STUDY OF THE $\Sigma^0 p$ CORRELATIONS FROM K^- ABSORPTIONS WITH KLOE

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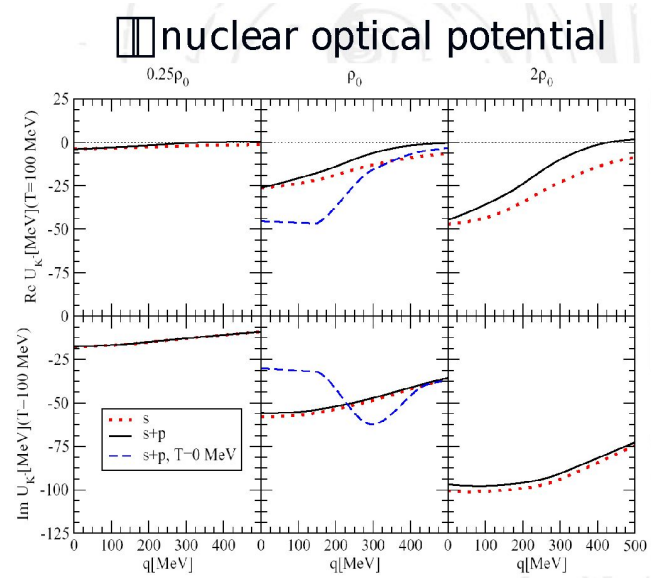
on behalf of the AMADEUS Collaboration

CONF12 – Thessaloniki – Tuesday 6 September 2016

K⁻ in nuclear matter and the $\bar{K}N$ potential

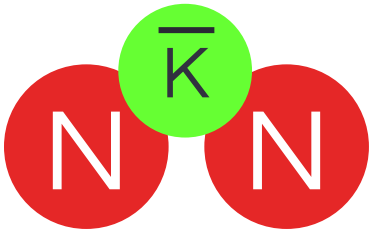
D. Cabrera, et al., PRC90 (2014) 055207

- K⁻ - nucleon interaction is attractive (kaonic atoms)
- **Absorption processes** have a large cross-section and should be taken into account



Kaonic Clusters

- K⁻ acting as glue between two or more nucleons → molecular state is formed
- It is predicted by most theories in the field but with very different **Binding Energy** and **Width**



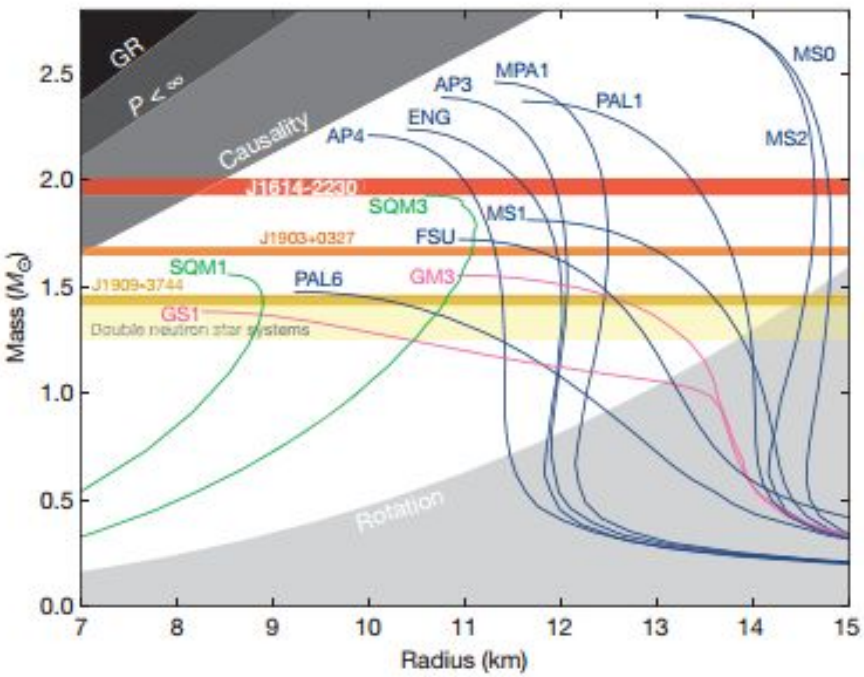
Prof. Nagae, HYP2015, Sep. 10, 2015

	Dote,Hyodo, Weise	Akaishi, Yamazaki	Barnea, Gal, Liverts	Ikeda, Sato	Ikeda, Kamano,Sato	Schevchenko ,Gal, Mares	Revai, Schevchenko	Maeda, Akaishi, Yamazaki
B (MeV)	17-23	48	16	60-95	9-16	50-70	32	51.5
Γ(MeV)	40-70	61	41	45-80	34-46	90-110	49	61
Method	Variational	Variational	Variational	Faddeev-AGS	Faddeev-AGS	Faddeev-AGS	Faddeev-AGS	Faddeev-Yakubovsky
Interaction	Chiral	Phenom.	Chiral	Chiral	Chiral	Phenom.	Chiral	Phenom.

$\bar{K}N$ interactions

- Models for neutron stars with K^- condensate inside, depending on the strength of the K^- - nucleon potential (**at large densities**)

- Measurements of 2 solar masses constrain the neutron star EOS to be **stiff**



- New precise experimental data is needed: KN(s) interactions, bound states,…

Experiments:

K⁻ Absorption

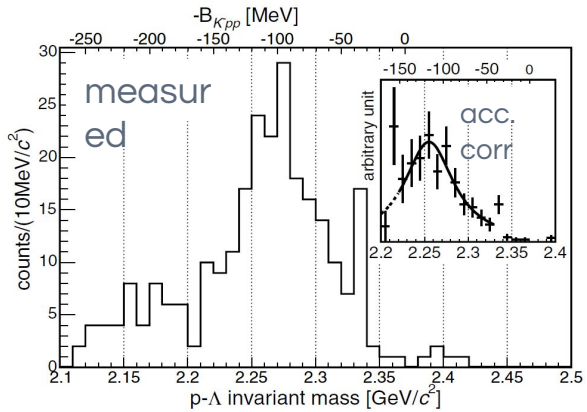
FINUDA

$K^- + A$

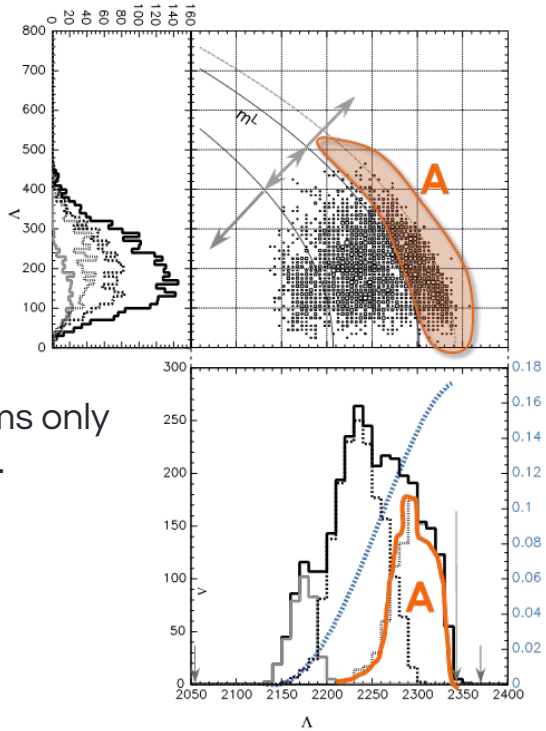
KEK-PS: E549

$$K^- +^4 He \rightarrow \Lambda + N + X$$

M. Agnello et al. Phys. Rev. Lett. **94** (2005)



B(ppK⁻) = 115 MeV
Γ(ppK⁻) = 67 MeVc^{-2}



T. Suzuki et al., Mod. Phys. Lett. A23 (2008) 2520

Selection of the different mechanisms only on the base of the ΛN missing mass.
A: associated to 2N absorption

Experiments:

K⁻ Absorption

FINUDA
$K^- + A$

KEK-PS: E549
$K^- +^4 He \rightarrow \Lambda + N + X$

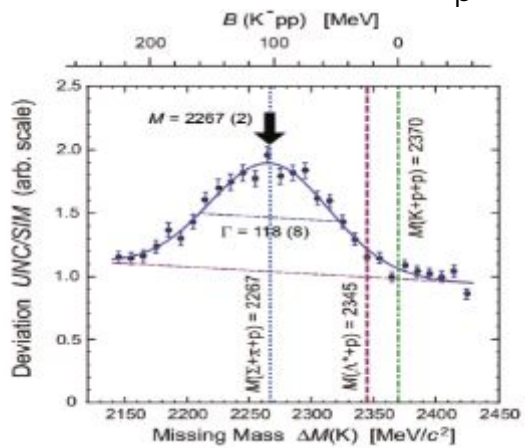
pp collisions

DISTO: deviation spectra,
Extraction of a signal

HADES: PWA analysis of the final state including all N* decaying into KL pairs
Extraction of upper limit

T. Yamazaki et al. Phys.Rev.Lett.104,(2010)

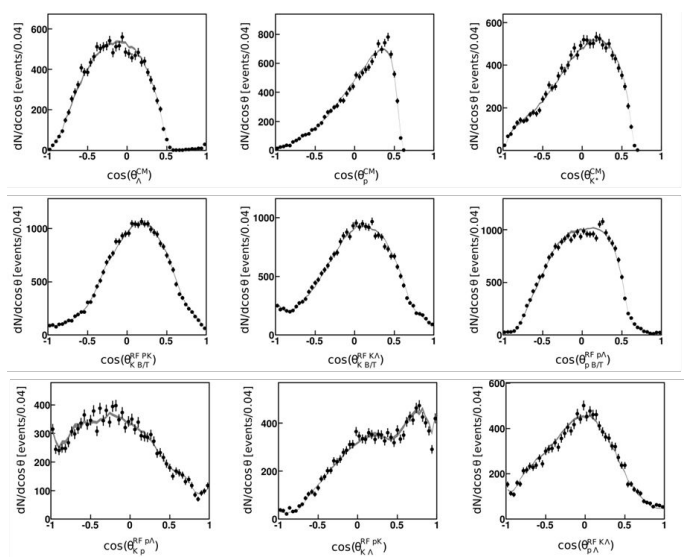
DISTO pp → p K⁺ Λ @ T_p = 2.85 GeV



B(ppK⁻) = 103 MeVc^{-2}
Γ(ppK⁻) = 118 MeVc^{-2}

G. Agakishiev et al., Phys.Lett. B742 (2015) 242-248

HADES pp → pK⁺Λ @ p = 2.85 GeV



● Data
PWA

Coherent Upper-Limit for the ppK-

Wave	Cross Section (μb)
0^+	1.9 – 3.9
1^-	2.1 – 4.2
2^+	0.7 – 2.1

Experiments:

K⁻ Absorption

FINUDA
$K^- + A$

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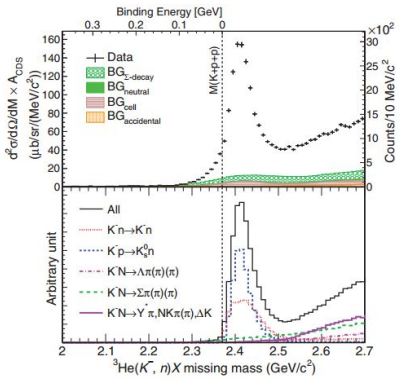
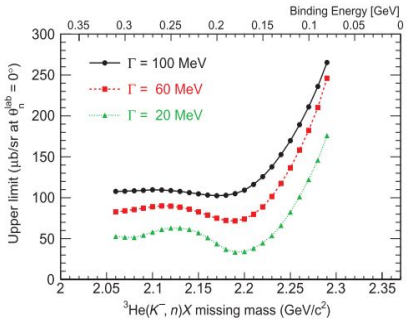
Recent results

LEPS/SPring-8
d(γ,K⁺π⁻)
J-PARC E27
d(π⁺, K⁺)
J-PARC E15
³He(K⁻,n)

T. Hashimoto et al., PTEP (2015) 061D01

J-PARC E15 : ³He(K⁻,n) @ 1 GeV/c

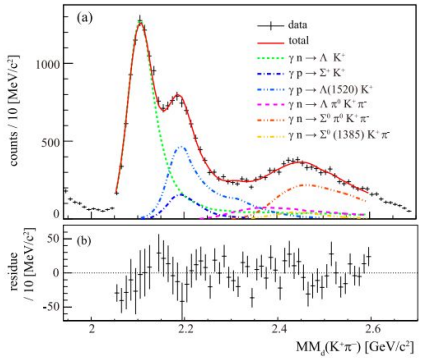


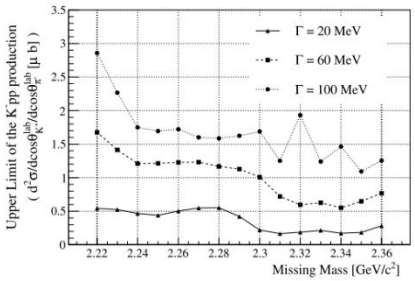


formation upper limit

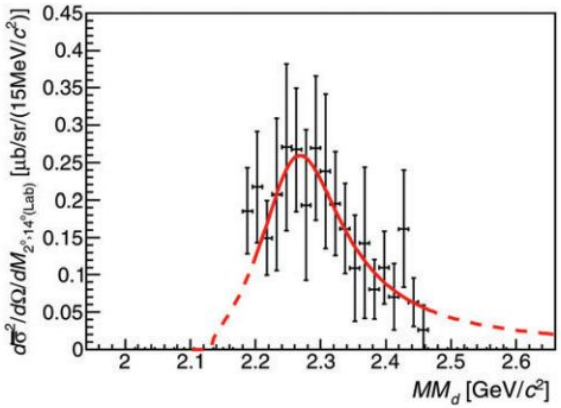
A.O. Tokiyasu et al., Phys. Lett. B 728 (2014) 616–621

LEPS/SPring-8: d(γ,K⁺π⁻) @ Eγ=1.5-2.4 GeV





formation upper limit

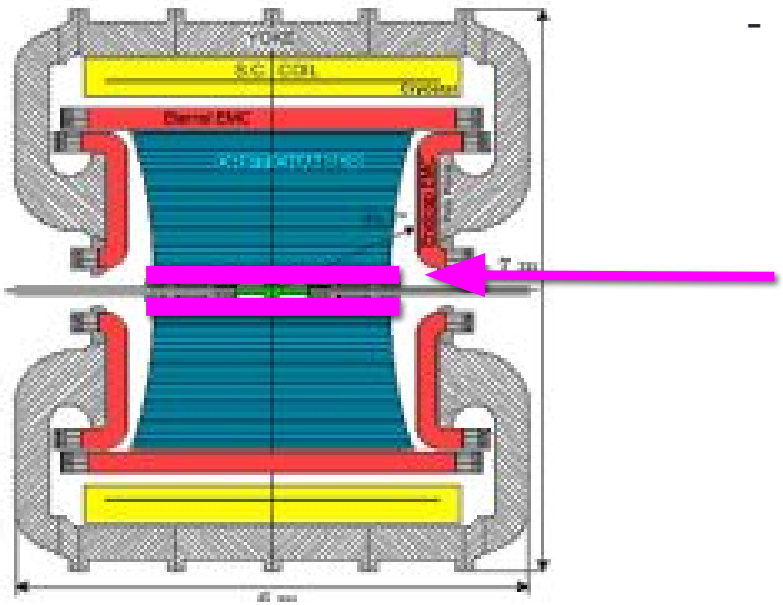


Y. Ichikawa et al., PTEP 2015, 021D01

J-PARC E27: d(π⁺, K⁺) @ 1.69 GeV/c

B =95 +18 −17 (stat.) +30 −21 (syst.) MeV
Γ = 162 +87 −45 (stat.) +66 −78 (syst.) MeV

K^- absorptions with KLOE



- 1.74 fb^{-1} analyzed from 2004/2005 data

$$K^-_{\text{stopped in-flight.}} + {}^{12}C \rightarrow \Sigma^0 p\, A$$

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

$$\Lambda \rightarrow p\pi^-$$

(detected particles)

•Absorptions in Inner Wall: $^{12}C + {}^{27}Al$

~ 1% of K^- stop (650μm + 100μm Al coating in both sides)

KLOE detector:

- Momentum resolution : $\sigma_p/p \sim 0.4$
- 4π-geometry with ~ 96% acceptance
- Calorimeter optimized for γ : $\sigma(m_{\gamma\gamma}) \sim 18$ MeV/c^2
- Vertex position resolution ~ 1 mm (in DC)

Goals of this Analysis

K- Absorption

- Pin down the contribution of the process:

$$K^- + NN \rightarrow \Sigma^0 + p$$

with respect to processes as:

$$K^- + NN \rightarrow \Sigma^0 + p \rightarrow p" + \Sigma^0" \; (FSI)$$
$$K^- + NNN \rightarrow \Sigma^0 + p + X$$
$$K^- + NNNN \rightarrow \Sigma^0 + p + X$$

Kaonic Bound States

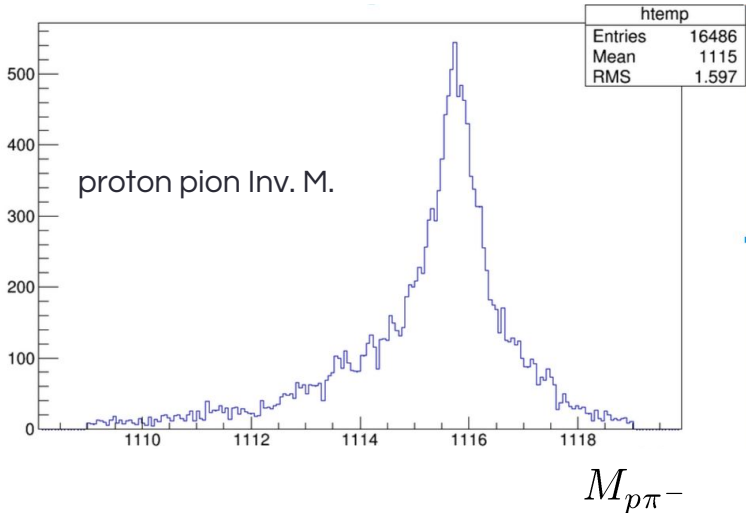
- Search for the formation of the **ppK⁻** and its decay in:

$$ppK^- \rightarrow \Sigma^0 + p$$

Yield Extraction and significance

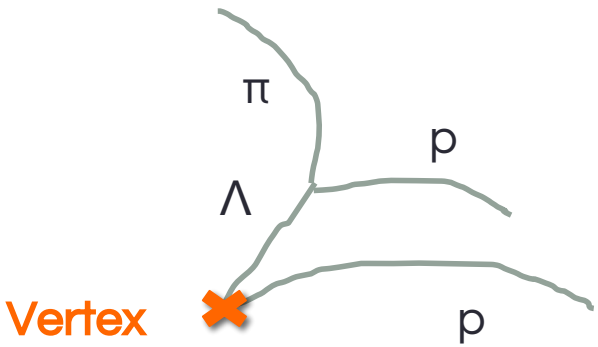
Analysis Steps

1) Lambda PID



M. Inv. Resolution σ = 0. 5 MeV

2) Primary proton ID

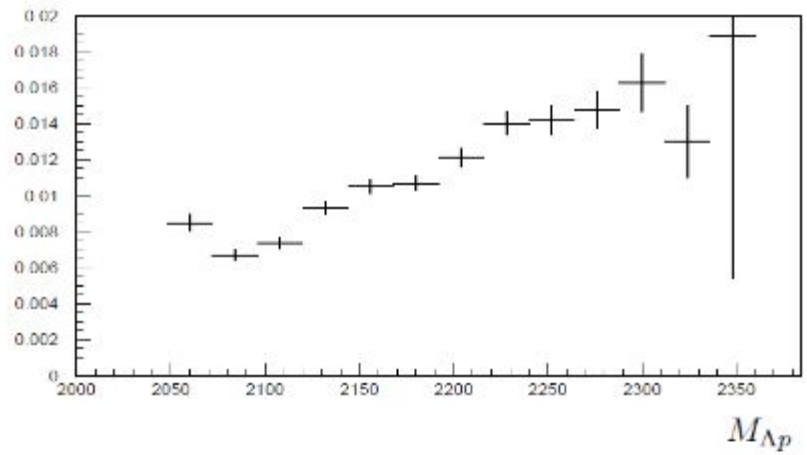


Λp common vertex
(contamination of Λd, Λt below 2%)

resolution

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}	$0.12 \pm 0.01\ cm$

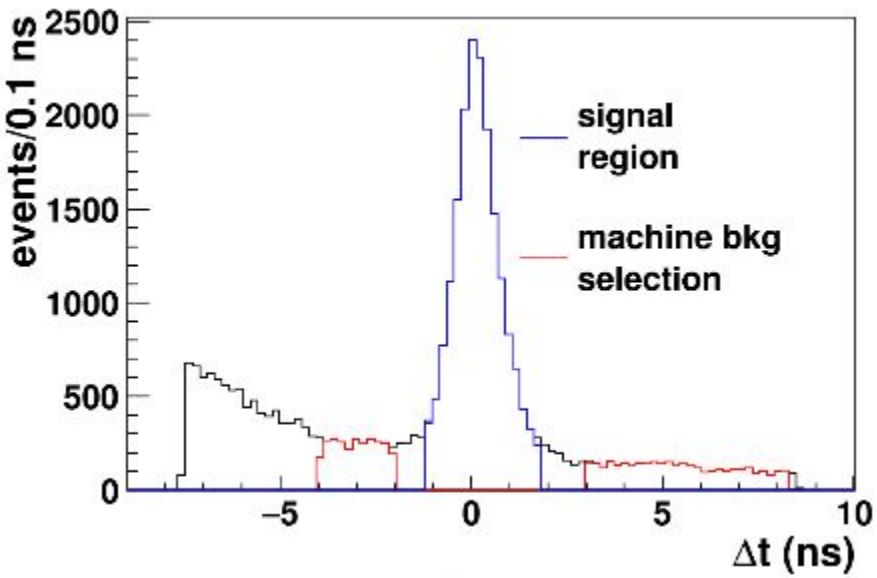
Relative accept. (a.u.)

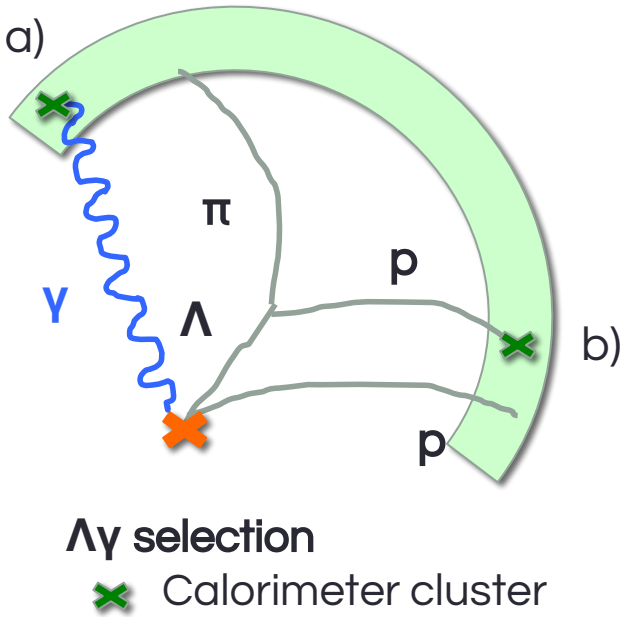


Analysis Steps

3) γ identification (from $\Sigma^0 \rightarrow \Lambda\gamma$) in the EMC

Time coincidence after the correction for the Λ path



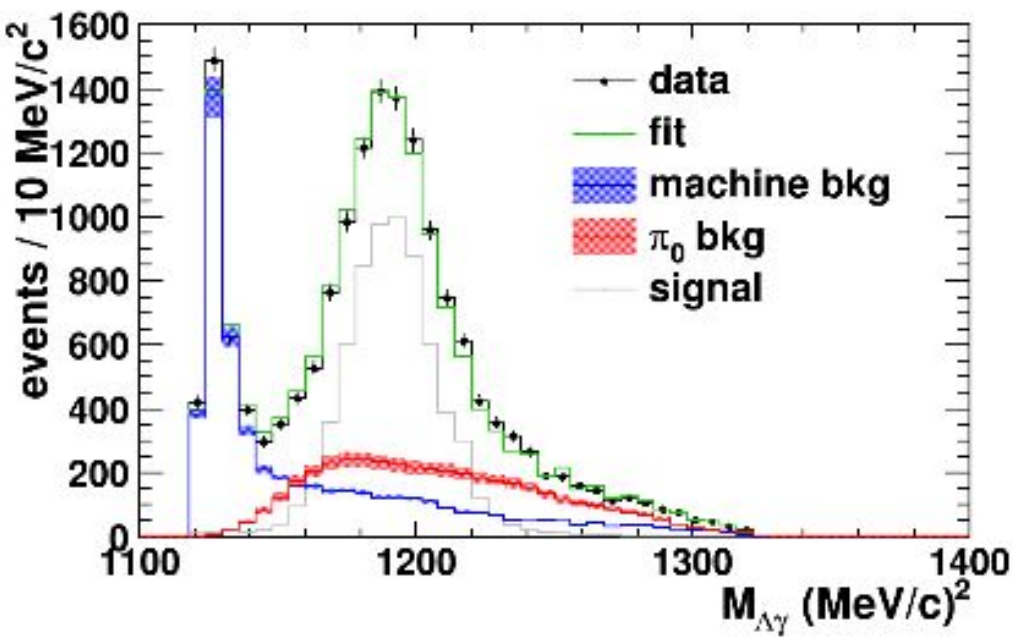


Background under the single-photon signal

Analysis Steps

4) Background evaluation and **extraction of the Σ^0 signal**

Prefit of the Λγ invariant Mass



Machine background

- Obtained from sideband analysis
- fixed via this fit and subtracted after normalization of the yield due to additional cut on the Σ^0 mass

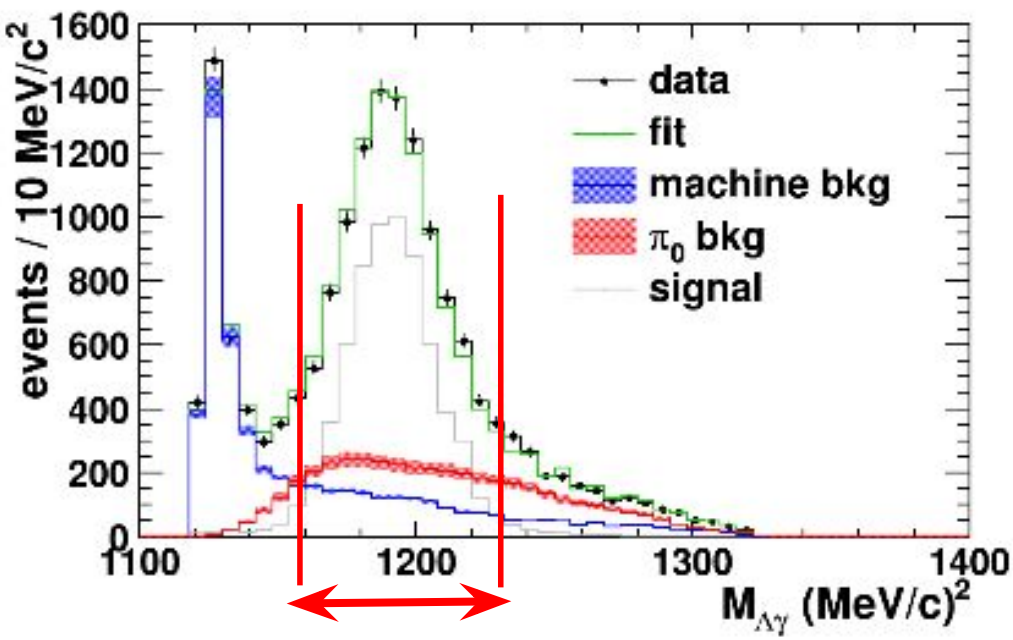
$\Lambda p \pi^0$ Background

- From $\Lambda p \pi^0$ experimental sample
- With one or two γ's detected
- Component used for the following fit but with Yield constrained with 2σ of prefit

Analysis Steps

4) Background evaluation and **extraction of the Σ^0 signal**

Prefit of the Λγ invariant Mass



Cut around Λγ mass:

-**keep** Σ^0 p signal + $\Lambda p \pi^0$ background

-**subtract** machine background

Machine background

- Obtained from sideband analysis
- fixed via this fit and subtracted after normalization of the yield due to additional cut on the Σ^0 mass

$\Lambda p \pi^0$ Background

- From $\Lambda p \pi^0$ experimental sample
- With one or two γ's detected
- Component used for the following fit but with Yield constrained with 2σ of prefit

Analysis Steps

5) Interpretation of the $\Sigma^0 p$ signal

Considered processes:

data	$K^- + A \rightarrow \Lambda\, p\, \pi^0$	π^0 background
	$K^- + A \rightarrow \Sigma^0(\pi) p(A')$	Uncorrelated background (low mom. protons)
simulations	$K^- + pp \rightarrow \Sigma^0 p$	2NA
	$K^- + ppn \rightarrow \Sigma^0 p\, n$	3NA
	$K^- + ppnn \rightarrow \Sigma^0 p\, n\, n$	4NA

Absorption simulation

$$K^- + pp \rightarrow \Sigma^0 p$$ 2NA

$$K^- + ppn \rightarrow \Sigma^0 p\, n$$ 3NA

$$K^- + ppnn \rightarrow \Sigma^0 p\, n\, n$$ 4NA

Ingredients:

- Nucleons momenta according to Fermi Distribution in ^{12}C
- Energy and momentum conservation
- Difference of mass between the initial and residual
- K- in-flight (p ~ 120 MeV/c) and at-rest 50%-50%

Absorption simulation

$$K^- + pp \rightarrow \Sigma^0 p$$ 2NA

$$K^- + ppn \rightarrow \Sigma^0 p\, n$$ 3NA

$$K^- + ppnn \rightarrow \Sigma^0 p\, n\, n$$ 4NA

2NA → Residual nucleus unfragmented/fragmented

2NA → **FSI** of Σ^0 and p with the residual nucleus

Ingredients:

- Nucleons momenta according to Fermi Distribution in ^{12}C
- Energy and momentum conservation
- Difference of mass between the initial and residual
- K- in-flight (p ~ 120 MeV/c) and at-rest 50%-50%

- Final state interaction of Σ^0 or p with other nucleons (1 or 2 collisions for Σ^0 and p with 50% probability)
- For 2NA different fragmentation scenarios for the rest-nucleus A' have been considered (modification only in Σ^0p invariant mass)

Analysis Steps

6) **Fit of the experimental data with the cocktail and extraction of the absorption yields.**

Simultaneous fit of signal components and pi0 bkg to:

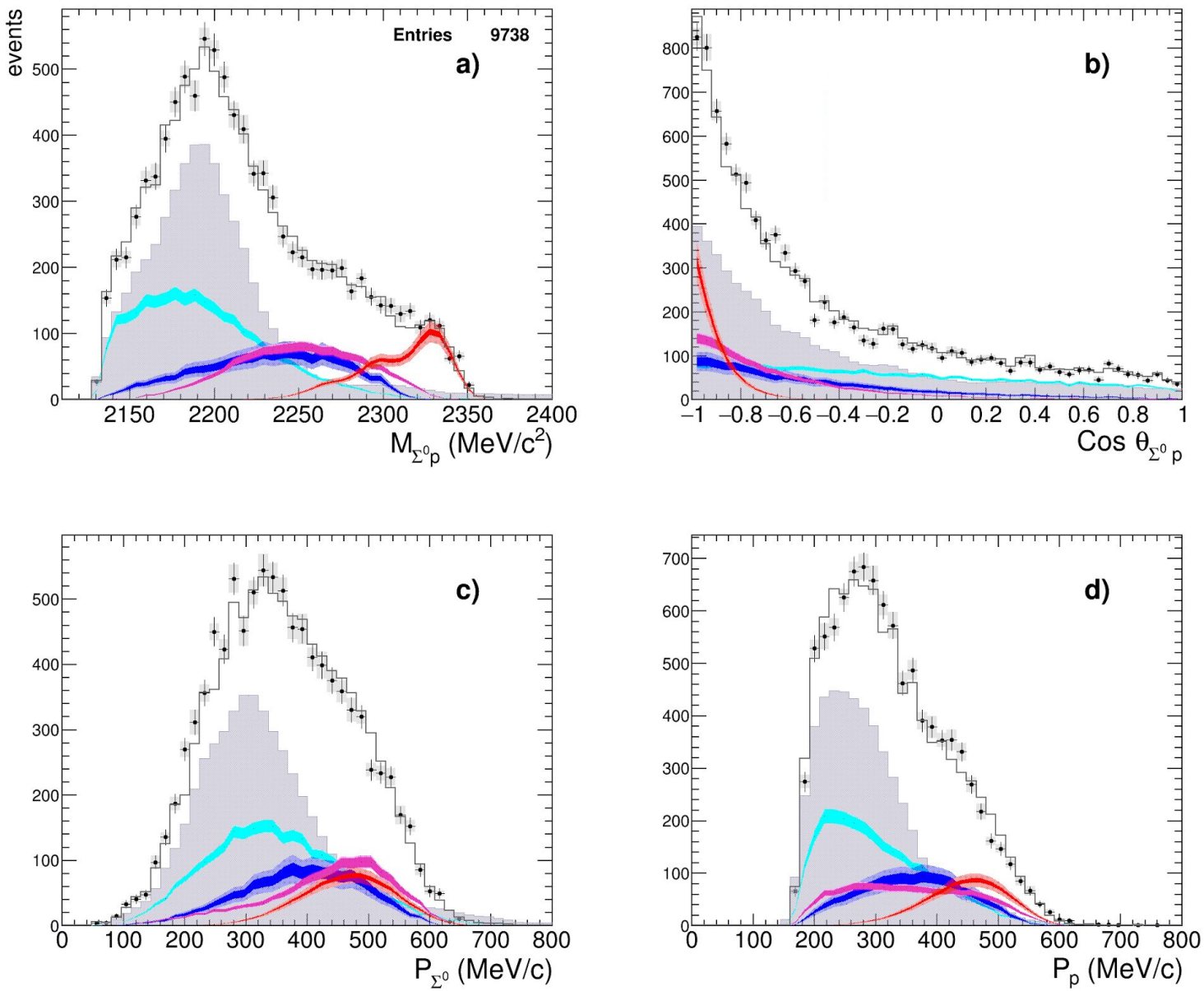
- Inv. M. $\Sigma^0 p$
- $\cos\theta(\Sigma^0 p)$
- $p_{\Sigma 0}$
- p_{proton}

Final fit

- data
- π^0 background
- 4NA+Uncorr.
- 3NA
- 2NA FSI
- 2NA QF
- Total fit

$$\chi^2 = 0.85$$

2NA-QF clearly separated from other processes



From the contributions to the fit, the yields are extracted for K⁻ stop

Absorption results

	yield / $K^-_{stop} \cdot 10^{-2}$	$\sigma_{stat} \cdot 10^{-2}$	$\sigma_{syst} \cdot 10^{-2}$
2NA-QF	0.127	$\pm$ 0.019	$^{+0.004}_{-0.008}$
2NA-FSI	0.272	$\pm$ 0.028	$^{+0.022}_{-0.023}$
Tot 2NA	0.376	$\pm$ 0.033	$^{+0.023}_{-0.032}$
3NA	0.274	$\pm$ 0.069	$^{+0.044}_{-0.021}$
Tot 3body	0.546	$\pm$ 0.074	$^{+0.048}_{-0.033}$
4NA + bkg.	0.773	$\pm$ 0.053	$^{+0.025}_{-0.076}$

2NA-QF: hyperon-nucleon production involving <u>only 2 nucleons</u>

- comprehends all possible fragmented states of the residual nucleus

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...is there room for the signal of a **ppK^- bound state**?

Repeat the fit with the <u>inclusion of a simulated bound state (Breit-Wigner)</u> in a grid with different values for the **Binding Energy** and **Width**:

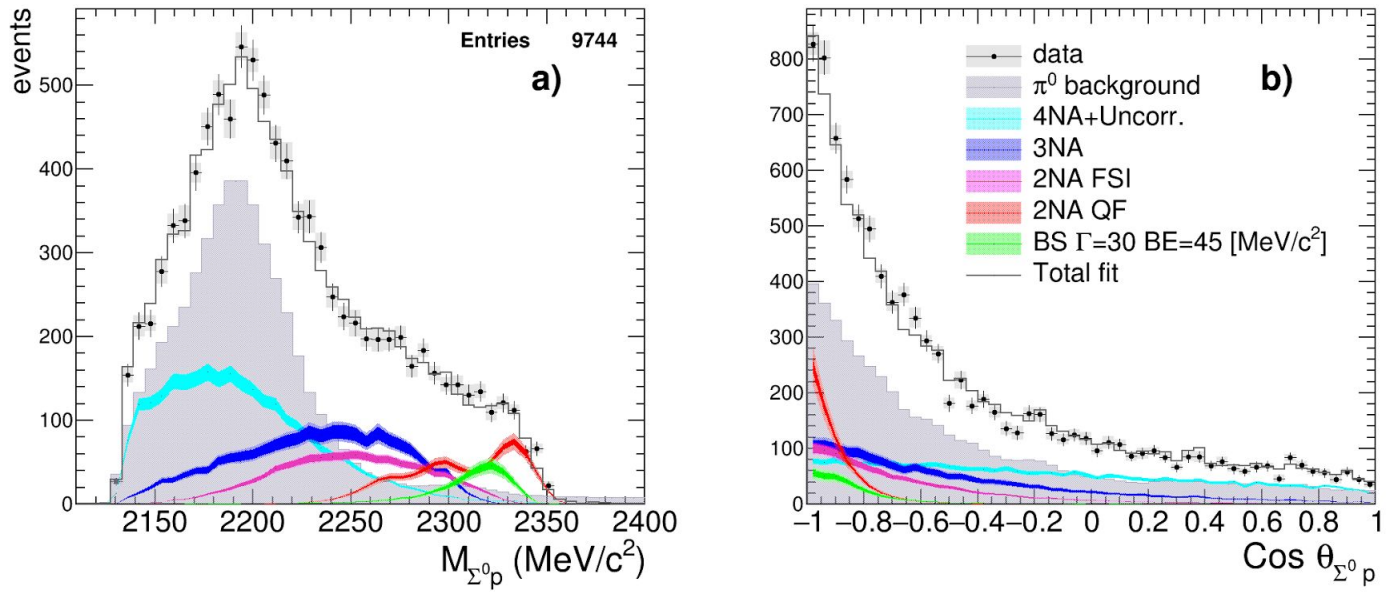
B.E. : 15-75 MeV/c^2 (15 MeV/c^2 steps)

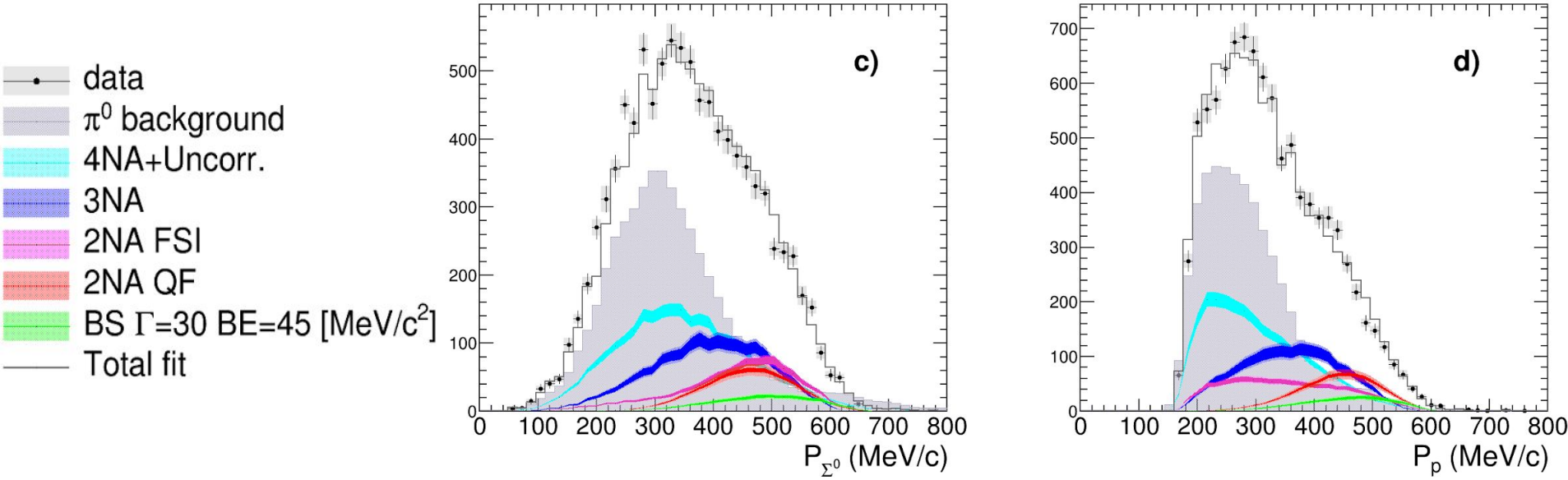
Width: 30-70 MeV/c^2 (20 MeV/c^2 steps)

Fit with ppK⁻

Best solution:
(best χ^2 and higher yield)
- B.E. = 45 MeV/c²
- Width = 30 MeV/c²

$$\chi^2 = 0.807$$

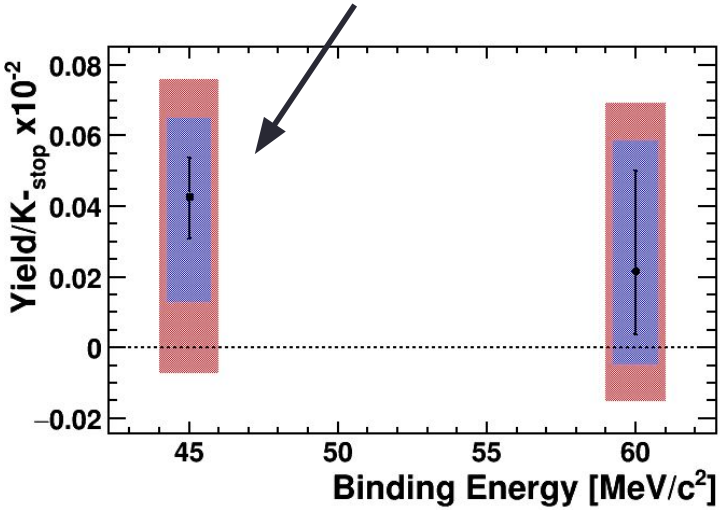




Evaluation of the significance of the ppK^- signal

For the best solution B.E. = 45 MeV/c^2, Width = 30 MeV/c^2

$$Yield/K^-_{stop} = (0.044 \pm 0.009 stat^{+0.004}_{-0.005} syst) \cdot 10^{-2}$$



(Width= 30 MeV/c^2)

Evaluation of the significance of the ppK⁻ signal

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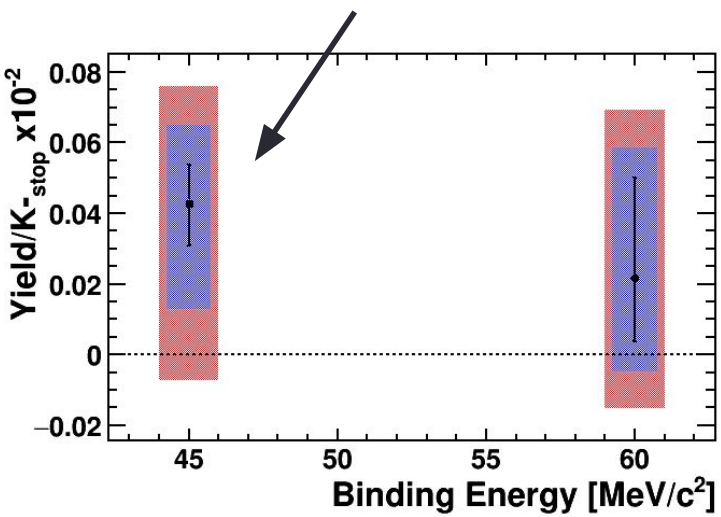
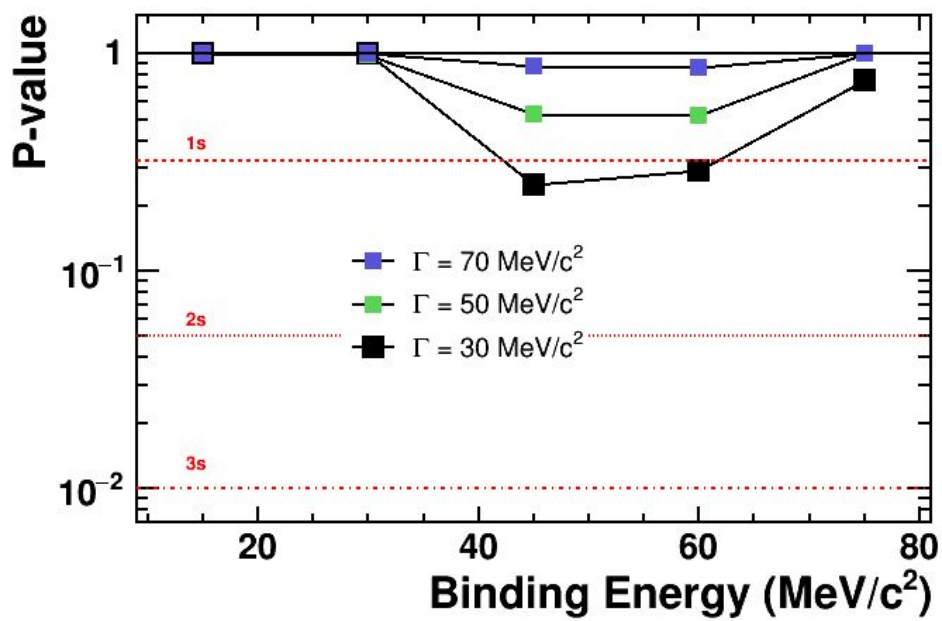


(Width= 30 MeV/c^2)

F-test evaluates extra parameter to the fit (corresponding to the bound state):

- Significance of **"signal" hypothesis** w.r.t "Null-Hypothesis" (no bound state)



Conclusions

The $\Sigma^0 p$ analysis has been completed for events in the DC wall $^{12}C + {}^{27}Al$

- Obtention of the **2NA-QF** yield:

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

- Bound state ppK^- yield for B.E. 45 MeV/c^2 and Width 30 MeV/c^2

$$Yield/K^-_{stop} = (0.044 \pm 0.009 stat^{+0.004}_{-0.005} syst) \cdot 10^{-2}$$

- the significance of the ppK^- signal is of **1σ** according to F-test

- Published in Physics Letters B 758 (2016) 134–139

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ThanK⁻ you for your attention!