# I segreti della stranezza studiati a DAFNE

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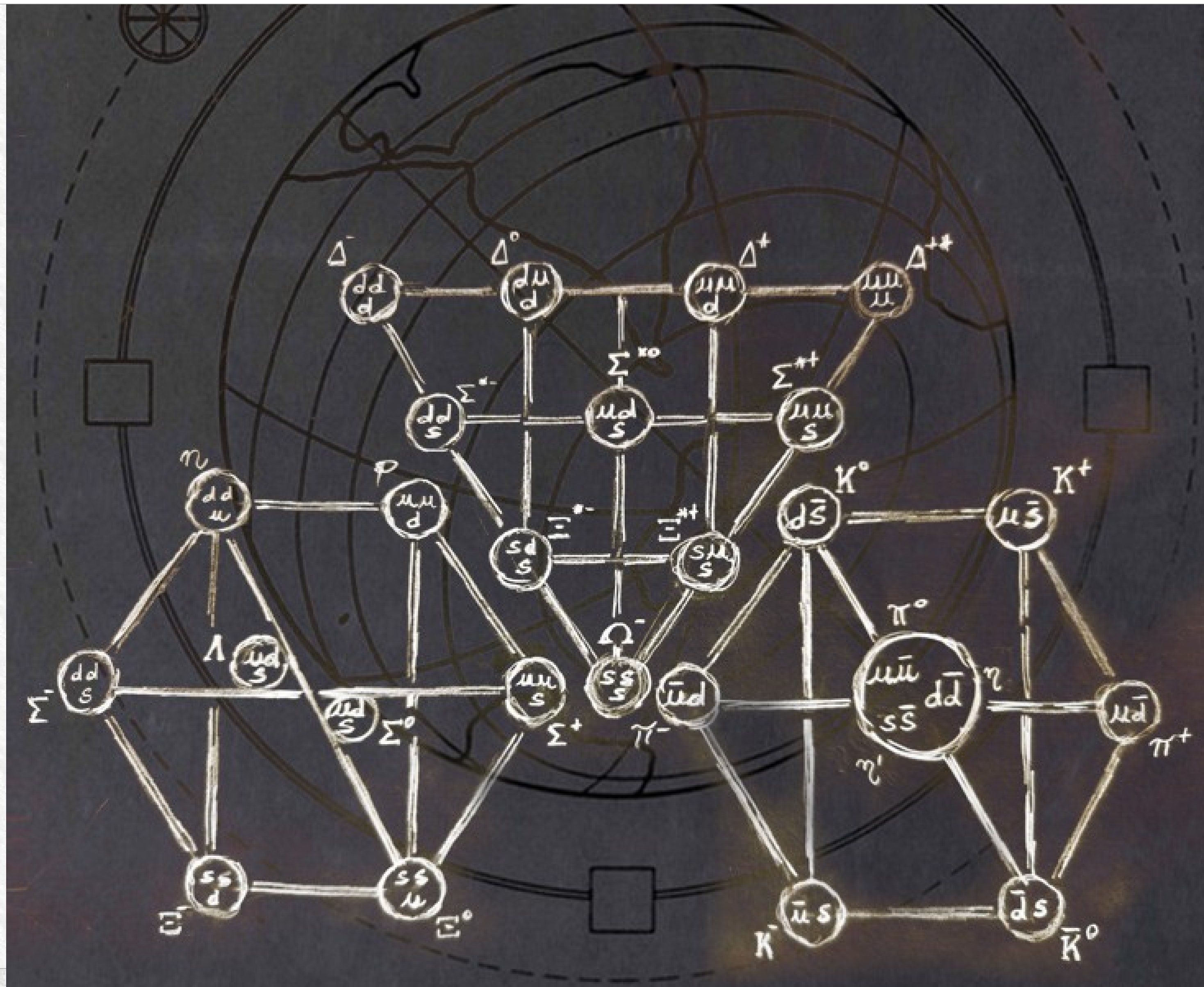
# kaonic matter .. deeper understanding the particles spectrum



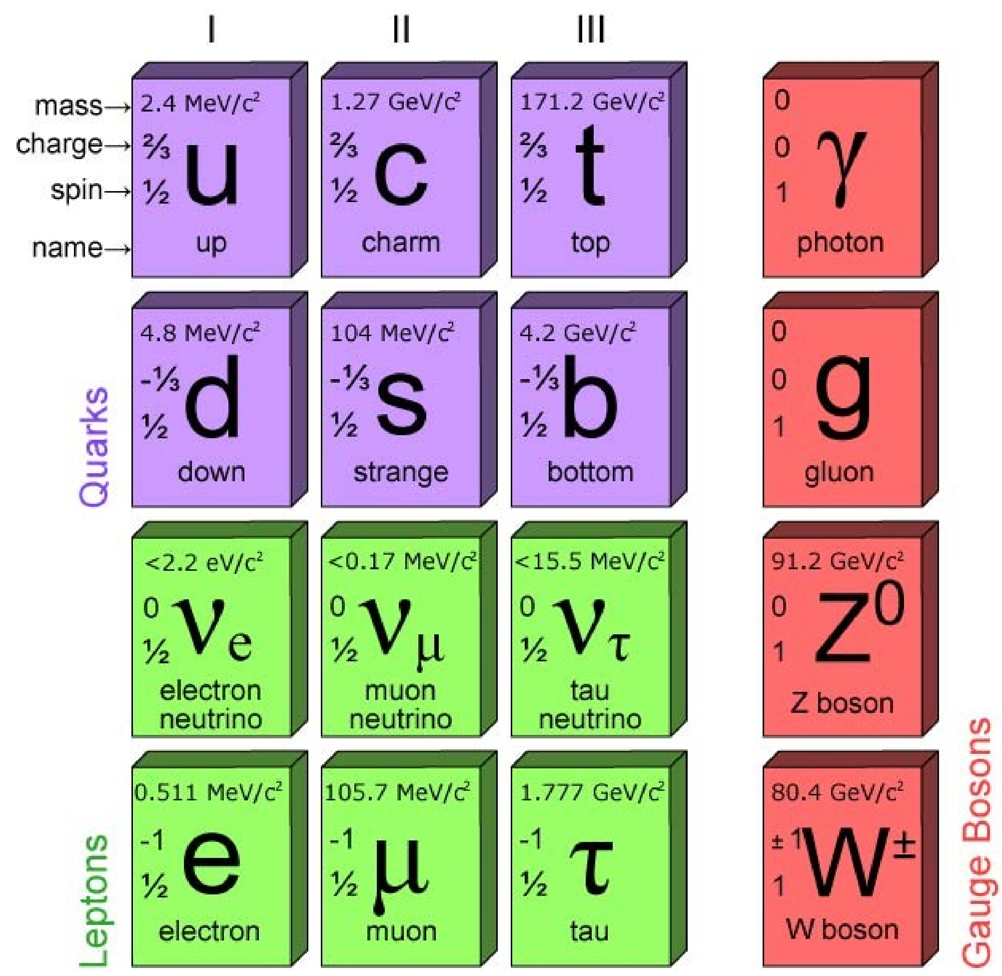
# Le particelle fondamentali

In natura esistono (per quanto ne sappiamo finora!) 4 Interazioni Fondamentali.

Esse sono «mediate» dallo scambio di particelle chiamate *bosoni* vettori (o bosoni di gauge), che le veicolano nello spazio causando l'interazione tra particelle «cariche».

La materia è formata da «*fermioni*».

Queste particelle acquisiscono massa attraverso il campo di Higgs.

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# QUARK ed i loro stati legati .. la fisica dell'interazione forte

free quarks (or fractionary charges) were never observed …
but more than two hundred of their bound states have been discovered:

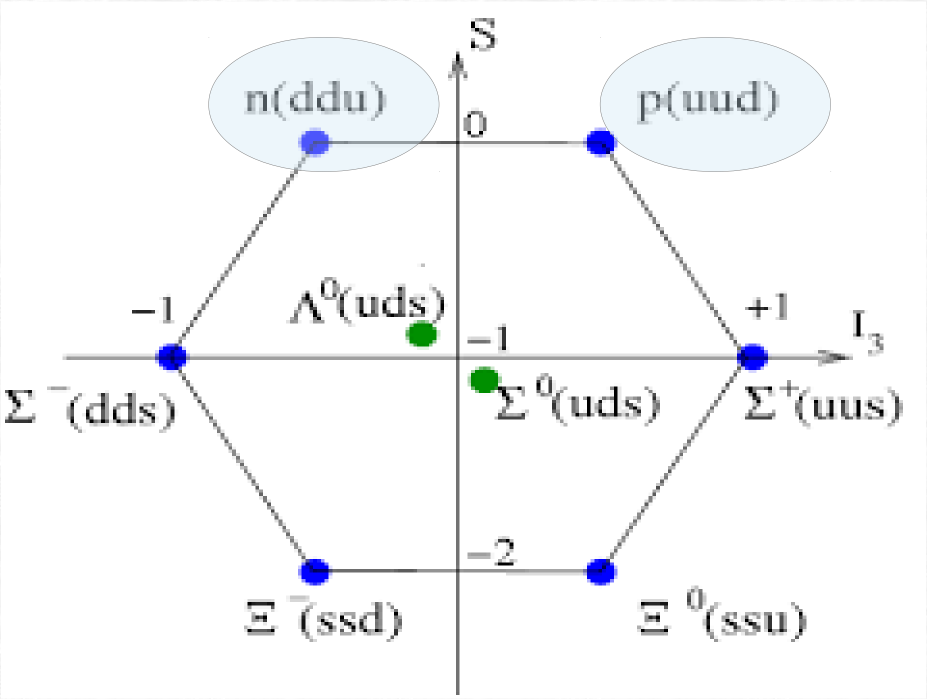
baryons - qqq fermioni (spin semintero)

mesons - $q\bar{q}$ bosoni (spin intero)

Ad ogni "sapore" di quark è associato un numero quantico additivo che è conservato nelle interazioni forte ed elettromagnetica.
L'interazione debole conserva solo il numero barionico.

Vita media di decadimento ↓ Forte
elettromagnetico
debole

# nucleoni … i barioni più leggeri

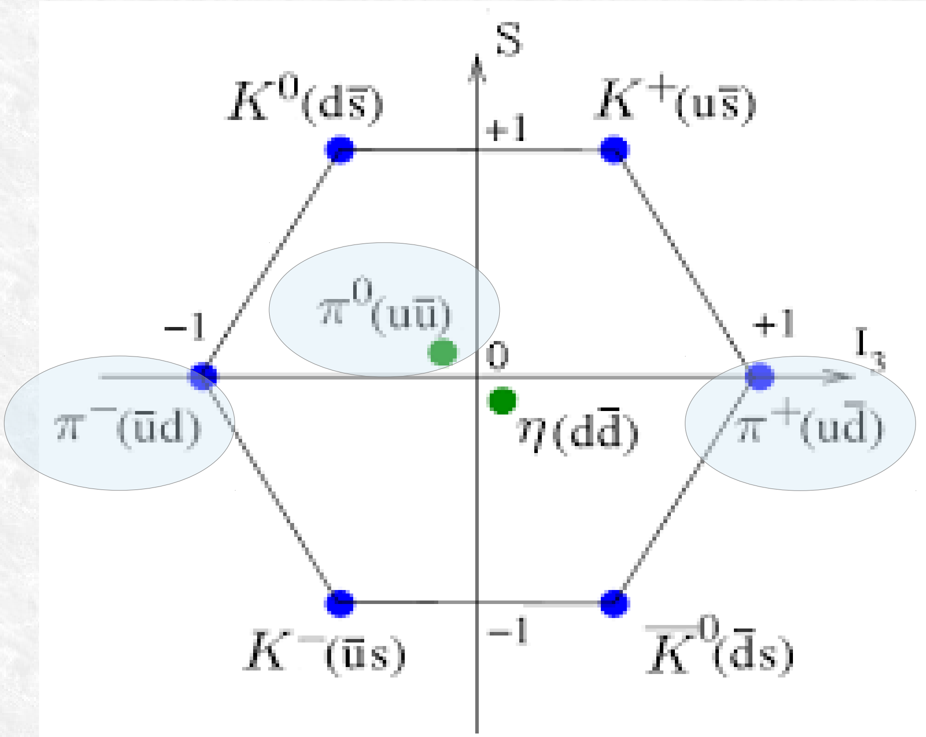



**non sono *strani***

**massa circa 940 MeV**

**1 eV = $1.782662 \times 10^{-36}$ kg**

# pioni … i mesoni più leggeri

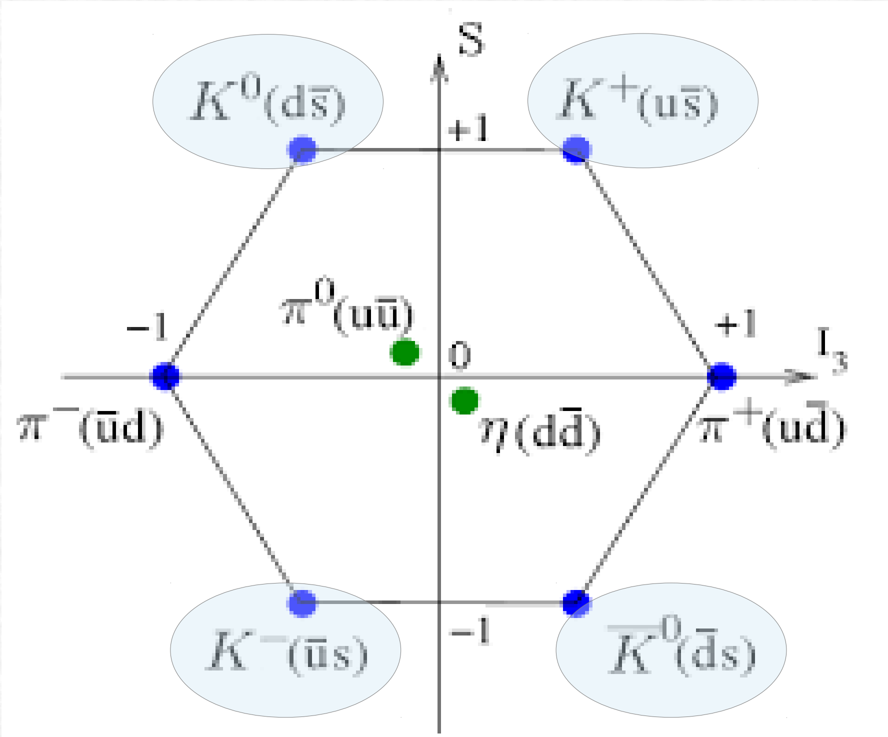



**non sono *strani***

**massa circa 140 MeV**

**scoperti per la prima volta nel 1947**
**nei raggi cosmici**
**in emulsione fotografica**
**contenente alogenuro d'argento**

# kaoni … i mesoni *strani* più leggeri




**massa circa 500 MeV**

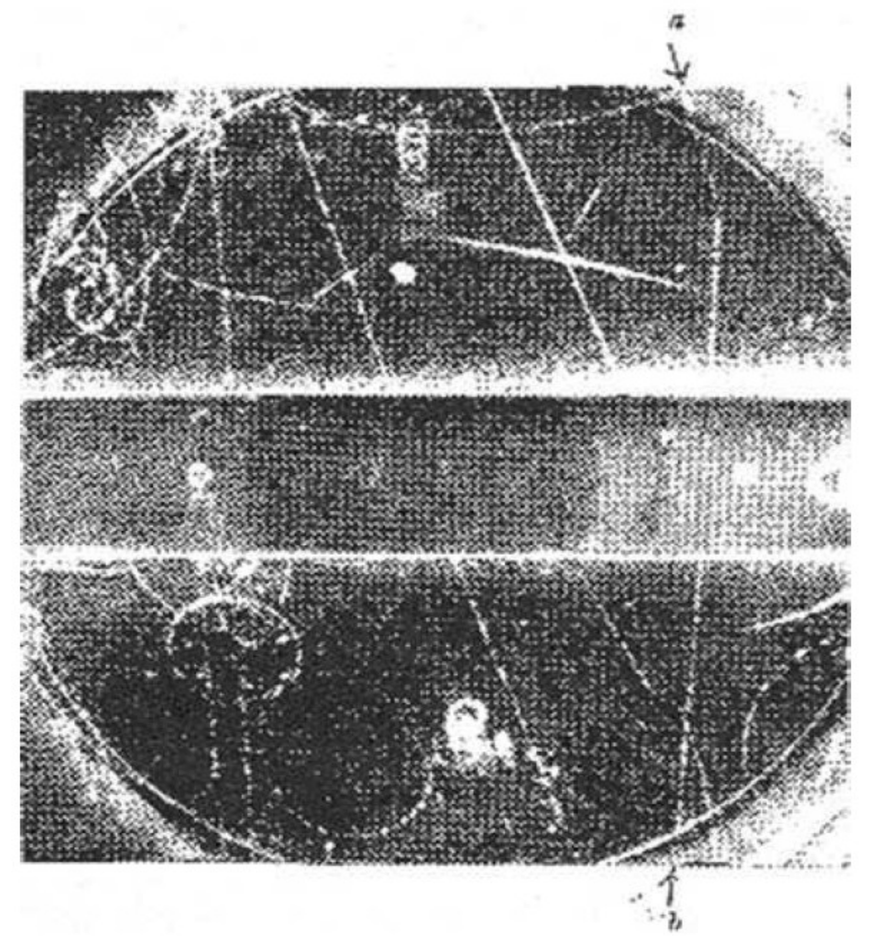
**scoperti anche loro nei raggi cosmici**

**prodotti in interazioni forti ma decadono debole (per questo strani)**

**sono i mesoni strani più leggeri → non possono decadere (conservando energia e stranezza per interazione forte)**

# kaoni … i mesoni *strani* più leggeri

$$K^+ \rightarrow \mu^+ + \nu_\mu$$



massa circa 500 MeV

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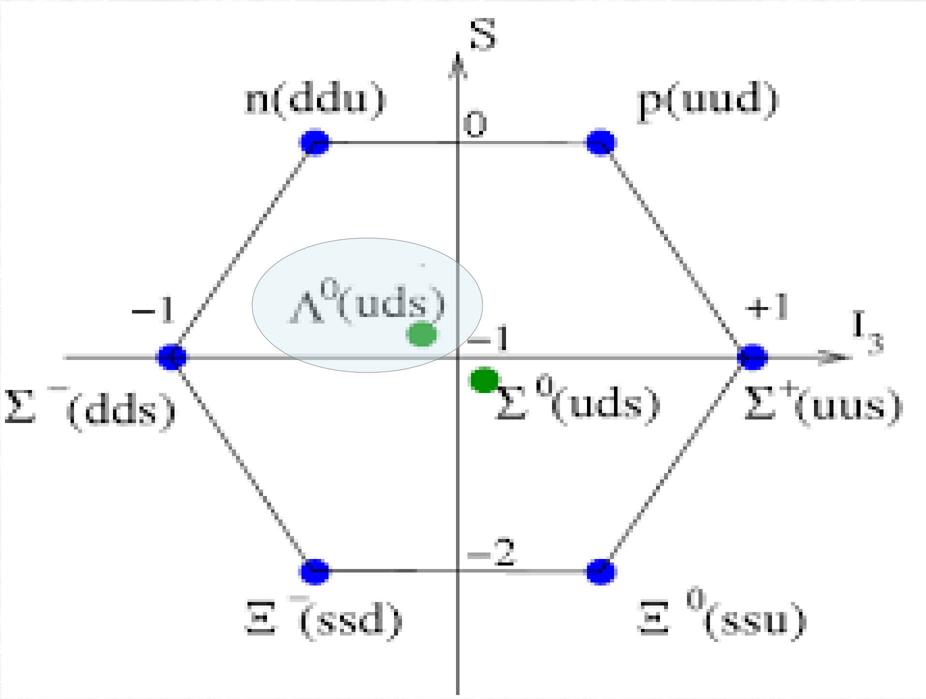
prodotti in interazioni forti ma decadono debole (per questo strani)

sono i mesoni strani più leggeri → non possono decadere (conservando energia e stranezza per interazione forte)

# $\Lambda$(1116) … il barione *strano* più leggero




**massa circa 1116 MeV**

**prodotta in interazioni forti ma decade debole:**

$$\Lambda \to \pi^- + p,$$

$$(uds) \to (d\bar{u}) + (uud)$$

$$S = -1 \qquad 0 \qquad 0$$

# RISONANZE : mesoni e barioni più leggeri possiedono *"stati eccitati"* che decadono forte

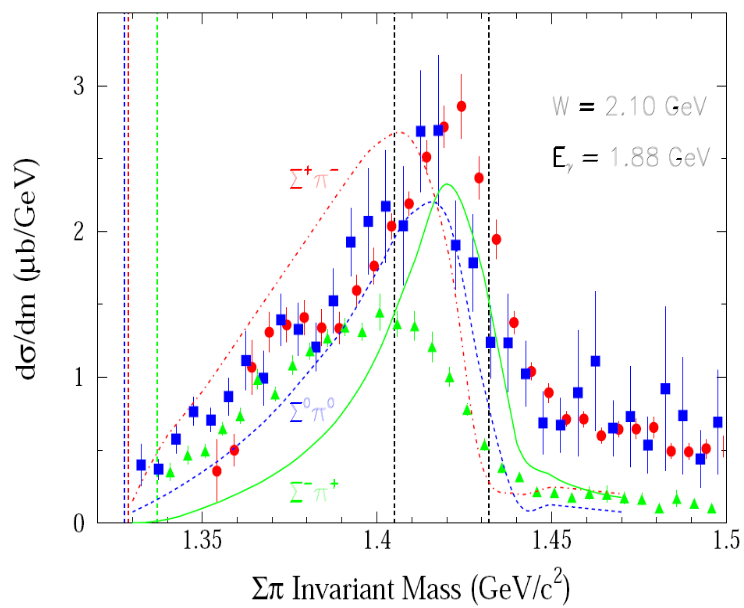
**Vivono troppo poco per essere osservate direttamente, devono essere studiate attraverso i loro prodotti di decadimento .. ex:**

$$K^- + p \rightarrow \Lambda(1405) \rightarrow \Sigma^0 + \pi^0$$

**la sua esistenza va inferita dalla misura dell'energia e dell'impulso delle particelle figlie, dalla conservazione di energia ed impulso otteniamo:**

$$W^2_{(\Lambda)} = (E_\Sigma + E_\pi)^2 - (p_\Sigma + p_\pi)^2$$

energy cons. momentum cons.



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$M^2_{(\Lambda)} = (E_\Sigma + E_\pi)^2 - (p_\Sigma + p_\pi)^2$

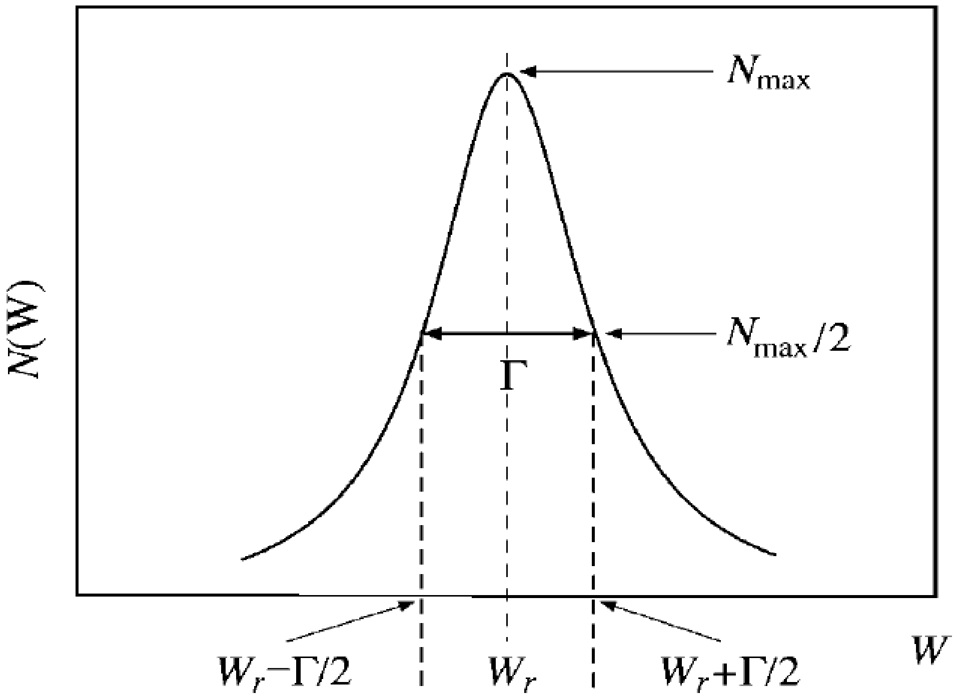
energy cons. momentum cons.

**La forma della risonanza è data dalla formula di Breit-Wigner :**

$$N(W) = \frac{K}{(W - W_r)^2 + \Gamma^2/4},$$

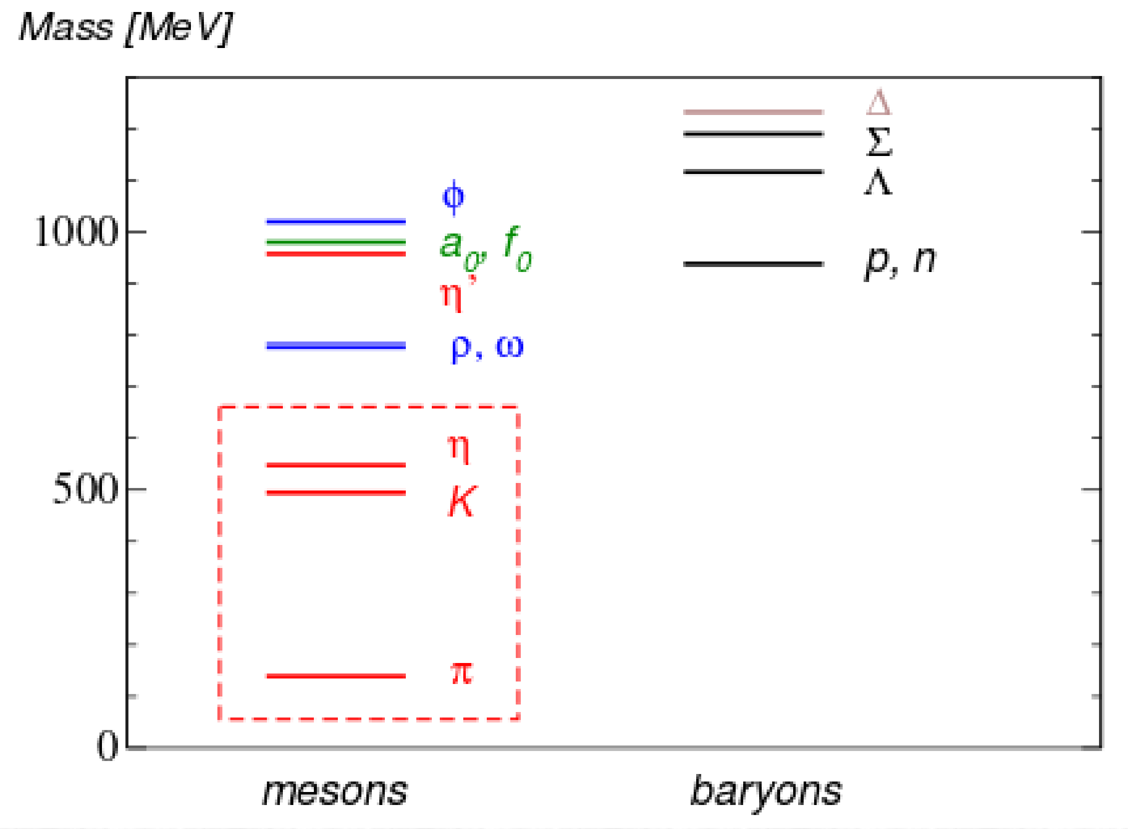
**La vita media è data dalla inderminazione energia tempo:**

$$\Delta W = \Delta E \approx \Gamma \equiv 1/\tau$$



# AMADEUS:
## Anti-kaonic Matter At DAΦNE: An Experiment with Unraveling Spectroscopy

**Why studying anti-kaonic matter?**




**QCD open problems:**

- **Particle spectrum: why these states?**

$$m_\pi \approx 138\ MeV$$
$$m_K \approx 494\ MeV$$
$$m_N \approx 939\ MeV$$
$$m_\Lambda \approx 1116\ MeV$$
$$m_\Sigma \approx 1193\ MeV$$

- Nuclear physics ↔ QCD?

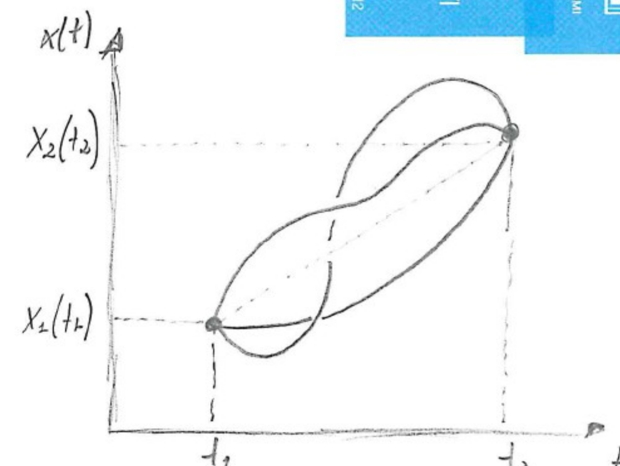
Possible solution: Effective field theories → Experimental support

# Lagrangiana



Consideriamo il moto di una particella per semplicità in una sola dimensione e siano $x(t)$, $\dot{x}(t)$ la sua posizione e la sua velocità. Se la particella è soggetta ad un potenziale $U(x)$ la sua equazione del moto è

$$F = ma = m\ddot{x}(t) = -\frac{\partial U}{\partial x}$$




Introduciamo la Lagrangiana:

$$\mathcal{L}(x(t), \dot{x}(t)) = T - U = \frac{m}{2}\dot{x}^2 - U(x)$$

ed il funzionale azione

$$S = \int_{t_1}^{t_2} \mathcal{L}(x(t), \dot{x}(t))\, dt$$

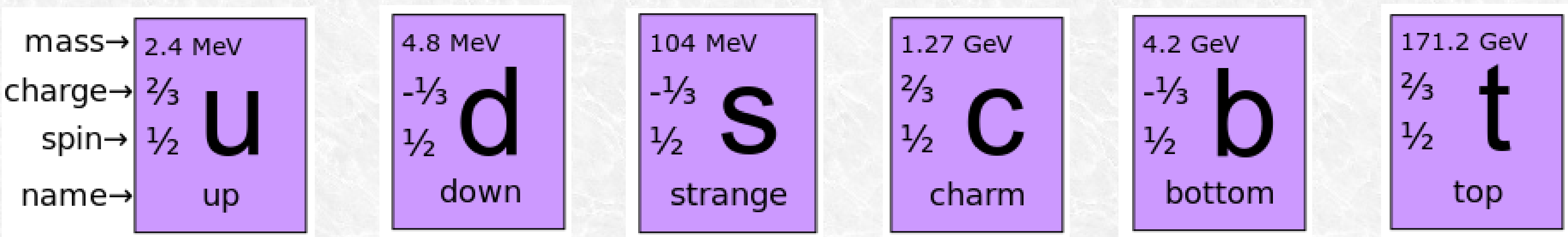
Il principio di azione stazionaria afferma che fra tutte le possibili traiettorie che connettono due punti $x_1(t_1)$ ed $x_2(t_2)$ la particella segue la traiettoria tale che $\delta S = 0$, da cui segue:

$$\frac{\partial \mathcal{L}}{\partial x} - \frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{x}} = 0 \quad \Rightarrow \quad -\frac{\partial U}{\partial x} = m\ddot{x}$$

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

- strong interaction is governed by QCD

- fundamental matter fields are quarks (6 flavors & 3 colors R , G , B)




- gauge fields are 8 gluons.

- in the massless limit ..

quark fields

gluon fields

$$\mathcal{L}^0_{\text{QCD}} = -\frac{1}{2}\text{tr}\,[G_{\mu\nu}G^{\mu\nu}] + \bar{q}i\gamma^{\mu}D_{\mu}q,$$

$$G_{\mu\nu} = \partial_{\mu}A_{\mu} - \partial_{\nu}A_{\mu} - ig[A_{\mu}, A_{\nu}], \qquad D_{\mu} = \partial_{\mu} - igA_{\mu}, \quad A_{\mu} = \sum_a T^a A^a_{\mu},$$

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

- since the massless Lagrangian can be decomposed:

$$\mathcal{L}^0_{\mathrm{QCD}} = -\frac{1}{2}\mathrm{tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{q}_R i\gamma^\mu D_\mu q_R$$

left and right handed quarks: $q_L = P_L q$ $q_R = P_R q$

it is invariant under independent unitary transformations of L/R-handed q

*chiral symmetry* of QCD $SU(3)_L$ x $SU(3)_R$

- quark condensate breaks down the symmetry to $SU(3)_V$

$$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_R q_L + \bar{q}_L q_R|0\rangle$$

SPONTANEOUS ch. symmetry breaking

- Nambu-Goldstone: *each broken symmetry introduces one massless boson in the physical particle spectrum*

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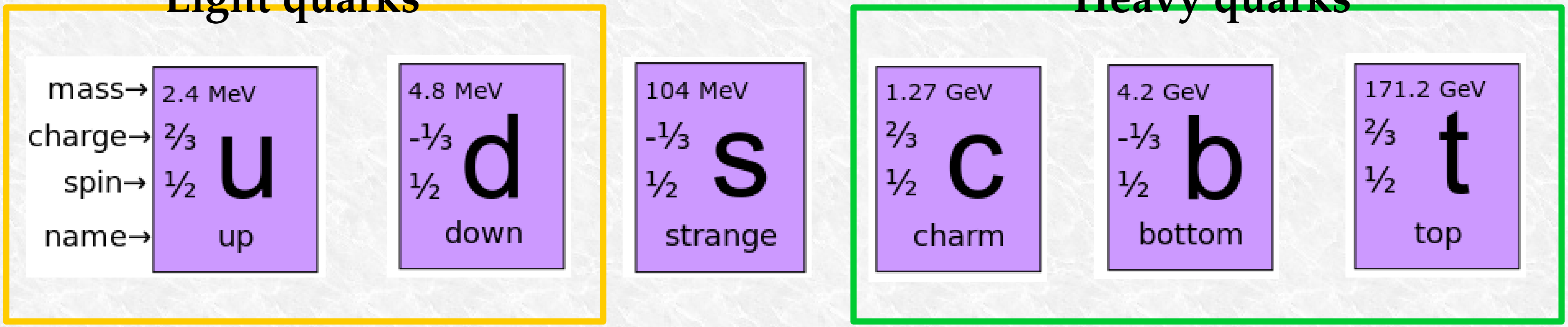
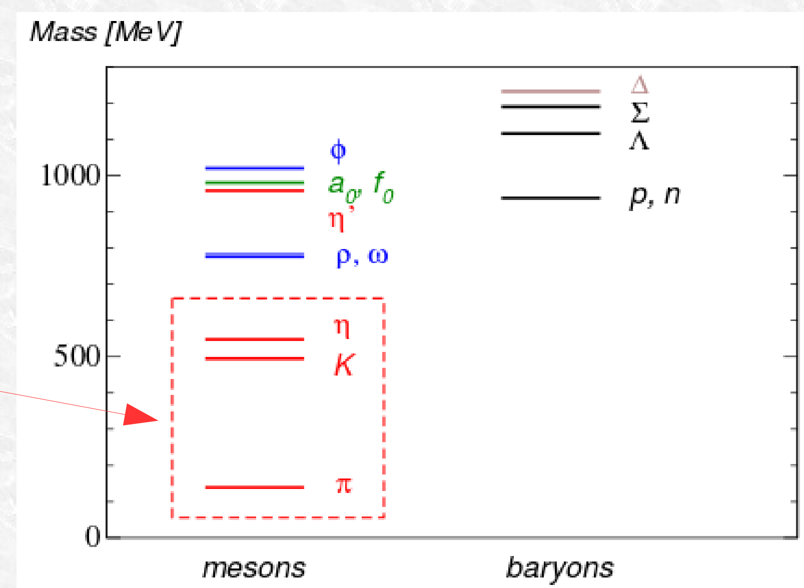
# Low-energy QCD in the u-d-s sector

- If we reduce to the three lightest flavors:

**Light quarks** **Heavy quarks**




- The *approximate* N-G bosons are the lightest mesons ($\pi$, K and $\eta$)



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

- Ch. symmetry is also broken by the finite quarks masses, because of the quark mass term:

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} - \bar{q} m q, \qquad m = \begin{pmatrix} m_u & & \\ & m_d & \\ & & m_s \end{pmatrix}$$

$m_u$, $m_d$ ~ few MeV ; $m_s$ ~ 150 MeV

EXPLICIT chiral symmetry breaking

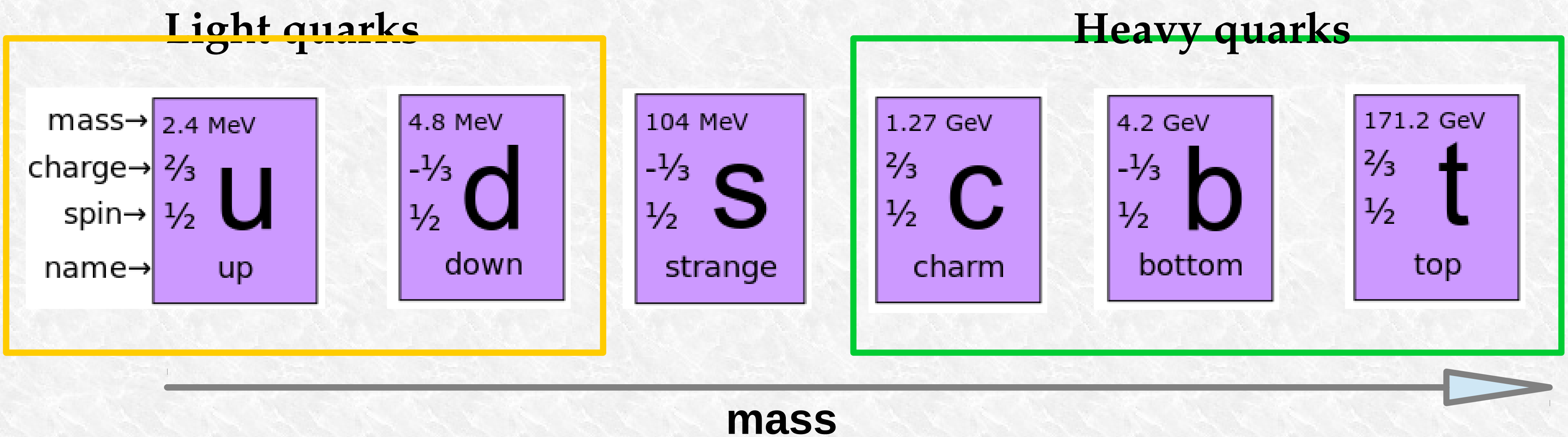
- s quarks are intermediate between light and heavy → test of the interplay among spontaneous and explicit ch. sy. breaking in low-energy QCD

# AMADEUS:
## Anti-kaonic Matter At DAΦNE: An Experiment with Unraveling Spectroscopy

**Why studing anti-kaonic matter?**

**(Why studing strangeness?)**

- The strange quarks are **intermediate in mass** between light and heavy quarks




**Quark masses ratios:**

$$\frac{m_u}{m_d} \approx 0.55 \qquad \frac{m_s}{m_d} \approx 22$$

The chiral symmetry is broken explicitly by the large strange quark mass

# AMADEUS:
## Anti-kaonic Matter At DAΦNE: An Experiment with Unraveling Spectroscopy

### Why studying anti-kaonic matter?

- The hadron masses originate from the **chiral symmetry breaking** mechanism

Gell-Mann-Oakes-Rennan formula:

$$M_\pi^2 = (m_u + m_d) \times |\langle 0|\bar{u}\,u|0\rangle| \times \frac{1}{F_\pi^2}$$

$$F_\pi = 92.2\ MeV$$

explicit spontaneous

$$M_K^2 = \frac{(m_u + m_s)}{2} \times |\langle 0|\bar{u}\,u + \bar{s}\,s|0\rangle|$$

➔ The **explicit** chiral symmetry breaking is caused by the non zero quark masses.

➔ The **spontaneous** chiral symmetry breaking is caused by the non zero quark condensate expectation value in vacuum

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Gell-Mann-Oakes-Rennan formula:

Chiral symmetry breaking terms

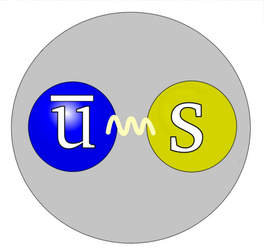
**In vacuum:** $\rho=0$

$$M_K^2=\frac{(m_u+m_s)}{2}\times|\langle 0|\bar{u}\,u+\bar{s}\,s|0\rangle|$$

**In medium:** $\rho>0$

$$M_K^{*2}=M_K^2\left(1-\frac{1}{F_\pi^2}\frac{\langle\rho|\bar{u}\,u+\bar{s}\,s|\rho\rangle}{\langle 0|\bar{u}\,u+\bar{s}\,s|0\rangle}\rho\right)$$

$K^-$ =




The kaons are the lightest mesons containing strangeness.

The **mass shift** of a meson in a nuclear medium provides information of the partial restoration of chiral symmetry in QCD and to understand how hadron masses are generated

# AMADEUS:
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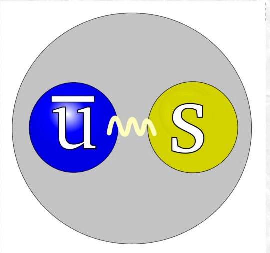
$K^- =$ 


The **mass shift** of a meson in a nuclear medium provides information of the partial restoration of chiral symmetry in QCD and to understand how hadron masses are generated

**In vacuum:** $\rho = 0$ $M_K =$ Mass of the kaon in vacuum

**In medium:** $\rho > 0$ $M_K^* =$ Mass of the kaon in medium

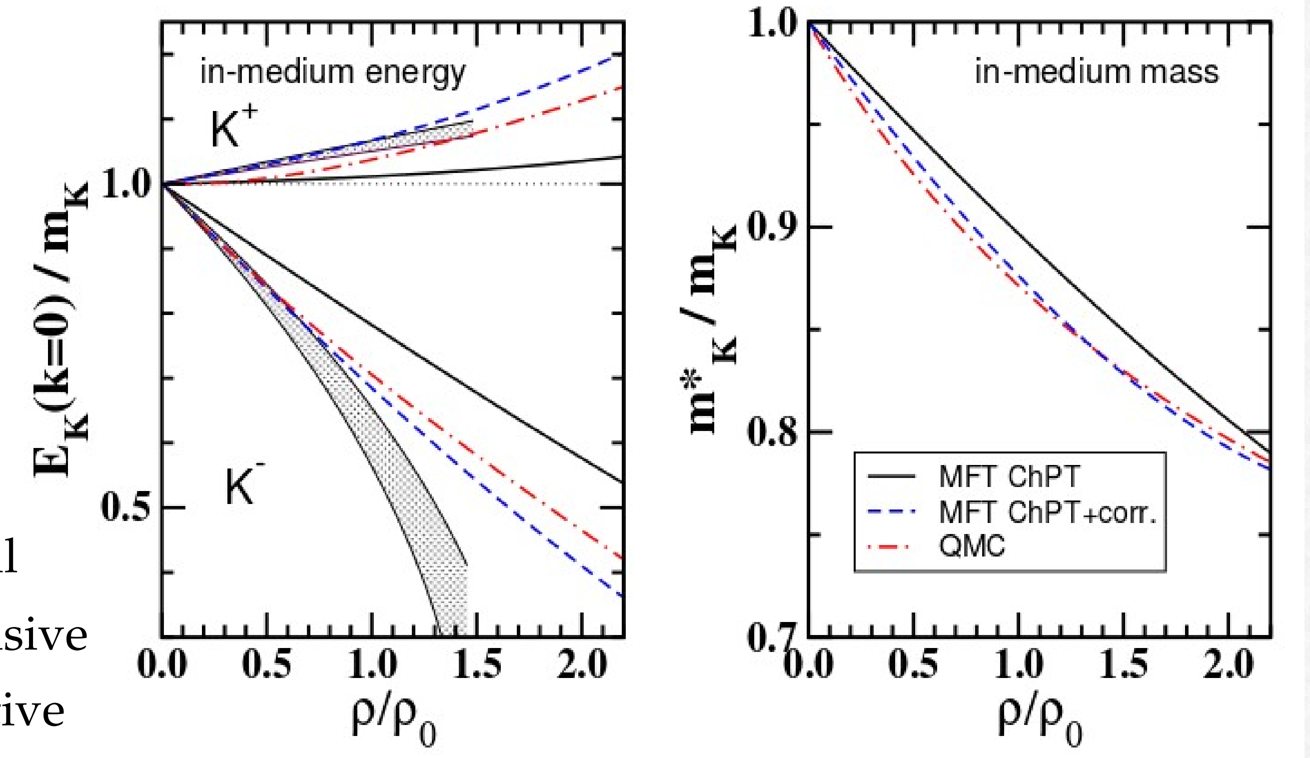
$$M_K^{*2} = M_K^2 \cdot \left[1 - B(\rho) \cdot \rho\right]$$

$B(\rho)$ needs to be set experimentally

# AMADEUS:
## Anti-kaonic Matter At DAΦNE: An Experiment with Unraveling Spectroscopy

Measurements on kaonic hydrogen indicates **attractive interaction** between anti-kaons and nucleons in nuclear medium.

The gray bands are the extrapolations from $K^+N$ scattering data and from kaonic hydrogen data




$$E_K(\boldsymbol{k}=0) = M_K^* + V_0$$

$V_0$ is the KN interaction potential

$V_0 > 0 \rightarrow$ the interaction is repulsive

$V_0 < 0 \rightarrow$ the interaction is attractive

$\overline{K}N$ interaction attractive $\rightarrow$ **Is it possible to form bound states of kaons in nuclei?**

If so, they are ideal to study kaon mass modification

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

- Ch. symmetry is also broken by the finite quarks masses, because of the quark mass term:

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} - \bar{q}mq, \qquad m = \begin{pmatrix} m_u & & \\ & m_d & \\ & & m_s \end{pmatrix}$$

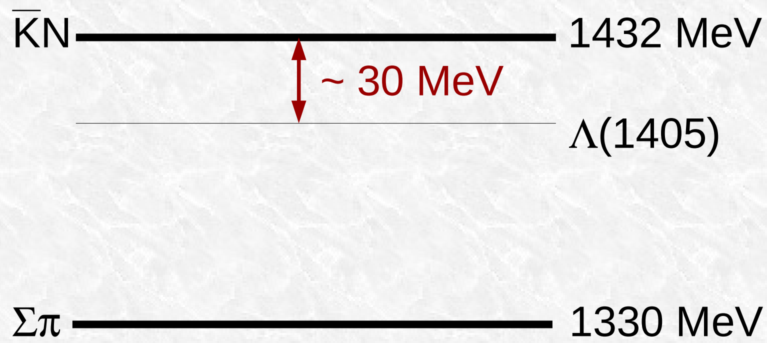
$m_u, m_d \sim$ few MeV ; $m_s \sim 100$ MeV

EXPLICIT ch. symmetry breaking

- At low-energy the non-perturbative effect of the strong interaction causes color confinement $\rightarrow$ asymptotic degrees of freedom are hadrons instead of quarks and gluons.

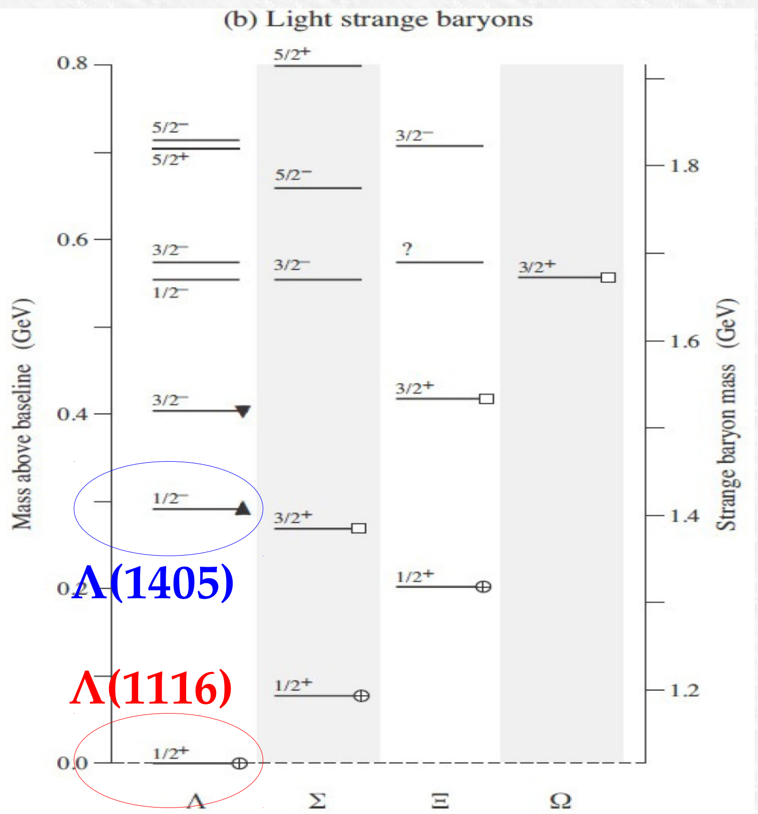
# The scientific case of the Λ(1405)

**Mass** = $1405.1^{+1.3}_{-1.0}$ MeV,
**Width** = 50.5 ± 2.0 MeV
$I = 0$, $S = -1$ , $J^p = 1/2^-$ ,
Status: **** ,
strong **decay** into Σπ




- 3 quark?
- **molecular?**
- **K̄N bound state?**
- pentaquark?

The **three quark model picture** has some difficulties to reproduce the Λ(1405). According to its negative parity, one of the quarks has to be excited to the $l = 1$ orbit. Similar to the nucleon sector, where one of the lowest negative parity baryon is the N(1535), **the expected mass of the Λ* is around 1700 MeV** (since it contains one strange quark). Another difficulty is the energy splitting observed between the Λ(1405) and the Λ(1520), if is interpreted as the spin-orbit partner ($J^p = 3/2^-$).

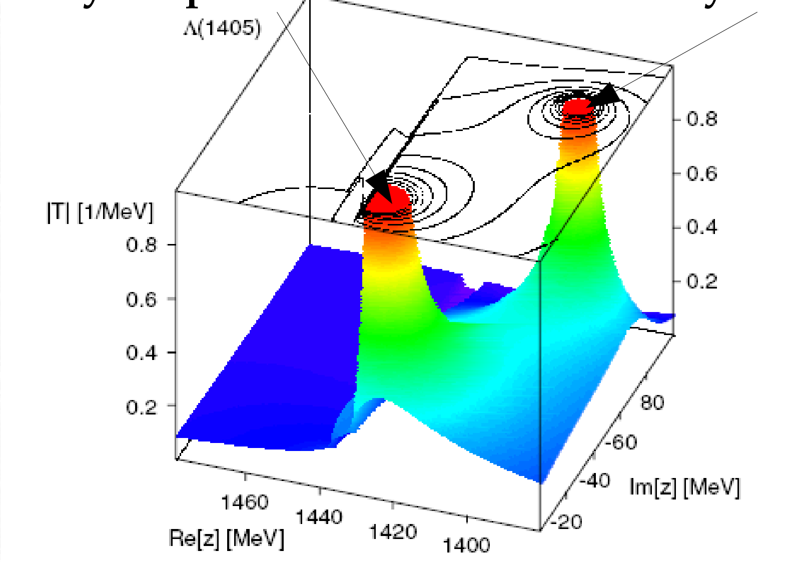



**R. Dalitz and collaborators first suggested to interpret Λ(1405) as an K̄N quasibound state.**

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

# The scientific case of the Λ(1405)

**mainly coupled to $\bar{K}N$** **mainly coupled to $\Sigma\pi$**




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

$$(z_1 = 1424^{+7}_{-23} - i26^{+3}_{-14} \qquad z_2 = 1381^{+18}_{-6} - i81^{+19}_{-8})\ MeV/c^2$$

Nucl. Phys. A881, 98 (2012).

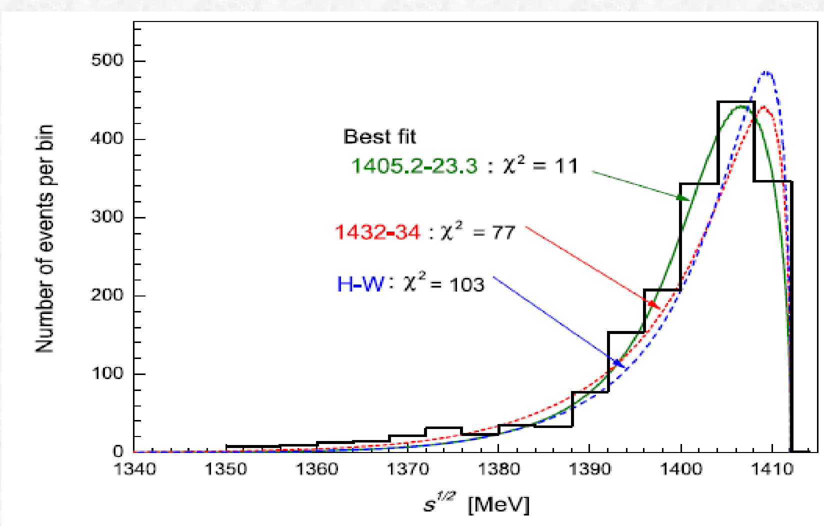



**Fig. 6.** Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

- Esmaili-Akaishi-Yamazaki model : the Λ(1405) does not have a double pole nature, is considered as a $\bar{K}$ - N bound state in the I = 0 channel

Physics Letters B 686 (2010) 23-28.

The position of the Λ(1405) is important to measure the $\bar{K}N$ Binding Energy (BE)

$$M_{\bar{K}N} = M_K + M_N - BE$$

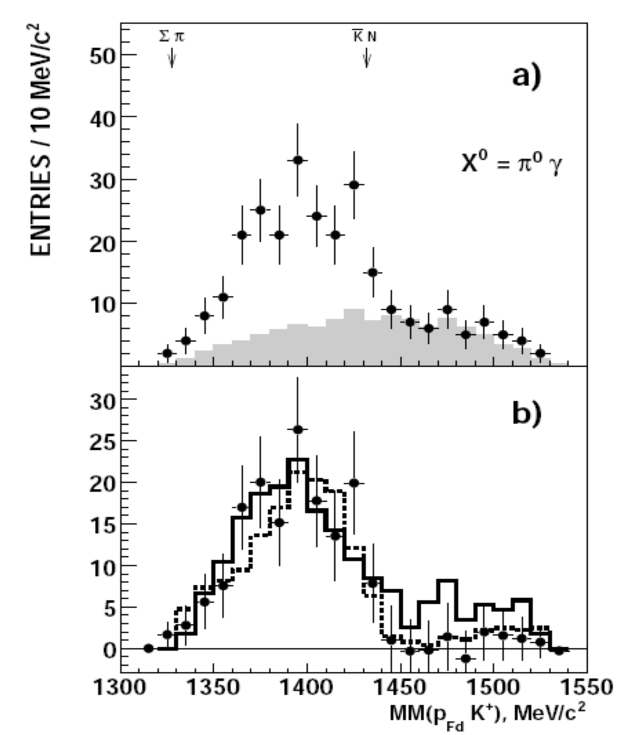
# The scientific case of the Λ(1405)

**Great importance to explore the Λ(1405) production in $\bar{K}N$ reactions decaying in $\Sigma^0\pi^0$** ($\Sigma^0$ decays electromagnetically in Λγ). **Golden, still poorly explored, channel** since the main source of background **Σ(1385) can not decay in $\Sigma^0\pi^0$** for isospin conservation.

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

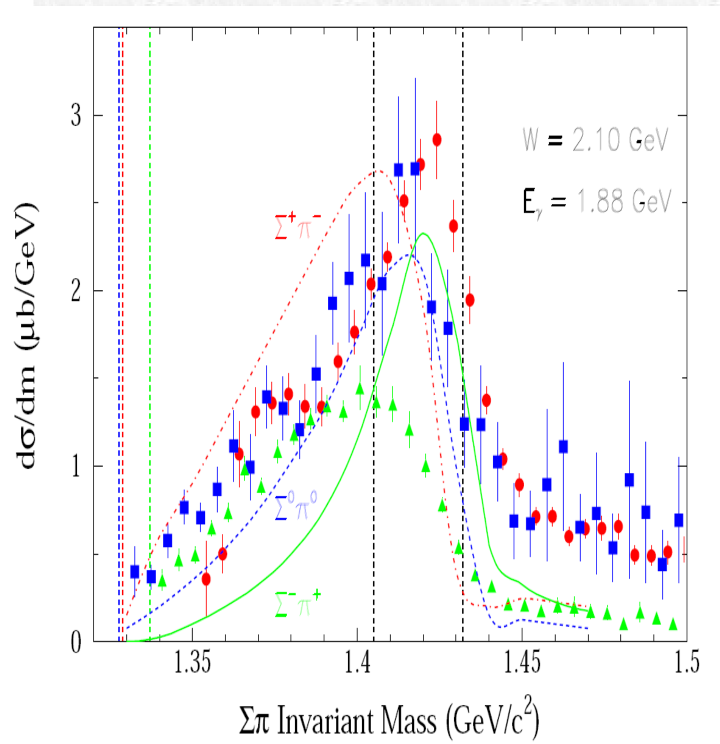
$pp \rightarrow pK^+ \Sigma^0\pi^0$

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



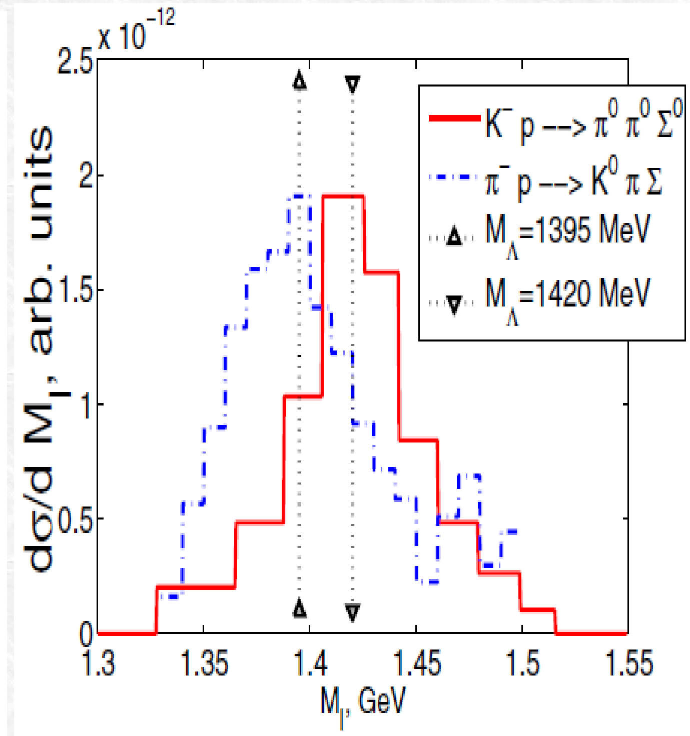

$\gamma p \rightarrow K^+ (\Sigma\pi)^0$

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




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

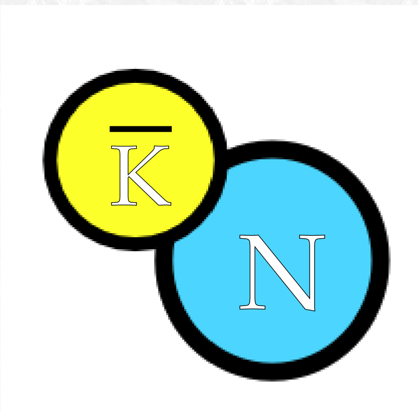
Magas et al. PRL 95, 052301 (2005) 034605 S. Prakhov, et al., Phys. Rev. C70 (2004)



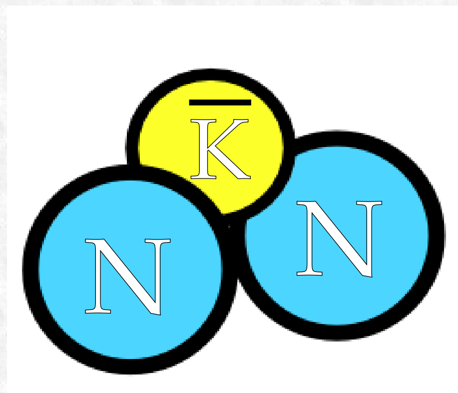
# Λ(1405) ... resonance or/and bound state?

**How strong is the interaction between anti-kaons and nucleons?**

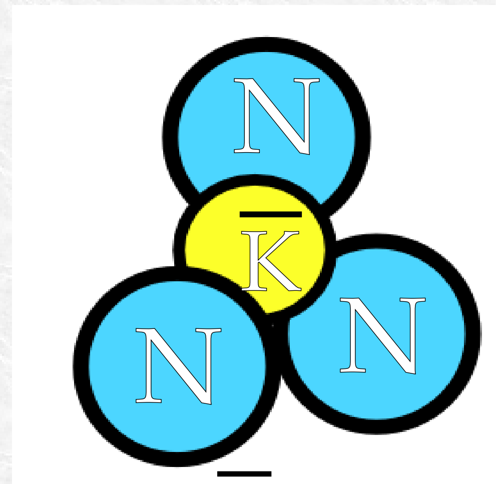
If this interaction is strong enough we might expect the formation of deeply bound kaonic nuclear clusters



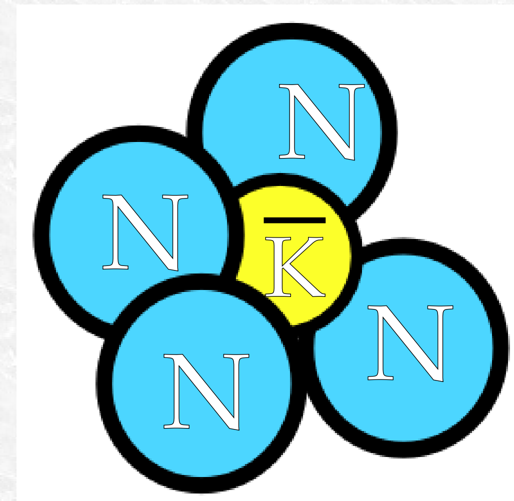

$\Lambda(1405)$




$\bar{K}NN$




$\bar{K}NNN$




$\bar{K}NNNN$

These kaonic bound states were predicted by Wycech (1986) and Akaishi & Yamazaki (2002) due to the strong $\bar{K}N$ attraction caused by the $\Lambda(1405)$ state.

If kaonic bound states exist, the $\bar{K}$ might mediate dense nuclear systems that will represent the **ideal conditions** to investigate the **hadron mass origin**.

# AMADEUS: the scientific goal

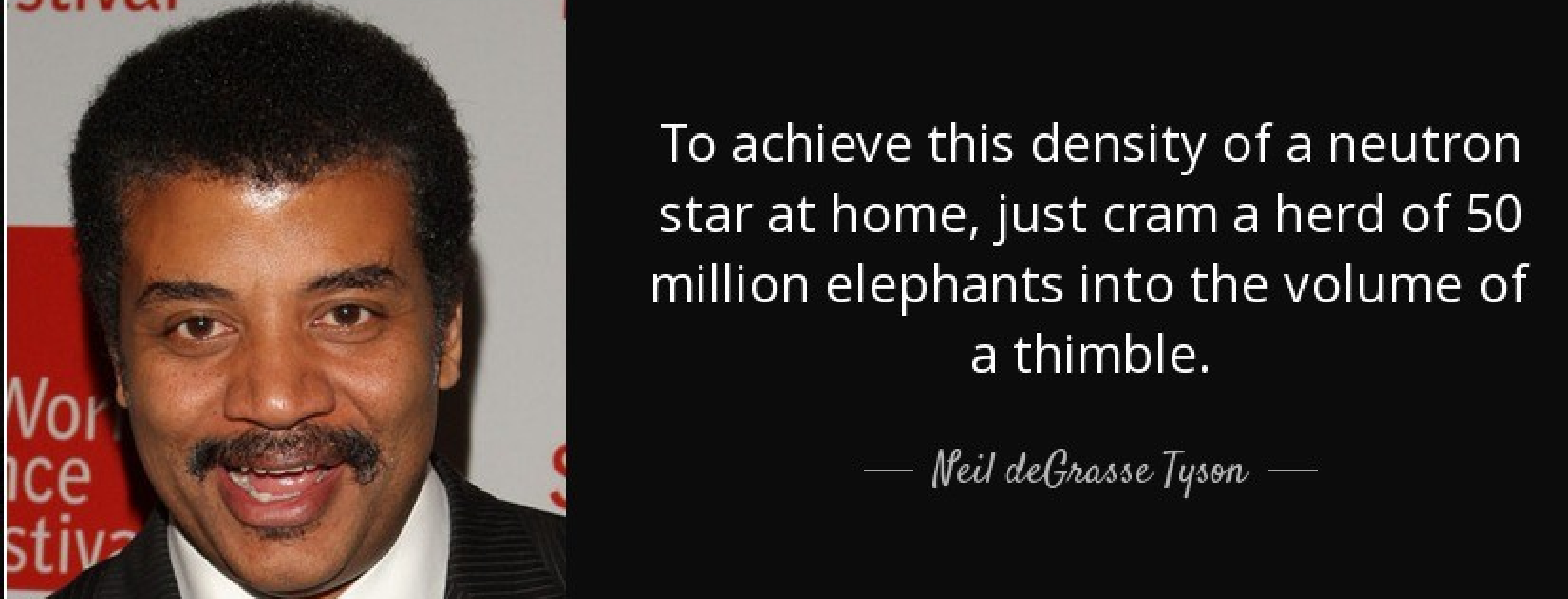
**Low-energy** $K^-$ interaction studies with **light nuclei** (H, $^4$He, $^9$Be, $^{12}$C) in order to extract conclusive constrains on:

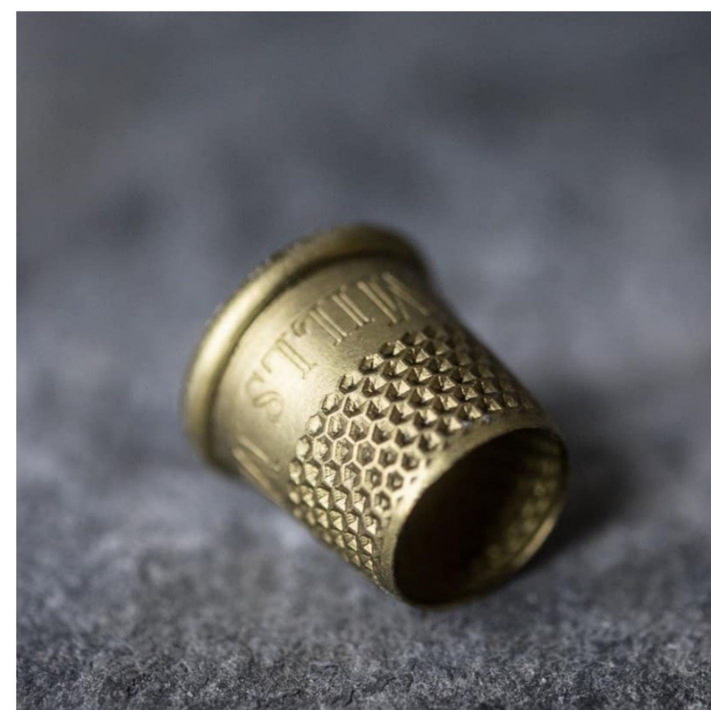
- **$\bar{K}N$ Potential** → how deep can an antikaon be bound in a nucleus?
  - $U_{\bar{K}N}$ strongly affects the position of the $\Lambda(1405)$ state
    → we investigate it through $(\Sigma-\pi)^0$ decay --- Y π CORRELATION
  - if $U_{\bar{K}N}$ is strongly attractive then possible $K^-$ multi-N bound states
    → we investigate through $(\Lambda/\Sigma-N)$ decay ---Y N CORRELATION

- **Y-N potential** → extremely poor experimental information from scattering data

Deep impact on models of neutrons stars structure

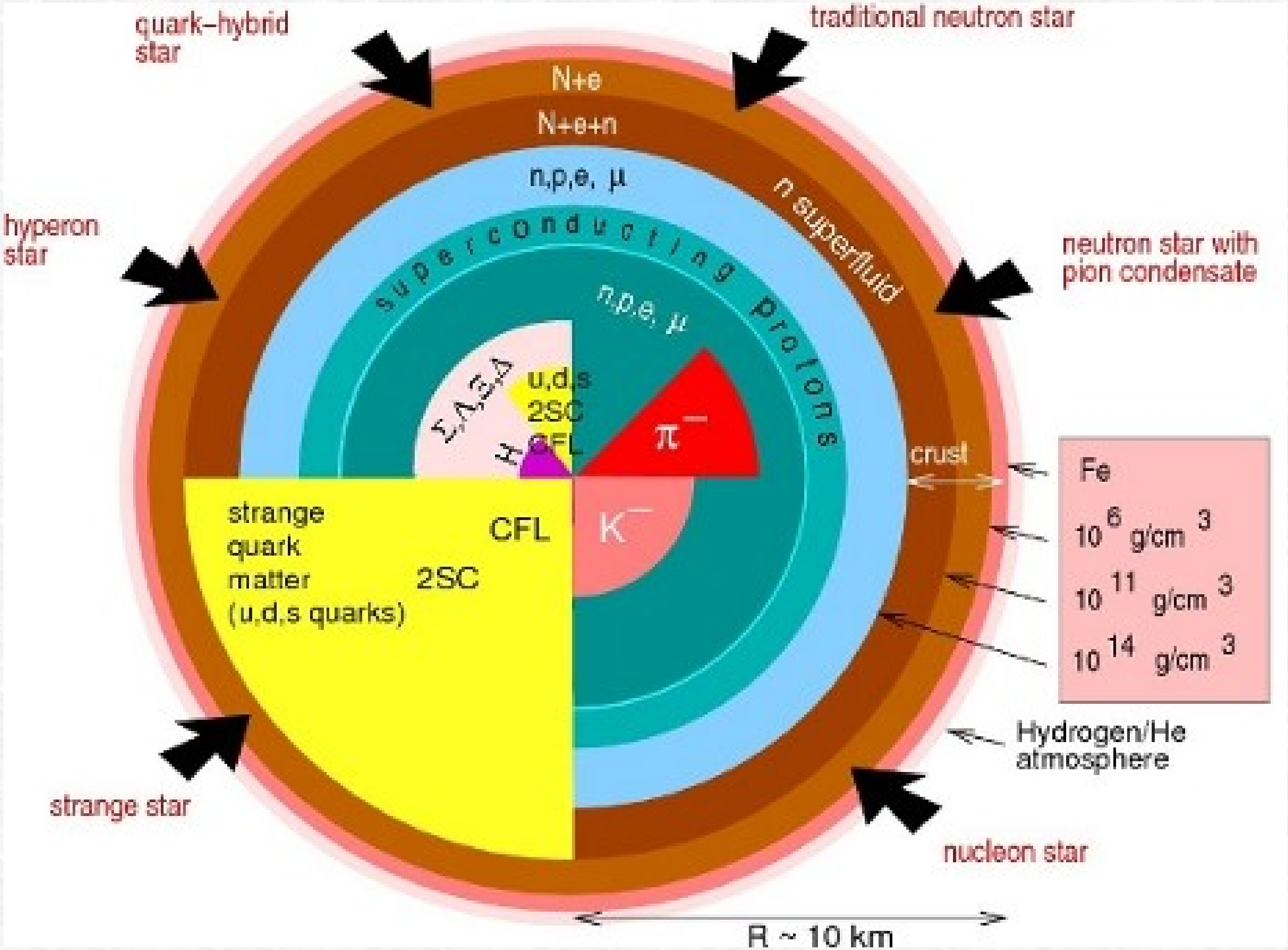

Neutron Star
Vancouver
www.kindaroomy.com


To achieve this density of a neutron star at home, just cram a herd of 50 million elephants into the volume of a thimble.
— Neil deGrasse Tyson —



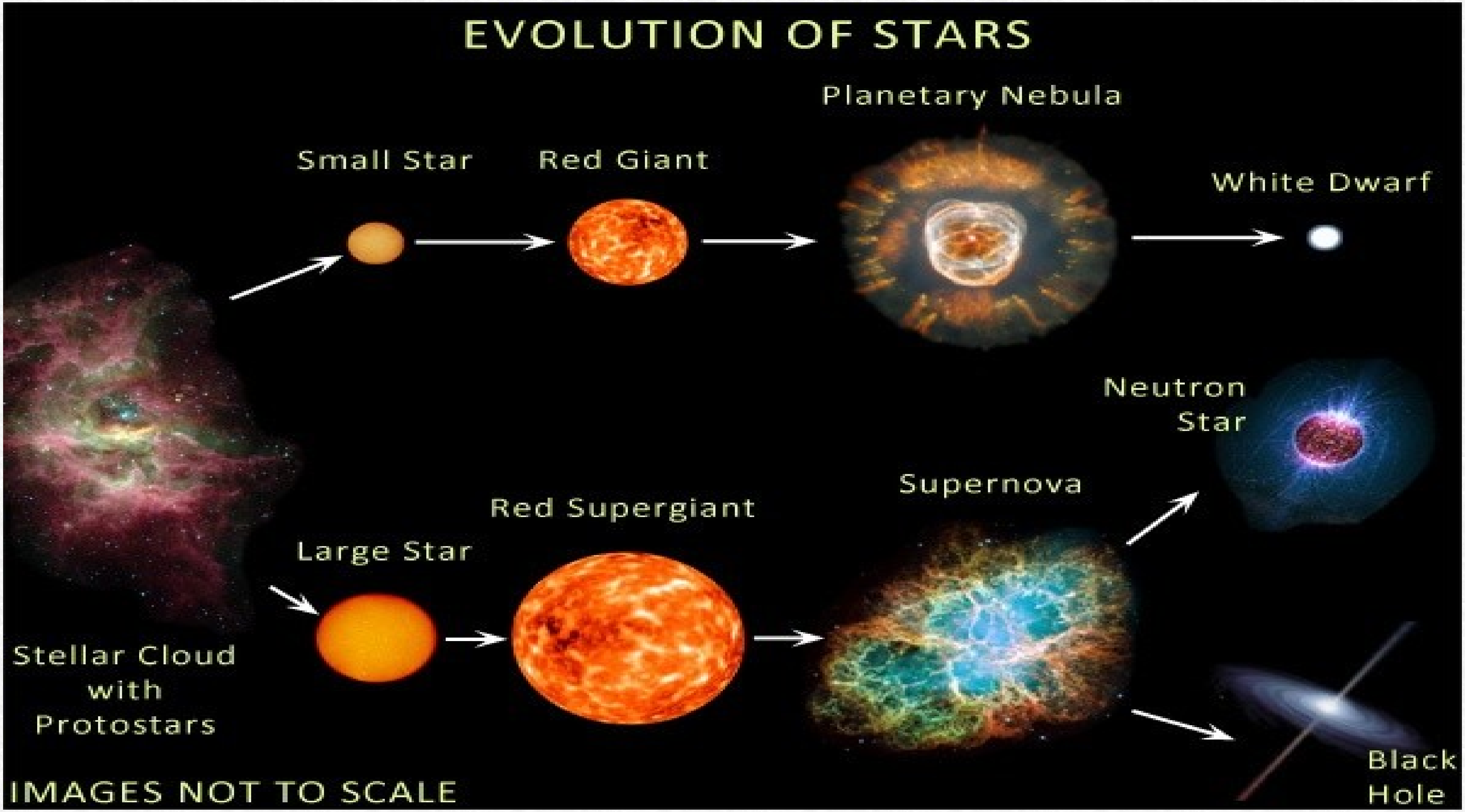
# Essential impact on the case of NEUTRON STARS

- Neutron stars are stellar objects made of **neutrons** plus some **protons** and **electrons**, but their composition is not yet clear and they could contain also **other particles**



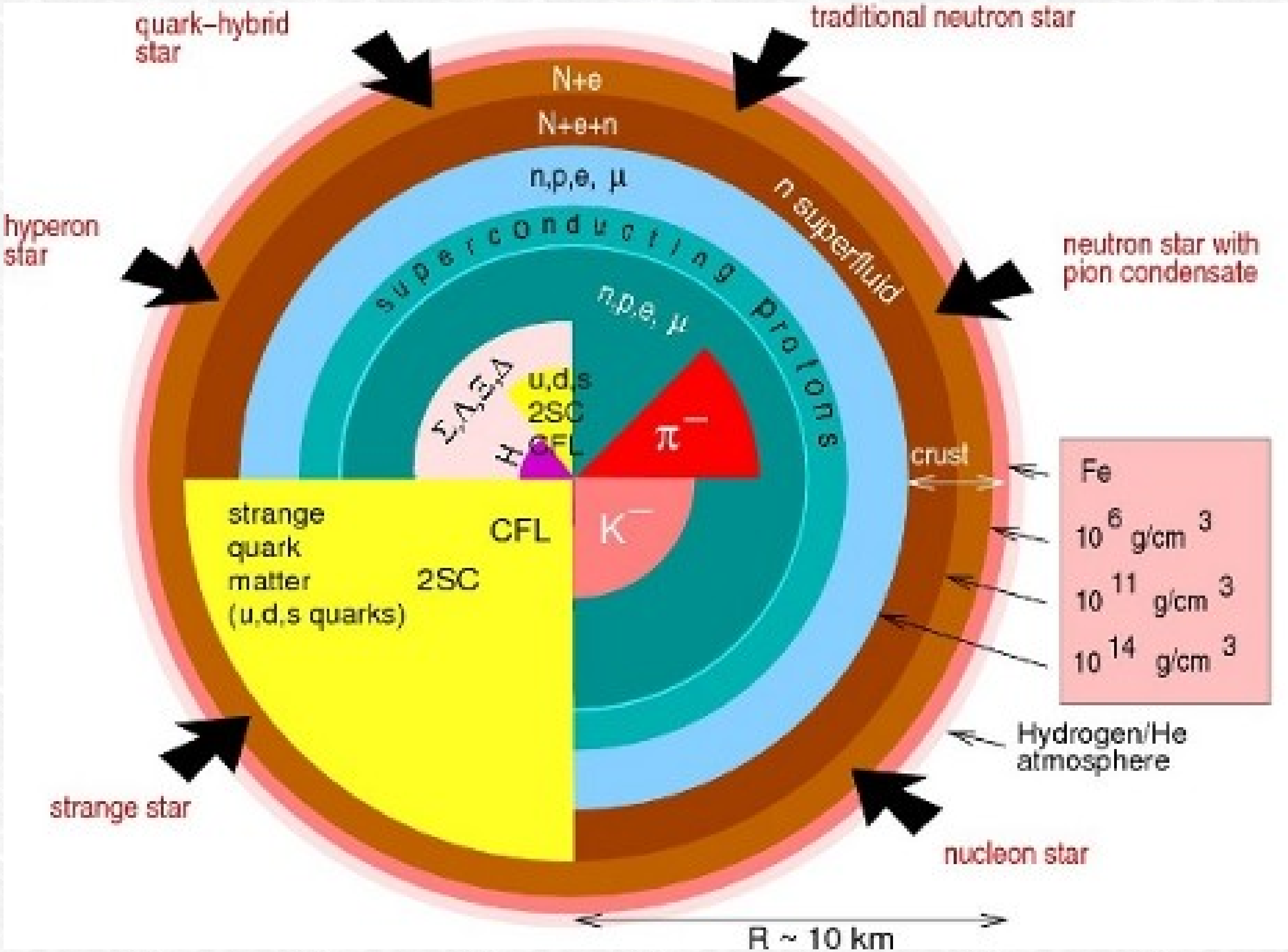
# What are NEUTRON STARS?

- They are the end-product of the evolution of massive stars, having a mass larger than about 10 solar masses and they are produced after an explosive phenomenon called **SuperNova**



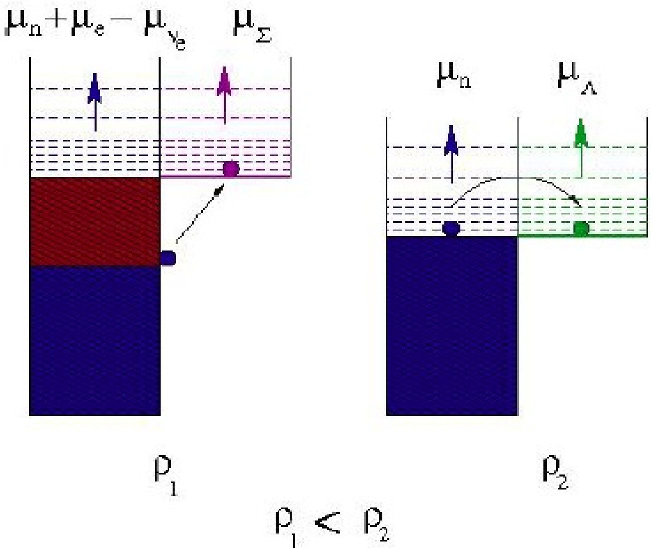
# Essential impact on the case of NEUTRON STARS

- Their mass is roughly between **1 to** (maybe) **3 solar masses**, but they are extremely small, with a **radius** of the order of **10 km** (the radius of the Sun is about 700000 km)



# Strangeness in NEUTRON STARS

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when $\mu_N$ is large enough to make the conversion of N into Y energetically favorable.




$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-} - \mu_{\nu_{e^-}}$$

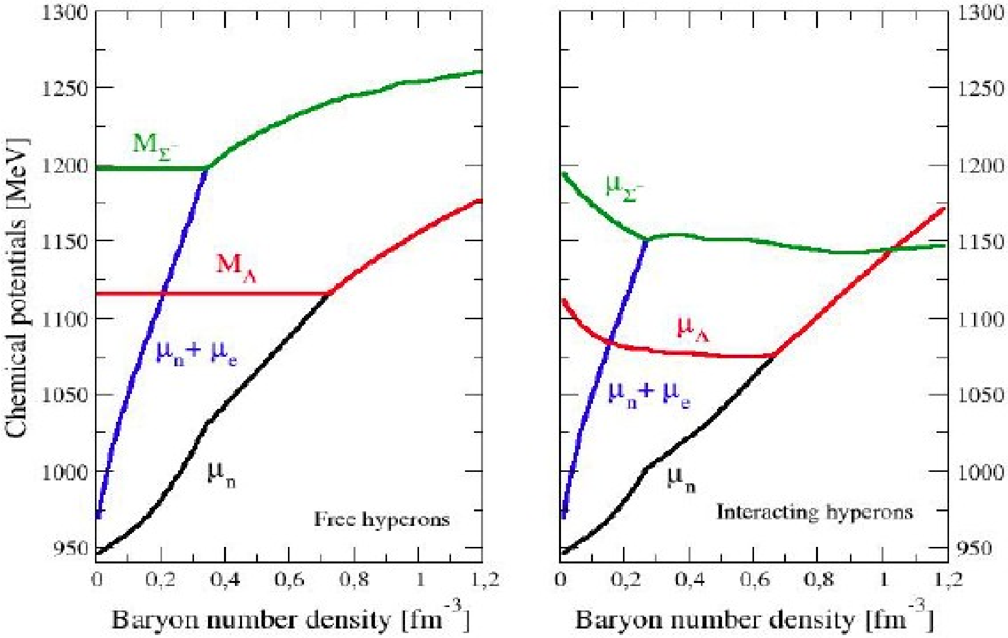
$$\mu_\Lambda = \mu_n$$

$$n + n \rightarrow n + \Lambda$$

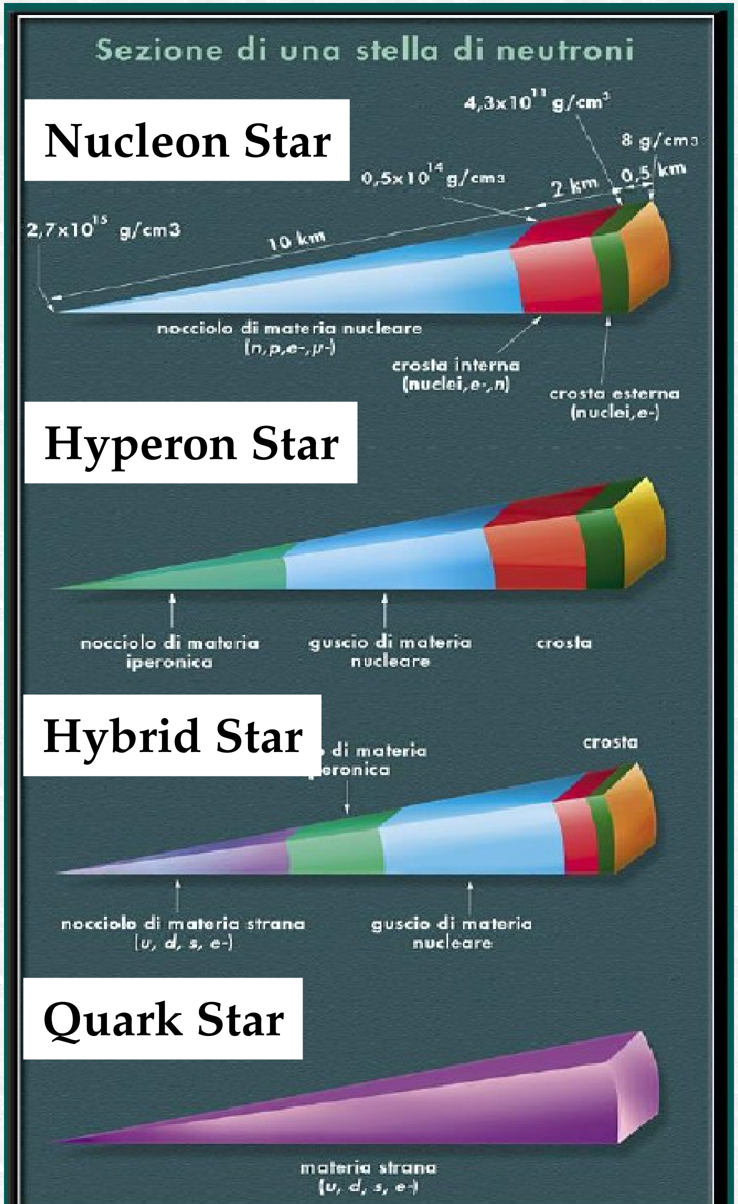
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$



# Essential impact on the case of NEUTRON STARS




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

## 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

## A M A D E U S proposal:

**Y N CORRELATION STUDIES**

Isolate hyperon scattering processes with:

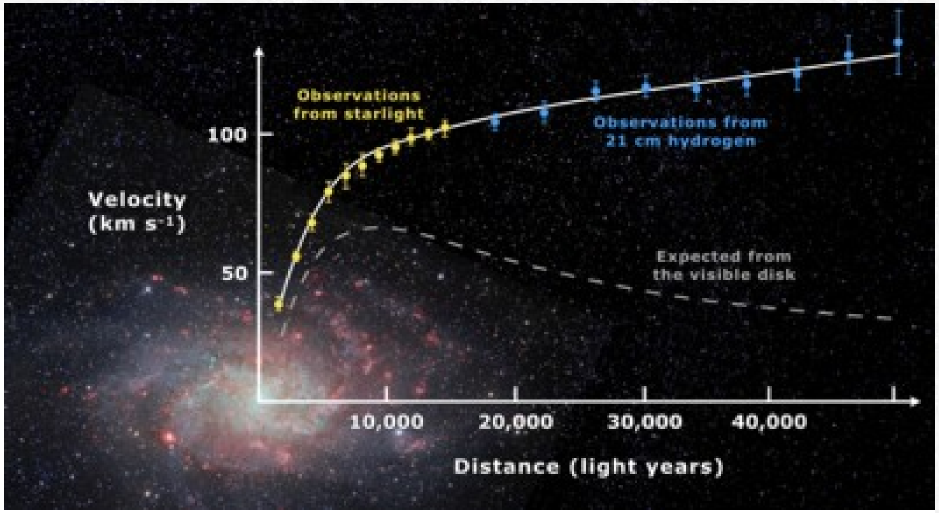
- single nucleon $Y\,N \rightarrow Y'\,N'$
- two nucleons $Y\,N_1 N_2 \rightarrow Y'\,N_1' N_2'$

# Λ(1405) conglomerates as Dark Matter candidates?

Dark Matter ... one of the biggest challenges of modern astrophysics,

originally introduced in order to explain the rotation curves of spiral galaxies,

DM is also required as a fundamental component (30%)of the Universe's energy content.




unfortunately DM to do not couple with radiation as baryonic matter, required in order to explain its invisibility to traditional astronomical observations.

DM candidates: elementary particles ? macroscopic objects (MACHOs) ?
the parameter space covered by the families of plausible DM candidates extends from $10^{-15}$ GeV of axions up to $10^{15}$ GeV of wimpzillas, and cross sections (from $10^{-35}$ pb of gravitinos up to 1 pb of neutrinos).

# Λ(1405) conglomerates as Dark Matter candidates?

**Families of particles beyond the Standard Model ex. arising from supersymmetric theories However,**

**search at the Large Hadron Collider (LHC) in order to unveil traces of missing energy and momentum in baryonic collisions - a typical signature of events with production of non-interacting DM - have still not shown clear features of such phenomena in large energy ranges,**

**The investigation of the density of MACHOs in the Milky Way and in extragalactic halos has shown that such objects are not abundant enough to represent a signicant fraction of the DM mass.**

**DM particles could self-interact via annihilation or decay to produce SM pairs, that subsequently annihilate into final-state photons. If the mass of the DM candidates is more than some GeV such photons could be detected on Earth through emission of Cherenkov radiation in the atmosphere.**

**New hypothesis stable Λ(1405) conglomerates, whose formation may be conceived during the Big-Bang Quark Gluon Plasma period in the early universe.**

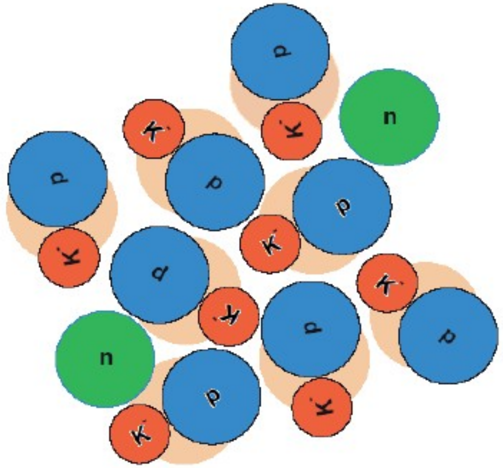
# Λ(1405) conglomerates as Dark Matter candidates?

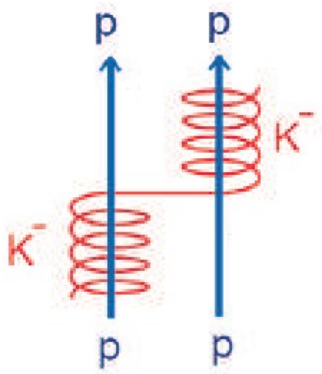
**Attractive isospin I=0 antikaon-nucleon (KbarN) strong interaction at energies below the threshold, conjectured to be strong enough to form a barKN bound state,**

**the Λ(1405) interpreted as a (KbarN) $_{I=0}$ bound state → the Binding Energy (BE) being about 27 MeV → BE for the Λ(1405) - Λ(1405) pair of 40 MeV is predicted,**

**increasing the number of Λ(1405), the binding energy per baryon (BE/A) would increases as a consequence of partial restoration of chiral symmetry, proportional to the baryon density,**

**conglomerates with baryon multiplicity A > 8 reach absolute stability with respect to both the strong and the weak interactions.**

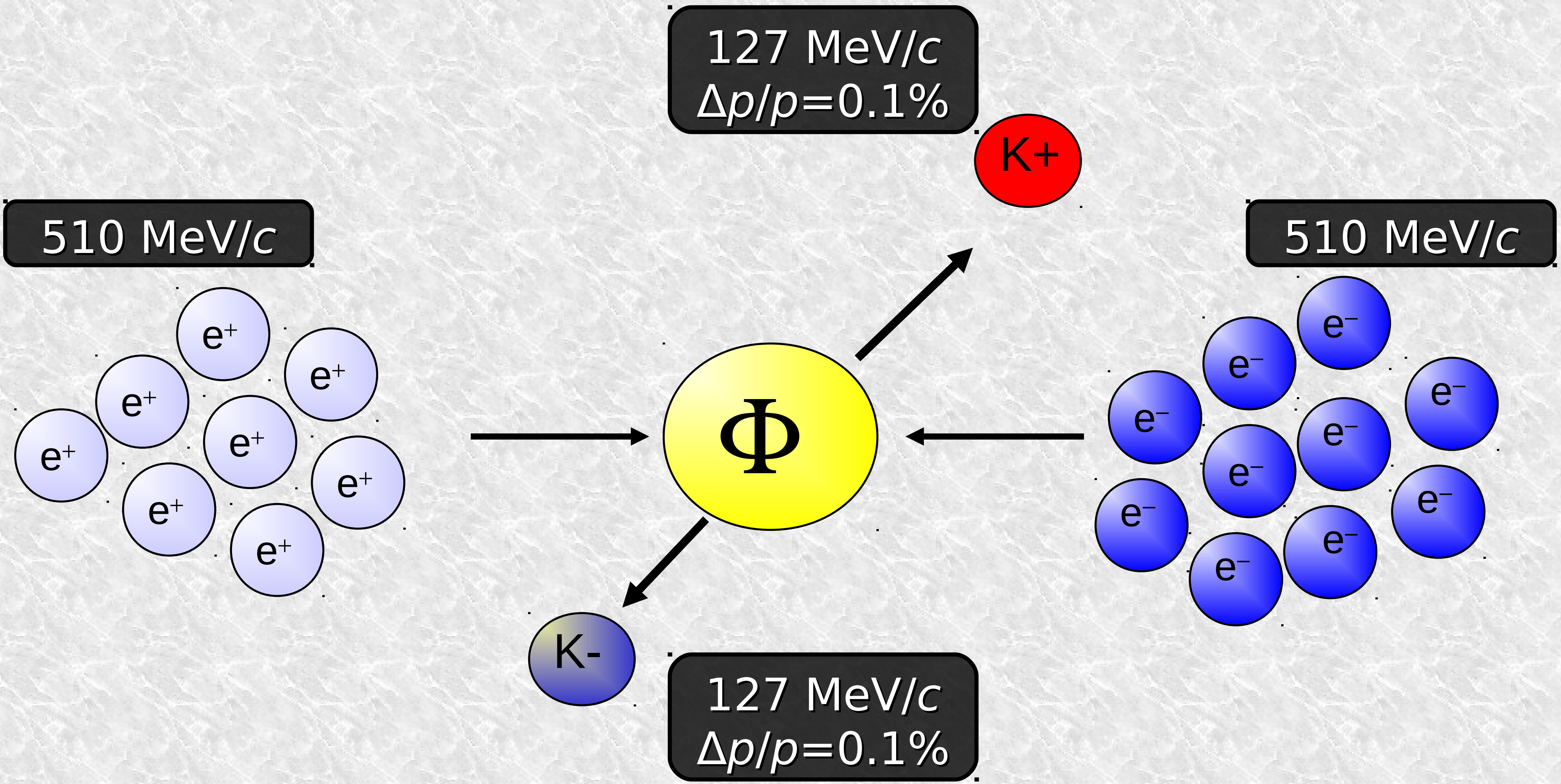



**BUT ... relativistic mean field calculations → including also a repulsive interaction to the model the BE/A saturates.**

# DAΦNE

# The DAFNE principle




Flux of produced kaons: about 1000/second

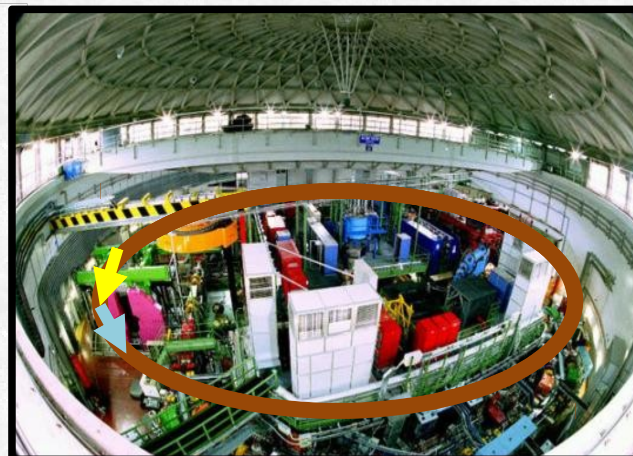
# AMADEUS & DAΦNE

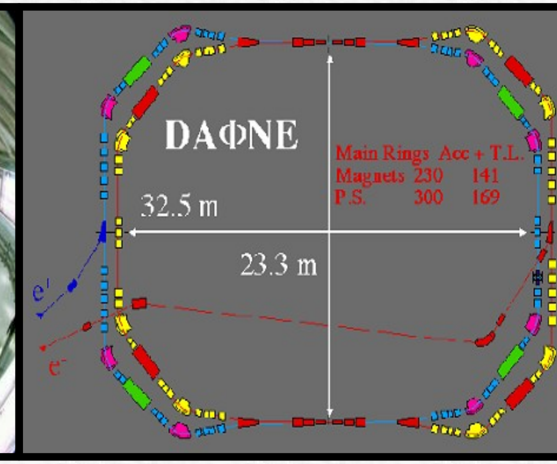
## DAΦNE

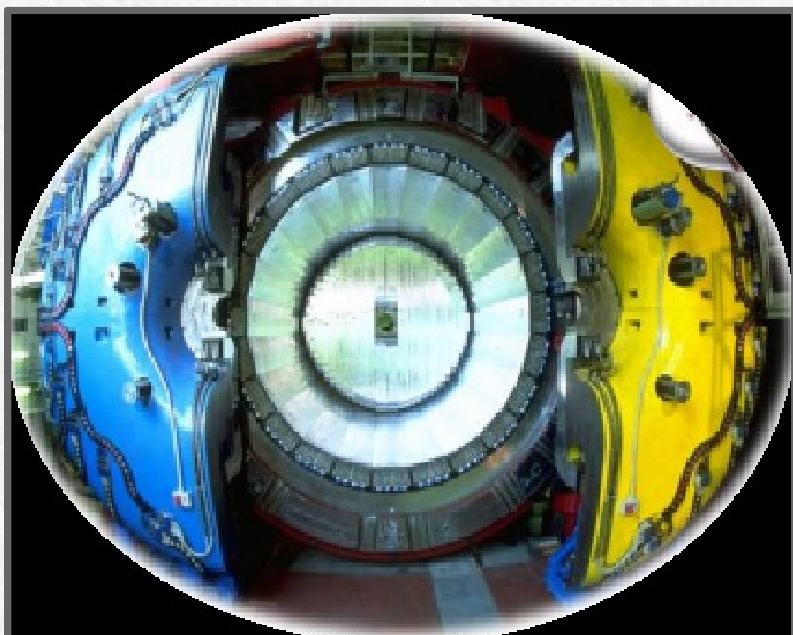
- double ring $e^+ e^-$ collider working at C.M. energy of $\phi$, producing **≈ 1000 $\phi$ /s**

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

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





## KLOE

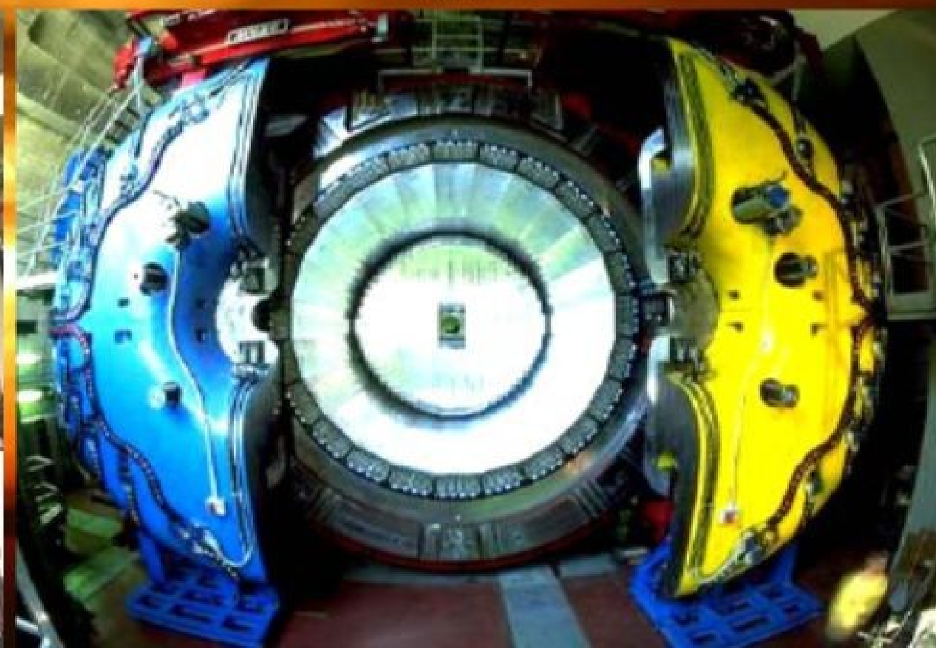
- Cilindrical drift chamber with a **4π geometry** and electromagnetic calorimeter
- **96% acceptance**
- optimized in the energy range of all **charged particles** involved
- **good performance** in detecting **photons and neutrons** checked by kloNe group [M. Anelli et al., Nucl Inst. Meth. A 581,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

# AMADEUS & DAΦNE

## The Kloe experiment at DAΦNE Φ-factory

**Multi-purpose detector for $K_{long}$ physics**

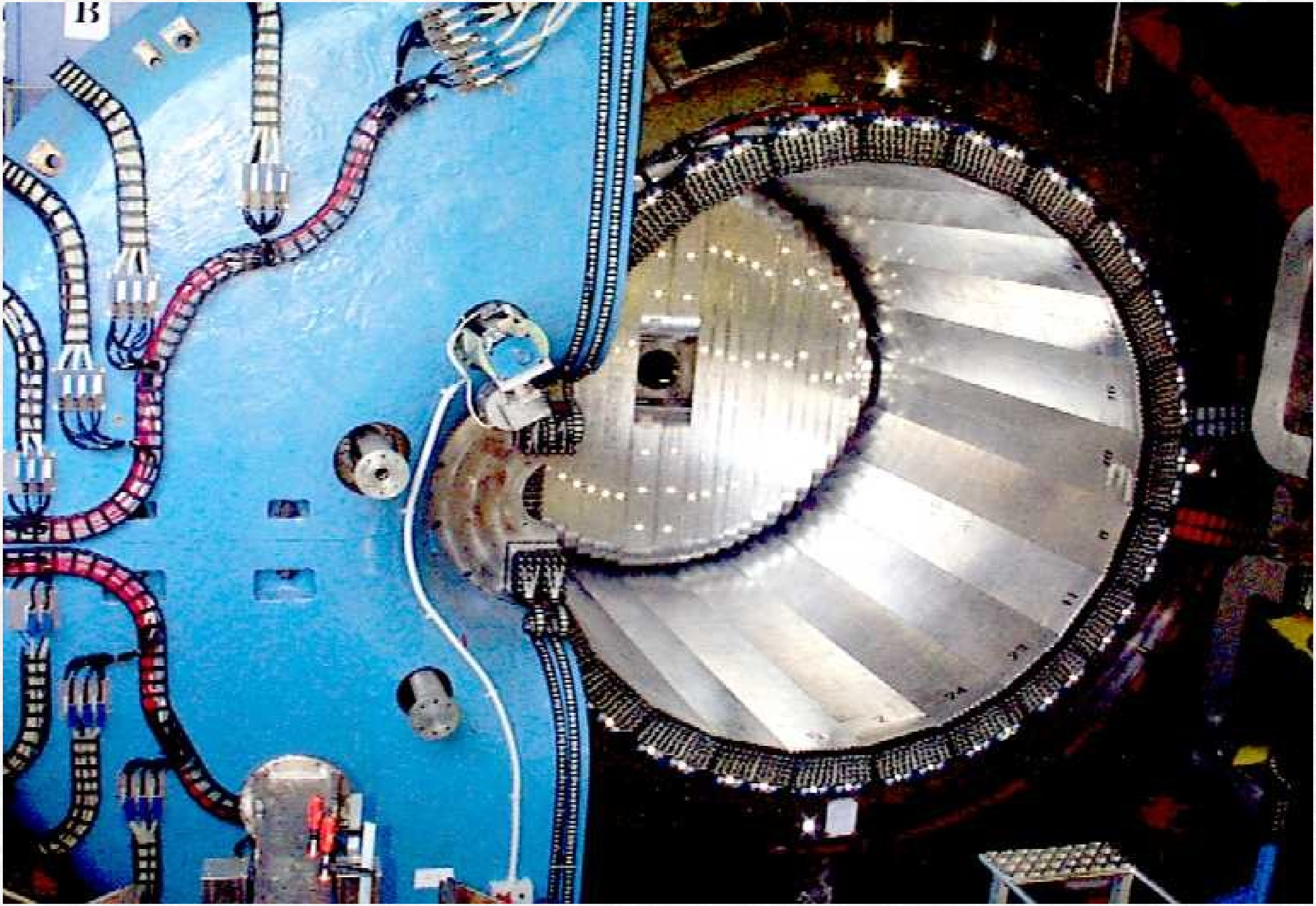
**$e^+e^-$ collider @ $\sqrt{s}$ = 1019.4 MeV**



- ❑ Thin CF structure, Ø = 4m, L = 4m;
- ❑ 52140 stereo wires, 12540 W sense wires, Al field wires;
- ❑ He/i-C4H10=90/10 gas mixture;
- ❑ $\sigma(p_T)/p_T$ ~ 0.4% (in 0.5T of the SC coil)

- ❑ Pb-scintillating fiber
- ❑ 24 barrel modules, 4m long * C-shaped End-caps for full hermeticity
- ❑ $\sigma_T = 54ps/\sqrt{E(GeV)}$
- ❑ $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$

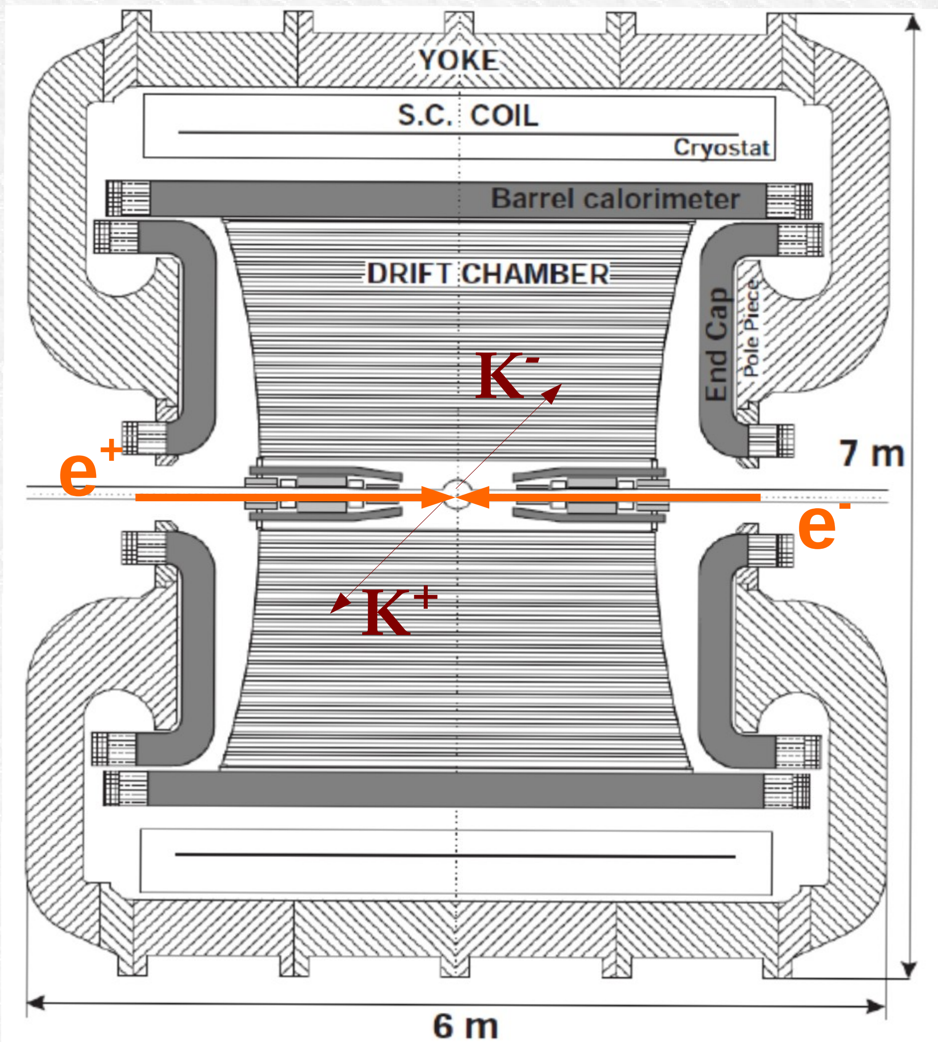
# AMADEUS & DAΦNE



# $K^-$ absorption on light nuclei

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 μm C foil , 150 μm Al foil).




Possibility to use **KLOE materials** as an **active target**

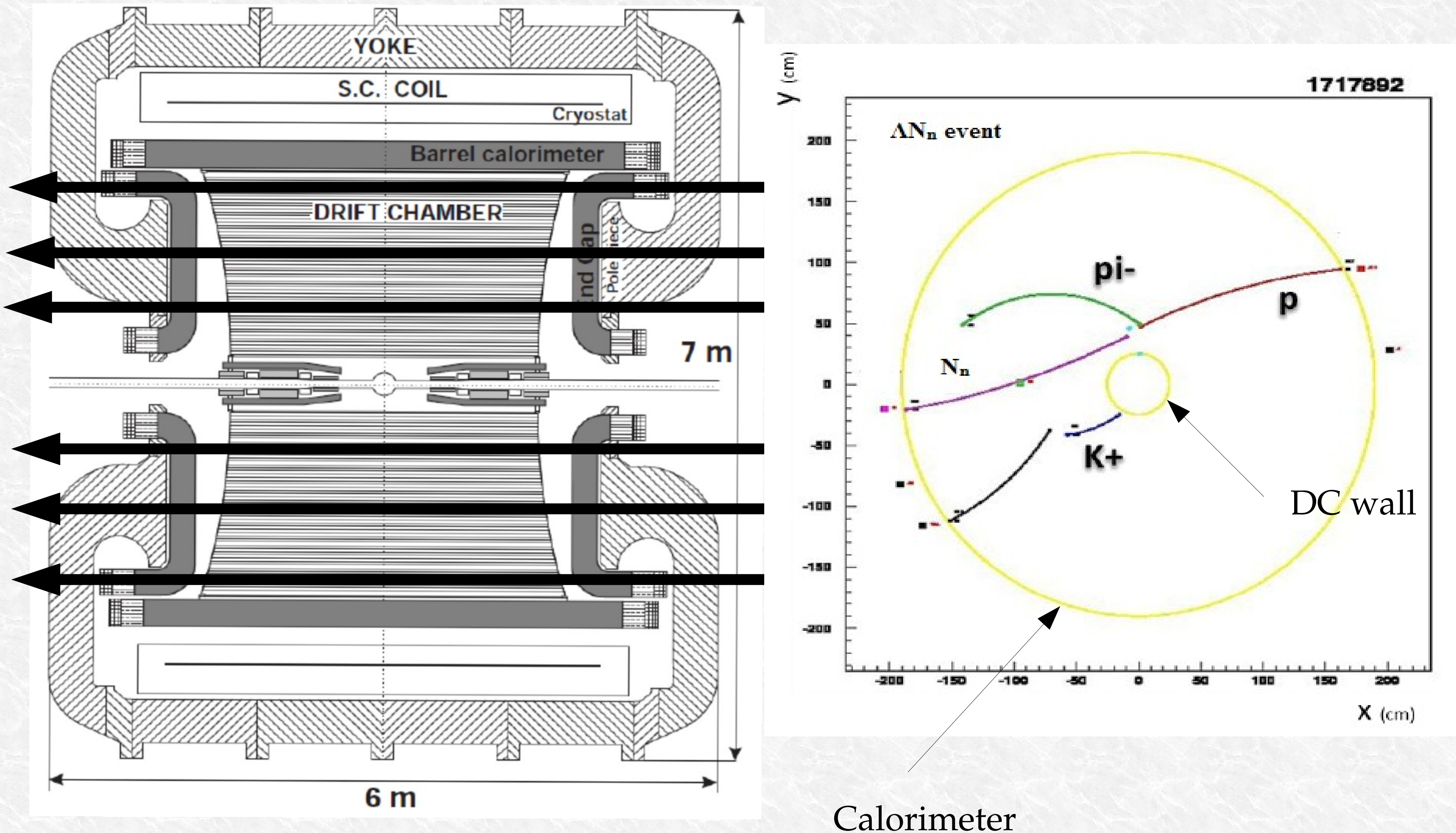
Advantage:

**excellent resolution** ..

$\sigma_{p\Lambda}$ = 0.49±0.01 MeV/c in DC gas

$\sigma_{m\gamma\gamma}$ = 18.3±0.6 MeV/$c^2$

# K$^-$ absorption on light nuclei



# AMADEUS: the scientific goal

**Low-energy** $K^-$ interaction studies with **light nuclei** (H, $^4$He, $^9$Be, $^{12}$C) in order to extract conclusive constrains on:

- **$\bar{K}$N Potential** → how deep can an antikaon be bound in a nucleus?

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

  - if $U_{\bar{K}N}$ is strongly attractive then possible $K^-$ multi-N bound states
    → we investigate through (Λ/Σ–N) decay ---Y N CORRELATION

- **Y-N potential** → extremely poor experimental information from scattering data

Deep impact on models of neutrons stars structure

# How search Λ(1405) signal?

**Production scheme:**

- K⁻ absorption experiments: the K⁻ beams are produced first and then captured from the target nuclei.

Example: $K^- + {}^4He \rightarrow \Lambda(1405) + pnn$

$\hookrightarrow \Sigma^0 + \pi^0 \rightarrow \Lambda\gamma + \gamma\gamma \rightarrow p\pi^- + \gamma\gamma$

# How search Λ(1405) signal?

## Analysis procedure:

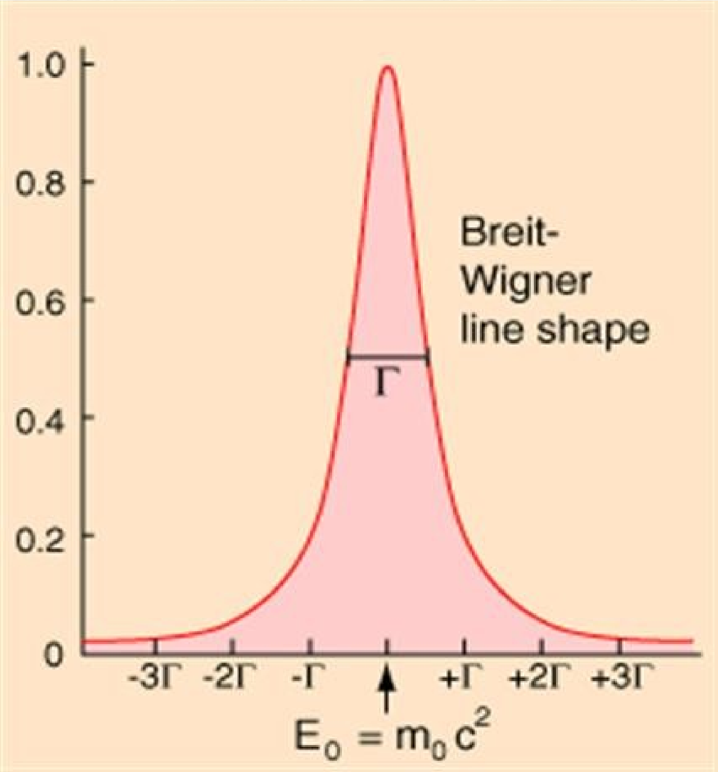
- Invariant mass spectroscopy: all the decay products of the particle have to be detected and their energy-momentum has to be determined. This allows the reconstruction of the invariant mass and hence the calculation of the "binding energy" and width (that is mean life) of this object.

Example: $K^- + {}^4He \rightarrow \Lambda(1405) + pnn$

$\Lambda(1405) \rightarrow \Sigma^0 + \pi^0$

$$M^2_{(\Lambda)} = (E_\Sigma + E_\pi)^2 - (p_\Sigma + p_\pi)^2$$

energy cons. momentum cons.



# How search Λ(1405) signal?

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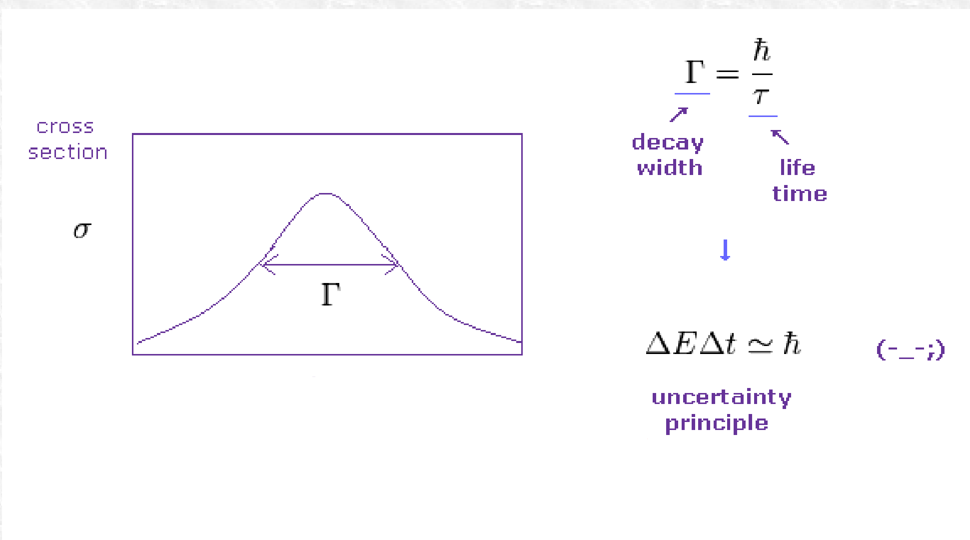
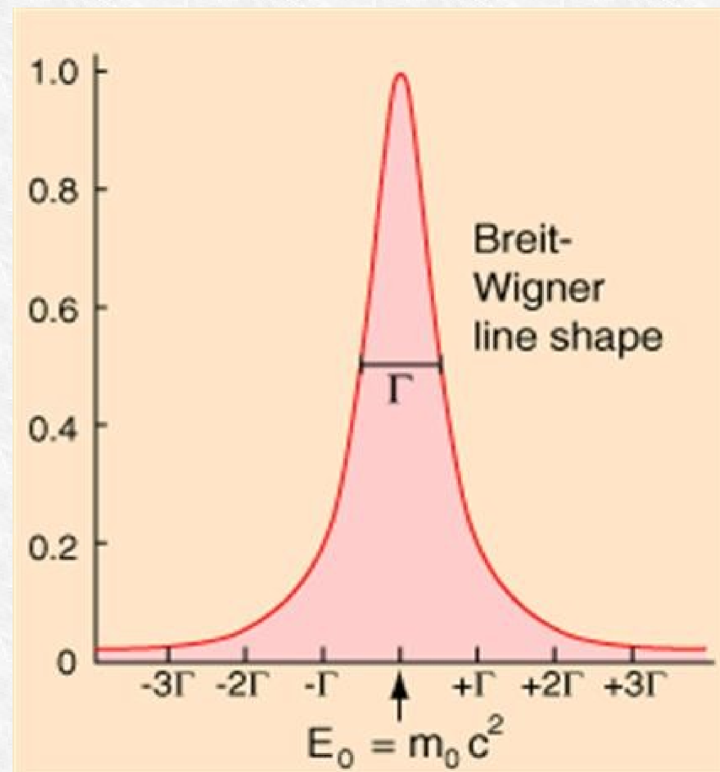
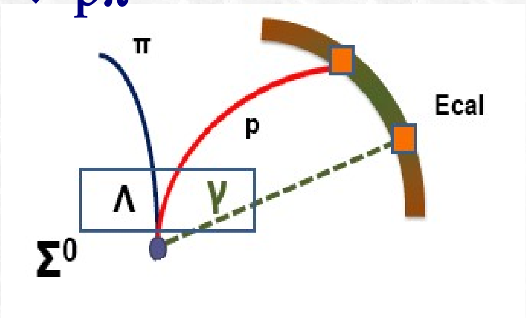


# particles identification, momentum energy measurement

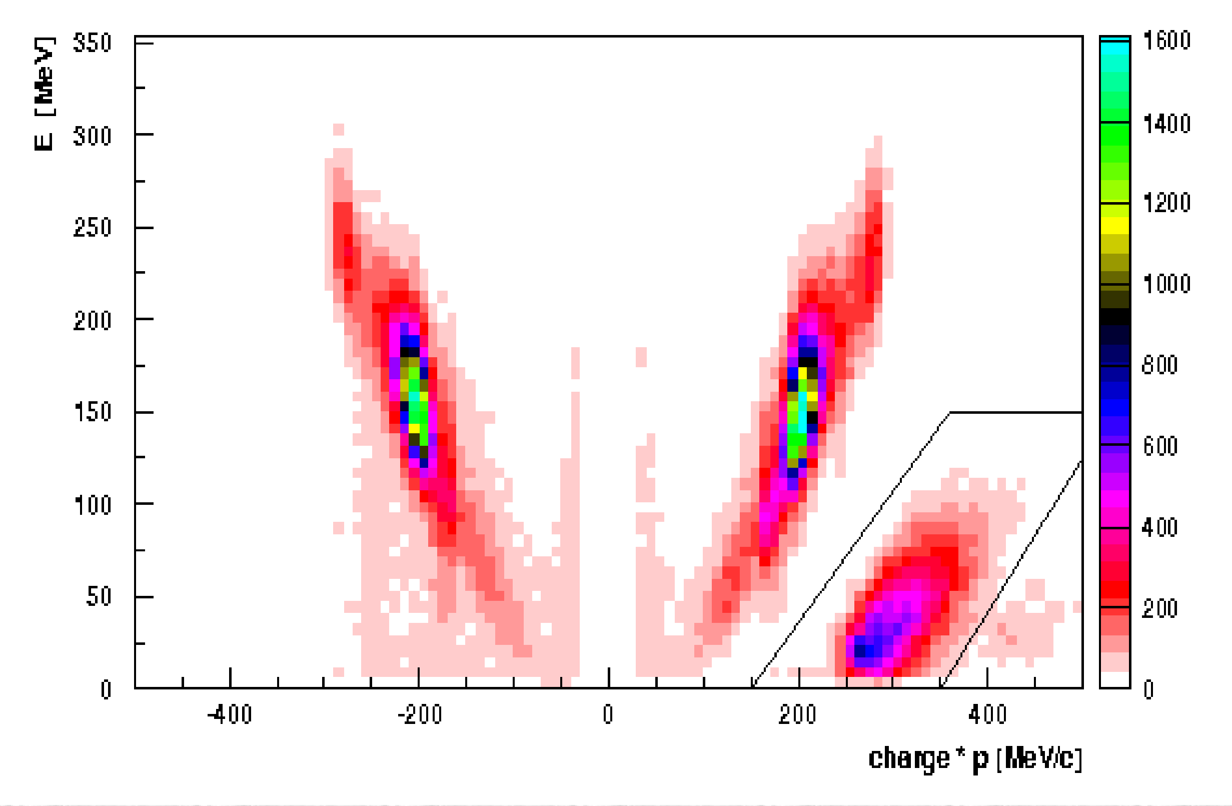
starting point .. reconstruction of the Λ decay vertex: Λ(1116) ➔ $p\pi^-$ (BR ~ 64 %)




requests:

- vertex with at least two opposite charged particles
- spatial position of vertex inside DC, or in DC entrance wall

Positive tracks are requested to have an associated cluster in the calorimeter and the correct *E* - *p*



# particles identification, momentum energy measurement

$$\Lambda(1405) \rightarrow \Sigma^0\pi^0 \rightarrow (\Lambda\gamma)(\gamma\gamma) \rightarrow (p\pi^-)\,3\gamma$$

1) 3 neutral clusters selection in calorimeter (no track!)

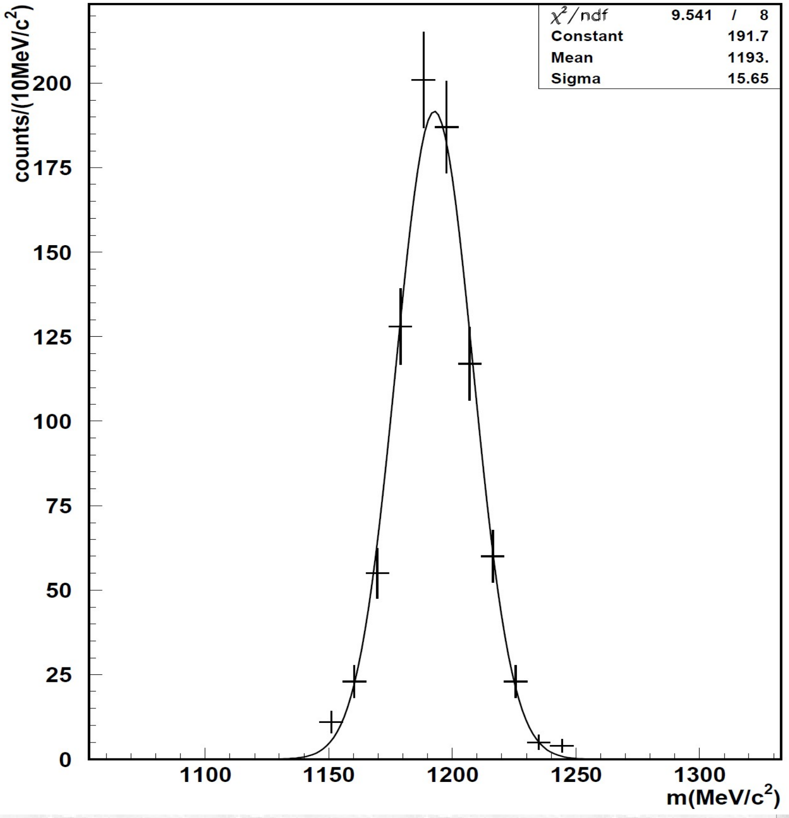
2) **photon clusters selection**: $\chi_t^2 = t^2/\sigma_t^2$ where $t = t_i - t_j$

time of flights in light speed hypothesis.

Three photons in time from the $\Lambda$ decay vertex $r_\Lambda$

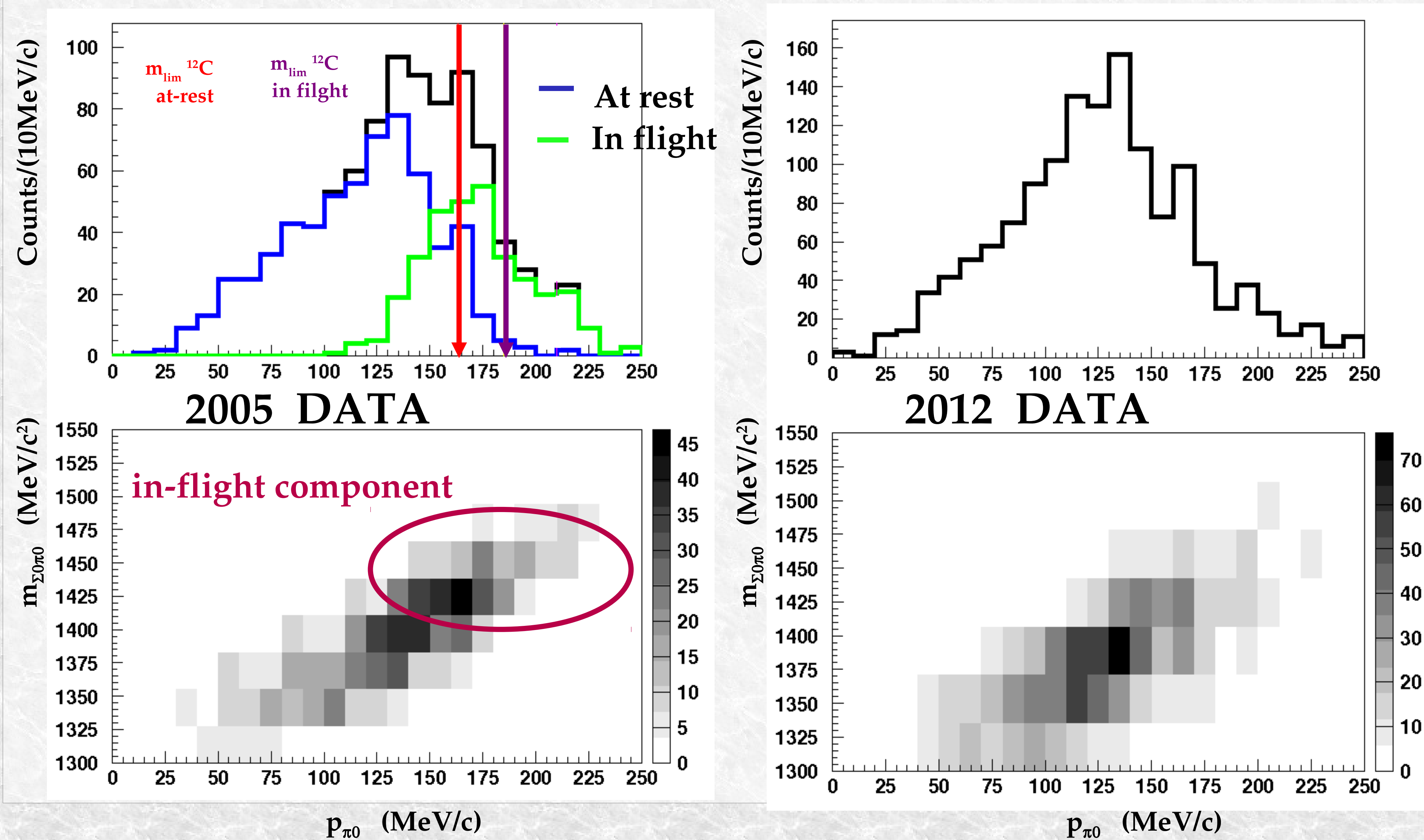
3) **photon clusters identification**: $\gamma_3$ from $\pi^0 \rightarrow \gamma_1\gamma_2$

$$\chi^2_{\pi\Sigma} = \frac{(m_{\pi^0} - m_{ij})^2}{\sigma^2_{ij}} + \frac{(m_{\Sigma^0} - m_{k\Lambda})^2}{\sigma^2_{k\Lambda}}$$



# Invariant mass spectrum

$p_{\pi 0}$ **resolution:** $\sigma_p \approx 12$ MeV/c



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  - if $U_{\bar{K}N}$ is strongly attractive then possible $K^-$ multi-N bound states
    → we investigate through ($\Lambda/\Sigma-N$) decay ---Y N CORRELATION

- **Y-N potential** → extremely poor experimental information from scattering data

Deep impact on models of neutrons stars structure

# How deep can an antikaon be bound in a nucleus?

## $K^{-}pp$ bound state.....the theory

Chiral SU(3)-based (Energy dependent) → Shallow~20 MeV

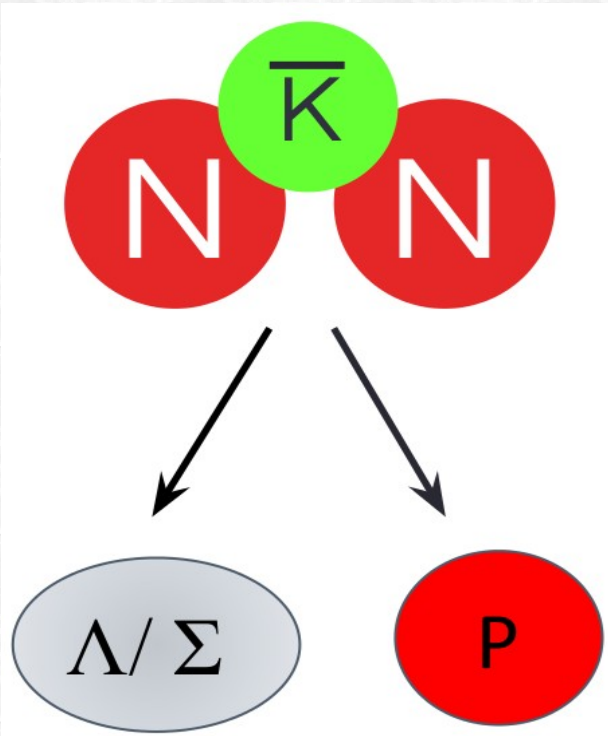
Phenomenological (Energy independent) → Deep~40-70 MeV

| | 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. |

**Large width** means short-life state → hard to measure

**Small width** means long-life state → easy to measure

# 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 <u>if</u> strong $\bar{K}$N interaction in the I=0 channel.**

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

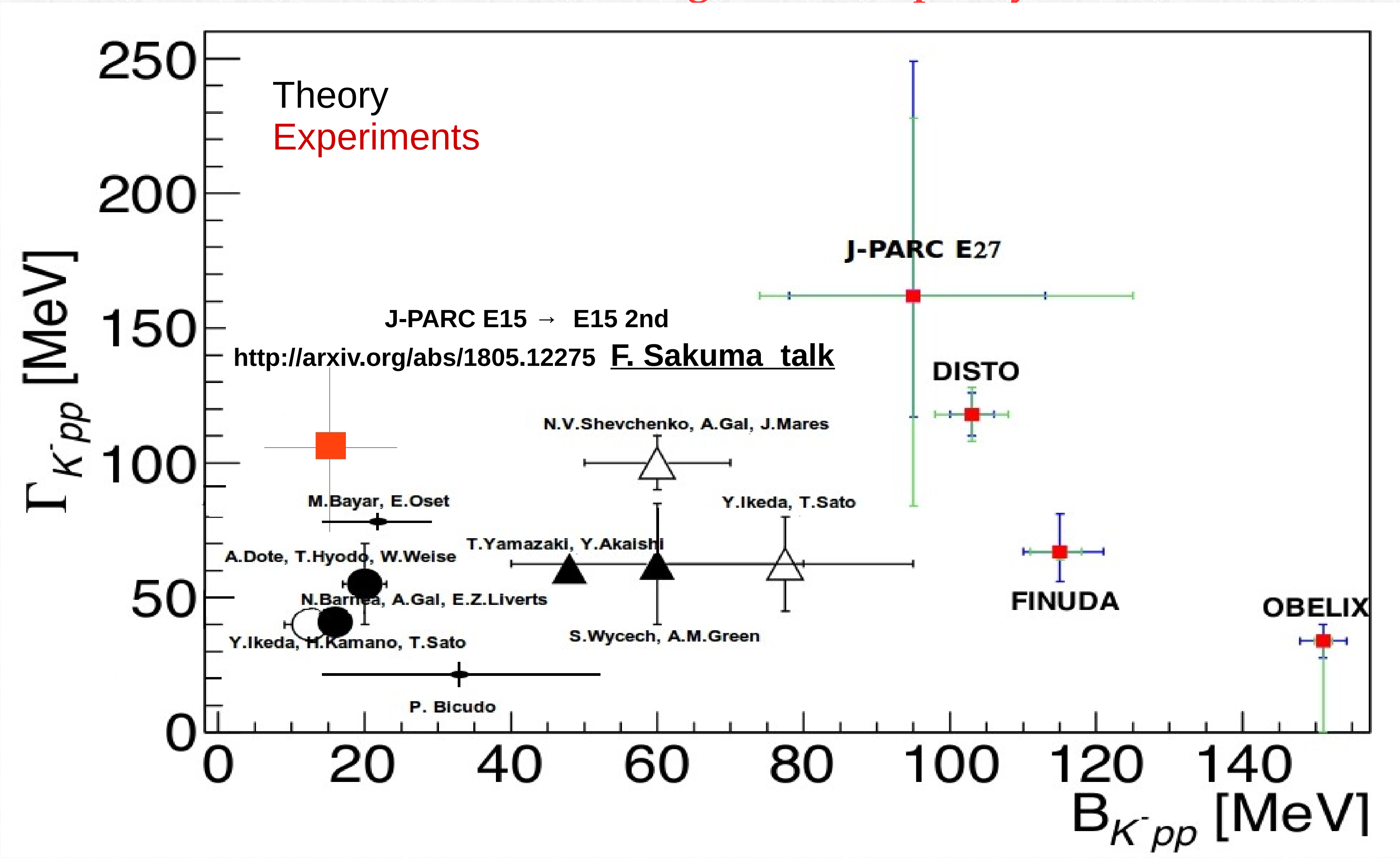
**$K^-$pp bound state**

| | 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]

# How search the kaonic bound states?

## Production schemes for kaonic bound states:

- <u>$K^-$ absorption experiments</u>: the $K^-$ beams are produced first and then captured from the target nuclei.

Examples:

$K^- + {}^3He \rightarrow (K^-pp) + n$
- $\rightarrow \Lambda + p$
- $\rightarrow \Sigma^0 + p$

$K^- + {}^4He \rightarrow (K^-ppn) + n$
- $\rightarrow \Lambda + d$
- $\rightarrow \Sigma^0 + d$

# How search the kaonic bound states?

**Analysis procedures to study kaonic nuclear clusters:**

- Invariant mass spectroscopy: all the decay products of the cluster have to be detected and their 4-momentum has to be determined. This allows the recostruction of the invariant mass of the decaying cluster and hence the calculation of the binding energy and width of this object.

Example: $K^- + {}^3He \rightarrow (K^-pp) + n$

$\rightarrow \Lambda + p$

$\rightarrow \Sigma^0 + p$

$$M^2_{(K\text{-}pp)} = (E_\Lambda + E_p)^2 - (p_\Lambda + p_p)^2$$

# Search for the $K^-pp$ bound state

**AMADEUS:**

- Invariant mass spectroscopy
- $K^-$ absorption experiment →

**Backgrounds**: the competiting processes in the search for kaonic bound states are the so-called single and multi-nucleon absorption processes.

EXAMPLE

Let us suppose we want to search the signal of $K^-pp$ bound state in $K^-$ interactions in $^4He$ through the $\Lambda p$ decay channel

$$K^- + {}^4He \rightarrow \Lambda + p + n + n$$

$$K^- + \text{“}pp\text{”} \rightarrow K^-pp \rightarrow \Lambda + p$$ → This is the process we want to search

**2NA**: $K^- + \text{“}pp\text{”} \rightarrow \Lambda + p$

$K^- + \text{“}pp\text{”} \rightarrow \Sigma^0 + p$

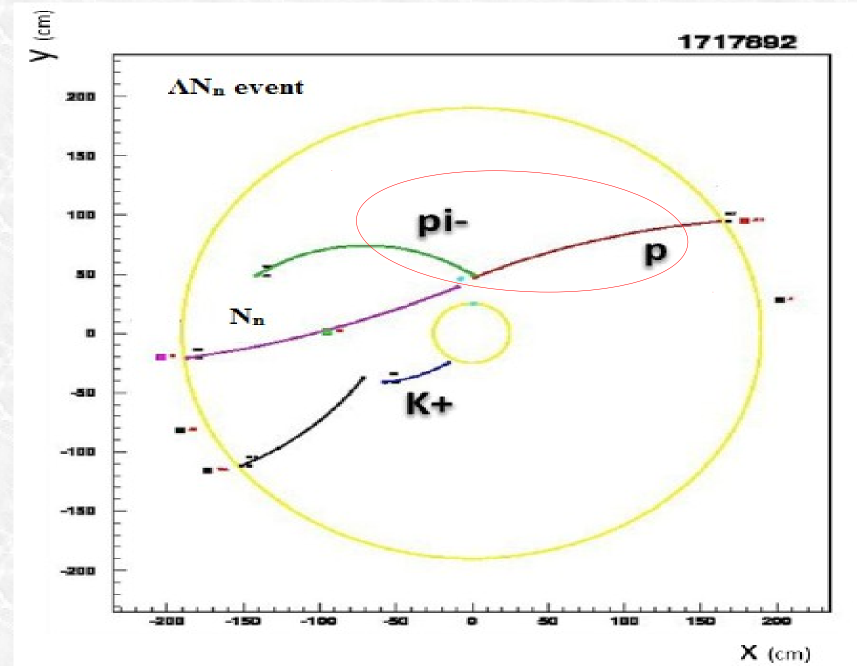
$\Sigma^0 + n \rightarrow \Lambda + n$

**$\Sigma^0$ to $\Lambda$ conversion processes**

**3NA**: $K^- + \text{“}ppn\text{”} \rightarrow \Lambda + p + n$

**4NA**: $K^- + \text{“}ppnn\text{”} \rightarrow \Lambda + p + n + n$

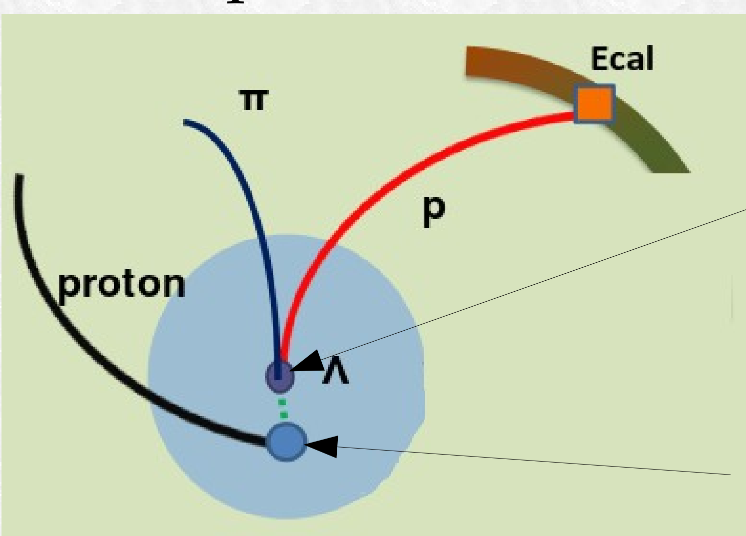
# Hadronic interaction vertex recostruction




1st Step: $\Lambda \rightarrow p + \pi^-$ identification

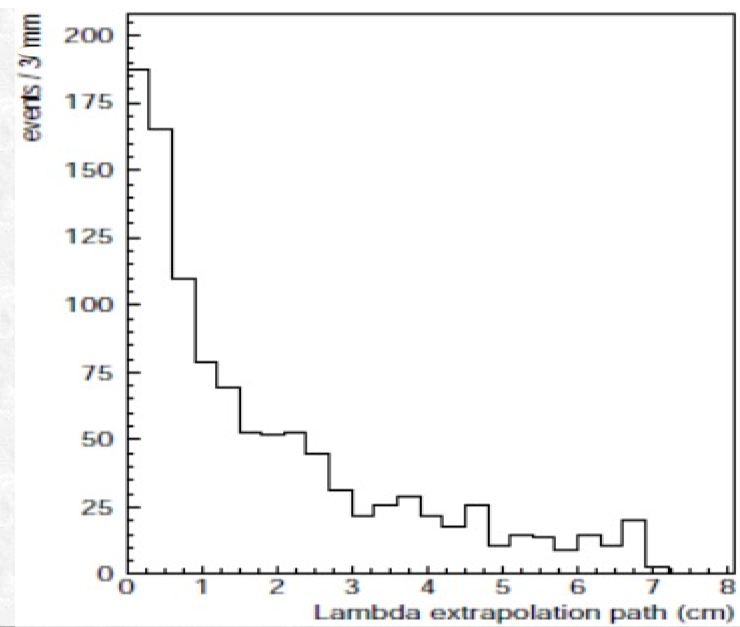
(BR = 63.9 ± 0.5 %)

2nd Step: **hadronic interaction vertex** searched extrapolating backwards the Λ path and an extra positive track

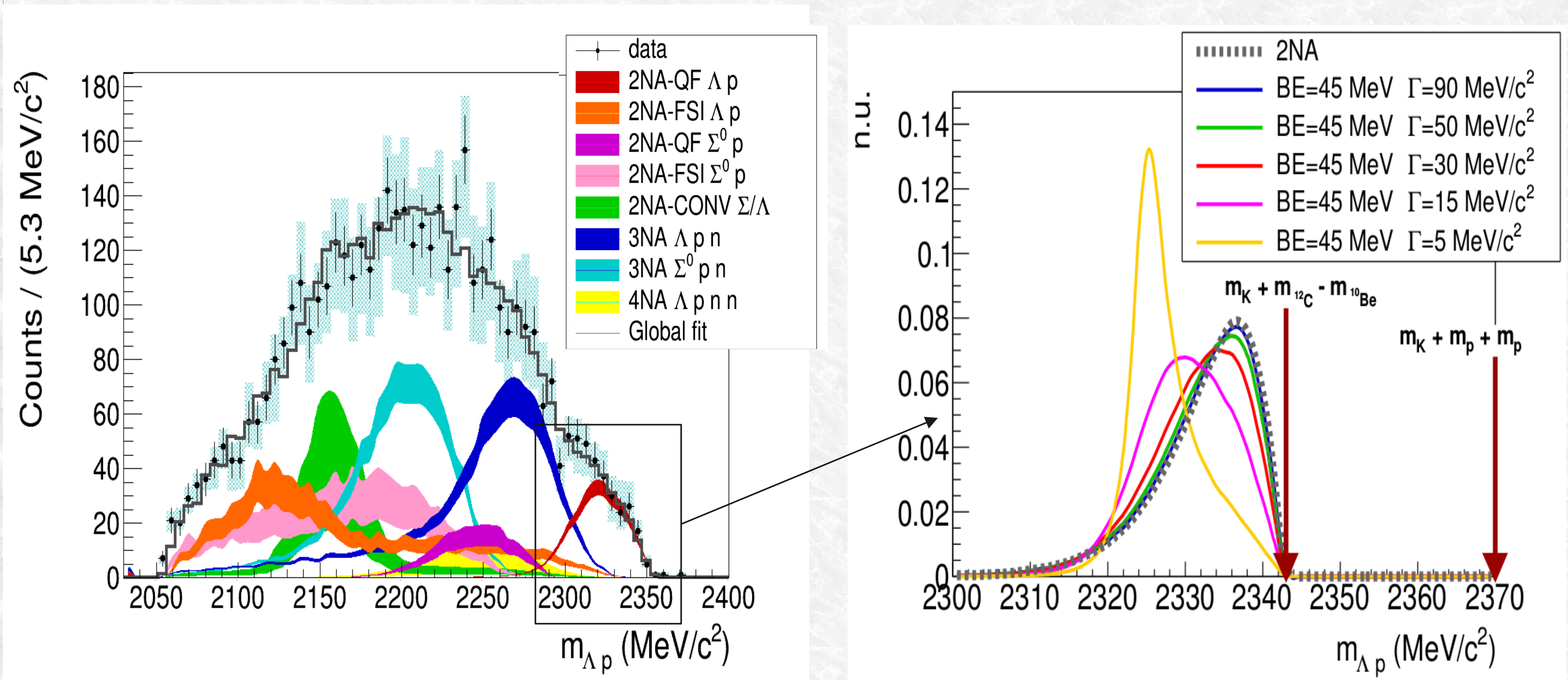



**Λ decay vertex**

**hadronic vertex**



# Λ p invariant mass



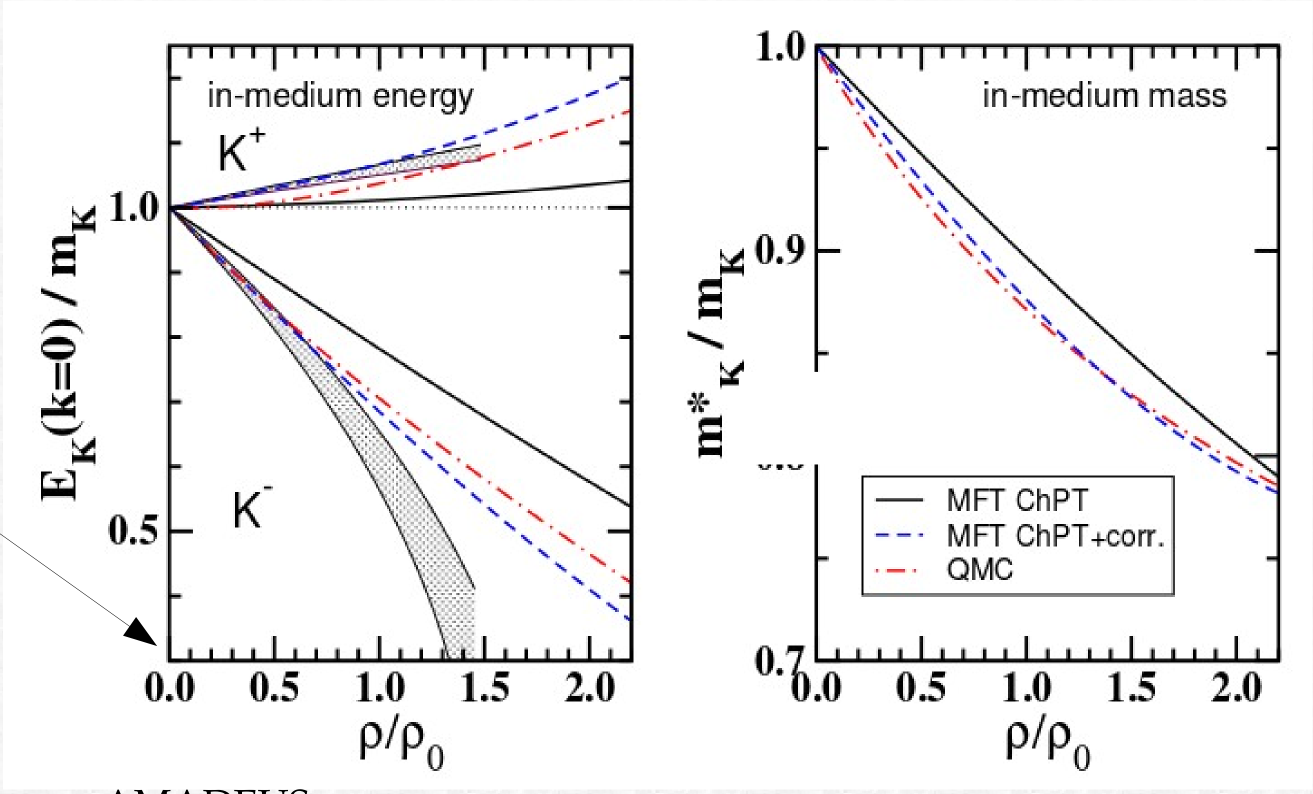

No evidence for a deeply bound state!

# From AMADEUS to SIDDHARTA

AMADEUS investigates the behavior of anti-kaons inside the nuclear medium.

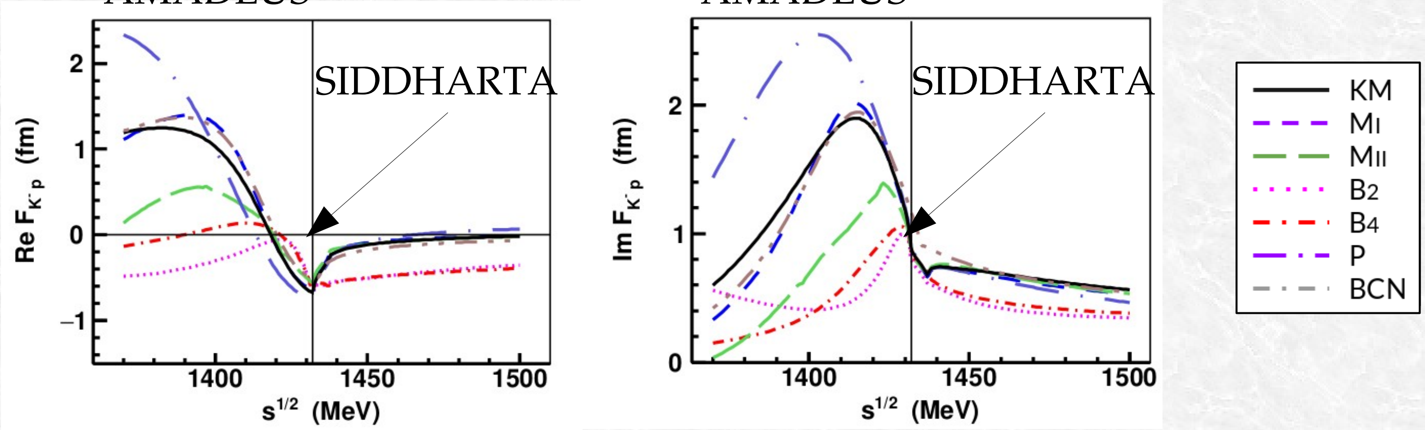
SIDDHARTA investigates the free interaction $\rho = 0$

of anti-kaons and nucleons at ZERO momentum




AMADEUS

AMADEUS



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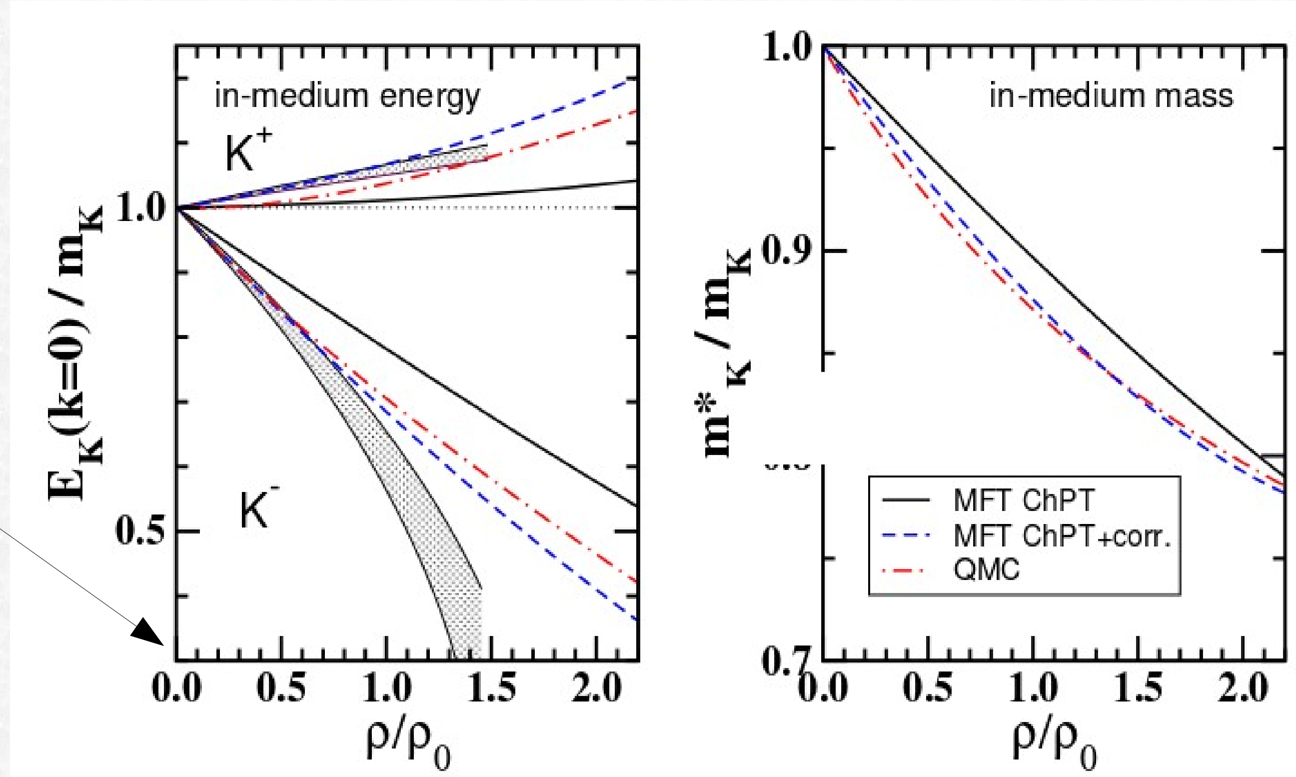
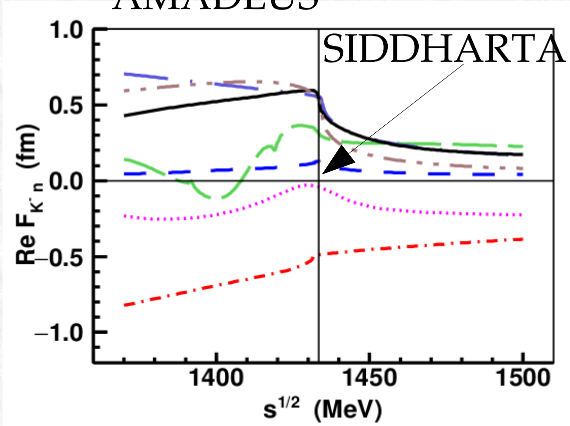
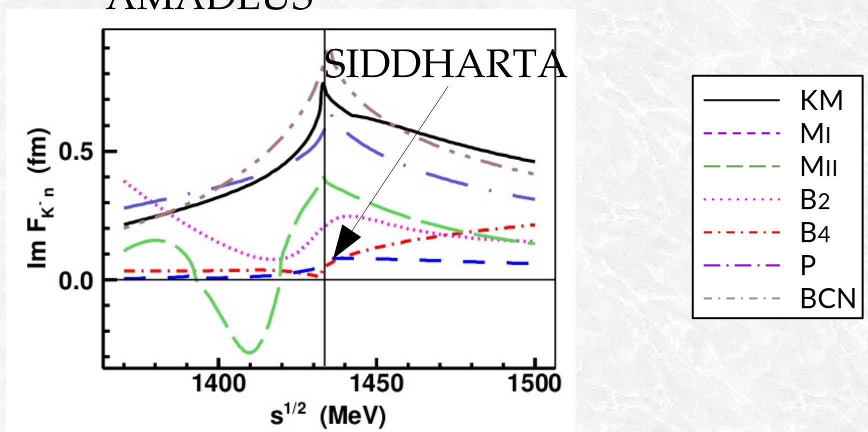


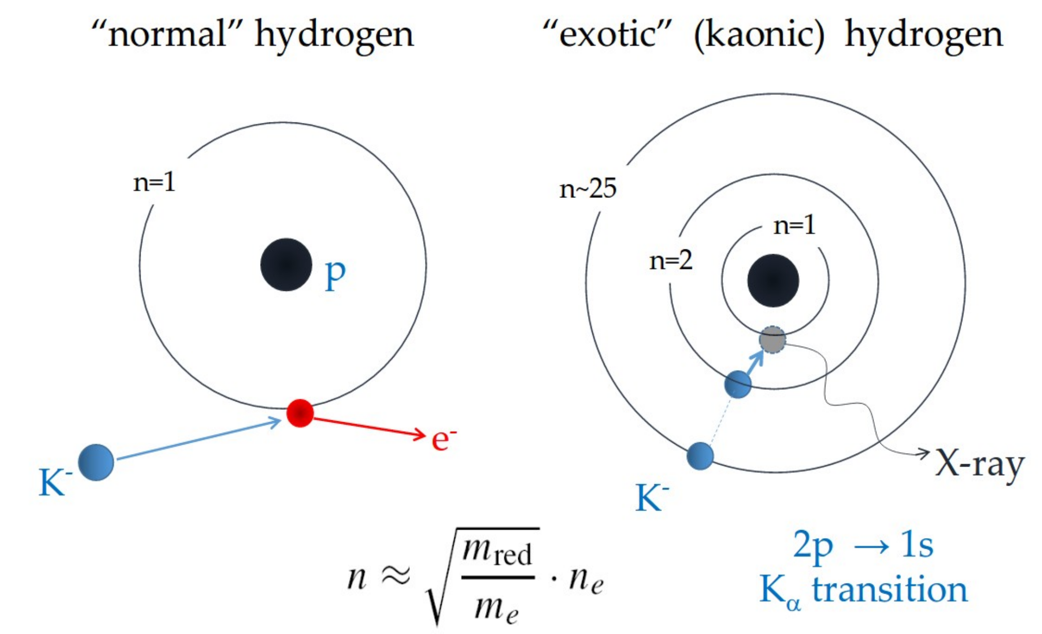

AMADEUS

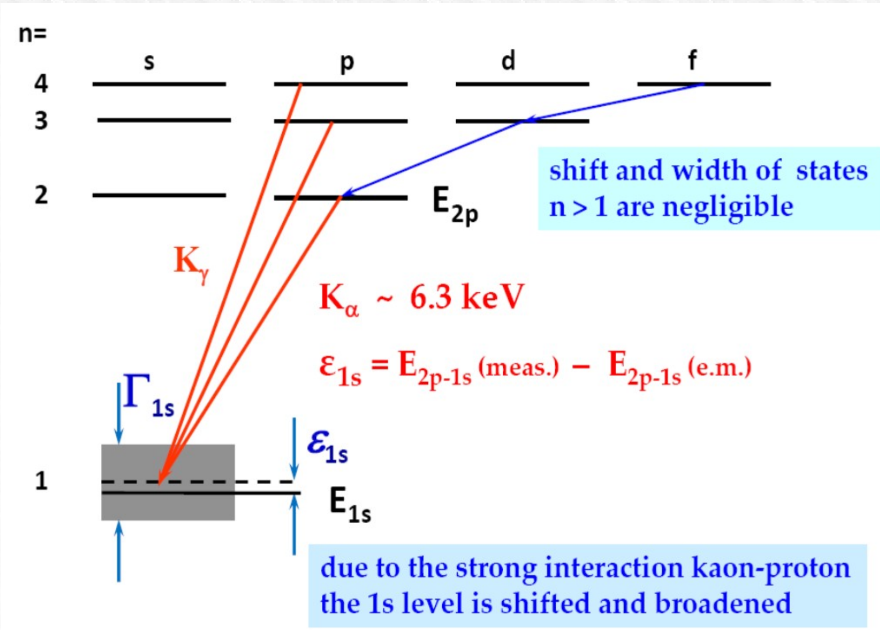



AMADEUS



# KAONIC ATOMS




Strong interaction causes a **shifting of the energy ($\varepsilon_{1s}$)** of the lowest atomic level from its purely electromagnetic value.

Absorption reduces the lifetime of the state, so X-ray transitions to this final atomic level are **broadened ($\Gamma_{1s}$)** .

# Anti-kaon nucleon scattering lengths

Deser-type relation connects shift $\varepsilon_{1s}$ and width $\Gamma_{1s}$ to $a_{K\text{-}p}$ and $a_{K\text{-}d}$:

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-p} = 412\,\tfrac{eV}{fm}\,a_{K^-p}$$

done by SIDDHARTA

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-d} = 601\,\tfrac{eV}{fm}\,a_{K^-d}$$

aim of SIDDHARTA-2

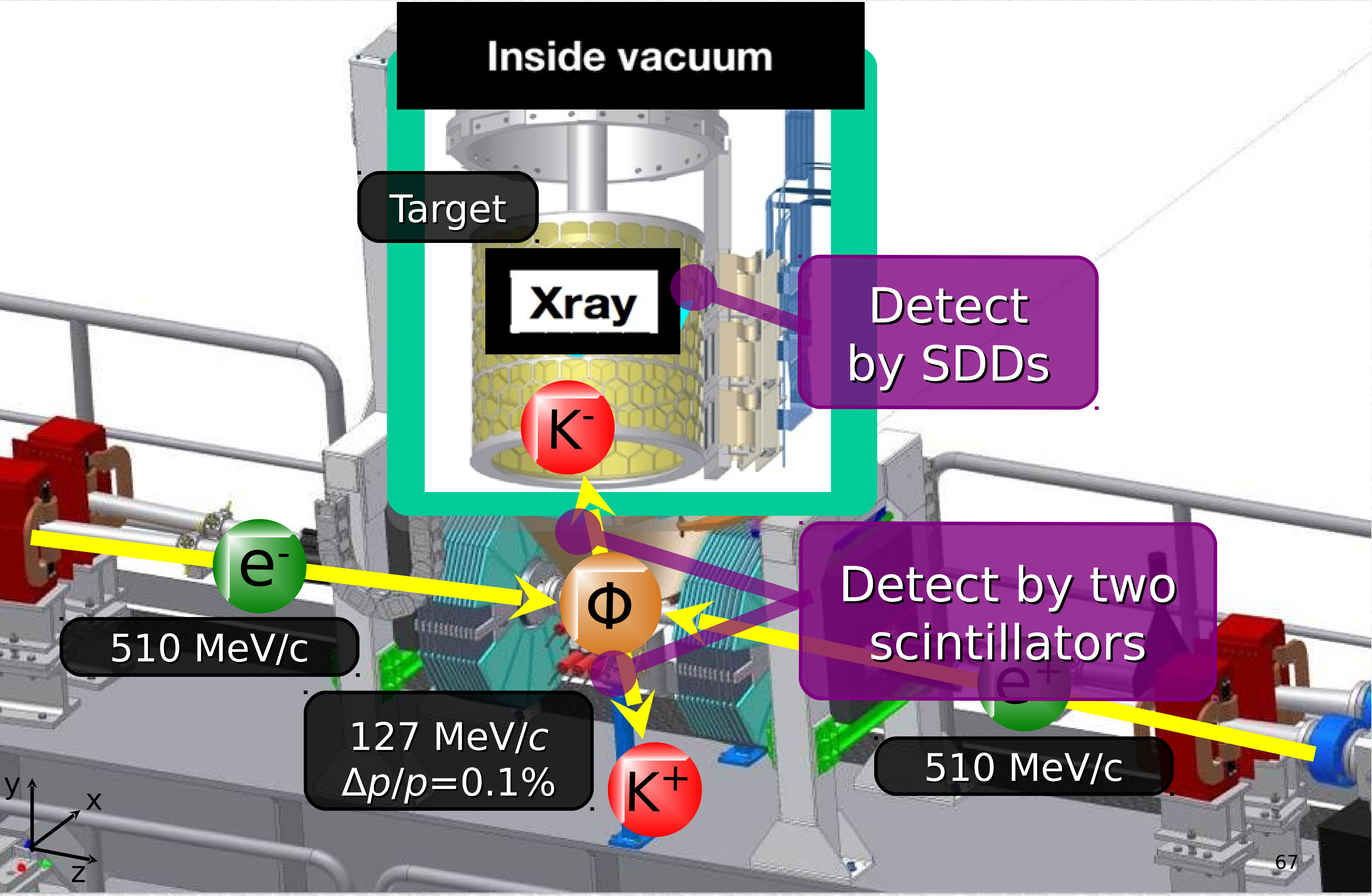
one can obtain the isospin dependent antikaon-nucleon scattering lengths

$$a_{K^-p} = \frac{a_0(I=0) + a_1(I=1)}{2}$$

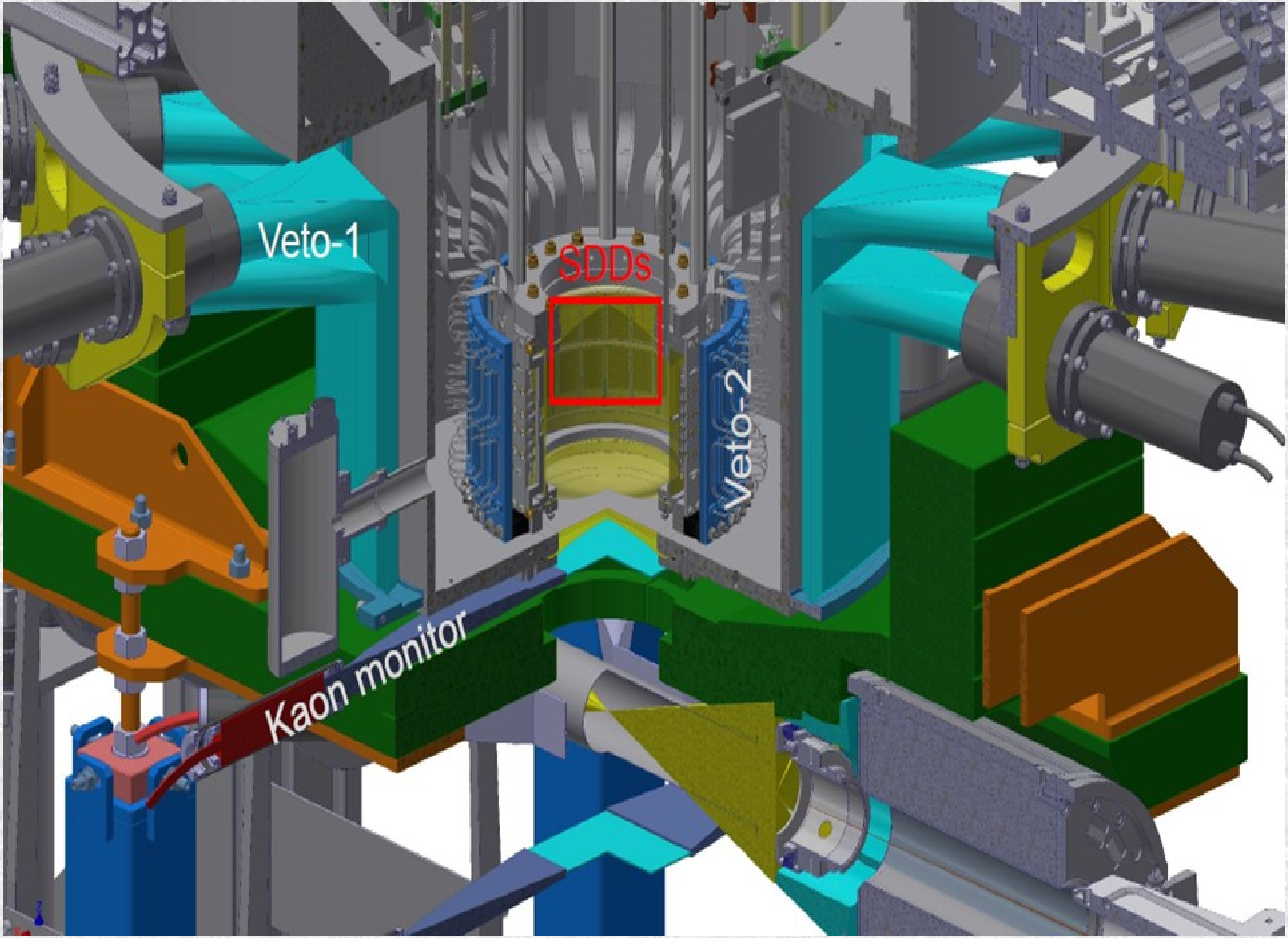
$$a_{K^-d} = \frac{1}{2}\frac{m_N + m_K}{m_N + \frac{m_K}{2}}(3a_1 + a_0) + C$$

→ **Fundamental inputs of low-energy QCD effective field theories**

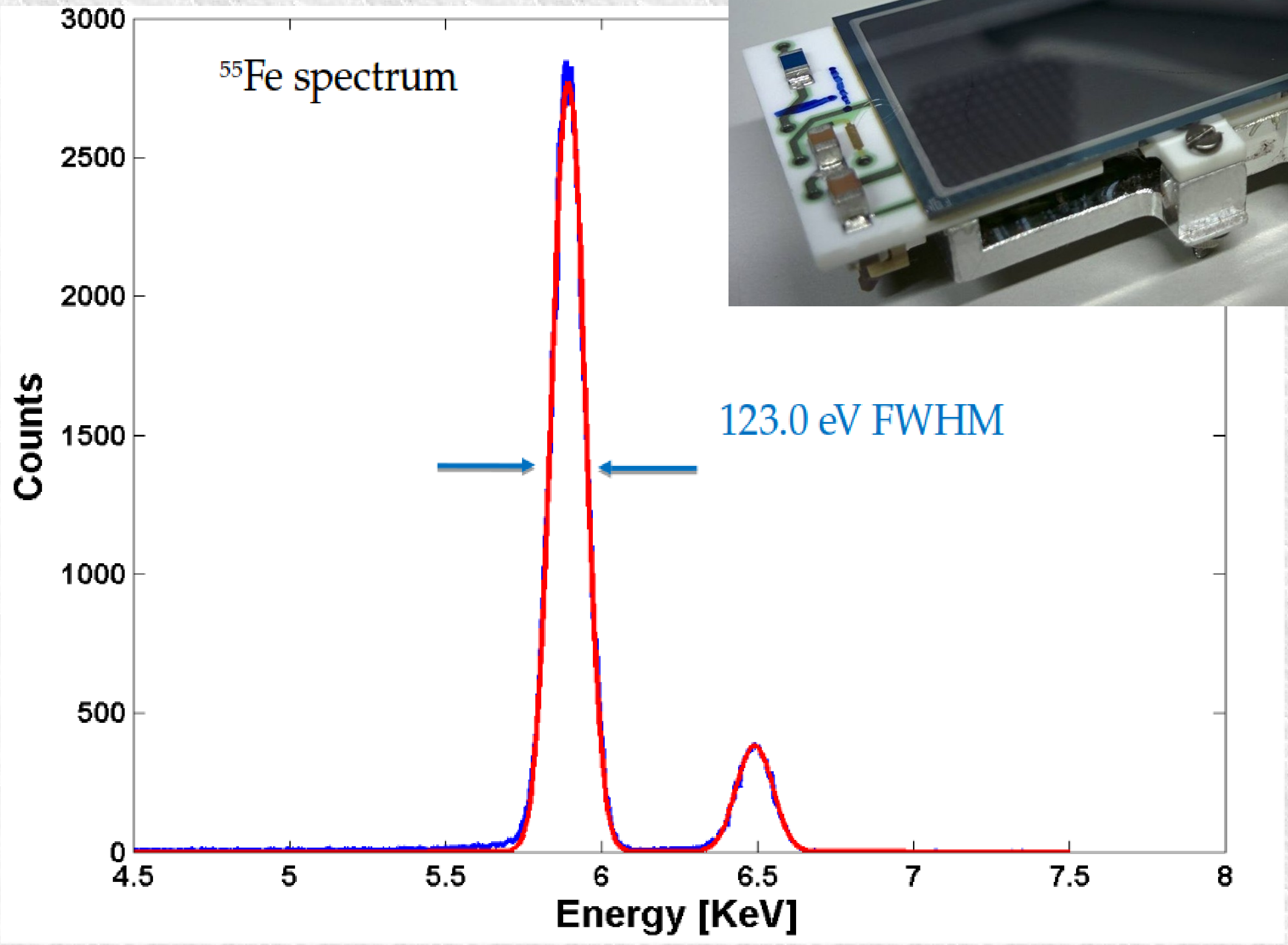
# SIDDHARTA-2 overview

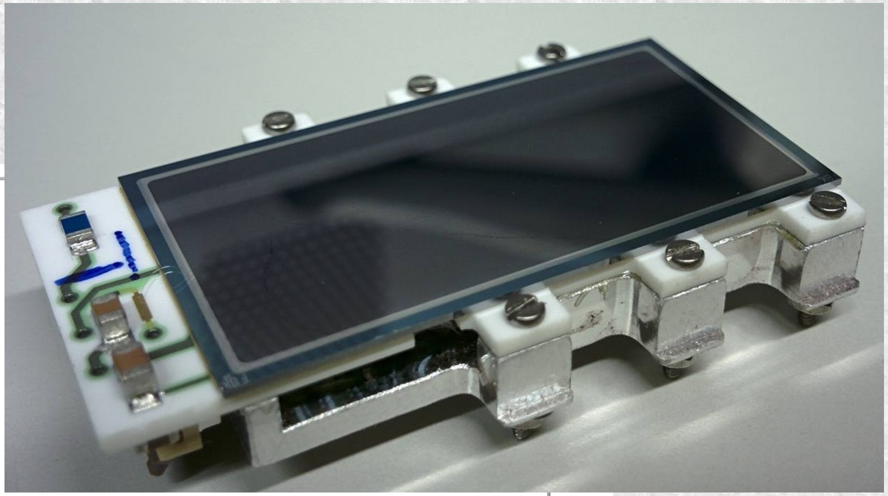


# SIDDHARTA-2 overview

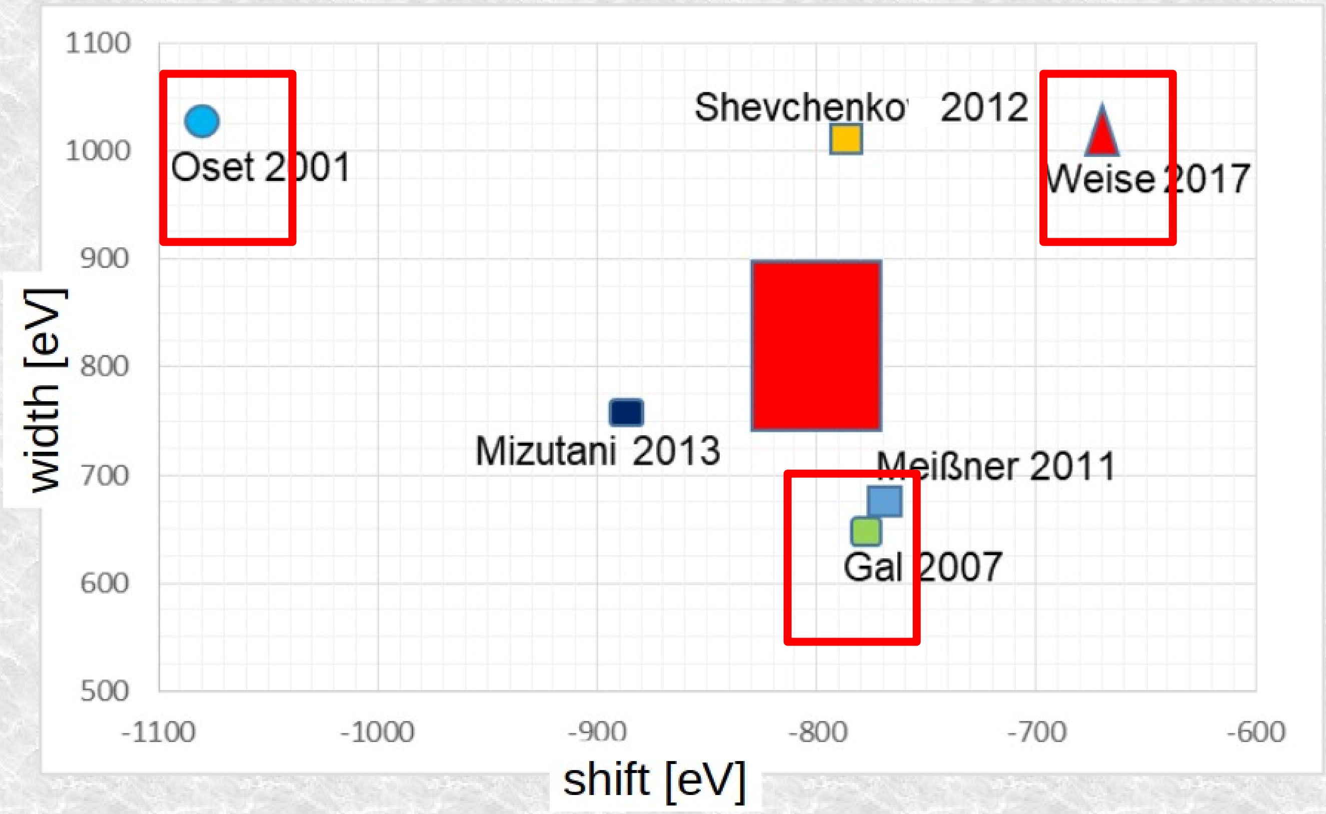


# SIDDHARTA-2 overview



# KAONIC-Deuterium puzzle



# SIDDHARTA-2

INSTALLATION OF THE SETUP WITH 8 SDDs AT DAΦNE
COMPLETED IN APRIL 2019

# Thank you :-)

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

- CHIRAL PERTURBATION THEORY

a chiral Lagrangian with effective degrees of freedom *U* takes the place of the QCD Lagrangian:

$$\exp(iZ) = \int \mathcal{D}q\mathcal{D}\bar{q}\mathcal{D}A_\mu \exp\left\{i\int d^4x\mathcal{L}_{QCD}\right\} = \int \mathcal{D}U \exp\left\{i\int d^4x\mathcal{L}_{eff}\right\}$$

lowest excitations (pseudoscalar mesons):

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

with chiral field $U(\Phi) = \exp\left\{\frac{i\sqrt{2}\Phi}{f}\right\}$

the counting rule is defined considering the meson momentum small respect to the ch. sy. Breaking scale $4\pi f \sim 1$ GeV.

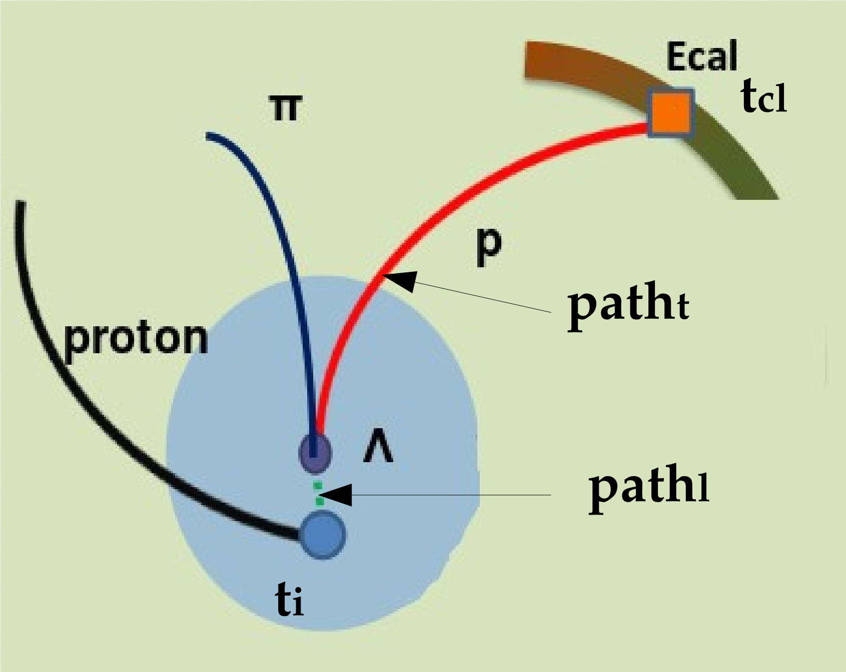
Similar for the baryon fields:

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

# Hadronic interaction vertex recostruction

For the selected Λp events, a check in the mass of the proton track can be done if it is associated with a cluster in the calorimeter, and one of the two particles from the lambda decay has as well an assiciated cluster. To calculate their mass by time of flight we use the time of the cluster ($t_{cl}$) of the lambda decay product and the time of the interaction ($t_i$):

$$t_i = t_{cl} - (path_t / v_t) - (path_l / v_l)$$




Using the time of the proton cluster in the calorimeter and $path_p$ we calculate the proton velocity $v_p$. The mass is calculated using the information of the proton momentum $p_p$:

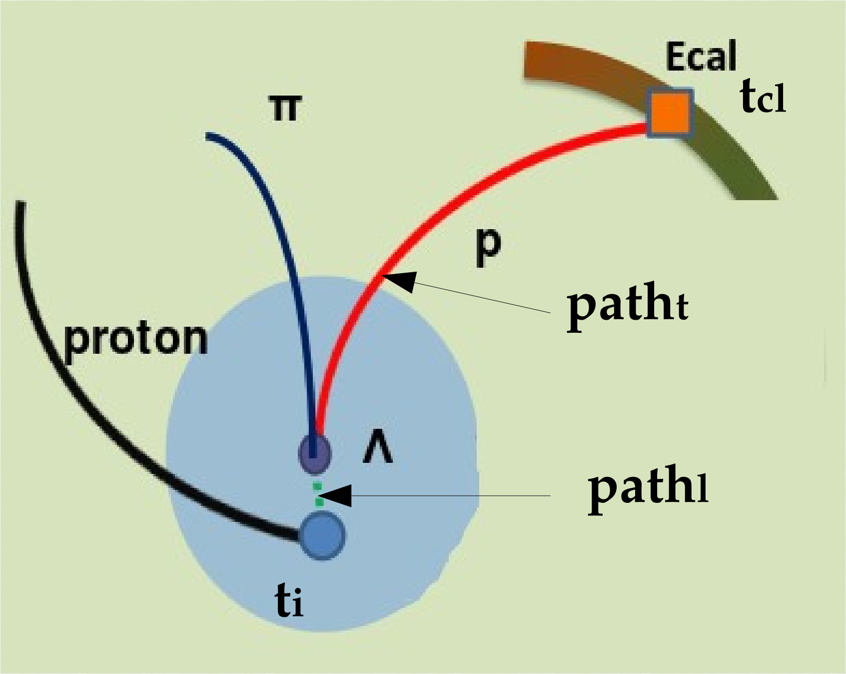
$$mass = p_p \cdot \sqrt{1/(v_p^2/c^2)}$$

# Hadronic interaction vertex recostruction

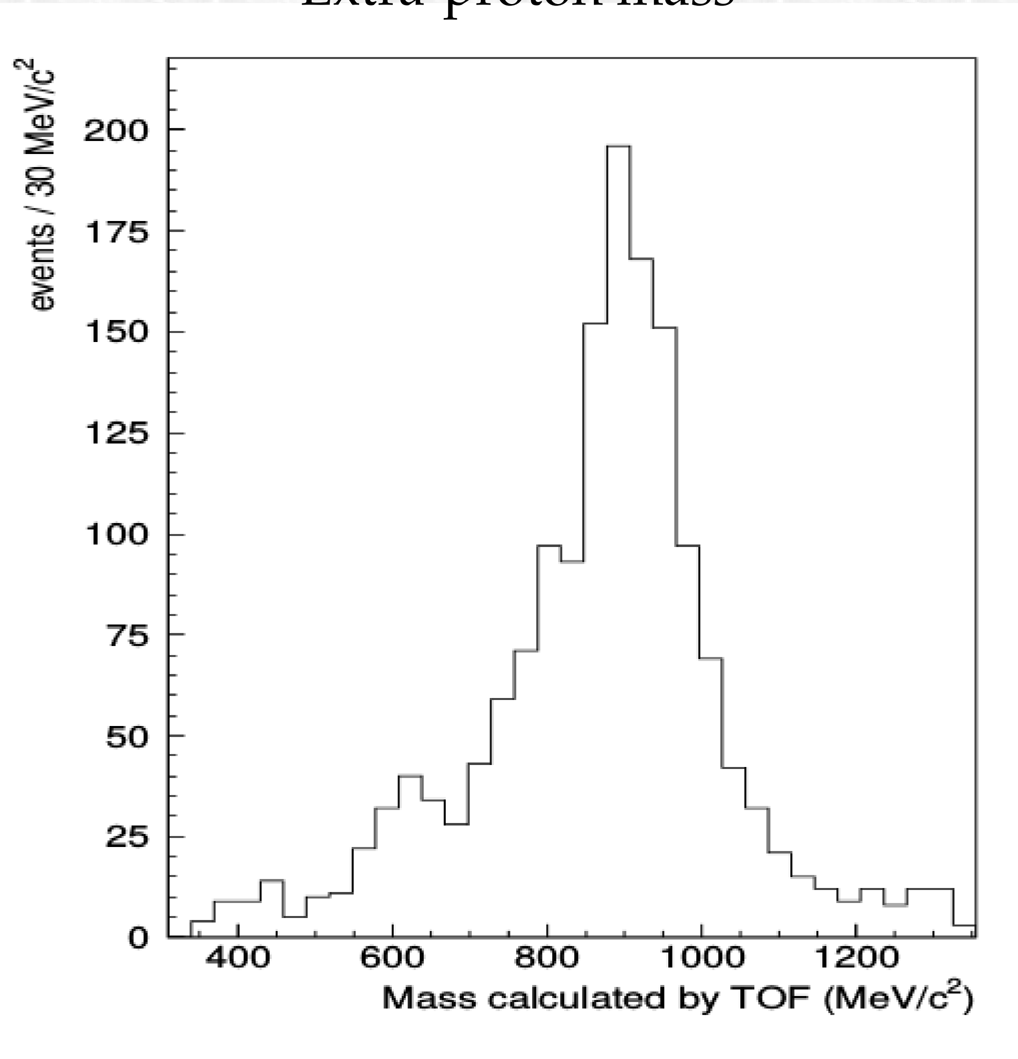
**Resolutions:**

From MC simulations of $K^-$ absorption in $^4He$

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

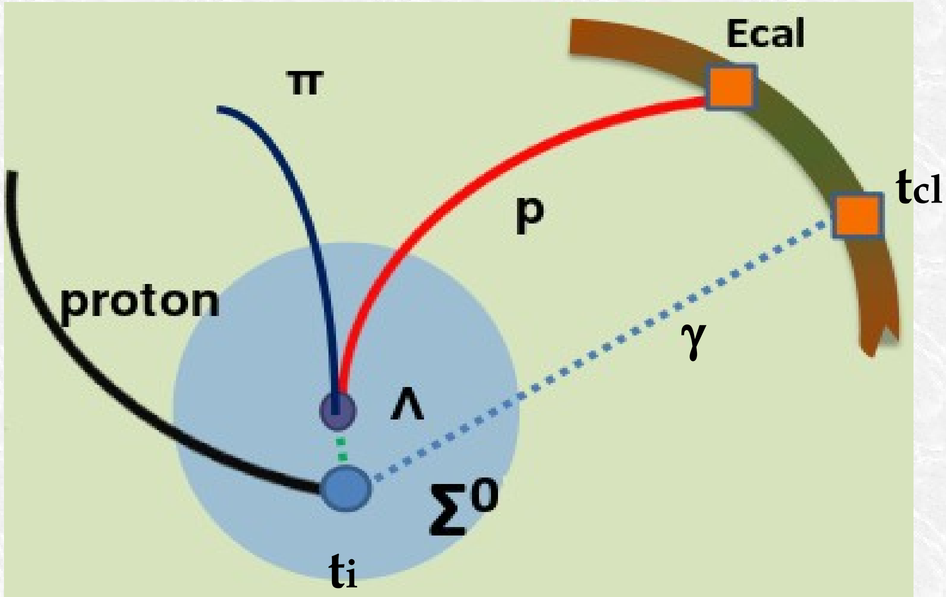



Extra-proton mass



# Hadronic interaction vertex recostruction

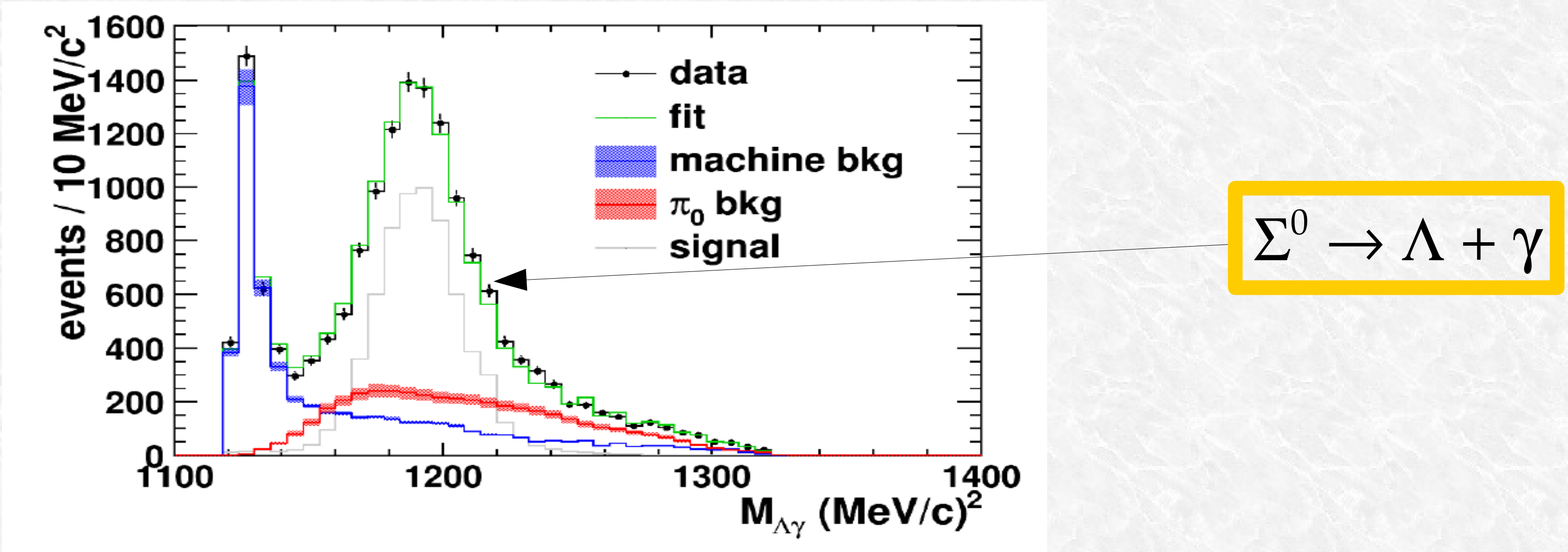
Additional photon signal at the hadronic vertex is required to select **$\Sigma^0$p events.**




The photon candidate selection:

1. search for neutral clusters in the calorimeter
2. calculate the hadronic interaction time ti, using the time time of the cluster of one of the lambda decay particles
3. calculate the distance between the hadronic vertex and the cluster position
4. the requirement is

$$Time\ of\ flight = t_{cl} - t_i = path_\gamma / c$$

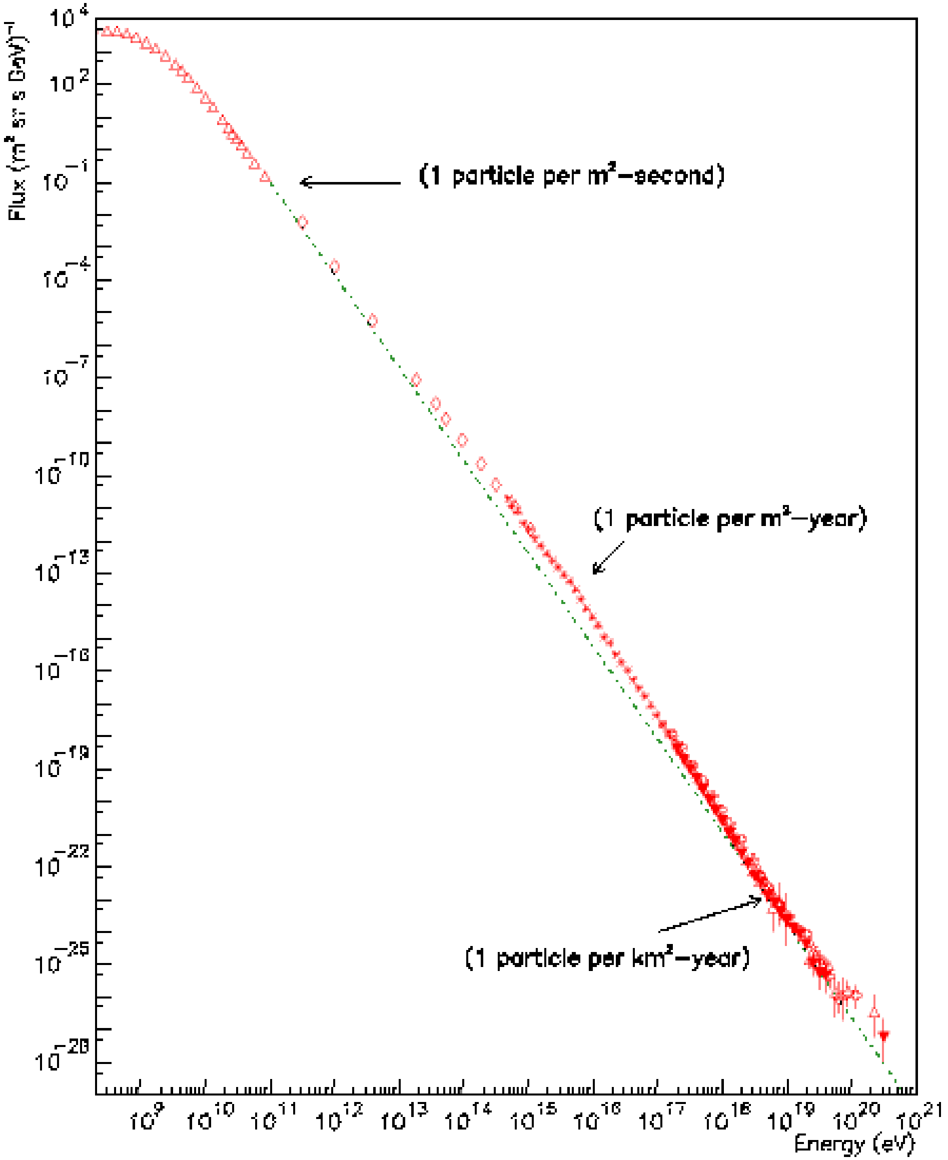


# I Raggi Cosmici

Sono particelle provenienti dalle differenti regioni dello spazio, intra- ed extra-galattiche.

Permettono di raccogliere informazioni sulla composizione dell'Universo lontano

Lo spettro di energia si estende su 21 ordini di grandezza.




Centro Fermi
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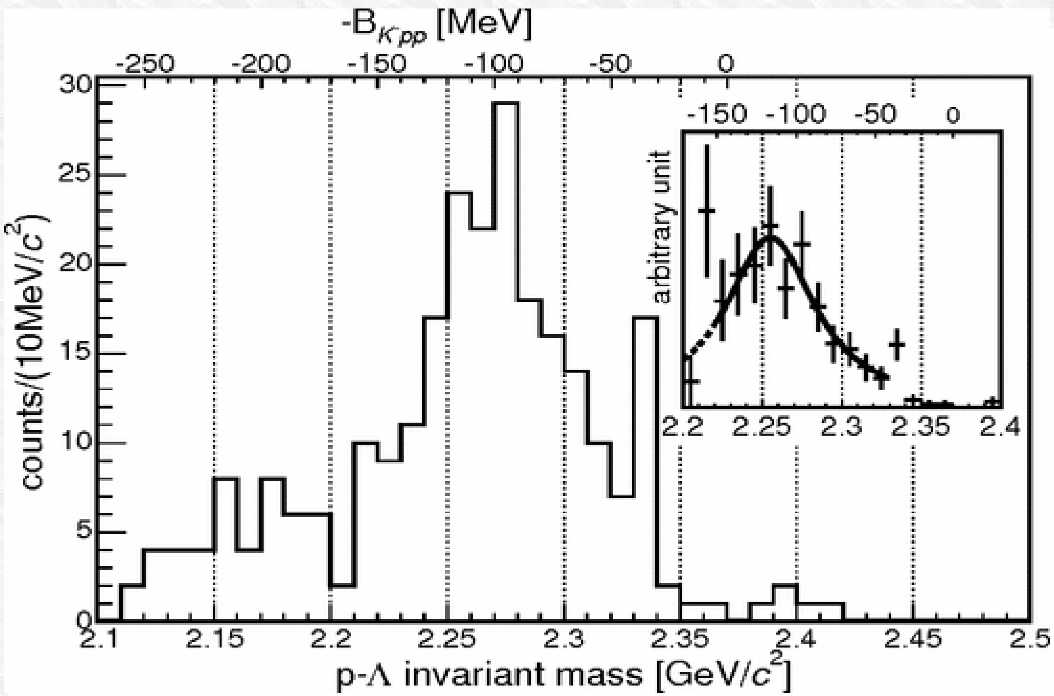
# Experimental studies in the Λp decay channel

- through K⁻ absorption experiments $K^- X \rightarrow \Lambda\, p\, X'$

**FINUDA at DAΦNE** (X= $^6$Li, $^7$Li, $^9$Be)
[M. Agnello et al., PRL94, 212303, 2005]

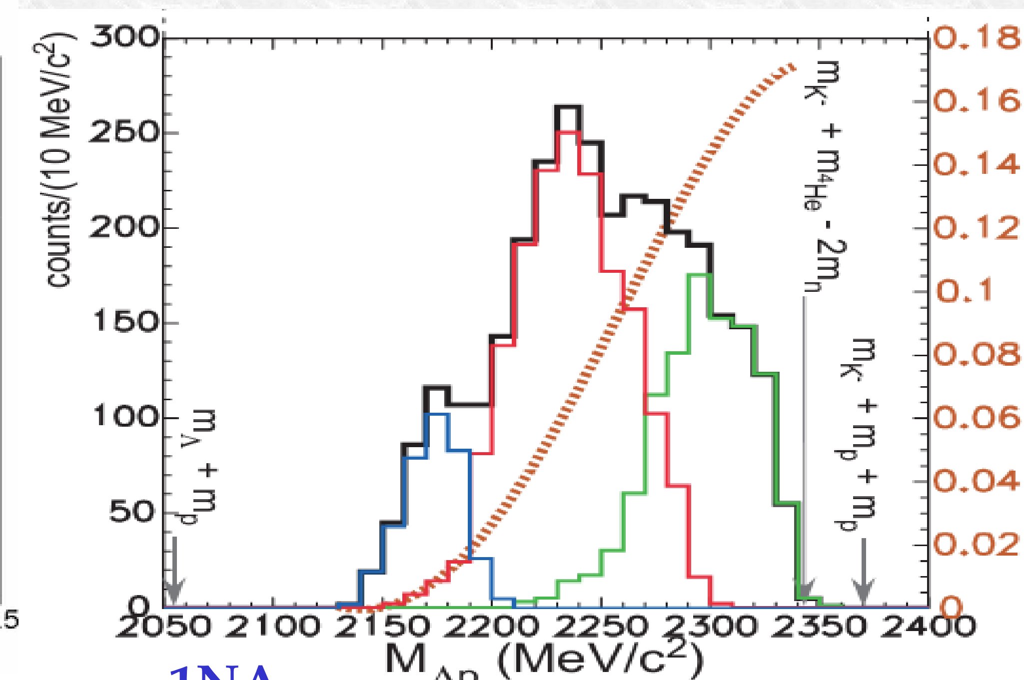
**Invariant mass spectroscopy**




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

**E-549 at KEK** (X= $^4$He)
[T. Suzuki et al., MPLA,23,2520, 2008]

**Missing mass spectroscopy**




1NA
ΣN/ΛN - DBKNS
2NA