New precision measurements of the strong interaction in kaonic hydrogen

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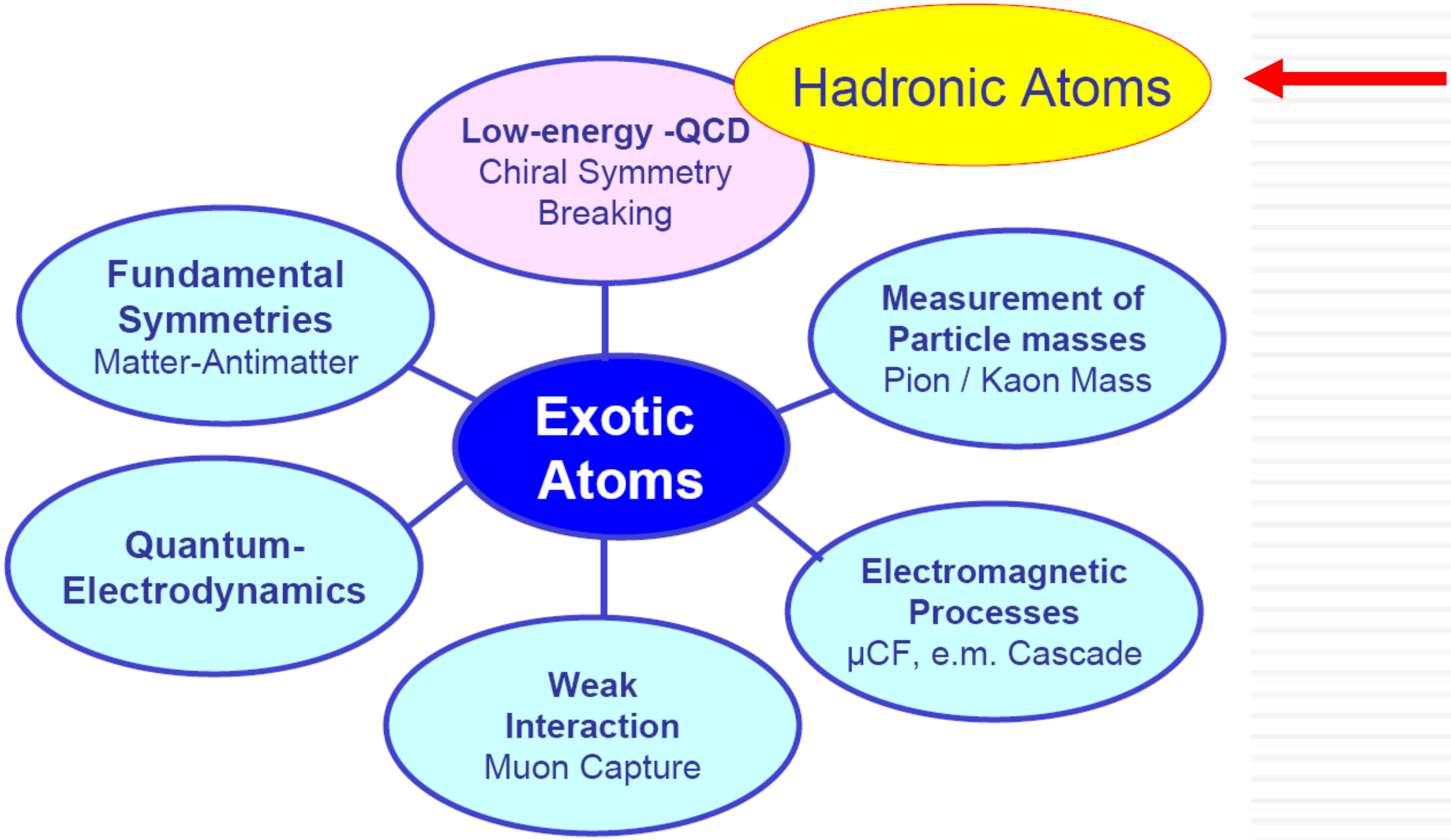
on behalf of the SIDDHARTA Collaboration

Outline

- Hadronic atoms
- Motivation for precision experiments
- Experimental method
- Kaonic hydrogen – kaonic deuterium
- DEAR Results vs. results from theory
- SIDDHARTA – new precision experiment
- Summary & Outlook

Exotic atoms – a broad research field

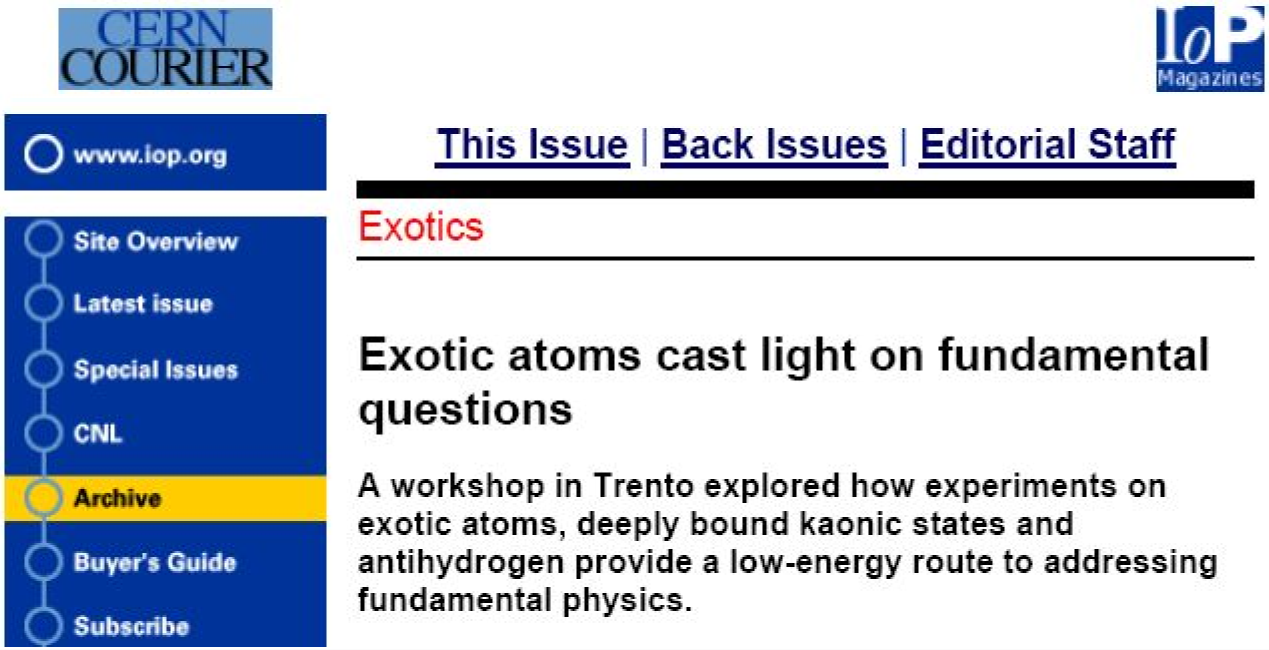
- Studies of fundamental interactions and symmetries



K^-p, K^-d
π-p, π-d
….

Hadronic atoms

Unique laboratory for studying strong interaction
at zero kinetic energy



Motivation

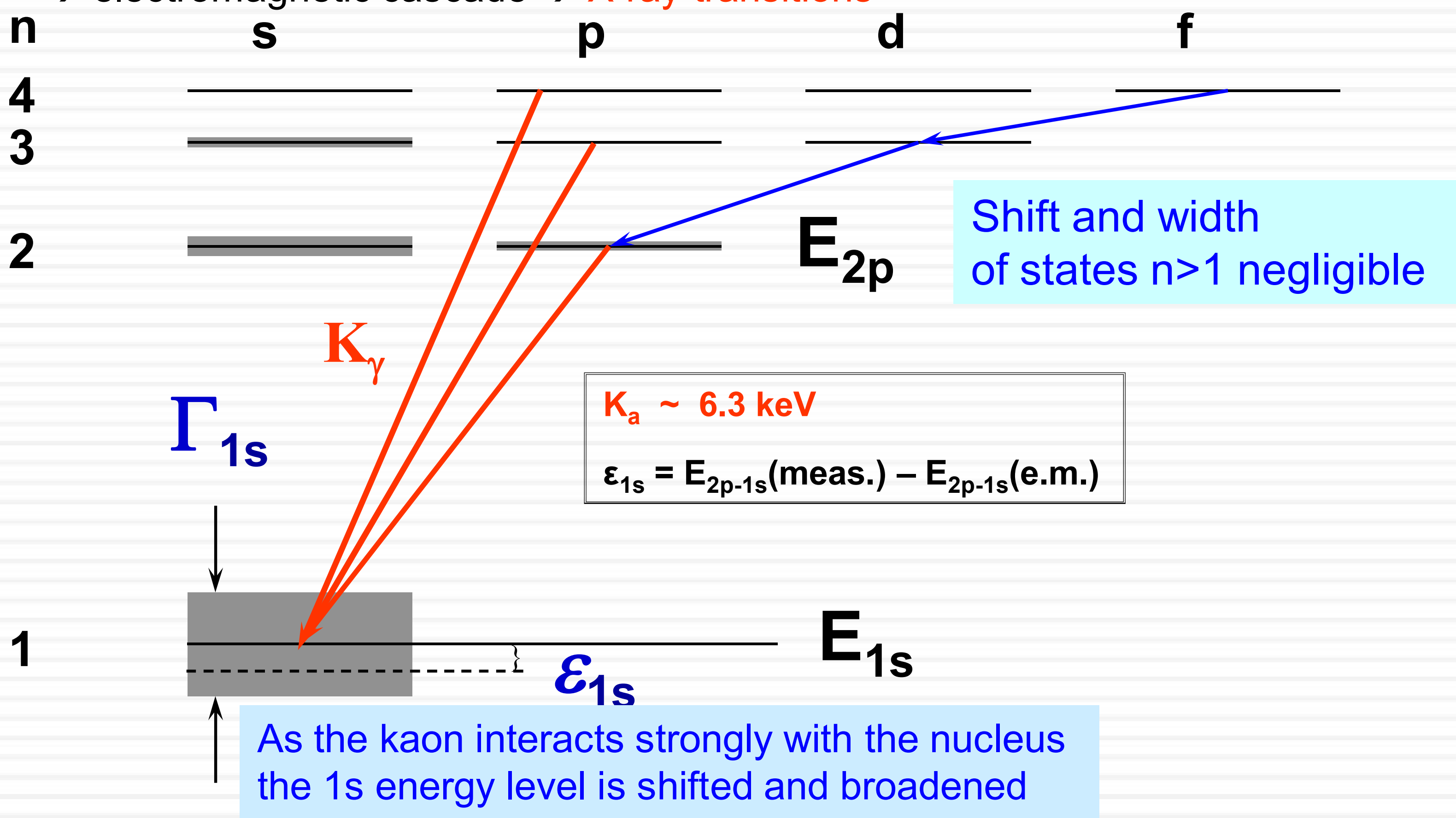
- ❖ $K^{-}p$ simplest exotic atom with strangeness
- ❖ strong interaction shift ε_{1s} and width Γ_{1s} directly observable by X-ray spectroscopy
- ❖ kaonic hydrogen „puzzle“ solved – but: precision data missing
- ❖ $K^{-}p$: Information on $\Lambda(1405)$ → kaonic nuclear clusters
- ❖ kaonic deuterium never measured before
- ❖ atomic physics: new cascade calculations to be tested → see talk given by M. Faifman at this Conference

Kaonic Hydrogen - Goals

- **Measurement of strong interaction shift and width of kaonic hydrogen and kaonic deuterium at the highest precision**
- Determination of the isospin-dependent scattering lengths near threshold
  - no extrapolation to zero energy
- Testing chiral symmetry breaking in systems with strangeness

Experimental method

Negative kaons stopped in H_2 → initial atomic capture →
→ electromagnetic cascade → X-ray transitions



Kaonic hydrogen

With a_0, a_1 for the I=0,1 S-wave KN scattering lengths in the isospin limit ($m_d = m_u$), μ being the reduced mass of the K^-p system, and neglecting isospin-breaking corrections:

$$\varepsilon + i\frac{\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-p} = 412\, fm^{-1}\cdot eV \cdot a_{K^-p}$$

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

„By using the non-relativistic effective Lagrangian approach a complete expression for the isospin-breaking corrections can be obtained; in leading order parameter-free modified Deser-type relations exist and can be used to extract scattering lengths from kaonic atom data“ (Meißner, Raha, Rusetsky, 2004)

$$\epsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_p\{1 - 2\alpha\mu_c(\ln\alpha - 1)a_p\}$$

Kaonic deuterium

For the determination of the isospin dependent scattering lengths a_0 and a_1 the hadronic shift and width of kaonic hydrogen *and* kaonic deuterium are necessary

Theoretical procedures are needed to connect the observables with the isospin-dependent scattering lengths

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

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

Impulse approximation term

$$a_{K^-d} = \frac{4\left[m_N + m_K\right]}{\left[2m_N + m_K\right]} \cdot a^{(0)} + C$$

$$a^{(0)} = \frac{1}{2}\left[a_{K^-p} + a_{K^-n}\right] = \frac{1}{4}\left[a_0 + 3a_1\right]$$

K^-p and K^-d atom properties

K^-p (K^-d) e.m. bound kaonic atoms
Bohr radius ~80 fm, binding energy ~9 keV

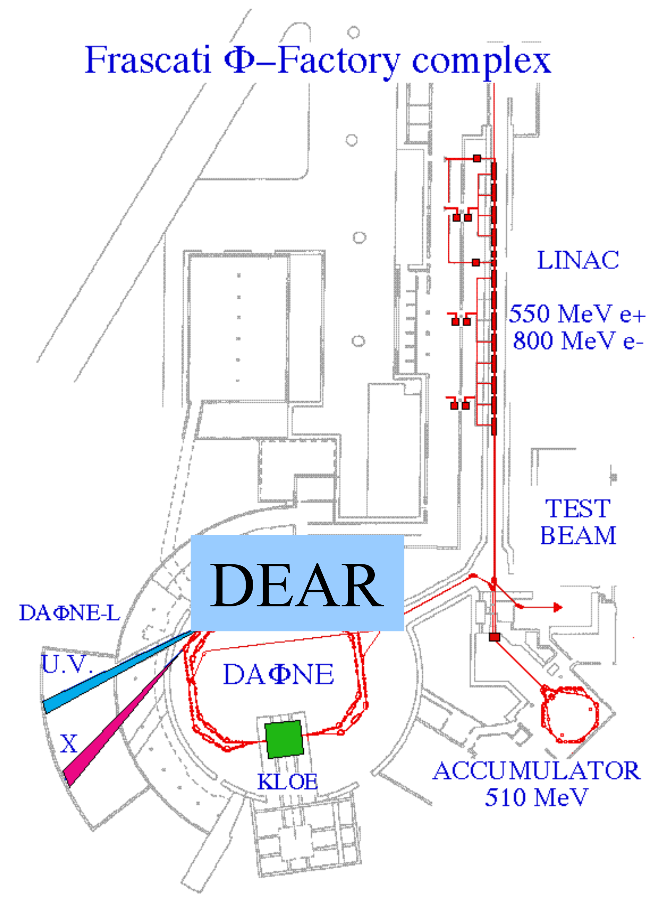
Kaonic atom	e.m. position of K_α line (eV)	ε (eV)	Γ (eV)	X-ray Yield
hydrogen	6480	≈ 200	≈ 250	~1-3 %
deuterium	7810	≈ 325*	≈ 630*	~0.2 %

*) A.N. Ivanov, M. Cargnelli, M. Faber, H. Fuhrmann, V.A. Ivanova, J. Marton, N.I. Troitskaya, J. Zmeskal, Eur.Phys.J. A 23 (2005) 79

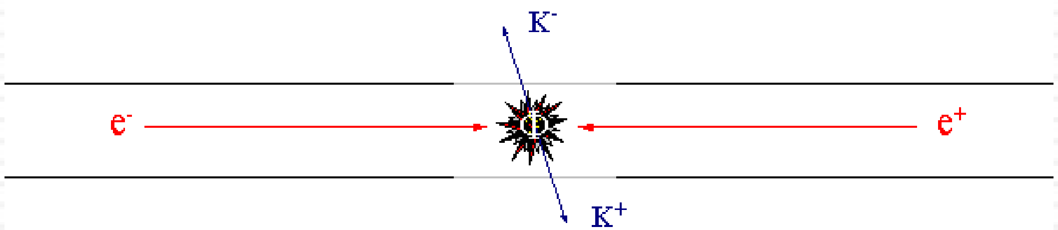
Kaonic Atoms @ DAΦNE: DEAR

DEAR
eXperiment
DAΦNE EXOTIC ATOMS RESEARCH

DAΦNE (LN Frascati)



electron – positron collider
collision energy tuned
to the Φ resonance
at 1.02 GeV c.m.

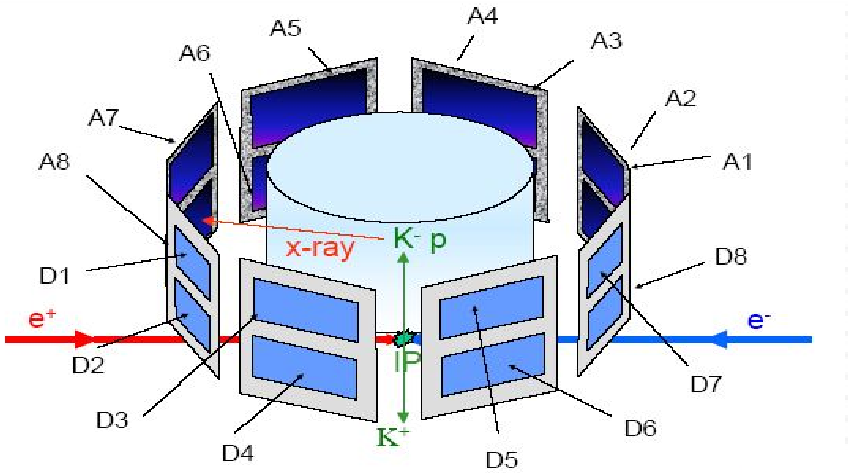


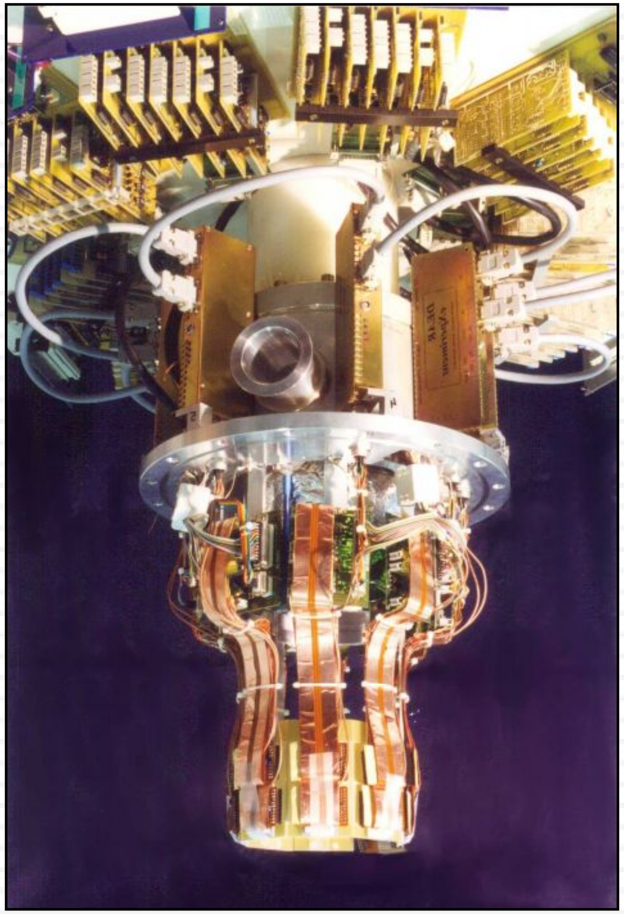
Setup at DAΦNE

X-ray detection by CCDs

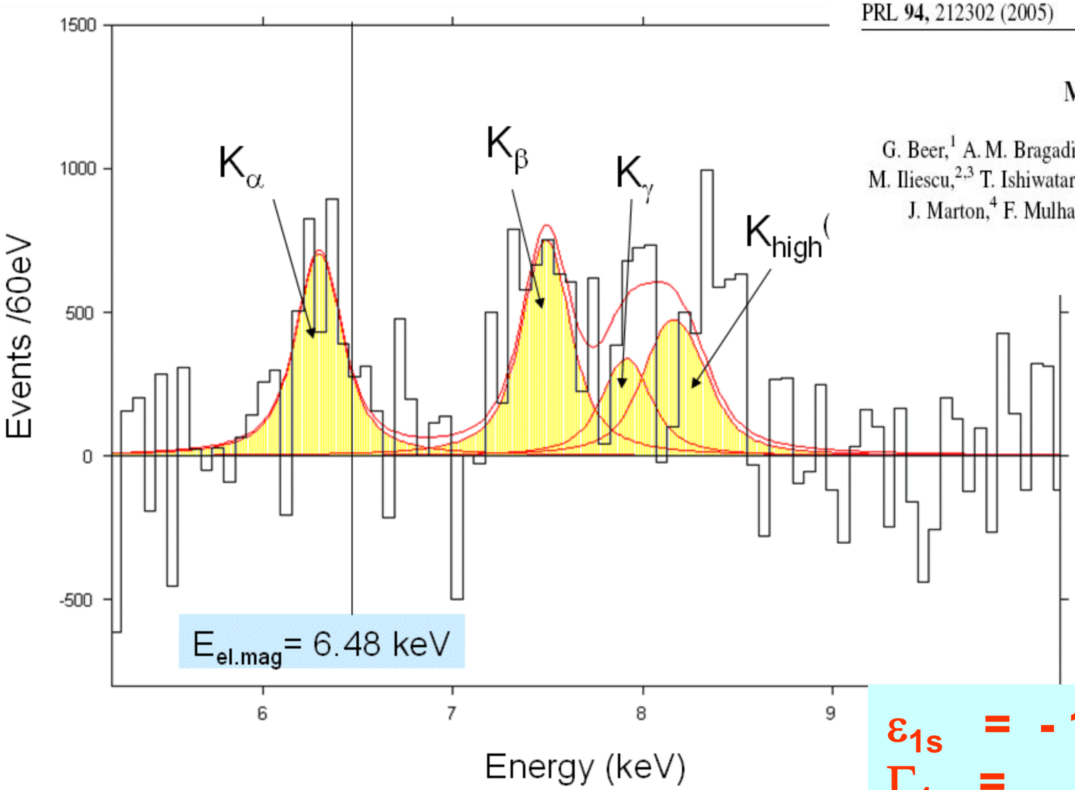
Array of 16 CCD55-30

-1242 x 1152 pixels / chip
- pixel size 22.5 x 22.5 μm
- total area per chip 7.24 cm^2
- depletion depth ~30 μm
- read-out time per CCD 2 min.
- energy resolution ~150 eV @ 6keV
- temperature stabilized at 165 K





Resulting $K^{-}p$ X-ray Spectrum



PRL 94, 212302 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

Measurement of the Kaonic Hydrogen X-Ray Spectrum

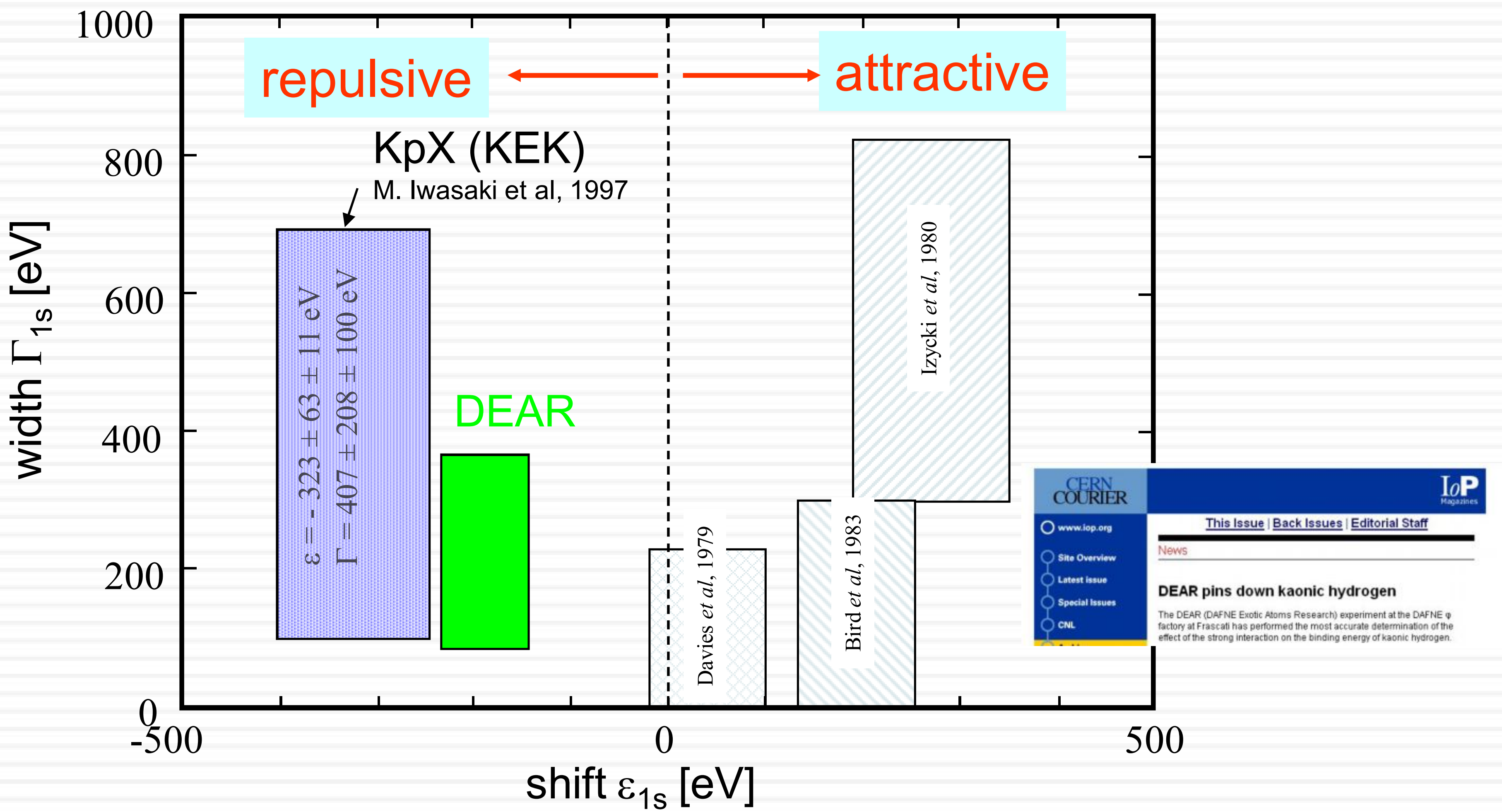
G. Beer,[1] A. M. Bragadireanu,[2,3] M. Cargnelli,[4] C. Curceanu-Petrascu,[2] J.-P. Egger,[5] H. Fuhrmann,[4] C. Guaraldo,[2] M. Iliescu,[2,3] T. Ishiwatari,[4] K. Itahashi,[6] M. Iwasaki,[6] P. Kienle,[4,7] T. Koike,[6] B. Lauss,[8] V. Lucherini,[2] L. Ludhova,[9] J. Marton,[4] F. Mulhauser,[9] T. Ponta,[3] L. A. Schaller,[9] R. Seki,[10,11] D. L. Sirghi,[2,3] F. Sirghi,[2] and J. Zmeskal[4]

(DEAR Collaboration)

ε_{1s} = - 193 ± 37 (stat.) ± 6 (syst.) eV

Γ_{1s} = 249 ± 111 (stat.) ± 30 (syst.) eV

DEAR Results



DEAR – Comparison with theory

B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 94, 213401 (2005)

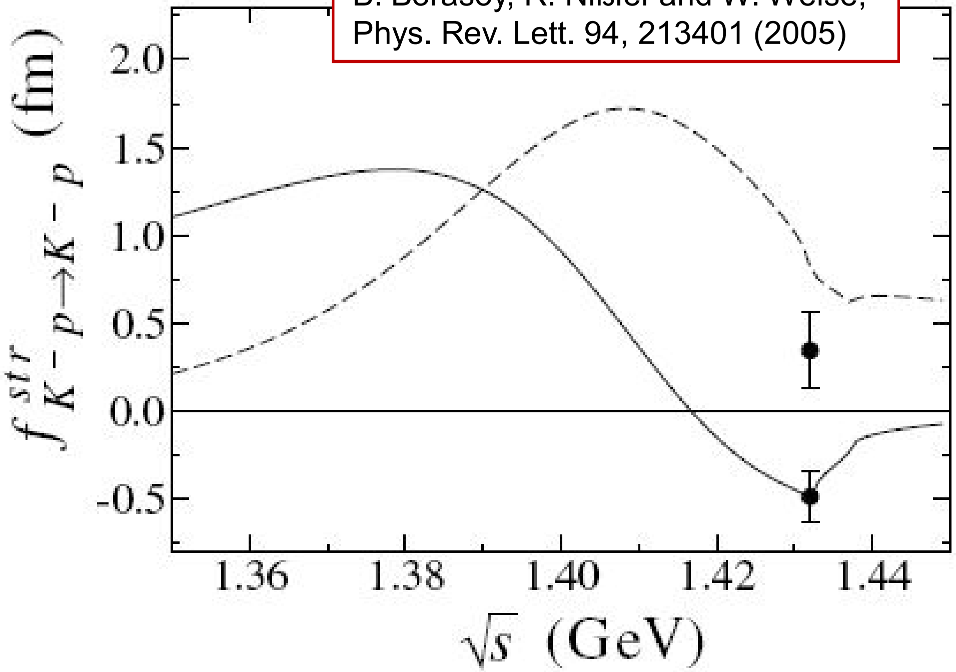


FIG. 1. Real (solid line) and the imaginary part (dashed line) of the strong $K^- p \to K^- p$ amplitude, $f^{\rm str}_{K^- p \to K^- p}$, as defined in the text. The data points represent the real and imaginary parts of the $K^- p$ scattering length, derived from the DEAR experiment [1] with inclusion of isospin breaking corrections according to Ref. [18].

A.N. Ivanov et al.,
Eur. Phys. J. A21 (2004) 11
J. Phys. G 31 (2005) 769
Eur. Phys. J. A25 (2005) 329

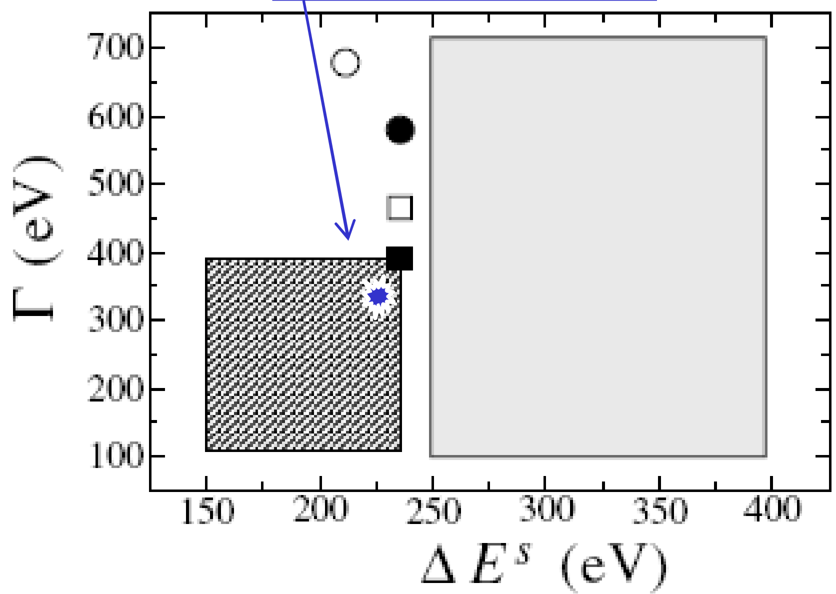


FIG. 4. Results for the strong-interaction shift and width of kaonic hydrogen from our approach, both by using the Deser-Trueman formula [28] (empty circle) and by including isospin breaking corrections [18] (full circle). The DEAR data are represented by the shaded box [1], and the KEK data by the light gray box [20]. The fit restricted to the DEAR data is represented by the small full rectangle (empty rectangle without isospin breaking corrections).

Conclusion

Precision data are urgently needed

From DEAR to SIDDHARTA

- Precision of the DEAR result limited by high soft X-ray background (S/N ~ 1:70)

- Next step: background reduction by using
  kaon – X-ray time correlation
  (S/N ~ 10:1 for kaonic hydrogen)

→ New X-ray detectors SDDs: JRA in I3HP (EU FP6)
in cooperation with LNF, MPG, PNSensor, Politecnico Milan, IFIN-HH
and new dedicated target-detector set-up

International Conference on Muon Catalyzed Fusion 2007

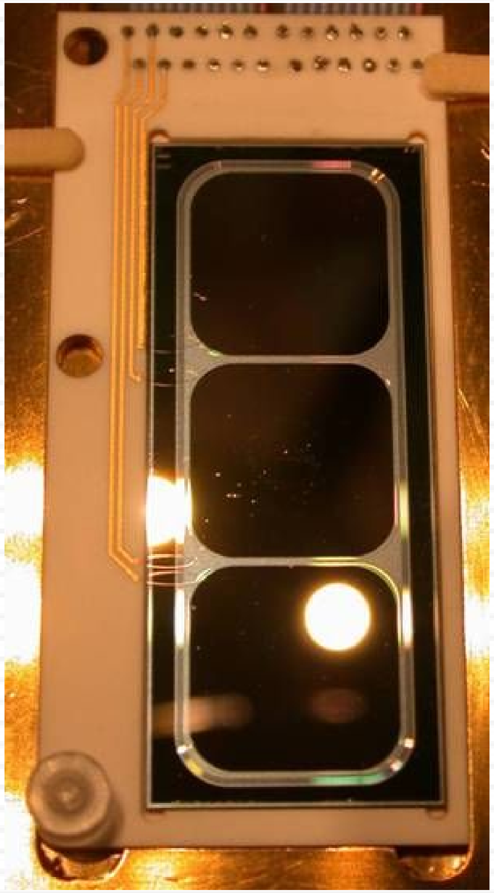
SIDDHARTA @ LNF

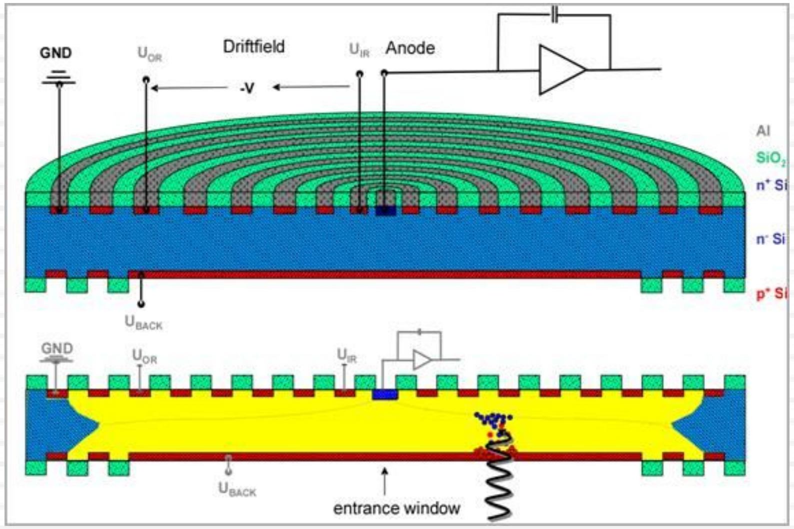
Silicon Drift Detectors for Hadronic Atom Research by Timing Application

Work supported by I3 HadronPhysics

Contract No. RII3-CT-2004-506078

Silicon Drift Detector SDD



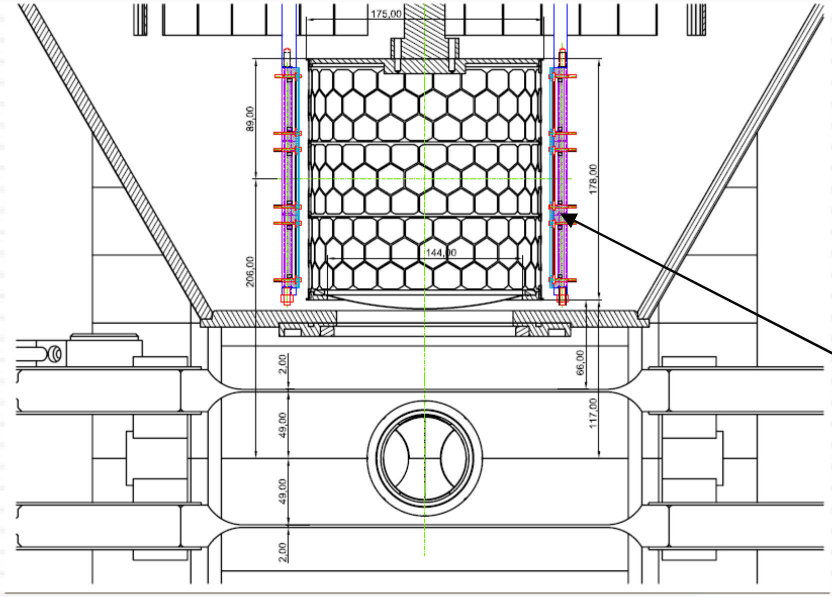


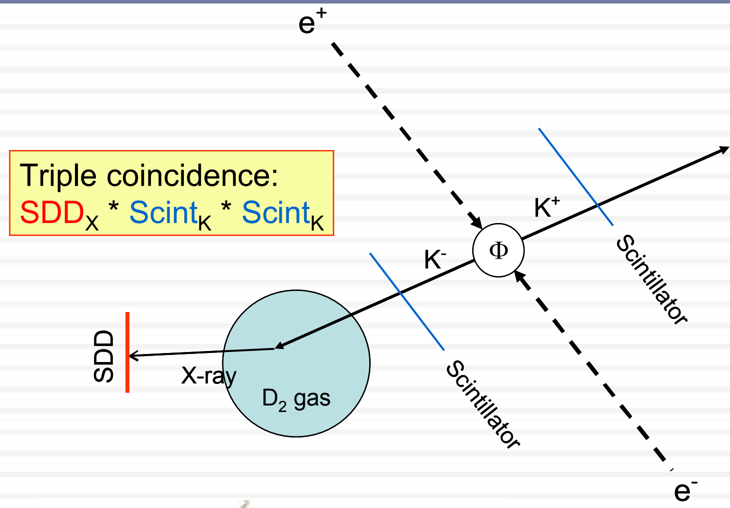
- SDD has small capacitance → low noise
- Good energy resolution - comparable with CCD
- But most important: timing capability

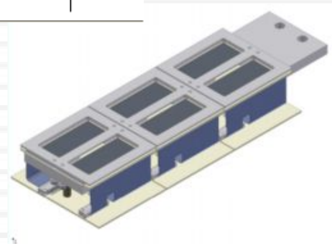
Large area SDD with 1 cm^2 active area
3 SDDs on 1 chip

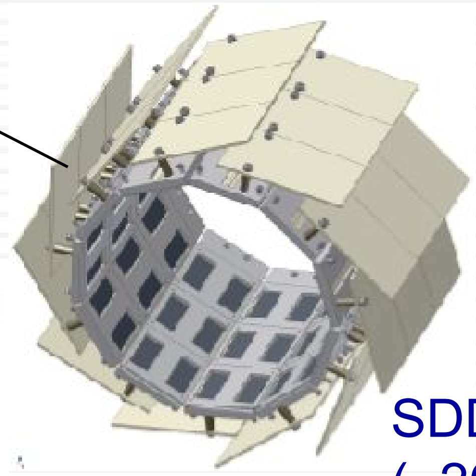
SIDDHARTA Setup

Cryogenic setup





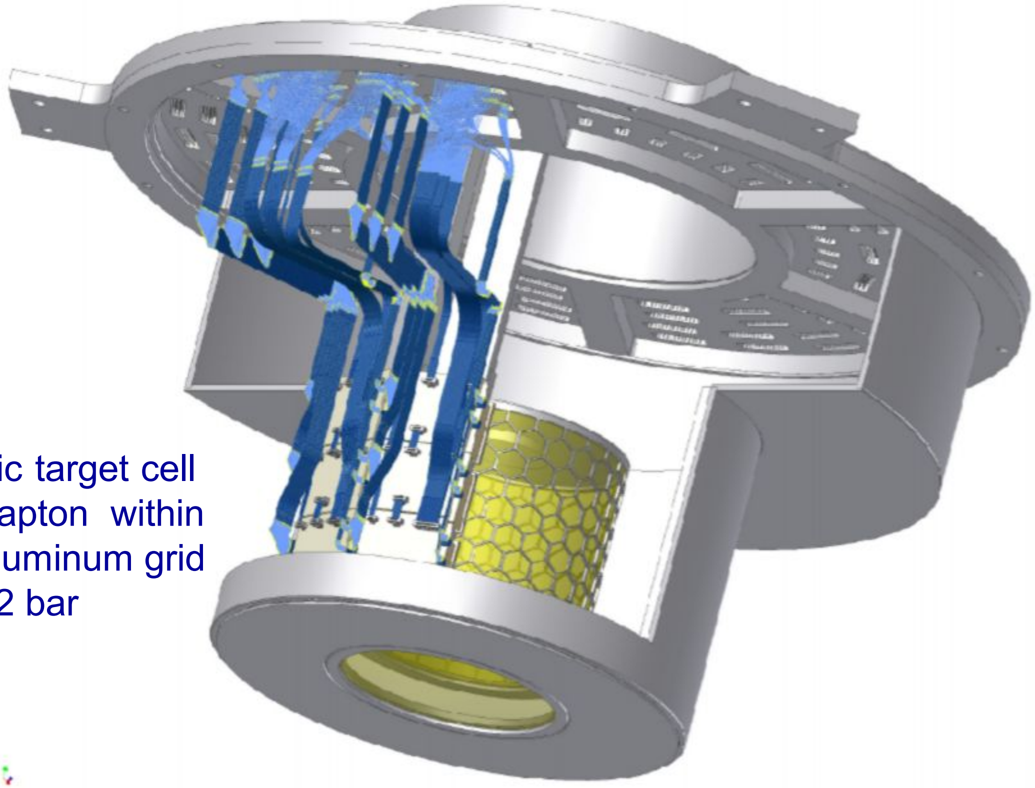




SDD array
(~200 SDDs)

SIDDHARTA Setup cont'd

Cryogenic target cell
50 µm Kapton within
a pure aluminum grid
$P_{work.} \sim$ 2 bar



Carefully selected structure materials analyzed by PIXE

Target cell – SDD array assembly

Cryogenic target cell

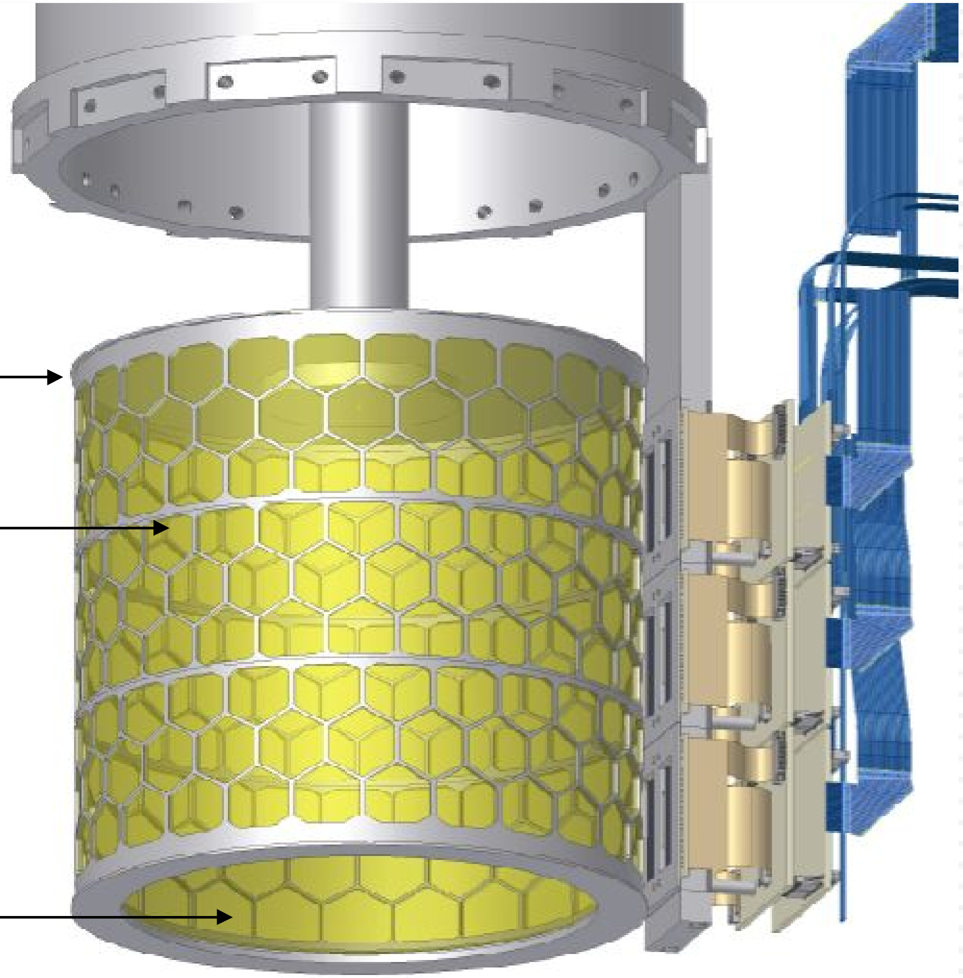
Cryogenic target cell

Temperature 22 K
Working pressure 2 bar

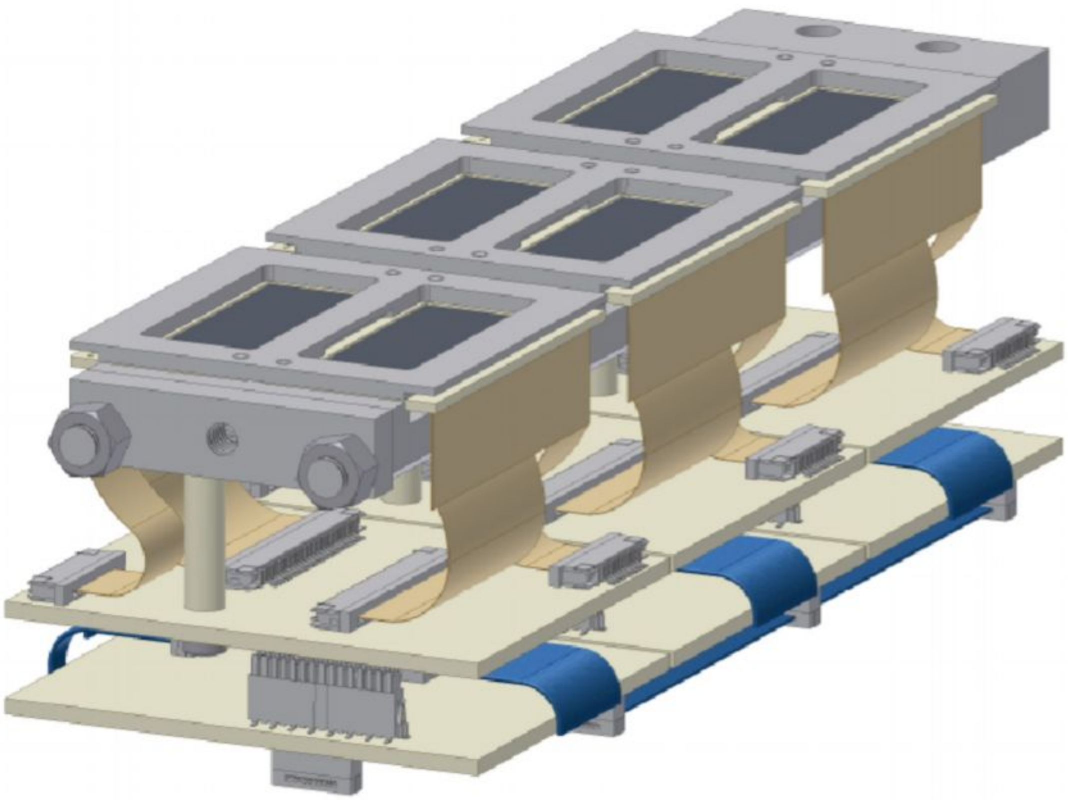
Alu-grid

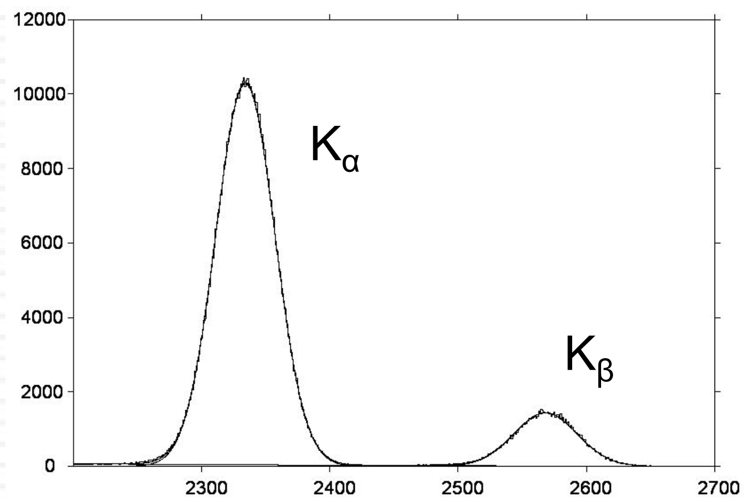
Side wall:
Kapton 50 μm

Kaon entrance
Window:
Kapton 50 μm



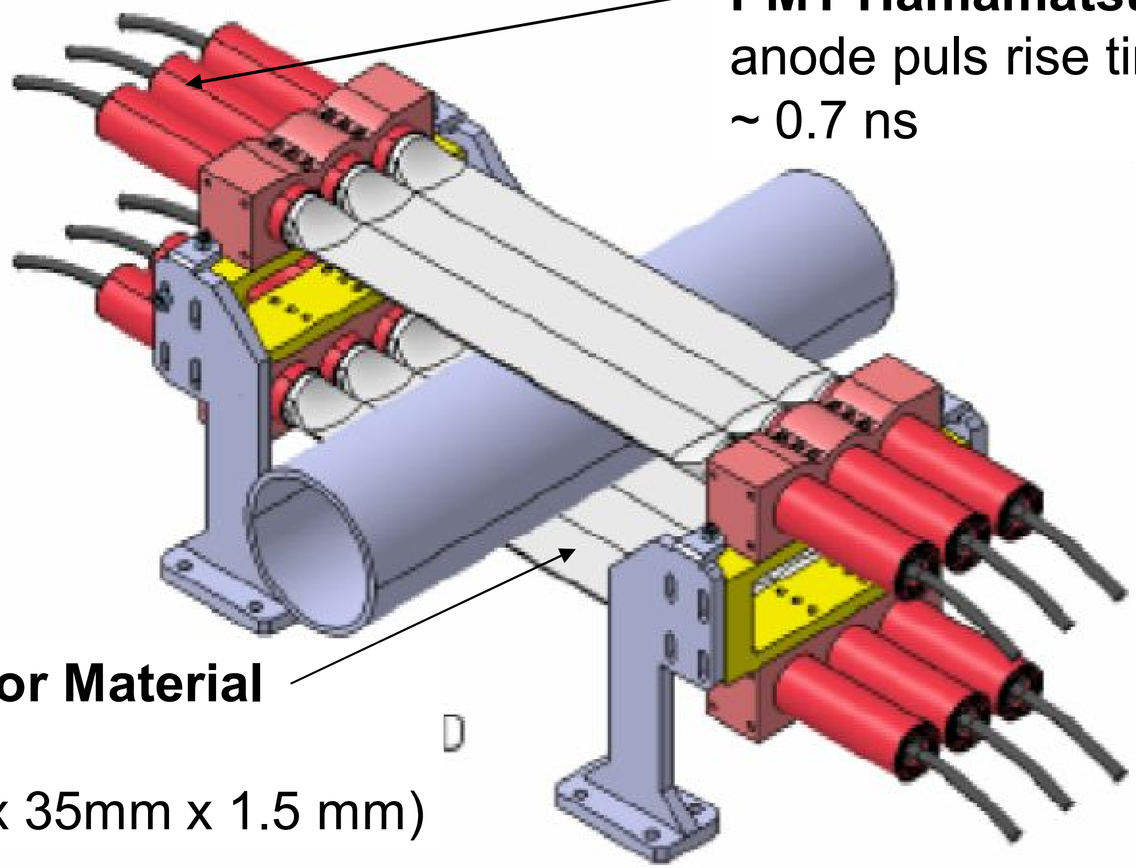
SDD unit (2x3x3 SDDs)





ΔE_{FWHM} ~ 138 eV @ 5.9 keV

Layout of the kaon trigger



PMT Hamamatsu R4998
anode puls rise time
~ 0.7 ns

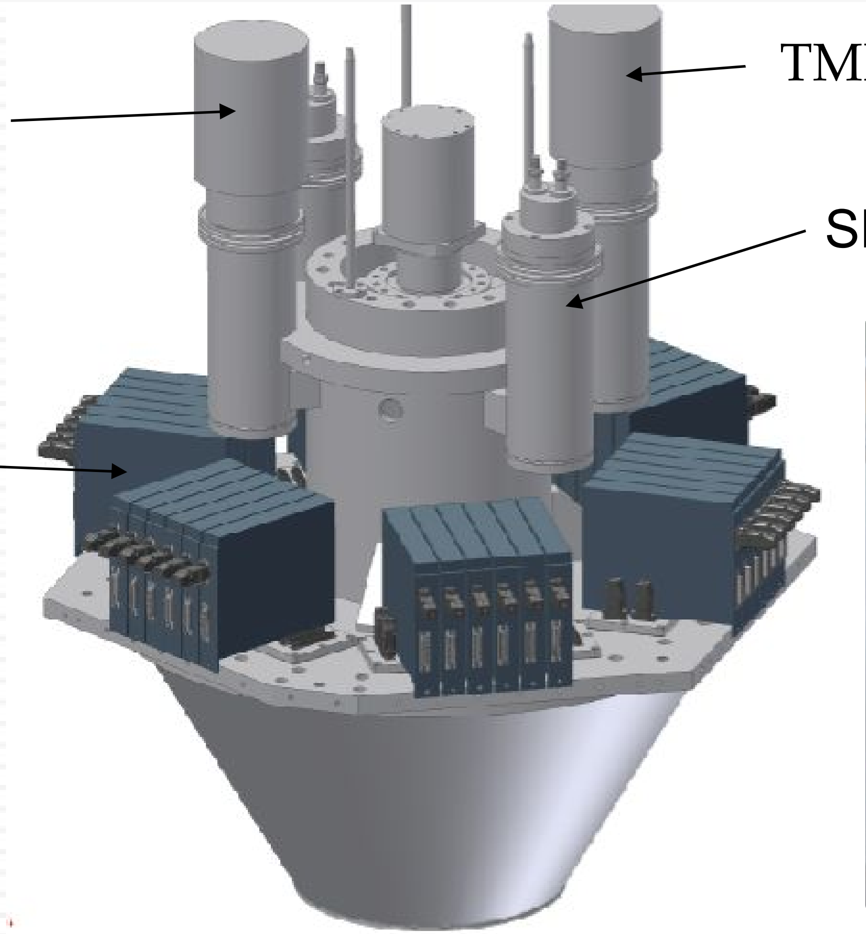
Scintillator Material
BC420
(200mm x 35mm x 1.5 mm)

SIDDHARTA apparatus

Target cooling

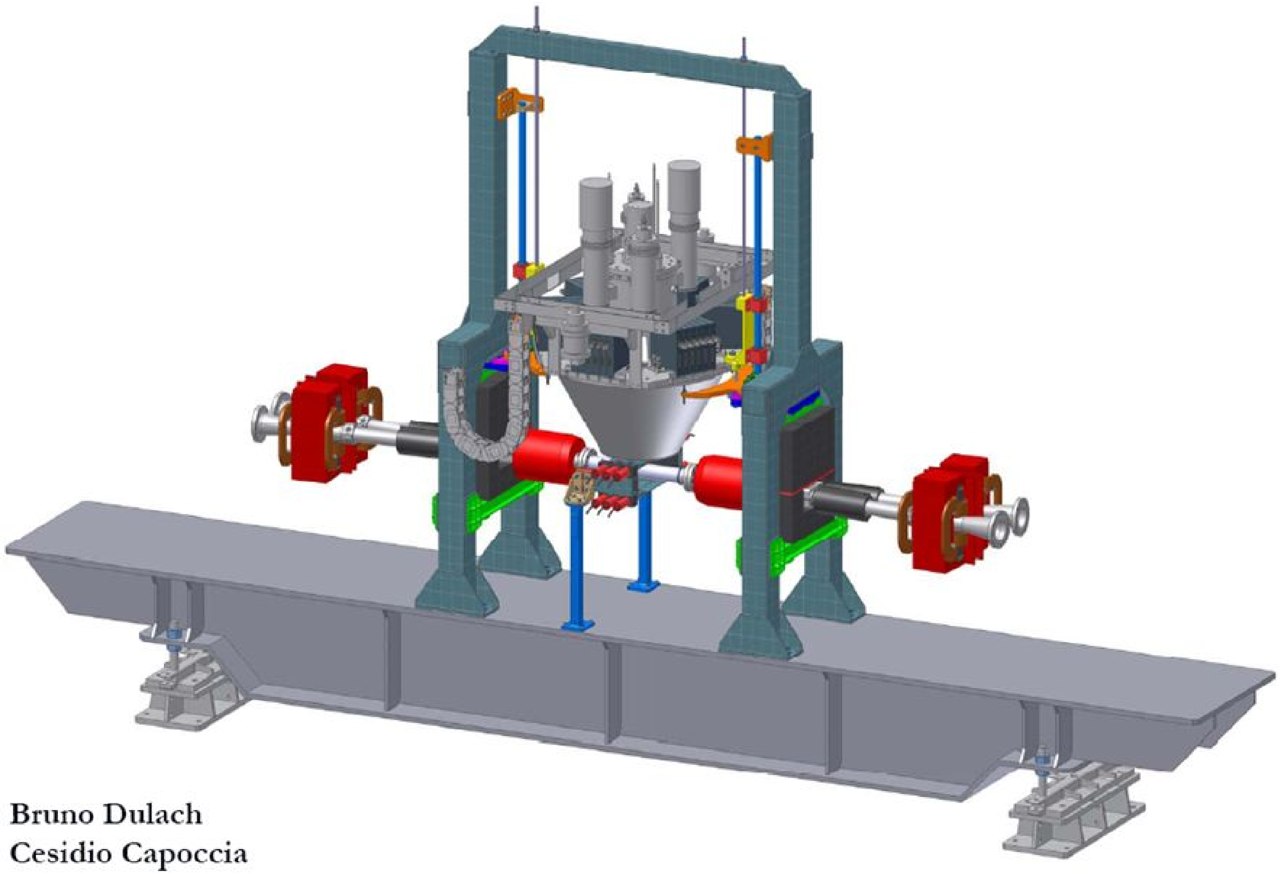
TMP

SDD cooling



HV- and voltage supply for SDDs and readout electronics

SIDDHARTA setup @ DAΦNE



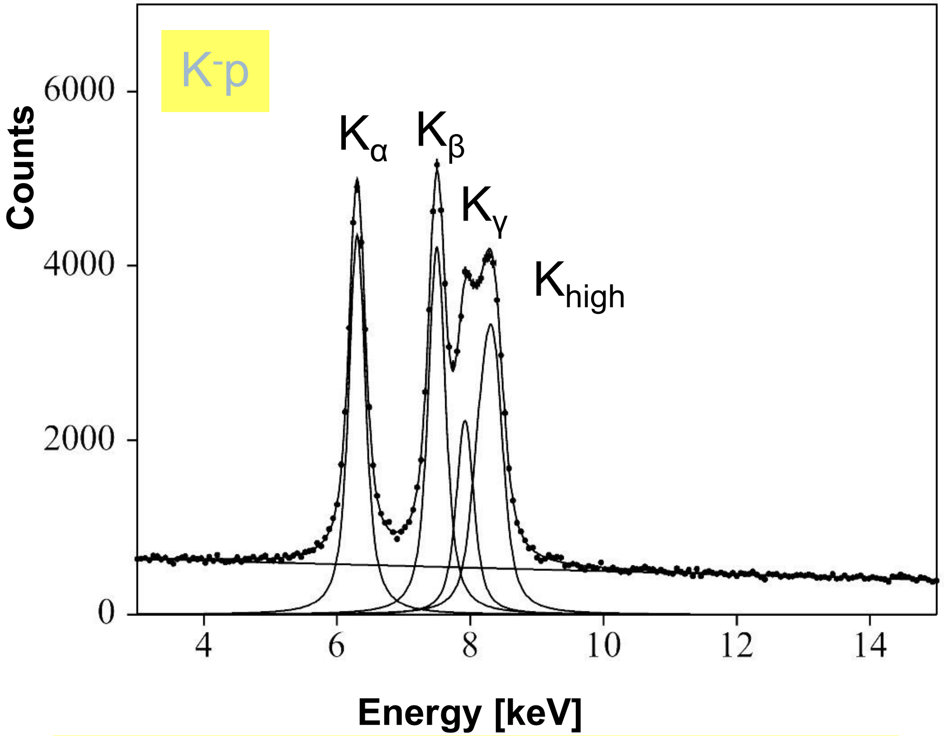
Bruno Dulach
Cesidio Capoccia

SIDDHARTA: Schedule

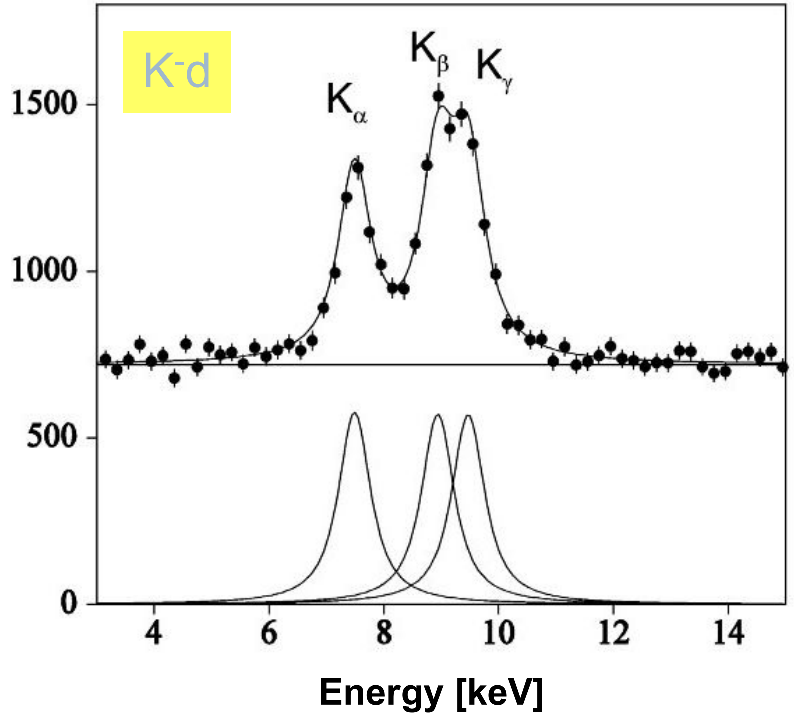
- Tuning of setup / optimization **100 pb^{-1}**
- Precision measurement of kaonic hydrogen **400 pb^{-1}**
- Measurement of kaonic deuterium **600 pb^{-1}**
- **Further options:**
  Kaonic helium studies (^3He and ^4He)

Monte Carlo Simulations

Monte Carlo simulated X-ray spectra
Measurement with SDD array and kaon trigger

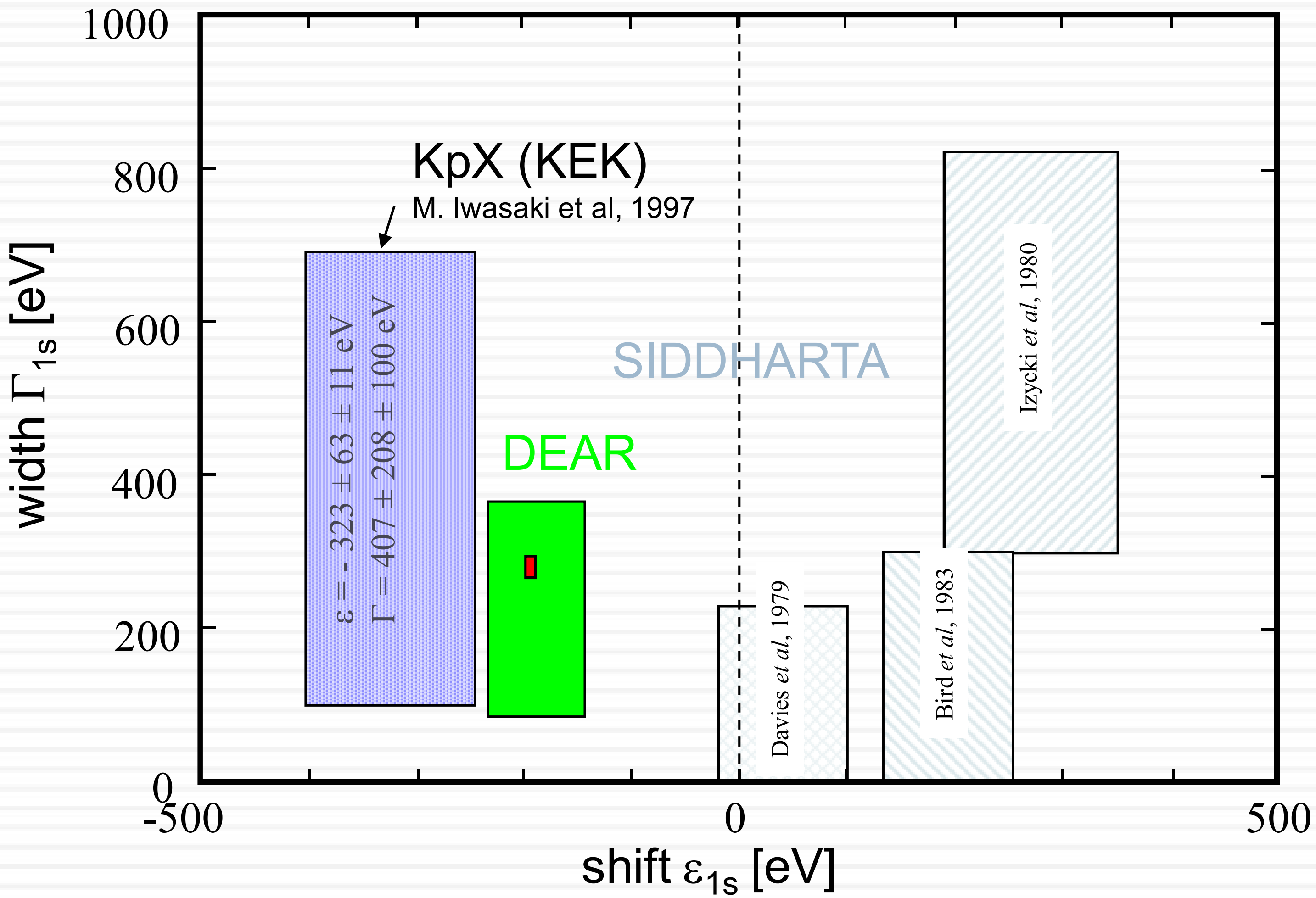


K^-p: ε_{1s} = 193 eV, Γ_{1s} = 249 eV, Y(K_α)=2%
$\Delta\ \varepsilon_{1s} \sim \pm 2$ eV, $\Gamma_{1s} \sim \pm$ 4,5 eV



K^-d: ε_{1s} = 325 eV, Γ_{1s} = 630 eV, Y(K_α)=0.2%
$\Delta\ \varepsilon_{1s} \sim \pm 15$ eV, $\Gamma_{1s} \sim \pm$ 40 eV

SIDDHARTA - Outlook

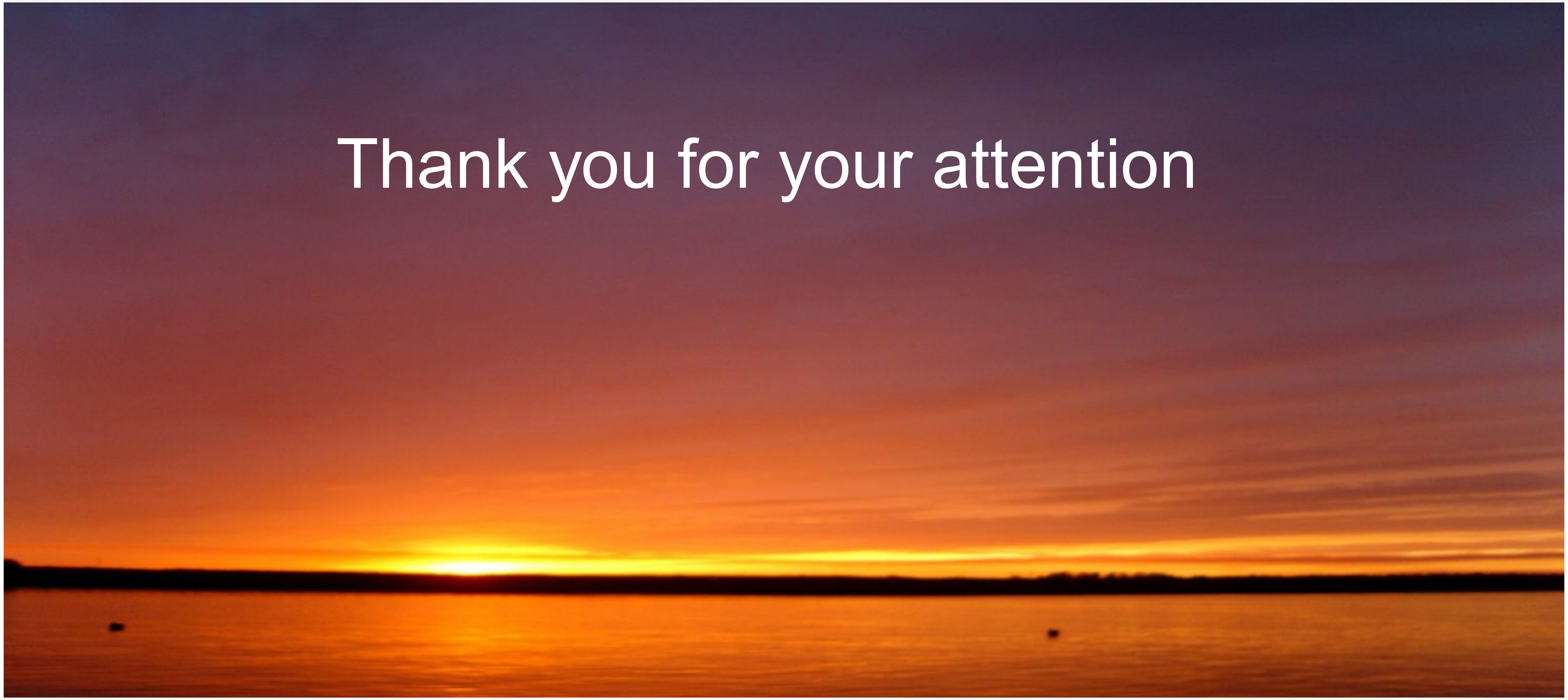


Summary

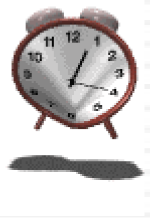
SIDDHARTA is well under way: KH, KD, …

Theoretical studies continue

DEAR finished successfully: most precise data on KH shift and width up to now


Thank you for your attention

Spare



Kaon: 60th Anniversary

1947

Discovery of the kaon (K meson). 'Strange' long lived particles discovered in cosmic ray events by Clifford Butler and George Rochester.