CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

K^-

Y* resonances investigation in low-energy kaon-nuclei hadronic interactions

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1) Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

2) INFN, Laboratori Nazionali di Frascati

3) Excellence Cluster Universe, Technische Universitat Munchen, Garching, Germany

4) National Centre for Nuclear Studies, Warsaw, Poland

on behalf of the AMADEUS collaboration

Strangeness in Nuclei and in Neutron Stars

University of Pisa, Pisa, Italy

21-22 May 2015

Study of Strongly Interacting Matter

HadronPhysics

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INFN

Istituto Nazionale di Fisica Nucleare

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?

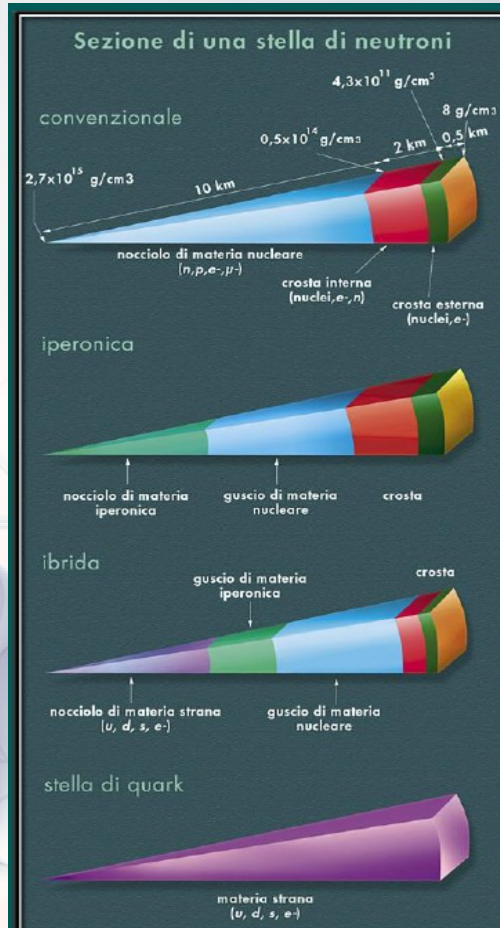
   - U_{KN} strongly affects the position of the $\Lambda(1405)$ state → we investigate it through $(\Sigma-\pi)^0$ decay --- Y π CORRELATION

   - if U_{KN} is strongly attractive then K^- NN bound states could appear → we investigate through $(\Lambda/\Sigma-N)$ 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

Essential impact on the case of NEUTRON STARS



I. Bombaci, A. Drago, INFN Notizie, n. 13, 15 (2003)

“Neutron

Nucleon Stars

Hyperon Stars

Hybrid Stars

Strange 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

Low-Energy QCD with Strange Quarks – competing models

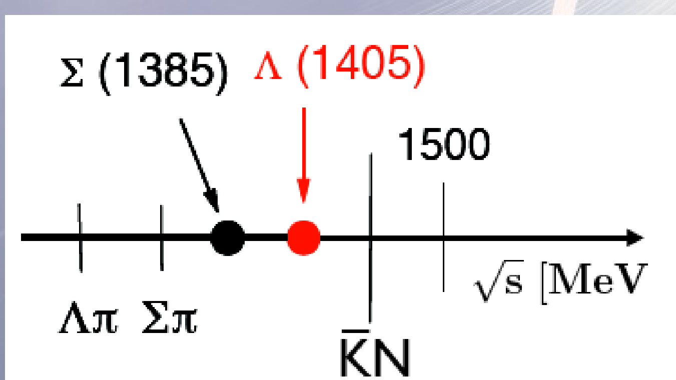
CHIRAL PERTURBATION THEORY
Interacting systems of NAMBU-GOLDSTONE BOSONS (pions, kaons) coupled to BARYONS

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

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

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

BECOUSE Λ(1405) just below K^-N threshold (1432 MeV)



—>

Solutions:

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

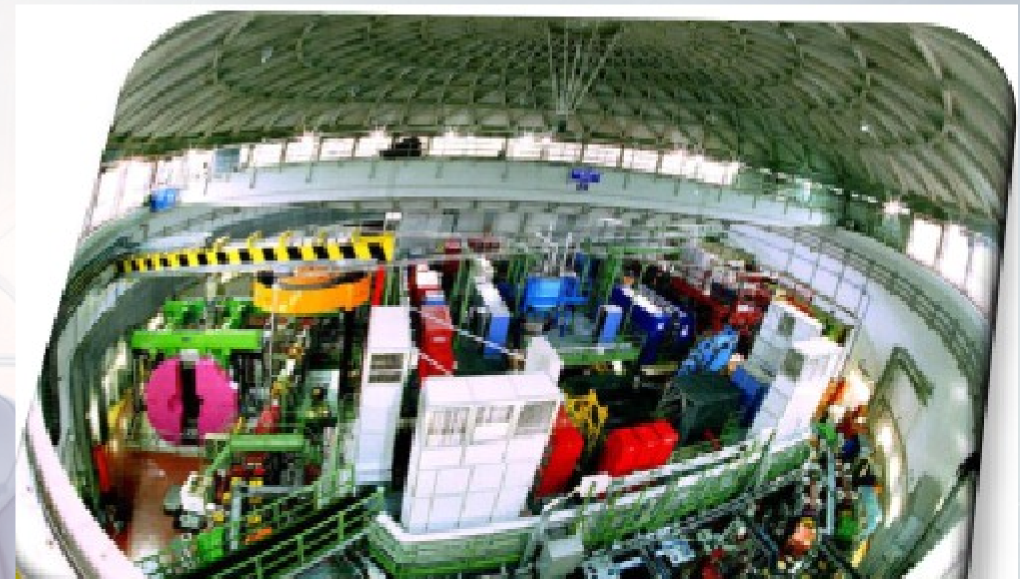
How to do that? ... KLOE & DAΦNE

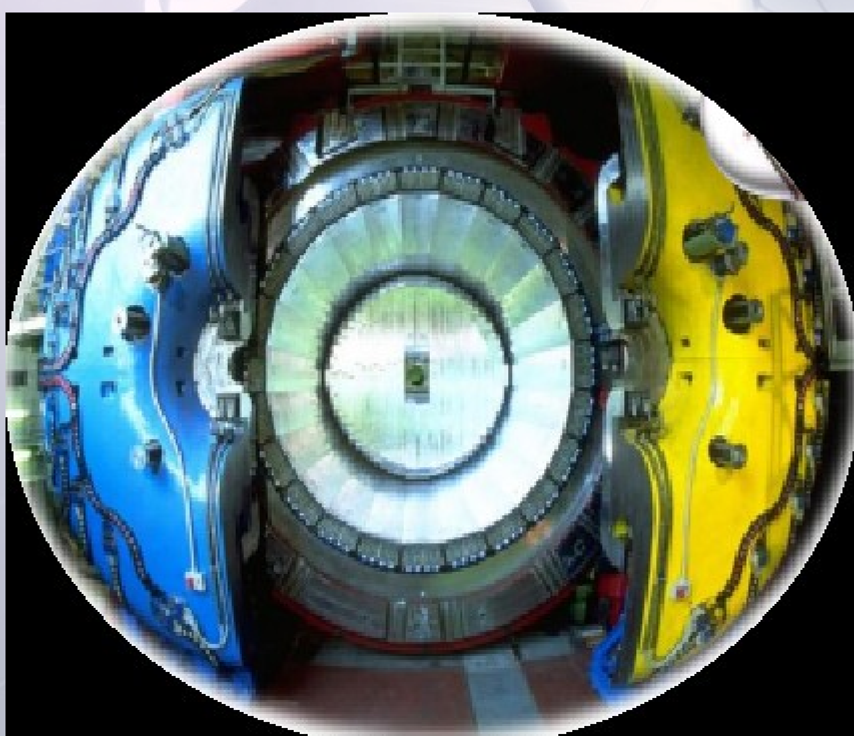
DAΦNE

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)))

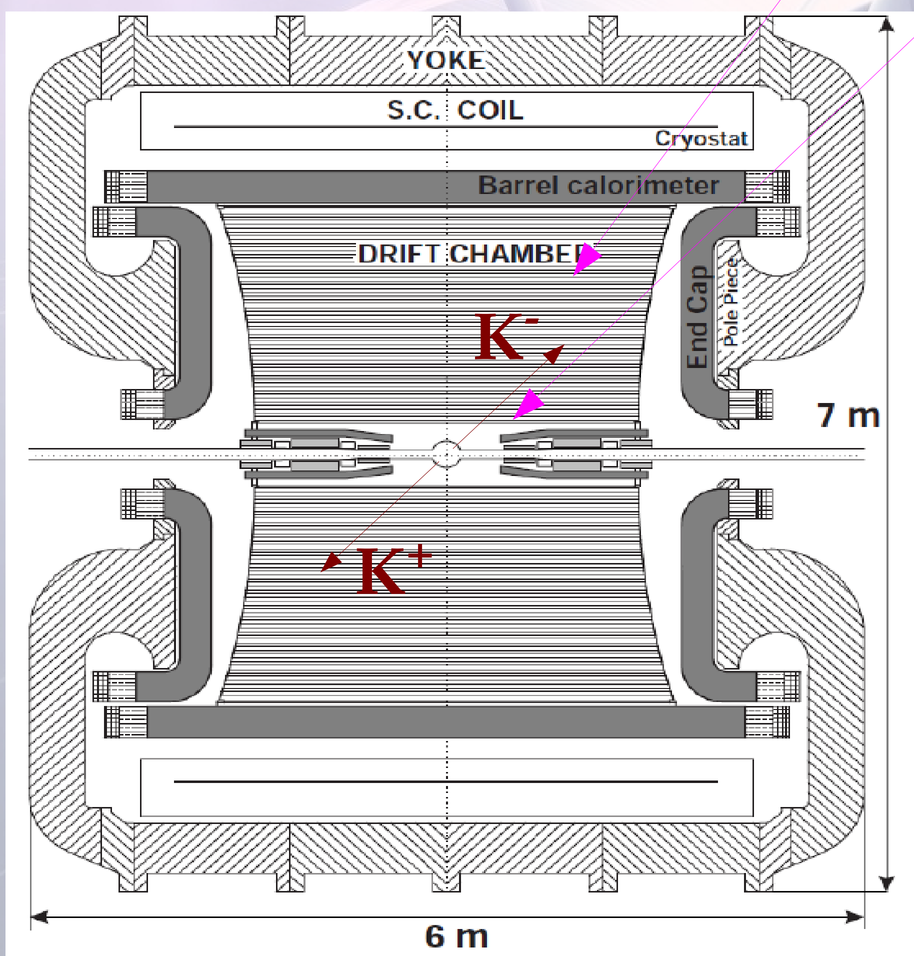
How to do that? ... K^- absorption on light nuclei

We are lookin for K^- absorption in

(H, ^{4}He, ^{9}Be, ^{12}C)

AT-REST (K^- absorbed from atomic orbit) or **IN-FLIGHT**

($p_K \sim 100$MeV)



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.

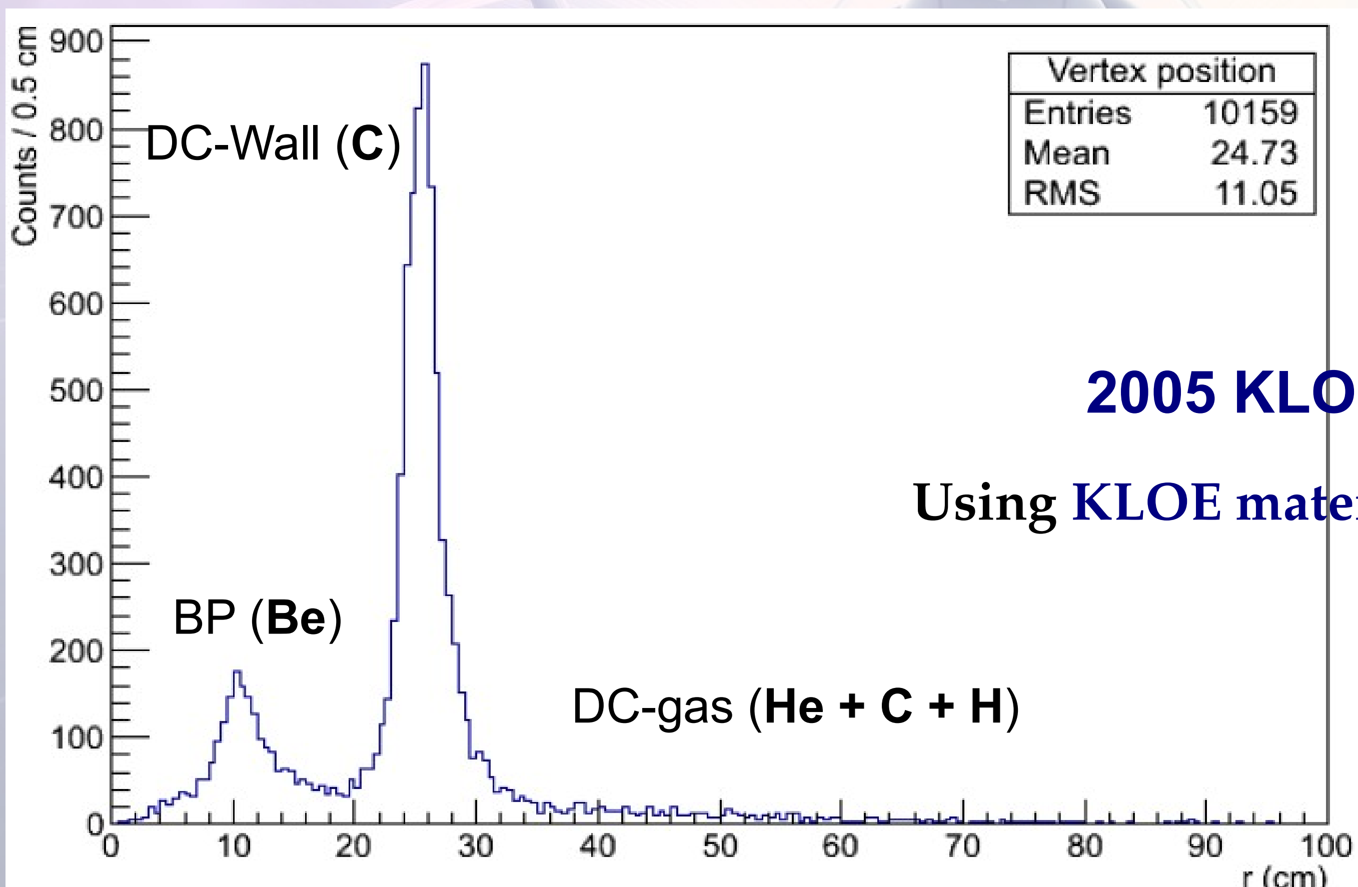
How to do that? ... K^- absorption on light nuclei

We are lookin for K^- absorption in

(H, ^{4}He, ^{9}Be, ^{12}C)

AT-REST (K⁻ absorbed from atomic orbit) or **IN-FLIGHT**

(p_K~100MeV)



2005 KLOE data A. R. + I. F.

Using KLOE materials as an active target

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

1) $Y\pi$ CORRELATION

'p' , 'n' BOUND nucleons

- K^- 'n' → $\Lambda\pi^-$ (direct formation) → $\Sigma(1385)$ I=1

- K^- 'p' → $\Sigma^0\pi^0$ → $\Lambda(1405)$ I=0
- K^- 'p' → $\Sigma^+\pi^-$ → $\Lambda^* + \Sigma^*$

To measure the amount of resonant capture → position of the resonance

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2) Y N CORRELATION

- K^- 'pp' → Λ/Σ^0 p (without YN scattering) → $(K^-\ \text{'pp'})^{B.S.}$
- K^- 'ppn' → Λ d (without YN scattering) → $(K^-\ \text{'ppn'})^{B.S.}$
- K^- α → Λ t → Alessandro's talk

search for possible bound states

- with YN scattering → to get information on U_{YN}

How to do that? ... topic of this talk

1) K^- Y π CORRELATION

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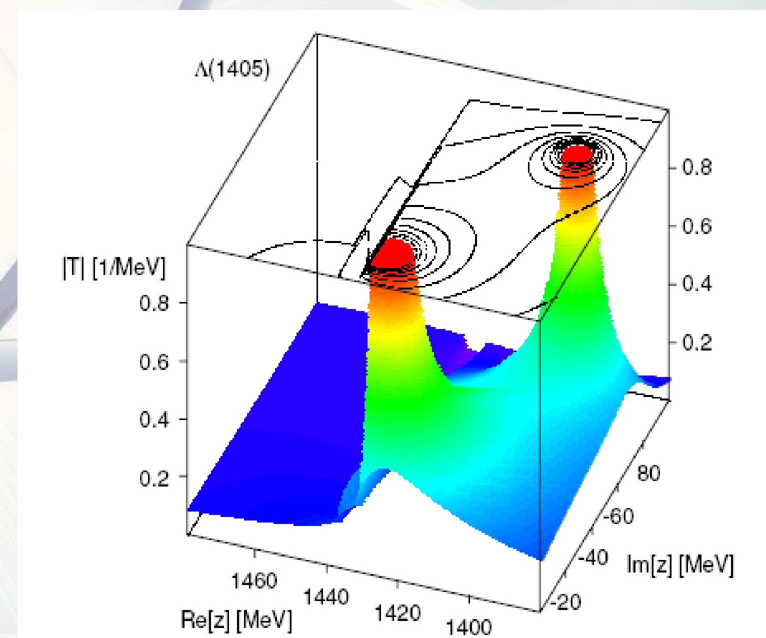
Λ(1405) .. resonance or/and bound state?

- 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):

two poles: ($z_1 = 1424^{+7}_{-23} - i\, 26^{+3}_{-14}$; $z_1 = 1381^{+18}_{-6} - i\, 81^{+19}_{-8}$) MeV (Nucl. Phys. A881, 98 (2012))

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?

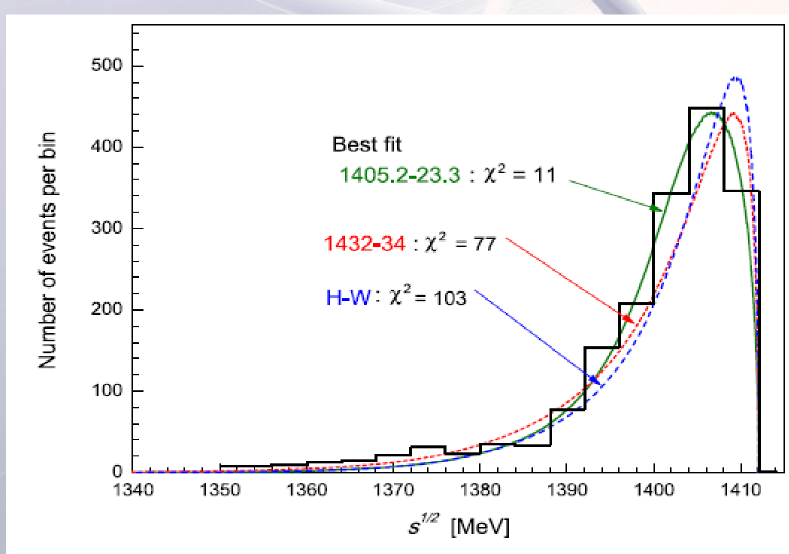


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

$\Lambda(1405)$ .. resonance or/and bound state?

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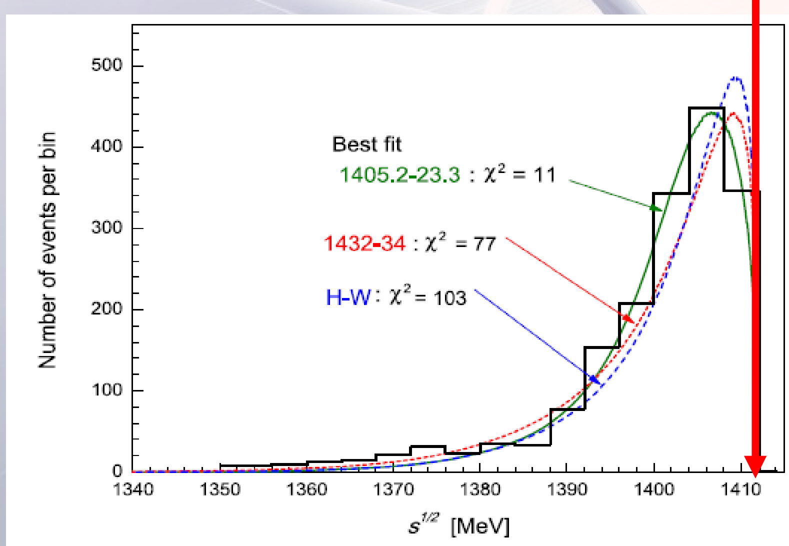

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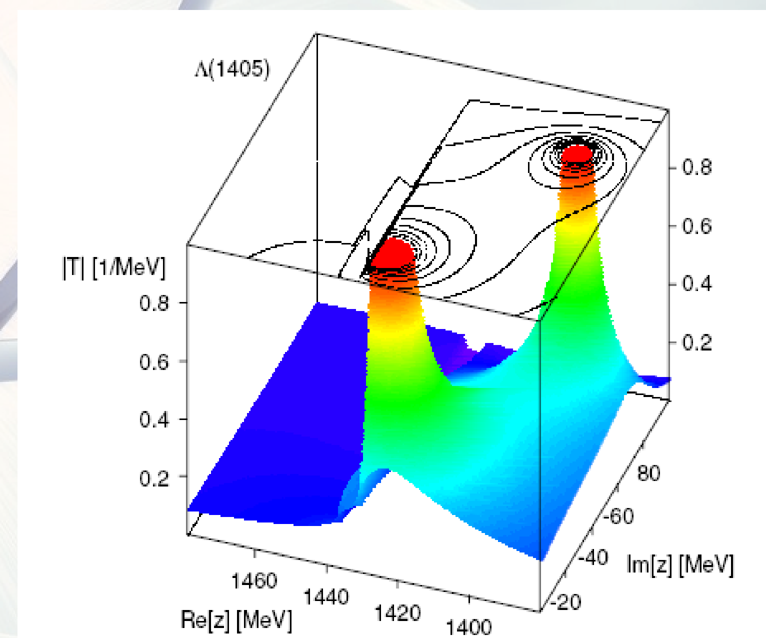

CUT AT THE ENERGY LIMIT AT-REST ?

NON RESONANT SHAPE ?

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

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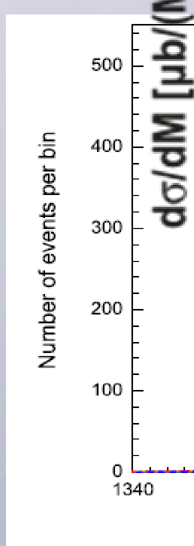
4) *two poles*: (z Phys. A881, 98 (2012))

mainly c depends on mechanism

- Akaishi-Es

Phys. Lett. B6



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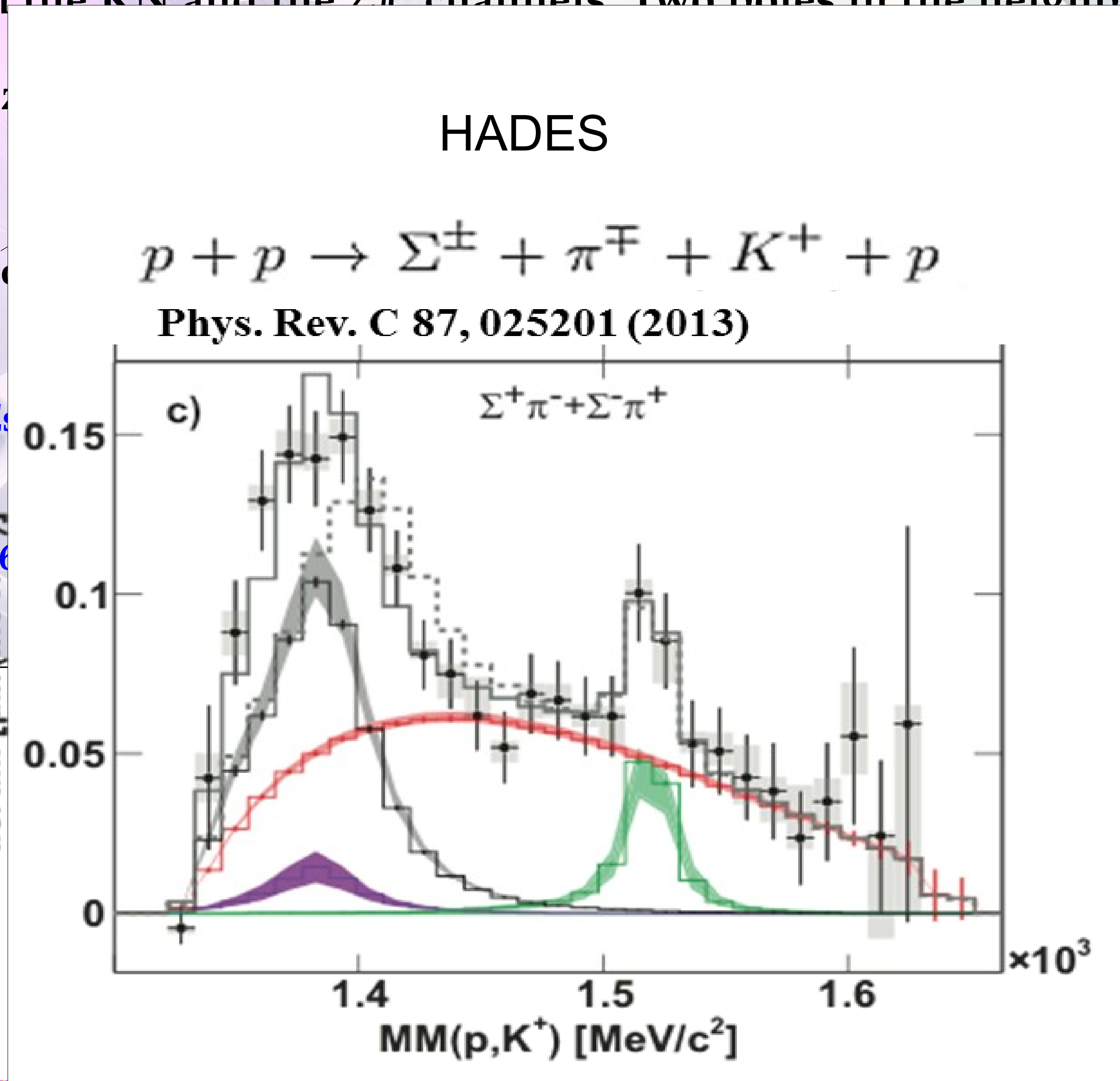
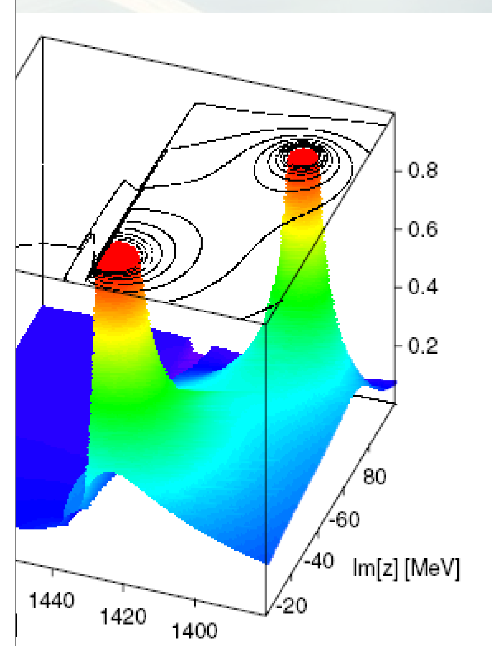




Λ(1405) .. resonance or/and bound state?

K⁻

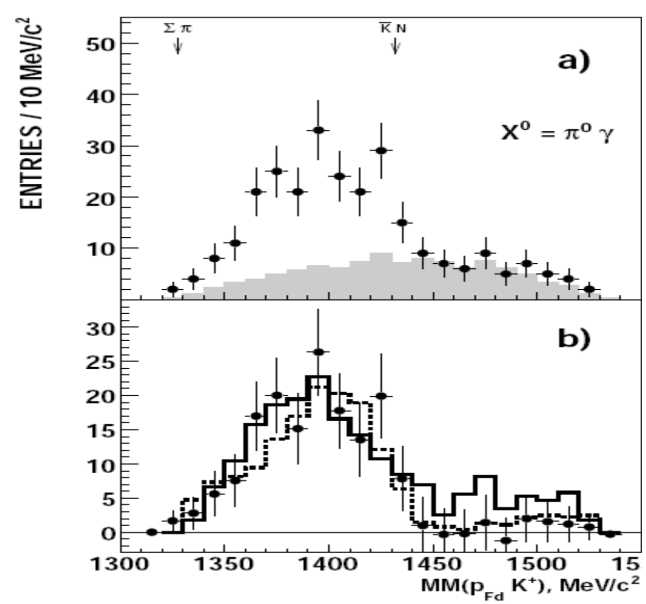
Λ(1405) is I = 0

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

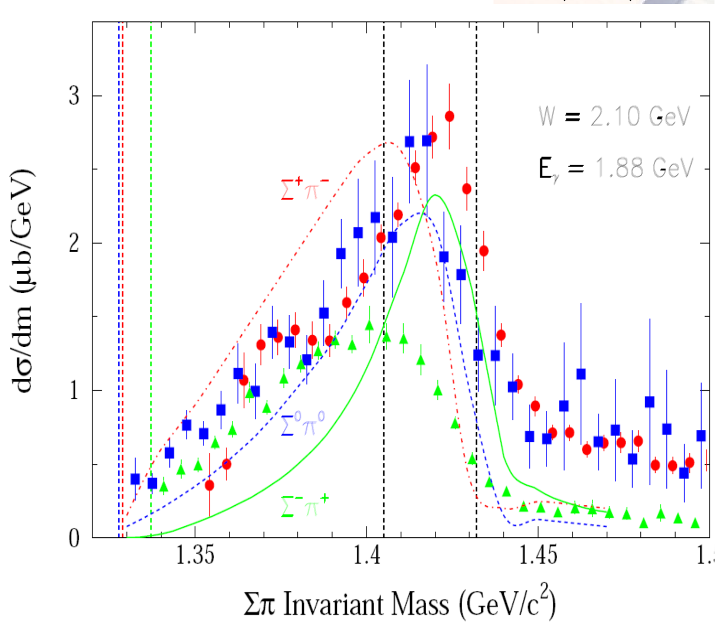
(free from Σ(1385) background I=1)

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

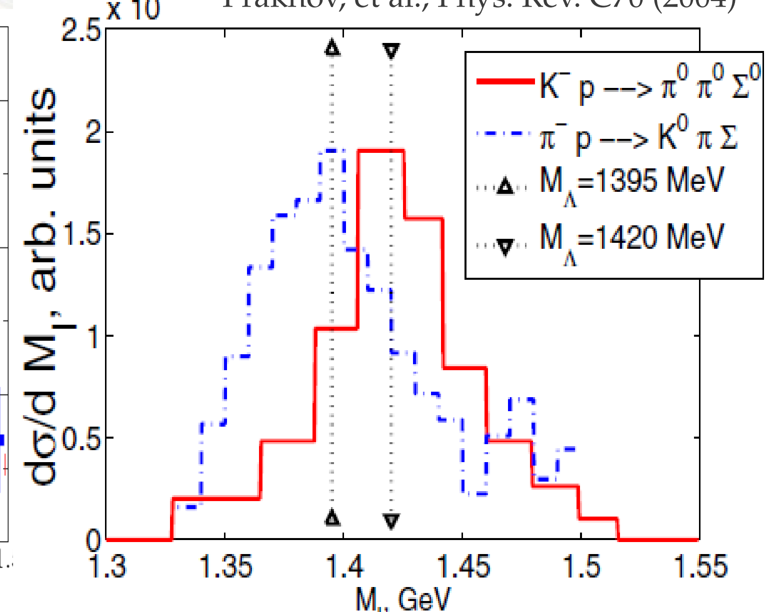
I. Zychor et al., Phys. Lett. B 660 (2008) 167



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)



$\Sigma^0\ \pi^0$ golden channel

- **production in $\bar{K}N$ reactions** **(only chance to observe the high mass pole)**

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

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

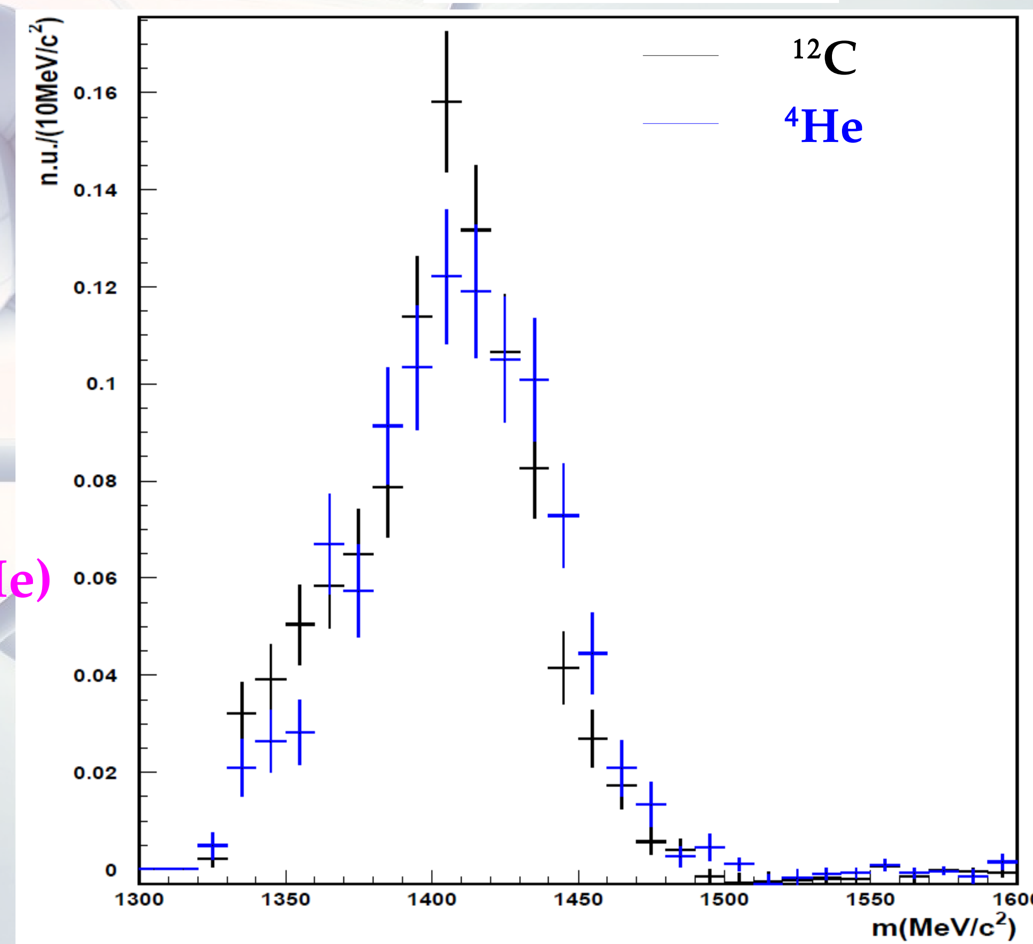
- **decay in $\Sigma^0\pi^0$** **(free from $\Sigma(1385)$ background, I=1)** →

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

$\Sigma^0\ \pi^0$ invariant mass spectra

in ^{4}He and ^{12}C.

$\sigma_m \approx$ *17 MeV/c²* (^{12}C) / $\sigma_m \approx$ *15 MeV/c²* (^{4}He)



$m_{\Sigma^0\pi^0}$ *spectrum*

$\Sigma^0 \pi^0$ channel

K⁻

Negligible ($\Lambda \pi^0$ + internal conversion) background = (3±1) % →

<u>no I=1 contamination</u>

$\Sigma^0 \pi^0$ ninvariant mass spectra

in ^{4}He and ^{12}C.

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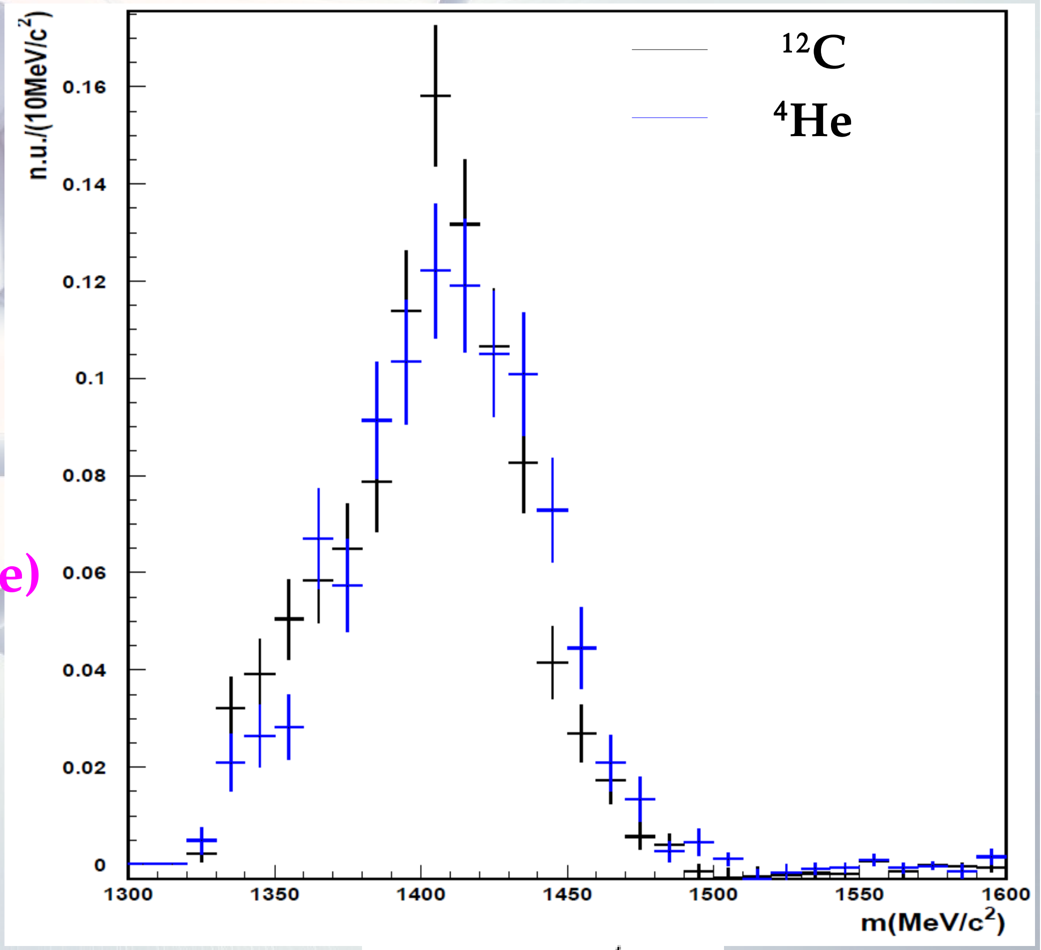


$m_{\Sigma^0\pi^0}$ spectrum

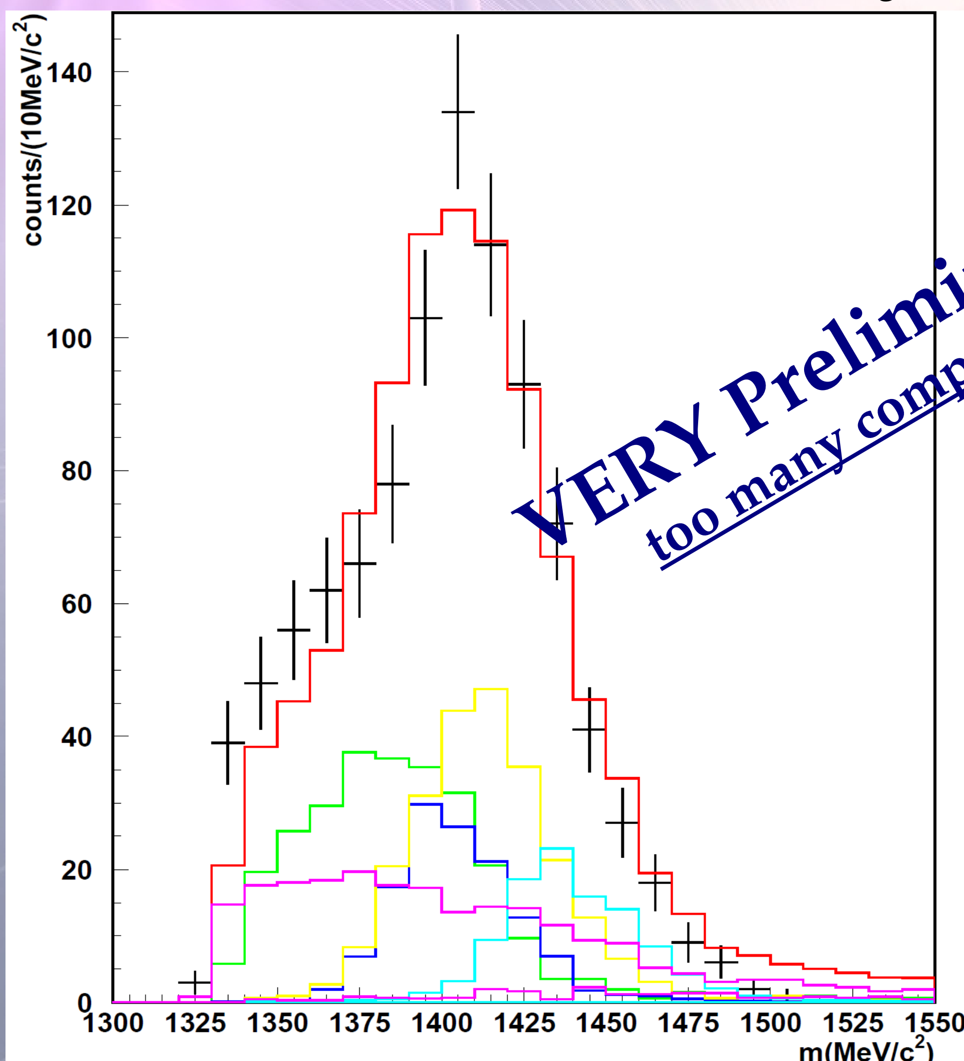
Fit of $\Sigma^0\pi^0$ spectrum in ^{12}C

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

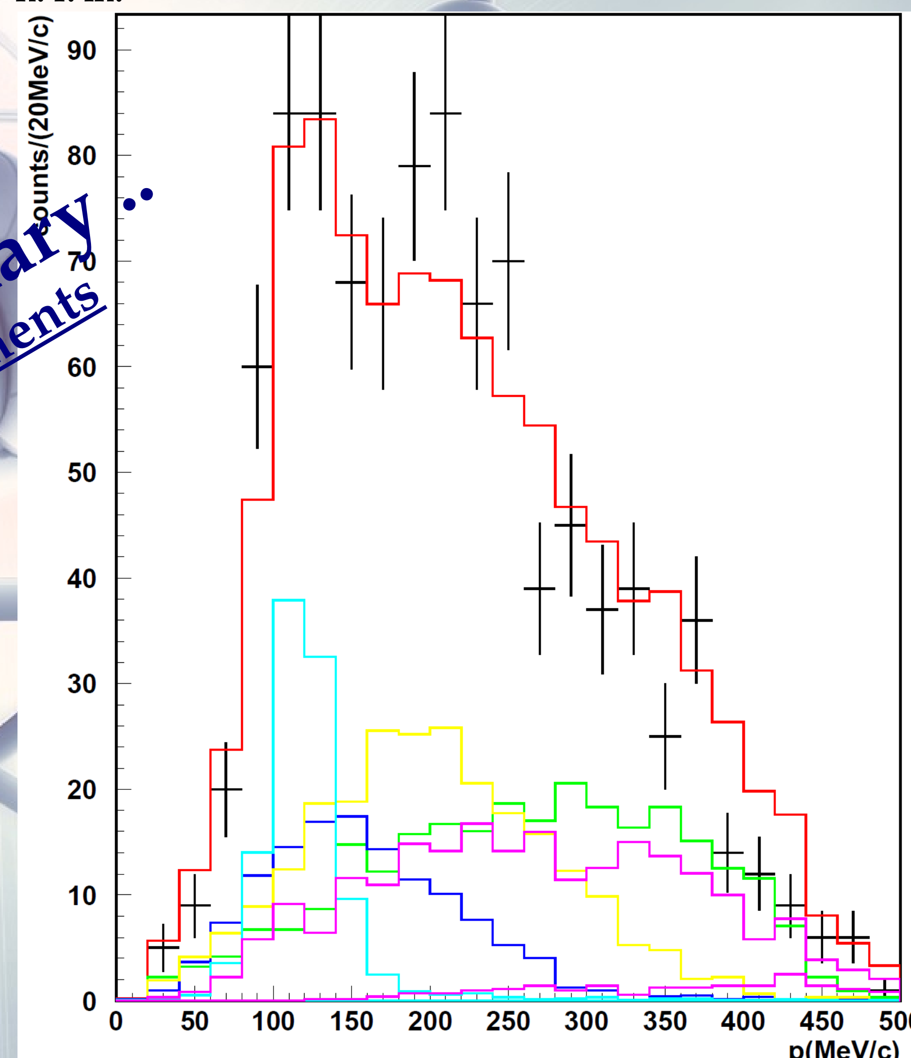
- **Global fit** (red)
- **Resonant component K^- C at-rest** (green)
- **n. r. K^- C at-rest** (blue)
- **n. r. K^- C in-flight** (yellow)
- **n. r. K^- H in-flight** (cyan)
- **$\Lambda^0\pi^0$ background + n. r. m.** (magenta)

VERY Preliminary ..

too many components



$m_{\Sigma0\pi0}$



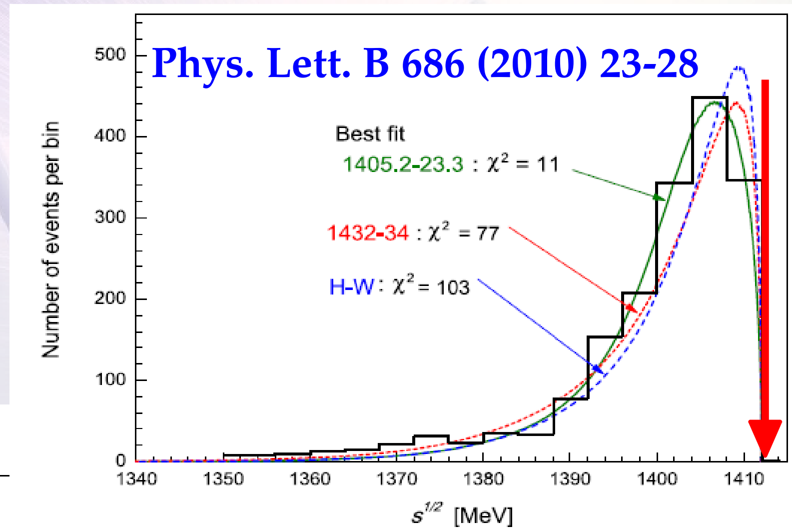
$p_{\Sigma0\pi0}$

$\Sigma^+\pi^-$ channel

K^-

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

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



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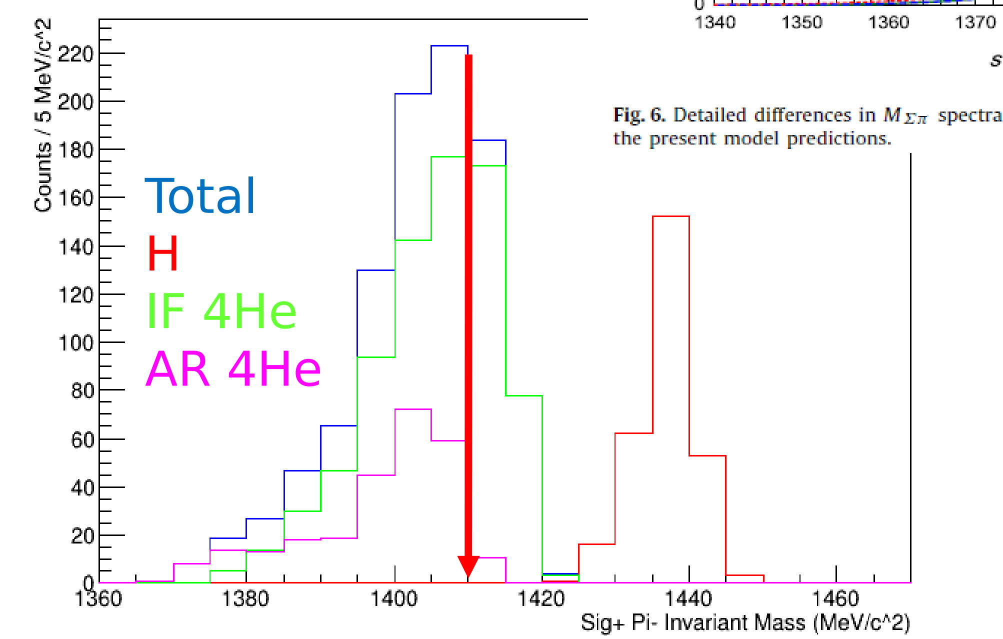
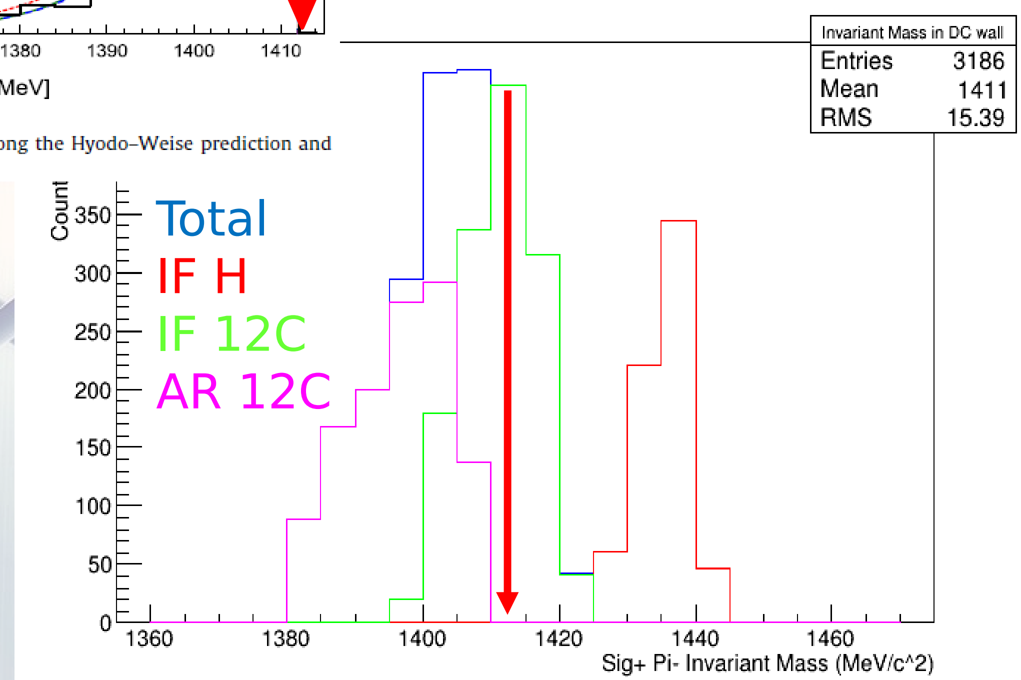


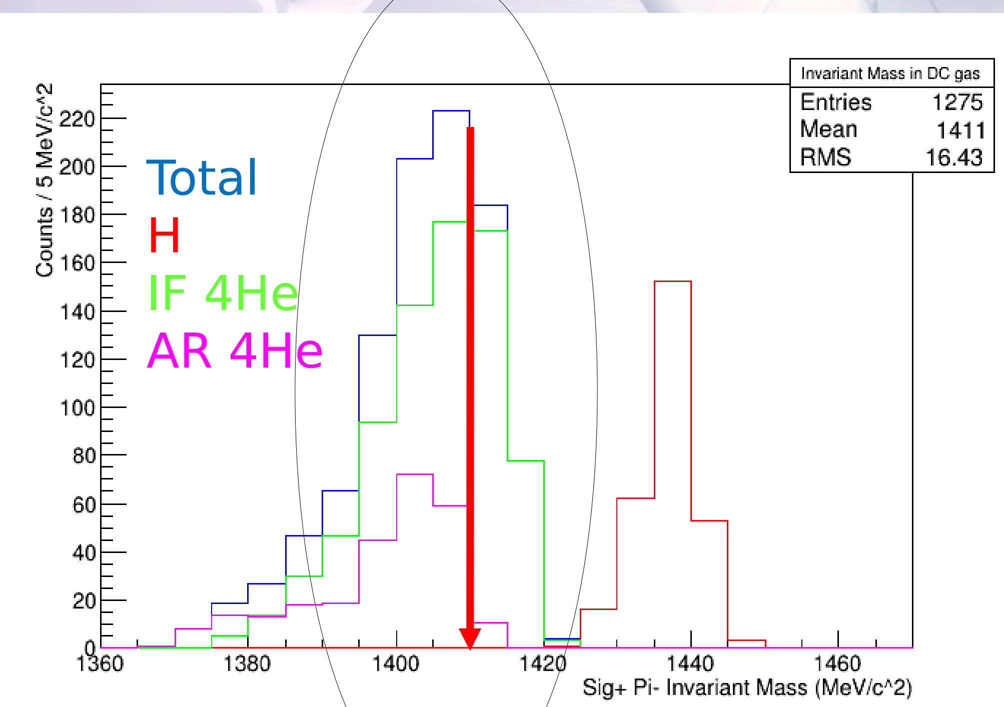


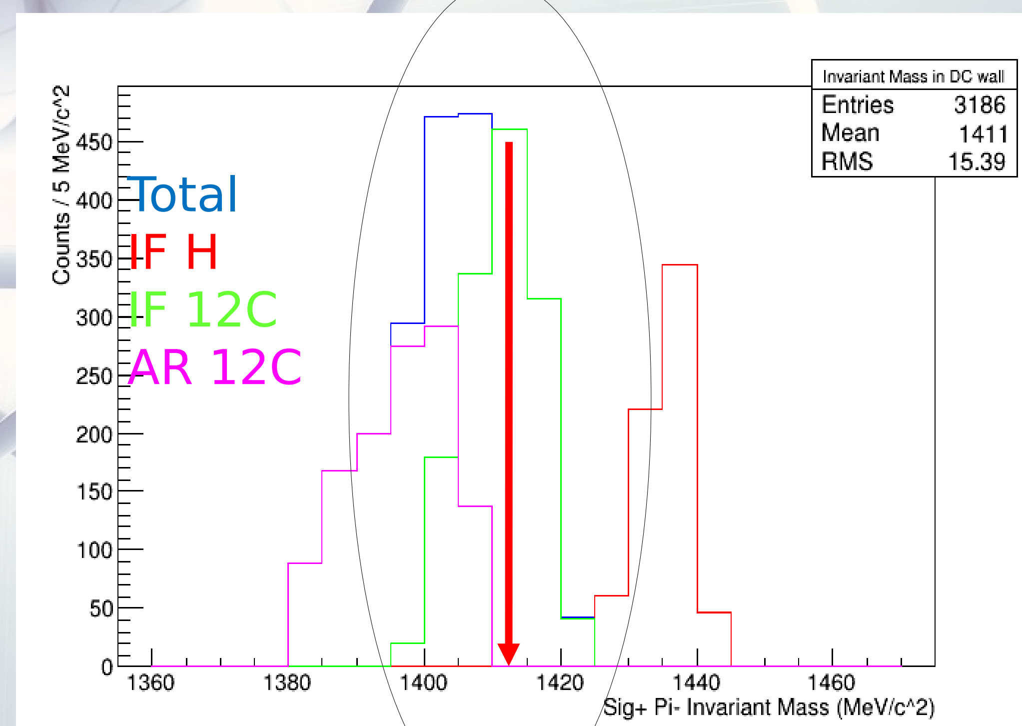
$\Sigma^+\pi^-$ channel

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

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

how much comes from resonance ?

Non resonant transition amplitude:

- Never measured before below threshold

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

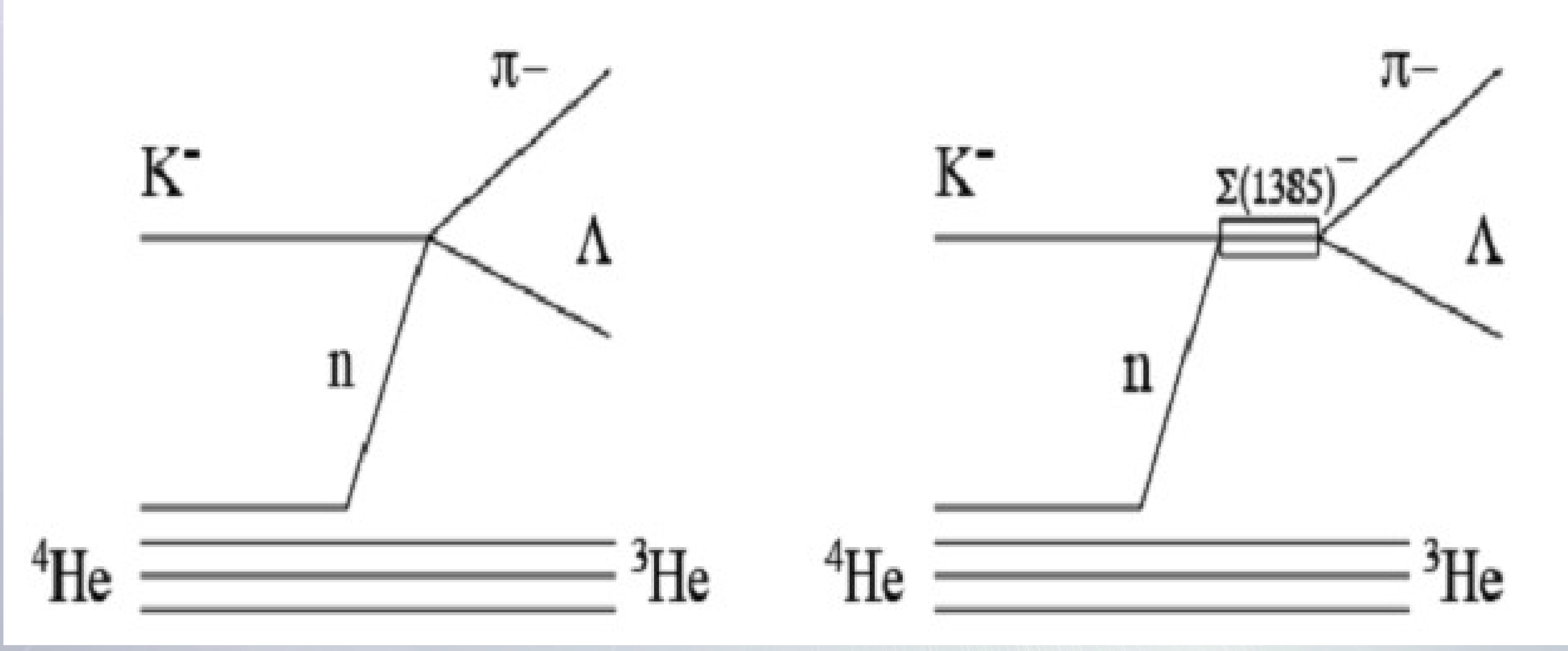
K^-

Resonant VS non-resonant

Investigated using:

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

In collaboration with Prof. S. Wycech

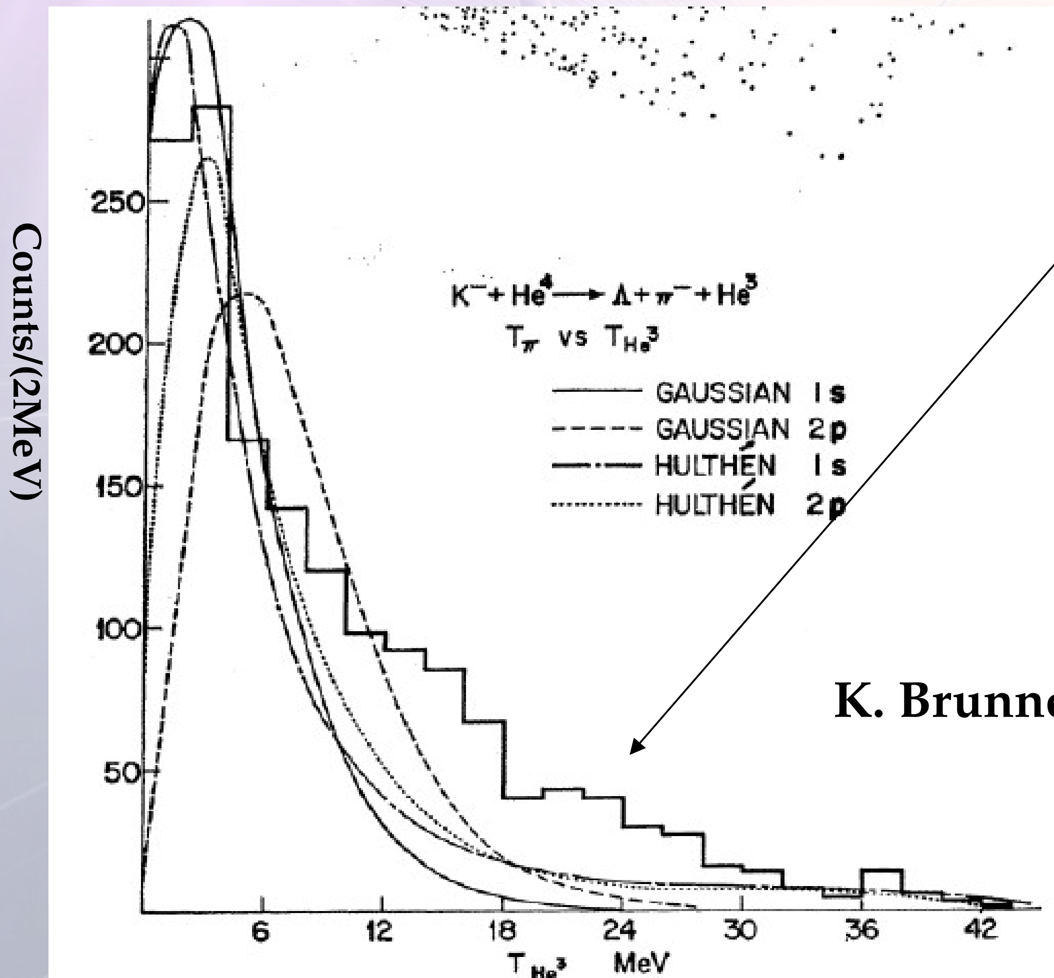


Channel: K^- $^4He \rightarrow$ $\Lambda\ \pi^-$ ^3He … the idea

K^-

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

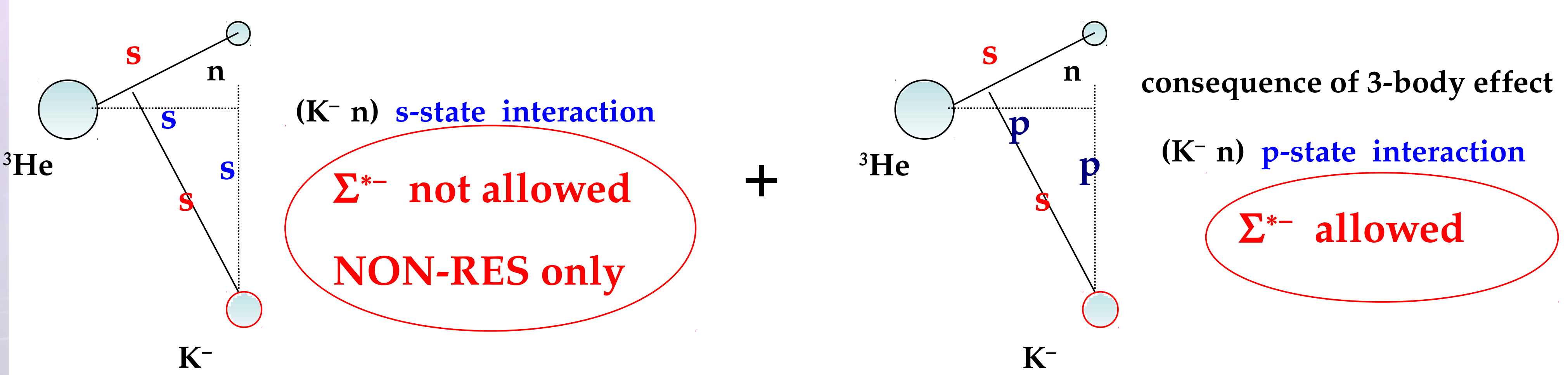
(K = 1, n=2, ^{3}He = 3)

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

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

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

atomic s-state capture:



- ($K^- \, {}^4He \rightarrow \Lambda \, \pi^- \, {}^3He$) 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: $K^- \; {}^4He \rightarrow \Lambda \, \pi^- \; {}^3He$ … the strategy

K^-

- Fit of the $p_{\Lambda\pi^-}$ observed distribution using calculated distributions :

$$P_s^{\,s}(p_{\Lambda\pi}) = |\Psi_N(p_{\Lambda\pi})|^2 \; |f^{\,s}(p_{\Lambda\pi})|^2 \; \rho$$ non-resonant

$$P_s^{\,p}(p_{\Lambda\pi}) = |\Psi_N(p_{\Lambda\pi})|^2 \; c^2 \; |2f^{\,\Sigma^*}(p_{\Lambda\pi})|^2 \; \rho/3 \; (kp_{\Lambda\pi})^2$$ resonant

Where $\rho = k\, p_{\Lambda\pi}^{\;2}$

the constant $c = M_K/(M_K+M_n) = 0.345$ re-couples the S x S waves to P x P waves

- To determine *for the first time* the amplitude of the N. R. capture:

↓

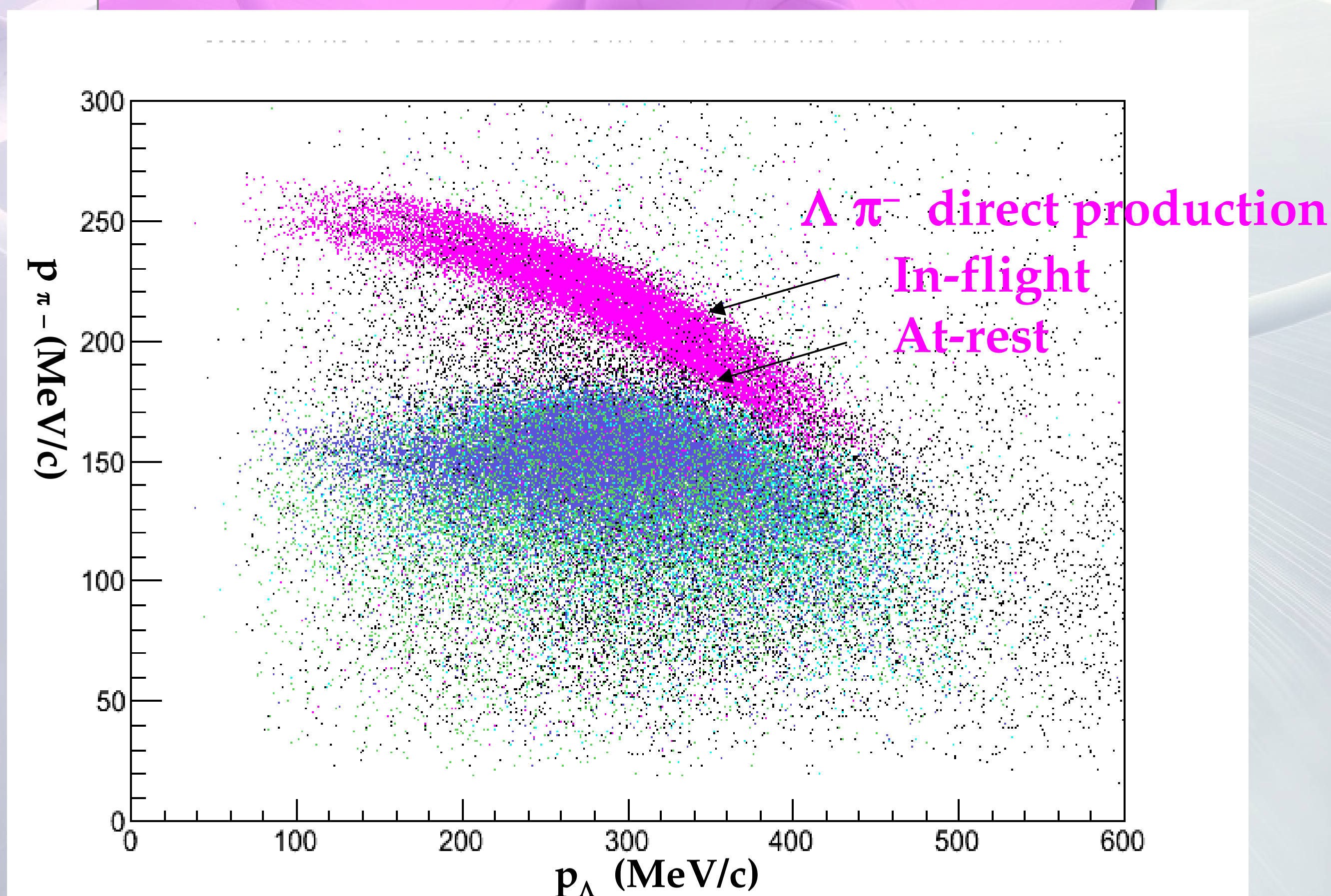
$|f^{\,N\text{-}R}{}_{\Lambda\pi}|$ given the fairly well known $|f^{\,\Sigma^*}{}_{\Lambda\pi}|$

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 Λ π⁻ production .. SIGNAL

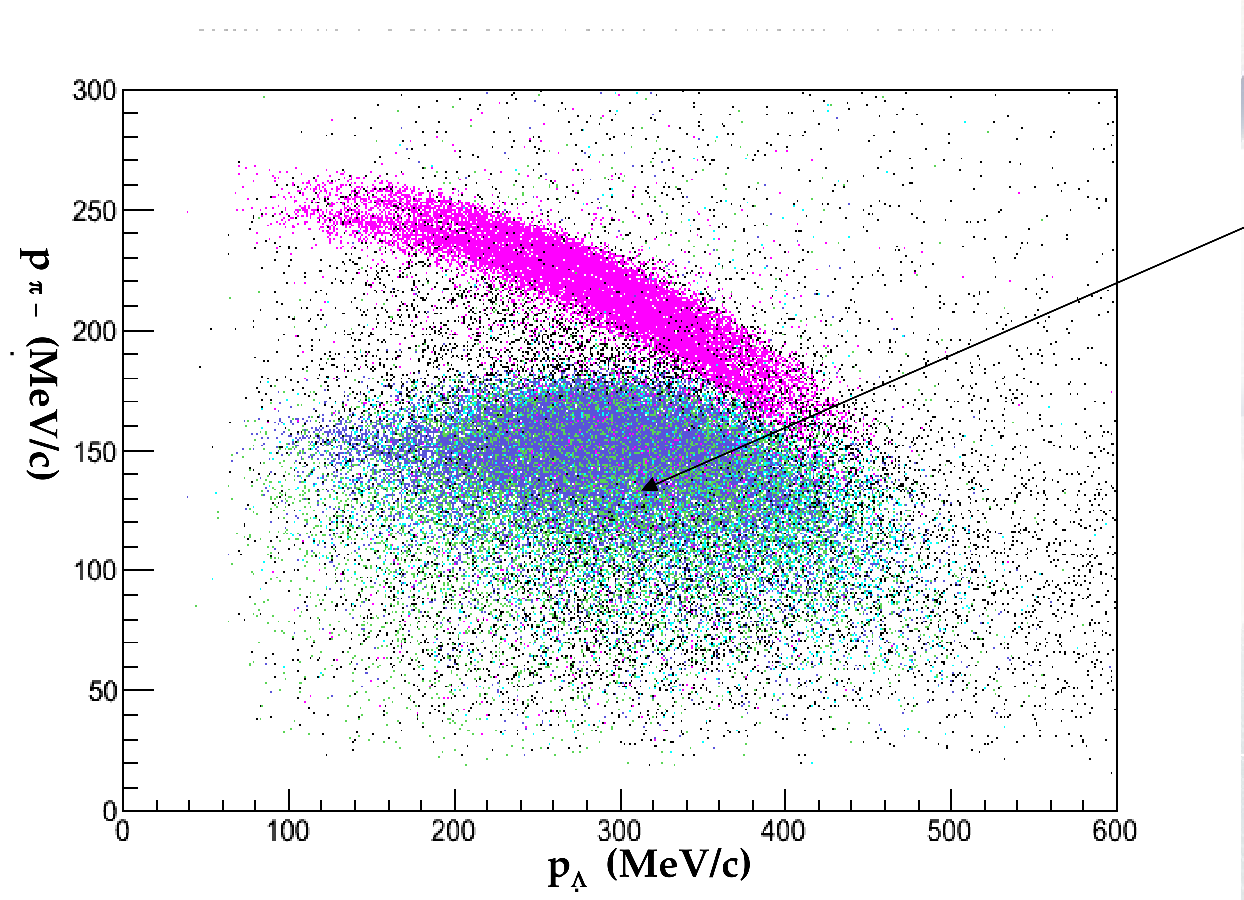


Channel: $K^- \, {}^4He \rightarrow \Lambda \pi^- \, {}^3He$ … calculated reactions

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

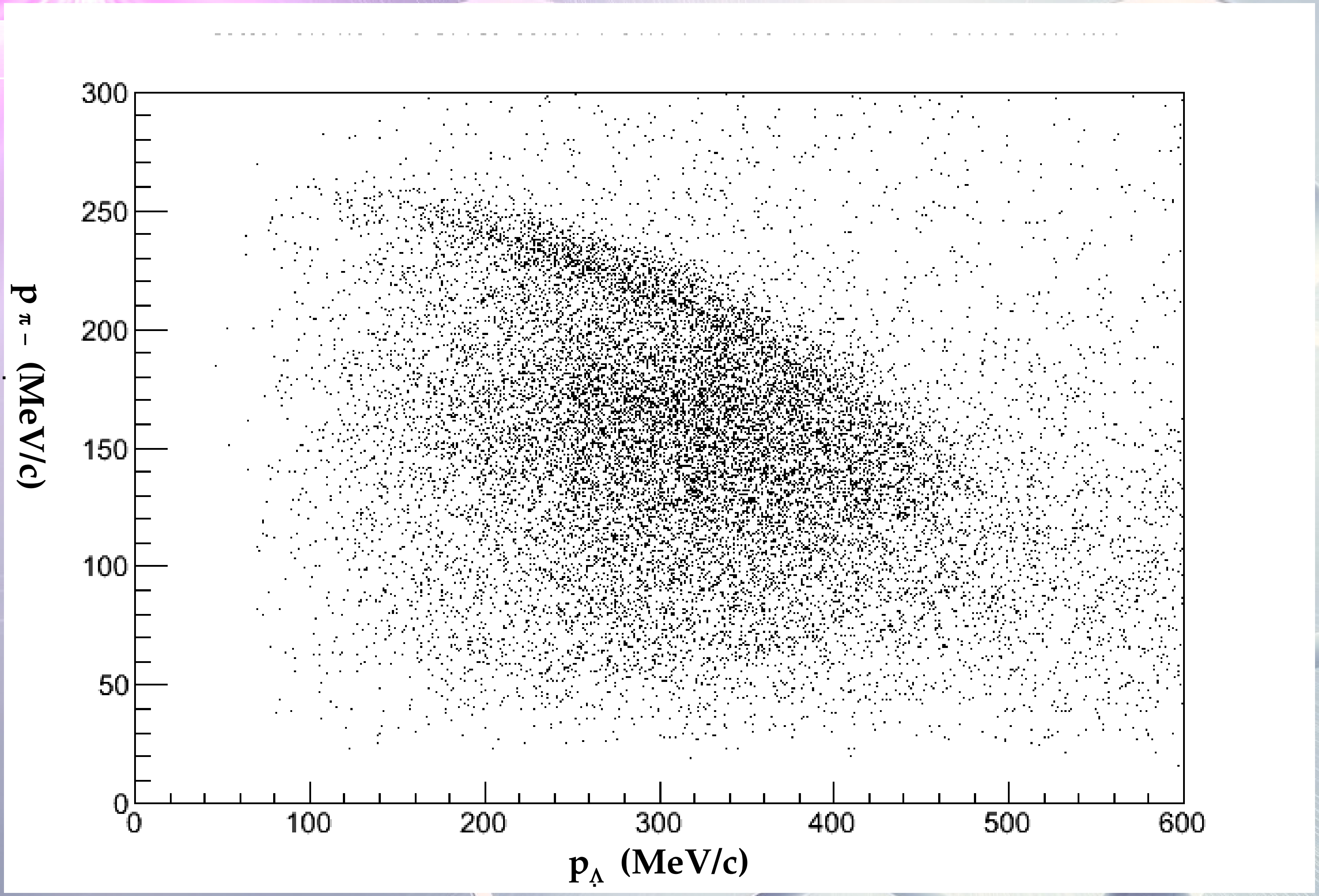
$\Lambda \pi^-$ production

Σ^0 p conversion

Σ^0 n conversion

Σ^+ n conversion

$K^- \ ^4He \rightarrow \Lambda \pi^- \ ^3He$ events selection



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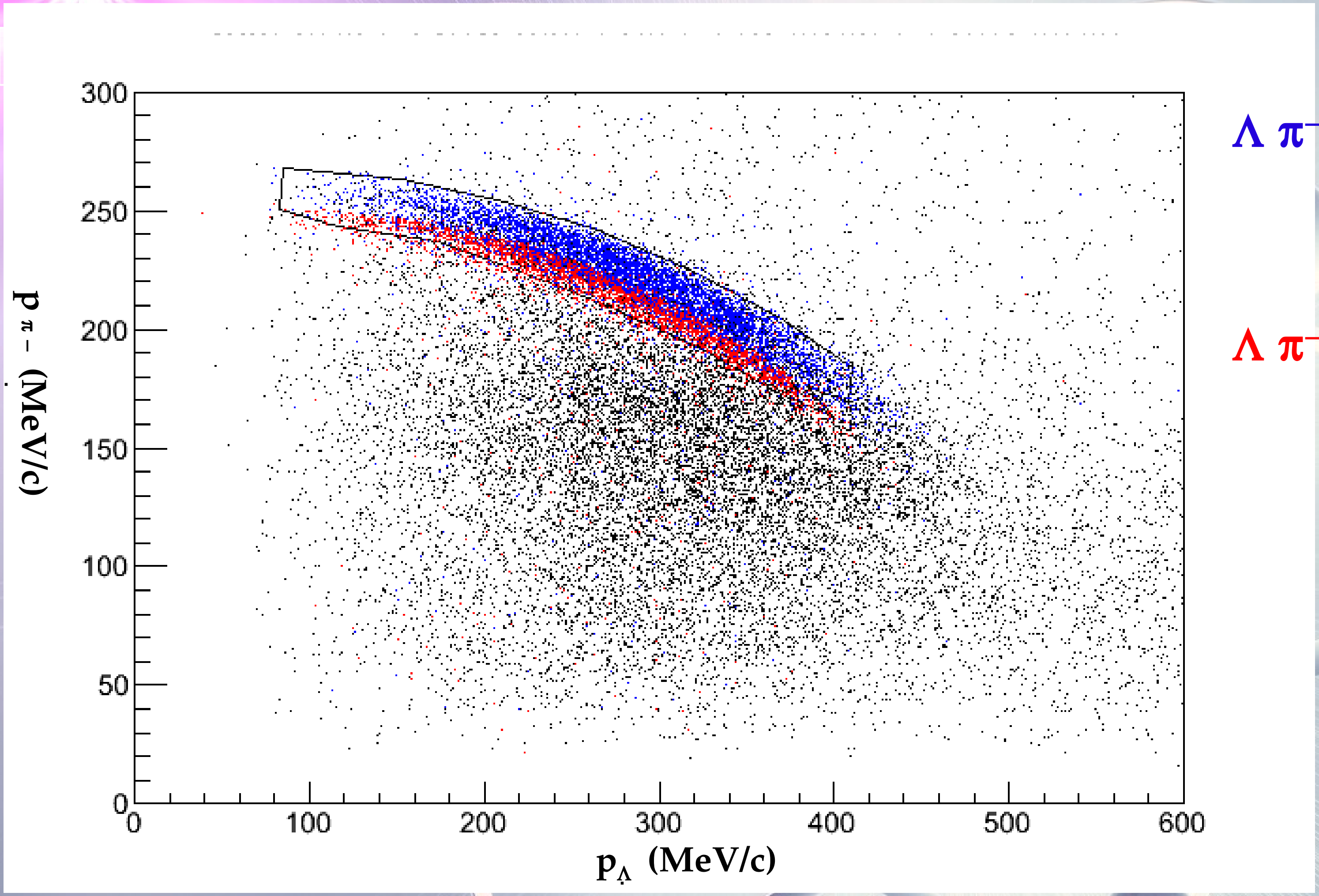


$\Lambda \pi^-$ direct production In-flight RES + N-R

$\Lambda \pi^-$ direct production At-rest RES + N-R

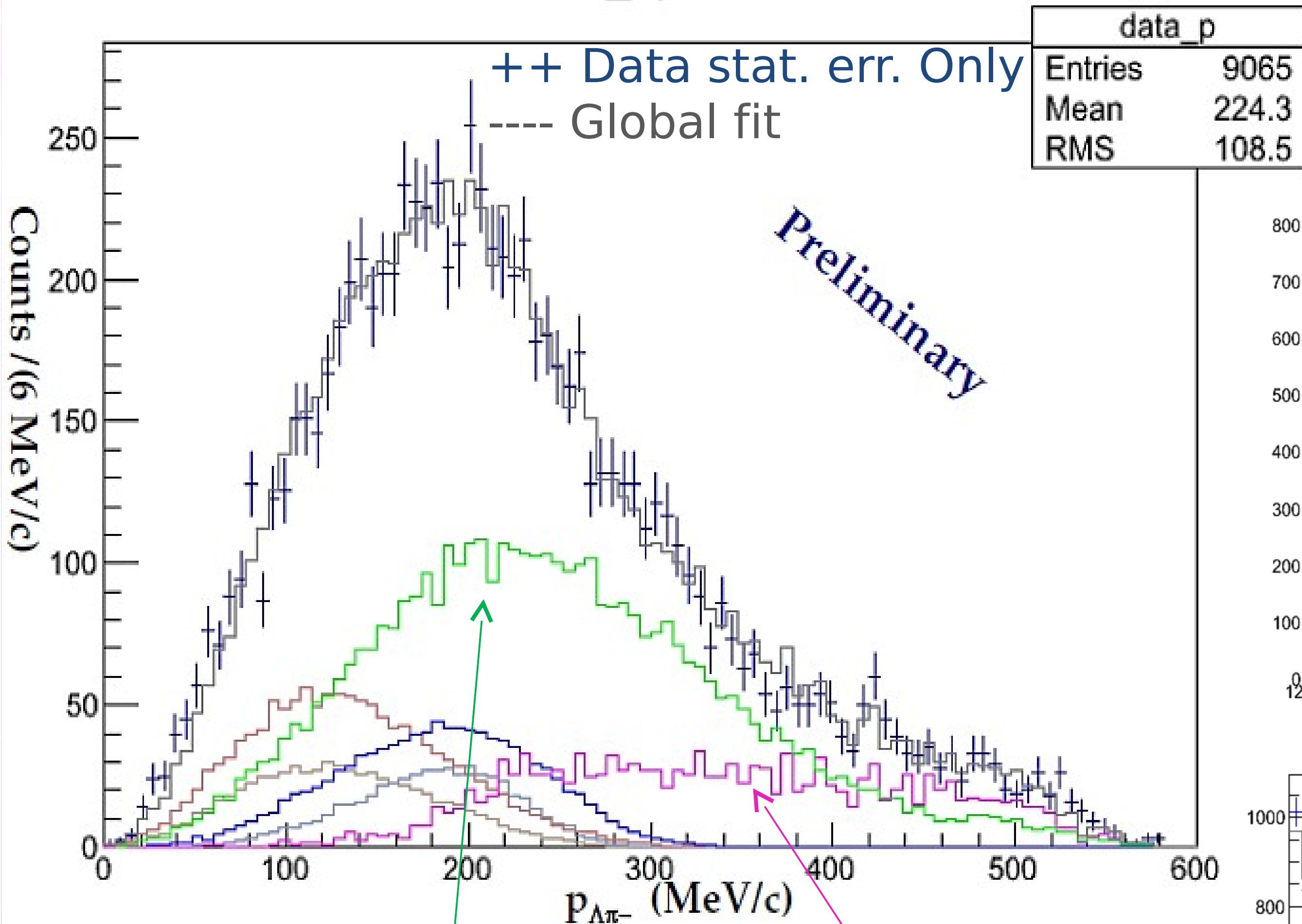
Background sources: - $\Lambda \pi^-$ events from Σ p/n $\rightarrow$ Λ p/n conversion

- $\Lambda \pi^-$ events from K^- ^{12}C absorptions in Isobutane

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

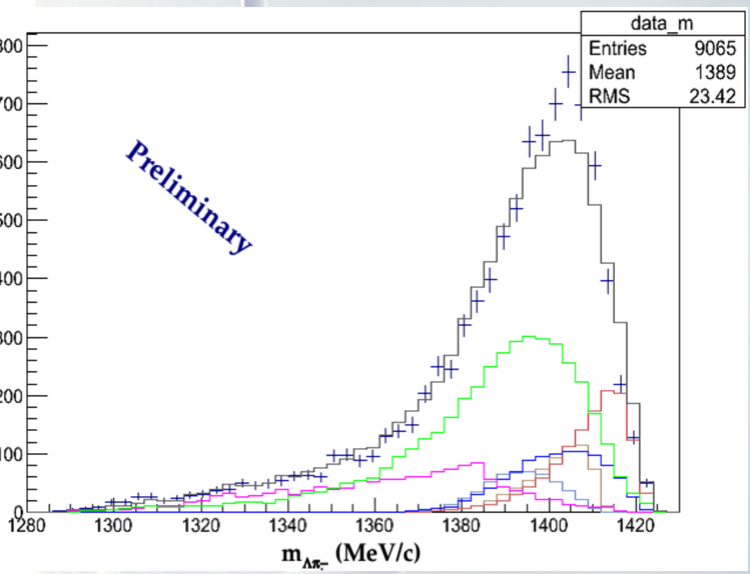
Simultaneous fit

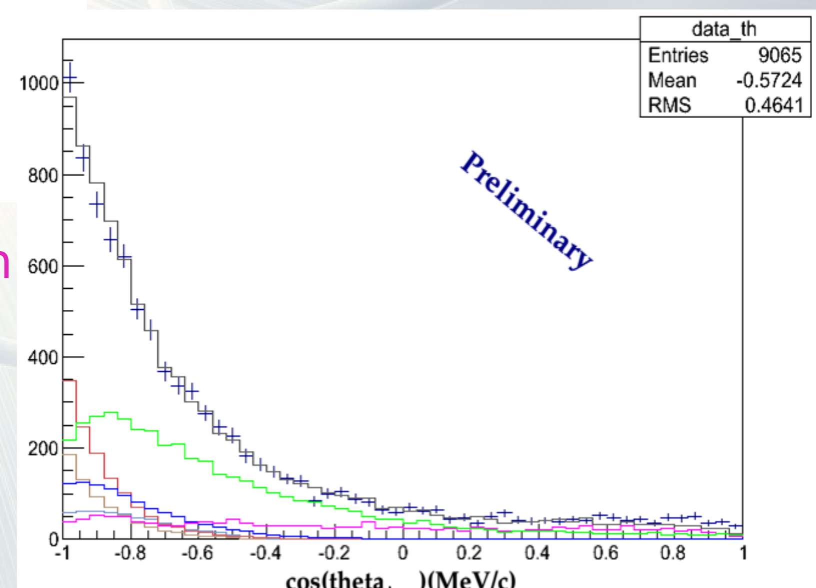
($p_{\Lambda\pi^-}$ - $m_{\Lambda\pi^-}$ - $\theta_{\Lambda\pi^-}$)



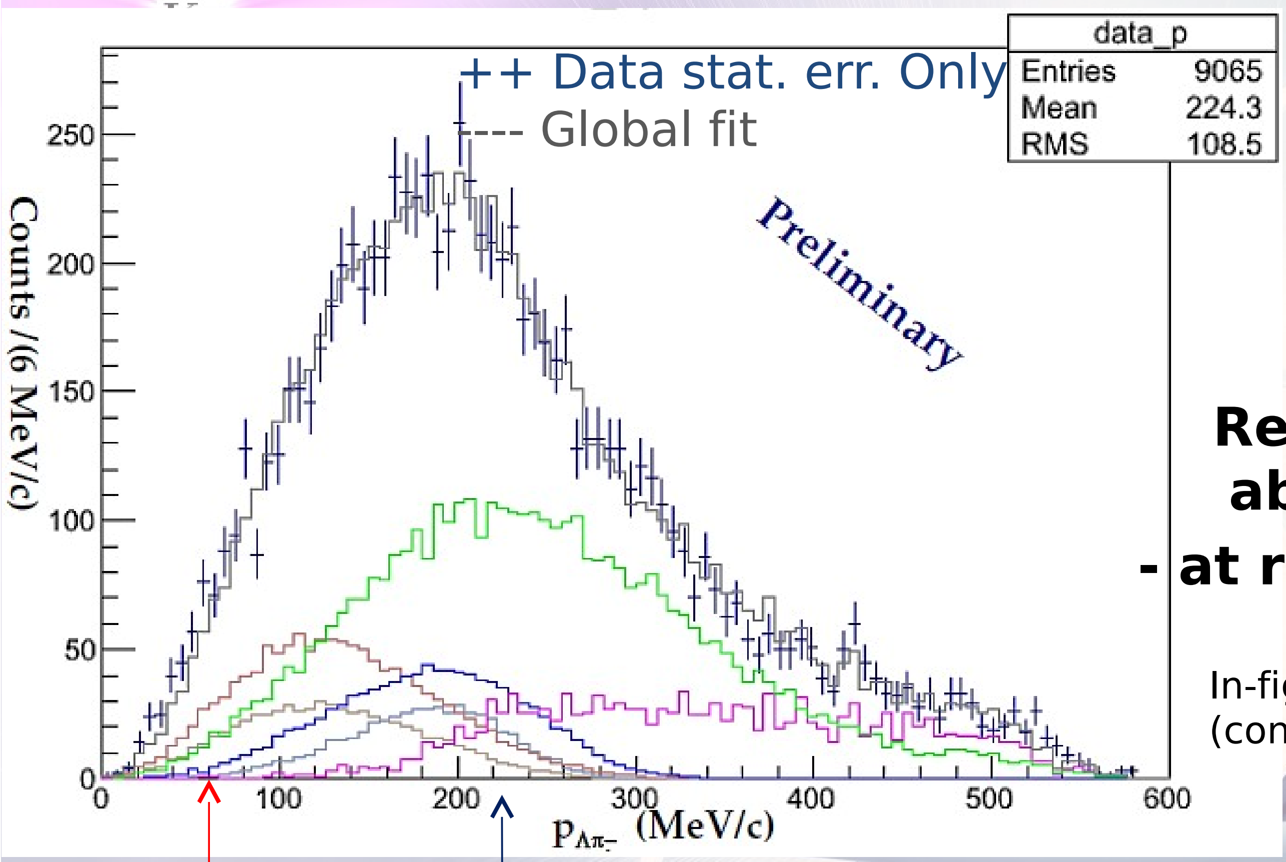
Absorptions in 12C
(from Carbon wall data)

Σ/Λ nuclear conversion
K-N→Σ π
→ΣN→ΛN'





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



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

Resonant Σ*
(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 Σ+π- data = 2.2 ± 0.05)

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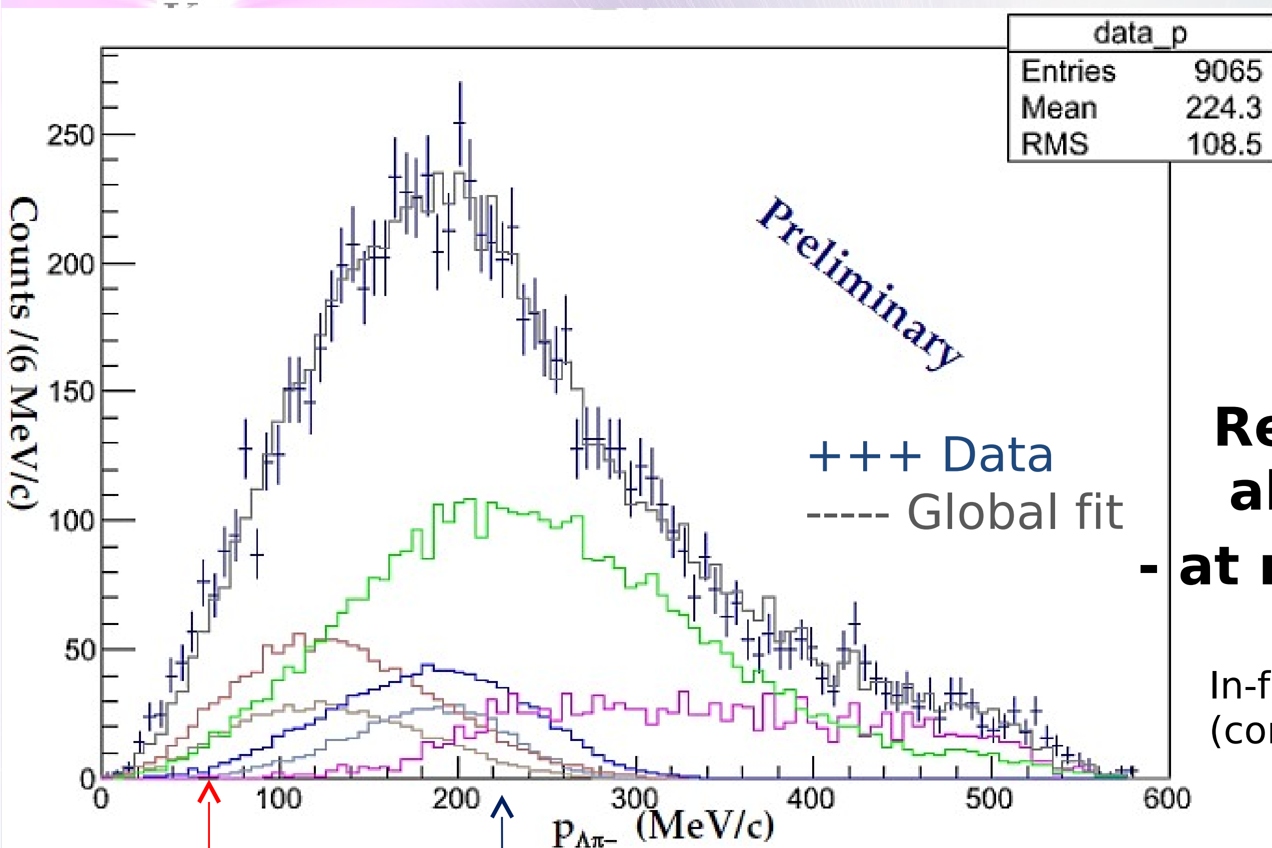

Non-Resonant **(in-flight)** **(at-rest)**

Resonant Σ* **(in-flight)** **(at-rest)**

Simultaneous fit

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

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(consistent with Σ+π- 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.

Further improvements

K^-

a) FSI of the Λ was found to introduce a correction to the amplitude < 3%.

b) FSI of the π is found to be negligible.

c) Introduction of P-state atomic capture

&

P-state in-flight capture.

d) Generalization of the phace space to the relativistic case (main correction for the negative pion)

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P-state in-flight capture.

d) Generalization of the phace space to the relativistic case (main correction for the negative pion)

c1) introduction of at-rest K- capture amplitudes from l=1 orbit

K^-

The fit will be improved by investigating the relative rate for captures from l=0 and l=1. New free parameter η.

The corresponding probability distributions are given by:

$$P^{atom}(f^s) = P^s_{ar}(\mathbf{p}_3)^{ar}[1 + \eta\, a^2(Rp_3)^2]$$

non resonant capture

contribution from l=1

$$P^{atom}(f^p) = P^p_{ar}(\mathbf{p}_3)[1 + \eta\, \frac{3 + \frac{2}{3}acR^2(p_3)^2 + \frac{1}{3}a^2c^2R^4(p_3)^4}{c^2\ (Rp_3)^2}]$$

resonant capture

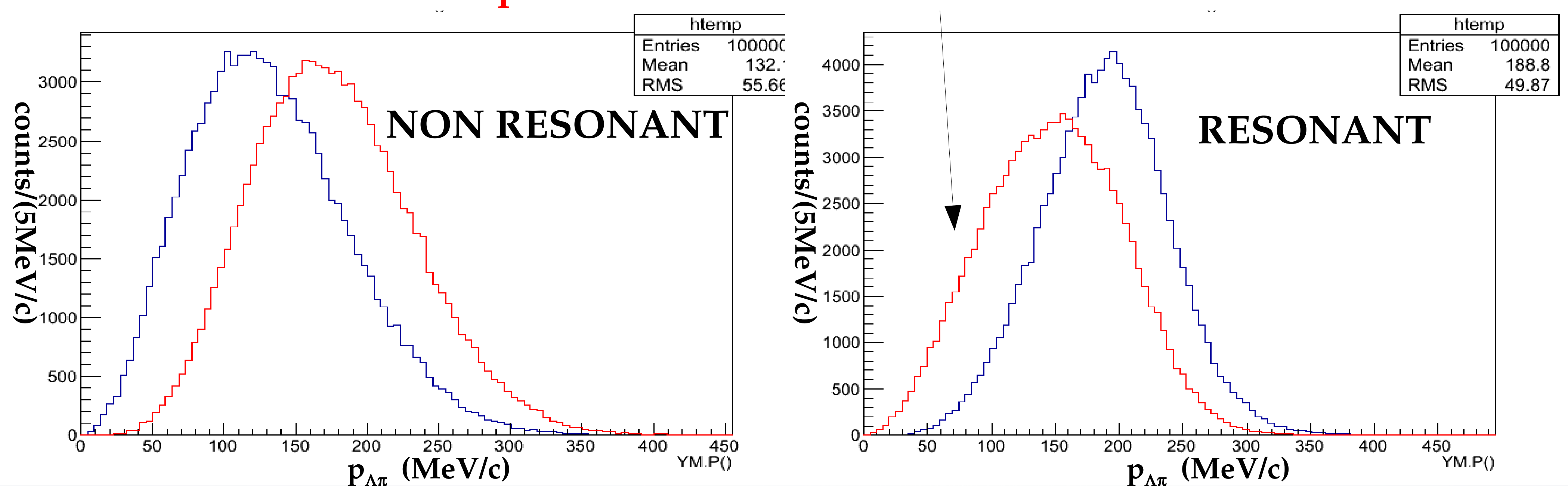
c1) introduction of at-rest K- capture amplitudes from l=1 orbit

K^-

Resonant capture from l=1 favourites small $p_{\Lambda\pi}$, and shifts the $m_{\Lambda\pi}$ distribution upwords ...

------ K- capture from l=0

------ K- capture from l=1



c2) introduction of P-state in-flight capture amplitudes

K^-

Contribution of l=1 capture in flight is obtained to contribute about ¼ of the l=0 capture.

The corresponding probability distributions are given by:

$$P^{flight}(f^s) = P^s_{if}(\mathbf{p})[1 + \frac{a^2R^4p^2(p_K)^2}{3}]$$

non resonant capture

contribution from l=1

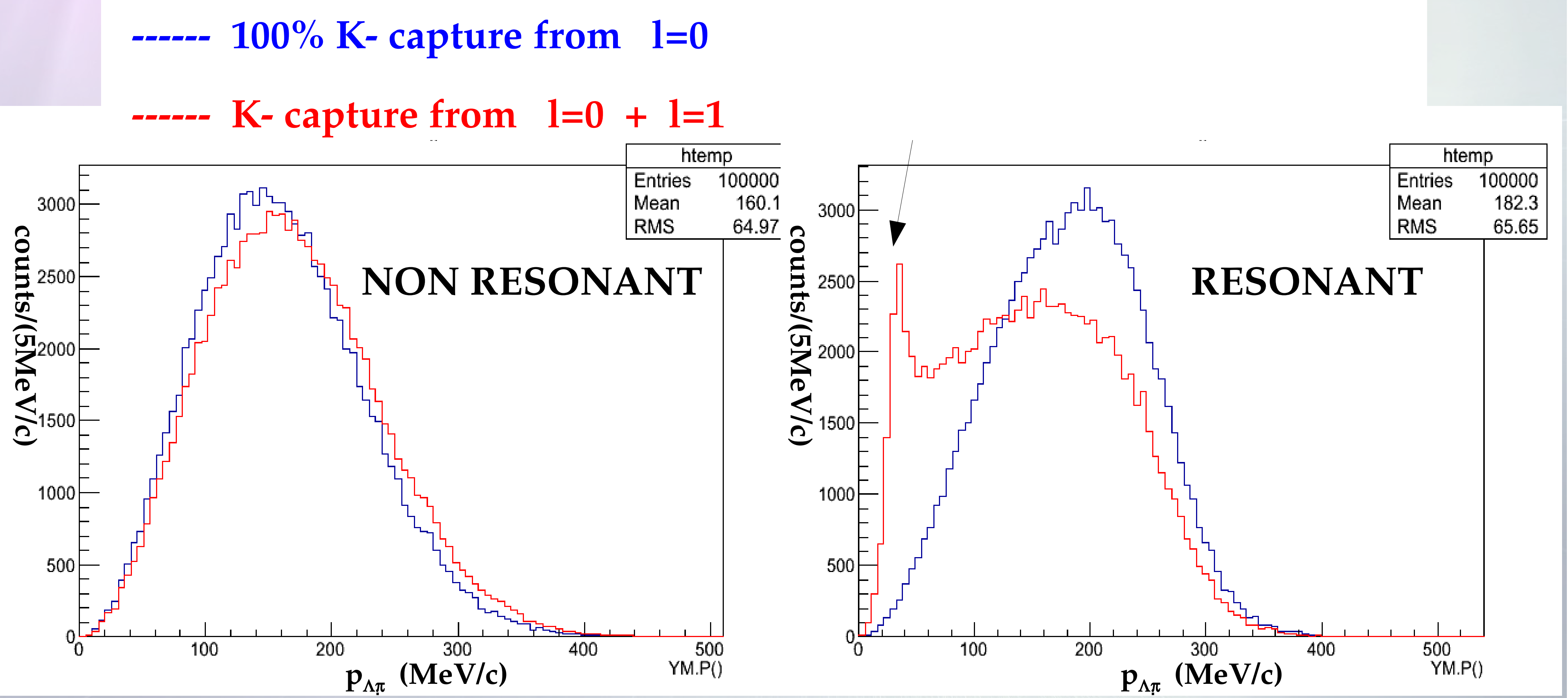
$$P^{flight}(f^p) = P^s_{if}(\mathbf{p})[1 + \frac{(p_K)^2 + \Theta}{p^2}]$$

resonant capture

c2) introduction of P-state in-flight capture amplitudes

K^-

At small $p_{\Lambda\pi}$ resonant capture from l=1 dominates, and shifts the $m_{\Lambda\pi}$ distribution below KN threshold ...



Further improvements

K^-

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&

P-state in-flight capture

d) generalization of the phace space to the relativistic case (main correction expected for the negative pion) <u>ONGOING</u>

Conclusions

- $m_{\Sigma\pi}$ 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 belw threshold

Next steps …

- Same 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⁻
Thanks

Scientific case of the Λ(1405)

Λ(1405) : mass = $1405.1^{+1.3}_{-1.0}$ MeV, width = 50 ± 2 MeV

I = 0, S = -1 , J^p = $1/2^-$, Status: ** , strong decay into Σπ**

Its nature has been a puzzle for decades: three quark state, unstable $\bar{K}N$ bound state, penta-quark, two poles??

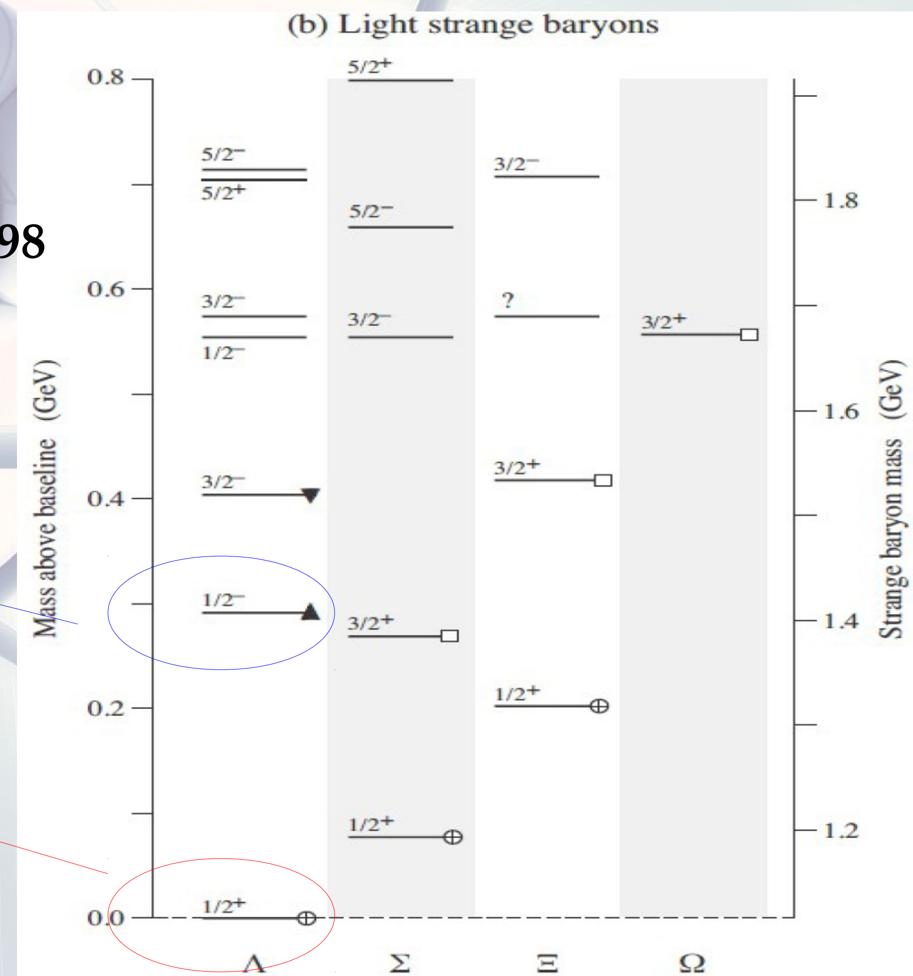
First experimental evidence:

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

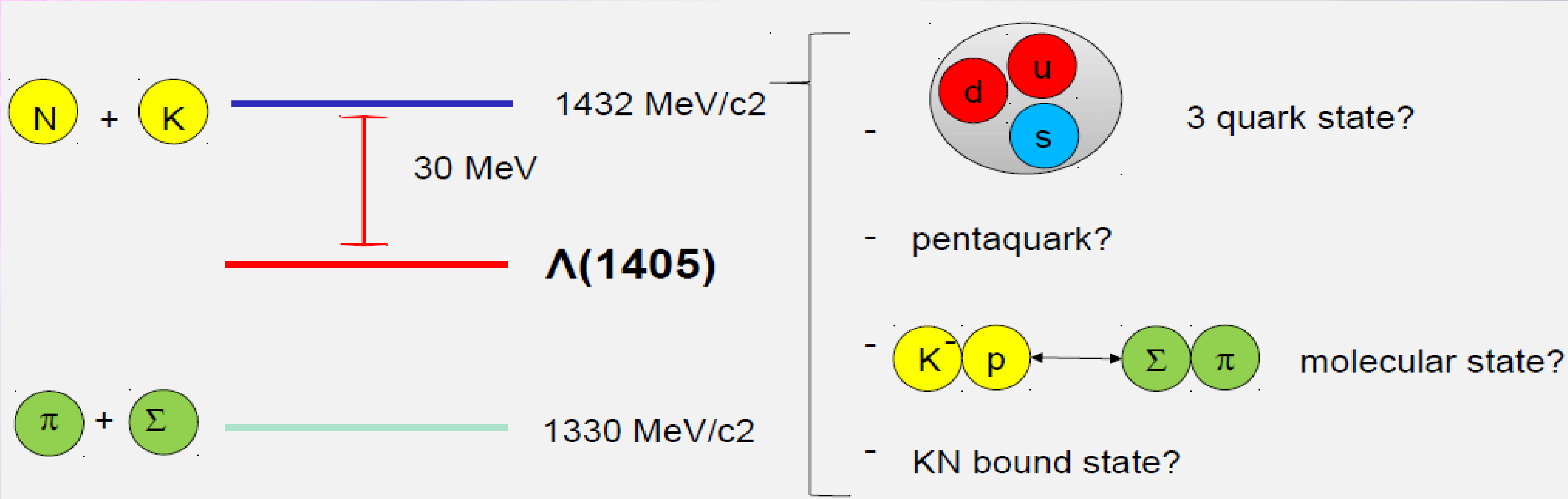
$K^- p \rightarrow \pi\pi\pi\Sigma$

Λ(1405)

Λ(1116)



Scientific case of the Λ(1405)



- The **three quark model picture:** Λ(1405) mass??

Similar to the nucleon sector N(1535), the expected mass of the Λ^* is around 1700 MeV.

- Energy splitting between the Λ(1405) and the Λ(1520) (spin-orbit partner ($J^p = 3/2^-$)) ??.

R. Dalitz and collaborators first suggested to interpret Λ(1405) as an $\bar{K}N$ quasibound state.

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

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

K^-

- **Fit of the $p_{\Lambda\pi^-}$ observed distribution using calculated distributions :**

$$P^s_{ar}(\mathbf{p}_3) = \zeta e^{-p_3^2 R^2} \, |f^s|^2 \, p_3^2 \sqrt{2\mu_{12} \left(\Delta_{ar} - \frac{p_3^2}{2\mu_{12,3}} \right)}$$

non-resonant

$$P^s_{if}(\mathbf{k}_{3,12}) = \zeta \, e^{-\left[-\mathbf{k}_{3,12} + \mathbf{p}_K \left(a + \frac{m_3}{m_T}\right)\right]^2 R^2} \, |f^s|^2 \, k_{3,12}^2 \sqrt{2\mu_{12} \left(\Delta_{if} - \frac{k_{3,12}^2}{2\mu_{12,3}} \right)}$$

$$P^p_{ar}(\mathbf{p}_3) = 2\pi \left| A^p_{if}(\mathbf{k}_{3,12}) \right|^2 \rho(\mathbf{p}_3) =$$

$$= \zeta \, \frac{4}{3} c^2 \, e^{-p_3^2 R^2} \, p_3^2 \left[\frac{\Gamma/2}{E_{if} - E_r + i\Gamma/2} \, \frac{0.80}{1.12} \right]^2 \left\{ 2\mu_{12} \left(\Delta_{ar} - \frac{p_3^2}{2\mu_{12,3}} \right) \right\}^{-3/2}$$

$$P^p_{if}(\mathbf{k}_{3,12}) \propto \frac{4}{3} c^2 \, e^{-\left[-\mathbf{k}_{3,12} + \mathbf{p}_K \left(a + \frac{m_3}{m_T}\right)\right]^2 R^2} \left[\frac{\Gamma/2}{E_{if} - E_r + i\Gamma/2} \, \frac{0.80}{1.12} \right] \cdot$$

$$\cdot \frac{\left(\mathbf{k}_{3,12} + \frac{m_1 + m_2}{m_T} \mathbf{p}_K \right)^2}{k_{3,12}^2} \left\{ 2\mu_{12} \left(\frac{\Delta_{if}}{k_{3,12}^2} - \frac{1}{2\mu_{12,3}} \right) \right\}^{-3/2} .$$

resonant

$K^- \, {}^4He \rightarrow \Lambda \, \pi^- \, {}^3He$ <u>background</u>

- **Σ p/n → Λ p/n conversion:**

  Each possible conversion channel was simulated

  Σ^0 p / Σ^0 n / Σ^+ n / At-rest / In-flight / from RES and N-R produced Σs

- **$\Lambda \, \pi^-$ events from $K^- \, {}^{12}C$ absorptions in Isobutane** (90% He, 10% C_4H_{10}):

  $K^- \, {}^{12}C$ DATA in the KLOE DC wall are used

  estimated contribution: $\%(K^- \, {}^{12}C) = 0.44 \pm 0.13$

  $N_{KC}/N_{KHe} = (n_{KC}/n_{KHe}) \cdot (\sigma_{KC}/\sigma_{KHe}) \cdot (BR_{KC}(\Lambda \pi^-)/BR_{KHe}(\Lambda \pi^-))$

  Nuovo Cimento 39 A 338-347 (1977)

  $K^- \, {}^{12}C$ still not calculated:

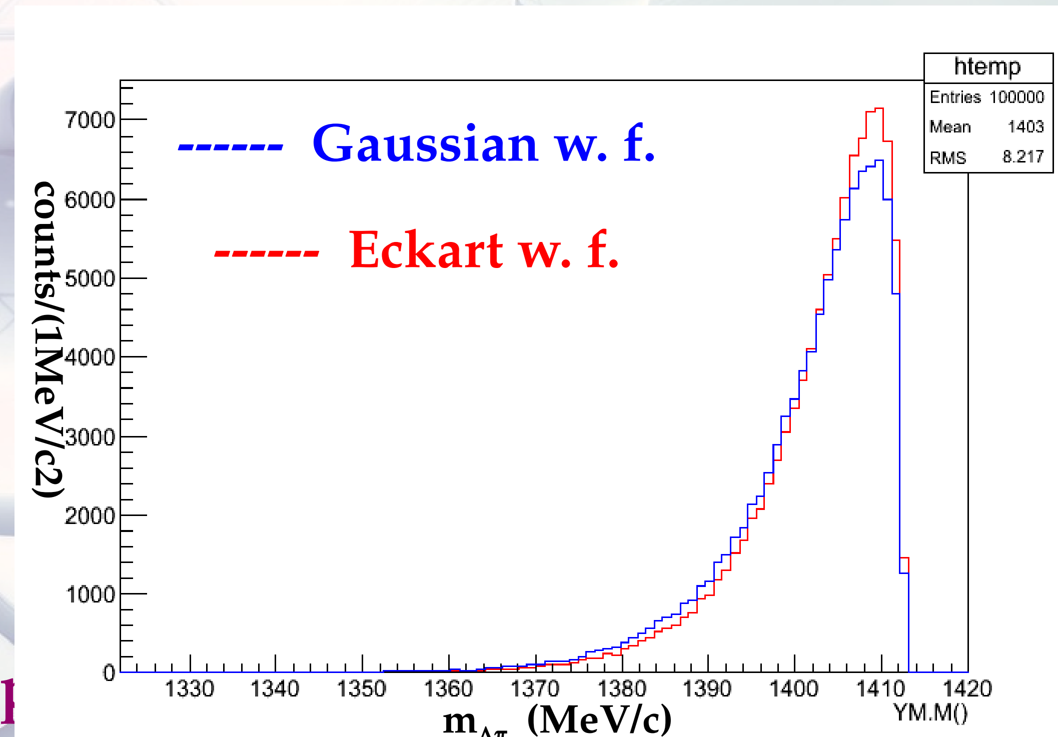
  - uncertain initial state of K meson $l_K = 1, 2, 3$
  - 4 nucleons in s-orbit , 8 nucleons in p-orbit
  - final state hyperon interactions

Last step

K^-

high invariant masses are still not well described.

We are improving the assumed initial neutron wave function (Gaussian) with Eckart wave function.



The theoretical p

The draft of the experimental paper only needs this last check and following evaluation of systematics (within June)

0.1 Estimate of the non-resonant transition amplitude module $|f^s|$

The momentum probability distributions of the produced $\Lambda\,\pi$ pairs, for the $K^- \, {}^4He \rightarrow \Lambda\pi^- \, {}^3He$ direct production capture at rest, assuming the kaon to be captured from an initial S atomic state, where calculated in the two cases in which the $K^- n$ interaction is S-wave (*non-resoanant* absorption) and P-wave (*resoanant* absorption). The obtained probability distributions are:

$$P^s_{ar}(\mathbf{p}_3) = \zeta e^{-p_3^2 R^2} \, |f^s|^2 \, p_3^2 \sqrt{2\mu_{12} \left(\Delta_{ar} - \frac{p_3^2}{2\mu_{12,3}} \right)} \quad (1)$$

$$P^p_{ar}(\mathbf{p}_3) = \zeta \, \frac{4}{3} c^2 \, e^{-p_3^2 R^2} \, p_3^2 \left[\frac{\Gamma/2}{E_{if} - E_r + i\Gamma/2} \, \frac{0.80}{1.12} \right]^2 \left\{ 2\mu_{12} \left(\Delta_{ar} - \frac{p_3^2}{2\mu_{12,3}} \right) \right\}^{-3/2} . \quad (2)$$

In previous Eqs. 1 and 2 the subscripts 1,2 and 3 correspond to *meson*, *neutron* (Λ) and ${}^3He$ respectively, μ_{12} and $\mu_{12,3}$ are reduced masses, R is the radius of the ${}^4He$ nucleous and $\mathbf{p}_3$ represents the momentum of the residual ${}^3He$ in the laboratory frame, which, for at-rest capture is related to the $\Lambda\,\pi$ pair momentum by the relation $\mathbf{p}_3 = \mathbf{p}_{\Lambda\pi}$. the constant c, which determines the recoupling of the $S\,x\,S$ waves into $P\,x\,P$ waves, is related to the masses of the interacting particles by:

$$c = \frac{m_1}{m_1 + m_2}. \tag{3}$$

The factor ζ, which is common factor to the two probability distributions, have no influence on the shape of the distributions, nor on the ratio between the resonant and non resonant probabilities.

The module of the non resonant transition amplitude can be extracted from the experimental distributions of the reconstructed $\Lambda\pi$ pairs, obtained selecting the direct hyperon-meson production events, cutting on the p_π - p_Λ scatterplot the region predicted by theoretical calculations. From the simultaneous fit of the reconstructed momentum ($p_{\Lambda\pi}$), invariant mass ($m_{\Lambda\pi}$) and angular correlation ($\theta_{\Lambda\pi}$), the ratio between the non-resonant produced $\Lambda\pi$ events and the resonant $\Lambda\pi$ produced pairs at-rest was estimated to be:

$$\frac{\text{non-resonant events}}{\text{resonant events}} = 1.3 \pm (0.1\,\text{stat}) \qquad \text{with} \qquad \frac{\chi^2}{\text{ndf - np}} = 1.6. \tag{4}$$

The ratio between the non-resonant and resonant measured number of events is a ratio between probabilities, and is then to be equated to the ratio between the integrals of the probability distributions (Eqs. 1 and 2).

$$\frac{\int_0^{pmax} P^s_{ar}(p_3)\, dp_3}{\int_0^{pmax} P^p_{ar}(p_3)\, dp_3} = \tag{5}$$

$$= \frac{|f^s|^2 \int_0^{pmax} e^{-p_3^2 R^2} p_3^2 \sqrt{2\mu_{12} \left(\Delta_{ar} - \frac{p_3^2}{2\mu_{12,3}}\right)} dp_3}{\int_0^{pmax} \frac{4}{3} c^2 e^{-p_3^2 R^2} p_3^2 \left[\frac{\Gamma/2}{E_{if} - E_r + i\Gamma/2} \frac{0.80}{1.12}\right]^2 \left\{2\mu_{12} \left(\Delta_{ar} - \frac{p_3^2}{2\mu_{12,3}}\right)\right\}^{-3/2} dp_3} = \quad (6)$$

$$= |f^s|^2 \cdot 8,94223471 \cdot 10^5 MeV^2 = 1.3 \pm (0.1\,\mathrm{stat}). \quad (7)$$

From Eq. 7 it follows that the module of the non resonant transition amplitude is given by:

$$|f^s| = 2.4 \cdot 10^{-1} \pm (0.01\,\mathrm{stat})\,\mathrm{fm} \quad (8)$$

a) generalization of the phace space to the relativistic case

K⁻

We stay with non-relativistic expressions for the kinetic energies of Λ and [4]He, for the π⁻, with momenta of about 200 MeV, the final state energy is generalized:

$$E_{\Lambda\pi} = \frac{p_3^2}{2m_3} + m_2 + \frac{p_2^2}{2m_2} + \sqrt{m_1^2 + p_1^2}$$

The non relativistic phace space element ..

$$d\rho(\mathbf{p}_3)^{nr} = \frac{4m_\pi m_\Lambda}{(2\pi)^4[m_\pi + m_\Lambda]} \sqrt{2\mu_{12}\left(Q_{ar} - \frac{p_3^2}{2\mu_{12,3}}\right)}\, p_3^2\, dp_3$$

assumes the following form for the at-rest capure..

$$d\rho(\mathbf{p}_3)^{ar} = \frac{4m_\pi m_\Lambda}{(2\pi)^4[\sqrt{m_\pi^2 + k_{12}^2} + m_\Lambda]} \sqrt{2\widetilde{\mu}_{12}\left(Q_{ar} - \frac{p_3^2}{2\mu_{12,3}}\right)}\, p_3^2\, dp_3$$

with:

$$k_{12} = \sqrt{2\widetilde{\mu}_{1,2}\,(Q - \frac{p_3^2}{2\mu_{12,3}} - \theta)}$$

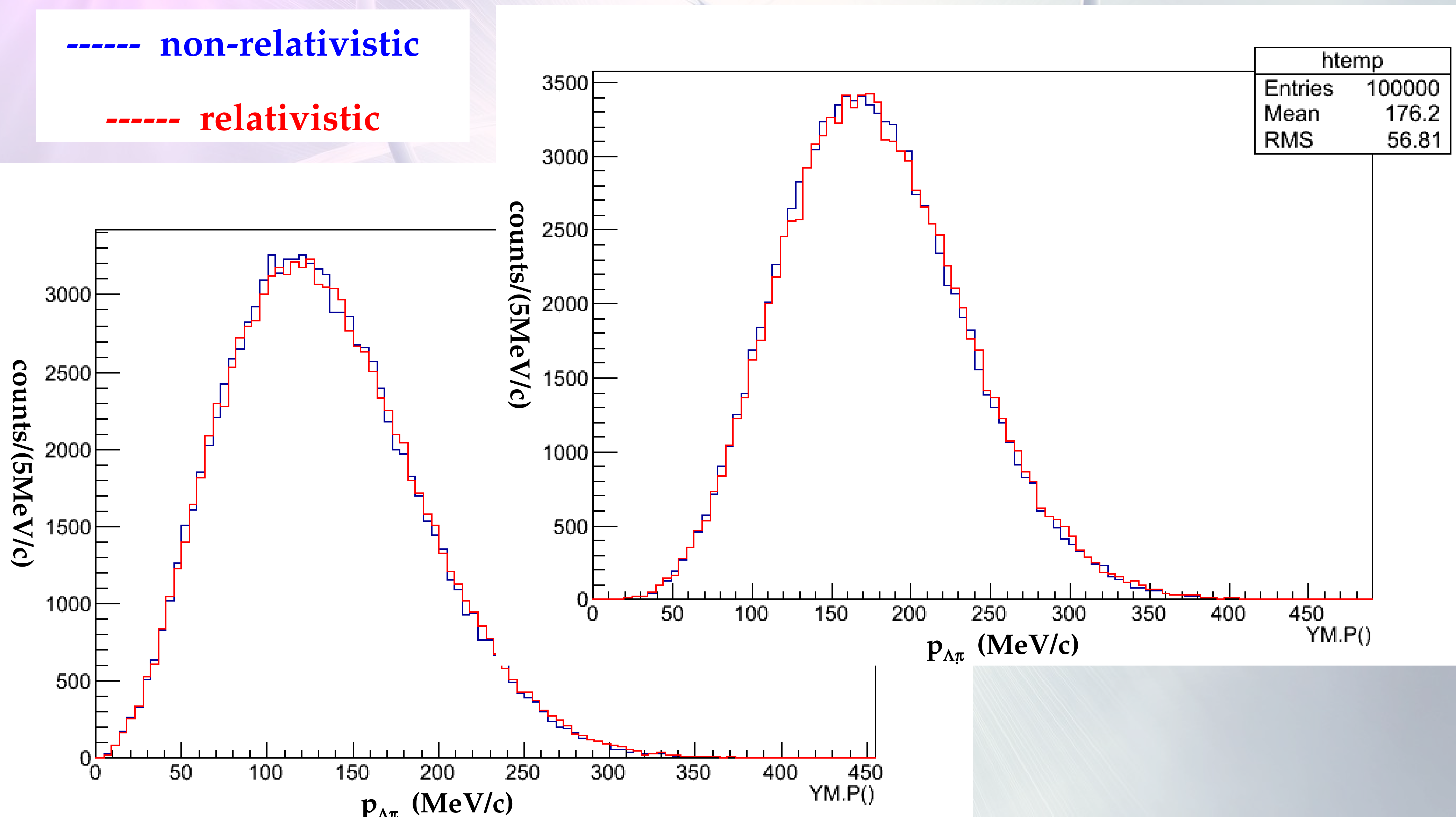
and

$$\widetilde{\mu}_{1,2} = \frac{m_2[\,2m_1 + Q_{ar} - p_3^2/2\widetilde{\mu}_{2,3}\,]}{m_1 + m_2 + Q_{ar} - p_3^2/2\widetilde{\mu}_{2,3}}$$

with similar expression for the in-flight capture case.

a) generalization of the phace space to the relativistic case

Momentum distributions of the $\Lambda\ \pi^-$ pairs, for at-rest K- capures from l=0 (left) and (l=1) right K- orbits



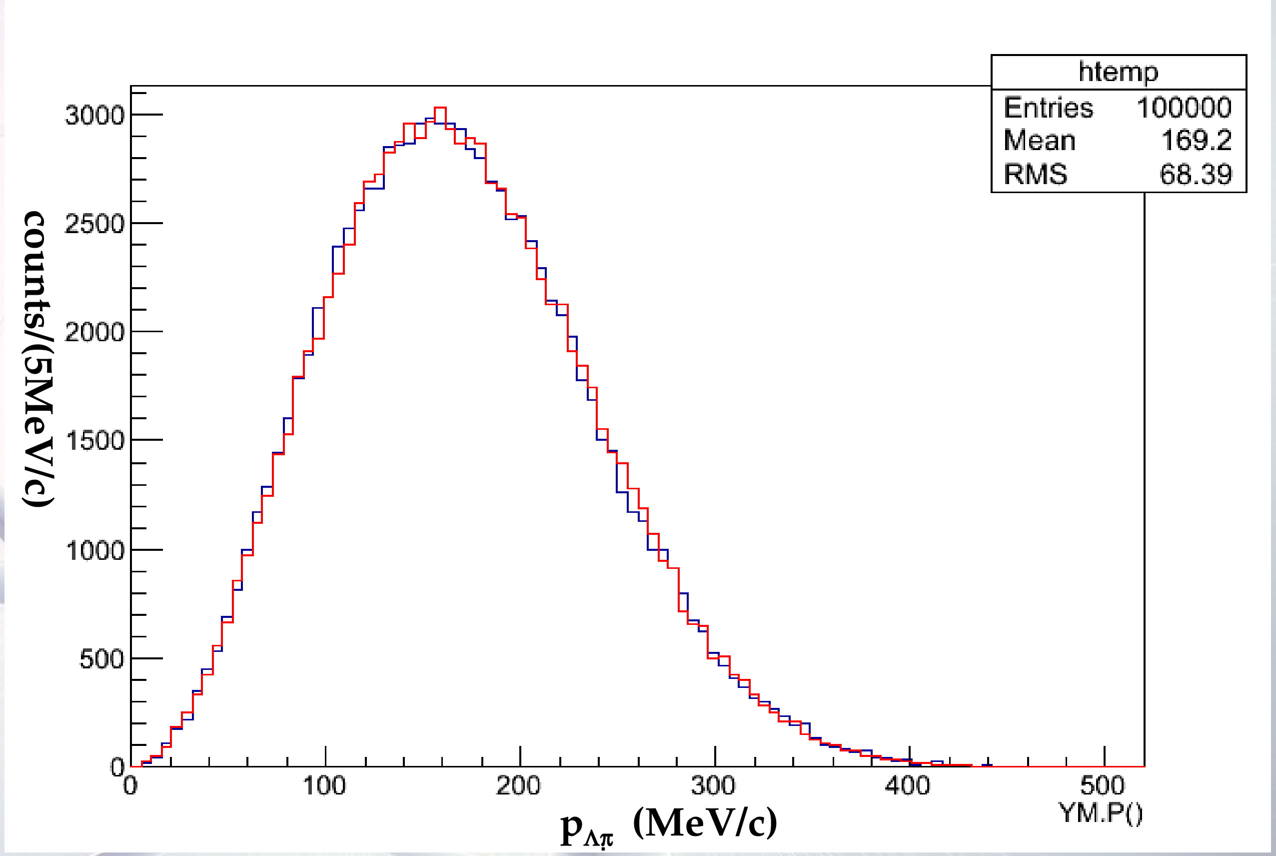
a) generalization of the phace space to the relativistic case

Momentum distributions of the Λ π^- pairs, for in-flight K- capures from l=0 + l=1

K- captures (l=1 contributes about 15%)

------ non-relativistic

------ relativistic



For both at-rest and in-flight captures the relativistic correction turns then to be negligible.

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 → Λ/Σ p

K⁻ppn → Λd

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

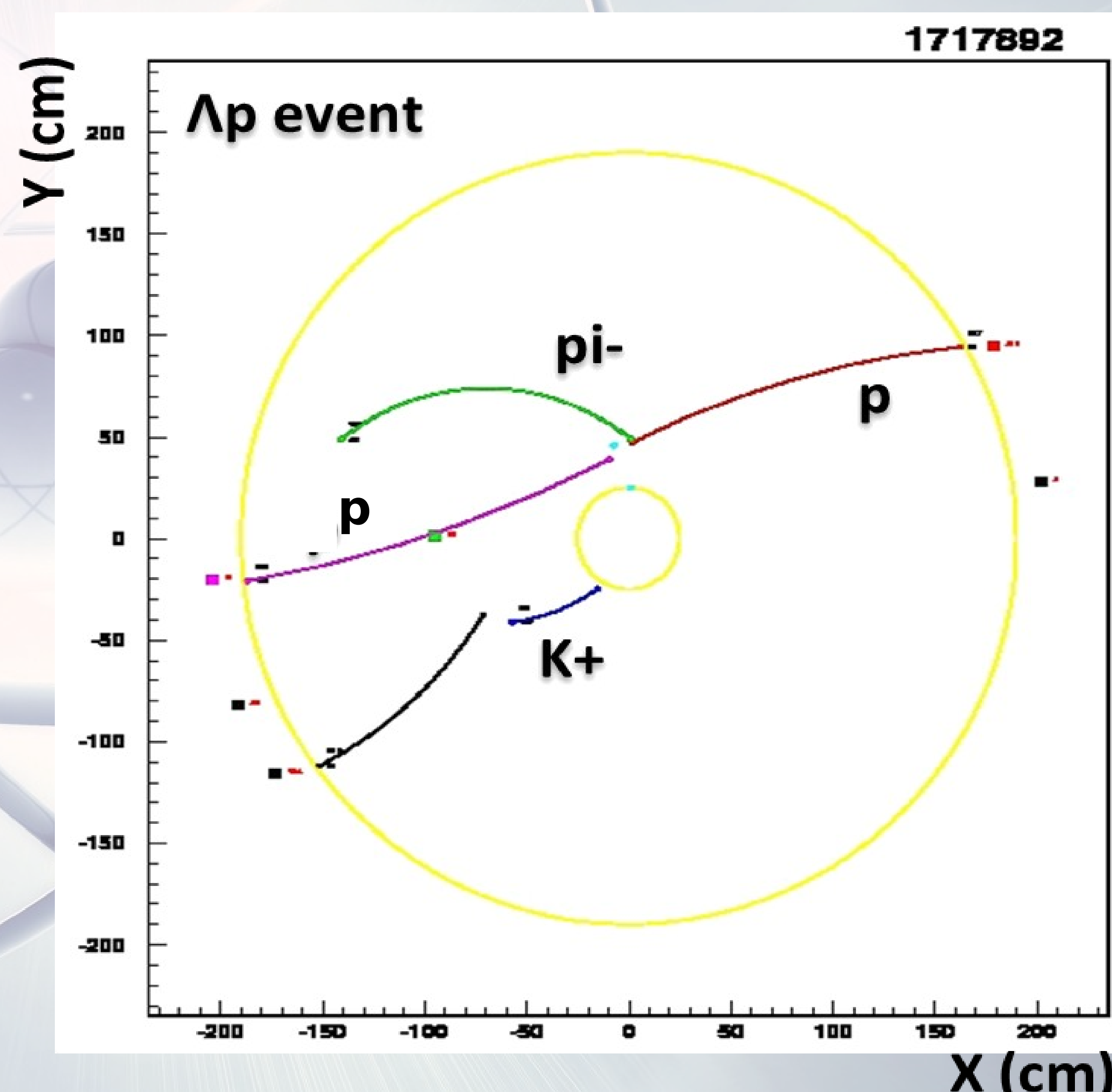
	Theoretical prediction	B.E (MeV)	Γ (MeV)
PRC76, 045201 (2002)	T. Yamazaki and Y. Akaishi	48	61
arXiv:0512037v2[nucl-th]	A. N. Ivanov, P. Kienle, J. Marton, E. Widman	118	58
PRC76, 044004 (2007)	N. V. Shevchenko, A. Gal, J. Mares, J. Revai	50~70	~100
PRC76, 035203 (2007)	Y. Ikeda and T. Sato	60~95	45~80
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

Λp correlation study

K- stopped **+ X → Λ** **p** **X’**
(in-flight)

Λ → pπ–

(detected particles)



Resolutions for events in GAS:

p_Λ	$0.49 \pm 0.01\ MeV/c$
p_p	$2.63 \pm 0.07\ MeV/c$
$M_{\Lambda p}$	$1.10 \pm 0.03\ MeV/c^2$
r_{vertex}	$0.12 \pm 0.01\ cm$

Λp correlation study

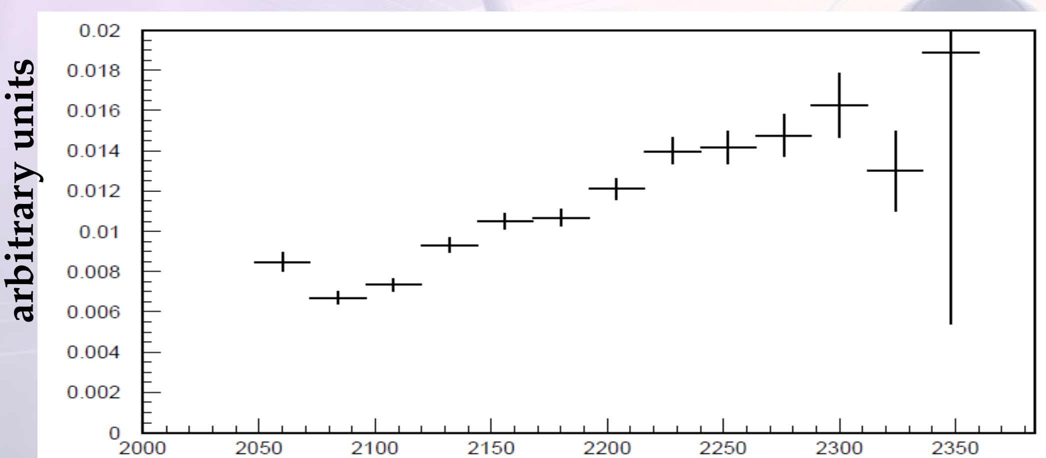
K⁻

K- stopped **+ X → Λ** **p** **X'**
(in-flight)

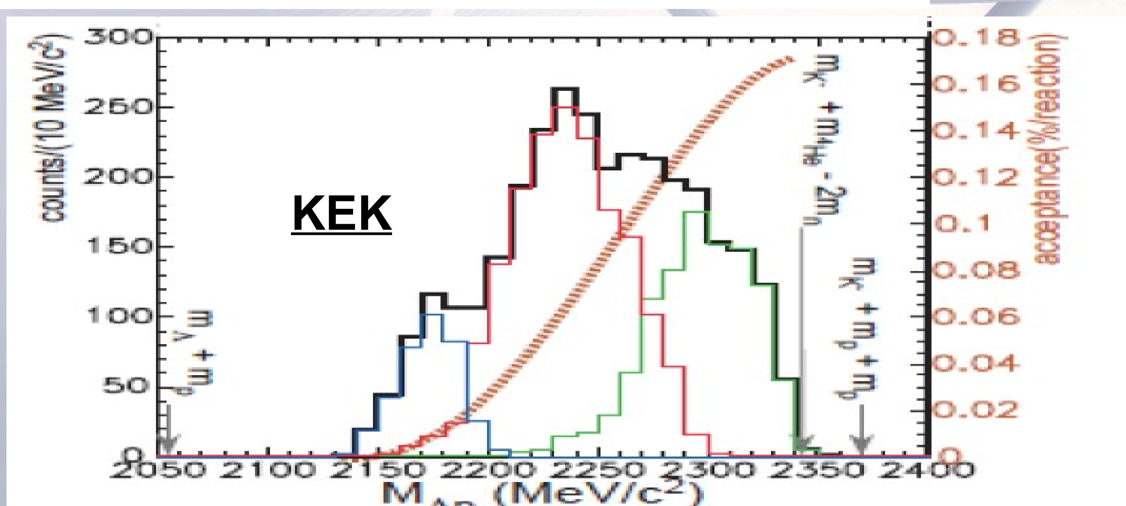
(detected particles)

↳ pπ−

Acceptance study with phase space **K- + 4He -> Λ p n n** MC simulation



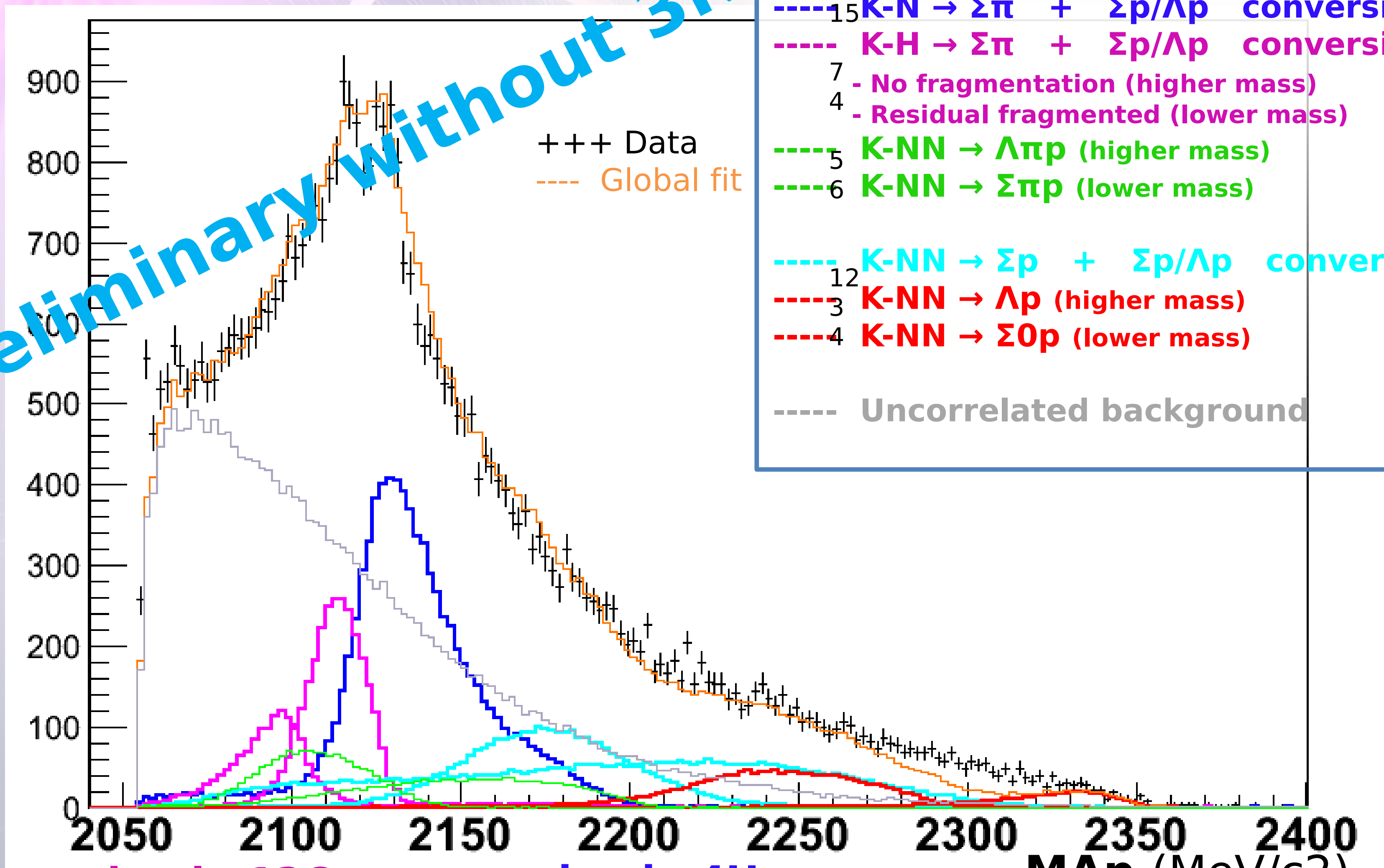
Projection of the acceptance function depending on : (PΛ,Pp,Minv Λp) on the Invariant mass plane



Λp correlation study

K⁻

Fit 3D (P_Λ, P_p, $\theta_{\Lambda p}$)



----- K-N → Σπ + Σp/Λp conversion in 4He

----- K-H → Σπ + Σp/Λp conversion in 12C

- No fragmentation (higher mass)
- Residual fragmented (lower mass)

----- K-NN → Λπp (higher mass)

----- K-NN → Σπp (lower mass)

----- K-NN → Σp + Σp/Λp conversion in 4He

----- K-NN → Λp (higher mass)

----- K-NN → Σ0p (lower mass)

----- Uncorrelated background

conversion in 12C

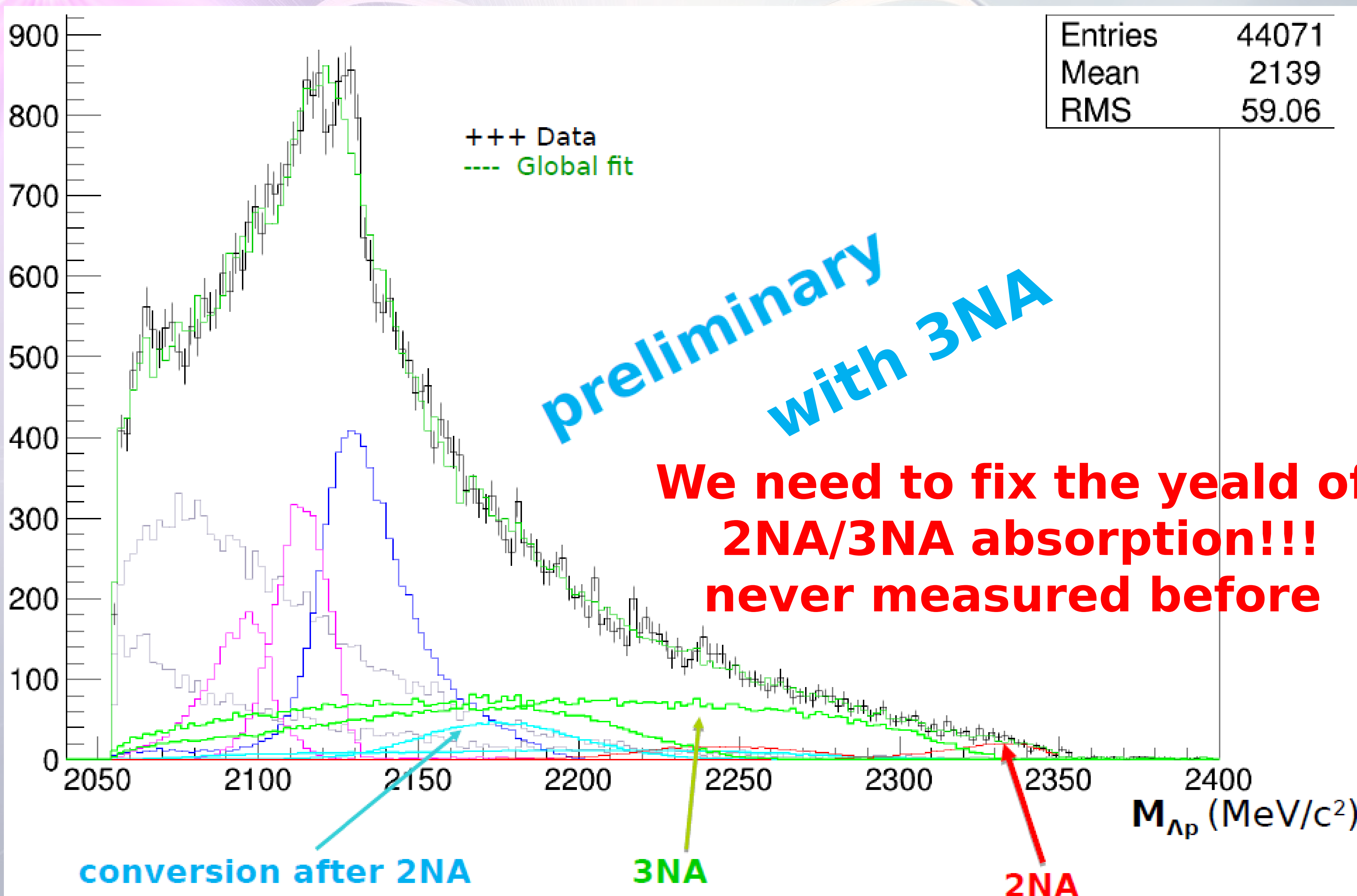
conversion in 4He

2NA direct production

conversion after 2NA: more energetic

Λp correlation study

Fit 3D (P_{Λ}, P_p, $\theta_{\Lambda p}$)



$\Sigma^0 p$ correlation study .. PART 2b

K^-

$K^-_{\text{stopped / in-flight}} + X \rightarrow \Sigma^0 \; p \; X'$

$\Sigma^0 \rightarrow \Lambda \gamma$

$\Lambda \rightarrow p \pi^-$

(detected particles)

GOLDEN channel for K-pp cluster search

free from $\Sigma N \rightarrow \Lambda N'$ conversion process!!!

never measured before

Σ^0p correlation study

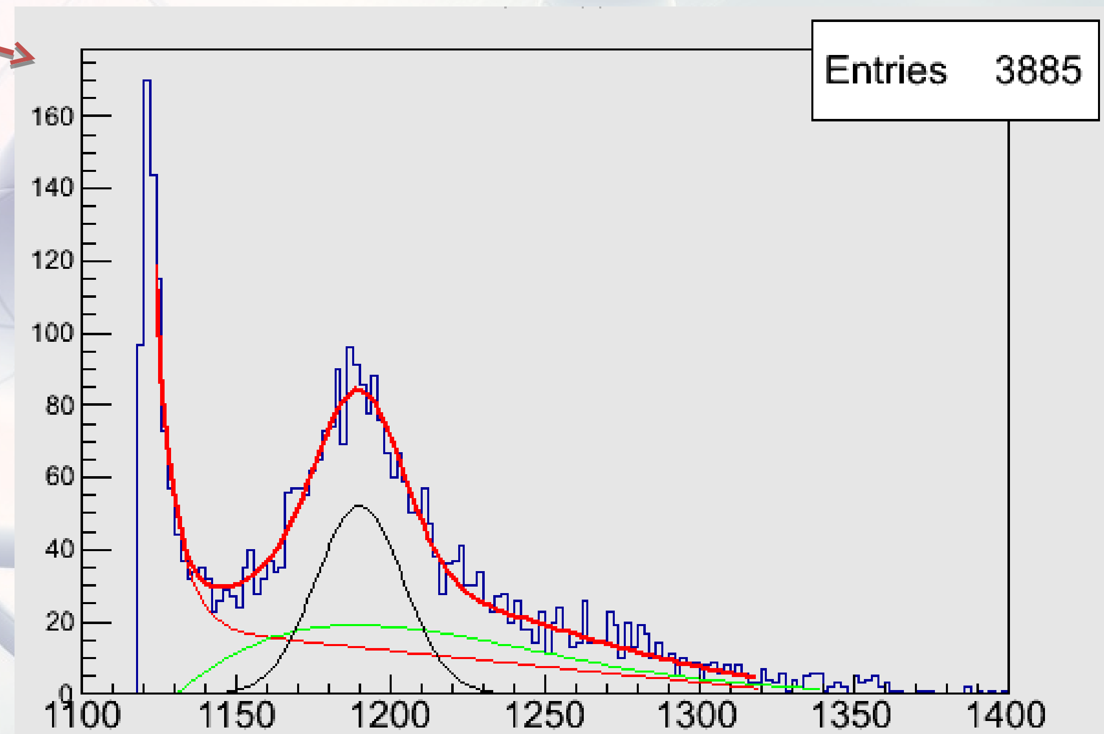
$K^-_{\text{stopped / in-flight}} + X \rightarrow \Sigma^0\ \mathbf{p}\ X'$

$\Sigma^0 \rightarrow \Lambda\gamma$

$\Lambda \rightarrow p\pi^-$

(detected particles)

Search for Σ^0 in the Λp sample (GAS events):

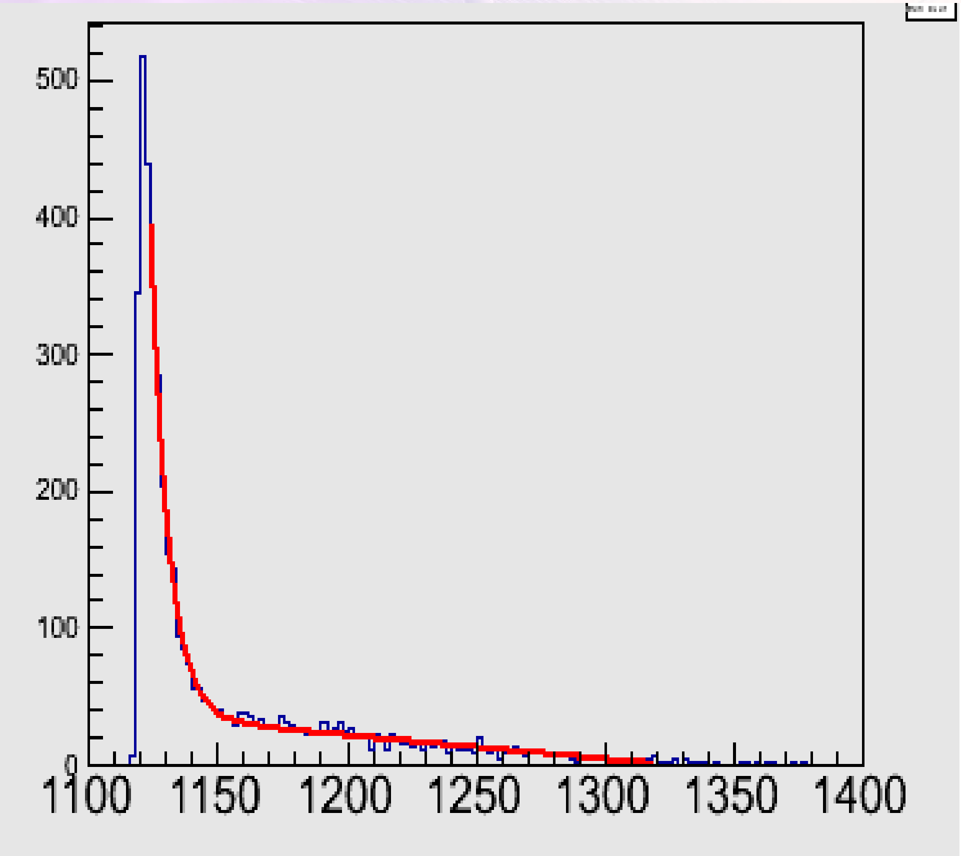


$M_{\Lambda\gamma}$ (MeV/c²)

$\Sigma^0 p$ correlation study

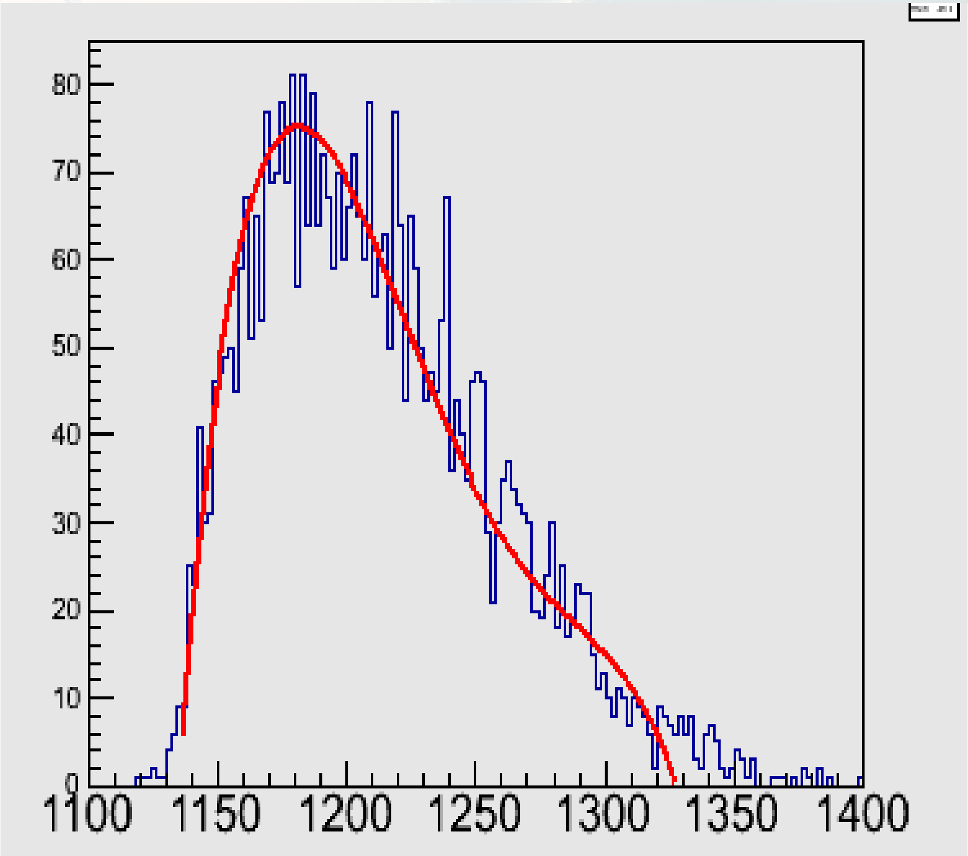
Two background sources:

Asynchronous background
(entering in the time selection window)



$M_{\Lambda\gamma}$ (MeV/c²)

Events with π^0 (double counting for those!)

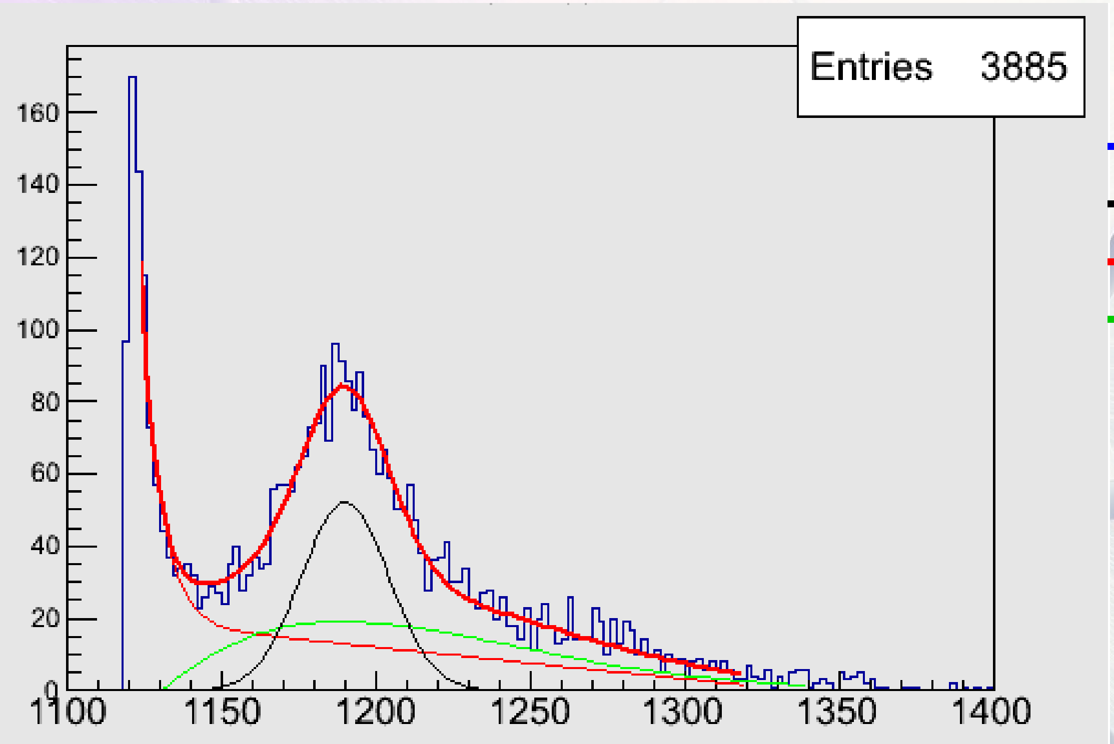


$M_{\Lambda\gamma}$ (MeV/c²)

$\Sigma^0 p$ correlation study

Two background sources:

- Asynchronous background (entering in the time selection window)
- Events with π^0 (double counting for those!)



$M_{\Lambda\gamma}$ (MeV/c²)

--- Data
--- Gaussian signal
--- Machine bkg
--- Pi0 bkg

Σ^0 mass resolution
$\sigma \sim 15$ MeV/c²
(compatible with MC simulations)

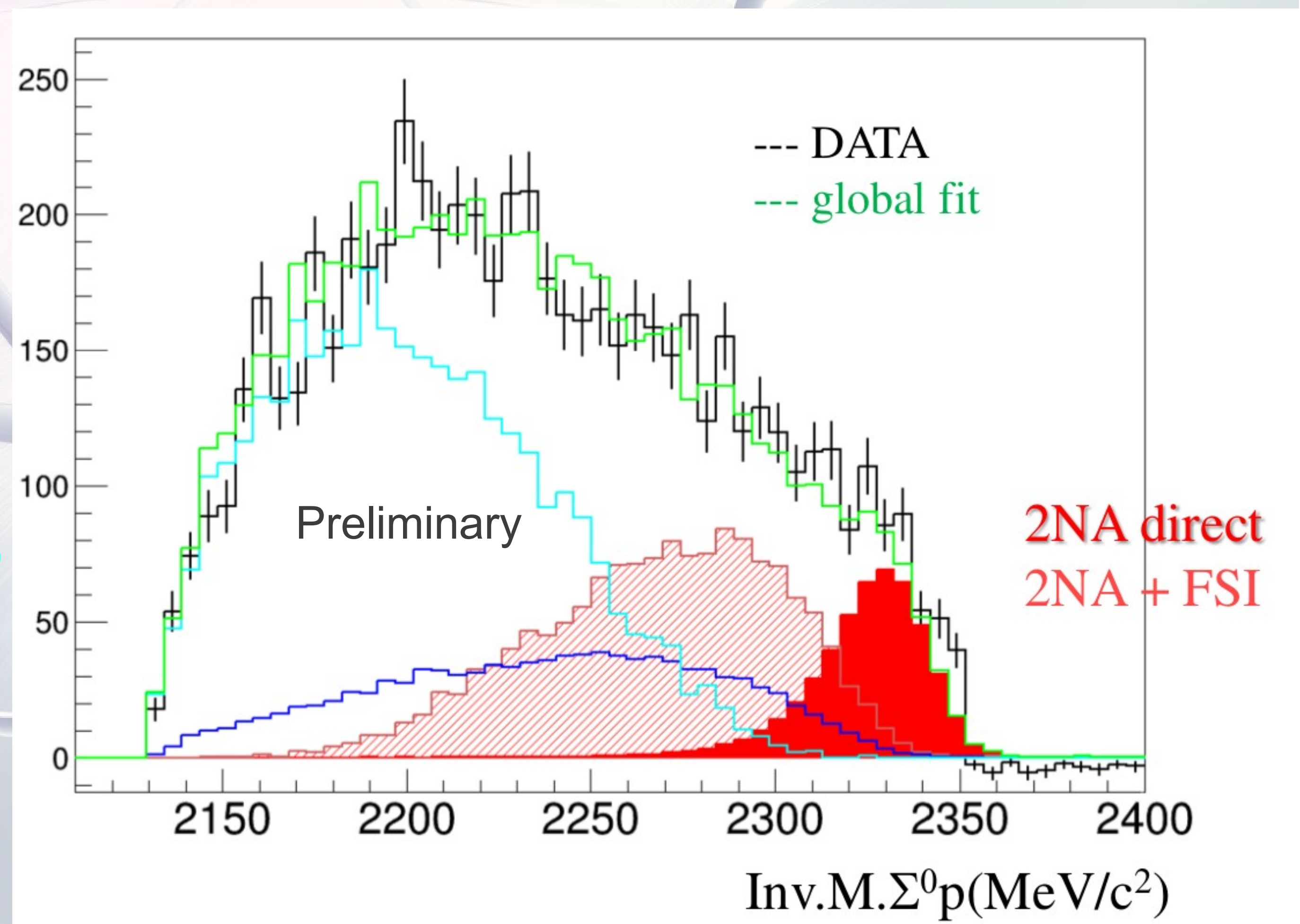
Σ^0p analysis

- Simultaneous fit to MC generated contributions in all the relevant physical quantities:
  - Momentum of proton, momentum of Σ^0, invariant mass, angle Σ^0p

2NA: K-pp → Σ^0p
(FSI means rescattering of Σ^0 or p with residual nucl)

3NA: K-ppn → Σ^0pn

Uncorr: other sources of protons, 4NA, FSI, spectators, etc.



Λp scientific case

K⁻

How deeply can an Antikaon be bound to a nucleus?

Possible bound states: K^-pp → Λp

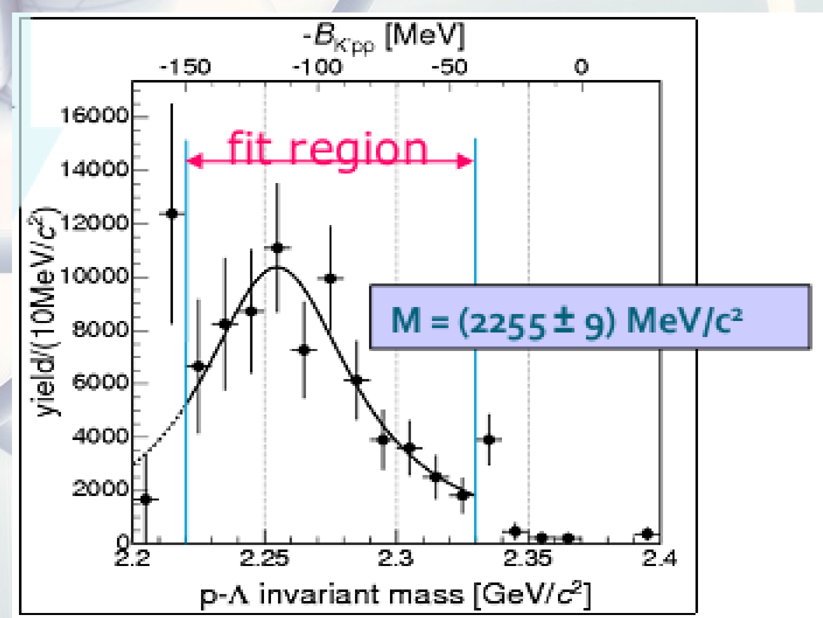
Experimental studies in the Λp decay channel

- pp collisions: DISTO (published), FOPI, HADES (E. Epple → monday afternoon session)
- Absorption experiments:

FINUDA

K- stopped + X -> Λp X'

6Li
X = 7Li
9Be



PRL94 (2005) 212303

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

Λp scientific case

K⁻

How deeply can an Antikaon be bound to a nucleus?

Possible bound states: K^-pp

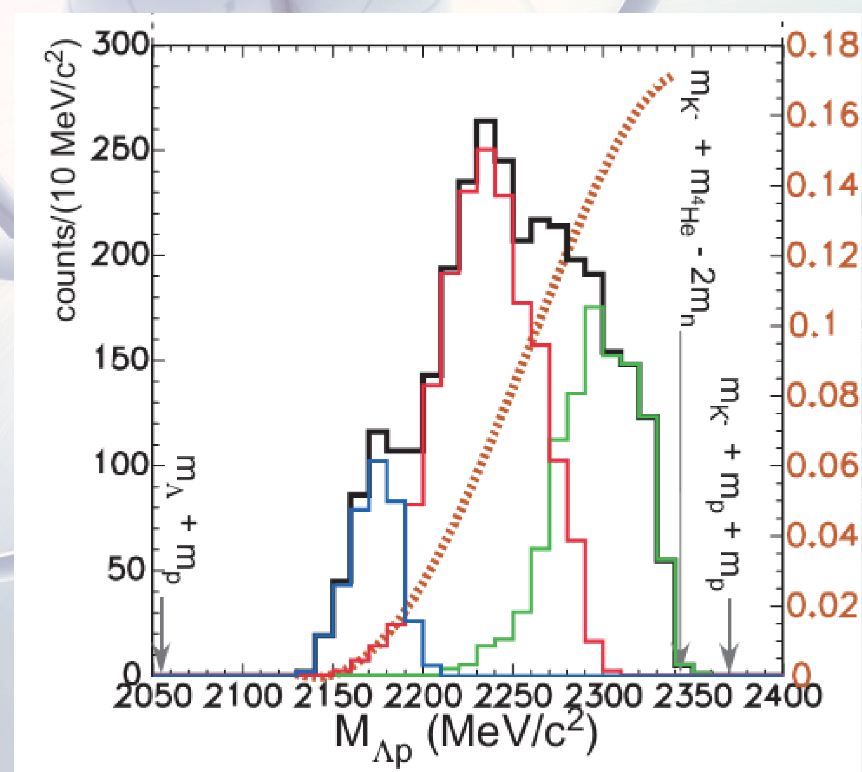
→ Λp

Experimental studies in the Λp decay channel

- pp collisions: DISTO (published), FOPI, HADES (E. Epple → monday afternoon session)
- Absorption experiments:

@KEK E-549

K- stopped + 4He -> Λp X



1NA

ΣN/ΛN - DBKS

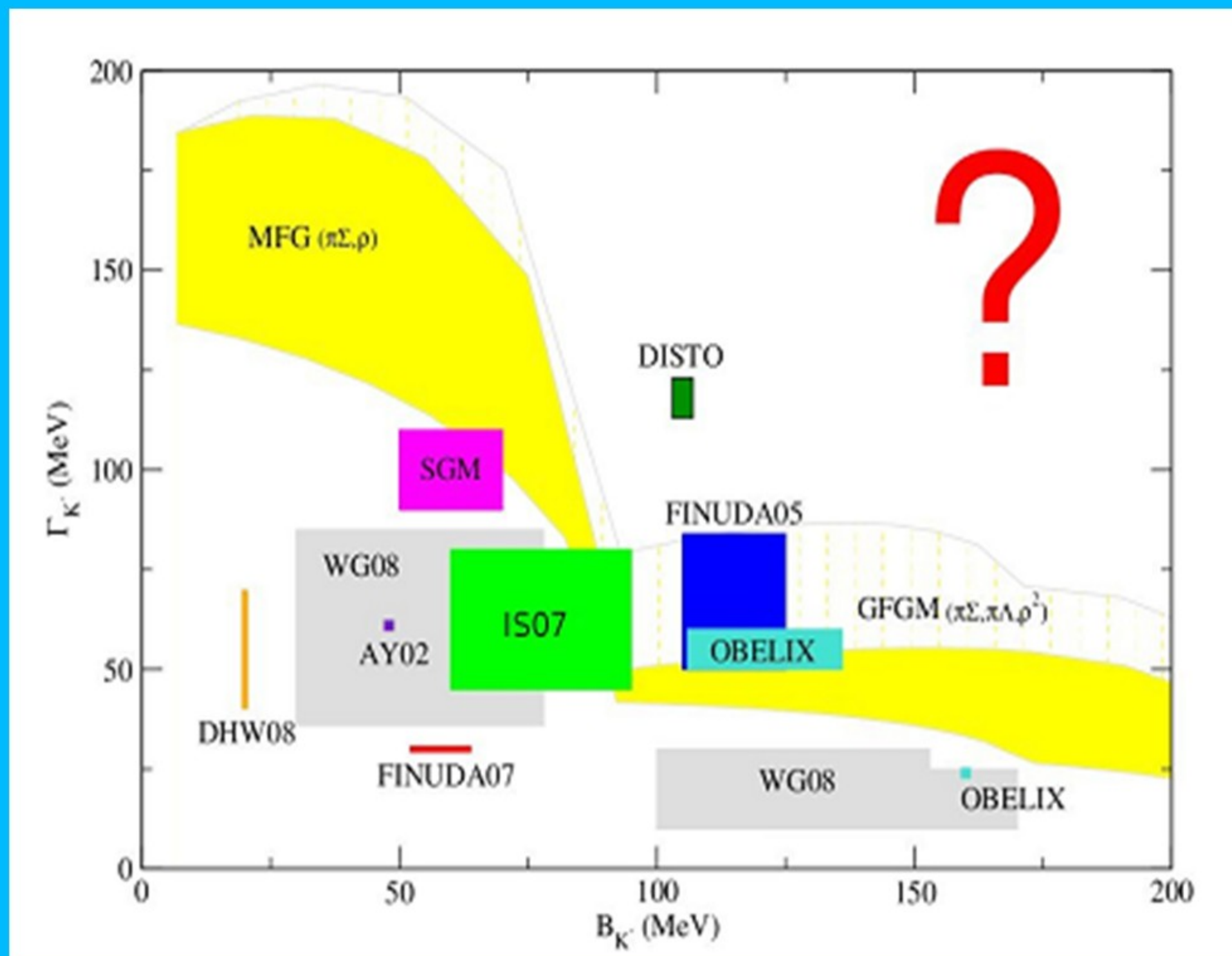
2NA

Λp scientific case

K⁻

How deeply can an Antikaon be bound to a nucleus?

Slide by J. Mares @ Trento ECT* Workshop



Experimen

- pp collisi … ple)
- Absorpti

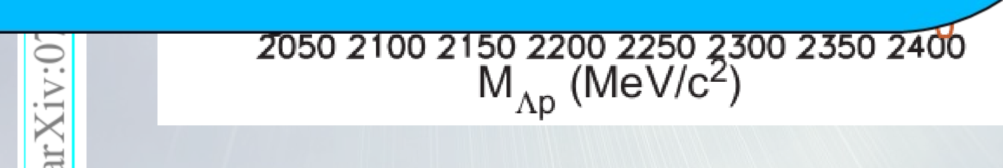
@KEK E-54

K- stoppec

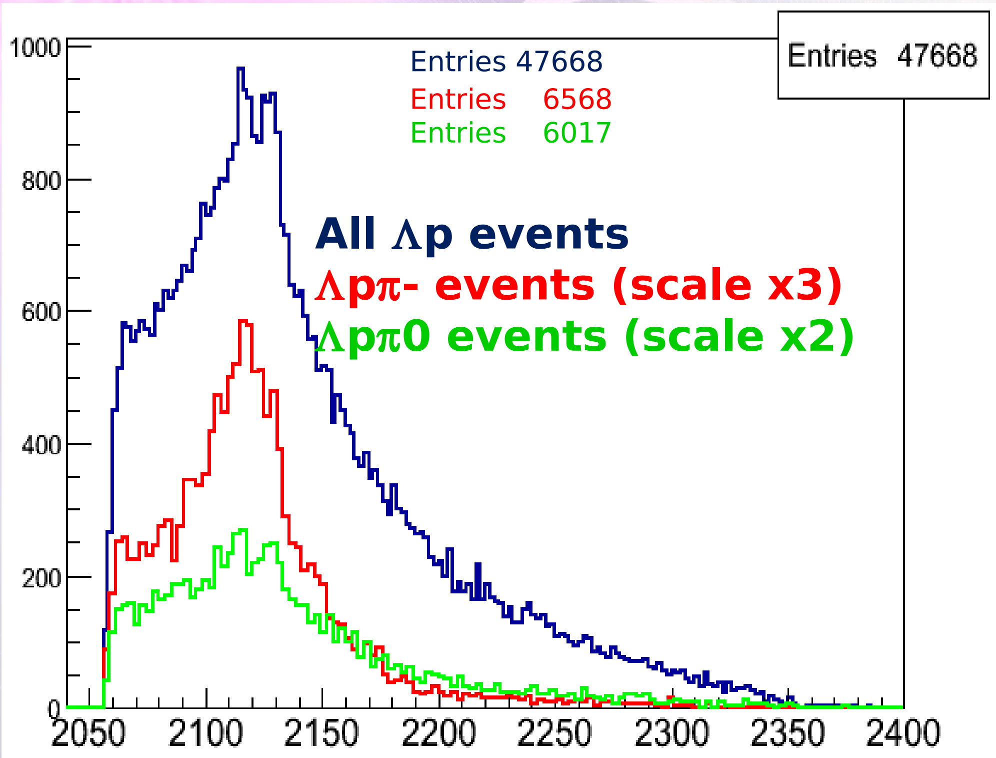
NA

N/ΛN - DBKS

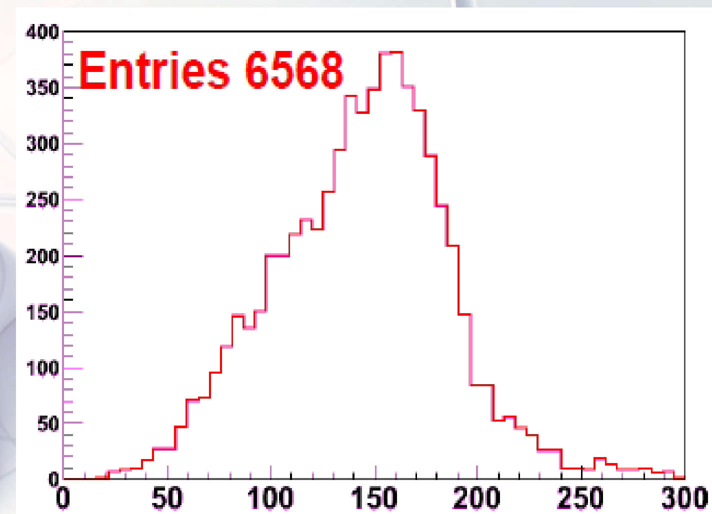
NA



Λp correlation study



MΛp (MeV/c2)



Pπ- (MeV/c)

- <u>Low</u> invariant mass: 1 Nucleon absorption followed by Σ/Λ nuclear conversion

  1NA: K-N→Σ **π**

  └→ΣN→**ΛN**

  Quasi-free (4He, 12C) or **free! (H)**

- <u>High</u> invariant mass: **2NA**: K-NN→**ΛN**

  3NA: K-NN→**ΛN**

K^-

Λp events, preliminary fit

- 1NA with Σ/Λ conversion:

K-N → Σπ + **Σp/Λp**

FINAL PRODUCED PARTICLES

- 2NA processes:

K-NN → Λ (Σ0) p

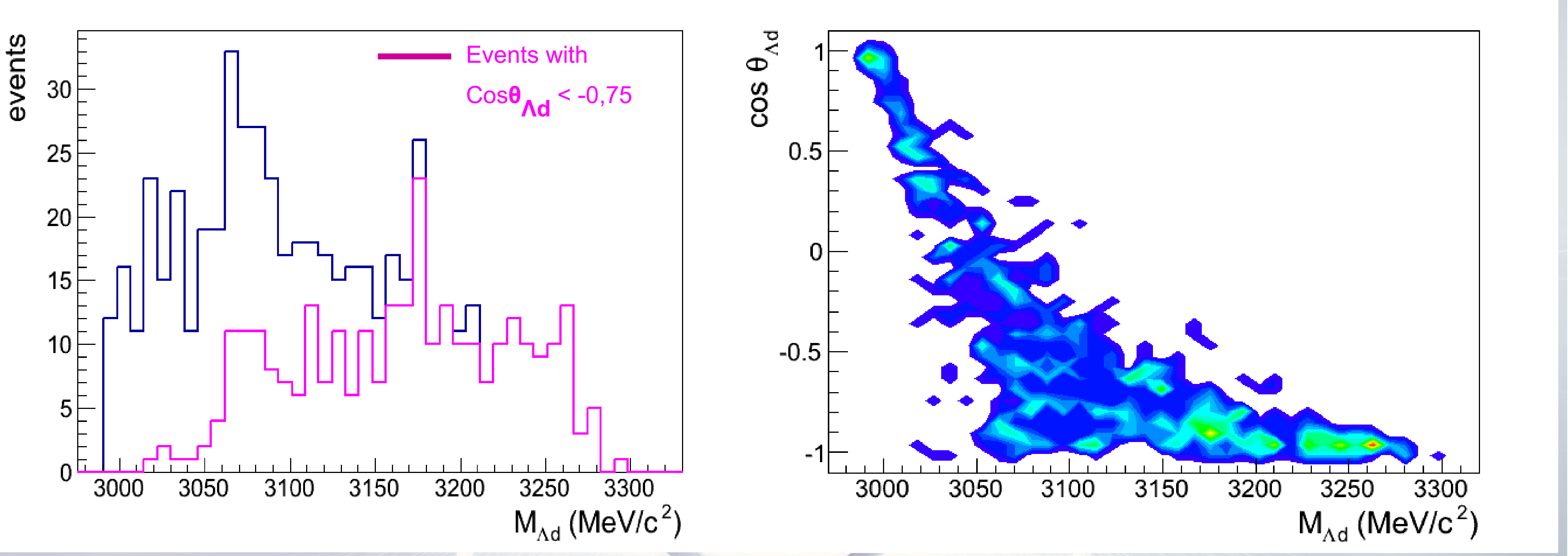
K-NN → Σ0p + **Σp/Λp** conversion in 4He

Pionic 2NA modes: **K-NN → YπN**

- Uncorrelated processes:

Simulation based in «spectator» protons from Λd correlated events in 12C

Λd search for a K-ppn cluster



- 572 Lambda-deuteron events in DC gas

- Structures at high Mass correlated with back-to-back events

K^-

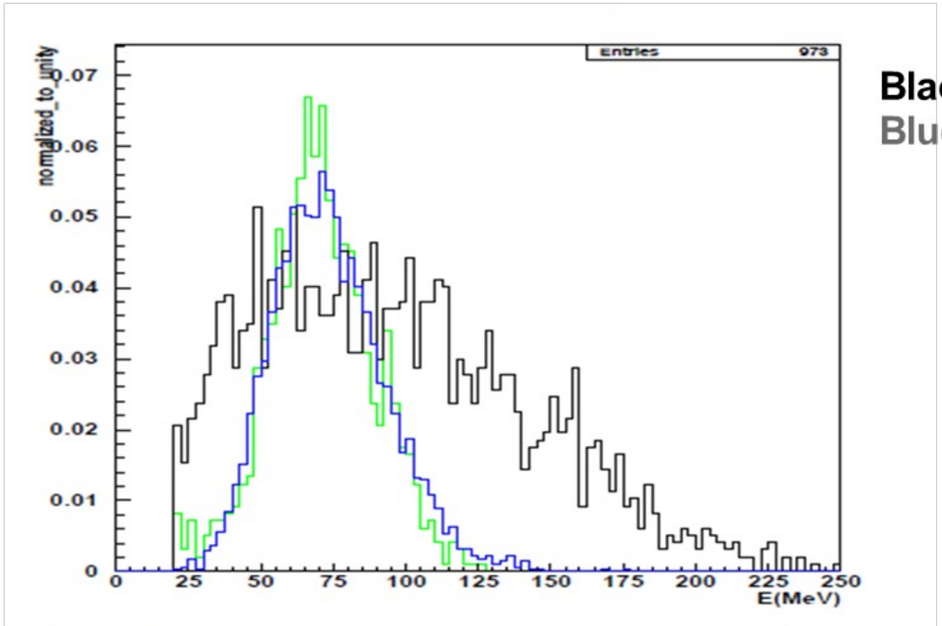
Status of the $\Lambda(1405)$

investigation through

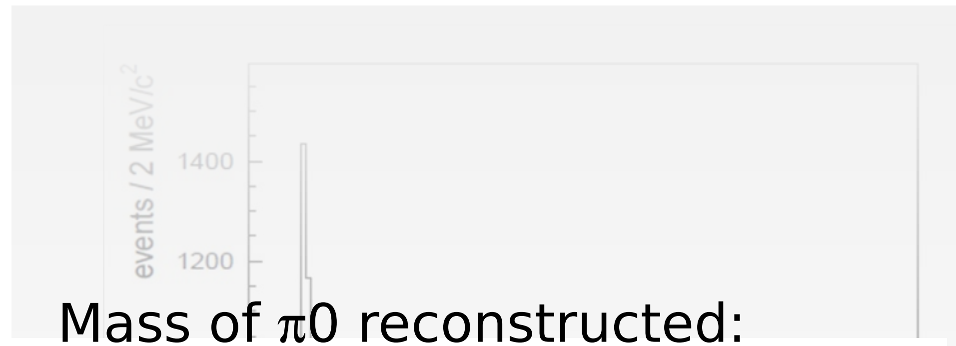
$\Sigma^0\pi^0$ / $\Sigma^+\pi^-$ correlation

KLOE: Study of $\Sigma\pi$ in 12C

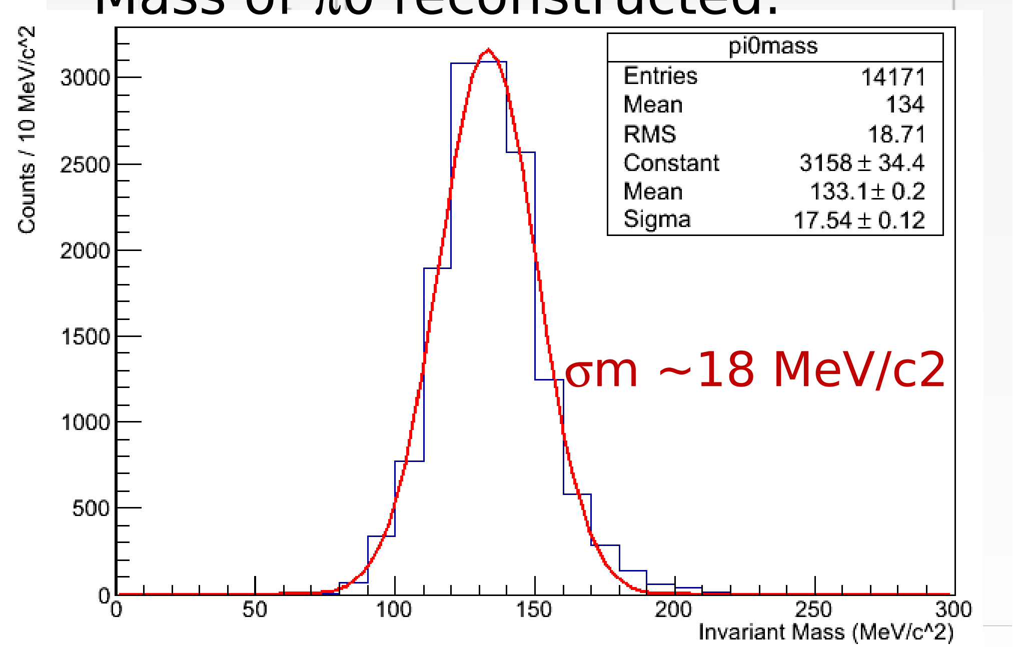
Use of the calorimeter: Photon detection



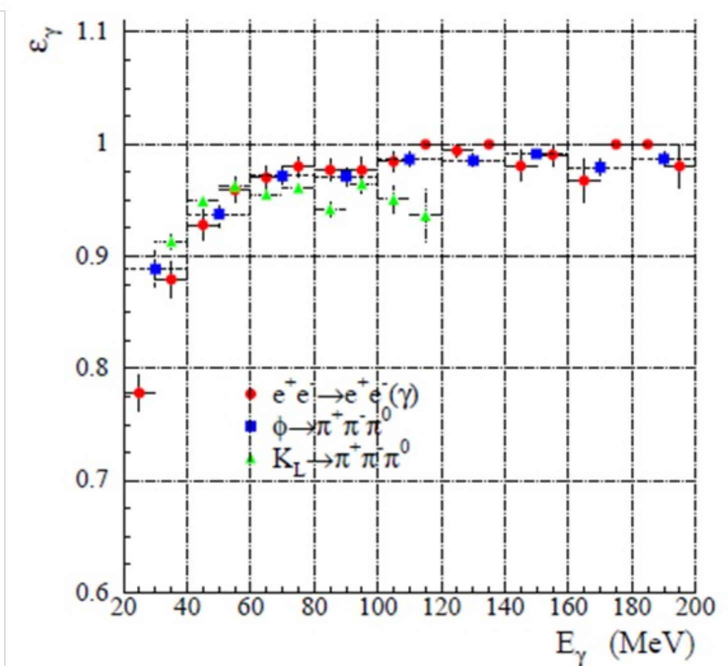
Black -> energy of photons from π^0
Blue -> energy of photons from Σ^0 -> $\Lambda\gamma$



Mass of π0 reconstructed:



Σ^0 contamination in Λp events

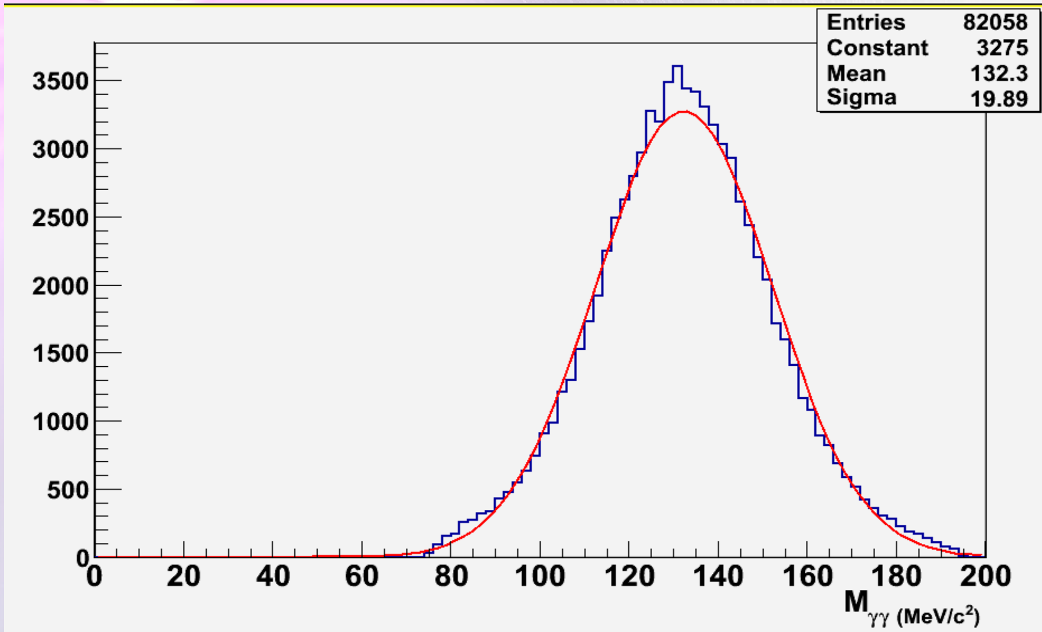


K^-

Ongoing analyses

$\Sigma^0\pi^0$ / $\Sigma^+\pi^-$ correlation

$\Sigma^0\pi^0$ correlation

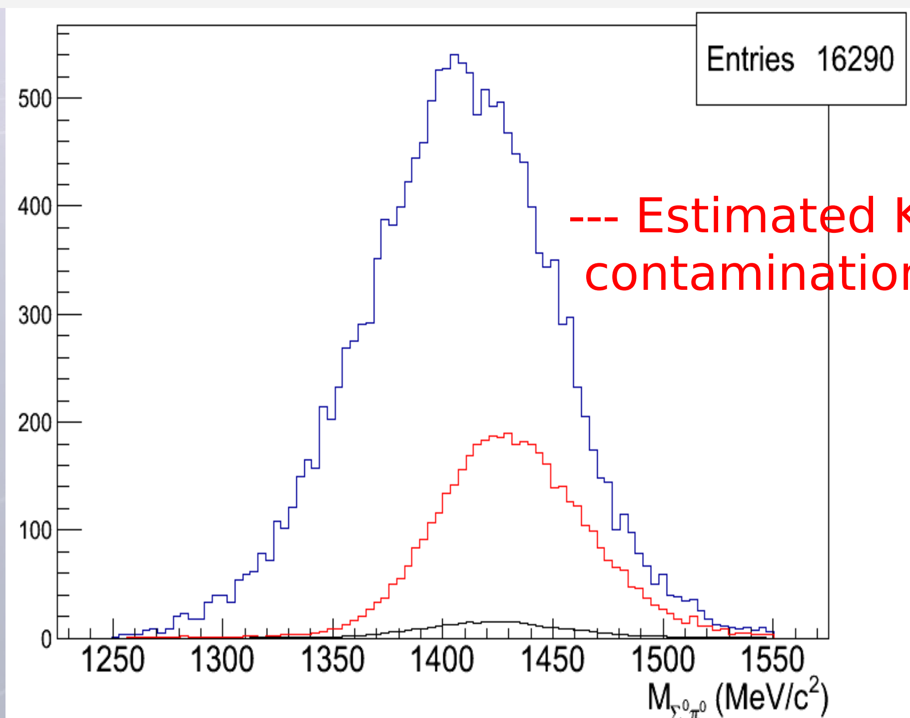


$K^- p \rightarrow \Sigma^0 \pi^0$ detected via: $(\Lambda\gamma)$ $(\gamma\gamma)$

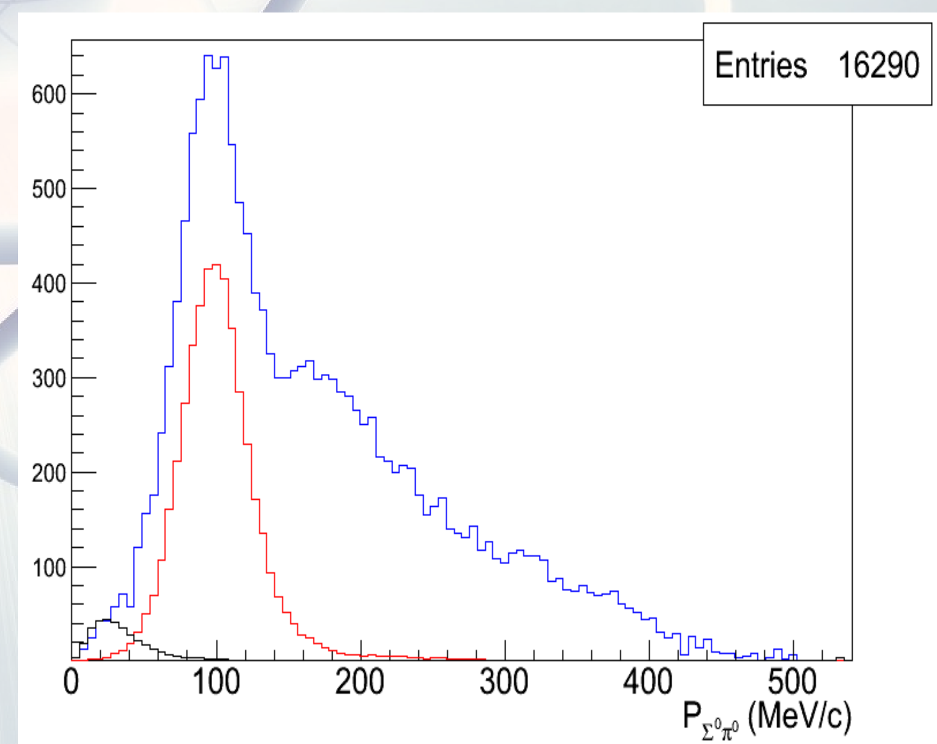
Negligible ($\Lambda \pi^0$ + internal conversion)

background = (3±1) % →

<u>no I=1 contamination</u>



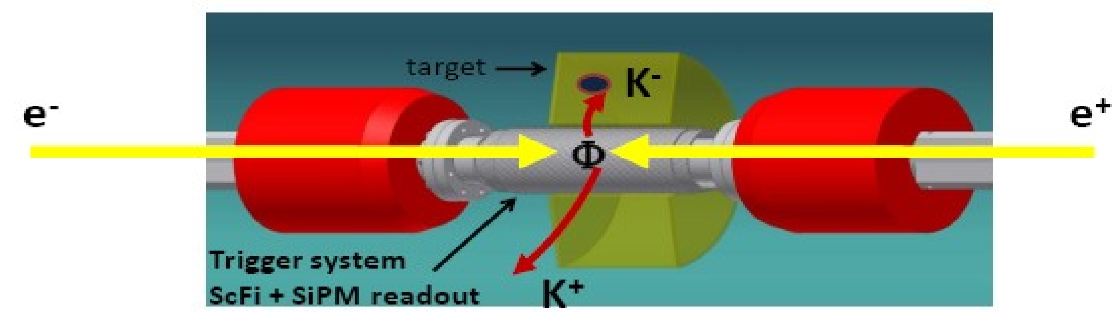
--- Estimated K-H contamination



Perspectives ..

AMADEUS experiment:

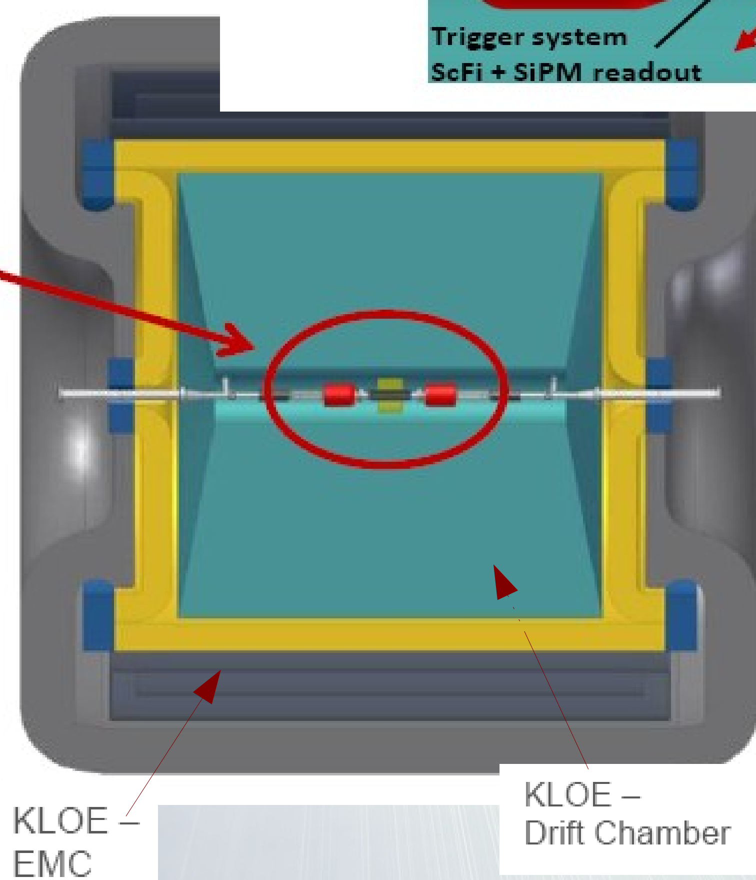
Implementation of dedicated solid targets & cryogenic gaseous targets (H, d, ^{3}He, ^{4}He) inside the KLOE DC.



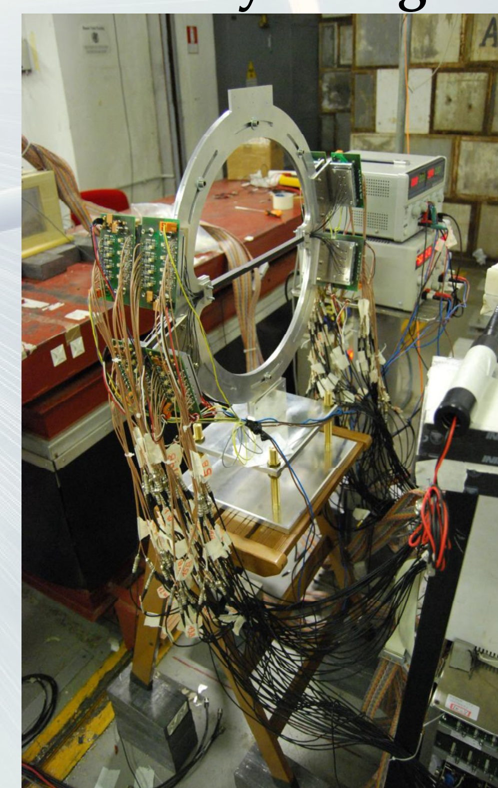
- The AMADEUS setup will be implemented in the 50 cm. gap in KLOE DC around the beam pipe:

- **Target** (A gaseous He target for a first phase of study)

- **Trigger** (1 or 2 layers of ScFi surrounding the interaction point)

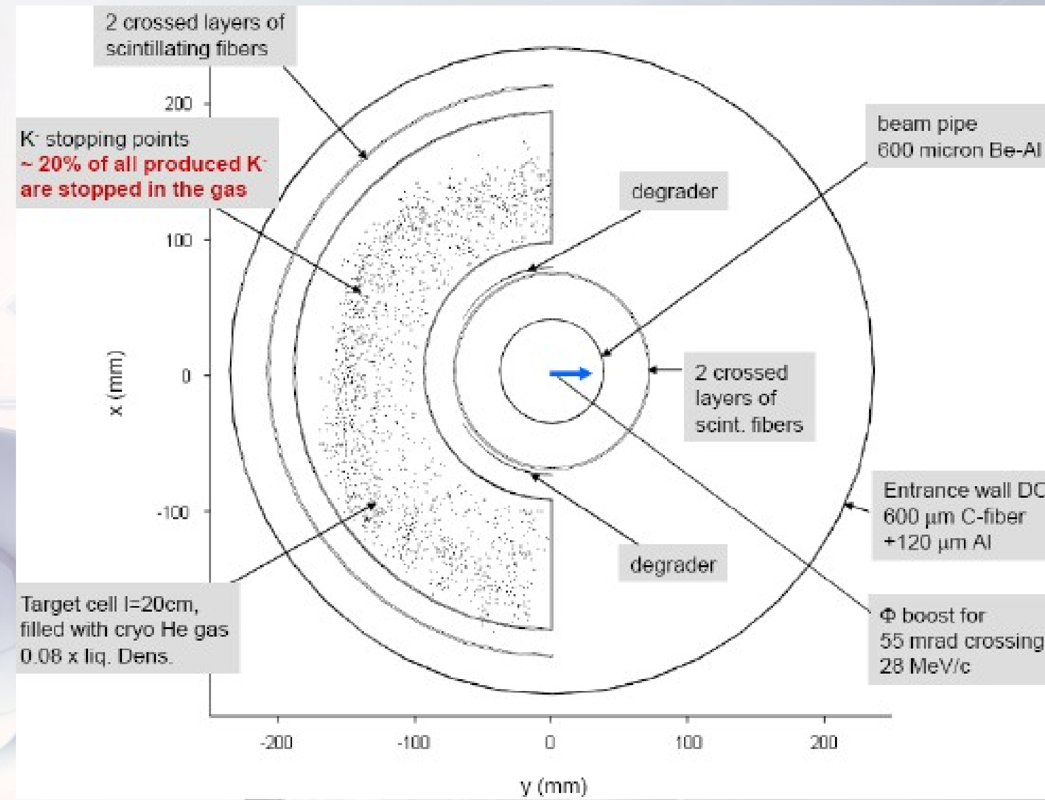


R&D activity is ongoing



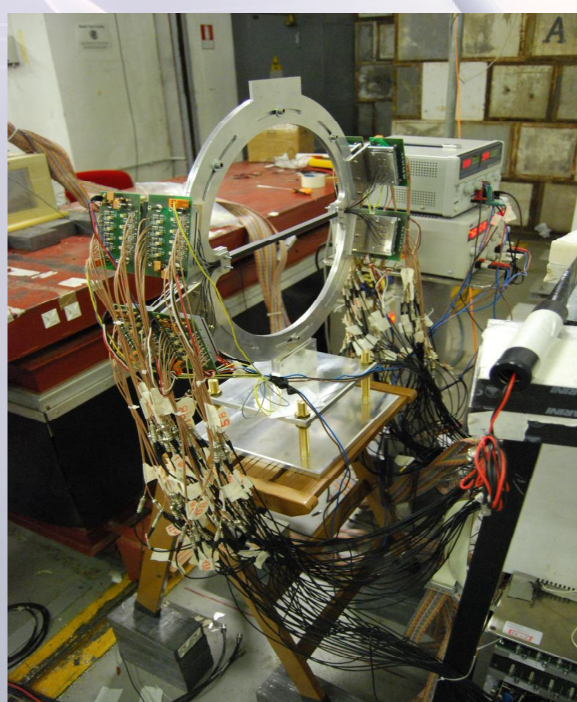
R&D activity is going on

prototipe of the trigger system
layers of BCF-10 fibers double cladded
free to rotate
read at both sides by Hamamatsu
S10362-11-050-U SiPM



time resolution obtained (σ) for kaons 300ps.

(Nuclear Inst. and Methods in Physics Research, A (2012), pp. 125-128).



Possible solution for a half-toroidal cryogenic target cell, inside a vacuum chamber, and two more layers of fibers.

Or TPC -GEM inner tracker.

Performances of a GEM-based TPC prototype for new high-rate particle experiments, Nucl.Instrum.Meth. A617 (2010) 183-185

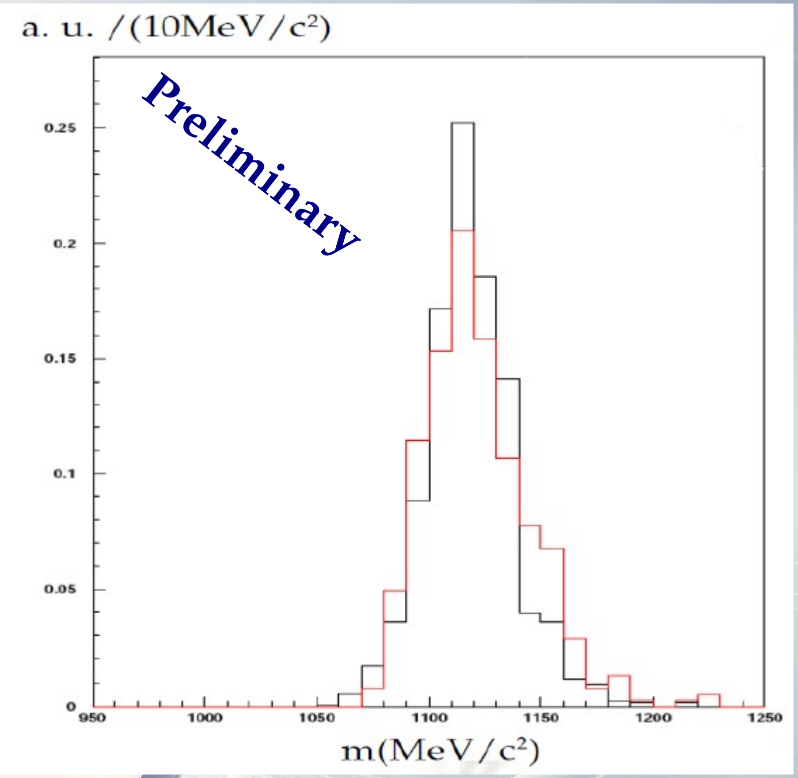
AMADEUS & DAΦNE

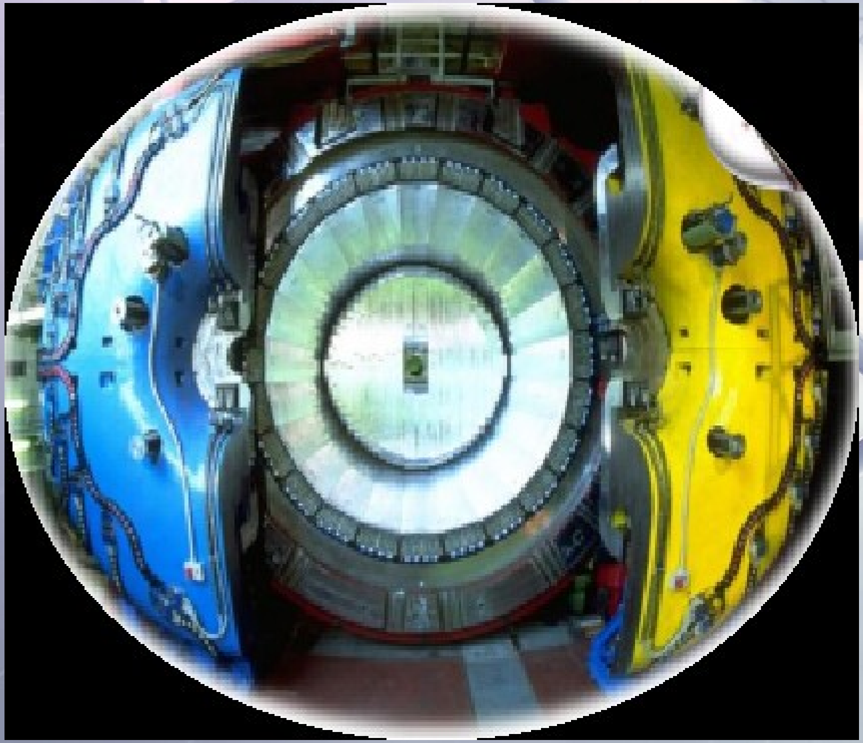
K^-

Completely neutral channel:
$\Lambda \rightarrow n\ \pi^0$
Possibility to detect neutrons!

black MC **red data**

Perspective: $\Sigma^-\pi^+ \rightarrow (n\pi^-)\ \pi^+$





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)))