How to achieve precision in physics

a case study - mass of the charged pion

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PREFACE

EXPERIMENT DESIGN

general considerations

think of all you can imagine – there will be more!

• MOTIVATION

- Is there an interesting physics question?
- Do we understand preconditions and possible show stoppers?
- Is there an appropriate experimental technique available

  for the envisaged precison (≈ method & statistics) ?
- Which level of accuracy (≈ systematics) is achievable?
- Impact of the expected result?

- # FIND YOUR LABORATORY

  - Acquire the pre-experiment level of knowledge
  - Understanding the laboratory conditions
  - Is the experiment affordable (money & man power)?
  - How to get it approved?

• EXPERIMENTAL APPROACH

- Planning set-up and experiment
- Do not underestimate mechanics!
- How to control an ongoing measurement and

  gather all necessary information and even more!
- Analysis strategy
- Uncertainties

- **ASSESSMENT**
  - **The result**
  - **New physics or experimental aspects**
  - **Assessment of limits**
  - **Presentation of results**
  - **Publication in an appropiate journal**
  - **New approaches and outlook**

EXAMPLE

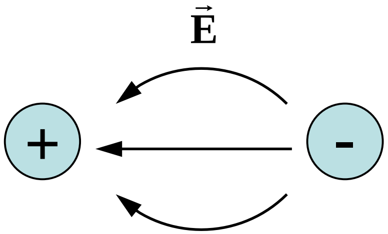
CHARGED PION MASS

$$\boldsymbol{\frac{\Delta m_\pi}{m_\pi} \approx 1ppm}$$

$$\boldsymbol{\tau_{\pi^\pm} = 26\,ns}$$

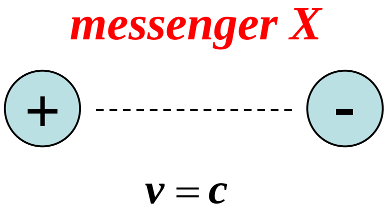
- **MOTIVATION**
- LABORATORY
- EXPERIMENTAL APPROACH
- SOME RESULTS

classical: in a field a force acts on a charge



quantum field theory: „virtual“ exchange particle

„exchange“ force

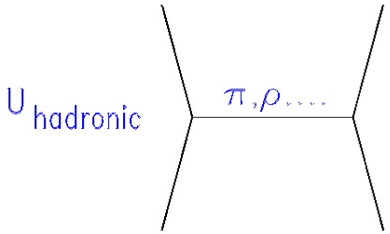


electromagnetic force **X = photon (γ)**

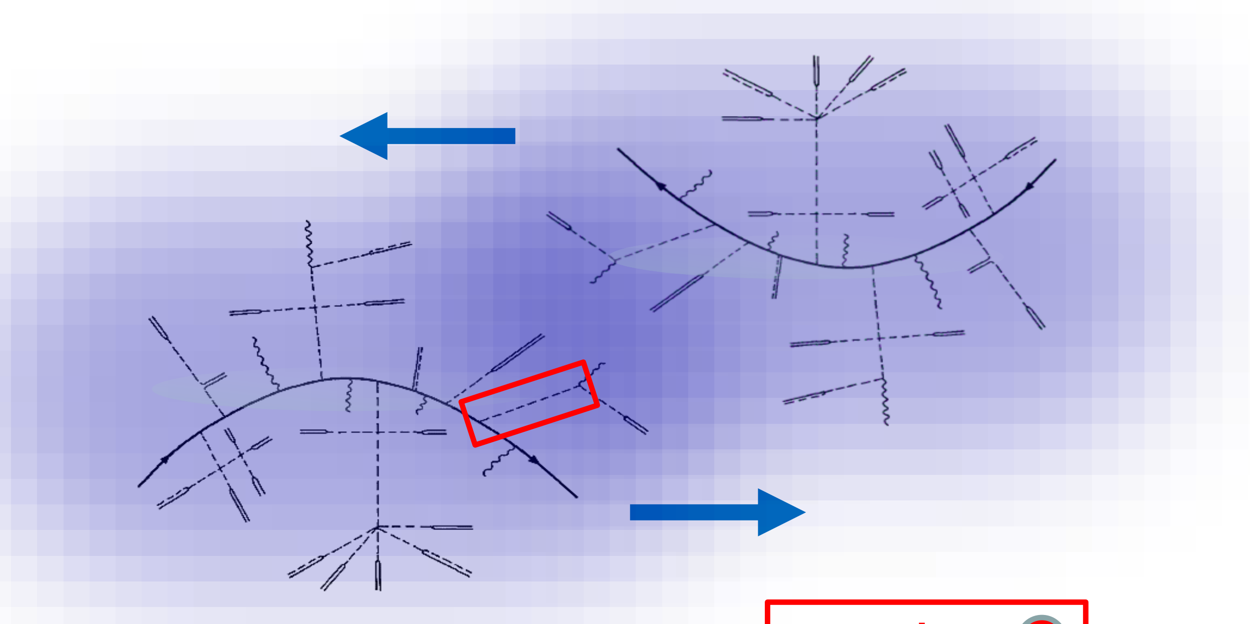
strong force **X = mesons** $\begin{pmatrix} \mathbf{p} \leftrightarrow \mathbf{n}\pi^{+} \\ \mathbf{n} \leftrightarrow \mathbf{p}\pi^{-} \end{pmatrix}$

strong-interaction potential U

medium and long range part



PIONS, NUCLEONS - INTERACTION in terms of QCD



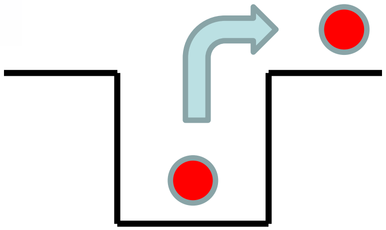
Nucleons with chiral loops,

- - - pions ●

CHIRAL PERTURBATION THEORY (χPT), …

NN ⇔ NN

NN ⇔ NNπ



Bring the pion out by inserting energy scattering (production experiments)

J. Gasser et al., Nucl. Phys. B307, 779 (1988)

Fig. 1. A typical term in the expansion (3.7) of the nucleon propagator. ——→—— nucleon; - - - pions; ∼∼∼ vector current; =·= axial vector current; --⊏ pseudoscalar density; ═══ scalar density.

PIONS – LIGHTEST CARRIER of NUCLEAR FORCE

charge Q		**$0, \pm 1$**	***isospin triplet***
mass M_π		**$\approx m_p / 7 \approx 270 \cdot m_e$**	
spin S		**0**	
size		$0.6 \cdot 10^{-15}$ m	
life time τ_0	$\pi^\pm$	**$26 \cdot 10^{-9}$ s**	**$m_{\pi\pm} \approx 139$ MeV/c^2**
	π^0	**$8 \cdot 10^{-17}$ s**	**$m_{\pi 0} \approx 135$ MeV/c^2**

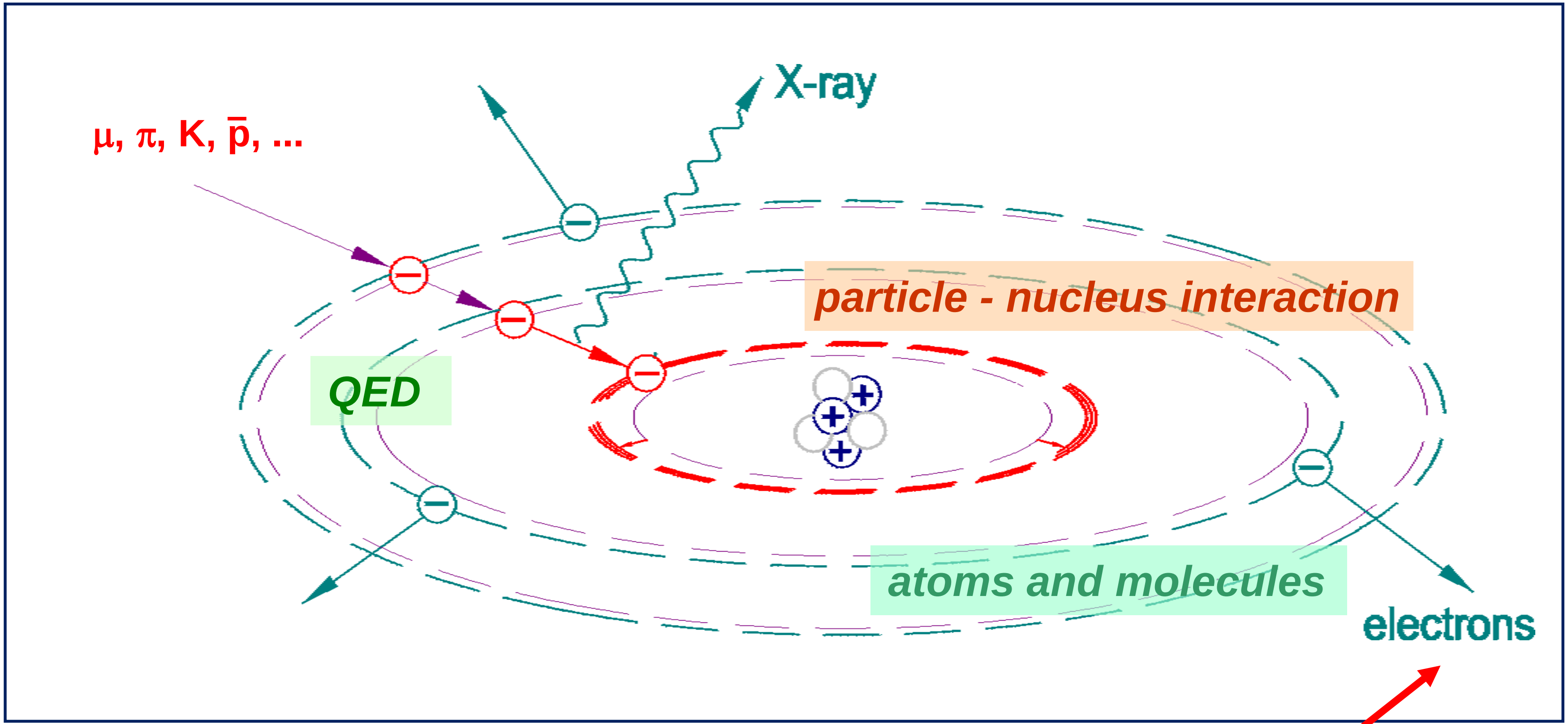
decay

$\pi^\pm \to \mu^\pm \nu$ *limit for the muon neutrino mass* $m_{\nu\mu}$ *(1973: dark matter?)*

$\pi^0 \to \gamma\gamma$ ***$n_{colour} = 3$!***

- MOTIVATION
- **LABORATORY**
- EXPERIMENTAL APPROACH
- SOME RESULTS

EXOTIC ATOMS



μ, π, K, $\bar{p}$, ...

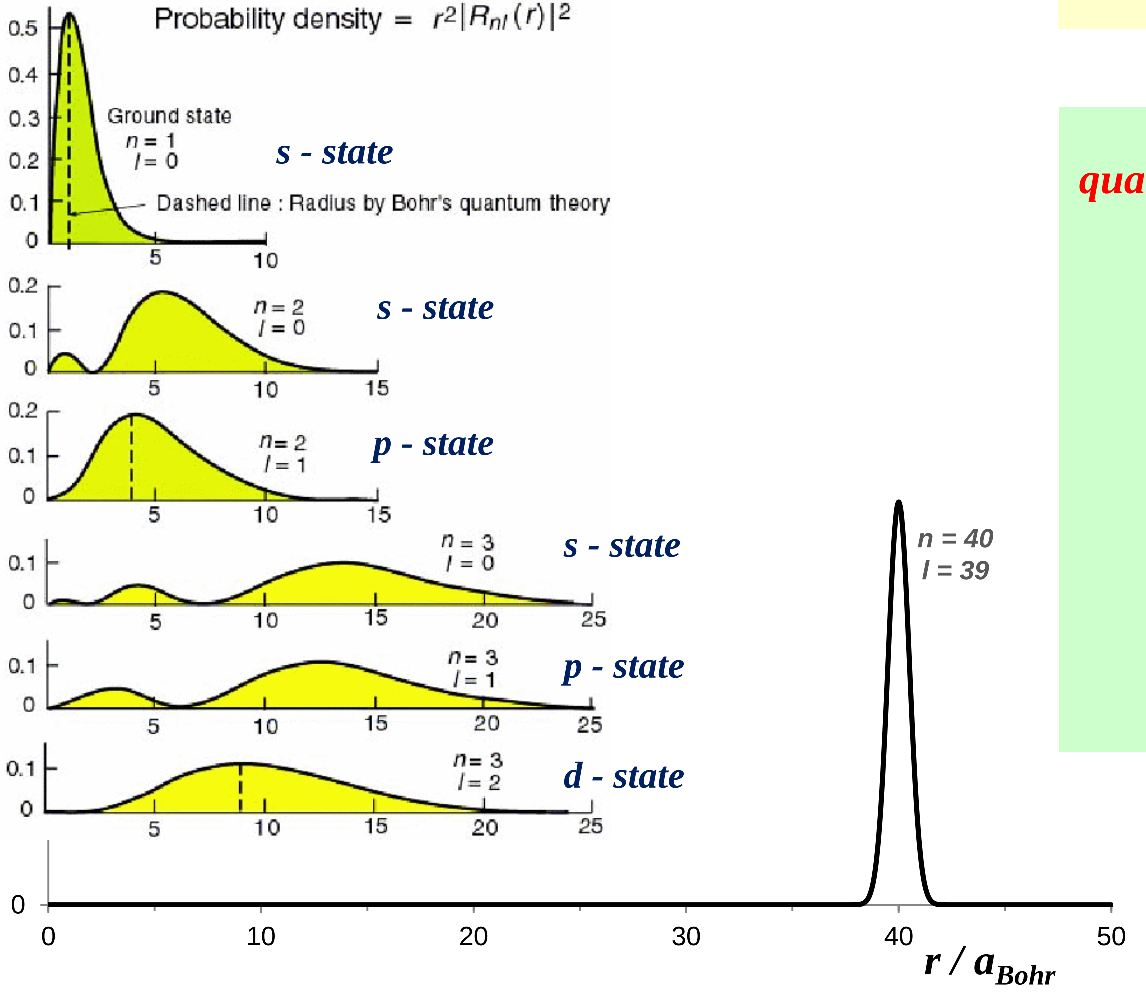
particle - nucleus interaction

QED

atoms and molecules

emitted by Auger effect !

ATOM



$$V_{Coulomb} = -\frac{Ze^2}{r}$$

quantisation of action: $E \cdot t = 2\pi\hbar$

$$a_n = \frac{\hbar c}{m_{red}\, c^2\alpha} \cdot \frac{n^2}{Z}$$

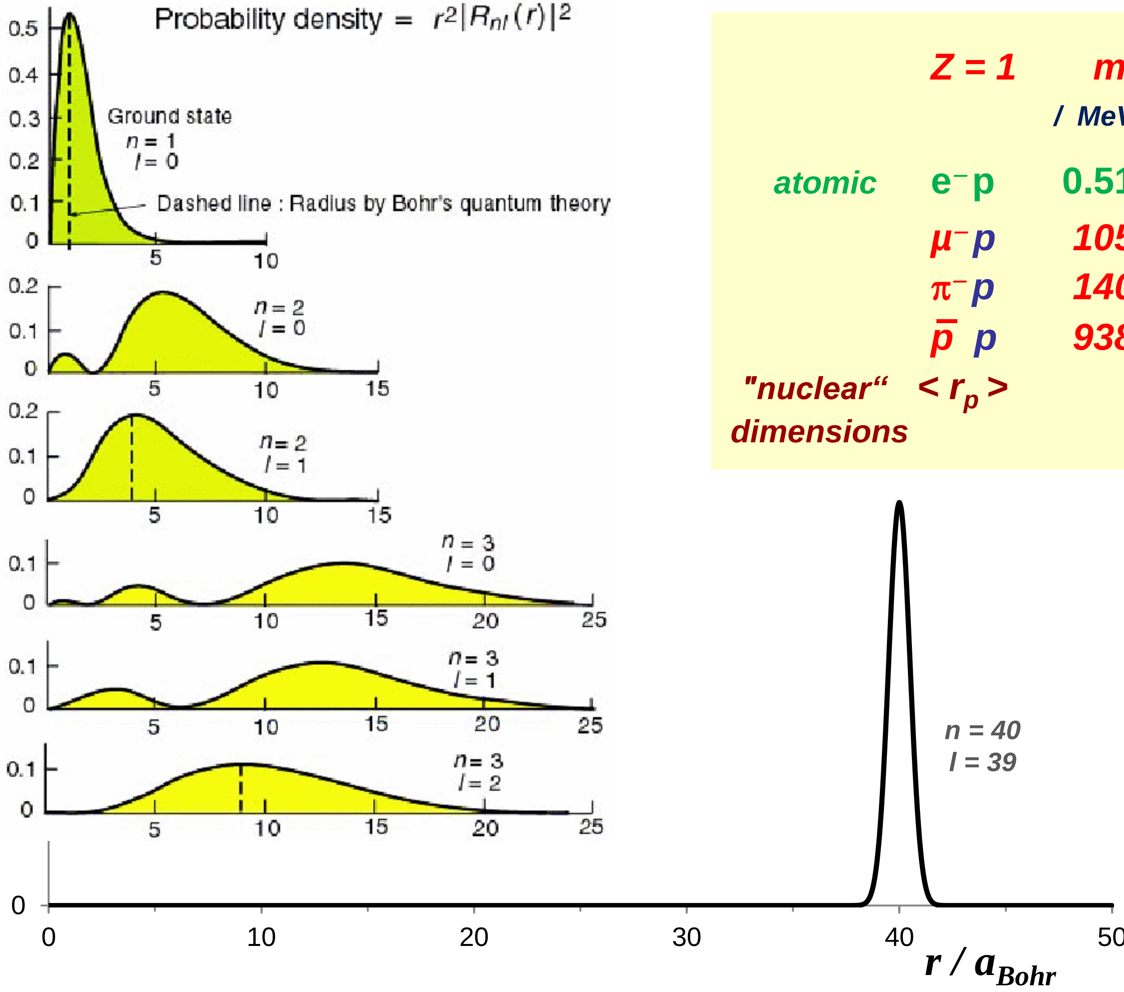
$$a_{Bohr} = \frac{\hbar c}{m_{red}\, c^2\alpha}$$

$$B_n = -\, m_{red}\, c^2\alpha^2 \cdot \frac{Z^2}{2n^2}$$

EXOTIC ATOM

replace electrons by heavier negatively charged particles

	$Z = 1$	m / MeV/c²	B_1 / keV	"Bohr" radius a_B / fm
atomic	e^-p	0.511	0.0136	$0.5 \cdot 10^5$
	μ^-p	105	2.6	279
	π^-p	140	3.2	216
	$\bar{p}\ p$	938	12.5	58
"nuclear“ dimensions	$< r_p >$			0.8



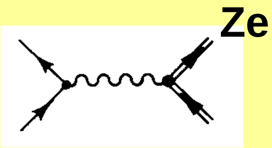
$$a_{16}(\pi^-) \approx a_1(e^-)$$

$$a_{40}(\bar{p}) \approx a_1(e^-)$$

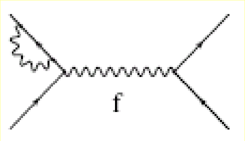
ATOMIC BINDING ENERGY

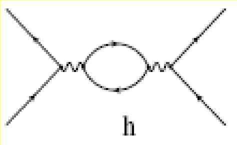
$E_B = E_{Coulomb}$

$-\frac{Ze}{r}$



$+ \Delta E_{QED}$





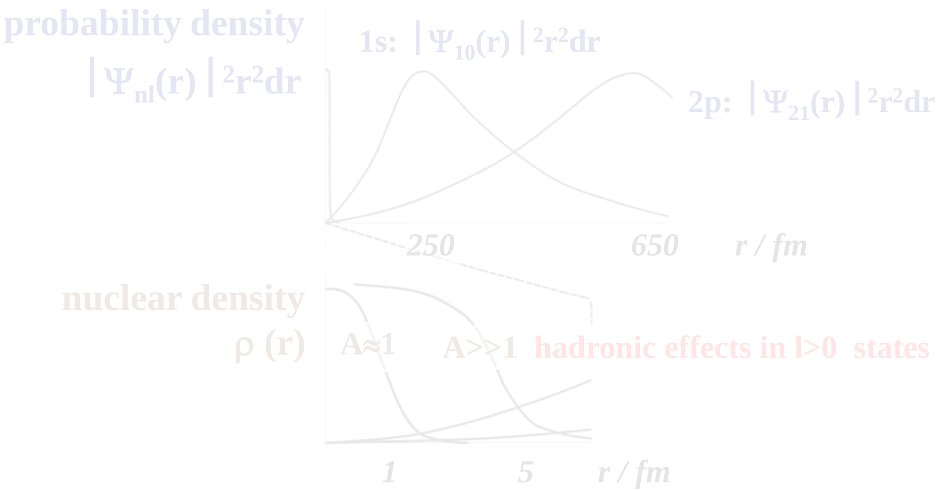
self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$

capture $x^- + [A(Z,N)Ze^-] \rightarrow \{[x^- A(Z,N)]ne^-\} + \text{few } e^-$

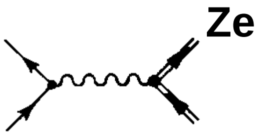
$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$



ATOMIC BINDING ENERGY

$E_B = E_{Coulomb}$ $\quad -\frac{Ze}{r}$



$+ \Delta E_{QED}$

self energy + *vakuum polarisation* + *higher orders*

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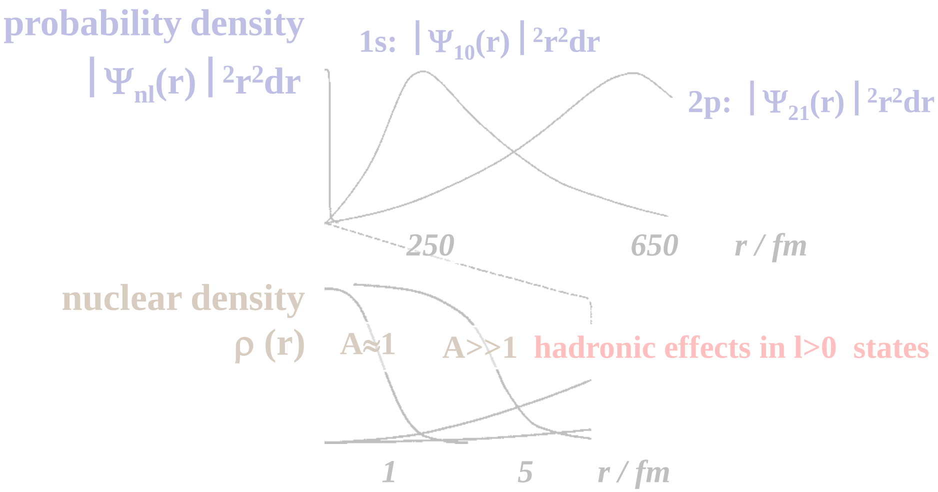
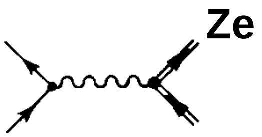


$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$

ATOMIC BINDING ENERGY

$E_B = E_{Coulomb}$ $\quad -\frac{Ze}{r}$



$+ \Delta E_{QED}$

self energy + *vakuum polarisation* + *higher orders*

$+ \Delta E_{screening}$

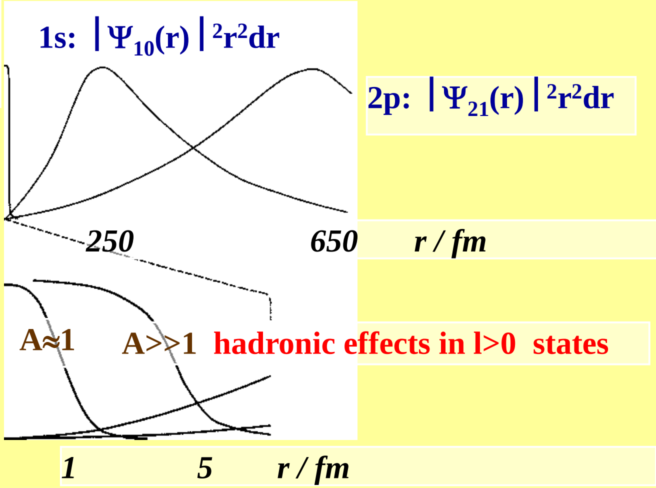
capture $\quad x^- + [A(Z,N)Ze^-] \rightarrow \{[x^- A(Z,N)]ne^-\}$ + *few* e^-

$+ \Delta E_{finite\ size}$

$+ \Delta E_{strong\ interaction}$

probability density
$|\Psi_{nl}(r)|^2 r^2 dr$

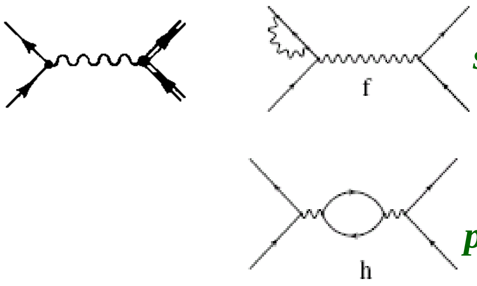
nuclear density
$\rho\ (r)$



hadronic effects in l>0 states

including STRONG INTERACTION

$$V_{Coulomb} = -\frac{Ze^2}{r} + \Delta E_{QED} + V_{strong\ interaction}$$



self energy

vakuum polarisation

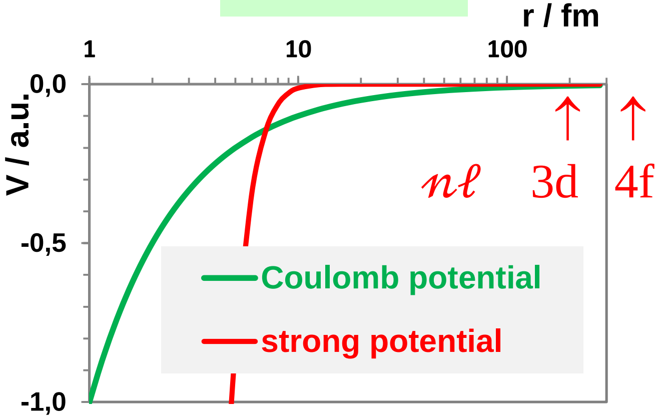
+ higher orders

Yukawa potential

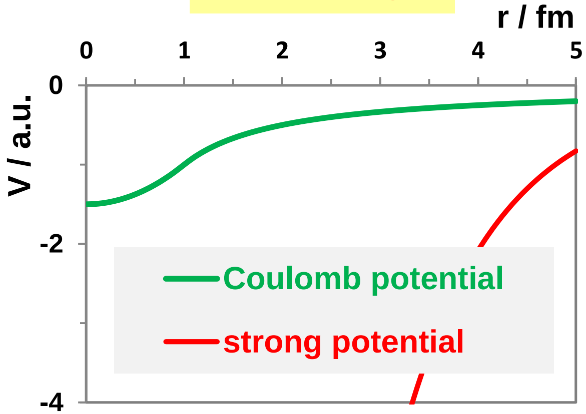
$$V_{strong} = g^2 \cdot \frac{e^{-\mu r}}{r}$$

$$\mu = \frac{\hbar c}{m_\pi c^2}$$

long range

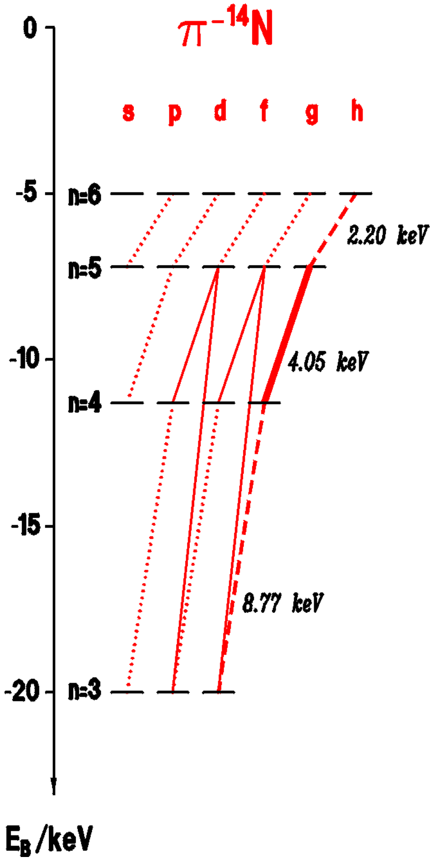


short range



level shift & broadening

CANDIDATE



measurement

πN(6h-5g) *low energy & yield ⇔ absorption losses*

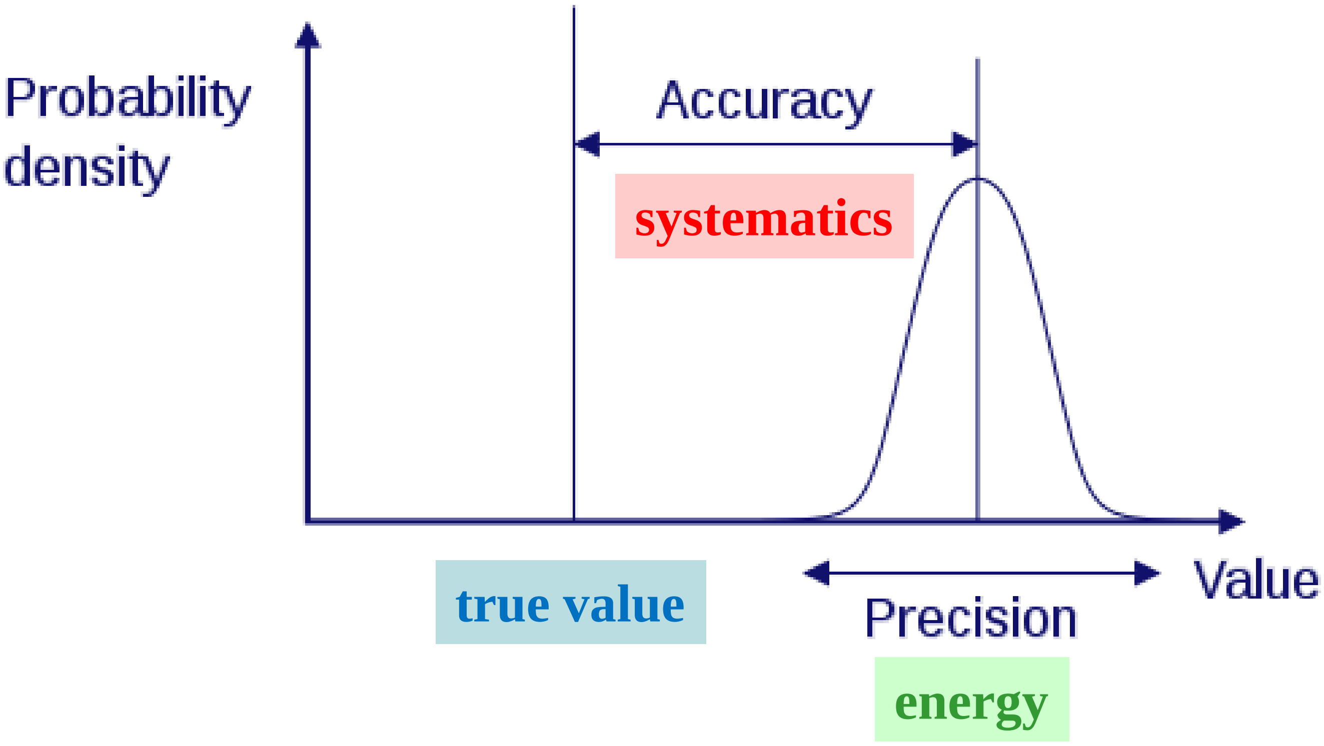
πN(5g-4f) ***best!***

πN(4f-3d) *strong-interaction corrections sizable*

- MOTIVATION
- EXOTIC ATOM
- **EXPERIMENTAL APPROACH**
- SOME RESULTS

SUMMARY OF

ALL EXPERIMENTAL PROBLEMS

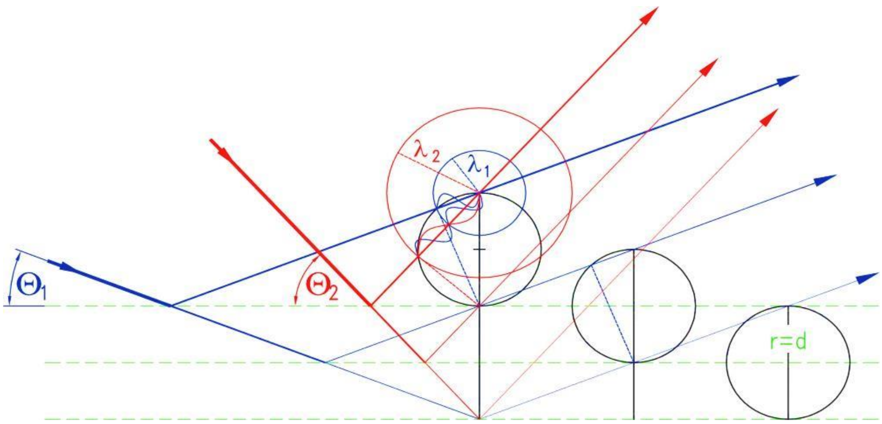


EXPERIMENT I

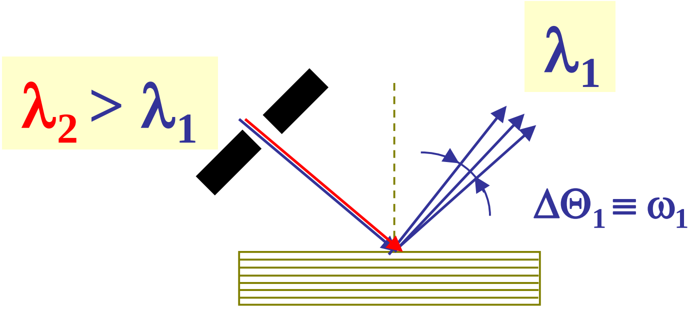
How to achieve the necessary precison in the energy determination ?

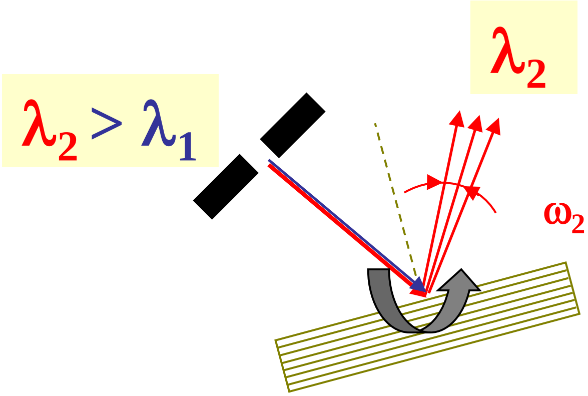
BRAGG'S LAW $n\lambda = 2d\cdot\sin\theta_B$

n	order of diffraction
λ	wave length
d	spacing of diffracting planes
θ_B	Bragg angle



ω	angular spread of reflection





τ_e	extinction length	*coherent reflection*
τ_a	absorption length	*incoherent*

usually $\tau_e << \tau_a$

EXPERIMENT II

How to produce a suitable X-ray source

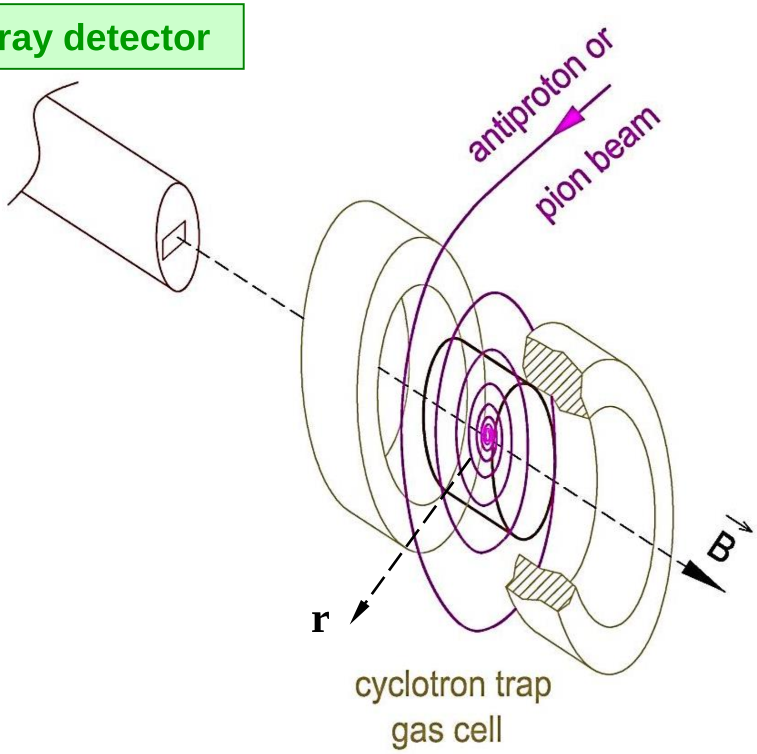
=

many of exotic atoms (statistics)?

CYCLOTRON TRAP

concentrates particles

X-ray detector



L. Simons, Physica Scripta 90 (1988), Hyperfine Int. 81 (1993) 253

"wind up" range curve

in a (weakly) focusing magnetic field

$$n = -\frac{\frac{\partial B}{B}}{\frac{\partial r}{r}} < 1$$ *field index*

increase in <u>stop density</u>

compared to a linear stop arrangement

pions (PSI)		x 200
antiprotons	(LEAR)	x 10^6

⇒ high X - ray line yields

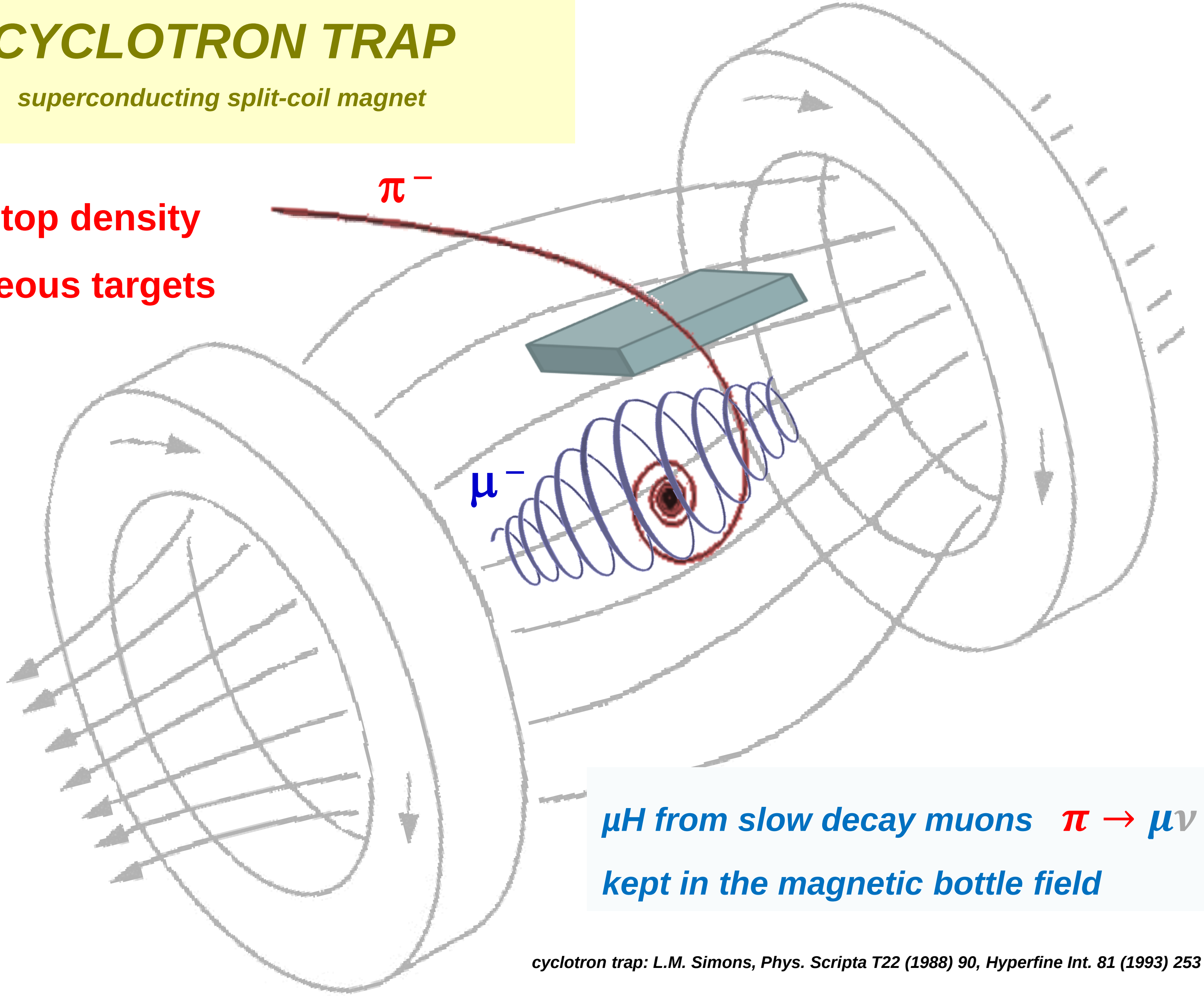
⇒ bright X - ray source

CYCLOTRON TRAP

superconducting split-coil magnet

high stop density

in gaseous targets



μH from slow decay muons $\pi \to \mu\nu$

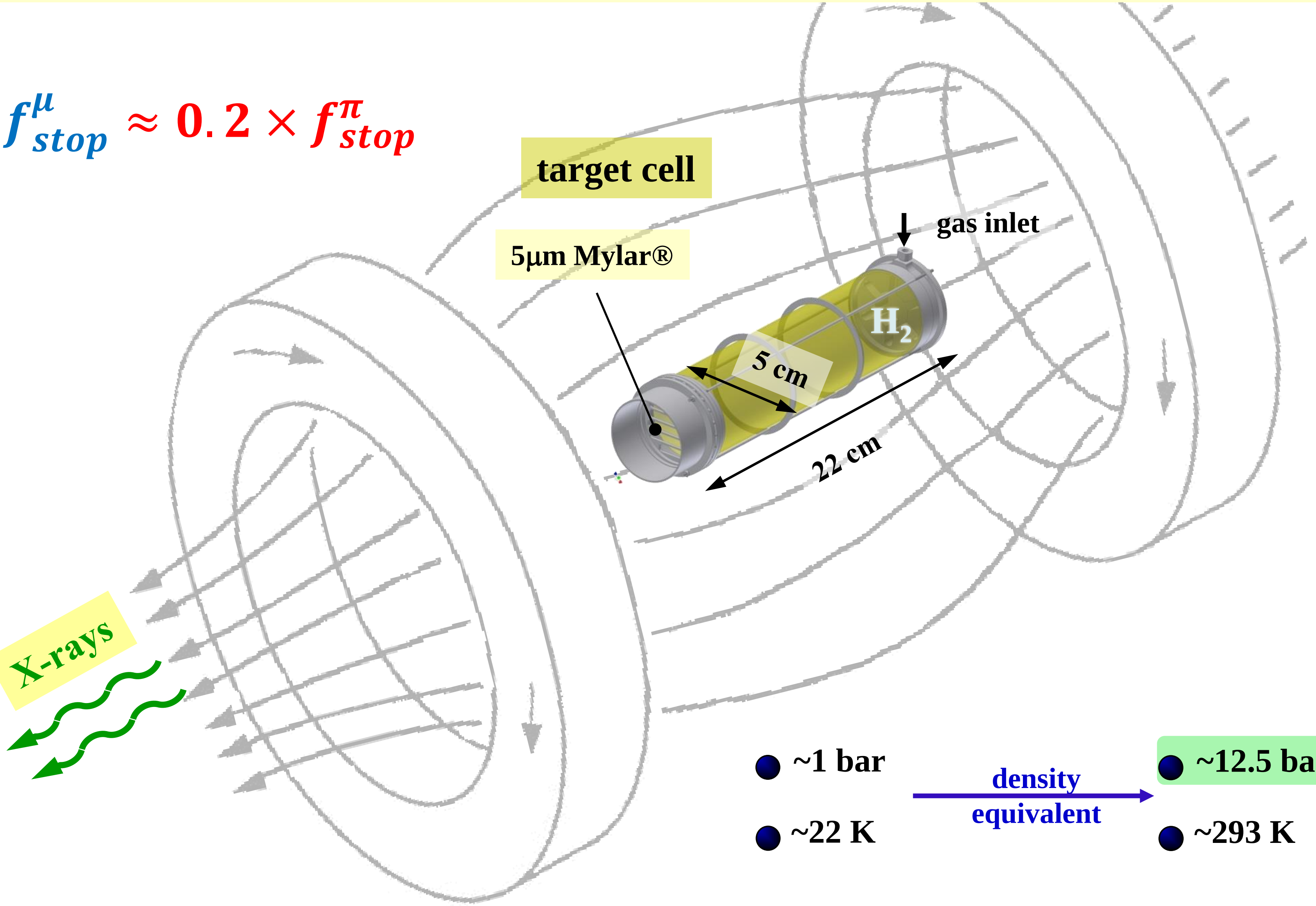
kept in the magnetic bottle field

cyclotron trap: L.M. Simons, Phys. Scripta T22 (1988) 90, Hyperfine Int. 81 (1993) 253

CYCLOTRON TRAP

pion and muon setup

$$f^{\mu}_{stop} \approx 0.2 \times f^{\pi}_{stop}$$



- ~1 bar
- ~22 K

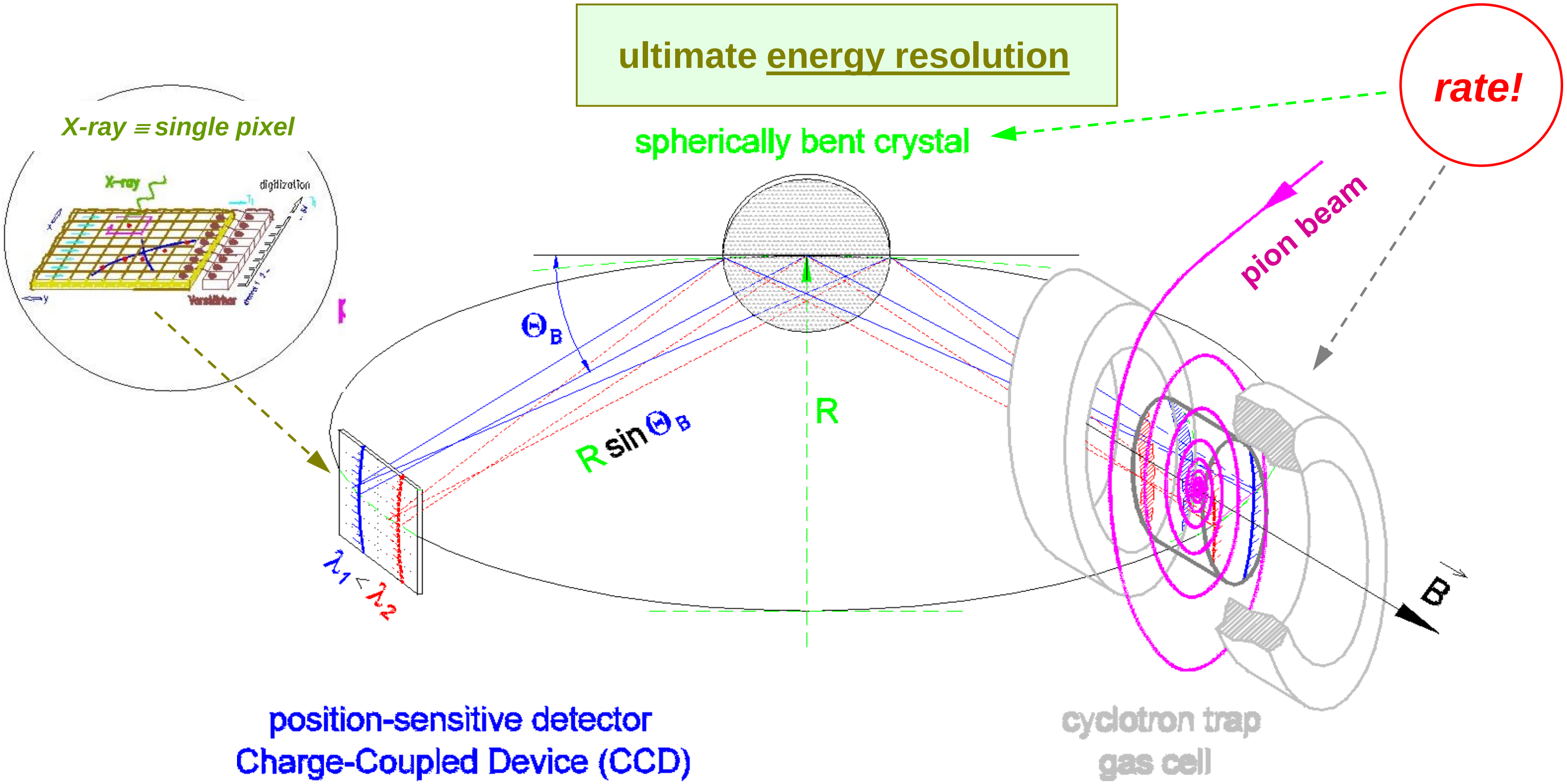
density equivalent →

- ~12.5 bar
- ~293 K

EXPERIMENT III

How to bring it together?

JOHANN-TYPE SET-UP



ultimate energy resolution

rate!

X-ray ≡ single pixel

spherically bent crystal

pion beam

position-sensitive detector
Charge-Coupled Device (CCD)

cyclotron trap
gas cell

position & energy resolution

⇒ **background reduction I**

by analysis of hit pattern

high stop density

⇒ **high X - ray line yields**

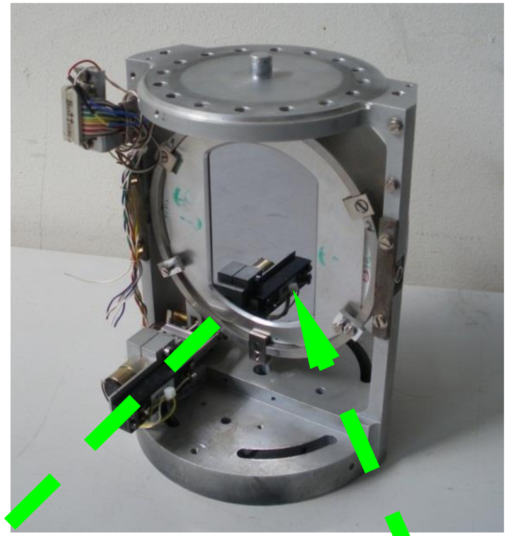
⇒ **bright X - ray source**

BRAGG CRYSTAL

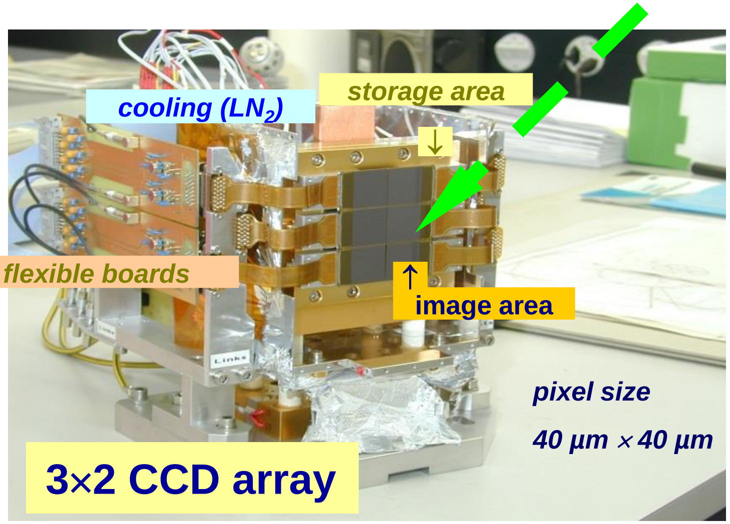
Si 111

spherically curved

R = 3 m
Φ = 10 cm



Large - Area Focal Plane Detector



pixel size

40 µm × 40 µm

3×2 CCD array

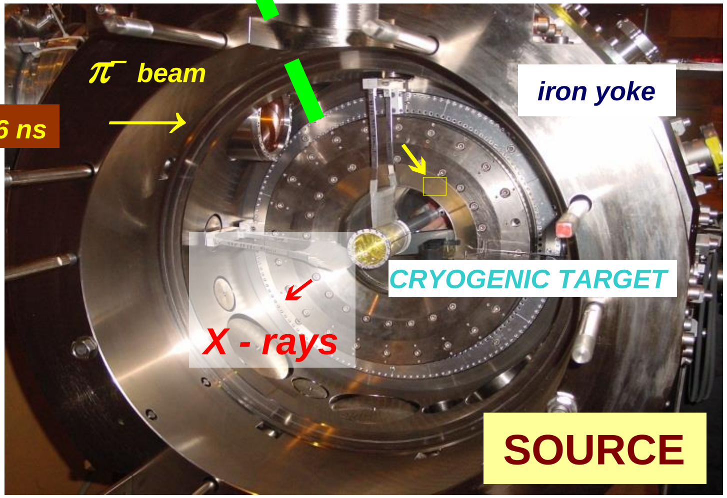
N. Nelms et al., Nucl. Instr. Meth 484 (2002) 419

CYCLOTRON TRAP

one coil removed

10^9 π/s

$\tau_{\pi\pm}$ = 26 ns



SOURCE

DETECTOR *crystal spectrometer* *Large - Area Focal Plane Detector*

CCD: charge-coupled device

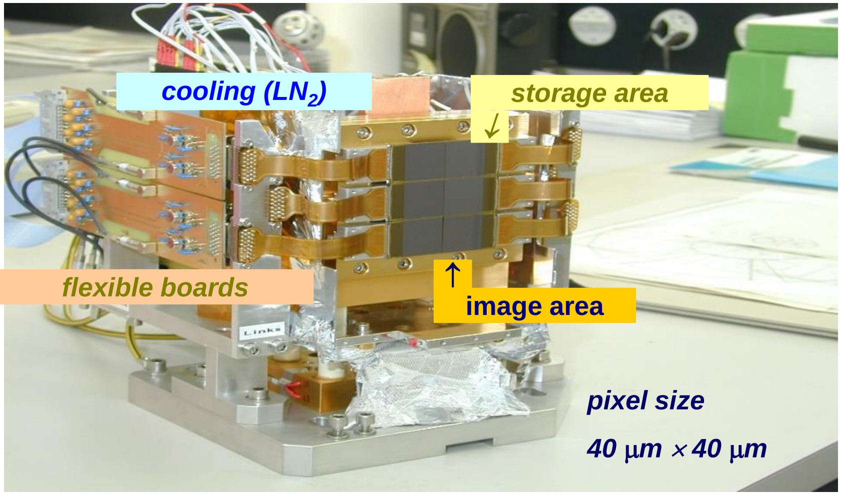
pixel distance

manufacturer
@ 20°C 40.0 µm ± 0.17 nm
@ -100°C 39.9775 µm ± 0.6 nm

P. Indelicato et al., Rev. Sc. Instr. 77 (2006) 043107

$\Delta \rightarrow$ 4.2ppm of M_{π}

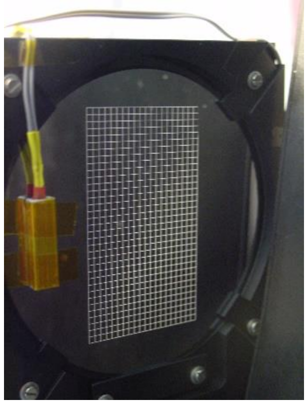
2 × 3 array of 24 mm × 24 mm devices



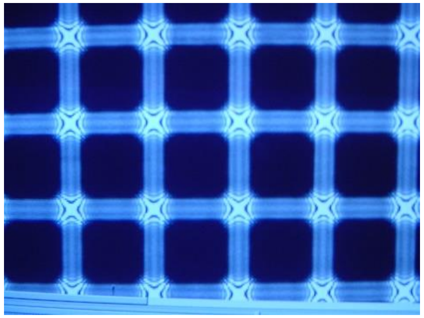
N. Nelms et al., Nucl. Instr. Meth 484 (2002) 419

1. try wire eroded mask
- gap ▤
- pixel size ?

***2. try nano mask** (C. David LNS/PSI)*



illuminated
by light source
at 6 m distance
T = 20°C



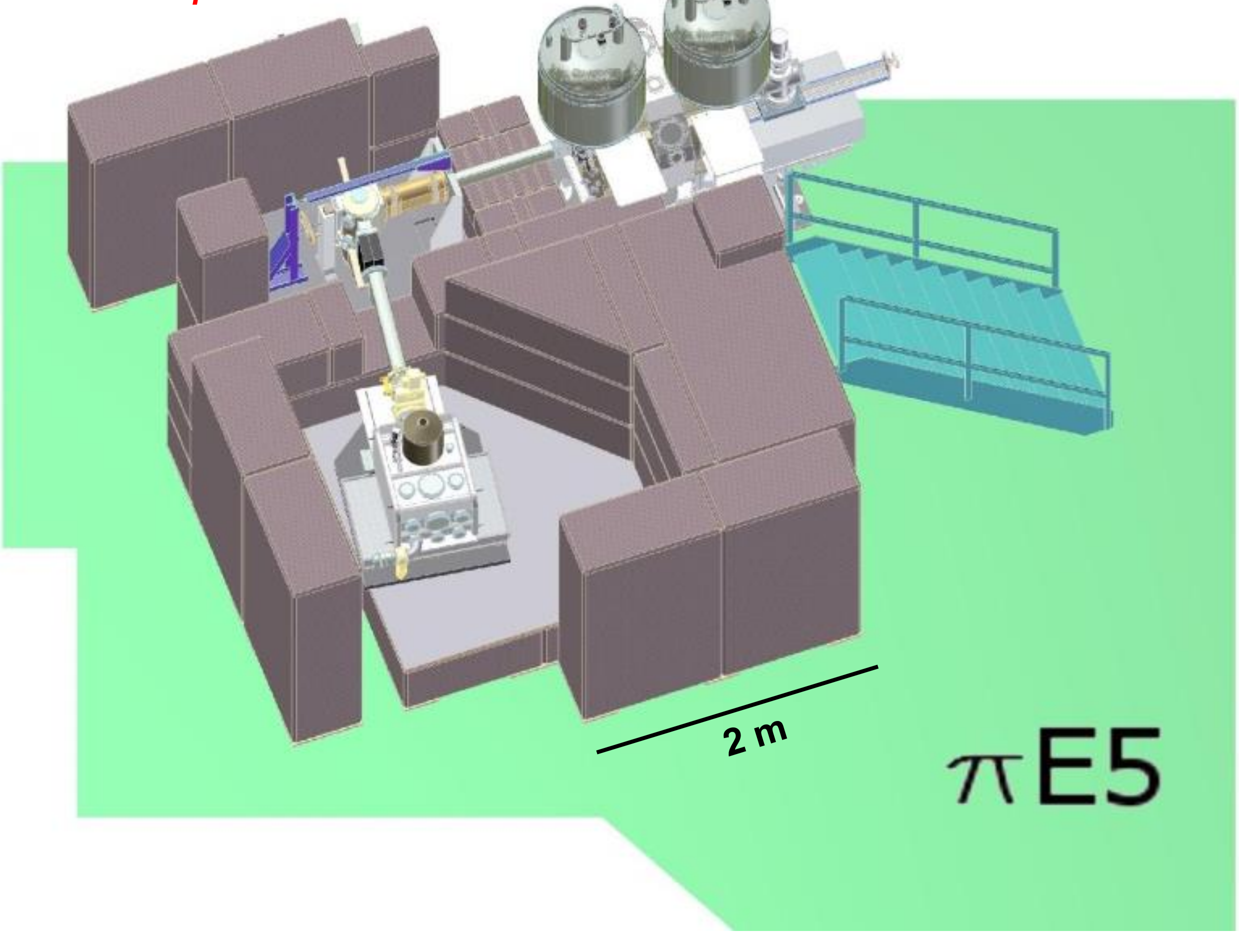
@ -100°C HOR 39.9802±0.0026 µm
VER 39.9794±0.0022 µm

SET-UP at the pion factory of Paul-Scherrer-Institute (Switzerland)

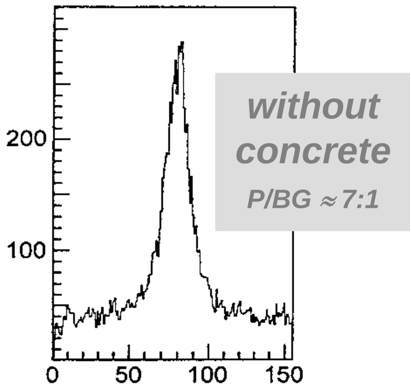
pion stops in gas: few %

all others: 1 pion makes 5 neutrons

$\approx 10^8\ \pi^-$



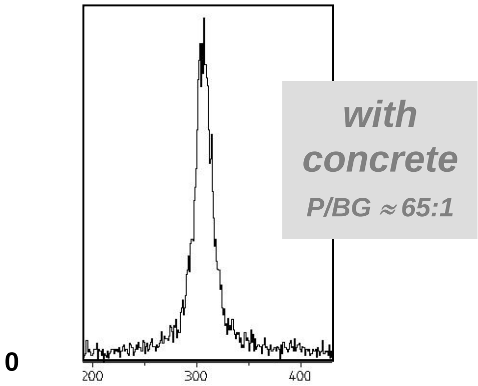
pionic hydrogen



without concrete

P/BG ≈ 7:1

peak/background x 10

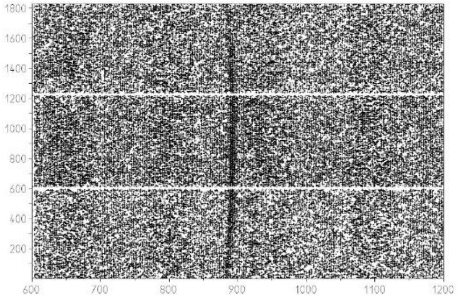


with concrete

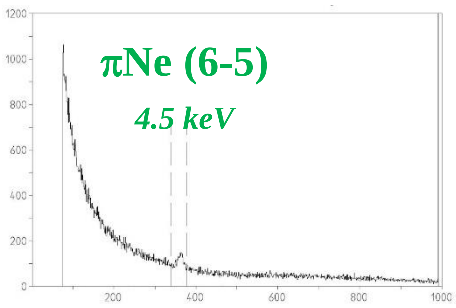
P/BG ≈ 65:1

background reduction II

SPECIAL DEMANDS FOR EXOTIC ATOMS



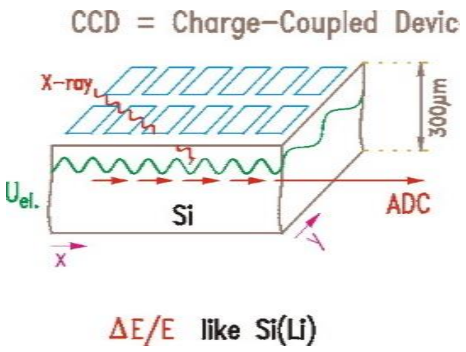
projection
onto axis of dispersion

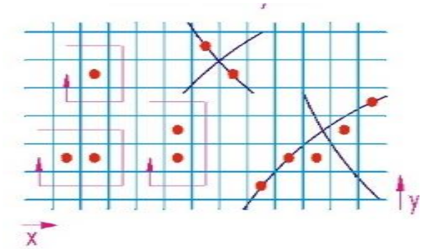


πNe (6-5)

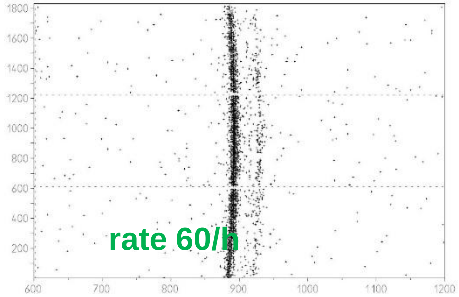
4.5 keV

→ **coordinate x or energy**



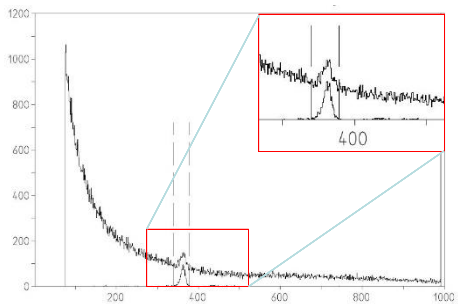


cluster analysis



rate 60/h

projection
onto axis of dispersion

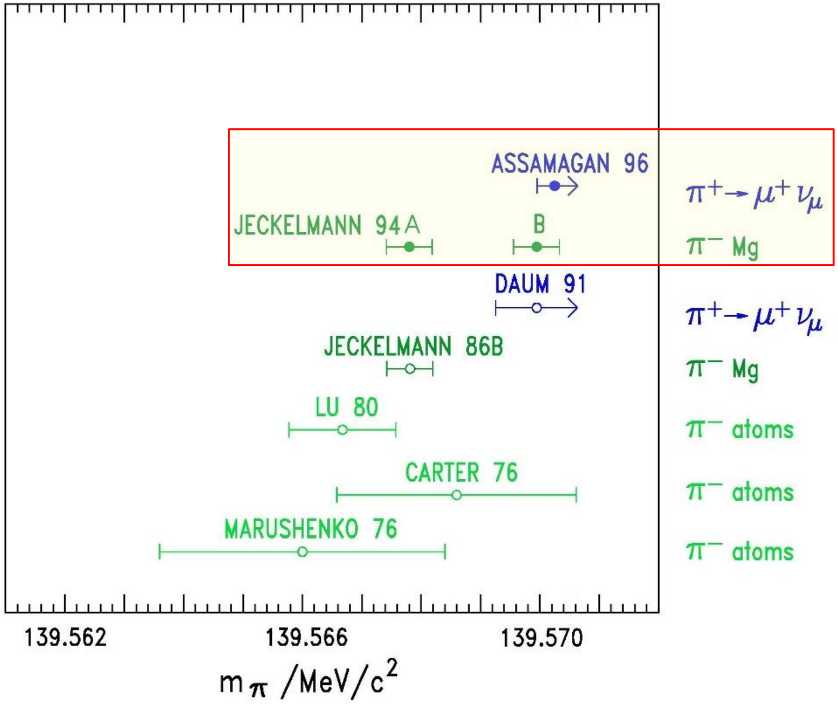


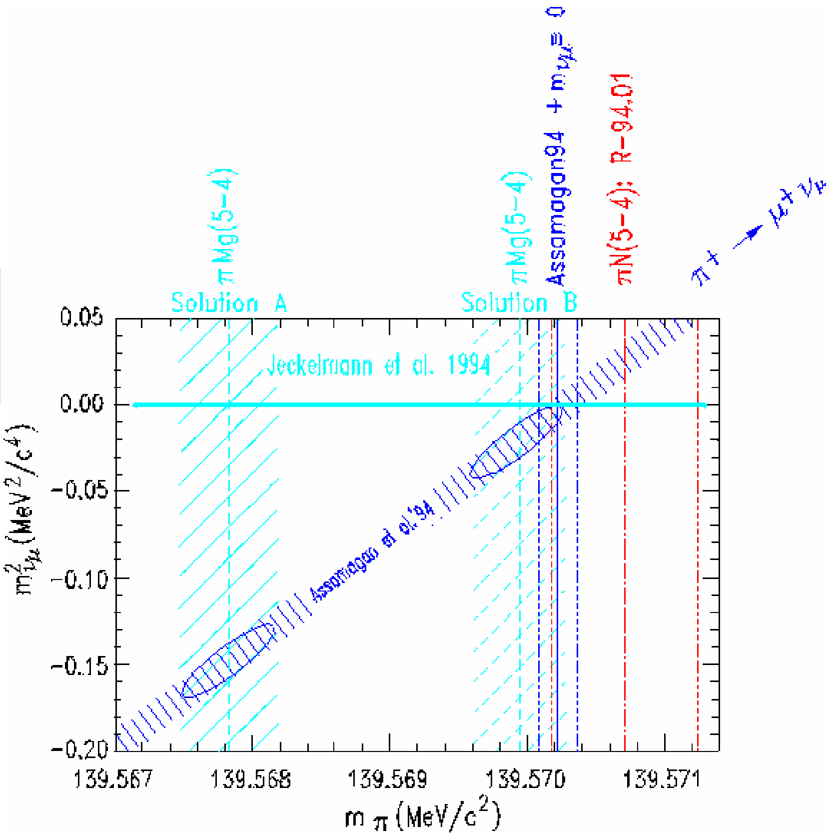
→ **coordinate x or energy**

EXPERIMENT IV

LET‘S DO IT!

STARTING POINT - two solutions for M_π





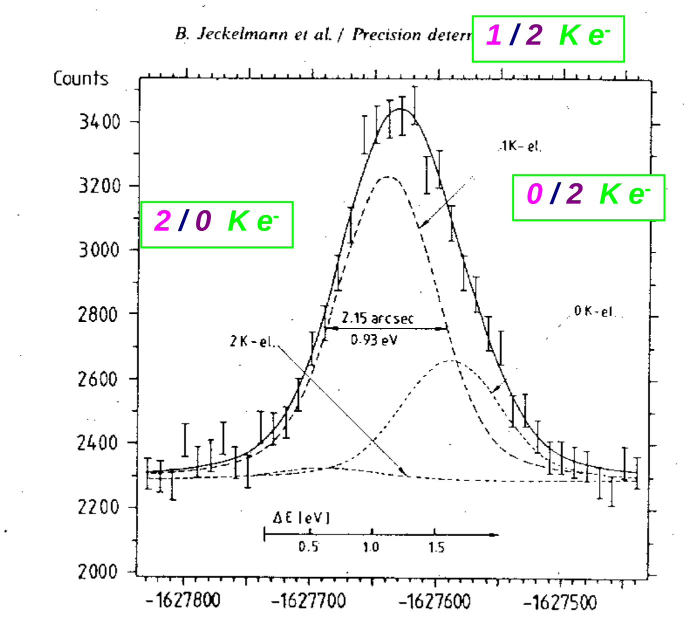
$A \Rightarrow m_{\nu\mu}^{2} < 0!$

π^-Mg (4f – 3d) $E_X = 25.9$ keV

measurement *DuMont (transmission-type) crystal spectrometer*

Mg solid state target - refilling of electrons

B. Jeckelmann, et al., Phys. Rev. Lett. 56 (1986) 1444.
B. Jeckelmann, et al., Nucl. Phys. A 457 (1986) 709.
B. Jeckelmann, P.F.A. Goudsmit, H.J. Leisi, Phys. Lett. B 335 (1994) 326.



1 / 2 K e⁻

0 / 2 K e⁻

2 / 0 K e⁻

interpretation A / interpretation B

$\Delta E_{exp} / E = 3$ppm

but

linewidth > resolution!

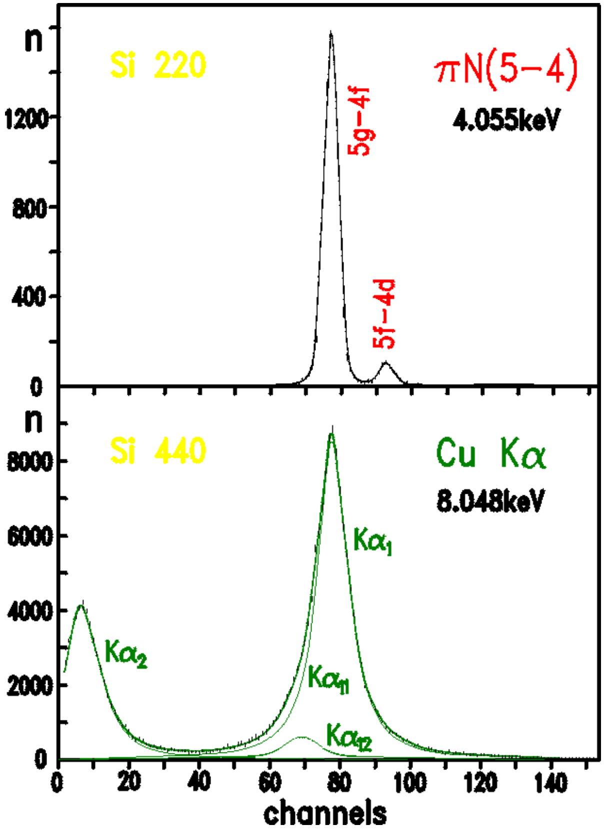
1 or 2 K electrons?

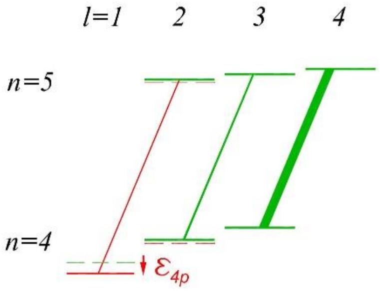
2 solutions A & B: $\Delta^{AB} = 15$ppm

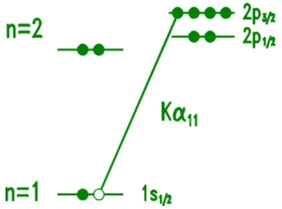
A $\Rightarrow$ $m_{\nu\mu}^2 < 0$!

FIRST STEP - *How to get rid of the electrons?*

N_2 gas target – no electrons because no refilling







energy calibration

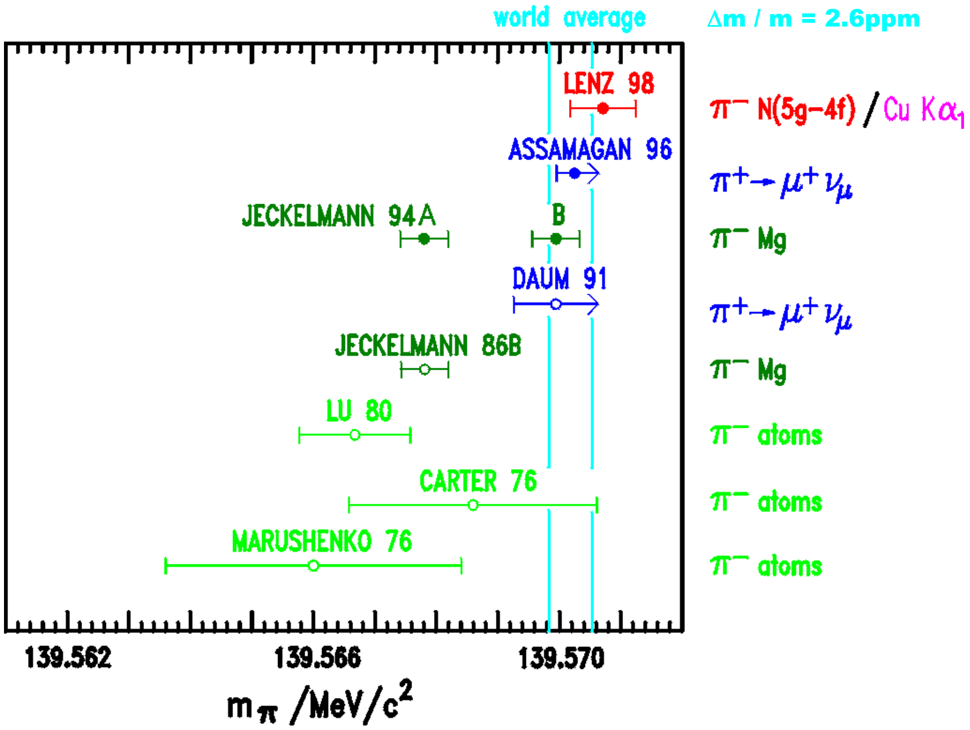
Cu K α line shape

from Deutsch et al. PR A 51 (1995) 283

Problems

- *large natural line width*
- *multiple ionisation ⇒ satellite lines*

RESULT



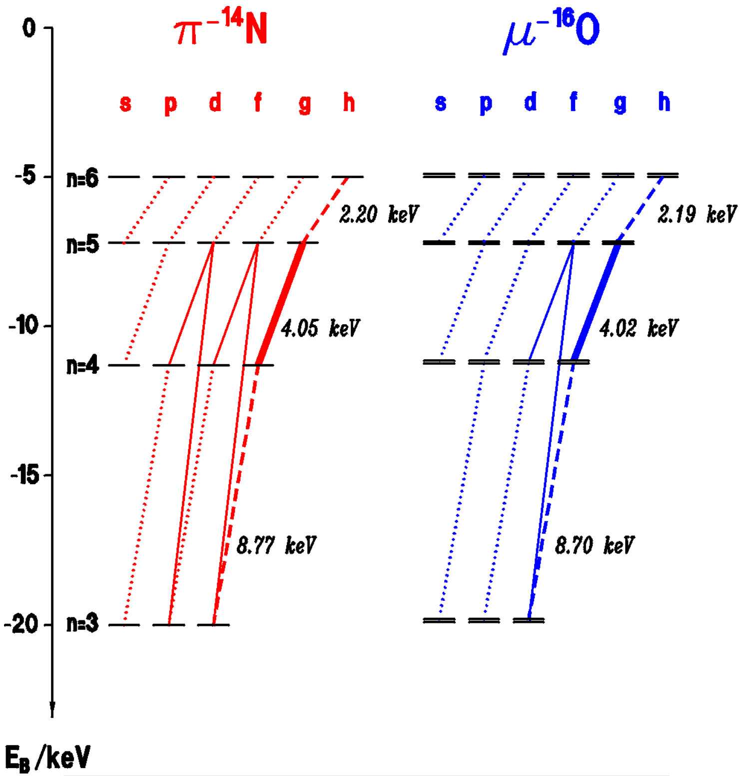
$\Delta m_\pi / m_\pi = 4ppm$

15ppm discrepancy removed

S. Lenz et al. PL B 416 (1998) 50

SECOND STEP - *How to improve the calibration standard?*

Energy calibration with muonic atom



simultanuous measurement

- point like Coulomb potential
- no electron screening
- $\dfrac{E_{\mu O(5g-4f)}}{E_{\pi N(5g-4f)}} = \dfrac{m_\mu}{m_p} + \cdots$

CPT

$\mu^+ \leftrightarrow \mu^-$

$\Delta m_\mu / m_\mu = 0.05\text{ppm}$

D. Groom et al. (PDG)

μO(5g-4f) **πN(5g-4f)**

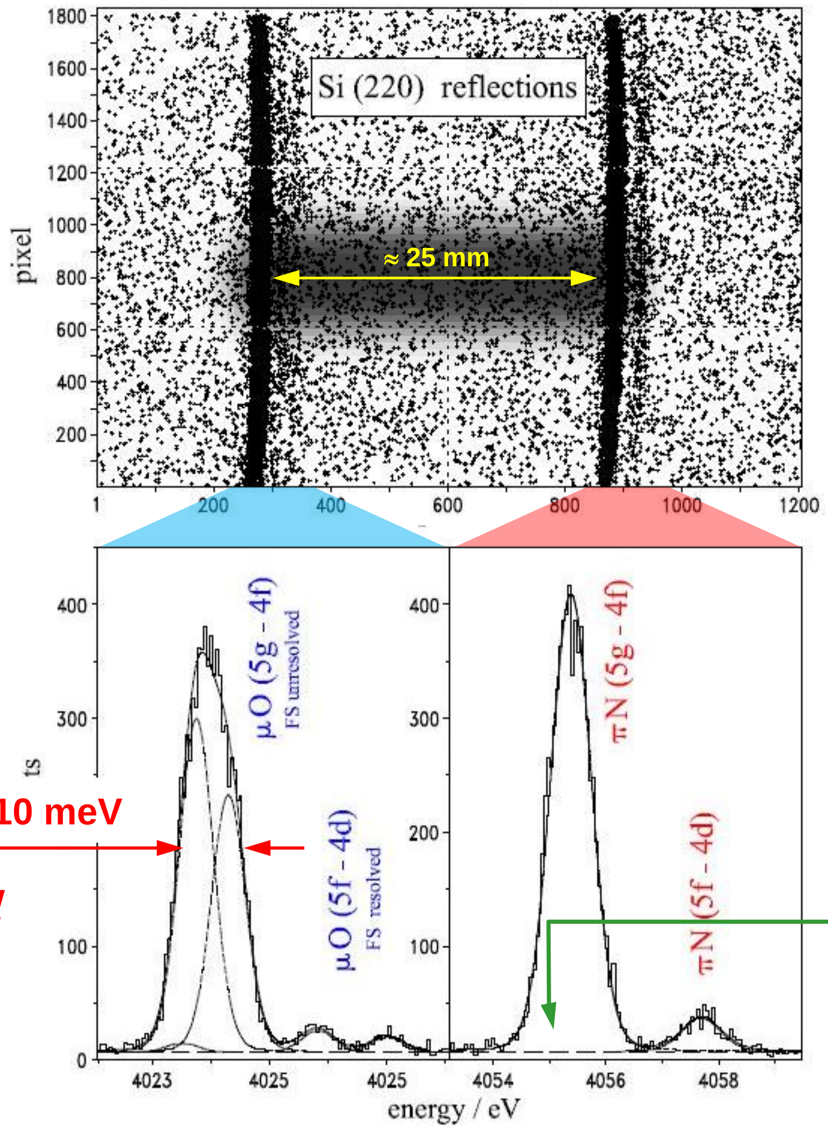
N_2 /O_2 mixture (10% / 90%)

@ 1.4 bar

9000 events per element

5 weeks measuring time

15 events / hour



ΔE = 750 ± 10 meV

resolution should be better!

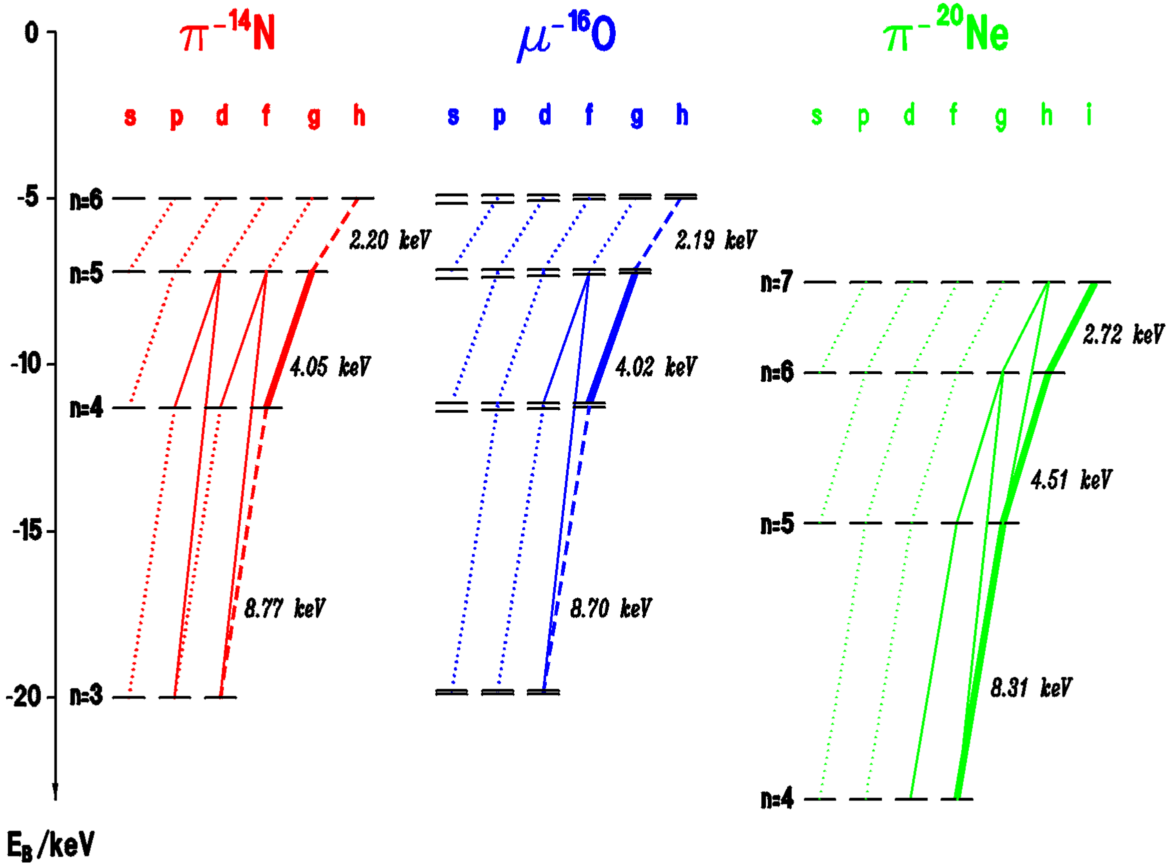
electronic satellite?

<u>Bayesian</u> analysis

$< 3 \cdot 10^{-6}$

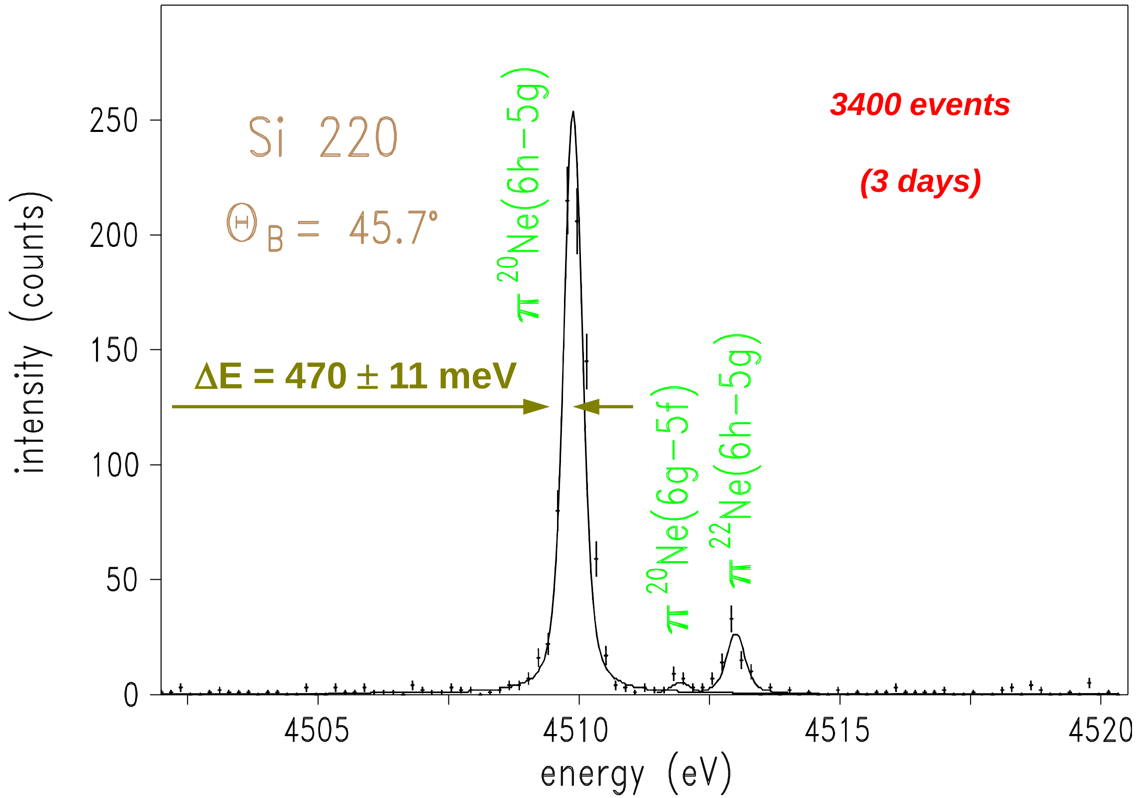
How to measure the spectrometer response?

measurement	*calibration*	*response function*
πN(5g-4f)	μO(5g-4f)	πNe(6h-5g)



RESPONSE FUNCTION *from exotic atoms*

no narrow γ - rays available for these energies



QED

πNe (6h-5g)

(4509.894 ± 0.001) eV

closest

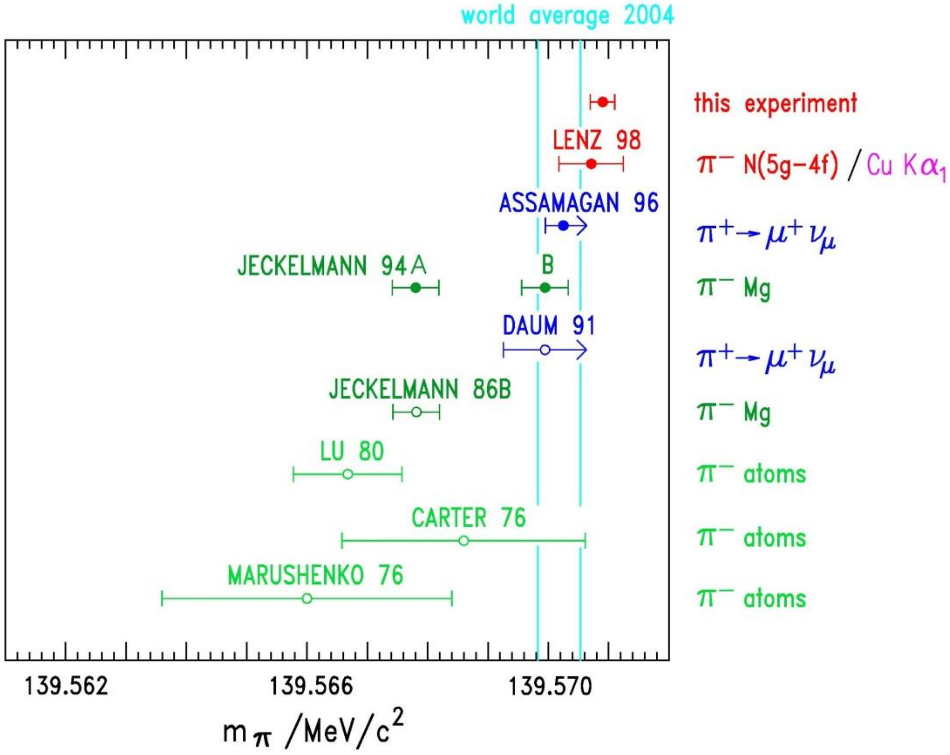
to energy of

πN/µO(5g-4f)

- **MOTIVATION**
- **LABORATORY**
- **EXPERIMENT**
- **ASSESSMENT of RESULTS**

RESULTS *relative to world average PDG 2004* (± 2.5ppm)

πN/Cu Kα	*1998*	+ 3.8 ± 3.8 ppm
πMg	*1994* B	- 1.7 ± 2.5 ppm
πN/μO	***2016***	**+ 4.2 ± 0.8_{stat} ± 1.0_{sys} (± 1.3) ppm**



139,57077 ± 0.00018 MeV/c^2 *2016*

M. Trassinelli et al., PL B 759 (2016) 583

S. Lenz et al., PL B 416 (1998) 50

cosmological limit (CMB) *2014*

$$\sum_j m_{i=} = 1.3\ eV/c^2$$

K.A. Olice et al. (PDG),
Chin. Phys. C 38,09001 (1998)

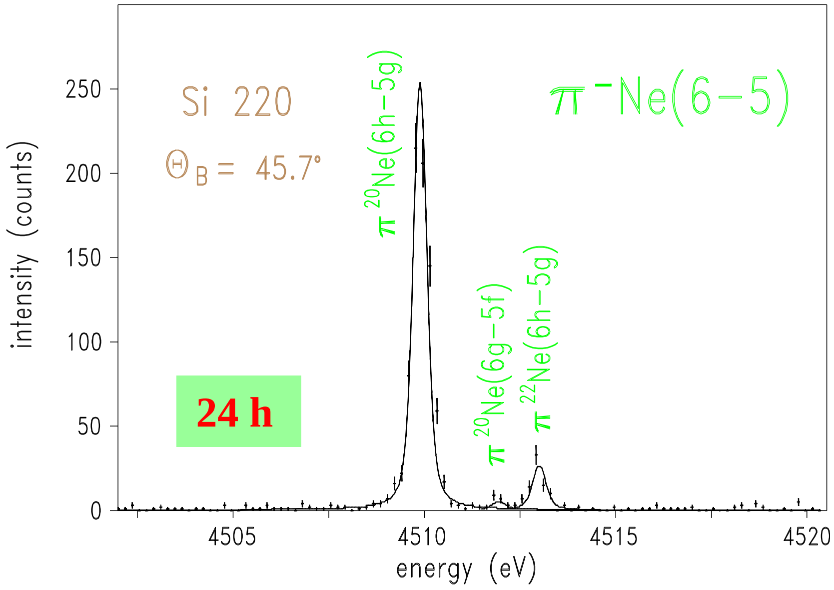
Side result: new X-ray standards

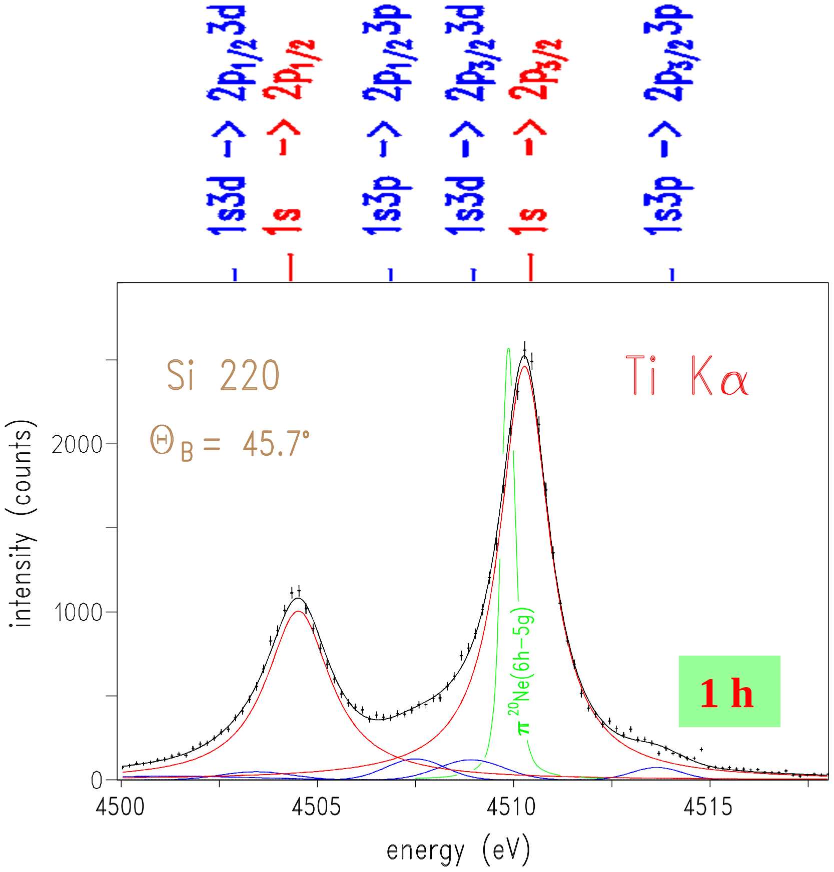
connect exotic- and electronic-atom X-rays

QED

πNe (6h-5g)

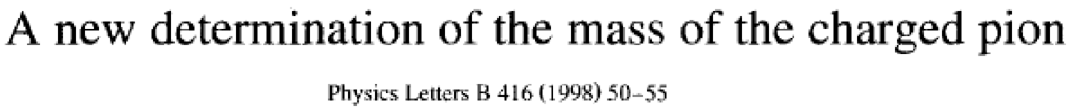
(4509.894 ± 0.001) eV





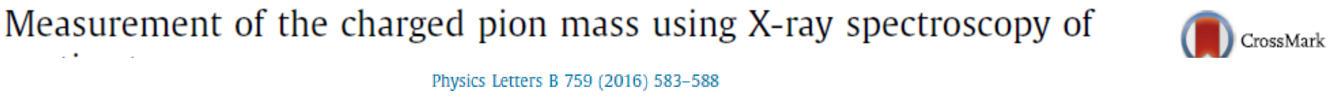
D.F.Anagnostopoulos et al., Phys. Rev. Lett. 91 (1999) 2018

Publication


A new determination of the mass of the charged pion

Physics Letters B 416 (1998) 50–55

1. STEP


Measurement of the charged pion mass using X-ray spectroscopy of

Physics Letters B 759 (2016) 583–588

2. STEP


VOLUME 91, NUMBER 24 PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2003

Low-Energy X-Ray Standards from Hydrogenlike Pionic Atoms

Side result


VOLUME 84, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 2000

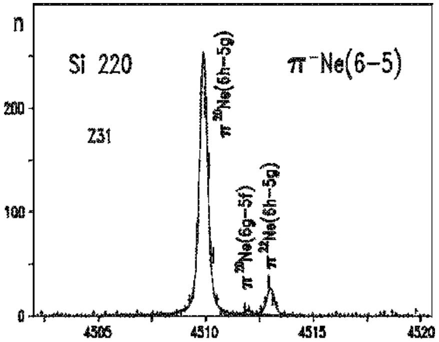
First Direct Observation of Coulomb Explosion during the Formation of Exotic Atoms

Side result

Limits

exotic atoms and molecules

Ne ⇔ N_2, O_2



response function
ΔE = 520 meV

πN/μO

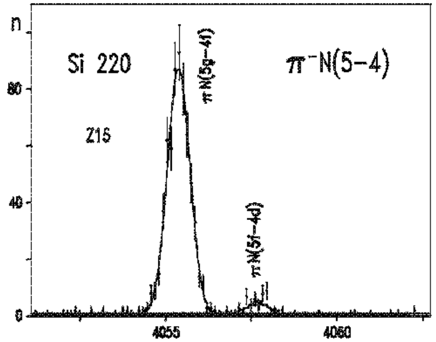
Coulomb explosion

molecule fragmentation

$(\pi^- N_2)^q$

$\downarrow$

$\leftarrow (\pi^- N)^{Q_1} \qquad N^{Q_2} \rightarrow$

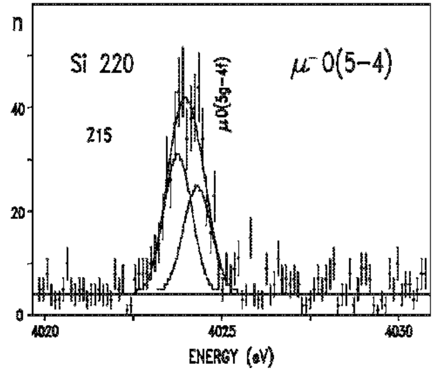


$\Delta E_{Doppler} \approx$ ***800 ± 100 meV***
$\Rightarrow q_1 \cdot q_2 \approx 9 \pm 2$

μO

count rate (≈ 1/10 of πN)

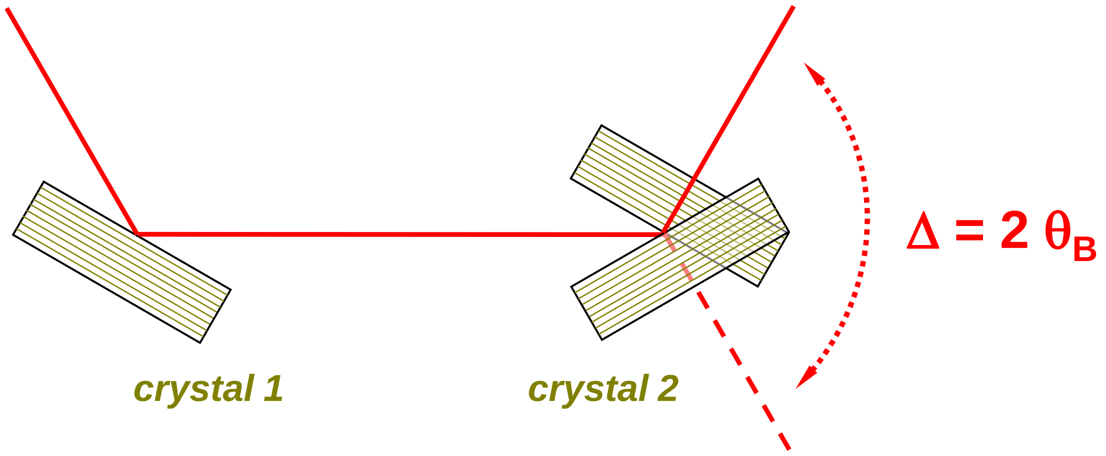
≈ 10000 per line / 6 weeks



$\Delta E_{Doppler} \approx$ ***900 ± 300 meV***
$\Rightarrow q_1 \cdot q_2 \approx 19 \pm 10$

T. Siems et al,
Phys. Rev. Lett. 84 (2000) 4573

Possible solution: double flat crystal spectrometer



Line shape: $R_1(\Theta) \otimes R_2(\Theta)$

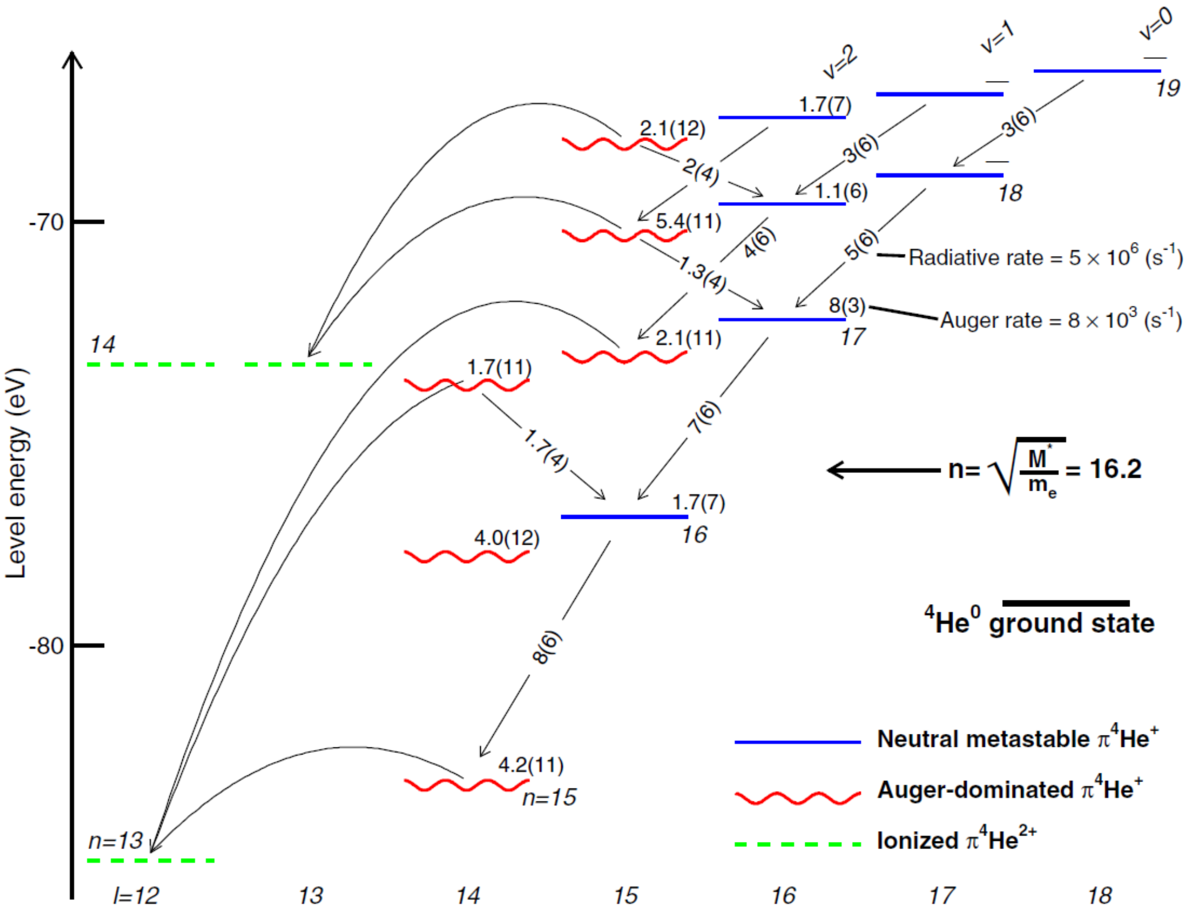
advantage

- *absolute angle calibration*
- *no Coulomb explosion (noble gas)*

disadvantage

- *accurate knowledge of lattice constant d* *Si* $\Delta d/d \approx 10^{-8}$
- “ “ *of* $\Delta\Theta$ind
- *measuring time (one measurement per bin)*

Outlook: Laser-induced excitation of metastable $\pi^{-}He^{+}$ states

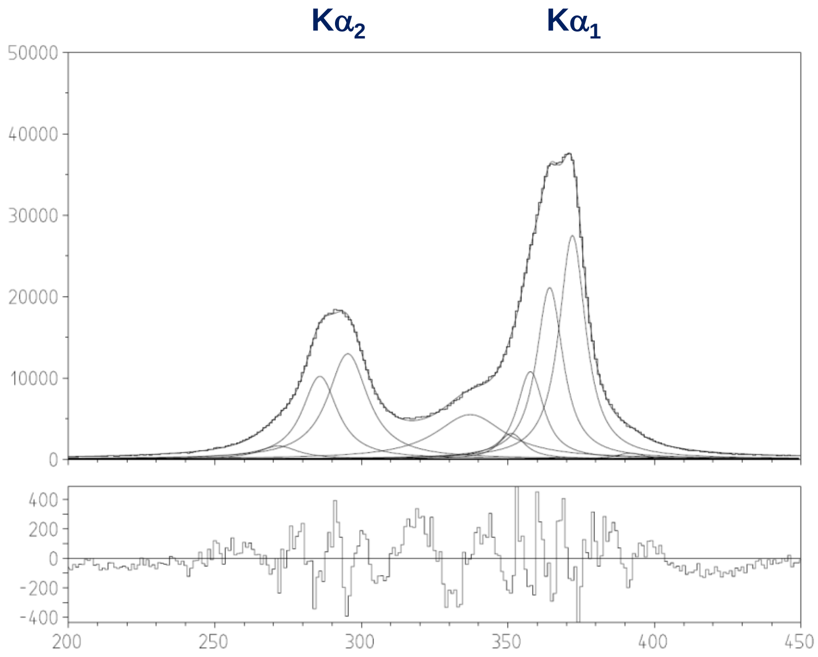


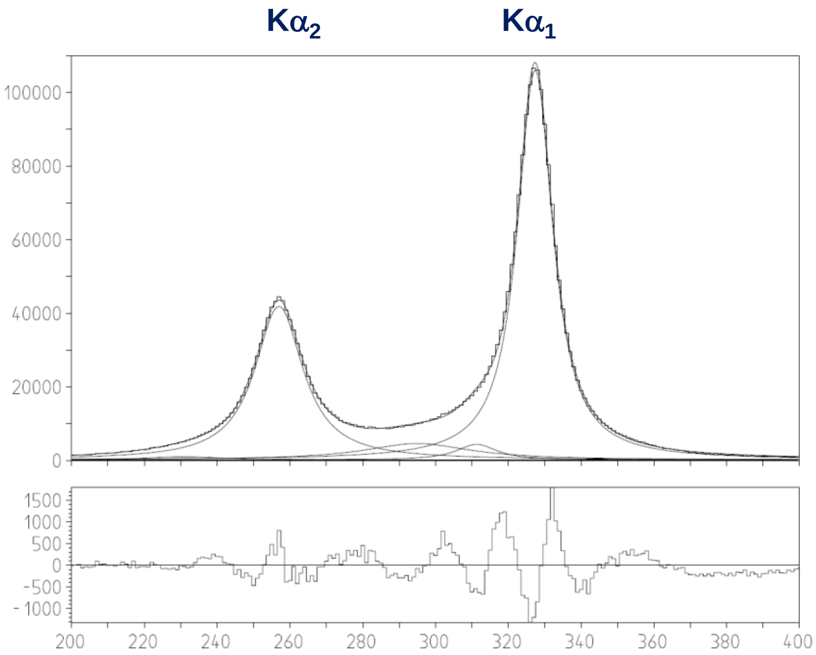
M. Hori, A. Sótér, V. I. Korobov, PR A 89, 042515 (2014)

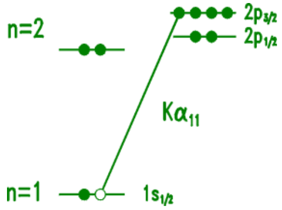
„Spin-off“: Chemical effects – Mn Kα

MnF_2 - core Mn^{2+}

Mn(V)-complex - core Mn^{5+}







$K\alpha_2$ ≈5888 eV
$K\alpha_1$ ≈5899 eV

M. Jabua / GTU 2016 PhD 2016

PION MASS collaboration

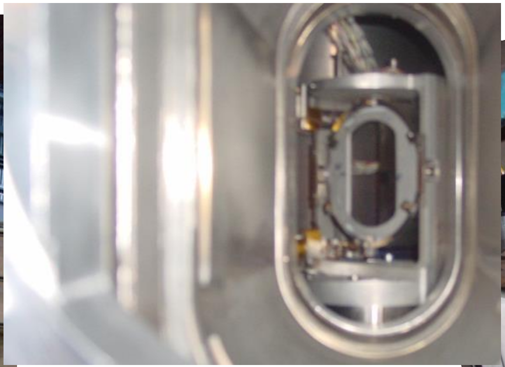
experiments R-94.01 & R-97.02

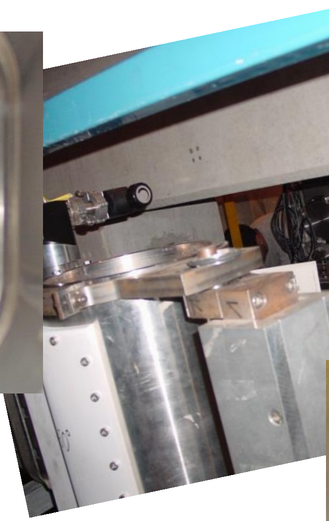
Paul-Scherrer-Institut (PSI), Villigen, Switzerland

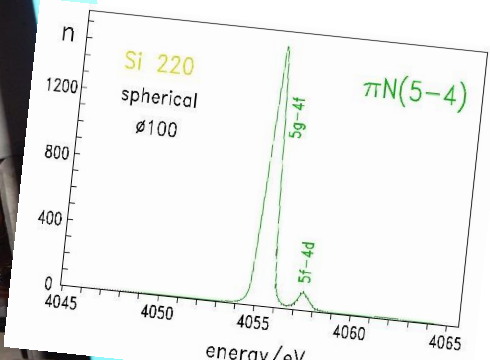
Ioannina[1] – Jülich[2] – Leicester[3] – Paris[4] – PSI[5]

D. F. Anagnostopoulos[1], G. Borchert[2], A. Dax[5], D Gotta[2], M. Hennebach[2], P. Indelicato[4],
Y.-W. Liu[5], B. Manil[4], N. Nelms[3], L. M. Simons[5], M. Trassinelli[4], A. Wells[3]

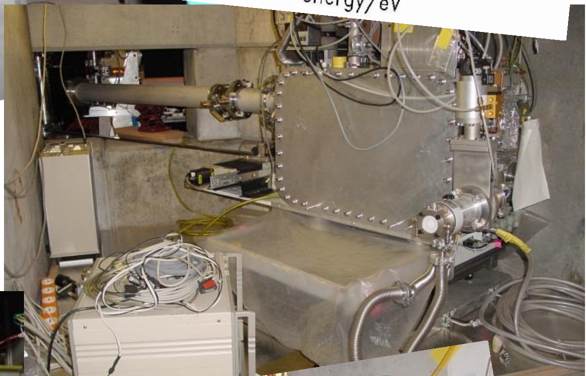
CCDs	*Leicester, PSI*
Crystal spectrometer	*Jülich*
Cyclotron trap	*PSI*
Data analysis	*Ioannina, Jülich, Paris*







n
1200
800
400
0
Si 220
spherical
ø100
5g–4f
5f–4d
πN(5–4)
4045
4050
4055
4060
4065
energy/eV



THANK YOU

11 18:40