Electroweak Physics

Lecture V:

Survey of Low Energy Electroweak Physics

(other than neutral current interactions)

Acknowledgements:

Slides from D. DeMille, G. Gratta, D. Hertzog, B. Kayser, D. Kawall, M.J. Ramsey-Musolf

Review

1. Introduction to Electroweak Physics
   - **Electroweak force properties; electron-positron collisions**
2. Status of Electroweak Physics
   - **Precision electroweak data from colliders**
3. Electroweak Physics at low Q^2
   - **Weak Neutral Current interactions**
   - **E158 experiment**
4. Weak Neutral Current Interactions (cont'd)
   - **Future Weak Neutral Current experiments**
   - **Strange Quarks in the Nucleon**
   - **Neutron Skin of a Lead Nucleus**

Muon g-2

- **The gyromagnetic ratio, g, relates spin angular momentum to the particle's magnetic moment**

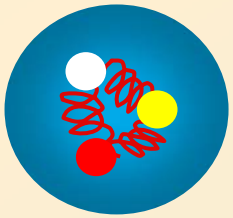
$$\vec{\mu}_S = g\left(\frac{e}{2m}\right)\vec{S}$$

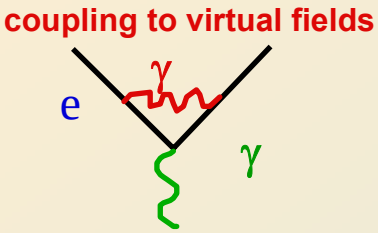
- **Dirac theory: point-like, spin-1/2 particles have $g = 2$, but ...**
  - » **proton**
  - » **hyperons**

  } **g >> 2**

  - » **electron**
  - » **muon**

  } **g almost equal to 2**

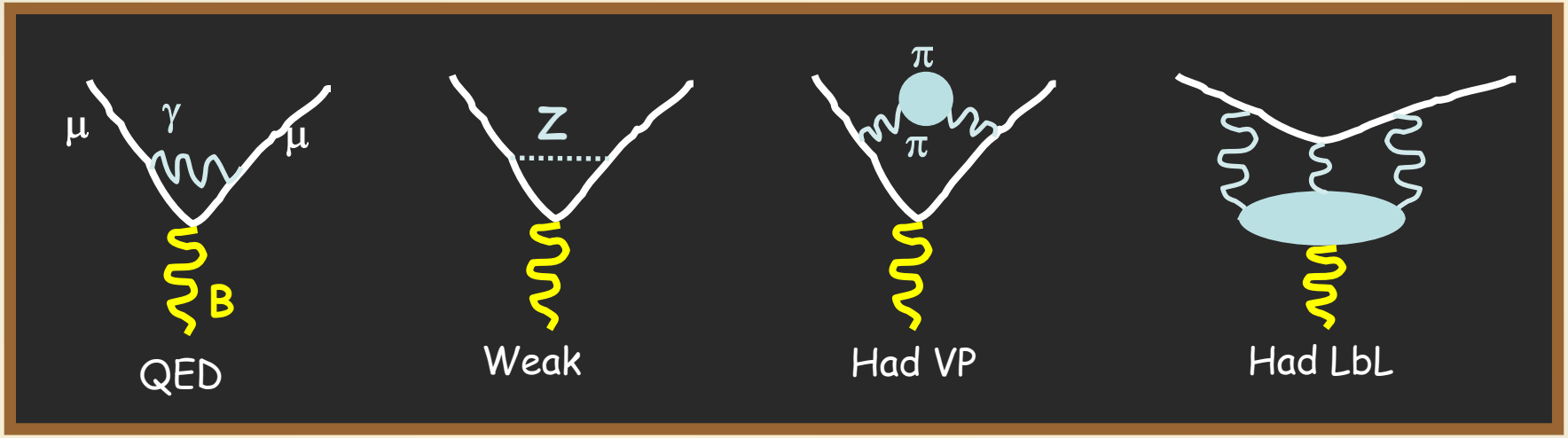




- **The muon *anomalous* magnetic moment is**

$$a_\mu = \frac{(g-2)_\mu}{2} \approx \frac{\alpha}{2\pi} \approx \frac{1}{800}$$

g ≠ 2 because of virtual loops, many of which can be calculated very precisely



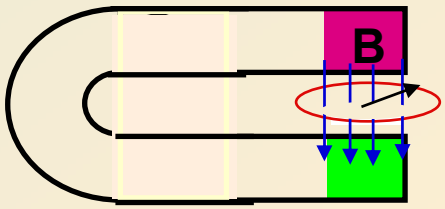
QED	Weak	Had VP	Had LbL
11 658 470.57(29)	15.4(3)	696.3(7) or 711.0(6)	+13.0(25)
(2003: +1.8 shift)			New: +50% shift ! Not agreed on yet

Units: $\times 10^{-10}$

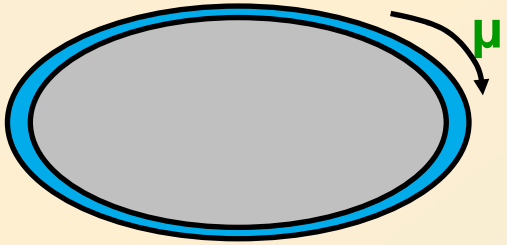
Others cannot …

Precession proportional to (g-2)

at rest



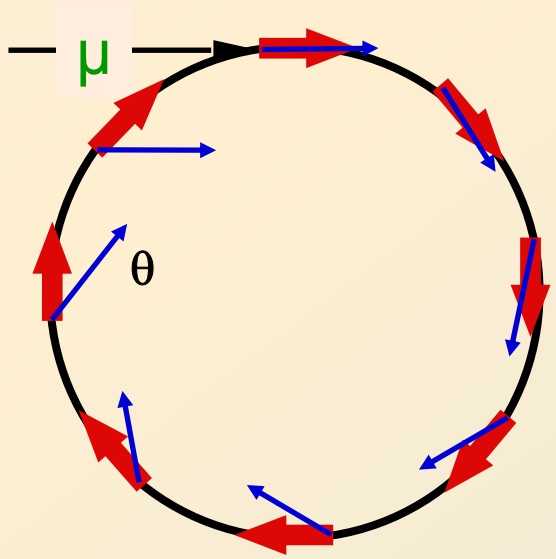
in flight



$$\omega_s = \frac{g}{2}\frac{eB}{mc} = \omega_L$$

$$\omega_s = \left[1 + \gamma\left(\frac{g-2}{2}\right)\right]\frac{eB}{mc\,\gamma}$$

$$\omega_c = \frac{eB}{mc\,\gamma}$$



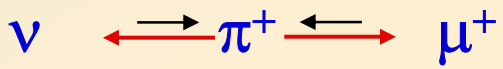
$$\Delta\omega = \omega_a = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

MOVIE

INDEPENDENT of γ !

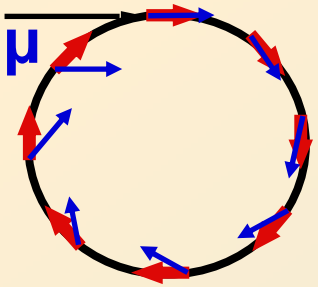
4 key miracles make it happen

- **Polarized muons**



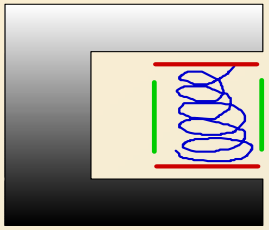
- **Precession proportional to (*g*-2)**

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

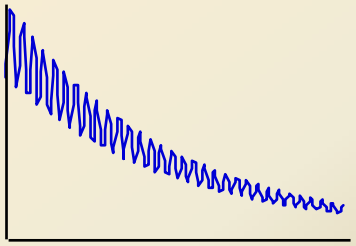


- **P_μ The magic momentum**
  ***E* field doesn't affect muon spin when γ = 29.3**

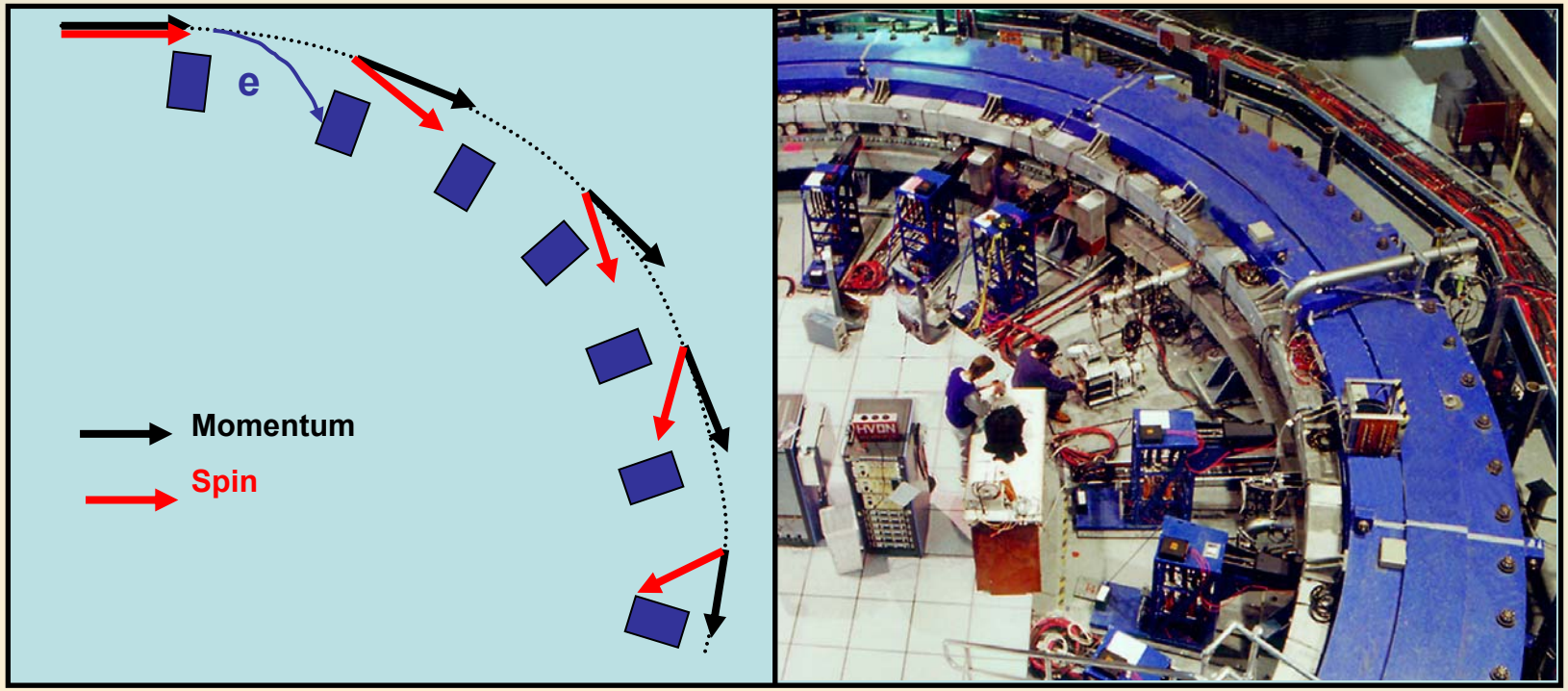
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$



- **Parity violation in the decay**



a_μ is proportional to the difference between the spin precession and the rotation rate

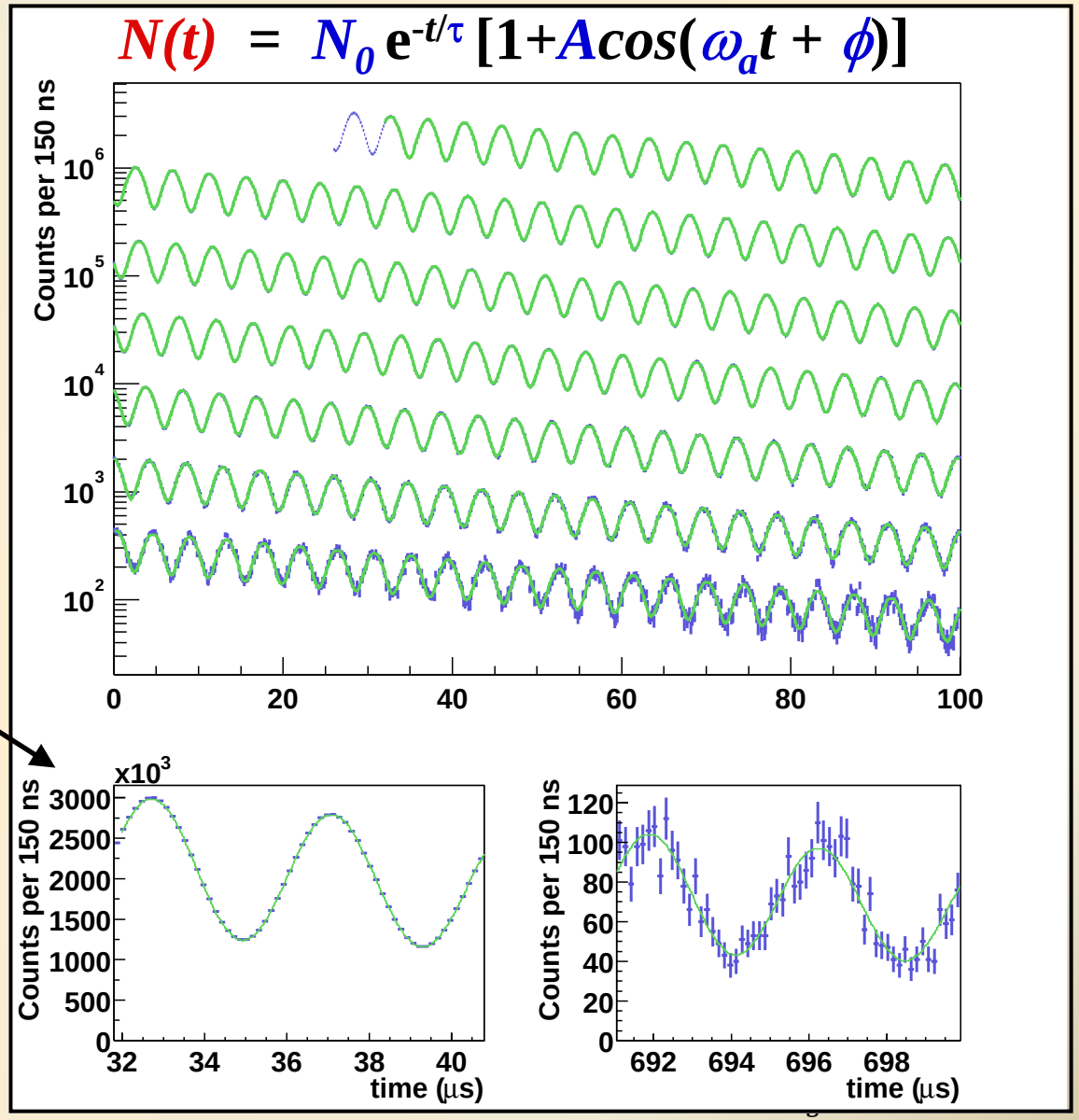


$$\Delta\omega = \omega_a = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

Fit to Simple 5-Par Function

Few billion events

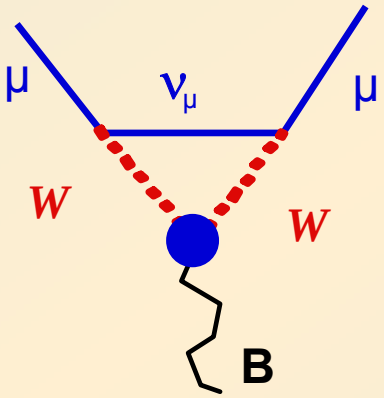
Getting a good χ^2 is a challenge

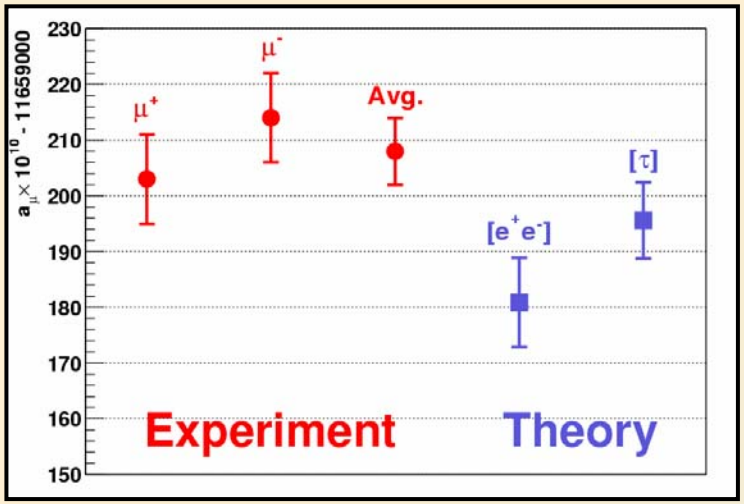


Results and Implications

Non-zero Δa_μ appeals to a catalog of *SM Extensions*

- **New physics …**
  - **SUSY**
  - **Leptoquarks**
  - **Muon substructure**
  - **Anomalous *W* couplings**





- **Theory is being improved**
- **New design to reduce error by factor of 2**

CC Weak Interaction within the SM

$$\boxed{L_{CC} = \frac{g}{2\sqrt{2}} W_\mu^+ \left[\overline{U_i} \gamma^\mu (1-\gamma^5) \mathbf{V}_{ij} D_j + \overline{\nu_k} \gamma^\mu (1-\gamma^5) l_k \right] + \text{h.c.}}$$

$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad \nu = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \qquad l = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\mathbf{V}\mathbf{V}^\dagger = \mathbf{V}^\dagger \mathbf{V} = I$$

$$\Downarrow$$

$$\sum_\beta V_{\alpha\beta} V^*_{\gamma\beta} = \delta_{\alpha\gamma}$$

PV in Charged Current Processes

$$M^{CC} \approx \frac{g^2}{8M_W^2}(V-A)\otimes(V-A)$$

Fermi Constants

μ decay $$\frac{G_F^{\mu}}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1+\Delta r_{\mu}\right)$$

β decay $$\frac{G_F^{\beta}}{\sqrt{2}} = \frac{g^2}{8M_W^2}V_{ud}\left(1+\Delta r_{\beta}\right)$$

New physics

$g^2/8M_W^2$ **is universal**

Universality obscured by $$G_F^{\beta}/G_F^{\mu} = V_{ud}\left(1+\Delta r_{\beta}-\Delta r_{\mu}\right)$$

Weak decays

$$d \to u\, e^- \bar{\nu}_e$$

$$s \to u\, e^- \bar{\nu}_e$$

$$b \to u\, e^- \bar{\nu}_e$$

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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \qquad \text{SM}$$

$$0.9968 \pm 0.0001 \qquad \text{Expt}$$

$$0.9487 \pm 0.0001 \qquad 0.0482 \pm 0.0000 \qquad 0.0000 \pm 0.0000$$

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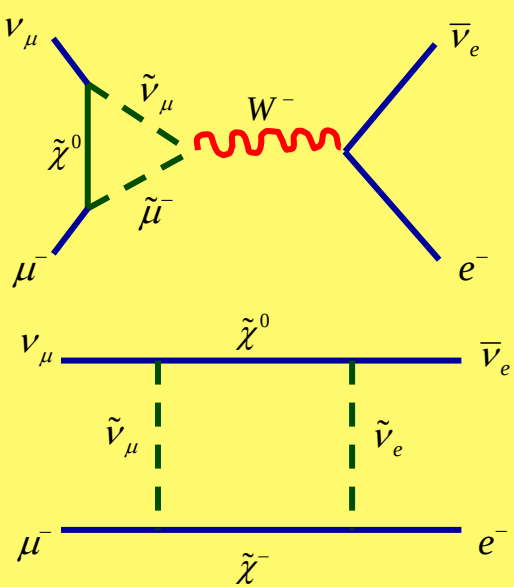


$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.00$$

$$+ \cdots$$

SUSY

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}| \left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

New physics

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1 + \Delta r_{\beta} - \Delta r_{\mu}\right)$$

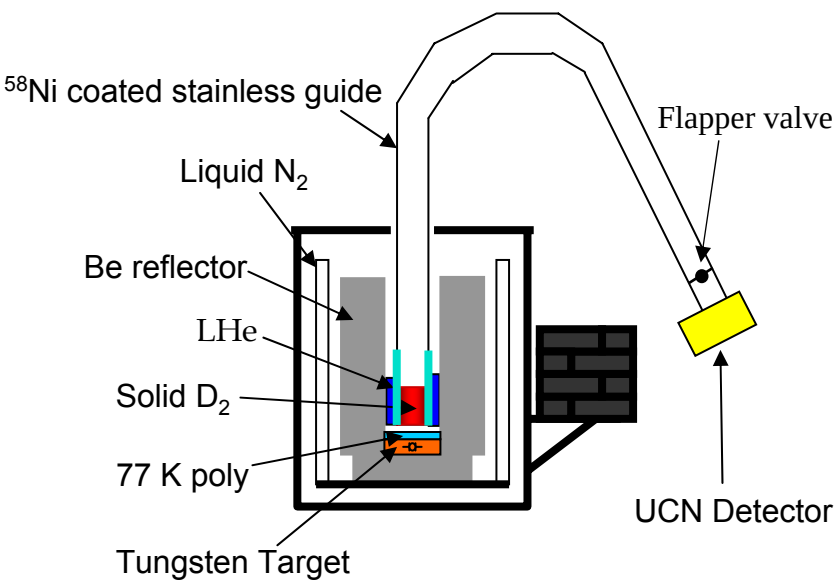
β-decay

$$n \rightarrow p e^- \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^+ \nu_e$$

$$\pi^+ \rightarrow \pi^0 e^+ \nu_e$$

Ultra cold neutrons



LANSCE: "UCN A"

$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e} + \cdots$$

Future SNS: Pulsed Cold Neutrons: "abBA"

Weak decays

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}|\left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

0^+ ! 0^+ "Superallowed"

$$Ft = ft\left(1 + \delta_R + \delta_{NS}\right)\left(1 - \delta_C\right)$$
$$= K/2(G_F^\beta)^2$$

Nuclear structure-dependent corrections

β-decay

$$n \to p e^- \bar{\nu}_e$$

$$A(Z,N) \to A(Z-1,N+1)\, e^+ \nu_e$$

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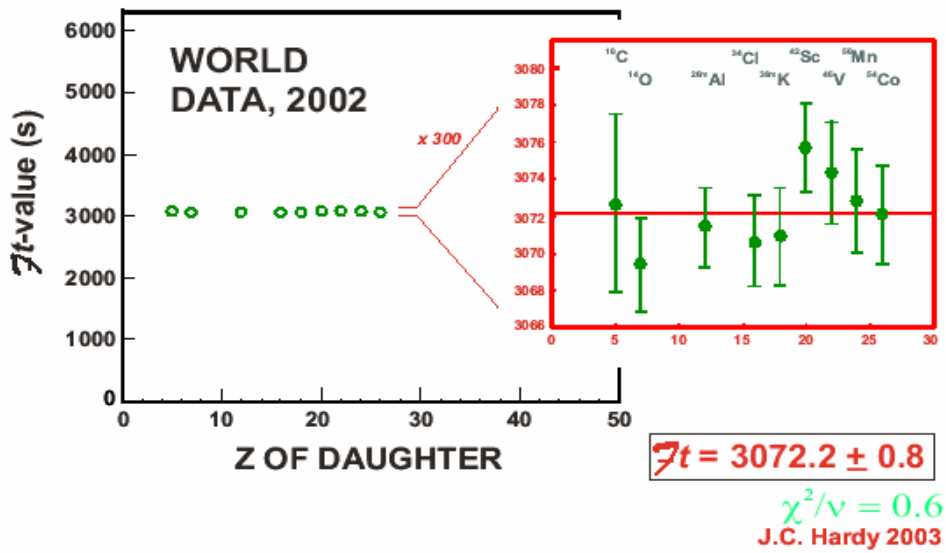

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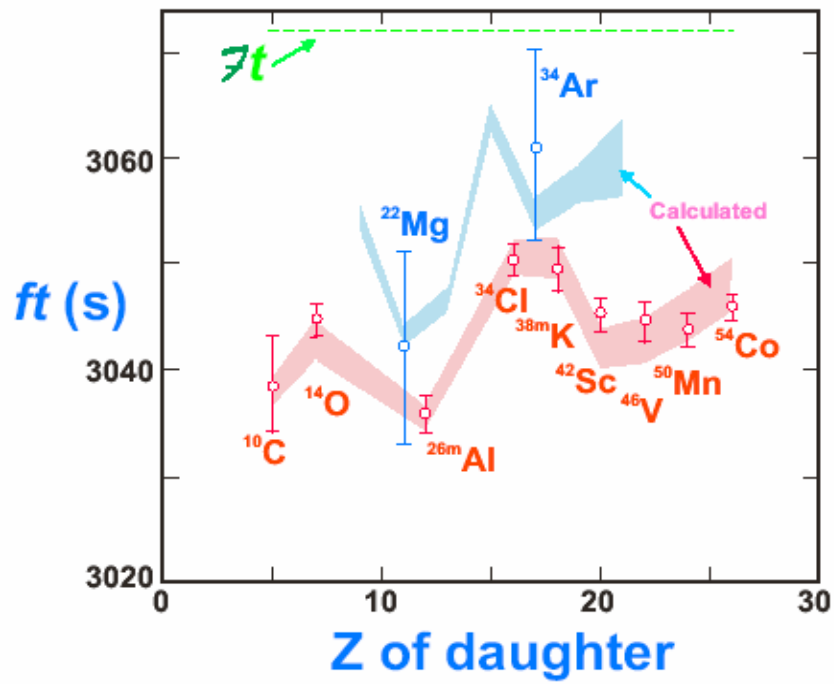

Weak decays

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β-decay

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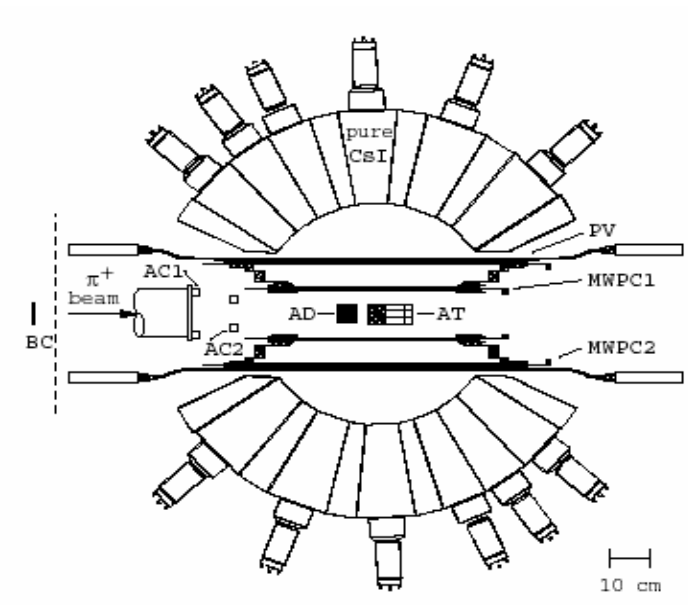
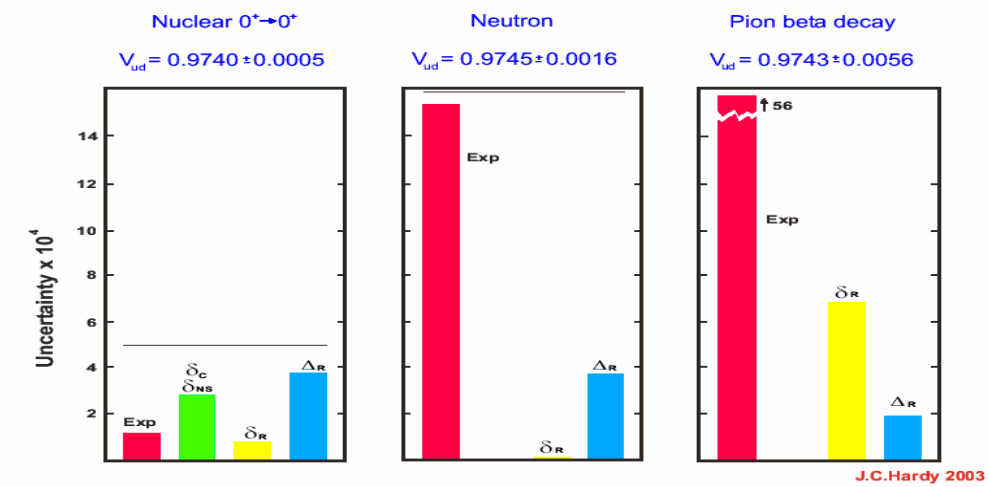
$$\pi^+ \to \pi^0\, e^+\, \nu_e$$

PSI: "Pi-Beta"





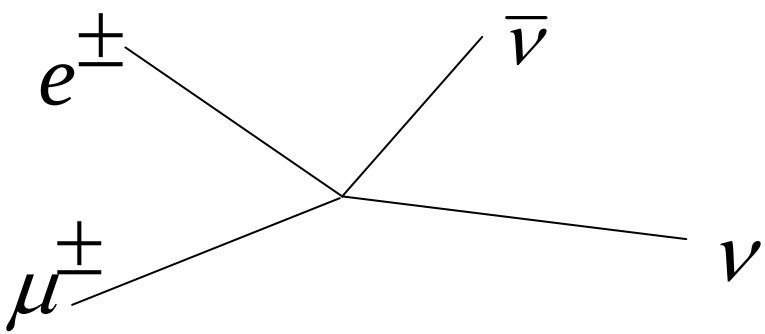
$$\Gamma\left(\pi^+ \to \pi^0 e^+ \nu_e\right) / \Gamma\left(\pi^+ \to \mu^+ \nu_\mu\right) \sim 1 \times 10^{-8}$$

Weak Decays (Ongoing)

- Muon lifetime (MuLan at PSI)
- Neutron lifetime (UCNA at LANSCE, NIST)
- Pion Decays (PiBeta at PSI)
- Kaon Decays (KLOE at INFN Frascati)
- Muon Michel Parameters (TWIST at TRIUMF)
  - Search for right-handed charged currents

TWIST physics motivation -- test the Standard Model for μ-decay

… Most general interaction does not presuppose the W



$$rate \sim \left| \sum_{\substack{\gamma=S,V,T \\ i,j=R,L}} g_{ij}^{\gamma} \left\langle \overline{\psi}_{e_i} \middle| \Gamma^{\gamma} \middle| \psi_{\nu_e} \right\rangle \left\langle \overline{\psi}_{\nu_\mu} \middle| \Gamma_{\gamma} \middle| \psi_{\mu_j} \right\rangle \right|^2$$

- ***S,V,T*** **= scalar, vector or tensor interactions**
- ***R, L*** **= right and left handed leptons (*e*, μ, or τ)**

Couplings in the present Standard Model

$$rate \sim \left| \sum_{\substack{\gamma=S,V,T \\ i,j=R,L}} g_{ij}^{\gamma} \left\langle \overline{\psi}_{e_i} \middle| \Gamma^{\gamma} \middle| \psi_{\nu_e} \right\rangle \left\langle \overline{\psi}_{\nu_\mu} \middle| \Gamma_{\gamma} \middle| \psi_{\mu_j} \right\rangle \right|^2$$

$\left\lvert g_{RR}^{S} \right\rvert = 0$	$\left\lvert g_{RR}^{V} \right\rvert = 0$	$\left\lvert g_{RR}^{T} \right\rvert \equiv 0$
$\left\lvert g_{LR}^{S} \right\rvert = 0$	$\left\lvert g_{LR}^{V} \right\rvert = 0$	$\left\lvert g_{LR}^{T} \right\rvert = 0$
$\left\lvert g_{RL}^{S} \right\rvert = 0$	$\left\lvert g_{RL}^{V} \right\rvert = 0$	$\left\lvert g_{RL}^{T} \right\rvert = 0$
$\left\lvert g_{LL}^{S} \right\rvert = 0$	$\boxed{\left\lvert g_{LL}^{V} \right\rvert = 1}$	$\left\lvert g_{LL}^{T} \right\rvert \equiv 0$

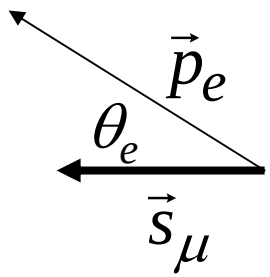
e^+ spectrum in x, $\cos\theta_e$

$$rate \sim x^2\left[3-3x+\frac{2}{3}\rho(4x-3)+3\eta x_o\left(\frac{1-x}{x}\right)+P_\mu\xi\cos\theta_e\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$

$$x \equiv \frac{E_e}{E_e^{\max}}$$

Spectral shape in x, $\cos\theta_e$ is characterized in terms of four parameters -- ρ, η, ξ, δ

P_μ is the muon polarization



$$x_o \equiv \frac{m_e}{E_e^{\max}}$$

$$E_e^{\max} \equiv \frac{m_\mu^2+m_e^2}{2m_\mu}$$

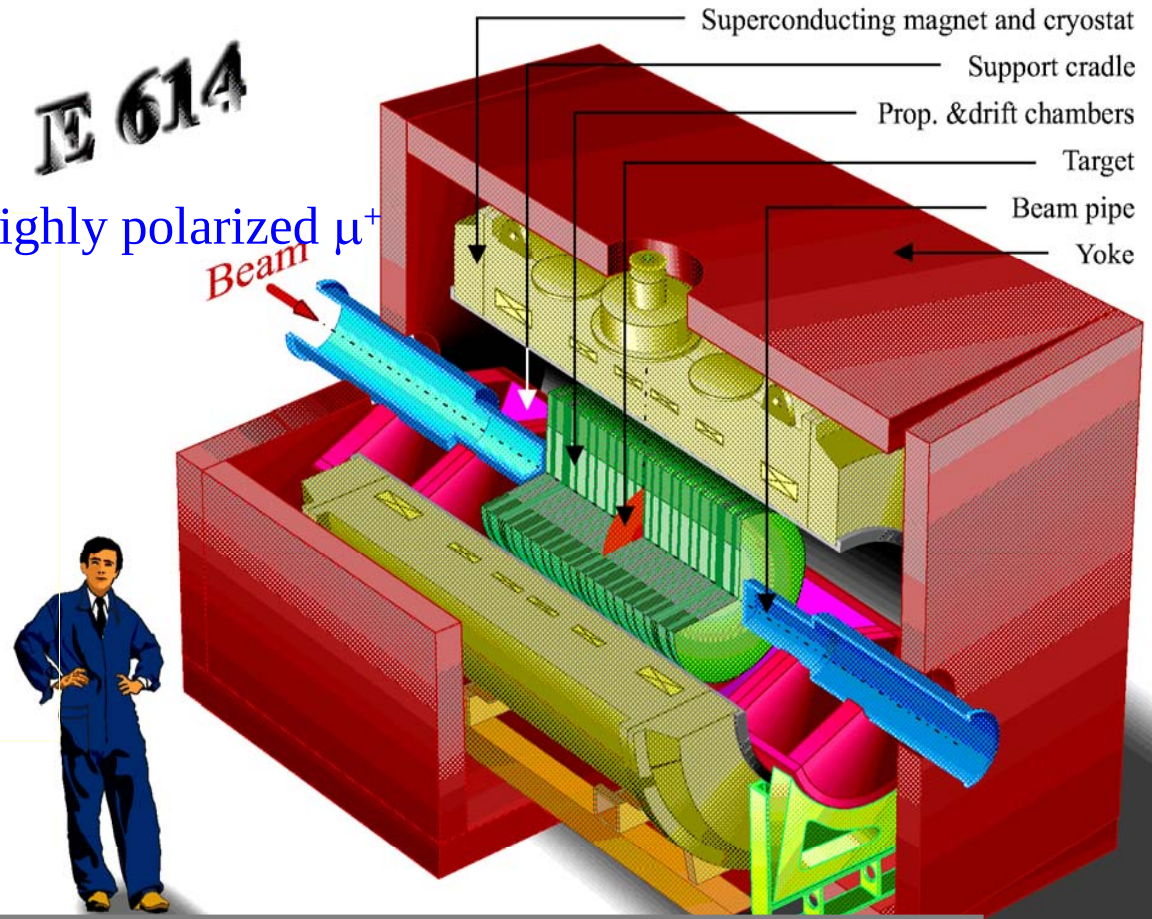
(L. Michel, A. Sirlin)

TWIST at TRIUMF

	SM
ρ	3/4
δ	3/4
ξ	1.0
η	0.0
$P_\mu \frac{\xi\delta}{\rho}$	1.0

E 614

Highly polarized μ^+



TWIST will measure ρ, ξ, δ in two steps -- 10^{-3} in 2004; ~3×10^{-4} in 2005/6

Discrete Symmetries

- P, C and CP violated
- CPT likely conserved (being tested)
- Therefore, T violation expected
- Baryon number violation
  - Proton decay?
- Lepton Number Violation
  - Neutrino mass and mixing
  - Charge lepton number violation?

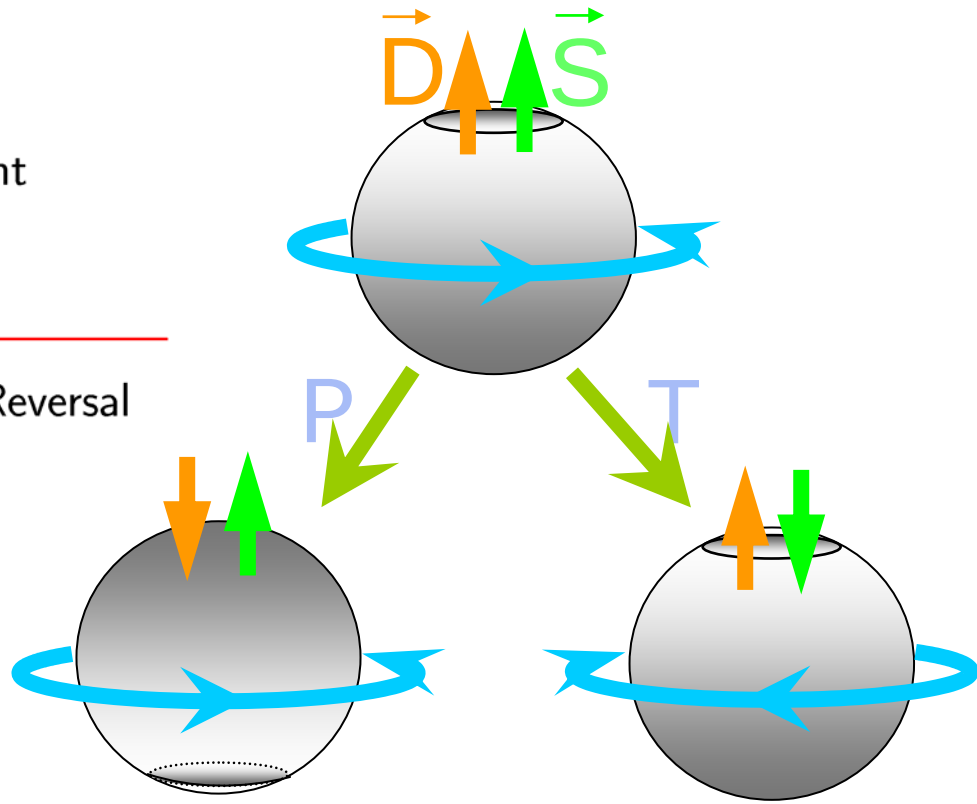
What is a Permanent Electric Dipole Moment (EDM) ?

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

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

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

- EDM is an analog of a 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 !!!

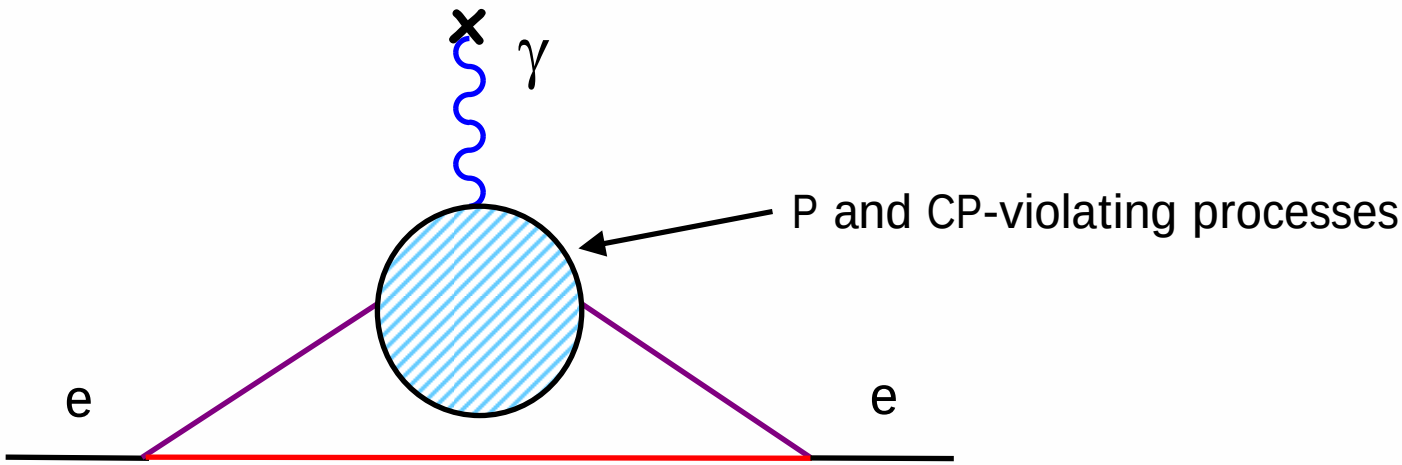
$\Rightarrow$ For fundamental particle to have EDM P and T must be violated

Why do we expect the electron EDM $d_e \neq 0$?

- EDMs violate P, T : through CPT theorem T-violation $\Leftrightarrow$ CP-violation
- P-violation observed, CP-violation observed in K and B mesons
- Can generate EDM in SM through radiative corrections

  $\Rightarrow$ In same way RC make $g_e \neq 2.0000$, RC can make $d_e \neq 0$

  $\Rightarrow$ Construct diagram with enough loops to incorporate P and CP-violating processes



- In SM need at least 4 loops - predicts $|d_e| \leq 1 \times 10^{-40}$ e·cm
- 13 orders of magnitude below current limit $|d_e| < 1.6 \times 10^{-27}$ e·cm !

(B.C. Regan, E.D. Commins, C.J. Schmidt, and D. DeMille, Phys. Rev. Lett. **88**, 071805 (2002).)

Electric dipole moment (EDM) searches may test new CP-violation

CKM

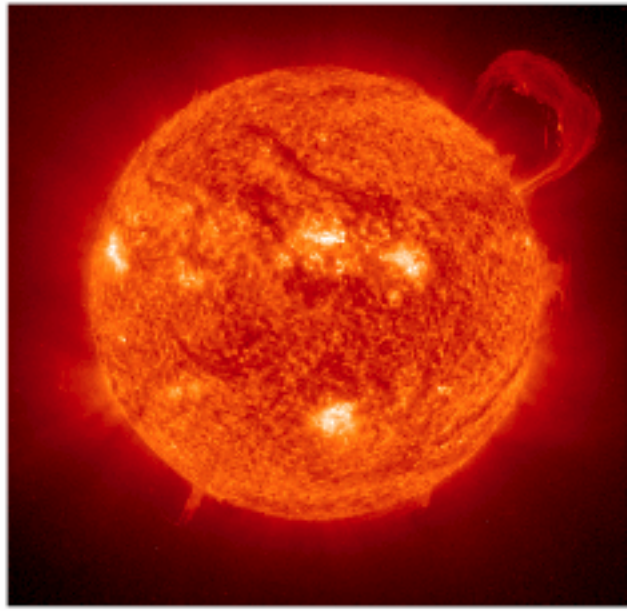
f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg	$< 10^{-33}$	$< 2.1\times10^{-28}$	$\rightarrow 10^{-32}$
μ	$< 10^{-38}$	$< 1.1\times10^{-18}$	$\rightarrow 10^{-24}$

If new CP violation is responsible for abundance of matter, will these experiments see an EDM?

Proton Decay & Neutrino Mass

- Small amount of baryon number violation expected
- Does the proton decay?
- Is the solar neutrino flux as expected?
- Birth of Underground Science!
- We now know neutrinos have mass
- We now understand the dynamics of hydrogen burning in the sun to ~1%…

ν_e are abundant by-products of nuclear fusion in the sun



$$p + p \rightarrow {}^2H + e^+ + \nu_e + 0.42 MeV$$

"pp" 99.75%

$$p + e^- + p \rightarrow {}^2H + \nu_e + 1.44 MeV$$

"pep" 0.25%

$${}^2H + p \rightarrow {}^3He + \gamma + 5.49\ MeV$$

86%

$${}^3He + {}^3He \rightarrow \alpha + 2p + 12.86 MeV$$

14%

$${}^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59 MeV$$

"hep" 2.4×10^{-5}

$${}^3He + p \rightarrow \alpha + e^+ + \nu_e$$

"^{7}Be" 99.89%

$${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e + 0.8617 MeV$$

$${}^7Li + p \rightarrow \alpha + \alpha + 17.35 MeV$$

0.11%

$${}^7Be + p \rightarrow {}^8B + \gamma + 0.14 MeV$$

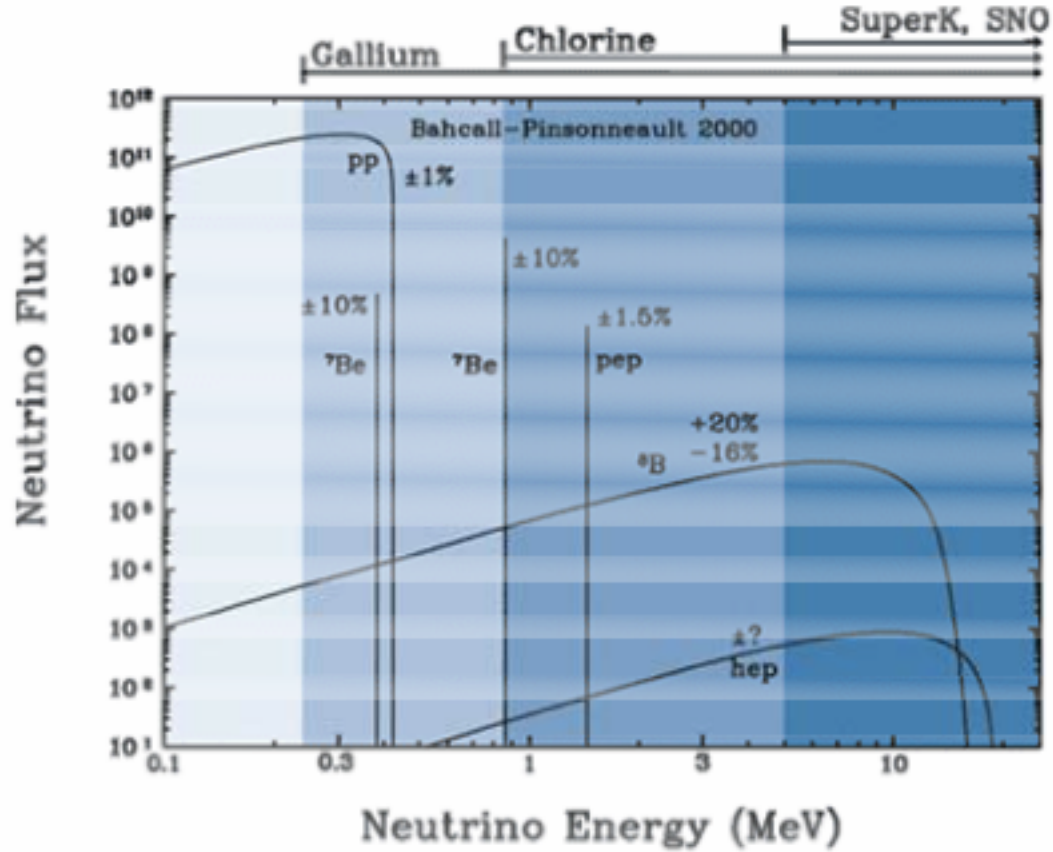
"^{8}B" 0.11%

$${}^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6 MeV$$

$${}^8Be \rightarrow \alpha + \alpha + 3 MeV$$

3 types of experiments detecting solar neutrinos

- Chlorine: $^{37}Cl+\nu_e=^{37}Ar+e^-$
  1 exp running >30 yrs (US)
- Gallium: $^{71}Ga+\nu_e=^{71}Ge+e^-$
  3 exp (Russia, Italy)
- Cerenkov: $e^-+\nu_e=e^-+\nu_e$
  3 exp (Japan, Canada)



Neutrinos and the New Paradigm

- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate the symmetry CP?

Dirac or Majorana neutrinos?

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A General Argument Suggesting Neutrinos Are Majorana Particles

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Electroweak Isospin Invariance), and its renormalizability.

Anything allowed by the symmetries occurs in nature.

The SM contains no ν_R field, only ν_L, and no ν mass.
This SM conserves the lepton number L defined by —

$$L[\text{lepton}] = -L[\text{antilepton}] = 1.$$

We now know that the neutrino does have mass.

If we try to preserve conservation of L, we accommodate this mass by adding to the SM a Dirac, L - conserving, mass term: $m_D \bar{\nu}_L \nu_R$.

To add the Dirac mass term, we had to add ν_R to the SM.

Unlike ν_L , ν_R carries no Electroweak Isospin.

Thus, no SM symmetry prevents the occurrence of the Majorana mass term $m_M \overline{\nu_R{}^c} \nu_R$.

This mass term causes $\nu \rightarrow \bar{\nu}$. It does not conserve L.

There is now no conserved quantum number to distinguish $\bar{\nu}$ from ν.

Thus, $\bar{\nu} = \nu$. We have Majorana neutrinos.

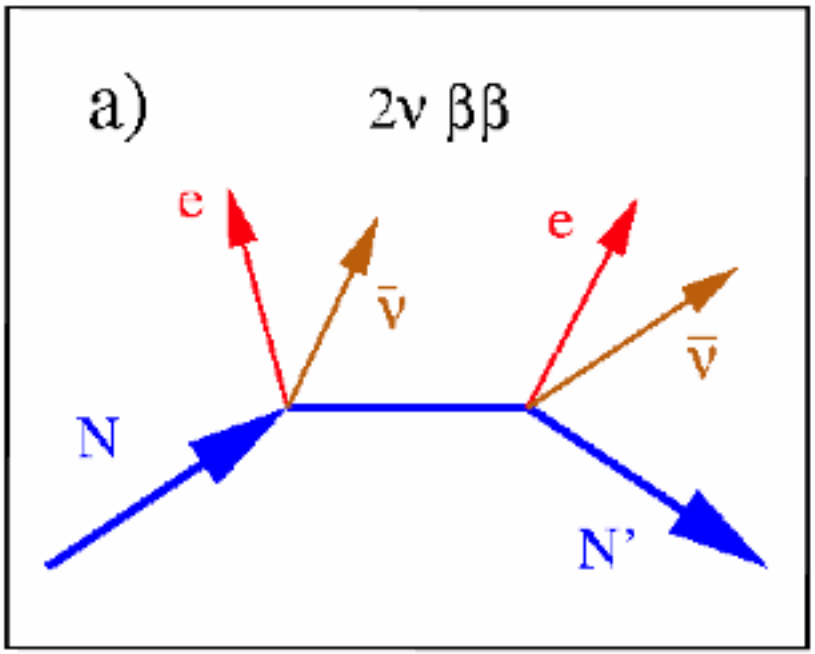
There are two varieties of ββ decay

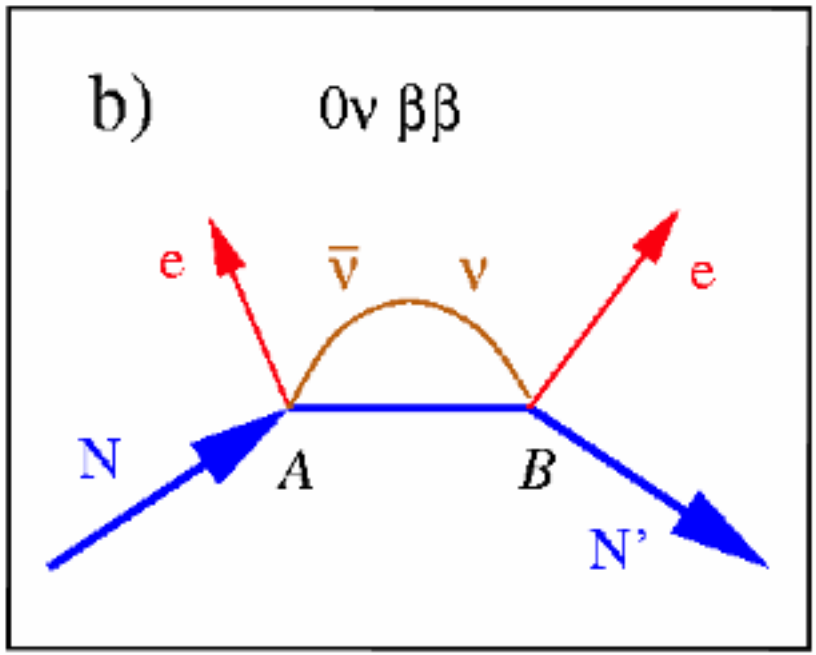
2ν mode: a conventional 2nd order process in nuclear physics

0ν mode: a hypothetical process can happen only if:

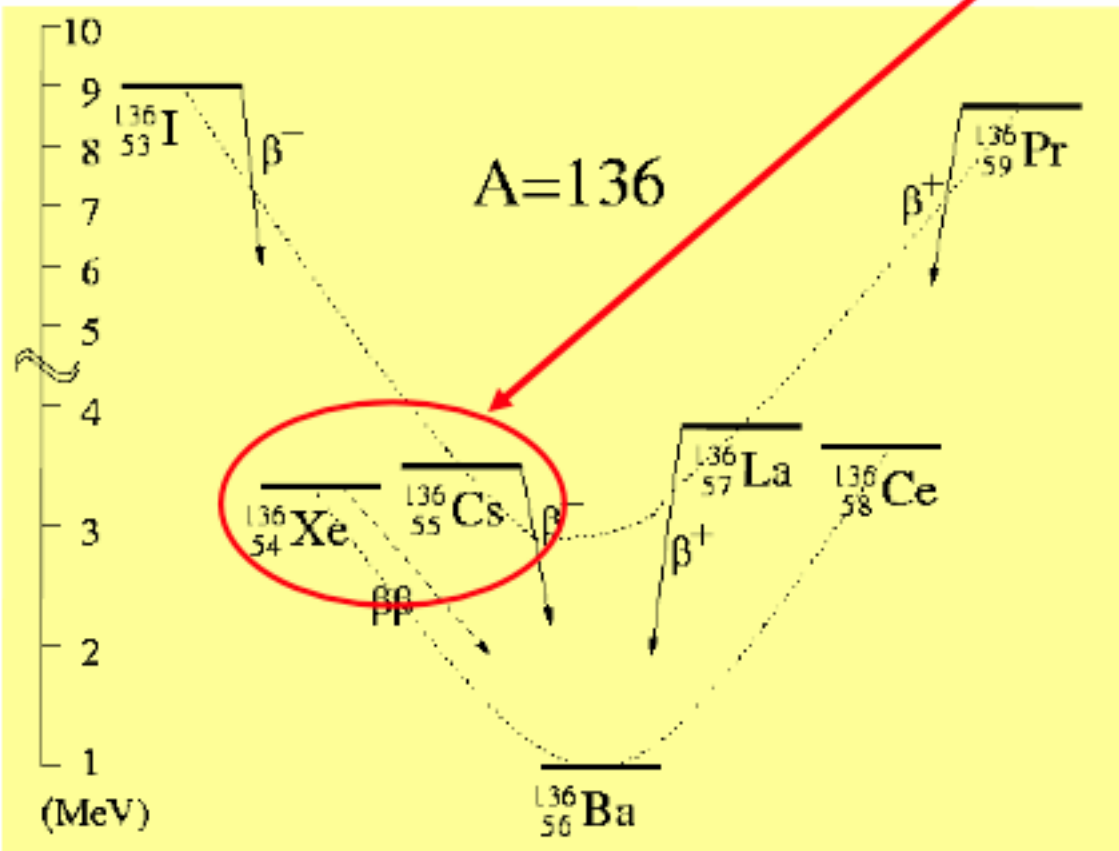
- $M_\nu \neq 0$
- $\bar{\nu} = \nu$

Since helicity has to "flip"





ββ always a second order process: only detectable if first order β decay is energetically forbidden



2νββ has been observed in a number of cases

0νββ has never been observed

Future Underground Science

- Precision solar neutrino spectra
- Neutrino MNS matrix parameters
  - CP Violation?
- Proton Decay
- Double Beta Decay
- …

Lepton Flavor Violation

When a muon stops in matter, the principal interactions are:

- Capture on Nucleus: $\mu^- N(Z,A) \rightarrow \nu_\mu N(Z-1,A)$
- Decay in Orbit: $\mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e$ (DIO)

Coherent conversion is $\mu^- N(Z,A) \rightarrow e^- N(Z,A)$, and the signal is a monoenergetic electron beyond the DIO endpoint.

The MECO experiment at BNL will measure:

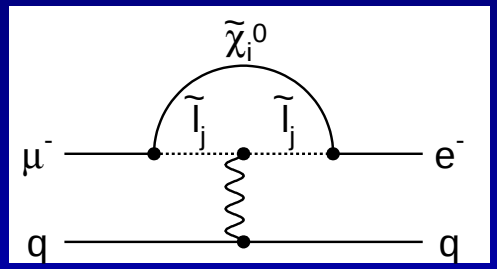
$$R_{\mu e} = \Gamma[\mu^- N(Z,A) \rightarrow e^- N(Z,A)] / \Gamma[\mu^- N(Z,A) \rightarrow \nu_\mu N(Z-1,A)]$$

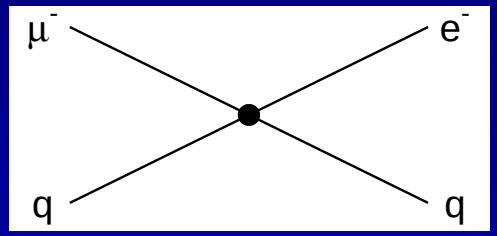
A single event implies $R_{\mu e} > 2 \times 10^{-17}$.

New Physics at High Energy Scales

Supersymmetry

Predictions at 10^{-15}

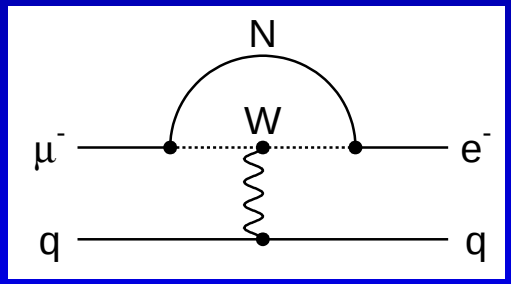


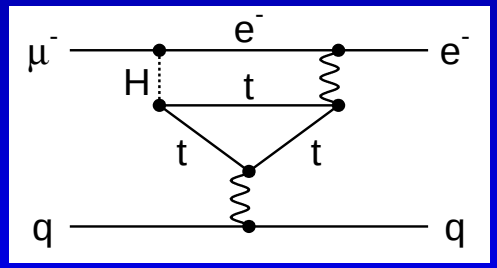


Compositeness

$\Lambda_C = 3000$ TeV

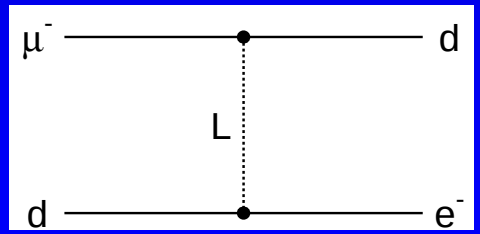
Heavy Neutrinos

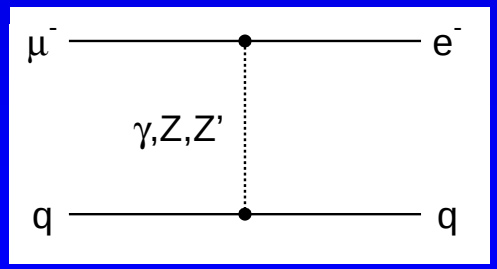




Higgs

Leptoquarks





Heavy Z', Anomalous Z coupling

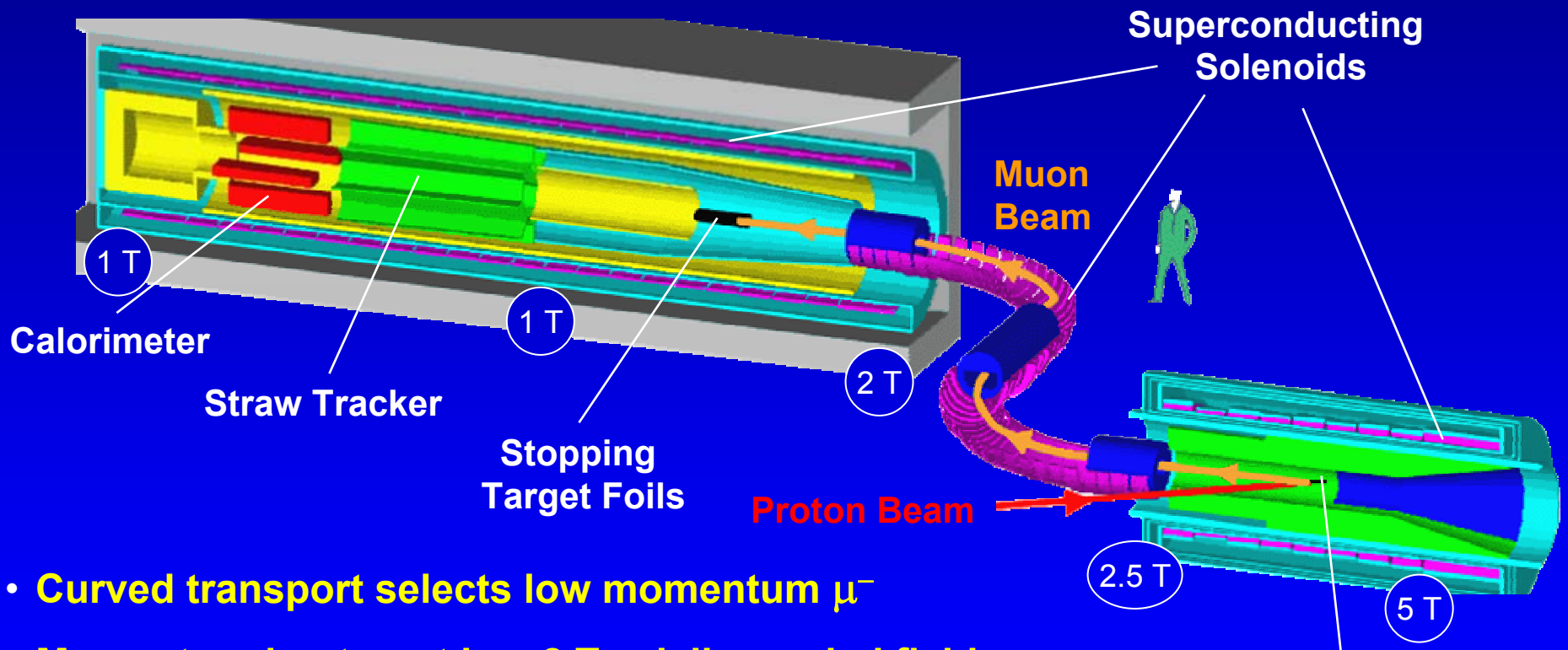
$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

Features of the MECO Experiment

- **1000–fold increase in μ beam intensity over existing facilities**
  - High Z target for improved pion production
  - Axially-graded 5 T solenoidal field to maximize pion capture

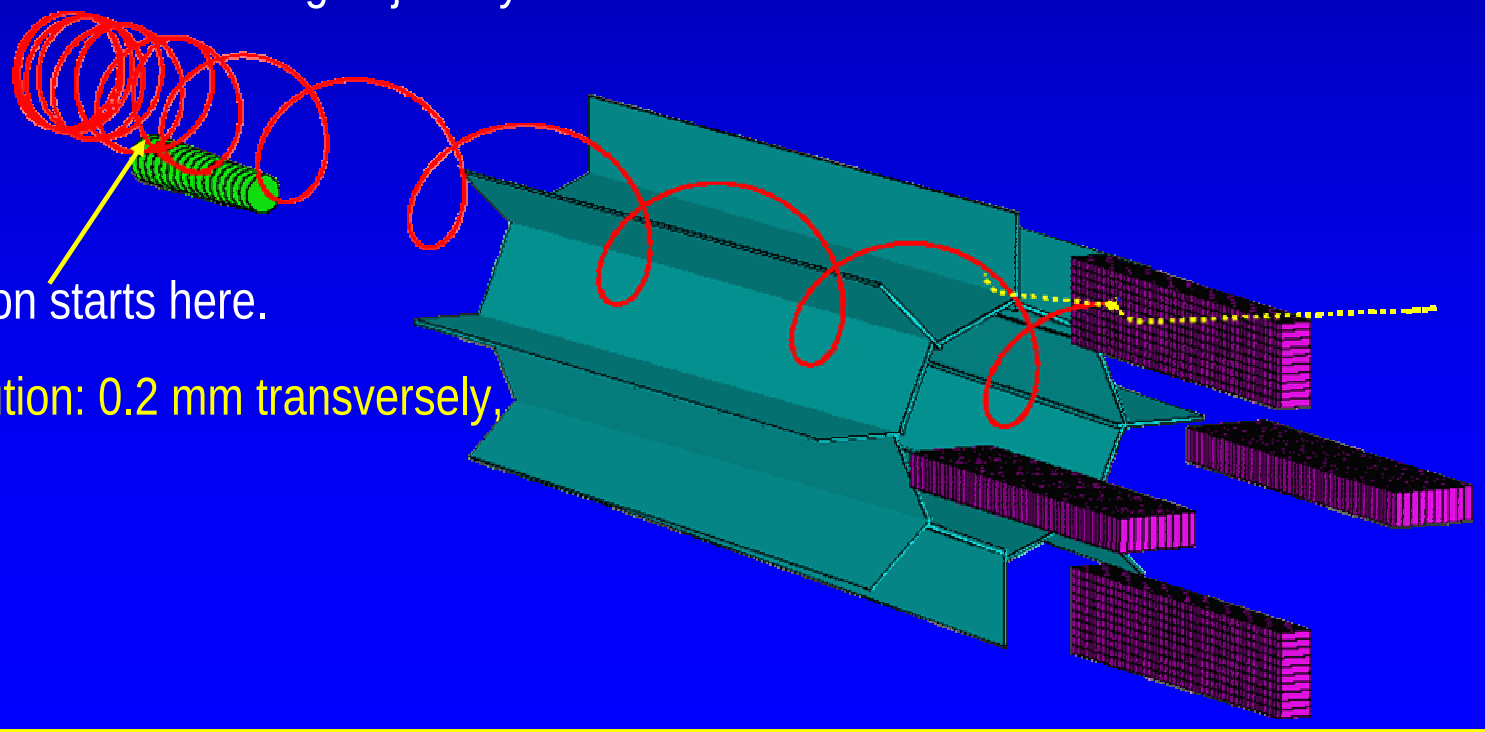


- **Curved transport selects low momentum μ^-**
- **Muon stopping target in a 2 T axially-graded field to improve conversion e^- acceptance**
- **High rate capability electron detectors in a constant 1 T field**

MECO Detector Elements

Magnetic spectrometer measures electron momentum with precision of 0.3% (rms)—essential to eliminate decay in orbit background. Consists of ~2800 axial straw tube detectors 2.6 m x 5 mm. 25 μm wall thickness.

~1200 element $PbWO_4$ (3.5 x 3.5 x 12 cm) calorimeter measures electron energy to ~5%, providing trigger and confirming trajectory.



Position resolution: 0.2 mm transversely, 1.5 mm axially

Summary

- An extraordinary amount has been learnt about electroweak physics in the past fifty years
- Further progress requires a coherent effort across High Energy Physics, Nuclear Physics and Particle Astrophysics
- Accelerator- and non-accelerator experiments will play equally important roles
- Together, we will finally address some of the outstanding questions unanswered by the current version of the electroweak theory
- Your generation can help towards generating the required unity and coherence