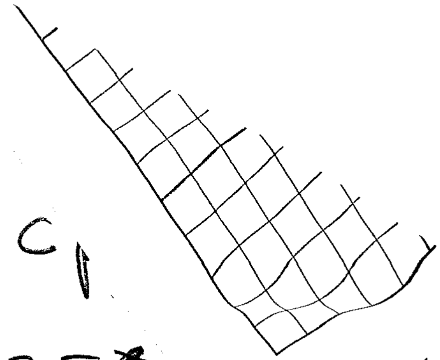
What is energy of Z^0_1 in



$$E_{Z^0_{1,2}} = \gamma_H \left(E^*_{Z^0} \pm \beta_H c_{\|}\right.$$

$$cp_{Z^0_{1,2}} = \gamma_H\left(\pm cp^*_{Z^0}\cos\theta^* + \beta E^*_{Z^0}\right)$$

$$cp_{Z^0_{1,2}} = cp^*_{Z^0}\sin\theta^*$$

(A) Maximum/Minimum Z^0 energies.

$$= \gamma_H\left(E^*_{Z^0} \pm \beta_H cp^*_{Z^0}\right)$$

$$\left.\begin{array}{l} = 701\text{ GeV (Max)} \\ \ 299\text{ GeV (Min)} \end{array}\right\} \text{Total energies, not Kinetic}$$

If #1 has $\underbrace{701\text{ GeV, \#2 } 299\text{ GeV}}_{\text{balance}}$

(B) "Energy Asymmetry"

$$\frac{E_{Z^0_1} - E_{Z^0_2}}{E_{Z^0_1} + E_{Z^0_1}} = \frac{2\gamma_H\beta_H cp^*_{Z^0}\cos\theta^*}{2\gamma_H E^*_{Z^0}}$$

$$= \underbrace{\beta_H\left(\frac{cp^*_{Z^0}}{E^*_{Z^0}}\right)}_{0.40}\cos\theta^*$$

$0.40 \quad \cos\theta^*$

(c) Subsequent Decays

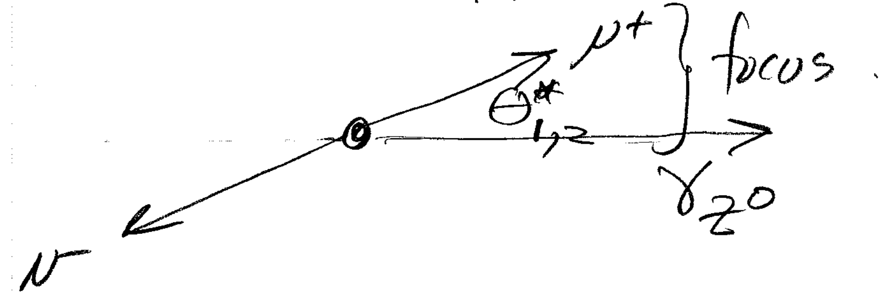
$Z^0_1 \to e^+e^-$ or $\mu^+\mu^-$

$Z^0_2 \to e^+e^-$ or $\mu^+\mu^-$

$\underbrace{\phantom{Z^0_2 \to e^+e^- \text{ or } \mu^+\mu^-}}$

2 more θ^*'s, some ϕ's too

→ complicated $Z^0_{1 \text{ or } 2}$ rest frame.



$m_\mu \ll m_{Z^0} \ldots \quad E^*_\mu \simeq \frac{1}{2} m_{Z^0} c^2 \simeq c p^*_\mu$

$$(\gamma_{Z^0_1})_{\underline{\underline{max}}} = \frac{701 \text{ GeV}}{91.2} = 7.69$$

$$(\beta_{Z^0_1})_{\underline{\underline{max}}} = \sqrt{1 - \frac{1}{\gamma^2_{Z^0}}} = 0.9915$$

"<u>Hardest</u>" μ or e

$$E_\mu = \gamma_{Z^0,max} \underbrace{\left(E^*_\mu + \beta_{Z^0_1,max}\, c p^*_\mu\right)}_{\text{about equal!}}$$

$$\simeq 7.69 \cdot (1 + (1)) \frac{1}{2} m_{Z^0} c^2 = \underline{\underline{701 \text{ GeV}}}!$$

Other ν from this decay ...

What is left? $\simeq 0$! (yes).

$$E_{\nu\,min} = \gamma_{Z^0\,max}\underbrace{\left(E_\nu^* - \beta_{Z^0,max}\, c p_\nu^*\right)}_{\simeq 0}$$

Correlation of energies is the key!

Reality: think

$114 \lesssim m_{H^0} c^2 \lesssim \underbrace{144\ \text{GeV}}$

not enough mass to make ZZ^0's

Onto Symmetry

Symmetry ... an operation that is interesting ...

Discrete: Mirror Image
Matter $\Longleftrightarrow$ Antimatter.

Continuous: Rotations, Translations

Correspond to <u>operators</u>

$$\underbrace{\{\underset{\sim}{R}_1, \underset{\sim}{R}_2, \ldots \underset{\sim}{R}_N\}}$$

Like numbers, with one <u>key difference</u>

$$\underbrace{\underset{\sim}{R}_1}_{\substack{\#1 \\ \text{second}}} \underbrace{\underset{\sim}{R}_2}_{\substack{\text{do } \#2 \\ \text{first}}} \neq \underset{\sim}{R}_2 \underset{\sim}{R}_1$$

<u>Example</u>: <u>Book</u>.

Rotations about axes don't commute...

$$\underline{\text{Rotation}}\,(x, \theta_x) = e^{-\frac{i\theta_x \underset{\sim}{J}_x}{\hbar}} = 1 - \frac{i\theta_x}{\hbar}\underset{\sim}{J}_x + \frac{1}{2!}\left(\frac{-i\theta_x}{\hbar}\underset{\sim}{J}_x\right)^2$$

$\underset{\sim}{J}_x$ ... operator that represents total angular momentum about x axis

<u>similar</u>: $\underset{\sim}{J}_y$, $\underset{\sim}{J}_z$

<u>Hearts of the matter</u>.

$$[\underset{\sim}{J}_x, \underset{\sim}{J}_y] = i\hbar \underset{\sim}{J}_z \quad \text{(Think cross product)}$$

→ No simultaneous eigenstates of all 3 components. or any 2!

→ $\tilde{J}_z$ chosen

→ $\tilde{J}^2 = \tilde{J}_x^2 + \tilde{J}_y^2 + \tilde{J}_z^2$ commutes with $\tilde{J}_x, \tilde{J}_y, \tilde{J}_z$ ...

$(\tilde{J}^2, \tilde{J}_z)$ form "CSCO"

eigenvalues...

$J^2 \Rightarrow \hbar^2 j(j+1) \qquad j = \frac{1}{2}, 1, \frac{3}{2}, 2, \ldots$

$J_z \Rightarrow m = -j\hbar, \ldots +j\hbar \quad (2j+1)$

What is this doing in particle physics?

NEW CONTINOUS + DISCRETE SYMMETRIES

Continuous: strong interaction is flavor independent

$m_u \neq m_d \neq m_s \neq m_c \neq m_b \neq m_t$

"Breaks" symmetry

$m_u, m_d \ll$ gluon energies

Me	You
u	$\tilde{u} = a u + b d$
d	$\tilde{d} = -b u + a d$

$\left.\begin{array}{l}\tilde{u} = a u + b d \\ \tilde{d} = -b u + a d\end{array}\right\}$ rotation IN "FLAVOR" SPACE

Like spin $\frac{1}{2}$ .. 2 states
choice of axis direction doesn't matter in spherically symmetric situation

"u" like spin "up" in abstract space.
"d" "down"

$\left(\begin{array}{c} u \\ d \end{array}\right\}$ iso spin "$\frac{1}{2}$", $\left.\begin{array}{l} u: +1/2 \\ d: -1/2 \end{array}\right\}$ third component I_z

I not J

Fun comes in looking at multiples

uud ... udd

$I_z = +\frac{1}{2}$ $\quad$ $I_z = -\frac{1}{2}$

strong interactions preserve
weak + e+m violate

Combining $\underbrace{\text{Angular Momentum}}$

OR

$\underbrace{\text{Isospin}}$

"CLASSIC": $\underset{\sim}{L} \to$ orbital

depends on wavefunction

$\underset{\sim}{S} \to$ spin

"fundamental" property of particle: $0\hbar$ (Higgs)

$\frac{1}{2}\hbar$ (fermions)

$\hbar$ (photon W, Z⁰, ...)

In a given situation,

"Total" angular momentum is conserved

$\boxed{\text{NOT}}$ $\underset{\sim}{L}^2$, $\underset{\sim}{L}_z$, $\underset{\sim}{S}_z$

$\boxed{\underset{\sim}{S}^2 \text{ is!}}$

$\frac{1}{2} \otimes \frac{1}{2}$

Example: Hydrogen, real spin

proton $\uparrow$ electron $\downarrow$ $\underset{\sim}{H}$ allows transition to   proton $\downarrow$ electron $\uparrow$

Transitions in time $\longrightarrow$ Energy!

$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ Singlet Ground State $S_z = 0$

es of "total spin" $\left\{ (\underset{\sim}{S}_p + \underset{\sim}{S}_e)^2 \rightarrow \hbar^2 \cdot 0 \cdot 1 = 0\hbar^2 \right.$ "total spin 0"

$|\uparrow\uparrow\rangle, \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle), |\downarrow\downarrow\rangle$ Triplet $S=1$ "total spin"

unlike $u\bar{u} \rightarrow d\bar{d}$ ... triplet has +

"singlet" η $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ ISOSPIN 0

Iso triplet $\left\{ \begin{array}{lll} \pi^+ \, |u\bar{d}\rangle & \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) & \pi^- \, |\bar{u}d\rangle \\ I_z = 1 & I_z = 0 & I_z = -1 \end{array} \right.$

"ISOTRIPLET"