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

- search for electric dipole moments
- charged lepton flavor violation
  - (e.g. $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$)
- muon (g-2)

- double β decay with no ν
- Møller scattering
- neutron β decay
- muon decay
- rare kaon decays
- dark matter searches

Charged Lepton Flavor Violation

Generations of leptons

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \qquad \begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix} \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix} \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$

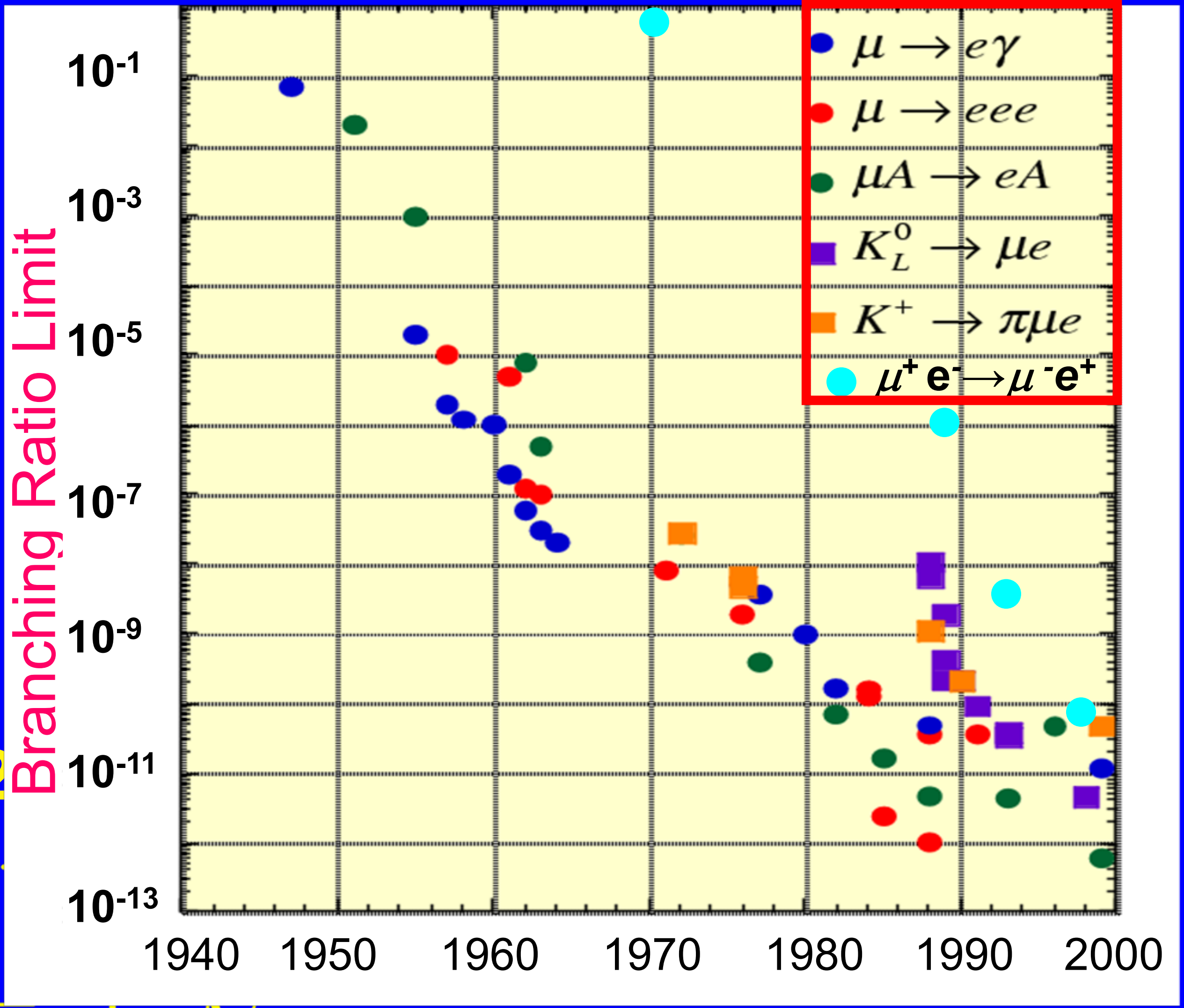
$l_e=+1$ $\quad l_\mu=+1$ $\quad l_\tau=+1$ $\qquad l_e=-1$ $\quad l_\mu=-1$ $\quad l_\tau=-1$

Lepton-flavor conserving: $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,\quad \pi^+ \to e^+ + \nu_e$

Lepton-flavor violating: neutrino oscillations, $\mu^+ \to e^+\gamma,\quad \mu^- + N \to e^- + N$

Lepton-number violating: double beta decay, $\mu^- + N \to e^+ + N'$

Charged Lepton Flavor (μ) Violation



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

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

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

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

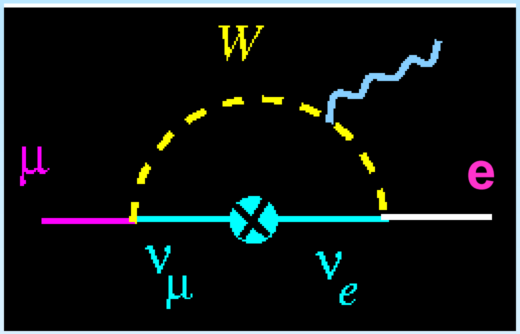
mono-energetic electron

Also $\tau \to \mu\gamma$...

CLFV in the muon sector

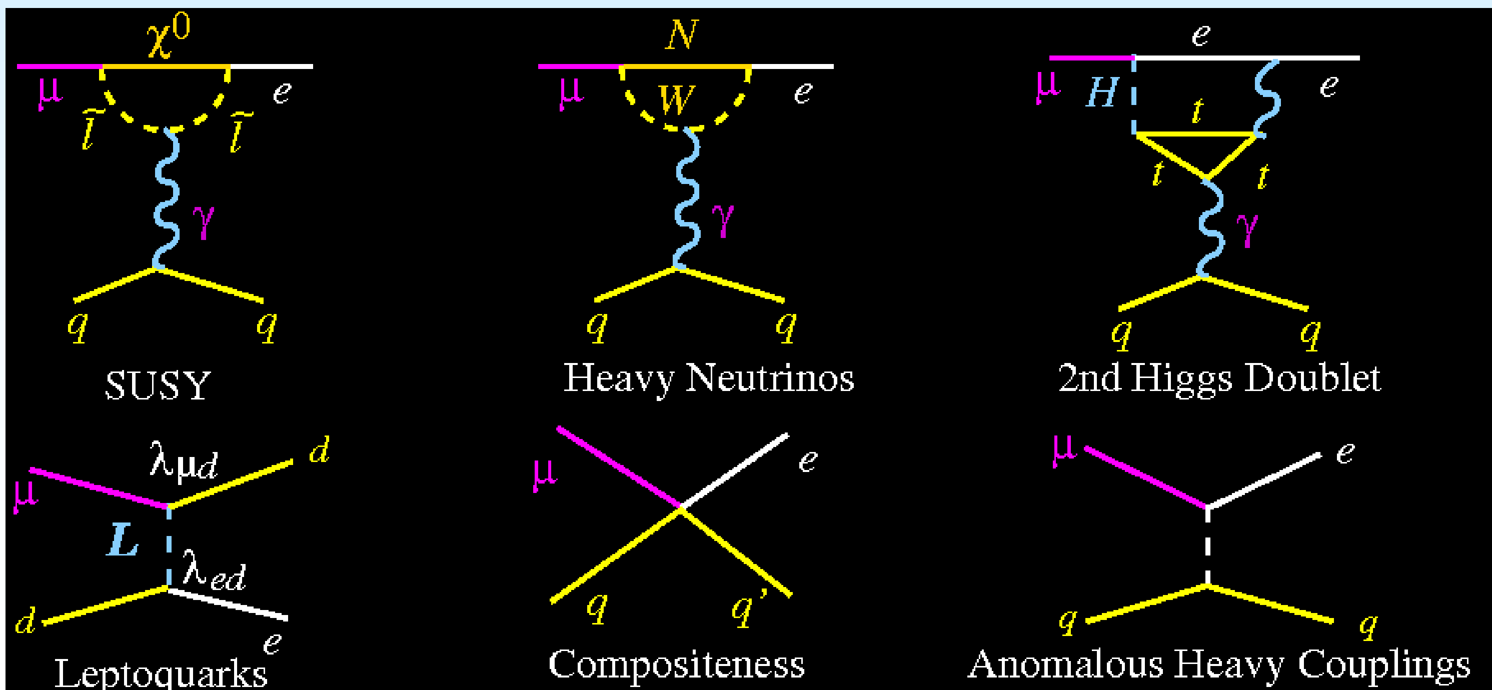
$$\mu^+ \to e^+\gamma; \;\; \mu^- + \mathcal{N} \to e^- + \mathcal{N}$$

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



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What is μe Conversion?

A muon converts to an electron in the field of a nucleus, with *no neutrinos produced*. The nucleus needs to be there to conserve energy and momentum!

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

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

- Example of charged Lepton Flavor Violation (CLFV)
- Related Processes:
  - $\mu \rightarrow e\gamma$, $\tau \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$, $\mu \rightarrow e^+e^-e$, $\tau \rightarrow e^+e^-e$, $\tau \rightarrow \mu^+\mu^-\mu$

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Muon to Electron Conversion

Current limits: $R_{\mu e} = \dfrac{\mu^- Au \rightarrow e^- Au}{\mu^- Au \rightarrow \text{capture}} < 7\text{x}10^{-13}$ (SINDRUM II)

Also: $R_{\mu e} = \dfrac{\mu^- Ti \rightarrow e^- Ti}{\mu^- Ti \rightarrow \text{capture}} < 4.3\text{x}10^{-12}$ (SINDRUM II)

$R_{\mu e} = \dfrac{\mu^- Ti \rightarrow e^- Ti}{\mu^- Ti \rightarrow \text{capture}} < 4.6\text{x}10^{-12}$ (TRIUMF)

New Mu2e proposal at FNAL: $R_{\mu e} = \dfrac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow \text{capture}} < 6\text{x}10^{-17}$ (90% c.l.)

x10000 improvement over current limit

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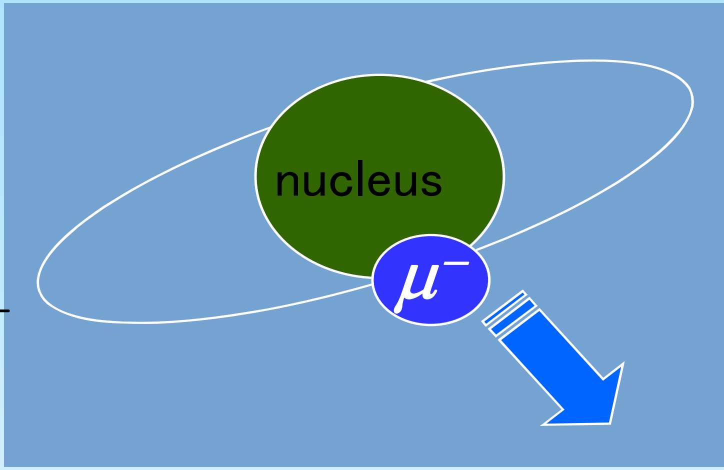
The Measurement Method in a Nutshell



- Stop negative muons in an aluminum target
- The stopped muons form muonic atoms
  - hydrogenic 1S level in aluminum nucleus
  - Bohr radius ~20 fm, Binding E~500 keV

$$r \propto \frac{n^2}{m_l Z}, \quad E \propto -\frac{m_l Z^2}{n^2}$$

  - Nuclear radius ~ 4 fm

    muon and nuclear wavefunctions overlap
  - Muon lifetime in 1S orbit of aluminum ~864 ns compared to 2.2 μsec in vacuum

  40% decay, $\mu^- + A(N,Z) \rightarrow A(N,Z) + e^- + \nu_\mu + \bar{\nu}_e$

  60% nuclear capture, $\mu^- + A(N,Z) \rightarrow X(N+1, Z-1) + \nu_\mu \quad (\mu^- + p \rightarrow \nu_\mu + n)$

  (capture is ~ sum of reactions over protons in nucleus)
- Look for a monoenenergetic electron from the neutrinoless conversion of a muon to an electron, leaving the nucleus in the ground state:

$$\mu^- + {}^{27}_{13}Al \rightarrow {}^{27}_{13}Al + e^- \qquad \text{Electron energy} \sim 105 \text{ MeV}$$

- Measured quantity: the ratio $R_{\mu e}$:

$$R_{\mu e} = \frac{\mu^- + {}^{27}_{13}Al \rightarrow {}^{27}_{13}Al + e^-}{\mu^- + {}^{27}_{13}Al \rightarrow X + \nu_\mu (capture)}, \text{ where X=A'(N,Z)+neutrons, protons,...}$$

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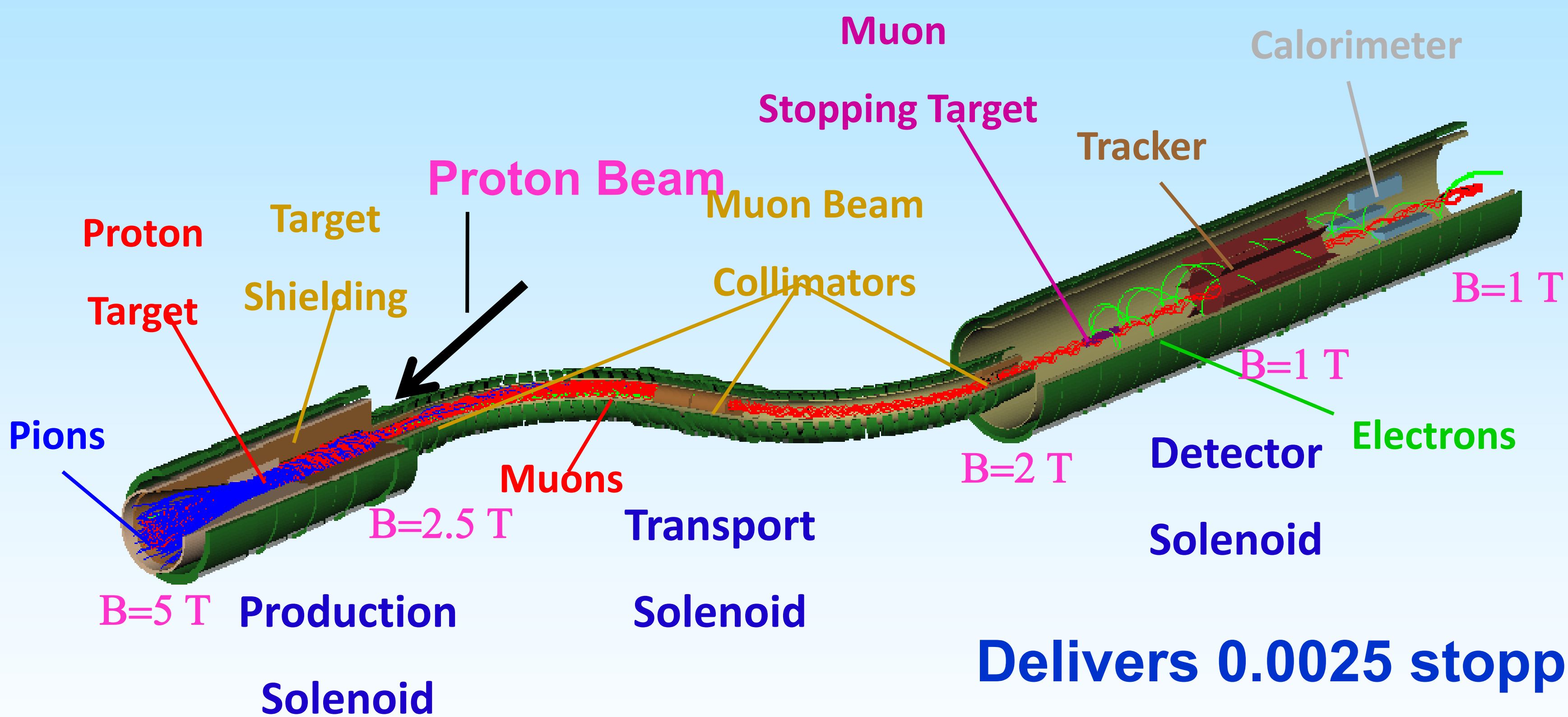
Proposed Mu2e Muon Beamline

Muons are collected, transported, and

detected in superconducting solenoidal magnets



Delivers 0.0025 stopped muons per 8 GeV proton

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Production Solenoid

Magnetic

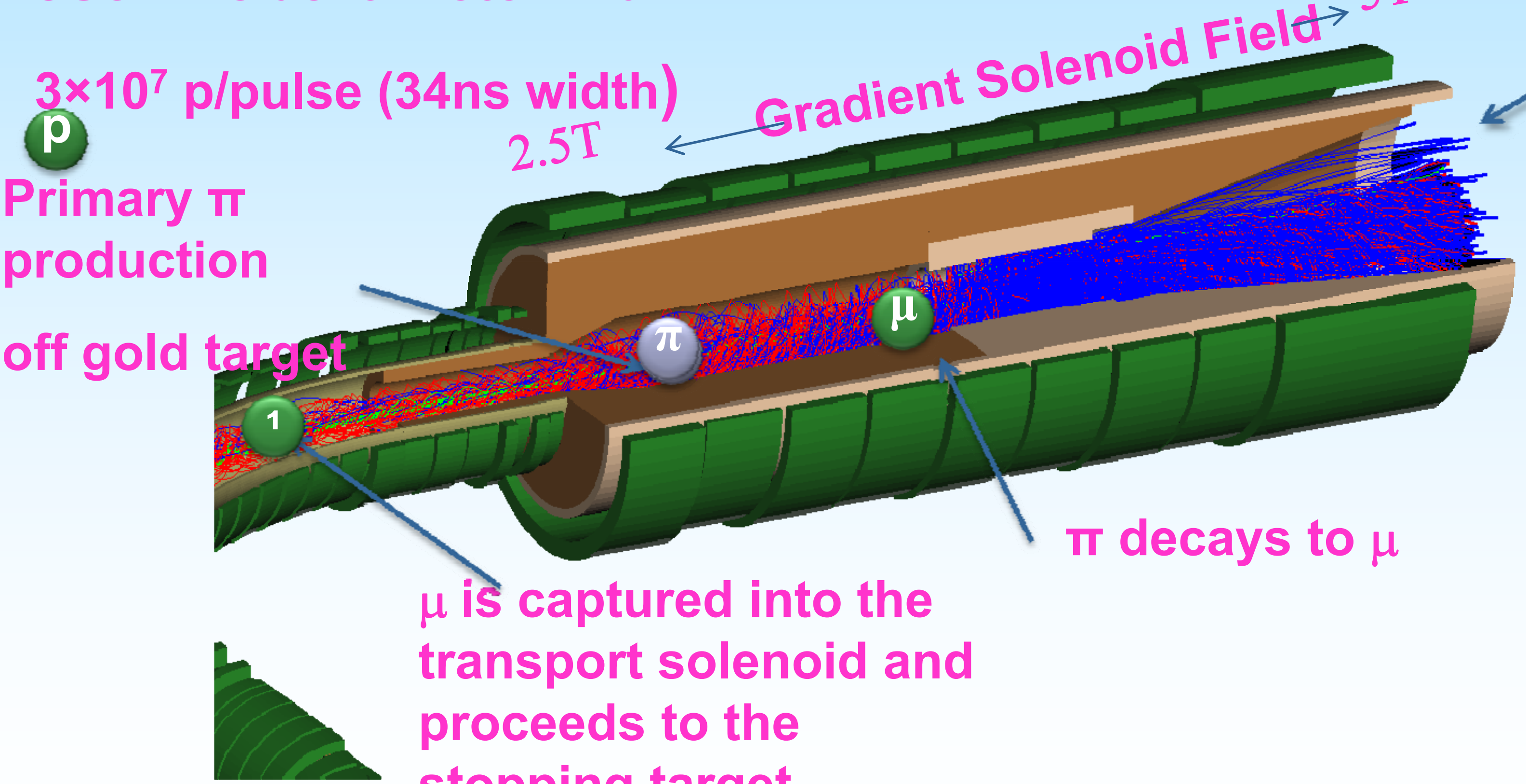
Mirror Effect

8GeV Incident Proton Flux

3×10^7 p/pulse (34ns width)

Primary π production

off gold target



π decays to μ

μ is captured into the transport solenoid and proceeds to the stopping target

Motion in a Solenoid with a Gradient Field

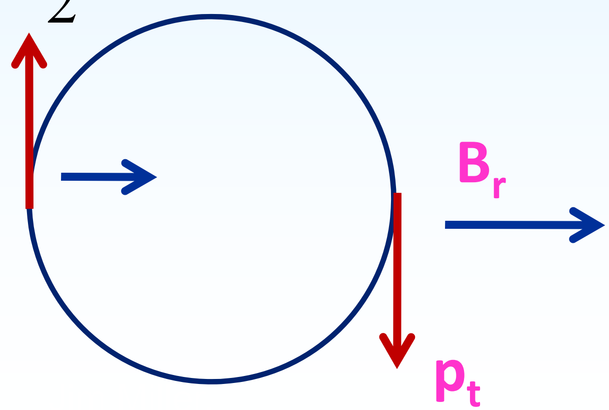
- In a magnetic field, low momentum charged particles tend to follow helical paths along the field lines.
- The magnetic moment of the particle associated with the helical motion is approximately constant. For a relativistic particle, p_t^2/B=constant,

$$\rightarrow \ p_t \propto \sqrt{B} \ \rightarrow \ p_t = p_{t0}\sqrt{B/B_0}, \quad p_l = \sqrt{p^2 - p_{t0}^2 B/B_0}$$

  - *p_l is continuously increasing in the direction of decreasing field*
    - Particle pitch increases when spiraling to lower field: p_t decreases and p_l increases.
    - Particle pitch decreases when spiraling to higher field: p_t increases and $|p_l|$ decreases.
  - **Particles are 'pushed' in the direction of lower field**

$$B_z = B_0 - |G_z| z \qquad B_r = \frac{1}{2}|G_z| r$$

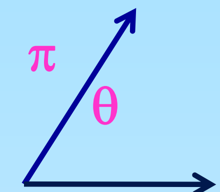
Note that *net* $q\mathbf{p}_t x \mathbf{B}_r$ points downstream regardless of q (if q flips sign, p_t reverses direction)



(B_z points out of page. Field decreases moving out of page, G_z <0.)

Magnetic Mirror

- If a particle spirals in the direction of higher field, p_t increases and $|p_l|$ decreases:



Solenoid axis

(~+B or ~-B)

$$p_t = p_{t0}\sqrt{B/B_0}, \quad p_l = \sqrt{p^2 - p_{t0}^2 B/B_0}$$

$$\sin\theta_{min} \equiv p_{t0}/p = \sqrt{B_0/B_{max}} \approx \sqrt{3.5/5} = 0.84$$

- $\rightarrow \theta < 123^0 \rightarrow$ Increases downstream flux of muons

•For a particle born in the middle of the PS, where B~3.5 T, the maximum pitch which can be reflected in the maximum 5T fIf the field becomes large enough, $p_t \rightarrow p, p_l \rightarrow 0$

and the particle is reflected, spiraling back toward lower field

If a particle is born near the target where B~3.5 T, then the *maximum* q (corresponding to minimum pitch) at the downstream end of the PS, where B=2.5 T, will be about 60^{0}.

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Transport Solenoid

Inner bore radius=25 cm

Length=13.11 m

Toroid bend radius=2.9 m

$$D = \frac{1}{2} \times \frac{q}{0.3 \times B} \times \frac{s}{R} \times p(\frac{1}{\cos\theta} + \cos\theta).$$

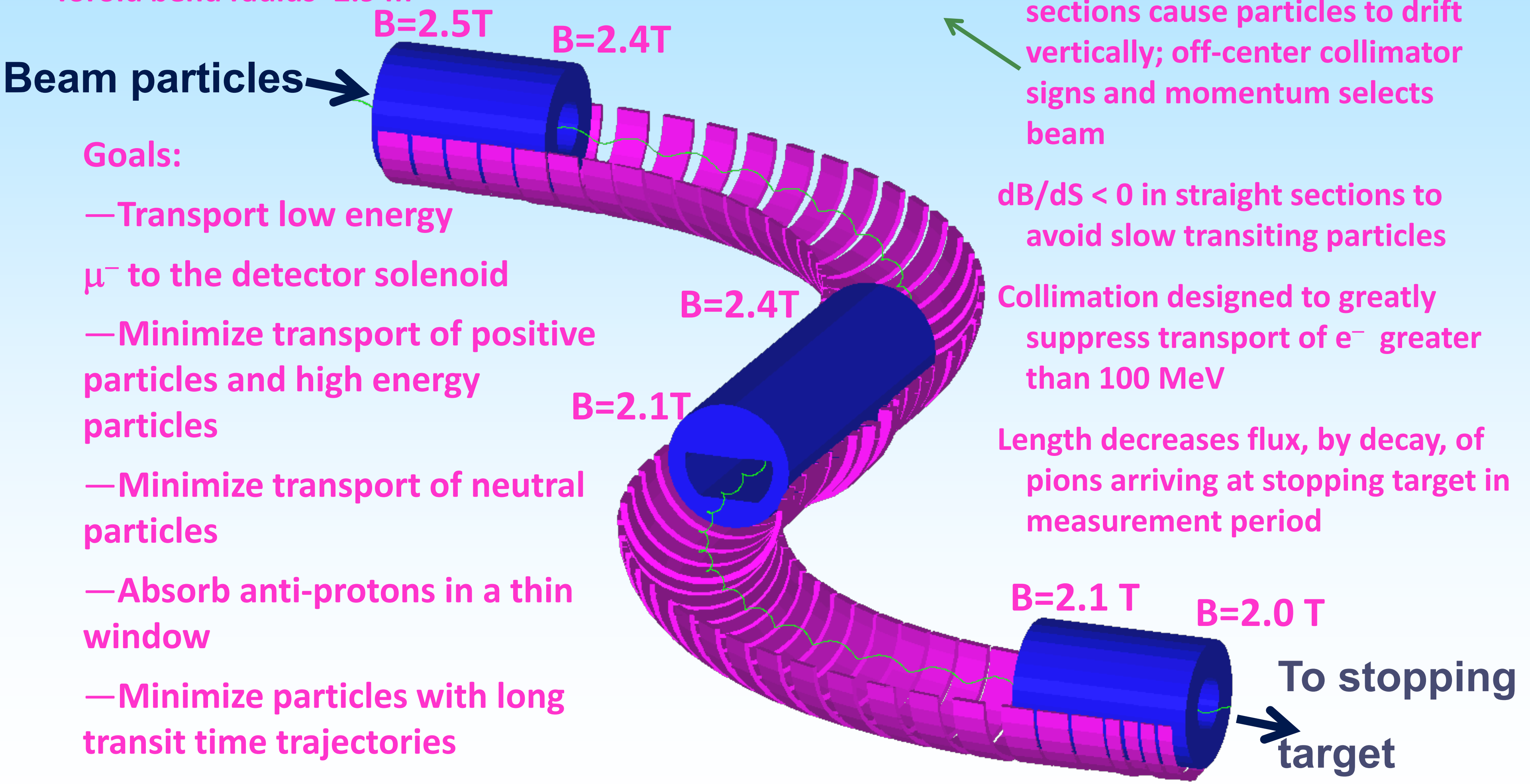
Curved sections eliminate line of sight transport of n, γ.

Radial gradients (dB_s/dR) in toroidal sections cause particles to drift vertically; off-center collimator signs and momentum selects beam

dB/dS < 0 in straight sections to avoid slow transiting particles

Collimation designed to greatly suppress transport of e^- greater than 100 MeV

Length decreases flux, by decay, of pions arriving at stopping target in measurement period



Goals:

—Transport low energy μ^- to the detector solenoid

—Minimize transport of positive particles and high energy particles

—Minimize transport of neutral particles

—Absorb anti-protons in a thin window

—Minimize particles with long transit time trajectories

Vertical Drift Motion in a Toroid

Toroidal Field: Axial field B_s=constant x 1/r. This gives a large dB_s/dr

Particle spiral drifts vertically (perpendicular to the plane of the toroid bend):

D= vertical drift distance

p_l=longitudinal momentum

p_t=transverse momentum

R=major toroid radius=2.9 m,

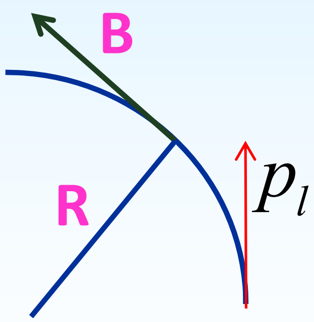
s/R = total toroid bend angle=90^0

D[m]=distance, B[T], p[GeV/c]

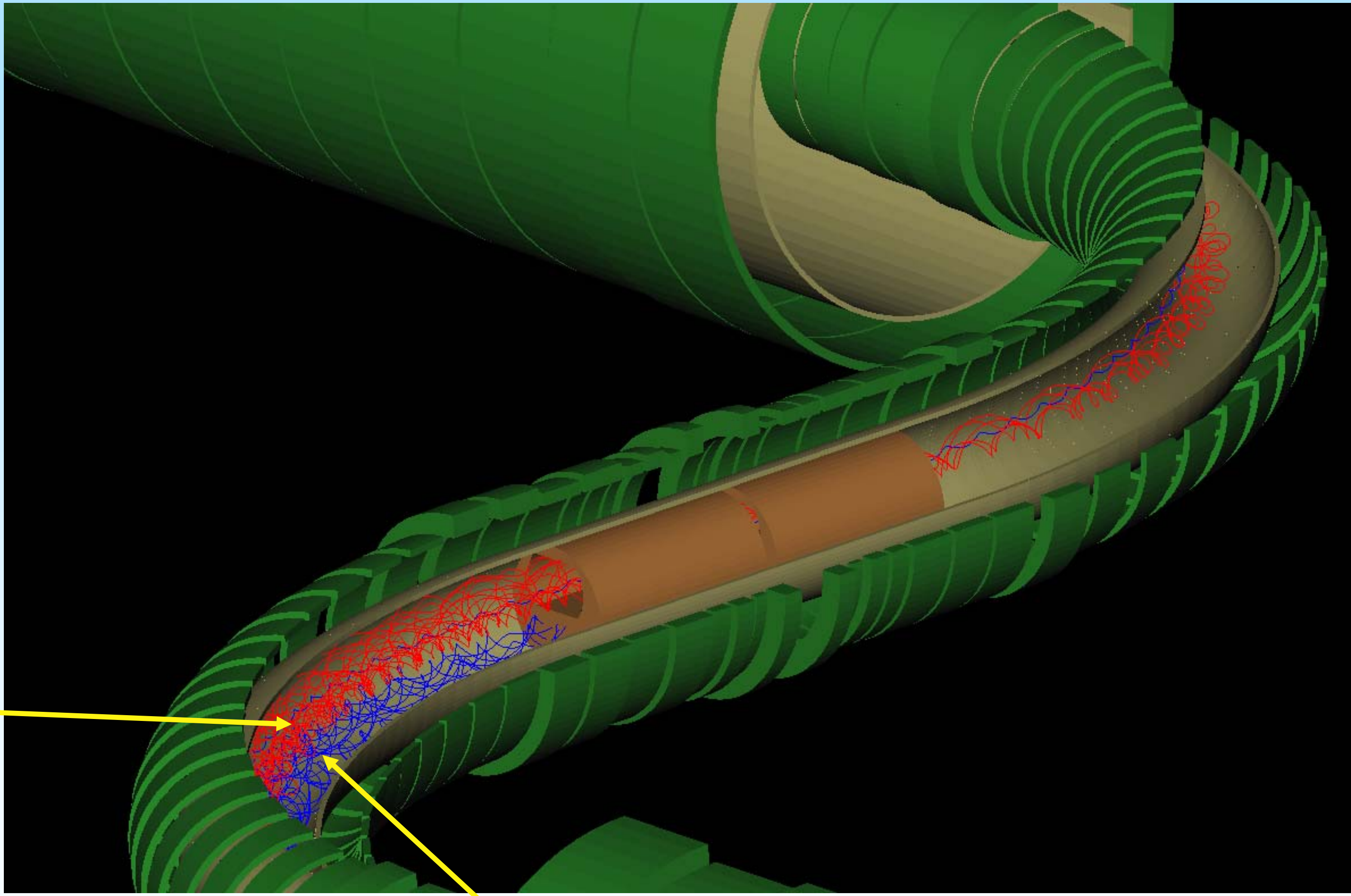
Toroid B field line

$$\text{Define} = \alpha = \frac{p_l}{p}$$

$$D = \frac{1}{2} \times \frac{q}{0.3 \times B} \times \frac{s}{R} \times p\left(\frac{1}{\alpha} + \alpha\right).$$



Separation of μ^- from μ^+



μ^-

μ^+

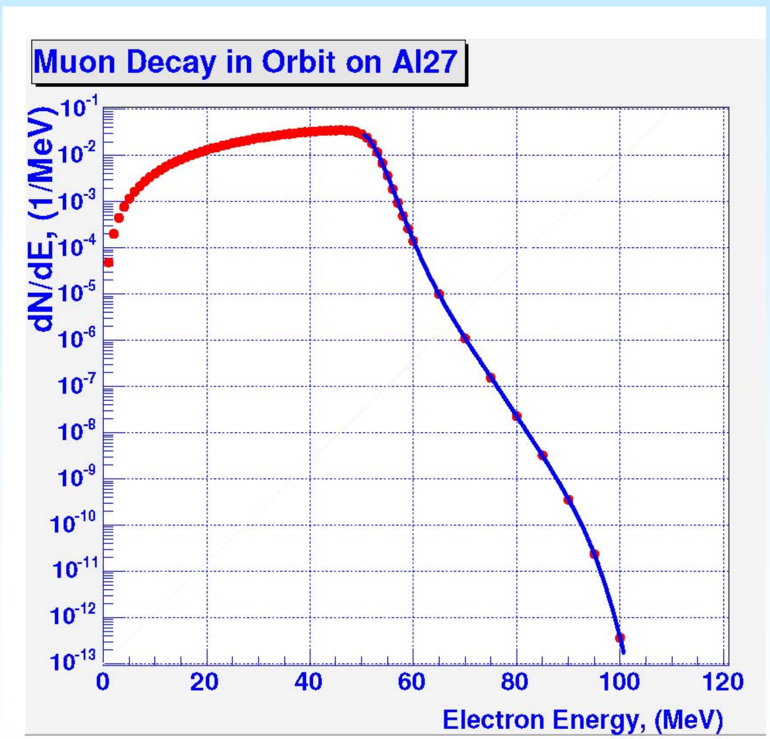
$$\text{pitch} = \frac{p_l}{p} = \cos\theta$$

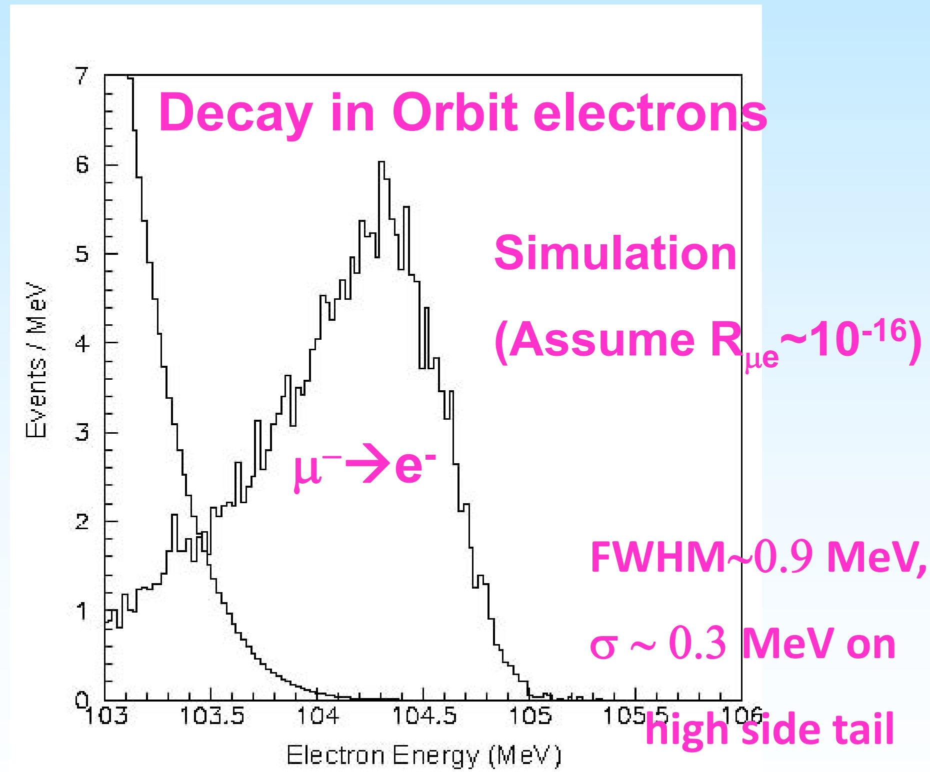
$$D = \frac{1}{2} \times \frac{q}{0.3 \times B} \times \frac{s}{R} \times p\left(\frac{1}{\cos\theta} + \cos\theta\right).$$

Backgrounds from Stopped Muons: Muon Decay in Atomic Orbit (DIO)

$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \overline{\nu}_e + \nu_\mu$$

- Conversion electrons of interest: $[\mu^- + \mathrm{Al}(13,27)]_{bound} \rightarrow \mathrm{Al}(13,27) + e^-$ (105 MeV)
- Electrons from decay of bound muons (DIO) -- kinematic endpoint equals conversion electron energy: $prob \propto (E_{endpt} - E)^5$





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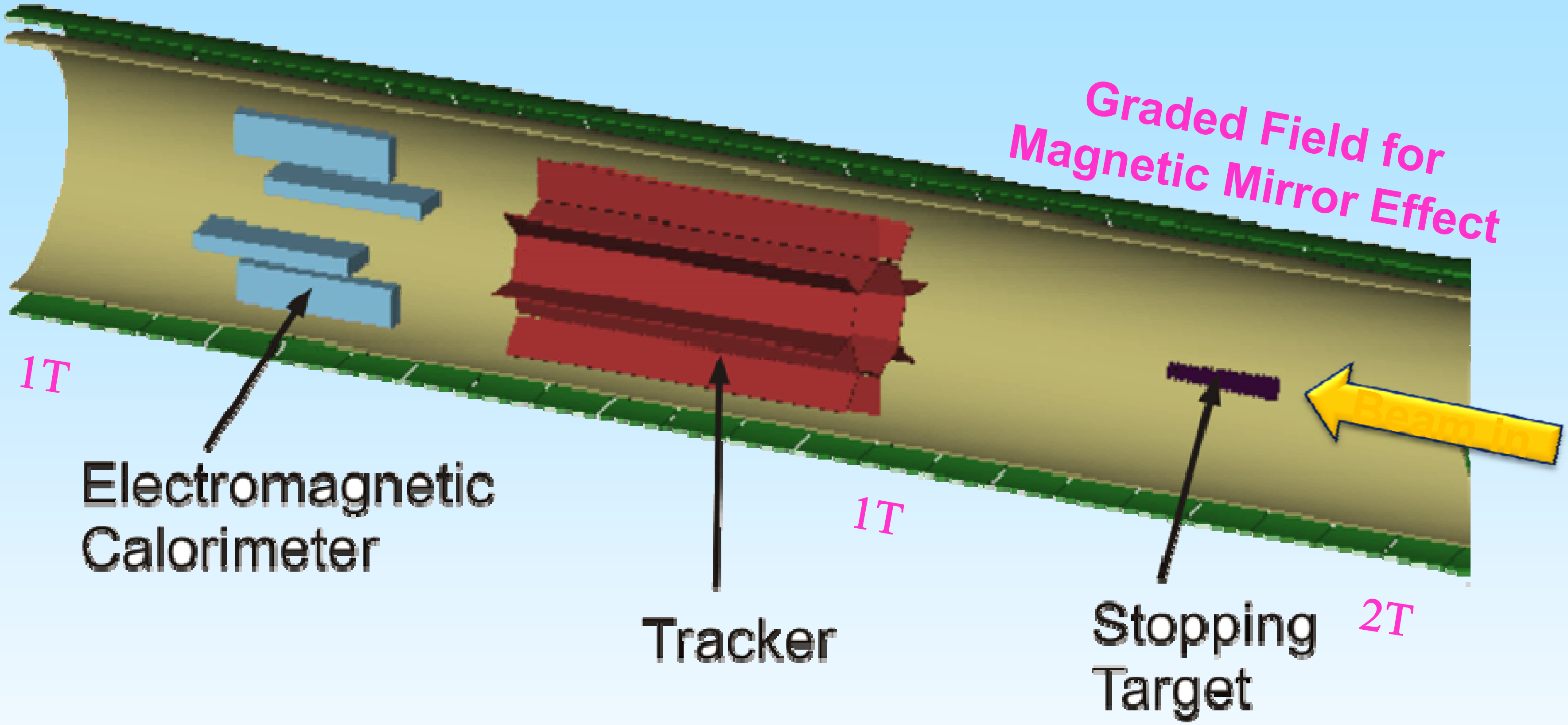
The Detector



- The detector is specifically designed to look for the helical trajectories of 105 MeV electrons
- Each component is optimized to resolve signal from the *Decay in Orbit* Backgrounds

Mu2e Schedule at FNAL

- Has Stage I approval at FNAL and strong endorsement of P5 Committee
- CD0- imminent
- CD1- next year- preliminary design and alternative technologies
- CD2- following year- money arrives for construction
- Construction until 2016 then data-taking
- Goals:

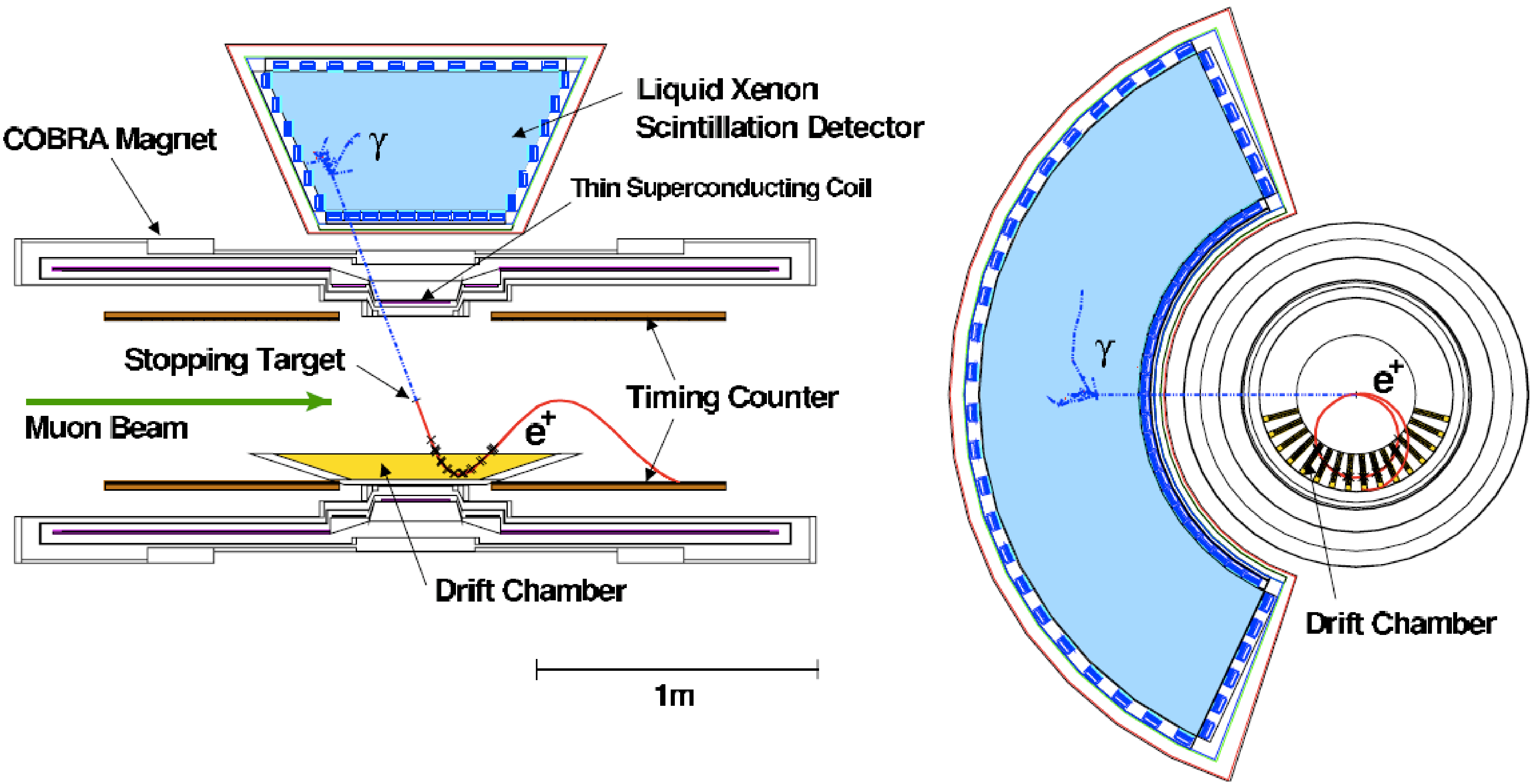
$$R_{\mu e} = \frac{Al + \mu^- \rightarrow Al + e^-}{Al + \mu^- \rightarrow N' + \nu_\mu + neutrons, protons, gammas} < 10^{-16}$$

$$R_{\mu^- e^+} = \frac{Ti + \mu^- \rightarrow Sc + e^+}{Ti + \mu^- \rightarrow N' + \nu_\mu + neutrons, protons, gammas} < 10^{-15} - 10^{-16}$$

- Factor of x10000 better than previous experiments
- Energy scales in the thousands of TeV for some processes

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

- First running is going on now



Electric Dipole Moment: ~~P~~ ~~T~~

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

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

$\vec{\mu}$, $\vec{d}$ $\parallel$ 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 ~~CP~~. Of course, we need new sources of ~~CP~~ to explain why we're here.

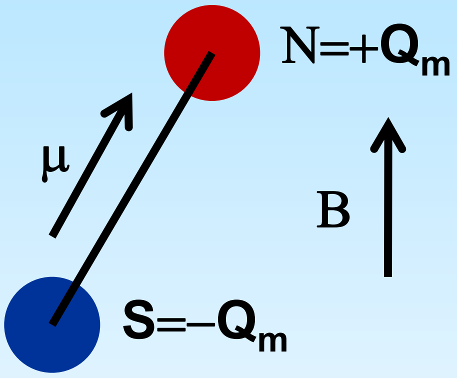
Sakharov conditions for baryogenesis:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

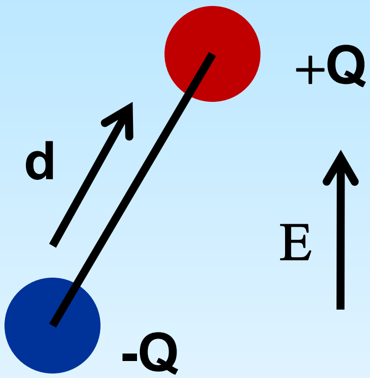
Basics of spinning particles in B and E Fields

The energy of interaction is

$$E = -\mu \bullet \mathbf{B} - \mu \bullet \mathbf{E}$$



$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}$$



$$\boldsymbol{\tau} = \mathbf{d} \times \mathbf{E}$$

For each case:

- In a uniform field, the net force is zero
- The torque tends to align the moment with the field.
- With an angular momentum directed along the moment, spin precesses like a top with precession vector directed along the field.

The present EDM limits on fundamental particles 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)

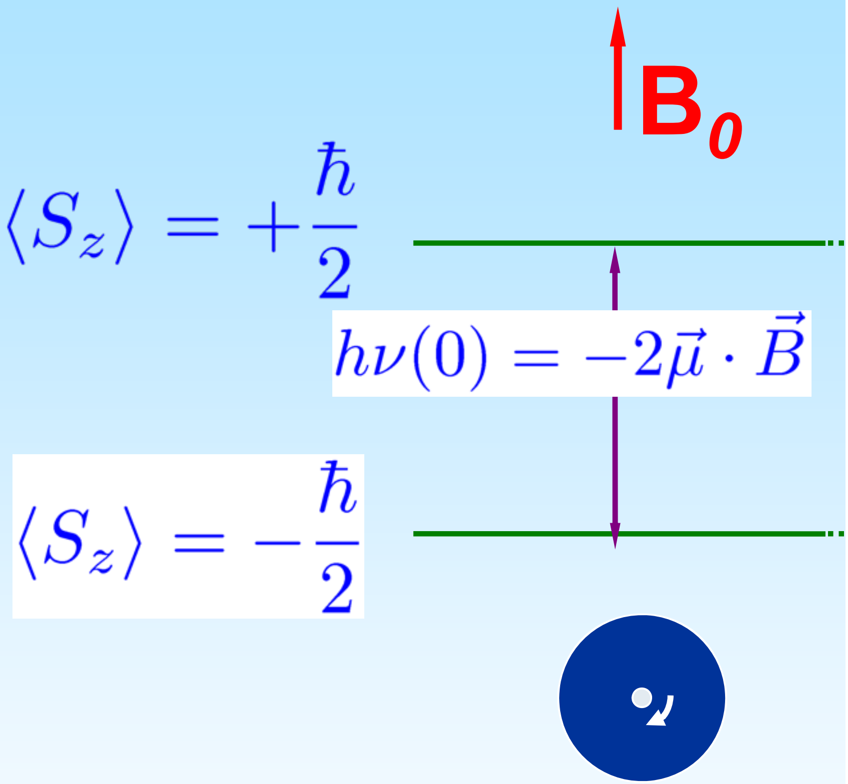
e^- PRL **88,** 071805 (2002)

μ arXiv:0811.1207v2 [hep-ex]

EDM Experiments

- The discovery of an EDM would (finally) provide evidence for non-standard model CP violation and would point toward new physics.
- 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, …
- I will focus on the proposed n EDM experiment at SNS, Oak Ridge
- How do we hold the neutrons in one place to make the measurement?

Principle of the “traditional” EDM measurements



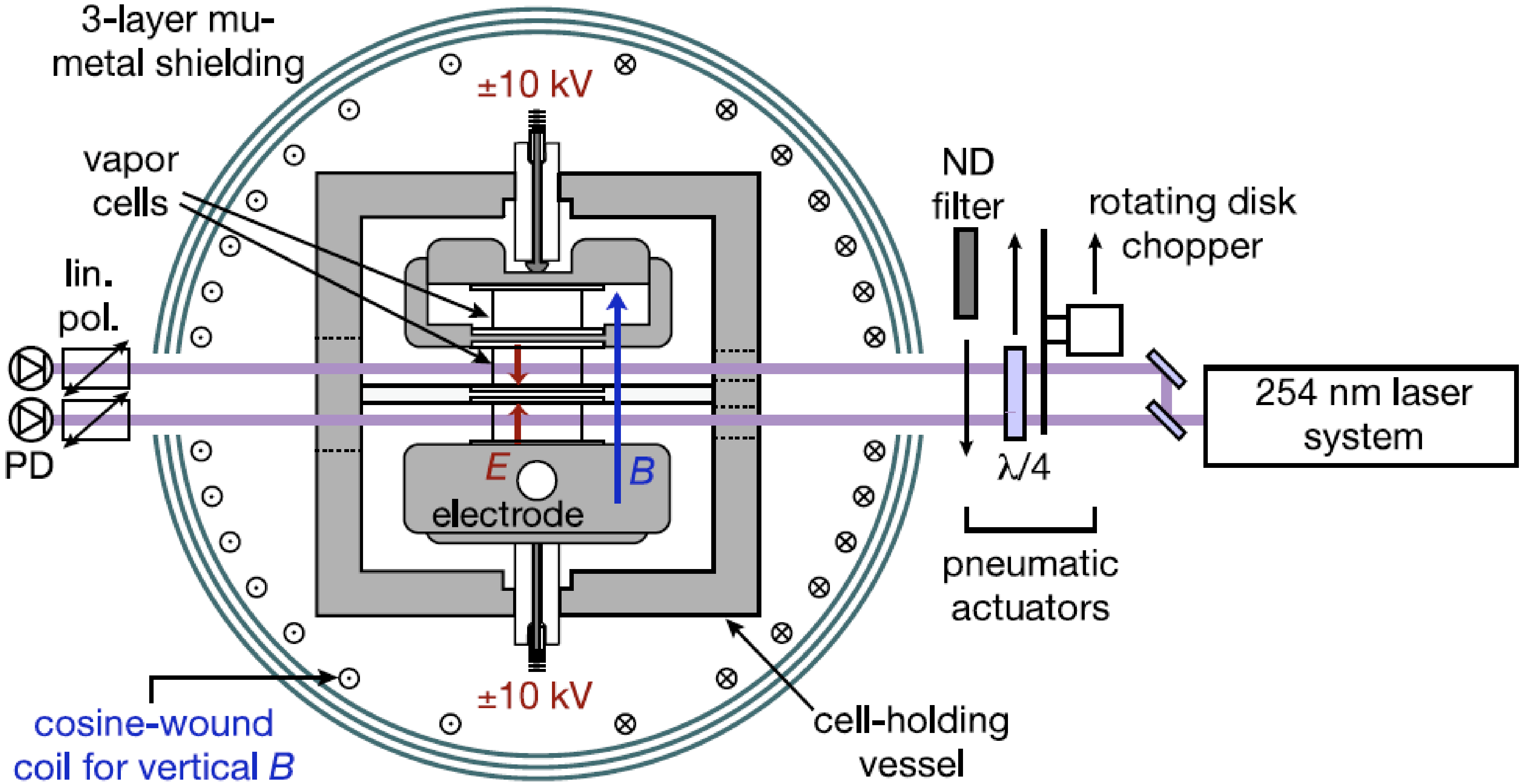
E=100kV/m

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

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

Animation by J. Karamath

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



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

Neutron EDM Experiment at Oak Ridge

ULTRACOLD NEUTRONS

Ultracold neutrons (UCN) have a low enough energy to be bottled. Their wavelength is long enough to feel a generally repulsive force (totally internally reflected) from certain materials as described by their Fermi potential. The minimum wavelength is material dependent; e.g. a good one is ^{58}Ni.

Properties:

$U_F \sim 200$ neV	$v \sim 5$ m/s	$\lambda \sim 500$ Å
$mg \sim 100$ neV/m		$\mu \sim 60$ neV/T

UCN can be bottled by
- materials
- the gravitational potential
- a gradient magnetic field

UCN can be polarized by
- magnetic fields
- gradient magnetic fields
- ^3He

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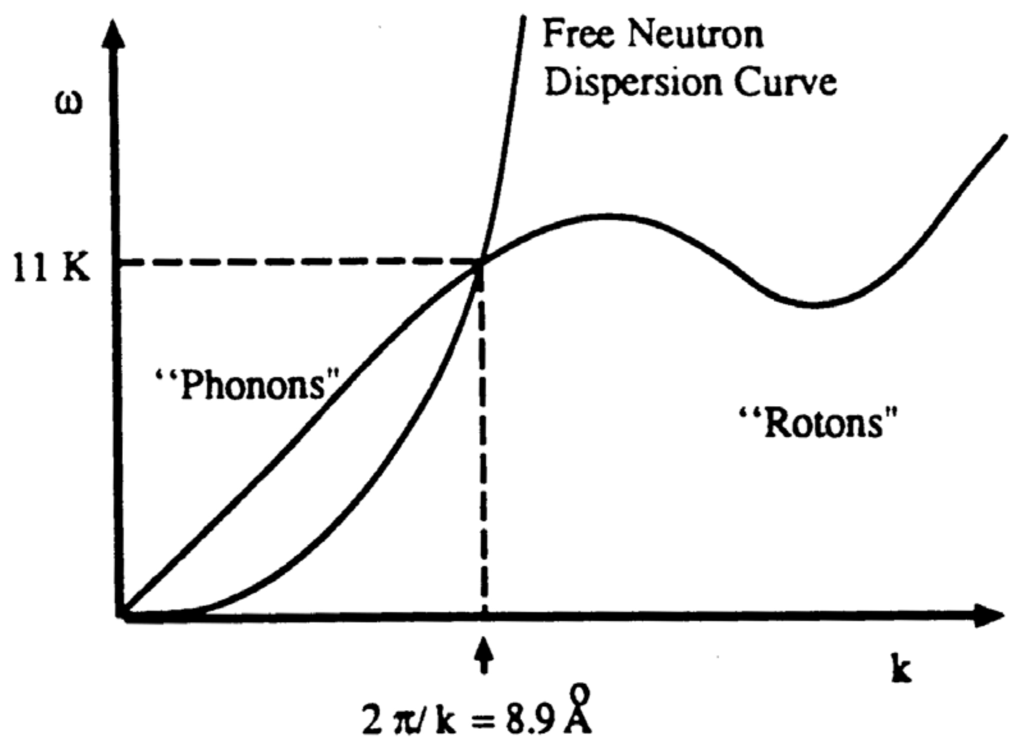
SUPERTHERMAL SOURCE OF UCNs

(Polarized) neutrons incident on superfluid ^{4}He at 0.3 K



Up-scattering

suppressed

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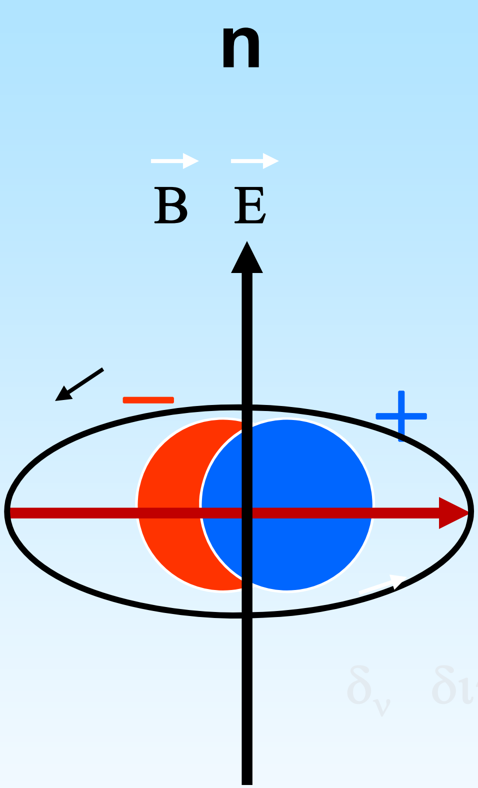
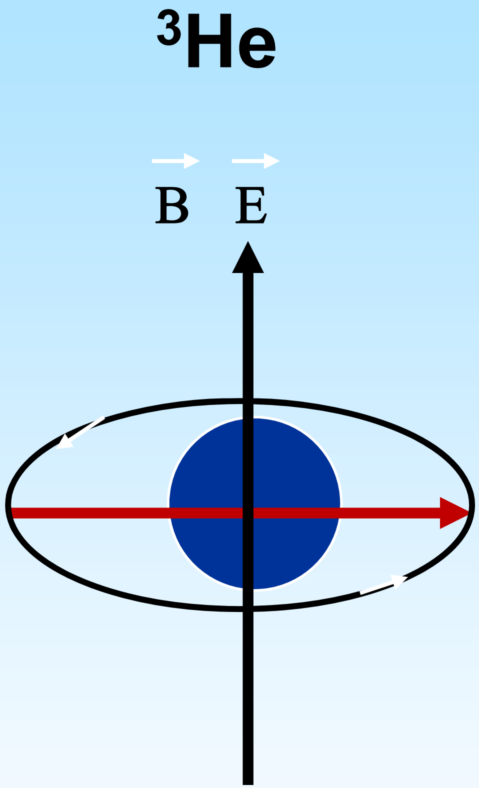
^3He MAGNETOMETRY





Look for a difference in precession frequency $\omega_n - \omega_3 \pm \omega_d$ dependent on E and corrected for temporal changes in ω_3

Monitor average B field by measuring average 3He precession frequency with SQUIDs→ 3He is a co-magnetometer

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^{3}He-DOPANT AS AN ANALYZER

$^3\vec{He} + \vec{n} \rightarrow t + p$

$\sigma(\text{parallel}) < 10^2$ b

$\sigma(\text{opposite}) \sim 10^4$ b

UCN loss rate ~

$1 - \vec{p}_3 \bullet \vec{p}_n = 1 - p_3 p_n \cos(\gamma_n - \gamma_3) B_0 t$

$|\gamma_n - \gamma_3| = |\gamma_n|/10$

^{3}He concentration must be adjusted to keep the lifetime τ reasonable for a given value of the ^{3}He polarization.

The proper value for the fractional concentration x = Atoms-^{3}He/Atoms-^{4}He ~ 10^{-10}.

^{3}He AS A DETECTOR

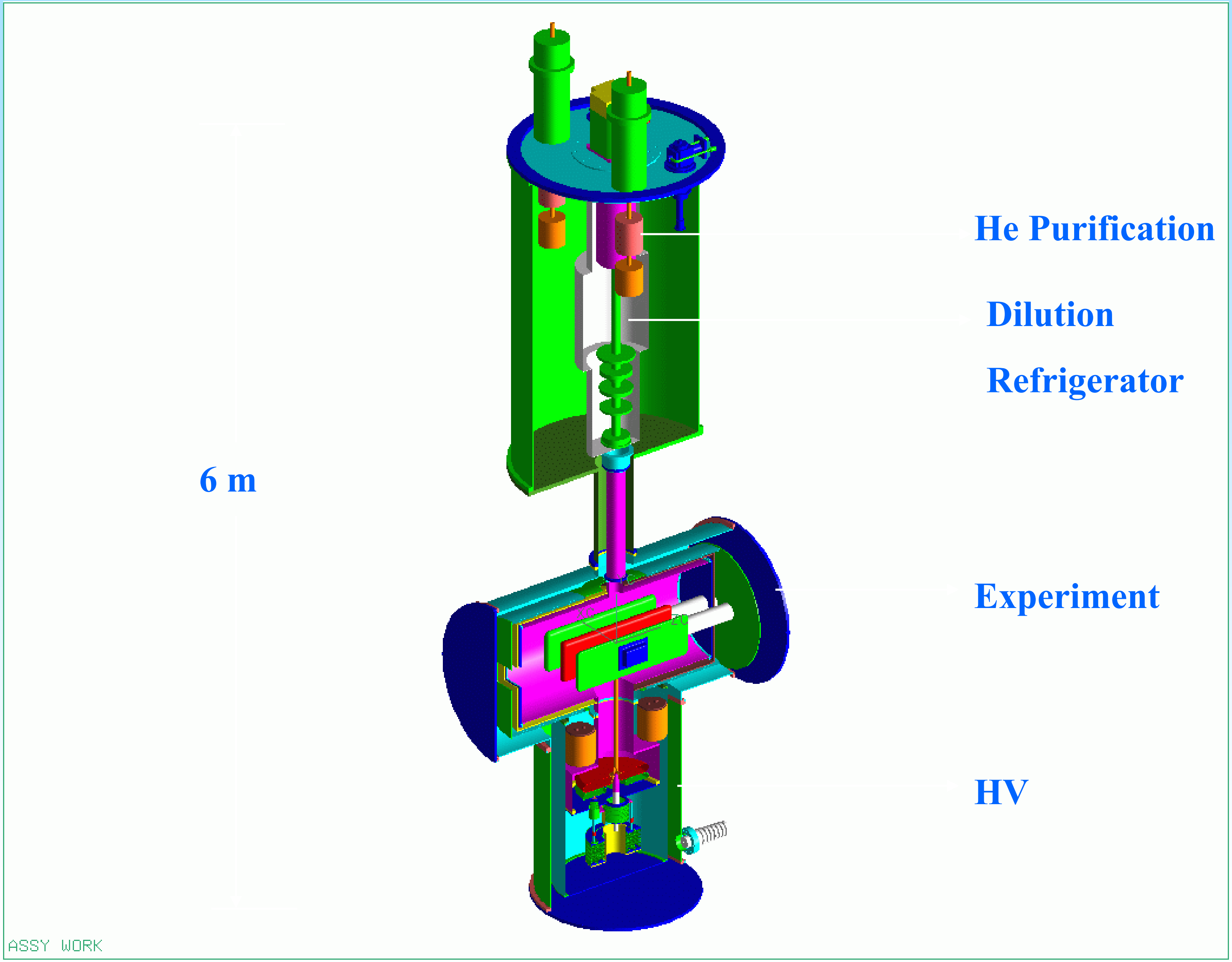
$$^3\vec{He} + \vec{n} \rightarrow t + p$$

t + p share 764 keV of kinetic energy. They scintillate while stopping in the ^{4}He. Light detected from the cell is a signature that the neutron had a polarization opposite to the ^{3}He.

The emitted light (~3 photons/keV) is in the XUV ~ 80 nm.

A wavelength shifter (TPB) is used to change it to the blue, where it can be reflected and detected. Getting the light out of a cryogenic system is a challenge.

The walls and the wavelength shifter must be made of materials that do not absorb neutrons or depolarize ^{3}He. For the neutrons, deuterated wavelength shifter and Ni will do; for the ^{3}He, ???



He Purification
Dilution
Refrigerator
6 m
Experiment
HV
ASSY WORK

nEDM Experiment at SNS (Oak Ridge)

Technical issues are being studied

CD2 next year

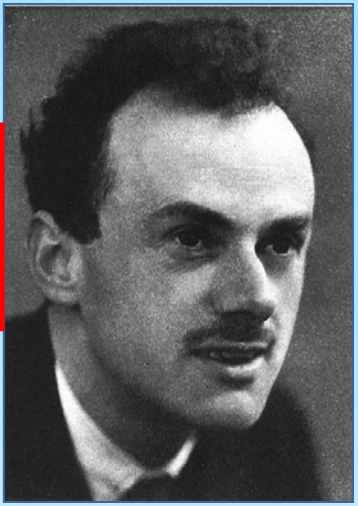
Plan to start taking data 2016

Goal: improve on current neutron EDM limit from

~few x 10^{-26} e-cm to ~ few x 10^{-28} e-cm

Muon Magnetic Moment: Muon g-2

In the beginning there was Dirac



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

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

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

dimension 5 operator

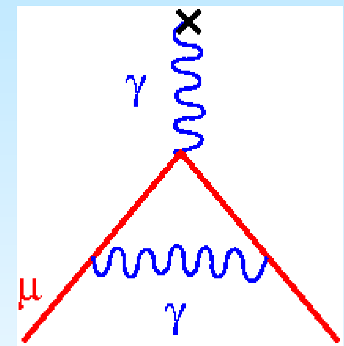
(only from loops)

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

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

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

For leptons, radiative corrections dominate the value of a ≃ 0.00116…



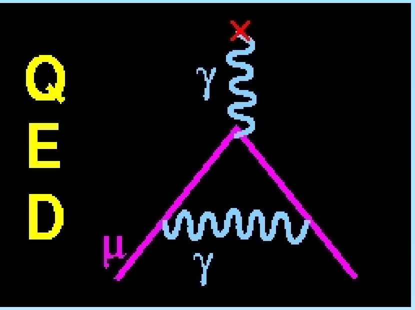
New Physics contribution to a at some scale Λ

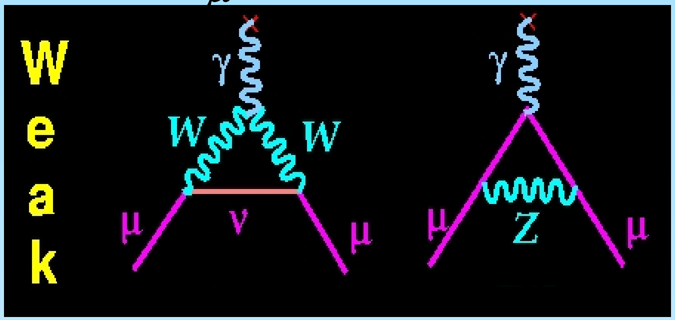
$$a(NewPhysics) = C \left(\frac{m}{\Lambda}\right)^2$$

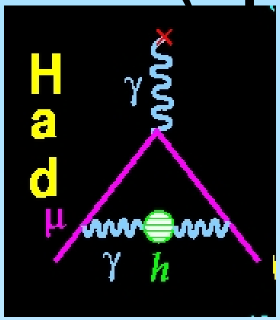
where C could be $\mathcal{O}(1)$, or

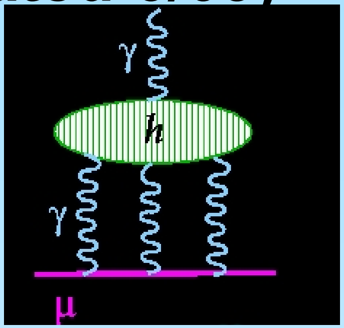
$\mathcal{O}(\alpha)$ **in weak coupling loop scenarios**

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









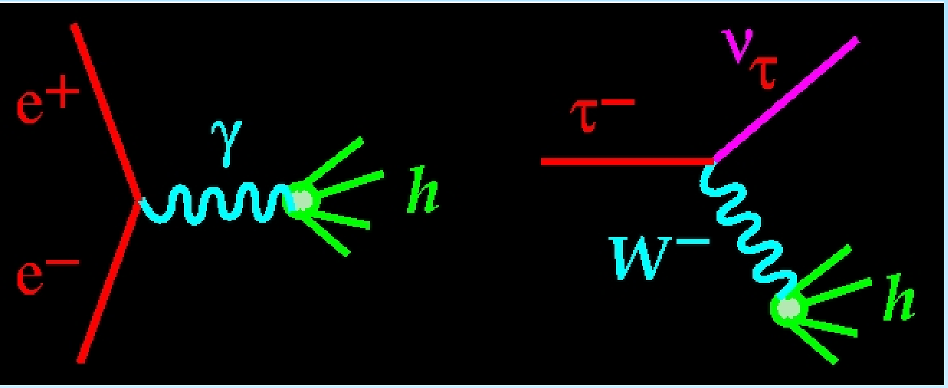
well known | **significant work ongoing**

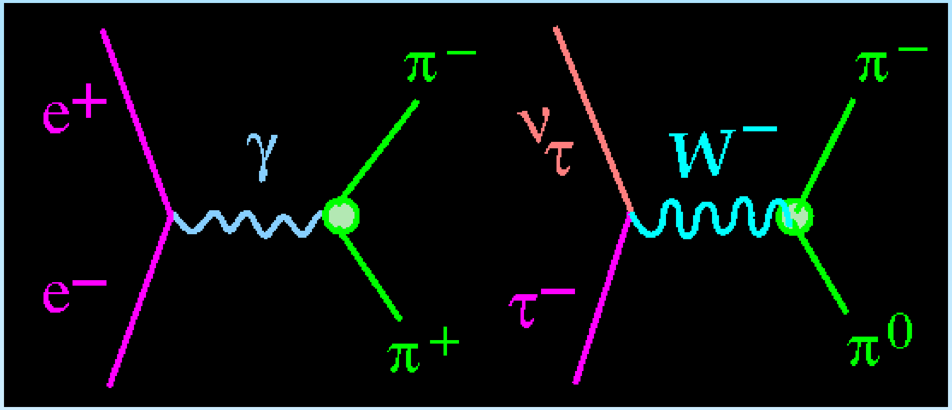
CONTRIBUTION	RESULT ($\times 10^{-11}$) UNITS
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 891 \pm 38_{\rm exp} \pm 19_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-97.9 \pm 0.9_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 773 \pm 50$

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

a(had) from hadronic τ decay?

Back



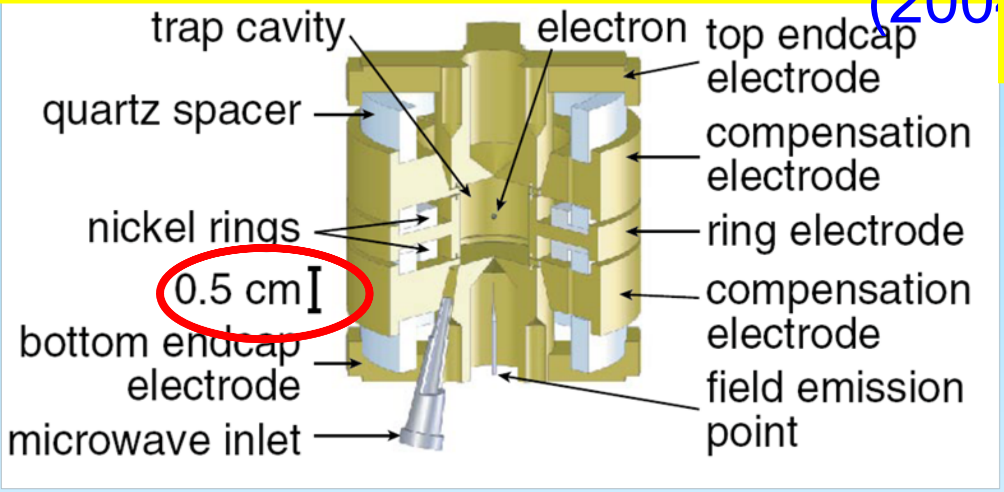


- Assume: CVC, no 2nd-class currents, isospin breaking corrections.
  - e^+e^- goes through neutral ρ
  - while τ-decay goes through charged ρ
- n.b. τ decay has no isoscalar piece, e^+e^- does
- There are inconsistencies in the comparison of e^+e^- and τ decay:

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

μ PRL, **92, 161802** (200

PR **D73,** 072003 (2006)



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

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

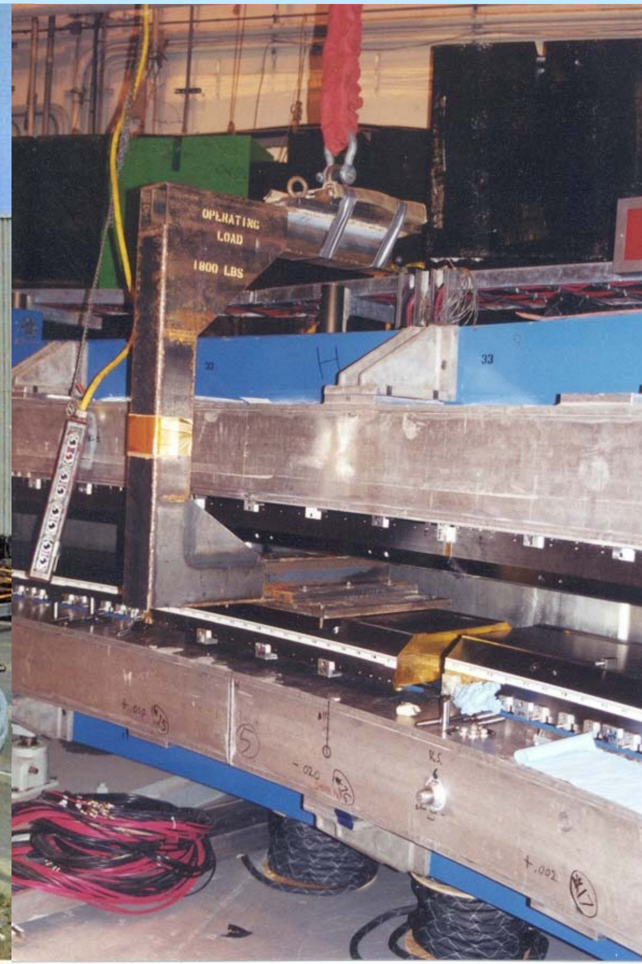
muon more sensitive to heavier physics by

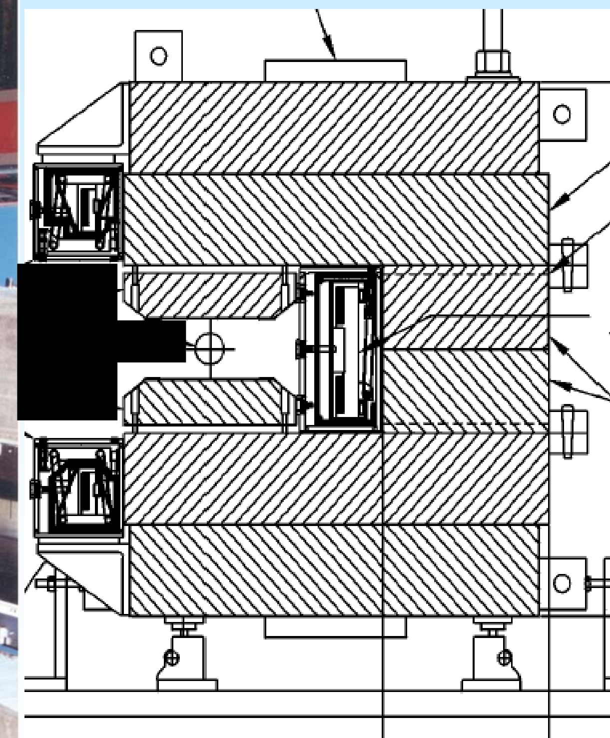
$$\sim \left(\frac{m_\mu}{m_e}\right)^2 \simeq 42,000$$

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

Ring relocation to Fermilab? Proposed at FNAL

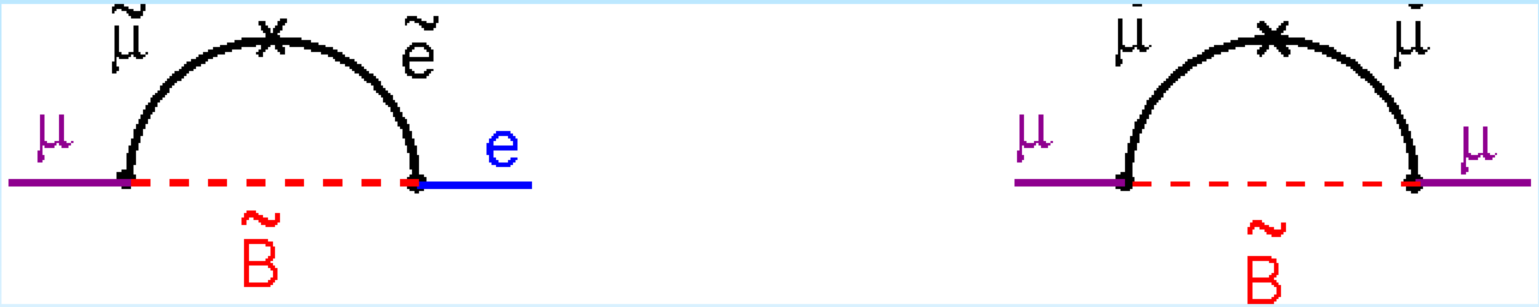
- Heavy-lift helicopters bring coils to a barge
- Rest of magnet is a “kit” that can be trucked to and from the barge





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

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



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

Philosophy of Muon g-2 Measurement

- Precess polarized muons in a very uniform magnetic field so that all muons precess at the same rate regardless of momentum; rate of precession of spin relative to momentum vector:

$$\boldsymbol{\omega} = -\frac{e}{m} a_\mu \mathbf{B} \qquad \text{(E field=0, EDM=0)}$$

- Need to hold muons in a storage ring: add electric quadrupole field to focus beam of muons

$$\boldsymbol{\omega} = -\frac{e}{m}[a_\mu \mathbf{B} - (a_\mu - \frac{1}{\gamma^2 - 1})\frac{\boldsymbol{\beta}\mathbf{x}\mathbf{E}}{c})]$$

- Choose p_μ=3.1 GeV/c so that $(a_\mu - \frac{1}{\gamma^2 - 1}) = 0$

- Use correlation of electron spin direction in muon decays to determine the direction of the spin at time of decay.

Spin Motion: difference frequency between ω_S and ω_C

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

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

0

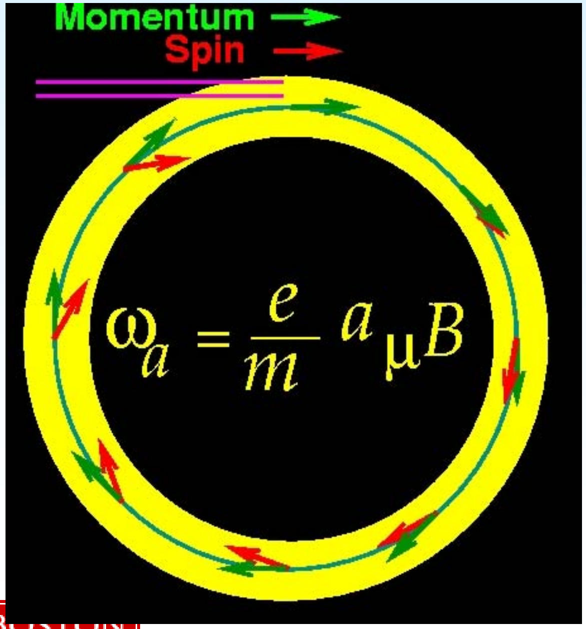
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

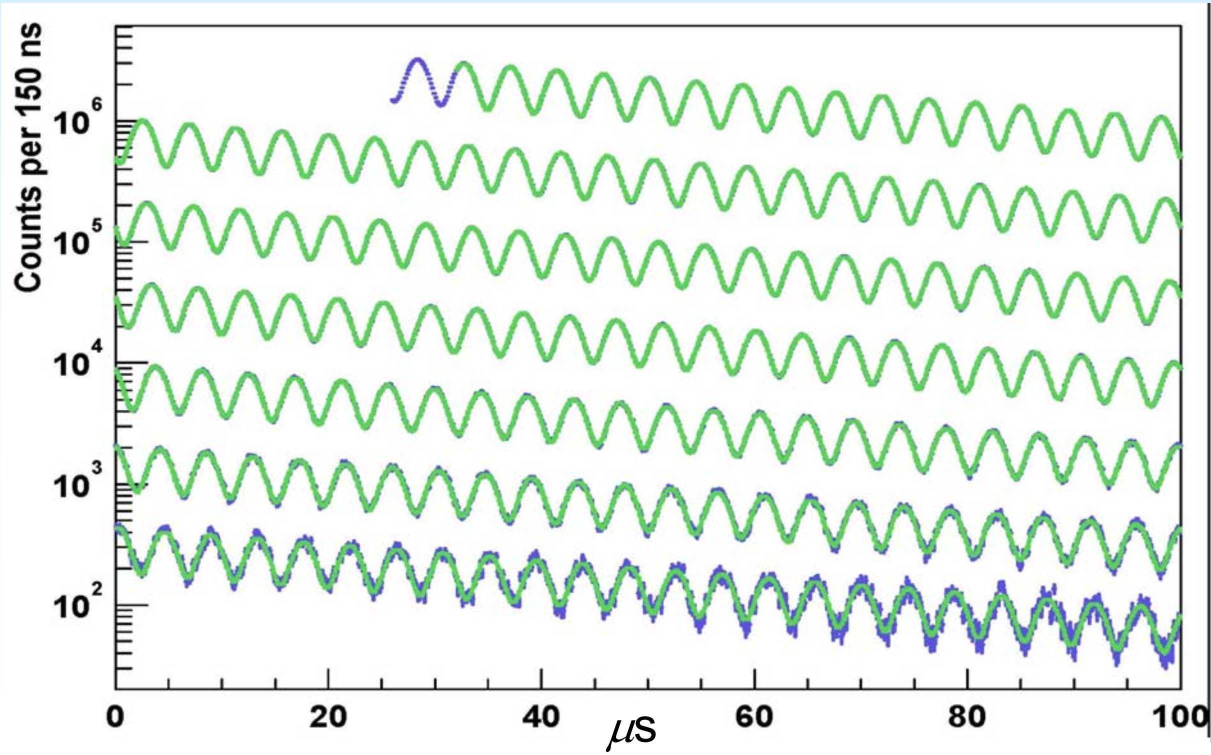
E_e : 0-3.1 GeV

$\gamma_{magic} = 29.3$

$p_{magic} = 3.09$ GeV/c

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





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

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

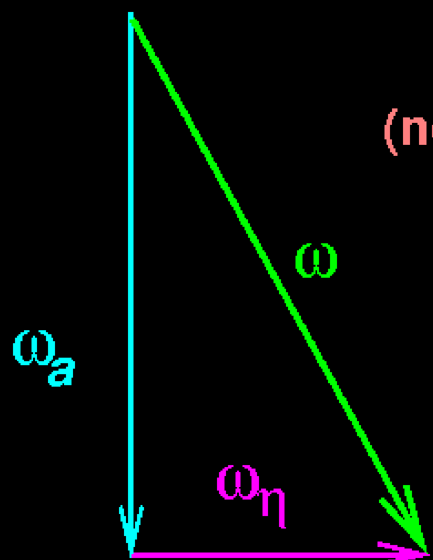
Use a radial E-field to turn off the ω_a precession

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

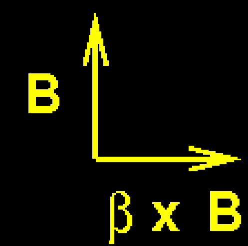
"Frozen spin"

PRL **93** 052001 (2004)

With ω_a = 0, the EDM ca
precess out of the plane



(not to scale)



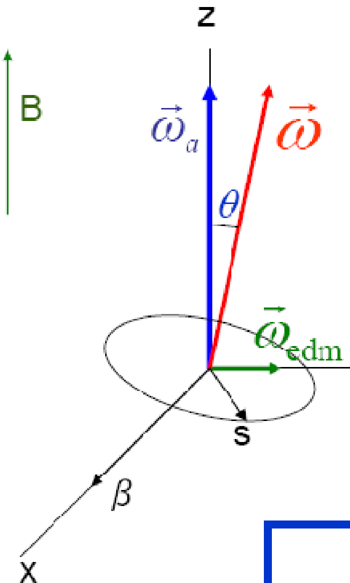
PSI, Ferminlab Project X,
J-PARC, NuFact?

Parasitic Muon EDM Measurement using straw tube arrays

Back

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

arXiv:0811.1207v1



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

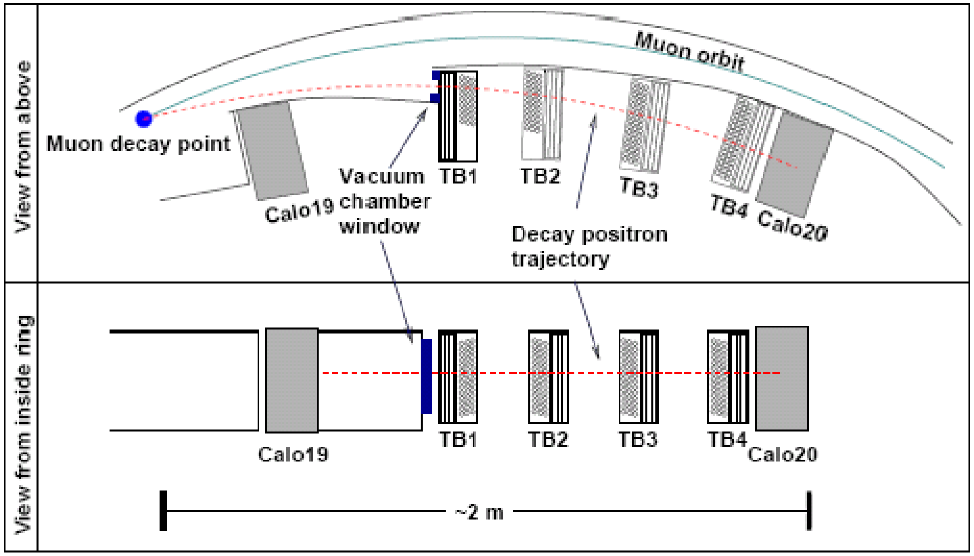
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

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

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

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

E821 straw-tube array

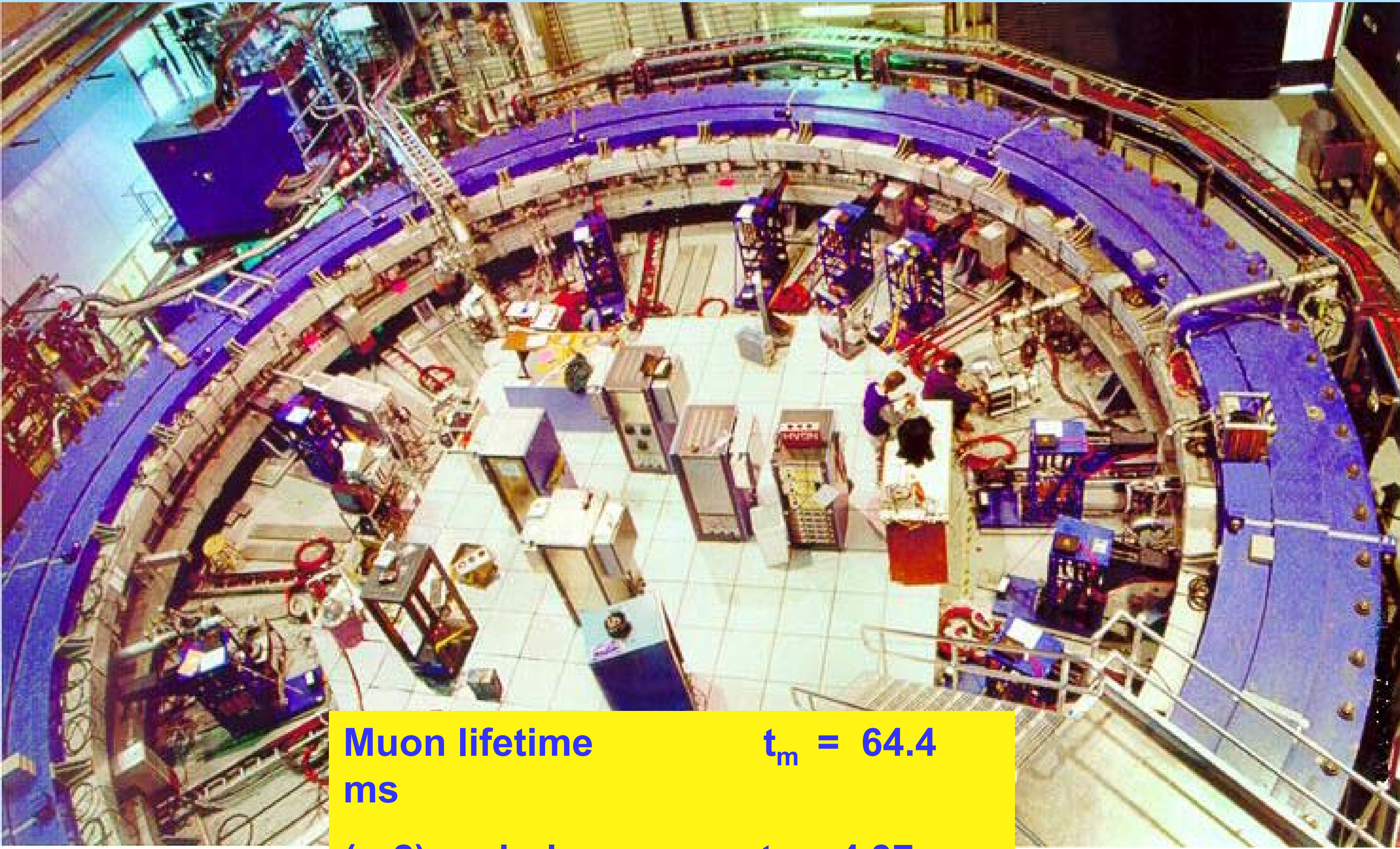


Summary

Three examples of experiments which can see new physics at energy scales at least as large as the LHC:

- Neutron EDM experiments
- Muon g-2: ~1 TeV, specific tests of SUSY
- Muon to electron conversion: will also test CLFV in SUSY complementary to LHC. In NP scenarios can reach to 1000’s of TeV, way beyond any conceivable accelerator- also likely the most sensitive CLFV reaction because of experimental advantages

muon (g-2) storage ring



Muon lifetime t_m = 64.4 ms

(g-2) period t_a = 4.37 ms

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)*

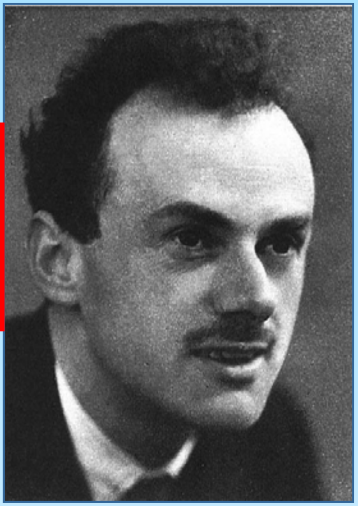
http://www.worldscibooks.com/physics/7273.html

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

Chapter 2

Electromagnetic Dipole Moments and New Physics

In the beginning there was Dirac



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

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

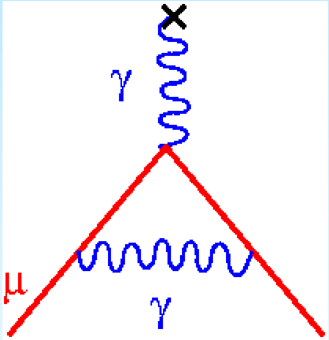
(only from loops)

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

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

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

For leptons, radiative corrections dominate the value of a ≃ 0.00116…



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

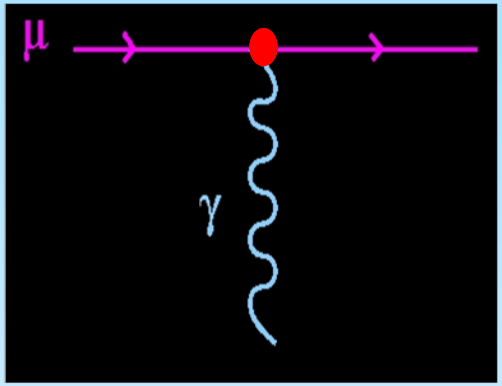
$F_3(0) = dQ$ electric dipole moment

$$+F_A\left(q^2\right)\left(\gamma_\mu q^2 - 2m_f q_\mu\right)\gamma_5$$

(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 Moment a_μ chiral changing

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

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

- Muon EDM

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

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

Transition Moments and Form Factors $f_i \rightarrow f_j$

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

$$\Gamma_\mu^{ij} = \underbrace{\left(q^2 g_{\mu\nu} - q_\mu q_\nu\right)\gamma^\nu\left[F_{E0}^{ij}\left(q^2\right) + \gamma_5 F_{M0}^{ij}\left(q^2\right)\right]}$$

chiral-conserving, flavor-changing amplitudes at $q^2 \neq 0$

e.g. $K^+ \rightarrow \pi^+ e^+ e^-; \quad \mu^+ \rightarrow e^+ e^+ e^-$

$$\underbrace{+i\sigma_{\mu\nu}q^\nu\left[F_{M1}^{ij}\left(q^2\right) + \gamma_5 F_{E1}^{ij}\left(q^2\right)\right].}$$

chiral-changing, flavor-changing amplitudes at $q^2 \neq 0$

e.g. $b \rightarrow s\gamma; \quad \mu \rightarrow e\gamma; \quad \tau \rightarrow \mu\gamma$

Magnetic Dipole Moments

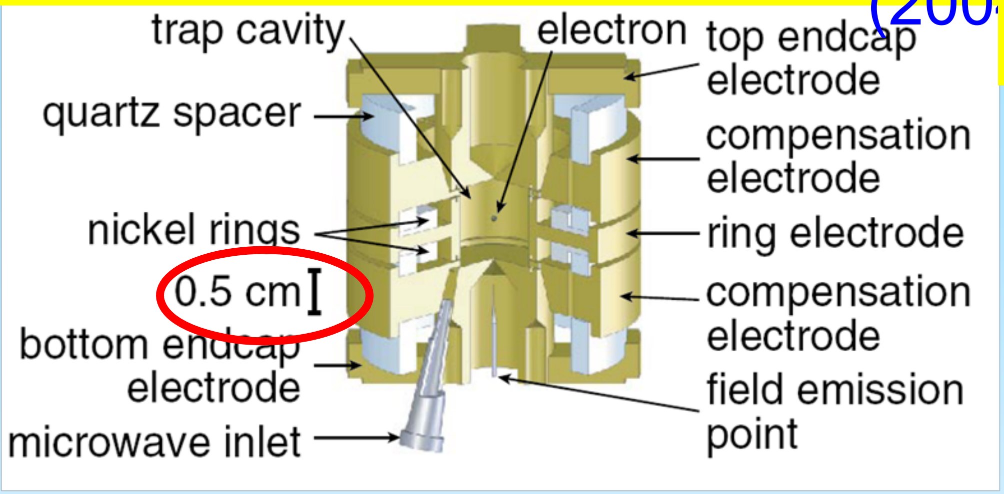
$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

Transition Dipole Moments

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

e PRL **100**, 120801 (2008) — μ PRL, **92, 161802** (2004)

PR **D73**, 072003 (2006)



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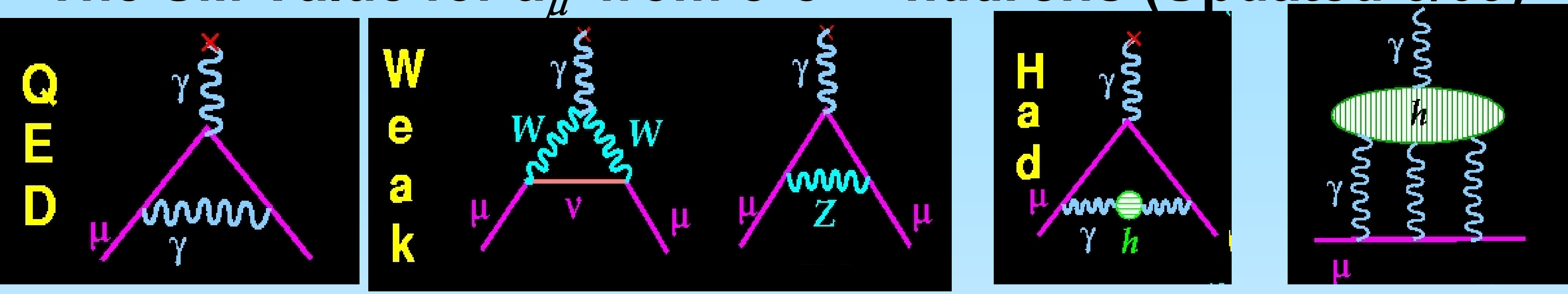

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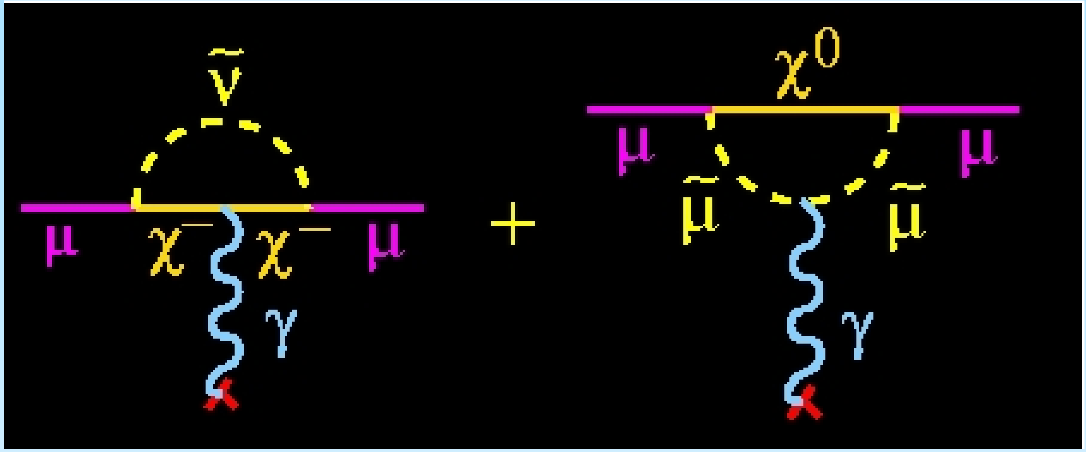
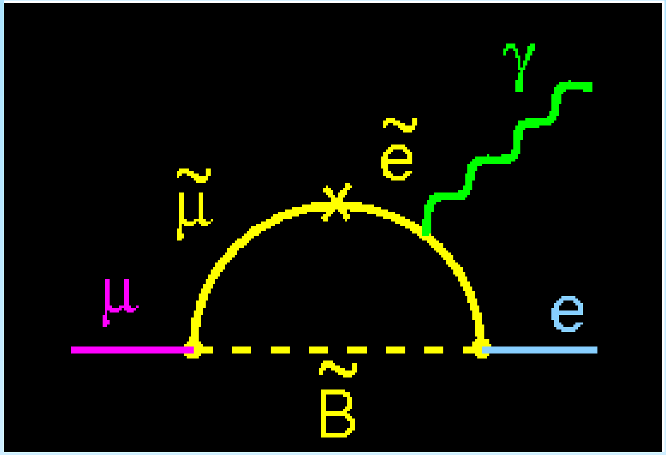
de Rafael, hep-ph arXiv:0809.3085 and Davier, et al.,hep-ph arXiv:0906.5443v1

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





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

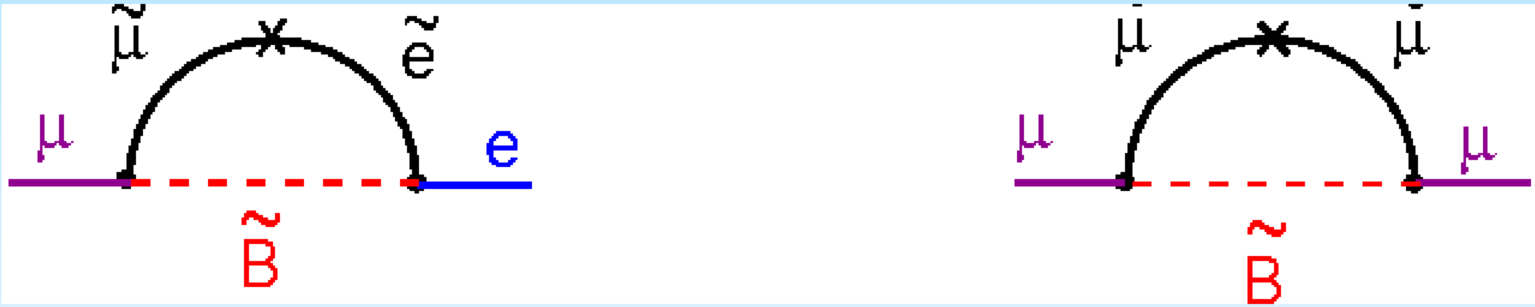
difficult to measure at LHC

Related processes in SUSY

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

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

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

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

- 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

$$\left.\begin{array}{l}\sigma_{stat} = \pm 0.1 \text{ ppm} \\ \sigma_{syst} = \pm 0.1 \text{ ppm}\end{array}\right\} \sigma = \pm 0.14 \text{ ppm}$$

Spin Motion: difference frequency between ω_S and ω_C

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

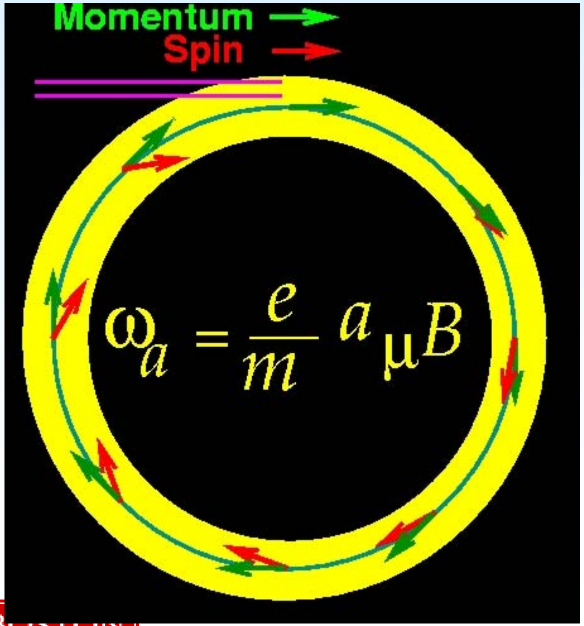
$$= -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

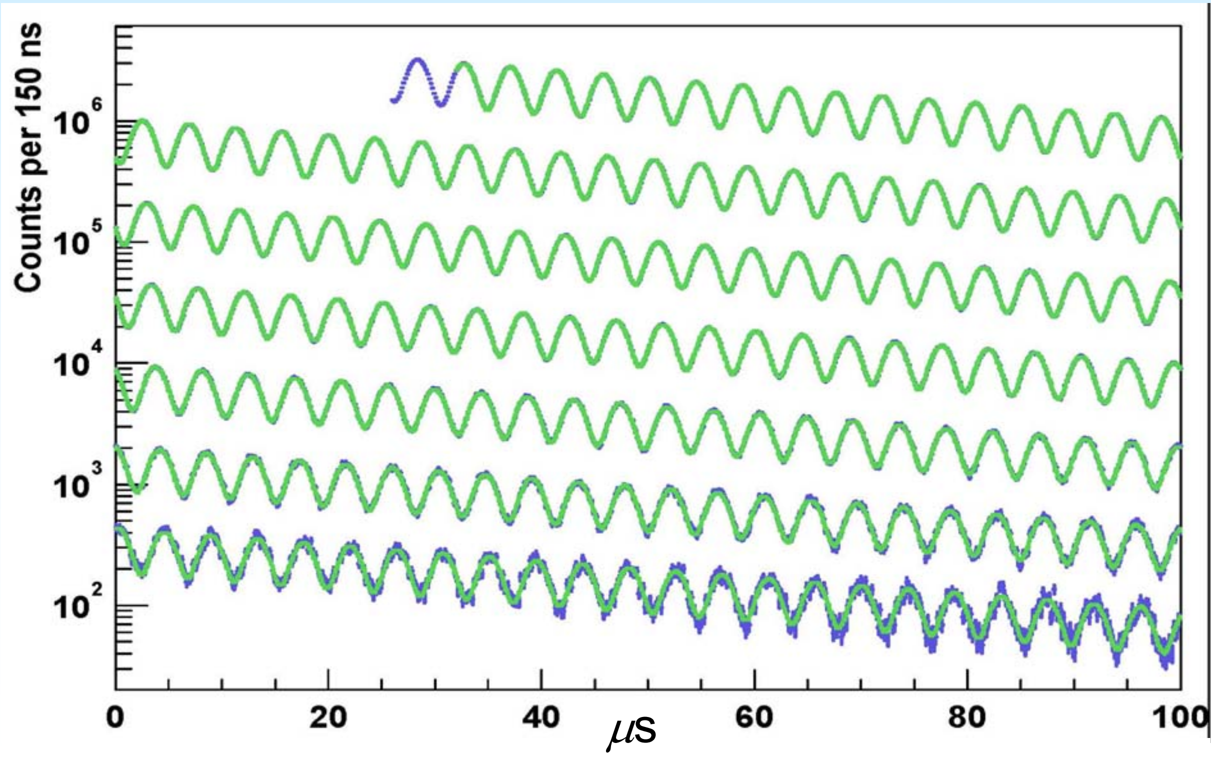
0

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

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

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



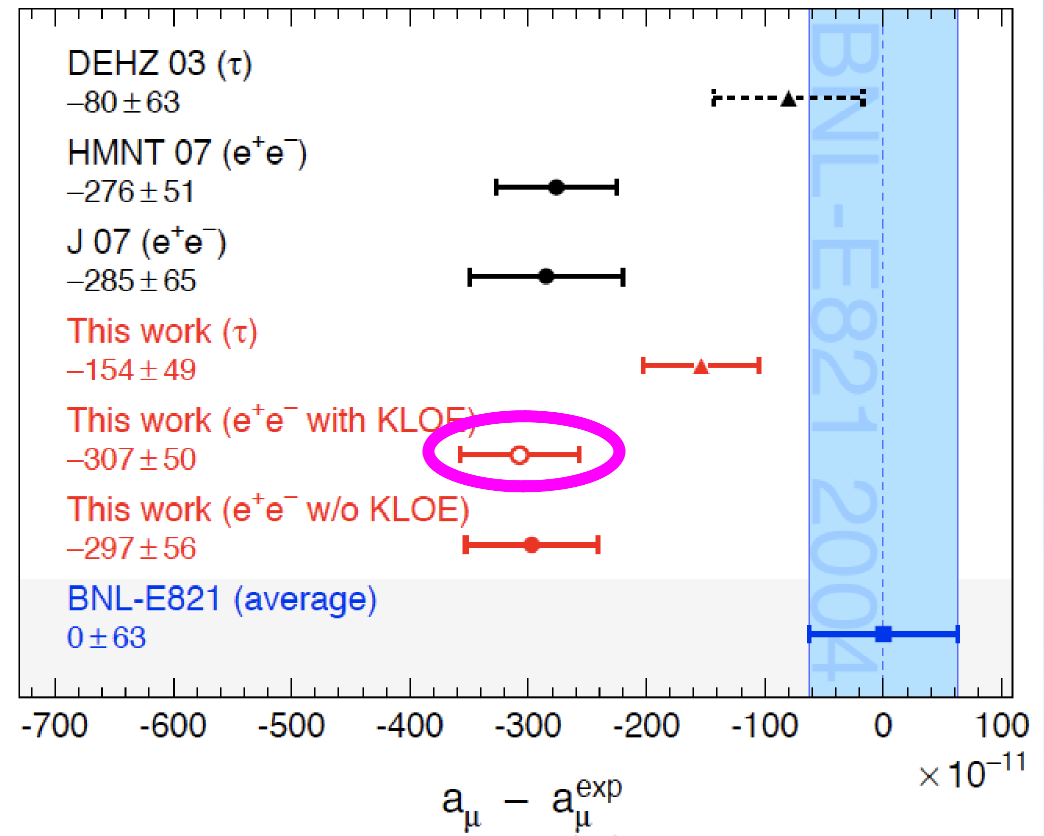


BOSTON UNIVERSITY

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



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

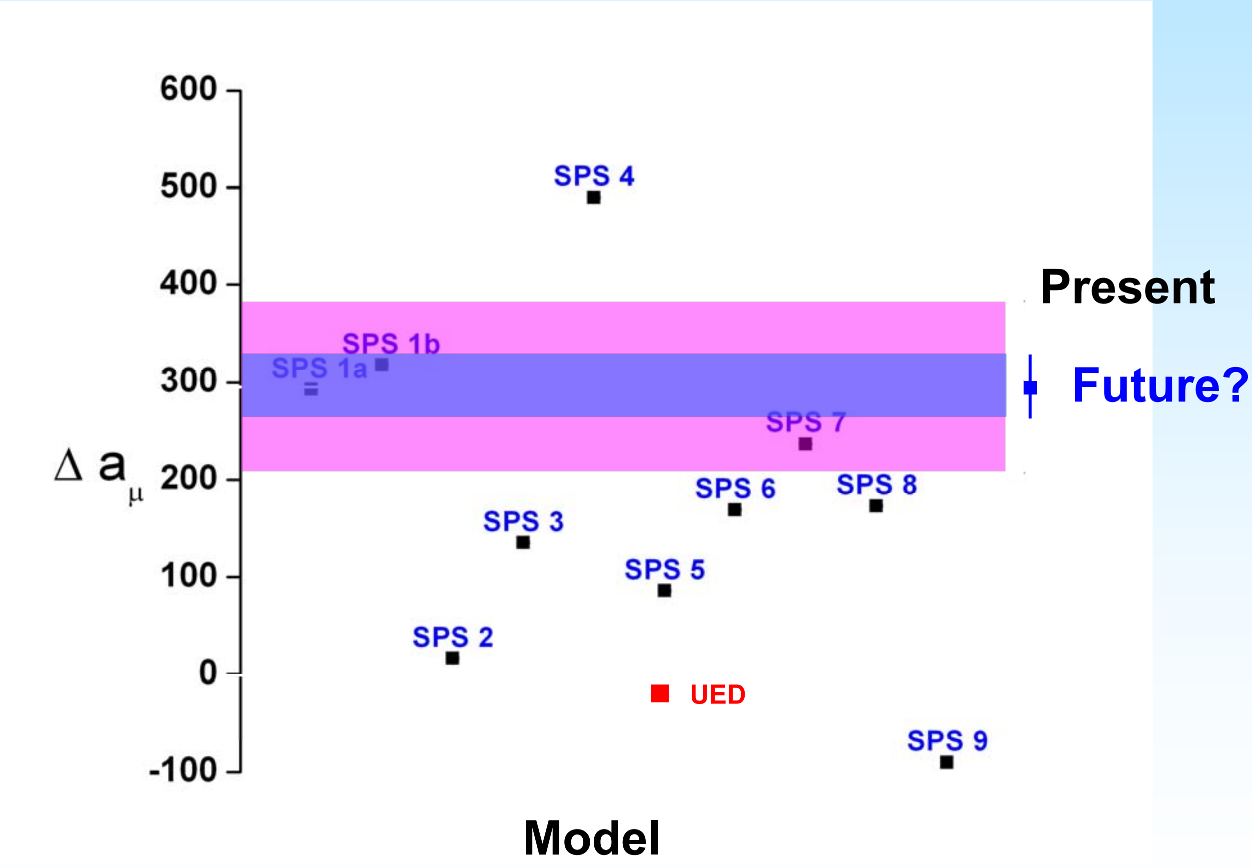
$$\Delta a_\mu^{(\mathrm{today})} = (307 \pm 81) \times 10^{-11}$$

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

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

Muon g-2 is a powerful discriminator …

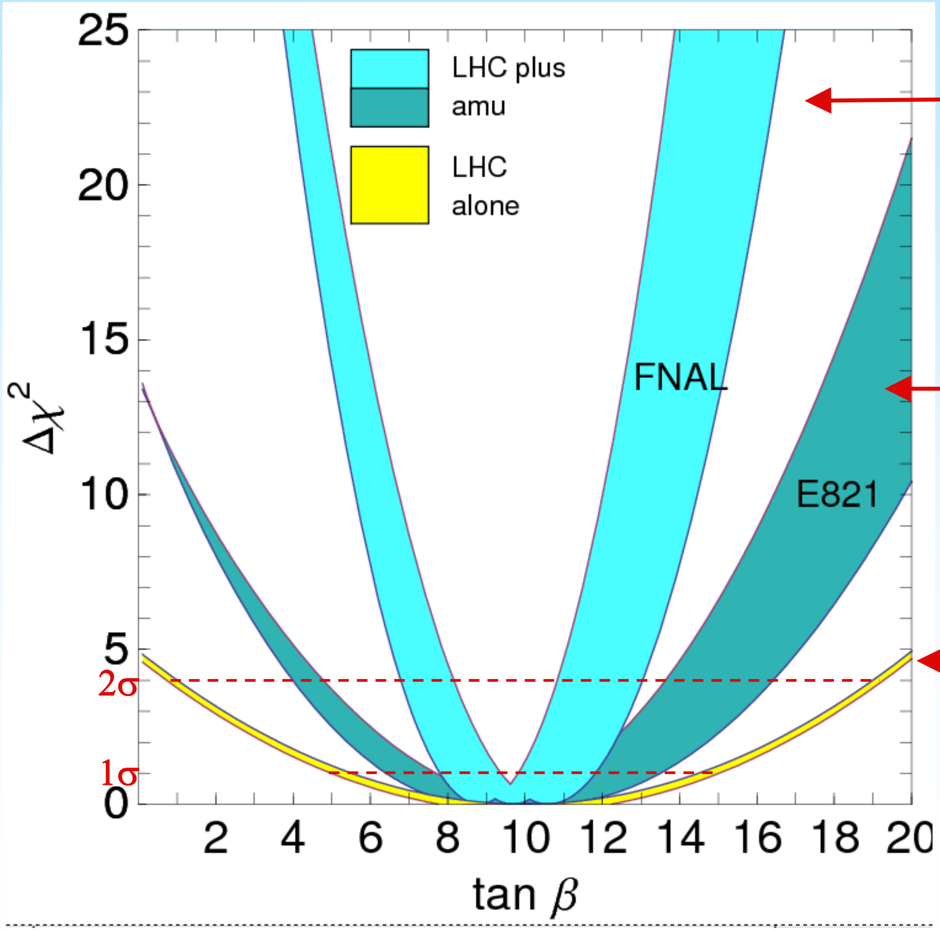
no matter where the final value lands!



SPS Definitions

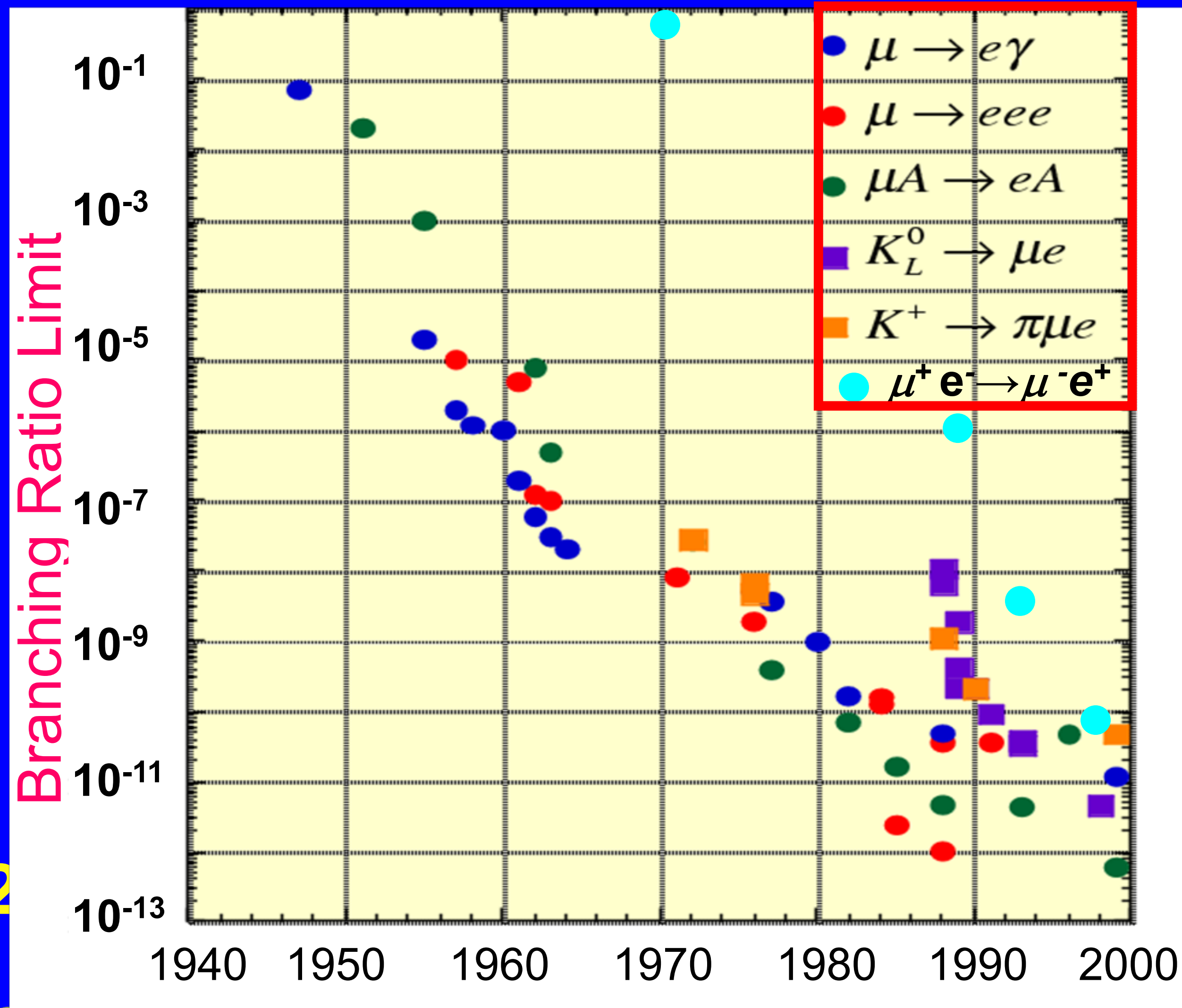
Suppose the MSSM point SPS1a is realized and the paramaters are determined at LHC- sgn(Δ) gives sgn(μ)

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



from D. Stöckinger

Charged Lepton Flavor (μ) Violation



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

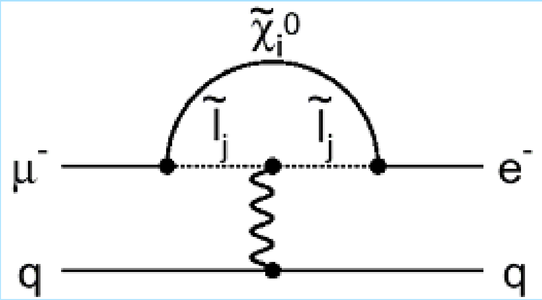
$\mu^+ \to e^+e^-e$

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

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

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

(2) whether one can distinguish various theore
dependence.

Relevant quark level interactions

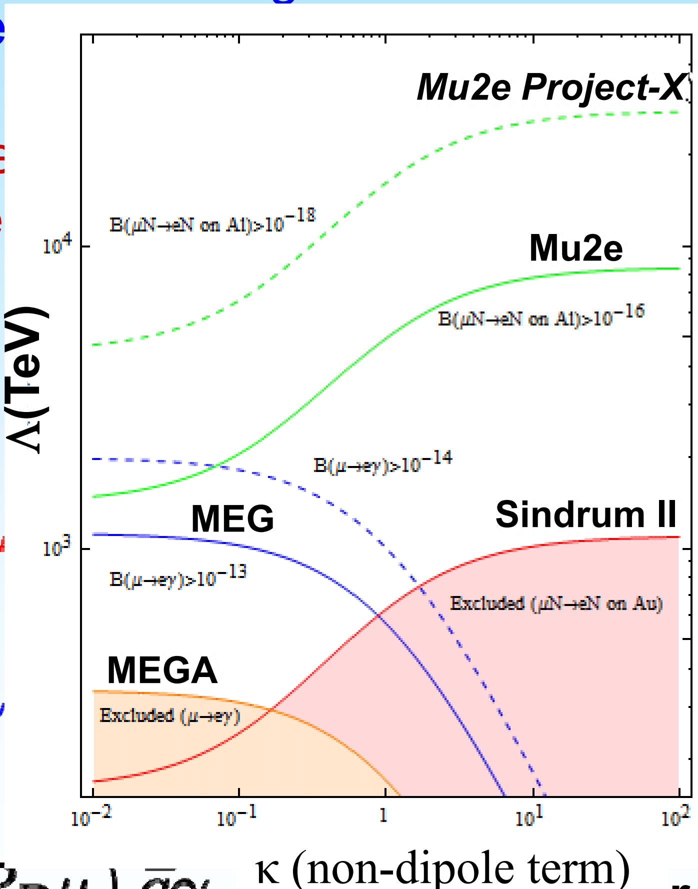
$$\mathcal{L}_{\rm int} = -\frac{4G_F}{\sqrt{2}}\left(m_\mu A_R \bar{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L\right.$$

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

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

e

vector

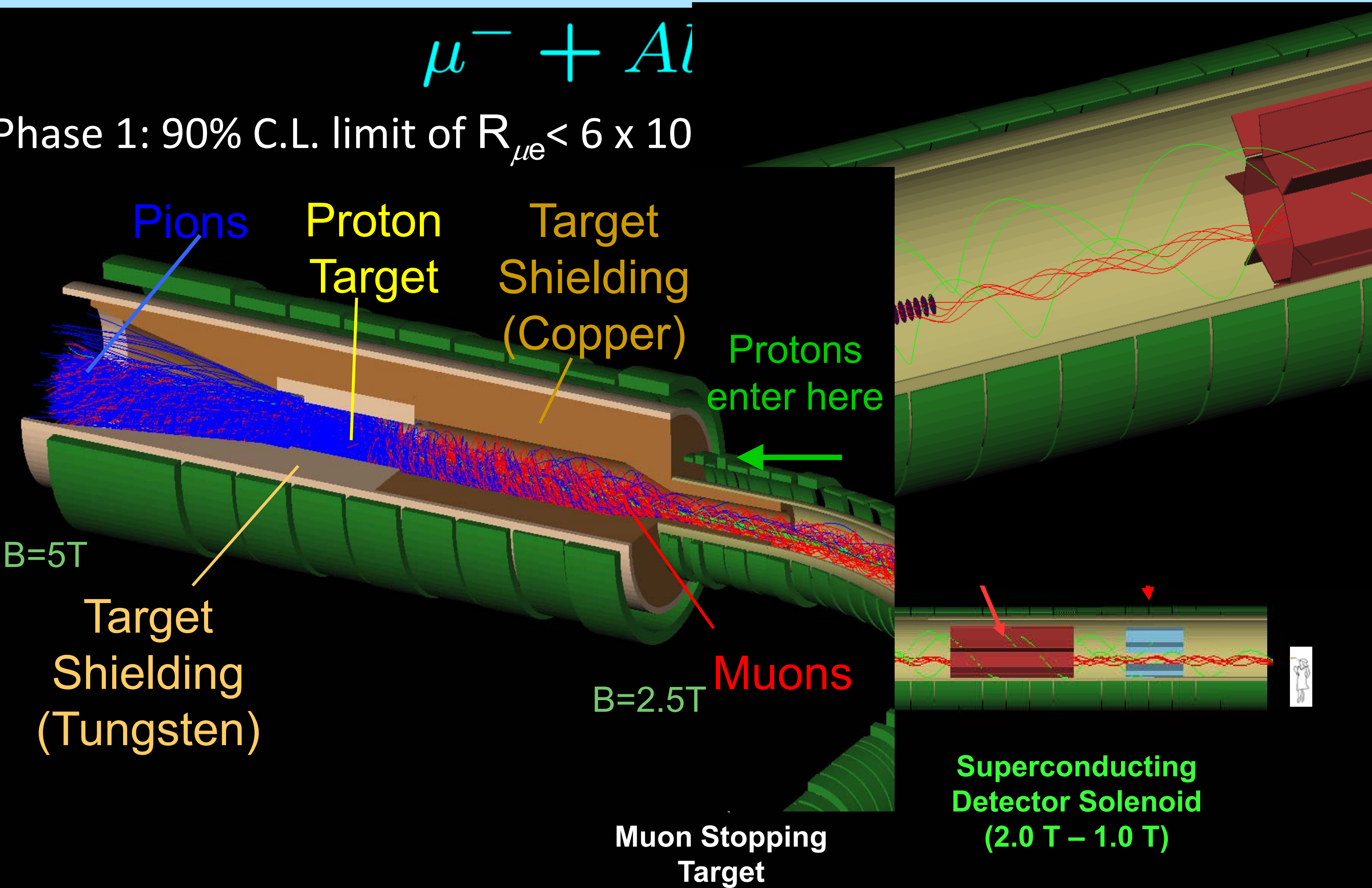


(fig, from Andrew Norman)

The μ2e Apparatus proposed for Fermilab (has stage 1 approval)

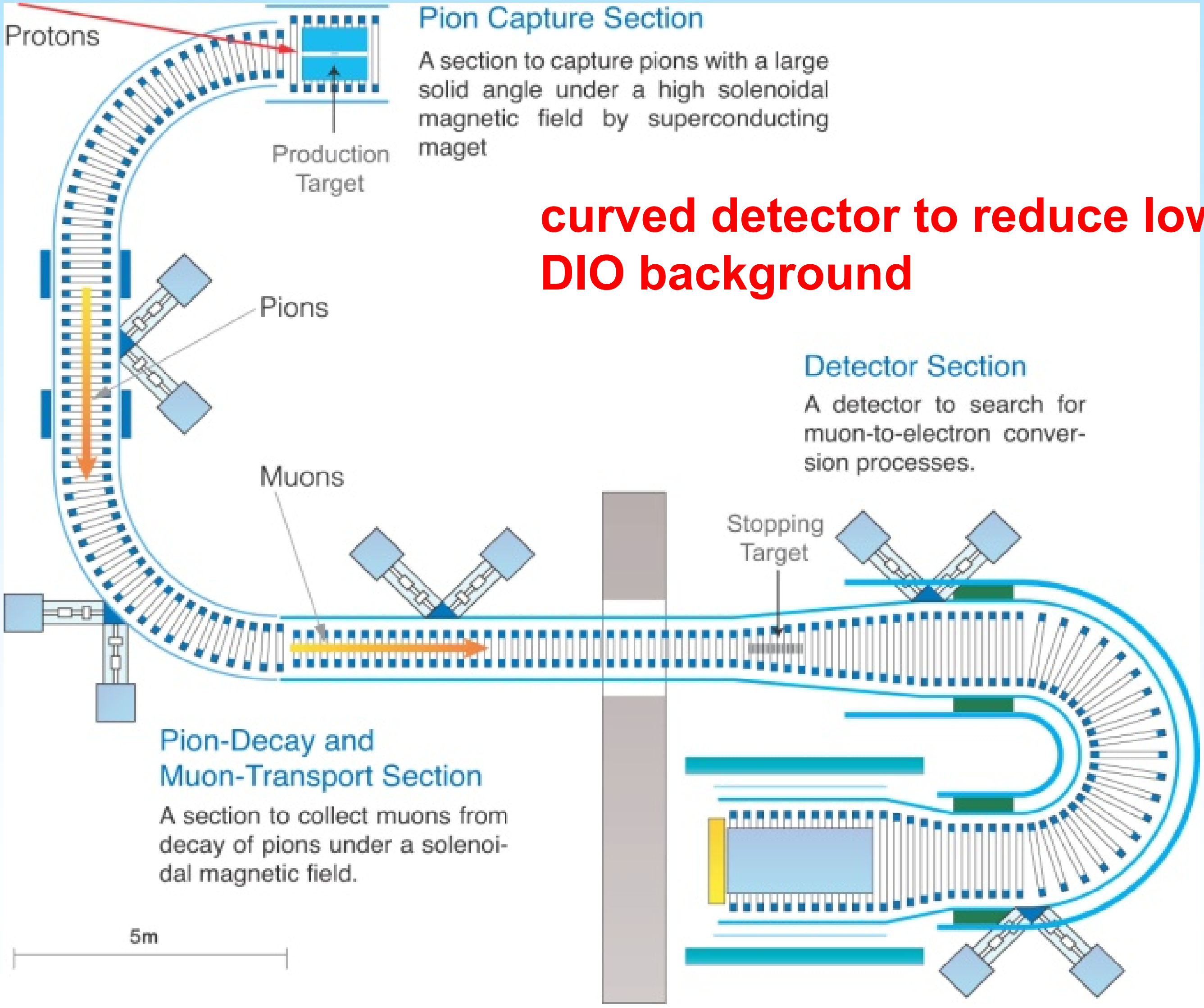
$$\mu^- + Al$$

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



COMET Proposal @ J-PARC

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



curved detector to reduce low E DIO background

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

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)

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

QCD vacuum state can be parameterized by:

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

$\not{P}$ $\not{T}$

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.

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

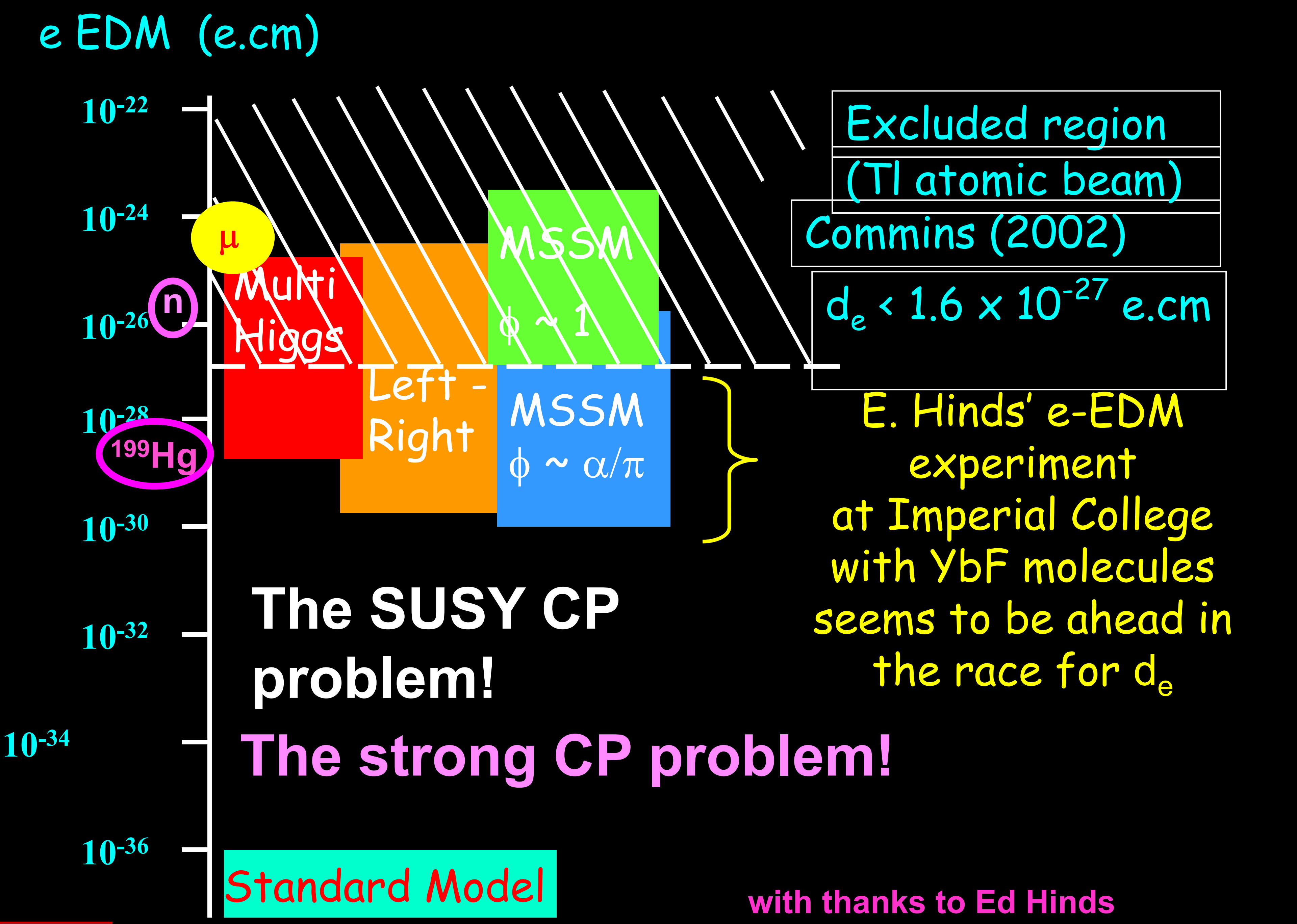
strong CP problem!

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

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

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.



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

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

0

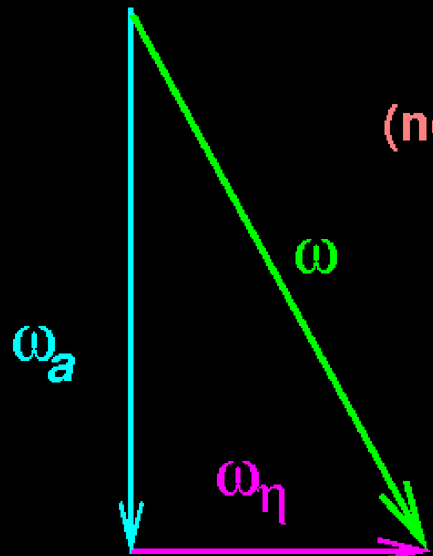
Use a radial E-field to turn off the ω_a precession

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

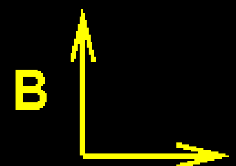
"Frozen spin"

PRL **93** 052001 (2004)

With ω_a = 0, the EDM ca
precess out of the plane

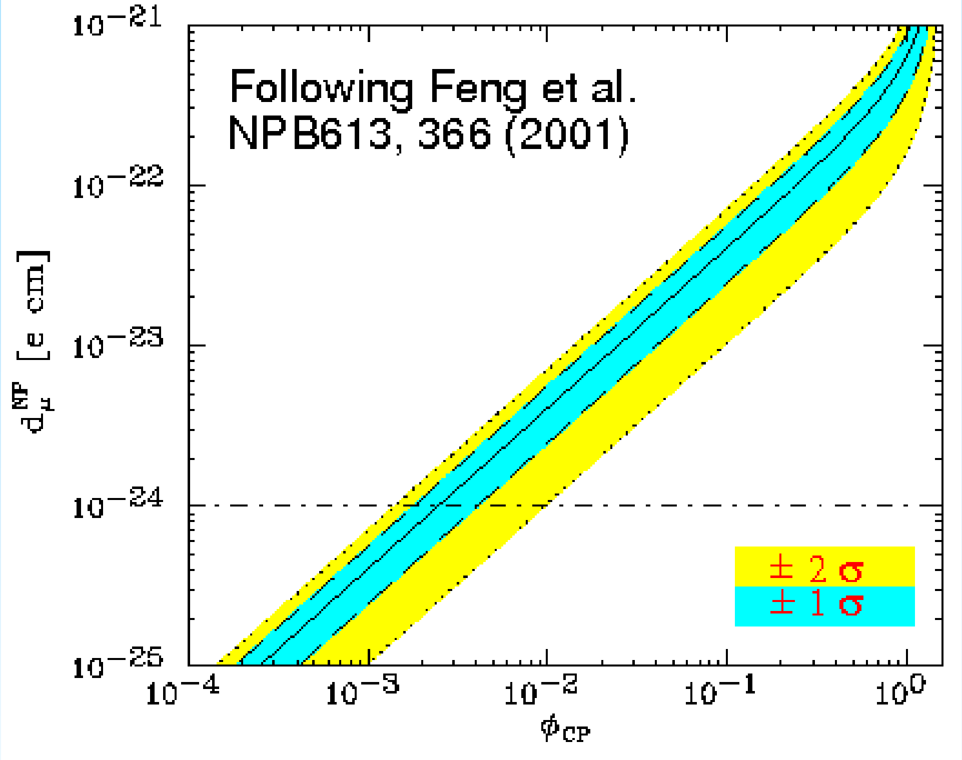


(not to scale)



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

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

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

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)

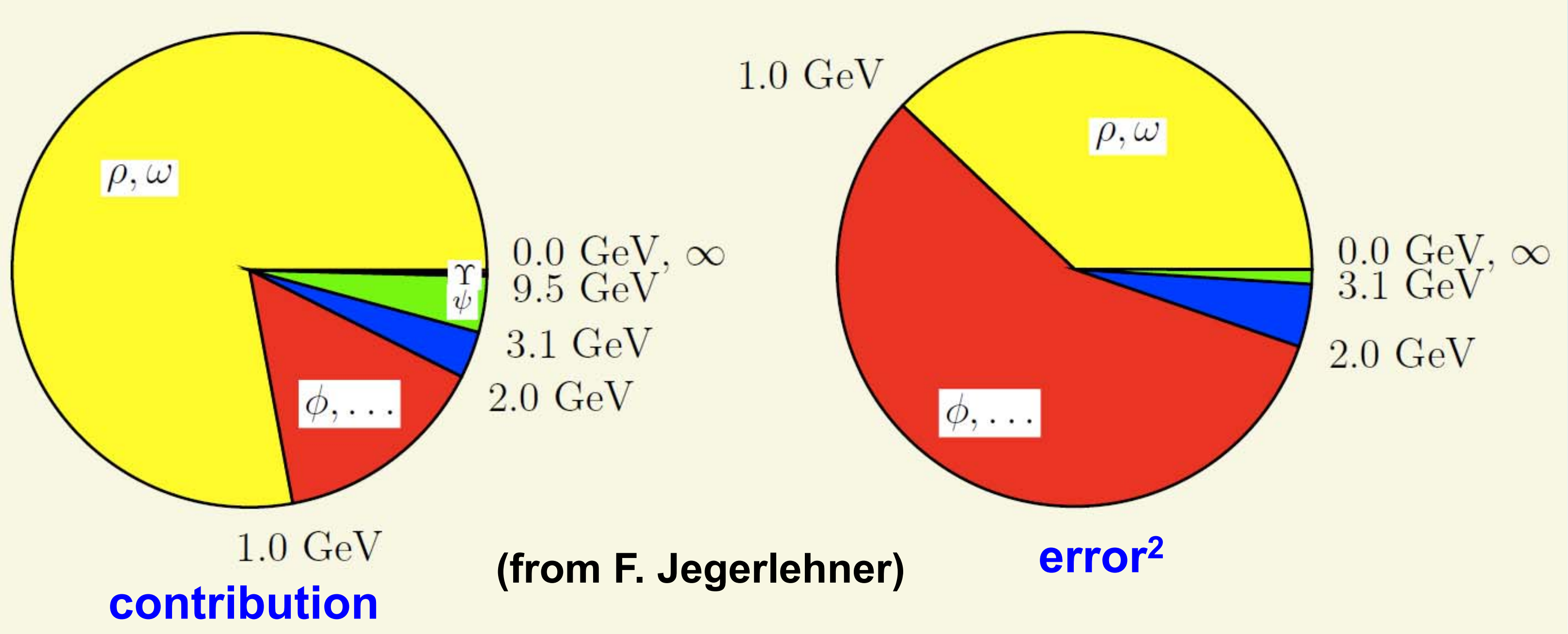
Possible topics for further discussion

- 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

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

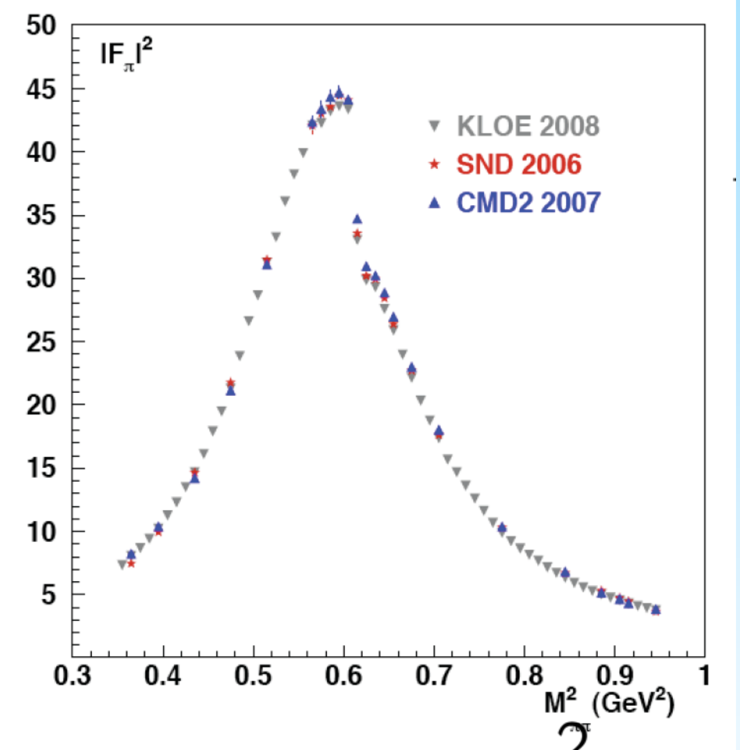


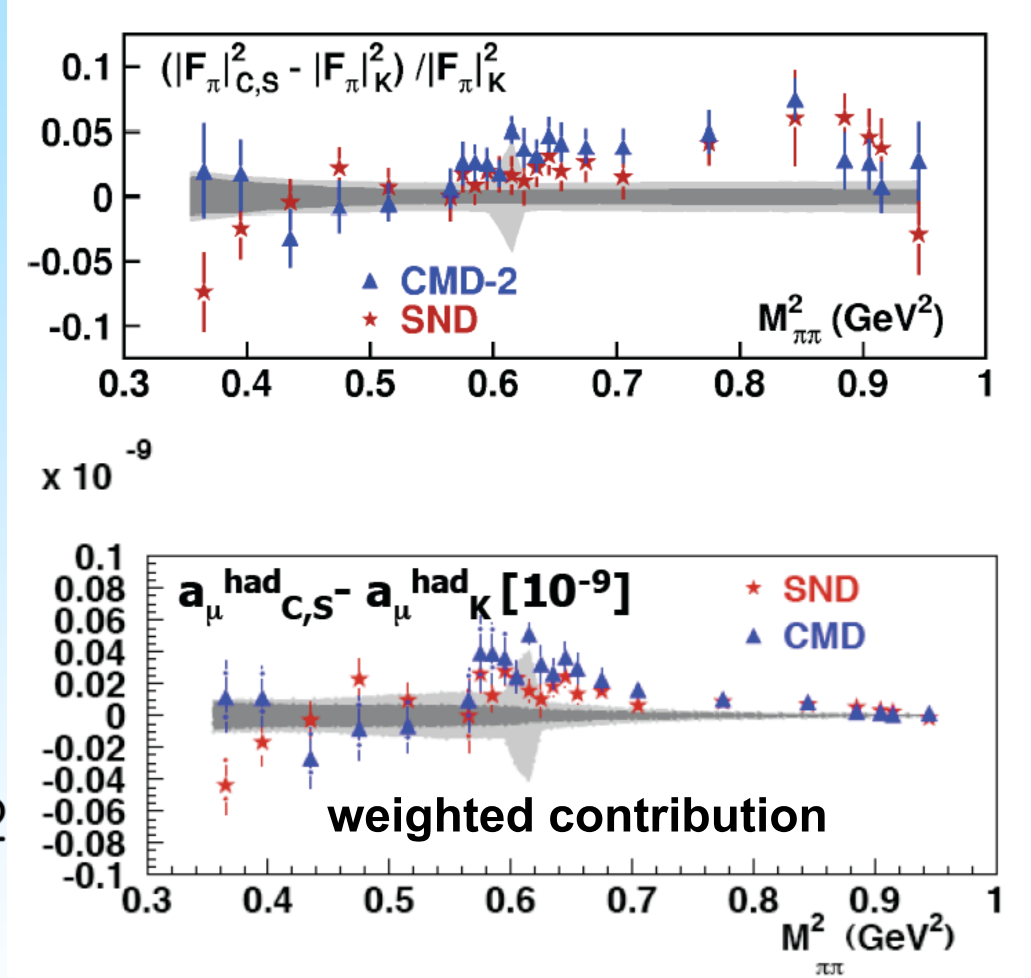
(from F. Jegerlehner)

- 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

$|F_\pi|^2$ 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 $a_\mu^{\rm Had} \simeq 1 - 4 \times 10^{-11}$

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

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Back

Suppose the hadronic contribution increased to remove the difference?

- A similar dispersion integral enters elsewhere

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

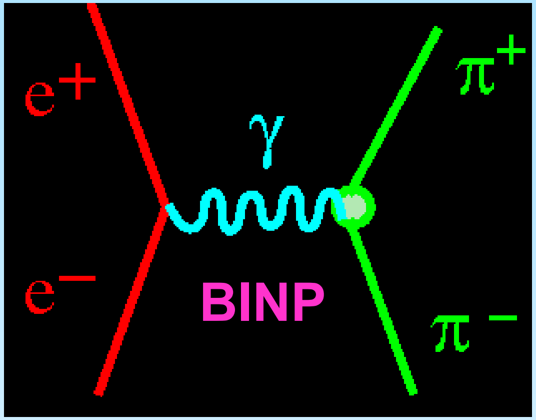
- Increasing σ(s) to remove the (g-2) difference lowers the Higgs mass limit **PRD 78, 013009 (2008)**

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

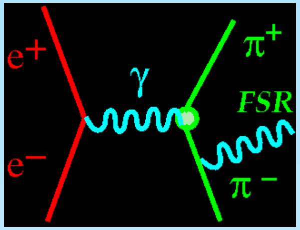
- This cross section is important for a_μ and for any precision EW physics.
- BaBar result soon. Future work continues in Frascati and Novosibirsk. Belle is also beginning to explore this possibility.

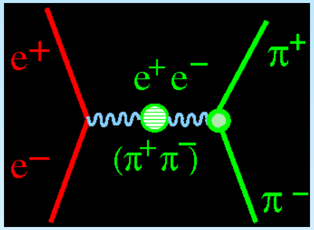
KLOE and BaBar use ISR (radiative return)

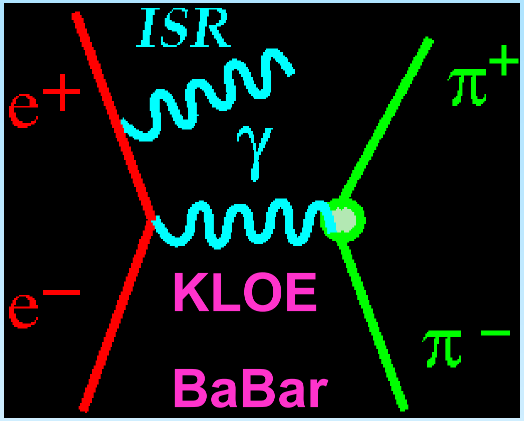
Back



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 $\mu - \pi$ separation
  - measures R (s) directly

Always the issue of radiative corrections

a(had) from hadronic τ decay?

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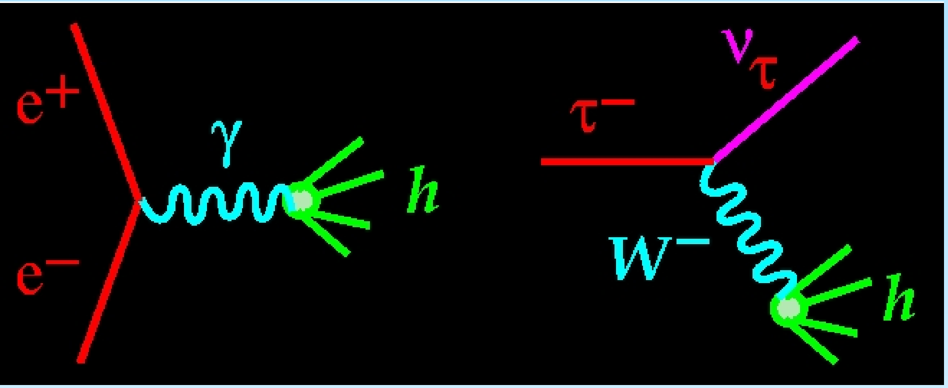
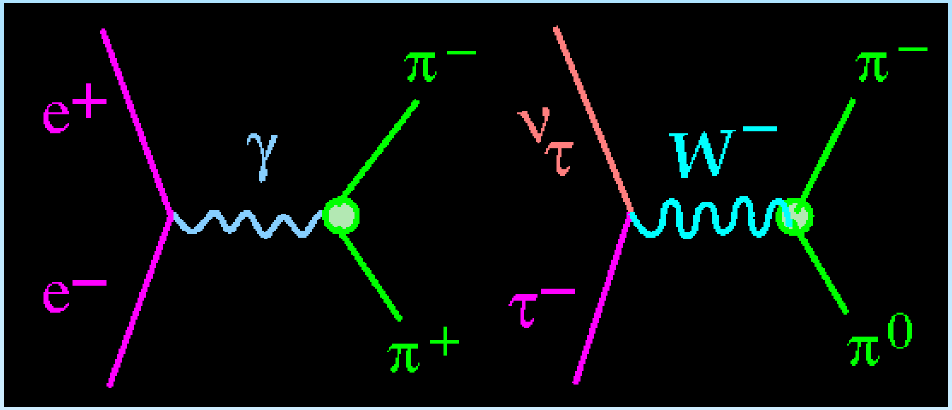




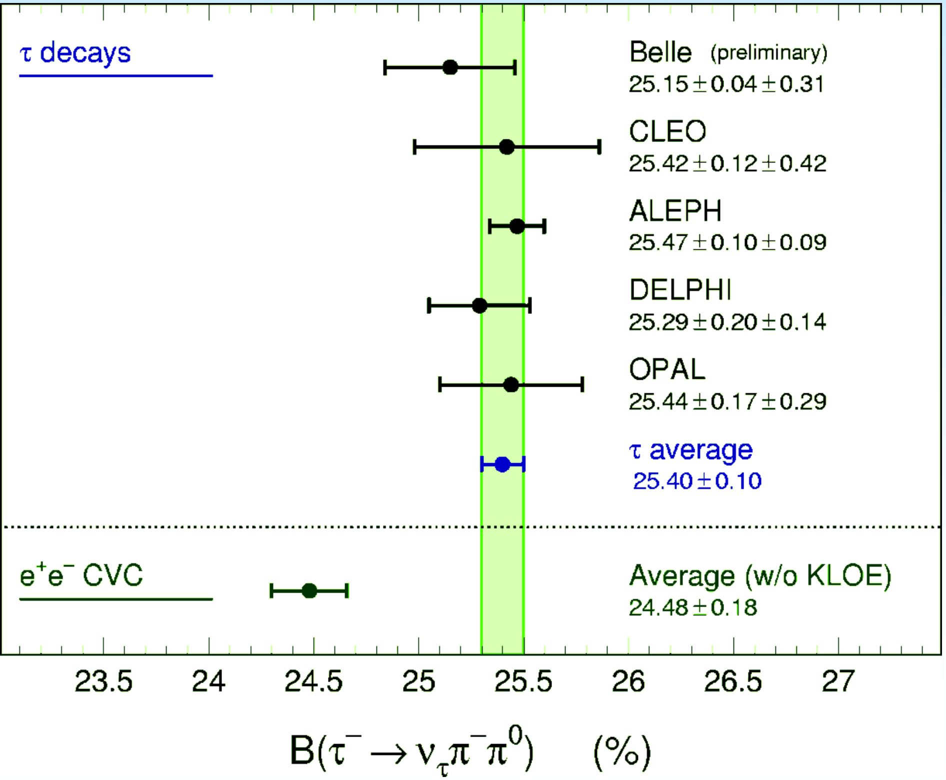
- Assume: CVC, no 2nd-class currents, isospin breaking corrections.
  - e^+e^- goes through neutral ρ
  - while τ-decay goes through charged ρ
- n.b. τ decay has no isoscalar piece, e^+e^- does
- There are inconsistencies in the comparison of e^+e^- and τ decay:

Testing CVC with one number (last year)

Back

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

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



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

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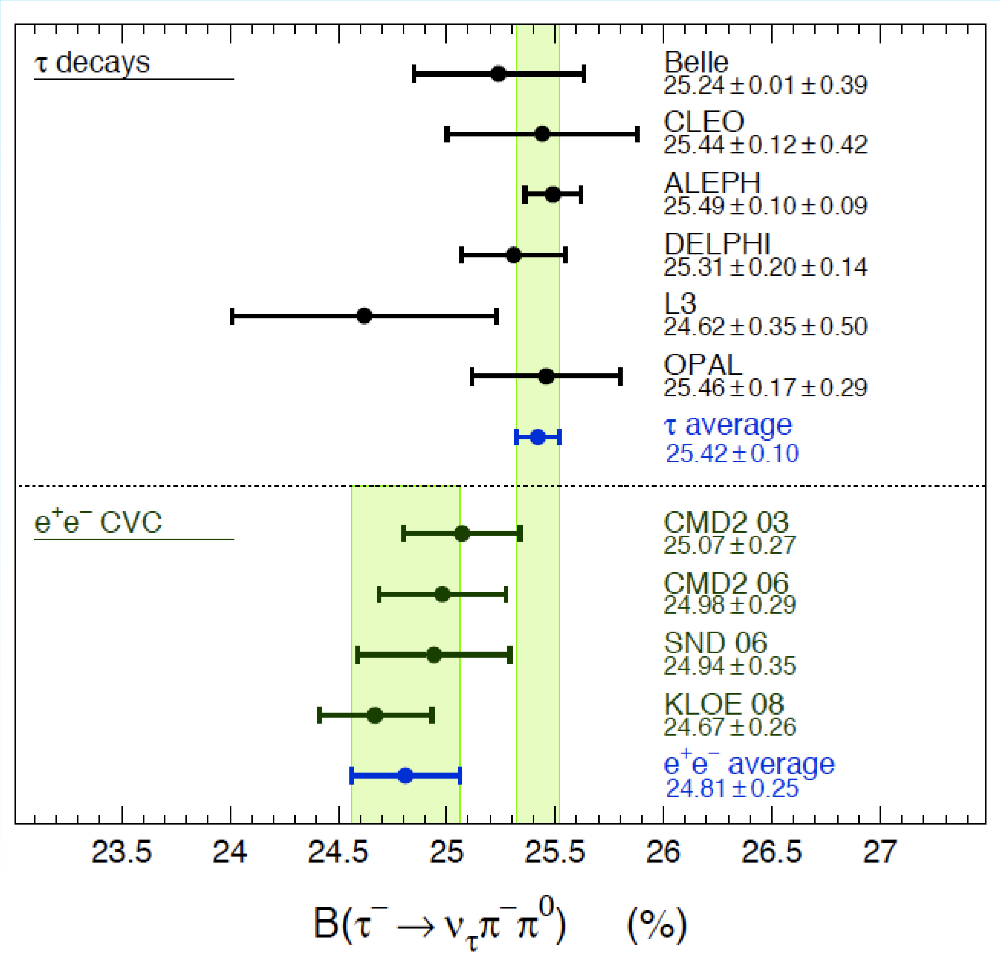
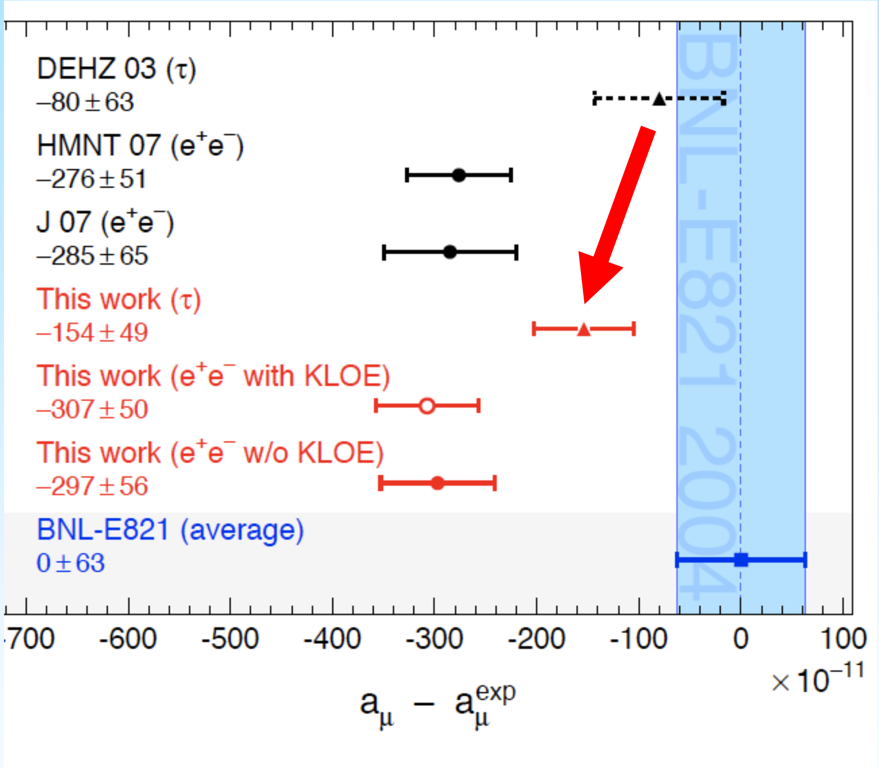
M. Davier, et al., arXiv:0906.5443v1 [hep-ph]



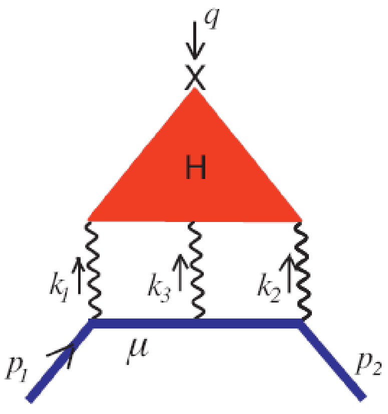


Hadronic Light–by–Light Scattering Contribution to the Muon Anomalous Magnetic Moment

Back

arXiv:0901.0306v1

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



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

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

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

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

Dynamical models with QCD behavior

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

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

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

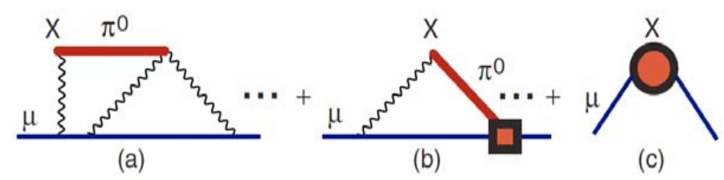
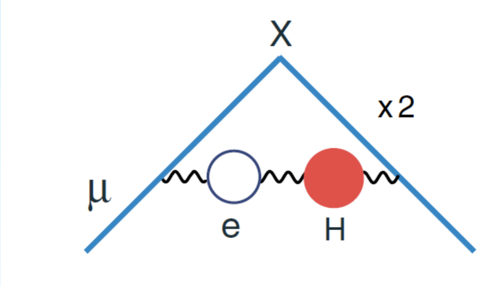
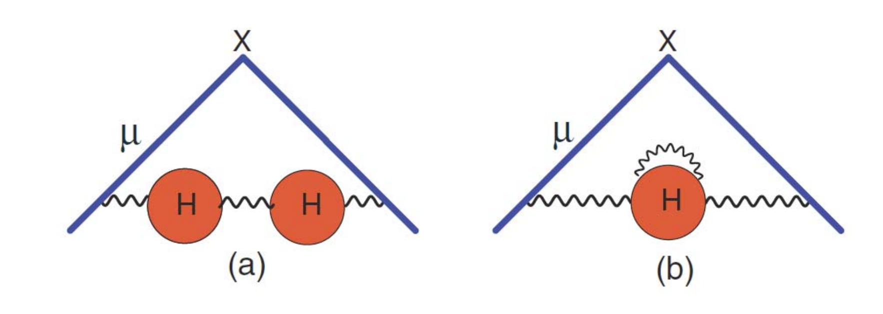


Figure 53. One Goldstone reducible diagrams in chiral perturbation theory.

Examples of other 3-loop hadronic contributions:





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

- 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±$\mathcal{O}(10^3)$	253.7±$\mathcal{O}(10^2)$	193.6
$M_{\tilde{\tau}_R}$	164.1±$\mathcal{O}(10^3)$	134.1±$\mathcal{O}(10^2)$	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±$\mathcal{O}(10^2)$	439.0±$\mathcal{O}(10^2)$	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±$\mathcal{O}(10^3)$	411.1±$\mathcal{O}(10^2)$	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

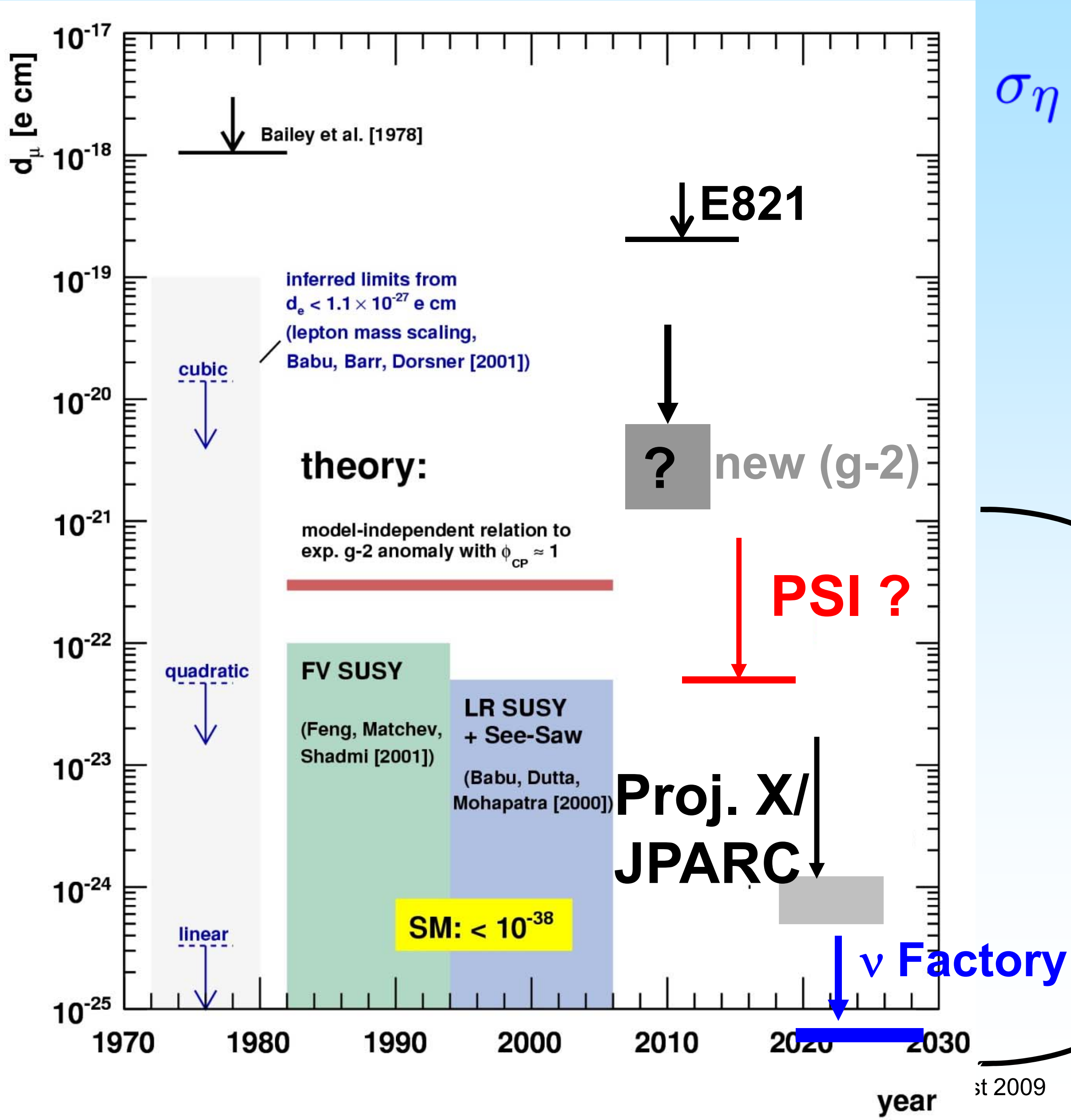
Present nEDM experiments

Back

- Cryo-EDM
  - on the floor at ILL, de-bugging the experiment
- Serebov et al., (ILL, Grenoble)
  - 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.
- SNS nEDM collaboration
  - has CD1, CD2 review in late 2009

Muon EDM Limits: Present and Future

Back



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

Need:

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

$d_\mu \simeq 10^{-23}$ e·cm

Dedicated storage rings

st 2009

PSI muon EDM storage ring

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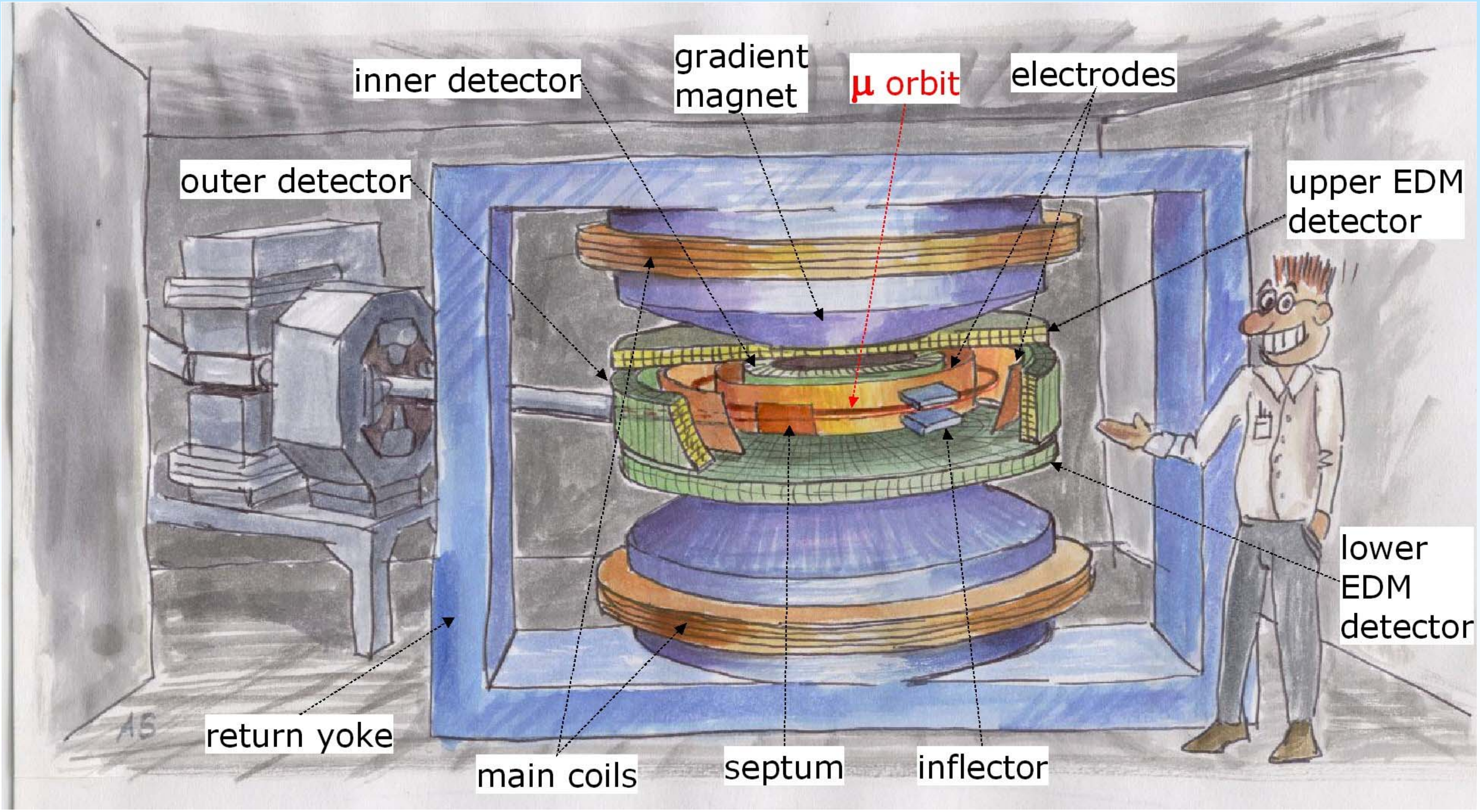


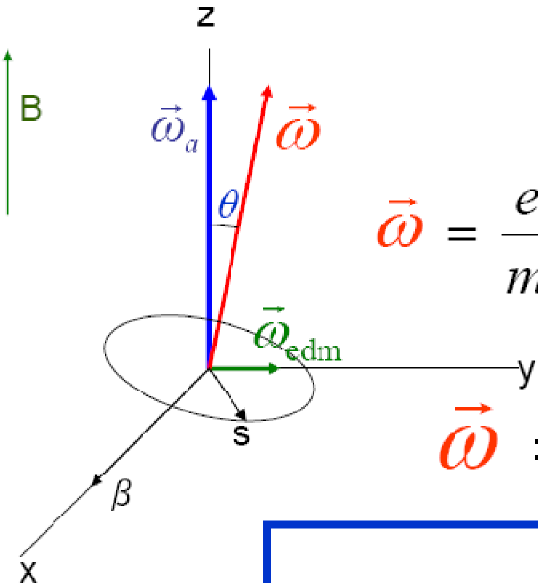
by A. Streun

Parasitic Muon EDM Measurement using straw tube arrays

[Back](#)

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

arXiv:0811.1207v1



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

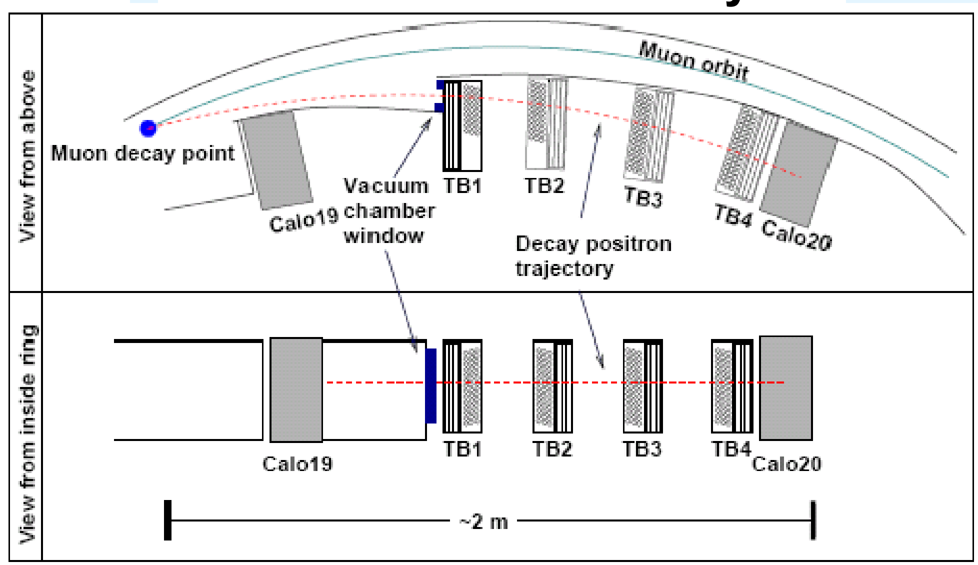
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

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

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

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

E821 straw-tube array



E821 Data: up-going/down-going tracks vs. time, (modulo the g-2 frequency):

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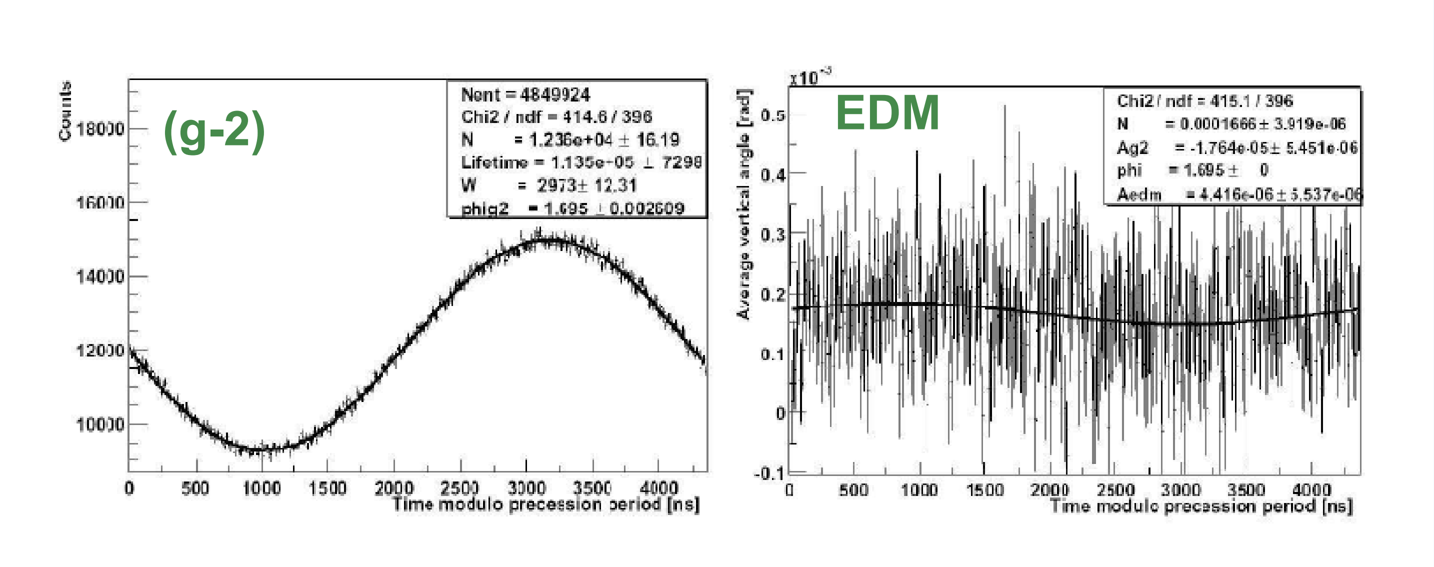


(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

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

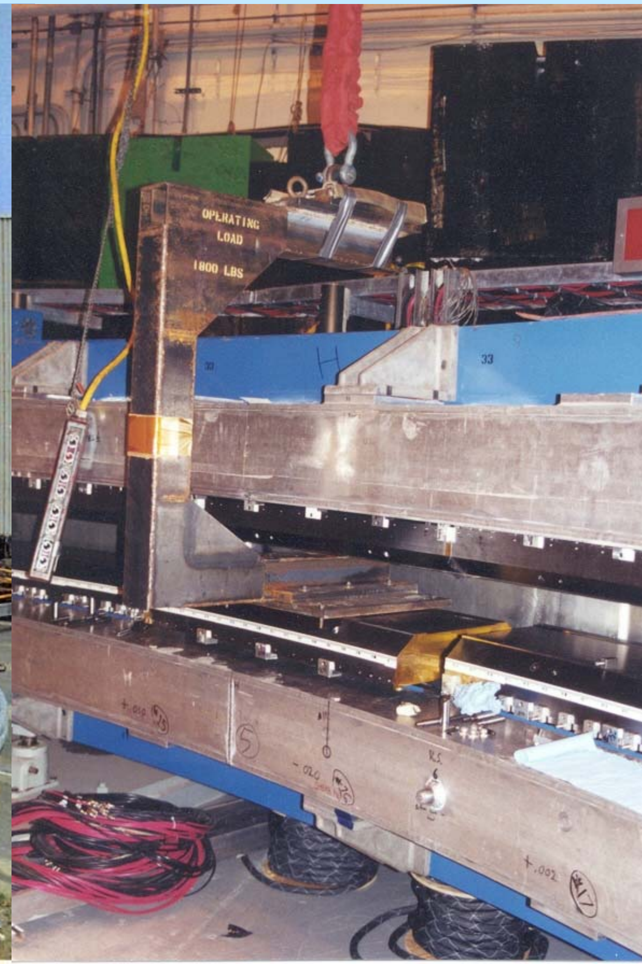
Back

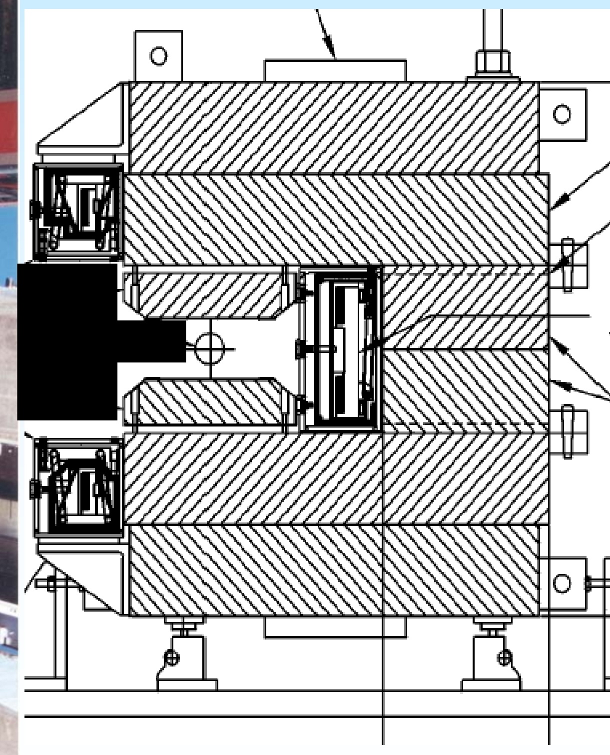
- Mu2e at Fermilab
  - Stage 1 approval from the PAC
  - CD0 expected soon
  - much work on design, simulations etc. underway
- COMET   PRISM/PRIME at J-PARC
  - under consideration by the PAC, many studies underway

Ring relocation to Fermilab

Back

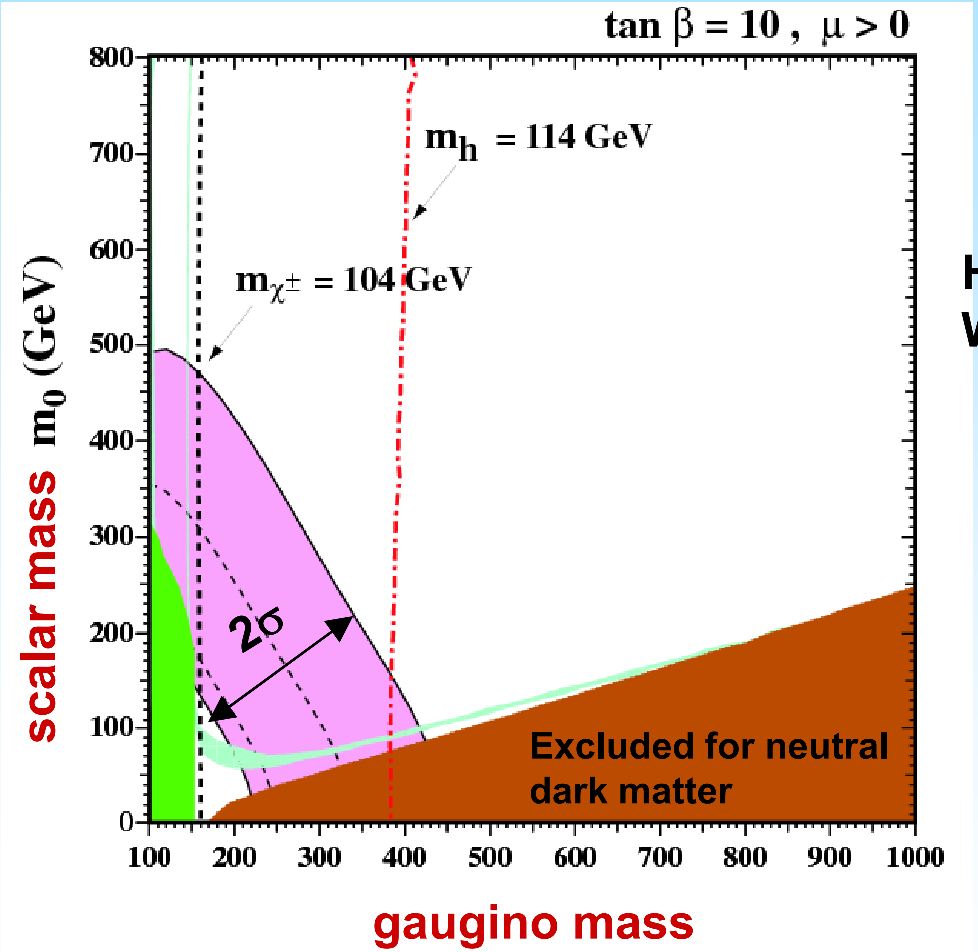
- Heavy-lift helicopters bring coils to a barge
- Rest of magnet is a "kit" that can be trucked to and from the barge





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

Back



Present:

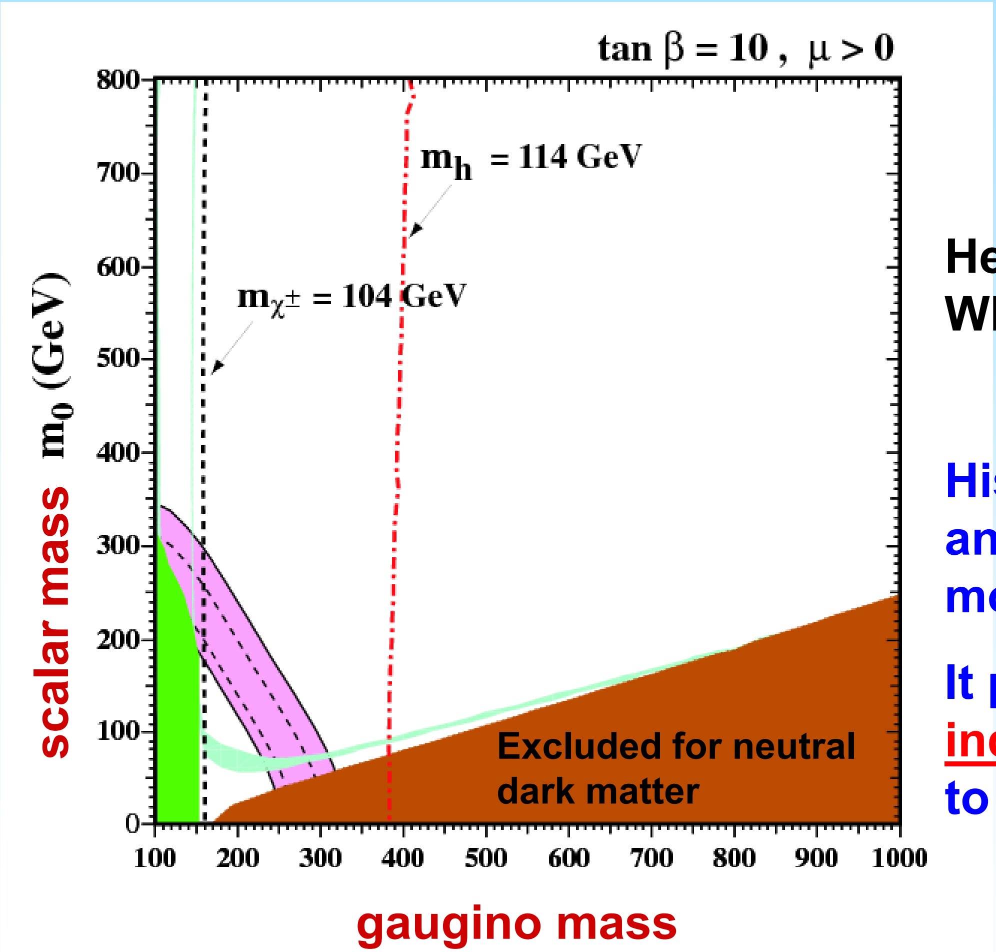
$\Delta a_\mu = 295 \pm 88 \times 10^{-11}$

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)

Back



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.

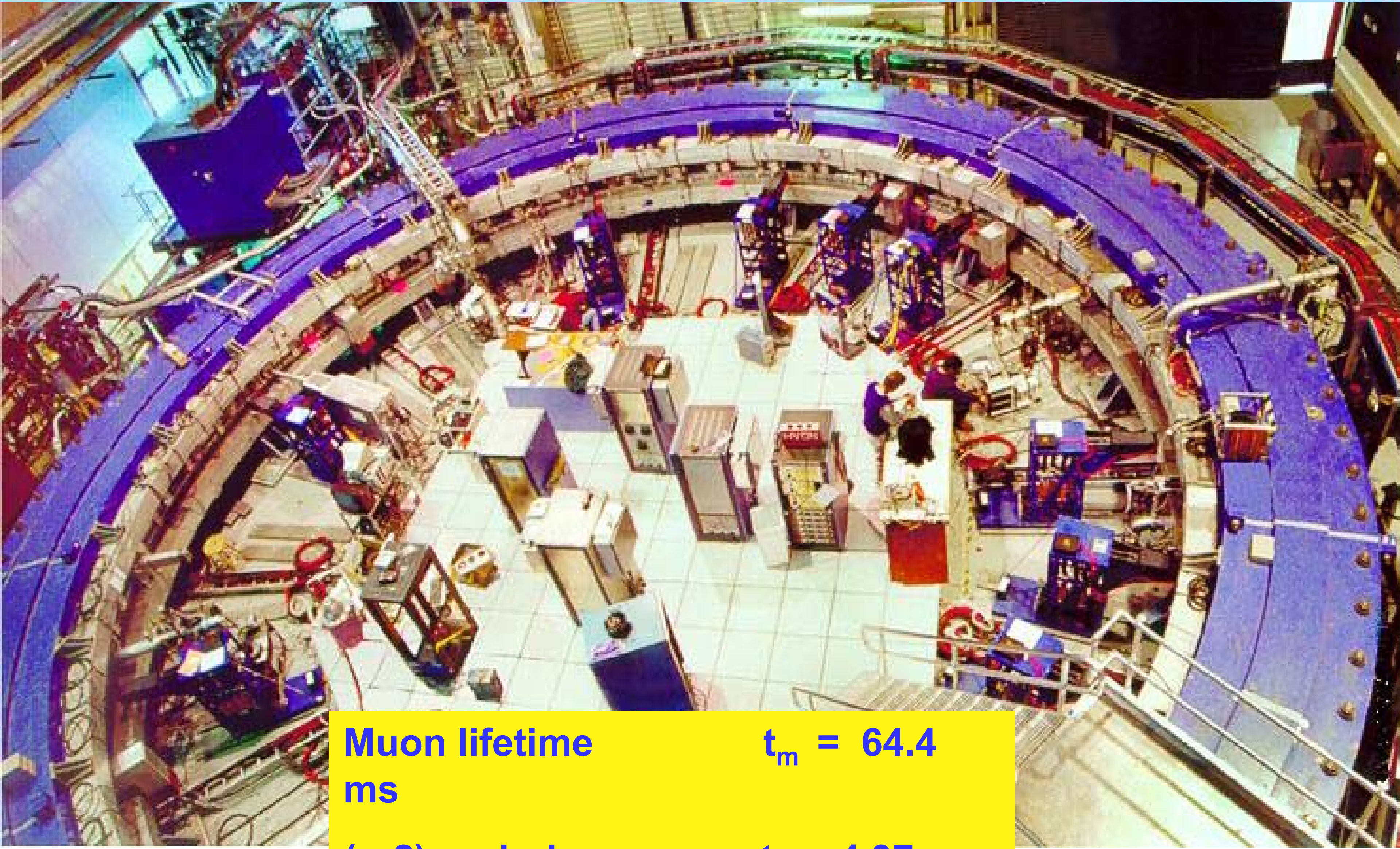
It provides constraints that are independent and complementary to high-energy experiments.

With new experimental and theoretical precision and same Δa_μ

courtesy Keith Olive

Thank you,
THE END

muon (g-2) storage ring

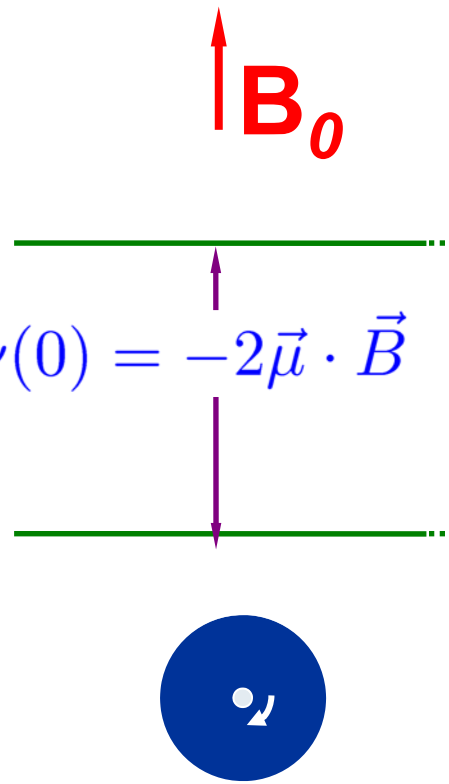


Muon lifetime t_m **= 64.4 ms**

(g-2) period t_a **= 4.37 ms**

BOSTON UNIVERSITY

Principle of the "traditional" EDM measurements



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

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

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

E=100kV/m

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

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

Animation by J. Karamath