K^-

Investigation of the low-energy kaons hadronic interactions in light nuclei by AMADEUS

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on behalf of the AMADEUS collaboration

ISU 2015 "Quest for visible and invisible strange stuff in the Universe"
LNF, INFN, Frascati 27/11/2015

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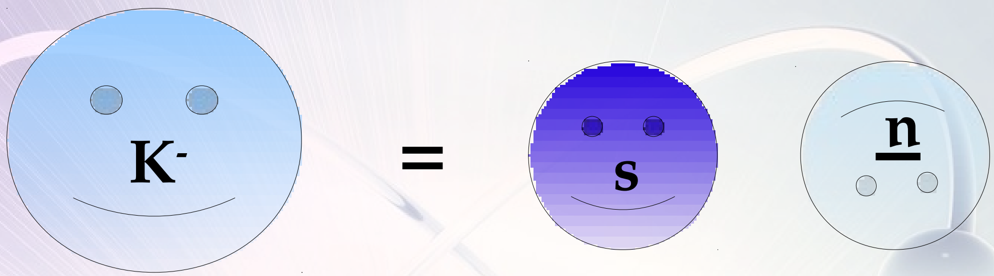
Why low-energy kaons hadronic interactions study?

K⁻



- Strange quarks are intermediate between “light” and “heavy”:
interplay between
spontaneous and explicit chiral symmetry breaking
in low-energy QCD

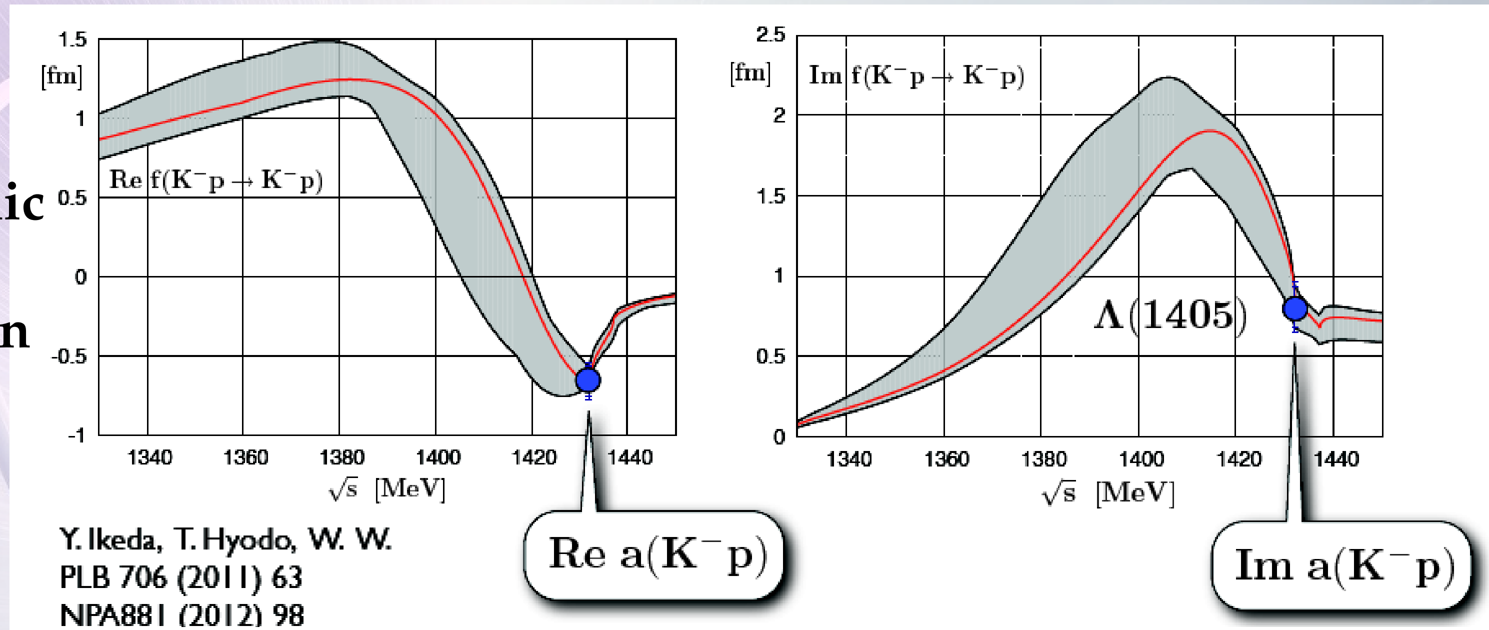
- BUT chiral perturbation theory <u>not applicable</u>

- high-precision antikaon-nucleon threshold physics test ground for
the different theoretical approaches

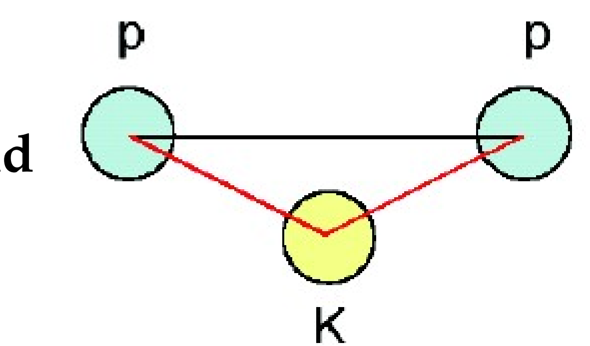
exploiting the attractive low energy $\bar{K}$ N interaction

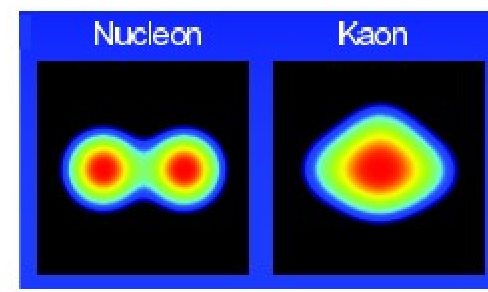
Why low-energy kaons hadronic interactions?

- K- p scattering, kaonic atoms & L(1405) structure investigation

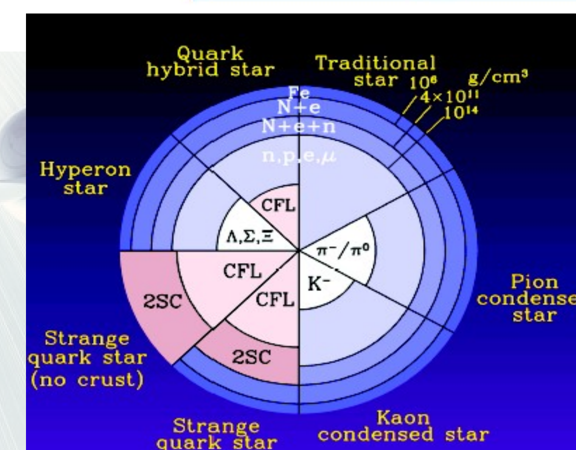


- Quest for quasi-bound K- NN/NNN systems





- Role of strangeness in dense baryonic matter, kaon condensation? Strange quark matter? Hyperons in NS?



Framework:
Low-Energy QCD
with Strange Quarks

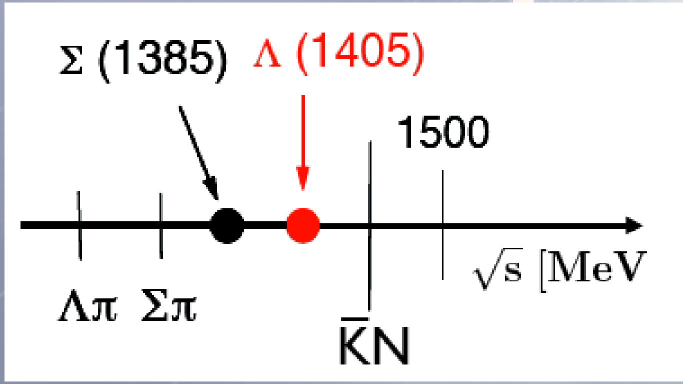
CHIRAL PERTURBATION THEORY
Interacting systems of NAMBU-GOLDSTONE BOSONS (pions, kaons) coupled to BARYONS

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

works well for low-energy pion-pion and pion-nucleon interactions

... but NOT for systems with strangeness S = –1

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



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Solutions:

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

The scientific goal of AMADEUS

K^-

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 Λ(1405) state → we investigate it through $(\Sigma-\pi)^0$ decay --- Y π CORRELATION

   - if U_{KN} is strongly attractive then possible K^- multi-N bound states → 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

AMADEUS & DAΦNE

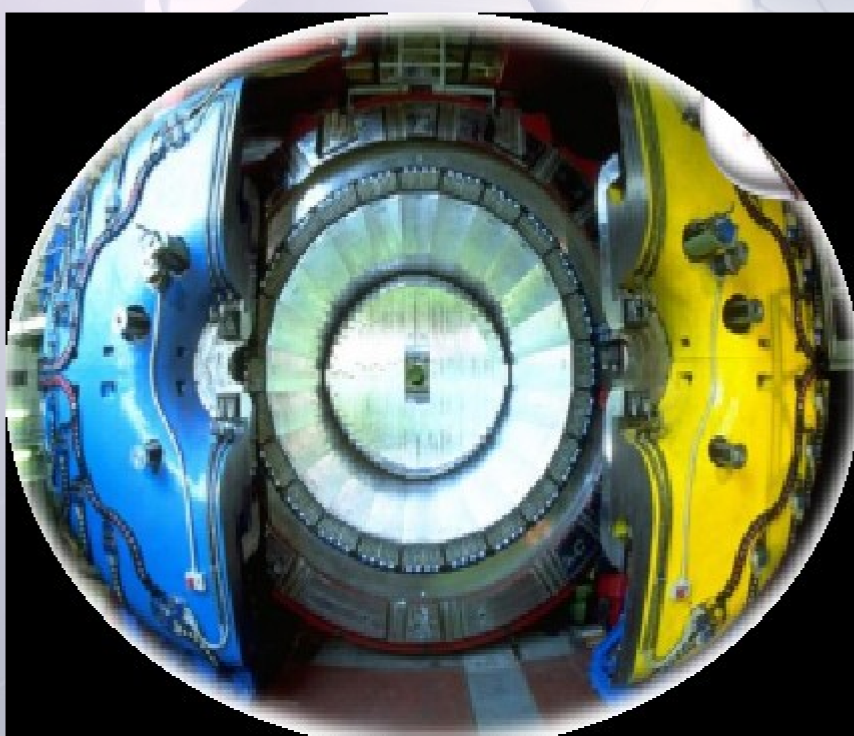
K^-

DAΦNE at LNF, INFN

Double ring $e^+ e^-$ collider working in C. M. energy of ϕ, producing ≈ 600 $K^+ K^-$ /s

$\phi \rightarrow K^+ K^-$ (BR = (49.2 ± 0.6)%)

- low momentum Kaons ≈ 127 Mev/c
- back to back $K^+ K^-$ topology



KLOE

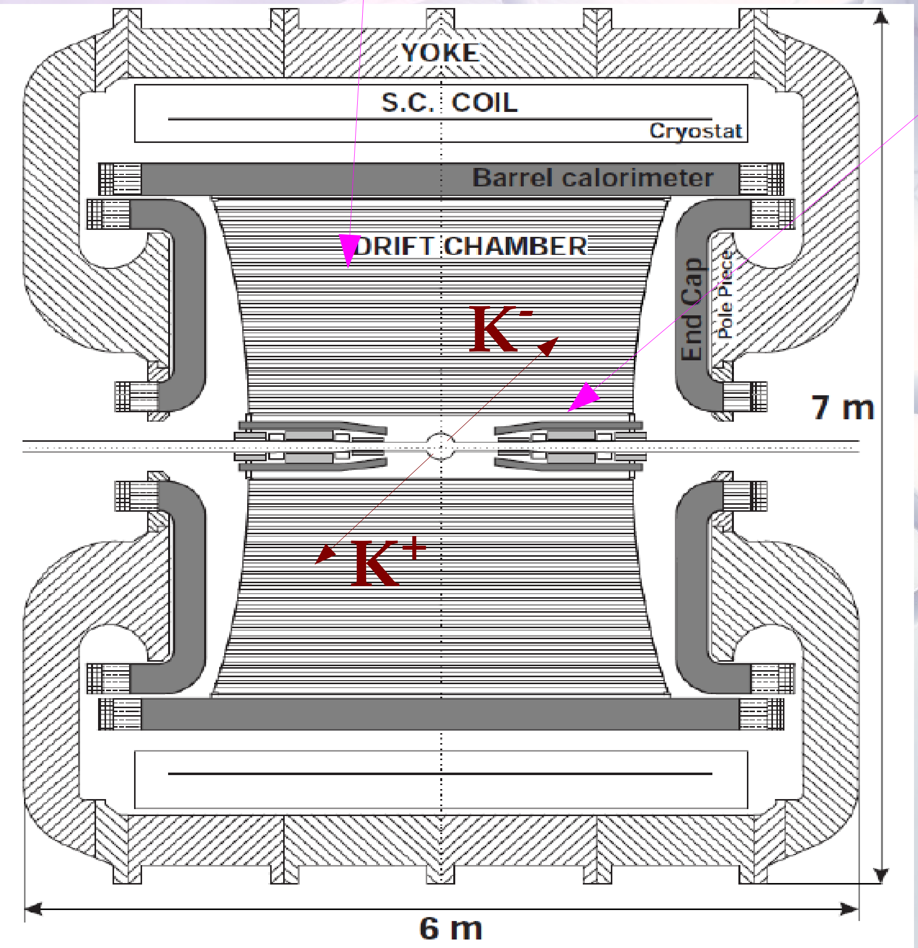
- 96% acceptance,
- optimized in the energy range of all charged particles involved
- good performance in detecting photons (and neutrons checked by kloNe group (M. Anelli et al., Nucl Inst. Meth. A 581, 368 (2007)))

How to do that? ... 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:

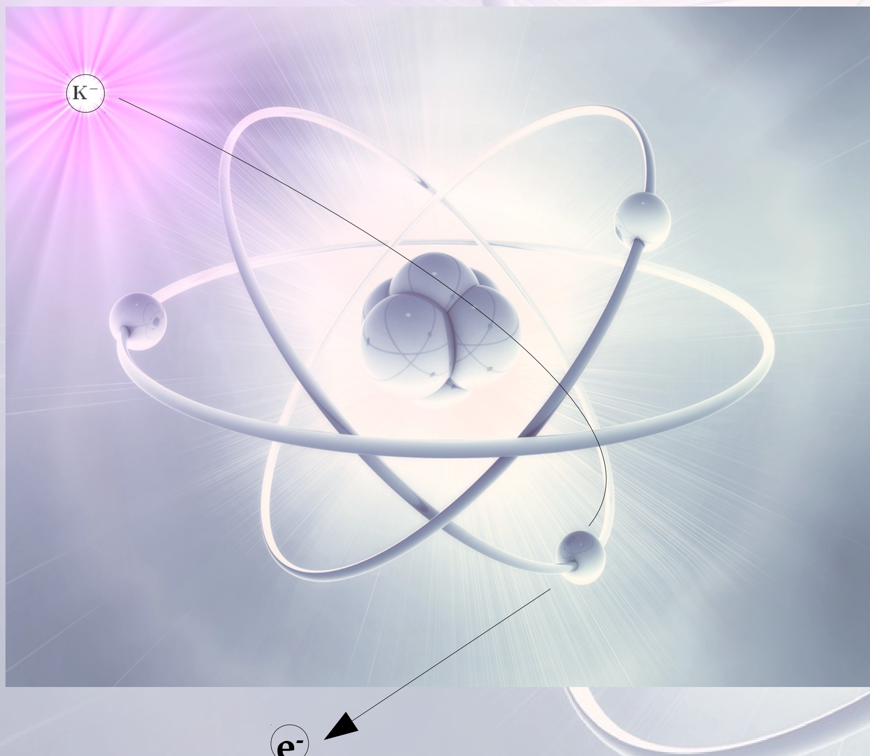
Not dedicated target → different nuclei contamination → complex interpretation .. but → new features .. K^- in flight absorption.

How to do that? ... K^- absorption on light nuclei

AT-REST

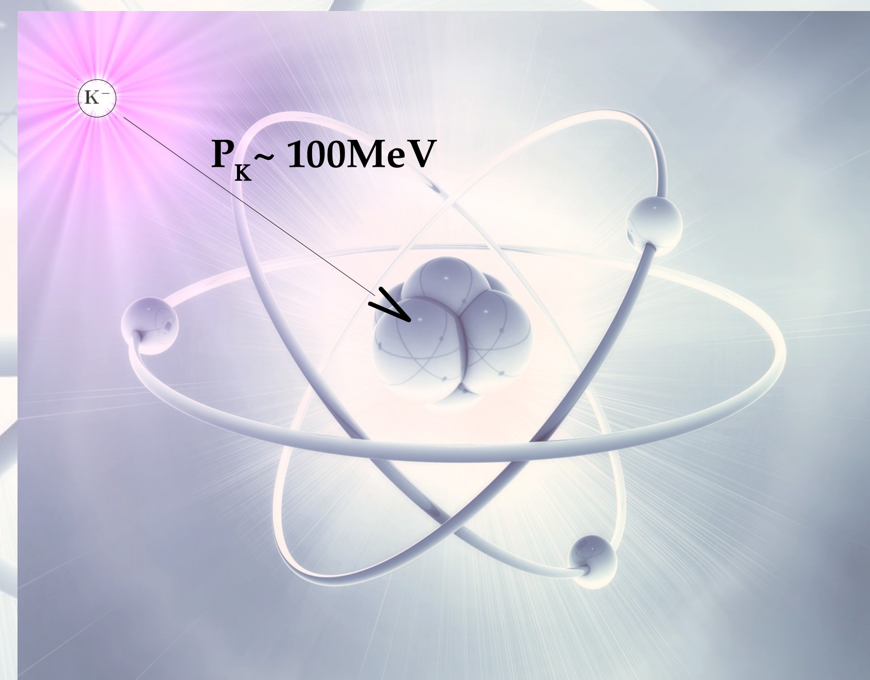
K^- absorbed from atomic orbit

(p_K ~ 0 MeV)



IN-FLIGHT

(p_K~100MeV)



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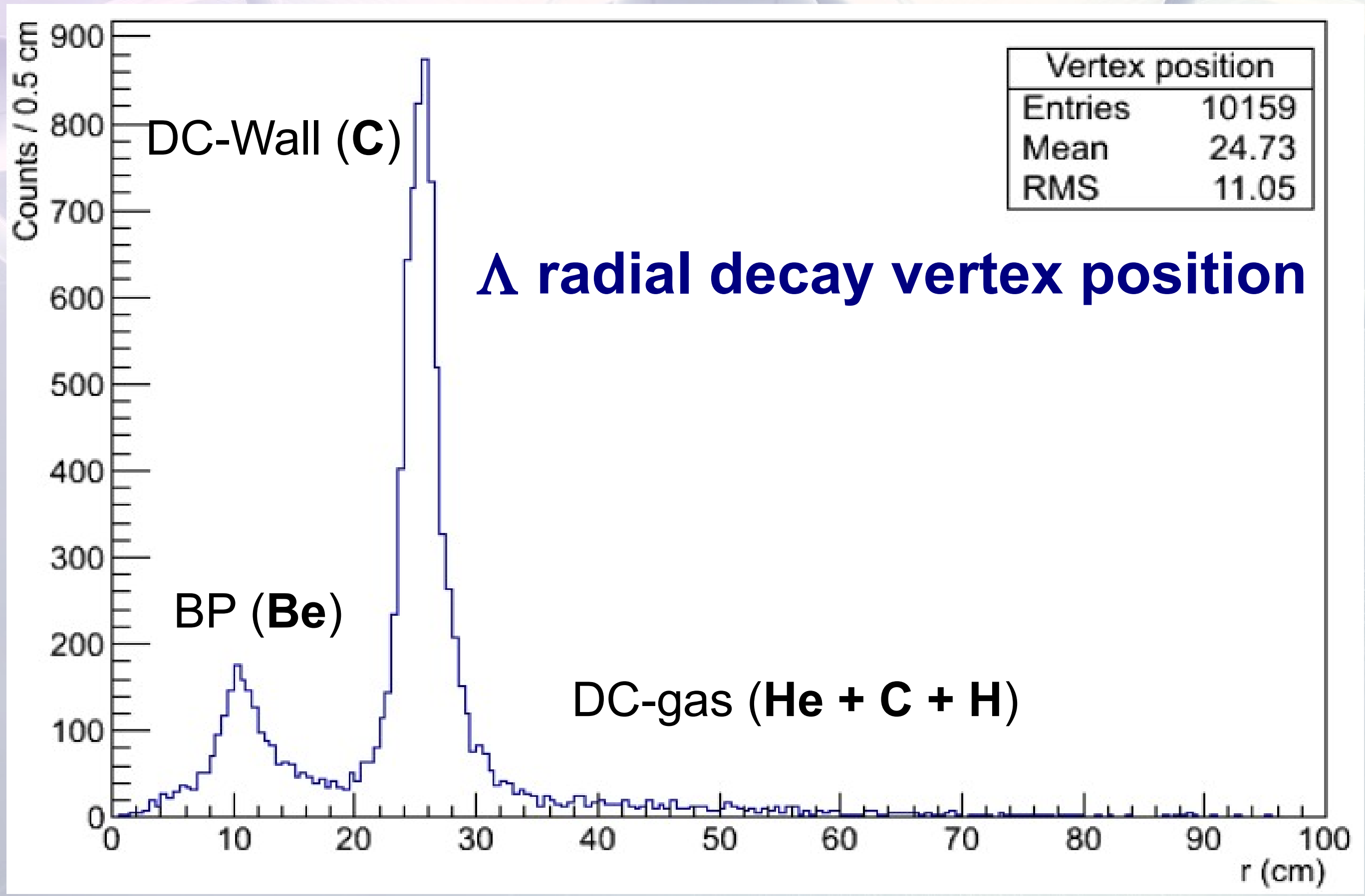

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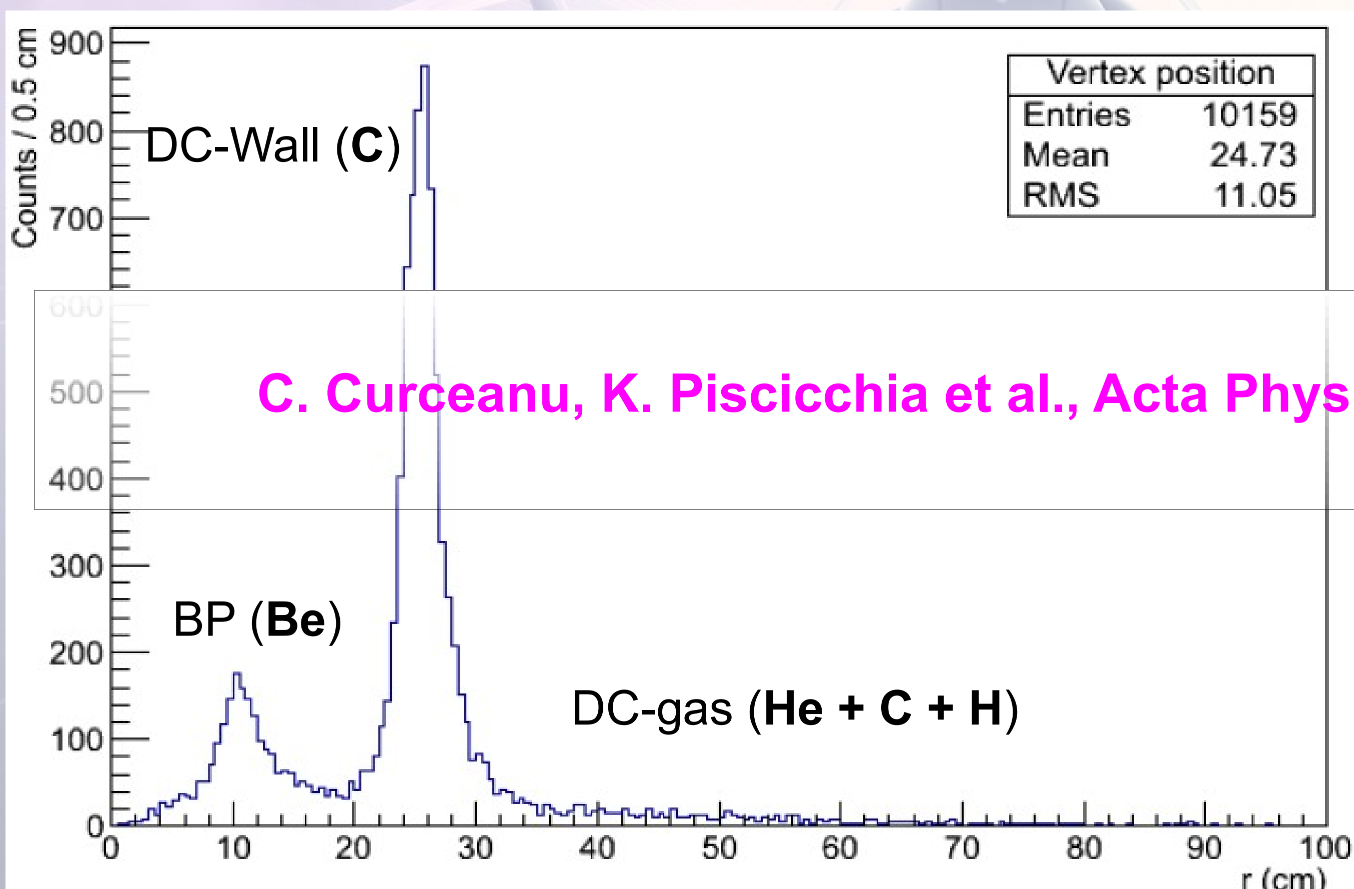


C. Curceanu, K. Piscicchia et al., Acta Phys.Polon. B46 (2015)1, 203

K^-

PART 1

Y π CORRELATION

resonant VS non-resonant production study

Λ(1405) .. resonance or/and bound state?

- **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):**

Jido D., Oller J. A., Oset E., Ramos A., Meissner U.-G., Nucl. Phys. A 725, 181 (2003), T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008), A. Cieply, J. Smejkal, Few Body Syst. 54 (2013) 1183

High mass → $\bar{K}N$ Low mass → Σπ → line-shape depends on production mechanism

- **Akaishi-Esmaili-Yamazaki phenomenological potential**

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

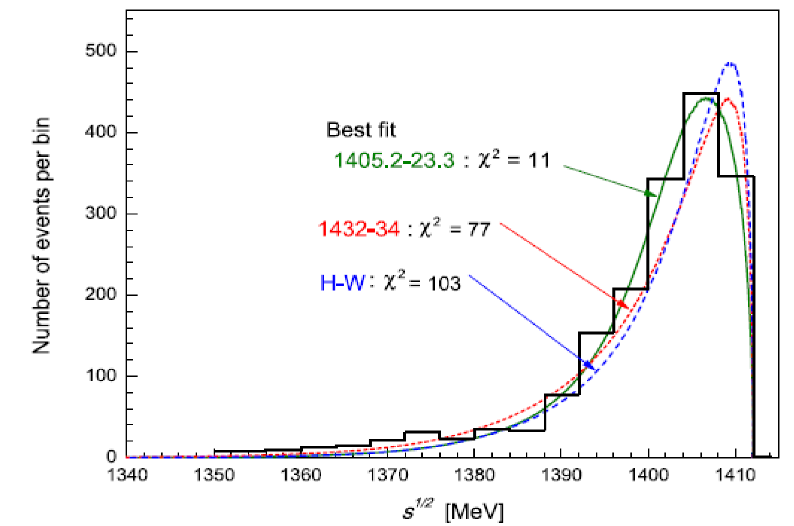
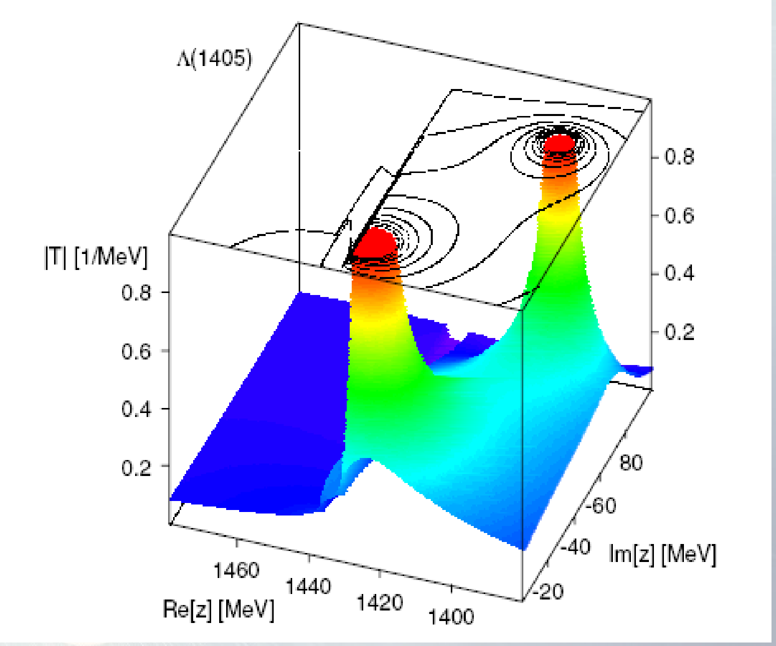


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.



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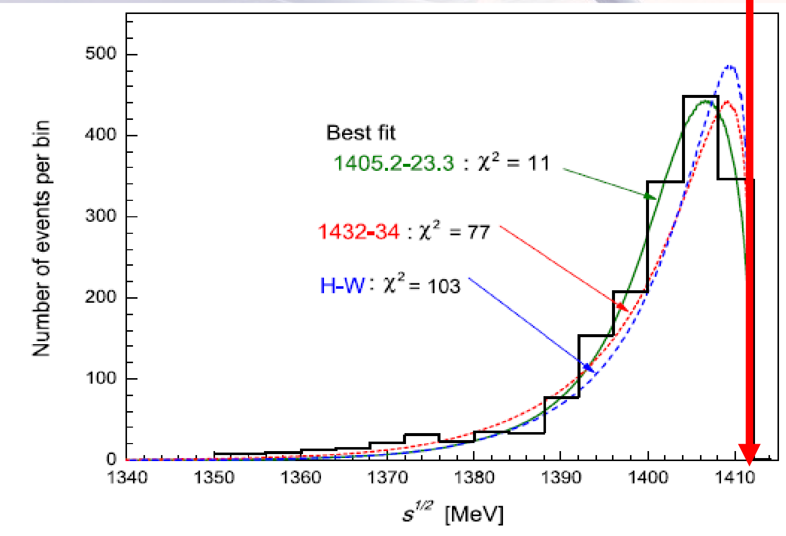

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"A study of $K^- \, {}^4He \rightarrow (\Sigma^\pm\pi^\mp) + {}^3H$ using slow instead of stopping K^- would be very useful in eliminating some of the uncertainties in interpretation"

D. Riley, et al. Phys. Rev. D11 (1975) 3065

CUT AT THE ENERGY LIMIT AT-REST ?

NON RESONANT SHAPE ?

Scientific case of the Λ(1405)

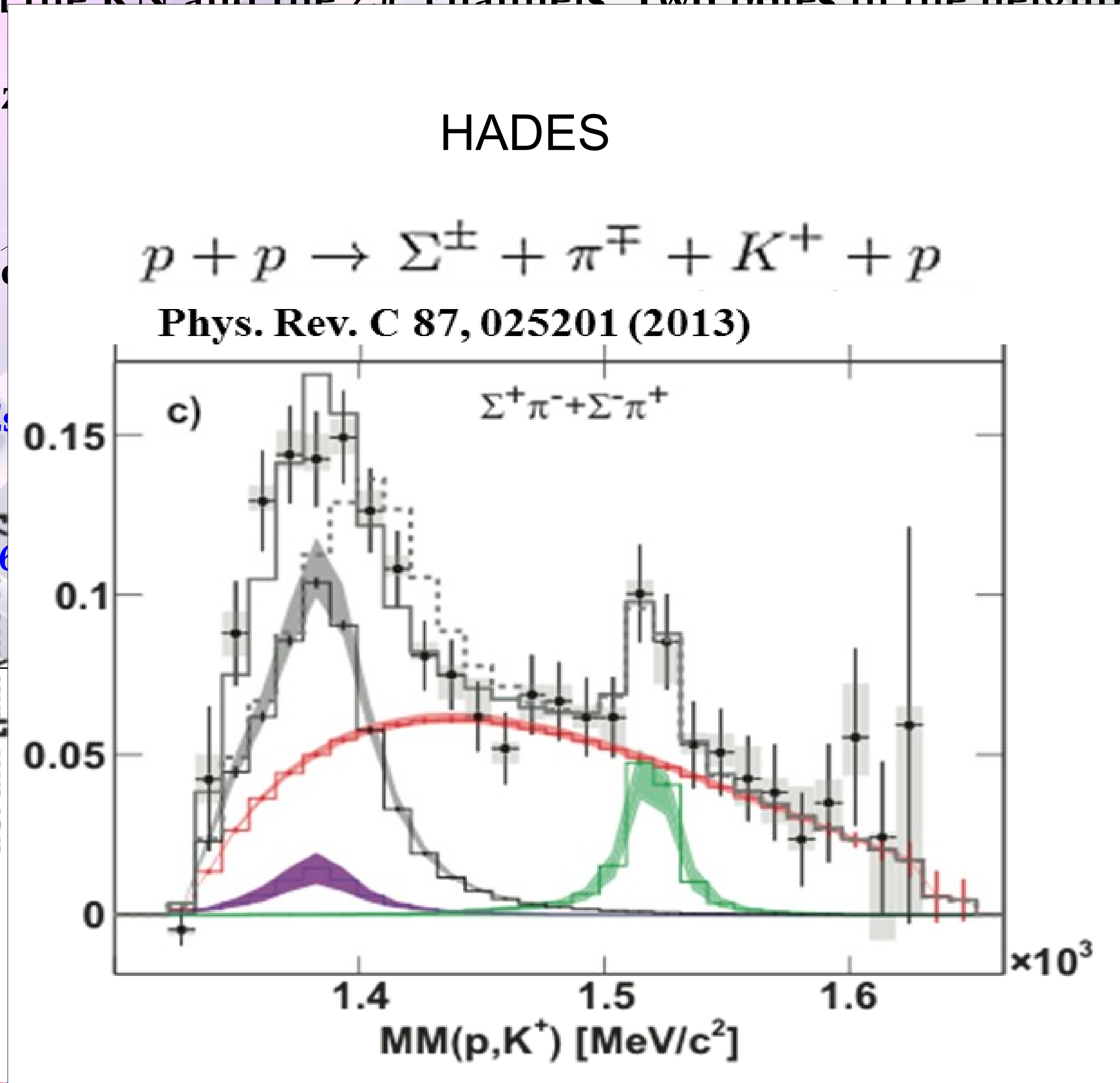
- Chiral unitary models: Λ(1405) is an I = 0 quasibound state emerging from the coupling between the $\bar{K}N$ and the $\Sigma\pi$ channels. Two poles in the neighborhood of the Λ(1405):

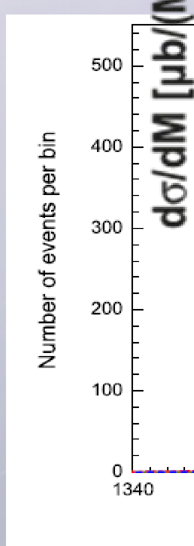
4) *two poles*: (z … Phys. A881, 98 (2012))

mainly c… depends on … mechanism

- Akaishi-E…

Phys. Lett. B…





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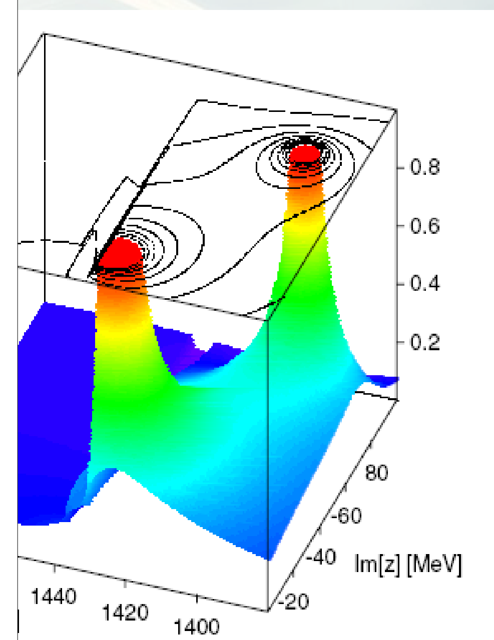


Scientific case of the $\Lambda(1405)$

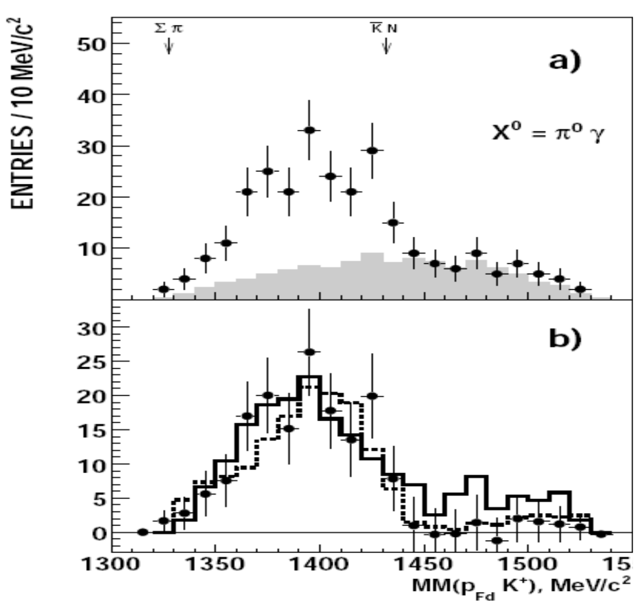
$\Lambda(1405)$ is I = 0

$\Sigma^0\pi^0$ (I =0) golden decay channel

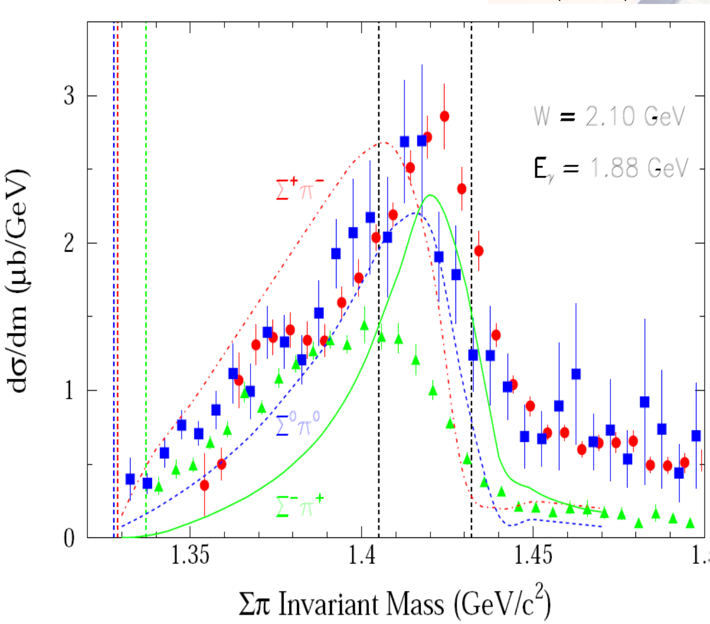
(free from $\Sigma(1385)$ background I=1)

The $\Sigma^0\pi^0$ spectrum was only observed in 3 experiments … with different line-shapes !

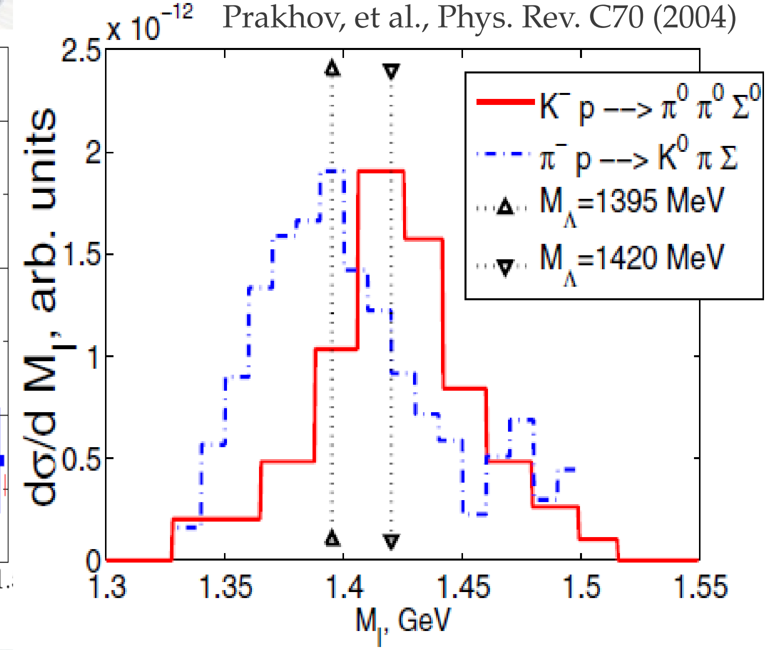
I. Zychor et al., Phys. Lett. B 660 (2008) 167



K. Moriya, et al., (Clas Collaboration) Phys. Rev. C 87, 035206 (2013)



Magas et al. PRL 95, 052301 (2005) 034605 S. Prakhov, et al., Phys. Rev. C70 (2004)



Ongoing fit of $\Sigma^0\pi^0$

K^-

8 component fit :

- **Resonant component K^- C at-rest/in-flight. $(M,\Gamma) = (1405 \div 1430\ ,\ 5 \div 52\ )$**

  better description of the resonance lineshape is needed, work in progress with the Prague group

- **Non resonant $\Sigma^0\pi^0$ K^- H production at-rest/in-flight**

- **Non resonant $\Sigma^0\pi^0$ K^- C production at-rest/in-flight**

- **$\Lambda\pi^0$ background ($\Sigma(1385)$ + I.C.)**

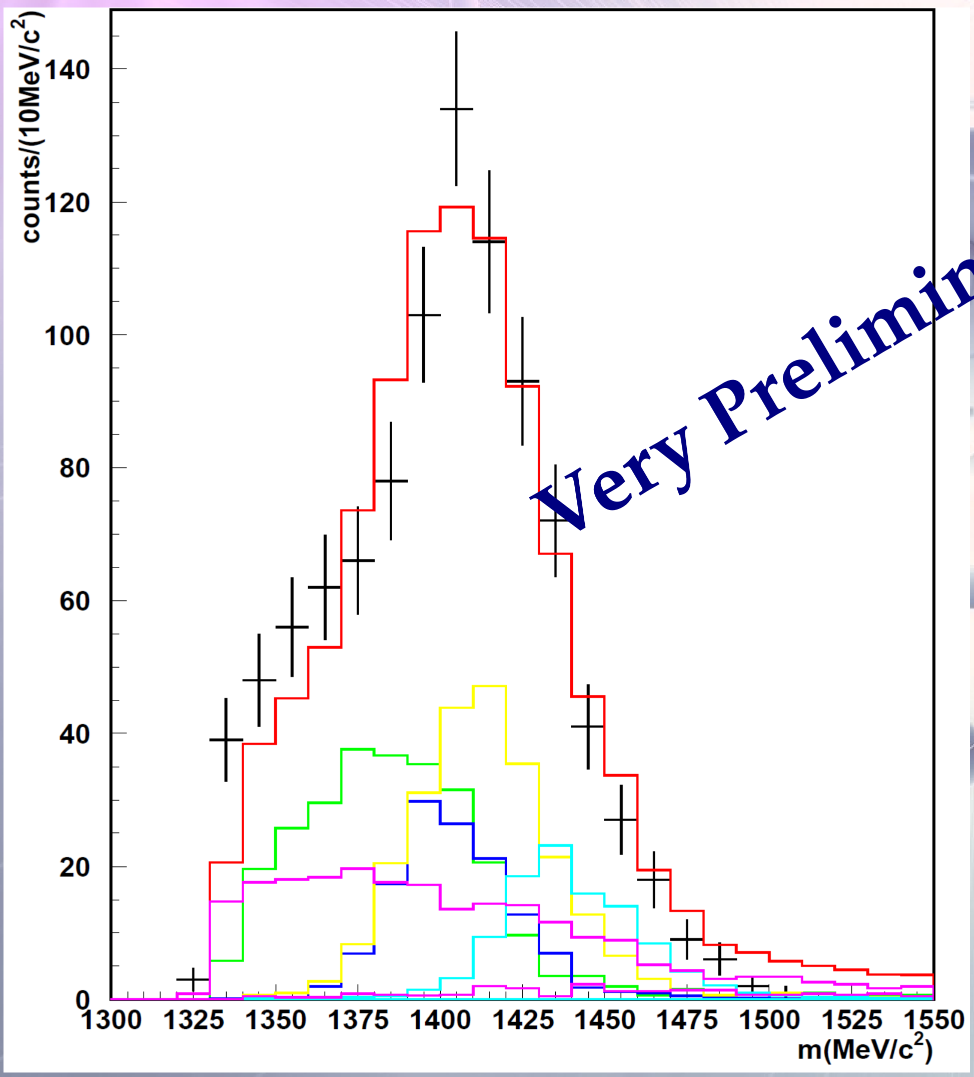
- **non resonant misidentification (*n.r.m.*) background**

Fit of $\Sigma^0\pi^0$ spectrum in C

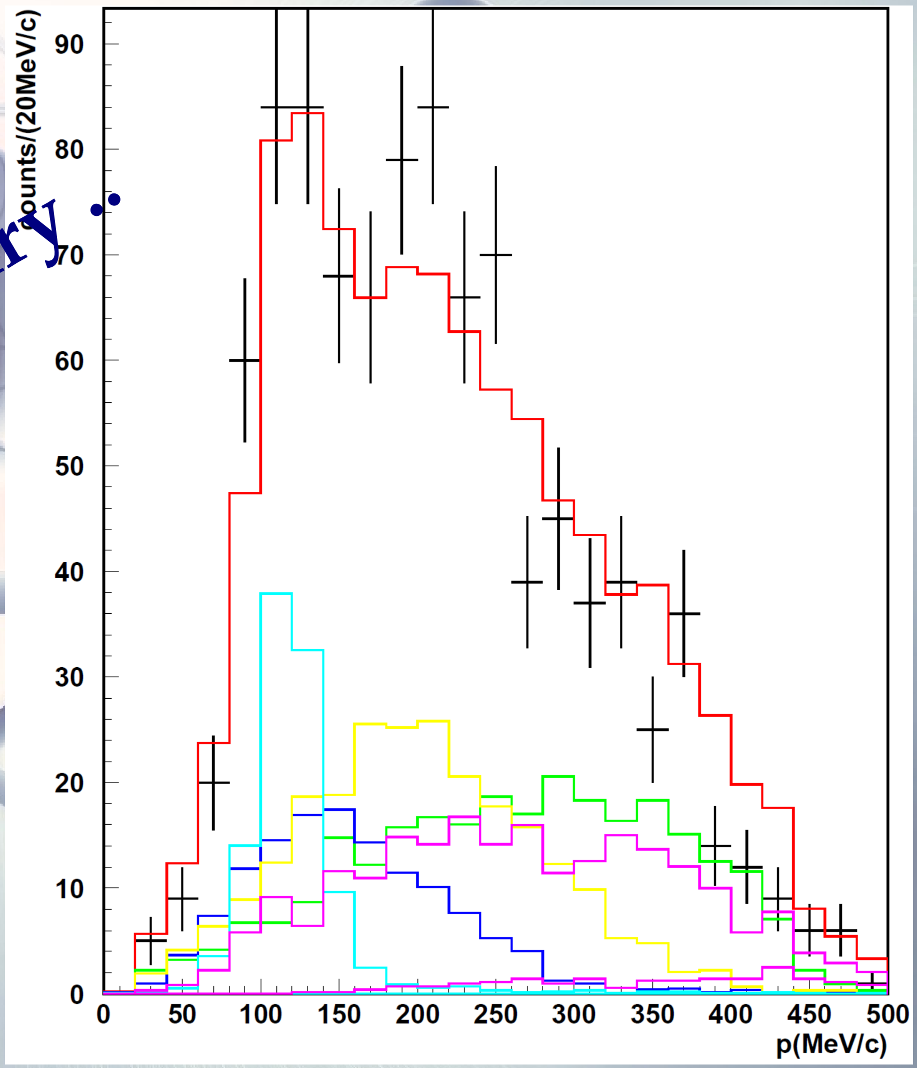
K⁻

χ^2_{min} /ndf ~ 1.7 corresponding to $(M_{min}, \Gamma_{min}) = (1426, 52)$ MeV/c²

- Global fit
- Resonant component K⁻ C at-rest
- n. r. K⁻ C at-rest
- n. r. K⁻ C in-flight
- n. r. K⁻ H in-flight
- $\Lambda^0\pi^0$ background + n. r. m.



$m_{\Sigma0\pi0}$



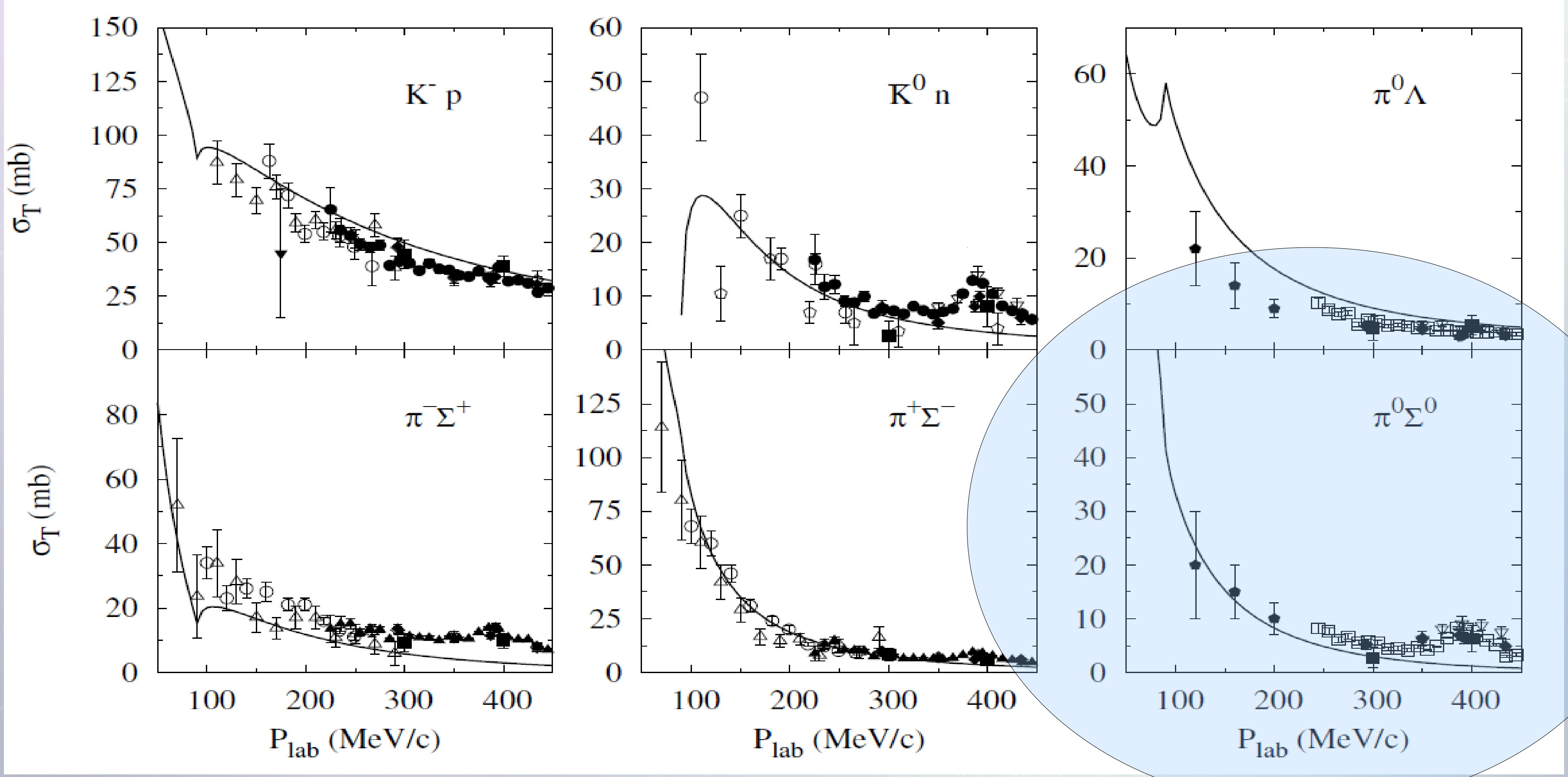
$p_{\Sigma0\pi0}$

K⁻

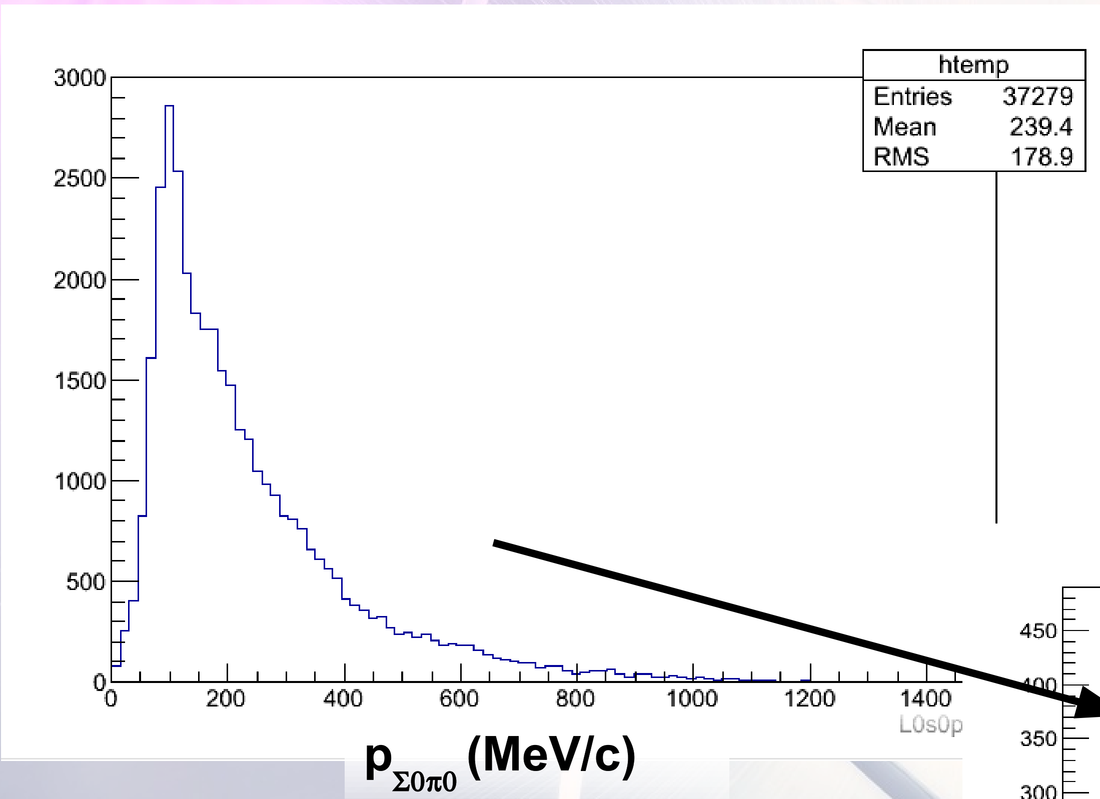
$K^- p \rightarrow \Sigma^0\pi^0$ cross section measurement at p_K~100 MeV/c

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

- $K^- p \rightarrow \Sigma^0\pi^0$ 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)

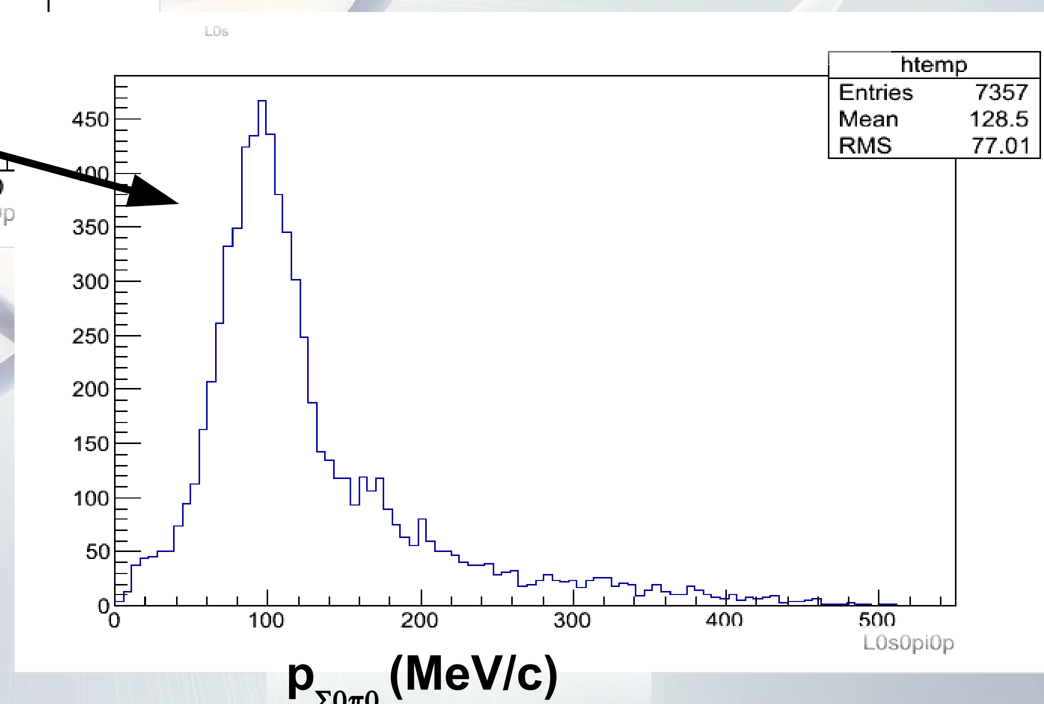


$K^- p \rightarrow \Sigma^0\pi^0$ cross section measurement at p_K~100 MeV/c



Cats 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 at p_K~100 MeV/c

K^-

Simultaneous fit of

- **Σ0-π0 momentum**
- **Σ0-π0 invariant mass**
- **Σ0-π0 angular correlation**

With 6 components:

- **K- H capture at-rest + in-flight → kinematics is closed**
- **K- 4He capture at-rest + in-flight (l_K = 1)**
- **K- 12C capture at-rest + in-flight (l_K = 2, kaon captured on valence proton)**

$$A_{K-p\rightarrow\Sigma0\pi0}(\mathbf{p}_{\Sigma0\pi0}) = \int d\mathbf{k}_{\Sigma0\pi0}\, d\mathbf{p}_R\, \phi_K(\mathbf{p}_K)\psi_p(\mathbf{k}_{pR})\, t(\mathbf{k}_{\Sigma0\pi0}, \mathbf{k}'_{\Sigma0\pi0}, E_{\Sigma0\pi0})\, \delta^3(\mathbf{p}_R - \mathbf{p}'_R).$$

Each process considered non-resonant (transition no momentum dependent)

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

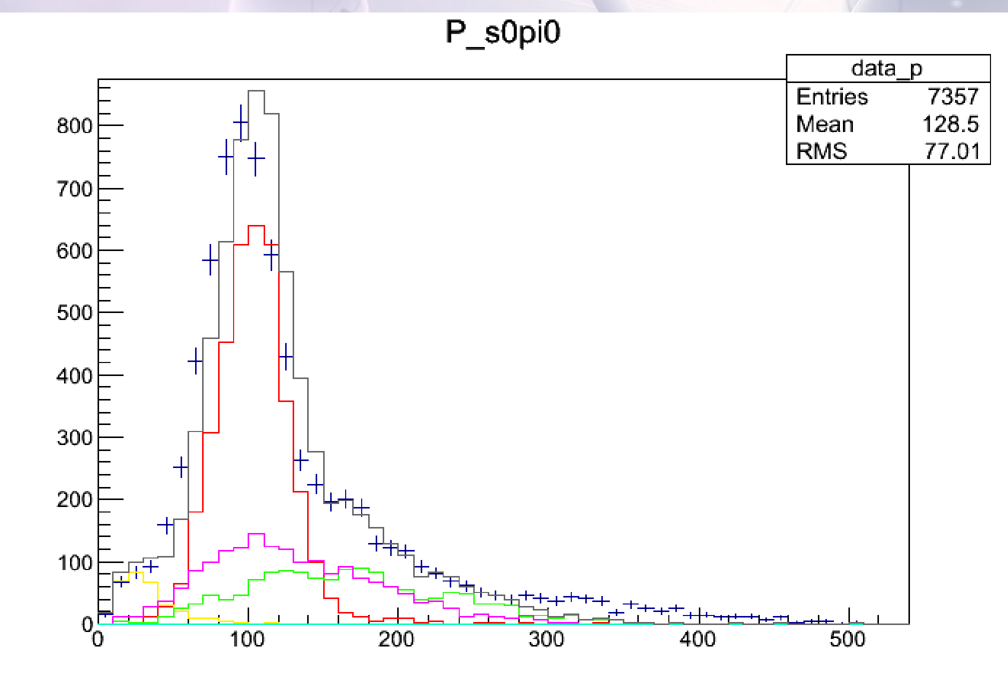
K⁻

Simultaneous fit of

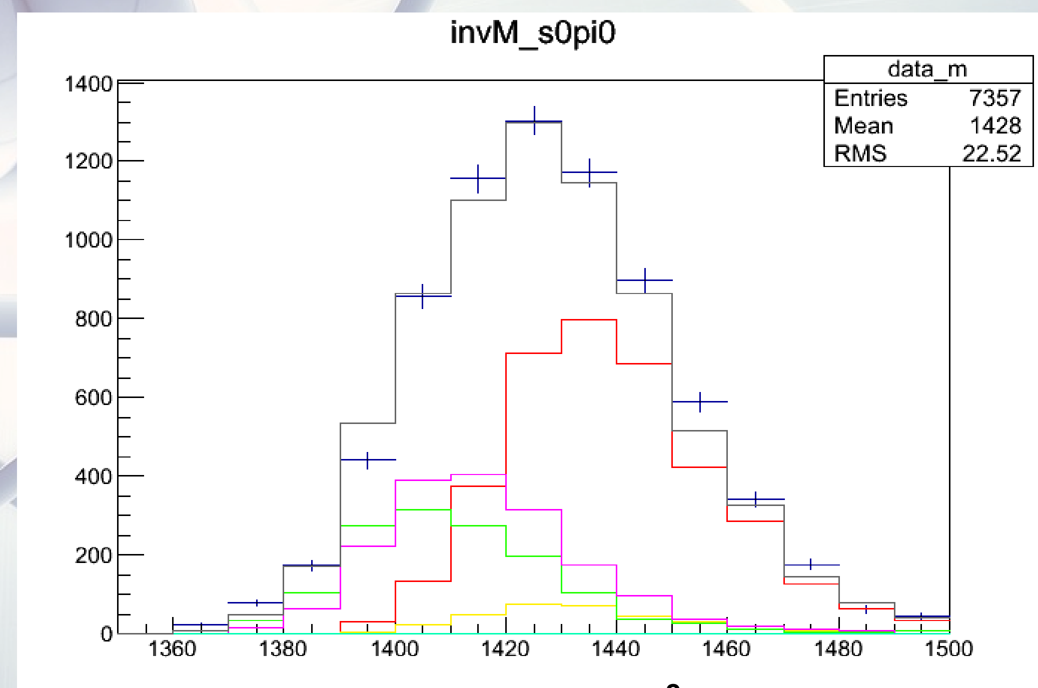
- Σ0-π0 momentum
- Σ0-π0 invariant mass
- Σ0-π0 angular correlation

With 6 components:

- K- H capture at-rest + in-flight
- K- 4He capture at-rest + in-flight
- K- 12C capture at-rest + in-flight



$p_{\Sigma0\pi0}$ (MeV/c)

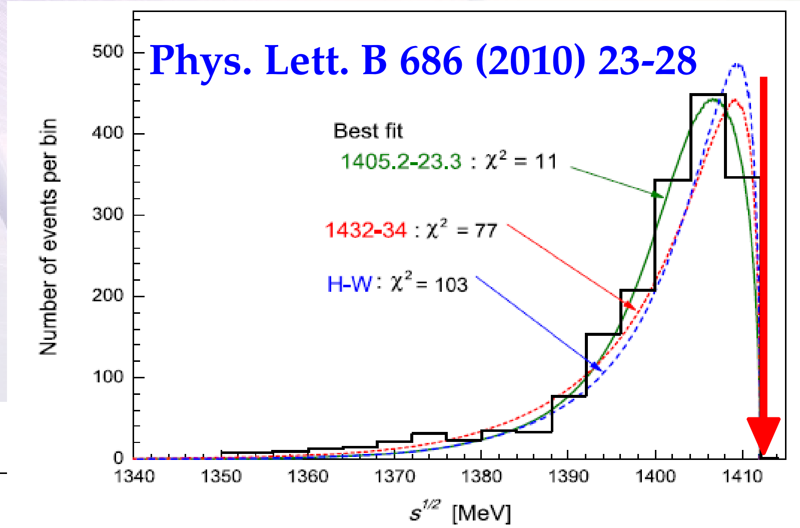


$m_{\Sigma0\pi0}$ (MeV/c^2)

$\Sigma^+\pi^-$ correlation

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

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



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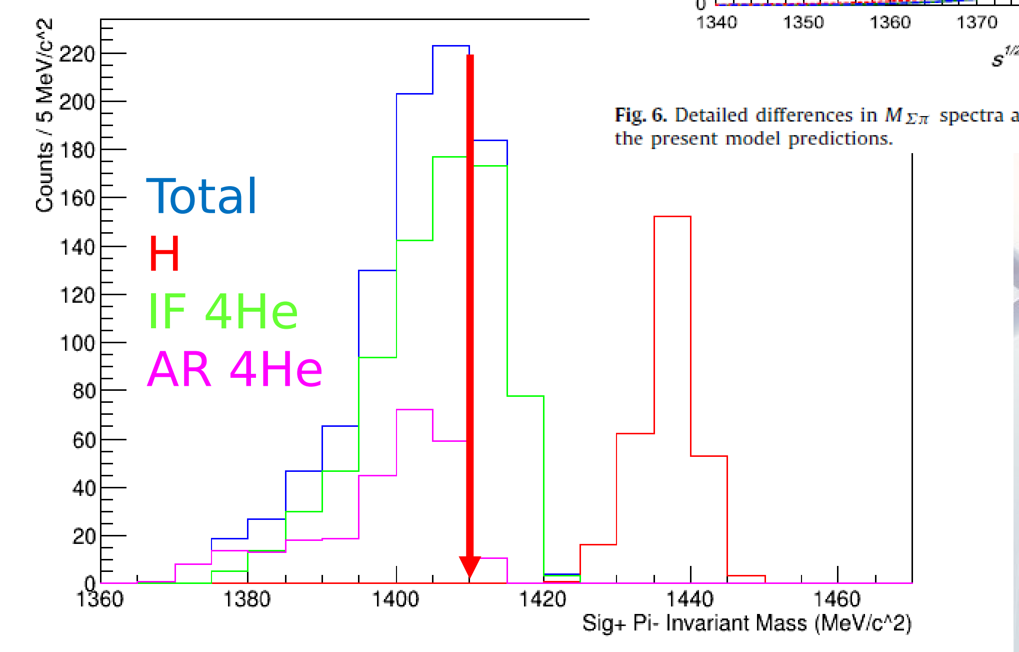

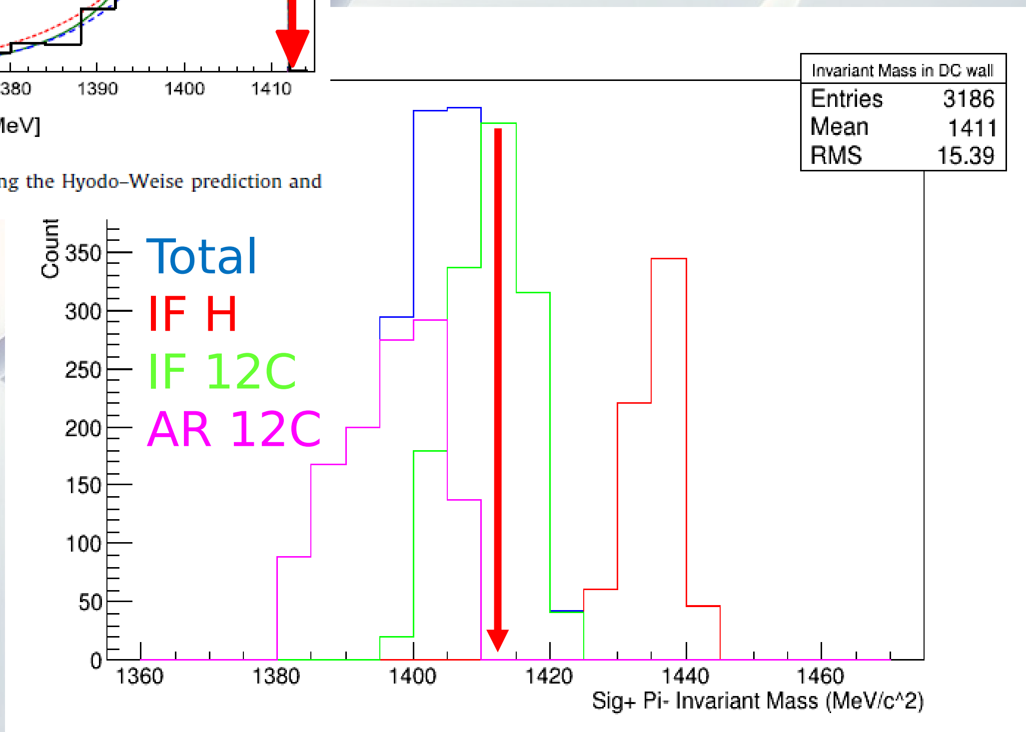

$\Sigma^+\pi^-$ correlation

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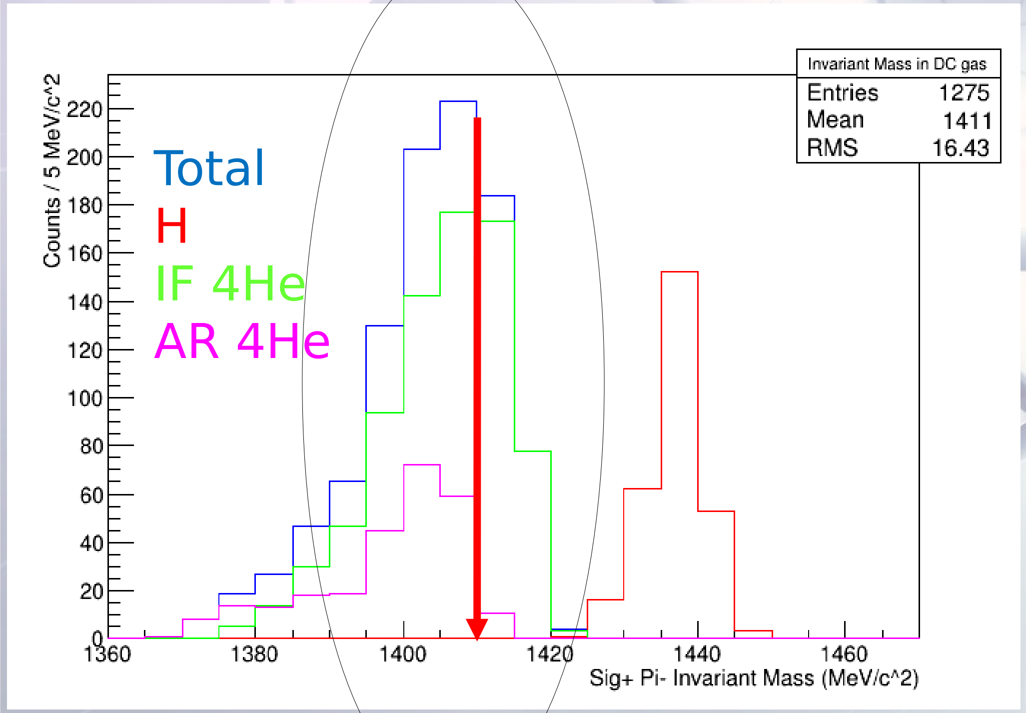
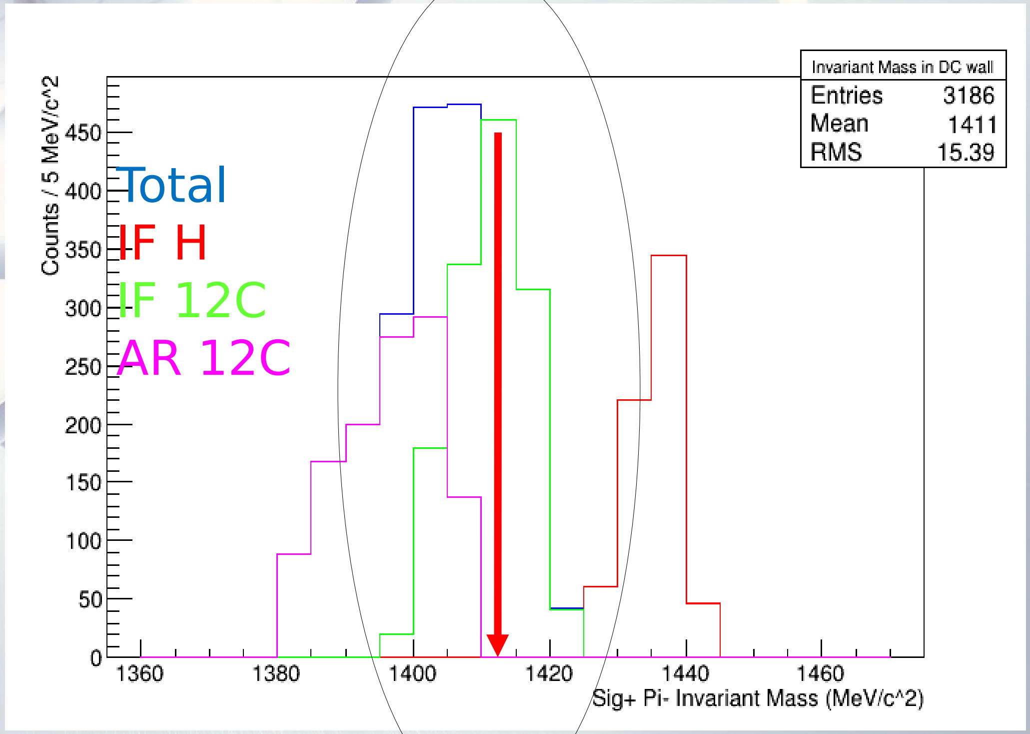
Possibility to disentangle: Hydrogen, in-flight, at-rest, K^- capture

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





Resonant VS non-resonant

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

how much comes from resonance ?

Non resonant transition amplitude:

- Never measured before below threshold

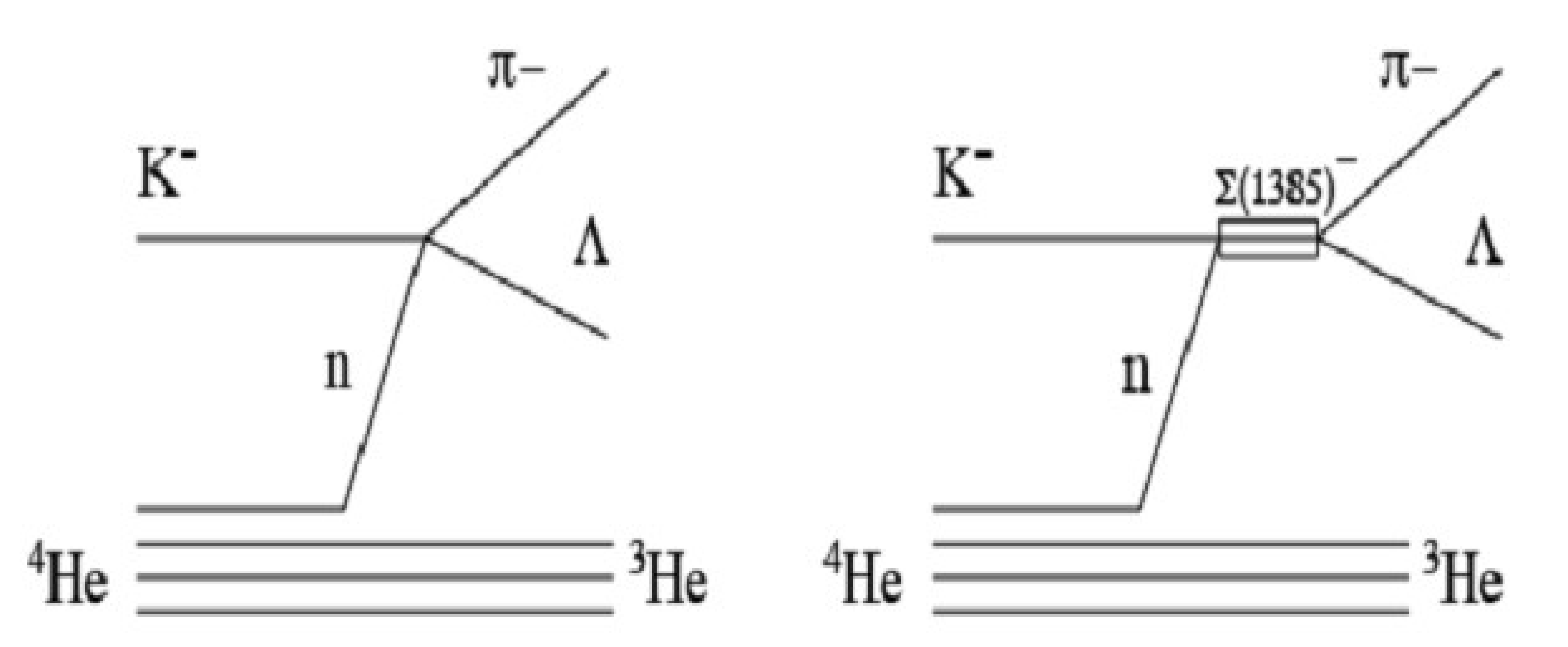
- few, old theoretical calculations (Nucl. Phys. B179 (1981) 33-48)

Resonant VS non-resonant

Investigated using:

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

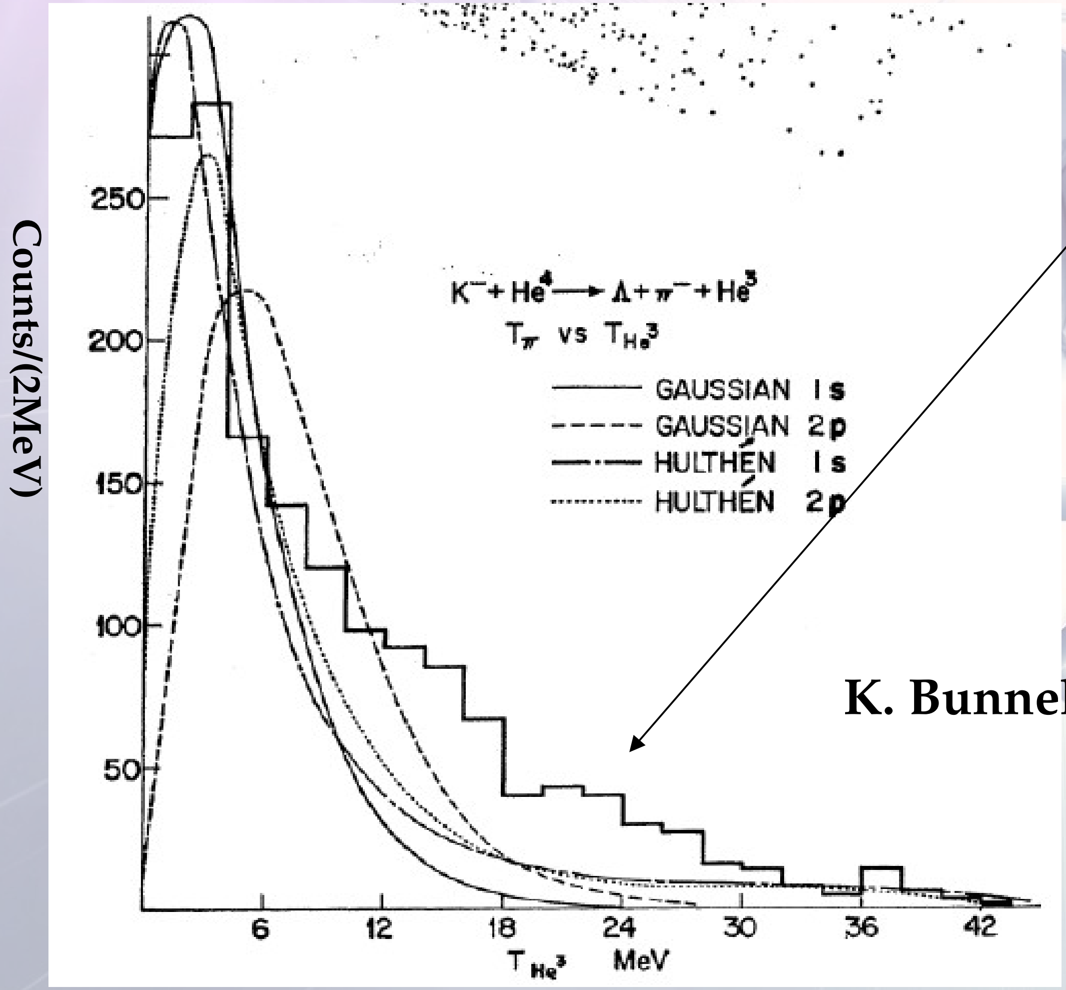
In collaboration with Prof. S. Wycech



Channel: $K^- \, {}^4He \rightarrow \Lambda \, \pi^- \, {}^3He$ … the idea

Bubble chamber experiments exhibit two components:

- Low momentum $\Lambda \pi^-$ pair → S-wave, I=1, non-resonant transition amplitude.
- High momentum $\Lambda \pi^-$ pair → P-wave resonant formation ?



Also exsists in S-state K-mesic atom

as a result of the

three body structure of the system

(K = 1, n=2, ${}^3He$ = 3)

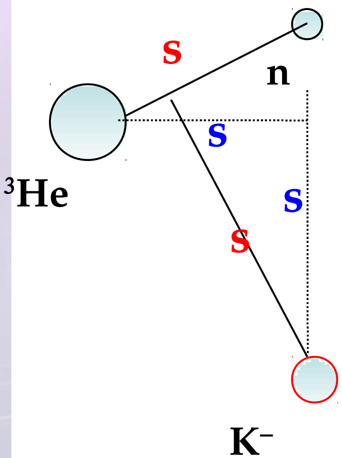
K. Bunnel et al., Phys.Rev. D2 (1970) 98

Channel: K^- $^4He \rightarrow \Lambda \pi^-$ ^3He … the idea

K⁻

$K^-(s=0)$ $^4He(s=0)$ $n(s=1/2)$ $\Sigma^{*-}(s=3/2) \rightarrow$ resonance p-wave only

atomic s-state capture:

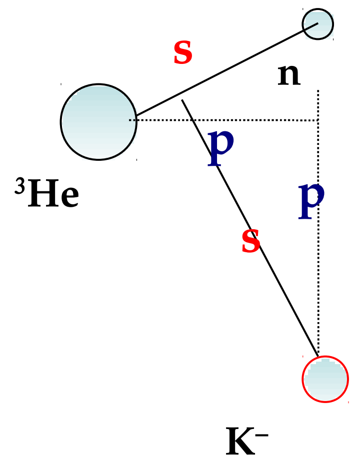


(K⁻ n) s-state interaction

Σ*⁻ not allowed

NON-RES only

+



consequence of 3-body effect

(K⁻ n) p-state interaction

Σ*⁻ allowed

- (K^- $^4He \rightarrow \Lambda \pi^-$ ^3He) absorptions from (n s) - atomic states dominate → consistent with ^4He bubble chamber data (Fetkovich, Riley interpreted by Uretsky, Wienke)

- Coordinates recupling enables for P-wave resonance formation

Channel: $K^- \, {}^4He \rightarrow \Lambda \, \pi^- \, {}^3He$ … <u>the strategy</u>

K^-

- **To determine *for the first time* the ratio resonant/non-res**

33 MeV below threshold

$|f^{N\text{-}R}_{\Lambda\pi}|$ given the fairly well known $|f^{\Sigma^*}_{\Lambda\pi}|$

Theoretical paper under finalization

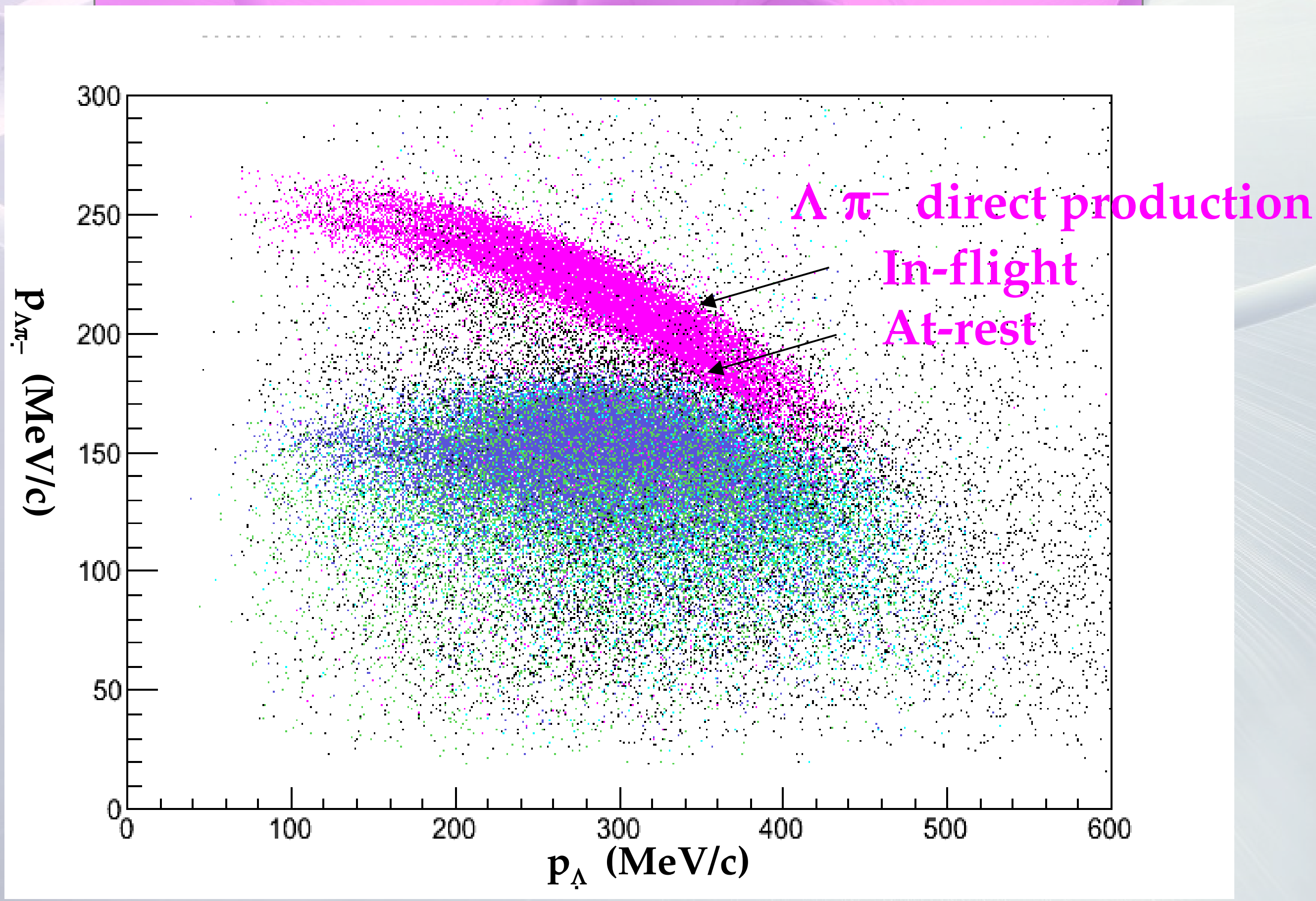
Channel: $K^- \, {}^4He \rightarrow \Lambda \pi^- \, {}^3He$ … calculated reactions

$K^- \, {}^4He \rightarrow \Lambda \pi^- \, {}^3He$

At-rest : S-wave non-Res / P-wave Σ(1385) Res

In-flight : S-wave non-Res / P-wave Σ(1385) Res

Direct $\Lambda \pi^-$ production .. SIGNAL

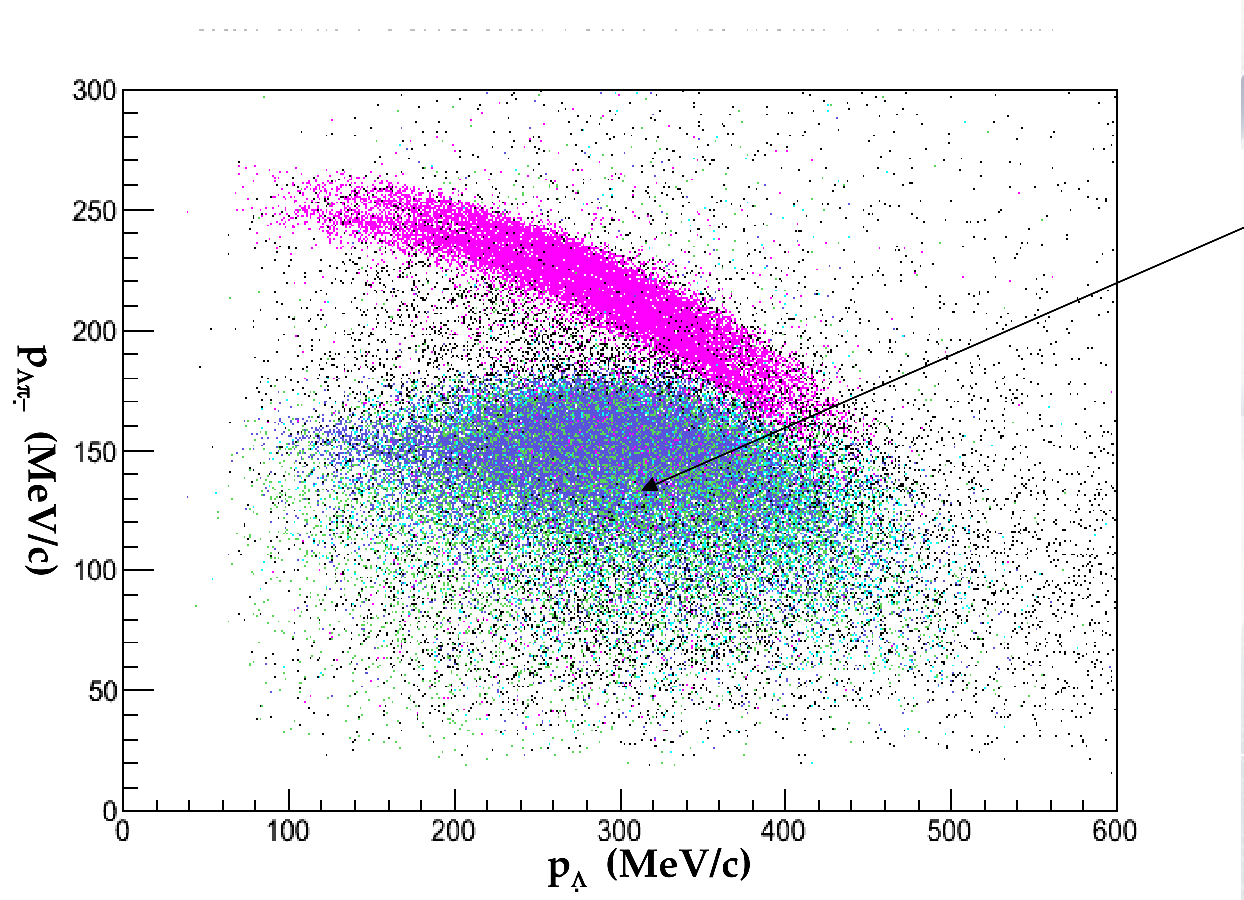


Channel: $K^- \, {}^4He \rightarrow \Lambda \pi^- \, {}^3He$ … calculated reactions

NOT Direct $\Lambda \pi^-$ production .. BACKGROUND

Λ comes from the Σ hyperon conversion on residual nucleons

$K^- N \rightarrow \Sigma^0\pi^- / \Sigma^+\pi^-$; $\Sigma N \rightarrow \Lambda N'$



NOT direct

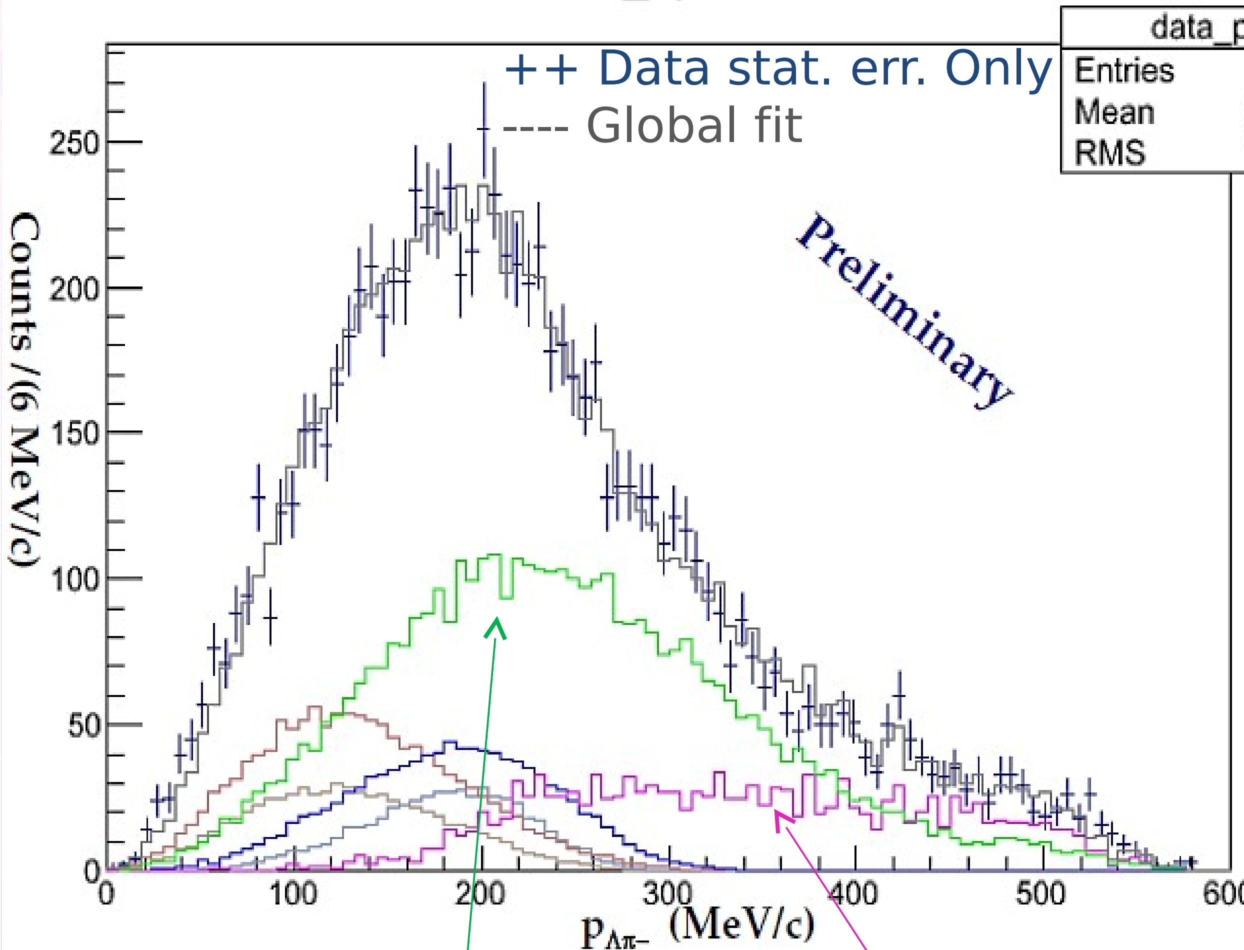
$\Lambda \pi^-$ production

Σ^0 p conversion

Σ^0 n conversion

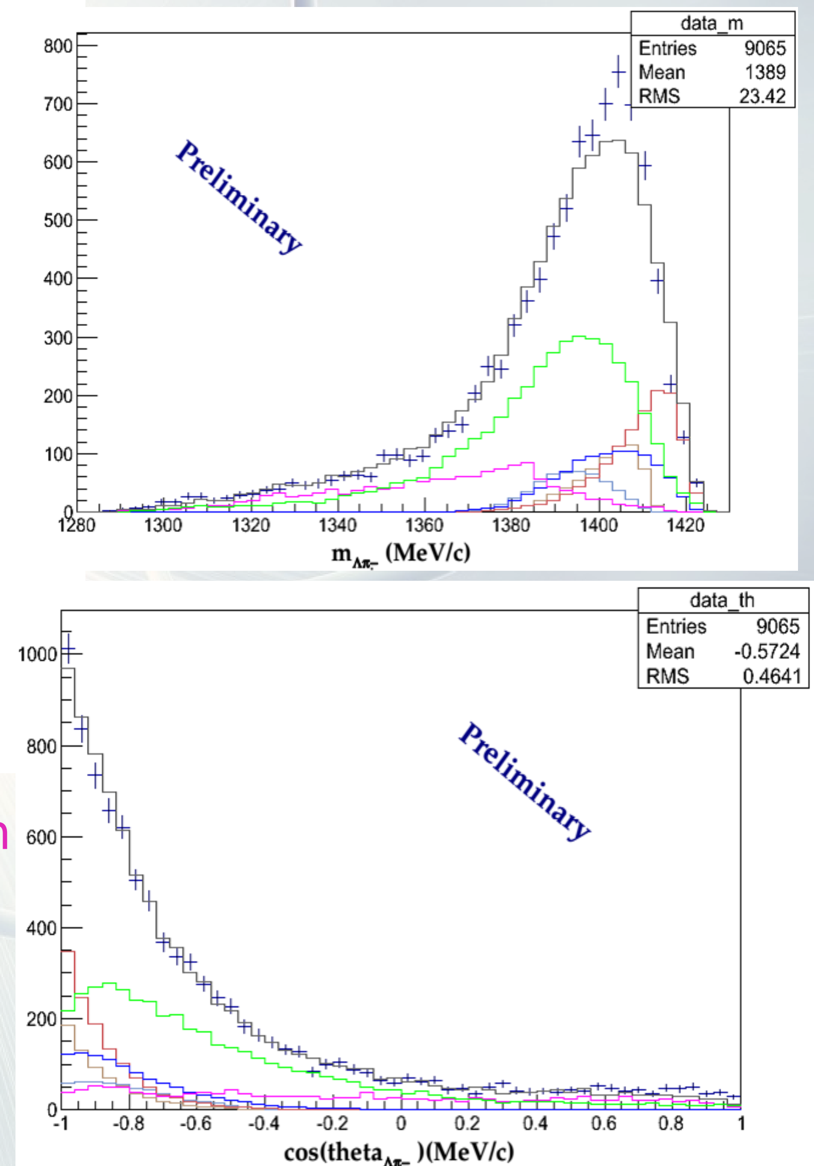
Σ^+ n conversion

$K^- \, {}^4He \rightarrow \Lambda \pi^- \, {}^3He$ preliminary fit



Simultaneous fit

$(p_{\Lambda\pi^-} - m_{\Lambda\pi^-} - \theta_{\Lambda\pi^-})$



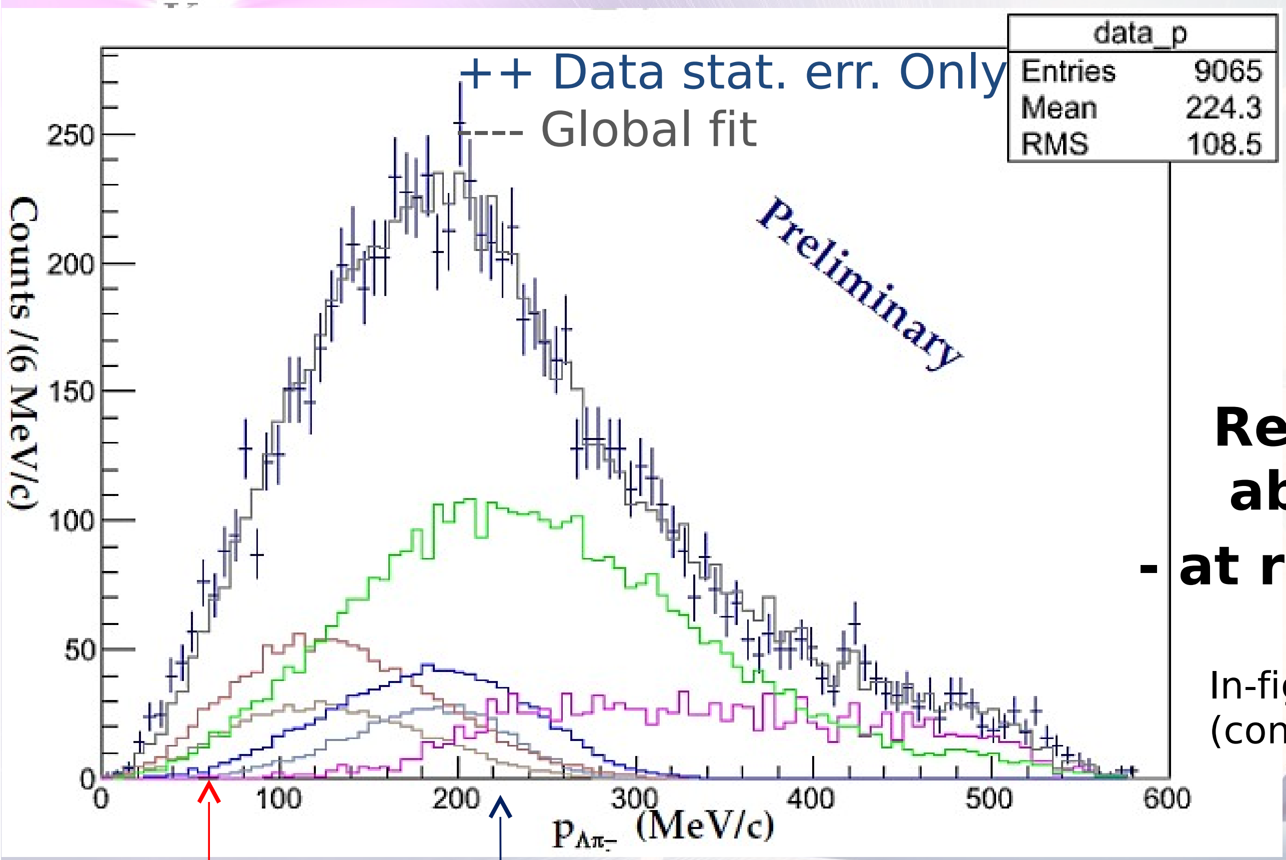
Absorptions in 12C (from Carbon wall data)

Σ/Λ nuclear conversion

K-N→Σ **π**

→ΣN→**Λ**N'

$K^- \, {}^4He \rightarrow \Lambda \pi^- \, {}^3He$ preliminary fit



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

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

Simultaneous fit

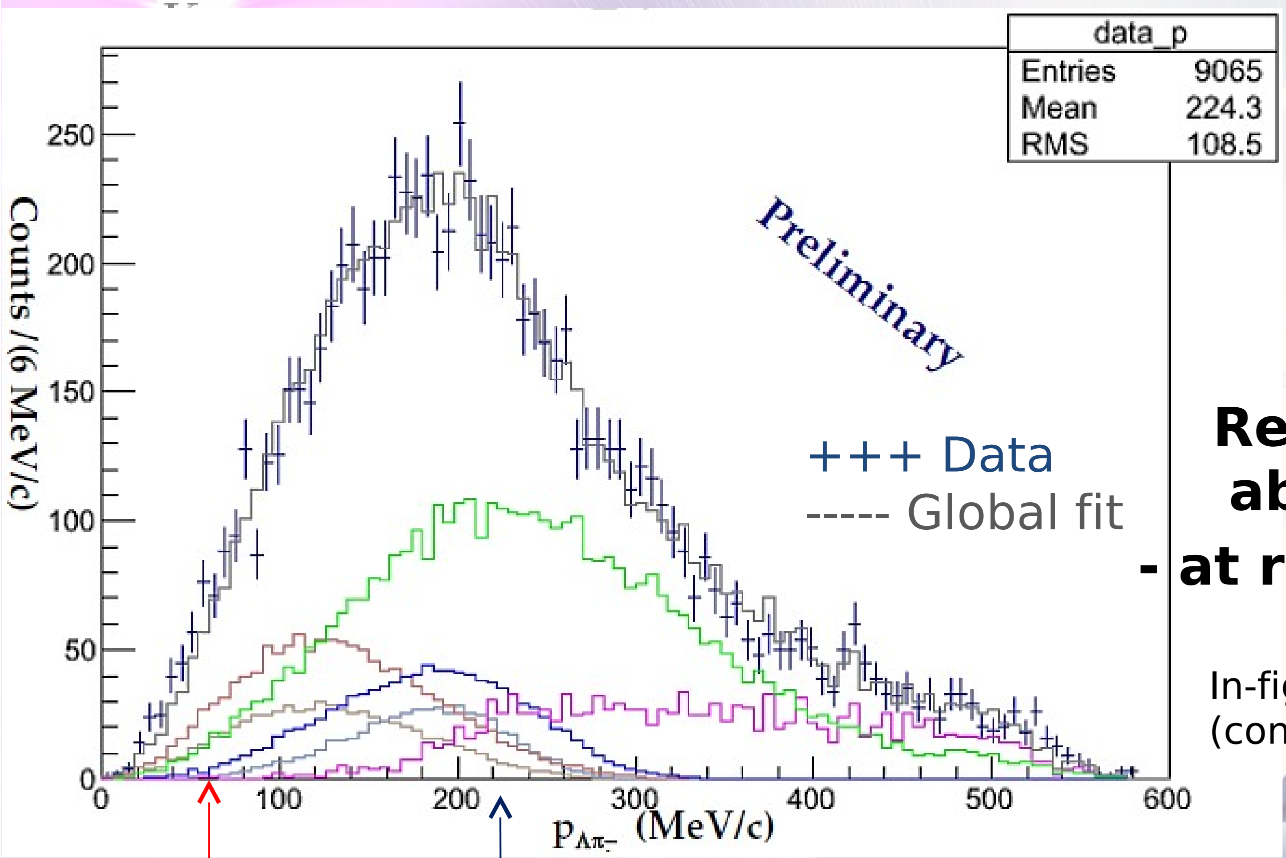
$(p_{\Lambda\pi^-} - m_{\Lambda\pi^-} - \theta_{\Lambda\pi^-})$

Resonant/non-resonant absorption ratio:

- at rest = 1.26 ± 0.06 (stat)

In-fight/at-rest ratio = 1.9 ± 0.4 (stat)
(consistent with $\Sigma+\pi-$ data = 2.2 ± 0.05)

$K^- \ ^4He \rightarrow \Lambda \pi^- \ ^3He$ preliminary fit



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

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

Simultaneous fit

($p_{\Lambda\pi^-}$ - $m_{\Lambda\pi^-}$ - $\theta_{\Lambda\pi^-}$)

Resonant/non-resonant absorption ratio:

- at rest = 1.26 ± 0.06 (stat)

In-fight/at-rest ratio = 1.9 ± 0.4 (stat)
(consistent with $\Sigma+\pi-$ data = 2.2 ± 0.05)

The **K-n→ Λπ–** S-wave amplitude |fs| (fm) is extracted

$E = -33 MeV$	$p_{lab} = 120\ MeV/c$	160	200	245
0.22(0.01+0.06)	0.33(11)	0.29(10)	0.24 (6)	0.28(2)
preliminary				

Λπ0 data from J. Kim, Nucl. Phys. B 129 (1977) 1.

Conclusions part 1

- $m_{\Sigma\pi}$ spectra show a **high invariant mass component** → associated to in-flight K^- capture

- **PRELIMINARY** $\Lambda\pi^-$ **first measurement of N-R $(I=1)_{\Lambda\pi}$ amplitude below threshold**

Next steps …

- **Analysis is ongoing for $\Sigma^0\pi^-$** → extraction of $|f^{N\text{-}R}_{\Sigma 0\pi-}(I=1)|$
- **Similar description of $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ production** → extraction of $|f^{N\text{-}R}_{\Sigma+\pi-}|$ and $|f^{N\text{-}R}_{\Sigma-\pi+}|$, a comparison of these could give an estimate of

$|f^{N\text{-}R}_{\Sigma+\pi-}(I=0) + f^{N\text{-}R}_{\Sigma+\pi-}(I=1)|$ against $|f^{N\text{-}R}_{\Sigma+\pi-}(I=0) - f^{N\text{-}R}_{\Sigma+\pi-}(I=1)|$

K^-

PART 2

Single & multi – nucleon K^- absorption

kaonic nuclear clusters

investigation through

Λ – d,t

correlation

Λp correlation study .. PART 2a

K⁻

How deeply can an Antikaon be bound to a nucleus?

Possible bound states: K^-pp – K^-ppn

$K^-pp \rightarrow \Lambda/\Sigma\ p$; $K^-ppn \rightarrow \Lambda d$

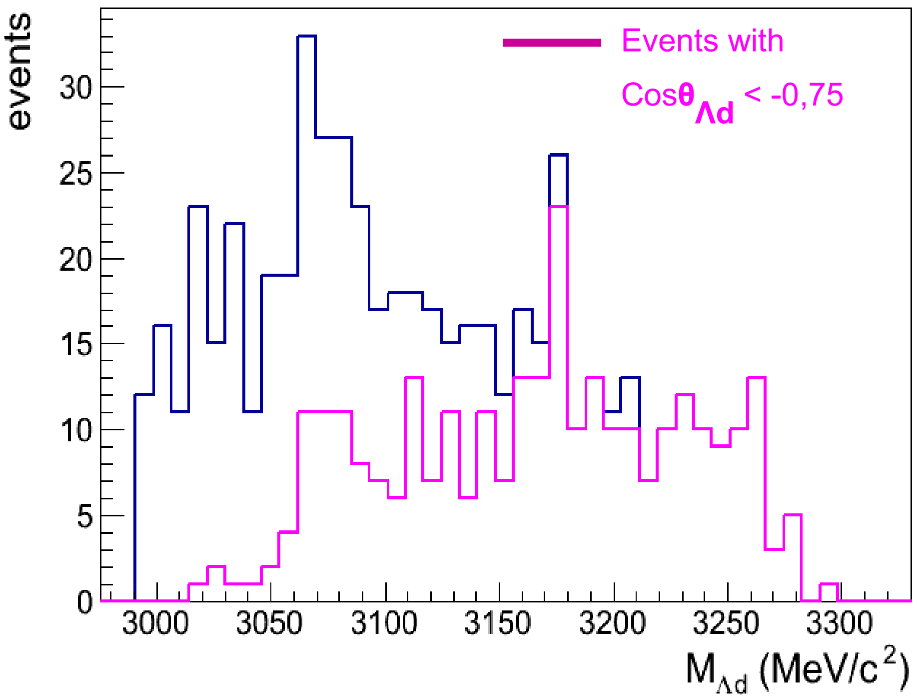
predicted due to the strong $\bar{K}N$ interaction in the I=0 channel. (Wycech (1986) - Akaishi & Yamazaki (2002))

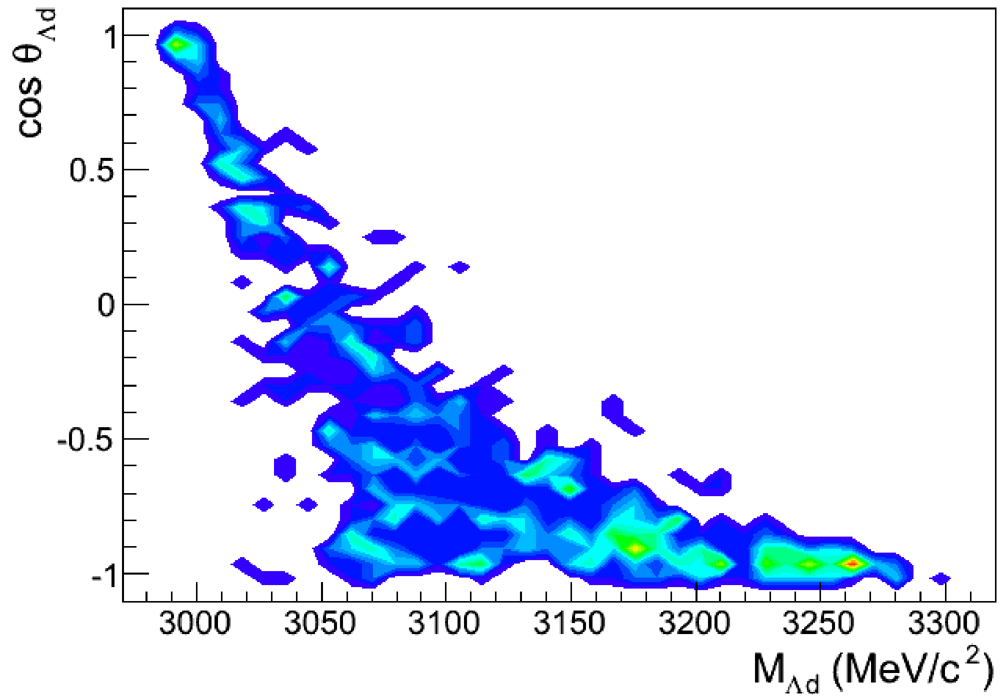
Different theoretical approaches:
- Few-body calculations solving Faddeev equations
- Variational calculations with phenomenological KN potential
- KN effective interactions based on Chiral SU(3) dynamics

K^-pp bound state

	Theoretical prediction	B.E (MeV)	Γ (MeV)
PRC76, 045201 (2002)	T. Yamazaki and Y. Akaishi	48	61
arXiv:0512037v2[nucl-th]	A. N. Ivanov, P. Kienle, J. Marton, E. Widman	118	58
PRC76, 044004 (2007)	N. V. Shevchenko, A. Gal, J. Mares, J. Revai	50~70	~100
PRC76, 035203 (2007)	Y. Ikeda and T. Sato	60~95	45~80
NPA804, 197 (2008)	A. Dote, T. Hyodo, W. Weise	20±3	40~70
PRC80, 045207 (2009)	S. Wycech and A. M. Green	56.5~78	39~60
PRL B712, 132-137 (2012)	Barnea et al.	15.7	41.2

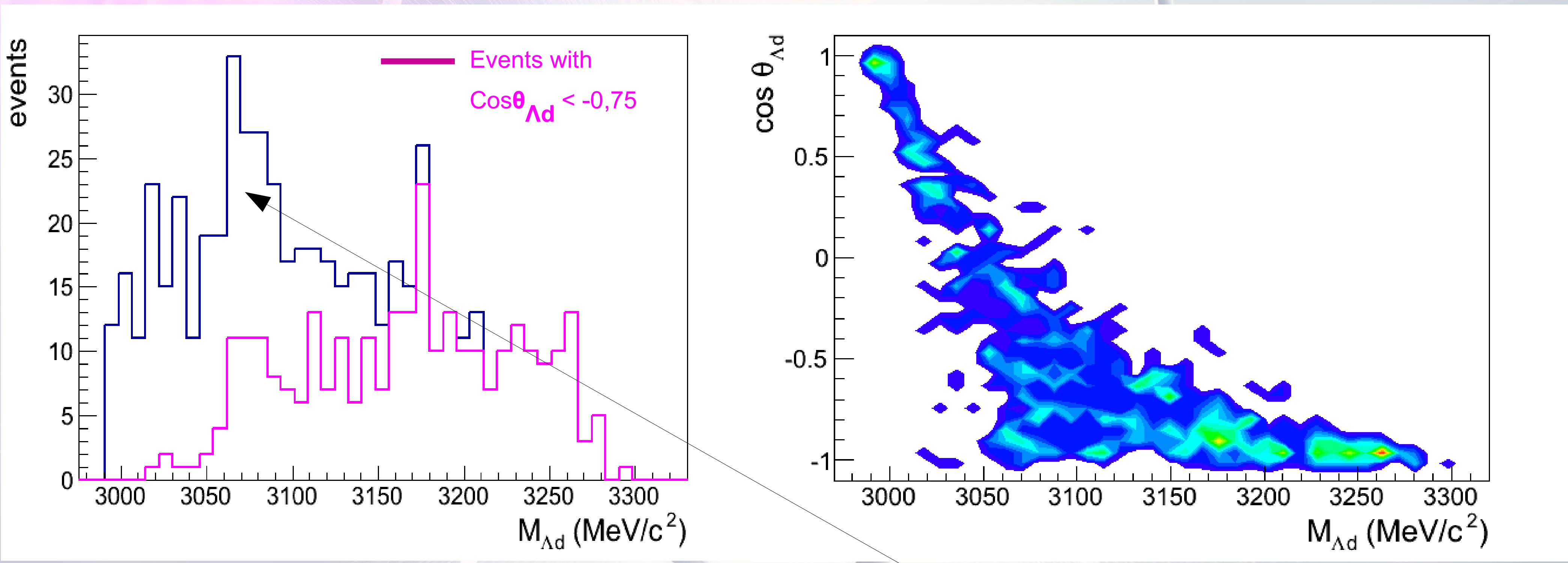
Λd search for a K-ppn cluster





- 572 Lambda-deuteron events in DC gas
- Structures at high Mass correlated with back-to-back events

Λd search for a K-ppn cluster



- Fit to be performed
- Possibility to extract information on the cusp effect

Λt correlation study

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

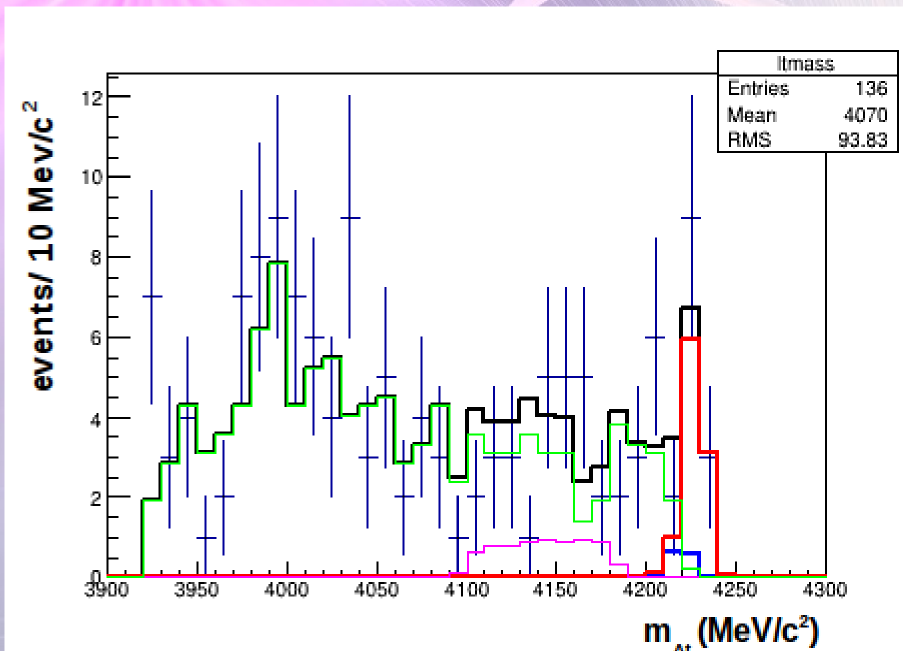
$BR(K^{-4}He \rightarrow \Lambda t) = (3 \pm 2) \times 10^{-4} / K_{stop}$ **global, no 4NA**

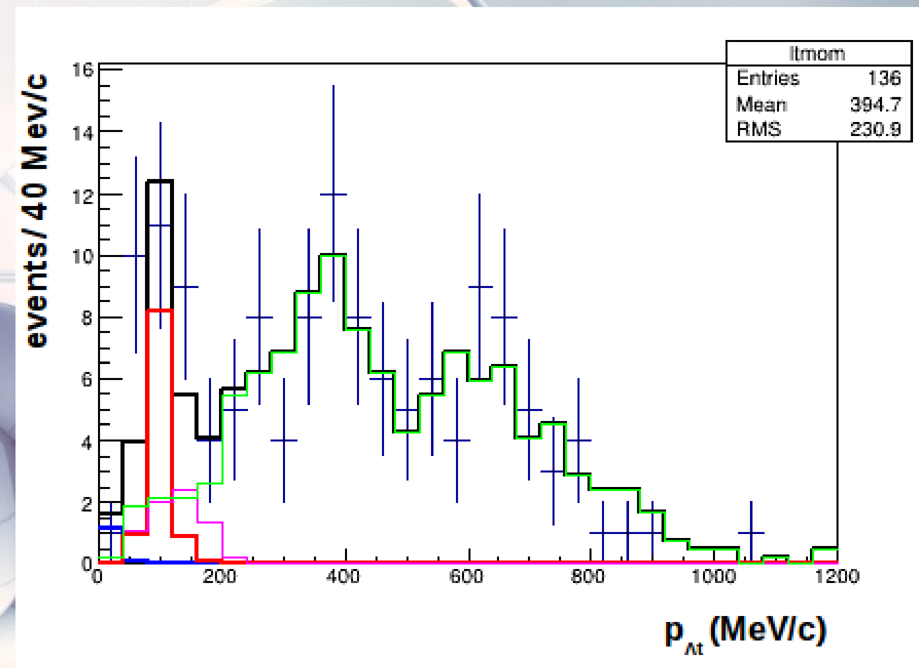
- **Solid targets**

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

Λt correlation studies in ^{4}He: mass, momentum and angle simulataneous fit

K^-





data

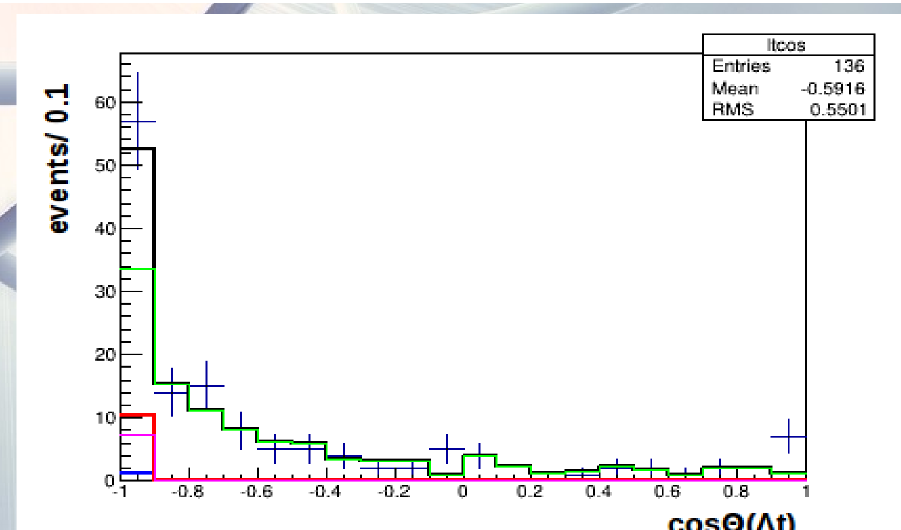
--- carbon data from DC wall

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

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

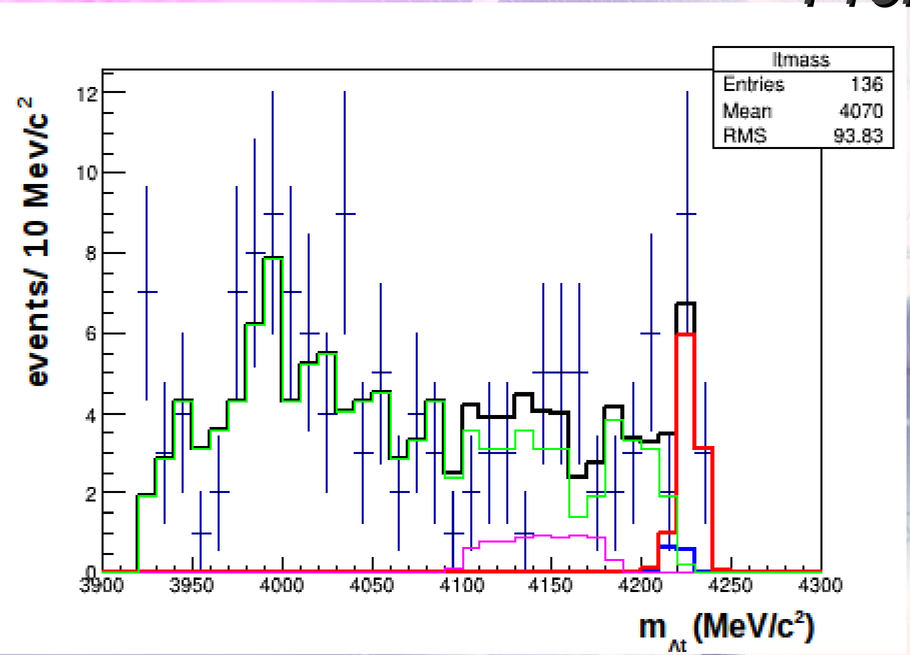
--- 4NA $K^- \, {}^4He \rightarrow \Sigma^0 t$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC

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



Λt correlation studies in ^{4}He: preliminary mass and angle simulataneous fit

Preliminary



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

parameters giving the contribution of the each process

data

--- carbon data from DC wall

--- 4NA $K^- {}^4$He → Λt in flight MC

--- 4NA $K^- {}^4$He → Λt at rest MC

--- 4NA $K^- {}^4$He → Σ^0t , Σ^0 → Λγ MC

--- 4NA $K^- {}^4$He → Σ^0t , Σ^0 → Λγ MC

Total number of events = 136

4NA $K^- {}^4$He → Λt at rest → 1 ± 1 events

4NA $K^- {}^4$He → Λt in flight → 12 ± 3 events

BR($K^- {}^4$He(4NA) → Λt) **< 1.3 × 10^{-4} /K_{stop}**

σ(100 MeV/c) ($K^- {}^4$He(4NA) → Λt) **=**

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

Conclusions part 2

K^-

BR(K^- ^{4}He(4NA) → Λt) **< 1.1 x 10^{-4} /K$_{stop}$**

4 NA cross section & 100MeV measured for the first time

σ(100 MeV/c) (K^- ^{4}He(4NA) → Λt) **=**

(0.41 ± 0.13 (stat) +0.01 -0.02 (sys)) mb

Paper in preparation


K^-
Thanks