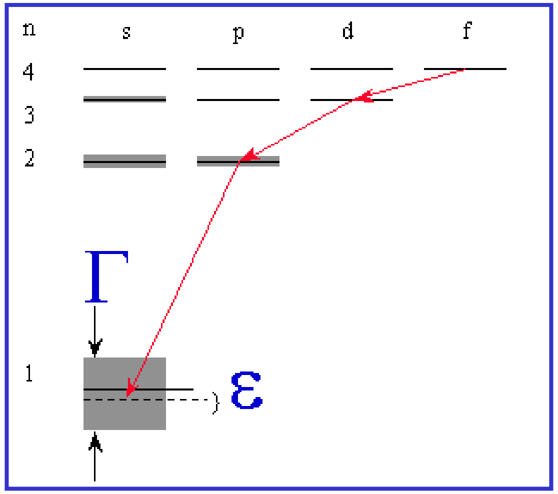
Kaonic atoms studies at DAFNE

Michael Cargnelli
Stefan Meyer Institute
Austrian Academy of Sciences, Vienna



Work supported by TARI-INFN

Contract No. RII3-CT-2004-506078

HadronPhysics I3
Study of Strongly Interacting Matter

On behalf of: The SIDDHARTA collaboration

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

POLITECNICO MILANO

MPE Garching

PNSensor Munich

Vienna

RIKEN

THE UNIVERSITY OF TOKYO

University of Victoria

IFIN-HH Bucarest

Hadronic atoms in QCD

Objects of type $(\bar{K}\ X)$, (π^-, X) with X = p, d, ^{3}He, ^{4}He,.. or even $\pi^+ \pi^-$ or π K

Bound electromagnetically, binding well known
Strong interaction (mediated by QCD) $\rightarrow$ modify binding
$\rightarrow$ decay of object

in some cases: small perturbation
$\rightarrow$ energy shift and width can be related to T-matrix elements at threshold
(Deser type formulas)
compare to results from low energy scattering experiments[2]

Low energy phenomena in strong interaction can not (yet?) be described in terms of quarks and gluons, instead effective theories are used (they have some degrees of freedom to accomodate experimental data)

[1] Deser relation in some cases not sufficient to compare to high precision experimental data
[2] Problems: extrapolation to E=0 and quality of old experimental data

QCD predictions

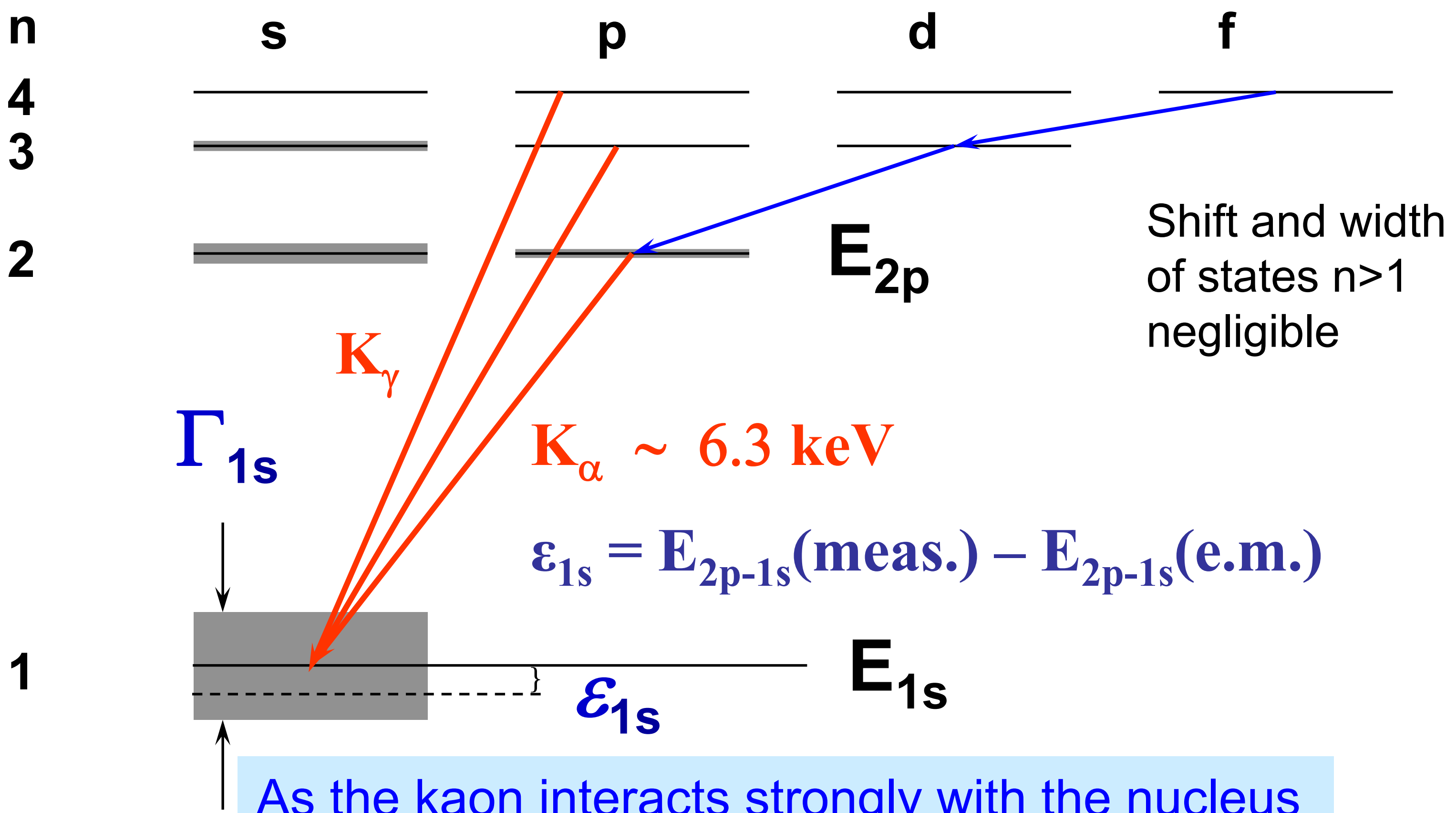
Chiral perturbation theory was extremely successful in describing systems like πH, but *can not be used for KH*. Main reason is the presence of the $\Lambda(1405)$ resonance only 25 MeV below threshold.

Effective field theory ↔ scattering data
Effective field theory ↔ atomic X ray data
Effective field theory ↔ energy, width of resonances

There exist non-perturbative coupled channel techniques which are able to generate the $\Lambda(1405)$ dynamically as a Kbar N quasibound state and as a resonance in the $\pi\ \Sigma$ channel

Kaonic hydrogen: formation, level transitions

Negative kaons stopped in H_2 → initial atomic capture (n ~ 25) → → electromagnetic cascade → X-ray transitions



As the kaon interacts strongly with the nucleus the 1s energy level is shifted and broadened

Note: radiationless transitions: KH(n,l) + H → KH(n',l') + H + E_{kin}
Doppler broadening is a correction in the πH case where the width ~1 eV, in KH width= 200-400 eV

Kaonic hydrogen – Deser formula

With a_0, a_1 standing for the I=0,1 S-wave $\bar{K}N$ 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, the relation reads:

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

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

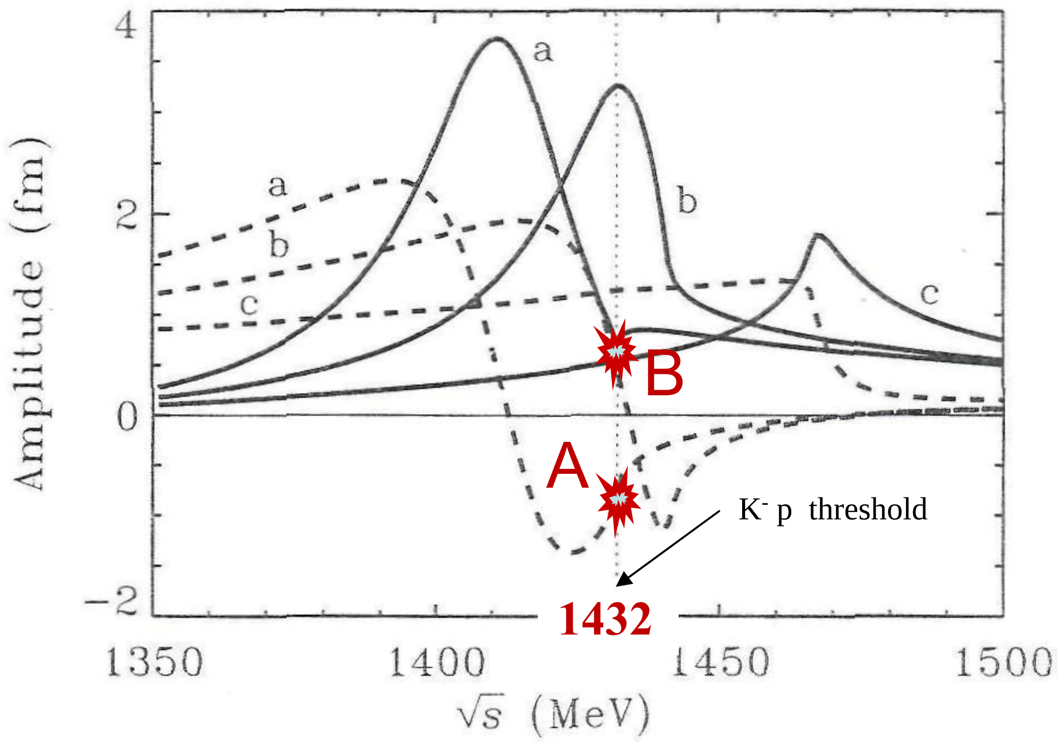
… a linear combination of the isospin scattering lengths a_0 and a_1
to disentangle them, also the kaonic deuterium scattering length is needed

„By using the non-relativistic effective Lagrangian approach a complete expresson 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 lenghts from kaonic atom data“[2]

[2]Meißner,Raha,Rusetsky, 2004

Influence of the nuclear medium on the Kbar N interaction

T. Waas, N. Kaiser, W. Weise, Phys. Lett. B 365 (1996) 12



„Kbar N interaction may cause kaon nucleon clusters"

- highly controversial
- new experiments planned

In free space, at threshold,

real part of $\mathbf{a_{K^-p}} < 0$ (point A)

→ **repulsive interaction**

In nuclear matter at rather low density (~0.2 ρ_0), at threshold, point B, real $\mathbf{a_{K^-p}} > 0$

→ **attractive interaction**

Real (dashed lines) and imaginary parts (solid lines) of the K^- p scattering amplitude in nuclear matter at different values of the Fermi momentum $\boldsymbol{p_F = (3\pi^2 \rho/2)^{1/3}}$, as a function of the total c.m. energy $\sqrt{s}$

a) free space, $p_F = 0$; **b)** ~ **0.2** $\boldsymbol{\rho_0}$, p_F = 150 MeV/c; **c)** ~ **1.4** $\boldsymbol{\rho_0}$, p_F = 300 MeV/c;

$\boldsymbol{\rho_0}$ = 0.17 fm^{-3}

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 !

Elaborate procedures needed to connect the observables with the underlaying physics parameters.

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

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

Impulse approximation term

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

larger then leading term

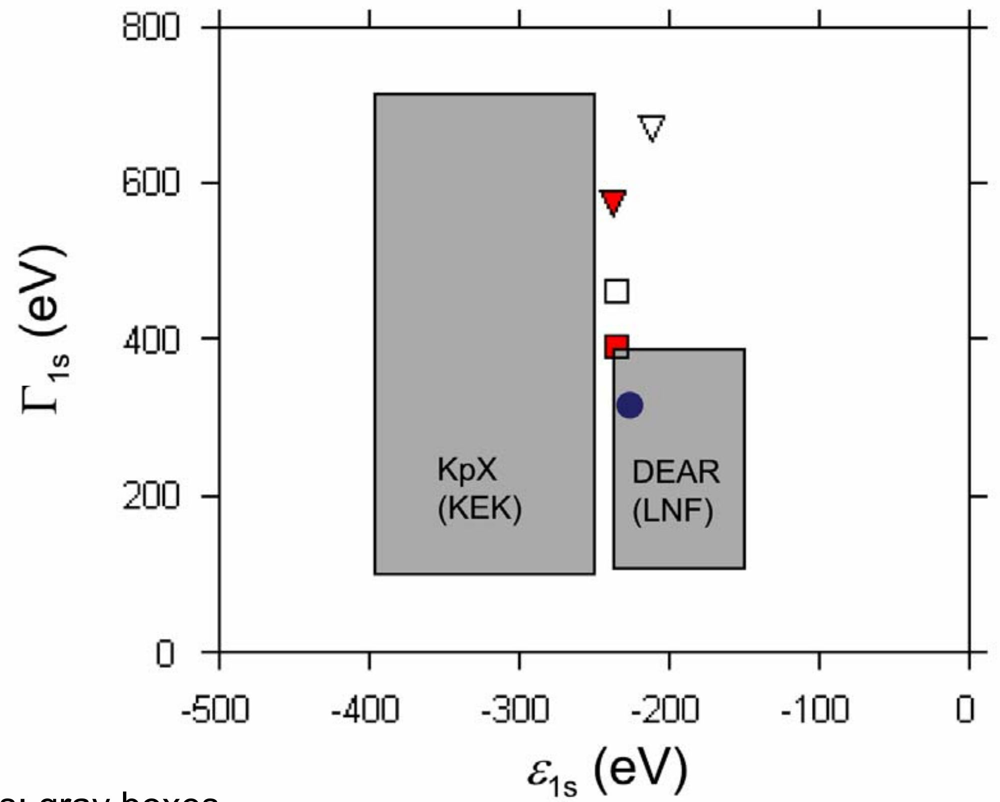
$$a^{(0)} = \frac{1}{2}\left[a_{K^-p} + a_{K^-n}\right] = \frac{1}{4}[a_0 + 3a_1]$$

"To summarize, one may expect that the combined analysis of the forthcoming high-precision data from DEAR/SIDDHARTA collaboration on kaonic hydrogen and deuterium will enable one to perform a stringent test of the framework used to describe low–energy kaon deuteron scattering, as well as to extract the values of a0 and a1 with a reasonable accuracy. However, in order to do so, much theoretical work related to the systematic calculation of higher-order corrections within the non-relativistic EFT is still to be carried out." (from: Kaon-nucleon scattering lengths from kaonic deuterium, **Meißner, Raha, Rusetsky, 2006,** arXiv:nucl-th/0603029)

Summary of physics framework and motivation

- Exotic (kaonic) atoms – probes for strong interaction
  - hadronic shift ε_{1s} and width Γ_{1s} directly observable
  - experimental study of low energy QCD. Testing chiral symmetry breaking in strangeness systems
- Kaonic hydrogen
  - Kp simplest exotic atom with strangeness
  - kaonic hydrogen „puzzle“ solved – but: precision data missing
  - kaonic deuterium never measured before
  - atomic physics: new cascade calculations (to be tested !)
- Information on Λ(1405) sub-threshold resonance
  - responsible for repulsive interaction at threshold
  - important for research on deeply bound kaonic states
    present / upcoming experiments (KEK,GSI,DAFNE,J-PARC)
- Determination of the isospin dependent KN scattering lengths
  - no extrapolation to zero energy

K^-p shift and width: experiments and theory



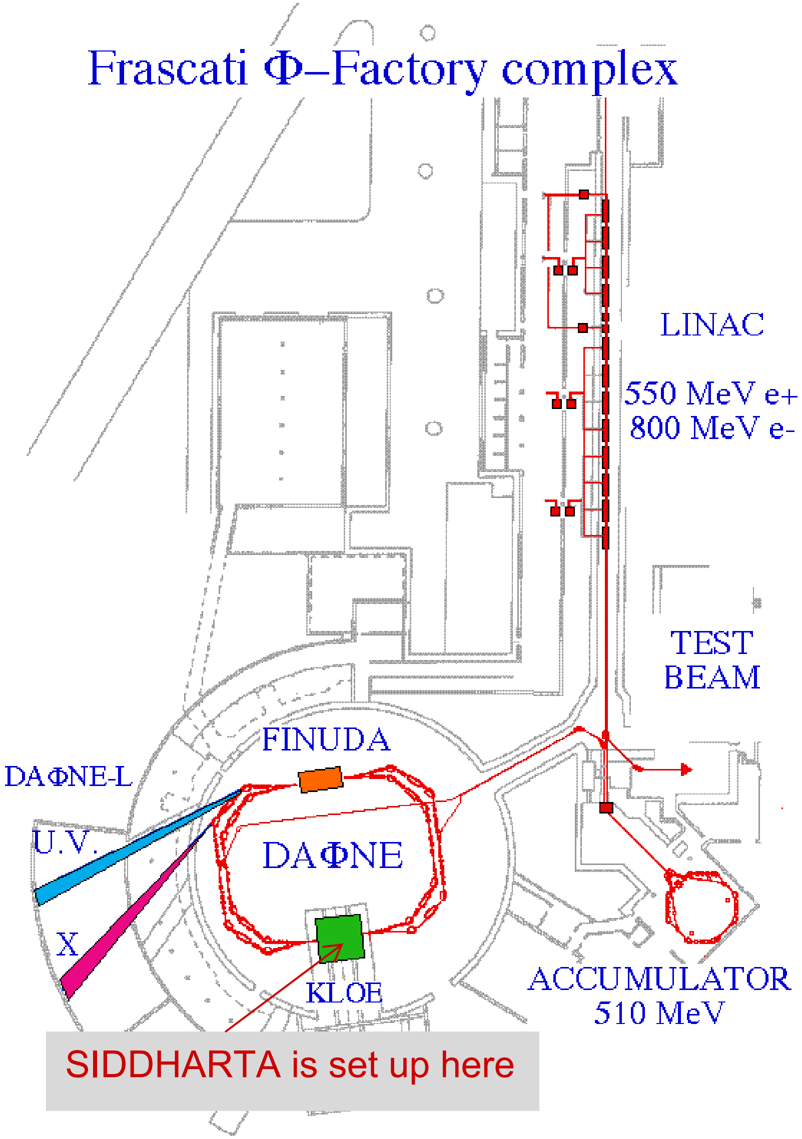
experimantal results: gray boxes,

- ▽ value in [a] if the authors apply the Deser formula on scattering lengths derived from a fit using scattering data, branching ratios, the $\pi\,\Sigma$ mass spectrum and the kaonic atom data from DEAR.
- ▼ value in [a] when they include isospin breaking corrections.
- □ ■ their fit restricted to DEAR data
- ● result from [b]

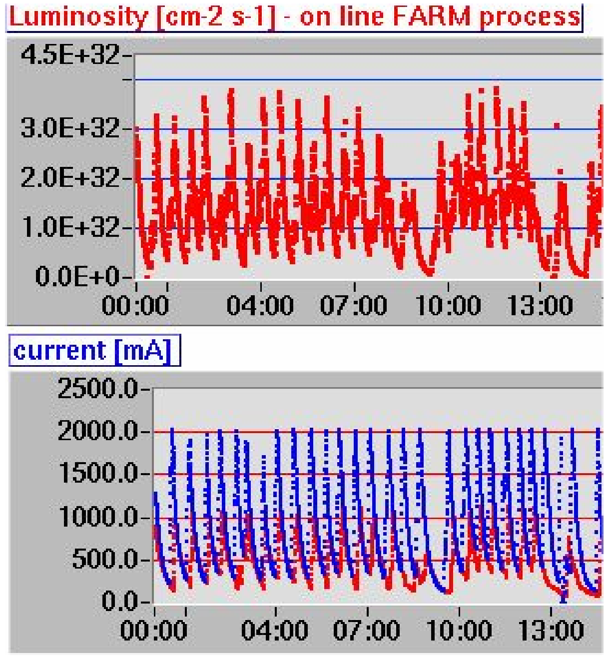
[a] B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 94, 213401 (2005)

[b] A.N. Ivanov et al., Eur. Phys. J. A21 (2004) 11, J. Phys. G 31 (2005) 769

DAΦNE



electron-positron collider, energy at phi resonance.
phi produced nearly at rest.
(boost: 55 mrad crossing angle)
charged kaons from phi decay: E_k ~ 16 MeV
degrade to < 4MeV to stop in gas target.



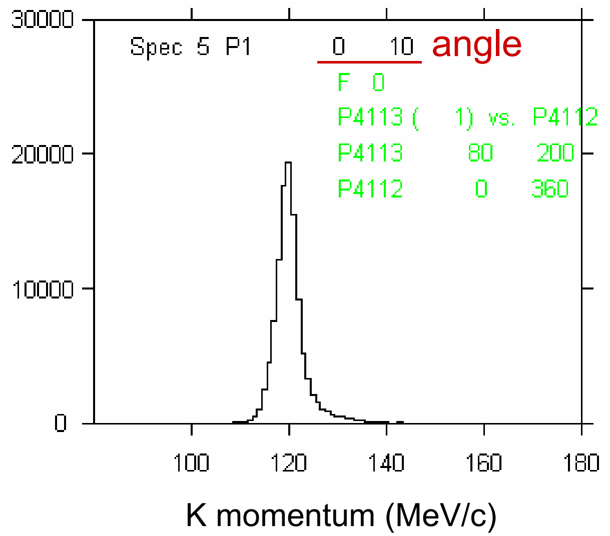
Φ production cross section ~ 3000 nb (loss-corrected)
Integr. luminosity currently **~ 6 pb^{-1} per day**[1)] (~10^7 $K^{\pm}$)
(DAFNE working in crabbed waist scheme)
Peak luminosity ~ 3 × 10^{32} cm^{-2} s^{-1} = 450 Hz $K^{\pm}$

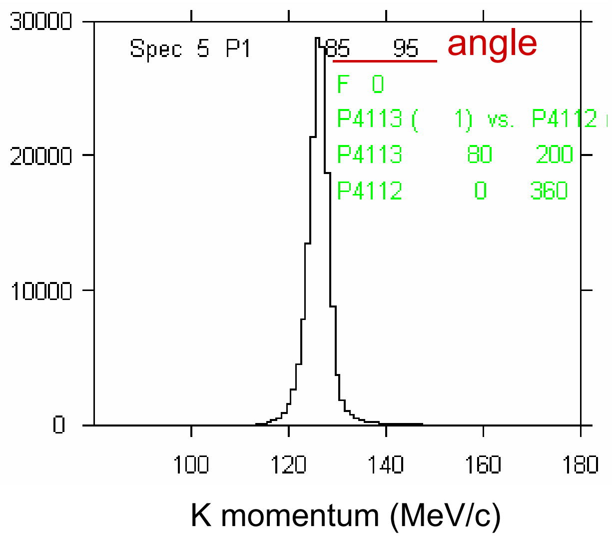
compare situation during DEAR data taking **(2002)**
currents ~ 1200/800 ~ 1 pb^{-1} per day, peak ~ 3×10^{31} cm^{-2} s^{-1}

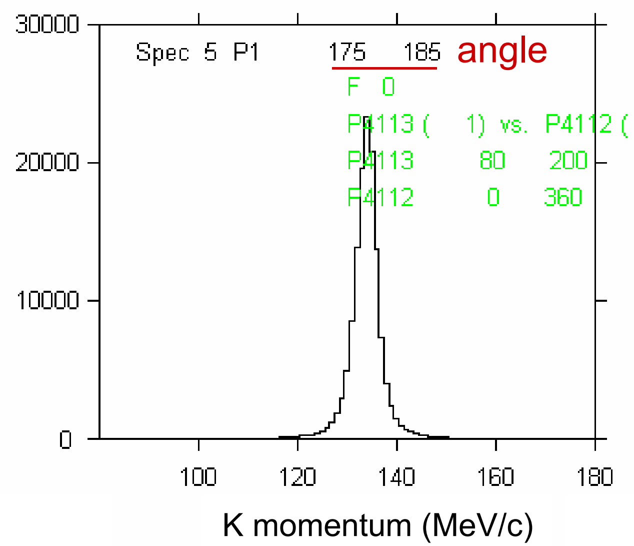
[1)] total luminosity 3 times higher, but we can use only kaons produced between injections.

KLOE data analyzed within the AMADEUS project

Kaon momentum - at the Φ vertex







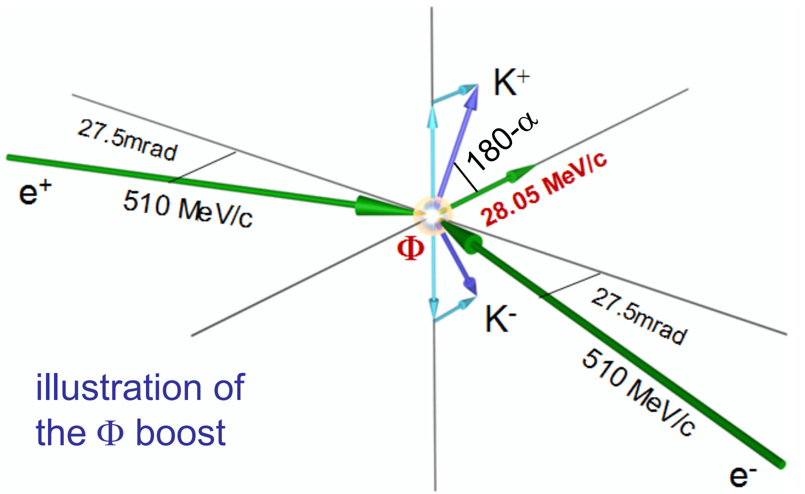
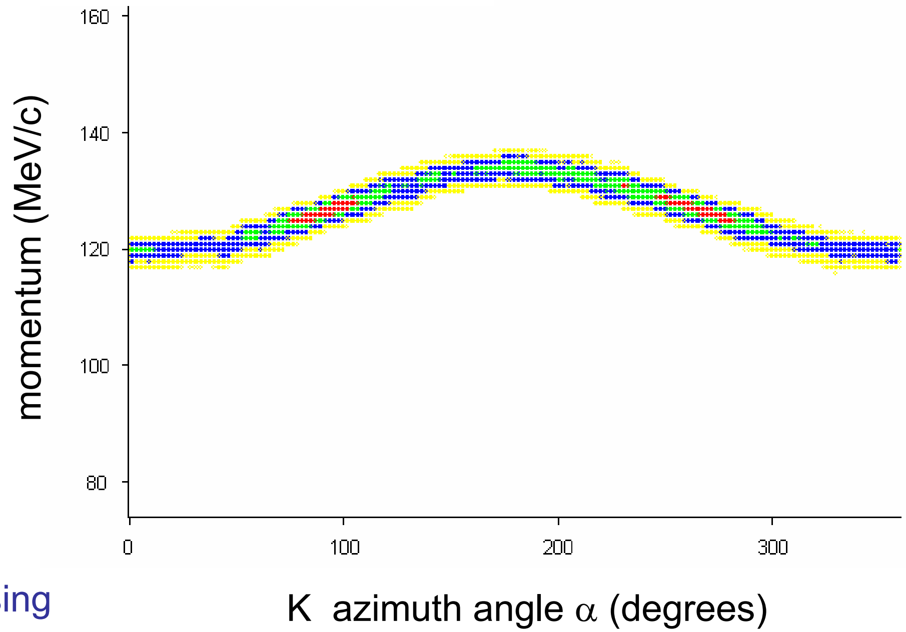
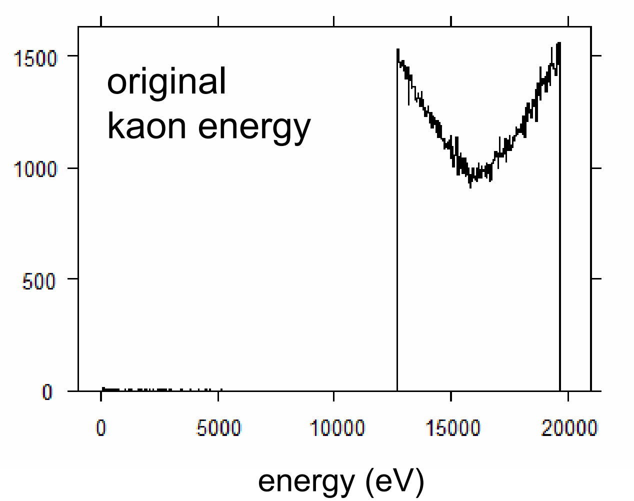


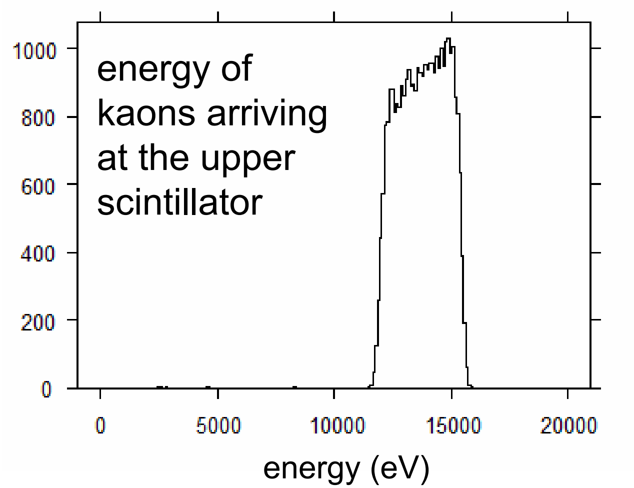
illustration of
the Φ boost



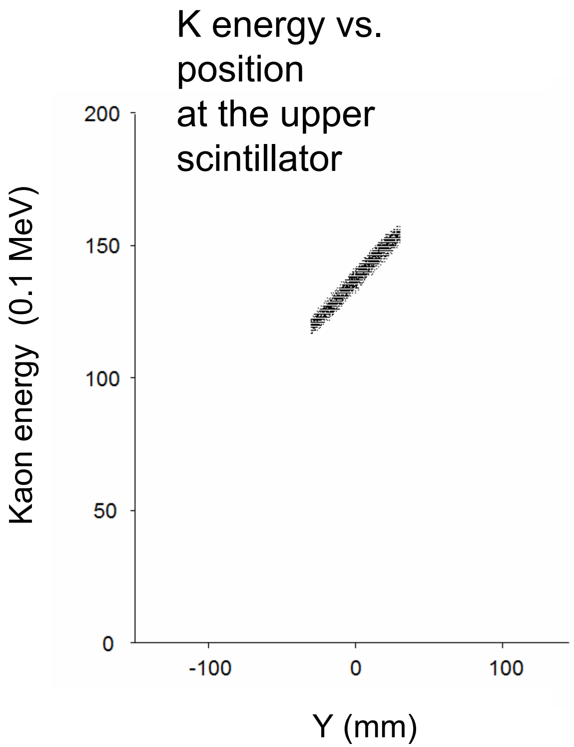
note: dafne was then operated at 30 mrad crossing angel (now: 55 mrad)

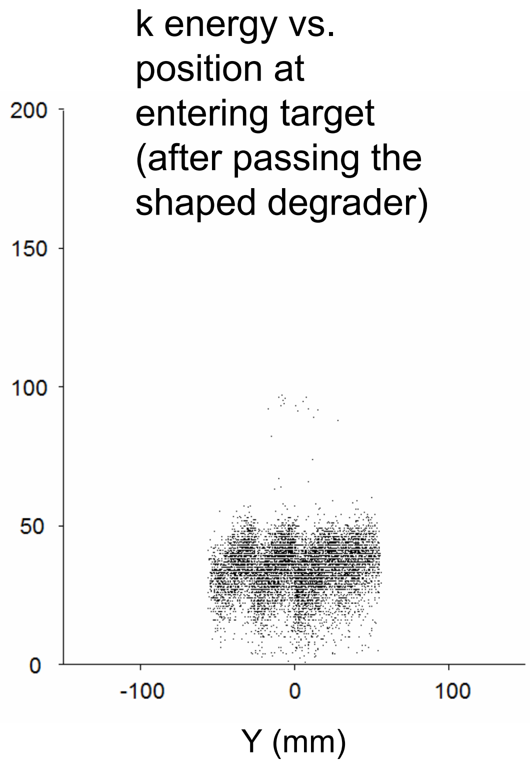
Simulation of kaon stopping

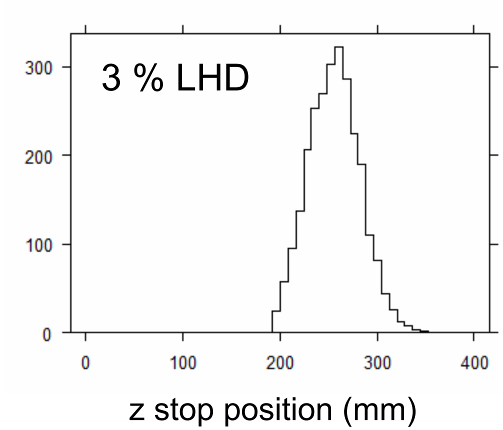


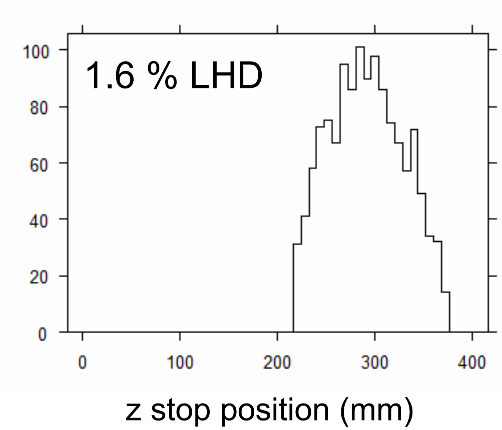


degrader optimization needs experimental fine tune ± 100 μm: material budget and dafne tune known with limited accuracy.









The challenge

to do low energy X ray spectroscopy at an accelerator !

The radiation environment produces **a lot of charge** in Si detectors

„Beam background" – Touschek scattering – stray 510 MeV $e^{\pm}$ - **Showers**
(not correlated to $e^{\pm}$ collisions)

Babha scattering - Showers

Pions from Phi or K^0 decay

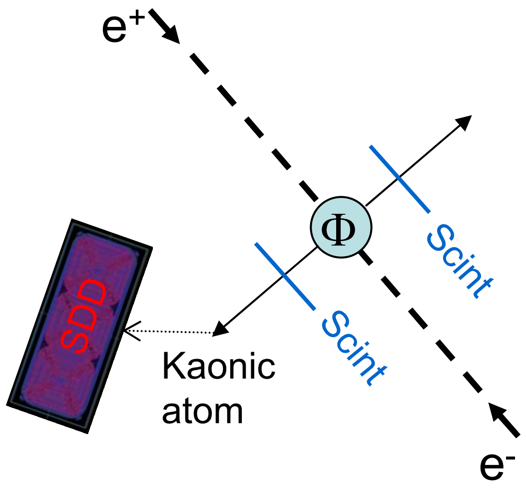
Muons, pions, electrons **from charged K decay** - hadronic background –
- trigger signal – remains in triggered setup

The DEAR experimental precision was limited by the signal vs. background ratio. The yield for deuterium is expected to be ~ 10 times smaller then for hydrogen, so a powerfull background suppression is needed!

From DEAR to SIDDHARTA

Need new X-ray detectors providing

- timing capability → background suppression by using the kaon - X ray time correlation
- excellent energy resolution
- high efficiency, large solid angle
- performance in accelerator environment



SDD (silicon drift detectors)

arrays of large SDDs in development

I3 Hadron Physics EU FP6 –

Joint Research Activity: **SIDDHARTA**

Triple coincidence:

$SDD_X * Scint_K * Scint_K$

in cooperation with LNF, MPG, PNSensor, Politecnico Milano, IFIN-HH.

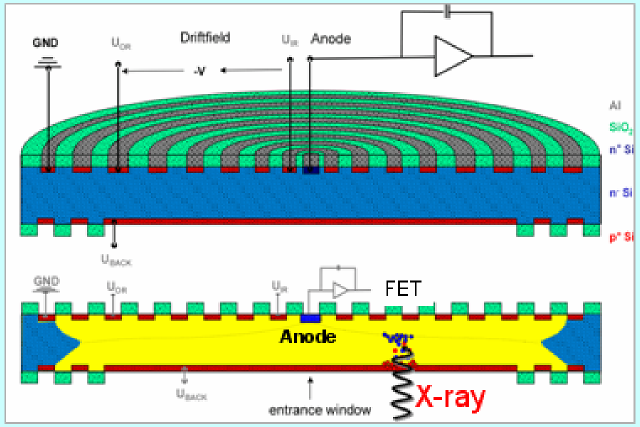
S: Signal, B: background, T: trigger rate, S_T : signal per trigger
Δt: coincidence width, A: accidental rate,
H_T: hadronic background per trigger

$$S / B = \frac{T \cdot S_T}{T \cdot (\Delta t \cdot A + H_T)}$$

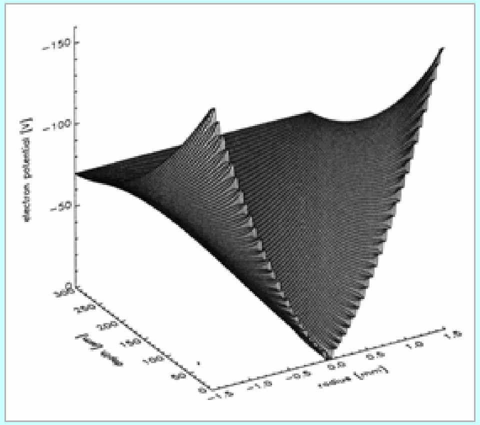
Function principle

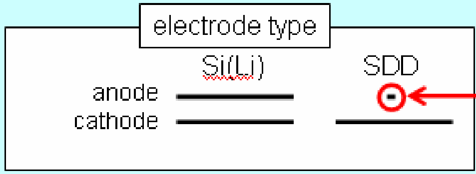
SDD (Silicon Drift Detector)

Schematic drawing



potential distribution





$Q = CV$

$= (\varepsilon_0 S / d)\, V$

Small capacitance

The small capacitance results in a large amplitude and a short rise time of the signal

Compared to conventional photodiodes SDDs can be operated at higher rates and have better energy resolution.

A lateral field makes the produced charge drift to the collecting anode.

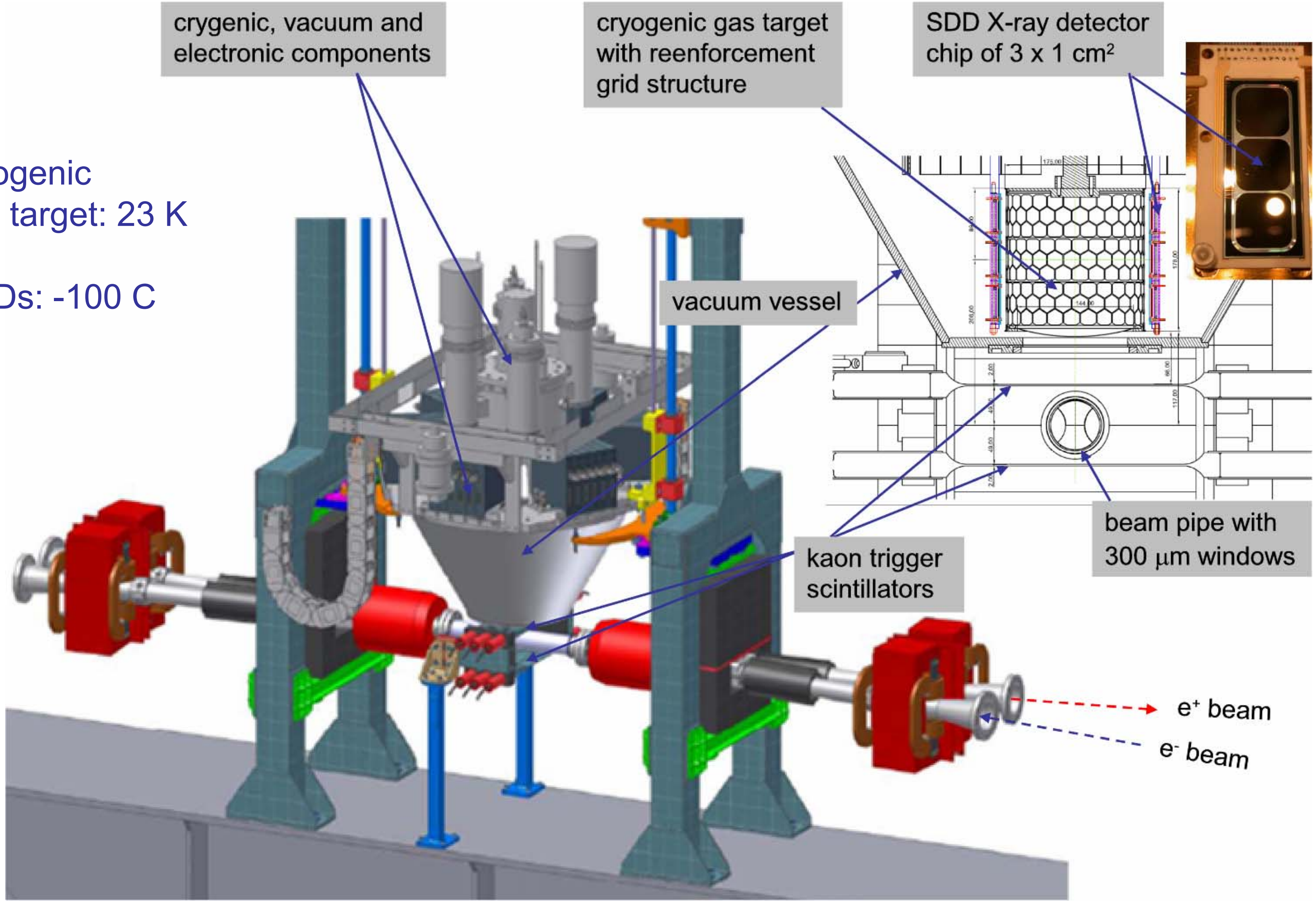
different from standard electronic devices:

- double sided structure
- not passivated
- large area chips
- arrangement of bond pads in the center

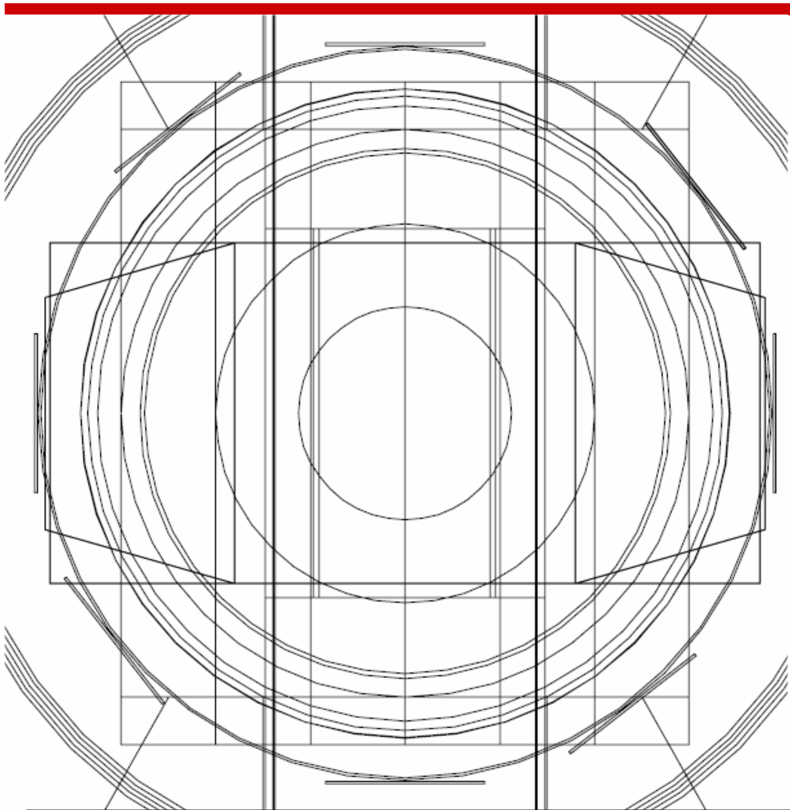
SIDDHARTA setup

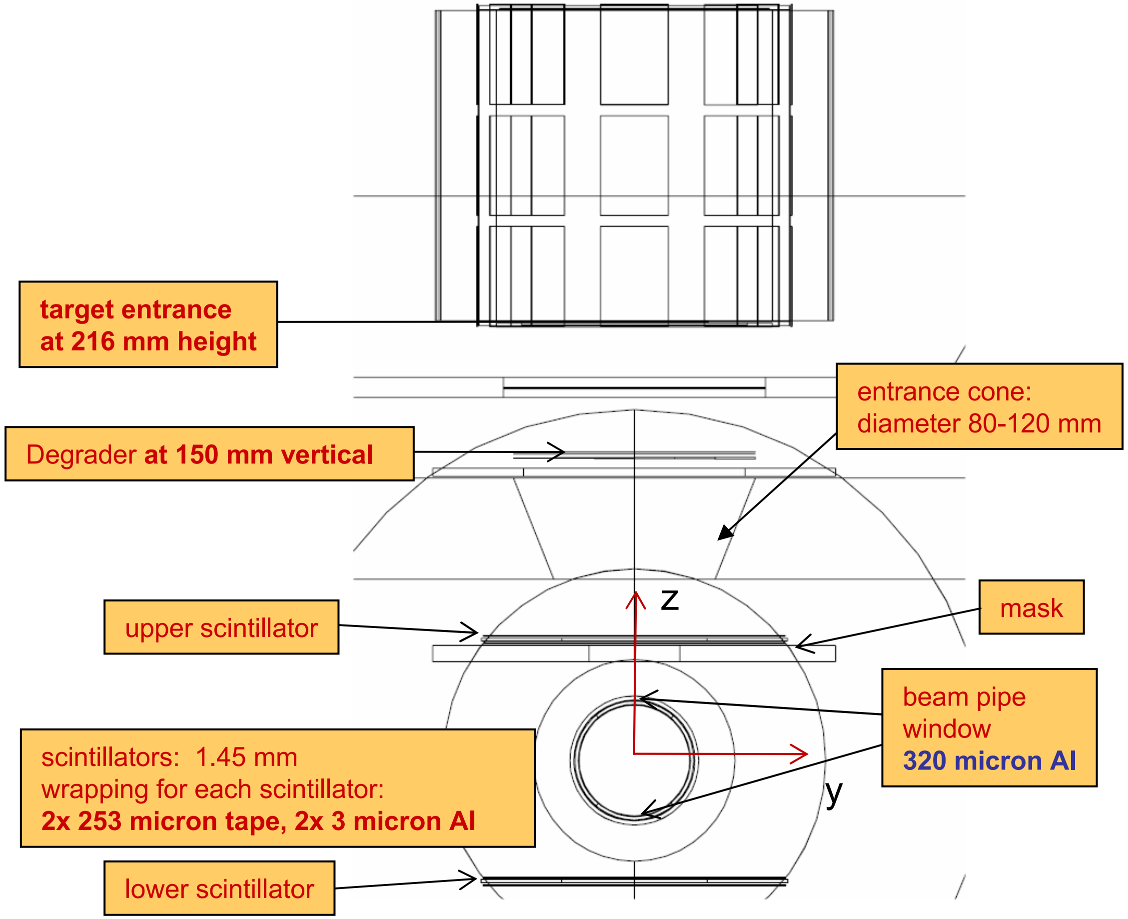
cryogenic
gas target: 23 K

SDDs: -100 C



GEANT geometry model





Stepped degrader at 150 mm vertical position.
Foils: mylar (=hostaphan)

+overall 0.1, 0.2,.. mm

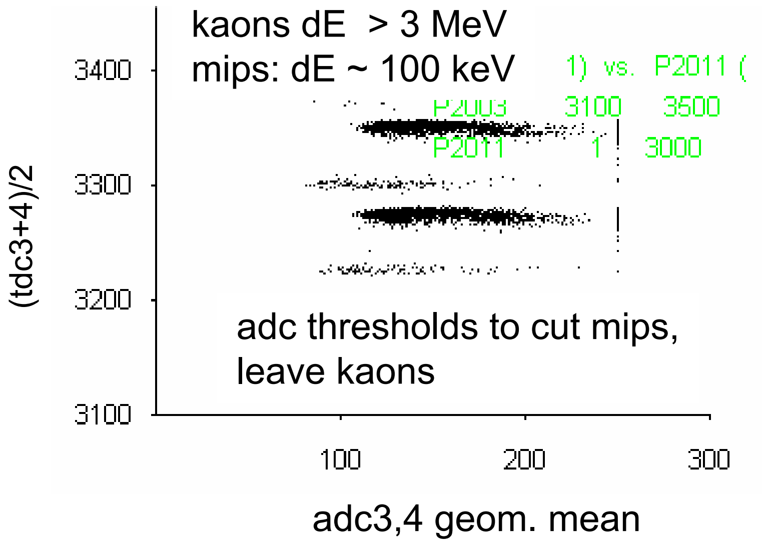
overall:	0.050 mm
Y: -60 -40 :	0.100 mm
Y: -40 -20 :	0.200 mm
Y: -20 0 :	0.400 mm
Y: 0 20 :	0.600 mm
Y: 20 40 :	0.700 mm
Y: 40 60 :	0.800 mm

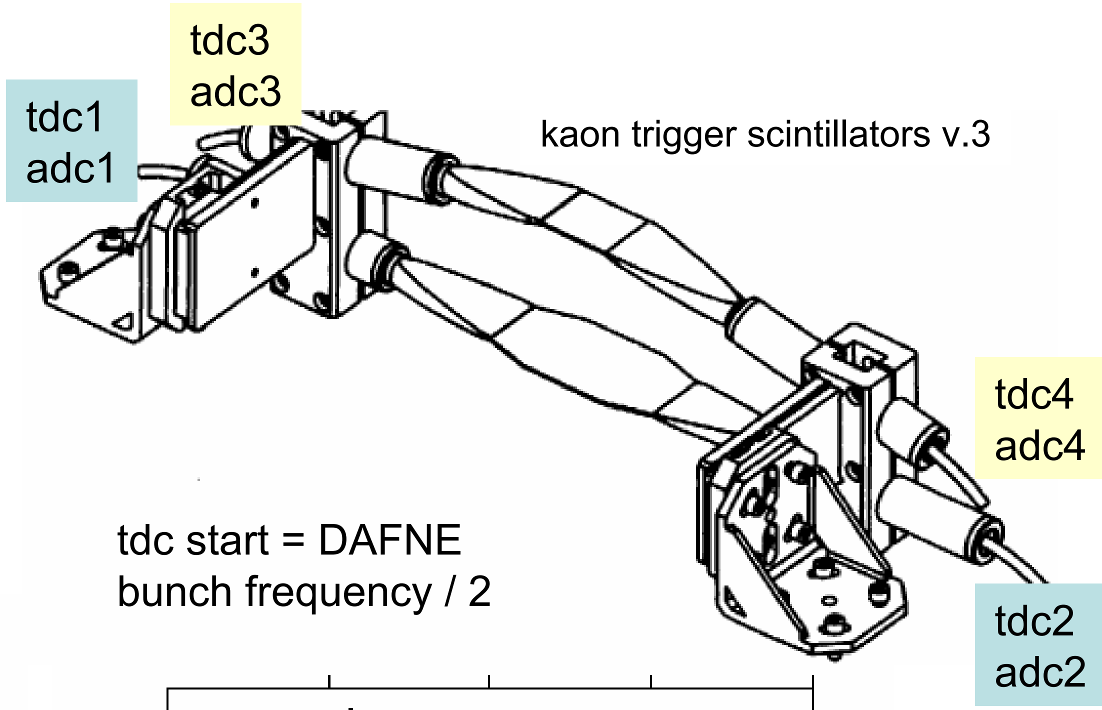
vacuum window: kapton 125 micron + paper 120 micron
target window: 100 micron Hostaphan

scintillator wrapping tape: taken as kapton[1]
the mask: 8 mm plexiglass, hole diameter= 45 mm, cylindr.

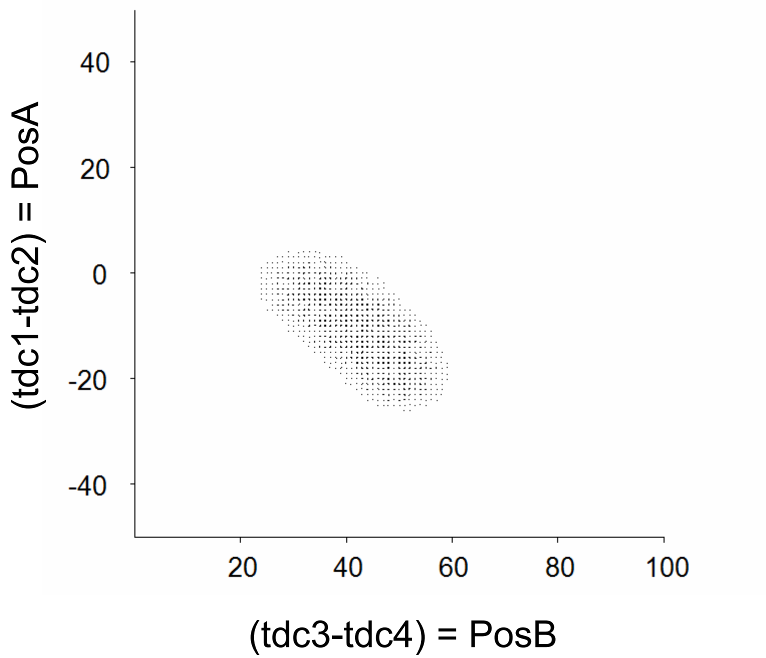
[1]) no essential difference in result if mylar is assumed

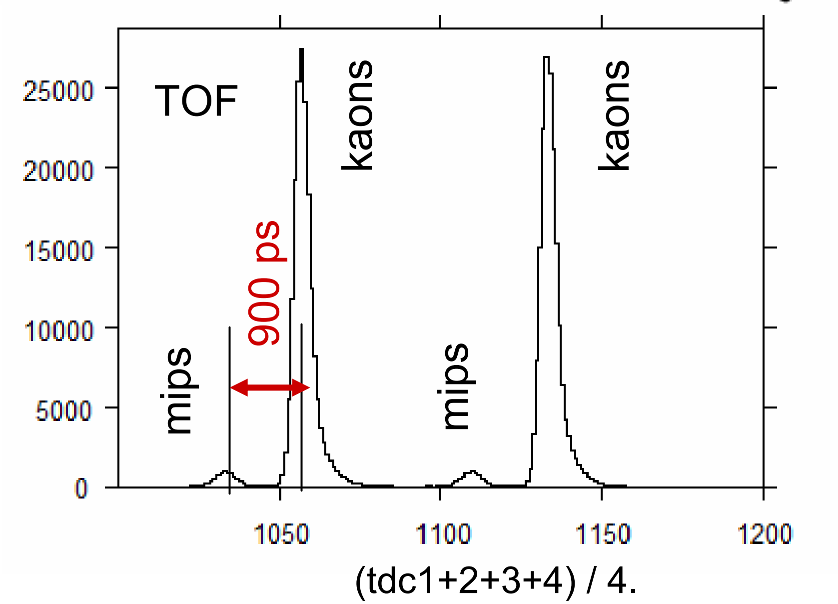
Kaon trigger



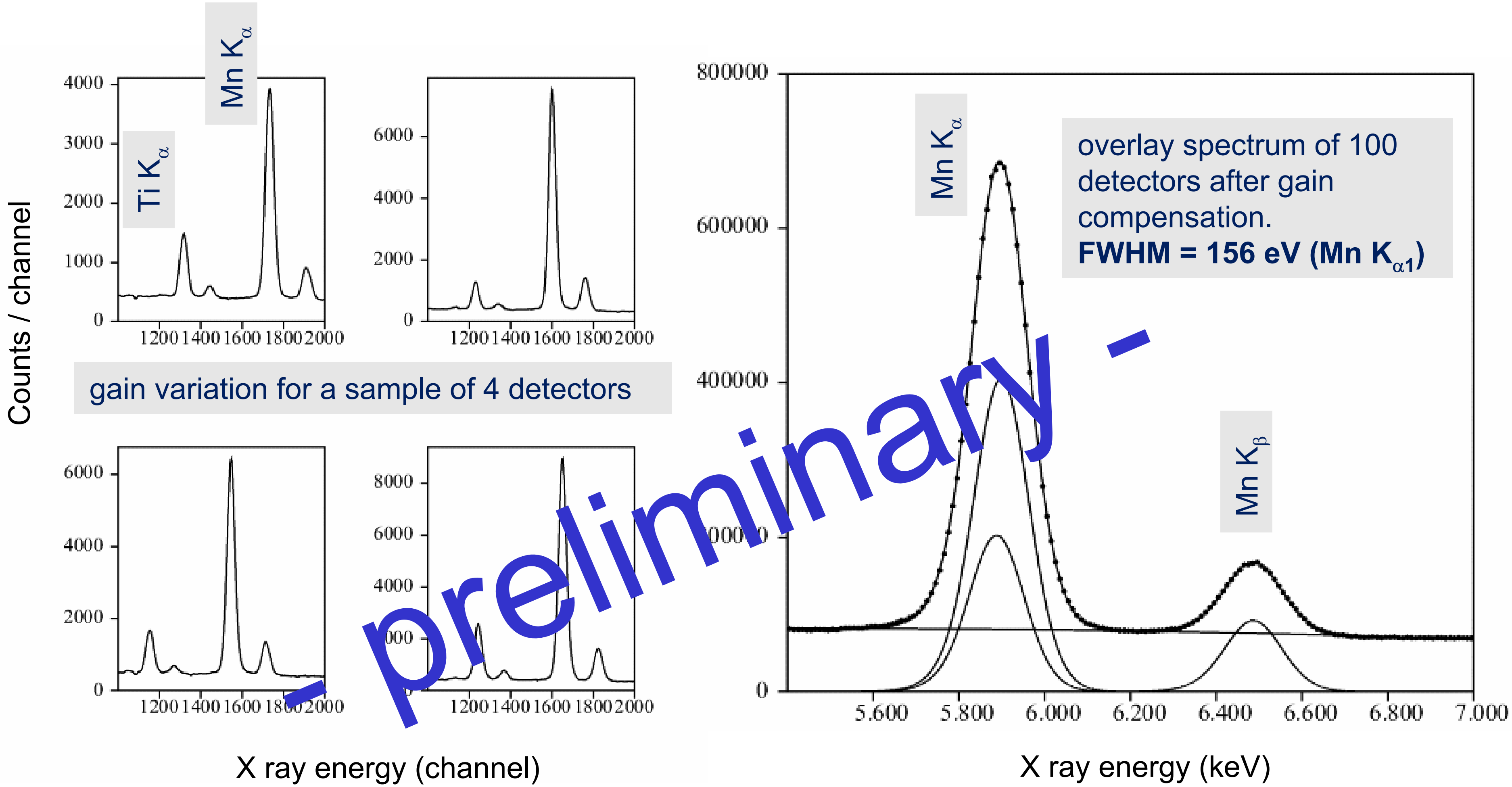


tdc start = DAFNE
bunch frequency / 2





First siddharta experimental spectra

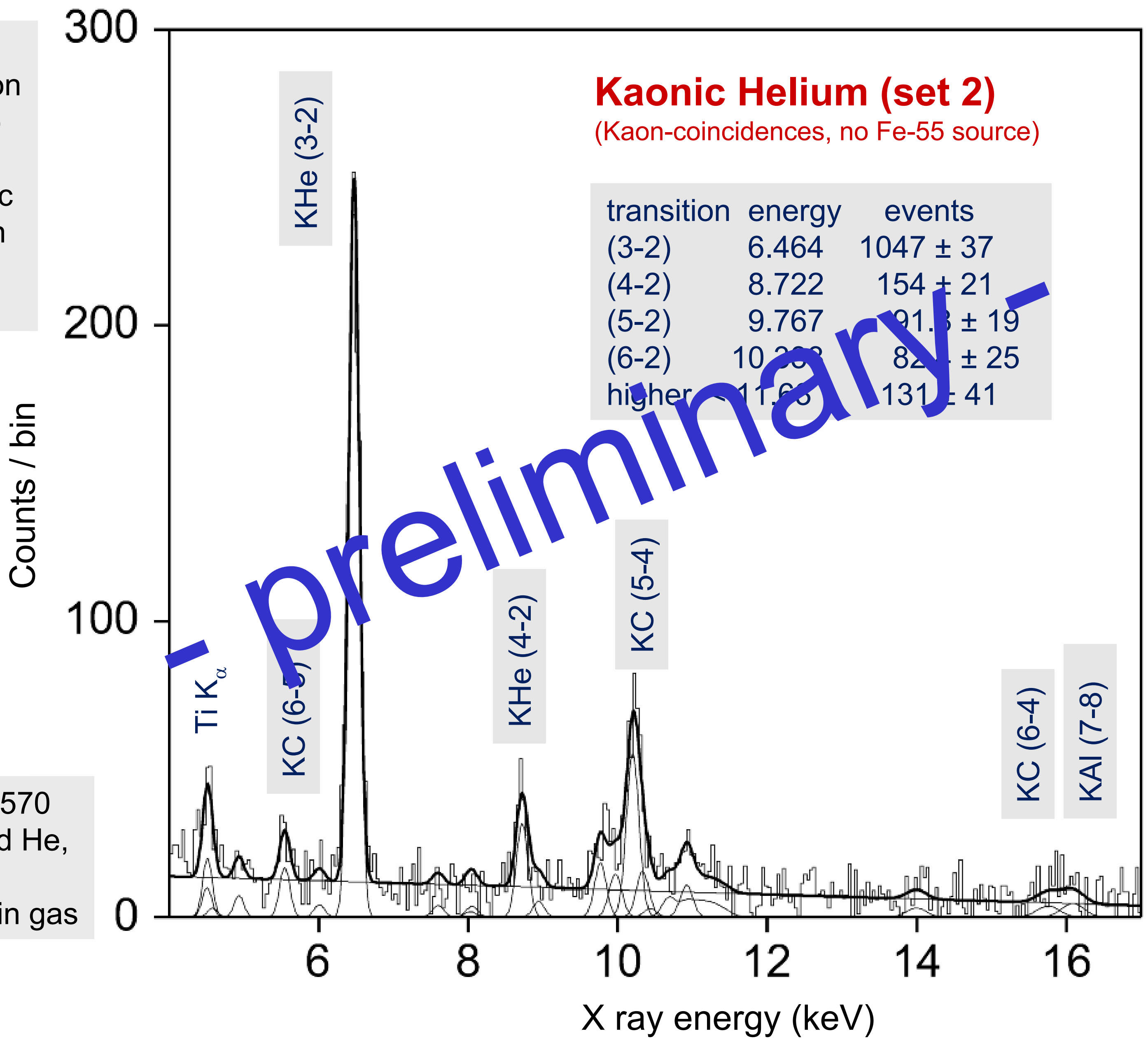


Test: Fe-55 source and Ti fluorescence lines used for inline energy calibration (simultaneously measuring the kaonic helium signal and the calibration lines)

First siddharta experimental spectra

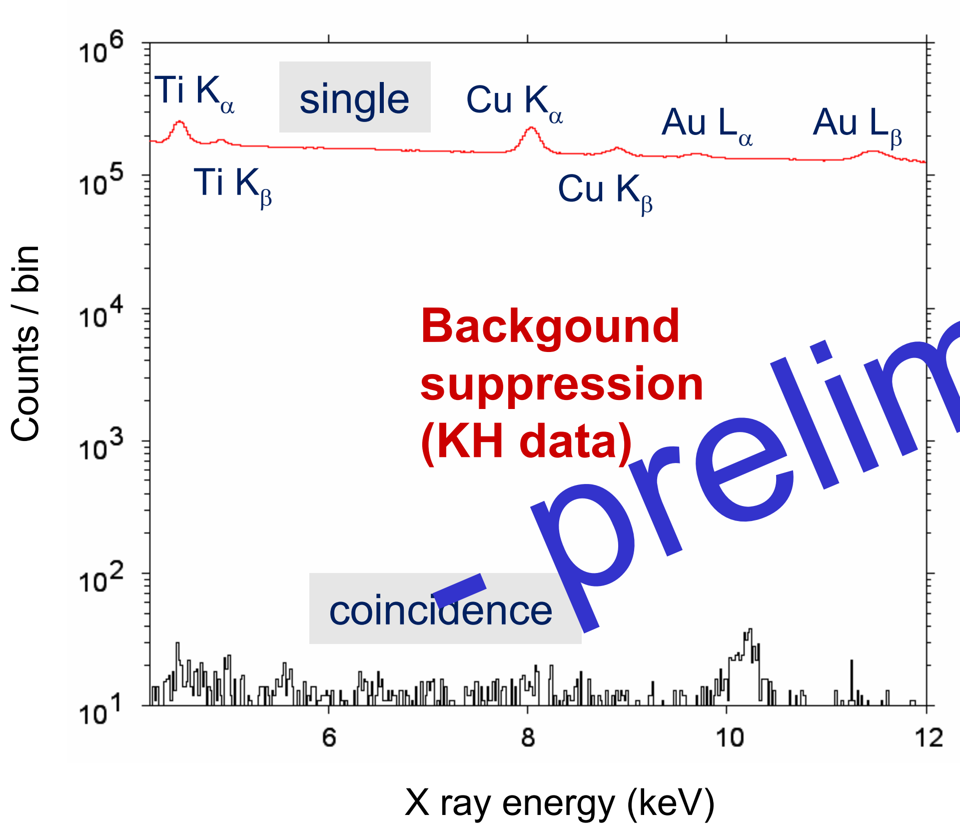
KHe used for gasstop optimization + physics interest[1])

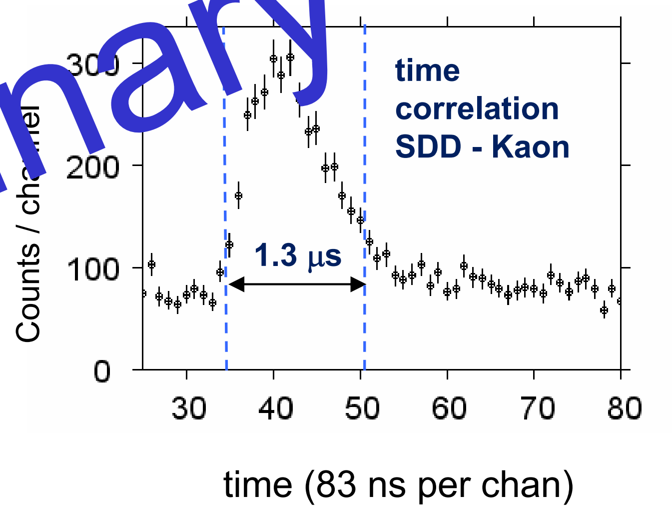
Calibration: periodic xray-tube switch on <u>during beam</u>
Ti + Cu K_α lines



[1]) compare KEK E570 KHe L lines in liquid He, consistent result, first measurement in gas

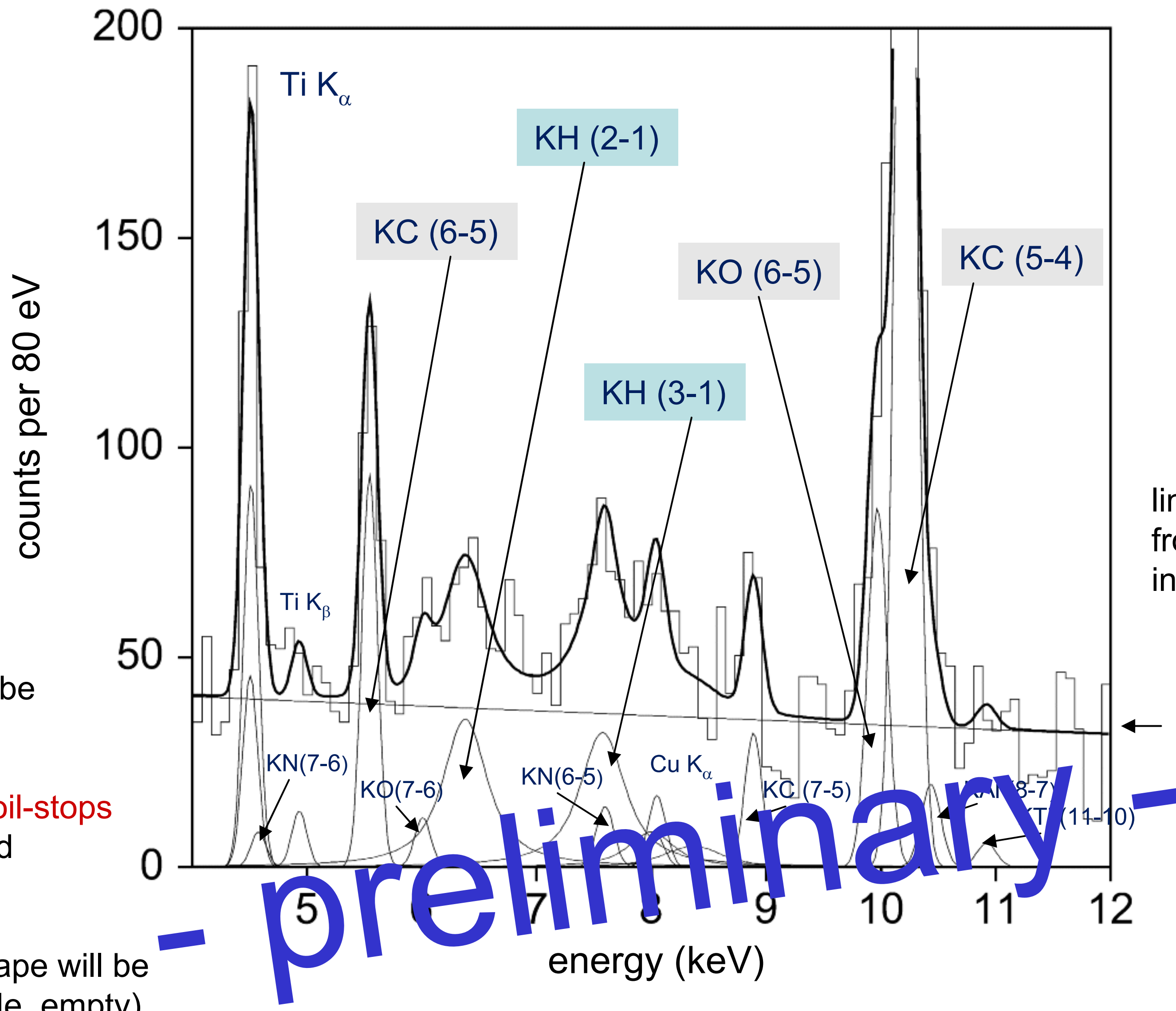
First siddharta experimental spectra





Data of ~ 250 pb^{-1} already acquired, *currently being analyzed*.
2nd data taking period with *improved setup* will start in September

First kaonic hydrogen spectrum (for data subset)



line pattern taken from total statistics incl. He

synchronous background

accidental background subtracted. acc/synch ~1

various cuts to be optimized.

gas-stops vs. foil-stops will be improved in setup-2

background shape will be measured (d, He, empty)

Summary

DEAR: most precise experimental result on K^-p shift and width up to now

Efforts in theory continue

SIDDHARTA well under way.   beam time NOW
K^-p up to 10 times higher precision then in DEAR expected
K^-d first measurement ever

Further perspectives at DAFNE: LOI for a search of kaonic nuclear clusters using the KLOE detector plus additional components