Time-Modulation of Orbital Electron Capture Decays by Mixing of Massive Neutrinos

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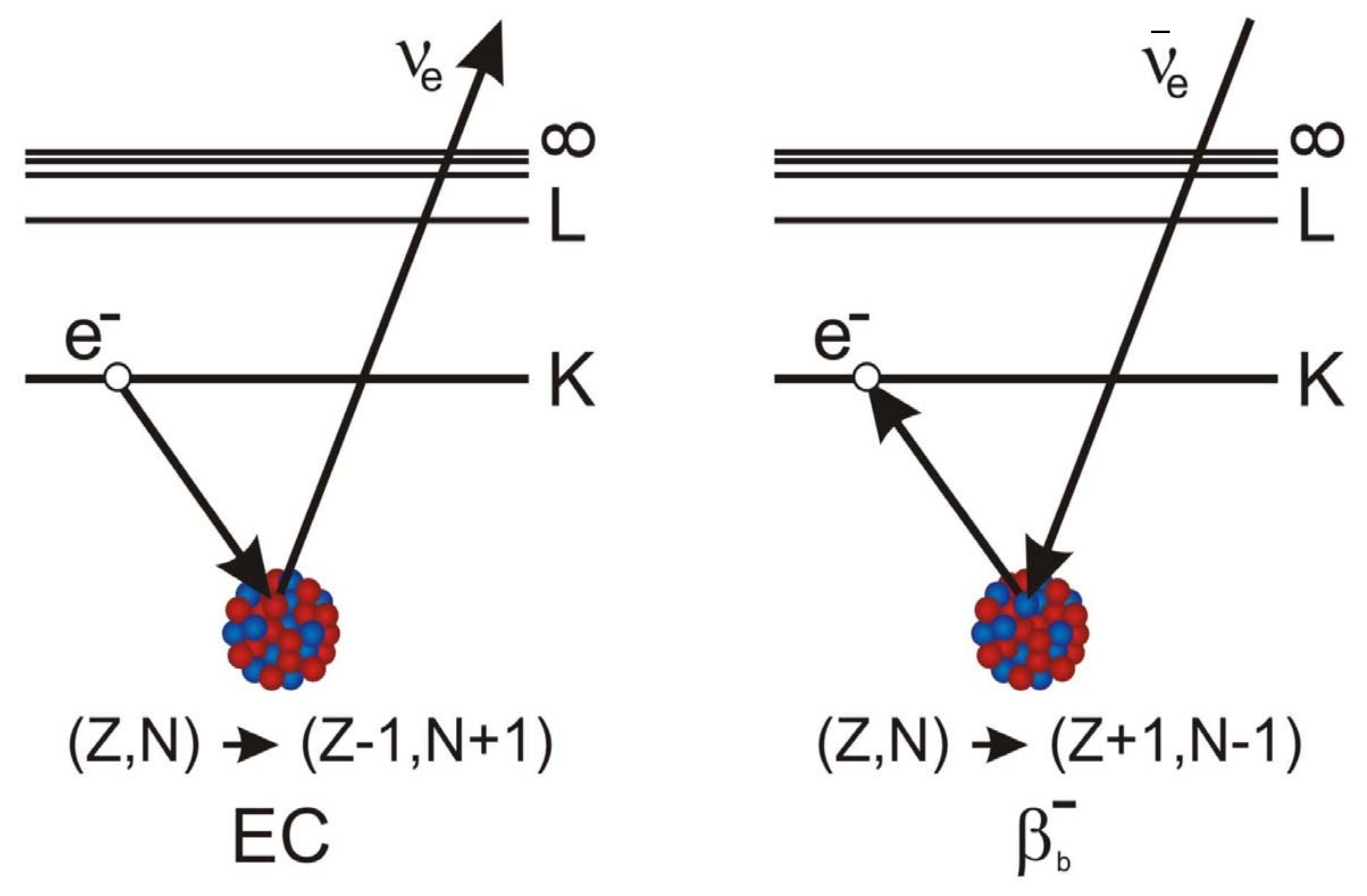
"In order to see something new, one has to do something new."

Georg Christoph Lichtenberg

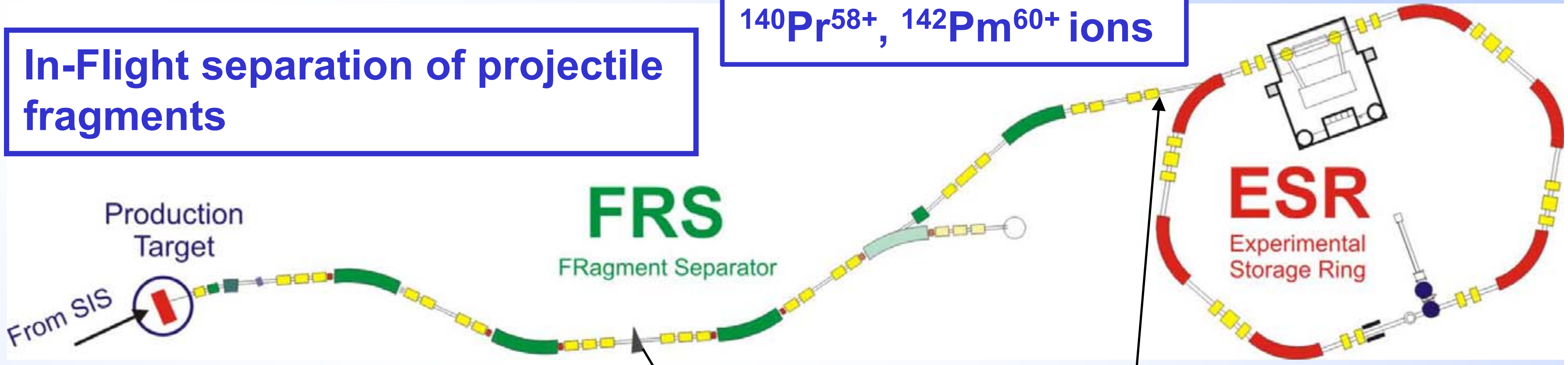
Study of 2-Body Weak EC and $ß_b$ Decays With a Pair of Entangled Lepton States and Mono-Energetic Neutrinos



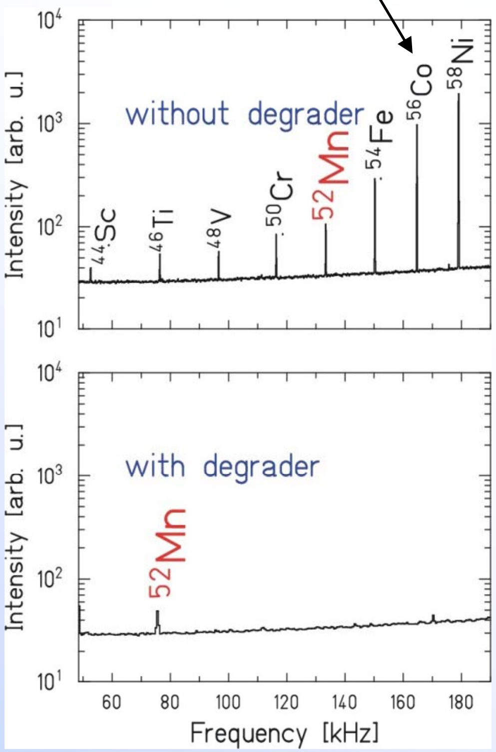
Production & Separation of H-like Nuclei

400MeV/u bunched $^{140}Pr^{58+}$, $^{142}Pm^{60+}$ ions

In-Flight separation of projectile fragments



1µs bunched 500 MeV/u ^{152}Sm beam

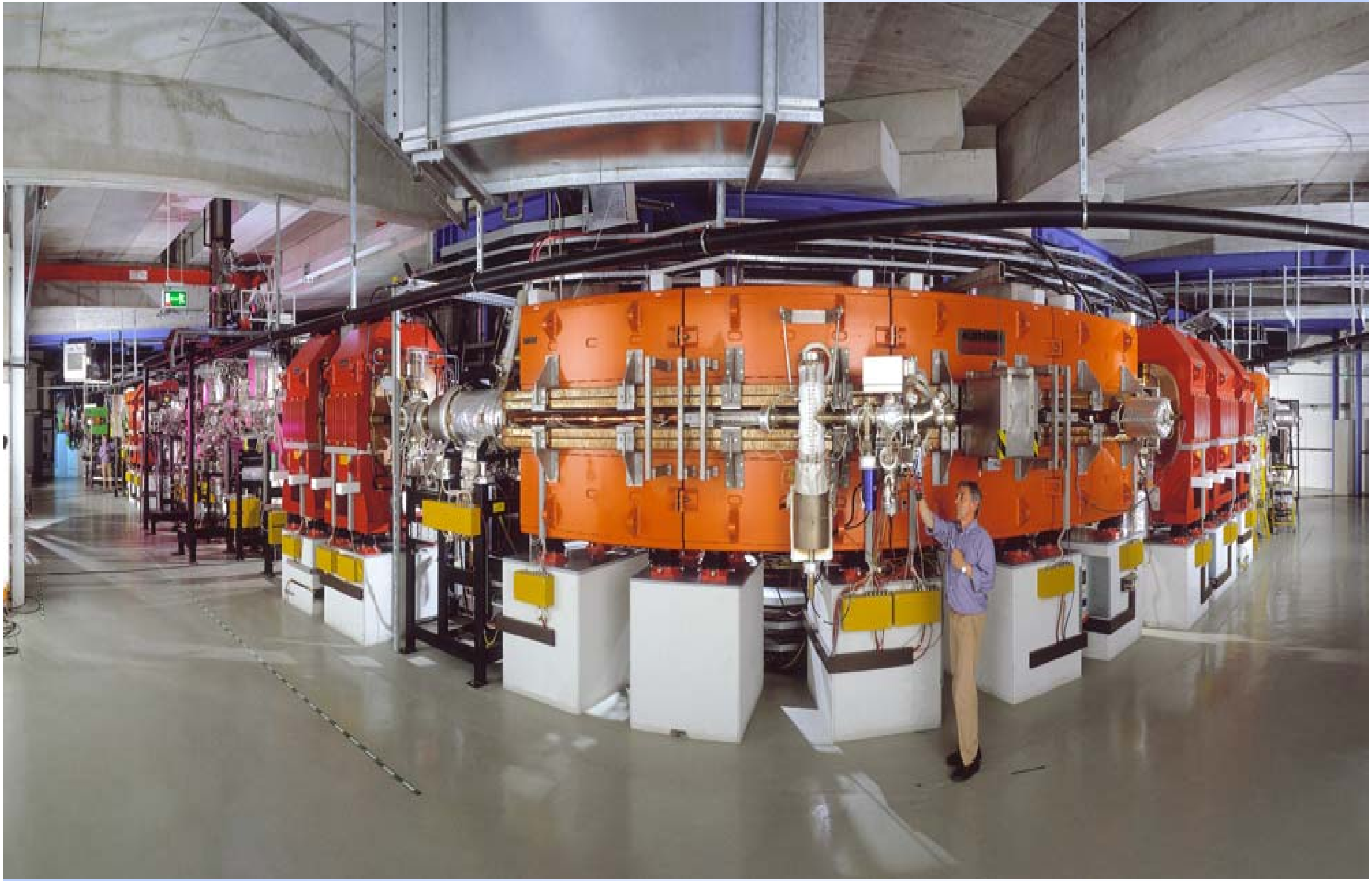


Cocktail of isotopic beams

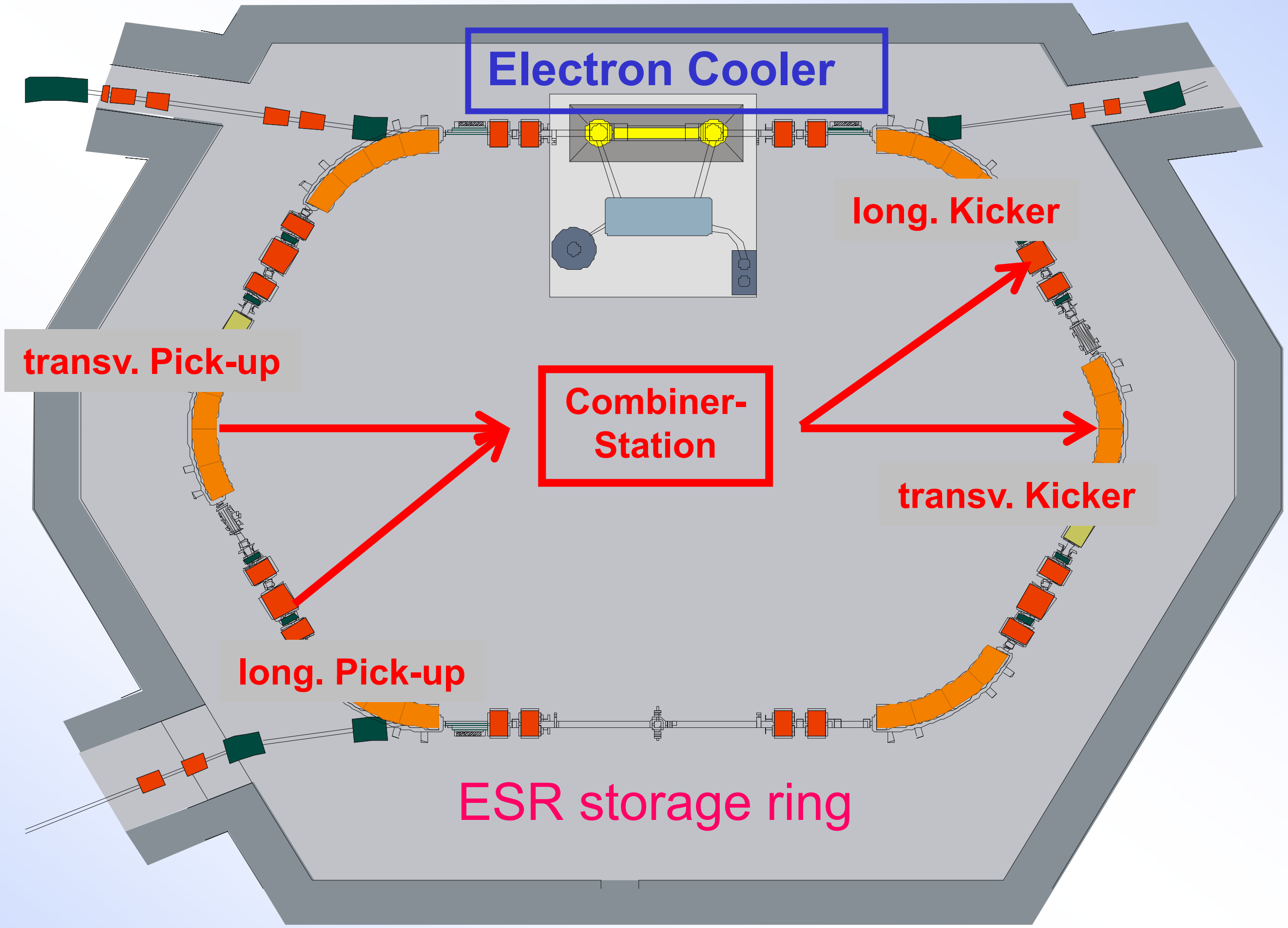
Mono-isotopic beam ->degrader (dE/dx~ Z²) followed by magnetic analysis

The Experimental Storage Ring ESR

in operation since 1990 at GSI Darmstadt

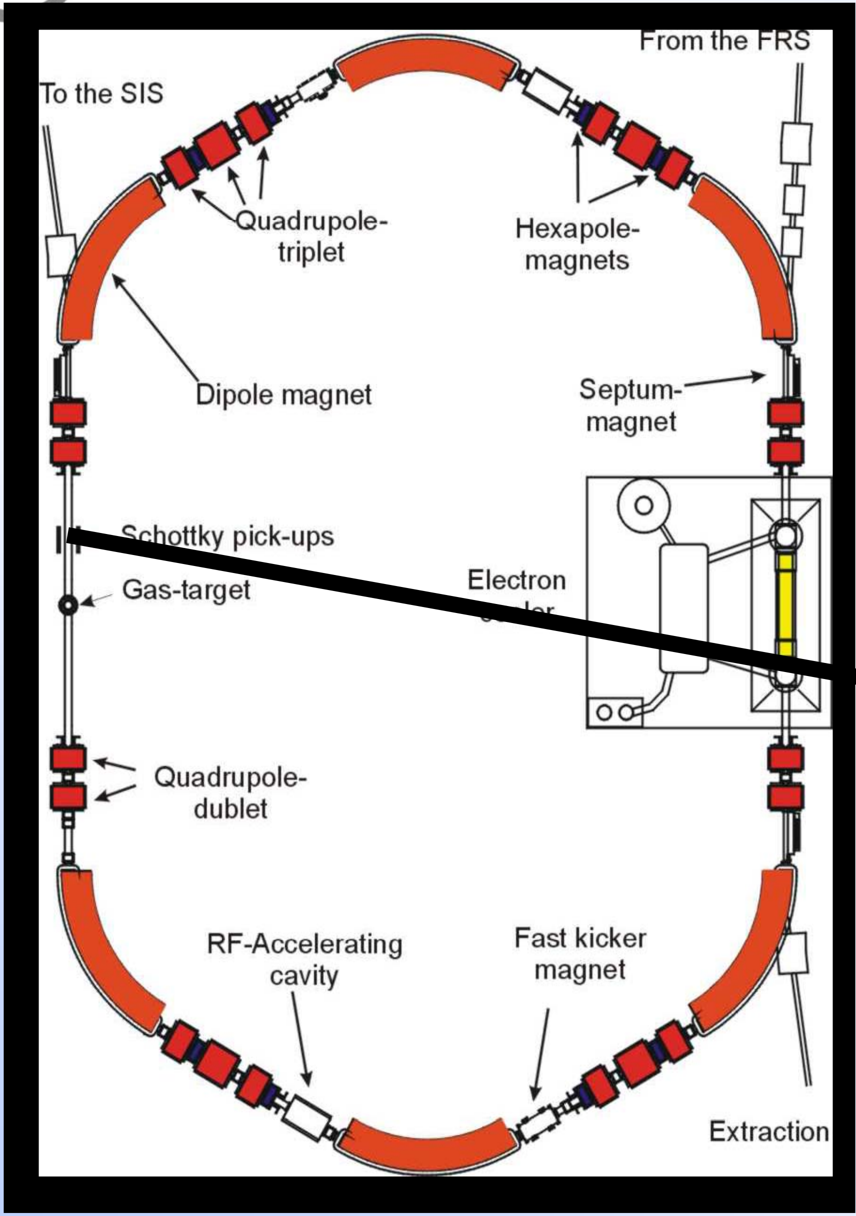


Stochastic and Electron Cooling in the ESR



Fast stochastic pre-cooling @ E= 400 MeV/u of few fragments followed by precision electron cooling

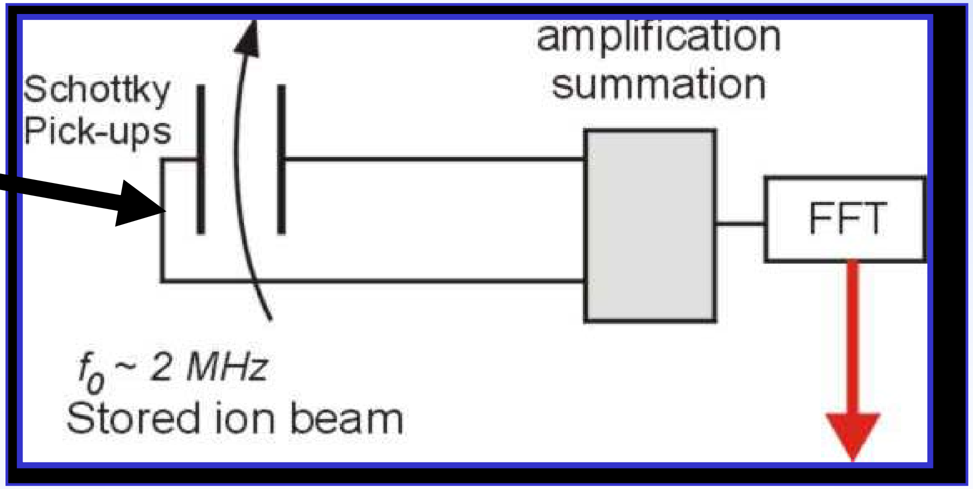
Schottky Mass Spectrometry (SMS)



Precision revolution frequency measurement for a precision observation of Δ(m/q) of a two-body EC or $ß_b$ decay

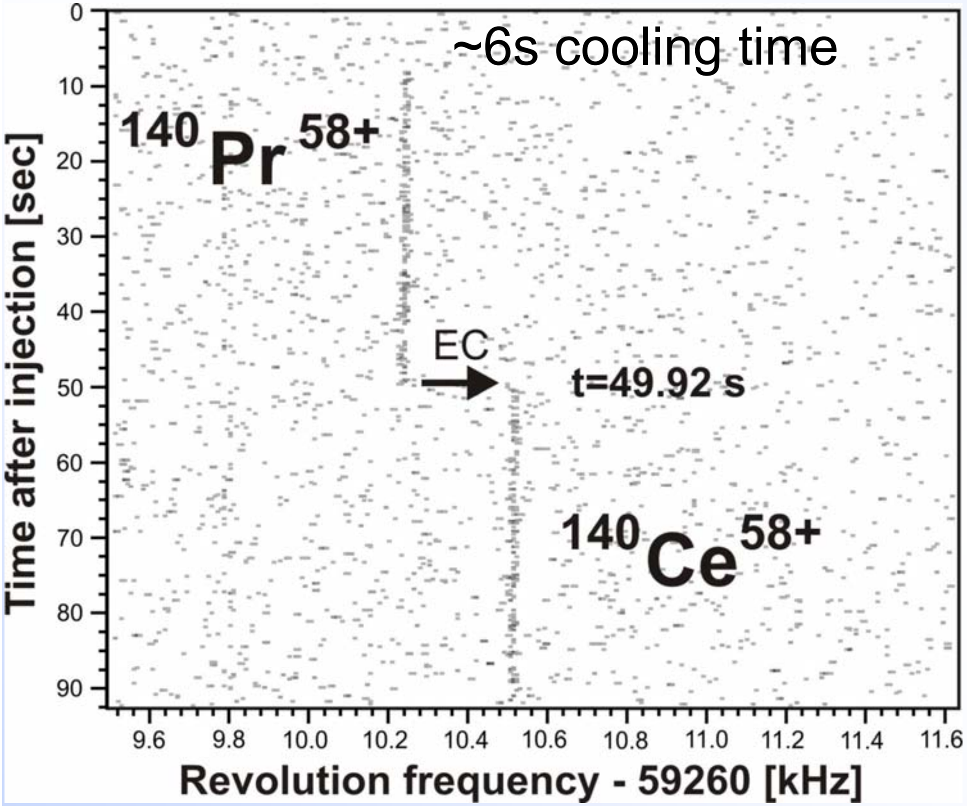
$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

By cooling $\frac{\Delta v}{v} \rightarrow 0$



Continuous Digitizing and storage of the FFT data

Single Ion, Time-Resolved EC-Decay Mass Spectroscopy



1. **Continuous observation**
2. **Parent/daughter correlation**
3. **Detection of all EC decays**
4. **Delay between decay and "appearance" →cooling**
5. **^{140}Pr: E_R = 44 eV**
   Delay: 900 (300) msec
   ^{142}Pm: E_R = 90 eV
   Delay: 1400 (400) msec

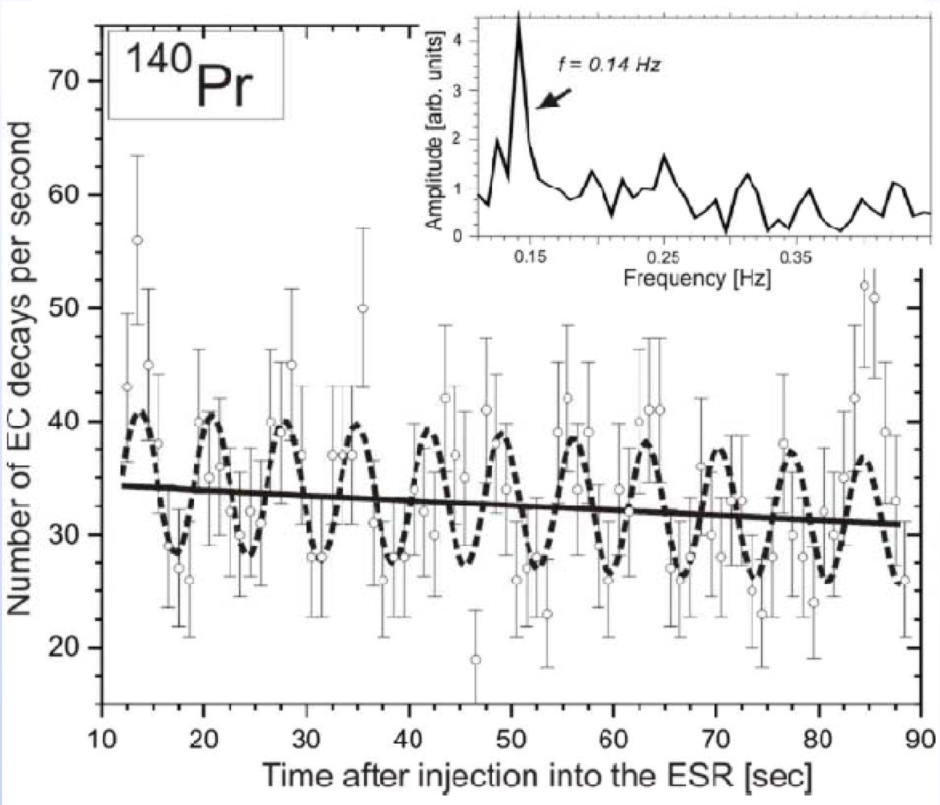
Electron neutrino ν_e is created at time t->**quantum-mechanically entangled** with daughter nucleus, **revealing all properties of ν_e**

Modulation of the $^{140}Pr^{58+}$ EC-Decay

Time differential observation τ_d < 1s corresponding δE >4x10^{-15}eV

Yu.A. Litvinov et al., Physics Letters B 664 (2008) 162

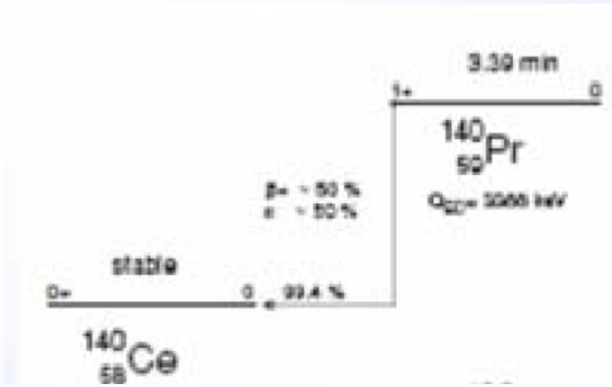
$$\frac{dN_{EC}(t)}{dt} = N(0) \cdot e^{-\lambda t} \cdot \widetilde{\lambda_{EC}}(t), \quad \widetilde{\lambda_{EC}}(t) = \lambda_{EC} \cdot [1 + a \cdot cos(\omega t + \phi)]$$



T= (7.06± 0.08)s

ΔE= 8.6x10^{-16} eV

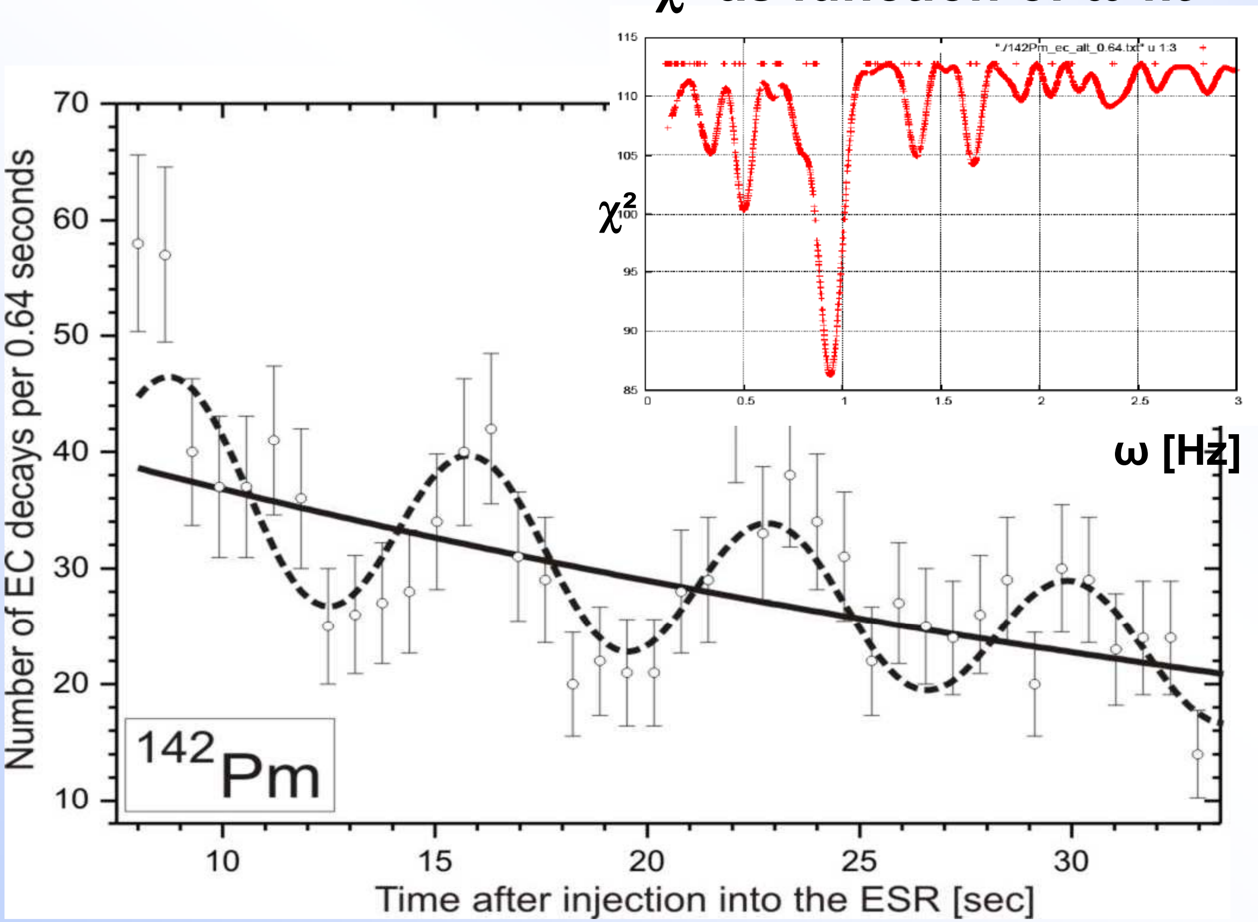
a= (0.18± 0.03)



Modulation of the $^{142}Pm^{60+}$ EC-Decay

Yu.A. Litvinov et al., Physics Letters B 664 (2008) 162

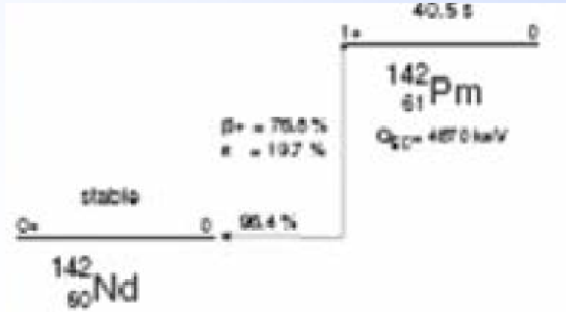
χ^2 as function of ω fit



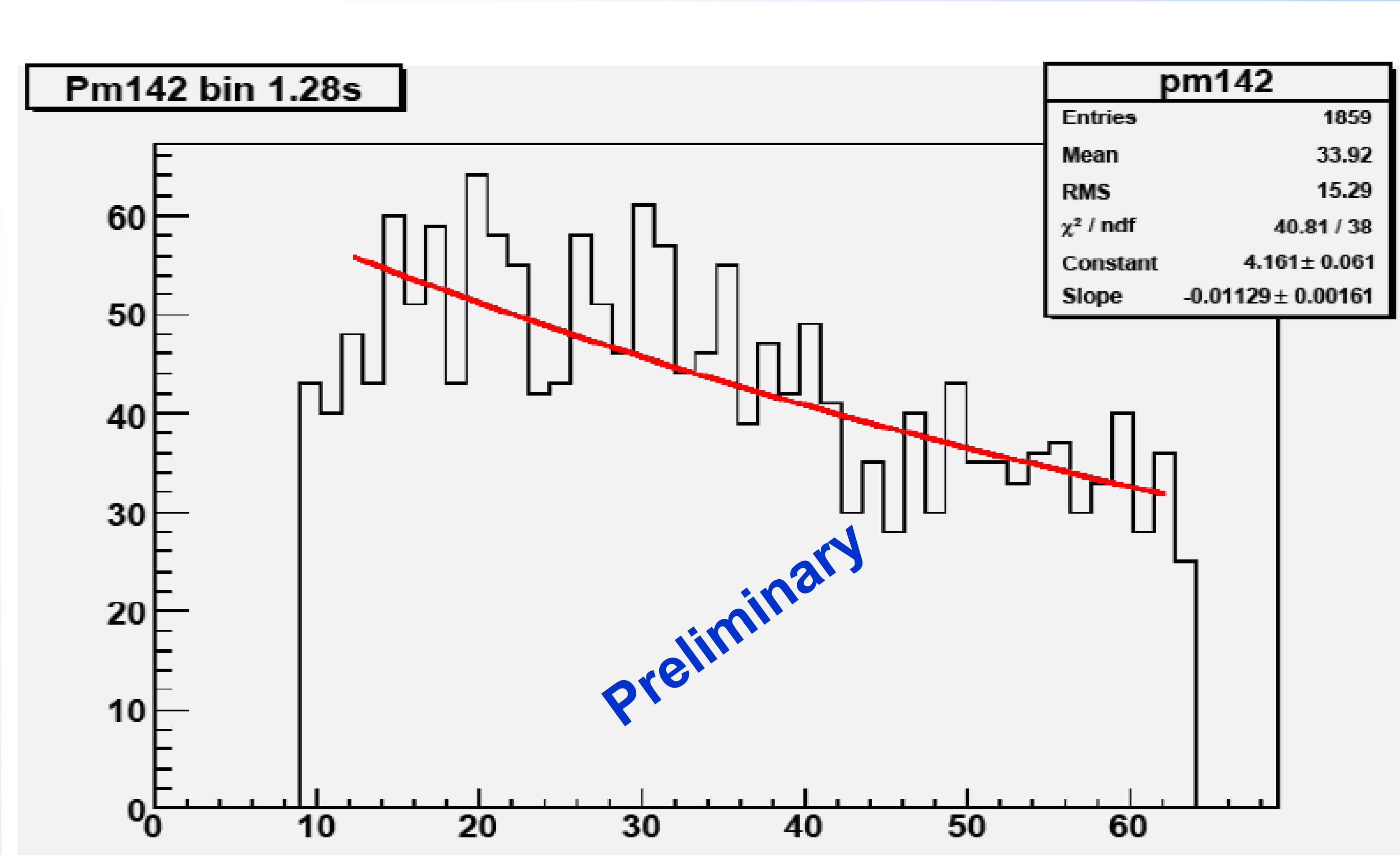
T= (7.10 ± 0.22)s

ΔE= 8.6x10^{-16} eV

a= (0.22 ± 0.03)



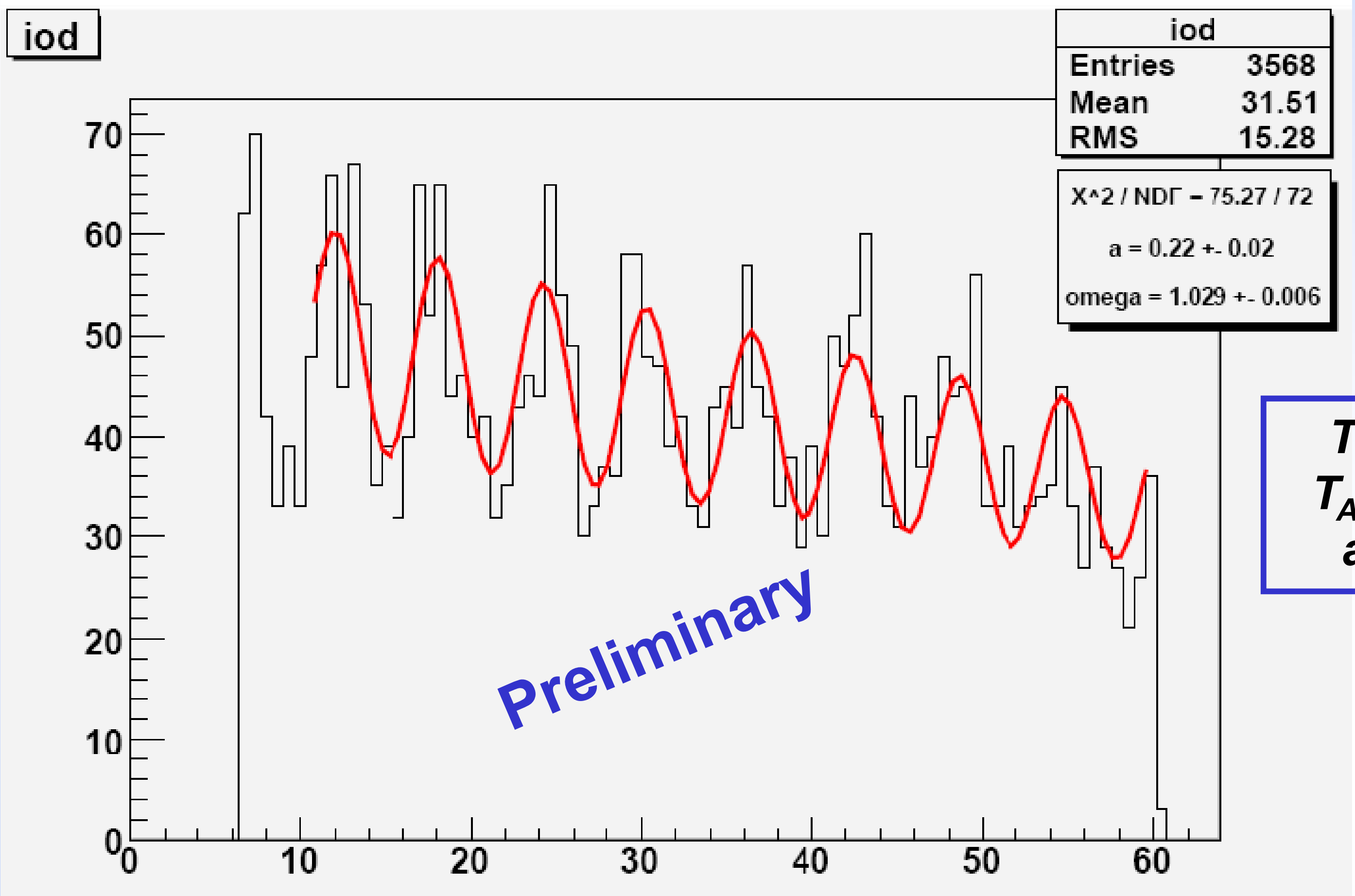
Decay Spectrum of ß$^+$ Branch of ^{142}Pm



The ß+ branch shows no modulation $a_{ß+}$= 0.03(3) ,
as predicted by Ivanov et al, PRL 101, 18250 (2008) for 3-body decay

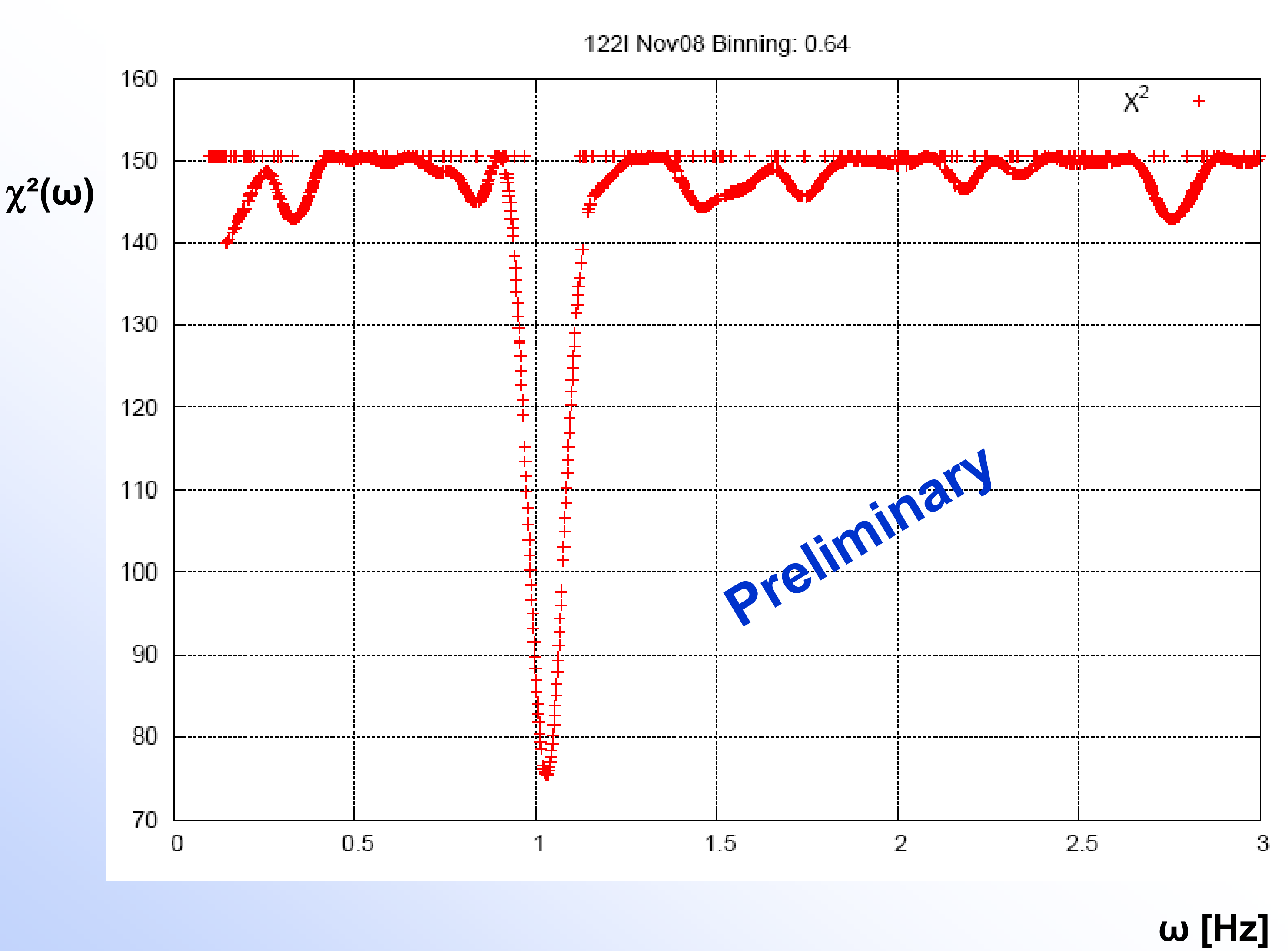
Modulation of $^{122}I^{54+}$ EC Decay

Test of *A(Z)*-scaling of modulation period *T*



T= 6.11(3) s
T_A = 6.14(6) s
a = 0.21(2)

$\chi^2(\omega)$ for the $^{122}I^{54+}$ EC Decay



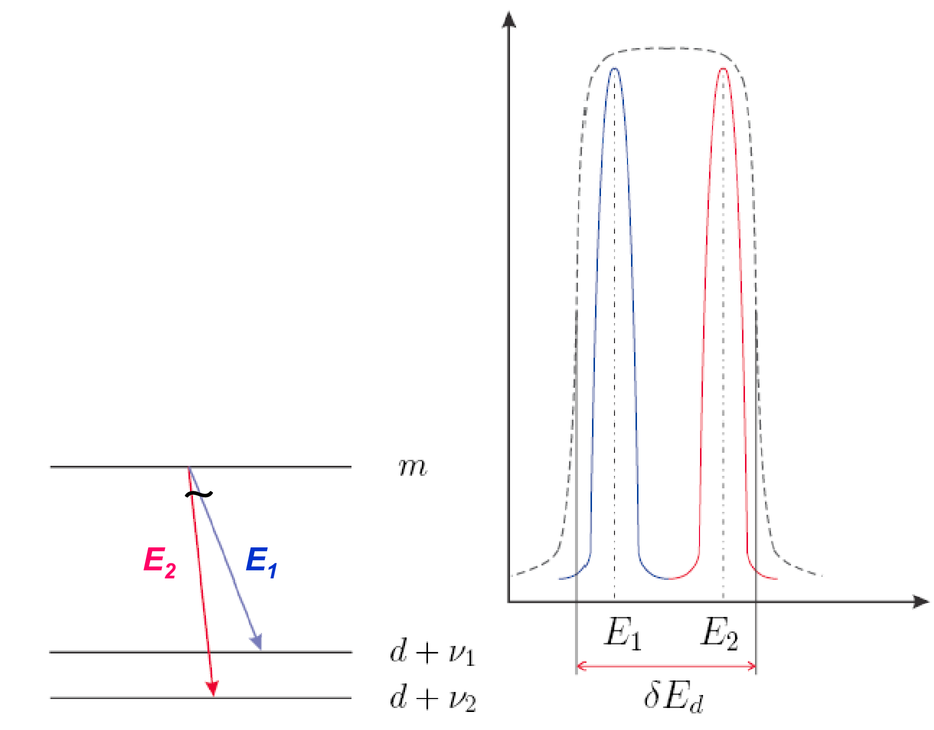
Towards Understanding the EC Decay Time Modulation

- The **3-body ß$^+$ decay** branch of ^{142}Pm shows **no modulation** in contrast to the **two-body EC branch** simultaneously measured
- This **excludes** various **experimental sources** and **quantum beats of the mother state** (Giunti, Lindner et al.)
- **Quantum beats** with massive neutrinos are only expected from a two-body final state (Ivanov et al, PRL 101, 18250 (2008)

Neutrino Quantum Beats (Schematic)

The mass eigenstates of the neutrino with different energies and momenta develop phase differences as function of time t between creation and decay, $\Delta\Phi = (E_2 - E_1)t$, which leads to the modulation of the decay probability (Quantum Beats)

Two decay paths from |*m*>->|*d*> with $\nu_1(E_1)$ and $\nu_2(E_2)$; not split mother state |m> (Giunti, Lindner et al.)



Observation of interference

if uncertainty δE_d by short τ_d

is larger than $(E_2 - E_1)$

$\delta E_d > (E_2 - E_1)$

$\delta E_d > 4\mathrm{x}10^{-15}$ eV for

$\tau_d < 1$s

$E_2 - E_1 = 0.86\mathrm{x}10^{-15}$ eV for T= 7s

$\Delta m_{21} = 2.22\mathrm{x}10^{-4}$ eV²

On the time–modulation of the K–shell electron capture decay of H-like $^{140}Pr^{58+}$ ions produced by neutrino mass differences

A. N. Ivanov [a*], R. Reda[b], P. Kienle[b,c†], nucl-th/ 0801.2121 v5 and PLB

Weak interaction with **mixed neutrino wave functions $U_{ej}\psi_{\nu j}$** with masses m_1,m_2, m_3

$$U_{e1} = \cos\vartheta_{12}\cos\vartheta_{13} \quad U_{e2} = \sin\vartheta_{12}\cos\vartheta_{13} \quad U_{e3} = \sin\vartheta_{13}\, e^{-i\delta_{CP}}$$

The transition matrix element is taken as **coherent sum** of the amplitudes to the states $I_f + \nu_j$ given by the expression

$$M(I_i \to I_f + \nu)(t) = \sum_j M(I_i \to I_f + \nu_j) = \sum_j U_{ej}\mathcal{M}_j(t)$$

Time Modulated Decay Constant with Two Frequencies ω_{21} and Ω_{21}

$$\frac{\lambda_{EC}^{(\mathrm{H})}(t)}{\lambda_{EC}^{(\mathrm{H})}} = 1 + a_{EC}\cos(\omega_{21}t) + \tilde{a}_{EC}\cos(\Omega_{21}t)$$

$$\lambda_{EC}^{(\mathrm{H})} = \frac{1}{2F+1}\,\frac{3}{2}|\mathcal{M}_{\mathrm{GT}}|^2|\langle\psi_{1s}^{(Z)}\rangle|^2\frac{Q_{\mathrm{H}}^2}{\pi},$$

Energy conservation:

$$\omega_{21} = \Delta m_{21}^2/2M_m$$

Momentum conservation:

$$\Omega_{21} = \Delta m_{21}^2/2Q_{\mathrm{H}}$$

$$a_{EC} = p\sin 2\vartheta_{12}\ ,\ \tilde{a}_{EC} = (1-p)\sin 2\vartheta_{12}.$$

Neutrino Mass Differences from Interfering Recoil Ions

H. Kleinert and P. Kienle (submitted to PRL)

- Difference of recoil energies of ions by massive neutrinos (m_1, m_2): $\Delta\omega = \Delta m^2/2M$ -energy conservation
- Difference of recoil energies of ions by massive neutrinos (m_1, m_2): $\Delta\omega = \Delta m^2/2Q$ –equal momenta
- The outgoing non-relativistic ions (T~40-100 eV) can be described by a superposition of spherical waves with energies and momenta (ω_1,k_1) and (ω_2,k_2)
- The radial current density of the recoil ions is:

$$j_r = \frac{g^2}{M_H r^2}\left[\cos^2\theta\, k_1 + \sin^2\theta\, k_2 + \sin\theta\cos\theta\,(k_1+k_2)\cos(\Delta k\, r - \Delta\omega\, t)\right]$$

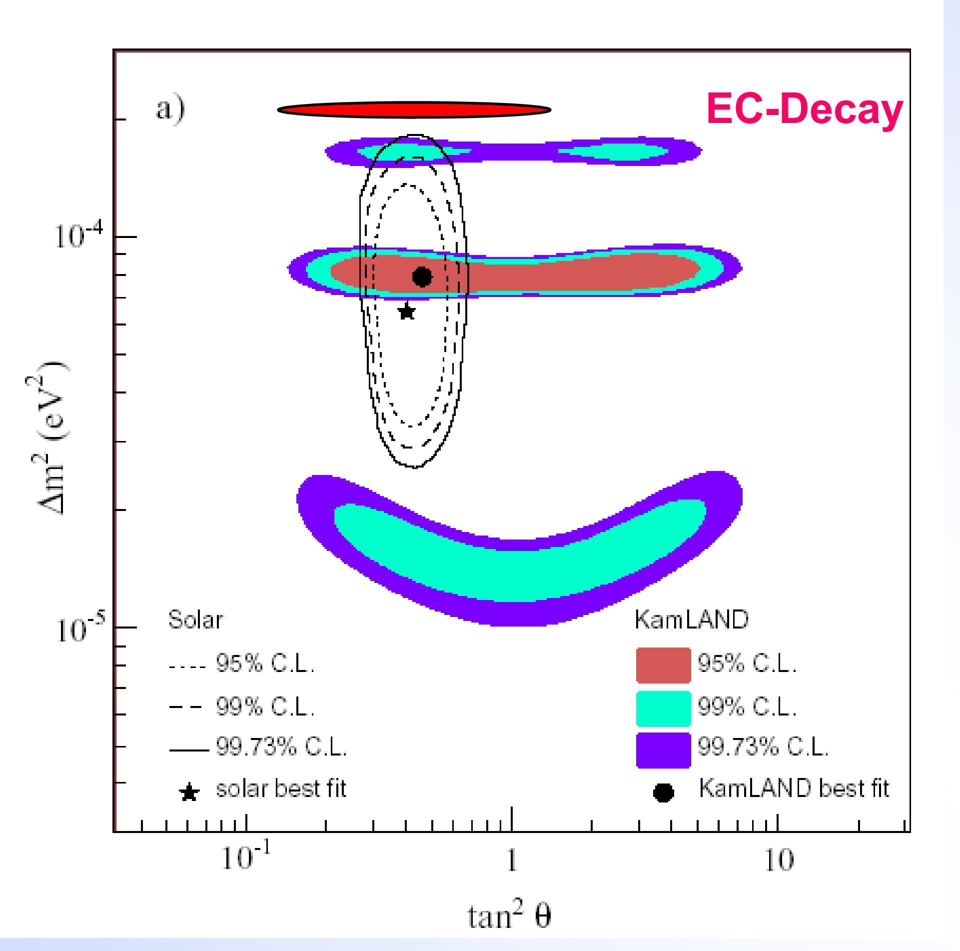
- Probability density of the outgoing ions shows beats:

$$\dot{P} = 4\pi g^2 \frac{\bar{k}}{M}\left[1 + \sin(2\theta)\cos(\Delta\omega\, t)\right]$$

Δm^2_{21} and θ_{21} from the Modulation Period T and the Amplitude a

- The modulation period of ^{140}Pr is T= 7.06(8) s and of ^{142}Pm T= 7.10(22) s with γ= 1.43 give Δm^2_{21}= 2.22(3)x10^{-4} eV²
- The agreement of T for both systems with *different Q* values and life times indicates M_m scaling of the period T as expected by theory. Confirmed by T= 6.11(3)s for ^{122}I decay (preliminary). So the low ω solution is observed experimentally.
- It is by a factor 2.75 larger than the value Δm^2_{21}= o.80(6)x10^{-4} eV² from KamLAND data
- With a modulation amplitude of a=0.20(2) from the ^{140}Pr, ^{142} Pm, and ^{122}I decay assuming p~ 0.2 , one gets the neutrino mixing angle comparable to the combined KamLAND and sun neutrino results

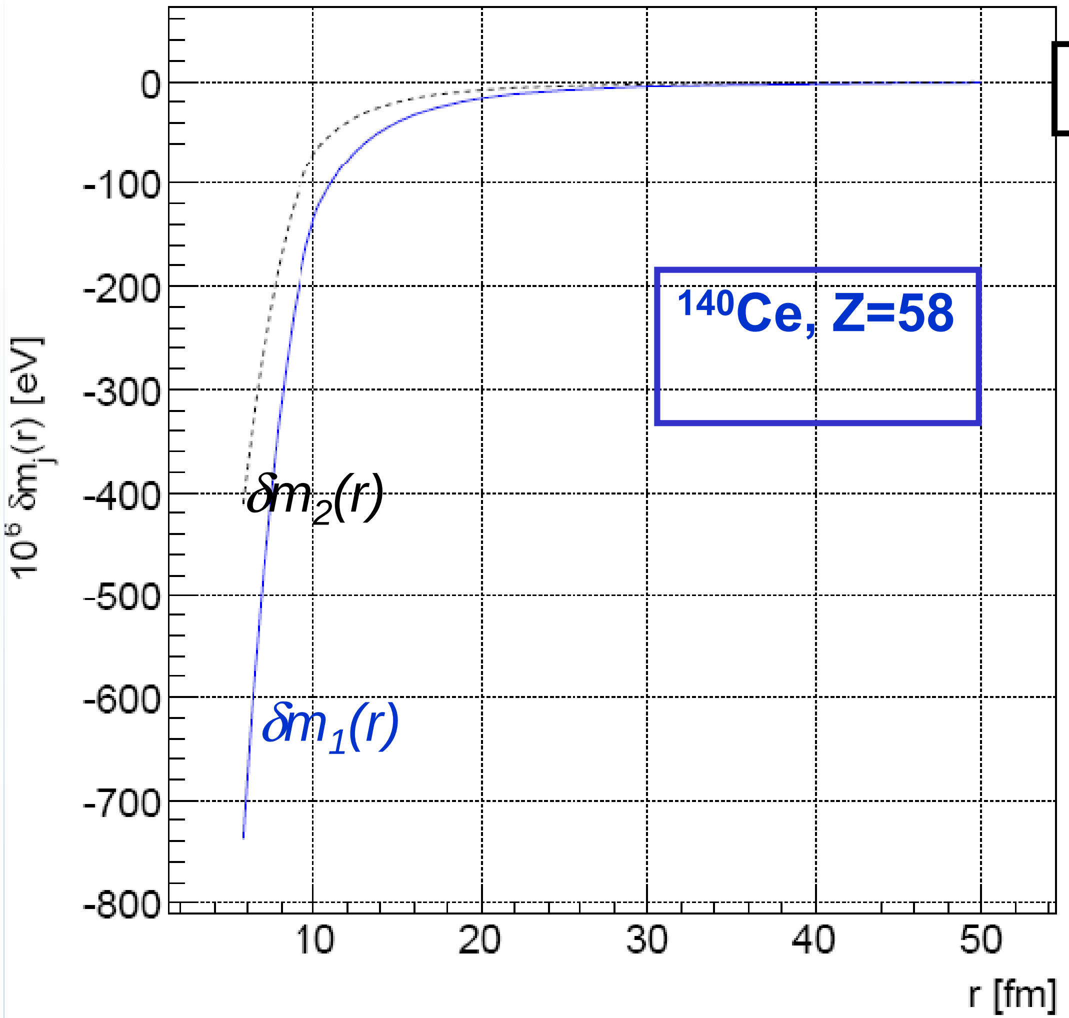
Solar, KamLAND, EC Results on Δm^2-$\tan^2\theta$



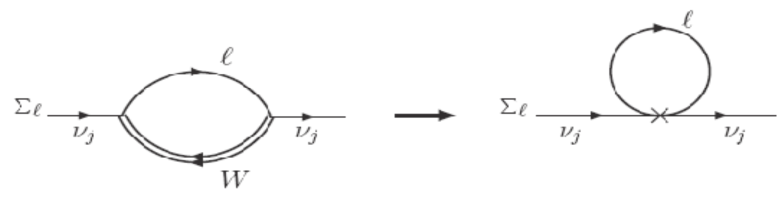
Neutrino Mass from Darmstadt Oscillations

A.N. Ivanov, E.L. Kryshen, M. Pitschmann and P.Kienle

(arXiv:0804.1311)



Vacuum polarisation by L-W loop



$$\delta m_1(R) = -7.37 \times 10^{-4}\,\mathrm{eV},$$
$$\delta m_2(R) = -4.11 \times 10^{-4}\,\mathrm{eV}.$$

The period of modulation is thus redefined as

$$T_d = \frac{4\pi\gamma M_d}{(m_2 + \delta m_2(R))^2 - (m_1 + \delta m_1(R))^2}. \quad (10)$$

$$\delta m_2^2(R) - \delta m_1^2(R) = (\Delta m_{21}^2)_{\mathrm{GSI}} - (\Delta m_{21}^2)_{\mathrm{exp}}, \quad (11)$$

Question: $(\Delta m^2_{21})_{exp}$?

Conclusion

- We have developed an **efficient, new method** for the study of **neutrino properties** by making use of **lepton entanglement** in **two body weak decays**, thus avoiding the inefficient direct detection of the neutrinos. The recoil ions show the neutrino interference pattern.
- **Time modulation** of EC decays of H- like ions of **^{140}Pr, ^{142}Pm and ^{122}I** (preliminary) were observed in the ESR storage ring, and **no modulation** of the **ß$^{+}$ branch of ^{142}Pm**.
- Using time dependent perturbation theory with wave functions of **massive neutrinos**, their properties, such as **mass, mixing, and vacuum polarisation** are tentatively derived. The interference pattern of the recoils shows the entanglement with massive neutrinos

Modulation of EC Decays (SMS) - Collaboration

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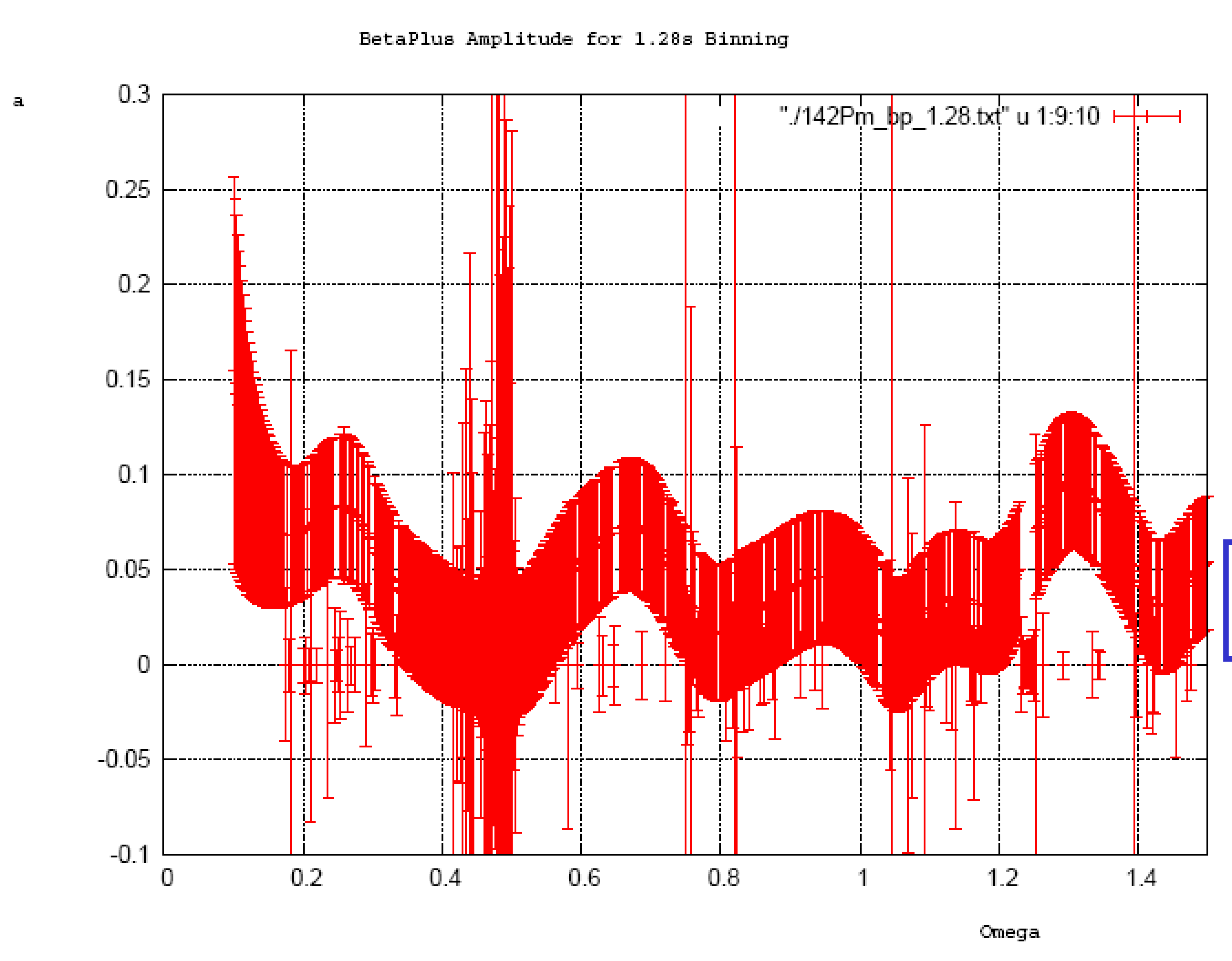
S. Williams, M. Winkler, N. Winckler, H. Wollnik, T. Yamaguchi

Thank you !

Amplitude of ß+ Modulation a(ω) for ^{142}Pm



a(ω=0.9)= 0.03±0.03