Parity-Violating Electron Scattering

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Ecole Internationale Joliot-Curie
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A unique probe of strange quarks in nucleons and the neutron skin of a heavy nucleus

Lecture 1

Outline of Lectures

- Lecture 1
  - Symmetries and Conservation Laws
  - Weak Interactions and the unified Electroweak Interactions
  - Quantum Electrodynamics and Electron Scattering
  - Parity-violating Electron Scattering
- Lecture 2
  - Strange Quark Form Factors
  - Neutron skin of a heavy nucleus
  - Future of parity-violating electron scattering

Introductory Remarks

- Student background and preparation varies
  - Most of you will have had nuclear and/or particle physics at an advanced level but I decided not to assume it.
  - I have some slides on basic undergraduate and graduate subatomic physics
- As postdoctoral researchers, you will learn to cope with imperfect knowledge
  - Qualitative rather than quantitative understanding
  - I am an experimentalist! I will focus on measurements but theory is critical. Unfortunately, I wont have time to justice to it.
- I will try to communicate the "big picture"
  - necessary general knowledge for students focused on other subfields

Parity Symmetry

Symmetries and Conservation Laws

Noether's Theorem: If Euler-Lagrange equation is invariant under any coordinate transformation, $\exists$ an integral of motion

Symmetry		conservation law
translation	⟺	momentum
time	⟺	energy
rotation	⟺	angular momentum

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Not just space-time symmetries: Invariance of Lagrangian/Hamiltonian

e.g. Charge Conservation $\quad [Q, H] = 0 \quad \frac{d < Q >}{dt} = 0 \quad Q|\Psi >= q|\Psi >$

Conserved Quantities/Quantum Numbers

Symmetries and Groups

Symmetry operations:

Group of all operations: display closure & Associativity and have identity and inverse

Finite Group ⟺ Discrete Symmetry

Infinite Group ⟺ Continuous Symmetry

In Physics, group operations can be represented by matrices

SO(n): n-D rotations

SO(3) ⟺ SU(2)

Invariance under SU(2): Angular Momentum Conservation

Discrete Symmetries
C, P & T

Parity P $\quad x, y, z \rightarrow -x, -y, -z \quad P\psi(\vec{r}) = \psi(-\vec{r})$

$P^2 = I$ Group has 2 elements, P and I

$[H, P] = 0 \Rightarrow H\psi = E\psi$ & $P\psi = \pi\psi \Rightarrow \pi = \pm 1$

If hamiltonian is invariant under parity transformations, then π is conserved and observable

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Charge Conjugation C $C|p> = |\bar{p}>$ All quantum numbers flip sign except mass and spin

particles that are its own anti-particles are eigenstates of C

$C|\gamma> = -|\gamma> \Rightarrow \pi^0 \rightarrow \gamma\gamma \Rightarrow C|\pi^0> = +|\pi^0> \Rightarrow \pi^0 \rightarrow \gamma\gamma\gamma$ forbidden

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Time Reversal T $\quad T\psi(t) = \psi^*(-t)$ reactions are reversible in principle if T is conserved

A Guiding Principle for Experimentalists

If a process is not explicitly forbidden, it must occur!

Discovering a rare process that violates a known symmetry is a powerful way to probe the fundamental laws of nature

Lepton Number Violation and Neutrinoless Double-Beta decay

T-Violation and the Electric Dipole Moment of elementary particles

Nuclear and Atomic Systems are fertile hunting grounds!

Discovery of Parity Violation

Particle Classification S^π e.g. pions: 0^- pseudoscalar mesons

Tau-theta puzzle (1956) $\theta^+ \rightarrow \pi^+\pi^0$ (P=+1) $\tau^+ \rightarrow \pi^+\pi^0\pi^0$ (P=-1)

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The SAME particle is produced in strong interactions, but decays via weak interactions;
P conserved in strong interactions, but not in weak interactions

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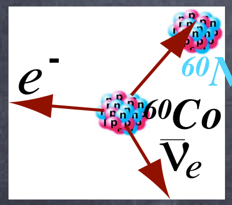
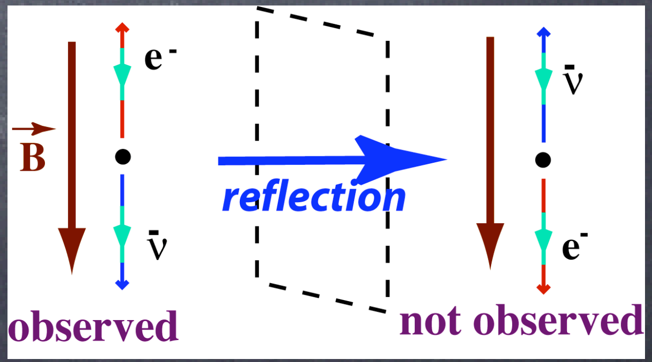


Weak decay of ^{60}Co Nucleus

C.S. Wu et al: Beta's in decays of ^{60}Co nuclei aligned in a magnetic field showed anisotropy



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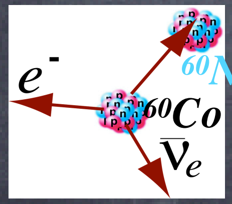

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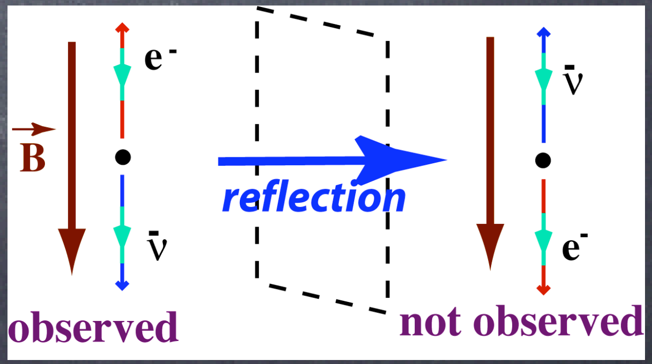
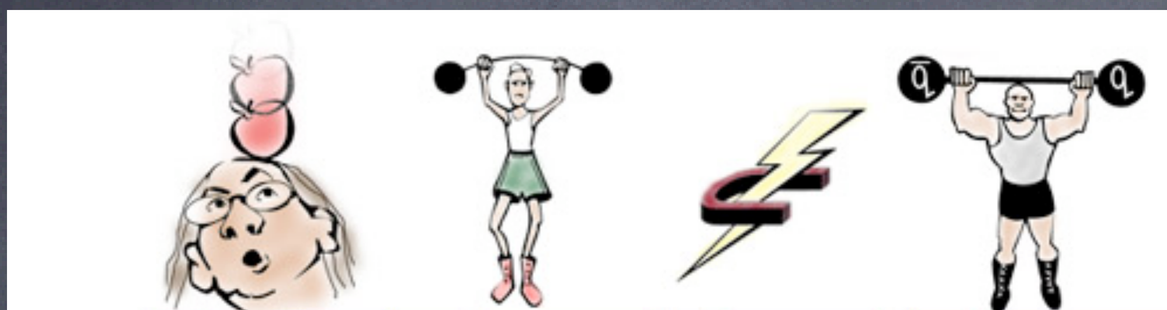


Classic example: Puzzle in accelerator result; theorists propose a solution; test on a different process (table-top)

Fundamental Interactions



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

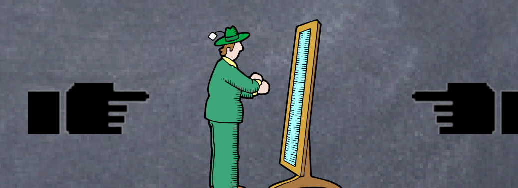
Radio-activity — *Electricity & Magnetism* — *Nuclei & Nucleons*

Gravity and Electromagnetic

Infinite range

Strong and Weak

10^{-15} meter



parity transformation

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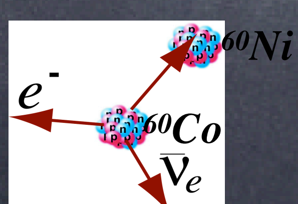

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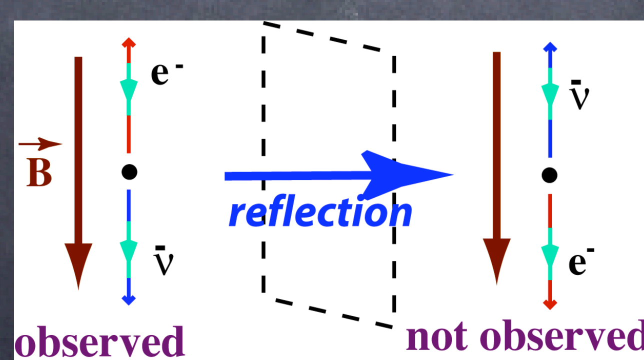

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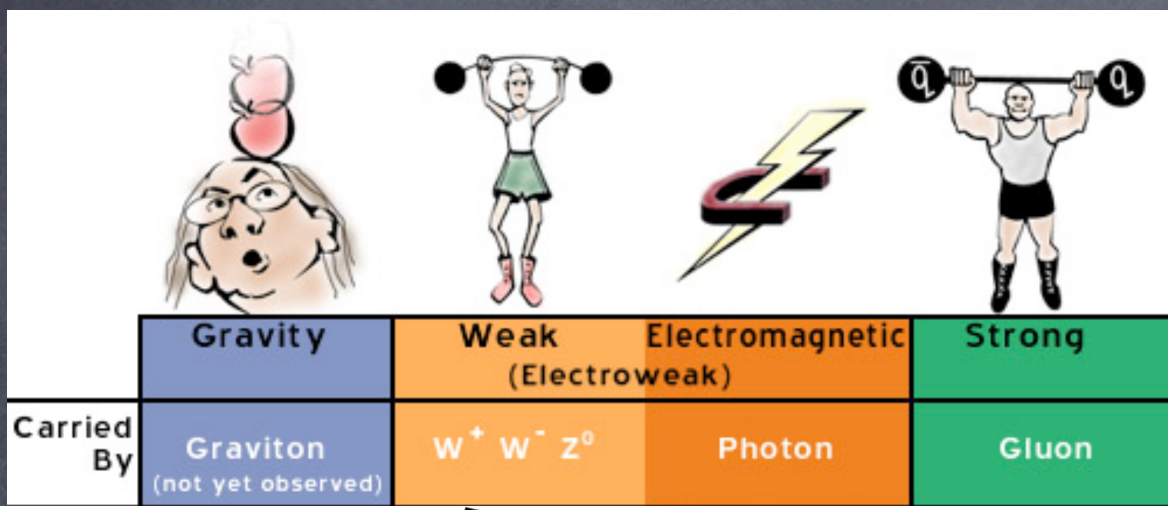

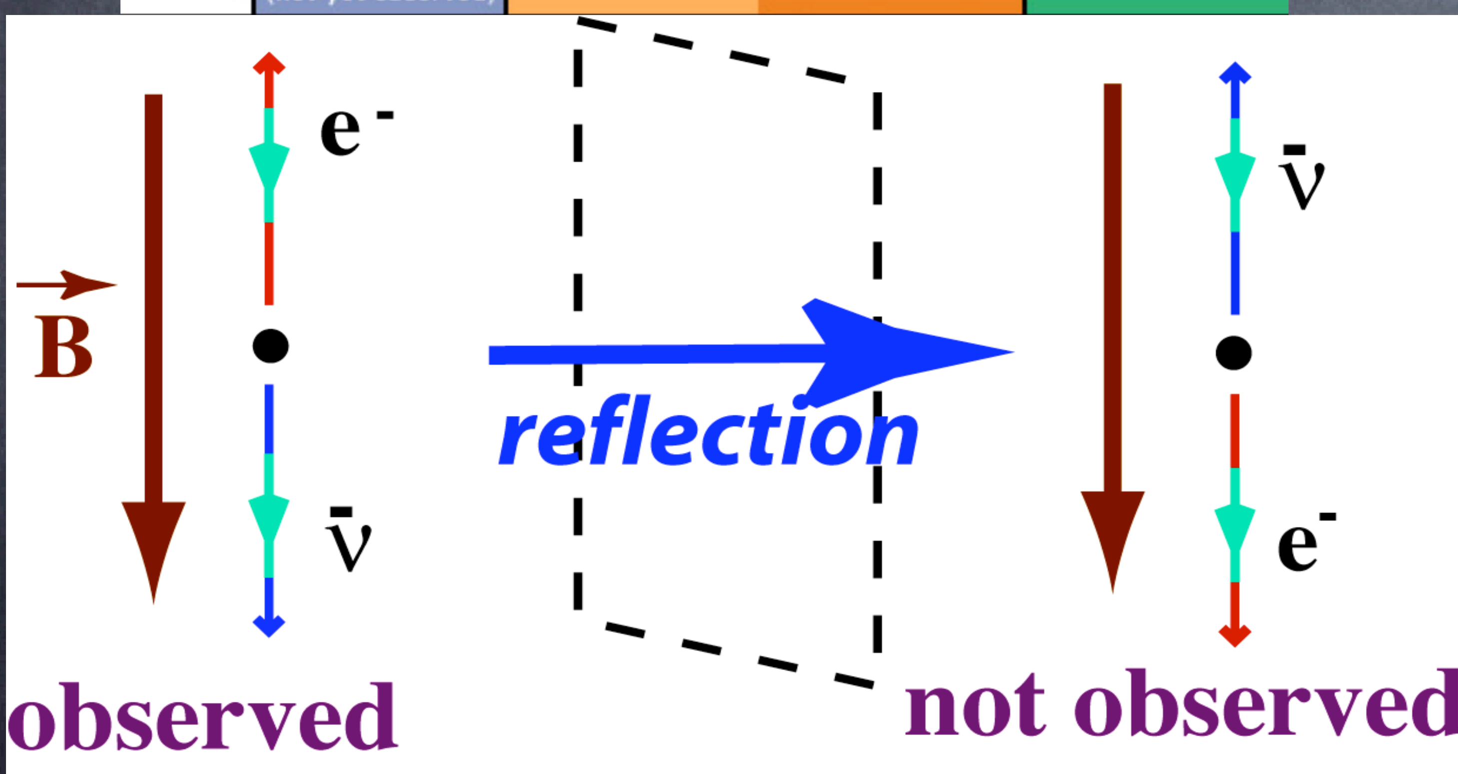

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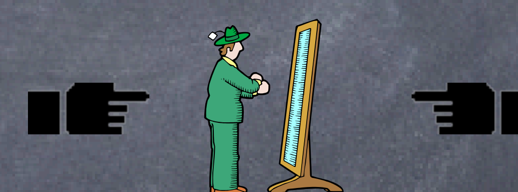

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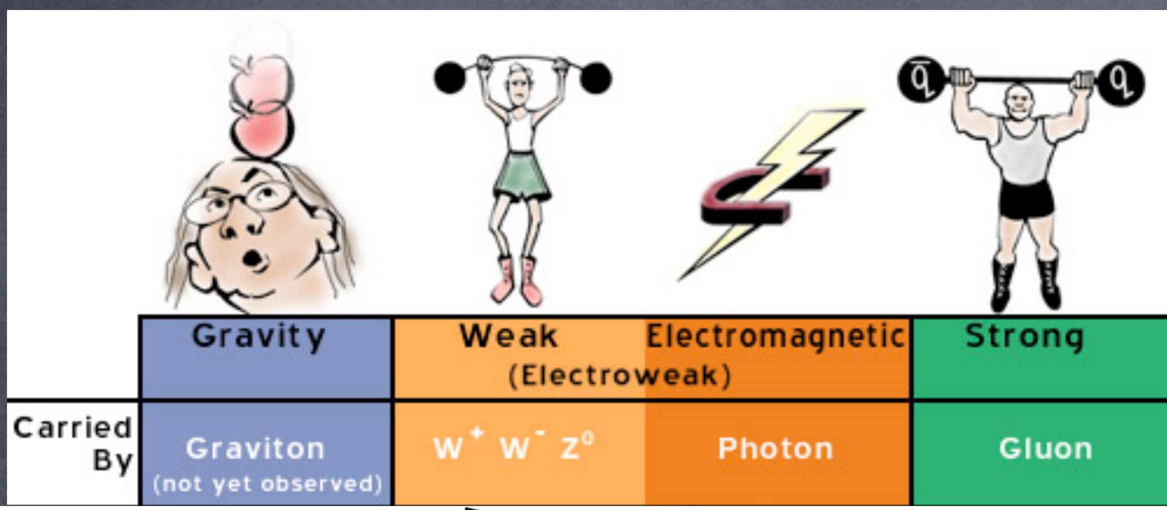

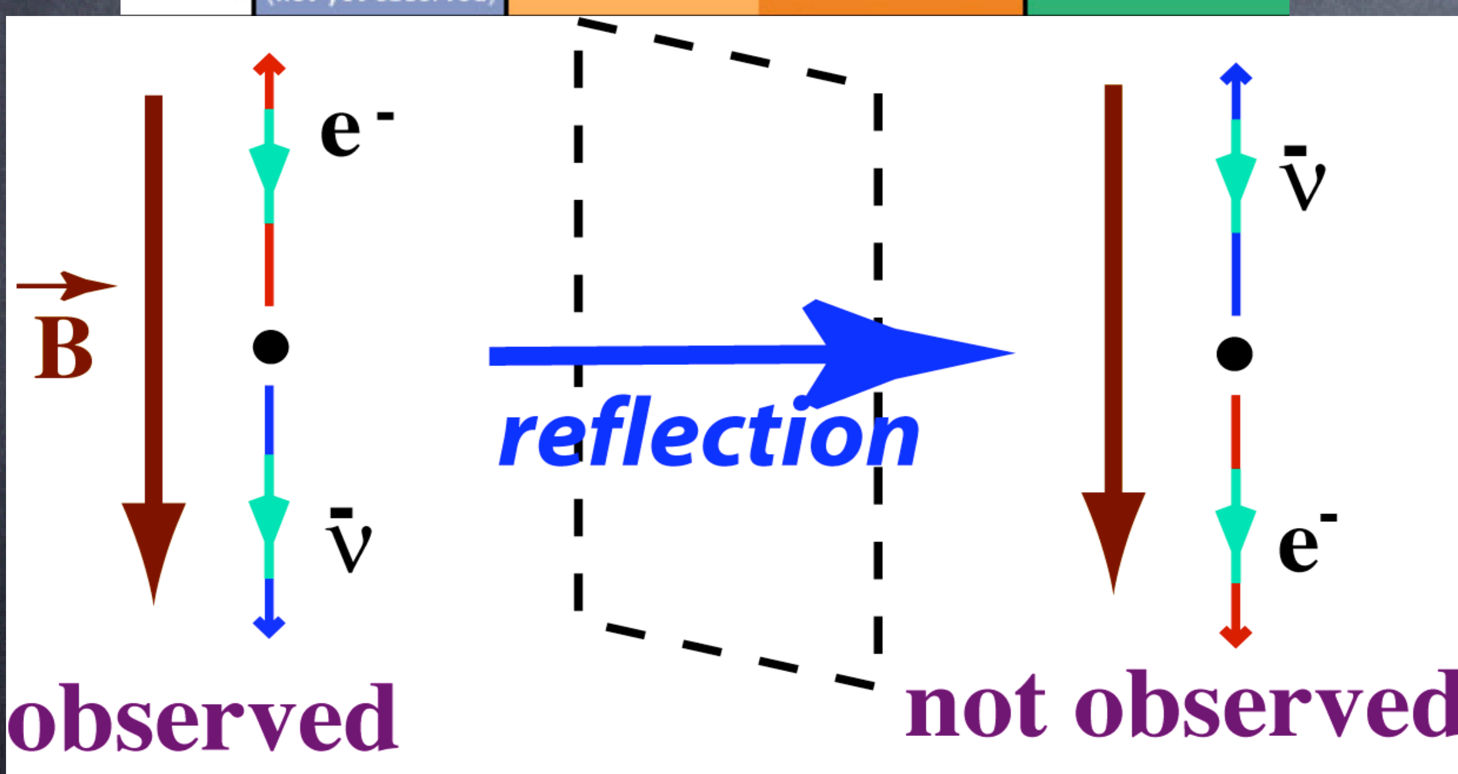

<u>Gravity and Electromagnetic</u>

Infinite range

<u>Strong and Weak</u>

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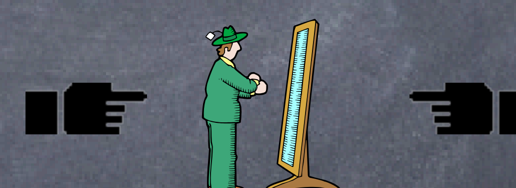

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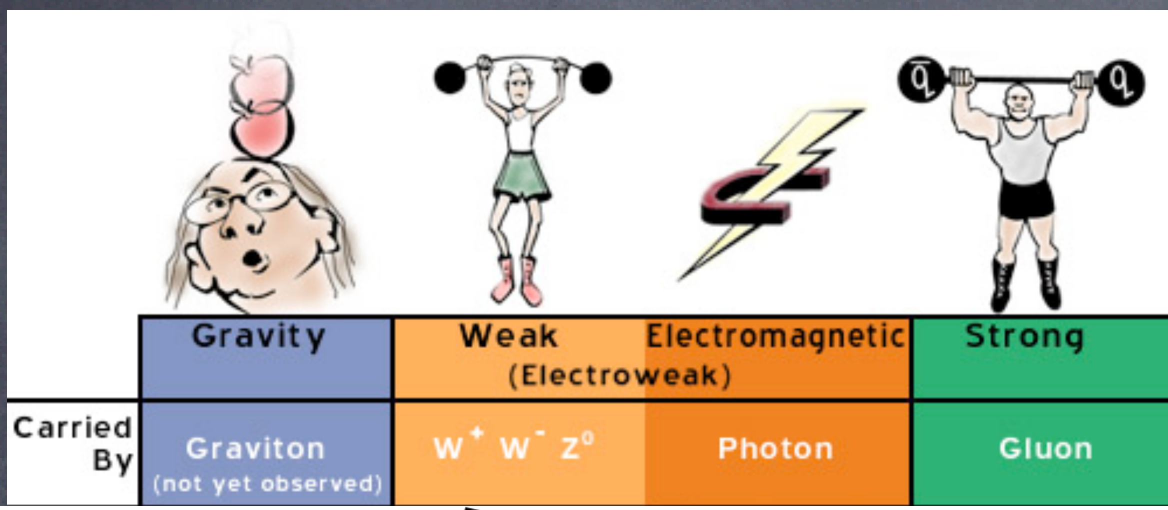
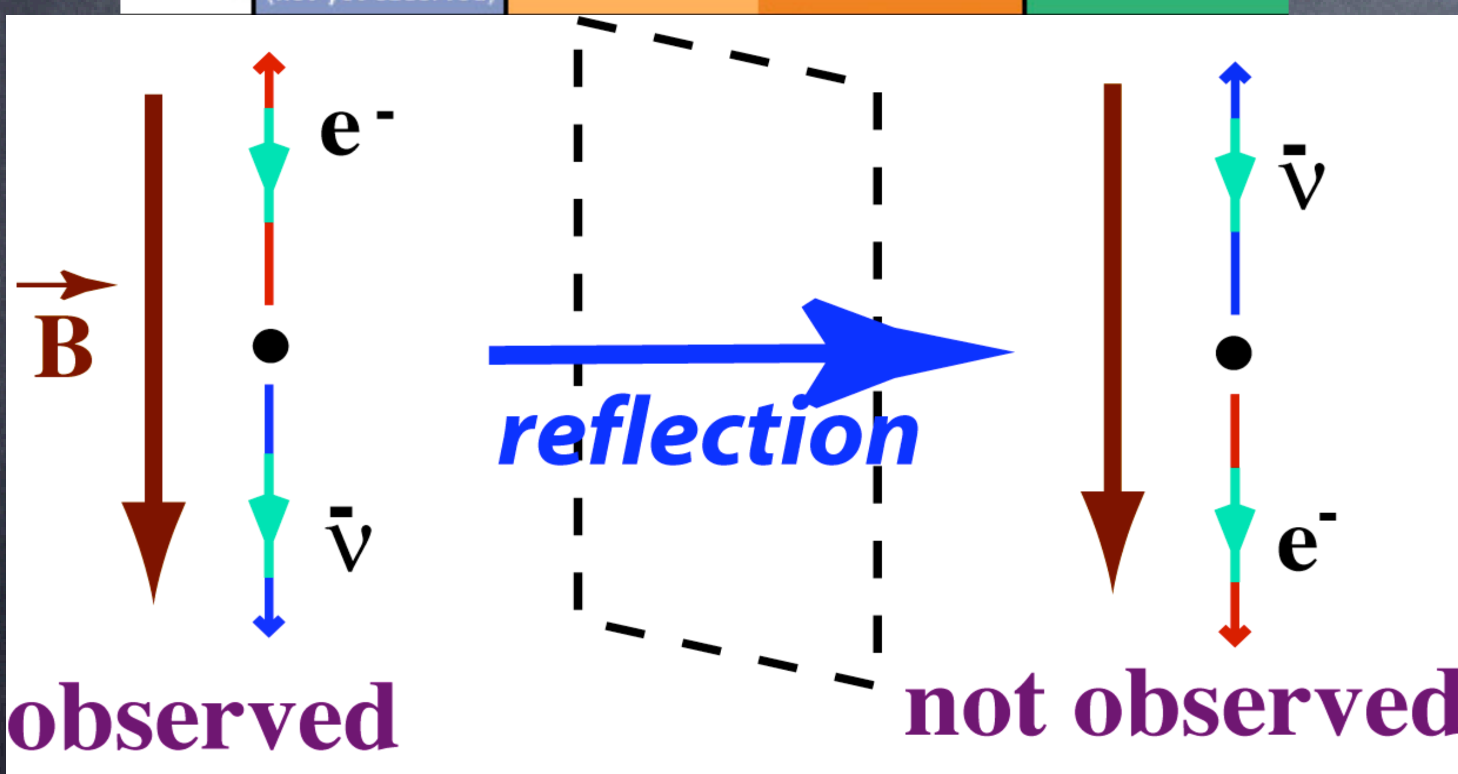
Charged Weak Interactions have pure V-A structure (maximal parity violation)

Fundamental Interactions





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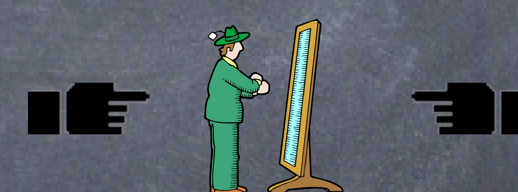

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What does this mean?

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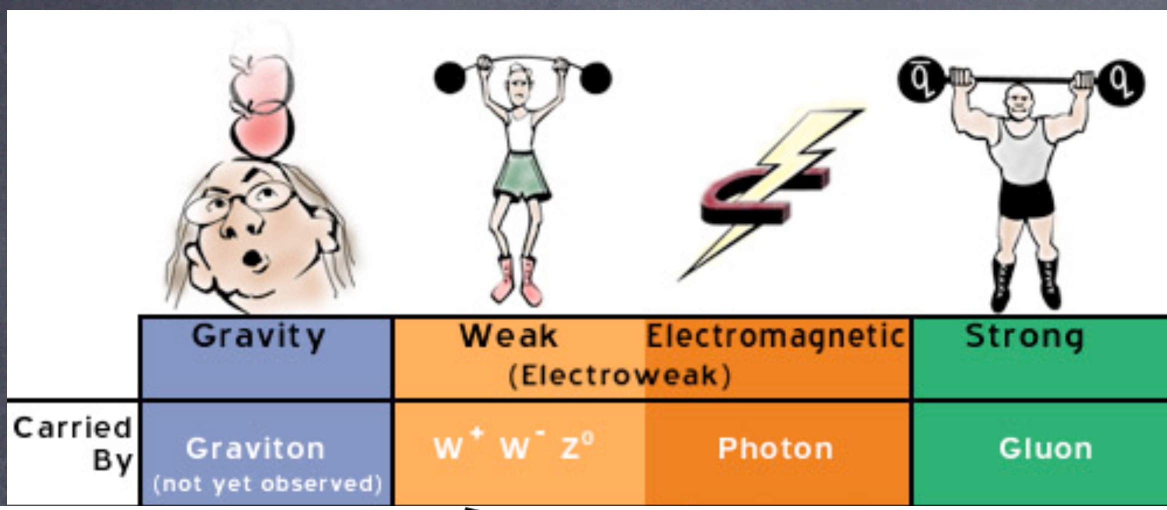
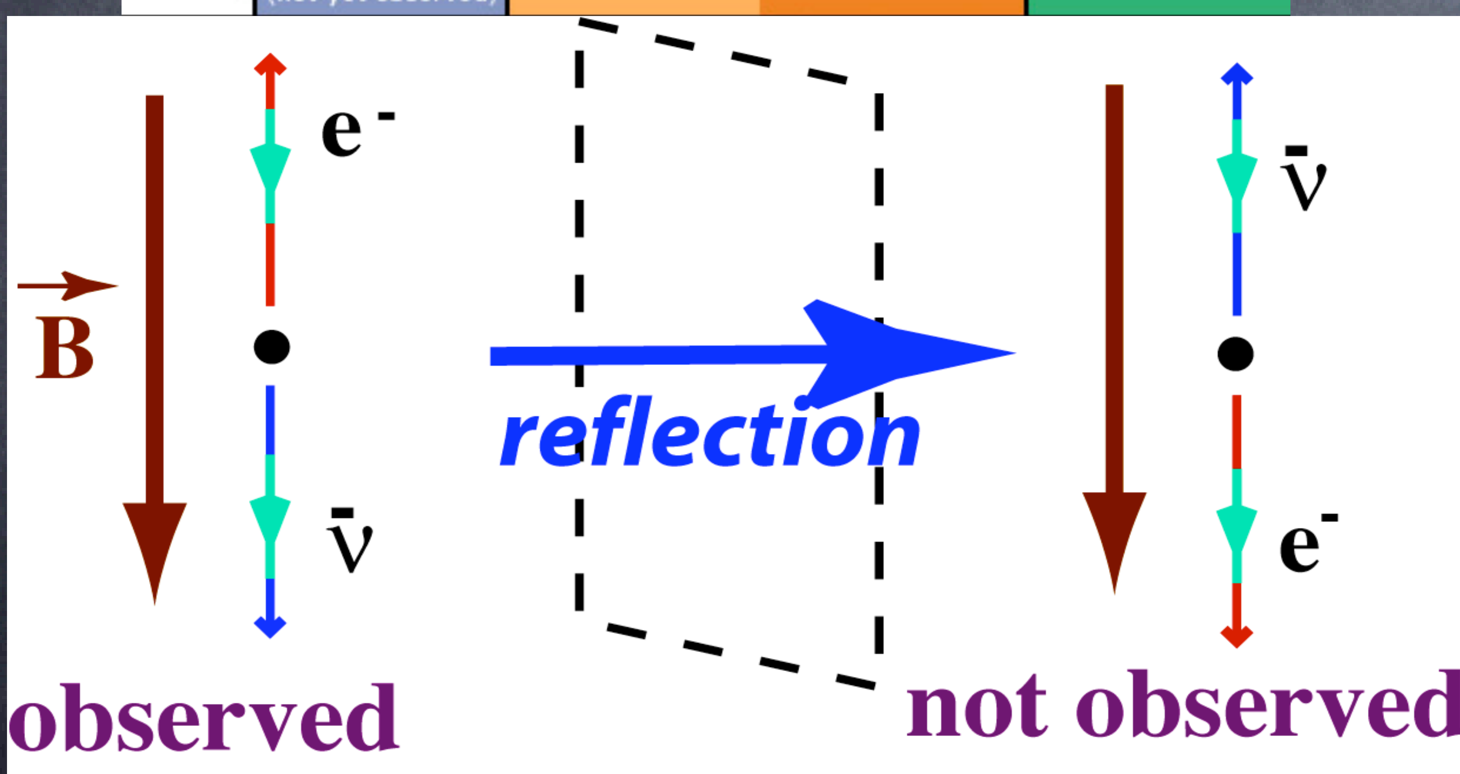
Fundamental Interactions

Why are weak interactions short range?





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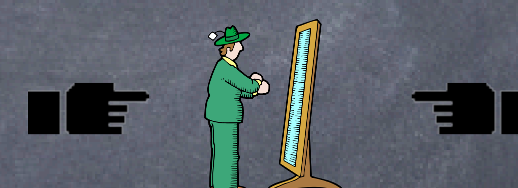

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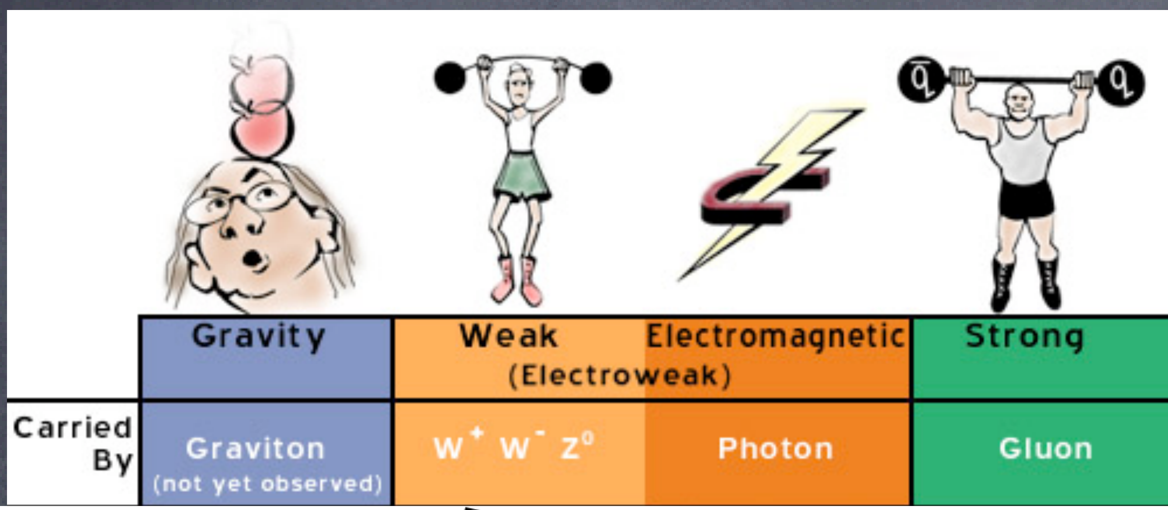
How are weak and EM interactions unified given P-Violation?



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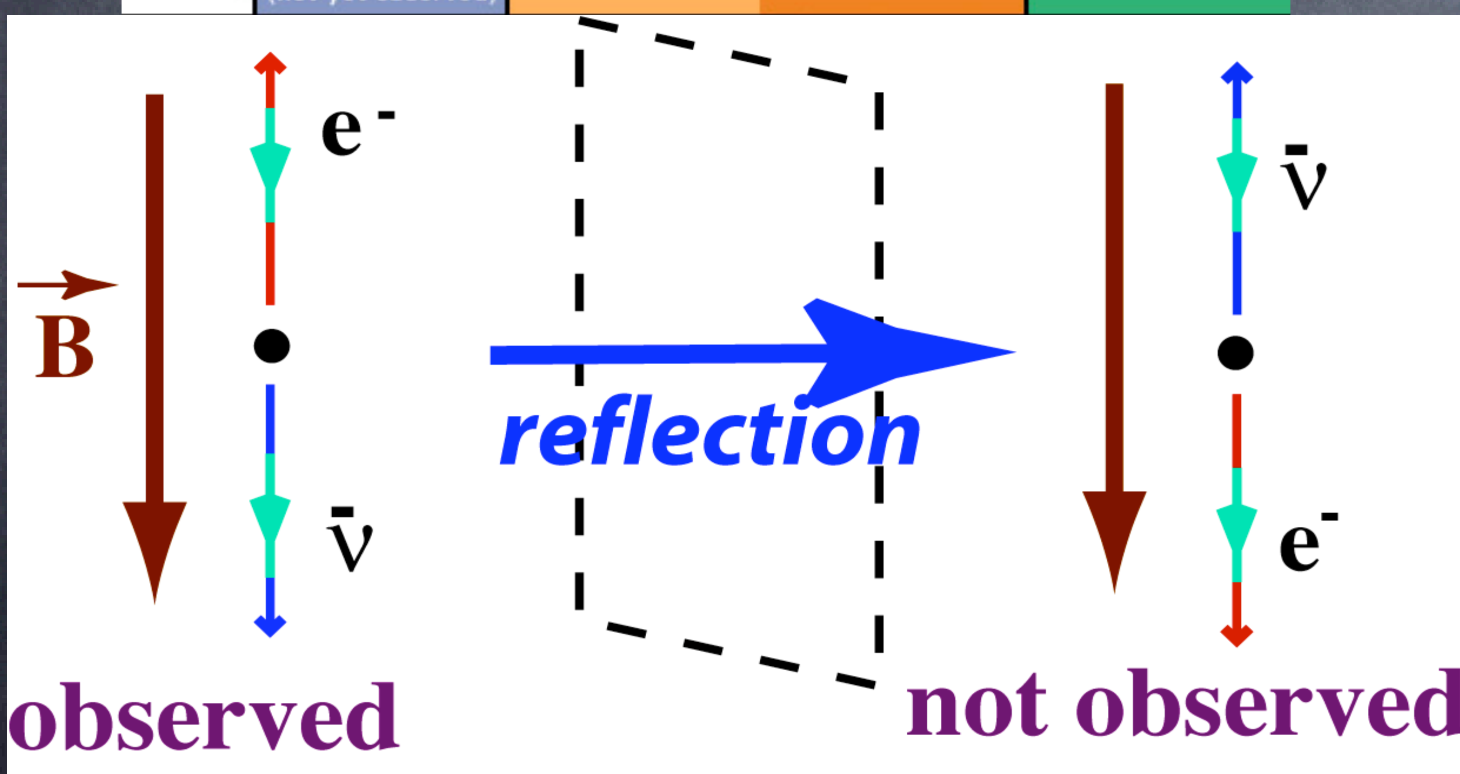

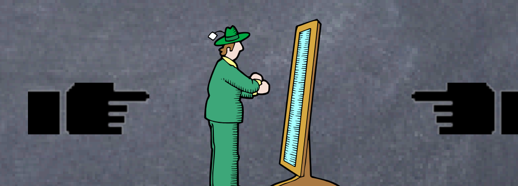

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Continuous Symmetries

Dirac free particle Lagrangian $\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$

U(1) Invariance: conserved current $\partial_\mu J^\mu = 0$

Local U(1) Invariance: $A_\mu J^\mu$ Electromagnetic Interactions

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Rotation in "Isospin Space"

$\begin{pmatrix} p \\ n \end{pmatrix}$ nucleon-nucleon interaction Hamiltonian invariant under SU(2) transformations in Isospin Space

$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ the "massless" left-handed electron and electron-neutrino are part of a similar "weak isospin" doublet

SU(2) invariance yields 3 independent conserved currents

(there are 3 independent 2x2 Pauli spin matrices)

Symmetries of the Electroweak Lagrangian

Accept the existance of u & d quarks, electrons, and electron-neutrinos

$SU(2)_L \times U(1)_Y$

4 conserved currents

local gauge invariance yields 4 bosons: W^+, W^-, W^0, B^0

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After spontaneous symmetry breaking via Higgs Mechanism:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

two weak charged currents	electromagnetic current	weak neutral current
$W^\pm$	γ	Z^0

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$SU(3)_c$ and gluons ⟺ Quantum Chromodynamics

Exact symmetries of nature: fully manifest in the early universe

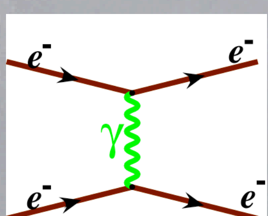
Unbroken exact symmetries: massless mediator & infinite range force

Electroweak Interactions

Charge & Handedness

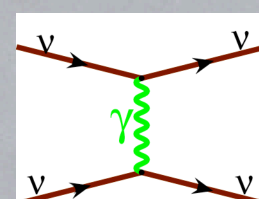
Electric charge determines strength of electric force

Electrons and protons have same charge magnitude: same strength



observed

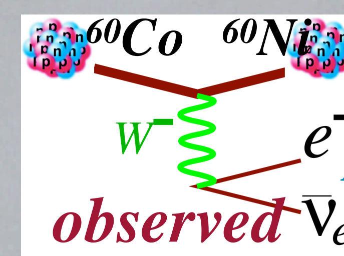
Neutrinos are "charge neutral": do not feel the electric force



not observed

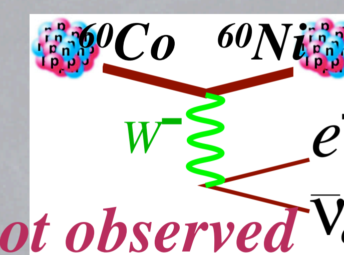
Weak charge determines strength of weak force

Left-handed particles (Right-handed antiparticles) have weak charge



observed $\bar{\nu}_{e_R}$ e^-_L *right-handed anti-neutrino*

Right-handed particles (left-handed antiparticles) are "weak charge neutral"



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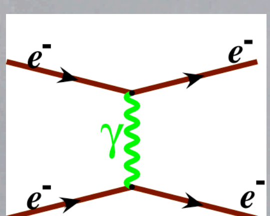

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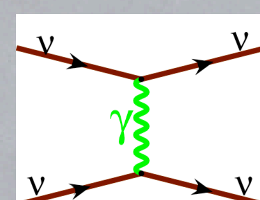

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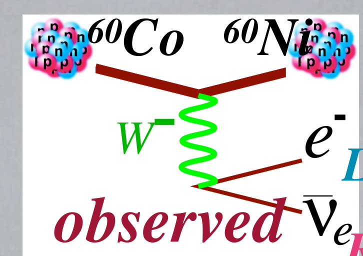

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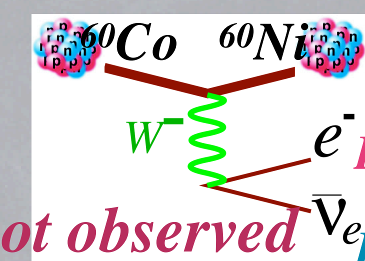

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For massless particles: $\gamma^5 u = (\vec{p} \bullet \vec{\Sigma}) u$

$$\vec{\Sigma} \equiv \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$$

$$\vec{p} \bullet \vec{\Sigma} \equiv h$$

helicity operator

Charge & Handedness

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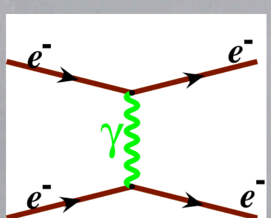

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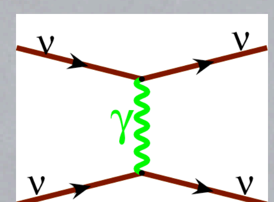

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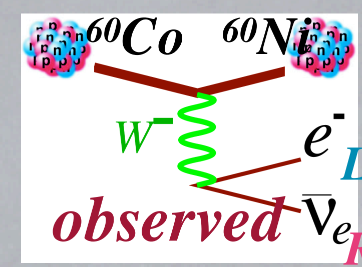

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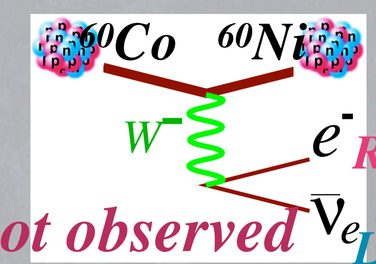

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helicity operator

$$\Sigma u = +u \Rightarrow \frac{(1-\gamma^5)}{2} u = 0$$

$$\Sigma u = -u \Rightarrow \frac{(1-\gamma^5)}{2} u = u$$

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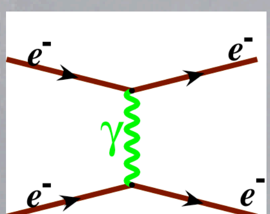

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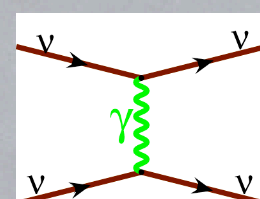

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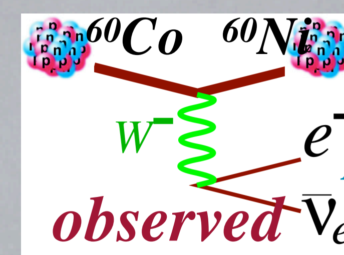

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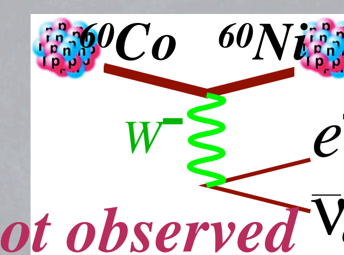


left-handed anti-neutrino

For massless particles: $\gamma^5 u = (\vec{p} \bullet \vec{\Sigma}) u$

$$\vec{\Sigma} \equiv \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$$

$$\vec{p} \bullet \vec{\Sigma} \equiv h$$

helicity operator

$$\Sigma u = +u \Rightarrow \frac{(1-\gamma^5)}{2} u = 0$$

$$\Sigma u = -u \Rightarrow \frac{(1-\gamma^5)}{2} u = u$$

$$P_L \equiv \frac{(1-\gamma^5)}{2} \qquad P_R \equiv \frac{(1+\gamma^5)}{2}$$

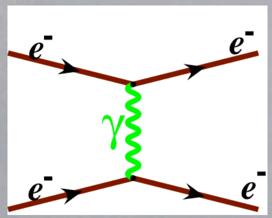
Left- and right-handed projections

$$P_{L,R} u \equiv u_{L,R} \qquad P_i P_j = \delta_{ij} P_j \qquad \sum_i P_i = I$$

Charge & Handedness

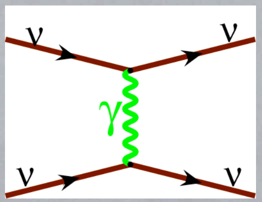
Electric charge determines strength of electric force

Electrons and protons have same charge magnitude: same strength



observed

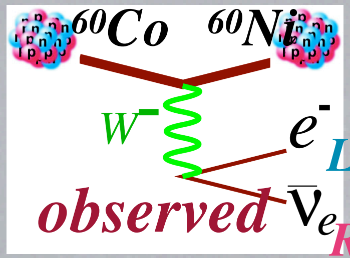
Neutrinos are "charge neutral": do not feel the electric force



not observed

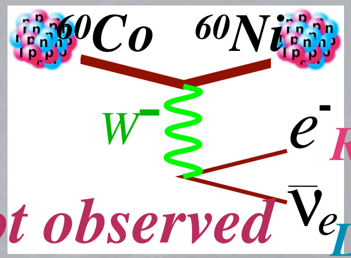
Weak charge determines strength of weak force

Left-handed particles (Right-handed antiparticles) have weak charge



e^-_L, $\bar{\nu}_{eR}$ right-handed anti-neutrino

Right-handed particles (left-handed antiparticles) are "weak charge neutral"



not observed e^-_R, $\bar{\nu}_{eL}$ left-handed anti-neutrino

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Left- and right-handed projections

$$P_{L,R} u \equiv u_{L,R} \qquad P_i P_j = \delta_{ij} P_j \qquad \sum_i P_i = I$$

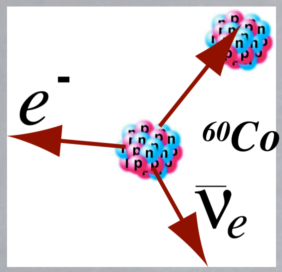
$$-\frac{G_F}{\sqrt{2}} \left[\bar{u}_L(Co) \gamma_\mu u_L(Ni) \right] \left[\bar{u}_L(e) \gamma^\mu v_R(\bar{\nu}) \right]$$

Only left-handed particles participate in charged weak interactions

Weak Interactions

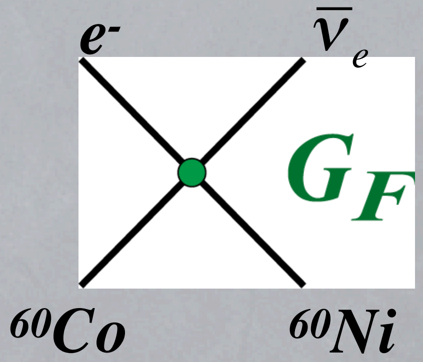
$J^\mu \sim \overline{\psi}\gamma^\mu\psi$ *vector* $J^\mu \sim \overline{\psi}\gamma^\mu\gamma^5\psi$ *axial-vector* *V-A Interaction*

V X A gives rise to pseudo-scalars



$$\mathcal{M} \sim -\frac{G_F}{\sqrt{2}}\left[\overline{u}(Co)\gamma_\mu(1-\gamma^5)u(Ni)\right]\left[\overline{u}(e)\gamma^\mu(1-\gamma^5)v(\overline{\nu})\right]$$

4-Fermi Contact interaction with maximal parity violation



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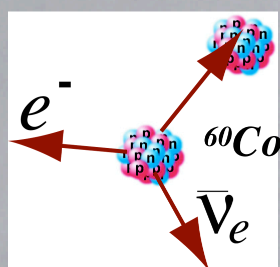

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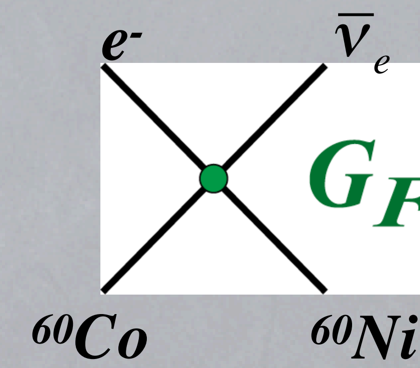

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$P_L \equiv \frac{(1-\gamma^5)}{2}$ ***left chirality operator***

Important: Helicity ≠ Chirality if m≠0!

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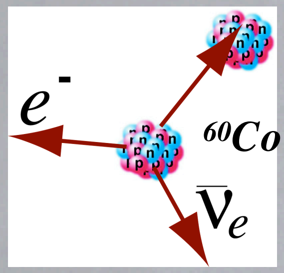

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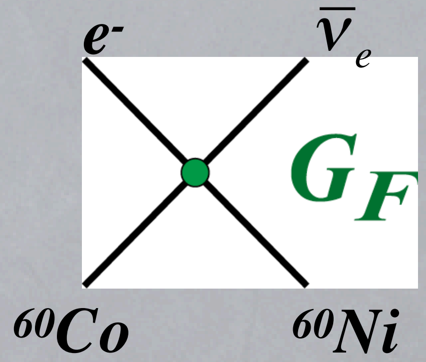

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Conserved but not Lorentz invariant!

(Can race past a massive particle and observe it spinning the other way)

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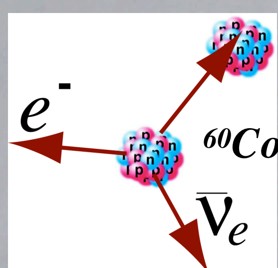

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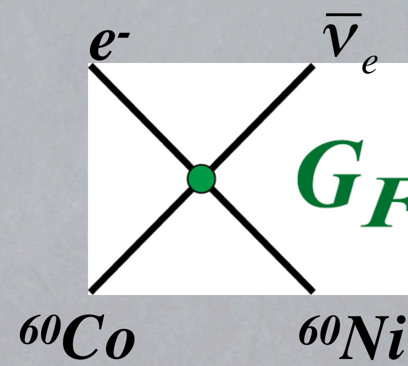

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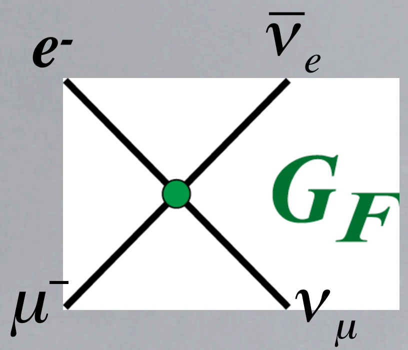
(Can race past a massive particle and observe it spinning the other way)

Chirality operator not conserved, but Lorentz invariant!

Freely propagating left-chiral projection will develop a right-chiral component

Weak Decay & Scattering



$$\mathcal{M} \sim -\frac{G_F}{\sqrt{2}}\left[\bar{u}(\nu_\mu)\gamma_\mu(1-\gamma^5)u(\mu)\right]\left[\bar{u}(e)\gamma^\mu(1-\gamma^5)v(\bar{\nu}_e)\right]$$

Each decay mode provides a partial width Γ_i

Lifetime

$$\tau = \frac{1}{\sum_i \Gamma_i}$$

Partial width has units of energy

Conversion factor: 197 MeV-fm

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi}$$

⇒ ***Muon lifetime in vacuum: 2.2 μs***

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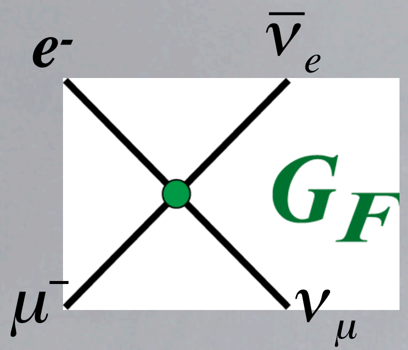

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Gedanken Experiments: The luxury of being a theorist

Consider

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

Can use same $\mathcal{M}$

$$\sigma = \frac{G_F E^2}{3\pi^2}$$

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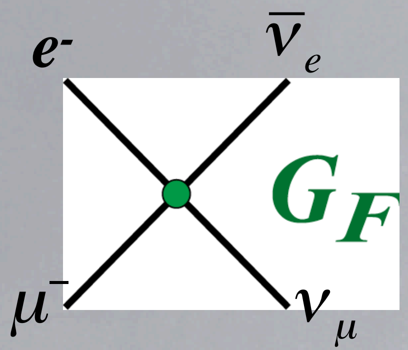

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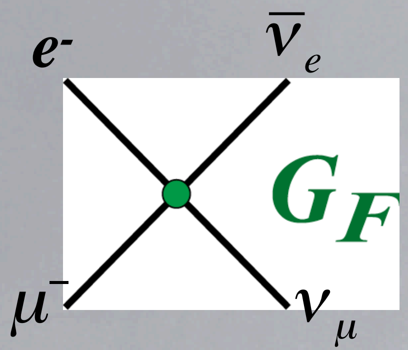

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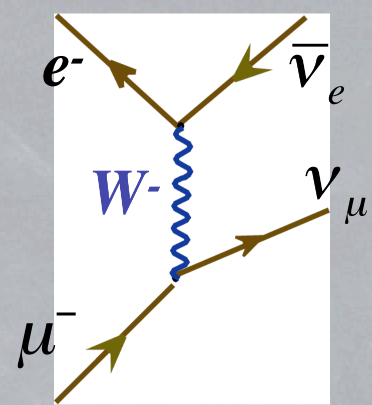
For E ~ 1 TeV, probability > 1!

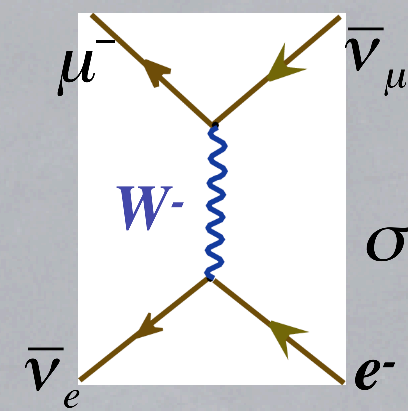
More particles going out than coming in

Massive Vector Bosons

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

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$





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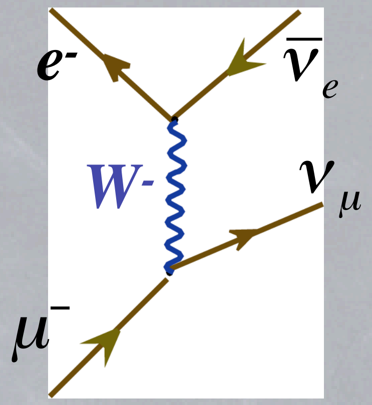

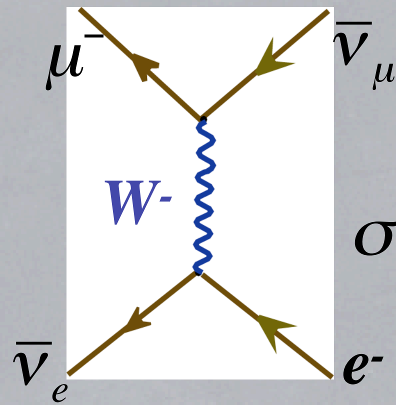

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Mass of the W between 10 and 100 GeV

$$V = \frac{1}{4\pi\varepsilon_0} \frac{q}{r} e^{-\left[\frac{mc}{\hbar}\right]r}$$

Short range

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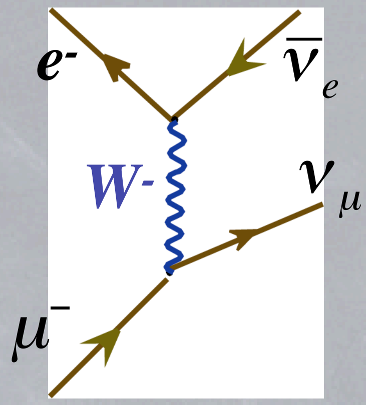

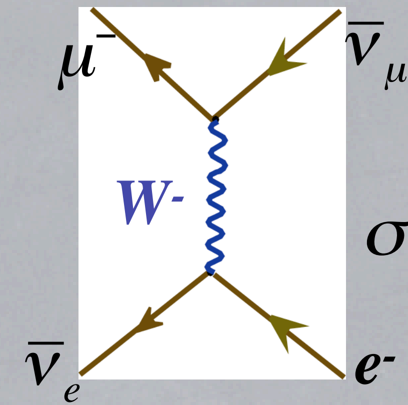

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Real W production

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu_e$$

Fixed target: $M^2_{new} \sim 2ME$

Collider: $M^2_{new} \sim 4E^2$

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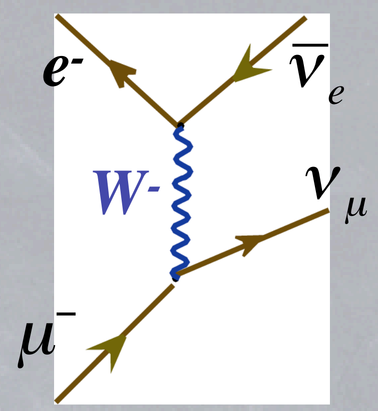

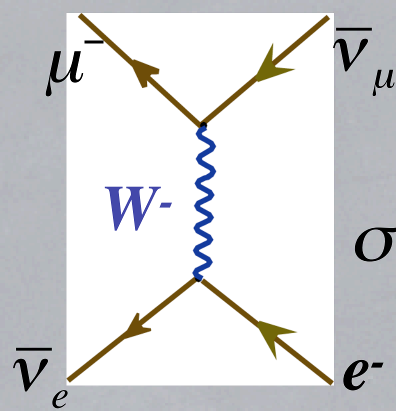

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Very short lifetime ⇔ **Large width**

$$A + B \rightarrow W^+ \rightarrow C + D$$

$$p(E) = \frac{\Gamma}{2\pi} \frac{1}{(E - m_W)^2 + (\Gamma/2)^2}$$

$$\sigma_{peak} \approx \frac{4\pi}{3m_W^2} \frac{\Gamma_{AB}}{\Gamma_{tot}} \frac{\Gamma_{CD}}{\Gamma_{tot}}$$

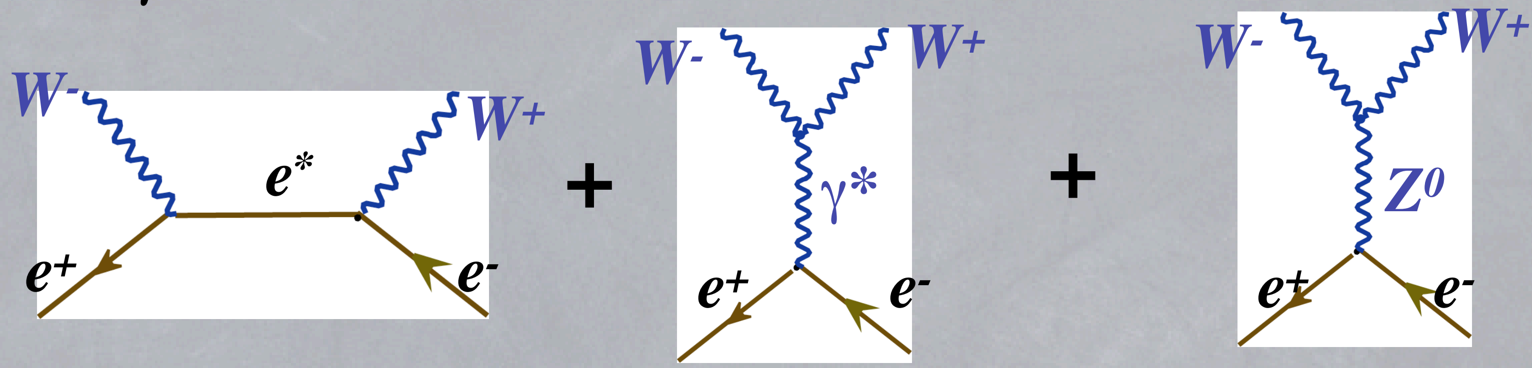
The Z Boson & Electroweak Unification

More gedanken experiments

$$e^+\nu_e \rightarrow W^+\gamma$$

Electron-positron collisions

$$e^+e^- \rightarrow W^+W^-$$



Unitarity violation forces important constraints

- *Need WWγ vertex: same charge as electron!*
- *Need a new, neutral massive weak boson: the Z^0*
- *One free parameter: θ_W, the weak mixing angle*

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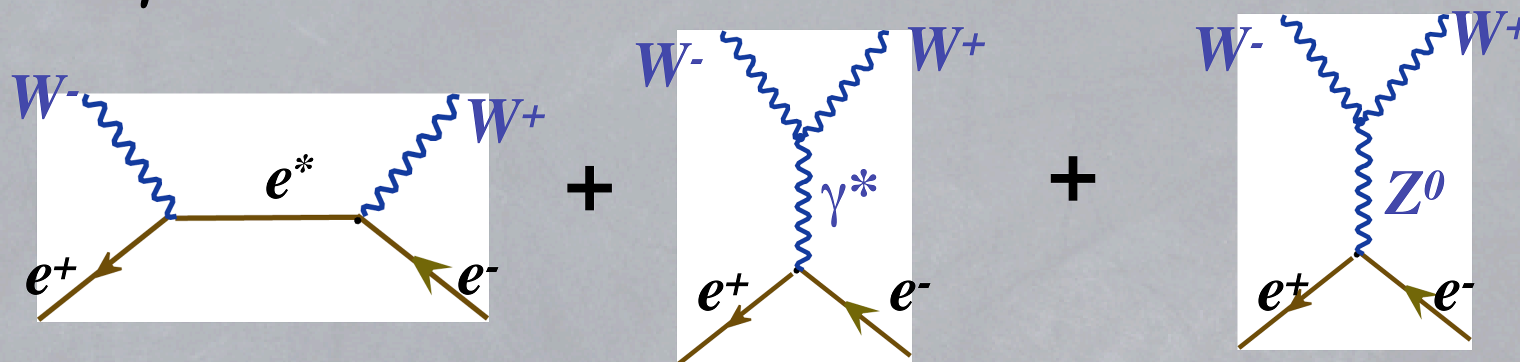

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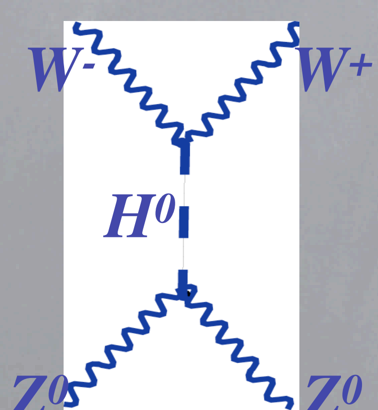

Scattering of longitudinal vector bosons (m=0)

- eeZ couplings depend on $\sin^2\theta_W$

$$\frac{m_W}{m_Z} = \cos\theta_W$$

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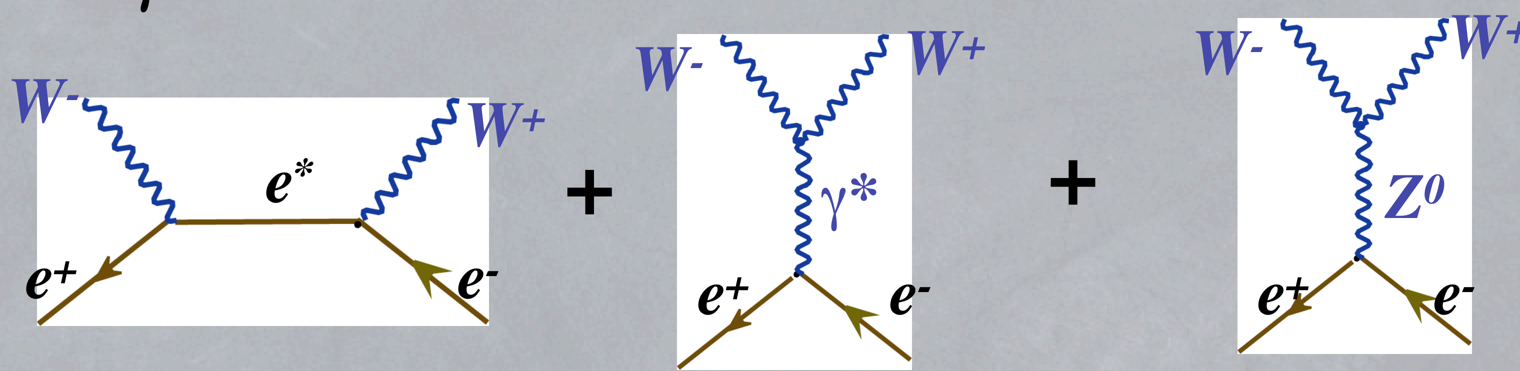

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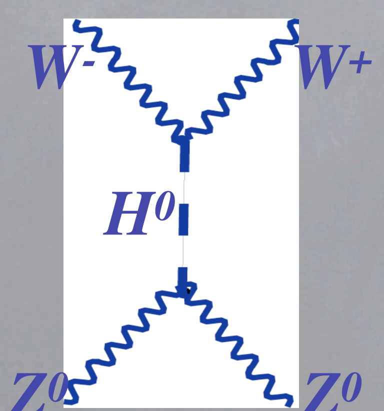
Something like this must occur



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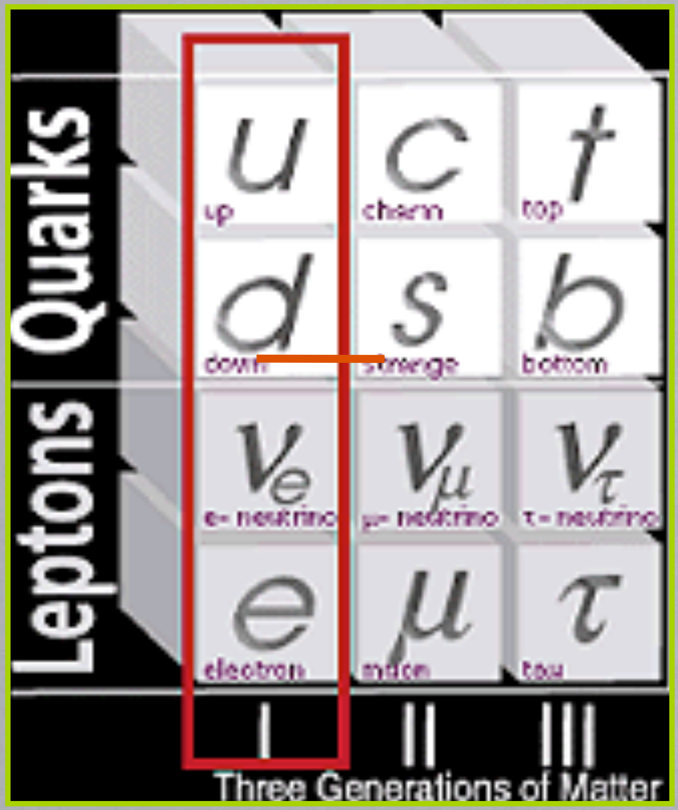
W & Z Charges



- Left-handed particles in isodoublets
- Right-handed particles iso-singlets
- Including neutrinos!

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

- *Ws and Zs are massive*
- *Ws have no couplings to right-handed particles*
- *Zs couple to both (provided the particles are charged): introduce g_L and g_R*
- *However, the Z couplings to left- and right-handed particles are different: parity violation, but not maximal*

Also use g_V and g_A:

$$g_V = g_L + g_R \qquad g_A = g_L - g_R$$

Vector and Axial-vector couplings

Electron Scattering

Quantum Electrodynamics

Free fermions fields are solutions to the Dirac equation $(i\gamma_\mu \partial^\mu - m)\psi = 0$

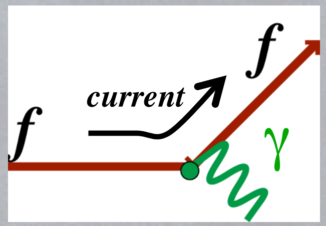
Corresponding Lagrangian: $\mathcal{L} \sim \quad \overline{\psi}(i\gamma_\mu \partial^\mu - m)\psi$

Local gauge invariance gives rise to interaction with photon field: $-J_\mu A^\mu$

Conserved electromagnetic current

$J^\mu = q\overline{\psi}\gamma^\mu\psi$ ***4-vector***

Feynman Rules: emission and absorption of virtual photons by fermion electromagnetic current



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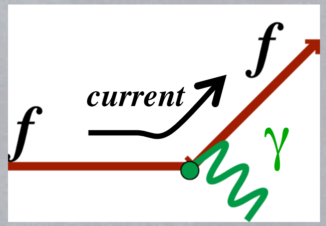
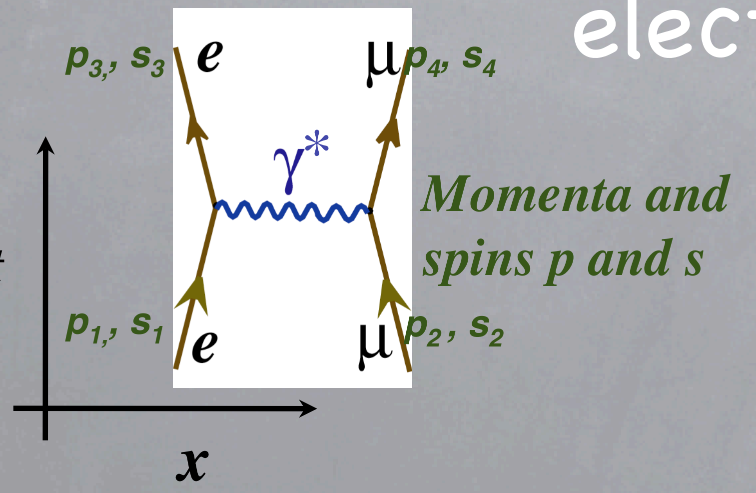


electron-muon scattering



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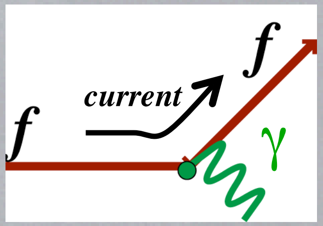
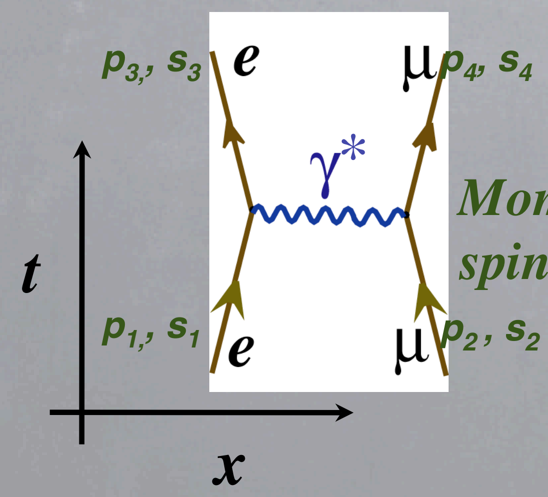


electron-muon scattering



Momenta and spins p and s

$$\mathcal{M} \sim -\frac{g_e^2}{(p_1 - p_3)^2}\left[\overline{u}^{s_3}(p_3)\gamma_\mu u^{s_1}(p_1)\right]\left[\overline{u}^{s_4}(p_4)\gamma^\mu u^{s_2}(p_2)\right]$$

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Free fermions fields are solutions to the Dirac equation $(i\gamma_\mu \partial^\mu - m)\psi = 0$

Corresponding Lagrangian: $\mathcal{L} \sim \quad \overline{\psi}(i\gamma_\mu \partial^\mu - m)\psi$

Local gauge invariance gives rise to interaction with photon field: $-J_\mu A^\mu$

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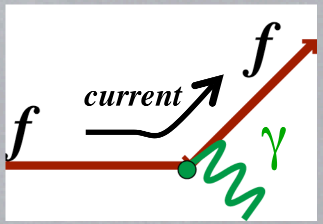

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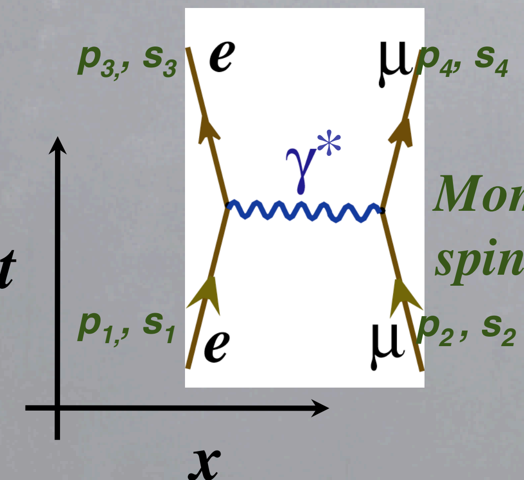

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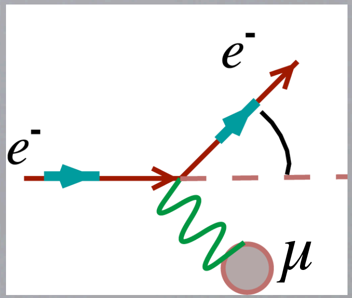

4-momentum transfer

Differential Cross Section $$\frac{d\sigma}{d\Omega} = \frac{4\alpha^2 E'^2}{q^4}\cos^2\frac{\vartheta}{2}$$

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

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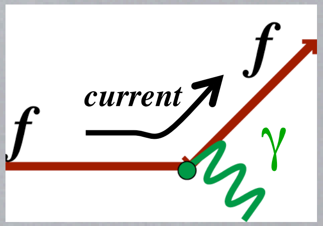

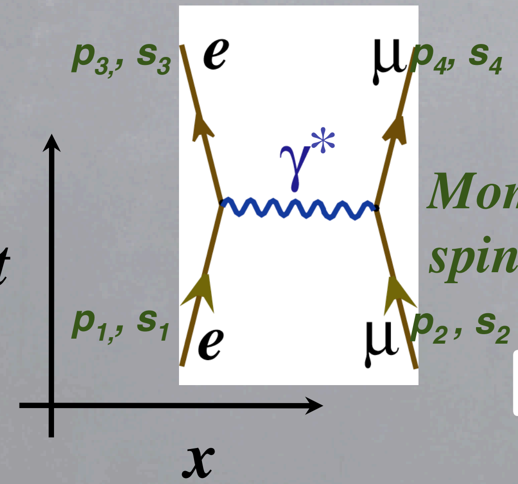

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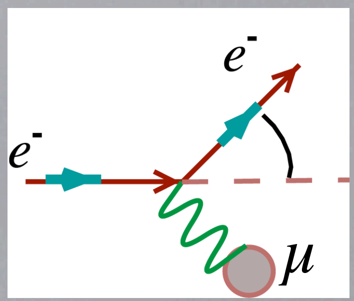
Heavy, spinless nucleus

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{4Z^2\alpha^2E^2}{q^4}$$



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Electromagnetic Probe of Hadron Matter

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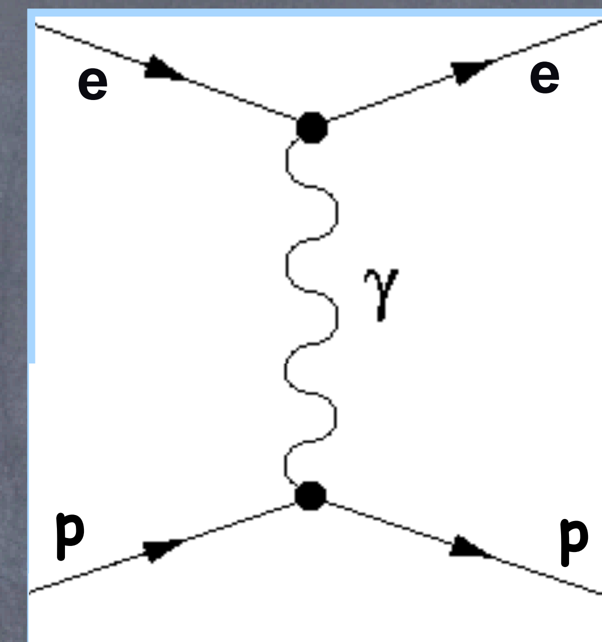
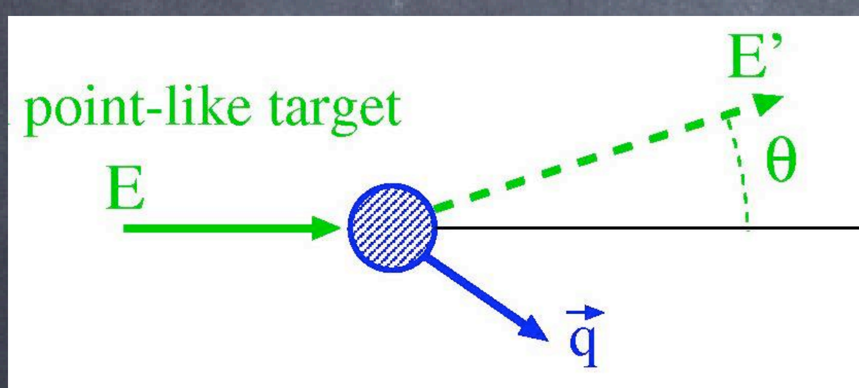


If photon carries low momentum -> long wavelength -> low resolution



$$Q \approx \frac{hc}{\lambda}$$

Q^2: 4-momentum of the virtual photon

Increasing momentum transfer -> shorter wavelength

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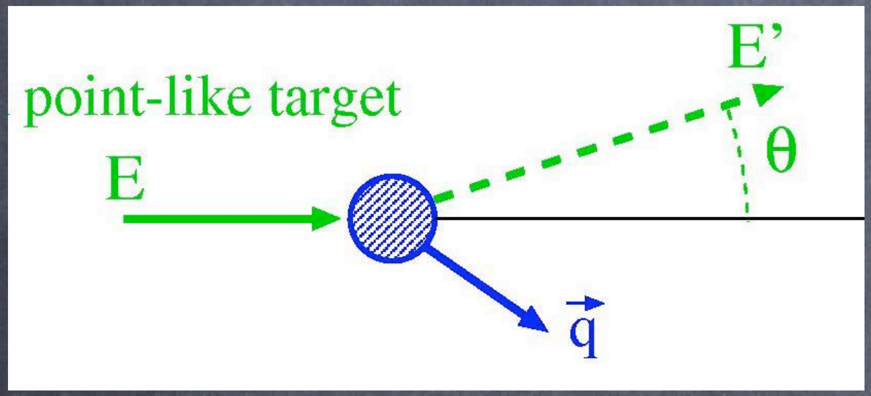

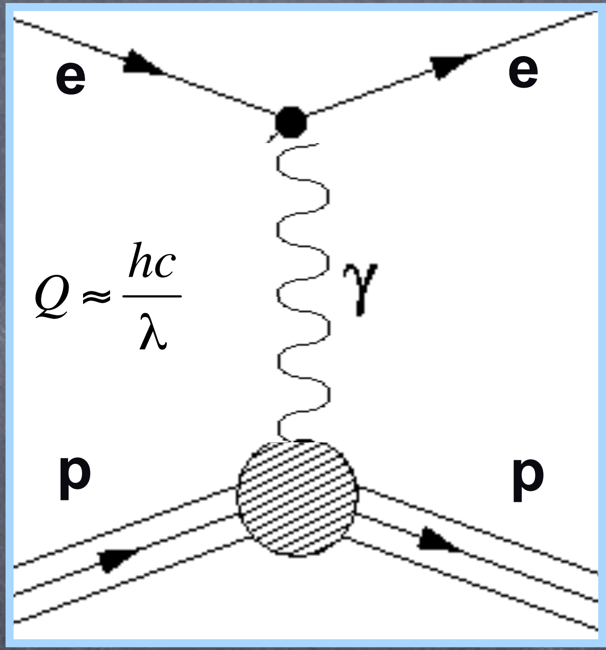

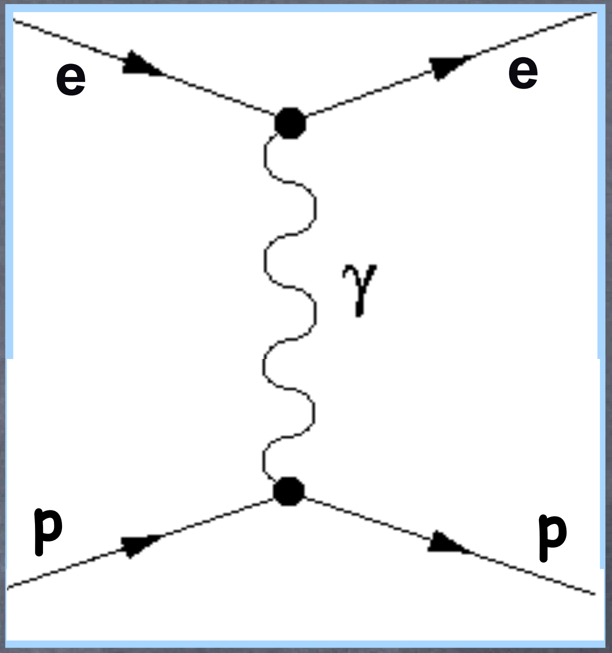

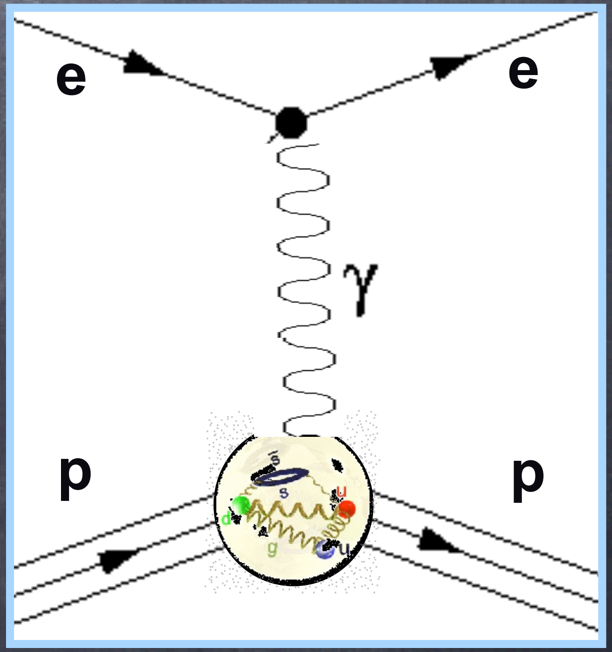

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Elastic e-p Scattering

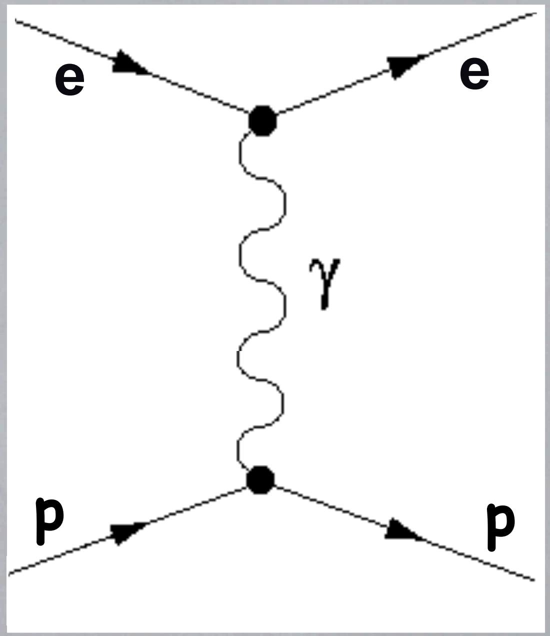
For a point-like target, accounting for target recoil:

Function of (E,θ).

Cross-section for infinitely heavy, fundamental target

τ=$Q^2/4M^2$ is a convenient kinematic factor

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\rm Mott} \left\{ 1 + 2\,\tau \tan^2(\theta/2) \right\}$$



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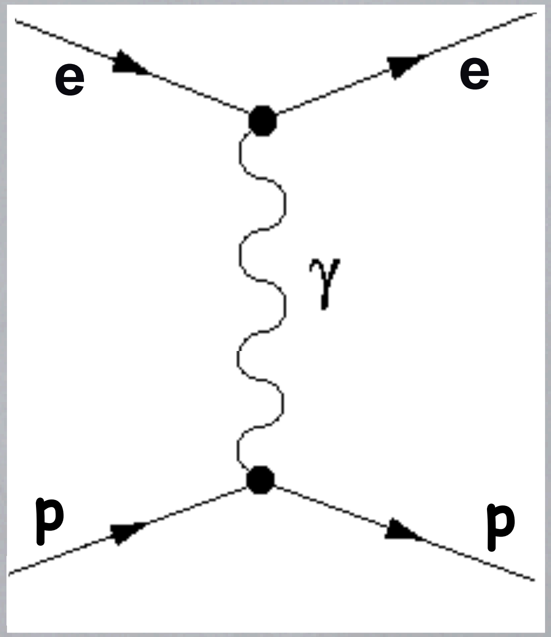

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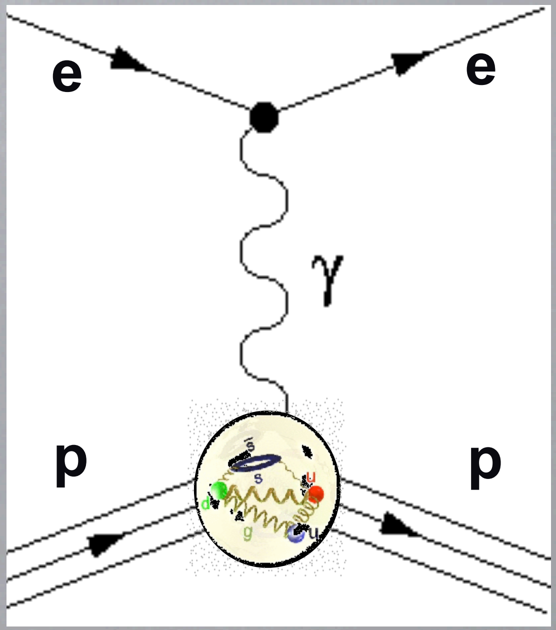
If proton is not point-like: The electric and magnetic form factors G_E and G_M parameterize the effect of proton structure.

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\rm Mott} \frac{E'}{E} \left\{\frac{(G_E^2 + \tau\, G_M^2)}{1+\tau} + 2\,\tau\, G_M^2 \tan^2(\theta/2)\right\}$$



If the proton were like the electron:

G_E = 1 (proton charge)

G_M = 1 (and the magnetic moment would be 1 Bohr magneton).

Finite Size of the Proton

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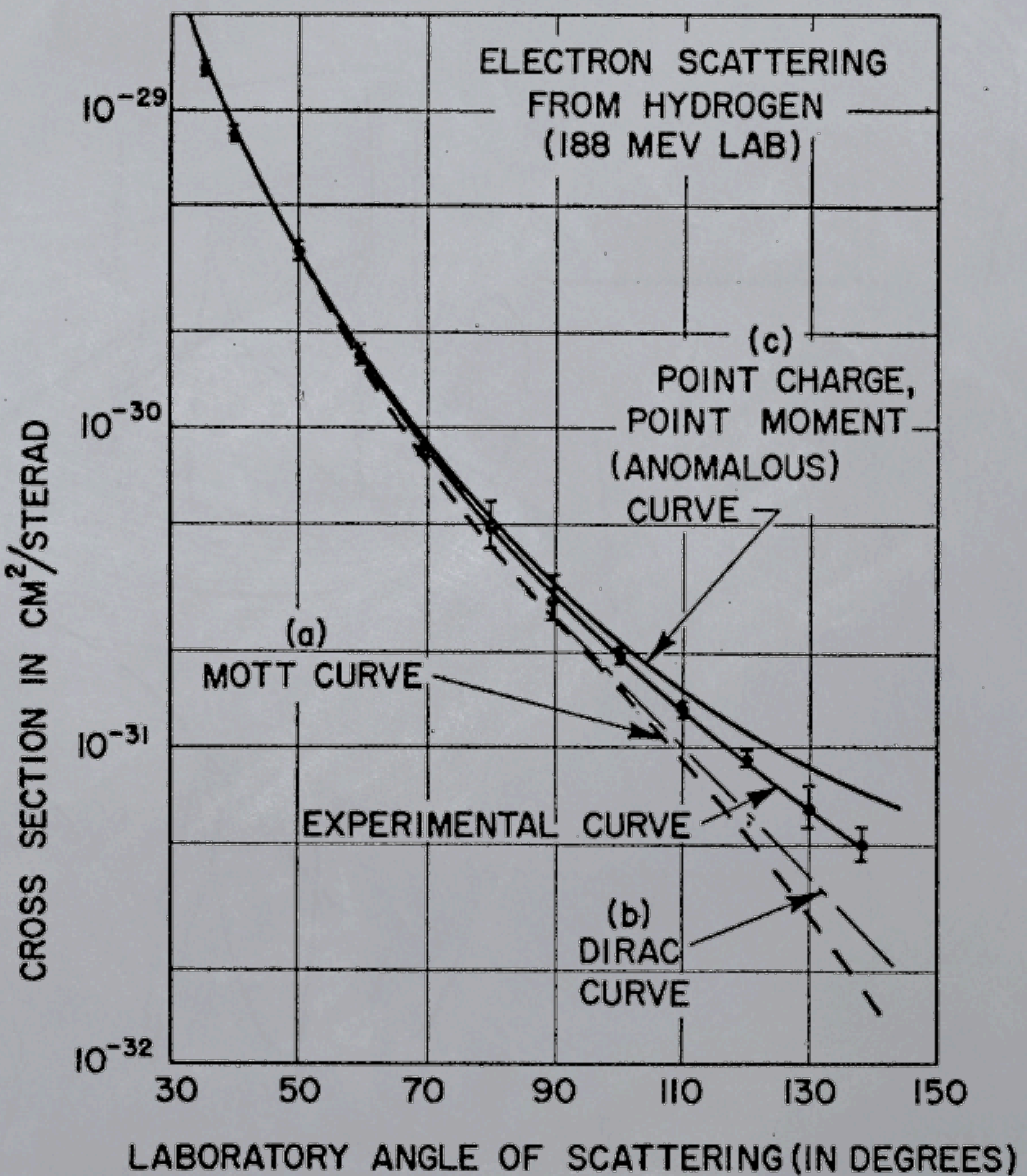

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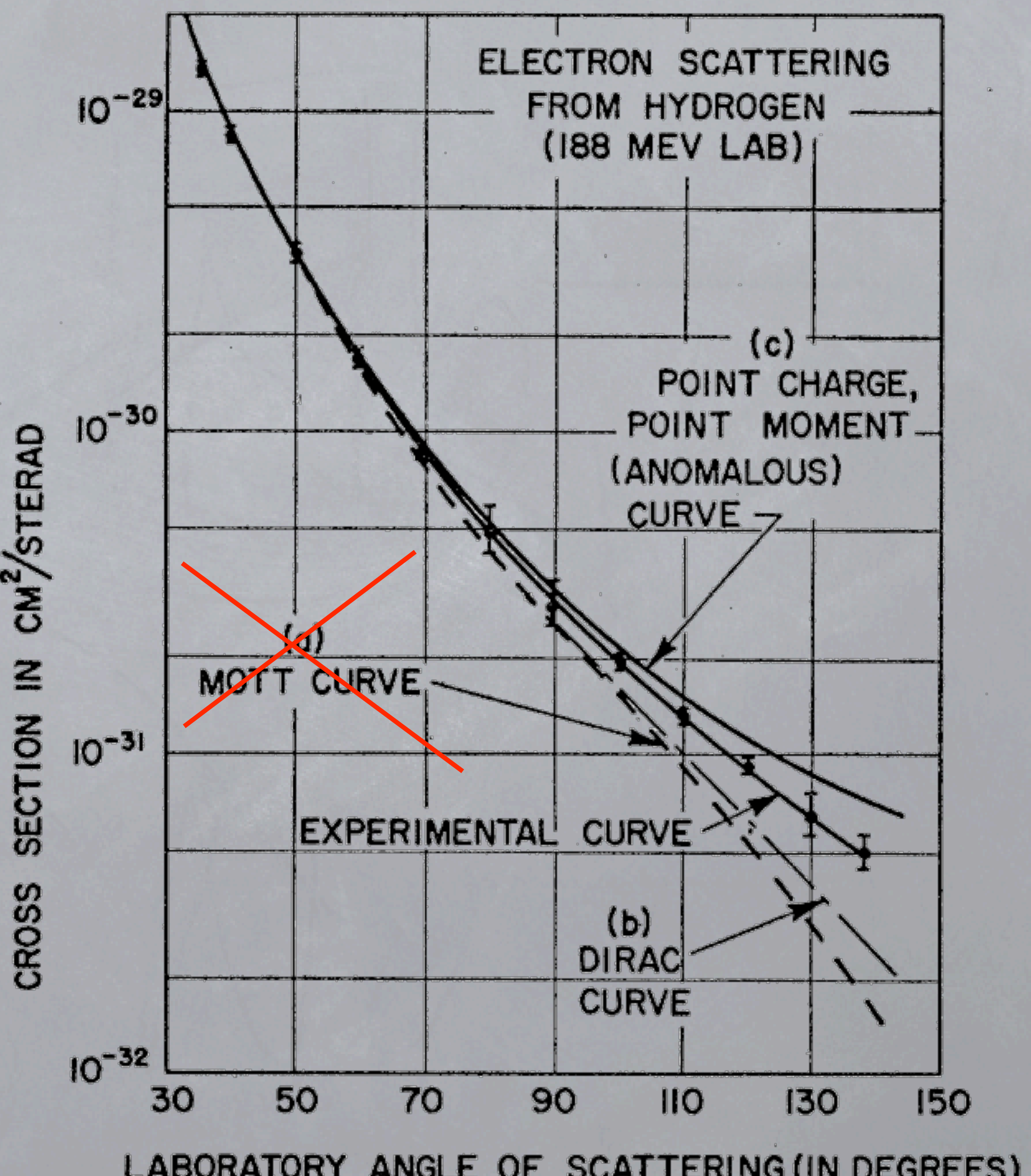

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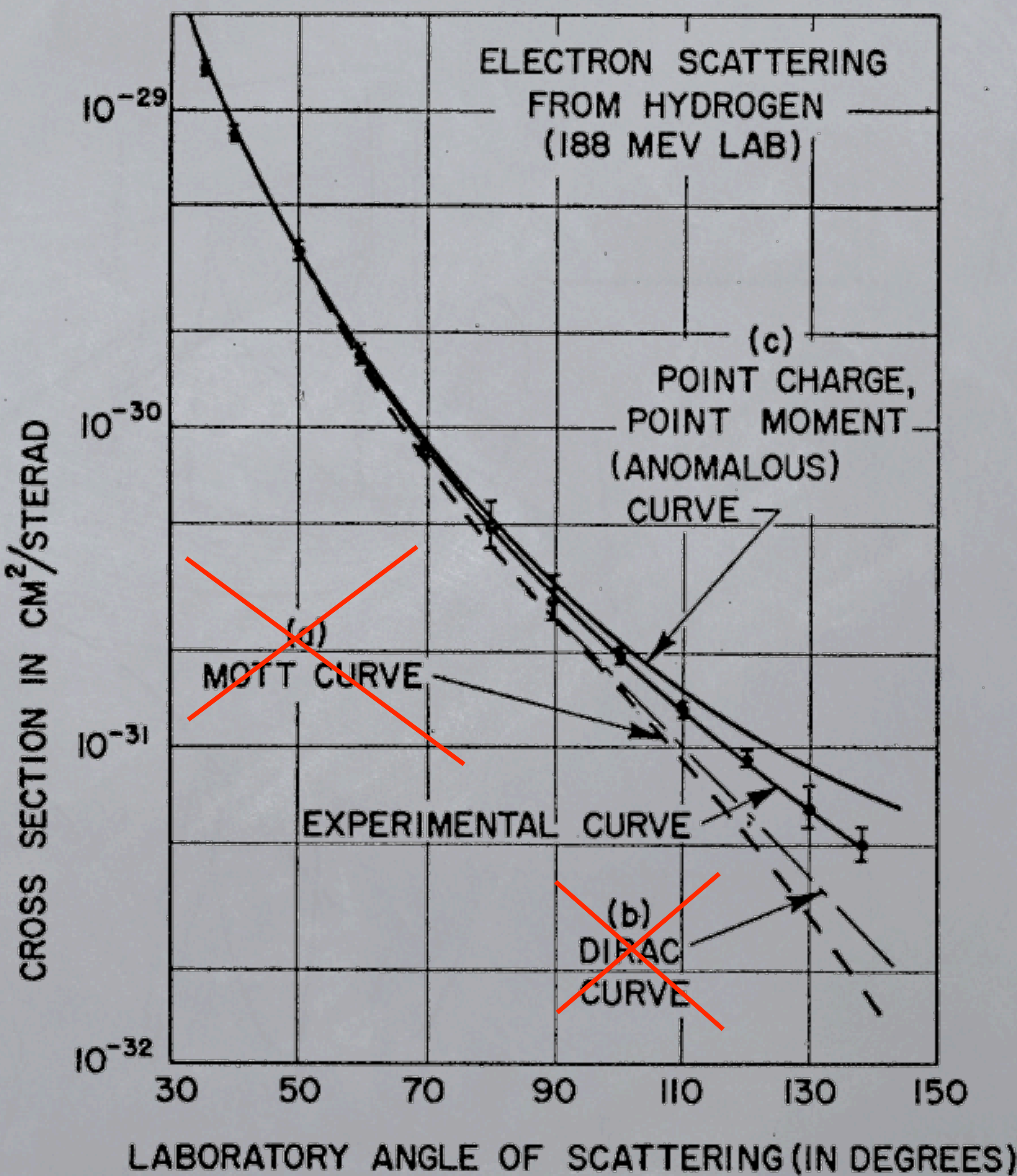

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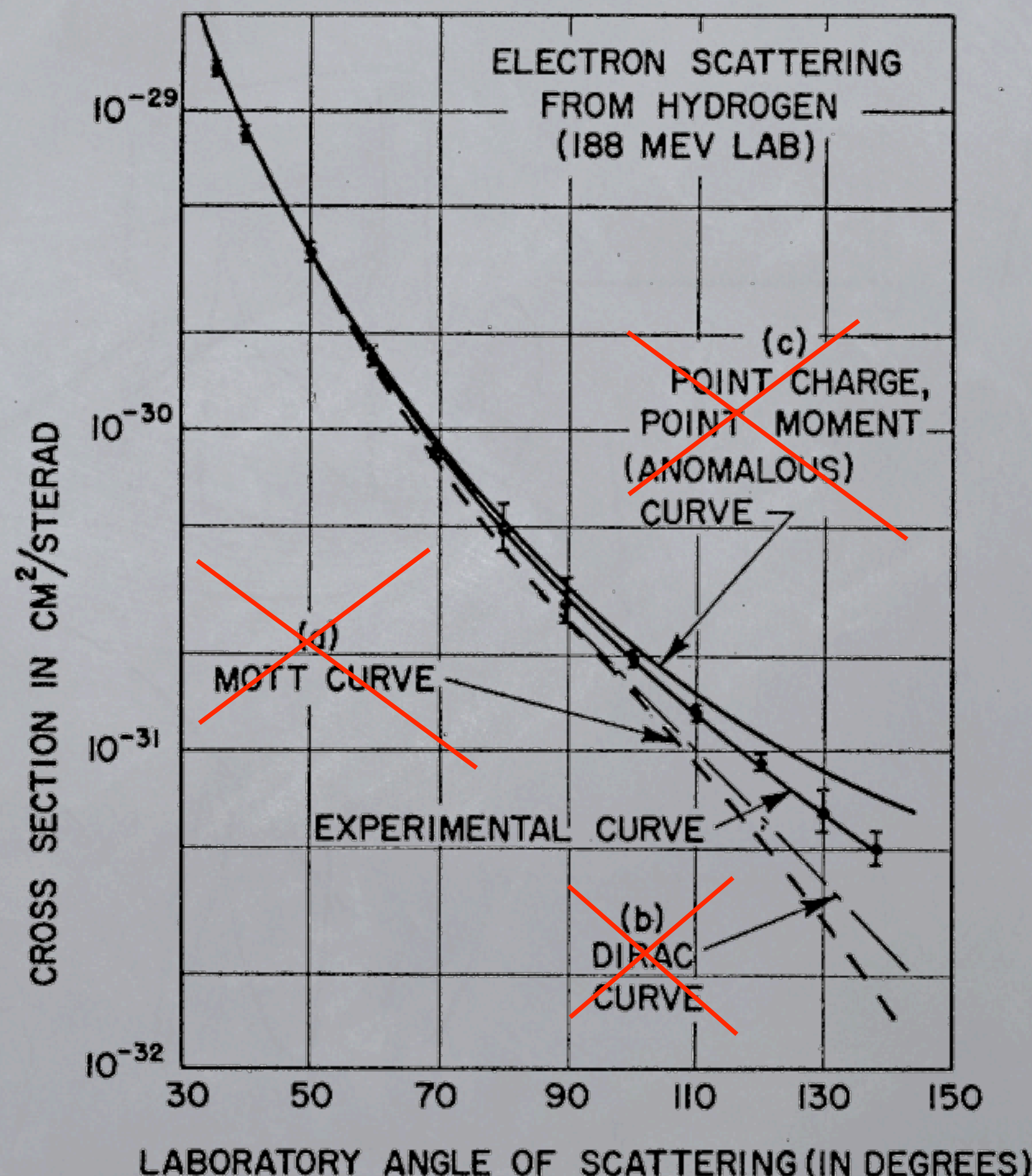

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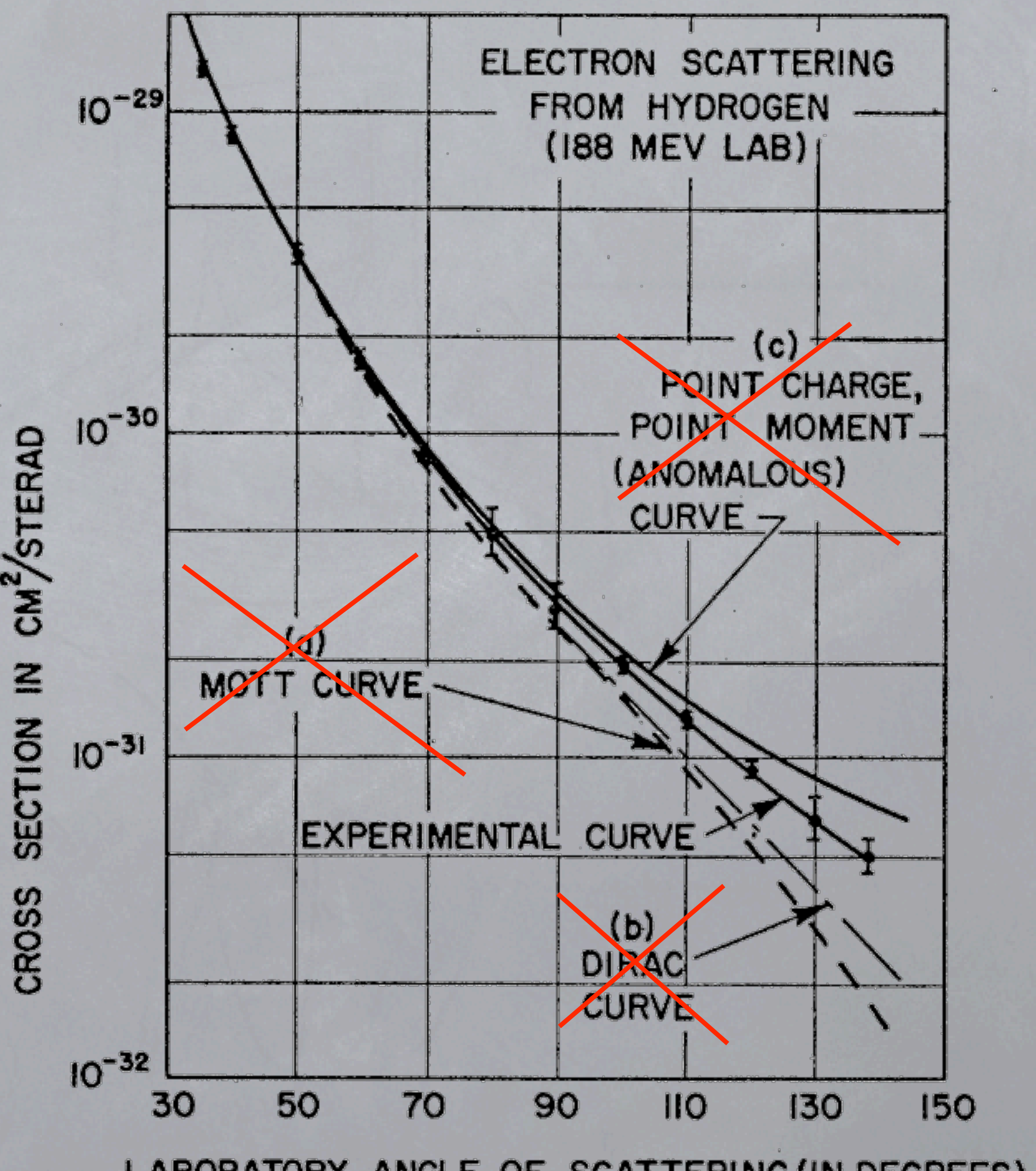

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Robert Hofstadter - Noble Laureate 1961

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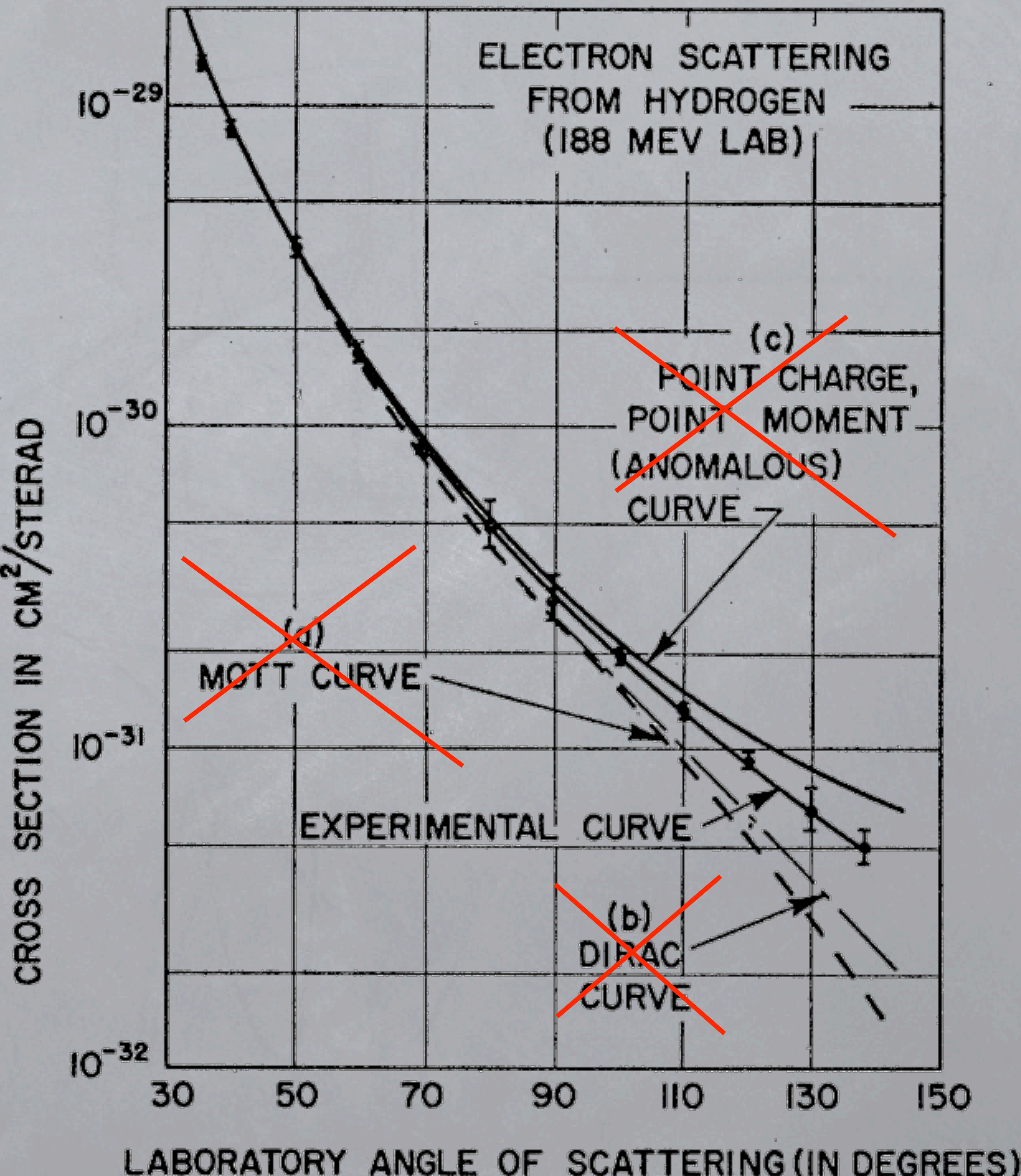


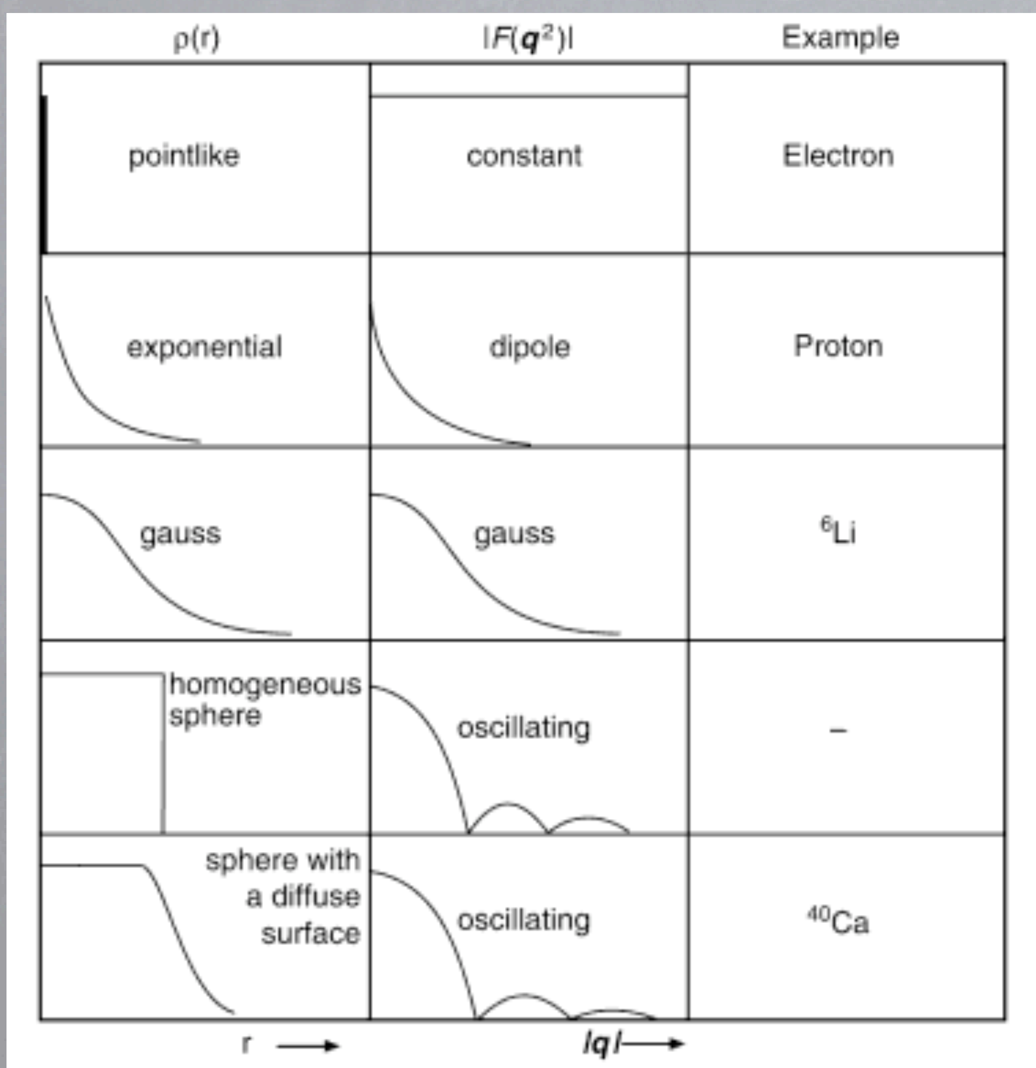
Nuclear Size

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left| F(q) \right|^2$$

The point-like scattering probability modified: account for Finite Target Extent with a "form factor"

$$F(q) = \int e^{iqr} \rho(r) d^3 r$$

Form factor is the Fourier transform of charge distribution



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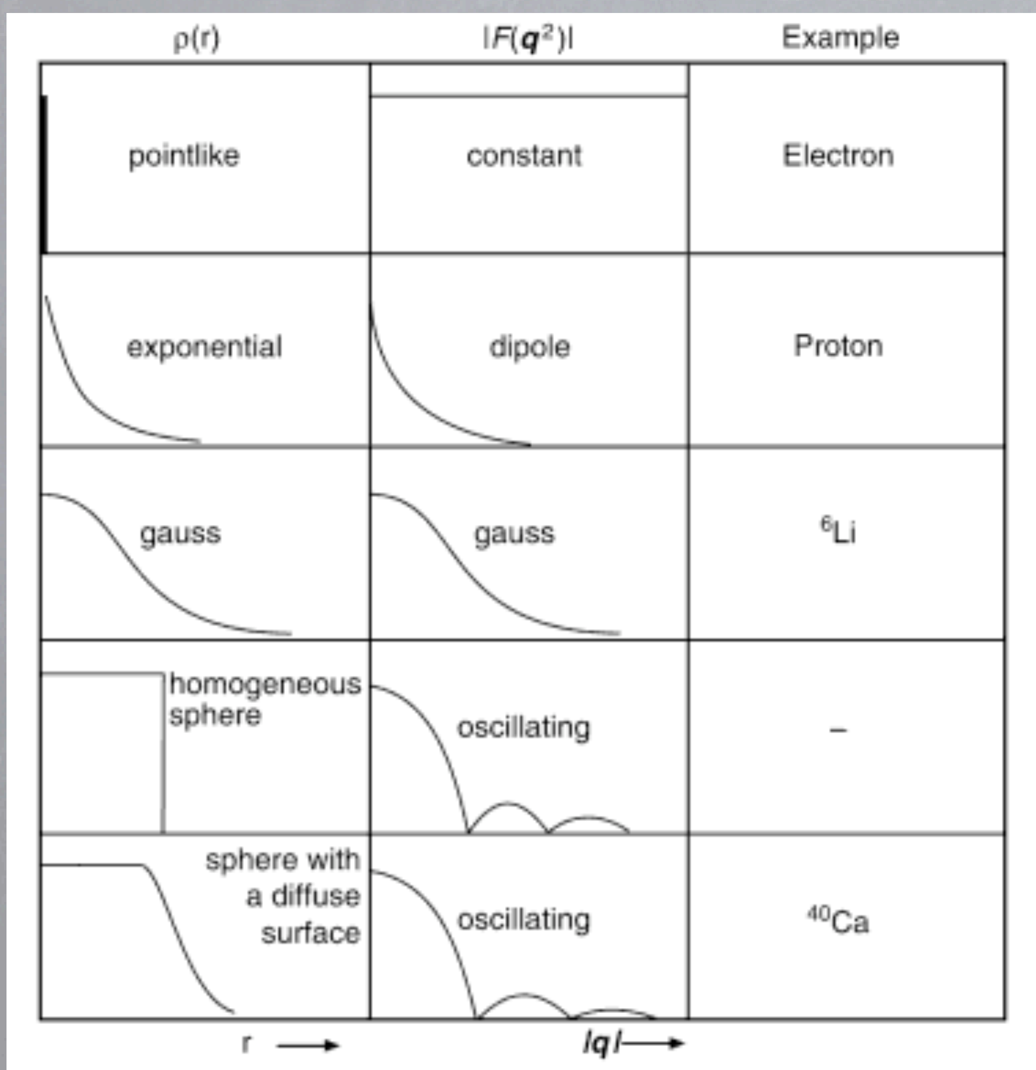

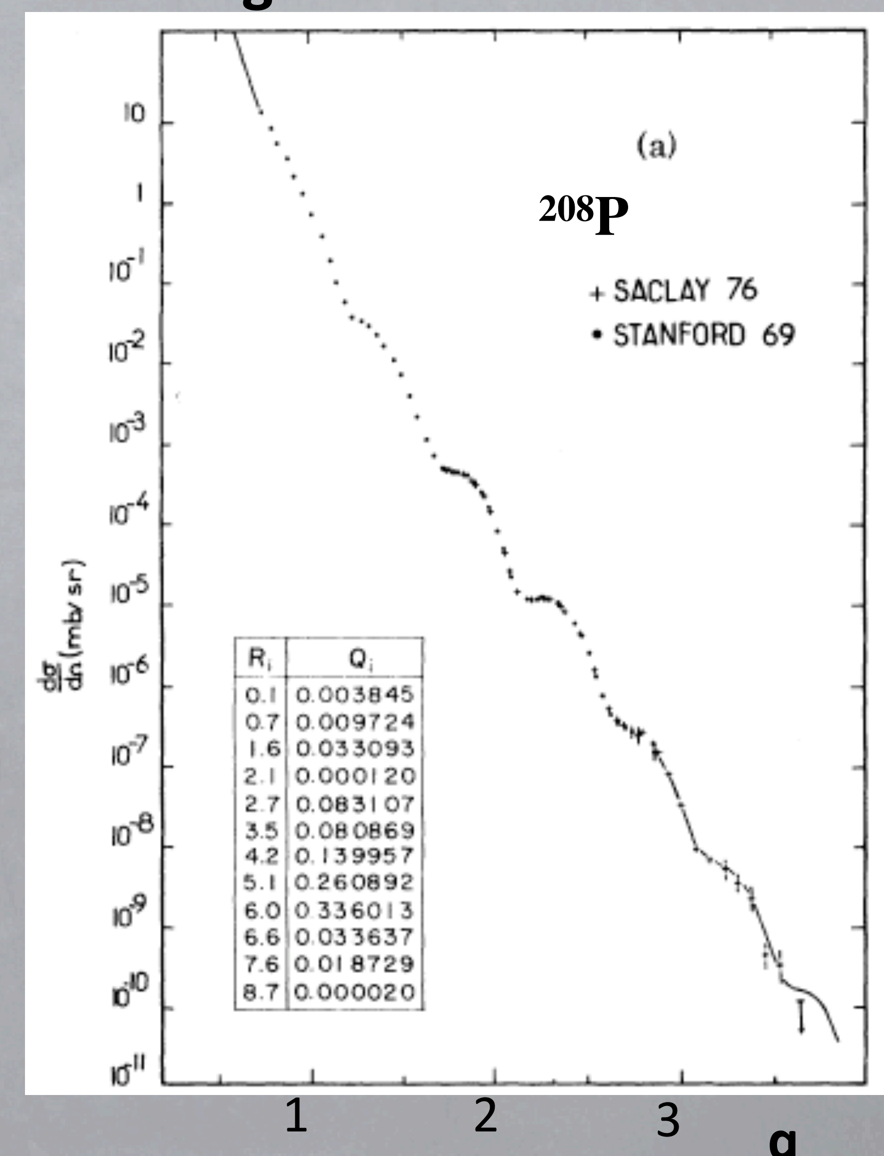

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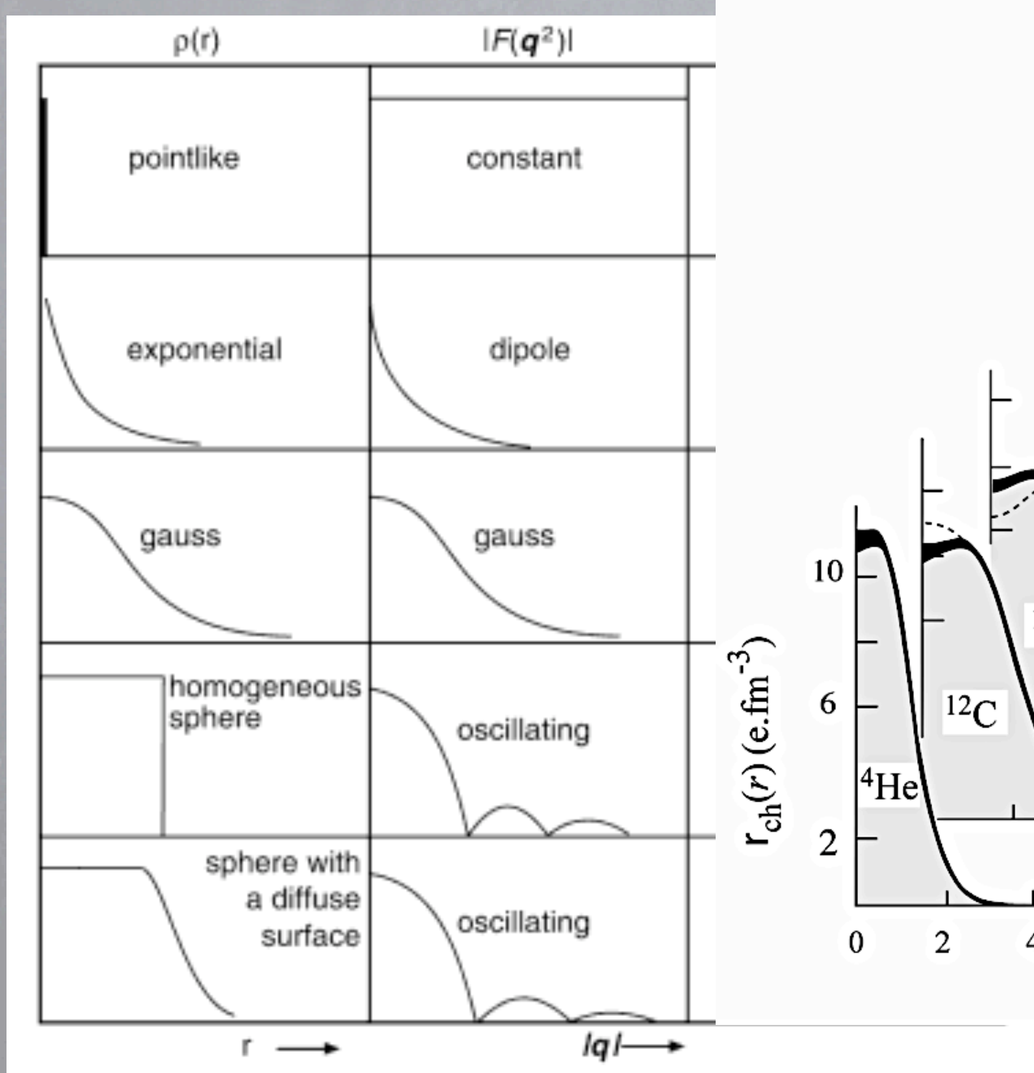

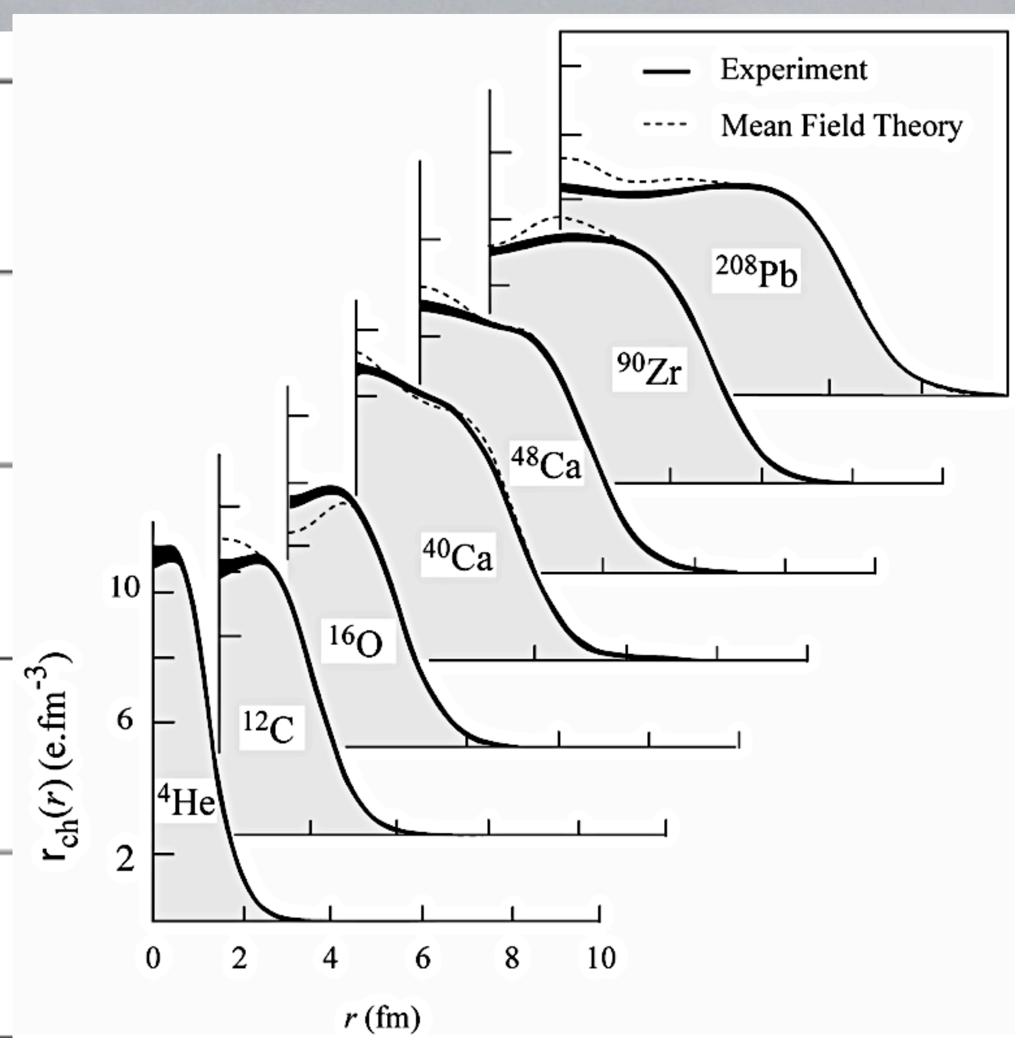

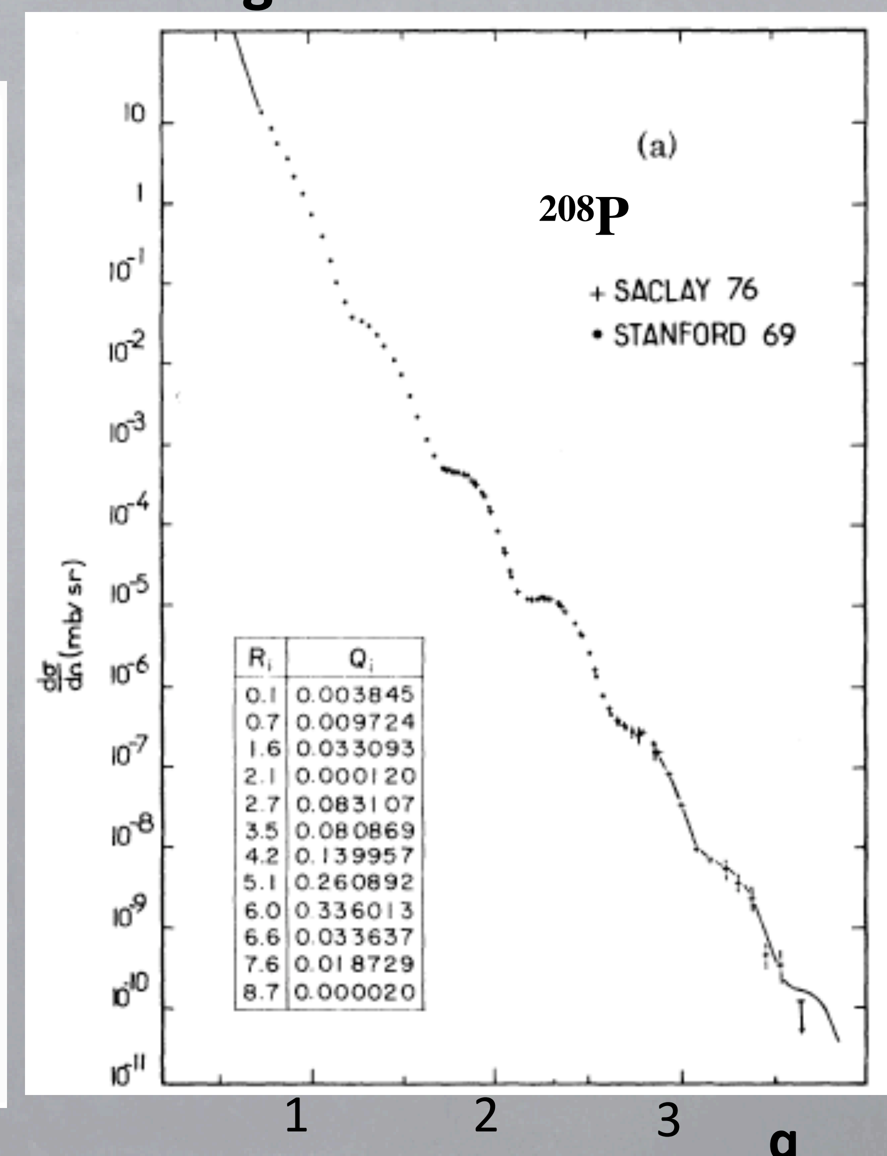

Parity-Violating Electron Scattering

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,

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

there exists an interaction

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

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.

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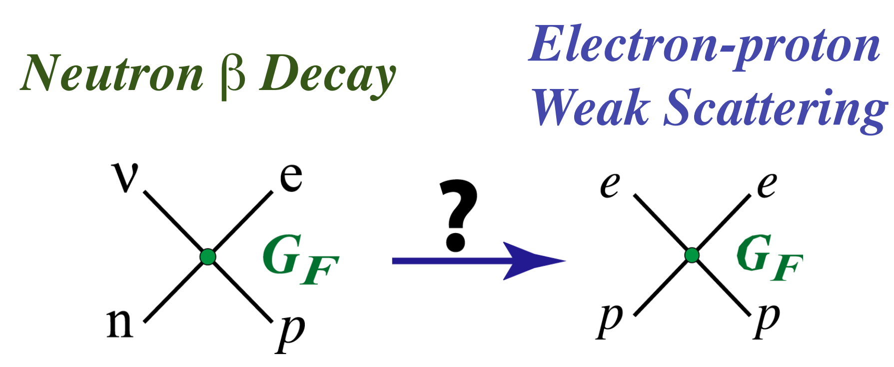

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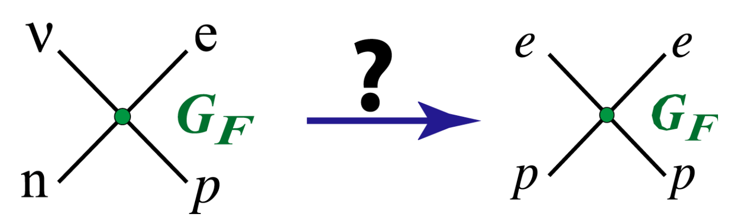
Neutron β Decay → *Electron-proton Weak Scattering*



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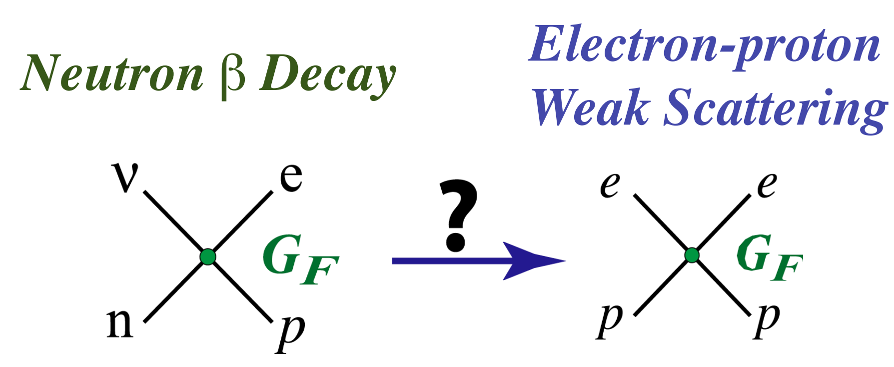

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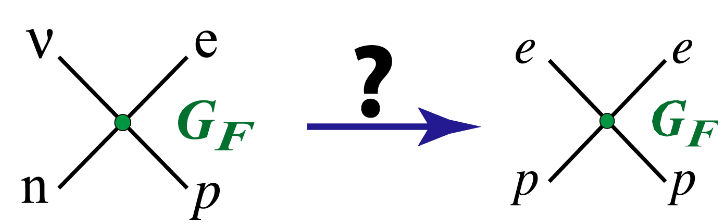

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$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -A_{LR}$$

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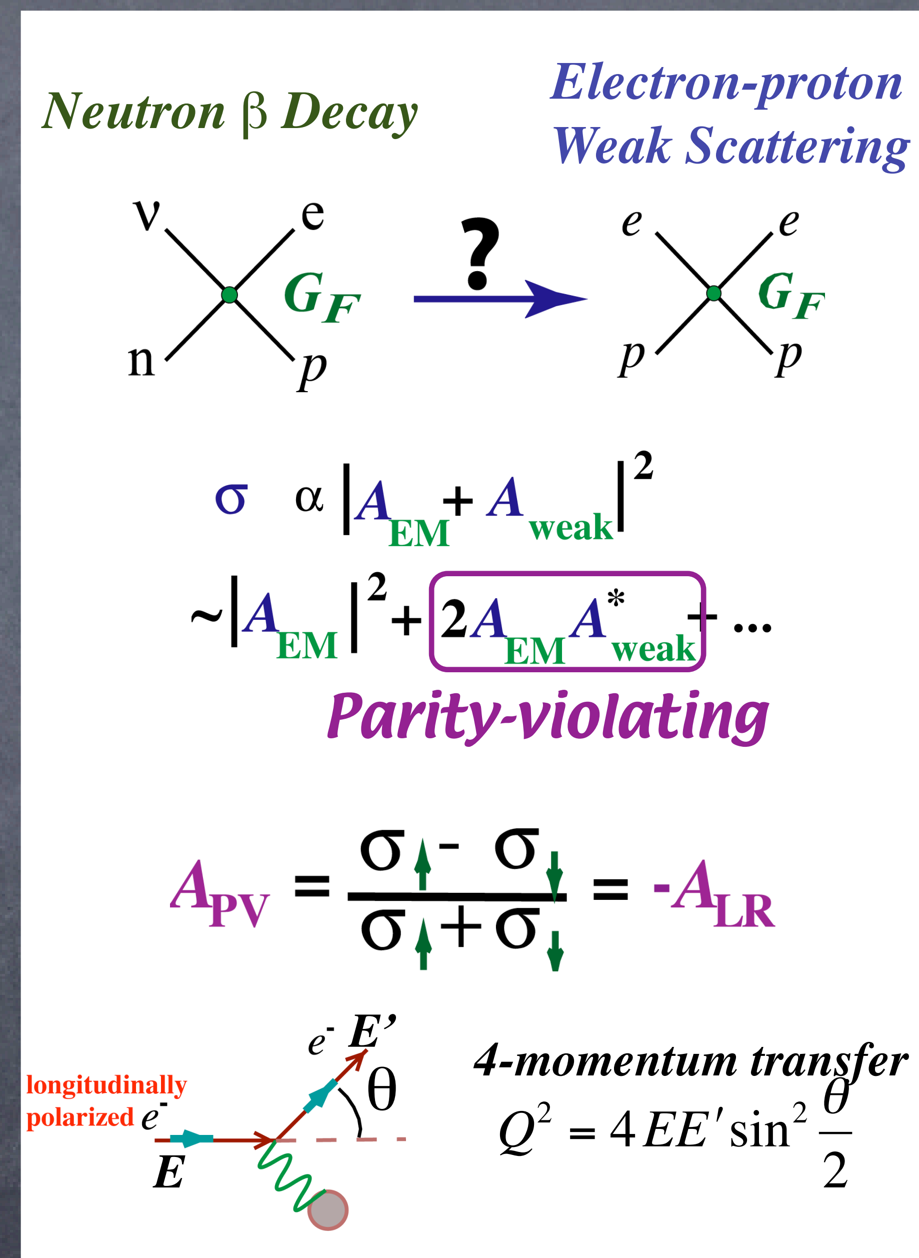
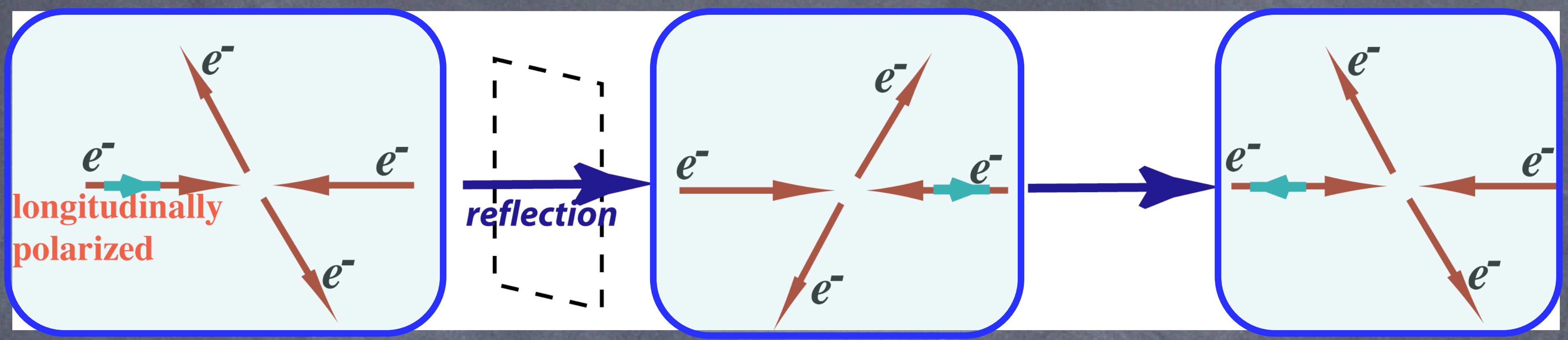


Observable Parity-Violating Asymmetry



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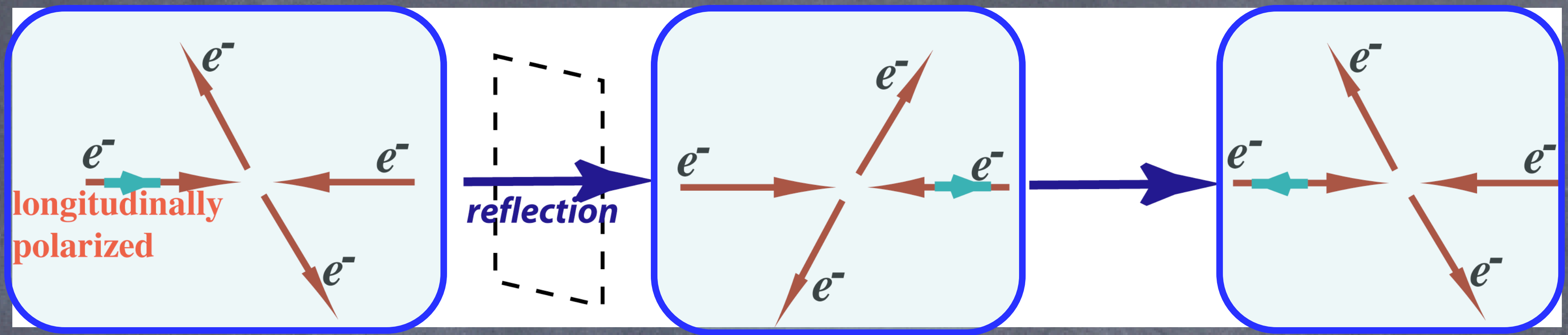

- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

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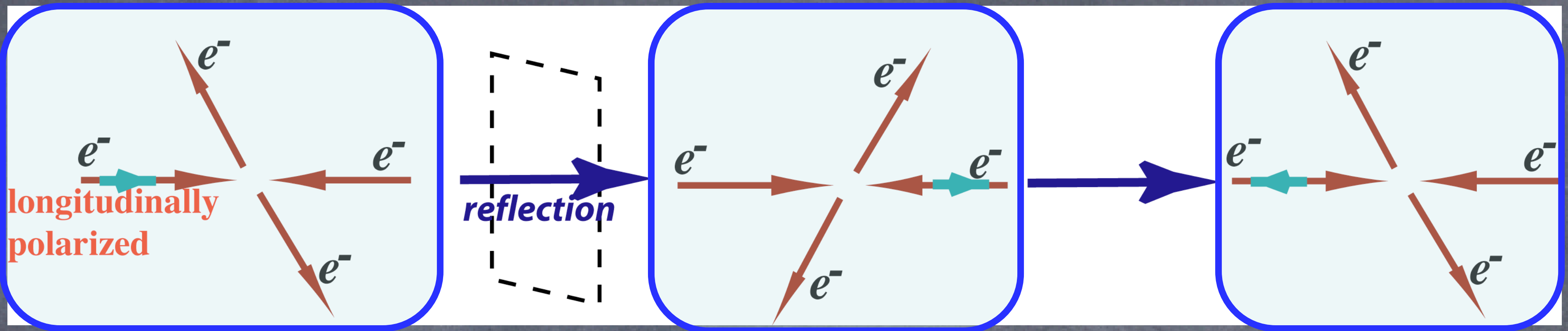

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The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, 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.

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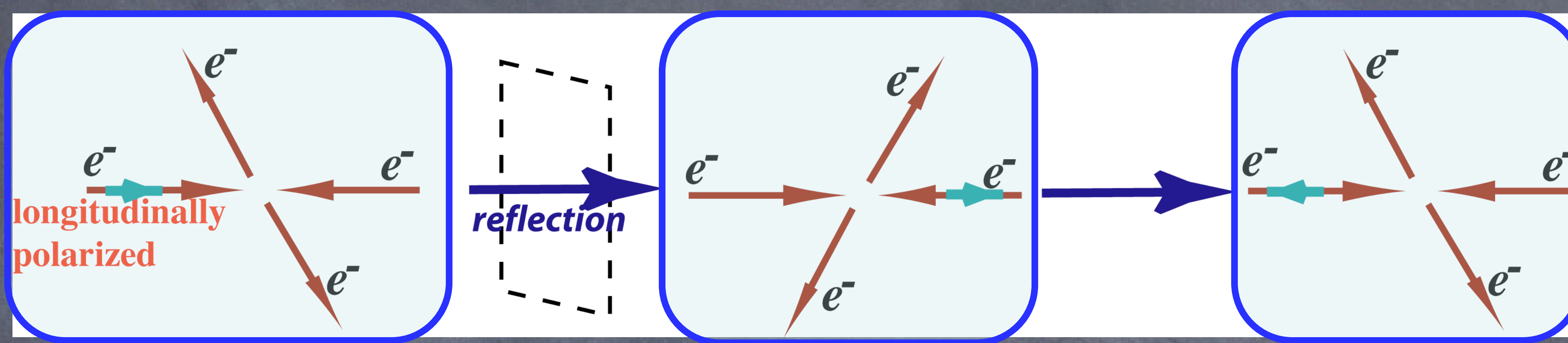

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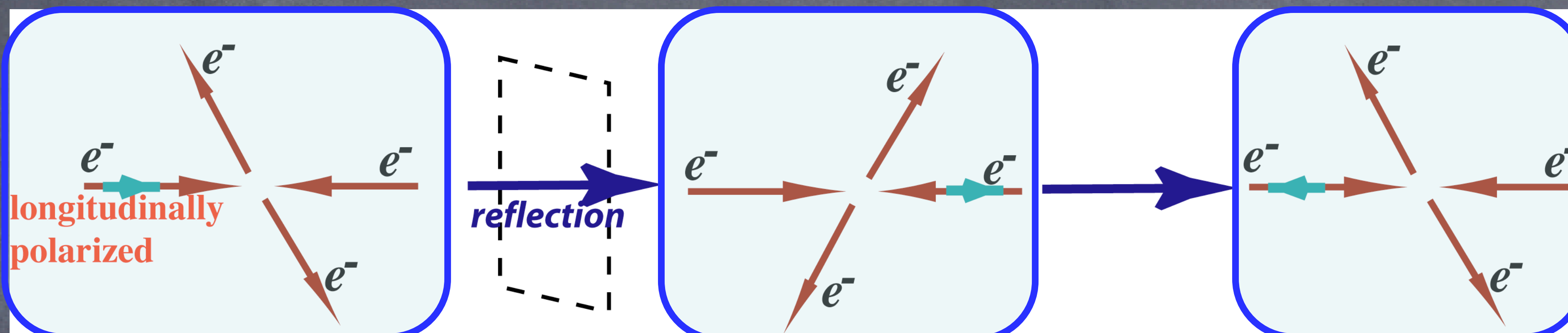

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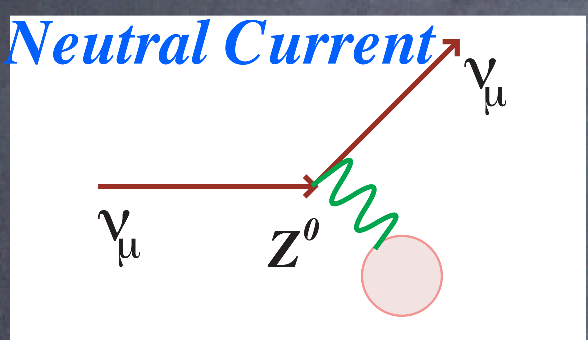
The idea could not be tested for 2 decades:
Several circumstances aligned to make this an important measurement

Weak Interaction Theory

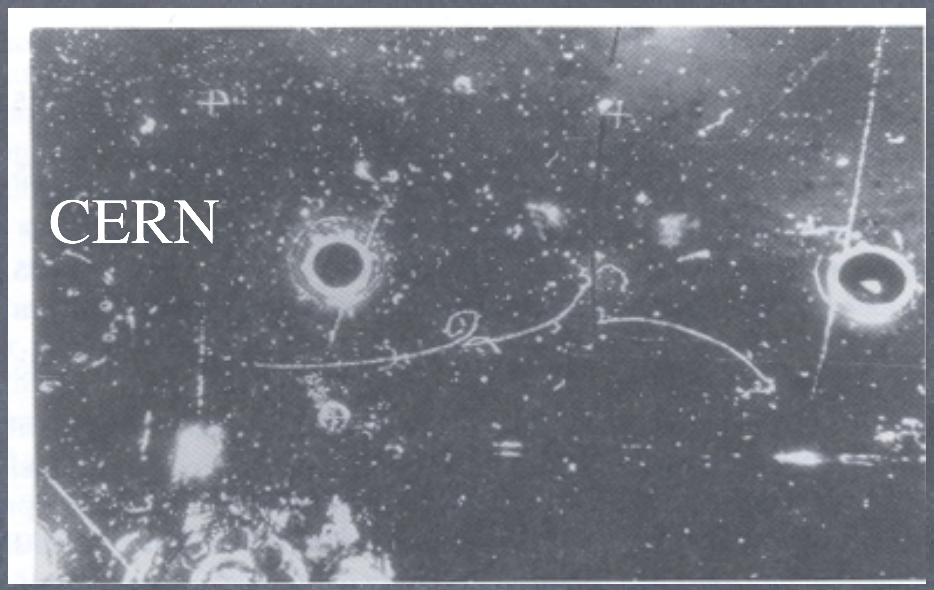
A Model of Leptons

Steve Weinberg - 1967

The Z boson incorporated



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



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	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$

30

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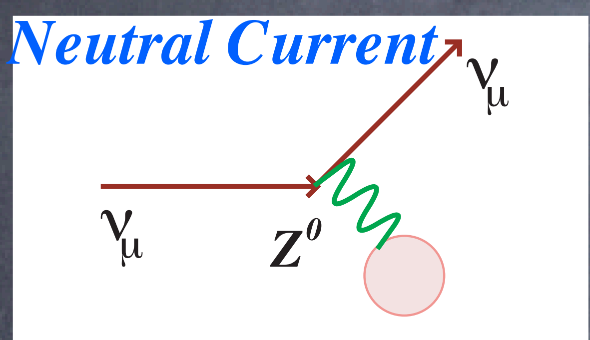

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Neutrino scattering measurements find θ_W is non-zero

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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

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

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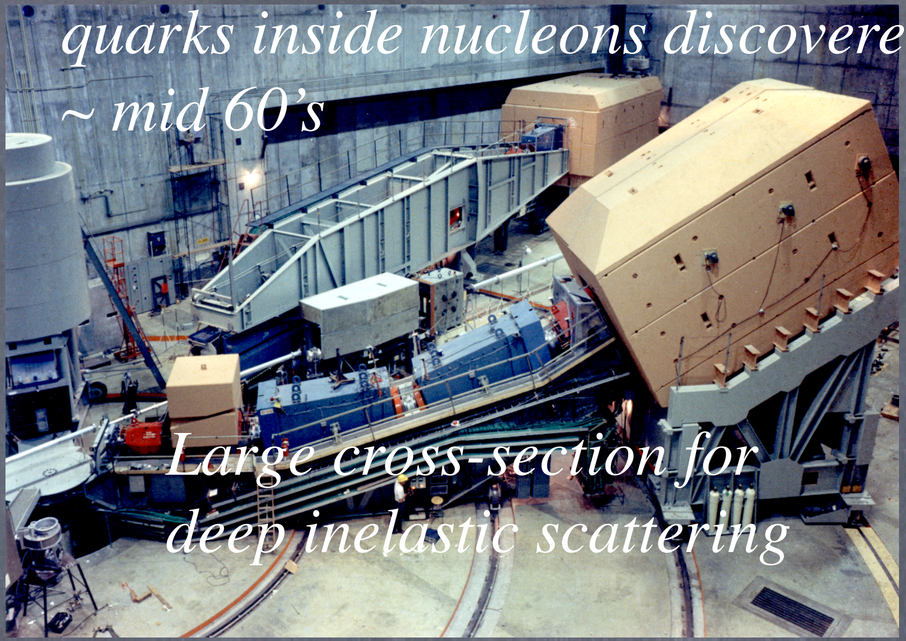

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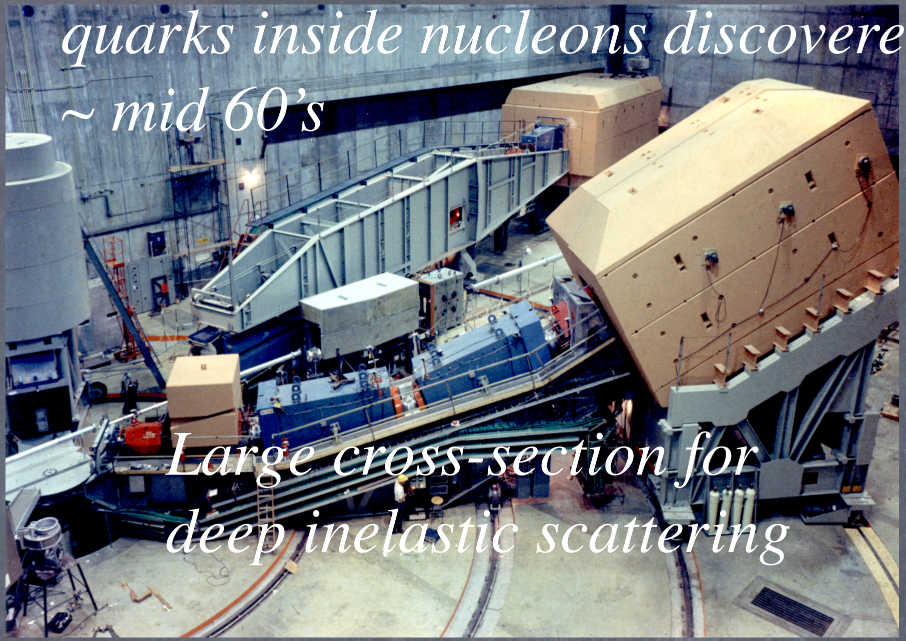

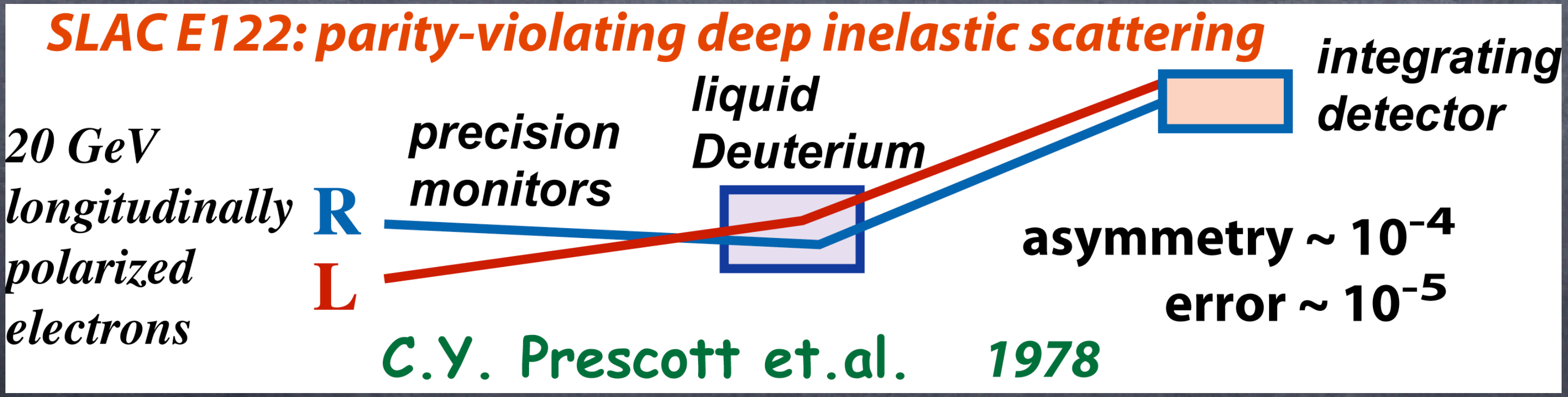

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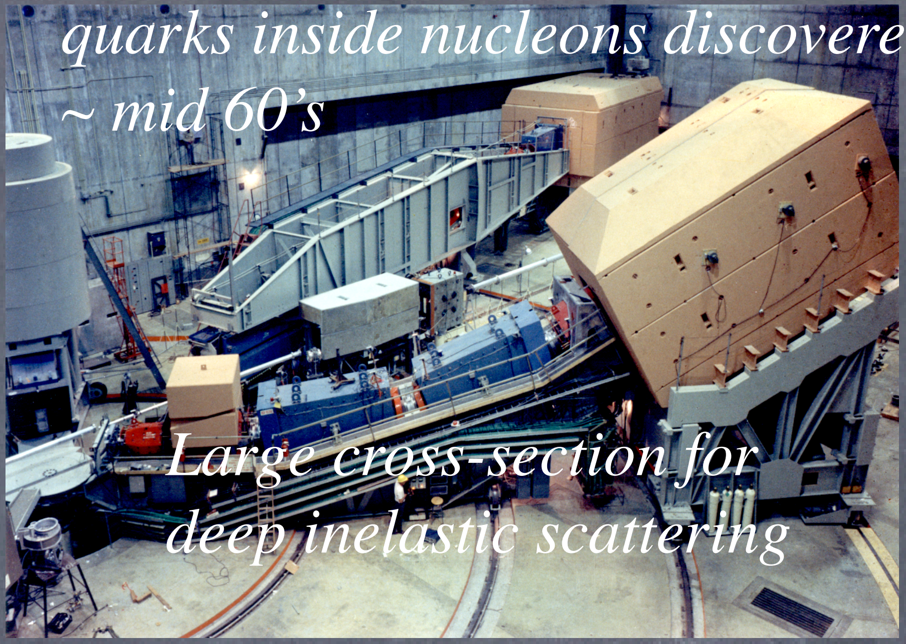

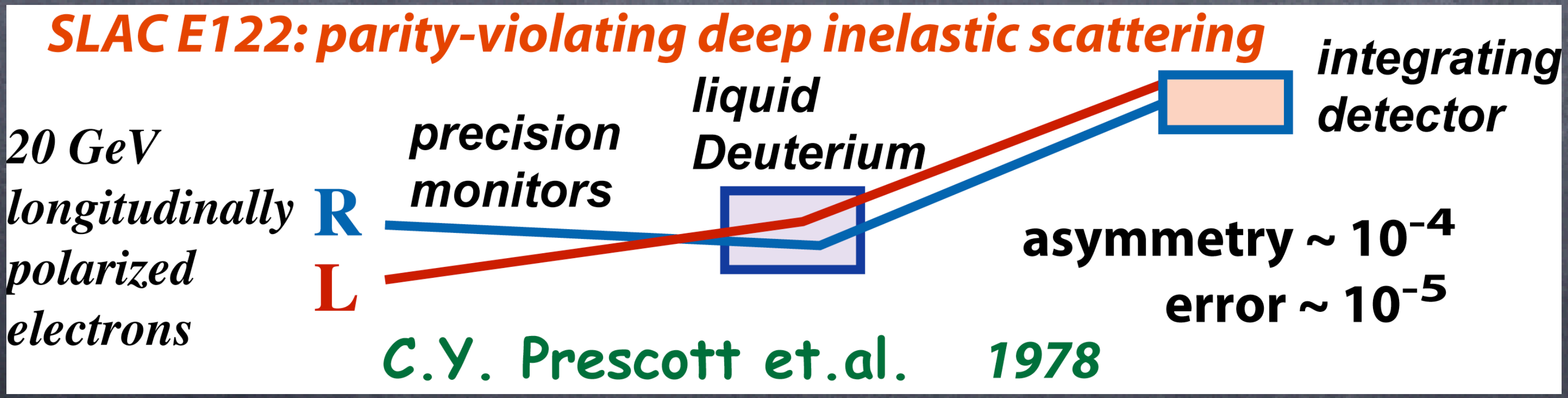

Final anchor for SU(2)XU(1):

Glashow, Weinberg, Salam awarded the 1979 Nobel Prize

Summary

- A very successful theoretical framework exists to describe electroweak interactions over a wide range of energy scales
- Neutral weak interactions can be used to probe novel aspects of hadron structure
- Parity-violating electron scattering is the ideal tool to probe low energy neutral weak interactions

Lecture 2 Overview

- Strange Quark Content of the Nucleon
- The HAPPEX and HAPPEXII experiments
- The Neutron Skin of a Heavy Nucleus
- The PREX Experiment
- Future Program of Parity-violating Electron Scattering