

Lecture 19: Weak Interactions

2) postulated by Pauli 1930 to preserve E, \vec{p} conservation in β decay.

$$n \rightarrow p + e^- + \bar{\nu}_e \quad \tau = 880 \text{ s} \approx 15 \text{ minutes}$$

Directly observed from nuclear reactor
 $\bar{\nu}_e$ 1953 Cowan, Reines

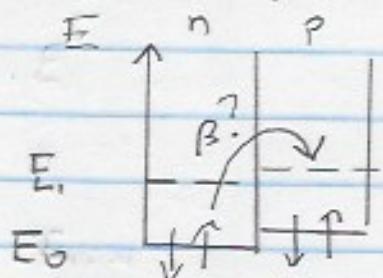
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Aside:

Q. Why is n inside light nuclei like He stable?

A. Pauli Exclusion principle

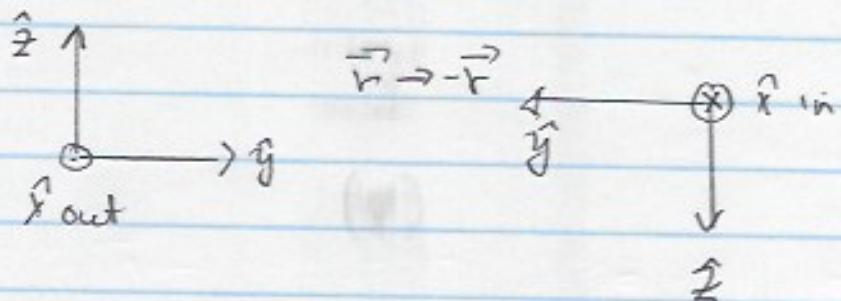
Simple model of nuclear energy states



n, p in separate
box because of
 $p\text{-}p$ Coulomb repulsion

β decay would require third proton to be in higher energy state.

Parity violation (β)

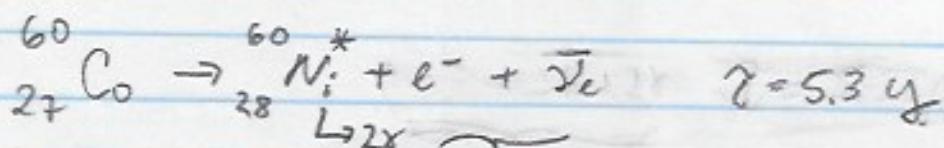


right handed coordinate \rightarrow left handed coordinate

Expect Parity conserved by fundamental interactions. History might freeze in parity violation, e.g. R-handed DNA
(some speculation that this preference might arise from handedness of electrons in cosmic rays)

Wu (1957) observed β in β decay

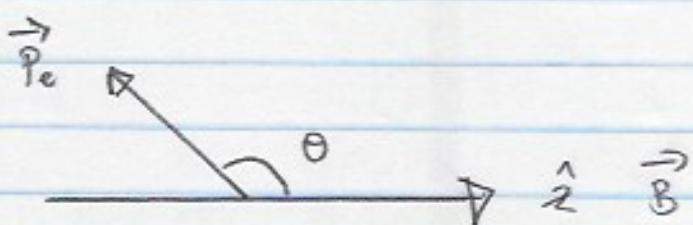
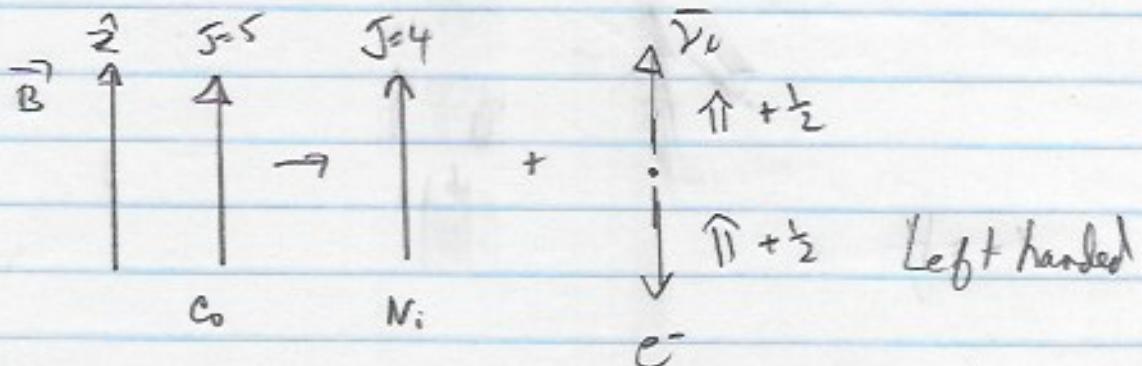
Polarized Cobalt ($J=5$) β decay to nickel ($J=4$)



$$\begin{array}{lll} J = 5 & = 4 & IJ = 1 \\ J_z = +5 & = +4 & \text{even} = +1 \end{array} \quad \text{Gamow-Teller}$$

\vec{B} defines \hat{z} direction

Electrons emitted preferentially in direction opposite to \vec{B} :



$$I(\cos\theta) = \frac{dN}{d\cos\theta} = \frac{N_0}{2} \left(1 + \alpha \frac{v}{c} \cos\theta \right)$$

For C_0 decay $\propto \times 0.6$

helicity

$$H = \frac{\vec{s} \cdot \vec{p}}{(\frac{\hbar}{2}) E} = \pm \frac{v}{c} \cos\theta$$

$+$ = Right handed

$-$ = Left handed

define I_+ $\vec{B} \parallel \hat{z}$

I_- $\vec{B} \parallel -\hat{z}$ reversed field

Polarization

$$P = \frac{I_+ - I_-}{I_+ + I_-} = \alpha \left(\frac{\nu}{c}\right)$$

Experimentally, $\alpha = -1$ \cancel{P}

Weak interaction is left handed

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Wu experiment (1957) used $^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + e^- + \bar{\nu}_e$ with electron $v/c \approx 0.6$.
 $\cos = \cos \theta$ where θ is polar angle with respect to the magnetic field.

$$I(\cos) \equiv \frac{dN}{d\cos} = \frac{N_0}{2} \left(1 + \alpha \frac{v}{c} \cos \right)$$

Helicity is

$$H = \frac{\vec{S} \cdot \vec{P}}{\frac{\hbar}{2} E} = \pm (v/c) \cos$$

Measure I_+ rate and flipped field rate I_- and therefore determine the polarization

$$P = \frac{I_+ - I_-}{I_+ + I_-}$$

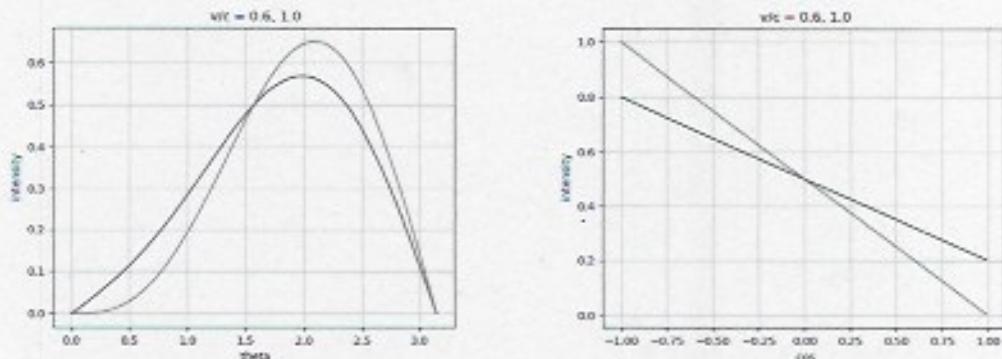


Figure 1: decay kinematics

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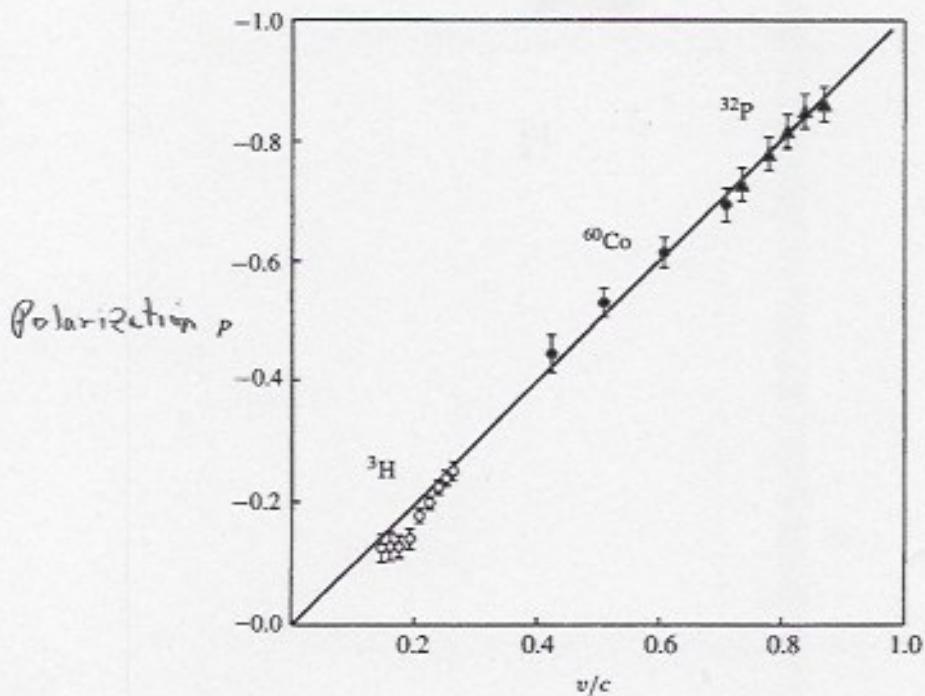


Fig. 7.6. The polarisation P of electrons emitted in nuclear β -decay, plotted as a function of electron velocity. The results demonstrate that $P = -v/c$, as in (7.16). After Koks and Van Klinken (1976).

Figure 2: $\alpha = -1$. Parity is violated with Left-handed helicity electrons.

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Structure of weak interaction

Weak isospin doublets ($I_W = \frac{1}{2}$)

Weak hypercharge Y

$$Q = I_W^3 + \frac{1}{2} Y$$

	Q	Y	I_W^3	
ν_e	0	-1	$+\frac{1}{2}$	x 3 families
e^-	-1	-1	$-\frac{1}{2}$	
—	—	—	—	
u	$\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{1}{2}$	
d'	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \bar{V} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \text{Weak} \\ \text{eigenstate} \end{pmatrix} = \begin{pmatrix} \text{CKM} \\ \text{Matrix} \end{pmatrix} \begin{pmatrix} \text{mass eigenstate} \end{pmatrix}$$

$$d' \cong \cos \theta_c d + \sin \theta_c s \quad \text{Cabibbo angle } \theta_c$$

$$s' \cong \sin \theta_c d - \cos \theta_c s \quad + \text{a bit of } b \text{ quark}$$

$$\sin \theta_c \cong 0.22 \quad \theta_c \cong 12.7^\circ$$

$$\cos \theta_c \cong 0.98 \quad \text{very precisely measured}$$

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Electroweak Unification

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Physical states are

massless photon (unbroken symmetry)

$$W^\pm \quad m_W \approx 80 \text{ GeV}$$
$$Z \quad m_Z \approx 91 \text{ GeV}$$

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

$$\sin^2\theta_W \approx 0.23$$

predicts spin-0 massive (1964)

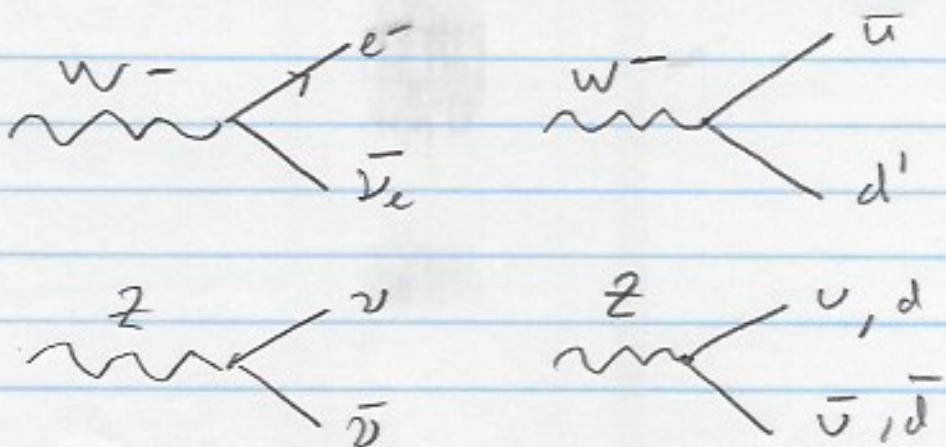
Higgs Boson

$$M_H = 125 \text{ GeV} \quad (2012)$$

Quarks and charged leptons (e, u, τ)
"Acquire" mass by interacting with Higgs

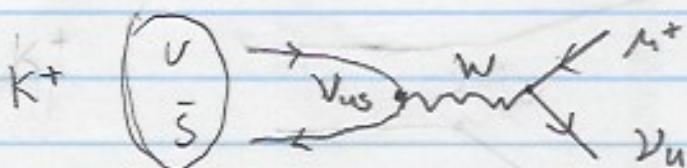
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Interactions:



Z does not change flavor.

Example of Weak decay:



CKM matrix element $V_{us} = \sin(\text{Cabibbo angle})$

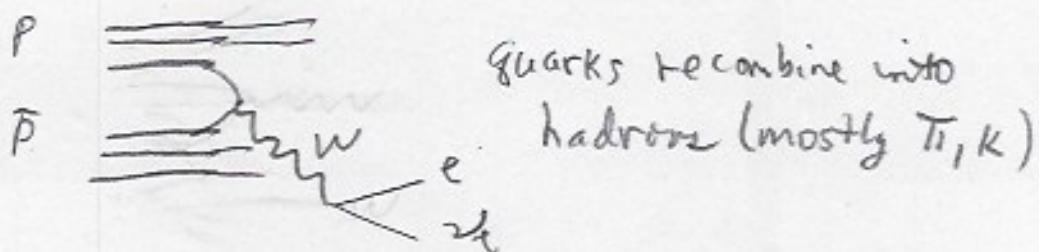
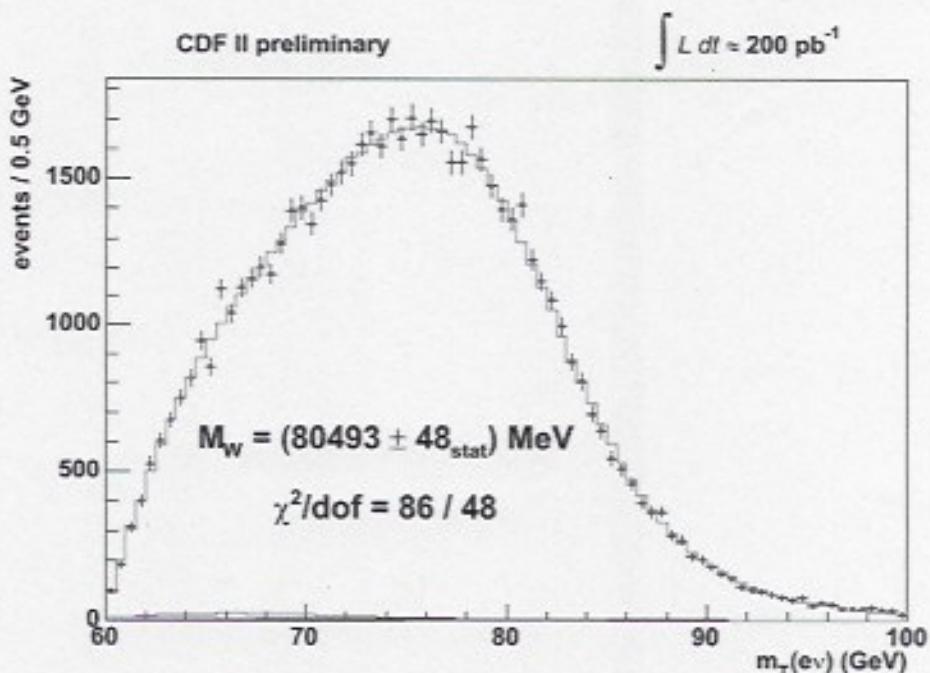
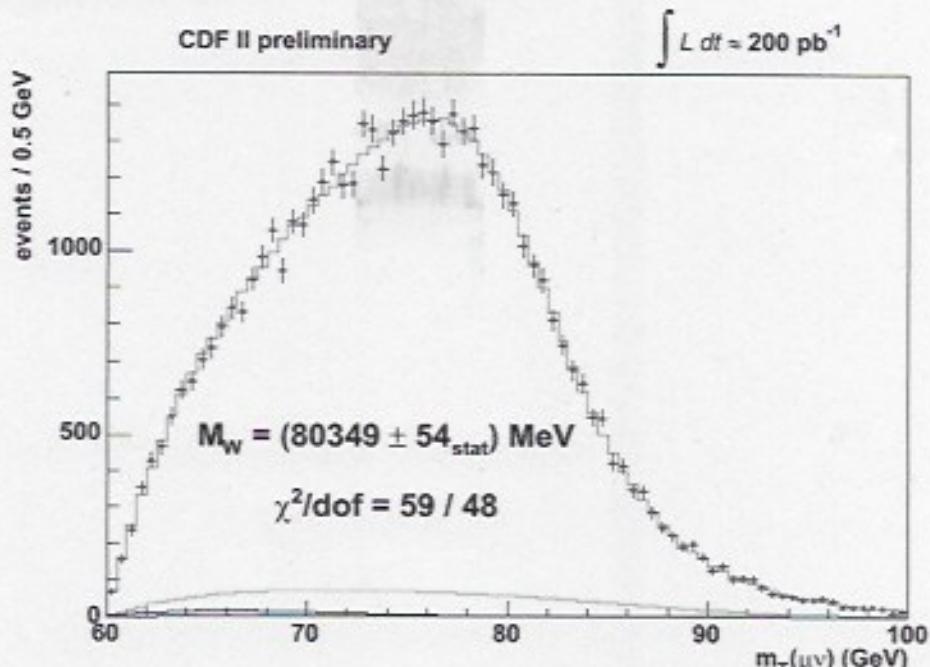
$p\bar{p} \rightarrow W + \text{hadrons}$

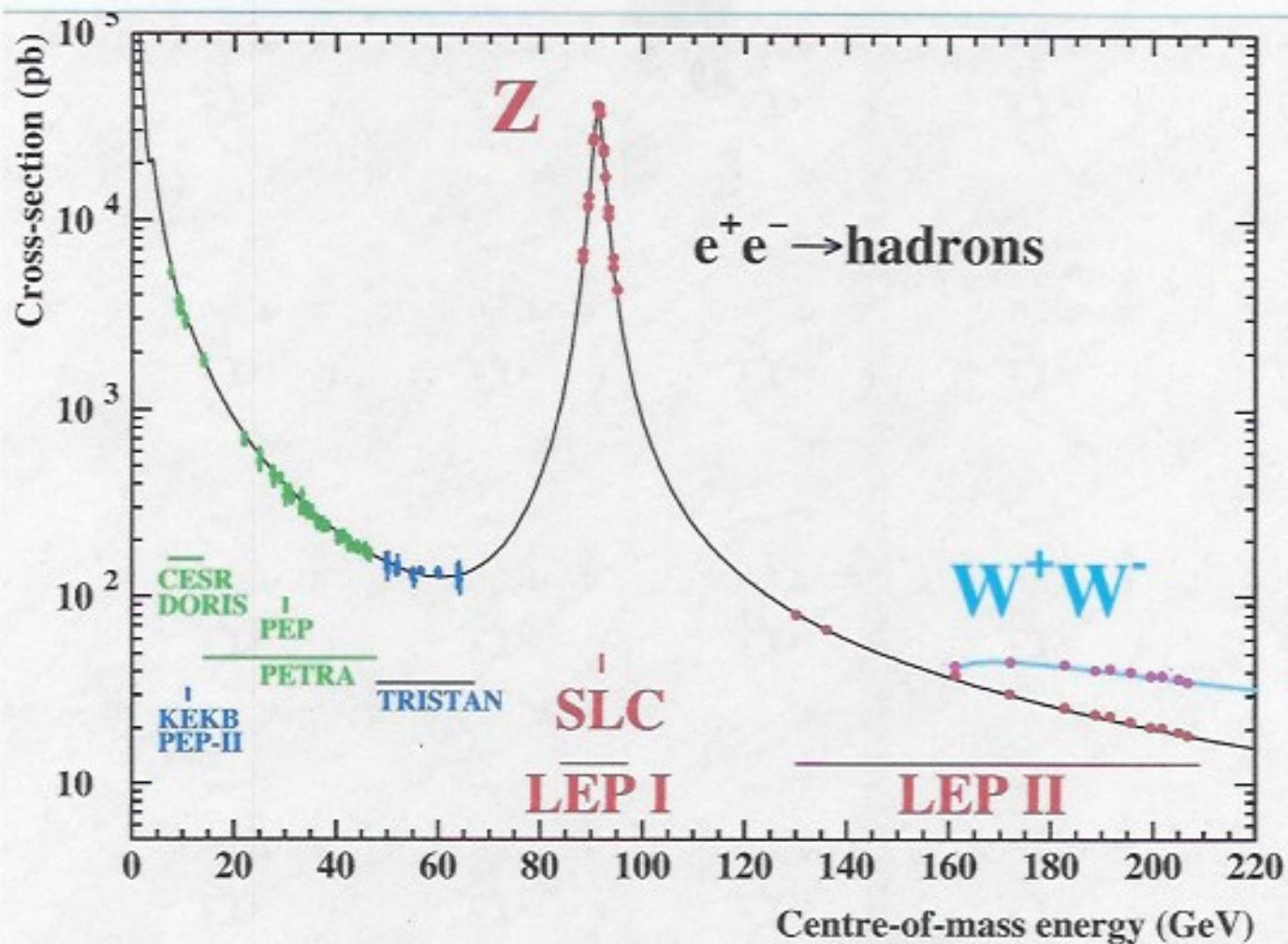
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$W \rightarrow \left\{ \begin{array}{l} e^+ \nu_e \\ \mu^+ \nu_\mu \end{array} \right.$

use momentum conservation \perp beam
to infer p_T^W

Transverse Mass Fits



The Z resonance

Γ_Z does not depend on decay channel

$Z \rightarrow$ quarks

\rightarrow charged leptons (e, μ, τ)

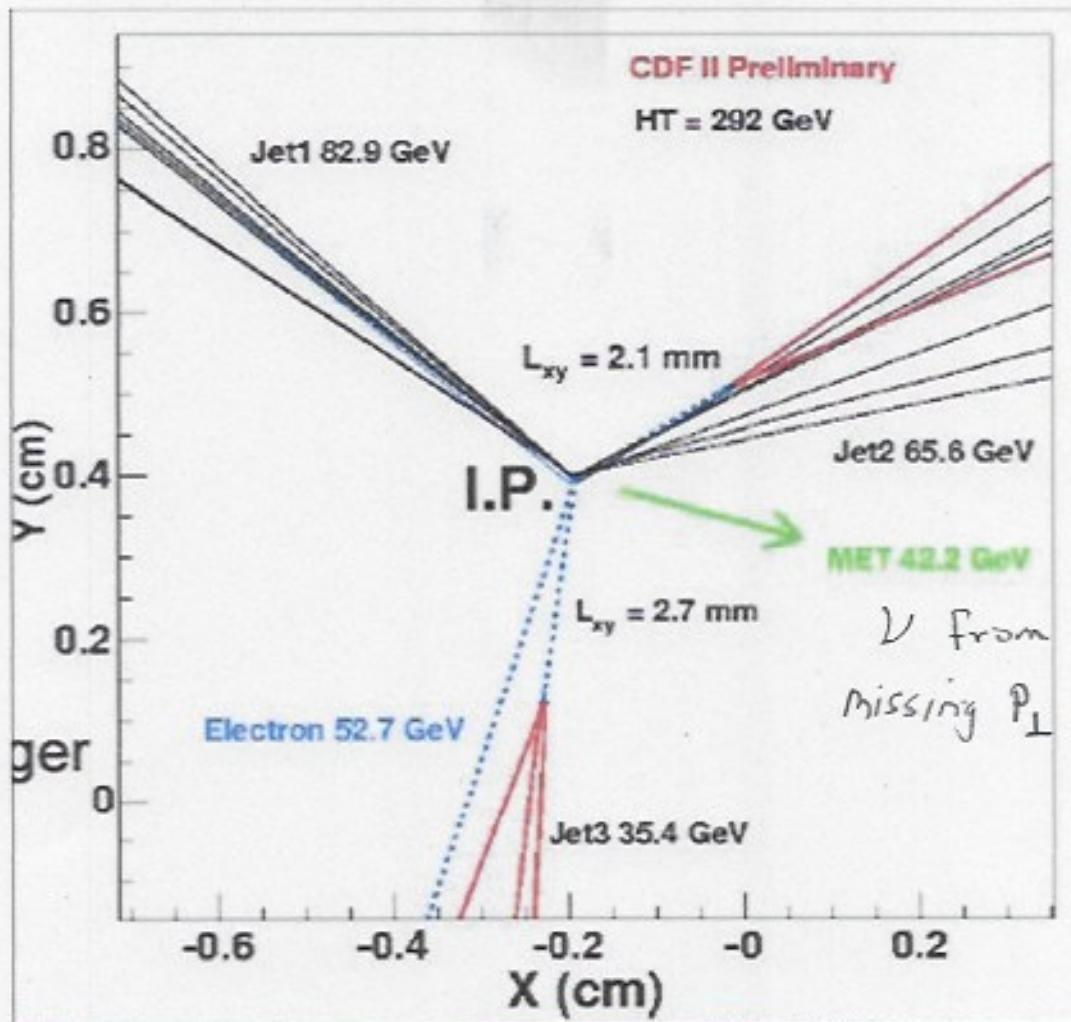
$\rightarrow \nu$ * light ν families in 3

$\nu m_\nu < m_Z/2$

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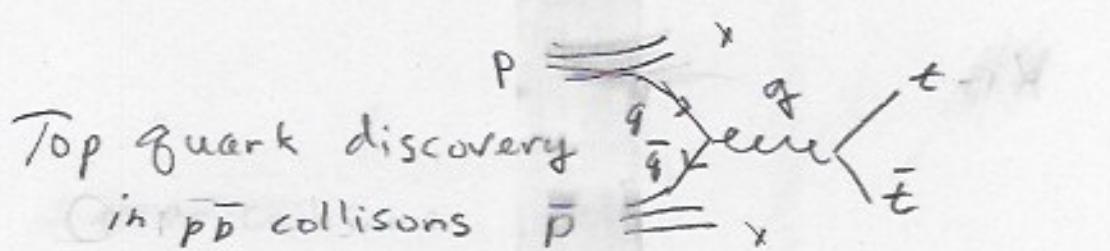
B lifetime = 1.6 pico seconds

CR = 480 μm



Precision measurement of tracks with silicon microstrip detectors allows b-quark "tagging" by displaced vertex

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$e + 4 \text{ jet event}$

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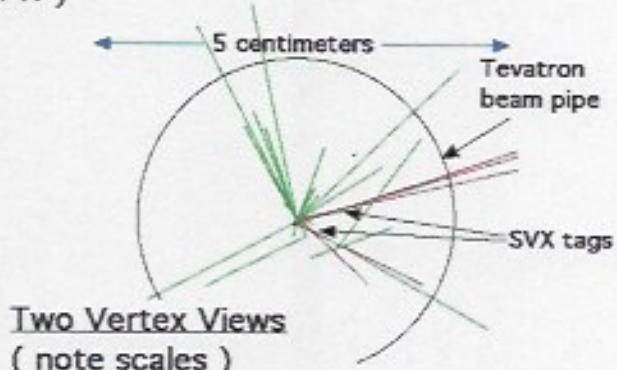
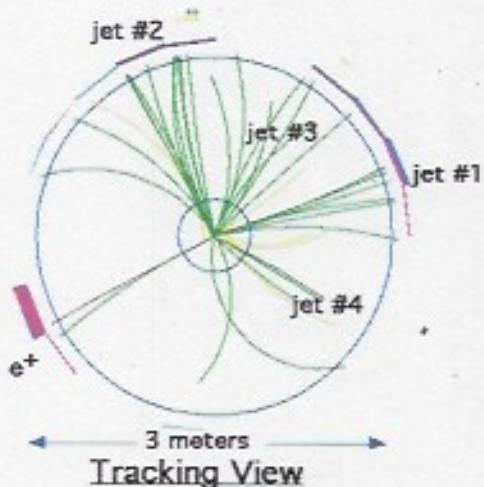
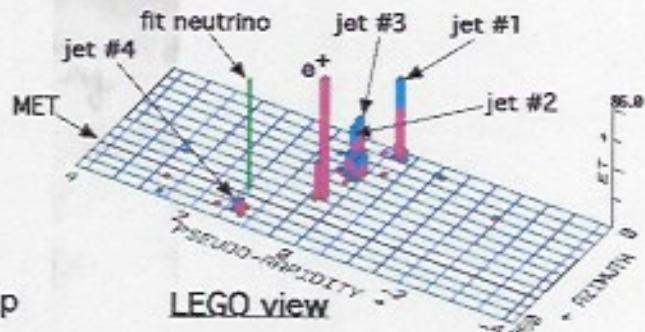
24-September, 1992

TWO jets tagged by SVX

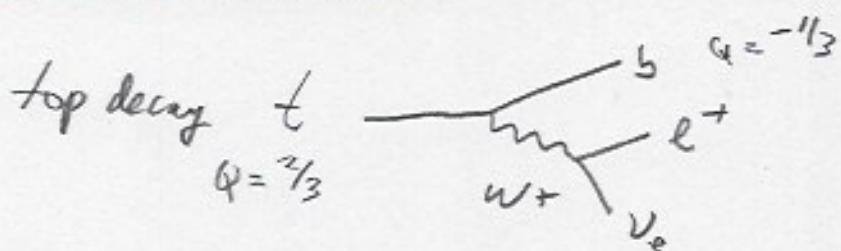
fit top mass is $170 \pm 10 \text{ GeV}$

e^+ , Missing E_T , jet #4 from top

jets 1,2,3 from top (2&3 from W)



The lower left figure shows the end-view of the tracking system along with the calorimetry, indicating a stiff track at 8 o'clock (one that shows almost no bending, and thus is measured to have a very high Momentum of about 40 GeV). That track, which does not have other high energy tracks nearby (we call this "isolated" track) also points directly to an energy deposit in the EM calorimetry consistent with the track momentum measured... thus confirming that this is a good electron candidate.

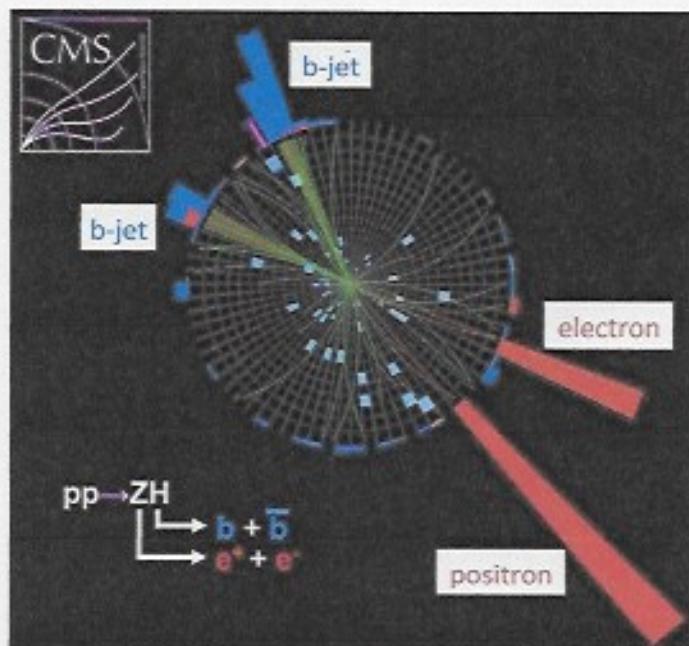


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Higgs decay event

$$pp \rightarrow ZH \xrightarrow{\gamma} b\bar{b}$$

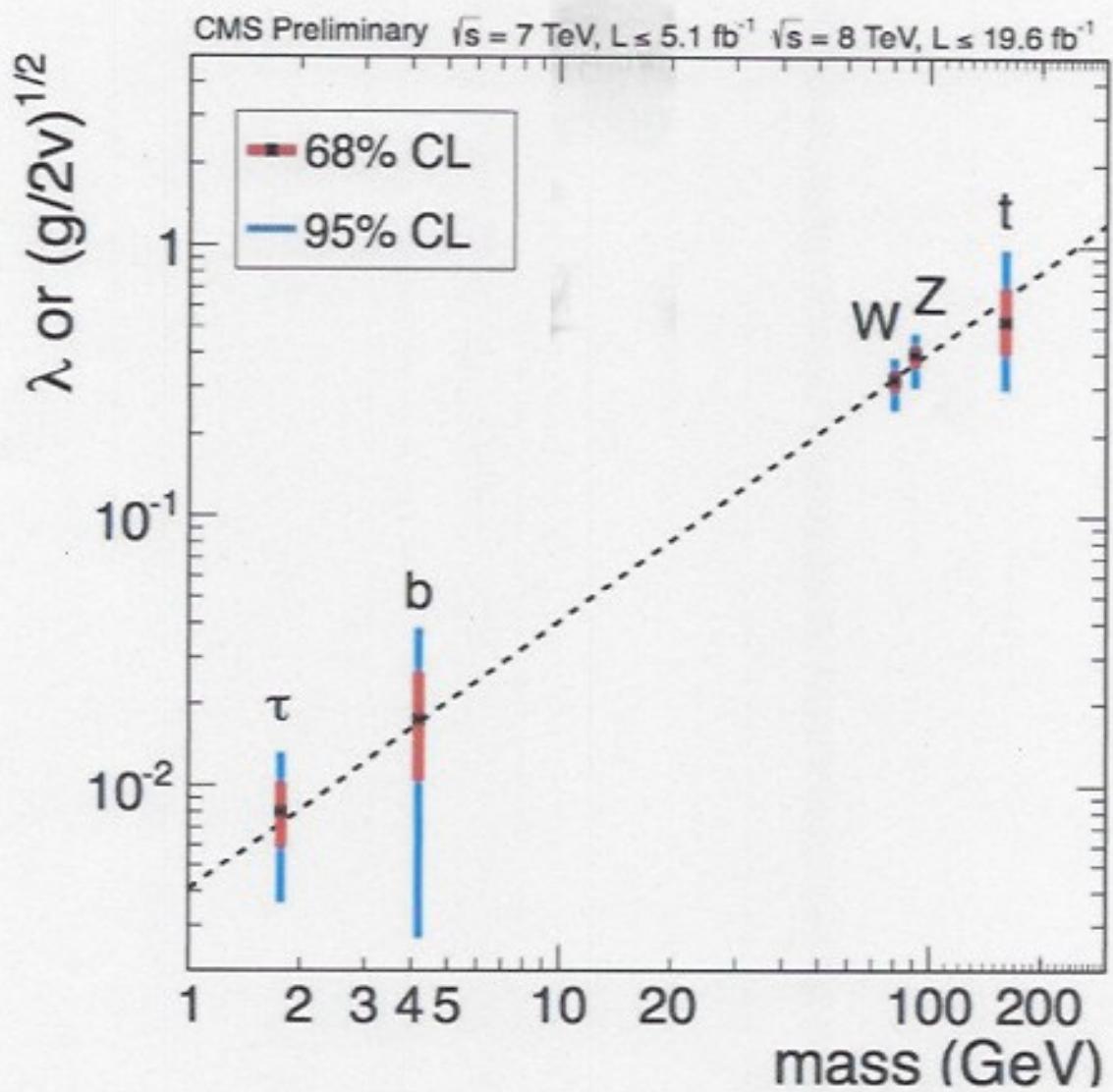
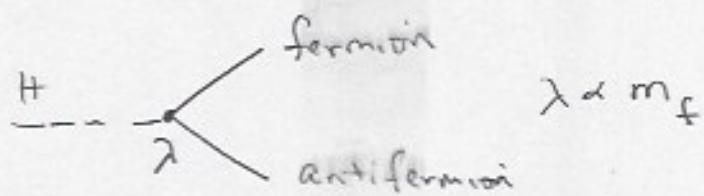
$\downarrow e^+e^-$



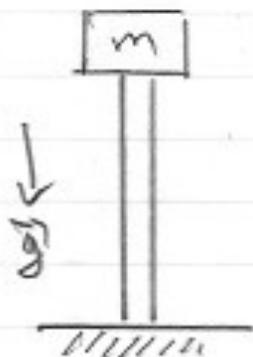
Since Higgs gives quarks mass
it couples most strongly to most
massive quark it can decay to in
 $g\bar{g}$ pair. Top is too heavy.

Standard Model precisely predicts
Higgs branching fractions (probabilities
to decay into specific final states)

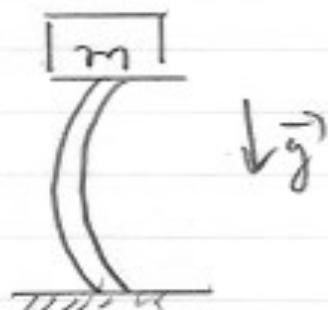
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Spontaneous Symmetry breaking
mechanical analog - compressed rod.



axial symmetry



state of lower
energy with bending
that chooses particular ϕ .

ground state breaks
symmetry

Some of the Open Questions

- Three families?
- Further unification of forces?

The Standard Model unifies
Electromagnetism & weak force
into "electroweak"

Unify electroweak and strong?
Grand unification

- Gravity?

String theory includes gravity
to date zero experimental evidence

- ν masses?

W couples only to left handed ν
so we don't know how to add
neutrino mass.