AMADEUS: K^- four nucleon absorption process in the Λ-triton channel

“Strange Matter Workshop Strangeness studies in Italy and Japan”

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

Investigation of **in-medium modification of the $\bar{K}$N interaction** fundamental for the low-energy QCD in the non perturbative regime.

Chiral perturbation theory (ChPT): effective field theory where mesons and baryons represent the effective degrees of freedom instead of the fundamental quark and gluon fields.

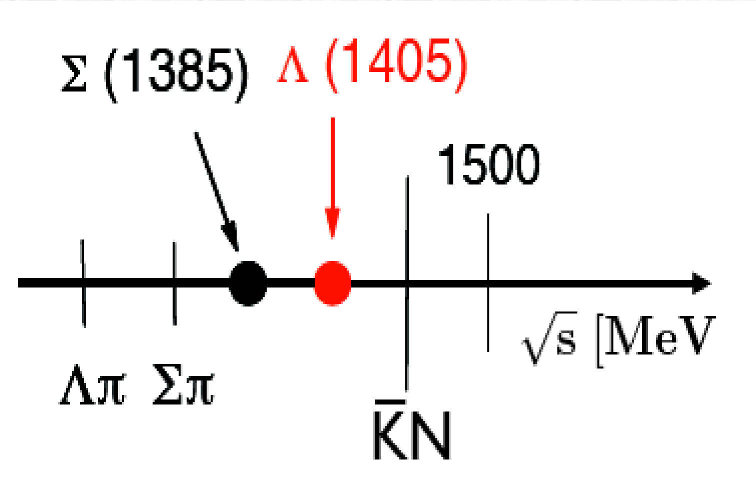
$$\mathcal{L}_{eff} = \mathcal{L}_{mesons}(\Phi) + \mathcal{L}_B(\Phi, \Psi_B)$$

- chiral symmetry is **spontaneously broken** → existence of massless and spinless Nambu-Goldstone bosons which are identified with the pions (SU(2)). Explicitly broken by quark masses.
- **very successful** in describing the πN, ππ and NN interactions in the low-energy regime.

Problematic extension of the theory to the s sector, not directly applicable to the $\bar{K}$N channel.

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

ChPT not applicable to the KN channel due to the emerging of the Λ(1405) and the Σ(1385) resonances just below the KN mass threshold (~1432 MeV)



- Λ(1405) I=0 $J^P = ½^-$
  M = $(1405.1^{+1.3}_{-1.0})$ MeV Γ = (50.5 ± 2.0) MeV
  decay modes: Σπ (I=0) 100%

- Σ(1385) I=1 $JP = 3/2^+$
  decay modes: Λ π (I=1) (87.0 ± 1.5) %
  Σ π (I=1) (11.7 ± 1.5) %

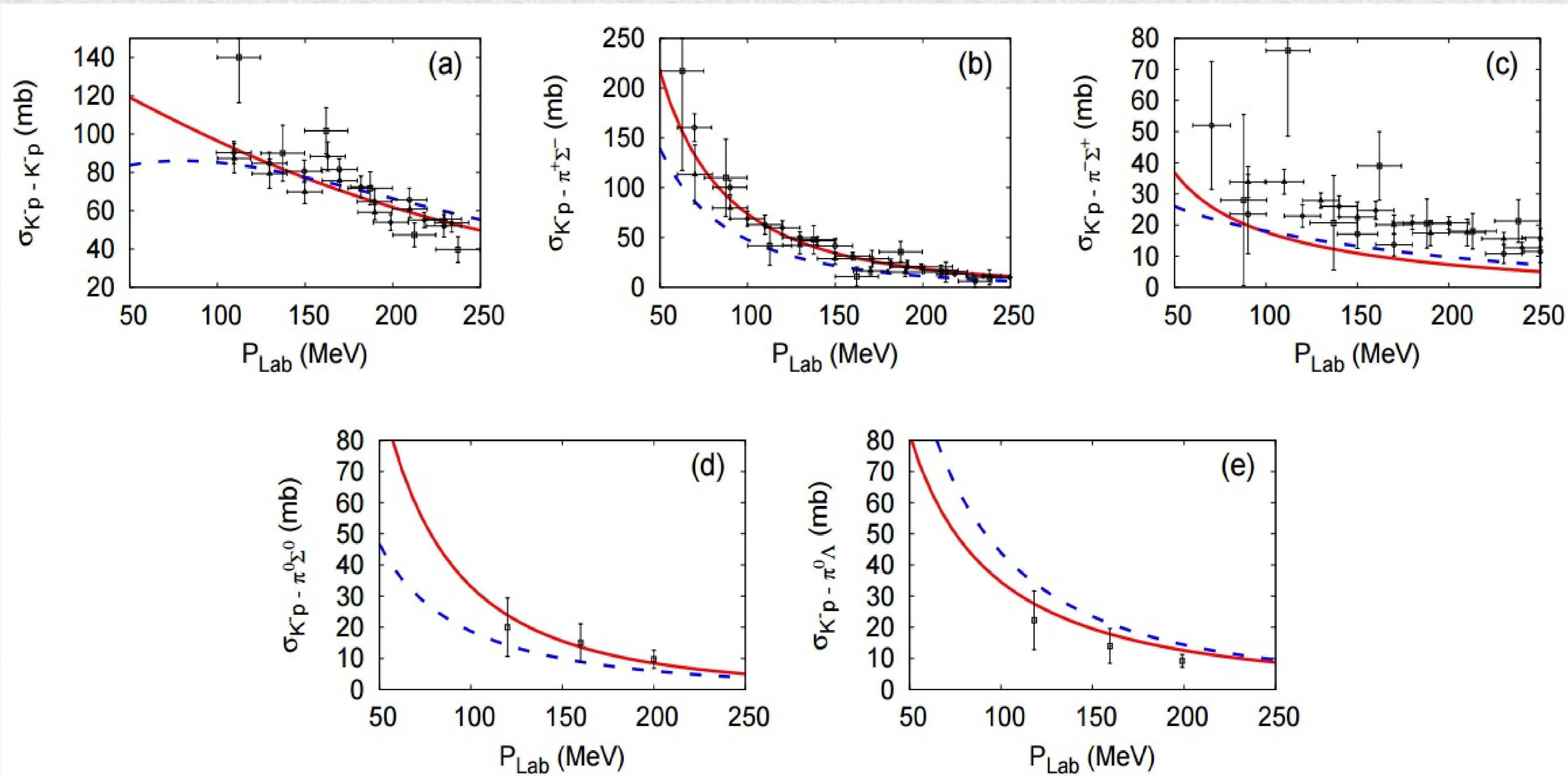
Possible solutions:

- ➢ **Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics**
- ➢ **Phenomenological K̄N and NN potentials**

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

The parameters of the models are constrained by the existing scattering data → above the threshold

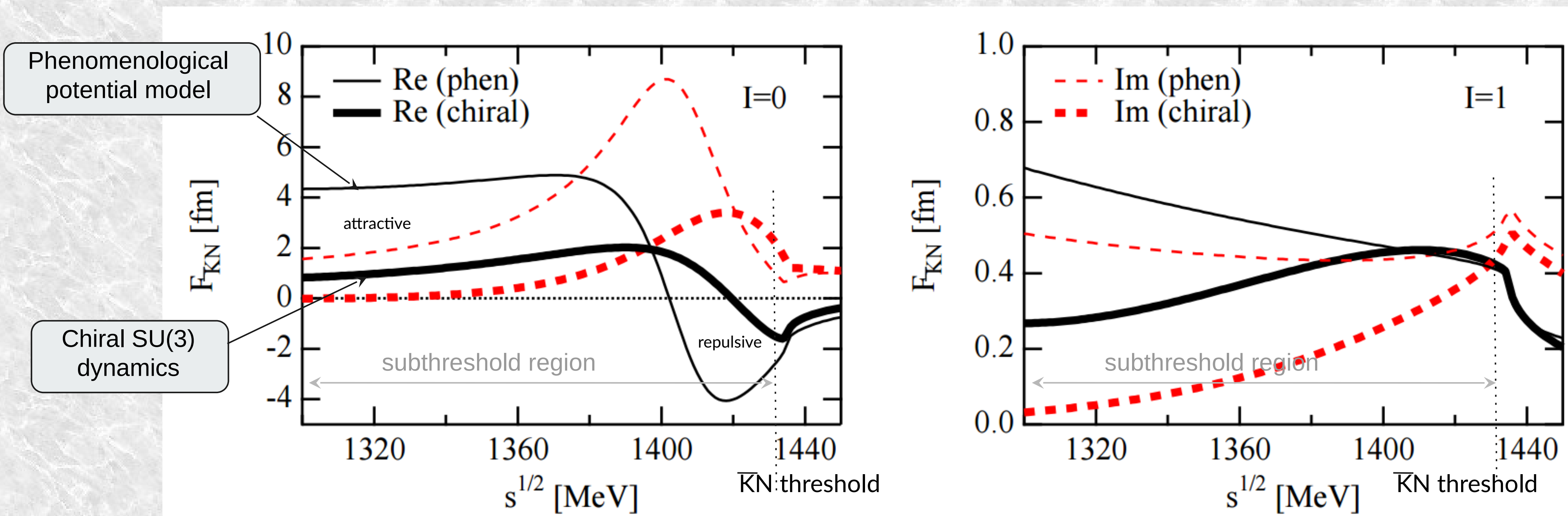
Phen. [Y. Ikeda and T. Sato, Phys. Rev. C76, 035203 (2007)]
Chiral [S. Ohnishi, Y. Ikeda, T. Hyodo, W. Weise, Phys.Rev. C93 (2016) no.2, 025207]



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

...but... large differences in the subthreshold extrapolations!
Significantly weaker attraction in chiral SU(3) models than in phenomenological potential models.

	Re	Im		
	thin solid line	thin dashed red line	**Phen.**	[Y. Akaishi, T. Yamazaki, Phys. Rev. C65, 044005 (2002)]
	thick solid line	thick dashed red line	**Chiral**	[Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B706, 63 (2011)]



The Λ(1405) case

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

two poles: about 1420 ; about = 1380 MeV

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

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

- Akaishi-Esmaili-Yamazaki phenomenological potential

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

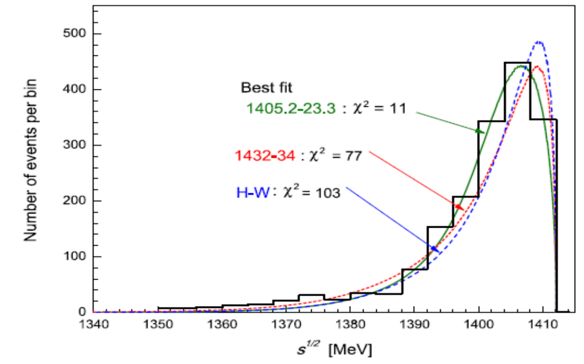
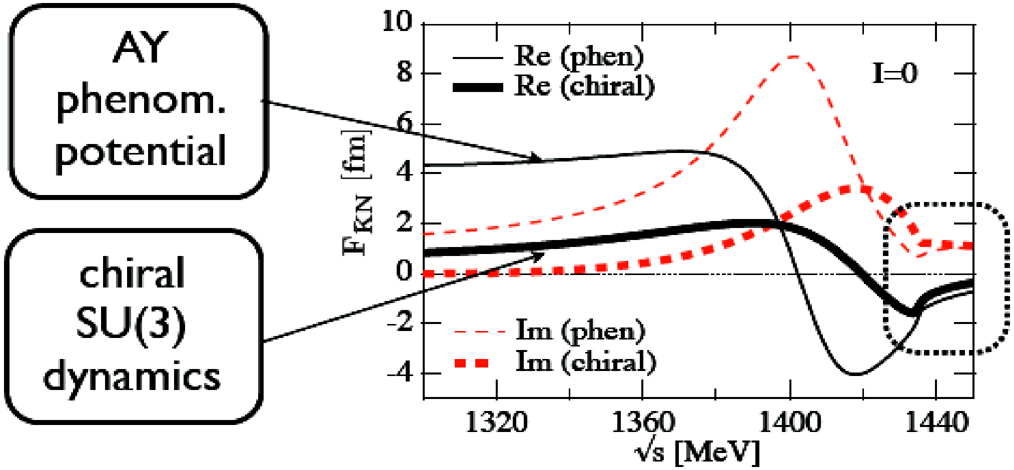
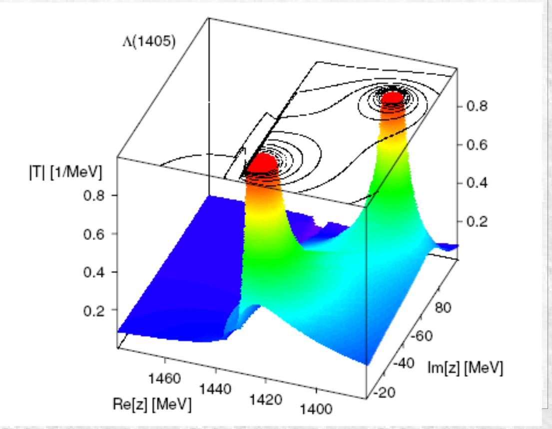


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

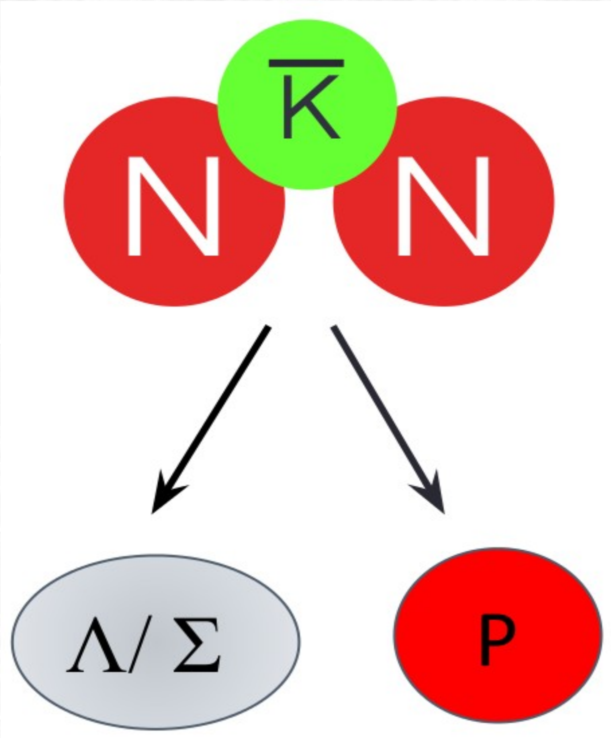


large differences in **subthreshold** extrapolations



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

How deep can an antikaon be bound in a nucleus?



Possible Bound States:

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

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

predicted if strong KN interaction in the I=0 channel.

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

K^-pp bound state

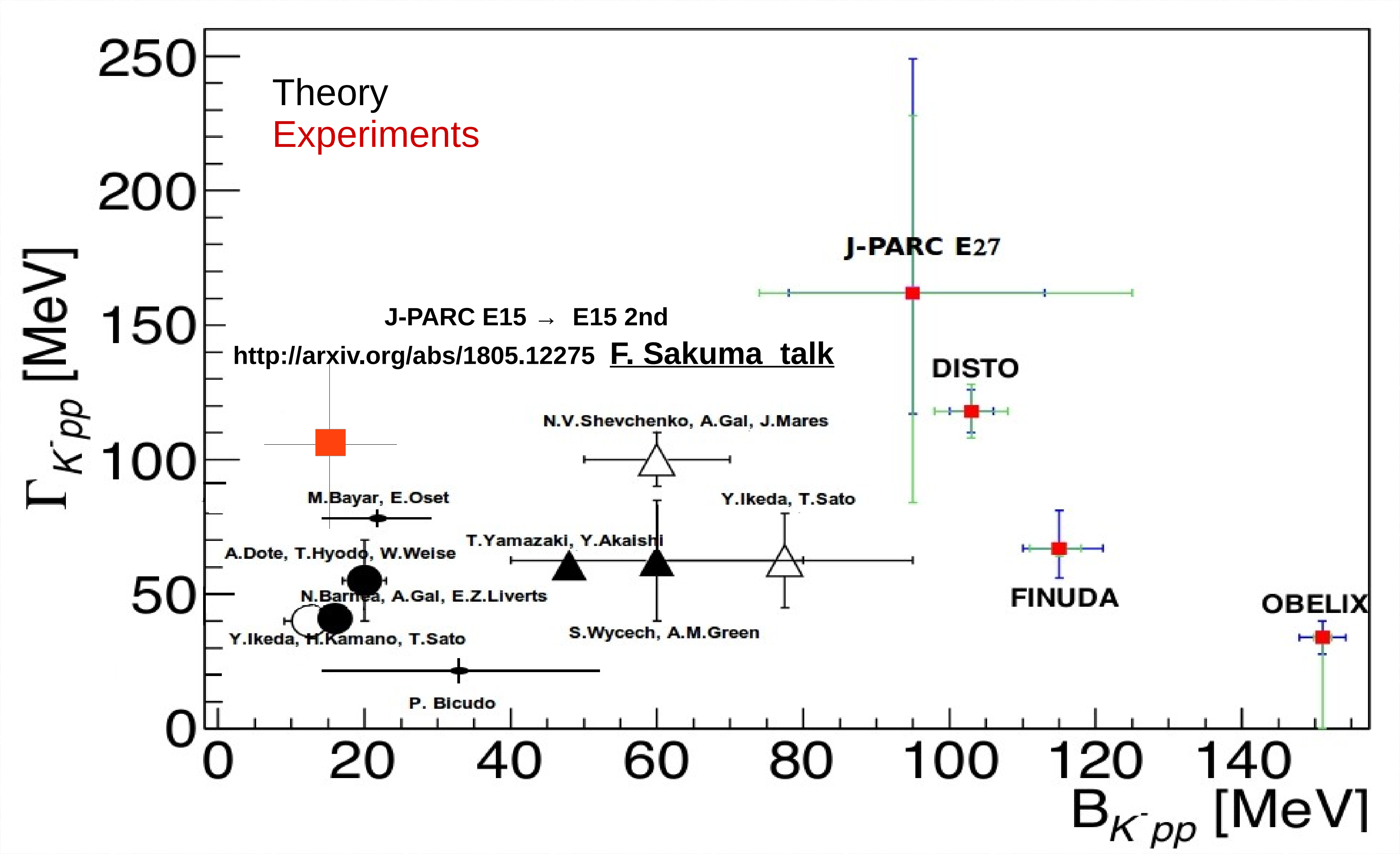
....at the end of 2015

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

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

How deep can an antikaon be bound in a nucleus?

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



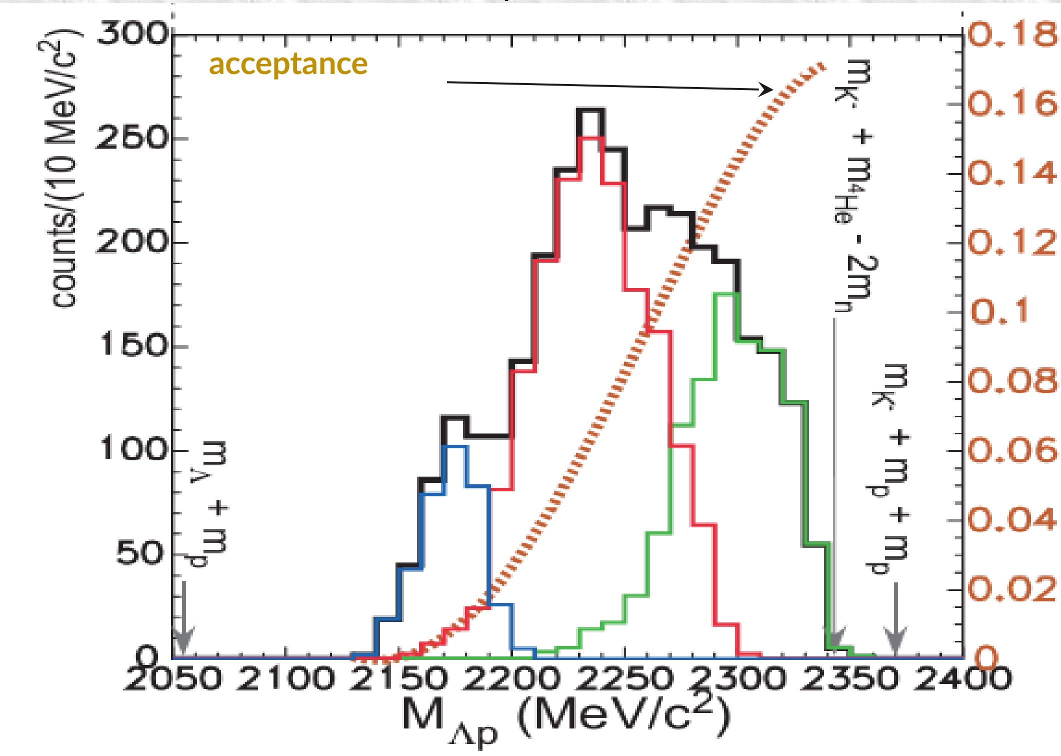
[from the talk of T. Nagae at HYP2015, Sep. 10, 2015]

Bound state search in K- induced reactions

E549 at KEK: $K^-_{stop} + {}^4He \rightarrow \Lambda + p + X'$

detected particles

[T. Suzuki et al., Mod. Phys. Lett. A23 (2008) 2520-2523.]



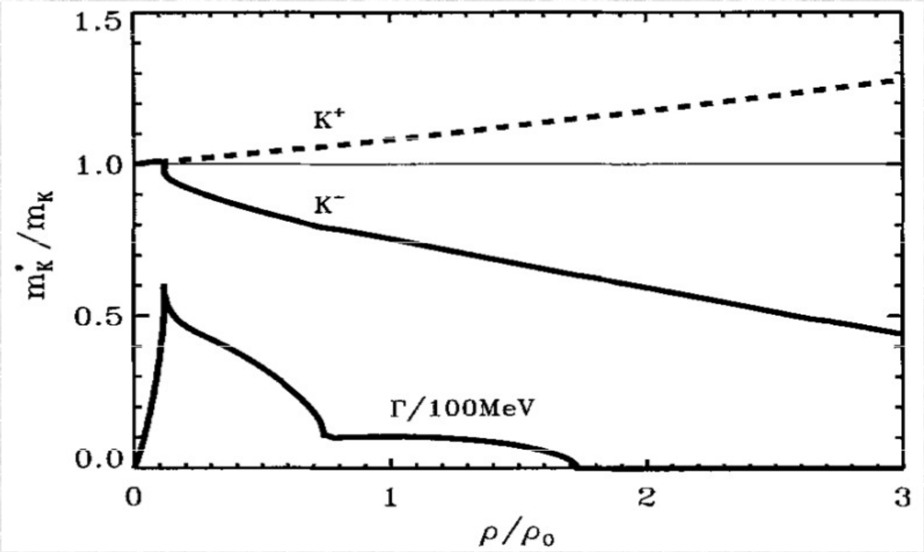
- **1NA**: K⁻ single nucleon absorption
- **2NA**: K⁻ two nucleon absorption
- **2NA + conversion**, **multi-nucleon**, or **Bound State**?

—>

Measurement of yields and shapes of the K- multi-nucleon yields is mandatory to solve the puzzle!

They are the counterpart of the non-resonant single nucleon capture

and K- multi-nucleon cross section?



In medium $\bar{K}$ properties investigated in heavy-ion & proton nuclei collisions, K^- mass modification extrapolated from the K^- production yield

—>

Transport models and collision calculations need the measurement of the K- multi-nucleon cross sections at low energy

...

still missing!

AMADEUS scientific case

- Nature of the $\Lambda(1405)$ & K^-N amplitude below threshold →
  Yπ CORRELATION STUDIES

- **K^- multi-nucleons** absorptions cross sections
- **kaonic nuclear clusters**

→ **YN CORRELATION STUDIES** (i.e. Λp, $\Sigma^0 p$, and Λt final states)

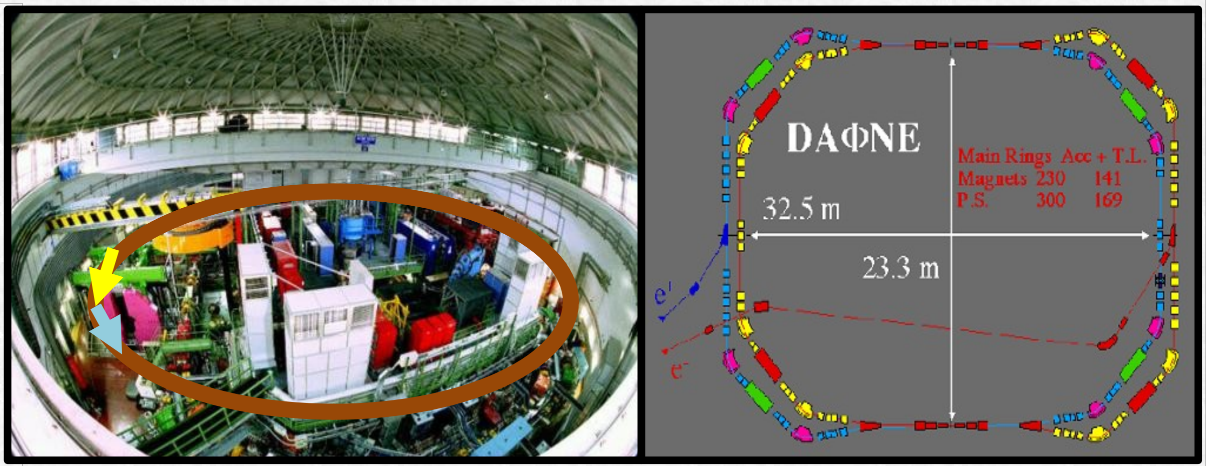
- Low-energy charged kaon **cross sections** for low momenta (100 MeV/c)

- **YN scattering** → **extremely poor experimental information from scattering data**
  (strong impact on the EoS of Neutron Stars
  Related to NS merging radiation + GW emission)

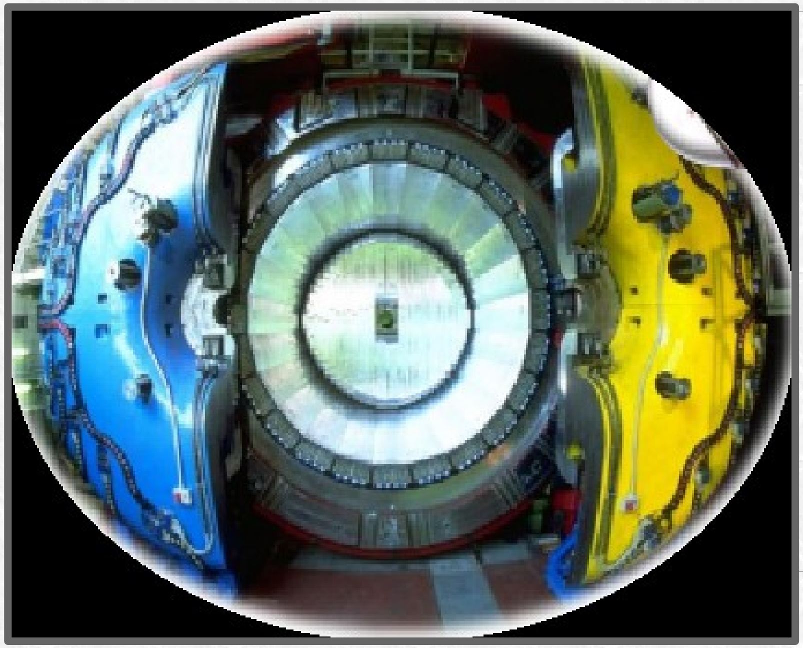
AMADEUS & DAΦNE

DAΦNE

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



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



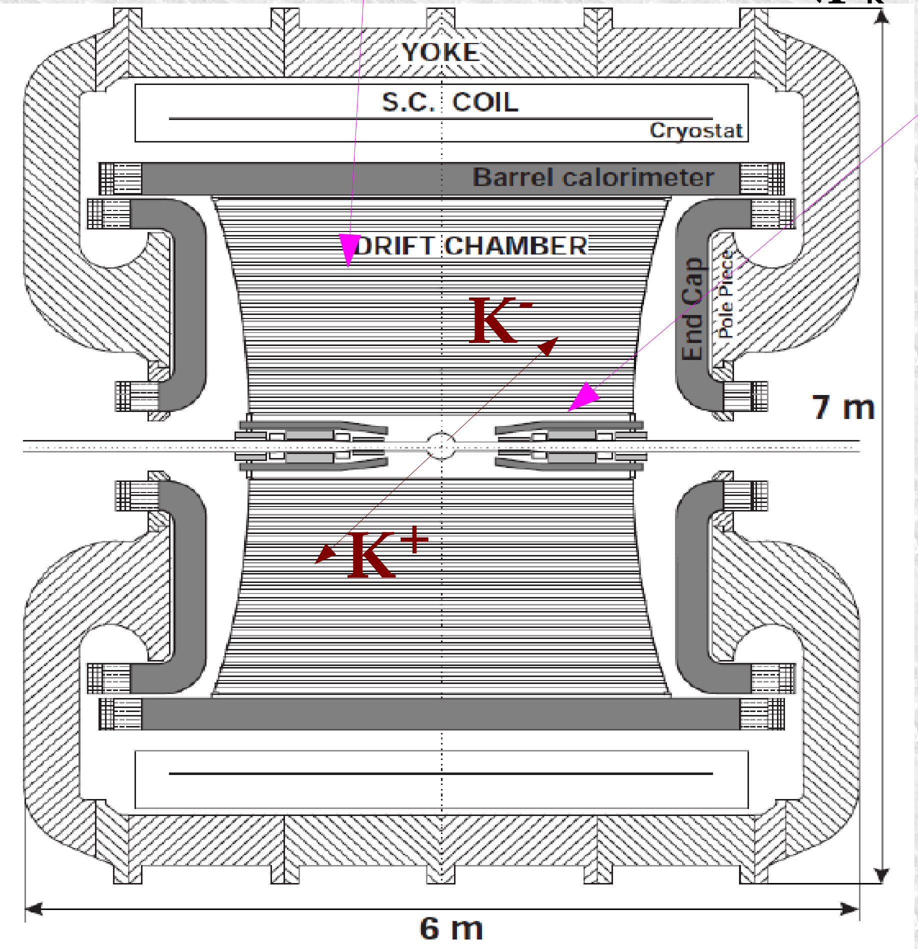
KLOE

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

K^- absorption on light nuclei

from the materials of the KLOE detector
DC gas (90% He, 10% C_4H_{10}) & DC wall (C + H)

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



Advantage:
excellent resolution ..
$\sigma_{p\Lambda}$ = 0.49±0.01 MeV/c in DC gas
$\sigma_{m\gamma\gamma}$ = 18.3±0.6 MeV/c^2

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

K^- - 4NA cross section & BR

Λt available data

Available data:

- in Helium :

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

$$\mathbf{BR}(K^{-4}He \rightarrow \Lambda t) = \mathbf{(3 \pm 2) \times 10^{-4} /K_{stop}}$$

global, no 4NA

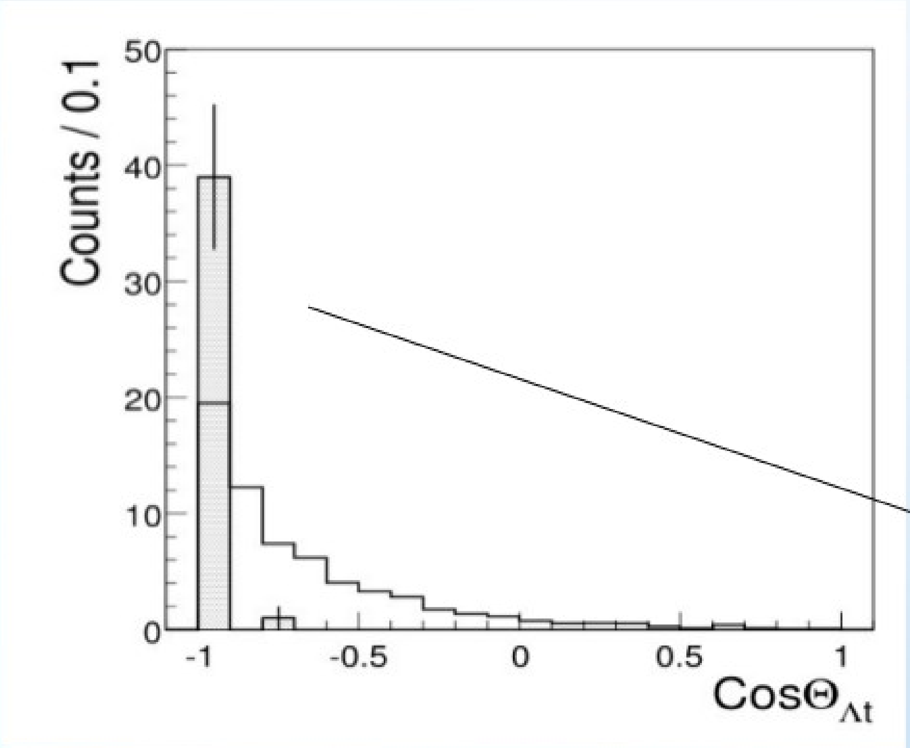
- Solid targets

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

Λt available data

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

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



Filled histogram= data

Open histogram = Phase space simulation

$K^- A \rightarrow \Lambda\, t\, A'$

Unclear back to back topology

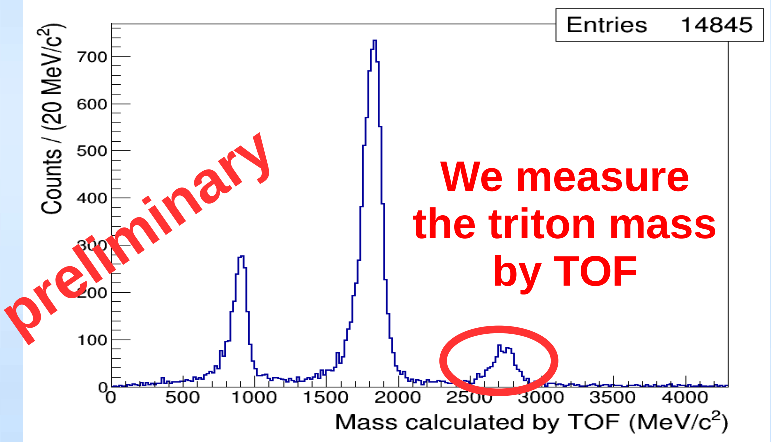
Λt emission yield → $10^{-3} - 10^{-4} / K^-_{stop}$

global, no 4NA

Experimental data only back-to-back

$K^- \, {}^4He \rightarrow \Lambda t$ cross section, DC gas sample contributing processes:

single nucleon absorption (1NA)

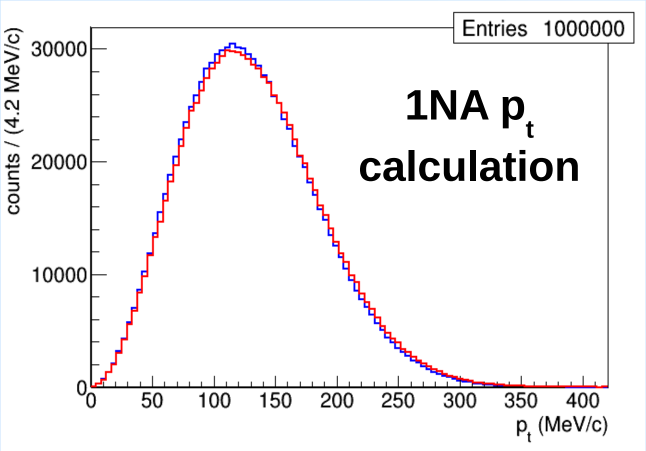


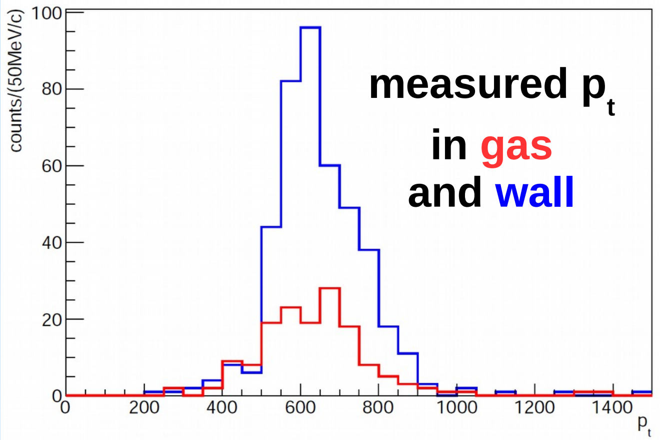
$K^- \, {}^4He \rightarrow \Lambda \, \pi^0 \, t_{res}$

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

Spectator tritons have low momentum:

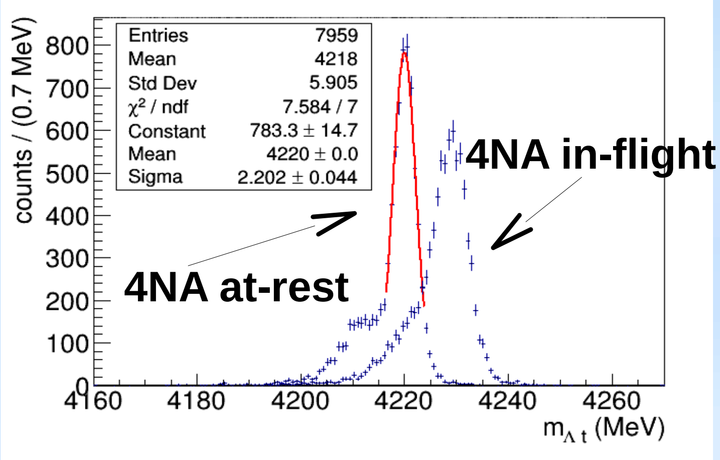
p_t ~ Fermi momentum





4NA processes – K^- absorbed on FREE α:

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



$K^- \ {}^4He \rightarrow \Lambda t$ cross section, DC gas sample contributing processes:

Main background: K^- absorption on ^{12}C (isobutane contamination)

4NA: $K^- \ {}^{12}C \rightarrow K^- (\alpha)^{bound} \ {}^8Be \rightarrow \Lambda/\Sigma^0 \ t \ {}^8Be$

7 MeV/c^2 lower invariant mass threshold respect to:

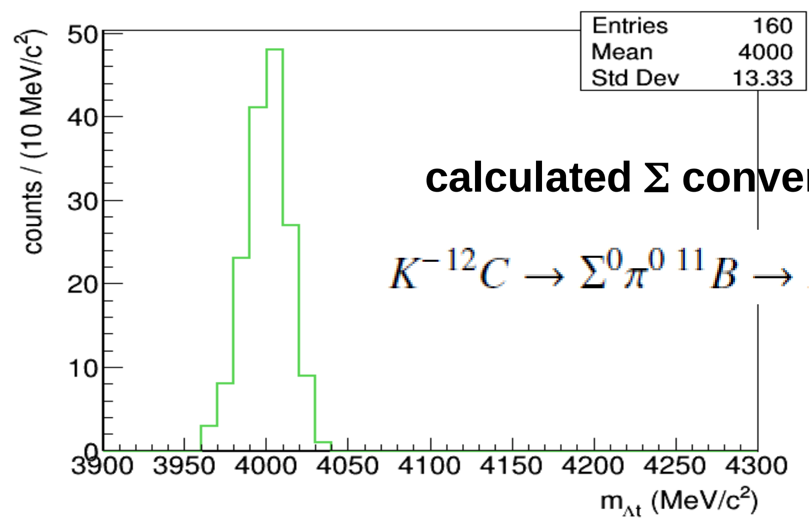
4NA: $K^- \ {}^4He \rightarrow K^- (\alpha)^{free} \rightarrow \Lambda/\Sigma^0 \ t$

+

all possible elastic/inelastic FSI processes with primary Λ/Σ formation

↓

uncorrelated Λt low invariant mass:

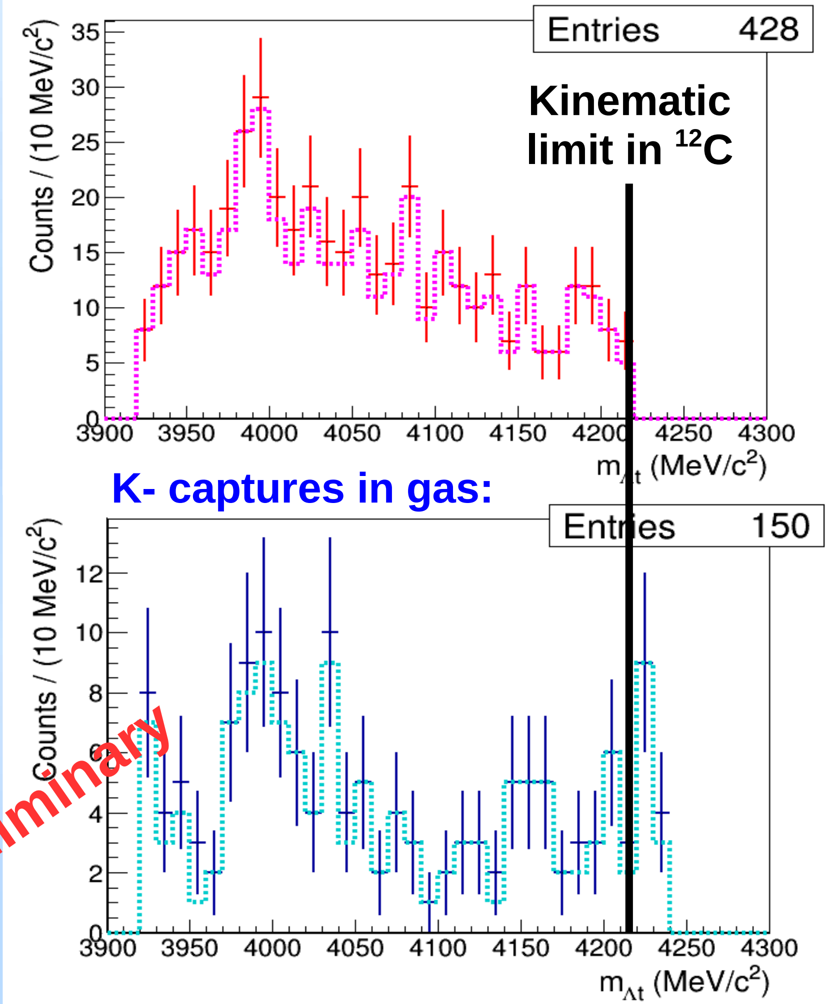


calculated Σ conversion:

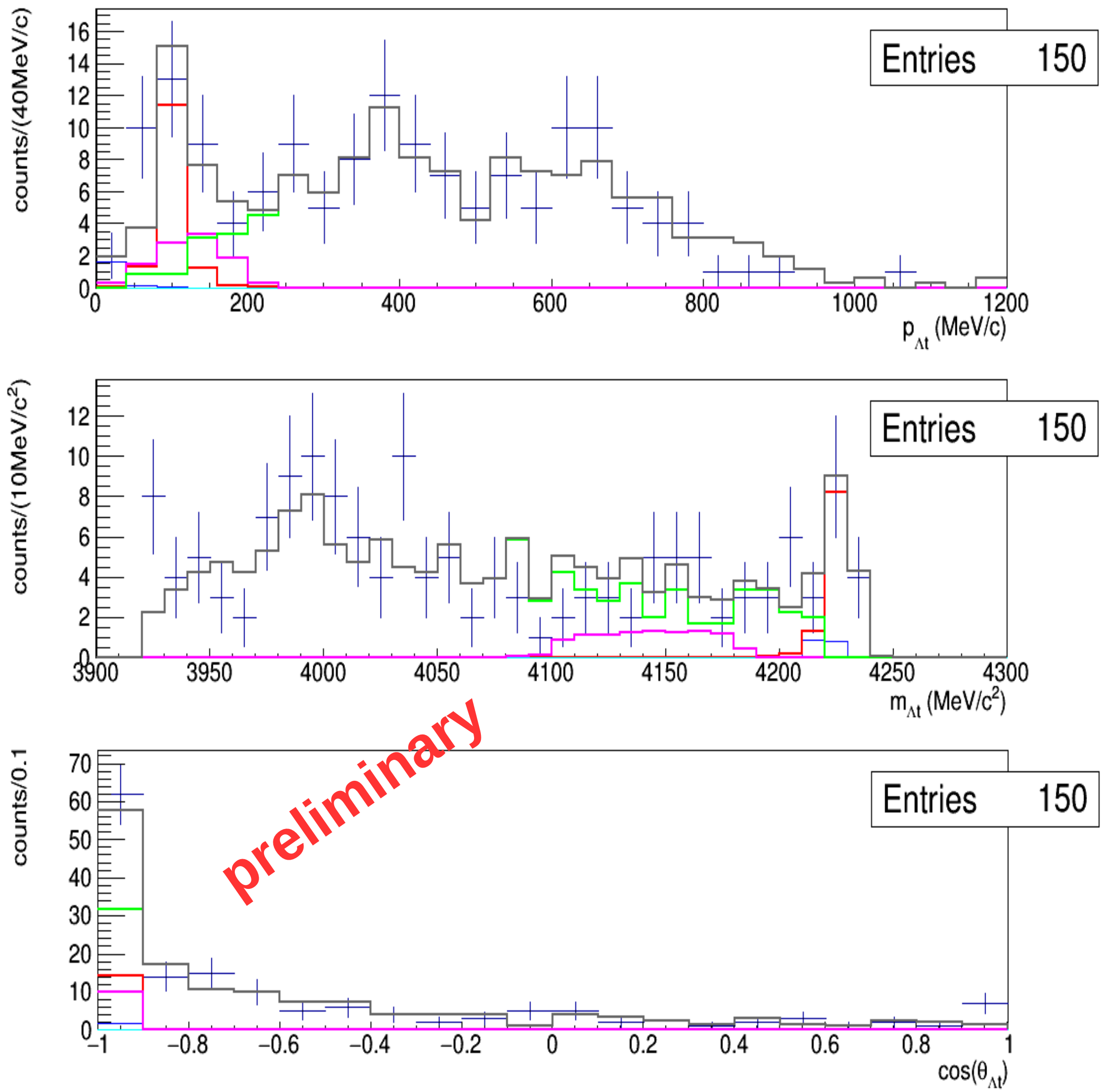
$$K^{-\,12}C \rightarrow \Sigma^0 \pi^{0\;11}B \rightarrow \Lambda t\, \pi^{0\;8}Be$$

Measured $K^- \ {}^{12}C$ sample from K- captures in wall:

K- captures in gas:



K- ^{4}He → Λt 4NA fit



data

--- carbon data from DC wall

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

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

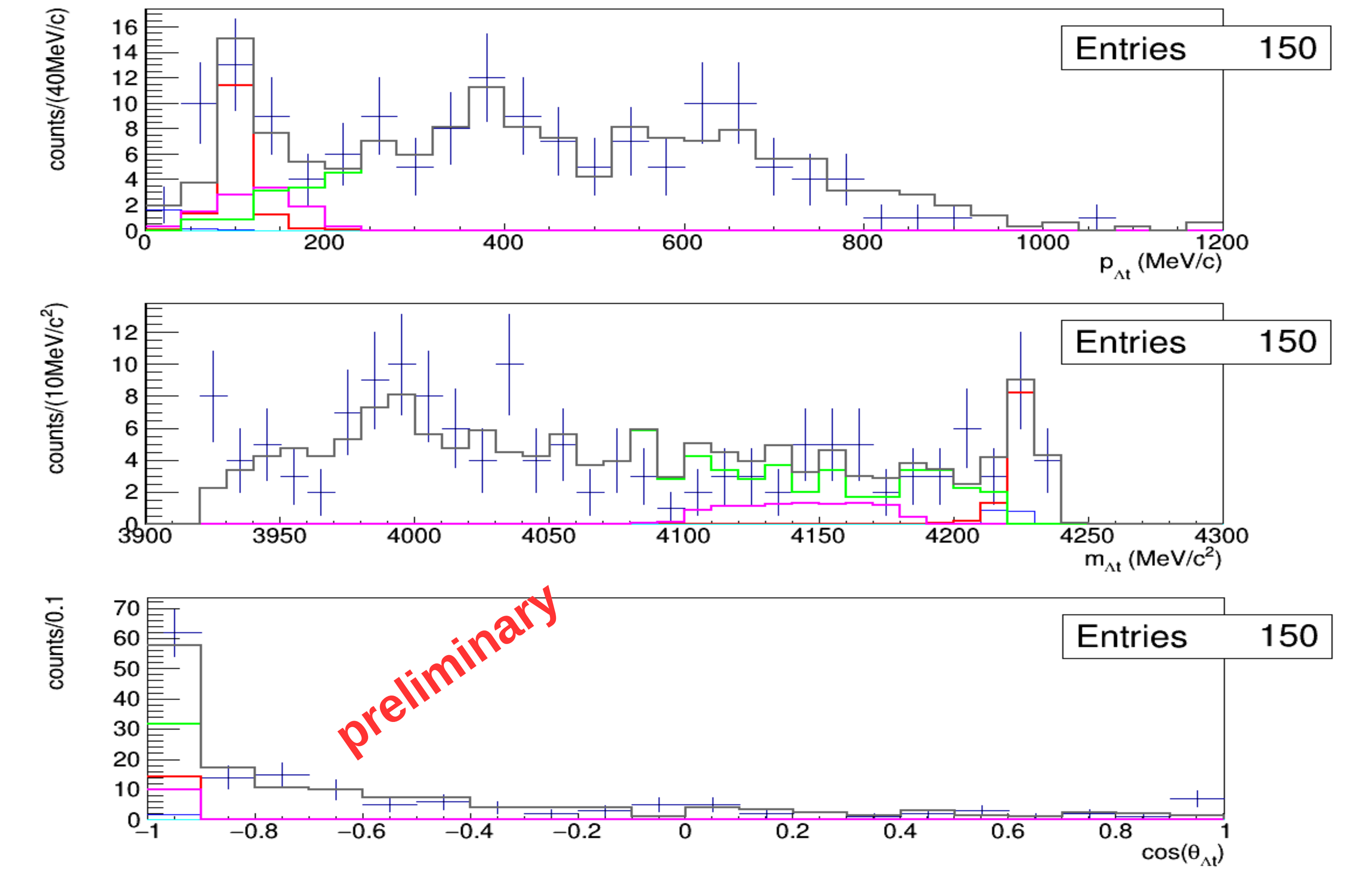
--- 4NA $K^- {}^4He \rightarrow \Sigma^0 t$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC

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

K- ^{4}He → Λt 4NA fit

BR(K^{-4}He(4NA) → Λt) **< 2.0 × 10^{-4} /K$_{stop}$ (95% c. l.)**

σ(100 **± 19** MeV/c) (K^{-4}He(4NA) → Λt) **=**
= (0.81 ± 0.21 (stat) $^{+0.03}_{-0.04}$ (syst)) mb



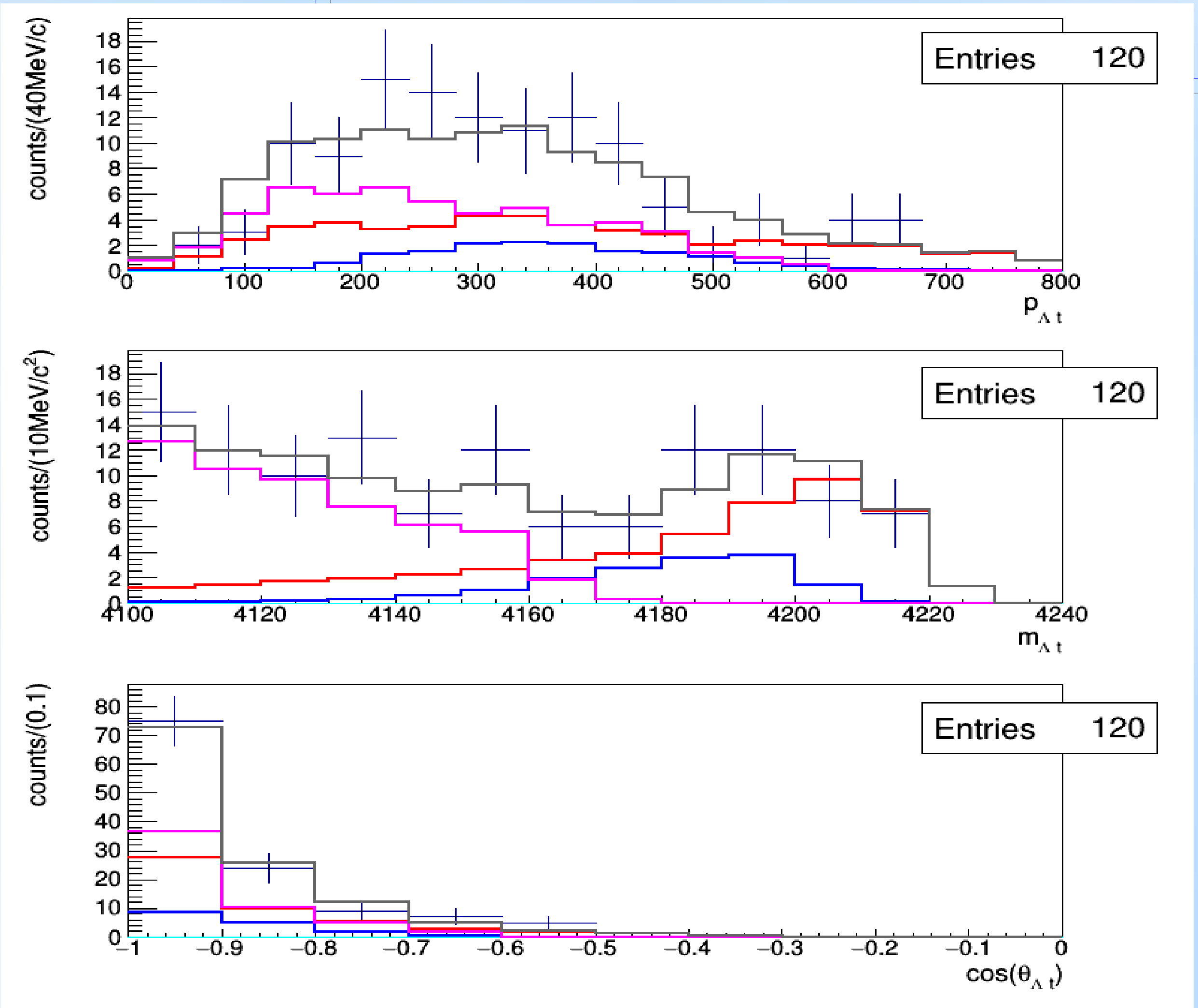
K- $^{12}C \rightarrow \Lambda/\Sigma^0 t\, ^8Be$ 4NA without FSI

preliminary

BR($K^{-4}He(4NA) \rightarrow \Lambda t$) = **$1.5 \pm 0.5 \times 10^{-4}$ (stat) $^{+0.7 \times 10\text{-}4}_{-0.3 \times 10\text{-}4}$ (syst) /K_{stop}**

σ($K^{12}C$ (4NA) $\rightarrow \Lambda t\, ^8Be$) = **$0.58 \pm 0.11$ (stat) $^{+0.03}_{-0.10}$ (syst) mb**

σ($K^{12}C$ (4NA) $\rightarrow \Sigma^0 t\, ^8Be$) = **$1.88 \pm 0.35$ (stat) $^{+0.21}_{-0.21}$ (syst) mb**



Thank you for your attention