The Exact and Approximate Symmetries of Electroweak Interactions

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Unique Low Energy Tests exploiting the special properties of Leptons, Nucleons and Nuclei

Outline of Lectures

On Friday, notes will contain comprehensive references for all lectures

- Standard Model of Electroweak Interactions
- Searches for Violations of Discrete Symmetries
- Charged Lepton Flavor Violation and Precision Weak Neutral Current experiments
- Precision Weak Charged Current Experiments & Electroweak Probes of Hadron Structure

Outline of Lecture #3

- Lepton Flavor Physics
- Lepton Flavor Violation Experiments
- Motivation for Precision Weak Neutral Current Experiments
- Parity-Violating Electron Scattering

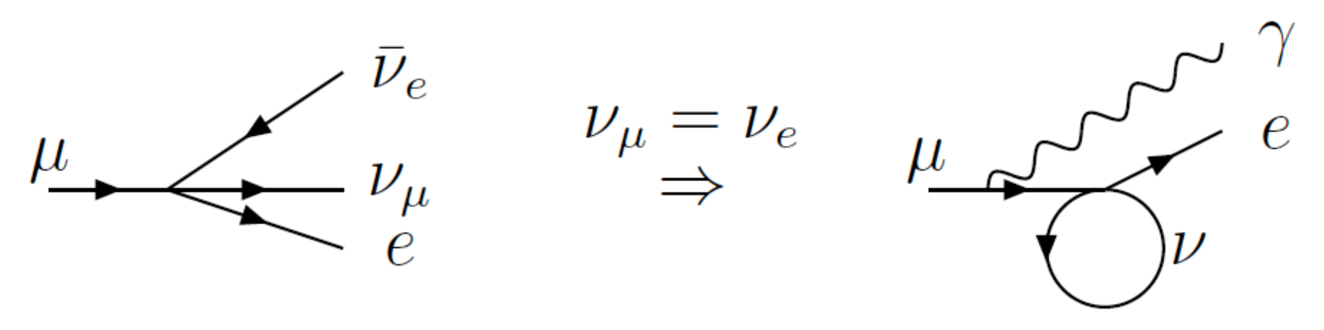
The Case for Multiple Neutrino Flavors

Recall: neutrinos and anti-neutrinos have opposite lepton numbers

We are obliged to introduce separate lepton numbers for each flavor. Why?

Consider $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ Is the muon-neutrino distinct?

If not, $\mu^- \rightarrow e^- \gamma$ is allowed Branching fraction ~ 10^{-4}



Found to be much smaller than predicted....implies the neutrinos are distinct and that leptons do not like to change flavor readily

The Birth of Accelerator Neutrino Physics

Charged pion leptonic decays

$\pi^- \to \mu^- \bar{\nu}_\mu$ $\pi^+ \to \mu^+ \nu_\mu$

electron mode highly suppressed:
pion is spin 0; a right-handed anti-neutrino must be accompanied by a right-handed lepton whereas the W boson likes to emit a left-chiral lepton

- At Brookhaven National Lab, ~ 10 GeV proton beam was directed to a heavy nuclear target
- Pions produced were channeled with magnets into a drift region
- At the end of the drift was a bunch of steel and concrete (lots of it!)
- The first accelerator neutrino beam!

$\bar{\nu}_\mu p \to \mu^+ n$ observed! $\bar{\nu}_\mu p \to e^+ n$ not observed!

1962 experiment: leads to Nobel Prize

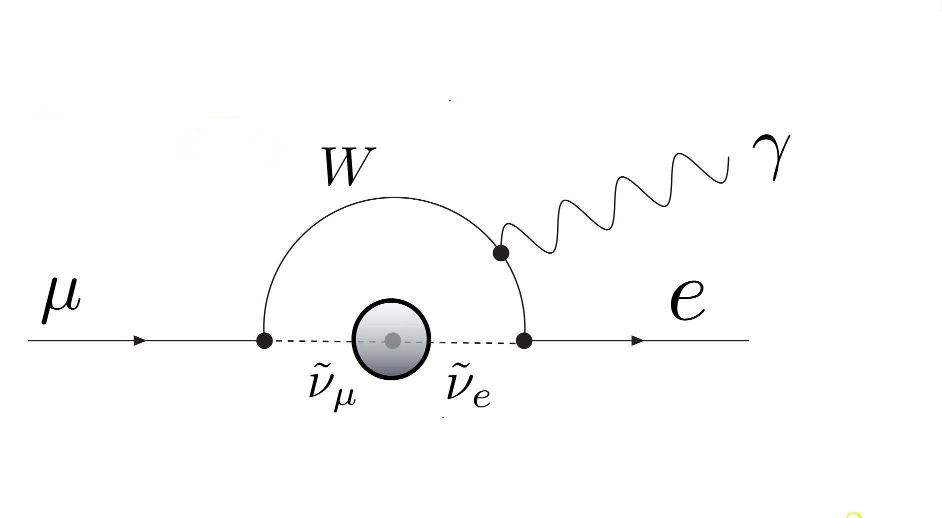
Lederman, Schwartz and Steinberger

We now know there are 3 distinct light neutrino flavors

Lepton Flavor Conservation

Is it exact? No! Neutrino Oscillations!

- ν's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well

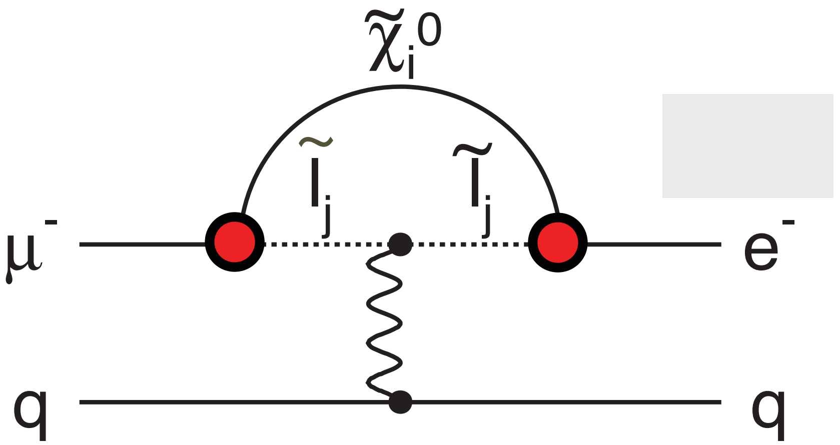


$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 < 10^{-54}$$

tiny standard model branching fraction

Supersymmetry

rate ~ 10^{-15}

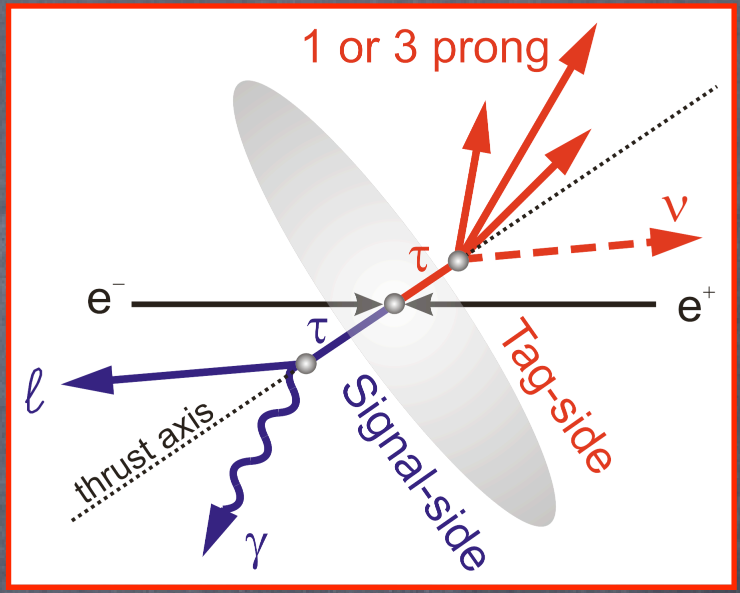


Searches for Charged Lepton Flavor Violation

μ or $\tau \to e\gamma$, e^+e^-e, $K_L \to \mu e$, ...

Need very high fluxes for required statistical reach

New high intensity kaon & muon beams and high luminosity e+e- colliders all over the world



Tau Decays at e+e- colliders

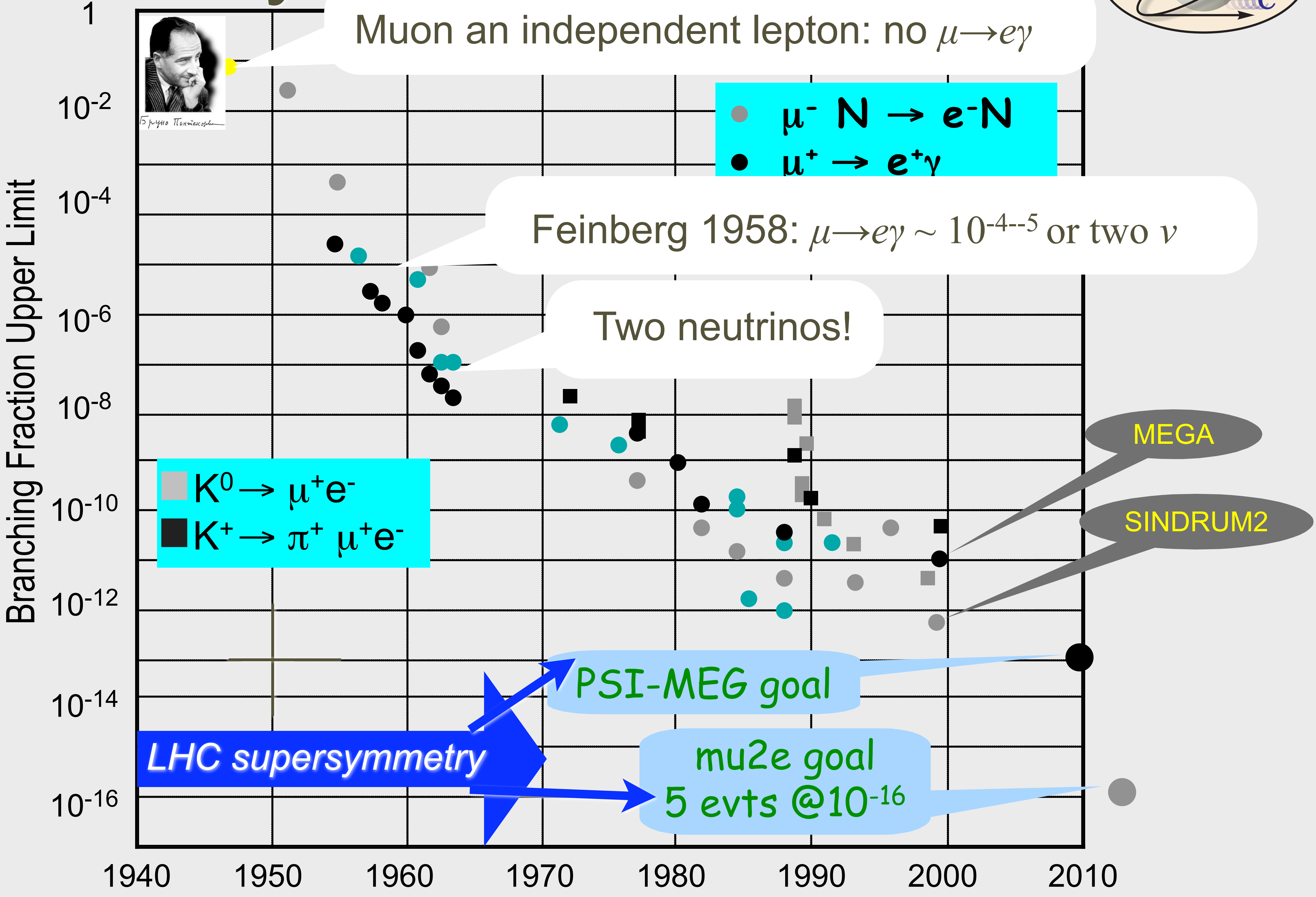
Mu2e @ Fermilab

muon converts to electron in the presence of a nucleus

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

Reach: 10^{-17}

History of CLFV Searches



Muon an independent lepton: no $\mu \rightarrow e\gamma$

Feinberg 1958: $\mu \rightarrow e\gamma \sim 10^{-4--5}$ or two ν

Two neutrinos!

MEGA

SINDRUM2

PSI-MEG goal

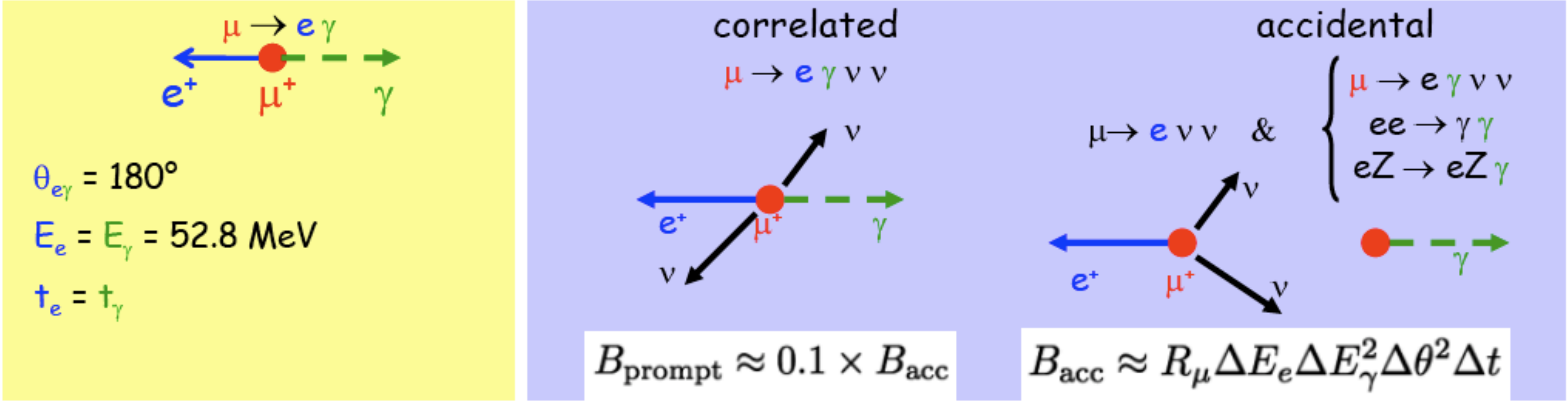
LHC supersymmetry

mu2e goal
5 evts @10^{-16}

$\mu^+ \rightarrow e^+\gamma$

signal

background



$\theta_{e\gamma} = 180°$

$E_e = E_\gamma = 52.8$ MeV

$t_e = t_\gamma$

$$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}}$$

$$B_{\text{acc}} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$$

accidental background dominant at high rate

➔ need to improve detection techniques and use continuous beam

Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cycle(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	6÷9	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	6÷7	1.2×10^{-11}
MEG	2010	0.8	4	0.15	19	3×10^7	100	1×10^{-13}

*quoted resolutions are FWHM

MEG at PSI

The beam

- located at Paul Scherrer Institut (CH)
- the most intense in the World ($>3\times10^8 \mu/s$ @ 2 mA)
- continuous (good for B_{acc} suppression)
- surface muons (28 MeV/c)

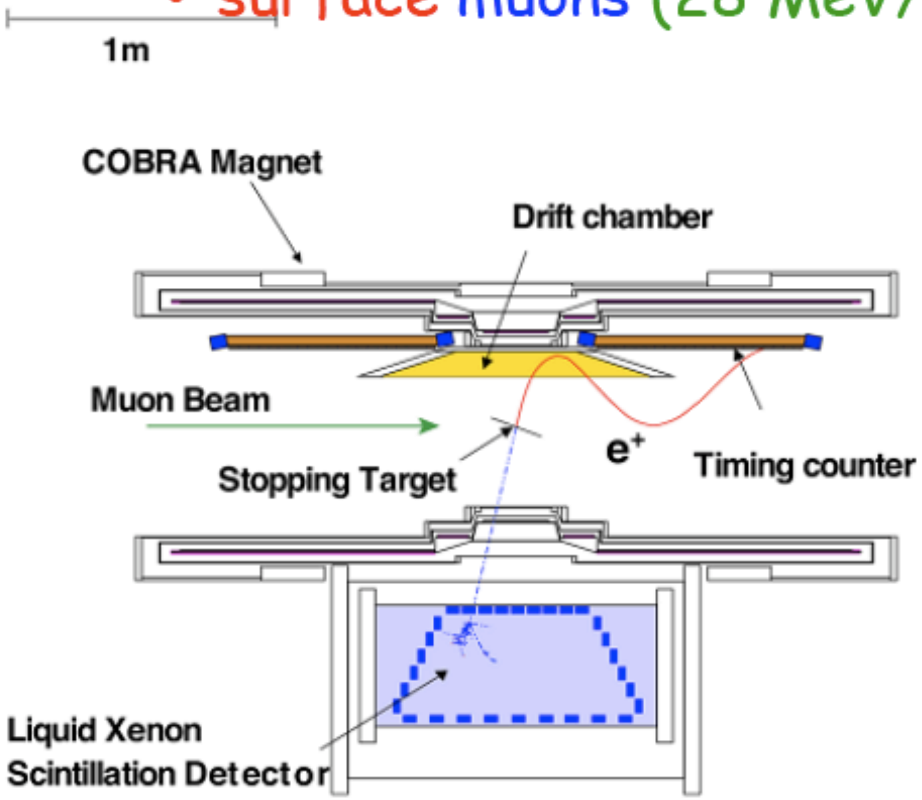
The detector

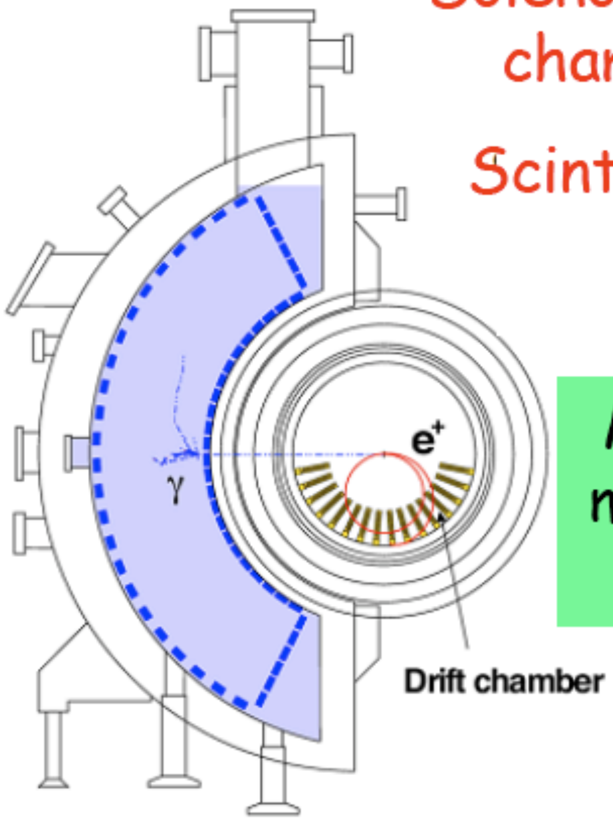
Beam of $3\times10^7\ \mu$ /sec stopped in a 175 μm target

Liquid Xenon calorimeter for γ detection (scintillation)

Solenoid spectrometer & drift chambers for e^+ momentum

Scintillation counters for e^+ timing



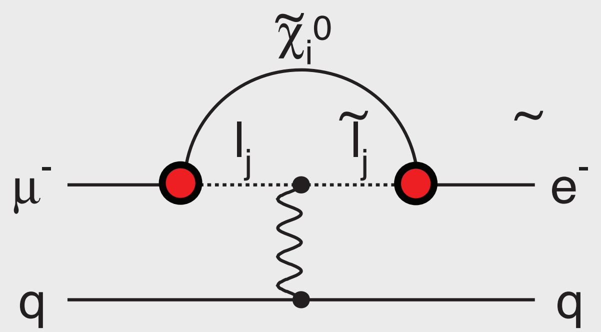


Matter effects must be minimized in order not to spoil the resolution

Contributions to μe Conversion

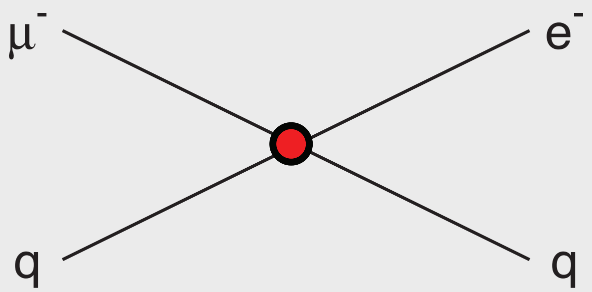
Supersymmetry

rate ~ 10^{-15}



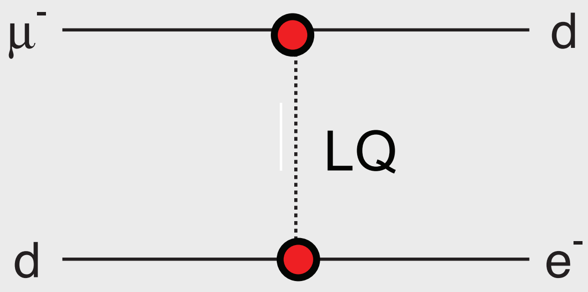
Compositeness

Λ_c ~ 3000 TeV



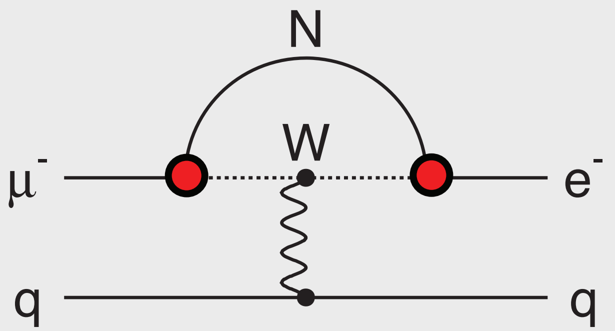
Leptoquark

M_{LQ} =
3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



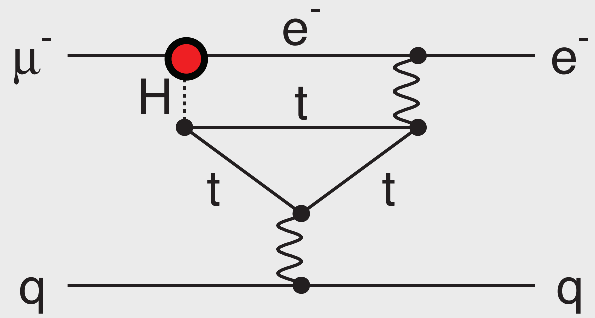
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



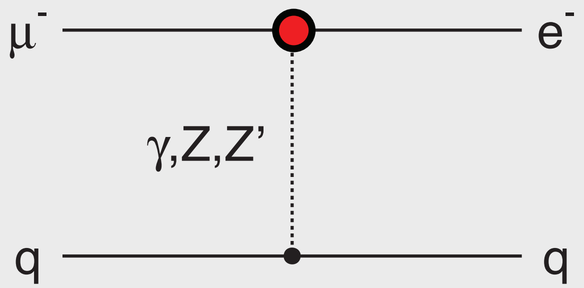
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$



Heavy Z'
Anomal. Z Coupling

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



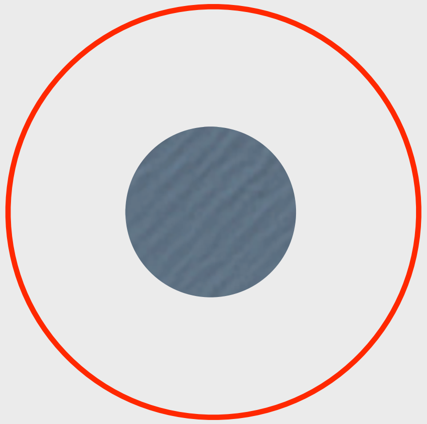
also see Flavour physics of leptons and dipole moments, arXiv:0801.1826

Muon to Electron Conversion

μ^- stops in thin Al foil

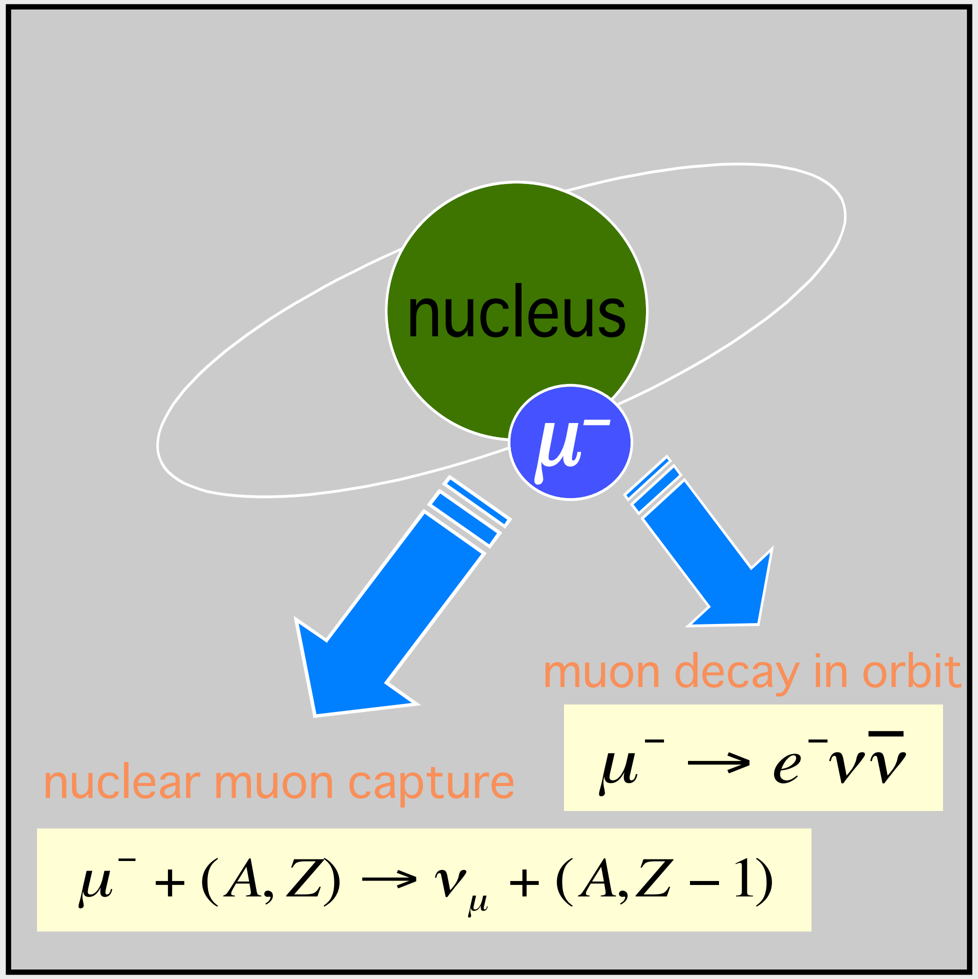
the Bohr radius is ~ 20 fm,
so the μ^- sees the nucleus

μ^- in 1s state



Al Nucleus
~4 fm

muon capture,
muon "falls into"
nucleus:
normalization



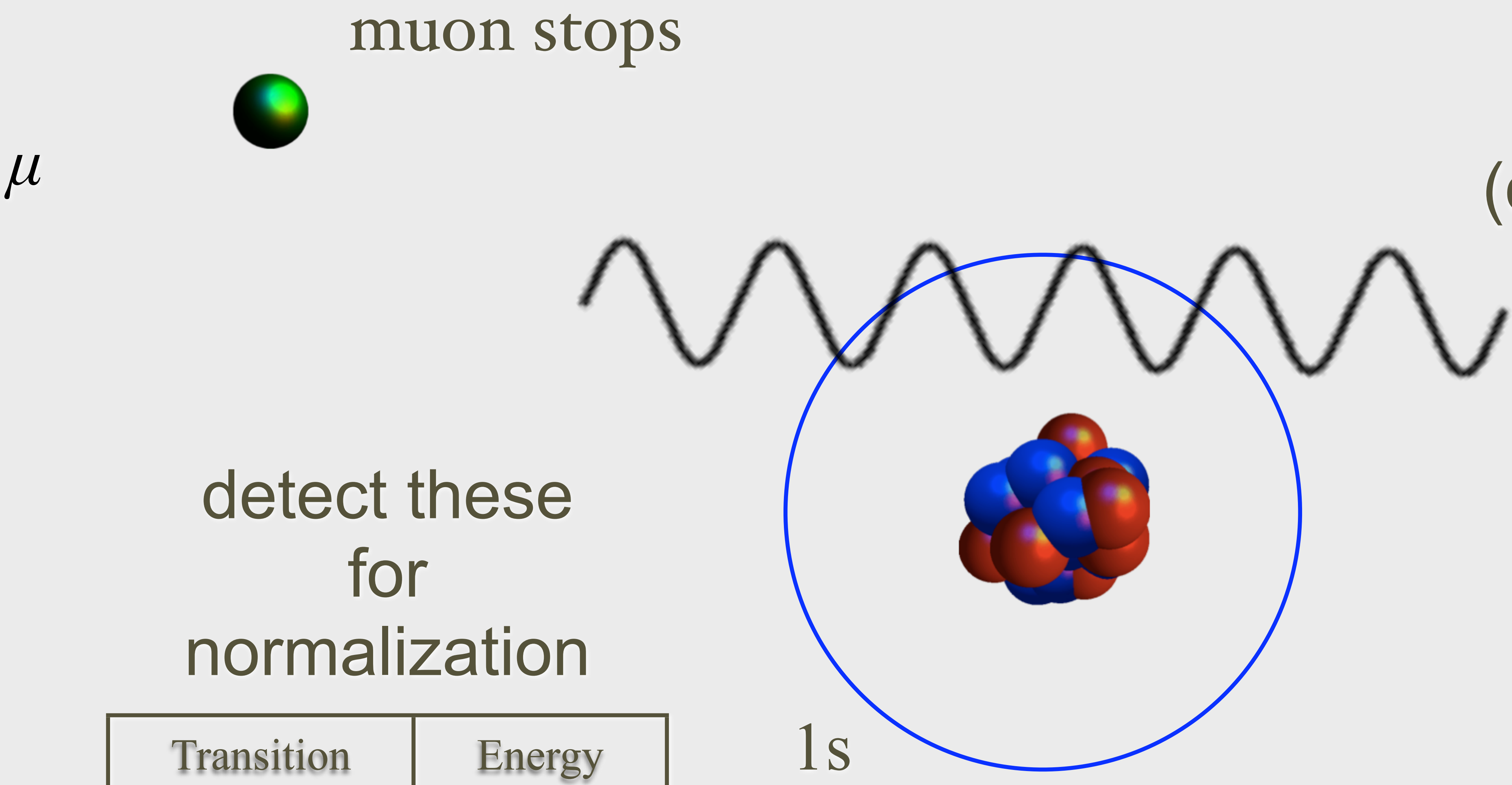
$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

60% capture
40% decay

Decay in Orbit:
background

Three Possibilities: Normalization



X-Rays from cascade (occurs in psec)

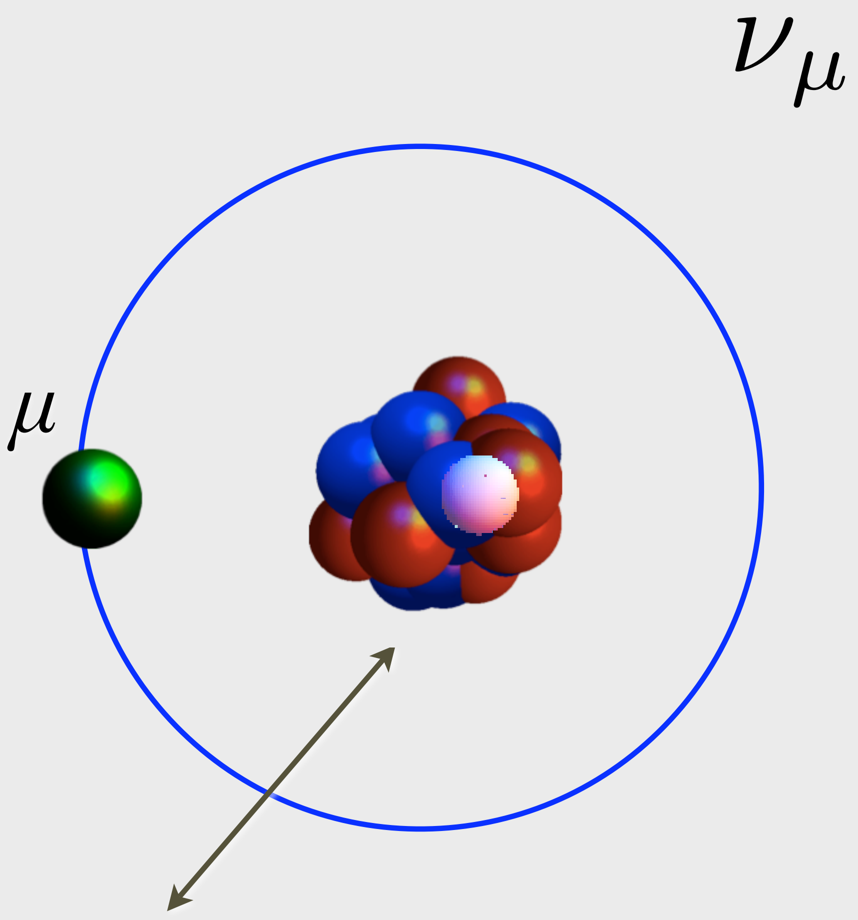
detect these for normalization

Transition	Energy
3d→ 2p	66 keV
2p→ 1s	356 keV
3d→ 1s	423 keV
4p→ 1s	446 keV

Normalization to Nuclear Capture

1) measure stop rate 2) calculate capture rate/stop

Kitano et al. ,Phys.Rev.D66:096002,2002, Erratum-ibid.D76:059902,2007. e-Print: hep-ph/0203110

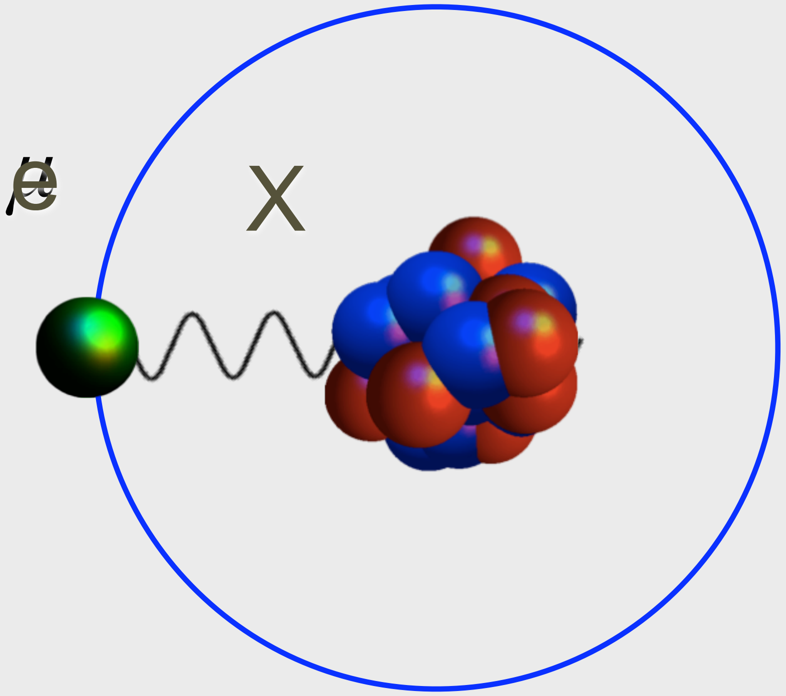


$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

$$\text{then compute } R_{\mu e} = \frac{\mu N \rightarrow eN}{\mu\ \mathrm{Al}(27,13) \rightarrow \nu_\mu\ \mathrm{Mg}(27,12)}$$

Three Possibilities: Signal

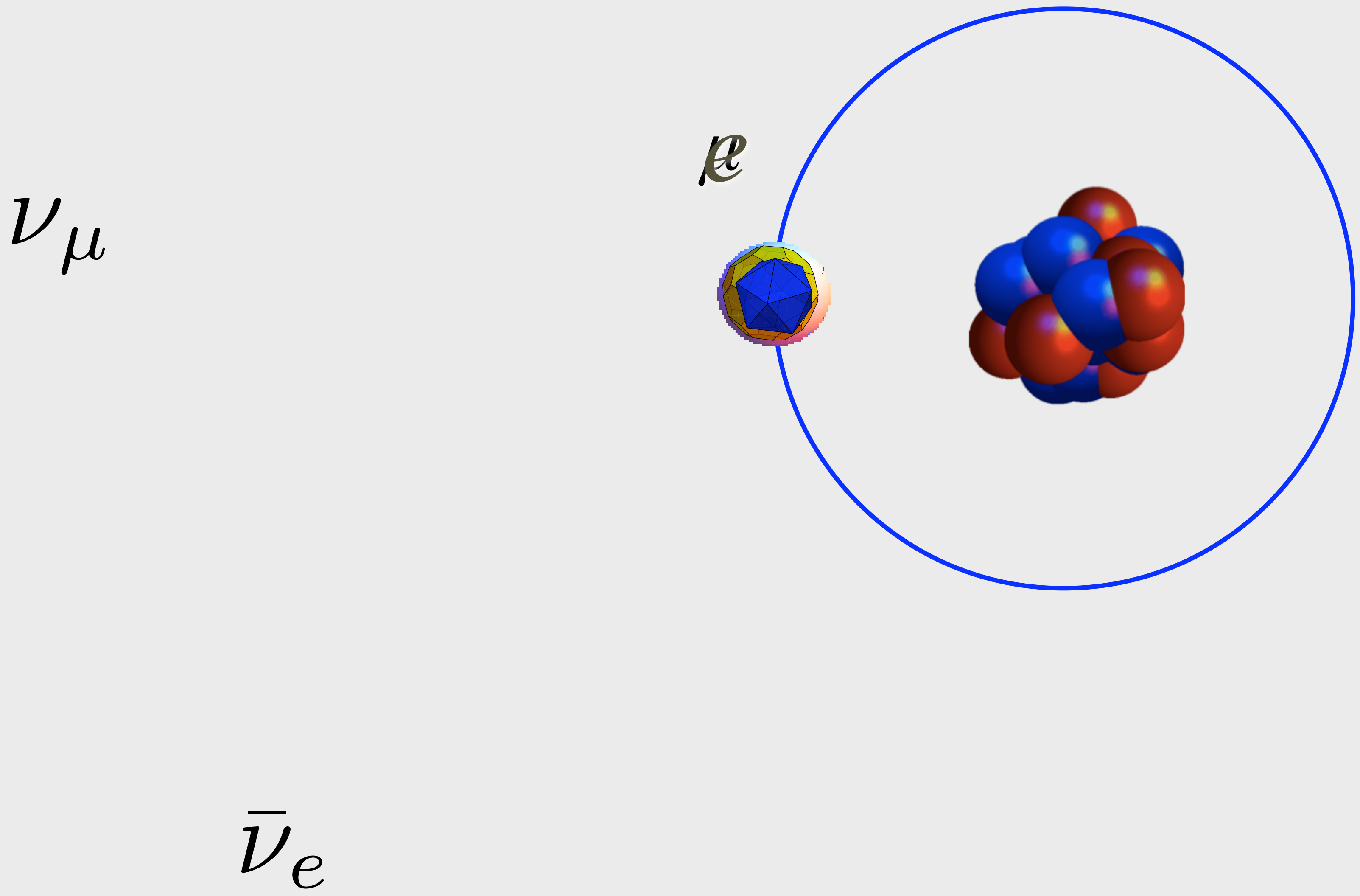
off to detector!



coherent recoil of nucleus

Three Possibilities: Background

this electron can be background;
let’s see how

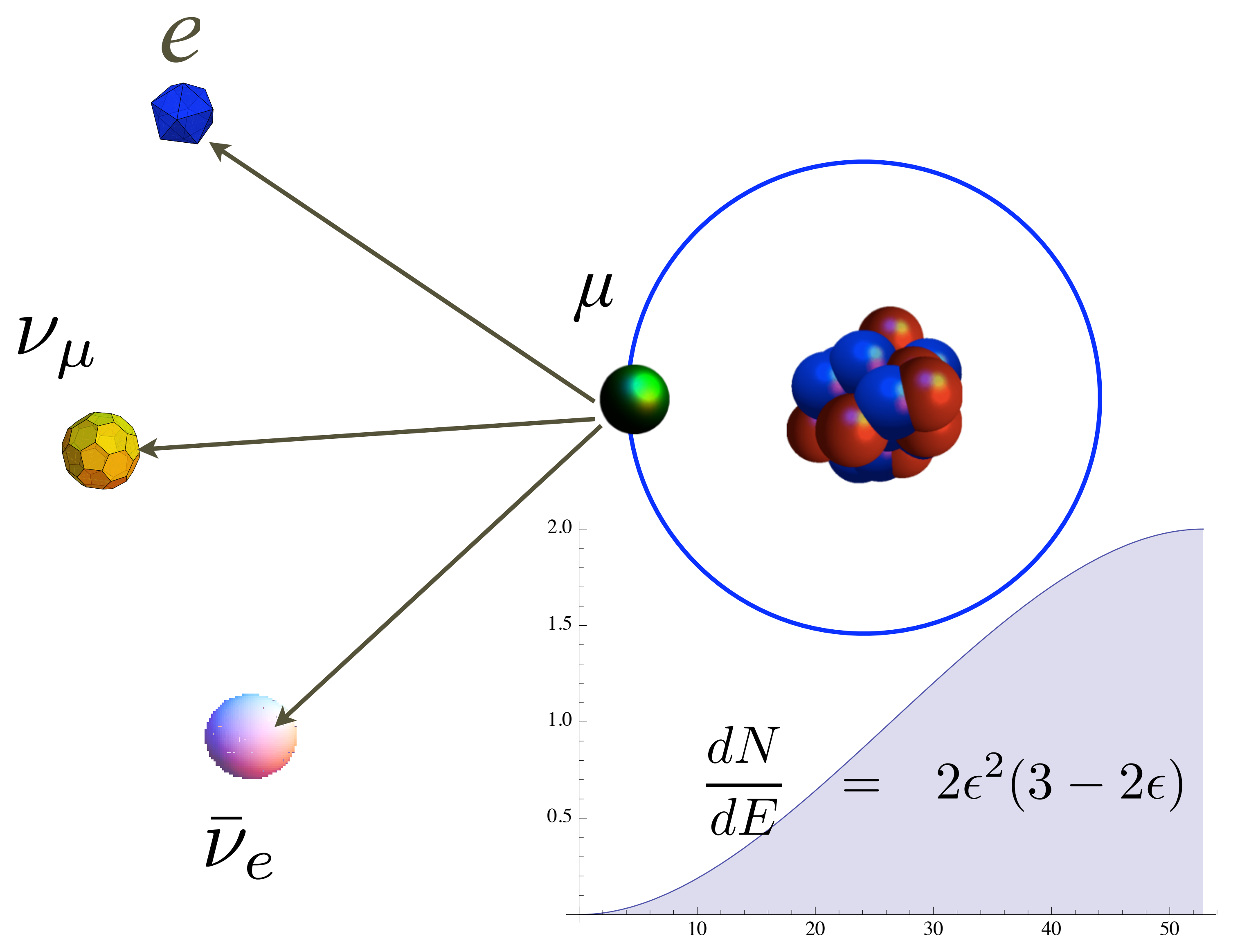


Decay-In-Orbit: Not always Background

- Peak and Endpoint of Michel Spectrum is at

$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

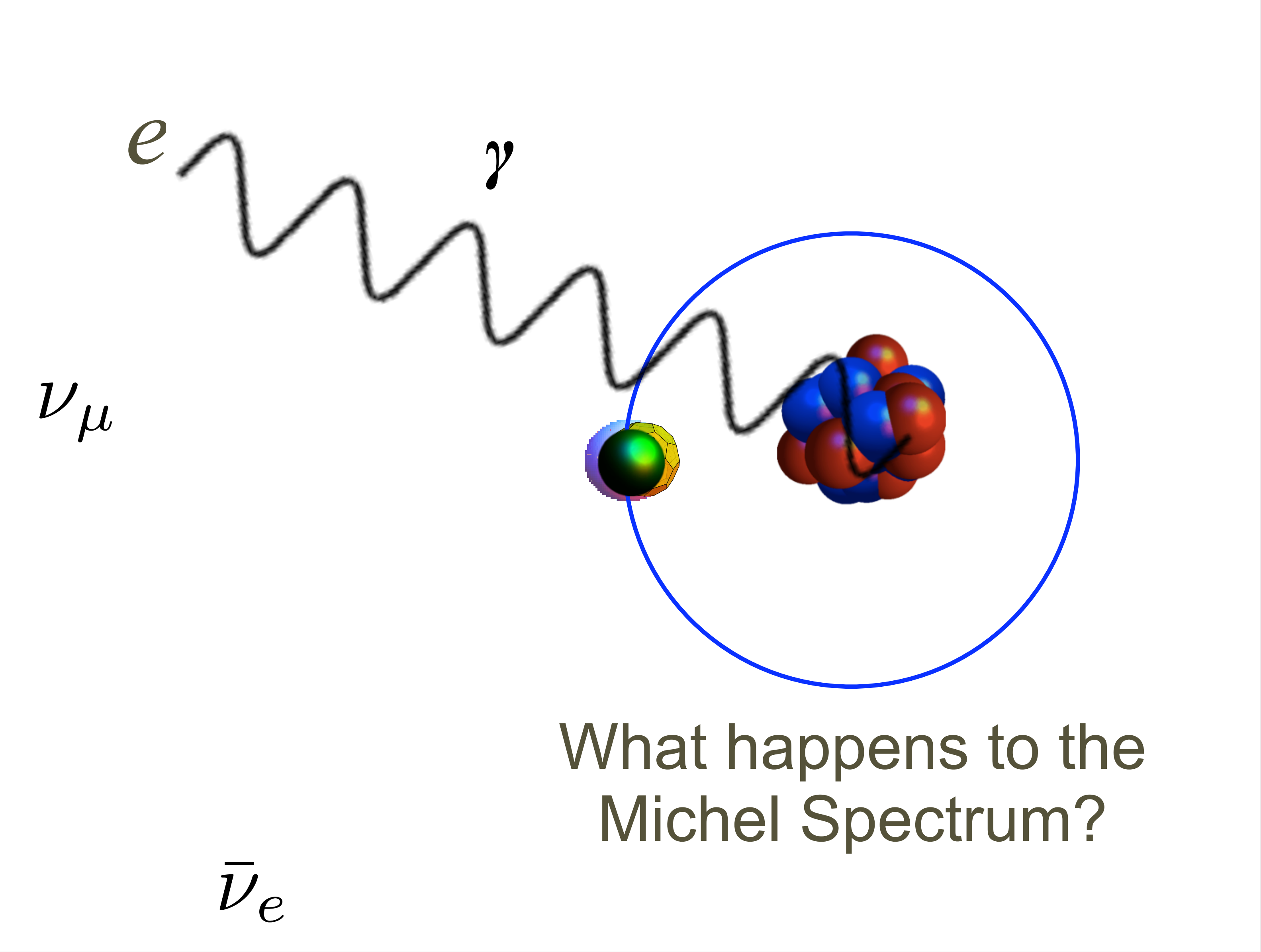
- Detector will be insensitive to electrons at this energy
- Recall *signal* at 105 MeV>>52.8 MeV



$$\frac{dN}{dE} = 2\epsilon^2(3-2\epsilon)$$

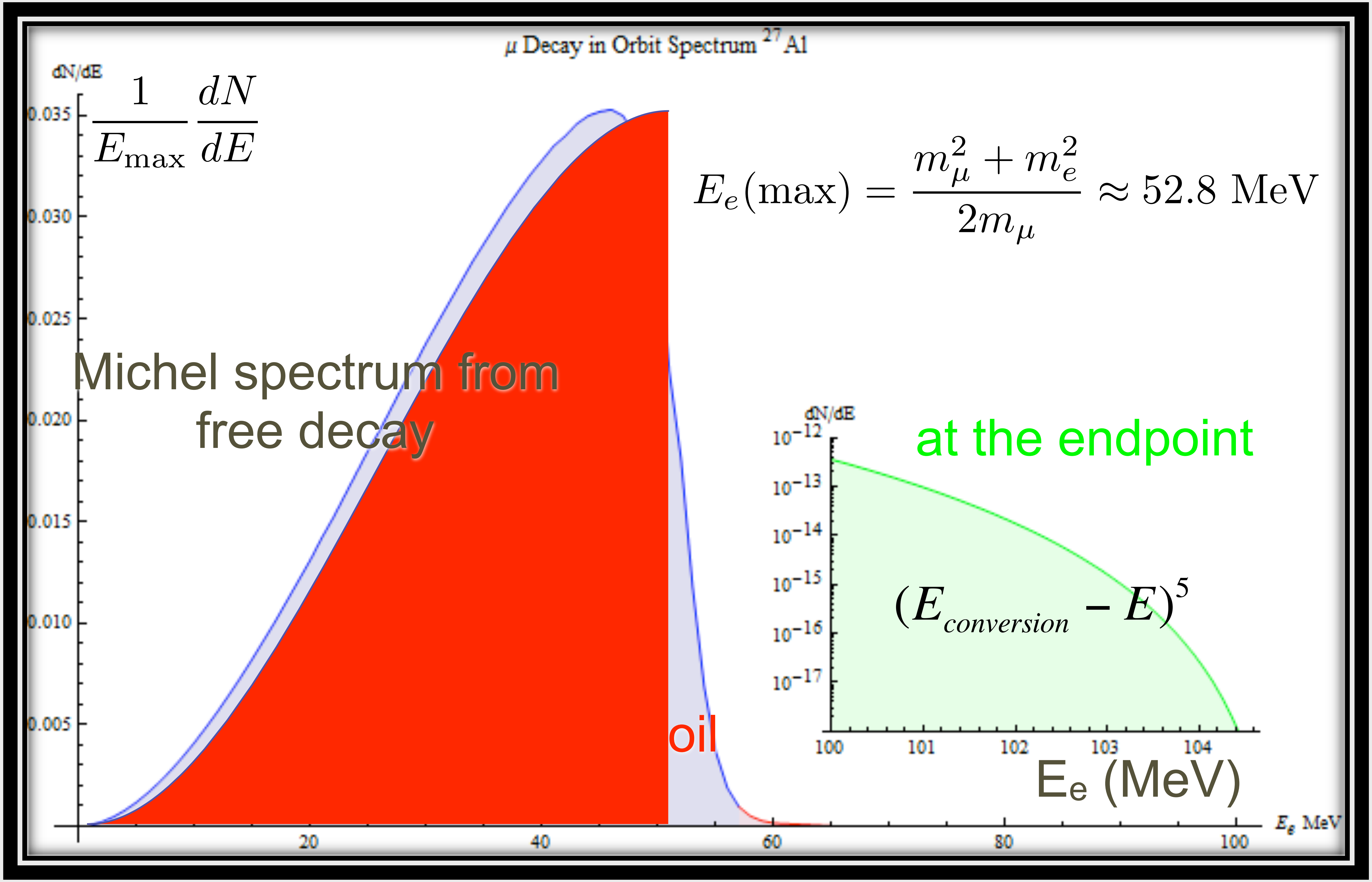
Decay-In-Orbit Background

- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, the DIO electron can be exactly at conversion energy (up to neutrino mass)



What happens to the Michel Spectrum?

Decay-in-Orbit Shape



$$\frac{1}{E_{\max}}\frac{dN}{dE}$$

$$E_e(\max) = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

Michel spectrum from free decay

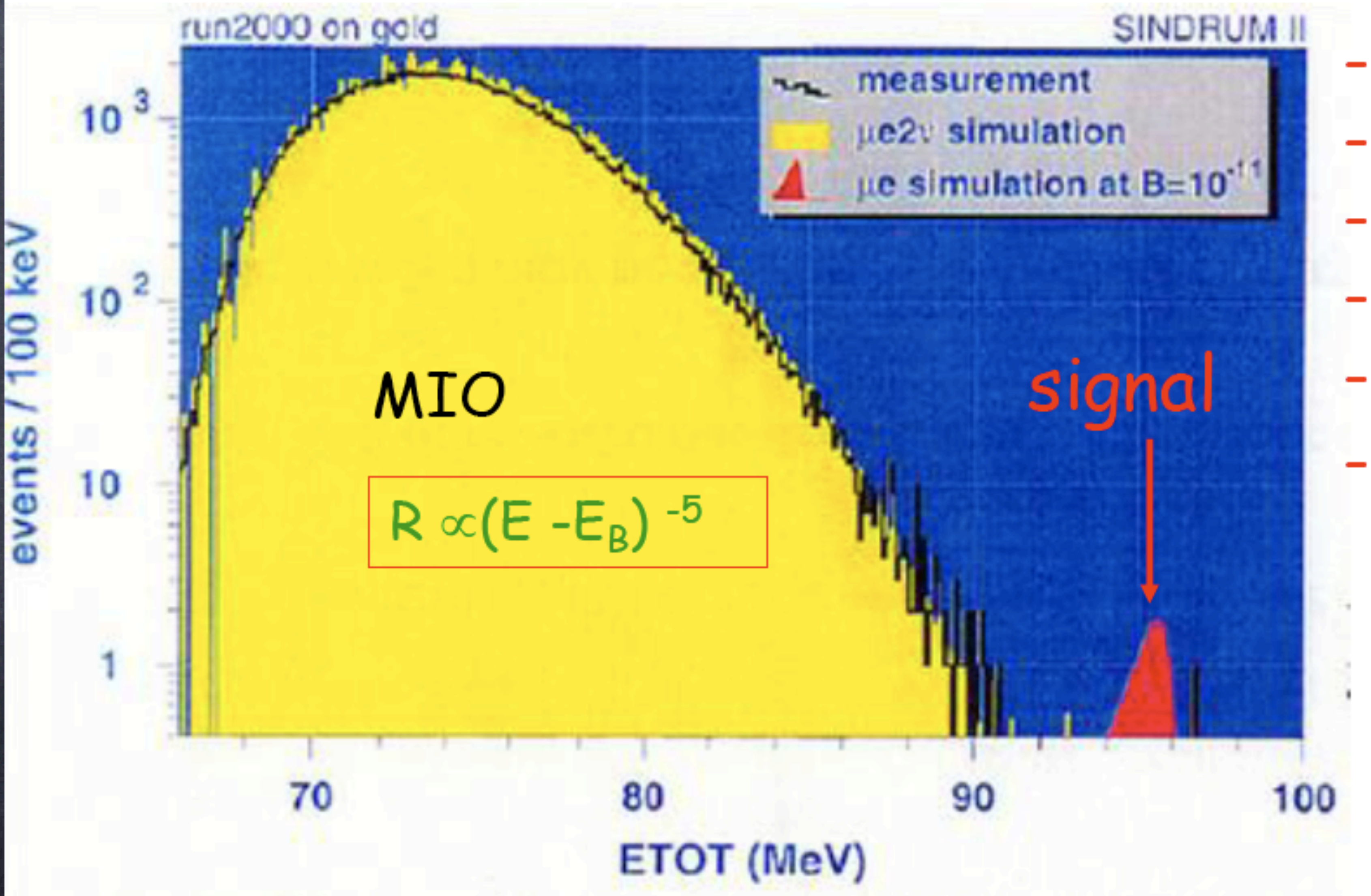
oil

at the endpoint

$$(E_{conversion} - E)^5$$

E_e (MeV)

SINDRUMII Result



SINDRUM II parameters

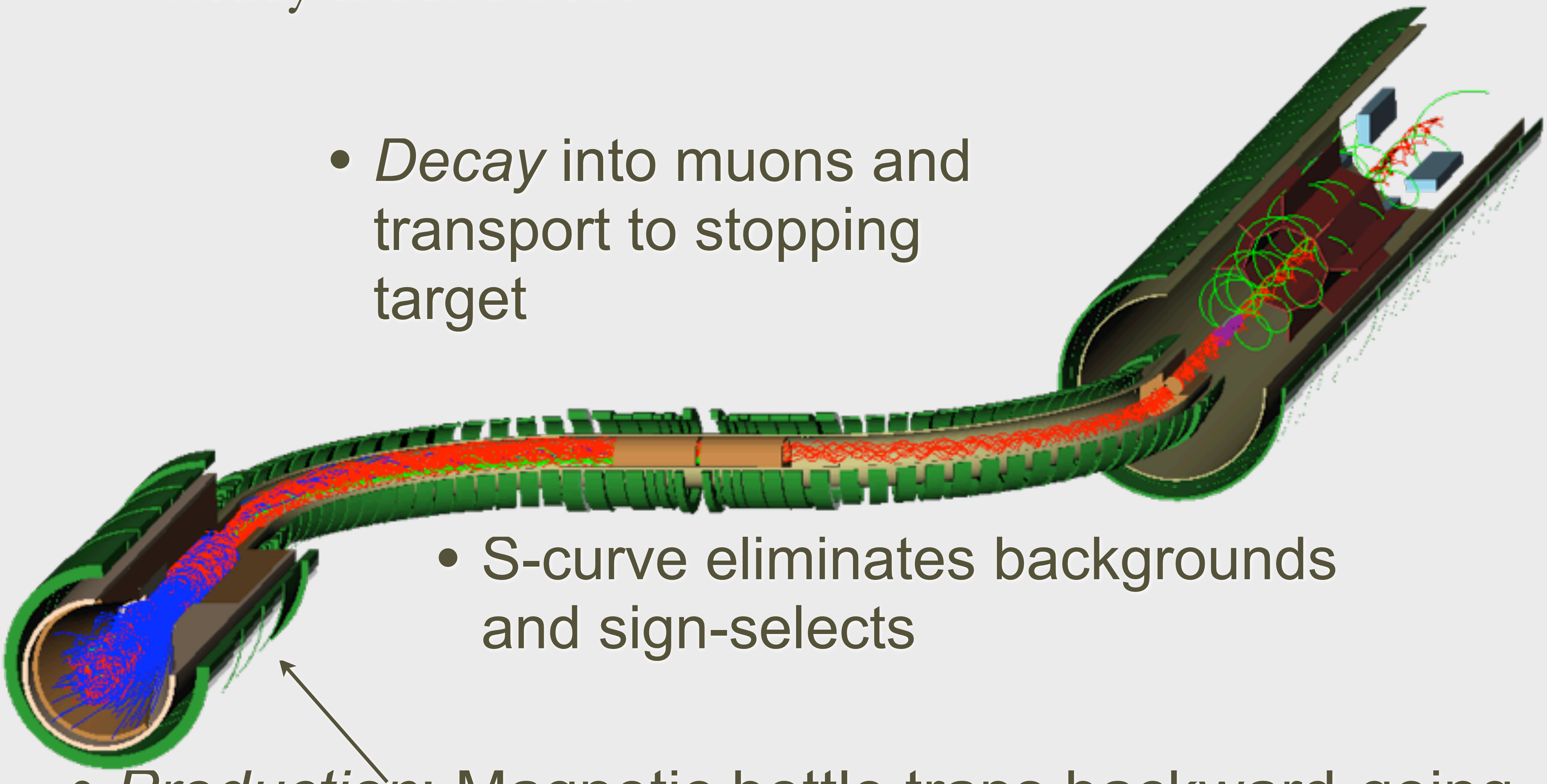
- beam intensity	$3\text{x}10^7\ \mu^-/s$
- μ^- momentum	53 MeV/c
- magnetic field	0.33T
- acceptance	7%
- momentum res.	2% FWHM
- S.E.S	$3.3\text{x}10^{-13}$
- $B(\mu\rightarrow e:Au)$	$8\text{x}10^{-13}$

A. Van der Schaaf, NOON03

Detector and Solenoid

~200 M$ Project at Fermilab
Ready around 2016

- *Tracking and Calorimeter*



- *Decay* into muons and transport to stopping target

- S-curve eliminates backgrounds and sign-selects

- *Production*: Magnetic bottle traps backward-going π that can decay into accepted μ's

Outlook for Rare Decays

- Falls under the category of “Intensity Frontier” physics
- participation of both nuclear and particle physicists
- major future muon physics initiatives at 3 labs: PSI (Switzerland), Fermilab (USA) and J-PARC (Japan)
- Also a topic at B-Factories and potential Tau-Charm Factories

New Contact Flavor Diagonal Interactions

Many theories predict new forces that disappeared when the universe cooled

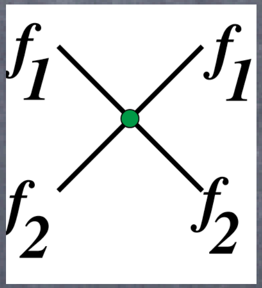
However, there are natural mechanisms to suppress "Flavor Changing Neutral Currents"

Need to look separately for Flavor Diagonal Interactions

Neutral Current Interactions are Flavor Diagonal

Consider $f_1\bar{f}_1 \to f_2\bar{f}_2$ or $f_1 f_2 \to f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2}\eta_{ij}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma^\mu f_{2j}$$



Eichten, Lane and Peskin, PRL50 (1983)

Different Λ's for all $f_1 f_2$ combinations and L,R combinations

Any new physics model can be characterized in this way:
Heavy Z's, compositeness, extra dimensions...

One goal of neutral current measurements at low energy AND colliders:
Access $\Lambda > 10$ TeV for as many $f_1 f_2$ and L,R combinations as possible

Colliders vs Fixed Target

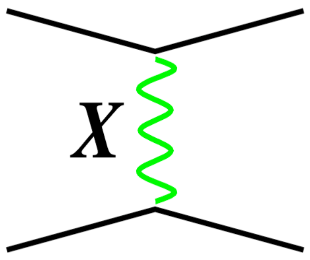
Colliders access scales Λ's ~ 10 TeV

Tevatron at Fermilab, LEP200 at CERN and HERA at DESY

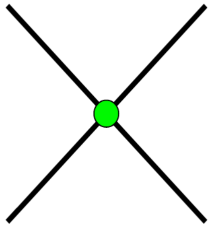
- L,R combinations accessed are parity-conserving

Z boson production accessed some parity-violating combinations but…

consider



$$A_X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2} \longrightarrow$$



Contact interaction

$Q^2 \sim M_Z^2$ **on resonance:** A_Z *imaginary* $\longrightarrow A_Z^2\left[1+\frac{A_X^2}{A_Z^2}\right]$

no interference!

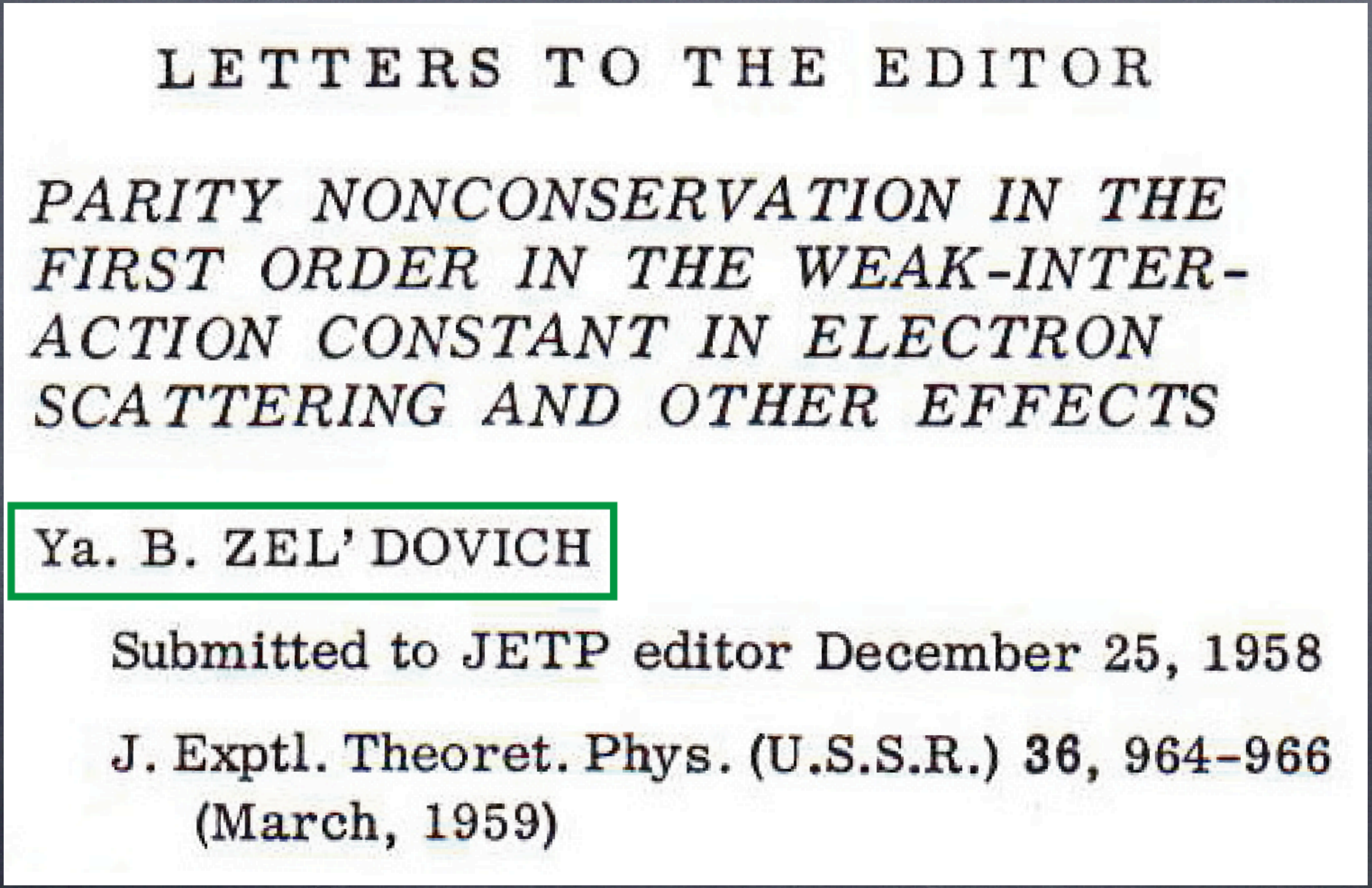
Window of opportunity for weak neutral current measurements at $Q^2 \ll M_Z^2$

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\, G_F} \longrightarrow$$

$\delta(g)/g \sim 0.1$
$\Lambda \sim 10$ TeV

$$\frac{\delta(\sin\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

A Classic Paper



LETTERS TO THE EDITOR

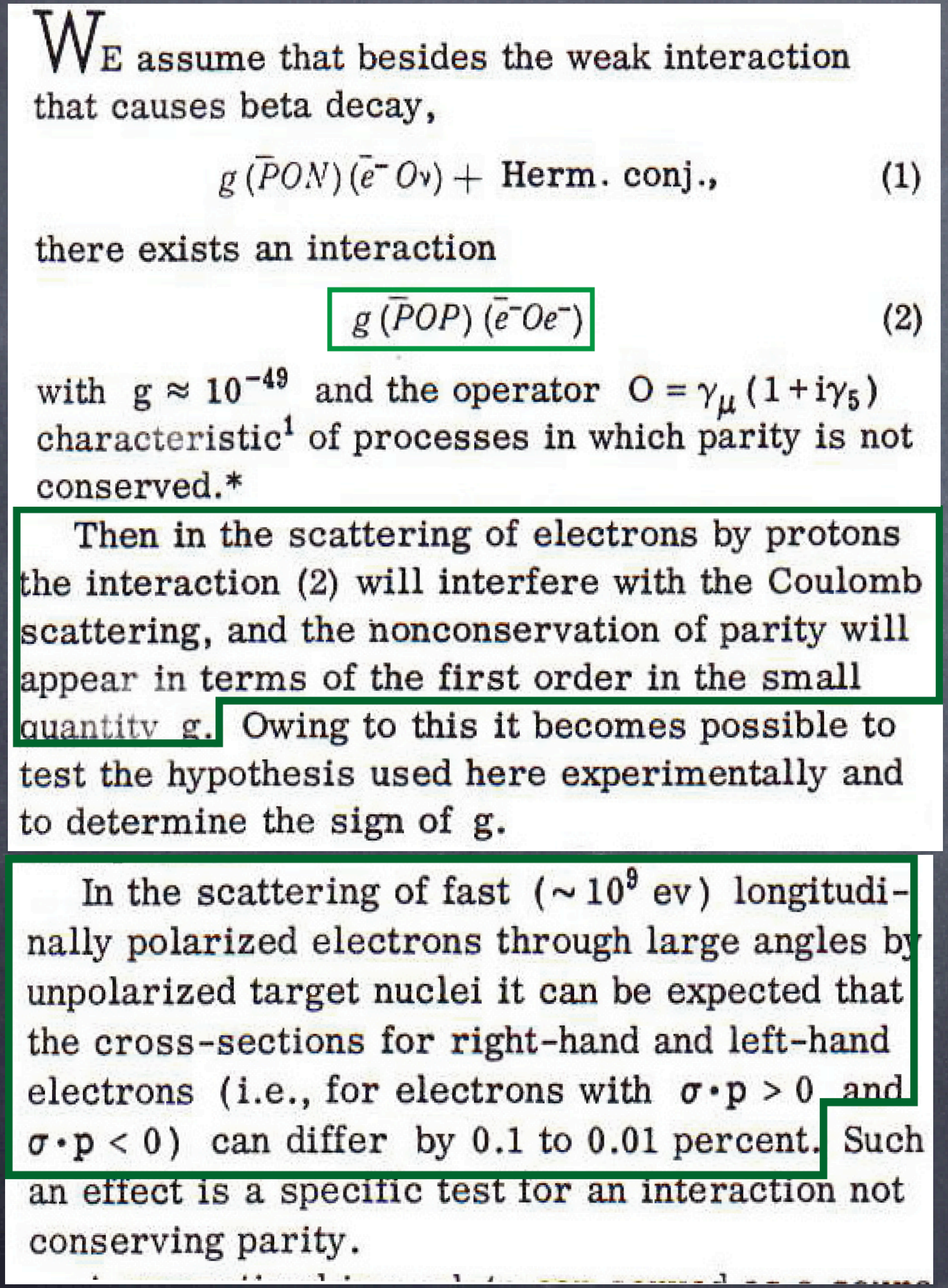
PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 964–966 (March, 1959)

Parity Violation in Electron Scattering?



We assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^- O\nu) + \text{Herm. conj.}, \qquad (1)$$

there exists an interaction

$$\boxed{g(\bar{P}OP)(\bar{e}^- Oe^-)} \qquad (2)$$

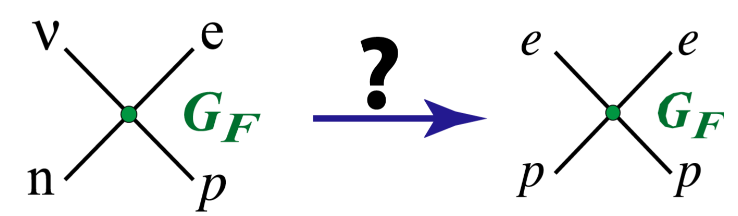
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

Neutron β Decay

Electron-proton Weak Scattering

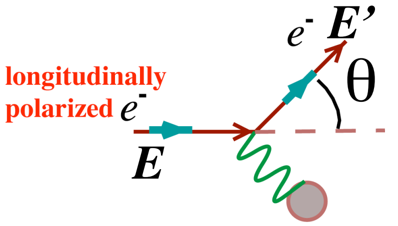


$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

$$\sim |A_{EM}|^2 + \boxed{2A_{EM}A^*_{weak}} + \ldots$$

Parity-violating

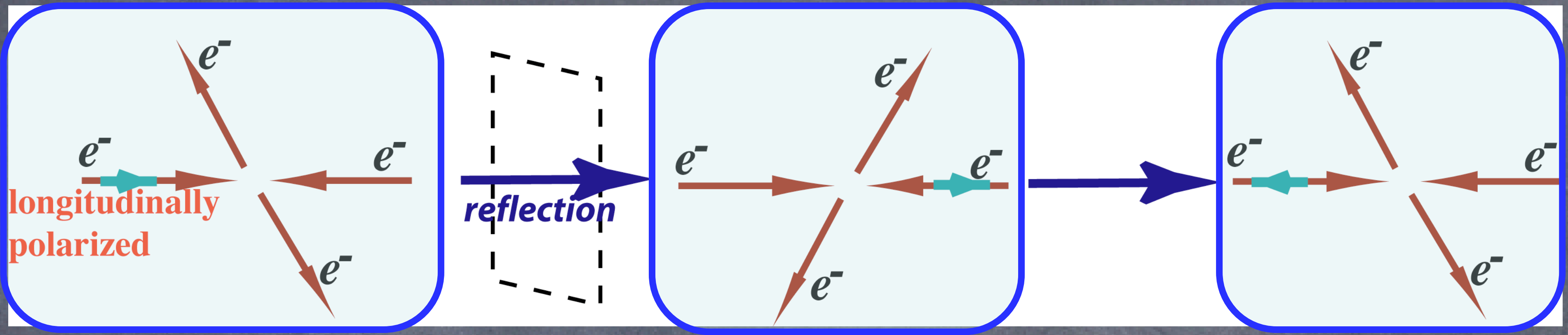
$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -A_{LR}$$



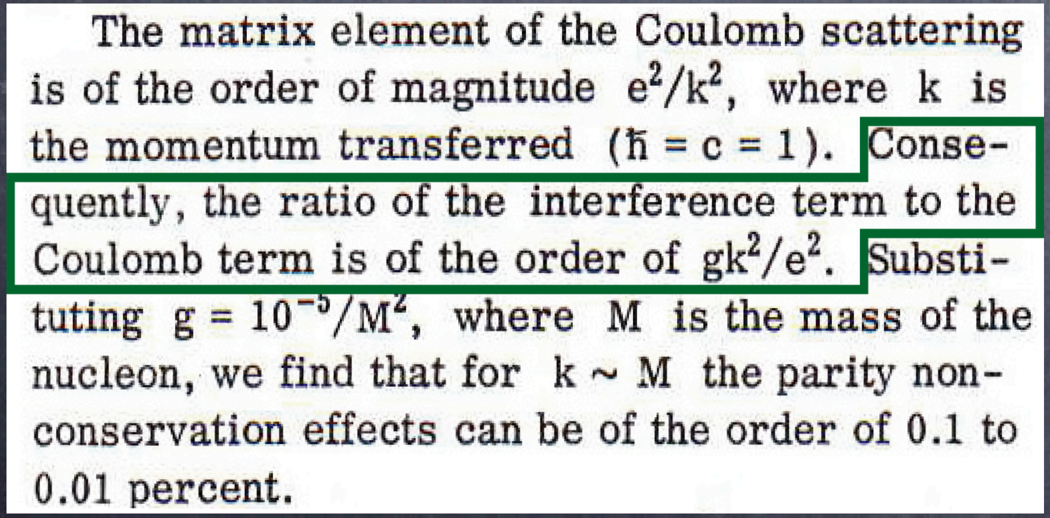
4-momentum transfer

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

Observable Parity-Violating Asymmetry



- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*



The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity nonconservation effects can be of the order of 0.1 to 0.01 percent.

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$A_{PV} \sim 10^{-4} \cdot Q^2(\mathrm{GeV}^2)$$

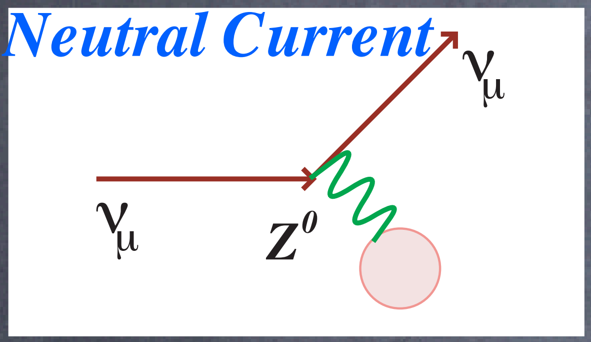
The idea could not be tested for 2 decades:
Several circumstances aligned to make this an important measurement

Weak Interaction Theory

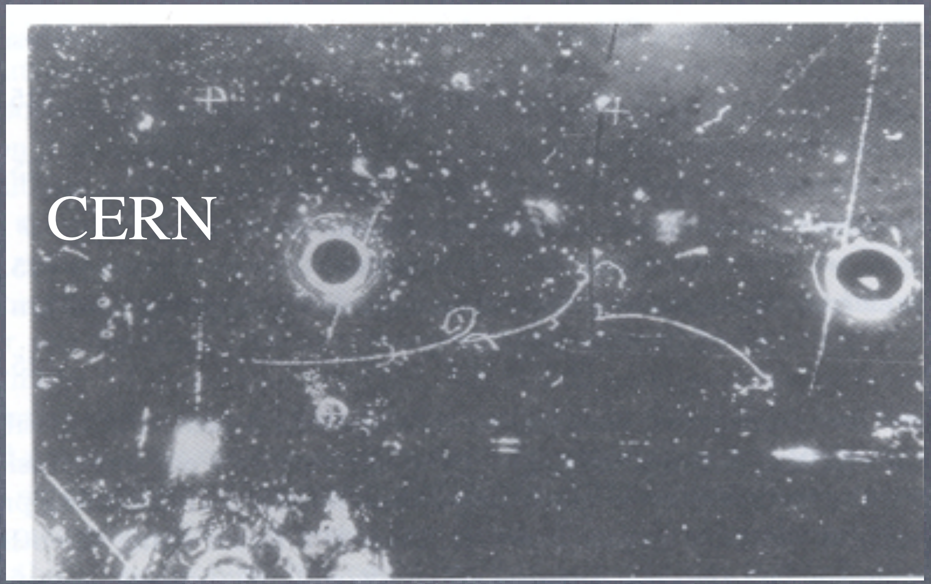
A Model of Leptons

Steve Weinberg - 1967

The Z boson incorporated



Gargamelle finds one ν_μ e^- event in 1973! (two more by 1976)



Neutrino scattering measurements find θ_W is non-zero

One free parameter: the weak mixing angle θ_W introduced

If θ_W were strictly zero, W & Z bosons would weigh exactly the same and right-handed particles would not exchange Z bosons either

	Left-	**Right-**
γ Charge	$0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$	$0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$
W Charge	$T = \pm \frac{1}{2}$	zero
Z Charge	$T - q \sin^2 \theta_W$	$-q \sin^2 \theta_W$

SLAC E122 Experiment

Parity Violation in Electron Scattering?

electron-nucleon scattering

Weinberg model

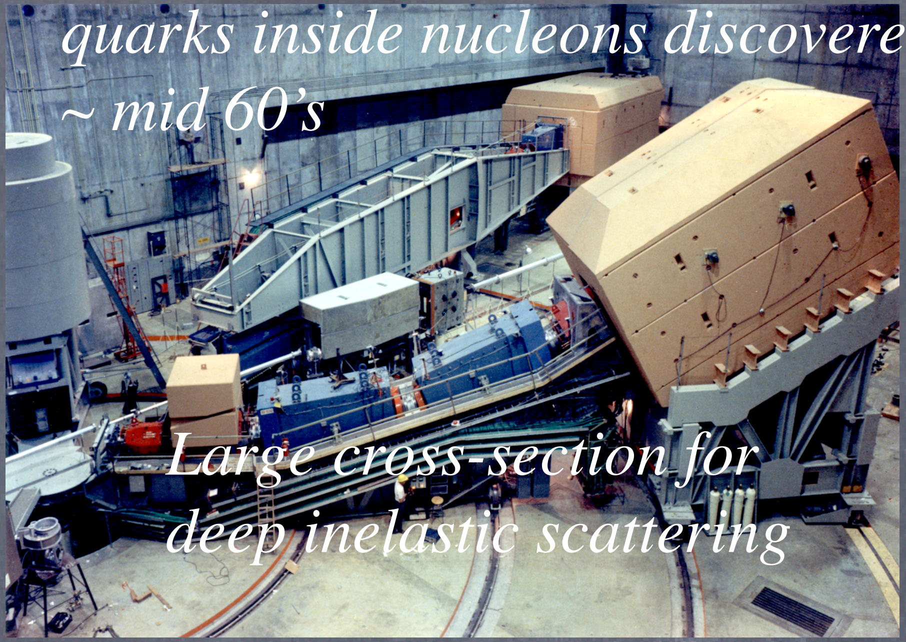
$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

Parity is violated

or

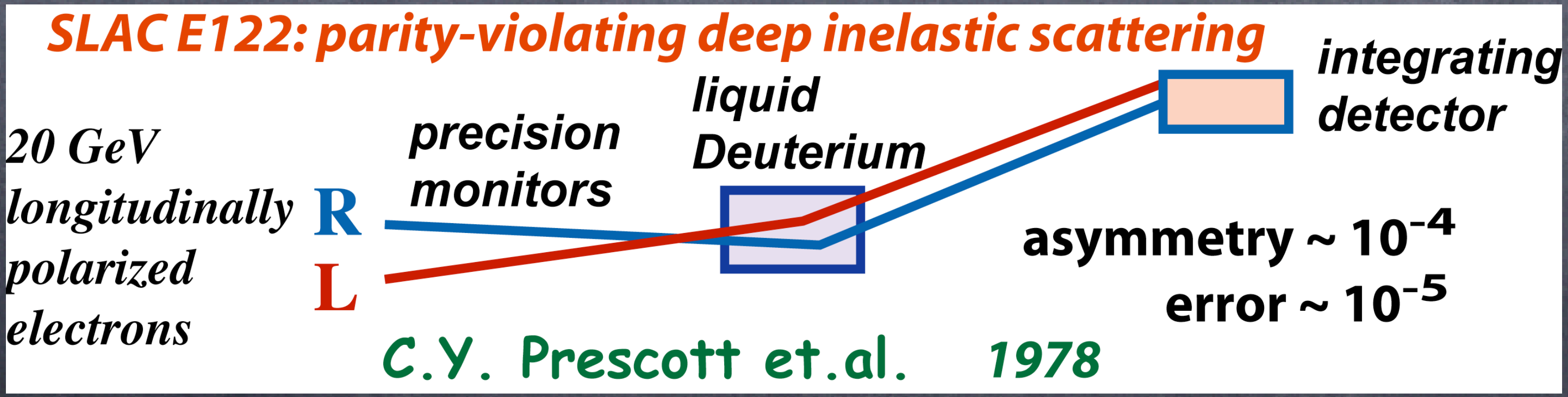
$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^0\\ e\end{pmatrix}_r$$

Parity is conserved



quarks inside nucleons discovered ~ mid 60's

Large cross-section for deep inelastic scattering



SLAC E122: parity-violating deep inelastic scattering

20 GeV longitudinally polarized electrons

precision monitors

liquid Deuterium

integrating detector

asymmetry ~ 10^{-4}

error ~ 10^{-5}

C.Y. Prescott et.al. *1978*

Final anchor for SU(2)XU(1):

Glashow, Weinberg, Salam awarded the 1979 Nobel Prize

Summary

- Especially after the discovery of neutrino mass, searches for charged lepton flavor violation are of great importance in the global search for physics beyond the standard model

- In some cases, the reach of these searches goes beyond that of the LHC

- Flavor diagonal super-weak neutral current interactions must be searched for as well since many new physics scenarios have a natural suppression of flavor changing neutral currents

- We will begin lecture 4 by discussing new such experiments that have comparable reach to the LHC