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

M. Trassinelli, D. F. Anagnostopoulos, G. Borchert, A. Dax, J.-P. Egger, D. Gotta, M. Hennebach, P. Indelicato, Y.-W. Liu, B. Manil, N. Nelms, L. M. Simons, A. Wells

Institut of NanoSciences of Paris, France

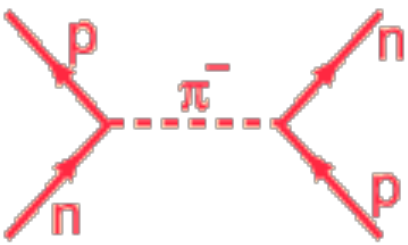
14th International Workshop on Meson Production, Properties and Interaction

2nd - 7th June 2016. Krakow, Poland

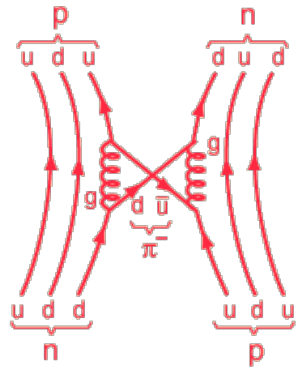
MESON 2016

Prediction and discovery of the pion

Predicted in 1935 by Yukawa to describe the strong interaction as exchange of particle [1]



≡



Expected mass ~ 200 m_e

http://hyperphysics.phy-astr.gsu.edu/hbase/forces/funfor.html

Discovered by emulsion photography (Pic du Midi) in 1947 [2]

Estimated mass ~ 1.5 m_μ

454 NATURE October 4, 1947 Vol. 160

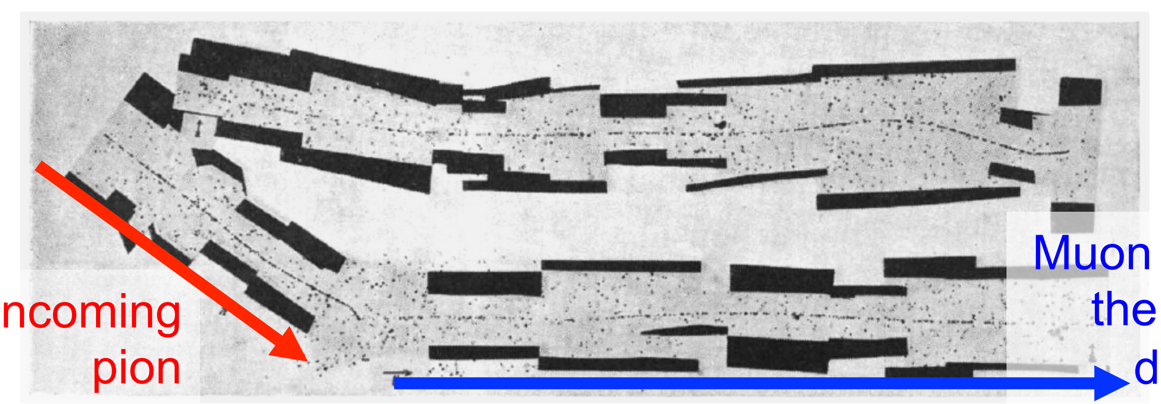
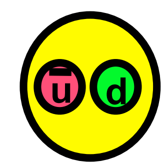


Fig. 1. OBSERVATION BY MRS. I. POWELL. COOKE × 95 ACHROMATIC OBJECTIVE; C2 ILFORD NUCLEAR RESEARCH EMULSION LOADED WITH BORON. THE TRACK OF THE μ-MESON IS GIVEN IN TWO PARTS, THE POINT OF JUNCTION BEING INDICATED BY a AND AN ARROW

Charged pion



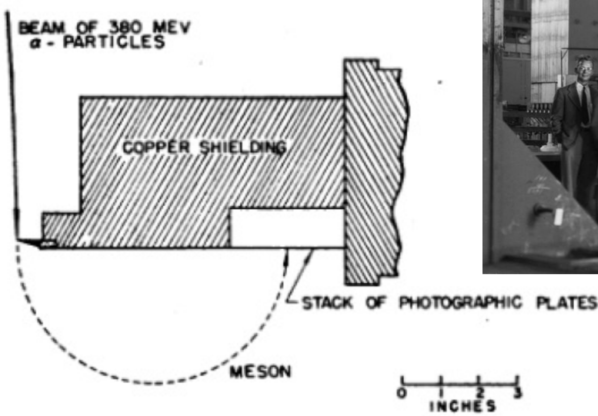
- m_π = 139.5 MeV/c
  = 254 m_e
- lifetime=26 ns
- composed by a quark and an antiquark

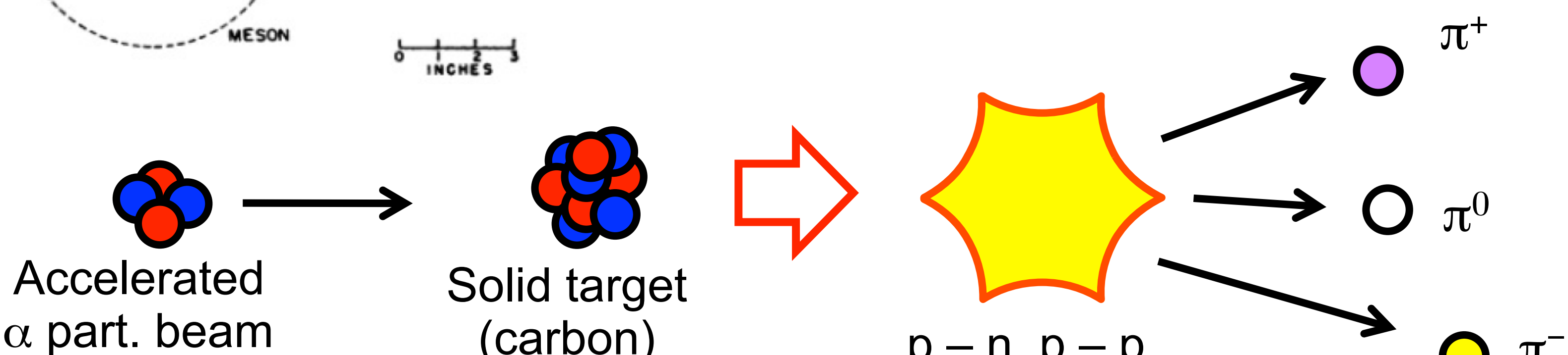
[1] H. Yukawa, Proc. Phys. and Math. Soc. Japan **17**, 48 (1935)
[2] C.M.G. Lattes *et al.*, Nature **160**, 453-456 and 486-492 (1947)

Pion production and first mass measurements

First controlled pion production at the 184” cyclotron in Berkeley in 1948 [1]

Estimated mass:
$m_\pi = 313 \pm 16\ m_e$



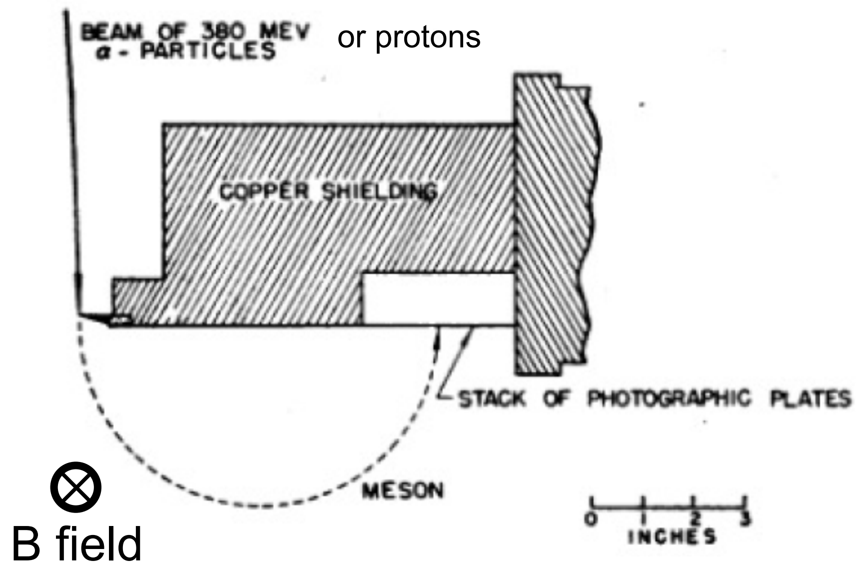


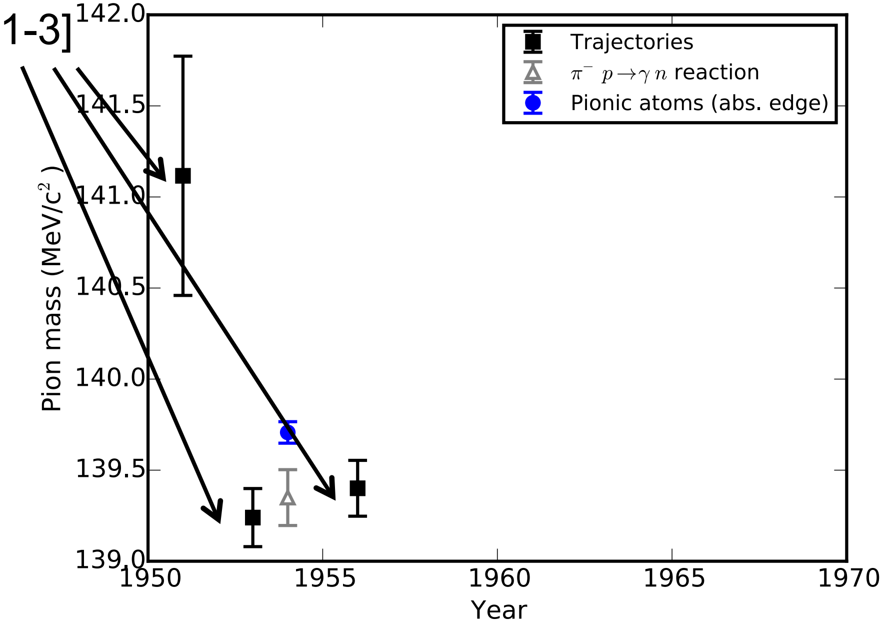
$p - n,\ p - p,\ \ldots$
$\rightarrow \pi^- + \pi^+ + \pi^0 + \ldots$

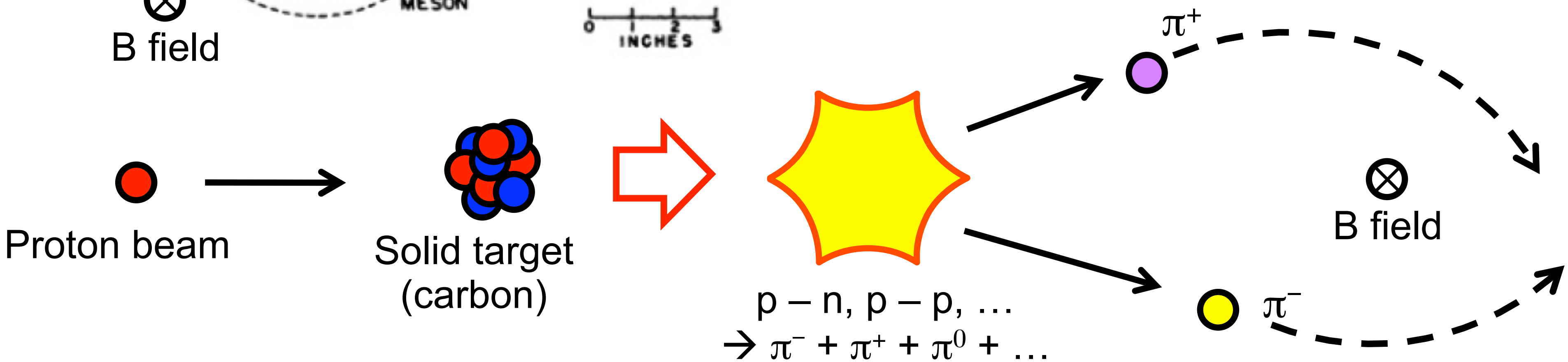
[1] E. Gardner and C. Lattes, Science **107**, 270-271 (1948)

First mass measurements

- Particle trajectories analysis Barkas et al. [1-3]



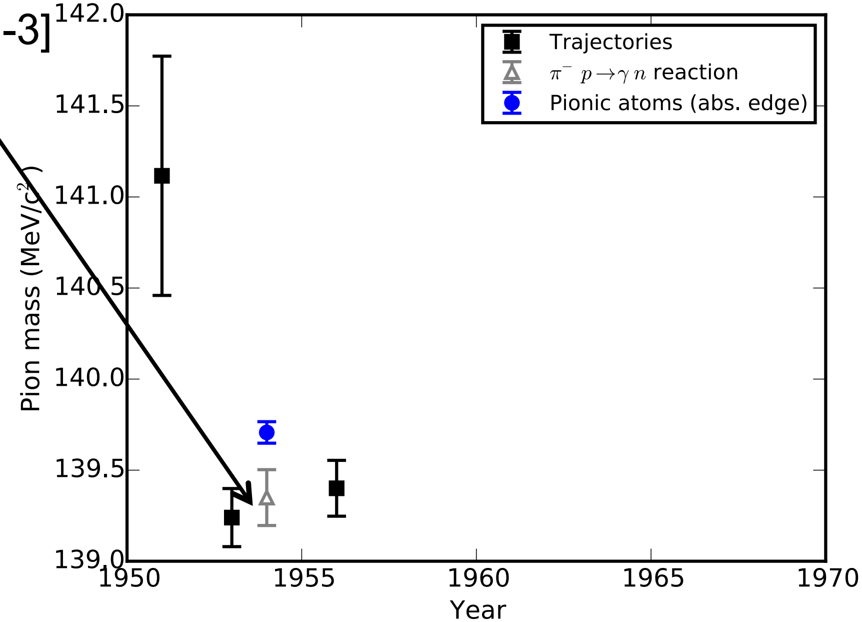


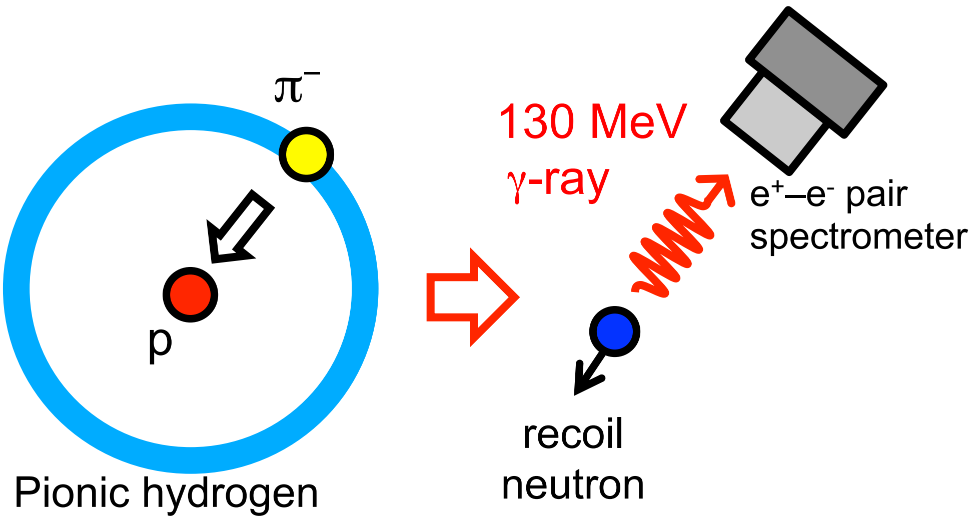


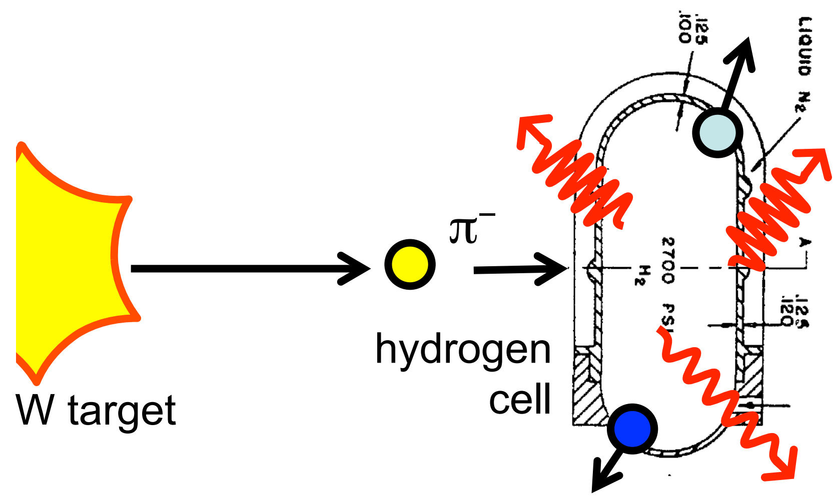
First mass measurements

- Particle trajectories analysis Barkas et al. [1-3]
- $\pi^- + p \rightarrow n + \gamma$ reaction Crowe et al. [4]

π^- stopped in a hydrogen cell
→ **pionic hydrogen** production
→ nuclear absorption of the pion

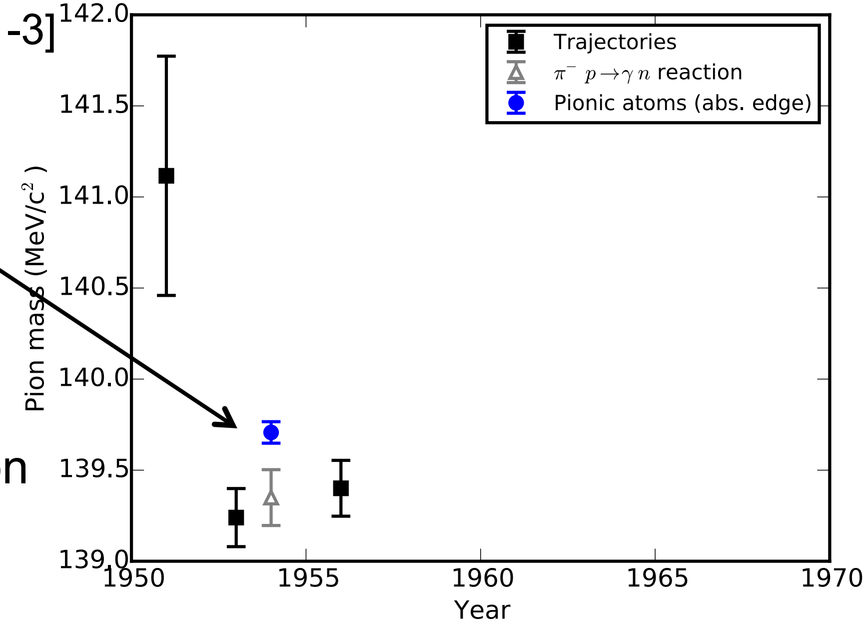






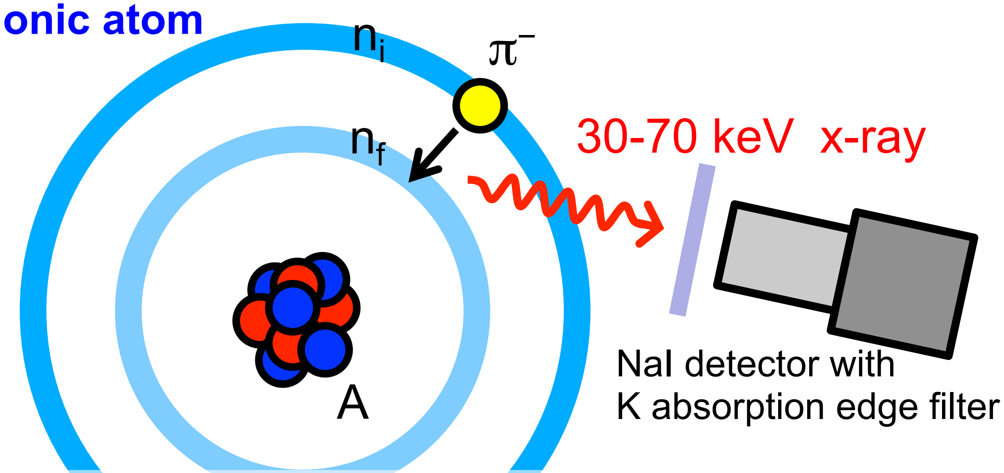
First mass measurements

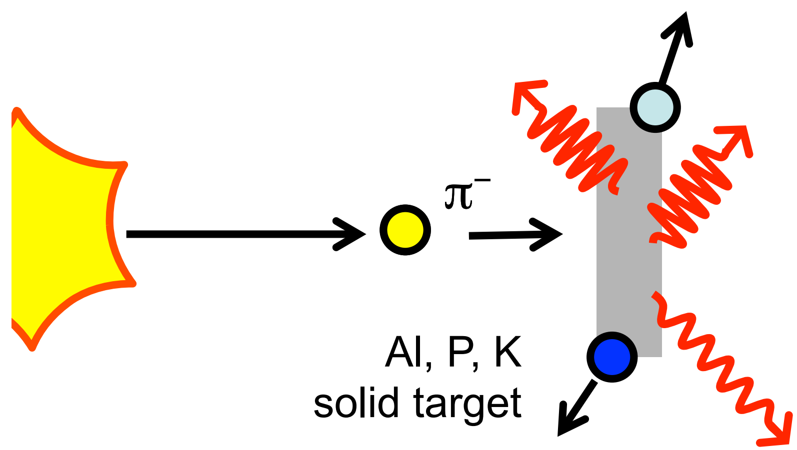
- **Particle trajectories analysis** Barkas et al. [1-3]
- $\pi^- + p \rightarrow n + \gamma$ reaction Crowe et al. [4]
- **Pionic atoms emission** Stearns et al. [5]



π⁻ stopped in a solid target (Al, P, K)
→ **pionic atoms** production
→ X-ray from atomic level de-excitation

Pionic atom

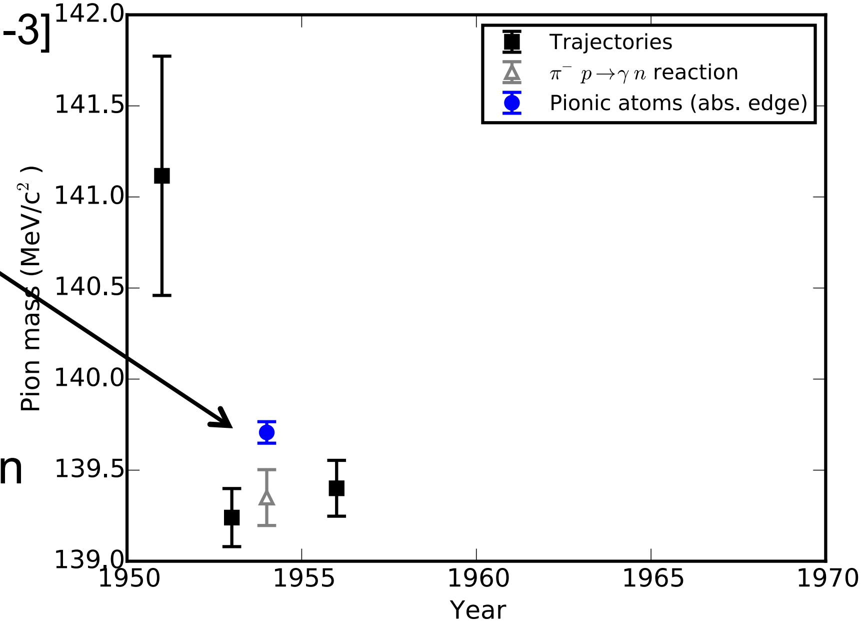




Electromagnetic bound system
Strong interaction as perturbation

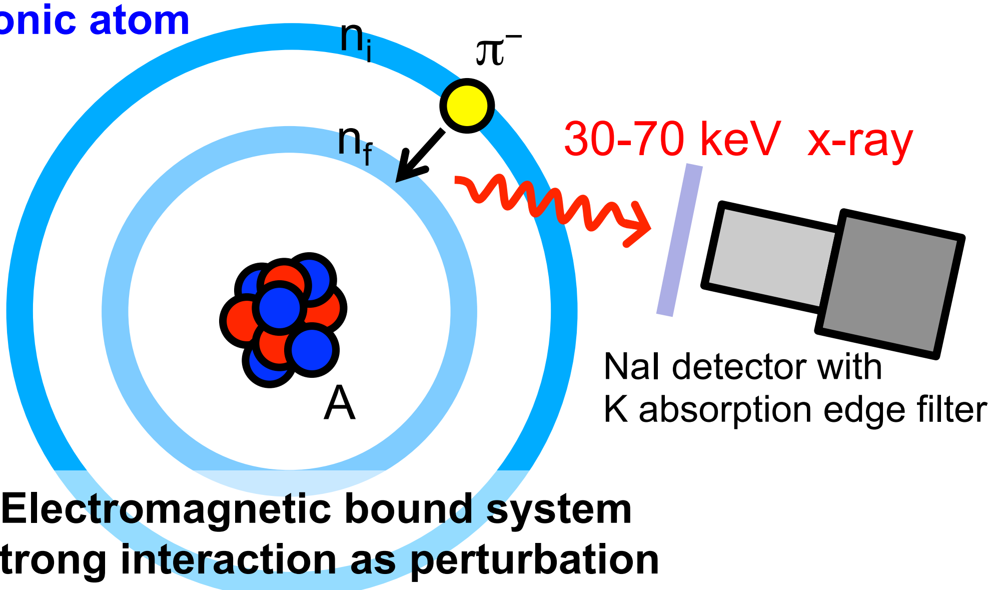
First mass measurements

- **Particle trajectories analysis** Barkas et al. [1-3]
- $\pi^- + p \rightarrow n + \gamma$ **reaction** Crowe et al. [4]
- **Pionic atoms emission** Stearns et al. [5]



π^- stopped in a solid target (Al, P, K)
→ **pionic atoms** production
→ X-ray from atomic level de-excitation

Pionic atom



Electromagnetic bound system
Strong interaction as perturbation

Z = atomic number,
m =reduced mass,
α = fine structure constant.

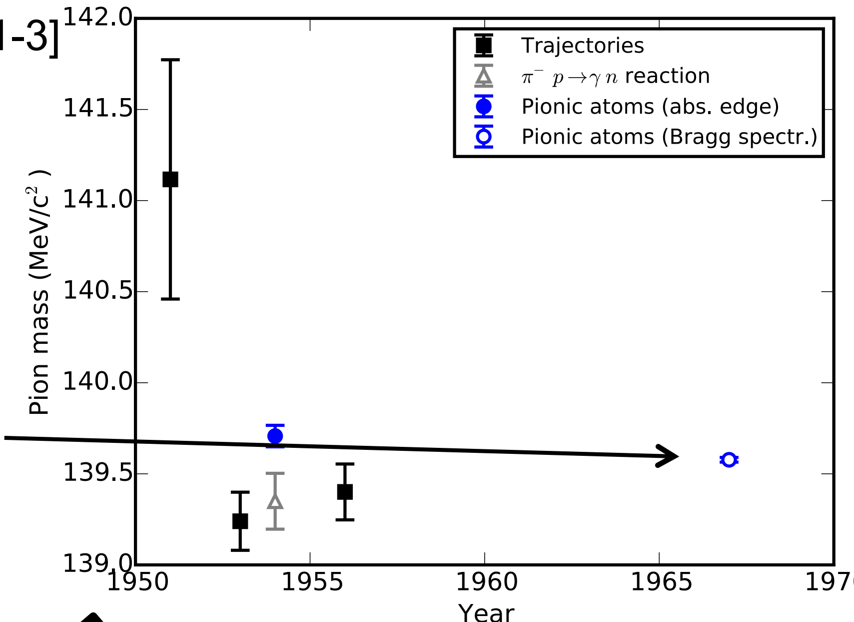
$$E_{\text{X-ray}} = mc^2 \frac{(Z\alpha)^2}{2} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) + \mathcal{O}(Z^4\alpha^4)$$

First mass measurements

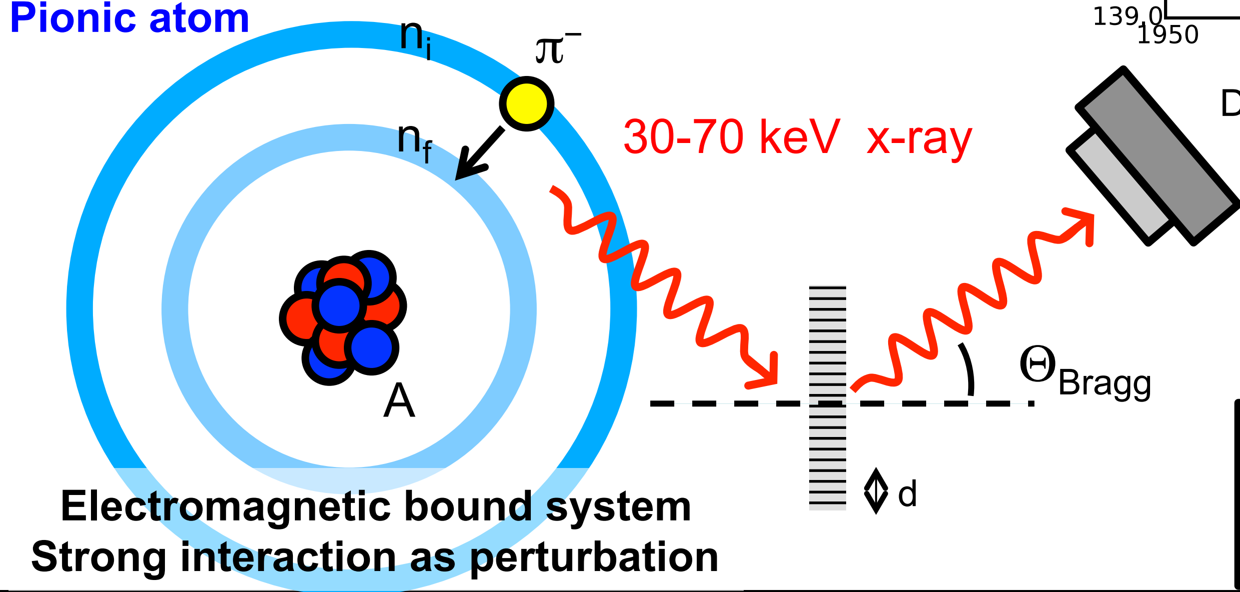
- Particle trajectories analysis Barkas et al. [1-3]
- $\pi^- + p \rightarrow n + \gamma$ reaction Crowe et al. [4]
- Pionic atoms emission Stearns et al. [5]

Higher pion beam intensity

→ **Bragg spectroscopy** Shafer et al. [6]



Pionic atom

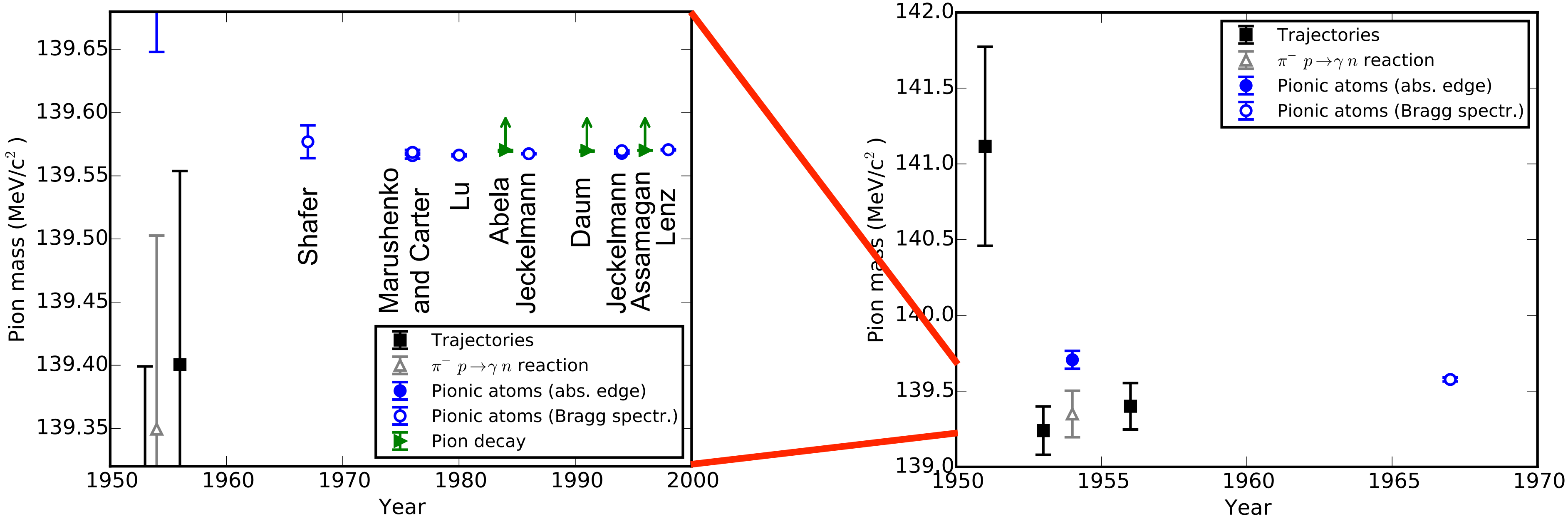


Electromagnetic bound system
Strong interaction as perturbation

The Bragg law

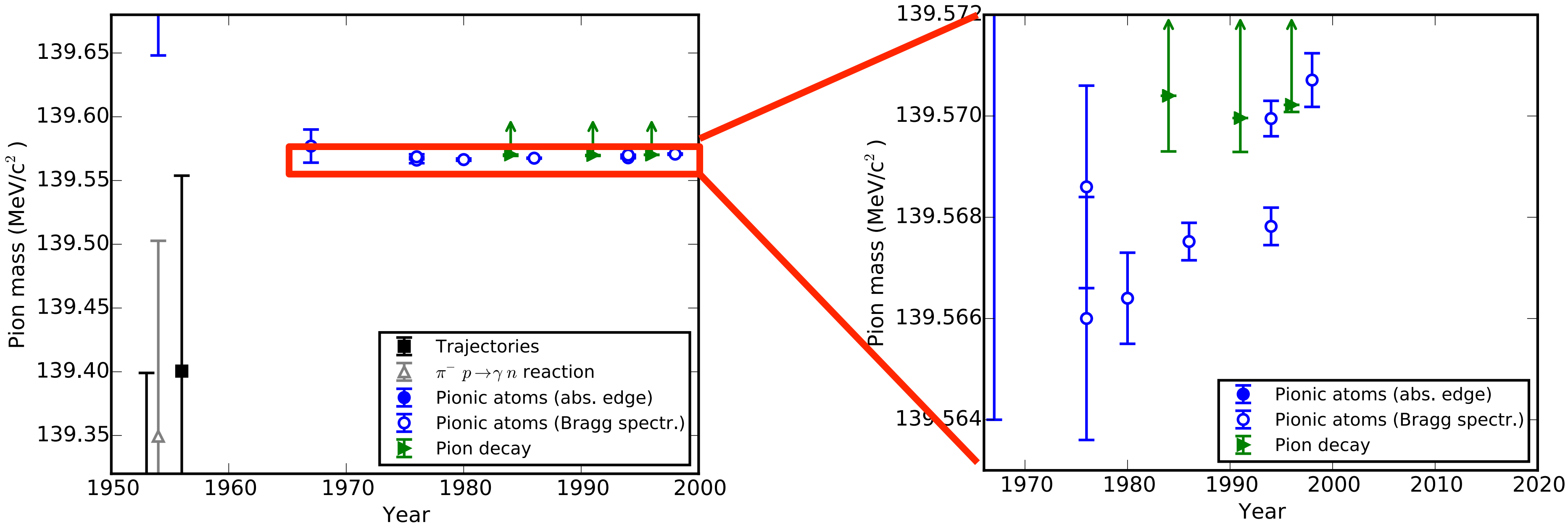
$$\frac{hc}{E} = 2d \sin \Theta_{\mathrm{Bragg}}$$

Pionic spectroscopy and pion decay measurements

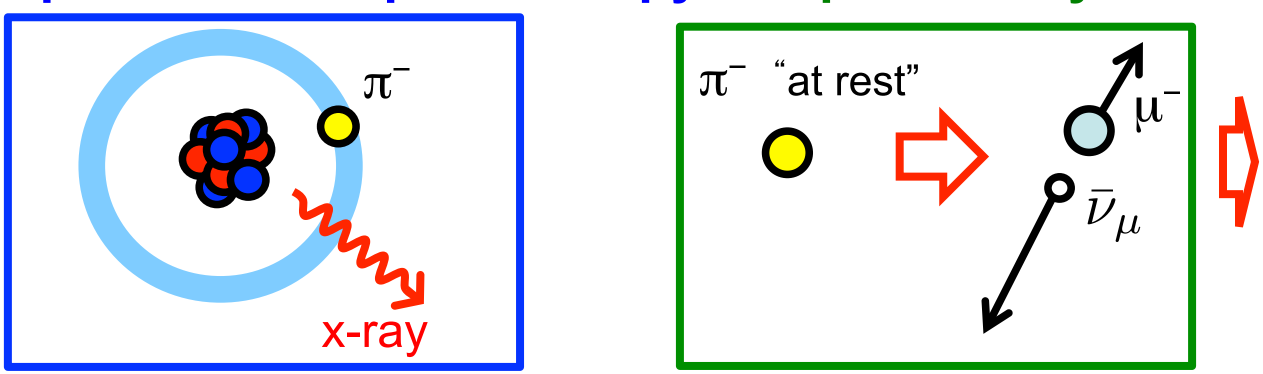


New **pionic atom spectroscopy** and **pion decay** measurements

Pionic spectroscopy and pion decay measurements



New **pionic atom spectroscopy** and **pion decay** measurements

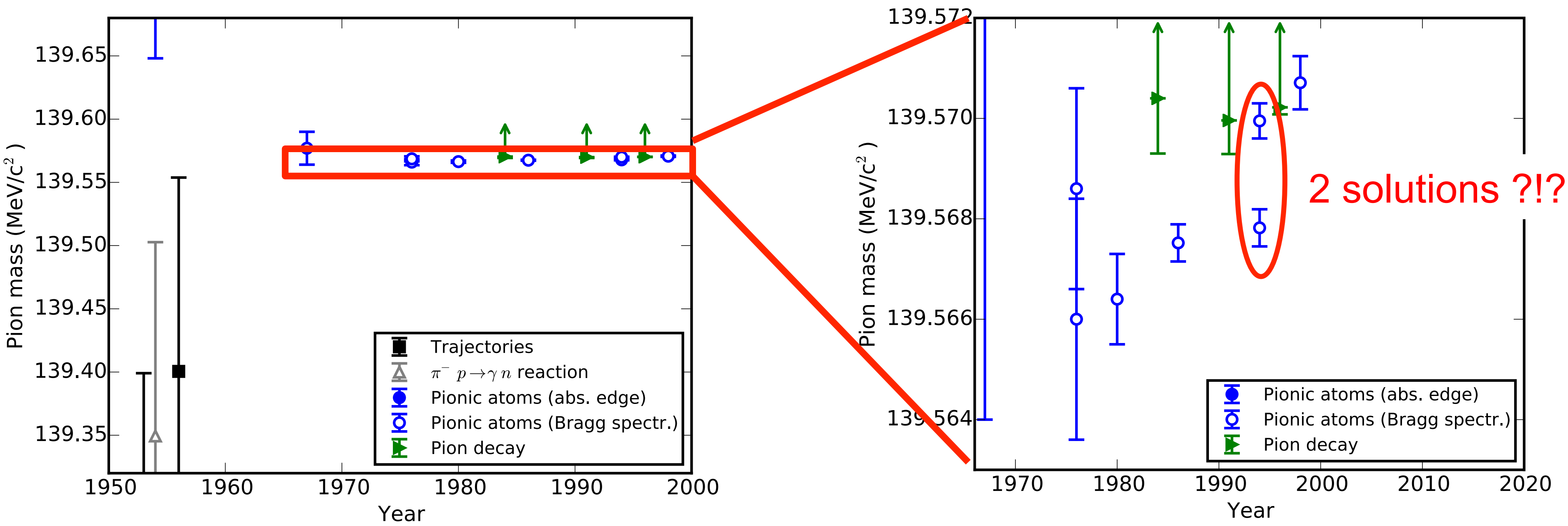


Measurement of **p_μ** (, m_μ)

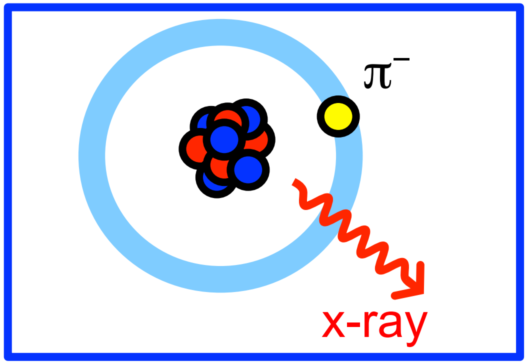
→ pion mass

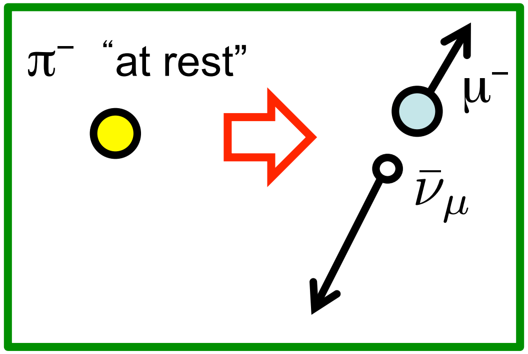
low boundary if no assumptions on the neutrino mass are made

Pionic spectroscopy and pion decay measurements



New **pionic atom spectroscopy** and **pion decay** measurements

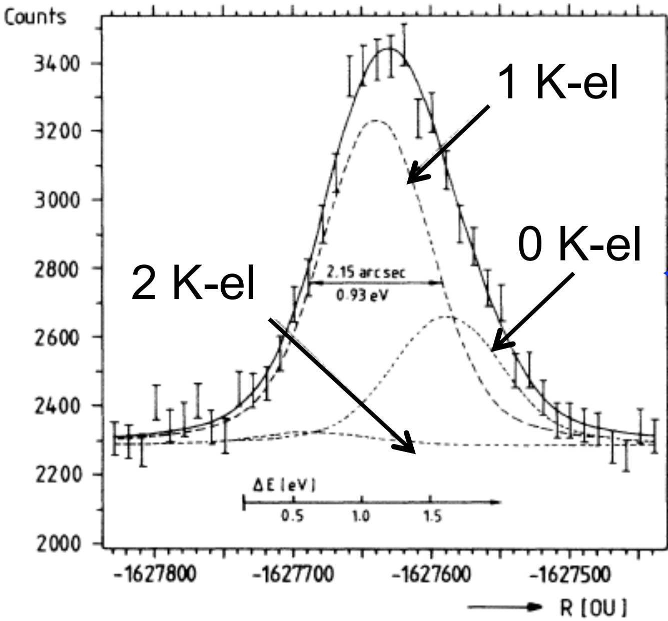




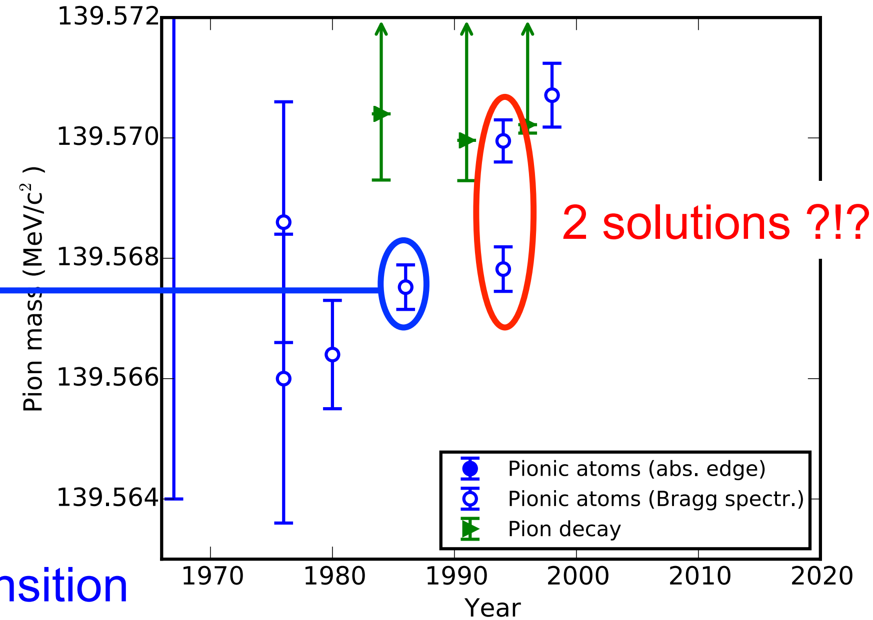
Measurement of
p_μ (, m_μ)

→ pion mass
low boundary if no assumptions on the neutrino mass are made

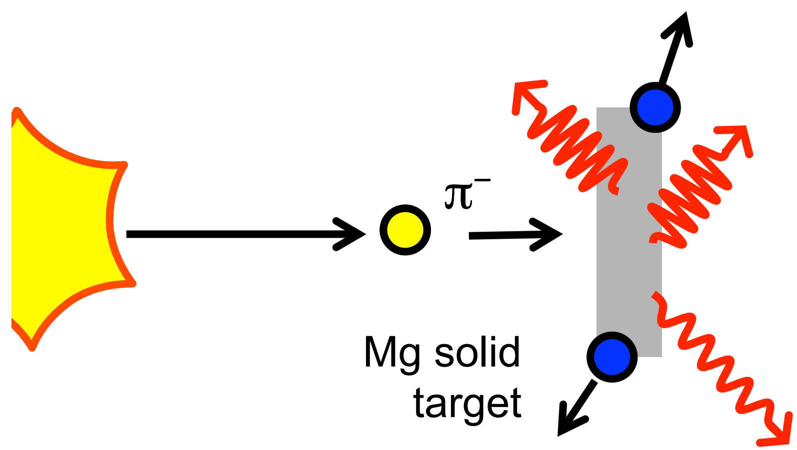
Pion mass measurement problems



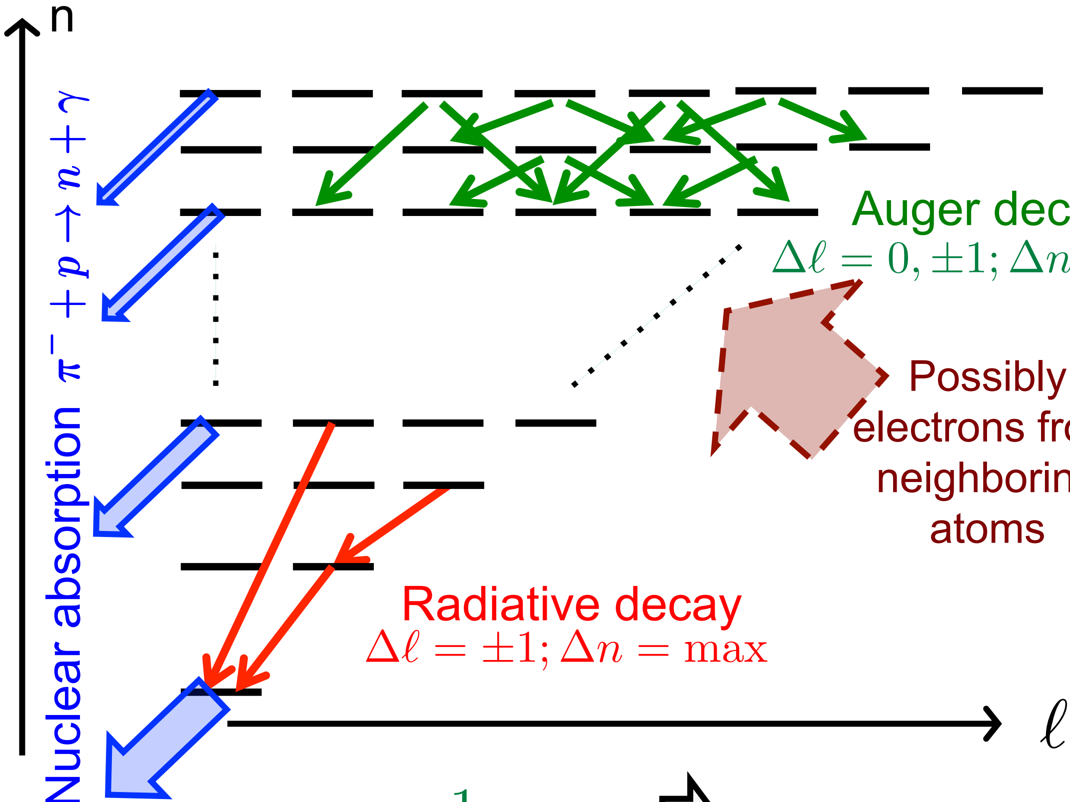
B. Jeckelmann *et al.*, Phys. Rev. Lett. **56**, 1444 (1986)



4f–3d πMg transition



Pionic atoms formation and atomic cascade



Capture at the radii of outmost electrons

$$n_\pi \sim n_{el}\sqrt{\frac{m_\pi}{m_{el}}} \sim n_{el} \times 16$$

De-excitation via Auger (electron emission) and radiative (X-ray emission) decay

$$\Gamma_{\text{Auger}} \propto \frac{1}{\sqrt{2\Delta E + 38\, eV}}$$ [1]

⇨ Dominates for large n

$$\Gamma_{\text{Auger}} \gg \Gamma_{\text{X-ray}} \text{ for } n \gg 1$$

$$\Gamma_{\text{X-ray}} \propto \Delta E^3$$ [2]

⇨ Dominates for small n

⇨
- Low Z + dilute targets → **no electrons remaining**
- Medium-high Z + dense targets → **remaining electrons**

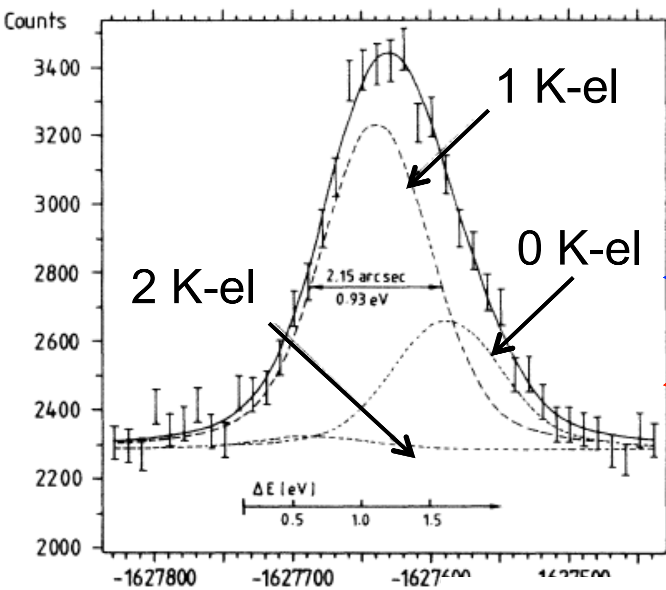
[1] M. Leon *et al.*, Phys. Rev. **127**, 636 (1962)
[2] H.B. Bethe *et al.*, *Quantum Mechanics of One- and Two-Electron Atoms*, 1957, Springer-Verlag.

PAUL SCHERRER INSTITUT PSI

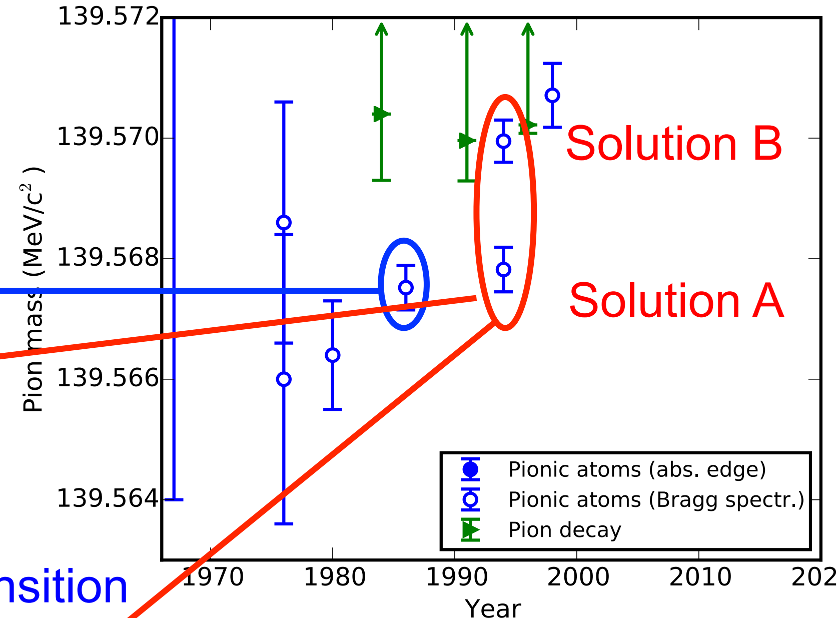
JÜLICH FORSCHUNGSZENTRUM

MESON 2016

Pion mass measurement problems



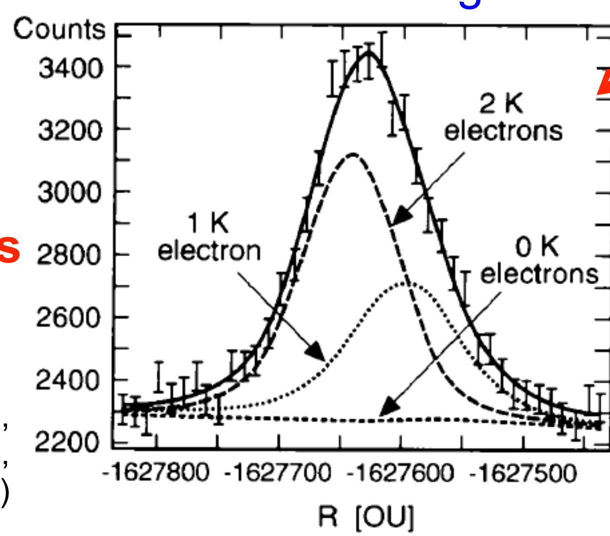
B. Jeckelmann *et al.*, Phys. Rev. Lett. **56**, 1444 (1986)



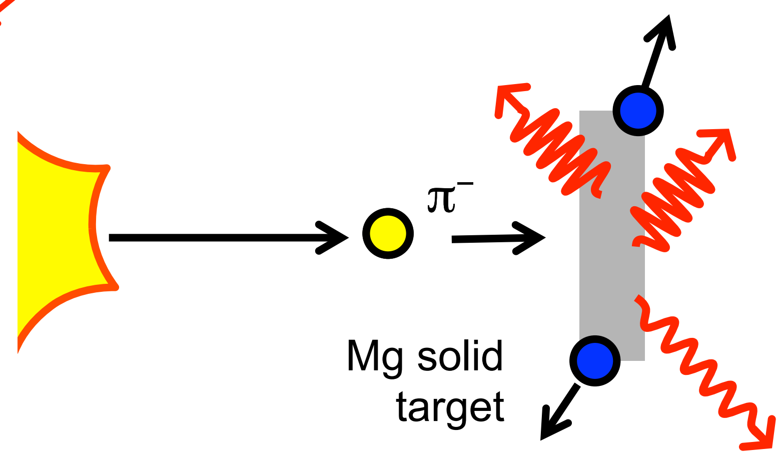
4f–3d πMg transition

Refilling from the neighboring atoms

→ **Two possibilities**

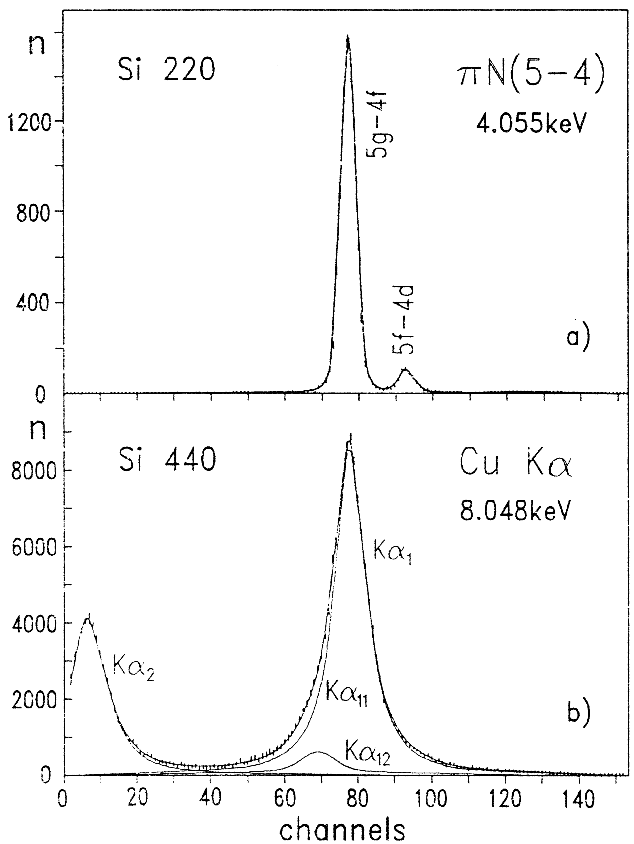


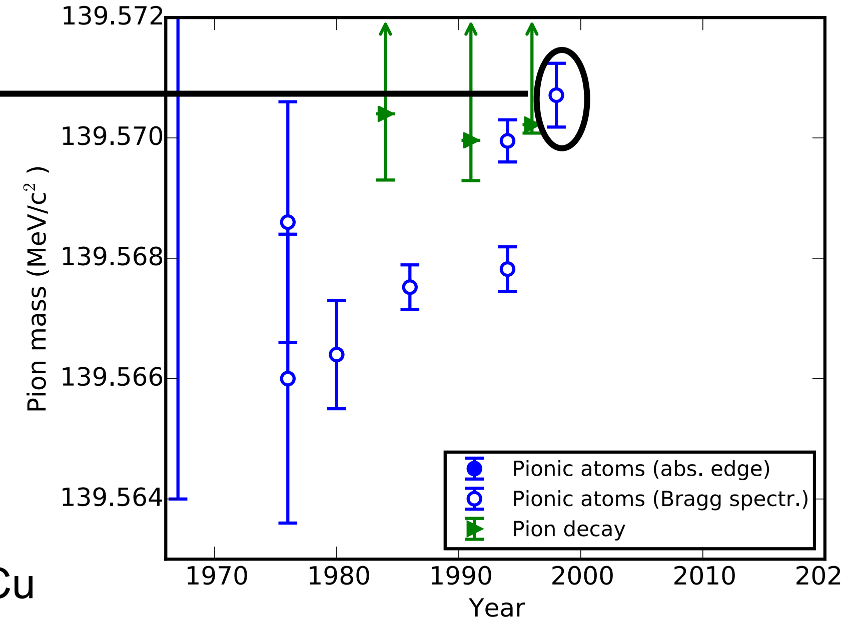
B. Jeckelmann *et al.*, Phys. Lett. B **335**, 326 (1994)



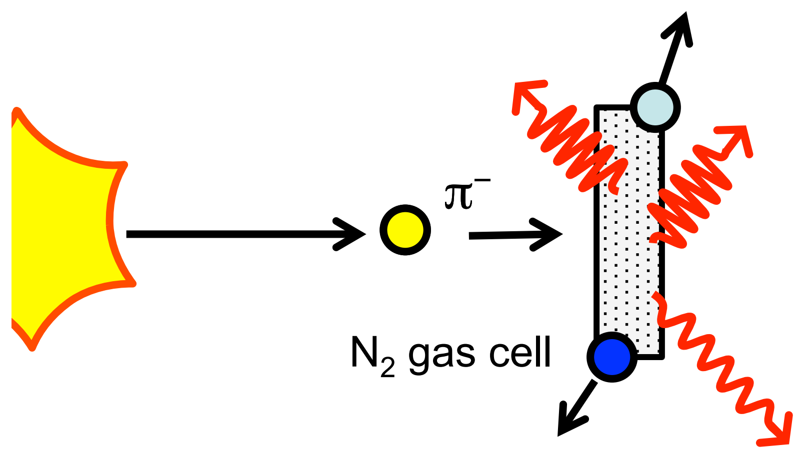
New measurement of the pion mass

New measurement of the pion mass with a gaseous target [1]





Calibration from Cu Kα fluorescence in a different diffraction order



[1] S. Lenz *et al.*, Phys. Lett. B **416**, 50 (1998)

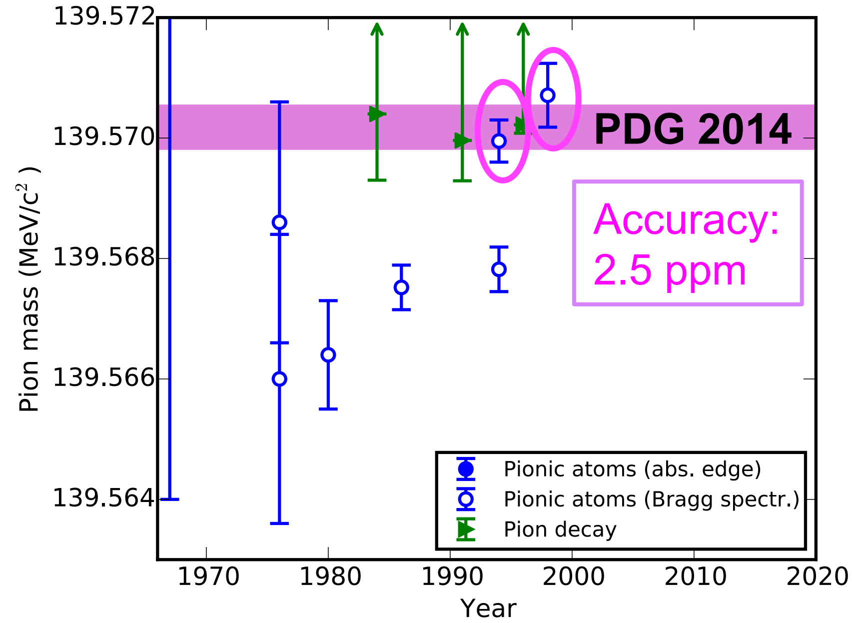
Present official value and new proposal

Present official value

Average between :

- Jeckelmann 1994 solution B (**solid target**)
- Lenz 1998 (**gaseous target**)

Particle Data Group. Chinese Phys. C **38**, 090001 (2014)



PSI proposal R-97-02

NEW PRECISION DETERMINATION OF THE CHARGED PION MASS

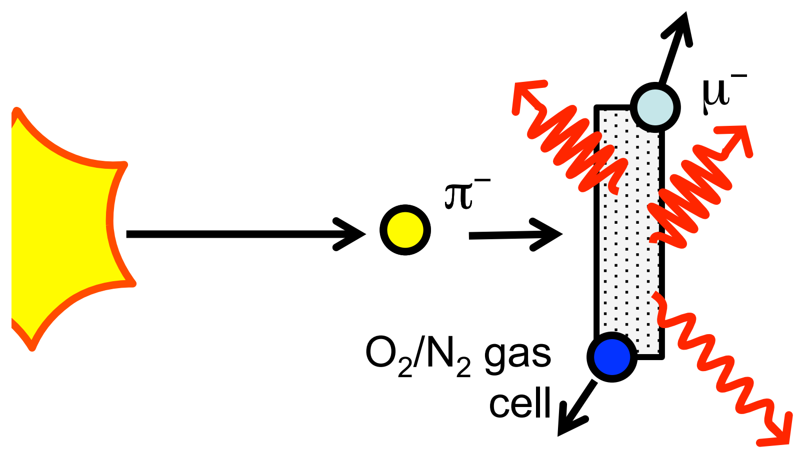
D. Anagnostopoulos[1], M. Augsburger[2], G. Borchert[1], D. Chatellard[2], M. Daum[3], J.-P. Egger[2], D. Gotta[1], P. Hauser[3], P. Indelicato[4], E. Jeannet[2], K. Kirch[3], O. W. B. Schult[1], Th. Siems[1], L. M. Simons[3]

- **Gaseous target**

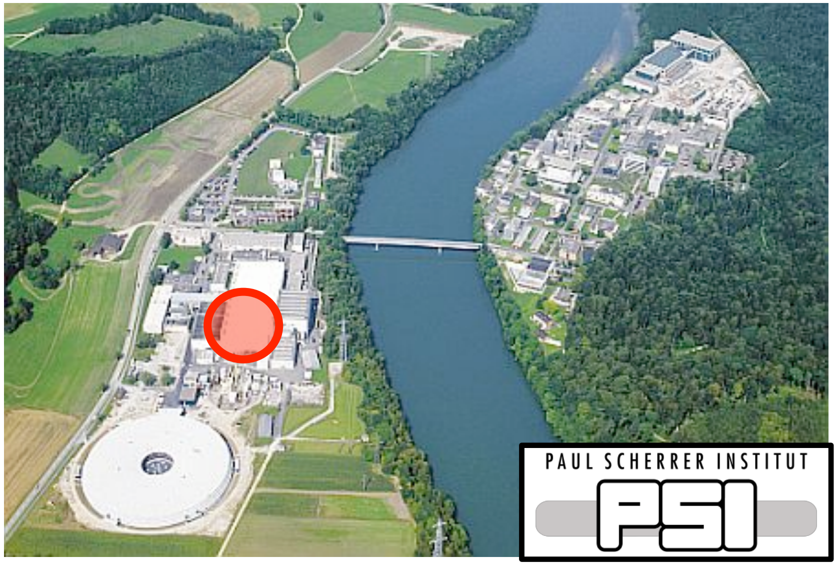
→ no remaining el. contamination

- **Muonic Oxygen** transition as **calibration**

→ high accuracy of the energy reference

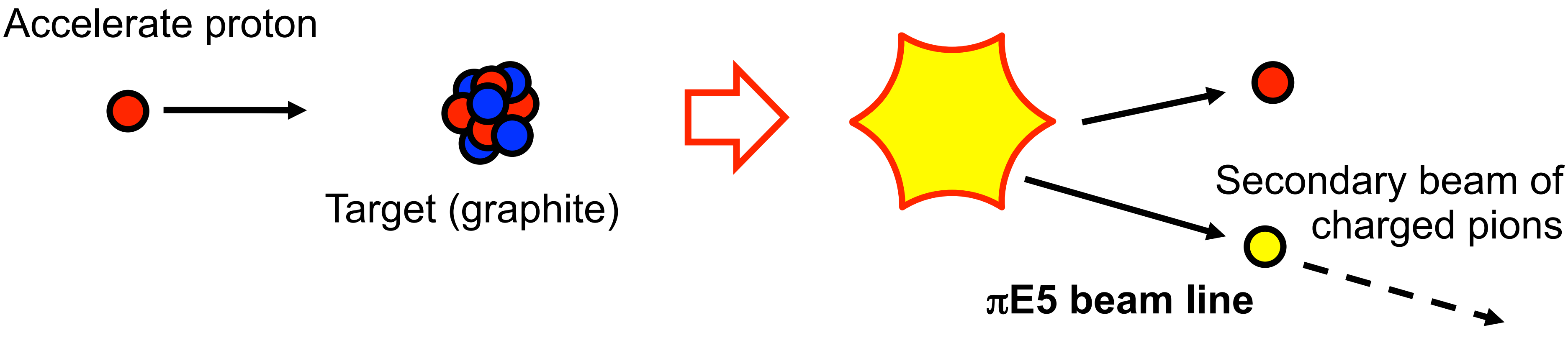


Pion beam production



Production at the Paul Scherrer Institut (Villigen, Switzerland)

- Proton beam :E_{kin}=590 MeV, I=1.9 mA
- Graphite target
- 10^8 pions/s, E_{kin}=110 MeV



Pionic and muonic atoms production

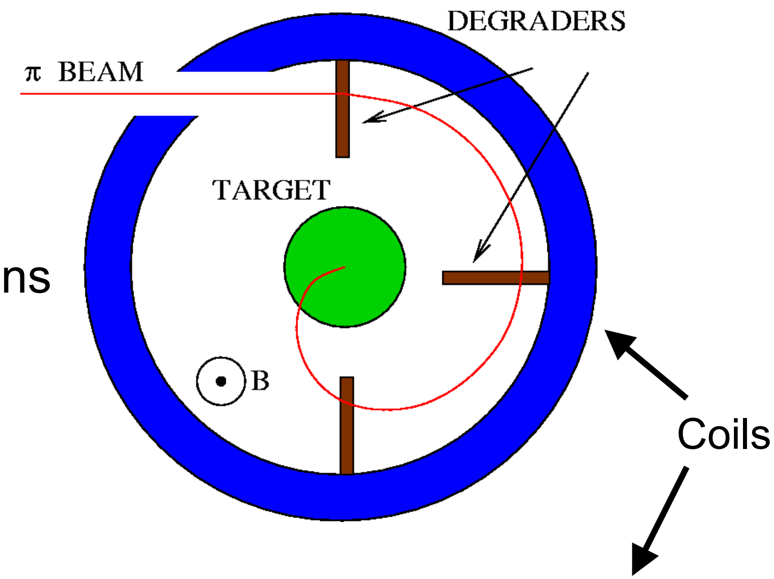
- Cyclotron trap to stop the pions:
  - strong magnetic field (B_{max}=3.5 Tesla)
  - plastic degraders (energy loss)

- Gaseous target:
  - N_2/O_2 gas mixture of 10%/90%
  - Room temperature and P = 1.4 bar

⇩

1-5% of the incoming pions are stopped inside the target

τ_{π^-}= 26 ns



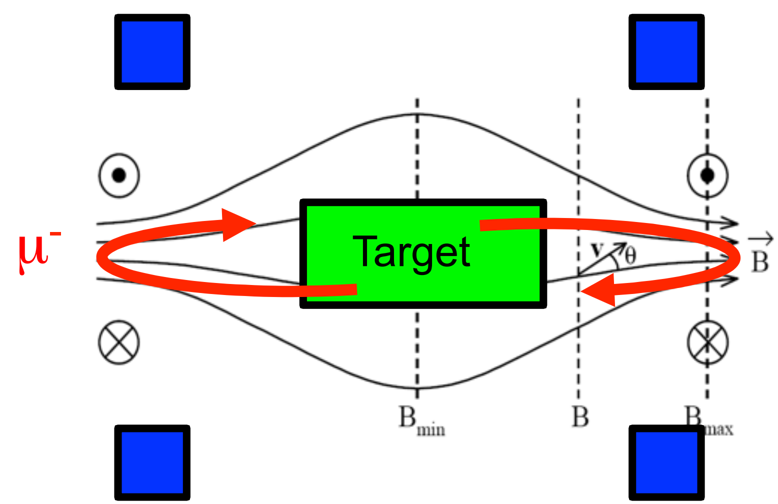
- Production and trapping of the muons

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

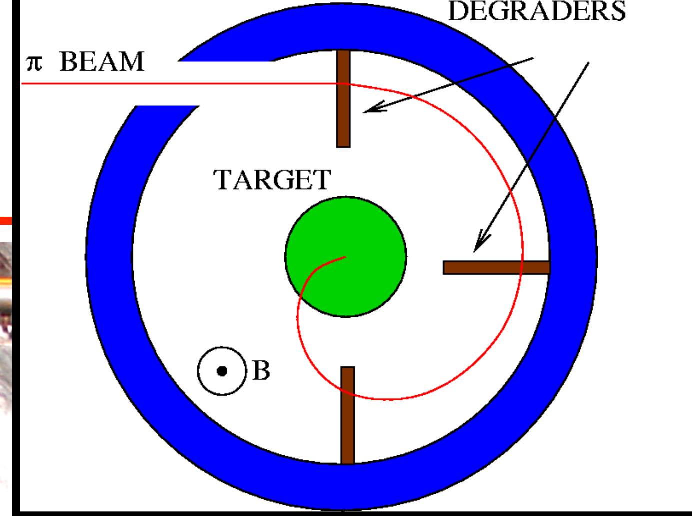
⇩

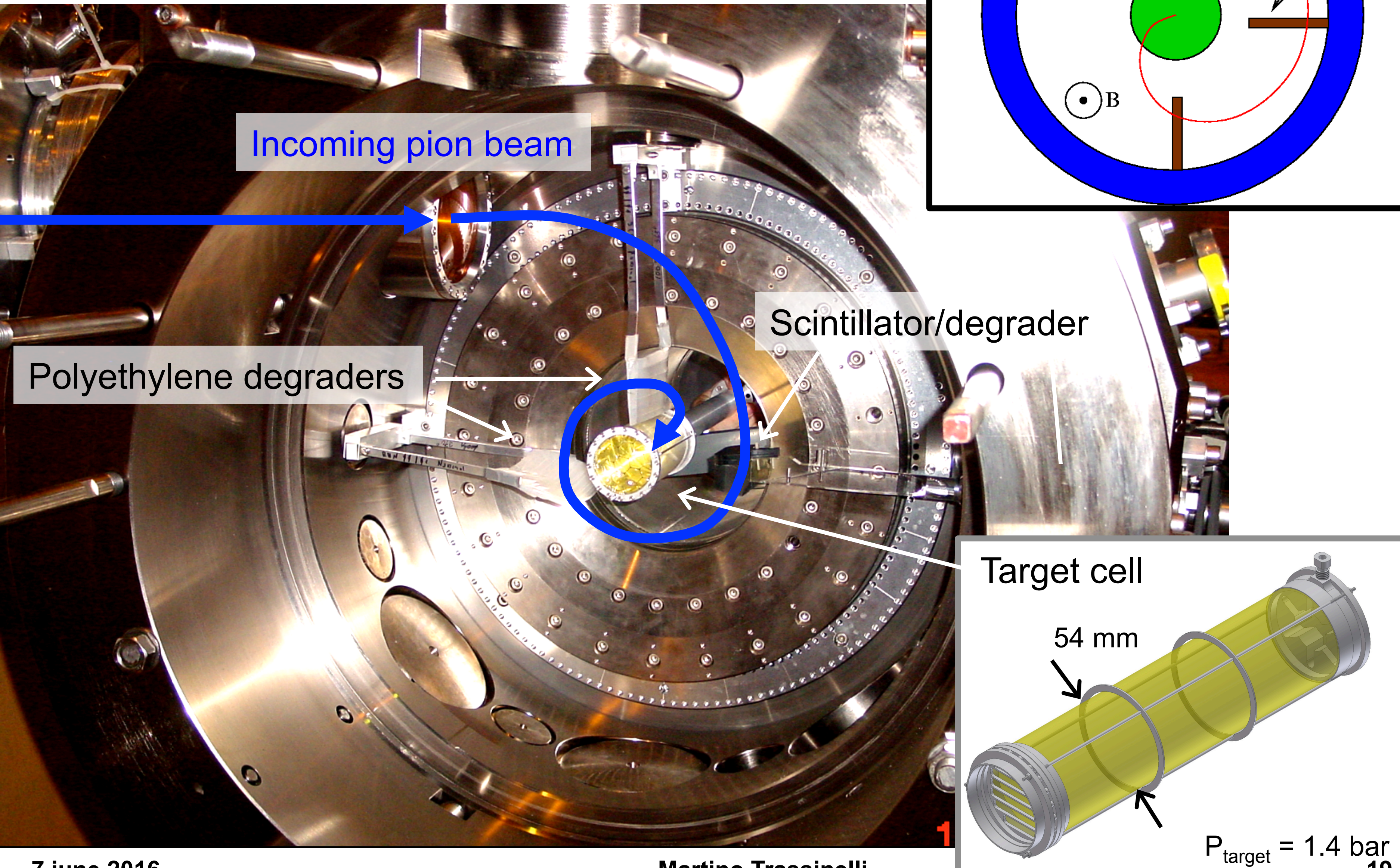
Formation of muonic and pionic atoms

N. of πN atoms = 10 x N. of μO atoms

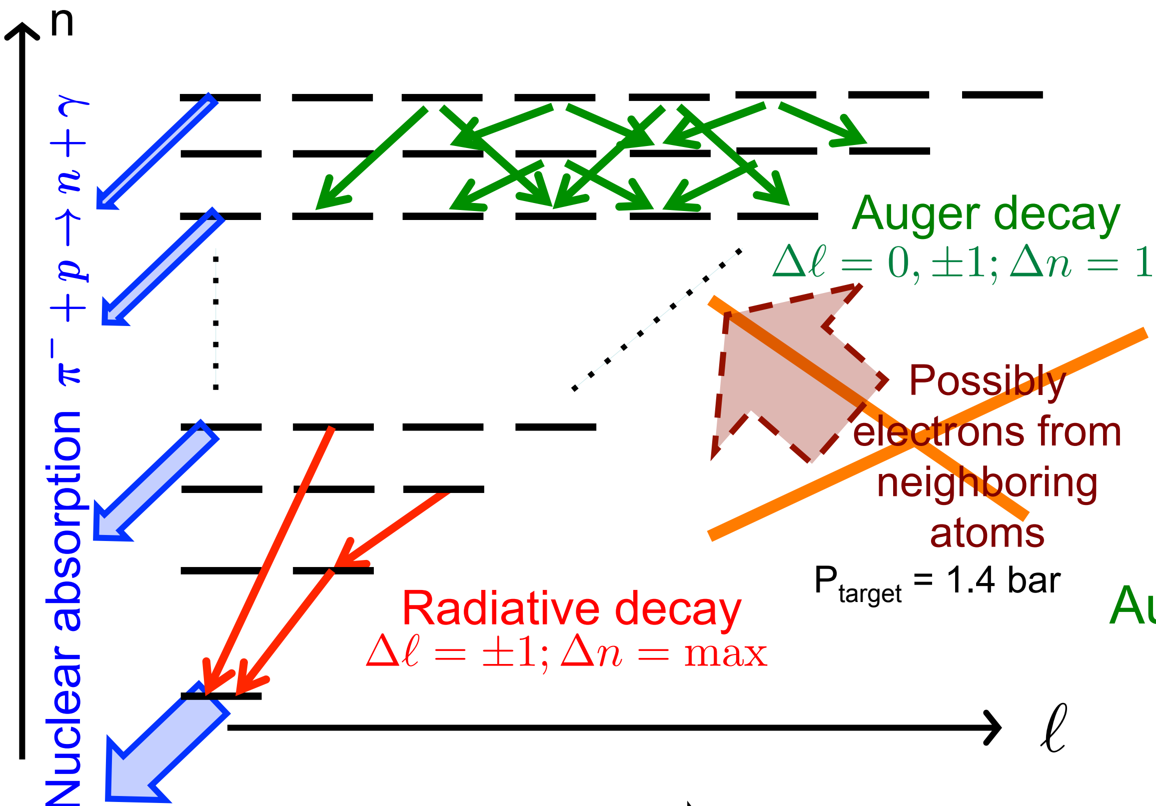


Cyclotron trap





Pionic atoms formation and atomic cascade with N_2 gaseous target



Capture at the radii of outmost electrons

$$n_\pi \sim n_{el}\sqrt{\frac{m_\pi}{m_{el}}} \sim n_{el} \times 16$$

De-excitation via Auger (electron emission) decay

Excited hydrogen-like pionic nitrogen [1,2]

$$\Gamma_{\text{Auger}} \propto \frac{1}{\sqrt{2\Delta E + 38\, eV}}$$

Dominates for n > 6-7

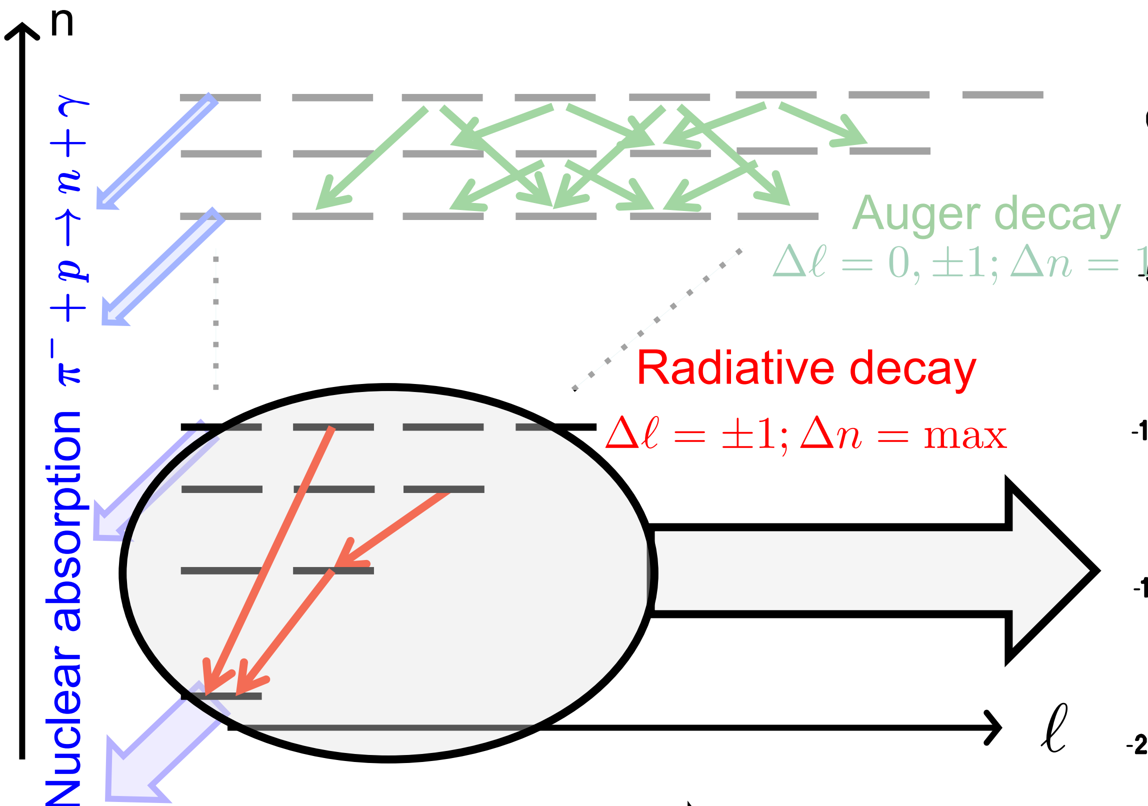
$$\Gamma_{\text{Auger}} \gg \Gamma_{\text{X-ray}} \text{ for } n \gg 1$$

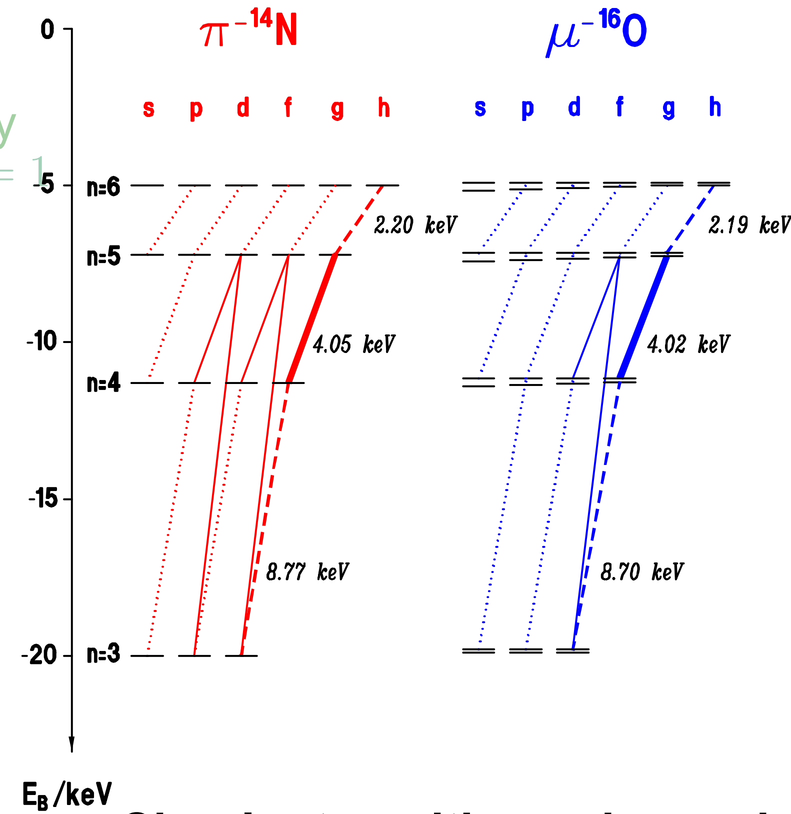
$$\Gamma_{\text{X-ray}} \propto \Delta E^3$$

Dominates for n < 6-7

[1] R. Bacher *et al.*, Phys. Rev. A **39**, 1610 (1989)
[2] K. Kirch *et al.*, Phys. Rev. A **59**, 3375 (1999)

Pionic atoms formation and atomic cascade with N_2 gaseous target





$$\Gamma_{\text{Auger}} \propto \frac{1}{\sqrt{2\Delta E + 38\, eV}}$$

Dominates for n > 6-7

$$\Gamma_{\text{Auger}} \gg \Gamma_{\text{X-ray}} \text{ for } n \gg 1$$

$$\Gamma_{\text{X-ray}} \propto \Delta E^3$$

Dominates for n < 6-7

Circular transition enhanced

$$|n, \ell = n\rangle \to |n-1, \ell = n-1\rangle$$

Strong interaction effects minimized

Pion mass measurement from πN and μO X-ray spectroscopy

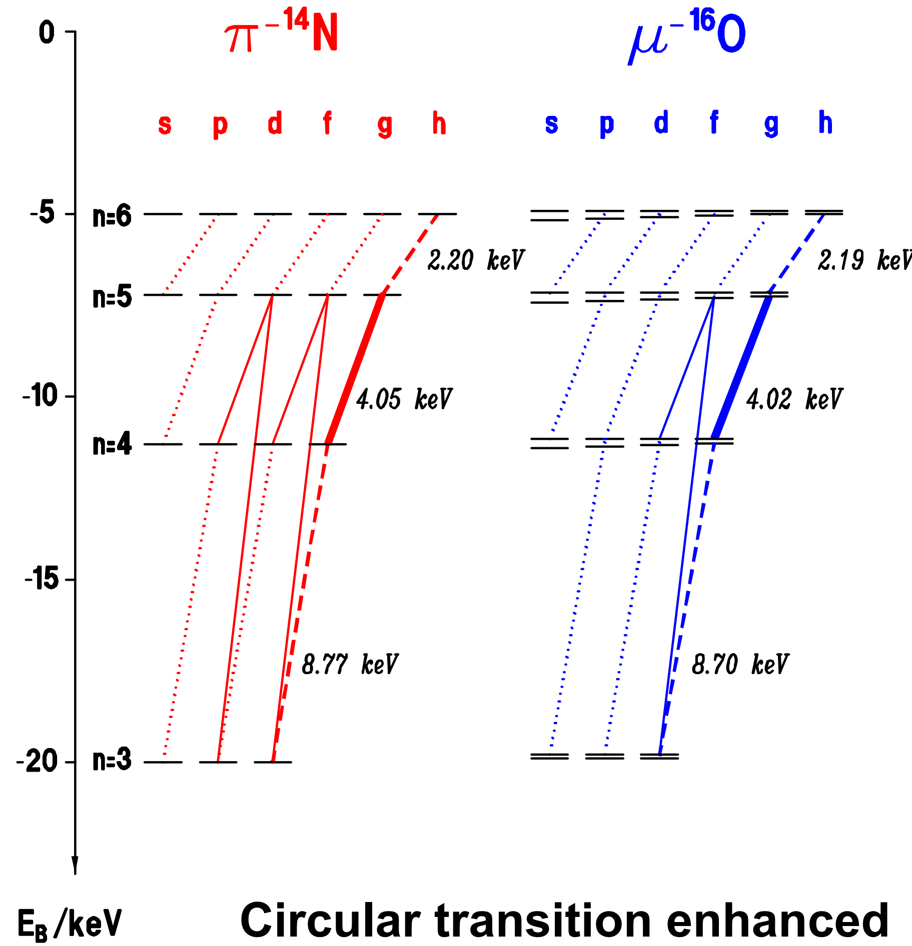
Pion mass (unknown) or muon mass (reference)

$$E_{\text{X-ray}} = mc^2 \frac{(Z\alpha)^2}{2}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) + \mathcal{O}(Z^4\alpha^4)$$

QED calculation only

Measurement of $E_{\text{X-ray}}$

⇨ X-ray diffraction spectroscopy



Circular transition enhanced

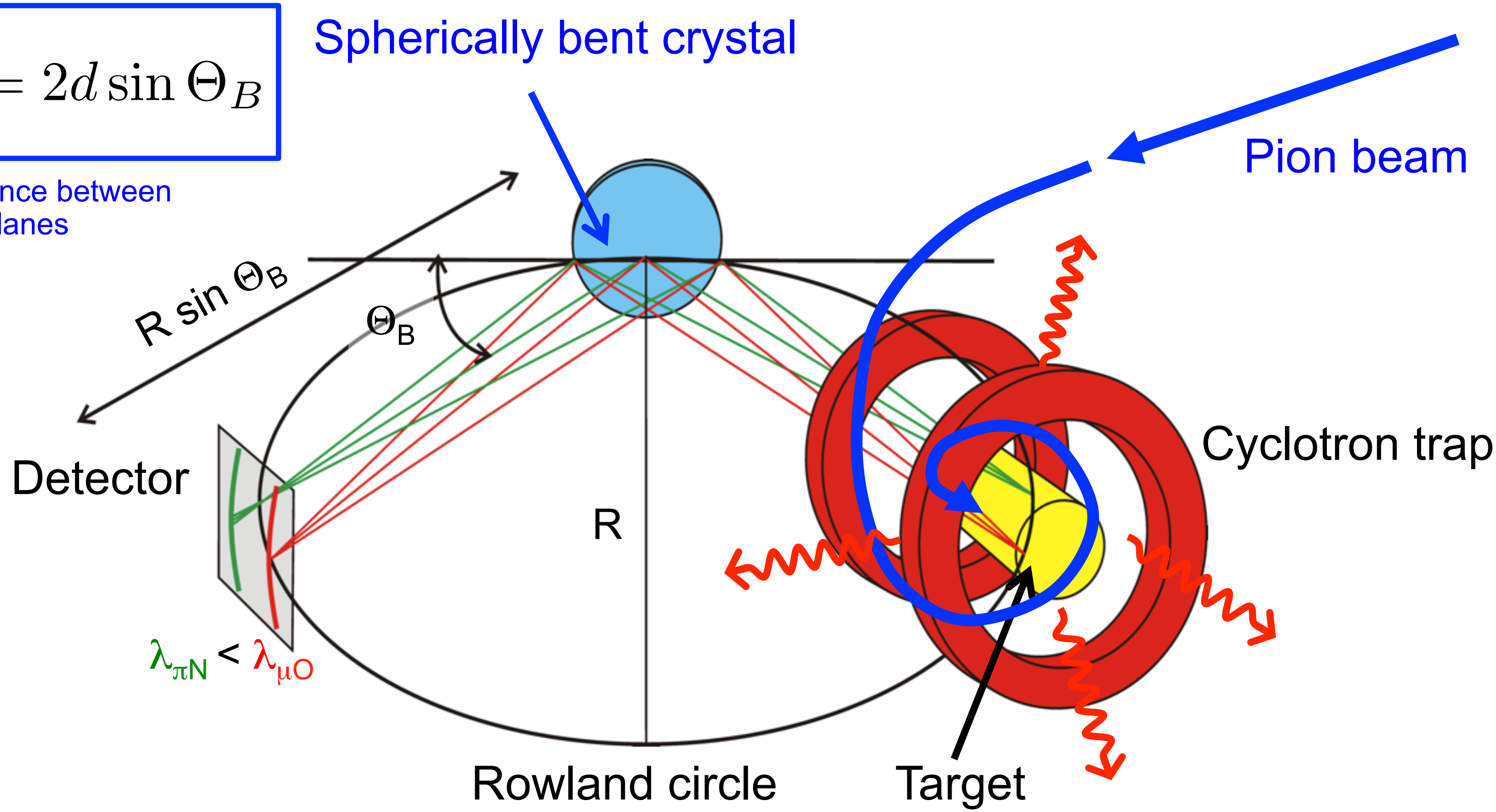
$|n, \ell = n\rangle \rightarrow |n-1, \ell = n-1\rangle$

Strong interaction effects minimized

X-ray Bragg spectroscopy with a Johann-type spectrometer [1-4]

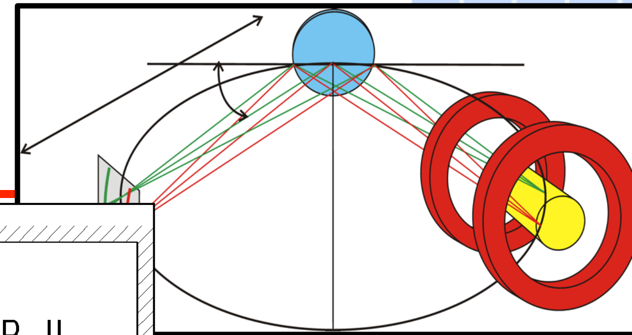
$$\frac{hc}{E} = 2d \sin \Theta_B$$

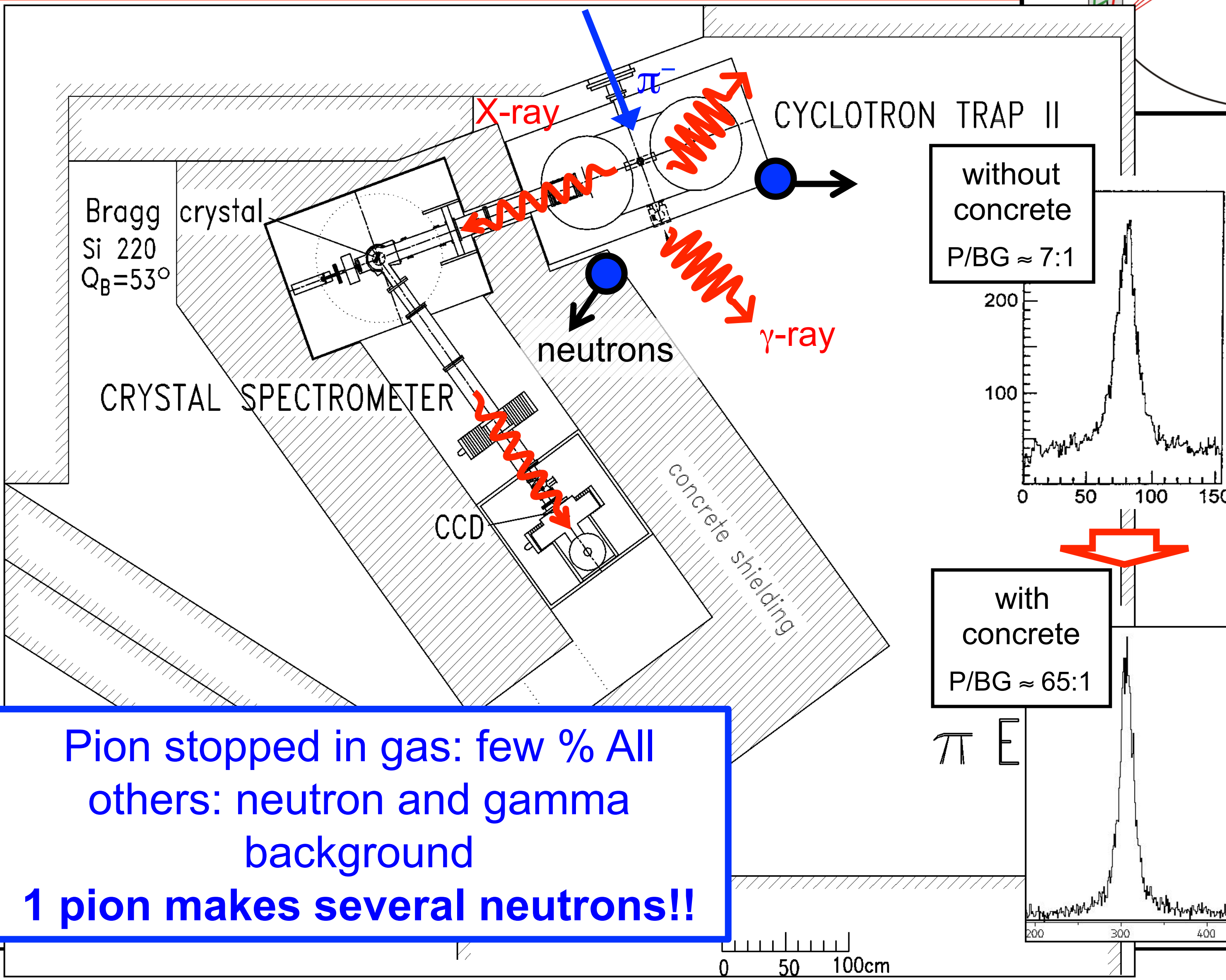
d = distance between crystal planes



[1] H.H. Johann, Zeitschrift für Physik **69**, 185 (1931)
[2] J. Eggs *et al.*, Zeitschrift für angewandte Physik **20**, 118 (1965)
[3] D. Gotta, Progress in Particle and Nuclear Physics **52**, 133 (2004)
[4] D. Gotta *et al.*, Spectrochim. Acta, Part B **120**, 9 (2016)

Set-up at PSI





Huge background on the CCD

⇩

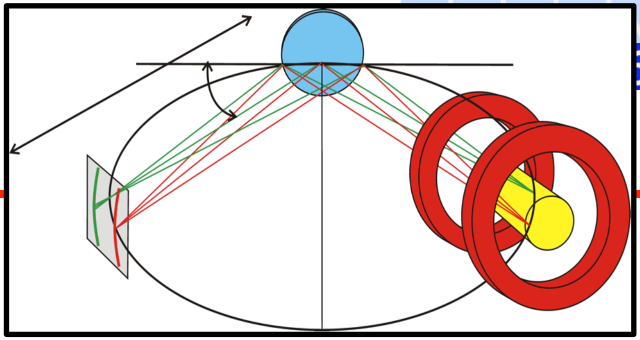
Heavy concrete

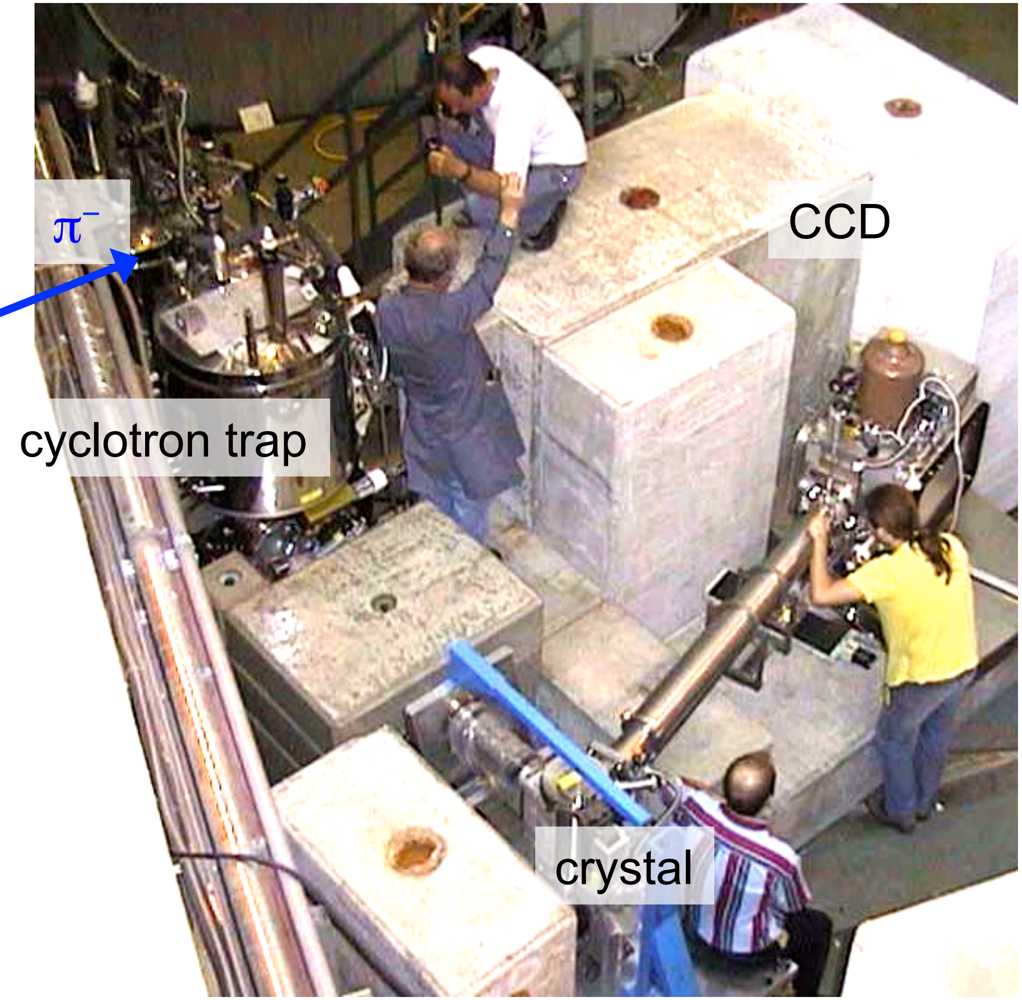
⇩

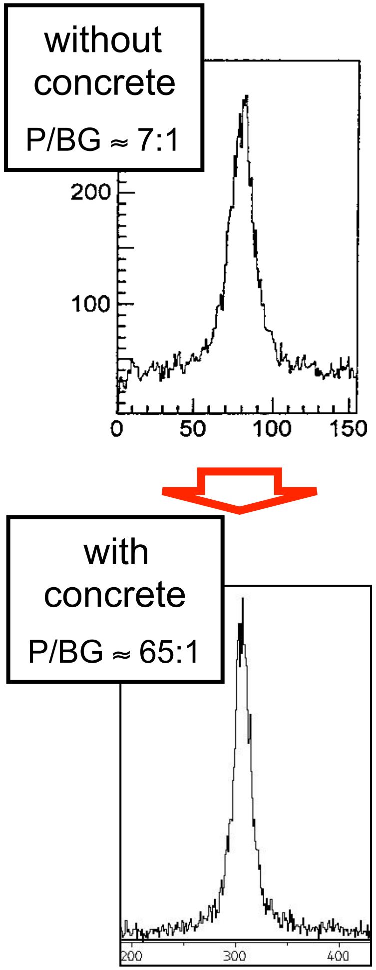
Peak-to-background increased by a factor of 10

Pion stopped in gas: few % All others: neutron and gamma background
1 pion makes several neutrons!!

Set-up at PSI







Huge background on the CCD

⇩

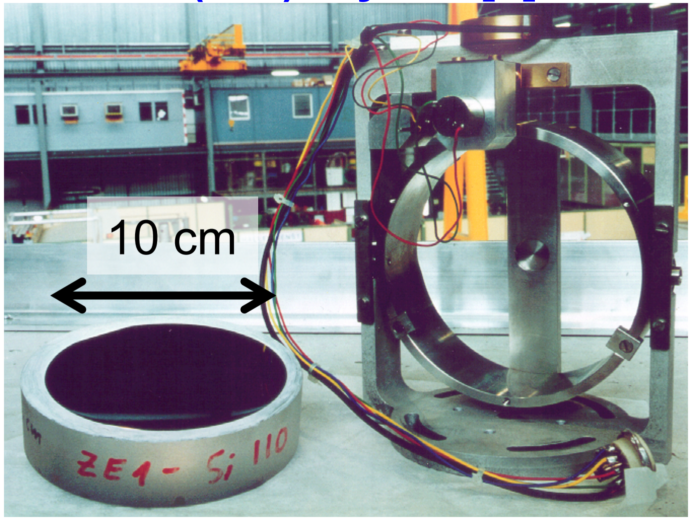
Heavy concrete

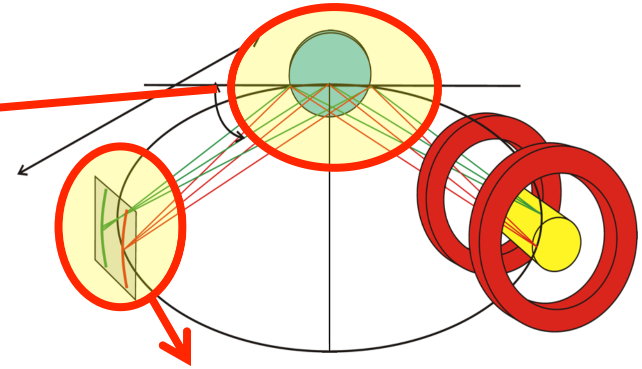
⇩

Peak-to-background increased by a factor of 10

Diffraction crystal and position sensitive detector

Si(110) crystal [1]

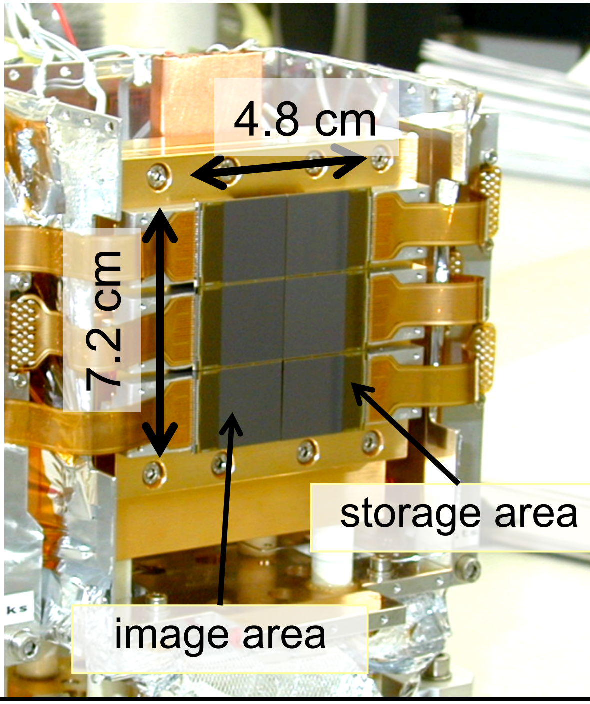




Radius of curvature: ~ 3 m
Diameter: 10 cm
Thickness: 290 µm
Support: polished quartz lens

Produced by Zeiss (Oberkochen, Germany)

2 × 3 X-ray CCD array with frame buffer [2,3]



pixel size 40 µm × 40 µm
600 × 600 pixels per chip
frame transfer ≈ 10 ms

data processing 2.4 s
operates at – 100°C

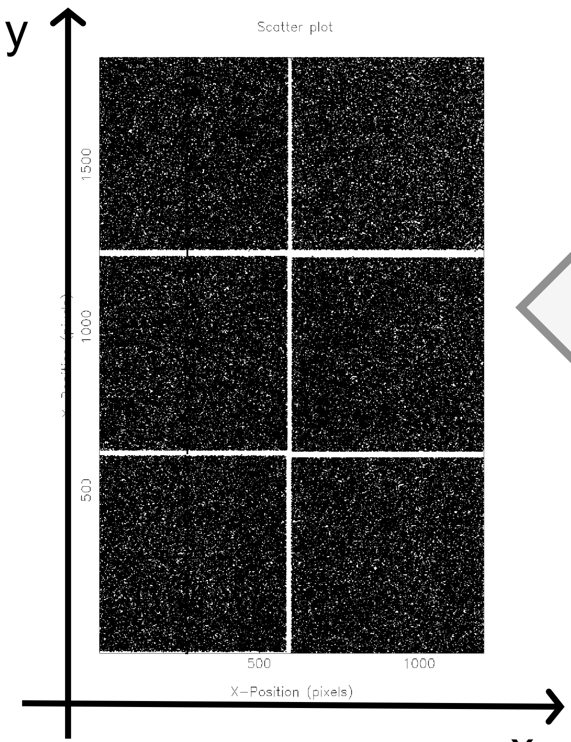
$\Delta E \approx 150$ eV @ 4 keV
Efficiency ≈ 90%

[1] D.S. Covita *et al.*, Rev. Sci. Instum. **79**, 033102-3 (2008)
[2] N. Nelms *et al.*, Nucl. Instrum. Methods A **484**, 419 (2002)
[3] P. Indelicato *et al.*, Rev. Sci. Instum. **77**, 043107 (2006)

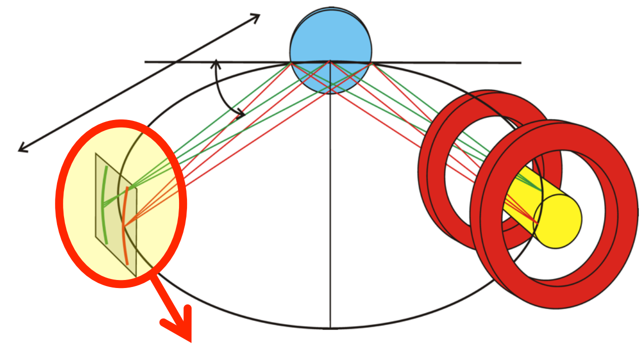
Data acquisition and pre-analysis

… after 5 weeks of data collection …

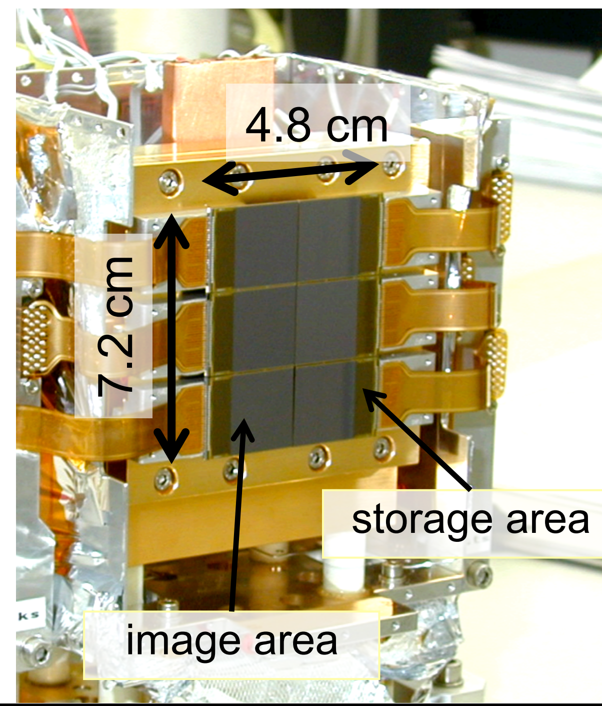
6000 counts in each line
Spectrometer transmission: 5×10^{-8}
Stability of the set-up monitored by 8 keV Cu Kα fluorescence line (fourth order reflection)



Raw data



2 × 3 X-ray CCD array with frame buffer [2,3]



pixel size 40 μm × 40 μm
600 × 600 pixels per chip
frame transfer ≈ 10 ms

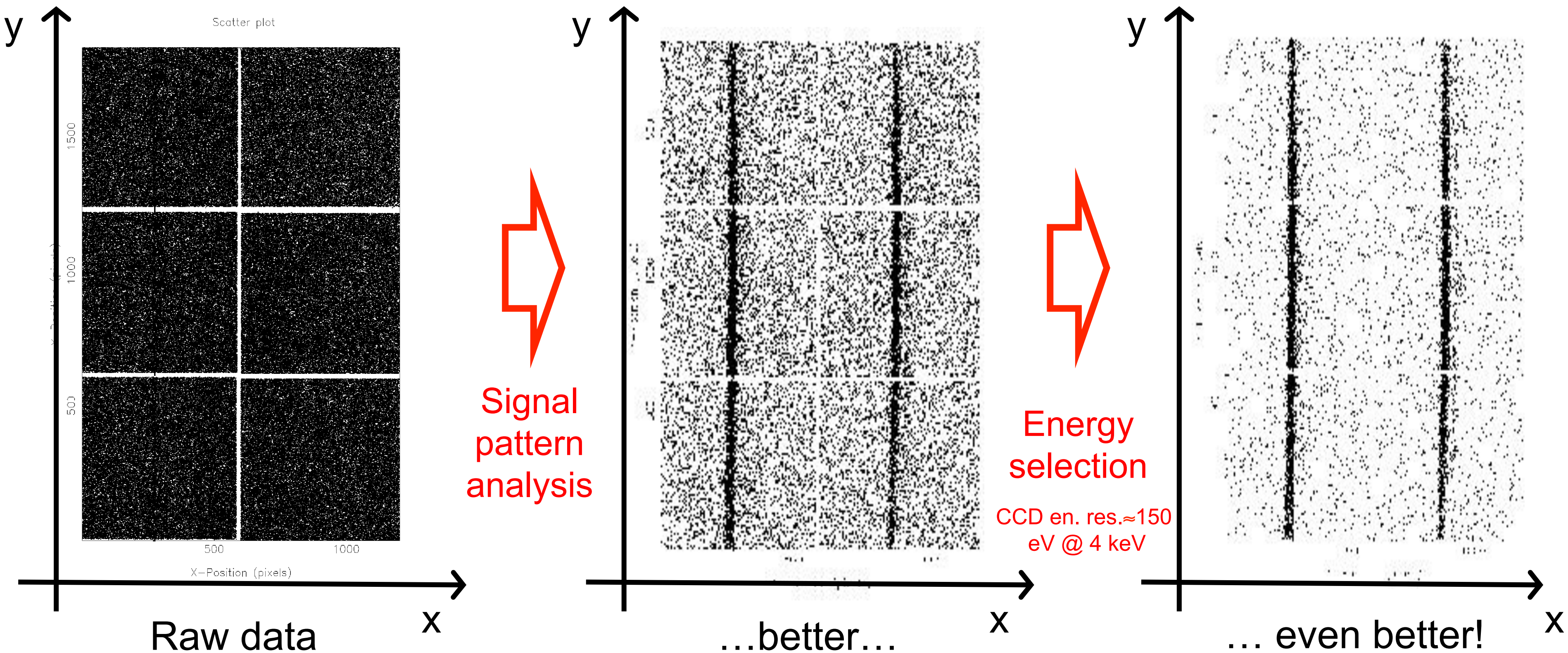
data processing 2.4 s
operates at – 100°C

$\Delta E \approx 150$ eV @ 4 keV
Efficiency ≈ 90%

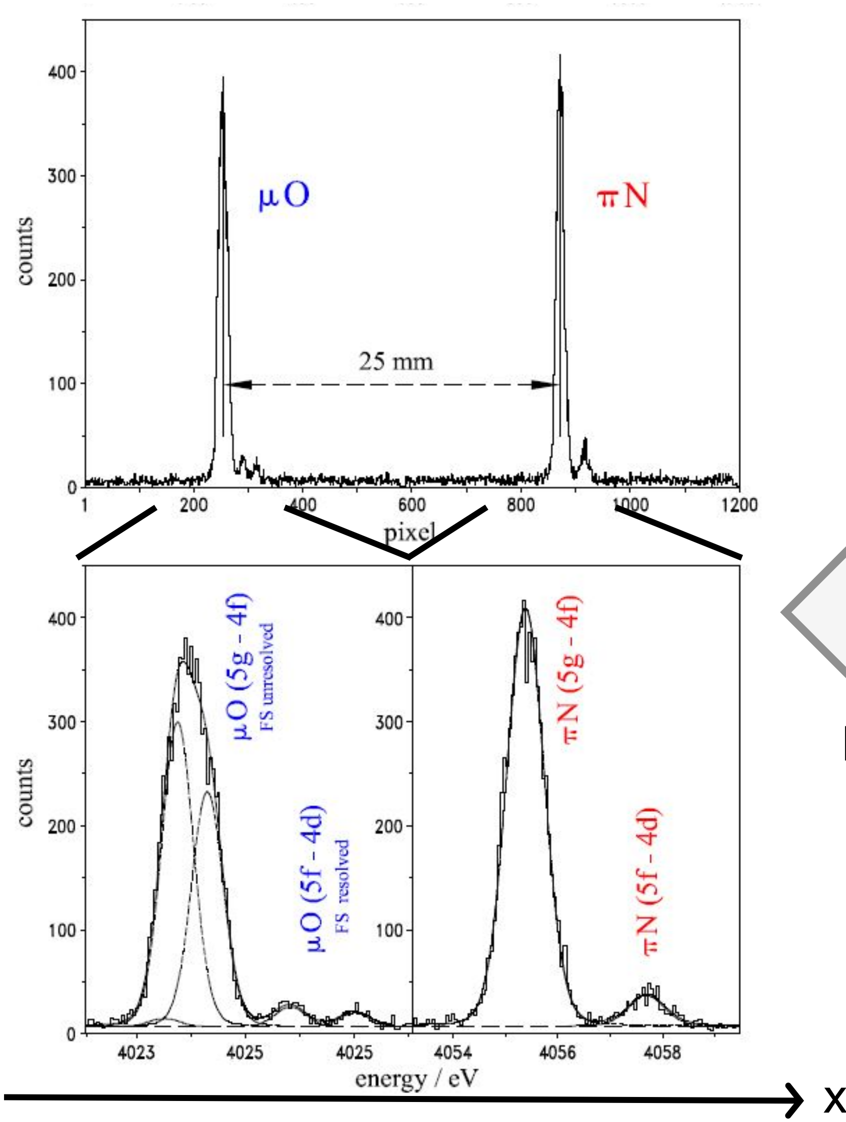
Data acquisition and pre-analysis

… after 5 weeks of data collection …

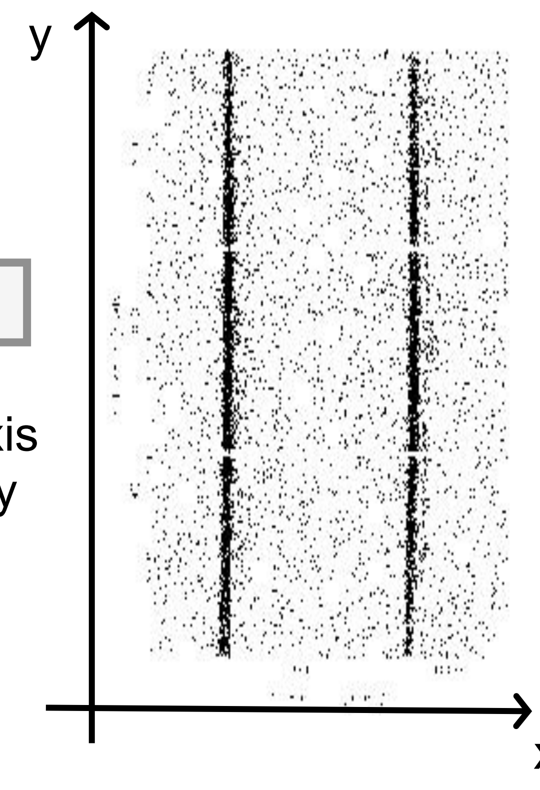
6000 counts in each line
Spectrometer transmission: 5×10^{-8}
Stability of the set-up monitored by 8 keV Cu Kα fluorescence line (fourth order reflection)



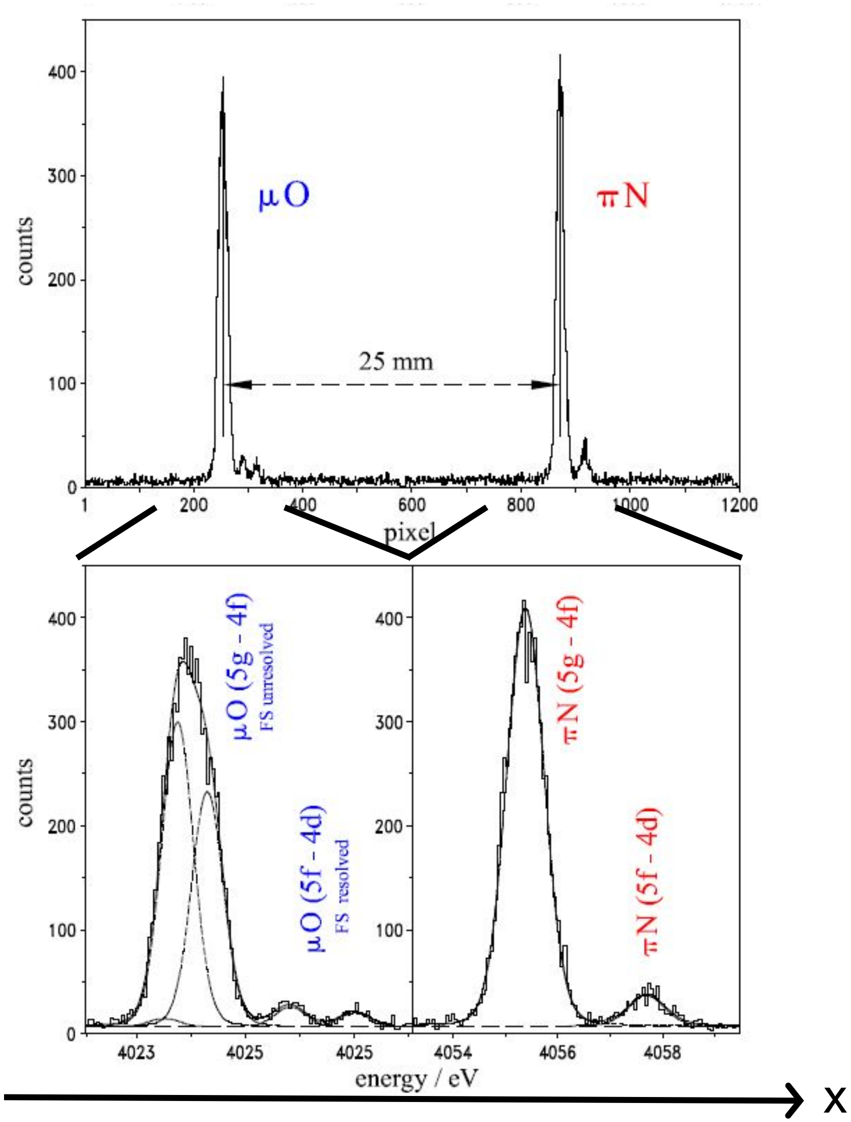
5g-4f transitions in πN and μO

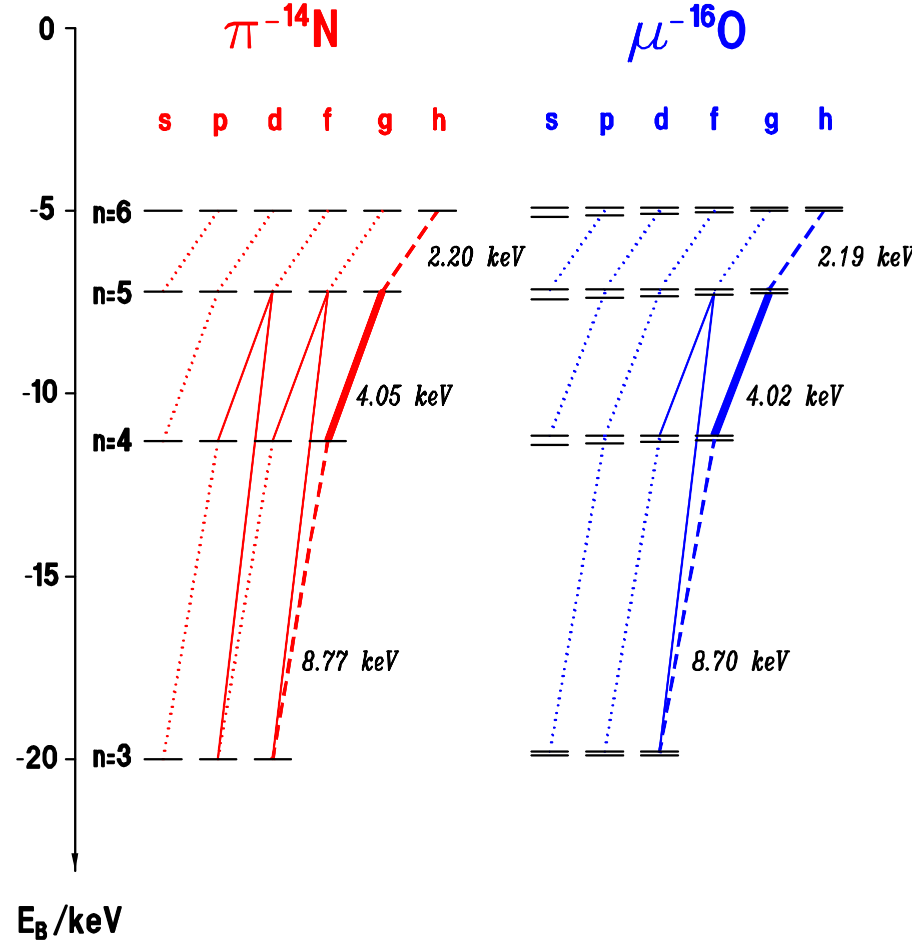


Projection on the x-axis (spectrometer energy dispersion axis)



5g-4f transitions in πN and μO





Muon = ½-spin particle

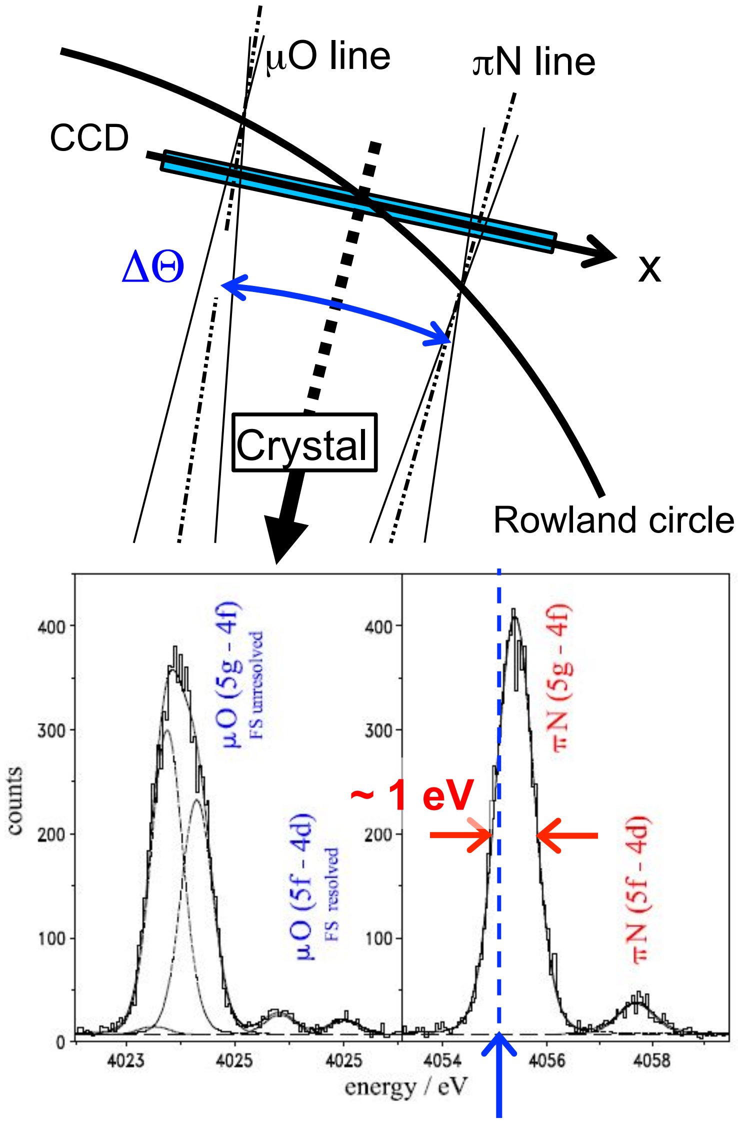
→ fine structure in μO

PAUL SCHERRER INSTITUT PSI

JÜLICH FORSCHUNGSZENTRUM

MESON 2016

Lines profiles and positions



Eventual position of the satellite line

Lines profile contributions:

- Doppler broadening from Coulomb explosion of O_2 and N_2 molecules
- Rocking curve of the crystal
- Defocussing

Monte Carlo simulations and spectrometer characterization [1-5]

Spectra modeling:

- Remaining electrons contribution (satellite line)
- Distance and amplitude between parallel and fine structure transitions
- Different width of the lines

Possible relative intensity:
< 3×10^{-6}
Obtained by hypothesis test via Bayesian evidence calculation

Fixed by the theory

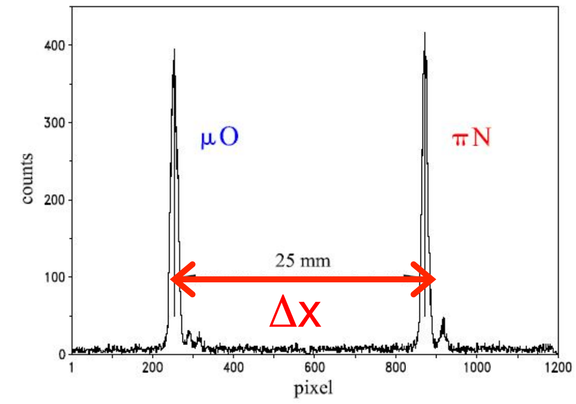
Information on the atomic de-excitation

[1] D.F. Anagnostopoulos *et al.*, Nucl. Instrum. Methods B **205**, 9 (2003)
[2] D.F. Anagnostopoulos *et al.*, Nucl. Instrum. Methods A **545**, 217 (2005)
[3] D.S. Covita, Ph.D. thesis University of Coimbra (2008)
[4] M. Theisen, Diplomarbeit thesis, University of Aachen (2013)
[5] D.E. Gotta *et al.*, Spectrochim. Acta, Part B **120**, 9 (2016)

From the line position to the pion mass

From the spatial diff. to the angular position diff.

$$\Delta\Theta = -2\arctan\left(\frac{\Delta x}{2D}\right)$$



$$\frac{hc}{E} = 2d\sin\Theta_B$$

Bragg law

Statistical uncertainty:
line positions: ± 0.045 pixel

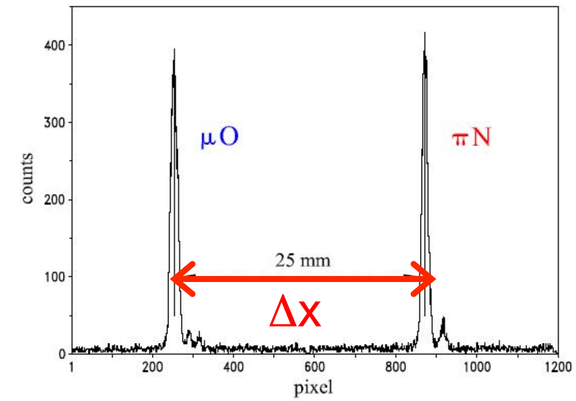
Systematics uncertainty:
crystal–detector distance,
CCD positions and pixel size [1], line modeling,
spectrometer response function [2-6],
Bragg law corrections [7], …

[1] P. Indelicato *et al.*, Rev. Sci. Instum. **77**, 043107 (2006)
[2] D.F. Anagnostopoulos *et al.*, Nucl. Instrum. Methods B **205**, 9 (2003)
[3] D.F. Anagnostopoulos *et al.*, Nucl. Instrum. Methods A **545**, 217 (2005)
[4] D.S. Covita, Ph.D. thesis University of Coimbra (2008)
[5] M. Theisen, Diplomarbeit thesis, University of Aachen (2013)
[6] D.E. Gotta *et al.*, Spectrochim. Acta, Part B **120**, 9 (2016)
[7] M.T., Ph.D. thesis Pierre et Marie Curie University (2005)

From the line position to the pion mass

From the spatial diff. to the angular position diff.

$$\Delta\Theta = -2\arctan\left(\frac{\Delta x}{2D}\right)$$



From the angular position diff. to the transition energy

$$E_{\pi N} = E_{\mu O}\frac{1}{\cos\Delta\Theta - \frac{\sqrt{1-[hc/(2dE_{\mu O})]^2}}{hc/(2dE_{\mu O})}\sin\Delta\Theta}$$

$$\frac{hc}{E} = 2d\sin\Theta_B$$

Bragg law

where

$$E_{\mu O} = f^{\text{QED}}_{\text{Dirac}}(m_\mu) = \tilde{m}_\mu c^2\frac{(Z\alpha)^2}{2}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) + \mathcal{O}^{\text{QED}}_{\text{Dirac}}(Z^4\alpha^4)$$

E(5g–4f πN) = 4055.397 ± 0.005 eV

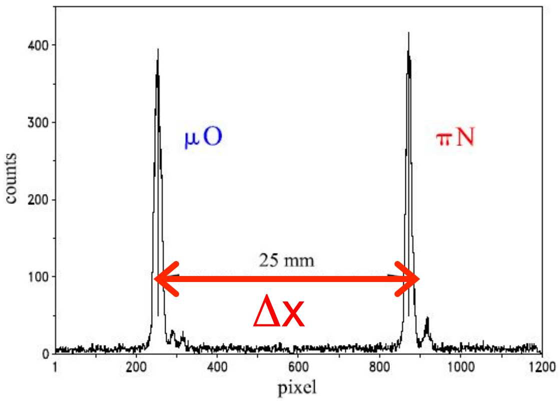
Crystal spacing, conversion constant,
QED calculation (for μO) [1-3], ...

[1] P. Indelicato, private comunication
[2] J. Desclaux et al., *Computational Approaches of Relativistic Models in Quantum Chemistry*, vol. 10, Elsevier, 2003.
[3] J. P. Santos et al., Phys. Rev. A 71 (2005) 032501

From the line position to the pion mass

From the spatial diff. to the angular position diff.

$$\Delta\Theta = -2\arctan\left(\frac{\Delta x}{2D}\right)$$



From the angular position diff. to the transition energy

$$E_{\pi N} = E_{\mu O}\frac{1}{\cos\Delta\Theta - \frac{\sqrt{1-[hc/(2dE_{\mu O})]^2}}{hc/(2dE_{\mu O})}\sin\Delta\Theta}$$

$$\frac{hc}{E} = 2d\sin\Theta_B$$

Bragg law

where

$$E_{\mu O} = f^{\mathrm{QED}}_{\mathrm{Dirac}}(m_\mu) = \tilde{m}_\mu c^2\frac{(Z\alpha)^2}{2}\left(\frac{1}{n_f^2}-\frac{1}{n_i^2}\right) + \mathcal{O}^{\mathrm{QED}}_{\mathrm{Dirac}}(Z^4\alpha^4)$$

From the transition energy to the **pion mass**

$$m_\pi = f^{-1}_{\substack{\mathrm{QED}\\ \mathrm{Klein\text{-}Gordon}}}(E_{\pi N})$$

QED calculation (for πN) [1], ...

[1] M. Trassinelli *et al.*, Phys. Rev. A **76**, 012510(2007)

πN transition energy calculations

The Klein-Gordon equation

$$\left(\frac{1}{c^2}[E + eV_0(r)]^2 + \hbar^2\nabla^2 - m^2c^2 - W(\mathbf{r})\right)\varphi(\mathbf{r}) = 0$$

$$E^{nl}_{(0)} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - l - 1/2 + \sqrt{(l+1/2)^2 - (Z\alpha)^2}\right]^2}}}$$

for Coulomb potential with point-like and infinite mass nucleus

5→4 πN QED transition energies details (in eV) [1]

	5g-4f	5f-4d
Coulomb	4054.1180	4054.7189
Finite size	0.0000	0.0000
Self-energy	−0.0001	−0.0003
Vacuum polarization (Uehling)	1.2485	2.9470
Vacuum polarization (Wichman-Kroll)	−0.0007	−0.0010
Vacuum polarization (loop after loop)	0.0008	0.0038
Vacuum polarization (Källén-Sabry)	0.0116	0.0225
Relativistic recoil	0.0028	0.0028
HFS shift	−0.0008	−0.0023
Total	4055.3801	4057.6914
Error	±0.0011	±0.0011

Strong interaction effects: 44 μeV 7 meV

[1] M. Trassinelli *et al.*, Phys. Rev. A **76**, 012510(2007)

List of systematic effects

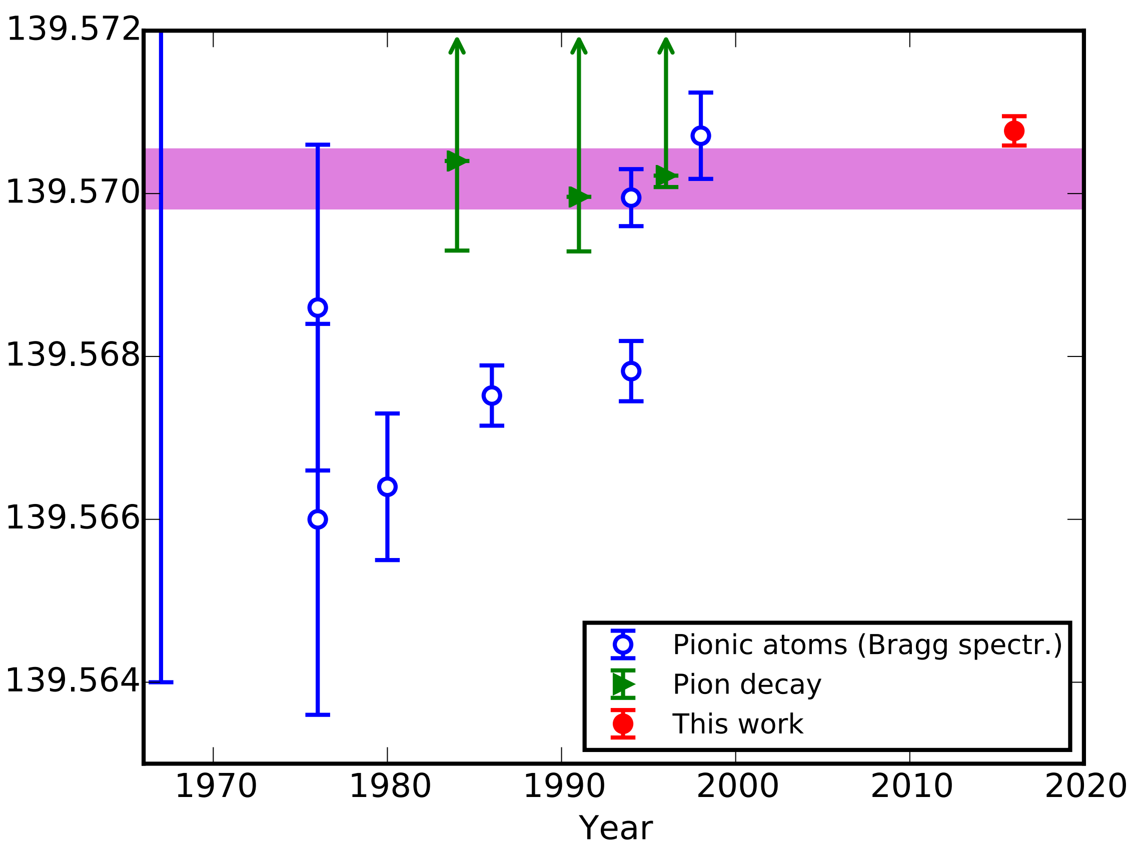
type of uncertainty	μO / arcsec	πN / arcsec	total / arcsec	uncertainty / ppb
index of refraction shift	13.22	12.94	- 0.28	± 20
silicon lattice constant				± 2
bending correction	14.01	13.71	0.30	± 20
penetration depth correction	-0.07	-0.07	0	± 4
focal length				± 670
CCD alignment				± 340
pixel distance				± 120
alignment of detector normal				$^{+0}_{-30}$
detector height offset				$^{+0}_{-35}$
shape of target window				± 100
shape of reflection				± 225
individual curvature correction				± 150
temperature correction				± 30
response function and Doppler broadening				$^{+290}_{-350}$
line pattern modelling				$^{+190}_{-290}$
fit interval				± 15
QED energy				± 350
conversion constant *hc*				± 2
$4f$ strong interaction 45 μeV		0.003	-0.003	± 10
$5g$ strong interaction 0.2 μeV		0.000	0.000	± 0
K electron screening				± 0
total systematic error				$^{+950}_{-1000}$
statistical error				± 820

Total uncertainty: $1.3\text{x}10^{-6}$

Statistical: $0.8\text{x}10^{-6}$

Systematics: $\sim 1\text{x}10^{-6}$

The new measurement of the pion mass



Particle data group [1]:
139.57018 ± 0.00035 MeV/c^2
→ **2.5x10^{-6}** accuracy

Our work [2]:
139.57077 ± 0.00018 MeV/c^2
→ **1.3x10^{-6}** accuracy

- No effect of eventual remaining K-shell electrons (<10^{-9})
- High accuracy calibration line (0.25x10^{-6} from theory calc.)

[1] Particle Data Group. Chinese Phys. C **38**, 090001 (2014)
[2] M. Trassinelli *et al.*, arXiv:1605.03300 (2016)

Additional results

Muonic neutrino mass

Pion decay measurement [1]

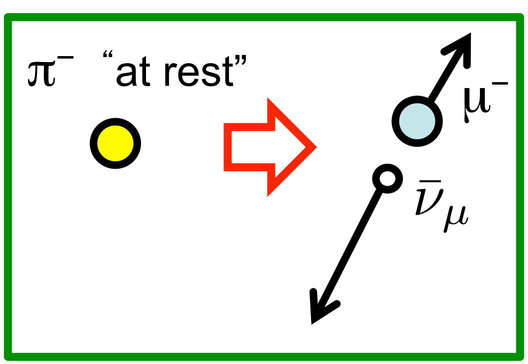
p_μ = 29.792006 ± 0.00011 MeV/c

Pion mass measurement [2]

m_π = 139.57077 ± 0.00018 MeV/c^2

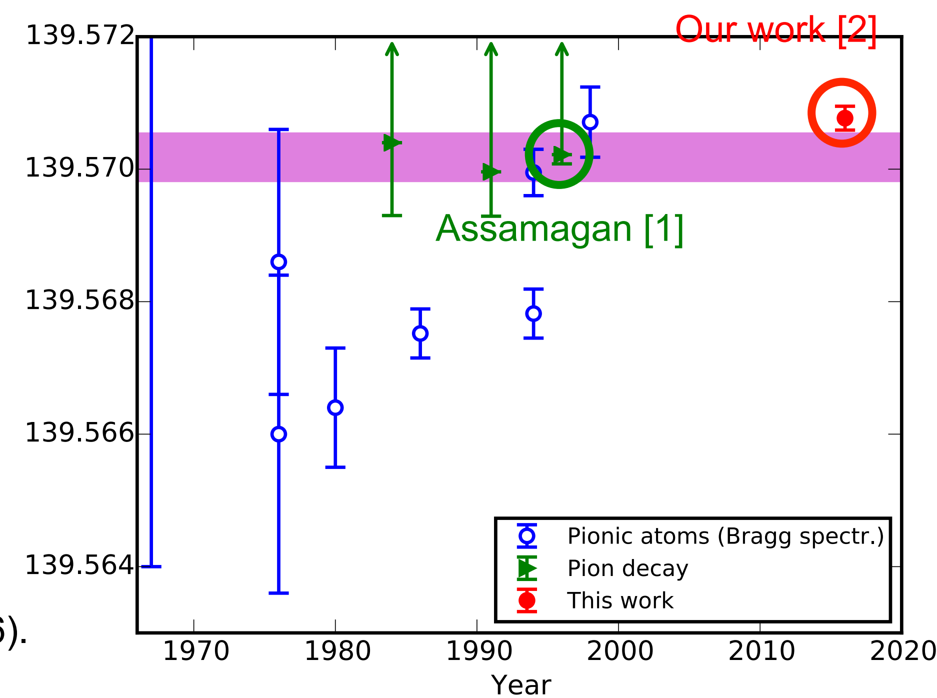
$$m_{\nu_\mu} \in [100, 244]\ keV/c^2$$ (90% c.l.)

in disagreement with astrophysical boundaries (WMAP and Planck) **<0.6–2.3 eV** and ^{3}H decay + ν oscillations



Measurement of **p_μ** (, m_μ)

→ pion mass **low boundary** if no assumptions on the neutrino mass are made



[1] K. Assamagan *et al.*, Phys. Rev. D **53**, 6065–6077 (1996).

[2] M. Trassinelli et al., arXiv:1605.03300, (2016)

Additional results

Muonic neutrino mass

Pion decay measurement
p_{μ} = 29.792006 ± 0.00011 MeV/c

Pion mass measurement
m_{π} = 139.57077 ± 0.00018 MeV/c^2

$$m_{\nu_\mu} \in [100, 244]\ keV/c^2$$ (90% c.l.)

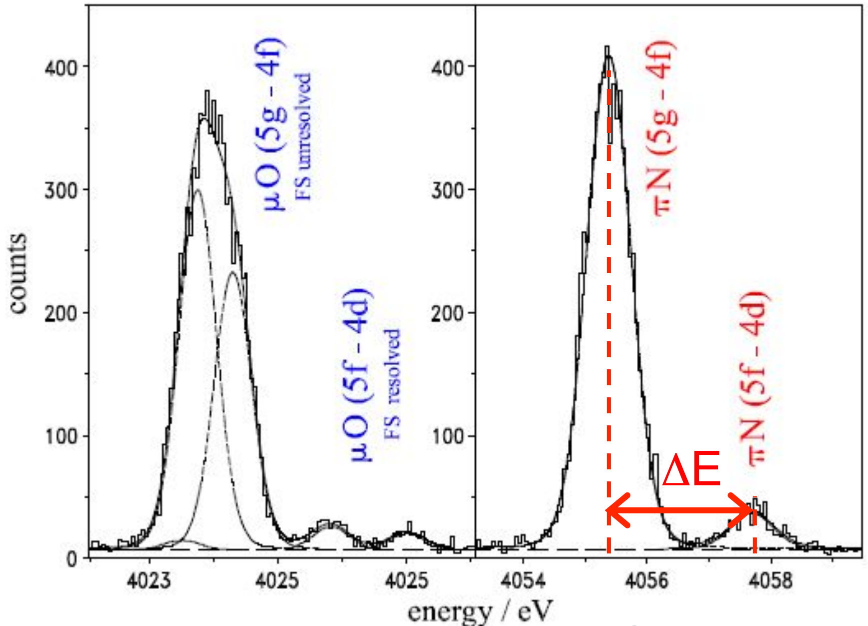
Klein-Gordon equation test

Relativistic quantum mechanic equation for spin-0 particles (+ QED corrections)

ΔE_{theory} = 2.318 ± 0.007 eV
error due to the strong int. corr.

ΔE_{exp} = 2.306 ± 0.015 eV 95% c.l.

0.4% accuracy test



Spin1/2
→ Dirac eq.

Spin 0
→ Klein-Gordon eq.

Additional results

Muonic neutrino mass

Pion decay measurement
p_μ = 29.792006 ± 0.00011 MeV/c

Pion mass measurement
m_π = 139.57077 ± 0.00018 MeV/c^2

⇒ $m_{\nu_\mu} \in [100, 244]\ keV/c^2$ (90% c.l.)

Klein-Gordon equation test

Relativistic quantum mechanic equation for spin-0 particles (+ QED corrections)

ΔE_{theory} = 2.318 ± 0.007 eV
error due to the strong int. corr.

0.4% accuracy test

ΔE_{exp} = 2.306 ± 0.015 eV 95% c.l.

X-ray standard from pionic atoms [1]

Accuracy of X-ray energies limited by the pion mass: good standard for the few keV regime [1]

[1] D.F. Anagnostopoulos *et al.*, Phys. Rev. Lett. **91**, 240801 (2003).

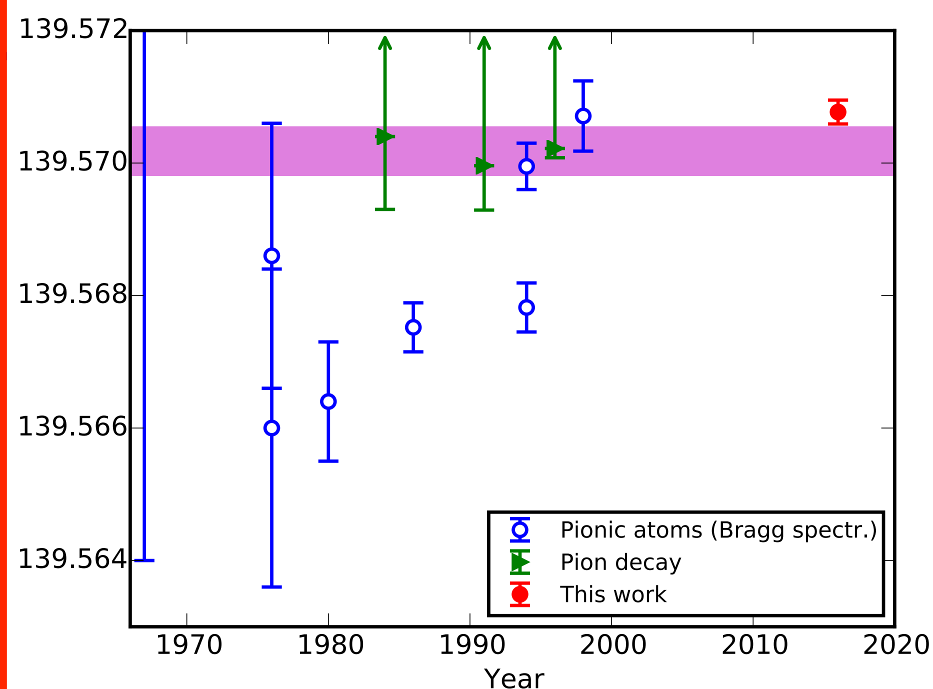
Conclusions

PSI proposal R-97-02

NEW PRECISION DETERMINATION OF THE CHARGED PION MASS

D. Anagnostopoulos[1], M. Augsburger[2], G. Borchert[1], D. Chatellard[2], M. Daum[3], J.-P. Egger[2], D. Gotta[1], P. Hauser[3], P. Indelicato[4], E. Jeannet[2], K. Kirch[3], O. W. B. Schult[1], Th. Siems[1], L. M. Simons[3]

Almost 20 year long story…



New measurement of the charged pion mass using X-ray spectroscopy exotic atoms

m_π = 139.57077 ± 0.00018 MeV/c^2

1.3x10^{-6} rel. accuracy,

PDG present acc. = 2.5x10^{-6}

- No remaining electron contamination
- High accuracy reference energy

M. Trassinelli et al., arXiv:1605.03300 (**2016**)

Thank you!

PION MASS collaboration

MESON 2016

Dept. of Material Science, University of Ioannina, Greece
D. F. Anagnostopoulos,

Forschungszentrum Jülich, IKP, JCHP, ZEL, Jülich, Germany
G. Borchert, **D. Gotta**, M. Hennebach,

Paul Scherrer Institut, Lab. for Part. Physics, Villigen, Switzerland
A. Dax, Y.-W. Liu, **L. M. Simons**

Institut de Physique de l'Univerisité de Neuchâtel, Switzerland
J.-P. Egger

Laboratoire Kastler-Brossel (LKB) UPMC ENS CNRS, Paris, France
B. Manil (PhD. in 2001), P. Indelicato,

Dept. of Physics and Astronomy, University of Leicester, England
N. Nelms (PhD. in 2002), A. Wells

Institute des NanoSciences de Paris, France
M.T. (PhD. in 2005 @ LKB)

Cascade theory

V. E. Markushin (PSI), Th. Jensen (ETHZ,PSI,LKB,FZJ,SMI), V. Pomerantsev, V. Popov (MSU)