Single vs multi nucleon absorption processes in the low-energy K-nuclei interactions

Ivana Tucaković
Università degli Studi di Roma "Tor Vergata"
LNF-INFN
ivana.tucakovic@lnf.infn.it

Investigating strangeness: from accelerators to compact stellar objects
LNF-INFN, Frascati
14th of May 2014

Experimental program of AMADEUS

Unprecedented studies of the low-energy charged kaons interactions in nuclear matter: solid and gaseous targets (d, ^{3}He, ^{4}He) in order to obtain unique quality information about:

- Nature of the controversial **Λ(1405)**
- Possible existence of **kaonic nuclear clusters** (deeply bound kaonic nuclear states)
- Interaction of **K^-** with **one** and **two nucleons.**
- Low-energy charged kaon **cross sections** for momenta lower than 100 MeV/c (missing today)
- Many other processes of interest in the low-energy QCD in strangeness sector
  → implications from particle and nuclear physics to astrophysics (dense baryonic matter in **neutron stars**)

Single and multi nucleon absorption processes in the Λp / Λd / Λt and Λp + π^- channels

How hadron masses and interactions change in nuclear medium .. approach by means of kaonic nuclear clusters. Deeply Bound Kaonic Nuclear States (ex. K^-pp – K^-ppn) predicted due to the strong KN interaction in the I=0 channel.
Wycech (1986) - Akaishi & Yamazaki (2002)

interpretation strongly depends on single and multi – nucleon absorption process:

1NA: **$K^-n \rightarrow \Lambda\pi^-$** (extra p only spectator) **pionic**

1NA: **$K^-N \rightarrow \Sigma\pi^-$, $(\Sigma N')\pi^- \rightarrow (\Lambda N')\pi^-$** (extra p from **Σ/Λ conversion**) **pionic**

2NA: **$K^-NN \rightarrow \Lambda N$**

2NA: **$K^-NN \rightarrow \Sigma N$, $(\Sigma N)N \rightarrow \Lambda N'(N)$** (**Σ/Λ conversion** on another nucleon)

Theoretical work on $K^{-}pp$

(MeV)	ATMS Yamazaki & Akaishi, PLB535 (2002) 70.	Variational Dote, Hyodo, Weise, PRC79 (2009) 014003.	Faddeev Shevchenko, Gal, Mares, PRL98 (2007) 082301.	Faddeev Ikeda & Sato, PRC79 (2009) 035201.	Variational Wycech & Green, PRC79 (2009) 014001.
B	48	17-23	50-70	45-80	40-80
Γ	61	40-70	90-110	45-75	40-85

Theoretical works are predicting the existance of $K^{-}pp$ state but different calculations are giving **large range** of the values for the binding energy and width

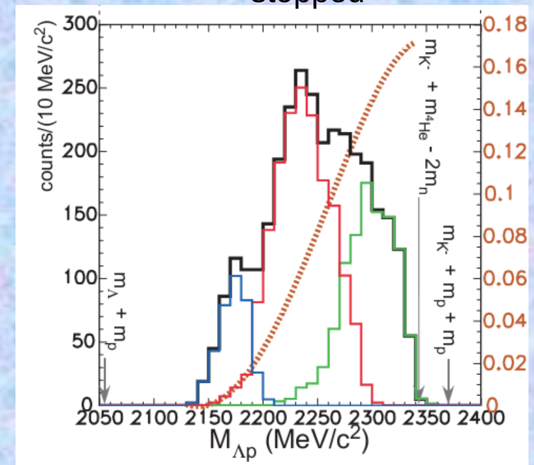
↓

Experimental data are needed to reveal this puzzle

Experiments on $K^{-}pp$

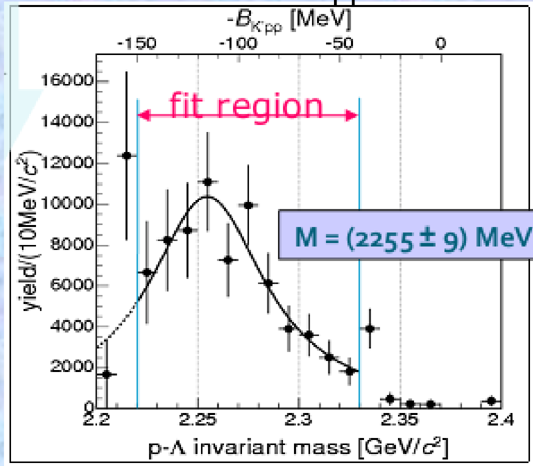
-Search in the invariant mass Λp channel for a ‘peak’ that would reveal a resonance, try to measure the width and the binding energy, asuming the formation of a K-pp cluster

KEK K- $_{stopped}$ + 4He -> Λp X



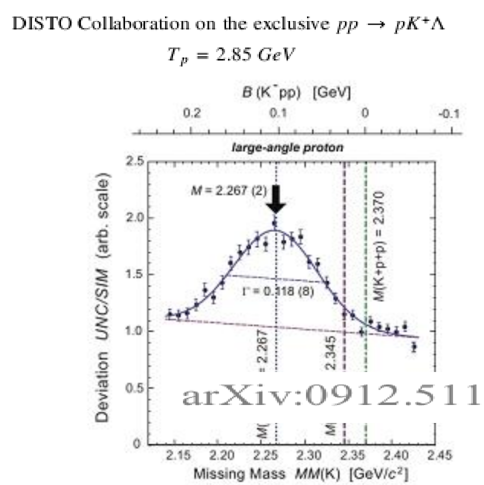
arXiv:0711.4943v1

FINUDA K- $_{stopped}$ + X -> Λp X’



$X = {}^{6}Li, {}^{7}Li, {}^{9}Be$

B = 115 $^{+6}_{-5}$ (stat) $^{+3}_{-4}$ (sys) **MeV**
Γ= 67 $^{+14}_{-11}$ (stat) $^{+2}_{-3}$ (sys) **MeV**



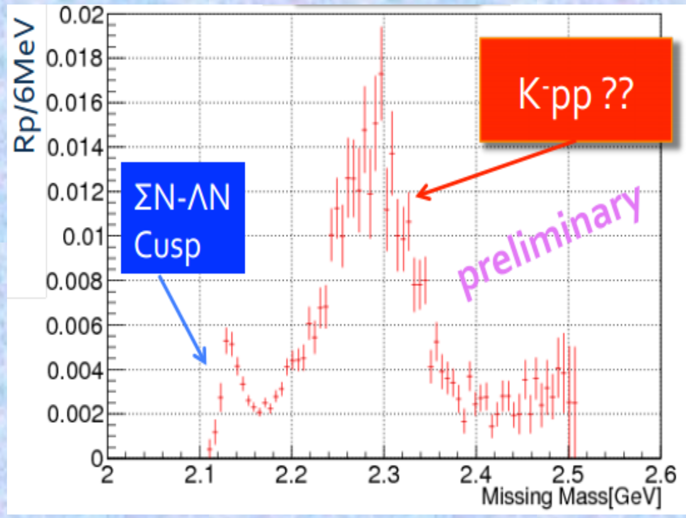
DISTO

Production via $pp \to pK^+\Lambda$ (2,85 GeV)

B = 105 ± 2 ± 5 MeV
Γ = 118 ± 8 ± 10 MeV

latest income

E27 @ J-Park



Theoretical work on *K⁻pp*

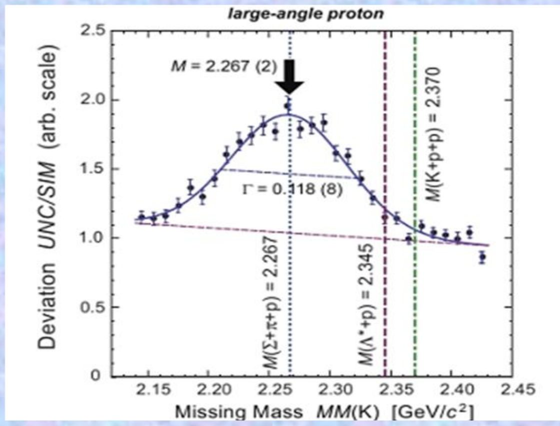
- It does exsist

(MeV)	ATMS Yamazaki & Akaishi, PLB535 (2002) 70.	Variational Dote, Hyodo, Weise, PRC79 (2009) 014003.	Faddeev Shevchenko, Gal, Mares, PRL98 (2007) 082301.	Faddeev Ikeda & Sato, PRC79 (2009) 035201.	Variational Wycech & Green, PRC79 (2009) 014001.
B	48	17-23	50-70	45-80	40-80
Γ	61	40-70	90-110	45-75	40-85

... a K^-pp puzzle

Experiments:

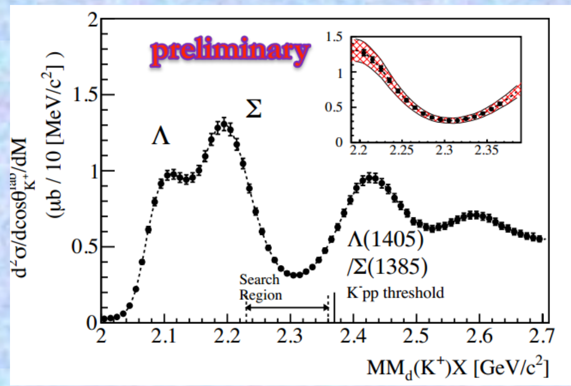
arXiv:0912.5116 [hep-ex]



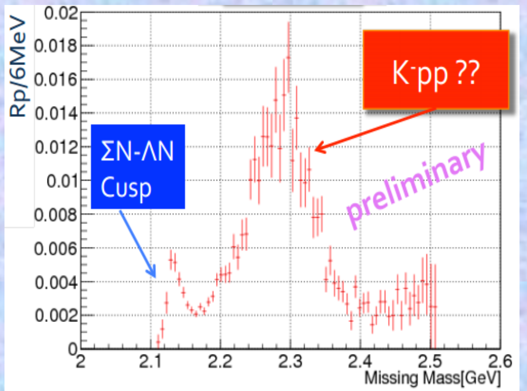
Production via $pp \rightarrow pK^+\Lambda$ (2,85 GeV)

B = 105 ± 2 ± 5 MeV
Γ = 118 ± 8 ± 10 MeV

DISTO

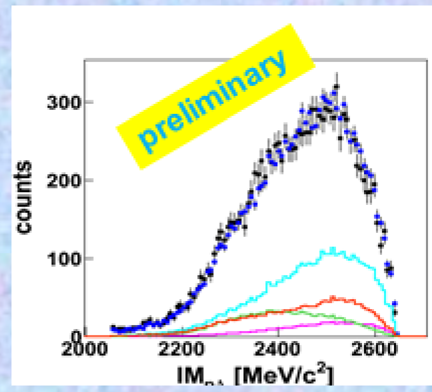


LEPS-Spring8



E27 @ J-Park

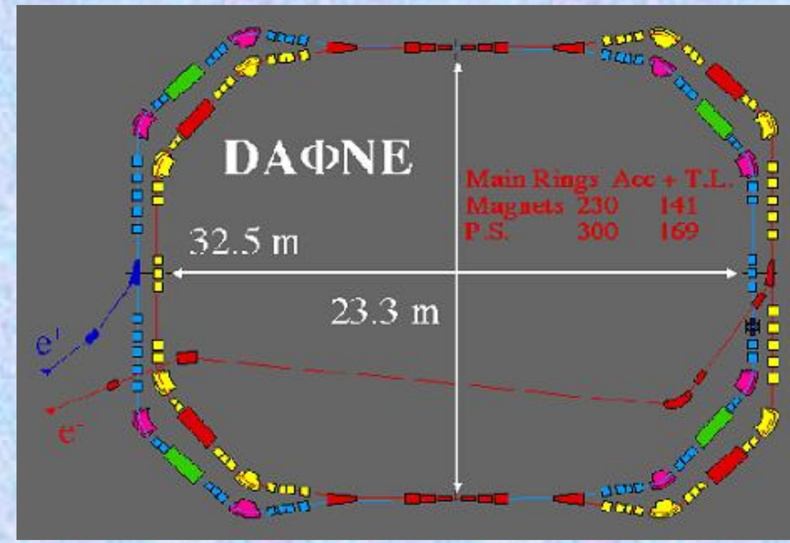
HADES

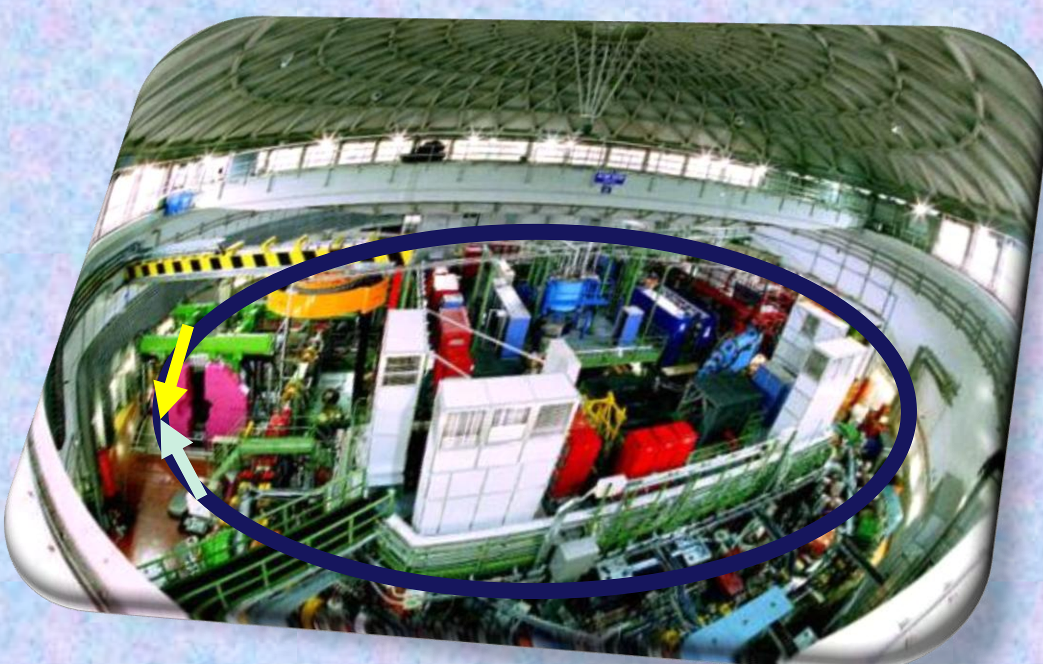


Contributions from N*, interferences using PWA

The DAΦNE e^+e^- collider

- Double ring e^+ e^- collider working in C.M. energy of Φ (≈ 500 MeV/c)
- $\Phi \rightarrow K^+ K^-$ (49.1%) (≈ 600 $K^+ K^-$ /s)



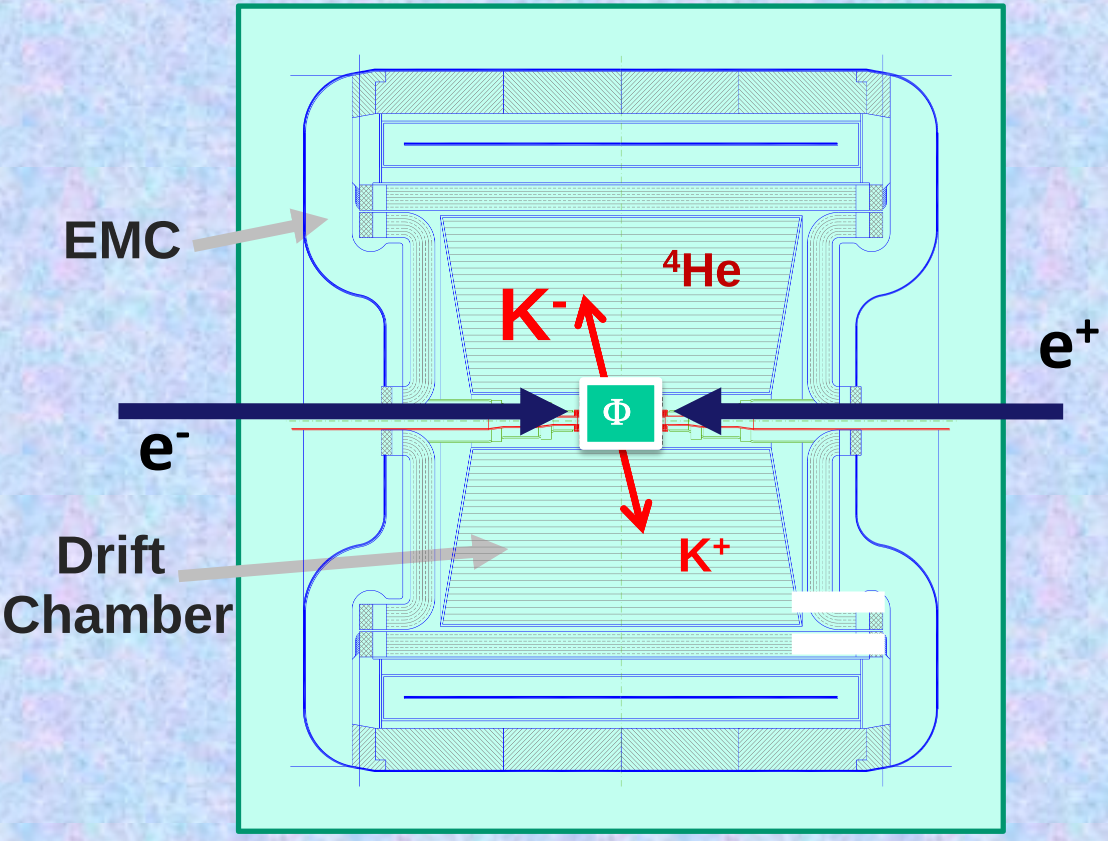


- low momentum Kaons (≈ 127 MeV/c)
- back to back $K^+ K^-$ topology

KLOE (2004-2005) data analysis

- Test the behaviour of the KLOE detector for hadronic physics purposes
- Possibility to study the phenomenon with an active target

how K+/K- events looks like nowadays in **KLOE:**



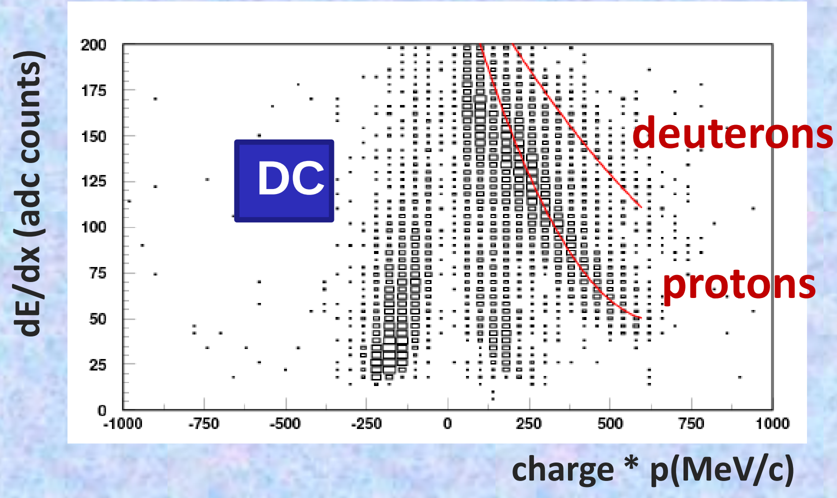
- The Drift Chamber (DC) of KLOE contains mailny **^{4}He (**90%, 10% *isobutane*)
- From analysis of KLOE data and Monte Carlo: **0.1 % of K^- stop in the DC volume** + 10 times more in the Carbon entrance wall of the DC
- This leads to hundreds of events with K^- hadronic interactions at rest

- Excellence acceptance
- Excellence resolution

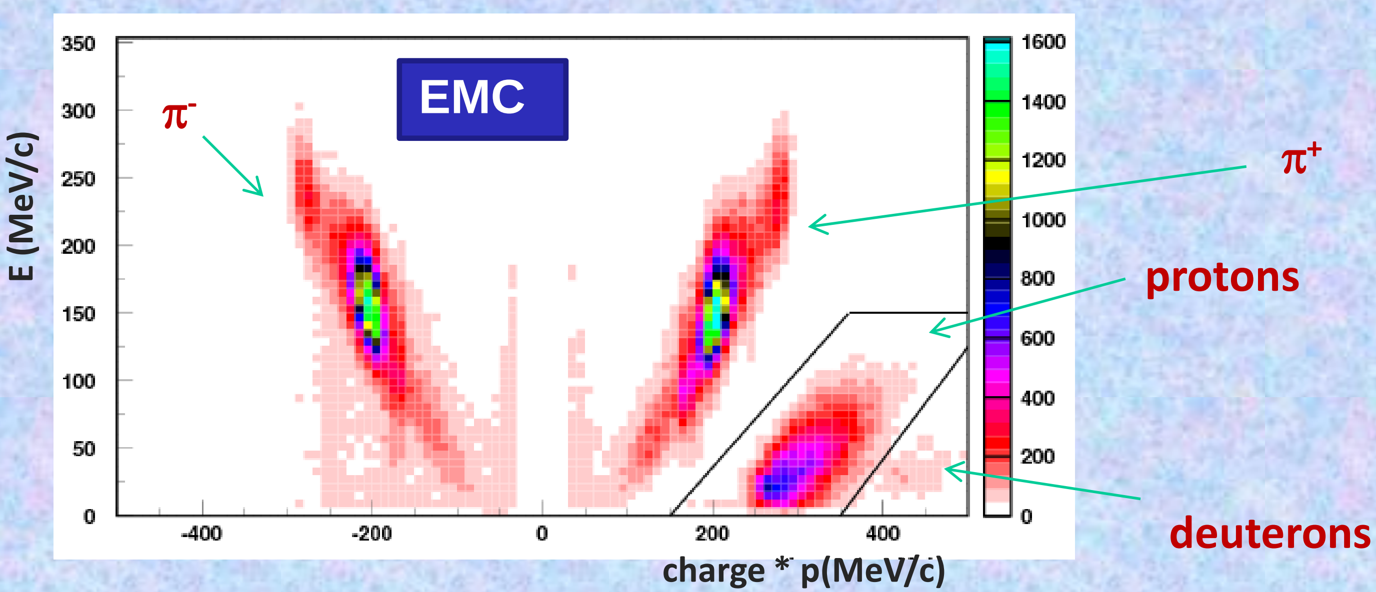
Particle identification

Lambda selection criteria: $\Lambda \longrightarrow p + \pi^-$

Search for vertices (by KLOE reconstruction) inside the Drift Chamber:
-negative particle: π^- identified by low dE/dx in DC gas



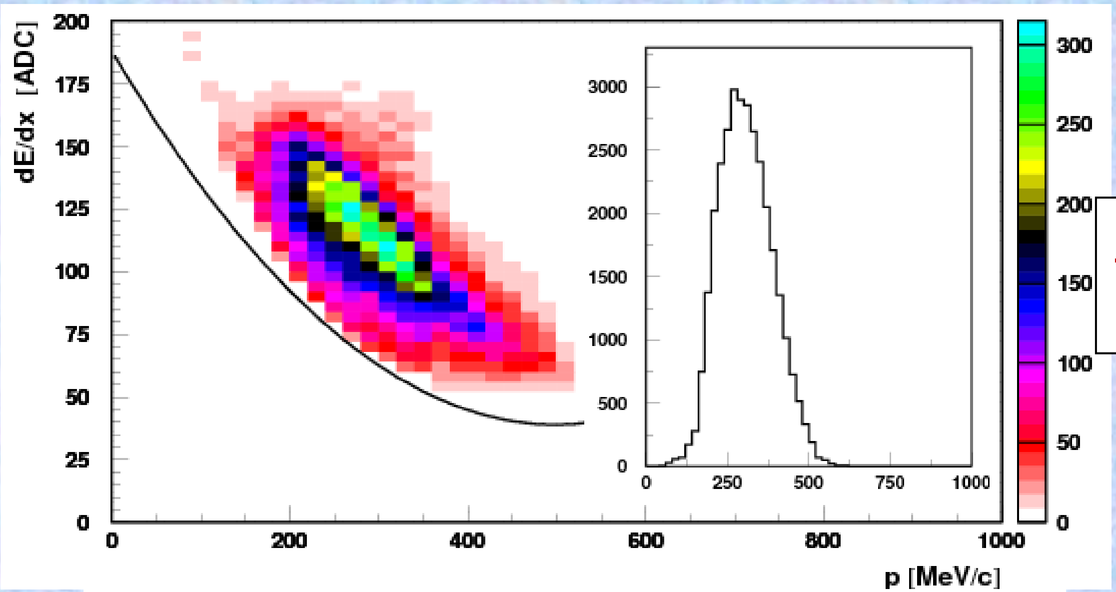
Protons associated with EMC cluster:



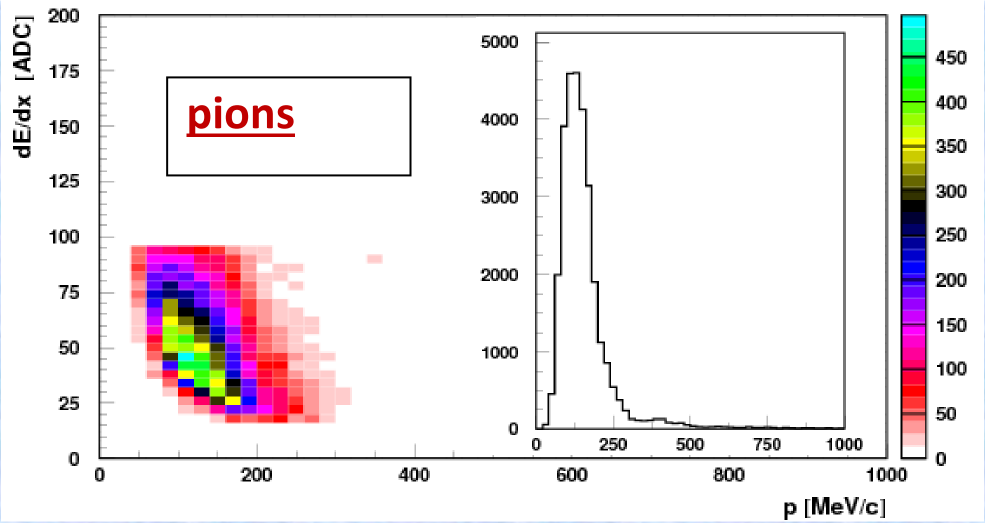
Particle identification

For **protons, if no cluster associated**, requirement:

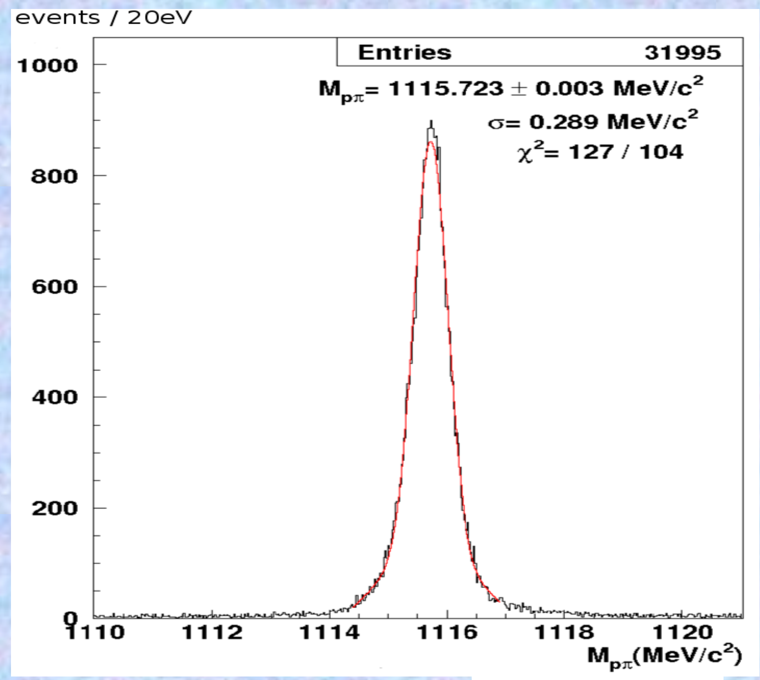
track reaching the calorimeter region + "proton signature" in the dE/dx of DC gas



protons without EMC-cluster
+ protons with EMC-cluster



Λ → p + π⁻

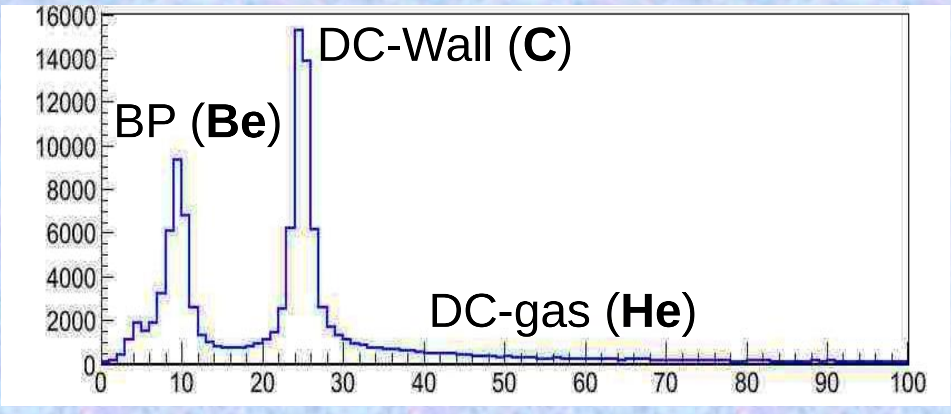


M_{inv} pπ (MeV/c²)

Analysis status

- Analyses of the 2004-2005 KLOE data: Stopped K^- absorption in light nuclei: ^{9}Be,^{12}C, ^{4}He. (2.2 fb^{-1} total, ~**1.4 fb^{-1} analyzed**)

Position of the K^- hadronic interaction inside KLOE:



r(cm)

Analysis status

- Analyses of the **2004-2005 KLOE data**: Stopped K^- absorption in light nuclei **($^9Be, ^{12}C, ^4He$)** (2.2 fb^{-1} total, 1.5fb^{-1} analyzed)

- Dedicated **2012** run with pure **Carbon target** inside KLOE
  4/6 mm of thickness (~90 pb^{-1}; analyzed 37 pb^{-1}, x1.5 statistics)

  - **Λp** from 1NA or 2NA (single or multi-nucleon absorption)
  - **Λd** and **Λt** channels
  - Λ (1405) -> **$\Sigma^0\pi^0$**
  - Λ (1405) -> **$\Sigma^+\pi^-$**
  - Σ (1385) -> **$\Lambda\pi^-$** (ΣN/ΛN internal conversion)

Analysis status

- Analyses of the **2002-2005 KLOE data**: Stopped K^- absorption in light nuclei **(^{9}Be, ^{12}C, ^{4}He)** (2.2 fb^{-1} total, 1.5fb^{-1} analyzed)

- Dedicated **2012** run with pure **Carbon target** inside KLOE
  4/6 mm of thickness (~90 pb^{-1}; analyzed 37 pb^{-1}, x1.5 statistics)

  - **Λp from 1NA or 2NA (single or multi-nucleon absorption)**
  - **Λd and Λt channels**

  → **this talk**

  - Λ (1405) -> **$\Sigma^0\pi^0$**
  - Λ (1405) -> **$\Sigma^+\pi^-$**
  - Σ (1385) -> **$\Lambda\pi^-$** (ΣN/ΛN internal conversion)

  → **talk by K. Piscicchia**

Λp analysis

1NA: **K^-n → $\Lambda\pi^-$** (extra p only spectator) **pionic**

1NA: **K^-N → $\Sigma\pi^-$, (ΣN')π^-** → **(ΛN')π^-** (extra p from **Σ/Λ conversion**) **pionic**

2NA: **K^-NN → ΛN**

2NA: **K^-NN → ΣN, (ΣN)N** → **ΛN'(N)** (**Σ/Λ conversion** on another nucleon)

Λp analysis

1NA: **$K^-n \rightarrow \Lambda\pi^-$** (extra p only spectator)

$K^-N \rightarrow \Sigma\pi^-$, $(\Sigma N)\pi^- \rightarrow (\Lambda N')\pi^-$

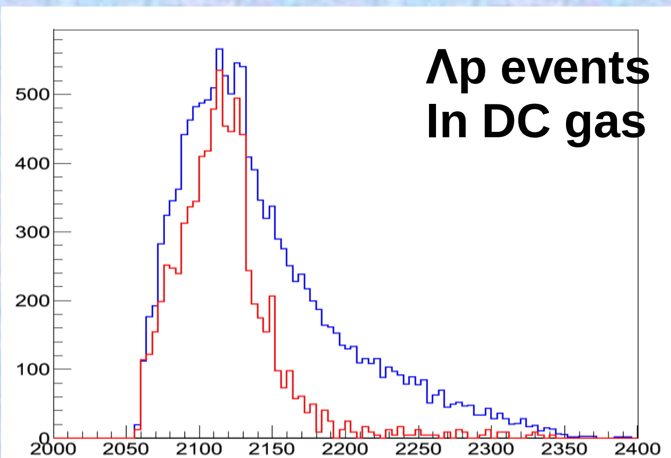
(extra p from **Σ/Λ** conversion)

2NA: **$K^-NN \rightarrow \Lambda N$**

$K^-NN \rightarrow \Sigma N$, $(\Sigma N)N \rightarrow \Lambda N'(N)$

(**Σ/Λ conversion** on another nucleon)

A disentanglement between single and multi-nucleon absorption can be achieved thanks to the **excellent acceptance:**

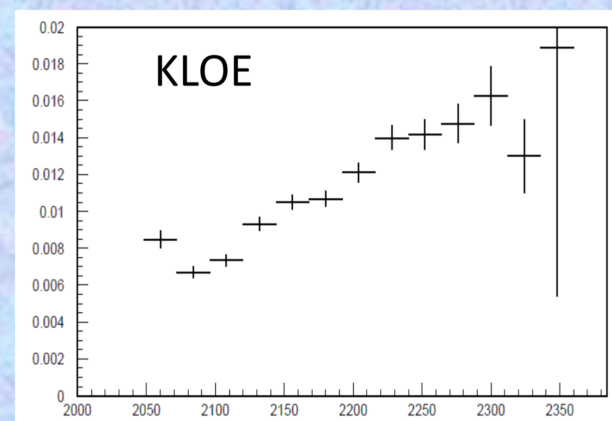


$M_{\Lambda p}$ (MeV)

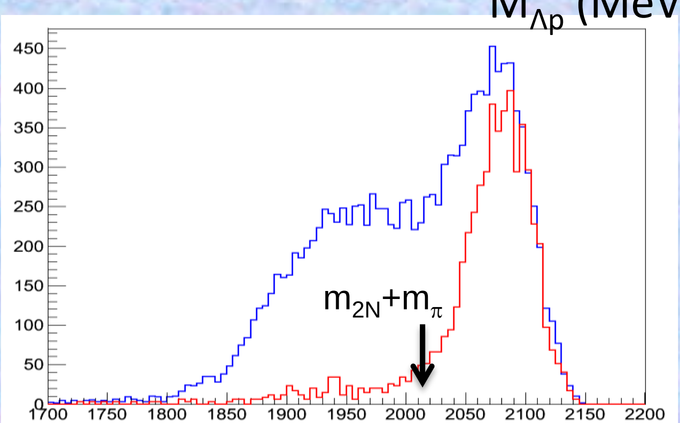
Λp all events

Λp + π^- events

(arbitrary normalization)

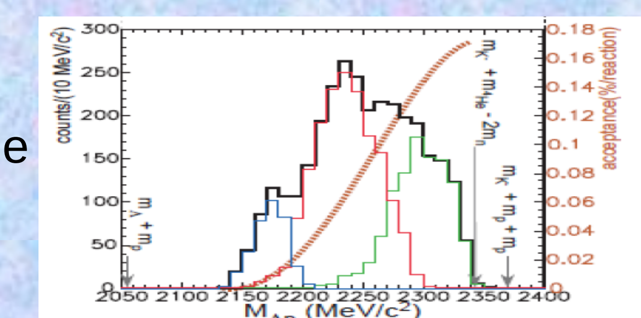


Acceptance in $M_{\Lambda p}$ (MeV)
(arbitrary normalization)



Λp missing mass (MeV)

The Λp missing mass for the **$\Lambda\pi^-p$** events lies exactly
In the $2N+\pi^-$ mass region



KEK-E549

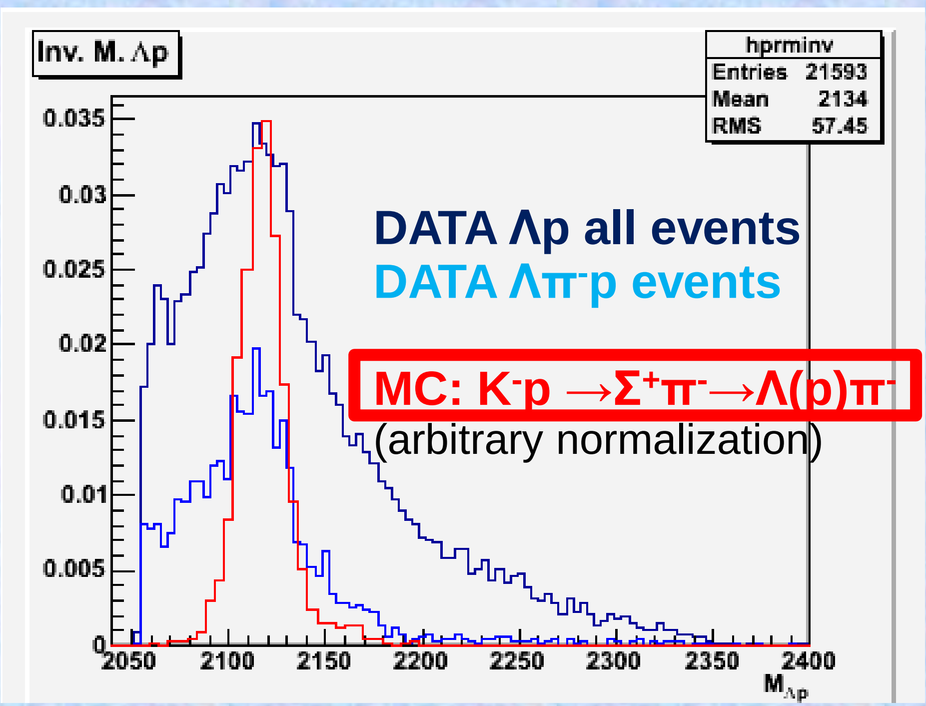
Mod.Phys.Lett.A23, 2520 (2008)

Λp analysis: MC 1NA

1NA + Internal Conversion $\Sigma(n)\rightarrow\Lambda(p)$
$K^-p \rightarrow \Sigma^+\pi^- \rightarrow \Lambda(p)\pi^-$

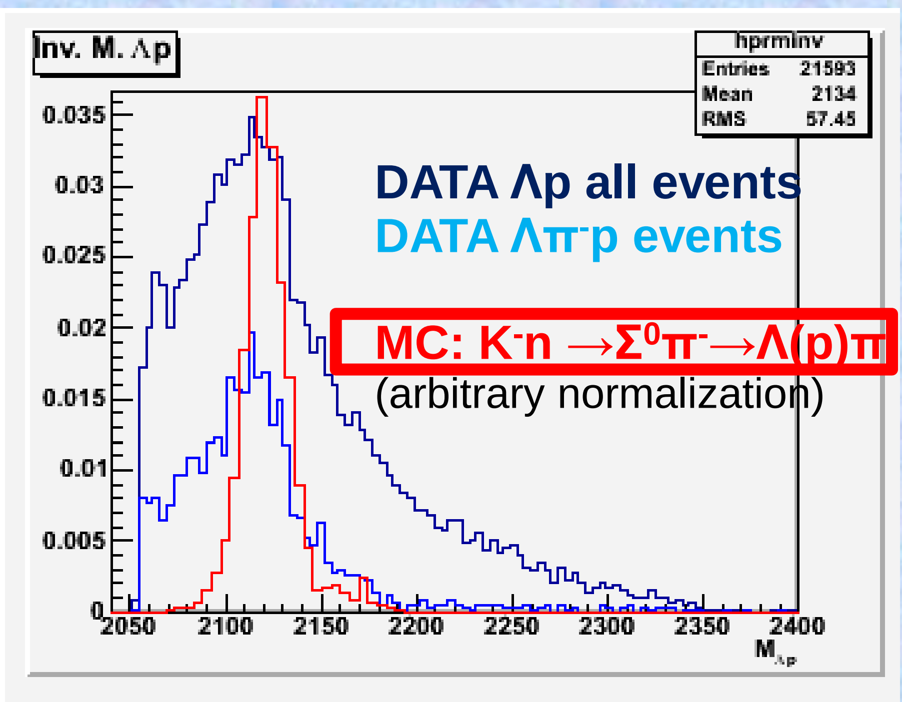
1NA + Internal Conversion $\Sigma(p)\rightarrow\Lambda(p)$
$K^-n \rightarrow \Sigma^0\pi^- \rightarrow \Lambda(p)\pi^-$

Σ^+ conversion



$M_{\Lambda p}$ (MeV/c^2)

Σ^0 conversion



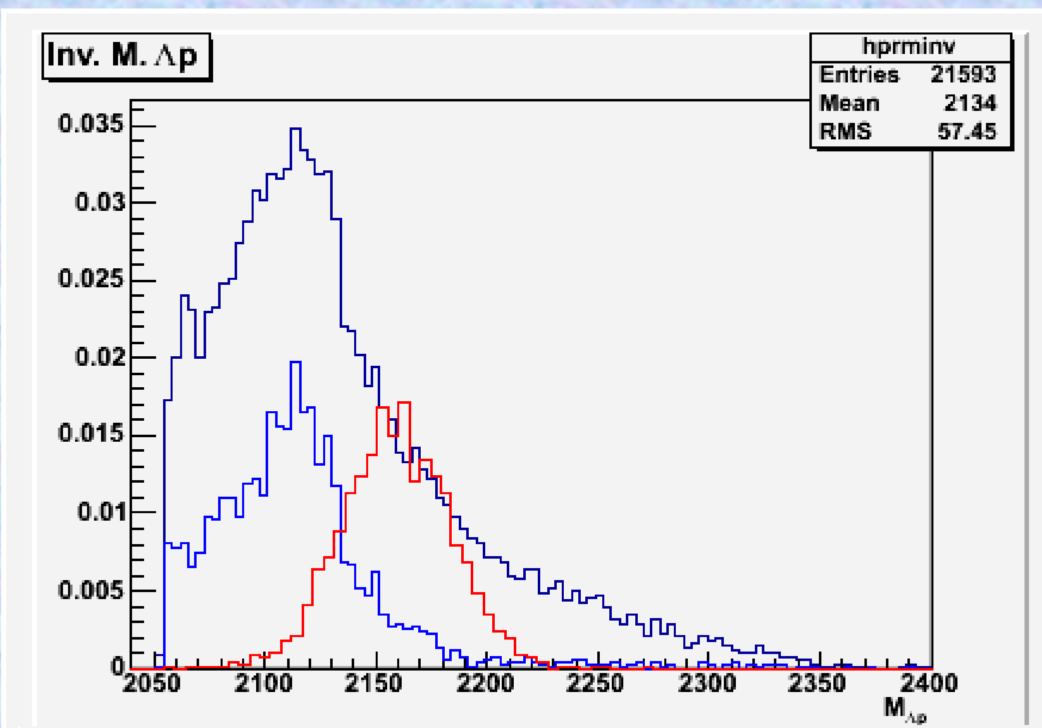
$M_{\Lambda p}$ (MeV/c^2)

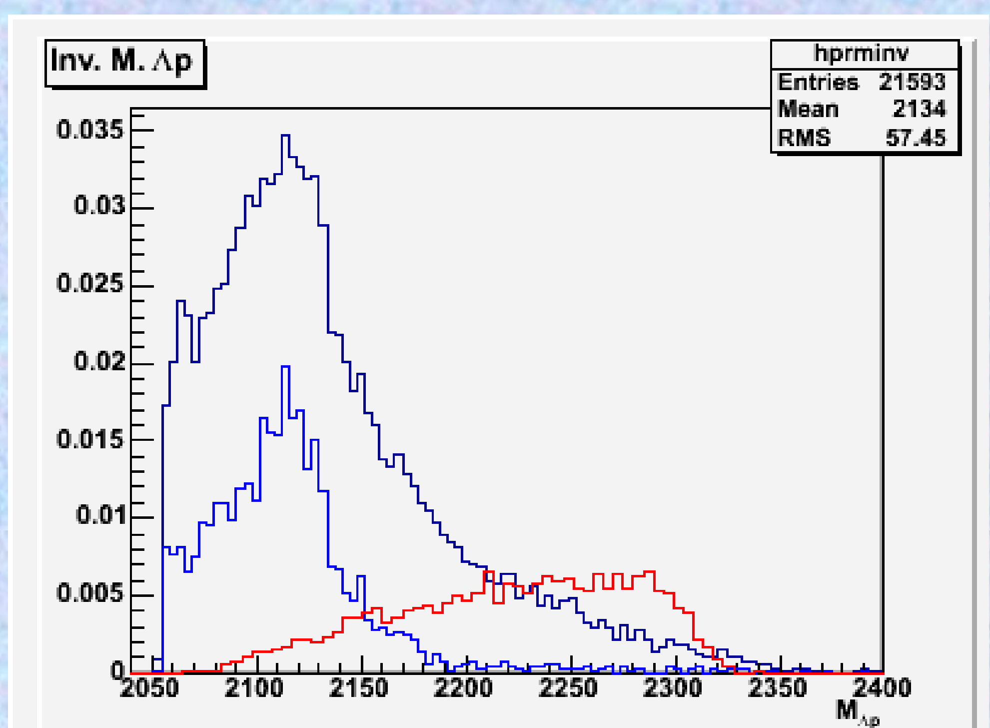
Λp analysis: MC 2NA

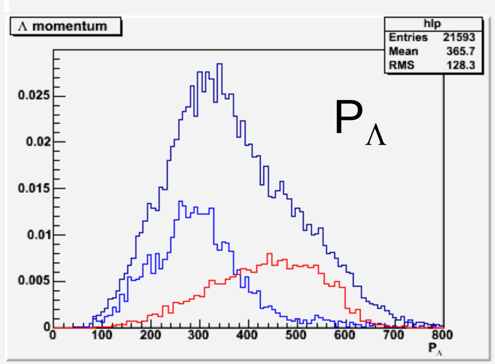
2NA absorption
Internal Conversion Σ(p)→Λ(p)
$K^-np \rightarrow \Sigma^0 n \rightarrow \Lambda(p)n$

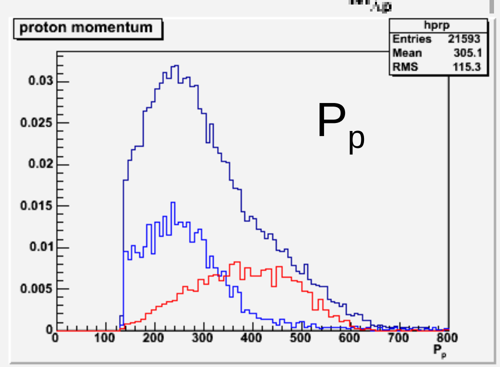
DATA Λp all events
DATA $\Lambda\pi^-p$ events
MC
(arbitrary normalization)

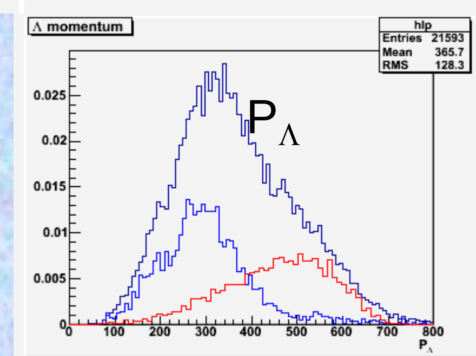
2NA absorption
Internal Conversion Σ(n)→Λ(n)
$K^-pp \rightarrow \Sigma^0 p \rightarrow \Lambda p(n)$

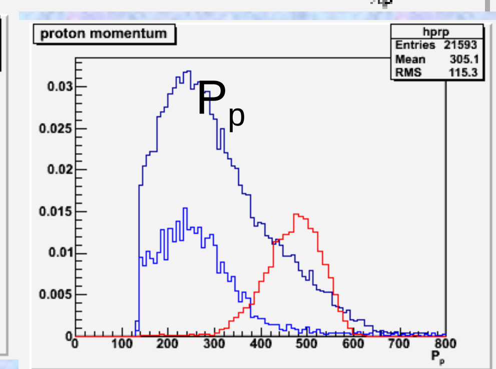












Calculation of the $K^- \, {}^4He \rightarrow \Lambda\pi^- \, {}^3He$ resonant and non-resonant production

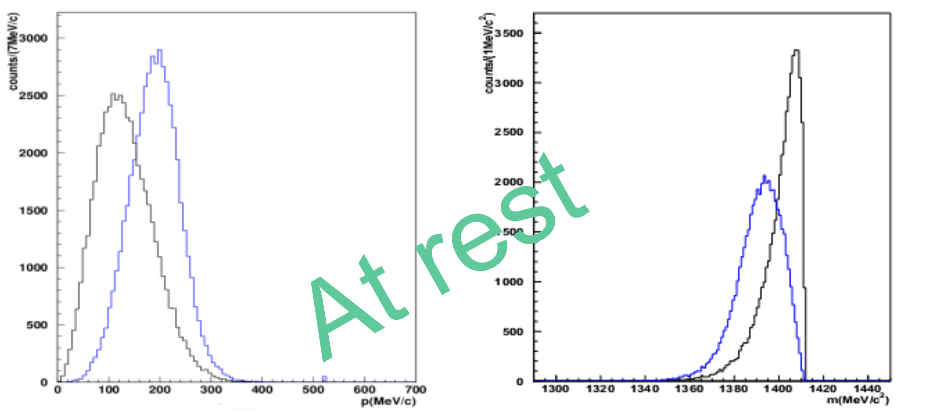


Figura 1: *Left:* $\Lambda\pi^-$ *momentum distributions* $P_s^s(p_{\Lambda\pi})$ *black,* $P_s^p(p_{\Lambda\pi})$ *blue.* *Right:* $\Lambda\pi^-$ *mass distributions* $P_s^s(m_{\Lambda\pi})$ *black,* $P_s^p(m_{\Lambda\pi})$ *blue.*

Performed by Kristian Piscicchia in collaboration with prof. Wycech

RESONANT
NON-RESONANT

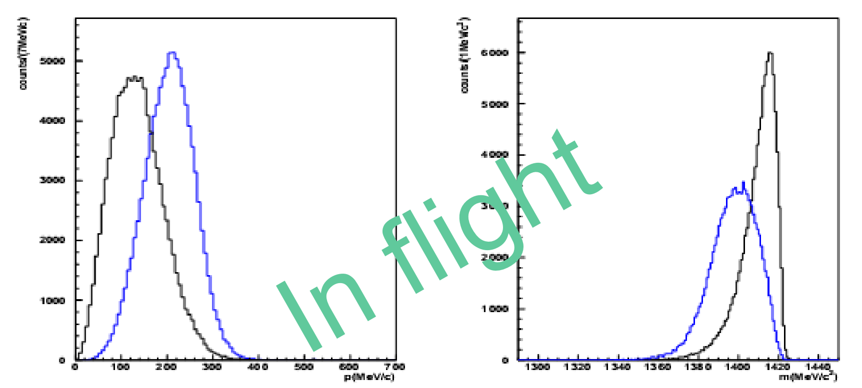


Figura 1: *Left:* $\Lambda\pi^-$ *momentum distributions* $P_{if}^s(p_{\Lambda\pi})$ *black,* $P_{if}^p(p_{\Lambda\pi})$ *blue.* *Right:* $\Lambda\pi^-$ *mass distributions* $P_{if}^s(m_{\Lambda\pi})$ *black,* $P_{if}^p(m_{\Lambda\pi})$ *blue.*

Λp analysis

Simulations made and data to be studied for the following processes:
(gas of the DC ^4He 90%, 10% isobutane C_4H_{10})

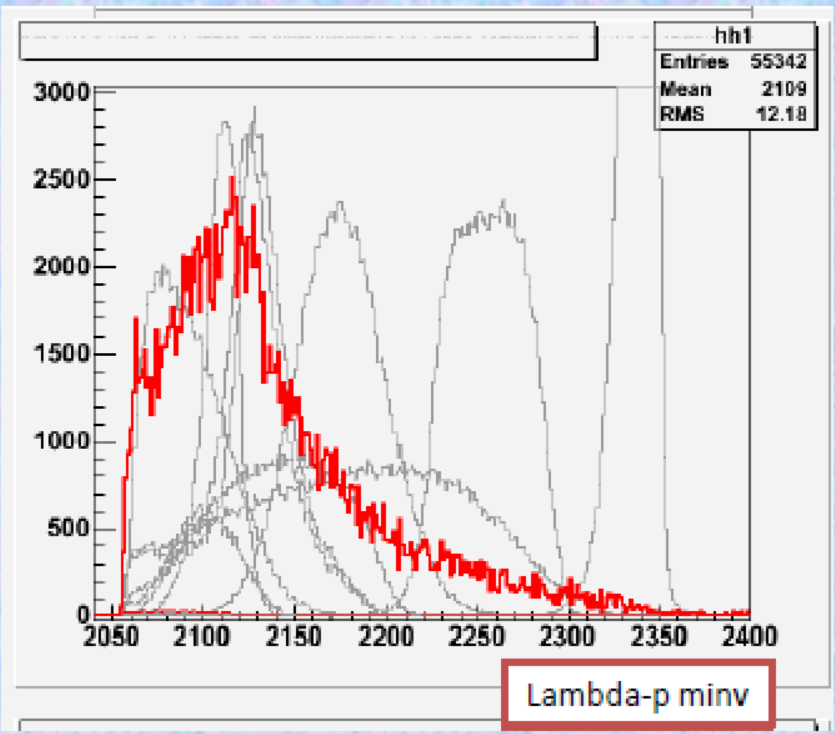
Single nuclear absorption (1NA)

1) $\mathbf{K^-}$ **H** → $\Sigma^+ \pi^-$ Σ^+ n/Λp (conversion on neutron from C)
   └→ **Λp**

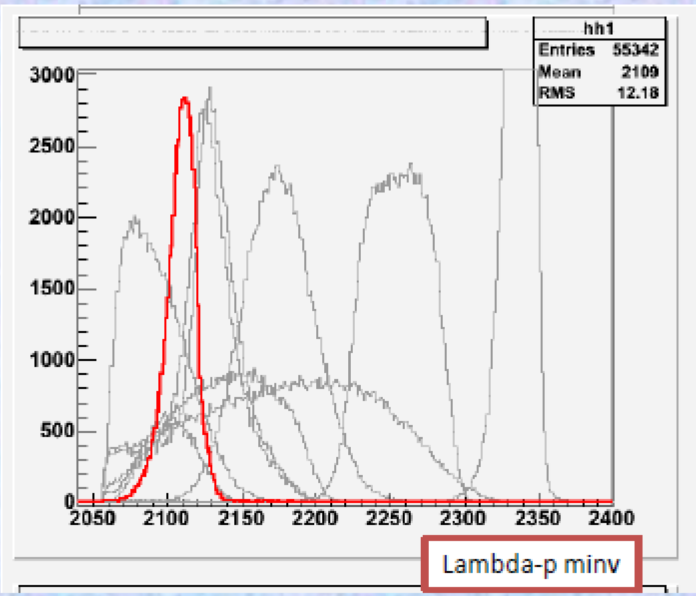
2) $\mathbf{K^-}$ **n** → $\Sigma^0 \pi^-$ Σ^0 p/Λp   (^{4}He ; 1NA)
   └→ **Λp(d)**

3) $\mathbf{K^-}$ **p** → $\Sigma^+ \pi^-$ Σ^+ n/Λp   (^{4}He ; 1NA)
   └→ **Λp(d)**

4) $\mathbf{K^-}$ **n** → $\Sigma^0 \pi^-$ Σ^0 n/Λn   (^{4}He ; 1NA)
   └→ **Λn(p)(p)**

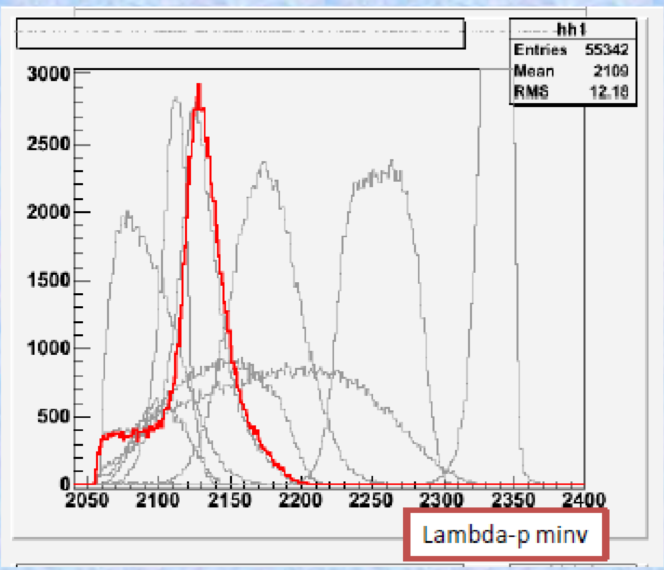


DATA

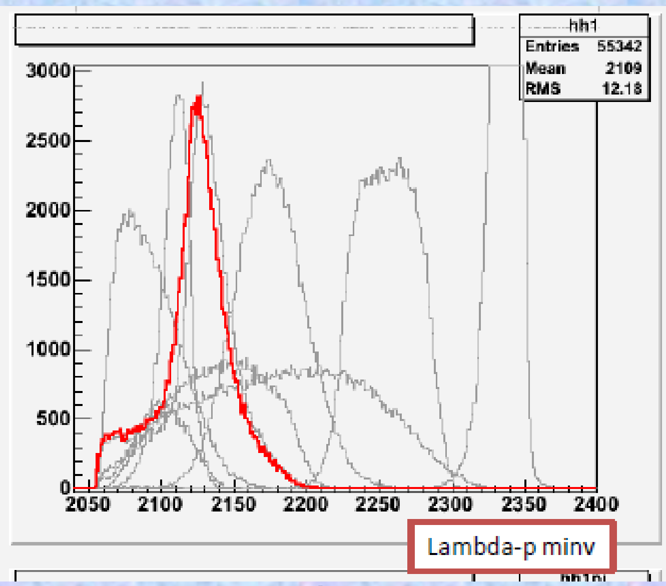


1)

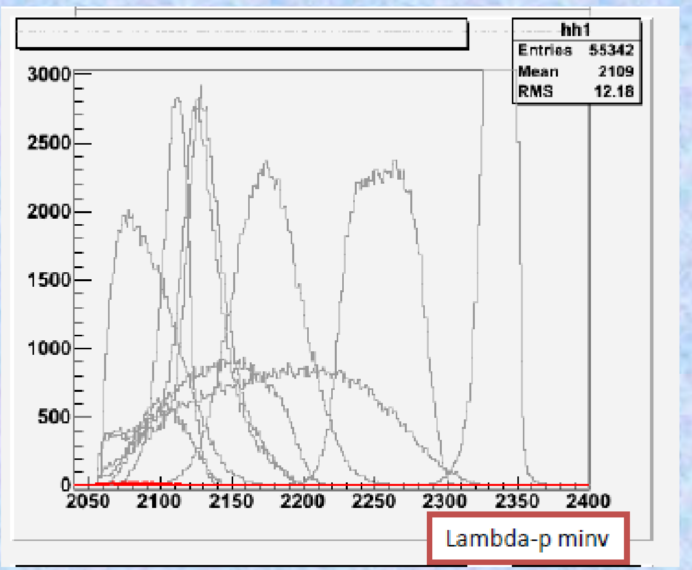
1NA with conversion



2)



3)



4)

Λp analysis

Simulations made and data to be studied for the following processes:
(gas of the DC ^{4}He 90%, 10% isobutane C_4H_{10})

Double nuclear absorption (2NA)
(all on ^{4}He)

5) $\mathbf{K^- pp \rightarrow \Lambda p(n)(n)}$

6) $\mathbf{K^- pp \rightarrow \Sigma^0 p(n)(n)}$

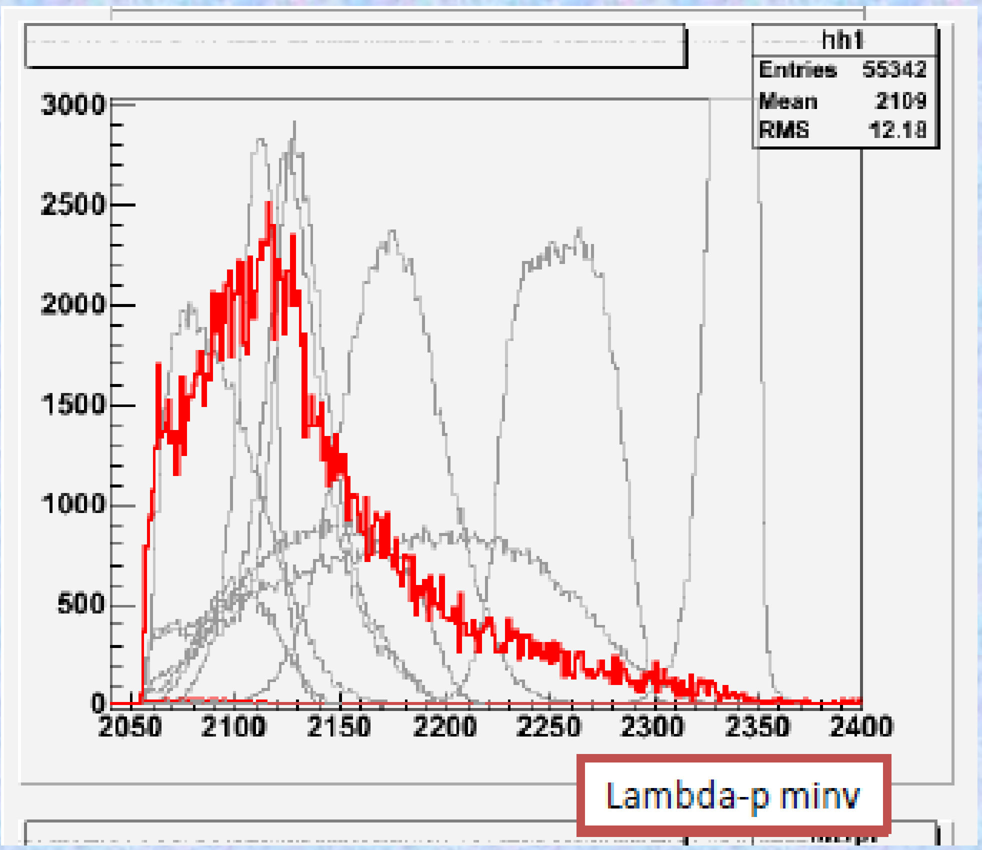
7) $\mathbf{K^- pn} \rightarrow \Sigma^0 n$ $\Sigma^0 p/\Lambda p$
└→ $\mathbf{\Lambda p(n)}$

8) $\mathbf{K^- pp} \rightarrow \Sigma^0 \mathbf{p}$ $\Sigma^0 n/\Lambda n$
└→ $\mathbf{\Lambda n(n)}$

9) $\mathbf{K^- pn} \rightarrow \Sigma^0 n$ $\Sigma^0 n/\Lambda n$
└→ $\mathbf{\Lambda n(p)}$

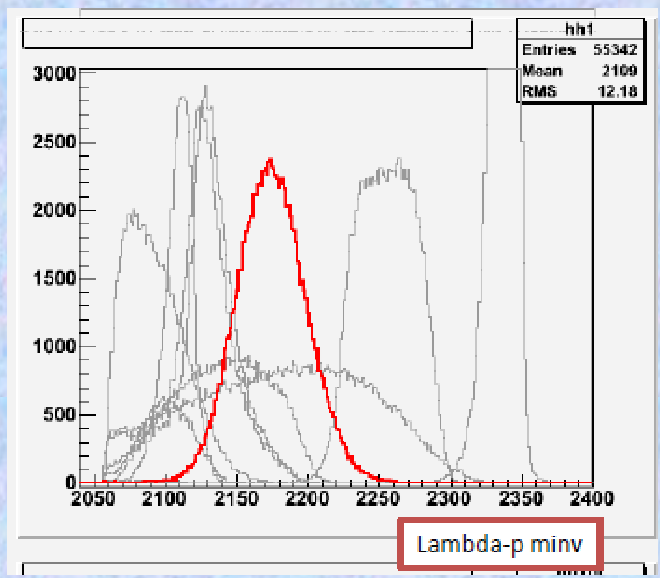
10) $\mathbf{K^- pn \rightarrow \Lambda \pi^- p(d)}$ (mesonic)

11) $\mathbf{K^- pn \rightarrow \Sigma^0 \pi^- p(d)}$ (mesonic)

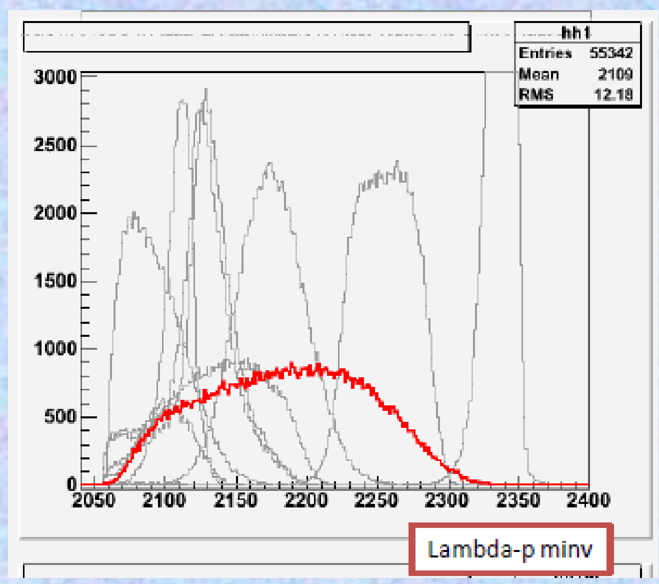


DATA

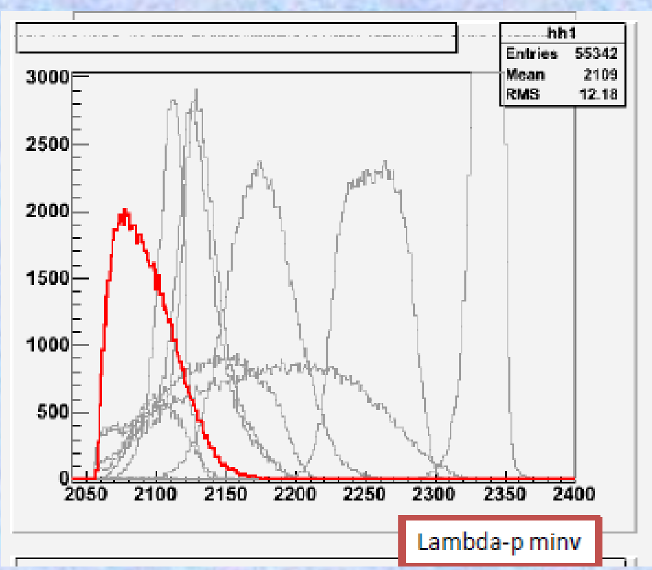
2 NA with conversion



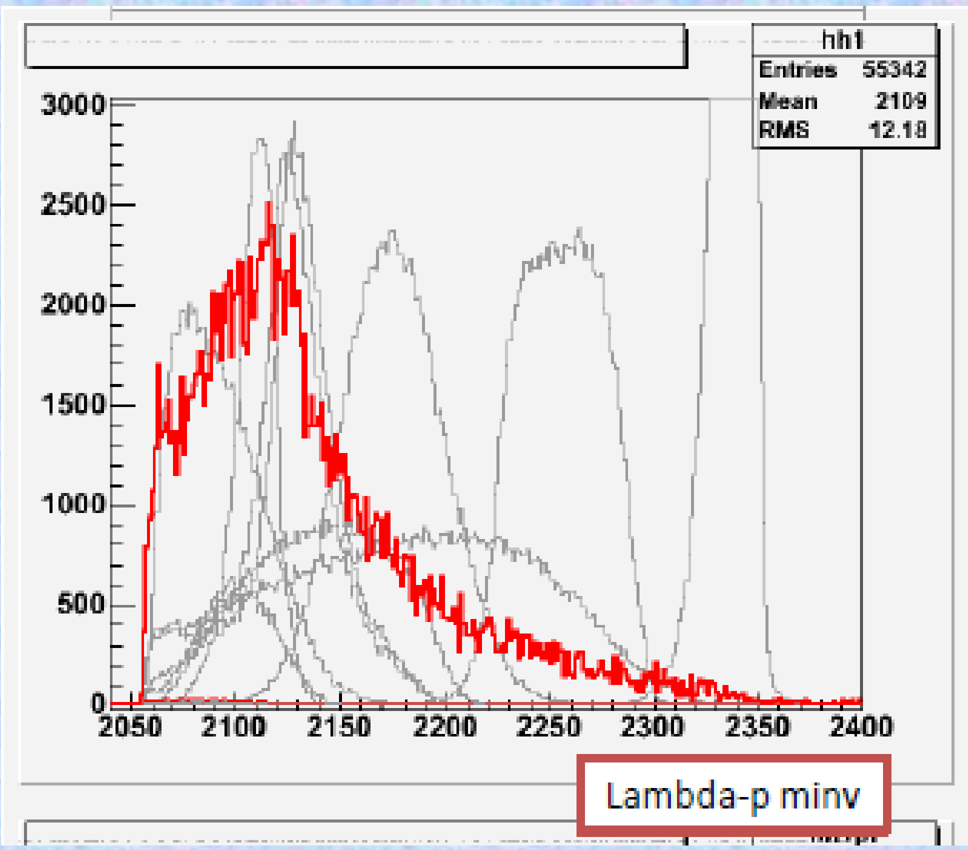
7)



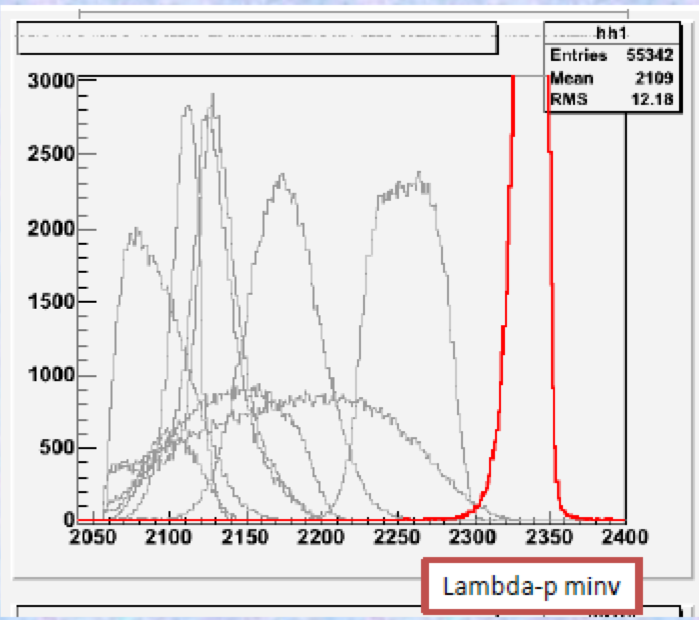
8)



9)

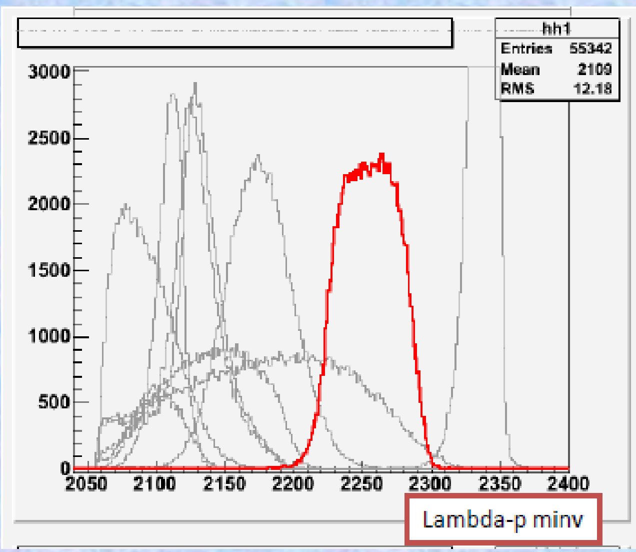


DATA

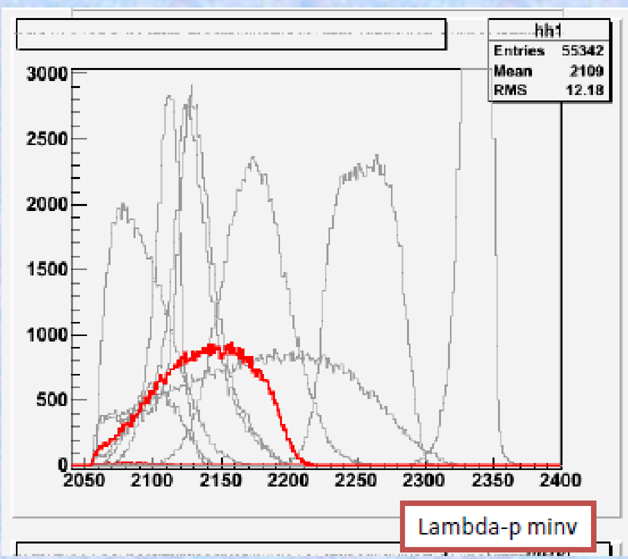


5)

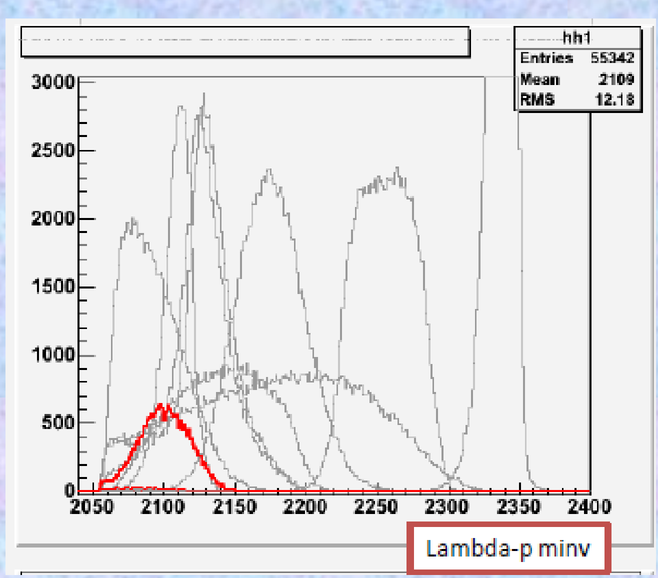
2NA direct formation of Σ^0 or Λ with p



6)



10)

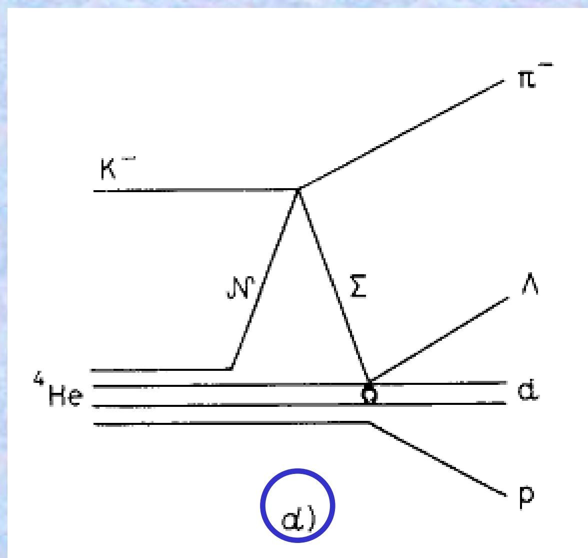


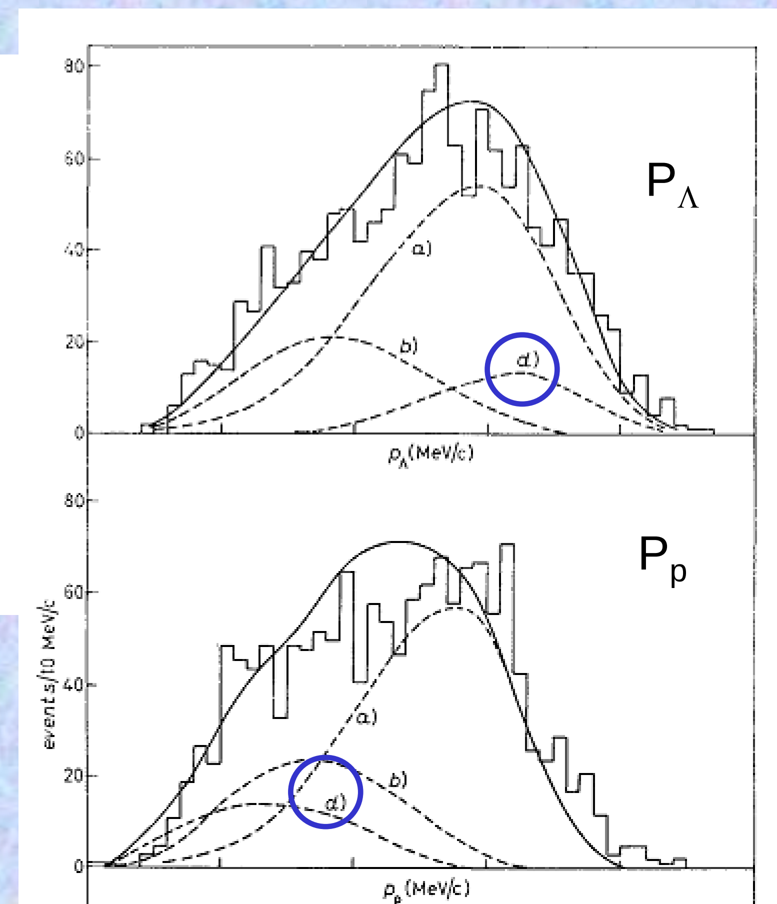
11)

Λp analysis

Another process to take into account:

- Low momentum proton process: **‘double nucleon conversion’**





IL NUOVO CIMENTO VOL. 49 A, N. 2 21 Gennaio 1979

A Study of the $\Lambda\pi^-$pd Final State Produced in K^--Meson Interactions at Rest in Helium (*).

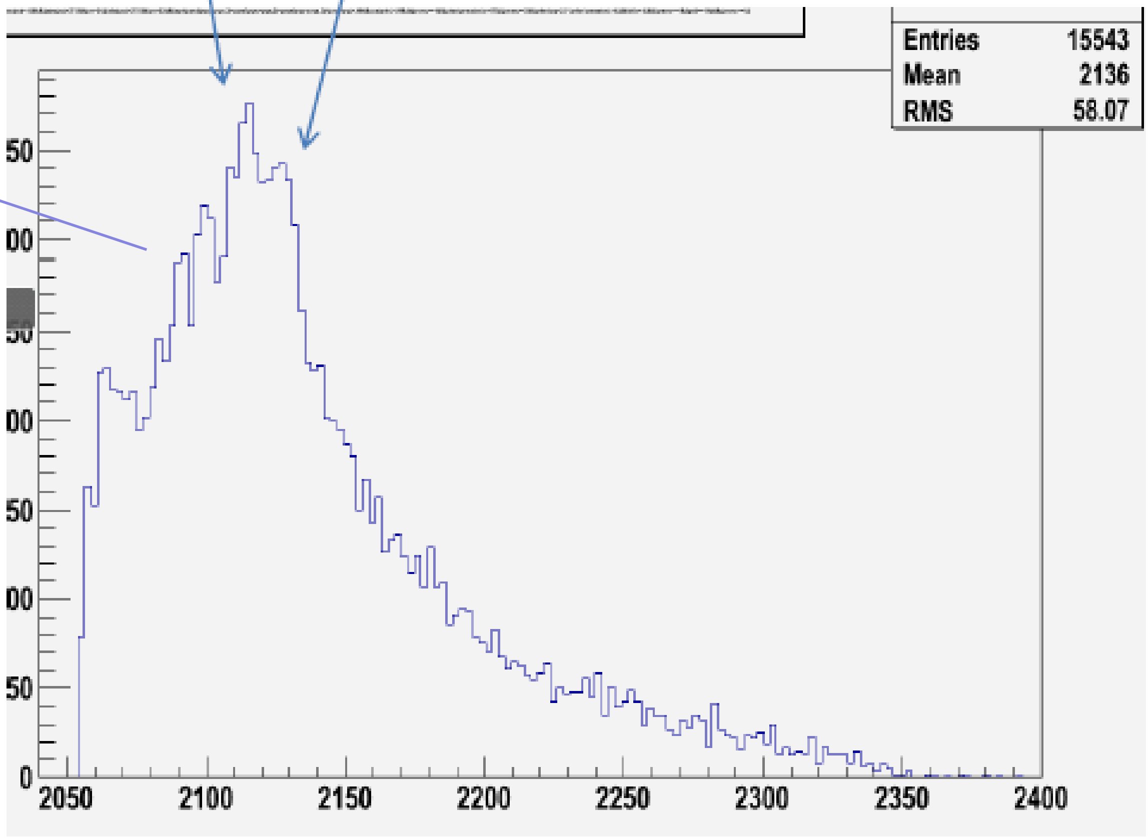
R. ROOSEN (**), C. VANDER VELDE-WILQUET and J. H. WICKENS (***)
Interuniversity Institute for High Energies, ULB-VUB - Brussels, Belgium

C. COMBER (*.*), D. H. DAVIS and D. N. TOVEE (.*.)
University College London - London, U. K.

Λp analysis

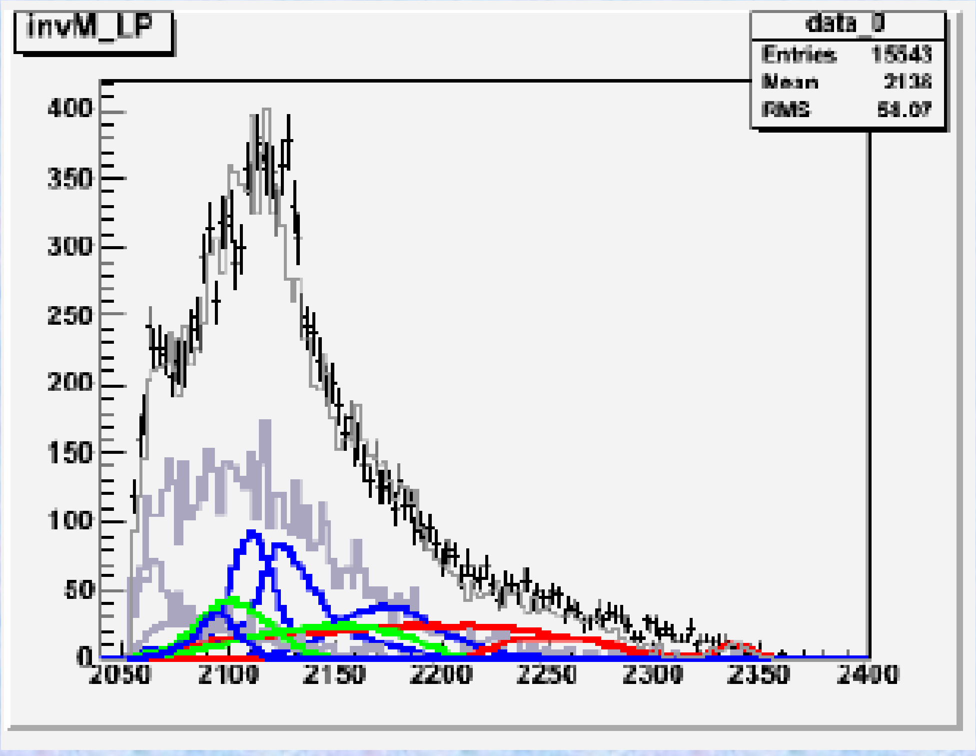
The 2 peaks: - hydrogen absorption + 12C conversion
- 4He conversion

Still to discuss

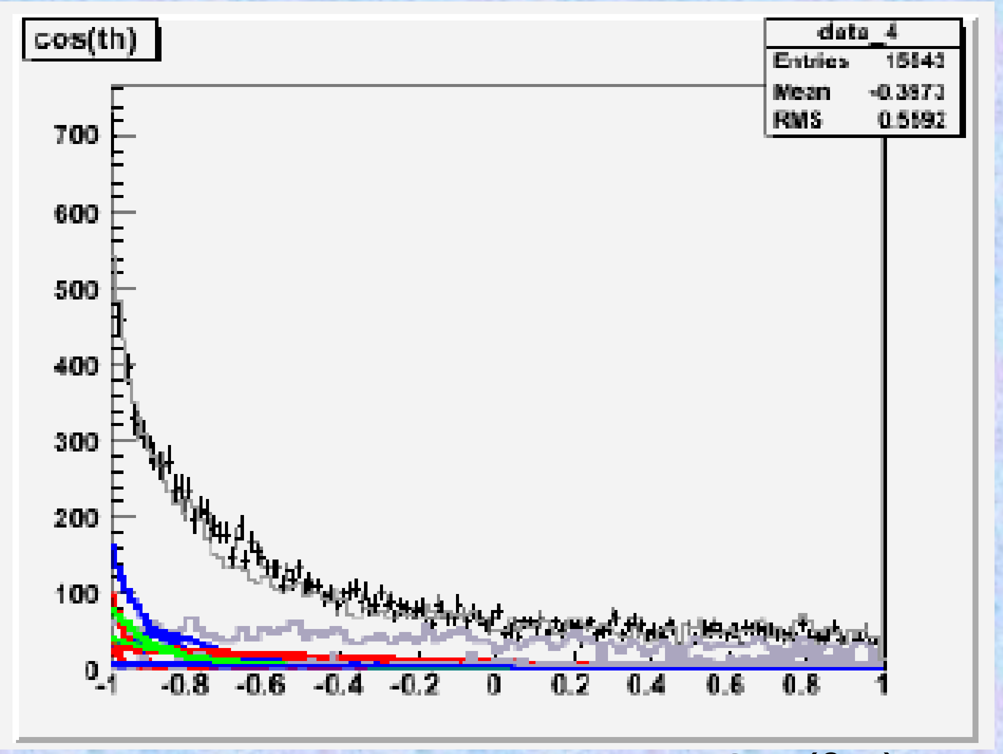


$M_{\Lambda p}$ (MeV/c^2)

Λp analysis



$M_{\Lambda p}$ (MeV/c^2)



$\cos(\theta_{\Lambda p})$

an **example** of the fit

Search for the 2NA: K-(pp) → **Λp**

Possible quantitative output: 2NA absorption rate per stopped Kaon

Katz et al.,
Phys.Rev.D1 (1970) 1267. **0.16 ± 0.03 (in He)**

Vander Velde-Wilquet et al.,
Il Nuovo Cimento,Vol.49A, N.2 (1979) **0.19 ± 0.03 (in C)** ← No $\Sigma-\Lambda$ rate

FINUDA and KEK has not published this number

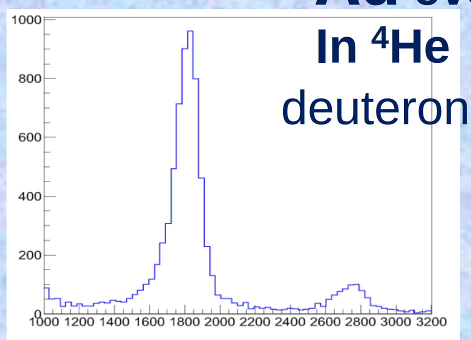
Λd analysis

- Search for signal of bound states in the **Λd** channel. Candidate to be a **K^-ppn** cluster. Observed spectra from FINUDA and KEK showing possible bound states in the in the high invariant mass region**.**

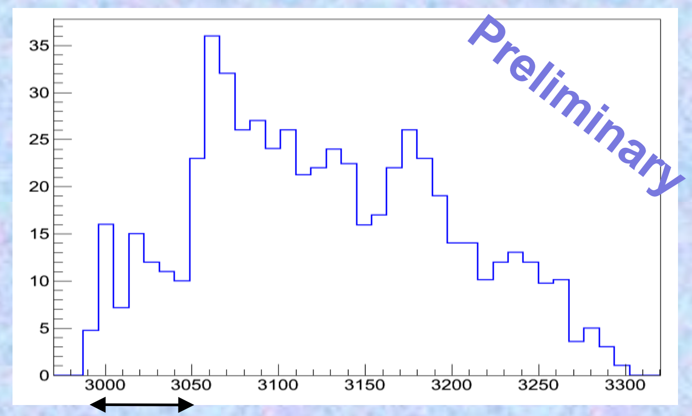
Λd events

In ^{4}He

deuterons →

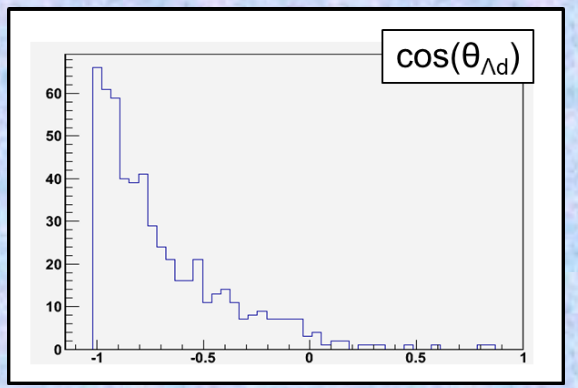


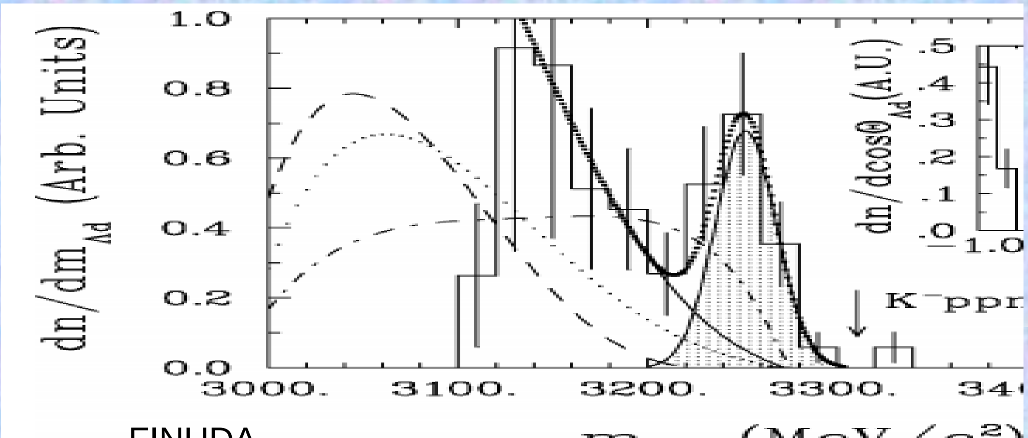
TOF Particle Mass (MeV)



low accept. region

$M_{\Lambda d}$ (MeV)

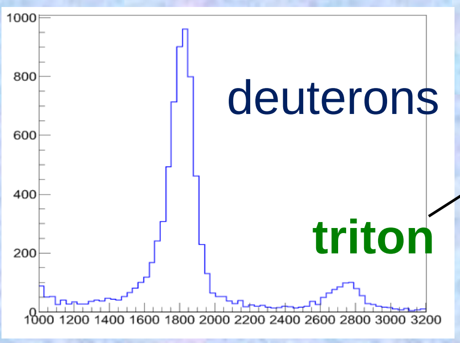




FINUDA
Phys. Lett. B 654 (2007) 80

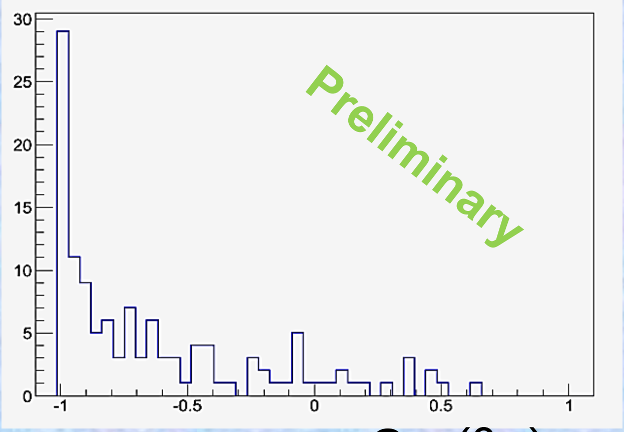
Λt analyses

Only FINUDA and an old experiment [M.Roosen, J.H. Wickens, Il Nuovo Cimento 66, (1981), 101] (with only 4 events!) have shown **Λt** spectra from K^- absorption

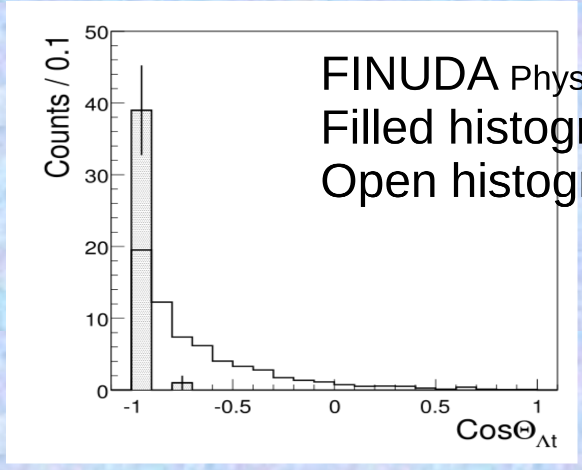


TOF Particle Mass (MeV)

Λt events
In ^{4}He



$Cos(\theta_{\Lambda t})$



FINUDA Phys.Lett.B 229, 229 (2008)
Filled histogram= data
Open histogram = Phase space simulation

Λp analysis and more

Conclusions

- Single and multi-nucleon absorption processes contributing the spectra are many - thorough study is needed for better understanding and to disentengle them from the possible signal due to the formation of a bound state

- **Quantitative information that can be extracted:**
  - 1NA/2NA absolute rate per stopped kaon in ^{4}He
  - 1NA/2NA $\Sigma - \Lambda$ conversion rates
- **Qualitative information:**
  - 1NA shape

- Other analysis undergoing

  Studies of Λd and Λt correlations in KLOE data will be investigated in the same manner

Thank you