Low energy capture of negatively charged kaons on light nuclei, the AMADEUS status and future physics case

Strange and non-strange mesons induced processes studies at DAFNE, J-PARC and RIKEN: present and future

10-11 July, LNF (INFN)

Kristian Piscicchia*

Laboratori Nazionali di Frascati (INFN)
Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

kristian.piscicchia@lnf.infn.it

Low-energy QCD in the u-d-s sector

$$\mathcal{L}_{eff} = \mathcal{L}_{mesons}(\Phi) + \mathcal{L}_B(\Phi, \Psi_B)$$

- **Chiral perturbation theory: interacting systems of N-G bosons (pions, kaons) coupled to baryons works well for ππ, πN, K^+N ..**

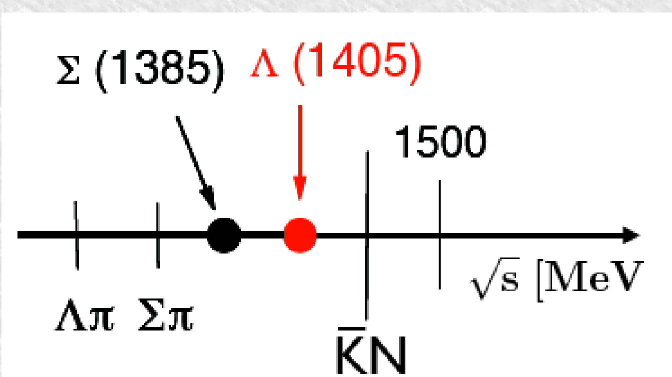
  NOT for K^-N !!

- **$K^- = (s\bar{u})$ strangeness = -1 , $K^+ = (\bar{u}s)$ strangeness = +1**

  strange baryons stable respect to strong interaction all have s = -1

- **the sub-threshold region is dominated by resonances → complex multichannel dynamics**

  Λ(1405) just below $\bar{K}N$ threshold (1432 MeV)



—>

Possible solutions:

- **Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics**
- **phenomenological $\bar{K}N$ and NN potentials**

The Λ(1405) case

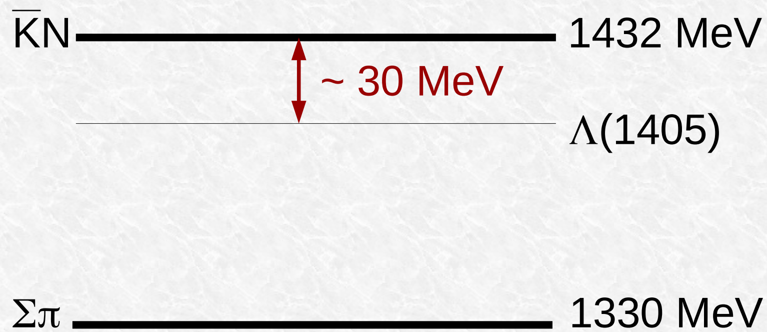
Mass = $1405.1^{+1.3}_{-1.0}$ MeV,

Width = 50.5 ± 2.0 MeV

$I = 0$, $S = -1$, $J^p = 1/2^-$,

Status: **** ,

strong **decay** into Σπ



- 3 quark?
- **molecular?**
- **K̄N bound state?**
- pentaquark?

Theoretical prediction Dalitz-Tuan (1959)

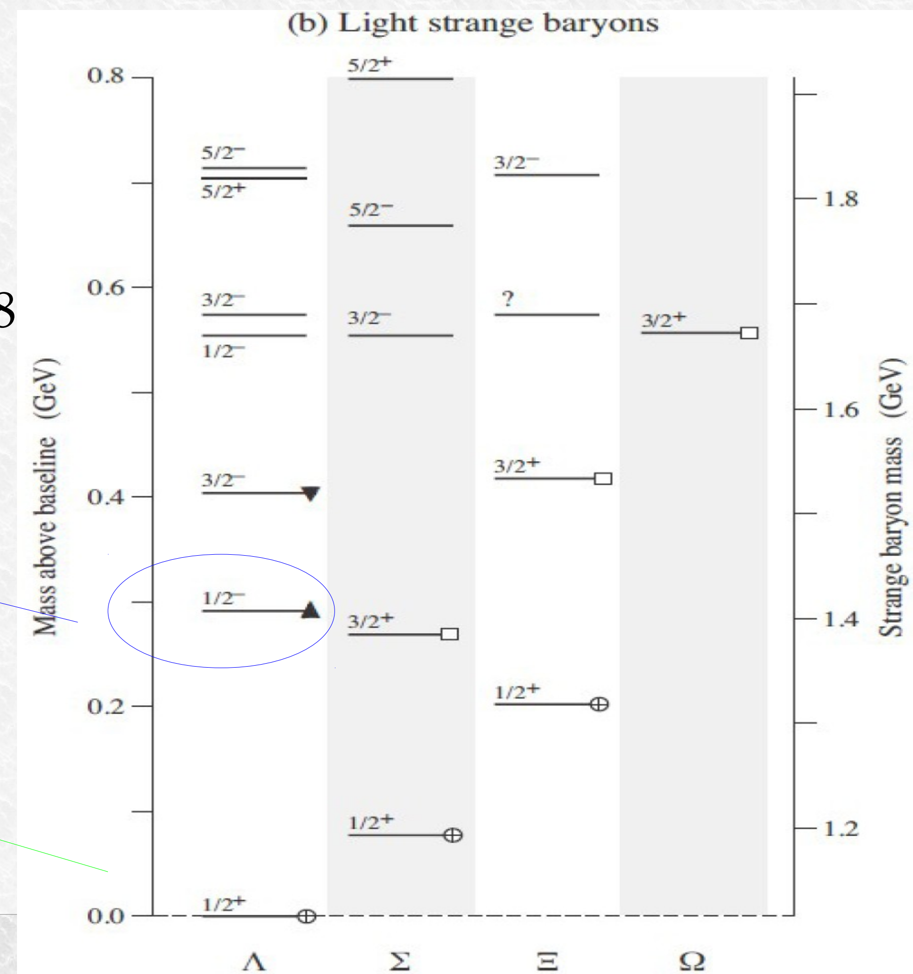
First experimental evidence:

M. H. Alston, et al., Phys. Rev. Lett. 6 (1961) 698

$K^- p \rightarrow \pi\pi\pi\Sigma$

Λ(1405)

Λ(1116)



The Λ(1405) case

Λ(1405) is located slightly below the $\bar{K}N$ threshold (1432 MeV)

Three quark model picture difficulties to reproduce the Λ(1405):

- According to its negative parity, one of the quarks has to be excited to $l = 1$

- nucleon sector, we find the N(1535) → the expected mass of the Λ^* is around 1700 MeV

- too big energy splitting observed between the Λ(1405) and the Λ(1520) interpreted as the spin-orbit partner ($J^p = 3/2^-$).

- pentaquark (4q + qbar in $l = 0$), but also predicts other, unobserved, excited baryons,

R. Dalitz and collaborators first suggested to interpret Λ(1405) as an KN quasibound state.

R.H. Dalitz, T.C. Wong and G. Rajasekaran, Phys. Rev. **153** (1967) 1617.

The $\Lambda(1405)$ case

BUBBLE CHAMBER search of the $\Lambda(1405)$:

- O. Braun et al. Nucl. Phys. B129 (1977) 1

K- induced reactions on d $\rightarrow$ $\Sigma^- \pi^+ n$ the resonance is found & 1420 MeV

- D. W. Thomas et al., Nucl. Phys. B56 (1973) 15

pion induced reaction $\pi^- p \rightarrow K^+ \pi \Sigma$ the resonance is found & 1405 MeV

- R. J. Hemingway, Nucl. Phys. B253 (1985) 742

$K^- p \rightarrow \pi^- \Sigma^+(1660) \rightarrow \pi^- (\pi^+ \Lambda(1405)) \rightarrow \pi^- \pi^+ (\pi\Sigma)$ & 4.2 GeV

analysed by Dalitz and Deloff $M = 1406.5 \pm 4.0$ MeV, $\Gamma = 50 \pm 2$MeV

The Λ(1405) case

THE "LINE-SHAPE" OF THE Λ(1405) DEPENDS ON THE OBSERVED CHANNEL !!

$$\frac{d\sigma(\Sigma^-\pi^+)}{dM} \propto \frac{1}{3}\left|T^0\right|^2 + \frac{1}{2}\left|T^1\right|^2 + \frac{2}{\sqrt{6}} Re(T^0 T^{1*})$$

$$\frac{d\sigma(\Sigma^+\pi^-)}{dM} \propto \frac{1}{3}\left|T^0\right|^2 + \frac{1}{2}\left|T^1\right|^2 - \frac{2}{\sqrt{6}} Re(T^0 T^{1*})$$

$$\frac{d\sigma(\Sigma^0\pi^0)}{dM} \propto \frac{1}{3}\left|T^0\right|^2$$

The Λ(1405) case

THE "LINE-SHAPE" OF THE Λ(1405) DEPENDS ON THE OBSERVED CHANNEL !!

$$\frac{d\sigma(\Sigma^-\pi^+)}{dM} \propto \frac{1}{3}\left|T^0\right|^2 + \frac{1}{2}\left|T^1\right|^2 + \frac{2}{\sqrt{6}} Re(T^0 T^{1*})$$

$$\frac{d\sigma(\Sigma^+\pi^-)}{dM} \propto \frac{1}{3}\left|T^0\right|^2 + \frac{1}{2}\left|T^1\right|^2 - \frac{2}{\sqrt{6}} Re(T^0 T^{1*})$$

$$\frac{d\sigma(\Sigma^0\pi^0)}{dM} \propto \frac{1}{3}\left|T^0\right|^2$$

IS DIFFERENT IN $\Sigma^+\pi^-$ VS $\Sigma^-\pi^+$

DUE TO ISOSPIN INTERFERENCE

The Λ(1405) case

THE "LINE-SHAPE" OF THE Λ(1405) DEPENDS ON THE OBSERVED CHANNEL !!

$$\frac{d\sigma(\Sigma^-\pi^+)}{dM} \propto \frac{1}{3}\left|T^0\right|^2 + \frac{1}{2}\left|T^1\right|^2 + \frac{2}{\sqrt{6}}Re(T^0 T^{1*})$$

$$\frac{d\sigma(\Sigma^+\pi^-)}{dM} \propto \frac{1}{3}\left|T^0\right|^2 + \frac{1}{2}\left|T^1\right|^2 - \frac{2}{\sqrt{6}}Re(T^0 T^{1*})$$

$$\frac{d\sigma(\Sigma^0\pi^0)}{dM} \propto \frac{1}{3}\left|T^0\right|^2$$

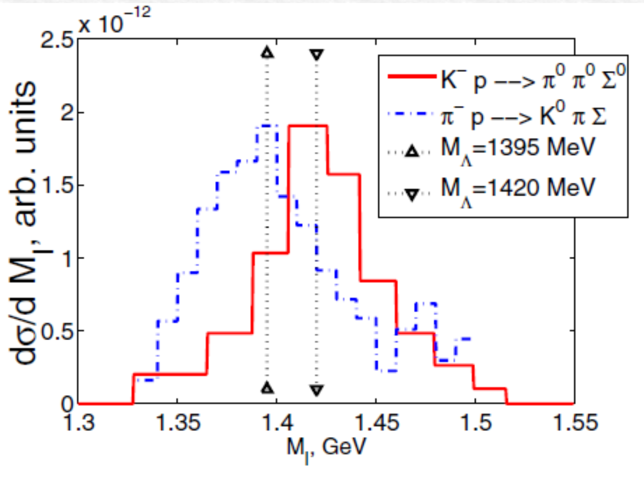
IS DIFFERENT IN $\Sigma^+\pi^-$ VS $\Sigma^-\pi^+$

DUE TO ISOSPIN INTERFERENCE

THE CLEANEST SIGNATURE OF THE Λ(1405) IS GIVEN BY THE NEUTRAL CHANNEL:

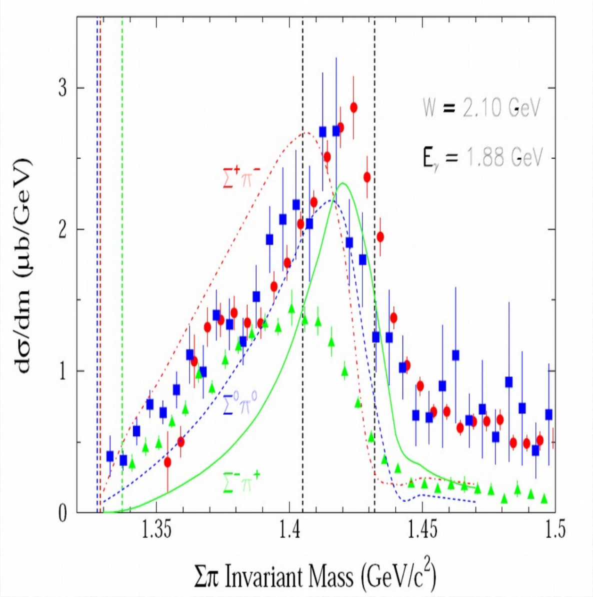
- is free from isospin interference
- is purely I = 0, no Σ(1385) contamination.

Λ(1405) .. the golden channel



Crystall Ball: $K^- p \rightarrow \Sigma^0\pi^0\pi^0$ for kaon momentum in the range (514-750 MeV/c). S. Prakhov et al. Phys Rev. C70 (2004) 03465

(**interpreted by Magas et al. PRL 95, 052301 (2005)**)



CLAS: $\gamma p \rightarrow K^+ \Sigma\pi$

AIP Conf.Proc. 1441 (2012) 296-298

COSY julich: $pp \rightarrow pK^+ \Sigma^0\pi^0$

(I. Zychor et al., Phys. Lett. B 660 (2008) 167)

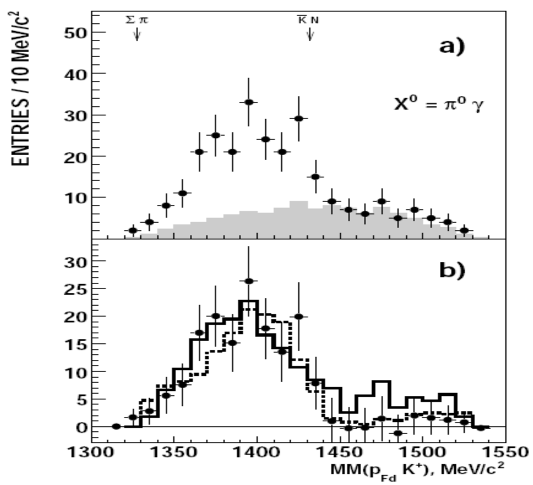
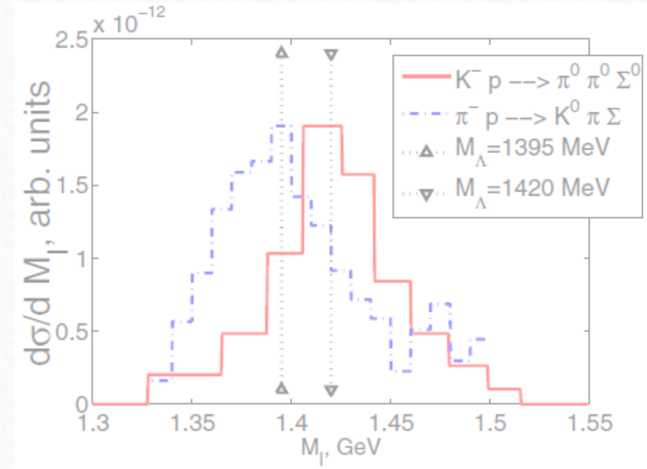


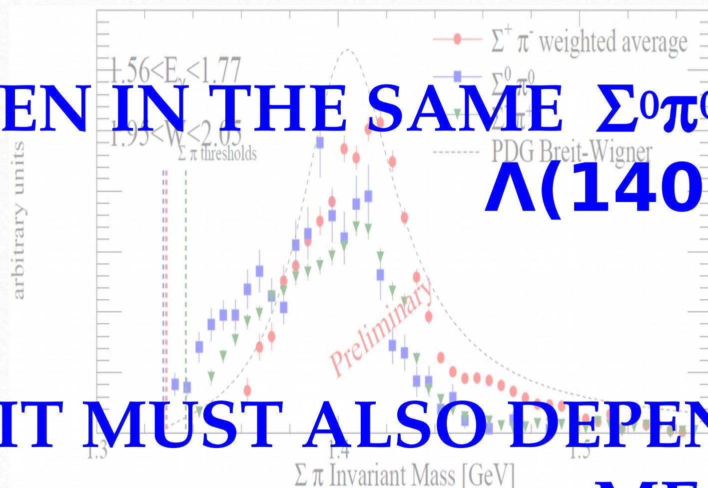
Fig. 4. a) Missing–mass $MM(p_{Fd}K^+)$ distribution for the $pp \rightarrow pK^+p\pi^-X^0$ reaction for events with $M(p_{Sd}\pi^-) \approx m(\Lambda)$ and $MM(pK^+p\pi^-) > 190\,\mathrm{MeV/c^2}$. Exper-

Λ(1405) .. the golden channel

Crystall Ball: $K^- p \to \Sigma^0\pi^0\pi^0$ for kaon momentum in the range (514-750 MeV/c). S. Prakhov et al. Phys Rev. C70 (2004) 03465

(Magas et al. PRL 95, 052301 (2005))





EVEN IN THE SAME $\Sigma^0\pi^0$ THE "LINE-SHAPE" OF THE Λ(1405) CHANGES

CLAS $\gamma p \to pK^+ \Sigma\pi$

AIP Conf.Proc. 1441 (2012) 296-298

IT MUST ALSO DEPEND ON THE PRODUCTION MECHANISM

COSY julich: $pp \to pK^+ \Sigma^0\pi^0$

(I. Zychor et al., Phys. Lett. B 660 (2008) 167)

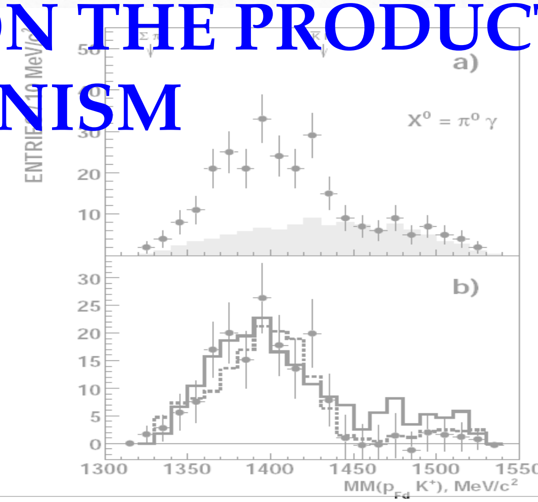


Fig. 4. a) Missing–mass $MM(p_{Fd}K^+)$ distribution for the $pp \to pK^+p\pi^-X^0$ reaction for events with $M(p_{Sd}\pi^-) \approx m(\Lambda)$ and $MM(pK^+p\pi^-) > 190\,\mathrm{MeV/c^2}$. Exper-

The Λ(1405) case

- Chiral unitary models: Λ(1405) is an I = 0 quasibound state emerging from the coupling between the $\bar{K}N$ and the Σπ channels. Two poles in the neighborhood of the Λ(1405):

two poles: about 1420 ; about = 1380 MeV

Phys. Lett. B 500 (2001), Phys. Rev. C 66 (2002), (Nucl. Phys. A 725(2003) 181) .. many others .. (Nucl. Phys. A881, 98 (2012)) .. others

mainly coupled to $\bar{K}N$ mainly coupled to Σπ → line-shape depends on production mechanism

- Akaishi-Esmaili-Yamazaki phenomenological potential

Phys. Lett. B 686 (2010) 23-28 Confirmation of single pole ansatz? ⟶

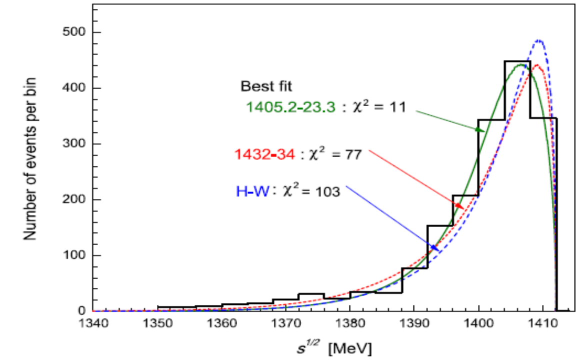
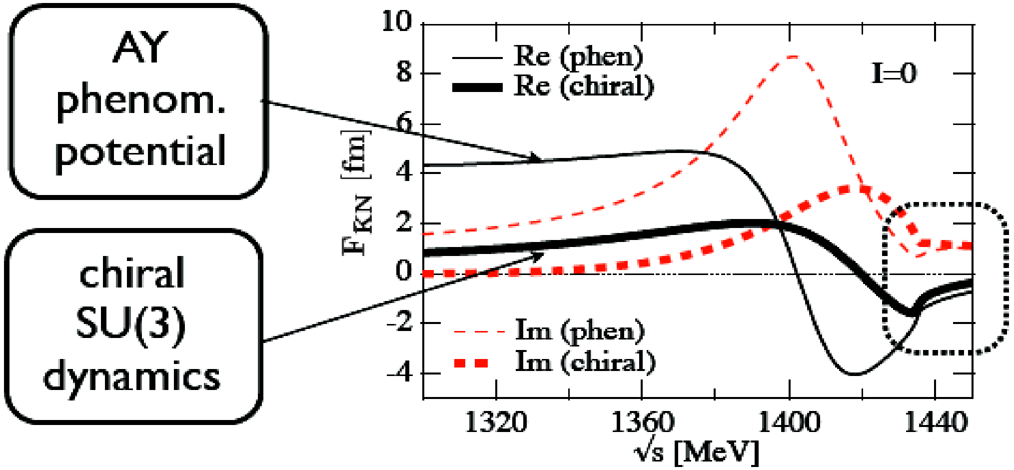
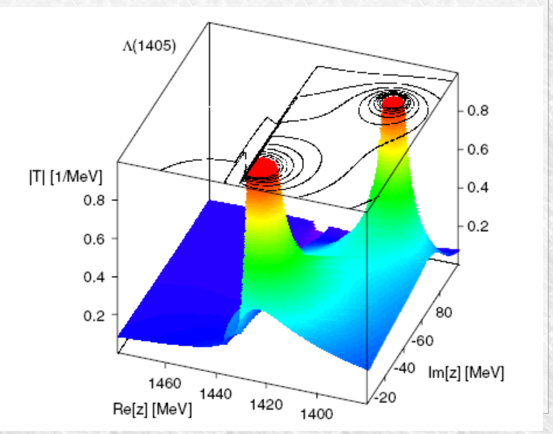


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.



large differences in **subthreshold** extrapolations



- **Chiral dynamics** predicts significantly **weaker attraction** than AY (local, energy independent) potential in **far-subthreshold** region

The Λ(1405) case

Two main biases:

- the kinematical energy threshold 1412 MeV

($M_K + M_p - |BE_p|$) the high pole energy region is closed,

- The shape and the amplitude of the NON-RESONANT

$\Sigma\pi$ production below KbarN threshold is unknown.

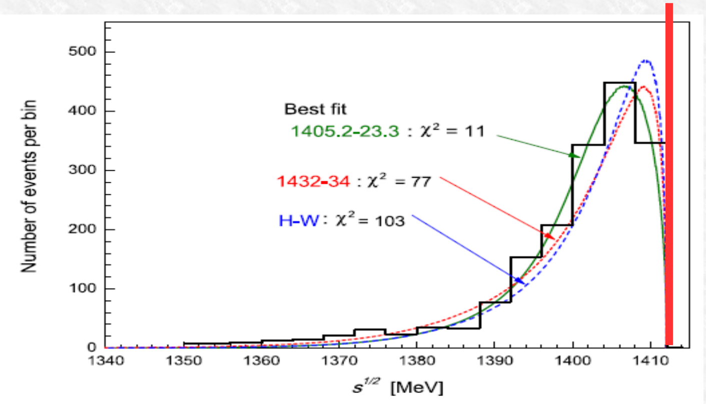


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

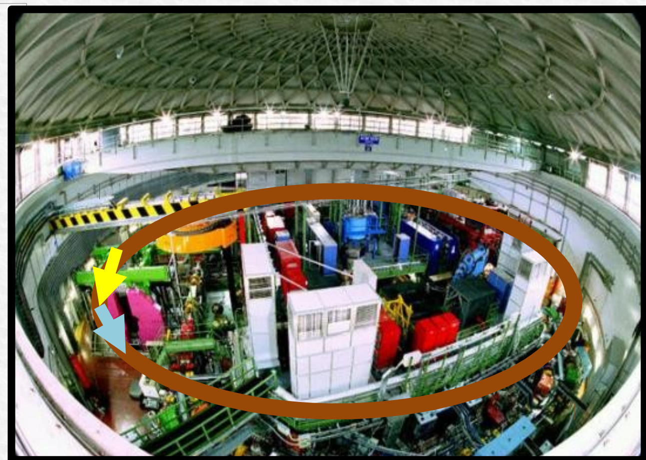
An ideal experiment:

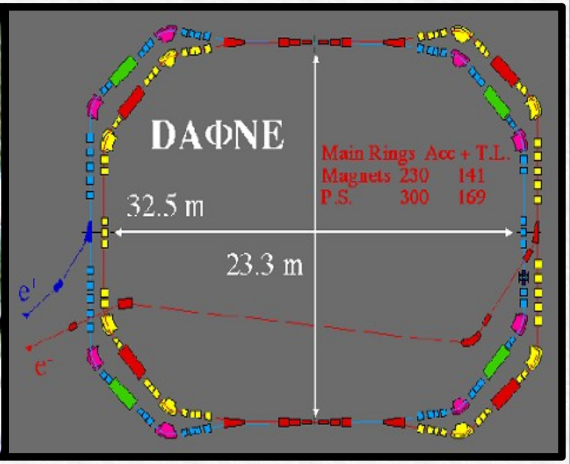
- Λ(1405) is produced in K- p absorption → mainly coupled to the high mass pole,
- Λ(1405) is observed in the $\Sigma^0\pi^0$ decay channel (pure isospin 0),
- K- is absorbed in-flight on a bound proton with p_K ~ 100 MeV, Σπ invariant mass gain of ~ 10 MeV to open an energy window to the high mass pole.
- Knowledge of the Σπ NON-RESONANT production amplitude.

AMADEUS & DAΦNE

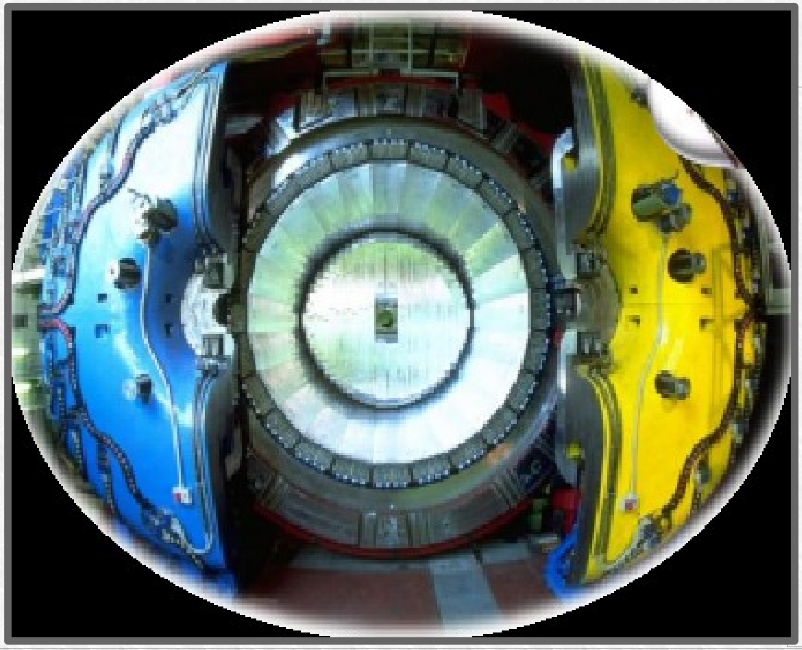
DAΦNE

- double ring $e^+ e^-$ collider working at C.M. energy of ϕ, producing **≈ 1000 ϕ /s**
$\phi \rightarrow K^+K^-$ (BR = (49.2 ± 0.6)%)
- **low momentum** Kaons ≈ 127 Mev/c
- **back to back** K^+K^- topology





AMADEUS step 0 → KLOE 2004-2005 dataset analysis ($\mathscr{L}$ = 1.74 pb^{-1})



KLOE

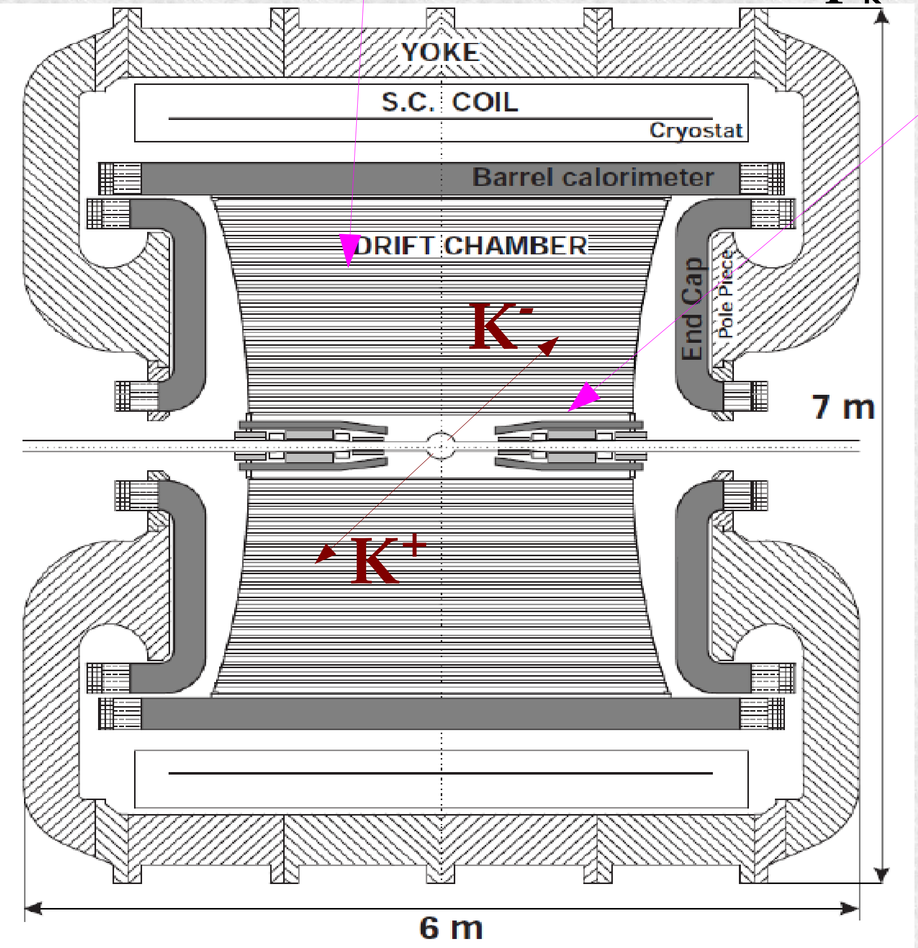
- Cilindrical drift chamber with a **4π geometry** and electromagnetic calorimeter
- **96% acceptance**
- optimized in the energy range of all **charged particles** involved
- **good performance** in detecting **photons and neutrons** checked by kloNe group [M. Anelli et al., Nucl Inst. Meth. A 581, 368 (2007)]

K^- absorption on light nuclei

from the materials of the KLOE detector

DC gas (90% He, 10% C_4H_{10}) & DC wall (C + H)

AT-REST (K^- absorbed from atomic orbit) or IN-FLIGHT (p_K~100MeV)



Advantage:

excellent resolution ..

$\sigma_{p\Lambda}$ = 0.49±0.01 MeV/c in DC gas

$\sigma_{m\gamma\gamma}$ = 18.3±0.6 MeV/c^2

Disadvantage:

Not dedicated target → different nuclei contamination → complex interpretation .. but → new features .. K^- in flight absorption.

The scientific goal of AMADEUS

Low energy QCD in strangeness sector is still waiting for experimental conclusive constrains on:

1) $\bar{K}$-N potential → how deep can an antikaon be bound in a nucleus?

- U_{KN} strongly affects the position of the $\Lambda(1405)$ state → we investigate it through $(\Sigma\text{-}\pi)^0$ decay --- Y π CORRELATION

- if U_{KN} is strongly attractive then K^- NN bound states should appear → we investigate through (Λ/Σ-N) decay --- Y N CORRELATION

2) Y-N potential → extremely poor experimental information from scattering data

- U_{YN} determines the strength of the final state YN (elastic & inelastic) scattering in nuclear environment → could be tested by Y N CORRELATION

The scientific goal of AMADEUS

Low energy QCD in strangeness sector is still waiting for experimental conclusive constrains on:

1) $\bar{K}$-N potential → how deep can an antikaon be bound in a nucleus?

- U_{KN} strongly affects the position of the $\Lambda(1405)$ state → we investigate it through $(\Sigma\text{-}\pi)^0$ decay --- Y π CORRELATION

- if U_{KN} is strongly attractive then K^- NN bound states should appear → we investigate through (Λ/Σ-N) decay --- Y N CORRELATION

2) Y-N potential → extremely poor experimental information from scattering data

- U_{YN} determines the strength of the final state YN (elastic & inelastic) scattering in nuclear environment → could be tested by Y N CORRELATION

K^- - N single nucleon absorption the case of the $\Lambda(1405)$

$\Lambda(1405)$ case

Phys.Rev.Lett.95:052301,2005

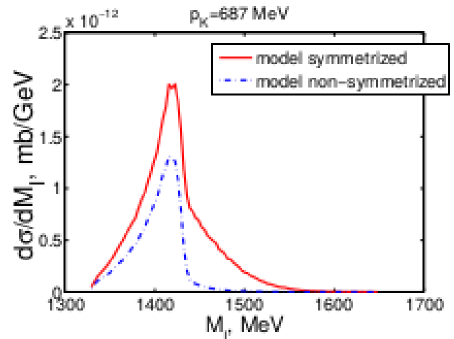


FIG. 4: Theoretical ($\pi^0\Sigma^0$) invariant mass distribution for an initial kaon lab momenta of 687 MeV. The non-symmetrized distribution also contains the factor 1/2 in the cross section.

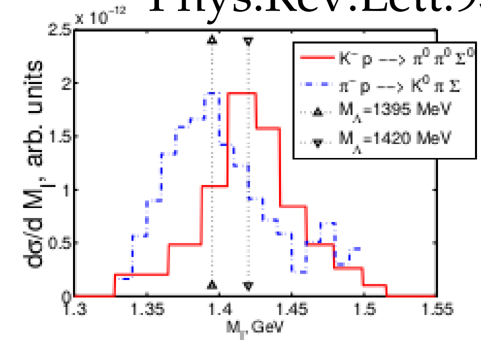
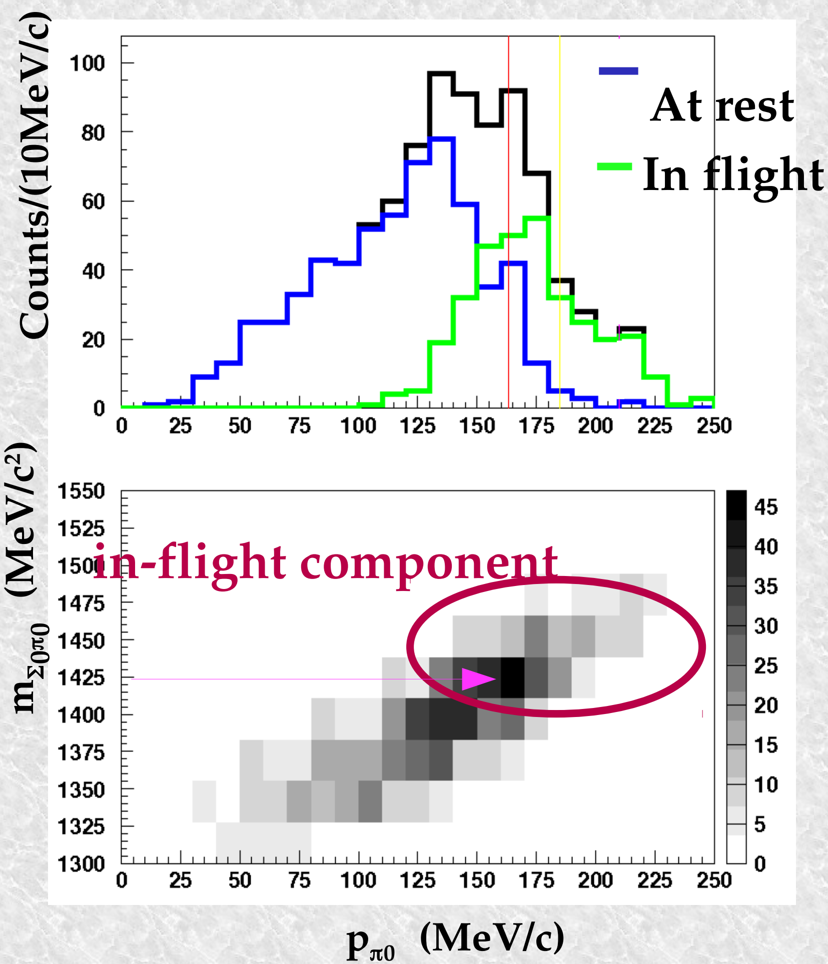
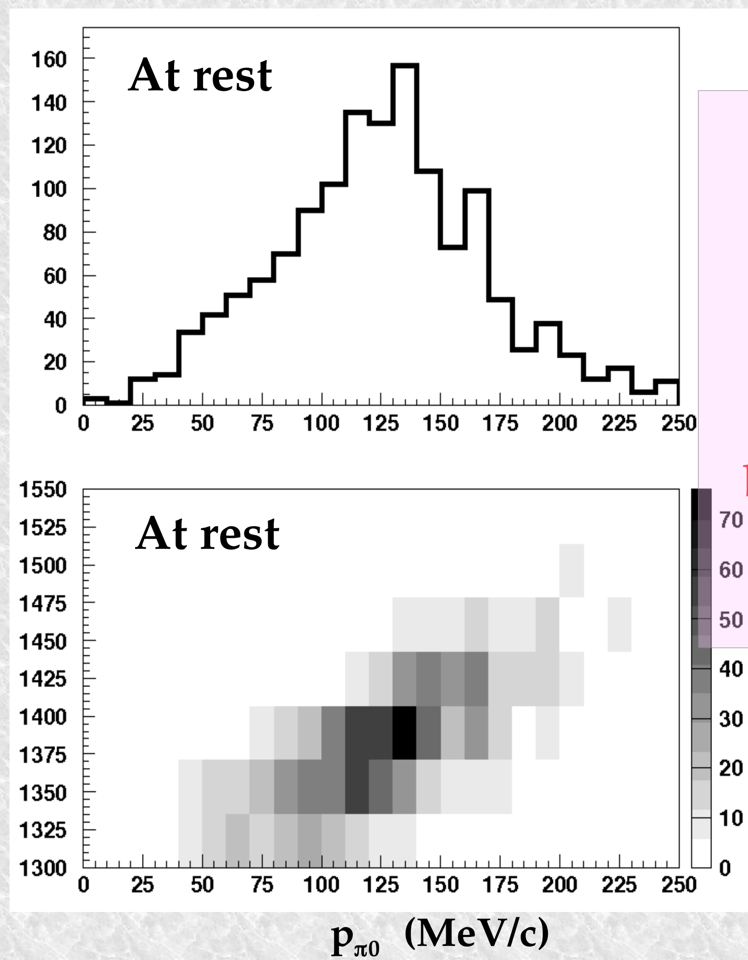


FIG. 5: Two experimental shapes of $\Lambda(1405)$ resonance. See text for more details.

$p_{\pi 0}$ resolution: $\sigma_p \approx 12$ MeV/c





IN-FLIGHT

K- 12C

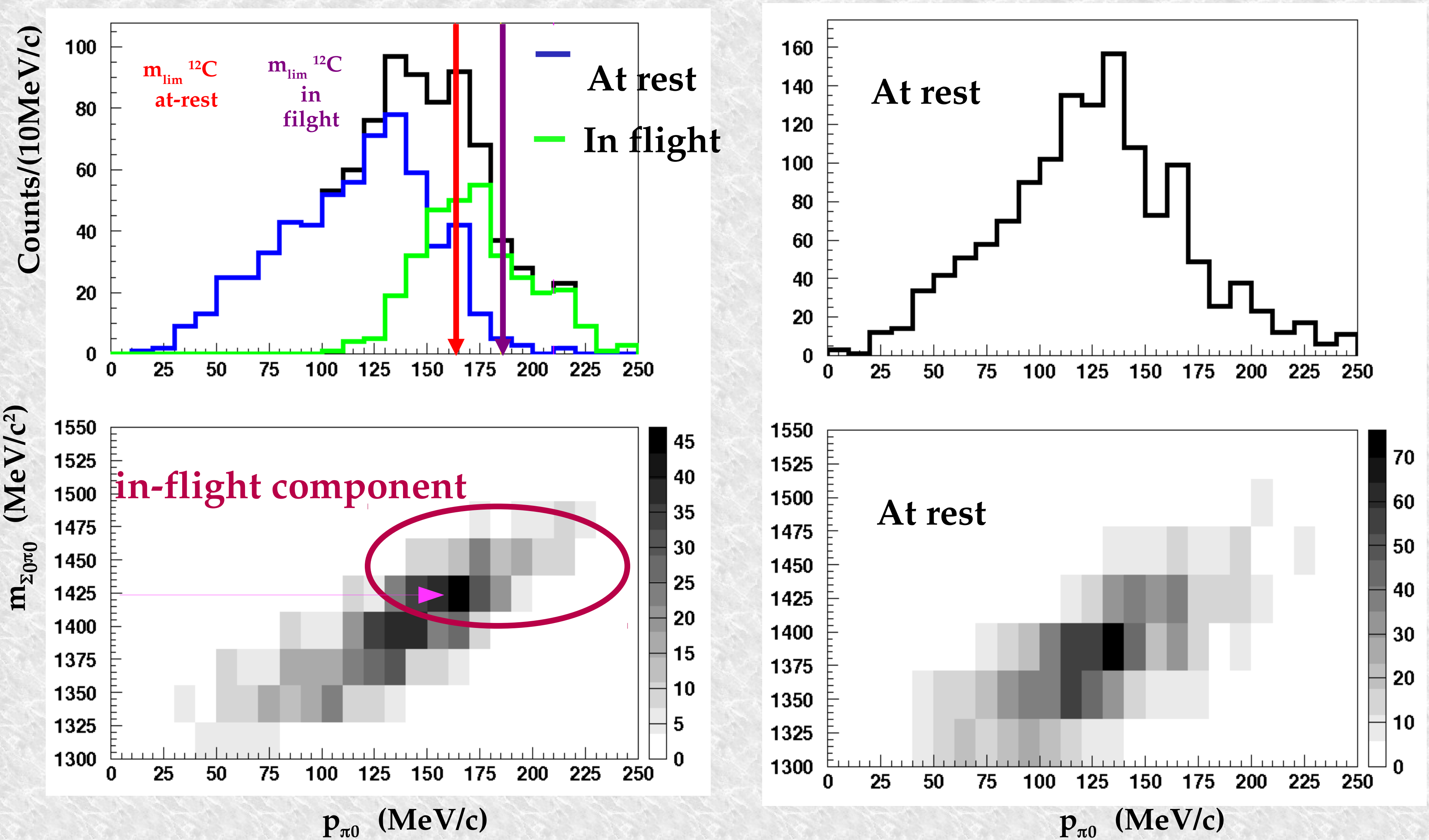
opens a window

between 1416 MeV

and K-Nth

Complex interpretation due to K- H absorptions ongoing

$p_{\pi 0}$ **resolution**: $\sigma_p \approx 12$ MeV/c



$\Sigma^+\pi^-$ correlation

$K^- p \rightarrow \Sigma^+ \pi^-$ detected via: $(p\pi^0)\ \pi^-$

Possibility to disentangle: Hydrogen, in-flight, at-rest, K^- capture

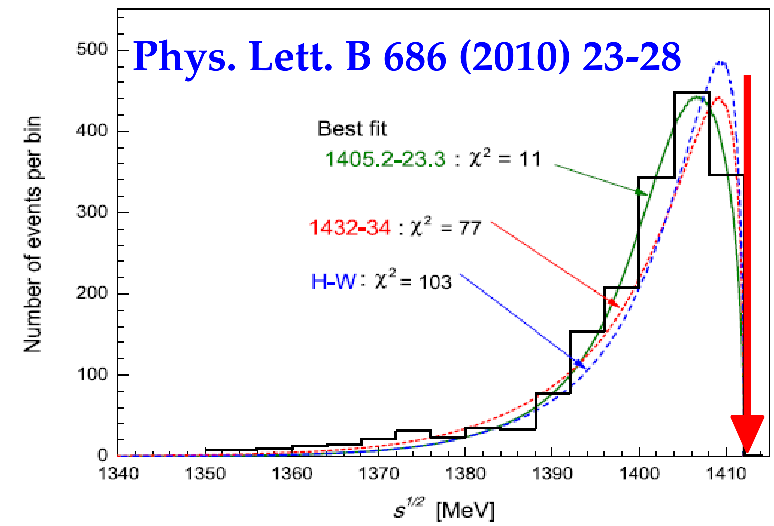
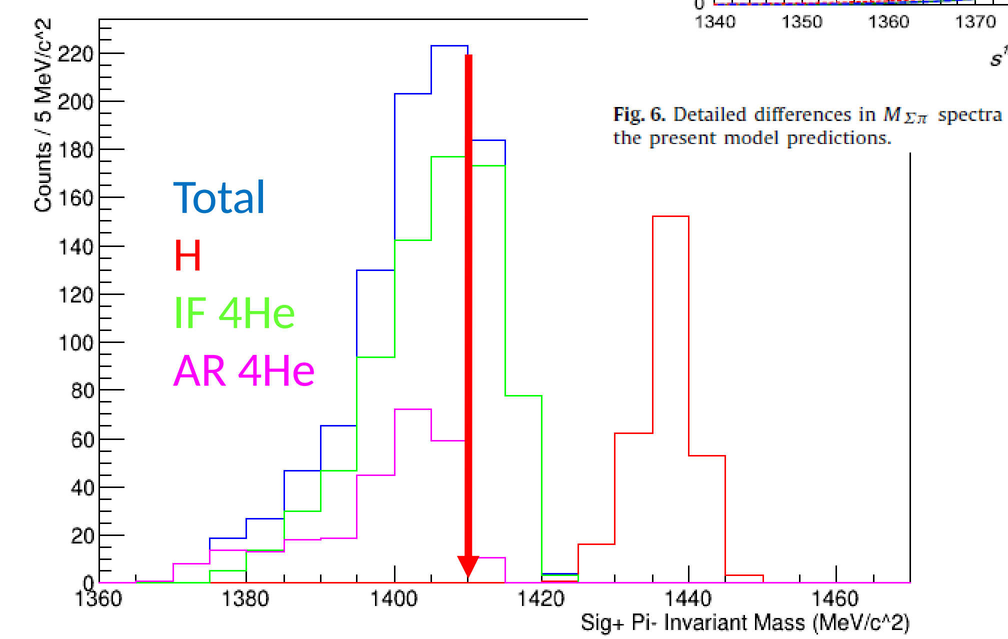
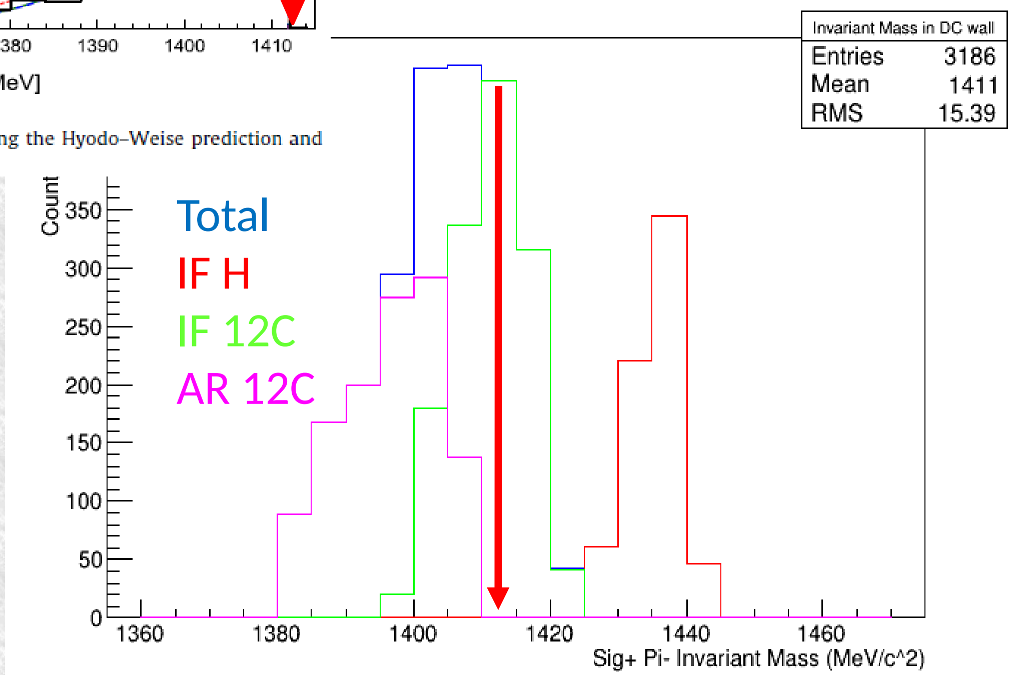


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

$p_{\pi-}$ resolution: $\sigma_p \approx 1$ MeV/c



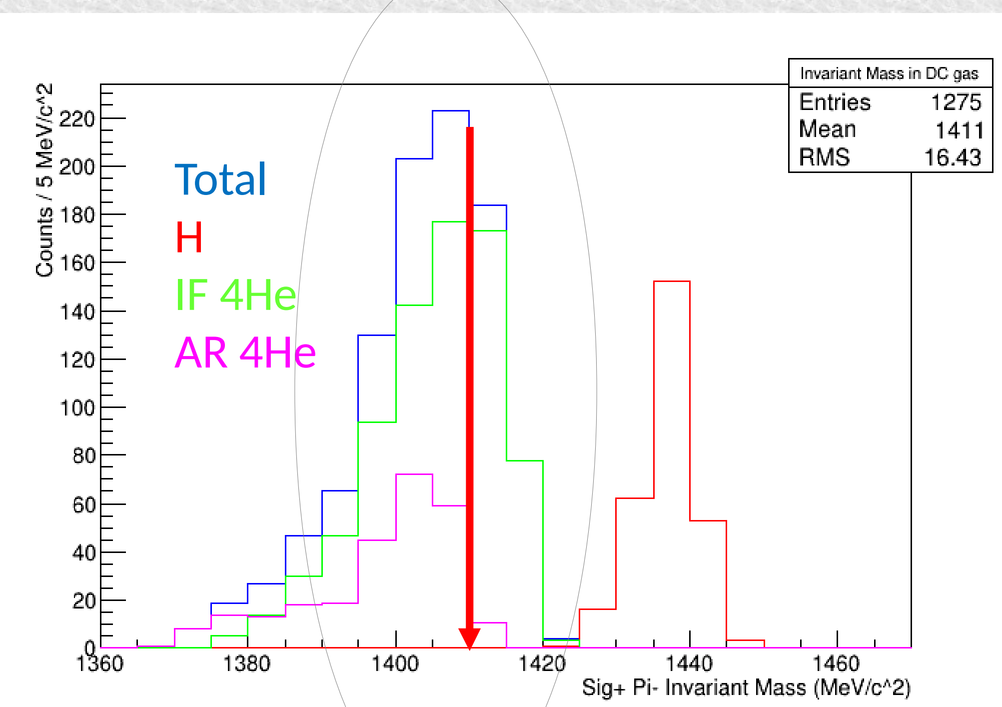


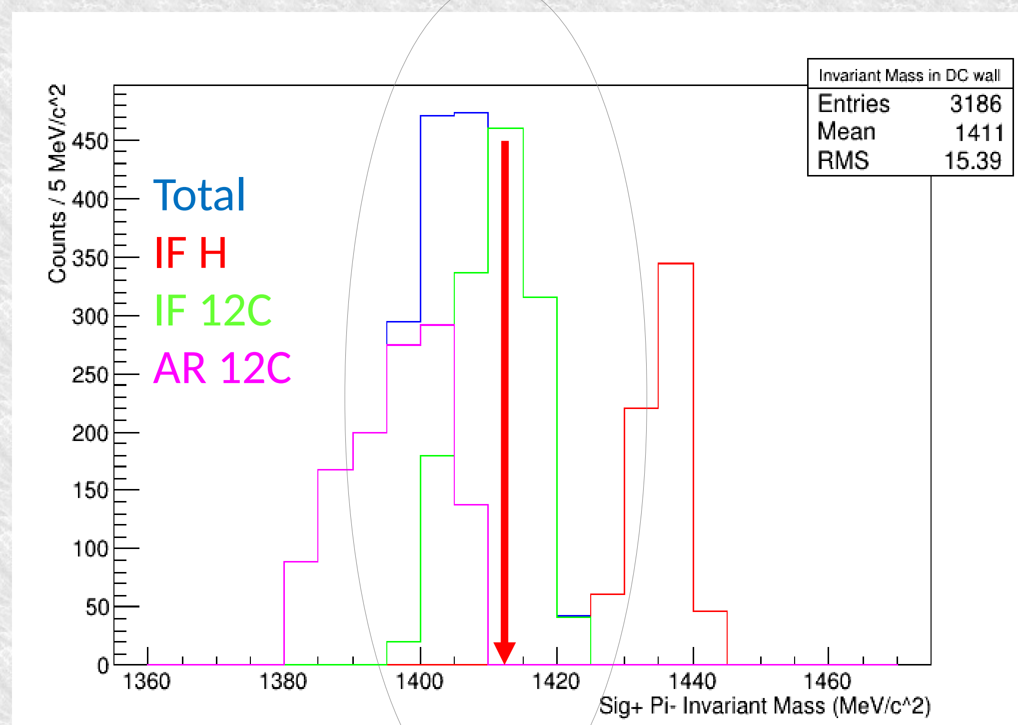
$\Sigma^+\pi^-$ correlation

$K^- p \rightarrow \Sigma^+ \pi^-$ detected via: $(p\pi^0)\ \pi^-$

Possibility to disentangle: Hydrogen, in-flight, at-rest, K^- capture

if resonant production contribution is important a high mass component appears!





Resonant VS non-resonant

$K^- N \rightarrow (Y^* ?) \rightarrow Y \pi$

in medium, how much comes from resonance ?

Non resonant transition amplitude:

- Never measured before below threshold

(33 MeV below threshold):

$$E_{Kn} = -|B_n| - \frac{p_3^2}{2\mu_{\pi,\Lambda,3He}},$$

- few, old theoretical calculations

(Nucl. Phys. B179 (1981) 33-48)

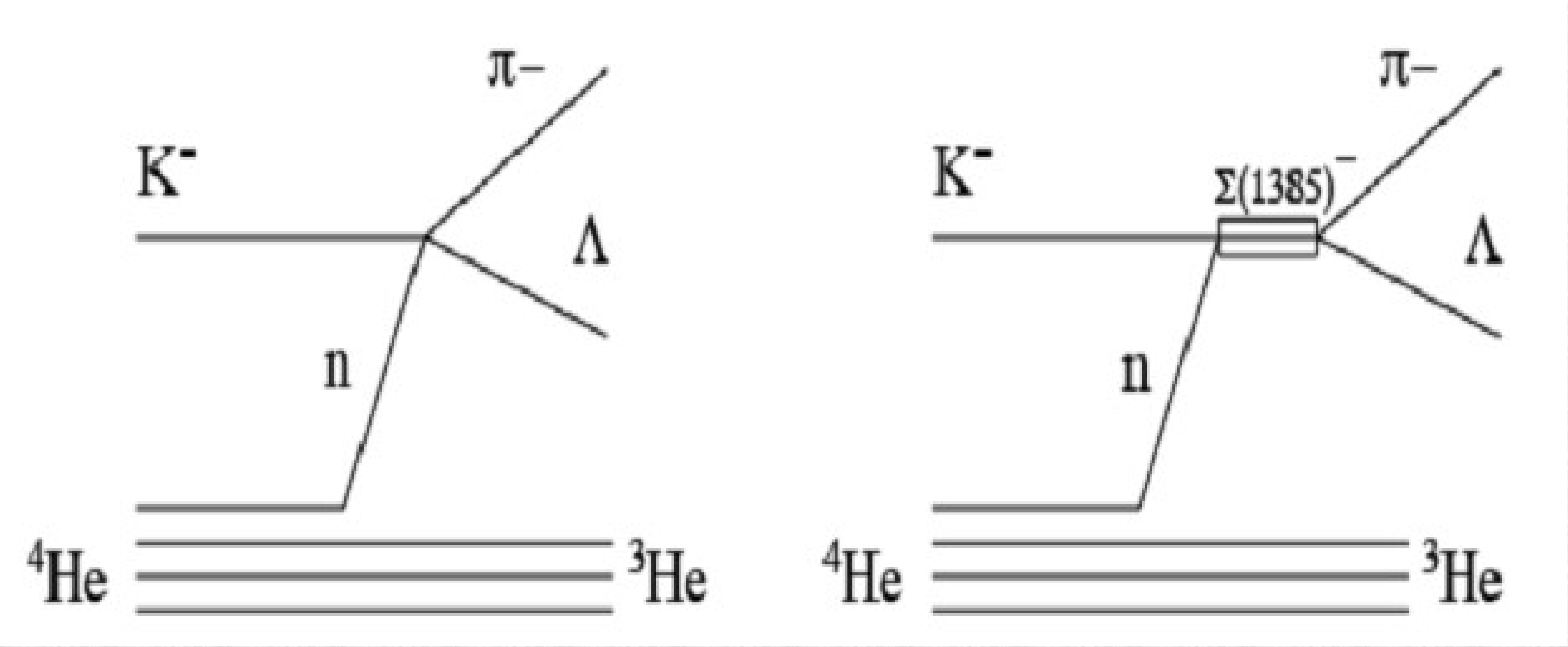
Resonant VS non-resonant

Investigated using:

K^{-}"n" $\rightarrow$ $\Lambda\pi^{-}$ direct formation in ^{4}He

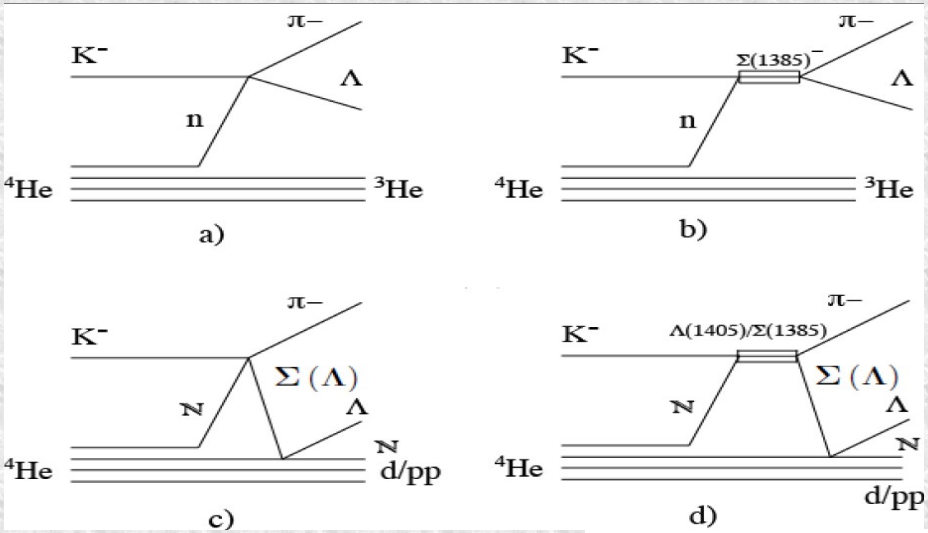
the goal is to measure $|f^{N\text{-}R}_{\Lambda\pi}(I=1)|$

to get information on $|f^{N\text{-}R}_{\Sigma\pi}(I=0)|$



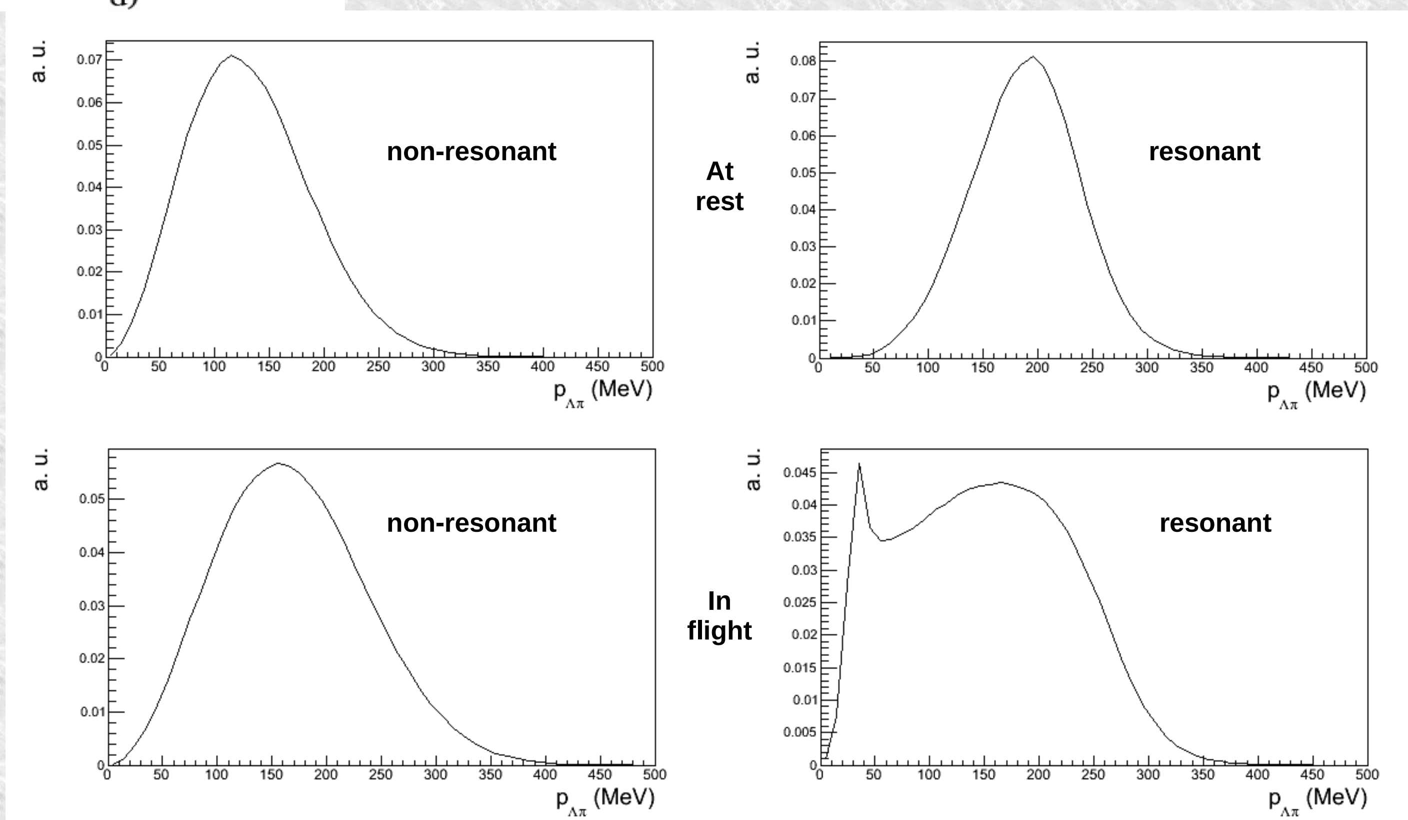
$K^{-}\,{}^{4}He \rightarrow \Lambda p^{-}\,{}^{3}He$ resonant and non-resonant processes

Nucl. Phys. A954 (2016) 75-93



Theoretical shapes for :

total $\Lambda\pi^-$ momentum spectra for the resonant (Σ^{*-}) and non-resonant (I = 1) processes were calculated, for both S-state and P-state K^- capture at-rest and in-flight. Corrections to the amplitudes due to Λ/π final state interactions were estimated.



Collaboration with S. Wycech

How to extract the $K^- n \to \Lambda\pi^-$ non resonant transition amplitude

simultaneous fit ($p_{\Lambda\pi^-}$ - $m_{\Lambda\pi^-}$ - $\cos(\theta_{\Lambda\pi^-})$) with signal and background processes :

- non resonant K^- capture at-rest from S states in ^{4}He
- resonant K^- capture at-rest from S states in ^{4}He
- non resonant K^- capture in-flight in ^{4}He
- resonant K^- capture in-flight in ^{4}He

- primary $\Sigma\pi^-$ production followed by the $\Sigma N \to \Lambda N'$ conversion process
- K^- capture processes in ^{12}C giving rise to $\Lambda\pi^-$ in the final state

In order to extract:

NR-ar/RES-ar & NR-if/RES-if

Results for the $K^- n \rightarrow \Lambda\pi^-$ non resonant transition amplitude

Channels	Ratio/Amplitude	σ_{stat}	σ_{syst}
RES-ar/NR-ar	0.39	$\pm$ 0.04	$^{+0.18}_{-0.07}$
RES-if/NR-if	0.23	$\pm$ 0.03	$^{+0.23}_{-0.22}$
NR-ar	12.00 %	$\pm$ 1.66 %	$^{+1.96}_{-2.77}$ %
NR-if	19.24 %	$\pm$ 4,38 %	$^{+5.90}_{-3.33}$ %
$\Sigma \rightarrow \Lambda$ conv.	2.16 %	$\pm$ 0.30 %	$^{+1.62}_{-0.83}$ %
K^{-12}C capture	57.00 %	$\pm$ 1.23 %	$^{+2.21}_{-3.19}$ %

TABLE I. Resonant to non-resonant ratios and amplitude of the different channels extracted from the fit of the $\Lambda\pi^-$ sample. The statistical and systematic errors are also shown. See text for details.

Preliminary

extracted:

NR-ar/RES-ar & NR-if/RES-if

Simultaneous momentum – angle – mass fit

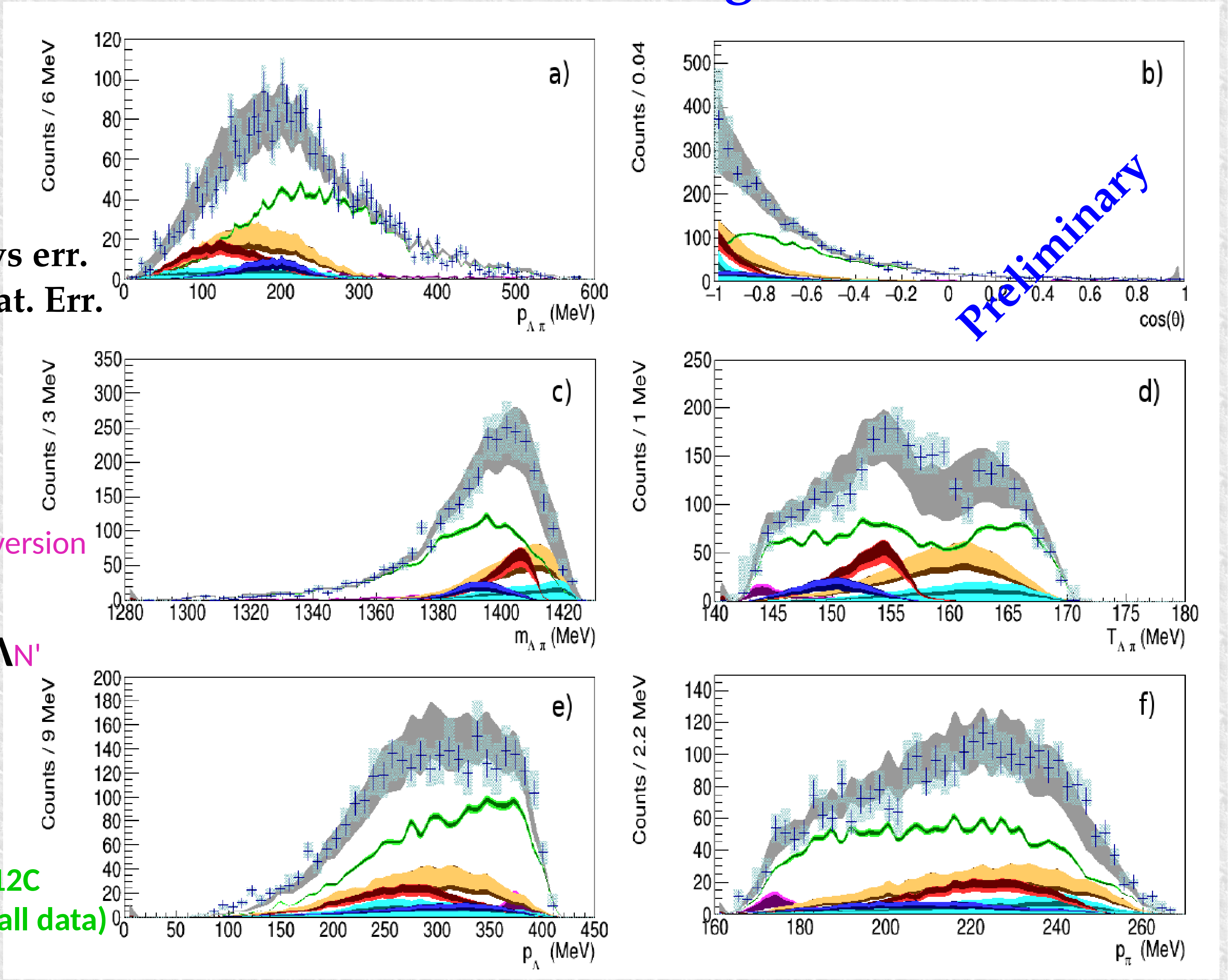
Light band sys err.
Dark band stat. Err.

Σ/Λ nuclear conversion

K-N→Σ **π**

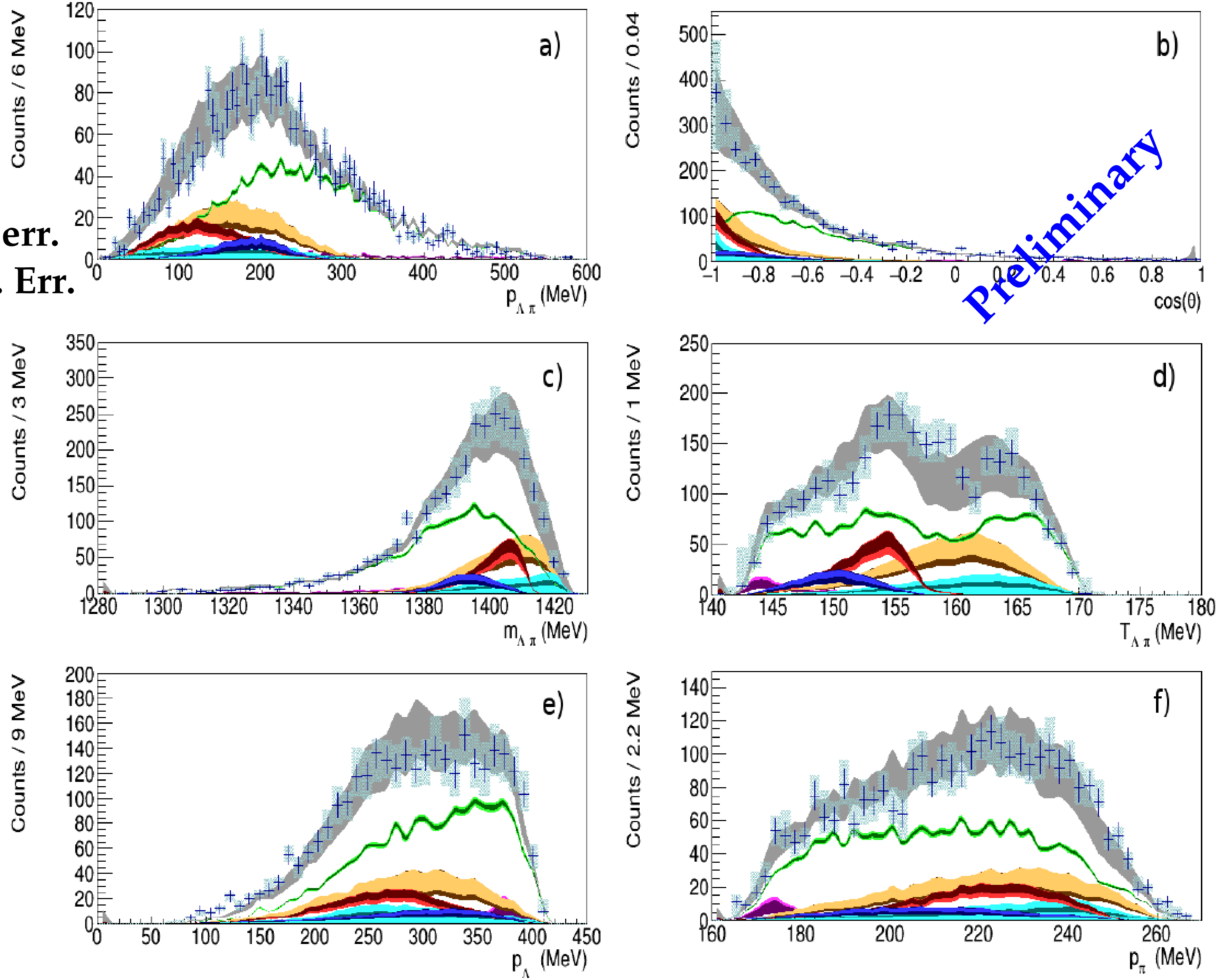
└→ ΣN→**Λ**N'

Absorptions in 12C
(from Carbon wall data)



Simultaneous momentum – angle – mass fit

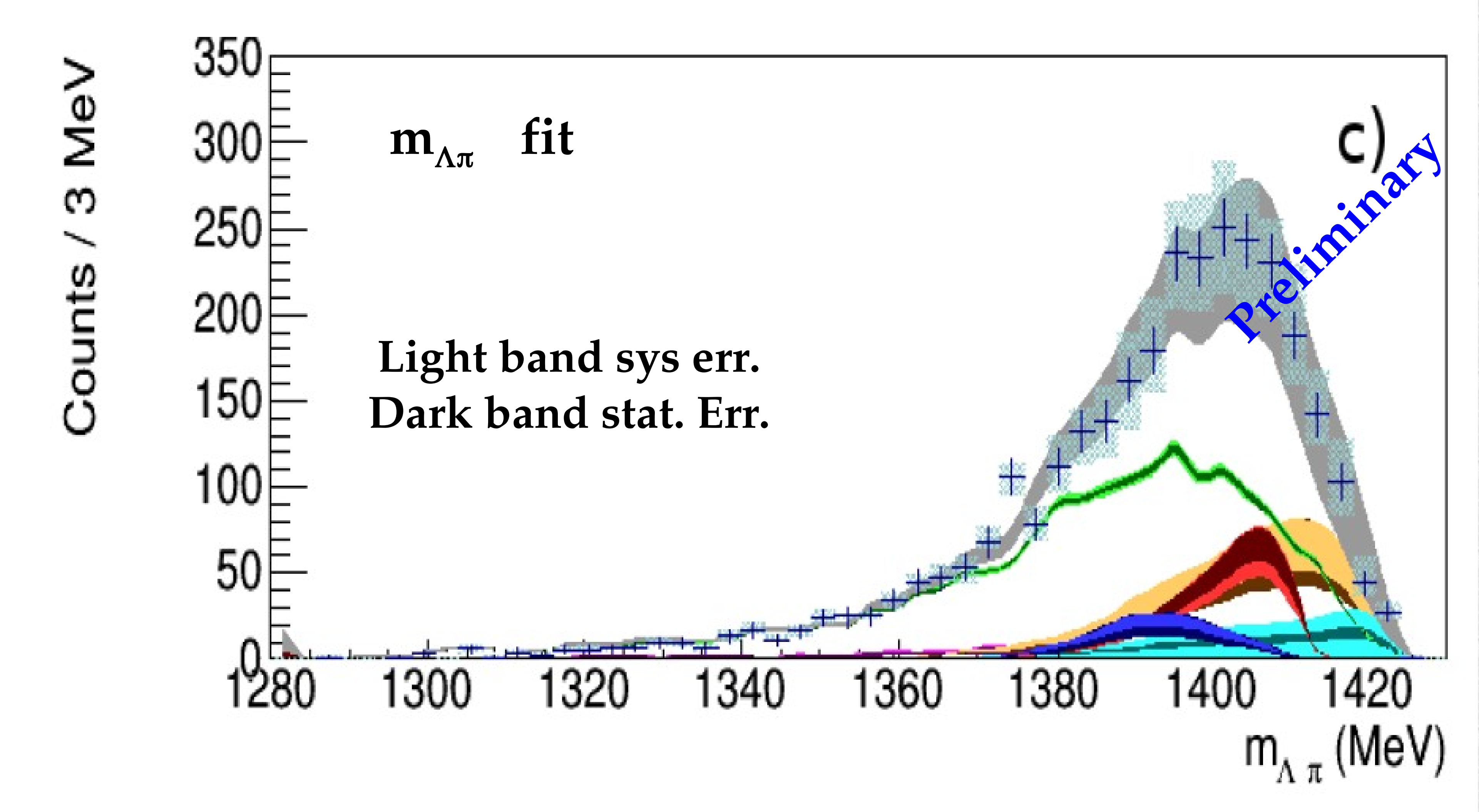
Light band sys err.
Dark band stat. Err.



Non-Resonant
(at-rest)
(in-flight)

Resonant Σ∗
(at-rest)
(in-flight)

Comparison



Non-Resonant
(at-rest)
(in-flight)

Resonant $\Sigma*$
(at-rest)
(in-flight)

Outcome of the measurement

From the well known Σ* transition probability:

Preliminary

$$\frac{\mathrm{NR-ar}}{\mathrm{RES-ar}} = \frac{\int_0^{pmax} P_{ar}^{nr}(p_{\Lambda\pi})\,dp_{\Lambda\pi}}{\int_0^{pmax} P_{ar}^{res}(p_{\Lambda\pi})\,dp_{\Lambda\pi}} =$$

$$= |f_{ar}^s|^2 \cdot 8,94 \cdot 10^5 \mathrm{MeV}^2 \,.$$

$$\rightarrow |f_{ar}^s| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst})\ \mathrm{fm}\,.$$

The sub-threshold result is compatible with corresponding values extracted from $K^- p \rightarrow \Lambda \pi^0$ cross sections above threshold

J. K. Kim, Columbia University Report, Nevis 149 (1966)

J. K. Kim, Phys Rev Lett, 19 (1977) 1074:

$E = -33$ MeV	$p_{lab} = 120$ MeV	160 MeV	200 MeV	245 MeV
$0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst}$	0.33(11)	0.29(10)	0.24 (6)	0.28(2)

Outcome of the measurement

$$|f^s_{ar}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst})\,\mathrm{fm}\,.$$

Preliminary

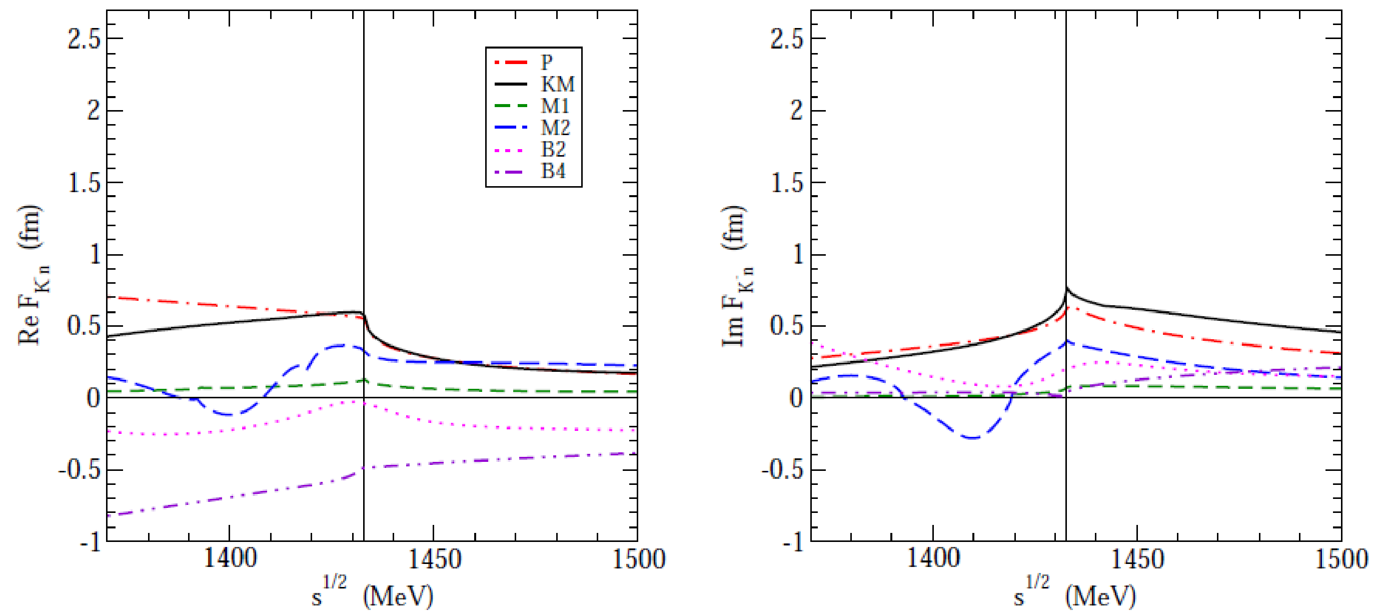
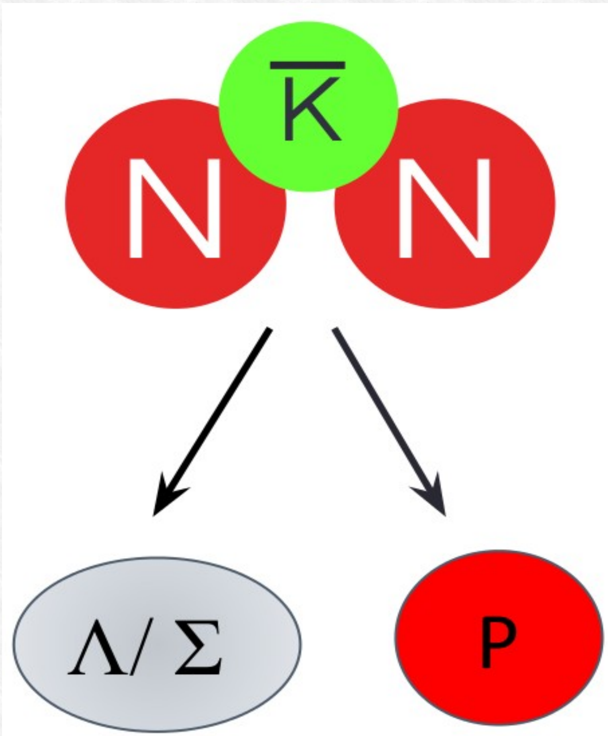


FIG. 1: Energy dependence of real (left) and imaginary (right) parts of free-space K^-p (top) and K^-n (bottom) amplitudes in considered chiral models (see text for details). Thin vertical lines mark threshold energies.

ArXiv:1704.07205v1 [nucl-th], accepted in Phys. Rev C
Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A 881 (2012) 98.

K^- - multiN absorption and search for bound states

How deep can an antikaon be bound in a nucleus?



Possible Bound States:

$$(K^- pp) \to \Lambda\, p \qquad (K^- ppn) \to \Lambda\, d$$
$$\to \Sigma^0 p \qquad\qquad \to \Sigma^0 d$$

predicted due to the strong $\overline{K}$N interaction in the I=0 channel.

[Wycech (1986) - Akaishi & Yamazaki (2002)]

K^-pp bound state

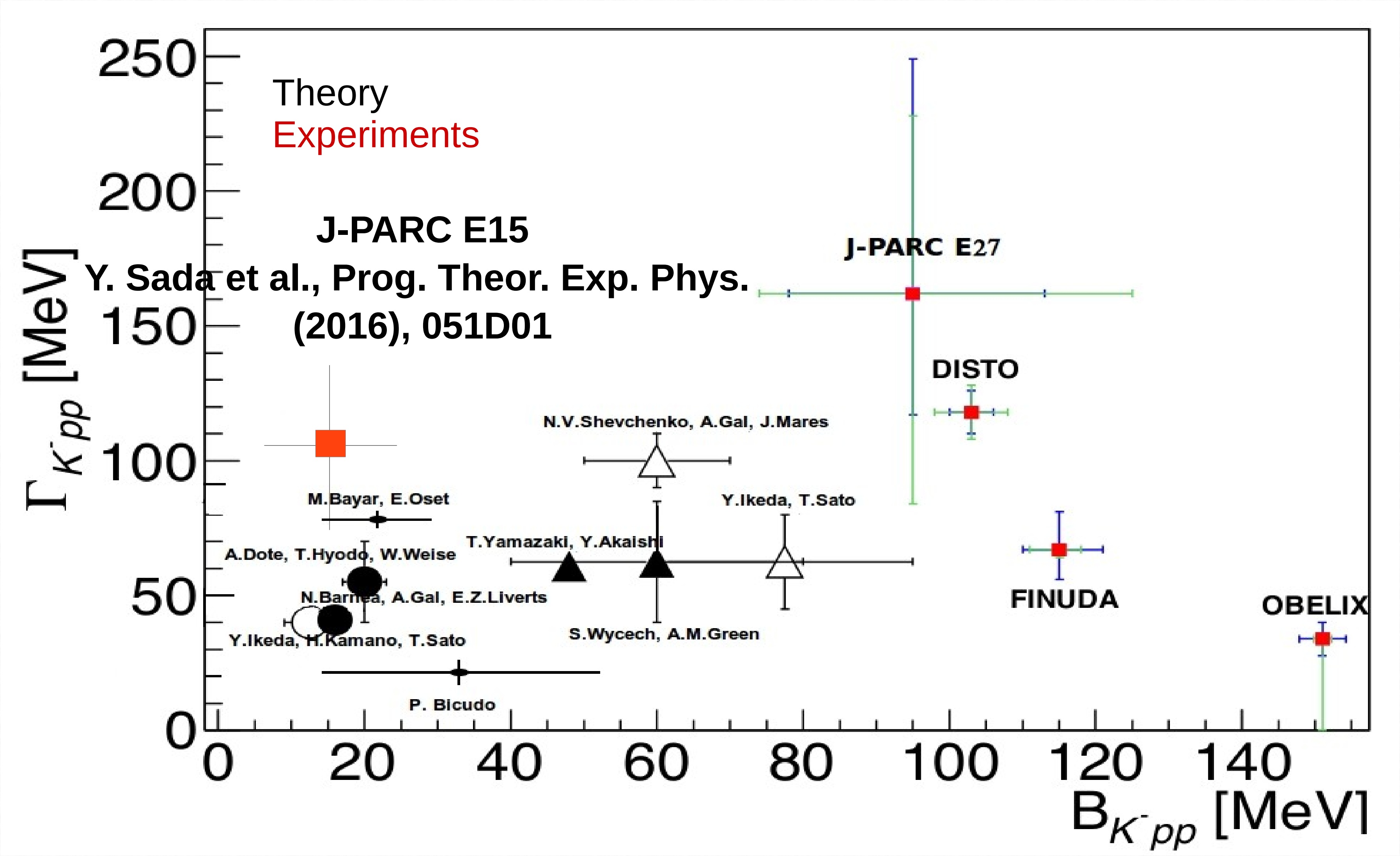
....at the end of 2015

	BE (MeV)	Γ (MeV)	Reference
Dote, Hyodo, Weise	17-23	40-70	Phys.Rev.C79 (2009) 014003
Akaishi, Yamazaki	48	61	Phys.Rev.C65 (2002) 044005
Barnea, Gal, Liverts	16	41	Phys.Lett.B712 (2012) 132-137
Ikeda, Sato	60-95	45-80	Phys.Rev.C76 (2007) 035203
Ikeda, Kamano, Sato	9-16	34-46	Prog.Theor.Phys. (2010) 124(3): 533
Shevchenko, Gal, Mares	55-70	90-110	Phys.Rev.Lett.98 (2007) 082301
Revai, Shevchenko	32	49	Phys.Rev.C90 (2014) no.3, 034004
Maeda, Akaishi, Yamazaki	51.5	61	Proc.Jpn.Acad.B 89, (2013) 418
Bicudo	14.2-53	13.8-28.3	Phys.Rev.D76 (2007) 031502
Bayar, Oset	15-30	75-80	Nucl.Phys.A914 (2013) 349
Wycech, Green	40-80	40-85	Phys.Rev.C79 (2009) 014001

Experiments reporting DBKNS		
KEK-PS E549	T. Suzuki at al. MPLA23, 2520-2523 (2008)	
FINUDA	M. Agnello et al. PRL94, 212303 (2005)	Extraction of a **signal**
DISTO	T. Yamazaki et al. PRL104 (2010)	Extraction of a **signal**
OBELIX	G. Bendiscioli et al. NPA789, 222 (2007)	Extraction of a **signal**
HADES	G. Agakishiev et al. PLB742, 242-248 (2015)	**Upper limit**
LEPS/SPring-8	A.O. Tokiyasu et al. PLB728, 616-621 (2014)	**Upper limit**
J-PARC E15	T. Hashimoto et al. PTEP, 061D01 (2015)	**Upper limit**
J-PARC E27	Y. Ichikawa et al. PTEP, 021D01 (2015)	Extraction of a **signal**

How deep can an antikaon be bound in a nucleus?

interpreted in
T. Sekihara, E. Oset, A. Ramos, Prog. Theor. Exp. Phys (2016) (12): 123D03

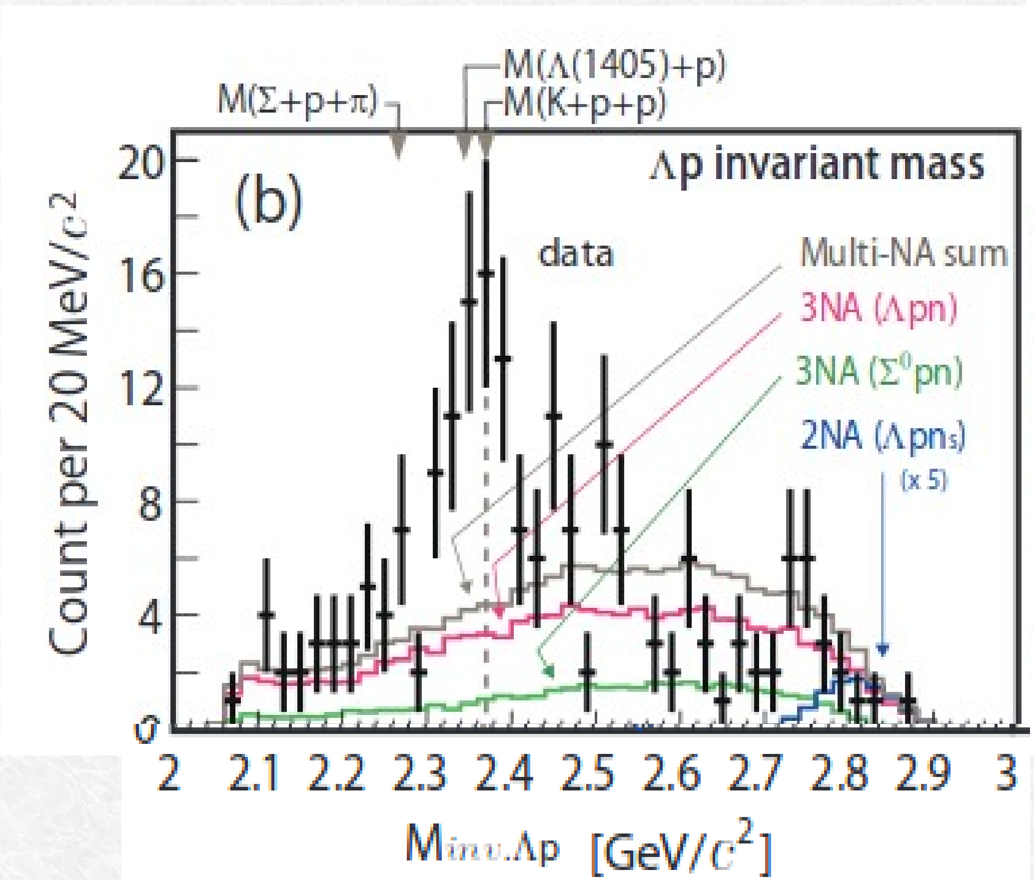


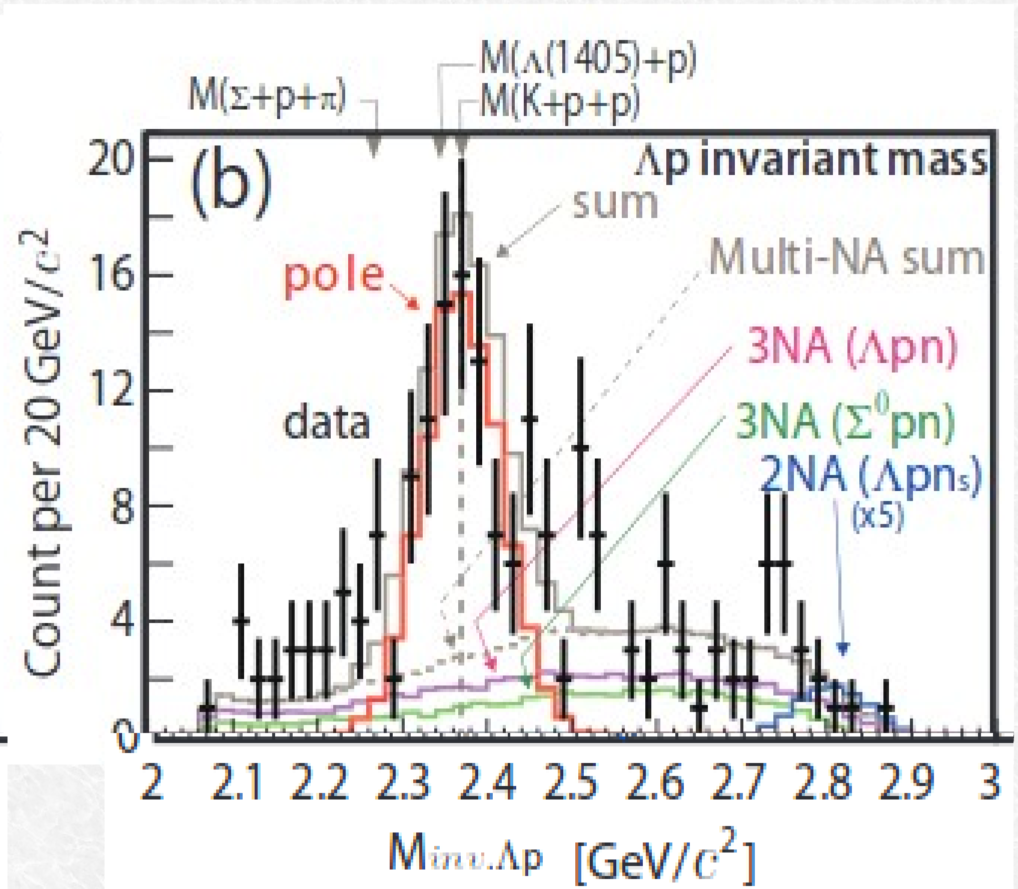
[from the talk of T. Nagae at HYP2015, Sep. 10, 2015]

J-PARC E15

$K^- + {}^3He \rightarrow \Lambda + p + n$

Invariant mass spectroscopy





[J-PARC E15 Collaboration: arXiv:1601.06876 [nucl-ex]]

M = 2355 +6 −8 (stat.) ± 12 (syst.) MeV/c2
Γ = 110 +19 −17 (stat.) ± 27 (syst.) MeV/c2

BE = 15 MeV

$K^{-}\ {}^{4}He \rightarrow \Lambda t$

4NA cross section and yield

Λt available data

Available data:

- in Helium :

- bubble chamber experiment
[M.Roosen, J.H. Wickens, Il Nuovo Cimento 66, (1981), 101]
K^- stopped in liquid helium, Λ dn/t search. 3 events compatible with the Λt kinematics were found

$$\mathbf{BR}(K^{-\,4}He \rightarrow \Lambda t) = \mathbf{(3 \pm 2) \times 10^{-4} / K_{stop}}$$ global, no 4NA

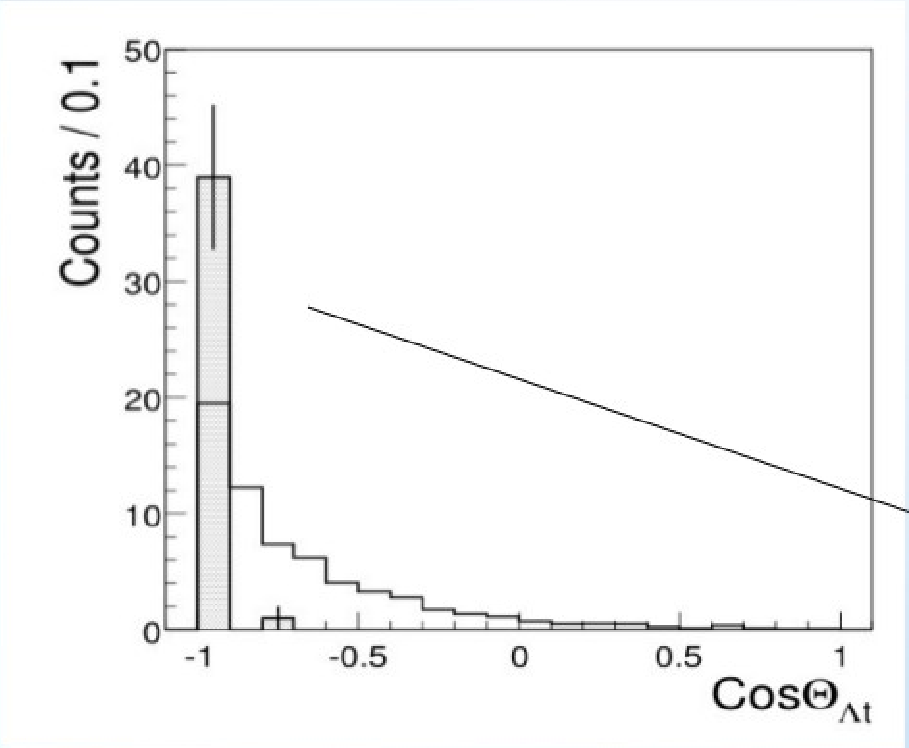
- Solid targets

- FINUDA [Phys.Lett. B669 (2008) 229]
(40 events in different solid targets)

Λt available data

FINUDA presented [Phys.Lett.B (2008) 229]:

- a study of Λ vs t momentum correlation and an opening angle distribution
- **40 events** collected and added together coming from different targets ($^{6,7}Li$, ^{9}Be)



Filled histogram= data

Open histogram = Phase space simulation

K- A → Λ t A'

Unclear back to back topology

Λt emission yield → $10^{-3} - 10^{-4} / K^-_{stop}$

global, no 4NA

Experimental data only back-to-back

Λt correlation studies in ^{4}He from the DC gas : contributing processes

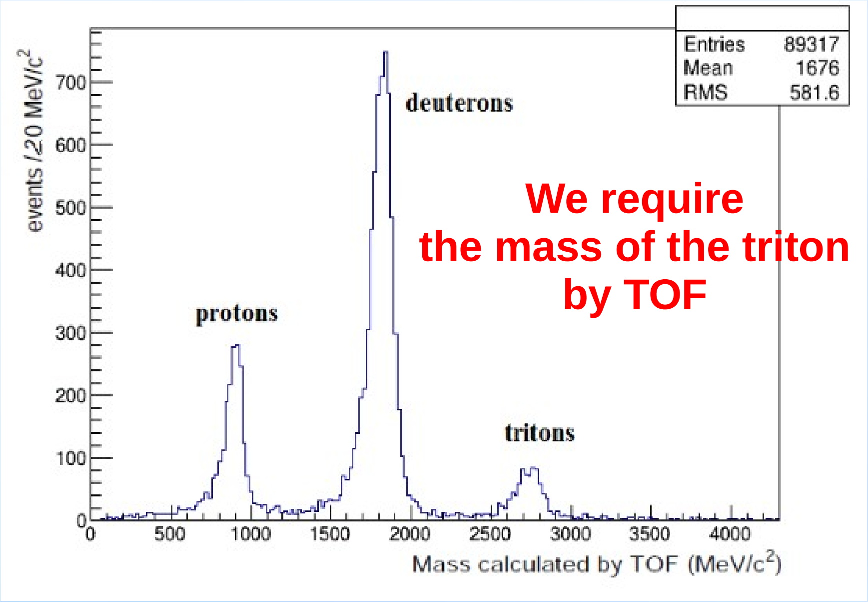
single nucleon absorption (1NA)

$$K^- \, {}^4He \rightarrow \Lambda \, \pi^0 \, t_{res}$$

$$K^- \, {}^4He \rightarrow \Sigma^0 \pi^0 \, t_{res} \quad , \quad \Sigma^0 \rightarrow \Lambda\gamma$$

conversion on triton:

$$K^- \, {}^4He \rightarrow \Sigma^0 \pi^0 \, t \quad , \quad \Sigma^0 t \, / \, \Lambda t$$



Tritons are spectators, too low momentum: p_t ~ Fermi momentum

<u>lower then the calorimeter threshold</u> (p_t ~ 500 MeV/c)

<u>checked by MC simulations</u>

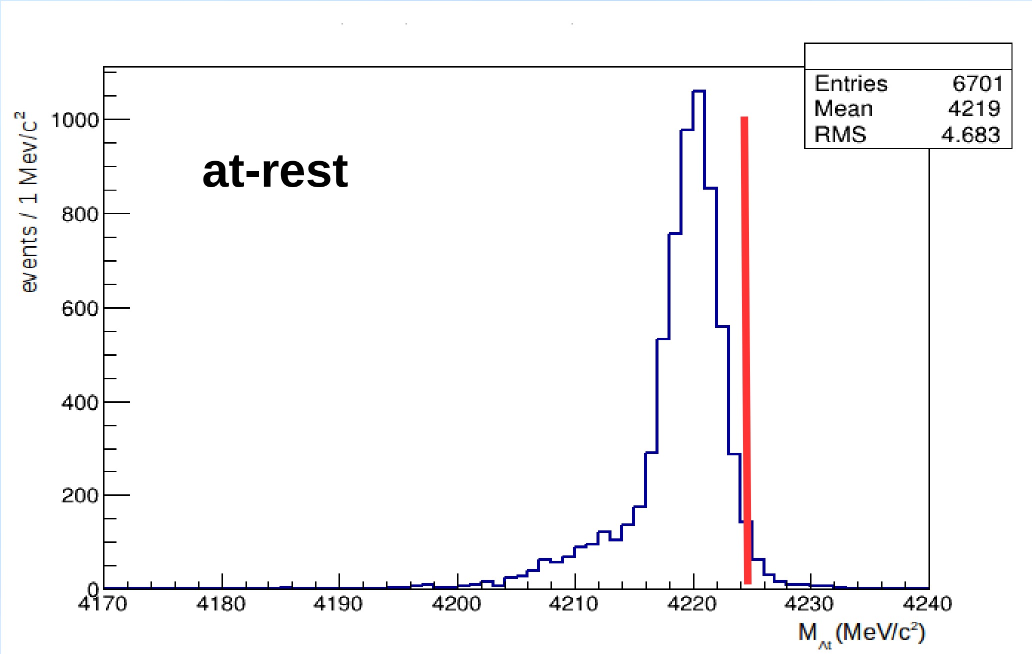
4NA processes – K⁻ absorbed by the α particle:

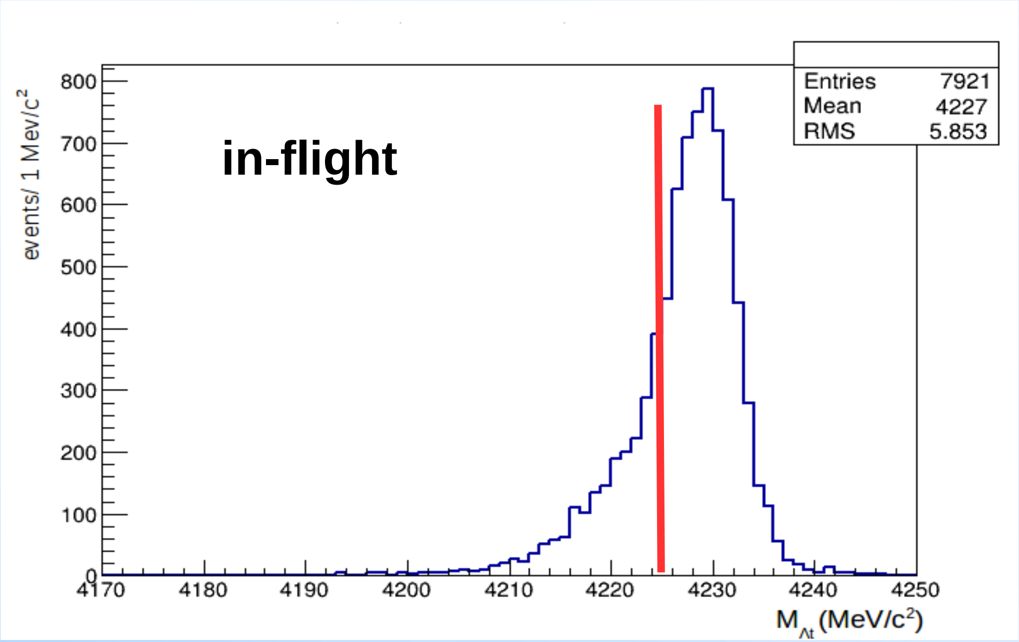
$$K^- \, {}^4He \rightarrow \Lambda t$$

$$K^- \, {}^4He \rightarrow \Sigma^0 t \quad , \quad \Sigma^0 \rightarrow \Lambda\gamma$$

conversion is suppressed by the Σ^0- t Back to back topology!

MC simulations: efficiency & resolution





mass threshold at-rest

$M_{\Lambda t}$ invariant mass resolution = 2.2 MeV/c^2

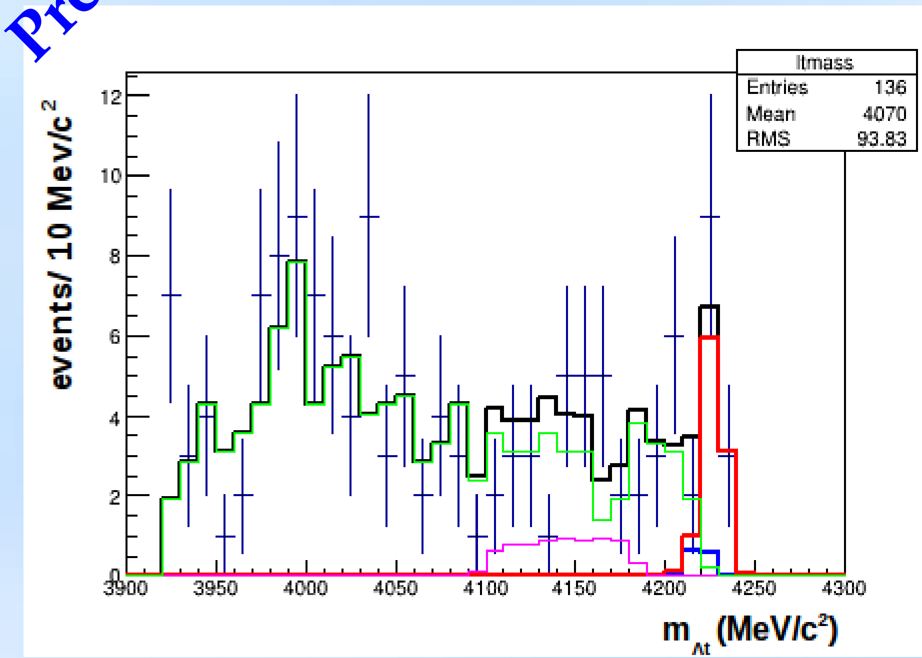
overall <u>detection + reconstruction efficiency</u> for 4NA direct Λt production :

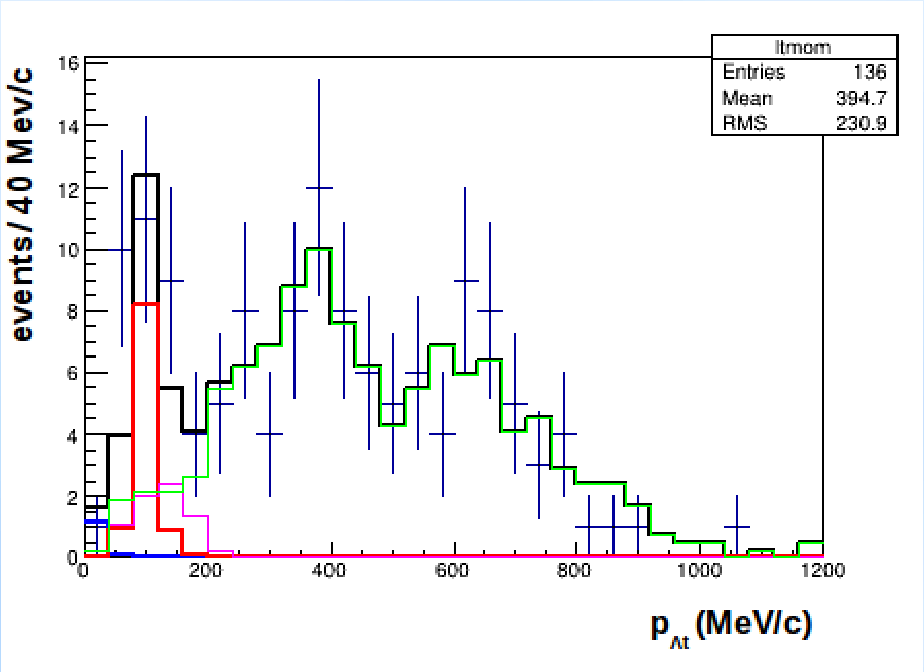
$$\epsilon_{4\mathrm{NA},ar,\Lambda t} = 0.0493 \pm 0.0006 \quad ; \quad \epsilon_{4\mathrm{NA},if,\Lambda t} = 0.0578 \pm 0.0006,$$

at-rest **in-flight**

Preliminary

K- ^{4}He → Λt 4NA cross section





data

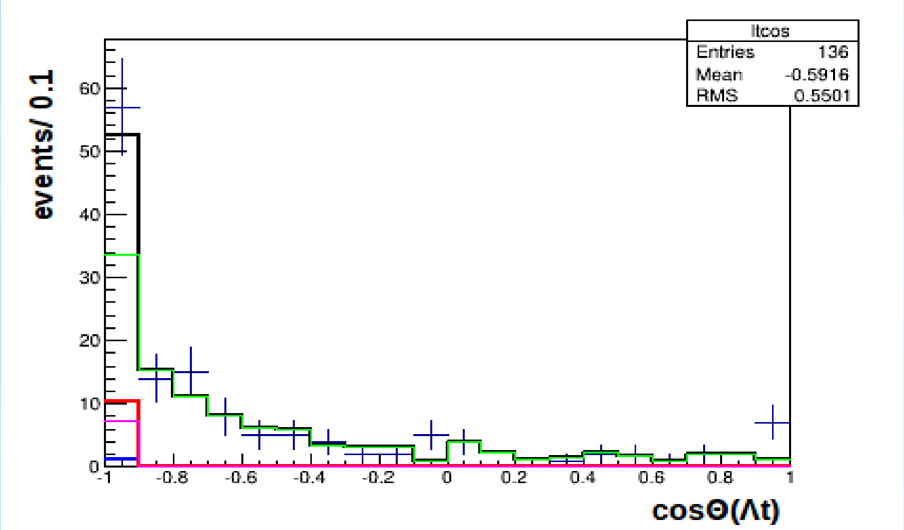
--- carbon data from DC wall

--- 4NA $K^- {}^4He \to \Lambda t$ in flight MC

--- 4NA $K^- {}^4He \to \Lambda t$ at rest MC

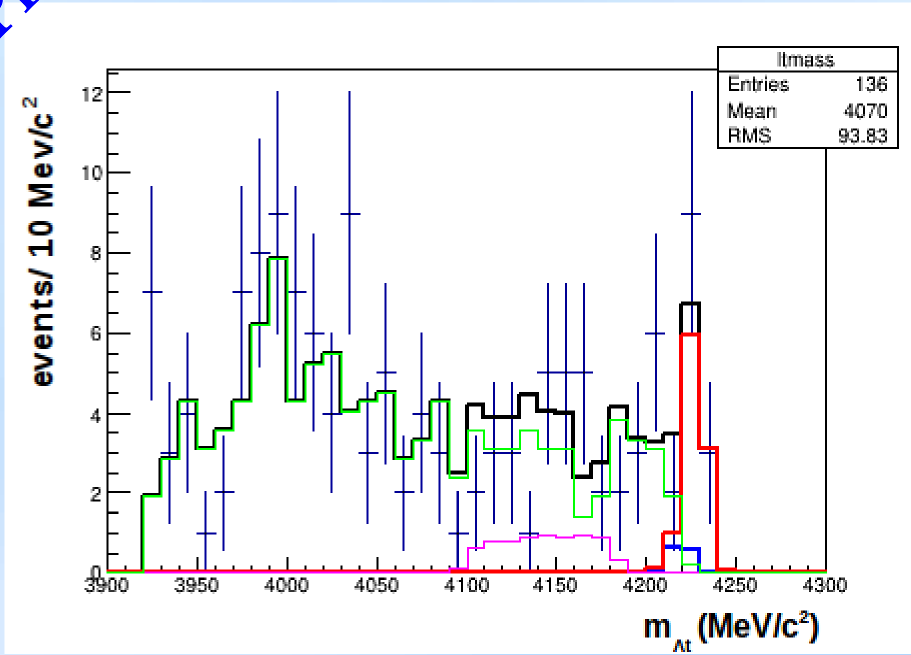
--- 4NA $K^- {}^4He \to \Sigma^0 t$, $\Sigma^0 \to \Lambda\gamma$ MC

--- 4NA $K^- {}^4He \to \Sigma^0 t$, $\Sigma^0 \to \Lambda\gamma$ MC



Preliminary

$K^- \, {}^4He \rightarrow \Lambda t$ 4NA cross section



data

--- carbon data from DC wall

--- 4NA $K^- \, {}^4He \rightarrow \Lambda t$ in flight MC

--- 4NA $K^- \, {}^4He \rightarrow \Lambda t$ at rest MC

--- 4NA $K^- \, {}^4He \rightarrow \Sigma^0 t$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC

--- 4NA $K^- \, {}^4He \rightarrow \Sigma^0 t$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC

Contribution to the spectra	Parameter value
K^{-4}He $\rightarrow \Lambda t$ at rest	0.01 ± 0.01
K^{-4}He $\rightarrow \Lambda t$ in-flight	0.09 ± 0.02
K^{-4}He $\rightarrow \Sigma^0 t$ in-flight	0.05 ± 0.03
K^{-12}C $\rightarrow \Lambda t$ experimental distribution from the carbon DC wall	0.85 ± 0.06
χ^2 / ndf	0.654

Total number of events = 136

4NA $K^- \, {}^4He \rightarrow \Lambda t$ at rest $\rightarrow$ 1 ± 1 events

4NA $K^- \, {}^4He \rightarrow \Lambda t$ in flight $\rightarrow$ 12 ± 3 events

BR($K^- \, {}^4He(4NA) \rightarrow \Lambda t$) **$< 1.3 \times 10^{-4} / K_{stop}$**

σ(100 ± **19** MeV/c) ($K^- \, {}^4He(4NA) \rightarrow \Lambda t$) **=**

$= (0.42 \pm 0.13(stat)\,^{+0.01}_{-0.02}(syst))$ mb

perspectives:

- **Sub-threshold K- n → $\Lambda\,\pi^-$ non resonant amplitude**

Nucl. Phys. A954 (2016) 75-93

$$|f^s_{ar}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst})\;\mathrm{fm}\,.$$

experimental paper finalised

next step extract the same info in I = 0 to interpret the $\Sigma^0\pi^0$ spectra

- **K- multiN absoption yields in Σ^0 p** Physics Letters B 758 (2016) 134

	yield / $K^-_{stop} \cdot 10^{-2}$	$\sigma_{stat} \cdot 10^{-2}$	$\sigma_{syst} \cdot 10^{-2}$
2NA-QF	0.127	$\pm$ 0.019	$^{+0.004}_{-0.008}$

Same analysis is ongoing in Λ p (R. Del Grande PhD thesis)

- **K- ^{4}He → Λt 4NA cross section** σ(100 **± 19** MeV/c) (K$^-$ ^{4}He(4NA) → Λt) **=**
= (0.42 ± 0.13(stat) $^{+0.01}_{-0.02}$ (syst)) mb **paper in preparation**

- **feasibility study of the Σ^0 - N/NN *two* and *three body forces* measurement from K-absoption in ^{4}He**

AMADEUS physics case

K^-

- establish the nature of the $\Lambda(1405)$ through the reaction:

$$K^- \, d \rightarrow \Sigma^0 \pi^0 \, n$$

  - search for K-multiN clusters, possible reactions:
    $K^- \, {}^4He \rightarrow$ "K-ppn" + n   in flight?

- Y – N/NN two & three body interaction (ex. Σ^0- N/NN from $K^- \, {}^4He$ induced reactions)

- $K^\pm$ N elastic & inelastic scattering below 100 MeV
  - also low momentum $K^\pm \, {}_Z^AX$ scattering for low Z gas targets

- Neutron rich hypernuclei

AMADEUS physics case

K^-

- establish the nature of the $\Lambda(1405)$ through the reaction:

$$K^- \, d \rightarrow \Sigma^0 \, \pi^0 \, n$$

  - search for K-multiN clusters, possible reactions:

    $K^- \, {}^4He \rightarrow$ "K-ppn" + n   in flight?

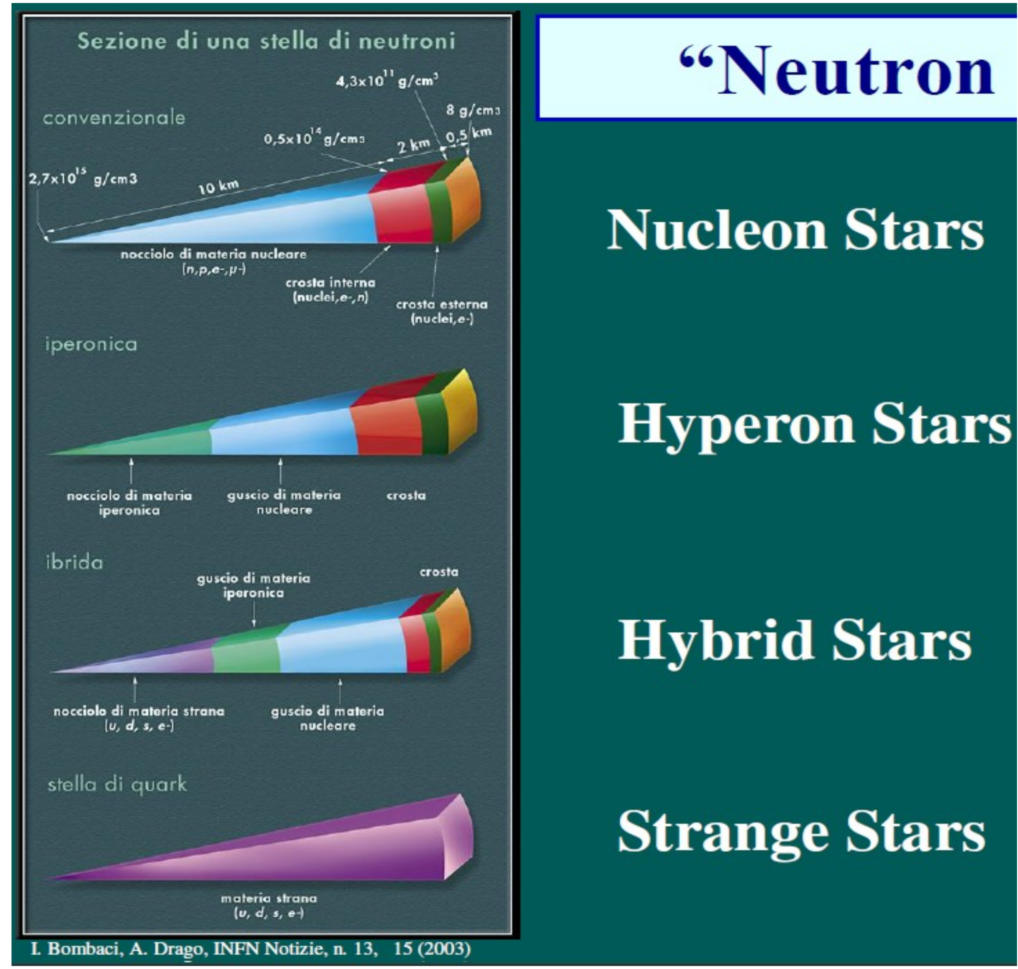
- **Y – N/NN two & three body interaction (ex. Σ^0- N/NN from K^- ${}^4He$ induced reactions)**

- $K^\pm$ N elastic & inelastic scattering below 100 MeV

  - also low momentum $K^\pm \, {}_Z^A X$ scattering for low Z gas targets

- Neutron rich hypernuclei

Y-N/NN interaction essential impact on the case of NEUTRON STARS



Microscopic approach to hyperonic matter EOS

input

2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)
e.g. Nijmegen, Julich models

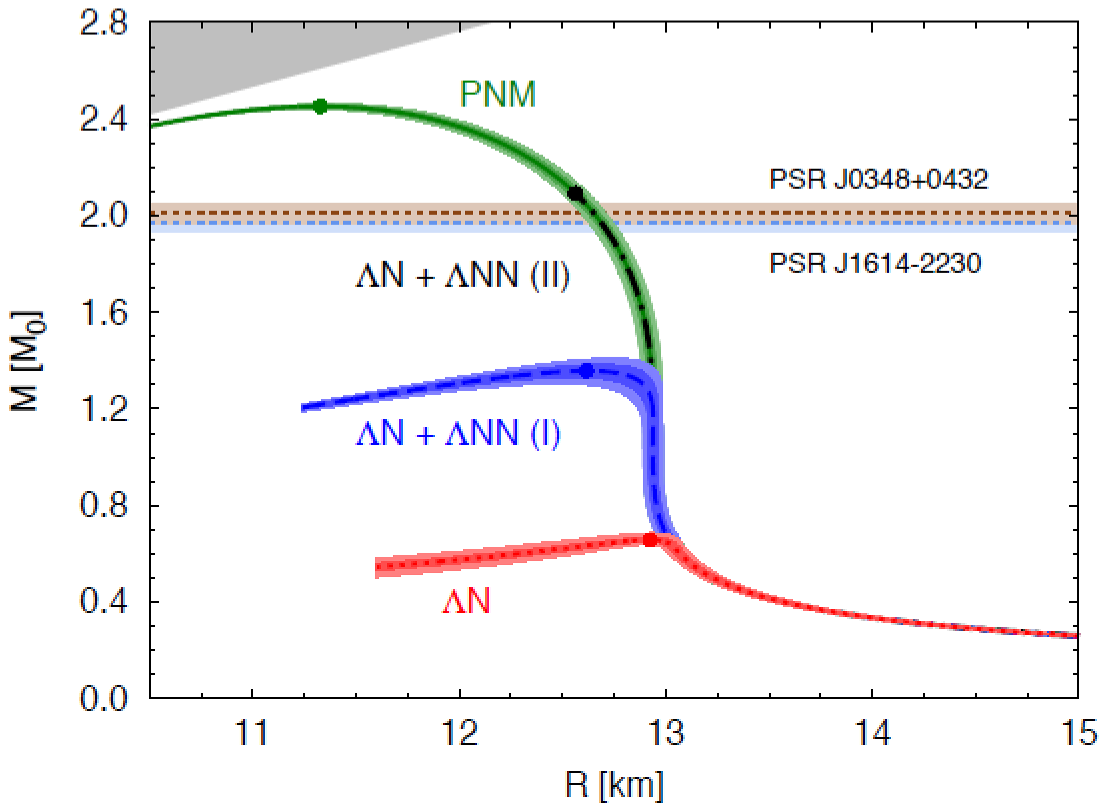
3BF: NNN, NNY, NYY, YYY

Hyperonic sector: experimental data

1. YN scattering (very few data)
2. Hypernuclei

No experimental information on Σ^0-N/NN interaction

Λ-neutron matter

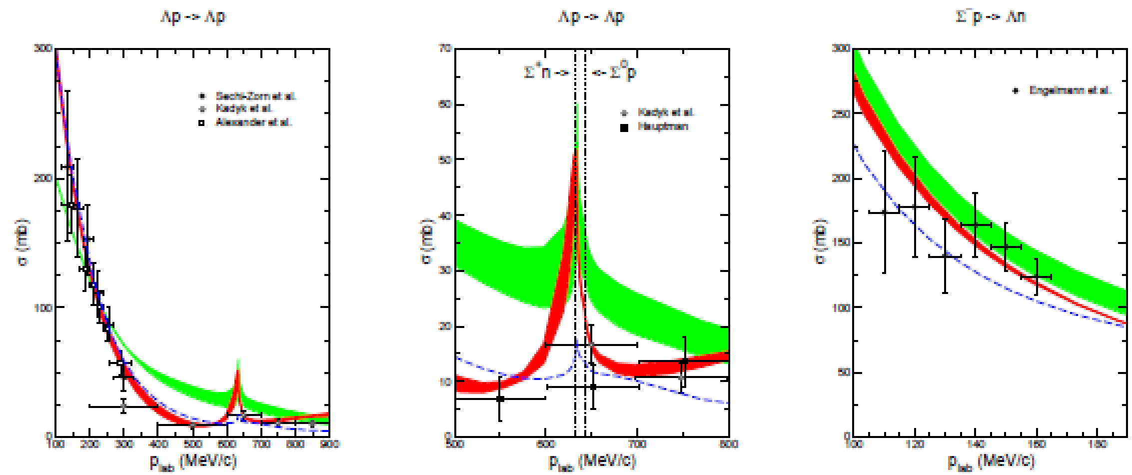


Lonardoni, Lovato, Gandolfi, Pederiva, PRL (2015)

Drastic role played by ΛNN. Calculations can be compatible with neutron star observations.

Note: no $v_{\Lambda\Lambda}$, no protons, and no other hyperons included yet...

No experimental information on Σ^0-N/NN interaction



Nucl. Phys. A 915 (2013) 24-58

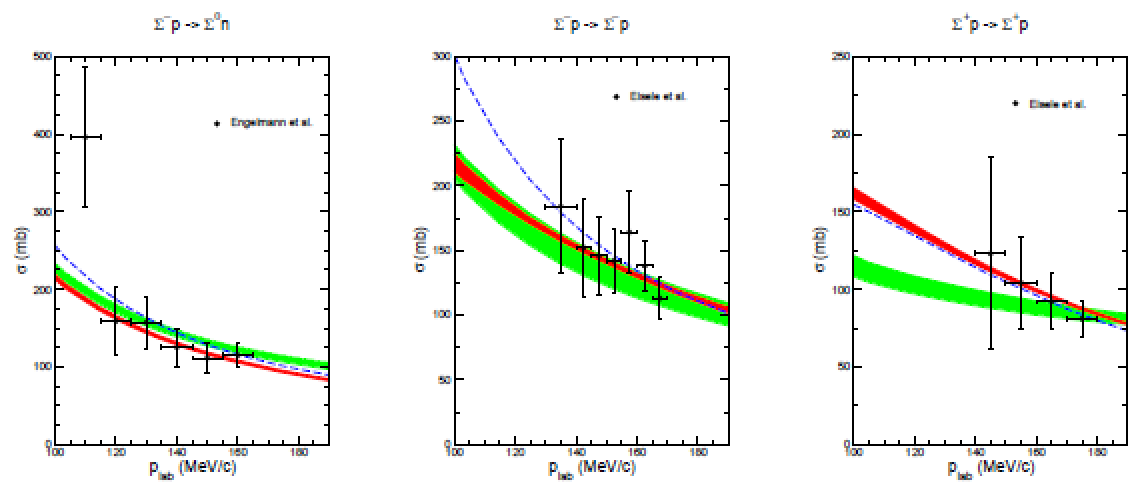


Figure 2: "Total" cross section σ (as defined in Eq. (24)) as a function of p_{lab}. The experimental cross sections are taken from Refs. [52] (filled circles), [53] (open squares), [65] (open circles), and [66] (filled squares) ($\Lambda p \rightarrow \Lambda p$), from [54] ($\Sigma^- p \rightarrow \Lambda n$, $\Sigma^- p \rightarrow \Sigma^0 n$) and from [55] ($\Sigma^- p \rightarrow \Sigma^- p$, $\Sigma^+ p \rightarrow \Sigma^+ p$). The red/dark band shows the chiral EFT results to NLO for variations of the cutoff in the range $\Lambda = 500, \ldots, 650$ MeV, while the green/light band are results to LO for $\Lambda = 550, \ldots, 700$ MeV. The dashed curve is the result of the Jülich '04 meson-exchange potential [36].

K^{-}

$(K^{-}\ ppn) + n \rightarrow \Sigma^{0}\, d + n$

3NA in ^{4}He

for the investigation of the

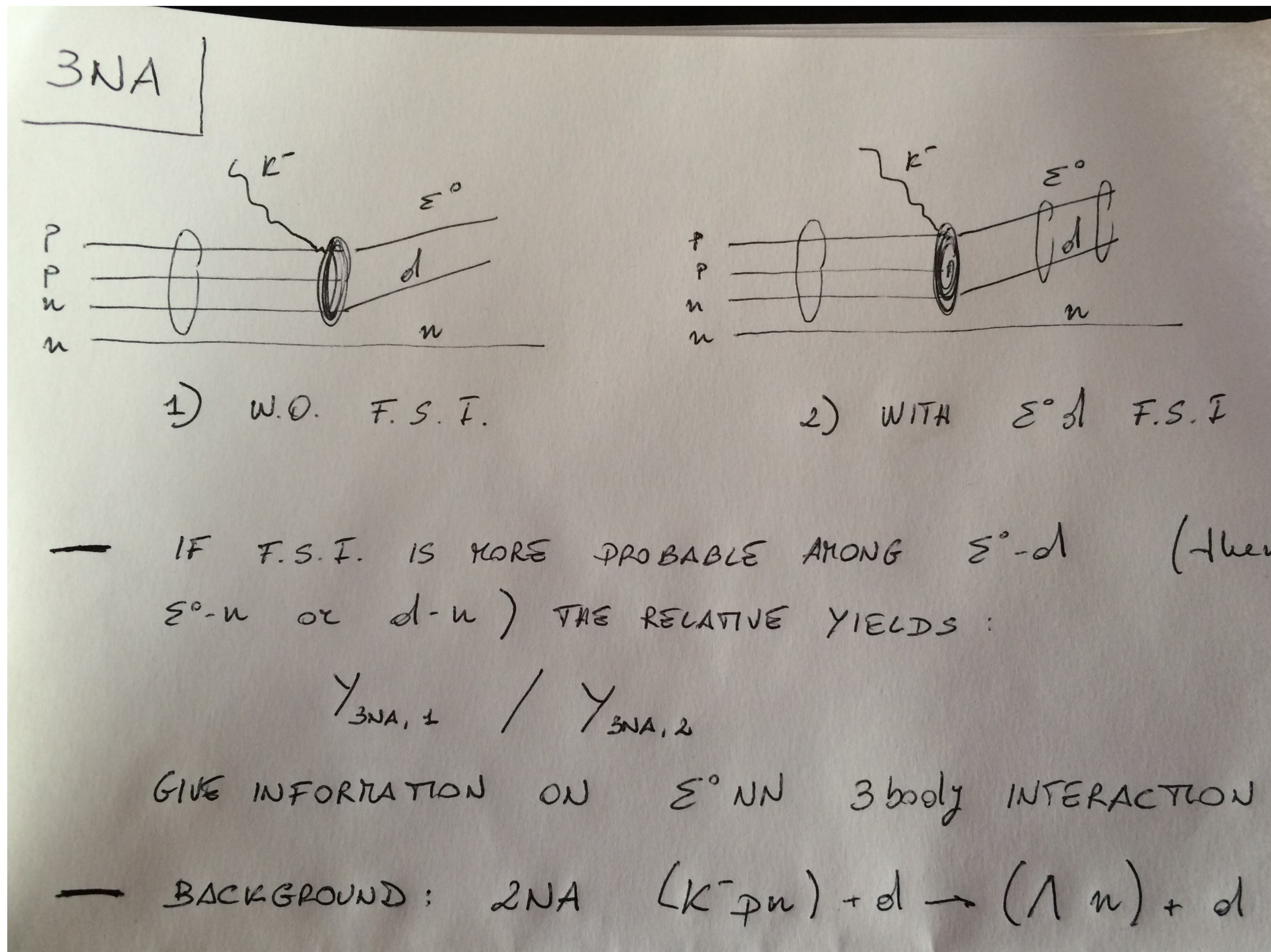
Σ^{0}-N & Σ^{0}-(NN) interaction

Involved reactions:

3NA - $(K^- ppn) + n \rightarrow \Sigma^0 d + n$

- **The Σ^0 identification (with respect to Λ) enables to avoid the dominant internal conversion background. Moreover there is presently no available Σ^0-N interacion data.**

- **4He good target no nuclear fragmentation can follow the 3NA primary process.**



Comparison with available data

3NA - $(K^- ppn) + n \rightarrow \Sigma^0 d + n$

Data correspond to K- captures in the ^{12}C solid target.

We will show that the most energetic part of the $m_{\Sigma 0d}$ invariant mass spectrum, correlated with high $p_{\Sigma 0}$ and p_d momenta, corresponds to the 3NA - $(K^- ppn)$ process

The Σ^0 d statistics corresponding to the sample of K- captures in the gas from the KLOE DC is much lower (1 order of mag.)

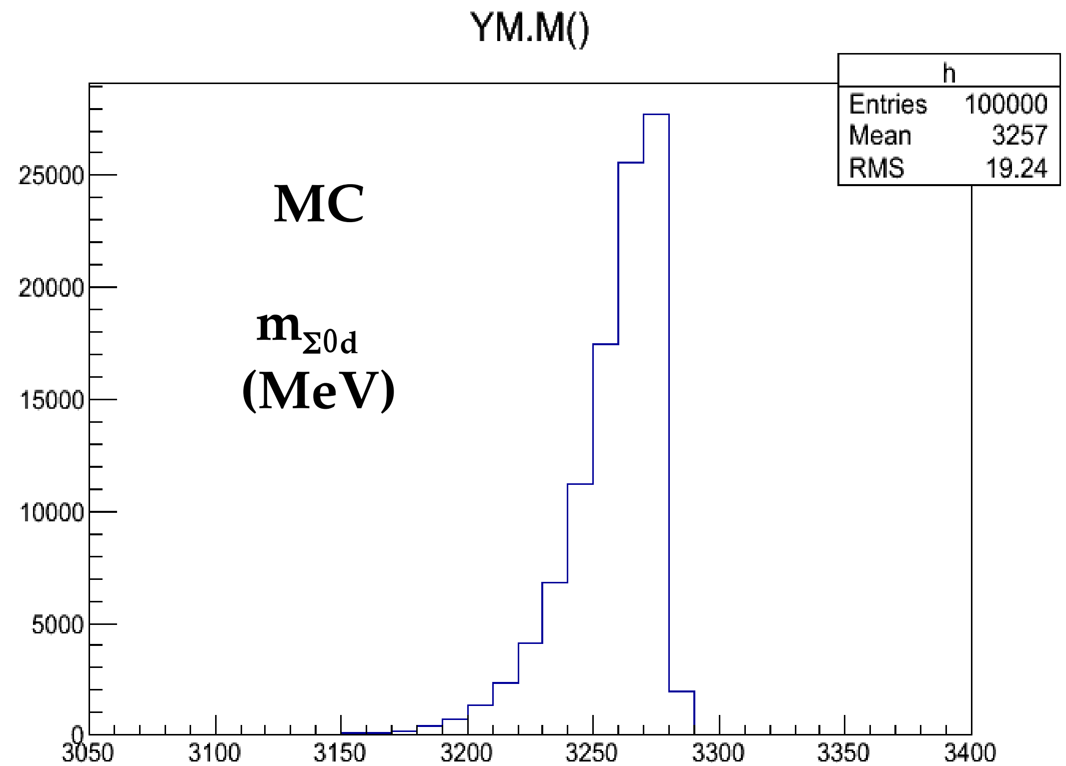
A dedicated measurement with pure ^4He target is mandatory!!

3NA

(K$^-$ ppn) + n $\rightarrow$ Σ^0 d + n

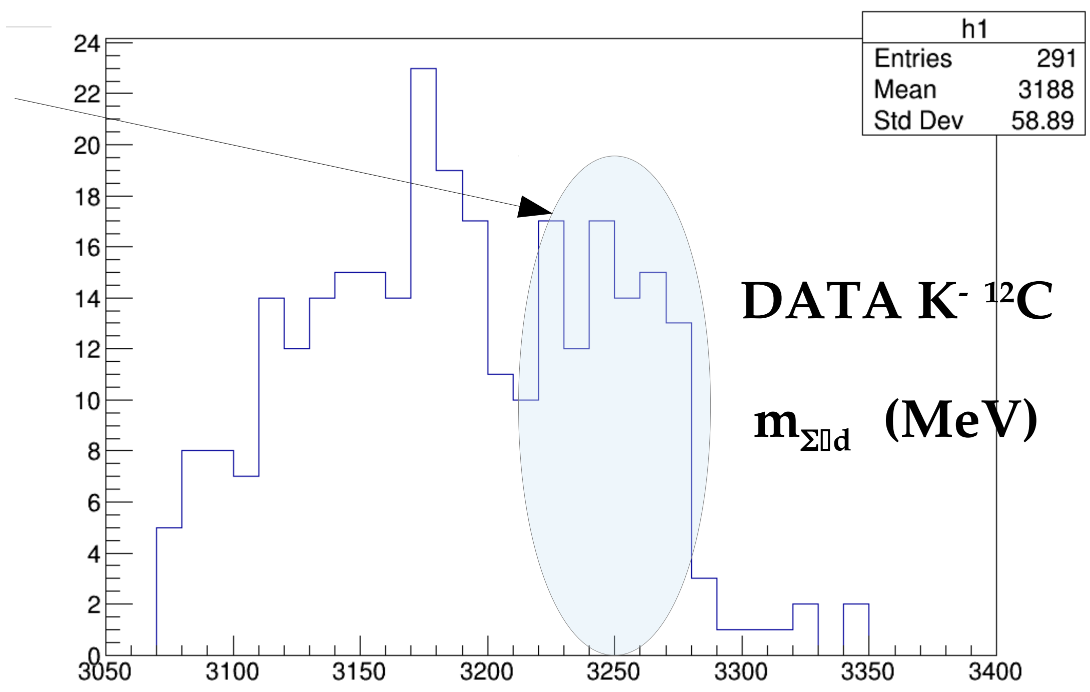
without FSI

Corresponds to the highest part of the invariant mass spectrum



the blue region is populated by:

free 3NA + 3NA followed FSI.



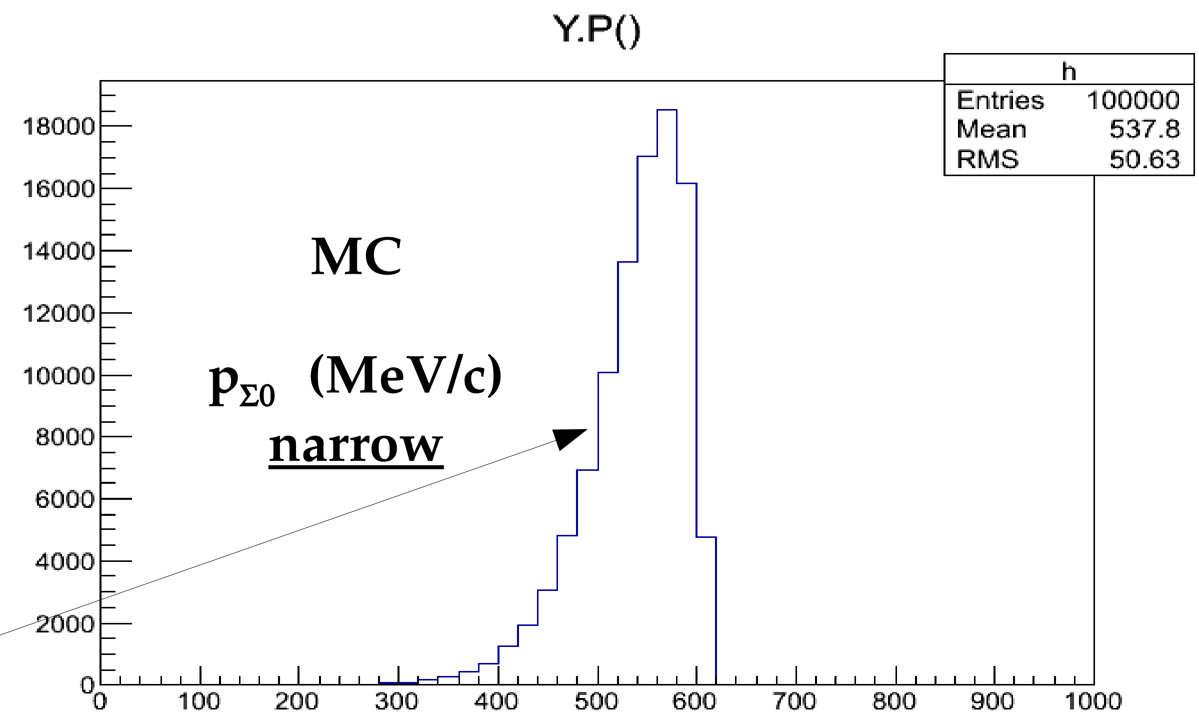
Lower energies (below 3220 MeV) probably involve 2NA and complex FSI processes with fragmentation of the residual ^{8}Be.

3NA

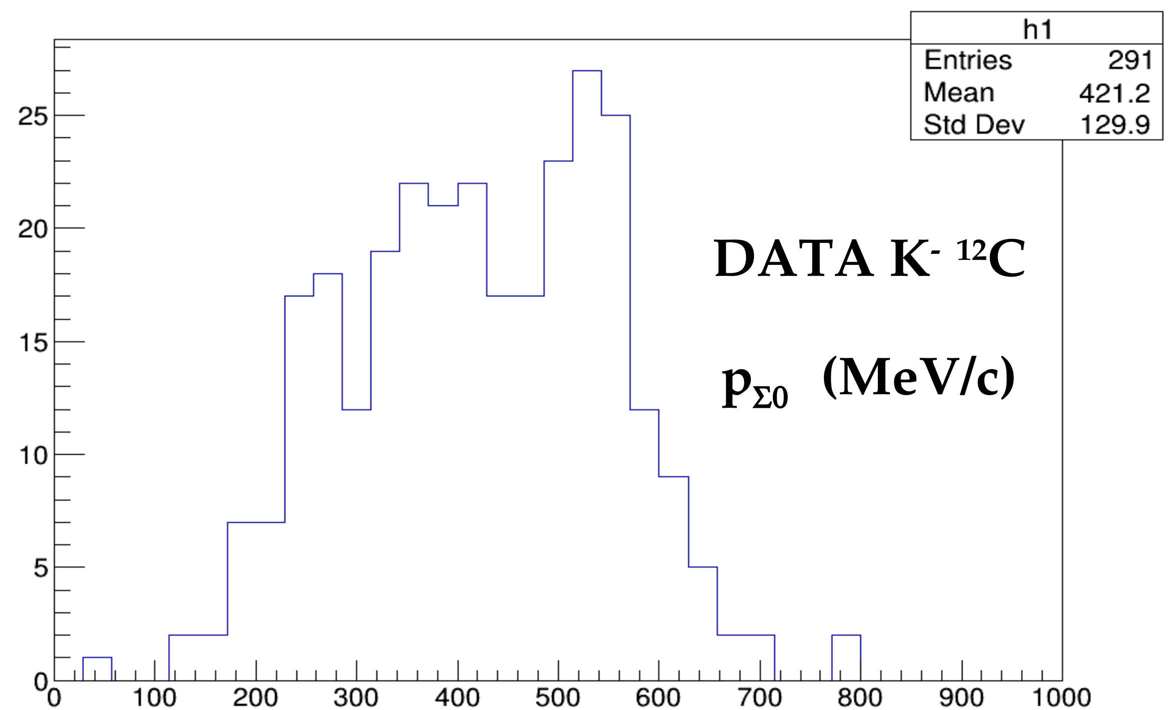
$(K^- ppn) + n \rightarrow \Sigma^0\, d + n$

without FSI

Corresponds to the highest part of the Σ^0 momentum spectrum.

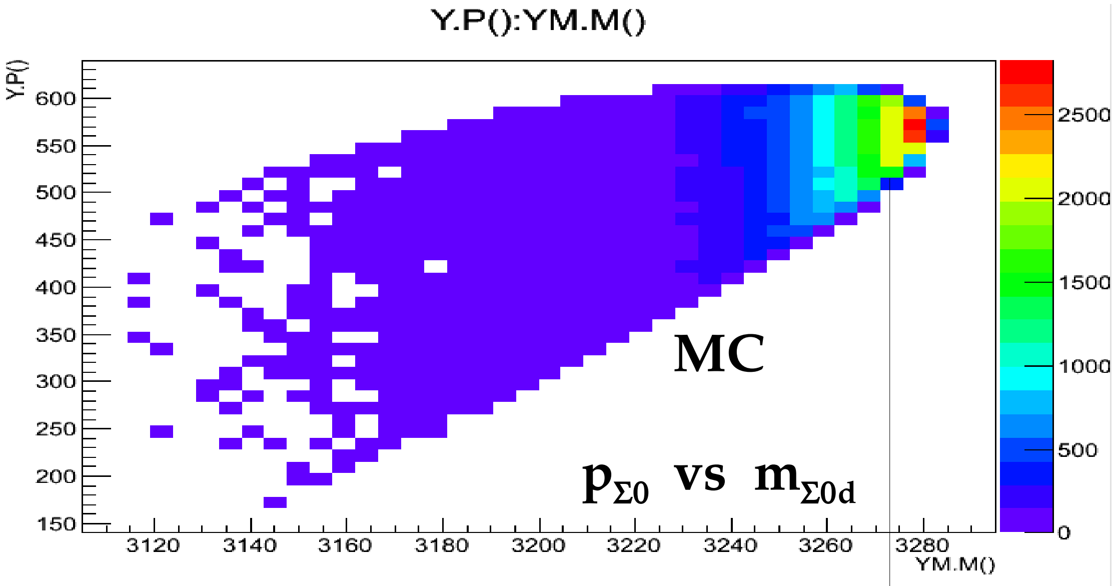


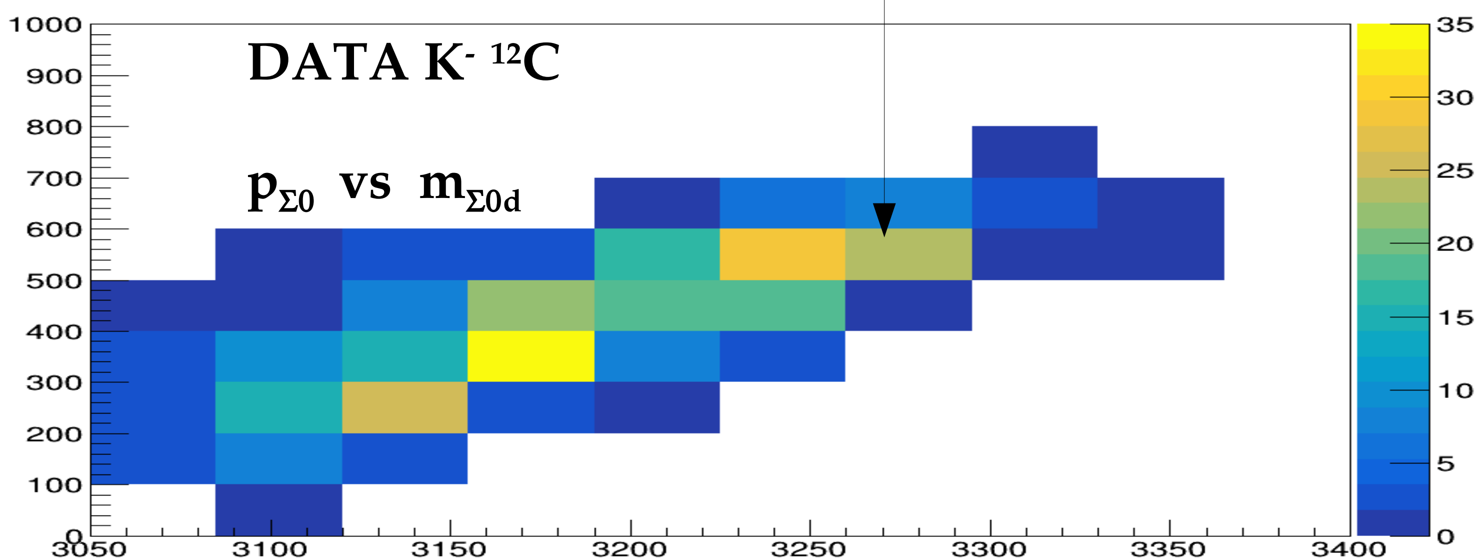
The narrow Σ^0 momentum distribution will enable to Σ^0-NN cross section at 550 ± 50 MeV/c.



3NA (K⁻ ppn) + n → Σ^0 d + n w. o. FSI

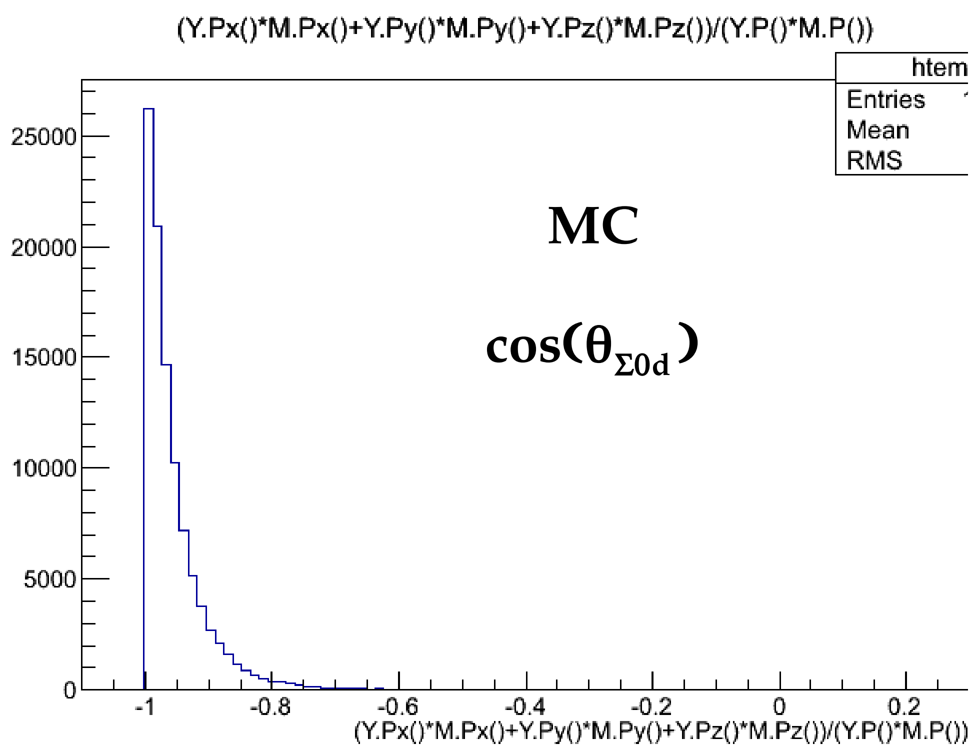
- clean mometum mass correlation

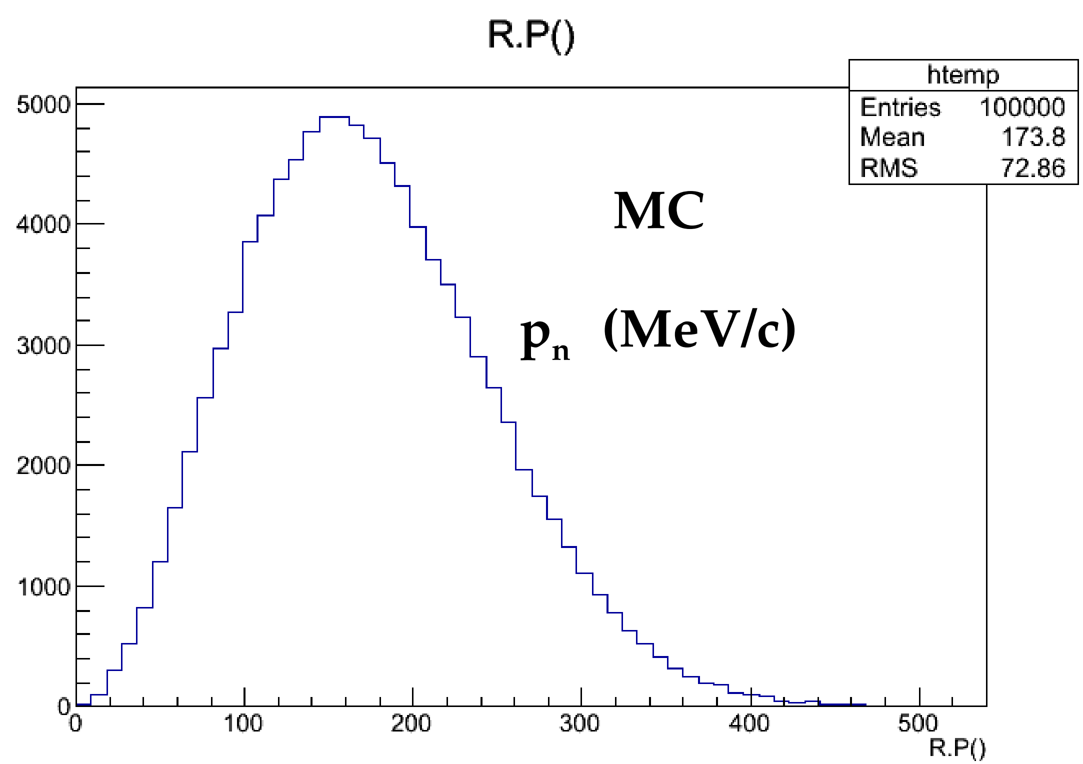




3NA - (K- ppn) + n → Σ0 d + n signature:

- Highest Σ0 - d angular correlation
- low Fermi momentum neutron





Using the same data set …

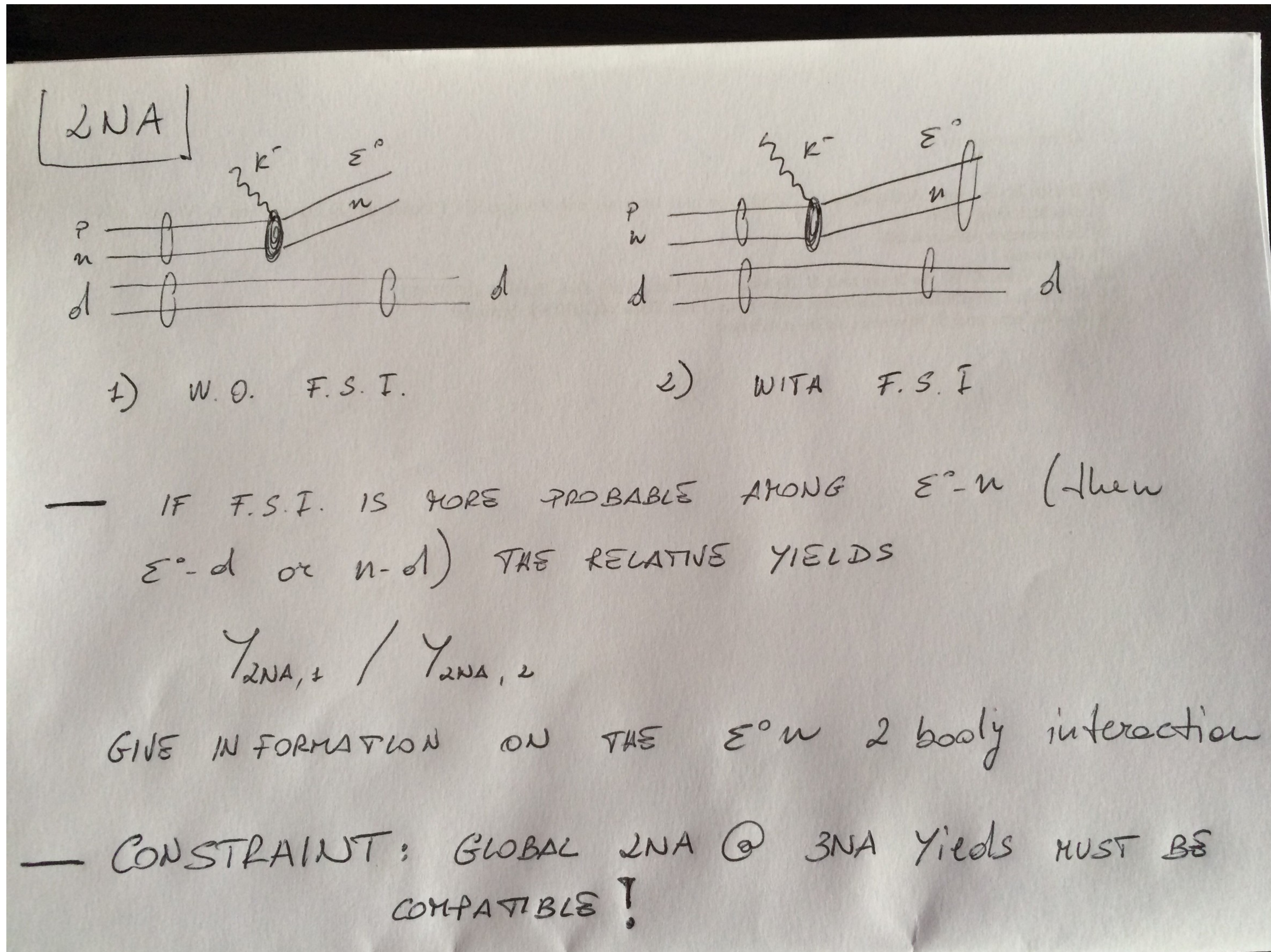
The compeeting process

2NA - (K⁻ pn) + d → Σ⁰ n + d

can be used to extract

the complementary

information:



Background reactions:

1NA - (K- p) + pnn $\rightarrow$ $\Sigma 0\ \pi 0$ n d

(K- n) + ppn $\rightarrow$ $\Sigma 0\ \pi -$ p d

- low energy (took away by the pion) not correlated $\Sigma 0$ d pairs. It is easy to be disentangled (similar to the $\Sigma 0$ p analysis).

Accurate calculations of the

FSI pocesses

are needed to extract the corresponding cross sections from the measured shapes.

AMADEUS physics case

K^-

- establish the nature of the $\Lambda(1405)$ through the reaction:

$$K^- \, d \rightarrow \Sigma^0 \, \pi^0 \, n$$

  - search for K-multiN clusters, possible reactions:
    $K^- \, {}^4He \rightarrow$ "K-ppn" + n   in flight?

- Y – N/NN two & three body interaction (ex. Σ^0- N/NN from $K^- \, {}^4He$ induced reactions)

- **$K^\pm$ N elastic & inelastic scattering below 100 MeV**

  - also low momentum $K^\pm \, {}_Z^AX$ scattering for low Z gas targets

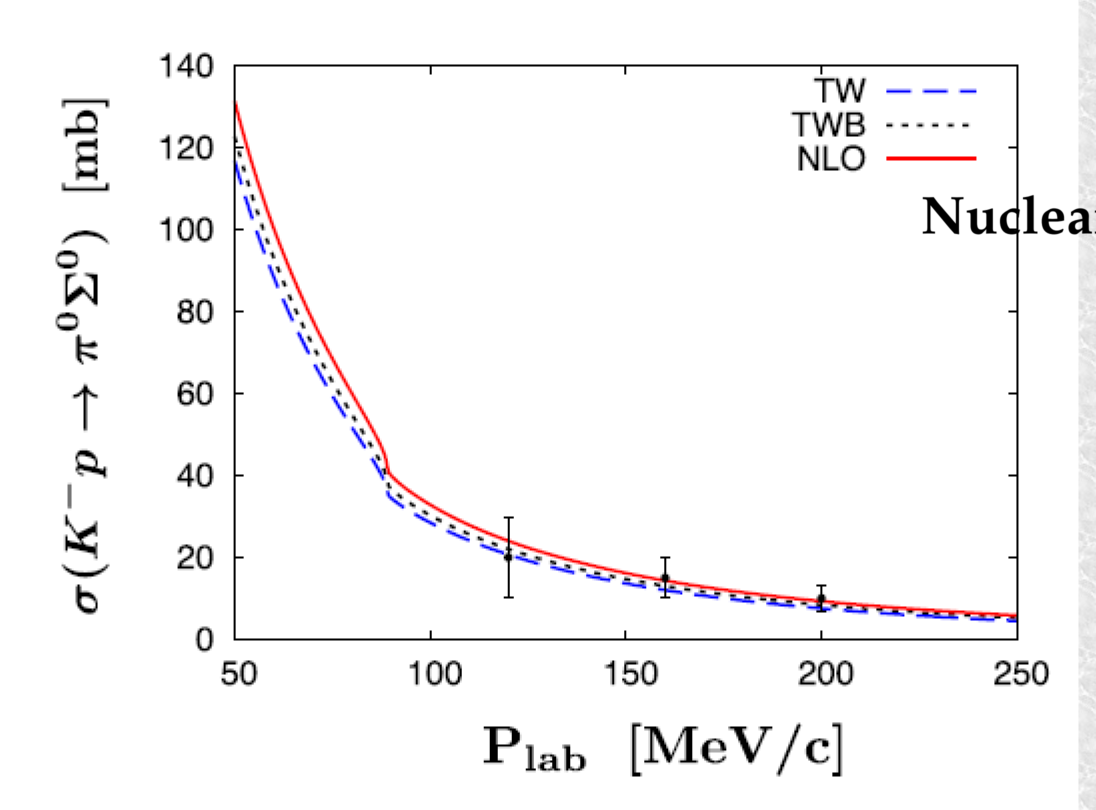
- Neutron rich hypernuclei

$K^- p \rightarrow \Sigma^0\pi^0$ cross section measurement at p_K~100 MeV/c

K^- N cross section measurement at p_K=100 MeV/c , an example..

- $K^- p \rightarrow \Sigma^0\pi^0$ cross section measurement at or below 100 MeV/c missing

- existing data at (120, 160, ..) MeV/c with big relative errors (about 50% & 120 MeV/c)



Nuclear Physics A 881 (2012) 98–114

$K^- p \rightarrow \Sigma^0\pi^0$ cross section measurement the strategy

We employ the following reaction, where p=H is a “quasi-free” proton in the C4H10 molecule

$$K^- p \rightarrow \Sigma^0\pi^0 \rightarrow (\Lambda(1116)\,\gamma_3)\,(\gamma_1\gamma_2) \rightarrow (p\pi^-)\ 3\gamma$$

- First we identify the $\Lambda(1116)$ through its decay in pion and proton
- then photon clusters are identified:

Photons selection

1) Select events with at least three neutral clusters ($E_{c1} > 20$ MeV) not from K decay ($K^+ \to \pi^+ \pi^0$)

2) **photon clusters selection**: a first minimization is performed $\chi_t^2 = t^2/\sigma_t^2$ where $t = t_i - t_j$ is the difference between time of flights in light speed hypothesis. This selects three photon clusters in time from the Λ decay vertex $\mathbf{r}_\Lambda$.

3) **photon clusters identification**: to distinguish photon clusters from π^0 decay, from γ_3 (due to Σ^0 decay) a second minimization is performed on $\chi_{\pi\Sigma}^2$:

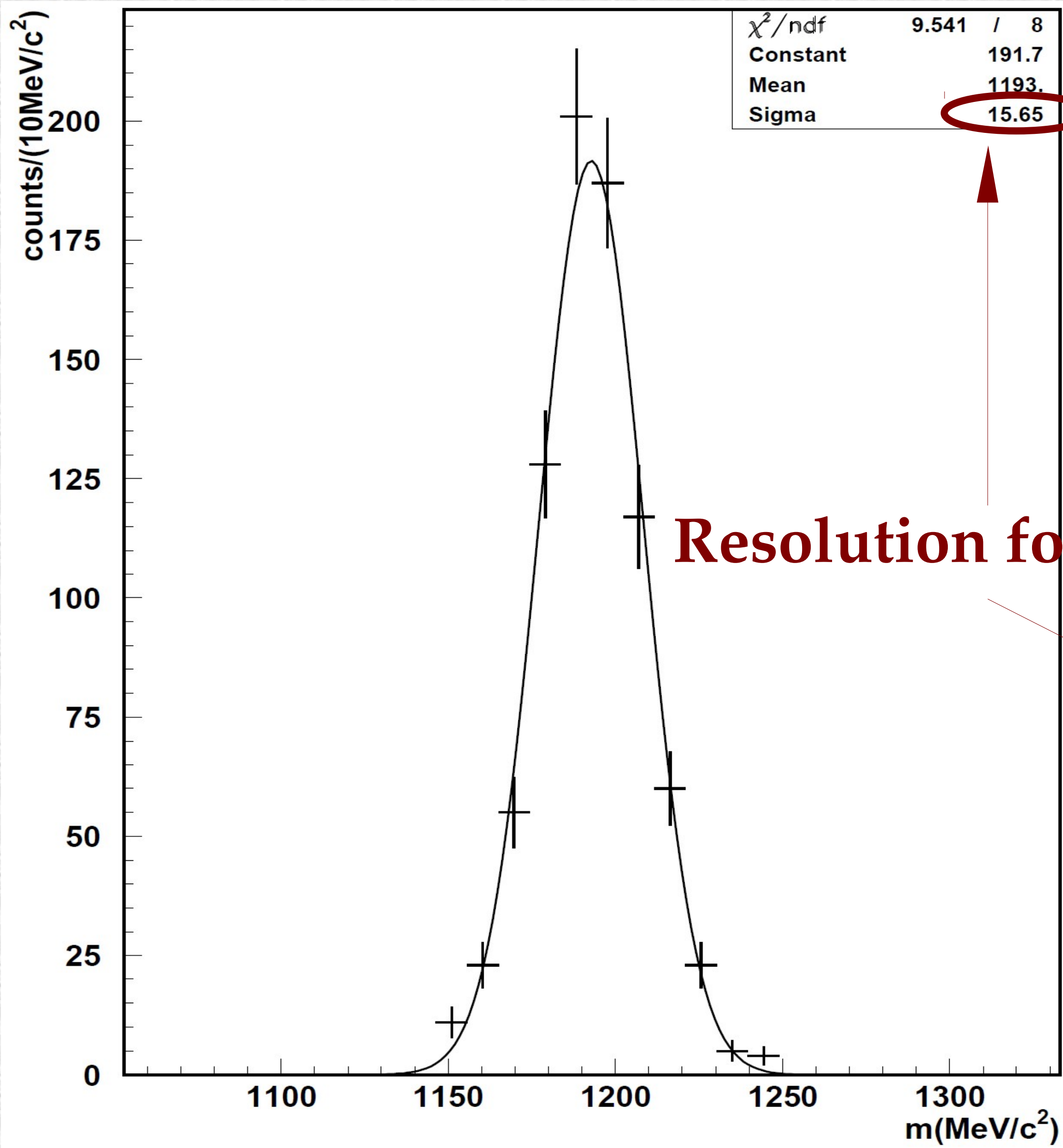
$$\chi^2_{\pi\Sigma} = \frac{(m_{\pi^0} - m_{ij})^2}{\sigma^2_{ij}} + \frac{(m_{\Sigma^0} - m_{k\Lambda})^2}{\sigma^2_{k\Lambda}}$$

i,j and *k* represent one of the previously selected candidate photon cluster.

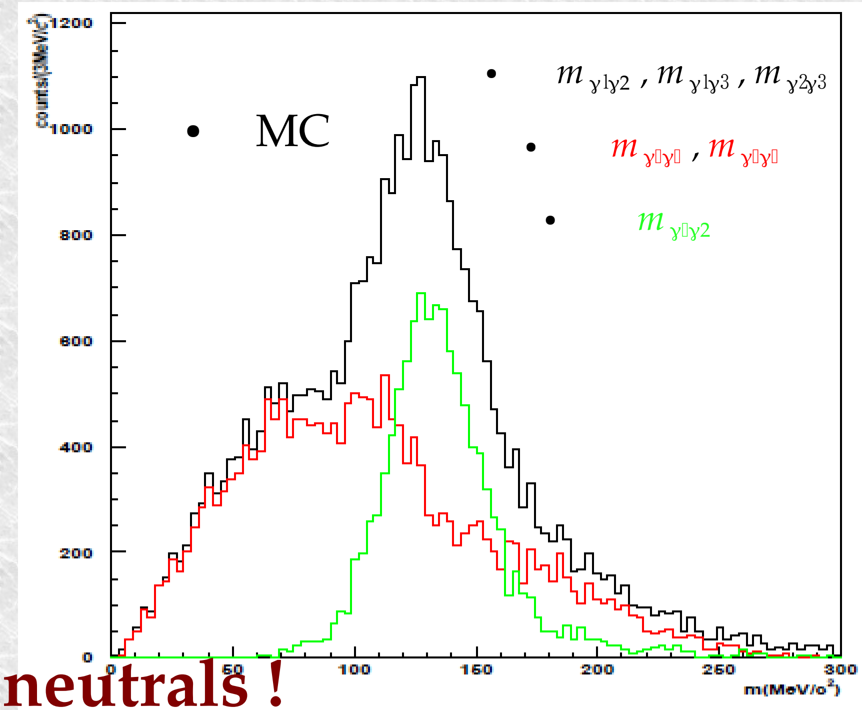
4) Cuts on χ_t^2 and $\chi_{\pi\Sigma}^2$ variables were optimized using MC simulations. Specific cuts are introduced in order to avoid the selection of splitted clusters or background for π^0

The algorithm has (from true MC information) an efficiency (98±1)% to identify photons and (78±2)% to select the correct triple of neutral clusters.

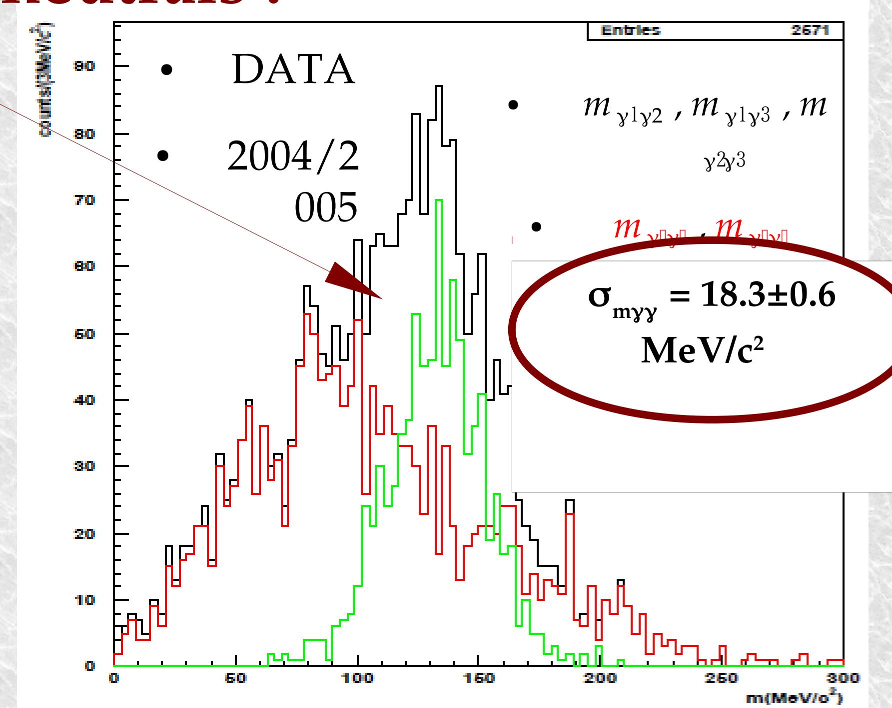
Photons selection



$m_{\Lambda\gamma 3}$

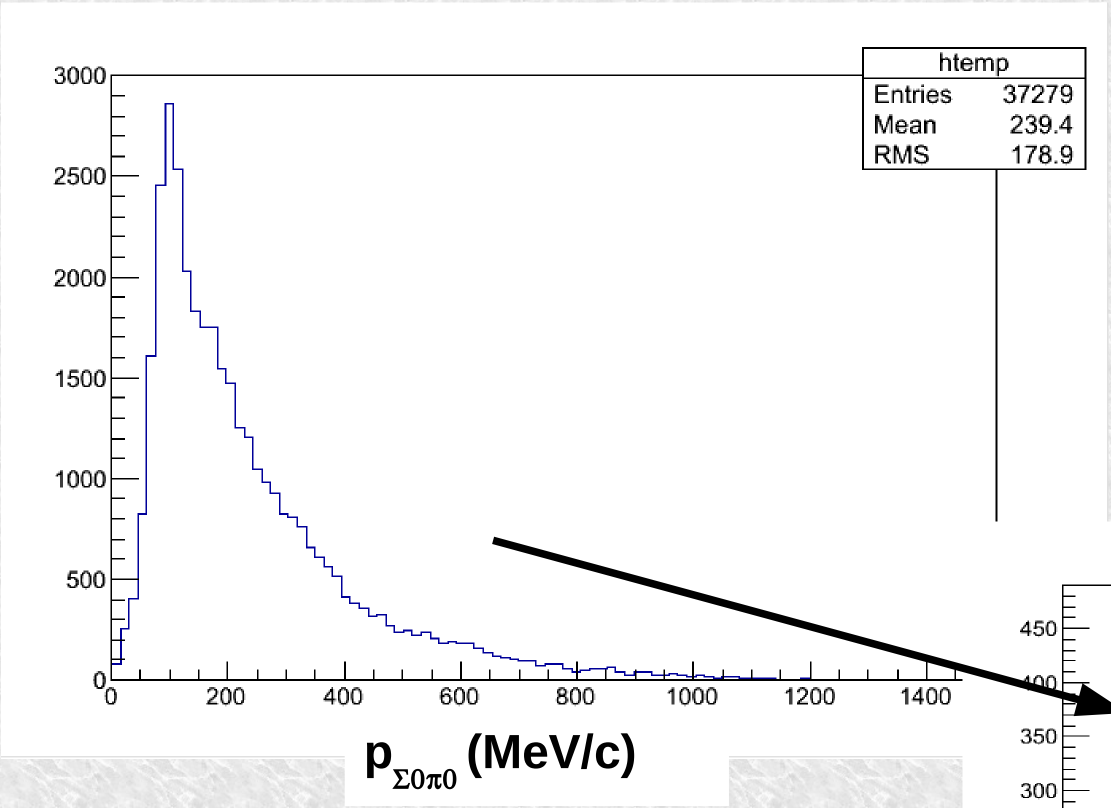


Resolution for neutrals !



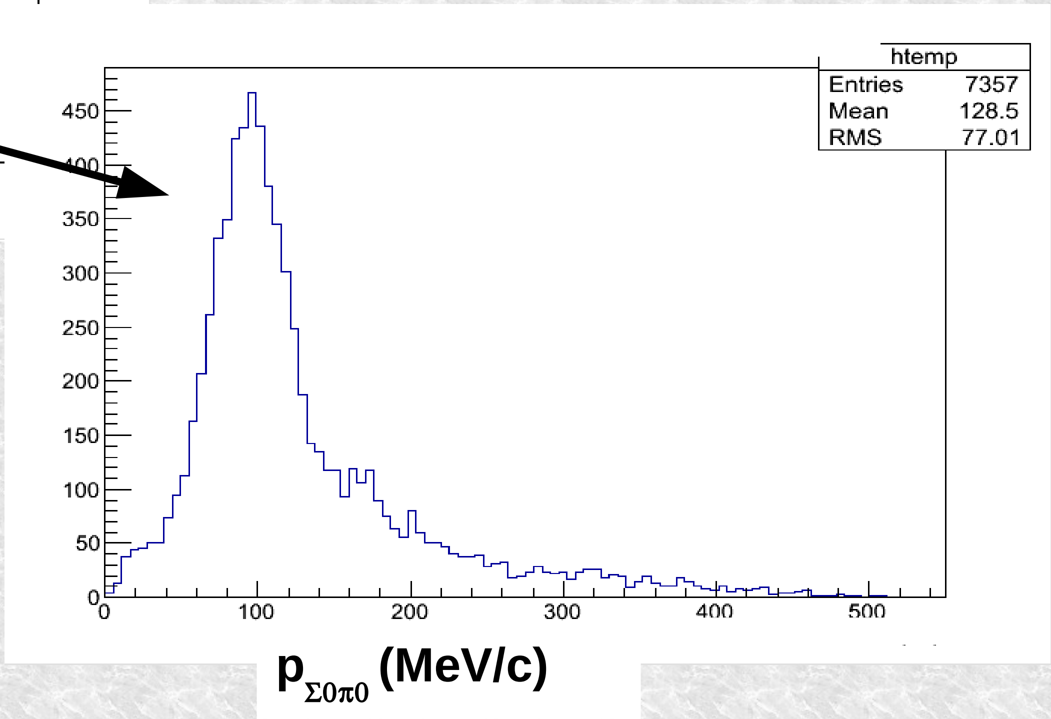
$\sigma_{m\gamma\gamma}$ = 18.3±0.6 MeV/c²

$\Sigma^0\pi^0$ total momentum spectrum clearly shows the p_K~100 MeV/c peak from K- H captures in-flight



Cuts based on K- H in-flight capture kinematics:

- $\Theta(p_\gamma - p_\gamma) \rightarrow$ π0 opening angle
- $p_{\pi0} \rightarrow$ π0 momentum
- $p_{\Sigma0} \rightarrow$ Σ0 momentum



$K^- p \rightarrow \Sigma^0\pi^0$ cross section measurement can be done

- K- H capture at-rest → kinematics is closed
- K- H capture in-flight (p_K = 90 MeV) → kinematics is closed
- K- H capture in-flight (p_K = 110 MeV) → kinematics is closed
- K- 4He capture at-rest + in-flight (l_K = 1)
- K- 12C capture at-rest + in-flight (l_K = 2, valence proton)