ROMA TRE
UNIVERSITÀ DEGLI STUDI

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

A Strangeness Adventure: Kaonic Atom Measurements with SIDDHARTA-2 at the DAΦNE Collider

FRANCESCO ARTIBANI

On the behalf of the SIDDHARTA-2 Collaboration

DISCRETE 2024 in Ljubljana
Dec 2 – 6, 2024

Outline

01 **Exotic Atoms**

- What is an exotic atom
- Kaonic Atoms
- Kaonic atoms and QCD

02 **The SIDDHARTA-2 Experiment**

- The DAΦNE Collider
- Physics goal
- Experimental Apparatus

03 **Preliminary Results**

- The First Results
- Kaonic Deuterium
- Future Projects

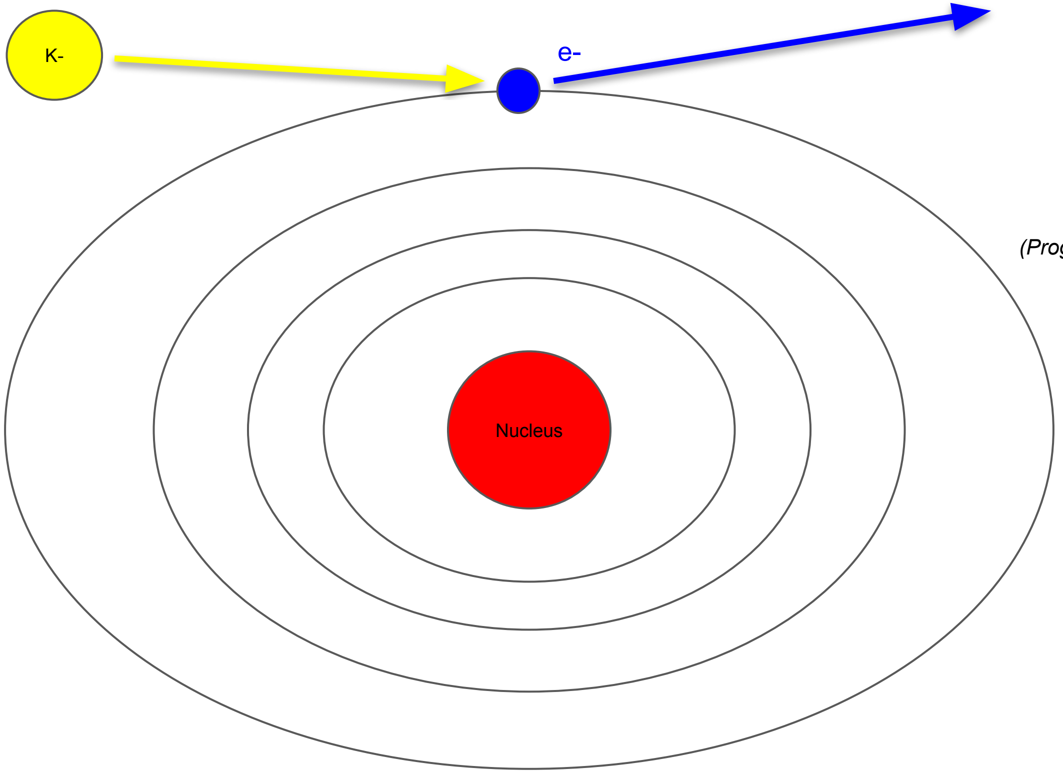
Conclusions

EXOTIC ATOMS

What is an Exotic Atom?

- Exotic atoms are systems in which a **negatively charged particle** stops in a material, replaces the outermost electron of an atom and **bounds to a nucleus**.
- Exotic atoms with muons, pions, kaons, antiprotons and hyperons were observed.
- In this talk I will focus on **kaonic atoms**, and on their connection with **low-energy strong interactions with strangeness.**

Kaonic Atoms: Formation



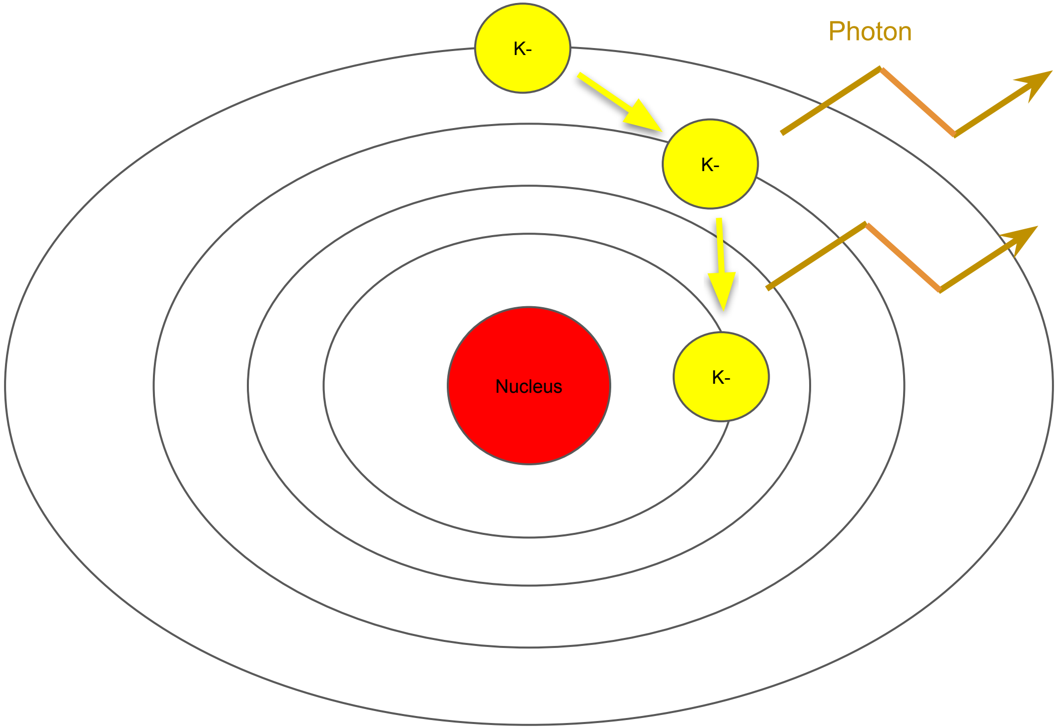
r_b^e ~ r_b^k

(Prog. Part. Nucl. Phys. ***61,*** *512–550, 2008)*

$$n \approx \sqrt{\frac{\mu}{m_e}} n_e$$

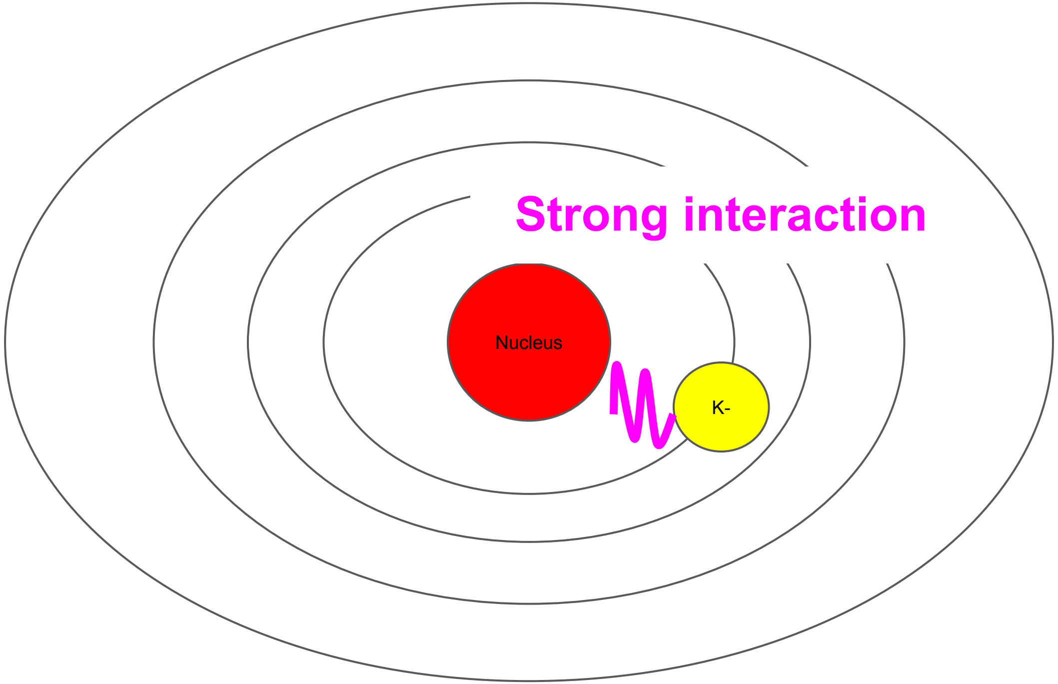
H n=1 level ~ KH n=25 level

Kaonic Atoms: Cascade



The KH de-excitation cascade in its last part is **radiative and in the X-ray region**.

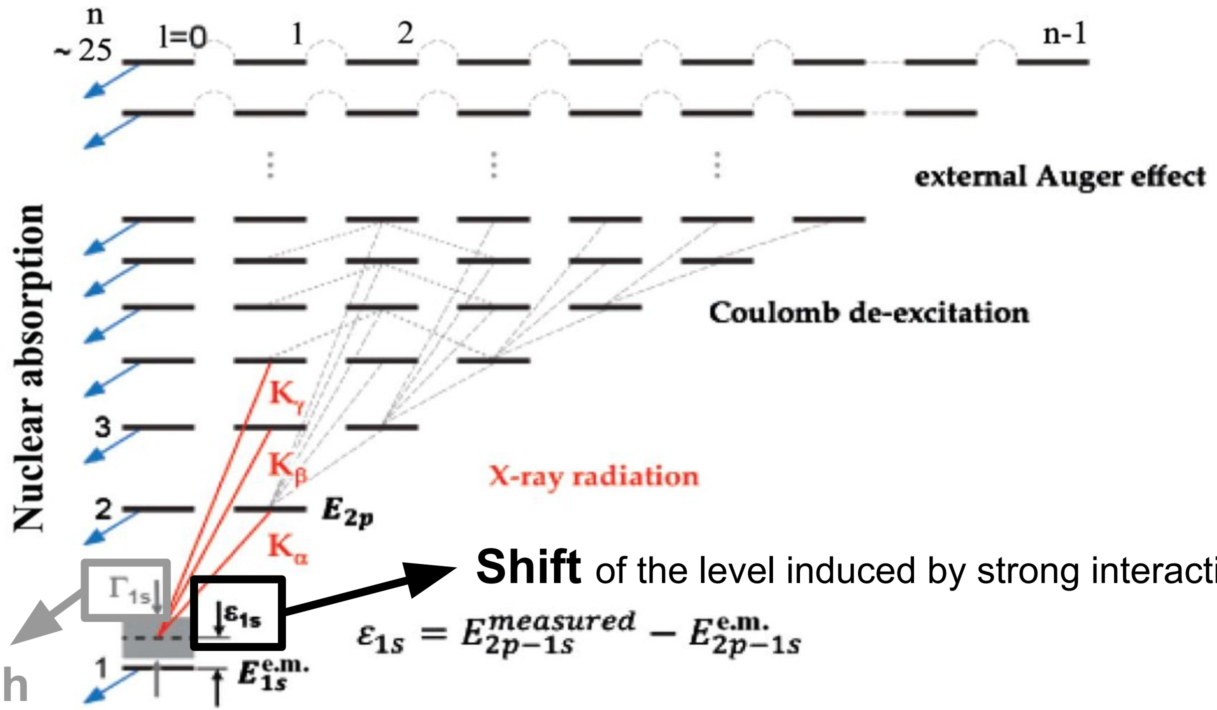
Kaonic Atoms: K-N Interaction



In the last level of the atom kaon interact with nucleus also by strong interaction, and then **interact at threshold with nucleons and** is absorbed.

The time to reach the last level is 1e-9s - 1e-12s, while τ_K=1e-8s

Kaonic Atoms in Low-energy Strong Interactions



Shift of the level induced by strong interactions.

$$\varepsilon_{1s} = E^{measured}_{2p-1s} - E^{e.m.}_{2p-1s}$$

Width

of the level induced by the small lifetime.

Kaonic Atoms in Low-energy Strong Interactions

Compute **σ** using a potential for strong interactions coming from different models based on χPT theory.

The cross-section at threshold is proportional to

Measurement of **shift** and **widths** of kaonic atoms

Deser-Trueman Formula

THEORY

Scattering Length

EXPERIMENT

(Rev. Mod. Phys, ***91****, June 2019)*

Kaonic Atoms in Low-energy Strong Interactions

- From **Kaonic Hydrogen**, the **K-p strong interaction at threshold** can be experimentally probed through **measuring shift and width of the 1s level**, and obtaining the **scattering length** though the improved Deser formula.

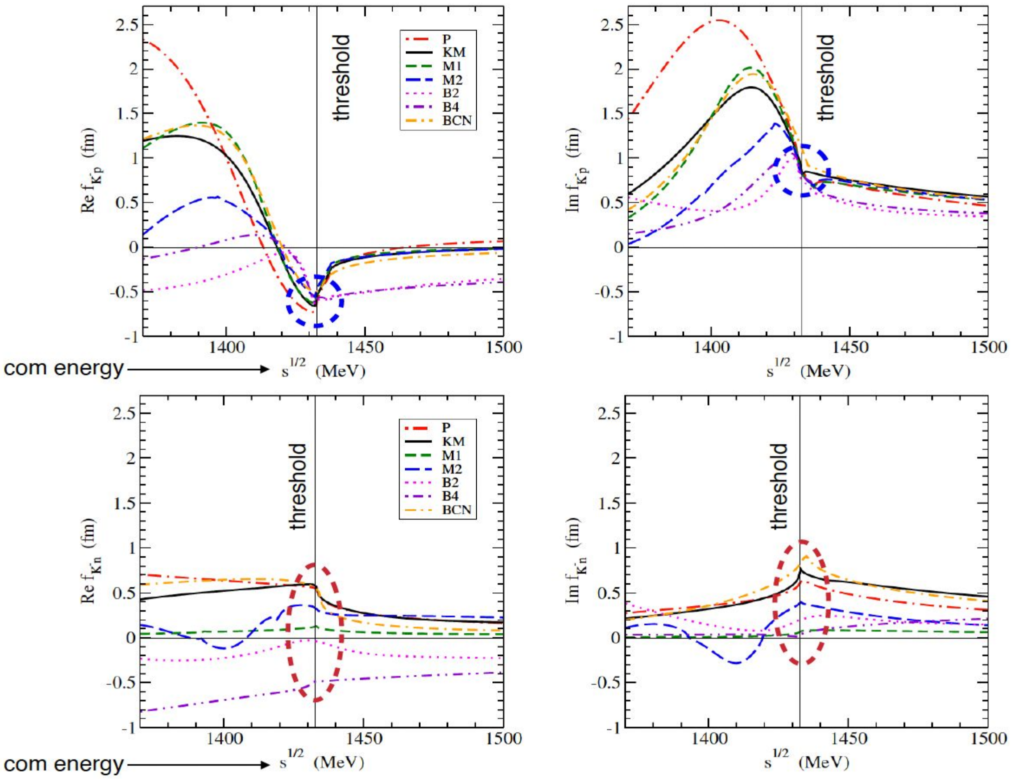
- Combining Kaonic Hydrogen and **Kaonic Deuterium** measurements, the **K-Nucleon isospin-dependent scattering lengths** can be probed, **exploring the behaviour of the isospin in these interactions at threshold**.

$$a_{\bar{K}p} = a_{\bar{K}H} = \frac{a_0 + a_1}{2}$$

$$a_{\bar{K}n} = a_1$$

$$a_{\bar{K}d} = k\,\frac{a_0 + 3\,a_1}{4} + C$$

Motivations



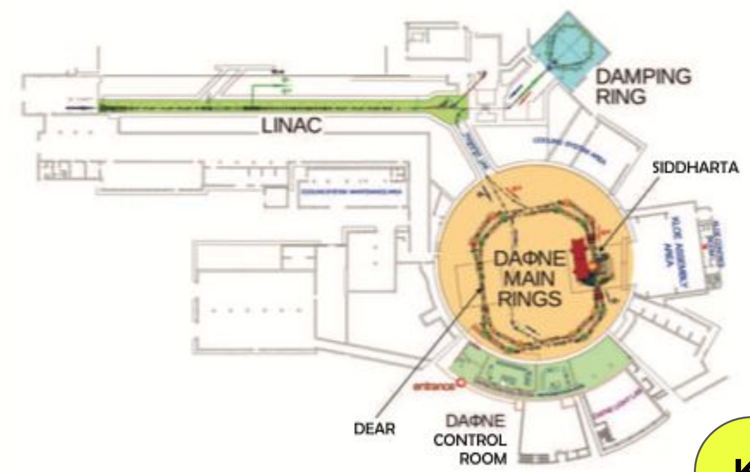
Measured by SIDDHARTA

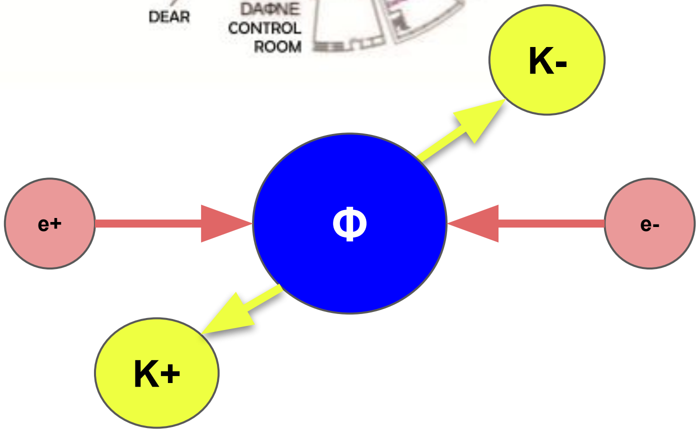
To be measured…

… by SIDDHARTA-2

THE SIDDHARTA-2 EXPERIMENT

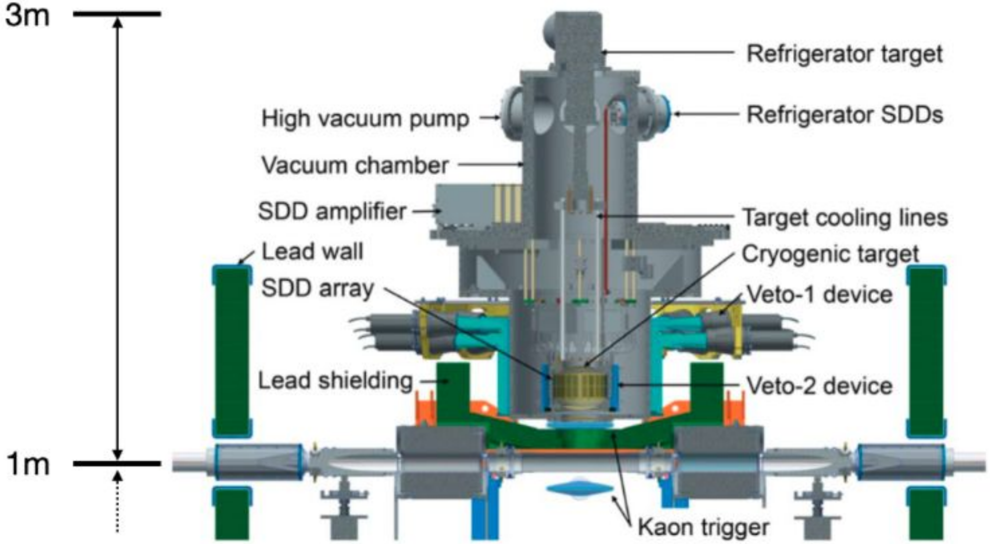
The DAΦNE Collider





- double ring lepton collider working at the **c.m. energy of Φ resonance** (Φ-factory) (m_Φ= 1.02 GeV)
- Φ decays in a couple of charged kaons with a **BR(Φ → K^+K^-) = 49%**
- The kaons are produced almost at rest (m_K = 493 MeV ⇒ **p_K =127 MeV**, β~0.26) with a small boost through the center of the rings.
- The Ks' momentum spread is almost null (Δp/p < 0.1%)

Experimental Setup



arXiv:2311.16144 [physics.ins-det]

- **Cryogenic gaseous target** in a Kapton Cell enclosed in a Vacuum chamber
- **384 Silicon Drift Detectors (SDDs)**, specially developed for kaonic atoms x-ray spectroscopy, providing a high energy efficiency (>98%) for x-ray energies between 5 keV and 12 keV
- **Kaon Trigger**: two fast plastic scintillators to cut on tof
- Complex **veto systems**: the key upgrade wrt SIDDHARTA together with the new, dedicated, SDDs.

PRELIMINARY RESULTS

The Road to KD Measurement

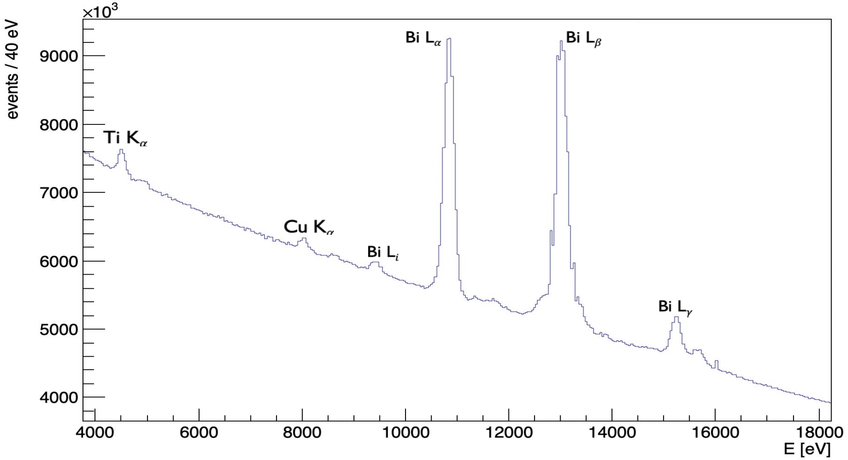
Kaonic Deuterium Run1 — **May – July 2023**

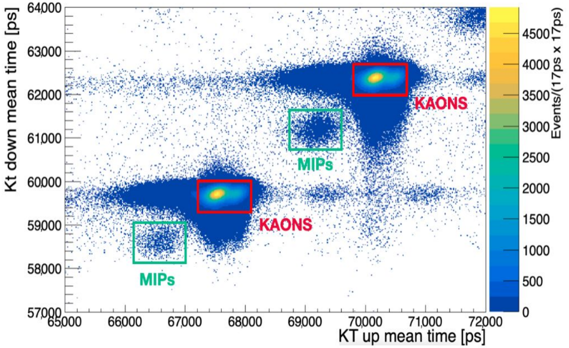
Kaonic Deuterium Run2 — **October – December 2023**

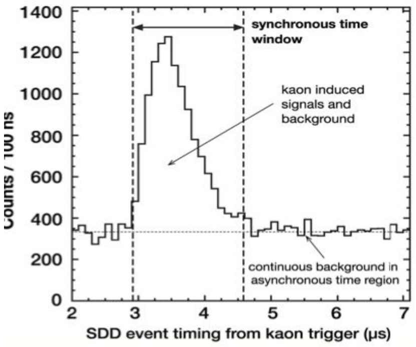
Kaonic Deuterium Run3 — **February – April 2024**

\+ Pre/post test measurement with gaseous (He, **Ne**) and solid (Li, B, Be) targets for each run.

Raw Spectrum and Background



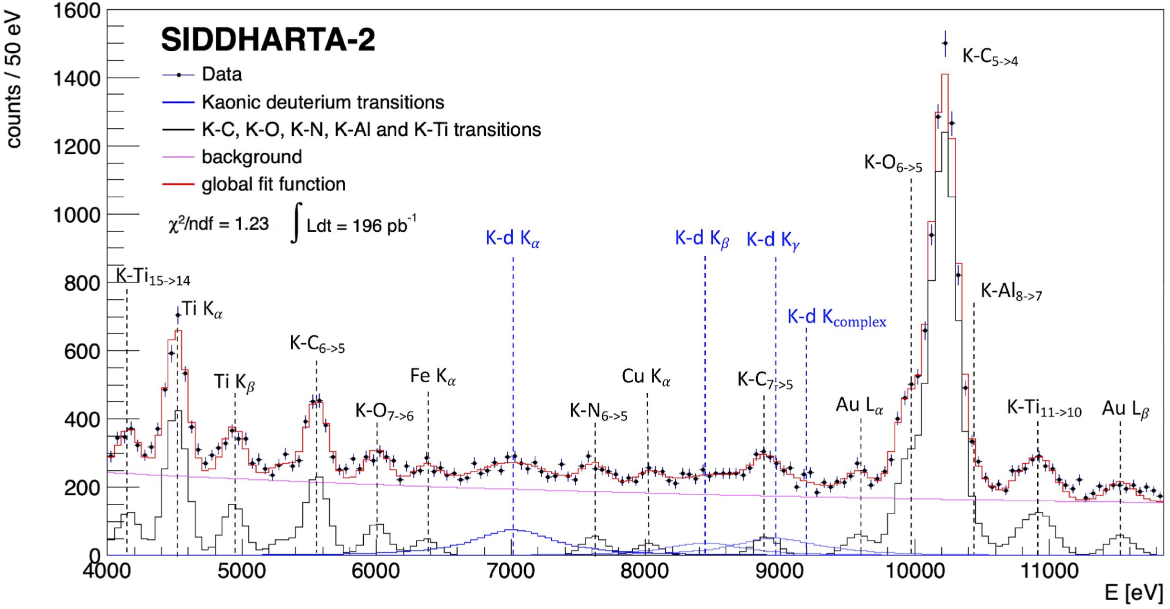




- **Asynchronous Background**. From EM showers produced near IP from beam losses
  → Avoided with **Kaon Trigger and SDD drift time**

- **Synchronous Background.** From Kaon absorption in setup material and other decay channels.
  → Avoided with **Veto systems**

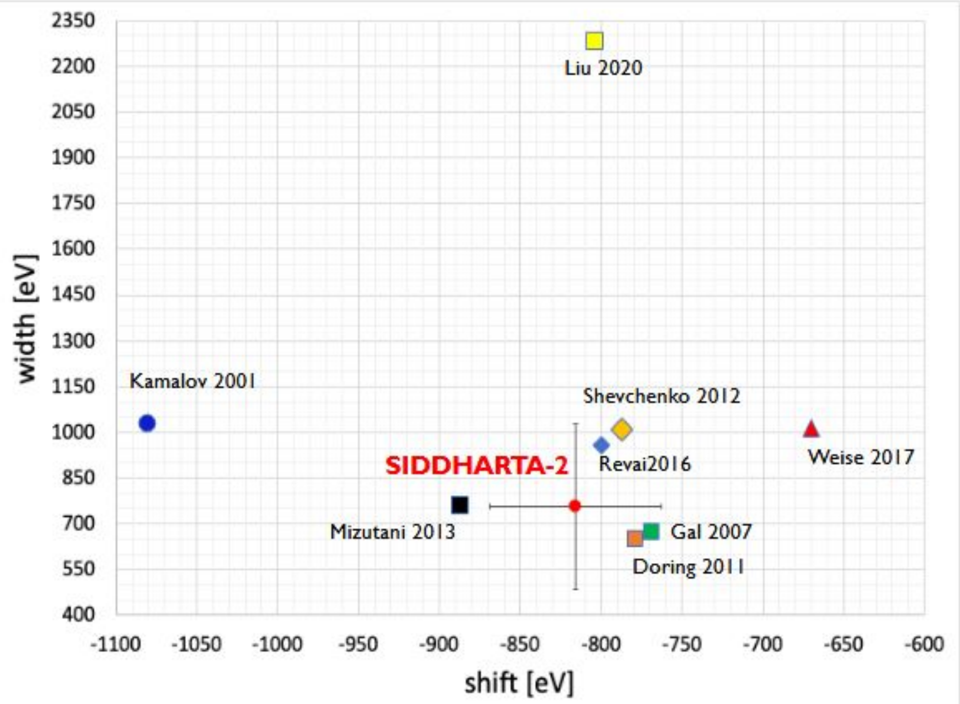
RUN1 Preliminary Result



$$f = pol_1(E) + \exp(E) + \sum_i \text{Gauss}(A_{Gi}, E_i, \sigma) + \text{Tail}(A_{Ti}, E_i, \beta, \sigma) +$$
$$A_{\text{Kd}_{2\to1}} \cdot \text{Voigt}(E_{2\to1}, \sigma, \Gamma_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{3\to1}} \cdot \text{Voigt}(E^{e.m.}_{3\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot \text{Voigt}(E^{e.m.}_{4\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{5\to1}} \cdot \text{Voigt}(E^{e.m.}_{5\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{6\to1}} \cdot \text{Voigt}(E^{e.m.}_{6\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{7\to1}} \cdot \text{Voigt}(E^{e.m.}_{7\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s})$$

$$\varepsilon_{1s} = E^{meas}_{2p\to1s} - E^{e.m.}_{2p\to1s} = -816 \pm 53\ (\text{stat}) \pm 2\ (\text{syst})\ \text{eV}$$
$$\Gamma_{1s} = 756 \pm 271\ (\text{stat})\ \text{eV}$$

RUN1 Preliminary Result



$$\varepsilon_{1s} = E^{meas}_{2p\to 1s} - E^{e.m.}_{2p\to 1s} = -816 \pm 53\ (\text{stat}) \pm 2\ (\text{syst})\ \text{eV}$$

$$\Gamma_{1s} = 756 \pm 271\ (\text{stat})\ \text{eV}$$

Conclusions

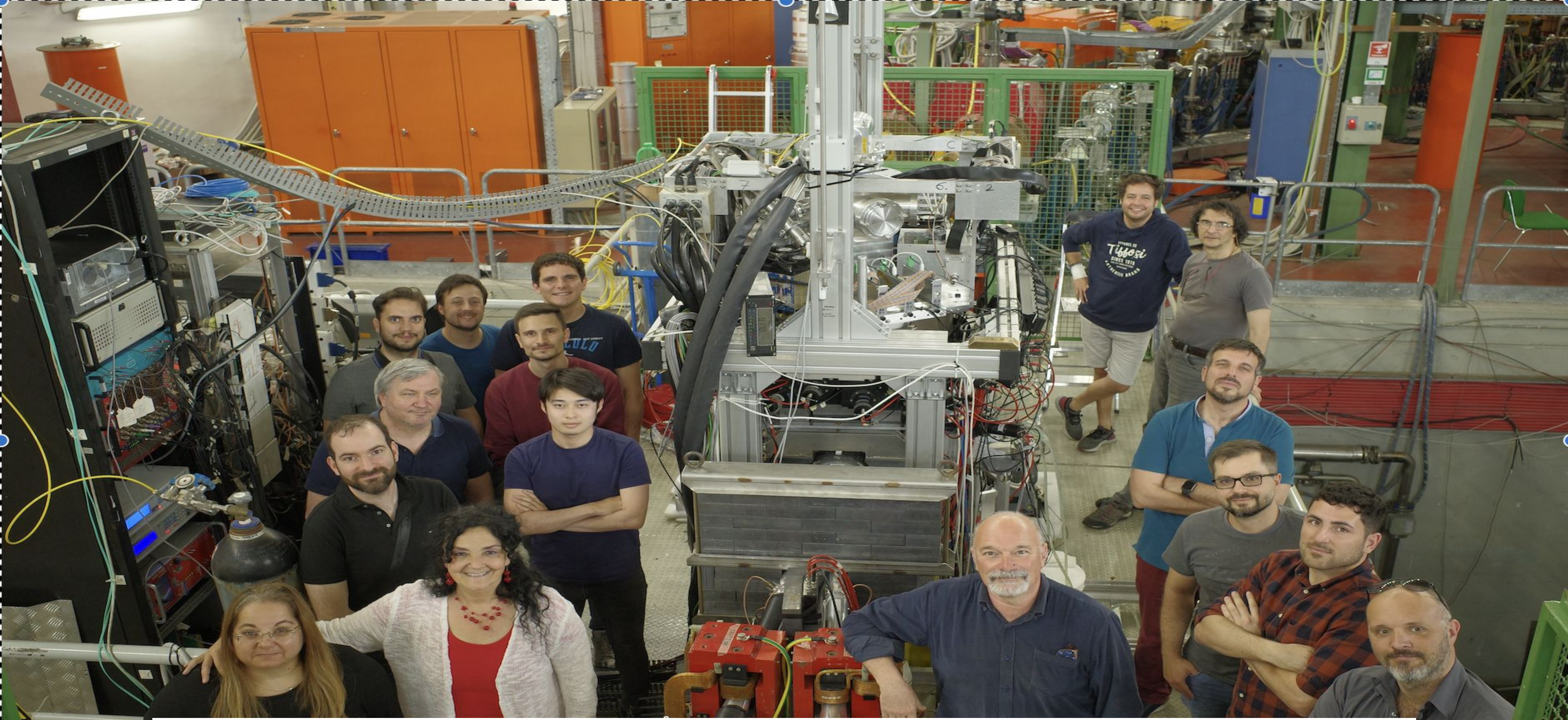
- **Measurements of kaonic atoms are important in the framework of low-energy strong interactions**, the KD shift and width measurement by the SIDDHARTA-2 collaboration is going to be revolutionary: it will permit to **fully disentangle the isospin-dependent scattering lengths**.

- Kaonic atoms measurements are also important to study **K-multiN interactions** and solve one of the issues highlighted by the PDG: **the kaon mass puzzle.**

\+ Parallely to the main goals, the SIDDHARTA-2 collaboration is also **developing new state-of-art X-ray deterctors** (CZT, SDDs, HPGE)

"The **most important experiment to be carried out in low energy K-meson physics today** is the **definitive determination of the energy level shifts in the K^-p and K^-d atoms**, because of their direct connection with the physics of $\bar{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H. Dalitz (1982)



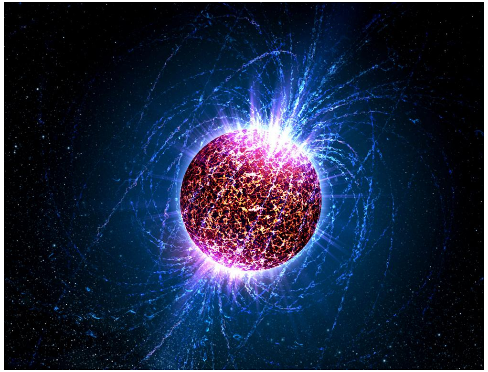
THANK YOU FOR YOUR ATTENTION

BACKUP

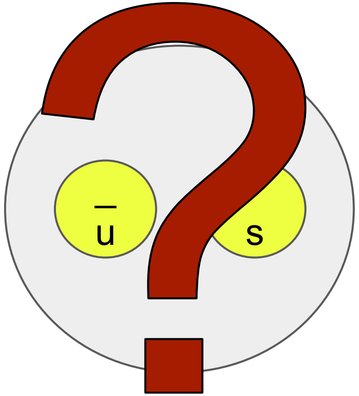
More on Kaonic Atoms

It is also important to study the kaonic atoms transitions with different **Z** and **n**:

- **Z,** because it is important to have a clear picture on the K-N and **K-multiN interactions in function of the nuclear density.**



- **n**, because it is a test of QED and it is important for possible measurement of **kaon mass and atomic cascades.**



Parallel Goals: HPGe & CZT

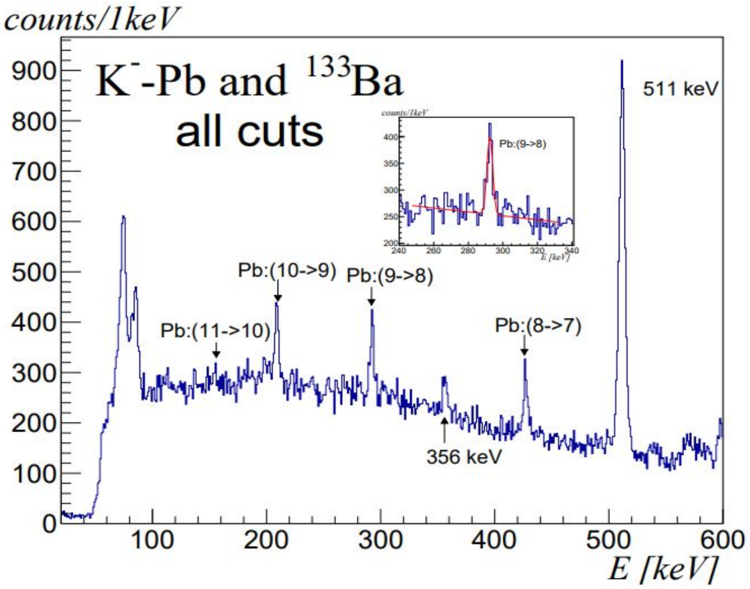
HPGe detector diameter ~60 mm,
height ~60 mm.

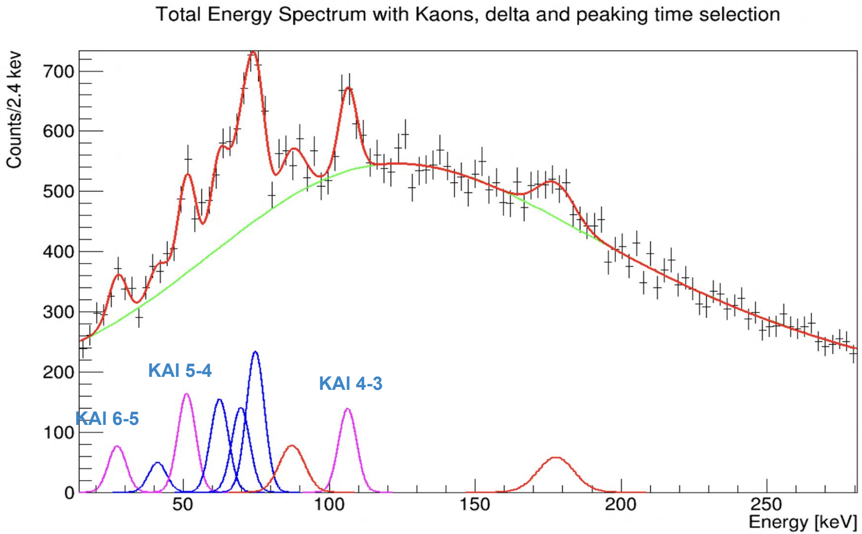
Goal: Heavy-kaonic atoms;
Kaon Mass from KPb.

8 13mm x 15mm x 5mm CZT Detectors

Goal: **Intermediate-Mass Kaonic Atoms**

Parallel Goals: HPGe & CZT



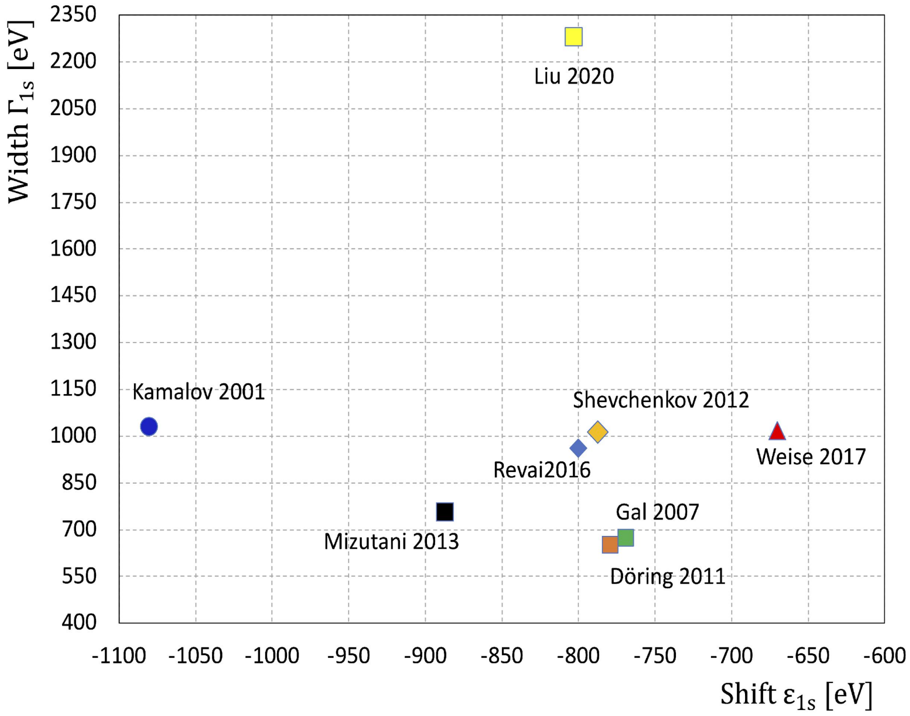


Future Perspective: EXKALIBUR

EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

Two accelerators and many detectors to measure kaonic atoms and probe K-N interaction, with applications from particle physics and QCD to Astrophysics and Dark Matter.

Scientific Goal



K-d transition energies predicted by QED (eV)					
K_{α}	K_{β}	$K_{complex}$			
2→1	3→1	4→1	5→1	6→1	7→1
7834.0	9280.2	9786.2	10020.4	10147.6	10224.3

Theoretical predictions

Reference	ε_{1s} (eV)	Γ_{1s} (eV)
Kamalov *et al.* (2001) [55]	-1080	1030
Gal (2007) [56]	-769	674
Döring *et al.* (2011) [57]	-779	650
Shevchenkov (2012) [58]	-787	1011
Mizutani *et al.* (2013) [59]	-887	757
Revai (2016) [60]	-800	960
Weise *et al.* (2017) [61]	-670	1016
Liu *et al.* (2020) [62]	-803	2280

Kaonic Atoms in Low-energy Strong Interactions

- From **Kaonic Hydrogen**, the **K-p strong interaction at threshold** can be experimentally probed through **measuring shift and width of the 1s level**, and obtaining the **scattering length** though the improved Deser formula.

- Combining Kaonic Hydrogen and **Kaonic Deuterium** measurements, the **K-Nucleon isospin-dependent scattering lengths** can be probed, exploring the behaviour of the isospin in these interactions.

$$a_{\bar{K}p} = a_{\bar{K}H} = \frac{a_0 + a_1}{2}$$

$$a_{\bar{K}n} = a_1$$

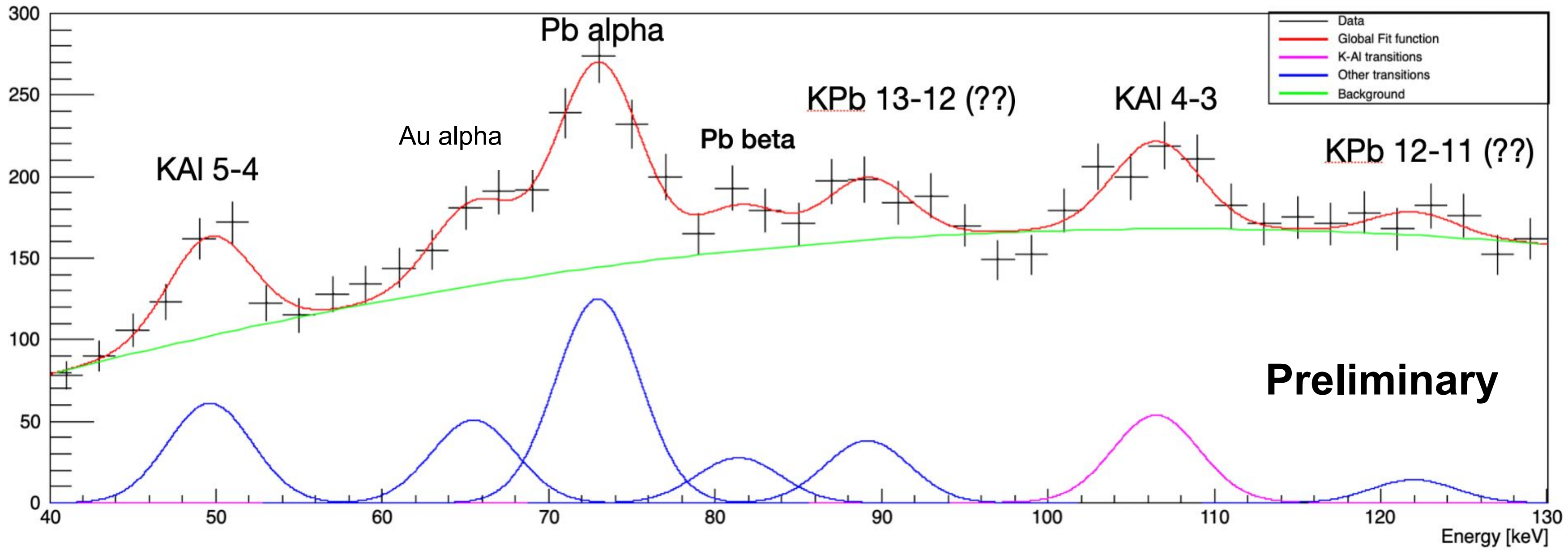
$$a_{\bar{K}d} = k\,\frac{a_0 + 3\,a_1}{4} + C$$

$$k = 4\,\frac{m_N + m_K}{2\,m_N + m_K}$$

Parallel Goal: The CZT Detector

Fixed shift and width to the values calculated with
BCN K^-N + phen. multiN model

Total Energy Spectrum with Kaons, delta and peaking time selection



Importance of kaonic Atoms in QCD

Why are these measurements so important?

$$\varepsilon_{1s}^{H} + \frac{i}{2}\Gamma_{1s}^{H} = 2\alpha^3\mu^2 a_{\bar{K}p}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}p} + \ldots\right] \qquad \varepsilon_{1s}^{D} + \frac{i}{2}\Gamma_{1s}^{D} = 2\alpha^3\mu^2 a_{\bar{K}d}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}d} + \ldots\right]$$

Antikaon-nucleon scattering lenghts

$$a_{K^-p} = \frac{1}{2}[a_1 + a_0] \qquad a_{\bar{K}n} = a_1$$

$$a_{\bar{K}d} = \frac{4[m_N + m_K]}{2m_N + m_K} Q + C$$

Isospin-dependent scattering lenghts:
either **input or output of phenomenological models on low-energy QCD**

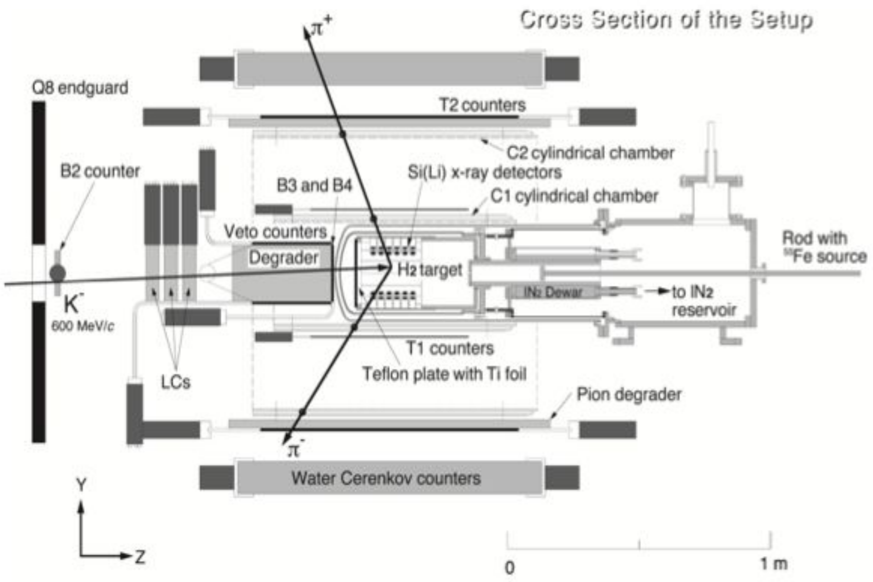
$$Q = \frac{1}{2}[a_{\bar{K}p} + a_{\bar{K}n}] = \frac{1}{4}[a_0 + 3a_1]$$

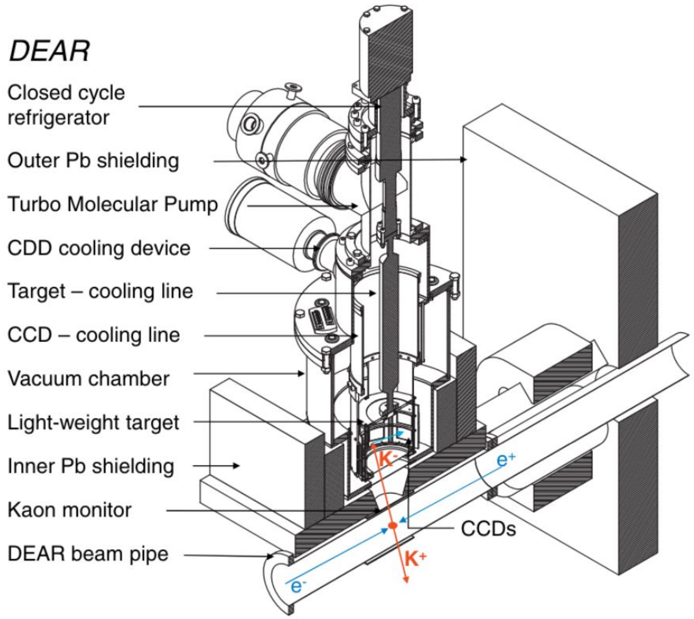
⇒ To fully disentangle the Isospin-dependent scattering lengths one needs the kaonic deuterium measurement

(Rev. Mod. Phys, **91***, June 2019)*

Modern Era Experiments

KpX at KEK vs **DEAR** at DAΦNE





- \+ A lot of Statistics
- \- High Background

- ● Acceptable statistics
- \+ Low Background

(Rev. Mod. Phys, ***91****, June 2019)*

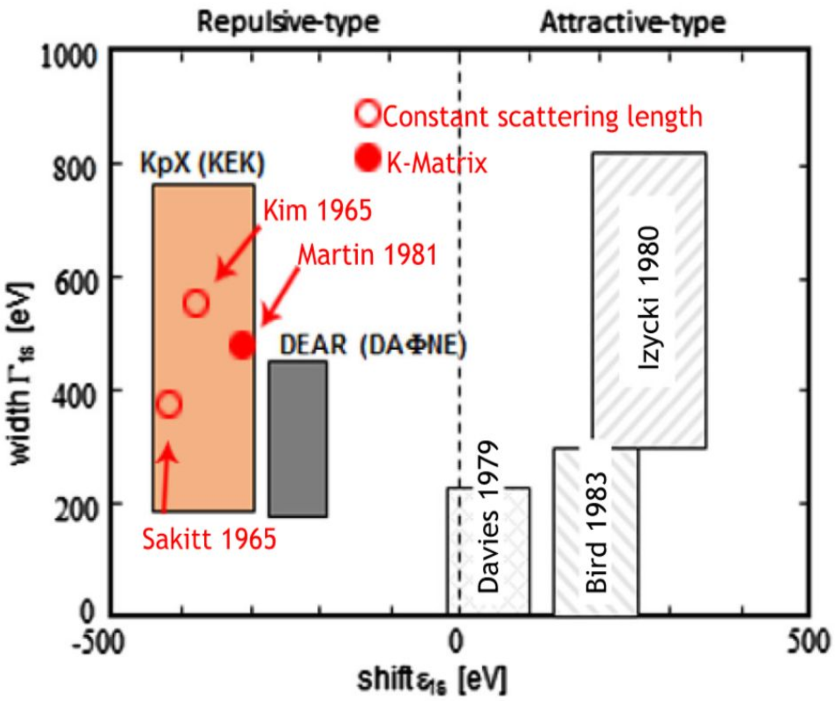
Old Era Experiments

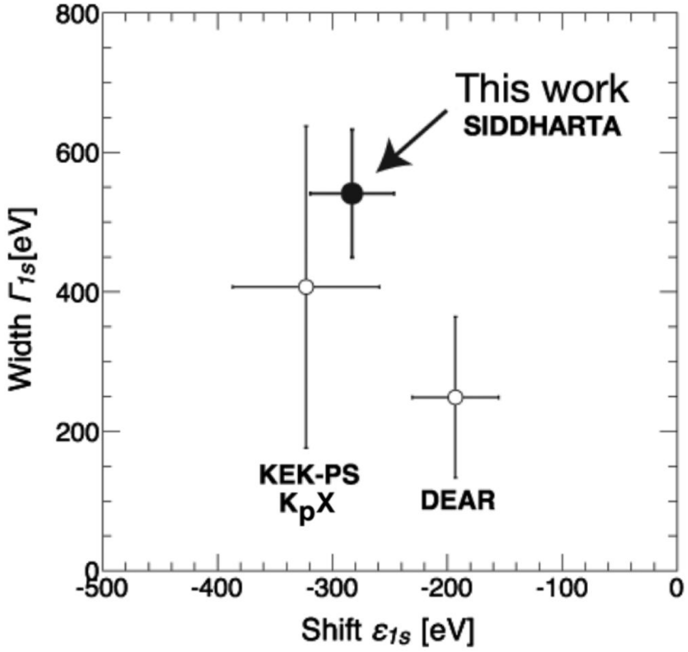
Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	$3 \to 2$	−0.04 ±0.03	–	–	–	[15]
		−0.035 ±0.012	0.03 ±0.03	–	–	[16]
Li	$3 \to 2$	0.002 ±0.026	0.055 ±0.029	0.95 ±0.30	–	[17]
Be	$3 \to 2$	−0.079 ±0.021	0.172 ±0.58	0.25 ±0.09	0.04 ±0.02	[17]
^{10}B	$3 \to 2$	−0.208 ±0.035	0.810 ±0.100	–	–	[18]
^{11}B	$3 \to 2$	−0.167 ±0.035	0.700 ±0.080	–	–	[18]
C	$3 \to 2$	−0.590 ±0.080	1.730 ±0.150	0.07 ±0.013	0.99 ±0.20	[18]
O	$4 \to 3$	−0.025 ±0.018	0.017 ±0.014	–	–	[19]
Mg	$4 \to 3$	−0.027 ±0.015	0.214 ±0.015	0.78 ±0.06	0.08 ±0.03	[19]
Al	$4 \to 3$	−0.130 ±0.050	0.490 ±0.160	–	–	[20]
		−0.076 ±0.014	0.442 ±0.022	0.55 ±0.03	0.30 ±0.04	[19]
Si	$4 \to 3$	−0.240 ±0.050	0.810 ±0.120	–	–	[20]
		−0.130 ±0.015	0.800 ±0.033	0.49 ±0.03	0.53 ±0.06	[19]
P	$4 \to 3$	−0.330 ±0.08	1.440 ±0.120	0.26 ±0.03	1.89 ±0.30	[18]
S	$4 \to 3$	−0.550 ±0.06	2.330 ±0.200	0.22 ±0.02	3.10 ±0.36	[18]
		−0.43 ±0.12	2.310 ±0.170	–	–	[21]
		−0.462 ±0.054	1.96 ±0.17	0.23 ±0.03	2.9 ±0.5	[19]
Cl	$4 \to 3$	−0.770 ±0.40	3.80 ±1.0	0.16 ±0.04	5.8 ±1.7	[18]
		−0.94 ±0.40	3.92 ±0.99	–	–	[22]
		−1.08 ±0.22	2.79 ±0.25	–	–	[21]
Co	$5 \to 4$	−0.099 ±0.106	0.64 ±0.25	–	–	[19]
Ni	$5 \to 4$	−0.180 ±0.070	0.59 ±0.21	0.30 ±0.08	5.9 ±2.3	[20]
		−0.246 ±0.052	1.23 ±0.14	–	–	[19]
Cu	$5 \to 4$	−0.240 ±0.220	1.650 ±0.72	0.29 ±0.11	7.0 ±3.8	[20]
		−0.377 ±0.048	1.35 ±0.17	0.36 ±0.05	5.1 ±1.1	[19]
Ag	$6 \to 5$	−0.18 ±0.12	1.54 ±0.58	0.51 ±0.16	7.3 ±4.7	[19]
Cd	$6 \to 5$	−0.40 ±0.10	2.01 ±0.44	0.57 ±0.11	6.2 ±2.8	[19]
In	$6 \to 5$	−0.53 ±0.15	2.38 ±0.57	0.44 ±0.08	11.4 ±3.7	[19]
Sn	$6 \to 5$	−0.41 ±0.18	3.18 ±0.64	0.39 ±0.07	15.1 ±4.4	[19]
Ho	$7 \to 6$	−0.30 ±0.13	2.14 ±0.31	–	–	[23]
Yb	$7 \to 6$	−0.12 ±0.10	2.39 ±0.30	–	–	[23]
Ta	$7 \to 6$	−0.27 ±0.50	3.76 ±1.15	–	–	[23]
Pb	$8 \to 7$	–	0.37 ±0.15	0.79 ±0.08	4.1 ±2.0	[24]
		−0.020 ±0.012	–	–	–	[25]
U	$8 \to 7$	−0.26 ±0.4	1.50 ±0.75	0.35 ±0.12	45 ±24	[24]

Table in (*Nucl. Phys. A,* **579,** *518-538, October 1994)* reporting the measured shifts and widths from 10 experiments for 25 kaonic atoms.
Nowadays, models are also based on these measurements

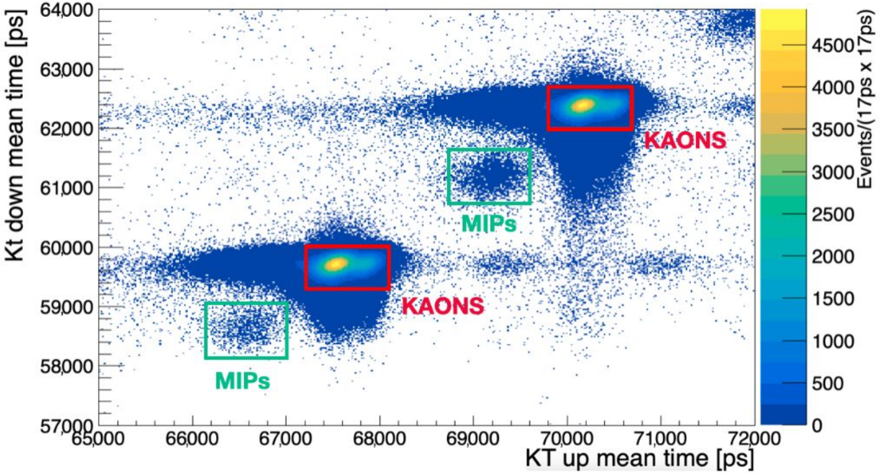
The Kaonic Hydrogen Puzzle



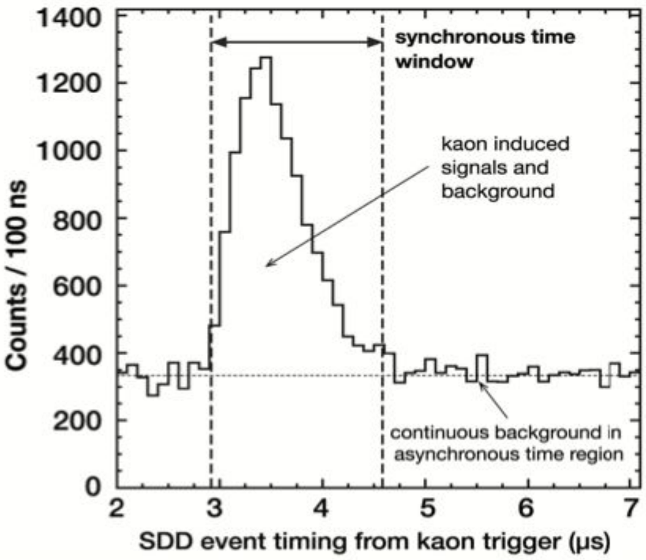


From *Rev. Mod. Phys*, **91**, *June 2019*

Experimental Setup: The Importance of Timing

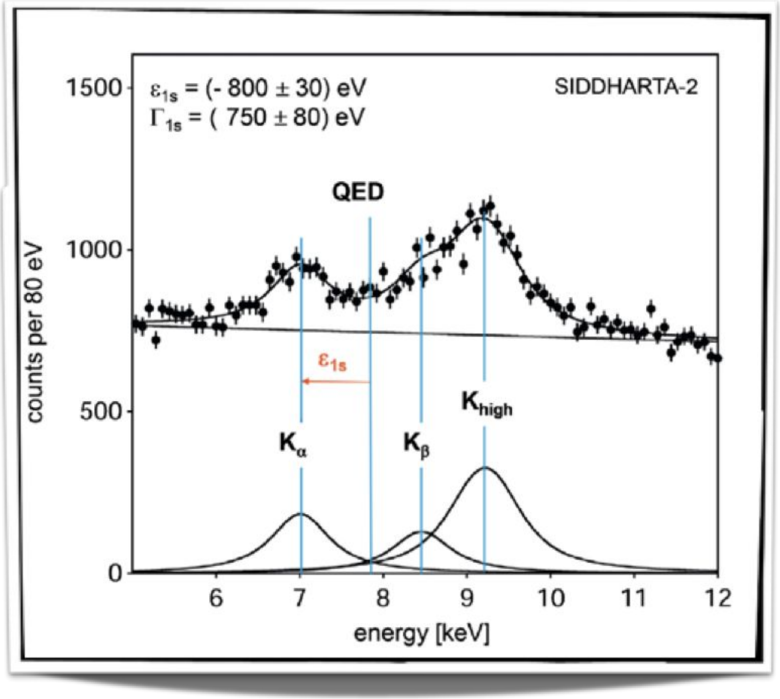


Time difference between DAΦNE RF and signal on kaon trigger, a window of slower particles (kaons) is clearly distinguishable from background



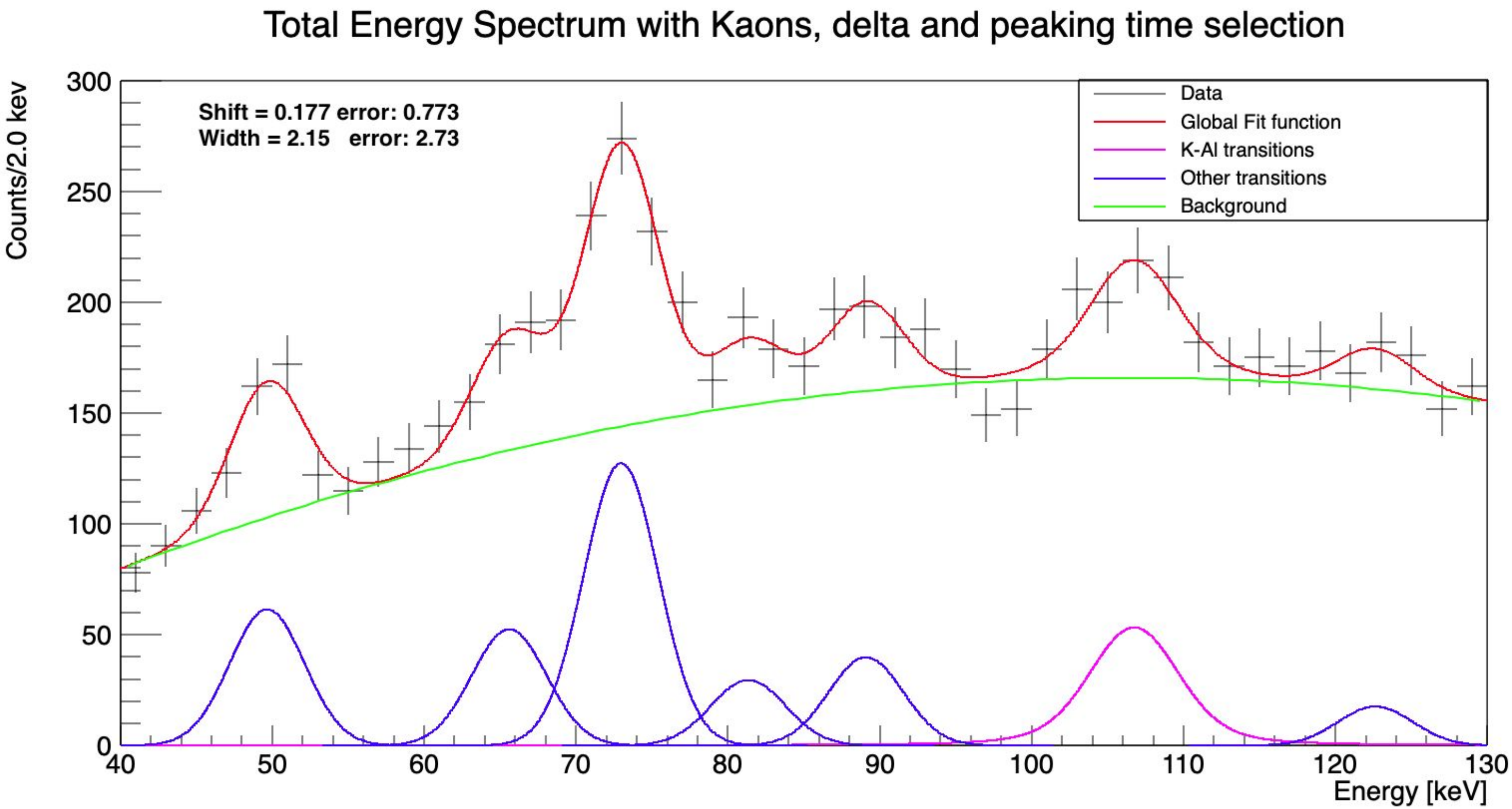
Time difference between a signal on the kaon trigger and a signal on SDDs, a clear signal due to the kaon induced events is distinguishable from uniform bkg.

Experimental Setup: The MC Simulation

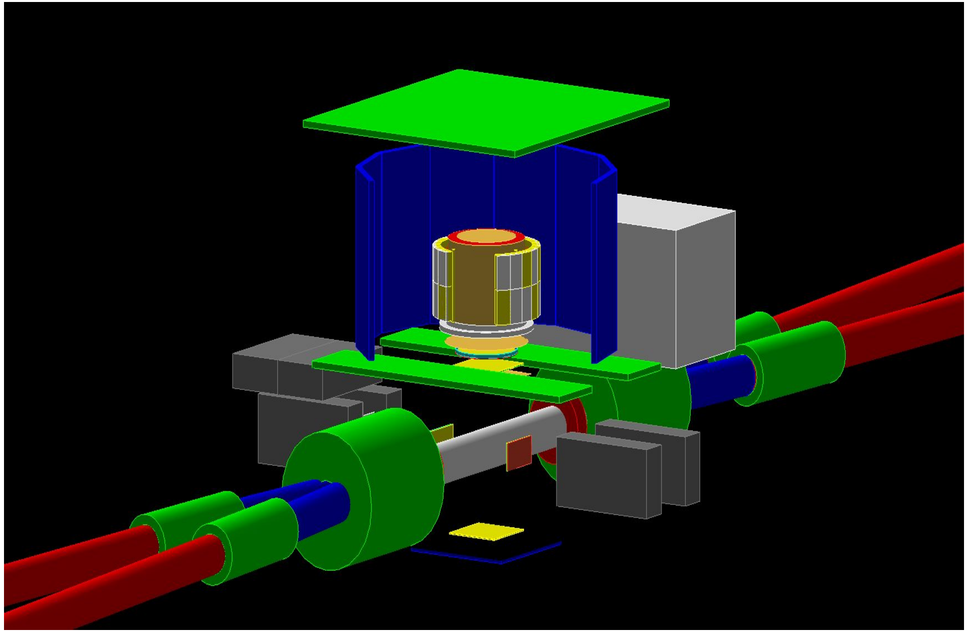


- 800 pb^{-1} simulated luminosity
- precision of about 30 eV and 80 eV respectively on shift and width obtained

Parallel Goal: The CZT Detector



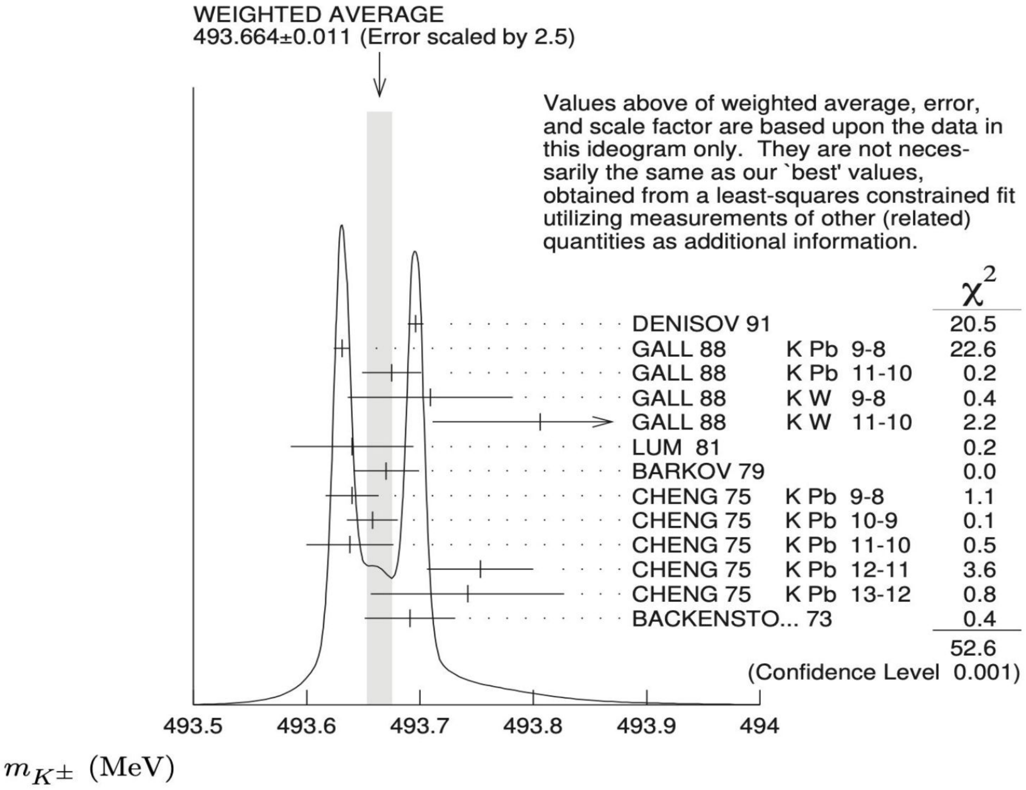
Experimental Setup: The MC Simulation



The MC simulation is essential to:

- **Study the material thickness** (~100 um can reduce a lot the statistics)
- **Study the expected results** (other kaonic atoms can be a background themselves)
- Study the **yield of the transition**, almost unknown.
- **Study possible cuts on timing and position** exploiting veto systems.

Parallel Goal: The Kaon Mass Puzzle



- The two most precise measurement of the kaon mass exploits kaonic atoms, but the measurements are not compatible, propagating the large uncertainty in other particle physics observables (D0 mass)

Aims of the collaboration:

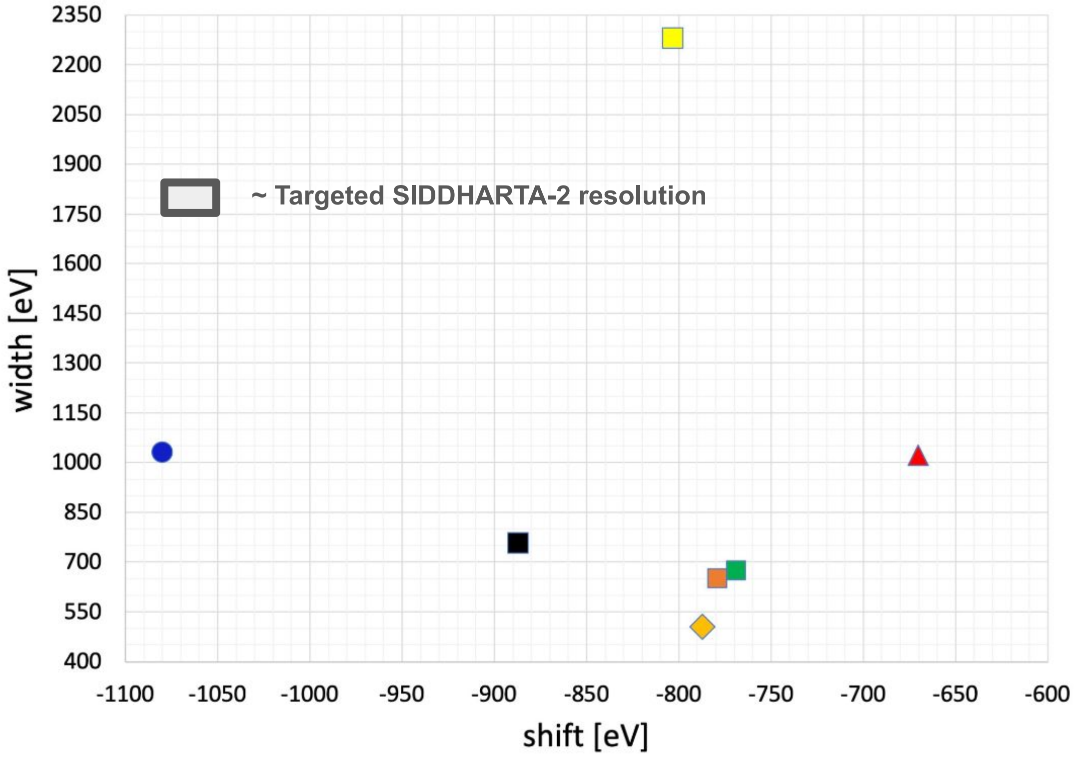
1. Reproduce the “pathological” measurement of GALL88 using HPGe detectors and K-Pb transitions
2. Do an independent measurement exploiting K-Ne transitions → AI techniques to control systematics.

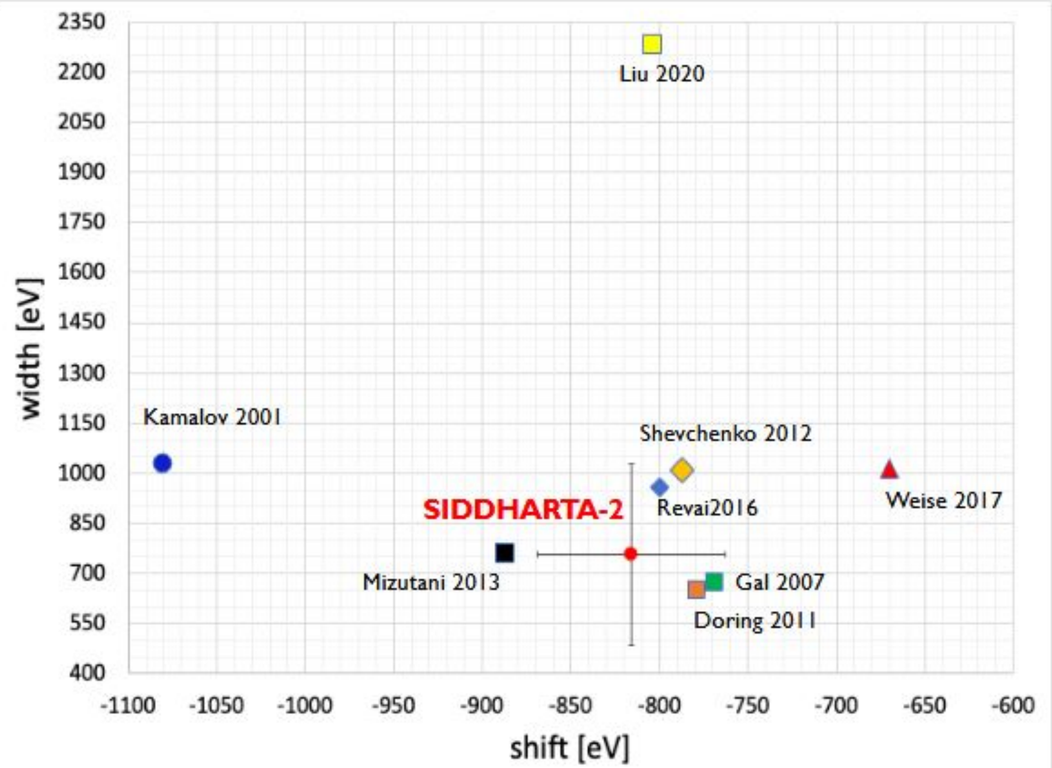
The SIDDHARTA-2 Experiment: Physics Goal

+ From SIDDHARTA exploratory measurement, combining data and Monte Carlo simulation, it turned out that the expected yield must be **Y(K_α KD) ~ 0.1%**

An accurate control on background is needed!

The SIDDHARTA-2 Experiment: Physics Goal





The analysis of the full dataset can potentially improve the statistical accuracy by a factor 2

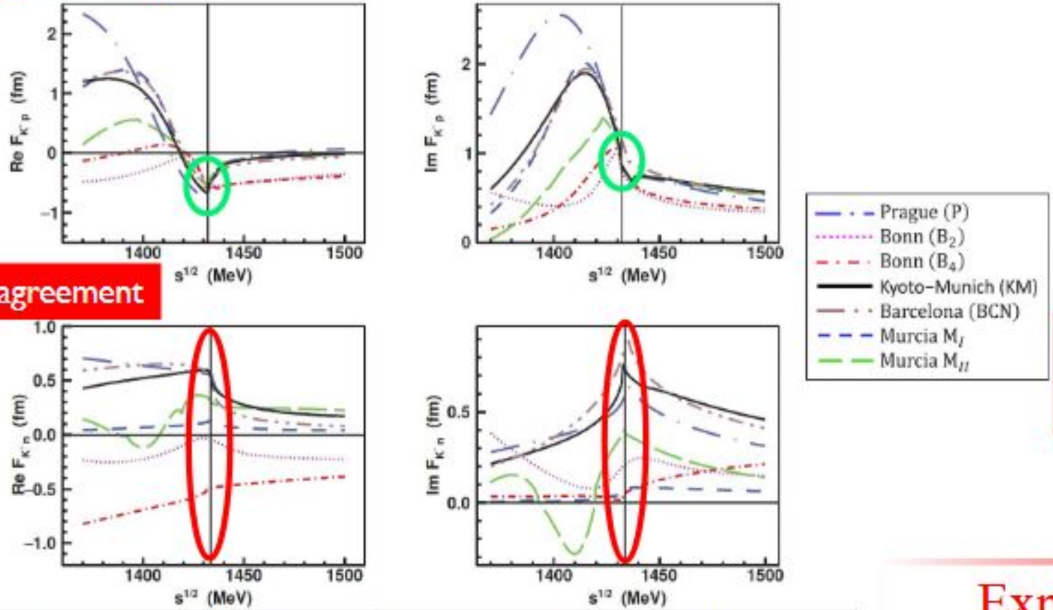
(precision similar to kaonic hydrogen measurement)

The SIDDHARTA-2 Scientific goal

Scientific goal: *first measurement ever of kaonic deuterium X-ray transition to the ground state* (1s-level) such as to determine its shift and width induced by the presence of the strong interaction, providing unique data to investigate the QCD in the non-perturbative regime with strangeness.

K-p: agreement

K-n: disagreement



Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

Combined analysis of the kaonic deuterium and kaonic hydrogen measurements

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_{K^-p}\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}\right)$$

(μ_c reduced mass of the K^-p system, α fine-structure constant)

U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$
$$a_{K^-n} = a_1$$

$$a_{K^-d} = \frac{k}{2}[a_{K^-p} + a_{K^-n}] + C = \frac{k}{4}[a_0 + 3a_1] + C$$
$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

Experimental determination of the Isospin-dependent K-N scattering length

On self-gravitating strange dark matter halos around galaxies
Phys.Rev.D 102 (2020) 8, 083015

Dark Matter studies

The modern era of light kaonic atom experiments
Rev.Mod.Phys. 91 (2019) 2, 025006

Fundamental physics, QED
New Physics

Kaonic atoms
Kaon-nuclei interactions (scattering and nuclear interactions)

Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice

Kaonic Atoms to Investigate
Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

Astrophysics
EOS Neutron Stars

The equation of state of dense matter

The charged kaon mass discrepancy

Severe consequences for nuclear and particle physics and all the processes in which charged kaons are involved

- The uncertainty on the charged kaon mass leads to an error of 50 keV (σ) on the D^0 mass
- Large uncertainty on the charmonium spectrum, in particular on precise values of charm-anticharm meson thresholds
- A particular case is that of $D^0\overline{D}^{*0}$ which lies within the measured width of the best-known candidate for a hadron-hadron molecule, the X(3872), an improved K-mass measurement would lead to a better interpretation of the X(3872), and of its radius.

C. Amsler, "Impact of the charged kaon mass on the charmonium spectrum", workshop, Frascati, 19 April 2021

- Impact on the K-N scattering lengths and sub eV measurement of K-nuclei interaction (kaonic atoms)

A new kaonic helium measurement in gas by SIDDHARTINO at the DAFNE collider D. Sirghi, F. Sirghi, F. Sgaramella, et al., J.Phys.G 49 (2022) 5, 055106

Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters, J-PARC E62 Collaboration, Phys.Rev.Lett. 128 (2022) 11, 112503

- Implications for studies in Bound State QED (BSQED)

Testing Quantum Electrodynamics with Exotic Atoms N. Paul, G. Bian, T. Azuma, S. Okada, and P. Indelicato, Phys. Rev. Lett. 126 (2021), 173001