Kaonic atoms studies at DAFNE: from SIDDHARTA-2 to future perspectives "

F. Sirghi and A. Scordo on behalf of SIDDHARTA-2 Collaboration

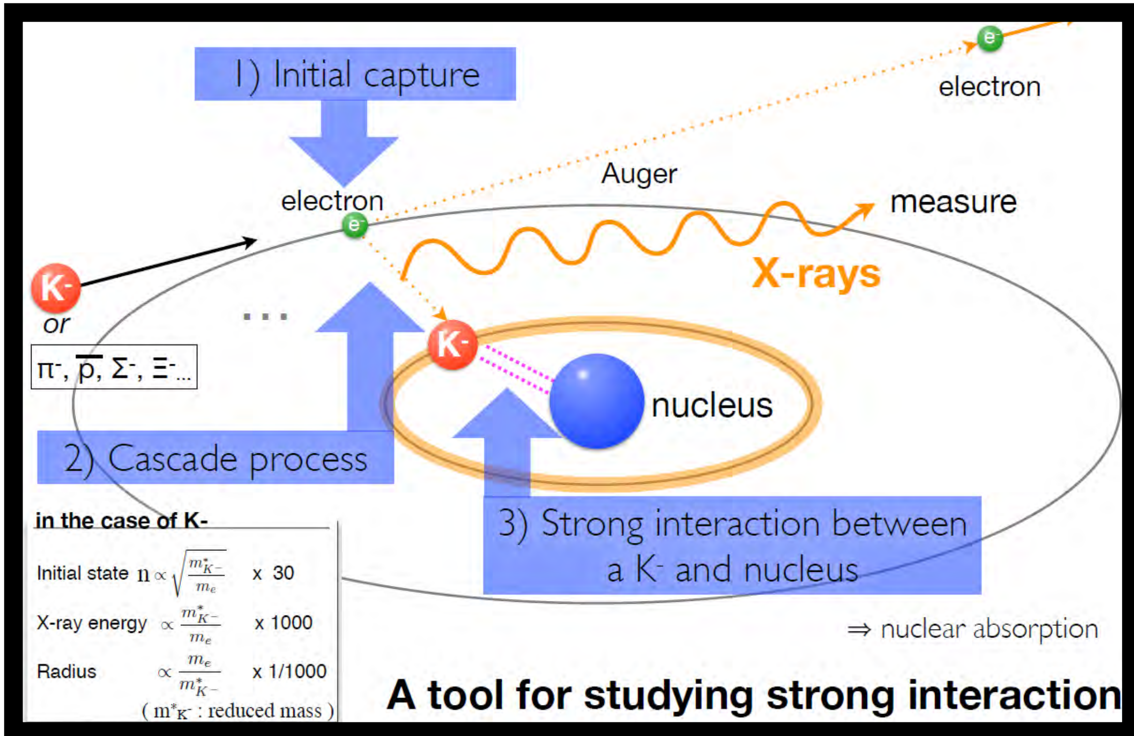
Monday, December 4th, Institute of Physics, Jagiellonian University, ul. Łojasiewicza 11, Kraków, Poland.

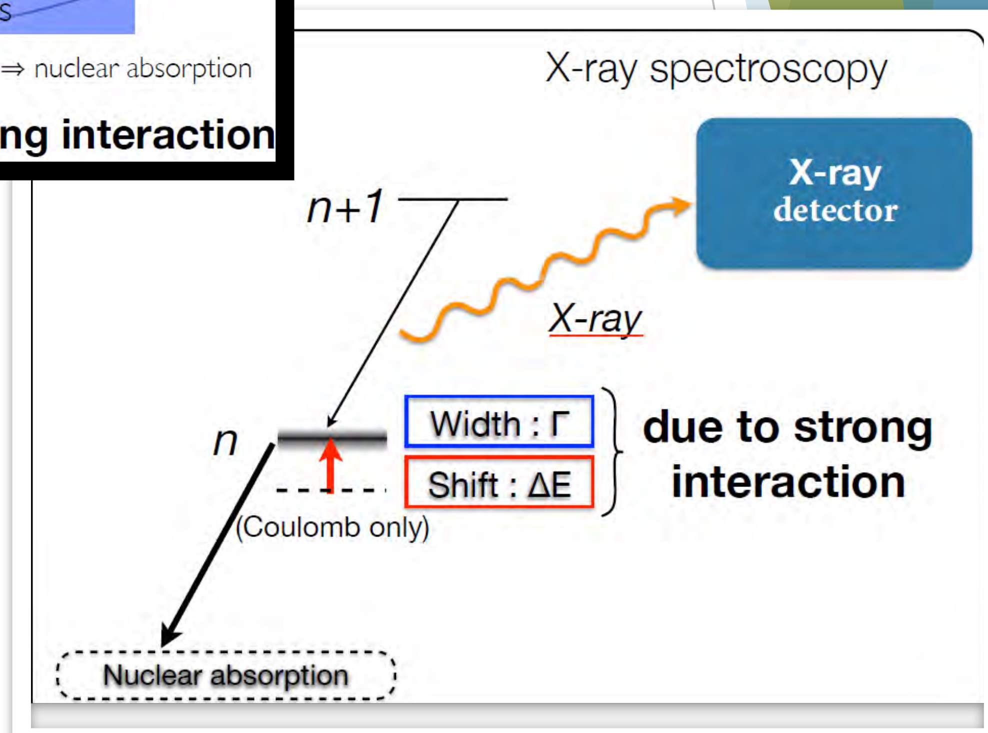
KAONIC ATOMS RESEARCH

Kaonic atoms are formed by stopping a *negatively charged kaon* in a target medium

H, He, D, N, …

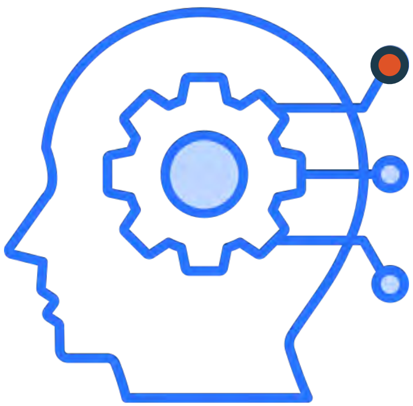
Li, Be, C, Al, …

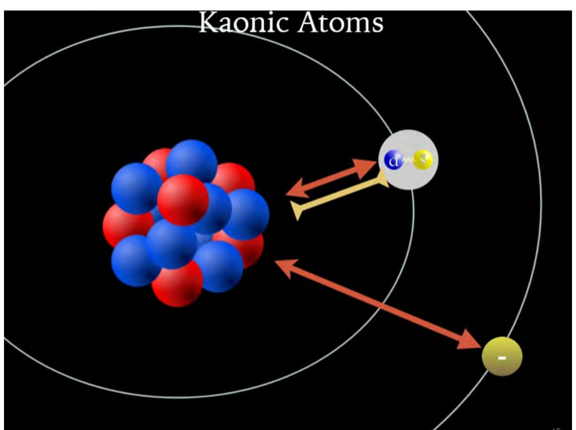




Strong interaction induced width Γ and shift ε obtained by measuring the X-rays emitted

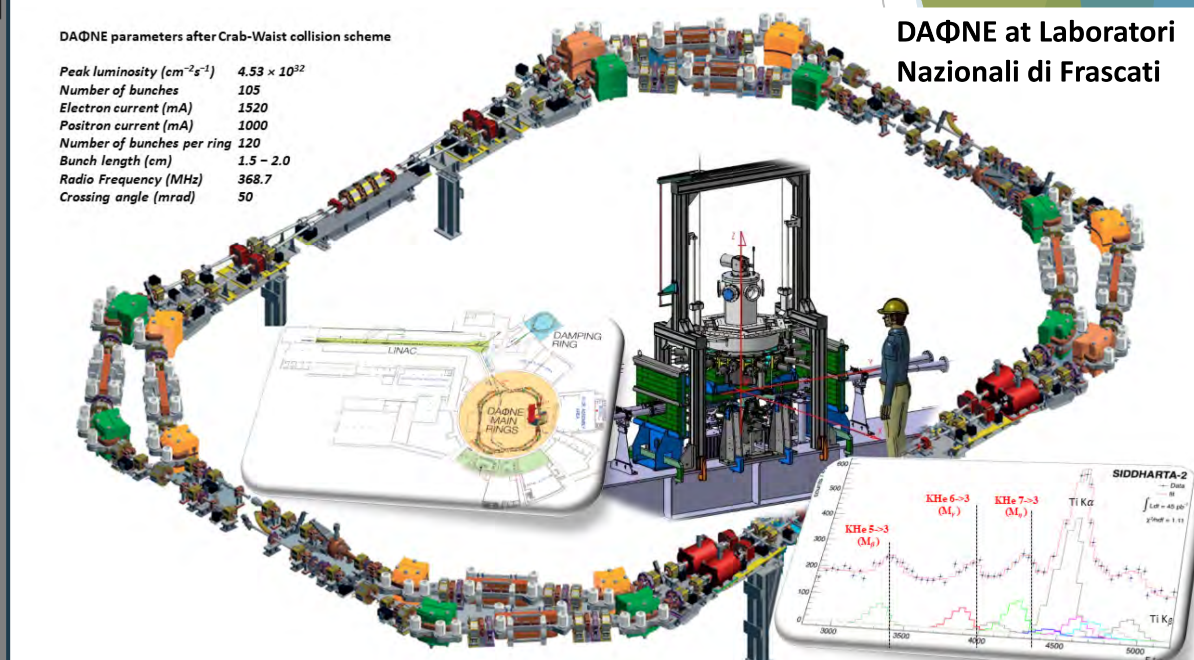
KAONIC ATOMS RESEARCH





SUCCES

Quality kaon beam

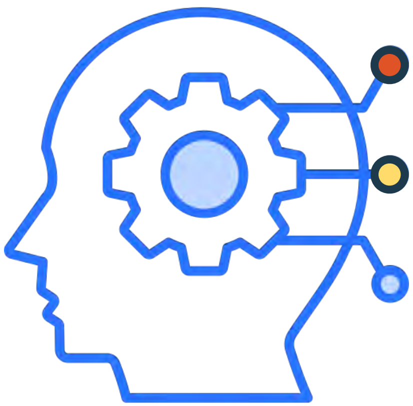


DAΦNE parameters after Crab-Waist collision scheme

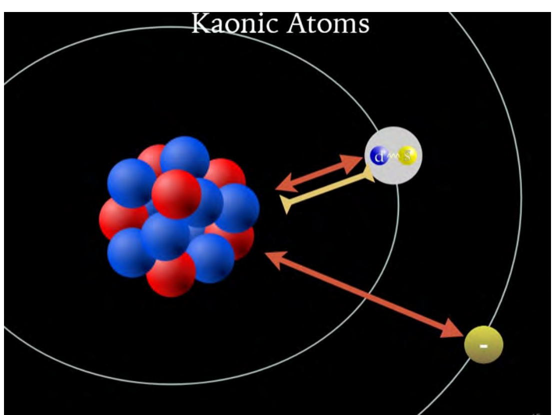
Peak luminosity ($cm^{-2}s^{-1}$)	*4.53×10^{32}*
Number of bunches	*105*
Electron current (mA)	*1520*
Positron current (mA)	*1000*
Number of bunches per ring	*120*
Bunch length (cm)	*1.5 – 2.0*
Radio Frequency (MHz)	*368.7*
Crossing angle (mrad)	*50*

- **$\Phi \rightarrow K^- K^+$ (48.9%)**
- **Monochromatic low-energy K^-**
  (~127 MeV/c ; $\Delta p/p$ = 0.1%)
- **Less hadronic background compared to hadron beam line**

KAONIC ATOMS RESEARCH



© Designed by Freepik

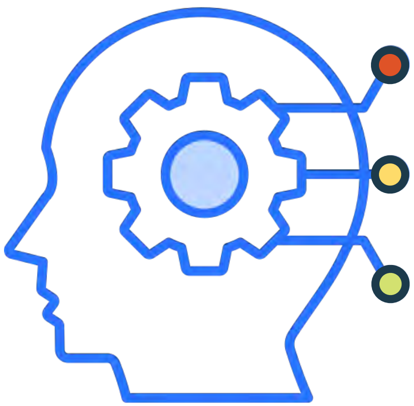


SUCCES

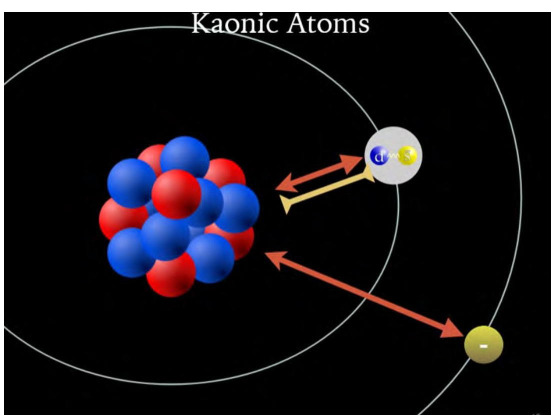
Quality kaon beam

Efficient x-ray detector system

KAONIC ATOMS RESEARCH



© Designed by Freepik

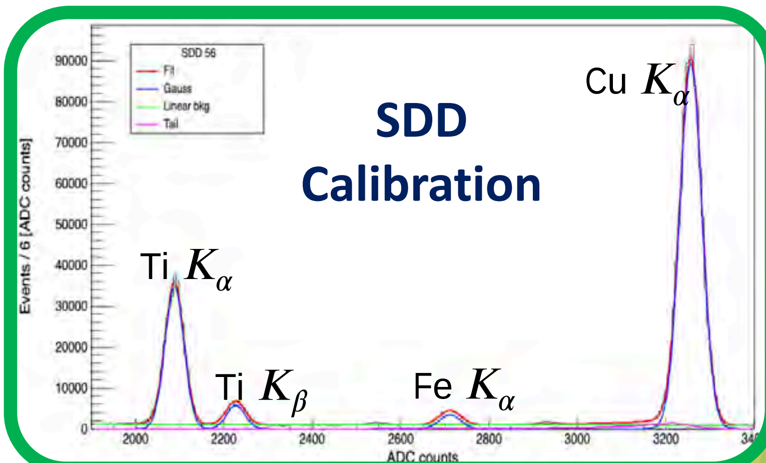


SUCCES

Quality kaon beam

Efficient x-ray detector system

Powerful analysis tools



Monte Carlo simulations, modern algorithms and machine learning techniques

Optimization of the setup and detectors response (trigger, SDDs, veto, …)

EXKALIBUR
SIDDHARTA-2
SIDDHARTA
DEAR
KAONIC ATOMS RESEARCH

Scientific Goal of SIDDHARTA-2

The first measurement of *kaonic deuterium* transitions to the fundamental 1s level
to extract the antikaon-nucleon isospin dependent scattering lengths (using also the measurement of kaonic hydrogen performed by SIDDHARTA)

e.g., Kaonic hydrogen

U.-G. Meißner et al, Eur Phys J C35 (2004) 349
(Deser-Type relation with isospin-braking correction)

$$\epsilon_{1s} + i\Gamma_{1s}/2 = 2\alpha^3 \mu_r^2 \boxed{a_{K^-p}} \left[1 + 2\alpha\, \mu_r\, (1 - \ln\alpha)\, a_{K^-p}\right]$$

Shift — K-p Kα x-ray

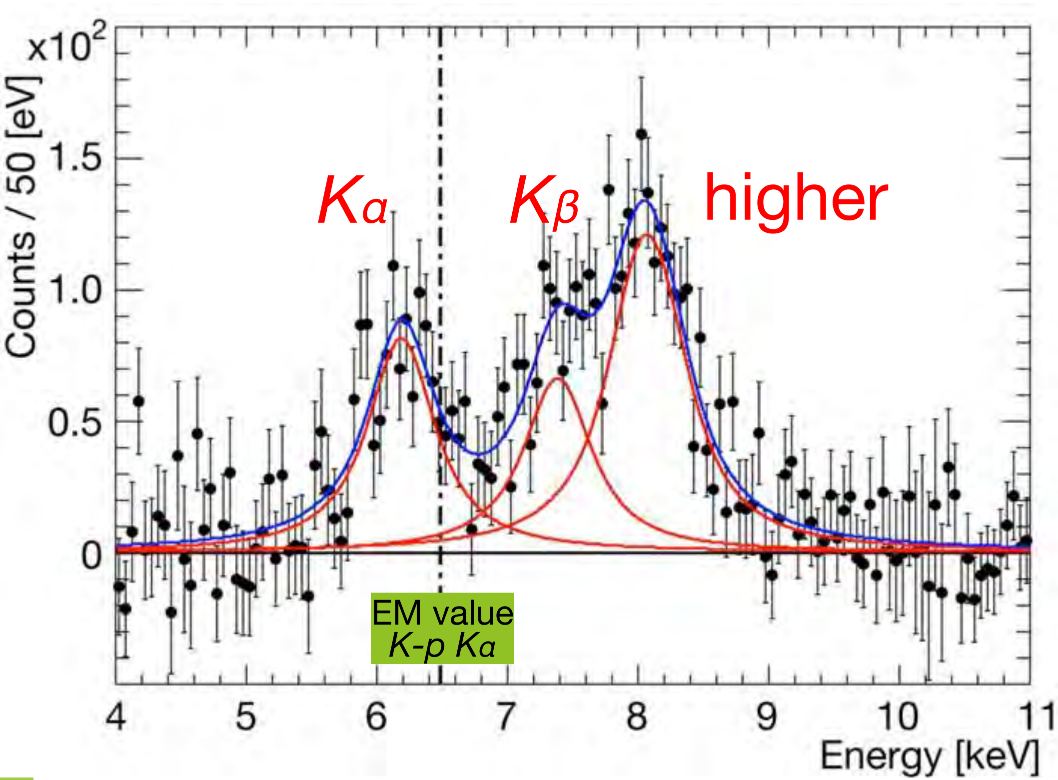
Width

K-p scattering length
(= K-p scattering amplitude at threshold)

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

SIDDHARTA (2009)

Kaonic hydrogen



$$\varepsilon_{1s}^{H} = -283 \pm 36(stat) \pm 6(syst)\,eV$$

$$\Gamma_{1s}^{H} = 541 \pm 89(stat) \pm 22(syst)\,eV$$

C. Curceanu et al., *Phys. Lett. B* 704 (2011) 113

Some considerations:

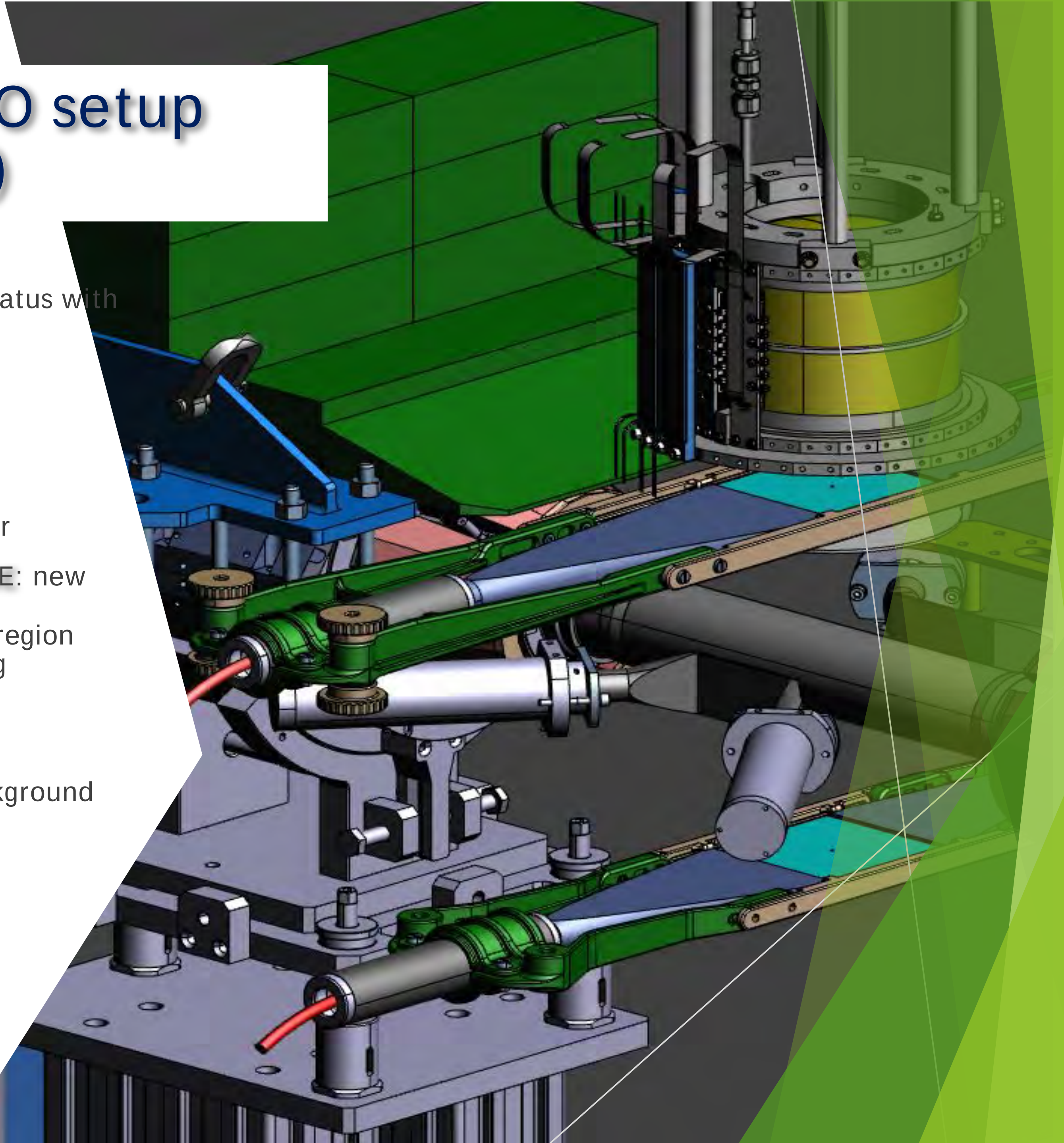
- The result itself put very strong constrains on various theoretical models
- Better precision < 10eV is desired
- *Kaonic deuterium is a MUST*
- Stable kaon source (not only high luminosity but also low background conditions)
- New setup design (maximize the signal, new detectors, target, veto systems, shielding's, ….)

SIDDHARTINO setup (2019-2021)

- The SIDDHARTA-2 apparatus with reduced SDD's channels
  - Target cell
  - 64 SDD's channels
  - Kaon Trigger
  - Luminosity detector
- commissioning of DAΦNE: new optics designed for our experiment, interaction region (new beam pipe, focusing magnets, …..)

- AIM: confirm when background conditions are similar to

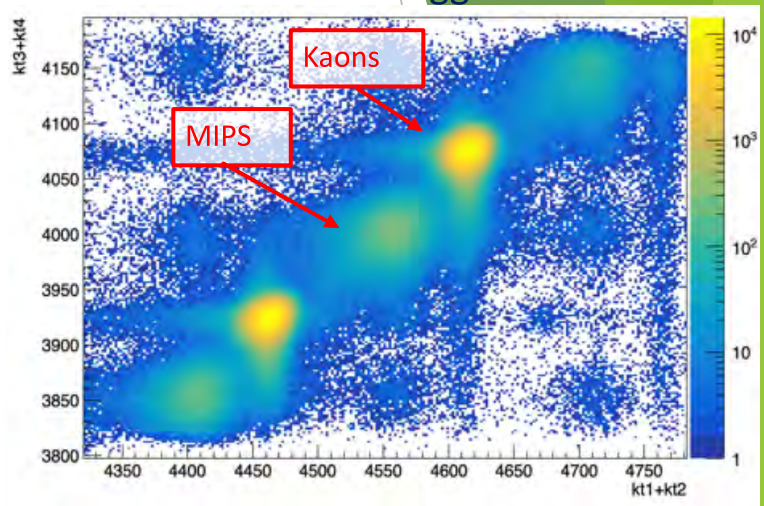
SIDDHARTA 2009

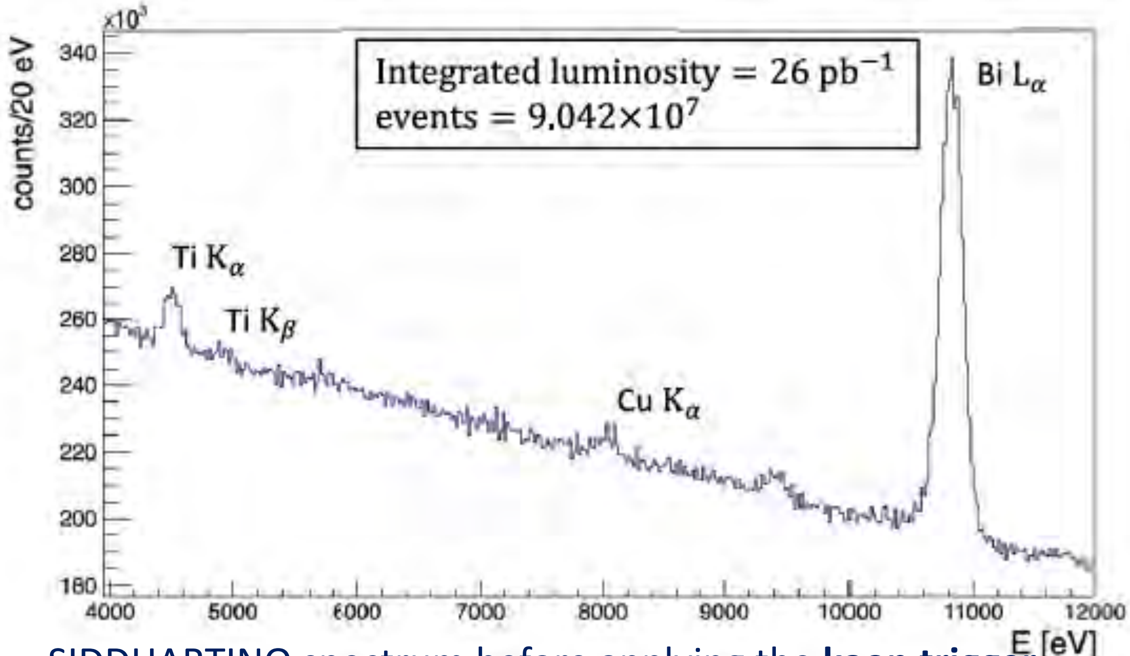


SIDDHARTINO (2021)
The kaonic ^{4}He 3d->2p (L_{α}) measurement

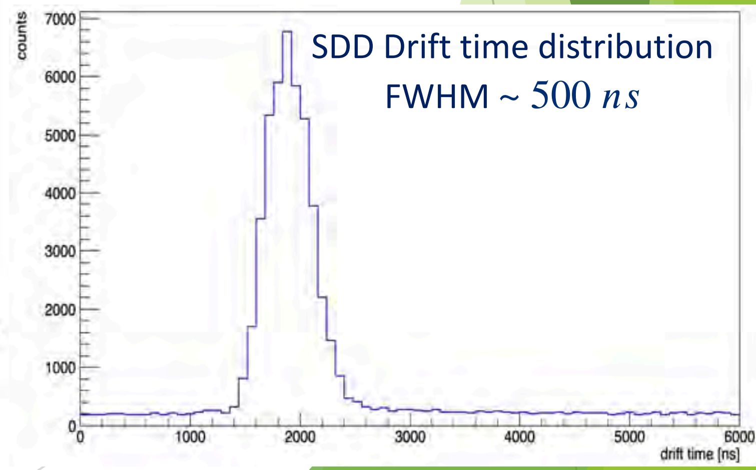
Optimization of the trigger and new SDDs during the DAΦNE beams commissioning phase in preparation for the K-d run through the **measurement of K-^{4}He 3d->2p transition**

Kaon Trigger

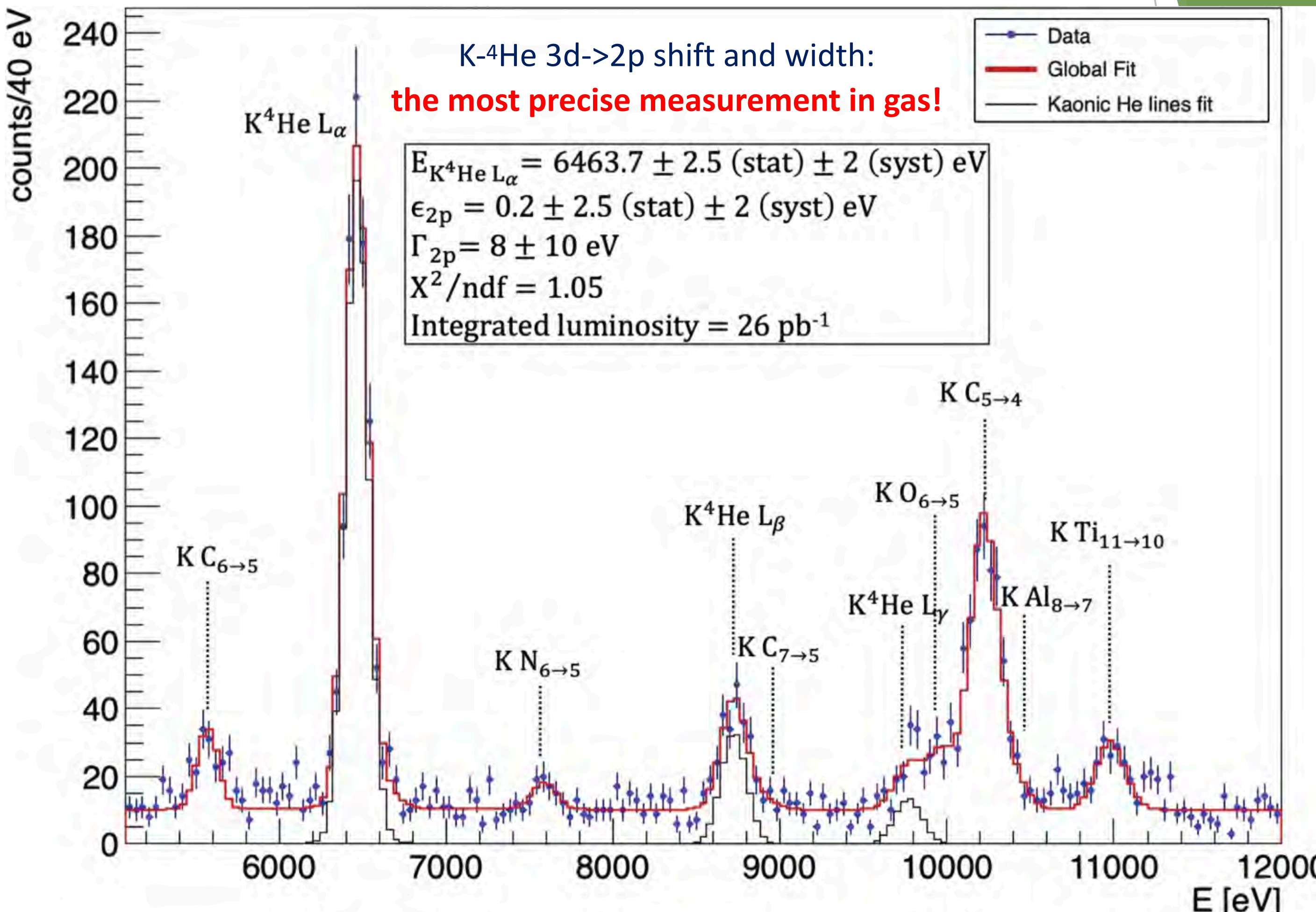




SIDDHARTINO spectrum before applying the **kaon trigger** and the **drift time rejection**

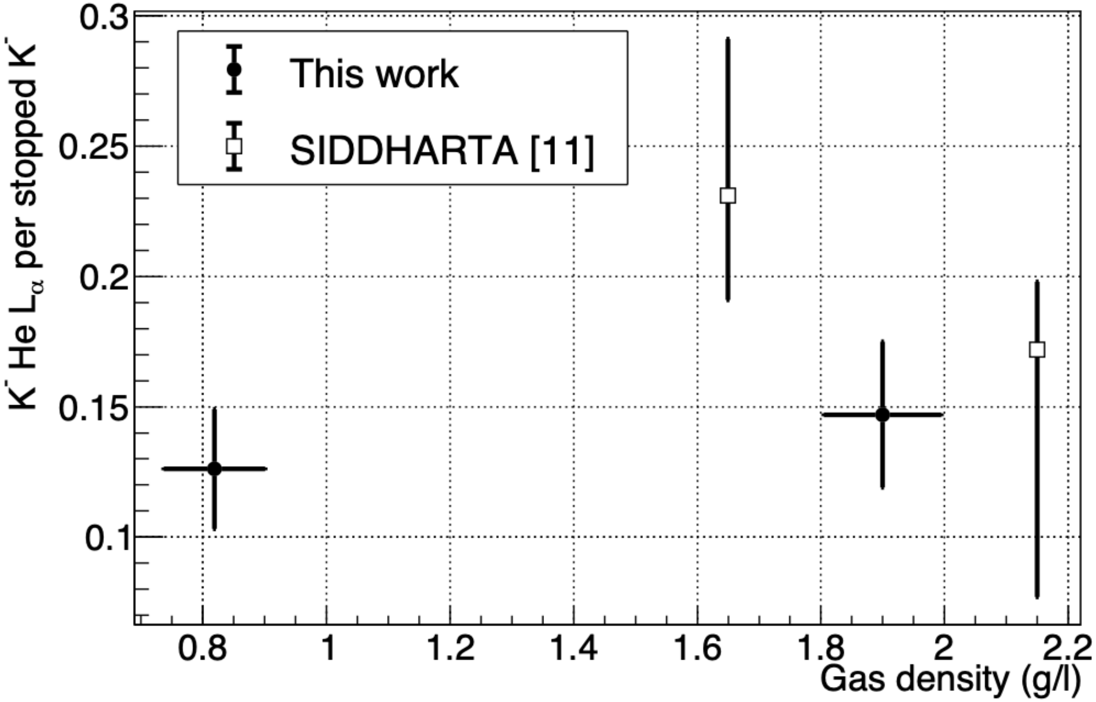


SIDDHARTINO (2021)
The kaonic ^{4}He 3d->2p (L_α) measurement



D Sirghi *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* 49 055106

SIDDHARTINO (2021)
The kaonic ^{4}He yield measurement



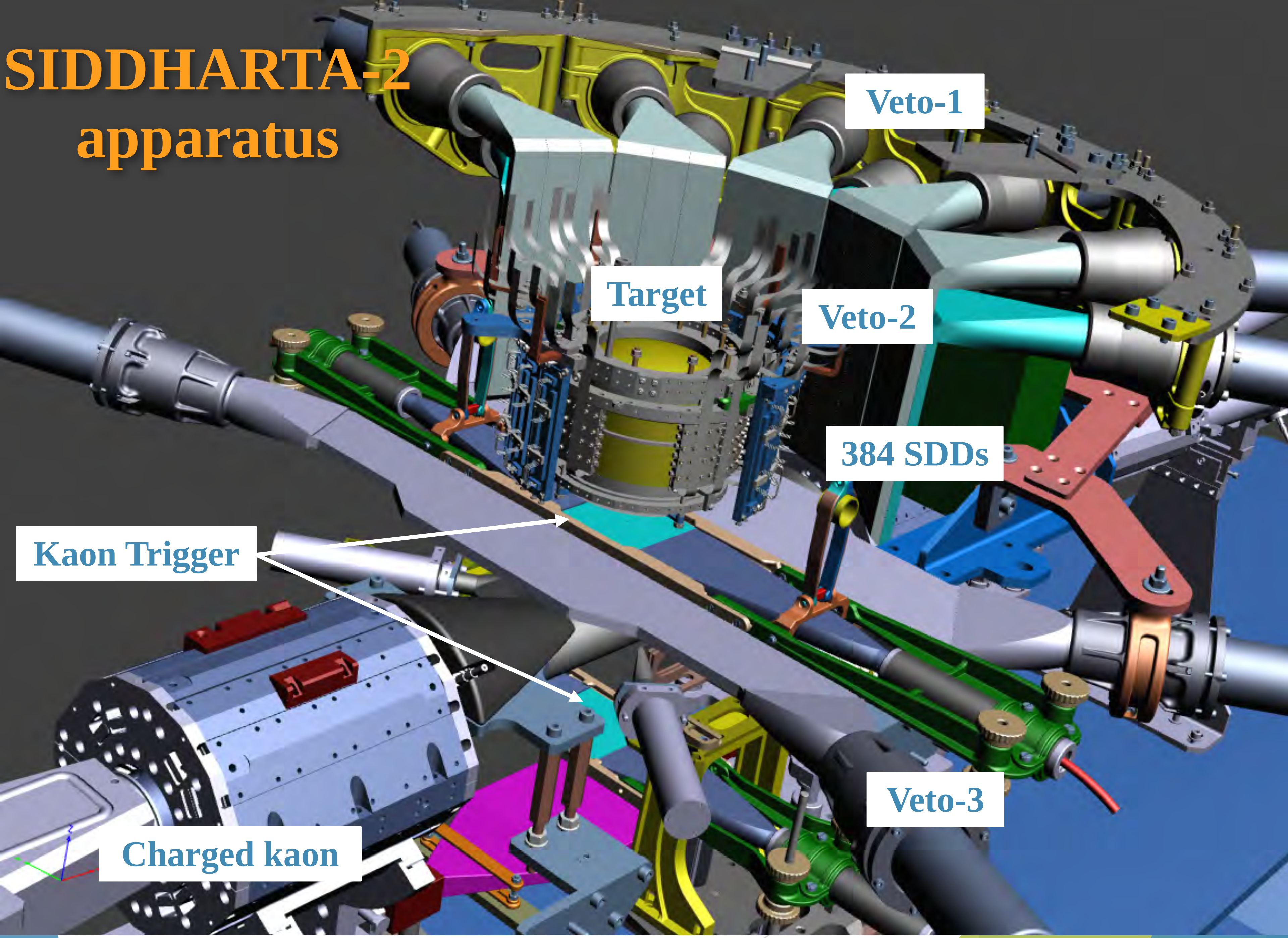
K-^{4}He low density run: 0.75% liquid helium density ->
yields at lowest measured density

Target optimization with He

Density	1.90 g/l	0.82 g/l
L_α yield	0.148 ± 0.027	0.126 ± 0.023
L_β/L_α	0.193 ± 0.042	0.133 ± 0.037
L_γ/L_α	0.035 ± 0.015	not detected

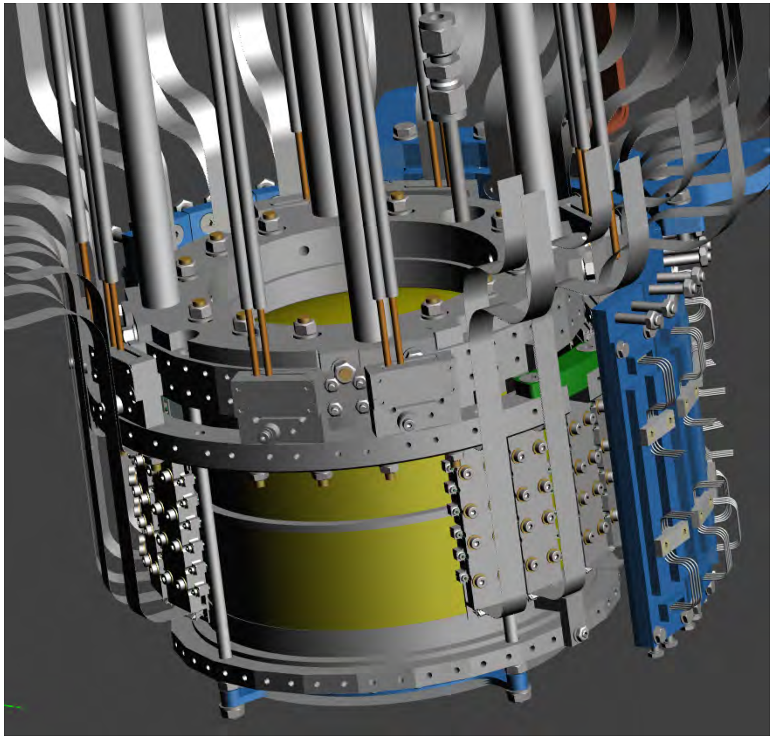
D.L. Sirghi, et al. Nuclear Physics A 1029 (2023) 122567

SIDDHARTA-2 apparatus



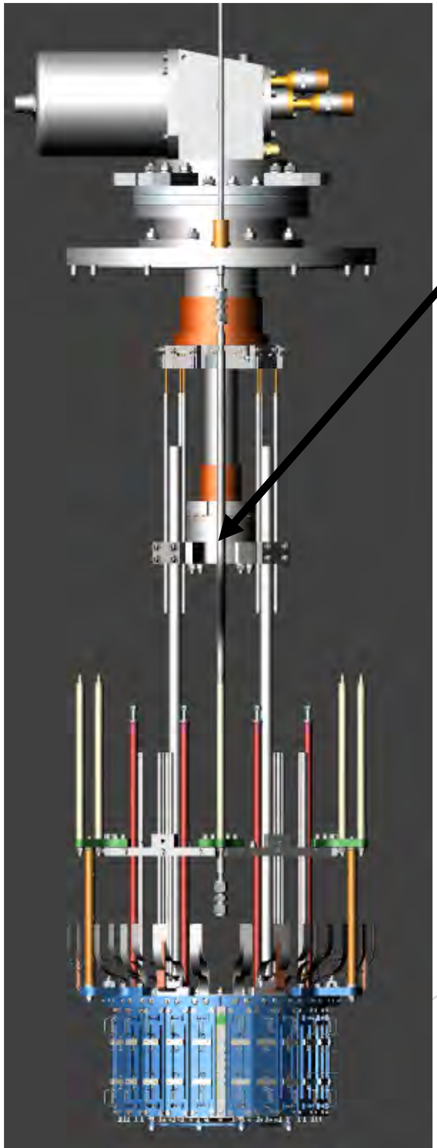
Optimization of SIDDHARTA-2 setup

✓ new solutions for the cooling scheme - target and SDD
✓ Better control of target parameters (pressure, temperature, density,….)

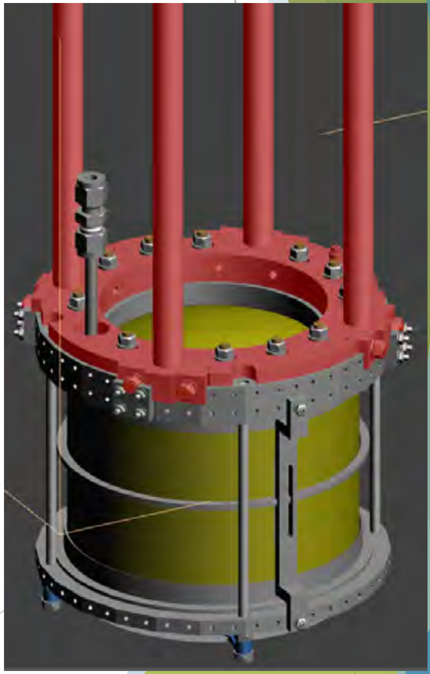


❖ Target + SDD cooling

Leybold MD10 – 18 W @ 20 K
target cell and SDDs are cooled
via ultra pure aluminum bars
T_{TC} = 20-30 K
T_{SDD} ~ 130 K

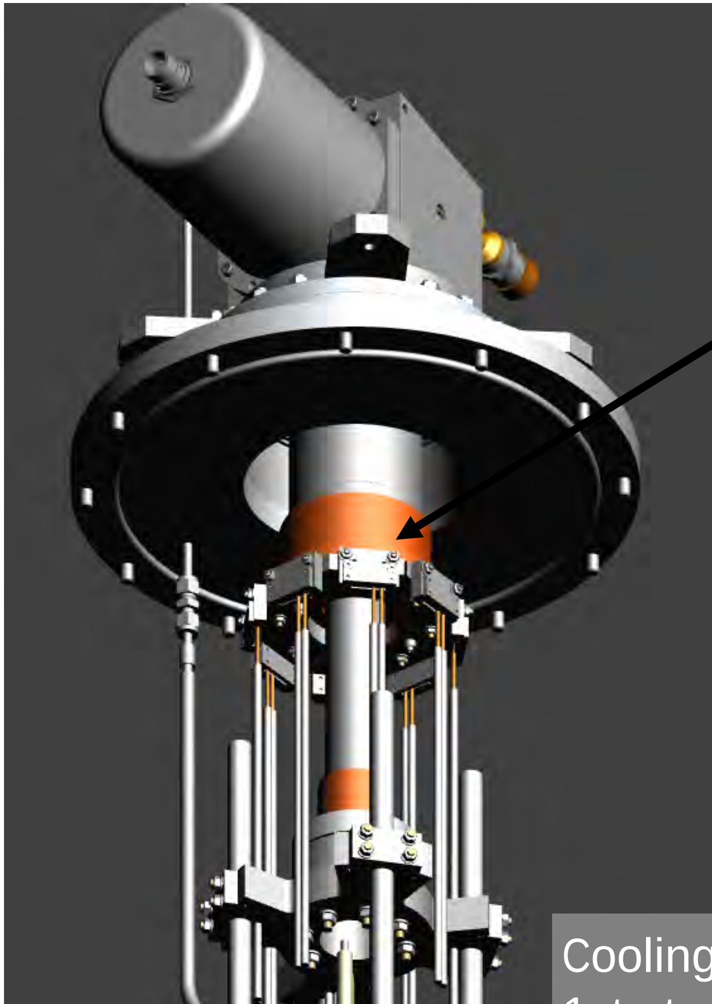


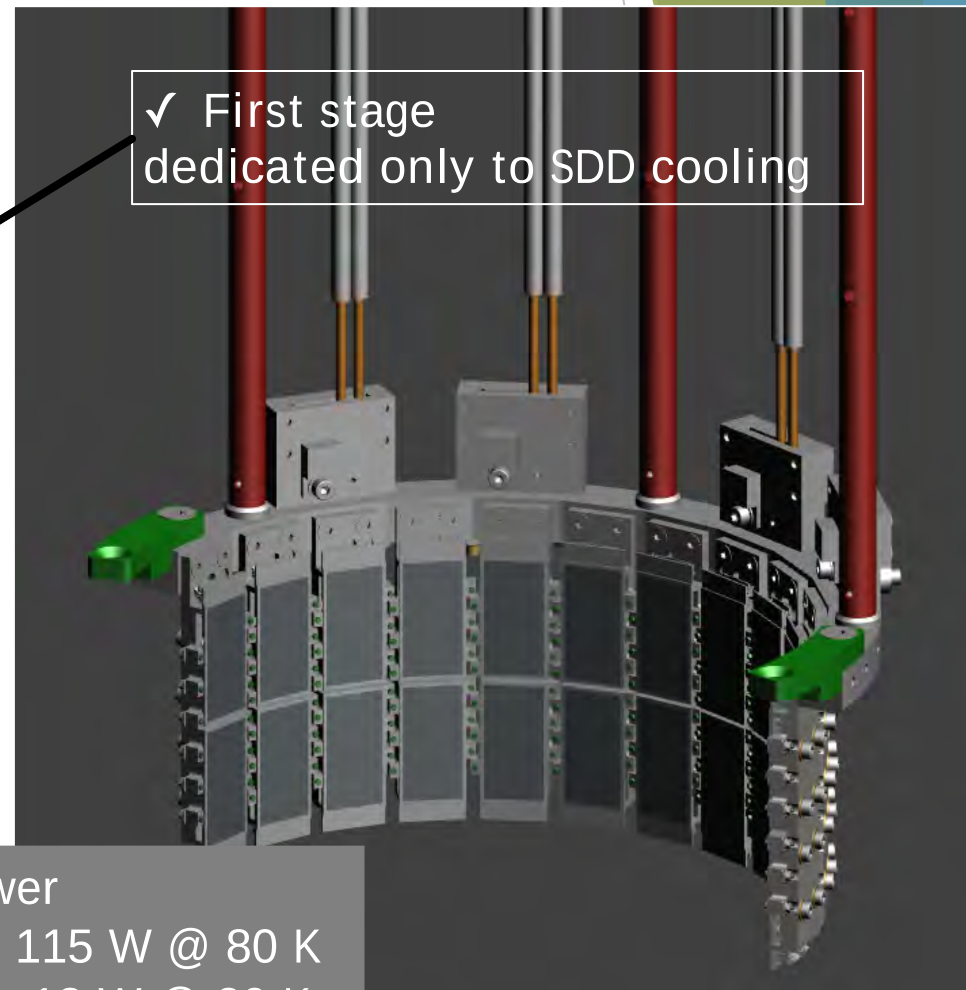
✓ Second stage dedicated to target cooling



Optimization of SIDDHARTA-2 setup

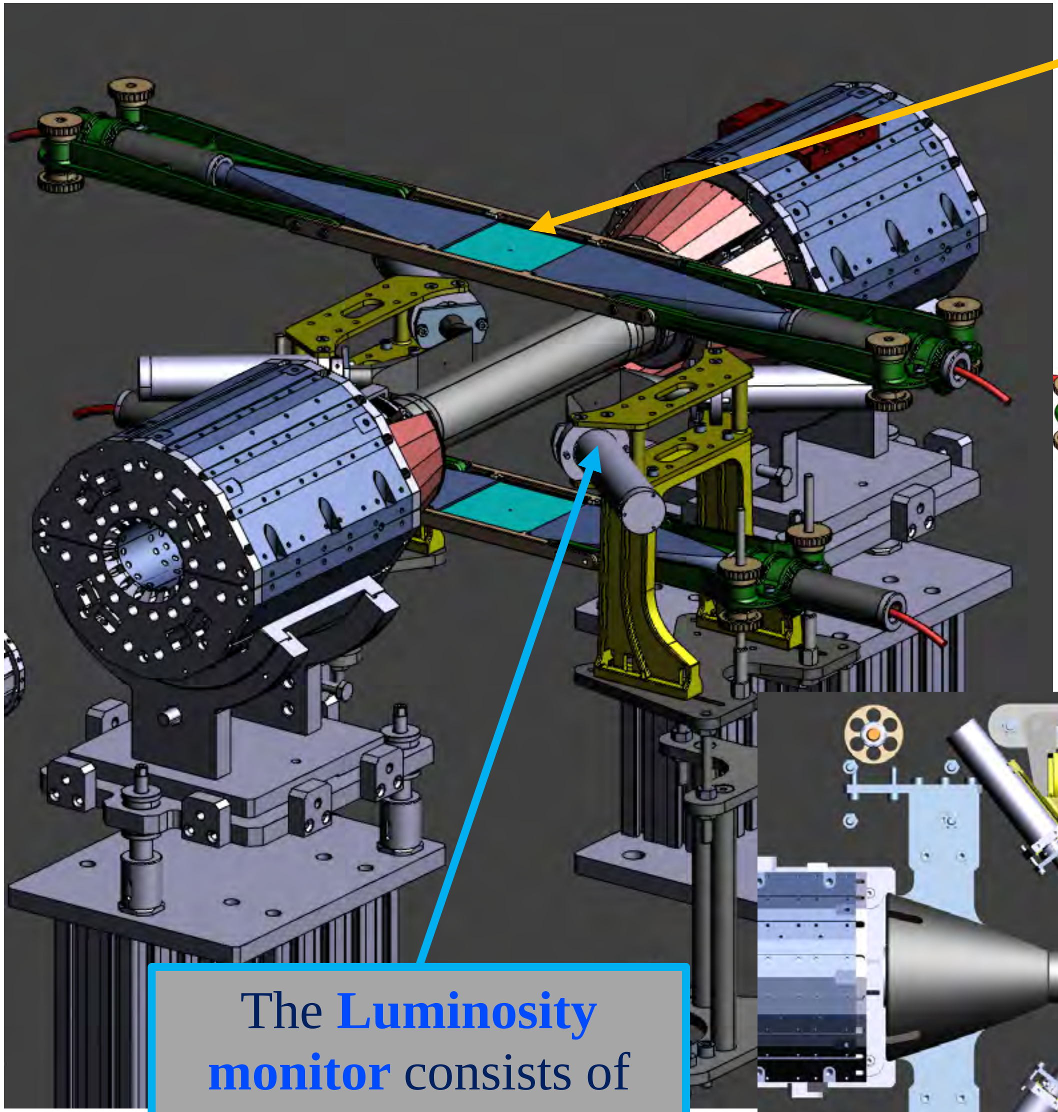
- ✓ new solutions for the cooling scheme - target and SDD
- ✓ Better control of target parameters (pressure, temperature, density,….)



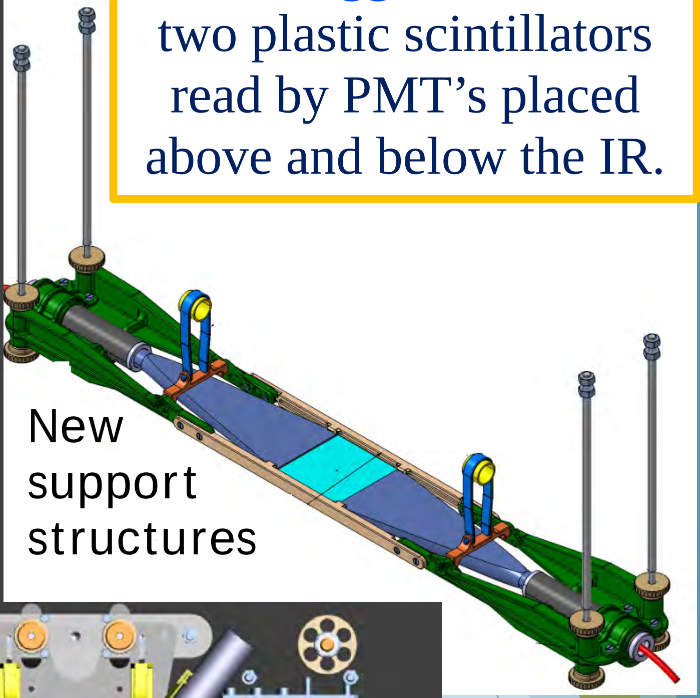


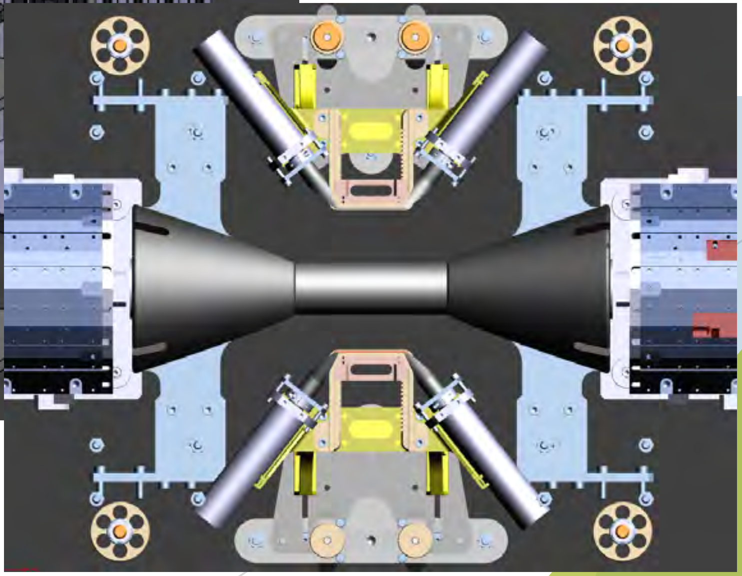
Cooling power
1st stage ~ 115 W @ 80 K
2nd stage ~ 18 W @ 20 K

Optimization of SIDDHARTA-2 setup



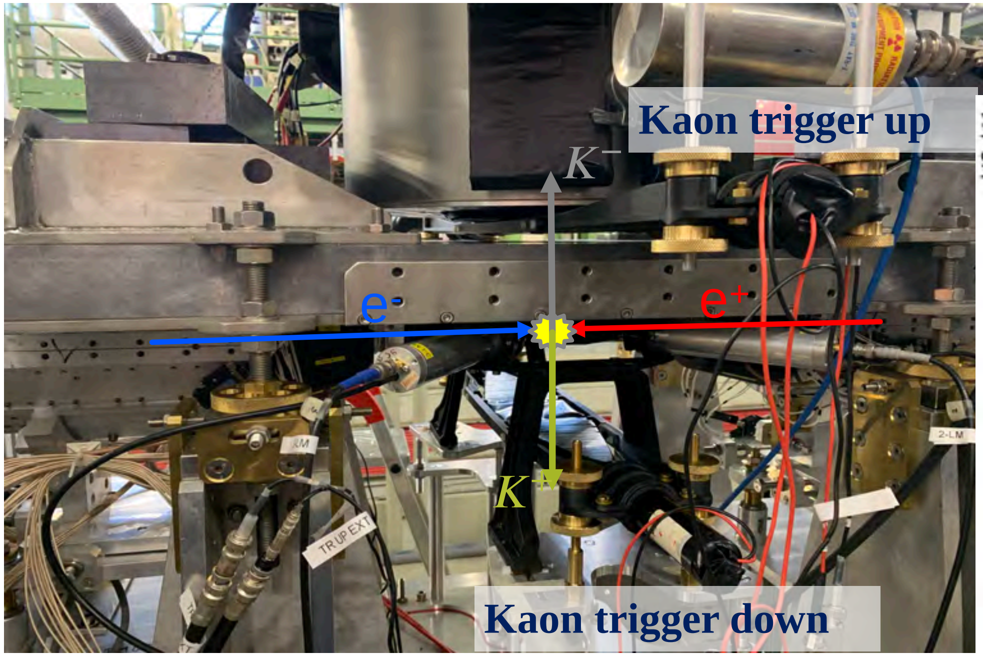
Kaon Trigger consists of two plastic scintillators read by PMT's placed above and below the IR.





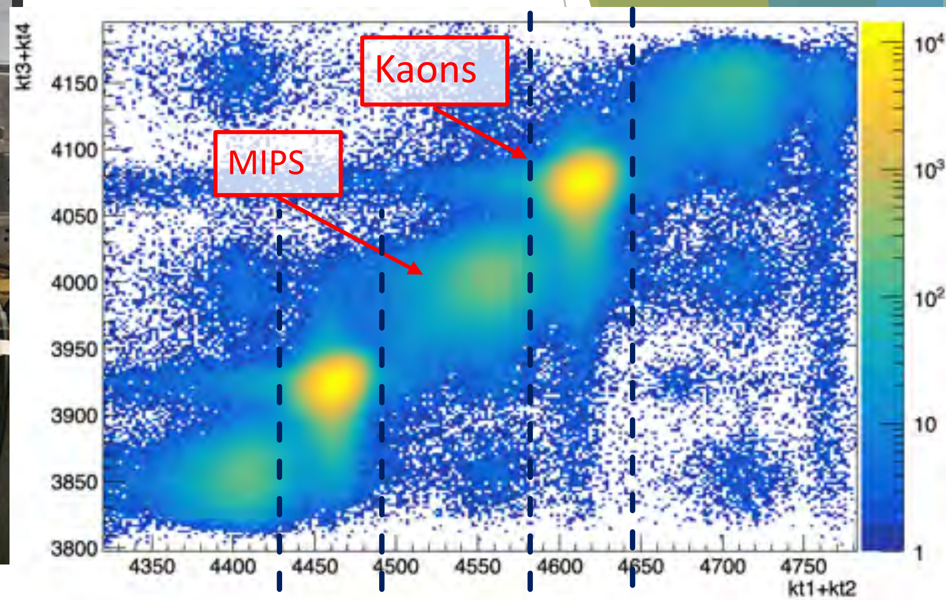
The **Luminosity monitor** consists of two plastic scintillators in the horizontal plane

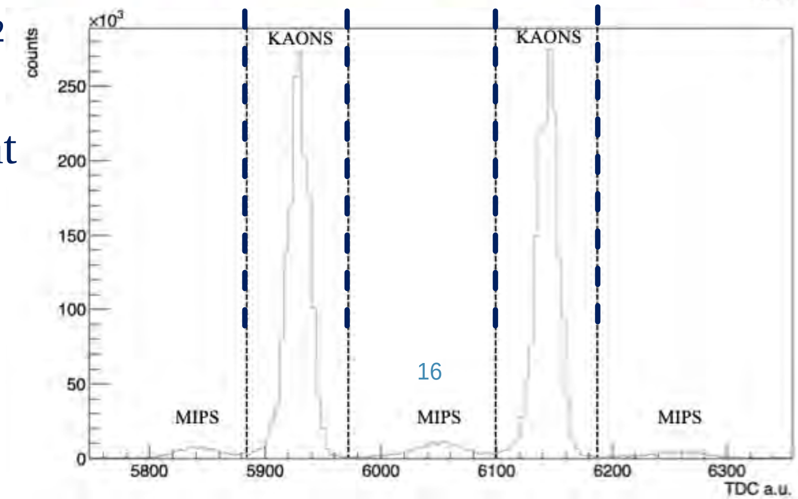
Optimization of SIDDHARTA-2 setup



The ToF is different for Kaons, m(K)~ 500 MeV/c²
and light particles
originating from beam-beam and beam-environment
interaction (MIPs).
Can efficiently discriminate by ToF Kaons and
MIPs!

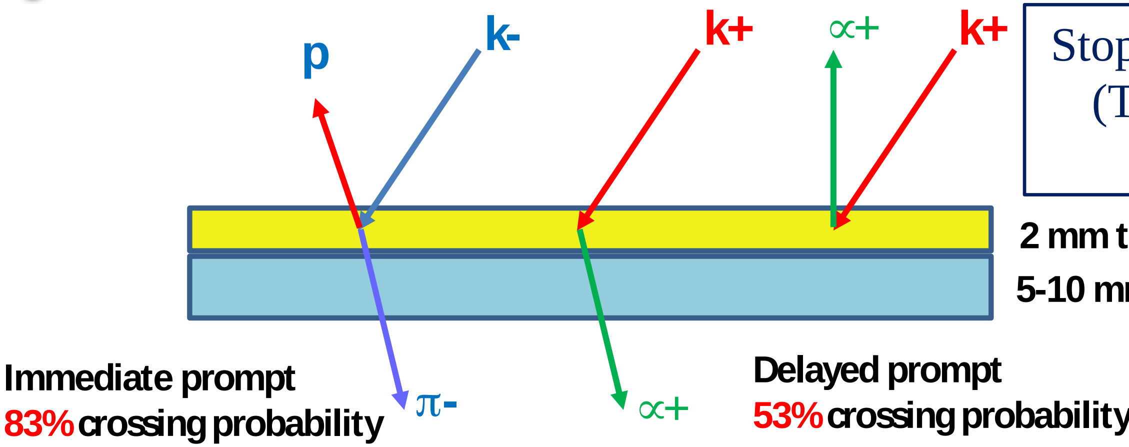
Kaon Trigger – event selection



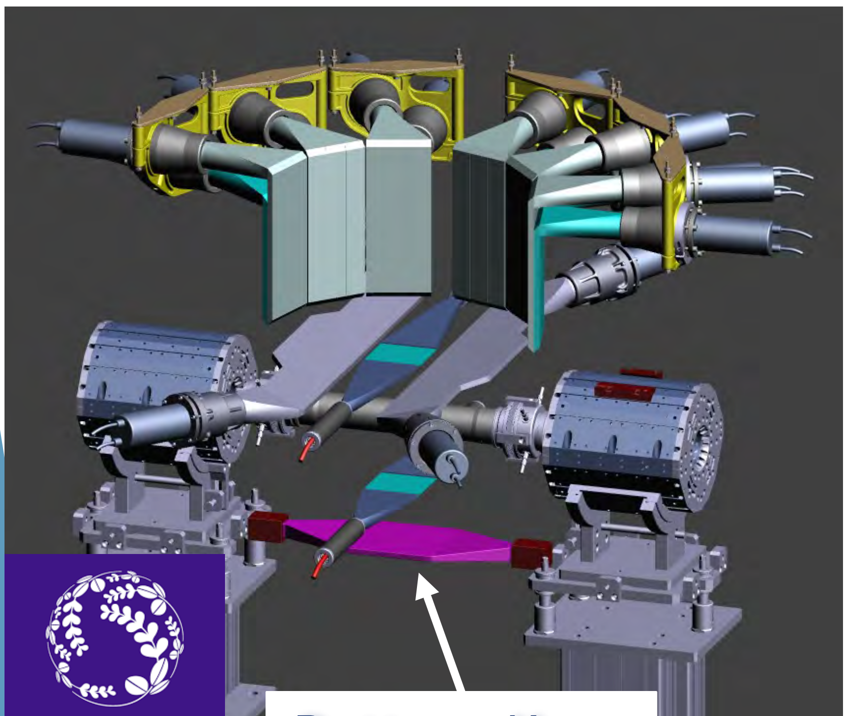


Optimization of SIDDHARTA-2 setup

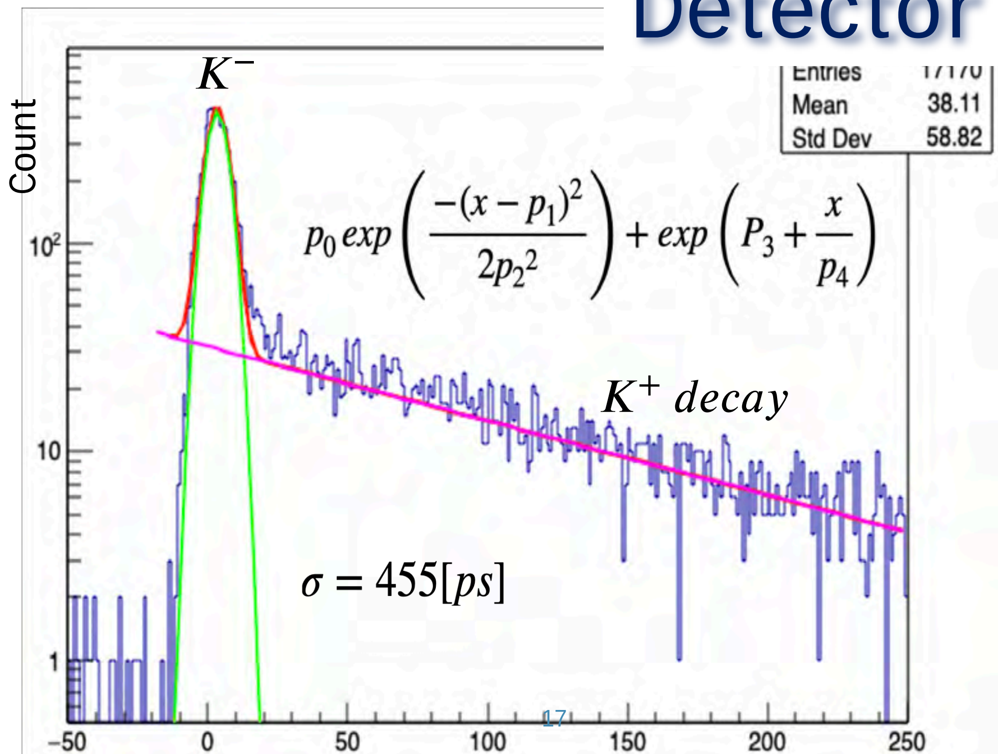
Stop both K^+ and K^- in a passive layer (Teflon) and detect secondaries in a scintillator



Bottom Kaon Detector



Bottom Kaon detector

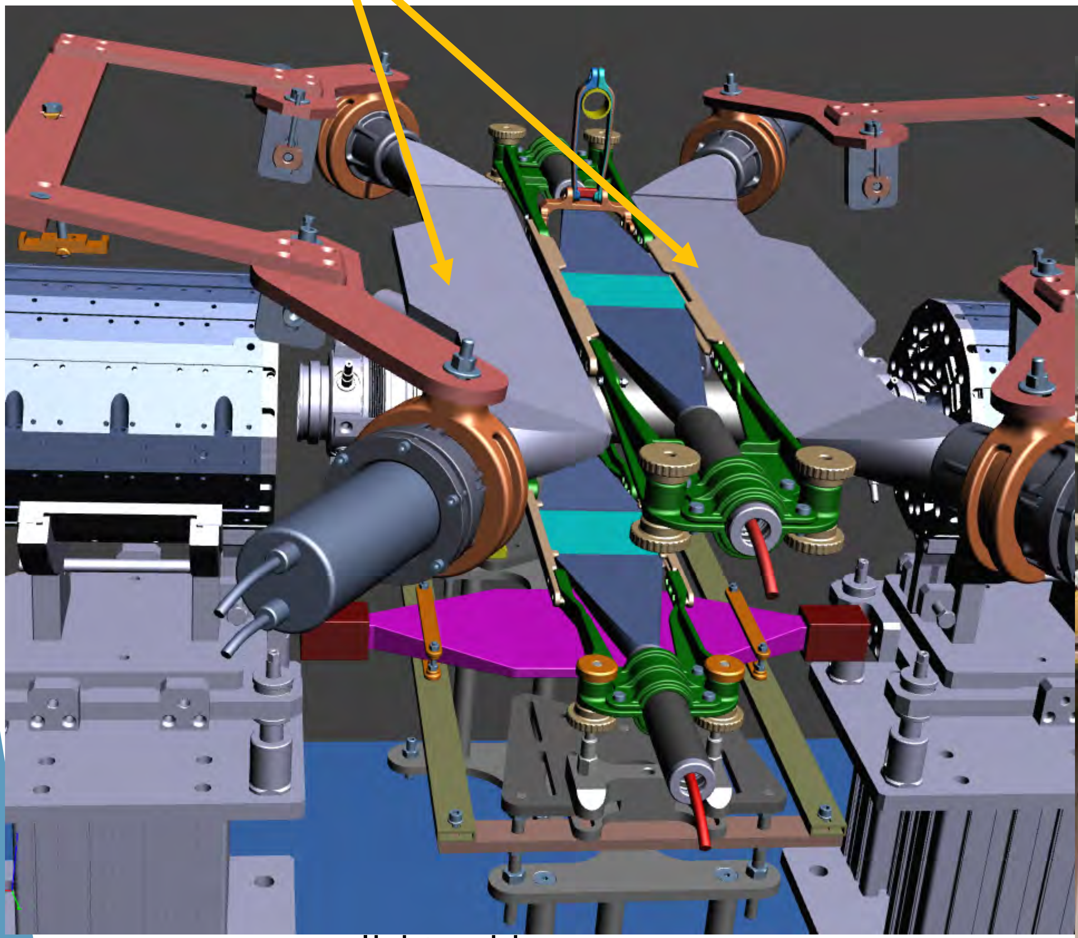


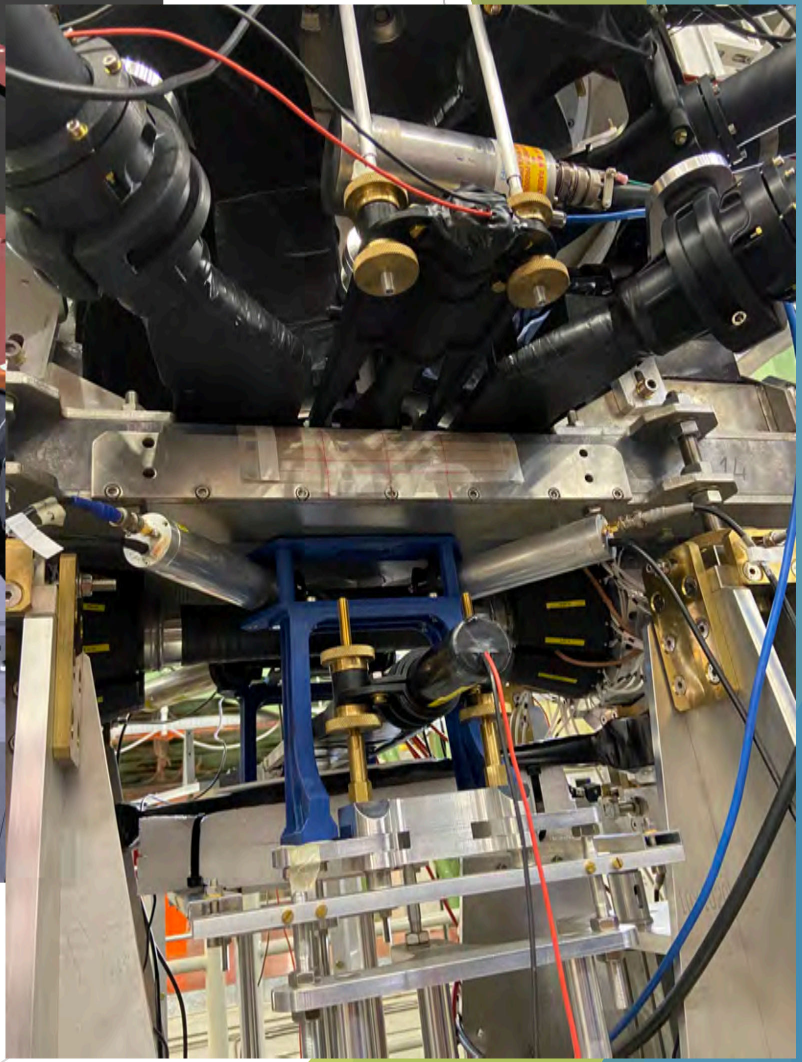
tdc (1 ch=100 ps)

Optimization of SIDDHARTA-2 setup

VETO system adds – VETO3

● 2 pairs of scintillator
640 x 130 x 10 mm^3 Scionix EJ-200
● R10533 PMTs Hamamatsu



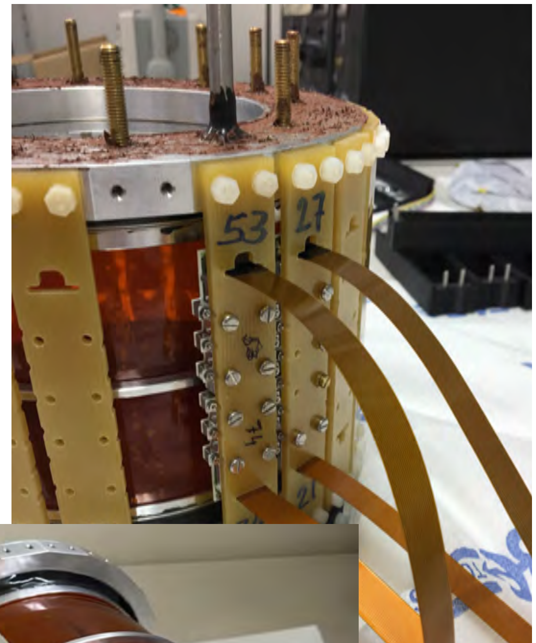


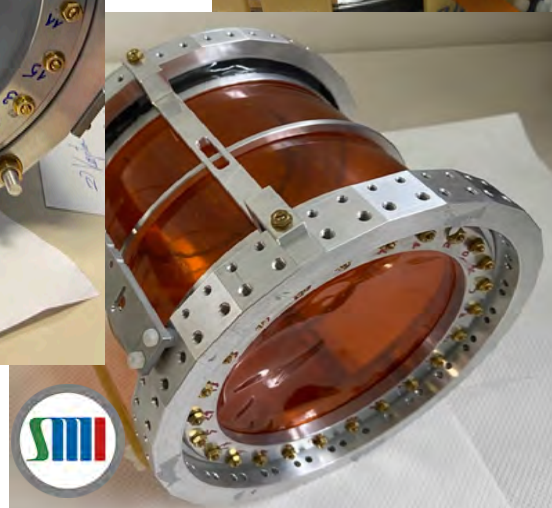
● light-guides
● Al tube + μMetal (0.1mm)
● reflective and light proof foil
● optical cement

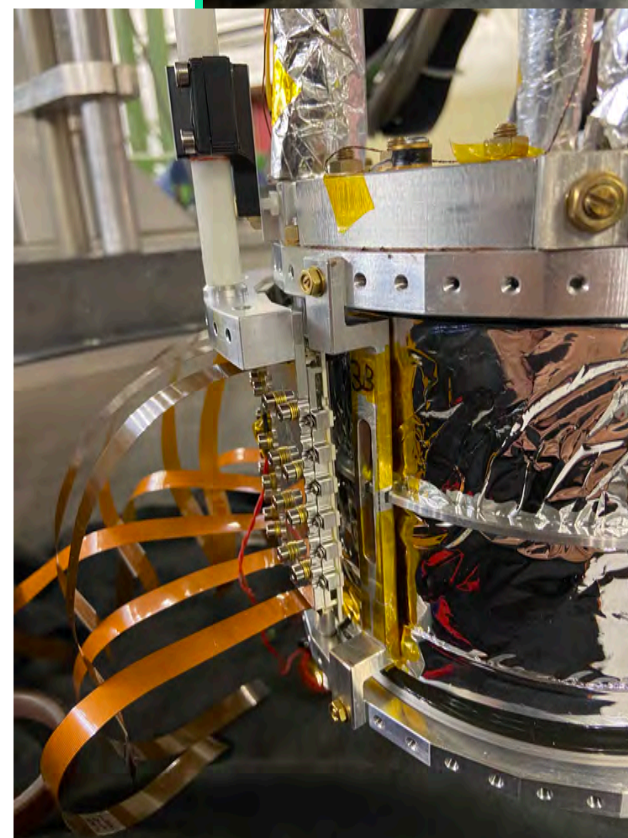
Optimization of SIDDHARTA-2 setup

✓ **Selected materials in different configuration:**

vacuum entrance windows
target walls
cooling supports

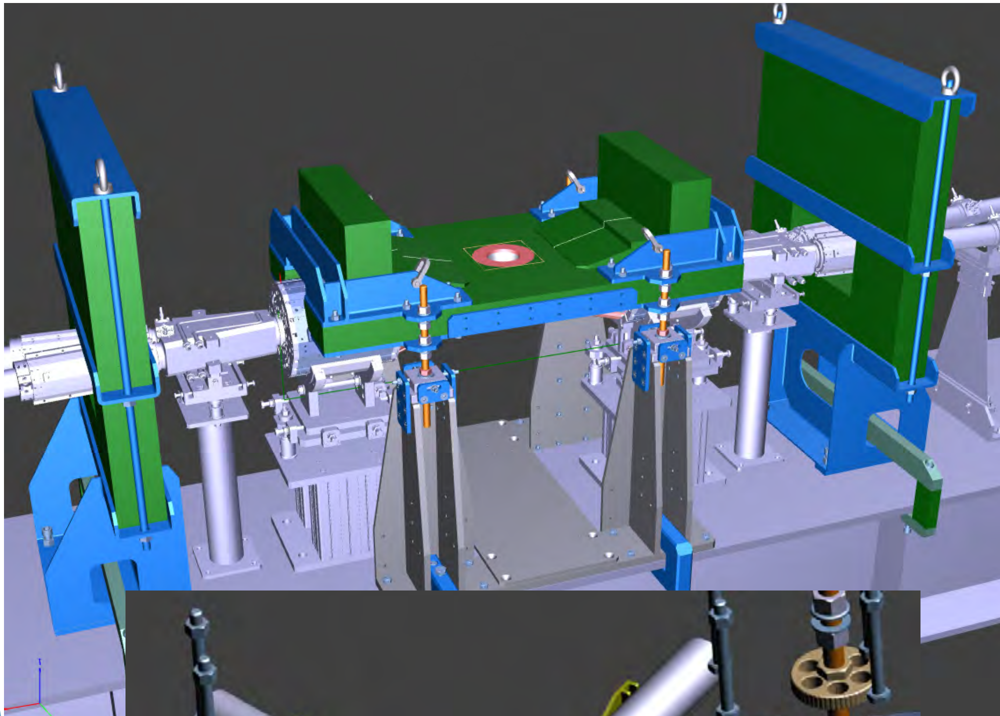




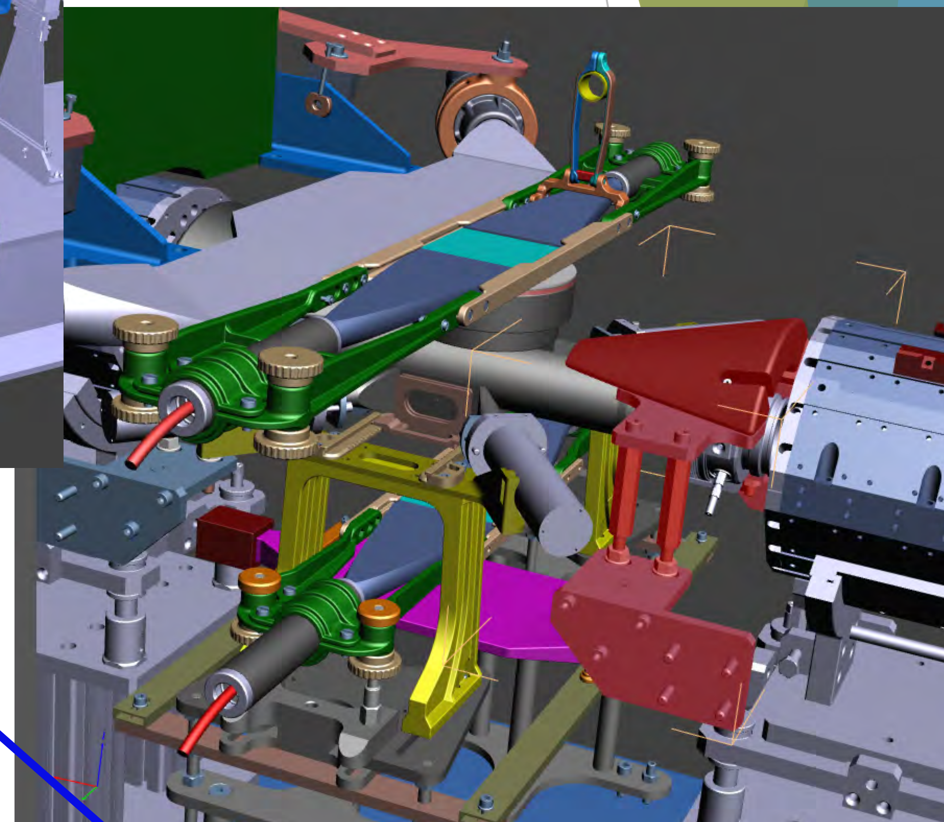


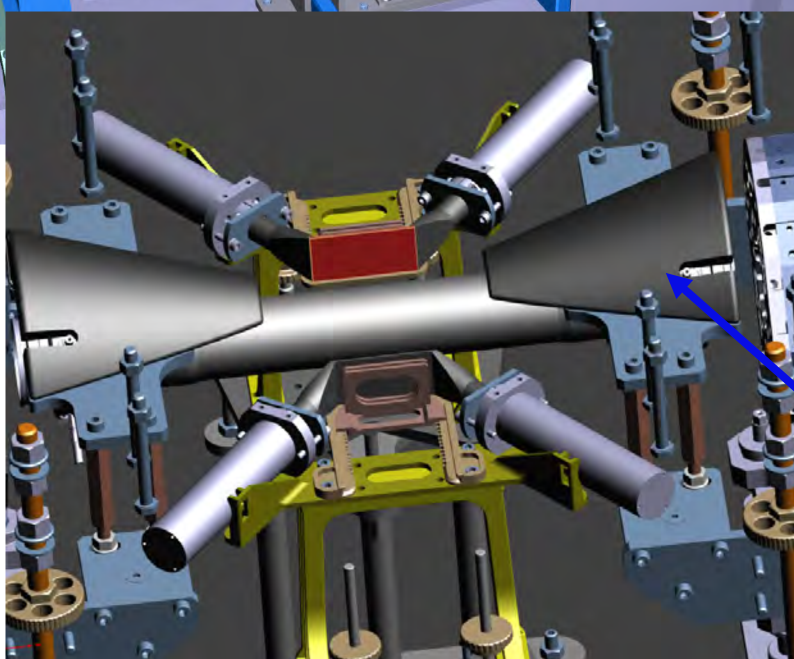
would eliminate Nitrogen and Oxygen contamination

Optimization of SIDDHARTA-2 setup

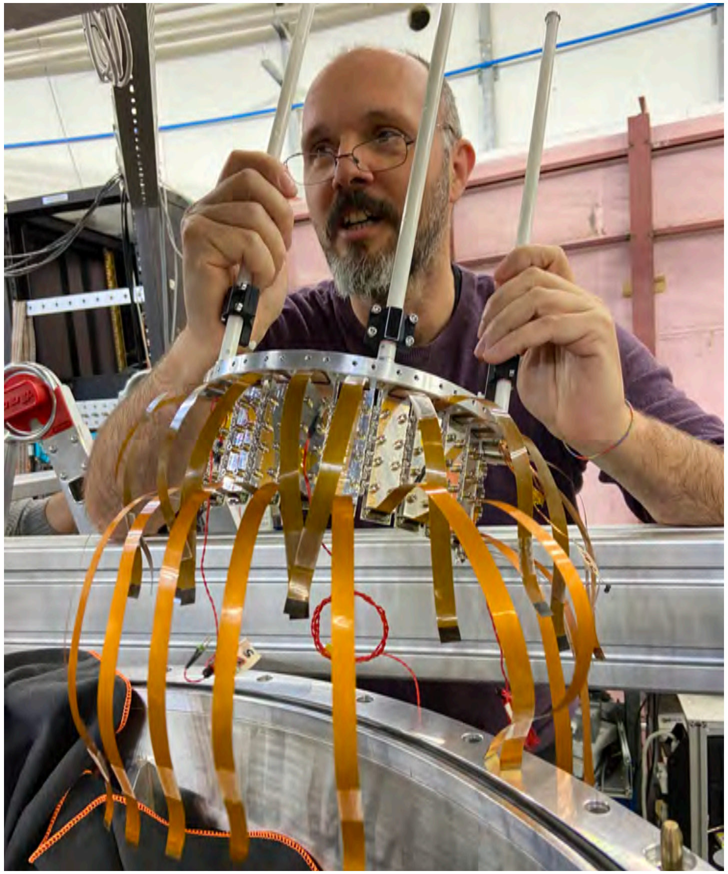


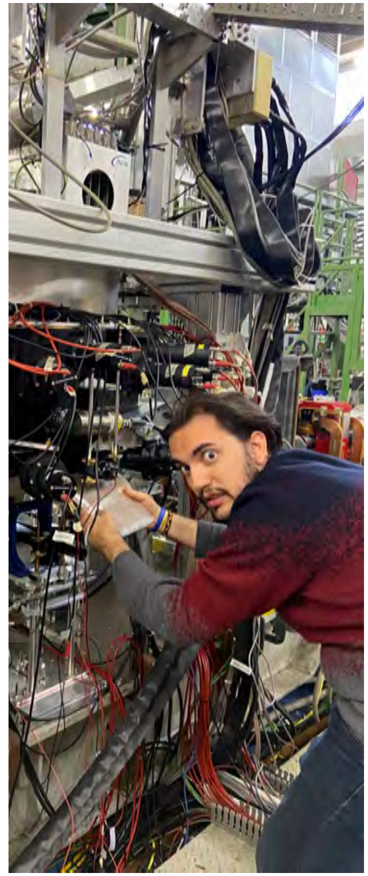
- Improve the lateral shielding around the vacuum chamber after adding VETO3 detector

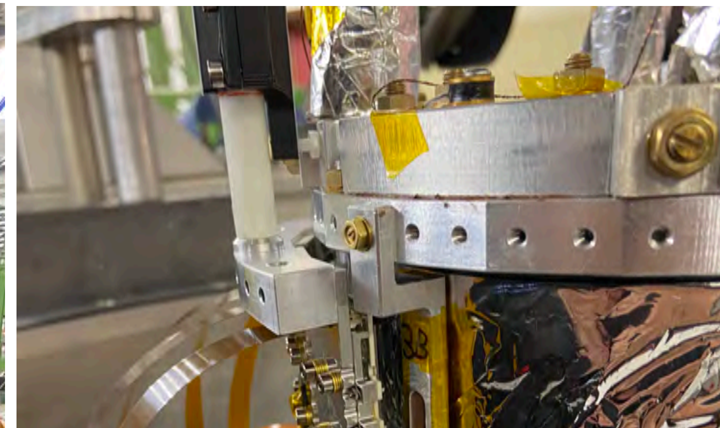


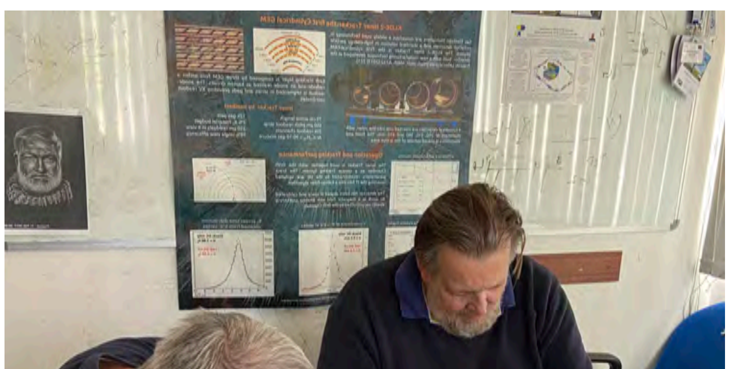


- Redesign and complete the bottom shielding near to IR



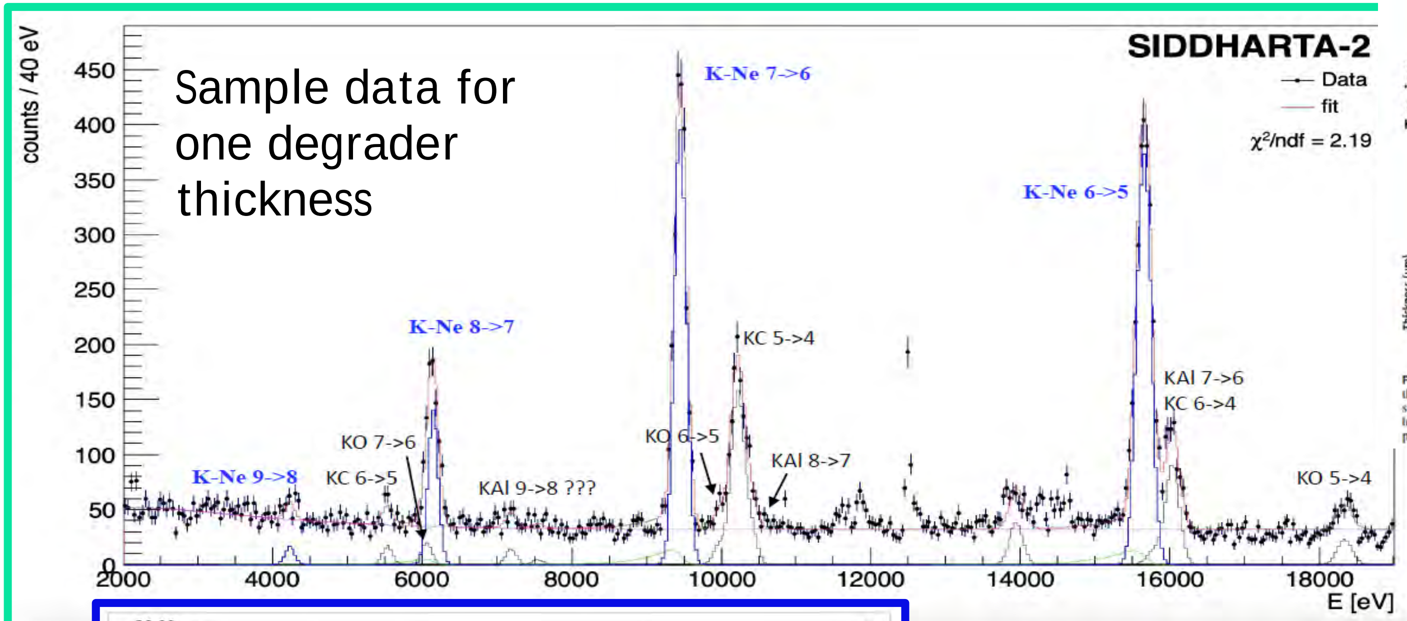






Optimization of SIDDHARTA-2 setup

Degrader optimization for Kaonic Neon



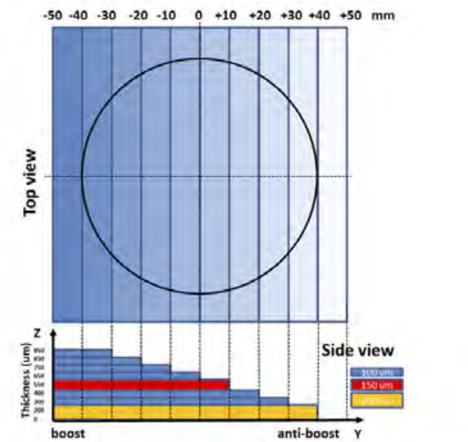
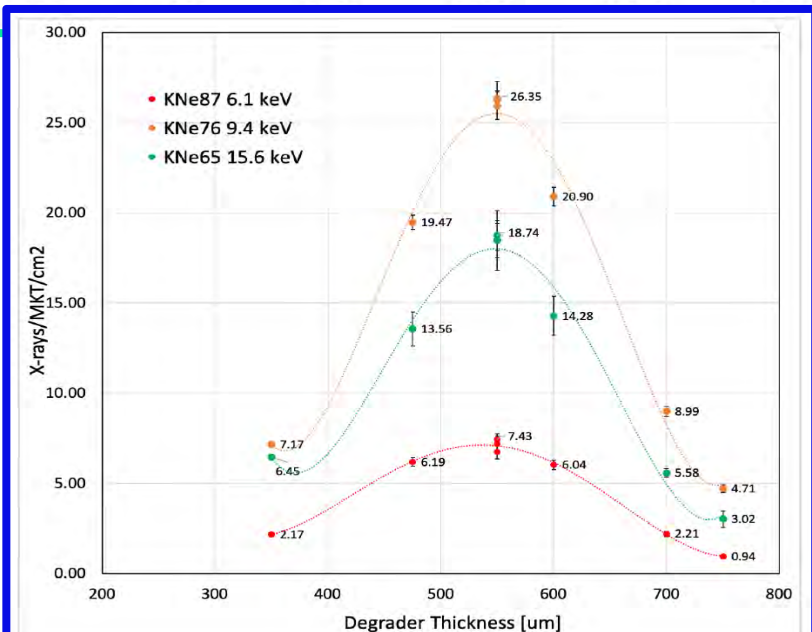
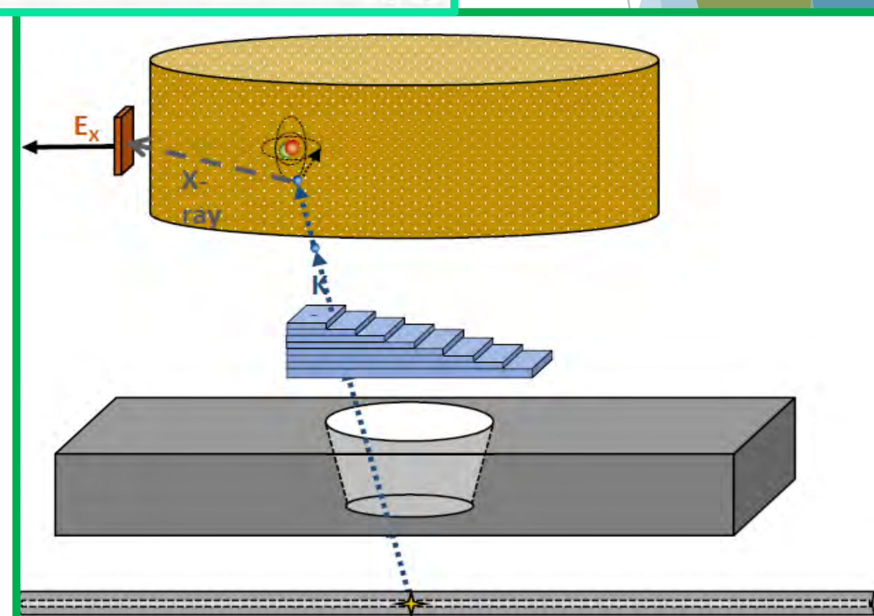


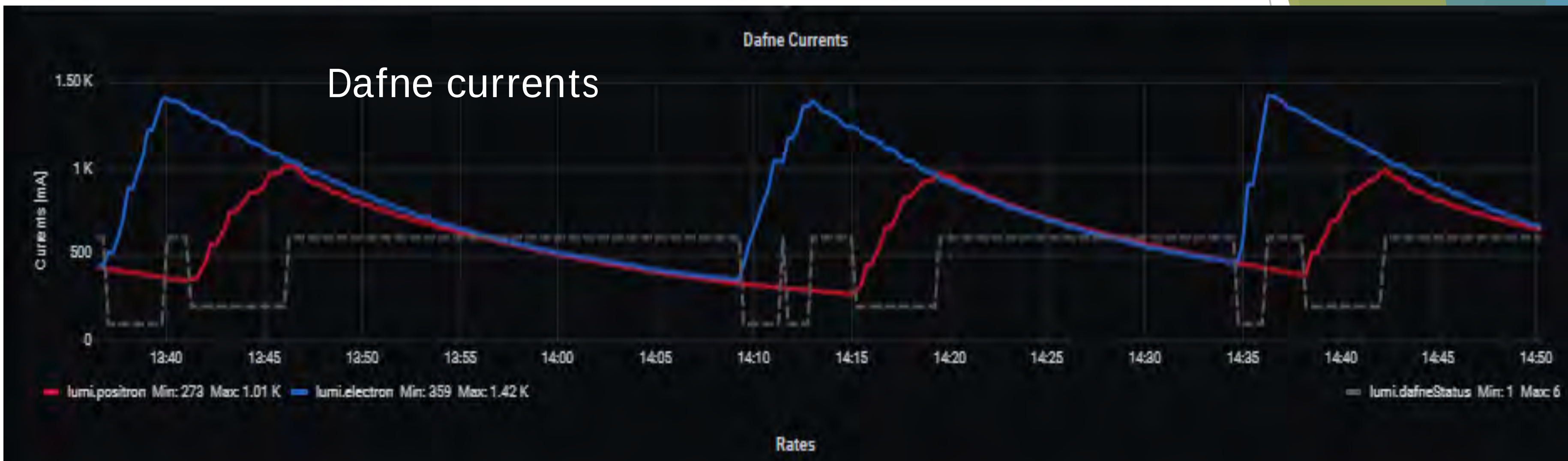
Figure 6. Nearest to optimal configuration of the Mylar degrader: the circle represents the size of the entrance window of the vacuum chamber; direction 'Y' points to the outer side of the DAΦNE ring, corresponding to the anti-boost side for kaons. The degrader has eight steps to compensate for the boost effect, with thicknesses shown in the lower part of the figure.





Optimization of SIDDHARTA-2 setup - results

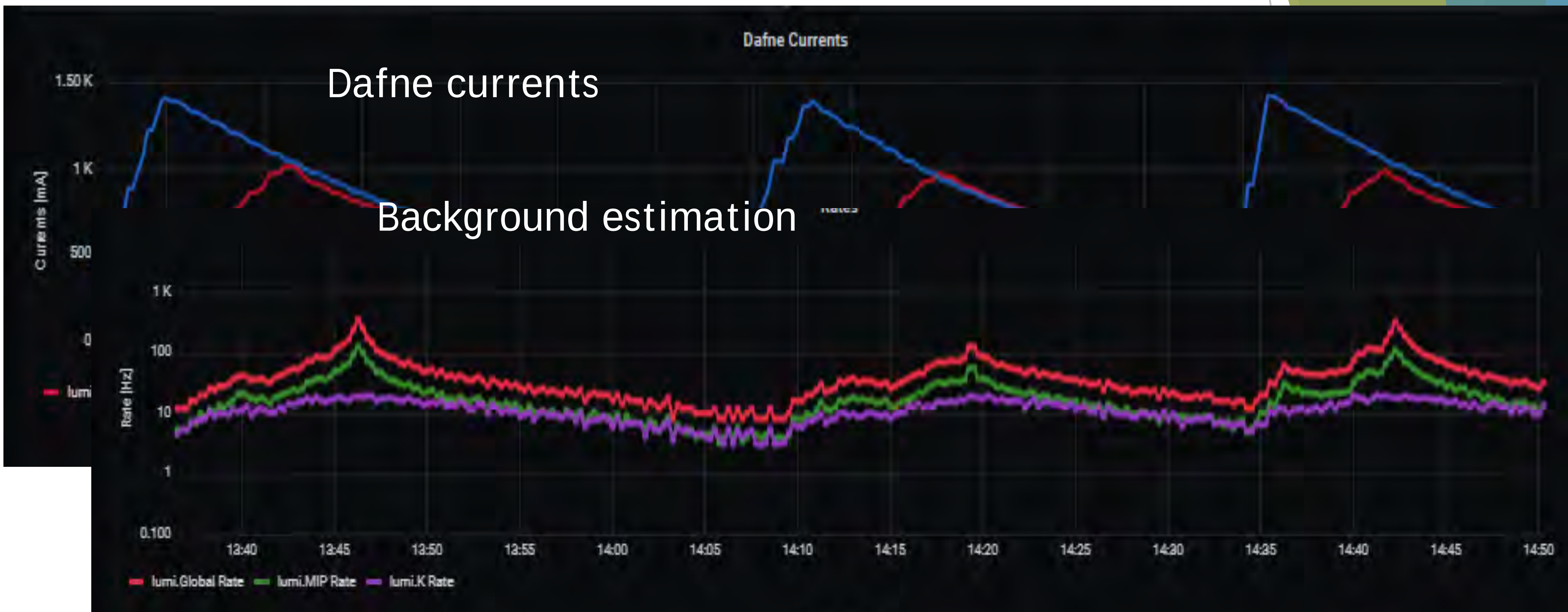
Online monitoring tools for fast feedback



Reduce background and improve KAON/SDD ratio

Optimization of SIDDHARTA-2 setup - results

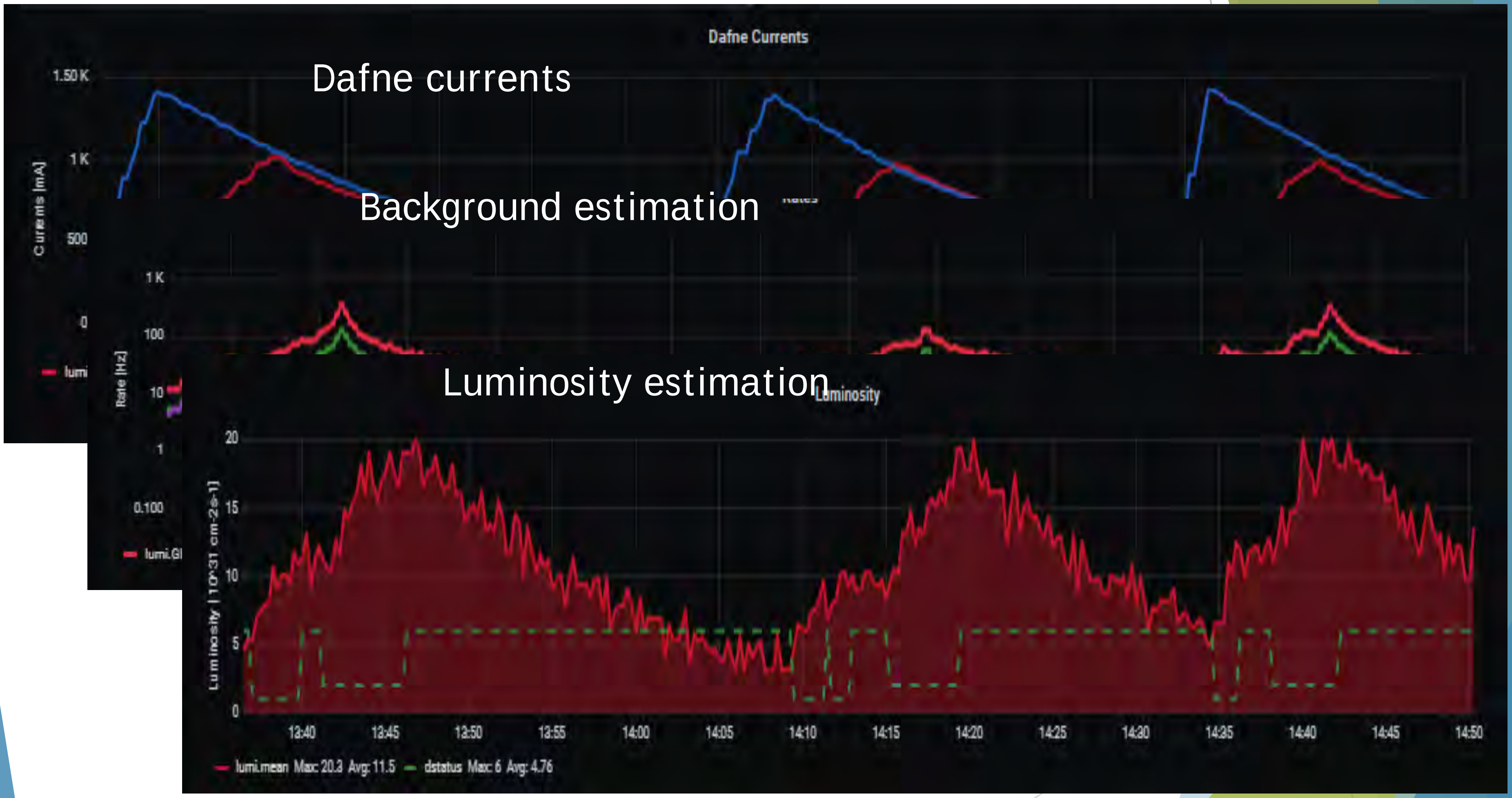
Online monitoring tools for fast feedback



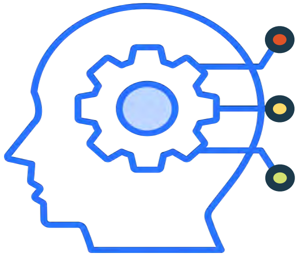
Reduce background and improve KAON/SDD ratio

Optimization of SIDDHARTA-2 setup - results

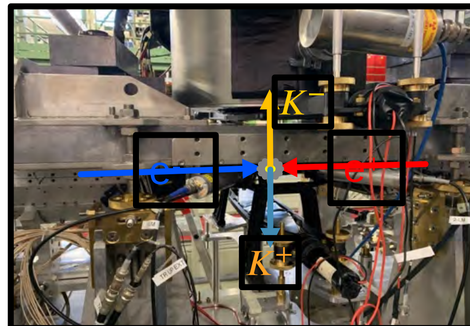
Online monitoring tools for fast feedback



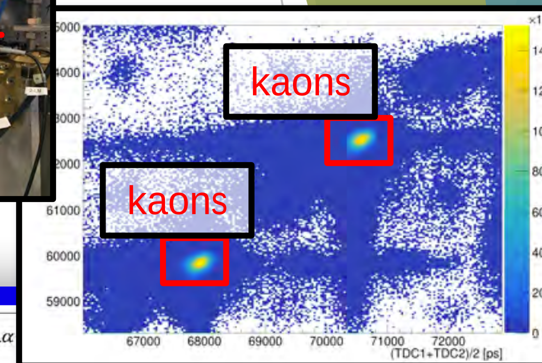
Reduce background and improve KAON/SDD ratio

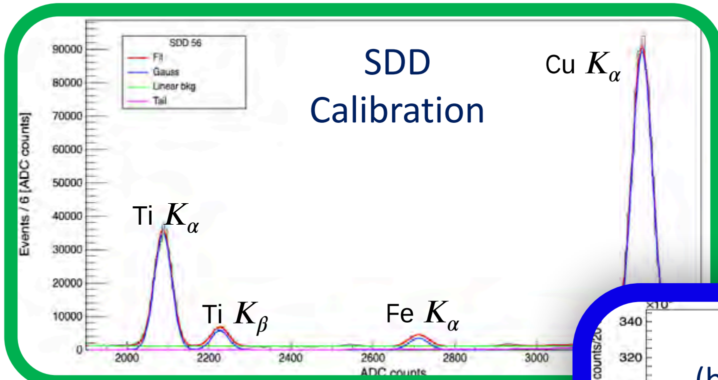


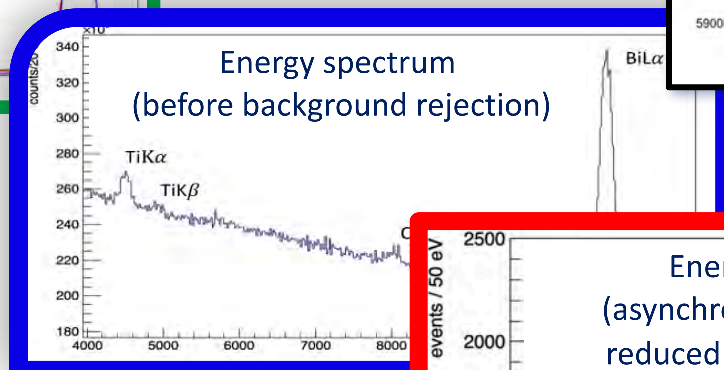
Powerful analysis tools
the steps in data analysis



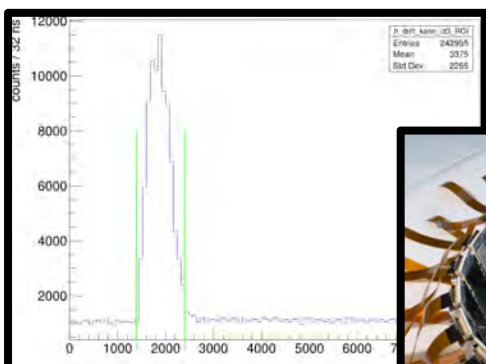
KAON TRIGGER



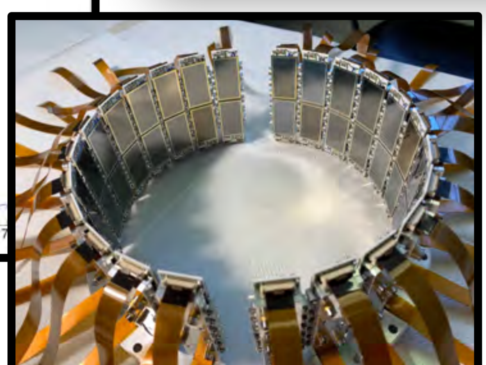


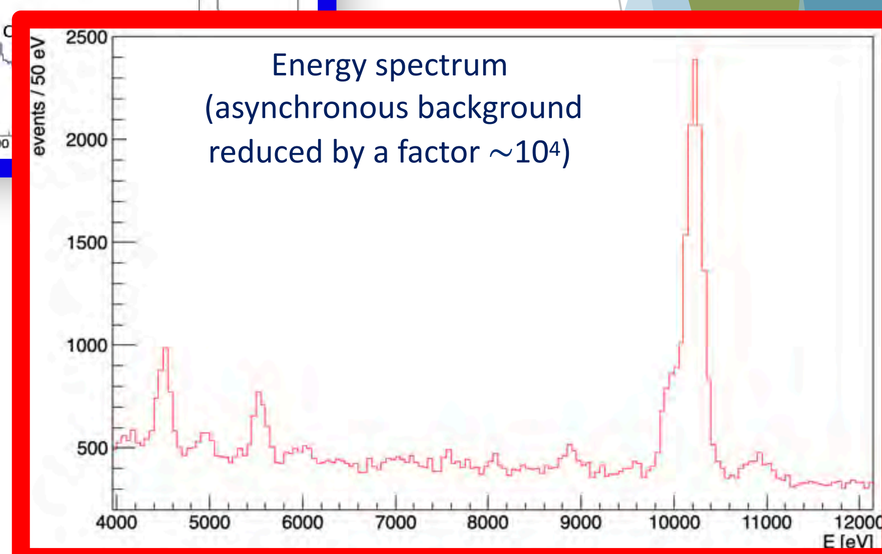


modern algorithms and machine learning techniques



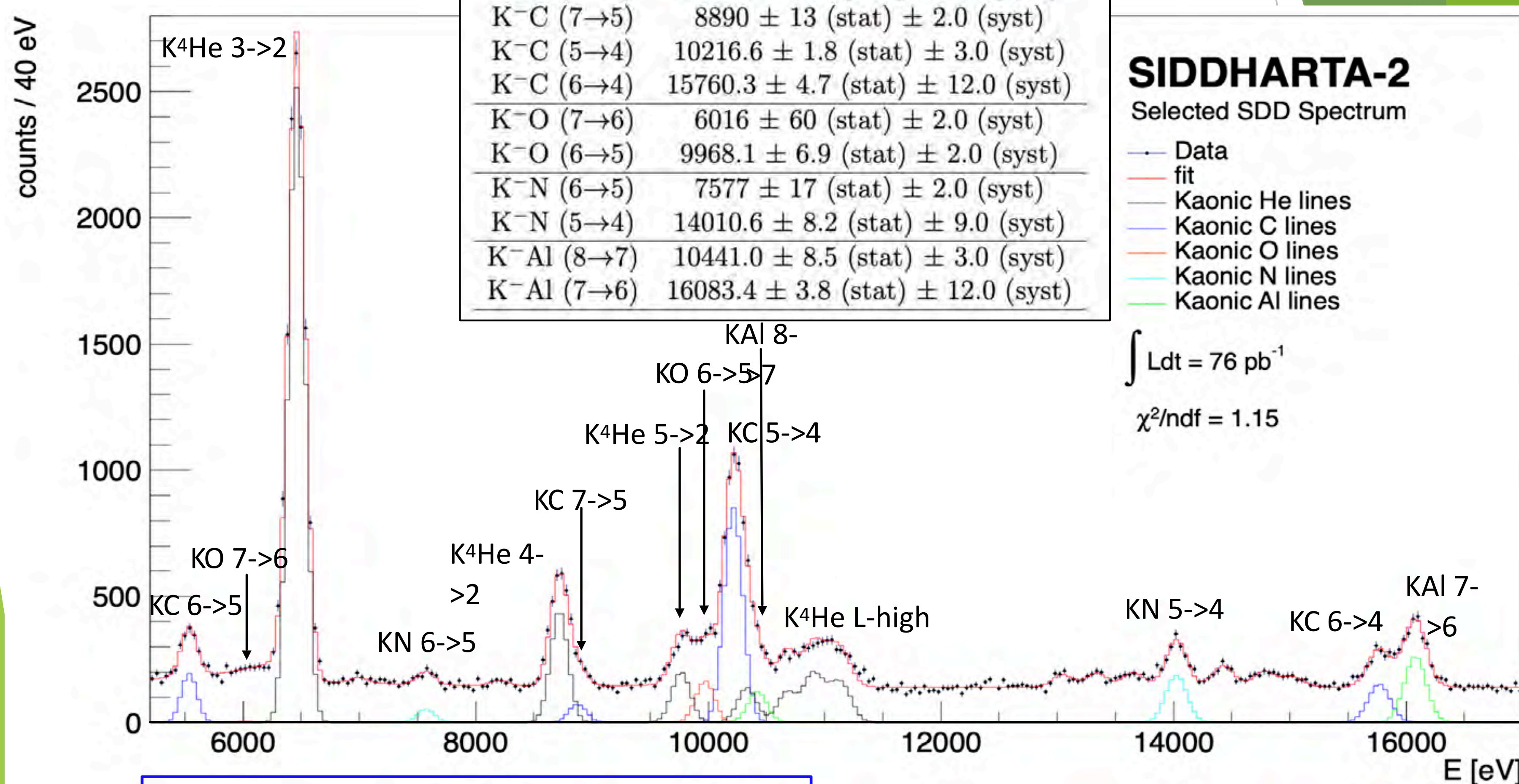
SDDs Drift Time





SIDDHARTA-2 (2022)
Measurements of high-n transitions in intermediate mass kaonic atoms

Transition	Energy (eV)
K^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (stat) ± 9.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-Al (7→6)	16083.4 ± 3.8 (stat) ± 12.0 (syst)

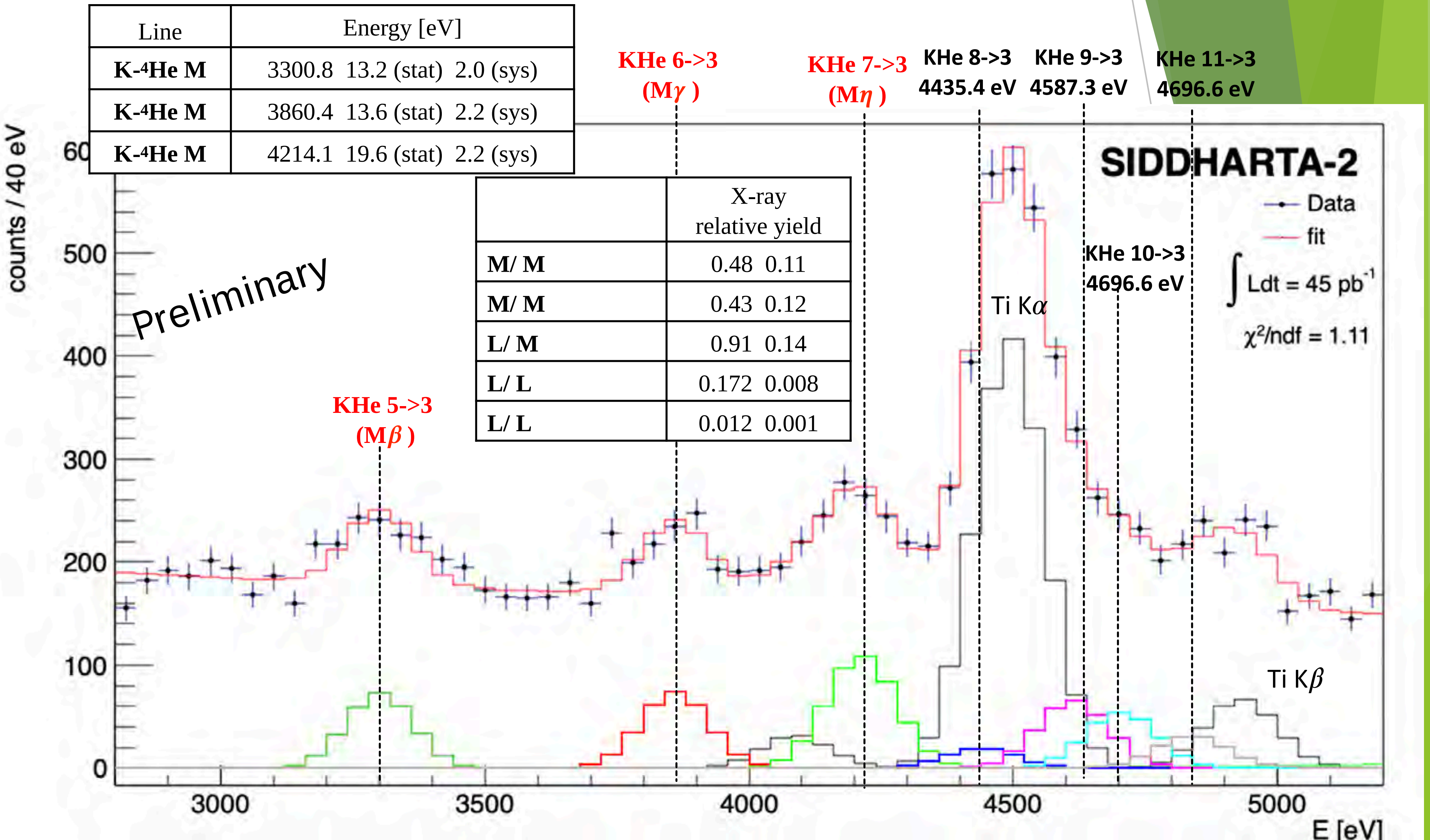


Sgaramella, F., *al. Eur. Phys. J. A* 59, 56 (2023)

SIDDHARTA-2 (2022)
Kaonic ^{4}He – M-type transitions

Line	Energy [eV]
K-^{4}He M	3300.8 13.2 (stat) 2.0 (sys)
K-^{4}He M	3860.4 13.6 (stat) 2.2 (sys)
K-^{4}He M	4214.1 19.6 (stat) 2.2 (sys)

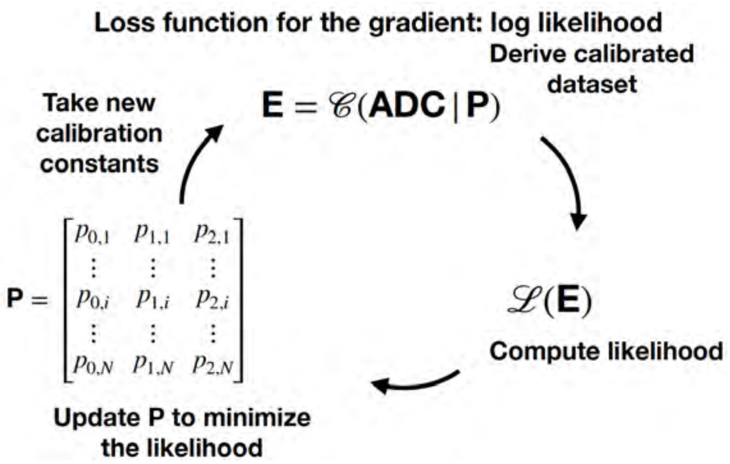
	X-ray relative yield
M/ M	0.48 0.11
M/ M	0.43 0.12
L/ M	0.91 0.14
L/ L	0.172 0.008
L/ L	0.012 0.001



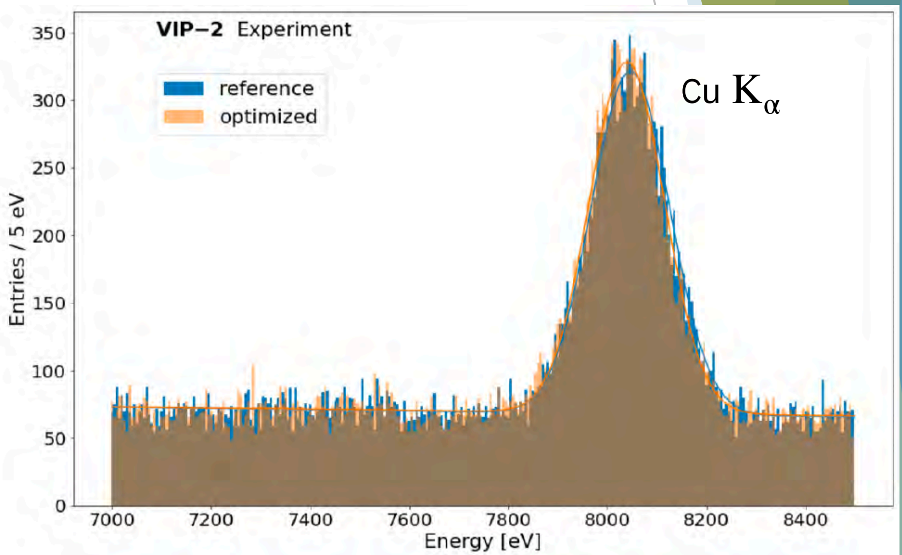
Sgaramella F., et al, submitted to J. Phys. G Nucl. Part. Phys

SDD energy calibration with ML and Differential Programming

The method can correct for miscalibration improving the systematic error and the energy resolution allowing to perform high precision measurement with an accuracy below 1 eV



	Position [eV]	FWHM [eV]	χ^2/ndf
Reference	8050 ± 1	185 ± 2	1.64
Optimized	8048 ± 1	176 ± 2	1.25



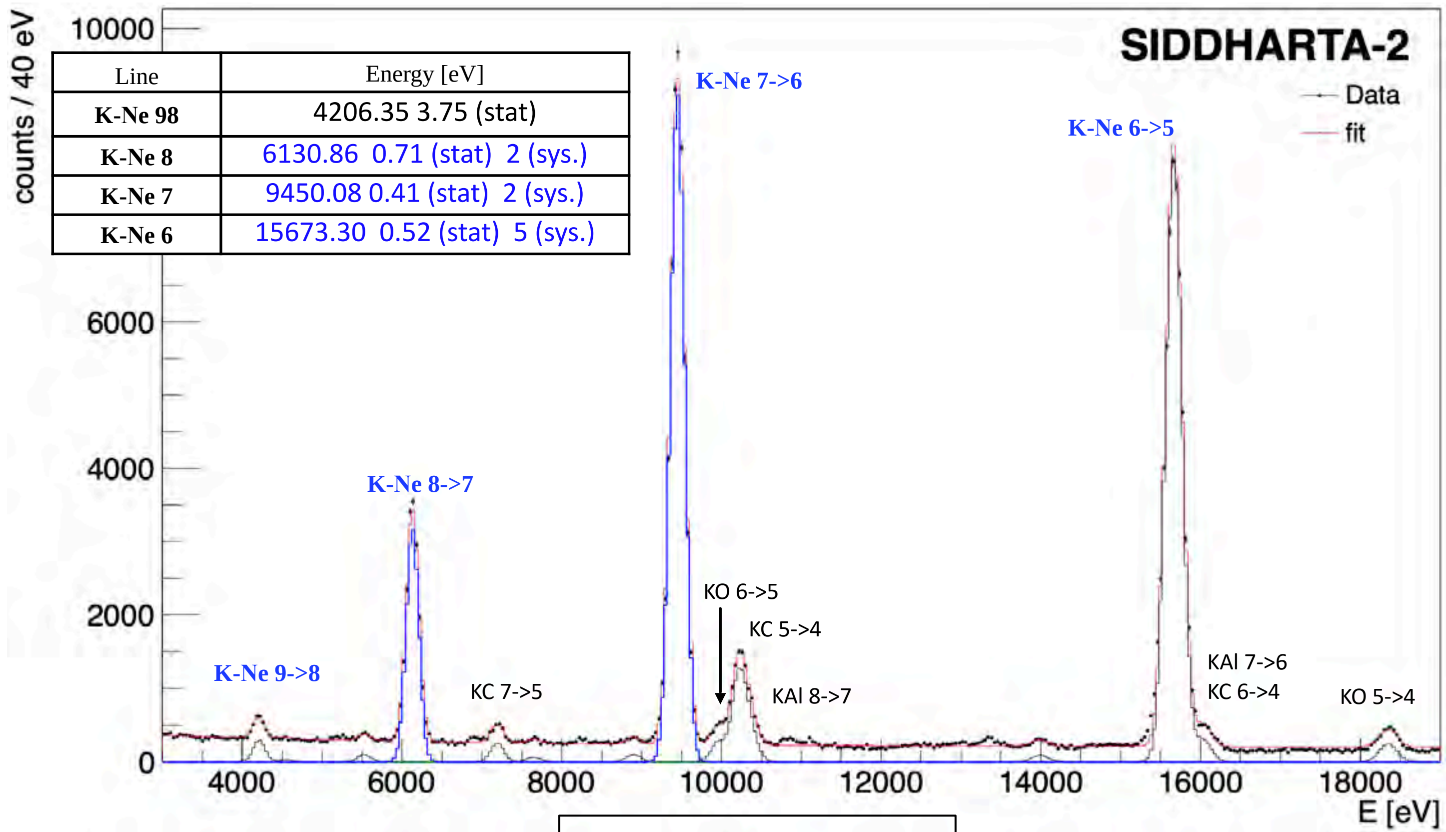
Fabrizio Napolitano et al 2023 Meas. Sci. Technol. in press
https://doi.org/10.1088/1361-6501/ad080a

… see the talk of S. Manti and F. Napolitano

The Kaonic Neon measurement (2023)

First measurement of kaonic neon X-ray transitions (record of precision < 1 eV)

Line	Energy [eV]
K-Ne 98	4206.35 3.75 (stat)
K-Ne 8	6130.86 0.71 (stat) 2 (sys.)
K-Ne 7	9450.08 0.41 (stat) 2 (sys.)
K-Ne 6	15673.30 0.52 (stat) 5 (sys.)



Paper in preparation

The (charged) Kaon mass puzzle and kaonic Neon

Kaon mass (K-Ne 8 $\longrightarrow$ 7and K-Ne 7 $\longrightarrow$ 6) =

493.671 $\pm$ 0.021 (stat) MeV

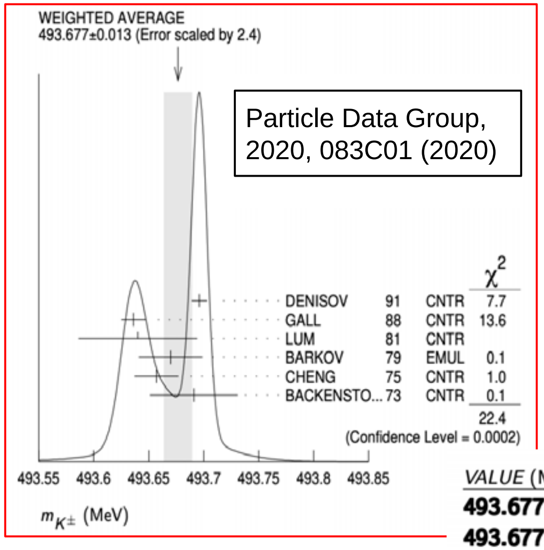
Kaon mass discrepancy

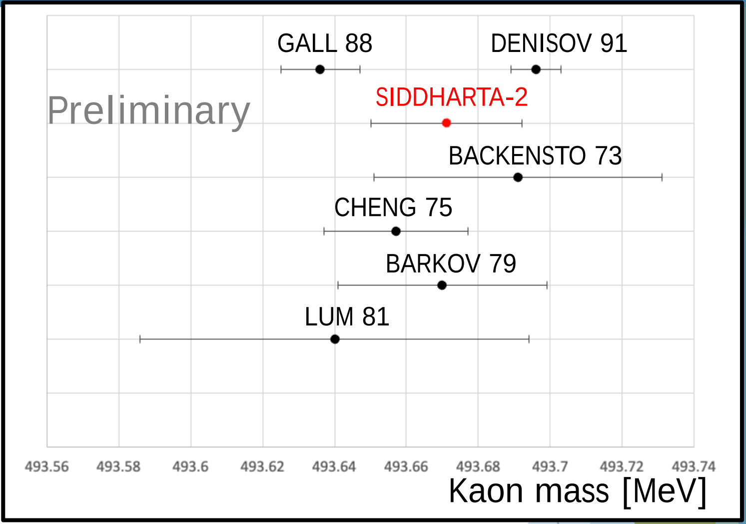
The kaonic Neon measurement to determine the K^- (K^+) mass

Less systematic uncertainty with respect to DENISOV 91 and GALL 88 measurements, thanks to the use of a low Z gas (Ne) target

It could solve the kaon mass discrepancy issue

Impact on the charmonium spectrum and on all processes in which charged kaons are involved

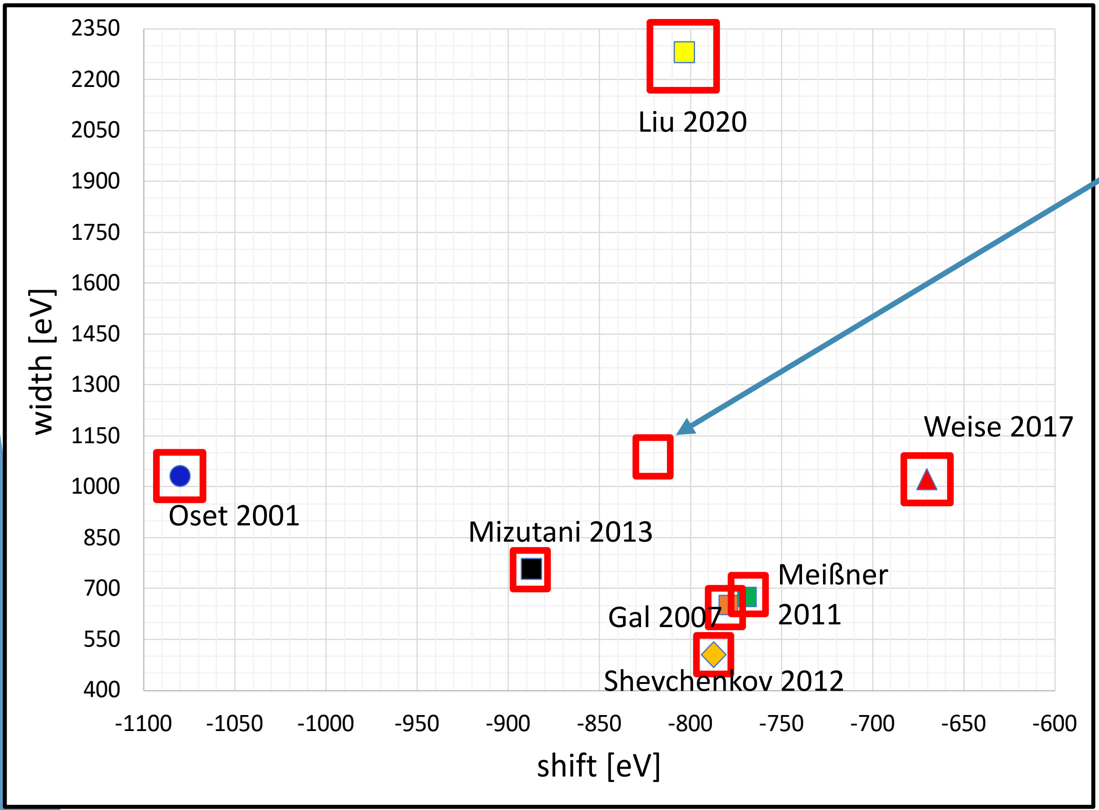


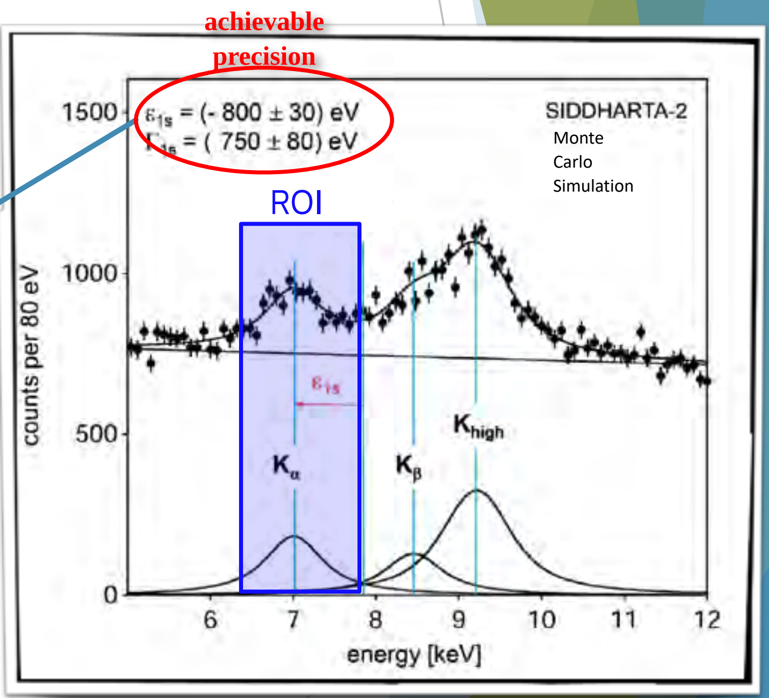


VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
493.677±0.016 OUR FIT	Error includes scale factor of 2.8.				
493.677±0.013 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.				
493.696±0.007	[1] DENISOV	91	CNTR	−	Kaonic atoms
493.636±0.011	[2] GALL	88	CNTR	−	Kaonic atoms
493.640±0.054	LUM	81	CNTR	−	Kaonic atoms
493.670±0.029	BARKOV	79	EMUL	±	$e^+e^- \rightarrow K^+K^-$
493.657±0.020	[2] CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	−	Kaonic atoms

Kaonic deuterium shift and width (Theoretical predictions)

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.





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

Conclusions

The SIDDHARTA-2 NEON run (technical run)
(application of modern algorithms and machine learning techniques)

First Kaonic deuterium run done - from May to July 2023
(optimized setup for about 110 pb^{-1} integrated luminosity) – analysis ongoing

We are confident in machine performance, ready and very motivated to continue the SIDDHARTA-2 program

Second Kaonic deuterium run – ongoing

(with optimized shielding, readout, veto, trigger, ….. for the remaining integrated luminosity: 600-700 pb^{-1} in 2023/2024)

Future plans

proposal to perform fundamental physics at the strangeness frontier at DAΦNE for a 3-years period (post-SIDDHARTA-2)

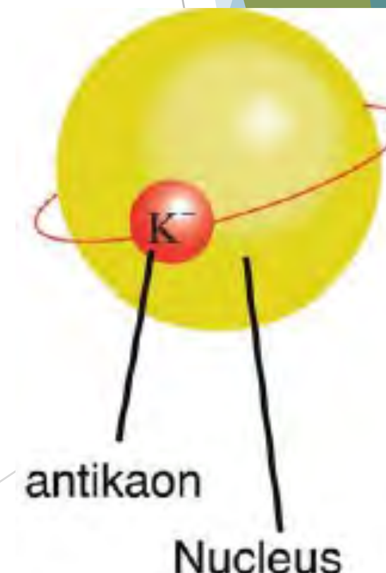
EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

Kaonic Hydrogen: 200 pb^{-1} – with SIDDHARTA2 setup – to get a precision < 10 eV (KH)

Selected light kaonic atoms (LHKA)

Selected intermediate and heavy kaonic atoms charting the periodic table (IMKA)

Ultra-High precision measurements of Kaonic Atoms (UHKA)



EXKALIBUR

Dedicated runs with different types of detectors:

SDD 1mm, CZT detectors, HPGe, crystal HAPG spectrometer-VOXES project

C. Curceanu et al., arXiv:2104.06076 [nucl-ex](2021)

C. Curceanu et al., Front. Phys. 11 (2023)

……….See talk of A. Scordo