Kaonic atoms measurements at the DAΦNE collider: the SIDDHARTA experiment

Young Researchers Meeting Rome 2012

Tor Vergata - 20 January 2012 - Third Edition

Alessandro Rizzo, LNF - INFN and University of Rome “Tor Vergata” - On the behalf of the SIDDHARTA collaboration

The SIDDHARTA collaboration

- 9 Institutes from 6 different countries around the world:

LNF-INFN, Frascati, Italy

SMI-ÖAW, Vienna, Austria

IFIN - HH, Bucharest, Romania

Politecnico, Milano, Italy

MPE, Garching, Germany

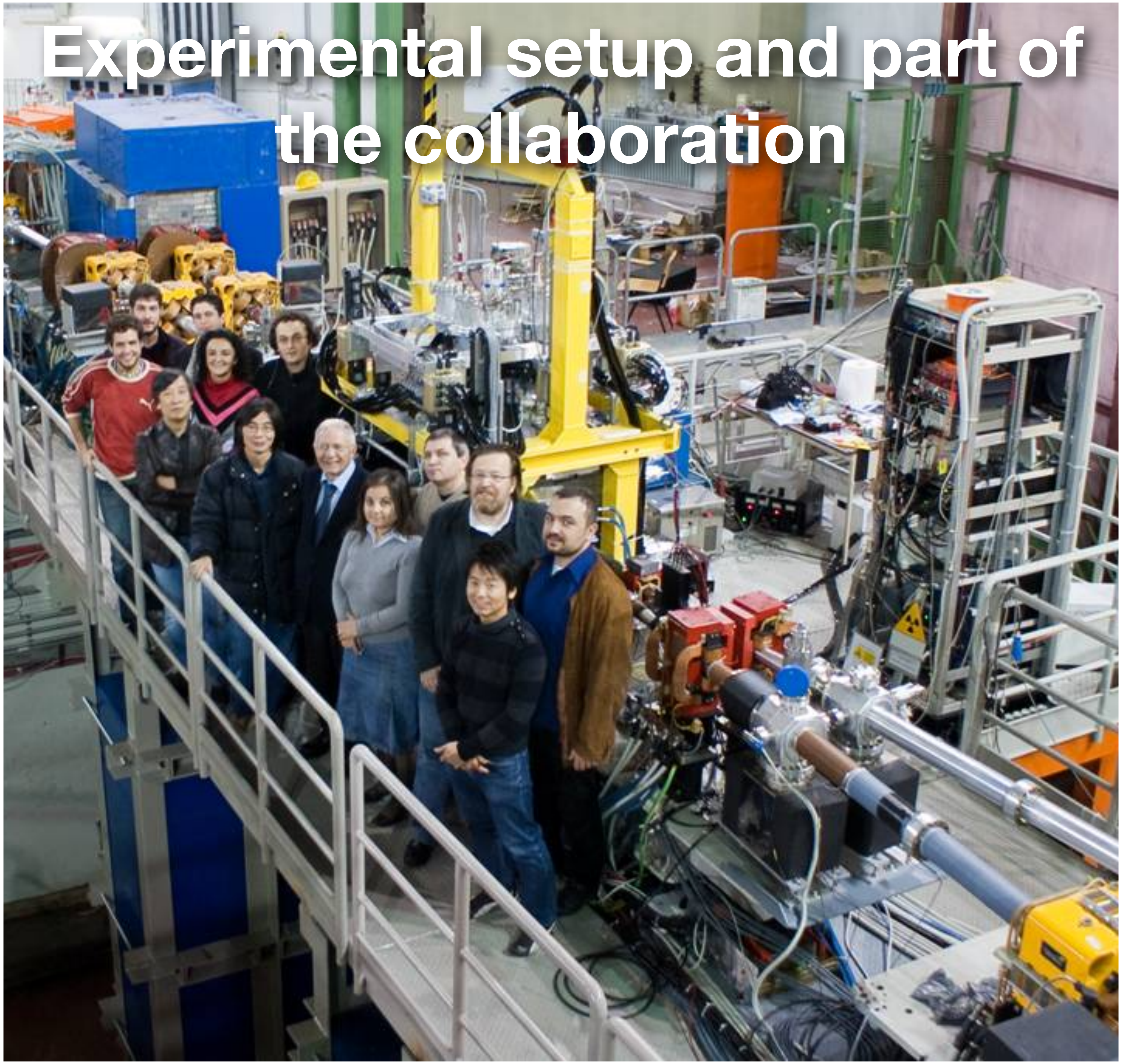
PNSensors, Munich, Germany

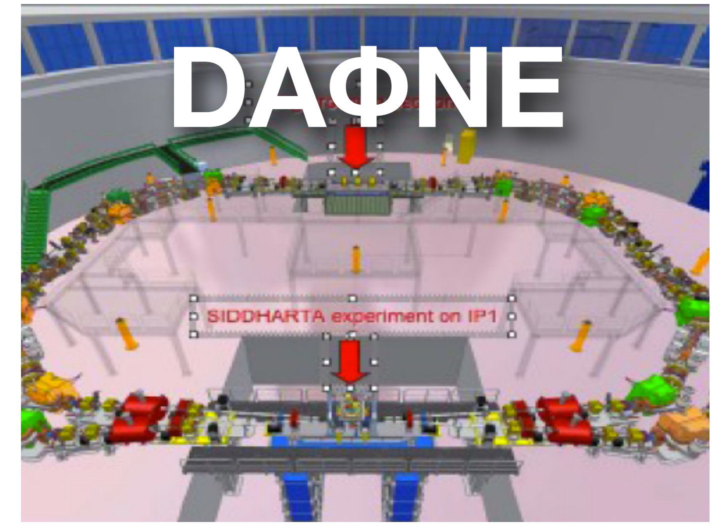
RIKEN, Japan

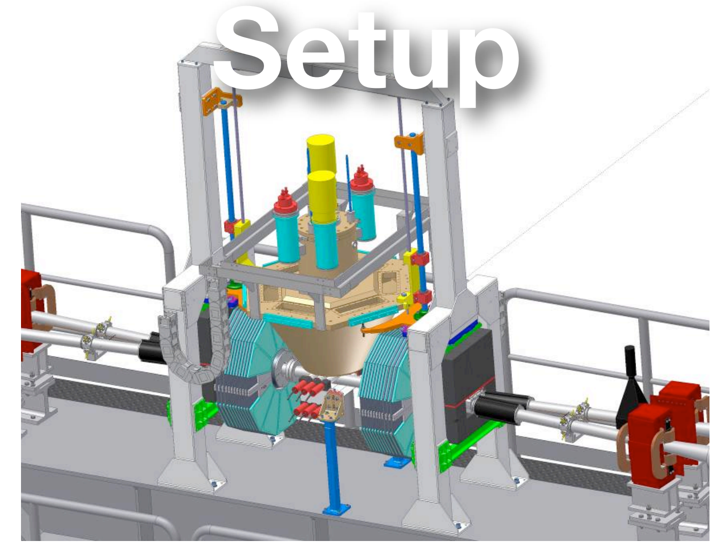
University of Tokyo, Japan

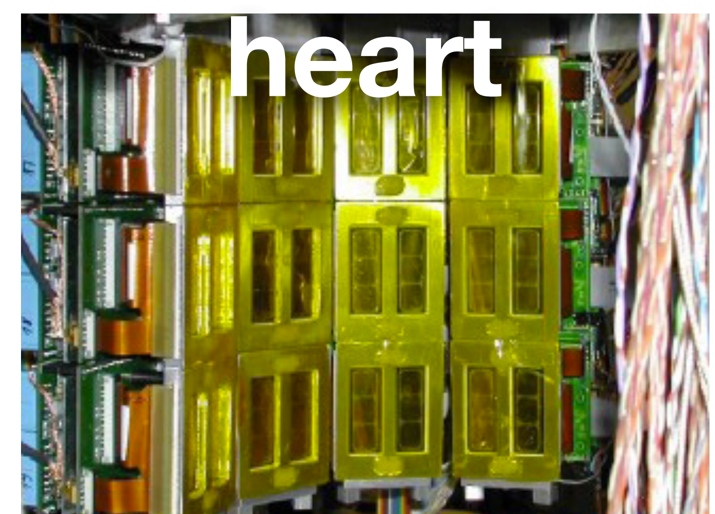
Victoria University, Canada

European Project









SIlicon **D**rift **D**etector for **H**adronic **A**tom **R**esearch by **T**iming **A**pplications

Overlook

- **Light Kaonic Atoms - Strong Interaction at low energies**
    - The 4 main phases of the “life” of an exotic atom
    - A closer glance to the cascade process
    - Cascade process in kaonic Hydrogen and Helium - competitor processes
- **The SIDDHARTA experiment**
    - Silicon Drift Detectors for spectroscopy
    - The experimental apparatus peculiarities
    - An example of the SIDDHARTA data: rejection of the background
- **Analysis Results**
    - KH results and the first explorative KD measurement
    - K^4He results
    - K^3He results
    - Future Perspectives

Light Kaonic Atoms

Main Phases and Peculiarities

SIDDHARTA: study of light kaonic atoms @DAFNE

What: **Bound systems**

Light Kaonic Atoms ∈ Hadronic Exotic Atoms [1][2]

Why: **K^- very near to the nucleus**: ideal framework to study **non-perturbative QCD** in the strangeness sector [2]

How: Peculiarities of an exotic atom: **4 main phases** [3]

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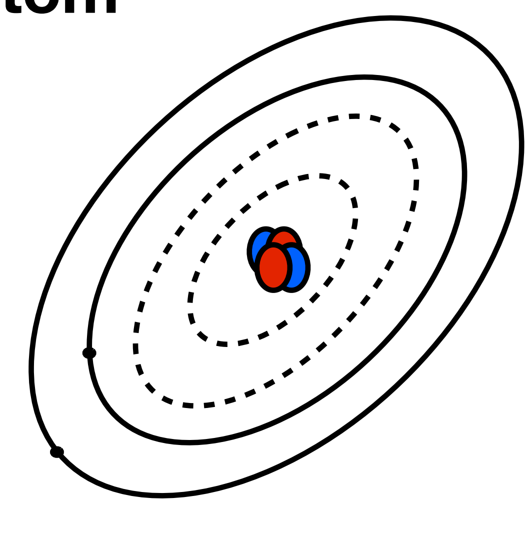

K^-

- **Capture** — K^- capture and atomic electron expulsion [4]
- **Formation** — Formation of the new bound system, with the main quantum number given by the formula: (KH n_0=29, K^4He n_0=25) [13]

$$n_0 = \sqrt{\frac{\mu}{m_e}}$$

  - μ = exotic atom reduced mass
  - n_e = capture orbital m.q.n.
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- **Cascade** — From n_0 level, K^- starts a series of em transitions towards the low energy levels. In the last transitions, when K^- is nearest to the nucleus, there is the strong force contribution too. [5]

  Last transitions: Radiative (X-ray band)! γ brings information about strong interaction!

  Through a precision spectroscopic measurement of KH, K^3He and K^4He transitions, SIDDHARTA allows to study non perturbative-QCD in the strangeness sector in system with few nucleons

- **Absorption** — End of the bound system with K^- nuclear absorption [6]

  LKA life-time ~ 10^(-12) sec
  K- lifetime = 1.24×10^(-8) sec

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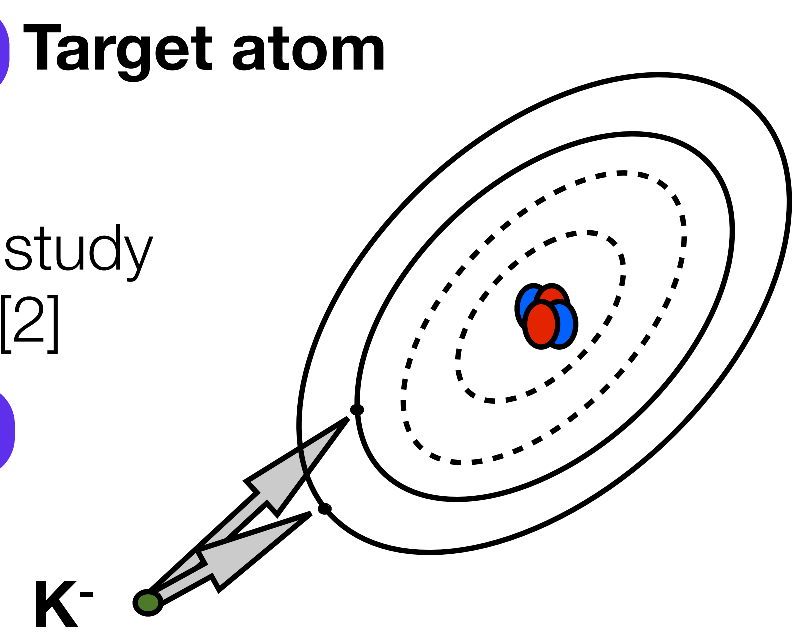

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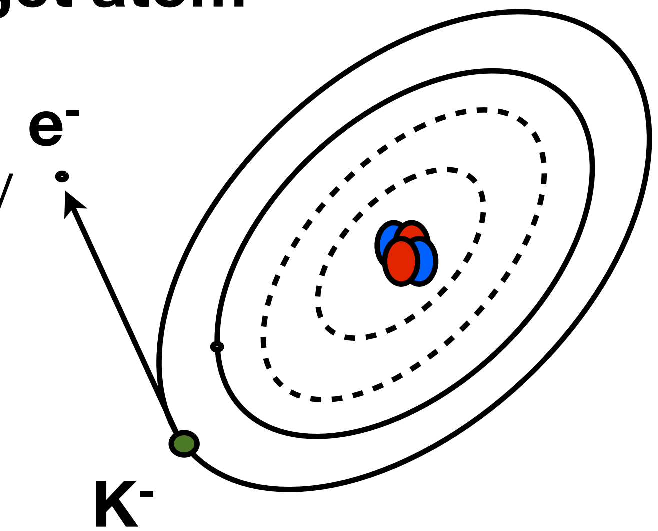

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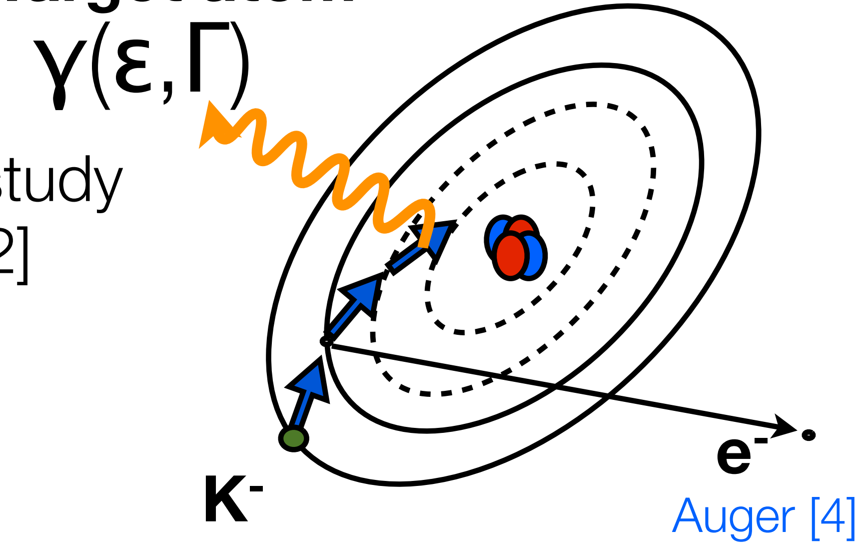

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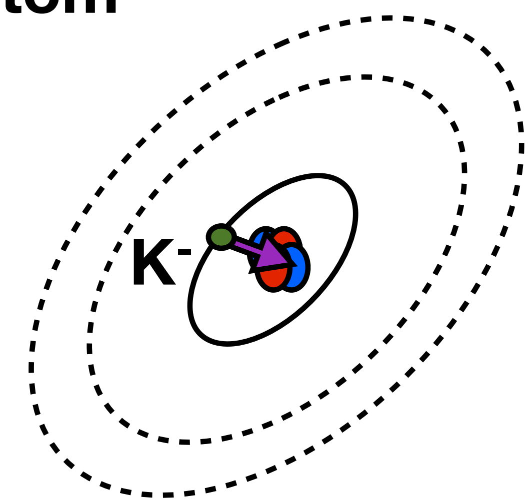

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The cascade process

.. and the strong interaction studies at low energies...

The Cascade Process

|r| NP $n_0 = \sqrt{\frac{\mu}{m_e}}$

CASCADE: 3 different phases function of the distance NP - Nucleus [6]

e^-
e^-
e^-

Depletion of the atomic shells

Electrons expulsion through **Internal Auger effect** [6]

Till total Depletion

hydrogenoid system NP - Nucleus [4][6]

START: Transition Energy > Electron (below) Ionisation Energy [6]

$\Gamma_\alpha \propto (\Delta E_{nn'})^{-1/2}$ $\Delta l = \pm 1$ [6]

Radiative Disexcitation suppressed by Auger emission for transitions with $\Delta n=1$

Point-like Nucleus Regime

Radiative Transitions ← **EM Interaction**

Energies: f(EM interaction, NP mass, A) (~KeV)

Taking the same value of the mass for an hadron and a lepton, the energies of the transition are in principle the same!

Particle-Nucleus interaction

Radiative Transitions ← **EM + STRONG**

Deser-Trueman Formula
No Isospin breaking corrections
[7][13][14]

$$\epsilon + i\Gamma/2 = 2\alpha^3\mu^2 a_{K^-p} = (412\ eV\ fm^{-1})\, a_{K^-p}$$
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Shift (ϵ) of the level energy [6]

Broadening of the width (Γ) of the level [6].

Complex scattering lengths [6]

Link between theory and the experimental measurement!

The Cascade Process

$n_0 = \sqrt{\frac{\mu}{m_e}}$

|r|

NP

e⁻

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From the measurement to the theory and back...

THEORETICAL $2\alpha^3\mu^2 a_{K^-p} = \varepsilon + i\Gamma$ **EXPERIMENTAL**

$a_{K^-p} = \lim_{p_K \to 0} T$

Deser-Trueman formula (no isospin breaking therms)

Complex Potentials in: **Klein-Gordon eq.** **Dirac eq.** **Schrodinger eq.**

Testing different optical potential models

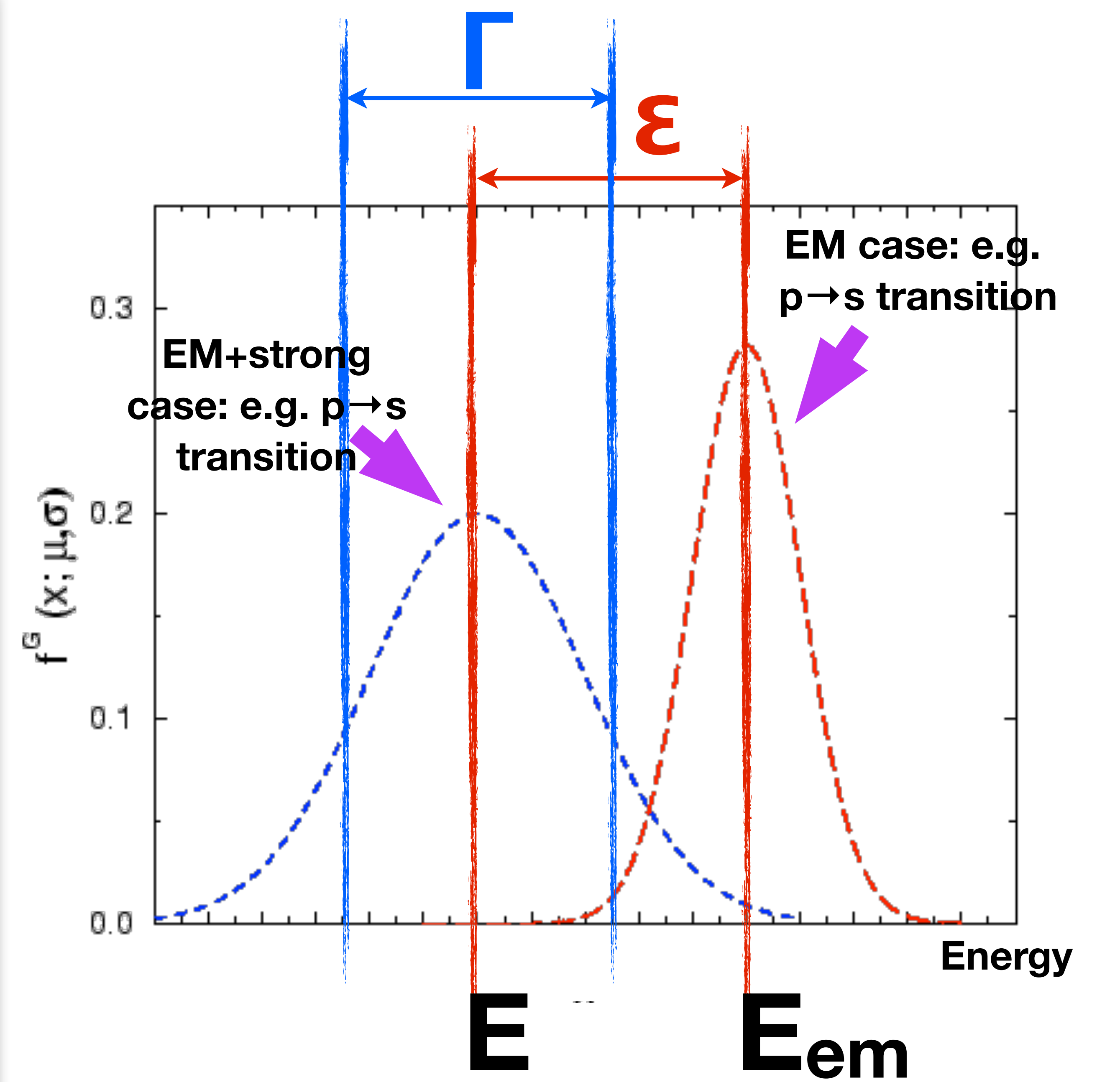
Chiral Perturbation Theory **Meson-Baryon effective Lagrangian**

Bethe-Salpeter eq. (Full Scattering Amplitude): $T_{K^-p \to K^-p}$

$a_{K^-p} = [T_{K^-p \to K^-p}]|_s$

Testing Chiral SU(3) dynamics and explicit XSB [43]

NO EXTRAPOLATIONS! A REAL THRESHOLD MEASUREMENT!!!



Spectroscopic measurement

Competitors
Processes

Cascade Process in exotic Hydrogen and Helium

Competitor processes: → **If EA is alone, after Auger Expulsion** → **Only radiative Transitions!** → **External!**

EA Interact with the other target atoms or molecules! $\sigma_{coll} \approx \pi \langle r_n \rangle^2$ [6][11] → **2 kind of processes** → **Collisions** / **Pervasiveness**

Collisions

Coulombian De-excitation

- Exotic Atom scattering with other atom/molecule of the target [31] → In a collision the energy release $\Delta E_{n \to n'}$ for step n→n' is converted into kinetic energy of x⁻p system and H [31]

$$(x^- p)_{n\ell} + H_2 \rightarrow (x^- p)_{n'\ell'} + H + H \qquad Z = 1 \qquad 1 \times 10^9/s$$

Elastic Scattering

- Exotic Atom scattering with a molecule of the target [32] → Collision energy brings molecule in an excited state (without scission) and the hadron in a lower energy level [32]

$$(x^- p)_{n\ell} + H_2 \rightarrow (x^- p)_{n\ell} + H_2^* \qquad Z = 1 \qquad 1 \times 10^9/s$$

Non-Collisional

External Auger emission

- Only H_2: formation process happens without molecular scission [10] → hadron transition energy goes to the other molecular e⁻ [10]

$$(x^- p)_{n\ell} + H \rightarrow (x^- p)_{n'\ell'} + P + e^- \qquad Z = 1$$

Auger Expulsion! [10]

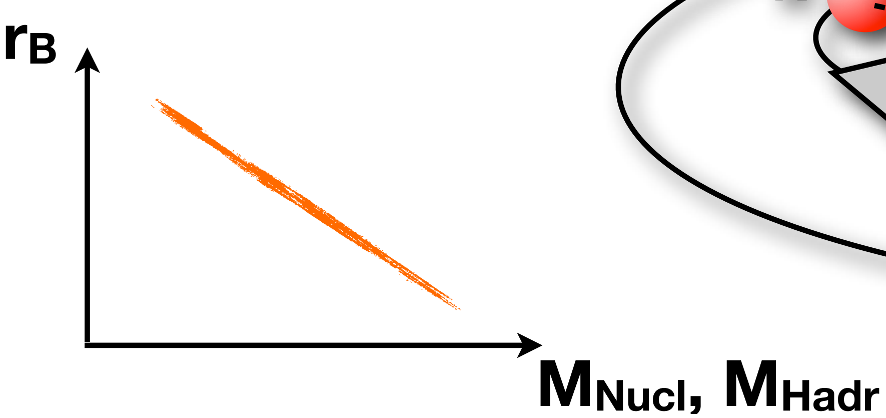
Counteract the development of a distinct circular cascade

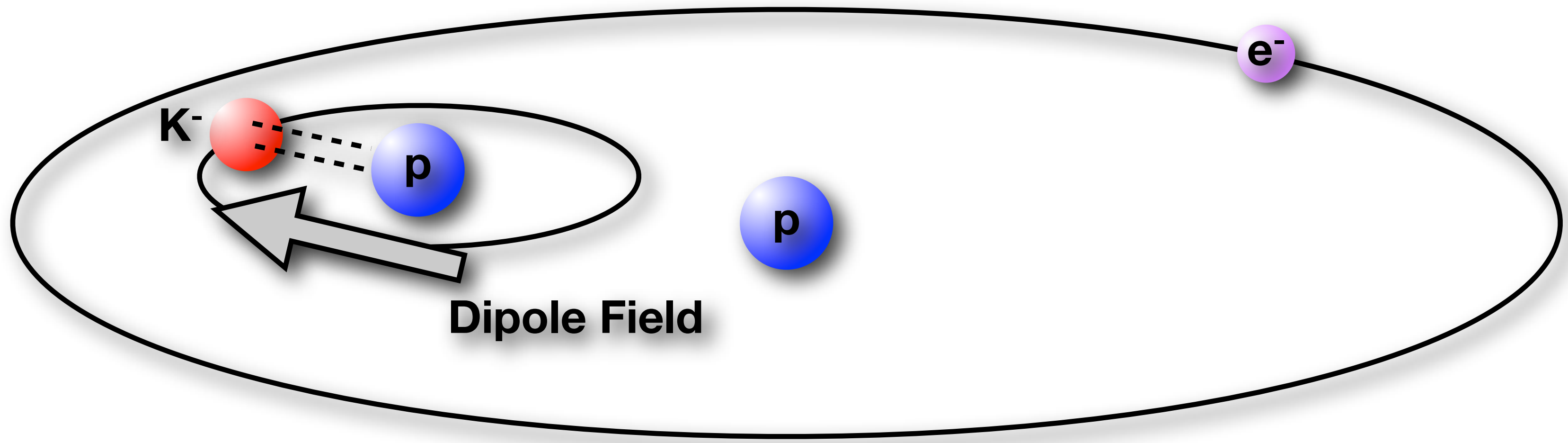
Cascade Process in exotic Hydrogen and Helium

Pervasiveness

Stark Mixing

Kaonic atoms are smaller than standard atoms!





Courtesy of Dr. S. Okada

Bohr Radius: $r_B = \hbar c / \mu c^2 \alpha Z$ [6],[9]

R_B(H)[0.5Å]≈1000 R_B(KH) [9][10]

Insertion of perturbative term H'=eEz

- e = electron charge
- E = Electric Field Intensity
- z = atomic region where **E//z**

Using Hydrogenoid wave-functions

Calculating Expectation values on |n l m>
[6] [10]

H' link states with same n and $\Delta \ell = \pm 1$

splitting in m that partially removes degeneration

energetic shift proportional to E

Density-dependent yield due to Stark mixing

Day-Snow-Sucher effect [12]

Cascade Process in exotic Hydrogen and Helium

Pervasiveness

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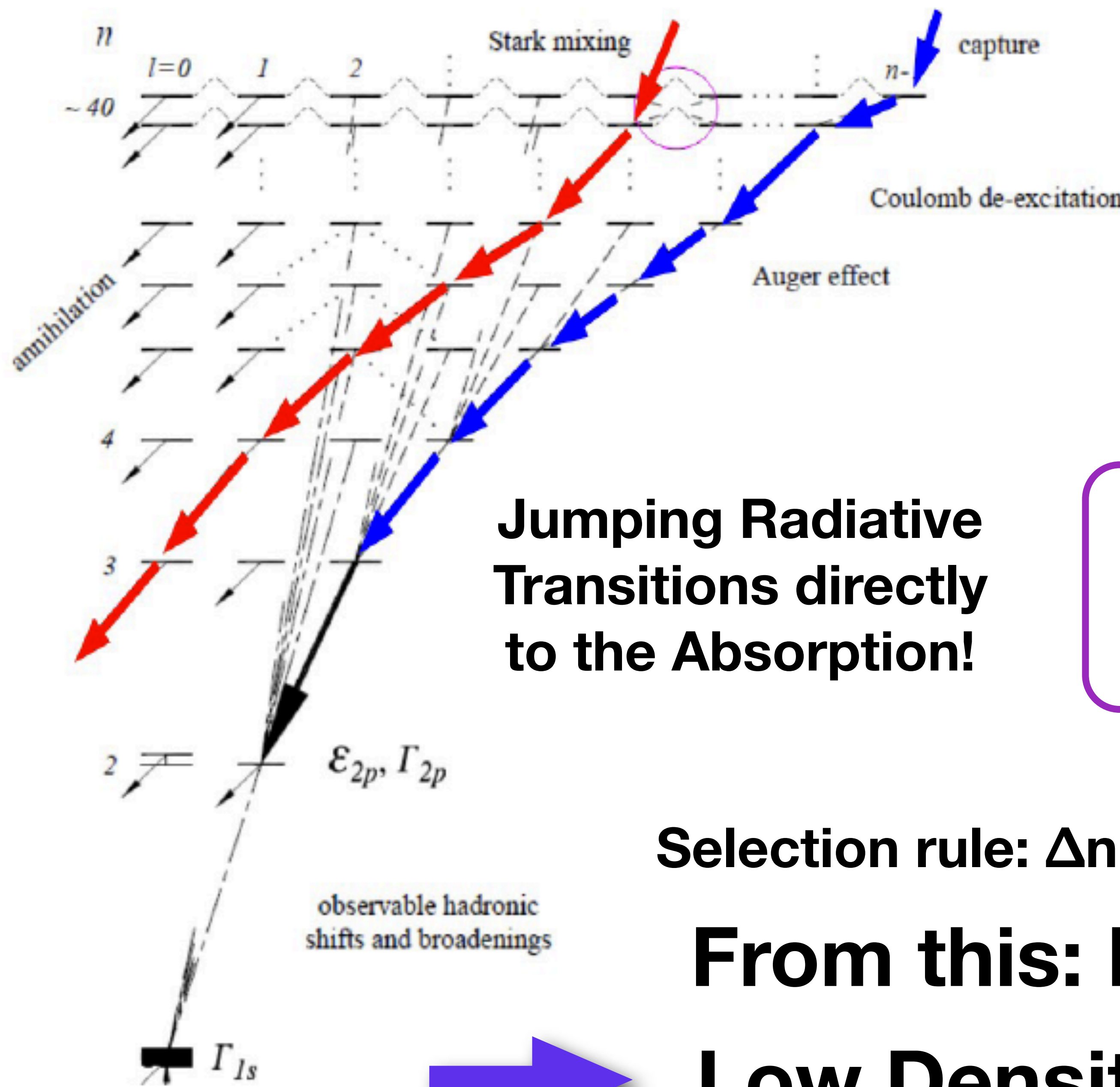


Jumping Radiative Transitions directly to the Absorption!

What's going on...

Classical Analog of a stark transition:

Deformation as a change of eccentricity and the orientation of the Keplerian Orbit along which NP moves in EA [38]

Selection rule: Δn=0, Δℓ =±1, Δm=0 [6] [10]

From this: KH puzzle (solved)

Low Density Gaseous target!

The SIDDHARTA experiment

Silicon **D**rift **D**etectors for **H**adronic **A**tom **R**esearch by **T**iming **A**pplication

Silicon Drift Detectors for spectroscopy

X-Ray spectroscopy measurement → Requests → **Good energy Resolution** / **Fast Detector**

SDD!

Detectors for tracking [17][18] → SIDDHARTA group: R&D to use them for spectroscopy

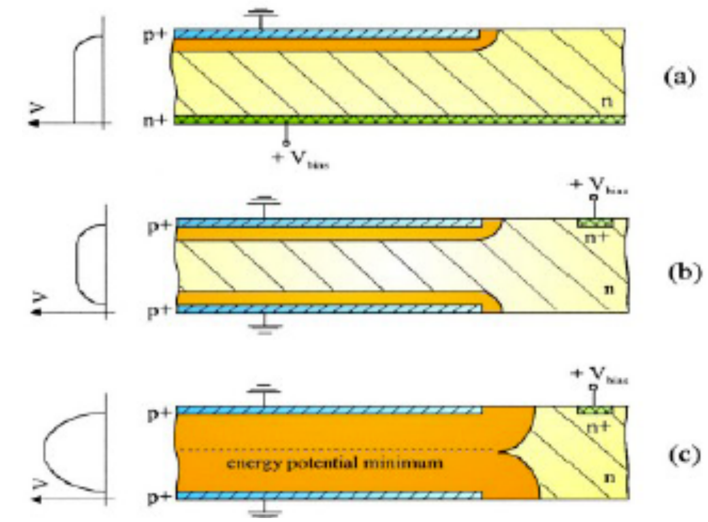
Very fast detectors → Trigger, High counts rate

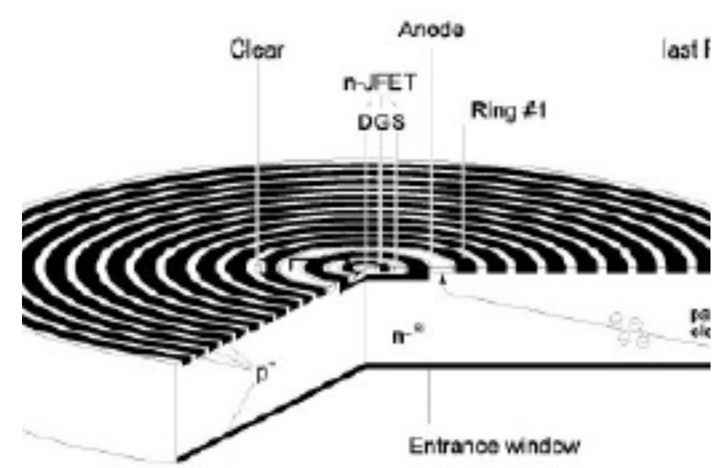
Working Principles [19]:

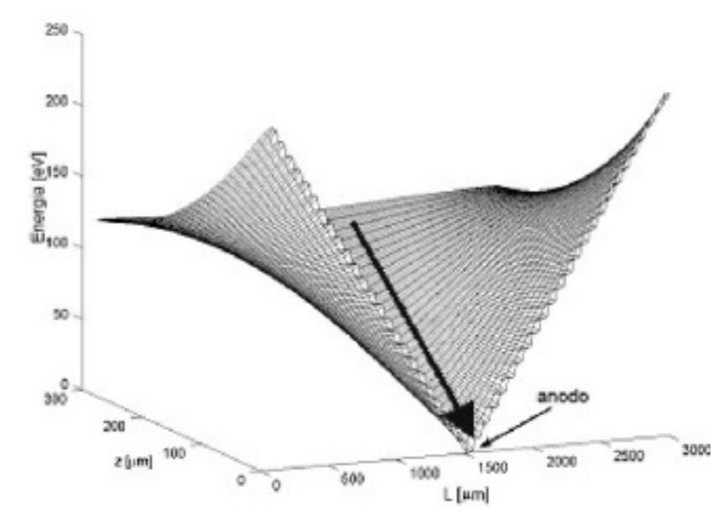
- Lateral Depletion
- Small anode capacitance
- Drift-Field

SIDDHARTA SDDs [20]:

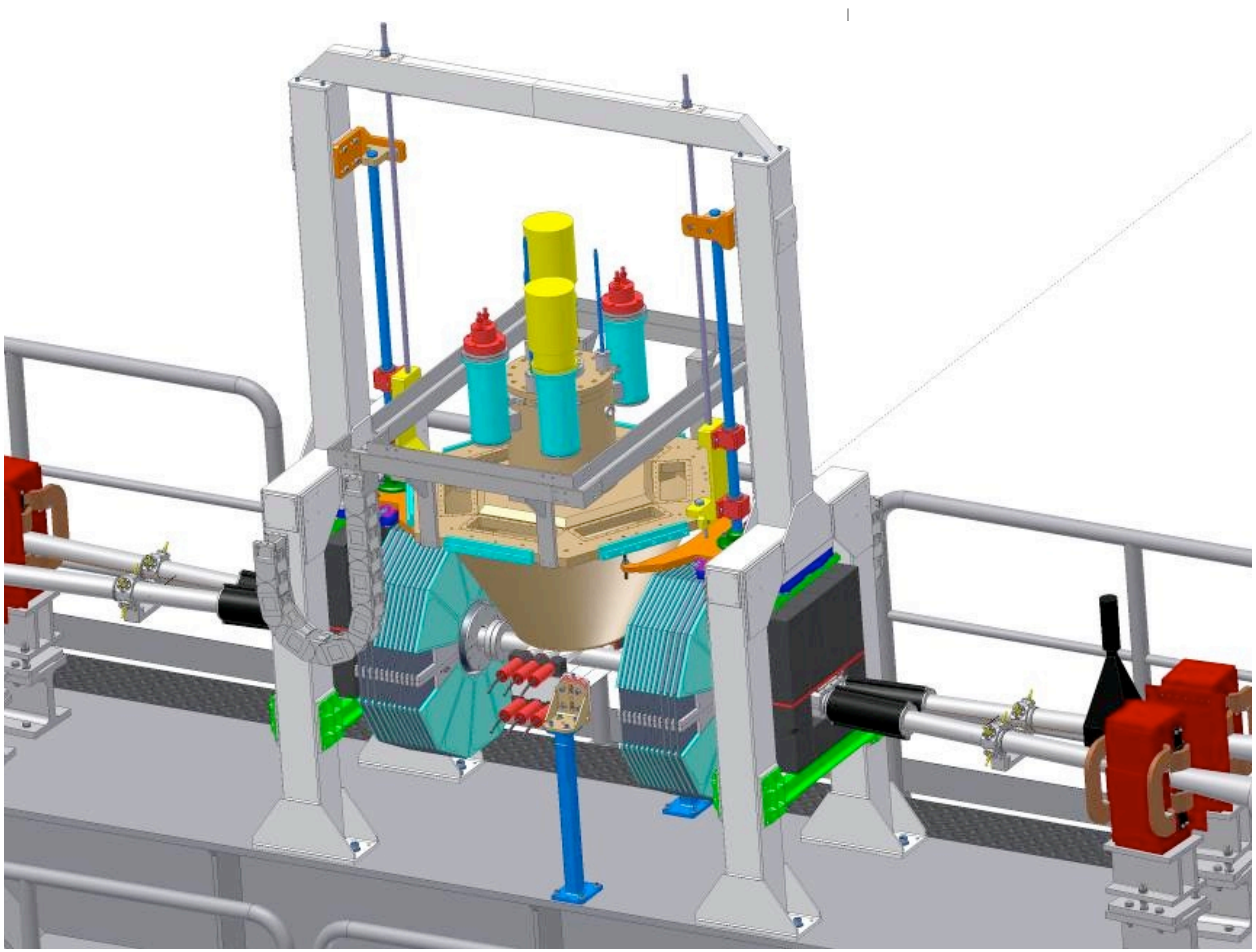
- 144 SDDs
- Arrays of 3 SDDs, $1cm^2 \times 450\mu m$
- Resolution = 150 eV@5.9KeV
- $V_{Back} \approx -120V$, $V_{Last\ Ring} \approx -250V$
- Collecting charge time 750 ns
- Total Shaping time (shaper)≈ 1 - 4 μs



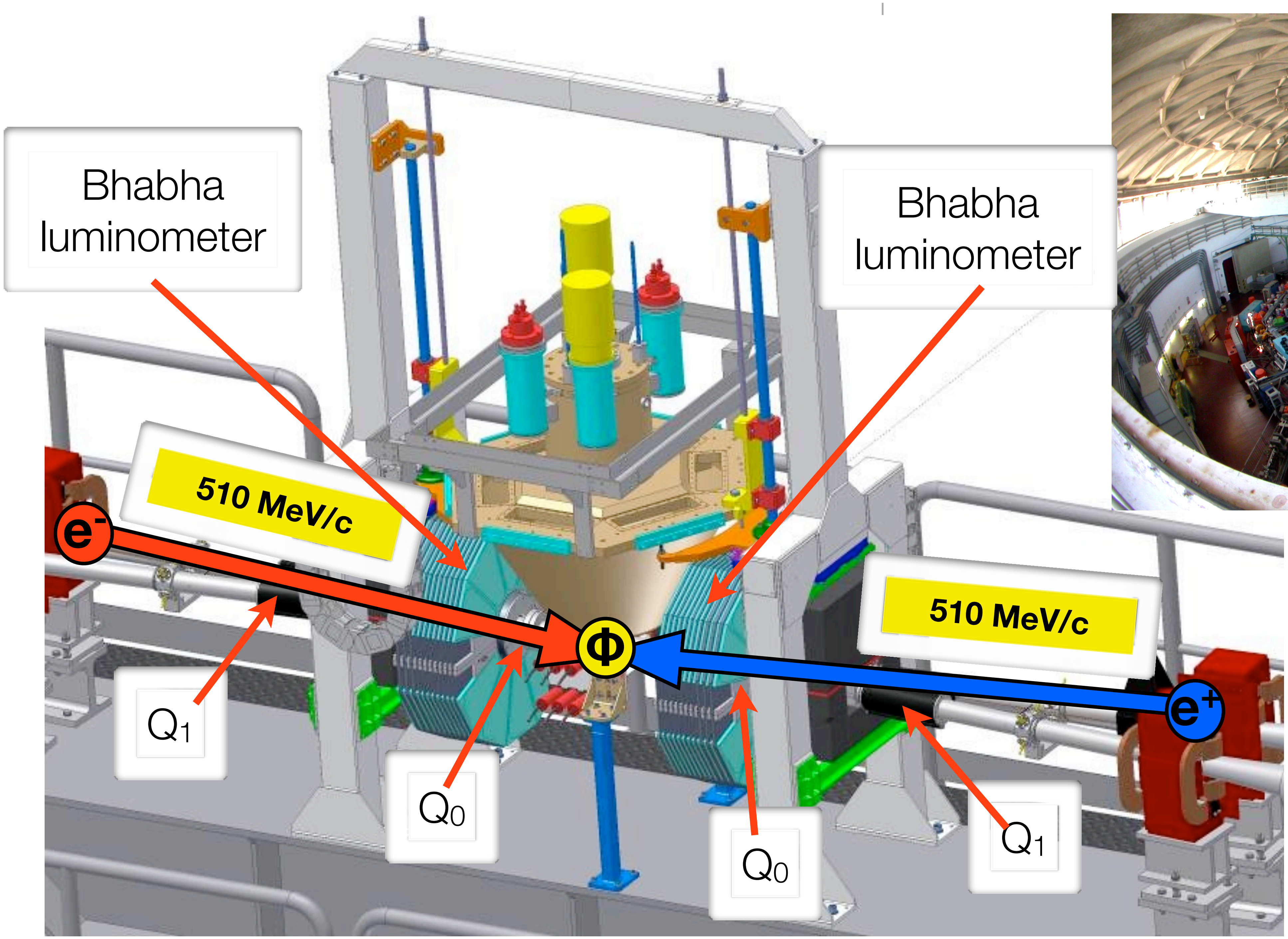




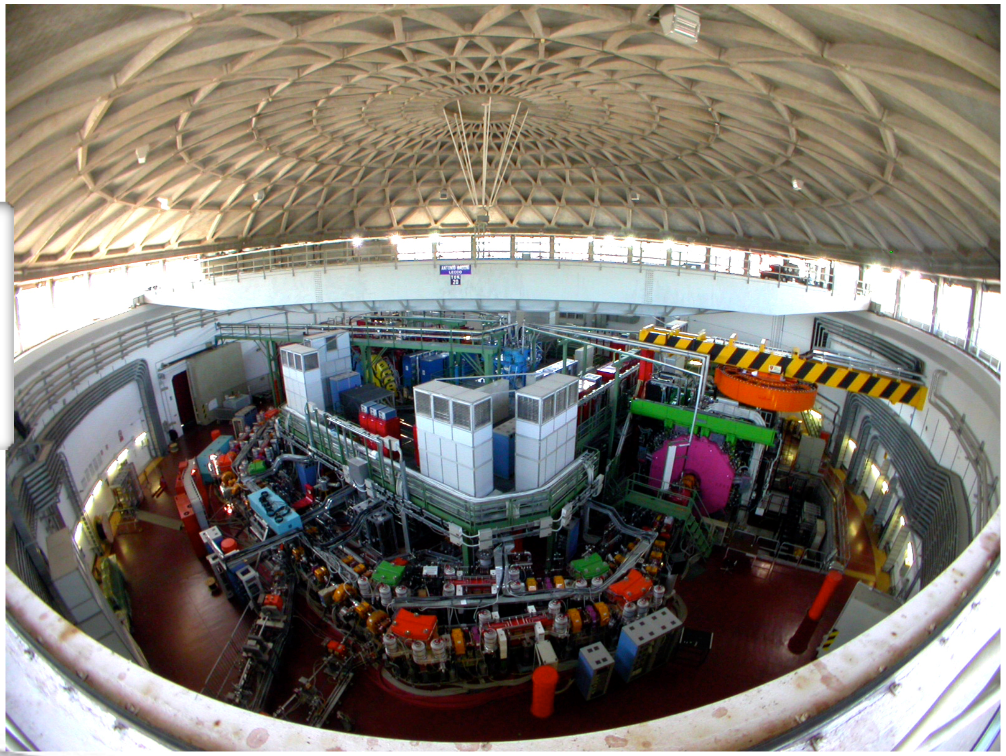
SIDDHARTA experimental setup @DAΦNE



SIDDHARTA experimental setup @DAΦNE



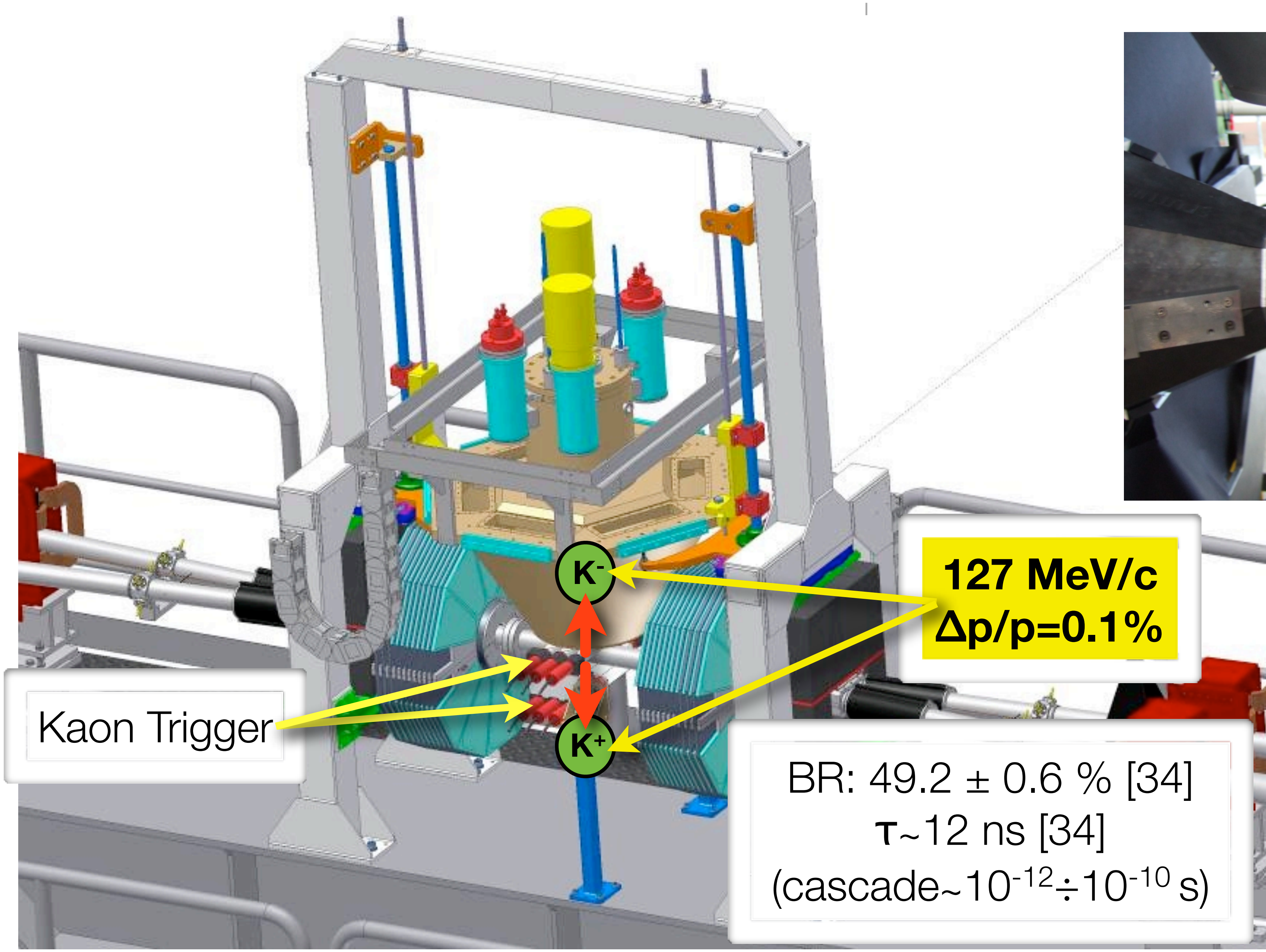
[21][22][23][24]

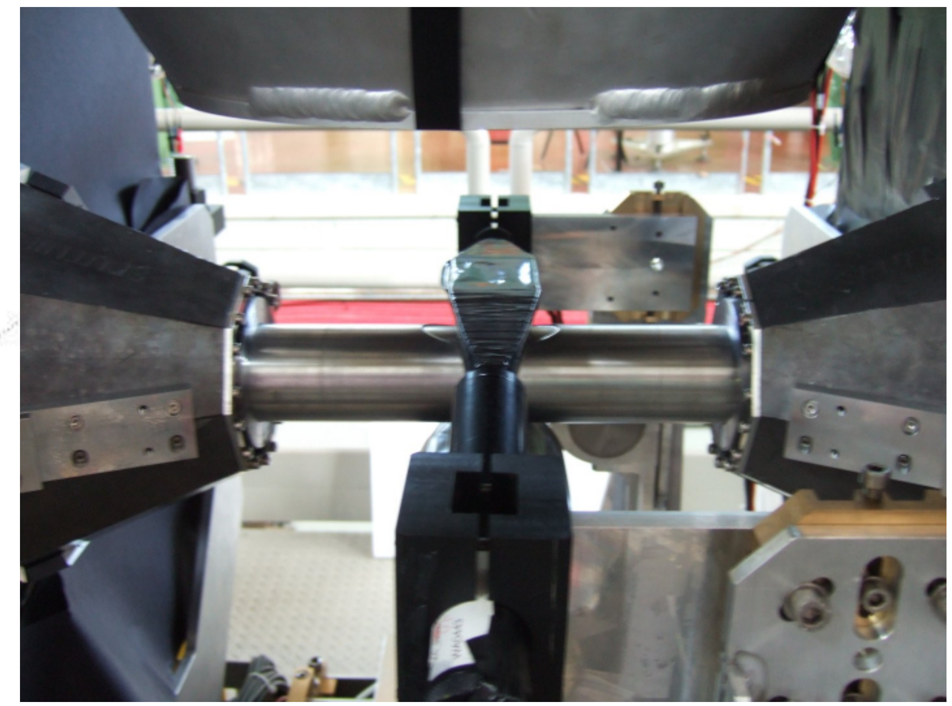


Upgraded DAΦNE

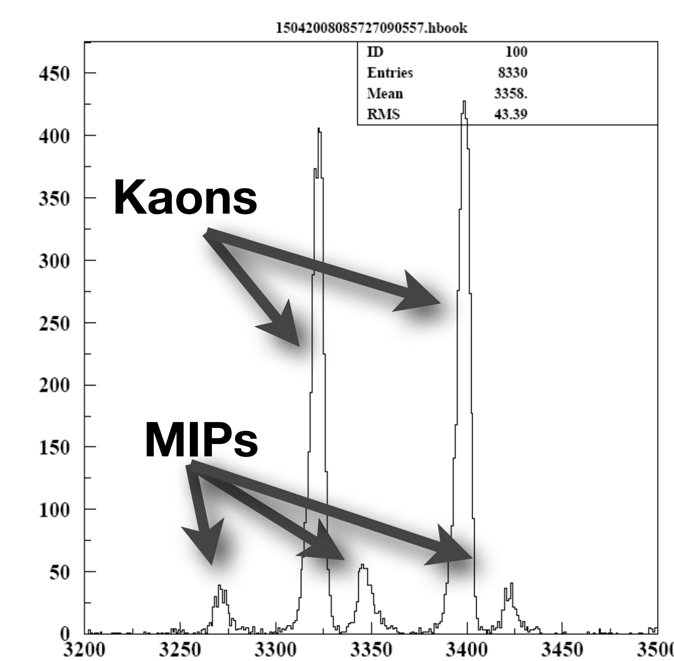
- Crab-Waist collisions [45]
- $L=5\times10^{32}cm^{-2}s^{-1}$[47]
- Monochromatic low-energy K^- (~127MeV/c)
- Less hadronic background due to the beam (compare to hadron beam line : e.g. KEK)
- couple dedicated sextupoles [45]

SIDDHARTA experimental setup





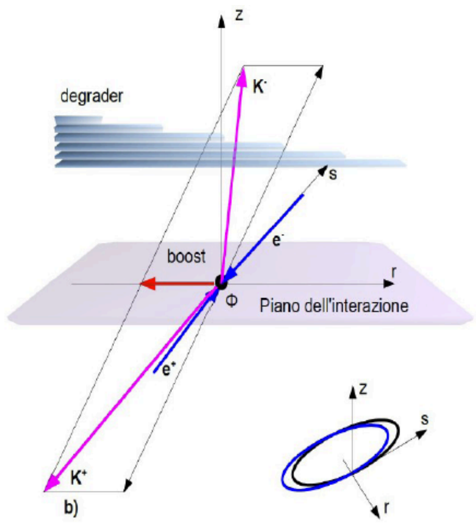
Kaon Trigger

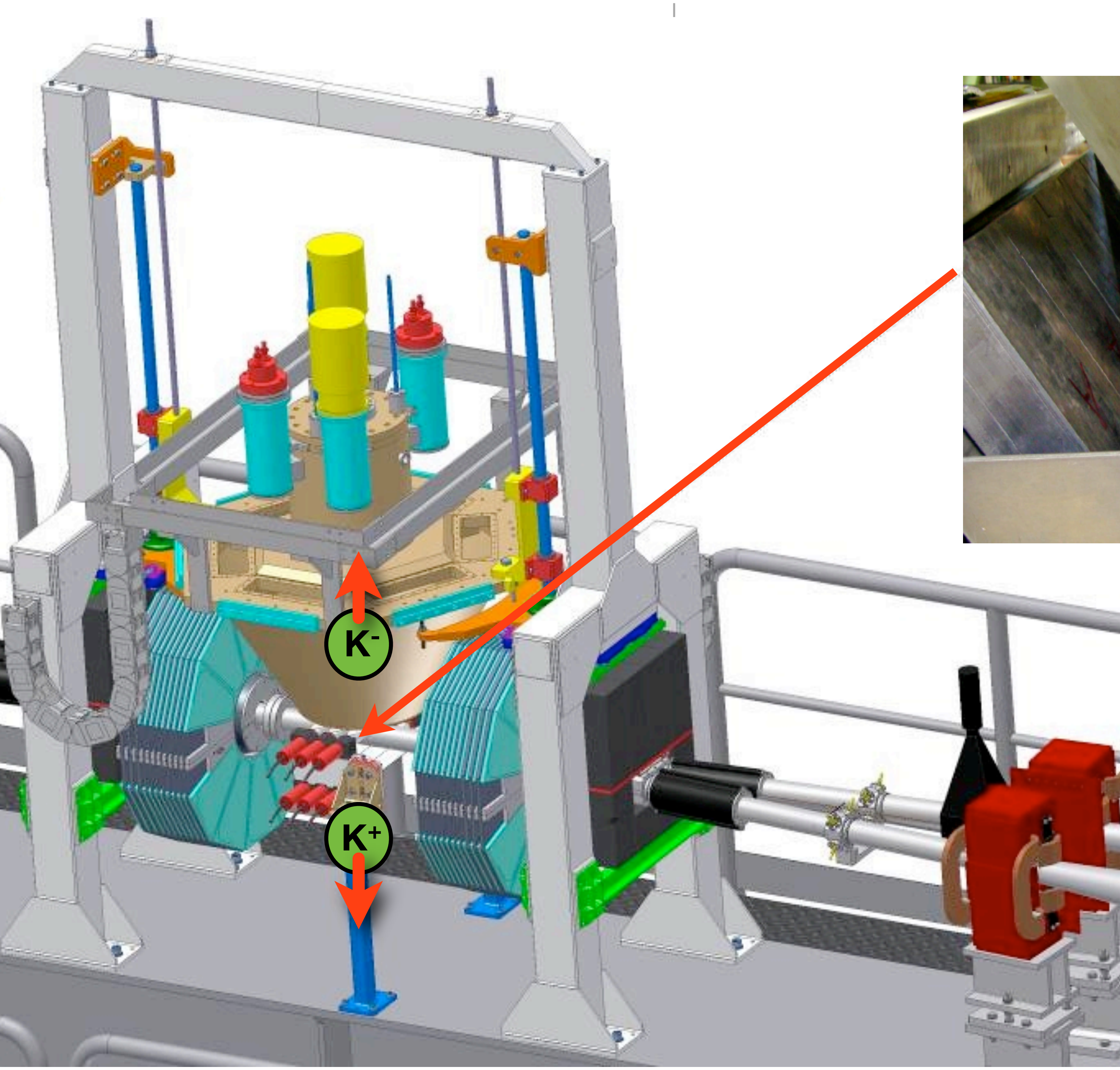


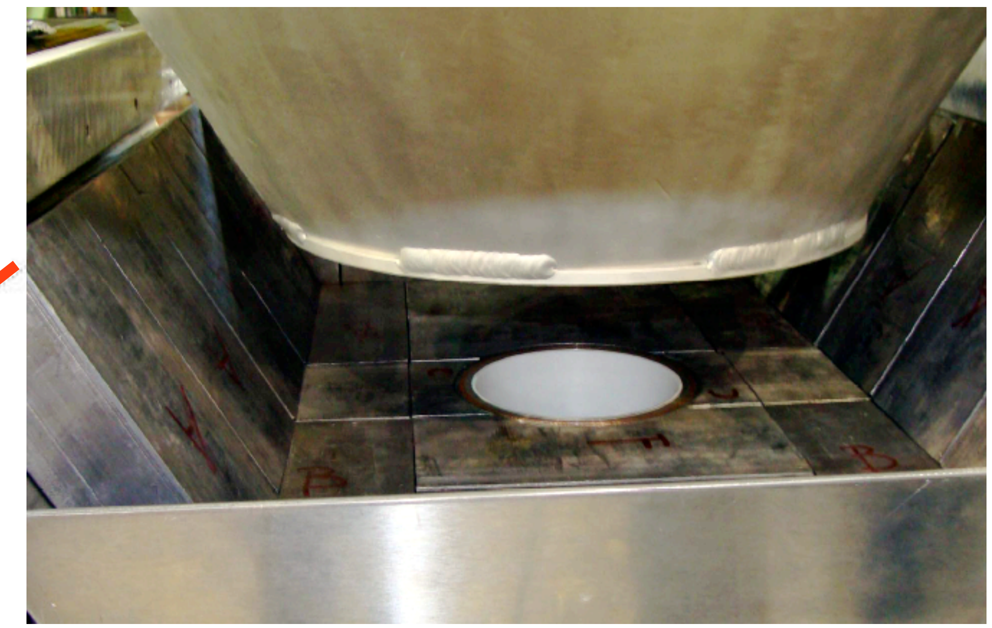
Kaon Trigger

- Kaons - MIPs TOF separation ≈ 1ns [25]
- Hamamatsu R4998, pulse rise time ~ 0.7 ns [26]
- Scintillator Material BC420 (150mm x 50mm x 2.0mm) [27]

SIDDHARTA experimental setup

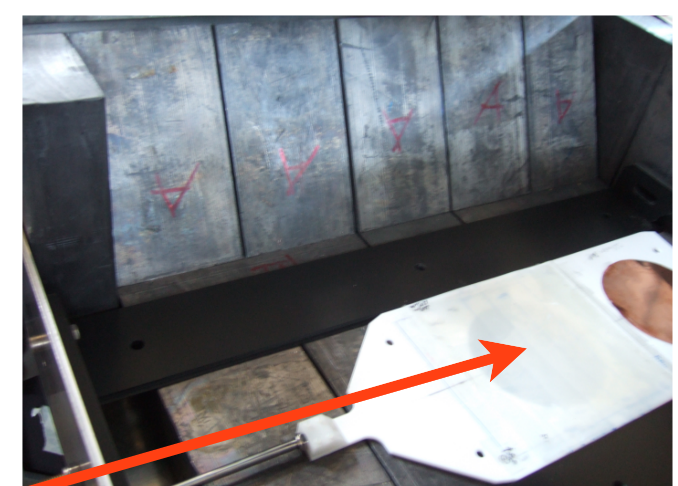






Lead Shield + Pb/Cu/ teflon collimator

Φ boost



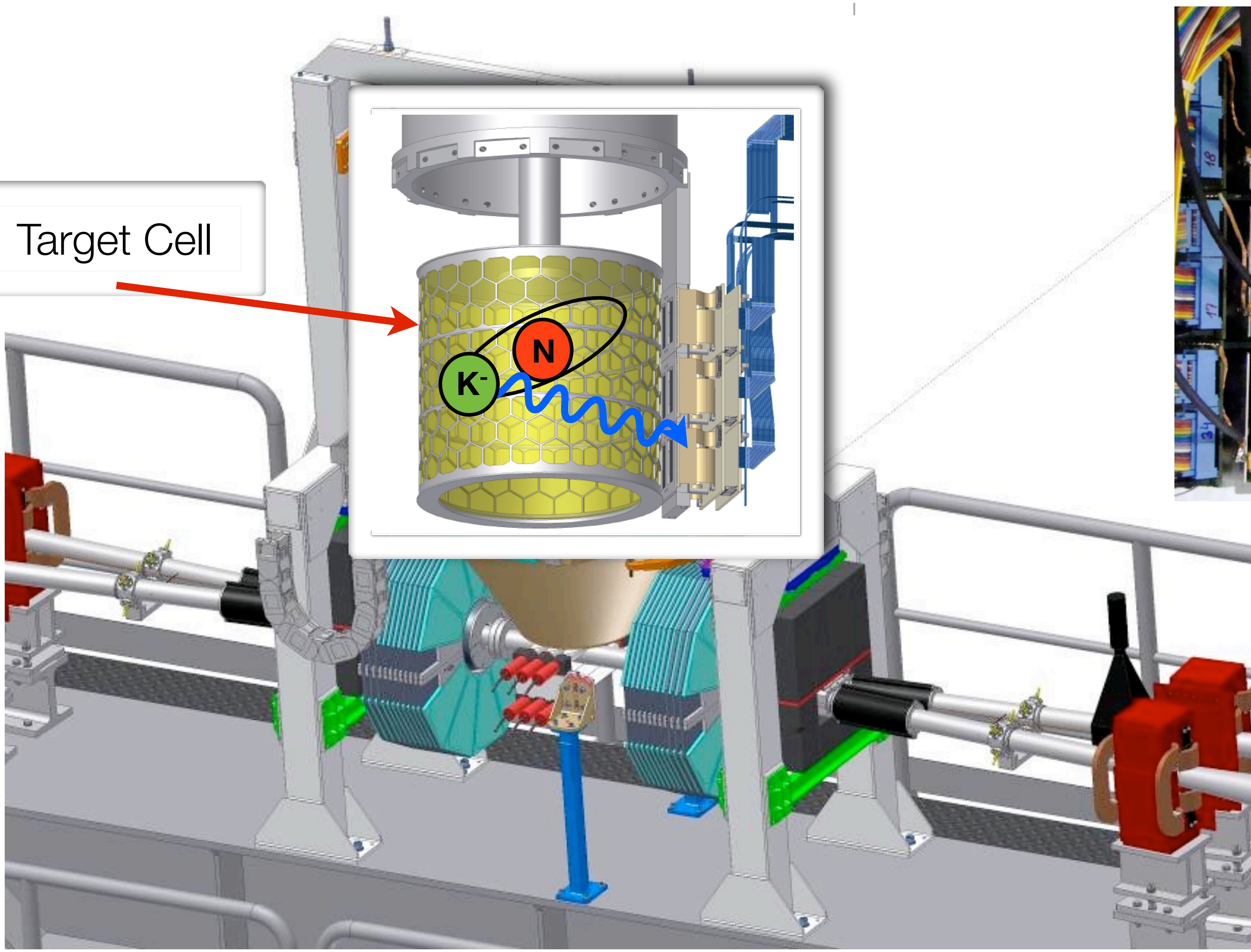
degrader

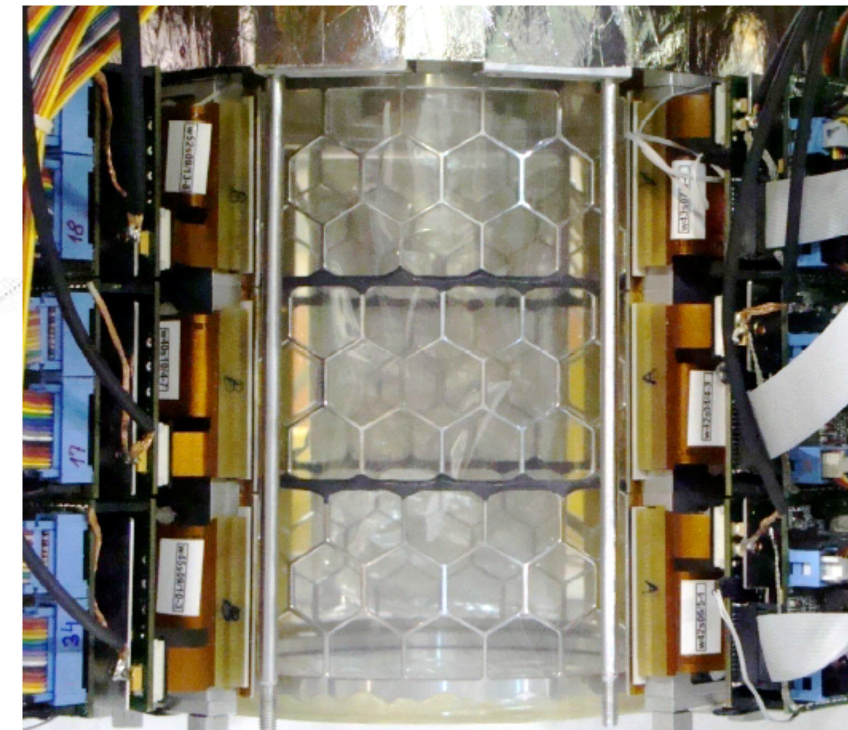
- mylar
- scaled thickness to compensate Φ boost [27]
- Optimization with K^4He measurements [10]

Degrader + Ti/Cu sandwich for calibration

SIDDHARTA experimental setup

Target Cell





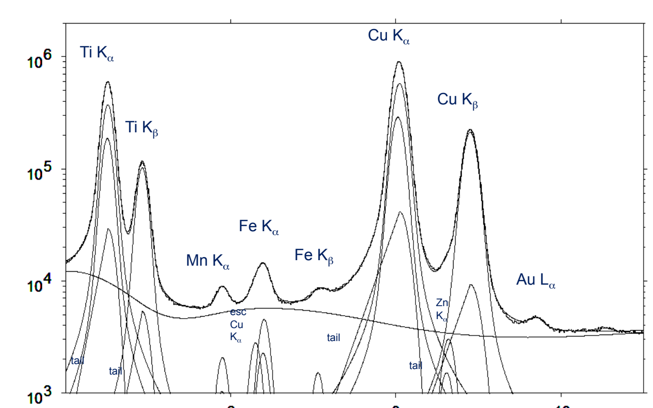
Target cell

- T= 23K, P=10^5Pa KH [28a]
- T= 20K, P=10^5Pa K^{3}He [28b]
- T= 27K, P=10^5Pa K^{4}He [28c]
- Alu Grid [28]
- Side wall: Kapton 50μm [28]

Calibration System

- sliding system (same of Kaon trigger)
- X-ray tube (40KV, 50μA) on the “sandwich”
- In-beam calibration

[25][26][27]



Analysis Result

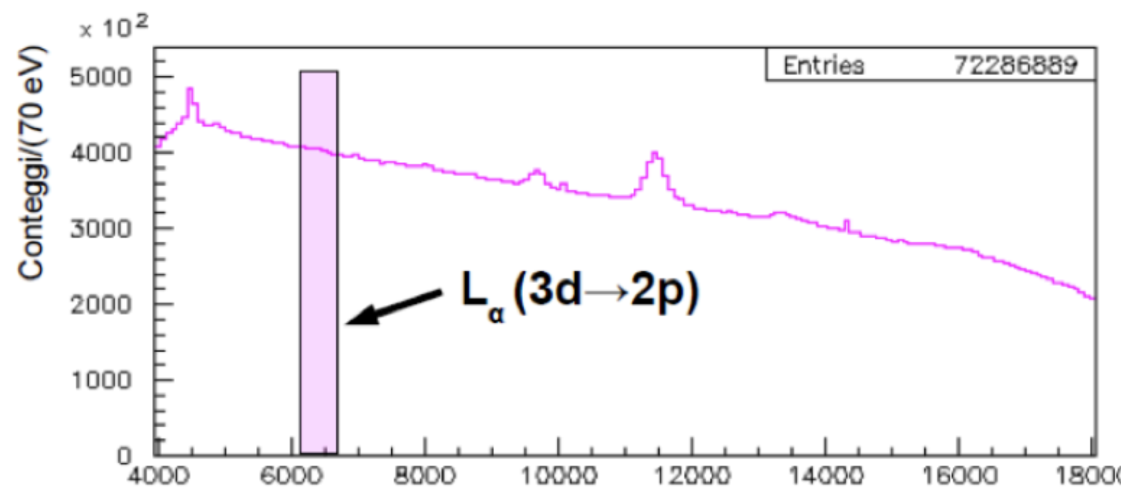
KH, K^4He and K^3HE

SIDDHARTA data and background suppression

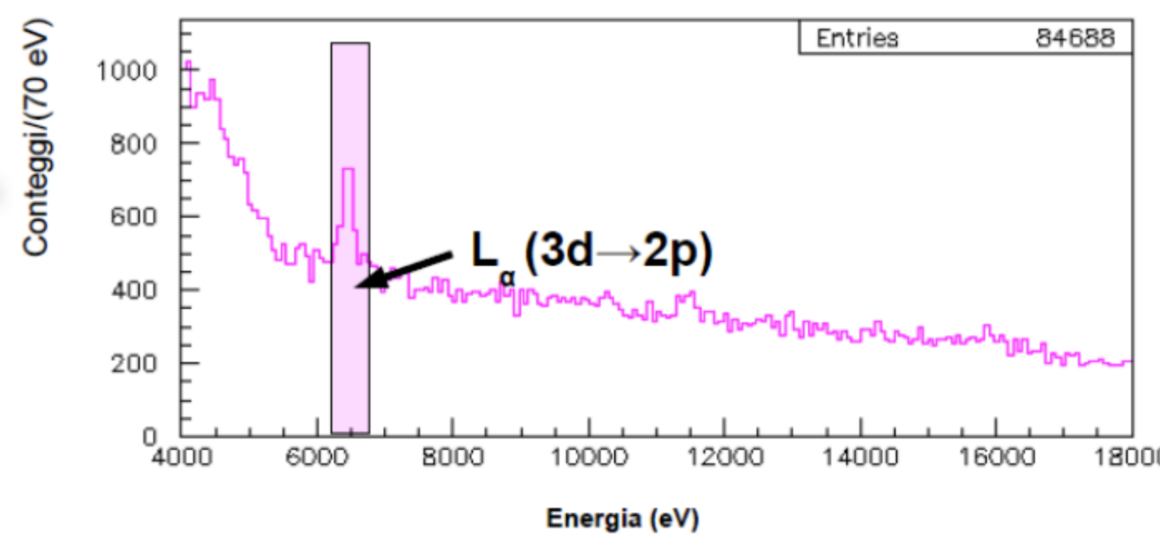
How SIDDHARTA works: example of data [10]

(KHe for degrader optimization)

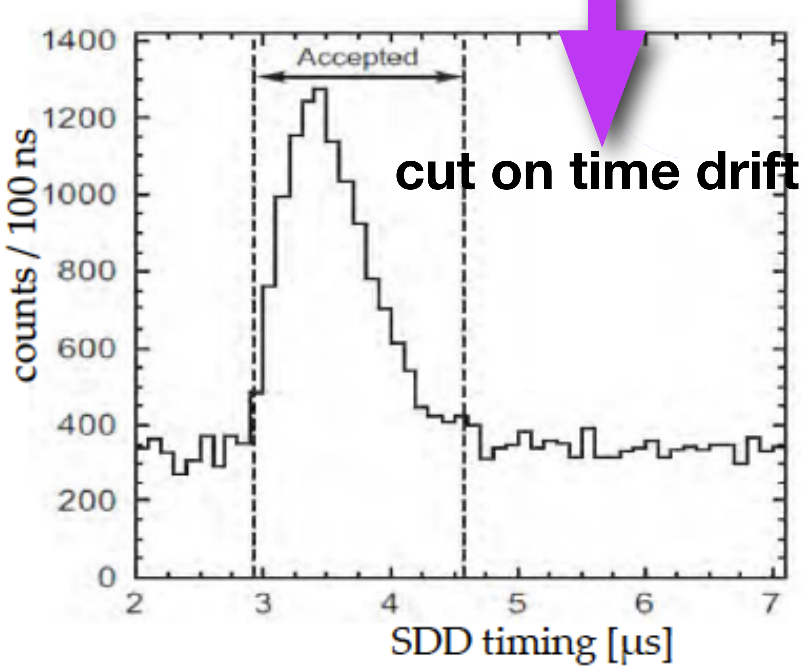
Total spectrum without any cut ("self-trigger")



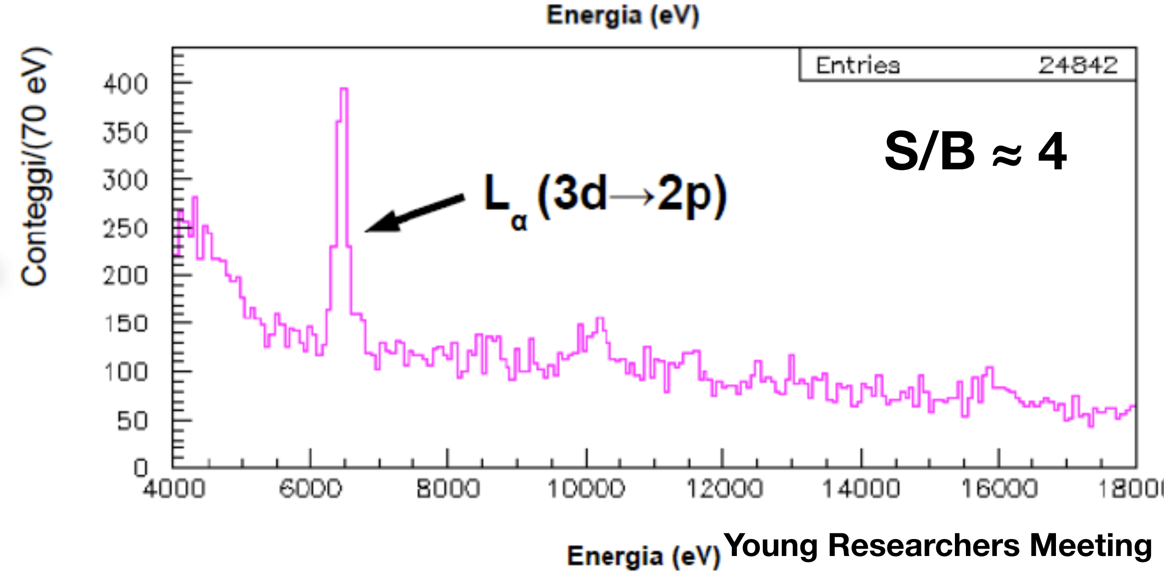
Selection of events: coincidence with kaon-trigger



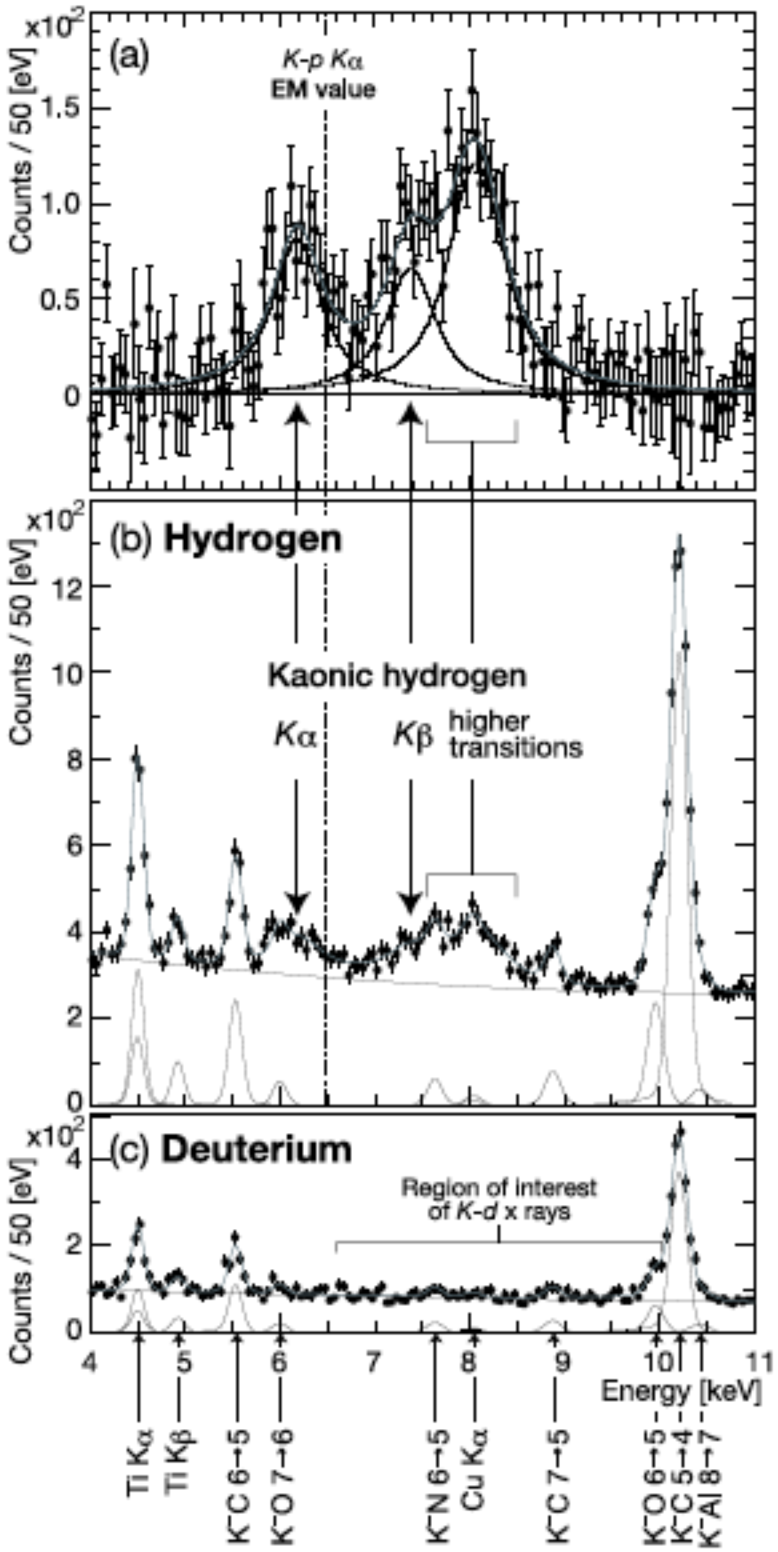
cut on time drift



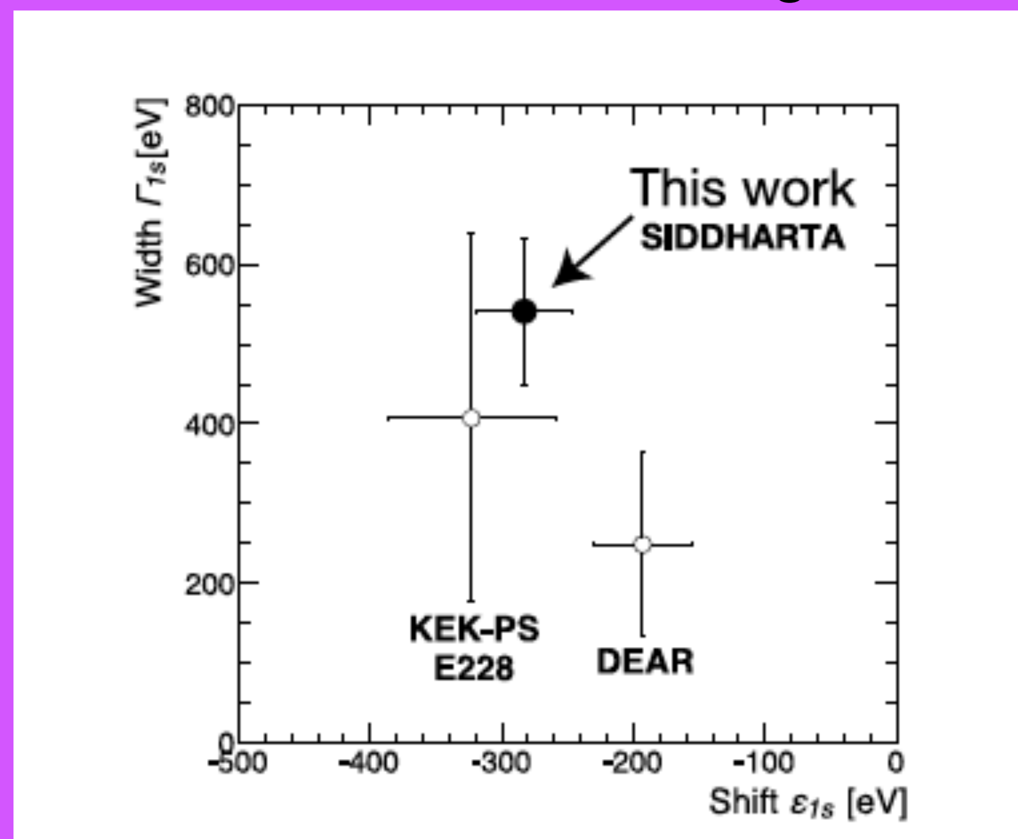
rate<20Hz



Present results: Kaonic Hydrogen



- Data accumulated over six months in 2009 (**340 pb^{-1} for the hydrogen and 100 pb^{-1} for the deuterium**)
- Refined Calibrations analysis
- **Global Simultaneous fit of KH and KD spectra**
- Normalisation to High-Statistic KC peak 5->4

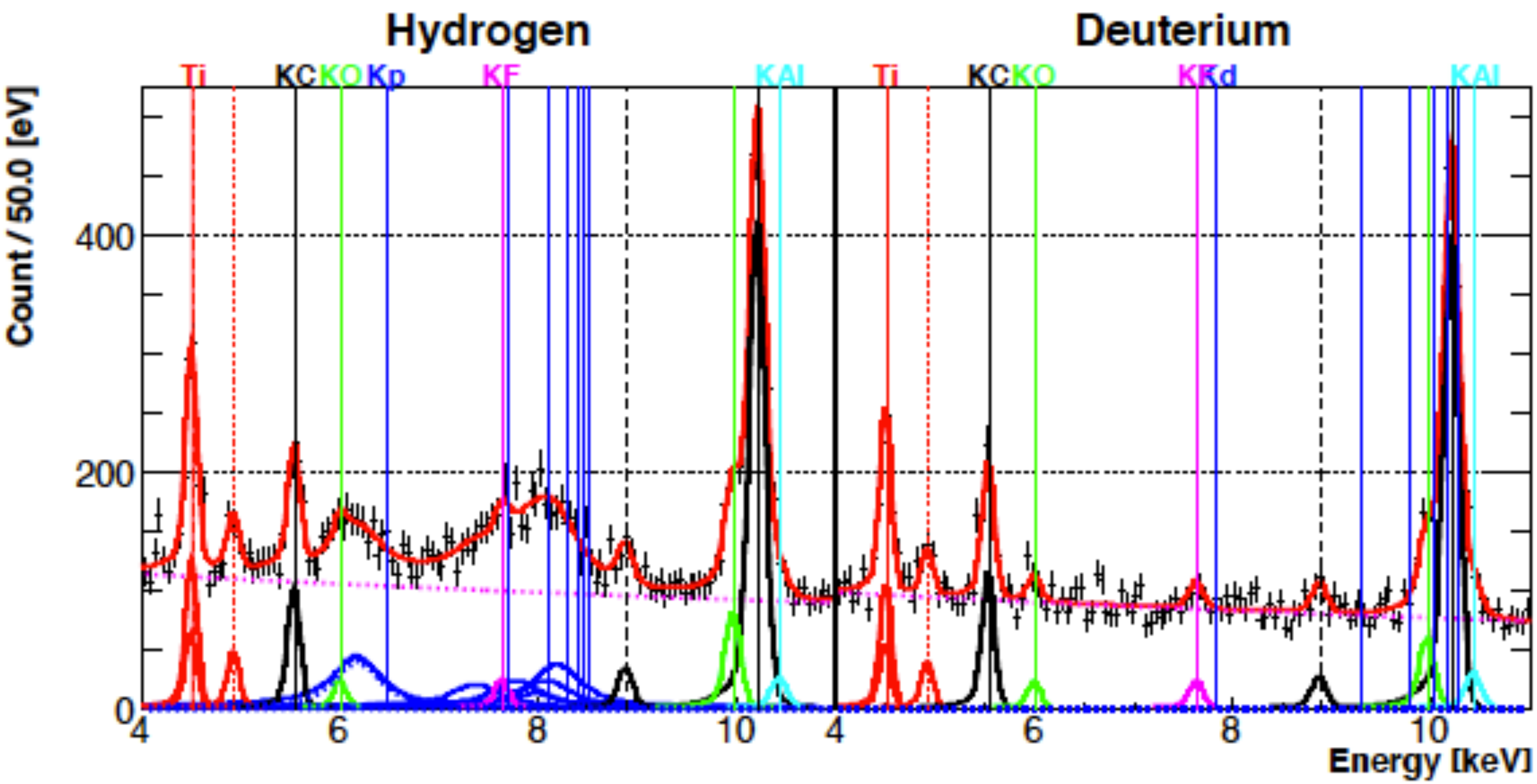


Physics Letters B 704 (2011), pp. 113-11

ε_{1s} = -283±36(stat)±6(syst) eV

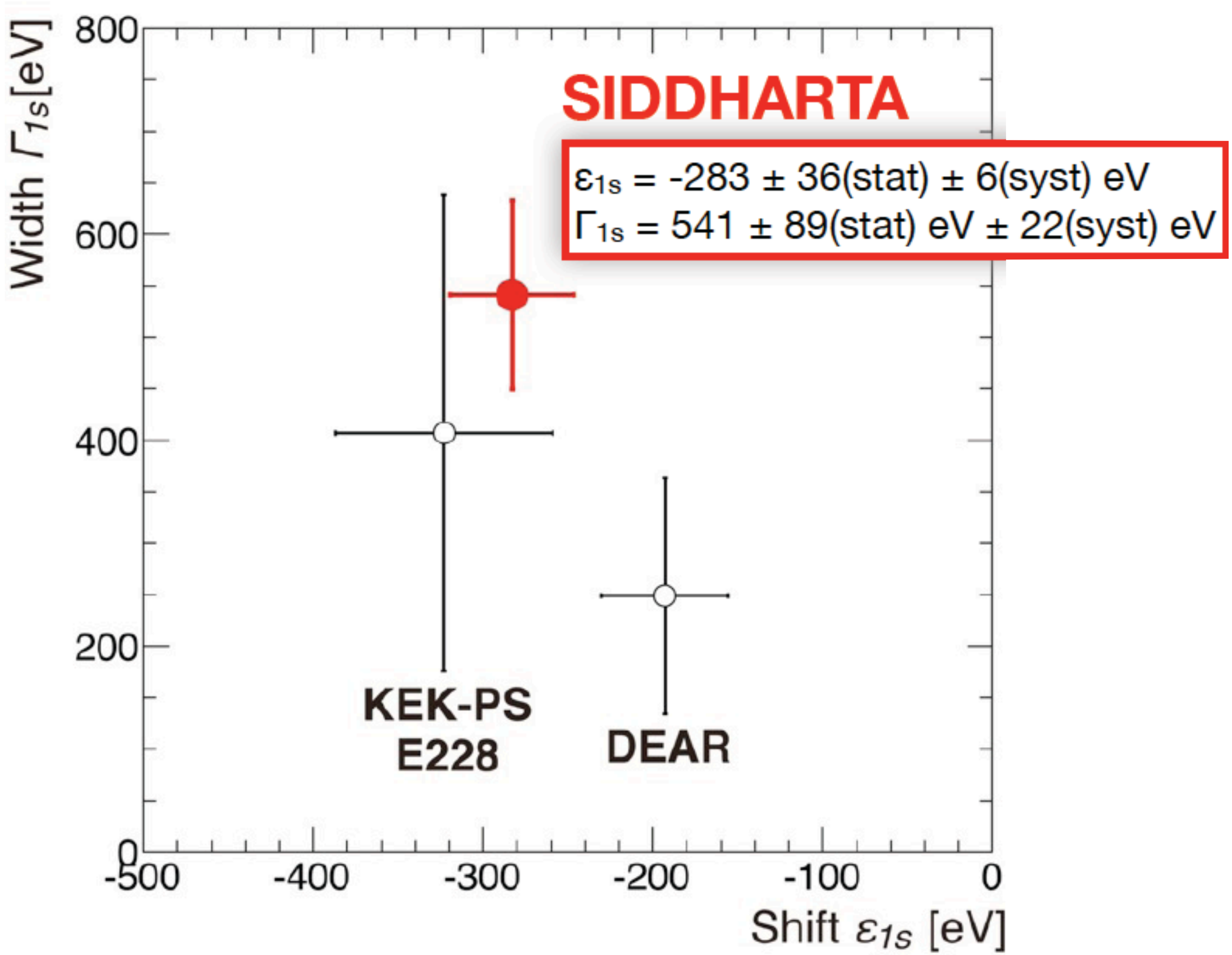
Γ_{1s} = 541±89(stat)±22(syst) eV

KH spectrum analysis: simultaneous fit with KD

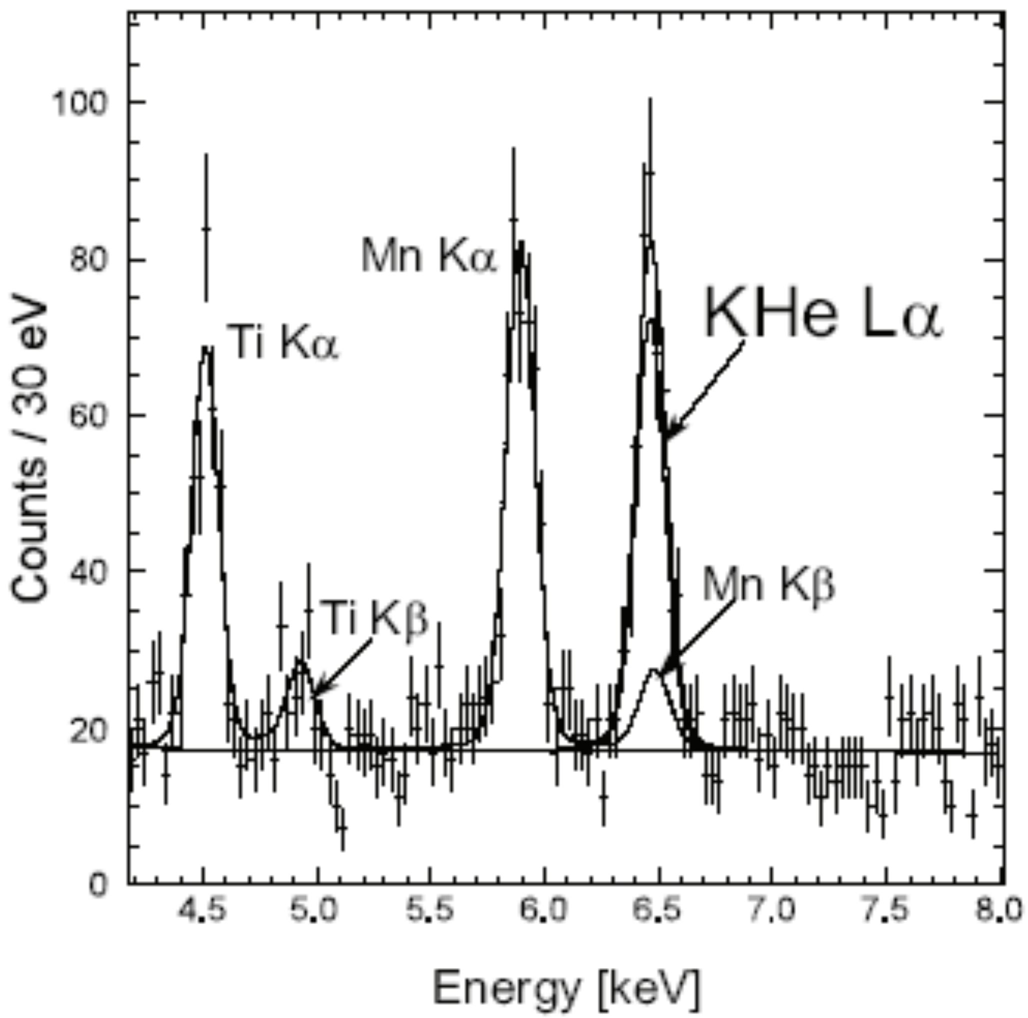


Deuterium data can be used to evaluate background of Hydrogen data.
The kaonic-hydrogen lines are represented by Lorentz functions convoluted with the detector response function, where the Lorentz width corresponds to the strong-interaction broadening of the 1s state

Present results: Kaonic Hydrogen



Present results: Kaonic Helium 4

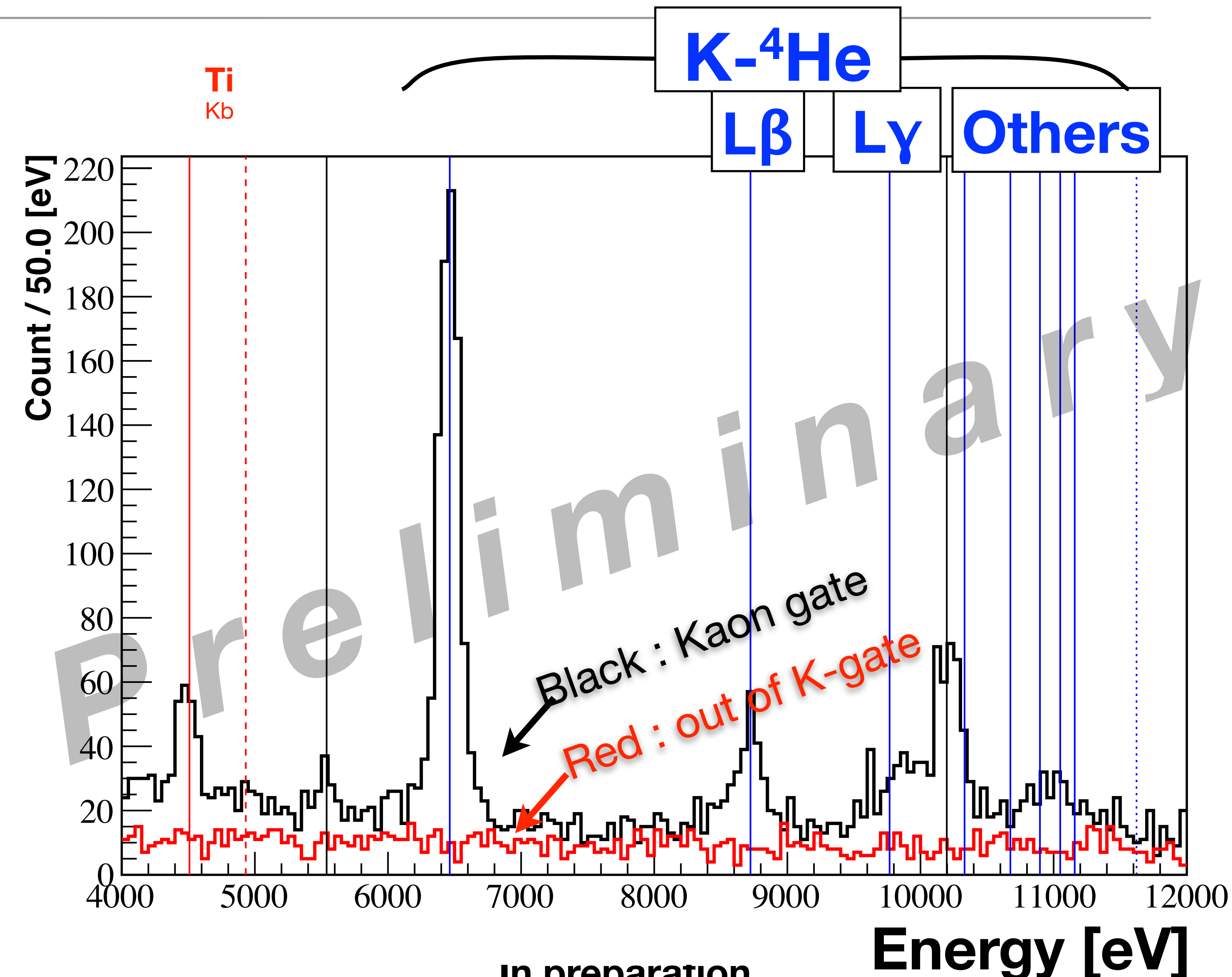


First SIDDHARTA paper on physics:
Phys. Lett. B 681 (2009) 310

Confirmed KEK E570 result using a gaseous target

First measurement with a gaseous target!

$$\Delta E = E_{\mathrm{exp}} - E_{\mathrm{e.m.}} = 0 \pm 6\ (\mathrm{stat}) \pm 2\ (\mathrm{syst})\ \mathrm{eV}$$



In preparation

Publication concerning yields of K^4He of the transition

More data on K^4He of the transition coming from: degrader optimisation and setup 2 (no ^{55}Fe source)

Present results: Kaonic Helium 3

K^3He never measured before!

Total data acquired: about 15 pb^{-1}

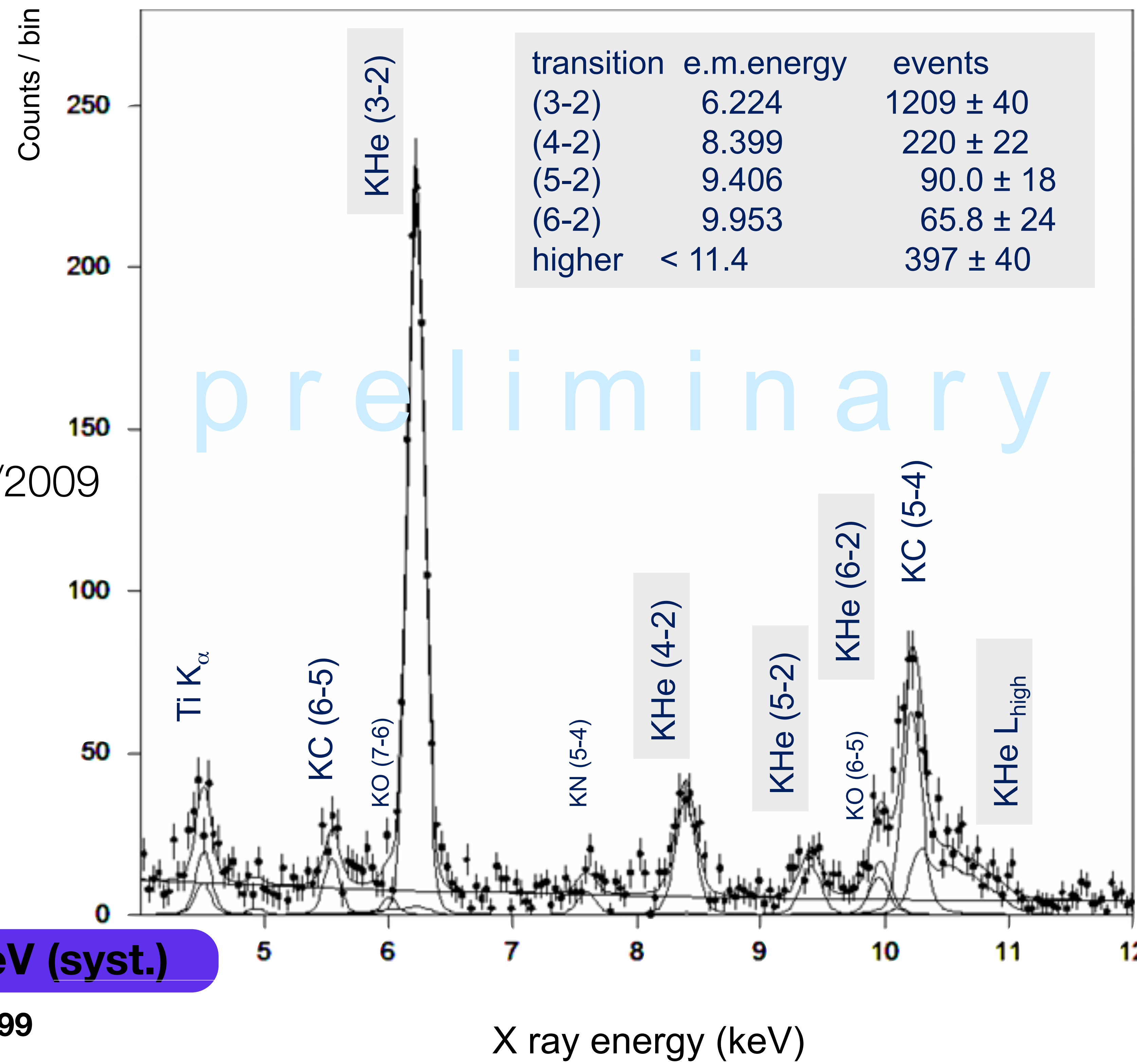
Short period of data taking: 3 - 7 /11/2009

High X-ray yield

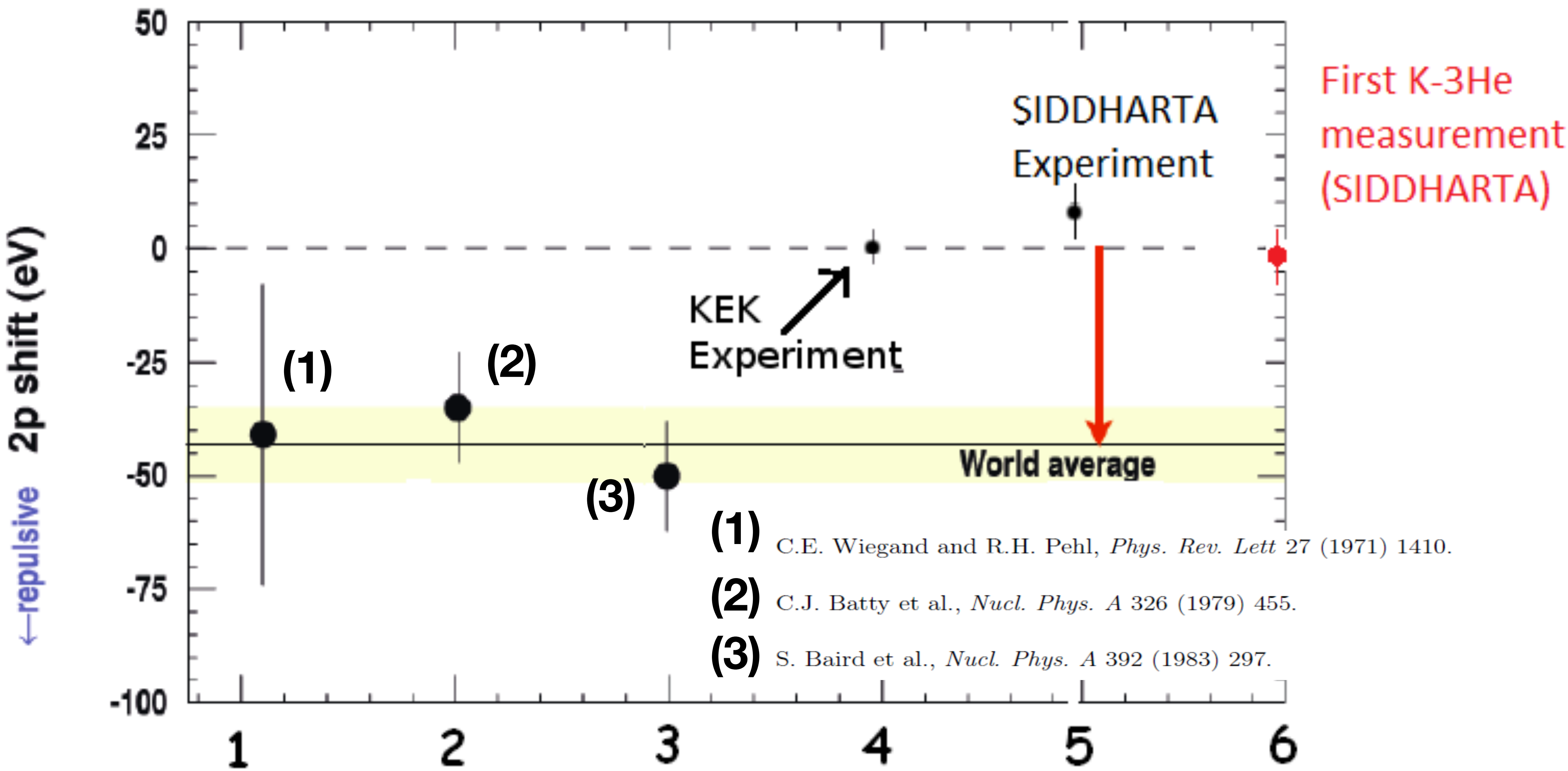
Analysis is still ongoing!

shift = - 1.7 eV ± 2.7 eV (stat.) ± 4 eV (syst.)

Published in: Phys. Lett. B 697 (2011) 199



Present results: Kaonic Helium 4



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Future Perspectives

SUMMARY:
- **K^-p** shift ~ 270 eV, width ~500 eV higher precision then in DEAR
- **K^-d** first measurement ever, exploratory measurement, small signal, significance ~ 2σ
- **K^4He** measured for the first time in gaseous target
- **K^3He** first time measurement

SIDDHARTA 2: to study an enriched scientific case [29] → In particular:

- **Kaonic deuterium measurement** (first time in the world), after the explorative measurement performed by SIDDHARTA

Difficulty: Low X-ray yeld →
- Geometry optimization: take SDDs closest to the target
- Shielding optimization: to further pull-down the background
- Improvement of the cooling system: to maximize the yield

- **Kaonic helium transitions to the 1s level** (and more precise measurements to 2p level). Direct X-ray yield measurement

Difficulty: Out of SDDs range →
- Enlarge SDDs' energy range (>30KeV), possible adjoint of other detectors

- **Study of other light (KO,KC) and heavier (KSi, KPb) kaonic atoms**
- **Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)**
- **Kaon mass precision measurement at the level of < 10 KeV** (KC 5->4 transition)

Thanks for your attention

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Backslides

A closer glance to the main phases:

Capture Process

- **CAPTURE** **Lot DoF:** { **Atomic Structure** / **n,l of the capturing orbital** } **[4]**

Difficult to study
- ☆ Difficult separation between capture and formation
- ☆ At fixed projectile energy and target density doesn't exist a single capturing state

An Intuitive Example: Maximising Capture Cross Section (LKA)

Kaon on Hydrogen Atom: Maximum of the Capture Cross Section when $v_K \approx v_e$

Fine-Structure constant: → $\frac{\text{speed of the orbital electron (n=1)}}{\text{speed of light}}$ → $v_e = \alpha \approx \frac{1}{137} m/s$ c=1 **[40]**

Kaon Kinetic Energy: $T = m_0(\gamma - 1)$ → $\frac{T_{cap} \approx 13.2 \text{ KeV}}{996 = m_K/m_e}$ = 1 Ry = 13.6 eV [40] Verifying k^-=493 MeV

We need thermalised hadron/lepton to maximise Capture Cross Section: **Production of Low Energy Particles** **Degrader (thermalisation)**

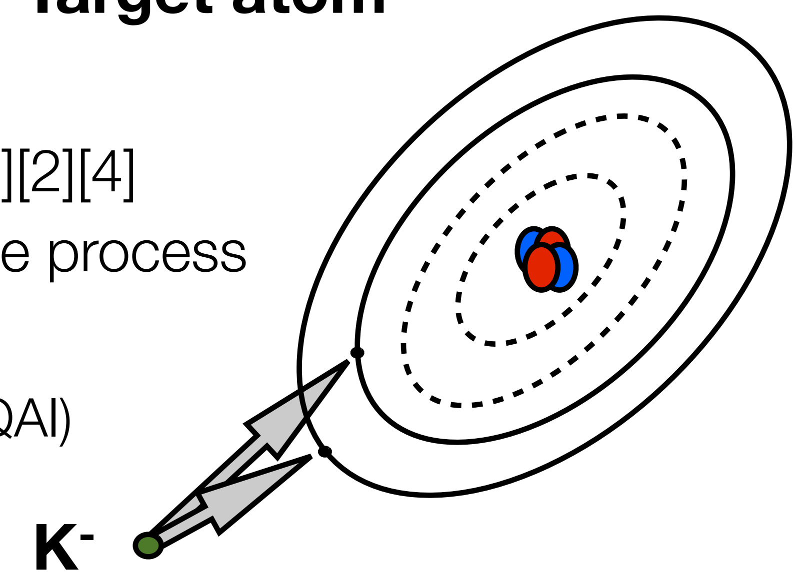
Meson Factory:	**p beam on a target**	**Production of Hadrons and Leptons**	Multipurpose approach (Spectrometer Selection) High Intensity (10^6 particles/sec) High μ,π background (pulsed beam, gate) Key role of the degrader (Higher energies)
Φ Factory:	**e^+e^- collider**	**K^- from Φ decay**	Only for KA, possibility to implement for ΣA (Absorption) Low Intensity, small background Degrader for the thermalisation fine tuning

A closer glance to the main phases:

Capture Process

Process with a lot DoF: ➡ **Difficulties for its theoretical description**

Target atom



- Theoretically ∄! Capture Orbital->Capture(atomic structure, n, l) [1][2][4]
- Very hard to distinguish between Capture, Formation and Cascade process

∃ several models for Capture →
- Perturbative (PWD, DW-CB)
- (Quasi-)Adiabatic Ionization (AI-QAI)
- Quasi-Classical (CTMC, FMD)

[Capture Window][4] ∋ q(E_k)
- Higher values: → Electron expulsion via em scattering K^- e^- [1][4]
- Lower values: →
  - Interaction K- electrons clouds. e^- expulsion via atomic levels rearrangement
  - Any direct interaction with e^-: e^- expulsion via atomic levels rearrangement in Formation process.

⬇

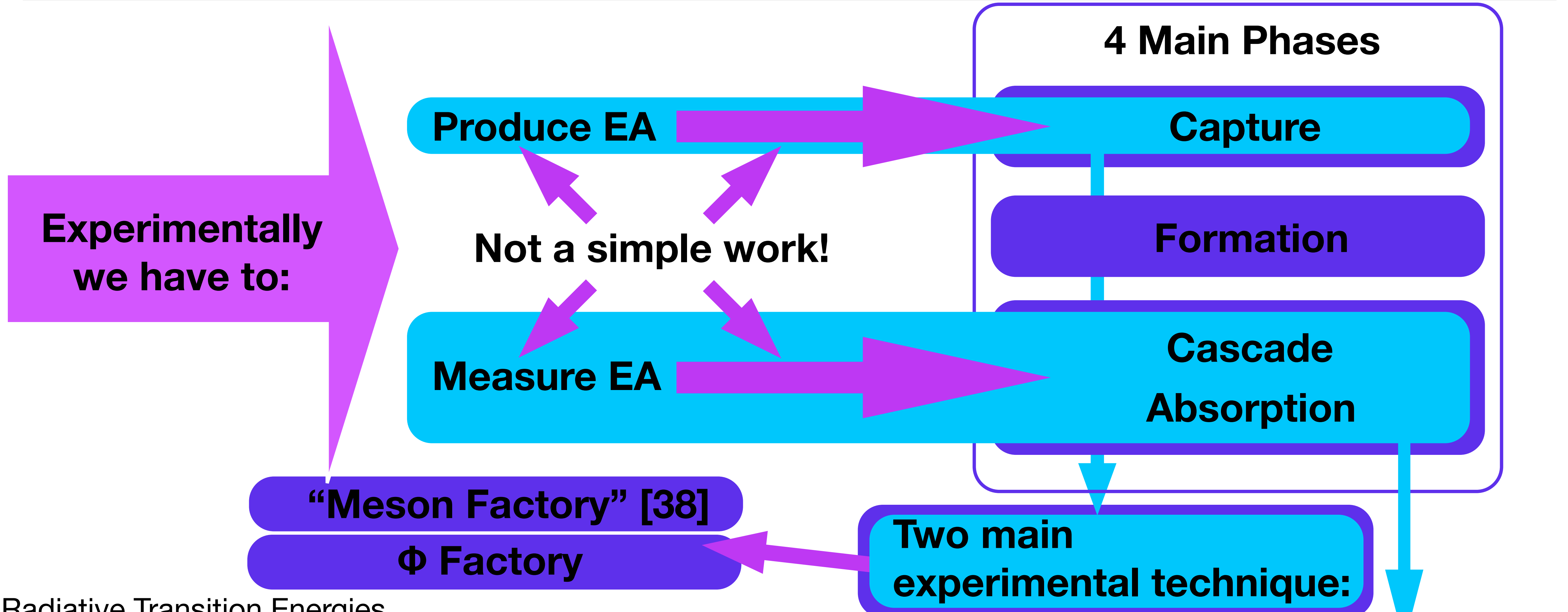
Hadron energy range that maximise Capture cross section ➡ When Capture cross section will be higher?

$v_K \approx v_{e-}$

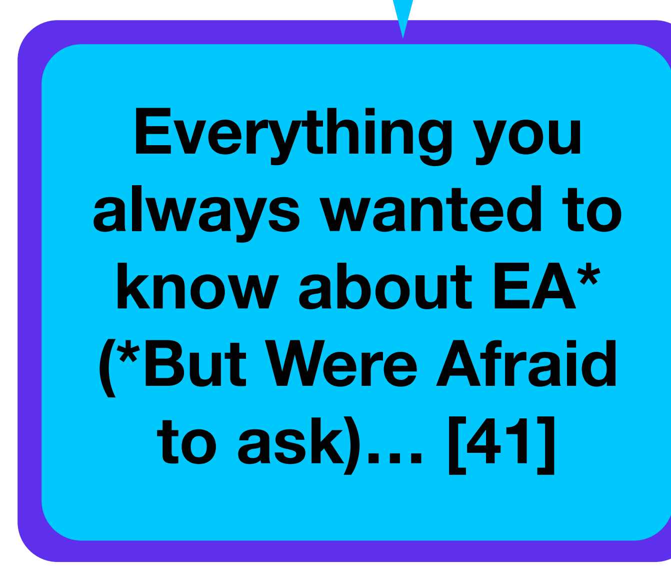
Example in Hydrogen [10]: α fine structure constant ➡ $v_e = \alpha \approx \frac{1}{137} m/s$ c=1

Hadron Kinetic Energy: $T = m_0(\gamma - 1)$ ➡ $T_{cattura} \approx 13.2\, KeV$

One of the most difficult experimental measurements



- Radiative Transition Energies
- Radiative Transition rate (From the photon intensity spectrum)
- Level Widths, determined from measured photon line widths
- Auger electron spectra
- Atomic and molecular formation rates, inferred from the photon intensity spectrum
- Radiative nuclear transition energies (isomer shifted, appearing in the atomic spectra)
- Radiative nuclear transition rates, inferred from the nuclear photon intensity spectrum
- Decay Debris particles resulting from decay of the exotic particle
- Nuclear reaction debris, resulting from absorption of the exotic particle by the nucleus



How to produce Exotic Atoms (KA)

Extract beam: p on a target — production of meson and barion — **Meson Factory [38]**

LEAR (Cern), PSI (Switzerland), TRIUMF (Canada), IYaF (Russia), RIKEN (japan), RAL (Great Britain) (2001) [38]

High Statistic

To produce KA, High πA background

Two ways are used to produce EA

Lepton Collider: — production of meson — **Φ Factories**

VEPP (Russia), DAFNE (Italy)

Low Statistic

Ideal for KA, low background

A closer glance to the main phases:

Cascade Process

For all the physical branch we want to study starting from EA → <u>The fundamental process to understand is the CASCADE PROCESS</u>

Peculiar process of the EA we are considering. The basics were understood studying LMA (only QED+few body)

Systematic Calculations only for Hydrogen isotopes (Z=1), for Z>1 qualitative estimates [38]

START:

After: { Capture and Formation } Theoretical: difficulty (or impossibility) to disentangle [14]

<u>DIFFERENCE!</u> : Theoretically we know when Cascade Starts!

Capture and Formation modify NP wave function

Cascade starts when NP wave function superimposing external atomic electron wave functions [14] → Precise Calculations

Considering:
- Atom formation: 10^{-12}-10^{-9} s (thermal, estimates) [41]
- Radiative Transitions: 10^{-15}-10^{-17} s (measurement, estimates) [41]
- Total atom lifetime: $\leq \tau_{NP}$ (2.2×10^{-6} s μ, 10^{-10}s Σ) [41]

Possibility to set a time gate to reject background!

Deser-Trueman formula (1/2)

Elastic scattering of a particle of momentum k on a target

Partial waves expansion of Scattering Amplitude [6][8]

$$f_l(\theta)=(2l+1)a_l k^{2l} P_l(\cos\theta) \xrightarrow{k\to 0} a_s$$

k->0 $\mathbf{a_s}$ s-wave scattering lenght

For exotic atoms → scattering + absorption → Optical potential → **Complex** s-wave scattering lenght

- μ = exotic atom reduced mass
- n_e = capture orbital m.q.n.
- M_x = captured adron mass
- m_e = electron mass

Relation between ε and Γ

expansion in terms of a_s/r_b

$$r_B=\hbar c/\mu c^2 \alpha Z \quad [6]$$

First term of the expansion (Deser formula) [6]

$$\epsilon_{nl}+i\frac{\Gamma_{nl}}{2}=-\frac{(2\pi\hbar^2)}{\mu}\bullet\left|\psi_{nl}(0)\right|^2\bullet a_s=-\frac{(2\hbar^2)}{\mu r_B^3}\bullet\frac{a_s}{n^3}$$

Following term (low energy p-wave) [6]

$$\epsilon_{nl}+i\frac{\Gamma_{nl}}{2}=-\frac{(6\pi\hbar^2)}{\mu}\bullet\left|\nabla\psi_{nl}(0)\right|^2\bullet a_p=-\frac{(3\hbar^2)}{16\mu r_B^5}\bullet a_p\bullet 32\frac{(n^2-1)}{3n^5}$$

Similar relations for states with higher angular momentum

Corrections due to coulombian and nuclear interferences are taken into account into higher order terms

Trueman expansion [30]

Deser-Trueman formula (2/2)

Considering a bound system K⁻ - proton (KH)

[7] Lower order term of Deser-Trueman relation: $\epsilon + i\Gamma/2 = 2\alpha^3\mu^2 a_{k^- p} = (412\ eV\ fm^{-1})\, a_{k^- p}$

Considering a bound system K⁻ - deuton (KD)

[7] Lower order term of Deser-Trueman relation: $\epsilon + i\Gamma/2 = 2\alpha^3\mu^2 a_{k^- d} = (601\ eV\ fm^{-1})\, a_{k^- d}$

Scattering lengths depend on isospin status of the system → Expression of a_{kp} and a_{kd} in terms of linear superposition of scattering singlet (I=0) and triplet (I=1) length [7]

[7] bound system K⁻ - proton (KH) $a_{k^- p} = 1/2(a_0 + a_1)$

[7] bound system K⁻ - deuton (KD)

$$a_{k^- d} = 2\,\frac{m_N + m_k}{m_N + m_k/2}\, a^{(0)} + C$$

lower order approximation of momentum (K- scattering on free p and n)

Contributions of higher order due to three body problem (Faddeev equations)

with $a^{(0)} = \frac{1}{2}(a_{k^- p} + a_{k^- n}) = \frac{1}{4}(3a_1 + a_0)$

link between complex scattering length and optical potential → **nuclear phase displacements [8]**

a>0 attractive potential
a<0 repulsive potential **[8]**

Kaonic Hydrogen Puzzle

How we have learned to perform LHA X-ray measurement

The Kaon-Nucleon Interaction at Low Energies [42]

Kbar-N interaction at low energies -> Complex Dynamical Aspects

Not Simple: K^-p and K^0bar n channels

- **Are coupled by charge exchange**
- **Strongly coupled to Several πY channels (Y = Σ,Λ) open at the K^-p threshold ($E_{c.o.m.}$=1432 MeV)**

K^-p -> K^-p
K^-p -> K^0bar + n - 5 MeV
K^-p -> π + Σ + 100 MeV
K^-p -> π^0 + Λ + 180 MeV

- **K^-p cross sections for elastic and Inelastic processes**
- **BR for K-p absorption at rest**

Available Experimental data

$$\gamma = \lim_{k\to 0} \frac{\sigma(K^-p \to \pi^+ \Sigma^-)}{\sigma(K^-p \to \pi^- \Sigma^+)} = 2.36 \pm 0.04$$

$$R_c = \lim_{k\to 0} \frac{\sigma(K^-p \to \text{charged particle})}{\sigma(K^-p \to \text{all final states})} = 0.664 \pm 0.0011$$

$$R_n = \lim_{k\to 0} \frac{\sigma(K^-p \to \pi^0 \Lambda)}{\sigma(K^-p \to \text{all neutral states})} = 0.189 \pm 0.015$$

- **π Σ invariant mass distribution below the K^-p threshold, which exhibits the Λ(1405) resonance**
- **The 1s level shift of the K^-p atom through X-ray measurement**

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Attractive!

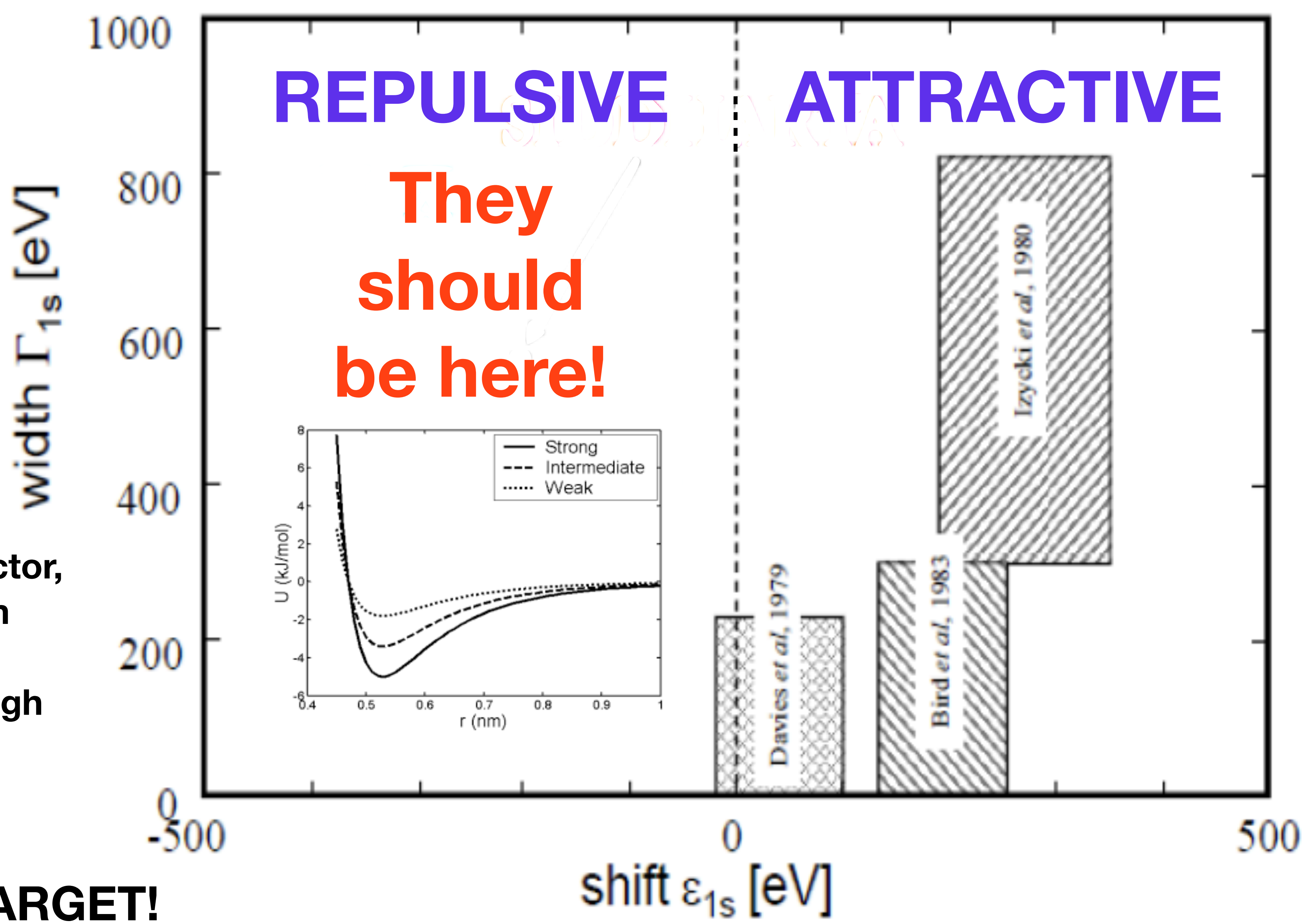
What's going on ...

Three different Experiments on KH saying the same thing...

Two Possibilities:

We didn't understand anything about Strong Interactions

We didn't understand the right experimental method

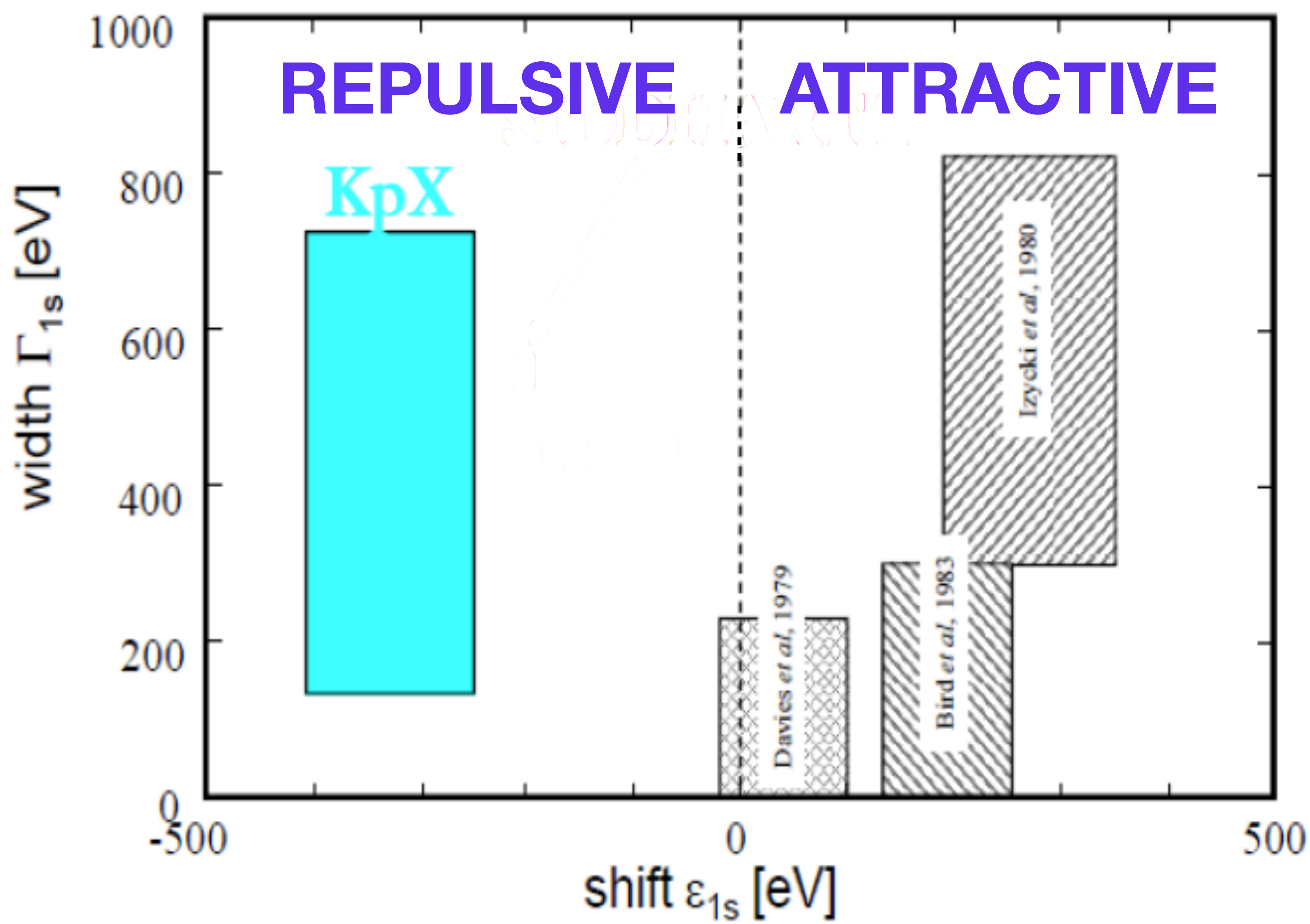


- **small solid angle of Si(Li) X-ray detector,**
- **the nuclear absorption of kaons from higher atomic states (Stark mixing),**
- **large background originating from high energy gamma rays and**
- **large fraction of kaons stopped in materials around the target. [45]**

Common point: LIQUID TARGET!

What’s going on ...

In 1997 KpX experiment at KeK (Japan) solved the puzzle...



Main difference: the use of gaseous Target!

What's going on ...

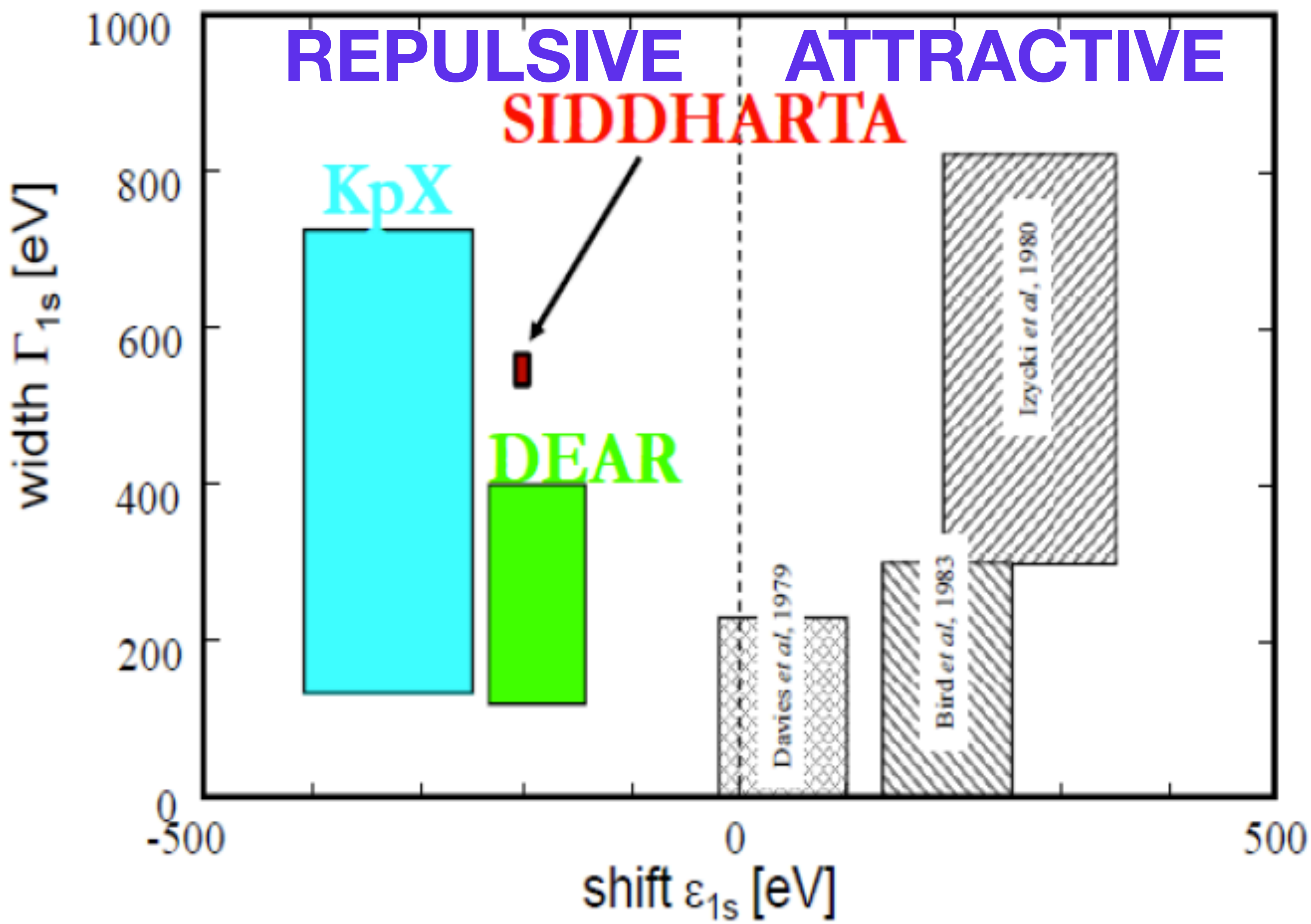
During the years several improvement in the technique...

Main Improvements:

The use of a Φ-Factory to have lower background

The use of very fast detectors that allow trigger improvement

Calibration in beam to check the stability



A great precision (~eV) is needed to disentangle theoretical models!

How to Prevent …

Competitor Processes

COLLISIONS

PERVASIVENESS

Function of EA MEAN FREE PATH

Here we can operate!

By Setting Carefully P,T of the target (STABLE)!

EA PRODUCTION:

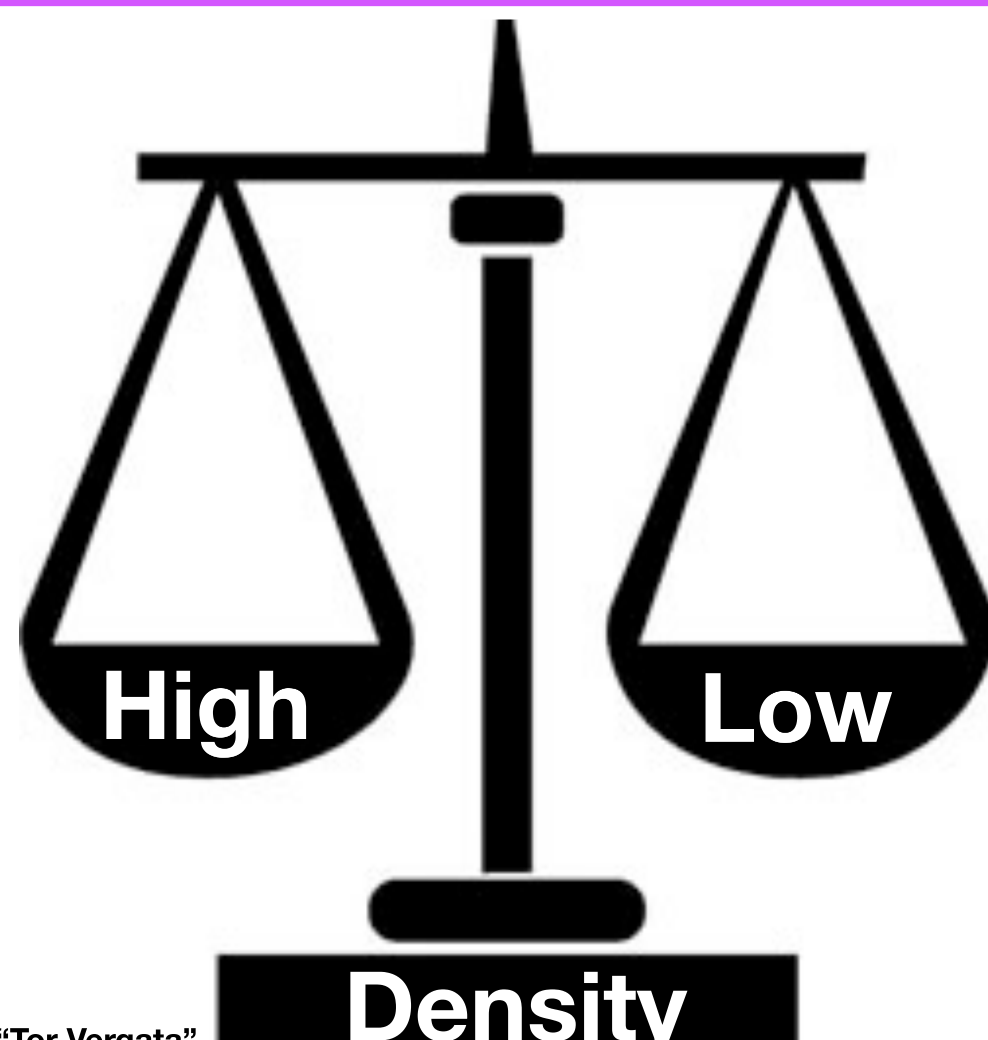
More NP stopped

High Number of EAs

Statistics couldn't be higher: γs can be re-absorbed

Competitor are dominant!

Possibility to see only BG



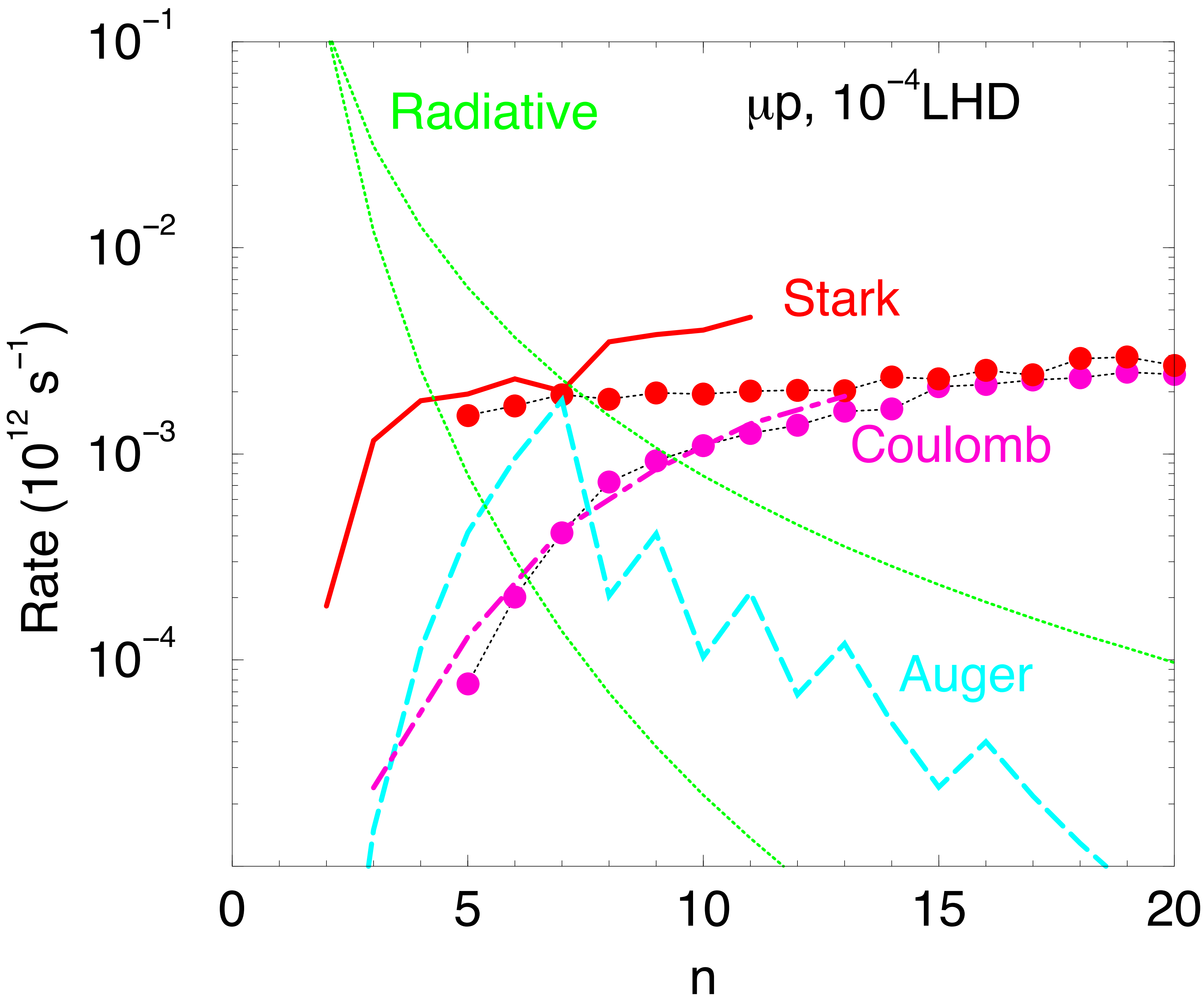
X-ray PRODUCTION

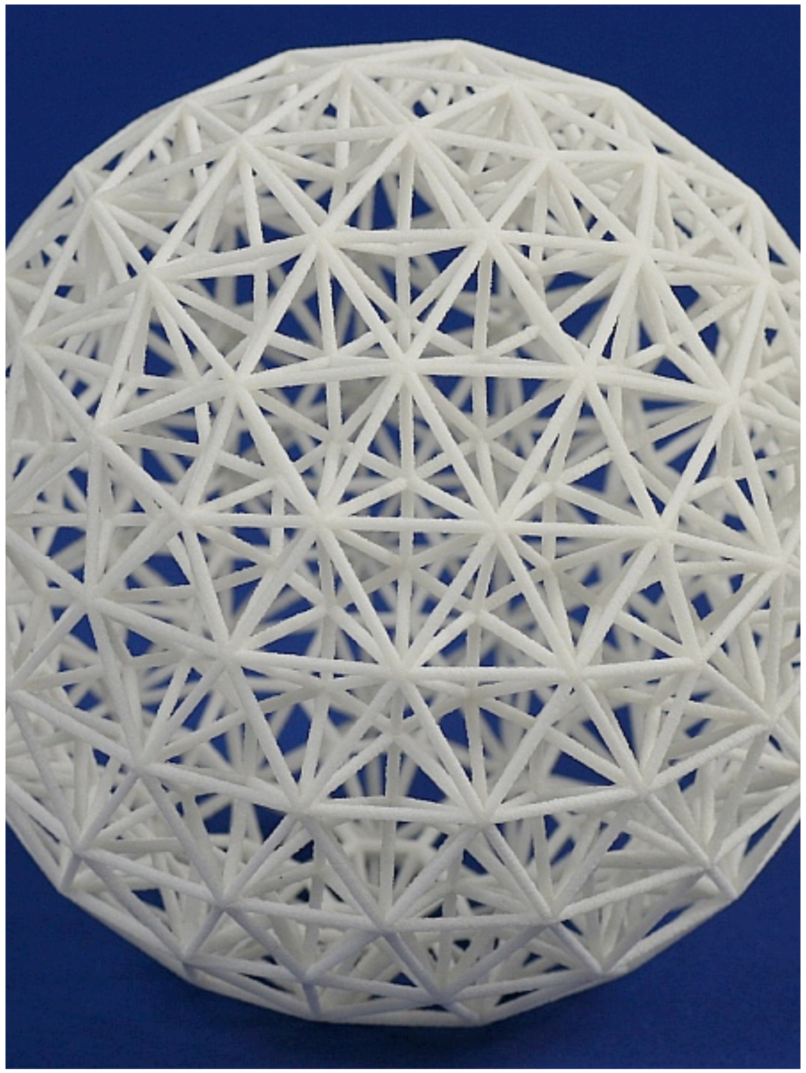
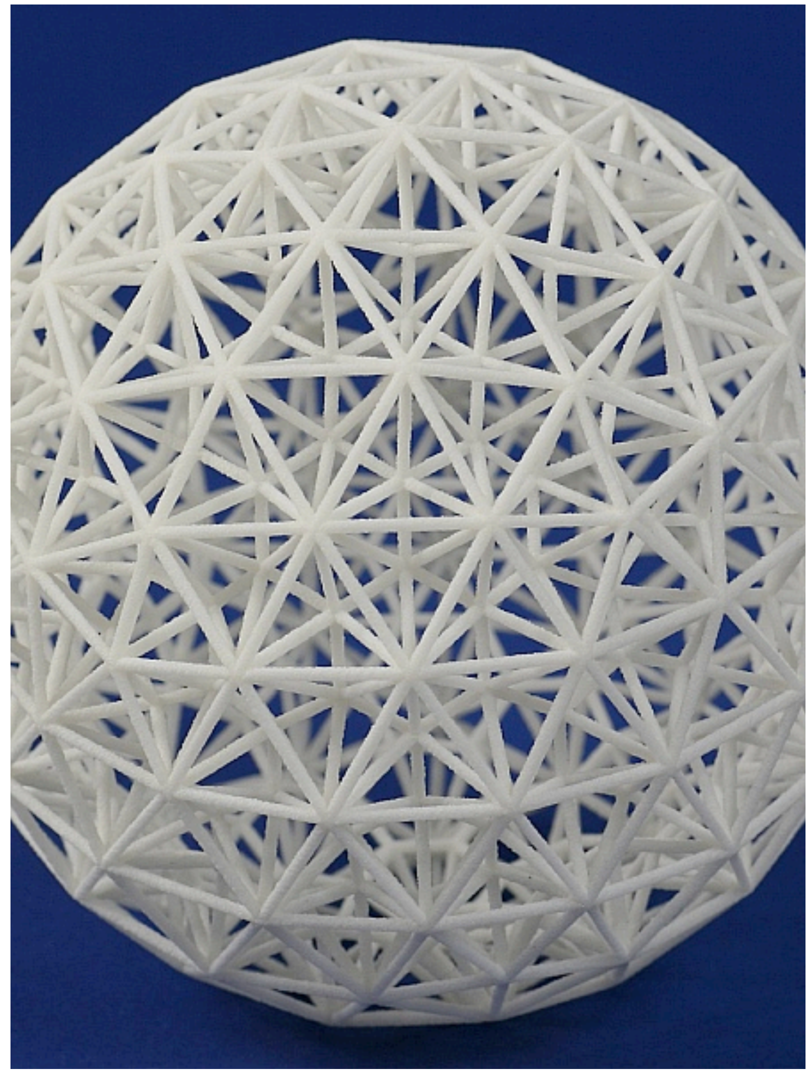
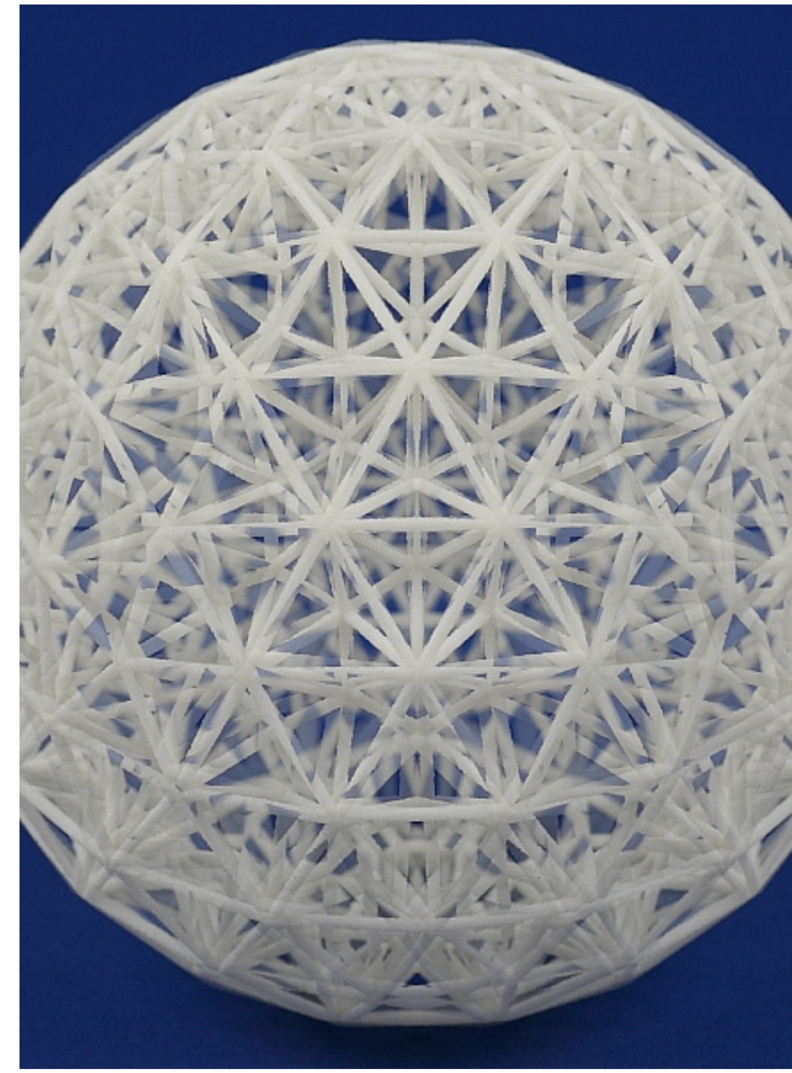
Minimising Collision and Pervasiveness

Increasing X-Ray Yield

Low Statistic: Possibility to enhance using magnetic trap

Processes - Rate

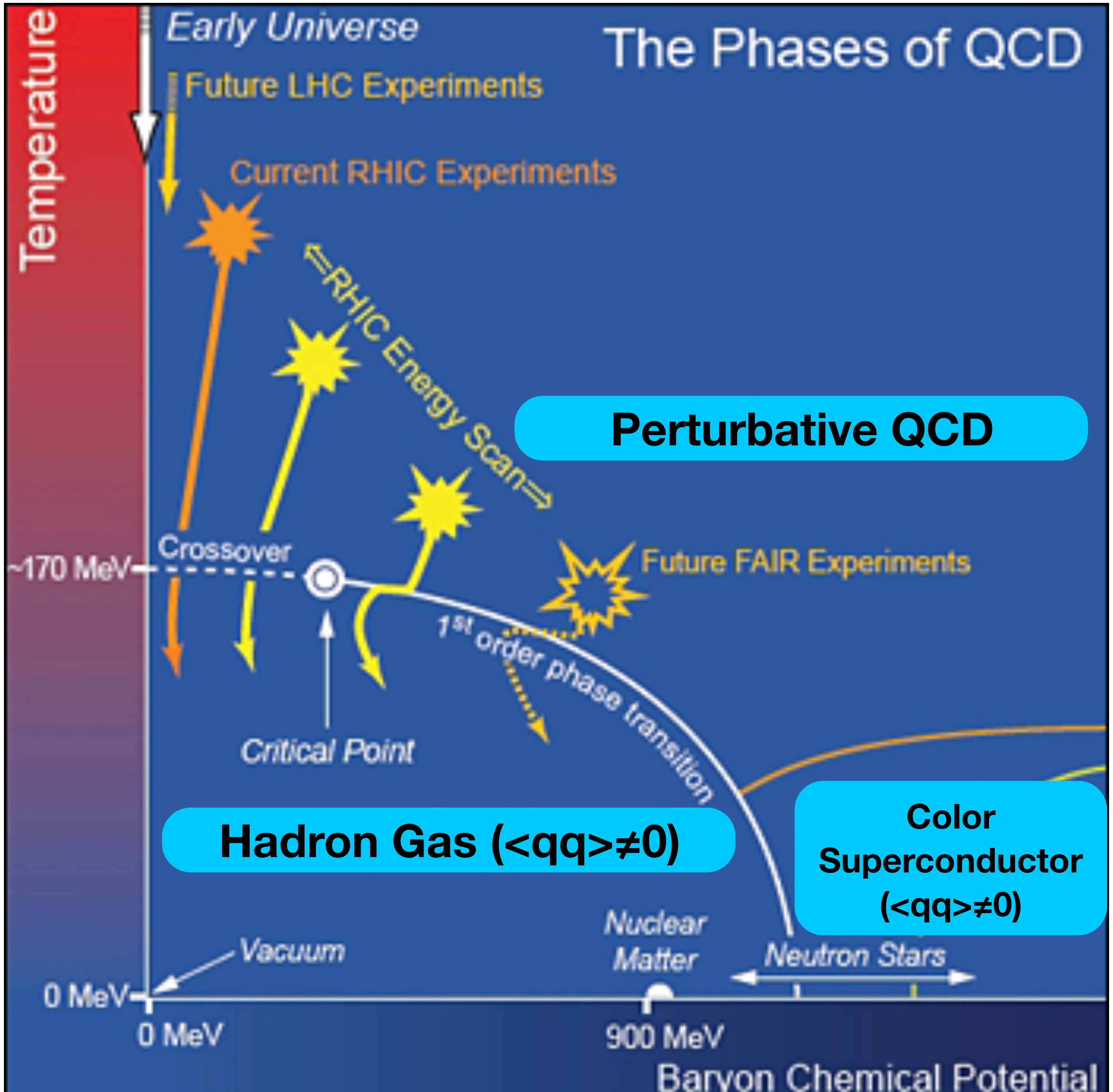


Theoretical Approach to Light Kaonic Atoms

Testing Chiral Perturbation Theory - Why LKA are so important

QCD phase diagram -



EAs are in The Hadron Gas Phase

Here, we need a different realisation of QCD (confinement)

In This phase, massless QCD Lagrangian is invariant under the full group of chiral transformation

$U_L(3) \times U_R(3)$

Chiral Condensate (i.e. ground state) not Invariant under this group

SSB - Starting point of XpT (effecive)

SSB of the full Chiral Group [43]

Chiral Transformation -> Rotations in the flavours space u,d,s (3 Flavours XpT)

The vacuum is not empty!
<qq>≠0

SSB

Applying to the g.s. rotations in the flavours space we find different results! So the vacuum is not invariant!

$U_L(3) \times U_R(3)$

$$L_0 = i\bar{q}\gamma^\mu D_\mu q = i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R$$

Massless (m_q=0)

Can be decomposed in: $U_L(1) \times U_R(1) \times SU_L(3) \times SU_R(3)$ 4 irreducible subgroups

$L \in U_L(3)$; $R \in U_R(3)$

Can be also expressed in therm of:

L=R vector transformation

$L=R^\dagger$ axial-vector transformation

Equivalent Decomposition: $U_V(1) \times U_A(1) \times SU_V(3) \times SU_A(3)$

Noether's theorem: conserved currents corresponding to the global symmetries

S: $m_q \neq 0$: Baryon Number Conservation in the Strong Interactions

AS: $m_q = m_{q'}$: Flavour symmetry of the hadronic spectrum

NS: Anomalously Broken at the quantum level (loop) of the theory

NS: octet of pseudo-scalar mesons -> octet of scalar meson parity doubling of the hadron spectrum

Not Observed! → **SSB of $SU_L(3) \times SU_R(3)$ in $SU_V(3)$ Subgroup**

Construction of the Effective Lagrangian [43]

SSB $SU_A(3)$

SSB of $SU_L(3) \times SU_R(3)$ in $SU_V(3)$ **8 Goldstone Boson (GB) spin 0 and odd parity $J^P=0^-$**

In the Hadron Spectrum with $J^P=0^-$: **Octet of light mesons $\pi^+, \pi^-, \pi^0, K^+, K^-, K^0$, K^0bar, η**

Separated from the rest of the spectrum with a mass gap characteristic for system with SSB

Identification! **$SU_A(3)$ Explicit breaking (mass therms)** **XpT as different realisation of QCD: we have moved the D.o.F. of the theory from g and q to the mesons!**

$G=SU_L(3) \times SU_R(3)$, $H=SU_V(3)$ $H \subset G$ → 8 GB → $\varphi(x)$ Real Field (8 component) → $g \in G$ → $\varphi \to \varphi' = F(g,\varphi)$

F = representation of G

Coset Space G/H is isomorphic to SU(3) → [43] → **GB can be represented with operator $U(x) \in SU(3)$**

Equivalence class: A left (right) coset of a group G with respect to the subgroup $H \subset G$ is an equivalence class of elements in G which only differ by right (left) multiplication with a member $h \in H$ and is denoted by gH (Hg).

$U(x)=\exp(2it^a\varphi^a(x)/f)$

$$t^a\varphi^a = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{1}{\sqrt{2}}\tilde{\pi}^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\tilde{\pi}^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta_8 \end{pmatrix} =: \frac{1}{\sqrt{2}}\hat{\phi}$$

f=pseudo-scalar decay constant in the chiral limit

$t^a=\lambda^a/2$ = generators of SU(3)

f measures the strength of meson decay into hadronic vacuum via axial-vector current

Physical basis

Construction of the Effective Lagrangian [43]

$$L_\phi = L_\phi\left(U, \partial U, \partial^2 U, \ldots\right)$$

Chiral Counting Scheme

Same symmetries of QCD
- **Lorentz Invariance**
- **C,P,T**
- **$SU_L(3)\times SU_R(3)$**

Interaction:

0^{th} order: constant (GB massless)

2^{nd} order: $L_\phi^{(2)} = \frac{f^2}{4}\langle \partial_\mu U \partial^\mu U \rangle$

Only even power of derivatives occurs

What we need to study KN scattering: RECIPE

To define and to put sources (connected: W[v,a,s,p])

v=vector
a=axial
s=scalar
p=pseudo-scalar

$$\chi = 2B_0(s+ip)$$

$$L_\phi(U) \rightarrow L_\phi(U,S) = L^{(free)} + L^{(source)}$$

Till now NO INTERACTION!

Requiring invariance under subgroup $SU_L(3)\times SU_R(3)$ for the Lagrangian:

Redefinition of covariant derivative [43]

$$L_\phi^{(2)} = \frac{f^2}{4}\langle \nabla_\mu U \nabla^\mu U \rangle + \frac{f^2}{4}\langle U^+\chi + \chi^+ U \rangle$$

To introduce the lowest lying octet of spin 1/2 baryons: n, p, Λ, Σ^+, Σ^-, Σ^0, Ξ^-, Ξ^0

$$B = t^a\Psi^a = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

A different approach to QFT

Leading order of the meson-baryon Lagrangian

axial-vector coupling baryon-meson [43] (LEC)

Meson field [43]

$$L^{(1)}_{\phi B} = \langle \bar{B}(i\gamma^{\nu} D_{\nu} - M_0) B\rangle - \frac{D}{2}\langle \bar{B}\gamma^{\mu}\gamma_5 \{u_{\mu}, B\}\rangle - \frac{F}{2}\langle \bar{B}\gamma^{\mu}\gamma_5 [u_{\mu}, B]\rangle$$

Baryon Octet mass in the Chiral limit

From the representation:

$$u(x) = e^{\frac{i}{f} t^a \hat{\phi}^a(x)} = e^{\frac{i}{\sqrt{2} f}\phi(x)}$$

Includes source

Bethe-Salpeter equation (from DSE [44])

$$Z_{\text{int}}[J] = \int D[\Phi] \exp\left[i\int d^4x L_0 + i\int d^4x \Phi(x) J(x) - i\frac{\lambda}{4!}\int d^4x \Phi^4(x)\right]$$

$$W[J] = -i\ln[Z[J]]$$

The Idea...

$$\frac{\delta W[J]}{\delta \phi(x)} = 0$$

BSE full scattering amplitude **Interaction Kernel** **Two Particle Propagator**

$$P = p + q = p' + q'$$

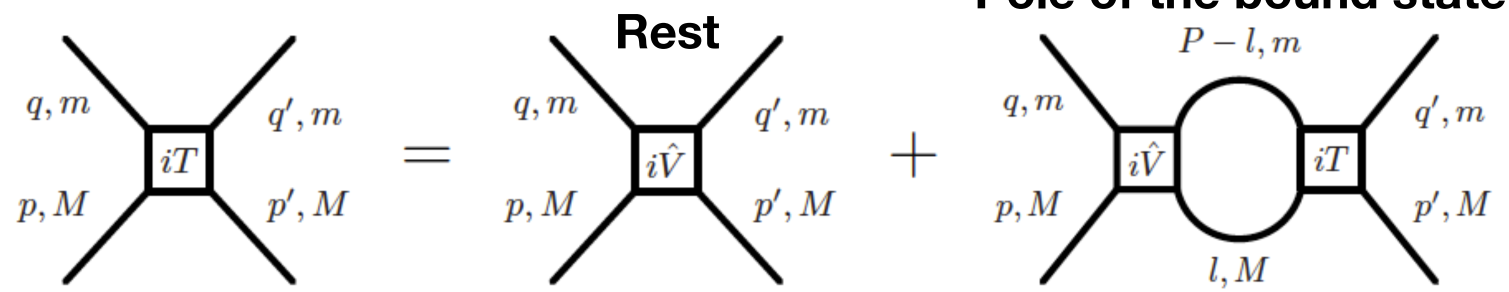
$$T(p', p, P) = \hat{V}(p', p, P) - \int \frac{d^d l}{(2\pi)^d} T(p', l, P)\, \tilde{G}(l, P)\, \hat{V}(l, p, P)$$

$$T = \hat{V} - T\tilde{G}\hat{V} \;\Rightarrow\; T = \hat{V} - \hat{V}\tilde{G}\hat{V} + \hat{V}\tilde{G}\hat{V}\tilde{G}\hat{V} - \ldots$$

Iteration solving...

4 point function -> Bound State propagator

Rest **Pole of the bound state**



$$a_{K^-p} = \frac{1}{8\pi\sqrt{s}} T_{K^-p\to K^-p}(s)\Big|_{s=(m_{K^-}+M_p)^2}$$

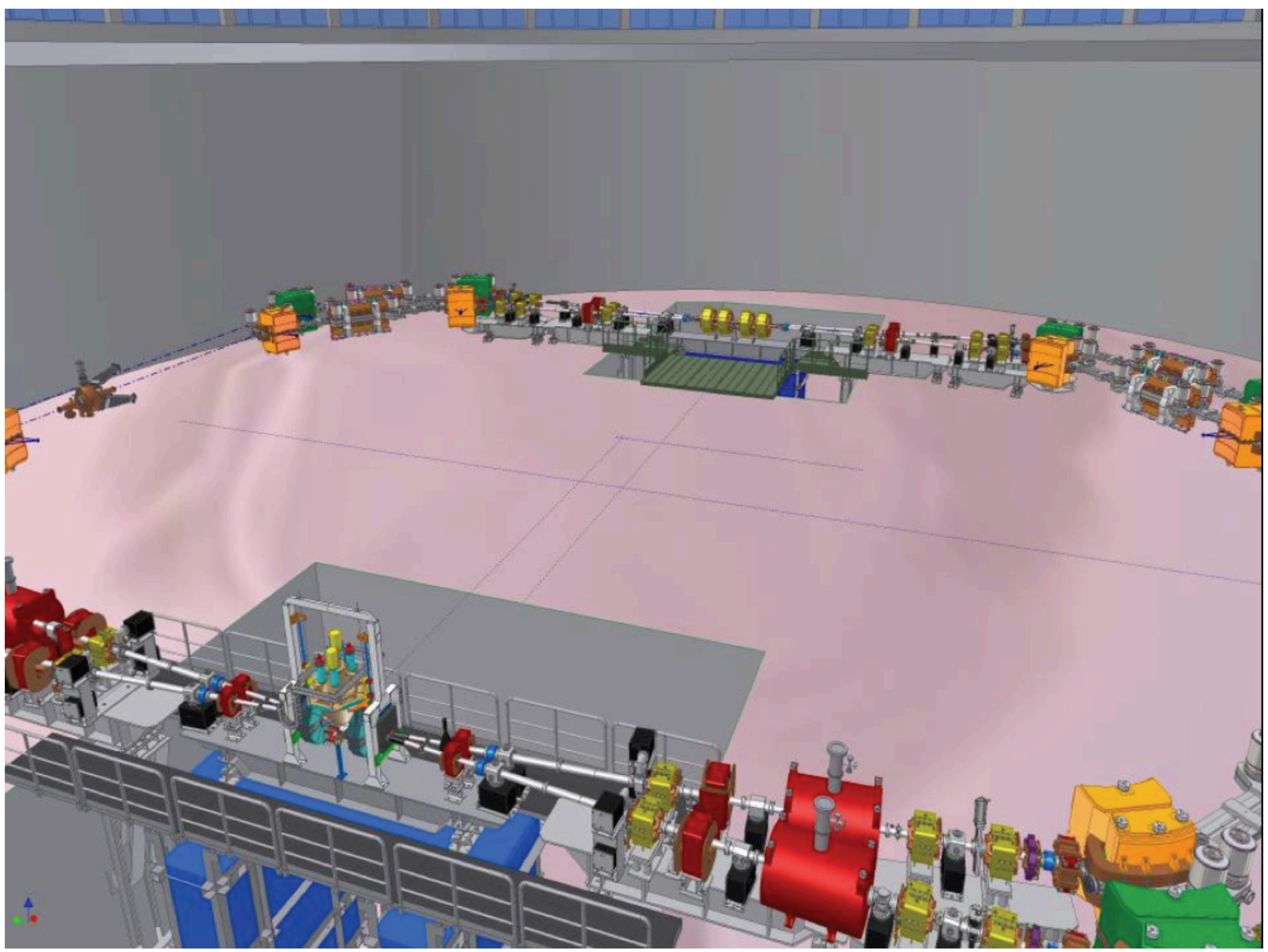
From KH! we are able to test Chiral Lagrangian (LECs)

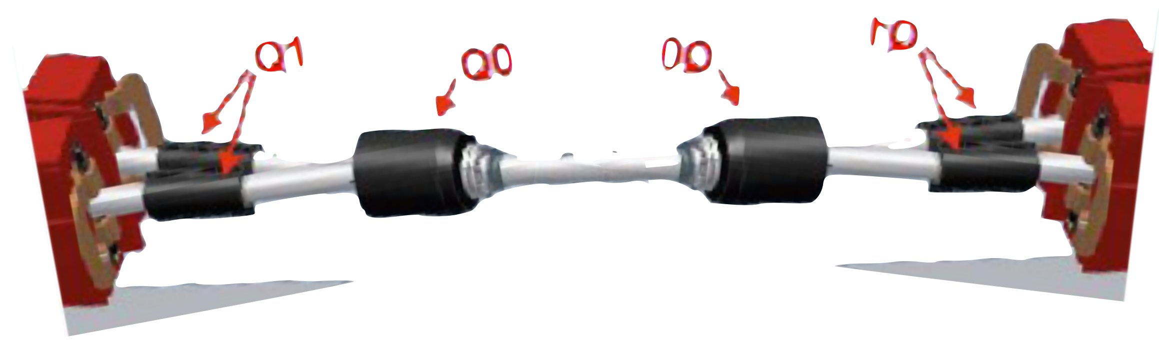
Upgraded DAΦNE

Crab-Waist collisions [45][47]

Enhance Luminosity through:

- reduction of the crossing angle at the Interaction Point (IP) between the two colliding beams [45]
- reduction of the transverse dimensions of the bunch, reducing betatron oscillation near IP [47]



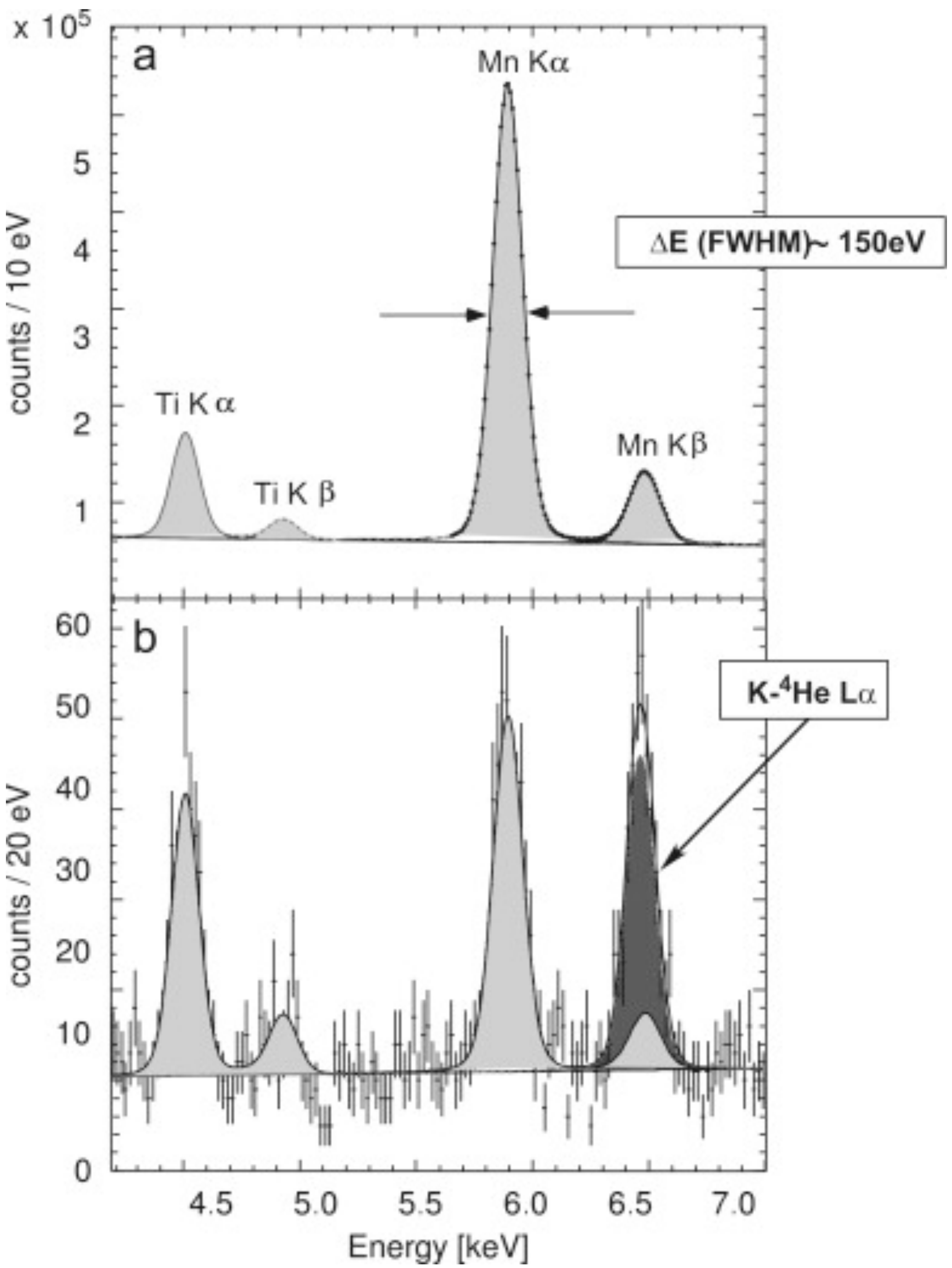


Using 6 new permanent magnet (SmCo) with nominal field: Q0 = 6.7 T, Q1 = 3 T [45]

Pair of dedicated sextupoles (symmetric position respect IP) [45]

Choose: Asymmetric collision scheme with only IP [45]

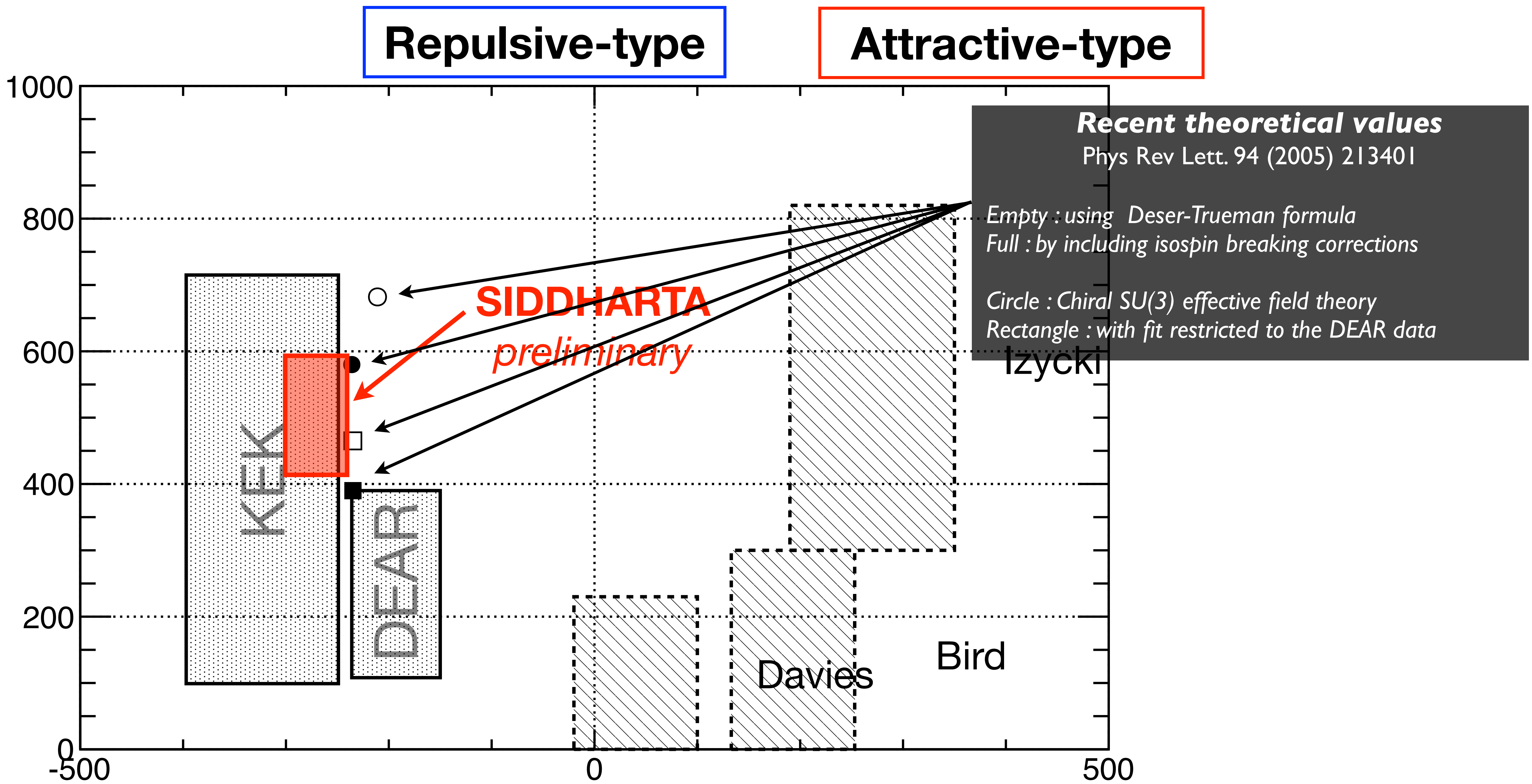
SDDs resolution



FWHM = 151 ± 2 eV (@5.9 KeV [Mn Kα]) [33]

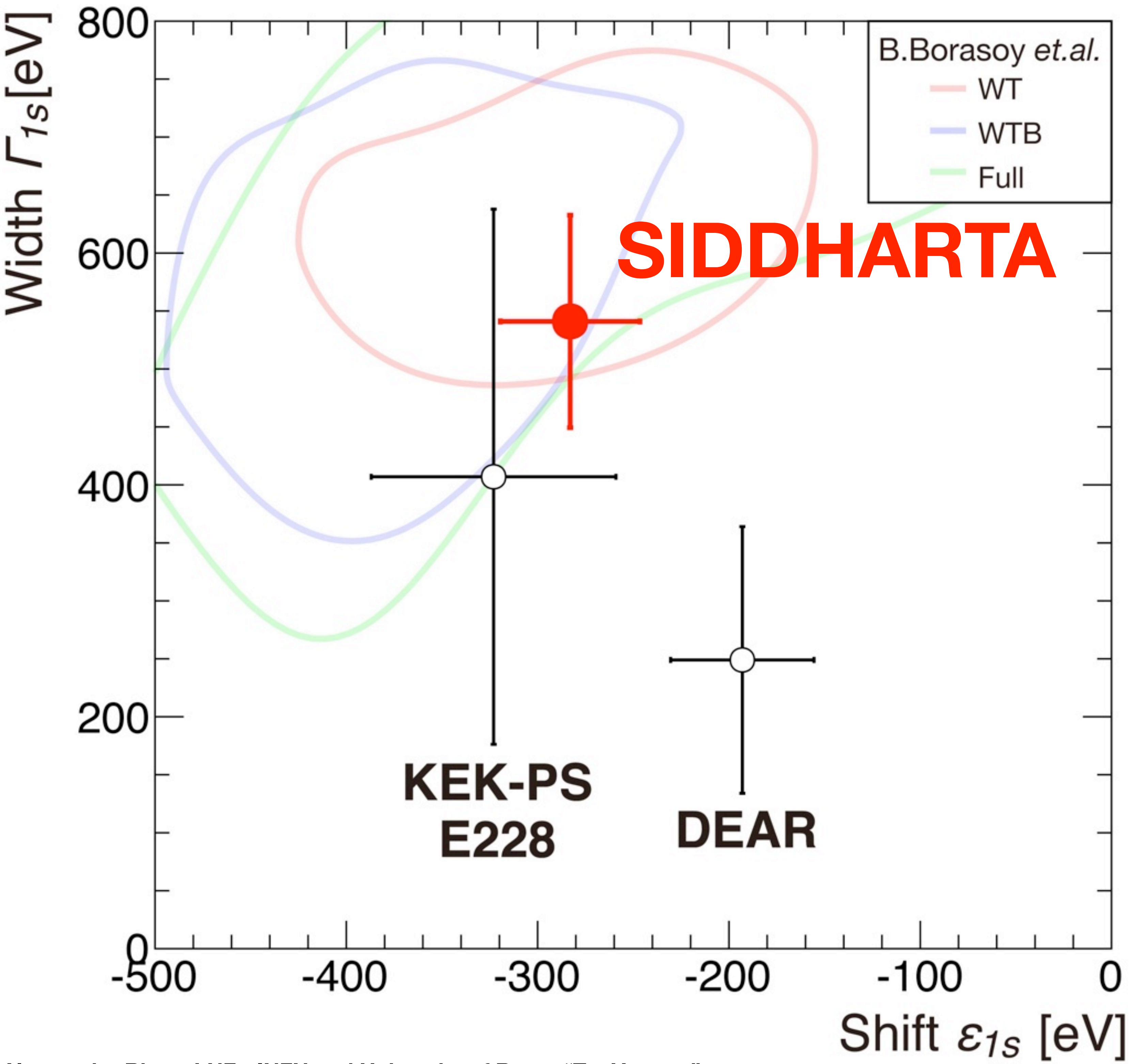
Stability ≈ ± 2 - 3 eV [33]

KH SIDDHARTA results- Comparison with the theoretical values



Courtesy of S. Okada

Comparison with recent theoretical values



B. Borasoy et.al., PRC74, 055201 (2006)

Chiral SU(3) unitary approaches

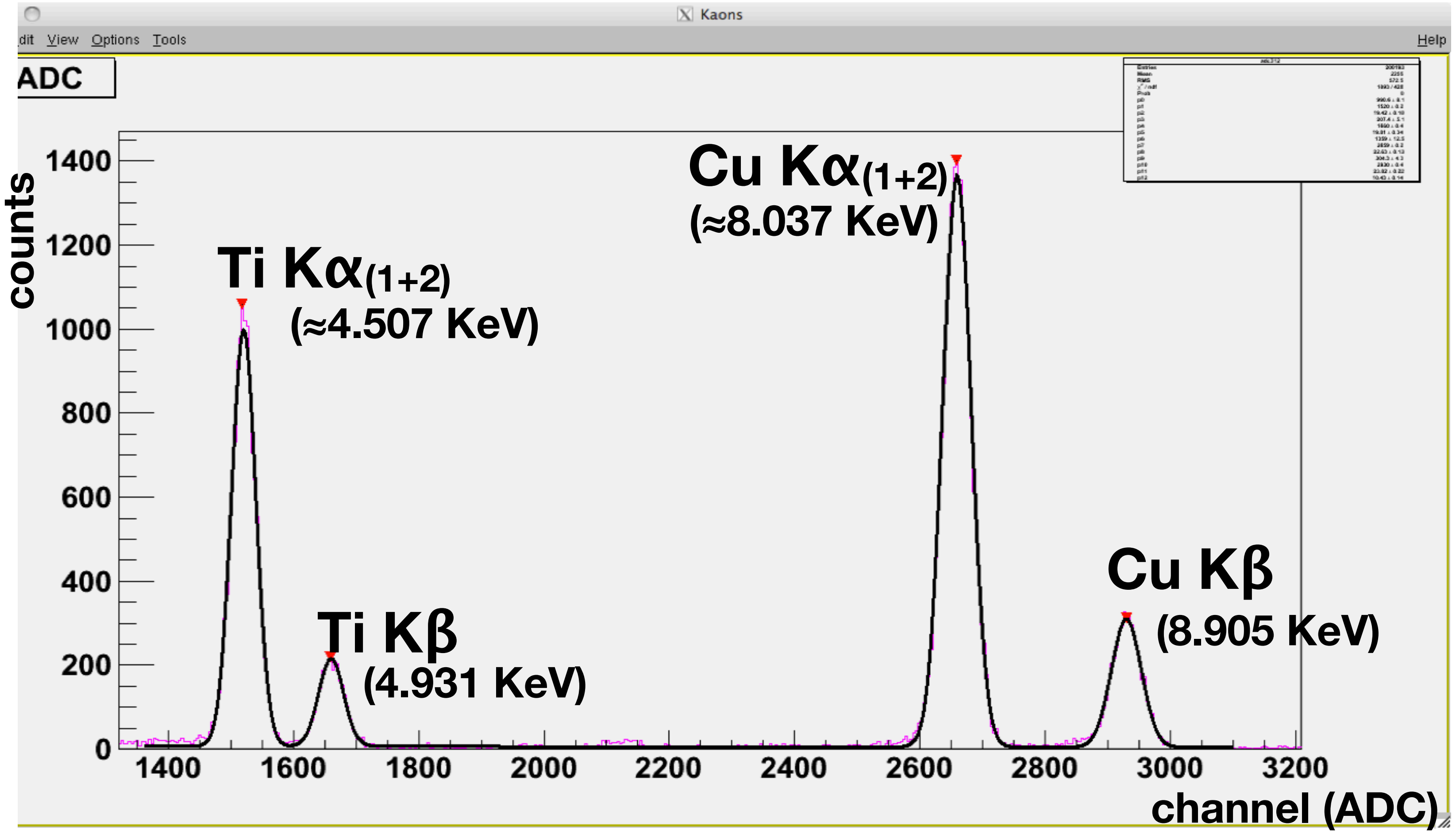
… providing a conservative range for the $K^{-}p$ scattering length constrained solely from $K^{-}p$ scattering data.

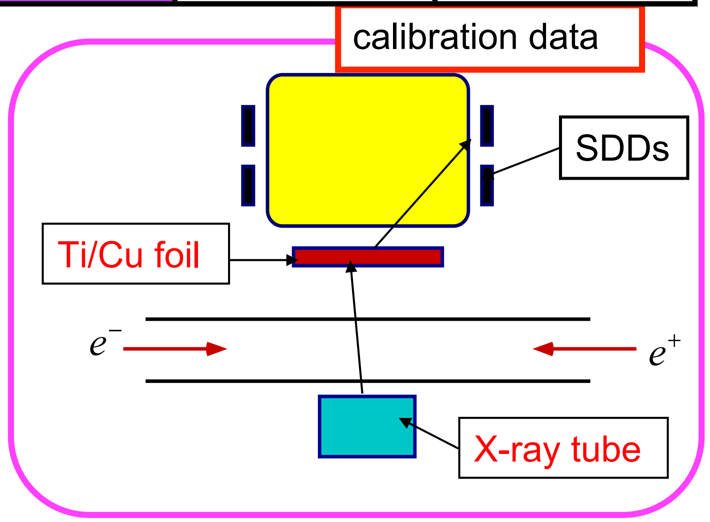
Weinberg-Tomozawa
Weinberg-Tomozawa-Born

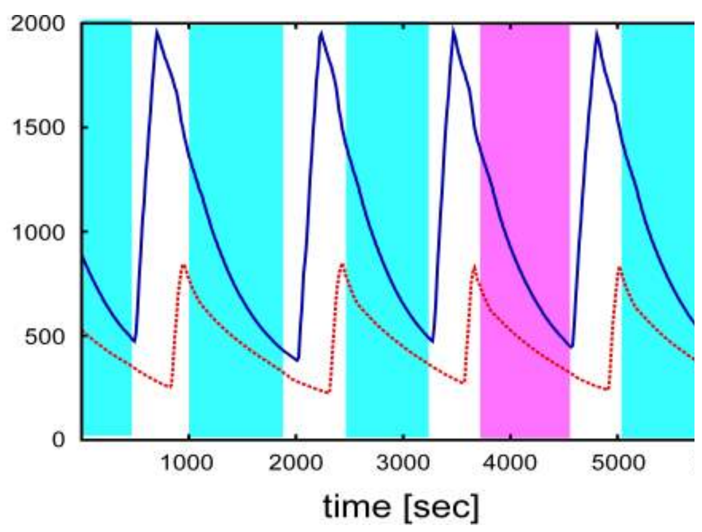
Data taking and calibrations

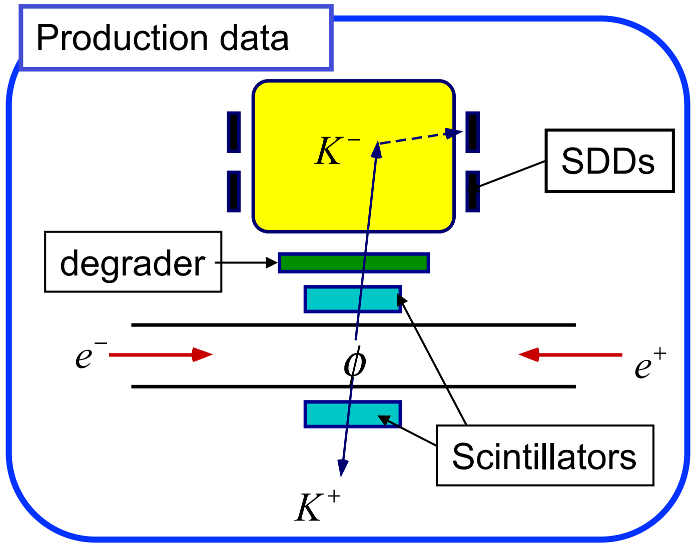
Calibrations of 144 SDDs every 4 our

Stability of the response is constantly monitored for each detector!





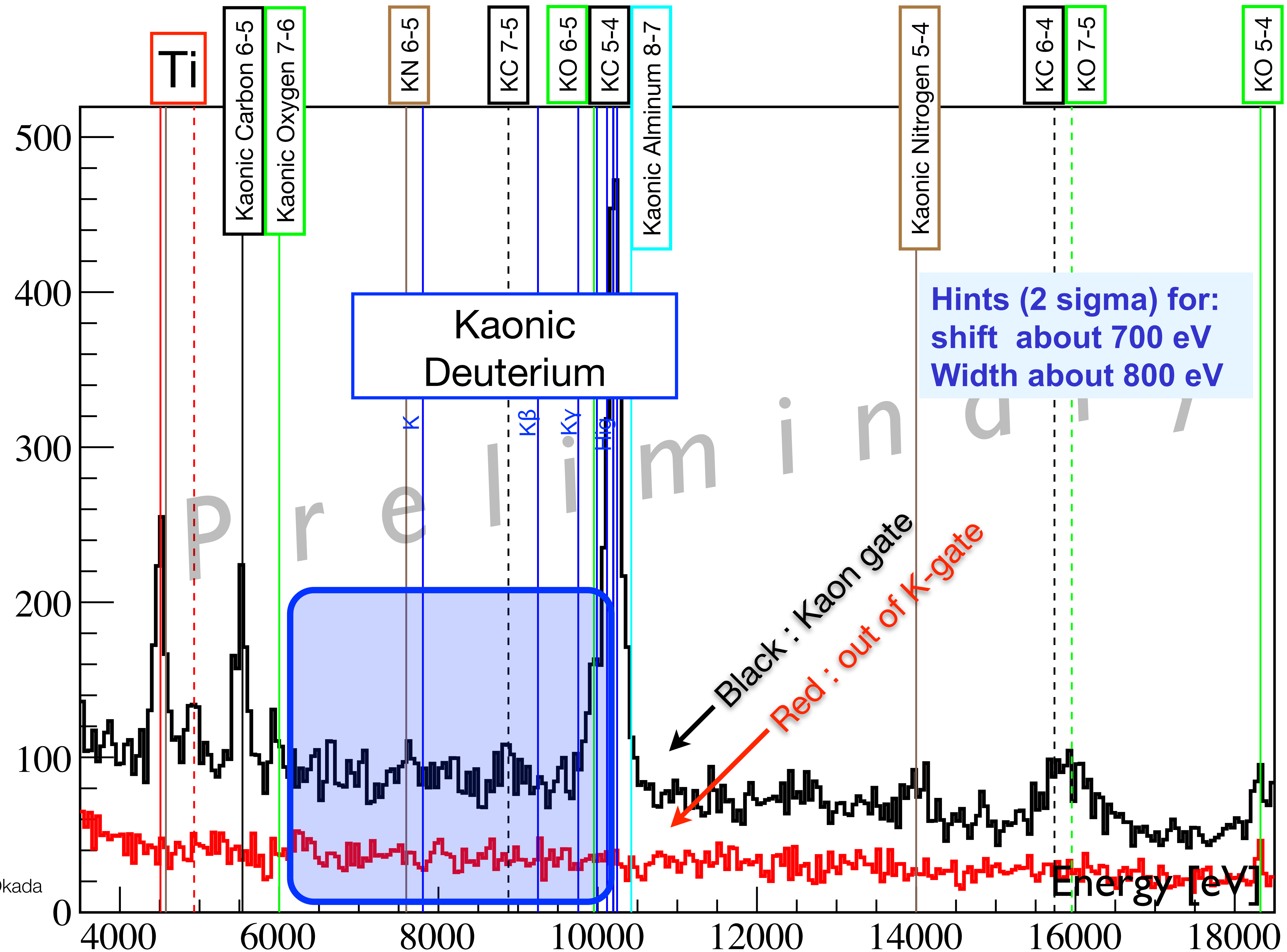




Removing the cross-talk events

Study of the response function of each detector (tails, shelf)

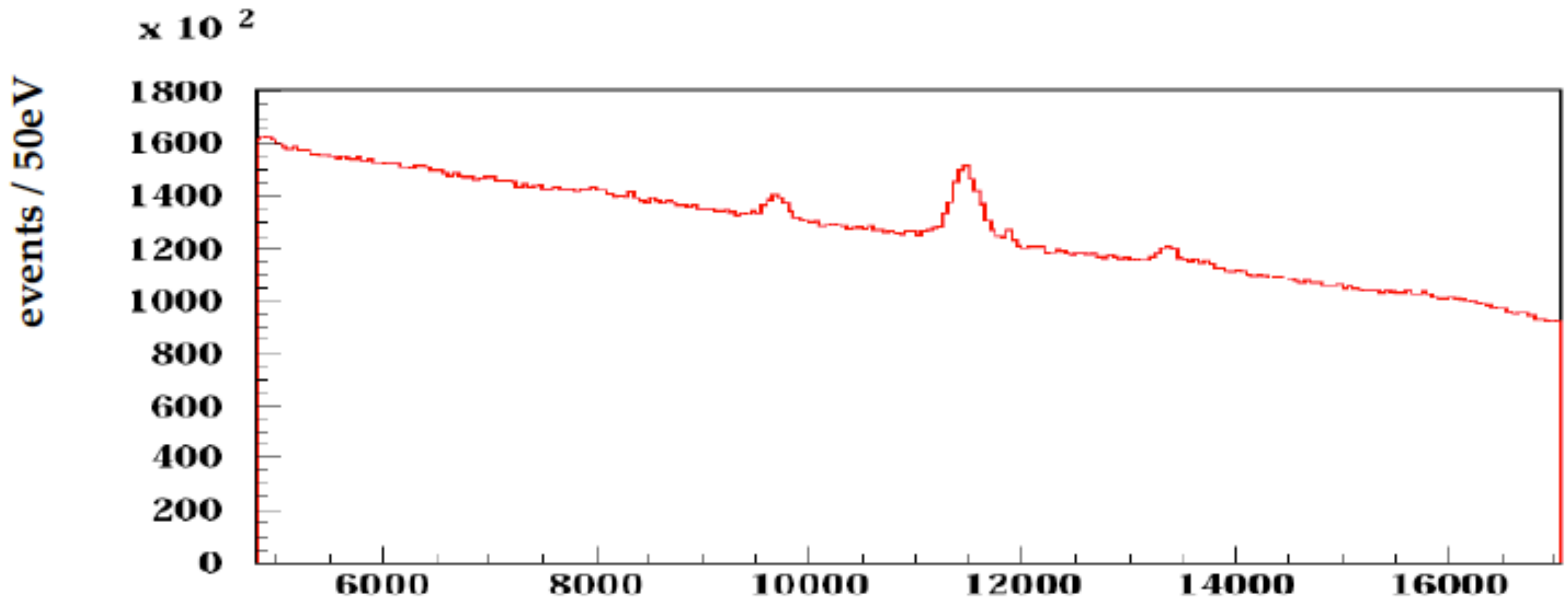
Kaonic Deuterium: spectrum

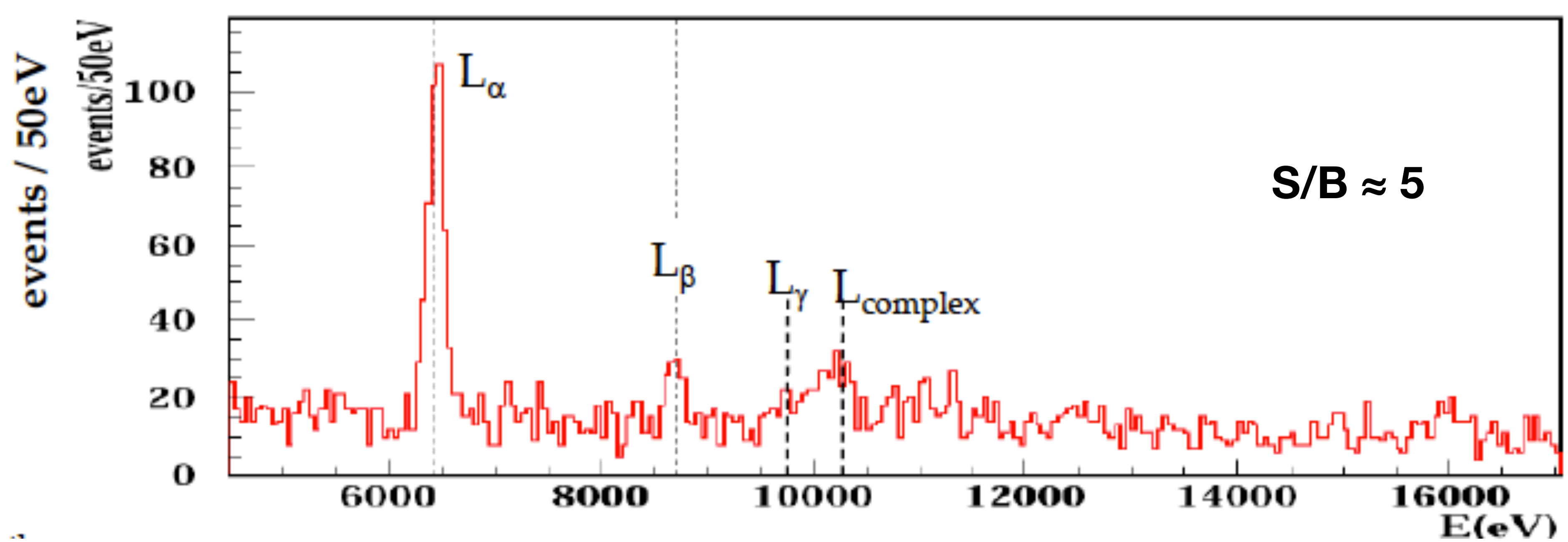


small signal
wide width

Courtesy of S. Okada

Background: K^4He





Muonic and Pionic Helium

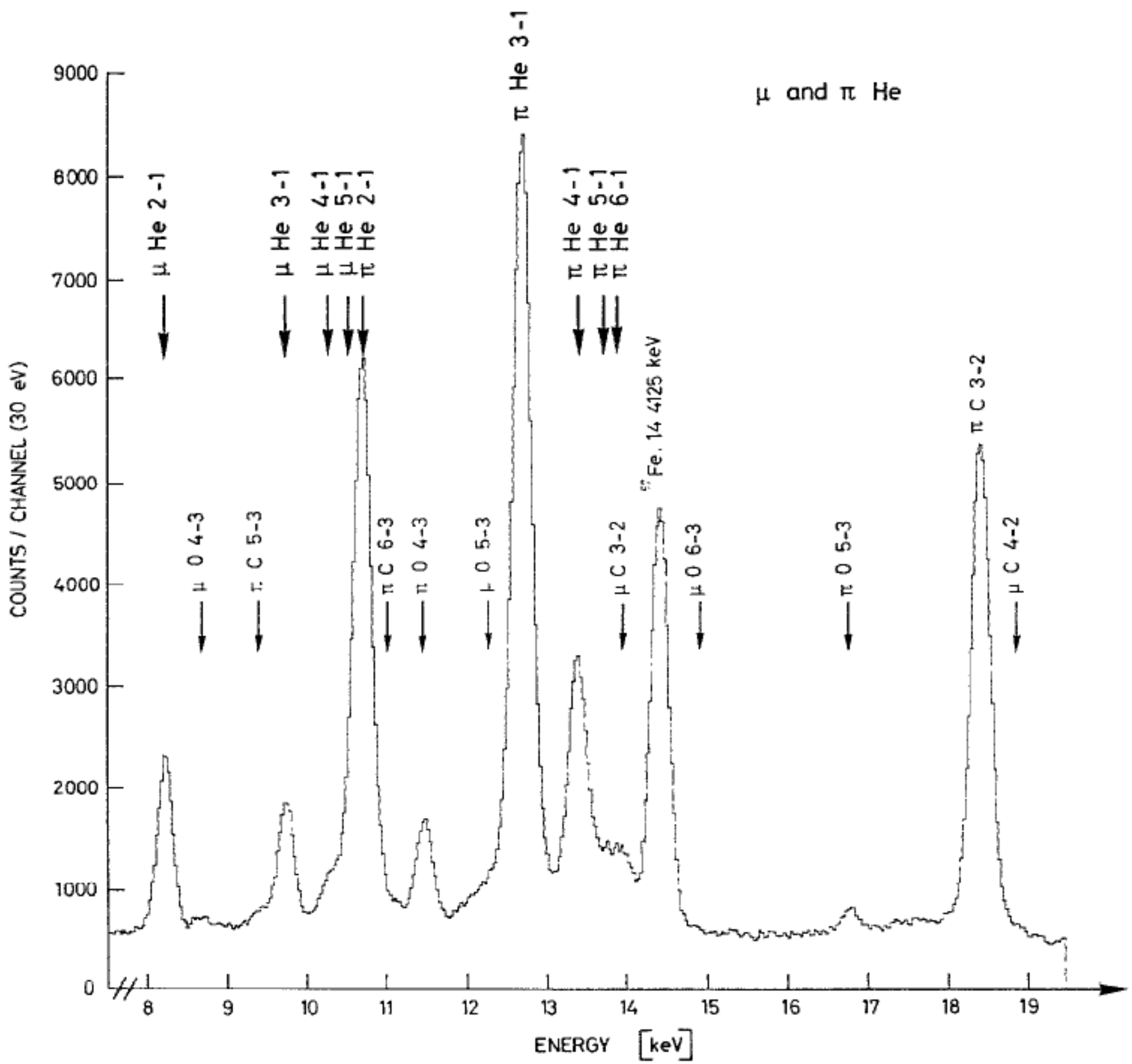


Fig. 2. Pionic helium spectrum.