Low-Energy Precision Experiments

David Hertzog
University of Washington

A selection that highlights the complementarity to the Energy Frontier

Perspective

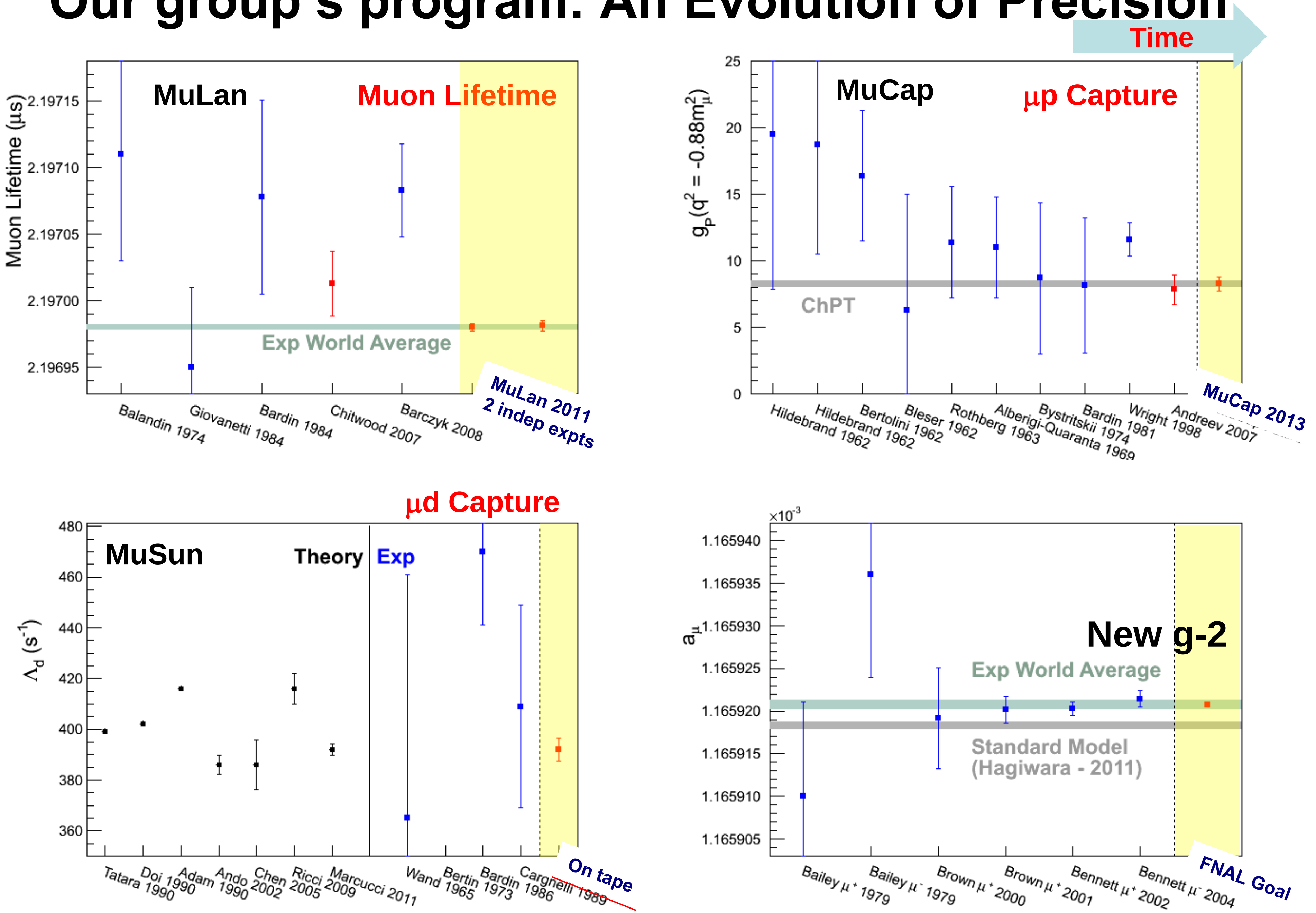
Resolved conflicts

Ongoing tug of war

Future attacks on the SM

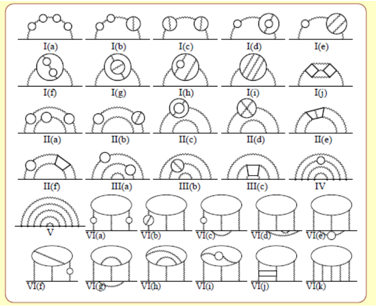
Many other instances might be cited, but these will suffice to justify the statement that "*our future discoveries must be looked for in the sixth place of decimals*."
— A.A. Michelson

Our group's program: An Evolution of Precision



Precision Physics Motivation 1: Establish the SM

- <u>SM parameters and laws</u>. Examples:
  - Masses **M_Z, M_W, M_H, m_b, m_t, m_e, m_u, m_ν, …**
  - Couplings: **α_{QED}, α_{Strong}, G_F, G_{grav}**
  - Structure of interactions ***$SU(3)_C x SU(2)_L x U(1)_Y$***
  - Broad issues
    - Numbers of generations
    - Mixing angles, quarks and neutrinos
    - Lepton number conservation
      - Majorana or Dirac neutrinos *
    - CP violation parameters
- The SM has been built on an enormous experimental foundation involving ***Precision*** and ***Energy*** frontiers … and, exquisite ***Theory***
  - **See A. Freitas talk, next !!**



Precision Physics Motivation II: Burning issues

- Can we sensitively test the SM limitations to help answer key questions:
  - Baryon Asymmetry of the Universe
  - EW symmetry breaking
- Are the Standard Model predictions complete?
  - What is missing?
  - What extensions are needed?
- The community has also begun to worry …

So far: No direct evidence for Supersymmetry, Extra Dimensions, 4th Generation, New Dynamics…

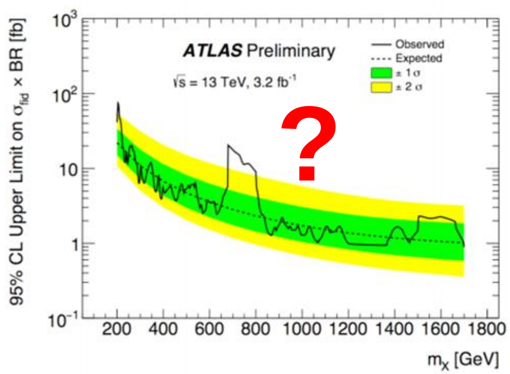
At The LHC!

The Higgs – Last Particle Ever Discovered?

Marciano: 2013

The unconquered Standard Model

Direct approach



The indirect approach

New Physics through precision and sensitivity

- Beta decay: μ, n, nuclei
  - TWIST, PERC, UCNA, ^{6}He*
- Muon anomaly
  - g-2
- cLFV
  - MEG, Mu2e, COMET, Mu3e
- EDMs
  - Hg, ThO, n, …
- PV electron scattering
  - Qweak, Moller, …
- Lepton universality
  - PEN, PIENU
- $0\nu\beta\beta$
  - KamLand-Zen*, Gerda, EXO, MJD, Cuore, …

SM Extensions
SUSY, …

SM Extensions
Dark Matter, SUSY, Dark Photons, many others

SM Extensions
SUSY, new interactions

Baryon Asymmetry
SUSY, θ_{QCD}

SM Extensions or $\sin^2\theta_W$
SUSY, Z', Dark Photons

SM Extensions
Various SUSY limits

Baryon Asymmetry
Majorana / Dirac neutrinos

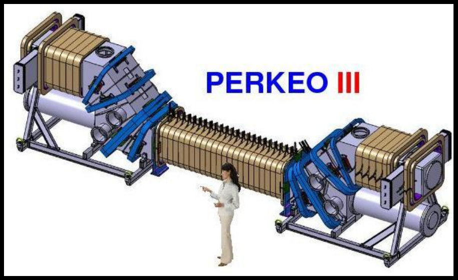
+ many Direct Dark Matter searches, Dark Photon searches, Axion searches, …

*Backup slide

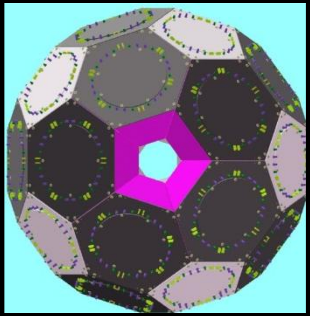
Resolved Conflicts:

Lesson: The Standard Model is hard to crack

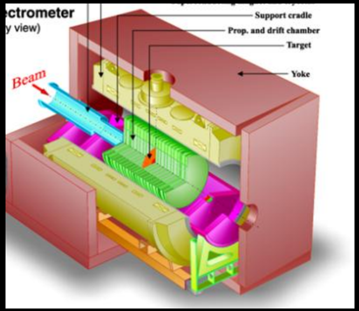
g_a, g_v, V_{ud} & "Row 1 unitarity"



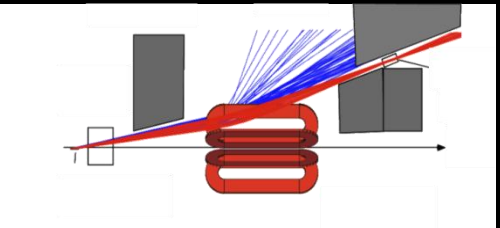
G_F, τ_μ, g_P



$\mathrm{Sin}^2\theta_W$



Michel parameters

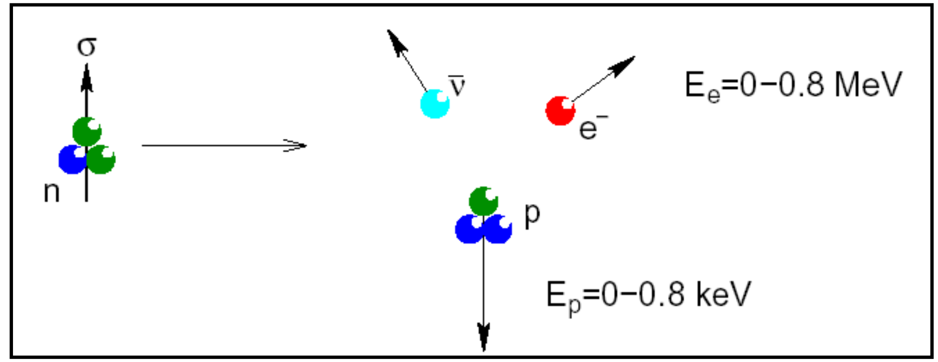


The Neutron as a Fundamental Laboratory

$n \rightarrow p^+ + e^- + \nu'_e$

neutron lifetime $\tau \approx 15$ min

β-endpoint energy: $E_{max} = 782$ keV



$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\upsilon}{E_e \cdot E_\upsilon} + b\frac{m_e}{E_e} + A\frac{\sigma_n \cdot \boldsymbol{p}_e}{E_e} + B\frac{\sigma_n \cdot \boldsymbol{p}_\upsilon}{E_\upsilon}\right]$$

$$\tau_n \propto 1/(g_A^2 + 3g_V^2)$$

$$a = \frac{1 - \left(\frac{g_A}{g_V}\right)^2}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$b = 0$$

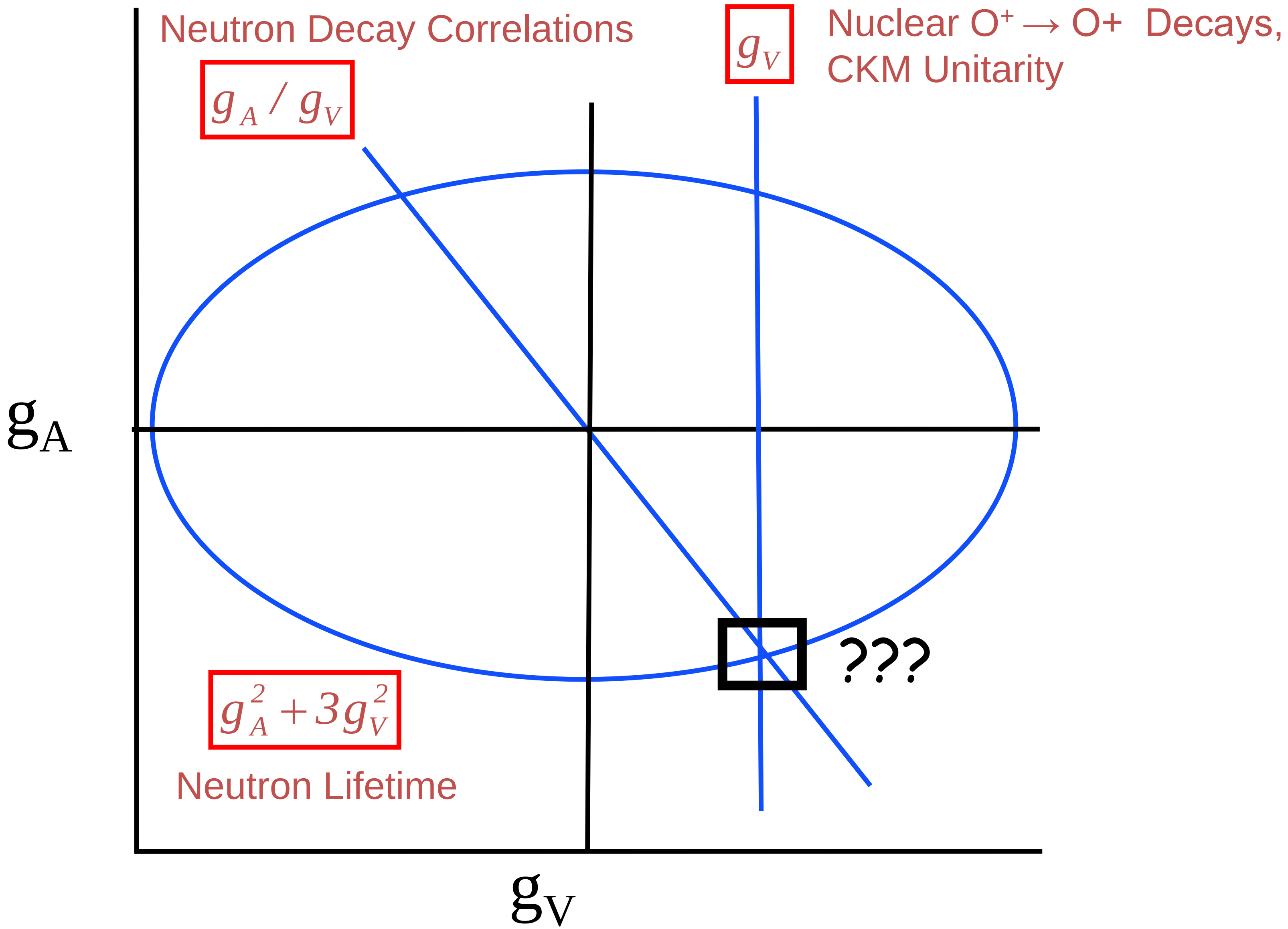
$$A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$B = 2\frac{\left(\frac{g_A}{g_V}\right)^2 - \left(\frac{g_A}{g_V}\right)}{1 + 3\left(\frac{g_A}{g_V}\right)^2}$$

Neutron beta decay measurements give:

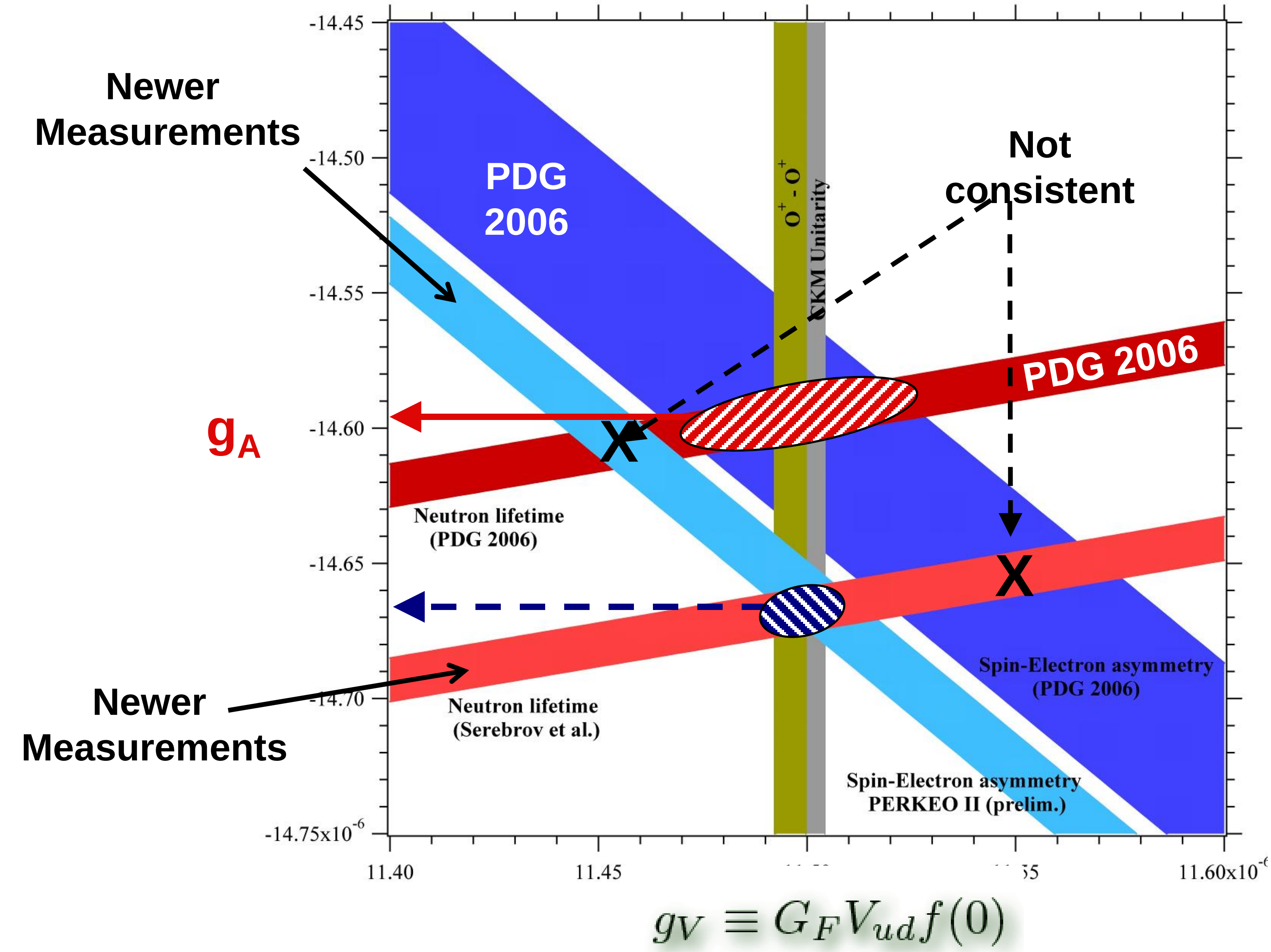
$$(g_A^2 + 3g_V^2)$$

$$g_A / g_V$$



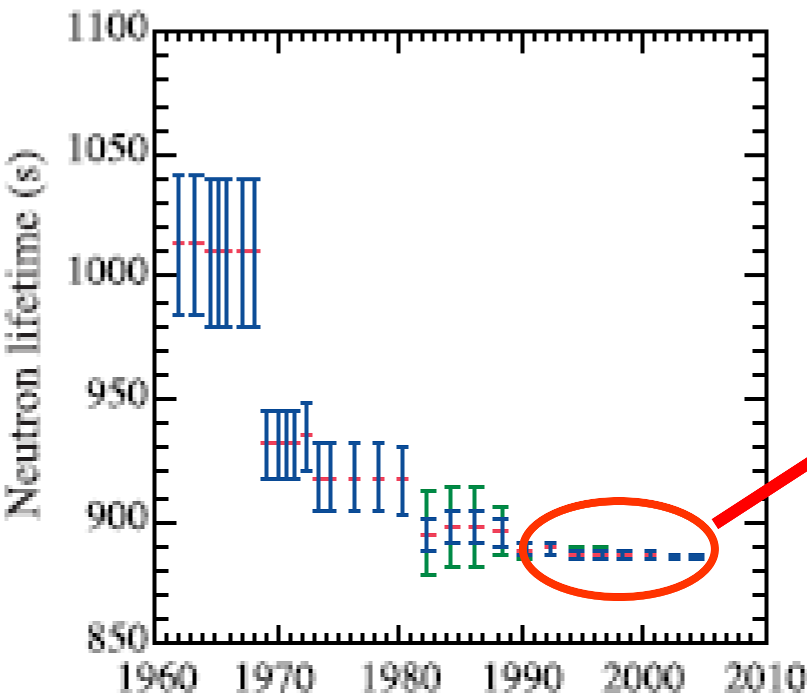
Neutron Decay Correlations
g_A / g_V
g_V
Nuclear $O^+ \rightarrow O+$ Decays,
CKM Unitarity
g_A
???
$g_A^2 + 3g_V^2$
Neutron Lifetime
g_V

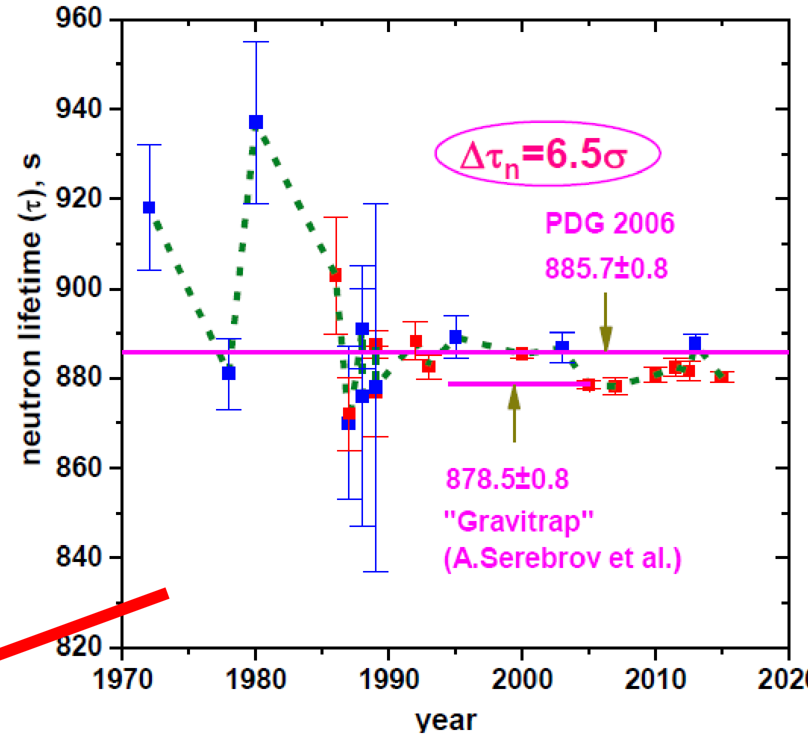
2007 picture: Lifetime and Correlations combine in a confused picture for the physics of g_A or unitarity

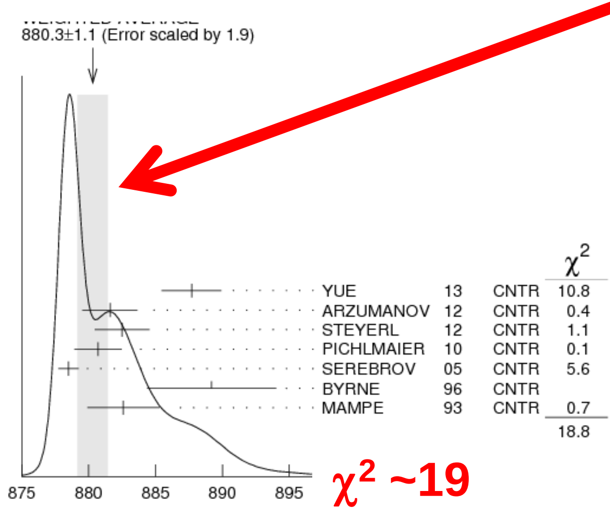


J. Nico, 2007

This well-known plot of Neutron Lifetime versus Time illustrates just how difficult this measurement is:



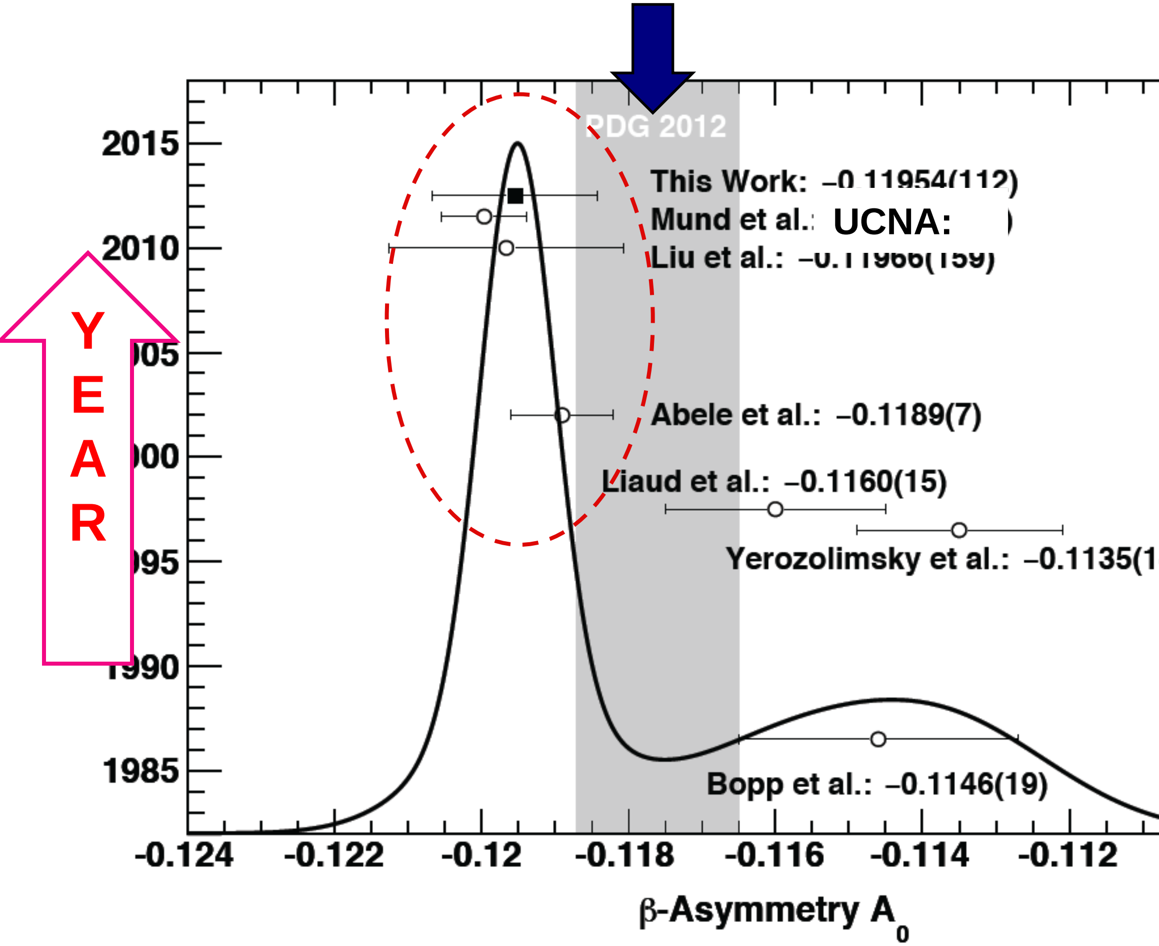




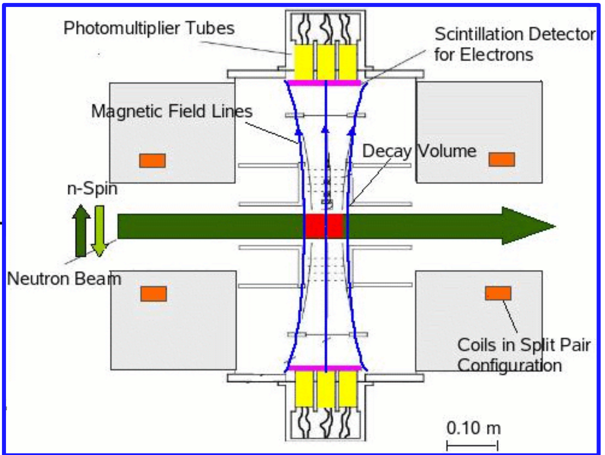
Reanalysis of bottle experiments by Serebrov, et al. part of adjustments

2015 Update on beta decay asymmetry

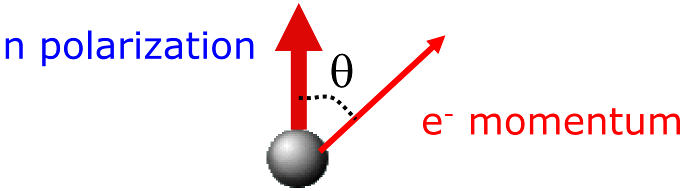
The PDG 2012 is no longer favored



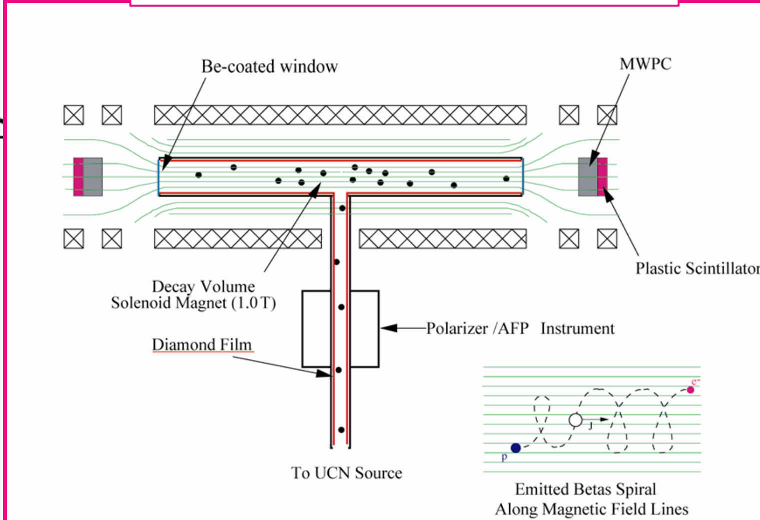
PERKEO II



The ILL efforts have defined the field for a long time



UCNA with ultracold n



2013 Update on beta decay asymmetry

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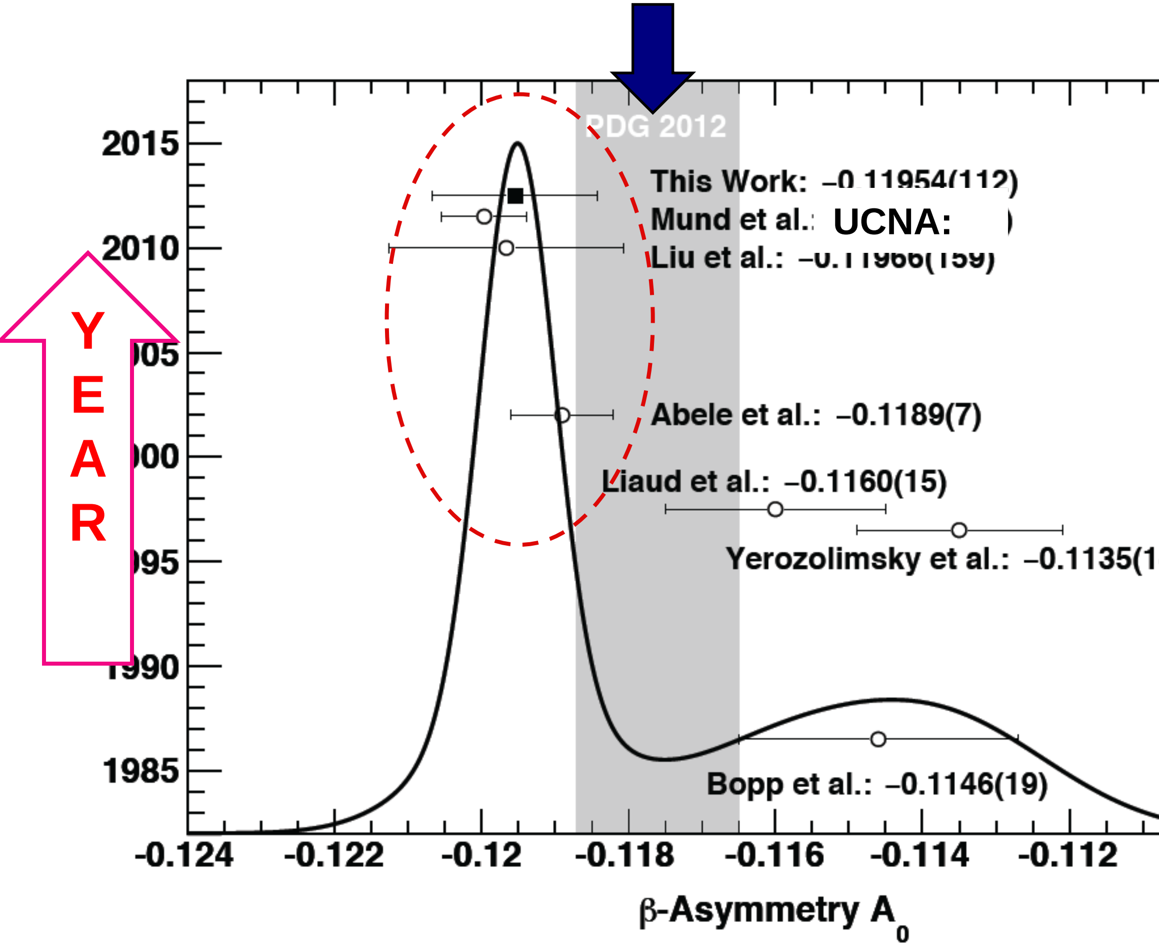

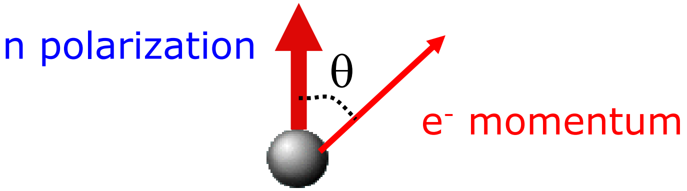

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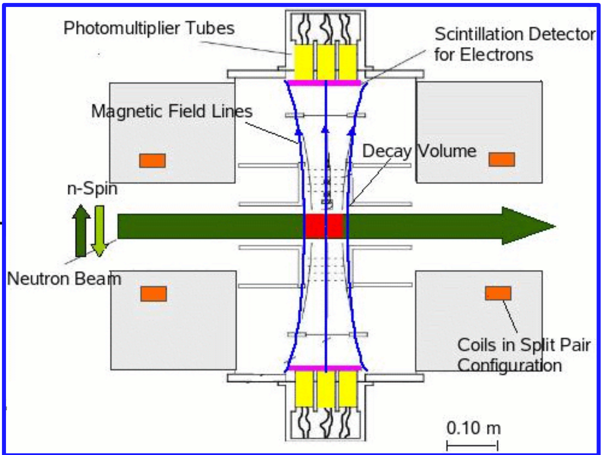
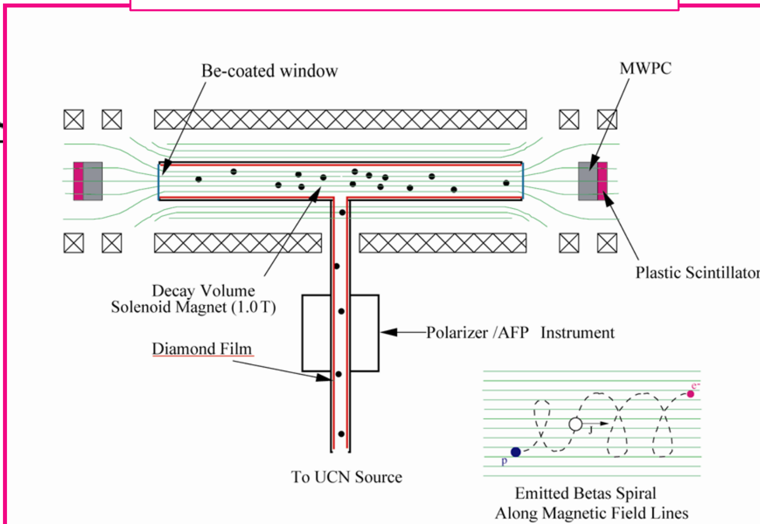


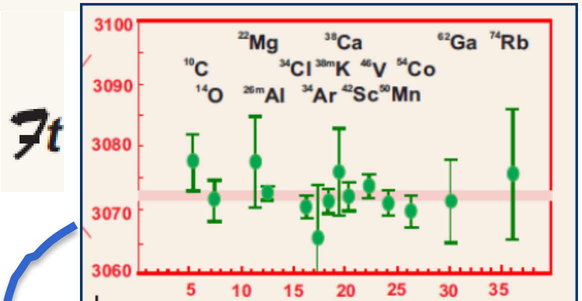
The ILL efforts have defined the field for a long time

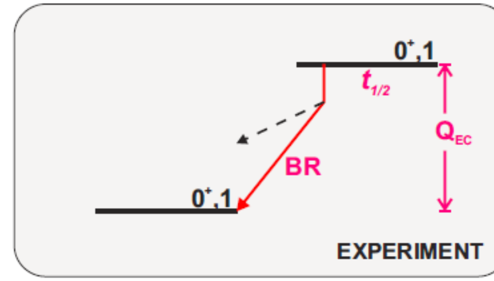
UCNA with ultracold n



And … SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$





$$ft = \frac{K}{G_V^2 <\tau>^2}$$

Tests of CKM Unitarity via nuclear beta, muon and Kaon decays at the 0.05% level

- Test CVC from many transitions
  - & validate correction terms

G_V constant to ± 0.013%

- Test for Scalar current

limit, $C_S/C_V = 0.0014\ (13)$

Then, *IF* CVC verified:

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

- Precise V_{ud} :

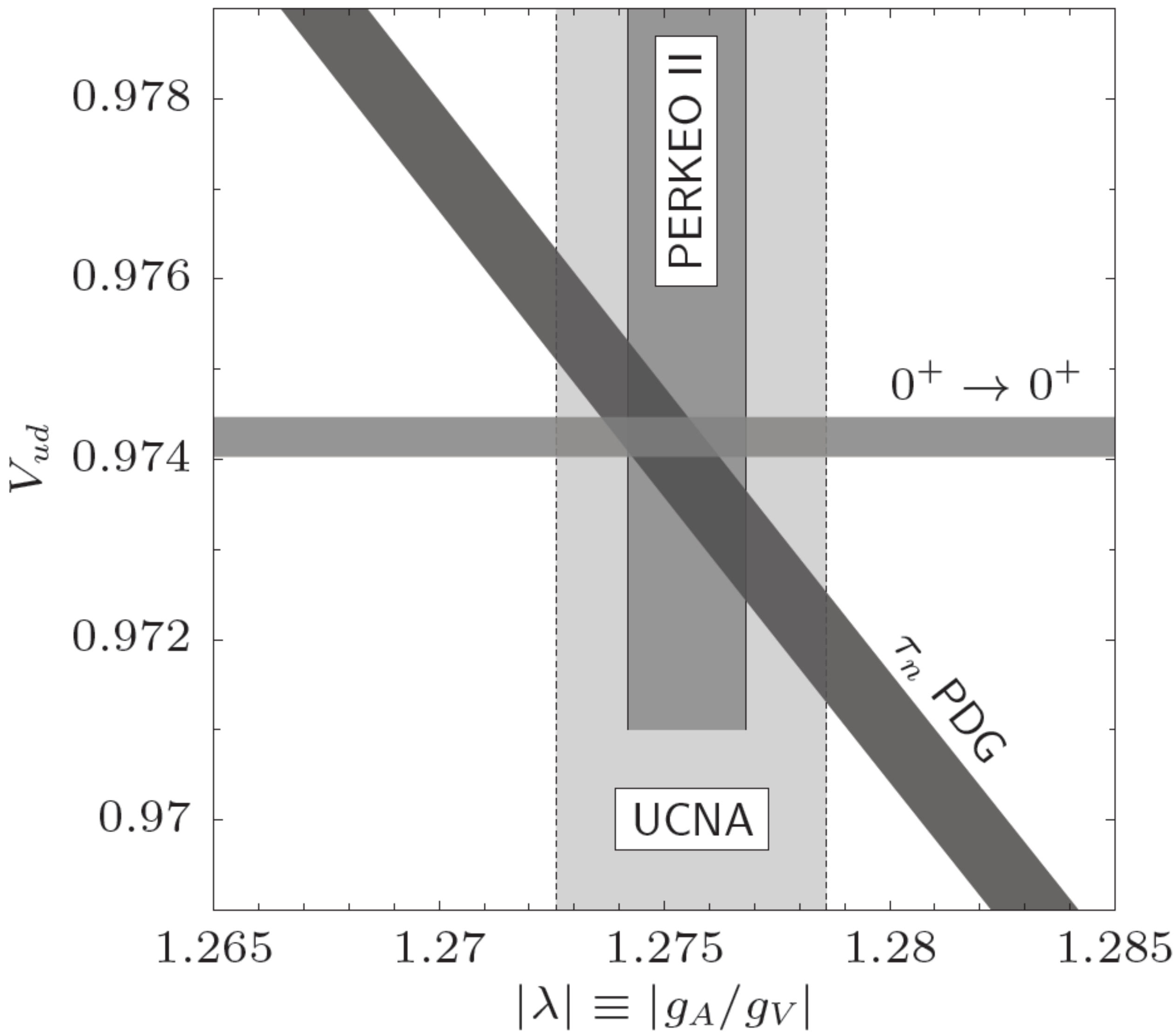
$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94900 \pm 0.00042$

- Test CKM unitarity

$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99992 \pm 0.00048$

J. Hardy

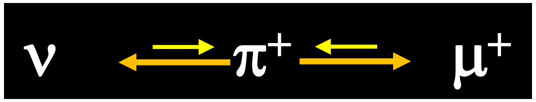
2015 Picture: Lifetime, Correlations, V_{ud} all painting a very consistent picture now IF we use the "precision" results only



Sorry, this plot is turned and arranged differently

Muon Primer

- **Mass ~ 207 m_e** **(50 ppb)**
  - **$(m_\mu/m_e)^2 \approx 43{,}000$ times more sensitive to "new physics" through quantum loops compared to electrons (taus would be better!)**
- **Lifetime ~2.2 μs** **(1 ppm)**
  - **High-intensity beams; can stop and study; can possibly collide**
- **Primary production: $\pi^+ \rightarrow \mu^+ \nu_\mu$** **(99.98%)**
  - **Polarized naturally:**

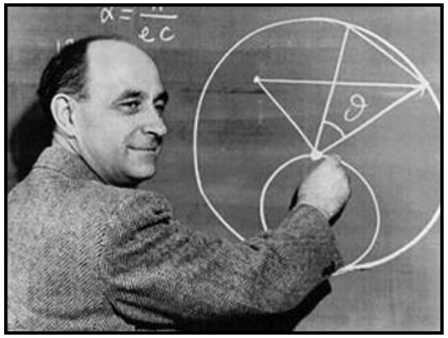


- **Primary decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$** **(~99%)**
  - **Purely weak; distribution in θ and *E* reveals weak parameters**
- **Lepton number is conserved**

(BRs 4 < 10^{-13})

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Muon Lifetime

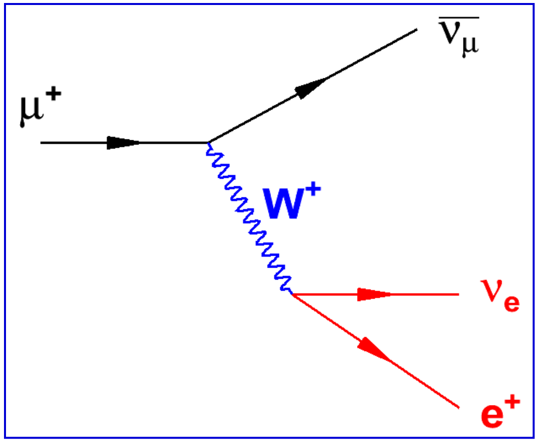


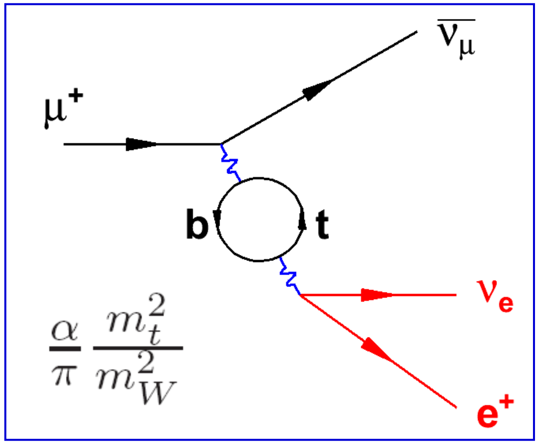
Fundamental electro-weak couplings

G_F	α	M_Z
15 ppm → 0.5 ppm	0.37 ppb	23 ppm

Implicit to all EW precision physics

$$\frac{G_\mathrm{F}}{\sqrt{2}} = \frac{g^2}{8M_\mathrm{W}^2}\left(1+\Delta r(m_\mathrm{t}, m_\mathrm{H}, \ldots)\right)$$

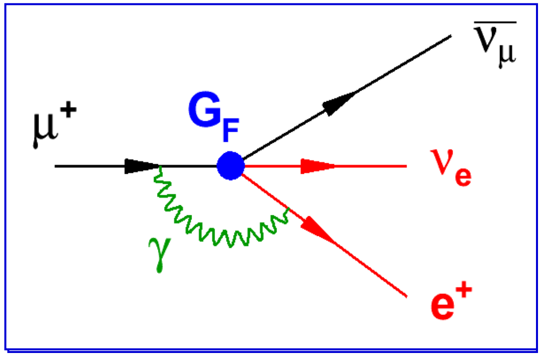




Uniquely defined by muon decay

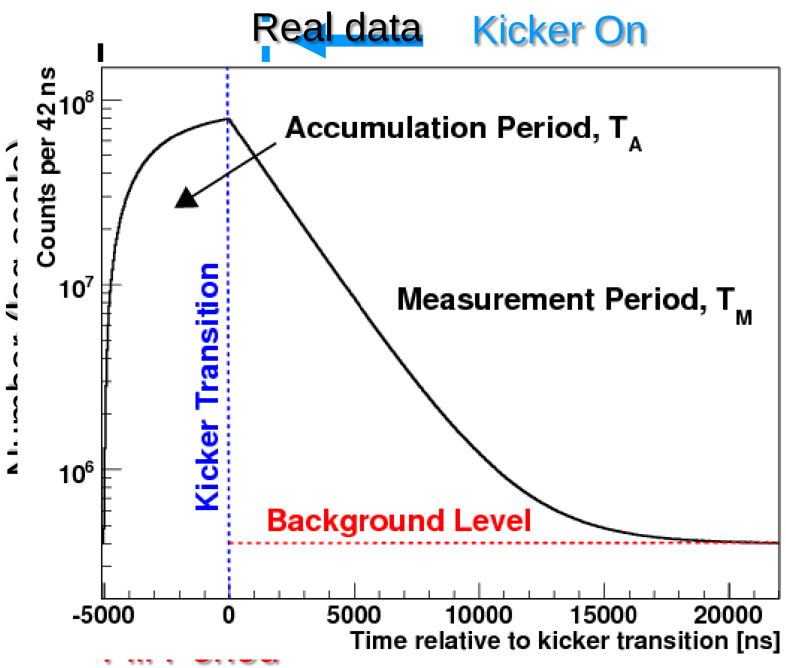
$$\frac{1}{\tau_{\mu^+}} = \frac{{G_\mathrm{F}}^2 m_\mu^5}{192\pi^3}(1+q)$$

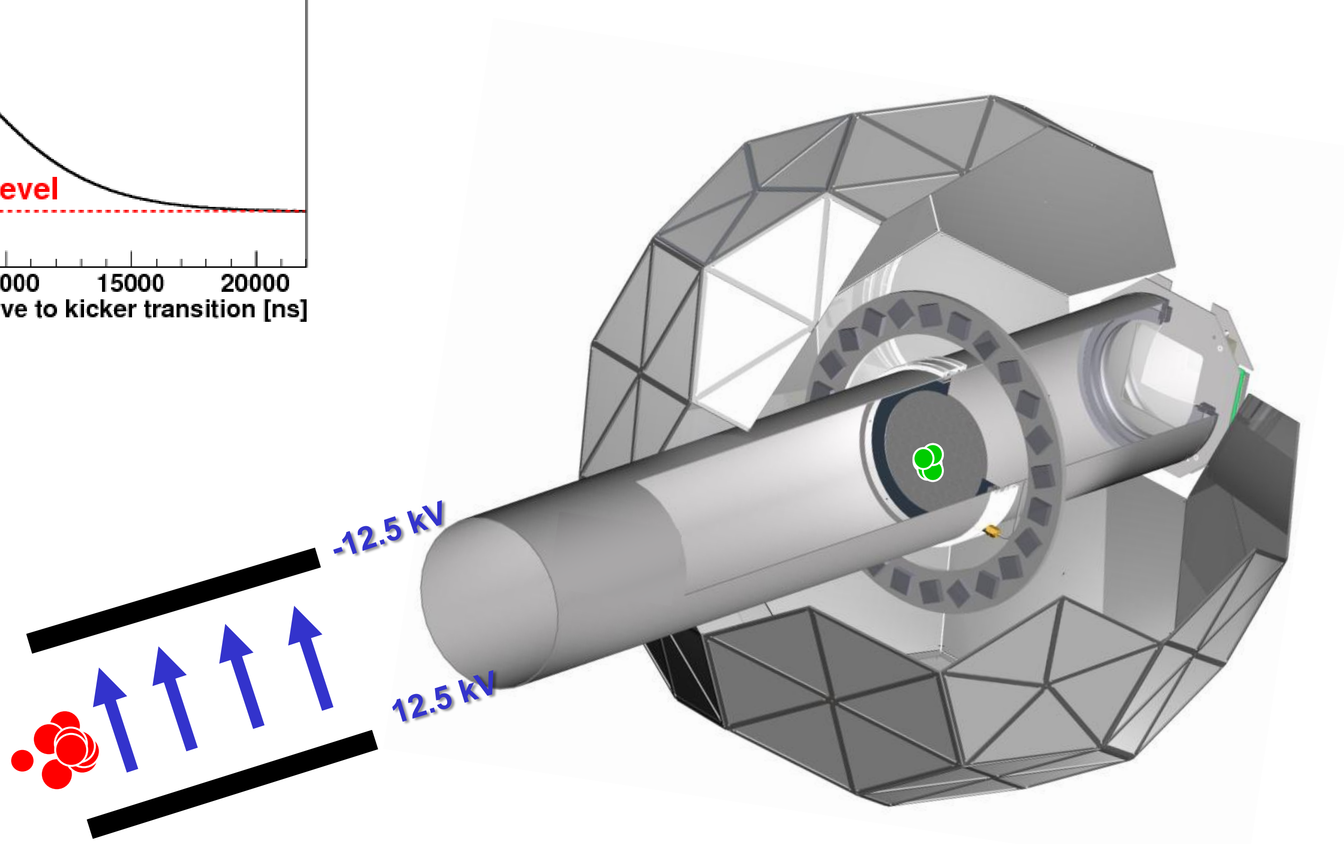
QED



Extraction of G_F from τ_μ :
reduced error from
15 to ~0.5 ppm

MuLan measured ~ 2 x 10^{12} decays

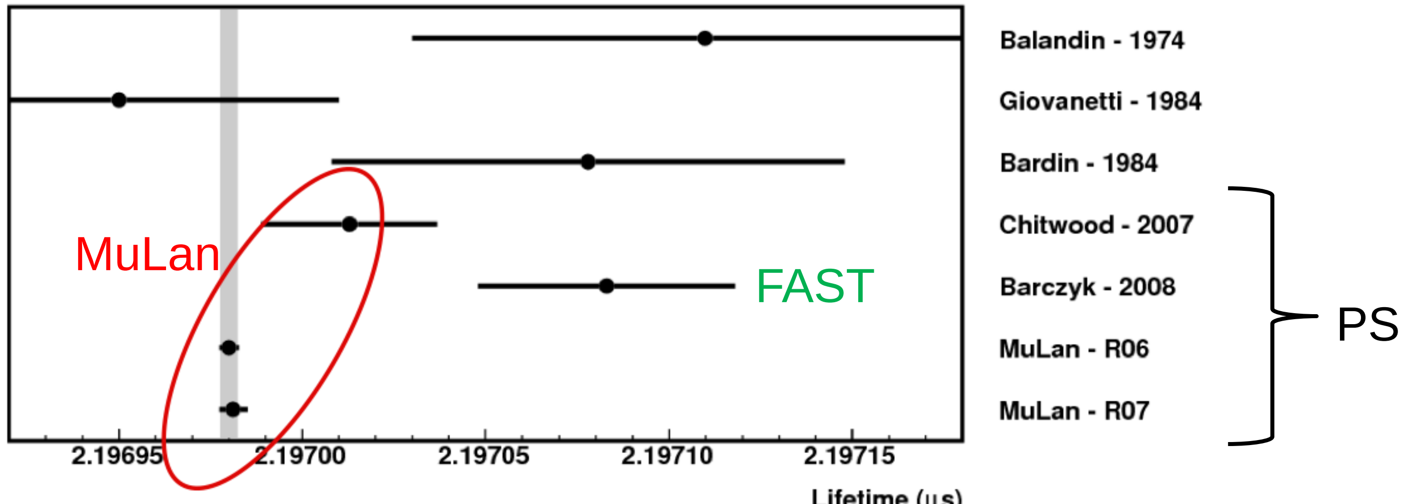




at PSI

Detector has symmetric design around stops

Final Results: Muon lifetime & Fermi constant



The most precise particle or nuclear or atomic lifetime ever measured

τ(R06) = 2 196 979.9 ± 2.5 ± 0.9 ps
τ(R07) = 2 196 981.2 ± 3.7 ± 0.9 ps

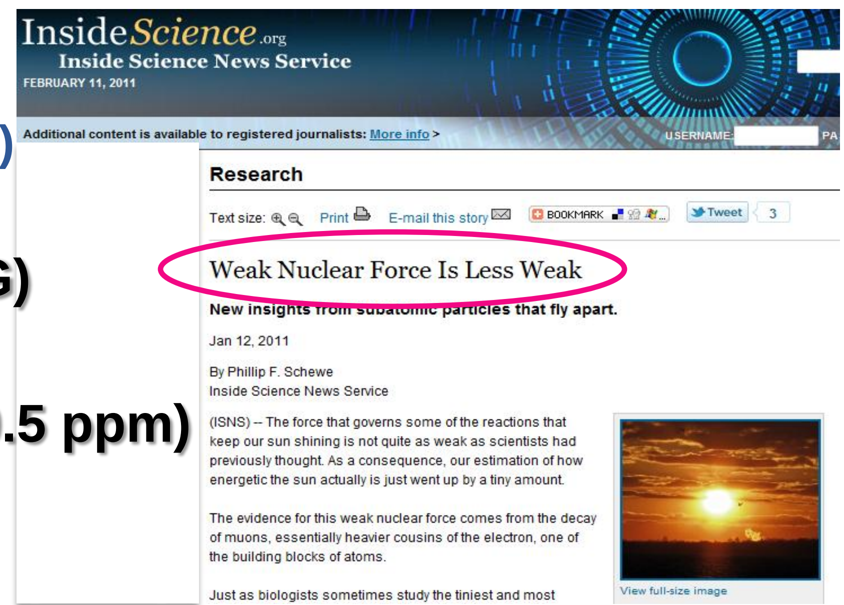
τ(Combined) = 2 196 980.3 ± 2.2 ps (1.0 ppm)

$\Delta\tau$(R07 – R06) = 1.3 ps

New G_F (30x improved since 1999 PDG)

G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (2013)


InsideScience.org
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Weak Nuclear Force Is Less Weak

New insights from subatomic particles that fly apart.

Jan 12, 2011

By Phillip F. Schewe
Inside Science News Service

(ISNS) -- The force that governs some of the reactions that keep our sun shining is not quite as weak as scientists had previously thought. As a consequence, our estimation of how energetic the sun actually is just went up by a tiny amount.

The evidence for this weak nuclear force comes from the decay of muons, essentially heavier cousins of the electron, one of the building blocks of atoms.

Just as biologists sometimes study the tiniest and most

View full-size image

Final results from *TWIST* measurement of muon decay parameters

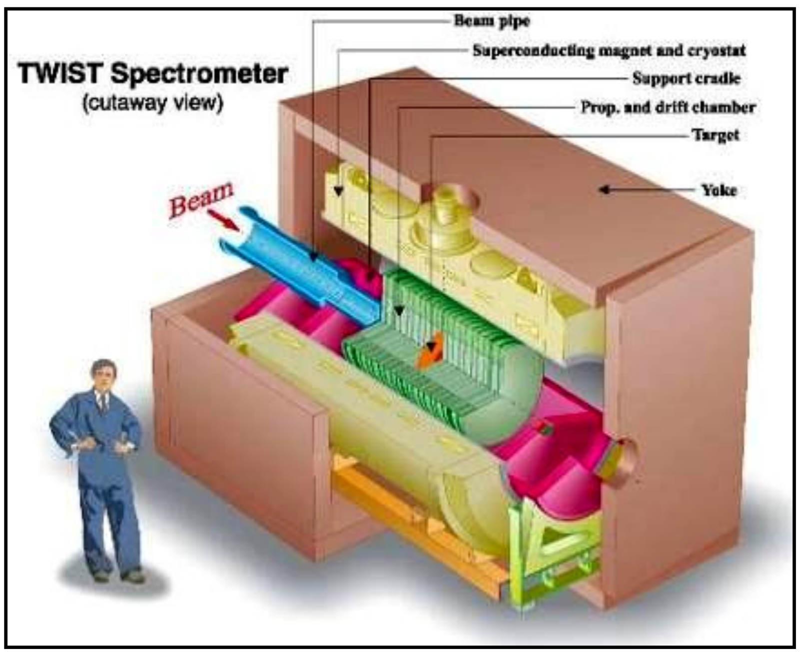
Is muon decay purely V-A?

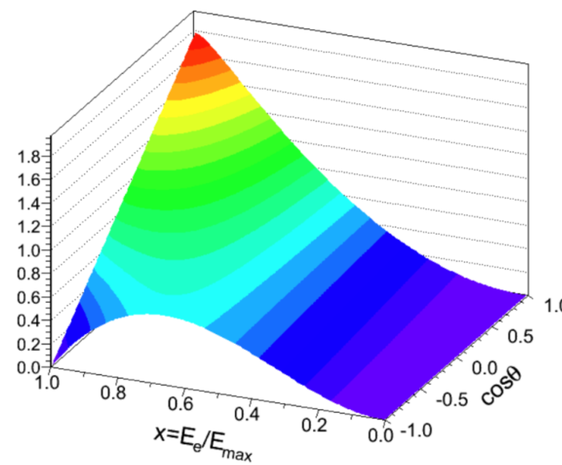
Sensitive to attractive SM extensions:

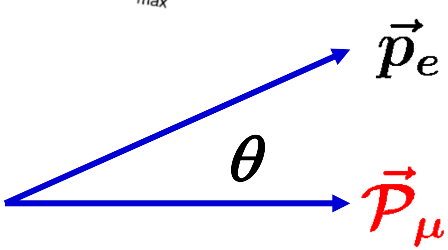
L-R symmetric models, which would permit a W_R

Basic idea:

Measure the energy and angular distribution of e^+ from $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$ and compare to Monte Carlo expectations





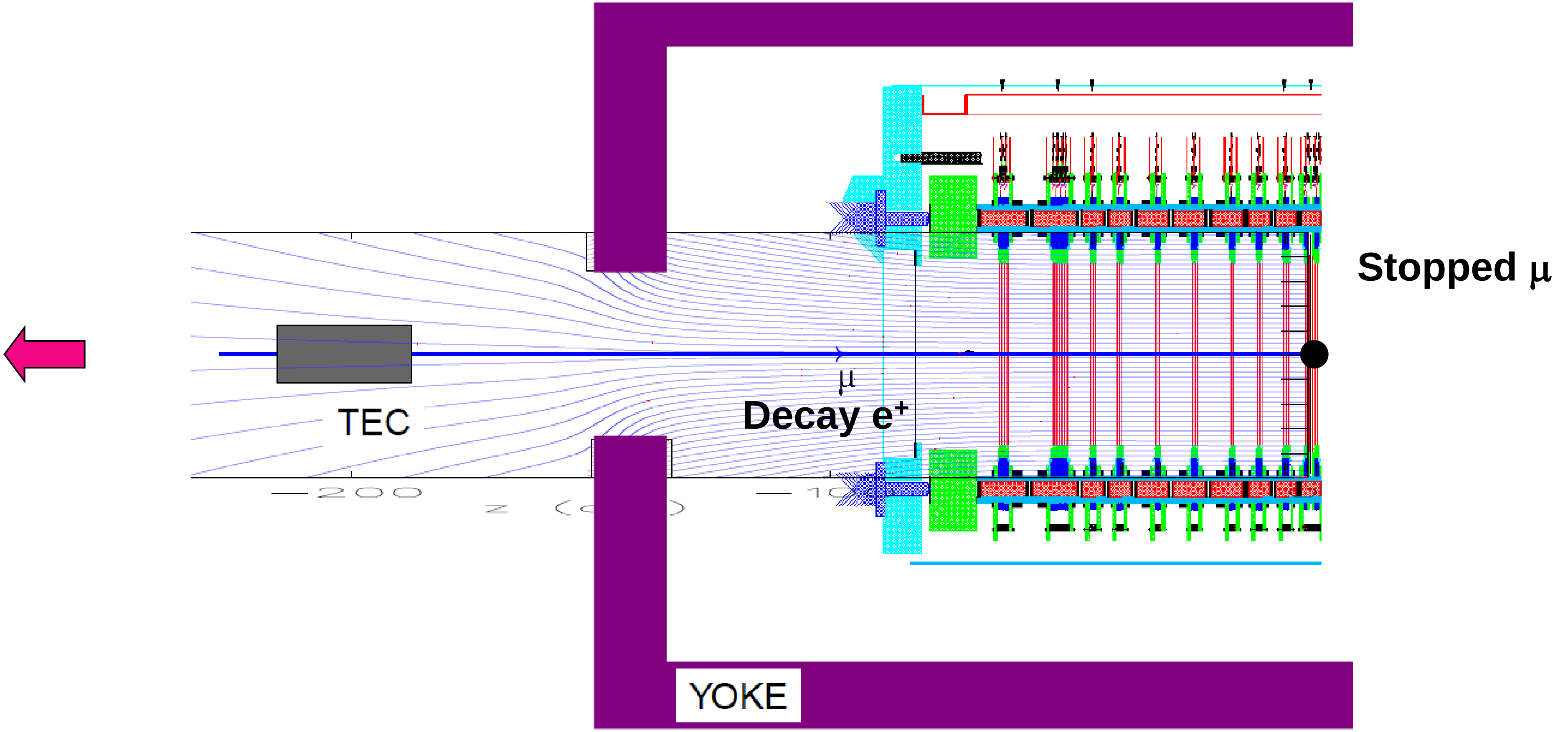


The formalism, "Michel" parameters

- Muon decay parameters ρ, η, $\mathcal{P}_\mu \xi$, δ
- Differential decay rate *vs.* energy and angle:

$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot$$

$$\{\mathcal{F}_{IS}(x, \rho, \eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x, \xi, \delta)\} + R.C.$$

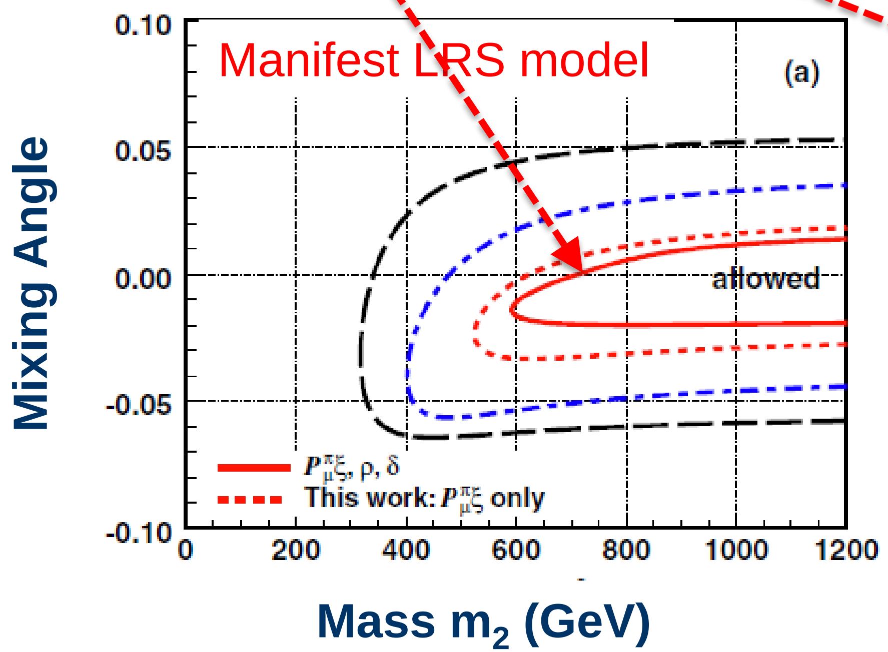


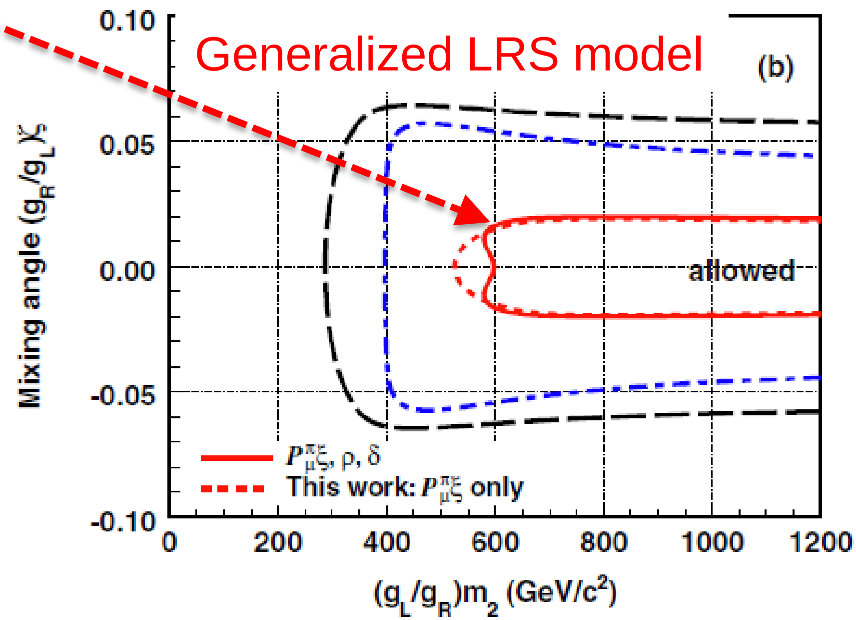
Michel Parameters: TWIST final results

SM	
¾	ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)
¾	δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)
1	$\mathcal{P}_\mu{}^\pi\xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)

"SM still okay"

Results mostly constrain right-handed muon terms

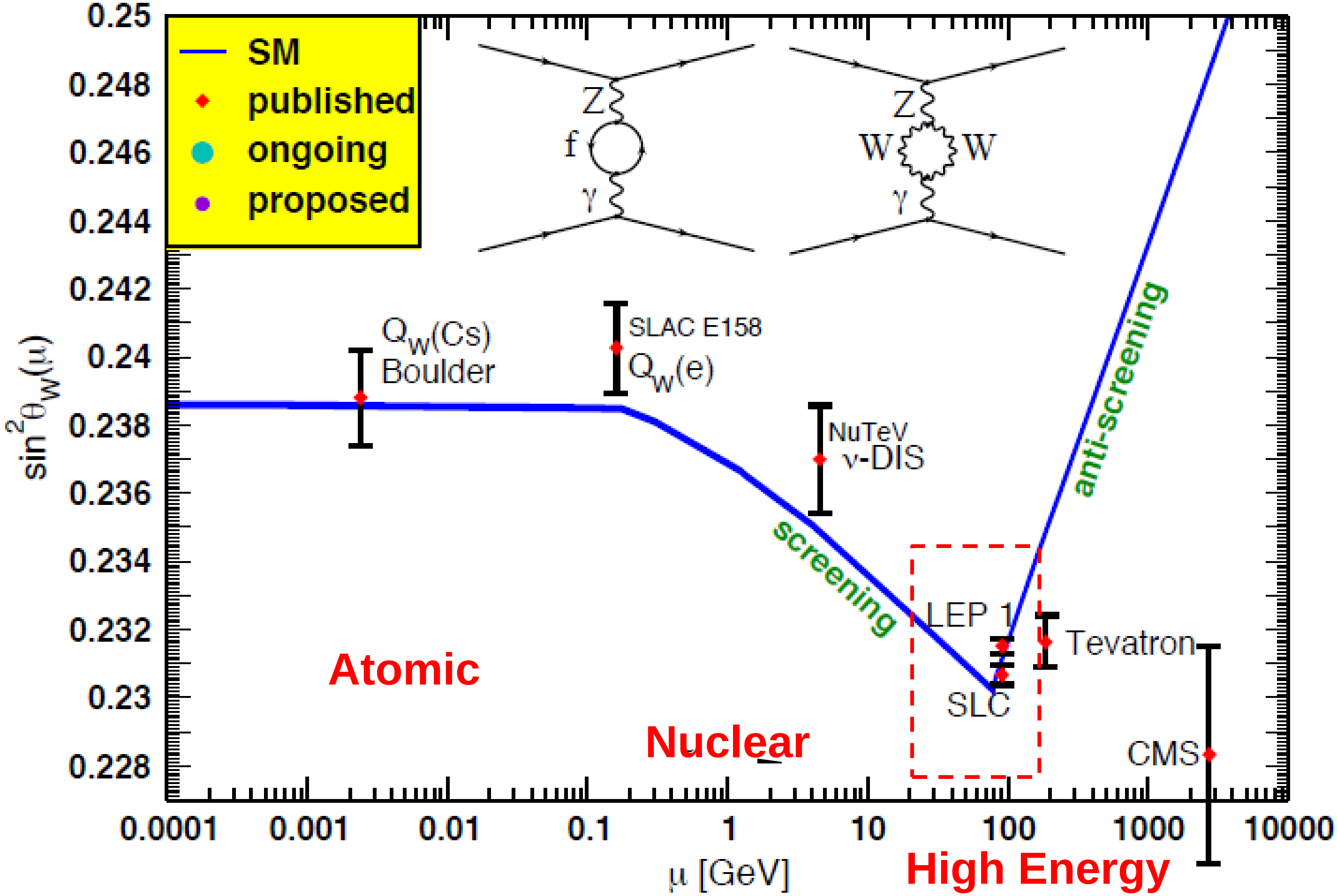




PHYSICAL REVIEW D **84**, 032005 (2011)

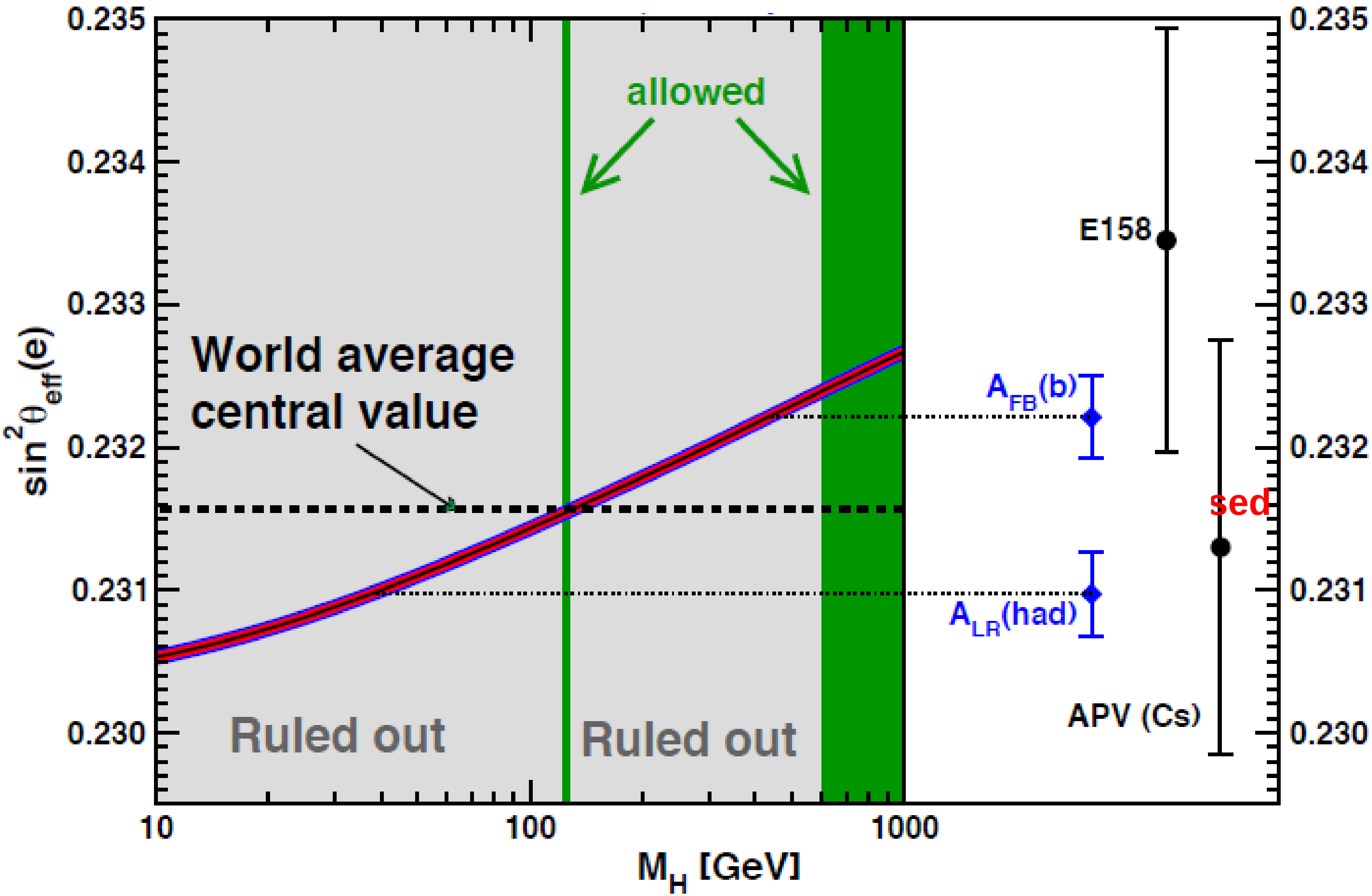
Phys. Rev. D 85, 092013 (2012)

Running of $\sin^2\theta_W(Q^2)$ and Tension with LEP and SLC



Next-generation efforts: Parity-Violating e^- Scattering

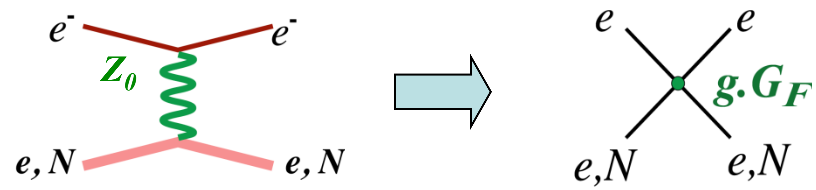
The precision measurement of the Higgs mass updates the story, fixing central value of $\sin^2\theta_W$



J. Erler

Next-Generation experiments sensitive to new, heavy, neutral current interactions?

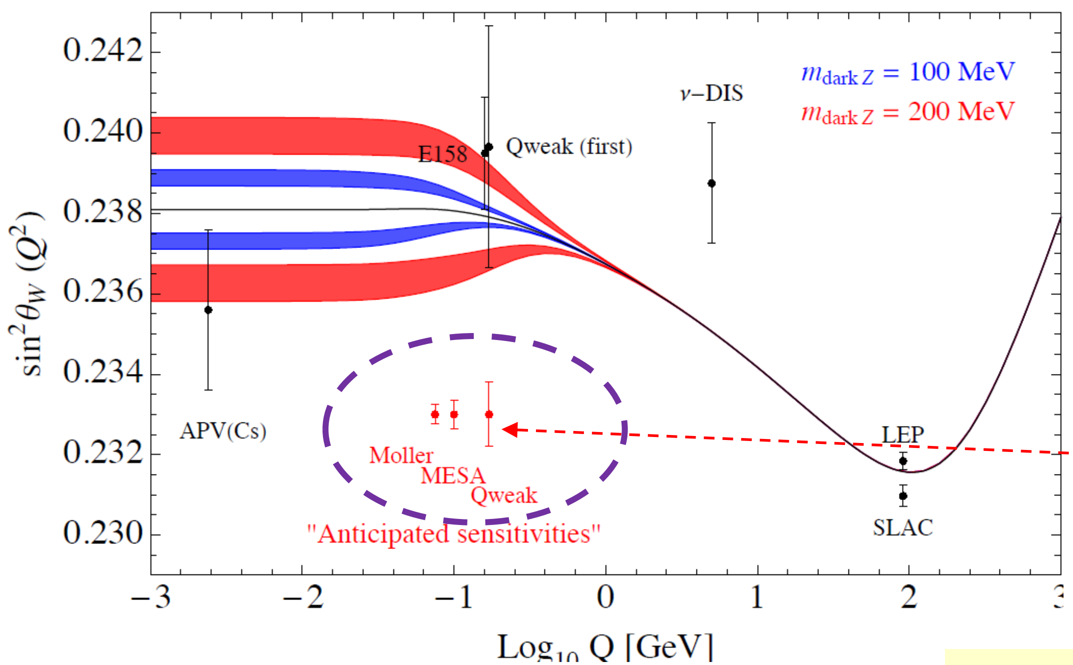
Heavy Z' s and neutrinos, technicolor, compositeness, extra dimensions, SUSY…



Sensitivity to TeV-scale contact interactions if:

- $\delta(\sin^2\theta_W) \leq 0.5\%$
- away from the Z resonance

Or, Dark Photons?

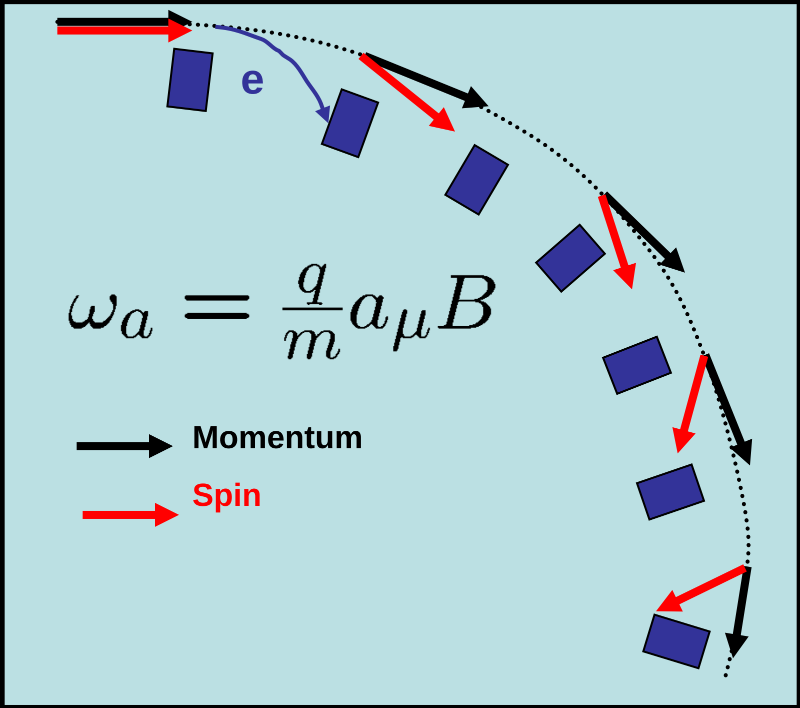


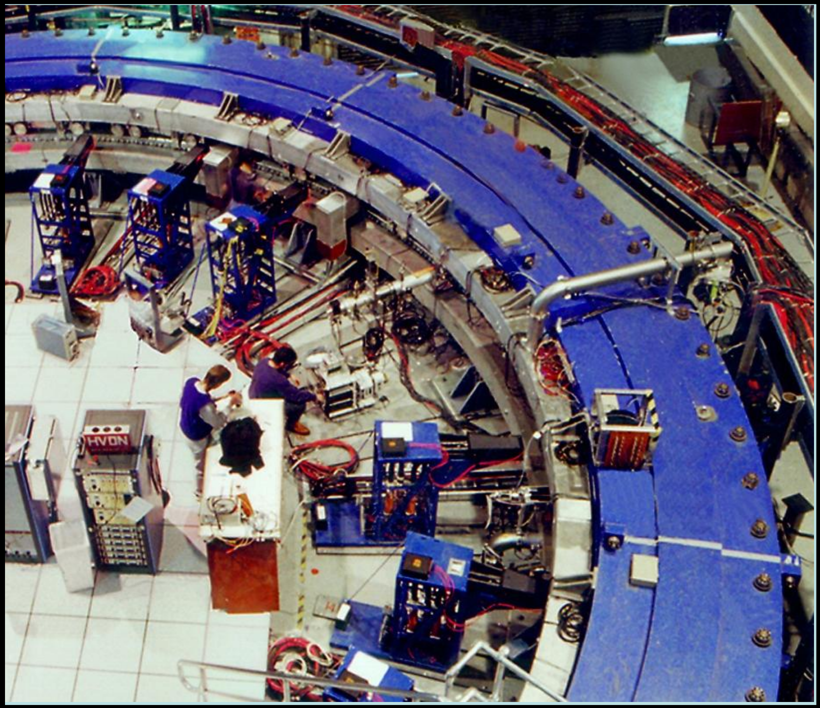
Q_{weak} result is due "very soon"

See next talk

Davoudiasl, Lee, Marciano '14

A Case for Challenging the Standard Model

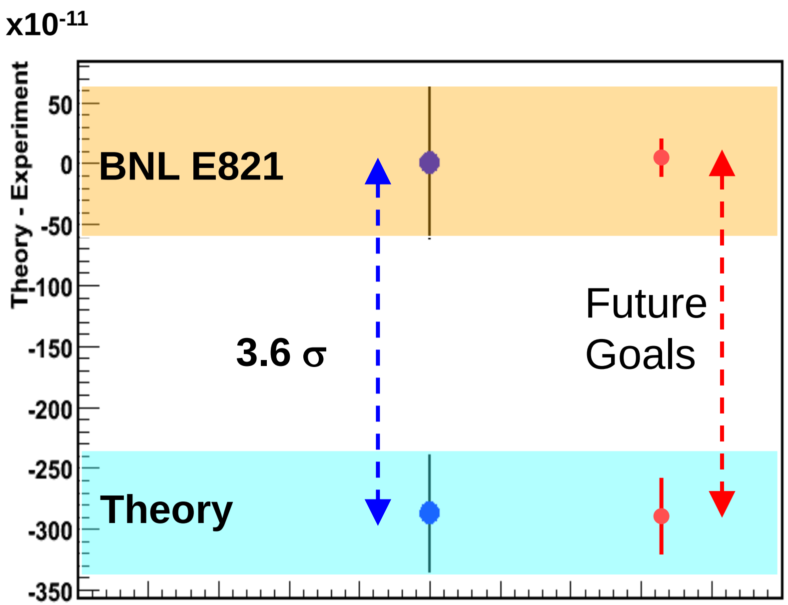




BNL result → $a_\mu(\text{Expt}) = 116\ 592\ 089\ (63) \times 10^{-10}$ (540 ppb)

The experiment compares how fast a muon spin rotates in a magnet compared to the predictions from theory

Comparison to Theory and future Goals for both



Goal: 140 ppb
FNAL E989

>7.5 σ if same central values

Expected Improvement
(data and lattice)

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (261 - 287 \pm 80)^{*} \times 10^{-11}$$

➡ 3.3 to 3.6 σ

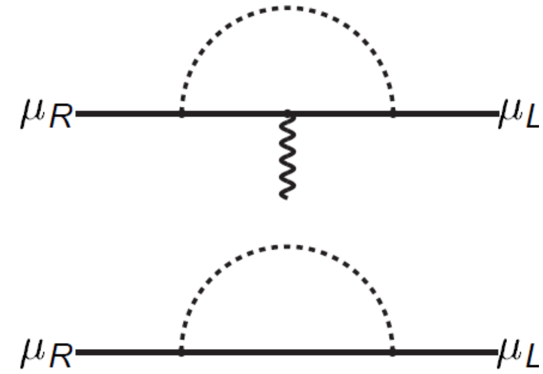
What is nature trying to tell us?

*range of typical SM evaluations

g-2 feature: Chirality flipping interactions for mass and charge (moment) terms

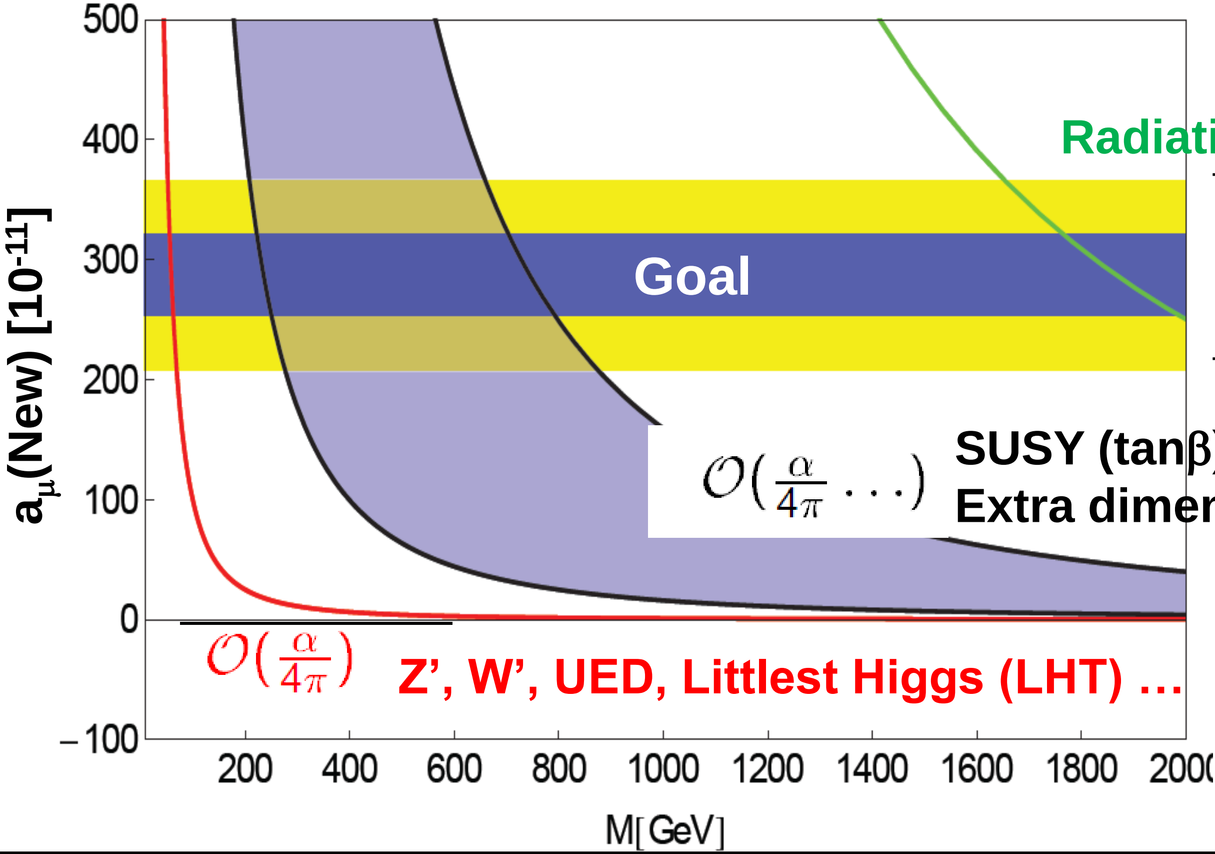
g – 2

m_μ



$$C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}, \quad \delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2$$

The coupling *C* is VERY model dependent



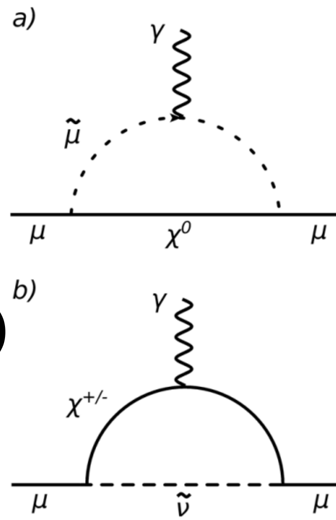
$\mathcal{O}(1)$

Radiative muon mass generation

Current Δa_μ

SUSY (tanβ), unparticles
Extra dimensions (ADD/RS)

Z', W', UED, Littlest Higgs (LHT) …



From D. Stockinger (See many of this g-2 presentations about new physics impact)

Post LHC Run 1 physics case strong as ever

Representative papers –a few weeks last spring – with g-2 in titles are typically refined models of SUSY; many more since then …

Natural Supersymmetry, Muon $g-2$, and the Last Crevices for the Top Squark

B. Paul Padley[1], Kuver Sinha[2], and Kechen Wang[3]

Large muon $(g-2)$ with TeV-scale SUSY masses for $\tan\beta \to \infty$

Markus Bach[a], Jae-hyeon Park[b], Dominik Stöckinger[a], Hyejung Stöckinger-Kim[a]

Muon $g-2$ in Anomaly Mediated SUSY Breaking

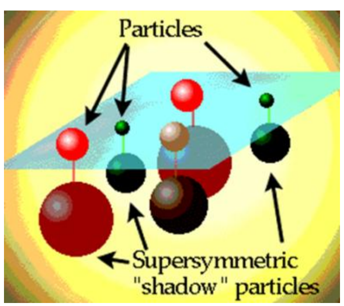
Debtosh Chowdhury[*] and Norimi Yokozaki[†]

Muon $g-2$ in Focus Point SUSY

Keisuke Harigaya[a], Tsutomu T. Yanagida[b] and Norimi Yokozaki[c]

Lepton-Specific Two Higgs Doublet Model as a Solution of Muon $g-2$ Anomaly

Tomohiro Abe[1], Ryosuke Sato[1] and Kei Yagyu[2]



Neutralinos and Sleptons at the LHC in Light of Muon $(g-2)_\mu$

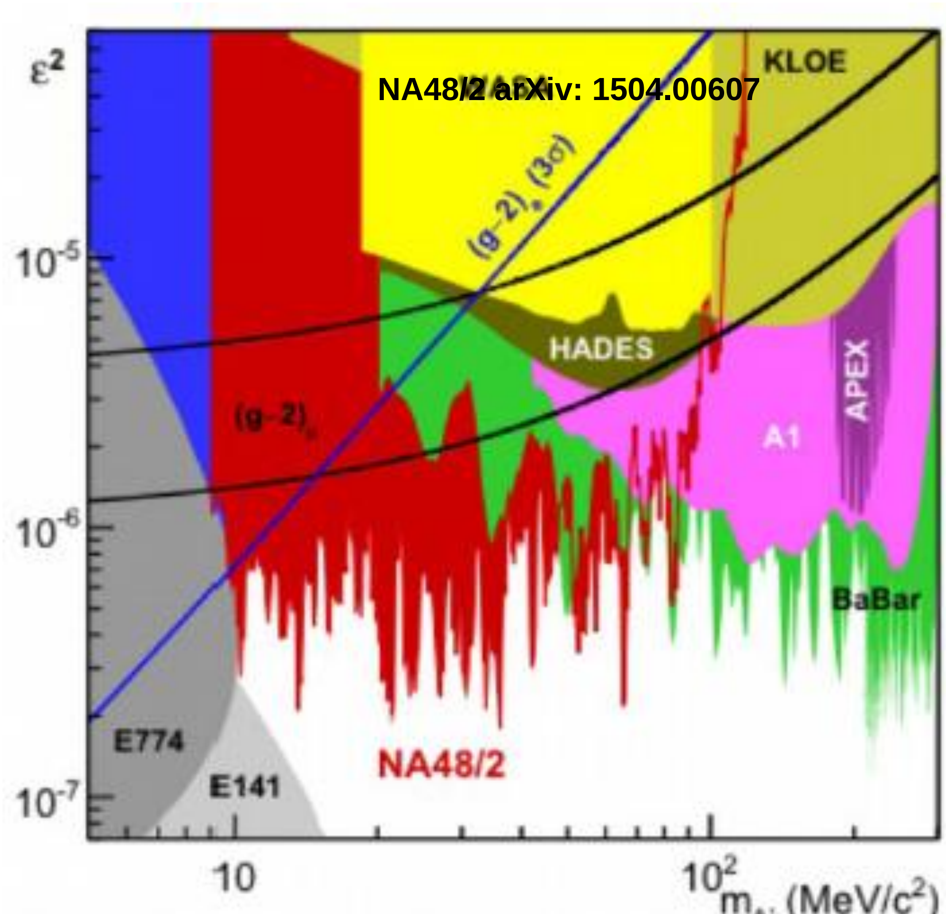
M. Adeel Ajaib[a,1], Bhaskar Dutta[b,2], Tathagata Ghosh[b,3], Ilia Gogoladze[c,4], Qaisar Shafi[c,5]

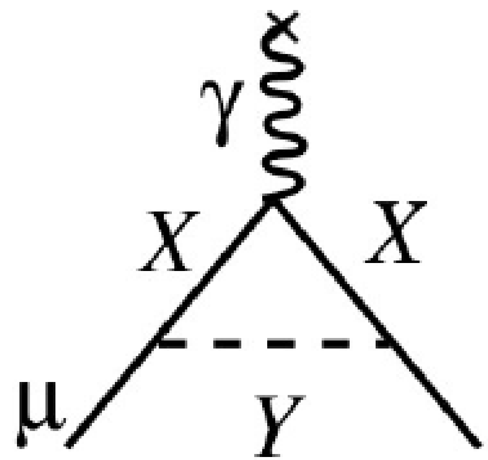
Now with more restricted spaces and tanβ range

Perhaps something at low scales … not seen at the LHC

Light vector space of dark photon → e^+e^- (<u>visible</u> decays) largely ruled out now

But, the "<u>invisible</u>" decay space is quite alive; Dark Z model also alive and connects to running of $\sin^2\theta_W$ vs Q





The key numbers that determine the precision of the "g-2 Test"

$$a_\mu(\text{New Physics}) \equiv a_\mu(\text{Expt}) - a_\mu(\text{SM})$$

- $a_\mu(SM) = a_\mu(QED) + a_\mu(Weak) + a_\mu(HVP) + a_\mu\,(Had\ HO) + a_\mu\,(HLbL)$

✓ ✓ ✓

A few remarks here

In E821 $\equiv \mathcal{R}_\mu(\text{E821}) = 0.003\,707\,206\,4(2\,0)$ **[0.54 ppm]**

- $a_\mu(\text{Expt}) = \dfrac{g_e}{2}\,\dfrac{\omega_a}{\tilde{\omega}_p}\,\dfrac{m_\mu}{m_e}\,\dfrac{\mu_p}{\mu_e}$

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

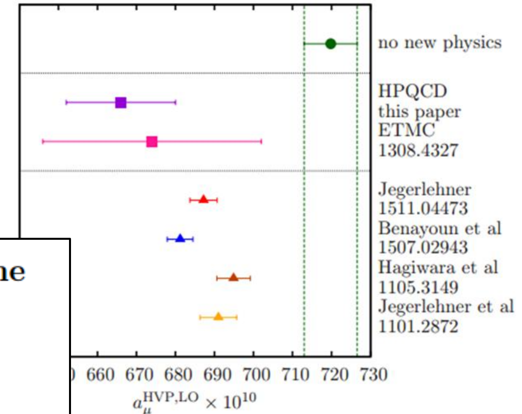
-.001519270384(12) [8 ppb]

206.768 2843(52) **[25 ppb]**

3 recent Lattice breakthroughs related to g-2

The hadronic vacuum polarization contribution to a_μ from full lattice QCD

Bipasha Chakraborty,[1] C. T. H. Davies,[1,*] P. G. de Oliveira,[1] J. Koponen,[1] and G. P. Lepage[2]
(HPQCD collaboration)[†]



- 2% precision on **HVP**;
- Physical pions, and u,d,s,c <u>**Connected**</u> loops

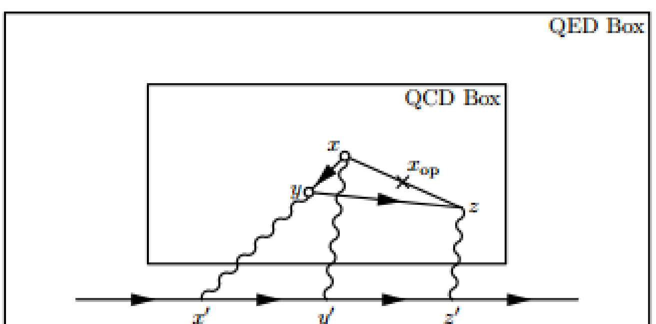
Calculation of the hadronic vacuum polarization disconnected contribution to the muon anomalous magnetic moment

T. Blum,[1] P.A. Boyle,[2] T. Izubuchi,[3,4] L. Jin,[5] A. Jüttner,[6] C. Lehner,[3,*]
K. Maltman,[7,8] M. Marinkovic,[9] A. Portelli,[2,6] and M. Spraggs[6]
(RBC and UKQCD Collaborations)

- <u>**Disconnected**</u> result: $(-9.6 \pm 3.3 \pm 2.3) \times 10^{-10}$

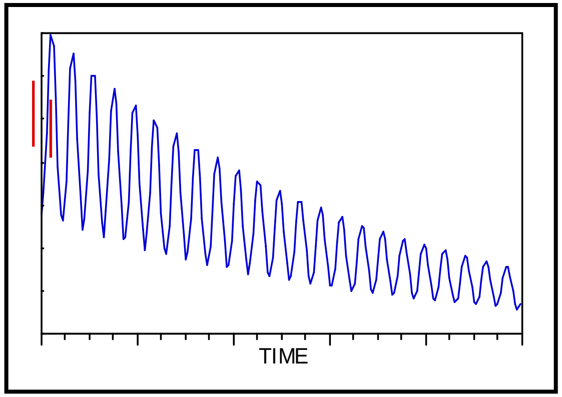
QCD Box in a QED Box to manage finite volume effects

Jin, Blum, Christ, Hayakawa, Izubuchi, Lehner



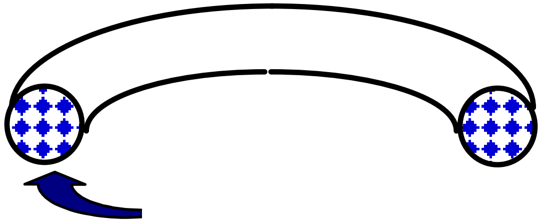
- 8% precision on **HLbL connected part**
- Physical pions, large lattice
- Missing connected can be handled

g-2 from 2 frequency measurements and a folding



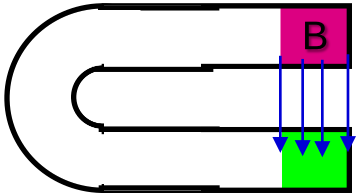
(1) Precession frequency

- **(1) Detectors involved**



(2) Muon distribution

- **(2) Measured and Simulated**

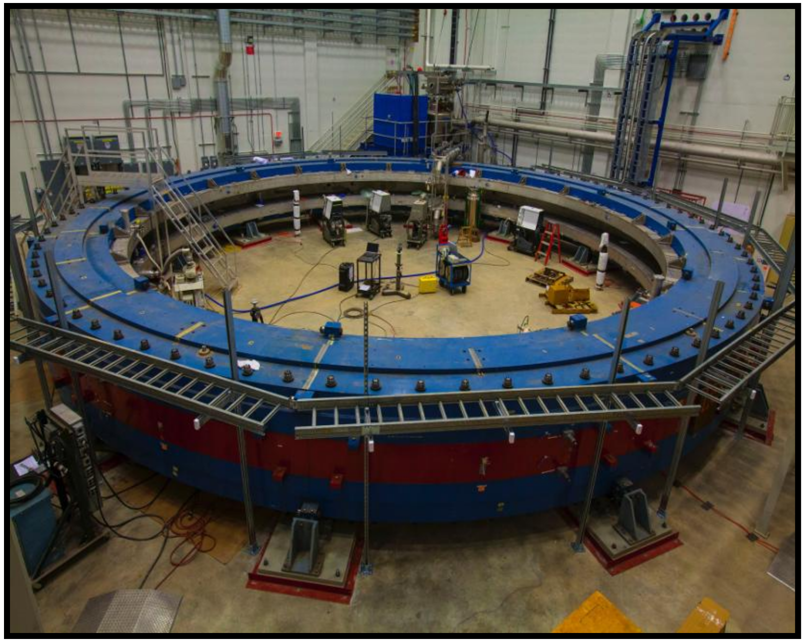


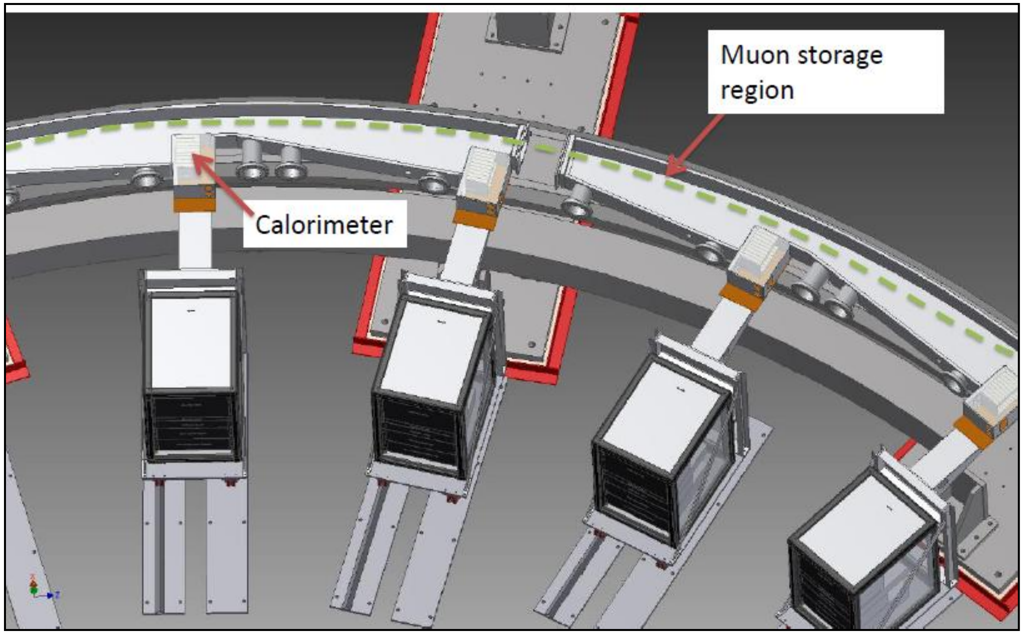
(3) Magnetic field

- **(3) In terms of proton NMR**

$$\boxed{(g-2) \propto \frac{(1)}{\left\langle \int (2)(3) \right\rangle}}$$

The Storage Ring is working
The Detectors are tested
Muon data starts in one year !!!

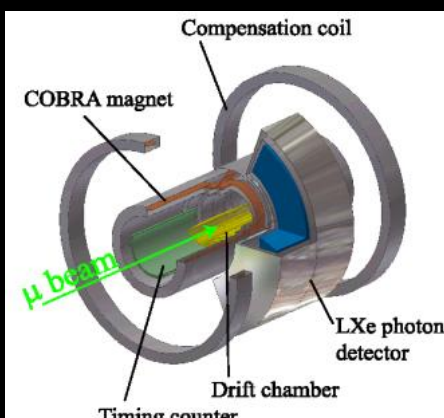


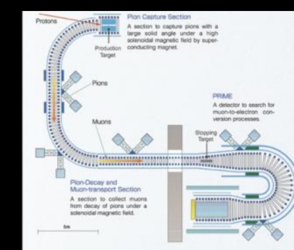


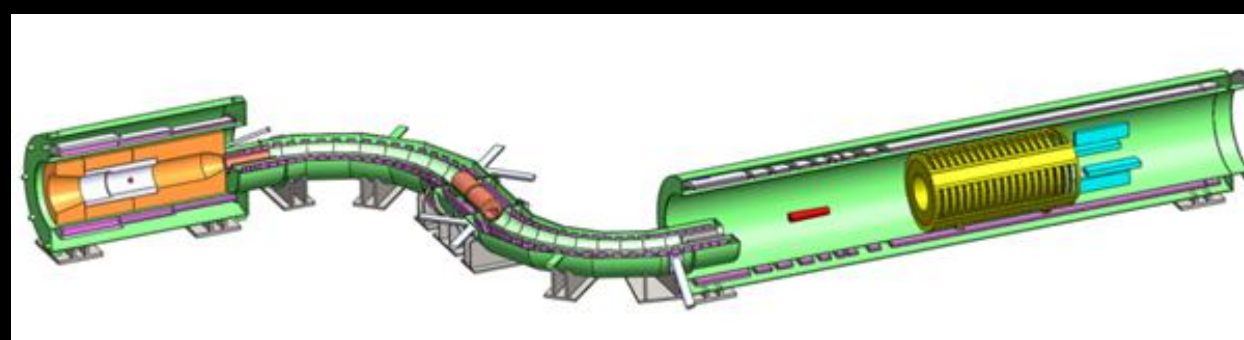
Impressive sensitivity to new physics when the SM theory "is zero" (or sort of)

Charged Lepton Flavor Violation

EDMs

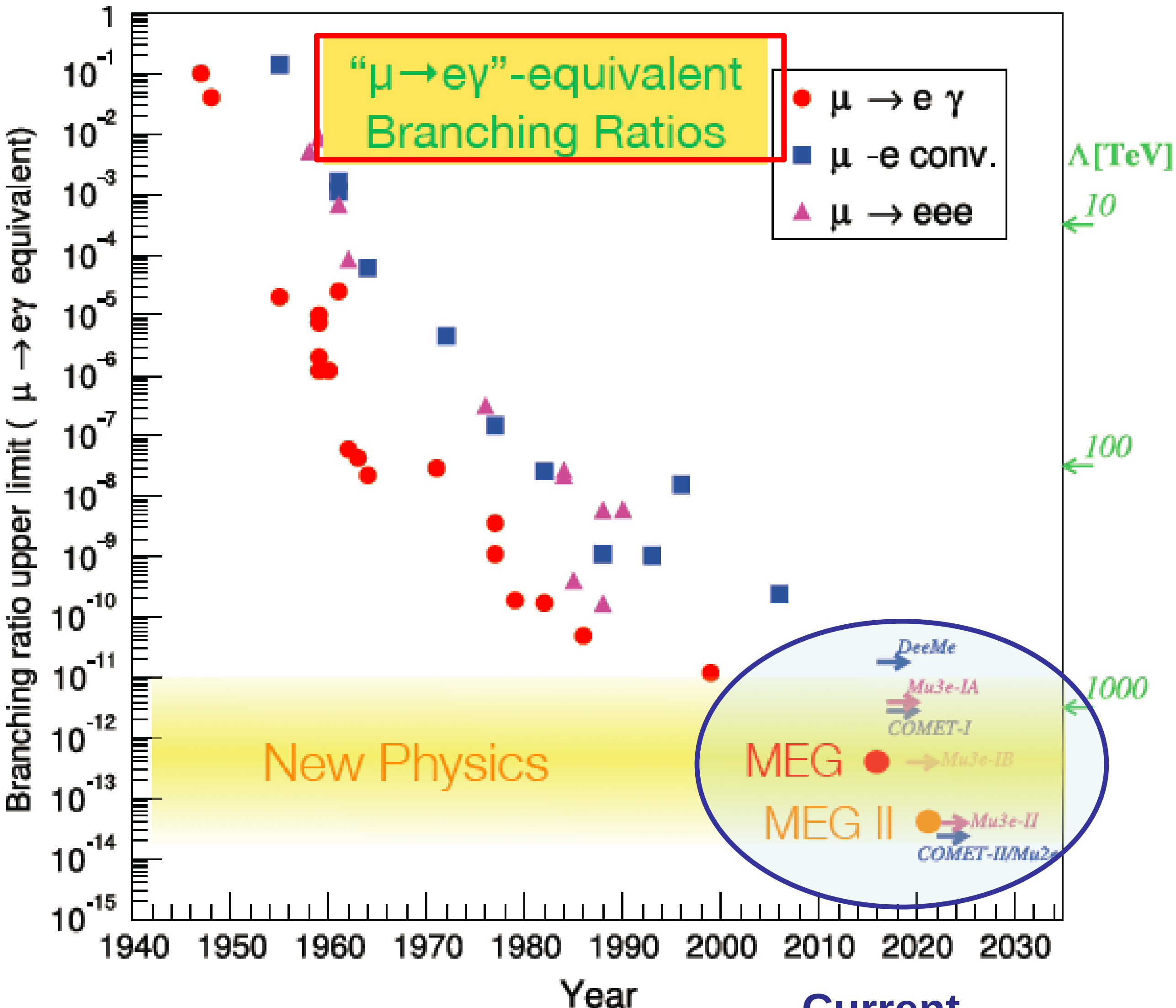






Charged Lepton Flavor Violation

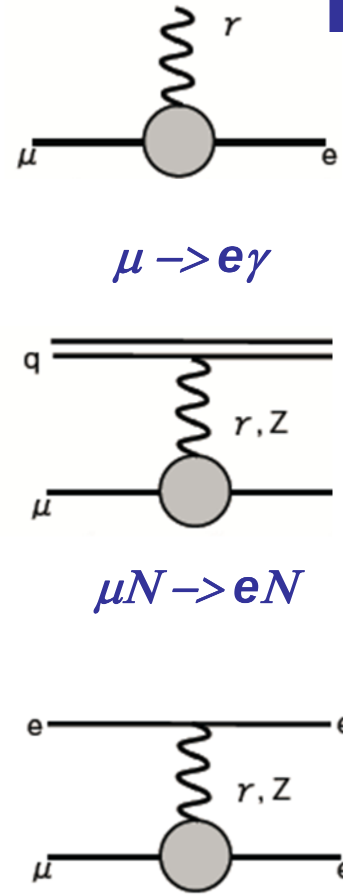
SM "allowed" but ***Unobservable*** ***e.g.,*** **$\mu \to e\gamma$ BR: 10^{-54}**



Current generation

For "dipole" like NP

Ratios



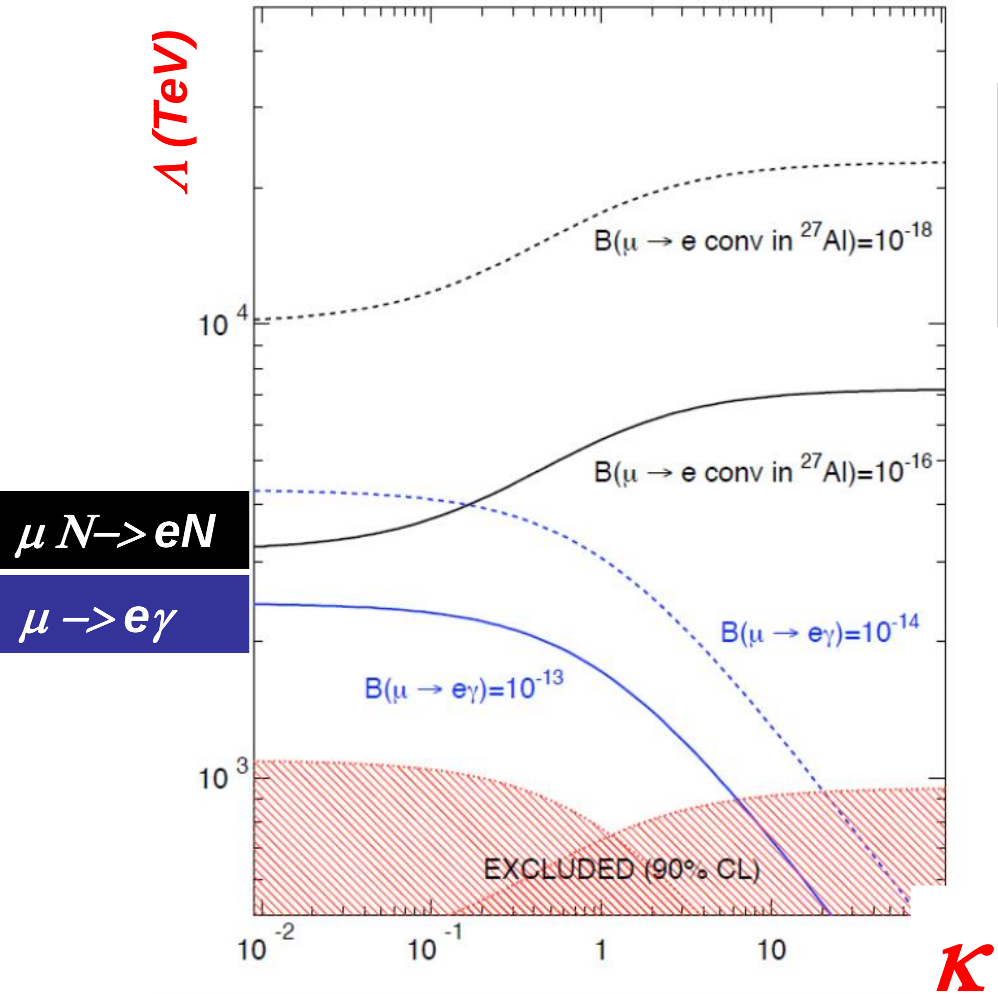
$\mu \to e\gamma$ — **1**

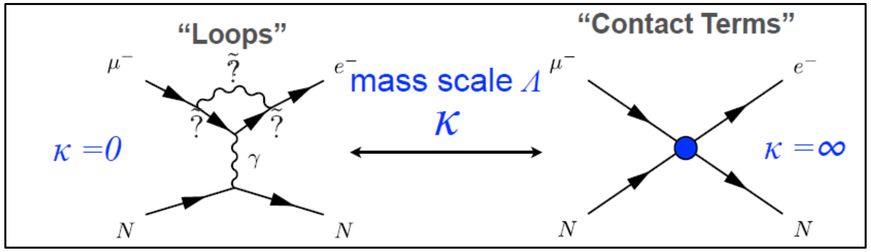
$\mu N \to eN$ — **1/390**

$\mu \to eee$ — **1/170**

But, life may not be just Dipole

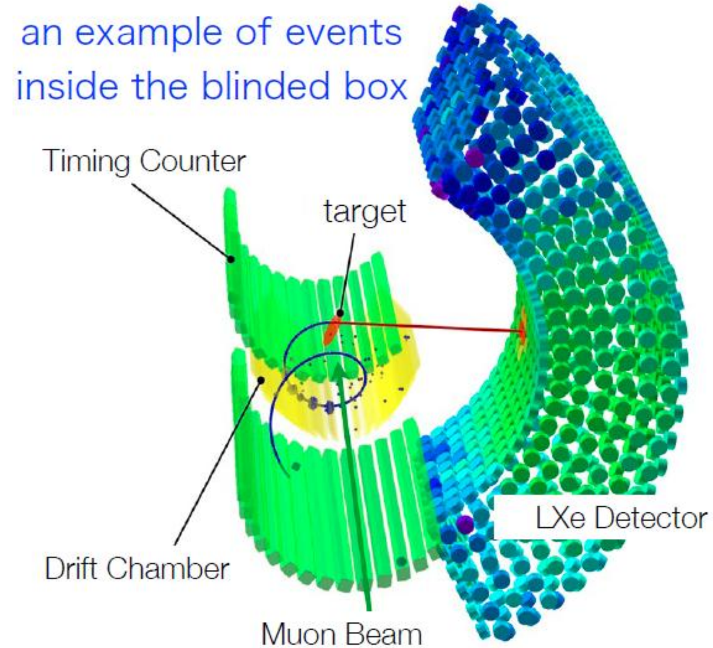
$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$



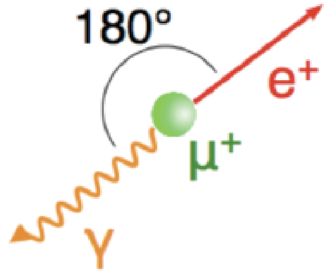


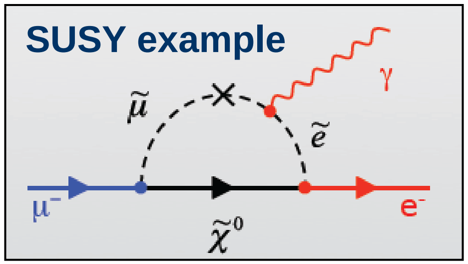
de Gouvěa

MEG: μ → eγ



Signal is back-to-back 53 MeV γ and e^+ from positive muons at rest





One potential path to CLFV

NEW 2016: $BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ @ 90% CL

x30 improvement compared to pre-MEG

MEG II Upgrade approved at PSI: Expect to improve by ano

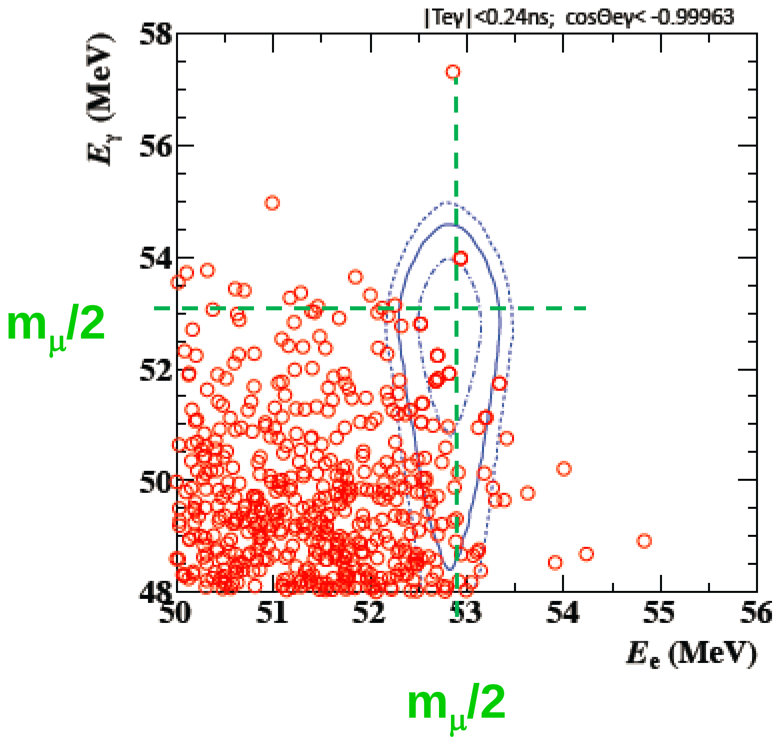
if $B(\mu \rightarrow e\gamma) < 10^{-13}$
(not seen at MEG)
little hopes to see
$\tau \rightarrow \mu\gamma$ at SuperB
(KEK)
Baldini

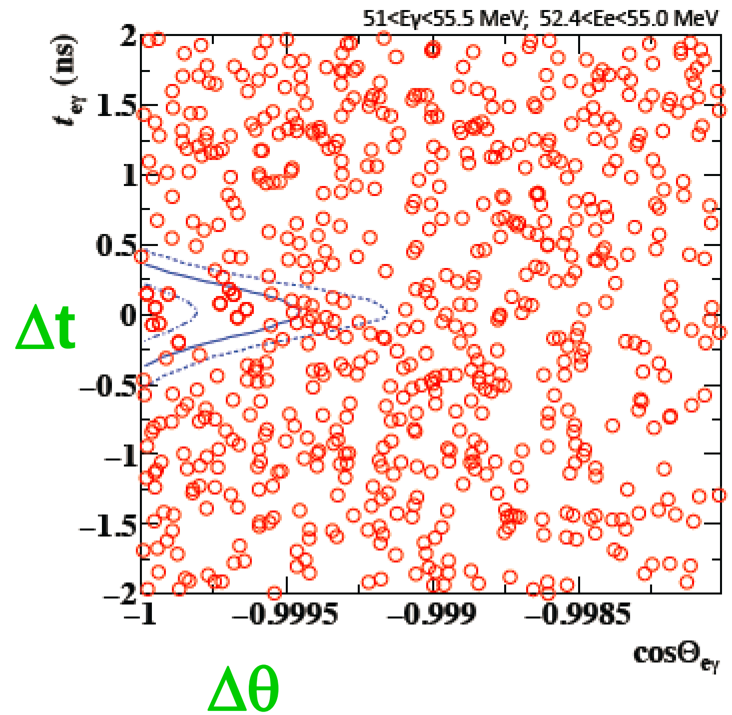
Note: For Belle II type facility, MEG I is allowing little room for tau discovery

http://arxiv.org/abs/1605.05081

Final MEG 4D Event Distribution

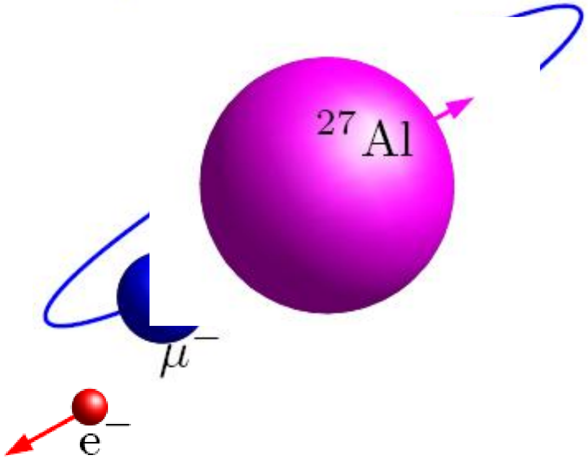
- **e and γ are back-to-back, $\Delta\theta = 180°$**
- **e and γ are simultaneous, $\Delta t = 0$**
- **$E_e = E_\gamma = m_\mu/2$**





Contours at 1, 1.64, and 2 σ

Perhaps the most sensitive approach will be coherent μ-to-e conversion



105 MeV
monoenergetic e-

$$\mu^- N \longrightarrow e^- N$$

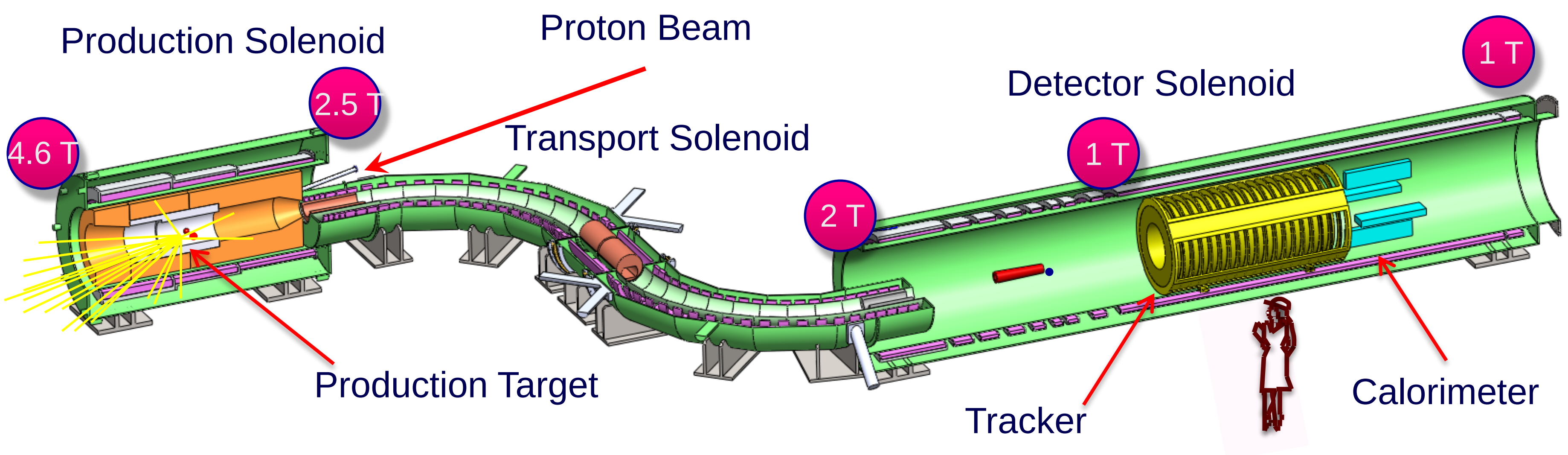
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

- **This signature is quite unique**
- **Goal $R_{\mu\varepsilon}$ to < 6 x 10^{-17} (90% C.L.)**
  - **Present is < 7 x 10^{-13} → So this is <u>very ambitious</u>**

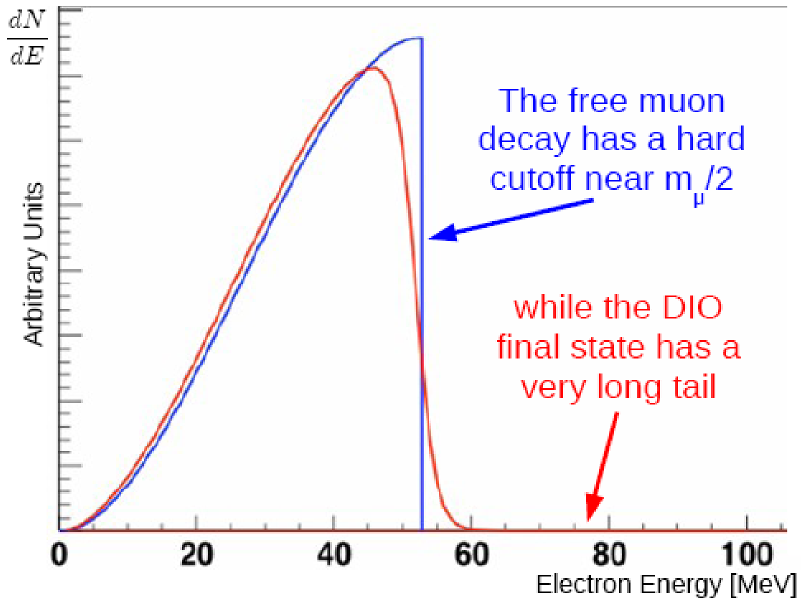
4 order of magnitude gain !!

How it is done

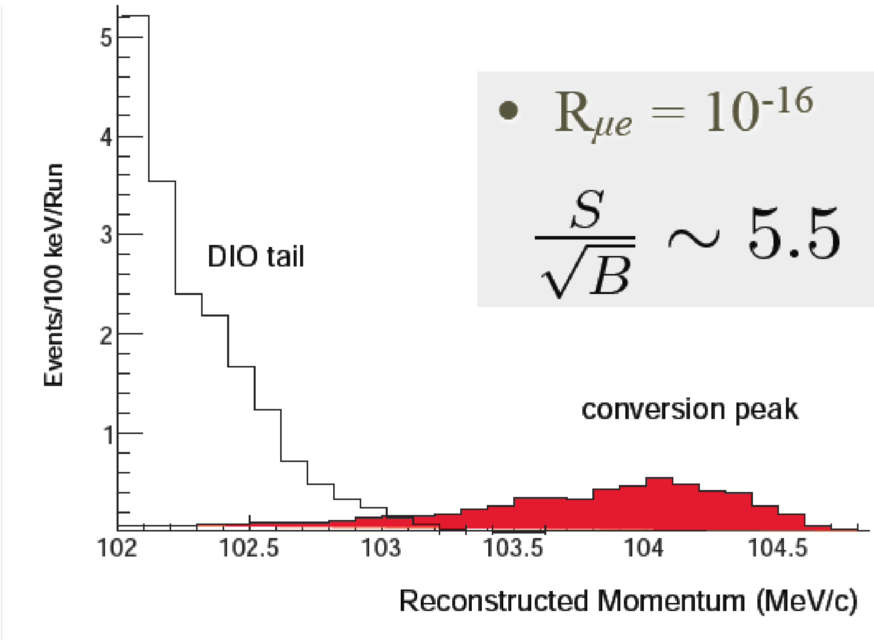
- **Need intense pulsed source of low-energy muons**
- **Stop in thin Al target**
- **Form muonic Al atoms.**
- **Observe**
  - **40% will decay “in orbit”;**
  - **60% will capture (hadronic junk emitted)**



Challenge: find signal above "Decay in Orbit" tail

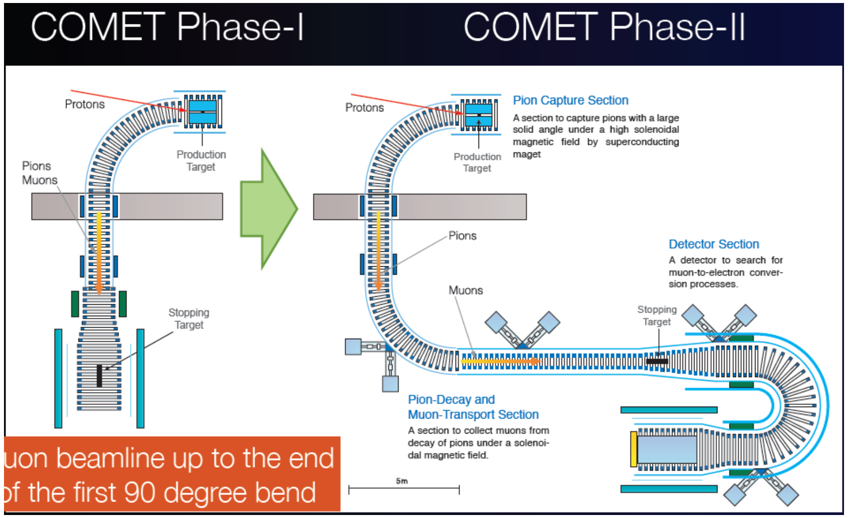


Resolution and Redundancy critical



- $R_{\mu e} = 10^{-16}$

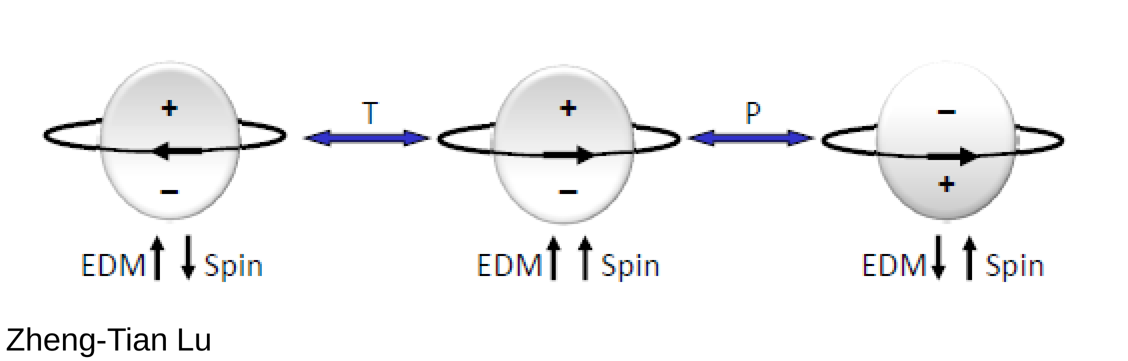
$$\frac{S}{\sqrt{B}} \sim 5.5$$



Similar: COMET in Japan

- Staged approach.
- Approved for Phase-1
  - Sensitivity: < **7x10^{-15}**
- Full phase later, similar to Mu2e

Permanent Electric Dipole Moments
(This field is big enough it has its own conferences)



EDM violates T → violates CP

New sources of CP → BAU ?

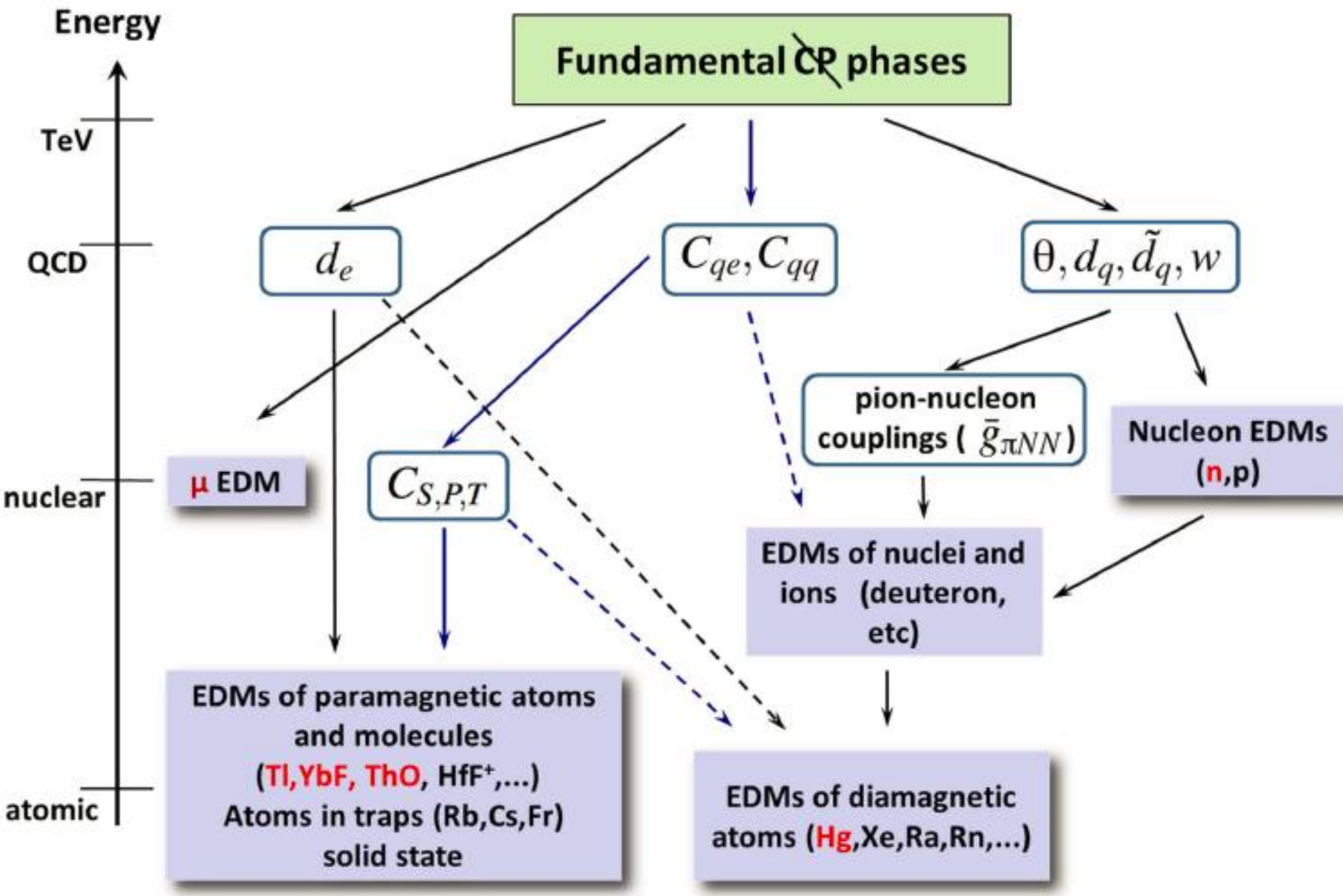
Experiments are largely the same:
Precess spin in B field with parallel and anti-parallel E
Measure the frequency difference

Current EDM Limits

Type	System	EDM Limit (e-cm)
Paramagnetic	YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$
Paramagnetic	ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$
Diamagnetic	^{199}Hg	$d_A = \cancel{(0.5 \pm 1.5) \times 10^{-29}}$ $(-2.20 \pm 2.75_{stat} \pm 1.48_{syst}) \times 10^{-30}$
Nucleon	Neutron	$d_n = (0.2 \pm 1.7) \times 10^{-26}$
Lepton	Muon	$d_\mu = (-0.1 \pm 0.9) \times 10^{-19}$

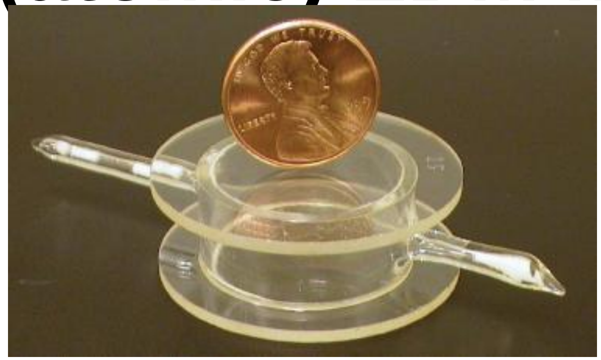
Many systems … mostly small

Graner et al,PRL 116, 161601 (2016)

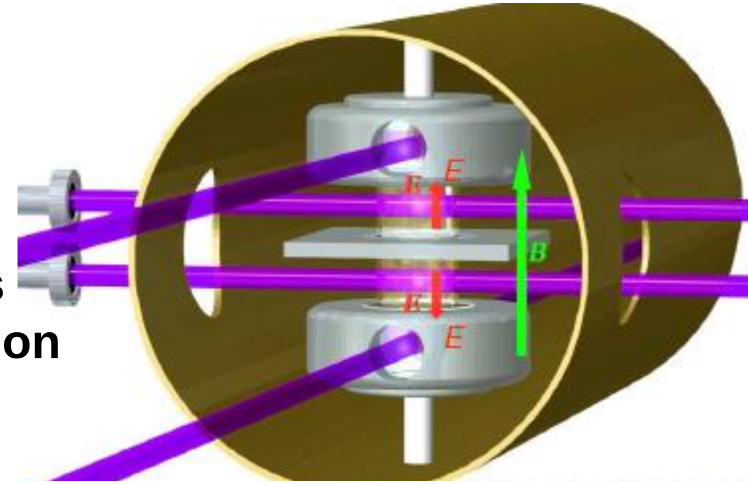


Energy
TeV
QCD
nuclear
atomic
Fundamental $\cancel{CP}$ phases
d_e
C_{qe}, C_{qq}
$\theta, d_q, \tilde{d}_q, w$
pion-nucleon couplings ($\bar{g}_{\pi NN}$)
Nucleon EDMs (n,p)
μ EDM
$C_{S,P,T}$
EDMs of nuclei and ions (deuteron, etc)
EDMs of paramagnetic atoms and molecules (Tl,YbF, ThO, HfF$^+$,...) Atoms in traps (Rb,Cs,Fr) solid state
EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn,...)

An typical experiment: The Seattle ^{199}Hg (atomic) EDM Measurement

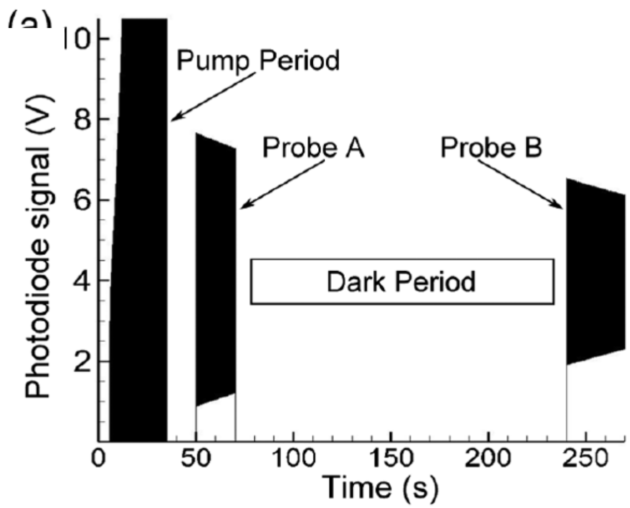


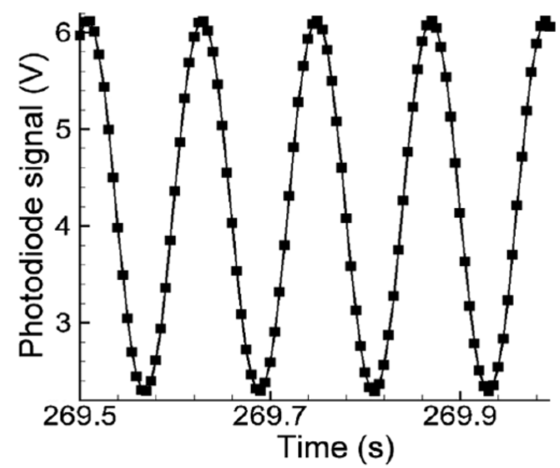
4 mercury vapor cells:
2 with opposite E fields
2 for B field normalization



$$\left.\begin{aligned} \omega_1 &= \frac{2\vec{\mu}\cdot\vec{B} + 2\vec{d}\cdot\vec{E}}{\hbar} \\ \omega_2 &= \frac{2\vec{\mu}\cdot\vec{B} - 2\vec{d}\cdot\vec{E}}{\hbar} \end{aligned}\right\} \omega_1 - \omega_2 = \frac{4\,d\,E}{\hbar}$$

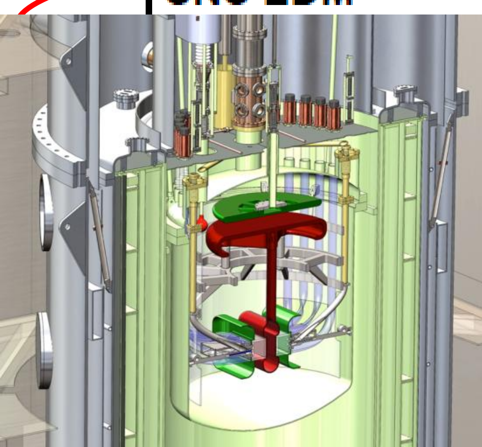
In principle, now best limits on $\theta_{QCD} < 1.5 \times 10^{-10}$





World-wide intense effort on nEDM

Exp	UCN source	cell	Measurement techniques	σ_d (10^{-28} e-cm)
ILL CryoEDM	Superfluid ^4He	^4He	Ramsey technique for ω External SQUID magnetometers	Phase1 ~ 50 Phase 2 < 5
PNPI – ILL	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω $\vec{E}$=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ω, external Cs & $^3\vec{He}$ magnetom.Possible Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vac.	Under Construction (similar to PSI	< 5
SNS EDM	Superfluid ^4He	^4He	$^3\vec{He}$ capture for ω $^3\vec{He}$ comagnetometer SQUIDS & Dressed spins	< 5
	Superfluid ^4He	Vac.	Phase I @ RCNP	< 10
	Solid D_2	Vac.	Under Development	< 5
	Crystal	Solid	R & D	~ 5 ?



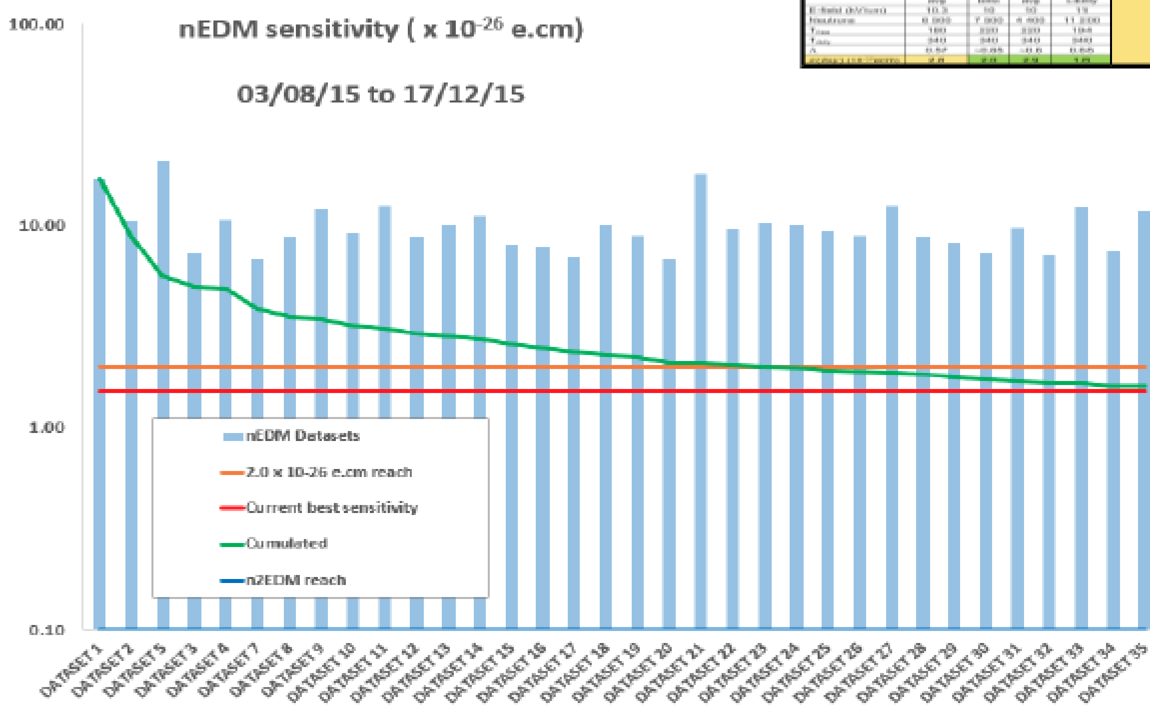
B. Filippone

The PSI nEDM experiment is progressing

2015: 124 days of nEDM data

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

	PSI 13	PSI 14		PSI 15
	avg	best	avg	good
E-field (kV/cm)	10.3	10	10	11
Neutrons	6 500	7 500	4 400	10 000
T_{free}	180	220	220	180
T_{duty}	340	340	340	340
A	0.57	0.65	0.6	0.8
	2.8	2.0	2.9	1.3



Cumulated sensitivity
$1.7 * 10^{-26}$ e.cm

This would represent the 1st step forward in >15 years !

Lessons and Promise of Low-Energy Precision Physics

- **The Standard Model is tough to crack**
- **Direct energy frontier experiments are the obvious way to explore …**
  - **But they can run out of resolution (kinematics)**
  - **And may not fully define the physics behind the finding**
- **High precision – in well selected efforts – can often reach beyond through loops**
  - **And, these observables will provide complementary clues about the nature of any new discoveries**

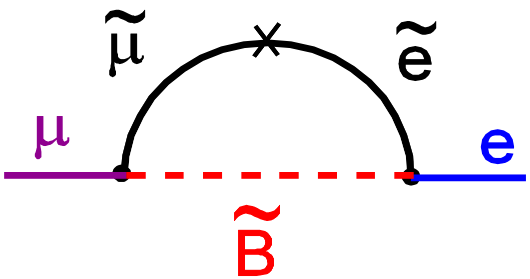
See also:
D.W. Hertzog, *Low-energy precision tests of the standard model: a snapshot*, Annalen Phys. **528**, 115 (2016)
T.P. Gorringe and D.W. Hertzog, *Precision Muon Physics*, Prog. Part. Nucl. Phys. **84**, 73 (2015)

Extras…

Connection between a_μ, μEDM and the cLFV transition moment $\mu \to e$

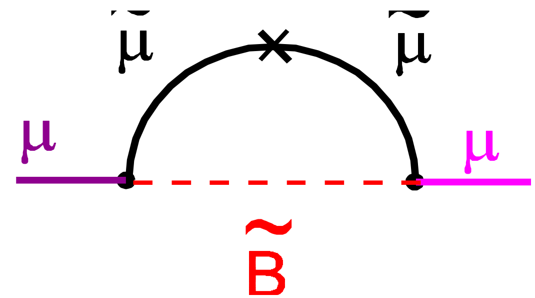
SUSY $\Longrightarrow$ slepton mixing

$\mu \to e$



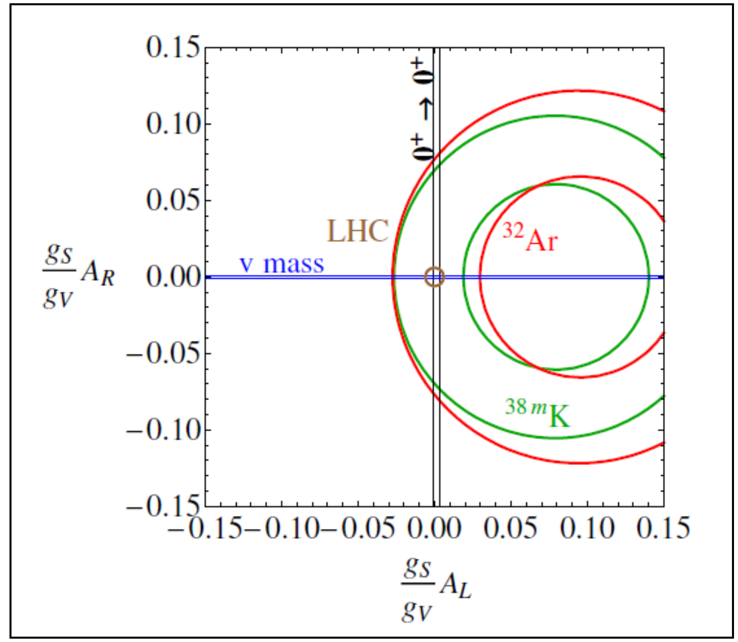
a_μ (real)

EDM (imaginary)

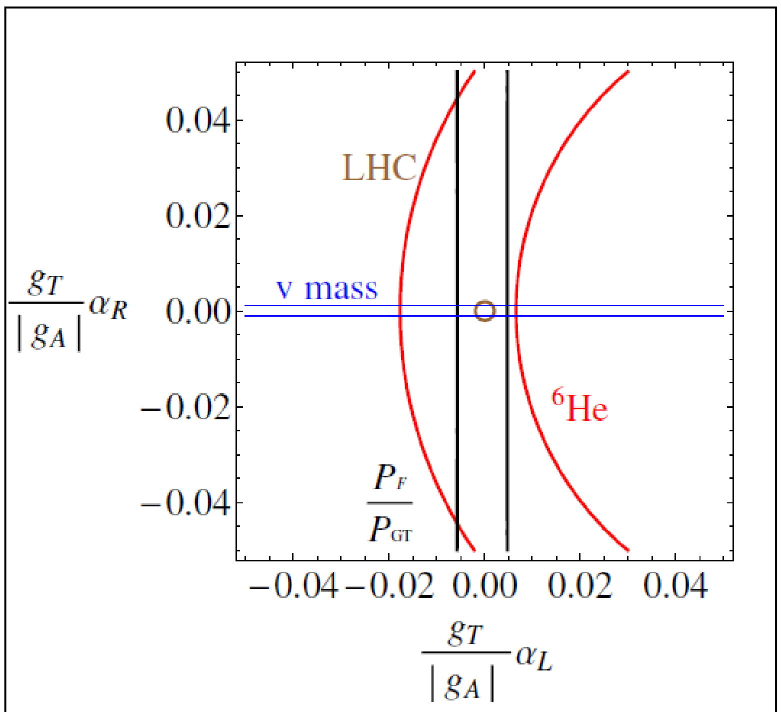


$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

Nuclear beta decay vs. the LHC for Scalar and Tensor currents …



Scalar bounds

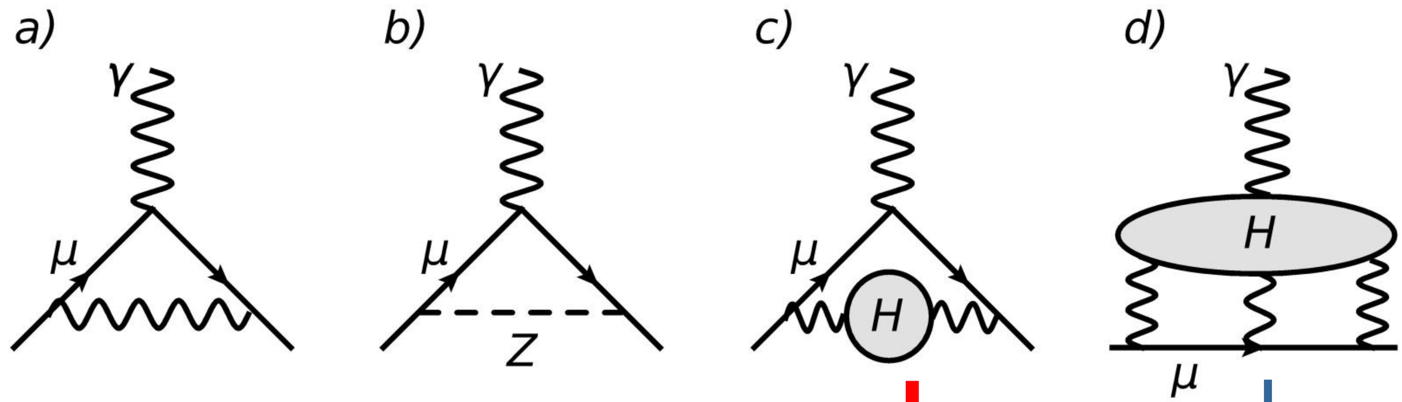


Tensor bounds

"In particular, the pp → e + MET + X channel is considered, where MET signifies Missing Transverse Energy. This channel is closely related to β decay, since it involves the ud¯ → eν¯process at quark level" (VWT see below)

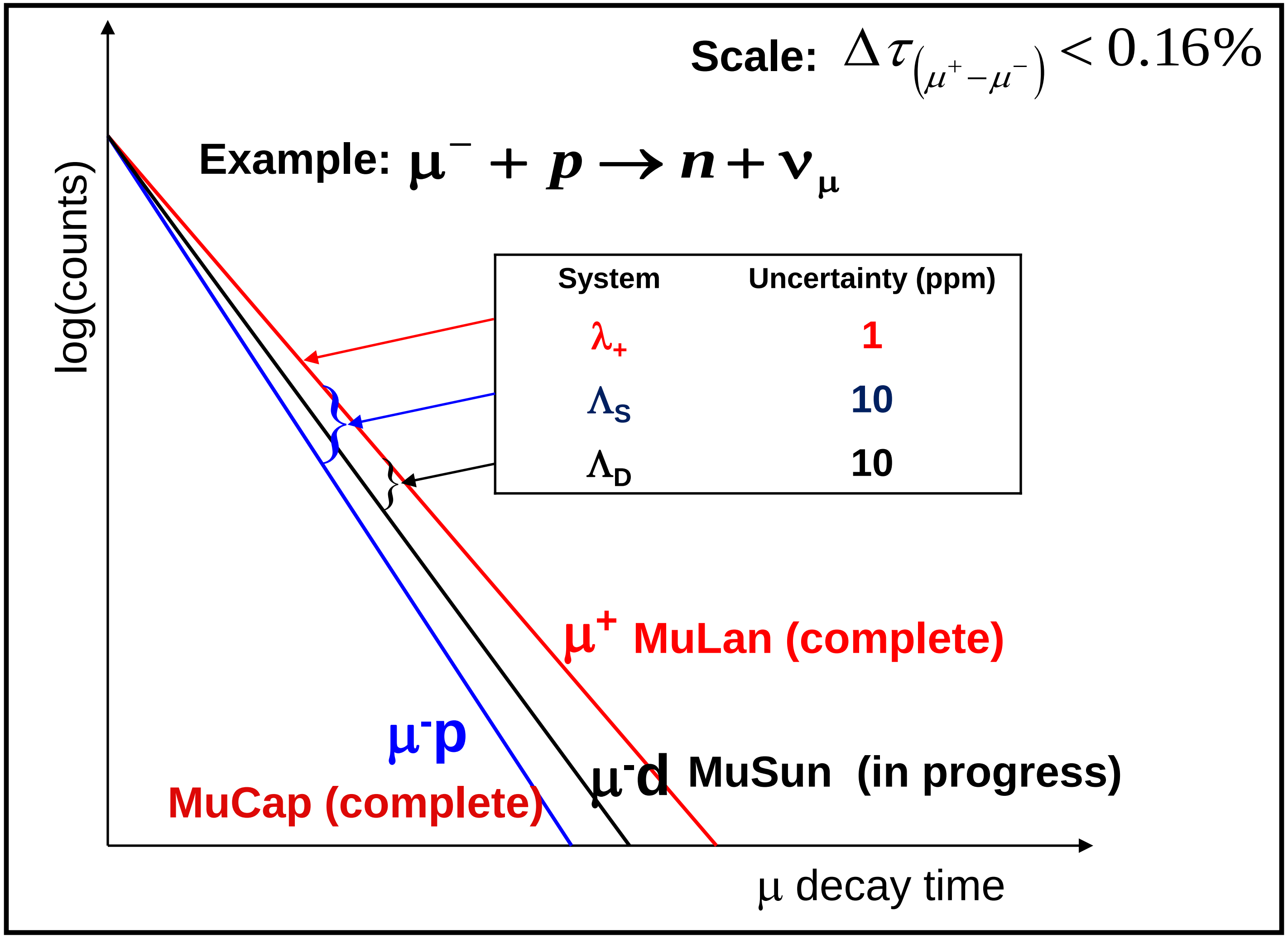
K.K. Vos, H.W. Wilschut and R.G.E. Timmermans, *Symmetry violations in nuclear and neutron beta decay*, Rev. Mod. Phys. **87**, 1483 (2015)

a_μ(SM): There are 2 contributions to worry about



	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP	$6\,923 \pm 42$
HVP	$6\,949 \pm 43$
HVP	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

The 1 ppm μ^+ lifetime is compared to the μ^- lifetime in gaseous p or d targets to determine the capture rate



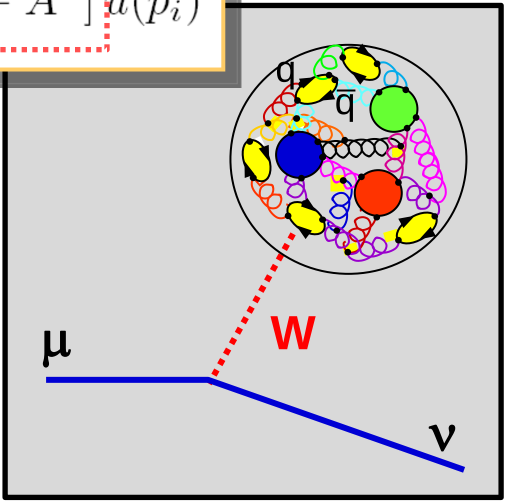
$$\frac{1}{\tau} = \Lambda_{\text{total}} = \Lambda_{\text{decay}} + \Lambda_{\text{capture}}$$

Extract physics here

The singlet muon capture Λ_S on the proton is sensitive to axial nucleon structure

Λ_S

$$\mathcal{M} = \frac{-iG_F V_{ud}}{\sqrt{2}} \overline{u}(p_\nu)\gamma_\alpha(1-\gamma_5)u(p_\mu)\overline{u}(p_f)\tau_- \boxed{[V^\alpha - A^\alpha]} u(p_i)$$

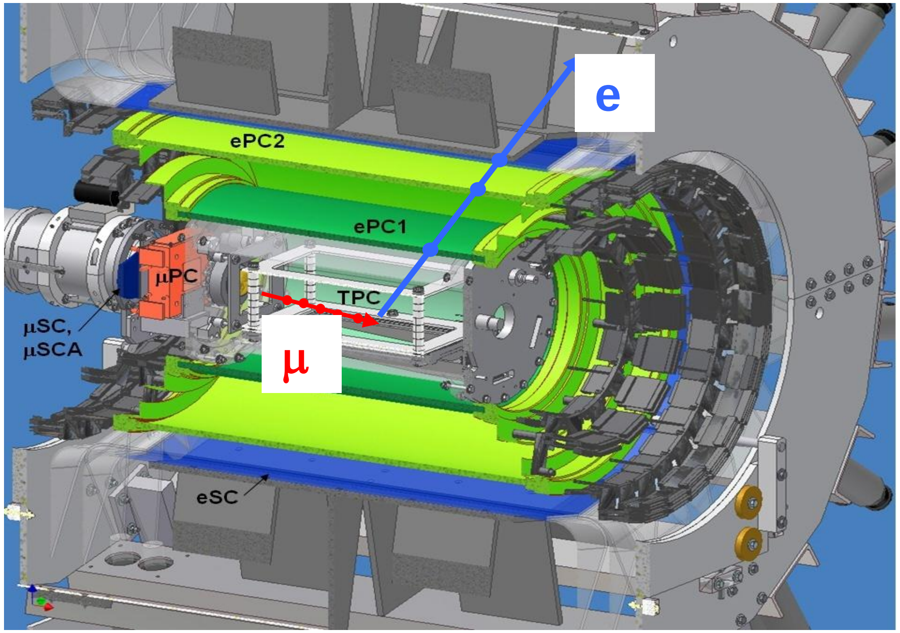


$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \frac{g_P(q^2)}{m_\mu}\,q_\alpha\,\gamma_5$$

$$\boxed{\frac{\Delta\Lambda_S}{\Lambda_S} = 1\% \quad \Rightarrow \quad \frac{\Delta g_P}{g_P} \approx 6.1\%}$$

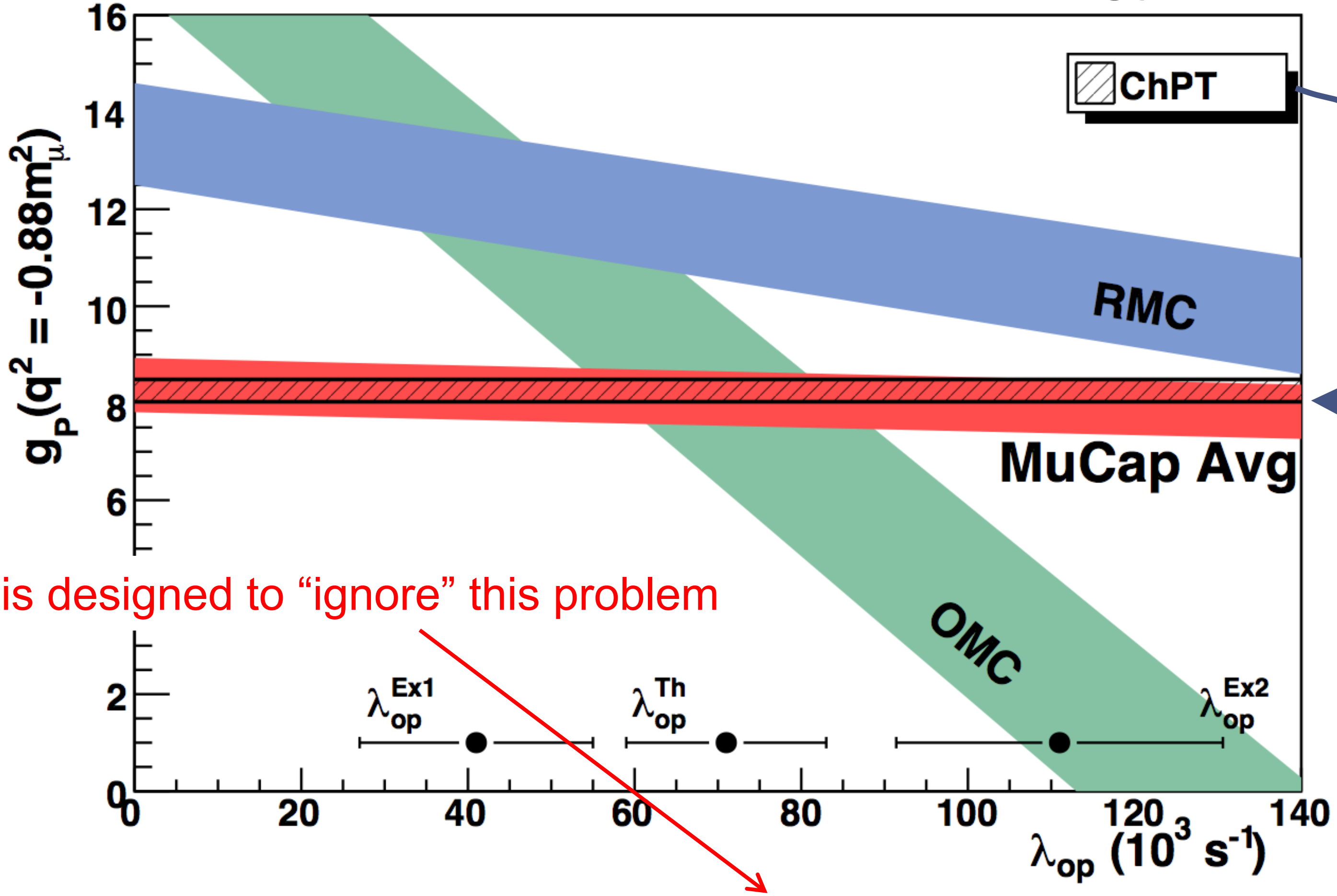
Technique: Precision lifetime measurement in an ultra-pure hydrogen time projection chamber



1st Precise and Unambiguous Result

Verifies Basic Prediction of Low-Energy QCD

Physics Axis



MuCap is designed to “ignore” this problem

Horizontal axis represents some not-well-known Mu-Molecular physics

Why do we say the result is Unambiguous ?

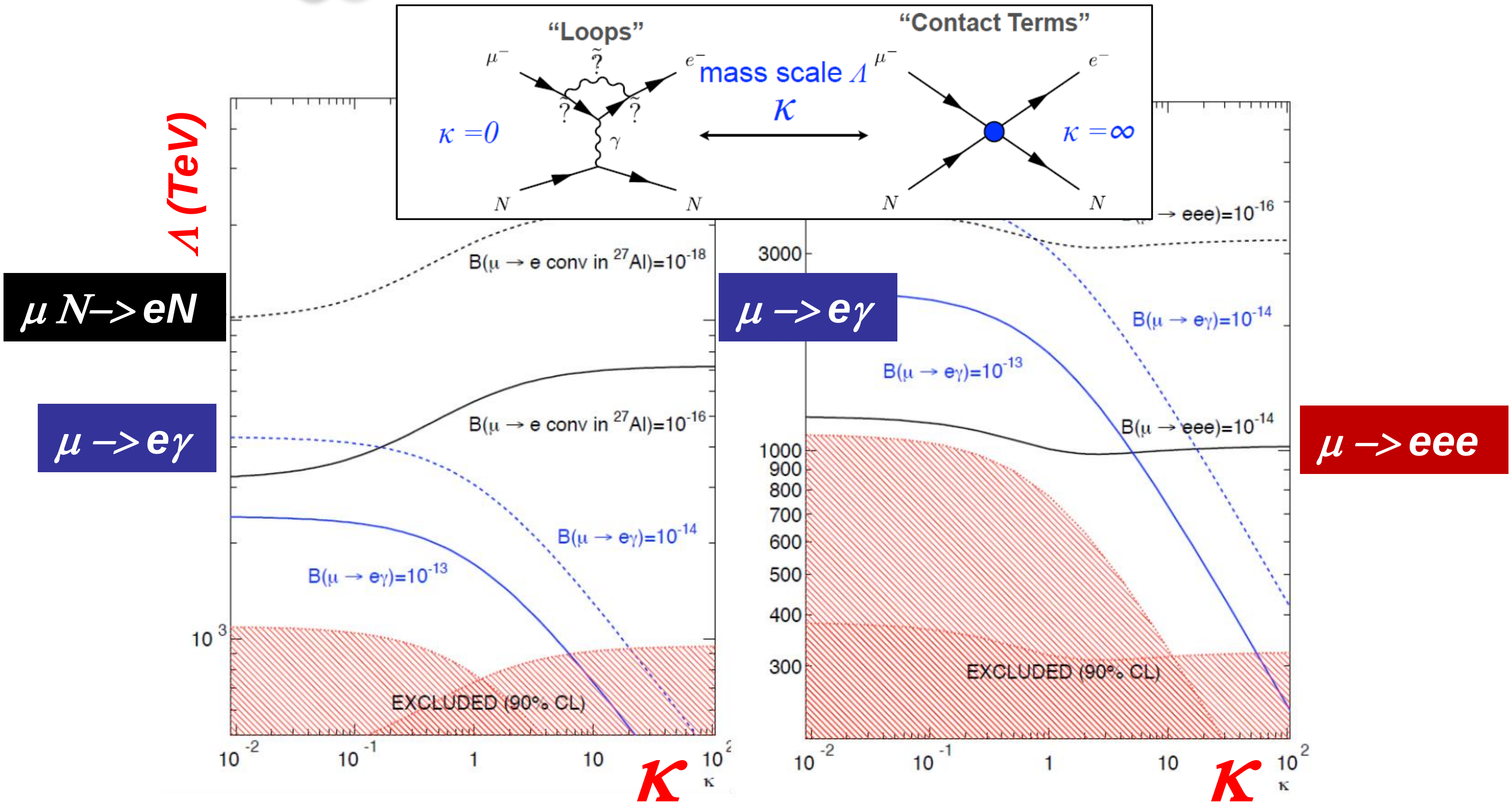
Phys.Rev.Lett. 110 (2013) 012504

Add in eee channel …

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} +$$

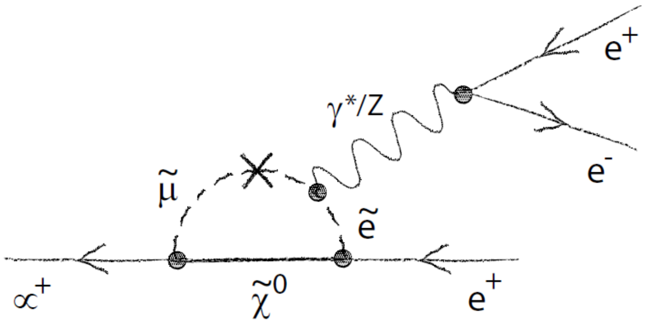
$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

or, $+ \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{e}_L\gamma^\mu e)$,



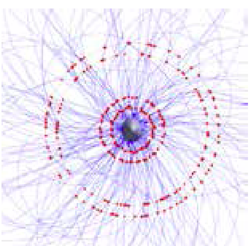
Next-generation: $\mu \rightarrow$ eee

(2013: approved at PSI)

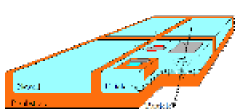


Typical comparison to $\mu \rightarrow e\gamma$ *without enhancement*

$$\frac{B(\mu \rightarrow eee)}{B(\mu \rightarrow e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$



- **Goal:**
  - **Finding 1 in 10^{16} muon decays**



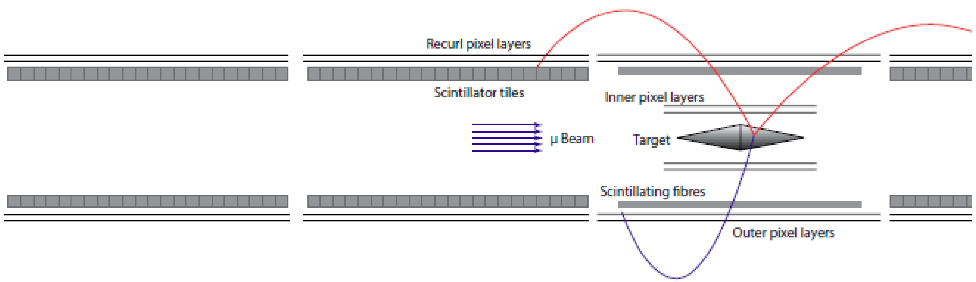
- **Special technique**
  - **High-voltage monolithic active pixel sensors**

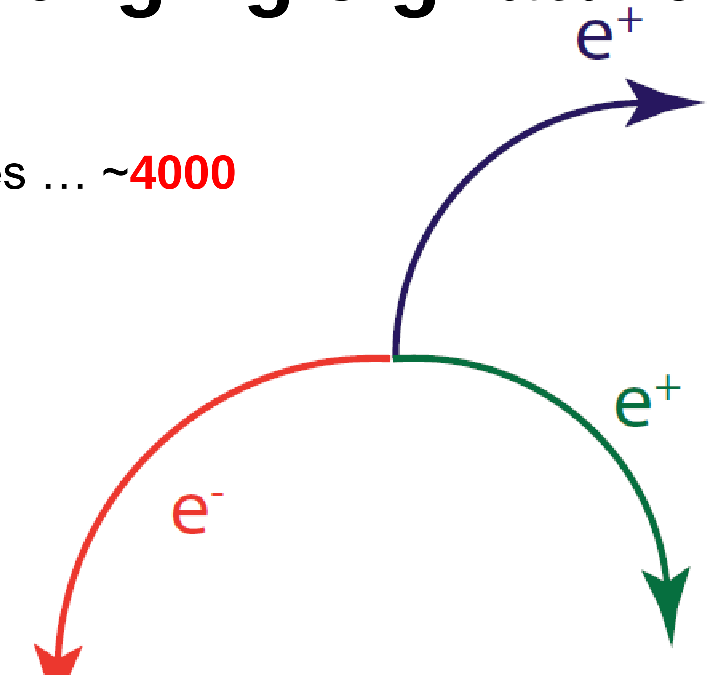
- **The detector**
  - **Minimum material, maximum precision**

Again, a unique and challenging signature

A staged approach is starting now

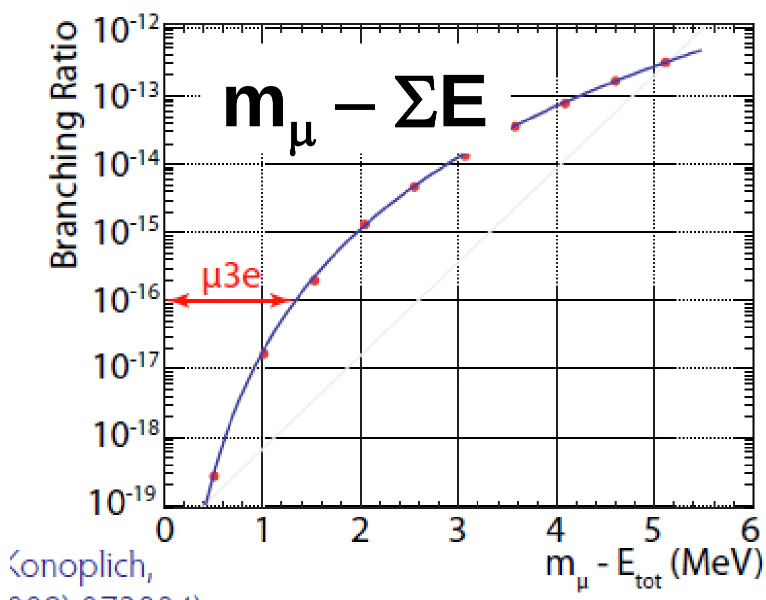
To achieve final statistics, extraordinary high rates … ~**4000 muons** are "sitting" on the target at any time !





10,000 times MuLan statistics
- **200 MHz muon rate**
- **Wow!!!**

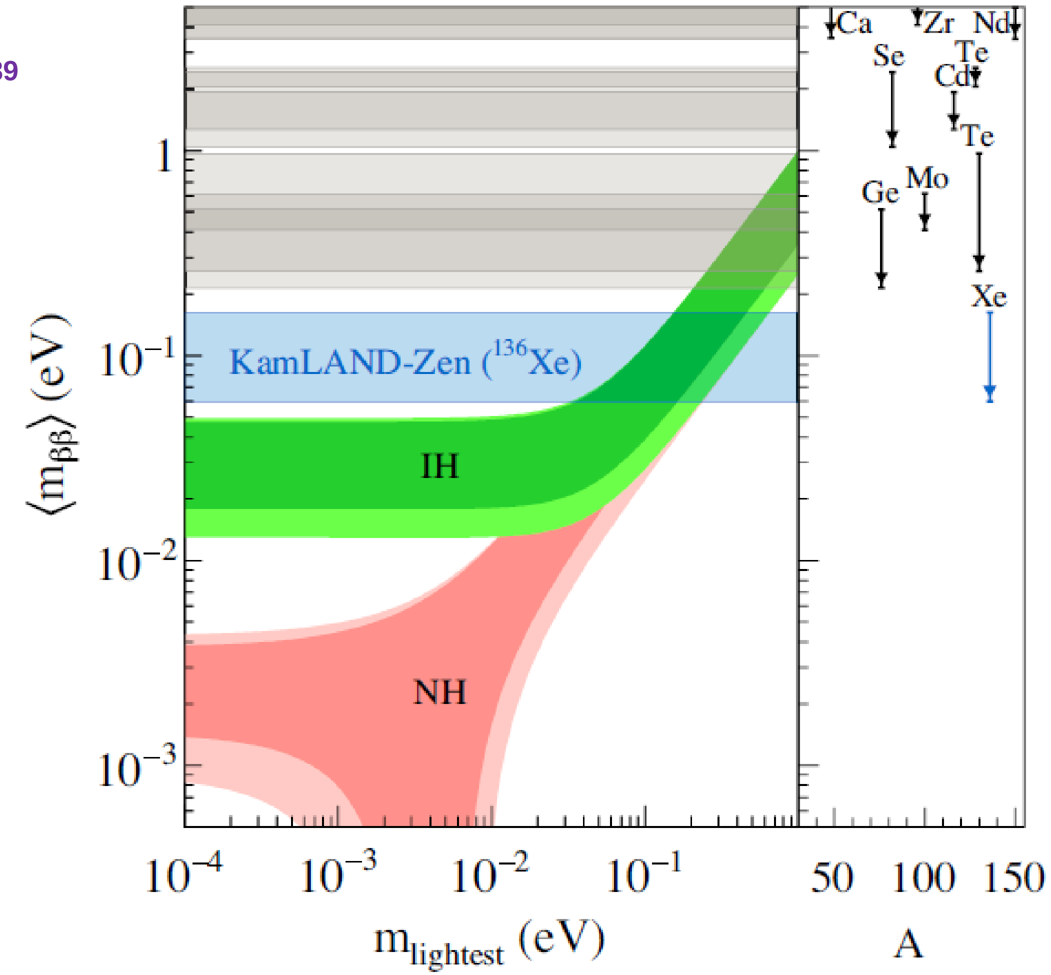
- **2 e^+, 1 e^-**
- **Common vertex**
- **Common time**
- **Σ energies = m_μ**
- **No energy > m_μ / 2**



An immediate aside …

*New KamLAND-Zen result a week ago …

http://arxiv.org/abs/1605.02889



- Majorana neutrino mass upper limits in range 60 – 161 meV
- Lightest neutrino mass < (180 – 470) meV