HADRON 2021

19TH INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE

Kaonic atoms precision measurements at DAFNE: SIDDHARTA-2 and future perspectives

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INFN-LNF

on behalf of SIDDHARTA-2 collaboration

SIDDHARTA-2 Collaboration

SIlicon Drift Detector for Hadronic Atom
Research by Timing Applications

LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN–HH, Bucharest, Romania
TUM, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada
Univ. Zagreb, Croatia
Helmholtz Institute Mainz, Germany
Univ. Jagiellonian Krakow, Poland
Research Center for Electron Photon Science (ELPH), Tohoku University, Japan

INFN LNF Istituto Nazionale di Fisica Nucleare

STRONG 2020

HadronPhysics I3 Study of Strongly Interacting Matter

HadronPhysics2 Study of Strongly Interacting Matter

HRZZ Croatian Science Foundation

FWF Der Wissenschaftsfonds

Farnesina Ministero degli Affari Esteri e della Cooperazione Internazionale

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SIDDHARTA-2 - scientific aim

To perform precision measurements

of kaonic atoms X-ray transitions (*shift* and *width*)

- **unique information about QCD in the non -perturbative regime in the strangeness sector not obtainable otherwise**

Starting with the

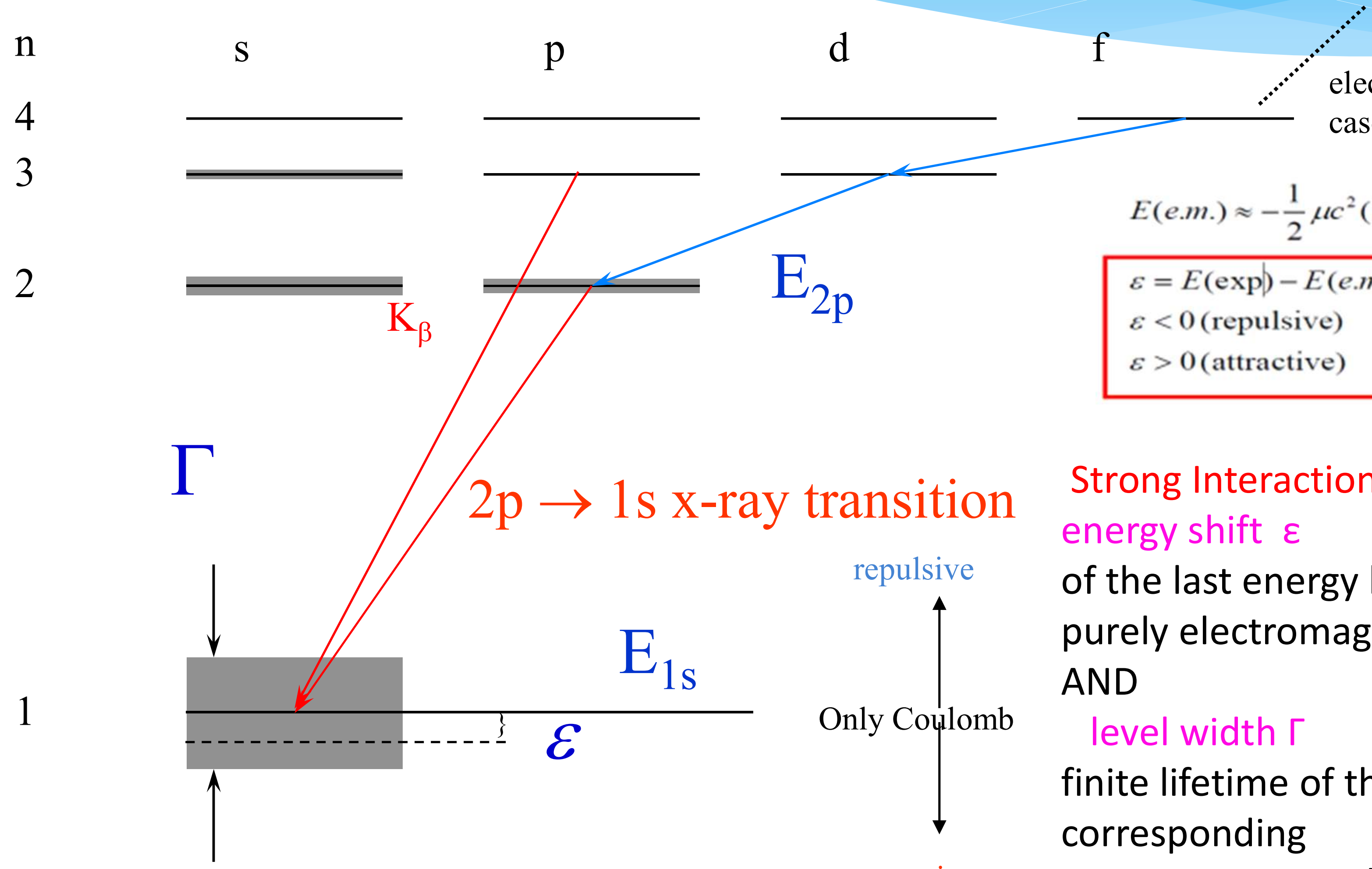
- **precision measurement for *kaonic hydrogen* – *done in 2009***
- **NOW first measurement of kaonic deuterium - autumn 2021**

To extract the antikaon-nucleon isospin dependent scattering lengths

- **chiral symmetry breaking (mass problem), EOS for neutron stars**

Kaonic Hydrogen atoms

K- captured in excited orbit, replacing the electron



$$E(e.m.) \approx -\frac{1}{2}\mu c^2 (Z\alpha)^2 \cdot \left[\frac{1}{n_i^2} - \frac{1}{n_f^2}\right]$$

$$\varepsilon = E(\exp) - E(e.m.)$$
$$\varepsilon < 0\,(\text{repulsive})$$
$$\varepsilon > 0\,(\text{attractive})$$

$$\varepsilon = E_{2p \to 1s}(\exp) - E_{2p \to 1s}(e.m.)$$

Strong Interaction causes:

energy shift ε

of the last energy levels form their purely electromagnetic values

AND

level width Γ

finite lifetime of the state corresponding

to an increase in the observed level width

SIDDHARTA-2: Kaonic Deuterium measurement

Kaonic deuterium run

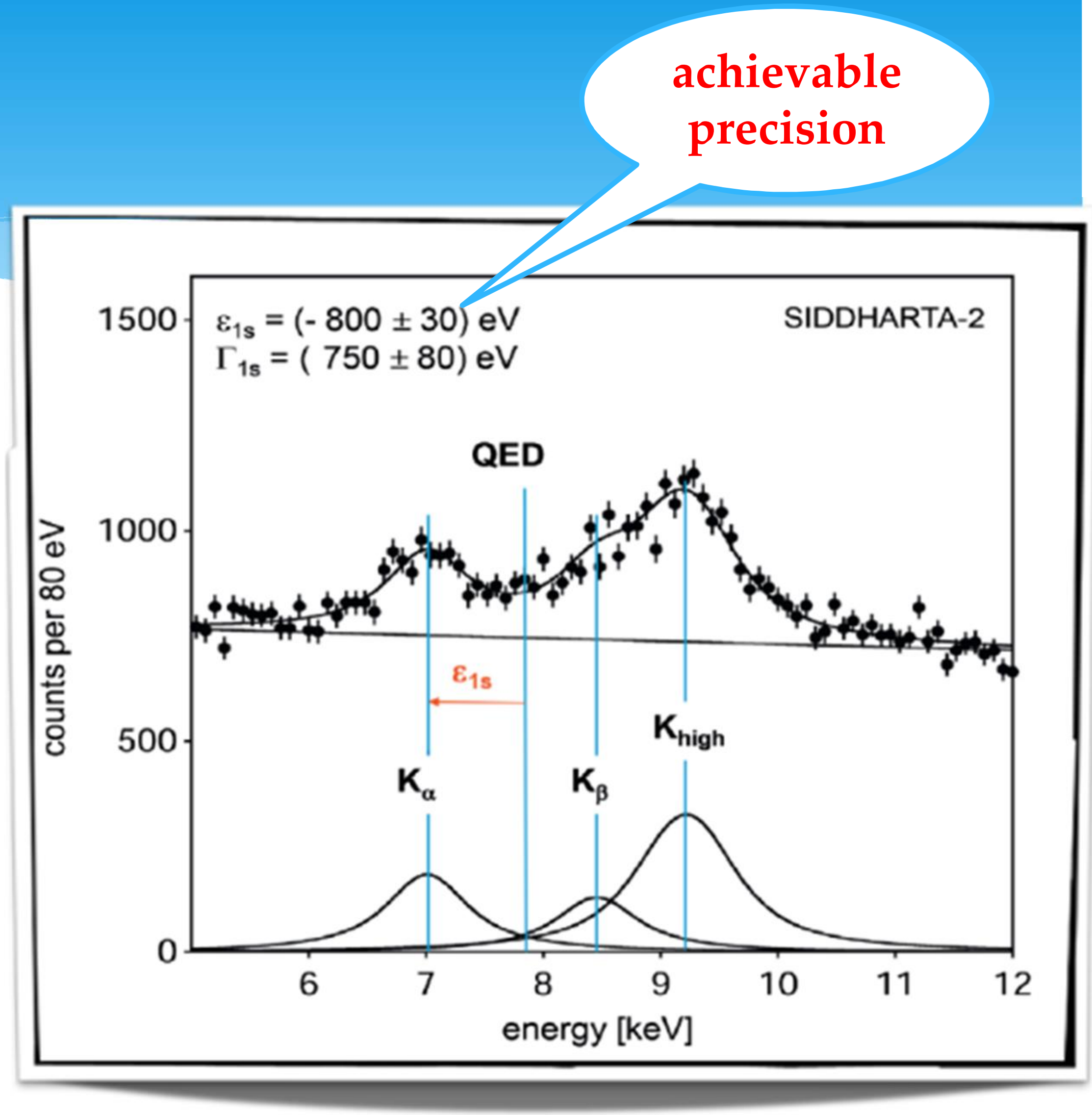
for S/B as 1/3:

for an integrated luminosity of 800 pb^{-1}

to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as $K^{-}p$) !

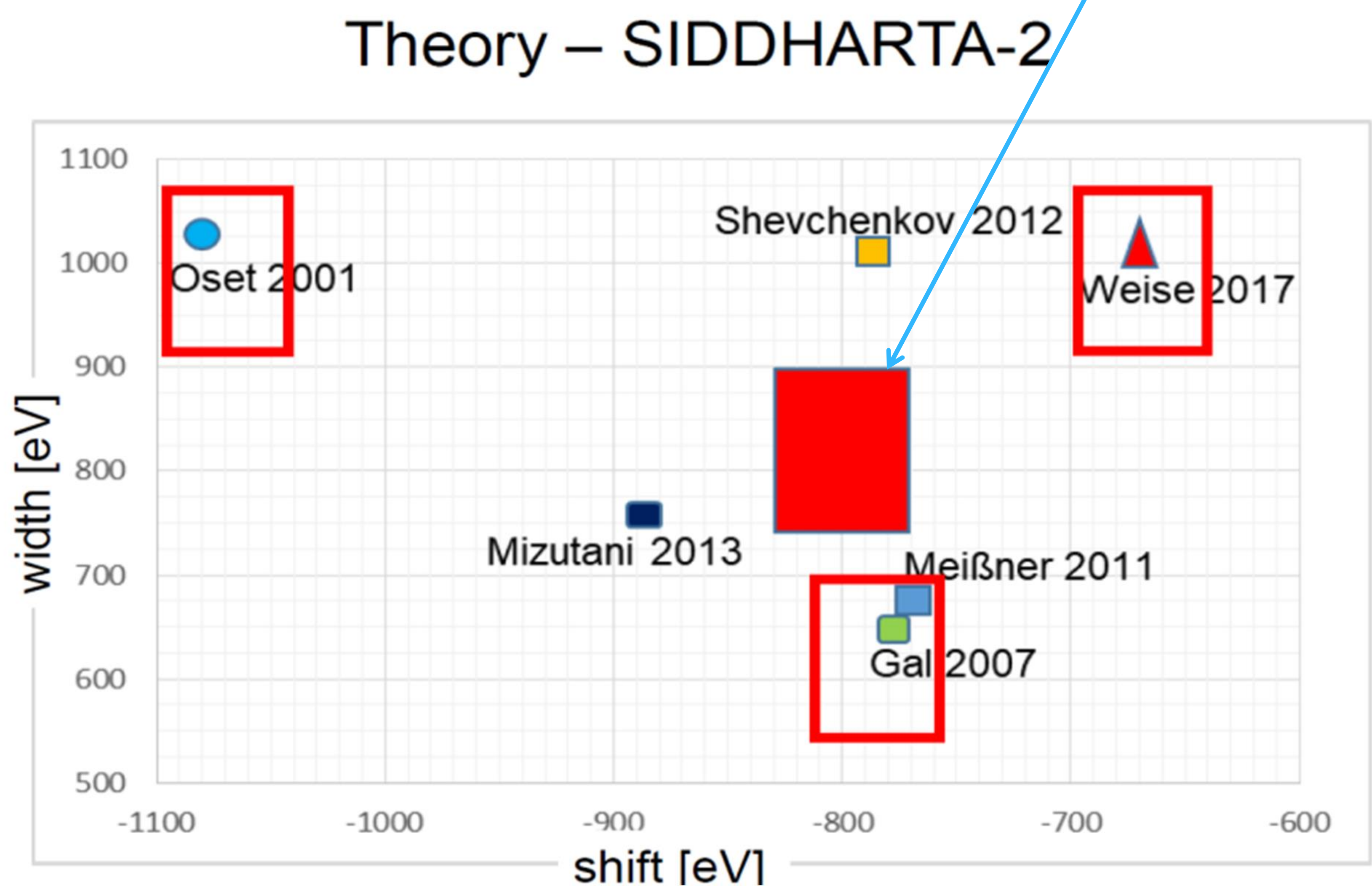
$\varepsilon_{1S} = -283 \pm 36(stat) \pm 6(syst)$ eV
$\Gamma_{1S} = 541 \pm 89(stat) \pm 22(syst)$ eV

2009 kaonic hydrogen measurement



Monte Carlo simulated spectrum

SIDDHARTA-2 targeted precision

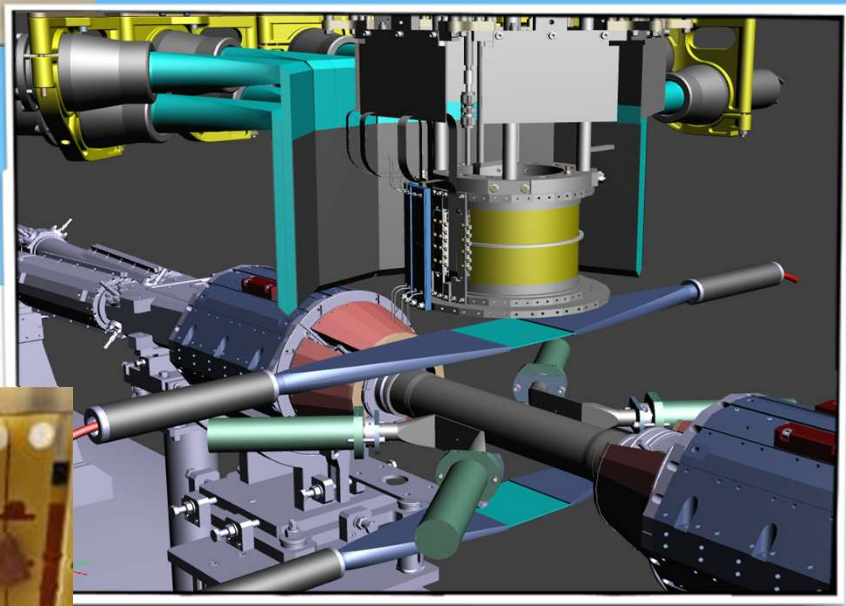


The experimental result will set essential constraints for theories and will help to disentangle between different theoretical approaches

SIDDHARTA-2 apparatus

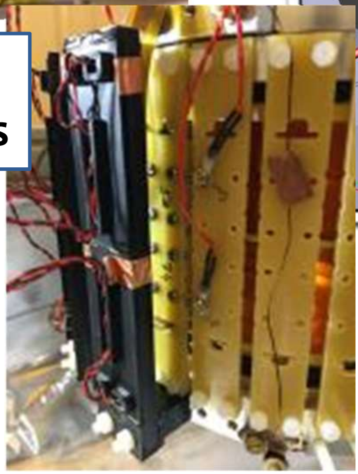
target filled with gas (deuterium)

equipped with 384 SDD channels

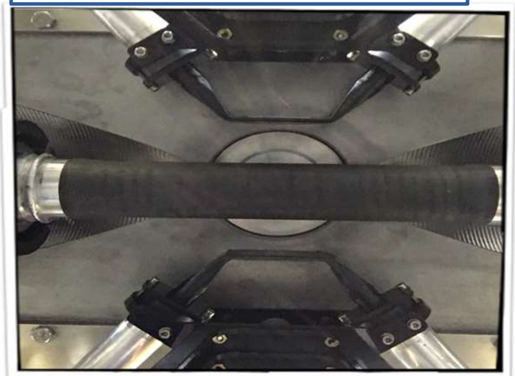


Kaon trigger

complete Veto systems



luminosity monitor

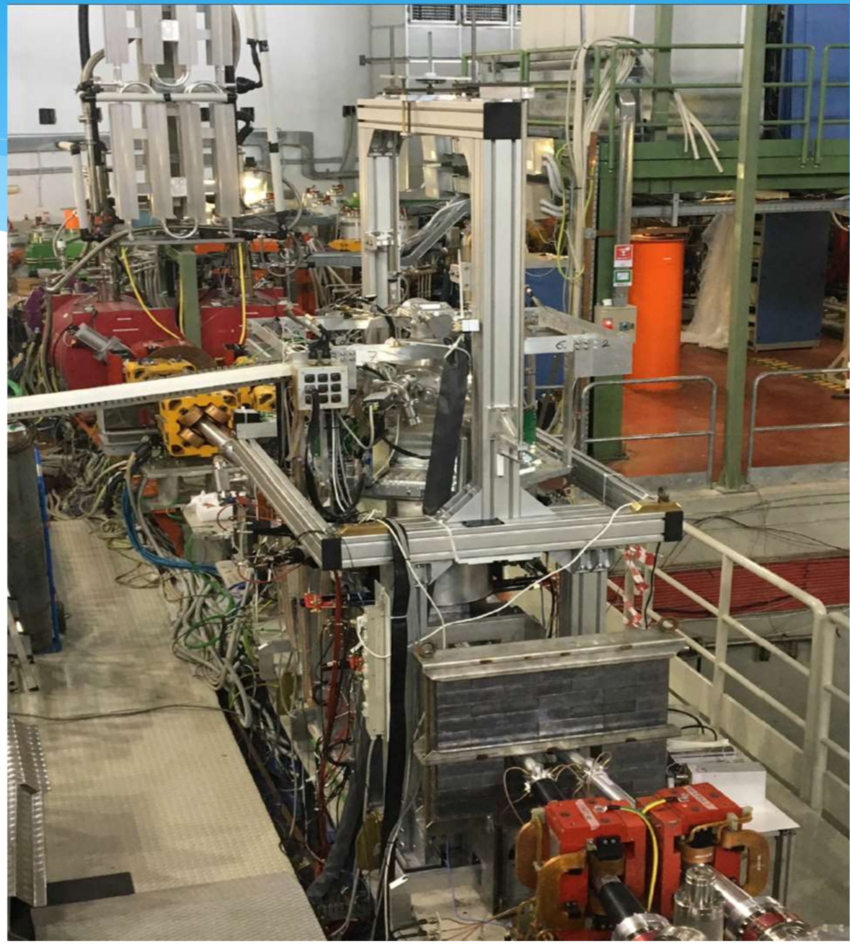


Ready for the first measurement of Kaonic Deuterium

SIDDHARTA-2 PRESENT STATUS

We finish the Phase1 SIDDHARTINO setup

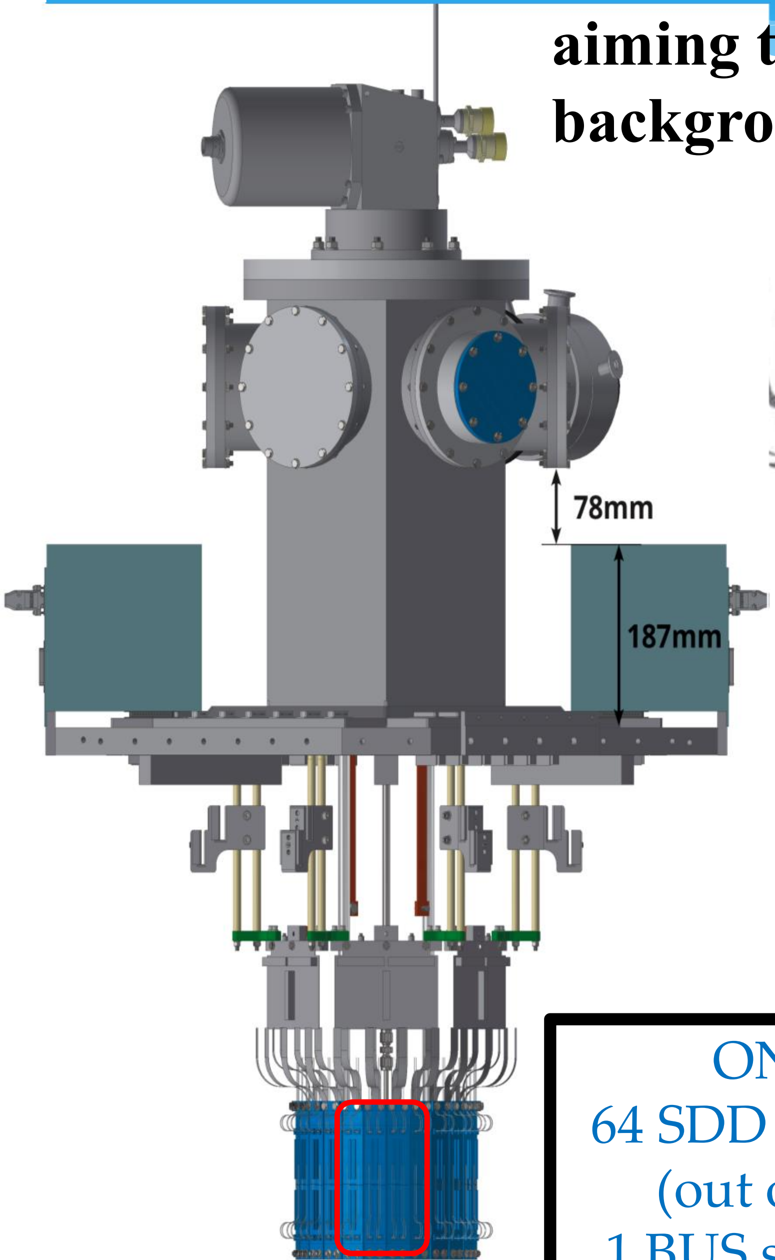
during the commissioning of DAΦNE optimization with the SIDDHARTINO setup for the K-^{4}He measurement (with 8 SDD arrays)

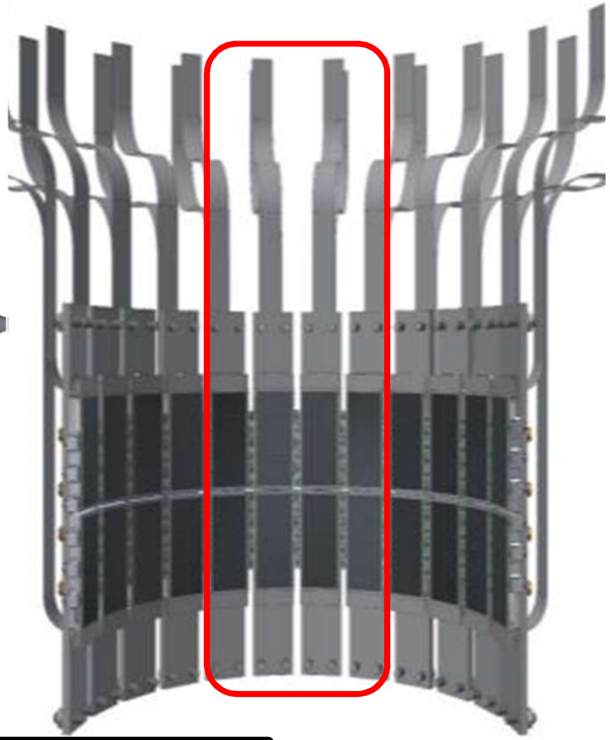


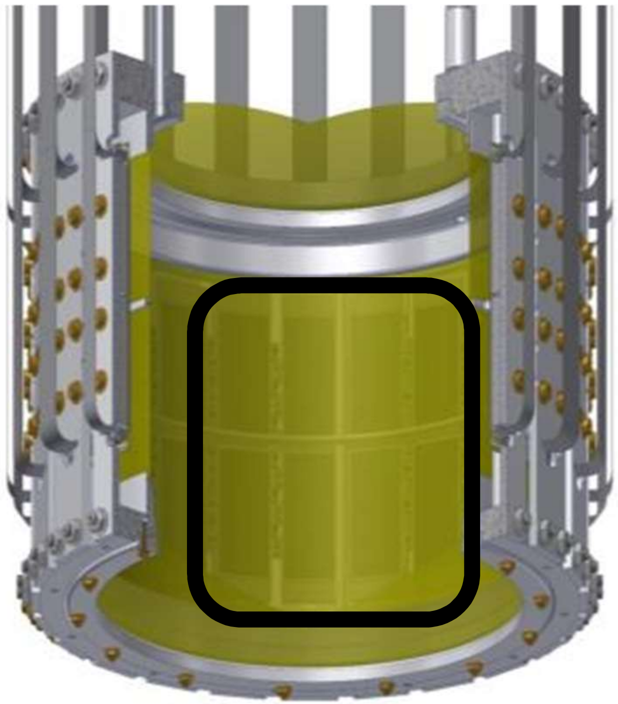
Aim: confirm when DAΦNE background conditions are similar to those in SIDDHARTA 2009

SIDDHARTINO = SIDDHARTA-2 with 8 SDDs arrays

aiming to measure kaonic helium to quantify the background in the new DAFNE configuration







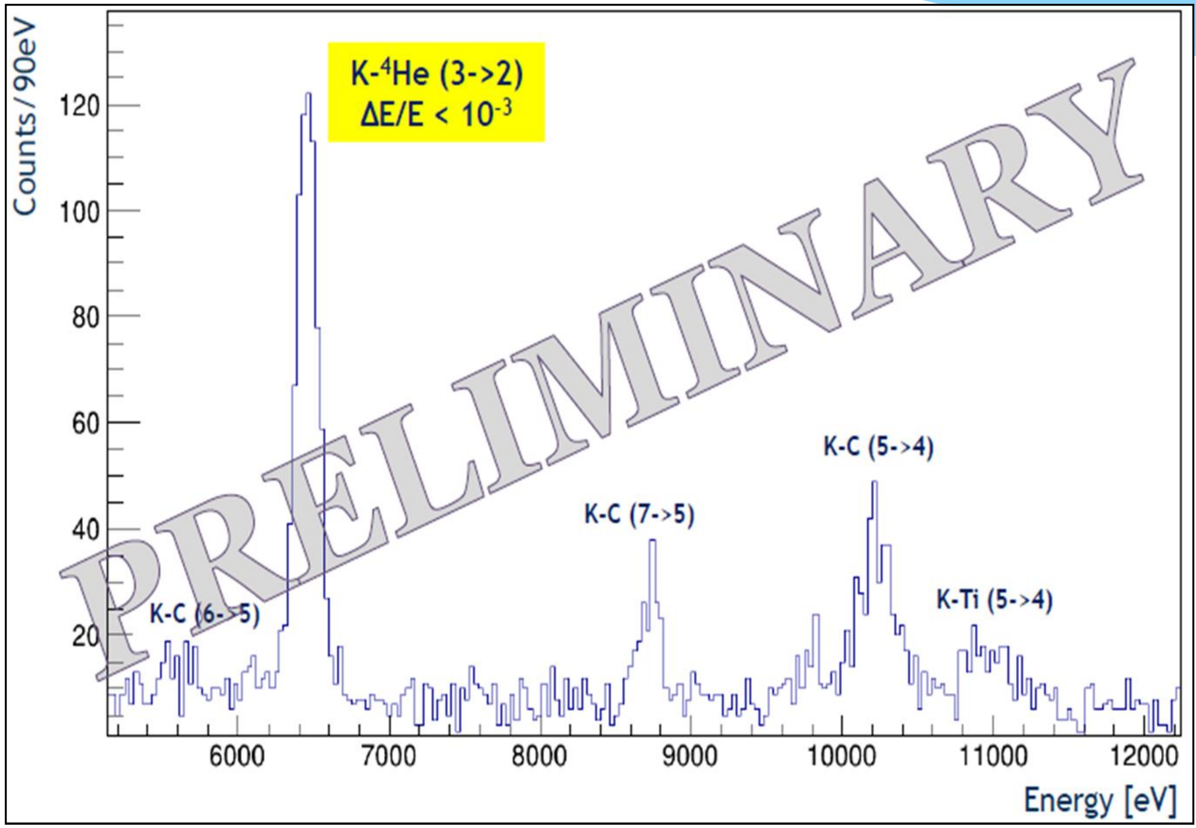
ONLY
64 SDD channels
(out of 384)
1 BUS structure

more details on talk of M. MILIUCCI, 29/07 h. 12:15
Light kaonic atoms high precision X-ray spectroscopy at the DAFNE collider: the SIDDHARTA-2 experiment

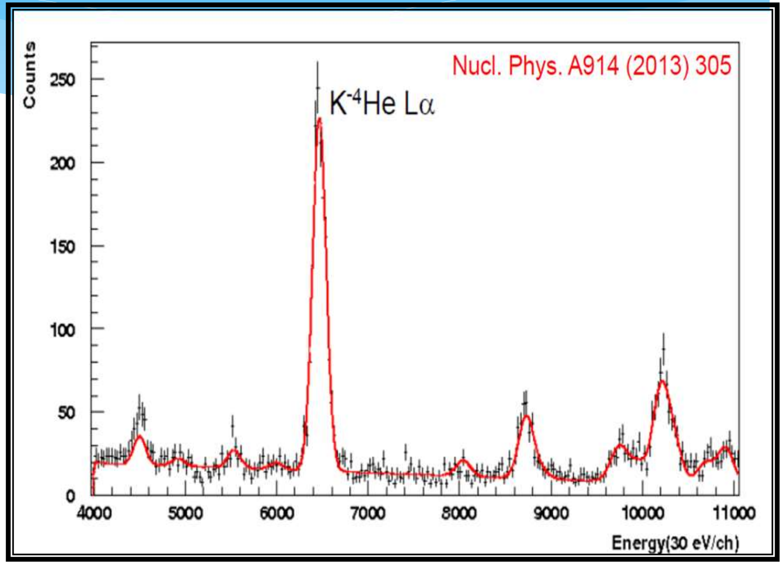
SIDDHARTA-2 @ DAΦNE

... precise adjustments ...

SIDDHARTINO – aim: K-^{4}He test measurement to set the working conditions for SIDDHARTA-2 by a comparison with SIDDHARTA (S/B)



SIDDHARTINO
measured spectrum for ~ 15 pb^{-1}



S/B was 10/1 for the K-^{4}He measurement with ~ 30 pb^{-1}

SIDDHARTA 2009
measured spectrum for ~ 30 pb^{-1}

SIDDHARTA-2 action plan

Action plan for Kaonic Deuterium measurement:

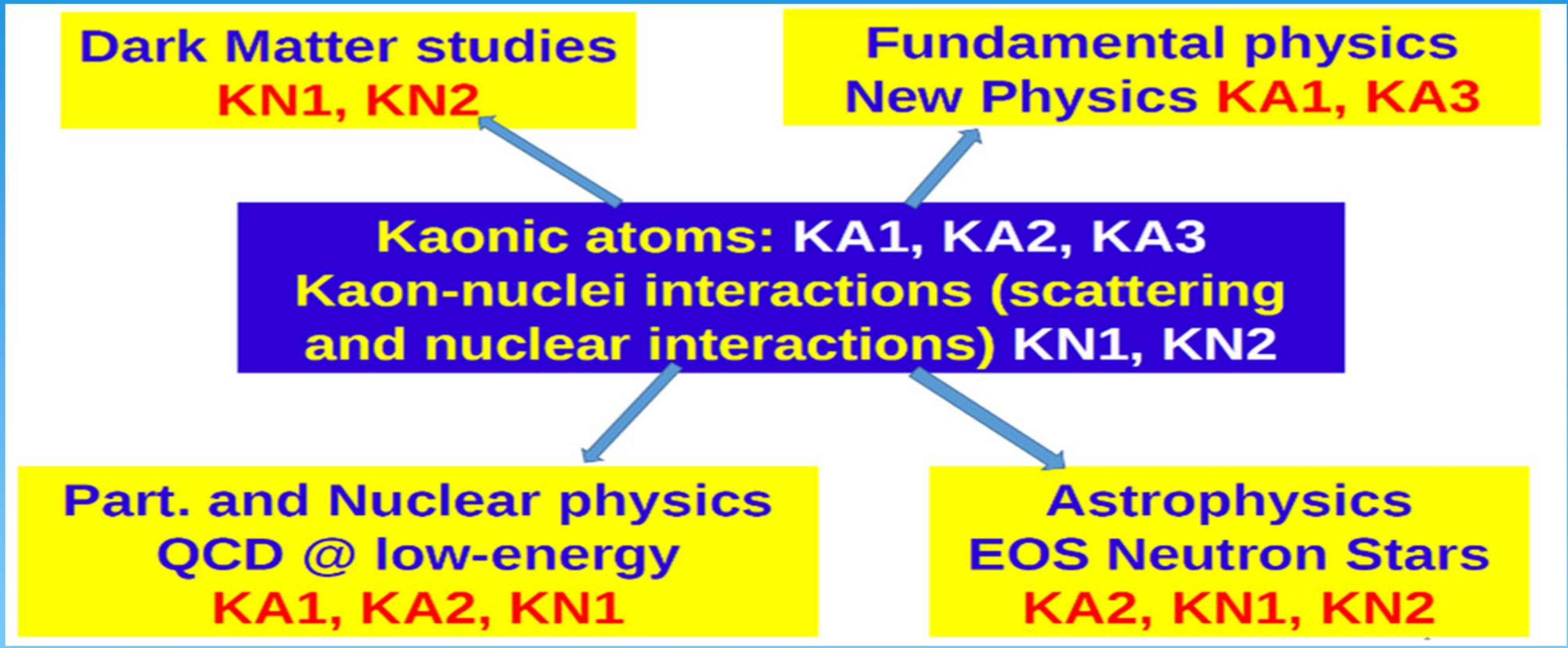
Install all the SDDs (48 SDD arrays), veto systems and start the *kaonic deuterium measurement* for a total integrated luminosity of **800 pb^{-1}**

- **First run with SIDDHARTA-2 setup as planned**
  (about 300 pb^{-1} integrated) – start in October 2021

- **Second run with optimized shielding, readout electronics and other necessary optimizations;**
  (for other 500 pb^{-1} integrated) – after summer 2022

Test runs for other kaonic atoms measurements (HPGE, 1mm SDD, …)

Future plans at DAΦNE



- DAΦNE is a unique machine to perform fundamental physics measurements at the strangeness frontier
- selected light and heavy kaonic atoms transitions (KA1, KA2, KA3)
- low-energy kaon-nucleon scattering processes (KN1)
- low-energy kaon-nuclei interactions (KN2)

Fundamental physics with kaonic atoms

Kaon mass discrepancy – impact on kaonic atoms; CPT, all physics where kaon mass is important such for charmed meson studies and searches beyond standard model

- **a new measurement is strongly required – PDG…**

The best D0 meson mass relies and is limited by the K- mass determination
(Simon Eidelman, Claude Amsler)

Example: Kaon mass measurement

Charged Kaon Mass

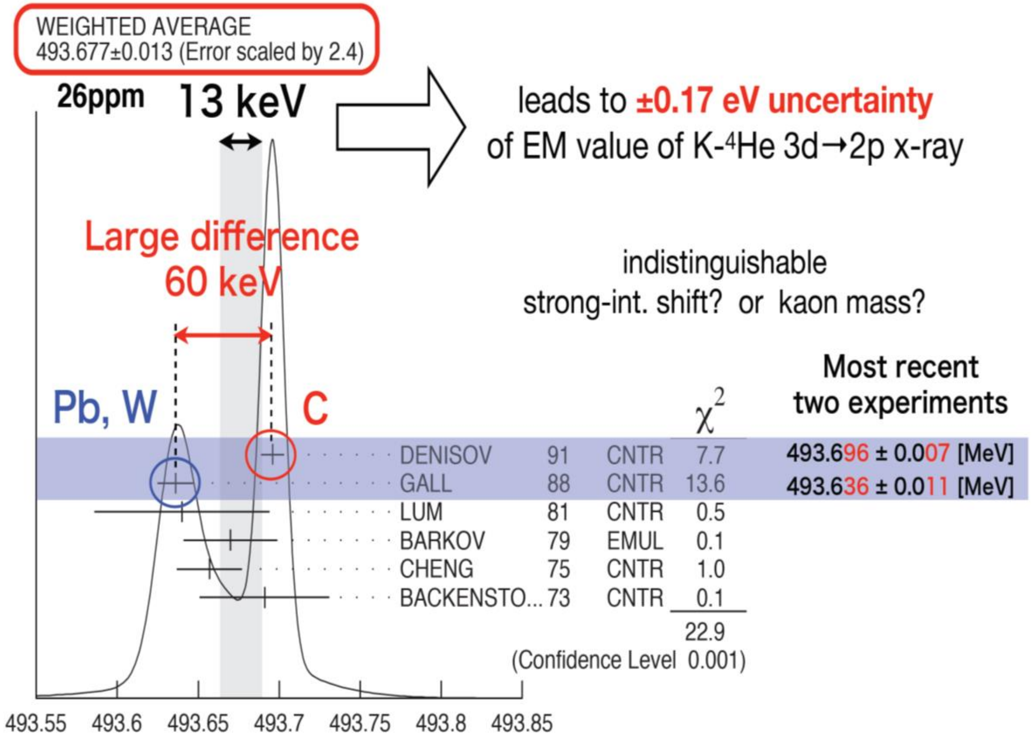
Claude Amsler[1] and Simon Eidelman[2,3,4]

[1]Stefan Meyer Institute, Vienna, Austria
[2]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[3]Novosibirsk State University, Novosibirsk, Russia
[4]Lebedev Physical Institute, Moscow, Russia

January 10, 2021

2003 [6]) was the first enigmatic state whose properties cannot be fully understood in the framework of the quark model. Despite very extensive efforts (the discovery paper with 1880 citations is one of the most cited experimental publications), there is no consensus today about its internal structure. The most popular explanation is that it is a mixture of a regular $q\bar{q}$ state and a $D^0\bar{D}^{*0}$ molecule. To test the validity of the molecular hypothesis it is of vital importance to know precisely how far the $\chi_{c1}(3872)$ state lies from the D^0D^{*0} threshold. Recently LHCb performed a study of $\chi_{c1}(3872)$ produced in decays of $B^\pm$ mesons and other b hadrons [7, 8]. Using the world-largest sample of almost 20k $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ decays, LHCb performed the most precise measurement of the $\chi_{c1}(3872)$ mass and of the energy difference $\delta E = m(D^0) + m(D^{*0}) - m(\chi_{c1}(3872)) = 0.07 \pm 0.12$ MeV. Again, the precision is limited by that of the charged kaon mass.

The precision on the D^0 mass also affects the mixing parameters in the D^0-$\bar{D}^0$ system [4], and in the long run, a more accurate kaon mass may become interesting for first-principle calculations on the lattice [9].



Uncertainty in electron screening. Gamma-ray contamination(Pb,W).

→ **new measurement with low-Z gas targets**

KA1: Kaon Mass and High Z kaonic atoms: HPGE

Feasibility test run during SIDDHARTA-2: KPb

Possible kaonic transitions to be measured:

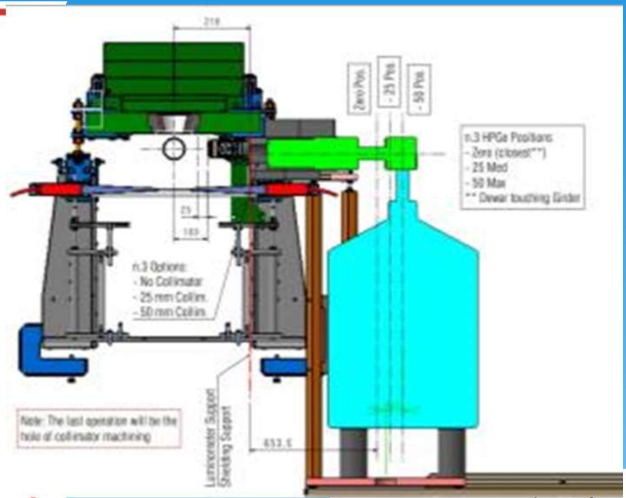
KC(2→1) : 340 keV
KC(3→1): 402 keV

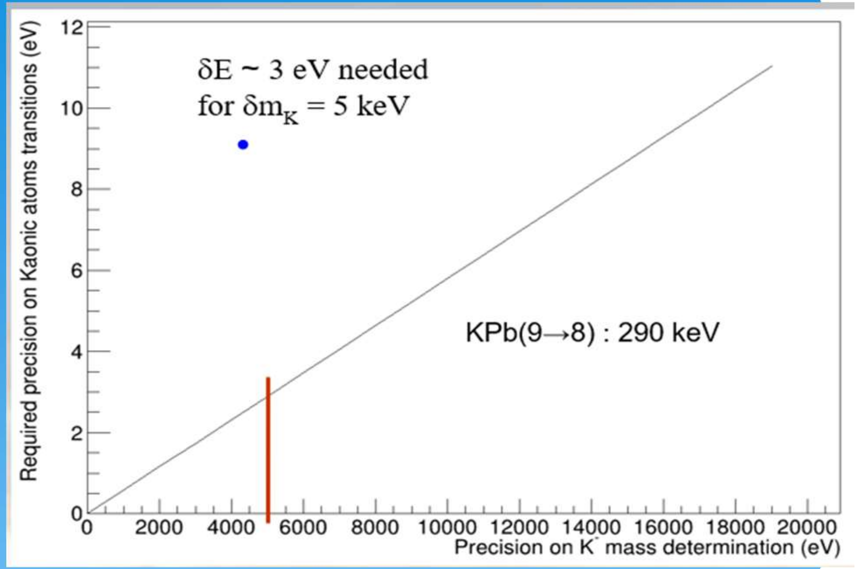
KSe(4→3): 733 keV
KSe(5→4): 339 keV
KSe(5→3): 1073 keV
KSe(6→5) : 184 keV
KSe(6→4): 524 keV

KZr(4→3): 1015 keV
KZr(5→4): 470 keV
KZr(5→3): 1485 keV
KZr(6→5) : 255 keV
KZr(6→4): 725 keV

KTa(6→5): 853 keV
KTa(7→6): 514 keV
KTa(7→5) : 1367 keV
KTa(8→7): 334 keV
KTa(8→6): 848 keV

KPb(6→5) : 1076 keV
KPb(7→6): 649 keV
KPb(8→7): 421 keV
KPb(8→6): 1070 keV
KPb(9→8): 289 keV





$$\sigma m_K = \frac{m_K^2}{\mu_{KN}^2}\,\frac{1}{Z^2}\,\frac{10^6}{26,6}\,\frac{\sigma E^K_{X\to Y}}{\left(\frac{1}{Y^2}-\frac{1}{X^2}\right)}$$

Target just behind the luminometer, which is used as trigger

Detector Key Points:
- Very large dynamic range
- Possibility to test High Z targets
- High resolution for precision measurements
- Rate capability up to 150 kHz

Dedicated measurements:

Targets : Se, Zr, Ta, Pb
(systematic errors minimisation, cascade processes in heavy kaonic atoms)
simultaneous measurements of atomic transitions from various n levels and with different Δn

~ 360 pb-1 (~ 30 days) of beamtime requested

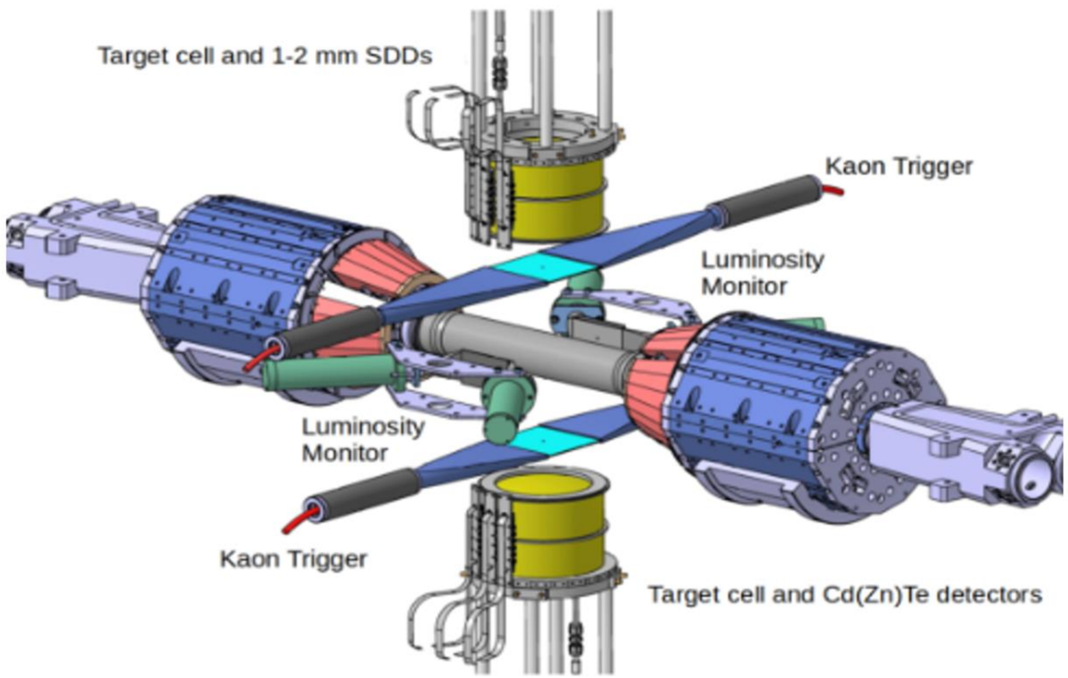
!!! Similar estimations for each target !!!

KA2: Light Kaonic Atoms Measurements

Expected impact:

- kaon-nuclei potential and chiral models below threshold and the nature of Λ(1405).
- astrophysics: search for dark matter with strangeness and the equation of state for neutrons stars
- 3He,4He (2p → 1s) transition: stronger constraints on the theoretical models describing the kaon-nucleon interaction in systems with more than two nucleons

Setup: SDD1mm & CdTe

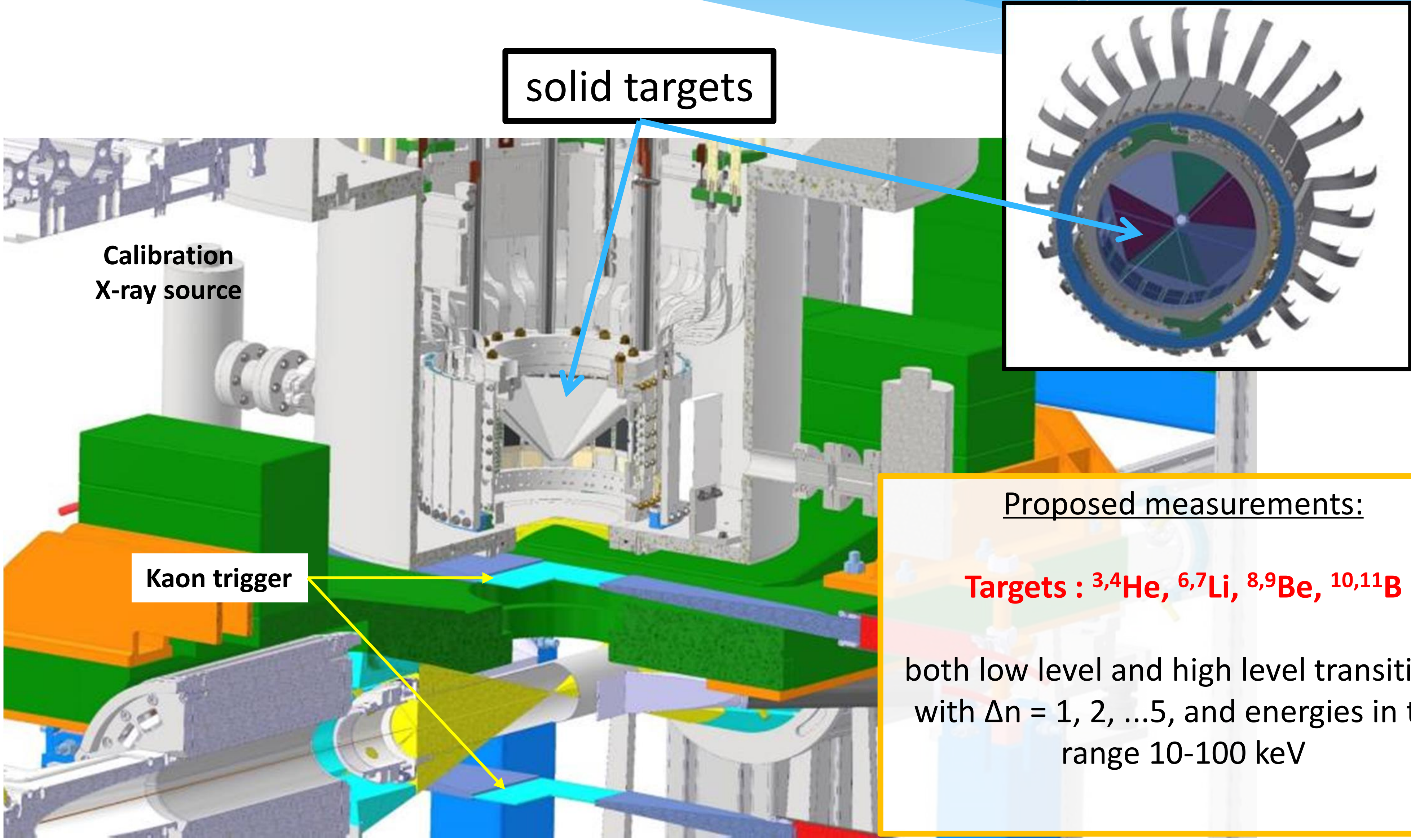


- Information on the nature of the Λ(1405) state can be obtained from the upper-level transitions of light kaonic atoms (different isotopes of KLi, KBe and KB[35])

Targets : ^{3,4}He, ^{6,7}Li, ^{8,9}Be, ^{10,11}B

both low level and high level transitions with Δn = 1, 2, ...5, and energies in the range 10-100 keV

KA2: Solid target system for light kaonic atoms



Proposed measurements:

Targets : ^{3,4}He, ^{6,7}Li, ^{8,9}Be, ^{10,11}B

both low level and high level transitions with $\Delta n = 1, 2, ...5$, and energies in the range 10-100 keV

New detectors - SDD 1mm / Cd(Zn)Te

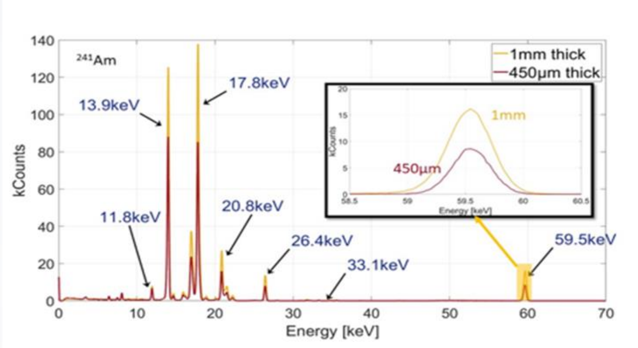
Possible kaonic transitions to be measured with 1-2 mm SDDs:

K^{3}He(2→1) : 33 keV
K^{4}He(2→1) : 35 keV

K^{6,7}Li(3→2) : 15 keV
K^{6,7}Li(4→2) : 20 keV

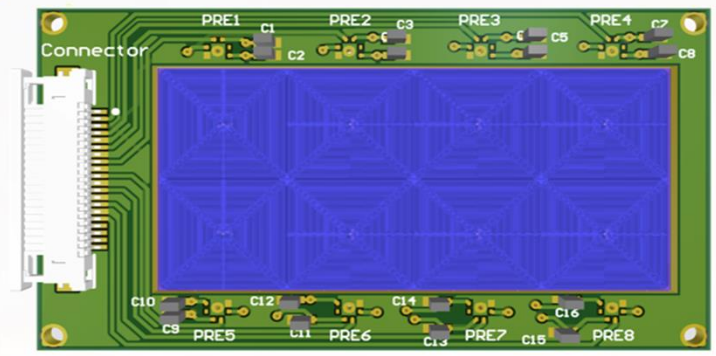
K^{8,9}Be(3→2) : 27 keV
K^{8,9}Be(4→2) : 37 keV
K^{8,9}Be(5→3) : 14 keV

K^{9,10,11}B(4→3) : 15 keV
K^{9,10,11}B(5→3) : 22 keV
K^{9,10,11}B(6→4) : 11 keV



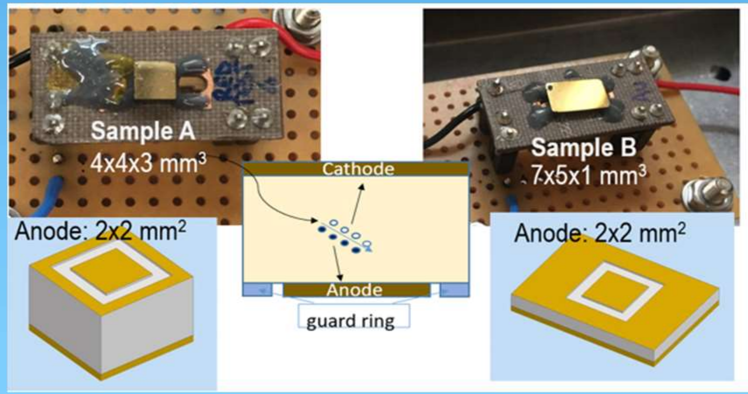
First XRF tests with known targets show very promising results

Prototypes of electronics boards are already available



FWHM ~ 150 eV (SDD)

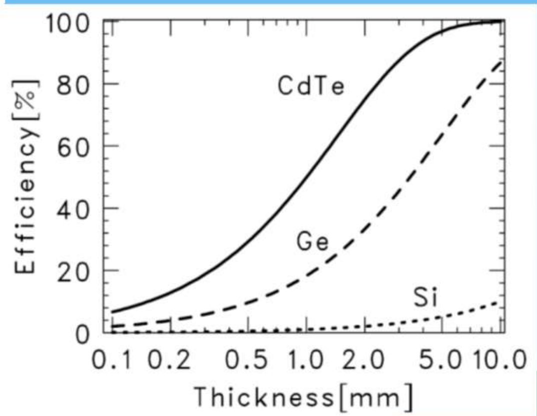
Cd(Zn)Te



Possible kaonic transitions to be measured with **CdTe detectors**:

K^{6}Li(2→1) : 81 keV
K^{6}Li(3→1) : 97 keV
K^{7}Li(2→1) : 82 keV
K^{7}Li(3→1) : 98 keV
K^{9,10}B(4→2) : 58 keV
K^{9,10}B(5→2) : 65 keV
K^{9,10}B(6→2) : 69 keV
K^{9,10}B(7→2) : 71 keV
K^{11}B(4→2) : 59 keV
K^{11}B(5→2) : 66 keV
K^{11}B(6→2) : 70 keV
K^{11}B(7→2) : 72 keV

required 300 pb-1 for each target



FWHM ~ 800 eV (CdZnTe)

CdTe (CdZnTe) detectors will be developed in the STRONG2020-ASTRA project

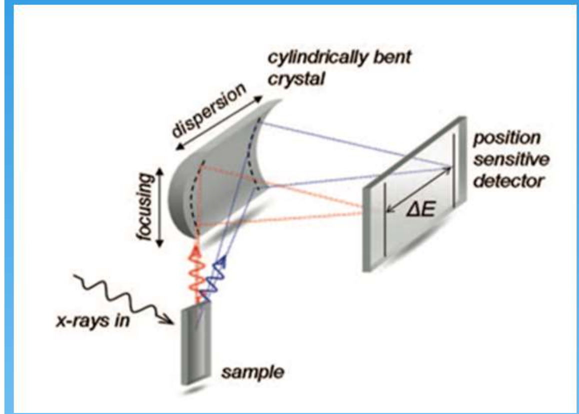
First prototypes will be available in 2022

KA3: sub-eV precision Kaonic Atoms measurements: VOXES spectrometer

Kaon-Nucleon interaction: Chiral or Phenomenological models?

There is only ONE possible solving measurment: The $K^{3,4}He$ isotopic shift measurement

Calculated quantity [1]	Phenomenologica [2]	Chiral [3]
ε (K^4He)	-0,41 eV	-0,09 eV
ε (K^3He)	0,23 eV	-0,1 eV
ε (K^4He) - ε (K^3He)	-0,64 eV	0,01 eV



Spectrometer with HAPG mosaic crystals in Von Hamos configuration:

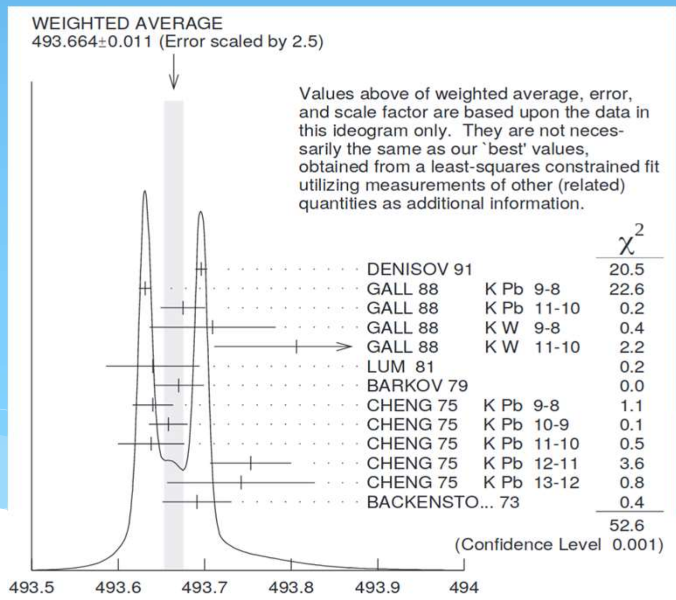
Solve the kaonic helium isotopic shift problem

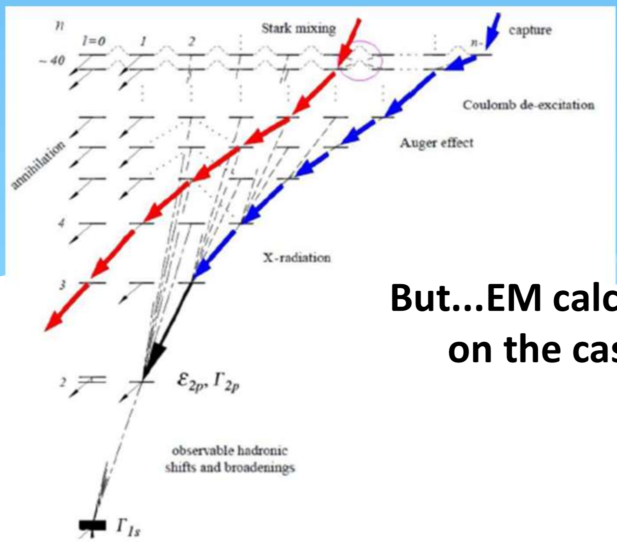
Precise determination of the K^- mass

Stronger constraints for the EM cascade models for kaonic atoms

… ALL IN PARALLEL

But...levels and calculated shifts depend on the K^- mass value...

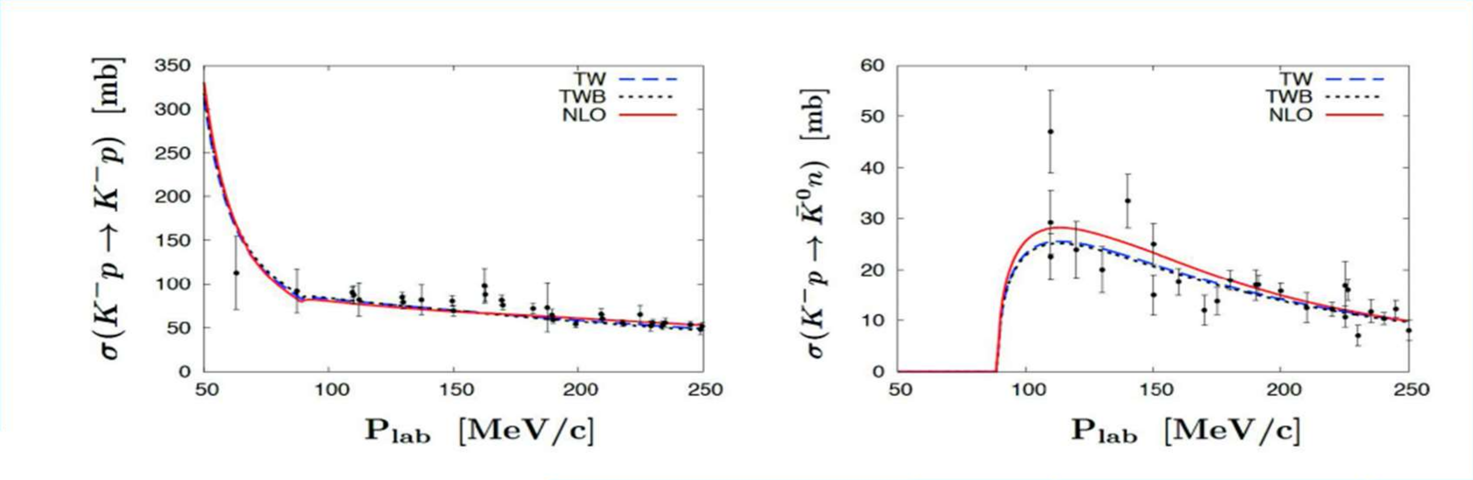




But...EM calculated levels depend on the cascade processes...

Kaon-nuclei scattering and interaction: KN1, KN2

- The present knowledge of total and differential cross sections of low energy kaon-nucleon reactions is very limited.
- Below 150 MeV/c there is a “desert” - the experimental data are very scarce and with large errors and practically no data exist below 100 MeV/c.
- Studies of Hyperon-nucleon, Hyeron-multinucleon (AMADEUS experience)
- Kaon-nucleon scattering/interaction data are fundamental to validate theories: chiral symmetries; lattice calculations; potential models etc.



Measurement of the low-energy scattering process of kaons, and of the Λ(1405) kaon induced production, on various targets such as hydrogen, deuterium, helium-3 and helium-4 using a GEM-TPC active target.

FUTURE at DAΦNE

arXiv:2104.06076v1 [nucl-ex] 13 Apr 2021

Fundamental physics at the strangeness frontier at DAΦNE.
Outline of a proposal for future measurements.

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The DAΦNE collider at INFN-LNF is a unique source of low-energy kaons, which was used by the DEAR, SIDDHARTA and AMADEUS collaborations for unique measurements of kaonic atoms and kaon-nuclei interactions. Presently, the SIDDHARTA-2 collaboration is underway to measure the kaonic deuterium exotic atom. With this document we outline a proposal for fundamental physics at the strangeness frontier for future measurements of kaonic atoms and kaon-nuclei interactions at DAΦNE, which is intended to stimulate discussions within the broad scientific community performing research directly or indirectly related to this field.

PACS numbers: 13.75.Jz, 36.10.-k, 36.10.Gv, 14.40.-n, 25.80.Nv, 29.30.-h, 29.90.+r, 87.64.Gb, 07.85.Fv, 29.40.-n, 29.40.Gx, 29.40.Wk

https://arxiv.org/pdf/2104.06076.pdf

Towards a LOI/Technical Design Report in preparation

Many theoreticians provided input and support

Ignazio Bombaci
Alessandro Drago
Isaac Vidana
Wolfram Weise, TU Munich
Avraham Gal, Jerusalem
Eli Friedman, Jerusalem
Jiri Mares. Prague
Oset & Ramos, Spain
Laura Tolos, Spain
Ulf Meissner, Bonn & China
Tony Thomas, Adelaide
Tetsuo Hyodo, Japan
Shota Ohnishi, Japan
Maxim Pospelov,
Randolf Pohl

invitation to all those interested to participate to this new adventure in strangeness physics !

Conclusions

- Kaonic Helium test measurement with SIDDHARTINO -> background w.r.t. SIDDHARTA and SIDDHARTA-2 for Kd goal (despite the pandemic difficult period)
- We are ready and very motivated to go on with SIDDHARTA-2 kaonic deuterium measurement
- We strongly believe that this is an opportunity which cannot be missed, since we propose to measure fundamental interaction processes which could not be measured till now, and which will have a huge and concrete impact, “now and here”, in particle and nuclear physics, astrophysics, cosmology and foundational Issues, supported by a strong international collaboration.

Part of the SIDDHARTA-2 collaboration

Thank you!

Spares

Priorities and readiness

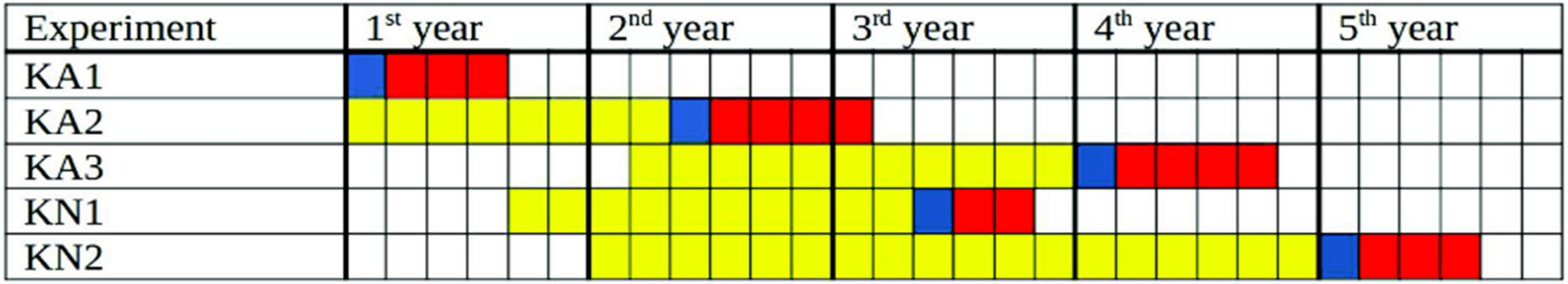

Fig. 1. Schematic Gantt Chart for Fundamental physics at the Strangeness Frontier at the DAΦNE Proposal: KA1 (see Sec. 2.1), KA2 (see Sec. 2.2), KA3 (see Sec. 2.3), KN1 (see Sec. 3.2), KN2 (see Sec. 3.3). Yellow: preparation phase. Blue: installation phase. Red: data taking.

New results of K-^{4}He 2p level shift

$E_{e.m.}$ = 6463.5±0.2 eV

E_{exp} = 6463.6±5.8 eV

$$\Delta E = E_{exp} - E_{e.m.} = 0 \pm 6(\text{stat}) \pm 2(\text{syst})\ \text{eV}$$

Published in PLB 681(2009) 310-314

More date on K-^{4}He 2p level shift

$$\Delta E = E_{exp} - E_{e.m.} = +5 \pm 3(\text{stat}) \pm 4(\text{syst})\ \text{eV}$$

$$K^{-4}\text{He}:\Gamma_{2p} = 14 \pm 8(\text{stat}) \pm 5(\text{syst})\ \text{eV}.$$

for a very first look at a possible isotope shift between kaonic3He and4He

Published in PLB 697(2011) 199

New K^4He results by KEK PS E570

PLB 653 (2007) 387

Transition	$3d \to 2p$	$4d \to 2p$	$5d \to 2p$
Measured energy (eV)	6466.7 ± 2.5	8723.3 ± 4.6	9760.1 ± 7.7
EM calc. energy (eV) [15]	6463.5	8721.7	9766.8

ΔE (eV)	Ref.
-41 ± 33	Wiegand *et al.* [5]
-35 ± 12	Batty *et al.* [6]
-50 ± 12	Baird *et al.* [7]
-43 ± 8	Average of above [1,7]
$+2 \pm 2$ (stat) ± 2 (syst)	Okada *et al.* [10]
0 ± 6 (stat) ± 2 (syst)	This work

ΔE_{2p} =2±2(stat.)±2(syst.) eV)

SIDDHARTA's results is consistent with the results obtained by E570 experiment

"kaonic helium puzzle" solved