Study of the $\Lambda(1405)$ resonance through its neutral and charged decay channels by AMADEUS @ DAΦNE

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22° European Conference on Few Body Problems in Physics
Krakow, Poland, 9-13 September 2013

Investigation of K^- interactions on light nuclei

(H, ^{4}He, ^{8}Be, ^{12}C)

Reactions:

K^- 'p' $\rightarrow$ $\Sigma^0\pi^0$ (non resonant) OR K^- 'p' $\rightarrow$ $\Lambda(1405) \rightarrow$ $\Sigma^0\pi^0$ (resonant)

K^- 'p' $\rightarrow$ $\Sigma^+\pi^-$ (non resonant) OR K^- 'p' $\rightarrow$ $\Lambda(1405)/\Sigma(1385) \rightarrow$ $\Sigma^+\pi^-$ (resonant)

K^- 'p' $\rightarrow$ $\Lambda\pi^0$ (non resonant) OR K^- 'p' $\rightarrow$ $\Sigma(1385) \rightarrow$ $\Lambda\pi^0$ (resonant)

'p' , 'n' BOUND nucleons

<u>AT-REST (K⁻ absorbed from atomic orbit) or IN-FLIGHT</u>

Scientific case: $\Lambda(1405)$

$\Lambda(1405)$: $(m, \Gamma) = (1405.1^{+1.3}_{-1.0}, 50 \pm 2)$ MeV, I = 0, S = -1 , $J^p = 1/2-$
Status: ****, strong decay into $\Sigma\pi$

Its nature is being a puzzle for decades:
1) three quark state: expected mass ~ 1700 MeV
2) penta quark: more unobserved excited baryons
3) unstable KN bound state
4) two poles: ($z1 = 1424^{+7}_{-23} - i\,26^{+3}_{-14}$; $z2 = 1381^{+18}_{-6} - i\,81^{+19}_{-8}$) MeV

mainly coupled to KN mainly coupled to $\Sigma\pi$ → line-shape depends on production mechanism

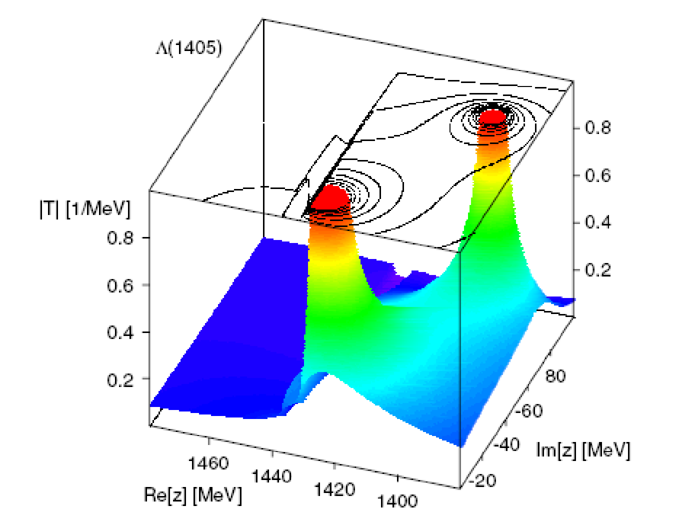
Line-shape also depends on the decay channel

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

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

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

Pure I=0 (free from $\Sigma(1385)$ background)



Scientific case: $\Lambda(1405)$

1) $m_{\pi\Sigma}$ spectra always cut at the at-rest limit (P_K~keV)
2) $(\Sigma^{\pm}\pi^{\pm})$ spectra have $\Sigma(1385)$ contribution
3) The $\Sigma^0\pi^0$ spectrum was observed in only
   3 experiments … with different line-shapes !

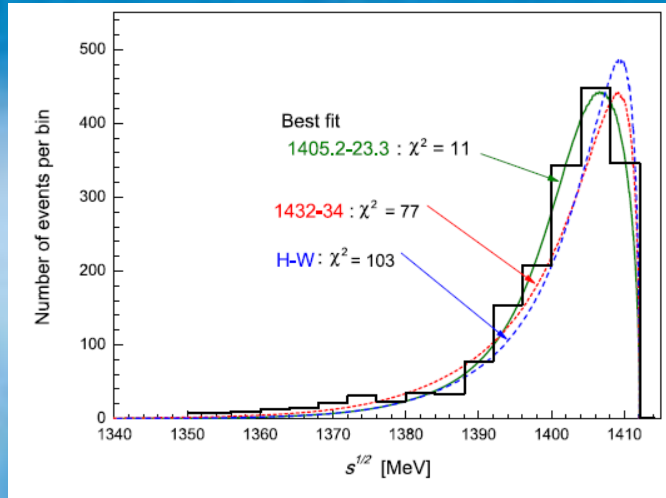
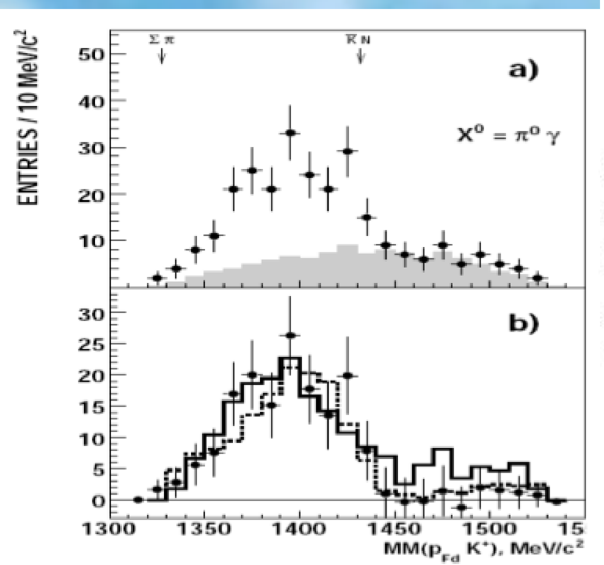


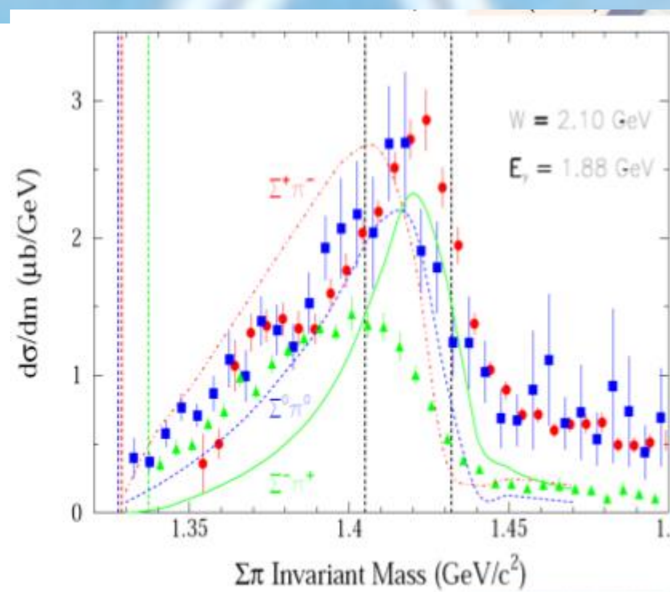
Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

D. Riley, et al. Phys. Rev. D11 (1975) 3065
Esmaili et el., Phys.Lett. B686 (2010) 23-28

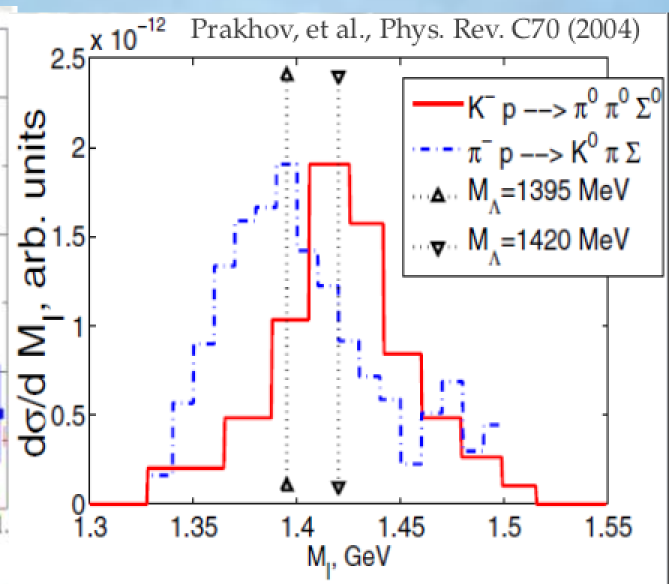
I. Zychor et al.,
Phys. Lett. B 660 (2008) 167



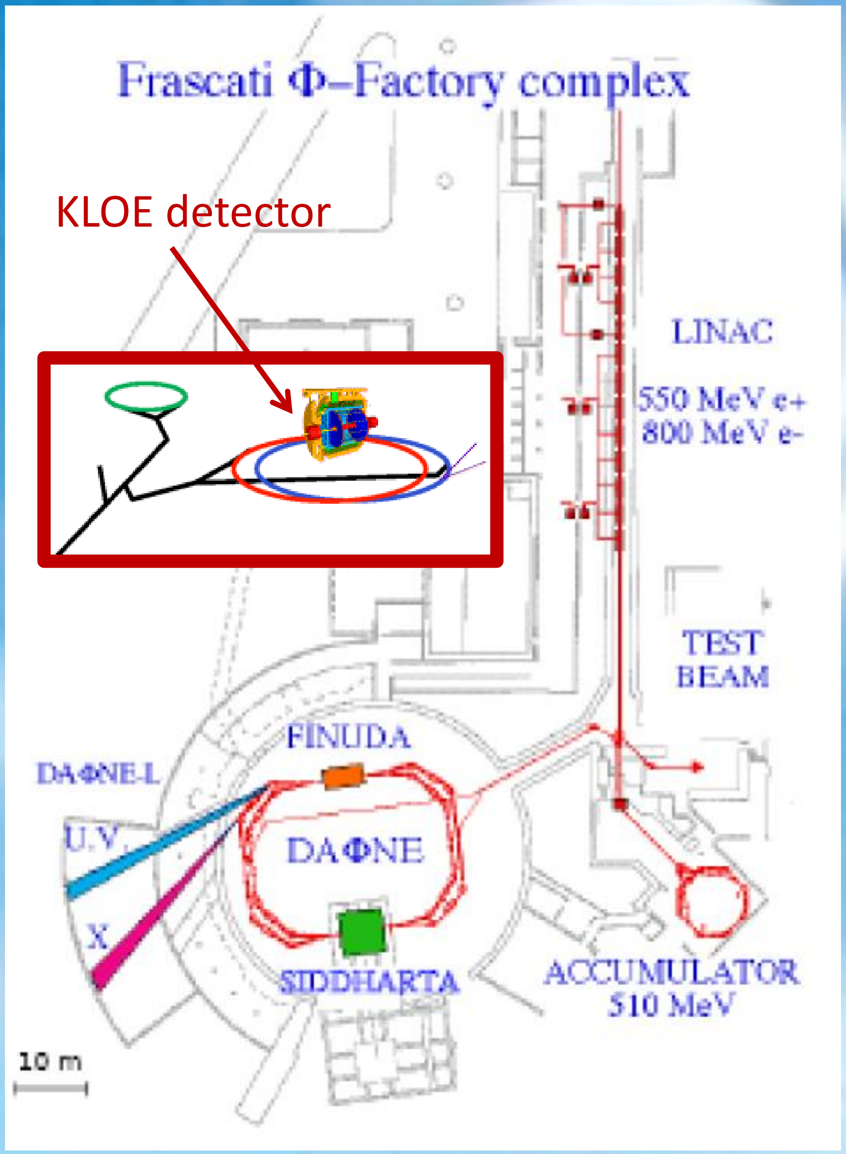
K. Moriya, et al., (Clas Collaboration)
Phys. Rev. C 87, 035206 (2013)



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



The DAΦNE accelerator



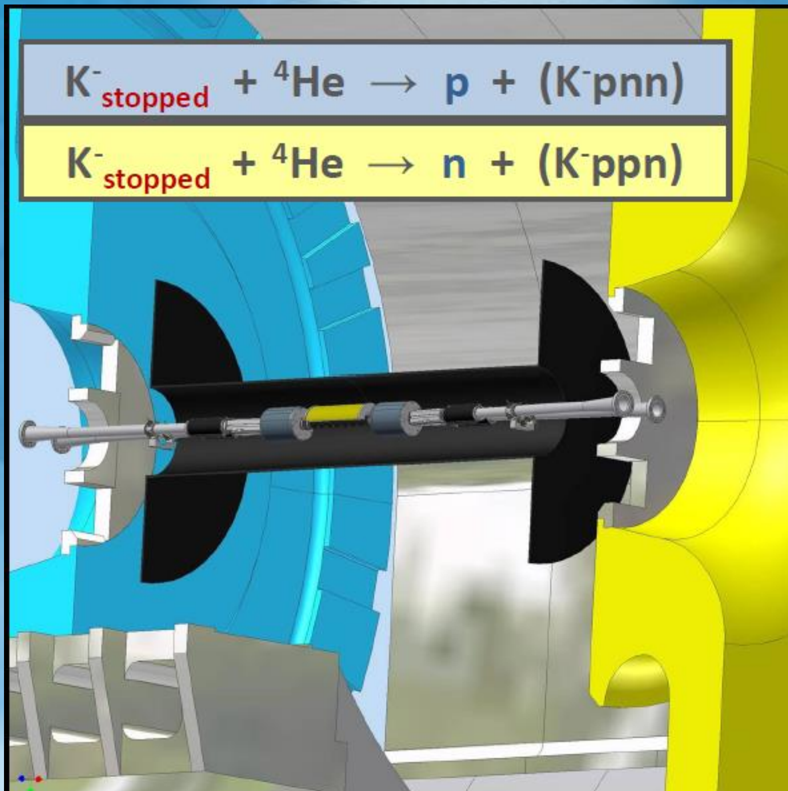
$e^+ e^-$ at 510 MeV -> Φ at-rest

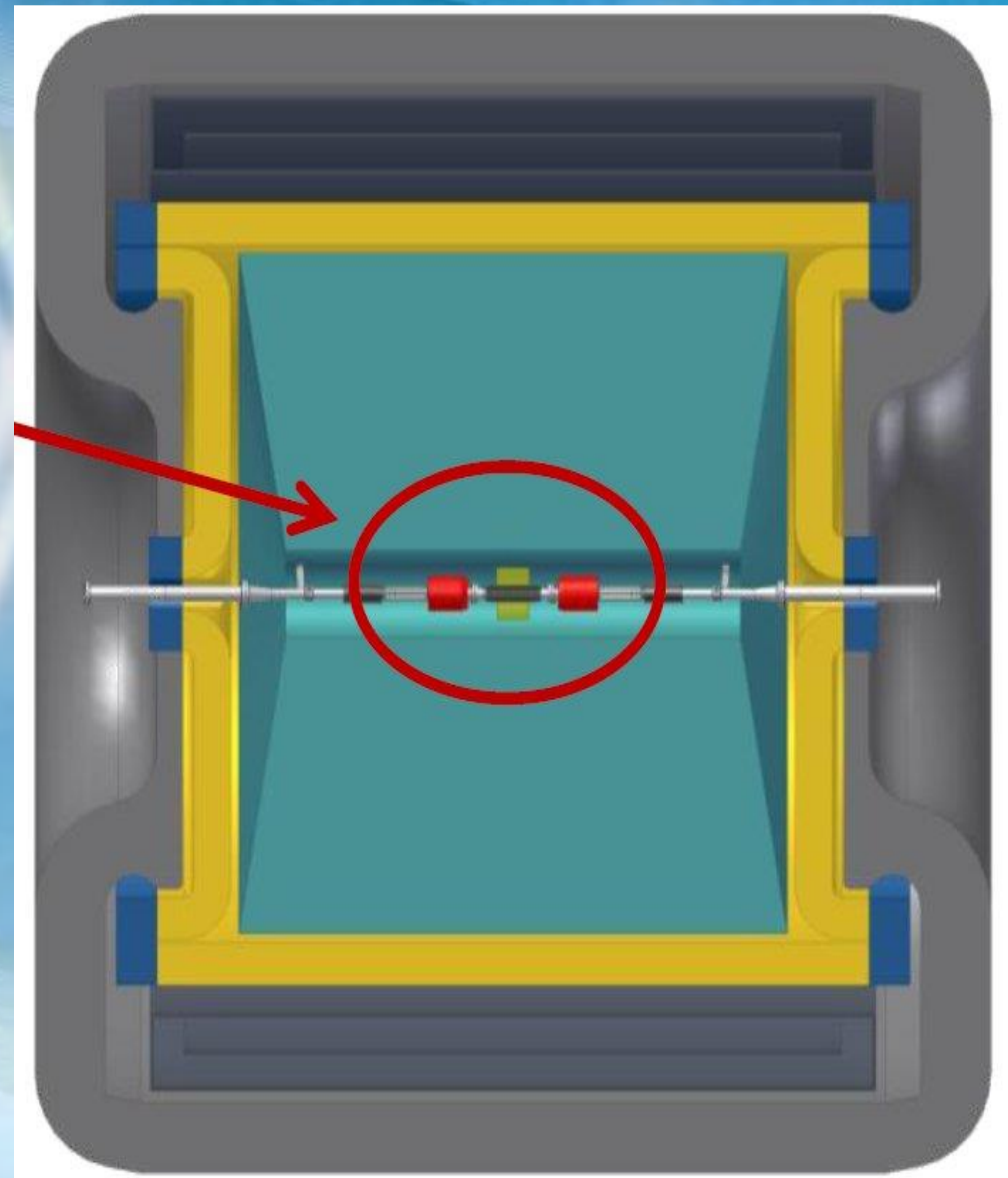
Φ resonance decays at 49.2 % in $K^+ K^-$ back to back pair

Monochromatic beam of low momentum K^- (p_k = 127 MeV/c)

➔ AMADEUS experiment

The AMADEUS experiment





Target: A gaseous He target for a first phase of study

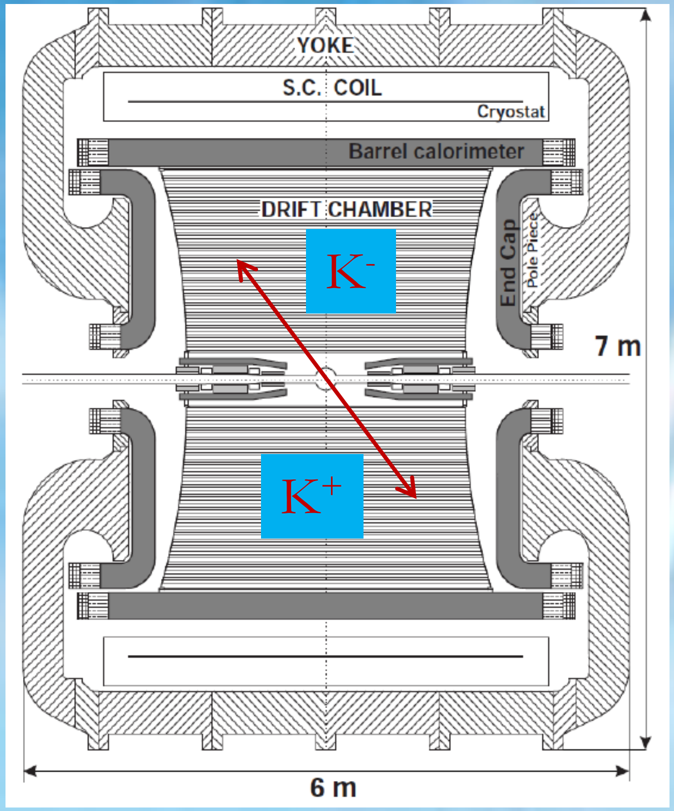
First 4π fully dedicated setup!

Low-energy K^- hadronic interactions studies with KLOE 2002-2005 data

MC simulations show that :

~ 0.1 of K^- stopped in the DC gas (90% He, 10% C_4H_{10})

~ 2% of K^- stopped in the DC wall (750 mm c. f. , 150 mm Al foil).



Possibility to use KLOE materials as an active target

Advantage:

unprecedent resolution : $\sigma_p/p \sim 0.4$ MeV/c

4π-geometry with ~ 96% acceptance

Calorimeter optimized for γ : $\sigma_m \sim 18$ MeV/c^2

Vertex position resolution ~ 1 mm (in DC)

Disadvantage:

Non dedicated target → different nuclei contamination → complex interpretation .. but → new features .. K^- in flight reactions.

AMADEUS step-0: Pure Carbon target inside KLOE (2012)

Dedicated run in november/december 2012 with a Carbon target 4/6 mm thickness

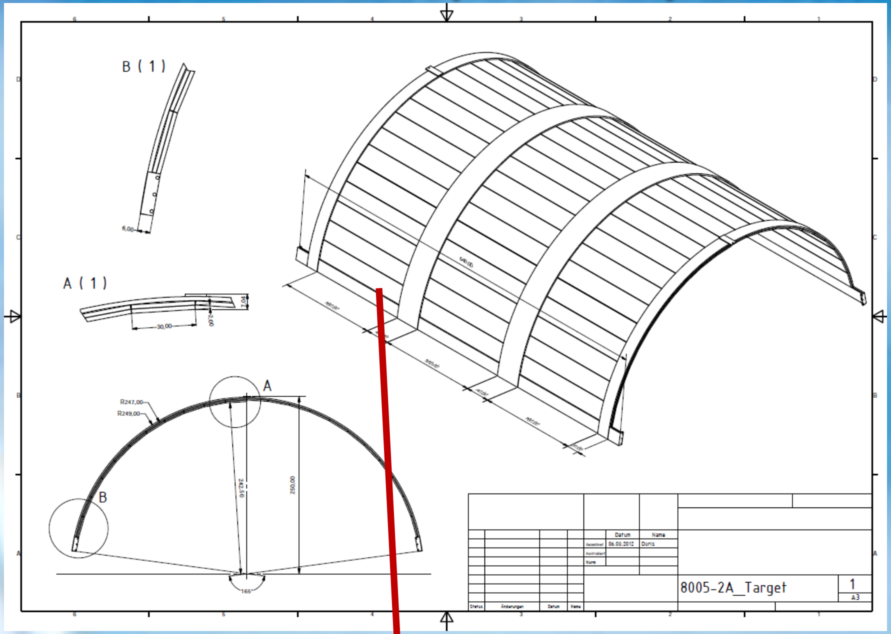
Advantages:

gain in statistics
($\sim$90 pb^{-1}; analyzed 37 pb^{-1}, x1.5 statistics)

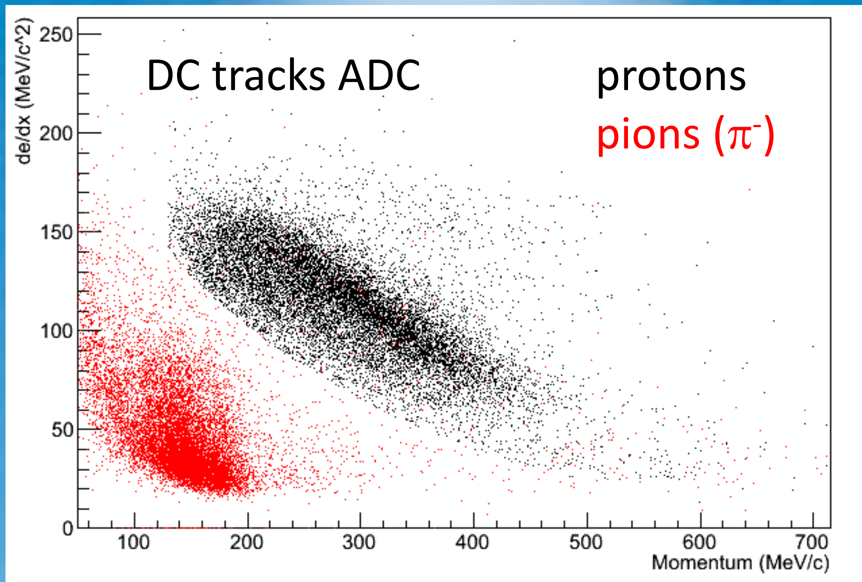
K^- absorptions occur in Carbon at-rest.

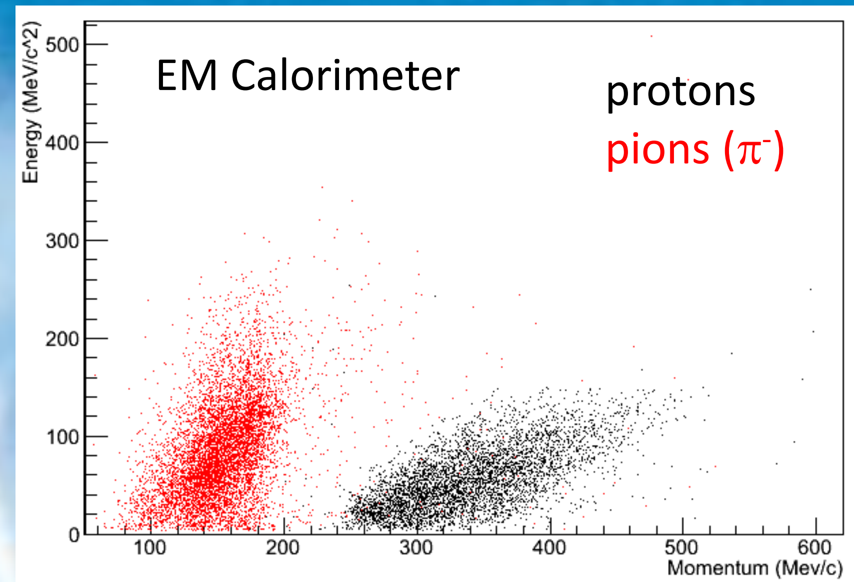
2005 data: at-rest + in-flight events

2012 data: ONLY at-rest events



Particle identification in KLOE: p, π^-, π^0

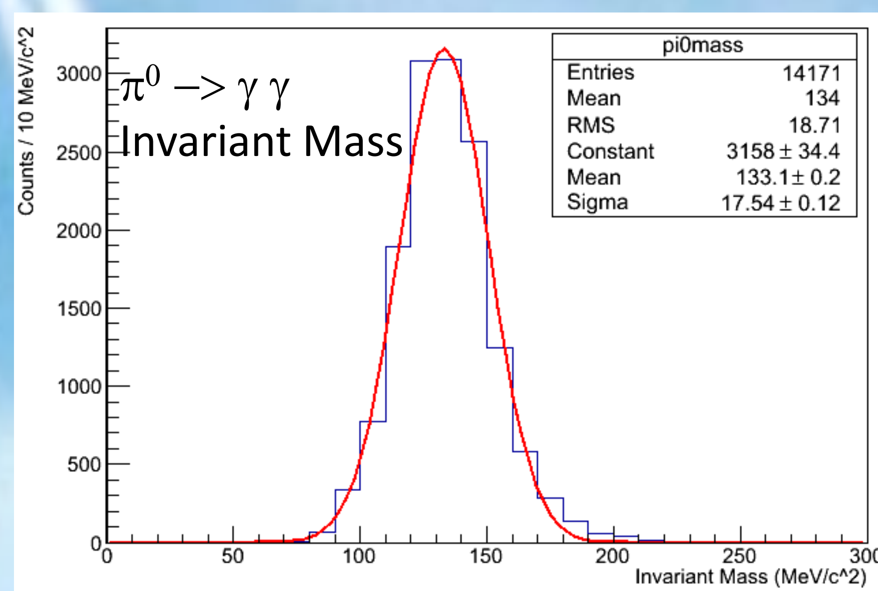




π^0 reconstructed minimizing the quantity:

$$\chi^2 = \frac{(t_{\gamma 1} - t_{\gamma 2})^2}{\sigma^2_{t_{12}}} = \frac{\left((t_{cl1} - \frac{|r_{cl1}|}{c}) - (t_{cl2} - \frac{|r_{cl2}|}{c})\right)^2}{\sigma^2_{t_{12}}}$$

Obtained resolution: $\sigma_m \sim 18$ MeV/c^2



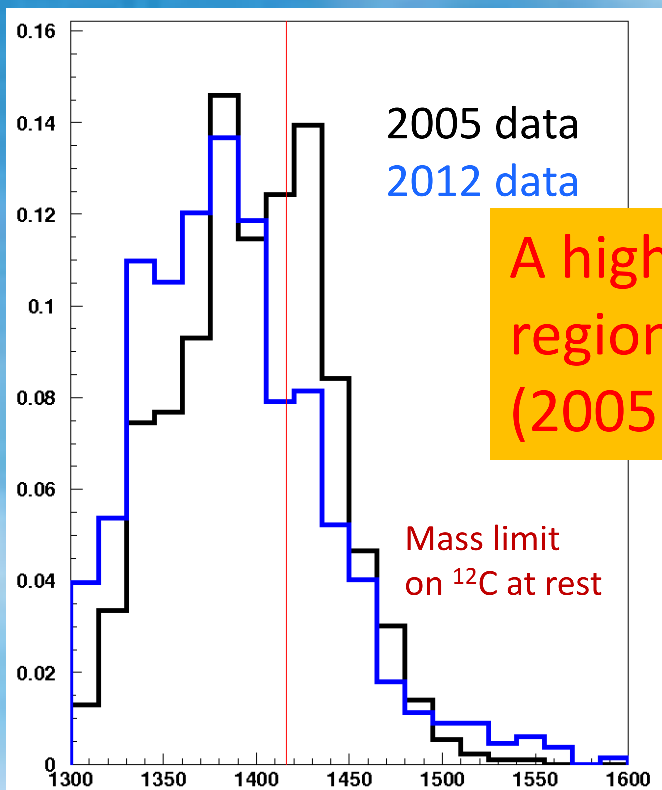
The neutral channel: $\Sigma^0\pi^0$

$\Sigma^0 \pi^0$ channel

Λ(1405) signal searched by K- interaction with a bound proton in Carbon

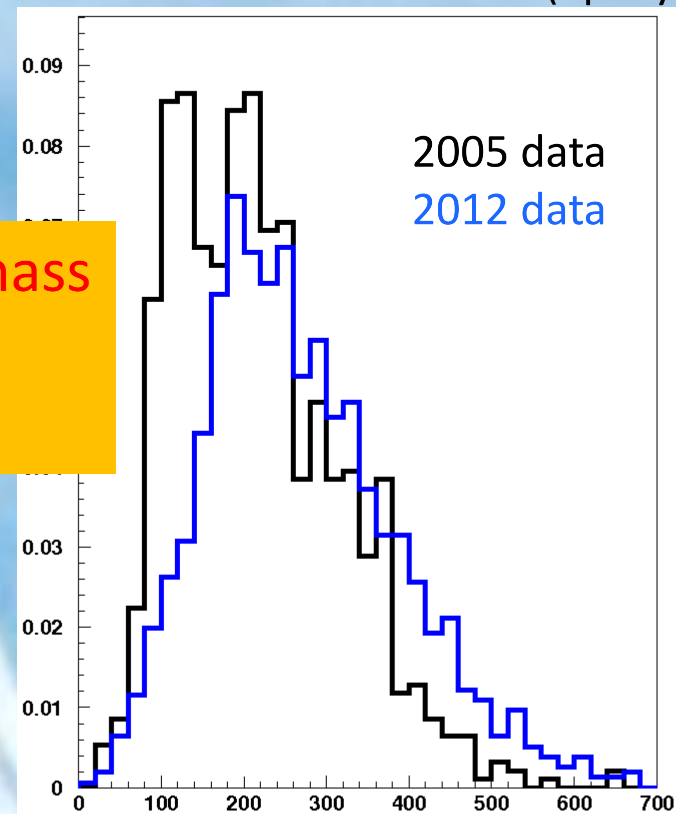
K- p $\rightarrow$ $\Sigma^0\pi^0$ detected via: $(\Lambda\gamma)(\gamma\gamma)$

Strategy : K- absorption in the DC entrance wall, mainly 12C with H contamination (epoxy)



Invariant Mass (MeV/c^2)

A higher invariant mass region is opened (2005 data)!!!



Momentum (MeV/c)

$m_{\pi 0 \Sigma 0}$ **resolution** $\sigma_m \approx 32$ MeV/c^2 ; $p_{\pi 0 \Sigma 0}$ **resolution:** $\sigma_p \approx 20$ MeV/c.

Negligible ($\Lambda\,\pi^0$ + internal conversion) background = (3±1) % → no I=1 contamination

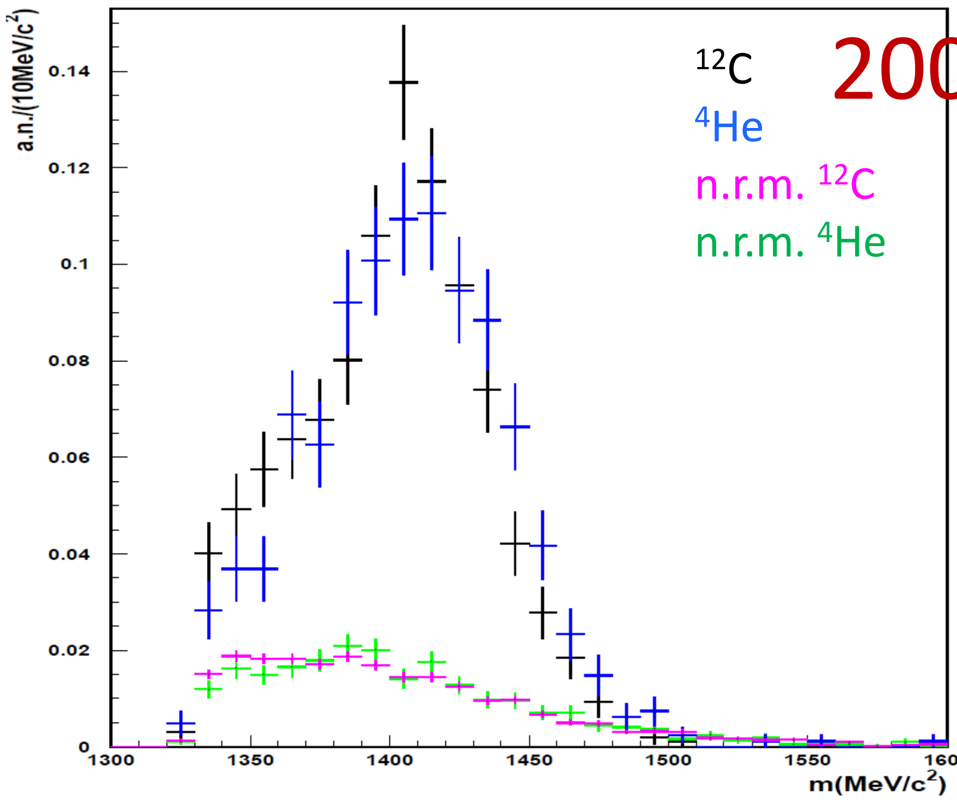
$\Sigma^0\,\pi^0$ channel

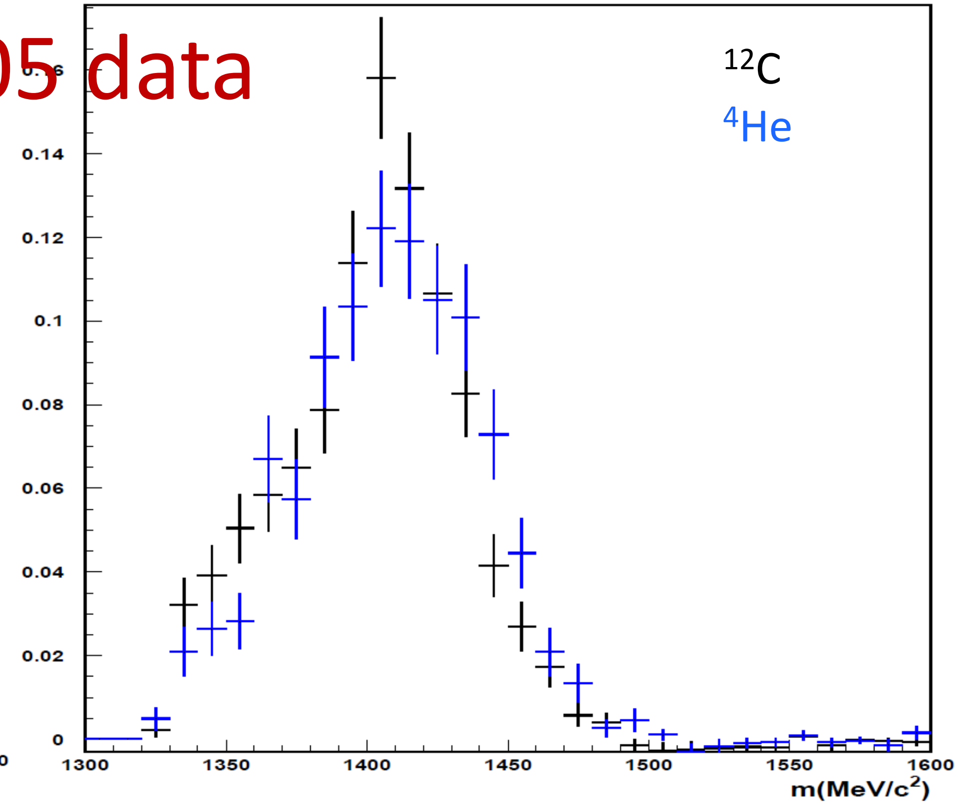
Invariant mass spectra with mass hypotesis on Σ^0 and π^0 non-resonant misidentification background subtracted (left)

$\sigma_m \approx 17$ MeV/c^2 (^{12}C) $\sigma_m \approx 15$ MeV/c^2 (^{4}He)

Similar $m(\Sigma^0\pi^0)$ shapes due to the similar kinematical thresholds for ^{4}He and ^{12}C.

2005 data

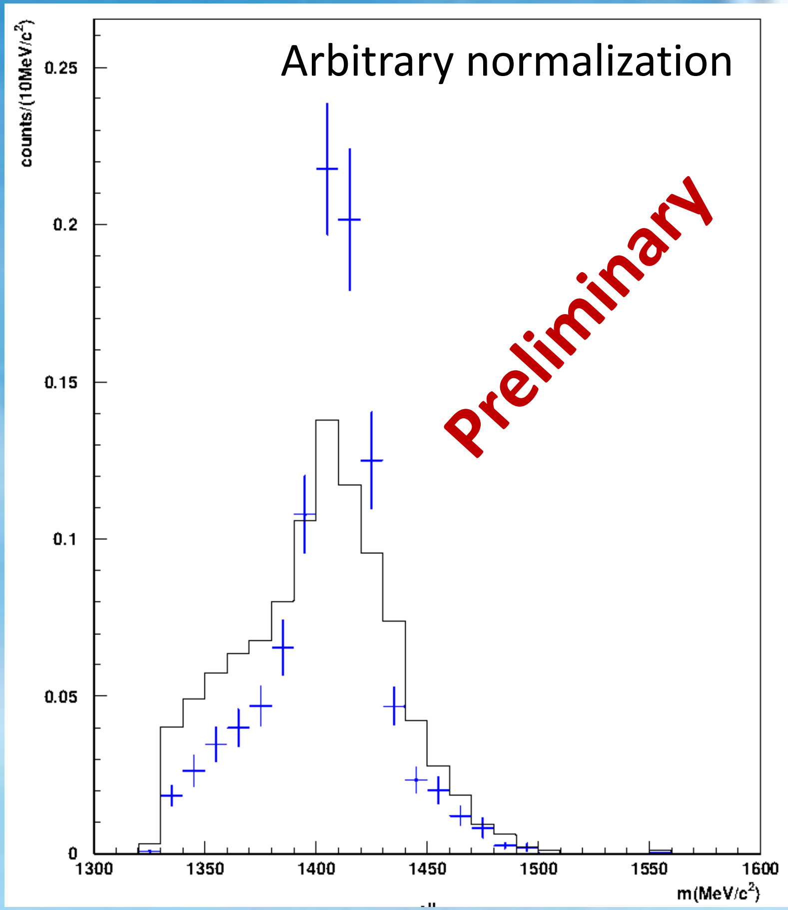


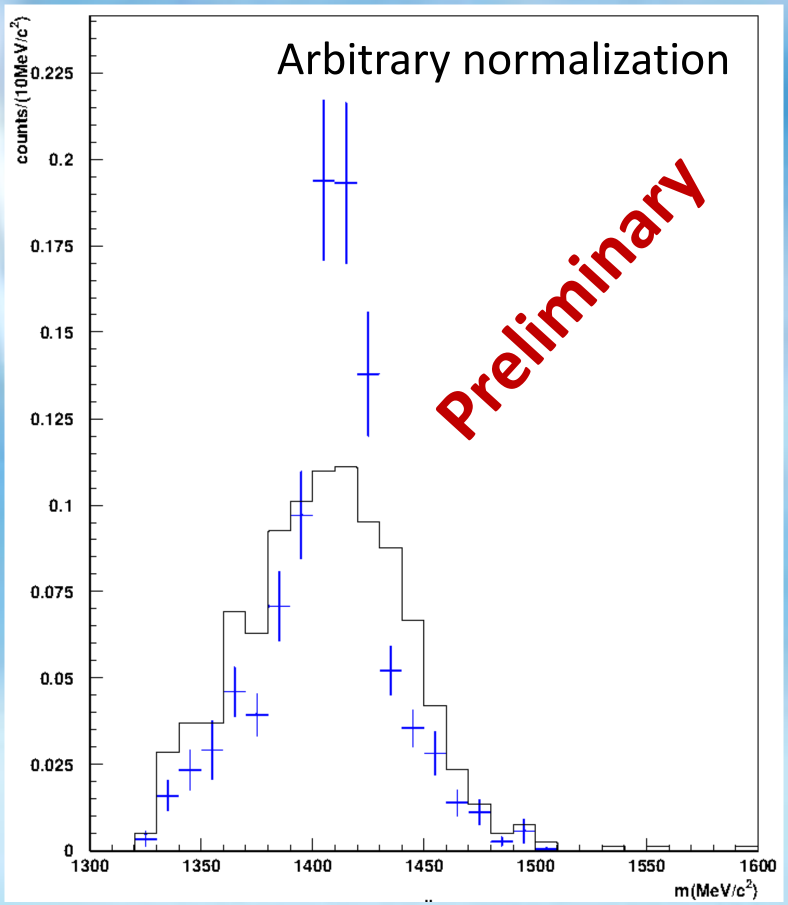


$\Sigma^0 \pi^0$ channel

Acceptance corrected $m(\Sigma^0\pi^0)$ spectra, DC wall (left) DC gas (right)

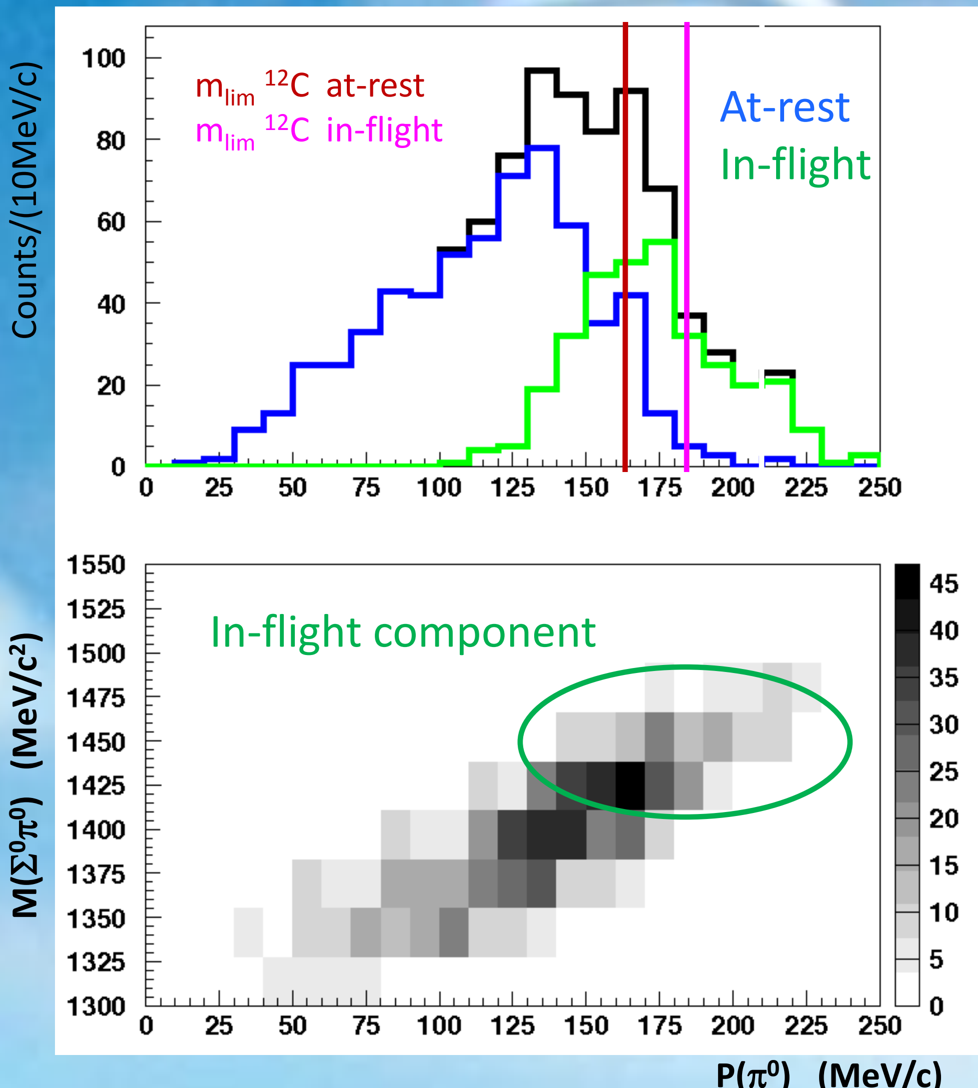
Acceptance function evaluated in
8 intervals of $p(\Sigma^0\pi^0)$ (between 0 and 700 MeV/c)
8 intervals of $\theta(\Sigma^0\pi^0)$ (between 0 and 3.15 rad)
30 intervals of $m(\Sigma^0\pi^0)$ (between 1300 and 1600 MeV/c2)

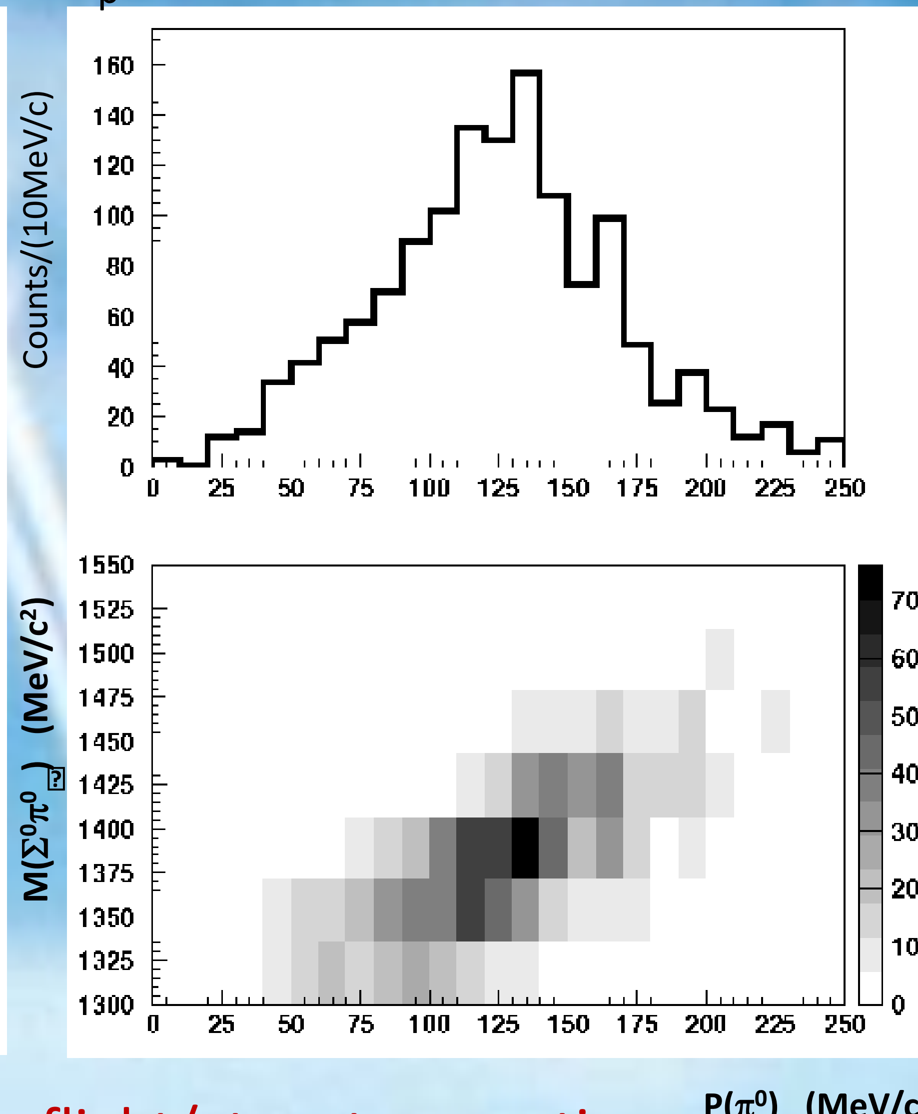




$\Sigma^0\ \pi^0$ channel : the π^0 momentum

$P(\pi^0)$ resolution: $\sigma_p \approx 12$ MeV/c





$P(\pi^0)$ could be used for in-flight/at-rest separation

The charged channel: $\Sigma^+\pi^-$

$\Sigma^+ \pi^-$ channel

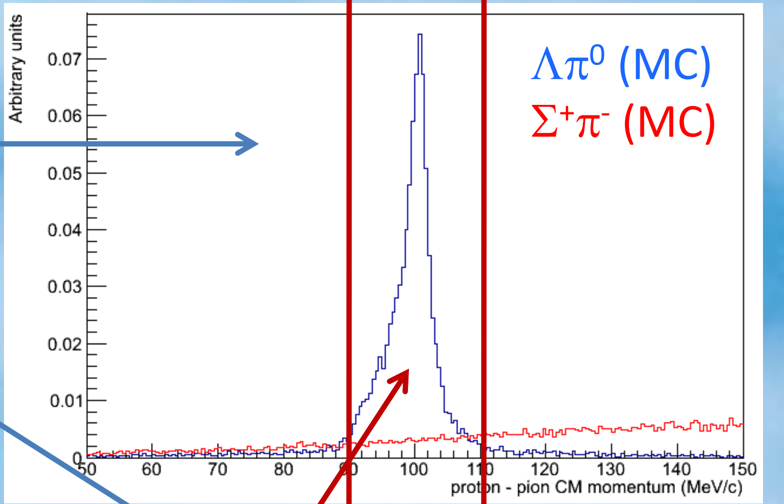
Reaction:

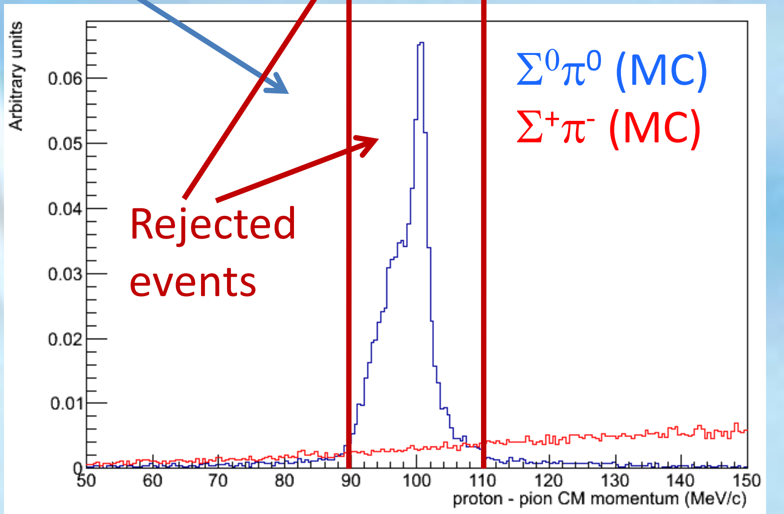
K^- 'p' --> $\Lambda(1405)/\Sigma(1385)$ --> $\Sigma^+\pi^-$ --> p π^0 π^- RESONANT

K^- 'p' --> $\Sigma^+\pi^-$ --> p π^0 π^- NON RESONANT

Possible hadronic backgrounds:

Interaction	First Output particles	Daughters particles	B. R.	Situation
K^-p	$\Lambda\,\pi^0$	$p\,\pi^-\,\pi^0$	64 %	Cut on Λ vertices
		$n\,\pi^0\,\pi^0$	36 %	No $p\pi^-$ vertex
K^-p	$\Sigma^+\,\pi^-$	$p\,\pi^0\,\pi^-$	52 %	SIGNAL
		$n\,\pi^+\,\pi^-$	48 %	No $p\pi^-$ vertex
K^-p	$\Sigma^0\,\pi^0$	$\Lambda(p\pi^-)\,\gamma\,\pi^0$	64 %	Cut on Λ vertices
		$\Lambda(n\pi^0)\,\gamma\,\pi^0$	36 %	No $p\pi^-$ vertex
K^-p	$\Sigma^-\,\pi^+$	$n\,\pi^-\,\pi^+$	100 %	No $p\pi^-$ vertex
K^-p	Λ	$p\,\pi^-$	64 %	No $p\pi^0$ vertex
		$n\,\pi^0$	36 %	No $p\pi^-$ vertex
K^-p	Σ^0	$\Lambda(p\pi^-)\,\gamma$	64 %	No π^0
		$\Lambda(n\pi^0)\,\gamma$	36 %	No $p\pi^-$ vertex
K^-n	$\Lambda\,\pi^-$	$p\,\pi^-\,\pi^-$	64 %	No π^0
		$n\,\pi^0\,\pi^-$	36 %	No $p\pi^-$ vertex
K^-n	$\Sigma^0\,\pi^-$	$\Lambda(p\pi^-)\,\gamma\,\pi^-$	64 %	No π^0
		$\Lambda(n\pi^0)\,\gamma\,\pi^-$	36 %	No $p\pi^-$ vertex
K^-n	$\Sigma^-\,\pi^0$	$n\,\pi^-\,\pi^0$	100 %	No $p\pi^-$ vertex
K^-n	Σ^-	$n\,\pi^-$	100 %	No $p\pi^-$ vertex



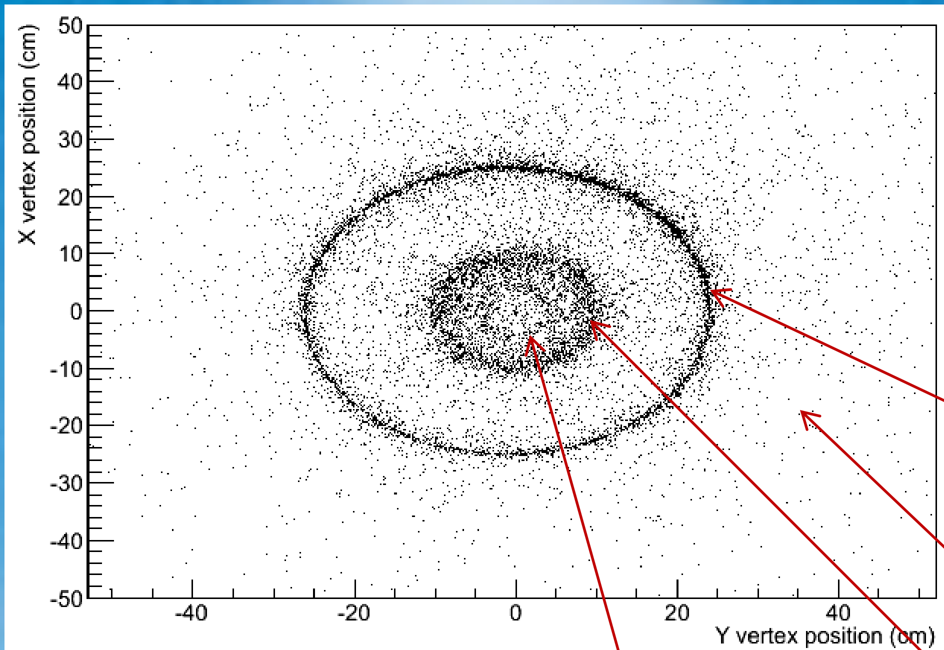


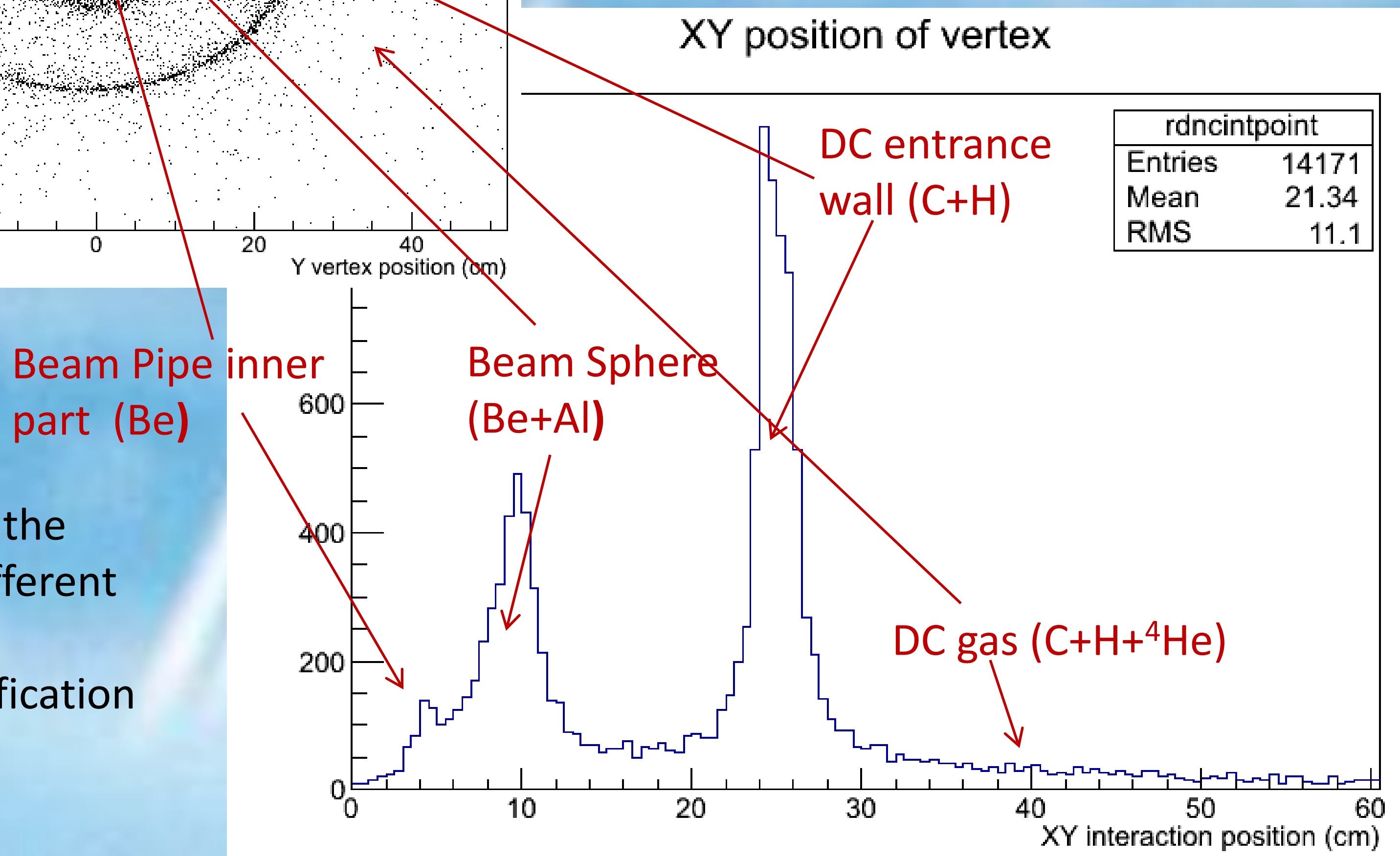
Residual background contamination:

$\Sigma^0\pi^0 = 1.1 \pm 0.3$ % $\Lambda\pi^0 = 0.4 \pm 0.1$ %

$\Sigma^+ \pi^-$ channel

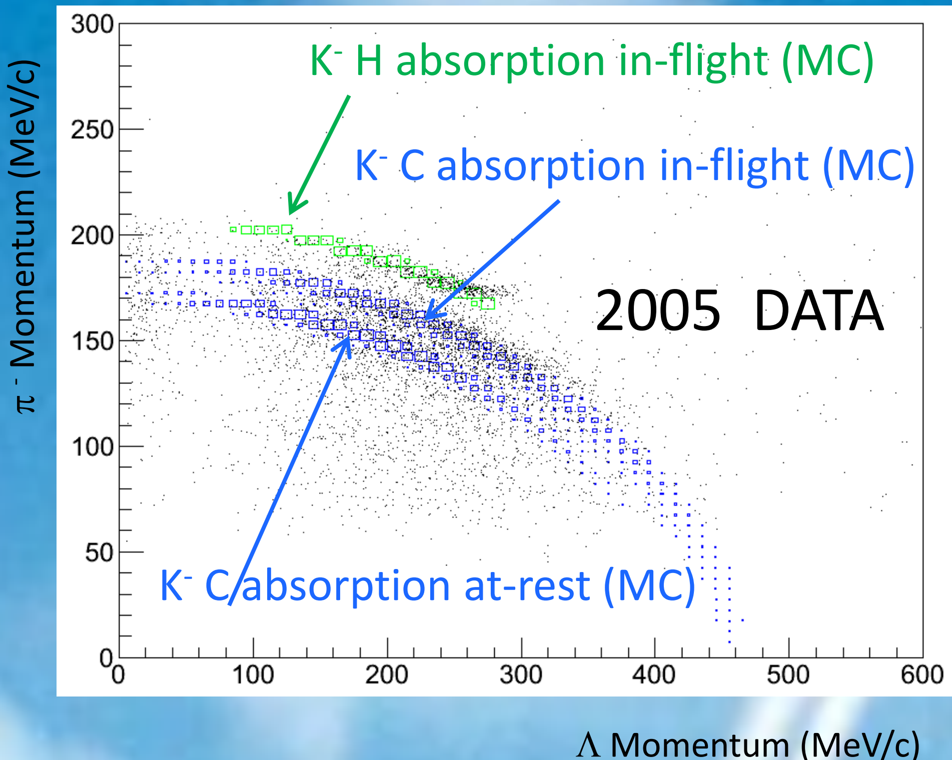
The reaction can be studied on several different materials: H, ^{4}He, ^{8}Be, ^{12}C





How can we study the reactions in the different materials?
We need an identification tool….

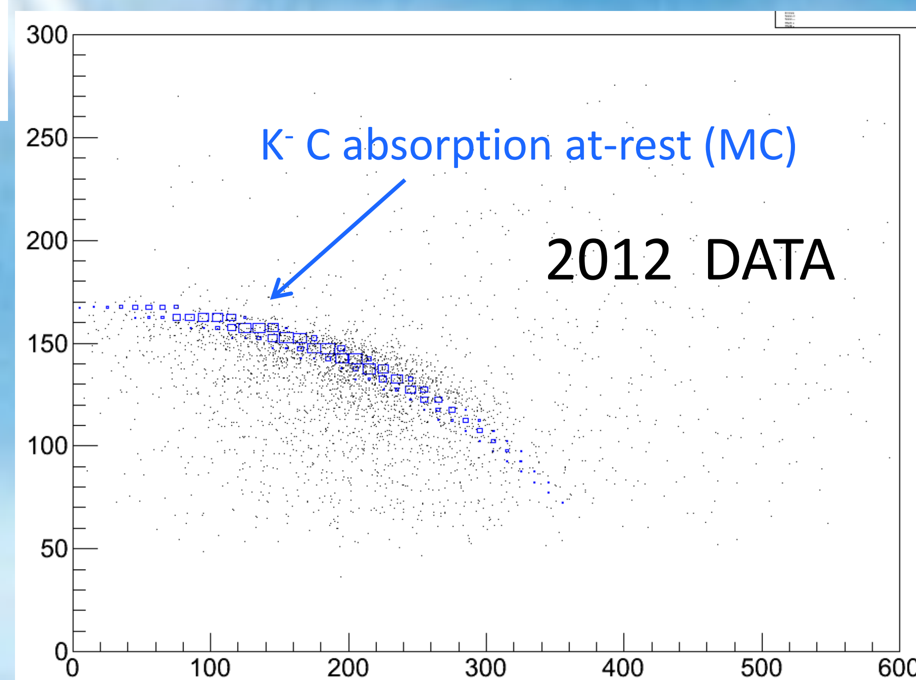
$\Sigma^+ \pi^-$ channel



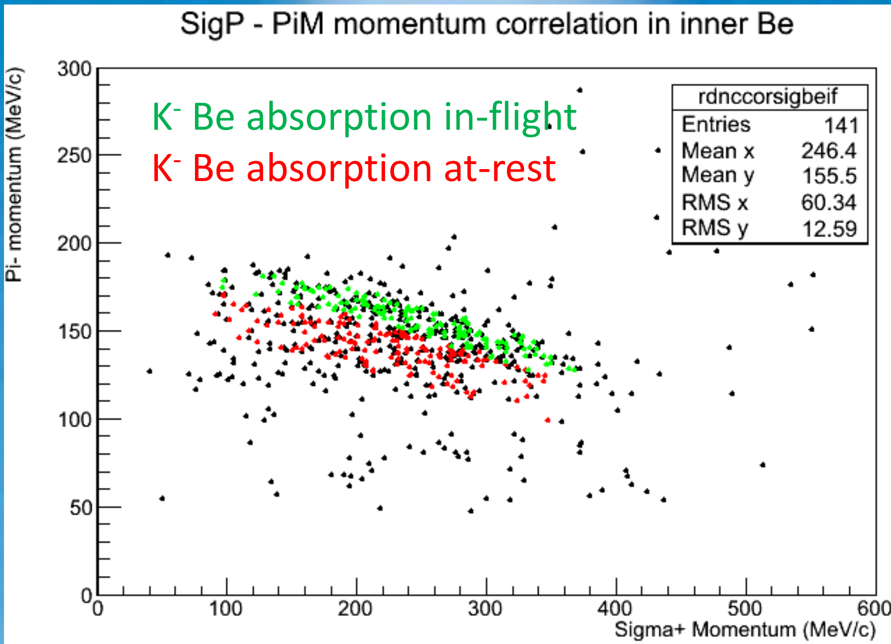
Complete understanding of different nuclear targets in different KLOE materials can be obtained from MC simulations

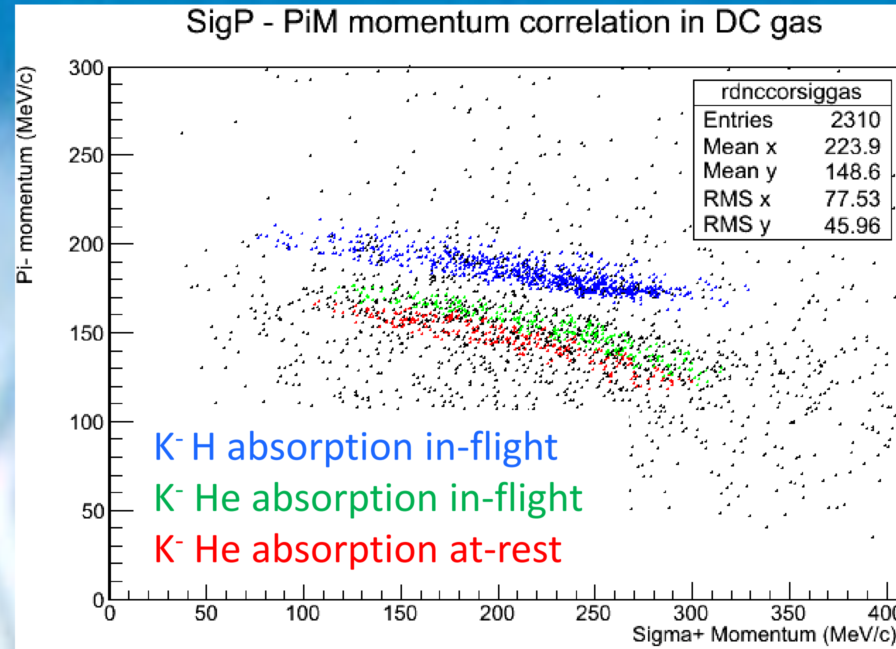
A K^- H contribution of ~ 10% is found

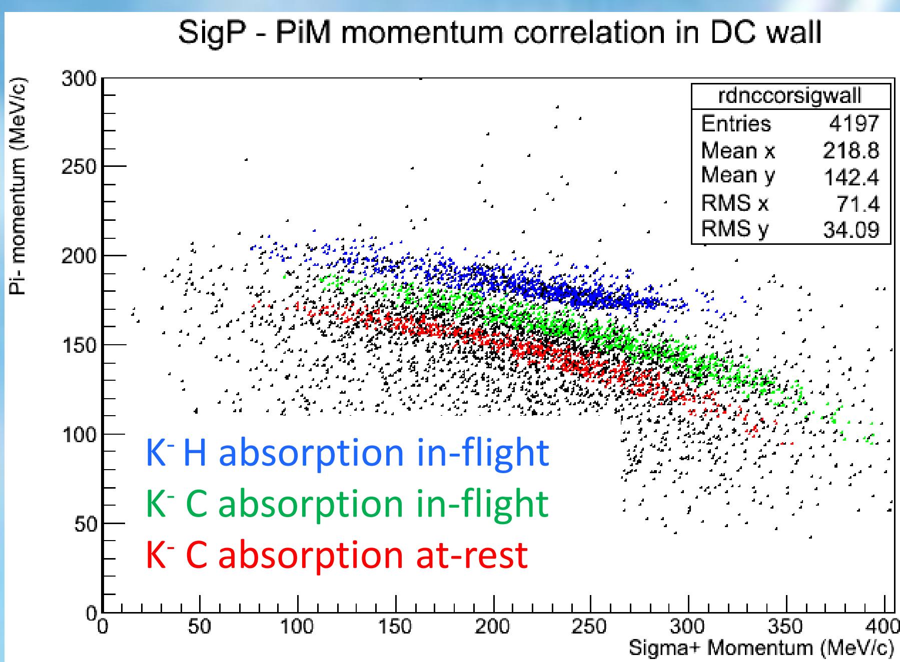
In-flight components are clearly evidenced by the excellent π^- resolution

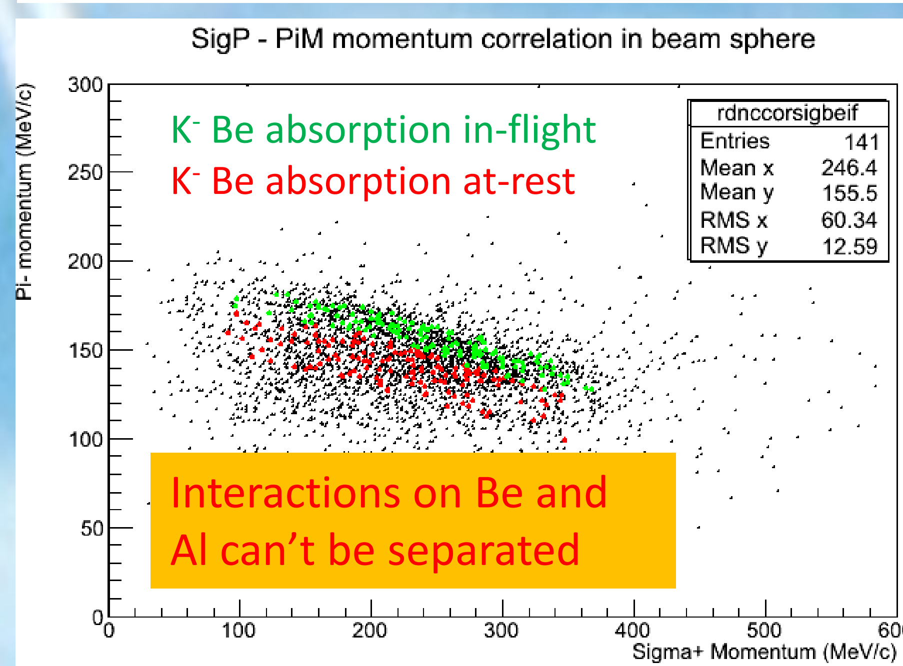


$\Sigma^+ \pi^-$ channel

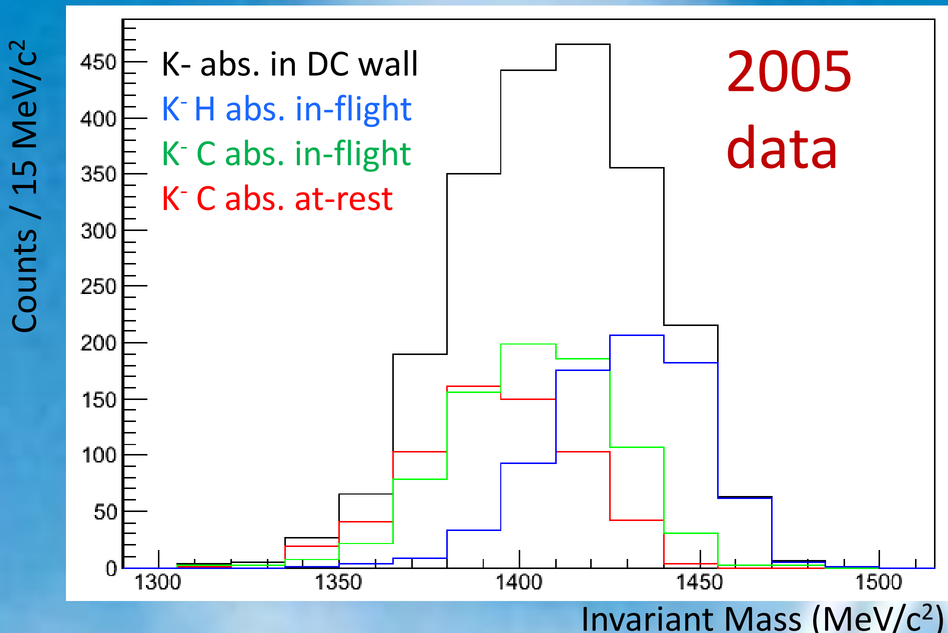


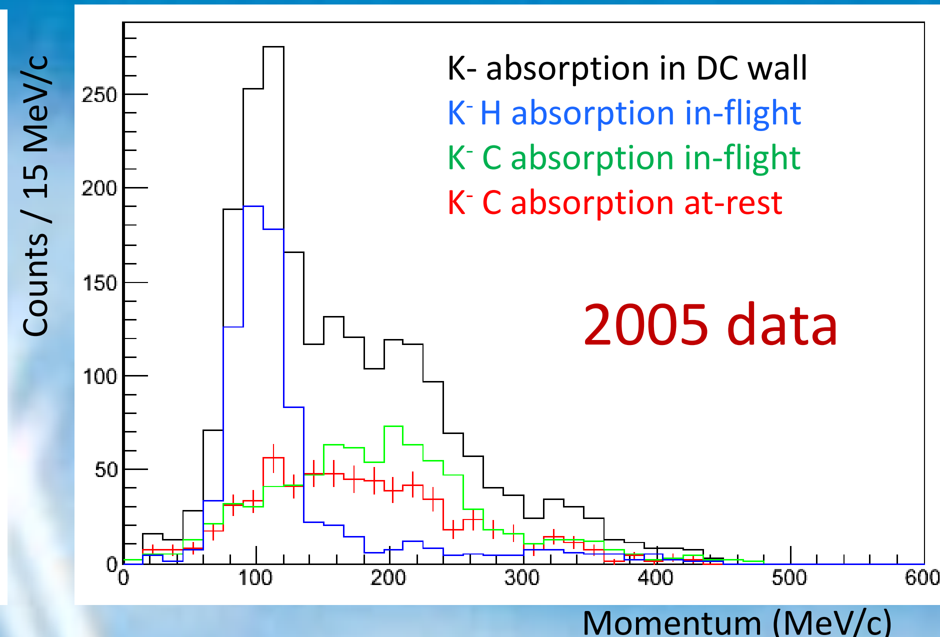


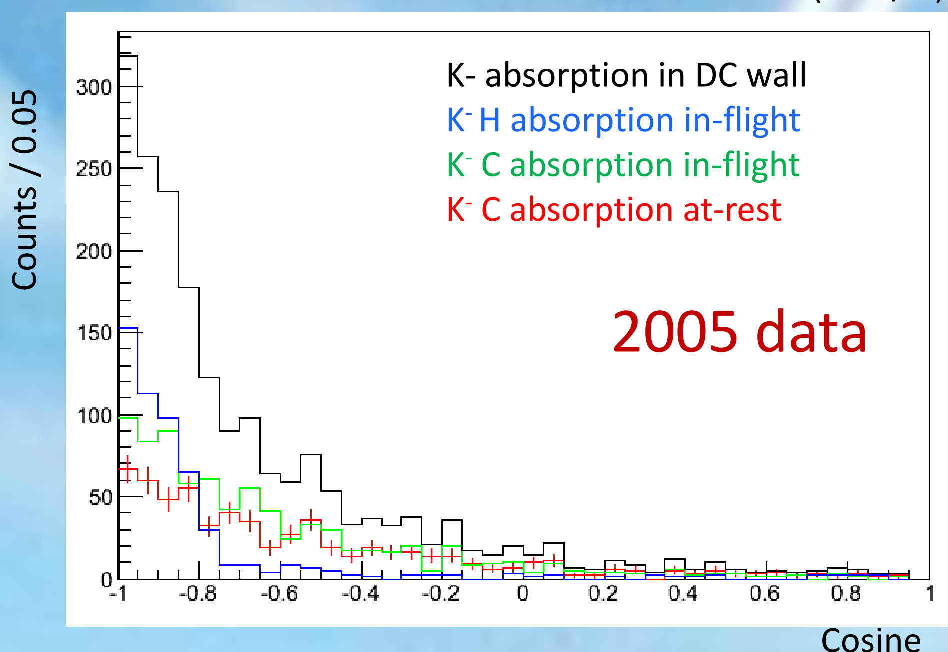


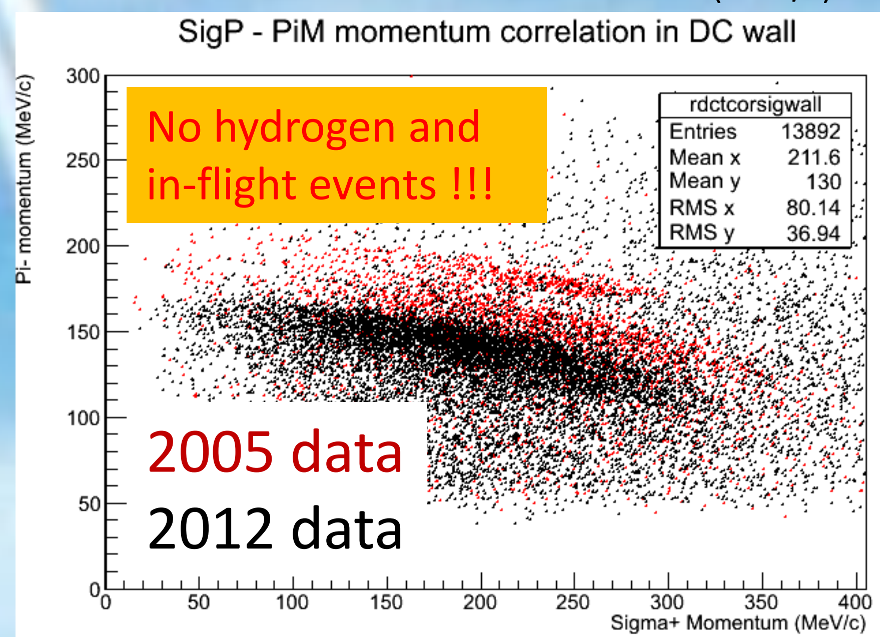


$\Sigma^+ \pi^-$ channel : DC wall and Carbon target

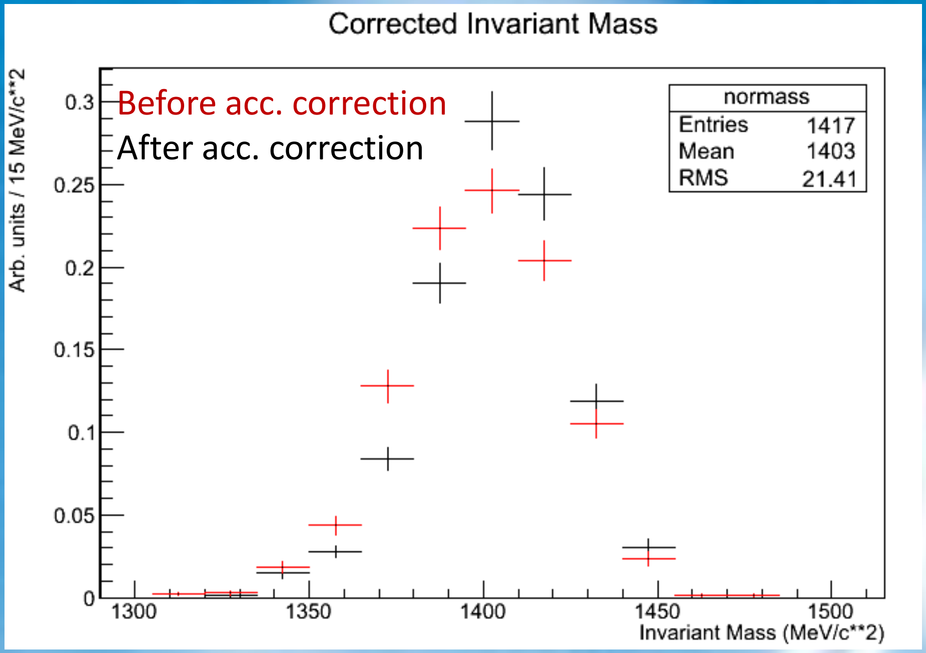


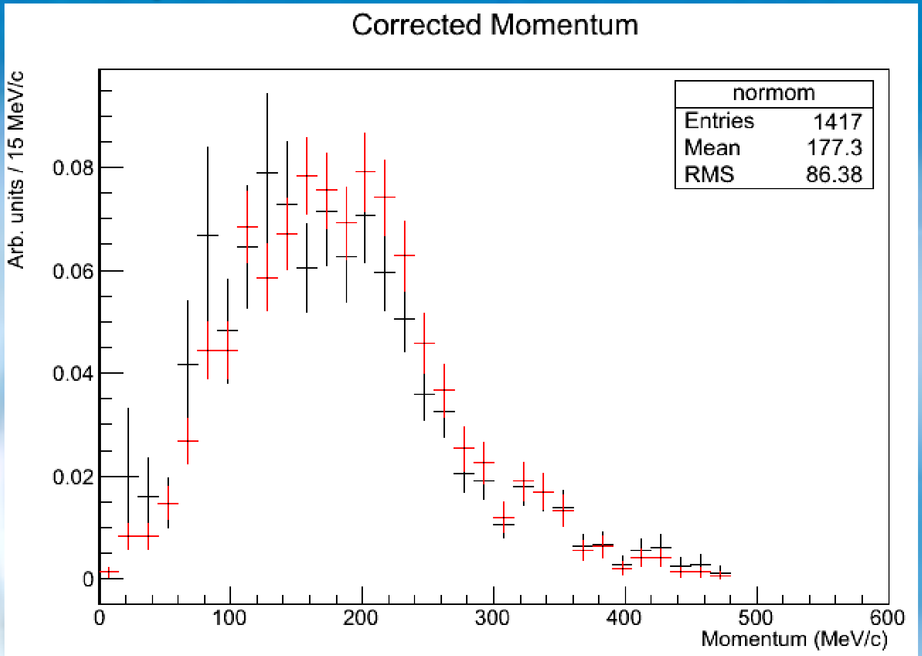


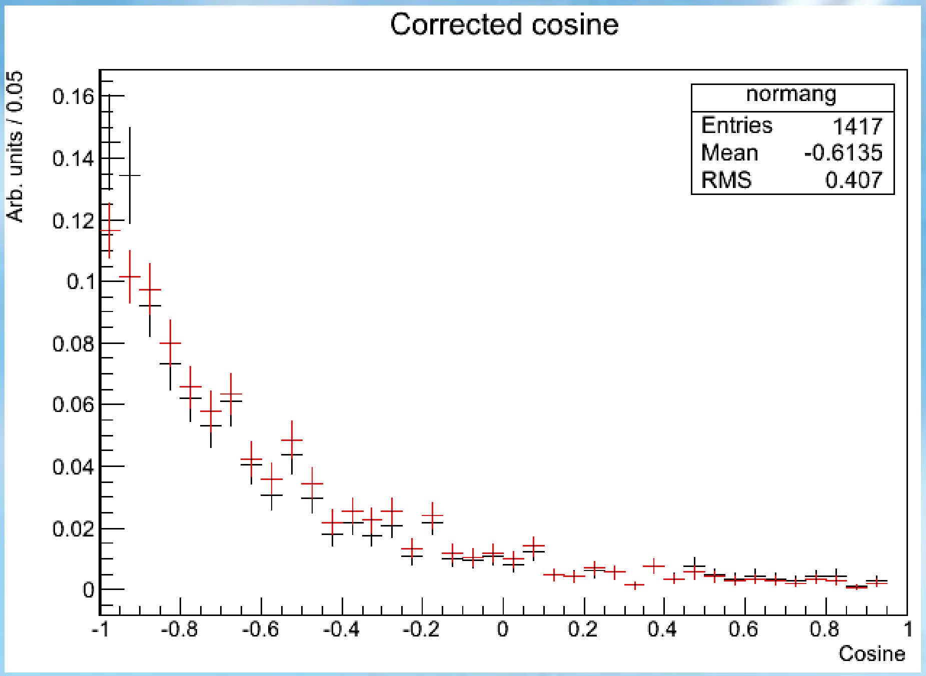




$\Sigma^+ \pi^-$ channel : corrected spectra in Carbon







Spectra have been corrected with an acceptance function obtained including both at-rest and in-flight MC simulations

Corrected spectra are normalized to 1

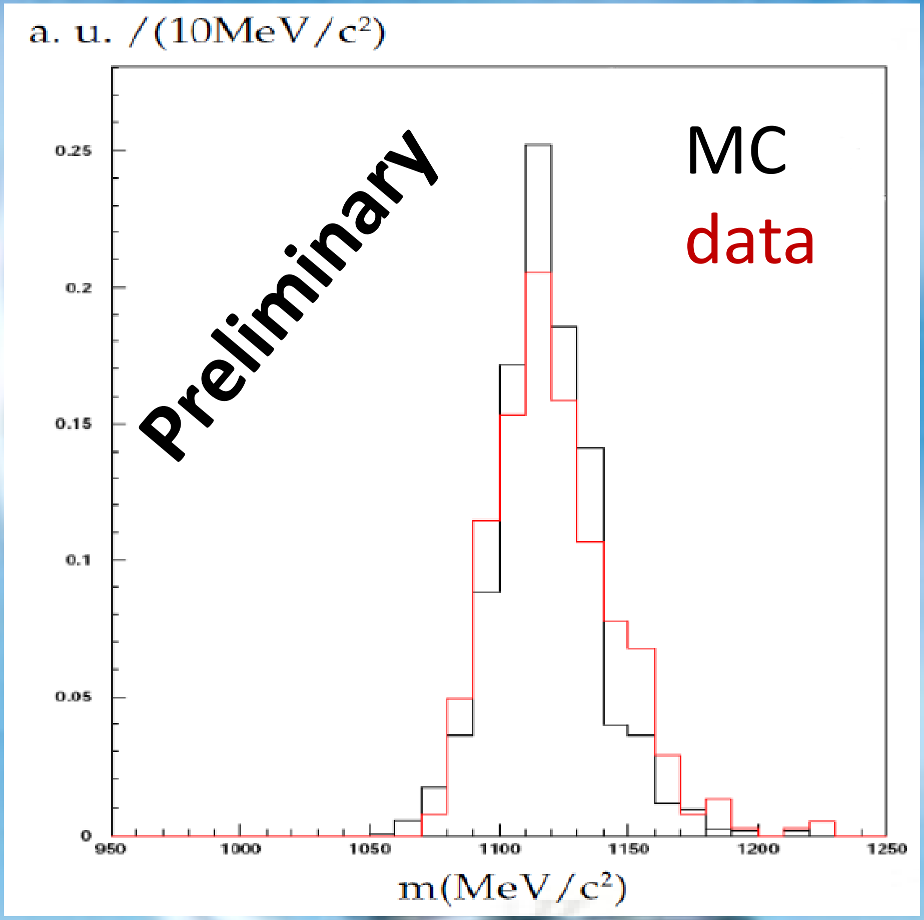
NO efficiency correction is included

$\Sigma^- \pi^+$ and Λ-->$n\pi^0$: the opening neutral channels

Completely neutral channel:

$\Lambda \rightarrow$ **n** π^0

Possibility to detect neutrons!



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

Conclusions…

- AMADEUS provides a unique opportunity for $\Lambda(1405)$ investigation
- Very promising results have been already obtained with the KLOE 2005 data
- First successful attempt to reconstruct neutrons => completely neutral channel
- Possibility to study In-flight and at-rest reactions individually

… and perspectives

- MC simulations for all the possible materials and acceptance correction
- MC simulations for the carbon target data
- MC simulations for resonant / non – resonant component identification
- Investigation of the Σ/Λ internal conversion effect (nucelar fragmentation?)
- Global fit of the data with all the possible components
- **AMADEUS experiment with dedicated targets**

Thanks for your attention

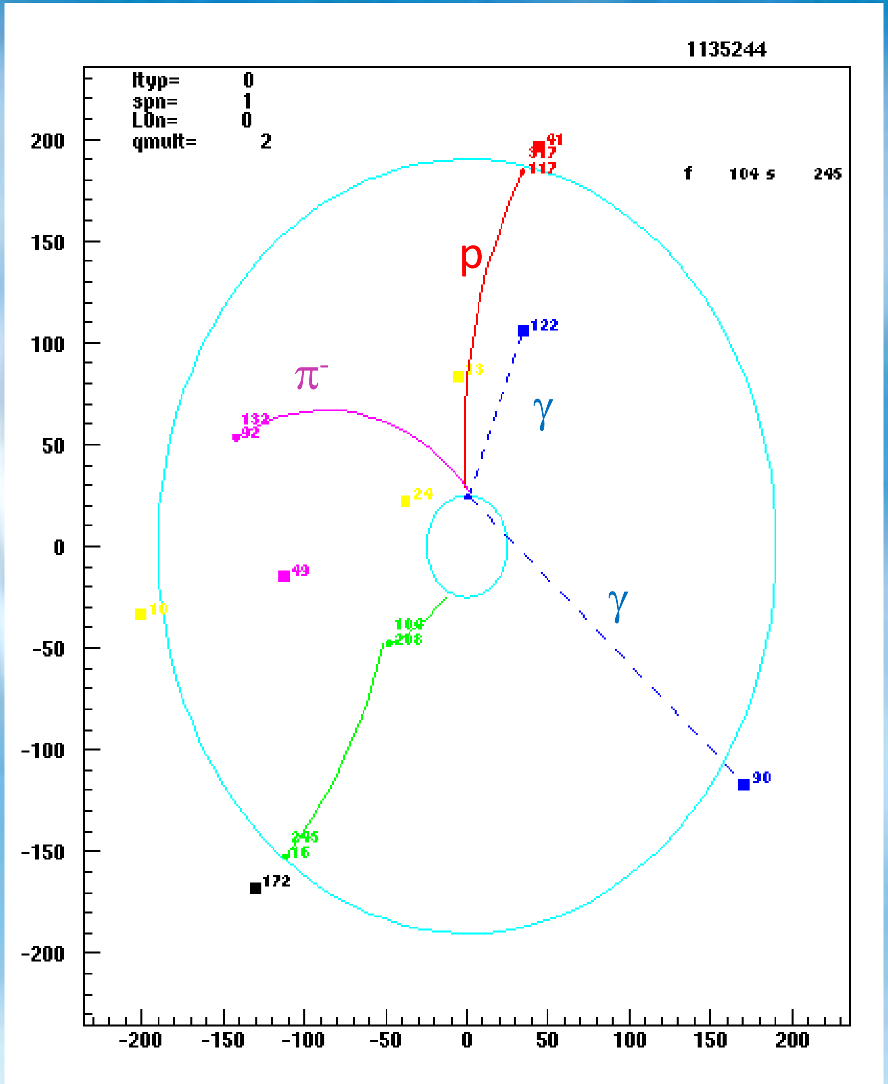
Spare slides

Studied channel

- What are we looking for:

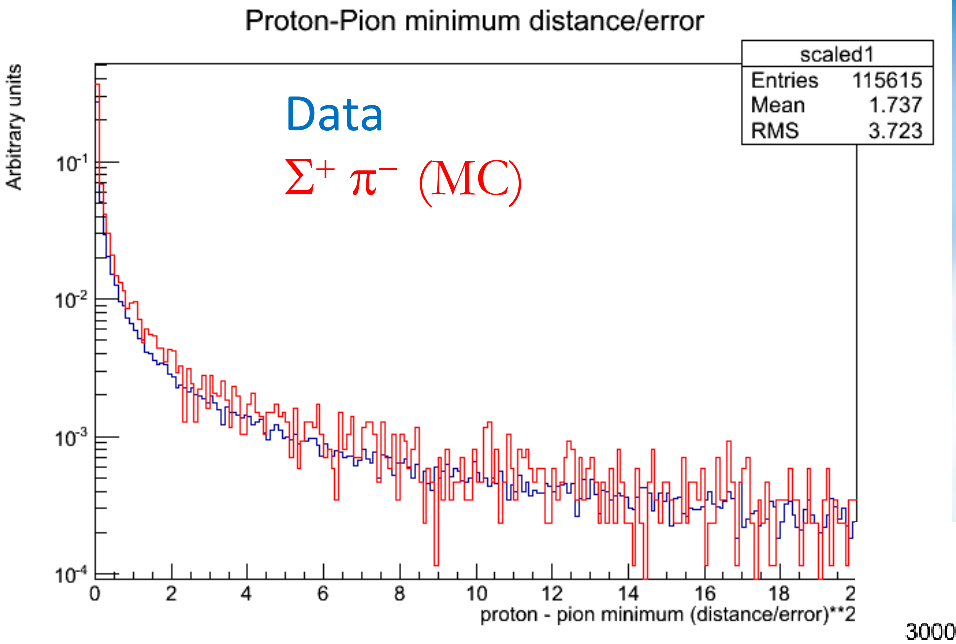
$K^- + p \dashrightarrow \Lambda^*(1405) \dashrightarrow \Sigma^+ + \pi^-$

$\quad \hookrightarrow p + \pi^0$



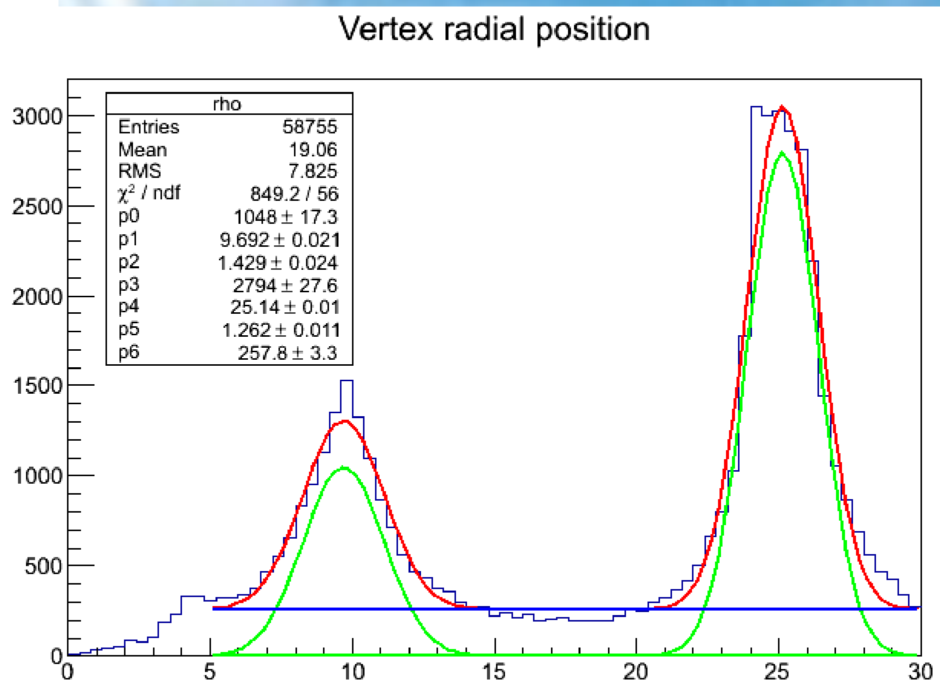
Since the Σ^+ almost immediately decays, p and π^- are associated to the same vertex

1) p π^- vertex reconstruction

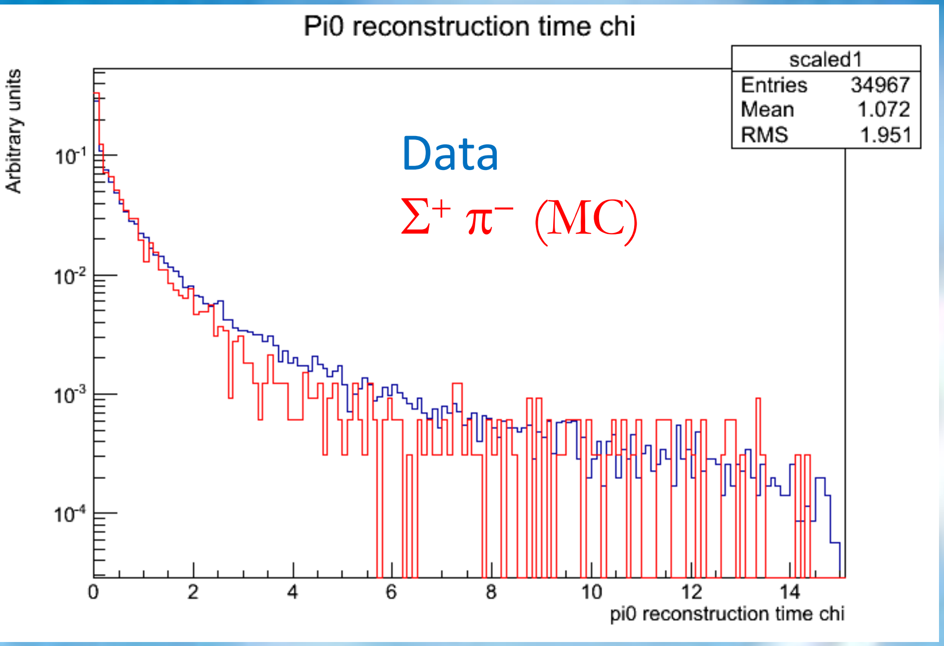


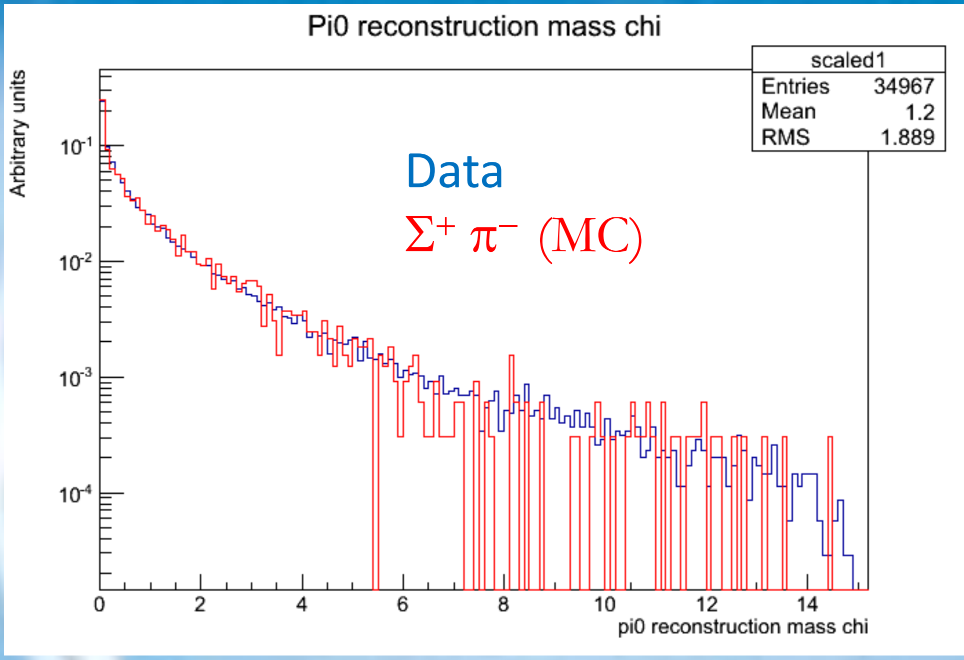
For each event, the best 4 p-π^- couples are selected using a procedure searching for the point of minimum distance between the tracks (PCA).

A cut value is chosen via an estimation of the S/B value in the XY vertex position plot.



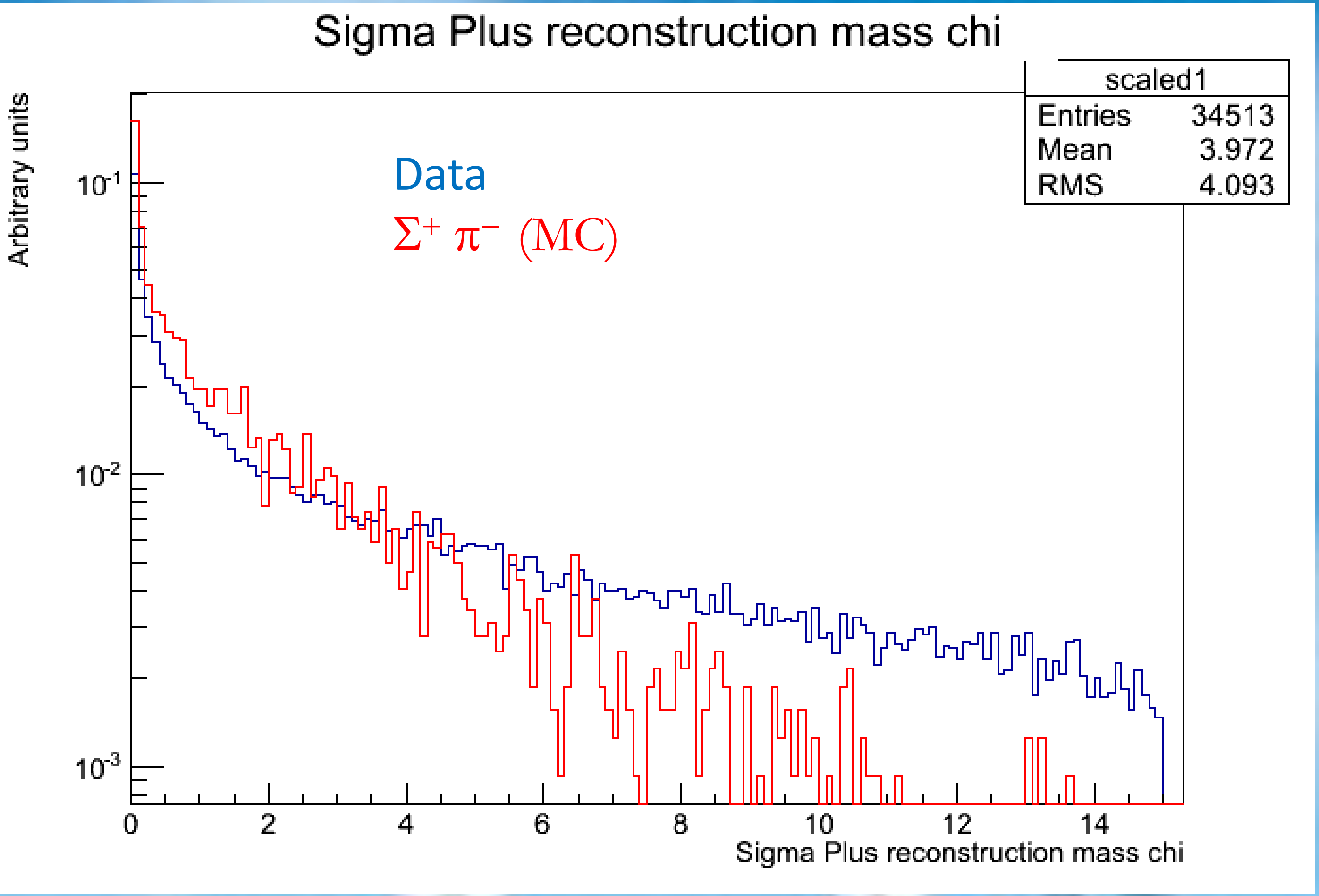
2) π^0 reconstruction





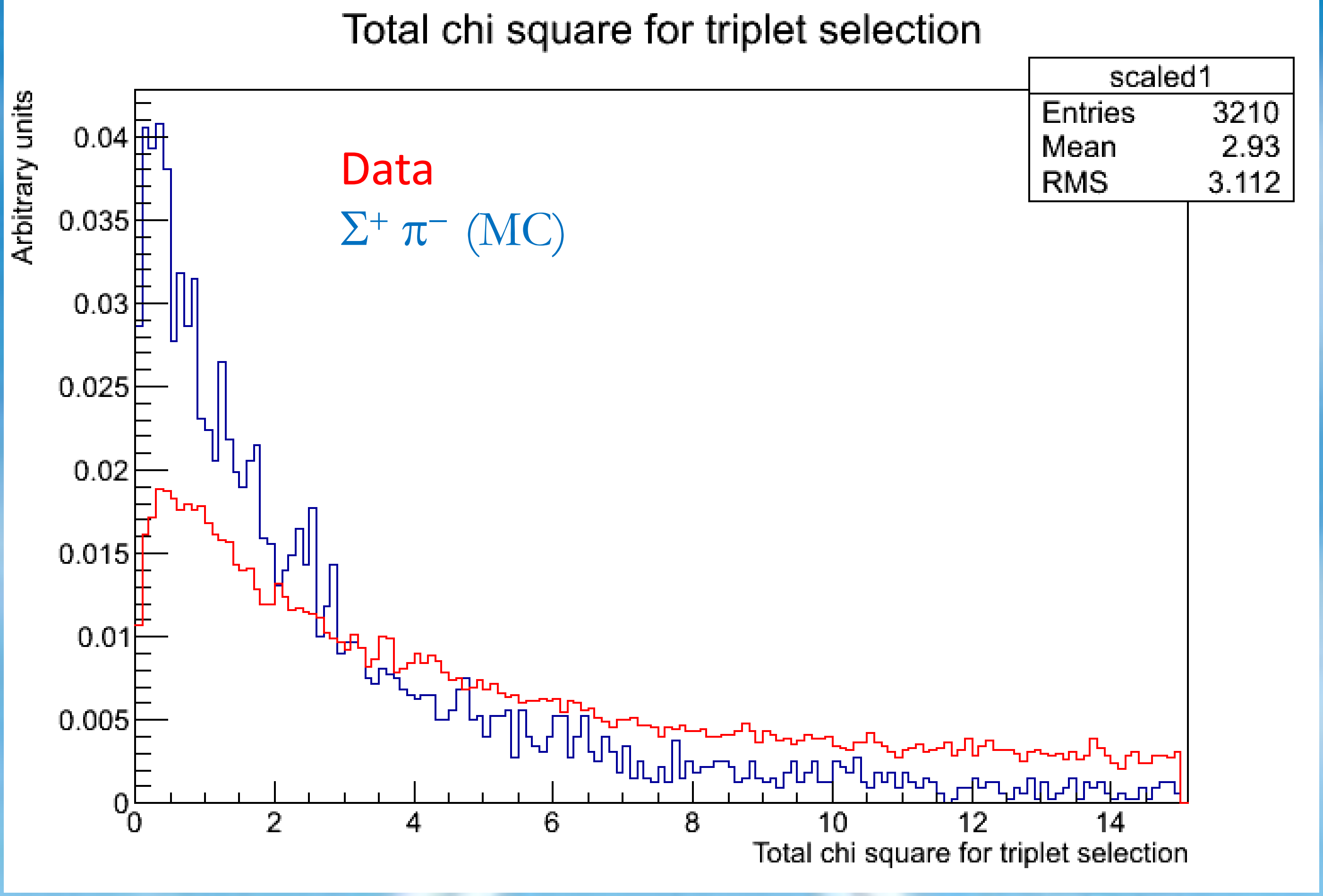
For each p π^- couple, the best 4 π^0 are searched looking for 2 photons in time from the PCA and minimizing a mass χ^2.

3) Σ^+ reconstruction



For each possible p-π^0 couple, the invariant mass is reconstructed and a mass χ^2 is calculated

4) Final triplets

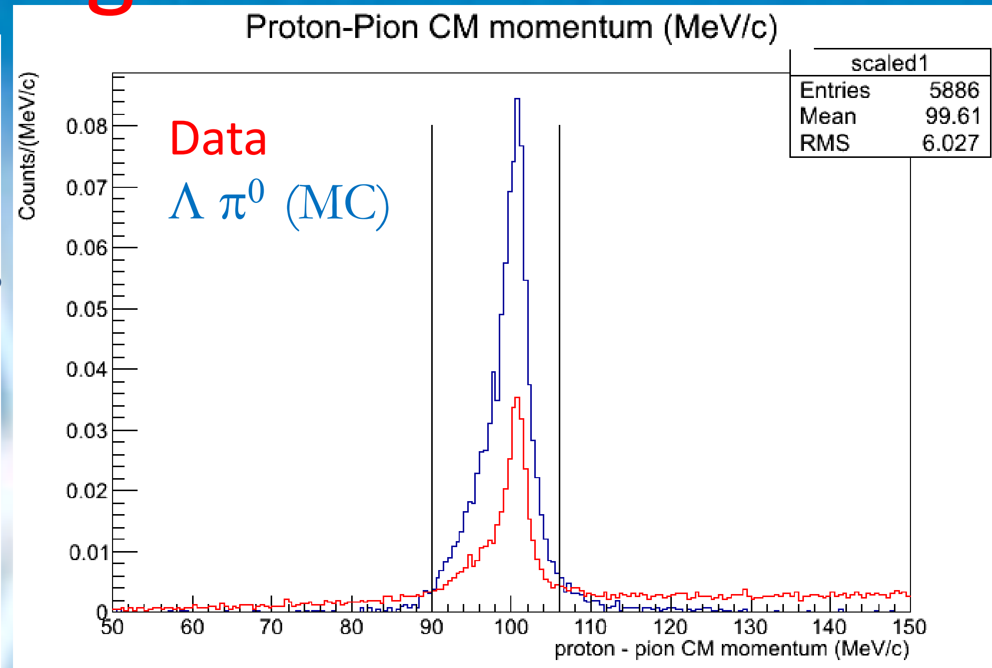


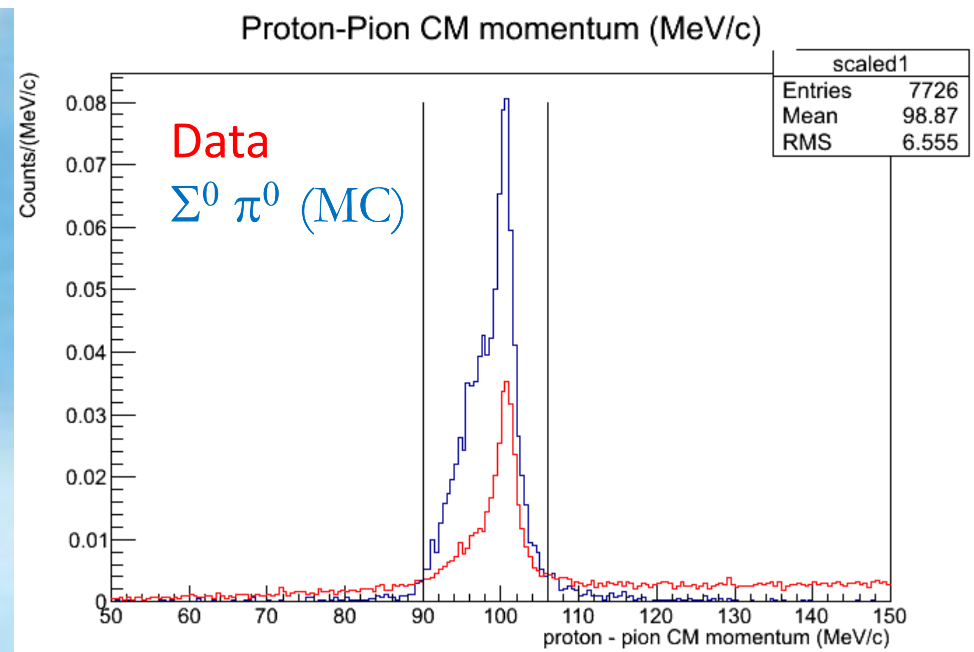
For each event, the final (p π^- π^0) triplet is selected minimizing the quantity:

$$\chi^2 = \sqrt{(\chi_t^2(\pi^0))^2 + (\chi_m^2(\pi^0))^2 + (\chi_m^2(\Sigma^+))^2}$$

5) Excluding Λ1116

Interaction	First Output particles	Daughters particles	B. R.	Situation
$K^- p$	$\Lambda \pi^0$	$p \pi^- \pi^0$	64 %	Cut on Λ vertices
		$n \pi^0 \pi^0$	36 %	No $p\pi^-$ vertex
$K^- p$	$\Sigma^+ \pi^-$	$p \pi^0 \pi^-$	52 %	SIGNAL
		$n \pi^+ \pi^-$	48 %	No $p\pi^-$ vertex
$K^- p$	$\Sigma^0 \pi^0$	$\Lambda(p\pi^-) \gamma \pi^0$	64 %	Cut on Λ vertices
		$\Lambda(n\pi^0) \gamma \pi^0$	36 %	No $p\pi^-$ vertex
$K^- p$	$\Sigma^- \pi^+$	$n \pi^- \pi^+$	100 %	No $p\pi^-$ vertex
$K^- p$	Λ	$p \pi^-$	64 %	No $p\pi^0$ vertex
		$n \pi^0$	36 %	No $p\pi^-$ vertex
$K^- p$	Σ^0	$\Lambda(p\pi^-) \gamma$	64 %	No π^0
		$\Lambda(n\pi^0) \gamma$	36 %	No $p\pi^-$ vertex
$K^- n$	$\Lambda \pi^-$	$p \pi^- \pi^-$	64 %	No π^0
		$n \pi^0 \pi^-$	36 %	No $p\pi^-$ vertex
$K^- n$	$\Sigma^0 \pi^-$	$\Lambda(p\pi^-) \gamma \pi^-$	64 %	No π^0
		$\Lambda(n\pi^0) \gamma \pi^-$	36 %	No $p\pi^-$ vertex
$K^- n$	$\Sigma^- \pi^0$	$n \pi^- \pi^0$	100 %	No $p\pi^-$ vertex
$K^- n$	Σ^-	$n \pi^-$	100 %	No $p\pi^-$ vertex





Principal hadronic background sources can be rejected setting a cut on the p-π^- CM momentum; the cut value is obtained from MC simulations.

A possible background: Σ-Λ Internal conversion

Possible background sources could be reactions like

Σ^+ internal conversion on neutron : $K^- + p + {}^8Li \rightarrow \Sigma^+ + \pi^- + (3p+5n\ ?)$

$+ (n)$

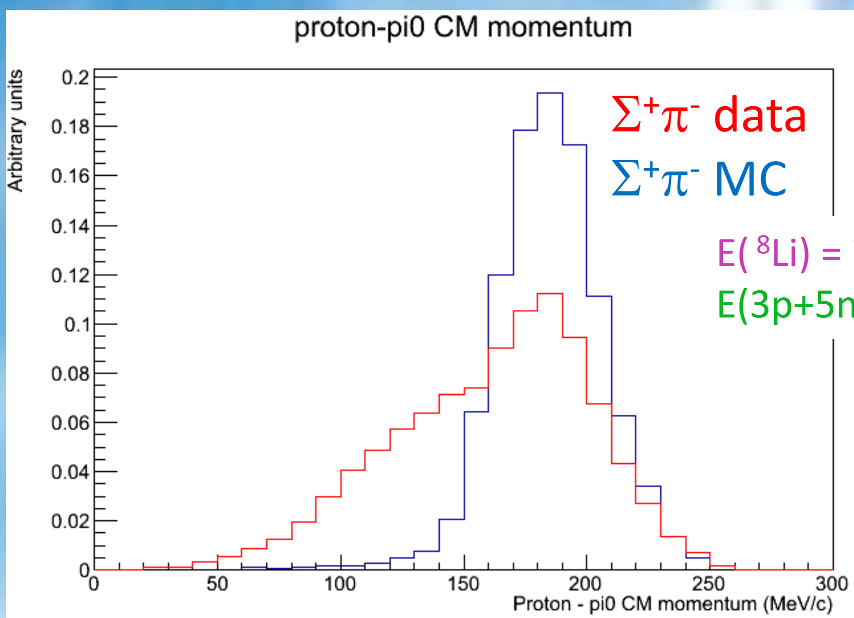
$\Lambda(1116) + p \rightarrow n + \pi^0 + p$

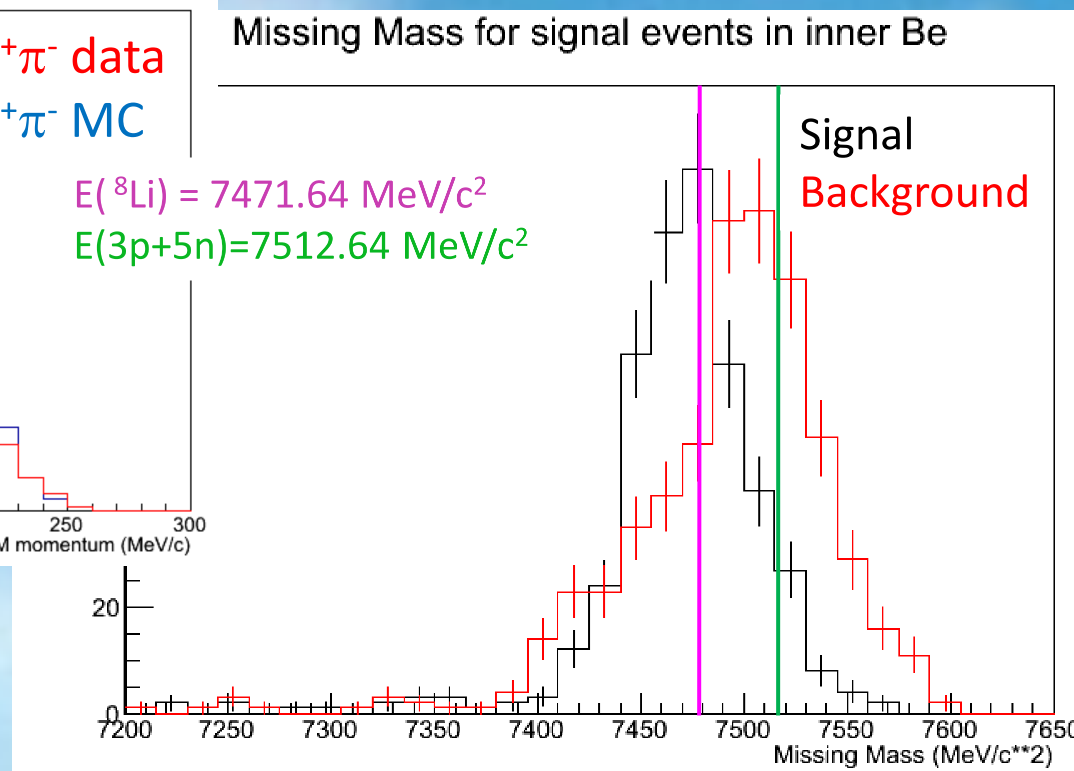
$\gamma\ \gamma$

Similar final states:

$K^- + p + {}^8Li \rightarrow p + \pi^- + \gamma + \gamma + {}^8Li$ (Signal)

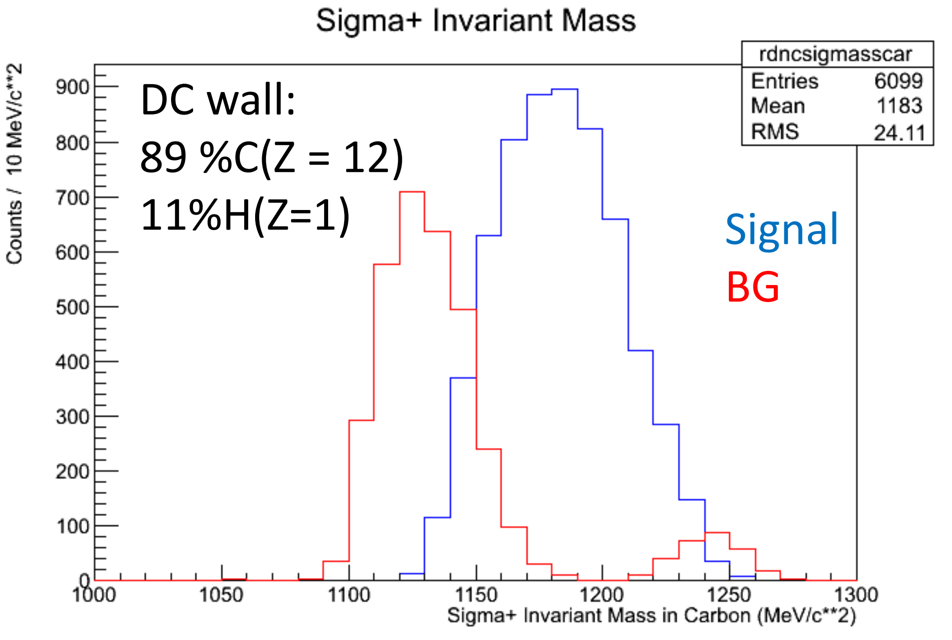
$K^- + p + {}^8Li \rightarrow p + \pi^- + \gamma + \gamma + (3p+5n\ ?)$ (BG)

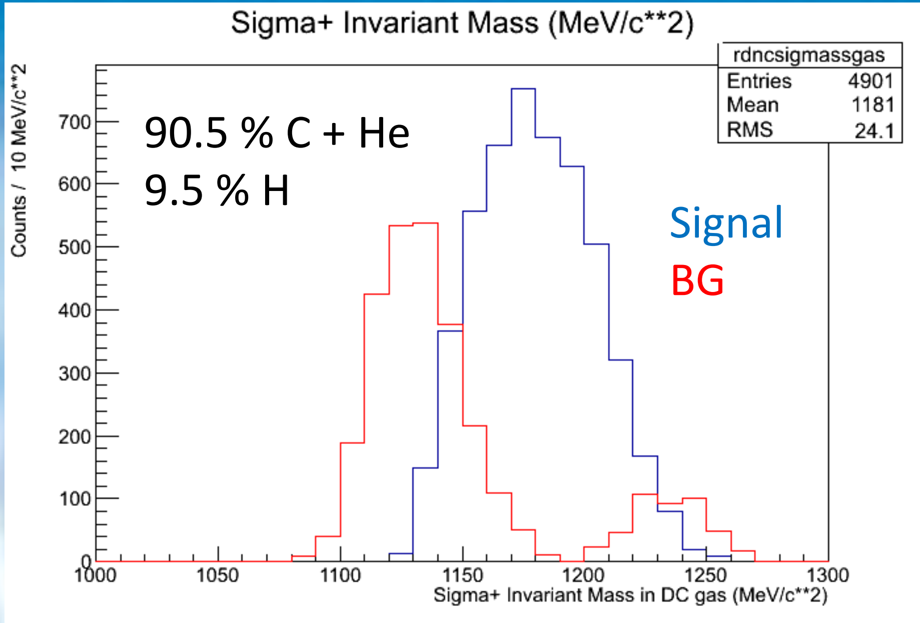


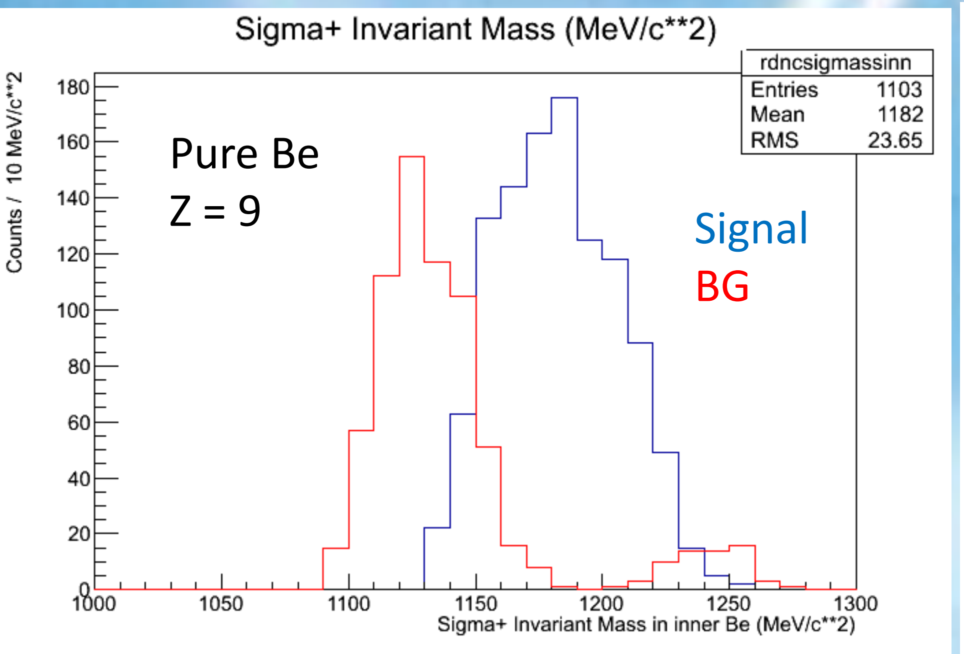


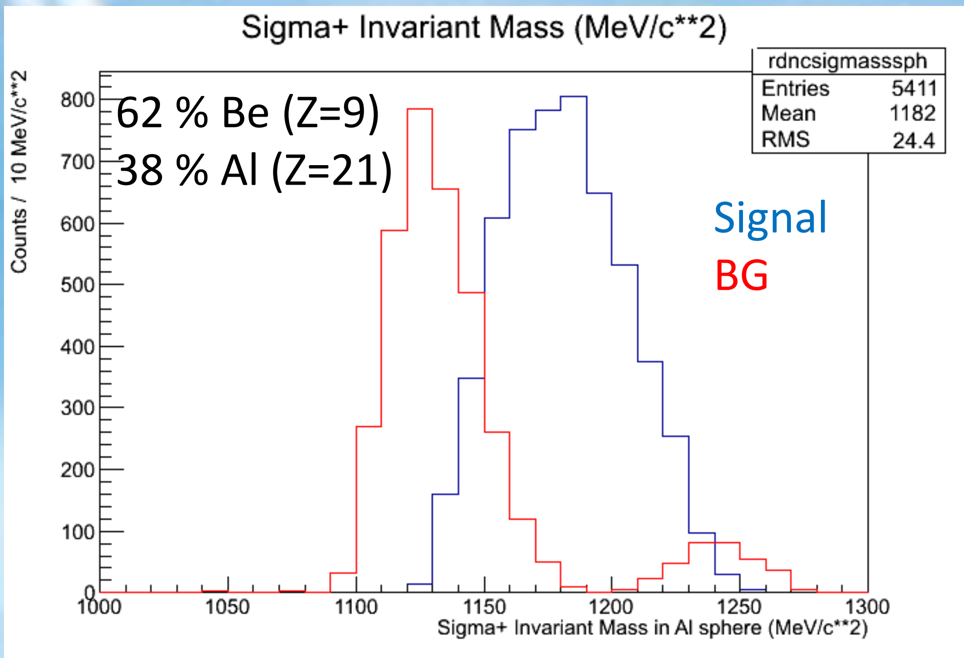
The missing mass analysis confirms the Σ-Λ internal conversion hypothesis

Internal conversion ratios





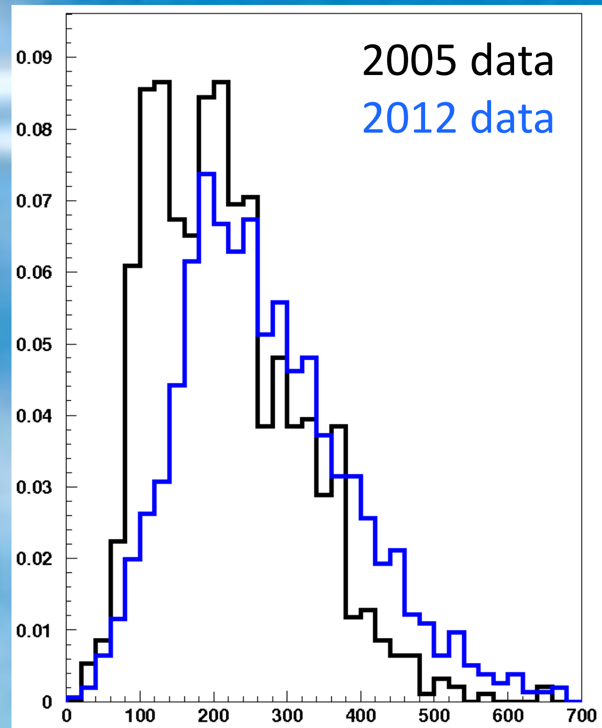


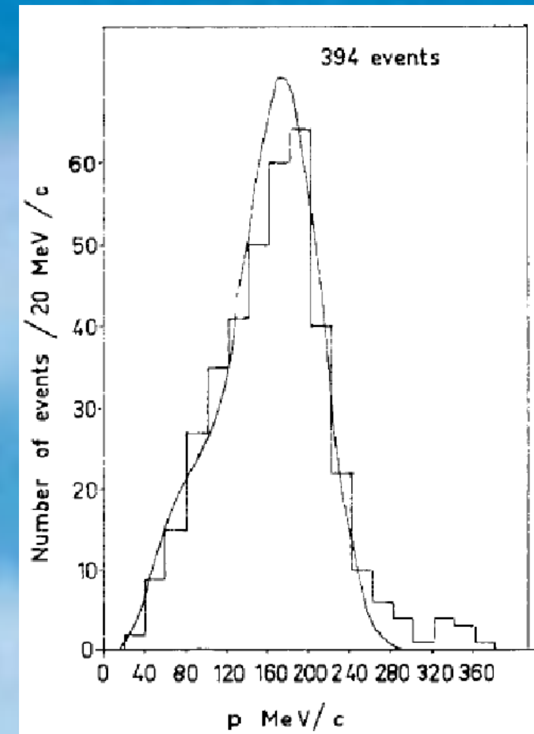


Comparison with K^- absorption in emulsion

A higher invariant mass region is opened!!!

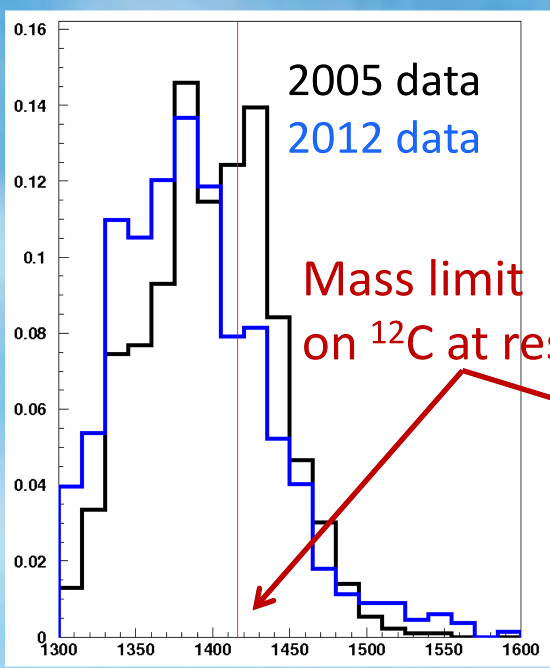
N.U.



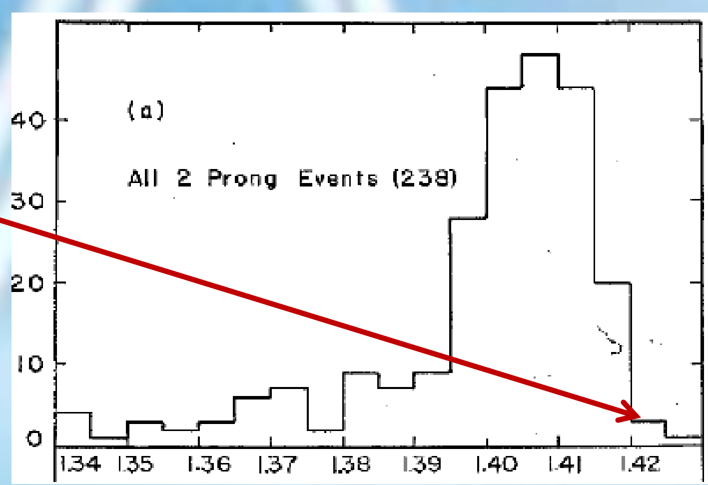


Momentum (MeV/c)

N.U.



Mass limit on ^{12}C at rest



Invariant Mass (MeV/c^2)

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

K^-

8 component fit, simultaneously $m_{\Sigma 0\pi 0}$ & $p_{\Sigma 0\pi 0}$:

- Breit-Wigner resonant component K^- C at-rest/in-flight. (M,Γ) = (1405 ÷ 1430 , 5 ÷ 52)
- 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 (Σ(1385) + I.C.)
- non resonant misidentification (*n.r.m.*) background

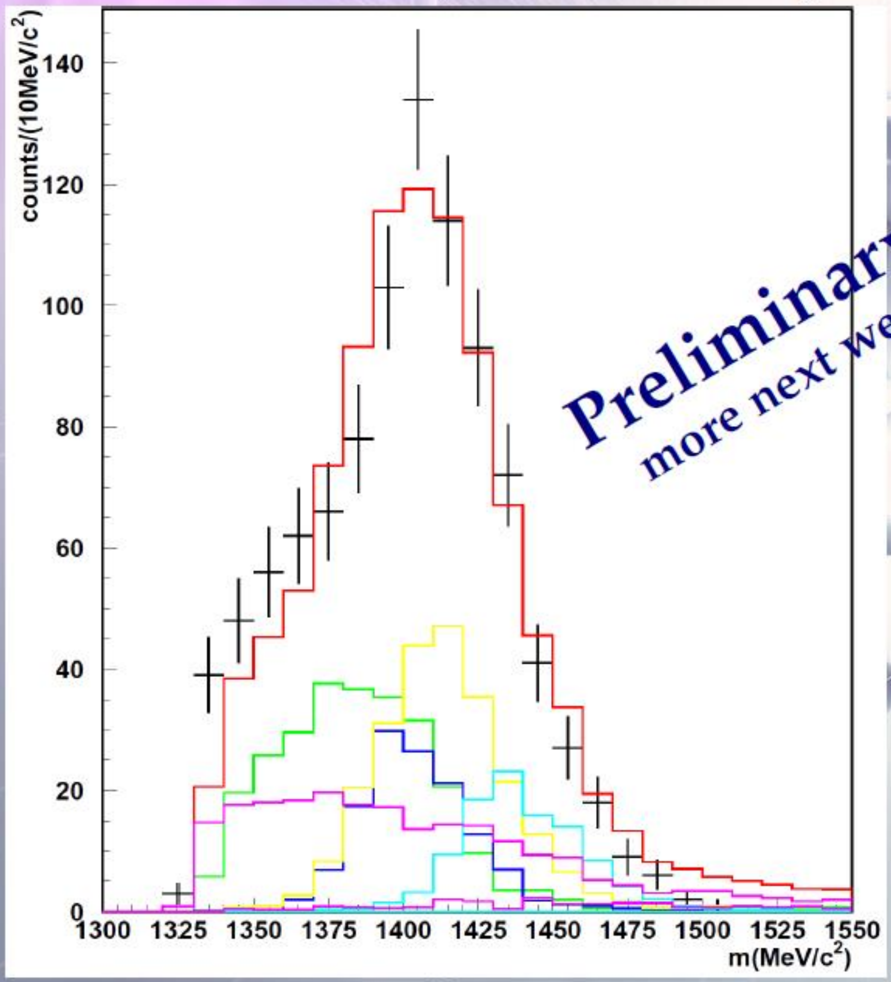
$K^-\ ^{12}C \rightarrow \Sigma^0\pi^0 + {}^{11}B$ (Boron spectator, left in ground state)

secondary interactions not taken into account.

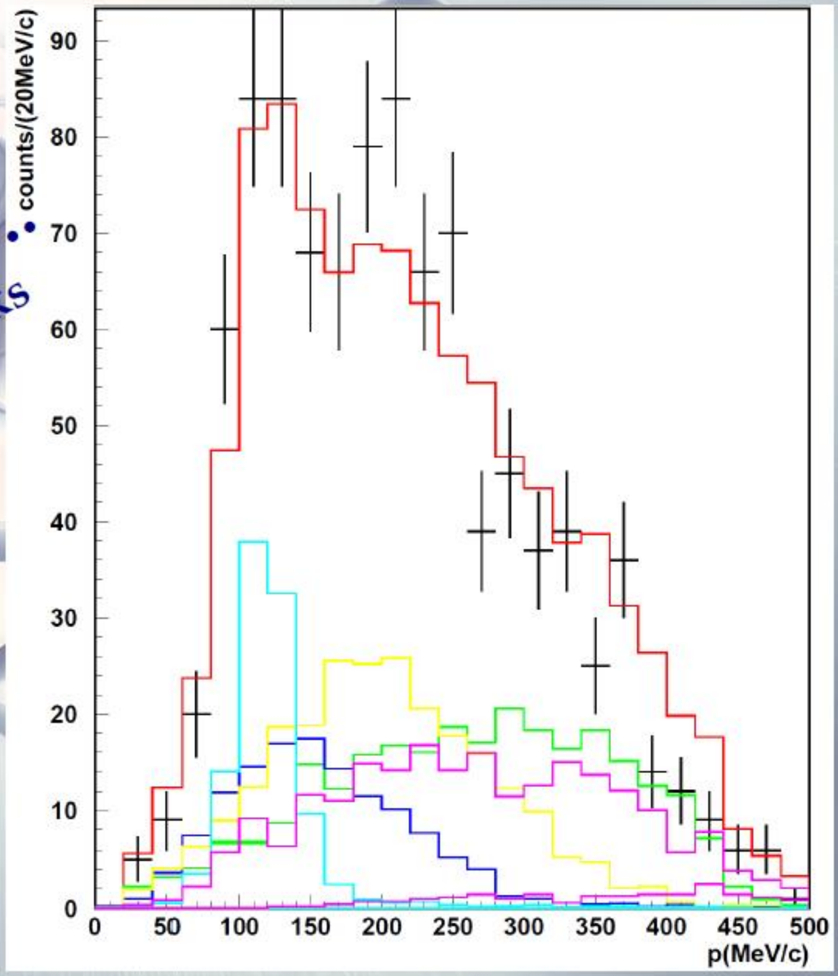
Fit of $\Sigma^0\pi^0$ spectrum in C

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

- 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.



$m_{\Sigma 0\pi 0}$



$p_{\Sigma 0\pi 0}$