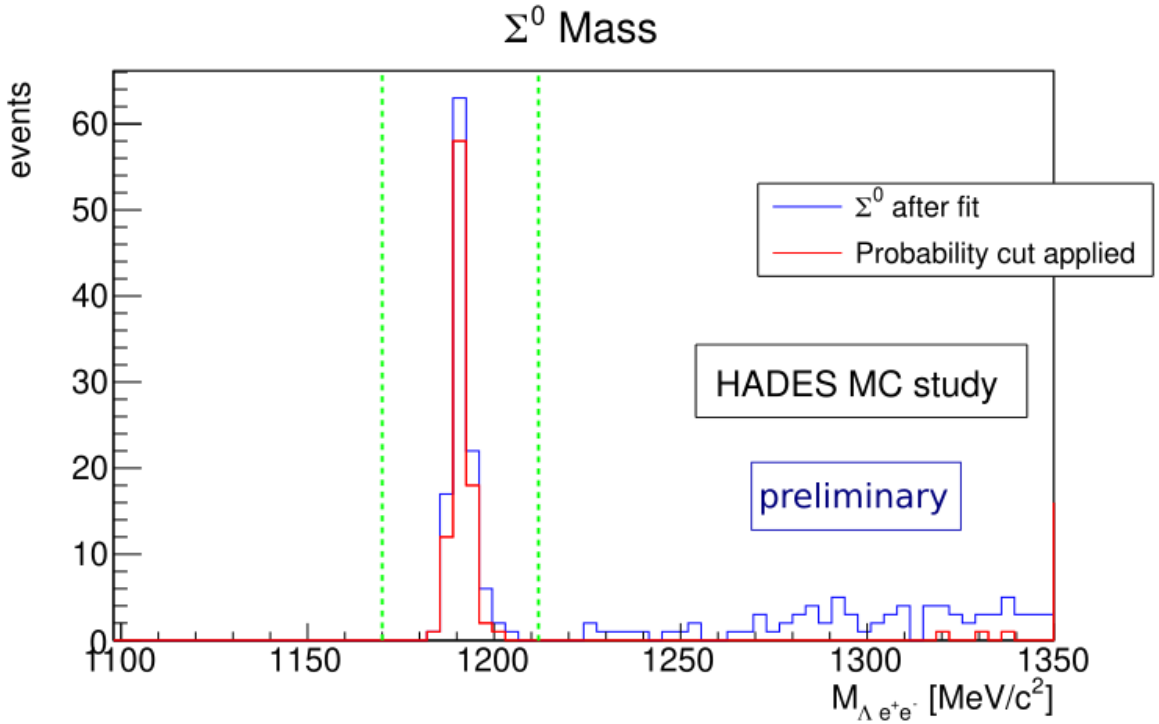
- Λ production vertex from e^+ and e^-
- Λ decay vertex from p and π^-
- Λ direction is given by vertex positions
- Kinematic fit ensures 4-momentum conservation in secondary vertex to reconstruct Λ momentum

Kinematic fitting software developed in Uppsala

Strategy I: Σ^0 Reconstruction

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

- $P(\chi^2) > 1\,\%$
- $1170\,\mathrm{MeV}/c^2 < m_\Sigma < 1216\,\mathrm{MeV}/c^2$
- In peak after fitting, selection: 92



Strategy I: Σ^0 Radiative Decay as Background Source

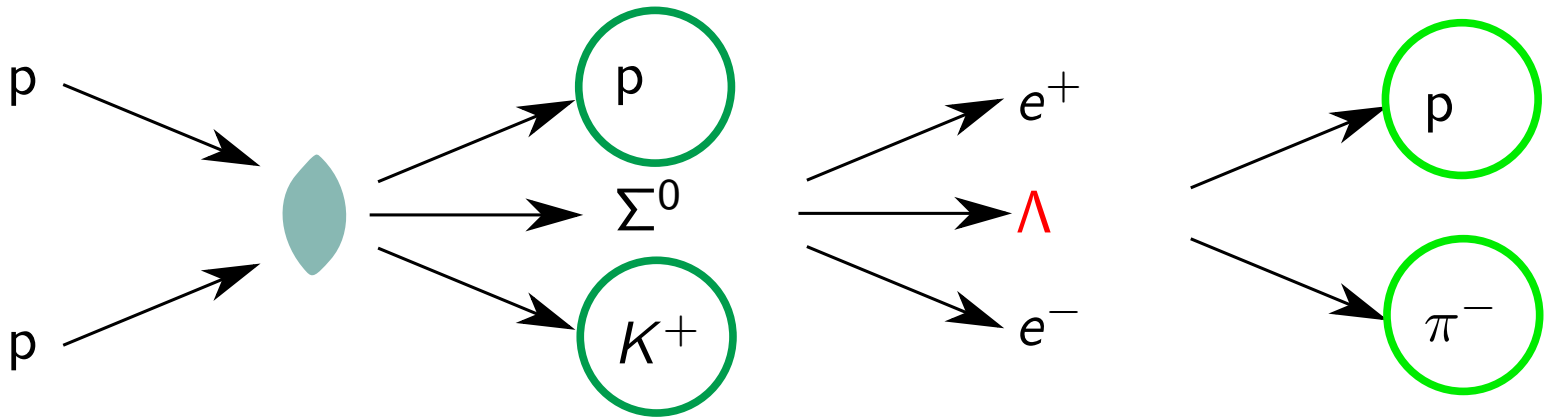
$\boldsymbol{pp \to pK^+\Sigma^0[\Lambda\gamma]}$

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

Strategy II: Λ Reconstruction

Vertex fit in secondary vertex

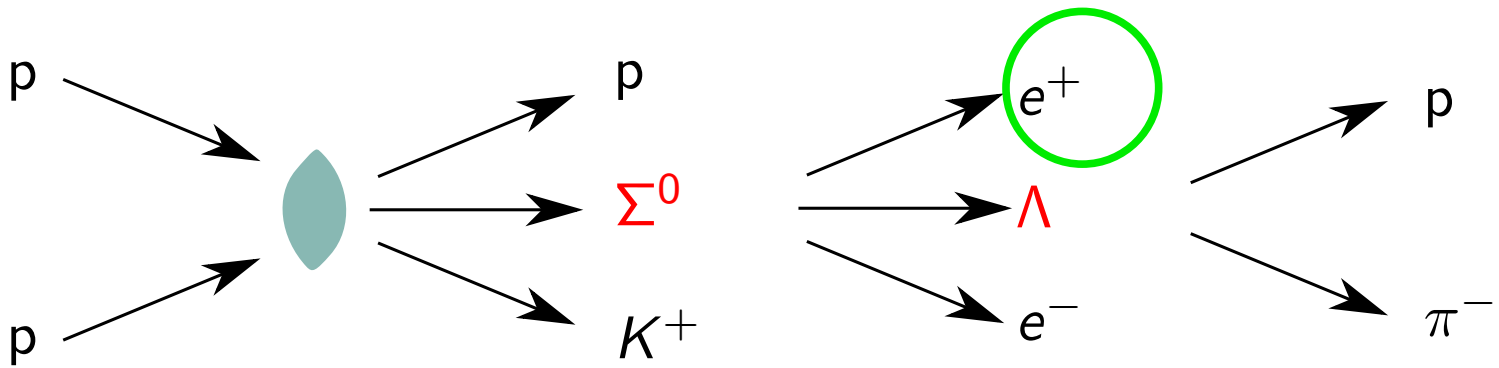


- Σ^0 decays in interaction point, Λ in secondary vertex
- Find two vertices from $p\pi^-$ and pK^+
- Λ direction is given by vertex positions
- Kinematic fit in secondary vertex to reconstruct Λ momentum

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

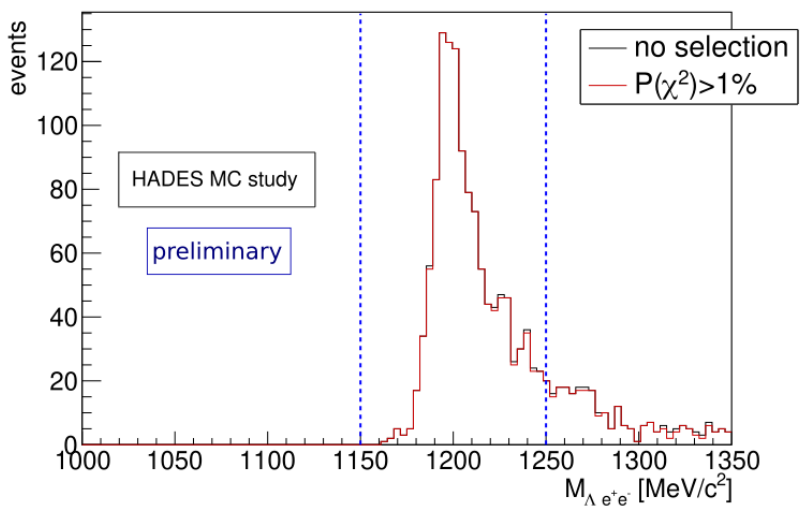
Kinematic fitting software developed in Uppsala

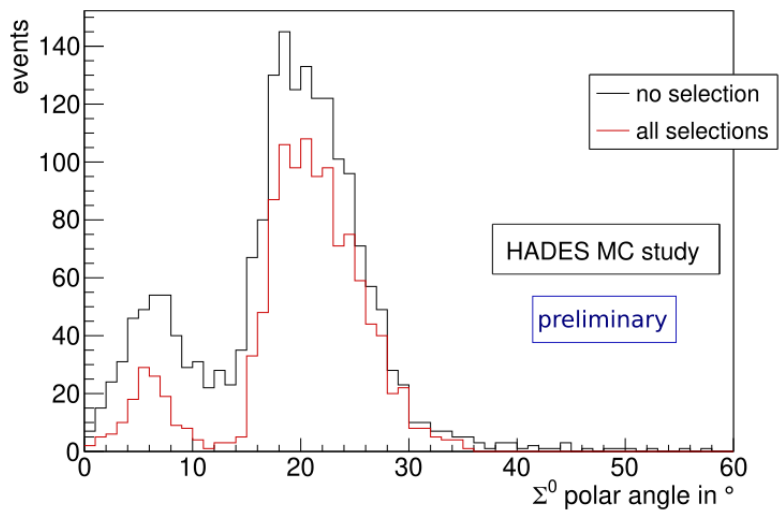
Strategy II: Σ^0 Reconstruction

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 μb
- 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

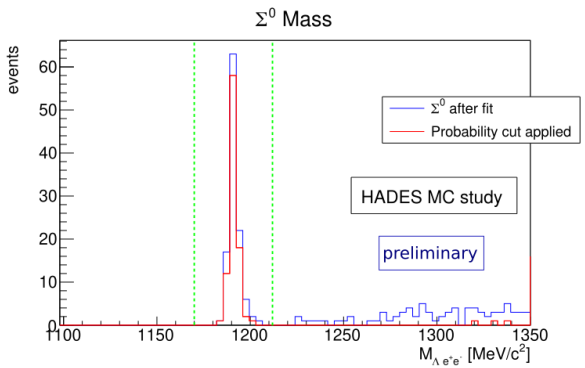
Apply background suppression selection

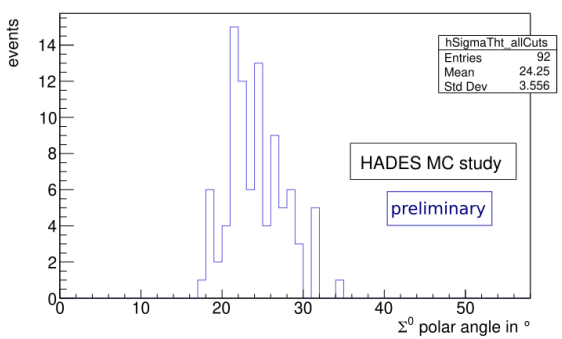
- Electron production vertex and hit structure
- **Signal:** -18 %; **BG:** -76 %
- New $S/\sqrt{S+B}$: 17

Strategy I and II

Strategy I

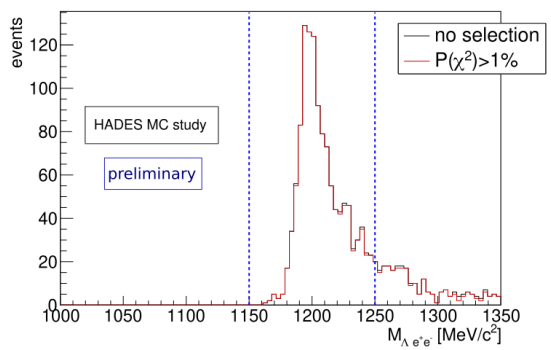
- Detected particles: e^-, e^+, p, π^-
- Very good background suppression
- Counts/day: 15

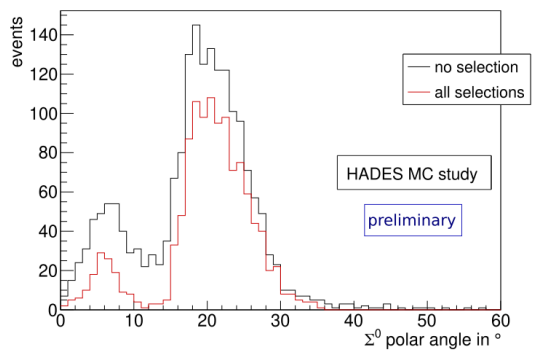




Strategy II

- Detected particles: p, K^+, e^-, p, π^-
- Full reaction
- More signal, more background
- Counts/day: 152





Outlook

Feasibility Study

- Fine-tune selection
- Optimize background suppression

Data

- Prepare detector and software for data taking in 2022
- Perform the measurement
- Get lots of exciting high quality data!

  ... and analyze them

Future

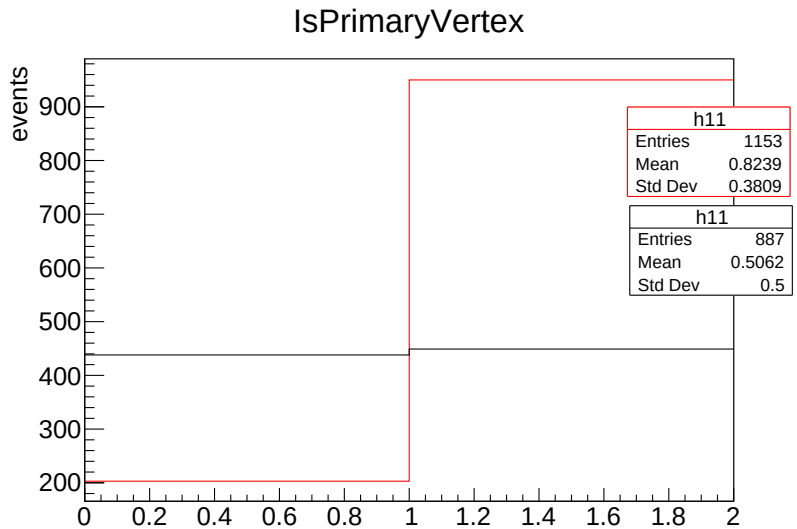
- Can this be done better with $\bar{P}$ANDA?

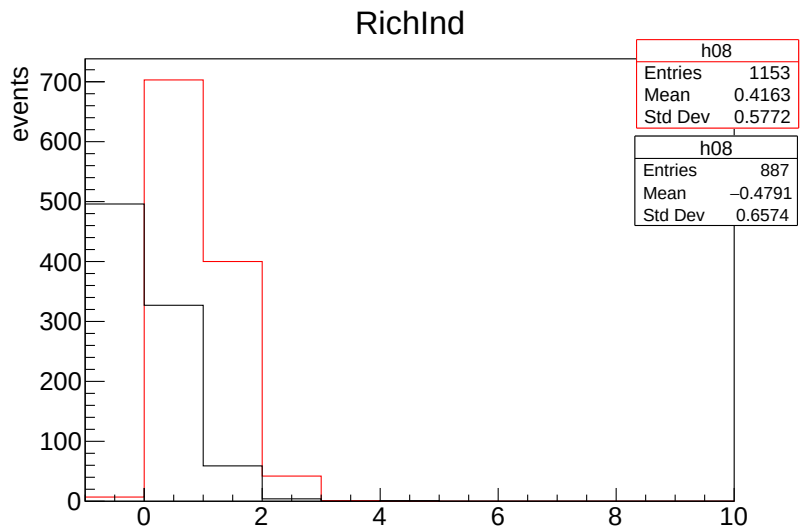
Hyperon beam time !!!Spring 2022!!!

BACKUP

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

Find background suppression criteria





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

Signal: 1153$\rightarrow$947; **BG:** 886$\rightarrow$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

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