Status and perspectives for low energy kaon-nucleon interaction studies at DAFNE: from SIDDHARTA to SIDDHARTA-2

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for the 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

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- SIDDHARTA-2 @ DAΦNE – present status
- SIDDHARTINO - K^--^4He test measurement
- SIDDHARTA-2 action plan
- Future plans at DAΦNE

The scientific aim

To perform precision measurements

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

- to obtain unique information about QCD in the non -perturbative regime in the strangeness sector

Starting with the

- most precise measurement for *kaonic hydrogen – done by SIDDHARTA in 2009*
- NOW first measurement of kaonic deuterium - autumn 2021 *by SIDDHARTA -2*

To extract the antikaon-nucleon isospin dependent scattering lengths

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

Deser Formula

Deser-type relation (including the isospin-breaking corrections) connects shift ε_{1s} and width Γ_{1s} to the real and imaginary part of $a_{K\text{-}p}$

$$\boxed{\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-p}[1 - 2\alpha\mu(ln\alpha - 1)a_{K-p} + \ldots]}$$

A similar formula holds for $a_{K\text{-}d}$

$$\boxed{\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-d}[1 - 2\alpha\mu(ln\alpha - 1)a_{K-d} + \ldots]}$$

The connection between the scattering lengths $a_{K\text{-}p}$ and $a_{K\text{-}d}$ and the s-wave $\bar{K}N$ isospin dependent (I=0,1) isoscalar a_0 and isovector a_1 scattering length:

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

$$a_{K-n} = a_1$$

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

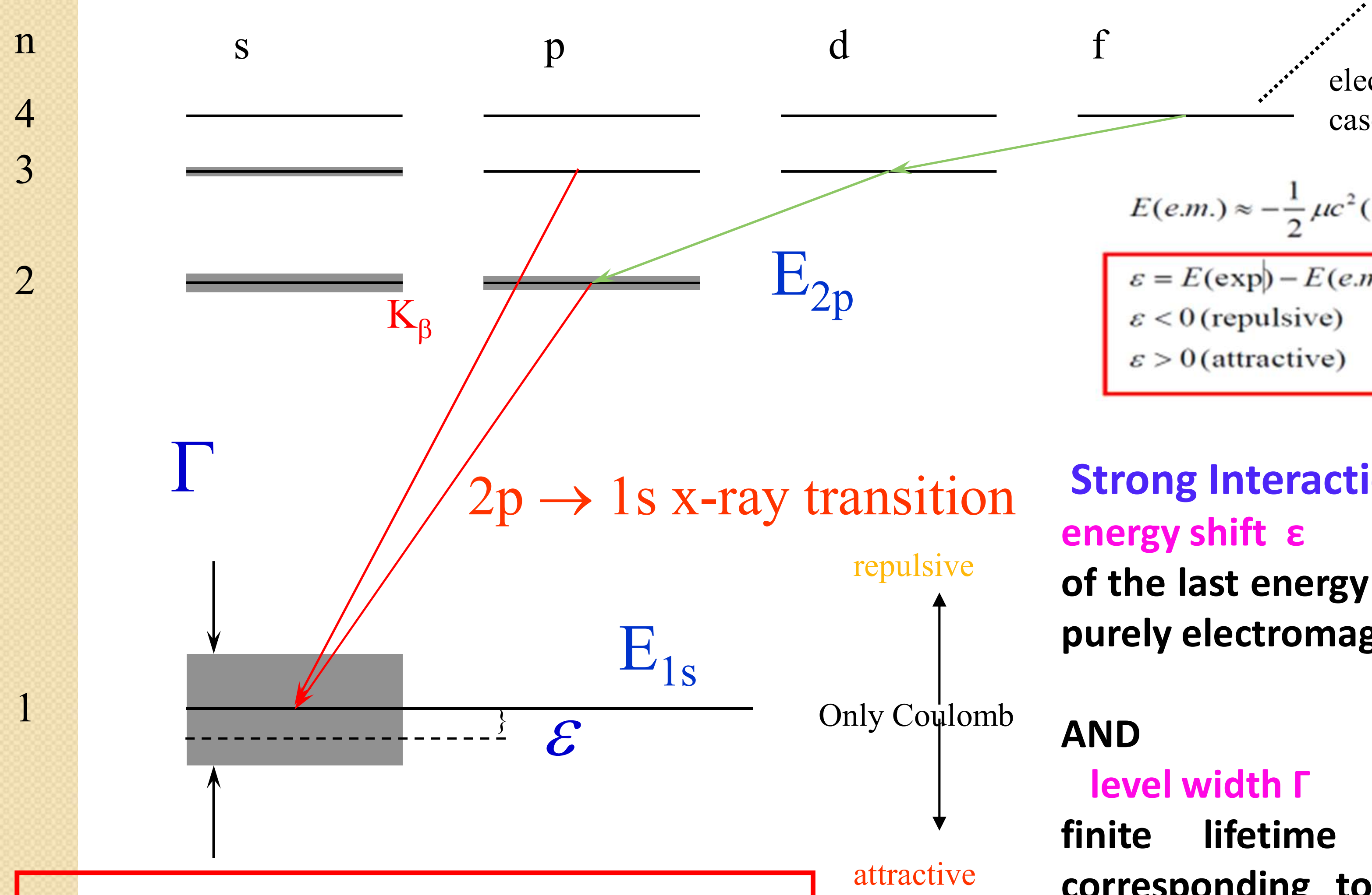
$$Q = \frac{1}{2}[a_{K-p} + a_{K-n}] = \frac{1}{4}[a_0 + 3a_1]$$

C, includes all higher-order contributions, namely all other physics associated with the K^-d three-body interaction.

Fundamental inputs
of low-energy QCD effective theories.

Kaonic atoms

K- captured in excited orbit, replacing the electron



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

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

Strong Interaction causes:

energy shift ε

of the last energy levels form their purely electromagnetic values

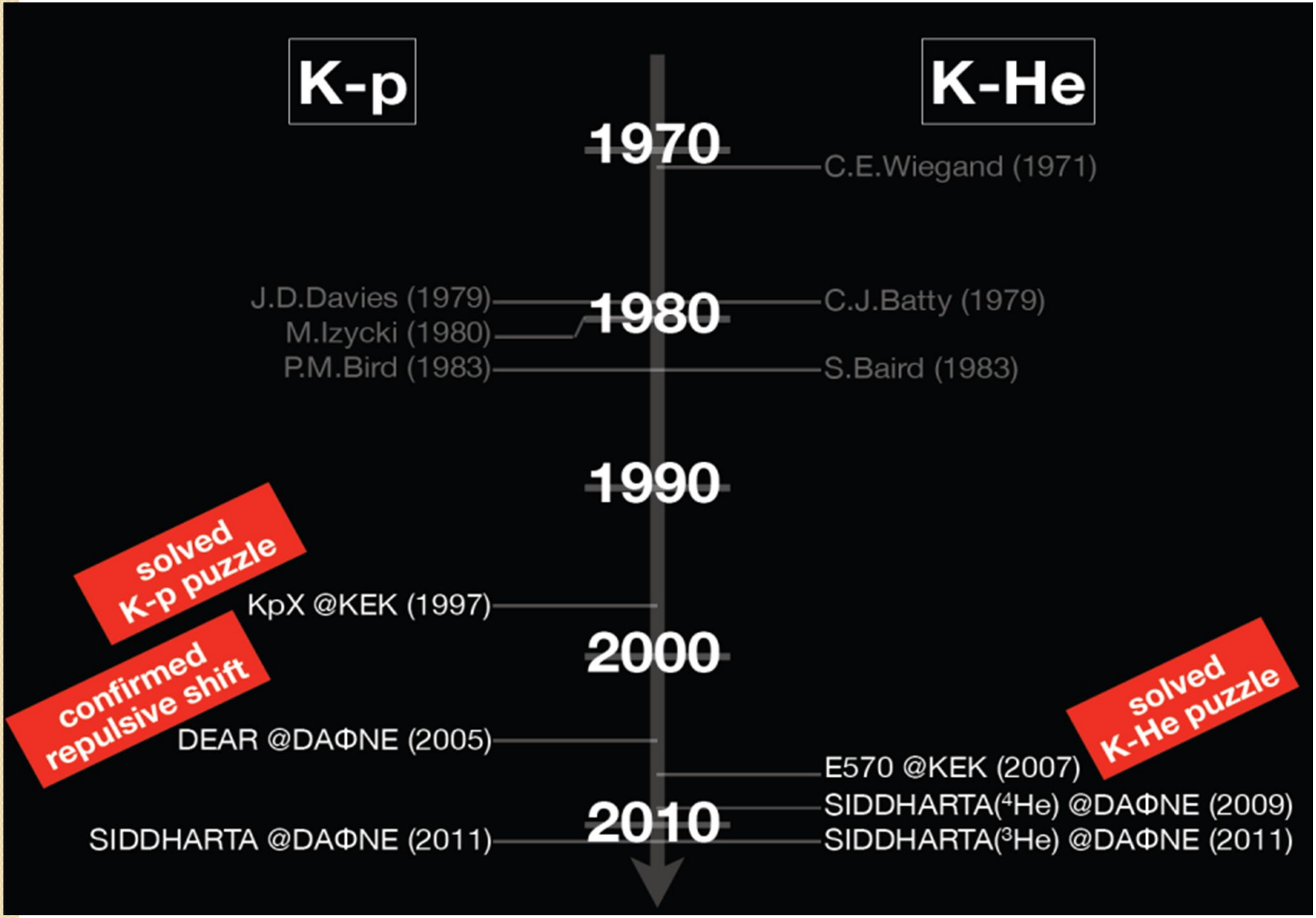
AND

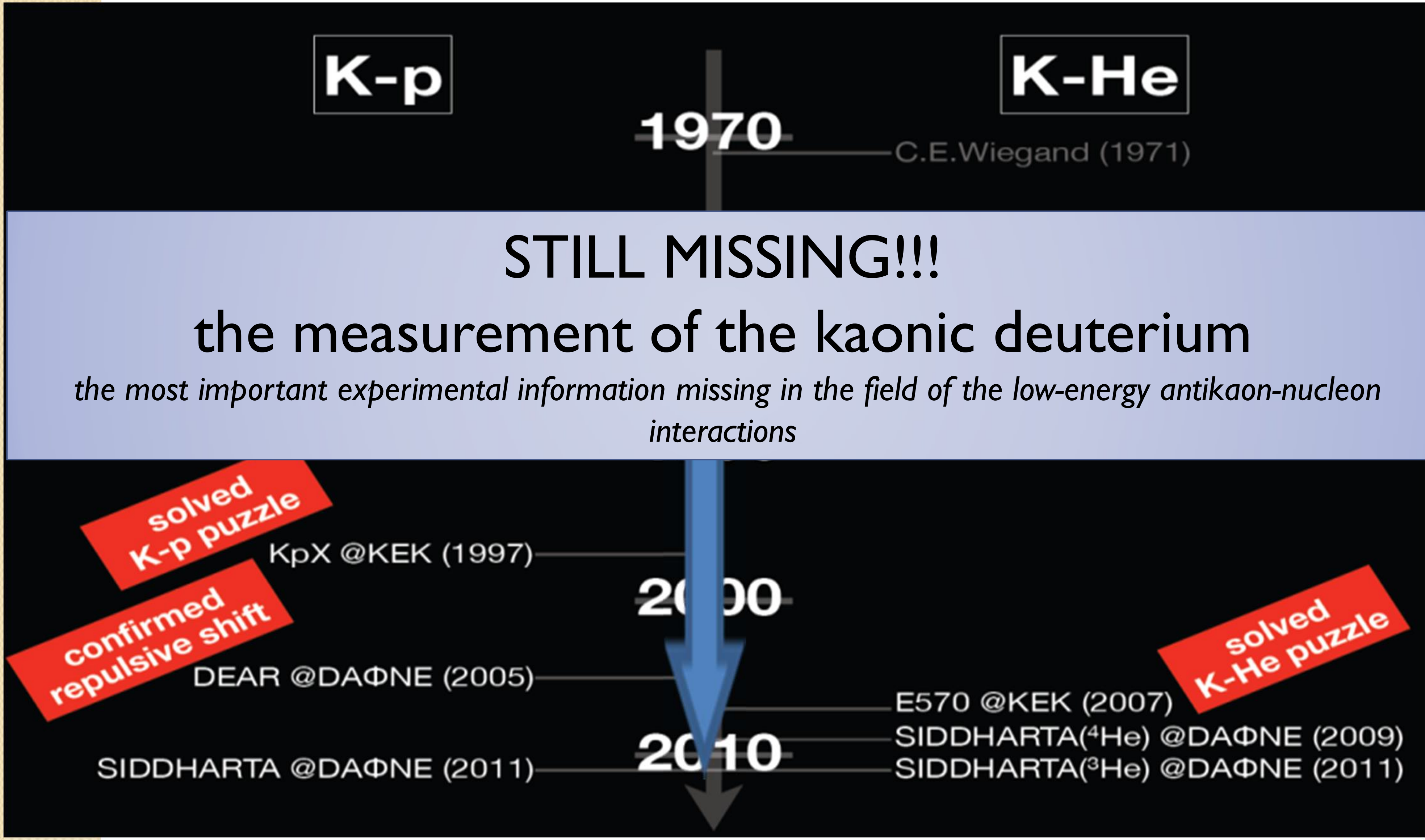
level width Γ

finite lifetime of the state corresponding to an increase in the observed level width

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

Kaonic atoms history





STILL MISSING!!!

the measurement of the kaonic deuterium

the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions

SIDDHARTA-2 collaboration

starting from 2019 at DAFNE accelerator

SIDDHARTA-2 improvements

SIDDHARTA-2 is a development both on the DAFNE collider side and on the experiment side.

SIDDHARTA-2 apparatus consists in a series of improvements with respect to the SIDDHARTA aiming to dramatically:

increase the S/B ratio and also the signal rate:

- **by gaining in solid angle**
- **taking advantage of new SDDs technology**

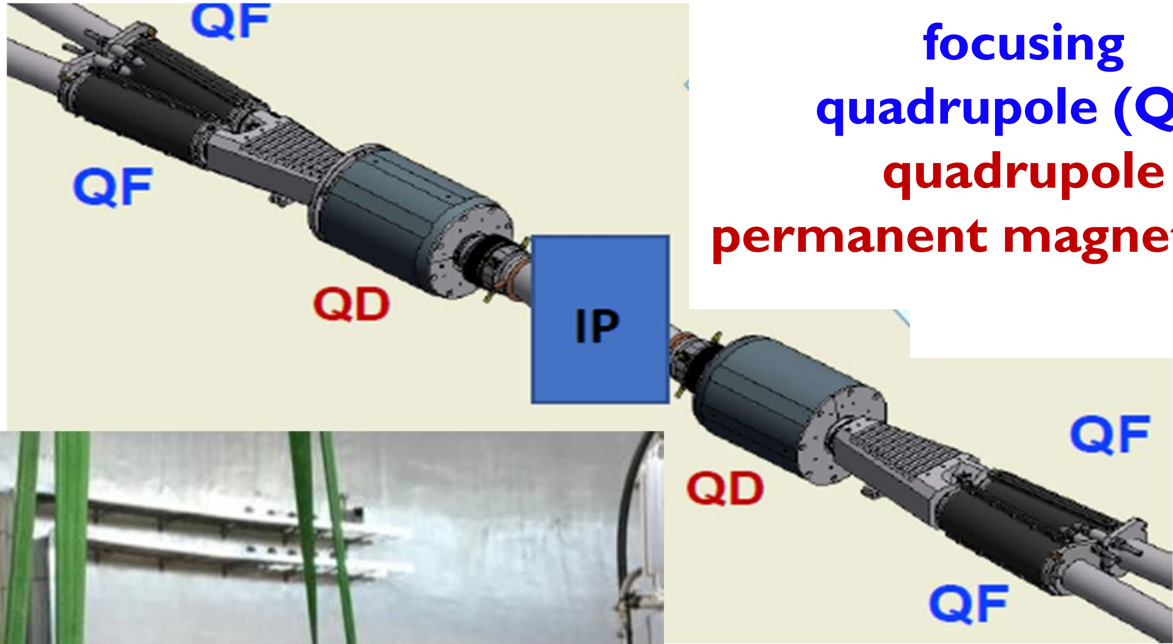
and

of the reduction of the background:

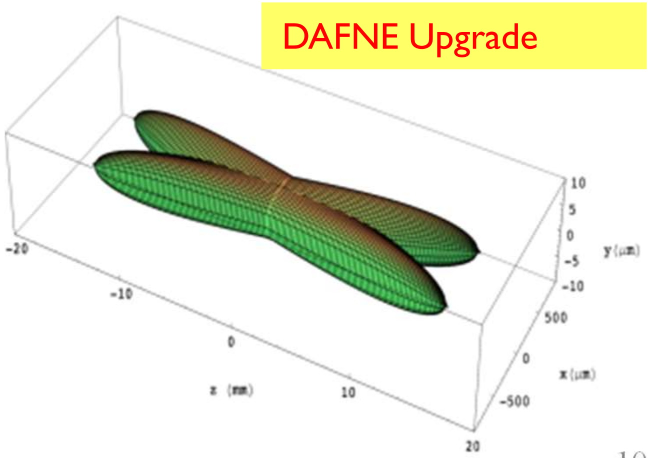
- **by improving the SDDs timing**
- **implementing of an additional veto system**

New interaction region on DAFNE collider

New optics for collisions with reduced horizontal and vertical beam dimensions

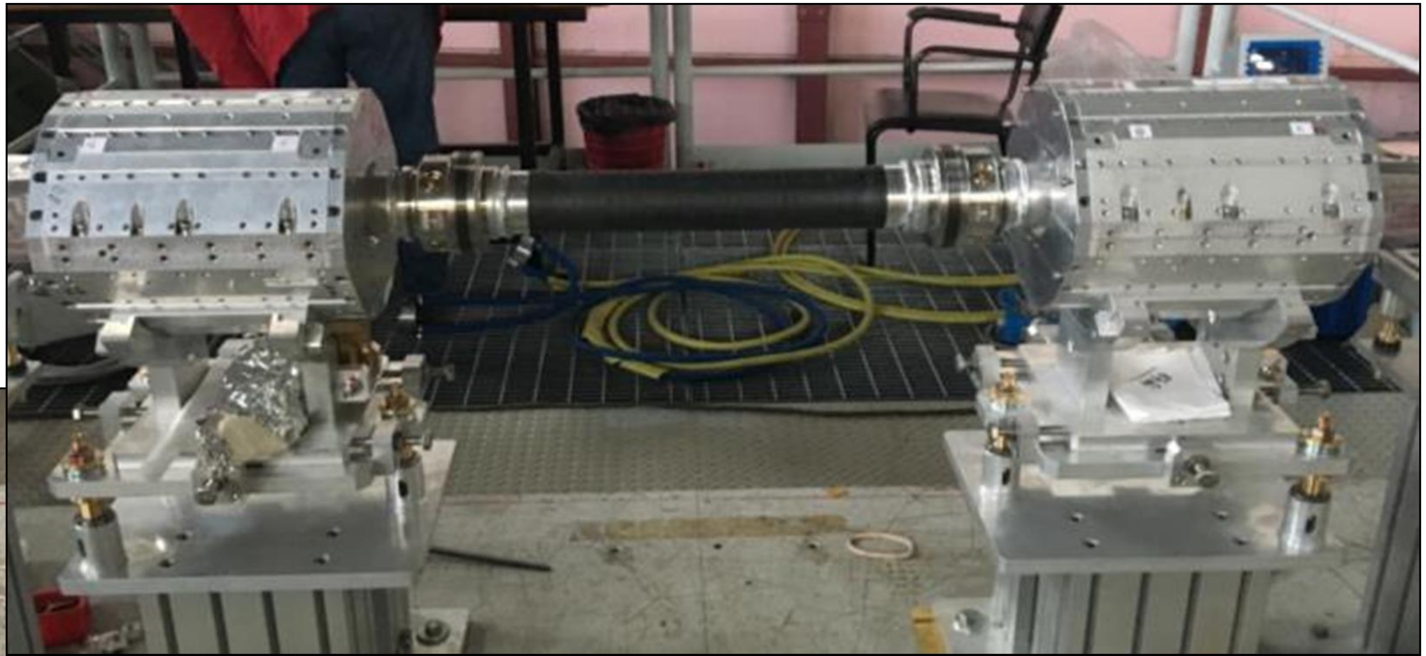


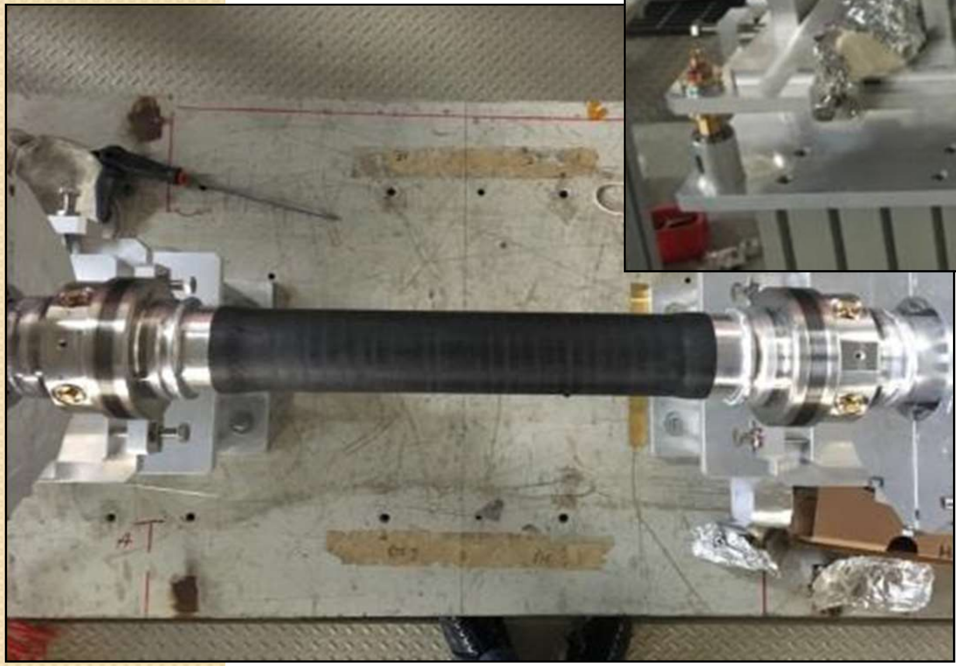
focusing quadrupole (QF)
quadrupole permanent magnet (QD)



New beam pipe

flanges removed
major source of
asynchronous
background



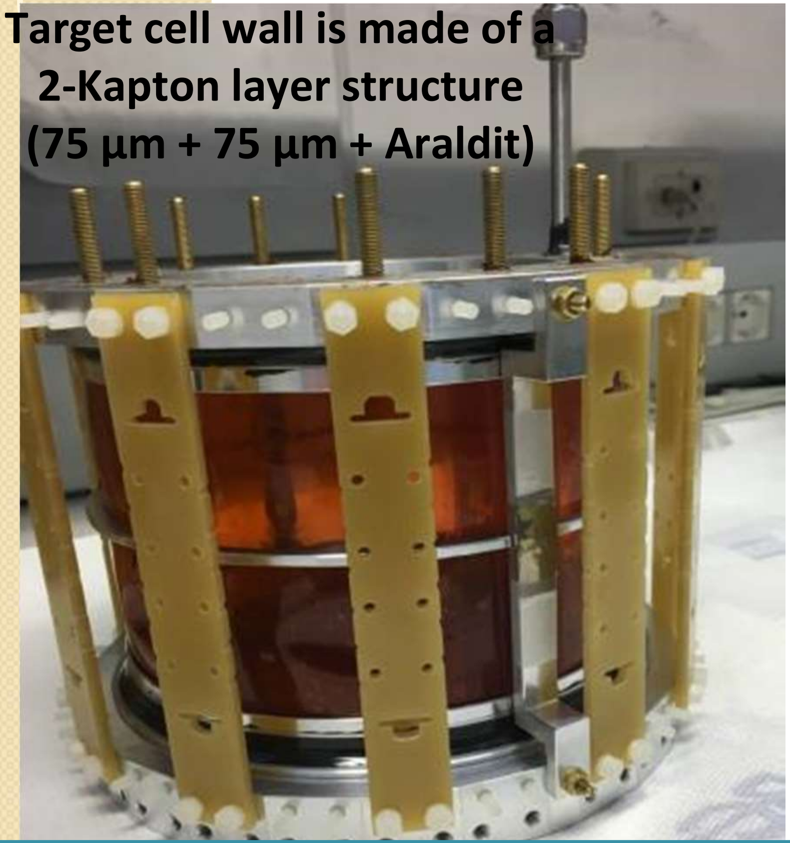


carbon fiber reinforcement
thickness ~ 500 micron
internal ultra pure aluminum
ø 55mm, thickness ~ 150 micron

DAΦNE luminosity monitor

Light target and Silicon Drift Detector assembly

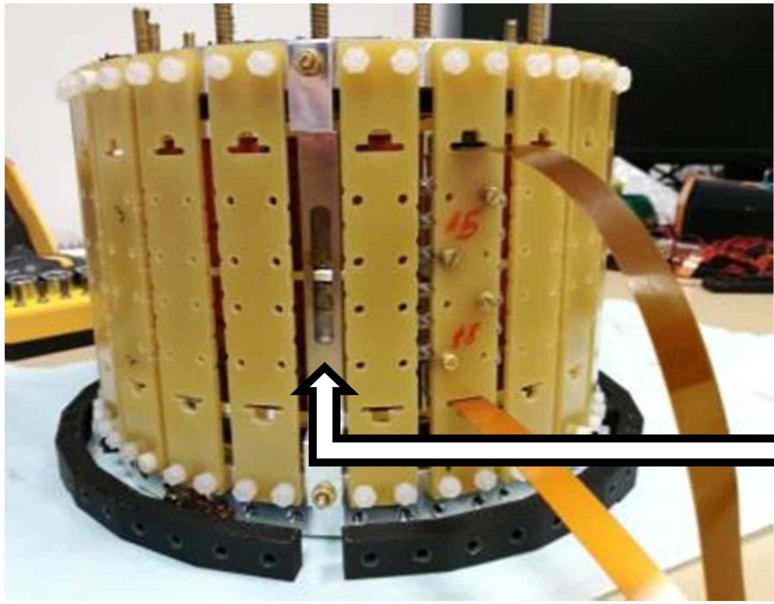
Target cell wall is made of a
2-Kapton layer structure
(75 µm + 75 µm + Araldit)



increase the target stopping power

almost double gas density with respect to SIDDHARTA (3% LHD)

SDDs placed 5 mm from the target wall



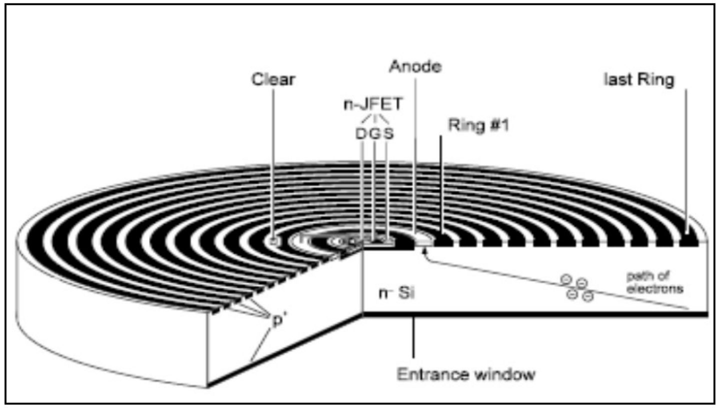
calibration foils inserted near to the SDD are activated by the X-ray tubes

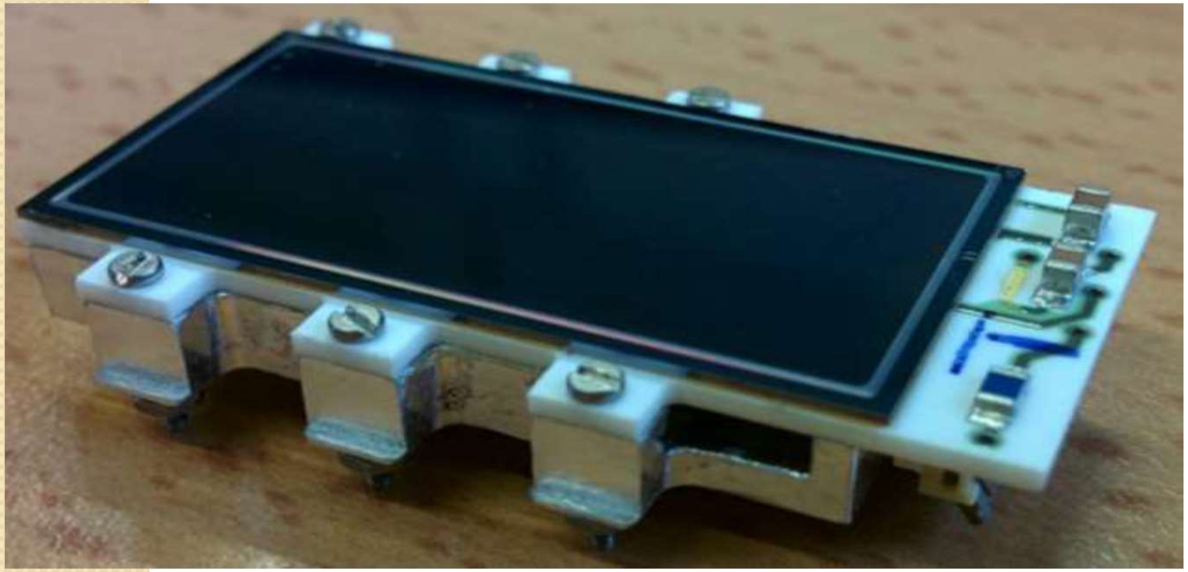
The new advance technology allow to setup a cryogenic target (20K) detector system with an efficient detector packing density, covering a solid angle for stopped kaons in the gaseous target of $\sim 2\pi$.

New technology for SDD detectors

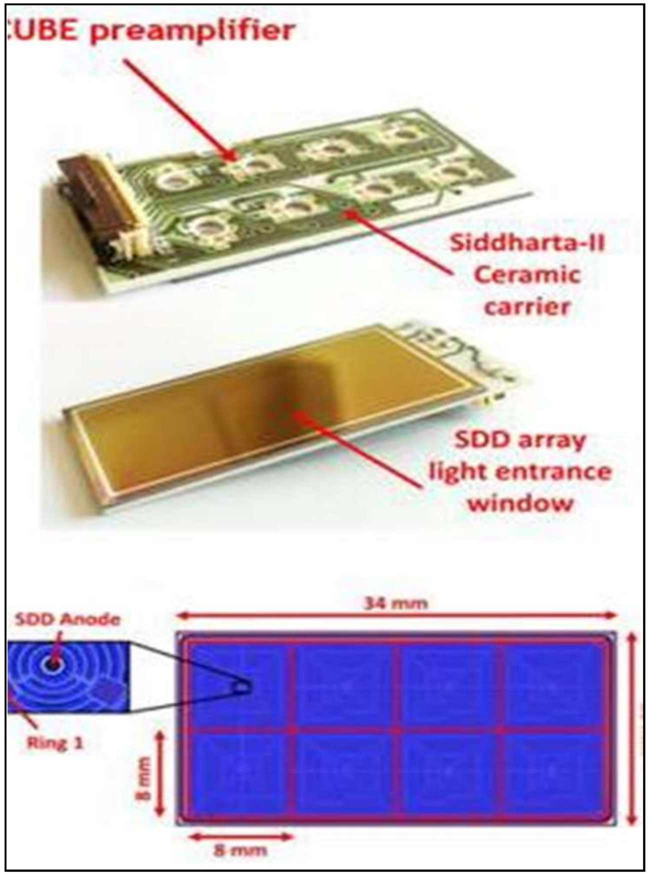
difference with respect to the SDDs in SIDDHARTA:

- **the change the JFET structure on the SDD chip to a complementary metal-oxide semiconductor integrated charge sensing amplifier CUBE**
- **able to operate at very low temperatures (< 50 K)**
- **better drift time (400ns vs. 800ns)**
- **reduction of the single element size – more compact assembly (from 10×10 to 8×8mm2 = 64mm2 – less dead area**





Monolitic 4x2 SDD array produced by Fondazione Bruno Kessler (FBK) in Trento, Italy

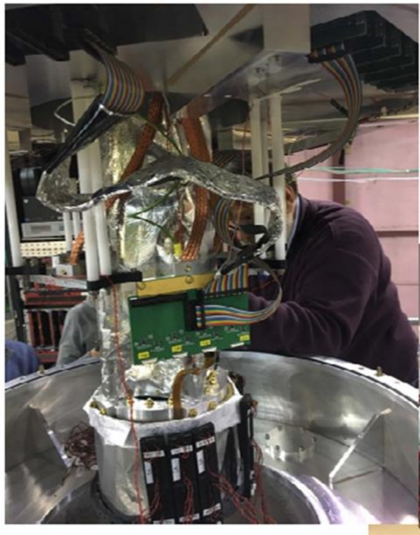


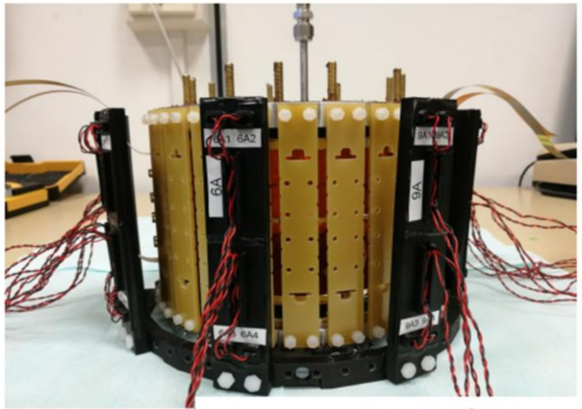
The Veto systems

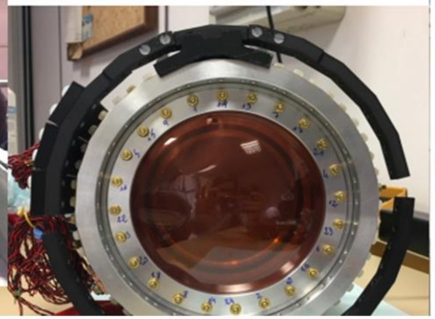
The veto-1 system:

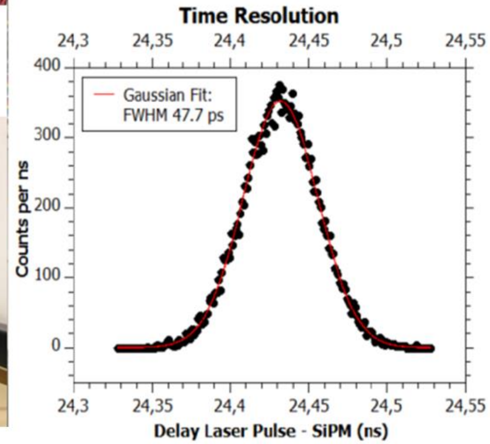
The veto-2 system:

an inner ring of scintillator tiles (SciTiles) placed as close as possible behind the SDDs for charge particle tracking

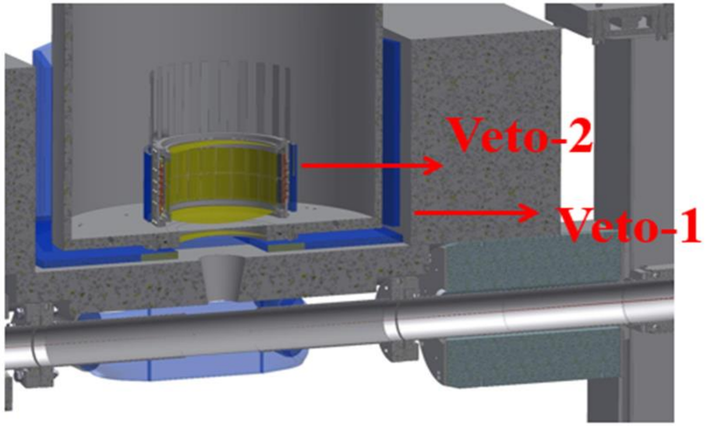






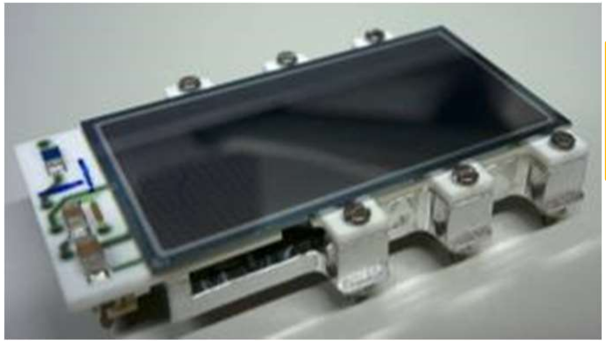


outer barrel of scintillators, acting as a gas stopping detector to identify the products of K- absorption on gas nuclei, characterized by a long moderation time (4-5 ns) (suppress the X-rays produce by the kaons stopped in gas from kaons stopped in setup material)

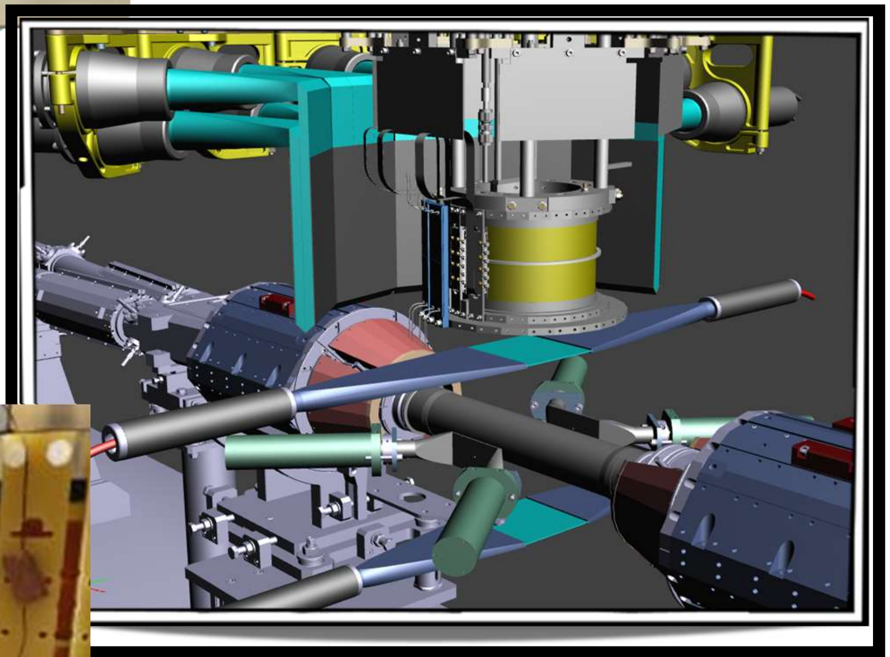


SIDDHARTA-2 APPARATUS in one slide

target filled with gas (deuterium)

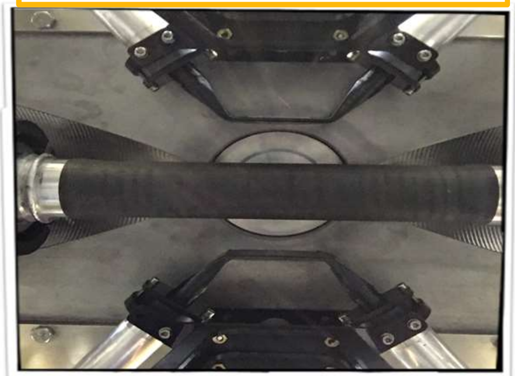


equipped with 384 SDD channels

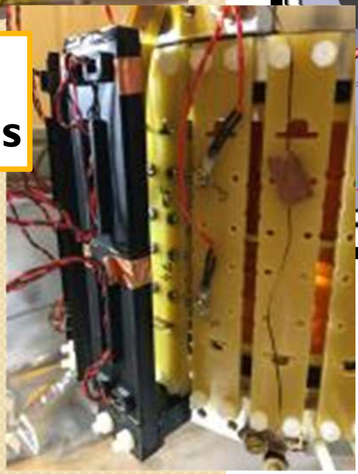


Kaon trigger

luminosity monitor

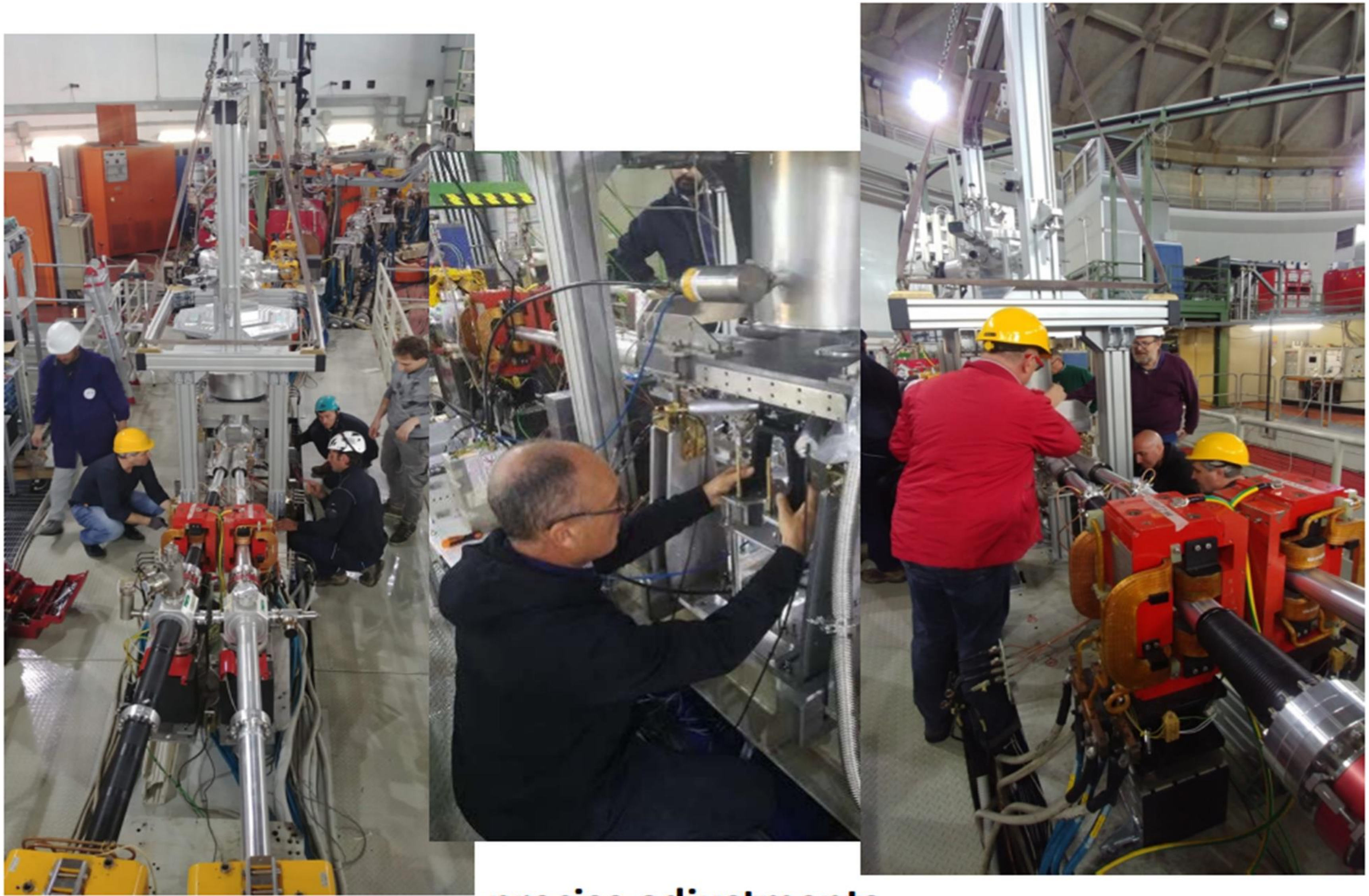


complete Veto systems



Ready for the first measurement of Kaonic Deuterium

SIDDHARTA-2 @ DAΦNE installation



... precise adjustments ...

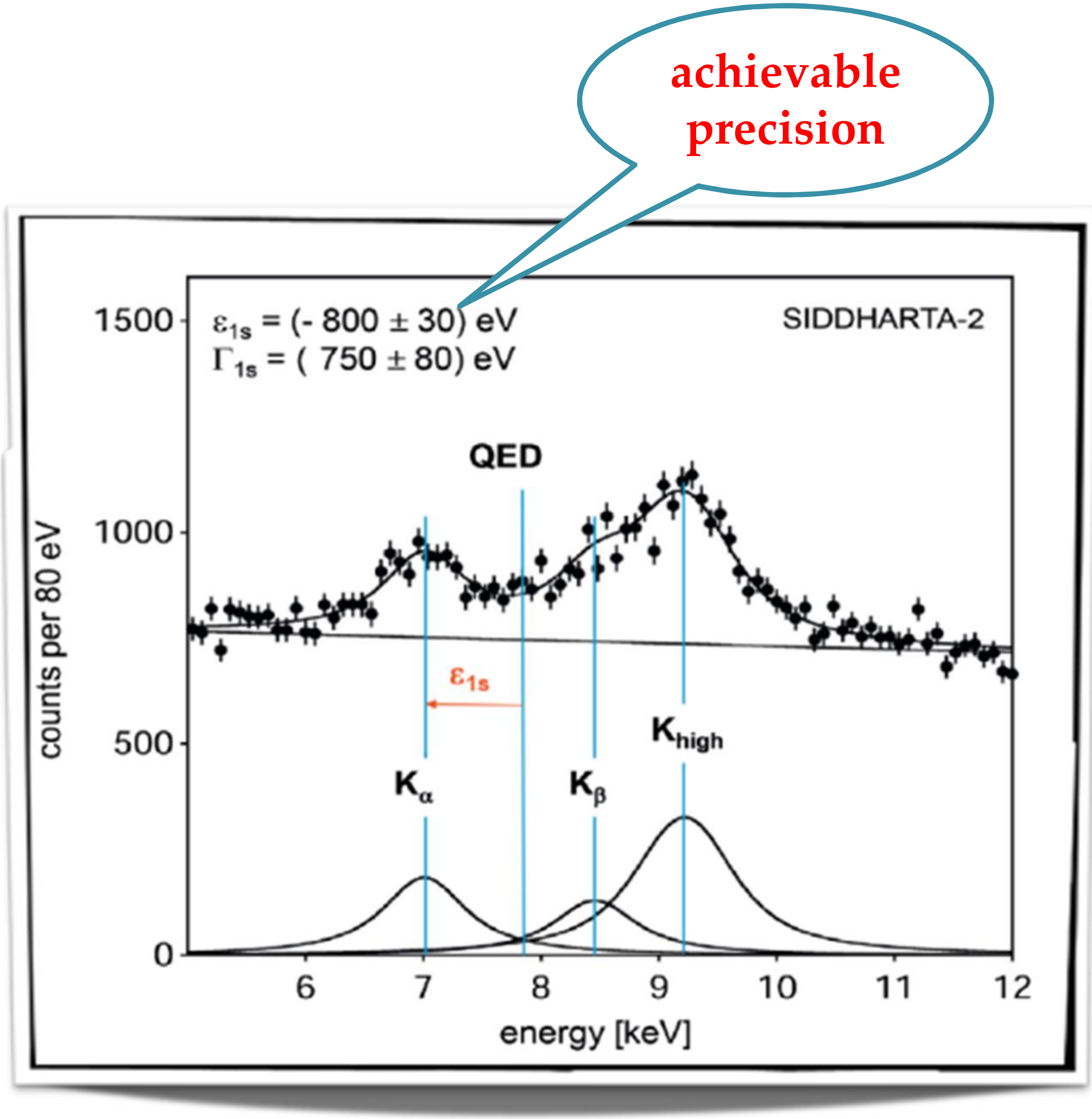
SIDDHARTA-2: Kaonic Deuterium measurement

Kaonic deuterium run

for S/B as 1/3:

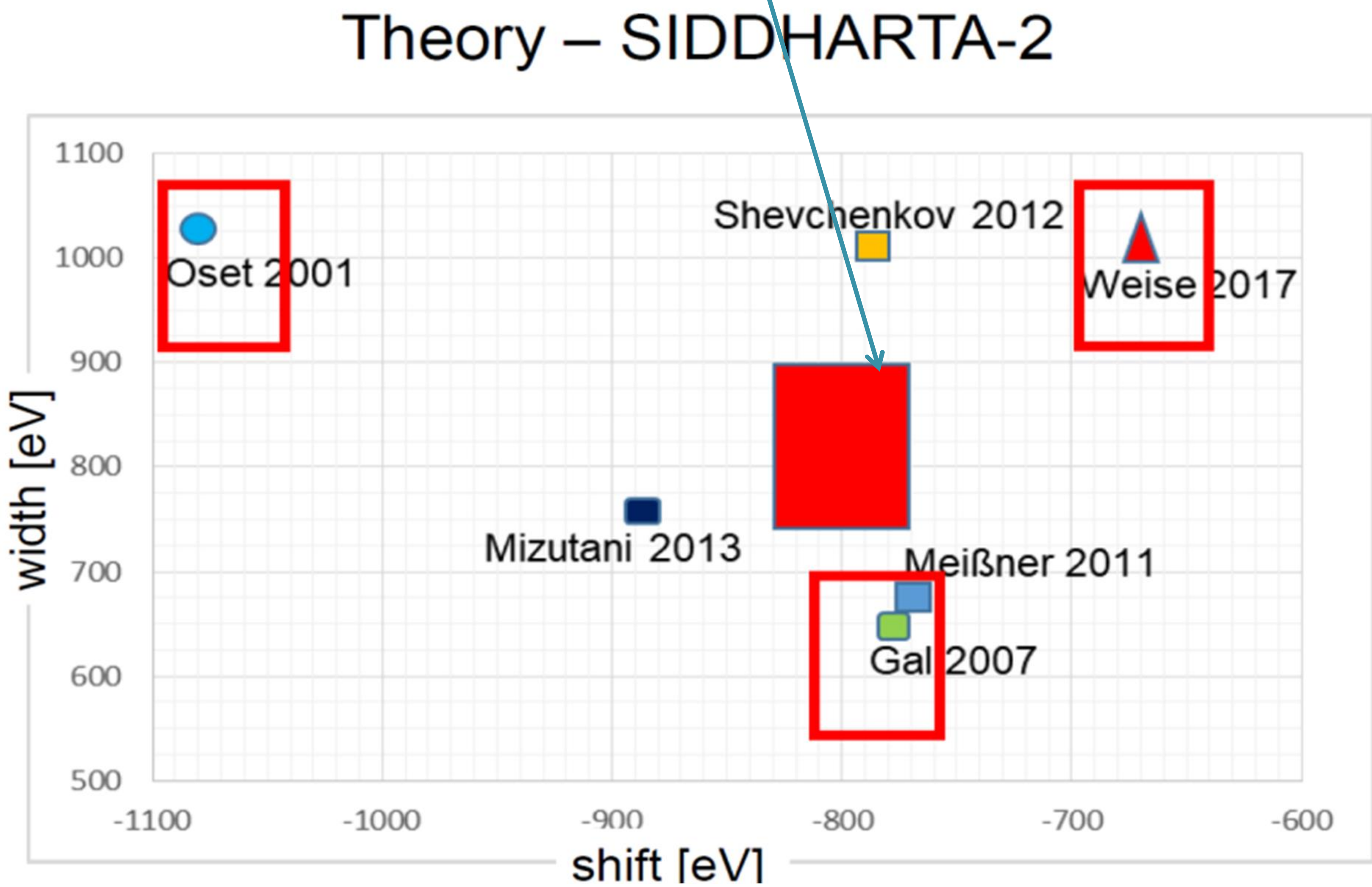
for an integrated luminosity of 800 pb^{-1}

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) !



Simulated SIDDHARTA-2 kaonic deuterium spectrum, assuming a shift of -800 eV and width Γ ~ 750 eV of the 1s state, as well as a Kα yield of 10^{-3}.

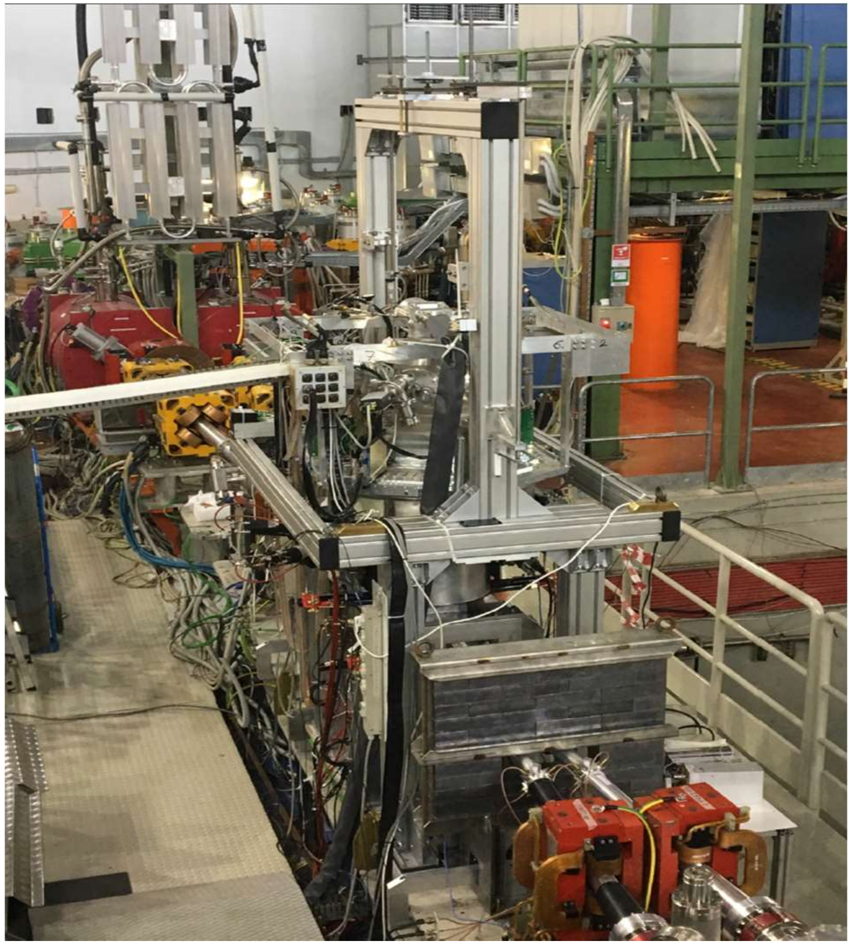
SIDDHARTA-2 targeted precision for deuterium



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

SIDDHARTA-2 PRESENT STATUS

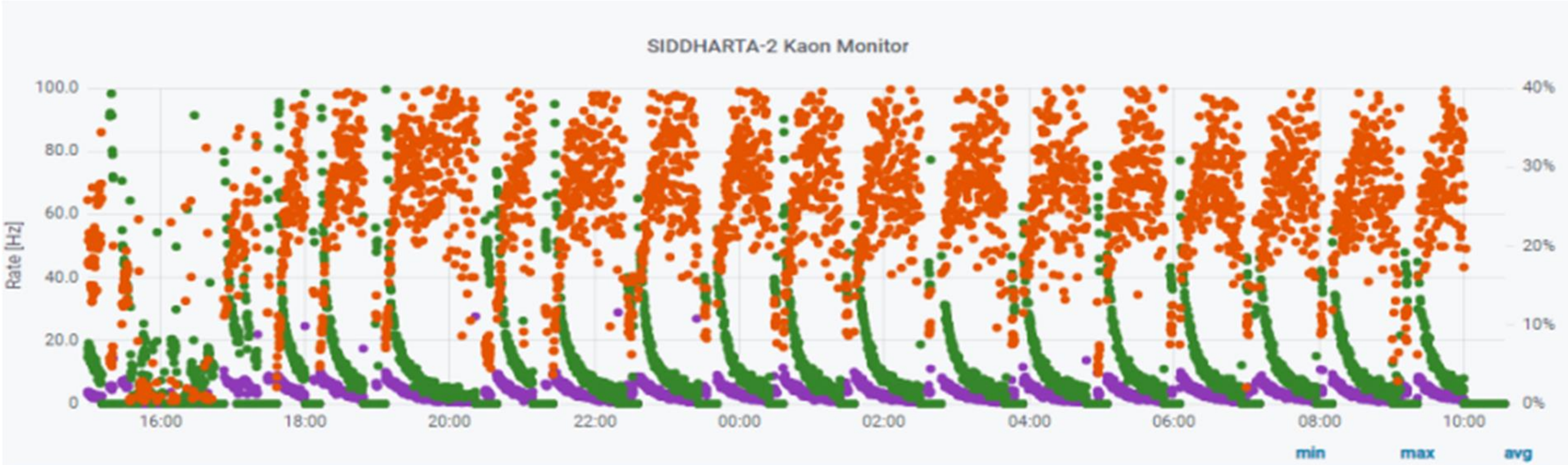
We conclude the Phase1 in June 2021 SIDDHARTINO setup



During the commissioning of DAFNE (new colliding optics, new interaction region) we perform refined optimization and the K-^{4}He test measurement with the SIDDHARTINO setup (only 8 SDD arrays)

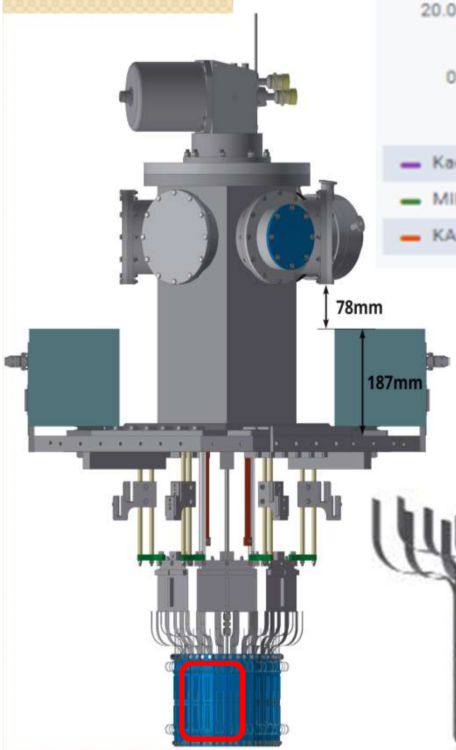
Aim: confirm when DAFNE background conditions are similar to the one measured in SIDDHARTA 2009

SIDDHARTINO = SIDDHARTA-2 with 8 SDDs arrays

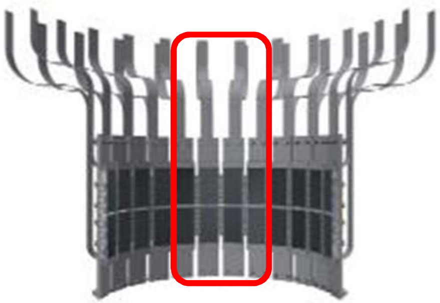


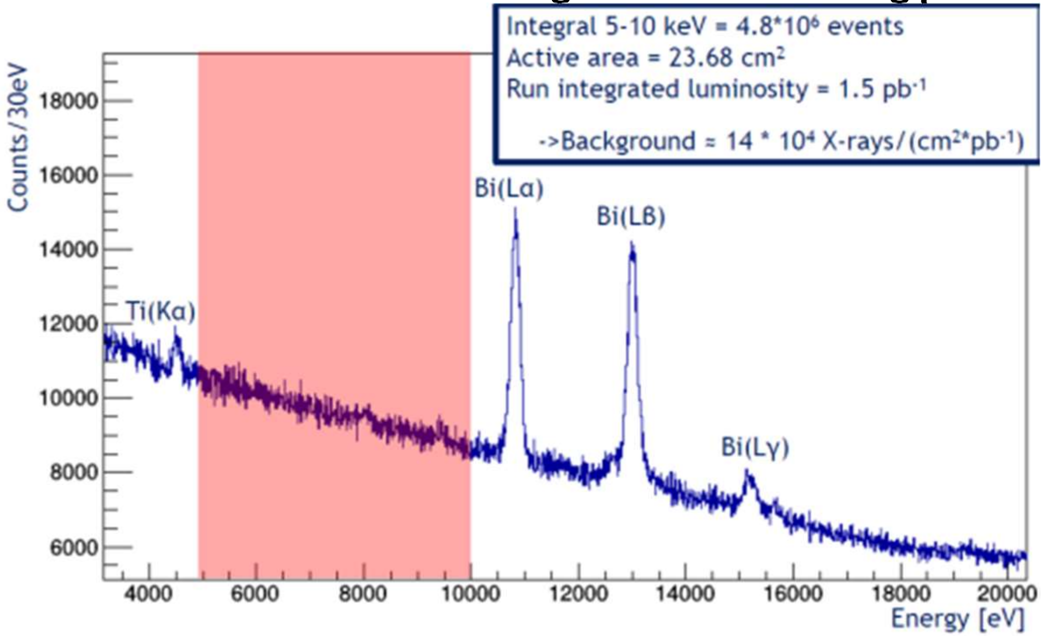
	min	max	avg
Kaon Rate	0	1.00 K	2.75
MIP Rate	0	18.00 K	17.02
KAON/MIP (right-y)	0.31%	100.00%	26.79%

On-line feedback is fundamental during the commissioning phase



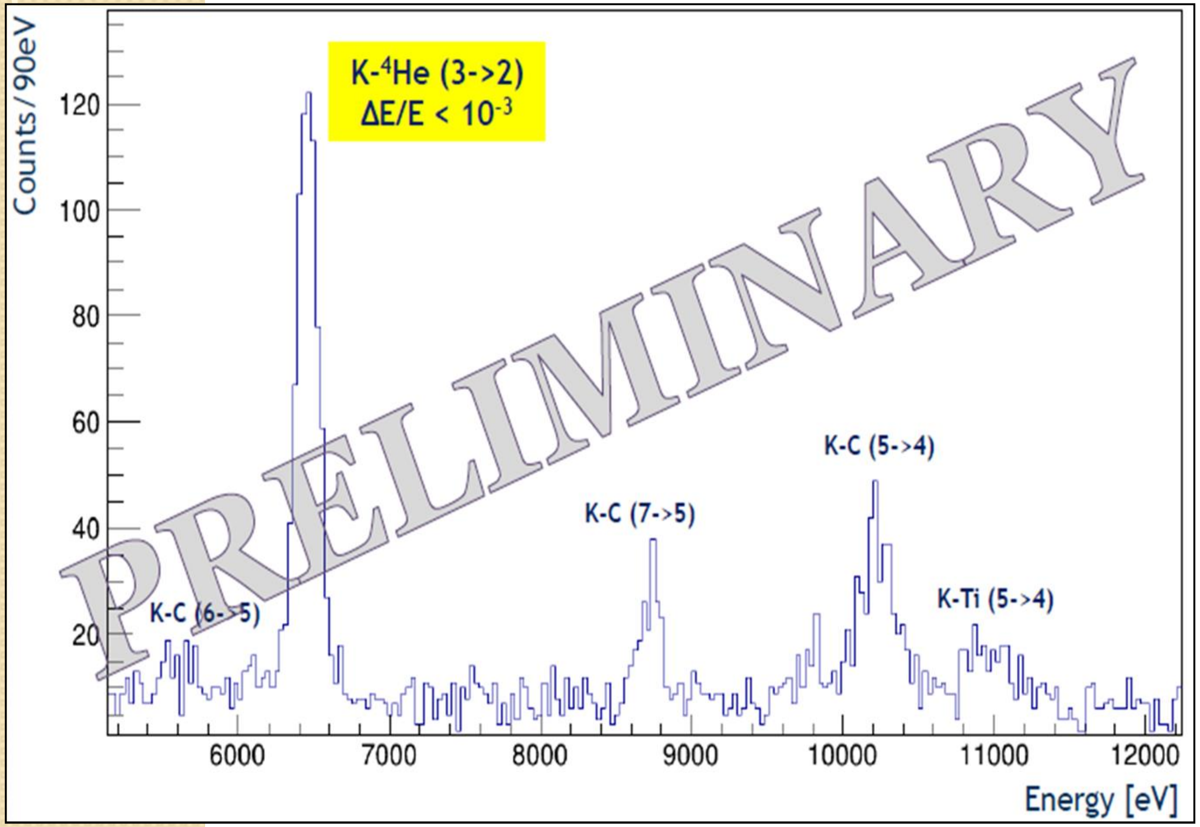
optimization of the SDDs response, trigger, DAQ, calibration procedure

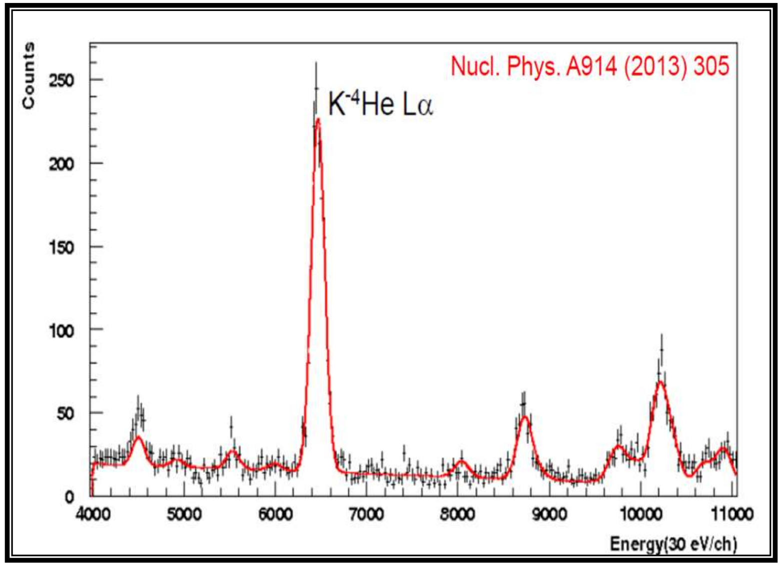




ONLY
64 SDD channels (out of 384)
1 BUS structure

SIDDHARTINO – K-^{4}He test measurement





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

SIDDHARTINO

measured spectrum for ~ 15 pb^{-1}

SIDDHARTA 2009

measured spectrum for ~ 30 pb^{-1}

Aim:

to set the working conditions for SIDDHARTA-2 by a comparison with SIDDHARTA (S/B)

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 futures kaonic atoms measurements (HPGE, 1mm SDD, …)

Future plans at DAΦNE

DAΦNE is a unique machine to perform fundamental physics measurements at the strangeness frontier with a strong impact on many sectors:

- selected targets for heavy (KPb) kaonic atoms transitions (HPGe)
strong impact in solving the charged kaon mass puzzle

- light (KHe, KLi, KBe) kaonic atoms transitions (Cd(Zn)Te, 1mm SDD's)

- Ultra-High precision (under eV) kaonic atoms measurements (VOXES)

- low-energy kaon-nucleon scattering processes (GEM-TPC active target)

- low-energy kaon-nuclei interactions

more details in: https://arxiv.org/pdf/2104.06076.pdf
Towards LOI/Technical Design Report in preparation

Heavy (high Z) kaonic atoms using High Purity GE

Charged Kaon Mass puzzle:

ready for a feasibility test run using Pb target

Possible kaonic transitions to be measured:

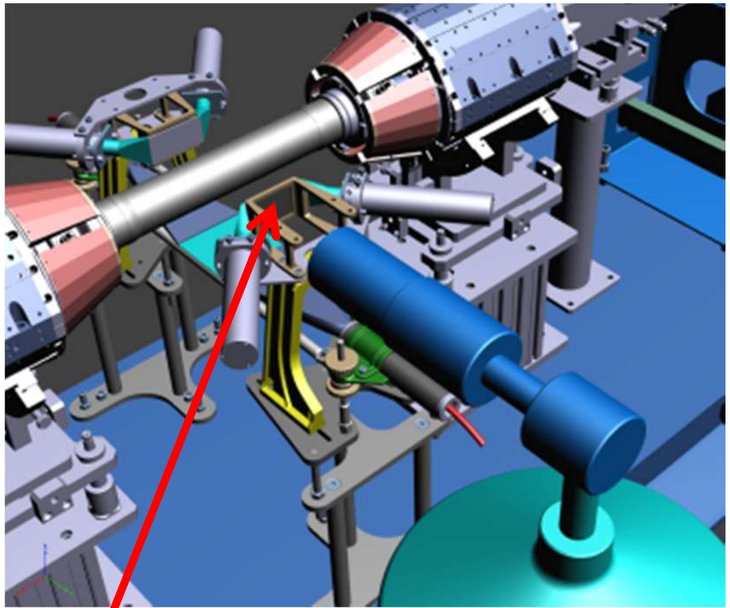
KC(2→1) : 340 keV
KC(3→1): 402 keV

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

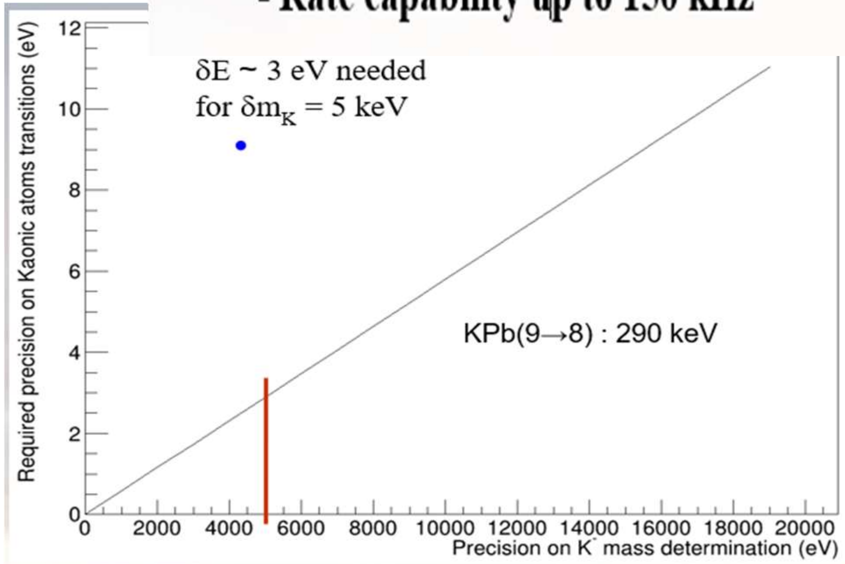
KTa(6→5): 853 keV
KTa(7→6): 514 keV
KTa(7→5) : 1367 keV
KTa(8→7): 334 keV
KTa(8→6): 848 keV

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



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 (~ 40 days) of beamtime requested

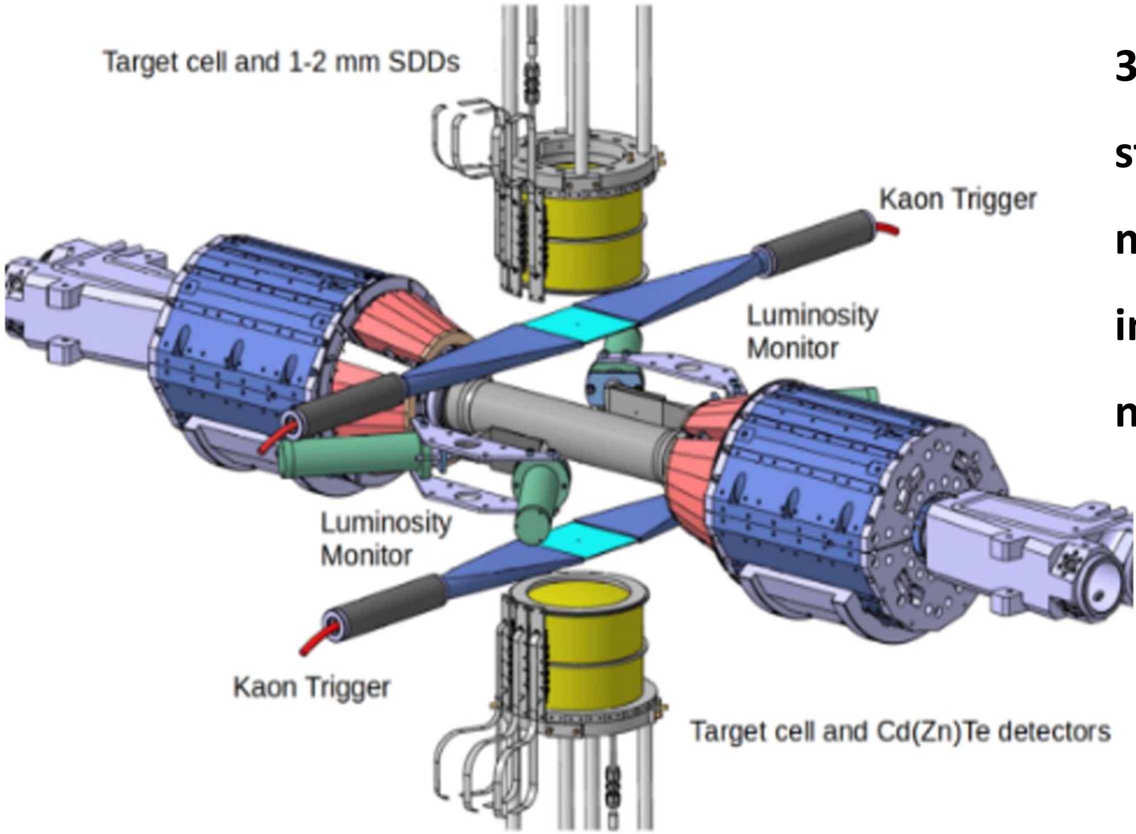
!!! Similar estimations for each target !!!

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**

Setup: SDD1mm & CdTe



- **In particular, the first measurement of 3He,4He (2p → 1s) transition, will put stronger constraints on the theoretical models describing the kaon-nucleon interaction in systems with more than two nucleons**

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

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

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

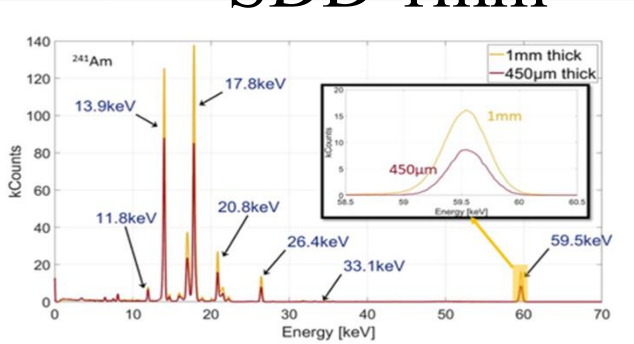
K^{3}He(2→1) : 33 keV
K^{4}He(2→1) : 35 keV

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

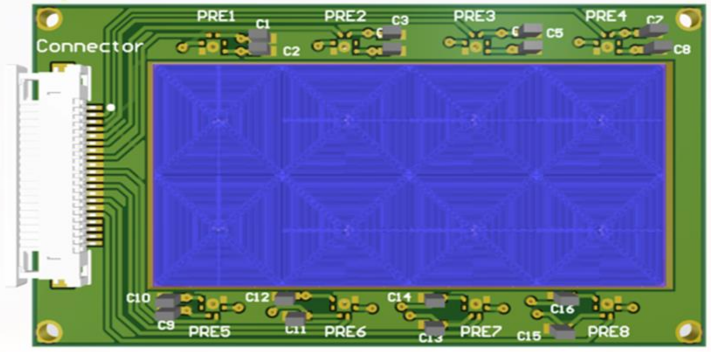
K^{9,10,11}B(4→3) : 15 keV
K^{9,10,11}B(5→3) : 22 keV
K^{9,10,11}B(6→4) : 11 keV

SDD 1mm



First XRF tests with known targets show very promising results

Prototypes of electronics boards are already available



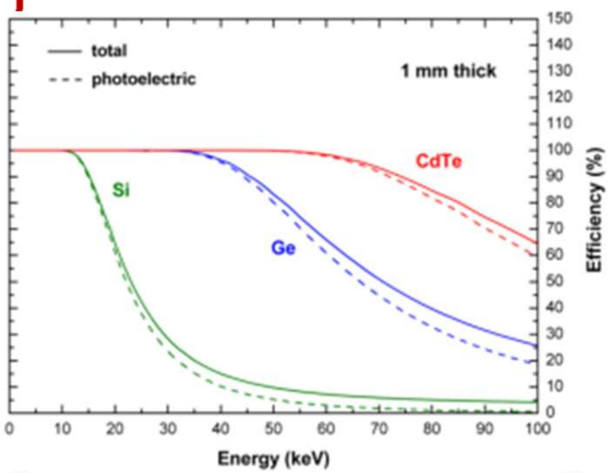
FWHM ~ 150 eV (SDD)

Cd(Zn)Te

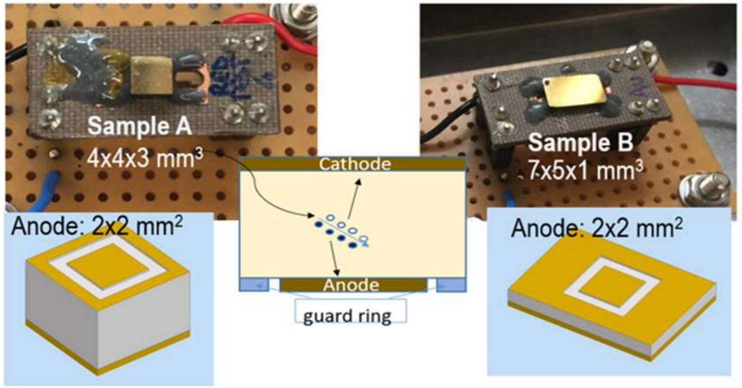
Possible kaonic transitions to be measured with **CdTe detectors**:

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



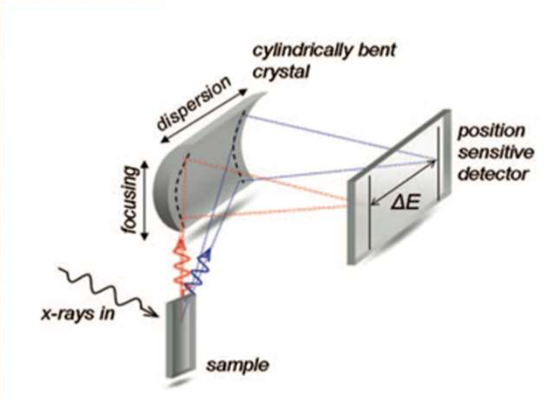
FWHM ~ 1000 eV



Cadmium(Zinc)Telluride detectors will be developed in the STRONG2020-ASTRA

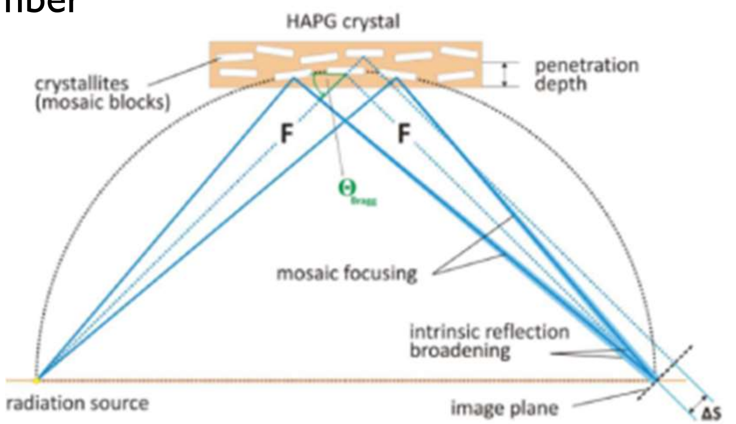
First prototypes will be available in 2022

Ultra-High precision (under eV) kaonic atom measurements (VOXES spectrometer)



Mosaic crystal consist in a large number of nearly perfect small crystallites.

Mosaicity makes it possible that even for a fixed incidence angle on the crystal surface, an energetic distribution of photons can be reflected



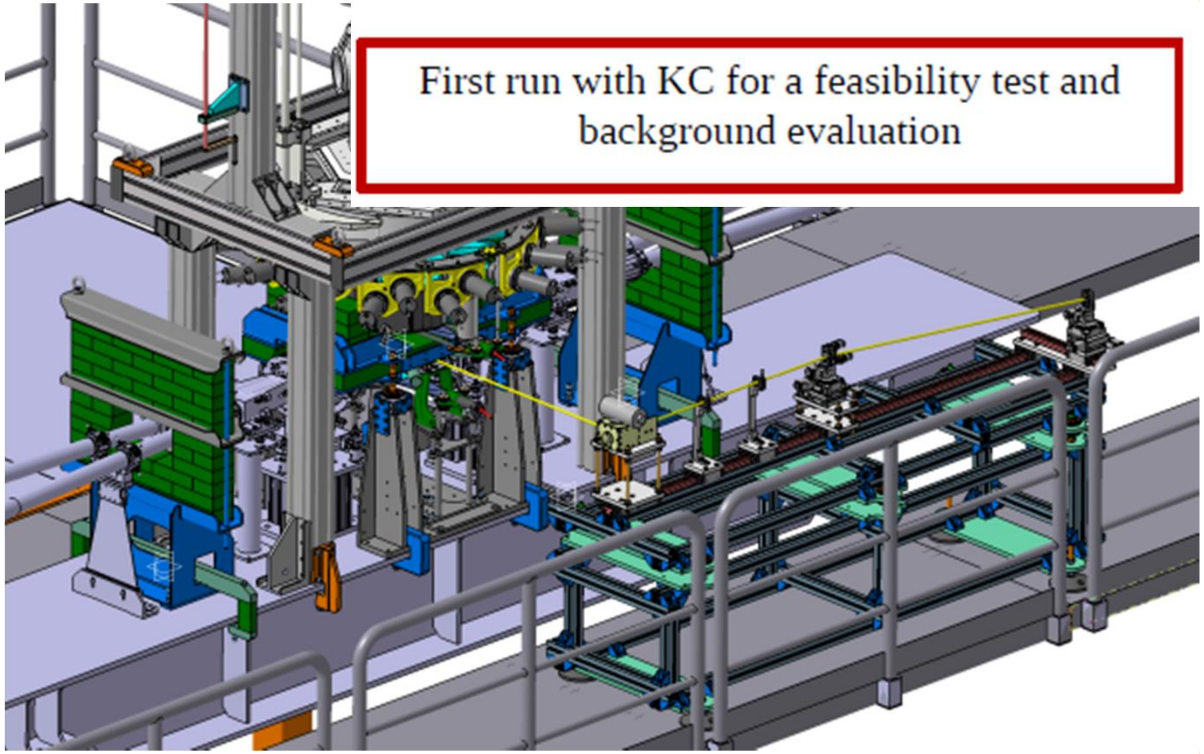
Spectrometer with
Highly Annealed Pyrolitic Graphite - **HAPG mosaic crystals in Von Hamos configuration**

From MC simulations,
assuming L = 1,4x10[32] (~ 10 pb^{-1} / day):

- ~ 1,4 recorded signals / day
- σ = 3,6 eV @ 8 keV (from Cu lab measurements)

~ 250 total events goal (δE ~ 0,2 – 0,3 eV)
~ 2000 pb^{-1} (~ 200 days) of beamtime requested

~ 50 total events goal (δE ~ 0,5 – 0,6 eV)
~ 400 pb^{-1} (~ 40 days) of beamtime requested



First run with KC for a feasibility test and background evaluation

Conclusions

- SIDDHARTINO apparatus was fully working and we conclude the phase 1 of the project performing the Kaonic 4Helium test measurement

- We are ready and very motivated to go on with SIDDHARTA-2 for kaonic deuterium measurement (full installation is ongoing)

- Several proposals and many interesting developments are already in advanced state

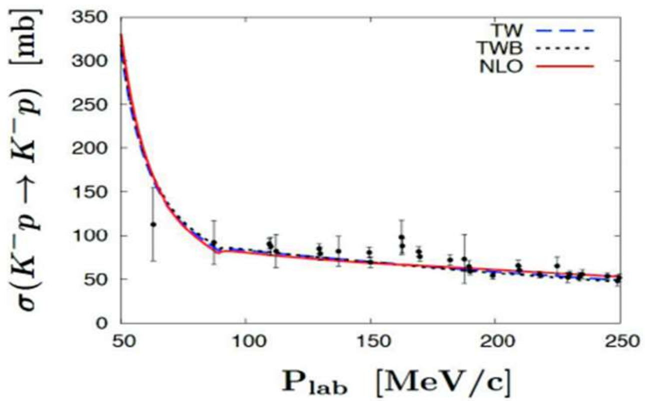
On behalf of the SIDDHARTA-2 collaboration

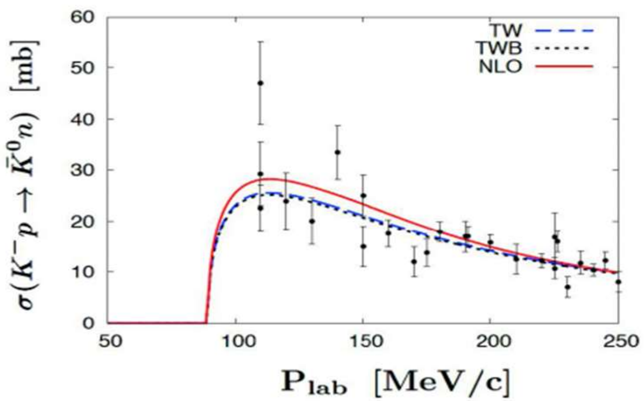
Thank you!

Spares

Kaon-nuclei scattering and interaction

- 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.

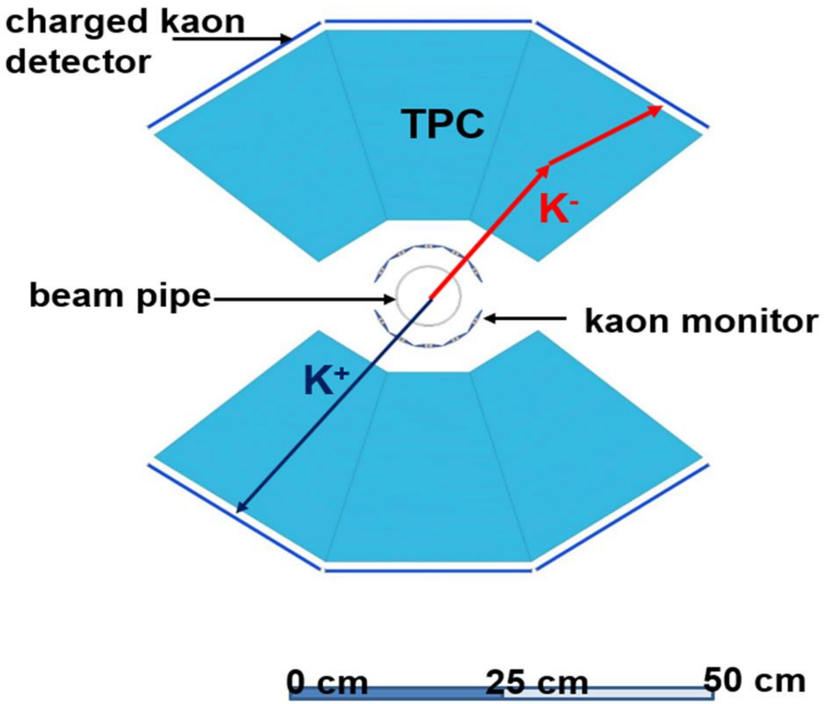


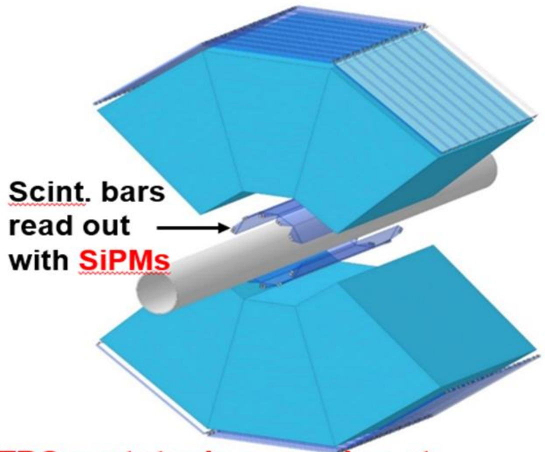


Measurement of the low-energy scattering process of kaons, and of the Λ(1405) kaon induced production, on various targets such as hydrogen, deuterium, helium-3 and helium-4 using a GEM-TPC active target.

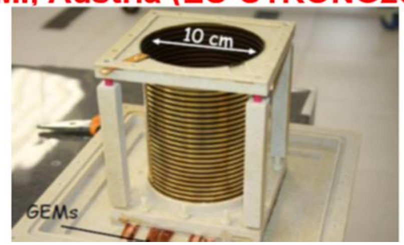
elastic scattering, layout

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.





TPC prototyping ongoing at:
Sendai Univ., Japan
SMI, Austria (EU-STRONG2020)



Time Projection Chamber (TPC) with a Gas Electron Multiplier (GEM) readout device, allows the study of kaons interactions directly in the TPC gas/target volume