# *Results from the kaonic hydrogen X-ray measurement at DAFNE and outlook to future experiments*

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On behalf of: The SIDDHARTA collaboration

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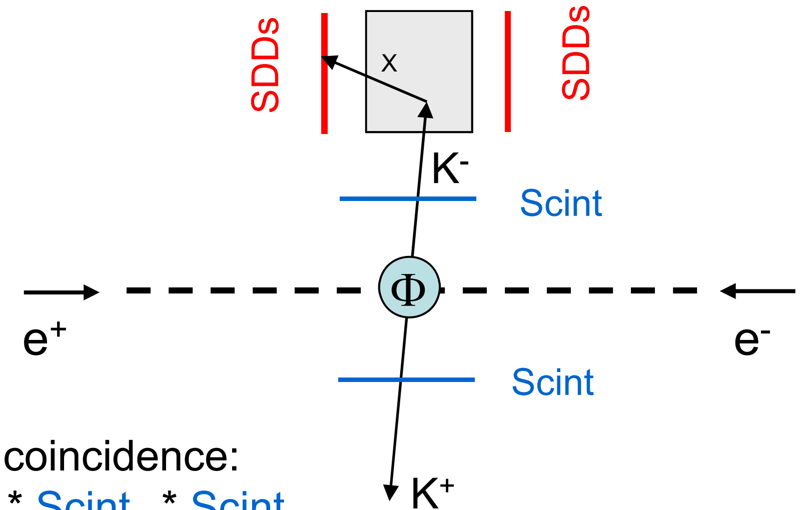
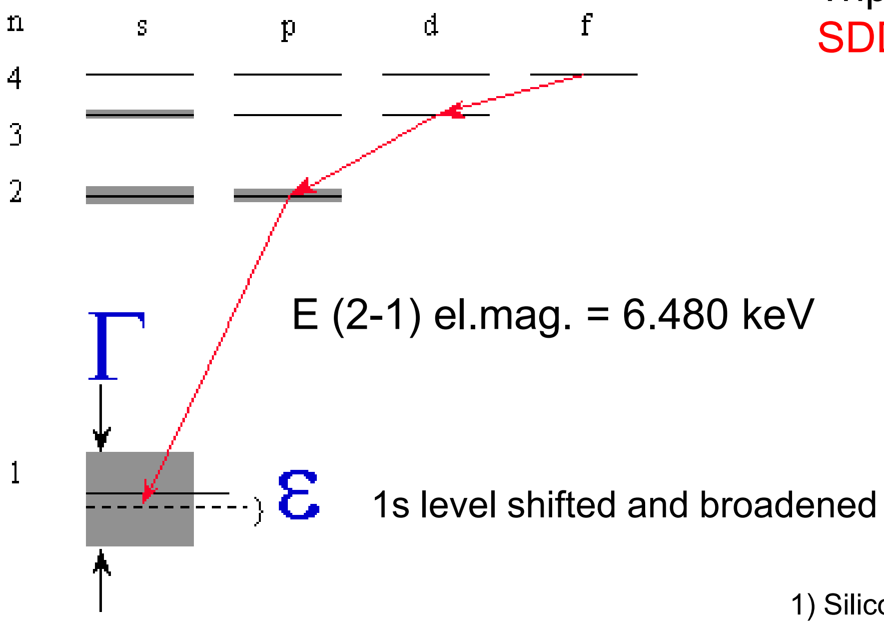
# *Content*

# *SIDDHARTA[1) ] - What is it ?*

Goal: measure the shift and broadening of X ray transition energies in light kaonic atoms. The ground state is affected by the strong interaction between the kaon and the nucleus. $\varepsilon, \Gamma$ are input for effective theories in low energy QCD




Triple coincidence:
$SDD_X$ * $Scint_K$ * $Scint_K$




New X-ray detectors (SDD silicon drift detectors)

- timing capability → background suppression
- excellent energy resolution
- high efficiency, large solid angle
- performance in accelerator environment

1) Silicon Drift Detectors for Hadronic Atom Research with Timing Application

# *Hadronic atoms*

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

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[1] type formulas)

compare to results from low energy scattering experiments[2]

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

[1] original 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

# *Theory and experiment*

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

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

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

.. needs input from experimental data
.. aims at accomodating *all* experimental evidence

High precision low-energy-QCD results can be compared with experimental data

# *Kaonic hydrogen – Deser formula*

With $a_0$, $a_1$ standing for the I=0,1 S-wave $\bar{K}N$ complex scattering lengths in the isospin limit ($m_d = m_u$), $\mu$ 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

# *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 $\varepsilon_{1s}$ and width $\Gamma_{1s}$ 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: more precise experimental data important

kaonic deuterium never measured before

atomic physics: new cascade calculations

## Information on $\Lambda$(1405) sub-threshold resonance

responsible for negative real part of scattering amplitude at threshold

important for the search for the controversial „deeply bound kaonic states”
present / upcoming experiments (KEK,GSI,DAFNE,J-PARC)

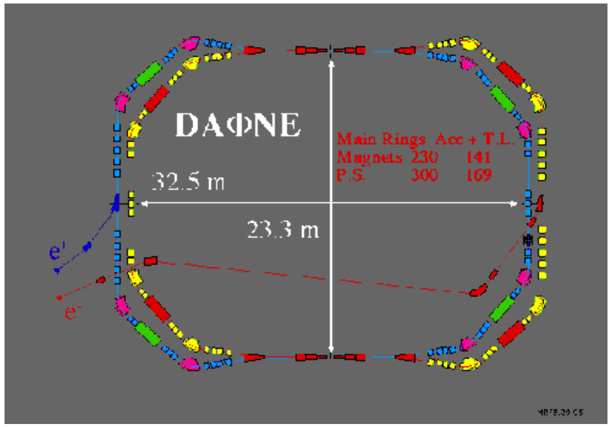
## Determination of the isospin dependent KN scattering lengths

no extrapolation to zero energy

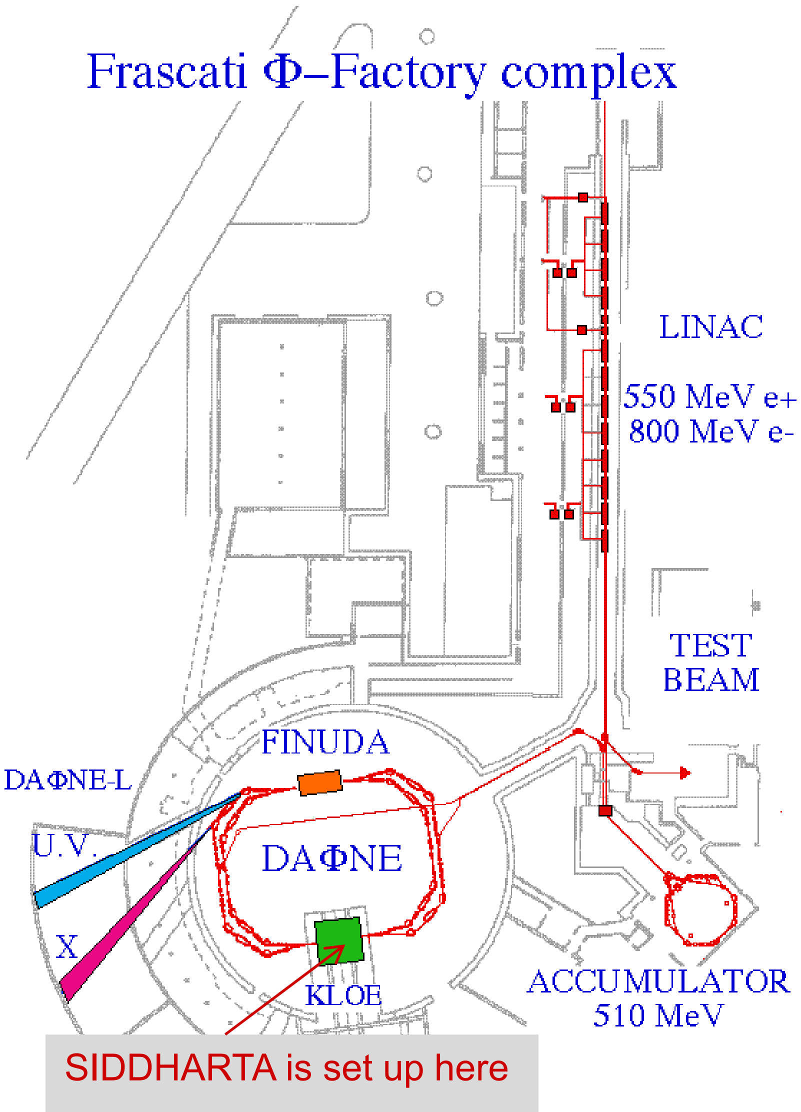
# *DAΦNE*

... „Double Annular Phi-factory for Nice Experiments“

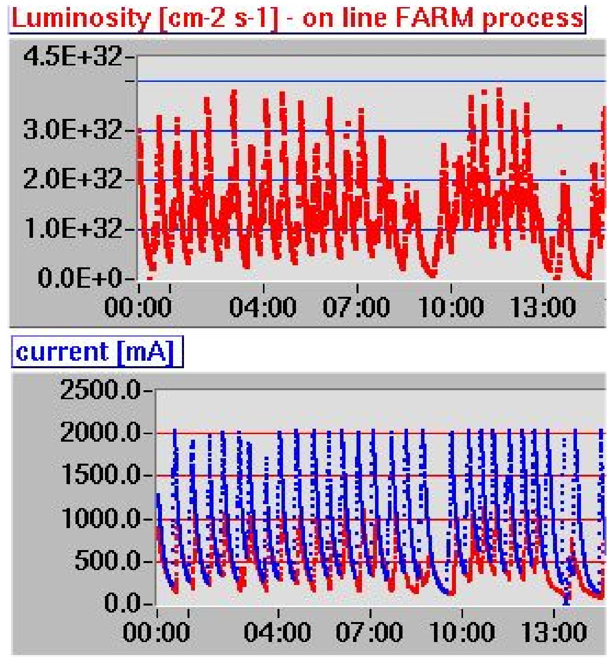
at Laboratory Nazionalidi Frascati dell‘INFN




# DAΦNE



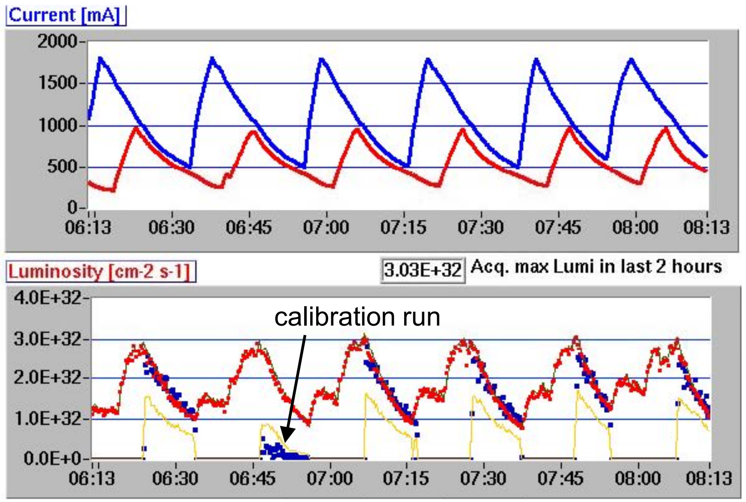

electron-positron collider, energy at phi resonance
phi produced nearly at rest.
(boost: 55 mrad crossing angle → 28 MeV/c)
charged kaons from phi decay: $E_k$ = 16 MeV
degrade to < 4MeV to stop in gas target

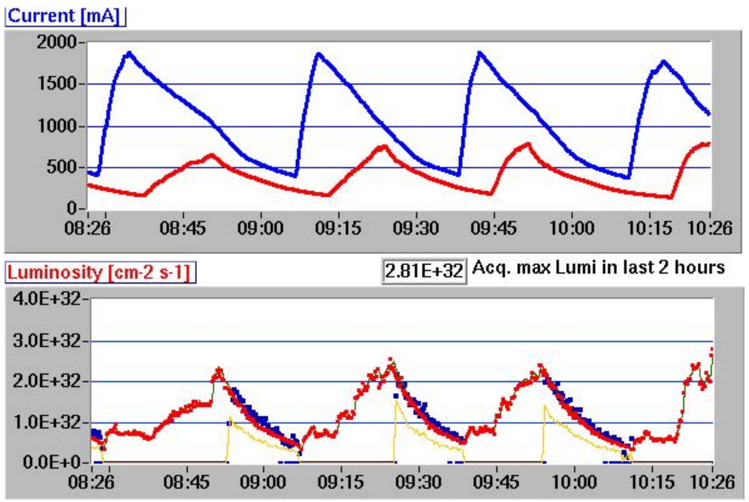



compare situation during DEAR data taking **(2002)**
currents ~ 1200/800 ~ 1 $pb^{-1}$ per day, peak ~ $3 \times 10^{31}$ $cm^{-2}$ $s^{-1}$

Φ production cross section ~ 3000 nb (loss-corrected)
Integr. luminosity 2009 **~ 6 $pb^{-1}$ per day** [1)] (~ $10^7$ $K^{\pm}$ )
(increased by crabbed waist scheme)
Peak luminosity ~ $3 \times 10^{32}$ $cm^{-2}$ $s^{-1}$ = 450 Hz $K^{\pm}$
[1)] we can not use kaons produced during injections.

# Luminosity




siddharta can work only between injections (blue dots, yellow line)

under good conditions during siddharta DAQ ~ 2.8e32 – 1.0e32 $cm^{-2}\ s^{-1}$ luminosity

compare to 2002 DEAR experiment:
~ 3.0e31 $cm^{-2}\ s^{-1}$
now up to 10 times higher !

siddharta integrated luminosity
on 23 Oct 2009: ~ 8 $pb^{-1}$ !

# *The experimental challenge*

... to do low energy X ray spectroscopy at an accelerator

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

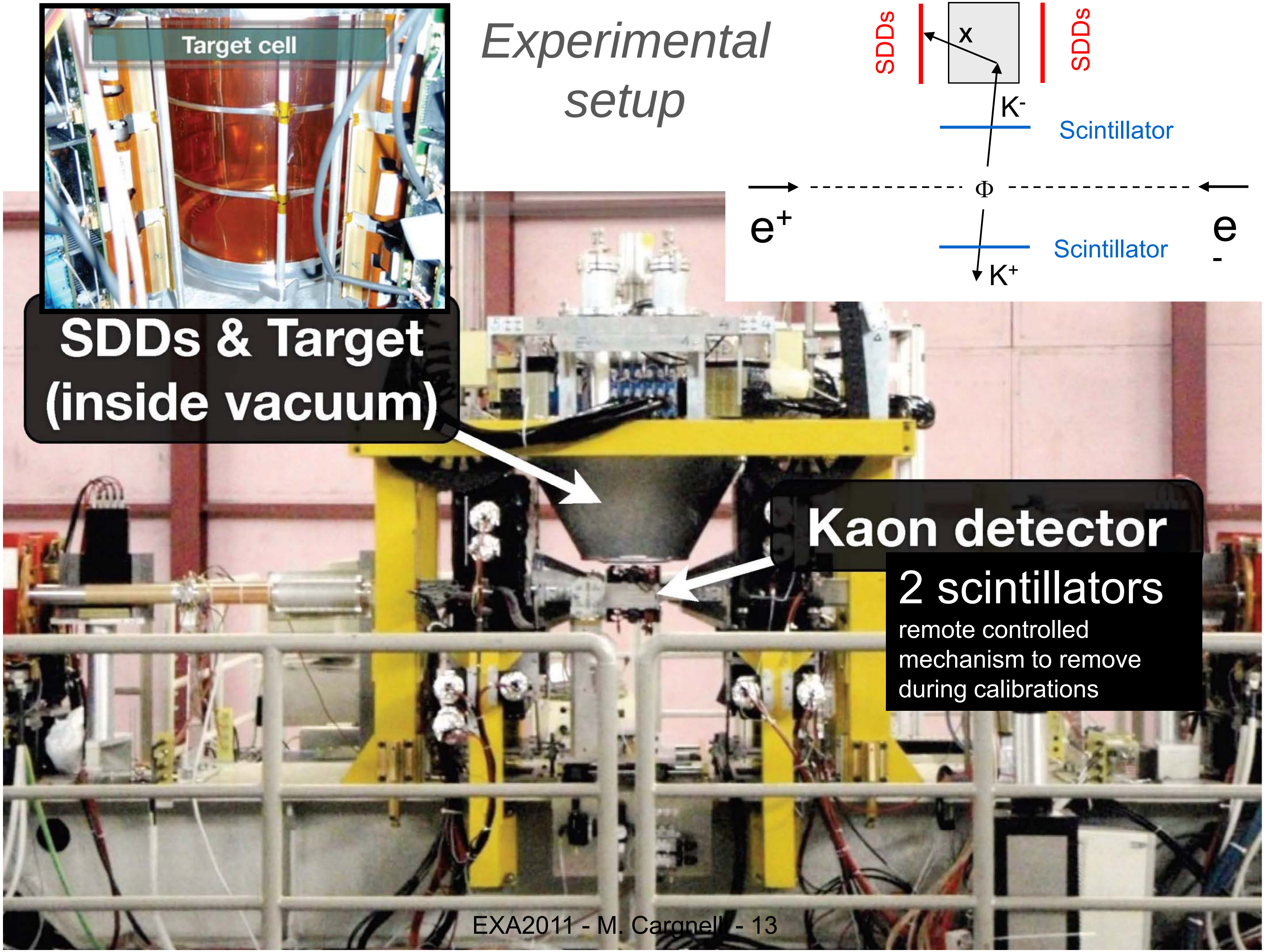
*„Beam background“* Touschek scattering – stray 510 MeV $e^{\pm}$ - **e.m. showers.**
$e^{\pm}$ from Babha scattering – Showers. **not correlated** to charged kaon pairs**:**
**(1) „accidentals“**

**μ, π, e** from K decay; **Λ, π,..** from $K^-$ absorption, kaonic X rays from $K^-$ wallstops
*synchronous background* – has trigger signal – remains in triggered setup
**(2) kaonic X ray lines**
**(3) continous kaon correlated background**

S: Signal, B: background,
T: trigger rate,
$S_T$ : signal per trigger
$\Delta t$: coincidence width
A: accidental rate
$B_T$: background in ROI, per trigger (lines+continous)

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

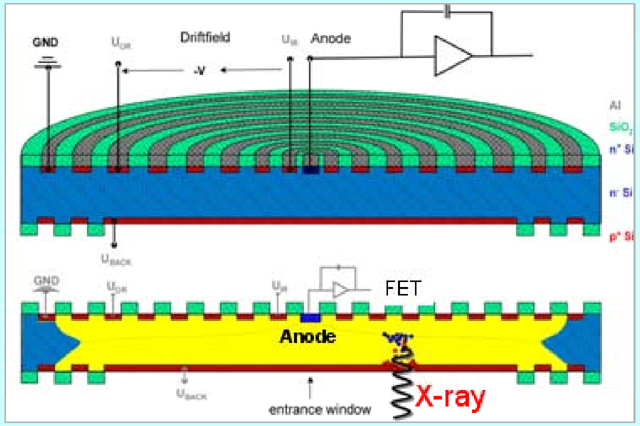
# *Experimental setup*



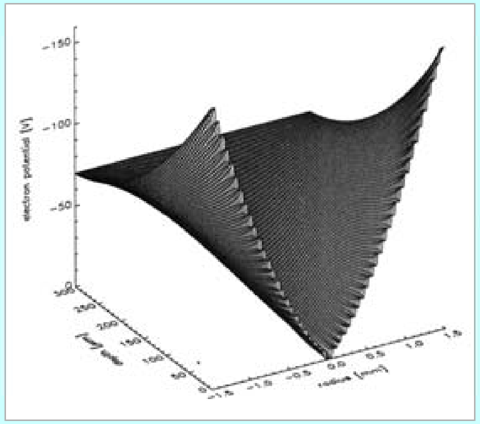
# Our X ray detectors

## SDD (Silicon Drift Detector)

Schematic drawing




potential distribution



| electrode type | Si(Li) | SDD |
|---|---|---|
| anode | ——— | ⊙ |
| cathode | ——— | ——— |

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

**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.

I3 Hadron Physics EU FP6 –
Joint Research Activity: **SIDDHARTA** - in cooperation with LNF, MPG, PNSensor, Politecnico Milano, IFIN-HH.

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

# *Data analysis*

What the data aquisition system stores:

- *energies* and detector numbers of  X ray hits
- event id-number, time-tag

if a kaontrigger happend:
- the *time correlation* between X-ray and kaon
- the kaon detector parameters

- DAFNE beam-current values

From this we derive in off-line analysis:

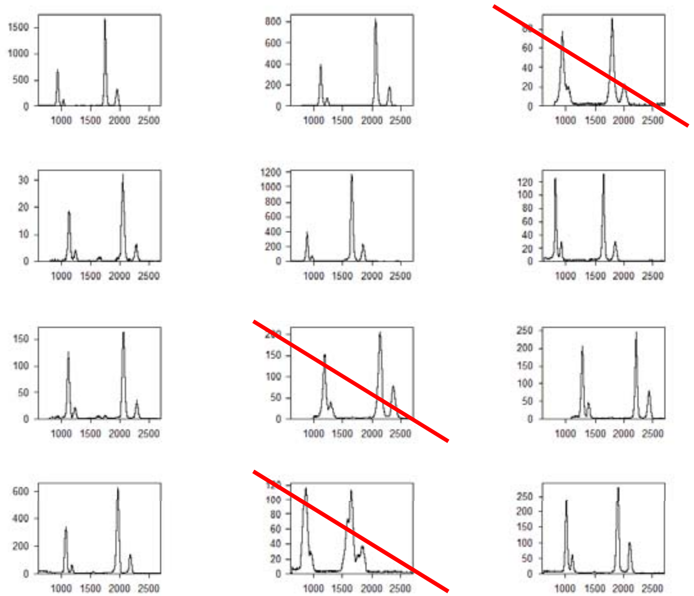
- the kaondetector TOF to discriminate against MIPS
- kaondetector position information from the timedifference of the PMs at both ends
- sdd rates (e.g. counts during last second)
- kaon rates ( -- „ --)
- number of hits without vs. hits with kaon coincidence
- multiplicity of hits
- kaons per X-ray

Analysis tasks:

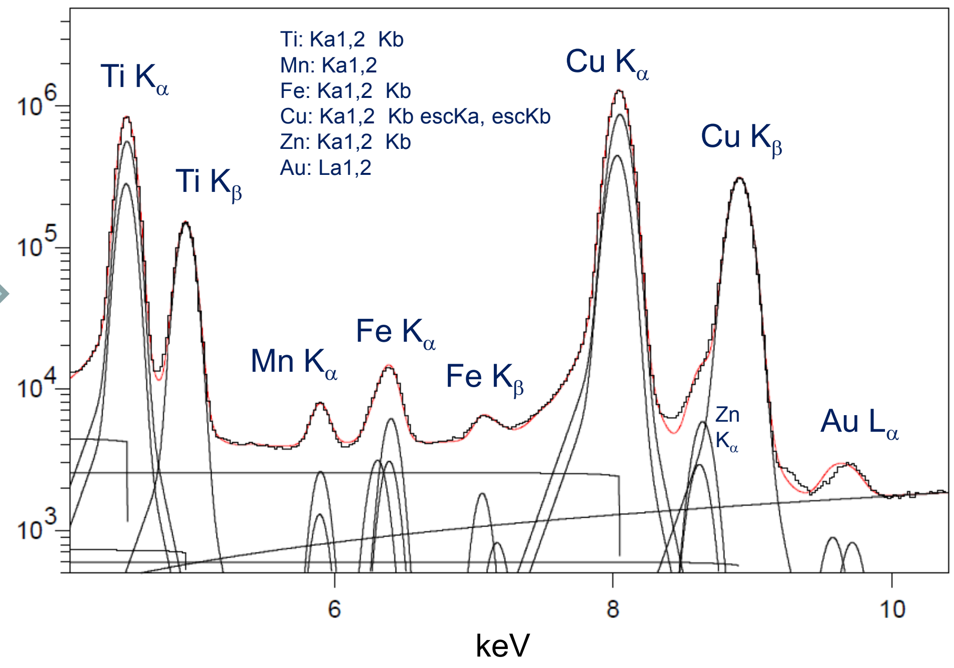
- periodically  calibrate  the  >100 individual detectors (gain alignment),  discard ‚bad‘ ones
- determine the energy resolution (response shape) of the summed detectors
- fit the spectrum with signal-components, background lines and continous background

# *Calibration*

every ~ 6h calibration run with X-ray tube + beam



summed spectrum of 1 calibration run ~ 100 detectors




in 10 min enough counts on each of the 133 detectors !
derive ADC channel of Ti Kα and Cu Kα position
calibrate each (channel => keV)
fit with gaussians
automatically select detectors using resolution- and chisquare cuts

excellent statistics, many lines identifyable

deviation from pure gaussian shape !
different approximations possible.
Here: convolution of with exponential tails:

$$z_i = \Sigma\, w_{i-j}\; y_j$$

$$w_k = \begin{cases} N \exp(-k\,\lambda_-) & k < 0 \\ 1 - \varepsilon & k = 0 \\ N \exp(-k\,\lambda_+) & k > 0 \end{cases} \qquad \Sigma\, w_k = 1$$

# *Calibration cont'd*

gain slightly changing with detector rate
and with presence of large signals

=> used X-ray tube DURING beam

studied rate dependance by varying X ray tube intensity

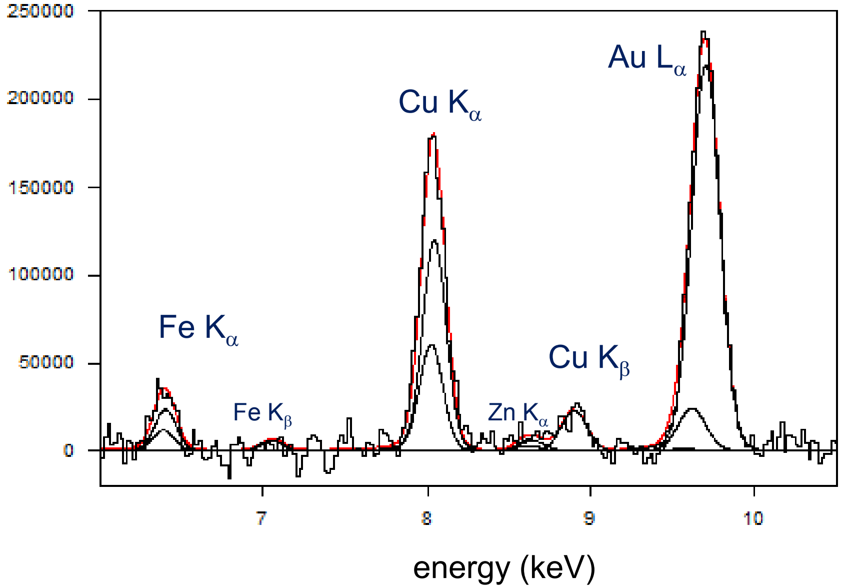
final energy adjustment at exact data-taking conditions
possible by looking at
a) the selftriggerspectra => Cu, Au
fluorescense lines excited by background $\varepsilon < 1$ eV
b) the coincidence spectra = kaonic lines from wallstopps KC,..
$\varepsilon \sim 2$ eV

Remark on the response shape of the SDDs

consider edge effects
charge transport depends on distance from anode
sum of gauss functions is not a gauss function
(adding different resolutions)
=> measured response understood

most precise response-shape from low rate X-tube measurement

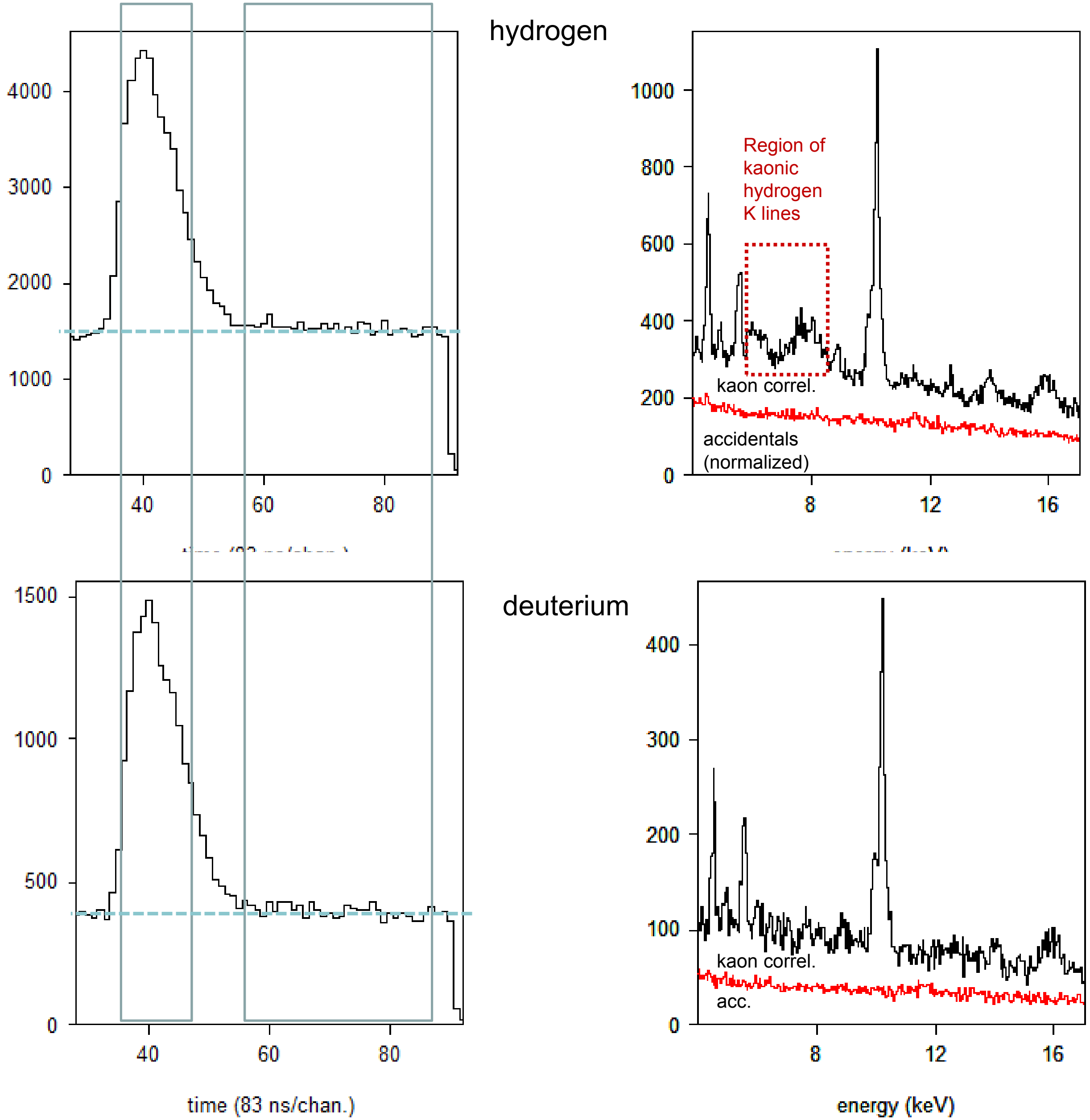
selftrigger spectrum,
continous background subtracted




FWHM @ Cu K$\alpha$ = 174 eV
consistant with X-tube
measurement (with low
intens.)

position of Cu K$\alpha$ ~ slightly
shifted as compared to the
periodic X-tube calibrations

# *Coincidence data*




K correlated background:

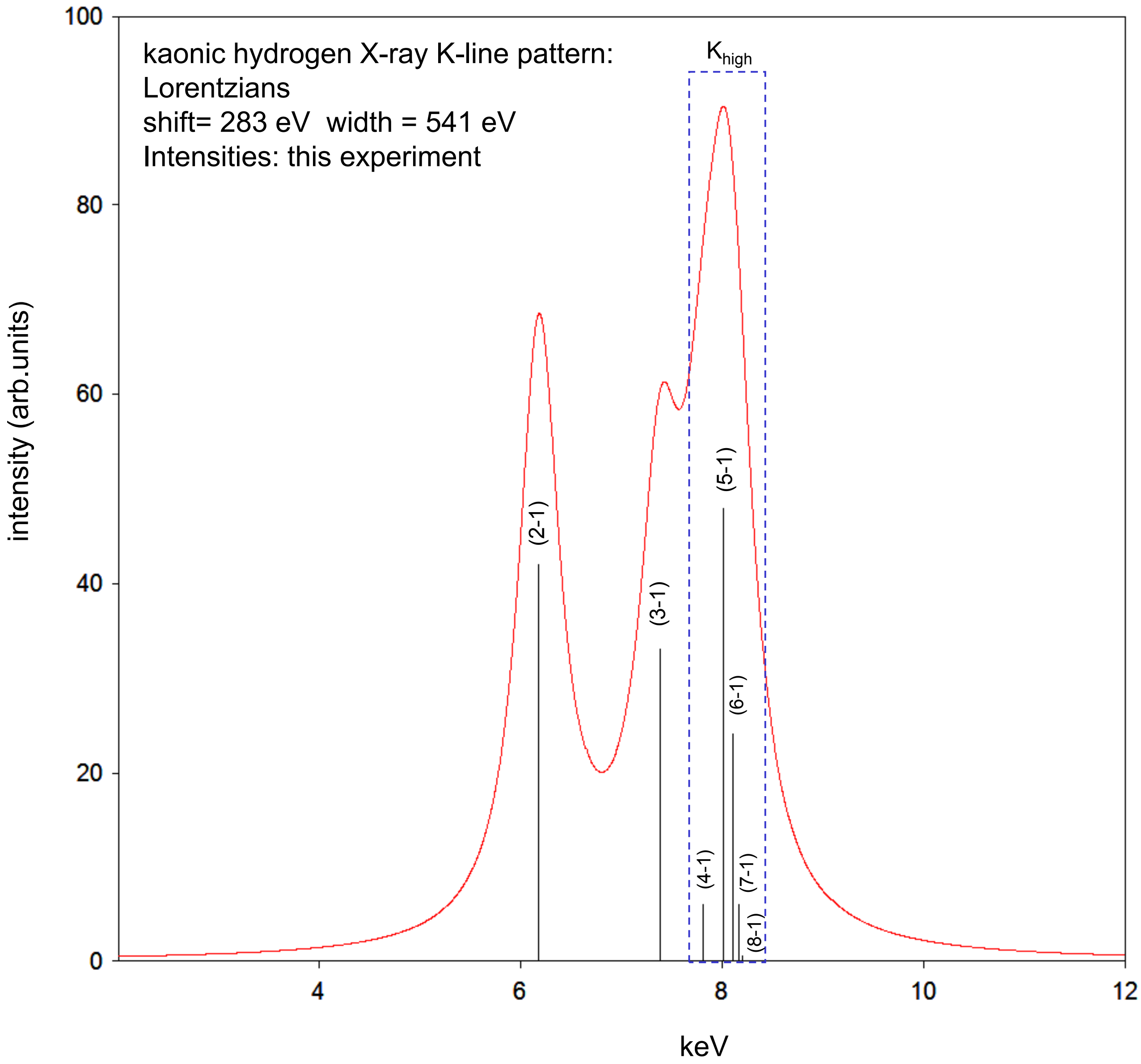
decay secondaries from $K^+$, $K^-$
$K^-$ absorption secondaries
$K^-$ kaonic X-rays, wallstops, gasstops

accidental background:

electromagnetic showers resulting
from lost $e^+$ $e^-$

# Fit model for the signal

| Transition | unshifted energy |
|---|---|
| KH (2-1) | 6.480 |
| KH (3-1) | 7.677 |
| KH (4-1) | 8.096 |
| KH (5-1) | 8.299 |
| KH (6-1) | 8.395 |
| KH (7-1) | 8.458 |
| ... | ... |
| KH (inf.) | 8.634 |




*overlapped distributions !*

*Intensity ratios not known precisely => fixing would introduce theory dependance*

*the individual intensities of the high transitions have large fit errors ..influence shift and width*

*=> focuse fit on $K\alpha$ $K\beta$, $K_{high}$ transitions influence only via their low energy tail (overlap)*

# Fit of the data

*iterative fit*

*step 1: fit which all transition energies coupled*

*step 2: with fixed positions of $K_{high}$, fit $K\alpha$ $K\beta$*

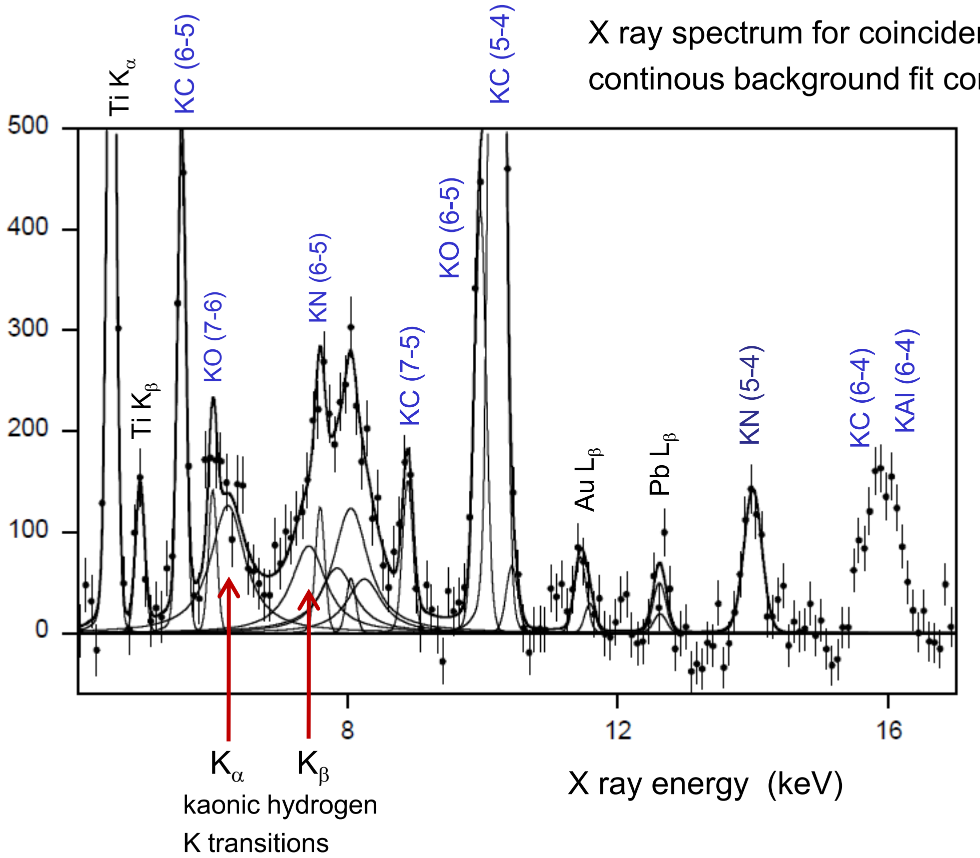
*step 3: use the obtained shift to modify the $K_{high}$ positions, resume at step 2*

*after a few loops consistancy for all transitions !*

background lines

| Transition | Energy |
|---|---|
| KC (6-5) | 5.545 |
| KC (5-4) | 10.200 |
| KC (6-4) | 15.759 |
| KC (7-5) | 8.888 |
| **KO (7-6)** | **6.007** |
| KO (6-5) | 9.969 |
| **KN (6-5)** | **7.596** |
| KN (5-4) | 13.996 |
| **Cu $K_\alpha$** | **8.04** |

intensities from simultaneous fit of the deuterium data, where the lines stand clear.




X ray spectrum for coincidence time-gate.
continous background fit component is subtracted

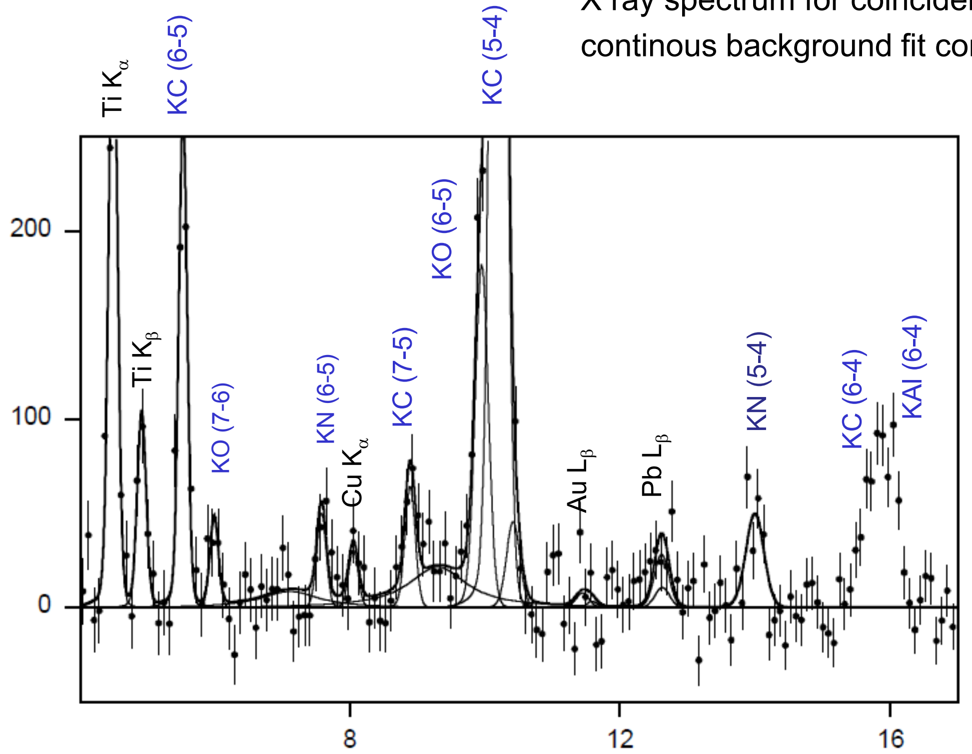
kaonic hydrogen:
shift= 283 +- 36 +- 6 eV width = 541 +- 89 +- 22 eV

Phys. Lett. B, accepted 2011-09-05

# Fit of the data (cont'd)

| Transition | unshifted energy |
|---|---|
| KD (2-1) | 7.81 |
| KD (3-1) | 9.25 |
| KD (4-1) | 9.76 |
| .. | .. |
| KD (inf.) | 10.41 |

X ray spectrum for coincidence time-gate.
continous background fit component is subtracted

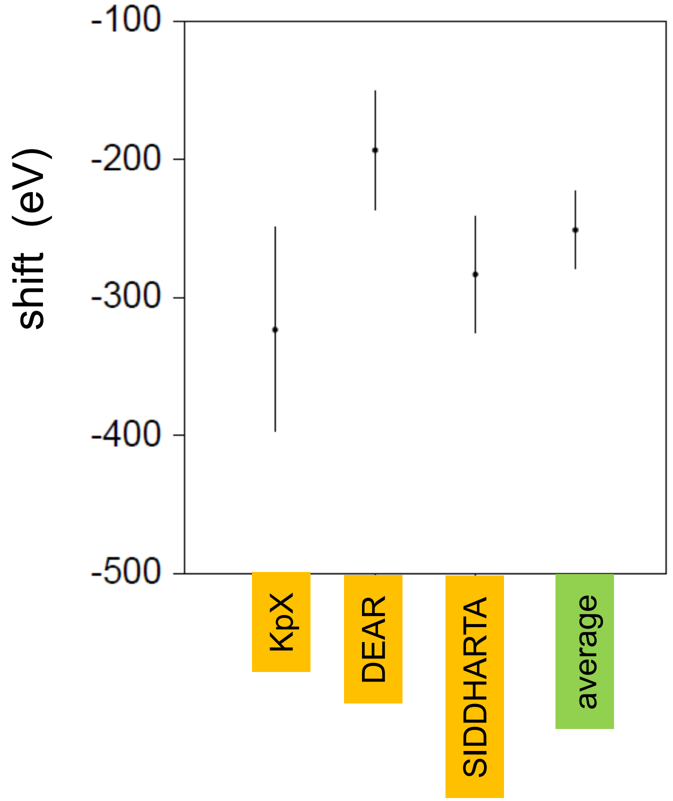


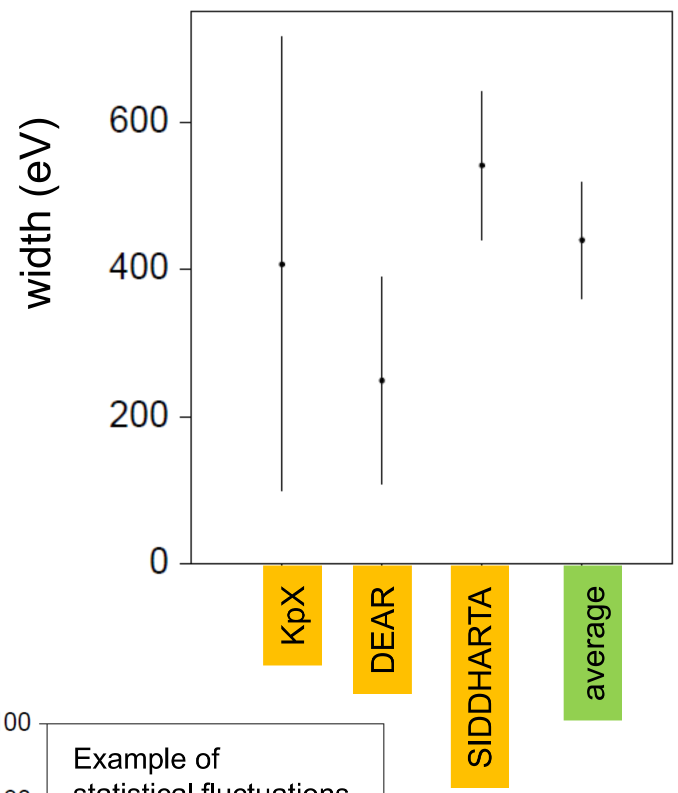

X ray energy (keV)

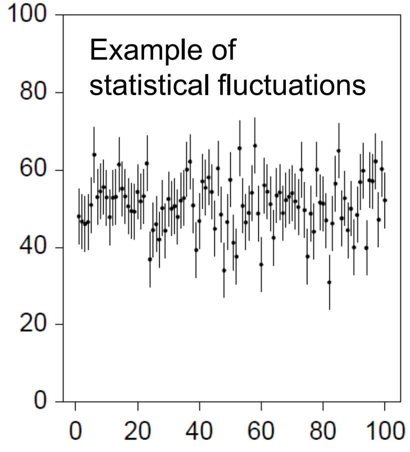
kaonic deuterium:

for fixed shift= 700 eV width = 1000 eV Kα / $K_{high}$ = 0.4
.. 2 sigma hint of a signal

# *Consistancy of KH experimental results ?*



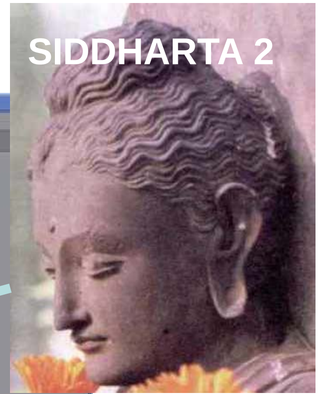



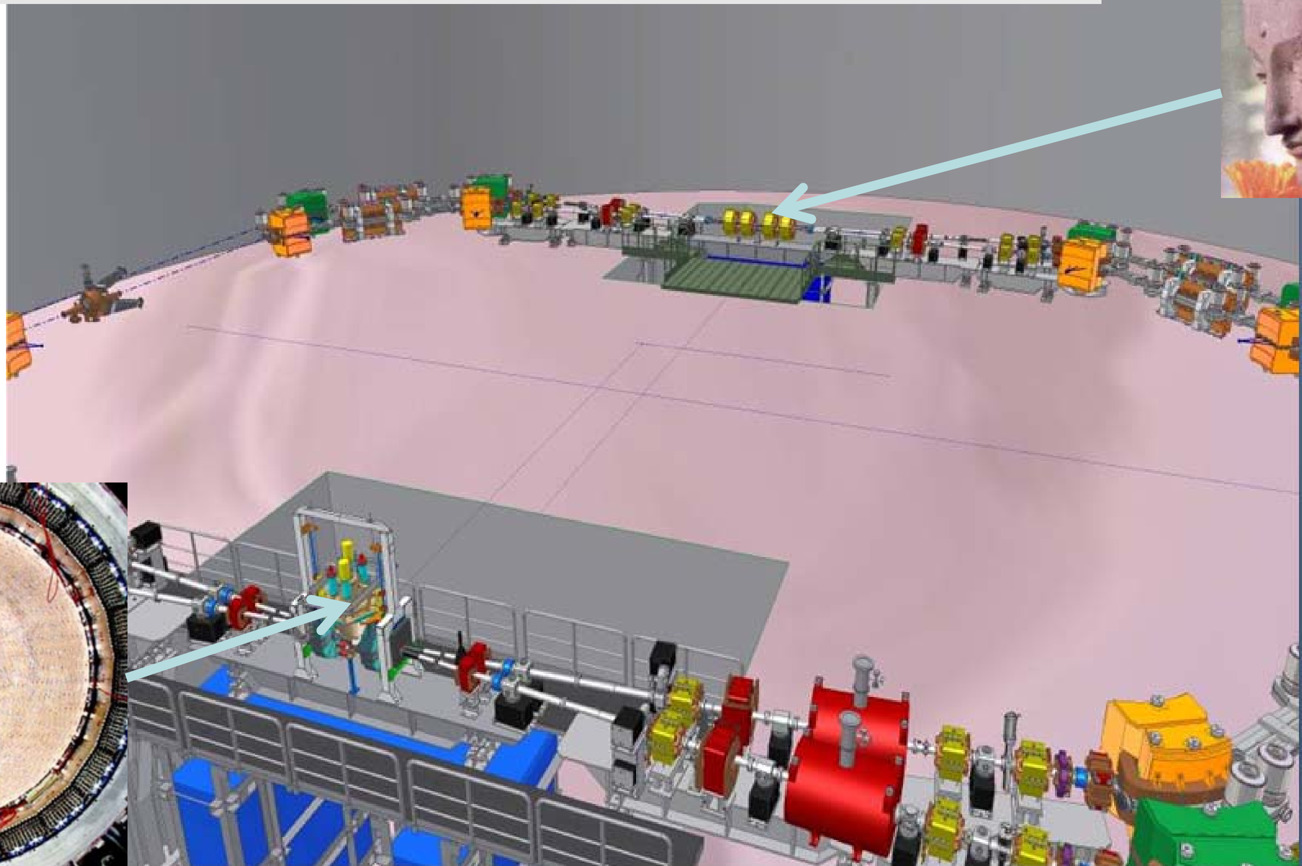

No significant (3 $\sigma$) inconsistancy !

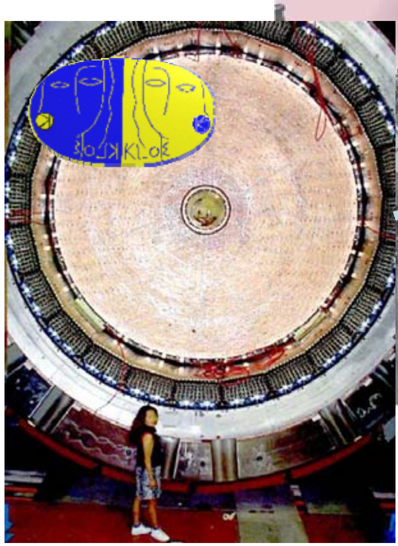
looking at the deviation of the 3 experimental points from the average:
reduced chi-square for 2 degrees of freedom
=> ~ 20 % propability

# *Towards SIDDHARTA-2*

proposed new operation scheme of DAFNE:
Experiments in both interaction zones.
After 1st KLOE data taking period done, eventual beam slots for SIDDHARTA-2 in 2012,2013 .. ?

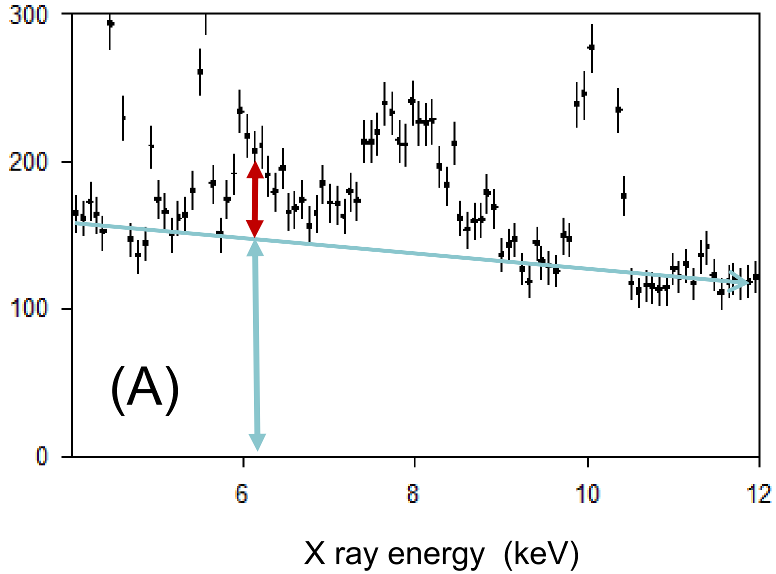


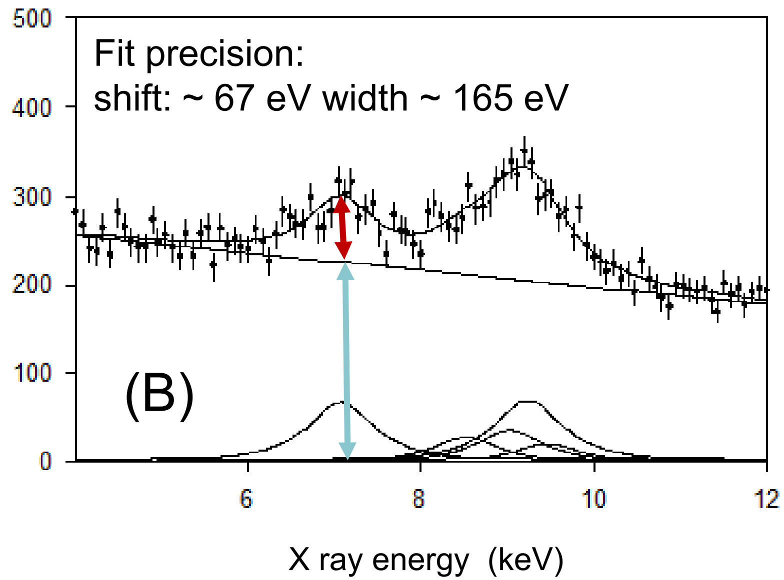


# *Requirements for a Kd measuremant*

SIDDHARTA Oct 2009 *data*
Lum = 100 $pb^{-1}$
I(2-1) ~ 700 events



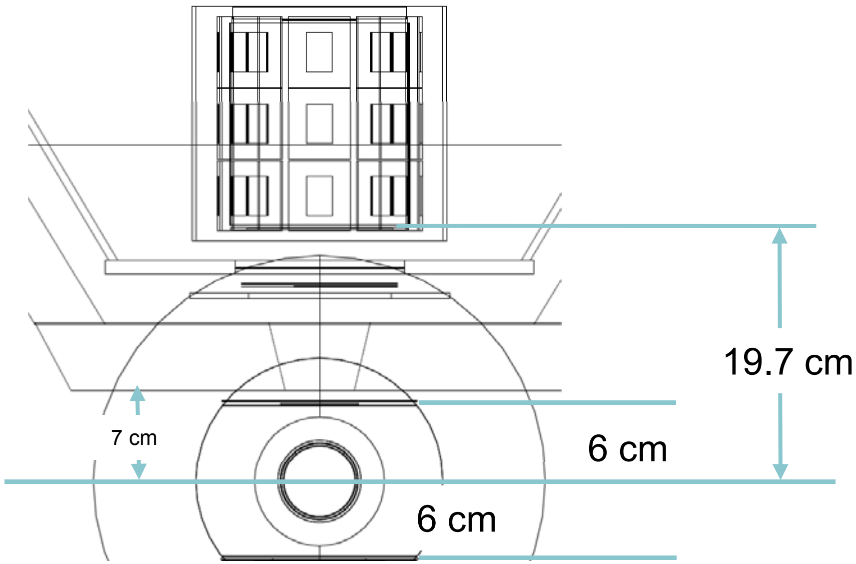

SIDDHARTA-2 *simulation* for
shift = -800 eV width = 800 eV
intens: 1000, 500, 200, 1200, 600, 100



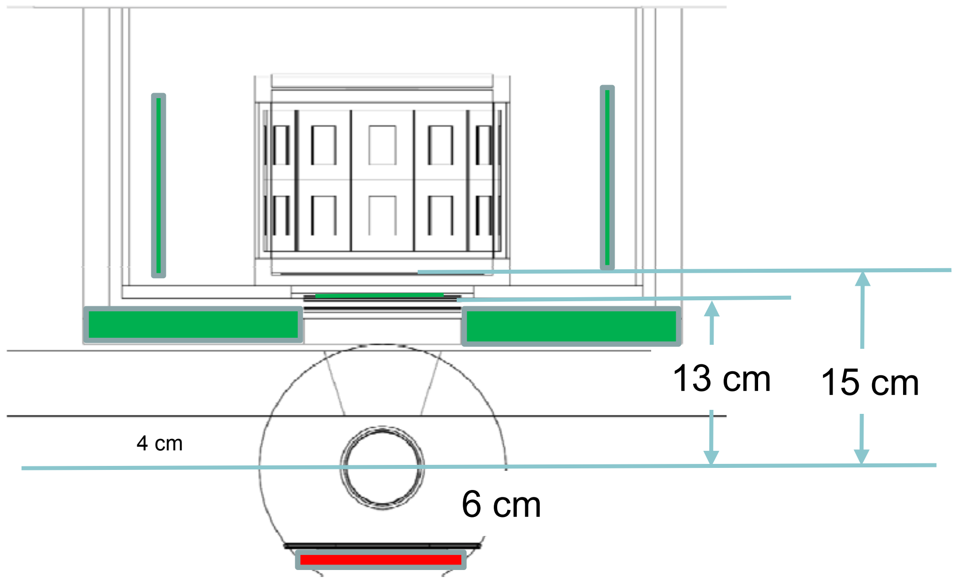

for yield ~ 1/10 of Kp yield and width ~ 2 Kp width
we need
~ 20 times reduction of background to get similar S/B
~ 1000 $pb^{-1}$ to get 1000 events in Kd (2-1) if efficiency of the setup is doubled

# *Compilation of changes*

Siddharta Oct. 2009




proposed SIDDHARTA-2 setup

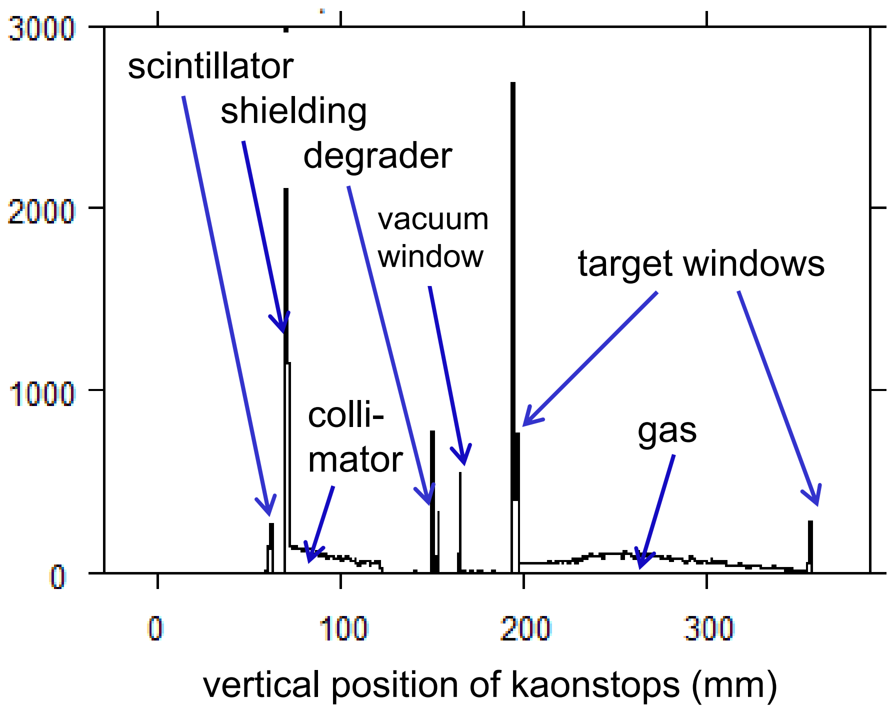


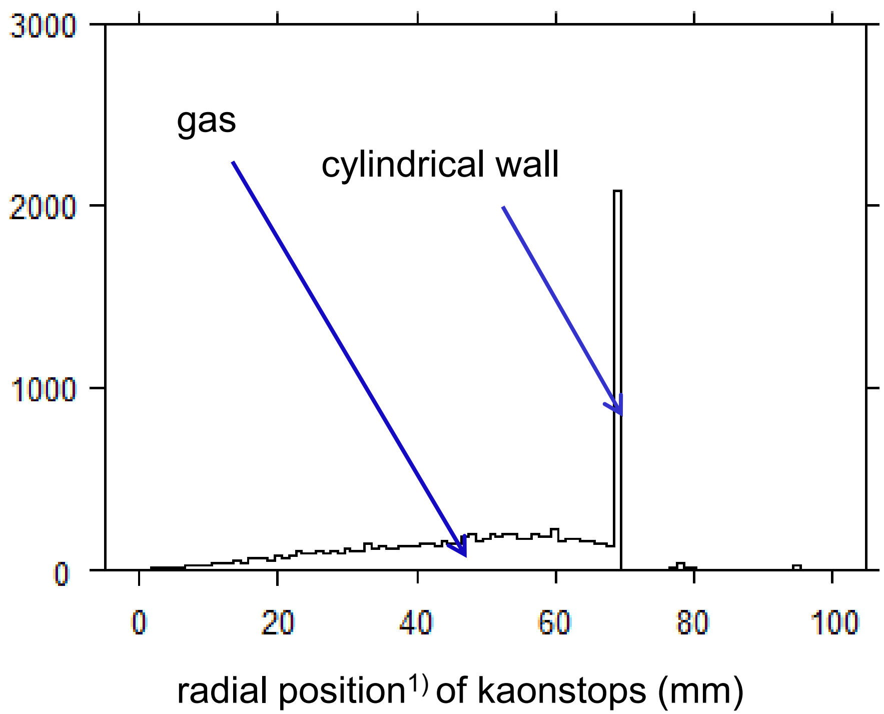

changed **geometry and gas-density**
added **kaon livetime counter** for $K^{+-}$ discrimination
added **anticounters**

Representation of the SIDDHARTA setup used in the Monte Carlo simulations.

The proposed SIDDHARTA-2 setup: Main features: geometry closer, gas density higher, upper kaon trigger detector directly in front of the entry window, kaon-livetime detector, activ shielding by anticoincidence counters, better timing resolution of the SDDs

# *Geometry and gas-density*




Simulation of kaon stopping (triggered events only)
for the configuration of Sept./Oct. 2009

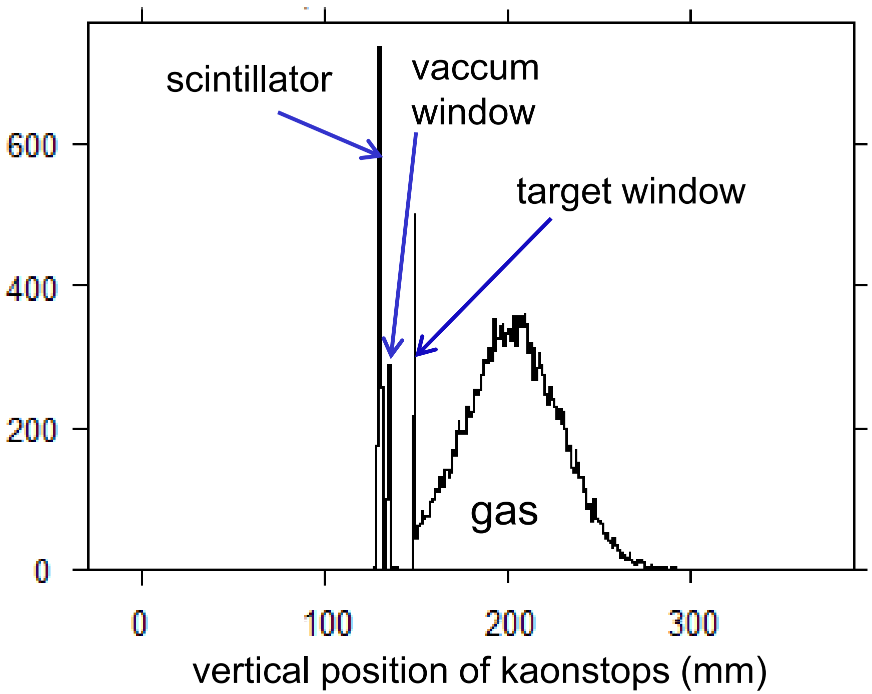
[1] for stops in the vertical range of the target cell

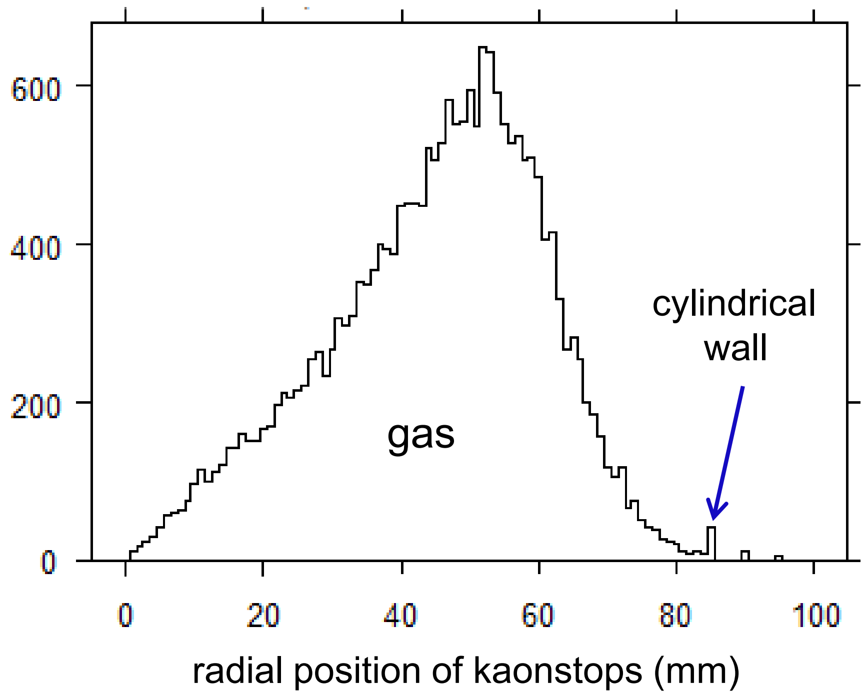
gas density ~ 1.5 % LHD

upper kaon trigger scintillator
49 x 60 $mm^2$
60 mm above IP

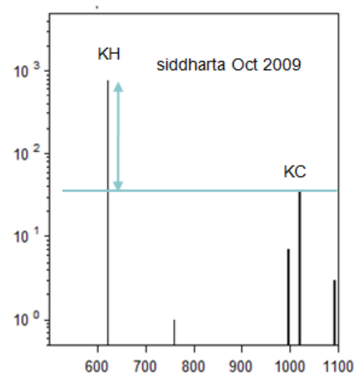
# *Geometry and gas-density (cont‘d)*

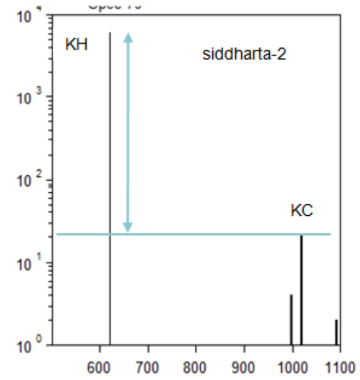
Simulation of kaon stopping (triggered events only) for the configuration of SIDDHARTA-2.
gas density 3 % LHD      upper kaon trigger scintillator:    90 mm diameter,   *near target window*



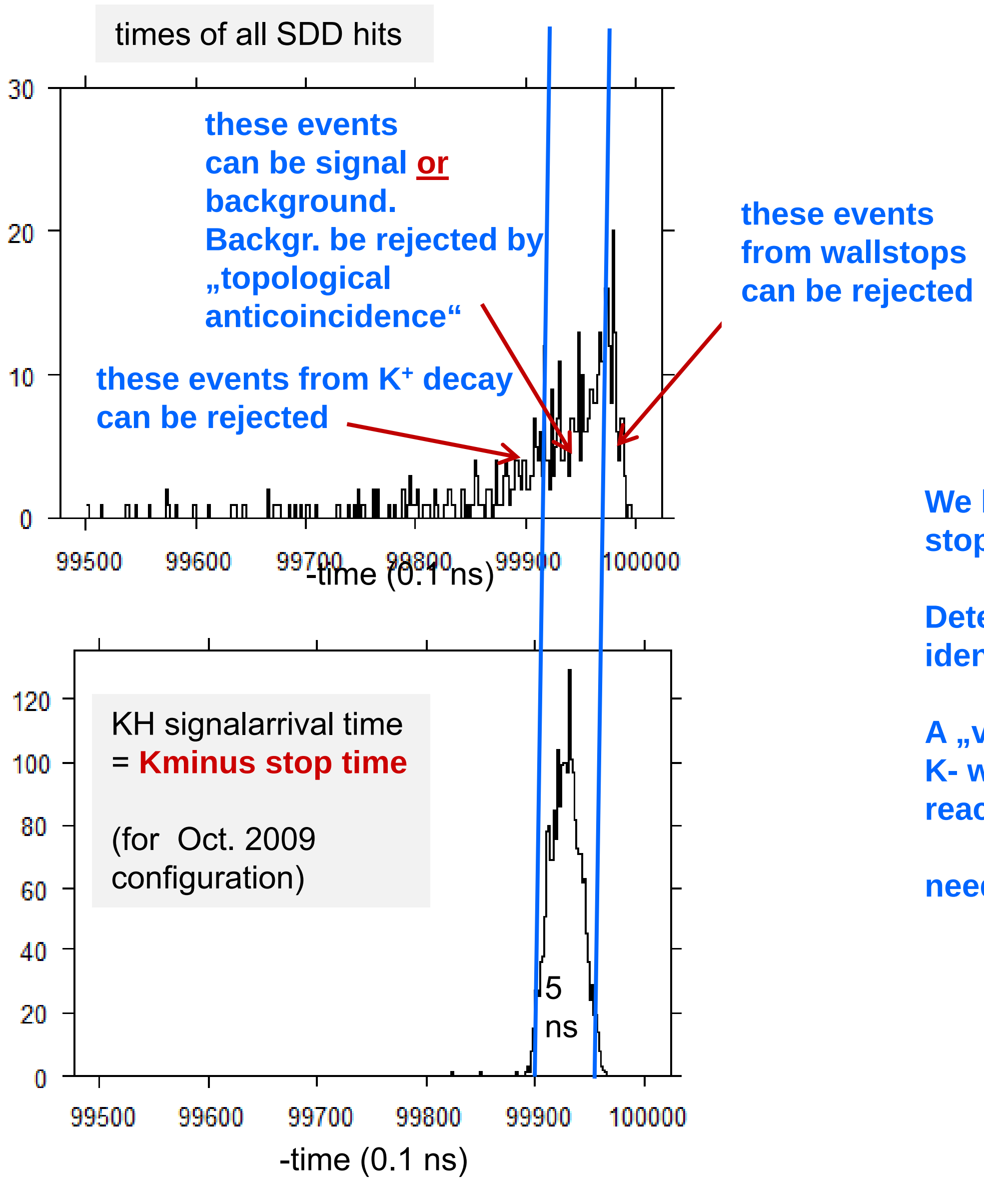




the fraction of triggered Kaons stopping in wall materials can be reduced drastically;
The *background from kaonic lines per gasstop is improved by ~ 20*



# *Detection of $K^-$ absorption secondaries by the scintillators*



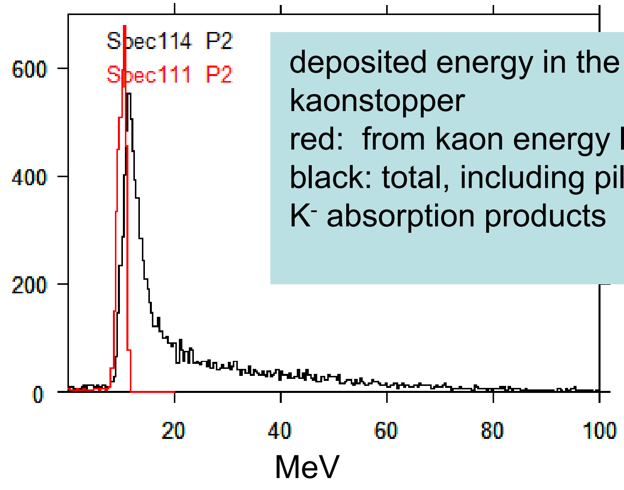

**We know the time window for kaons stopping in the gas.**

**Detection of delayed secondary identifies a $K^+$ which can be rejected.**

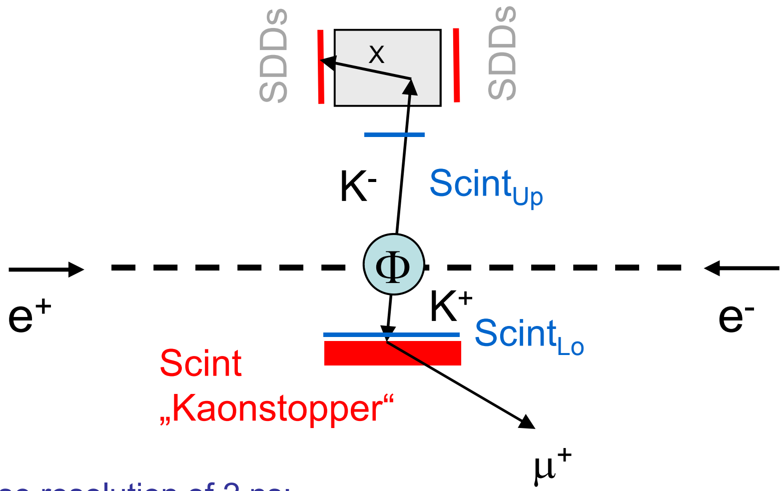
**A „very prompt“ secondary means that the K- was stopped and absorbed before reaching the gas ..reject.**

**need large solid angle!**

# $K^{+-}$ discrimination

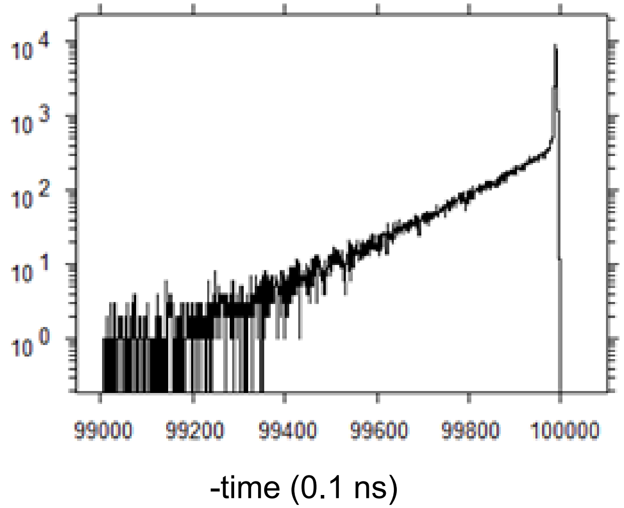



deposited energy in the kaonstopper
red: from kaon energy loss
black: total, including pileup with $K^-$ absorption products

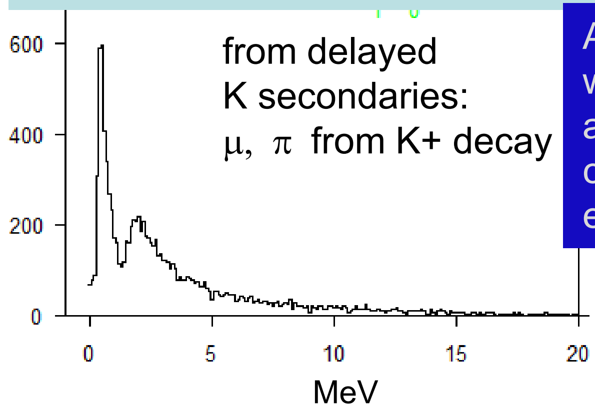



for a double pulse resolution of 2 ns:
if the stopped Kaon was a $K^+$ we will see the decay particles with high propability: $e^{-2/12.2} = 0.85$

time of last hit in the kaonstopper




deposited energy in the kaonstopper
... delayed gate

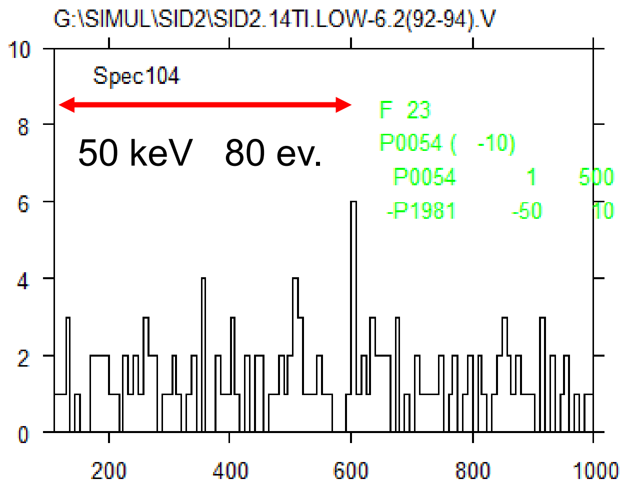



from delayed K secondaries:
μ, π from K+ decay

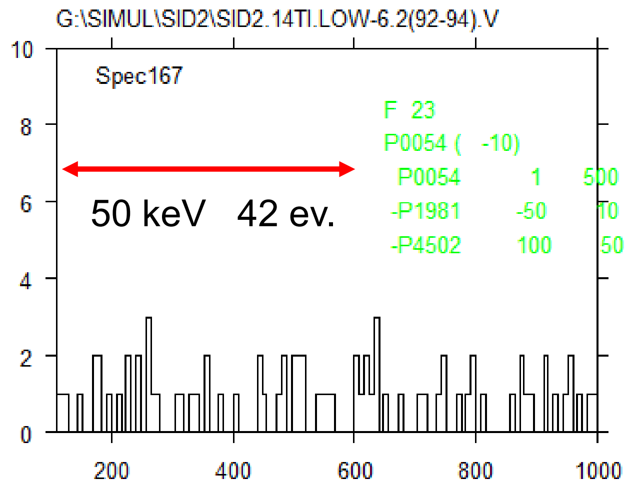
A flash-ADC with 100 ns range and < 1 ns resolution can give double hit and energy information

# *Kaon correlated continous background*

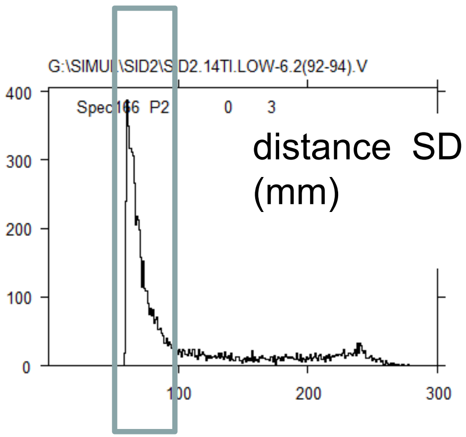
w/o with
prompt topological anticoincidence*)




dep. Energy 0.1 keV / chan




dep. Energy 0.1 keV / chan




distance SDDhit - Anticounterhit (mm)

*) muons and pions from kaon decay or absorption, passing through SDD and anticounter behind are removed.
Detected signal KD X-rays accompanied by a pion from kaon absorption **remain,** because the pion goes another direction (big distance of the hits)

kaon-correlated: kaonic X-rays from wallstops /Signal; continuous background /Signal /keV at ROI

| | new geometry & gas density | better timing resolution | $K^{\pm}$ discrimination | del'd anti-coincidence | prompt anti-coincidence | total improvement factor |
|---|---|---|---|---|---|---|
| Signal | 2.5 | | 0.8 | | | **2.0** |
| kaonic X-rays from wallstops /Signal | 20 | | | | | **20** |
| continuous background /Signal /keV at ROI | 3.8 (ratio of gasstops vs. decay+wallstops increased) | | 2 (events due to decay of $K^{+}$ removed) | | 2 (charged particle veto) | **15.2** |
| beam background (asynchron) | 4.8 (less trigger per signal) | 1.5 (smaller coincidence gate) | | 3 („active shielding") | | **21.6** |

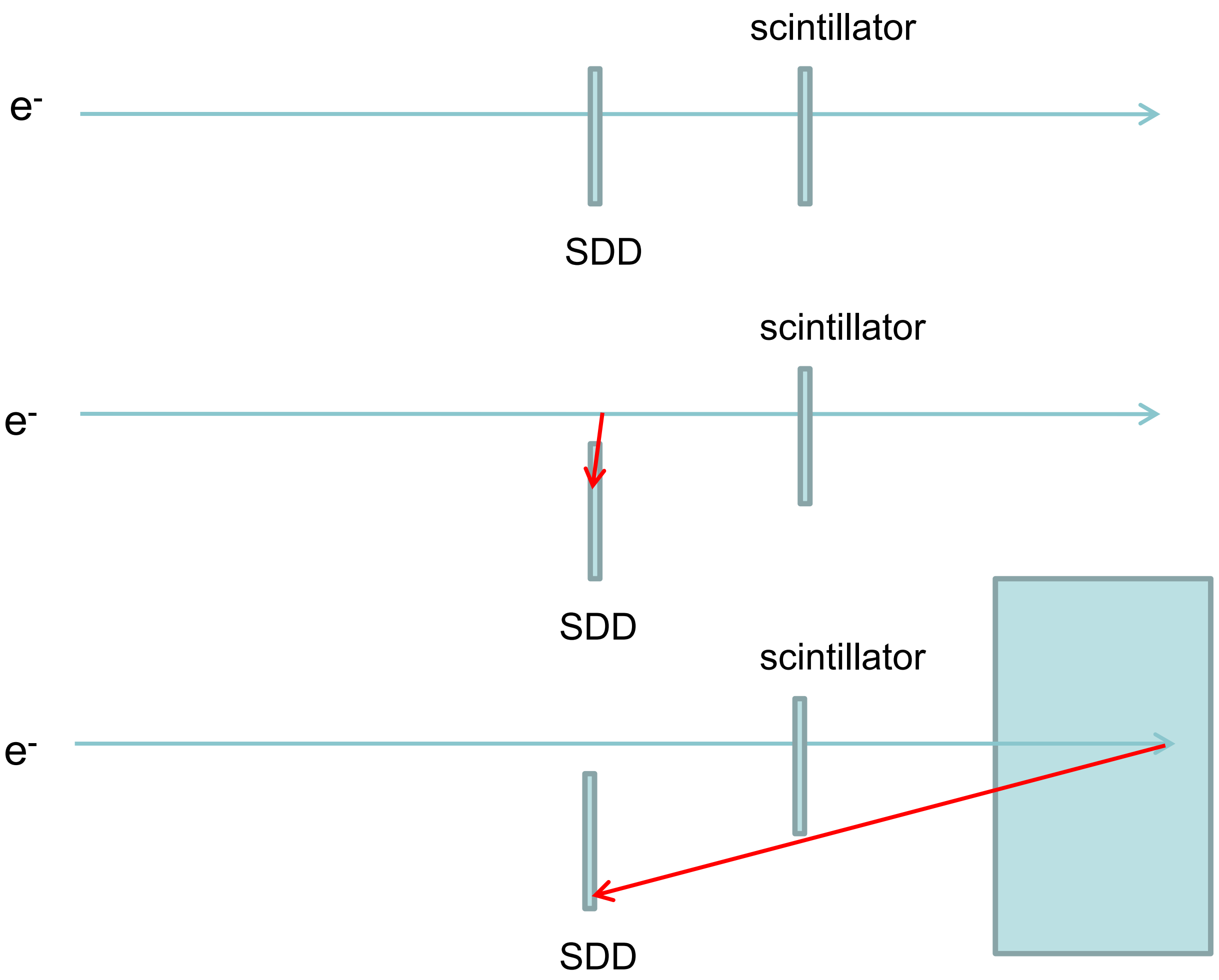
„delayed anticoincidence": the timewindow of the kaon-stopping is left out. Events during that time are $K^{-}$ absorption secondaries, which are welcome.

„prompt anticoincidence": if the topological distance of the SDD and the scintillator seeing the particle is small, then remove the events, it is likely to be a MIP passing the SDD.
Large distance: The SDD hit may be kaonic X-ray signal, acompanying kaon absorption.

CONCLUSION: IF the future DAFNE background in the FINUDA pit is comparable to the 2009 background at the KLOE side, and the Kd yields are not much smaller then 1/10 of the Kp yields THEN a quantitative Kd measurement is feasible (with ~ 1000 $pb^{-1}$)

# *Example for preparatory measurements*

512 MeV electrons from BTF, SDD + scintillator, get response to MIPS !




case 1:
low energy tails in SDD-response to traversing MIP

case 2:
X ray or e produced nearby, in SDD module

case 3:
X ray or e produced from showers in massive material

# *Summary and Outlook*

Measurements of kaonic helium: see talk of T. Ishiwatari, this conf. L$\alpha$ shifts published

$K^-p$ results:
shift $\varepsilon_{1s}$ = -283+-36+-6 eV width $\Gamma_{1s}$ = 541+-89+-22 eV
published in Phys. Lett. B

$K^-d$ first measurement ever, exploratory measurement, signal hints, significance ~ 2$\sigma$

hopefully.. extension of the experimental program: SIDDHARTA-2
with improved technique - measure Kd, other light atoms, heavys, Kp $\rightarrow \gamma \Lambda^*$
Preparations under way. Start 2012,13 ?

Thanks for your attention !