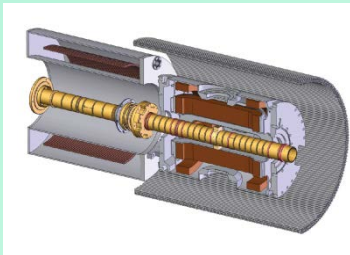
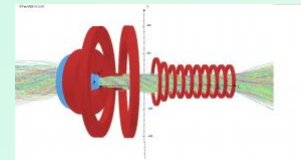
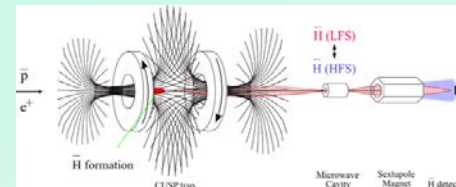
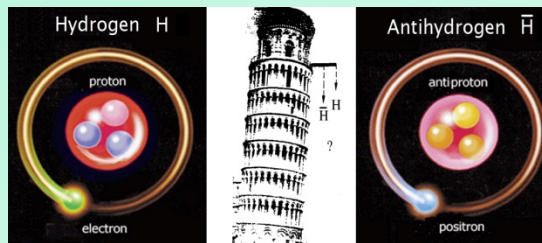
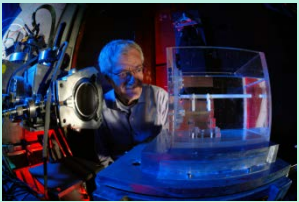
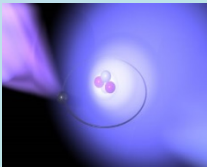
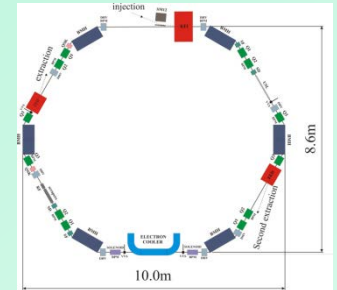




Experimental Overview of Testing Fundamental Symmetries

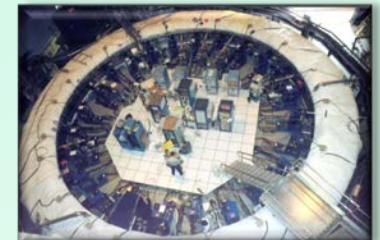
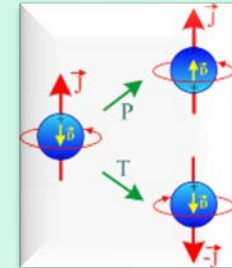
- What's new?
- What can we do next ?
- What's needed to be done ?
- Where come anti-protons in ?





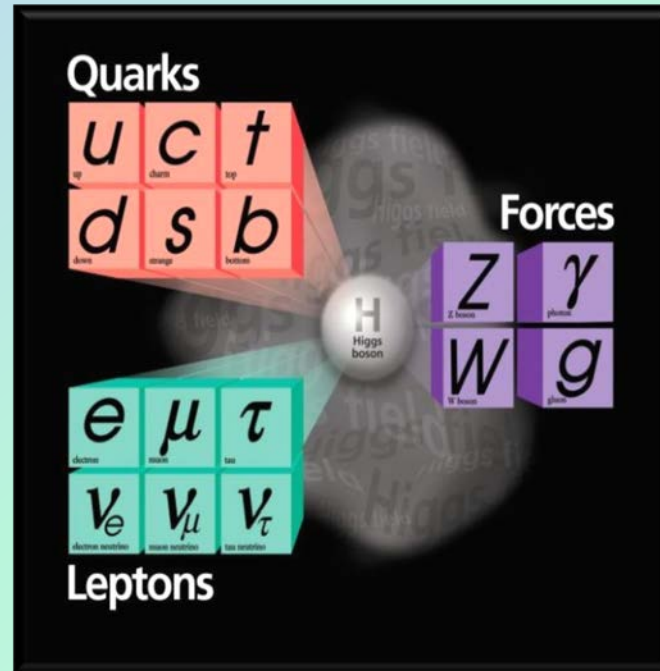
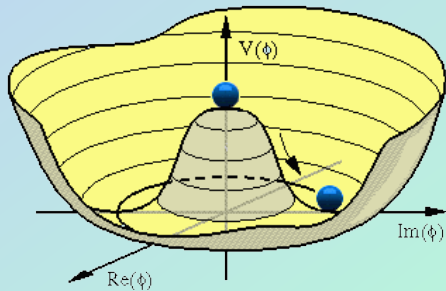
Experimental Overview of Testing Fundamental Symmetries

- LHC finds Higgs! – Standard Model Complete ! → Major Success !
- What next? - High energy? - High precision? → Not everything !
- Gravity
- Lorentz Invariance
- Discrete Symmetries CPT, C, P, T, CP
 - Pbar Experiments, EDMs, Parity Violation
- Global Symmetries B,L ; Flavour Symmetries
 - $2\beta 0\nu$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu N \rightarrow eN$, $\mu^+e^- \rightarrow \mu^-e^+$
- Precision tests of Standard Model
 - Neutrinos, Constants, Muon Magnetic Anomaly ...

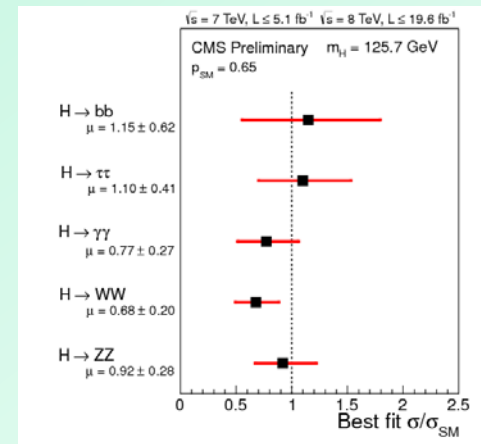
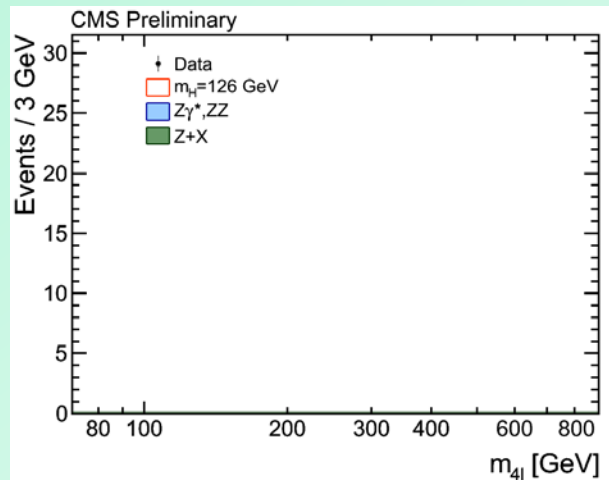
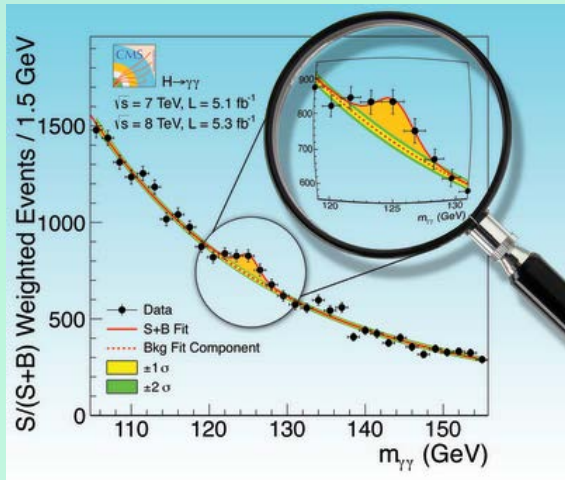


- **A Theory is only as good as it is experimentally verified.**
- **A Theory without experimental verification has no standing.**
- **An Experiment that verifies what is known already - is education.**

All Standard Model Particles are there !



**Biggest Surprise:
No Surprise**



What Next ?

- Some: Worry who gets a price .
 - Some: New machines at higher energies to go beyond SM.
 - Some: Look precisely and search for deviations from SM.
 - Some: Fill in the remaining understanding of details.
- All legitimate and important for progress !
- No *natural* way to be preferred ! Let's look at some possibilities.
- By the way: Every Precision Experiment has a discovery potential.
Independent whether there is or Not a Theory, yet.

The Standard Model(s)

Elementary Particles				
Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	g gluon
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Leptons	e electron	μ muon	τ tau	W W boson
I II III			Force Carriers	
Three Families of Matter				

- **Excellent Description of ALL Observations**
- **However, many Open Questions**

Why 3 generations ?

Why some 30 parameters?

Why one electric charge ?

What about CP violation ?

Why matter-antimatter asymmetry?

.....

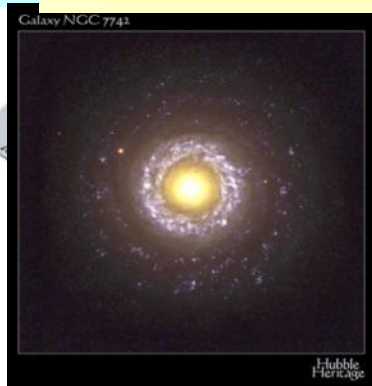
- **Gravity not included**

No Combine Theory of Gravity and Quantum Mechanics.

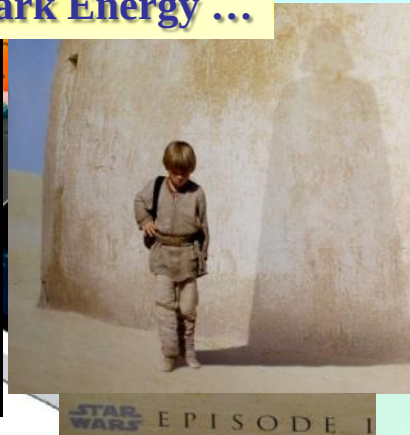
- **Contents of the Cosmos**

What's the other 96% beyond matter ?

Dark Matter – Dark Energy ...



© Hu & White Scientific American 2004



Anti-Protons

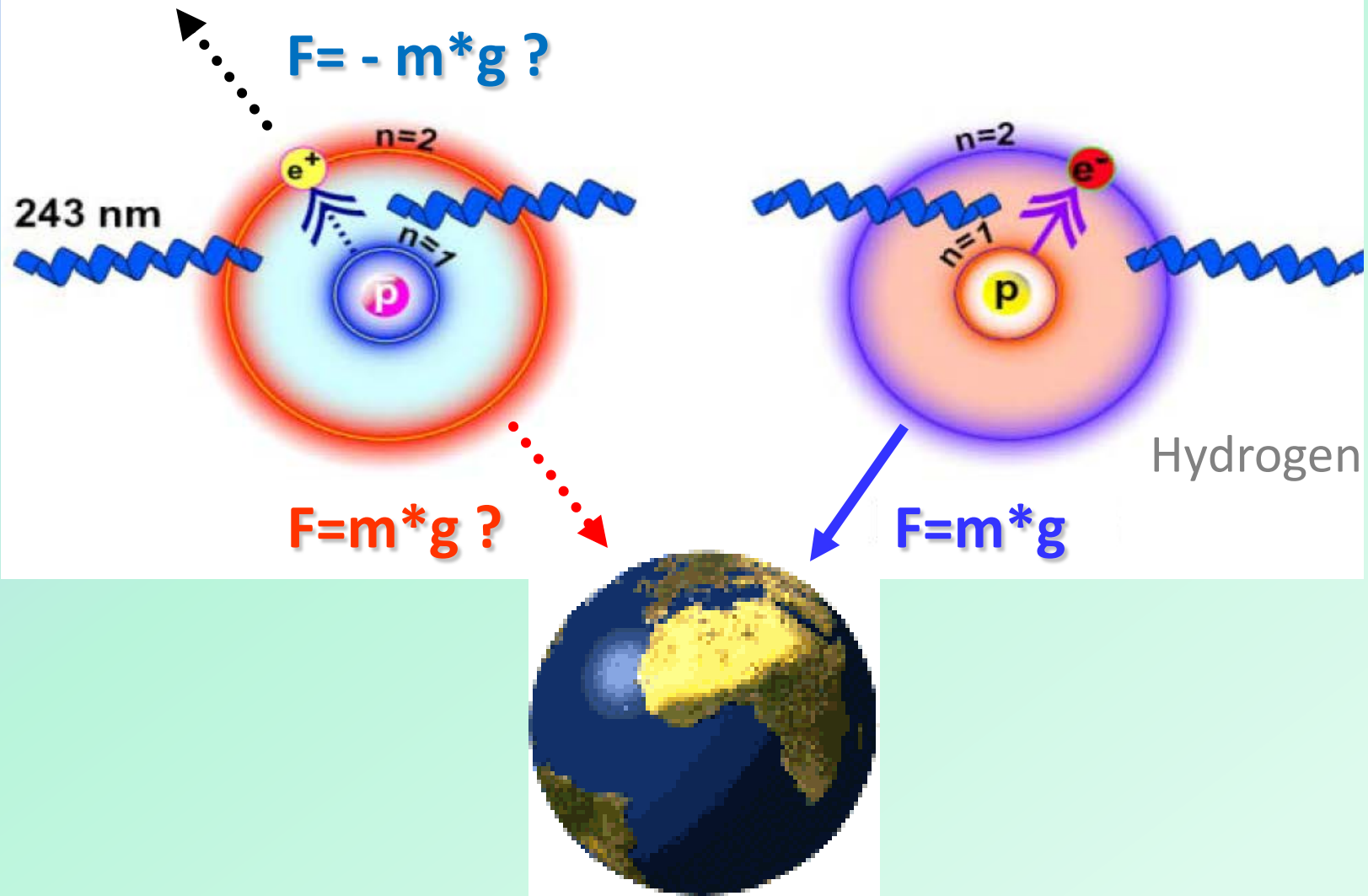
- **CPT Tests**
(anti-hydrogen, 1S-2S, 1S HFS)
- **Elementary Physics**
(Does antimatter fly up?)
- **Fundamental Constants**
(masses, magnetic moments, charges, ...)
- **Here: Few Examples Only**
(without prejudice – we have all week to find out)
- **Few Non- $\bar{p}$ Examples also**

Gravity

- Little known
- Combination with Quantum Mechanics ?
- Anti-matter Gravity ?



(Anti-)Hydrogen Gravity Tests

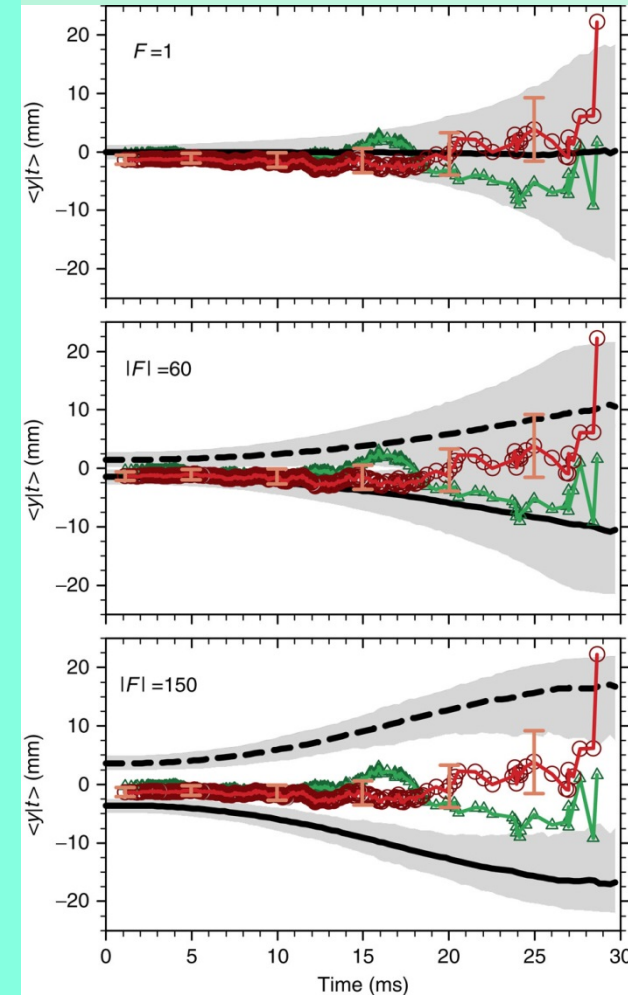
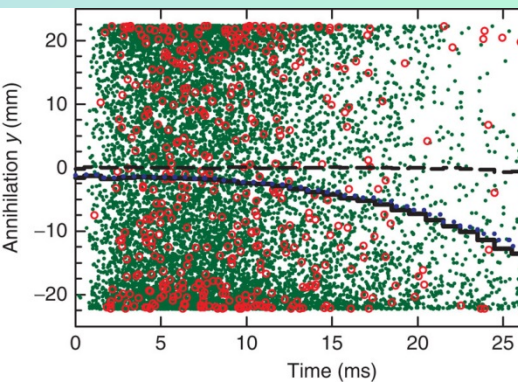
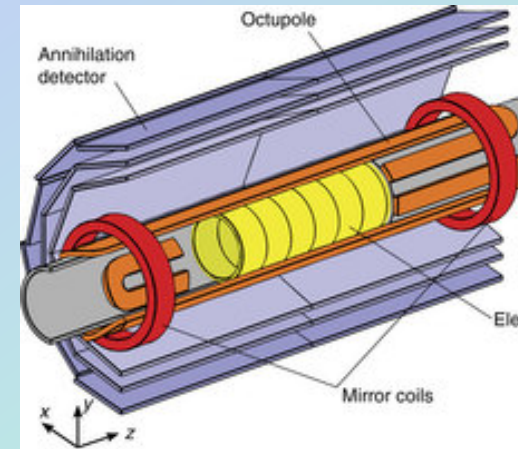


Unique Possibility

Anti-Hydrogen Gravity

Based on data *excluded*:
... the possibility that the
gravitational mass
of antihydrogen is
more than 110 times
its inertial mass.

Also *excluded*
that it *falls upwards*
with a gravitational
mass *more than 65*
times its inertial
mass.



The ALPHA Collaboration & A. E. Charman,
Nature Communications 4, 1785, 30 April 2013

Discrete Symmetries

C,P,T,CP,CPT

Anti-Proton Magnetic Moment

PRL 110, 130801 (2013)

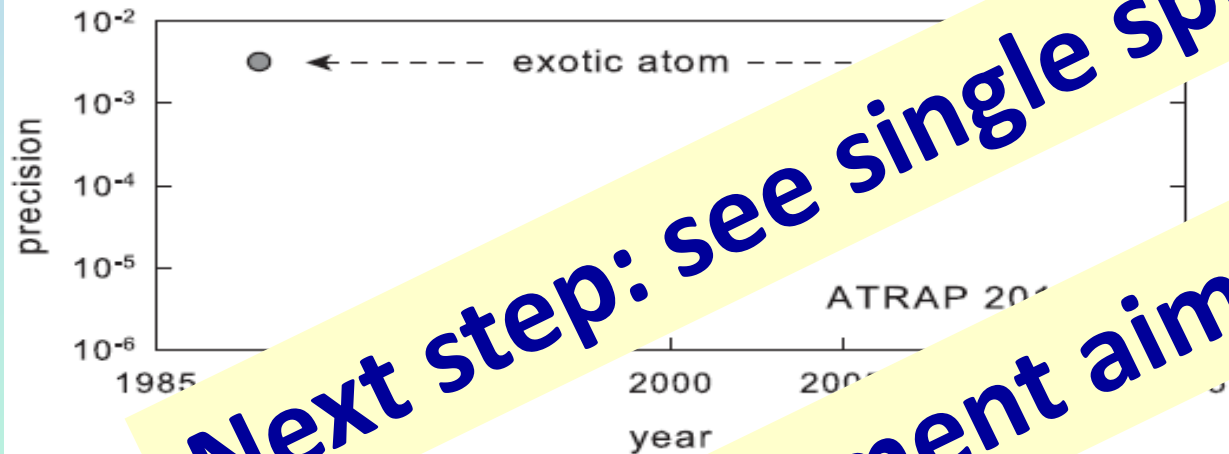
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
29 MARCH 2013

One-Particle Measurement of the Antiproton Magnetic Moment

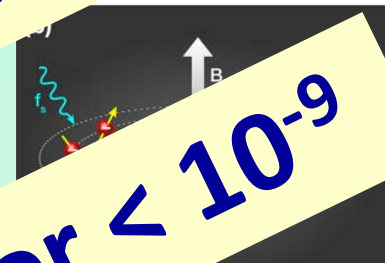
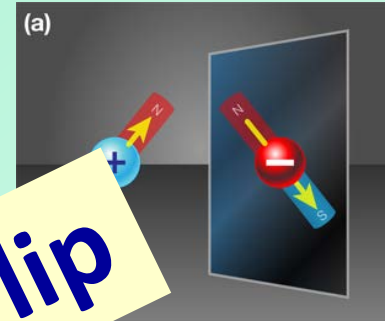
J. DiSciaccia,¹ M. Marshall,¹ K. Marable,¹ G. Gabrielse,^{1,*} S. Ettenauer,¹ E. Tardiff,¹ R. Kalra,¹ D. W. Fitzakerley,²
M. C. George,² E. A. Hessels,² C. H. Storry,² M. Weel,² D. Grzonka,³ W. Oelert,^{3,4} and T. Seifick³

$$\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005 \text{ to } 5 \text{ ppb}$$

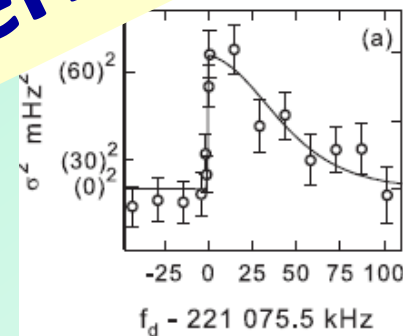
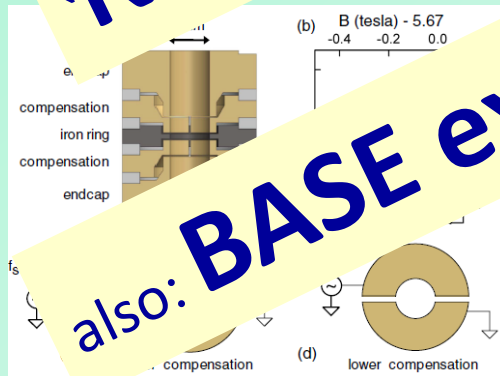


Next step: see single spin flip

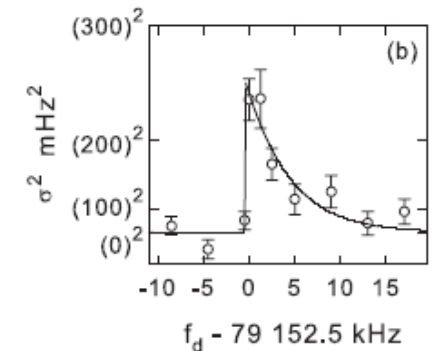
also: BASE experiment aims for $< 10^{-9}$



Viewpoint:
Antiprotons Reflect a Magnetic Symmetry
E.R. Hudson, D. Saltzberg,
Physics 6, 36 (2013)

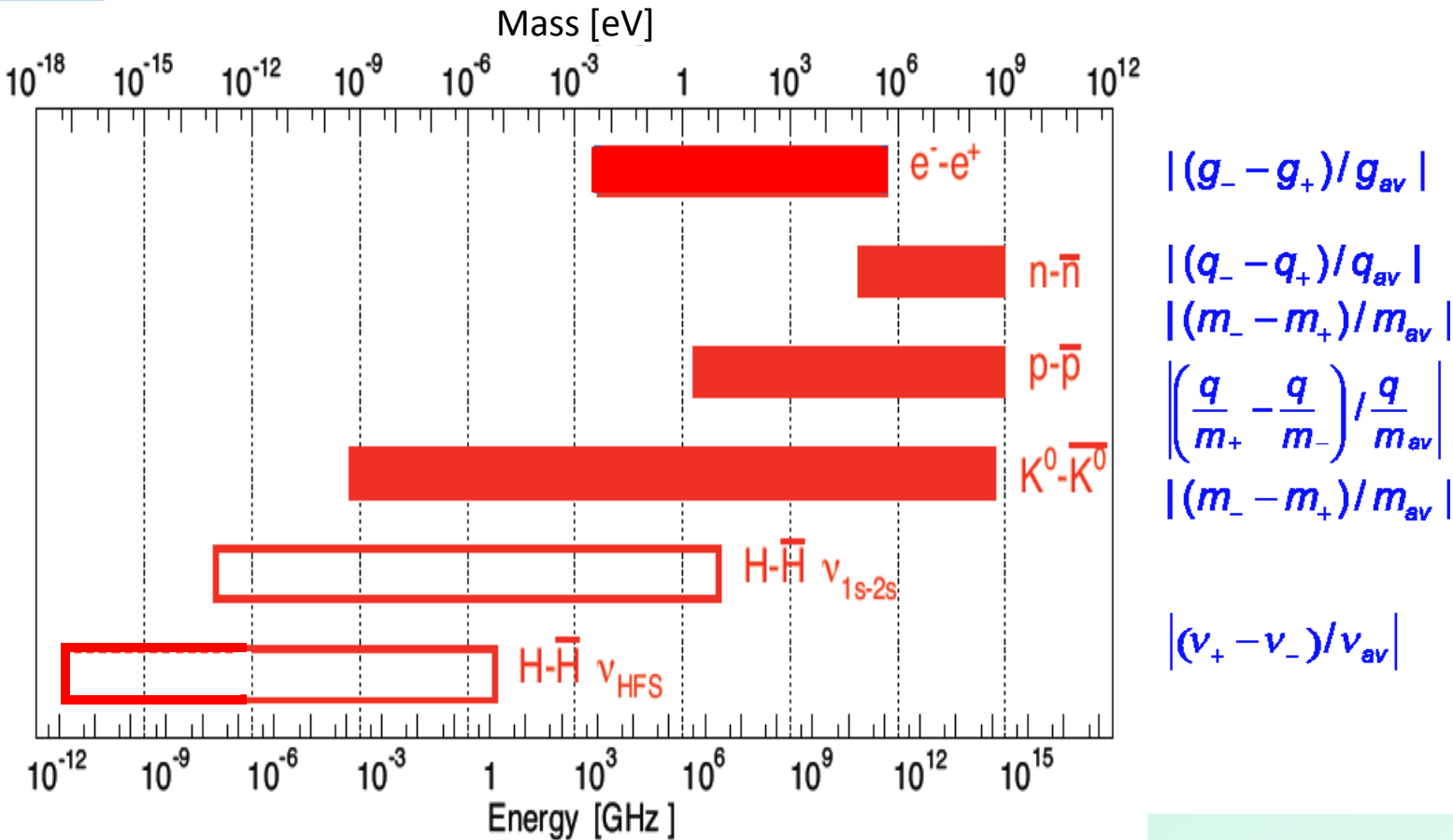


excitation fraction



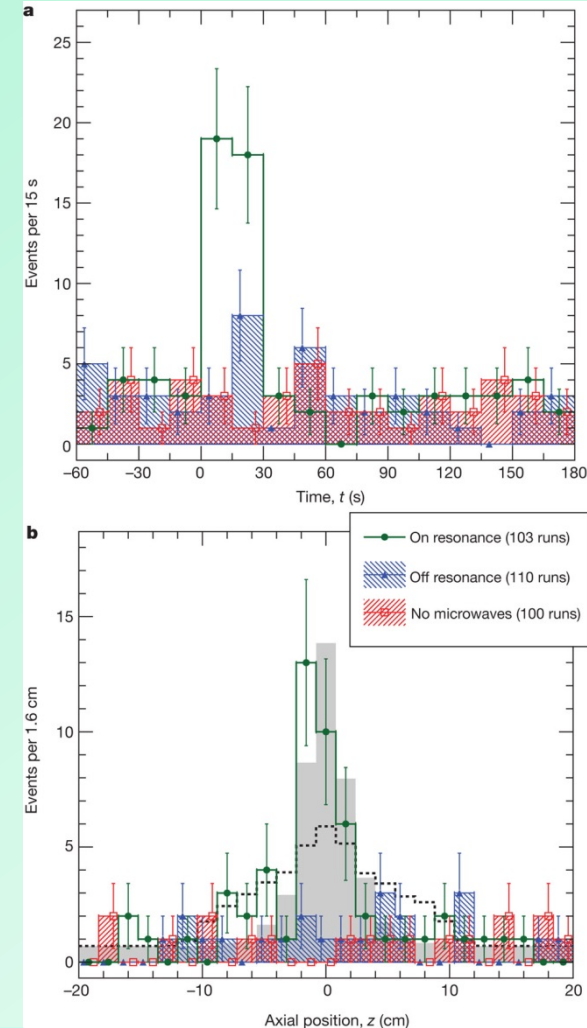
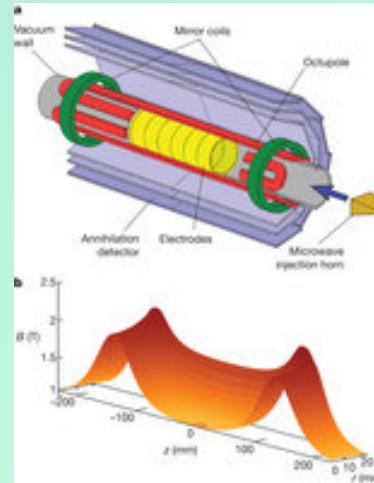
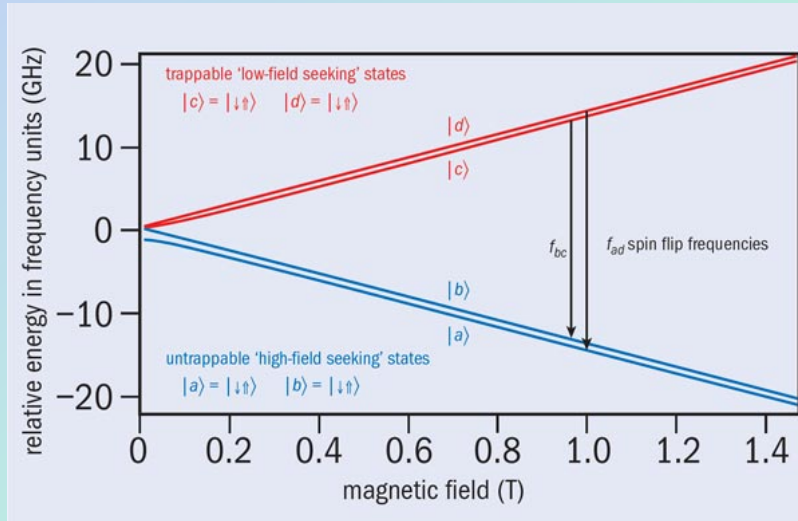
Verifications of **CPT** symmetry

Using the Kostelecky *et al.* Standard Model Extension scheme



Anti-Hydrogen Hyperfine Structure

First spectroscopy of an Anti-Atom



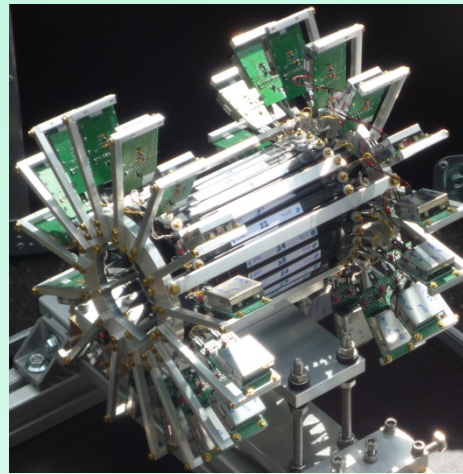
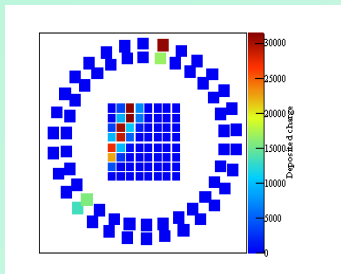
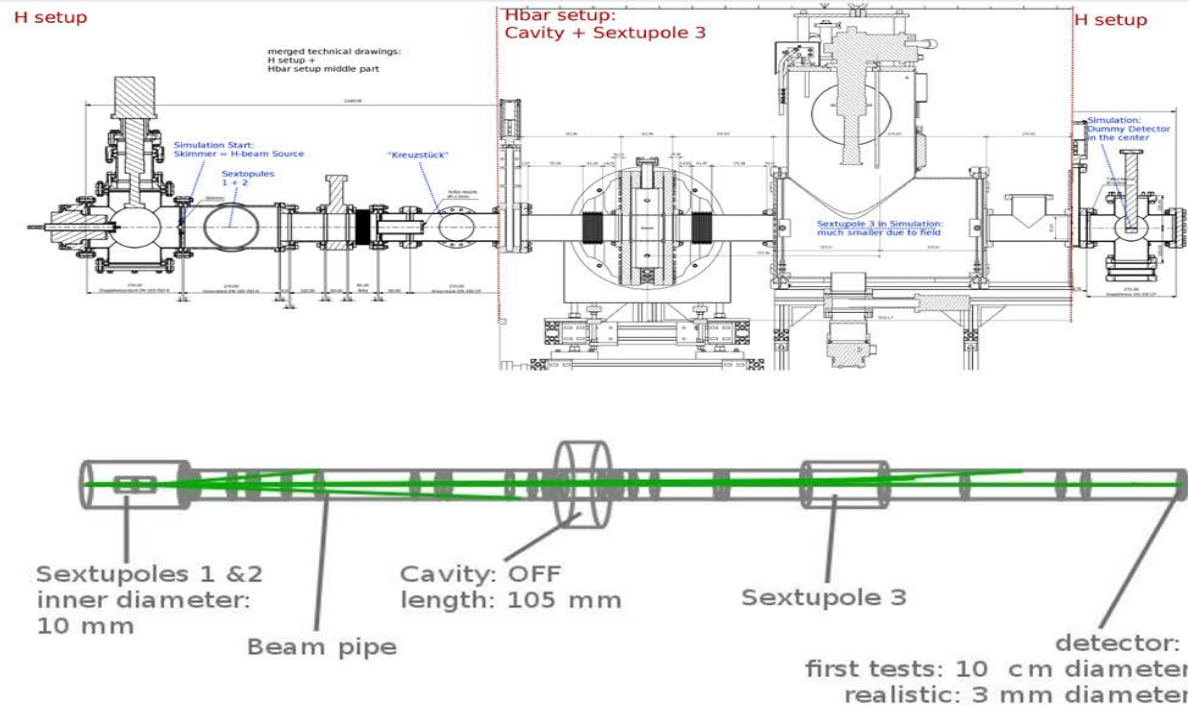
“...resonant microwave radiation to flip the spin of the positron in antihydrogen ...”

“... spin flip causes trapped anti-atoms to be ejected ...”

C. Amole et al. Nature 483, 439–443 (22 March 2012)

Anti-Hydrogen Hyperfine Structure

Rabi Apparatus



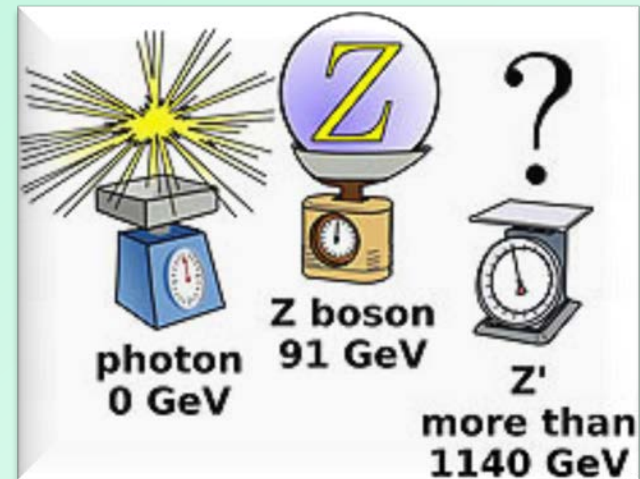
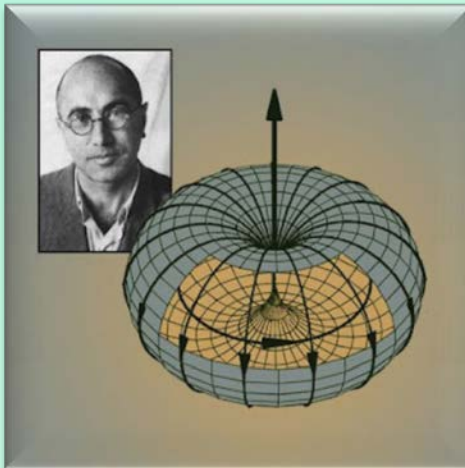
**ASACUSA
Collaboration**

E. Widmann, Y. Yamazaki et al.

Parity

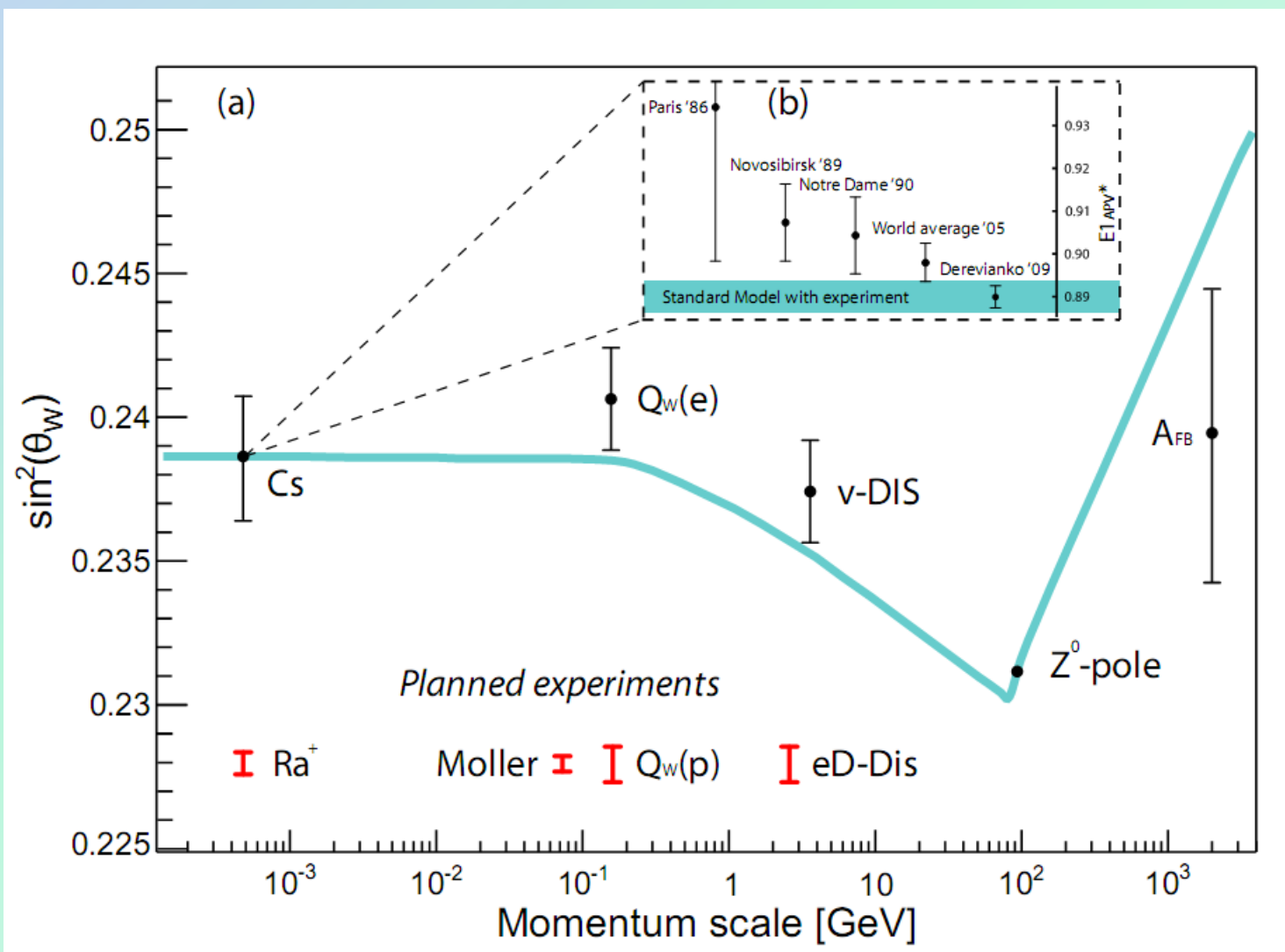
In Atoms

- *n– distribution , anapole moment*
- *Search for New Physics (Z', leptoquarks, ...)*
- *Running of Weinberg angle ($\sin^2 \theta_w$)*



Atomic Parity Violation (APV)

Running of the Weinberg angle



→ Progress in theory caused data points to move

Some Recent Atomic Parity Violation Activities

Cs the Standard @ Bolder

S.C. Bennett, C.E. Wieman Phys.Rev.Lett. 59R16 (1999)

Fr atom traps @ Legnaro, ~~Stony Brook~~ TRIUMF

G. Stancari et al. E.Phys.J. 150, 389 (2007); G. Gwinner et al., Hyperf. Int. 172, 45 (2006)

Yb biggest APV effects observed @ Berkeley

K.Tsigutkin et al, Phys.Rev. A81, 032114 (2010)

Ba⁺ novel idea @Seattle

J.A. Sherman et al, Phys.Rev. A 78, 052514 (2008)

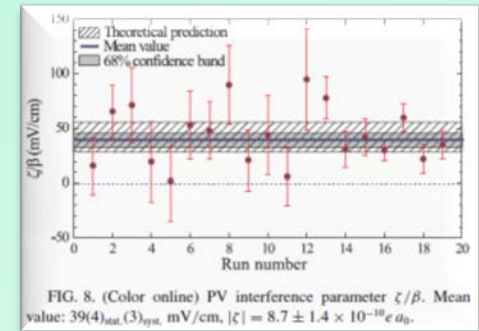
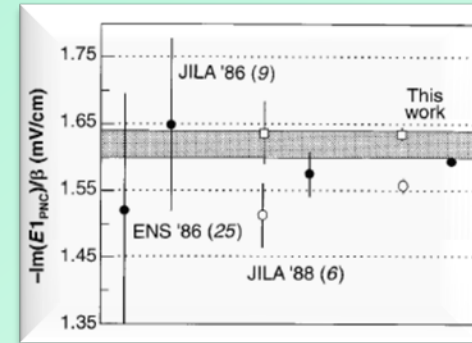
Ra⁺ advantageous system @KVI / RUG

O.O. Versolato et al., Phys. Lett. A 375, 3130 (2011)

G.S. Giri et al., Phys. Rev. A 84, 020503 (2011)

SrF NEW: slowed down SrF molecule @KVI / RUG

S. Hoekstra et al, KVI (2013)



55 Cs Cesium 132.90545	2 8 18 18 8 1
56 Ba Barium 137.327	2 8 18 18 8 2
87 Fr Francium (223)	2 8 18 32 18 8 1
88 Ra Radium (226)	2 8 18 32 18 8 2

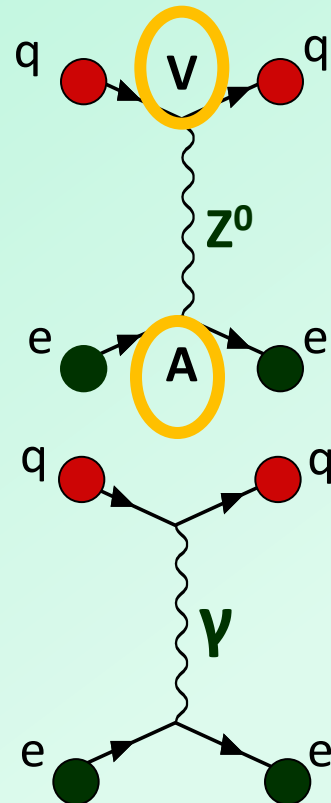
Atomic Parity Violation (APV)

Weak interaction (parity conserving and parity violating)

- Mediated by Z^0 bosons, $M_Z \approx 91 \text{ GeV}$, Range $< 10^{-18} \text{ m}$
- Atomic states acquire tiny admixture of opposite-parity states
- Strength grows *faster than* Z^3 ($\rightarrow$ Bouchiat (1974))
- Nucleus also has a *weak charge* Q_W ; all quarks add coherently

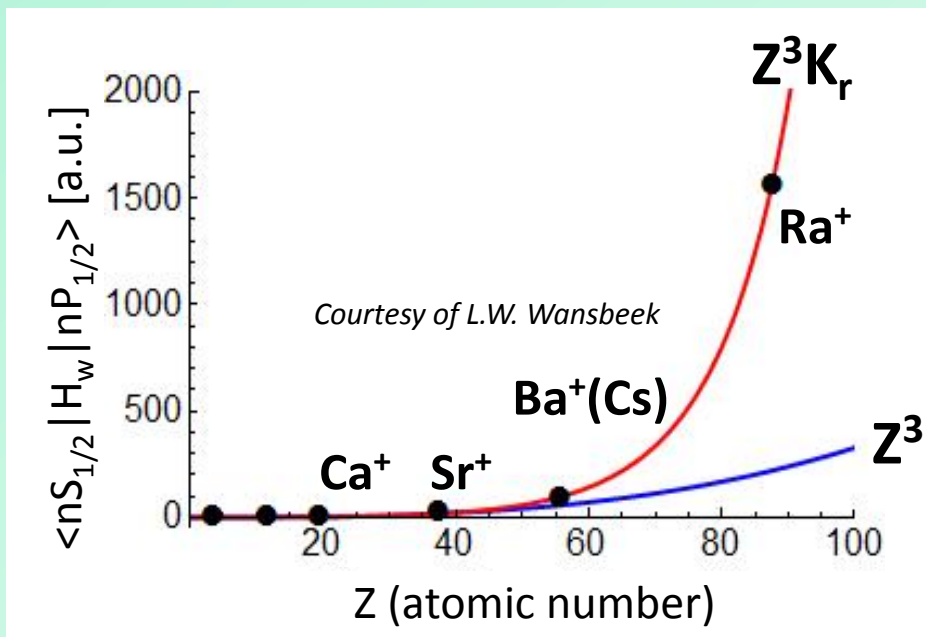
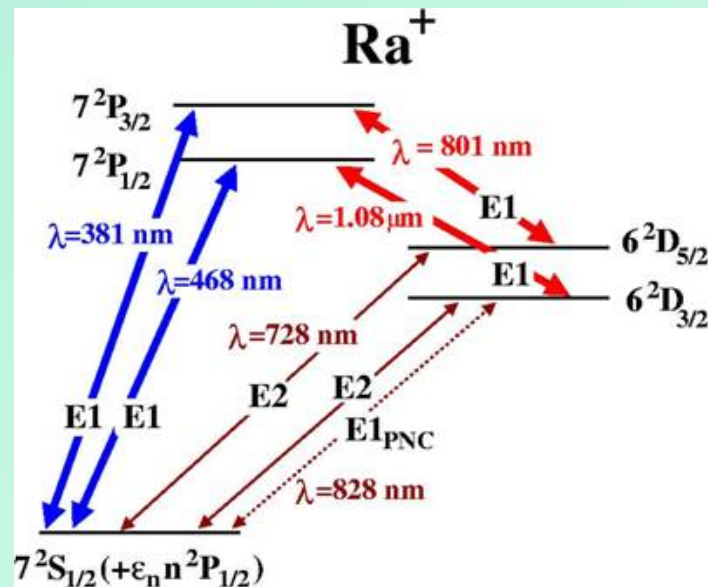
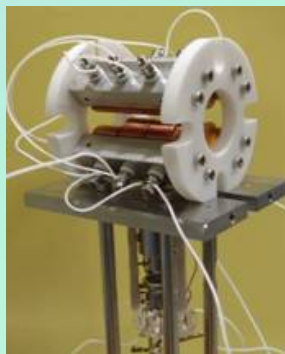
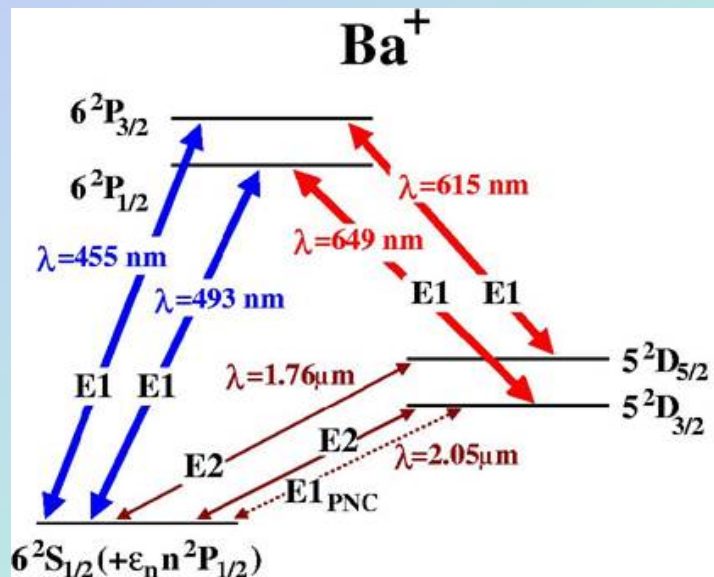
$$Q_W = -N + (1 - 4 \sin^2 \theta_W)Z + \text{rad. corr.} + \text{"new physics"}$$

- Primarily the neutrons contribute
- Tiny effects $\rightarrow$ Interference with γ exchange
- Nevertheless $\rightarrow$ Bounds on Z possible at $>5 \text{ TeV}$ (full LHC $< 4.5 \text{ TeV}$)



Atomic Parity Violation (APV)

The Best Atoms/Ions



Relative Strength

55 Cs 0.9	56 Ba 2.2
87 Fr 14.2	88 Ra 46.4

Radium for APV

Accuracy of single ion Experiment

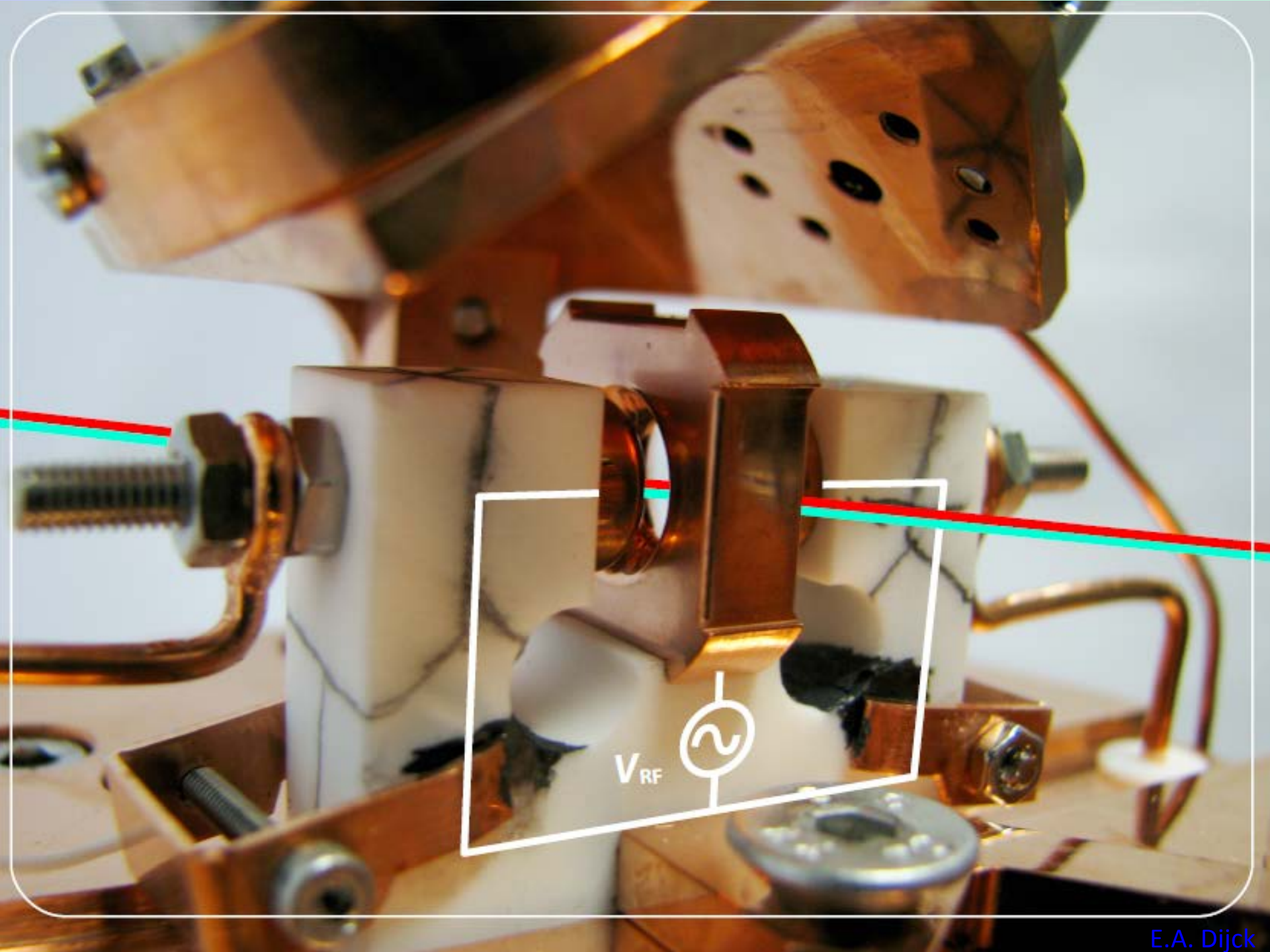
$$\frac{\mathcal{E}^{\text{PNC}}}{\delta \mathcal{E}^{\text{PNC}}} \cong \frac{\mathcal{E}^{\text{PNC}} E_0}{\hbar} f \sqrt{N \tau t}$$

E_0 = Light electric field amplitude, τ = Coherence time
 N = Number of ions = 1, t = Time of observation

	Coherence Time	Projected Accuracy	Measurement Time
Ba ⁺	80 sec	0.2%	1.1 day
Ra ⁺	0.6 sec	0.2%	1.4 day

55 Cs 0.9	56 Ba 2.2
87 Fr 14.2	88 Ra 46.4

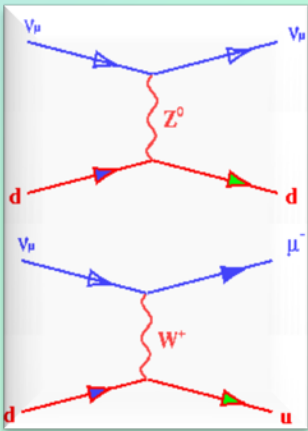
→ 10 days for 5 fold improvement over Cs



Parity

In Molecules

Molecules have close lying states of opposite parity

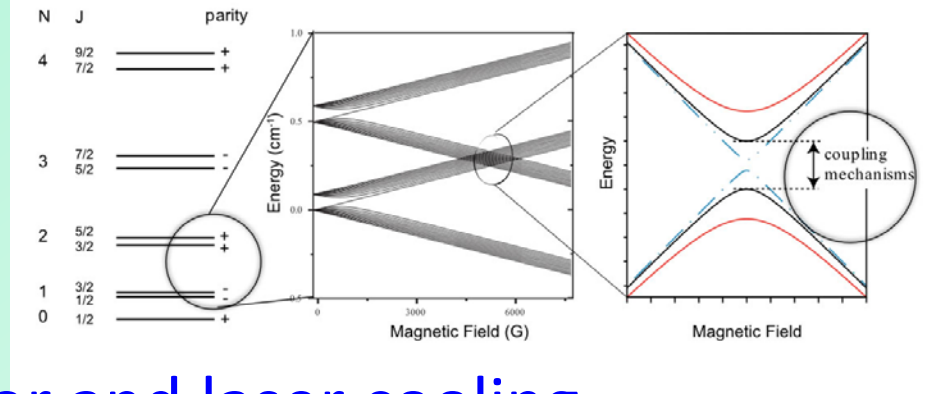


$$\left[\begin{array}{c} \text{EM} \\ \gamma \\ \text{Weak} \\ Z \end{array} \right]^2 = \left[\begin{array}{c} \text{EM} \\ \gamma \end{array} \right]^2 + 2 \left[\begin{array}{c} \text{EM} \\ \gamma \\ \text{Weak} \\ Z \end{array} \right] + \left[\begin{array}{c} \text{Weak} \\ Z \end{array} \right]^2$$

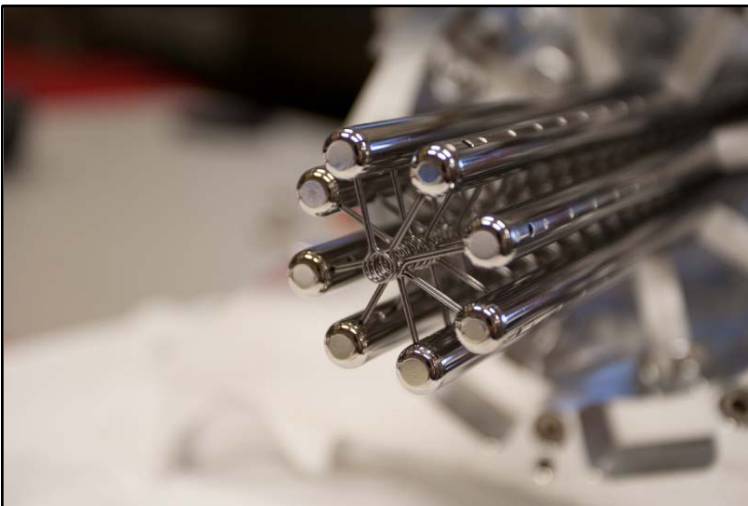
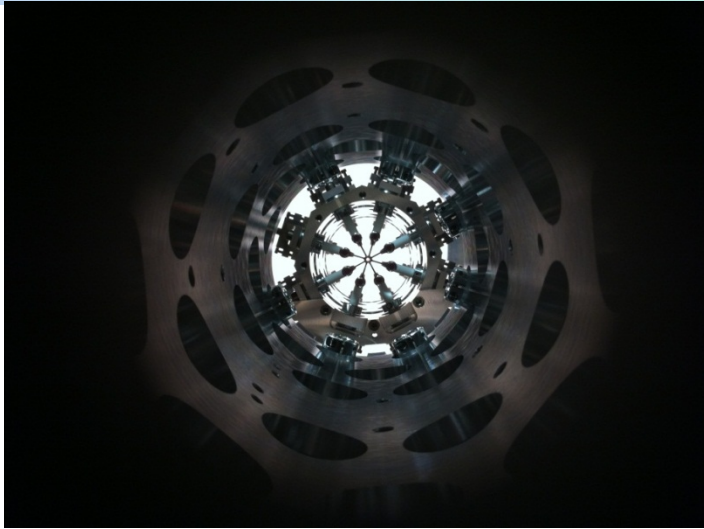
The diagram on the right illustrates the expansion of the squared sum of electromagnetic (EM) and weak interactions. It shows the squared sum of EM and Weak interactions, which is equal to the squared EM interaction plus twice the product of EM and Weak interactions (circled in blue) plus the squared Weak interaction.

Precision Measurements with Molecules

- Heavy diatomic molecules (SrF , RaF ,..) are suitable for precision measurements (parity violation, eEDM)
- Large enhancement due to almost degenerate rotational levels
- Ultracold molecules by a traveling wave decelerator and laser cooling
- Benefit from the long interaction time provided by a cold, trapped sample



Traveling wave decelerator

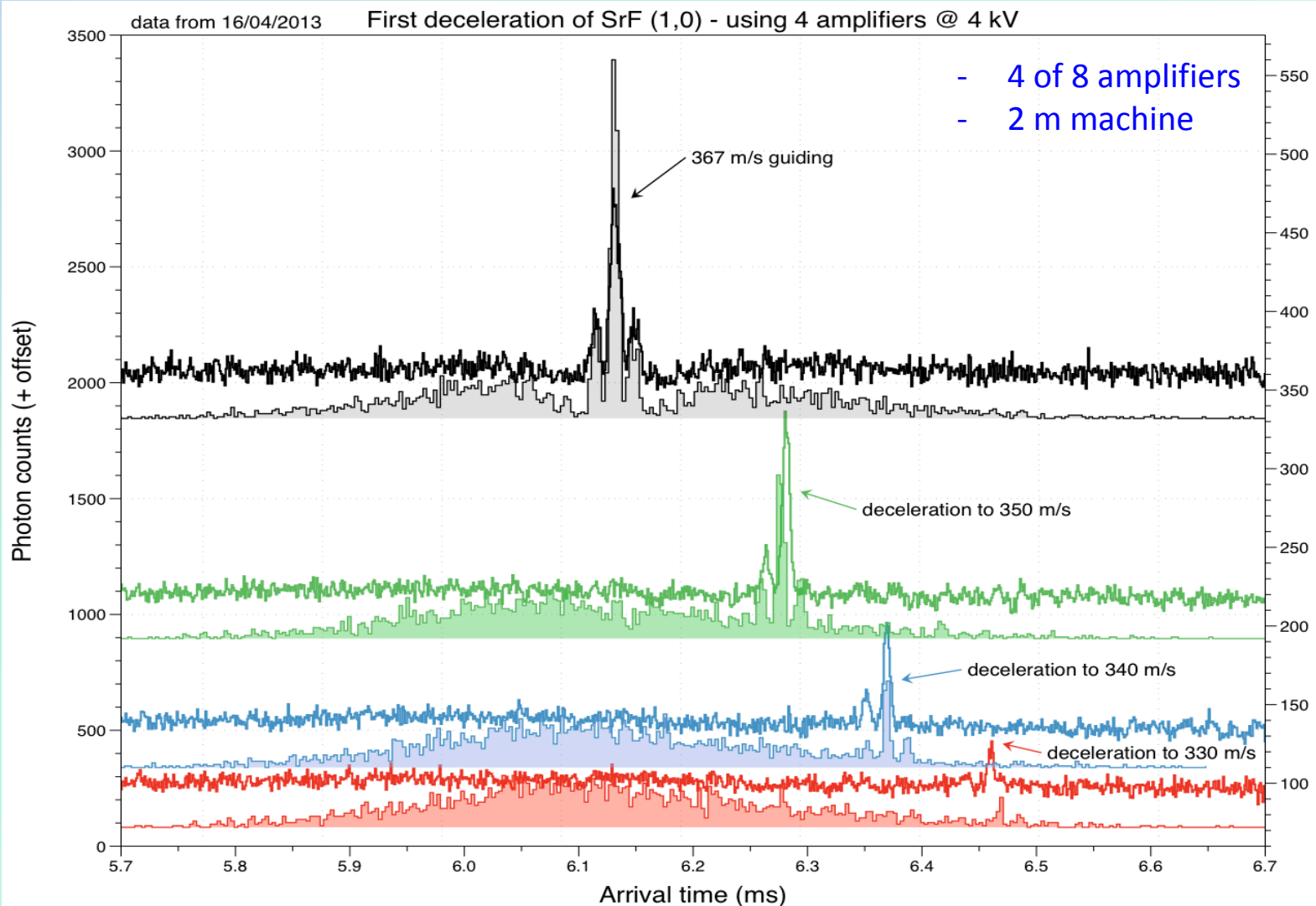


5 m of decelerator
10 modules of 50 cm
3360 ring electrodes
diameter electrode: 4 mm

SrF Slowed Down

Signal and Simulations

Laser



Fundamental Physics

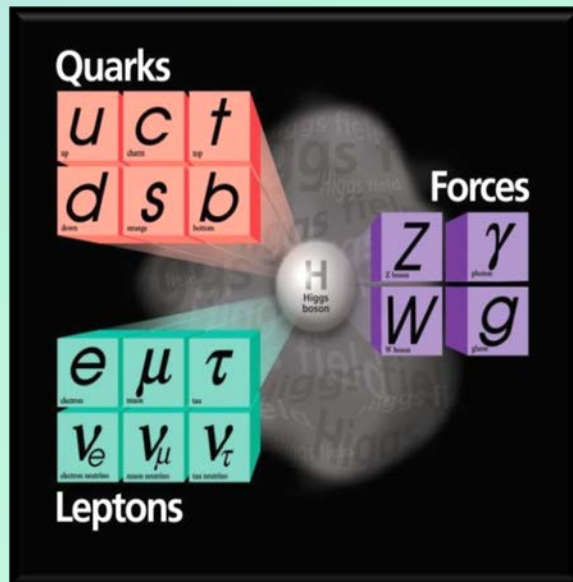
Applied Physics

go hand in hand

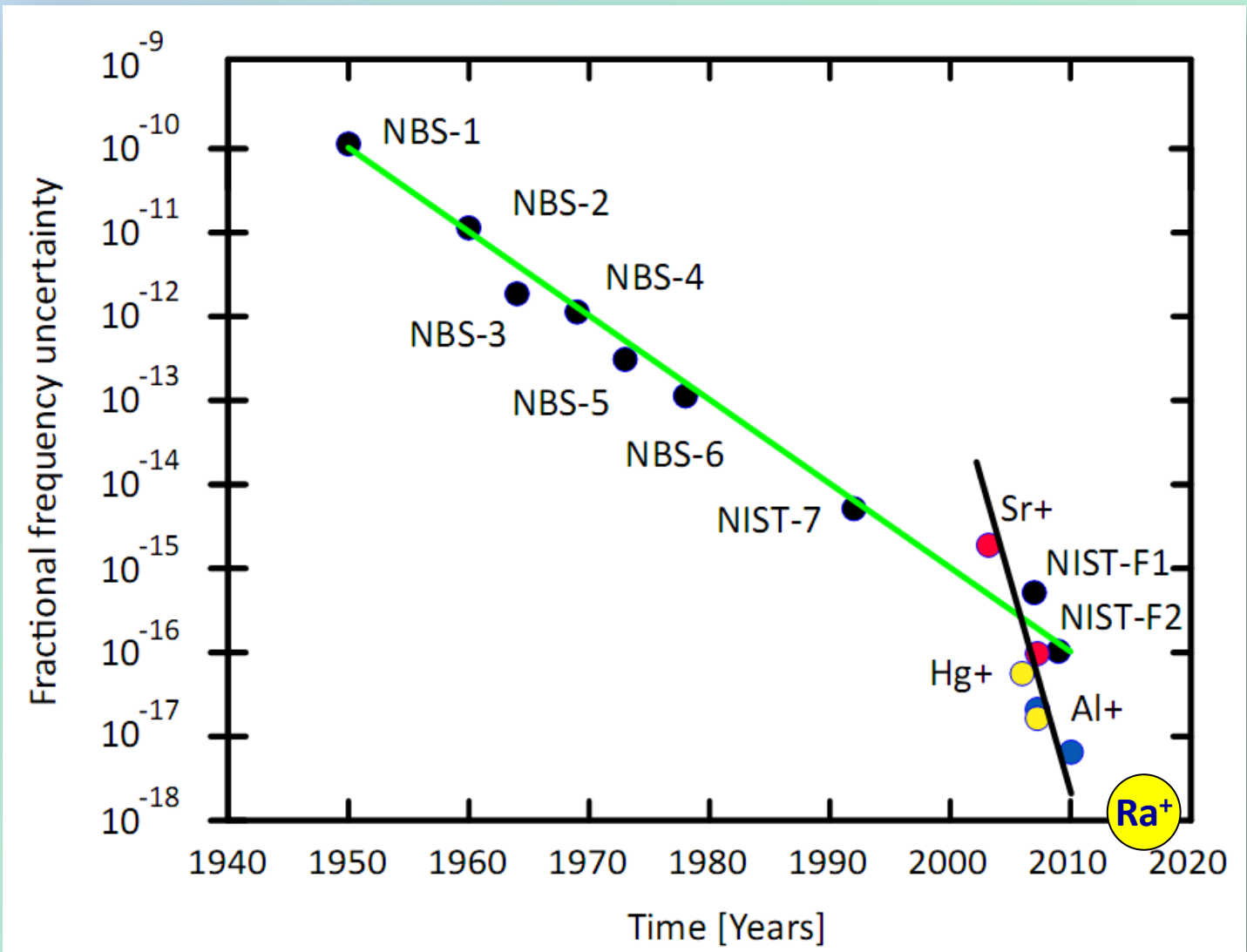
Some cases with Great Potential for

➤ **Fundamental Physics**
&

➤ **a Clock**

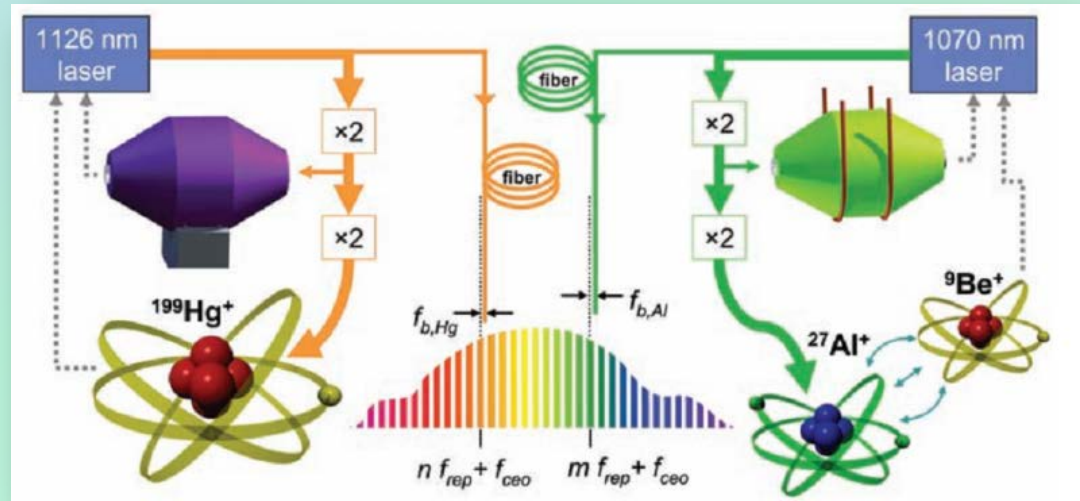


Accuracy of Frequency Standards



Sensitivity to $\dot{\alpha}$

$$\frac{\dot{\nu}}{\nu} = A \frac{\dot{\alpha}}{\alpha}$$

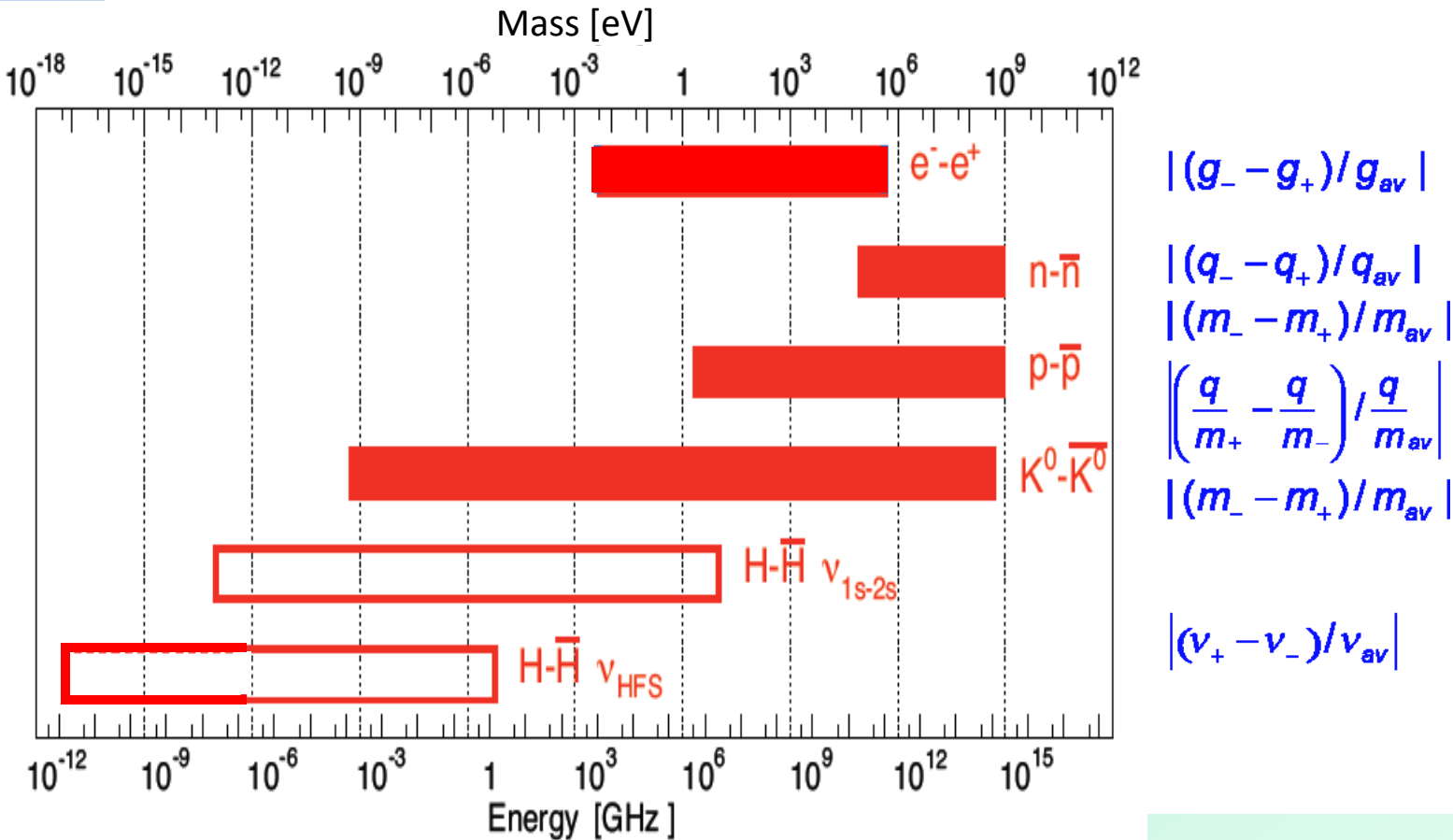


Ion	A	Transition
Sr+	0.43	$2S_{1/2}-2D_{5/2}$
Hg+	-2.94	$2S_{1/2}-2D_{5/2}$
In+	0.18	S_0-P_0
Al+	0.008	S_0-P_0
Ba+	2.52	$6^2S_{1/2}-5^2D_{3/2}$
Ba+	2.44	$6^2S_{1/2}-5^2D_{5/2}$
Ra+	3.00	$7^2S_{1/2}-6^2D_{3/2}$
Ra+	2.77	$7^2S_{1/2}-6^2D_{5/2}$

O.O. Versolato et al., Phys. Rev. A **83**, 043829 (2011)

Verifications of **CPT** symmetry

Using the Kostelecky *et al.* Standard Model Extension scheme



Can we dream of a H clock? And compare it to another clock?

Rare decays

Flavour Symmetry

$$2\beta 0\nu, \mu \rightarrow e\gamma, \mu \rightarrow eee, \mu N \rightarrow eN, \mu^+e^- \rightarrow \mu^-e^+$$

Complementary Information

Rare muon decays: $\mu \rightarrow e \gamma$

PRL **110**, 201801 (2013)

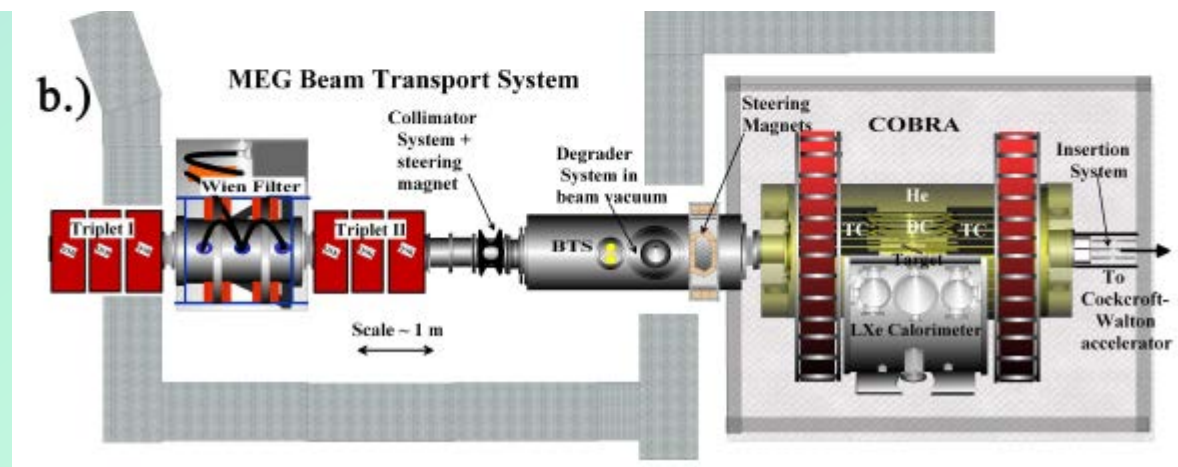
PHYSICAL REVIEW LETTERS

week ending
17 MAY 2013

New Constraint on the Existence of the $\mu^+ \rightarrow e^+ \gamma$ Decay

J. Adam,^{1,2} X. Bai,³ A. M. Baldini,^{4a} E. Baracchini,^{3,5,6} C. Bemporad,^{4a,4b} G. Boca,^{7a,7b} P. W. Cattaneo,^{7a} G. Cavoto,^{8a} F. Cei,^{4a,4b} C. Cerri,^{4a} A. de Bari,^{7a,7b} M. De Gerone,^{9a,9b} T. Doke,¹⁰ S. Dussoni,^{4a} J. Egger,¹ Y. Fujii,³ L. Galli,^{1,4a} F. Gatti,^{9a,9b} B. Golden,⁶ M. Grassi,^{4a} A. Graziosi,^{8a} D. N. Grigoriev,^{11,12} T. Haruyama,⁵ M. Hildebrandt,¹ Y. Hisamatsu,³ F. Ignatov,¹¹ T. Iwamoto,³ D. Kaneko,³ P.-R. Kettle,¹ B. I. Khazin,¹¹ N. Khomotov,¹¹ O. Kiselev,¹ A. Korenchenko,¹³ N. Kravchuk,¹³ G. Lim,⁶ A. Maki,⁵ S. Mihara,⁵ W. Molzon,⁶ T. Mori,³ D. Mzavia,¹³ R. Nardò,^{7a} H. Natori,^{5,3,1} D. Nicolò,^{4a,4b} H. Nishiguchi,⁵ Y. Nishimura,³ W. Ootani,³ M. Panareo,^{14a,14b} A. Papa,¹ G. Piredda,^{8a} A. Popov,¹¹ F. Renga,^{8a,1} E. Ripiccini,^{8a,8b} S. Ritt,¹ M. Rossella,^{7a} R. Sawada,³ F. Sergiampietri,^{4a} G. Signorelli,^{4a} S. Suzuki,¹⁰ F. Tenchini,^{4a,4b} C. Topchyan,⁶ Y. Uchiyama,^{3,1} C. Voena,^{8a} F. Xiao,⁶ S. Yamada,⁵ A. Yamamoto,⁵ S. Yamashita,³ Z. You,⁶ Yu. V. Yudin,¹¹ and D. Zanello^{8a}

(MEG Collaboration)

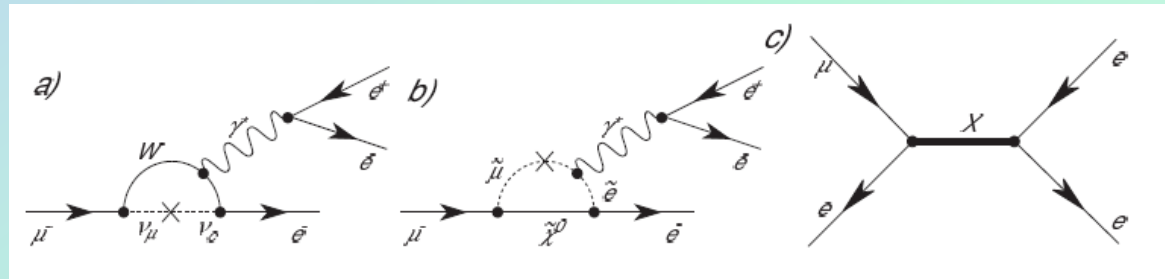
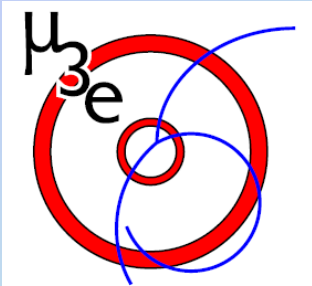


5.7×10^{-13} (90% confidence level)

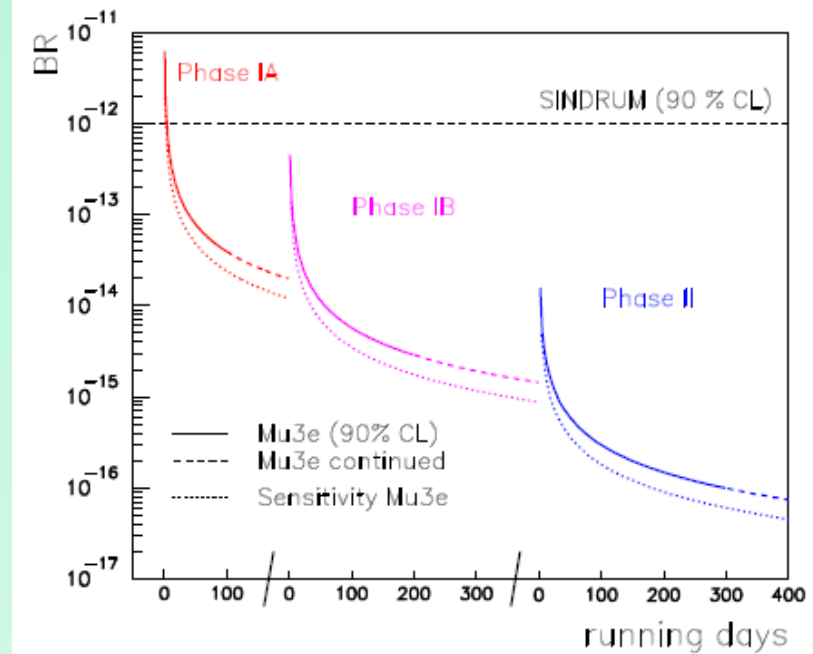
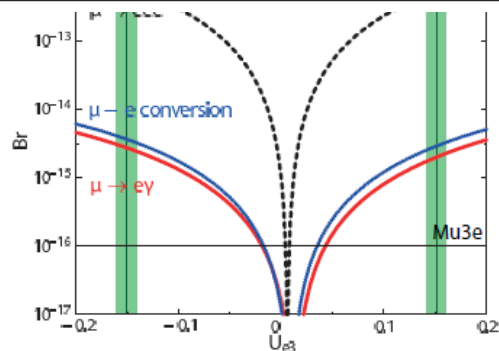
→ proposal for one order of magnitude improvement @ PSI (2013)

Mu3e @PSI

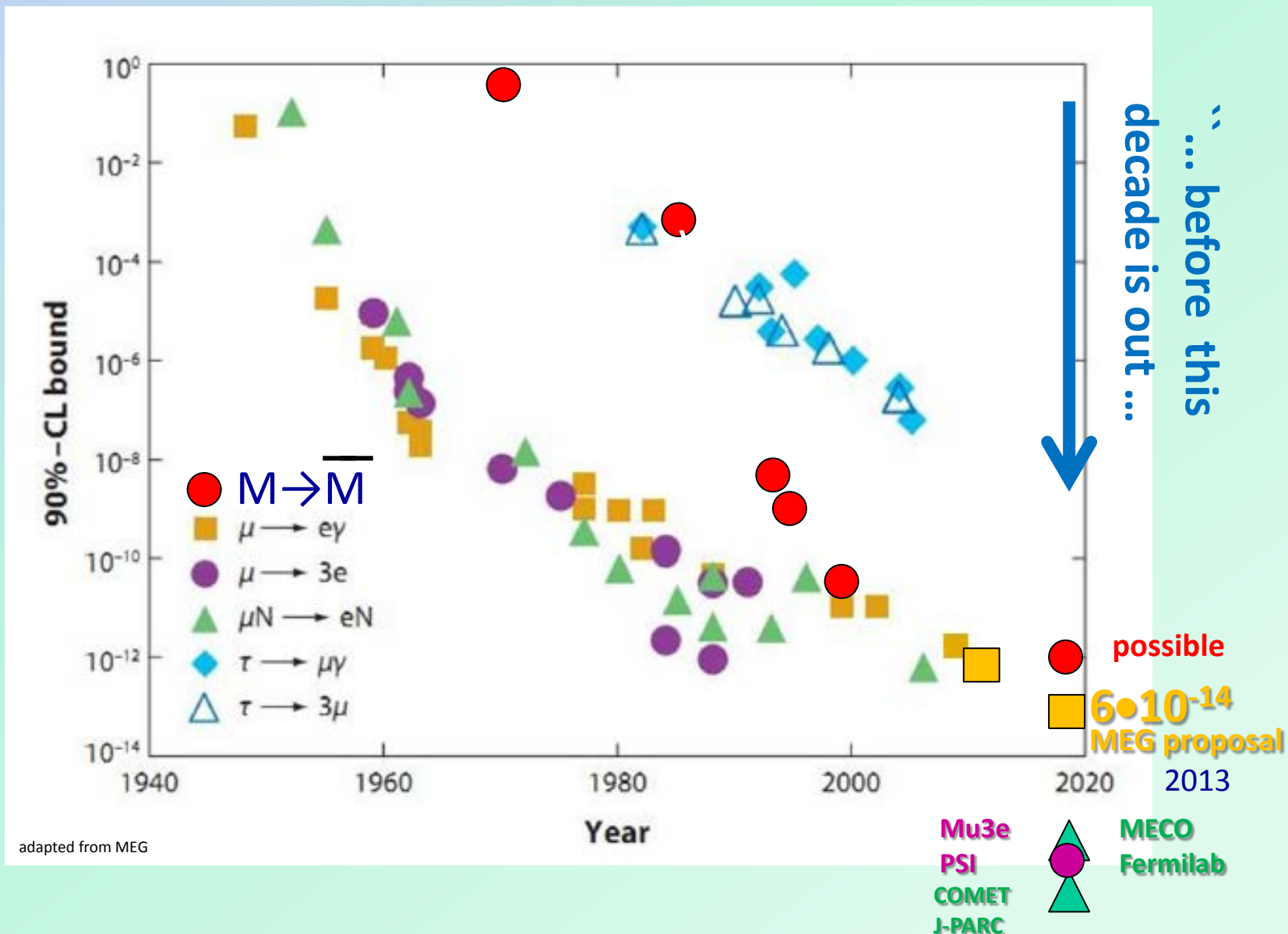
Blondel et al. 2013



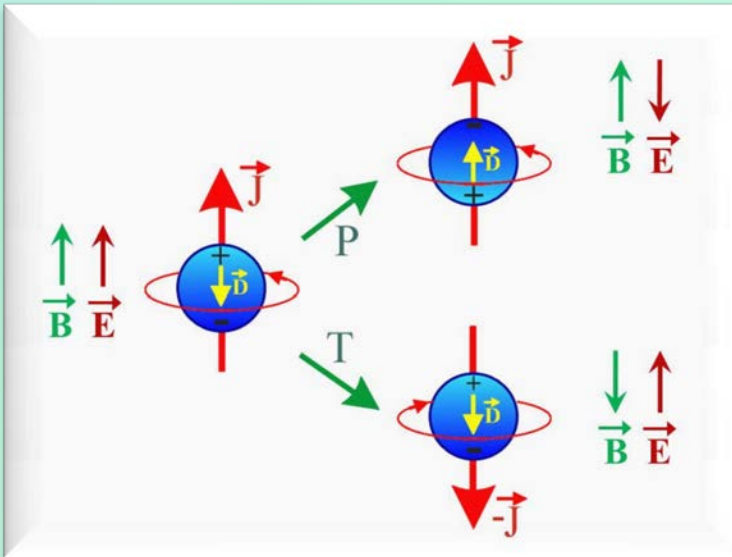
	Phase IA	Phase IB	Phase II
Backgrounds:			
Michel	0	$< 2.5 \cdot 10^{-18}$	$5 \cdot 10^{-18}$
$\mu \rightarrow eee\nu\nu$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$1 \cdot 10^{-17}$
$\mu \rightarrow eee\nu\nu$ and accidental Michel	0	$< 2.5 \cdot 10^{-21}$	$7.5 \cdot 10^{-18}$
Total Background	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$2.3 \cdot 10^{-17}$
Signal:			
Track reconstruction and selection efficiency	26 %	39 %	38 %
Kinematic cut (2σ)	95 %	95 %	95 %
Vertex efficiency (2.5σ) ²	98 %	98 %	98 %
Timing efficiency (2σ) ²	-	90 %	90 %
Total efficiency	24 %	33 %	32 %
Sensitivity:			
Single event sensitivity	$4 \cdot 10^{-16}$	$3 \cdot 10^{-17}$	$7 \cdot 10^{-17}$
muons on target rate (Hz)	$2 \cdot 10^7$	$1 \cdot 10^8$	$2 \cdot 10^9$
running days to reach $1 \cdot 10^{-15}$	2600	350	18
running days to reach $1 \cdot 10^{-16}$	-	3500	180
running days to reach single event sensitivity	6500	11 700	260



Some Rare Decay experiments of Interest

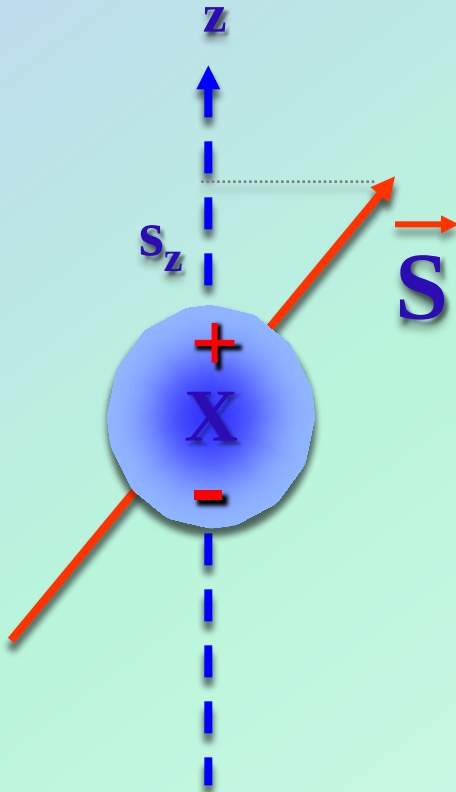


EDMs



$$H = -(\vec{\mu} \cdot \vec{B} + \vec{D} \cdot \vec{E})$$

Spin of Fundamental Particles



$\vec{S}$ is the only vector characterizing a non-degenerate quantum state

magnetic moment:

$$\vec{\mu}_x = 2(1 + a_x) \mu_{0x} c^{-1} \vec{S}$$

electric dipole moment:

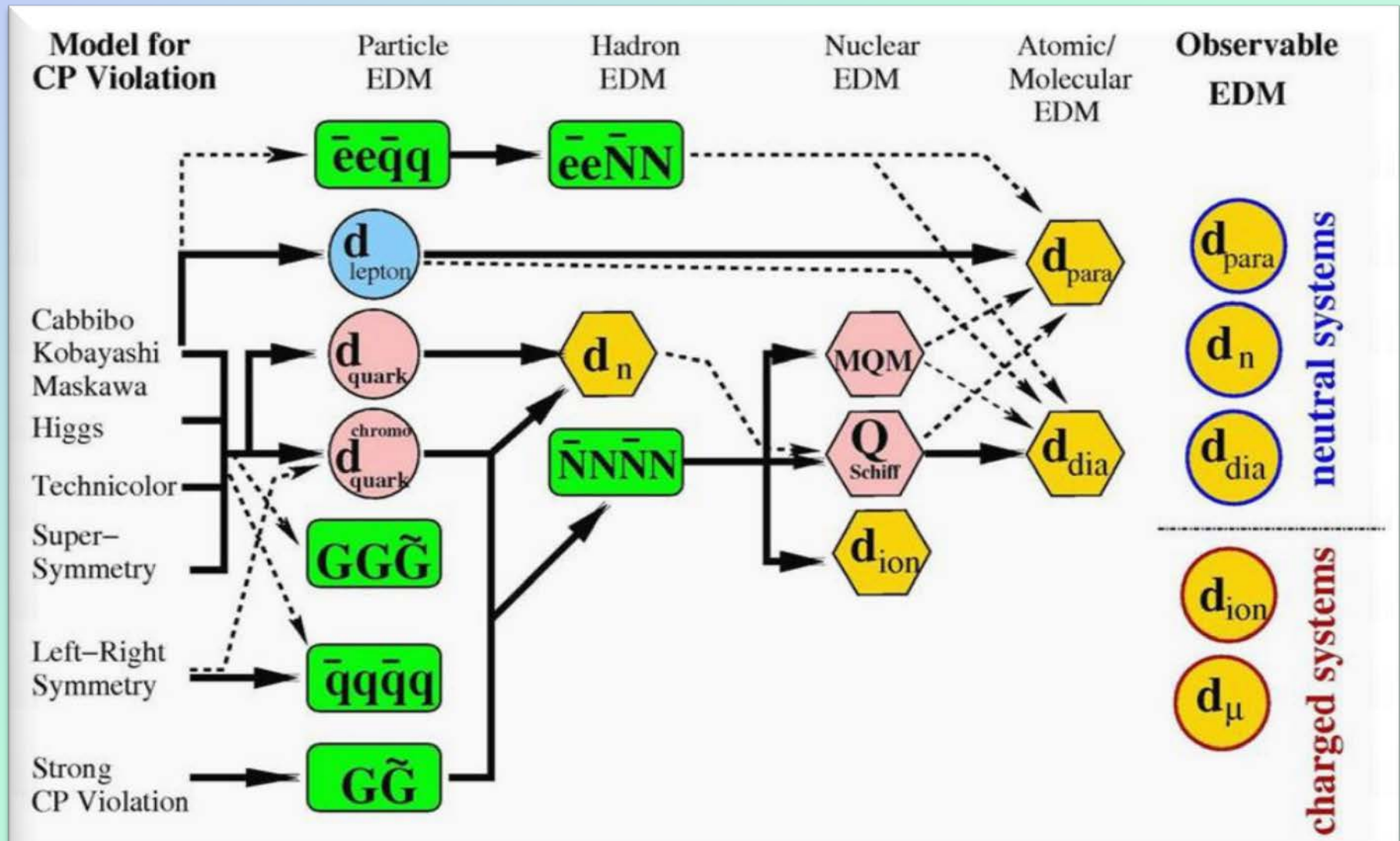
$$\vec{d}_x = \eta \mu_{0x} c^{-1} \vec{S}$$

magneton:

$$\mu_{0x} = e\hbar / (2m_x)$$

$$\mu_{0x} c^{-1} S = \begin{cases} 9.7 \cdot 10^{-12} \text{ e cm (electron)} \\ 4.6 \cdot 10^{-14} \text{ e cm (muon)} \\ 5.3 \cdot 10^{-15} \text{ e cm (nucleon)} \end{cases}$$

Possible Sources of EDMs



The numerically best experiment until now- ^{199}Hg @Seattle – Leaves somewhat restricted room for SUSY ...

Lines of attack towards an EDM

Free Particles

neutron
muon
deuteron
bare nuclei ?
...

- particle EDM
- unique information
- new insights
- new techniques
- **challenging technology**

Atoms

Hg Xe
Tl
Cs Rb
Ra Rn
Fr ...

- electron EDM
- nuclear EDM
- enhancements
- **challenging technology**

Electric Dipole Moment
goal:
new source of ~~CP~~

- electron EDM
- strong enhancements
- **systematics ??**

Molecules

YbF
PbO
PbF, ThO
HfF⁺, ThF⁺
...

Condensed State

garnets
($\text{Gd}_3\text{Ga}_5\text{O}_{12}$)
($\text{Gd}_3\text{Fe}_2\text{Fe}_3\text{O}_{12}$)
solid He ?
liquid Xe

Atomic/Molecular Enhancement Factors

for Electron EDM

Particle		Rb	Cs	Th	Fr	Ra	PbO	YbF
Enhancement		24	125	585	1 150	40 000	60 000	1 600 000

Flambaum, Dzuba, 2012

→ different theorists agree, typically at 30% level



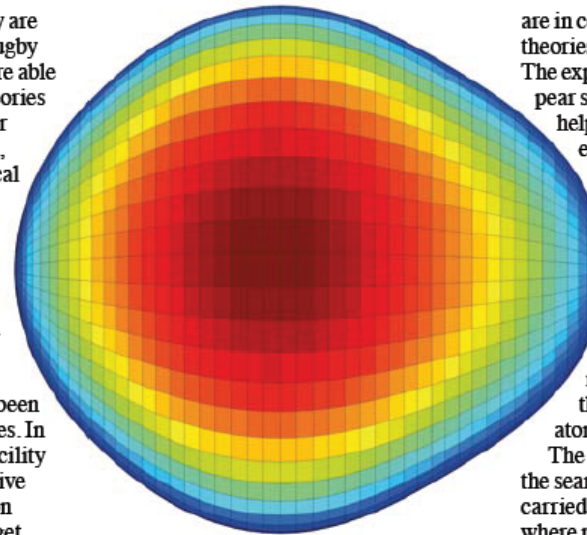
CERN

Are some atomic nuclei pear shaped?

Most atomic nuclei that exist naturally are not spherical but have the shape of a rugby ball. While state-of-the-art theories are able to predict this behaviour, the same theories have predicted that for some particular combinations of protons and neutrons, nuclei can also assume an asymmetrical shape like a pear, with more mass at one end of the nucleus than the other. Now an international team studying radium isotopes at CERN's ISOLDE facility has found that some atomic nuclei can indeed take on this unusual shape.

Most nuclear isotopes predicted to have pear shapes have for a long time been out of reach of experimental techniques. In recent years, however, the ISOLDE facility has demonstrated that heavy, radioactive nuclei, produced in high-energy proton collisions with a uranium-carbide target, can be selectively extracted before being accelerated to 8% of the speed of light. The beam of nuclei is directed onto a foil of isotopically pure nickel, cadmium or tin where the relative motion of the heavy accelerated nucleus and the target nucleus creates an electromagnetic impulse that excites the nuclei.

By studying the details of this excitation process it is possible to infer the nuclear



The shape of ^{224}Ra as deduced from the experiments at ISOLDE.

shape. This method has now been used successfully to study the shape of the short-lived isotopes ^{220}Rn and ^{224}Ra . The data show that while ^{224}Ra is pear shaped, ^{220}Rn does not assume the fixed shape of a pear but rather vibrates about this shape.

The findings from the teams at ISOLDE

are in contradiction with some nuclear theories and will help others to be refined. The experimental observation of nuclear pear shapes is also important because it can help in experimental searches for atomic electric dipole moments (EDMs). The Standard Model of particle physics predicts that the value of the atomic EDM is so small that it will lie well below the current observational limit. However, many theories that try to refine the model predict values of EDMs that should be measurable. Testing these theories requires improved measurements, the most sensitive being to use exotic atoms whose nuclei are pear shaped.

The new measurements will help to direct the searches for EDMs currently being carried out in North America and in Europe, where new techniques are being developed to exploit the special properties of radon and radium isotopes. The expectation is that the data from the nuclear-physics experiment at ISOLDE can be combined with results from atomic-trapping experiments that measure EDMs to make the most stringent tests of the Standard Model.

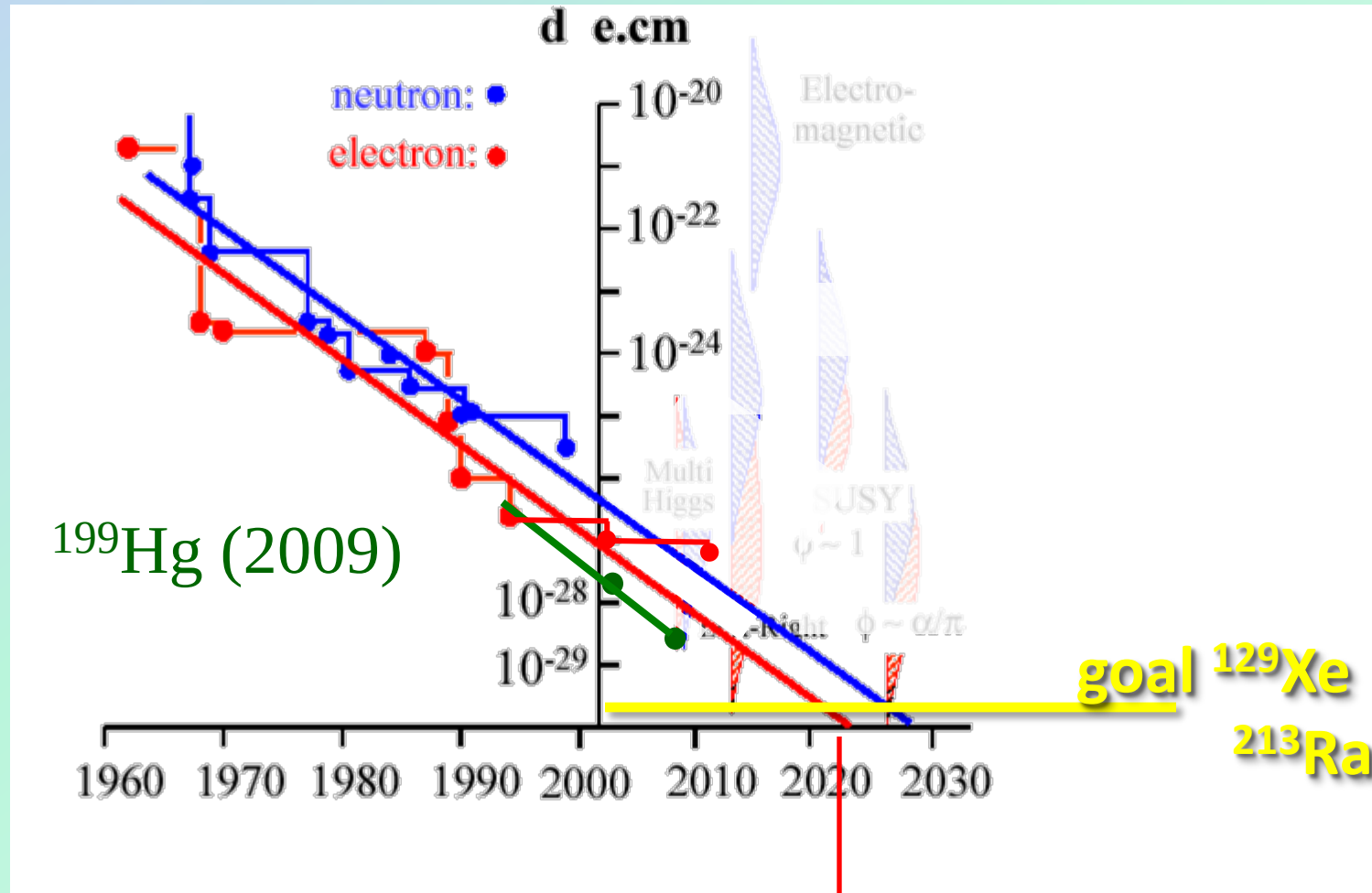
• Further reading

L.P. Gaffney *et al.* 2013 *Nature* 497 199.

*L.P. Gaffney et al.
Nature 497, 199, 09 May 2013*

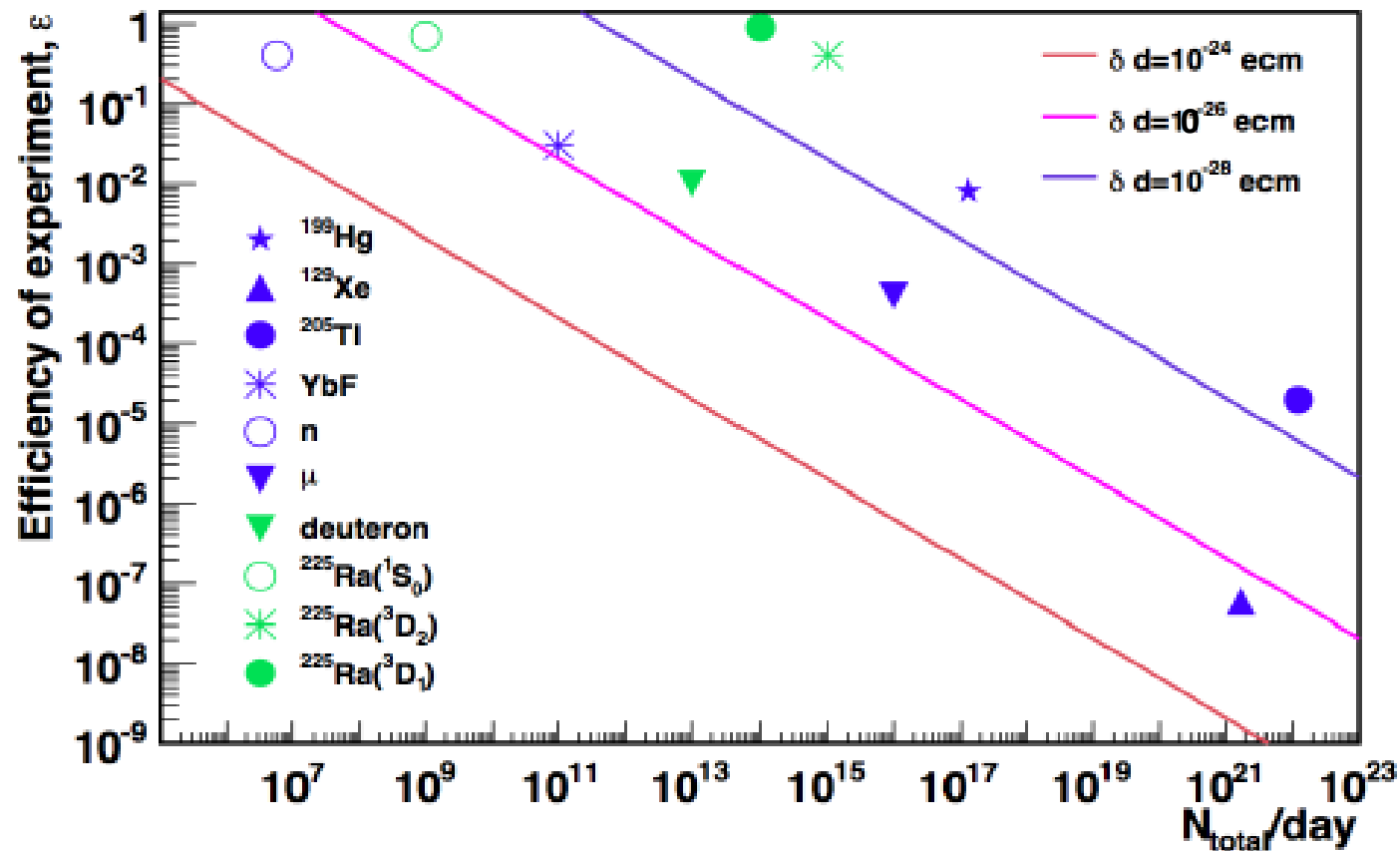
“... We conclude that $^{219,221}\text{Rn}$ are likely to have smaller octupole-enhanced EDMs than $^{223,225}\text{Ra}$, though more favourable Rn candidates may emerge from future studies of the low-lying structure of heavier isotopes. ...

Limit on EDM vs Time



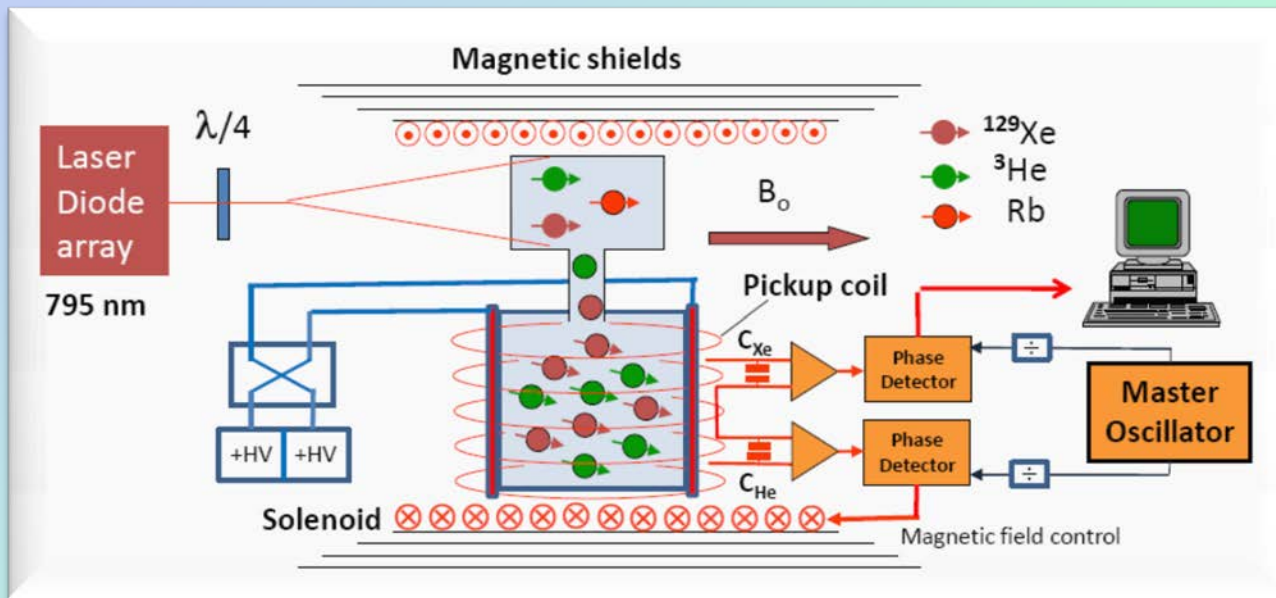
$$d_e (\text{SM}) < 10^{-37}$$

EDM Experiments: Efficiency



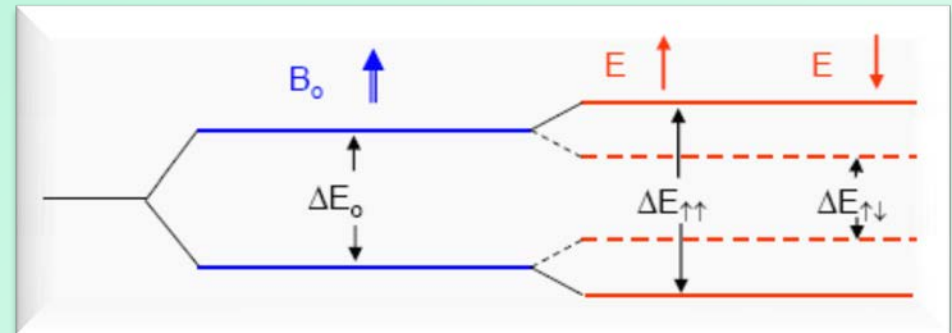
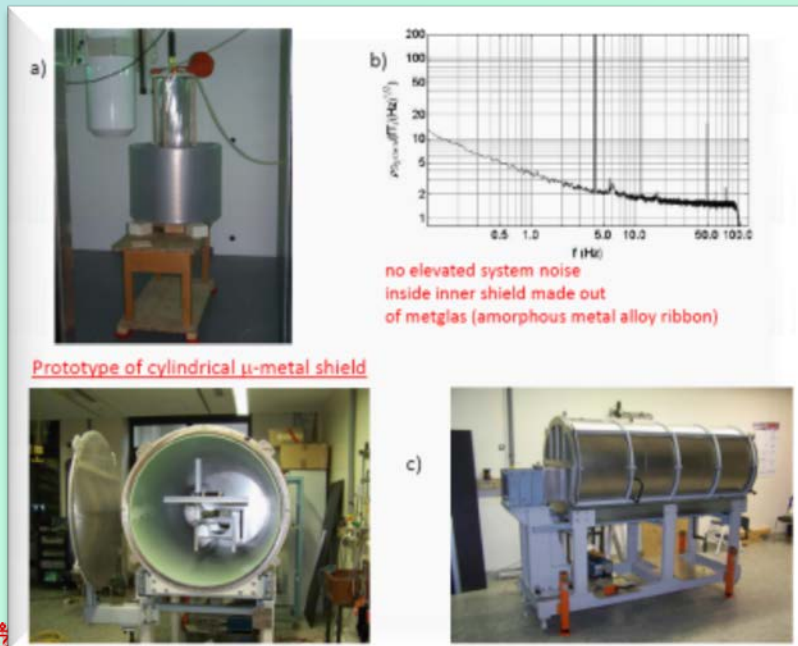
$$\delta d = \frac{\hbar |\vec{I}|}{EP\epsilon\tau\sqrt{N_{\text{total}}}}$$

EDM Search from $^3\text{He}/^{129}\text{Xe}$ Clock Comparison



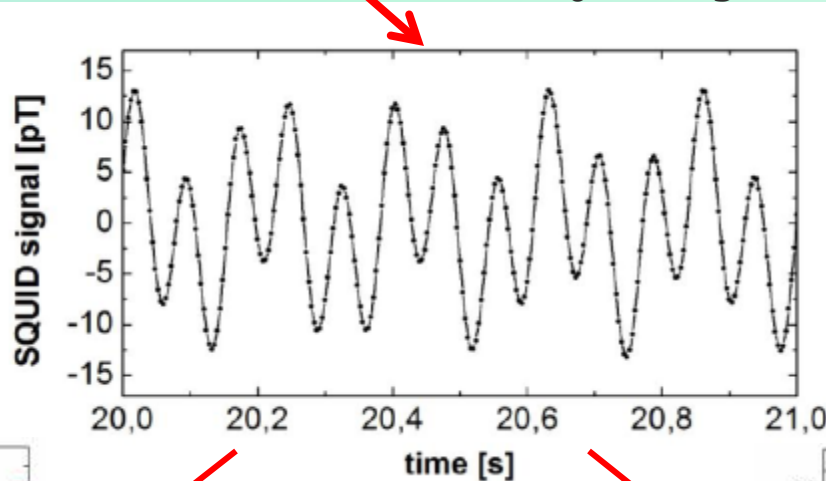
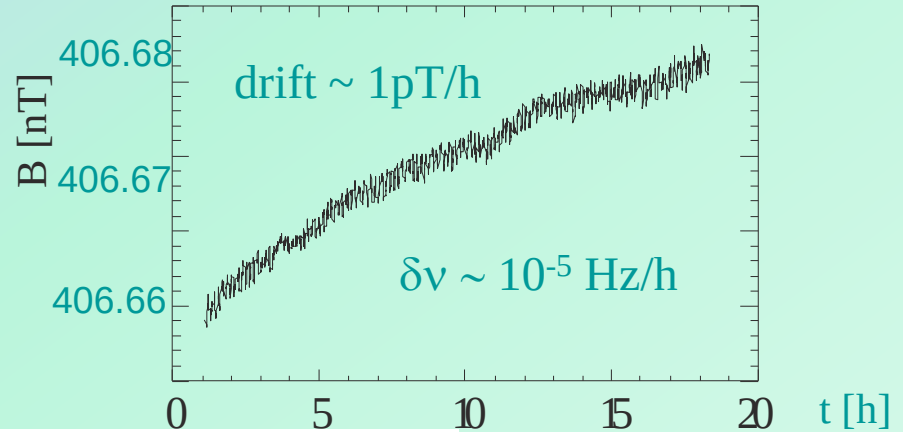
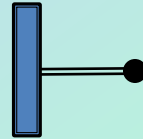
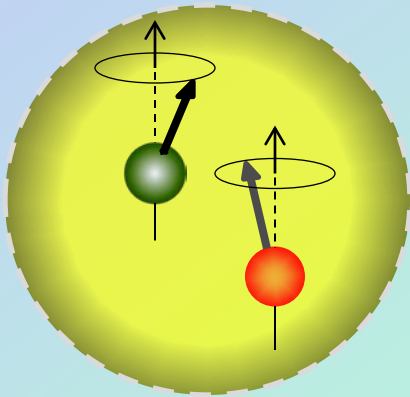
$$^3\text{He}: T_2^* = (60.2 \pm 0.1)h$$

$$^{129}\text{Xe}: 4h < T_2^* < 6h$$



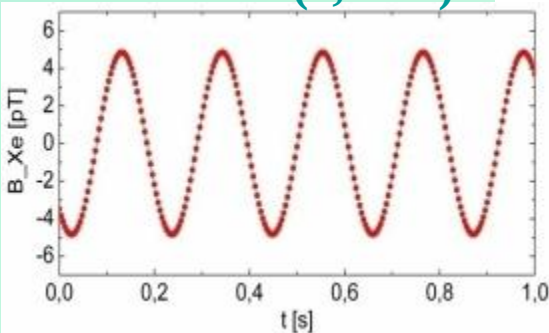
- present limit $d_{Xe} < 3 \times 10^{-27}$ ecm
- goal gain 3 orders of magnitude
- note $d_{Hg} < 3,1 \times 10^{-29}$ ecm

$^3\text{He} / ^{129}\text{Xe}$ clock comparison to get rid of magnetic field drifts

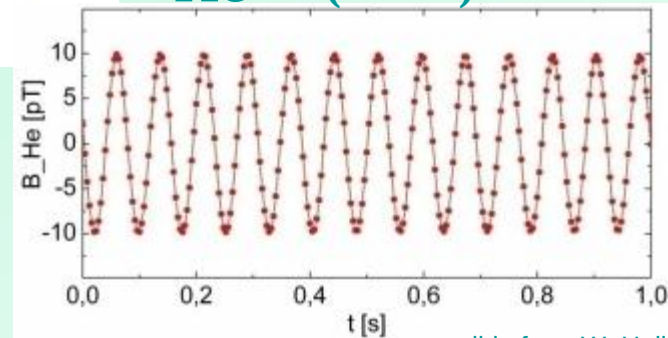


$$\omega_L = 2\pi\nu_L = \gamma |\vec{B}|$$

^{129}Xe (4,7 Hz)



^3He (13 Hz)

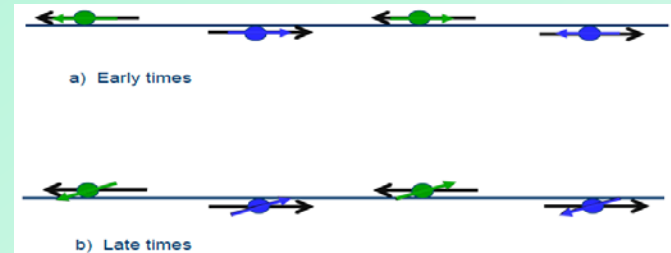
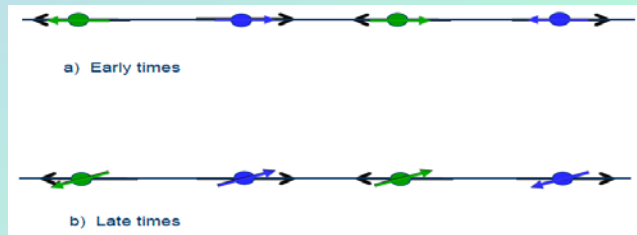


$$\Delta\Phi = \Phi_{\text{He}} - \frac{\gamma_{\text{He}}}{\gamma_{\text{Xe}}} \cdot \Phi_{\text{Xe}} \stackrel{!}{=} \text{const.}$$

EDMs and Anti-Protons ?

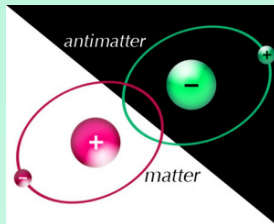
- Suggested@Fermilab: proton EDM search with 10^{-29} ecm sensitivity
(Y.Semertzidis, storage ring EDM collaboration)

0.7 GeV/c, all electric storage ring, bending radius > 40 m and E field some 10 MV/m



Counter-rotating beams	0.7 GeV/c	$>80\%$ vertical polarization	$\sim 4 \times 10^{10}$ total protons/store
<200 m beam base length	Repetition period: 20 minutes	Beam energy: ~ 1 J	Average beam power: ~ 1 mW
Beam emittance: 95%, normalized	Horizontal: 2 mm-mrad	Vertical: 6 mm-mrad	$(dp/p)_{\text{rms}} \sim 2 \times 10^{-4}$

- Principle works also with antiprotons



- Issues are: spin coherence time
- Spin detection
-
- Not the sign or origin of particles

LIV

Search for Lorentz Invariance Violation

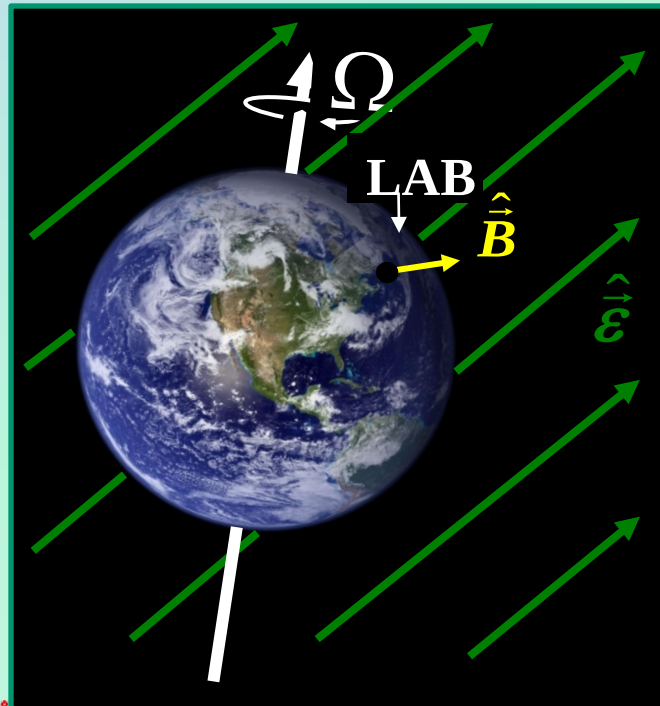
- mind boggling precision achieved
 - all electromagnetic
 - history tells: Sometimes effects only in weak interactions
 - Therefore Now: Experiments on Weak Interactions.
-
- Plenty of chances for $\bar{p}$ precision experiments

Search for violation of Lorentz /CPT violation

Modified Dirac equation for a free spin ½ particle (w=e,p, $\bar{p}$,n,...)

$$\left(\underbrace{i\gamma^\mu \partial_\mu - m_w}_{\text{standard Dirac Eq.}} \underbrace{- a_\mu^w \gamma^\mu - b_\mu^w \gamma_5 \gamma^\mu + i e_\nu^w \partial^\nu - f_\nu^w \gamma_5 \partial^\nu + i \frac{1}{2} g_{\lambda\mu\nu}^w \sigma^{\lambda\mu} \partial^\nu}_{\text{CPT violating}} \underbrace{- \frac{1}{2} H_{\mu\nu}^w \sigma^{\mu\nu} + i c_{\mu\nu}^w \gamma^\mu \partial^\nu + i d_{\mu\nu}^w \gamma_5 \gamma^\mu \partial^\nu}_{\text{CPT preserving terms}} \right) \Psi = 0$$

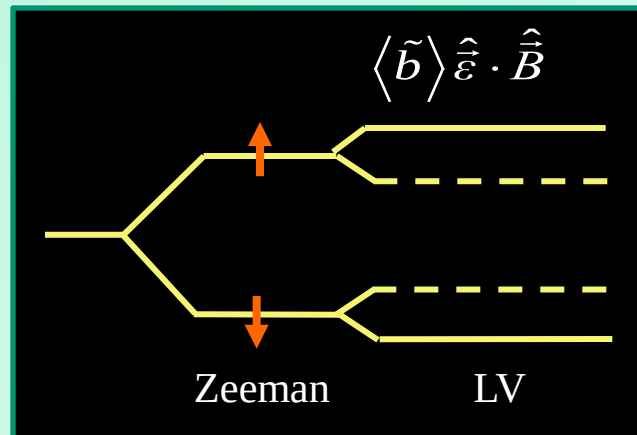
Lorentz violating terms



$$H = -\vec{\mu} \cdot \vec{B} - \vec{b} \cdot \vec{\sigma}$$

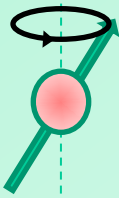
$$\rightarrow \underbrace{\nu = \frac{2}{h} \mu B}_{\nu_{\text{Zeeman}}} + \underbrace{\frac{2}{h} \langle \tilde{b} \rangle \cos(\hat{\varepsilon}, \hat{B})}_{\nu_{LV}}$$

$$a_\mu^w, b_\mu^w, \dots \approx \eta_w \cdot \left(\frac{m_w}{M_{\text{Planck}}} \right)^n$$



$$\tilde{b}_e \approx 10^{-25} \text{ GeV}$$

see e.g.
A. Kostelecky and C. Lane
Phys. Rev. D 60, 116010 (1999)



^3He , ^{129}Xe clocks based on free spin precession
yield best limit due to long spin coherence times

$$T_{2,\text{He}}^* > 60 \text{ hours}$$

$$T_{2,\text{Xe}}^* = 4 - 6 \text{ hours}$$

in Lorentz violating Standard Model extension
(Kostelecky)

$$V = -\tilde{b} \cdot \vec{\sigma}$$

limiting parameter
for experiment

Coefficient	Proton	Neutron	Electron
$\tilde{b}_X$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Y$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Z$	—	—	10^{-30} GeV
$\tilde{b}_T$	—	10^{-27} GeV	10^{-27} GeV

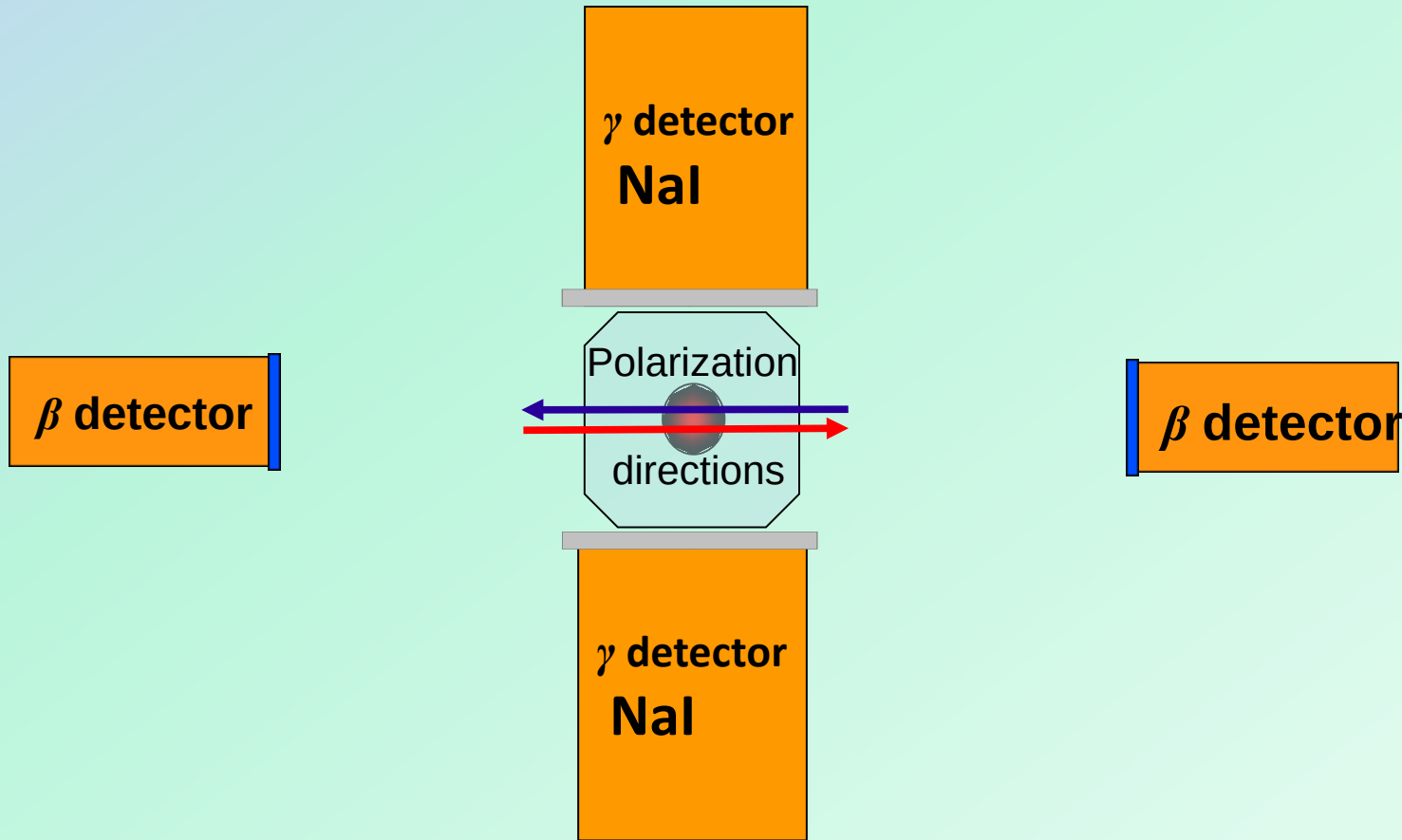
$$\tilde{b}_{\perp}^n = \leq 3.72 \cdot 10^{-32} \text{ GeV} \quad (95\% \text{ C.L.})$$

C. Gemmel et al.,
Phys.Rev.D82, 111901(2010)

$\Rightarrow$ limit on the bound neutron,
 $\Rightarrow$ better limits in the pipeline

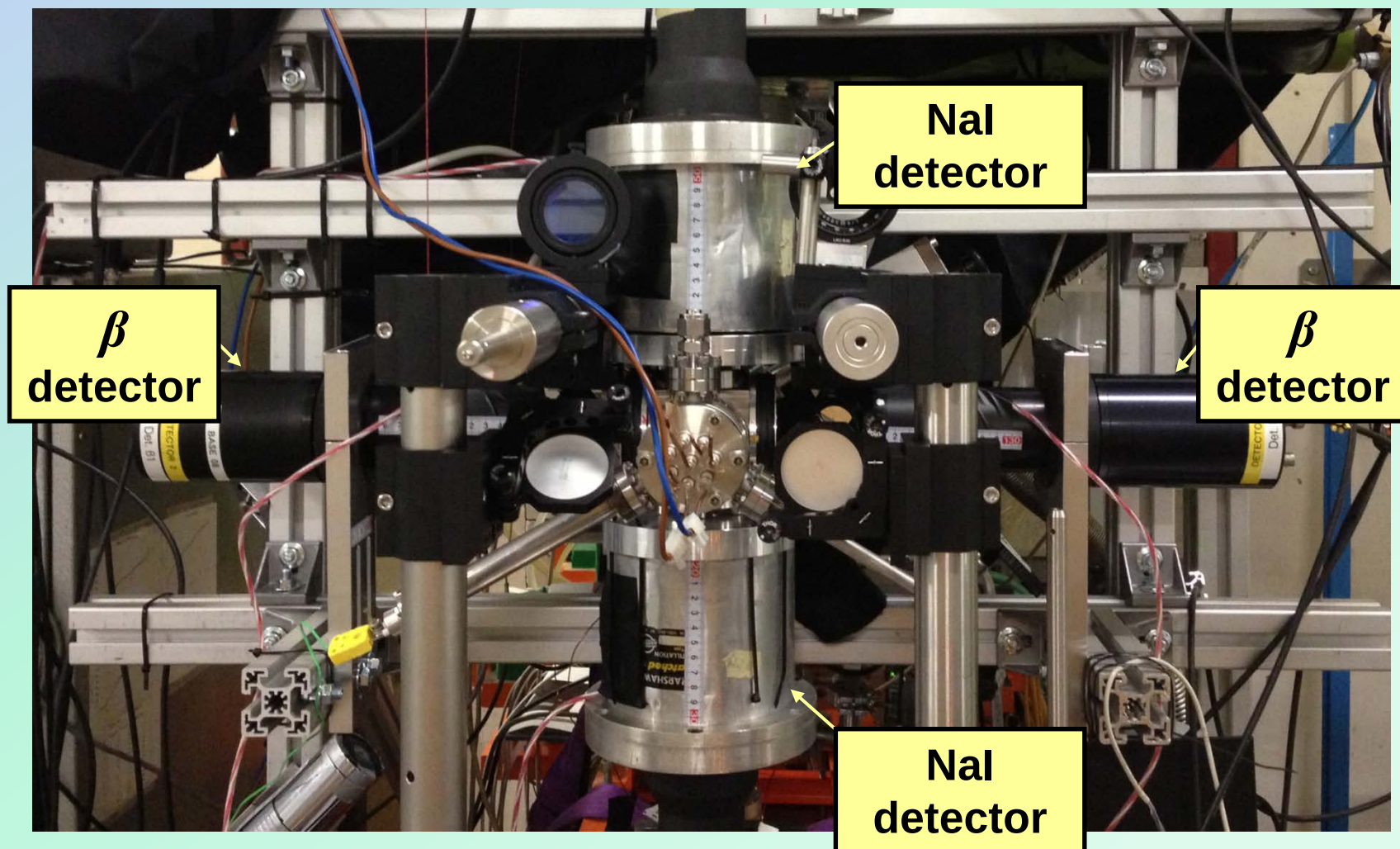
Experimental setup

7



Experimental setup

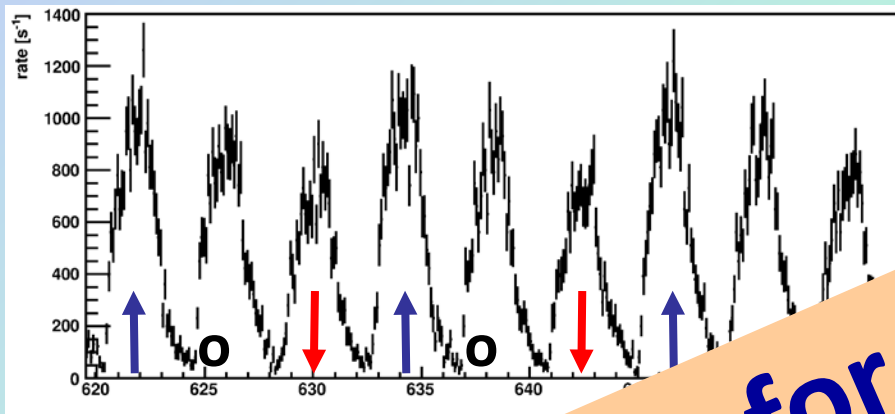
7



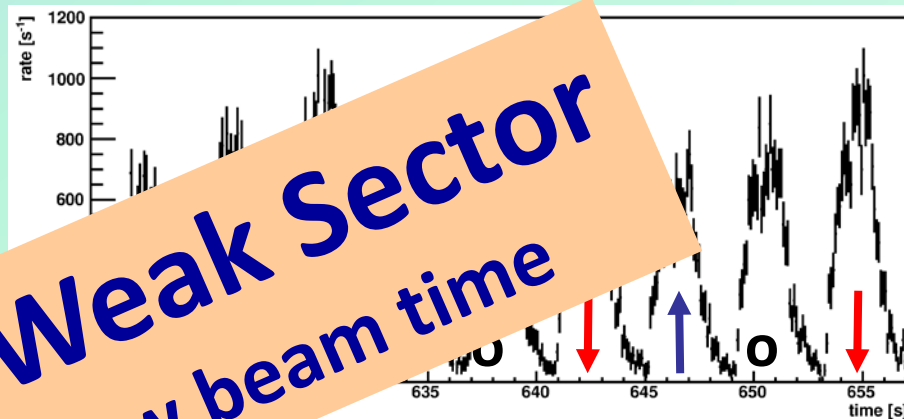
β detectors – measure polarization

8

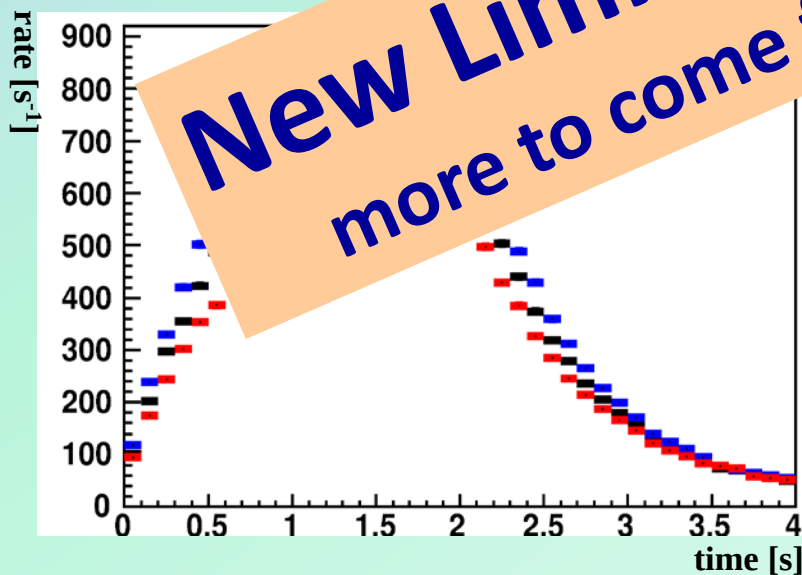
Left



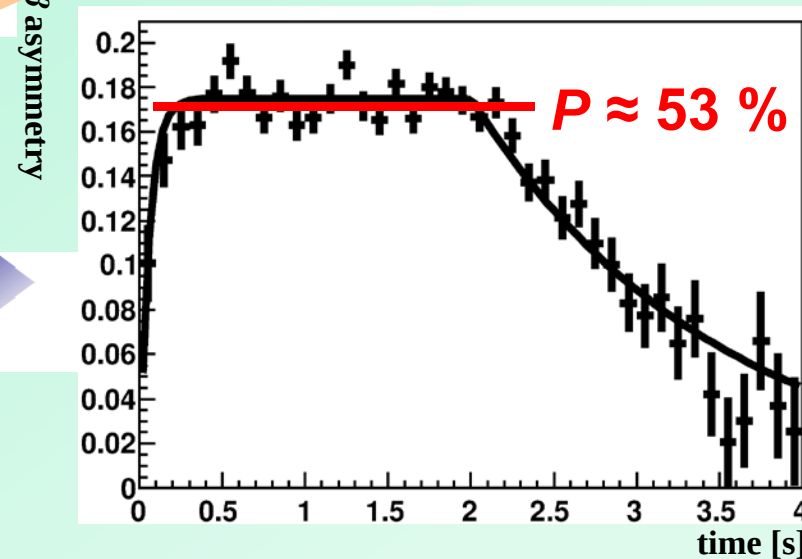
Right



Combined



Cross ratio



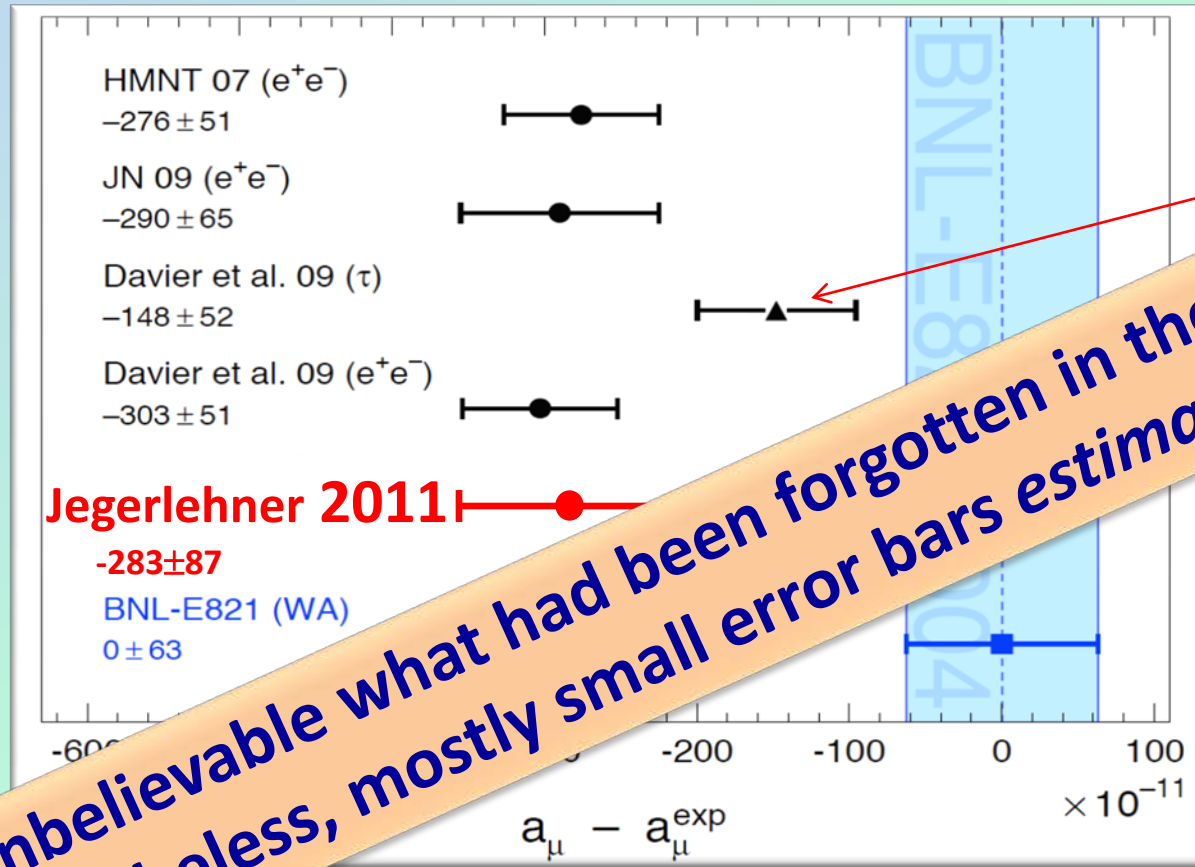
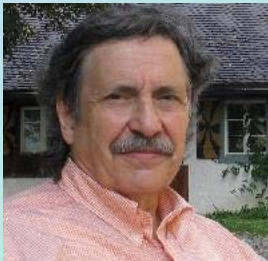
New Limits for Weak Sector
more to come from new beam time

muon g-2

- **Measure Muon Magnetic Anomaly**
- **Now 3σ to 4σ deviation from now stable theory**
- **New effort at Fermilab picking up speed fast**



Muon Magnetic Anomaly



Almost unbelievable what had been forgotten in the past –
Nevertheless, mostly small error bars estimated

There is now a **some 4 σ** difference between Standard Model and Experiment

- Includes forgotten parts relating to isospin breaking

By the way, CPT test:

μ^+ and μ^- appear to be the same at

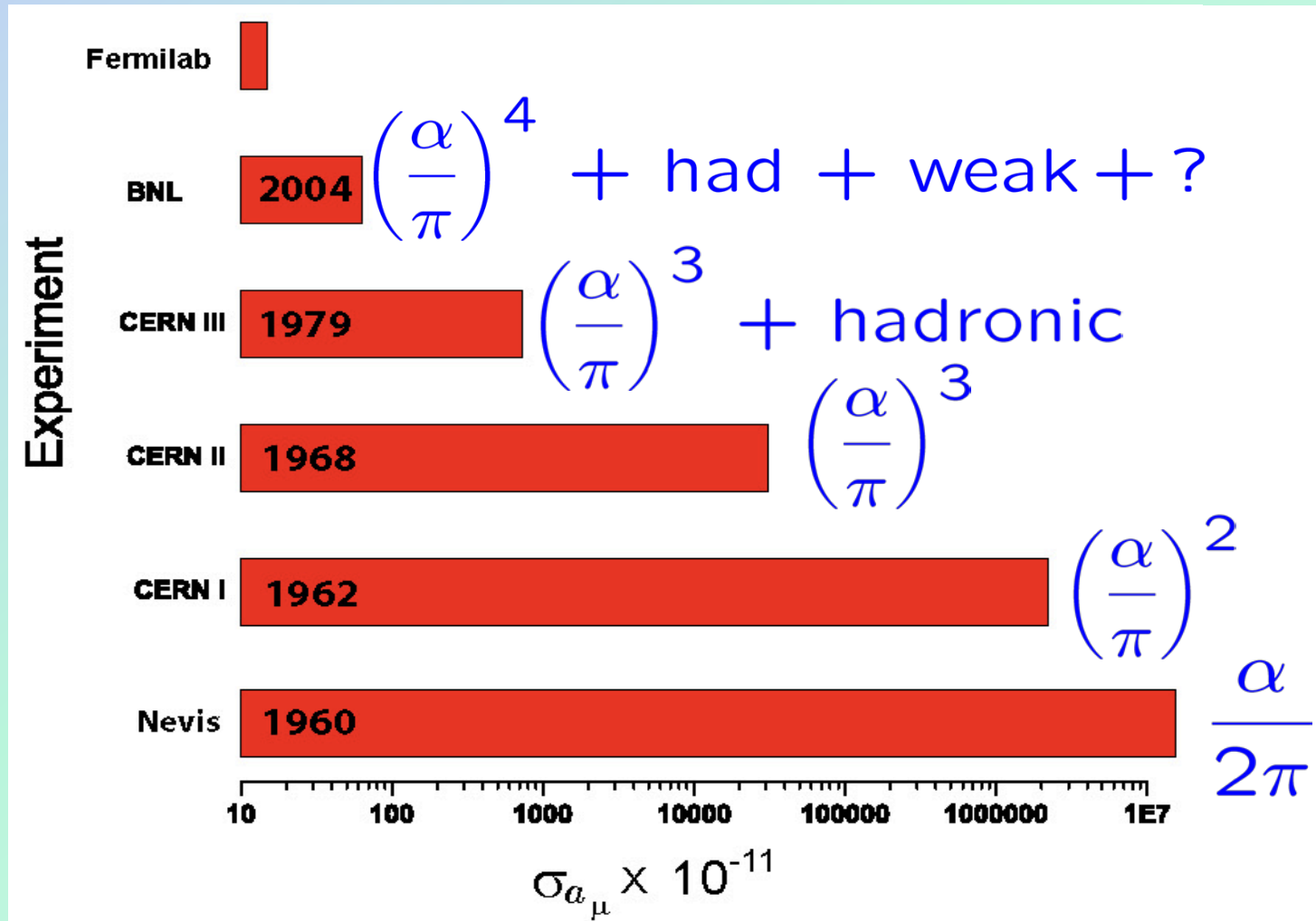
some $7 \cdot 10^{-7}$ (0.7 ppm)

in the *magnetic anomaly*, i.e.

some $7 \cdot 10^{-10}$ (0.7 ppb)

in the *magnetic moment*

Contributions to Muon Magnetic Anomaly

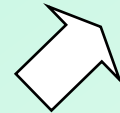
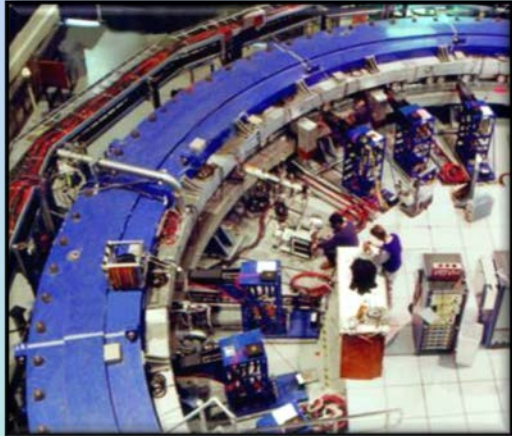


Different types of new physics lead to very different δa_μ (N.P.)

- SUSY, RS, ADD, ... : strong parameter constraints
- Z' , UED, LHT, ... : ruled out if deviation confirmed



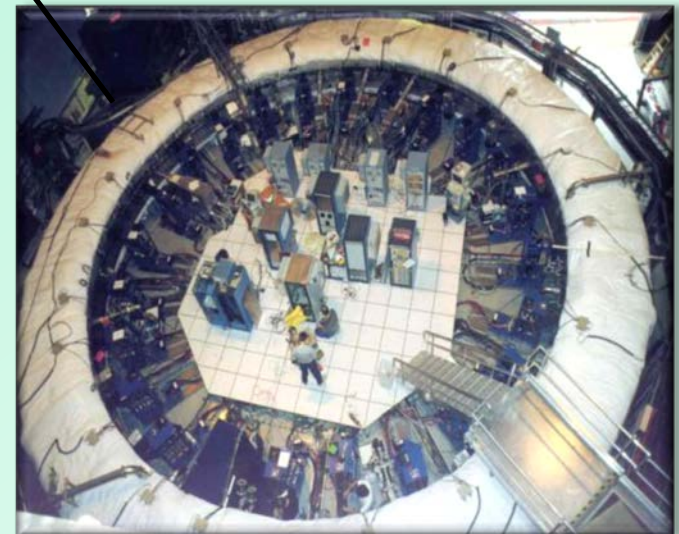
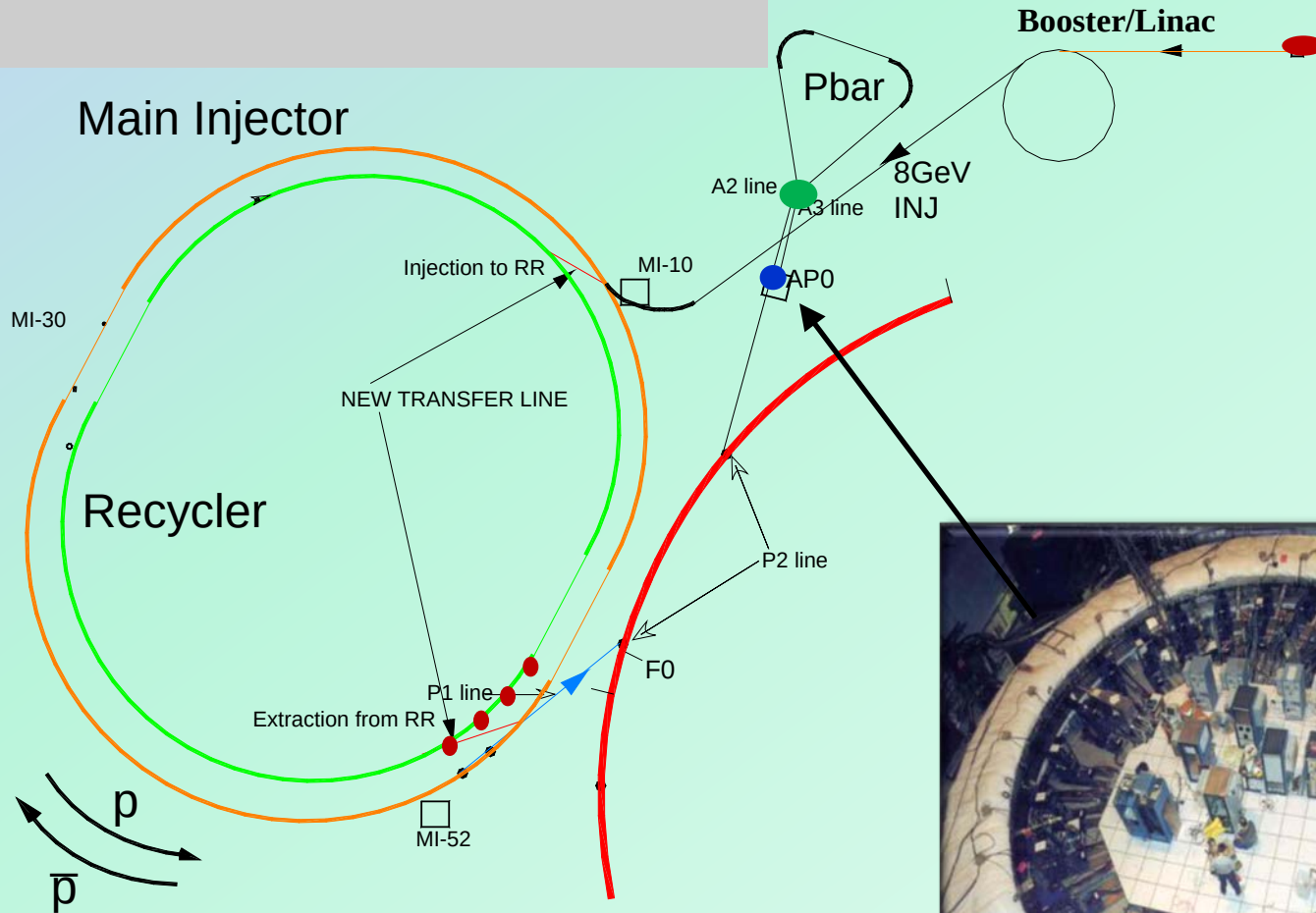
The Future



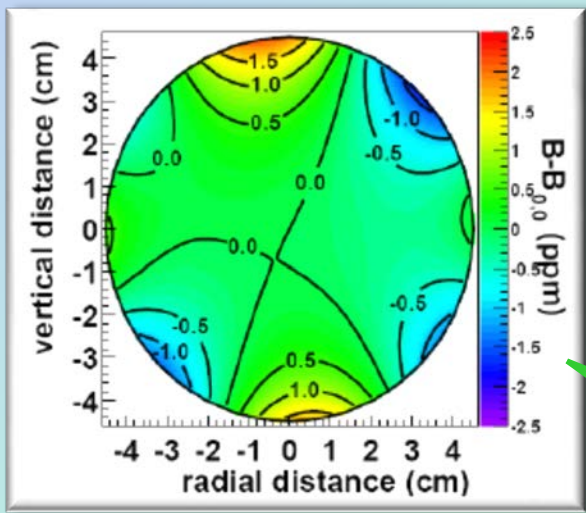
Brookhaven → FERMILAB

for 5 times improvement

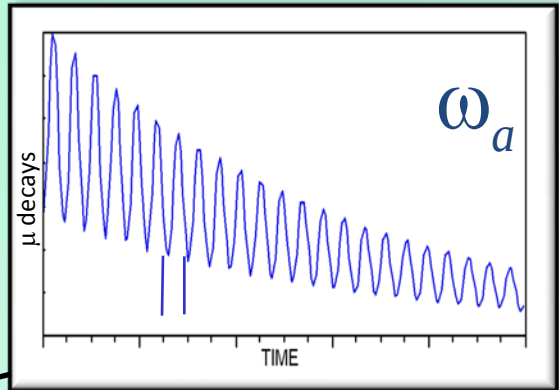
Muon g-2 @ FERMILAB



The Anomaly is obtained from 3 well-measured Quantities



ω_p



ω_a

New experiment @Fermilab

$\frac{\omega_a}{\omega_p}$

ω_p

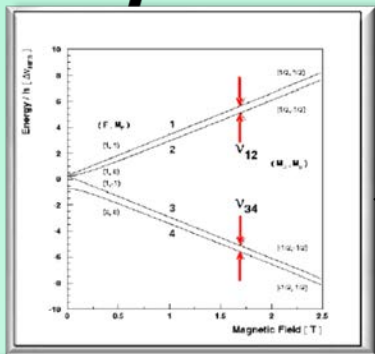
$\frac{\omega_a}{\omega_p}$

a_μ

=

$\frac{\mu_\mu}{\mu_p}$

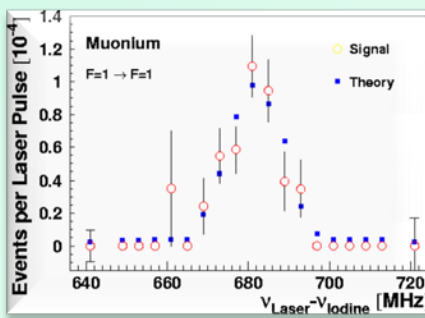
Muonium HFS



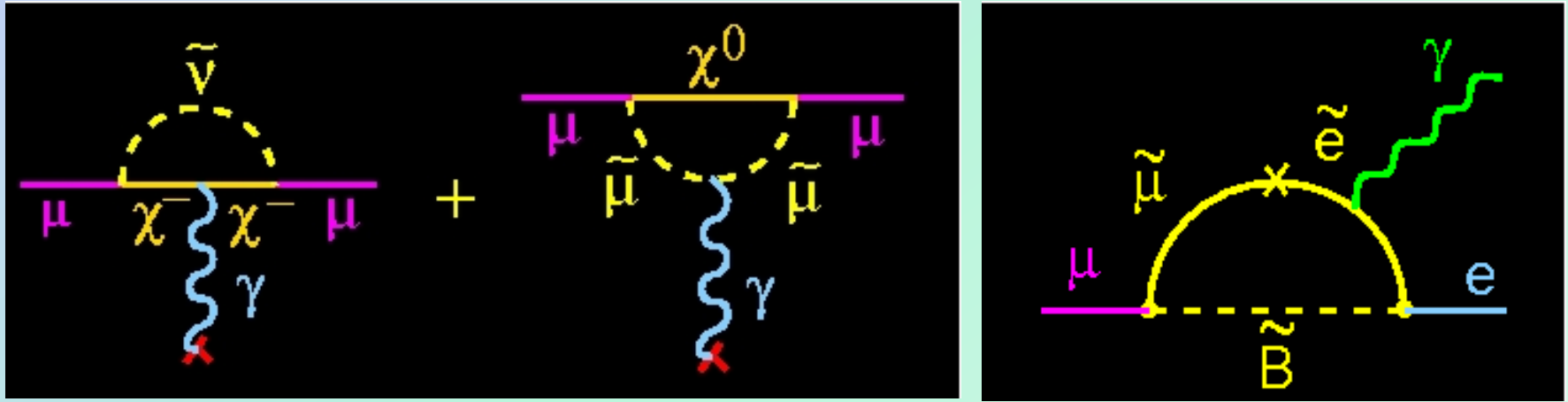
$\mu_\mu/\mu_p = 3.183\,345\,24(37) \quad (120 \text{ ppb})$
 $= 3.183\,345\,39(10) \quad (31 \text{ ppb})$

New experiment(s) @J-PARC

Muonium 1S – 2S



a_μ is sensitive to a wide range of new physics, e.g. SUSY



$$a_\mu(\text{SUSY}) \simeq (\text{sgn} \mu) 130 \times 10^{-11} \tan \beta \left(\frac{100 \text{ GeV}}{\tilde{m}} \right)^2$$

difficult to measure at LHC

Related processes in SUSY

$$\mu^+ \rightarrow e^+ \gamma; \quad \mu^- + \mathcal{N} \rightarrow e^- + \mathcal{N}$$

Other Models

Technicolor

small Δa_μ

Littlest Higgs with T-parity

small Δa_μ

Universal Extra Dimensions

small Δa_μ

Randall Sundrum

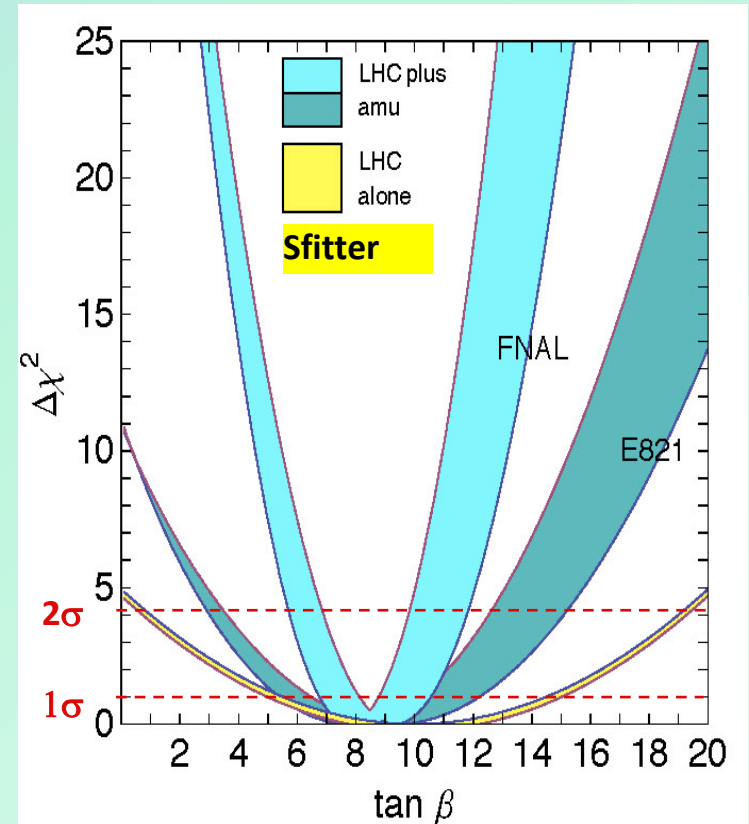
could accommodate large Δa_μ

Two Higgs doublets, shadow Higgs

small Δa_μ

Additional light bosons that can affect EM interactions (difficult to study at LHC)

secluded U(1), etc., could have significant Δa_μ



The error budget for a new experiment represents a continuation of improvements already made during E821

Systematic uncertainty (ppm)	1998	1999	2000	2001	E821 final	P989 Goal
Magnetic field – w_p	0.5	0.4	0.24	0.17		0.07
Anomalous precession – w_a	0.8	0.3	0.31	0.21		0.07
Statistical uncertainty (ppm)	4.9	1.3	0.62	0.66	0.46	0.1
Systematic uncertainty (ppm)	0.9	0.5	0.39	0.28	0.28	0.1
Total Uncertainty (ppm)	5.0	1.3	0.73	0.72	0.54	0.14

Reality in
Modern Science:

Big PR
Requested to
Raise Money

US Press on 8 May 2013:

Coil/ Crystat transport

Particle Storage Ring To Move From New York's Brookhaven Lab To Fermilab In ...

Huffington Post - 12 hours ago

"Fermilab can generate a much more intense and pure beam of **muons**, so the **Muon** g-2 experiment should be able to close that margin of error," Chris Polly, project manager for Fermilab, said in a statement. "If we can do that, this experiment could indicate ...



Move Over, Space Shuttle: There's a New Science Giant Cruising the US This ...

Scientific American (blog) - 5 hours ago

The 50-foot-wide ring, filled with superconducting coils, was built in the 1990s at Brookhaven National Laboratory on New York's Long Island as part of an experiment to investigate the properties of the **muon**, a heavy, short-lived cousin of the electron.

Giant Particle Storage Ring to Stop in Lemont on Journey to Fermilab

Patch.com - 15 hours ago

A particle storage ring spanning 50 feet in diameter will make a stop in Lemont this summer during a 3,200-mile journey from New York to Illinois. The giant electromagnet is headed to Fermi National Accelerator Laboratory, just outside Batavia, where it will ...

Honk If You Love Muons: 3200 Mile Trip Planned For Muon G-2 Storage Ring

CleanTechnica - 17 hours ago

A gigantic set of steel and aluminum rings 50 feet across, the electromagnet at the heart of the **Muon** g-2 storage ring, will soon make a 3,200-mile trip from Brookhaven National Laboratory to Fermi National Accelerator Laboratory. This high-tech loaner will be ...



50-foot magnet to travel 3200 miles for experiment

DVICE - 5 hours ago

The **Muon** g-2 storage ring will travel 3,200 miles from the Brookhaven National Laboratory in New York to the Fermi National Accelerator Laboratory in Illinois to be part of a particle physics experiment. It is expected to leave New York in early June and arrive ...

Revolutionary Muon Experiment to Begin With 3200-mile Move of 50-Foot-Wide ...

Lab Manager Magazine - 13 hours ago

The experiment is called **Muon** g-2 (pronounced gee-minus-two), and will study the properties of **muons**, tiny subatomic particles that exist for only 2.2 millionths of a second. The core of the experiment is a machine built at Brookhaven in the 1990s, and the ...

Giant 50-foot magnet to make cross-country trek for physics experiment

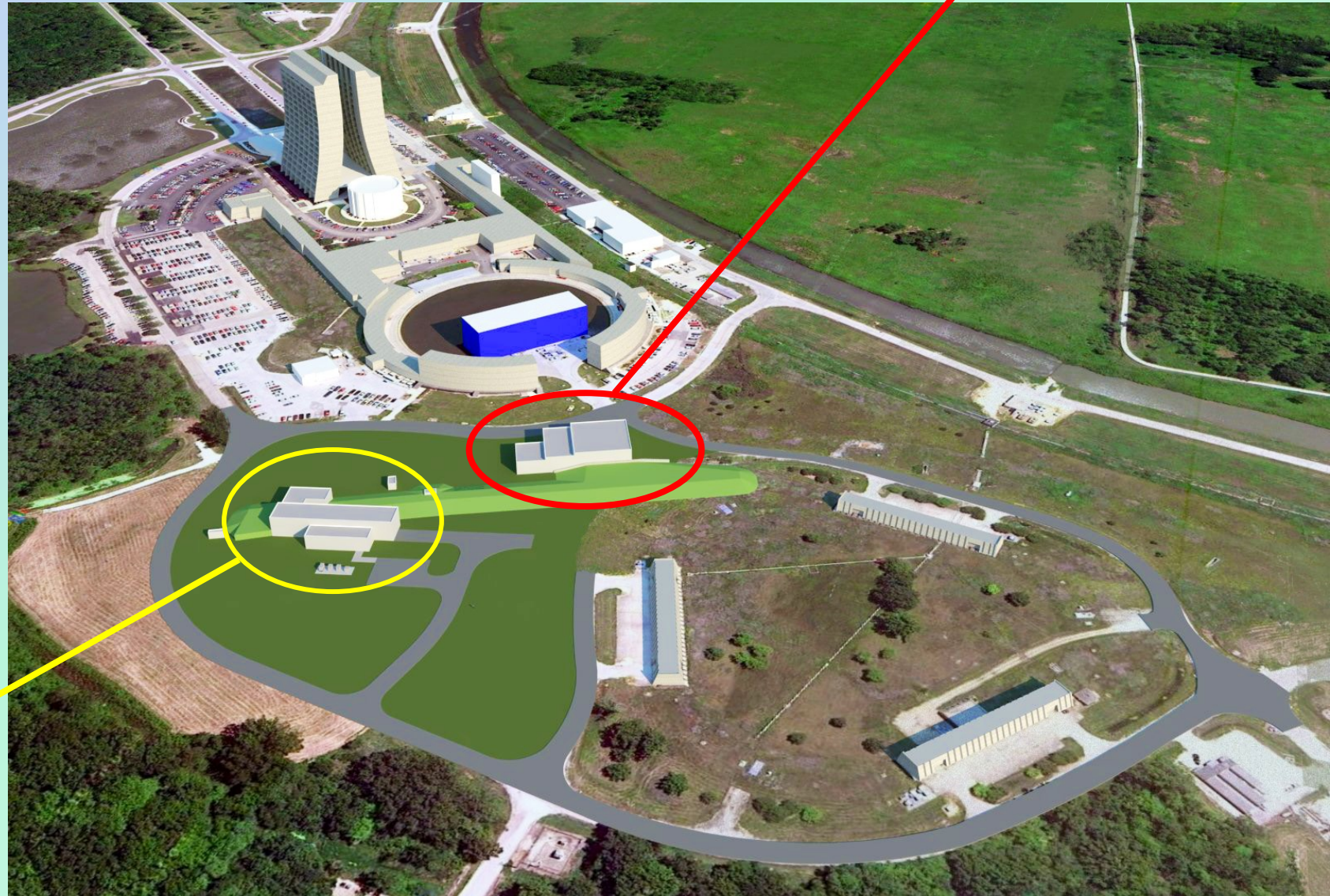
Space Daily - May 9, 2013

The **Muon** g-2 team has devised a plan to make the 3,200-mile journey that involves loading the ring onto a specially prepared truck that will transport it to a barge that will bring it down the East Coast, around the tip of Florida and up the Mississippi River to ...

NIU students, faculty in physics, engineering contribute to Fermilab's Muon g-2 ...

Fermilab LandScaping

g-2



$\mu N \rightarrow e N$



MUON CAMPUS - GROUNDBREAKING

DATE: 05-04-2013
UPDATE BY: JH

2013-KJ



Summary

- Numerous possibilities to find New Physics
- All well motivated
- Not one is more justified than any other
- Pbar experiments well on an excellent track

Thank You !