Precision
~~Low Energy~~ Searches for BSM Physics:
The other path to the summit

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http://wallpapers.jurko.net/pic/1085/

The Precision Path to the Summit

- muon (g-2)
- search for electric dipole moments
- charged lepton flavor violation
  - (e.g. $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$)
- double β decay with no ν
- Møller scattering
- neutron β decay
- muon decay
- rare kaon decays
- dark matter searches
- ...

I wish to acknowledge up front that I have borrowed heavily from articles in the new World Scientific book

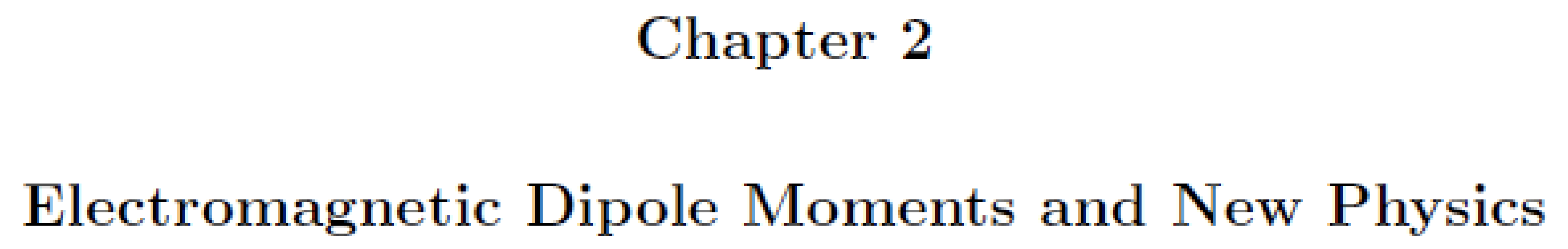
Advanced Series on Directions in High Energy Physics - Vol. 20

LEPTON DIPOLE MOMENTS

edited by **B Lee Roberts** *(Boston University, USA)* **& William J Marciano** *(Brookhaven National Laboratory, USA)*

http://www.worldscibooks.com/physics/7273.html

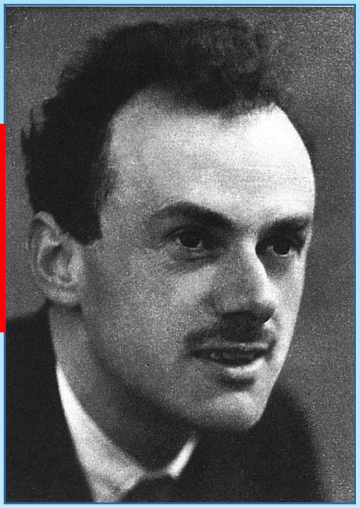
Especially the article by Andrzej Czarnecki and William J. Marciano:



Chapter 2

Electromagnetic Dipole Moments and New Physics

In the beginning there was Dirac



$$\boxed{i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)}$$

predicted electron magnetic moment

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}, \quad e > 0$$

$$g \equiv 2$$

However, experimentally g > 2; need to add a Pauli term

$$\frac{Qe}{4m} aF_{\mu\nu}(x)\sigma^{\mu\nu}\psi(x)$$

dimension 5 operator

(only from loops)

where a is the anomaly, $g = 2(1 + a)$

In the QED, a becomes an expansion in (α/π) from loops

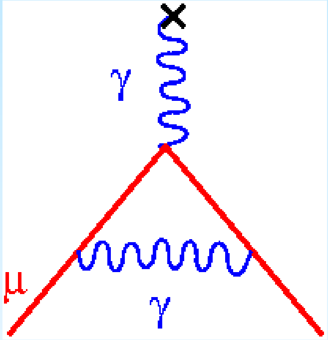
$$a = \sum_{j=1} C_j \left(\frac{\alpha}{\pi}\right)^j$$

$\frac{\alpha}{2\pi}$

JULIAN SCHWINGER

2·12·1918 — 7·16·1994

For leptons, radiative corrections dominate the value of $a \simeq 0.00116\ldots$



New Physics contribution to a at some scale Λ

$$a(NewPhysics) = C\left(\frac{m}{\Lambda}\right)^2$$

where C could be $\mathcal{O}(1)$, or

$\mathcal{O}(\alpha)$ in weak coupling loop scenarios

What if we introduced the additional Pauli-like term

$$\frac{i}{2} d F_{\mu\nu}(x) \sigma^{\mu\nu} \gamma_5 \psi(x)$$

Electric Dipole Moment, EDM

where the EDM is defined as

$$\vec{d} = \eta \left(\frac{Qe}{2mc} \right) \vec{s}$$

Parameterize the effect of new physics on a and d by:

$$d(NP) = a(NP) \left(\frac{e}{2m} \right) \tan \phi^{NP}$$

Electromagnetic Form Factors:
(q = momentum transfer, Q = charge)

$$\left\langle f\left(p'\right)\left|J_{\mu}^{em}\right|f\left(p\right)\right\rangle = \bar{u}_{f}\left(p'\right)\Gamma_{\mu}u_{f}\left(p\right)$$

$$\Gamma_{\mu} = F_{1}\left(q^{2}\right)\gamma_{\mu} + iF_{2}\left(q^{2}\right)\sigma_{\mu\nu}q^{\nu} - F_{3}\left(q^{2}\right)\sigma_{\mu\nu}q^{\nu}\gamma_{5}$$

$F_1(0) = Qe$ electric charge

$F_2(0) = a\frac{Qe}{2m}$ anomalous magnetic moment

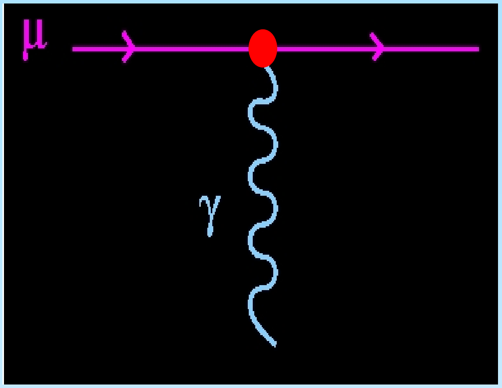
$F_3(0) = dQ$ electric dipole moment

$$+F_{A}\left(q^{2}\right)\left(\gamma_{\mu}q^{2} - 2m_{f}q_{\mu}\right)\gamma_{5}$$

(anapole moment which we ignore in this talk)

Magnetic and Electric Dipole Interactions

$$\Gamma_\beta = eF_1\bar{\psi}_R\gamma_\beta\psi_R + \frac{ie}{2m}F_2\bar{\psi}_R\sigma_{\beta\delta}q^\delta\psi_L + HC$$



- Muon Magnetic Dipole Momoment a_μ chiral changing

$$\bar{u}_\mu[eF_1(q^2)\gamma_\beta + \boxed{\frac{ie}{2m_\mu}F_2(q^2)\sigma_{\beta\delta}q^\delta]u_\mu}$$

$$F_1(0) = 1 \qquad F_2(0) = a_\mu$$

- Muon EDM

$$\bar{u}_\mu\left[\frac{ie}{2m_\mu}F_2(q^2) - F_3(q^2)\gamma_5\right]\sigma_{\beta\delta}q^\delta u_\mu$$

$$F_2(0) = a_\mu \qquad F_3(0) = d_\mu;\ \text{EDM}$$

Electric Dipole Moment: $\cancel{P}$ $\cancel{T}$

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s} \qquad \vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \boxed{\vec{d}\cdot\vec{E}}$$

$\vec{\mu},\ \vec{d}\ \|$ to $\vec{\sigma}$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

Transformation Properties

If *CPT* is valid, an EDM would imply non-standard model $\cancel{CP}$. Of course, we need new sources of $\cancel{CP}$ to explain why we're here.

Transition Moments and Form Factors $f_i \to f_j$

$$\left\langle f_j\left(p'\right)\left|J_\mu^{\mathrm{em}}\right| f_i(p)\right\rangle = \bar{u}_j\left(p'\right)\Gamma_\mu^{ij} u_i(p),$$

$$\Gamma_\mu^{ij} = \underbrace{\left(q^2 g_{\mu\nu} - q_\mu q_\nu\right)\gamma^\nu\left[F_{E0}^{ij}\left(q^2\right) + \gamma_5 F_{M0}^{ij}\left(q^2\right)\right]}_{\text{chiral-conserving, flavor-changing amplitudes at } q^2 \neq 0}$$

$$\text{e.g. } K^+ \to \pi^+ e^+ e^-; \quad \mu^+ \to e^+ e^+ e^-$$

$$\underbrace{+ i\sigma_{\mu\nu}q^\nu\left[F_{M1}^{ij}\left(q^2\right) + \gamma_5 F_{E1}^{ij}\left(q^2\right)\right]}_{\text{chiral-changing, flavor-changing amplitudes at } q^2 \neq 0}.$$

$$\text{e.g. } b \to s\gamma; \quad \mu \to e\gamma; \quad \tau \to \mu\gamma$$

Magnetic Dipole Moments

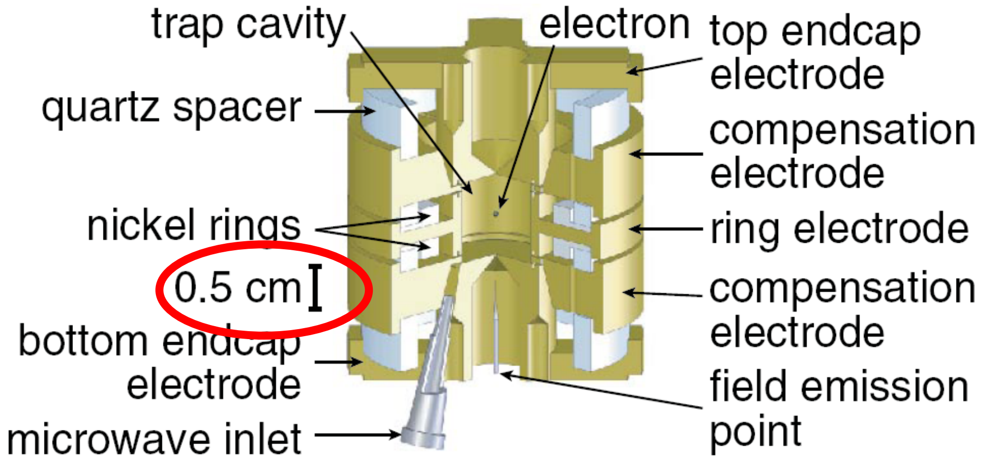
$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

Transition Dipole Moments

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

e PRL **100,** 120801 (2008)

μ PRL, **92, 161802** (2004)
PR **D73,** 072003 (2006)



$$a_e = (115\,965\,218\,073 \pm 28) \times 10^{-14}\ (0.24\ \text{ppb})$$

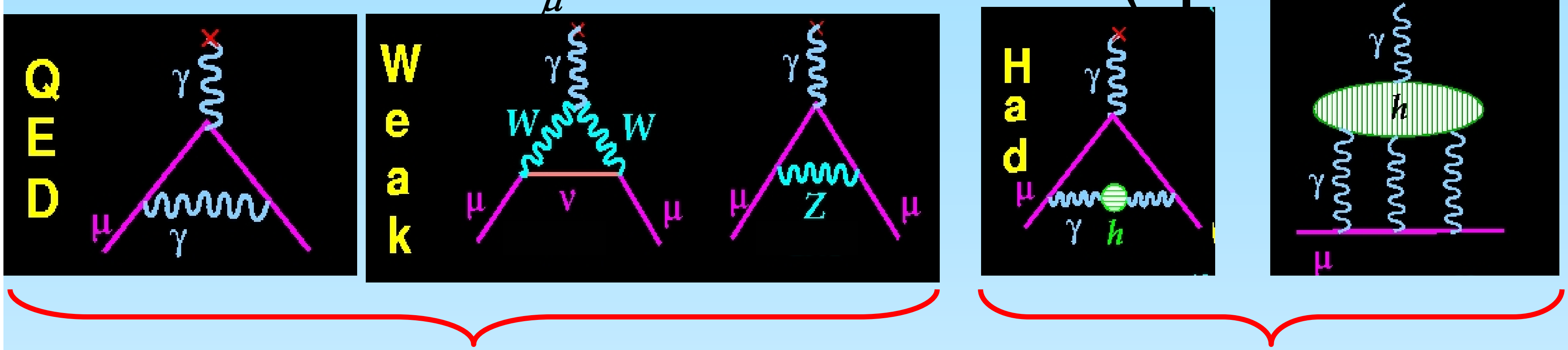
$$a_\mu = (116\,592\,080 \pm 63) \times 10^{-11}\ (0.54\ \text{ppm})$$

muon more sensitive to heavier physics by

$$\sim \left(\frac{m_\mu}{m_e}\right)^2 \simeq 42{,}000$$

and interpretation of the electron anomaly limited by precision of independent measurements of α, ~4.5 ppb.

The SM Value for a_μ from $e^+e^- \rightarrow$ *hadrons* (Updated 6/09)



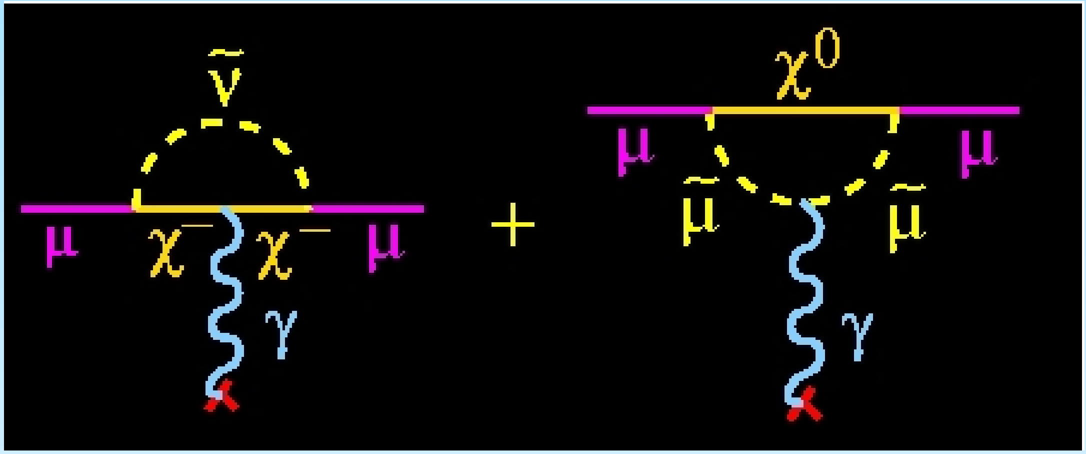
well known

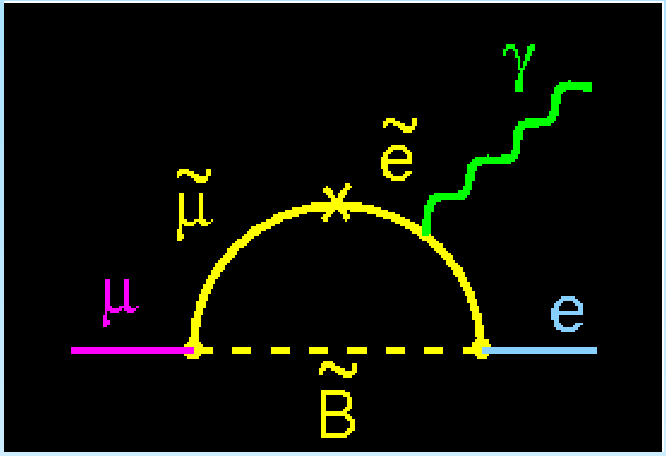
significant work ongoing

CONTRIBUTION	RESULT ($\times 10^{-11}$) UNITS
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 891 \pm 38_{\text{exp}} \pm 19_{\text{rad}} \pm 7_{\text{pQCD}}$
HVP(ho)	$-97.9 \pm 0.9_{\text{exp}} \pm 0.3_{\text{rad}}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 773 \pm 50$

de Rafael, hep-ph arXiv:0809.3085 and Davier, et al.,hep-ph arXiv:0906.5443v1

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





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

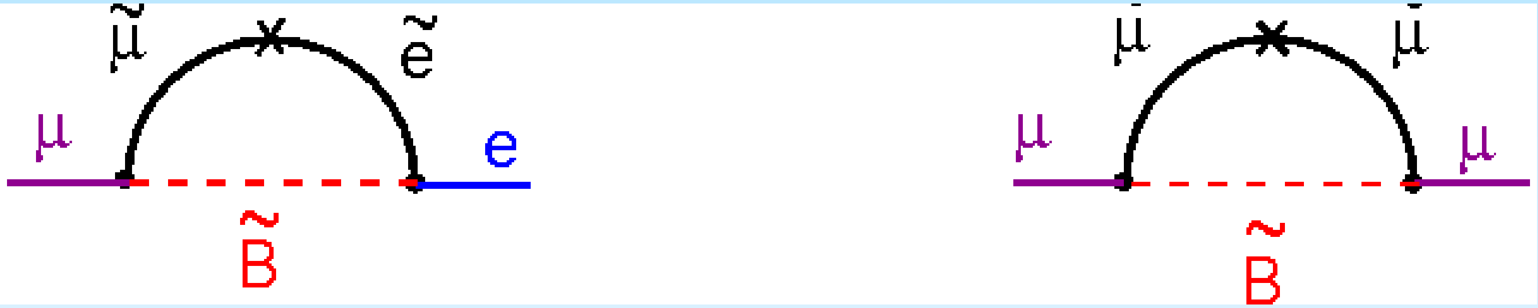
difficult to measure at LHC

Related processes in SUSY

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

Connection between MDM, EDM and the lepton flavor violating transition moment $\mu \to e$

SUSY $\Rightarrow$ slepton mixing **MDM, EDM**



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

The a_μ Experiments:

- E821 at Brookhaven
  - superferric storage ring, magic γ, $\langle B\rangle_\theta$ ± 1 ppm

$$\left.\begin{aligned}\sigma_{\text{stat}} &= \pm 0.46 \text{ ppm}\\ \sigma_{\text{syst}} &= \pm 0.28 \text{ ppm}\end{aligned}\right\}\quad \sigma = \pm 0.54 \text{ ppm}$$

- P989 at Fermilab
  - move the storage ring to Fermilab, improved shimming, new detectors, DAQ,
  - new beam structure that takes advantage of the multiple rings available at Fermilab, more muons per hour, less per fill of the ring

$$\left.\begin{aligned}\sigma_{\text{stat}} &= \pm 0.1 \text{ ppm}\\ \sigma_{\text{syst}} &= \pm 0.1 \text{ ppm}\end{aligned}\right\}\quad \sigma = \pm 0.14 \text{ ppm}$$

Spin Motion: difference frequency between ω_S and ω_C

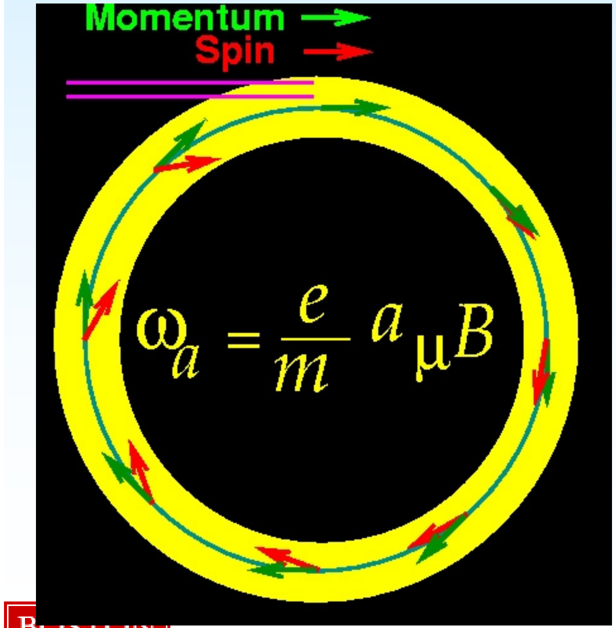
$$\vec{\omega}_a = \omega_S - \omega_C$$

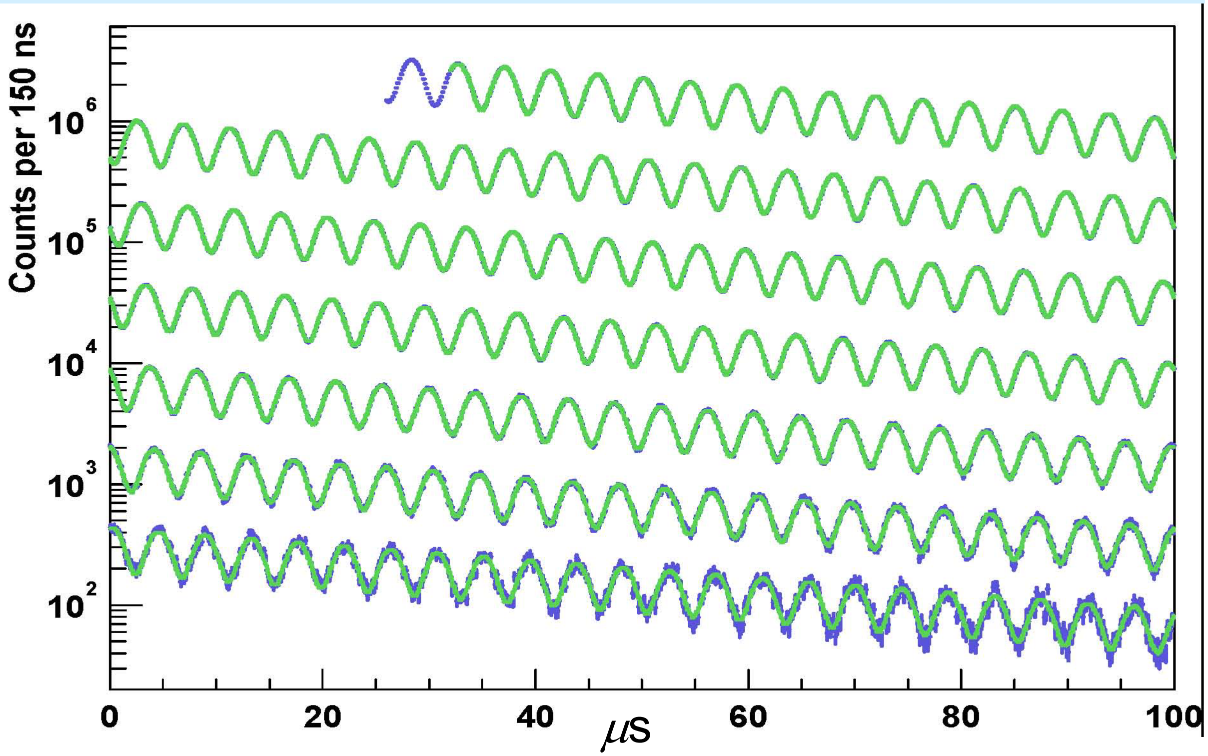
$$= -\frac{e}{m}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

$$\gamma_{\mathrm{magic}} = 29.3$$

$$p_{\mathrm{magic}} = 3.09\ \mathrm{GeV}/c$$

Count number of decay e^- with $E_e \geq 1.8$ GeV

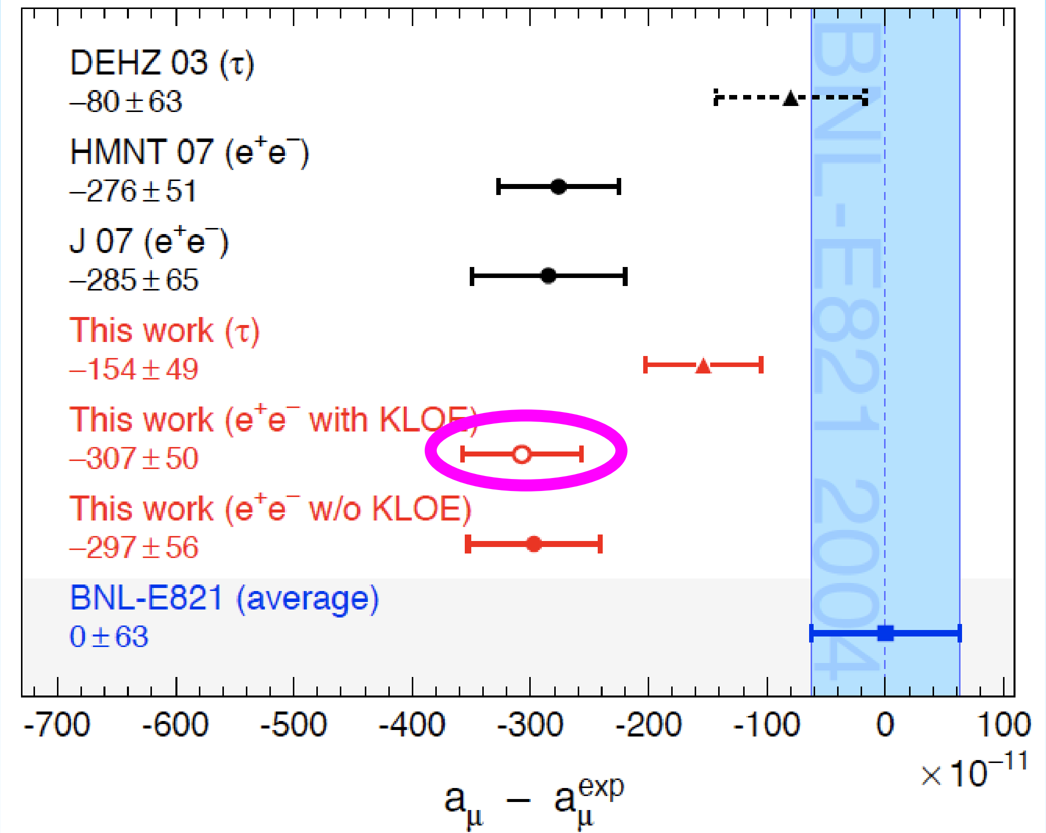




E821 achieved 0.54 ppm; e^+e^- based theory 0.43 ppm Hint is 3.8σ (new data from BaBar in Aug, KLOE in ?)

S-M = de Rafael, arXiv:0809.3085

Davier, et al.,hep-ph arXiv:0906.5443v1



$$a_\mu = 116\,592\,080(63) \times 10^{-11} \quad (0.54\,\text{ppm})$$

$$\Delta a_\mu^{(\text{today})} = (307 \pm 81) \times 10^{-11}$$

$$a_\mu^{EW} = 154(1)(2) \times 10^{-11}$$

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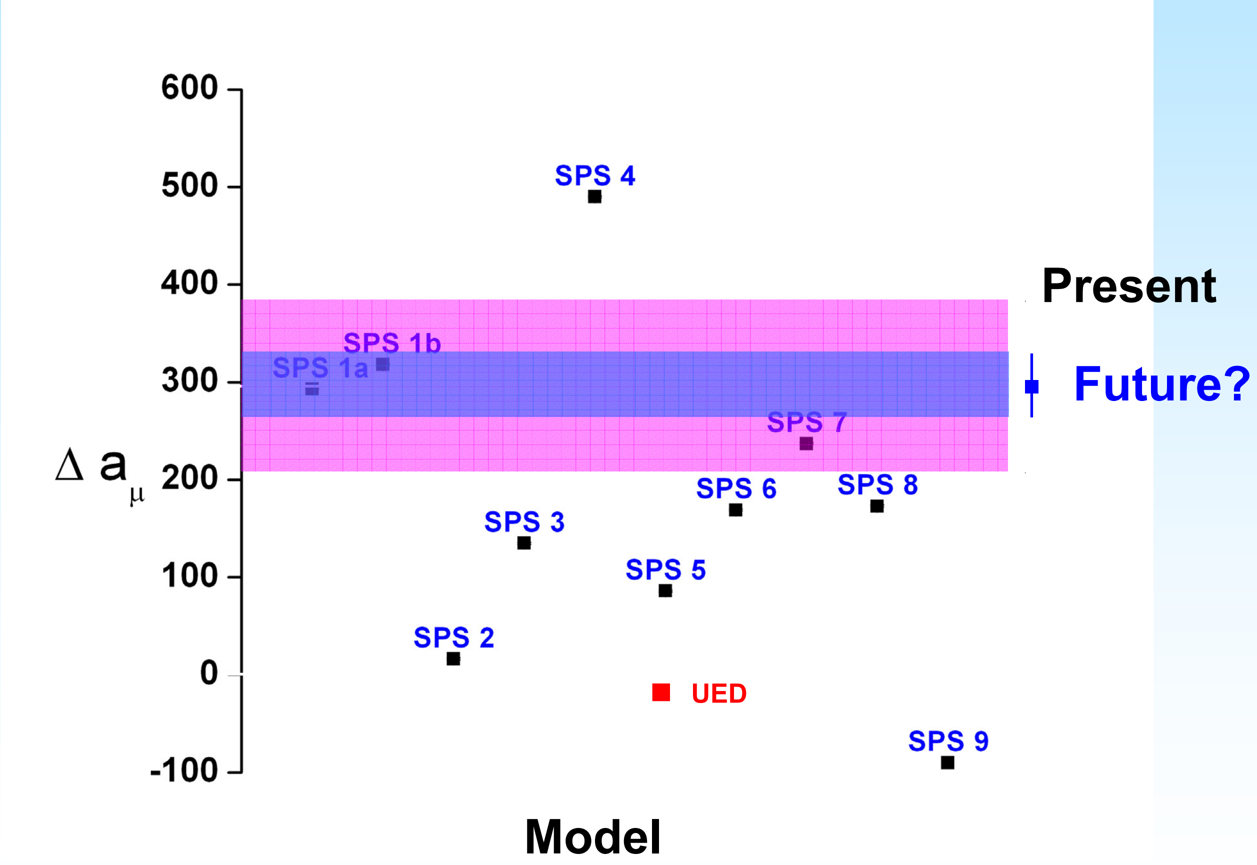
The **Snowmass Points and Slopes** give benchmarks to test observables with model predictions

Muon g-2 is a powerful discriminator …

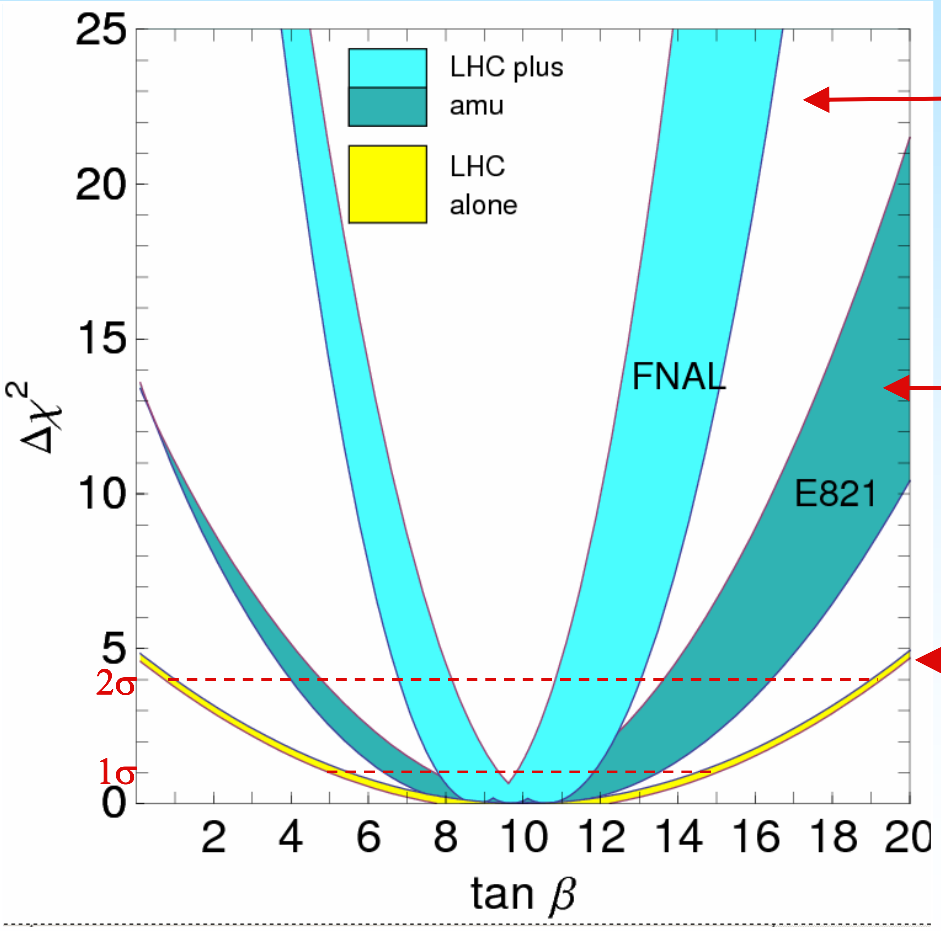
no matter where the final value lands!



SPS Definitions

Suppose the MSSM point SPS1a is realized and the paramaters are determined at LHC- sgn(Δ) gives sgn(μ)

- sgn (μ) difficult to obtain from the collider
- tan β poorly determined by the collider



New g-2

Old g-2

LHC (Sfitter)

from D. Stöckinger

Charged Lepton Flavor (μ) Violation

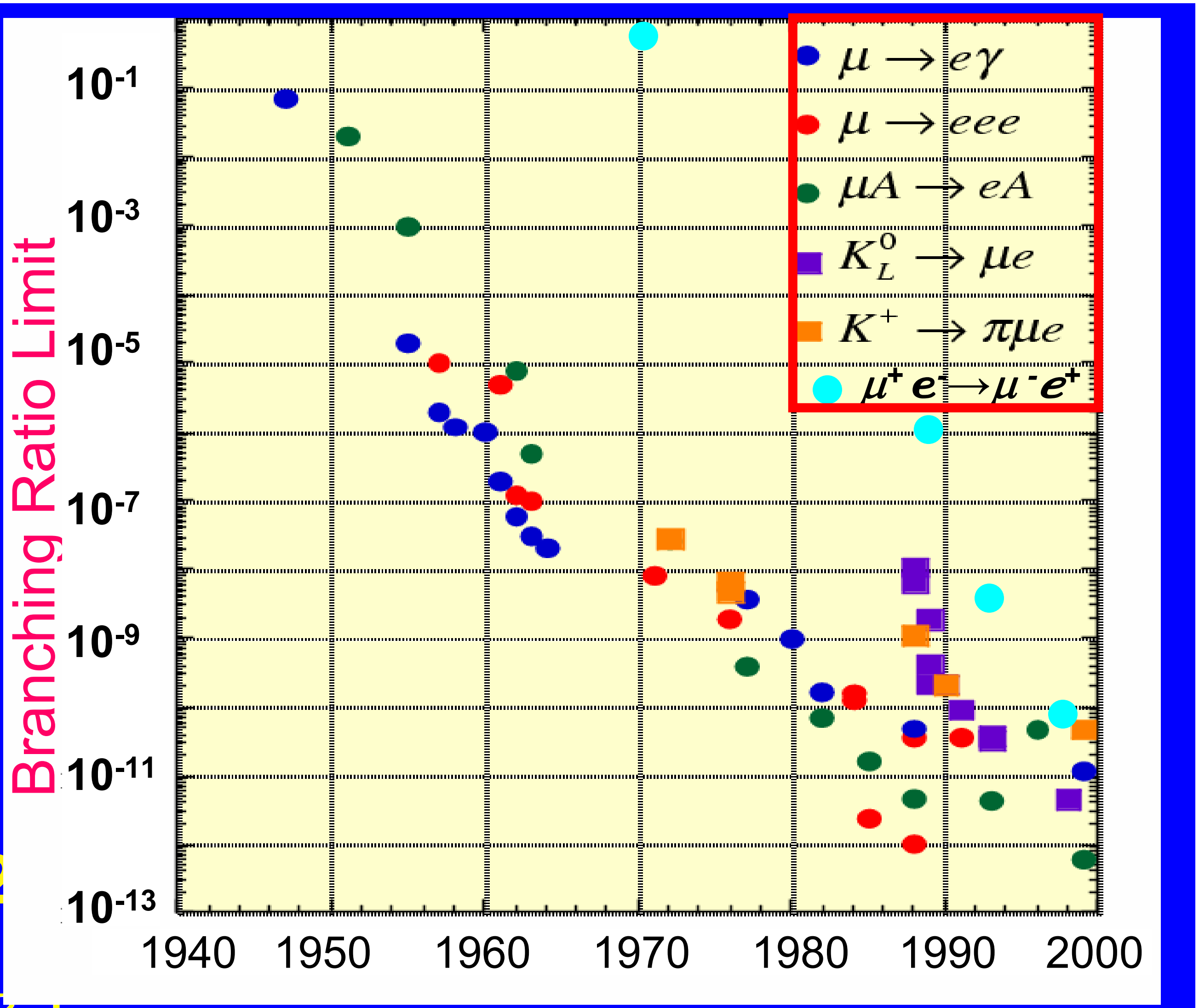
$\mu^+ \to e^+\gamma$ **2-body final state**

$\mu^+ \to e^+e^-e^+$

$\mu^- + \mathcal{N} \to e^- + \mathcal{N}$ **mono-energetic electron**

$(\mu^+e^-) \to (\mu^-e^+)$

Charged Lepton Flavor (μ) Violation



$\mu^+ \to e^+\gamma$ 2

$\mu^+ \to e^+e^-e$

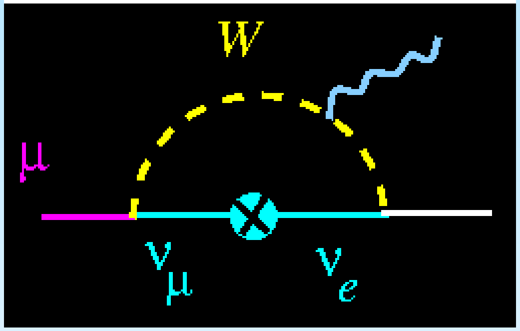
$\mu^- + \mathcal{N} \to e^- + \mathcal{N}$ **mono-energetic electron**

$(\mu^+e^-) \to (\mu^-e^+)$

CLFV in the muon sector

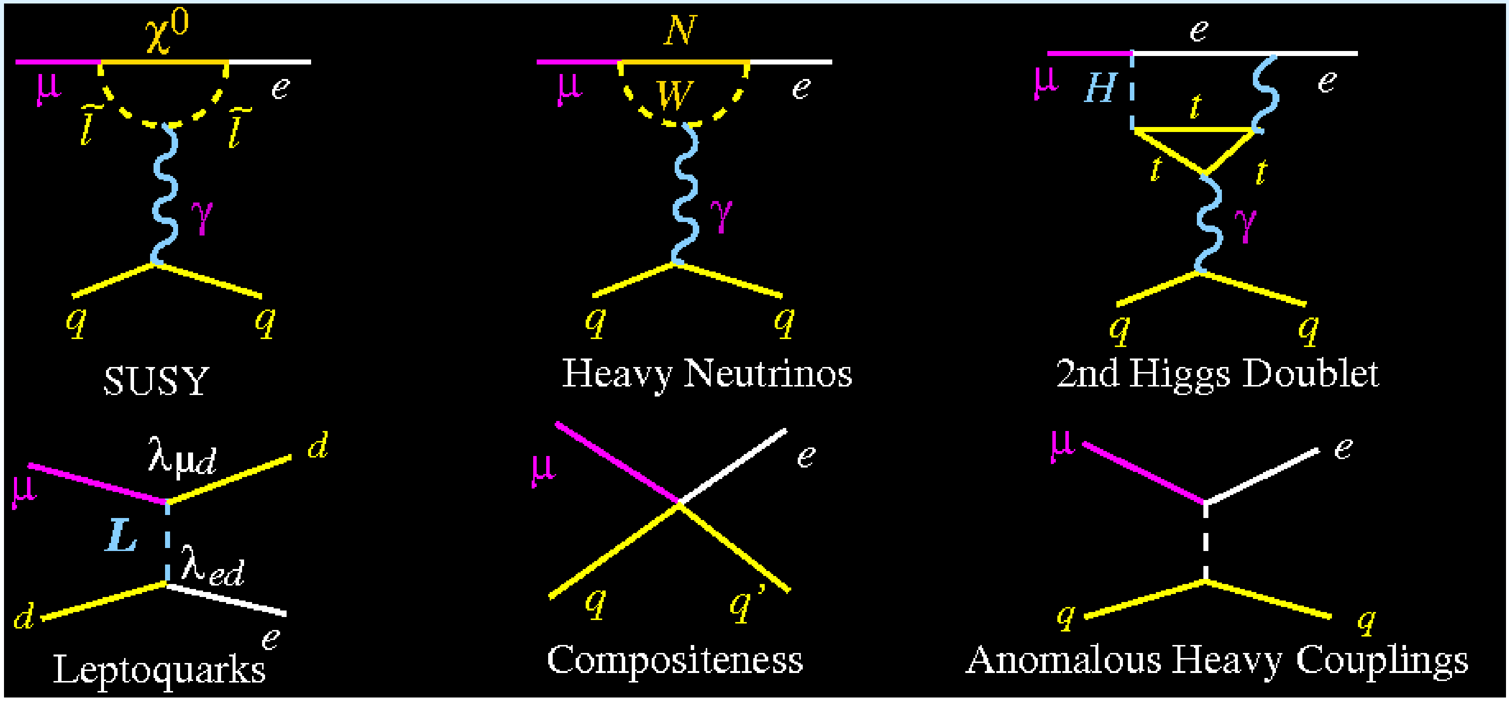
$$\mu^+ \to e^+\gamma; \;\; \mu^- + \mathcal{N} \to e^- + \mathcal{N}$$

SM



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{\ell} V^*_{\mu\ell}V_{e\ell}\frac{m^2_{\nu_\ell}}{M^2_W}\right|^2 \leq 10^{-54}$$

BSM



SUSY

Heavy Neutrinos

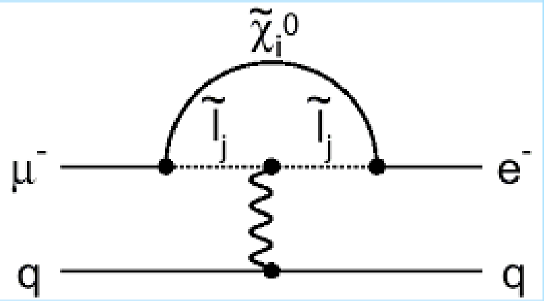
2nd Higgs Doublet

Leptoquarks

Compositeness

Anomalous Heavy Couplings

μe - conversion operators



R.Kitano, M.Koike and Y.Okada. 2002

have calculated the coherent μ-e conversion branching ratios in various nuclei for general LFV interactions to see:

(1) which nucleus is the most sensitive to mu-e conversion searches,
(2) whether one can distinguish various theoretical models by the Z dependence.

Relevant quark level interactions

$$\mathcal{L}_{\text{int}} = -\frac{4G_F}{\sqrt{2}}\left(m_\mu A_R \bar{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L \bar{\mu}\sigma^{\mu\nu}P_R e F_{\mu\nu} + \text{h.c.}\right)$$

Dipole

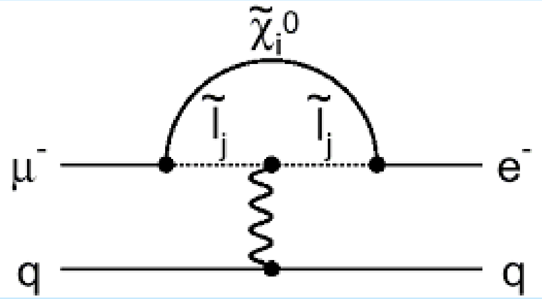
$$-\frac{G_F}{\sqrt{2}}\sum_{q=u,d,s}\left[\left(g_{LS(q)}\bar{e}P_R\mu + g_{RS(q)}\bar{e}P_L\mu\right)\bar{q}q\right.$$

Scalar

$$\left.+\left(g_{LV(q)}\bar{e}\gamma^\mu P_R\mu + g_{RV(q)}\bar{e}\gamma^\mu P_R\mu\right)\bar{q}\gamma_\mu q + \text{h.c.}\right]$$

Vector

μe - conversion operators



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have calculated the coherent μ-e conversion branching ratios in various nuclei for general LFV interactions to see

(1) which nucleus is the most sensitive to mu-e

(2) whether one can distinguish various theore dependence.

Relevant quark level interactions

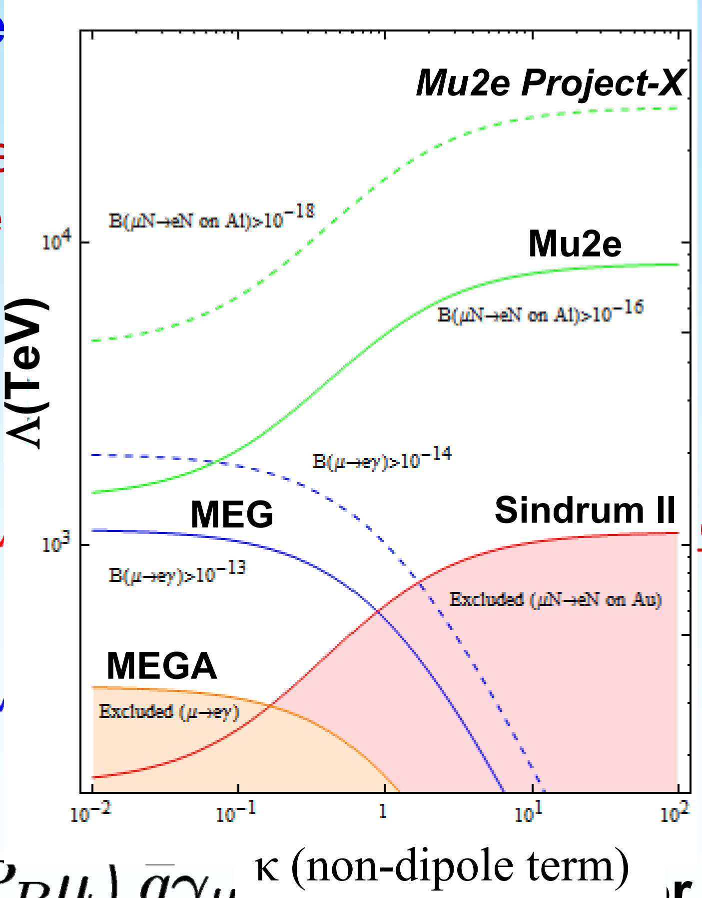
$$\mathcal{L}_{\rm int} = -\frac{4G_F}{\sqrt{2}}\left(m_\mu A_R \bar{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L\right.$$

e

$$-\frac{G_F}{\sqrt{2}}\sum_{q=u,d,s}\left[\left(g_{LS(q)}\bar{e}P_R\mu + g_{RS(q)}\bar{e}P_L\right.\right.$$

$$+\left(g_{LV(q)}\bar{e}\gamma^\mu P_R\mu + g_{RV(q)}\bar{e}\gamma^\mu P_R\mu\right)\bar{q}\gamma_\mu$$

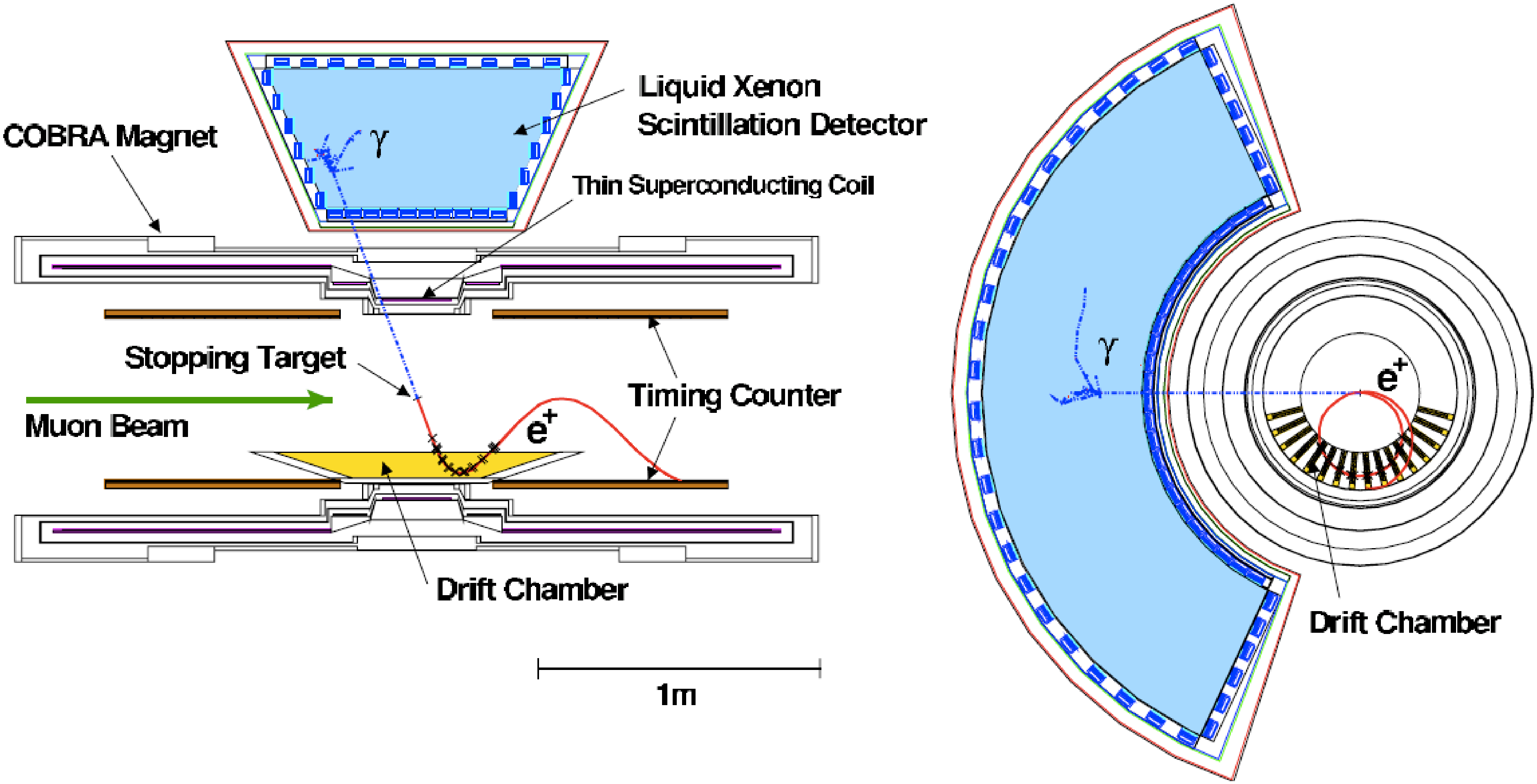
r



(fig, from Andrew Norman)

Presently active: $\mu^+ \to e^+ \gamma$ (MEG @ PSI)

- First running is going on now

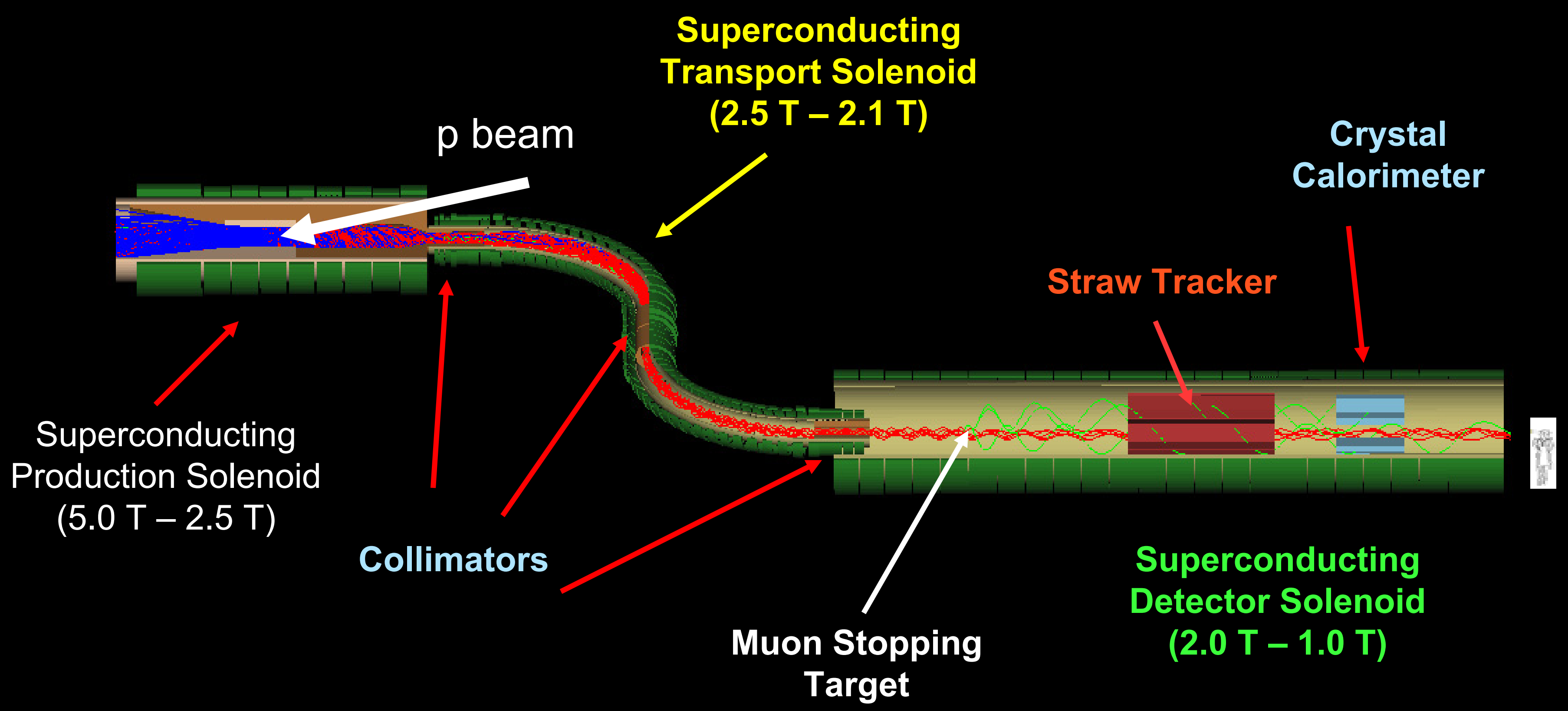


The $\mu 2e$ Apparatus proposed for Fermilab (has stage 1 approval)

$$\mu^- + Al \rightarrow e^- + Al$$

Phase 1: 90% C.L. limit of $R_{\mu e} < 6 \times 10^{-17}$

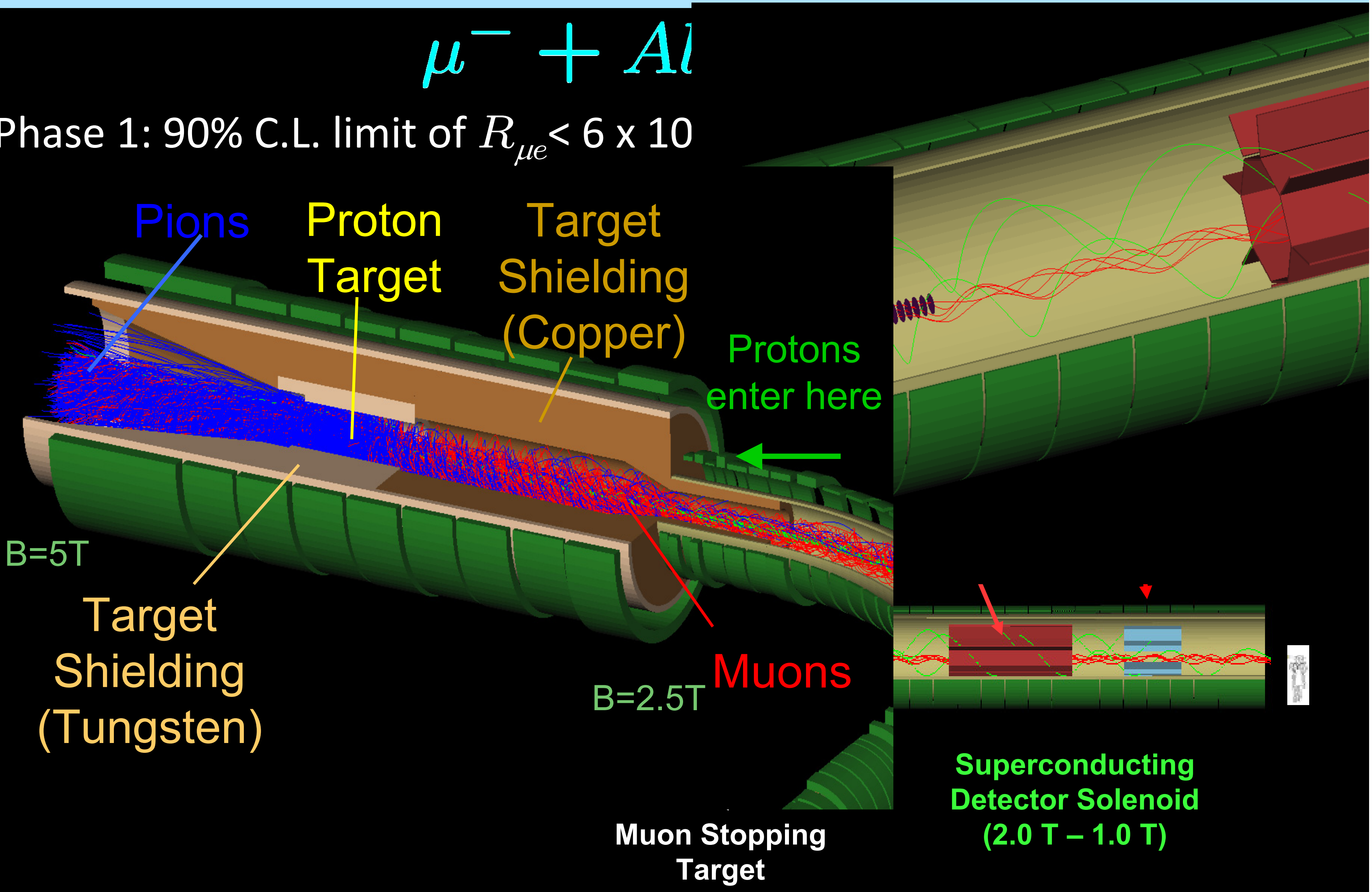
Phase 2: 90% C.L. limit of $R_{\mu e} \lesssim 10^{-18}$



The $\mu 2e$ Apparatus proposed for Fermilab (has stage 1 approval)

$\mu^- + Al$

Phase 1: 90% C.L. limit of $R_{\mu e}$< 6 x 10

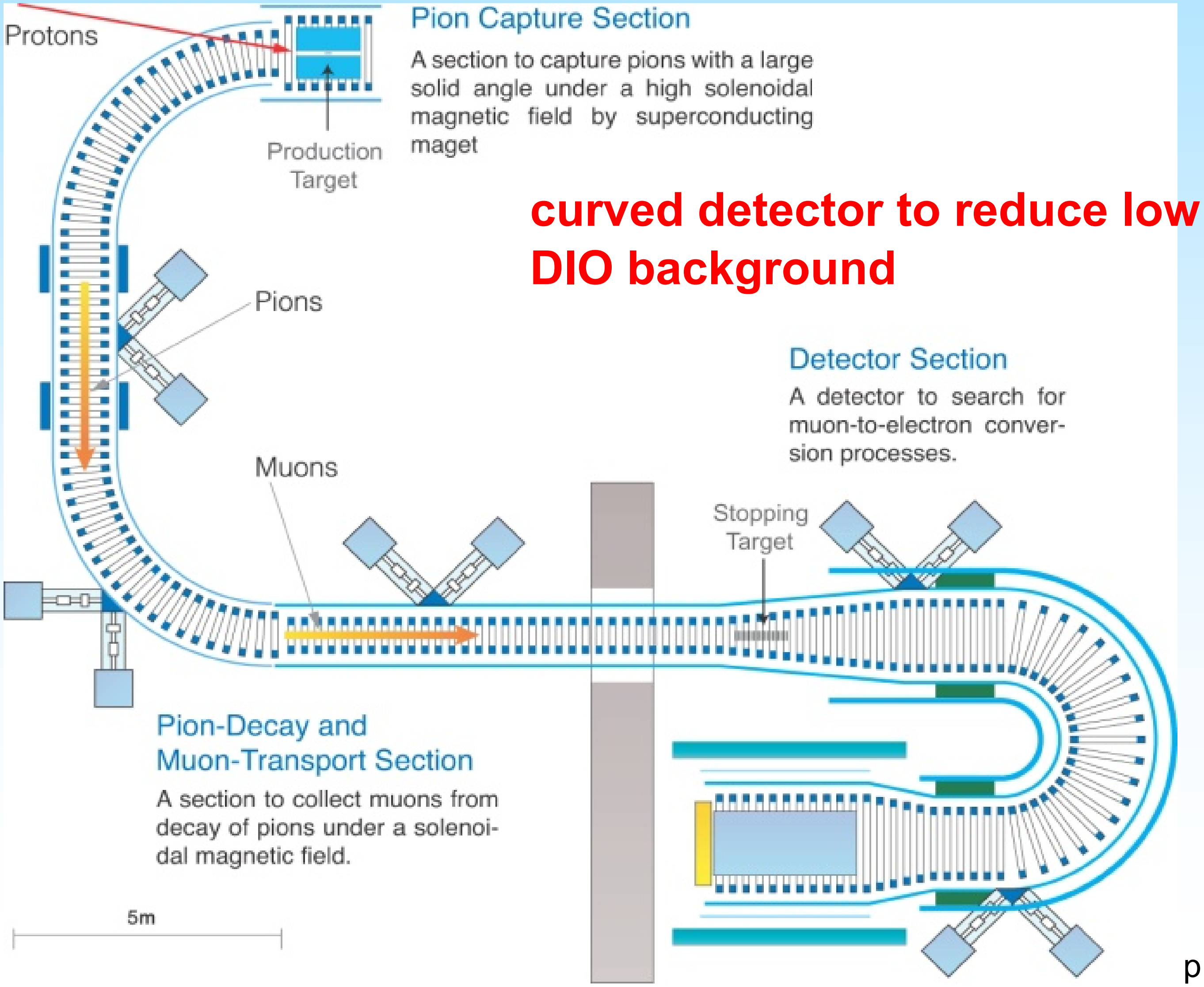


COMET Proposal @ J-PARC

μe conversion

90% CL $R_{\mu e} < 10^{-16}$

curved detector to reduce low E DIO background



$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s} \qquad \vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

Electric Dipole Moment: The search for non-SM ~~CP~~

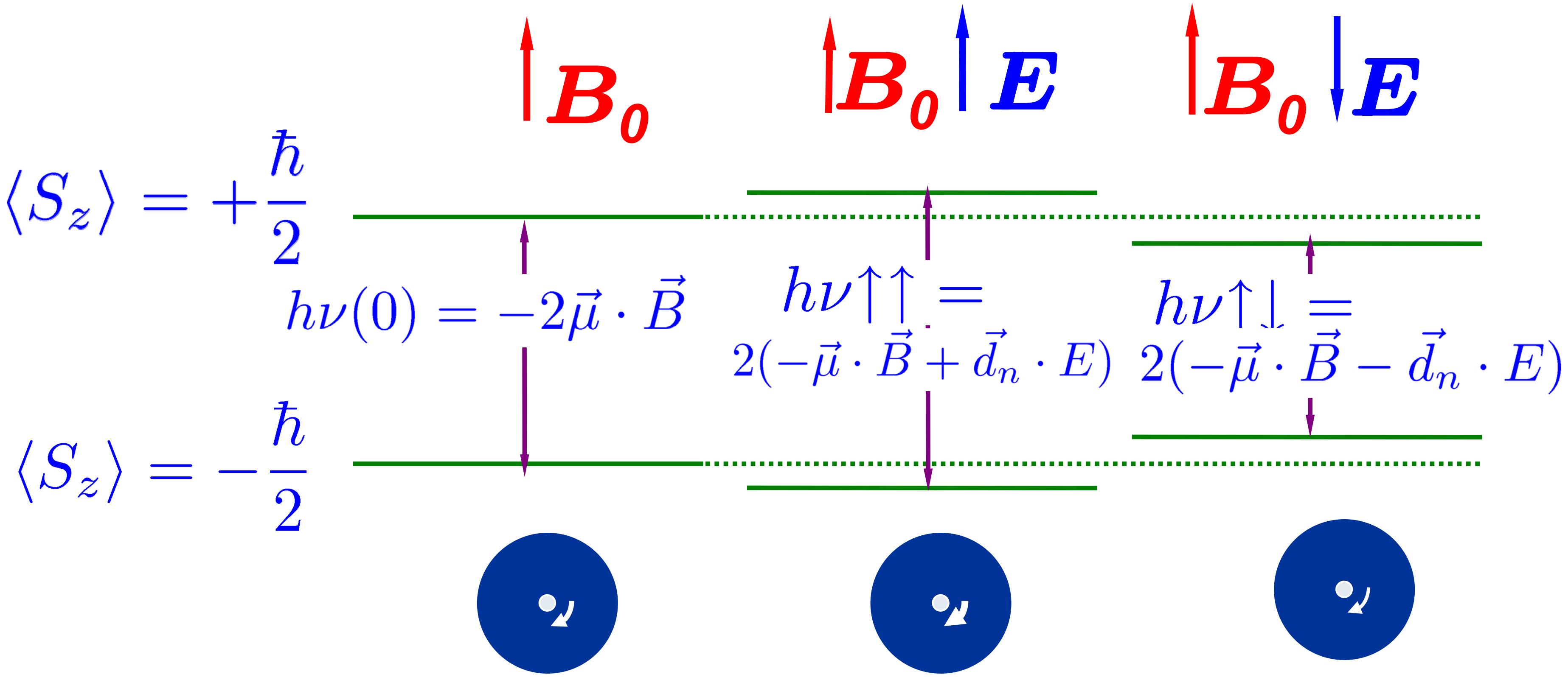
torque

$$\vec{N} = \vec{\mu} \times \vec{B}$$

or $= \vec{d} \times \vec{E}$

Phys. Rev. 78 (1950)

Principle of the "traditional" EDM measurements



$$\langle S_z\rangle = +\frac{\hbar}{2}$$

$$h\nu(0) = -2\vec{\mu}\cdot\vec{B}$$

$$h\nu\uparrow\uparrow = 2(-\vec{\mu}\cdot\vec{B}+\vec{d}_n\cdot E)$$

$$h\nu\uparrow\downarrow = 2(-\vec{\mu}\cdot\vec{B}-\vec{d}_n\cdot E)$$

$$\langle S_z\rangle = -\frac{\hbar}{2}$$

E=100kV/m

$$\nu_{\uparrow\uparrow} - \nu\uparrow\downarrow = \Delta\nu = \frac{4d_nE}{h}$$

$$d_n = 10^{-28}\, e\cdot\text{cm} \Rightarrow \Delta\,\nu = \times 1\times 10^{-8}\,\text{Hz}$$

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Animation by J. Karamath

EDMs of Hadronic Systems, p, n, d, ${}^{199}Hg$

QCD vacuum state can be parameterized by:

$$\mathcal{L}^{eff}_{QCD} = \mathcal{L}_{QCD} + \theta \frac{g^2_{QCD}}{32\pi^2} F^{a\mu\nu} \tilde{F}_{a\mu\nu} \quad a = 1, 2, \ldots, 8$$

$$\cancel{P} \quad \cancel{T}$$

Physical quantity is the sum of θ and the overall phase of the quark matrix, $\bar{\theta} = \theta + \arg(\det M)$ which is constrained by the non-observation of a neutron EDM.

$$|d_n| \simeq 3.6 \times 10^{-16} \bar{\theta}\, e \cdot \mathrm{cm} \quad \Rightarrow \quad \bar{\theta} \lesssim 10^{-10}$$

strong CP problem!

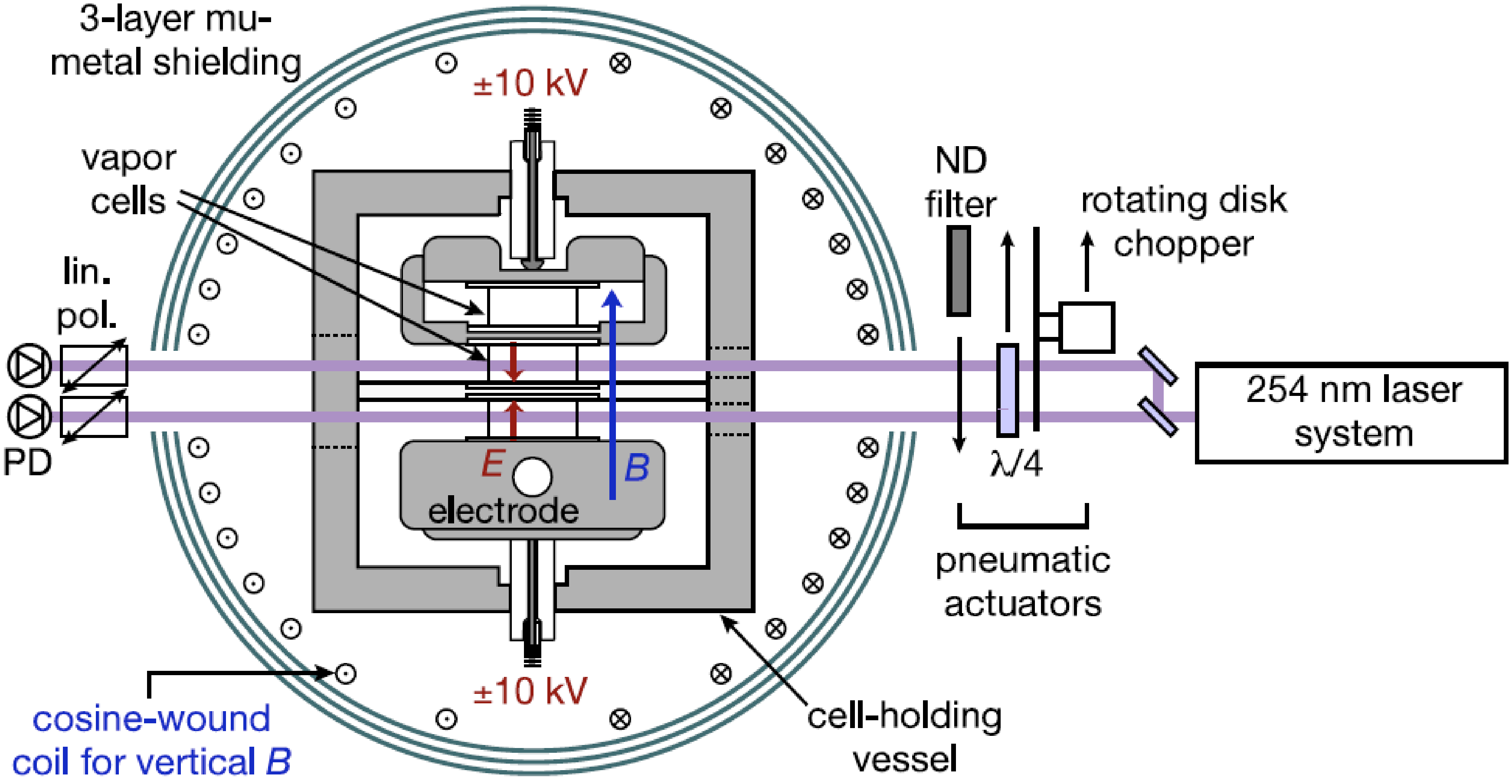
We have the form factors $F_{2_{n,p}}(0)$ and $F_{3_{n,p}}(0)$ (the aMDM and EDM) which we can write as isovector and isoscalar contributions:

$$F^{(I=1)}_{2N} = \frac{F_{2p} - F_{2n}}{2} \simeq 1.85, \quad F^{(I=0)}_{2N} = \frac{F_{2p} + F_{2n}}{2} \simeq -0.06$$

Conclude isovector dominates aMDM, what about $F_3(0)$?

- Lattice is better at determining the isovector part.
  - both isoscalar and isovector EDMs are predicted by the various models (see Pospelov and Ritz in Ann. Phys, or Lepton Moments for a detailed discussion).
- Measuring both the proton and neutron EDM will constrain the models, and help understand new sources of CP.

New Result! ^{199}Hg - PRL **102**, 101601 (2009)



$$d(^{199}Hg) = (0.49 \pm 1.29_{stat} \pm 0.76_{syst}) \times 10^{-29}\, e\,\mathrm{cm}$$

The present EDM limits are orders of magnitude from the standard-model value

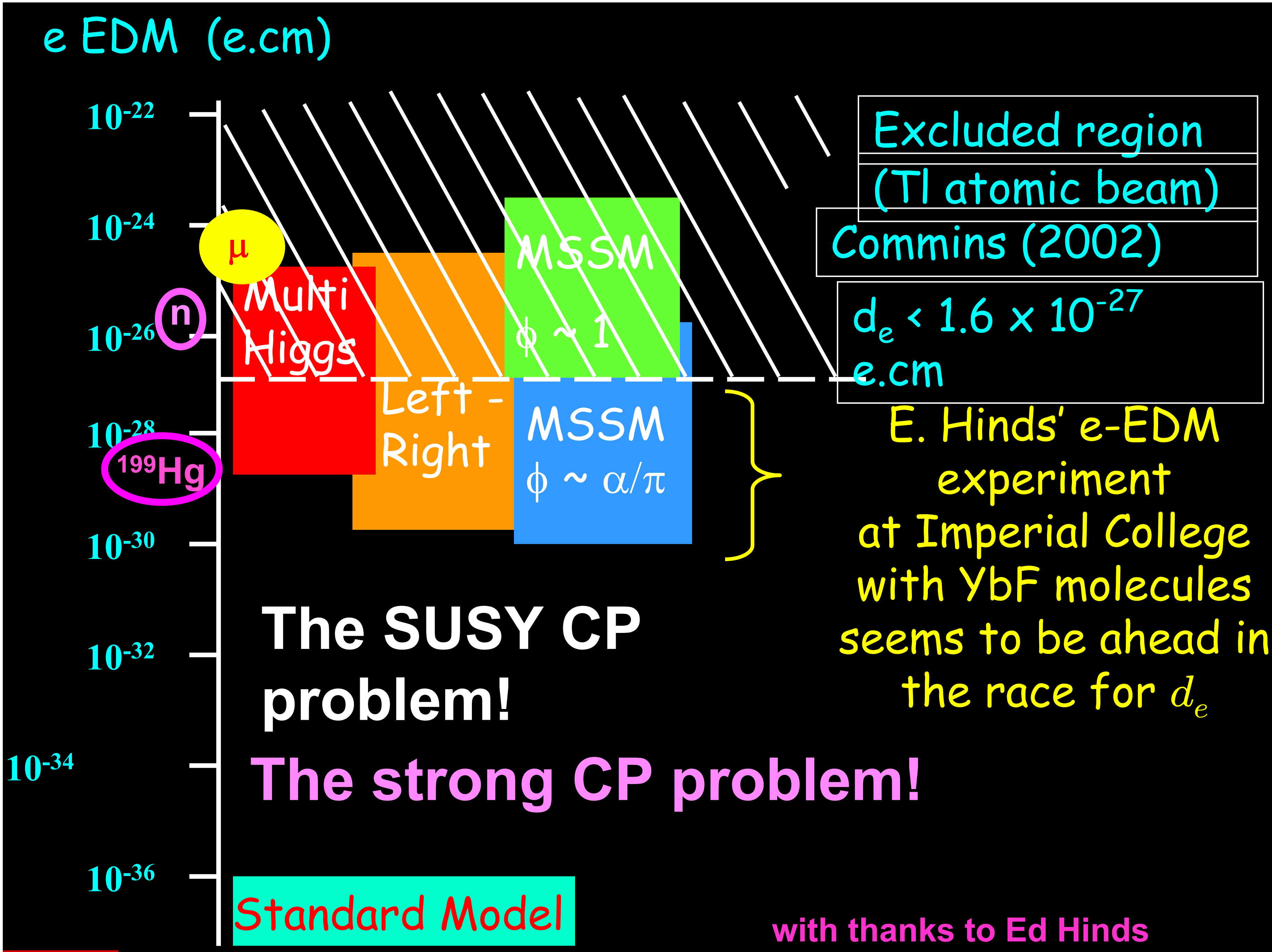
Particle	***Present EDM limit*** **(e-cm)**	***SM value*** **(e-cm)**
p	7.9×10^{-25}	
n	2.9×10^{-26}	$\simeq 10^{-32}$
^{199}Hg	3.1×10^{-29}	
e^-	$\sim 1.6 \times 10^{-27}$	$< 10^{-41}$
μ	1.8×10^{-19} (E821)	$< 10^{-38}$

References: n PRL **97,** 131801 (2006)

p, ^{199}**Hg** PRL **102**, 101601 (2009)

e^- PRL **88,** 071805 (2002)

μ arXiv:0811.1207v2 [hep-ex]



E. Hinds' e-EDM experiment at Imperial College with YbF molecules seems to be ahead in the race for d_e

The SUSY CP problem!

The strong CP problem!

with thanks to Ed Hinds

Storage ring p, d, μ EDM Experiments (not at magic γ)

$$\vec{\omega} = -\cancelto{0}{\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}$$

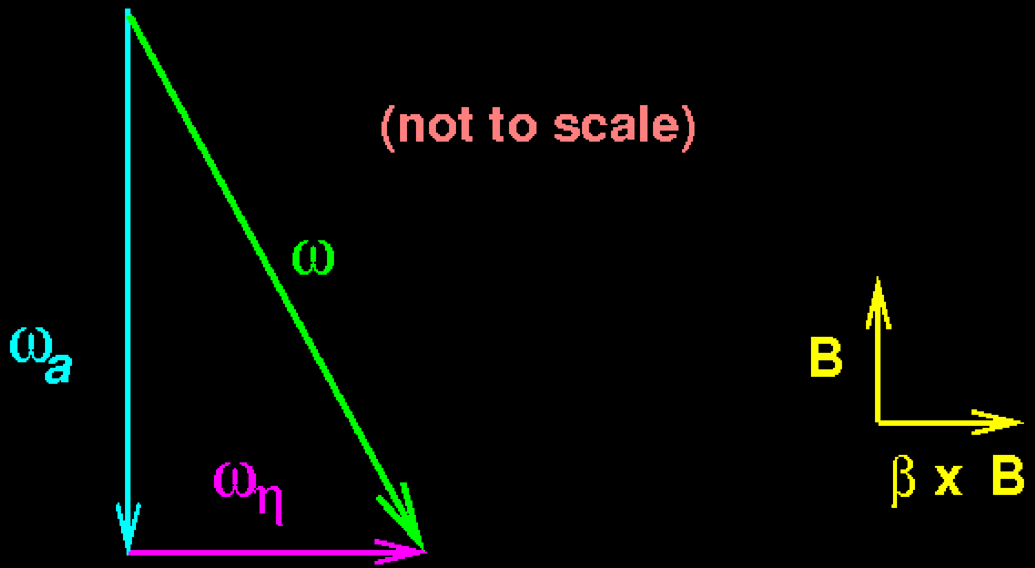
Use a radial E-field to turn off the ω_a precession

$$+ \frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

“Frozen spin”

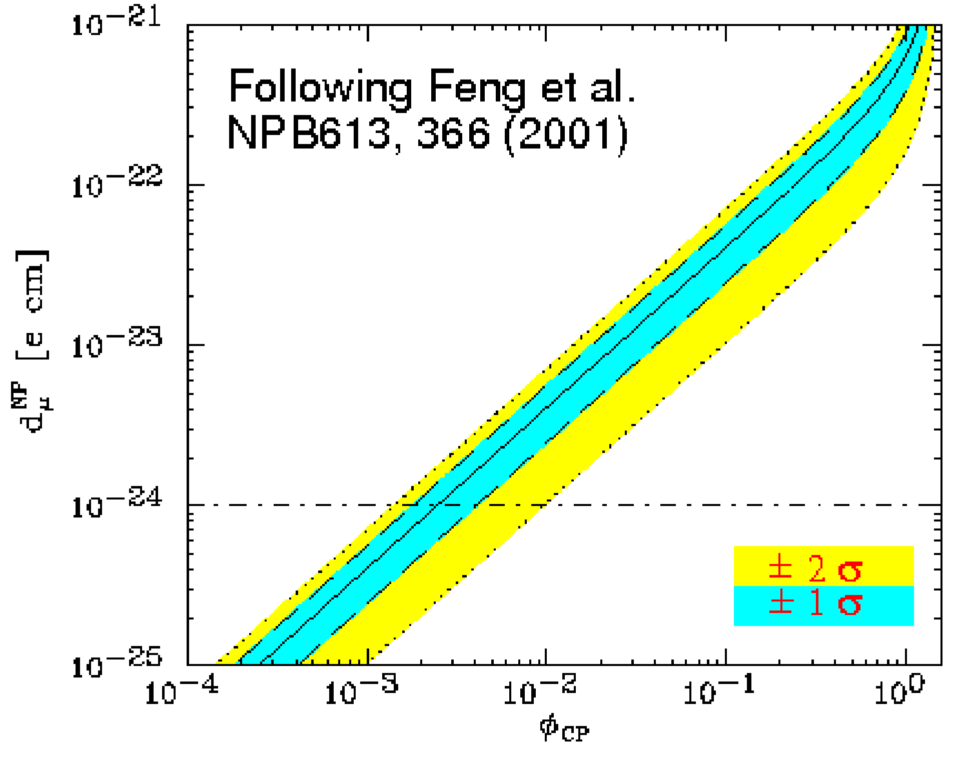
PRL **93** 052001 (2004)

With $\omega_a = 0$, the EDM ca
precess out of the plane



**PSI, Ferminlab Project X,
J-PARC, NuFact?**

a_μ implications for the muon EDM assuming same New Physics participates (recall that (Δ^{today}=307(81) X10^{-11})



Assuming that

$$a_\mu^{\rm NP} = 300(100) \times 10^{-11}$$

$$d_\mu^{\rm NP} \simeq 3 \times 10^{-22} \left(\frac{a_\mu^{\rm NP}}{3 \times 10^{-9}} \right) \tan \phi_{CP} \quad {\rm e \cdot cm}$$

where ϕ_{CP} is a CP violating phase.

Either d_μ is **of order 10^{-22} e cm**, or the CP phase is strongly suppressed!

Summary: A definitive signal for any of these processes would change our view of nature!

- Exciting opportunities exist to explore the TeV scale and beyond with dipole moments.
- There appears to be a difference between a_μ and the standard-model prediction at the ≃3.8 σ level.
  - if confirmed it would fit well with SUSY expectations
- The discovery of an EDM would (finally) provide evidence for non-standard model CP violation and would point toward new physics.
- The observation of charged lepton flavor violation would signal the discovery of new physics, and perhaps probe the PeV scale
- Experiments proposed or underway:
  - n EDM (Oak Ridge, Grenoble (2), PSI)
  - p EDM d EDM (Brookhaven)
  - e EDM Imperial College, Yale, Harvard, Colorado, Amherst, Penn State, Texas, Osaka, Indiana, …
  - μ LFV (PSI, Fermilab, J-PARC)
  - μ g-2 (P989@Fermilab, J-PARC)
  - μ EDM (suggestions at PSI, J-PARC and Fermilab)

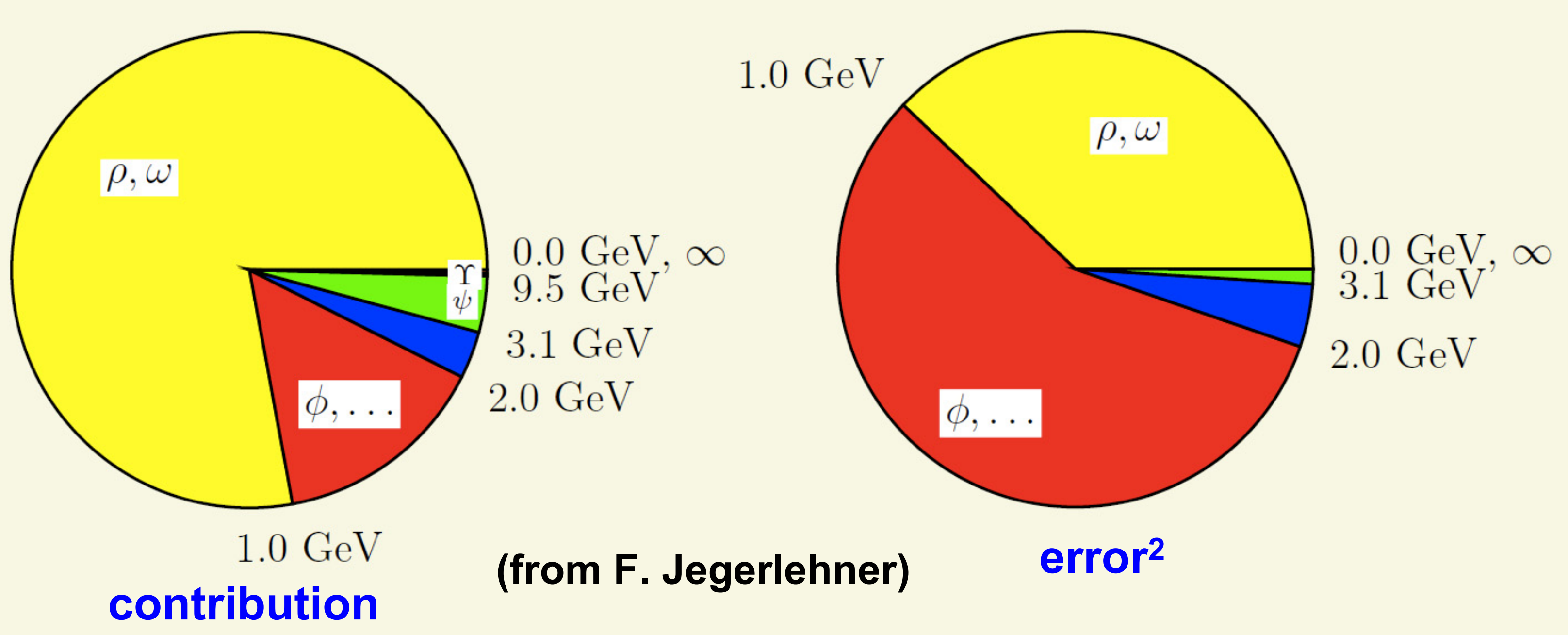
Possible topics for further discussion

- Theory
  - Current / future status of (g-2) hadronic vacuum polarization
  - Current / future status (g-2) hadronic light-by-light
  - Use of initial state radiation to measure $R(s)$
  - Use of τ-decay data for the hadronic contribution?
  - What are the SPS points?
  - CMSSM Constraints?
  - Show us more about the Sfitter results w/wo g-2
  - How general is the UED "small effect" prediction?
- Experiments
  - What are the neutron EDM experiments?
  - Muon EDM experiments
  - What's the status of the muon to electron conversion experiments?
  - What is involved in moving the (g-2) storage ring to Fermilab?

Analyticity and the optical theorem:

Back

$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \quad \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$



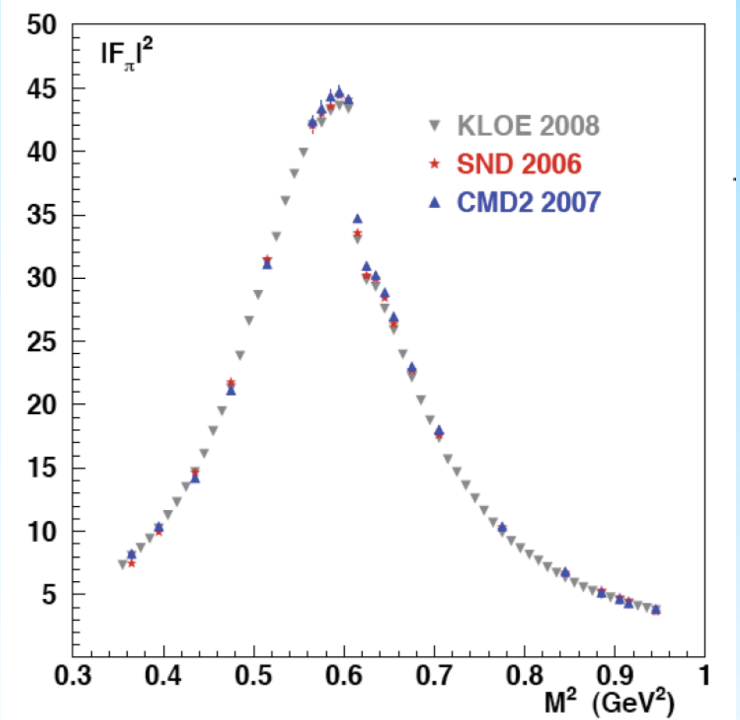
(from F. Jegerlehner)

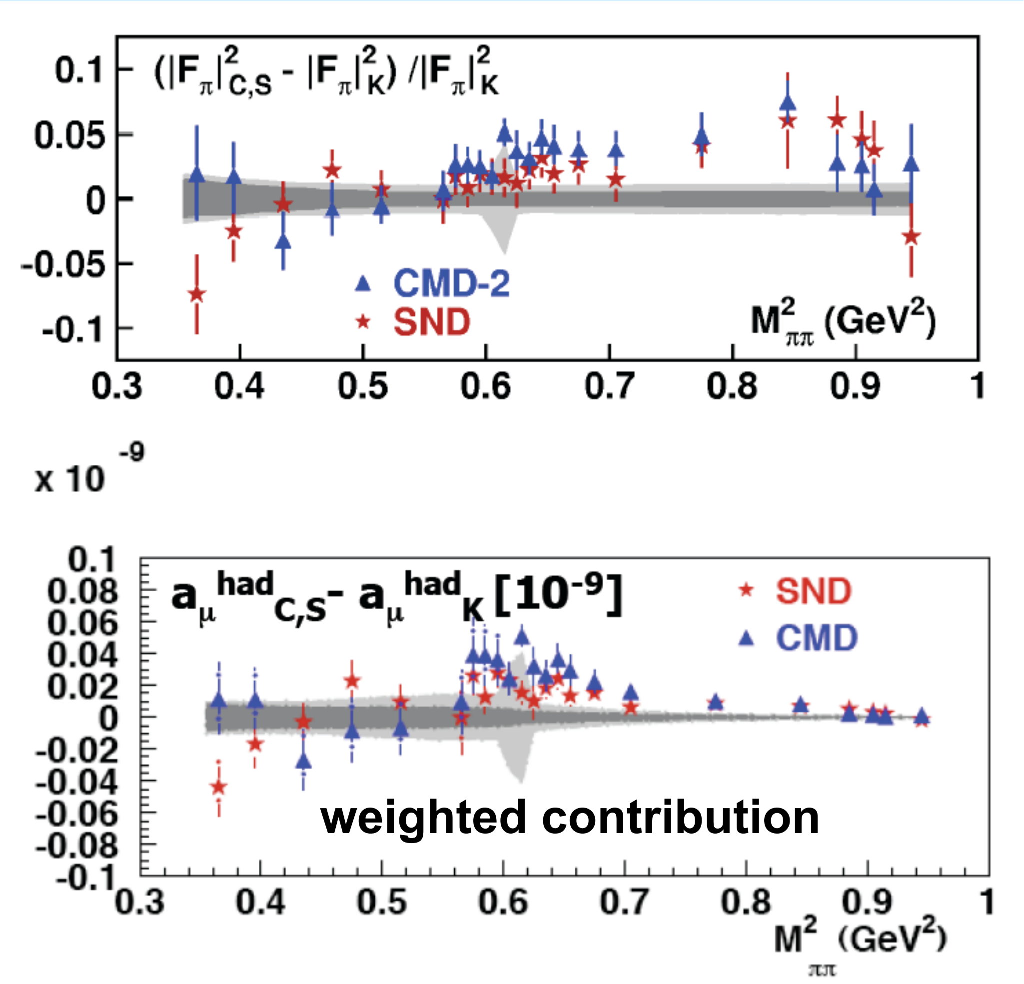
- Future efforts will reduce errors
  - Additional KLOE data (in hand, near term)
  - CMD3 at VEPP2000, up to 2.0 GeV (next 5 years)
  - perhaps Belle

BOSTON UNIVERSITY

$|F_\pi|^2$ from KLOE, CMD2 and SND agree well

Back





$$\sigma_{e^+e^-\to\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta_\pi^3|F_\pi|^2$$

pt. to pt. difference in $a_\mu^{\mathrm{Had}} \simeq 1 - 4\times 10^{-11}$

recall that: $a_\mu^{\mathrm{Had}}(\mathrm{LO}) = 6\,908\,(44)\ \times\ 10^{-11}$

Back

Suppose the hadronic contribution increased to remove the difference?

- A similar dispersion integral enters elsewhere

$$\Delta\alpha^{(5)}_{\rm had}(M_Z) = \frac{M_Z^2}{4\alpha\pi^2} P \int_{4m_\pi^2}^{\infty} ds \frac{\sigma(s)}{M_Z^2 - s}$$

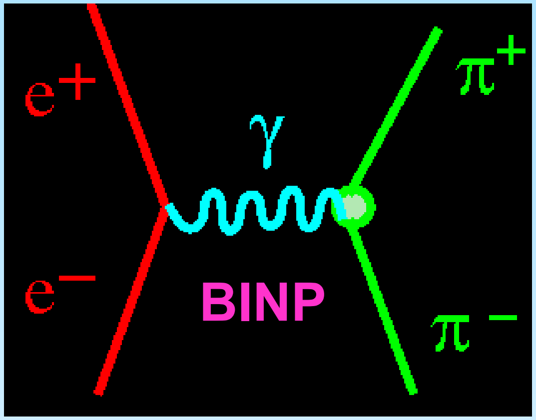
- Increasing $\sigma(s)$ to remove the (g-2) difference lowers the Higgs mass limit **PRD 78, 013009 (2008)**

$$M_H \leq 150 \text{ GeV} \,(95\%\text{C.L.}) \;\rightarrow \simeq 130 \text{ GeV}$$

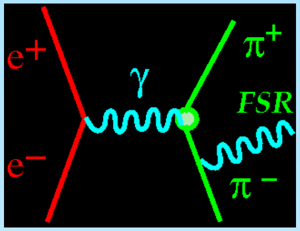
- This cross section is important for a_μ and for any precision EW physics.
- BaBar result soon. Future work continues in Frascati and Novosibirsk. Belle is also beginning to explore this possibility.

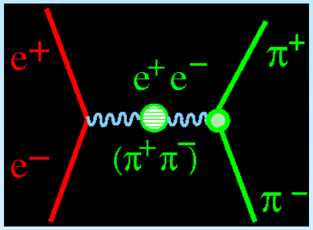
KLOE and BaBar use ISR (radiative return)

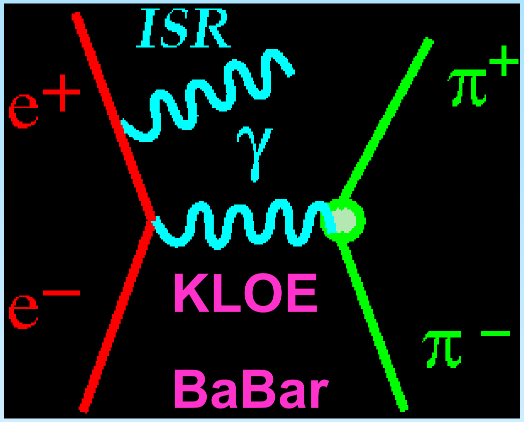
Back



scan e^+e^- beam energy







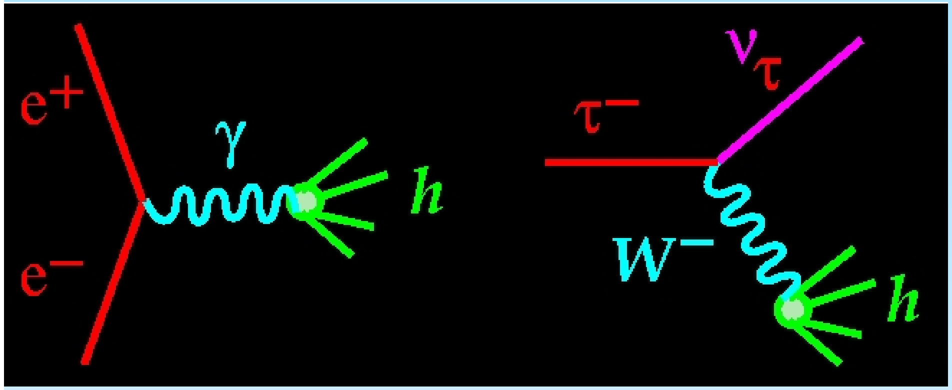
use ISR to lower collision energy

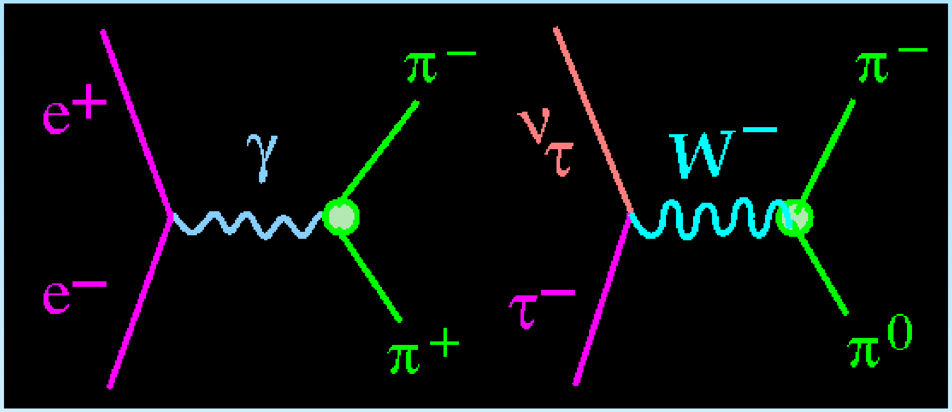
- KLOE
  - sit on ϕ, γ is soft and goes down the beam pipe
  - in data published thus far, use theory to calculate mm cross section.
  - have $\mu\,\mu$ data being analyzed
- BaBar
  - runs on the Υ 4s, the γ is hard, and is detected
  - excellent particle ID with μ – π separation
  - measures $R\,(s)$ directly

Always the issue of radiative corrections

Back

a(had) from hadronic τ decay?





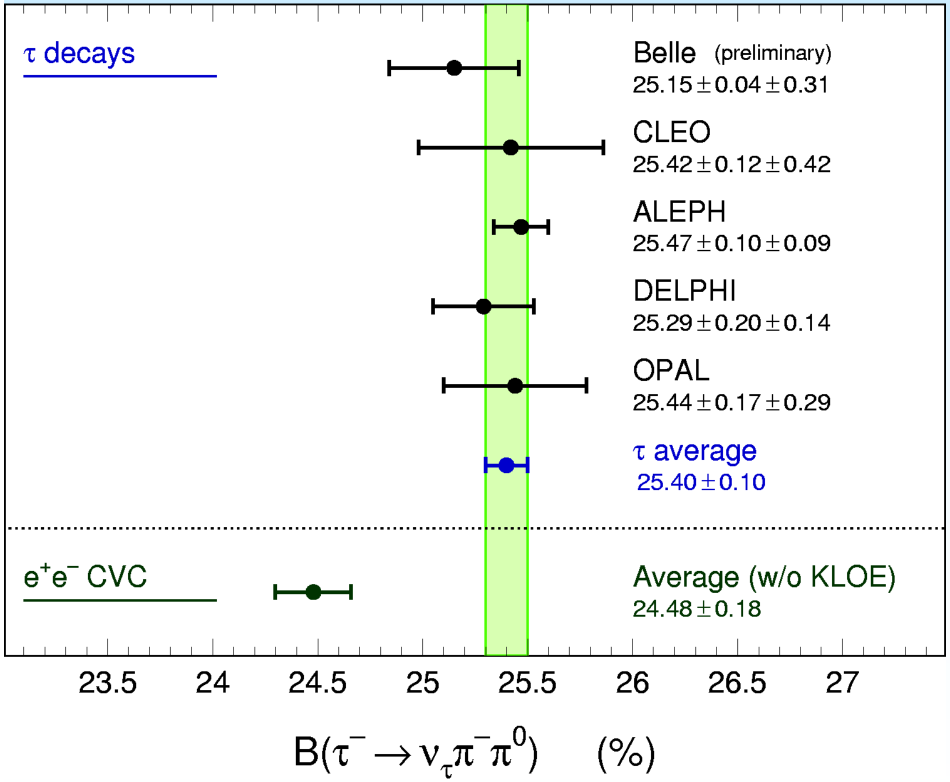
- Assume: CVC, no 2nd-class currents, isospin breaking corrections.
  - e^+e^- goes through neutral ρ
  - while τ-decay goes through charged ρ
- n.b. τ decay has no isoscalar piece, e^+e^- does
- There are inconsistencies in the comparison of e^+e^- and τ decay:

Testing CVC with one number (last year)

Back

Infer τ branching fractions (more robust than spectral functions) from e^+e^- data:

$$BR_{CVC}(\tau^- \to \pi^-\pi^0\nu_\tau) = \frac{6\pi|V_{ud}|^2 S_{EW}}{m_\pi^2}\int_0^{m_\tau} ds\,\mathrm{kin}(s)\,\nu^{SU(2)-\mathrm{corrected}}(s)$$



Difference: BR[τ] – BR[e^+e^- (CVC)]:

Mode	$\Delta(\tau - e^+e^-)$	\`Sigma'
$\tau^- \to \pi^-\pi^0\nu_\tau$	+ 0.92 ± 0.21	4.5
$\tau^- \to \pi^- 3\pi^0\nu_\tau$	– 0.08 ± 0.11	0.7
$\tau^- \to 2\pi^-\pi^+\pi^0\nu_\tau$	+ 0.91 ± 0.25	3.6

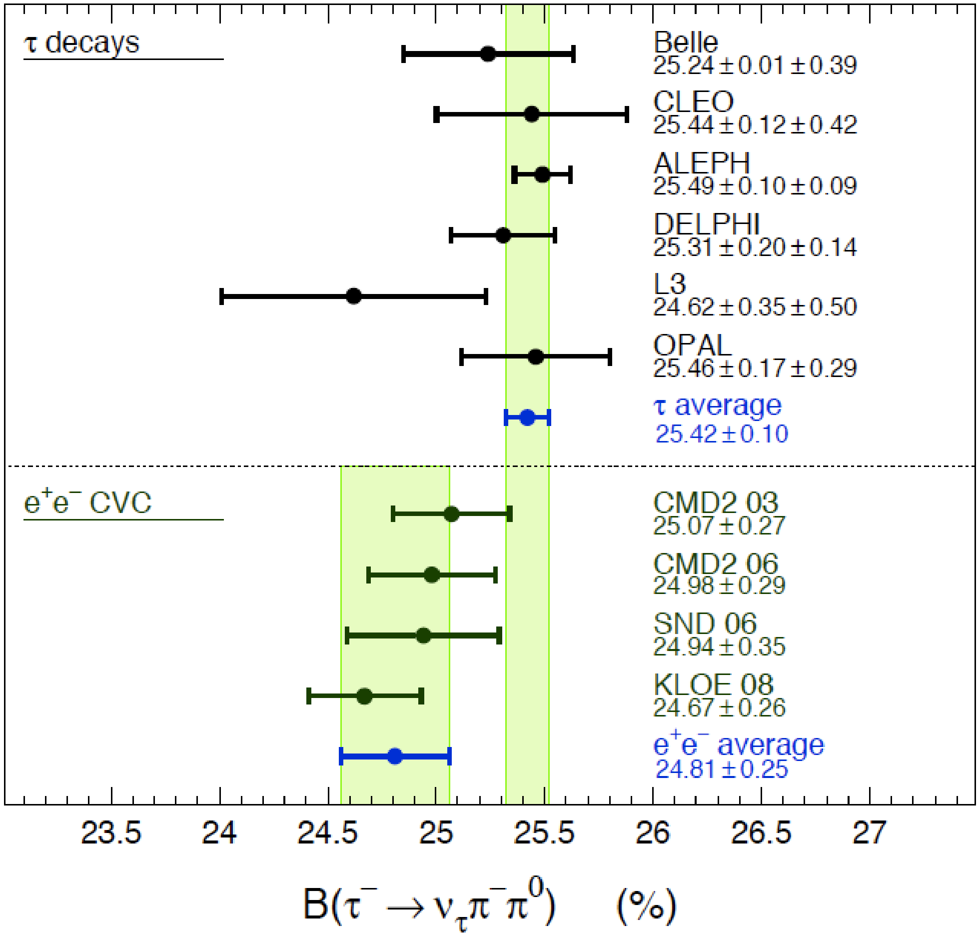
ee data on $\pi^-\pi^+\pi^0\pi^0$ not satisfactory

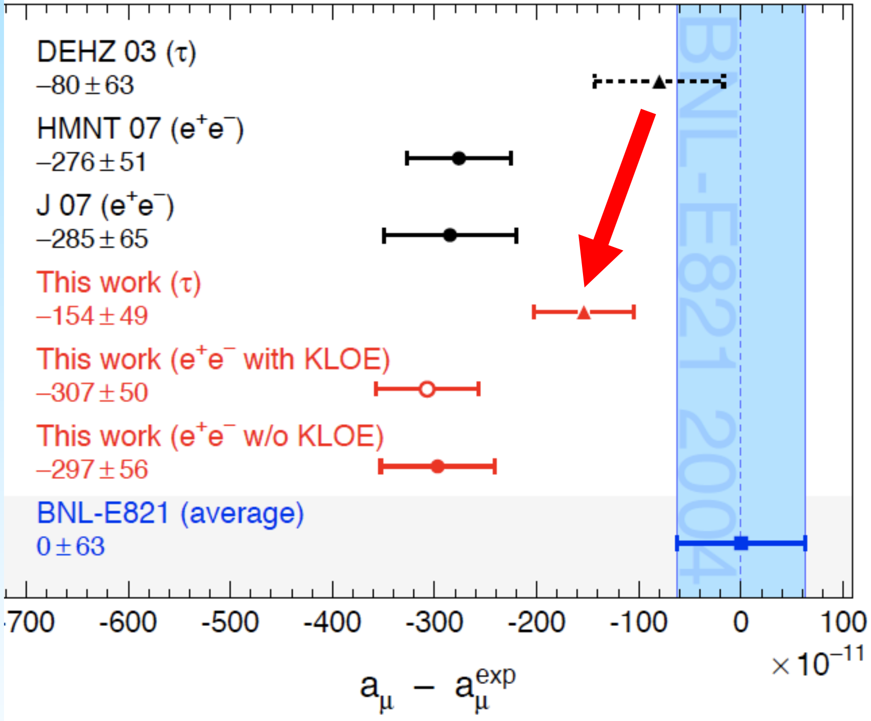
from Michel Davier

recent preprint, to be published in EPJ

Back

M. Davier, et al., arXiv:0906.5443v1 [hep-ph]



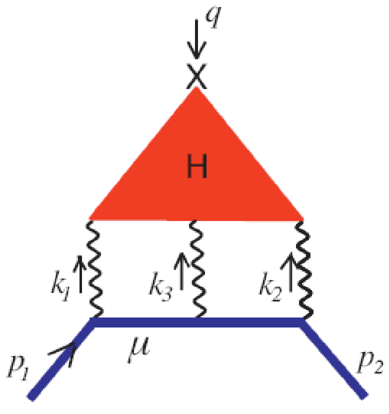


Hadronic Light–by–Light Scattering Contribution to the Muon Anomalous Magnetic Moment

Back

arXiv:0901.0306v1

Joaquim Prades[a], Eduardo de Rafael[b] and Arkady Vainshtein[c]



$$a^{\rm HLbL}(\pi\,,\eta\,,\eta') = (11.4 \pm 1.3) \times 10^{-10}$$

$$a^{\rm HLbL}({\rm scalars}) = -(0.7 \pm 0.7) \times 10^{-10}$$

$$a^{\rm HLbL}(\pi{-}{\rm dressed\ loop}) = -(1.9 \pm 1.9) \times 10^{-10}$$

$$a^{\rm HLbL}({\rm pseudovectors}) = (1.5 \pm 1) \times 10^{-10}$$

Dynamical models with QCD behavior

$$a_\mu^{\rm HLBL} = 105\ (26) \times 10^{-11}$$

Note, with $\Delta a_\mu = 295 \times 10^{-11}$ … If HLBL is the source of the difference with SM, it would need to increase by 11 σ ....

Back

The π^0 (Goldstone) contribution fixes sign of the contribution **From χpt and large N_c QCD**

$$a_\mu^{[\chi pt]} = \left(\frac{\alpha}{\pi}\right)^3 \left\{ \frac{N_c^2}{48\pi^2}\frac{m_\mu^2}{F_\pi^2}\ln^2\left(\frac{\mu}{m}\right) + \mathcal{O}\left[\ln\left(\frac{\mu}{m}\right)+\kappa(\mu)\right]\right\}$$

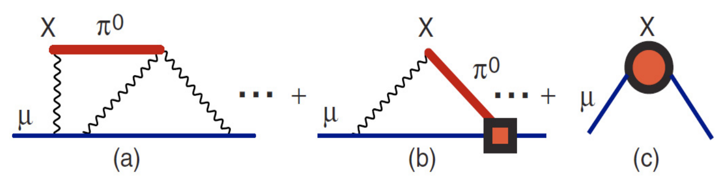
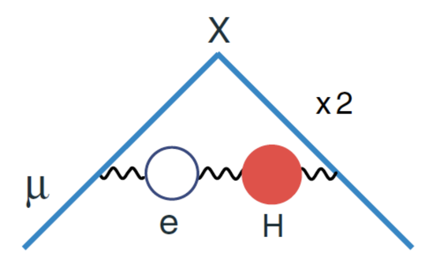
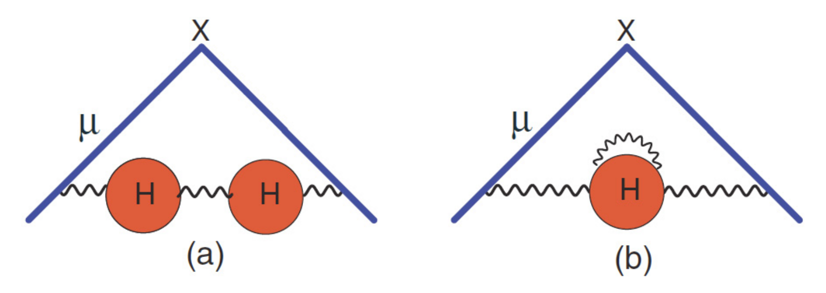


Figure 53. One Goldstone reducible diagrams in chiral perturbation theory.

Examples of other 3-loop hadronic contributions:





$$a_\mu^{\mathrm{H6}} = -97.9\ (.9) \times 10^{-11}$$

- The magnitude of the HLBL is about the same as the magnitude of the 3-loop HVP which can be calculated from the dispersion relation.
- It's hard to believe that the HLBL would be huge compared to the other 3-loop contributions.

Back

How general is the UED "tiny effects" prediction?

- UED models (1D) typically predict "tiny" effects
  - Incompatible with a Δa_μ of ~ 300 x 10^{-11}

The statement refers to the UED models originally proposed and studied by Appelquist, Cheng, and Dobrescu, and also by Rizzo in 2000/2001. The results for g-2 in the UED models with one extra dimension is (according to these references) below 50 x 10^{-11} as written in our proposal.

While there might be modified UED models with larger contributions to g-2, this again demonstrates that g-2 is very powerful tool to discriminate between different new physics models. (D. Stockinger)

Sfitter LHC global fit

Back

(Alexander, Kreiss, Lafaye, Plehn, Rauch, Zerwas; Les Houches 2007, Physics at TeV Colliders)

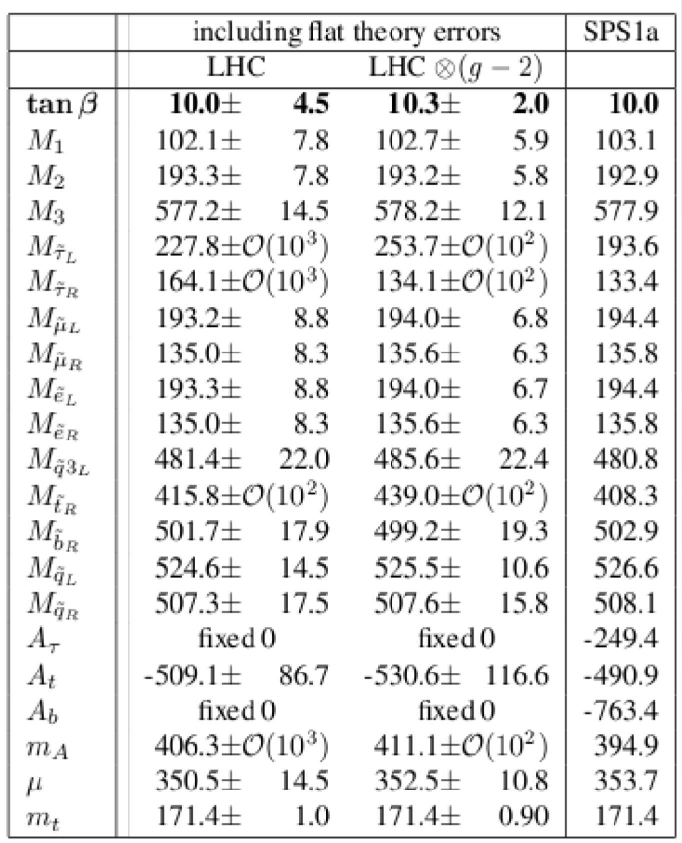
Confirmation of tanbeta measurement by comprehensive global fit.

Improvement of tanbeta-error with current g-2:

4.5 -> 2.0

estimated improvement with future g-2:

4.5 -> 1.0



	including flat theory errors		SPS1a
	LHC	LHC $\otimes (g-2)$	
$\tan\beta$	**10.0± 4.5**	**10.3± 2.0**	**10.0**
M_1	102.1± 7.8	102.7± 5.9	103.1
M_2	193.3± 7.8	193.2± 5.8	192.9
M_3	577.2± 14.5	578.2± 12.1	577.9
$M_{\tilde{\tau}_L}$	$227.8 \pm \mathcal{O}(10^3)$	$253.7 \pm \mathcal{O}(10^2)$	193.6
$M_{\tilde{\tau}_R}$	$164.1 \pm \mathcal{O}(10^3)$	$134.1 \pm \mathcal{O}(10^2)$	133.4
$M_{\tilde{\mu}_L}$	193.2± 8.8	194.0± 6.8	194.4
$M_{\tilde{\mu}_R}$	135.0± 8.3	135.6± 6.3	135.8
$M_{\tilde{e}_L}$	193.3± 8.8	194.0± 6.7	194.4
$M_{\tilde{e}_R}$	135.0± 8.3	135.6± 6.3	135.8
$M_{\tilde{q}3_L}$	481.4± 22.0	485.6± 22.4	480.8
$M_{\tilde{t}_R}$	$415.8 \pm \mathcal{O}(10^2)$	$439.0 \pm \mathcal{O}(10^2)$	408.3
$M_{\tilde{b}_R}$	501.7± 17.9	499.2± 19.3	502.9
$M_{\tilde{q}_L}$	524.6± 14.5	525.5± 10.6	526.6
$M_{\tilde{q}_R}$	507.3± 17.5	507.6± 15.8	508.1
A_τ	fixed 0	fixed 0	-249.4
A_t	-509.1± 86.7	-530.6± 116.6	-490.9
A_b	fixed 0	fixed 0	-763.4
m_A	$406.3 \pm \mathcal{O}(10^3)$	$411.1 \pm \mathcal{O}(10^2)$	394.9
μ	350.5± 14.5	352.5± 10.8	353.7
m_t	171.4± 1.0	171.4± 0.90	171.4

Result for the general MSSM parameter determination at the LHC in SPS1a. Flat theory errors (non-gaussian) are assumed. The fit is done with and without inclusion of the current measurement of g-2.

With g-2, many are improved, some significantly

SPS points and slopes

Back

- SPS 1a: ``Typical '' mSUGRA point with intermediate value of tan_beta.
- SPS 1b: ``Typical '' mSUGRA point with relatively high tan_beta; tau-rich neutralino and chargino decays.
- SPS 2: ``Focus point '' scenario in mSUGRA; relatively heavy squarks and sleptons, charginos and neutralinos are fairly light; the gluino is lighter than the squarks
- SPS 3: mSUGRA scenario with model line into ``co-annihilation region''; very small slepton-neutralino mass difference
- SPS 4: mSUGRA scenario with large tan_beta; the couplings of A, H to b quarks and taus as well as the coupling of the charged Higgs to top and bottom are significantly enhanced in this scenario, resulting in particular in large associated production cross sections for the heavy Higgs bosons
- SPS 5: mSUGRA scenario with relatively light scalar top quark; relatively low tan_beta
- SPS 6: mSUGRA-like scenario with non-unified gaugino masses
- SPS 7: GMSB scenario with stau NLSP
- SPS 8: GMSB scenario with neutralino NLSP
- SPS 9: AMSB scenario

SPS PLOT

www.ippp.dur.ac.uk/~georg/sps/sps.html

Present nEDM experiments

Back

- Cryo-EDM

ILL KURE University of Sussex Science & Technology Facilities Council UNIVERSITY OF OXFORD
CryoEDM

  - on the floor at ILL, de-bugging the experiment
- Serebov et al., (ILL, Grenoble)

nEDM collaboration

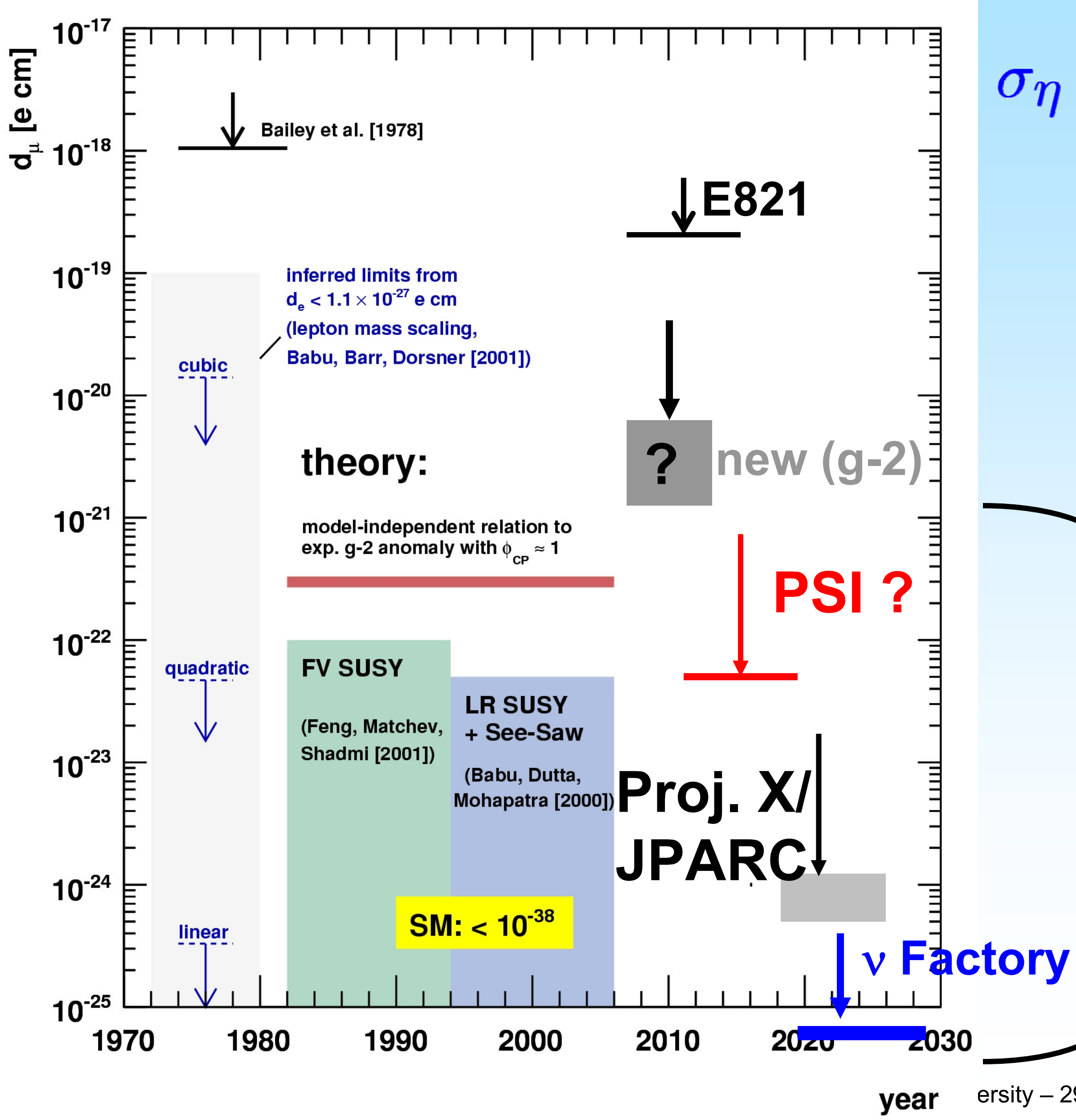
  - on the floor at ILL
- Paul Scherrer Institut, UCN Source
  - Source being developed. Will use previous Sussex-RAL apparatus in phase 1, new apparatus in phase 2.

nEDM

- SNS nEDM collaboration
  - has CD1, CD2 review in late 2009

Muon EDM Limits: Present and Future

Back



$$\sigma_\eta = \frac{\sqrt{2}}{\gamma\tau(e/m)\beta B A\sqrt{N}}$$

Need:

$NA^2 = 10^{16}$ for

$d_\mu \simeq 10^{-23}\ e\cdot$cm

Dedicated storage rings

PSI muon EDM storage ring

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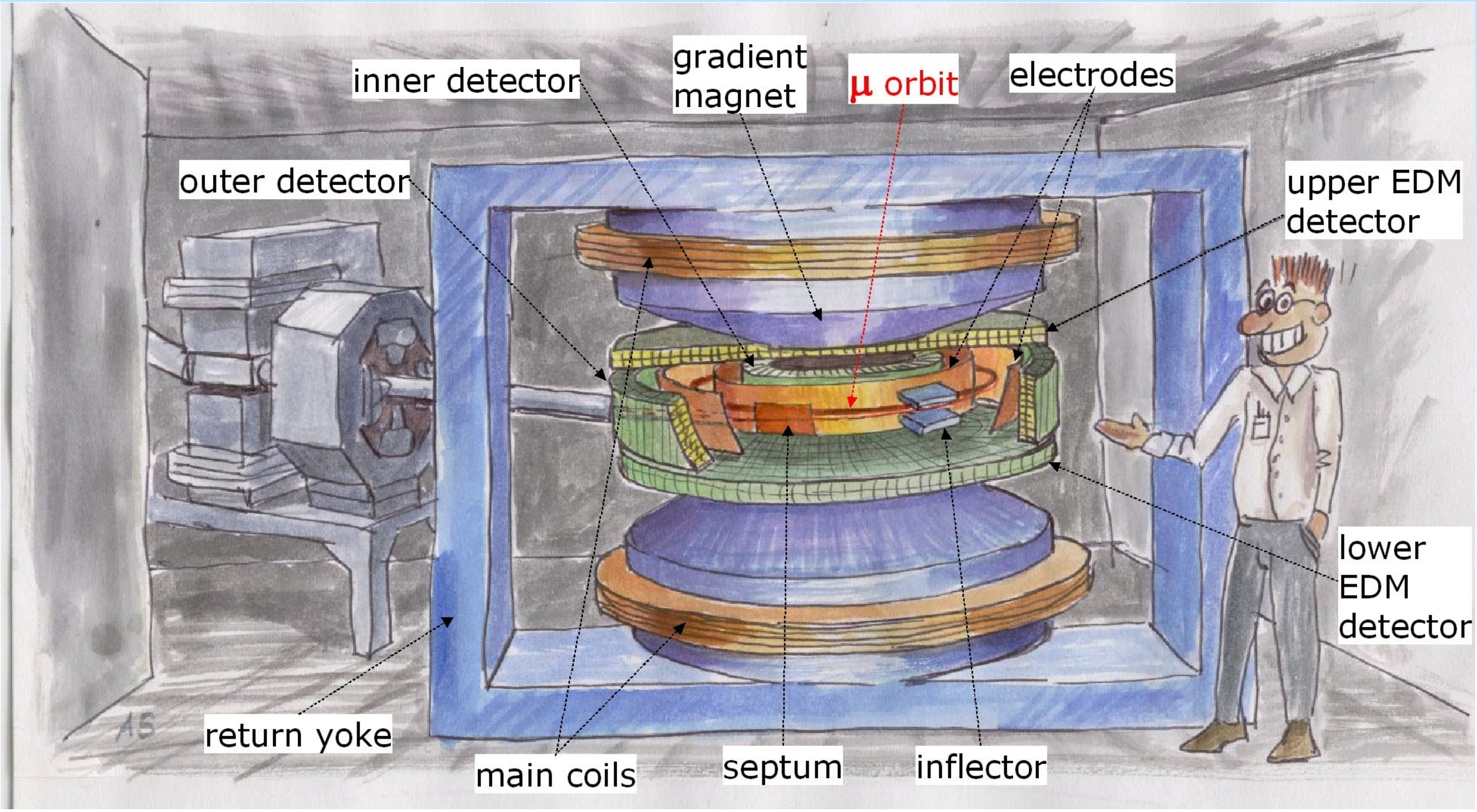


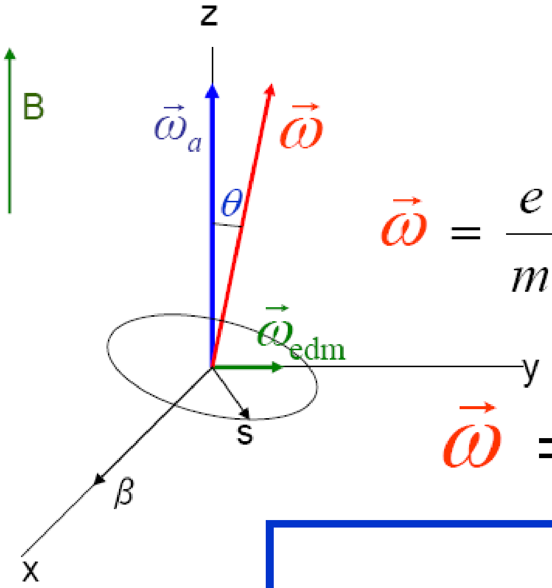
by A. Streun

Parasitic Muon EDM Measurement using straw tube arrays

from E821 $d_\mu < 1.8 \times 10^{-19}\, e\,\mathrm{cm} \rightarrow \sim \text{few}\ 10^{-21}$

Back

arXiv:0811.1207v1



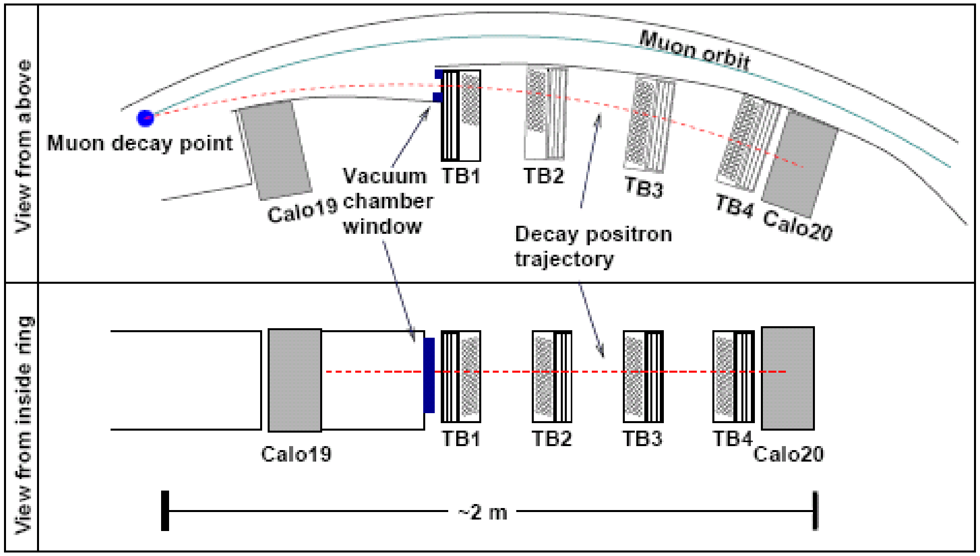
$$\vec\omega = \frac{e}{m}\left\{a\vec B + \frac{\eta}{2}\left(\vec\beta\times\vec B\right)\right\}$$

$$\vec\omega = \vec\omega_a + \vec\omega_{\mathrm{edm}}$$

$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$

The EDM tips the precession plane, producing an up-down oscillation with time (out of phase with ω_a)

E821 straw-tube array



Measure upward-going vs. downward-going decay electrons vs. time with straw tube arrays

E821 Data: $^{\text{up-going}}/_{\text{down-going}}$ tracks vs. time, (modulo the g-2 frequency):

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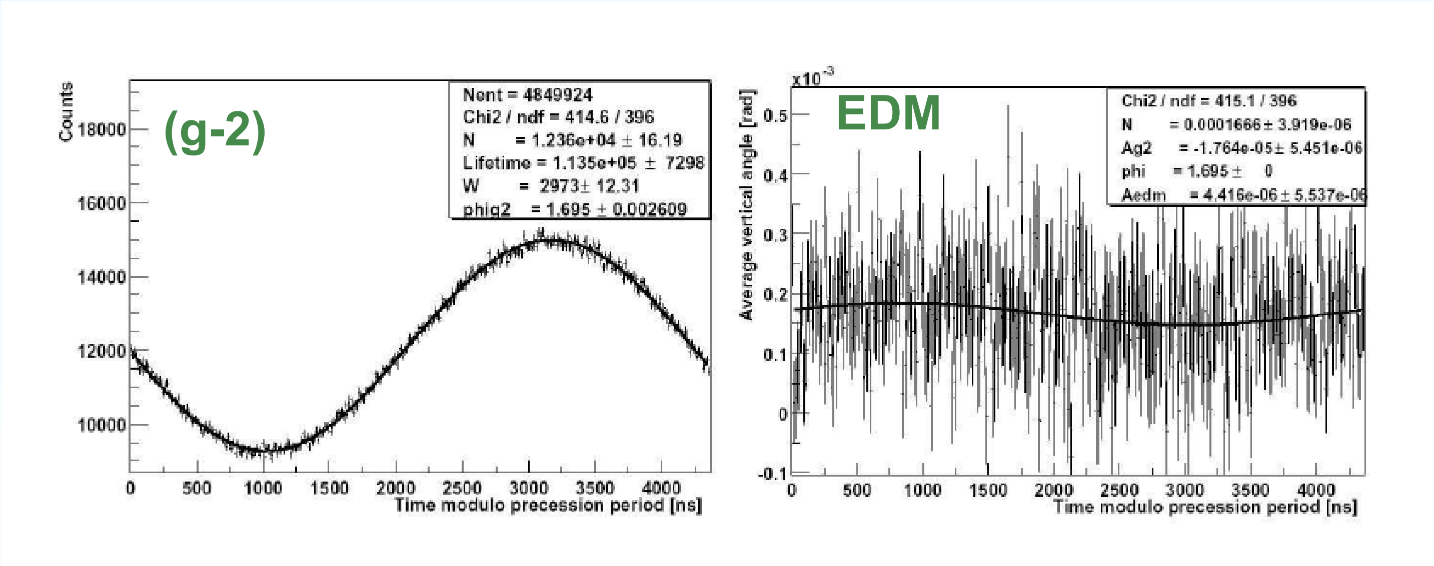


(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

EDM Signal: Average vertical angle modulo g-2 period. Out-of-phase by 90° from g-2; this is the EDM signal

- BNL traceback measurement was entirely statistics limited
  - – 1 station
  - – Late turn-on time
  - – Small acceptance
  - – Ran 2 out of 3 years

Status of the $\mu \rightarrow e$ experiments

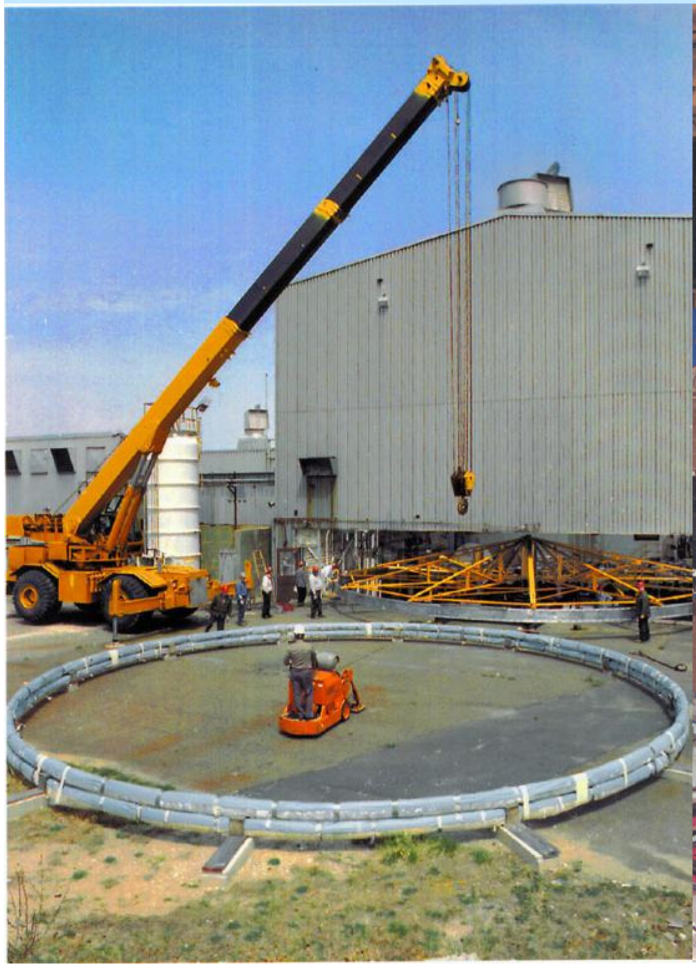
Back

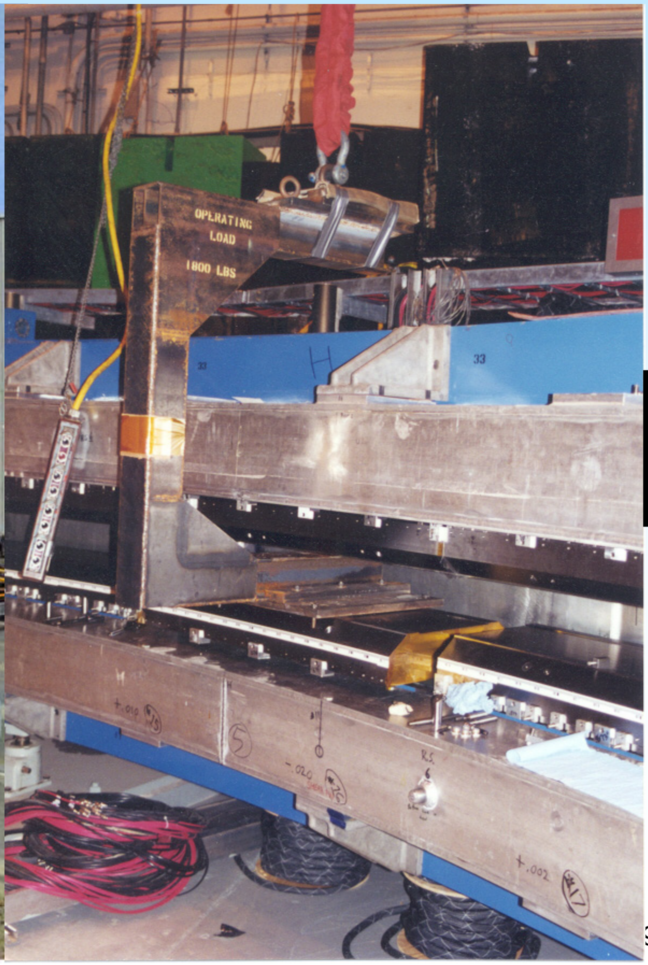
- Mu2e at Fermilab
  - Stage 1 approval from the PAC
  - CD0 expected soon
  - much work on design, simulations etc. underway
- COMET   PRISM/PRIME at J-PARC
  - under consideration by the PAC, many studies underway

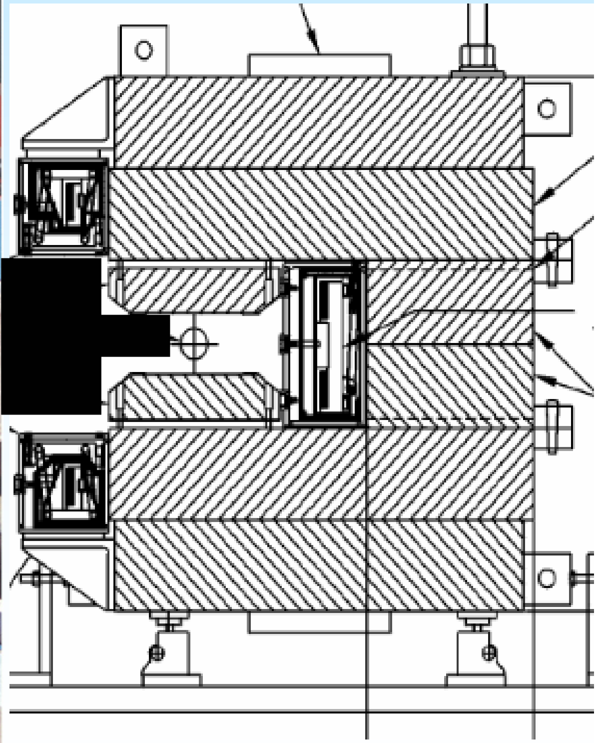
Ring relocation to Fermilab

Back

- Heavy-lift helicopters bring coils to a barge
- Rest of magnet is a “kit” that can be trucked to and from the barge

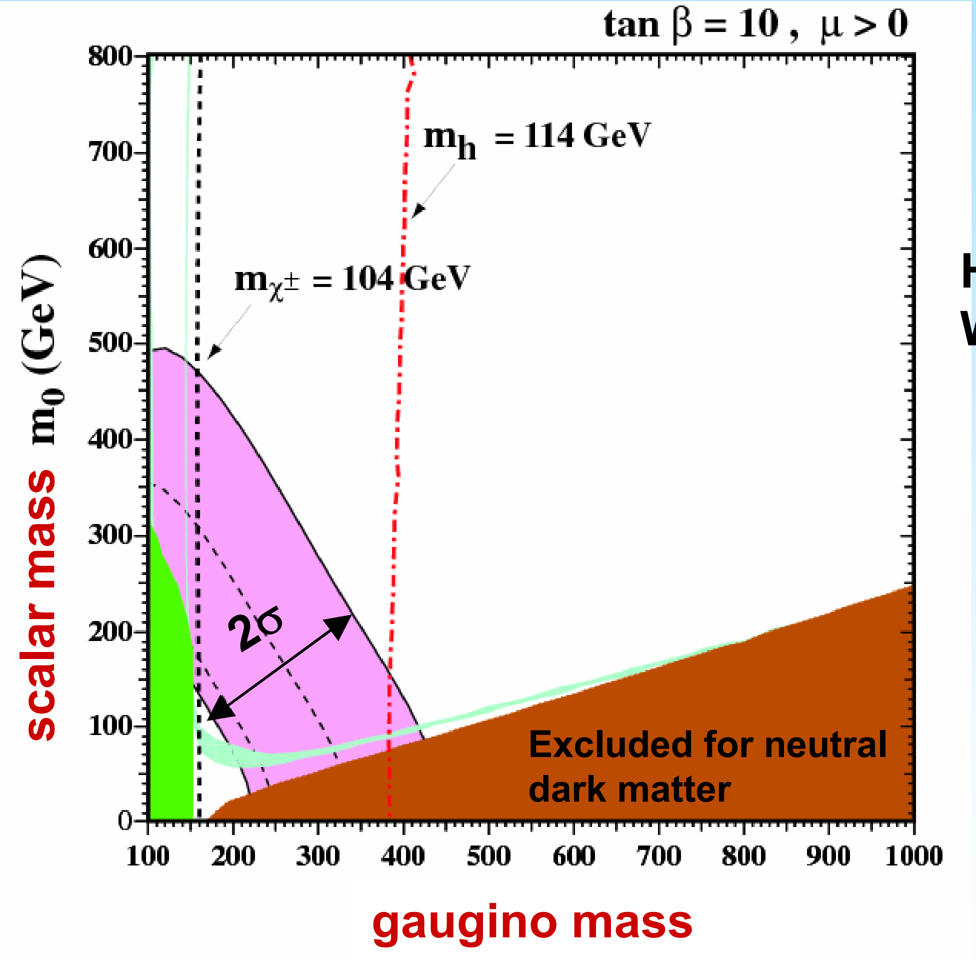






Typical CMSSM 2D space showing g-2 effect (note: NOT an exclusion plot)

Back



Present:
$\Delta a_\mu = 295 \pm 88 \times 10^{-11}$

Here, neutralino accounts for the WMAP implied dark matter density

courtesy Keith Olive

Typical CMSSM 2D space showing g-2 effect (note: NOT an exclusion plot)

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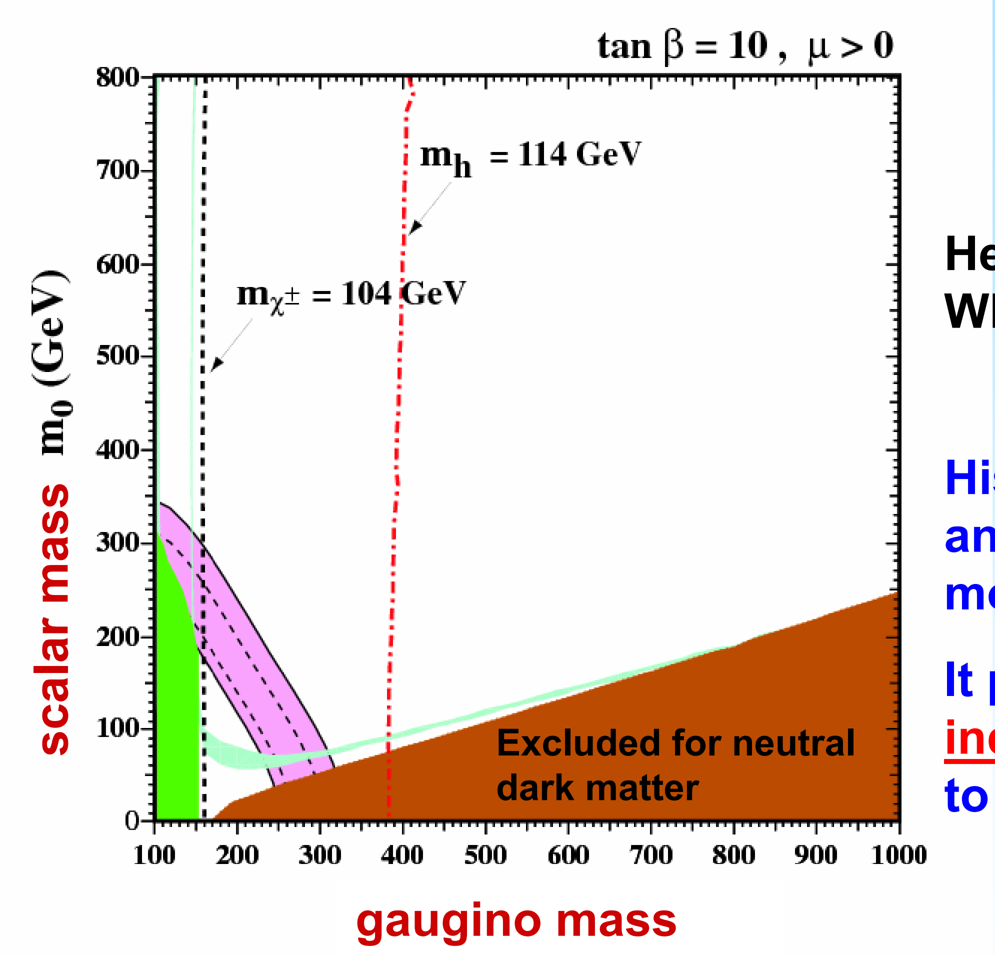


Future
$\Delta a_\mu = 295 \pm 34 \times 10^{-11}$

Here, neutralino accounts for the WMAP implied dark matter density

Historically muon (g-2) has played an important role in restricting models of new physics.

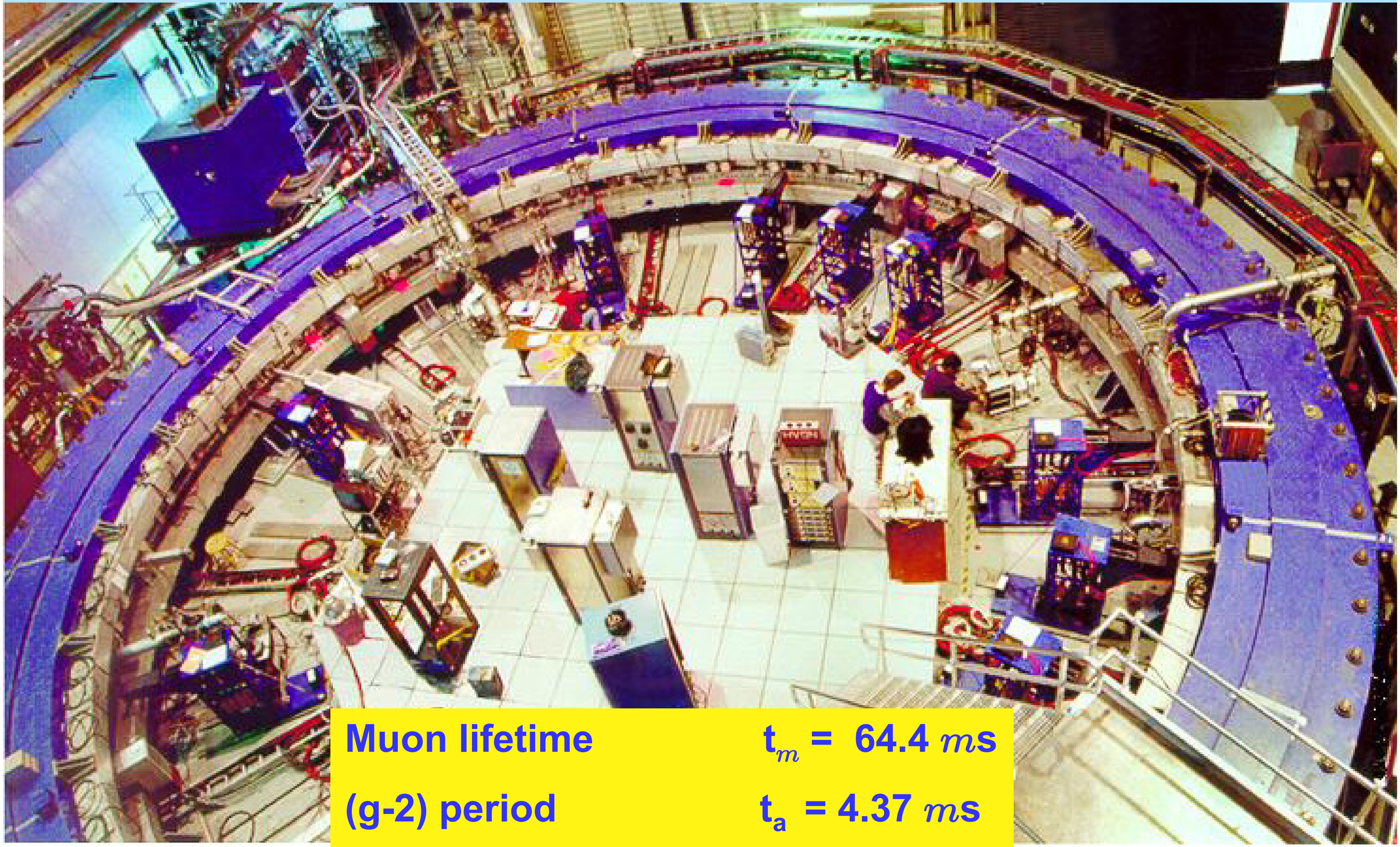
It provides constraints that are independent and complementary to high-energy experiments.

With new experimental and theoretical precision and same Δa_μ

courtesy Keith Olive

Thank you,
THE END

muon (g-2) storage ring



Muon lifetime	t_{m} = 64.4 ms
(g-2) period	t_a = 4.37 ms
Cyclotron period	t_C = 149 ns