Physics 225A → "Discovery in Experimental Particle Physics"

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5103 Broida – Office Hours to be determined

Pre-Reqs: • U.G. Physics Degree
• Ability to research in library online
• Desire to make experimental discovery

Context: Experimental Particle Physics is at a Transition:

Either: Great Discoveries at the CERN (European Laboratory of Particle Physics in Geneva, Switzerland)
→ at least H^0, "Standard Higgs"
→ Supersymmetry
→ at most, "paradigm shift"

History : ~1890 → 1950 "Natural Science" era of particle physics

→ small teams
→ truly remarkable discoveries
- structure of matter (Rutherford - Bohr Atom)
- antimatter
- weak interaction (Parity violation ~1957)

1950 → present : "Big Science" era

→ influence of Manhattan Project
→ big teams, $
→ SSC (Cancelled) then LHC are culmination
→ future depends on LHC results.

Future → Return to "Natural Science," or more "Big Science".

In either case, an emphasis on "How to discover" is appropriate (Probably always true in E.P.P.).

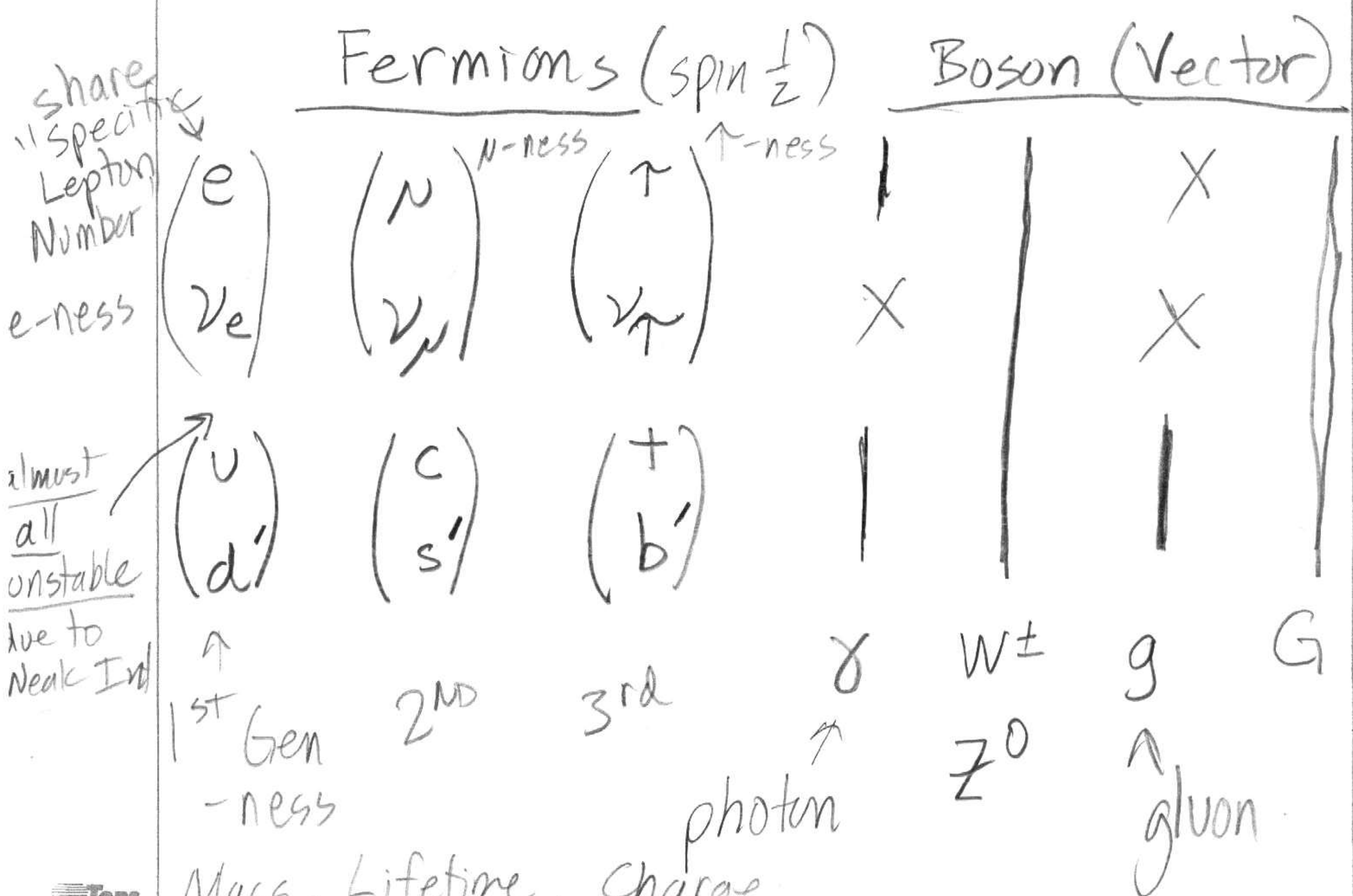
Outline: Intermingle overviews with case studies

~~Case St.~~	~~Overview~~ Overviews
Electron Discovery	
	Magnetic Spectrometry
	Calorimetry
Proton	
	Scattering
Neutron	
Positron	Bremmstrahlung
Muon	
	Integrated Exp.
Pion	↓
Resonances	
Particle/Antiparticle Mixing	
2ν	

Course Requirements:

- → Class Attendance
- → Occasional Problem Sets (~5)
- → 15' presentation in last week or 2 of quarter
- → Willingness to skeptically question.

First Overview:



Mass, Lifetime, Charge.

All have **mass**, in HEP,

$mc^2 \rightarrow 10^6$ electron-volts
$= MeV$

$10^9 \rightarrow GeV$

Dealt with in various ways...

e: $m_e c^2 = 0.511$ MeV

$m_e = 0.511$ MeV/c^2

or: $c = 1$ and $m_e = 0.511$ MeV

measure (?)

Recall $E = \sqrt{(mc^2)^2 + (cp)^2}$

not thought of as "interesting"

so, cp also has units of energy, or...

$p \rightarrow$ MeV/c, GeV/c

All have **mean lifetimes** τ

Probability of survival... $P(t)$

$$dP = -P \frac{dt}{\tau}$$

equality of dt

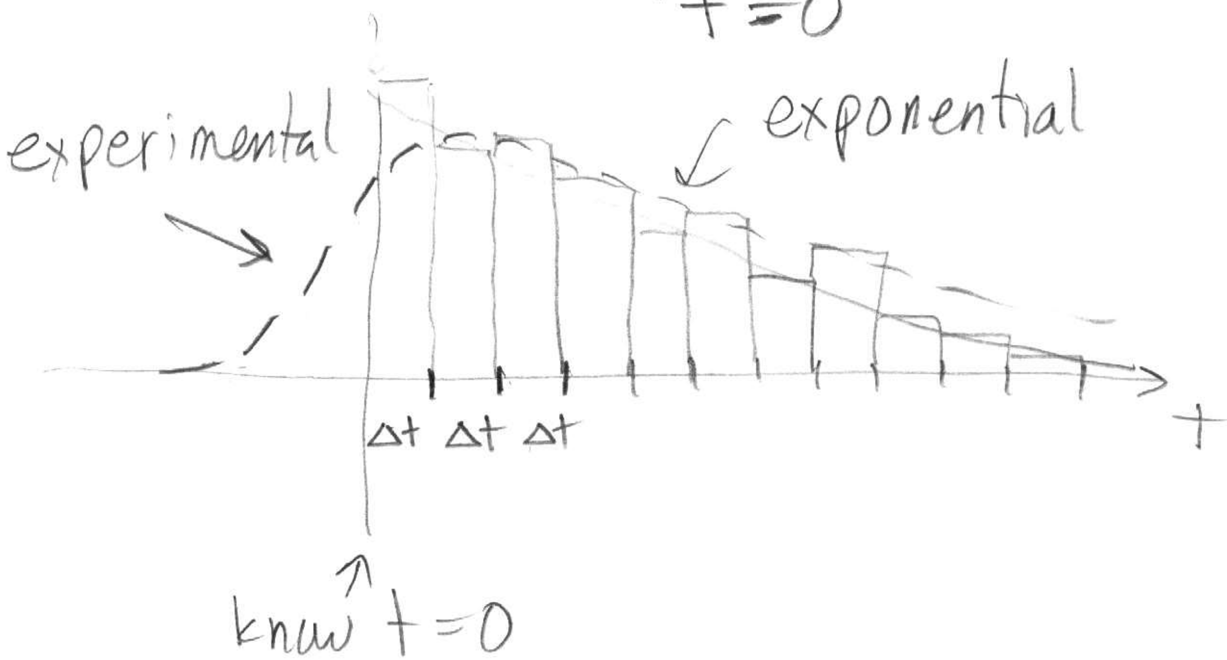
$$P = e^{-t/\tau}$$

TOPS

$$\langle t \rangle = \frac{\int t P \, dt}{\int P \, dt} = \frac{\tau^2 \int_0^\infty z e^{-z} dz}{\tau \int_0^\infty e^{-z} dz}$$

$$\langle t \rangle = \tau$$

Experimentally, often know instant of birth... "t = 0"



Repeatedly make particle at t = 0, measure decay time, "bin it" in a "histogram"

- Can measure exponential slope
- "smearing" → "fair" function, doesn't change mean.
- slope ≈ independent of start time

Lifetimes generally more interesting than masses... lifetimes tell you about the...
various CHARGES of the fermions.
(so do scattering cross sections)
Must "correct out" effects due to the masses. CHARGES → "more interesting" than masses

Masses

$$\begin{pmatrix} 0.511_e \\ \otimes_{\nu_e} \end{pmatrix} \begin{pmatrix} 106_\mu \\ \otimes_{\nu_\mu} \end{pmatrix} \begin{pmatrix} 1780_\tau \\ \otimes_{\nu_\tau} \end{pmatrix} \text{MeV}$$

$$\begin{pmatrix} \sim 2_u \\ \otimes_{d'} \end{pmatrix} \begin{pmatrix} \sim 1300_c \\ \otimes_{s'} \end{pmatrix} \begin{pmatrix} \sim 174{,}000_t \\ \otimes_{b'} \end{pmatrix} \text{MeV}$$

→ Precise masses difficult because of complications of gluons.

⊗ → means the "partner" of the top row is.....

NOT AN EIGENSTATE OF THE "TOTAL" HAMILTONIAN.
aka MASS

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} |\nu_i\rangle$$

ν_1, ν_2, ν_3

↑ called the "MNS Matrix" lots of interest

↖ "mass" eigenstates ⇒ "Higgs"

etc for ν_μ

$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle$$

"CKM" matrix

"mass" eigenstates

$m_d c^2 \sim 5$ MeV

$m_s c^2 \sim 100$ MeV

$m_b c^2 \sim 4.5$ GeV
(confused by)

Lifetimes

$e^- \rightarrow$ stable (?) charge cannot go to lower energy (mass) state

ν's $\rightarrow$ stable (?)

$\mu^- \rightarrow$ $\boxed{\tau_\mu \rightarrow 2.20\ \mu s}$

→ used to determine the "weak charge"

$c\tau_\mu \cong 659$ m (≈ 1 km)

∴ in most experiments, ($\lesssim 10$m)

μ is effectively "stable"

$\tau^- \rightarrow \tau_\tau \rightarrow 0.291$ ps (10^{-12} s)

tests "universality" of weak charge

$c\tau_\tau \simeq 87\ \mu m$

∴ in most experiments, τ's decay inside

→ Huge effort starting ≃ 1985 to see τ lifetime u, d, s, c, b, t always unstable

↳ all <u>can</u> be unstable!

key question... is there a <u>lower</u> mass (rest energy) state available

→ <u>More Later</u> { Hadrons < Baryons, Mesons

$\boxed{\gamma, g, G}$: mass ≡ 0 (big, big deal)

dealing this very hard

$W^\pm$: mass ≃ 80.4 GeV

Z^0 : mass ≃ 91.2 GeV

$$\theta_W \simeq \cos^{-1}\left(\frac{m_{W^\pm}}{m_{Z^0}}\right)$$

↳ Weak or Weinberg Angle

<u>θ_W</u>: mixing angle between fields that make up γ, Z^0.

$\tau_{W^\pm}$, τ_{Z^0} so small,
time-energy uncertainty principle.

$$\Delta \tau \sim \hbar$$

$$\Delta E\,(c\tau) \sim \hbar c = \underline{197 \text{ MeV-fm}}$$

$$\Delta E \sim \frac{197}{c\tau} \text{(MeV-fm)} \quad (200)$$

or visa versa

ΔE: Γ or Full Width at Half Max

$\underline{Z^0}$: (Plot) — Fantastically Well Measured

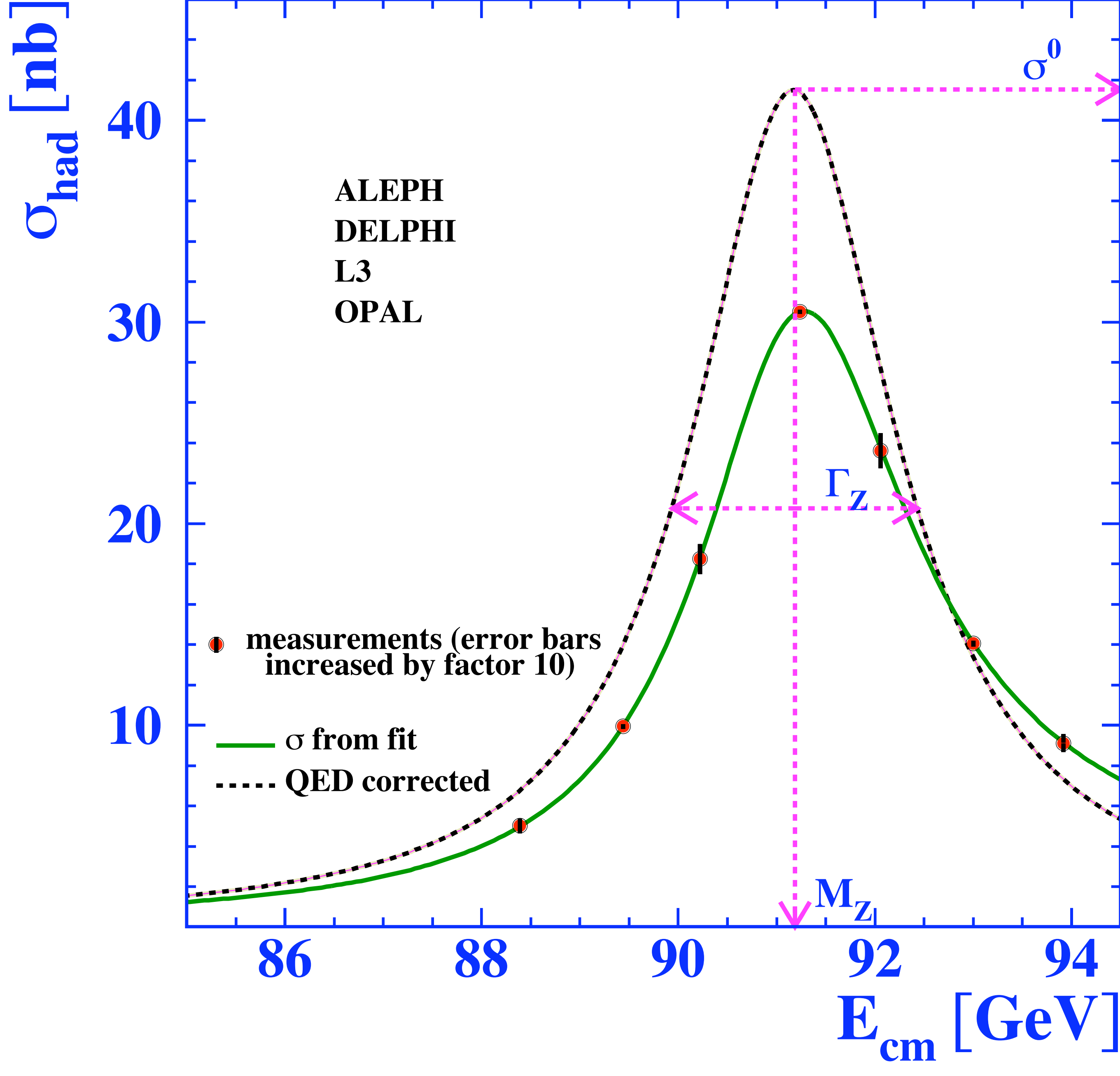
$$\Gamma \cong 2.50 \text{ GeV}$$

$$c\tau \sim \frac{197}{2500} \frac{\text{MeV-fm}}{\text{MeV}}$$

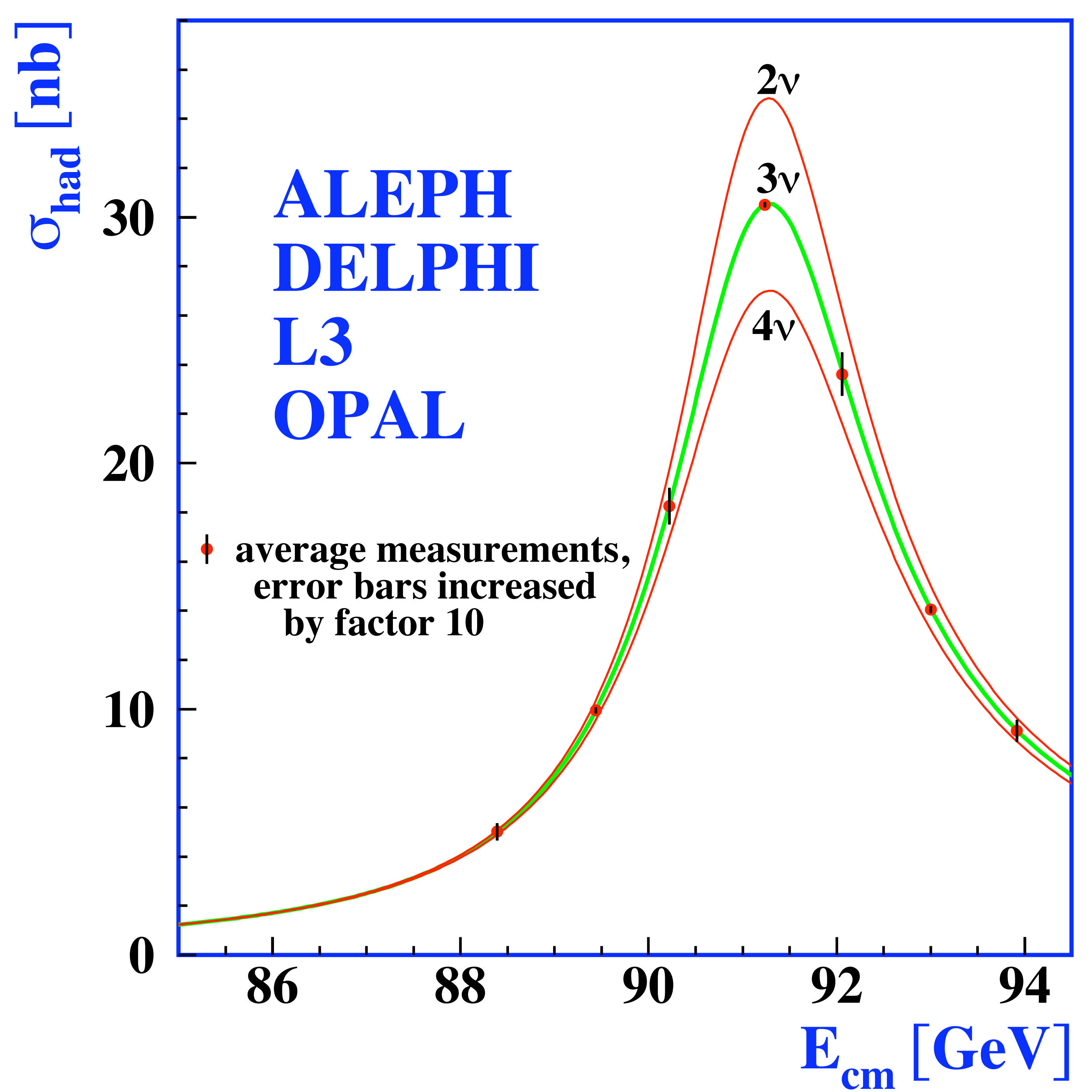
$$c\tau \sim 0.08 \text{ fm} \quad (10^{-15}\text{ m})$$

↑ not physically measureable

$\underline{W^\pm : \ 2.14 \text{ GeV}}$



σ_had [nb]
40
30
20
10
ALEPH
DELPHI
L3
OPAL
σ^0
Γ_Z
M_Z
measurements (error bars
increased by factor 10)
σ from fit
QED corrected
86
88
90
92
94
E_cm [GeV]



σhad [nb]
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by factor 10
0
10
20
30
86
88
90
92
94
Ecm [GeV]

Charges and Feynman Diagrams

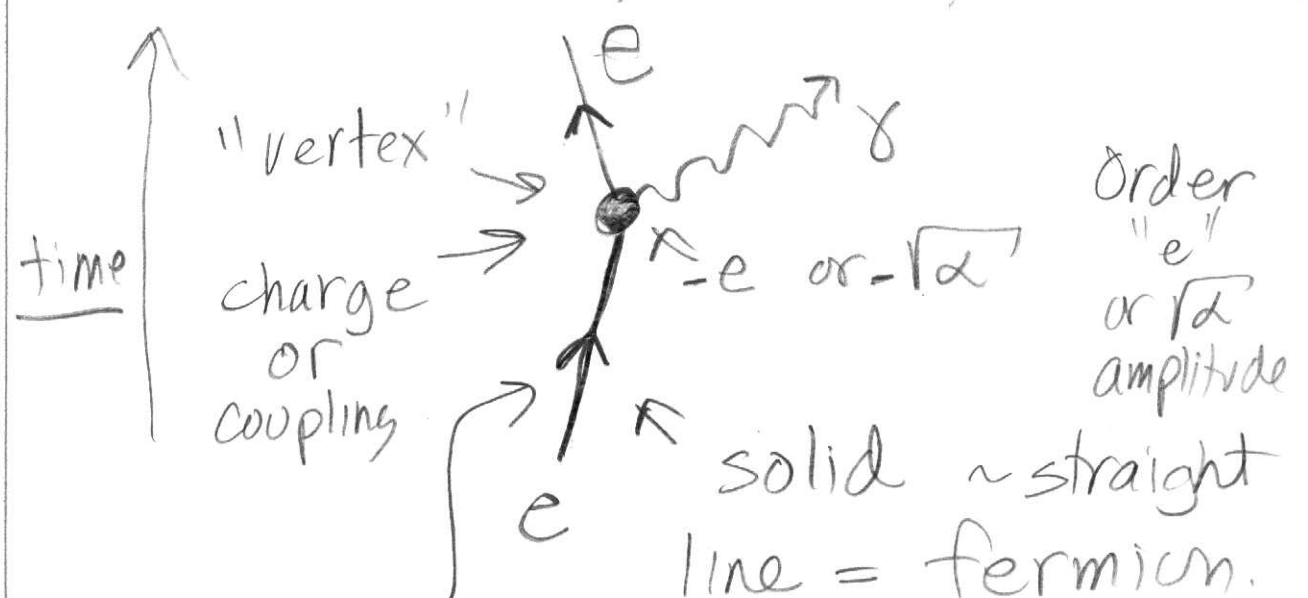
↓

crucial concept

Many levels

Qualitative → most precise calcs ever.

Allows computation of $\langle f | \hat{\mathcal{H}} | i \rangle$, $\langle \psi | \hat{\mathcal{H}} | \psi \rangle$, perturbatively



arrow forward means particle. (e^-)

Many quantities that go into the vertex must also come out

- Energy - momentum
- Electric Charge
- Specific Lepton Number ... electron-ness

• others (Quarkness, Helicity...)

The vector bosons couple to the fermions at the vertex; (Go back to picture)

⇒ process there would be spontaneous decay of an electron into $e + \gamma$

$$e \rightarrow e + \gamma$$

⇒ can this really happen?

✱ NO, Energy-Momentum

4-vector $\quad p_{e_1} = p_{e_2} + p_\gamma$

$$p_{e_1}^2 = m_e^2 = (p_{e_2} + p_\gamma)^2$$

$c = 1!$ $\quad m_e^2 = m_e^2 + \underbrace{2p_{e_2} \cdot p_\gamma}_{\text{not always } 0!} + 0$

$$2(E_{e_2}E_\gamma \underbrace{- \vec{p}_{e_2} \cdot \vec{p}_\gamma}_{> 0})$$

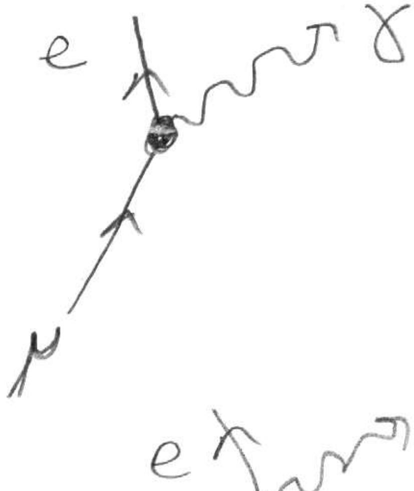
$\gamma \longleftarrow \circ \longrightarrow e_2$

⇒ If it could happen,
amplitude $(\langle f|\mathcal{H}|i\rangle) \propto -e$ ← charge on e.

Dimensionless: $\frac{-e}{\sqrt{\hbar c}} = -\sqrt{\alpha}$

Electric charge				magnetic charge
$-e$	e	μ	τ	0
0	ν_e	ν_μ	ν_τ	0
$+\frac{2}{3}e$	u	c	t	0
$-\frac{1}{3}e$	d'	s'	b'	0

(magnetic charge: don't talk about much.)



? μ-ness in
e-ness out
no direct amplitude

? electric charge
not same in + out

Antiparticles:

- Flip all additive quantum numbers

e^- ⟶ e^+ (Charge obvious)

↑

1 e-ness −1 e-ness (CPT)

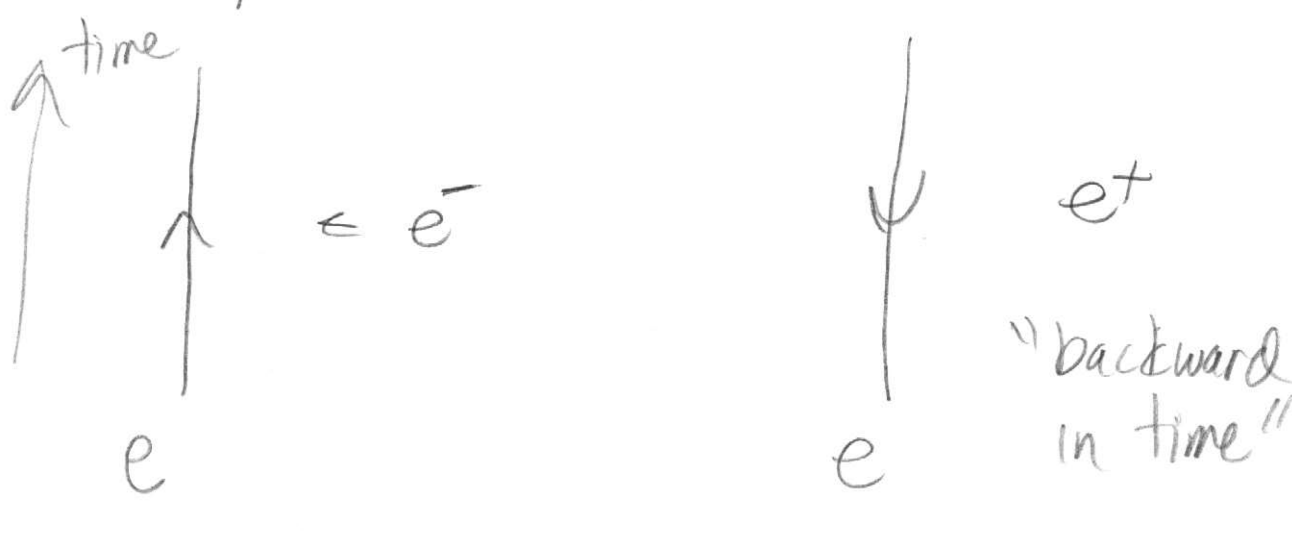
identical rest energy (CPT)

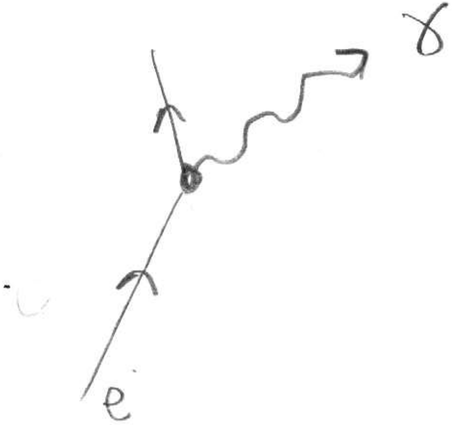
"Twinning" #1

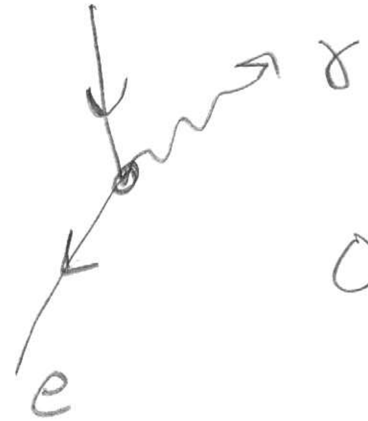
"Twinning" #2 → "supersymmetry"

e^- $+\frac{1}{2}$, $-\frac{1}{2}$ ⟶ e^-_L spin 0, e^-_R spin 0

On Feynman Diagram,

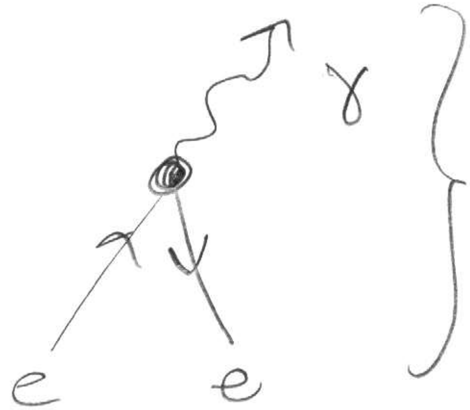






$O(\sqrt{\alpha})$

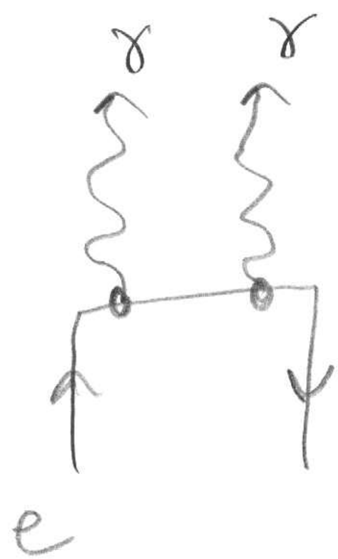
$e^- \to e^- \gamma$ $\qquad$ $e^+ \to e^+ \gamma$



$e^+ e^- \to \gamma$

↑ if real, cannot happen. (Energy-momentum)

First Real Process:



Amplitude: $(\sqrt{\alpha})^2 = \alpha$

<u>Rate</u> or <u>Cross Section</u>

$|\langle f | \underset{\sim}{H} | i \rangle|^2 \propto \alpha^2$