Rapidity

\[ \gamma \equiv \frac{1}{2} \ln \frac{E+p_z}{E-p_z} = \frac{1}{2} \ln \frac{\sqrt{M_{ee}^2 + p_z^2} + p_z}{\sqrt{M_{ee}^2 + p_z^2} - p_z} \]

\[ x_1 = \frac{E+p_z}{\sqrt{s}} \]
\[ x_2 = \frac{E-p_z}{\sqrt{s}} \]

\[ y = \frac{1}{2} \ln \frac{x_1}{x_2} \]

\[ \frac{x_1}{x_2} = e^{2y} \]

\[ x_1 x_2 = \frac{M^2}{s} \]
\[ x_1^2 e^{-2y} = \frac{M^2}{s} \]

\[ x_1 = \frac{M}{\sqrt{s}} e^y \]
\[ x_2 = \frac{M}{\sqrt{s}} e^{-y} \]

could transform to

\[ \frac{d^2 \sigma}{dM dy} \] actually easier.
Decays

Problem

\[ Z^0 \rightarrow \ell^+ \ell^- \sim 3.3\% \text{ per charged lepton} \]

\[ W^\pm \rightarrow e^\pm \nu_e \sim 10\% \]

At LHC, TeV, \[ Z^0 \rightarrow q\bar{q} \rightarrow \text{jets} \]

\[ W \rightarrow q, \bar{q} \rightarrow \text{jets} \]

Hard to separate from background

Higgs Boson

1. Spin = 0
2. mass a "free parameter"
3. Essential for completing standard model
   keeps "wrong helicity" branching ratios from \( \infty \)
4. \[ H \rightarrow q\bar{q} \leftrightarrow m_H \]

(!)
Makes mass

\[ *H \rightarrow \text{condensed field} \]

Key point:

\[ H \rightarrow q \bar{q} \quad \Gamma (H^0 \rightarrow q \bar{q}) \]

\[ \frac{\Gamma}{\Gamma \text{tot}} \propto m_{q}^{2} \]

\[ \Rightarrow \text{Heavy Quarks favored} \]

\[ \Rightarrow ZZ^0, WW^- \text{ also favored if } m_H \text{ large enough} \]

\[ \text{5) LEP: } \]

\[ 115 \text{ GeV} \leq M_{H^0} \leq 165 \text{ GeV} \]

\[ \text{not above } H^0 \rightarrow ZZ^0 \]

\[ \text{barely } H^0 \rightarrow W^+W^- \]

\[ H^0 \rightarrow Z^0Z^0 \]
What does it do?

mostly $H^0 \rightarrow b\bar{b}$ (plot).

⇒ really hard

⇒ hope

$1.5 \text{ ps life}$

\[ \begin{array}{c}
\bar{b} \quad b \\
H^0
\end{array} \]

separated vertices

"Golden Mode" ⇒ $H^0 \rightarrow Z^0Z^0$

\[ \rightarrow 4e \quad 2e2\nu \]

"Discovery" plot
Production:

Mainly

\[ \sigma = \frac{\alpha s^2 G_F M_{h^2}^2}{11 \sqrt{2} 2^5 3^2} \, 8 \left( s^2 - M_{h^2}^2 \right) \quad \text{(narrow width)} \]

\[ \Rightarrow \text{you calculate} \]

\[ \Rightarrow \text{plot} \]

\[ \Rightarrow \text{discovery plot} \]
Sensitivity to Higgs Mass due to "higher order" effects

1. Running with $Q^2$

\[ \nu \rightarrow W \rightarrow u \]

$Q^2 \sim \text{few GeV}^2$

$Q^2 \sim (100)^2 \text{GeV}^2$

\[ e^+ \rightarrow \nu \bar{\nu} \gamma \]

Vertex couplings are not constant, vary with $Q^2$ or length scale.

2. Loops + $\tau$ very heavy

\[ W^+ \rightarrow W^+ \]

\[ W^+ \rightarrow W^+ \]

\[ W^+ \rightarrow W^+ \]

2 plots
General View Point

Higgs is "light", \( \leq 200 \text{ GeV/c}^2 \)

\[ \begin{array}{c}
\text{H} \\
\text{X} \\
\text{X} \\
\text{H}
\end{array} \]

\( \text{spin 0} \)

\( X \to \text{unknown, but problem is, would make the Higgs \( \infty \) in mass (effectively).} \)

Idea: \( X' \)

\[ \begin{array}{c}
\text{H} \\
\text{X'} \\
\text{X'}
\end{array} \]

\( \text{with sign!} \)

\( X \to \text{fermion} \)

\( X' \to \text{boson} \)

"Supersymmetry" Table
Key idea:

- "Gauge Couplings" of superpartners...
  \( \gamma, Z^0, W^+, g \)

same as original partners

\[
\begin{align*}
e^- & \quad \tilde{e}^- \\
\text{spin } \frac{1}{2} & \quad \text{spin } 0 \\
\text{"scalar" electron} & \\
\end{align*}
\]

Identical: em charge

Weak charge

color charge

Woops: \( \tilde{e}^- \rightarrow e_L + e_L \)\( \rightarrow \) \( Z^0 \)

Two 1 scalars: \( \rightarrow \tilde{e}^- \rightarrow \tilde{e}^- \rightarrow \tilde{e}^- \)
* Superpartners have a new quantum \#...

"$P$" Parity... conserved (maintains stable proton).

See table.

Meaning: very important:
superpartners must be pair produced...

*Mixing*

Spin-\(\frac{1}{2}\) partners of:

\(\gamma, Z^0, H^0 (\leq 21)\)

\(\tilde{\gamma}, \tilde{Z^0}, \tilde{H^0}\)

are not eigenstates!

Lightest: \(\tilde{\chi}_0\)... cannot decay
Spin $\frac{1}{2}$ partners of $W^+/H$

$\tilde{W}^+ / H^+$ can mix.

$\chi^+_1, \chi^+_2$

- Decays: $gg \rightarrow \tilde{g}\tilde{g}$

$\tilde{g}\tilde{g}$ pair

$\tilde{g}$, stuck with $R$-parity

usually $M_{\tilde{g}} > M_{\chi^0}$

Maybe: $\chi^0 \rightarrow g g$

$\chi^0$
$\chi^0 \rightarrow$ escapes undetected
$\rightarrow$ missing energy

LHC:

\[ \text{jet (g)} \]

\[ p \rightarrow \text{jet (g)} \]

\[ p \rightarrow \text{missing energy} \]

Usually: all SUSY pair production causes missing energy.

- Masses of partners/s-p can be different