Fundamental Symmetries

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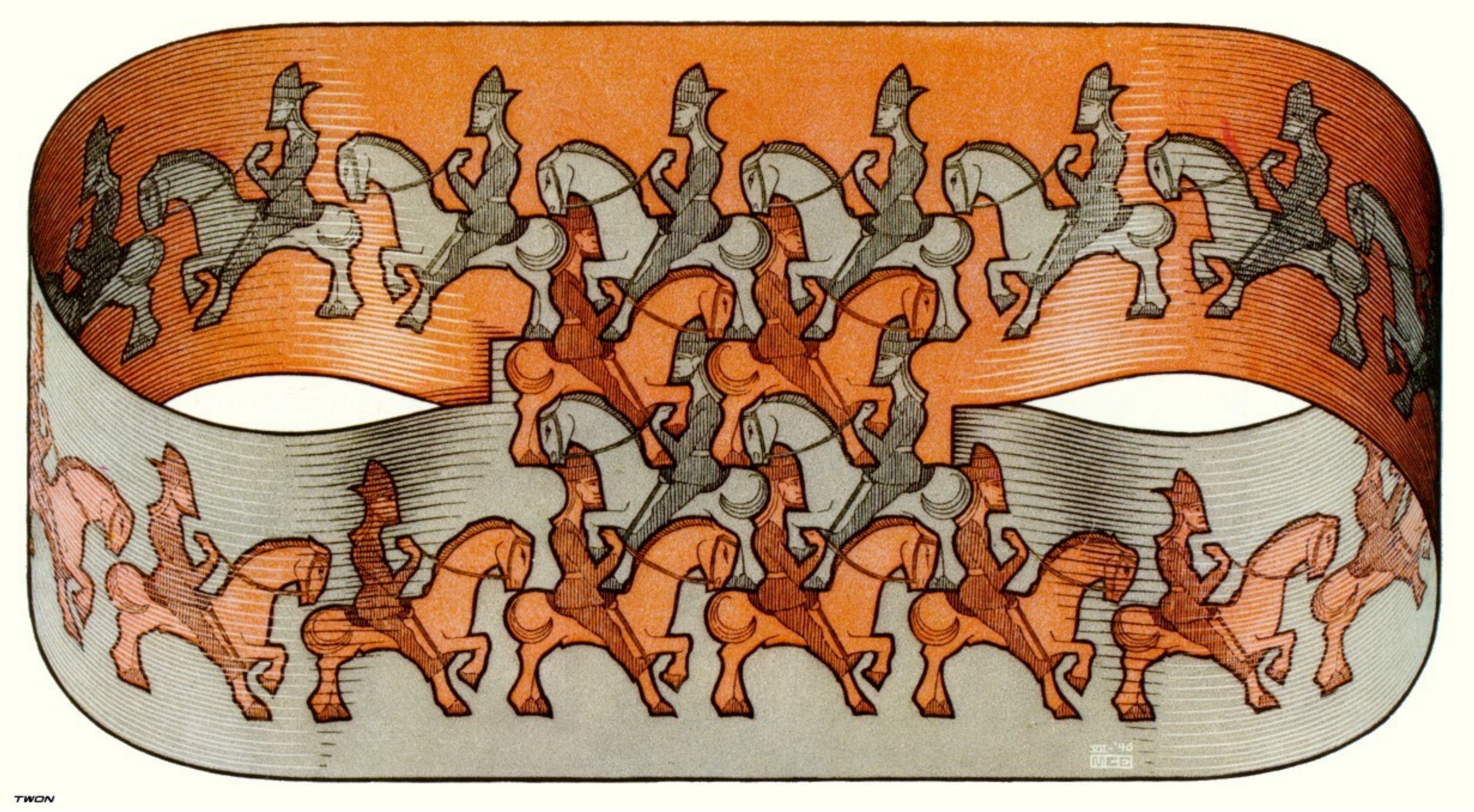


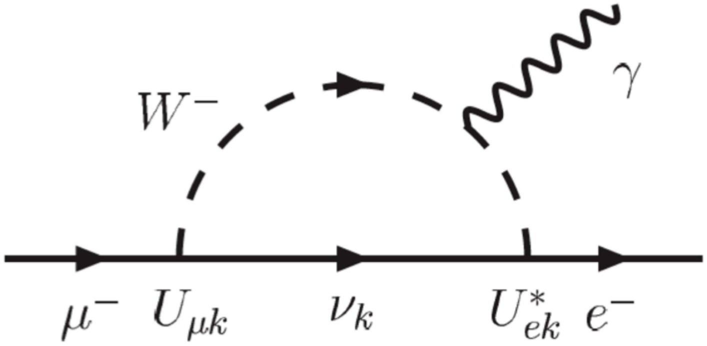
Fundamental Symmetries : Overview

- Standard Model : Inadequacies
- Experimental Tests of Standard Model and Symmetries
    - Baryon Number Violation : Proton Decay
    - Parity Violation : MOLLER at JLab
    - Charged Lepton Flavor Violation : $\mu N \to eN$
    - Electric Dipole Moment Searches : e, μ, n, p, nuclei
    - Precision Test of the Standard Model : Muon g-2
- Summary and Outlook

- My experience : experimentalist, worked on polarized deep-inelastic scattering, muonium hyperfine structure (test of bound state QED), muon g-2, electron EDM searches in polar diatomic molecules, polarized proton-proton scattering with PHENIX collaboration at RHIC - to measure Δg and $\Delta \bar{u}$ and $\Delta \bar{d}$, new muon g-2

Low Energy Tests of the Standard Model : Charged Lepton Flavor Violation CLFV

- Observation of neutrino oscillations implies neutrinos have mass, and lepton flavor is violated (certainly for neutral leptons)
- Accommodated in SM without a satisfying explanation
- Non-zero neutrino mass leads to *charged* LFV through SM physics alone, but rate impossibly low to detect
- Consider massive neutrino contribution to CLFV muon decay $\mu \to e\gamma$:



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M_W^2}\right| < 10^{-54}$$

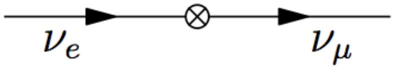
⇒ $U_{\alpha k}$ are elements of lepton mixing matrix; $\alpha = e,\ \mu,\ \tau$ are flavor eigenstates, $k = 1,\ 2,\ 3$ are the mass eigenstates

⇒ CLFV detection would be unambiguous evidence of physics beyond SM

⇒ CLFV occurs in most scenarios of physics beyond SM at BRs accessible by new experiments

⇒ Some are sensitive to mass scales well beyond LHC ($>$ 1000 TeV !)

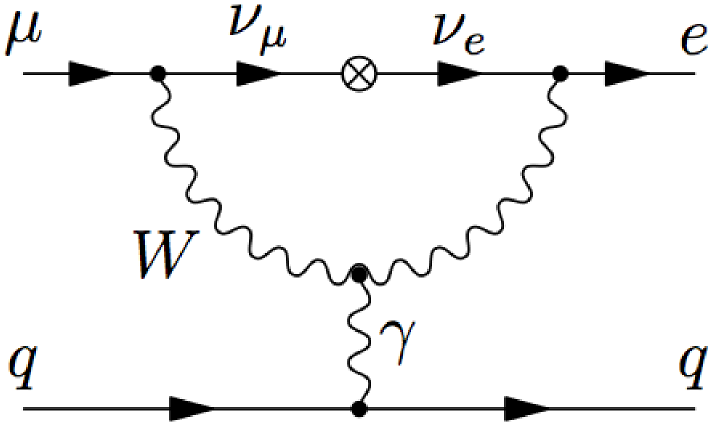
Low Energy Tests of the Standard Model : CLFV



- What about *charged* lepton flavor violation (CLFV)? Many possible channels :
- Compare coherent conversion $\mu^- \; N \;\; \rightarrow \;\; e^- \; N$ in field of a nucleus to capture rate

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

- Best limit $\mu \rightarrow e$ in field of gold nucleus $R_{\mu e} < 7 \times 10^{-13}$ (90% C.L.) SINDRUM II at PSI
- $\mu^- \rightarrow e^-$ in field of nucleus actually possible in the SM from neutrino oscillations
- Suppressed since loop amplitudes proportional to $\left(\Delta m_{ij}^2 / M_W^2\right)^2$, neutrino mass differences $|\Delta m_{ij}| << M_W$
- SM fraction $R_{\mu e}$ at level of 10^{-54}, factor 10^{40} below current limits!



Low Energy Tests of Symmetries of the Standard Model : CLFV

- CLFV has never been observed experimentally in other channels either
- Current limit BR$(\mu^+ \to e^+\gamma) \leq 2.4 \times 10^{-12}$ (MEG PSI, 2010)
- Current limit BR$(\mu^+ \to e^+e^-e^+) \leq 1.0 \times 10^{-12}$ (SINDRUM I/PSI 1988)
- $\tau \to eee$, $K_L \to \mu e$, ...

⇒ CLFV would be unambiguous evidence of new physics beyond the SM

⇒ Many BSM theories predict huge enhancements, rate of $\mu^- N \to e^- N$ within a few orders of current limit

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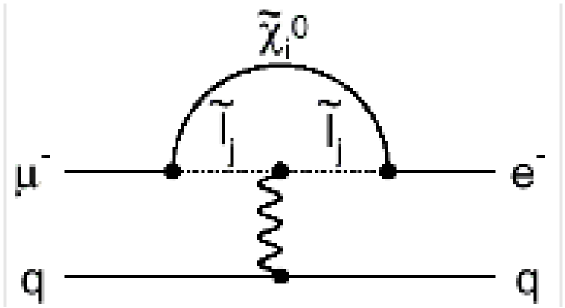
- Motivates Mu2e search for charged lepton flavor violation (CLFV) at Fermilab (R. Bernstein, J. Miller)

⇒ Mu2e will probe 10^4 beyond SINDRUM II sensitivity,
mass scales well beyond LHC ($>$1000 TeV)
(thanks to R. Bernstein and A. Gaponenko for material, see also CDR : arXiv:1211.7019)

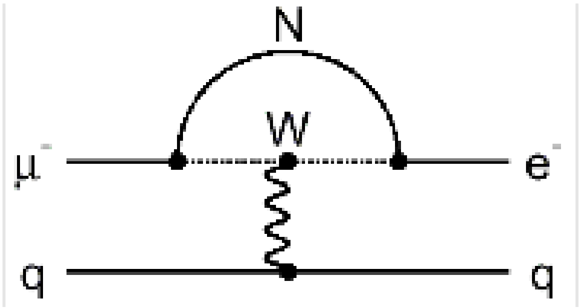
Low Energy Tests : Mu2e Search for μ^- to e^- Conversion

Many possible contributions to μ to e conversion from physics beyond the Standard Model

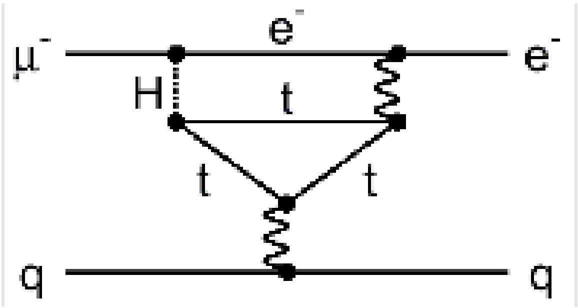
Loops



Supersymmetry

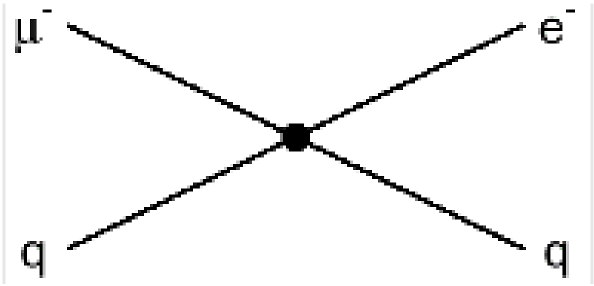


Heavy Neutrinos

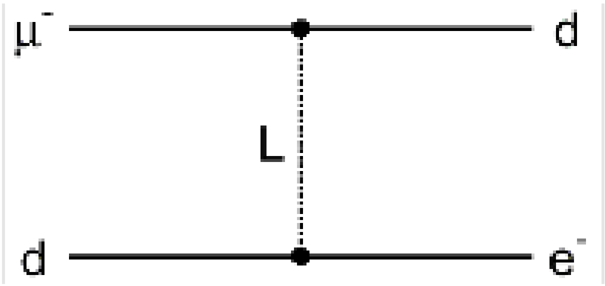


Two Higgs Doublets

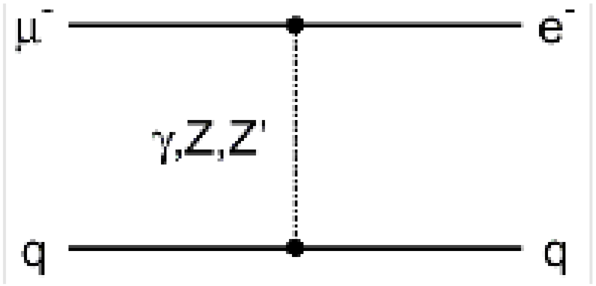
Contact Terms



Compositeness



Leptoquarks



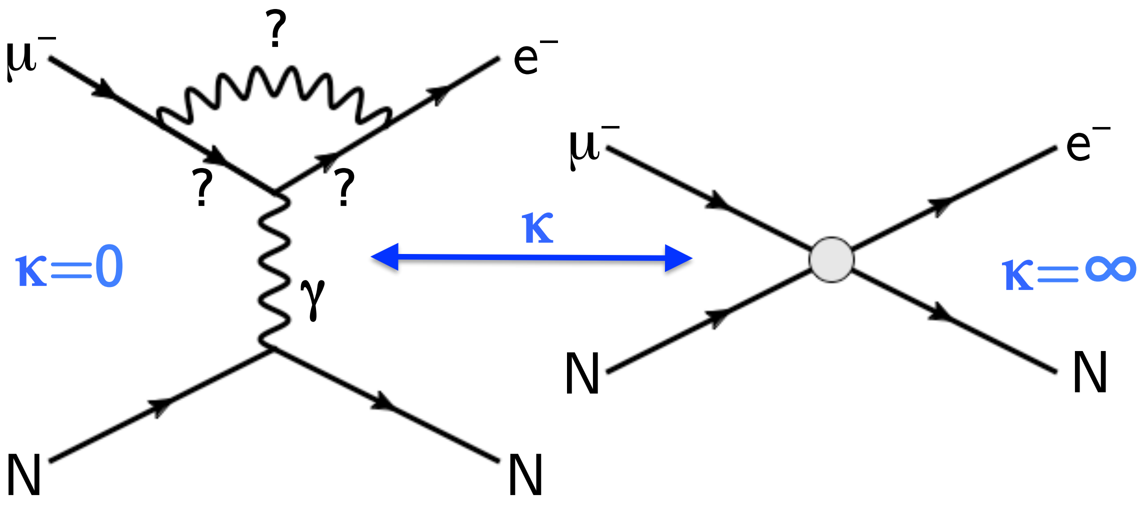
New Heavy Bosons

- Note that SUSY loop with sleptons similar to contribution to $g_\mu - 2$: probing similar physics (Mu2e probes off-diagonal terms)
- See Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. **58**, 315 (2008)

Low Energy Tests : Mu2e Search for μ^- to e^- Conversion

- Effective, model-independent CLFV Lagrangian :

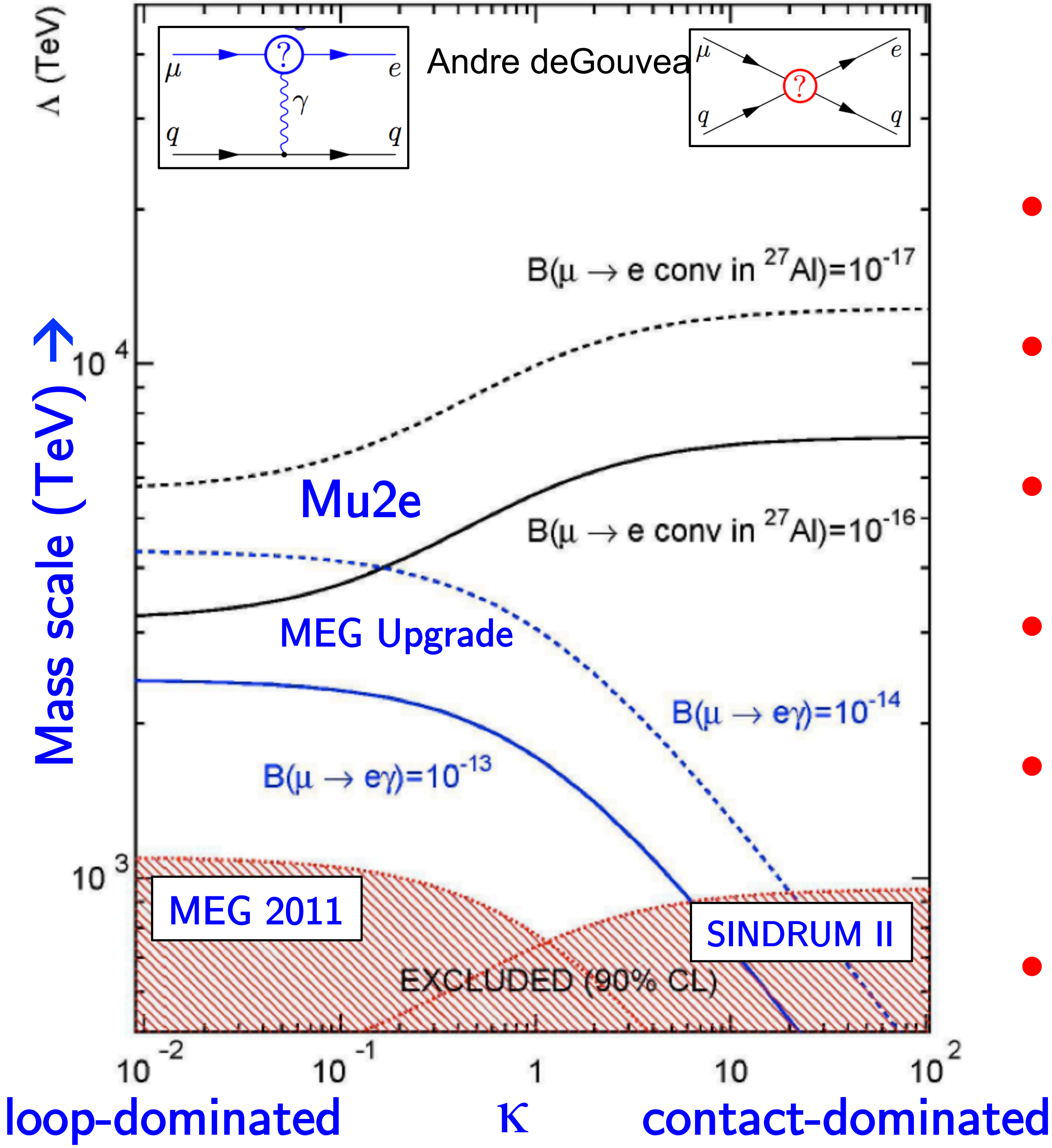
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\,\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\,\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$



- Small κ ⇔ loop dominated interactions
- Supersymmetry, heavy neutrinos, ...
- Contributes to $\mu^- \to e^- + \gamma$ when photon real

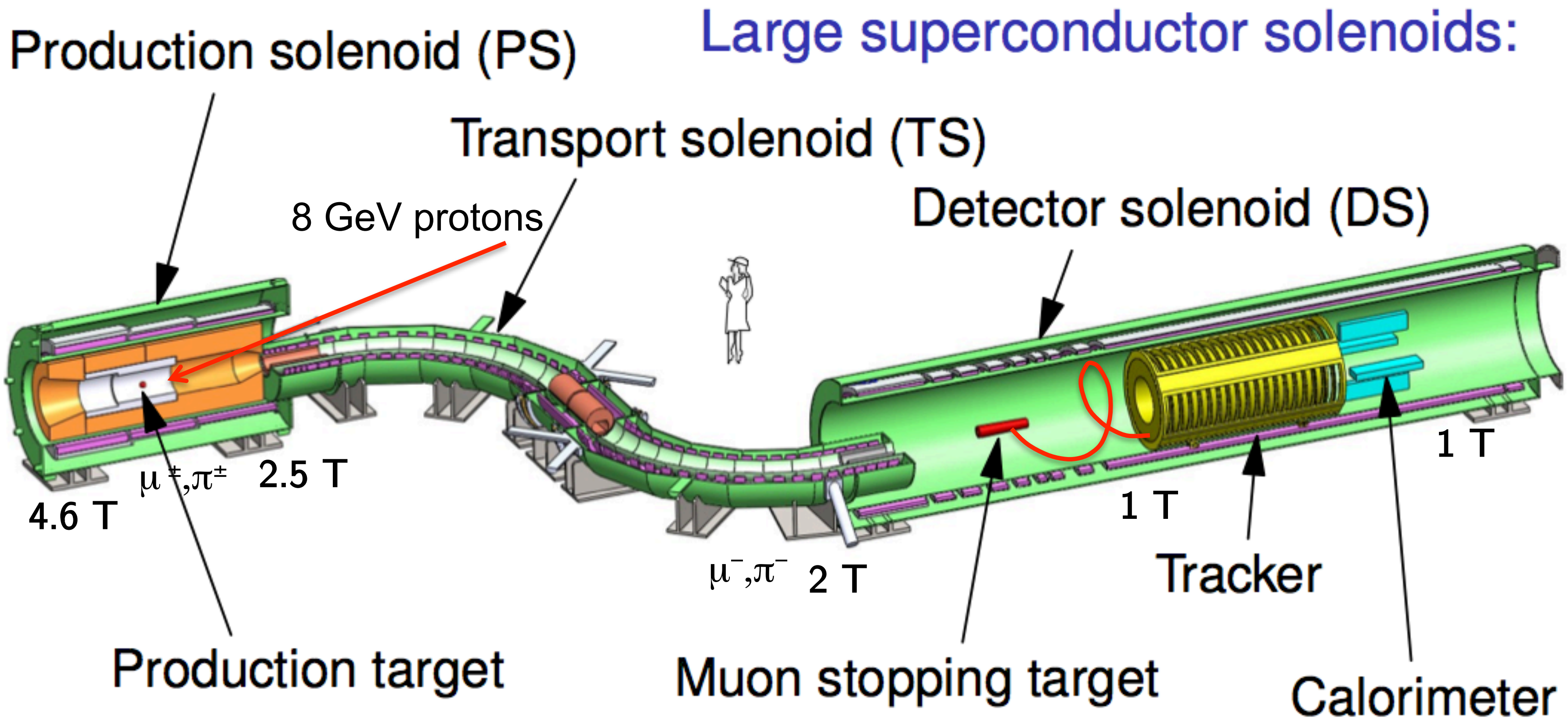
- Large κ ⇔ contact dominated interactions
- New, heavy particles : leptoquarks, heavy Z', ...
- No contribution to $\mu^- \to e^- + \gamma$

Low Energy Tests : Mu2e Search for μ^- to e^- Conversion



- Mu2e aims at a factor 10^4 improvement over SINDRUM II
- Physics reach to 10^4 TeV, well beyond LHC
- Similar sensitivity to loop-dominated physics as MEG upgrade, 6×10^{-14}
- Mu2e is the most sensitive CLFV expt for most models
- Addresses crucial issues in physics of lepton families and near-conservation of lepton flavor
- Very high discovery potential

The Mu2e Experimental Technique in a 25 m long nutshell



- 8 GeV protons, 3.7×10^{7}/200 ns pulse, 1.7 μs period, on tungsten target, produces $\pi^{\pm}$
- 4.6 T to 2.5 T axial gradient in production solenoid field collect and direct $\pi^{\pm}$, $\mu^{\pm}$ to S-shaped transport solenoid
- Transport solenoid + collimators guide low energy (≈ 50 MeV/c) μ^{-} to Al foil target
- Minimizes transport of neutrals, high energy, positive particles, no line of site to Al target
- Not shown : Cosmic ray veto, proton beam extinction monitor, stopping target monitor

The Mu2e Experimental Technique in a 25 m long nutshell

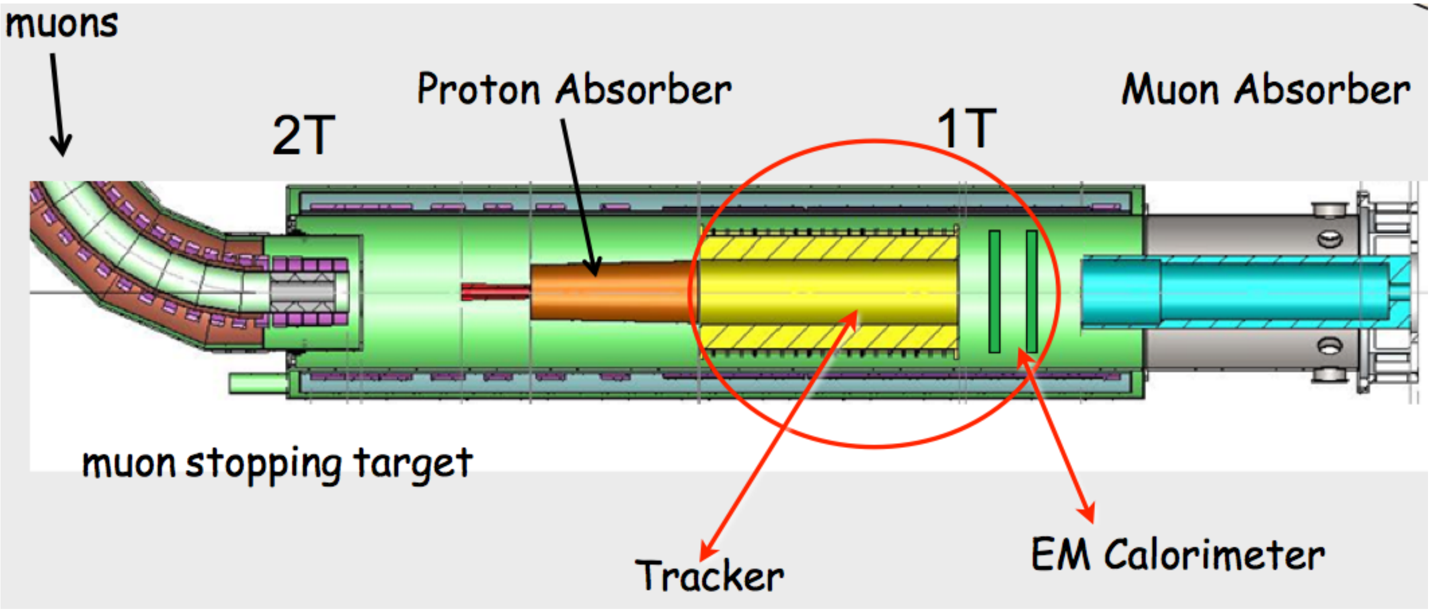
- Stop $\approx 60K$ low energy μ^- per proton pulse in aluminum foil targets (0.0016 μ/p)
- μ^- captured in orbit in Al, emits x-rays as de-excites into 1S, lifetime $\tau^{\rm Al}_{\mu,1S} = 864$ ns
- Detect x-rays from 66-446 keV from cascade to 1S which takes ps
  $\Rightarrow$ use to determine muon stopping rate
- Radius of μ^- orbit in Al $\approx$ $a_0 \times m_e/(m_\mu \times Z) = 20$ fm, overlaps Al nucleus radius $\approx$ 4 fm

(1) μ^- captured by nucleus (60%) : $\mu^- + \mathrm{Al}(A = 27, Z = 13) \rightarrow \nu_\mu + \mathrm{Mg}(A = 27, Z = 12)$

(2) μ^- decays in orbit (40%) : $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$, most serious background

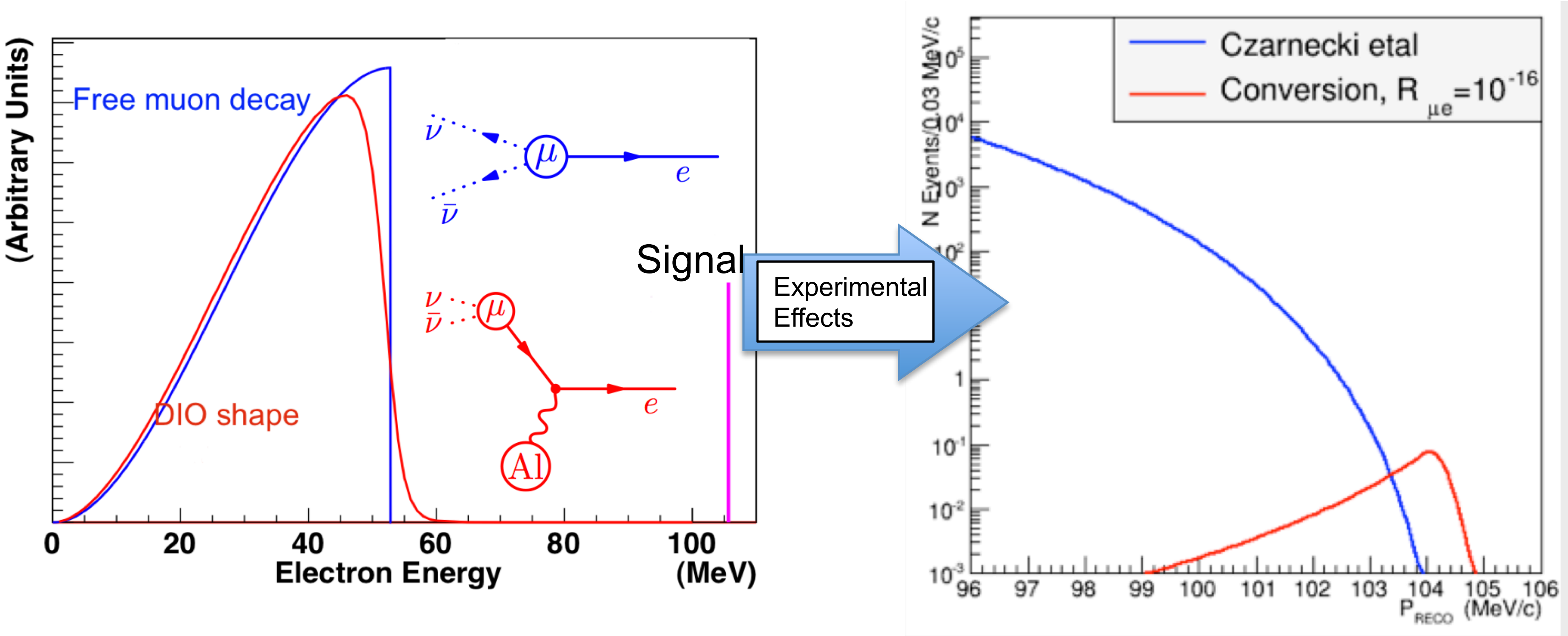
(3) $\mu^- \rightarrow e^-$ conversion, monoenergetic e^- with $E_e = m_\mu c^2 - E_{\rm recoil} - E_{\rm 1S\ binding} = 104.97$ MeV

- Momentum determined with tracker to $\sigma(p) < 180$ keV, calorimeter measures E, trigger



Mu2e Backgrounds and Pulse Structure

- Biggest background from μ^- decay in orbit
- Michel spectrum free decay endpoint : E(max) $= \frac{m_\mu^2 + m_e^2}{2m_\mu} =$ 52.8 MeV
- But : e^- recoil off nucleus after μ decay pushes endpoint to conversion energy
- Spectrum drops off as $(E_{\text{Conv}} - E)^5$
- A. Czarnecki *et al.*, Phys. Rev. D **84**, 013006 (2011)



Mu2e Backgrounds and Pulse Structure

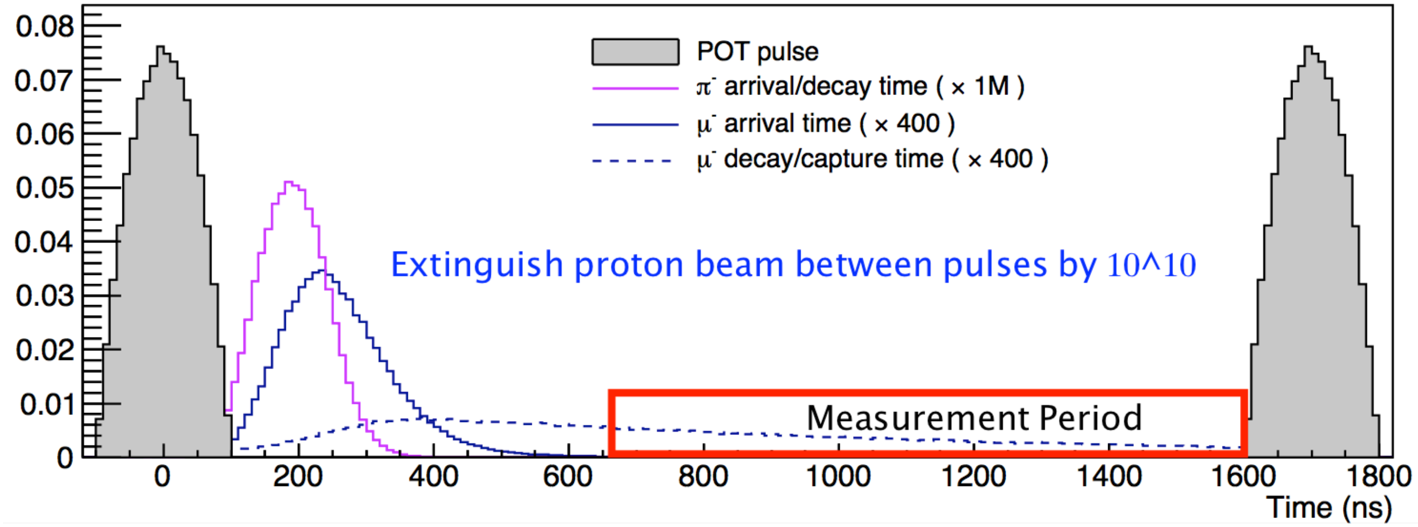
- Prompt background : Radiative π Capture : $\pi^- + ^{27}_{13}\mathrm{Al} \rightarrow ^{27}_{12}\mathrm{Mg} + \gamma$, $E_\gamma \leq 139.6$ MeV
- γ up to m_π, peak at 110 MeV, if $\gamma \rightarrow e^+e^-$ converts asymmetrically, looks like signal
- Many pions in muon beam, produces a prompt background

⇒ Reduce impact by delayed measurement period after π decay, 10^{11} suppression of RPC

- Delayed background : Antiproton-Induced Radiative π Capture
- $\bar{p}$ from production target travel slowly to Al stopping target during measurement period
- Annihilation of $\bar{p}$ produces π, possible RPC+asymmetric photon conversion looks like signal

⇒ $\bar{p}$ slow, dE/dx large, window in TS reduces background, annihilate far from Al target

- Cosmic ray muons knock e^- from stopping target, reduce with cosmic ray veto



Extinguish proton beam between pulses by 10^10

Measurement Period

Mu2e Background and Signal Expectations

- Assuming 3 years of 1.2×10^{20} protons/year (8 kW beam power)
- Expect ≈ 0.0016 stopped muons/proton
- Expect $\approx 5 \times 10^{17}$ stopped muons
- Inter-pulse extinction 10^{-10}
- Cosmic ray veto eff. 99.99%
- Background Expectations ⇒

Background Source	Expected Events
μ decay in orbit	0.22±0.06
Antiproton induced	0.10±0.05
Cosmic rays	0.05±0.013
Radiative π capture	0.03±0.007
μ decay in flight	0.01±0.003
π decay in flight	0.003±0.0015
Scattered beam e^-	0.0006±0.0003
Radiative μ capture	$<2\times10^{-6}$
Total	0.4±0.1

⇒ $R_{\mu e}$ (single event sensitivity) $\approx 2 \times 10^{-17}$, $R_{\mu e}$ (90% C.L.)$=6 \times 10^{-17}$

⇒ Clear, near-ideal experimental signature : single, monoenergetic particle (easier than coincidence like $\mu^- \to e^- \gamma$)

⇒ Commissioning, running in 2020

The Mu2e Experiment at Fermilab : The Takeaway

- CLFV is one of the most important yet poorly understood issues in fundamental physics
- Most new physics models have no requirement on LF conservation - violation may be just around the corner
- Mu2e complementary to LHC, which is not well-suited to study CLFV except in select circumstances.
- Mu2e (along with the COMET proposal at JPARC) will be the most sensitive of the CLFV experiments, $10000\times$ better than previous experiments.
- Fermilab beam lines are well-suited to produce lots of pulsed protons.
- Solenoidal collection system together with the Fermilab beam will produce the most powerful source of muons in the world.
- Physics reach is impressive : factors of 10^4 improvement, energy scales of 1000s of TeV

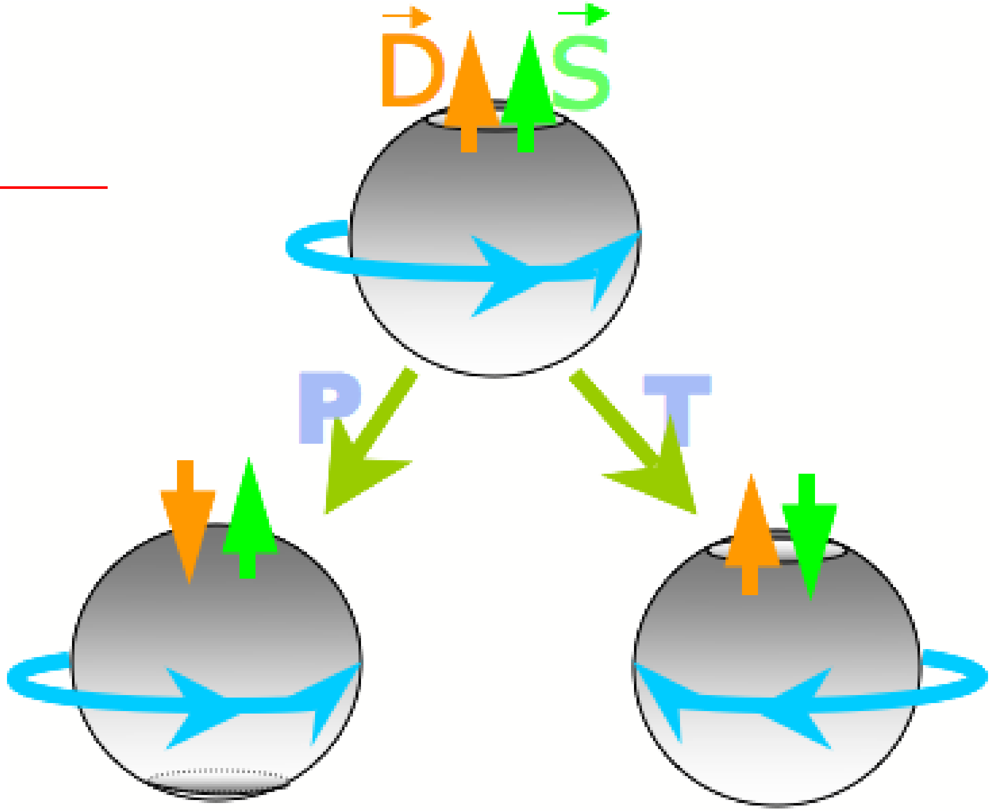
What is a Permanent Electric Dipole Moment (EDM) ?

- Non-relat. Hamiltonians of bare spin 1/2 particle with magnetic moment $\vec{\mu}$ and EDM $\vec{d}$

$$H_{\text{Magnetic Dipole}} = -\vec{\mu}\cdot\vec{B} \; = \; -\,\mu\vec{\sigma}\cdot\vec{B}$$

$$H_{\text{Electric Dipole}} = -\vec{d}\cdot\vec{E} \; = \; -\,d\vec{\sigma}\cdot\vec{E}$$

- EDM is analog of magnetic dipole moment
- Manifests itself as a linear Stark effect



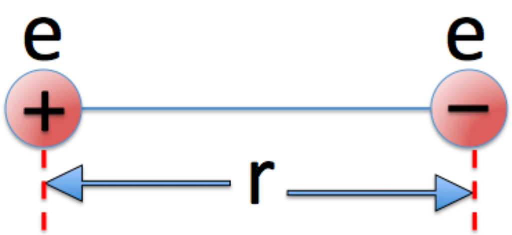
Behavior of Moments under Parity and Time Reversal

	$\vec{\sigma} \sim \vec{r}\times\vec{p}$	$\vec{B} \sim \vec{j}\times\vec{r}/\lvert\vec{r}\rvert^3$	$\vec{E} \sim -\vec{\nabla}V$
P	even	even	odd
T	odd	odd	even

- $H_{\text{Magnetic Dipole}}$ is P-even and T-even
- $H_{\text{Electric Dipole}}$ is P-odd and T-odd !!!

$\Rightarrow$ For fundamental particle to have an EDM, P and T must be violated

Don't Polar Molecules have Electric Dipole Moments ?



Dipole moment of a polar molecule :

$$\vec{d} = \sum e_i \vec{r}_i \; = \; e\, r\, \hat{z} \; \simeq \; \mathrm{e\ a_0} \; \simeq \; 5 \times 10^{-9}\ \mathrm{e \cdot cm}$$

Reconsider the EDM of a polar molecule :

- Dipole moment parallel to internuclear axis ⇒ averaged out by rotation
- Do polar molecules really exhibit a linear Stark shift under $H_{\mathrm{EDM}} = -\vec{d} \cdot \vec{E}_{\mathrm{ext}}$?

$$E_i' = E_i + \langle \Psi_i | H_{\mathrm{EDM}} | \Psi_i \rangle + \sum \frac{|\langle \Psi_j | H_{\mathrm{EDM}} | \Psi_i \rangle|^2}{E_i - E_j} \;\simeq\; E_i + \frac{(\vec{d} \cdot \vec{E}_{\mathrm{ext}})^2}{E_i - E_j}$$

$$|\Psi_i' \rangle \;\approx\; |\Psi_i\rangle + |\Psi_j\rangle \frac{\langle \Psi_j | H_{\mathrm{EDM}} | \Psi_i \rangle}{E_i - E_j}$$

- Energy eigenstates Ψ_i are eigenstates of parity but $H_{\mathrm{EDM}} = -\vec{d} \cdot \vec{E}_{\mathrm{ext}}$ is P-odd
- $\vec{E}_{\mathrm{ext}}$ field mixes opposite parity states - *induces* dipole, E shift *quadratic* in $\vec{E}_{\mathrm{ext}}$
- No linear Stark shift !

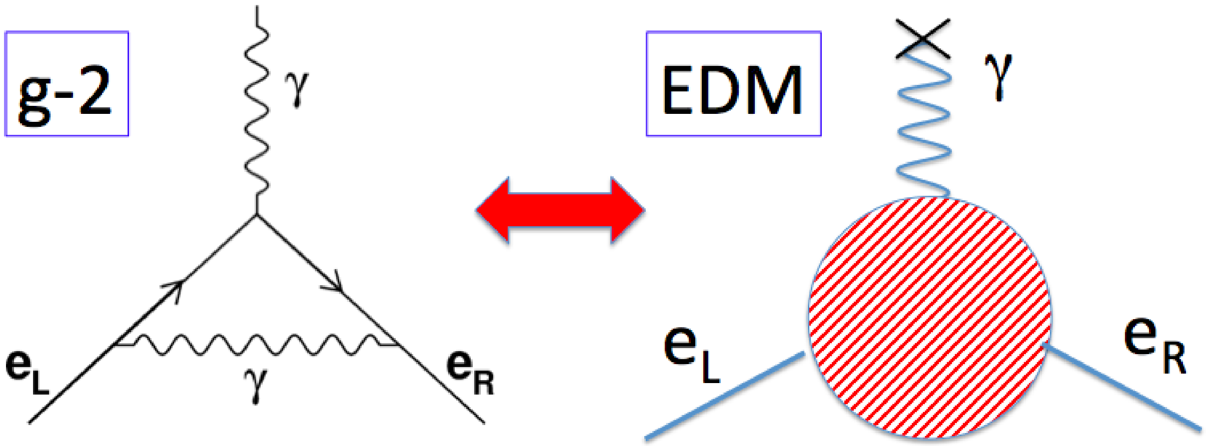
- Only permanent EDM makes mixed parity ground state and *linear* Stark effect

Why do we expect the electron, proton, neutron, nucleus ... EDMs $d \neq 0$?

- EDMs violate P, T : through CPT theorem T-violation ⇔ CP-violation
- P-violation observed, CP-violation observed in K and B mesons
- Can generate EDM using Standard Model physics through radiative corrections

⇒ In same way radiative corrections make $g_e \neq 2.0000$, RC can make $d_e \neq 0$

⇒ Construct diagram with enough loops to incorporate P and CP-violating processes



- In SM need at least 4 loops - predicts $|d_e| \leq 1 \times 10^{-38}$ e·cm
- 11 orders of magnitude below current limit $|d_e| < 1.0 \times 10^{-27}$ e·cm !

(Ed Hinds with YbF at Imperial College; J.J. Hudson *et al.*, Nature **473**, 493 (2011).)

- Reference scale "dipole moment" of a molecule $\approx e \times a_0 \approx 5 \times 10^{-9}$ e·cm

Current limits on electron, proton, neutron, nuclear EDMs

$\Rightarrow$ There is no evidence for a non-zero permanent electric dipole moment of a fundamental particle, despite searching since the 1950s : Should we give up?

Particle/Atom	SM value [e·cm]	Current EDM Limit	d_n equivalent
Neutron	$\approx 10^{-32} - 10^{-31}$	$< 2.9 \times 10^{-26}$	2.9×10^{-26}
^{199}Hg		$< 3.1 \times 10^{-29}$	5.8×10^{-26}
^{129}Xe		$< 6 \times 10^{-27}$	6×10^{-23}
Proton	$\approx 10^{-32} - 10^{-31}$	$< 7.9 \times 10^{-25}$	7.9×10^{-25}
Deuteron	$\approx 10^{-32} - 10^{-30}$		
Electron	$\approx 10^{-40} - 10^{-38}$	$< 1.0 \times 10^{-27}$	

Neutron Limits : C.A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006)

Mercury Limits : W.C. Griffiths *et al.*, Phys. Rev. Lett. **102**, 101601 (2009).

Electron Limits : J.J. Hudson *et al.*, Nature **473**, 493 (2011); D.M. Kara *et al.* arXiv:1208.4507

Current and Future limits on electron, proton, neutron, nuclear EDMs

$\Rightarrow$ There is no evidence for a non-zero permanent electric dipole moment of a fundamental particle $\Rightarrow$ but there may be soon !

Particle/Atom	SM value [e·cm]	Current EDM Limit	Future Goal	d_n equivalent
Neutron	$\approx 10^{-32} - 10^{-31}$	$< 2.9 \times 10^{-26}$	10^{-28}	10^{-28}
^{199}Hg		$< 3.1 \times 10^{-29}$	10^{-29}	2×10^{-26}
^{129}Xe		$< 6 \times 10^{-27}$	$10^{-30} - 10^{-33}$	$10^{-26} - 10^{-29}$
Proton	$\approx 10^{-32} - 10^{-31}$	$< 7.9 \times 10^{-25}$	10^{-29}	10^{-29}
Deuteron	$\approx 10^{-32} - 10^{-30}$		10^{-29}	$3 \times 10^{-29} - 5 \times 10^{-31}$
Electron	$\lesssim 10^{-40}$	$< 1.6 \times 10^{-27}$	$10^{-29} - 10^{-31}$	

Some Current and Future Experimental Efforts

Electron EDM	Hadronic EDMs
Cs Trap : Penn. St., UTexas	Ultracold Neutrons : SNS, ILL, PSI, Munich
Cs Fountain : LBNL	^{199}Hg Cell : Seattle/Princeton
PbO Cell : Yale	^{129}Xe Cell : Tokyo Inst. of Tech.
ThO Beam : Yale/Harvard	^{129}Xe Liquid : Princeton, Garching/Munich
YbF Beam : Imperial	^{223}Rn Trap : TRIUMF,Michigan
PbF Trap : Oklahoma	^{213,225}Ra trapped : KVI, Argonne
HfH$^+$: JILA	Proton storage ring : BNL ?
GdIG Solid : Amherst,Yale,Indiana	Deuteron storage ring : Jülich ?

Why do we expect the electron, proton, neutron, ... EDMs $d \neq 0$?

- SM prediction is so small ⇒ any observation $d_{n,p,e} \neq 0$ definitive evidence of new physics

Reasons to expect there is new physics leading to $d_{n,p,d,e}$ large enough to detect :

- Sakharov showed CP-violation required to generate matter-antimatter asymmetry in universe
  - CP-violation in SM $> 10^5$ too small to account for observations
  - Expect new sources of CP-violation
  - EDMs could be dramatically enhanced
- Most SM extensions predict many new particles and CP-violating phases
  - Predict dramatically enhanced EDMs : $|d_e| \approx 10^{-26} - 10^{-31}$ e·cm !

    $|d_{n,p,d}| \approx 10^{-25} - 10^{-31}$ e·cm !

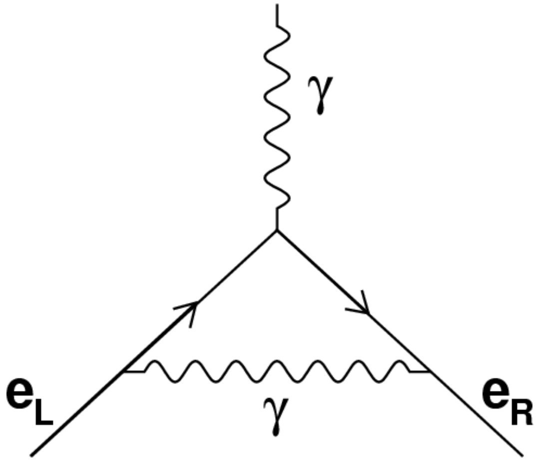
⇒ Observed matter-antimatter asymmetry and theoretical prejudice suggest significant sources of T-violation beyond SM

⇒ $d_{n,p,d,e} \neq 0$ definitive evidence of new physics

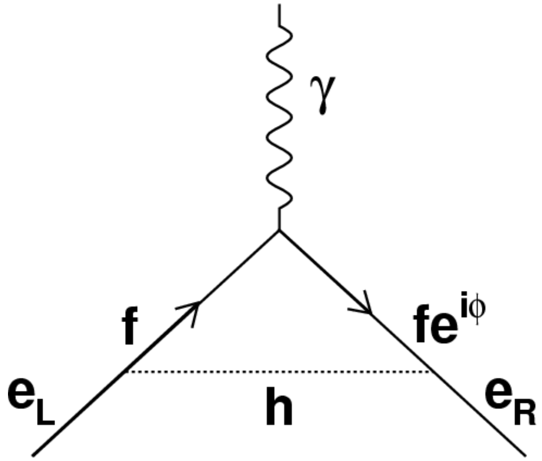
⇒ Predicted $d_{n,p,d,e}$ within range accessible to new experiments

⇒ Good time to look for EDMs ! Must-do physics !

Dimensional Analysis Motivated Estimation of an EDM



$\Longleftrightarrow$



⇒ Energy shift from anomalous mag. moment

$$\Delta E \;\approx\; (g-2)\;\; \mu_B\; |\mathbf{B}|/2$$
$$\approx\; \frac{\alpha}{2\pi}\,\frac{e\hbar}{2m_e c}\;|\mathbf{B}|$$

⇒ Energy shift from an electric dipole moment

$$\Delta E \;\approx\; d_e \cdot \mathbf{E}$$
$$\approx\; \frac{\alpha}{2\pi}\,\frac{e\hbar}{2m_e c}\;|\mathbf{E}| \times \left(\frac{f}{e}\right)^2 \sin(\phi)\left(\frac{m_e}{m_h}\right)^2$$

$$\boxed{d_e \;\approx\; e\,\frac{\alpha}{4\pi}\;\sin(\phi)\,\frac{m_e}{m_h^2}, \quad \sin(\phi) \approx 1}$$

$$\Rightarrow d_e \;\approx\; \frac{1}{137\cdot 4\pi}\,\frac{1.05\times 10^{-27}}{2\cdot 9.1\times 10^{-28}\cdot 3\times 10^{10}}\left(0.5\times 10^{-6}\right)^2\left(\frac{1\ \mathrm{TeV}}{m_h}\right)^2\; e\cdot\mathrm{cm}$$

$$\approx\; 5\;\times\;10^{-27}\left(\frac{1\ \mathrm{TeV}}{m_h}\right)^2\; e\cdot\mathrm{cm};\quad \text{for quarks } d_f \text{ almost 10 times larger}$$

⇒ Current limit $|d_e| < 1.0\times 10^{-27}$ probes TeV mass scale, future experiments even more !

Effective Low Energy MSSM CP-violating Lagrangian

(From D. Demir *et al.*, Nucl. Phys. B **680**, 339 (2004))

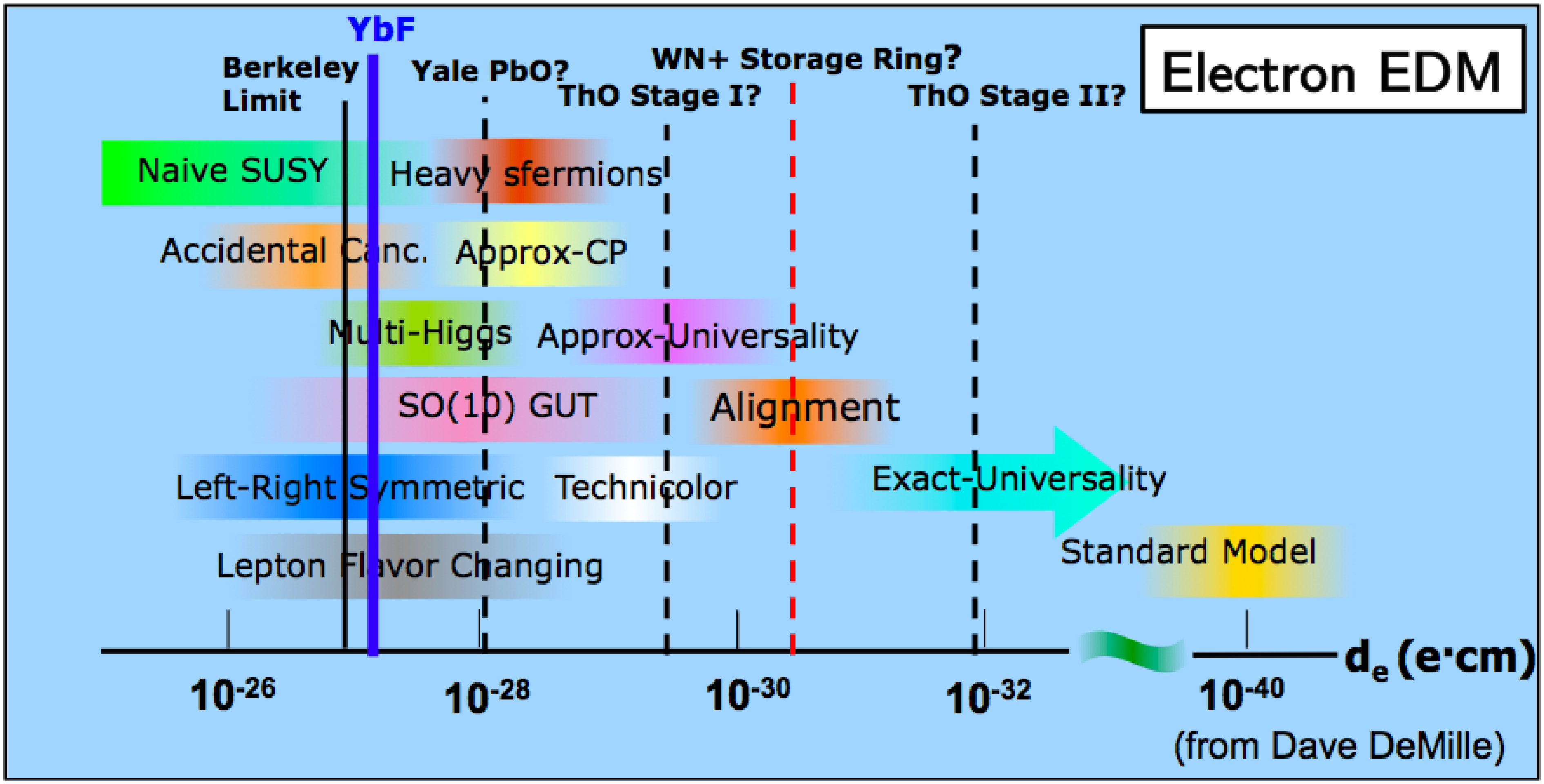
$$\mathcal{L}_{\text{eff}} = \frac{g_s^2}{32\pi^2}\bar{\Theta}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3}wf^{abc}G^a_{\mu\nu}\tilde{G}^{\nu\beta,b}G^{\mu,c}_{\beta} - \frac{i}{2}\sum_{i=e,u,d,s} d_i\bar{\Psi}_i\gamma_5\sigma^{\mu\nu}\Psi_iF_{\mu\nu} - \frac{i}{2}\sum_{i=e,u,d,s} d_i^c\bar{\Psi}_i g_s\gamma_5\sigma^{\mu\nu}\lambda^a\Psi_iG^a_{\mu\nu}$$

- Contributions : $\bar{\Theta}$, Weinberg 3-gluon, EDMs of e and quarks d_i, chromo-edms of quarks d_i^c
- $|d_n|$ limits $\rightarrow\ \bar{\Theta} < 1 \times 10^{-10}$, *a priori* $\bar{\Theta} \approx 0 - 2\pi$
    - If Peccei-Quinn axions exist $\bar{\Theta} \rightarrow 0$
    - Radiative corrections to $\bar{\Theta}$ may induce non-negligible EDM
- The CP-odd term cubic in $G^a_{\mu\nu}$ seldom dominates the EDM of a nucleon
- For given manner of SUSY breaking $w,\ d_i,\ d_i^c$ can be calculated
    - From quark level to nucleon level involves nuclear models : $w,\ d_{u,d,s},\ d^c_{u,d,s} \Rightarrow d_n,\ d_p$
    - $d_n = -d_p \approx 3 \times 10^{-16}\ \bar{\theta}$ e·cm if CP-violation due to $\bar{\theta}_{\text{QCD}}$
    - $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u + 0.83e(d_u^c + d_d^c) - 0.27e(d_u^c - d_d^c)$
    - $d_p = \frac{4}{3}d_u - \frac{1}{3}d_d + 0.83e(d_u^c + d_d^c) + 0.27e(d_u^c - d_d^c)$
    - $d_n = \eta\,(\Delta_d d_d + \Delta_u d_u + \Delta_s d_s)$, ...
    - $d_p \approx d_n$ if dominated by heavy quarks, d_d from other combinations of terms

⇒ Need measurements in many systems $d_p,\ d_n,\ d_d$, ... to extract parameters of CP violation

- d_e "easily" extracted from EDM, d_A, observed in atom or molecule

Electron EDMs : what can we learn?



(from Dave DeMille)

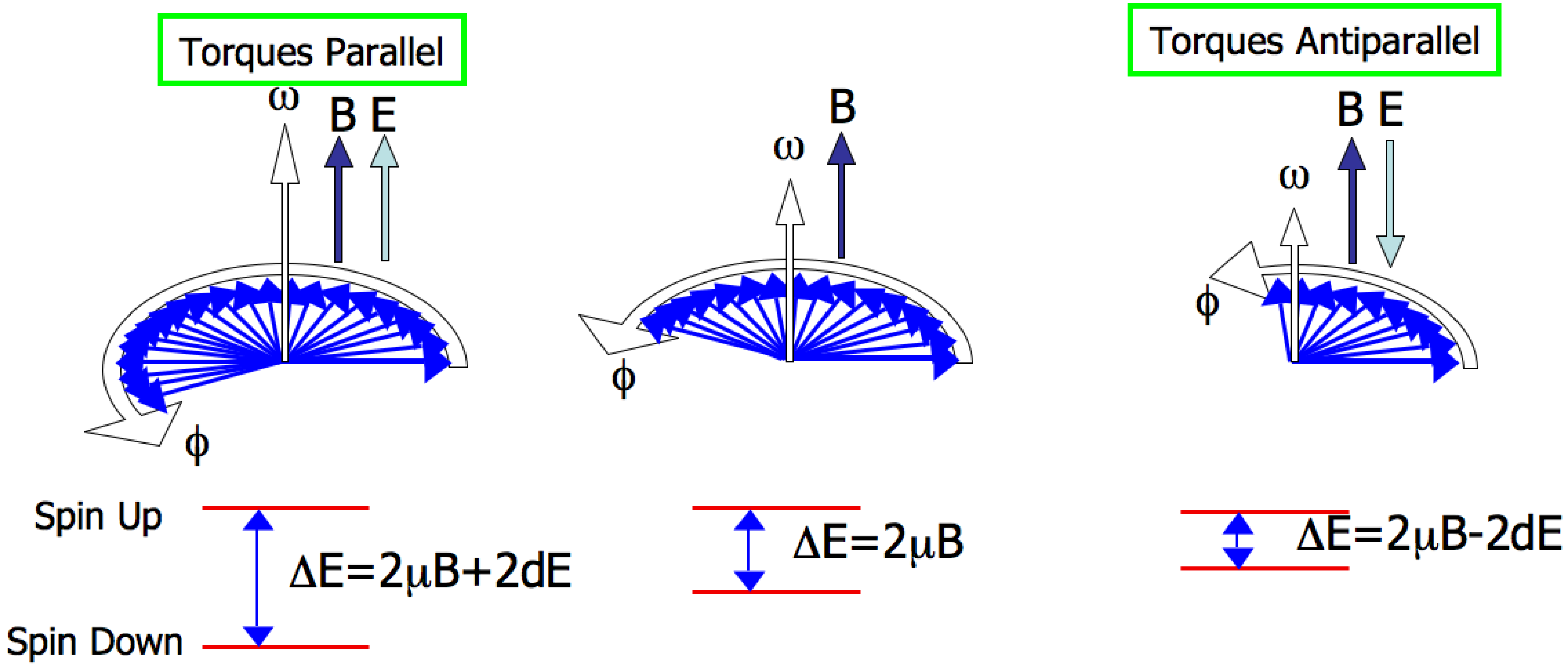
- d_e is powerful probe of new physics, probing scales of 10s of TeV

⇒ Even a null result is interesting !

- Many possible sources of CP violation; need EDM searches in μ, τ, n, p, d, ^{3}He, ...
- Thanks to Dave DeMille for material

Algorithm for finding an EDM

- Put system with unpaired spins in parallel E and B fields
- Spin polarize system perpendicular to fields (superposition of spin up and down)
- Torques from E and B fields lead to precession through angle ϕ in coherence time τ
- Flip E wrt B, look for change in ϕ ($i.e.$ look for energy shift).



- Look for precession frequency shift $\Delta\nu = 4dE/h$
- For $E = 100$ kV/cm, $d_e = 1 \times 10^{-27}$ e·cm $\Rightarrow$ $\Delta\nu \approx 20$ nHz $\Leftrightarrow$ $B \approx$ few $\times 10^{-14}$ G
- Lessons : Maximize E and precession angle ϕ $\Leftrightarrow$ maximize observation time τ, and counting statistics

Amplifying the Electric Field with a Paramagnetic Polar Molecule

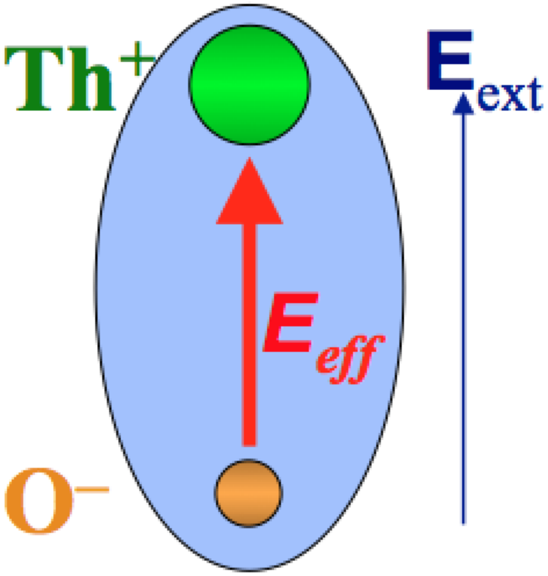
- Try to detect d_e in neutral atom or molecule in $\vec{E}_{\rm ext}$
- Naively, net $\vec{E}$ on e^- in atom is zero $\Rightarrow$ no linear Stark shift observable
- Sandars discovery : relativistic effects yield $\Delta E \equiv \vec{d}_a \cdot \vec{E}_{\rm ext} \equiv R d_e E_{ext}, \quad R \gg 1, \quad d_a \gg d_e$
- Energy shift due to electron EDM in atom can be larger than EDM shift of bare e^- in same field (R is -585 in thallium, 100 kV/cm $\Rightarrow$ -58 MV/cm)
- In polar molecules, large internal fields : can be fully polarized along external fields of order 10 V/cm
- Valence electron feel fields $E_{\rm eff} \approx \alpha^2 Z^3 e/a_0^2 \approx 100$ GV/cm (ThO*)
- Bohn & Meyer : internal field of PbO a(1) state ≈ 25 GV/cm, ThO H state 104 GV/cm, WC 54 GV/cm

- Use heavy polar molecules with unpaired electron spin,
- Polarize $\vec{E}_{\rm int}$ along $\vec{E}_{\rm ext}$
- Polarize unpaired e^- parallel/anti-parallel to $\vec{E}_{\rm int}$
- Look for $\Delta E = d_e E_{\rm int}$:

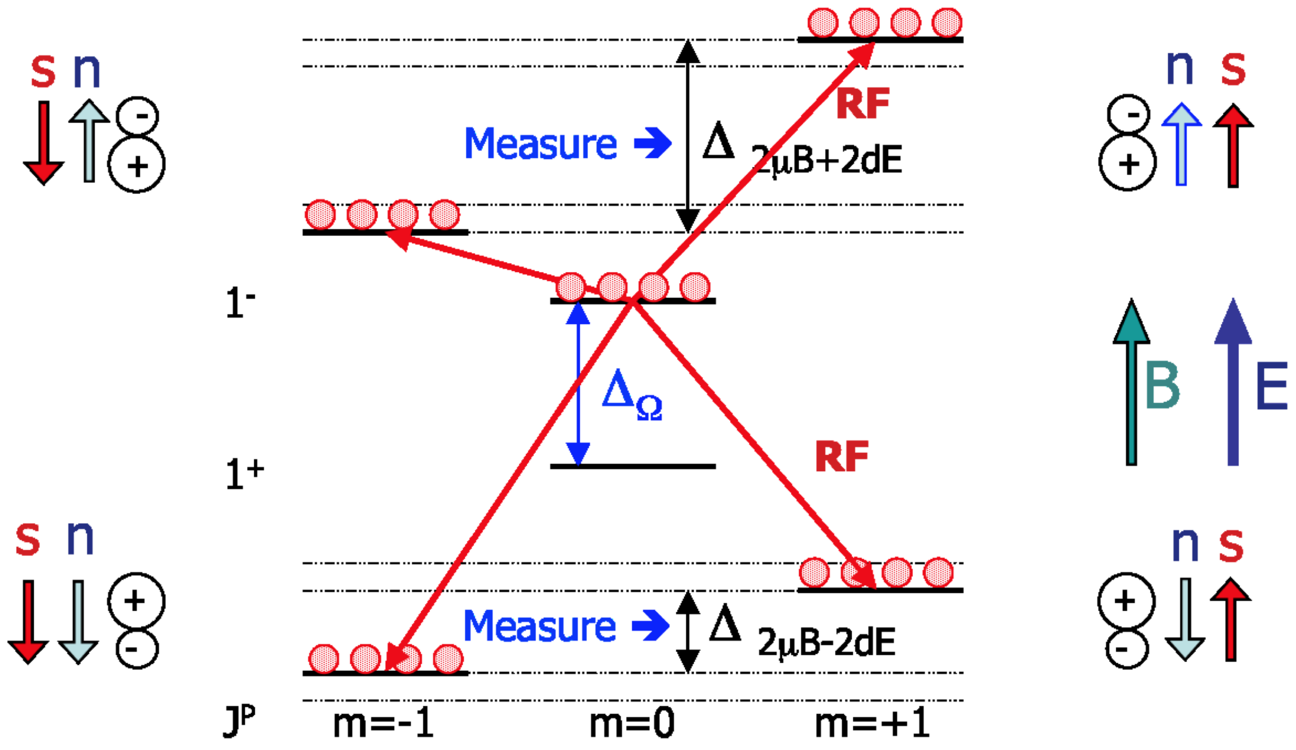
$$d_e = 1 \times 10^{-29}\ \text{e·cm} \Leftrightarrow 120\ \mu\text{Hz}$$
$$d_e = 1 \times 10^{-31}\ \text{e·cm} \Leftrightarrow 1.2\ \mu\text{Hz}$$

- Motivates searches in PbO, YbF, HfF$^+$, ThO, WC

$\Rightarrow$ YbF, now sets best limit $|d_e| < 1.0 \times 10^{-27}$ ecm
J.J. Hudson *et al.*, Nature **473**, 493 (2011).

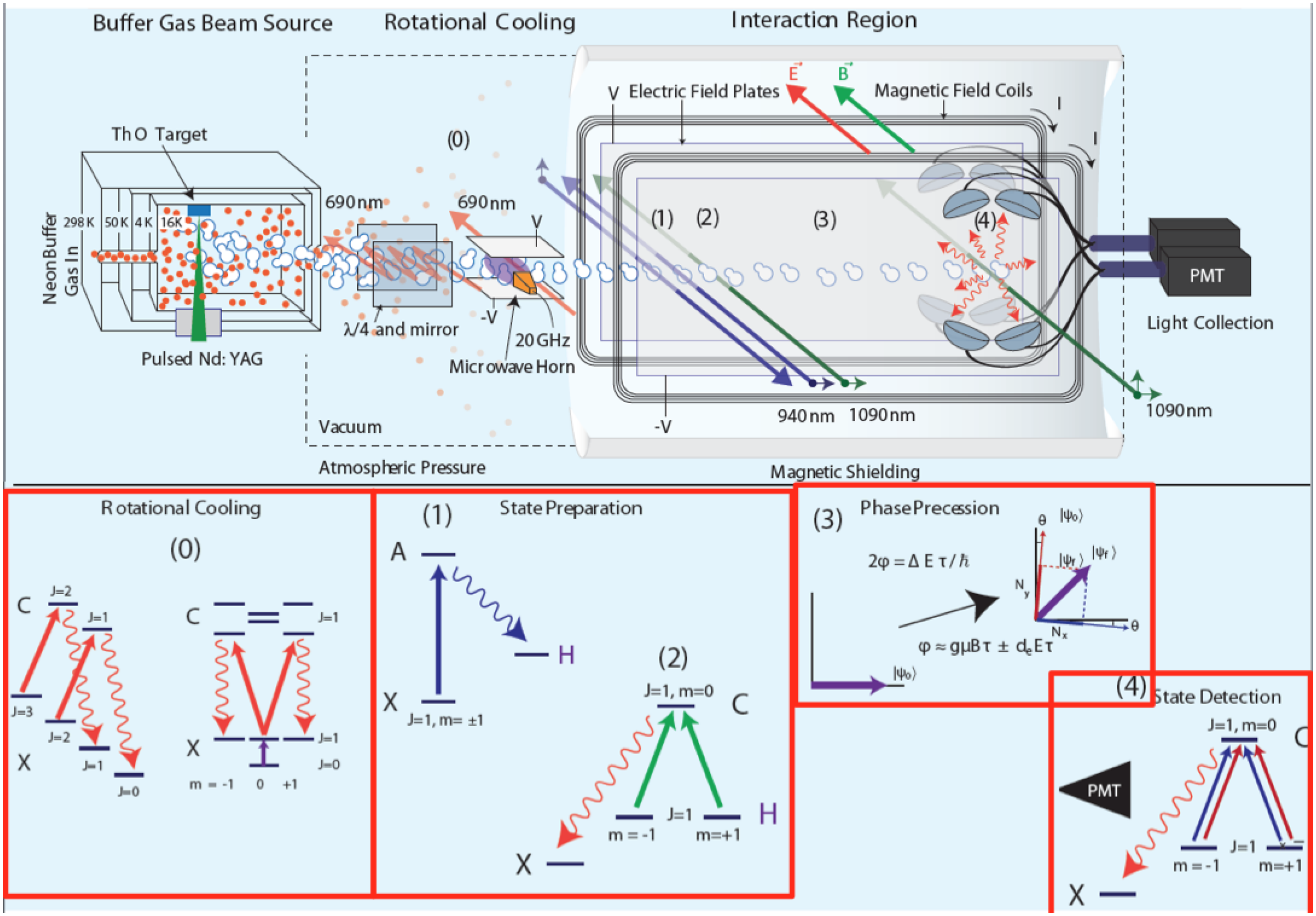


Electron EDM search in Hund's case (c) Polar Molecule



- Prepare superposition : $|\psi_N(t=0)\rangle = \frac{1}{\sqrt{2}}\left[|M=1,N\rangle + |M=-1,N\rangle\right]$
- $M = \pm 1$ levels have different energies in $B,\ E$ fields, acquire relative phase shifts
- $\phi_E \approx d_e \mathcal{E}_{\text{eff}} N t,\ \ \phi_B \approx g_J \mu_B B t$
- After time τ, components acquire relative phase shifts :
  $|\psi_N(t=\tau)\rangle = \frac{1}{\sqrt{2}}\left[e^{i\phi}|M=1,N\rangle + e^{-i\phi}|M=-1,N\rangle\right]$
- Detect projection of spin on $\hat{x}$ and $\hat{y}$ axes, look for E-field dependent shift

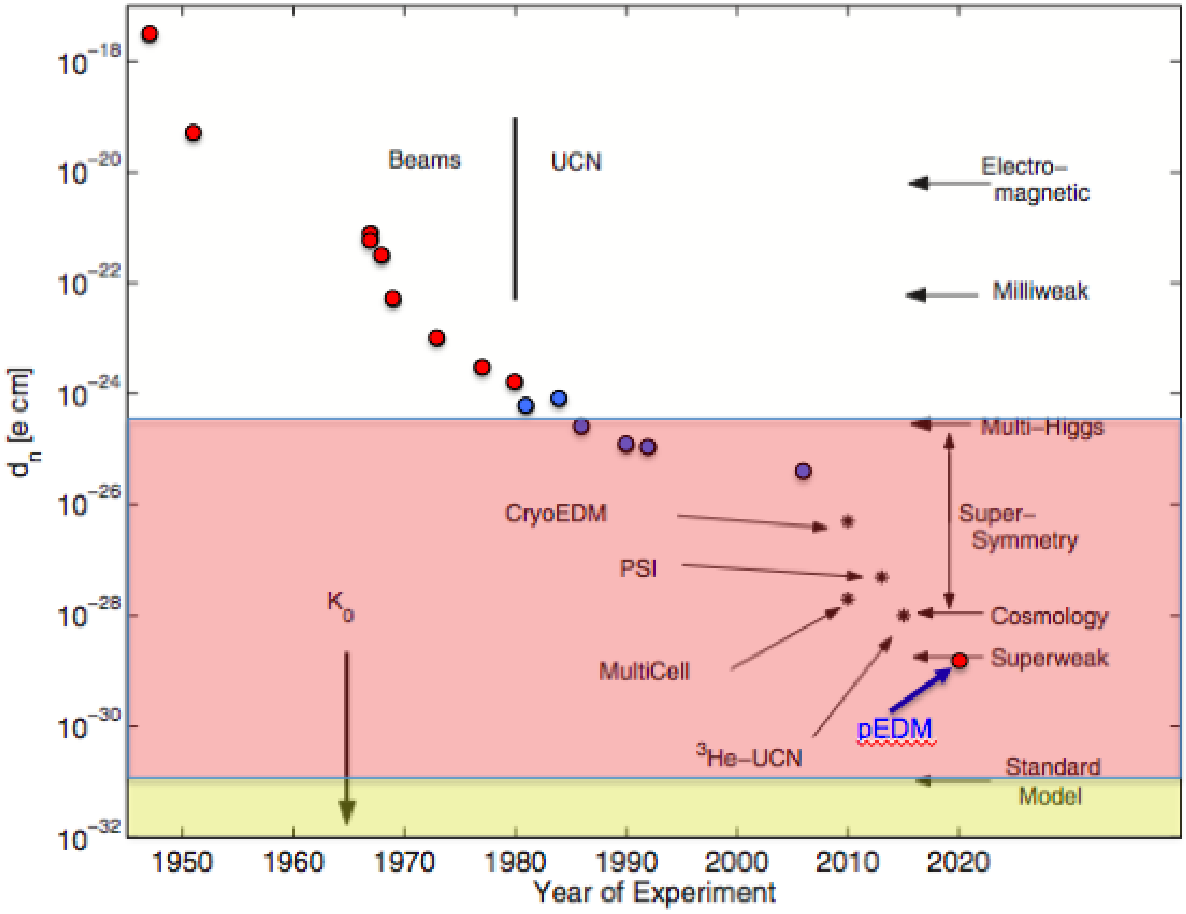
Electron EDM in ThO* : ACME (D. DeMille, J. Doyle, G. Gabrielse)



- Preliminary data : $\delta d_e(\mathrm{stat}) = 5 \times 10^{-29}$ e·cm in $T \approx 80$ hours
- Gain in $\sqrt{N}$ of 300 appears possible - ultimate limit below 10^{-30} e·cm?

History and Future of Neutron EDM limits

J. Phys. G: Nucl. Part. Phys. **36** (2009) 104002 S K Lamoreaux and R Golub



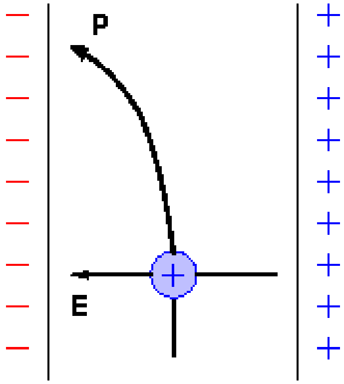
- Sensitive to much of SUSY parameter space, and scales of 100s of TeV, phases of $\lesssim 10^{-5}$ rad

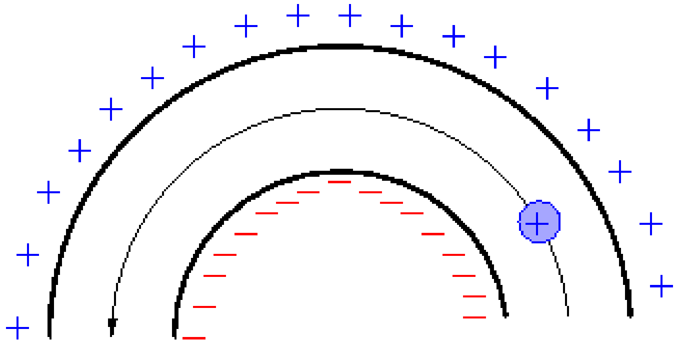
$$d_f \approx e_f \frac{\alpha}{4\pi} \sin(\phi) \frac{m_f}{\Lambda^2} \quad f = \text{quark},\ \text{lepton}$$

$$d_p \approx (10^{-22} - 10^{-24}) \times \left(\frac{1\ \text{TeV}}{M_{\text{SUSY}}}\right)^2 \sin\phi \quad \text{e} \cdot \text{cm (at 1 loop)}$$

New approach to measuring an EDM (Y. Semertzidis, BNL, Khriplovich, Rathmann, ...)

- Put particle in $\vec{E}$ field, look for EDM-induced torque on spin : $\vec{\tau} = \vec{d} \times \vec{E} = \frac{d\vec{s}}{dt}$
- <u>But</u> charged particle will accelerate away - unless we use $\vec{E}$ and/or $\vec{B}$ fields to trap particle

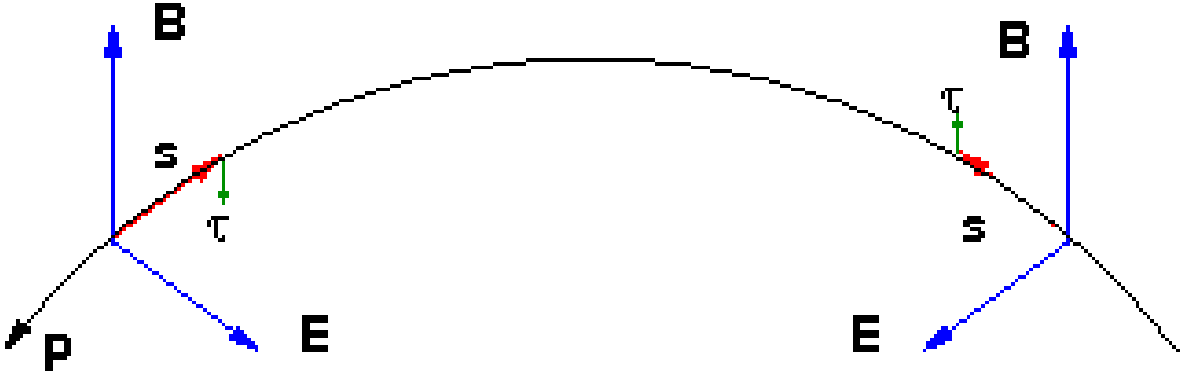




But in particle rest frame in magnetic storage ring, particle sees radial $\vec{E}$ and vertical $\vec{B}$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} + \vec{\mu} \times \vec{B}$$

- First term precesses spin out of plane : this is the EDM signal
- Second term precesses spin in plane



- Consider difference between spin and cyclotron precession frequencies :

$$\omega_a = \omega_{spin} - \omega_{cyc}$$

$$\omega_a = \frac{(g-2)}{2}\frac{e}{mc}B \equiv a\frac{e}{mc}B$$

- If $g \neq 2, \ \omega_a \neq 0$, sensitivity to EDM dramatically reduced
- Need to cancel anomalous precession, but how?

Approach to deuteron EDM measurements in a magnetic storage ring

- Method to cancel anomalous precession depends on particle species and its g factor
- $\boldsymbol{\tau}_{EDM} = d\boldsymbol{s} \times \boldsymbol{E} = d\boldsymbol{s} \times (\boldsymbol{v} \times \boldsymbol{B})/c = -d\boldsymbol{B}(\boldsymbol{s}\cdot\boldsymbol{v})/c + d\boldsymbol{v}(\boldsymbol{s}\cdot\boldsymbol{B}) \approx -d\boldsymbol{B}(\boldsymbol{s}\cdot\boldsymbol{v})/c$
- For $g \neq 2$, spin and cyclotron frequencies are different : $\langle \boldsymbol{s}\cdot\boldsymbol{v}\rangle \approx 0$
- For deuteron, a=-0.143, spin lags behind momentum
- Solution : add radial electric field to push deuteron out : lengthens orbit and cyclotron period, but B, ω_s unchanged
- There is a ratio of E/B that increases path length just enough so $\omega_c = \omega_s$
- Diameter increases by about 20%

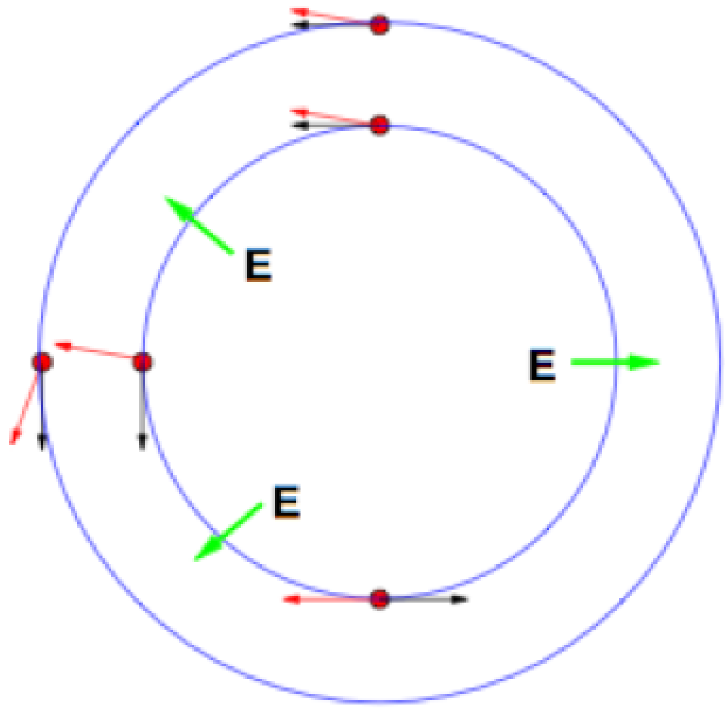
$$\boldsymbol{\omega}_{\boldsymbol{a}}^{\mathrm{lab}} = -\frac{q}{mc}\left[a\boldsymbol{B} + \left\{a - \left(\frac{mc}{p}\right)^2\right\}\frac{\boldsymbol{v}\times\boldsymbol{E}}{c}\right]$$

$\Rightarrow$ Set $E = \dfrac{aB\beta\gamma^2}{1 - a\beta^2\gamma^2}$

- This makes term in $[\ \ ] = 0 \quad \Rightarrow \quad \omega_a = 0$
- Requires ring with $\boldsymbol{E}$ and $\boldsymbol{B}$ fields, challenging

$\Rightarrow$ Huge opportunity for COSY/Jülich?

- What about the proton?



New approach to proton EDM : Magic Momentum Storage Ring

- For a storage ring using only vertical $\vec{E}$ fields (all quantities in lab frame) :

$$\vec{\omega}_a = -\frac{e}{mc}\left[a - \left(\frac{mc}{p}\right)^2\right]\vec{\beta}\times\vec{E}$$

- For proton, $a = (g-2)/2 = 1.79$: Eliminate ω_a at "magic" mom. $p = \frac{mc}{\sqrt{a}} = 0.70$ GeV/c
- Spin is frozen along mom., maximum sensitivity to EDM precessing spin out of plane :

$$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{\mu}\times\boldsymbol{B} + \boldsymbol{d}\times\boldsymbol{E}, \quad \text{where } |\boldsymbol{s}| = \hbar/2$$

$$\Rightarrow \omega_v = \frac{2\left(\mu B_r + dE_r\right)}{\hbar} \quad \text{is angular precession frequency of spin out of plane}$$

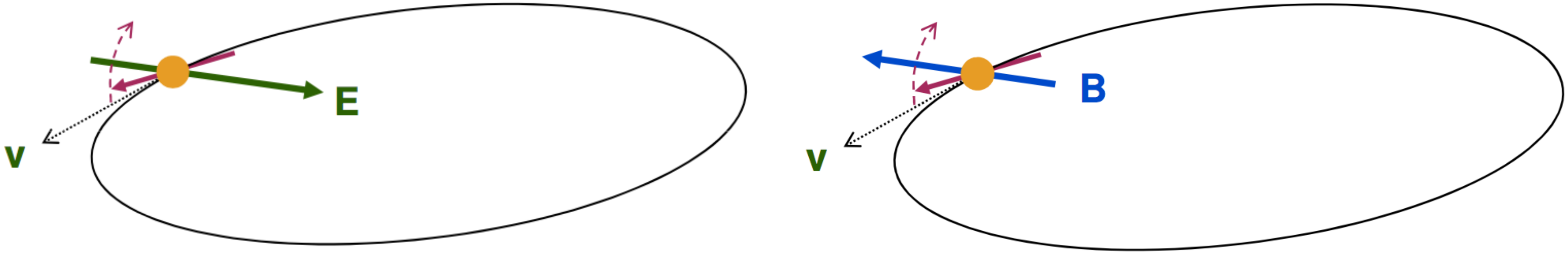
- The precession due to an EDM at the level of 10^{-29} e·cm given by :

$$\omega_v^{\mathrm{EDM}} = \frac{2dE}{\hbar} = \frac{2dEc}{\hbar c} = \frac{2\times 1\times 10^{-31}\ \mathrm{e\cdot m}\times 10.5\ \mathrm{MV/m}\times 0.95\times 3\times 10^{8}\ \mathrm{m/s}}{197\ \mathrm{MeV\cdot fm}}$$

$$\omega_v^{\mathrm{EDM}} = 3\ \mathrm{nrad/s}, \quad \theta(t) = 3\,\frac{\mathrm{nrad}}{s}\times\tau, \quad \tau \text{ is measurement time}$$

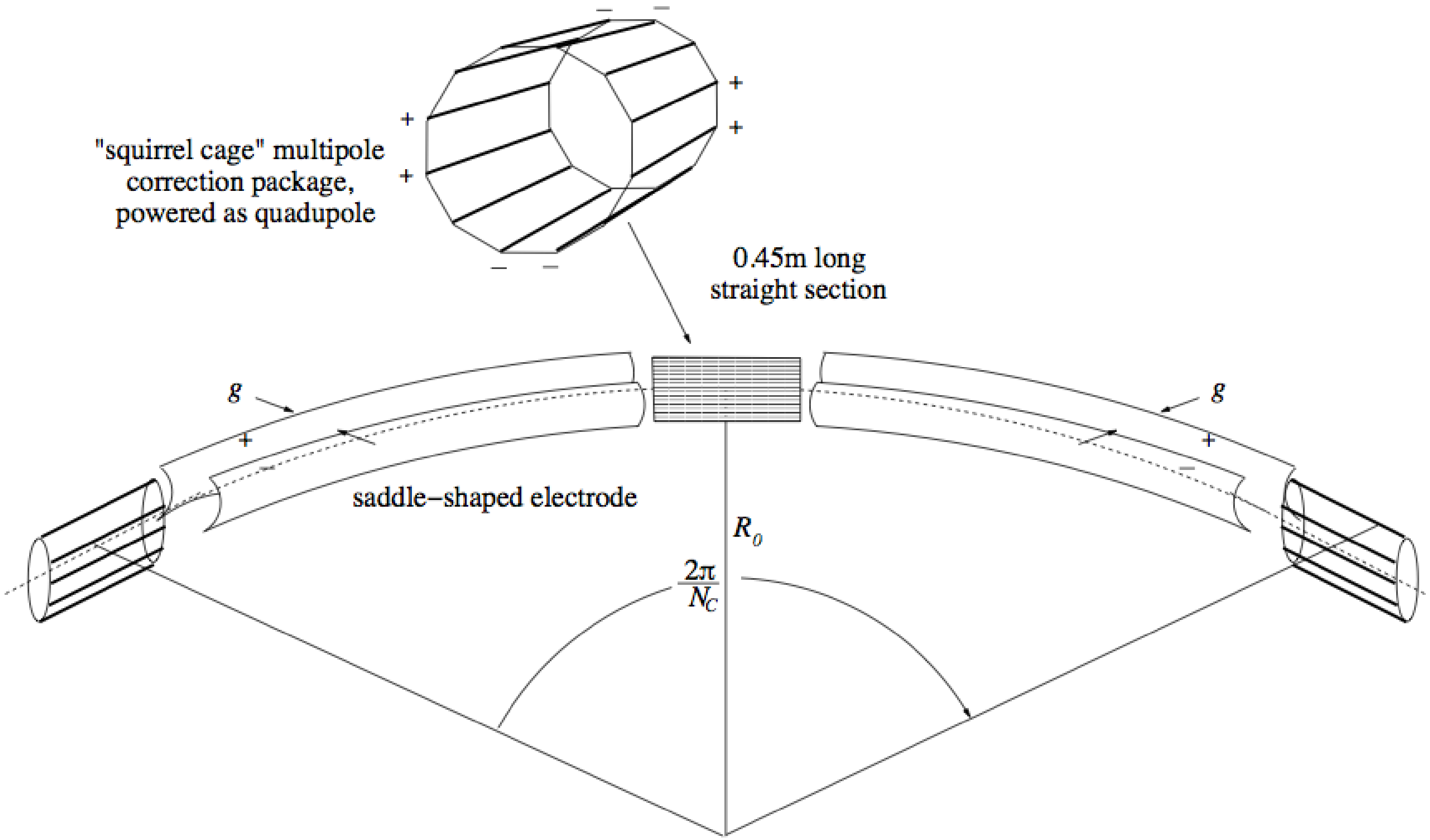
- That works out to 5° per year. Maximize θ by maximizing E and measurement time τ
- Precession into vertical also caused by a radial magnetic field $\boldsymbol{B}_r$
- Effect on precession is indistinguishable from an EDM - is this fatal?

New approach to proton EDM : Magic Momentum Storage Ring



- Gravity? Balancing gravity requires vertical Lorentz force from B_r or E_v
- Lab frame E_v has components of B_r^{mot} in proton rest frame
- This radial magnetic field B_r^{mot} precesses spin in same manner as EDM
- B_r^{mot} seen by protons to balance gravity, yield precession 30 times greater than pEDM of 10^{-29} e·cm !
- Solution : Inject CW and CCW beams (same helicity), simultaneously
- Torques from B_r^{mot} in same direction for both beams, those from EDM in opposite
- Subtracting CW and CCW precession signals isolates EDM from gravity
- That solves problems due to vertical electric fields
- What about ambient radial magnetic field ? How small must they be?

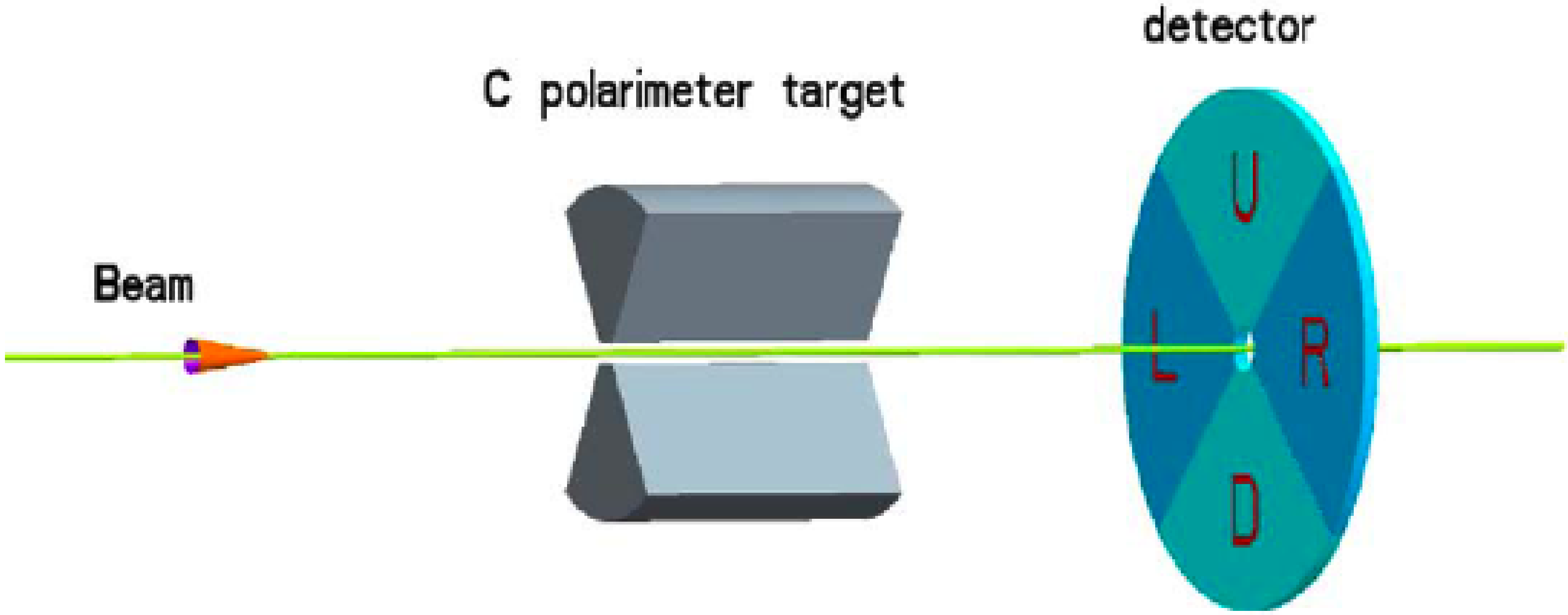
Single Cell of Proton EDM Storage Ring



- Long electrodes have gap g=3 cm, ± 160 kV, 16 meters long (in 5 pieces)
- Electrodes are saddle-shaped to maximize spin coherence time, $E \sim r^{0.2}$
- Straight sections 0.45 m long, incorporate electrodes for correcting beam optics

Challenges of a Proton EDM Measurement in a Storage Ring : Polarimetry

- Major advances made at COSY and Ed Stephenson (Indiana)
- Proton spin direction determined with polarimeter based on elastic pC scattering
- Vertical polarization yields difference in left-right scattering rates : P=(L-R)/(L+R)
- $d_p = 10^{-29}$ e cm corresponds to 3 ppm effect in ratio
- Polarimeter systematics : beam motion on target, beam position and angle, rate effects, gain changes
- Most advanced and well understood part of proton EDM effort



Challenges of a Proton EDM Measurement in a Storage Ring : Spin Coherence

- Major advances made at COSY and Ed Stephenson (Indiana)

$$\begin{aligned}\vec{\omega}_a &= -\frac{e}{mc}\left[a-\left(\frac{mc}{p}\right)^2\right]\vec{\beta}\times\vec{E}\\ d\omega_a &= 2\frac{e}{mc}\left(\frac{mc}{p}\right)^2\beta E\times\frac{dp}{p}\\ &= \frac{dp}{p}\times 10^7\ \mathrm{rad/s}\end{aligned}$$

- If $dp/p \approx 2.5\times 10^{-4}$, spin coherence time less than a millisecond!
- Will use RF cavity to cancel this first order effect, keep spins frozen

$$\text{At second order} \ : \ d^2\omega_a = \left(\frac{dp}{p}\right)^2\frac{3}{2}\times 10^7\mathrm{rad/s} \approx 1\ \mathrm{rad/s}$$

- Electrode design, length of straight sections, sextupoles adjusted so $d^2T_{\mathrm{rev}}/d\gamma^2 = 0$
- Sextupole with radial E field $\propto\ x^2-y^2$, help correct 2nd order effect from $(dp/p)^2$

⇒ Spin coherence time : Use RF and sextupoles to reduce $d\omega_a/dp$ and $d^2\omega_a/dp^2$

  - Novosibirsk has achieved 10^7 turns, need $10^3\ s \Leftrightarrow 10^9$ turns
  - Have demonstrated SCT >35 s at COSY with deuterons (electron-cooled) in Jan 2011
  - Challenging, but appears possible

Limitation on the pEDM experiment due to radial magnetic fields

- Non-zero ambient $\boldsymbol{B}_r$ mimics EDM, and results in vertical Lorentz force
- Lorentz force in opposite directions for CW and CCW beams
- Compensated by net vertical electric field : $\boldsymbol{E}_v = -\boldsymbol{\beta} \times \boldsymbol{B}_r$
- Spin precession in vertical due to $\boldsymbol{B}_r$ using lab-frame quantities (see Jackson) :

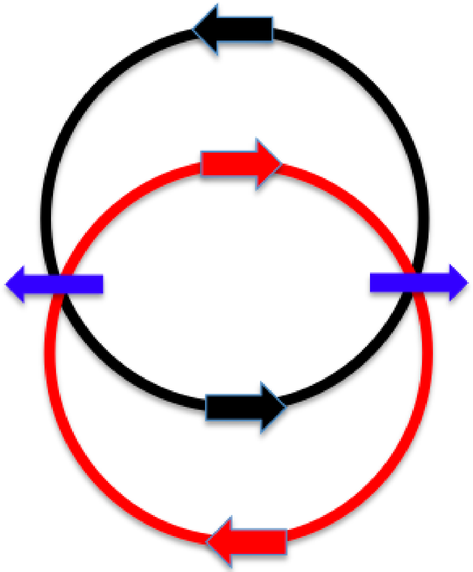
$$\begin{aligned}
\frac{d\boldsymbol{s}}{dt} &= \frac{e}{mc}\boldsymbol{s}\times\left[\left(\frac{g}{2} - 1 + \frac{1}{\gamma}\right)\boldsymbol{B}_r - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\boldsymbol{\beta}\times\boldsymbol{E_v}\right] \\
&= g\frac{e}{2mc}\frac{1}{\gamma^2}\boldsymbol{s}\times\boldsymbol{B}_r \\
&= \frac{1}{\gamma^2}\boldsymbol{\mu}\times\boldsymbol{B}_r \quad \text{(normal relation modified by E field)}
\end{aligned}$$

⇒ What magnitude of $\boldsymbol{B}_r$ is equivalent to EDM precession into the vertical ω_v?

$$\begin{aligned}
\hbar\omega_v &= 2\mu B_r/\gamma^2 \Rightarrow \\
B_r &= \frac{\hbar\omega_v}{2\mu}\gamma^2 = \frac{1.05\times10^{-34}\ \mathrm{J\cdot s}\times 3\times10^{-9}\ \mathrm{rad/s}\times 1.25^2}{2\times1.41\times10^{-26}\ \mathrm{J/T}} = 2.2\times10^{-17}\ \mathrm{T}
\end{aligned}$$

⇒ Net radial magnetic field of 0.22 pG (0.022 fT!) would causes precession equivalent to pEDM of $d_p = 10^{-29}\ e{\cdot}$cm

Separated counter-circulating beams produce a magnetic dipole



- To detect splitting, consider $\boldsymbol{B}$ fields created by beams
- For displacements from origin by δx and δy, $\boldsymbol{B}$ from single beam :

$$\boldsymbol{B}(r,\phi) = \frac{\mu_0}{4\pi}\frac{2I}{r}\left\{\left[-\sin\phi + \left(-\frac{\delta x}{r}\sin 2\phi + \frac{\delta y}{r}\cos 2\phi\right)\right]\hat{\boldsymbol{x}} + \left[+\cos\phi + \left(-\frac{\delta x}{r}\cos 2\phi + \frac{\delta y}{r}\sin 2\phi\right)\right]\hat{\boldsymbol{y}}\right\}$$

- If CW & CCW beams split by $\pm\delta y$, can detect at $\phi = \{0,\pi\}$ looking at $\boldsymbol{B}\cdot\hat{\boldsymbol{x}}$
- To move signal off of DC, modulate the vertical tune at ω_m between 20 Hz and 1 kHz
- Set $Q_y \Rightarrow Q_y \times (1 - m\cos(\omega_m t))$ where modulation depth $m \approx 0.1$

$$\Rightarrow \boldsymbol{B}(r,\phi=(0,\pi),\omega_m) \;=\; \frac{\mu_0}{4\pi}\frac{2I}{r}\left[\frac{\delta y \times 4m\cos\omega_m t}{r}\right]\hat{\boldsymbol{x}}.$$

- Modulating 3 pm splitting of beams by 20% yields peak field of 0.6×10^{-3} fT at ω_m
- Can try to measure such fields with SQUIDs (noise $\leq$1 ft/$\sqrt{Hz}$ at ω_m, average)

Estimate of Sensitivity to Proton EDM

$$\delta d_p \approx \frac{1.4\hbar}{eE_R AP\sqrt{N_c f T_{\text{tot}}\tau_{\text{coh}}}}$$

E_R : 10.5 MV/m radial electric field strength

A : 0.6 analyzing power of polarimeter

P : 0.8 proton beam polarization

N_C : 4×10^{10} protons stored per cycle

f : 0.0055% useful fraction of events

T_{tot} : 10^4 number of fills of storage ring

τ_{coh} : 10^3 seconds spin coherence time

$$\boxed{\delta d_p \approx 2.5\times10^{-29}\ e\cdot\text{cm / year}}$$

Compares favorably with current limit $|d_n| \leq 10^{-26}$ e·cm

Comparable with goal at SNS of $\delta d_n \approx 10^{-28}$ e·cm

Summary of prospects for Proton EDM Storage Ring Experiment

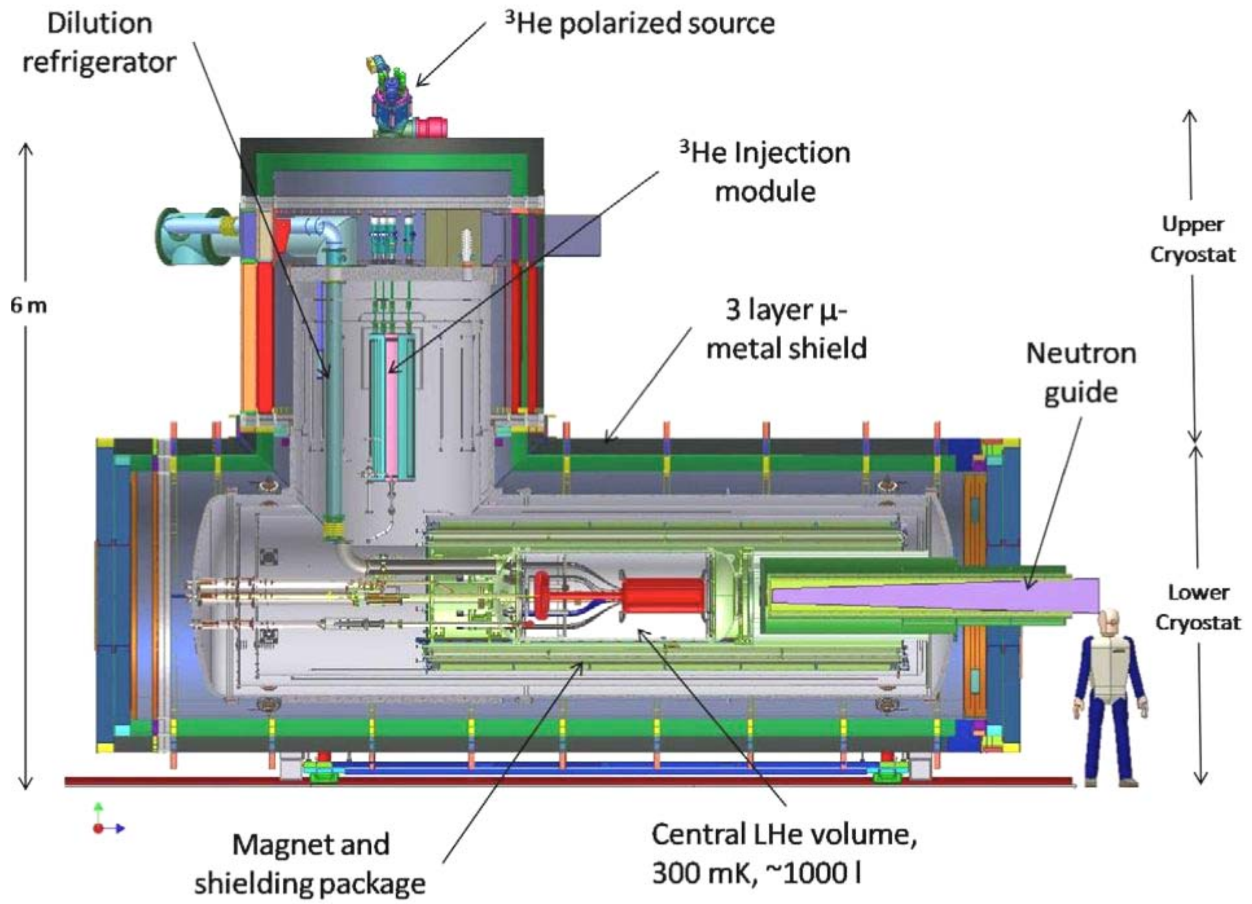
- New approach could lead to factor 1000 improvement, to $d_p \leq 10^{-29}$ e·cm
- Probes mass scale of 100s of TeV : huge implications for SUSY and other models
- Needs R and D funding
- No red flags - systematics from image charges, fields from other beam, geometric phases, ... seem controllable

- Storage ring searches for EDMs in protons, deuterons, ^{3}He are must-do physics!
- Physics reach can be 100s of TeV, well beyond LHC

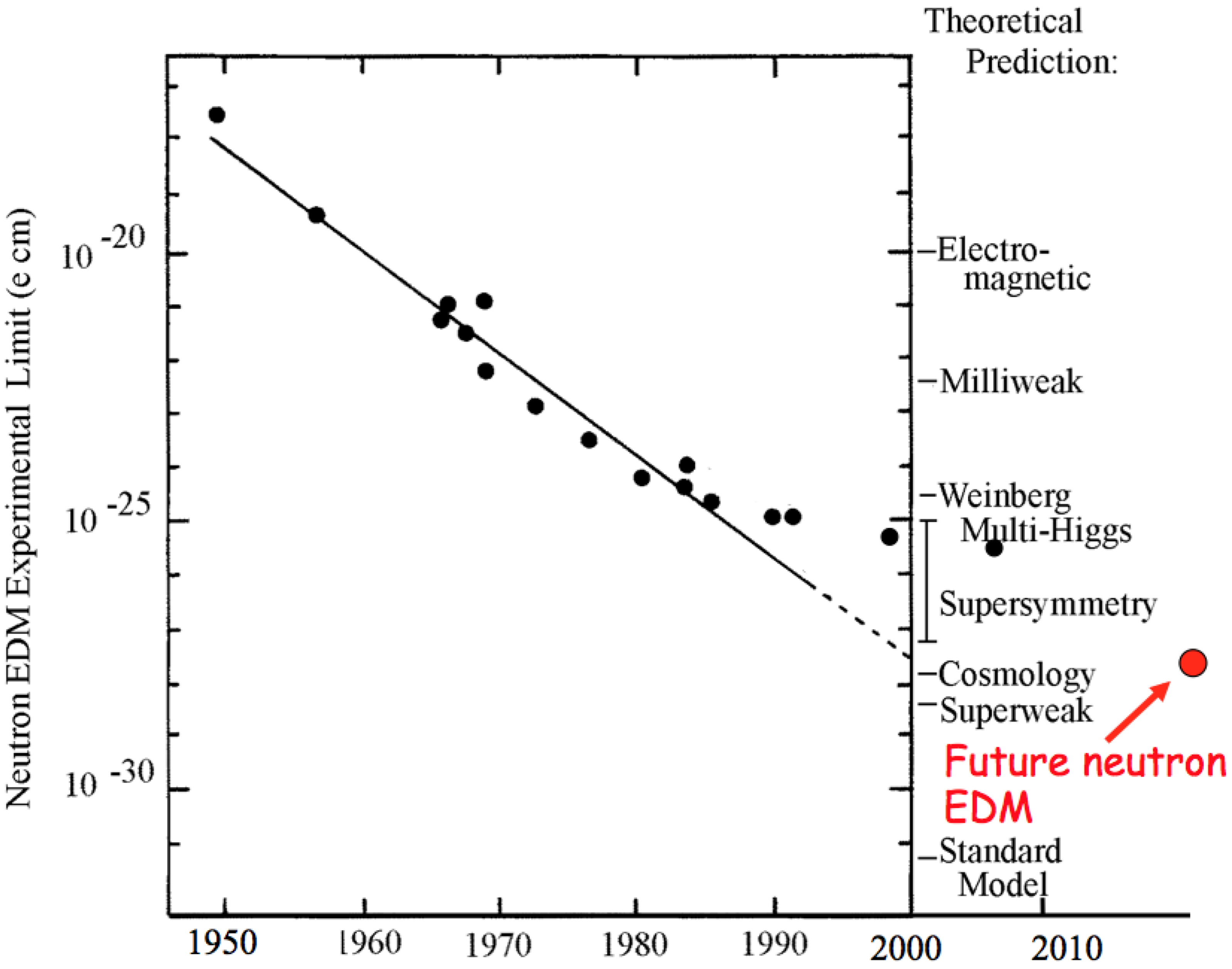
$\Rightarrow$ Even null results are interesting !

Neutron EDM Experiment at the Spallation Neutron Source (SNS)

- One of many next generation neutron EDM experiments (SNS, CryoEDM at ILL, PNPI at ILL, PSI, Munich, TRIUMF, JPARC)
- Current limit $d_n < 3 \times 10^{-26}$ e cm (C.A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006))
- SNS nEDM aims for factor 100 improvement $\Rightarrow d_n < 4 \times 10^{-28}$ e cm (90% C.L.).
- Experiment concept based on R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1 (1994)

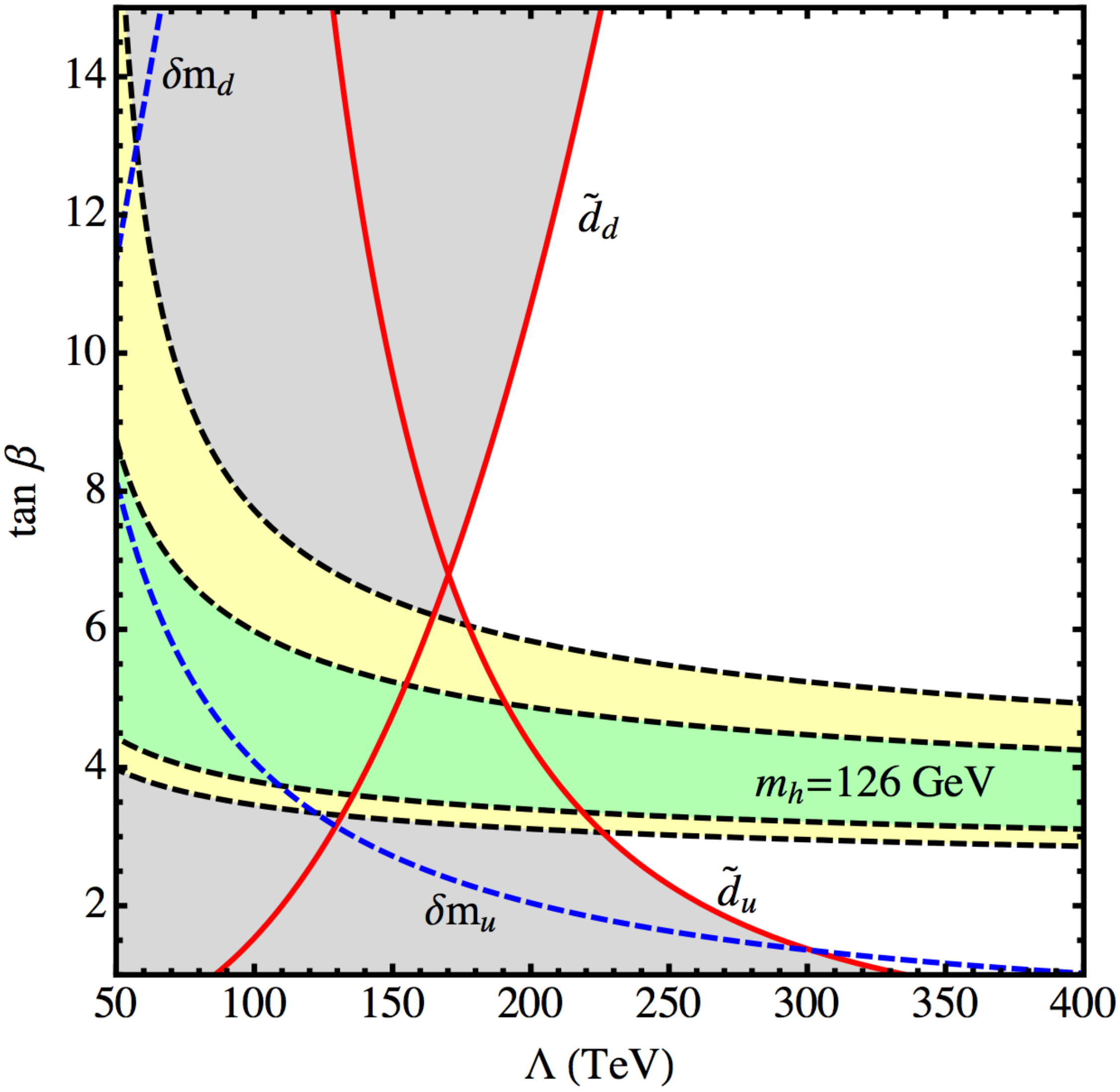


History of nEDM measurements



- Thanks to Brad Filippone for much of the material

What can be gained?



- McKeen, Pospelov, Ritz hep-ph 1303.1172
- Limits on $d_u,\ d_d$ from UW Hg EDM
- $d_f \approx c_1 \frac{m_f}{\Lambda^2_{\rm SUSY}} \theta_{\rm CP}$
- Factor of 100 on EDMs pushes limits on SUSY by factor 10
- Nuclear EDMs constrain new physics beyond LHC

Overview of SNS Neutron EDM Experiment

- Make cell of superfluid ^{4}He at 300 mK, impose uniform $\mathbf{B_0} \approx 10 - 50$mG, large uniform E field $\approx$ 100 kV/cm
- Inject cold (12K, 8.9Å, 0.95 meV) polarized neutrons into cell, they scatter off He to near rest with emission of phonon (become ultra-cold neutrons)
- Inject polarized ^{3}He atoms into cell, spins parallel to magnetic field (comagnetometer, $d_{\rm 3He} << d_n$)
- Apply perpendicular $\mathbf{B_1}$ field $\pi/2$ pulse to precess spins $\perp$ to $\mathbf{B_0}$
- Measure n and ^{3}He spin precession frequencies, remove reduced polarization ^{3}He
- Flip $\mathbf{E_0}$, refill cell, look for difference :

$$h\nu_n = -2\mu_n B_0 + 2d_n E_0 \Rightarrow h\nu_n = -2\mu_n B_0 - 2d_n E_0 \Rightarrow |\Delta\nu| = 4d_n E_0/h$$

- Repeat cycle

What's so hard about that?

- $\mathbf{B_0} \approx 1$ mG, $\mathbf{E_0} \approx 50$ kV/cm, $d_n = 4 \times 10^{-27}$ e cm $\Rightarrow \Delta\nu = 0.19\mu$Hz (<1 ppm of ν_n)
- Record setting UCN density would be 500 cm^{-3} : Suppose 2 cells of 4000 cm^3, only 4×10^6 neutrons/measurement cycle
- How do you measure spin precession rate of a few million neutrons?

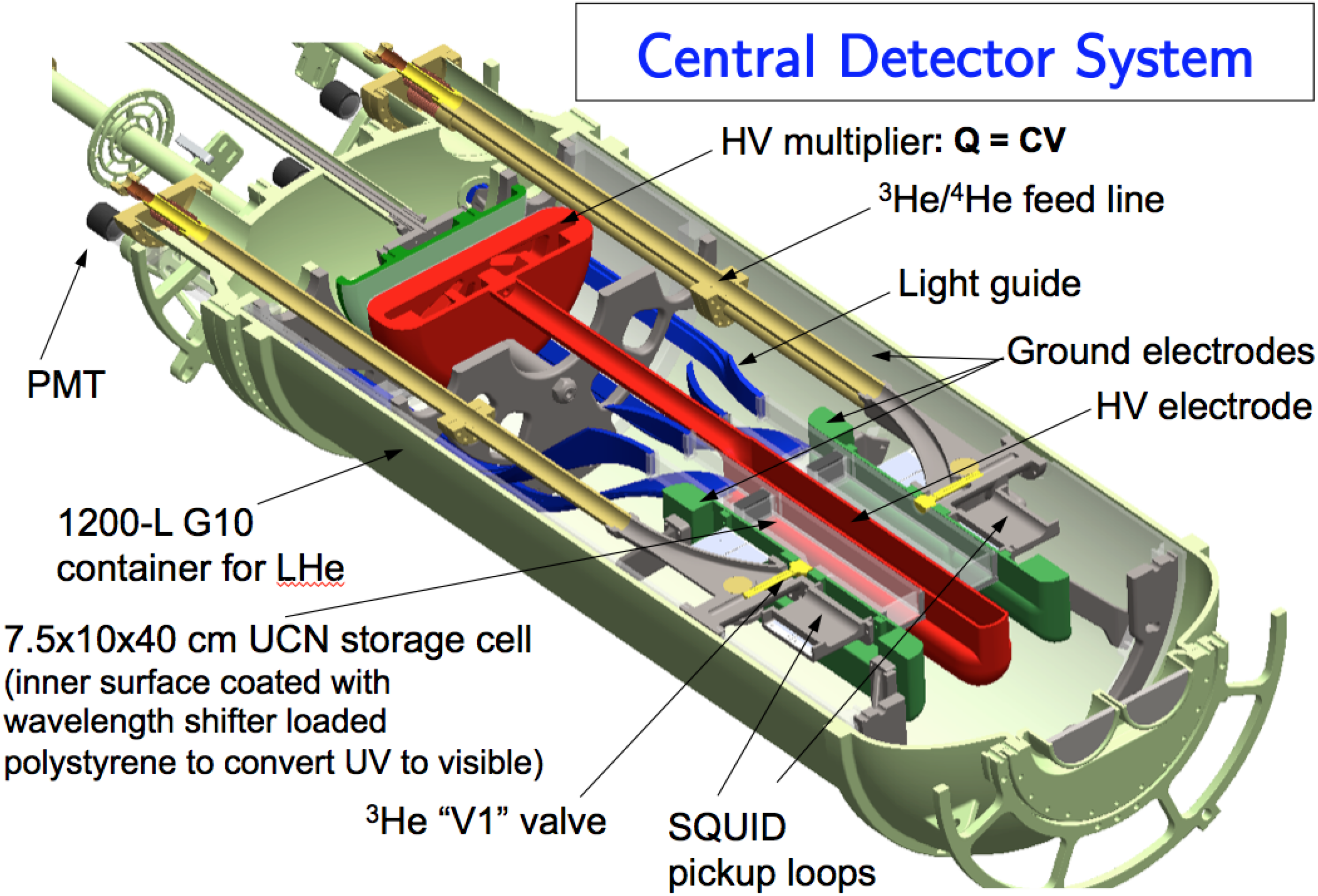
Overview of SNS Neutron EDM Experiment

- Mix in polarized ^{3}He : Absorption n+^{3}He→p+t+764 keV occurs preferentially for n, ^{3}He spins antiparallel ($\sigma(\uparrow\uparrow) \approx\ 10^2$ b, $\sigma(\uparrow\downarrow) \approx\ 10^4$ b)

⇒ Scintillation light :
$I_{\rm scint}(t) \approx 1 - \mathbf{P}_{^3He}(t) \cdot \mathbf{P}_n(t) = 1 - P_{\rm ^3He} P_n \cos\left[(\gamma_n - \gamma_{\rm 3He})B_0 t \pm 2 d_n E t/\hbar\right]$

- Adjust ^{3}He concentration to maximize sensitivity, $^3{\rm He}/^4{\rm He} \approx 10^{-10}$
- Use SQUIDS to measure ^{3}He precession $\nu_{^3He} \approx$ 3 Hz determines B_0, scint. determines $\nu_3 - \nu_n\ \approx$ 0.3 Hz and possible EDM signal
- $|\gamma_n - \gamma_{\rm 3He}| \approx |\gamma_3|/10$, reduces sensitivity to B field systematics
- New techniques to improve sensitivity :
  - Improved UCN density and storage time
  - Increased electric field strength $>$ 50 kV/cm
  - Use of superconducting shield : reduced B field noise
  - $\vec{n} \cdot ^3\vec{\rm He}$ capture+detection of light : efficient technique for measuring n spin precession
- Good control of systematics :
  - Uses ^{3}He co-magnetometer (sensitive to $\mathbf{B}$, but has $d_{\rm 3He} << d_n$)
  - $\mathbf{B}$ field measurement with SQUIDs *and* RF spin-dressing technique
- Actually measure in two cells simultaneously with same sign B_0, opposite E_0

SNS nEDM : A Technical Marvel

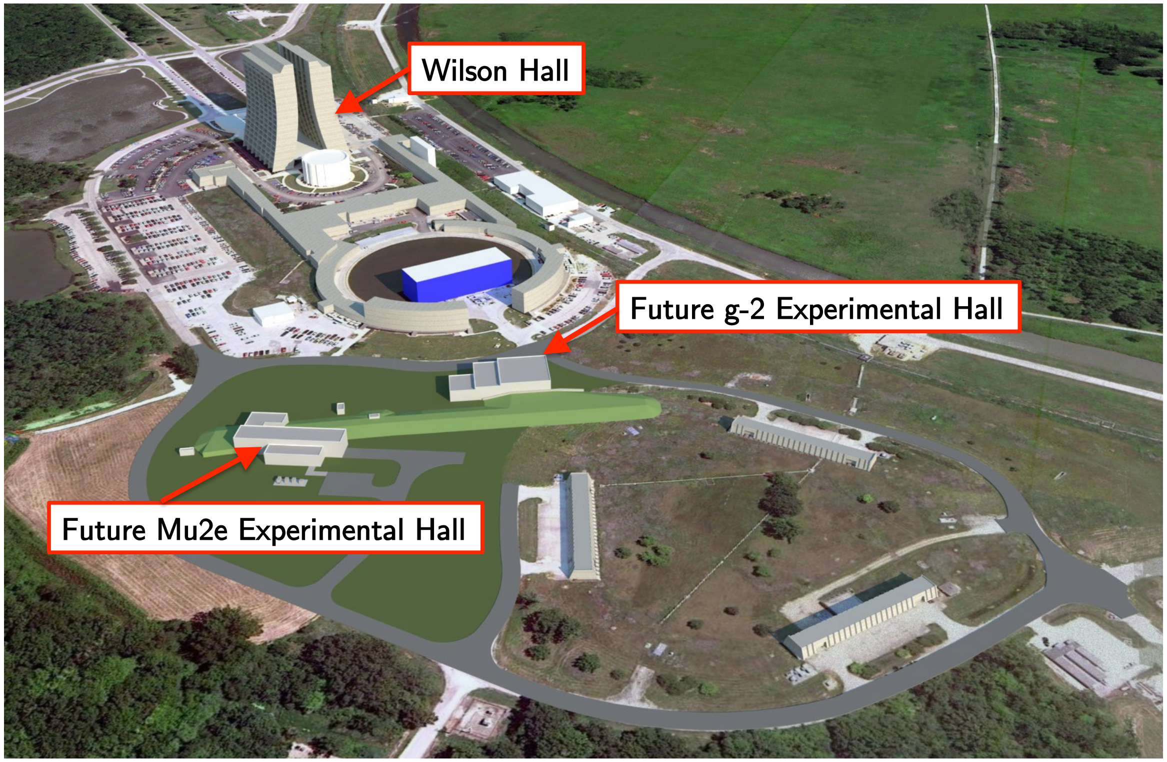


Projected systematic uncertainties and statistical sensitivity

Error Source	Systematic error (e-cm)	Comments
Linear vxE (geometric phase)	$< 2 \times 10^{-28}$	Uniformity of B_0 field
Quadratic vxE	$< 0.5 \times 10^{-28}$	E-field reversal to <1%
Pseudomagnetic Field Effects	$< 1 \times 10^{-28}$	$\pi/2$ pulse, comparing 2 cells
Gravitational offset	$< 0.2 \times 10^{-28}$	With E-field dependent gradients < 0.3nG/cm
Heat from leakage currents	$< 1.5 \times 10^{-28}$	< 1 pA
vxE rotational n flow	$< 1 \times 10^{-28}$	E-field uniformity < 0.5%
E-field stability	$< 1 \times 10^{-28}$	$\Delta E/E < 0.1\%$
Miscellaneous	$< 1 \times 10^{-28}$	Other vxE, wall losses

⇒ Statistical sensitivity (90% C.L.) in 3 calendar years $\approx 3 - 5 \times 10^{-28}$e cm

The New Muon g-2 Experiment E989 at Fermilab



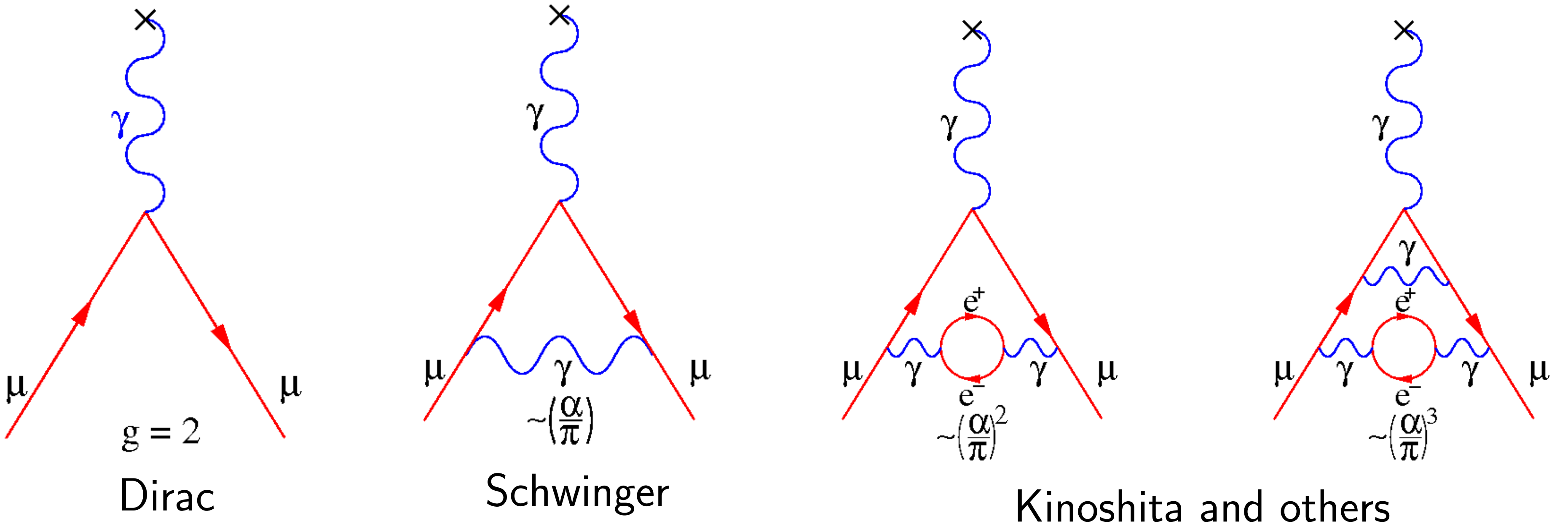
Goal : Measure the muon anomalous magnetic moment, a_μ, to 0.14 ppm, a fourfold improvement over the 0.54 ppm precision of Brookhaven E821

Anomalous part of the Magnetic Moment

- Recall magnetic moment interaction $H_{\text{Zeeman}} = -\boldsymbol{\mu} \cdot \boldsymbol{B}$

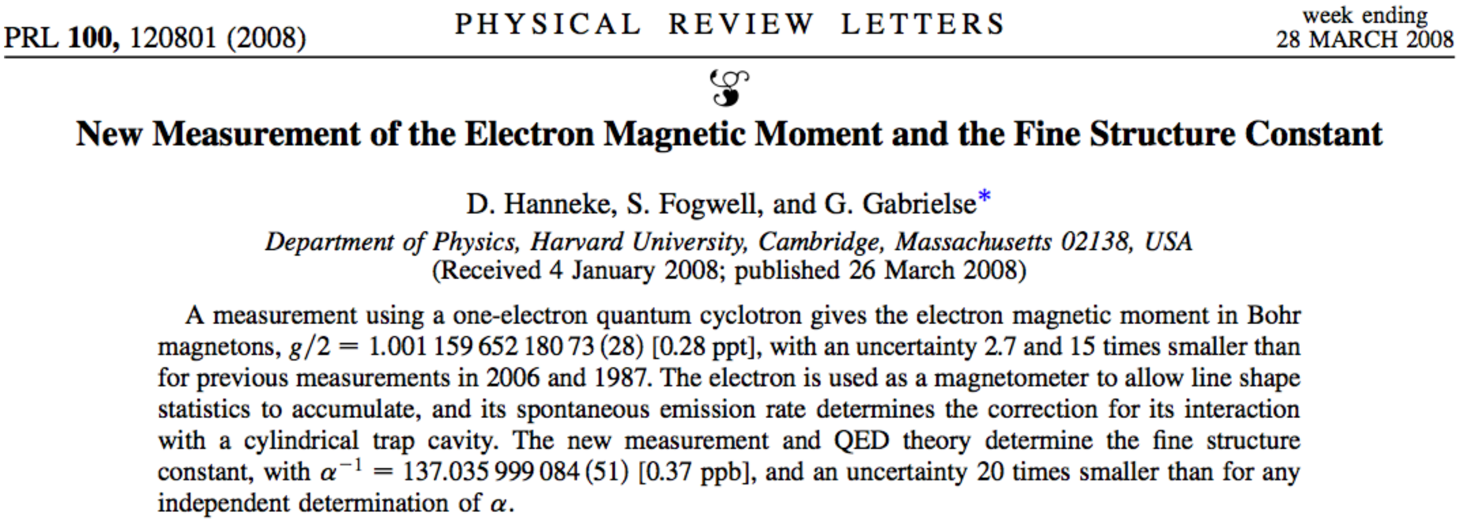
$$\boldsymbol{\mu} = -\, g \frac{e}{2mc} \boldsymbol{S}, \quad \boldsymbol{S} = \frac{\hbar}{2} \boldsymbol{\sigma} \text{ from quantum mechanics}$$

- Dimensionless g-factor can be predicted from theory
- 1947 : 0.1% discrepancies in spectroscopy. G. Breit suggests $g_e = 2 + \epsilon$
- 1948 : Measurements of Kusch and Foley found g_e deviates from 2
- 1948 : Schwinger QED calculation of *anomalous* part of g_e factor, a_e where $g_e \equiv 2(1+a_e)$



- $a_e = \alpha/2\pi \approx 0.00116$ due to *radiative corrections* from virtual particles in loops
- 1 part in 850 effect, huge success for QED !

The Anomalous Magnetic Moment of the Electron



PRL **100,** 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

D. Hanneke, S. Fogwell, and G. Gabrielse*

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(Received 4 January 2008; published 26 March 2008)

A measurement using a one-electron quantum cyclotron gives the electron magnetic moment in Bohr magnetons, $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], with an uncertainty 2.7 and 15 times smaller than for previous measurements in 2006 and 1987. The electron is used as a magnetometer to allow line shape statistics to accumulate, and its spontaneous emission rate determines the correction for its interaction with a cylindrical trap cavity. The new measurement and QED theory determine the fine structure constant, with $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], and an uncertainty 20 times smaller than for any independent determination of α.

- g_e most precisely known quantity in physics, to 0.28 ppt

PRL **100,** 120801 (2008) PHYSICAL RE

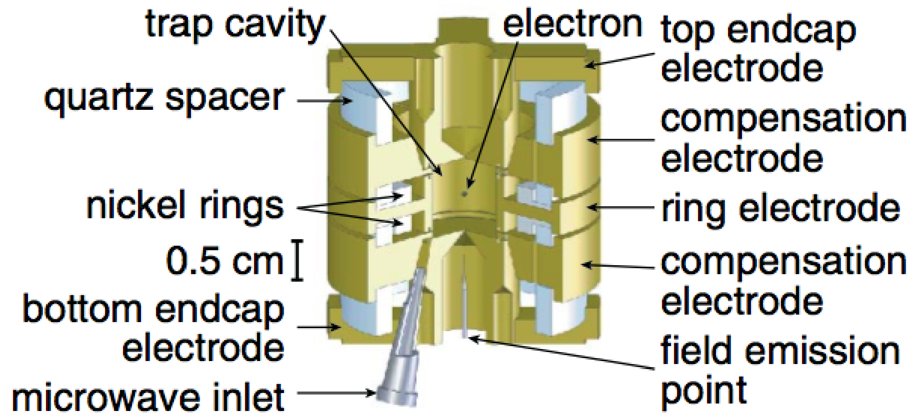


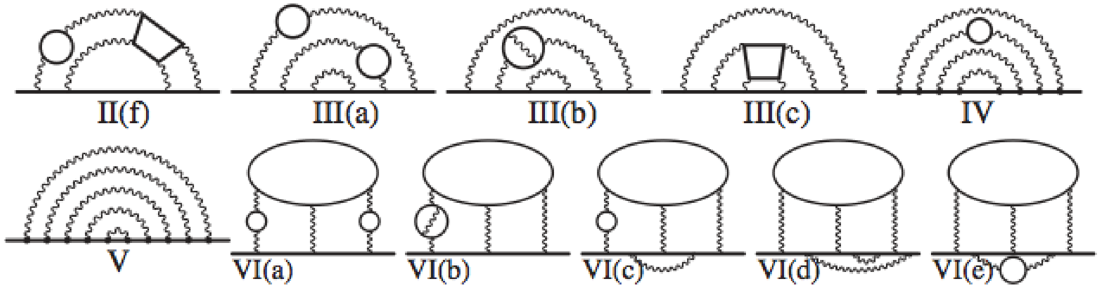
FIG. 2 (color). Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.

- Penning trap for single electron
- Magnetic confinement in radial
- Electrodes for vertical confinement
- Trapped for months
- $a_e = (g_e - 2)/2$ determined to 0.24 ppb

Theory of the Anomalous Magnetic Moment of the Electron

$$\frac{g_e}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + \ldots + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu,\tau} + a_{\text{hadonic}} + a_{\text{weak}}$$

- T. Kinoshita 9 years for QED calculation of 12672 Feynman diagrams for $C_{10}(\alpha/\pi)^5$, T. Aoyama *et al.*, Phys. Rev. Lett. **109**, 111807 (2012).



- Extract α, compare with other measurements, confirms QED at ppt level

⇒ $a_e = (g_e - 2)/2$ determined to 0.24 ppb

- Muons live 2.2 μseconds - why bother measuring a_μ ?
- Sensitivity to new physics : $\Delta a_{e,\mu}(\text{New Physics}) \approx C\left(\frac{m_{e,\mu}}{\Lambda}\right)^2$

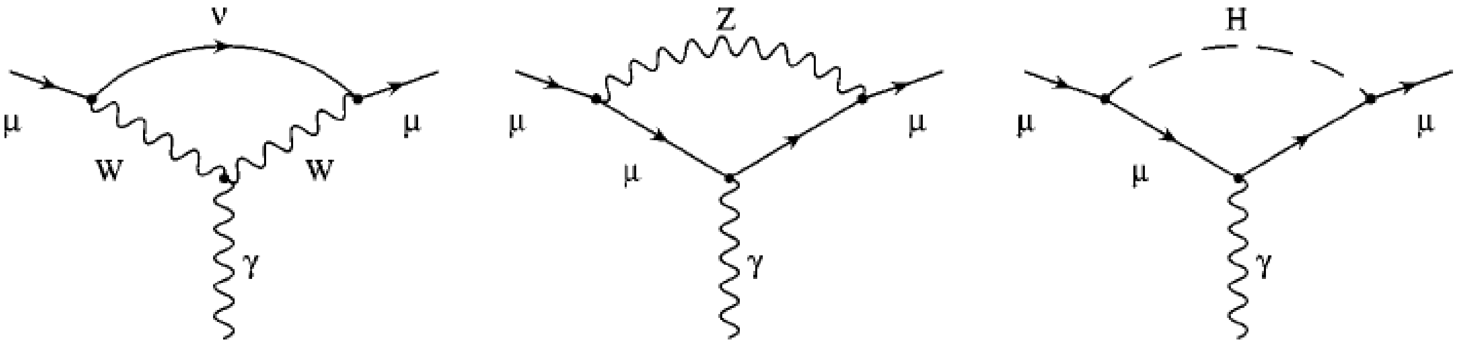
⇒ Muon mass 206 times electron mass, so new physics contribution 40,000 times larger

⇒ New physics contribution of 0.24 ppb on a_e corresponds roughly to 9 ppm on a_μ

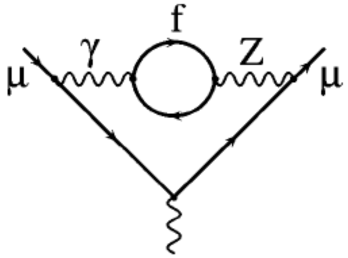
- a_μ known from Brookhaven E821 to 0.54 ppm, hope to push at Fermilab to 0.14 ppm

Contributions to the Anomalous Magnetic Moment of the Muon

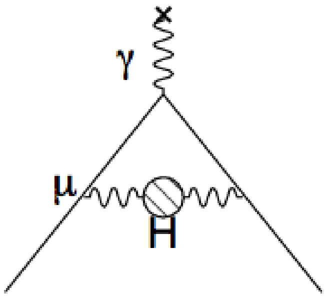
$$a_\mu(\text{Standard Model}) = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$



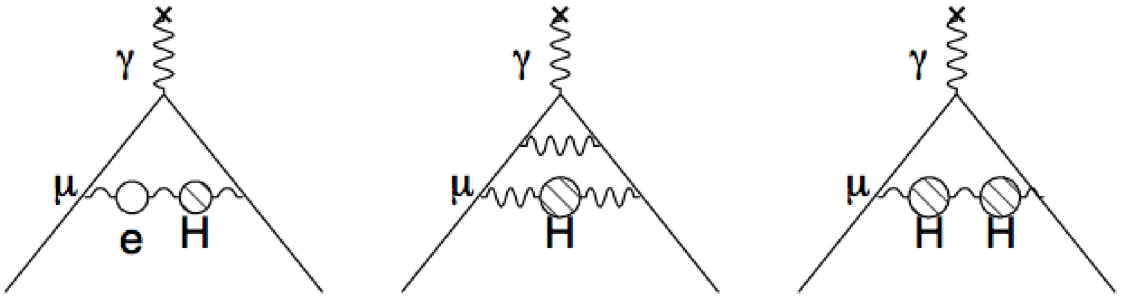
EW 1 Loop



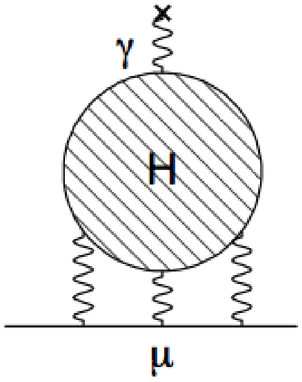
EW 2 Loop



Hadronic Leading Order



Higher Order

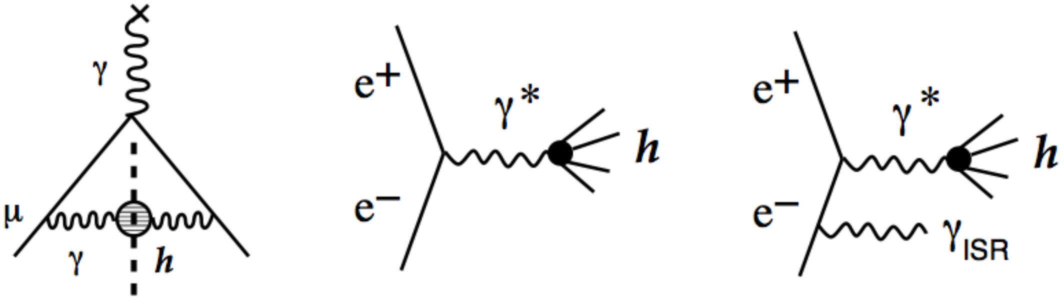


Light-by-Light

⇒ a_μ gets contributions from all physics - including the unknown

Low Energy Precision Frontier : The Anomalous Magnetic Moment of the Muon

$a_\mu^{\text{had;LO}}$ can be extracted from measurements by SND, CMD2, BaBar, KLOE, Belle; Lattice



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

- CMD3 will measure up to 2.0 GeV, using energy scan and ISR, good cross-check
- KLOE will measure $\gamma^* \to \pi^0$, might reduce uncertainty on a_μ(Had;LBL)

Standard Model prediction, in units of 10^{-11} : (M. Davier *et al.* Eur. Phys. J. C **71**, 1515 (2011))

a_μ(QED) = 116 584 718.951 ± 0.080(α^5)
a_μ(HadVP; LO) = 6 923. ± 42(Exp)
a_μ(HadVP; HO) = -97.9 ± 0.8(Exp) ± 0.3(Rad)
a_μ(Had; LBL) = 105. ± 26
a_μ(Weak; 1 loop) = 194.8
a_μ(Weak; 2 loop) = -40.7 ± 1(Had) ± 2(Higgs)

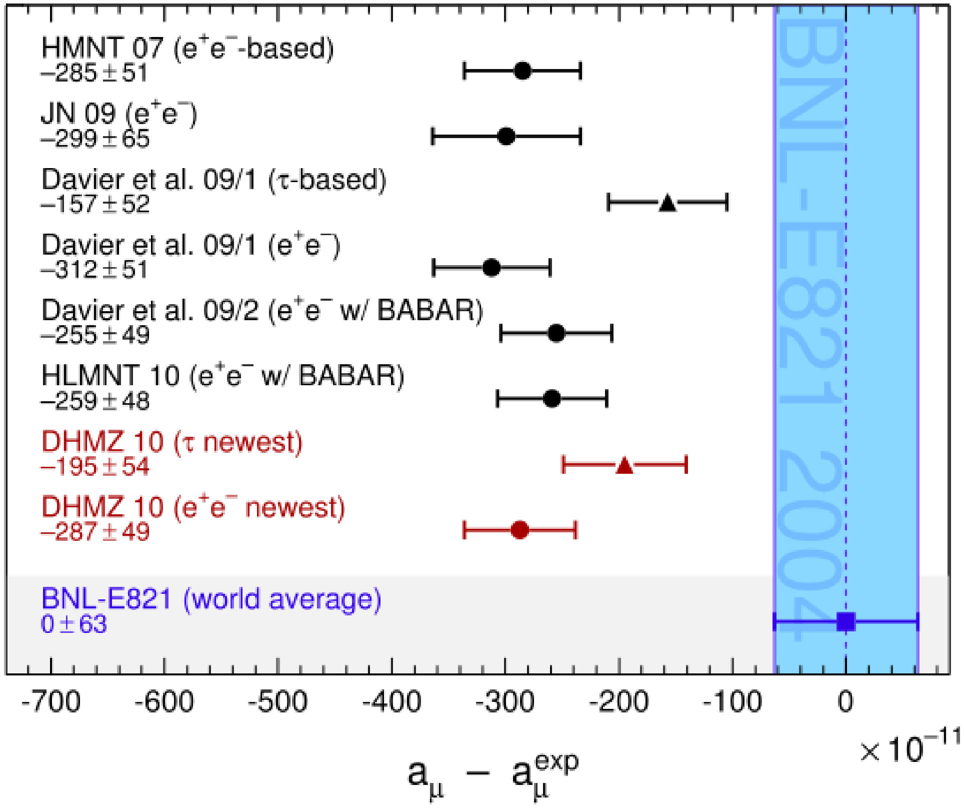
⇒ a_μ(SM) = 116 591 803. ± 49 × 10^{-11} (0.42 ppm)

Brookhaven E821 $g_\mu - 2$ Results (G.W. Bennett *et al.* Phys. Rev. D **73**, 072003 (2006))

In units of 10^{-11} :

$$a_\mu(\text{Expt}) = 116\,592\,089 \pm 54 \pm 33 \quad (0.54 \text{ ppm})$$
$$a_\mu(\text{SM}) = 116\,591\,803 \pm 49 \quad (0.42 \text{ ppm})$$

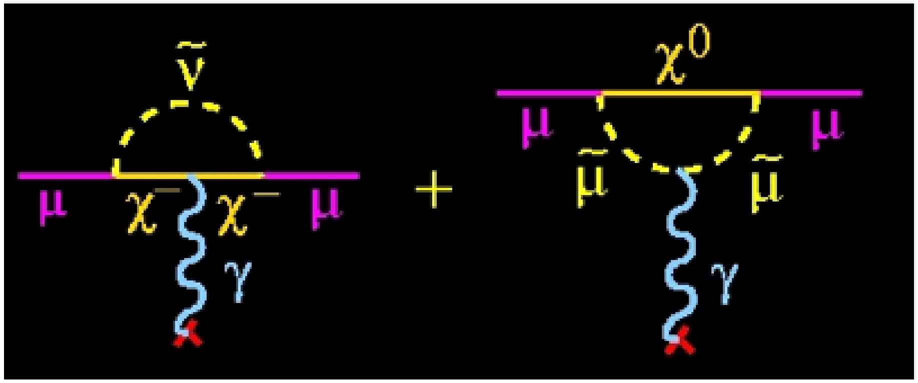
$$\boxed{a_\mu(\text{Expt}) - a_\mu(\text{SM}) = 286 \pm 80 \ (3.6\sigma)}$$



- ⇒ Theory (HVP from e^+e^-, no τ) from M. Davier *et al.*, Eur. Phys. J. C **71**, 1515 (2011).
- ⇒ Deviation is large compared to weak contribution and uncertainty on hadronic terms
- ⇒ Signature of new physics?
- ⇒ Deviation doesn't reach 5σ threshold for discovery - need to reduce uncertainties
- ⇒ Need to do a better experiment! Need to reduce theoretical uncertainties

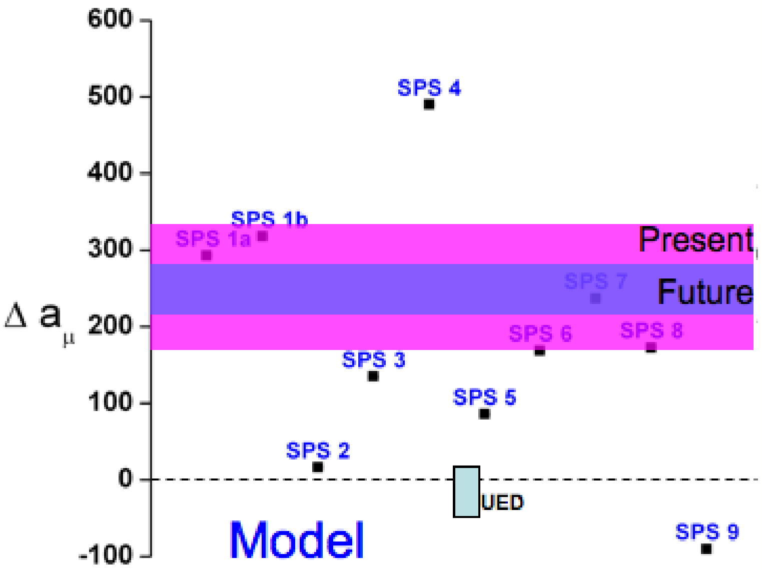
Low Energy Precision Tests : Beyond the Standard Model

- a_μ is sensitive to variety of new physics; including many SUSY models



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

⇒ μ and $\tan\beta$ are difficult to measure at LHC, $g_\mu - 2$ can provide tighter constraints



- Snowmass Points and Slopes take benchmark points in SUSY parameter space and predict observables
- Muon g-2 is a powerful discriminator amongst models of physics
- *Regardless of the final value*, it strongly constrains *all* the possibilities

Low Energy Precision Tests : Motivation for reducing uncertainty on a_μ

- Many well motivated theories predict large Δa_μ - new g-2 can constrain parameters
- Many well motivated theories predict tiny Δa_μ - if large Δa_μ found by new g-2, these are excluded
- Some models predict similar signatures at LHC but distinguishable by Δa_μ (MSSM and UED (1D), Littlest Higgs)
- New g-2 sensitive to parameters difficult to measure at LHC [tan(β), sgn(μ)]
- Provides constraints on new physics that are independent and complementary to LHC, CLFV ($\mu \to e$), EDMs, ...

⇒ Even agreement with the Standard Model would be very interesting

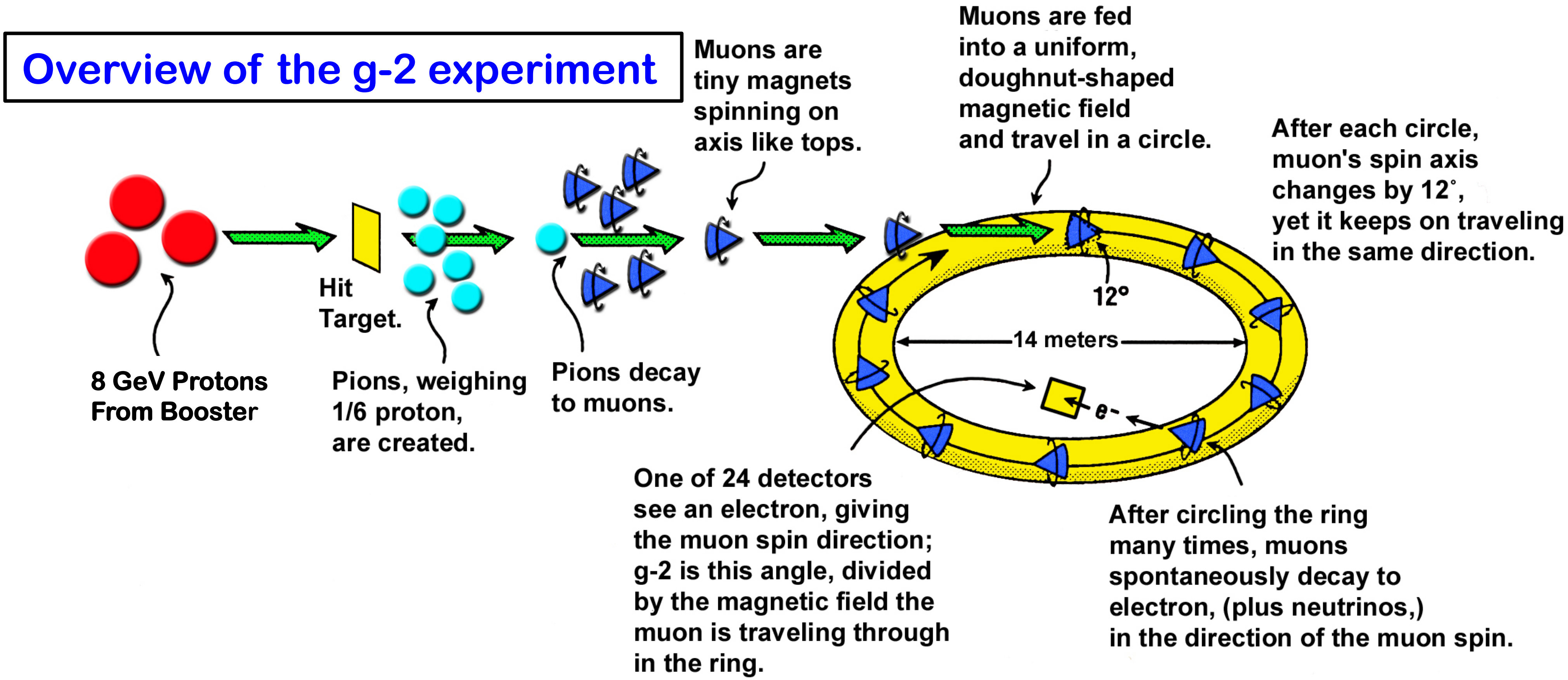
⇒ Sensitivity to new particles with TeV scale mass

⇒ Many reasons to pursue a new measurement of a_μ at Fermilab, reduce δa_μ from 0.54 ppm → 0.14 ppm

The Future : E989 at Fermilab

- E989 will measure the Muon Anomalous Magnetic Moment to ± 0.14 ppm precision
- Factor of 4 improvement possible due to advantages at Fermilab

The g-2 Experiment in a Nutshell



Overview of the g-2 experiment

8 GeV Protons From Booster

Hit Target.

Pions, weighing 1/6 proton, are created.

Pions decay to muons.

Muons are tiny magnets spinning on axis like tops.

Muons are fed into a uniform, doughnut-shaped magnetic field and travel in a circle.

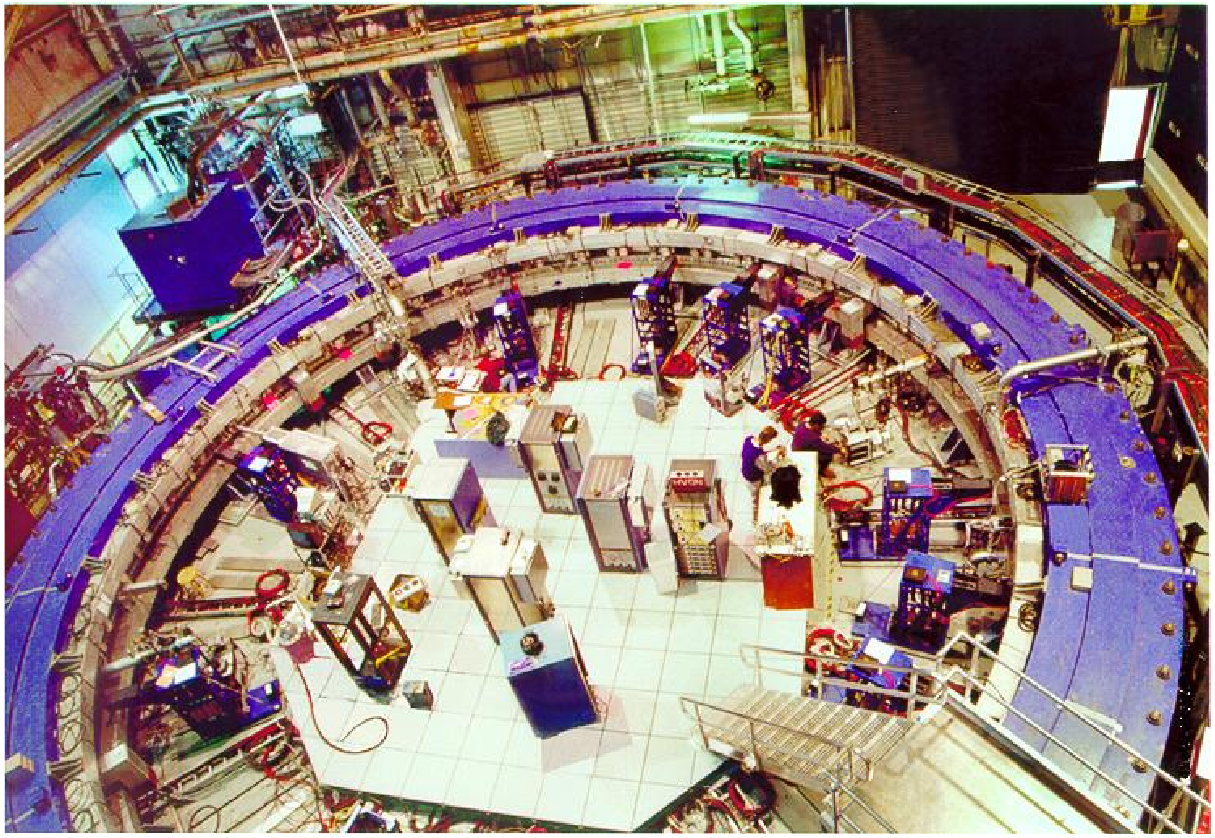
After each circle, muon's spin axis changes by 12°, yet it keeps on traveling in the same direction.

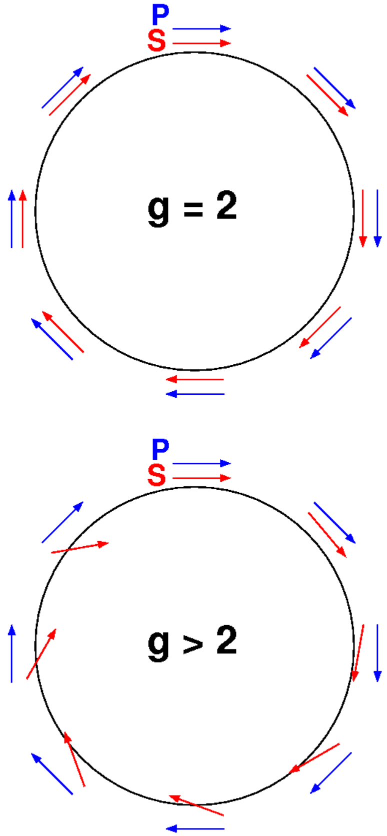
One of 24 detectors see an electron, giving the muon spin direction; g-2 is this angle, divided by the magnetic field the muon is traveling through in the ring.

After circling the ring many times, muons spontaneously decay to electron, (plus neutrinos,) in the direction of the muon spin.

- Just like a_e use a Penning trap, except 7.112 meter radius, 650 tons
- Muons enter storage ring through a SC inflector that cancels storage ring $\boldsymbol{B}$ field
- Muons kicked onto orbit by pulsed magnetic field
- Muons confined vertically by electric quadrupoles

Experimental Procedure : Based on BNL E821 Muon $g_\mu - 2$ Experiment





- Inject polarized muons at 3.094 GeV/c into superferric storage ring, radius = 711.2 cm
- Muon spin precesses in homogeneous 1.45 T field, time dilated lifetime of 64.4 μs, measure for 700 μs

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c \quad : \quad \text{difference between spin and cyclotron frequencies}$$

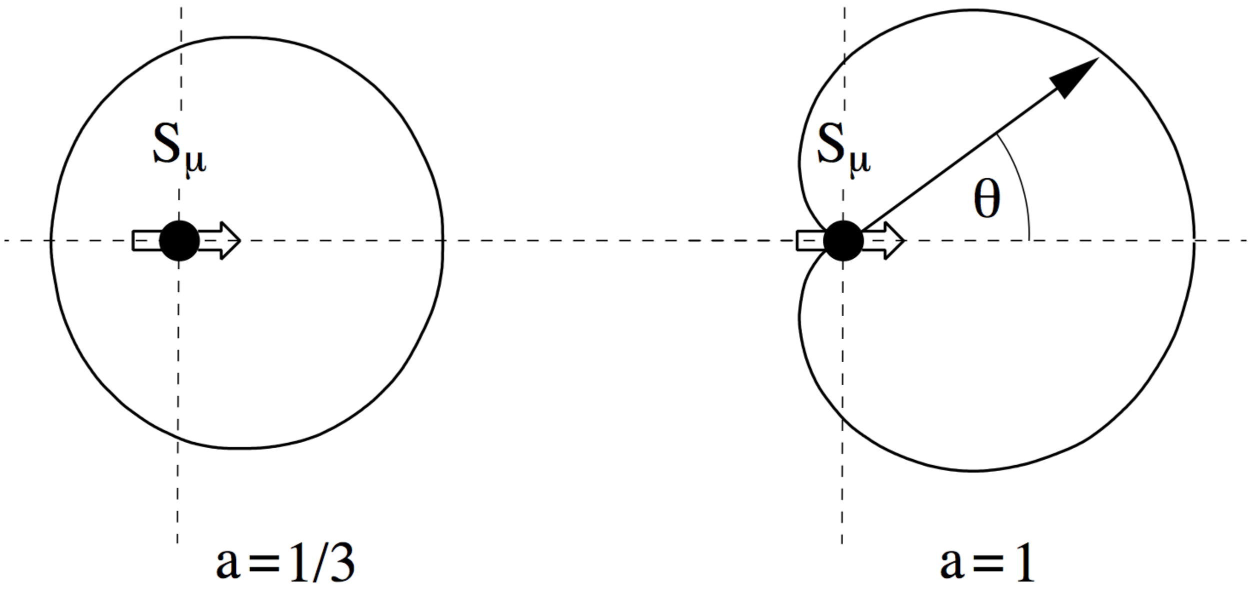
$$\vec{\omega}_a = -\frac{q}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right] \quad \Rightarrow \text{ at } \gamma = 29.3 \quad \Rightarrow \quad \vec{\omega}_a = -\frac{q}{mc}\left[a_\mu \vec{B}\right]$$

$\Rightarrow$ To determine a_μ, need to measure ω_a and B (weighted by muon distribution)

- Sub-ppm corrections applied due to vertical betatron motion (pitch correction) and muons not at magic γ

How will we measure ω_a ?

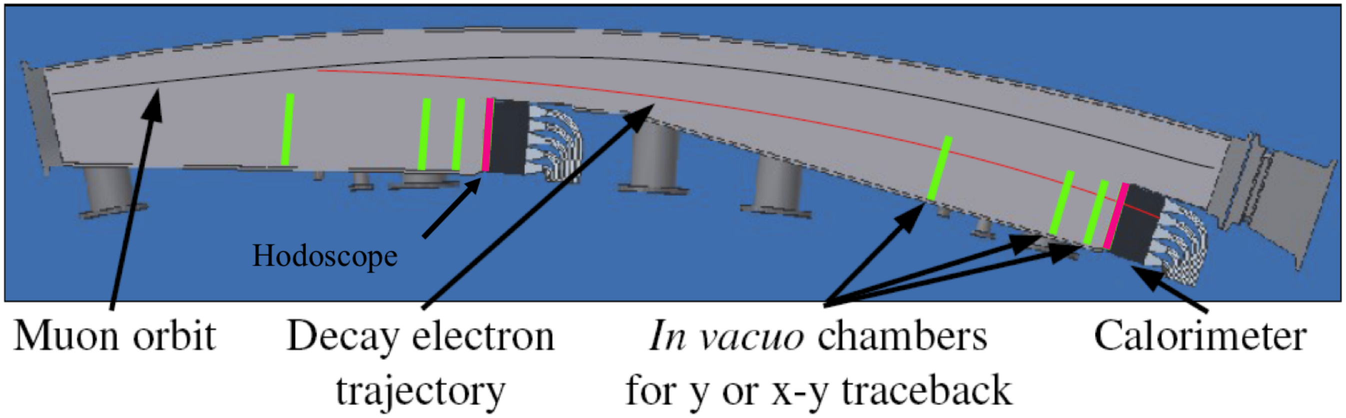
- To measure ω_a, need to know muon spin direction when it decayed
- Nature is kind here : muon decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ is self-analyzing due to PV
- Muon spin direction correlated with decay positron direction

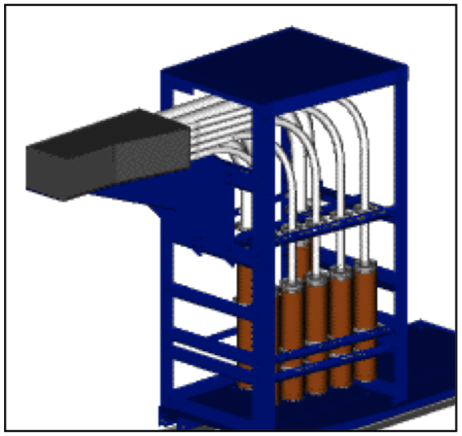


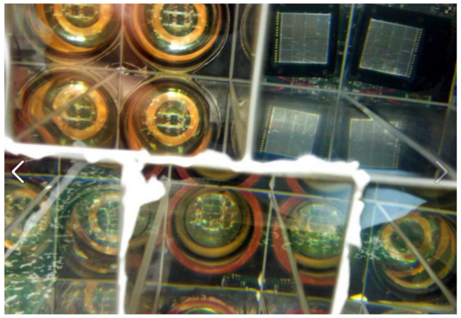
- Averaged over all positron energies, forward-backward asymmetry wrt muon spin is a=1/3
- For highest energy positrons (3.1 GeV), asymmetry a=1
- Detect decay e^+ above 1.8 GeV ⇔ cut on θ^*, reconstruct muon spin direction versus time

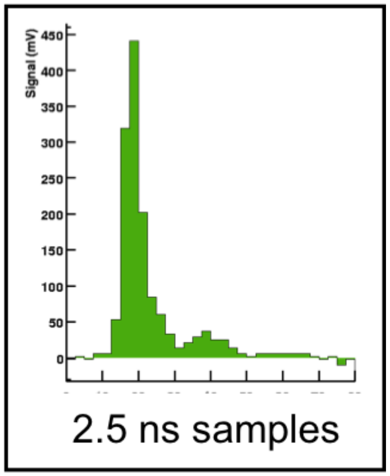
How will we measure ω_a ?

- Decay e^+ curve inward in $\boldsymbol{B}$ field, detect with 24 crystal calorimeter stations
- Smaller Moliere radius, greater segmentation, greater immunity to pileup then BNL E821, SiPMs instead of PMTs
- Signals digitized with 500 MHz waveform digitizers for 700+μs, extract e^+ signals offline





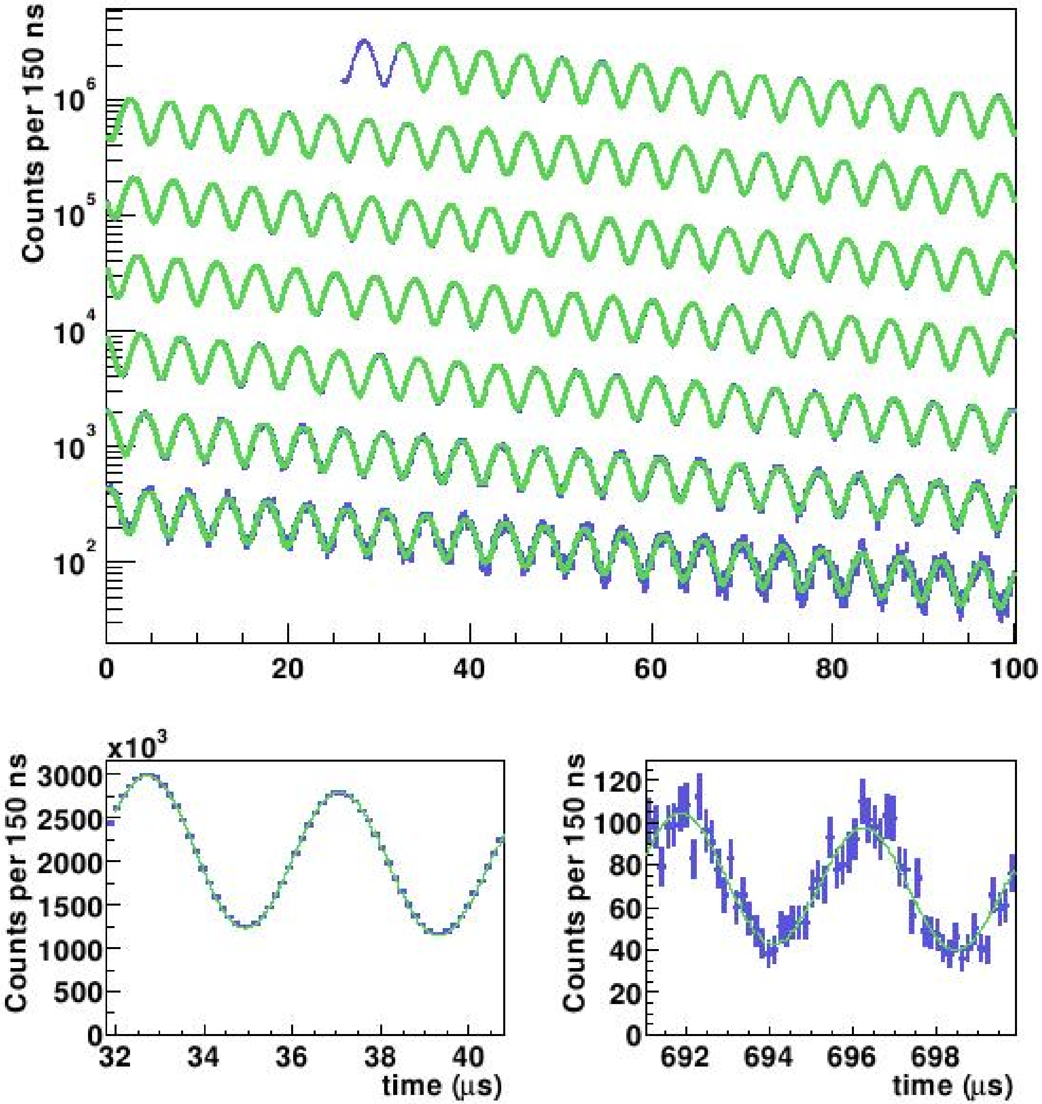




2.5 ns samples

Measurement of ω_a

$$N_{\text{ideal}}(t) = N_0 \exp\left(-t/\gamma\tau_\mu\right)\left[1 - A\cos\left(\omega_a t + \phi\right)\right]$$

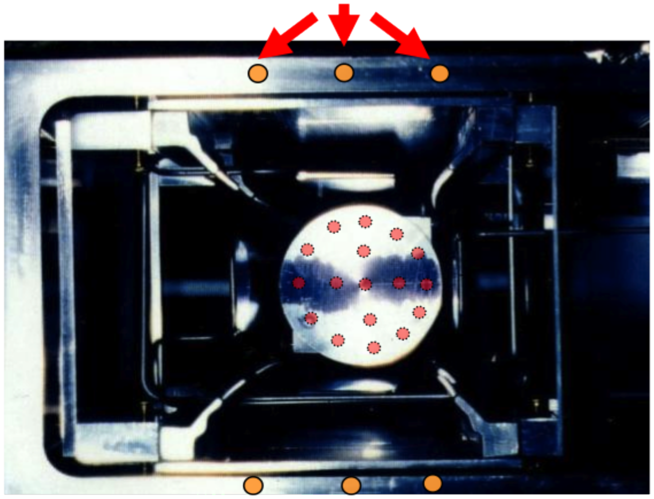


- Corrections for muon losses, pileup, modulation from coherent betatron oscillations

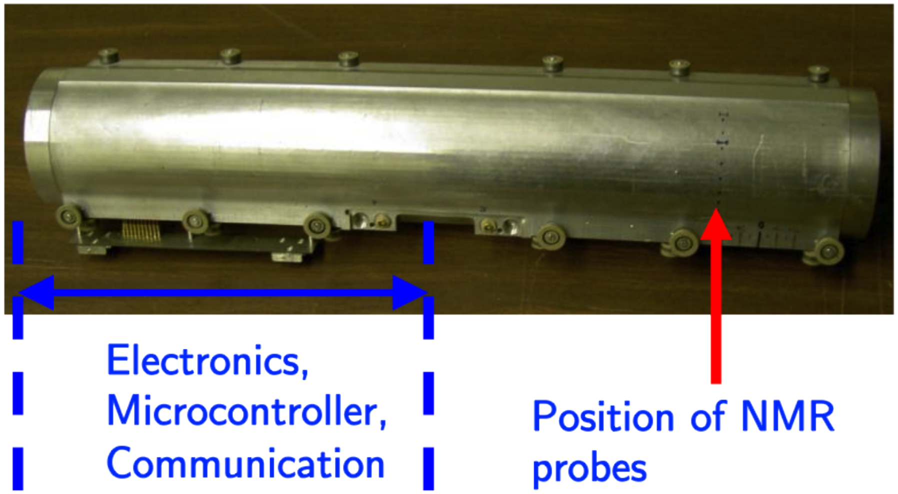
Magnetic Field Measurement using Pulsed NMR

- Monitor field during data taking with 100s of fixed NMR probes outside vacuum chambers
- NMR trolley measures field inside storage volume, relate measurements to fixed probes
- Absolute calibration probe relates trolley measurements to free proton frequency ω_p

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes

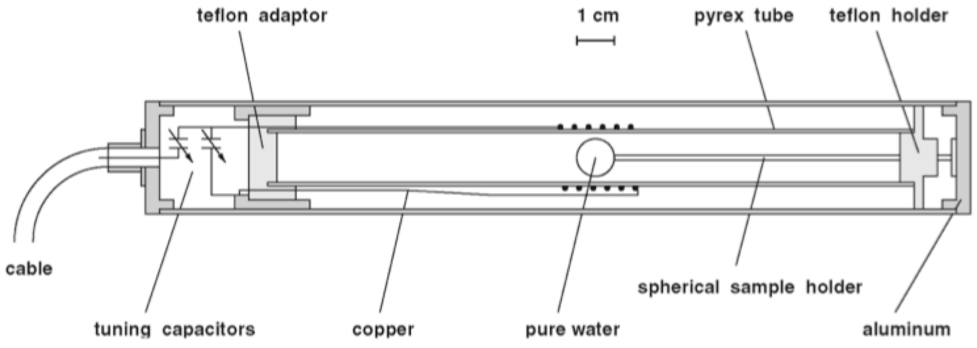


Electronics,
Microcontroller,
Communication

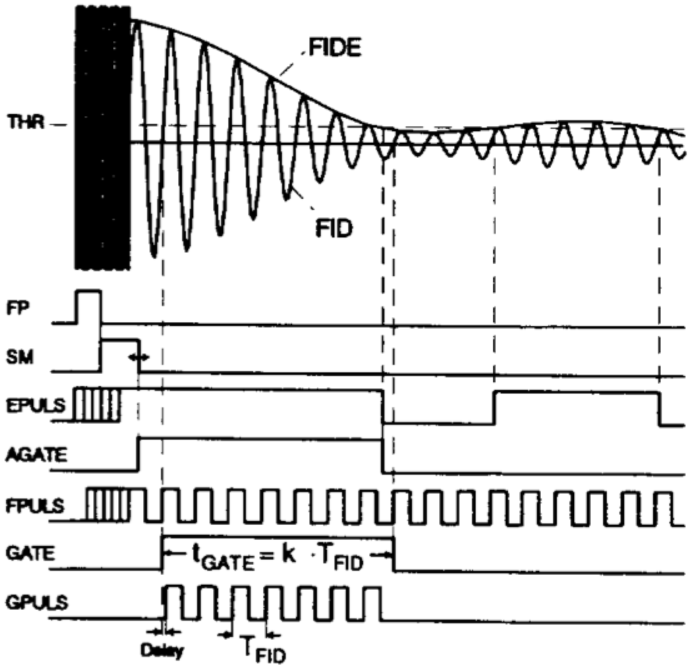
Position of NMR probes

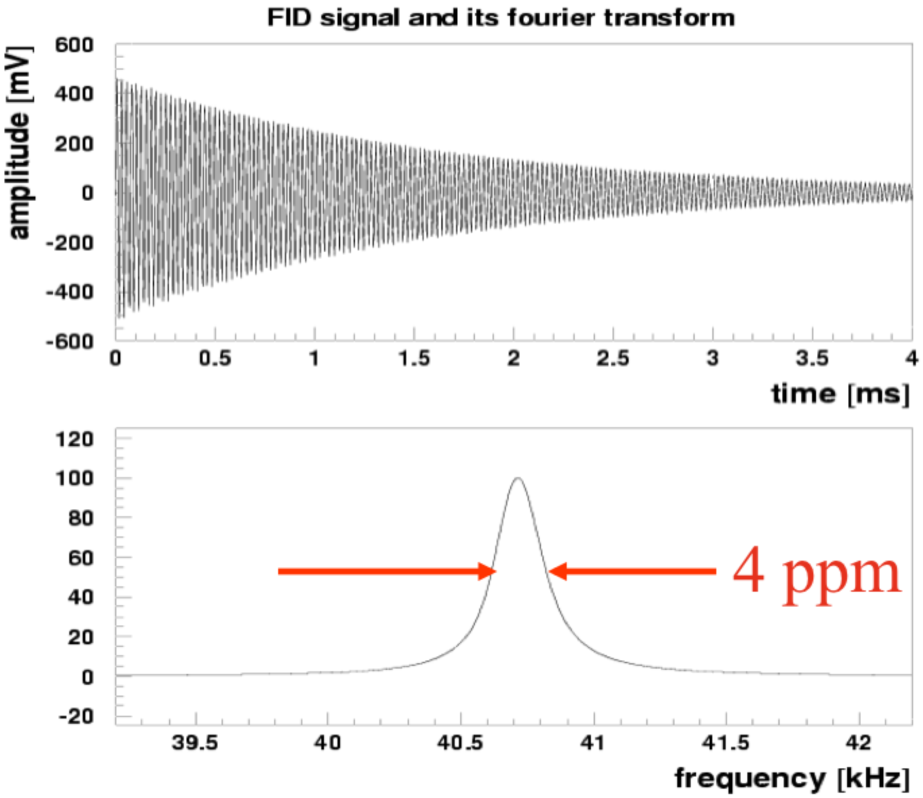
Absolute calibration probe with spherical water sample

Magnetic Field Measurement using Pulsed NMR



(a) Absolute calibration probe





- $\boldsymbol{B}_0$=1.45 T $\Leftrightarrow$ $\nu_0 =$ 62 MHz
- Count zero crossings of FID after mixing (≈50 kHz), 20 ppb resolution

- ω_{meas}(sph,H$_2$O,T)=[1-σ(H$_2$O,T)]ω_p(free), σ(H$_2$O,T)≈ $25.790(14) \times 10^{-6}$, shielding of proton in water

$\Rightarrow$ Express $\boldsymbol{B}$ field, weighted by muon distribution, in terms of ω_p(free) to 70 ppb

E989 : Fermilab offers advantages, factor 4 improvement possible

Recycler

- Rebunches 8 GeV protons from booster

Target Station

- Target + focusing lens

Decay Line

- Target to M2 to M3 to delivery ring

⇒ 900 m long decay channel for $\pi \Rightarrow \mu$
reduced π and p in ring,
factor 20 reduction in hadronic flash

⇒ 4× higher fill frequency than E821

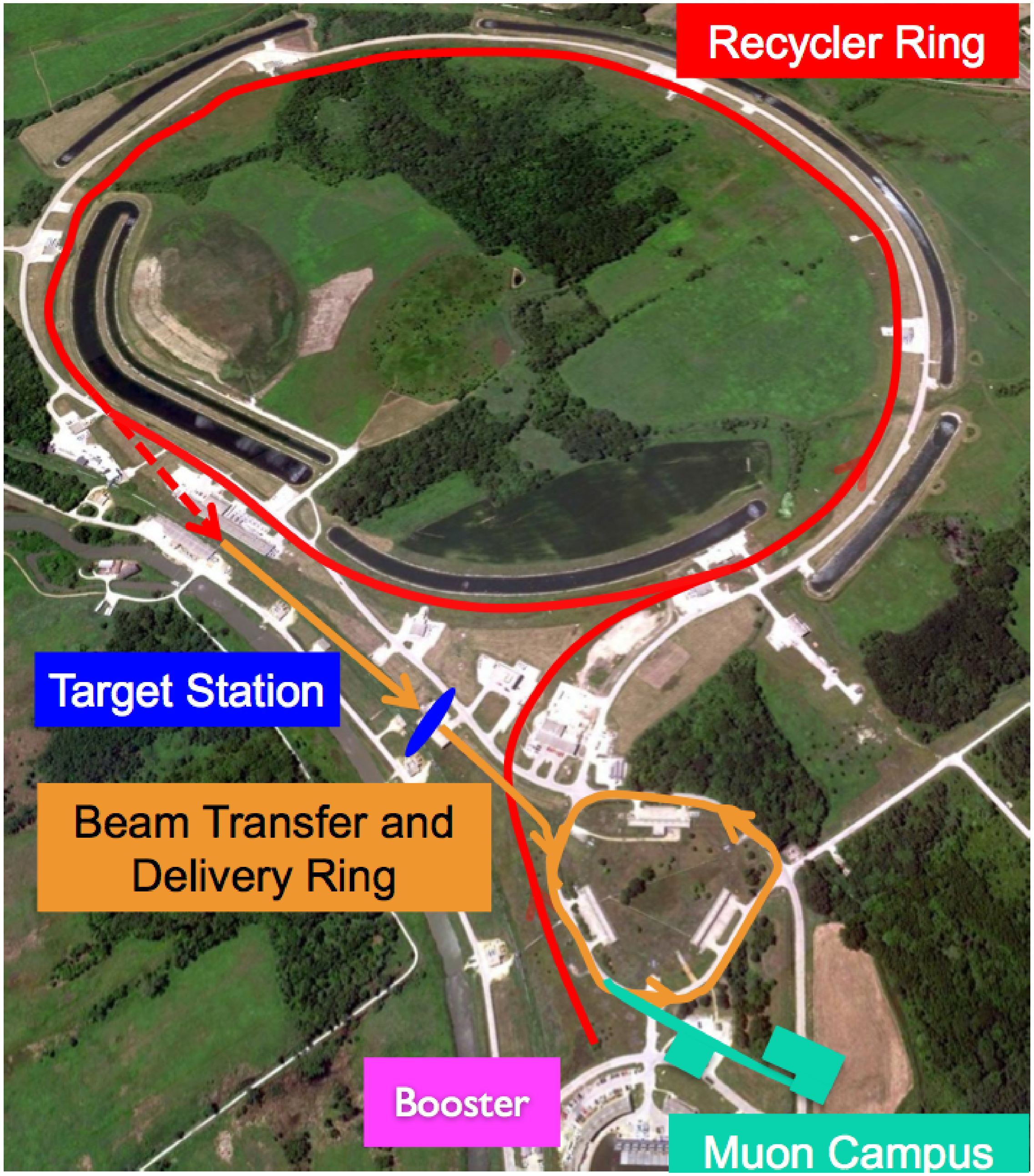
⇒ Muons per fill about the same

⇒ 21 times more detected e^+, 2×10^{11}

⇒ Better temperature control in experimental hall

⇒ Reduction in systematics by factor of 3 without major modifications

⇒ First data 2016



New muon g-2 Summary

- Experiment under development to measure a_μ to 0.14 ppm, fourfold improvement over BNL E821
- Reduction in statistical uncertainty by factor 4; reduce ω_a, ω_p systematics by factor 3

- Hope to motivate improvements in theory and more exp. work :
  - Currently δa_μ(HadVP,LO) $=$ 0.36 ppm, and δa_μ(Had,LBL) $=$ 0.23 ppm
- Before E821 (1983), expt. known to 7 ppm, theory to 9 ppm : now 0.54 and 0.42 ppm

- Regardless of where final result for a_μ lands :
  - Precision test Standard Model
  - Determine parameters (tan(β)) or viability of many new physics models predicting $\Delta a_\mu \neq 0$ (SUSY models)
  - UED (1D) predict tiny effects incompatible with $\Delta a_\mu << 300 \times 10^{-11}$
  - Constraint on all future models
  - Provide complementary information to direct searches at LHC, CLFV, EDMs

- Apart from the rich physics - it's a great experience

Fundamental Symmetries Summary

- Symmetries play an enormous role in the Standard Model - they determine the Lagrangian
- 't Hooft, Phys. Rev. Lett. **37**, 8 (1976) :
  "When one attempts to construct a realistic model of nature one is often confronted with the difficulty that most simple models have too much symmetry."
- Broken symmetries important too - usually really interesting physics involved
- The searches for violations of old symmetries, and searches for new symmetries (SUSY, GUTs) will bring about a New Standard Model