Klaus Jungmann
RAL, January 2005
Fundamental Interactions

Fundamental Symmetries and Interactions

Beta Beam Workshop

Rutherford Appleton Laboratory,17-18 of January, 2005

- **Forces and Symmetries**
- **Fundamental Fermions**
- **Discrete Symmetries**
- **Properties of Known Basic Interactions**

⇒ only touching a few examples

Klaus Jungmann, Kernfysisch Versneller Instituut,Groningen

Recommendations of NuPECC working group 2003

Physics Topics

- The Nature of Neutrinos
  - Oscillations / Masses / $0\nu2\beta$-decay
- T and CP Violation
  - edm's, D (R) coeff. in β-decays, D^0
- Rare and Forbidden Decays
  - $0\nu2\beta$-decay, n-n^{bar}, M-M^{bar}, $\mu\rightarrow e\gamma$,
  - $\mu \rightarrow 3e$, μ N$\rightarrow$ N e
- Correlations in β-decay
  - non V-A in β-decay
- Unitarity of CKM-Matrix
  - n-, π-β, (superallowed β), K-decays
- Parity Nonconservation in Atoms
  - Cs, Fr, Ra, Ba^+, Ra^+
- CPT Conservation
  - n, e, p, μ
- Precision Studies within The Standard Model
  - Constants, QCD,QED, Nuclear Structure

Adequate Environment

Human resources

- Theoretical Support
- Positions at Universities
  - Experimentalists and Theorists

Facilities

- High Power Proton Driver
  - Several MW
  - Target Research
- Cold and Ultracold Neutrons
- Low Energy Radioactive Beams
- Improved Trapping Facilities
- Underground Facilities

Recommendations
Relating to a MW Proton Machine

Physics Topics

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What are we concerned with ?

fundamental := " forming a foundation or basis a principle, law etc. serving as a basis"

Standard Model

- **3 Fundamental Forces**
  - **Electromagnetic Weak Strong**
- **12 Fundamental Fermions**
  - **Quarks, Leptons**
- **13 Gauge Bosons**
  - **γ, W^+, W^-, Z^0, H, 8 Gluons**

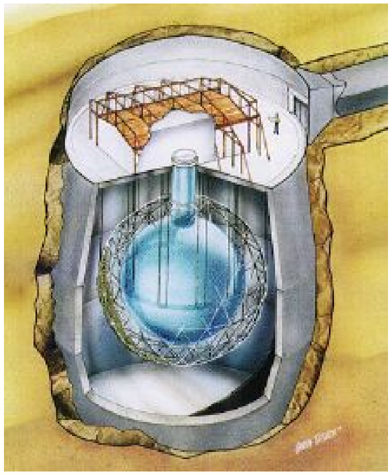
However

- **many open questions**
  - **Why 3 generations ?**
  - **Why some 30 Parameters?**
  - **Why CP violation ?**
  - **Why us?**
  - **…..**
- **Gravity not included**
- **No Combind Theory of Gravity and Quantum Mechanics**

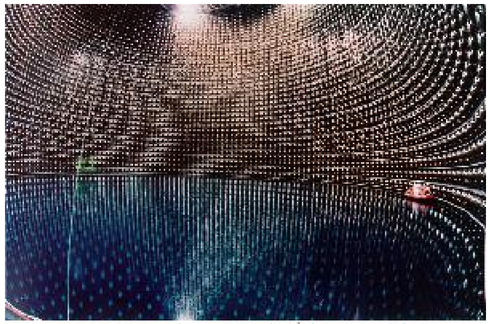
Fundamental Fermions

- **Neutrinos**
  - **Neutrino Oscillations**
  - **Neutrino Masses**
- **Quarks**
  - **Unitarity of CKM Matrix**
- **Rare decays**
  - **Baryon Number**
  - **Lepton Number/Lepton Flavour**
- **New Interactions in Nuclear and Muon β-Decay**

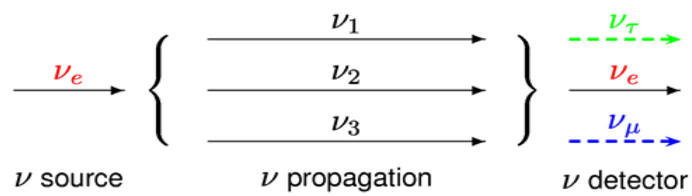
Neutrino-Experiments



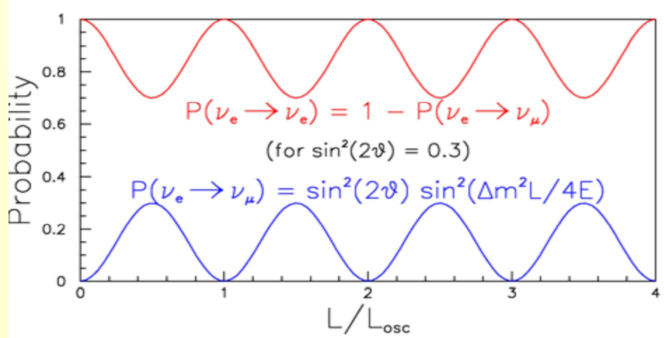
SNO



Superkamiokande



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\Theta) * \sin^2\left(\frac{\Delta m_{ij}^2 * L}{4E}\right)$$



Recent observations could be explained by oscillations of massive neutrinos.

Many Remaining Problems

- **really oscillations ?**
- **sensitive to Δm^2**
- **Masses of Neutrino**
- **Nature of Neutrino**
  - **Dirac**
  - **Majorana**

  → Neutrinoless Double β-Decay
- **Direct Mass Measurements are indicated**

  → Spectrometer
- **Long Baseline Experiments**

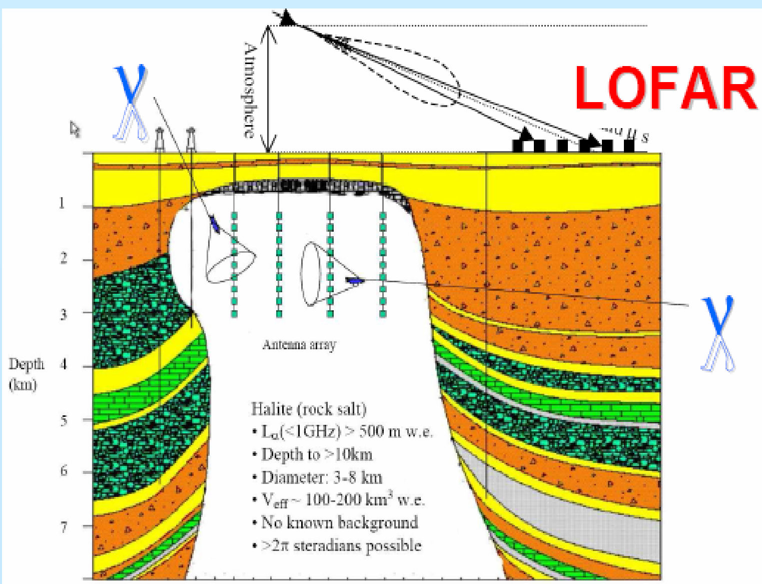
  → β-beams

  → new neutrino detectors ?

Neutrino-Experiments
Are there new detection schemes ?

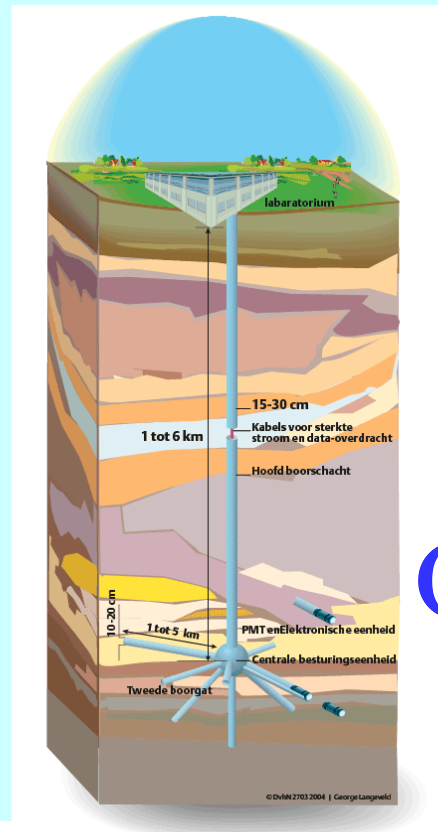
- **Water Cherenkov**
- **Scintillators**
- **Liquid Argon**
- **. . .**

- **Air shower ?**
- **Salt Domes ?**



Only for Non-Accelerator Neutrinos ?

- **Directional sensitivity for low energies ?**



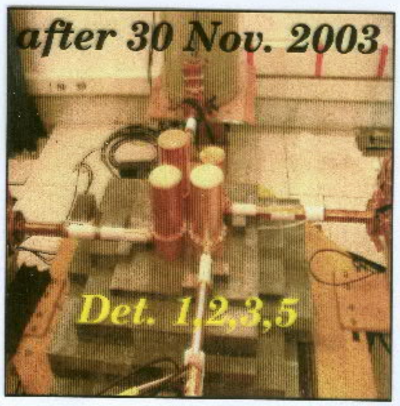
Θ_{13}?

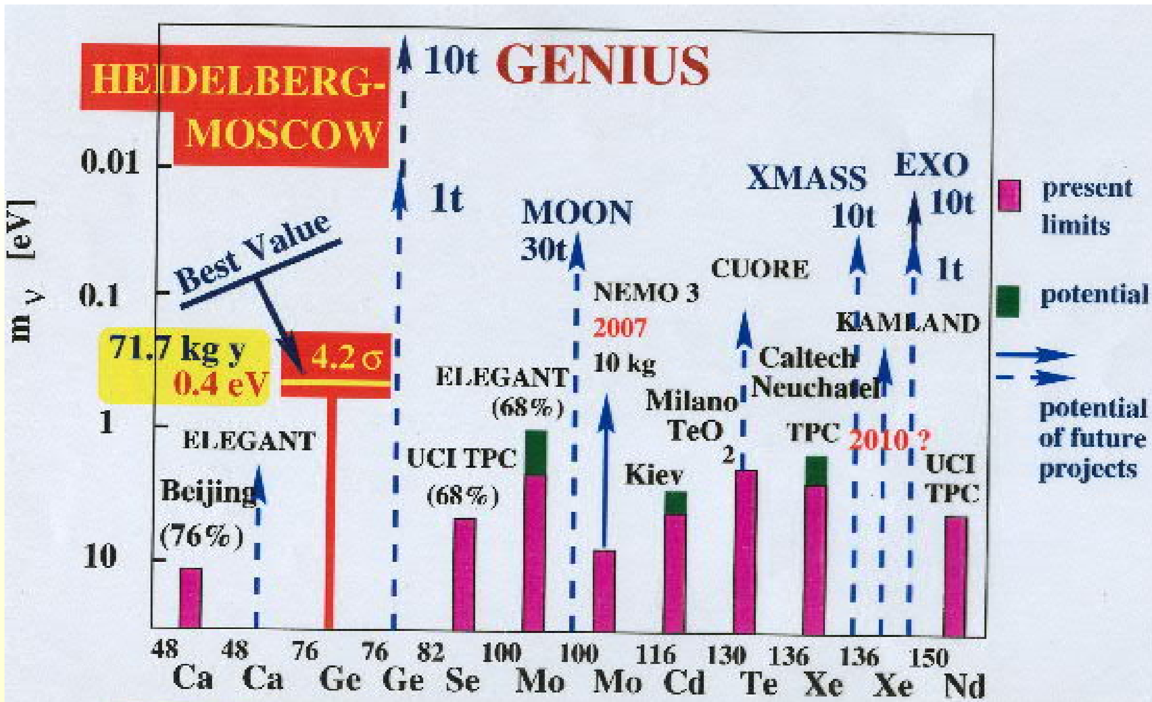
from R. de Meijer & A. v.d. Berg

Neutrinoless Double β-Decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

$$1/T_{1/2} = G_{0\nu}(E_0,Z)\,|M_{GT} + (g_V/g_A)^2 \cdot M_F|^2 \langle m_\nu \rangle^2$$

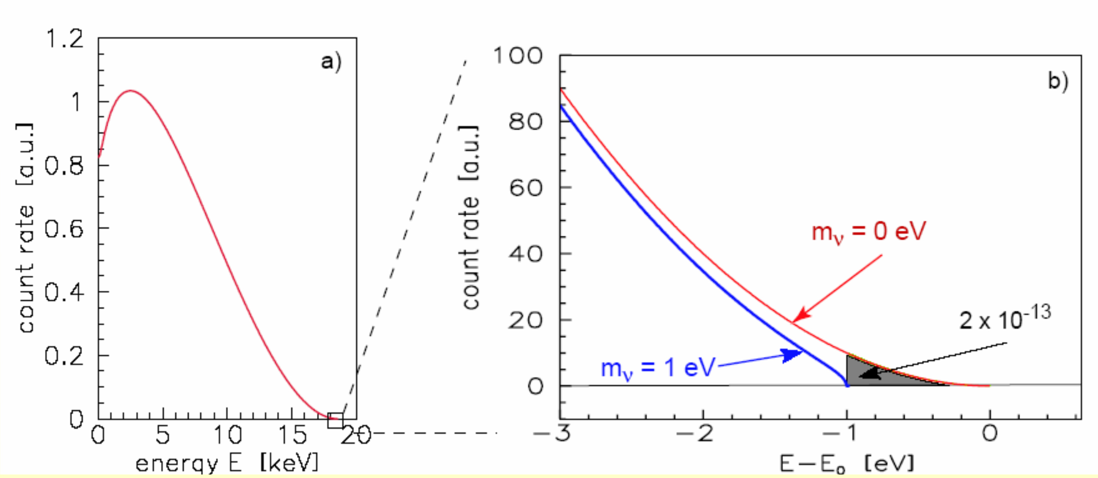


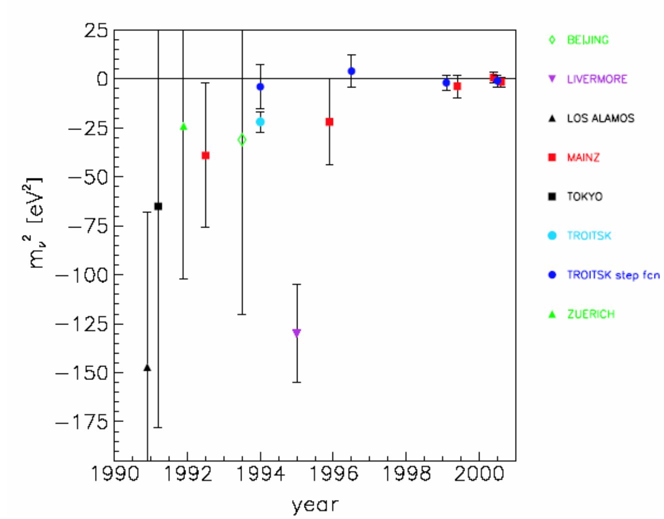


CUORICINO

- confirmation of Heidelberg-Moscow needed
- independent experiment(s) with different technologies required
- need nuclear matrix elements

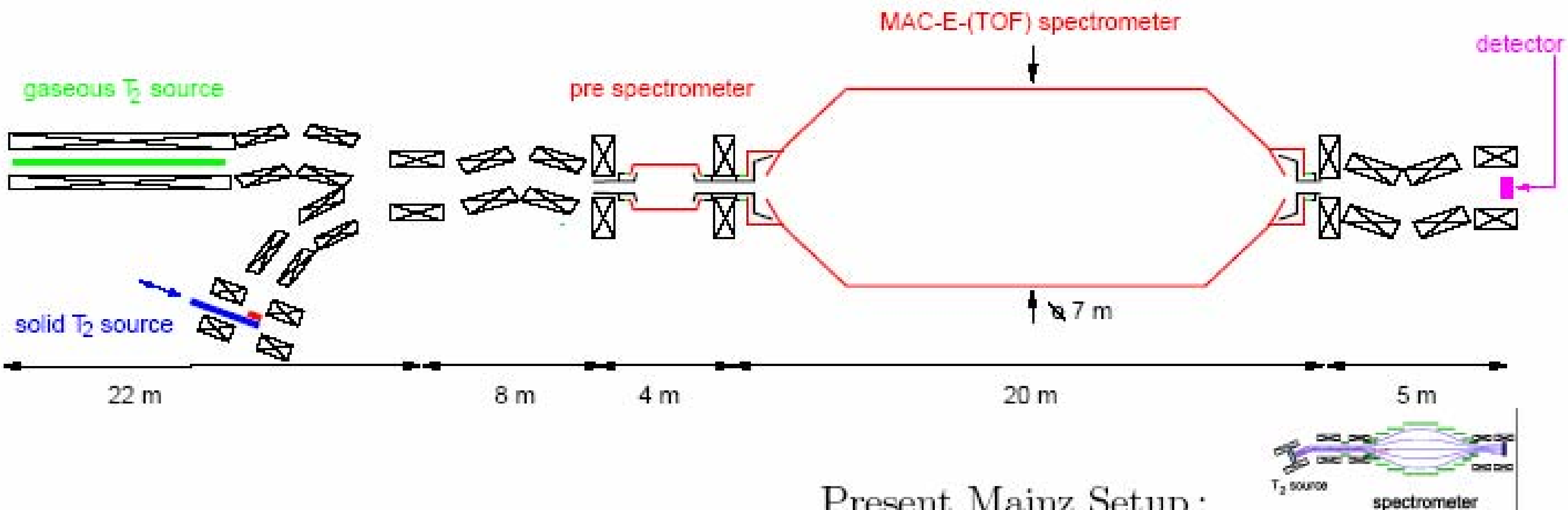
Direct ν mass Measurements: Towards KATRIN





Present Limit : $m(\nu_e) < 2.2$ eV (95% C.L.)

KATRIN sensitivity : some 10 times better



Fundamental Fermions

- Neutrinos
  - Neutrino Oscillations
  - Neutrino Masses
- **Quarks**
  - **Unitarity of CKM Matrix**
- Rare decays
  - Baryon Number
  - Lepton Number/Lepton Flavour
- New Interactions in Nuclear and Muon β-Decay

Unitarity of Cabbibo-Kobayashi-Maskawa Matrix

CKM Matrix couples weak and mass quark eigenstaes:

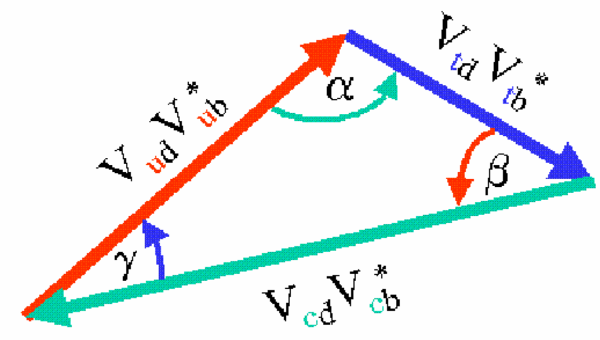
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

$$\begin{pmatrix} \mathbf{0.9739(5)} & \mathbf{0.221(6)} & 0.0036(12) \\ 0.223(4) & 0.9740(8) & 0.041(3) \\ 0.008(4) & 0.0041(4) & 0.9992(2) \end{pmatrix}$$

Unitarity:

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$



Often found:

Nuclear β-decays

$\Delta = 0.0032\ (14)$

Neutron decay

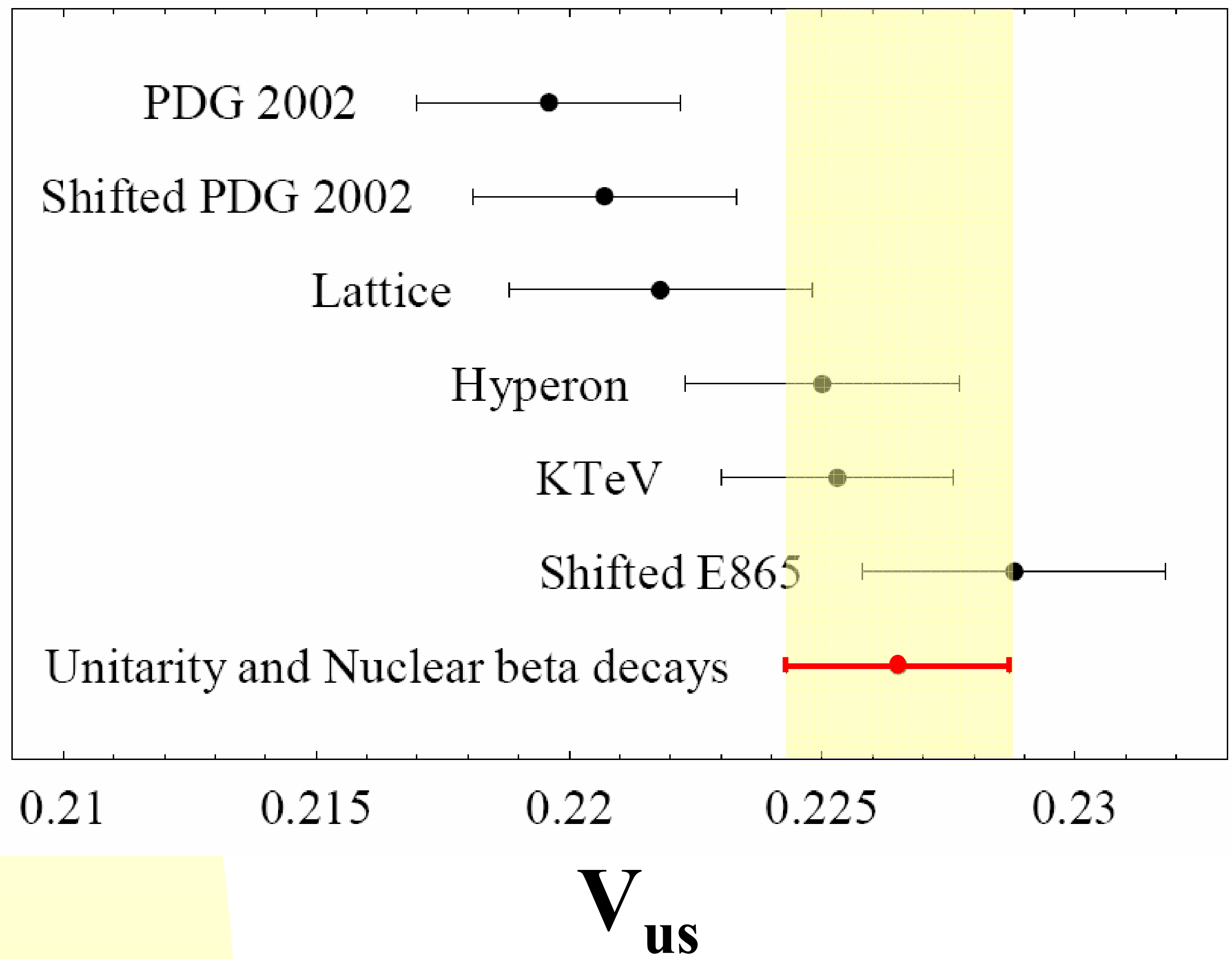
$\Delta = 0.0083(28)$

$\Delta = 0.0043(27)$

?

If you pick your favourite V_{us} !

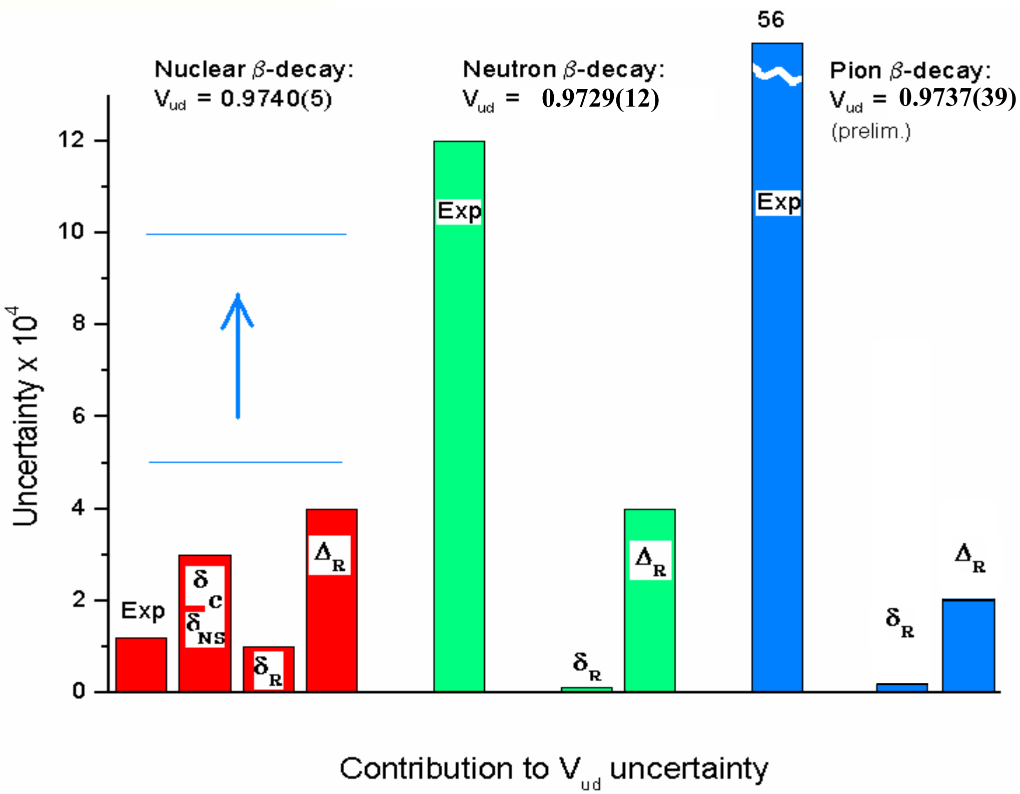
Unitarity of Cabbibo-Kobayashi-Maskawa Matrix

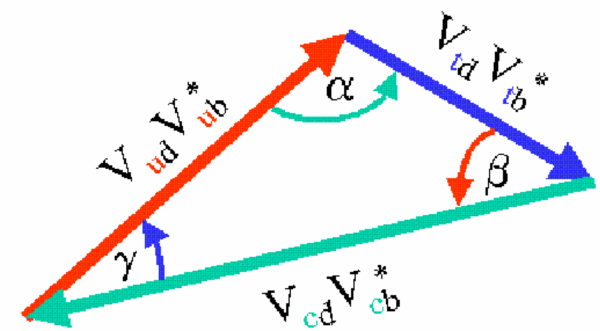


A. Czarnecki
W. Marciano,
A. Sirlin,
Hep-ph/0406324

Unitarity of Cabbibo-Kobayashi-Maskawa Matrix

Experimental Possibilities





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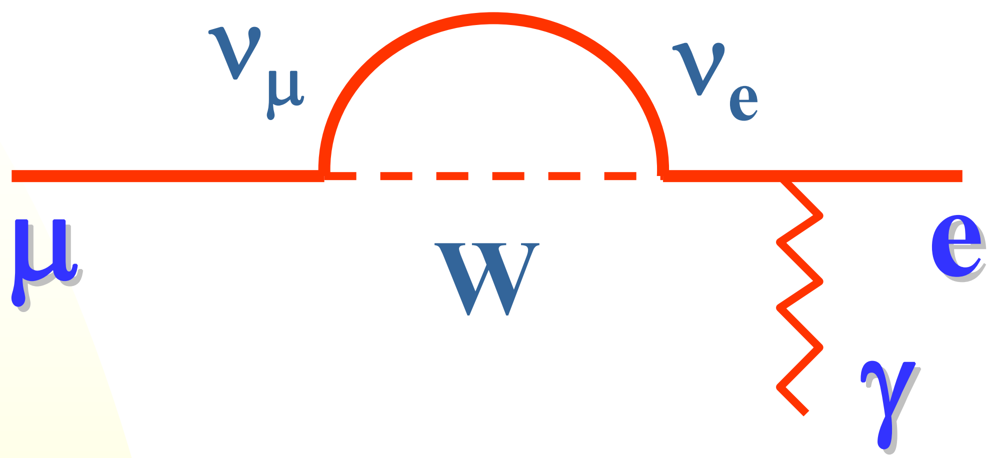
Do Neutrino Oscillations Imply Charged Lepton Number Violations within Standard Theory ?

e.g. through:



$$BR(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\,\gamma)}{\Gamma(\mu \to e\,\bar{\nu}\,\nu)} = 10^{-39}\left(\frac{m^2_{\nu_1} - m^2_{\nu_2}}{400\mathrm{eV}^2}\right)$$

A.A. Godzev et al., Phys.Lett B338, 212 (1994)

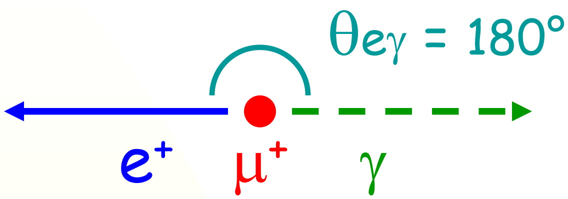
⇒ no real chance yet

BUT

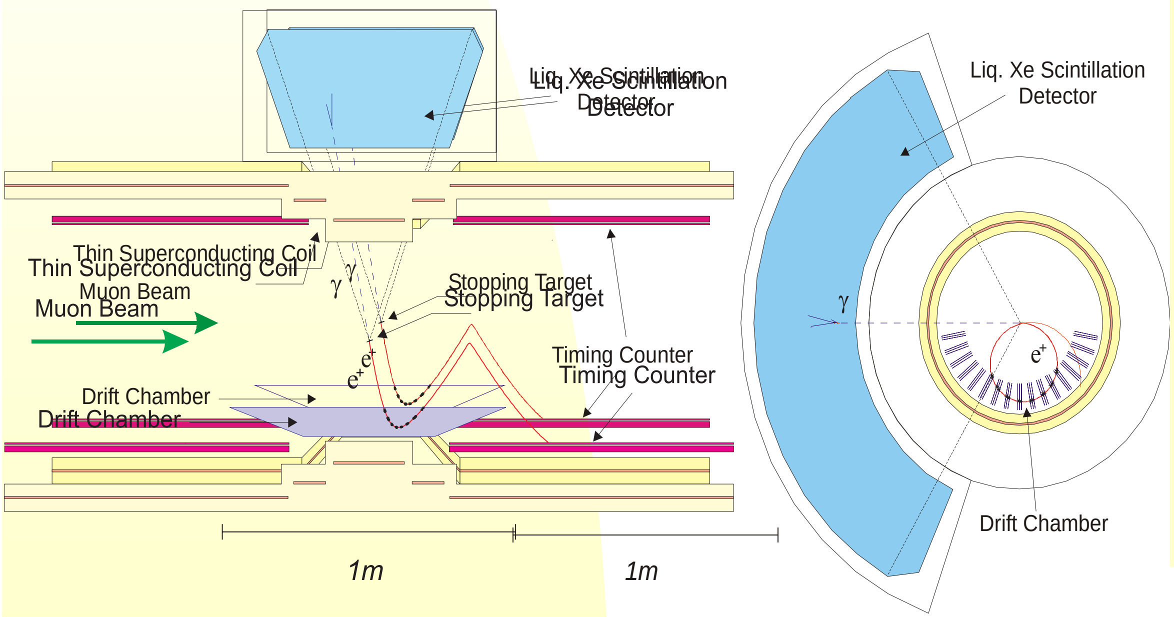
Higher values predicted in Speculative Models

The MEG experiment at PSI aims for $\mu \to e\,\gamma$

Easy signal selection with μ^+ at rest



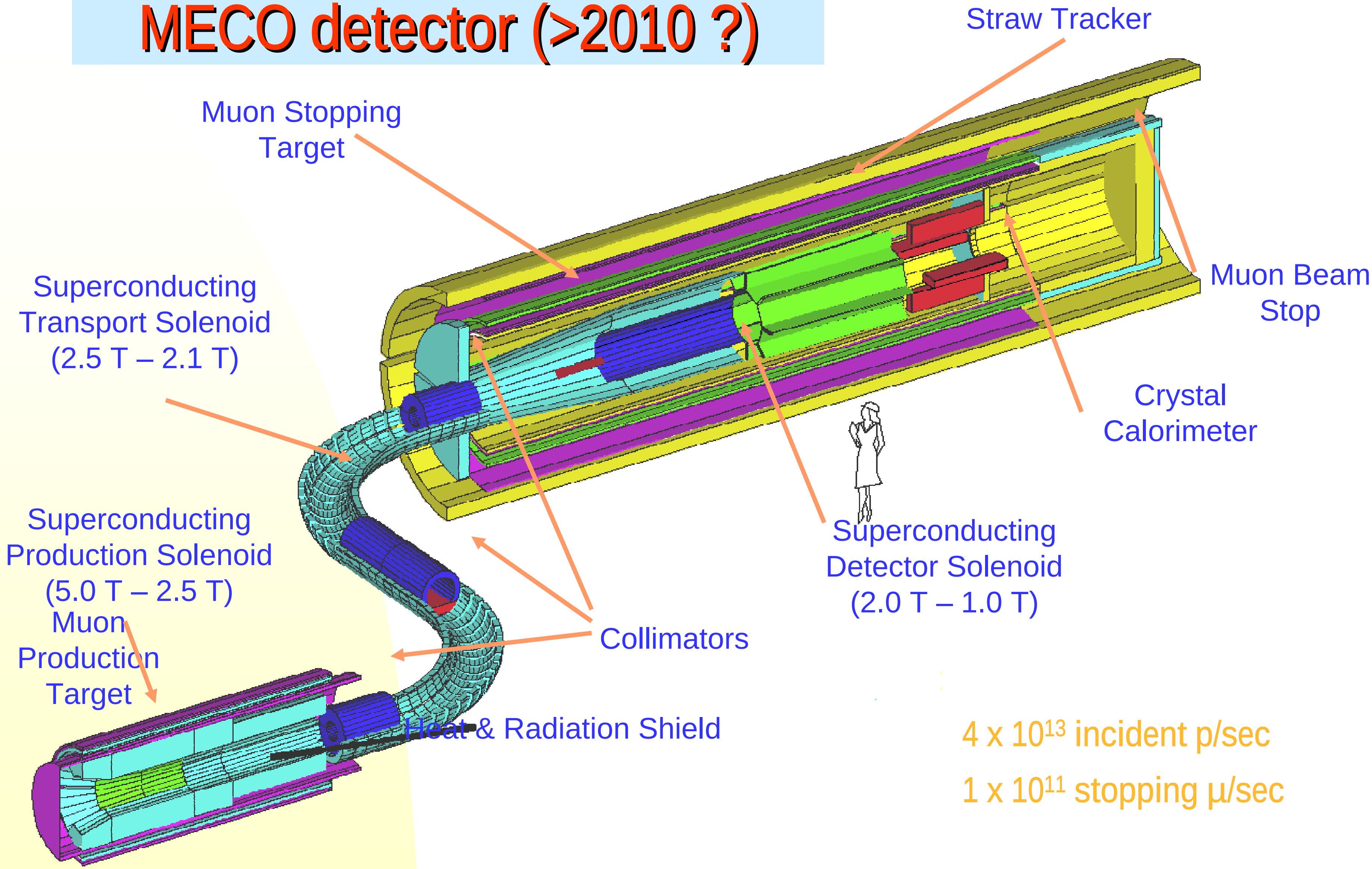
$E_e = E_\gamma = 52.8$ MeV



Detector outline

- Stopped beam of >10^7 μ /sec in a 150 μm target
- Liquid Xenon calorimeter for γ detection (scintillation)
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm
- Solenoid spectrometer & drift chambers for e^+ momentum
- Scintillation counters for e^+ timing

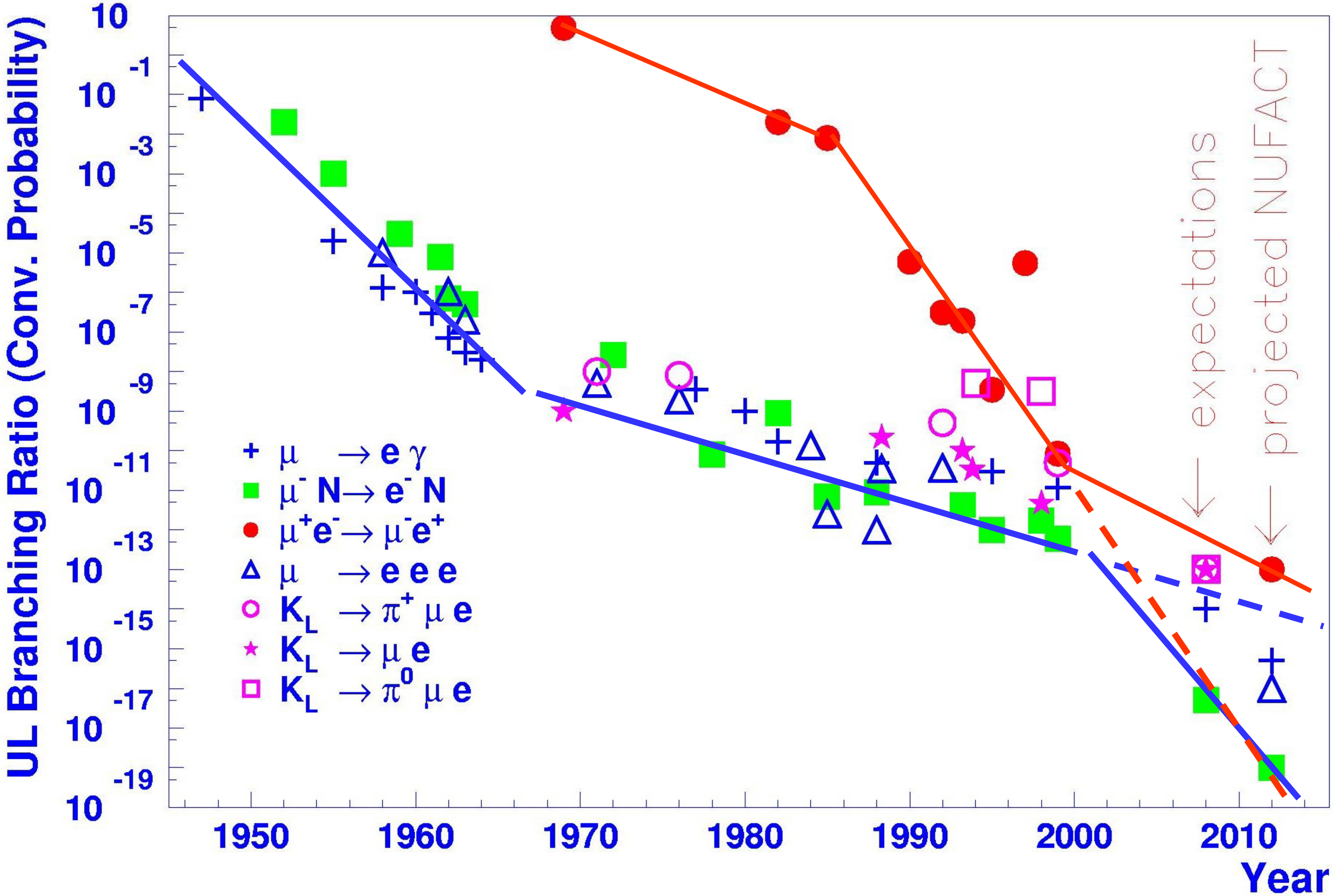
$\mu^- N \rightarrow e^- N$ Future plans
MECO detector (>2010 ?)



4×10^{13} incident p/sec

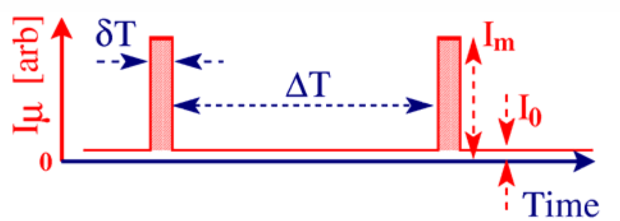
1×10^{11} stopping μ/sec

Searches for Lepton Number Violation



Muon Physics Possibilities at Any High Power Proton Driver i.e. ≥ 4 MW

Experiment	q_μ	$\int I_\mu dt$	I_0/I_μ	δT [ns]	ΔT [μs]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{19}	$< 10^{-10}$	≤ 100	≥ 1	< 20	< 10
$\mu^- N \to e^- N^\ddagger$	$-$	10^{19}	n/a	n/a	n/a	< 20	< 10
$\mu \to e\gamma$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu \to eee$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{16}	$< 10^{-4}$	< 1000	≥ 20	1...4	1...2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20	4	1...10
$transvers.polariz.$	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 0.02	30-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^3$	3100	10^{-2}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^3$	≤ 1000	$\leq 10^{-3}$
M_{HFS}	$+$	10^{15}	$< 10^{-4}$	≤ 1000	≥ 20	4	1...3
M_{1s2s}	$+$	10^{14}	$< 10^{-3}$	≤ 500	$\geq 10^3$	1...4	1...2
μ^- $atoms$	$-$	10^{14}	$< 10^{-3}$	≤ 500	≥ 20	1...4	1...5
$condensed\ matter$ $(incl.bio\ sciences)$	$\pm$	10^{14}	$< 10^{-3}$	< 50	≥ 20	1...4	1...5



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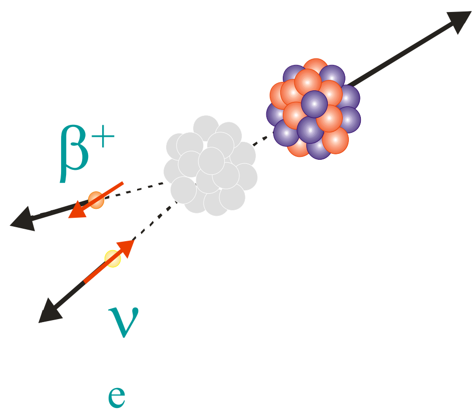
New Interactions in Nuclear and Muon β-Decay

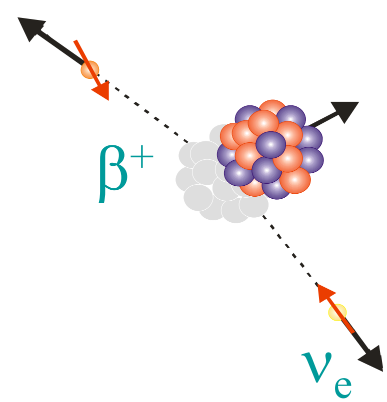
In Standard Model:
Weak Interaction is
V-A

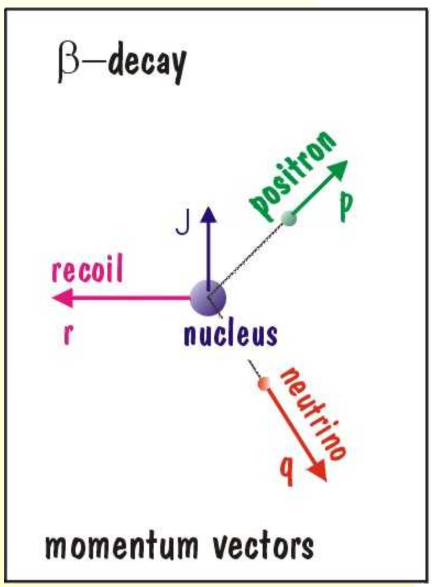
In general β-decay
could be also
S , P, T

Vector [Tensor]



Scalar [Axial vector]





$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\,\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\,\Gamma\,\frac{m_e}{E} + \langle\boldsymbol{J}\rangle\cdot\left[A\,\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\,\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E}\right] + \langle\boldsymbol{\sigma}\rangle\cdot\left[G\,\frac{\boldsymbol{p}}{E} + Q\,\langle\boldsymbol{J}\rangle + R\,\langle\boldsymbol{J}\rangle\times\frac{\boldsymbol{p}}{E}\right]$$

⇒ nuclear β-decays, Experiments in Traps
⇒ muon decays, Michel parameters

Traps for weak interaction physics :

1. Atom traps :

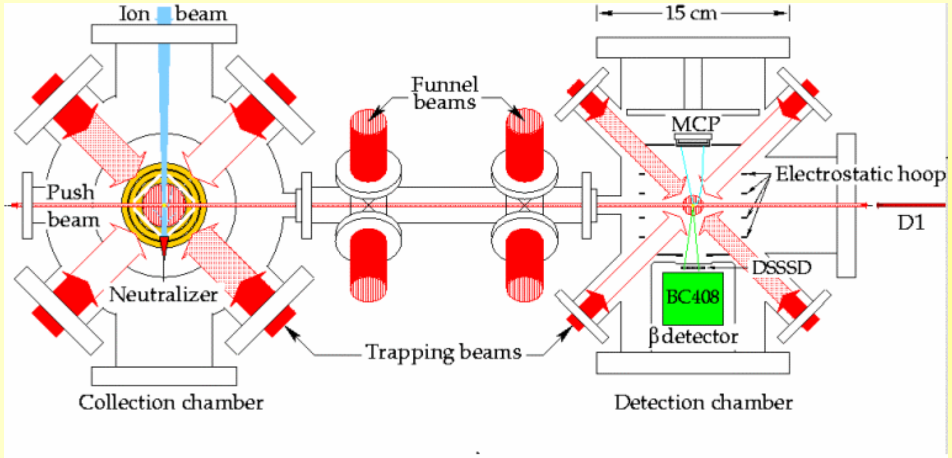
- **TRIUMF-ISAC, ^{38m}K, βν-correlation (J. Behr et al.)**
  A. Gorelov et al., Hyperfine Interactions 127 (2000) 373
- **LBNL & UC Berkeley, ^{21}Na, βν-correlation (S.J. Freedman et al.)**
  N. Scielzo, Ph. D. Thesis (2003)
- **LANL Los Alamos, ^{82}Rb, β-asymmetry (D. Vieira et al.)**
  S.G. Crane et al., Phys. Rev. Lett. 86 (2001) 2967
- **KVI-Groningen, Na, Ne, Mg, D-coefficient (K. Jungmann et al.)**
  Ra, EDM experiment
  G.P. Berg et al., NIM B204 (2003) 526

2. Ion traps :

- **LPC-Caen, ^{6}He, βν-correlation (O. Naviliat-Cuncic et al.)**
  G. Ban et al., NIM A518 (2004) 712
- **WITCH, Leuven-ISOLDE, ^{35}Ar, βν-correlation (N. Severijns et al.)**
  D. Beck et al., Nucl. Inst. Methods Phys. Res., A 503 (2003) 567
- **CPT-trap Argonne, ^{14}O, βν-correlation (G. Savard et al.)**
  G. Savard et al., Nucl. Phys. A654 (1999) 961c
- **ISOLTRAP-CERN, mass for 0+ → 0+ decays (K. Blaum et al.)**

from N. Severijns

Some TRAPS for Weak Interaction Studies



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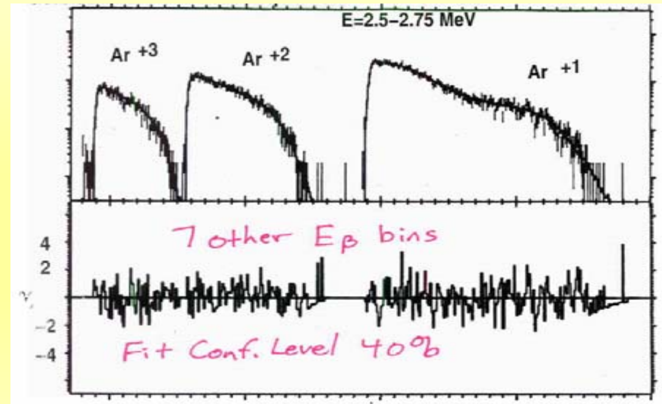
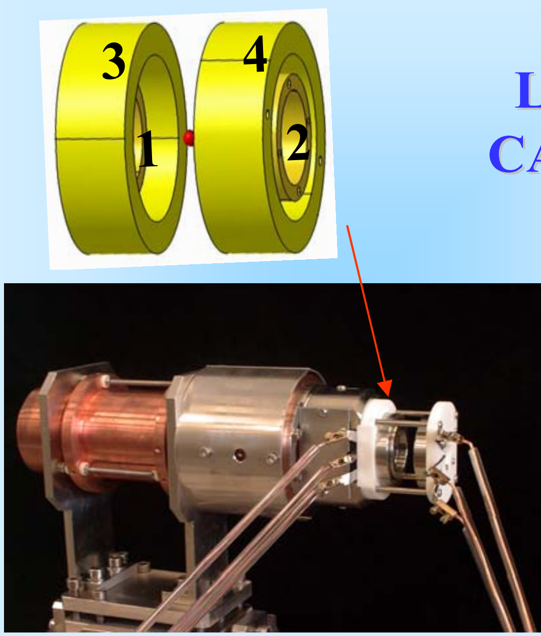
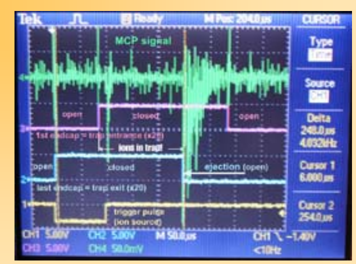


TRIUMF



LPC
CAEN



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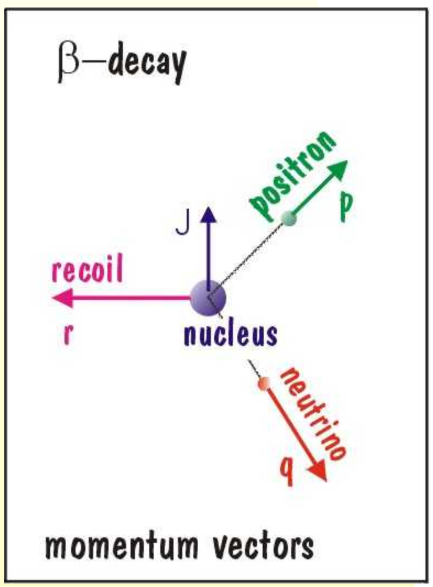


Vector [Tensor] **Scalar [Axial vector]**

[21]Na Berkeley:
Scielzo,Freedman, Fujikawa, Vetter
PRL 93, 102501-1 (3 Sep 2004)

$a_{exp} = 0.5243(91)$
$a_{theor} = 0.558(6)$

??

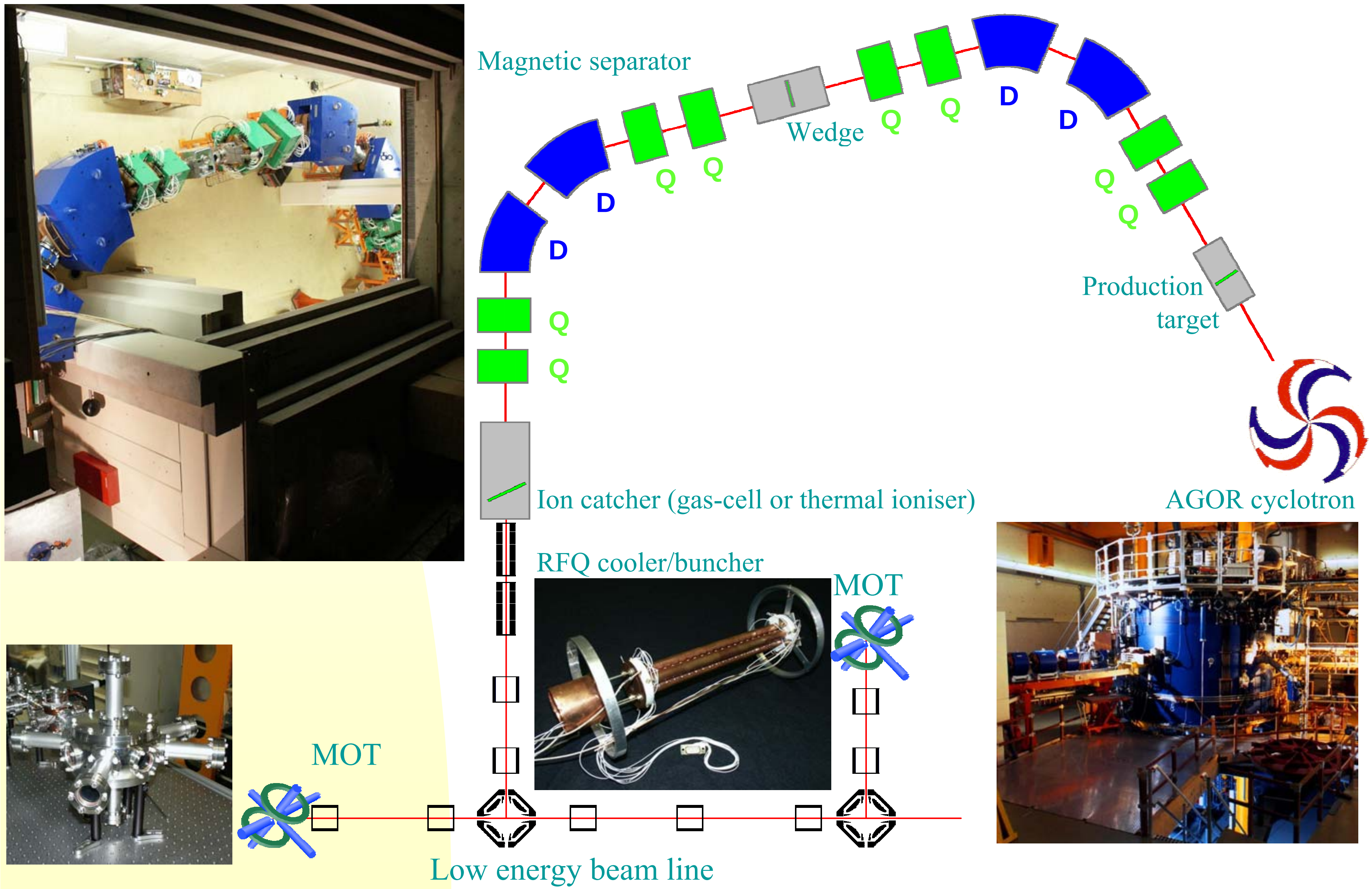
[38m]K TRIUMF
A. Gorelov et al.
nucl-ex/0412032(14 Dec 2004)

$a_{exp} = 0.9978(30)(37)$
$a_{theor} = 1$

⇒ nuclear β-decays, Experiments in Traps
⇒ muon decays, Michel parameters

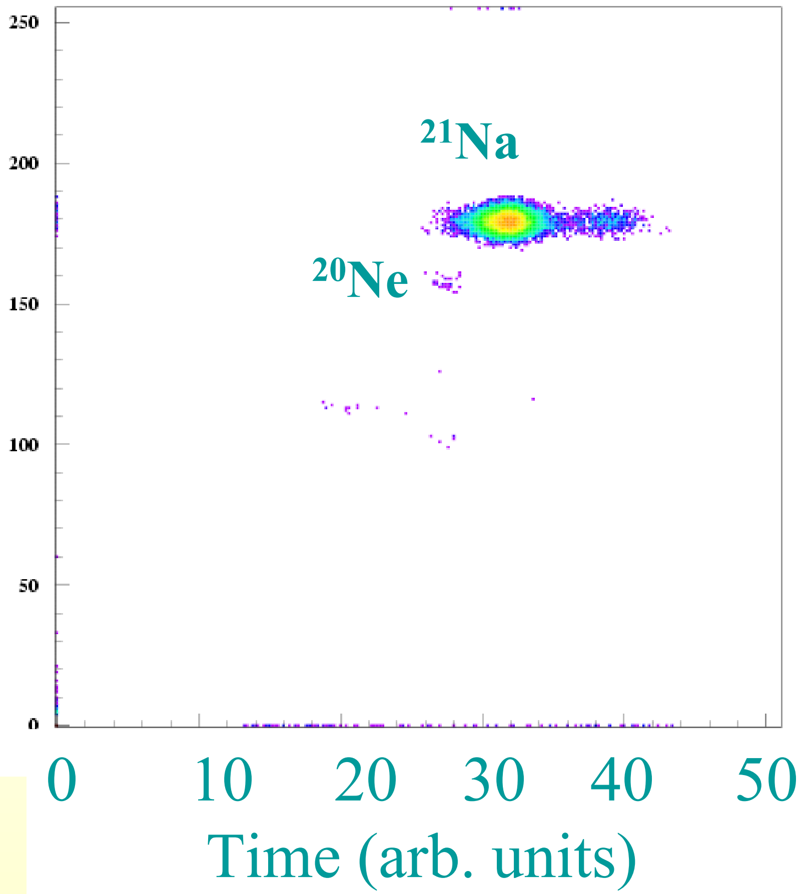
TRIμP

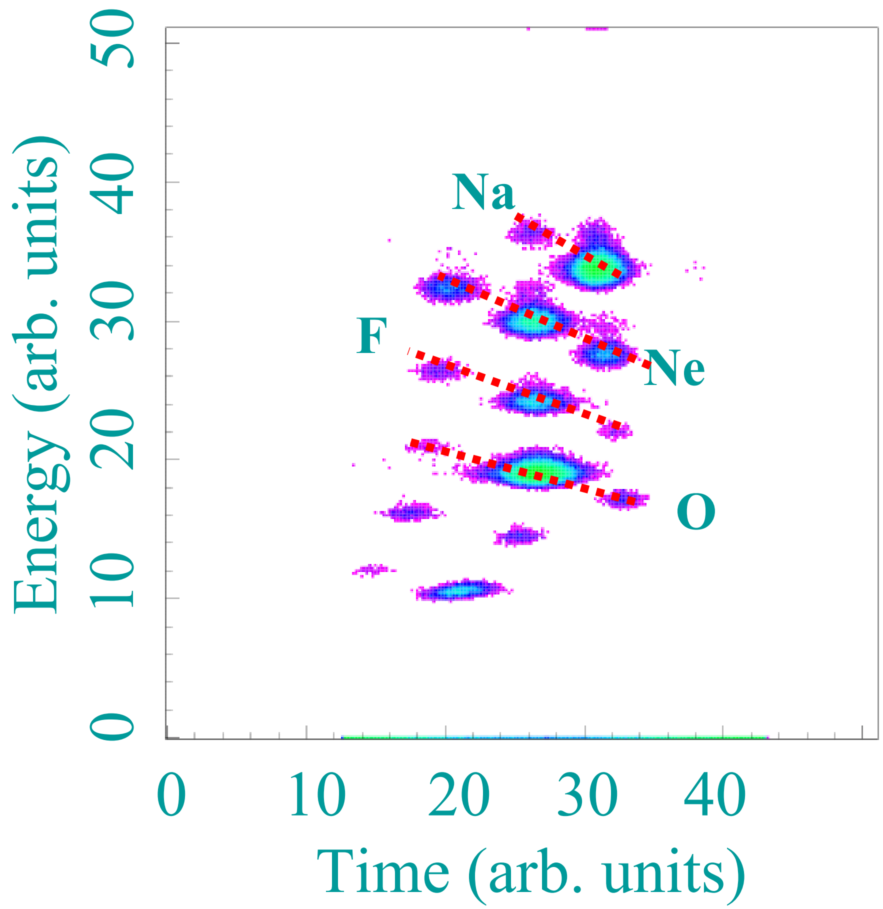
Combined Fragment and Recoil Separator



TRIμP

Separator commissioning





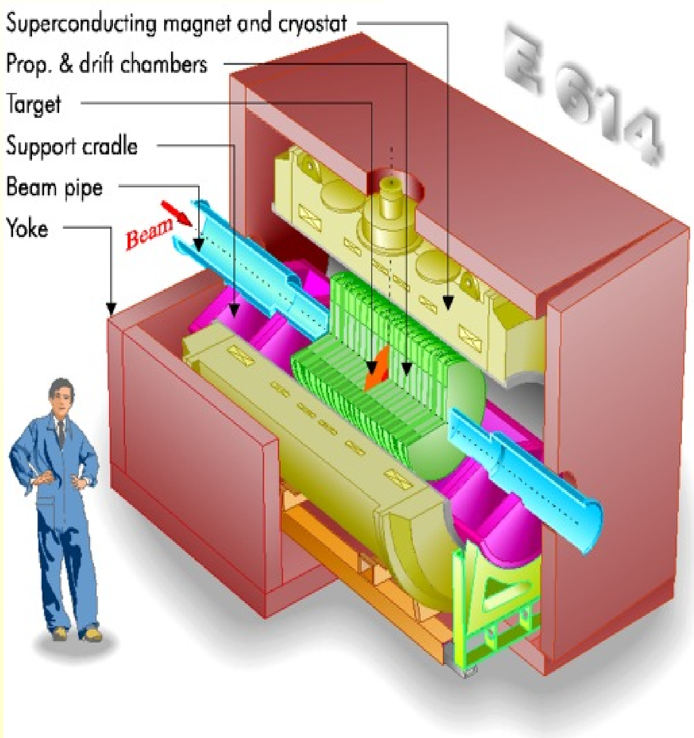
Yield of ^{21}Na at the focal plane: 5.3 MHz/kW

Now achieved: > 99% ^{21}Na

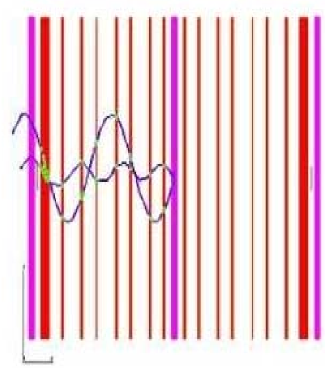
Muon Decay: Michel Parameters

TRIUMF Weak Interaction Symmetry Test: “TWIST”

http://twist.triumf.ca/~e614/experiment.html



tracking of e^+ from polarized muon decay



	PDG 02	V-A
ρ	0.7518 (26)	0.75
δ	0.7486 (38)	0.75
η	-0.007 (13)	0
ξ	1.0045 (86)	1
ξ'	0.998 (45)	1
ξ''	0.65 (36)	1
η	0.012 (16)	0
α/A	-0.0002 (43)	0
β/A	-0.0015 (63)	0

goal: detemine ρ, δ, $P_\mu \xi$ with a relative precision at the 10^{-4} level

prelim. results expected in 2004

from O. Naviliat-Cuncic

Discrete Symmetries

- **Parity**
  - **Parity Nonconservation in Atoms**
  - **Nuclear Anapole Moments**
  - **Parity Violation in Electron-Scattering**
- **Time Reversal and CP-Violation**
  - **Electric Dipole Moments**
  - **R and D Coefficients in β-Decay**
- **CPT Invariance**

The World according to Escher

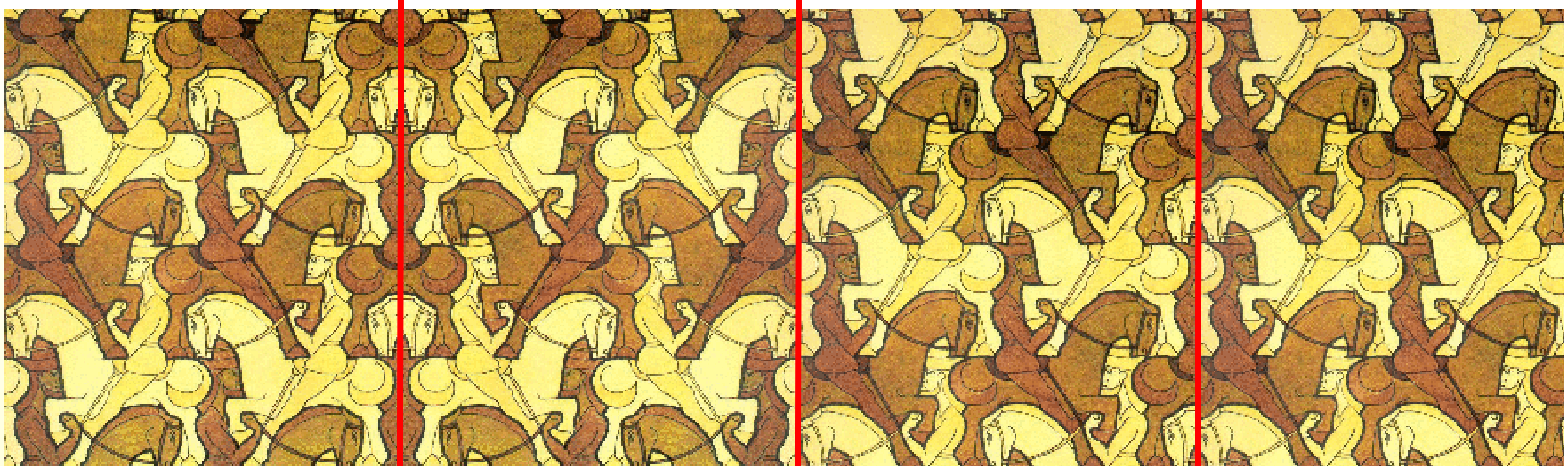
P C T

start

matter

anti-matter

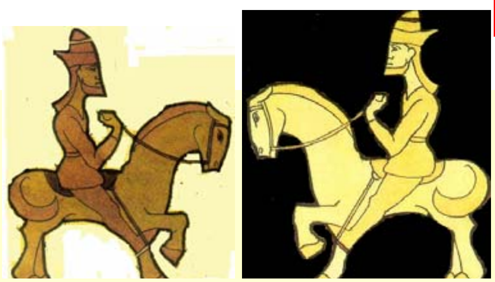
identical to start



mirror image

time →

← time



anti-particle e^+

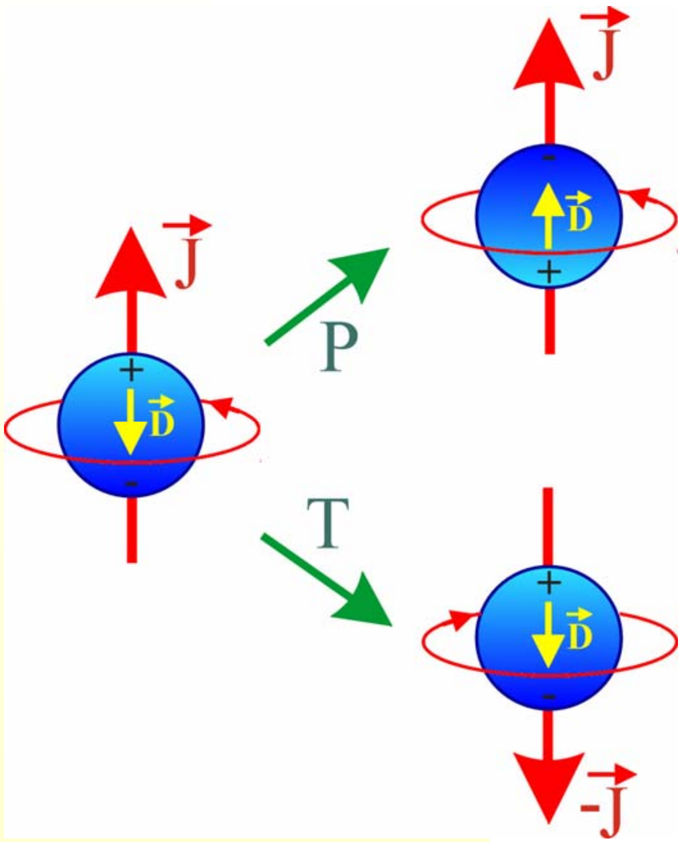
particle e^-

from H.W. Wilschut

Discrete Symmetries

- Parity
  - Parity Nonconservation in Atoms
  - Nuclear Anapole Moments
  - Parity Violation in Electron-Scattering
- **Time Reversal and CP-Violation**
  - **Electric Dipole Moments**
  - R and D Coefficients in β-Decay
- CPT Invariance

Permanent Electric Dipole Moments Violate Discrete Fundmental Symmetries



EDM violates:

- **Parity**
- **Time reversal**
- **CP- conservation**

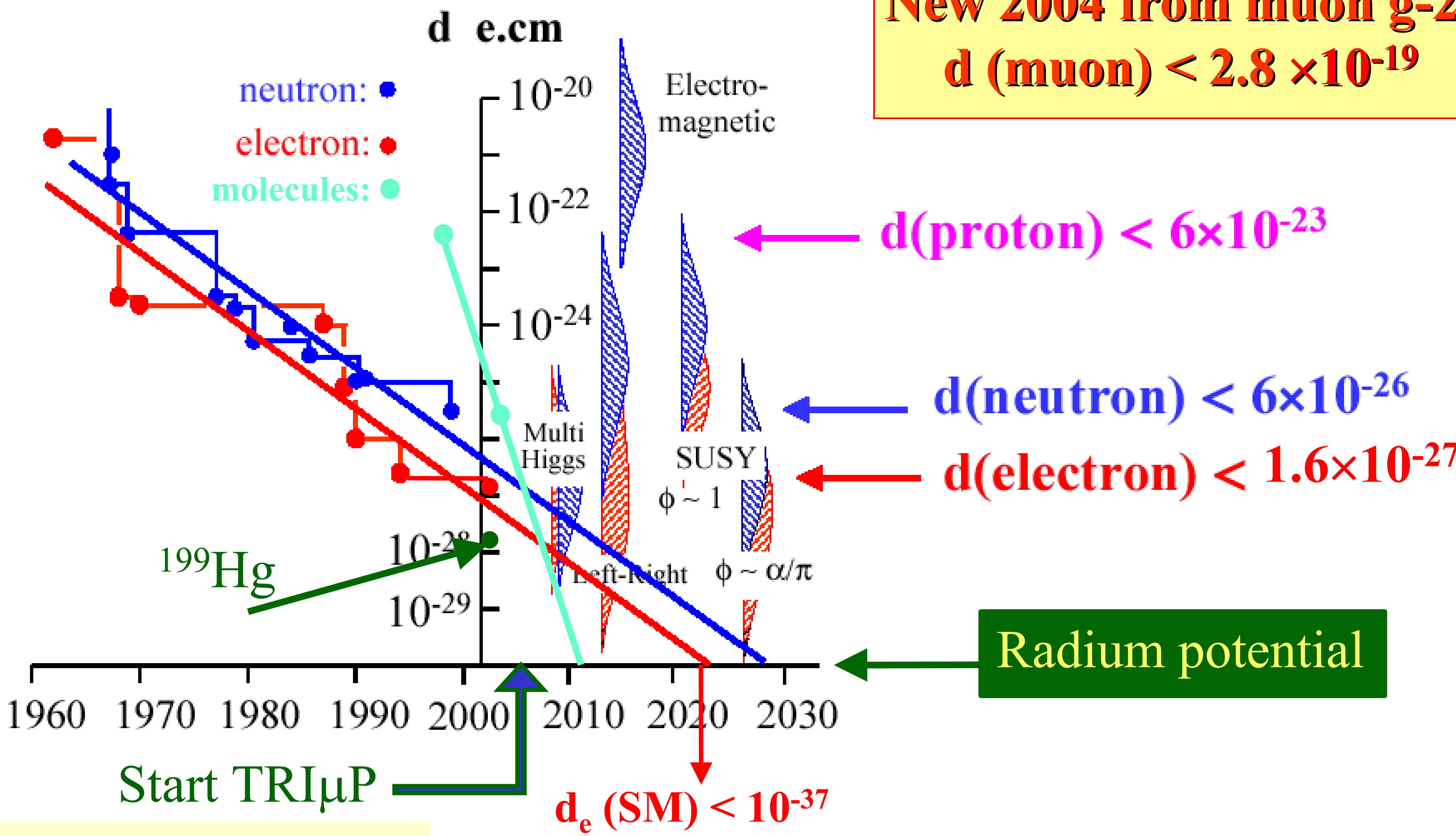
(if **CPT** conservation assumed)

Standardd Model values are tiny, hence:

An observed EDM would be Sign of New Physics beyond Standard Theory

Some EDM Experiments compared

New 2004 from muon g-2:
d (muon) < 2.8 ×10^{-19}



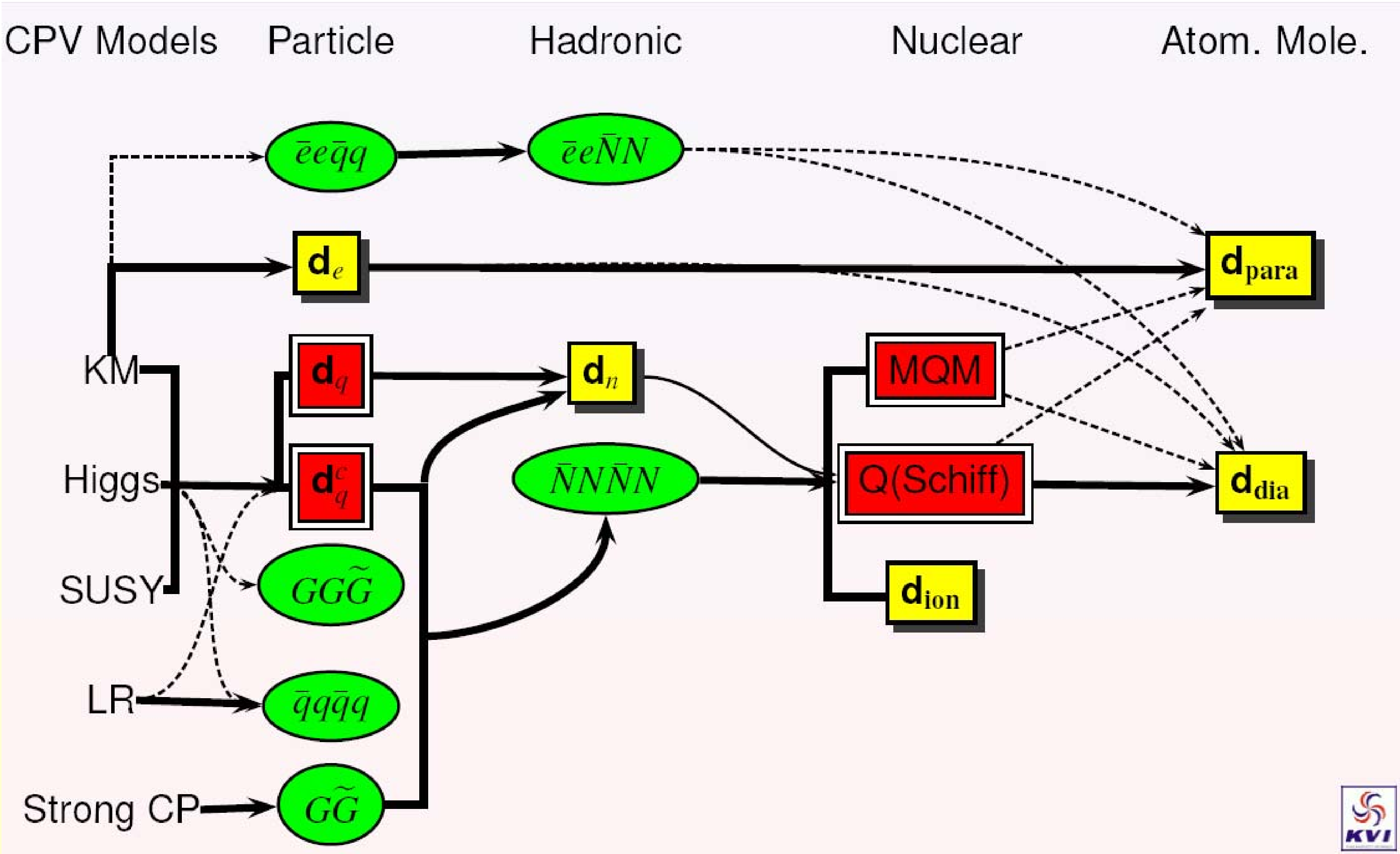
after E.Hinds

EDMs – Where do they come from ?

(are they just “painted“ to particles? Why different experiments?)

▪ electron	intrinsic ?
▪ quark	intrinsic ?
▪ muon	second generation different ?
▪ neutron/ proton	from quark EDM ? property of strong interactions ? new interactions ?
▪ deuteron	basic nuclear forces CP violating? pion exchange ?
▪ ^{6}Li	many body nuclear mechanism ?
▪ heavy nuclei (e.g. Ra, Fr)	enhancement by CP-odd nuclear forces, nuclear “shape“
▪ atoms	can have large enhancement, sensitive to electron or nucleus EDMs
▪ molecules	large enhancement factors , sensitive to electron EDM
▪ . . .	

Origin of EDMs



from C.P.. Liu

Generic EDM Experiment

Preparation of "pure" $\vec{J}$ **state** → **Interaction** with $\vec{E}$ **- field** → **Analysis** of **state**

Polarization

η contains all physics – "e cm" values by themselves not very helpful

$\mu_x = e\hbar/2m_x$

Electric Dipole Moment: $\vec{d} = \eta\, \mu_x\, c^{-1}\, \vec{J}$

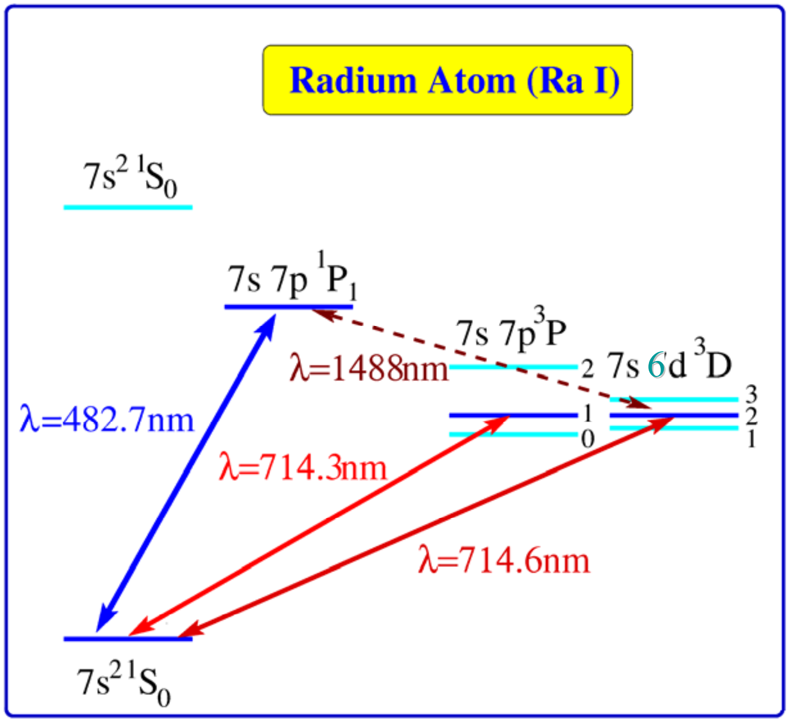
Spin precession : $\vec{\omega}_e = \frac{\vec{d} \bullet \vec{E}}{\hbar} \frac{\vec{E} \times \vec{J}}{|\vec{E} \times \vec{J}|}$

Example: $d=10^{-24}$ e cm, E=100 kV/cm, J=1/2

ω_e **= 15.2 mHz**

TRIμP

Radium Permanent Electric Dipole Moment



Benefits of Radium

- near degeneracy of $^3P_1$ and $^3D_2$
  ⇒ ~ 40 000 enhancement
- some nuclei strongly deformed
  ⇒ nuclear enhancement 50~1000

^3D : electron spins parallel

⇒ electron EDM

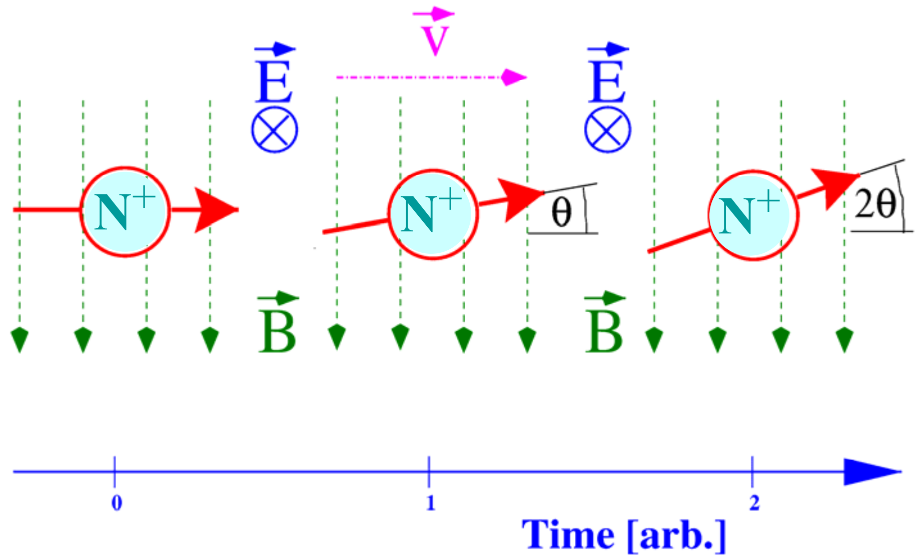
^1S : electron Spins anti-parallel

⇒ atomic / nuclear EDM

Ra also interesting for weak interaction effects
Anapole moment, weak charge
Dzuba el al., PRA, 062509 (2000)

How does a ring edm experiment work ?

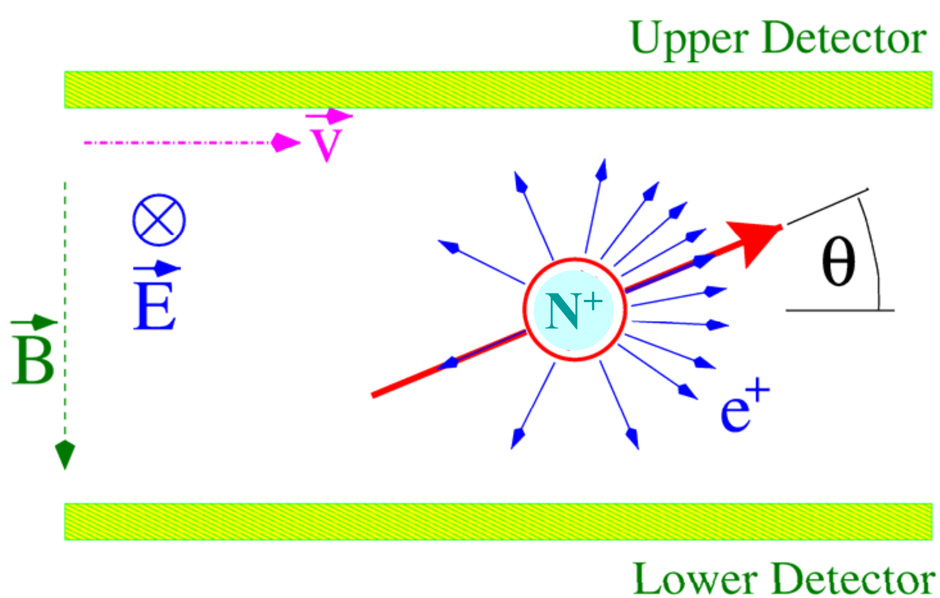
- Exploit huge motional electric fields for relativistic particles in high magnetic fields
- stop g-2 precession
- observe spin rotation



- Concept works
- also for (certain)
- Nuclei: d, ^{6}Li, ^{213}Fr, . .

For muons exploit decay asymmetry

- One could use β-decay
- In general: any sensitive polarimeter works



One needs for a successful experiment:

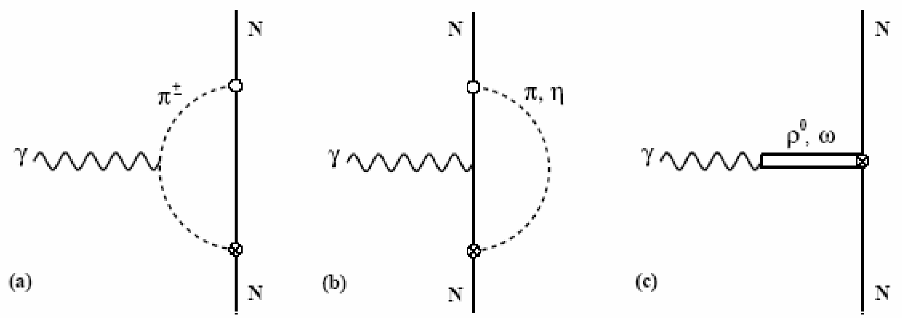
- polarized, fast beam
- magnetic storage ring
- polarimeter

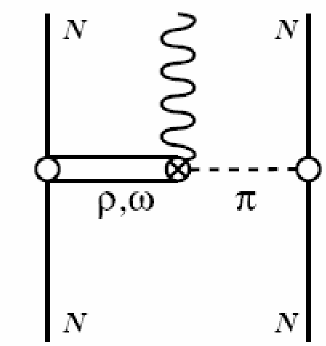
Some Candidate Nuclei for EDM in Ring Searches

Nucleus	Spin J	μ/μ_N	Reduced Anomaly a	$T_{1/2}$
$^{139}_{57}La$	7/2	+2.789	-0.0305	
$^{123}_{51}Sb$	7/2	2.550	-0.1215	
$^{137}_{55}Cs$	7/2	+2.8413	0.0119	30y
$^{223}_{87}Fr$	3/2	+1.17	<0.02	22 min
$^{6}_{3}Li$	1	+0.8220	-0.1779	
$^{2}_{1}H$	1	+0.8574	-0.1426	
$^{75}_{32}Ge$	1/2	+0.510	+0.195	82.8 m
$^{157}_{69}Tm$	1/2	+0.476	0.083	3.6 m

Need Schiff moment calculations:
Particularly in region of octupole deformed nuclei

Why a deuteron edm experiment





Deuteron: $$d_{\mathcal{D}} = -4.67\, d_d^c + 5.22\, d_u^c$$

Neutron: $$d_n = -0.01\, d_d^c + 0.49\, d_u^c$$

" Thus, these two EDM measurements probe different linear combinations of d_d^c and d_u^c in this case. Moreover, the deuteron could be significantly more sensitive than the neutron. "

C.P. Liu and R.G.E Timmermans, nucl-th/0408060, PRC accepted (2004)

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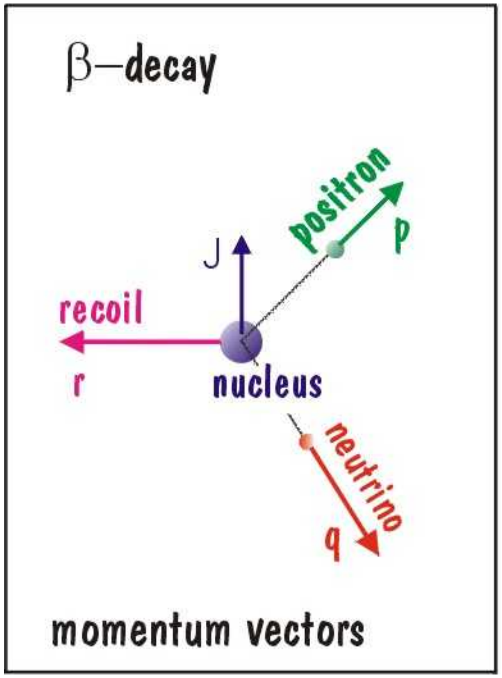
- CPT Invariance

Time Reversal Violation in β-decay: Correlation measurements

$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\mathbf{p}\cdot\hat{\mathbf{q}}}{E} + b\Gamma\frac{m_e}{E} + \langle \mathbf{J}\rangle \cdot \left[A\frac{\mathbf{p}}{E} + B\,\hat{\mathbf{q}} + D\frac{\mathbf{p}\times\hat{\mathbf{q}}}{E}\right] + \langle \boldsymbol{\sigma}\rangle \cdot \left[G\frac{\mathbf{p}}{E} + Q\,\langle \mathbf{J}\rangle + R\,\langle \mathbf{J}\rangle \times \frac{\mathbf{p}}{E}\right]$$



R and ***D*** test both Time Reversal Violation

- ***D*** → most potential
- ***R*** → scalar and tensor (EDM, *a*)
- technique *D* measurements yield *a*, *A*, *b*, *B*

$$\langle \vec{J}\cdot\vec{p}\times\vec{q}\rangle \neq 0 \quad ?$$

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- Time Reversal and CP-Violation
  - Electric Dipole Moments
  - R and D Coefficients in β-Decay
- **CPT Invariance**

CPT – Violation
Lorentz Invariance Violation

What is best CPT test ?

often quoted:

- $K^0 - \overline{K^0}$ mass difference (10^{-18})
- $e^- - e^+$ g- factors ($2 * 10^{-12}$)

- We need an interaction with a finite strength !

New Ansatz (Kostelecky)

- K^0 $\approx 10^{-18}$ GeV/c²
- n $\approx 10^{-30}$ GeV/c²
- p $\approx 10^{-24}$ GeV/c²
- e $\approx 10^{-27}$ GeV/c²
- μ $\approx 10^{-23}$ GeV/c²
- Future: Anti hydrogen $\approx 10^{-22}$ GeV/c²

CPT tests

$$r_K = \frac{|m_{K^0} - m_{\overline{K^0}}|}{m_{K^0}} \le 10^{-18}$$

$$r_e = \frac{|g_{e^-} - g_{e^+}|}{g_{avg}} = 1.2 \cdot 10^{-3} \cdot \frac{|a_{e^-} - a_{e^+}|}{a_{avg}} \le 2 \cdot 10^{-12}$$

? Are they comparable- Which one is appropriate ?

⇒ Use common ground, e.g. energies

generic CPT and Lorentz violating DIRAC equation

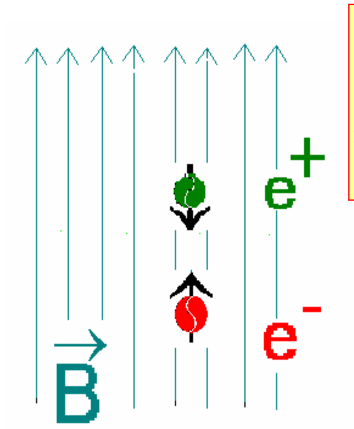
$$(i\gamma^\mu D_\mu - m - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

$$iD_\mu \equiv i\partial_\mu - qA_\mu$$

a_μ, b_μ break CPT

$a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}, H_{\mu\nu}$ break Lorentz Invariance

Leptons in External Magnetic Field



$$\Delta\omega_a = \omega_a^{l^-} - \omega_a^{l^+} \approx -4b_3^l$$

$$r_l = \frac{|E^{l^-}_{spin\ up} - E^{l^+}_{spin\ down}|}{E^{l^-}_{spin\ up}} \approx \frac{\hbar\Delta\omega_a}{m_l c^2}$$

Bluhm , Kostelecky, Russell, Phys Rev. D 57, 3932 (1998)

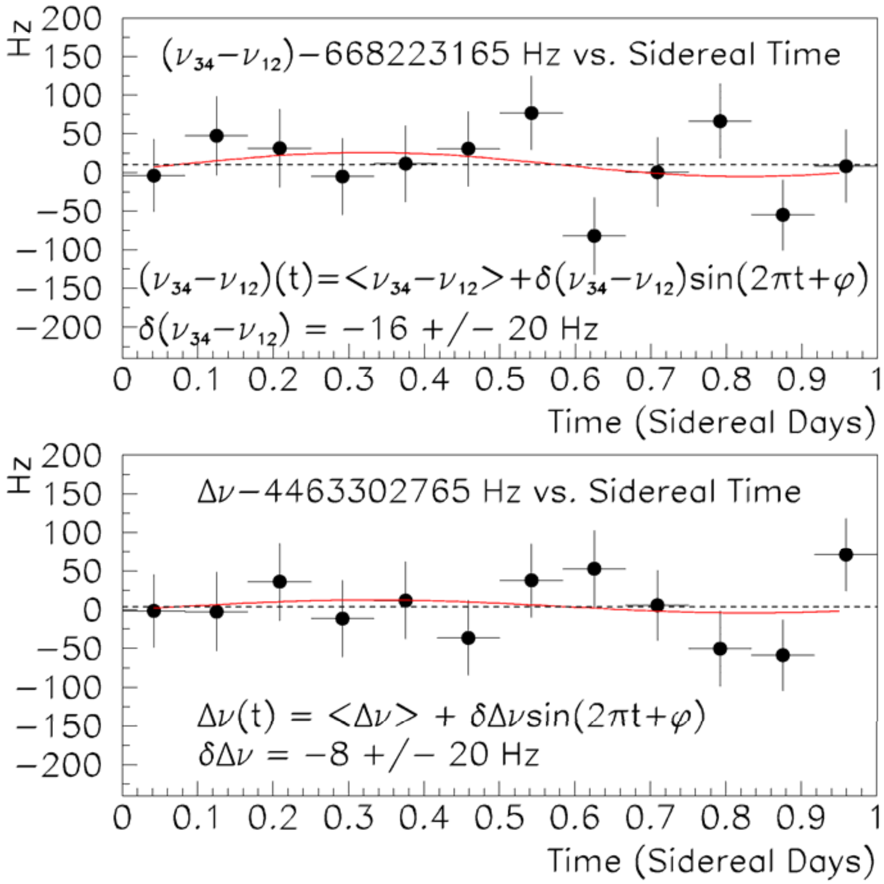
For g-2 Experiments :

$$r_l = \frac{\hbar\omega_c}{m_l c^2} \cdot \frac{|a_{l^-} - a_{l^+}|}{a_{avg}}$$

Dehmelt, Mittleman, Van Dyck, Schwinberg, hep-ph/9906262

⇒ *electron* $r_e \le 1.2 \cdot 10^{-21}$ *muon* $r_\mu \le 3.5 \cdot 10^{-24}$

CPT and Lorentz Invariance from Muon Experiments



V.W. Hughes et al., Phys.Rev. Lett. 87, 111804 (2001)

Muonium:

new interaction below

$2 * 10^{-23}$ GeV

Muon g-2:

new interaction below

$4 * 10^{-22}$ GeV (CERN)

15 times better expected from BNL when analysis will be completed

Properties of Known Basic Interactions

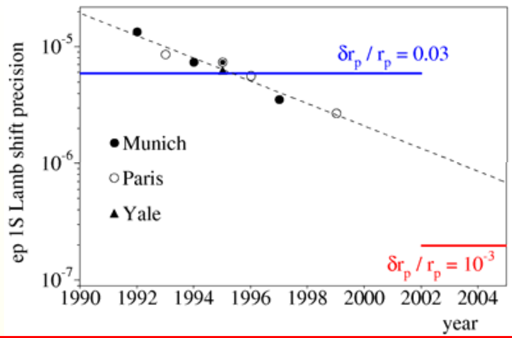
- **Electromagnetism and Fundamental Constants**
  - **QED, Lamb Shift**
  - **Muonium and Muon g-2**
  - **Muonic Hydrogen and Proton Radius**
  - **Exotic Atoms**
  - **Does α_{QED} vary with time?**

- **QCD**
  - **Strong Interaction Shift**
  - **Scattering Lengths**

- **Gravity**
  - **Hints of strings/Membranes?**

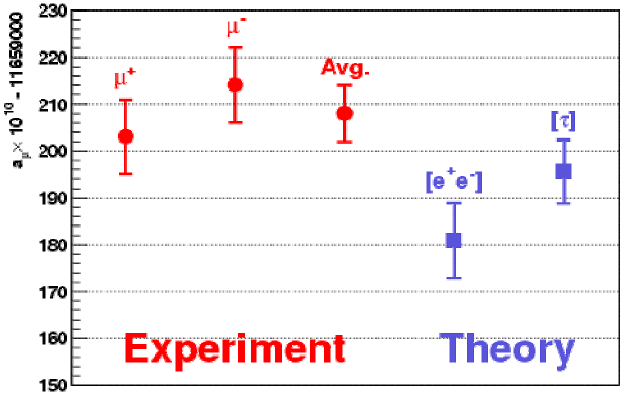
Properties of known Basic Interactions

"Proton Radius"

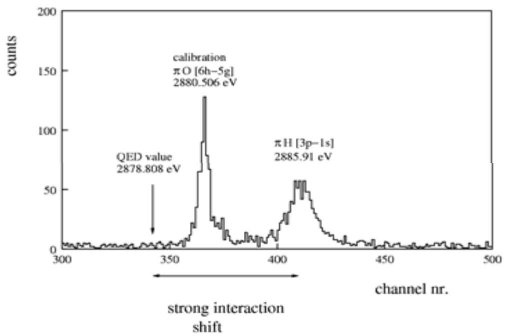


Muonic Hydrogen Lamb Shift

Muon g-2



Strong Interaction Shift



Pionic Hydrogen

Search for New Physics

What are the hardronic corrections?

- $e^+ + e^- \rightarrow$ hadrons
- $e^+ + e^- \rightarrow \gamma +$ hadrons

New activities planned

- statistics limited experiment
- J-PARC, BNL, ...
- Fundamental constants needed
- Muonium

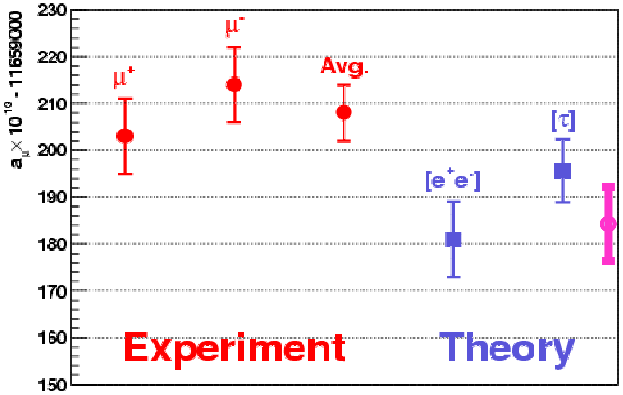
Why a Muon EDM or g-2 Experiment ?

- The muon magnetic anomaly a_μ and the muon electric dipole moment d_μ are
  real and imaginary part of one single complex quantity.
- $d_\mu = 3*10^{-22} *(a_\mu^{NP} / 3*10^{-9}) * \tan \phi_{CP}$ e cm

  a New Physics related muon magnetic anomaly would be related to an EDM through a CP violating phase ϕ_{CP}.

- Particular models (L/R symmetry) predict nonlinear mass scaling for lepton EDMs. For muon $5*10^{-23}$ e cm possible.

Muon g-2



Newest Theory Offer:
2.5 σ from Experiment

Properties of Known Basic Interactions

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  - **Exotic Atoms**
  - **Does α_{QED} vary with time?**
- **QCD**
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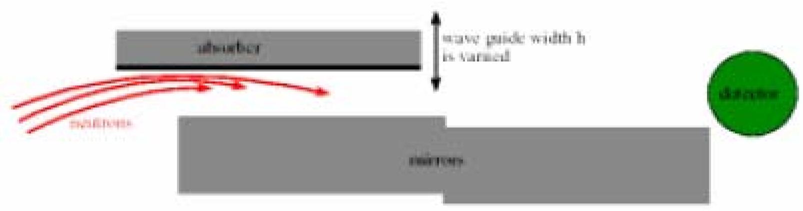
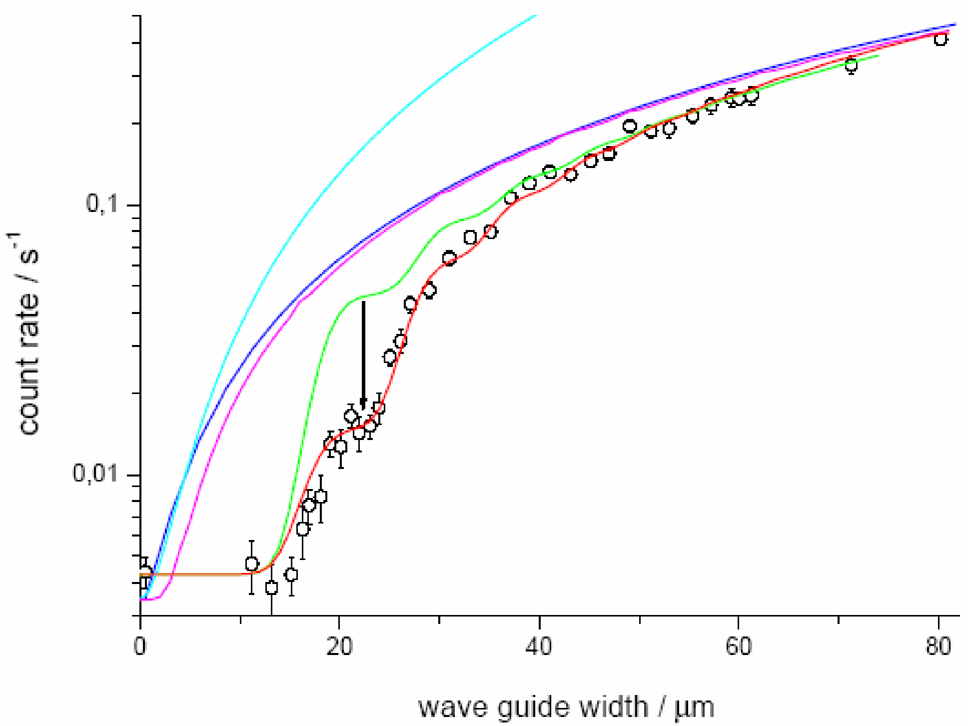
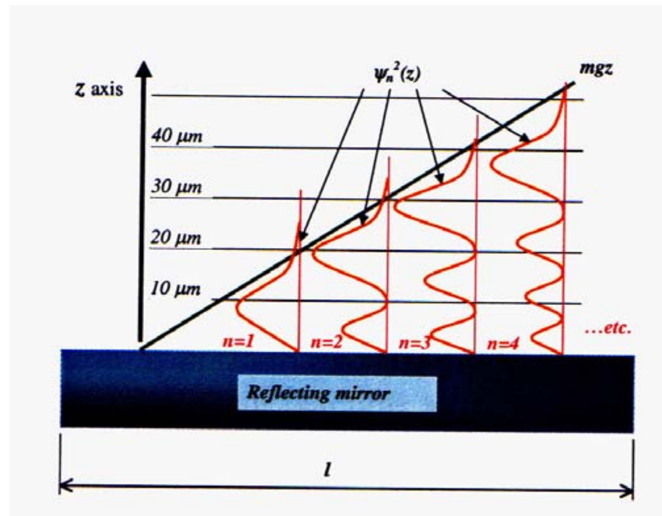
  - **Scattering Lengths**
- **Gravity**
  - **Hints of strings/Membranes?**

Standing Waves of Ultra Cold Neutrons in a gravitational field







What's needed ?

Physics Topics	High Power Proton Driver ~ 1GeV	High Power Proton Driver ~ 30 GeV
➢ **The Nature of Neutrinos**		
➢ Oscillations / Masses / $0\nu2\beta$-decay	$\otimes$	$\otimes$
➢ **T and CP Violation**		
➢ edm's, D (R) coeff. in β-decays, D^0	$\otimes$	$\otimes$
➢ **Rare and Forbidden Decays**		
➢ $0\nu2\beta$-decay, n-n^{bar}, M-M^{bar}, $\mu\rightarrow e\gamma$,	$\otimes$	
➢ $\mu \rightarrow 3e$, $\mu N \rightarrow N e$	$\otimes$	
➢ **Correlations in β-decay**		
➢ non V-A in β-decay	$\otimes$	
➢ **Unitarity of CKM-Matrix**		
➢ n-, π-β, (superallowed β), K-decays	$\otimes$	$\otimes$
➢ **Parity Nonconservation in Atoms**	-	-
➢ Cs, Fr, Ra, Ba^+, Ra^+		
➢ **CPT Conservation**		
➢ n, e, p, μ	$\otimes$	$\otimes$
➢ **Precision Studies within The Standard Model**		
➢ Constants, QCD, QED, Nuclear Structure	$\otimes$	$\otimes$

Summary Trento ‘Fundamental Interactions’ Workshop, June 2004

Experiments requiring Theory

Atomic ParityViolation: New Physics potential ?
Atomic Theory?
EDMs: Schiff moments of deformed nuclei ?
Relation of forw.scatt. to fundamental issues
$0\nu2\beta$ experiments:
Nuclear Matrix elements
g-2 experiments:
hadronic corrections
CPT: What are small
numbers good for?
. . .

Theory requiring Experiments

Schiff moments for EDM exp. (Ra,Rn)
Nature of neutrinos: Dirac/Majorana
Confirmation of HDM $0\nu2\beta$ expt.
CP violation for neutrinos
direct neutrino mass measurements
Variation of α ?
Values of fundamental Const.
Hadronic vac. polarization
Cosmic background ν’s
. . .

Physics Issues

Fundamental Symmetries
& Interactions

Forces &Symmetries
Fundamental Fermions
Discrete Symmetries
Properties of known Interactions

Atomic Parity Violation:
Bohr-Weiskopf Effect,
Breit Interaction
β-decay:
Atomic Shell Corrections ?
Variation of constants other than α

Loose Ends

Less Urgent Activities

Conclusions

- Large number of Possibilities to
  - Find Physics Beyond Standard Theory
  - Determine Standard Model important Parameters
- Urgent issues to be solved in Theory and Experiment
- In the area of Fundamental Symmetries and Interactions there is large overlap between Astro-, Particle-, and Nuclear- Physics

  $\Rightarrow$ Fields merge

  $\Rightarrow$ Low energy Precision and High Energy Direct approaches are complementary
- Enourmous benefit from a High Power Proton machine expected
- Coordinated approaches could be well beneficial

Let's just do it √

Thank YOU !

Fundamental Symmetries and Interactions

Drawing on :

- **Work of NuPECC Long Range Plan Working group on Fundamental Interactions, 2003 :**

  K. Jungmann (NL), H. Abele (D), L. Corradi (I), P. Herczeg (USA), I.B. Khriplovich (RU), O. Nviliat (F), N. Severijns (B), L. Simons (CH), C. Weinheimer (D), H.W. Wilschut (NL) H. Leeb (A), C. Bargholtz (S)

  Assisted by: W. Heil, P. Indelicato, F. Maas, K. Pachucki, R.G Timmermans, C. Volpe, K. Zuber

- **NSAC Long Range Plan 2002**
- **EURISOL Physics Case 2004**
- **Workshop on “Fundamental Interactions“ at ECT*, June 21-25, 2004**

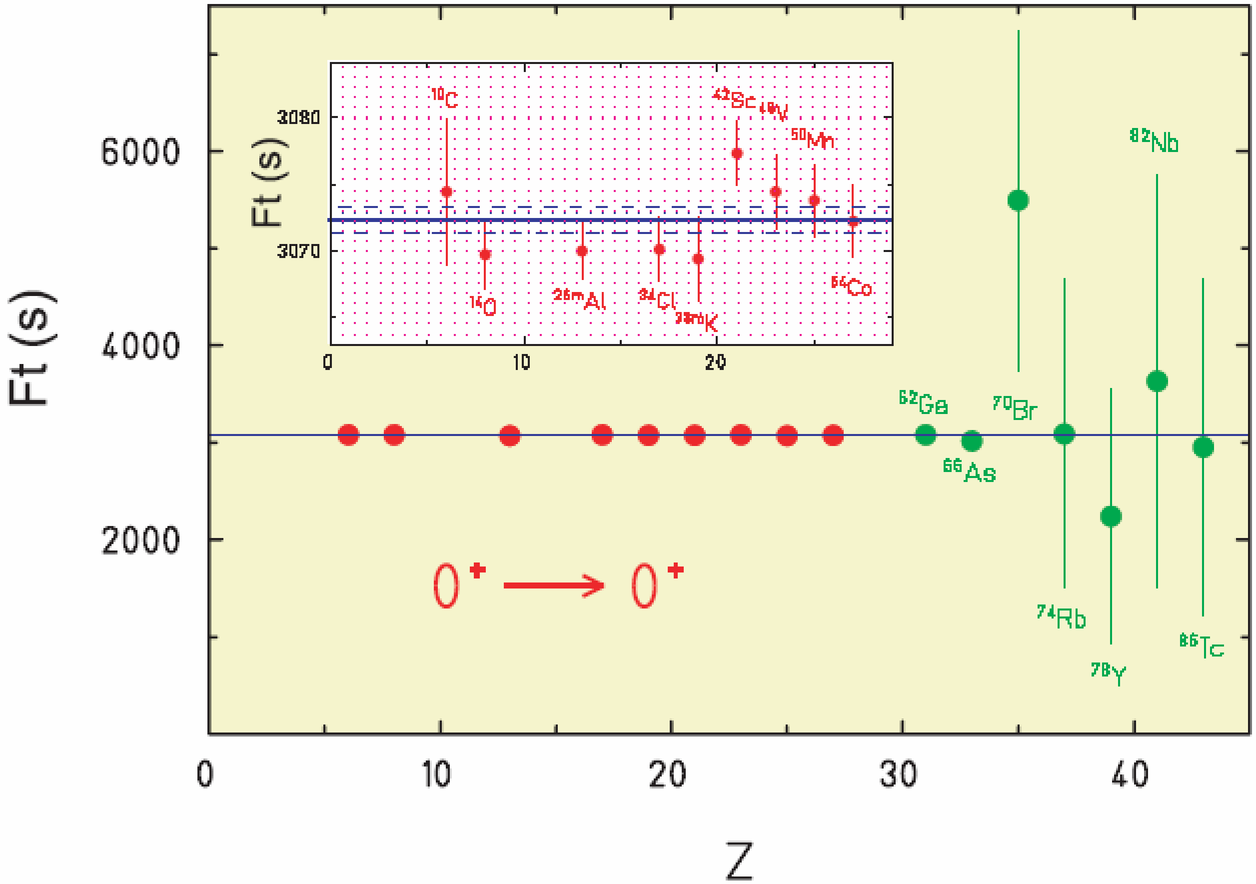


Fig. 42: Super-allowed 0+ → 0+ transitions which allow us to test the CVC hypothesis of the weak interaction. The values for the heavier nuclei have been measured using the relatively weak intensities from present radioactive beam facilities. Using these data to check the theoretically determined corrections needs higher statistical precision.

EDM: What Object to Choose ?

particle	limit on edm $|d|$ [e cm] (95% C.L.)	system	improvement factor	new physics limits [e cm]
e	1.9×10^{-27}	^{205}Tl	> 1	10^{-27}
μ	1.05×10^{-19}	rest frame E	10^3	10^{-22}
τ	3.1×10^{-16}	$(e^+e^- \to \tau^+\tau^-\gamma)$	10^4	10^{-20}
p	6.5×10^{-23}	^{205}Tl-F	10^4	5×10^{-26}
n	7.5×10^{-26}	ultracold neutrons	> 1	5×10^{-26}
Λ	1.5×10^{-16}	rest frame E	10^7	10^{-23}
^{199}Hg	2.1×10^{-28}	^{199}Hg	> 1	10^{-28}
Ξ^0	?	as Λ	?	10^{-23}

Table 1: Current limits on edm's, converted to a common 95% confidence limit. The improvement factor indicates how much the measurement needs to be improved to yield new physics limits. No data in the charmed sector

Precession frequency ω due to a particle with anomalous magnetic moment $a = g/2 - 1$ and edm d

$$\omega = -\frac{e}{m}\left[a\mathbf{B} - a\frac{\gamma}{\gamma+1}\mathbf{v}(\mathbf{v}\cdot\mathbf{B}) - \left(a - \frac{1}{\gamma^2-1}\right)\mathbf{v}\times\mathbf{E}\right]$$
$$-\frac{d}{2}\left[\mathbf{E} - \frac{\gamma}{\gamma+1}\mathbf{v}(\mathbf{v}\cdot\mathbf{E}) + \mathbf{v}\times\mathbf{B}\right]$$

^{205}Tl: $d = -585\, d_e$

^{199}Hg:

$d \propto$ nucl$\times$atom

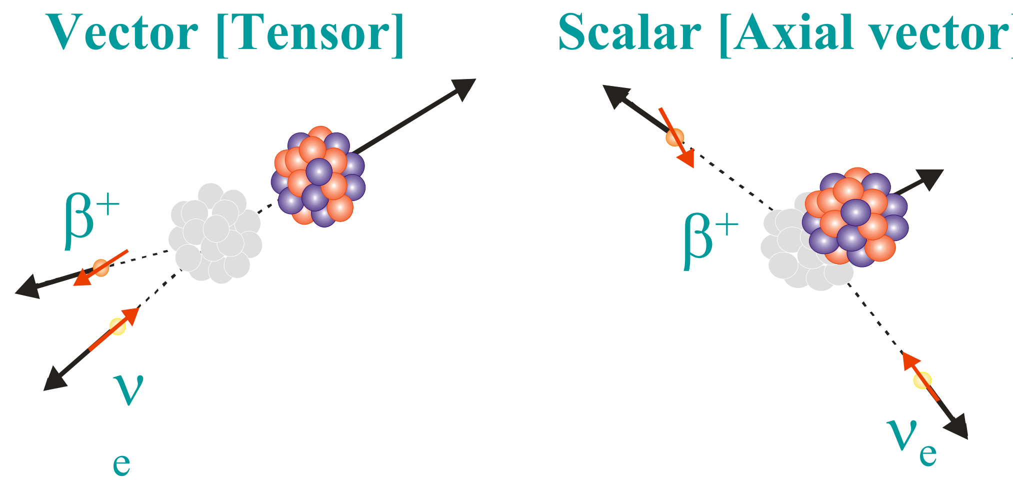
Ra: Ra/Hg=$(10^{>1})(10^{>3})$

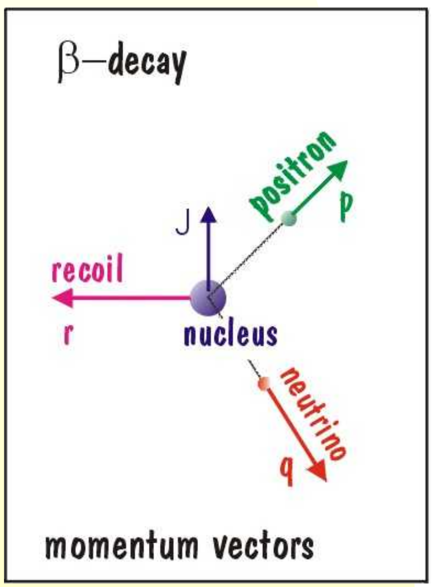
Theoretical input needed

New Interactions in Nuclear and Muon β-Decay

In Standard Model:
Weak Interaction is
V-A

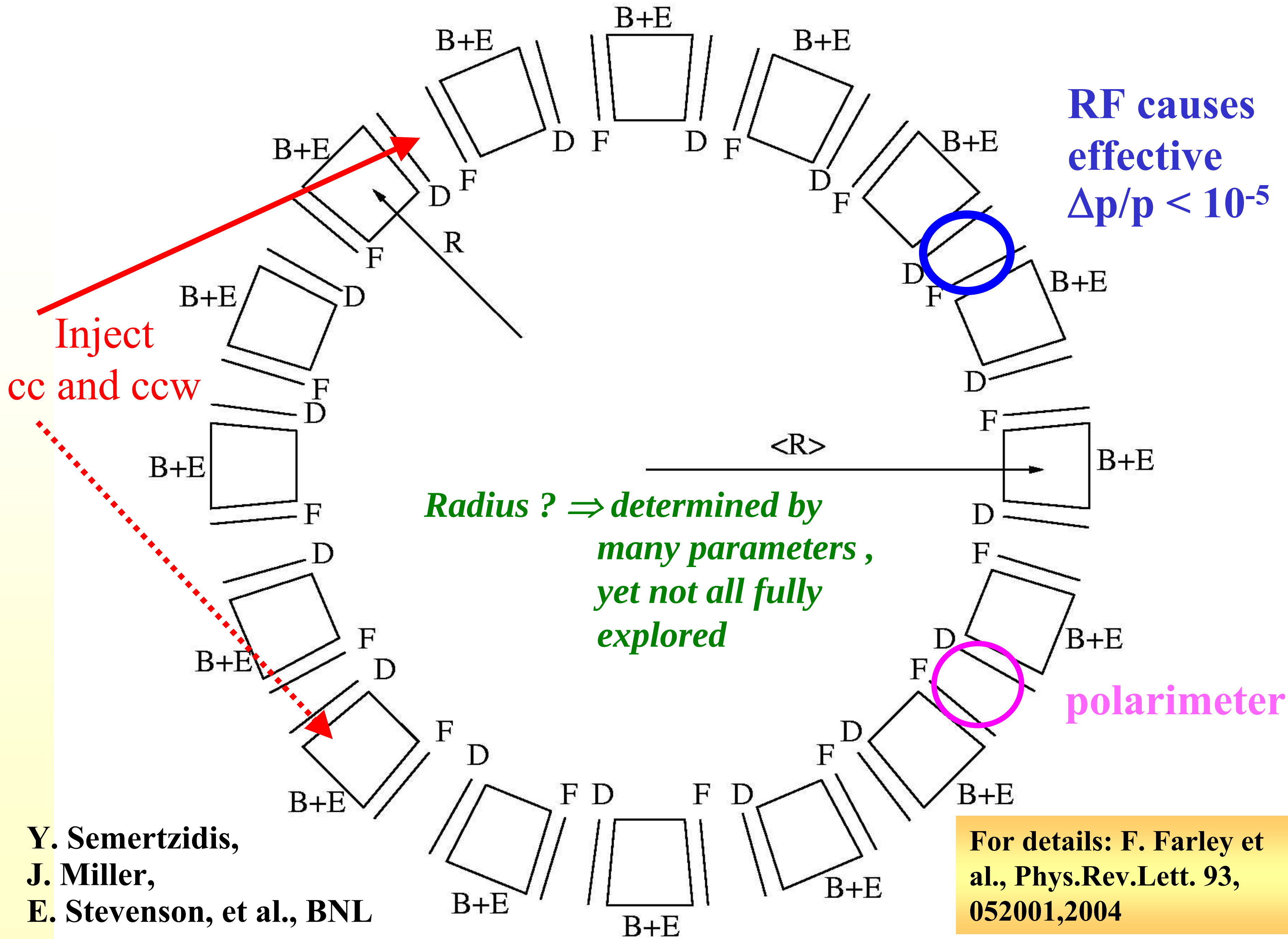
In general β-decay
could be also
S , P, T





$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\,\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\,\Gamma\,\frac{m_e}{E} + \langle \boldsymbol{J}\rangle \cdot \left[A\,\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\,\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E}\right] + \langle \boldsymbol{\sigma}\rangle \cdot \left[G\,\frac{\boldsymbol{p}}{E} + Q\,\langle \boldsymbol{J}\rangle + R\,\langle \boldsymbol{J}\rangle \times \frac{\boldsymbol{p}}{E}\right]$$

⇒ nuclear β-decays, Experiments in Traps
⇒ muon decays, Michel parameters

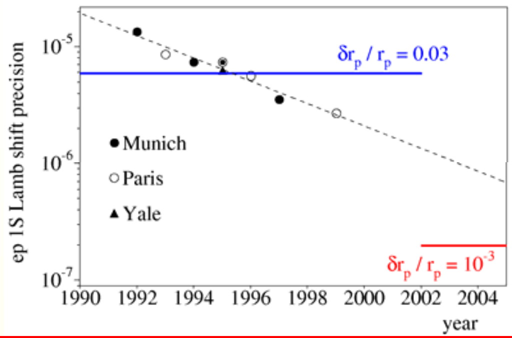


Y. Semertzidis,
J. Miller,
E. Stevenson, et al., BNL

For details: F. Farley et al., Phys.Rev.Lett. 93, 052001,2004

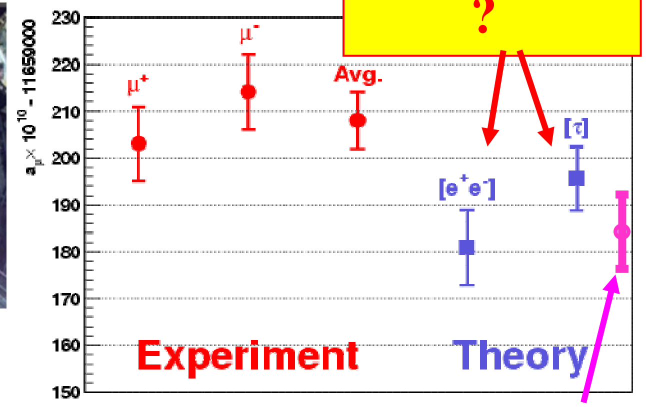
Properties of known Basic Interactions

"Proton Radius"



Muonic Hydrogen Lamb Shift

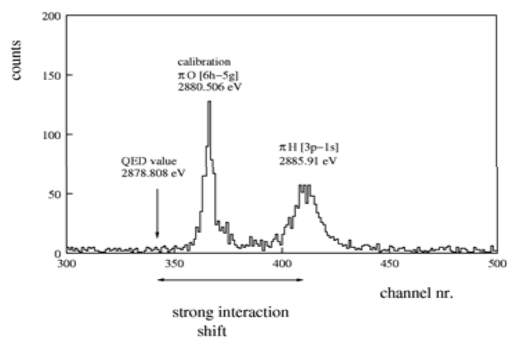
Muon g-2



ρ^0, ρ^+ mass difference overlooked ?

Newest Theory Offer:
2.4 σ from Experiment

Strong Interaction Shift



Pionic Hydrogen

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- $e^+ + e^- \rightarrow \gamma$ + hadrons

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