Particle Physics: The Standard Model

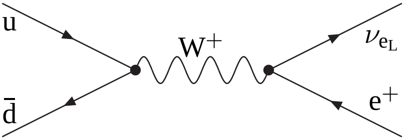
Dirk Zerwas

LAL
zerwas@lal.in2p3.fr

April 18 and April 25, 2013

The Pion Decay

$$\begin{aligned} \pi^+ &\rightarrow e^+ \nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

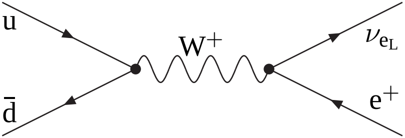
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')$$

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\pi^+ \rightarrow e^+\nu_{e_L}$$
$$-\bar{d}(\mathbf{p}')u(\mathbf{p}) \rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})$$



- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

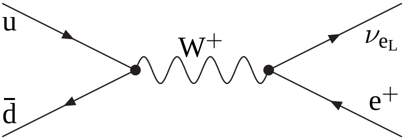
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')$$

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\begin{aligned} \pi^+ &\to e^+ \nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\to e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

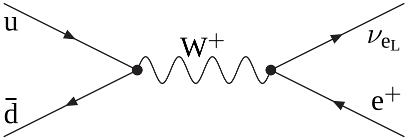
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$T_{fi} = \bar{v}(\mathbf{p}') \frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu \frac{1-\gamma_5}{2} u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k}) \frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu \frac{1-\gamma_5}{2} v(\mathbf{k}')$$

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\pi^+ \rightarrow e^+\nu_{e_L}$$
$$-\bar{d}(\mathbf{p}')u(\mathbf{p}) \rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})$$



- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

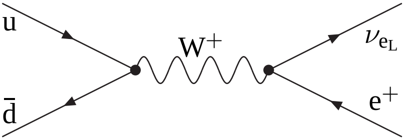
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')$$

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\begin{aligned}\pi^+ &\rightarrow e^+\nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})\end{aligned}$$



- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

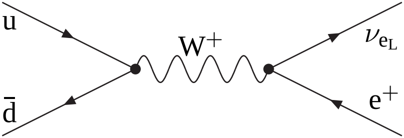
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p})\frac{g^{\mu\nu}}{q^2-m_W^2}\bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')$$

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\begin{aligned} \pi^+ &\rightarrow e^+ \nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



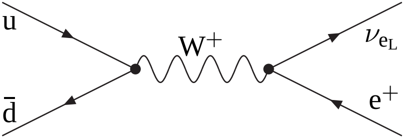
- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$\begin{aligned} T_{fi} &= \bar{v}(\mathbf{p}') \frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu \frac{1-\gamma_5}{2} u(\mathbf{p}) \\ &\quad \frac{g^{\mu\nu}}{q^2-m_W^2} \\ &\quad \bar{u}(\mathbf{k}) \frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu \frac{1-\gamma_5}{2} v(\mathbf{k}') \\ \frac{G_F}{\sqrt{2}} &= \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} \\ &= \frac{e^2}{8\sin^2\theta_W m_W^2} \end{aligned}$$

The Pion Decay

$$\begin{aligned} \pi^+ &\rightarrow e^+ \nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



- $1 - \gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

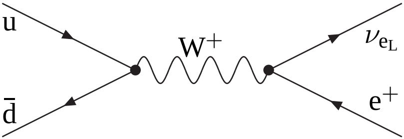
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')$$

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\pi^+ \rightarrow e^+ \nu_{e_L}$$
$$-\bar{d}(\mathbf{p}')u(\mathbf{p}) \rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})$$



- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

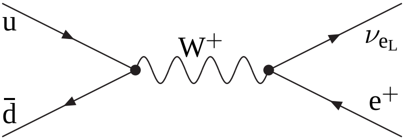
$$T_{fi} = \bar{v}(\mathbf{p}') \frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu \frac{1-\gamma_5}{2} u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2 - m_W^2} \bar{u}(\mathbf{k}) \frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu \frac{1-\gamma_5}{2} v(\mathbf{k}')$$

- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\begin{aligned} \pi^+ &\to e^+ \nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\to e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

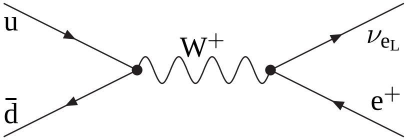
$$\begin{aligned} T_{fi} &= \bar{v}(\mathbf{p}') \frac{e}{\sqrt{2}\sin\theta_W} \gamma_\mu \frac{1-\gamma_5}{2} u(\mathbf{p}) \\ &\quad \frac{g^{\mu\nu}}{q^2 - m_W^2} \\ &\quad \bar{u}(\mathbf{k}) \frac{e}{\sqrt{2}\sin\theta_W} \gamma_\nu \frac{1-\gamma_5}{2} v(\mathbf{k}') \end{aligned}$$

$$\begin{aligned} \frac{G_F}{\sqrt{2}} &= \frac{e}{\sqrt{2}\sin\theta_W} \frac{1}{2} \frac{1}{m_W^2} \frac{e}{\sqrt{2}\sin\theta_W} \frac{1}{2} \\ &= \frac{e^2}{8\sin^2\theta_W m_W^2} \end{aligned}$$

- $1 - \gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

The Pion Decay

$$\begin{aligned} \pi^+ &\rightarrow e^+ \nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



- $1 - \gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

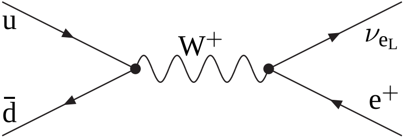
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')$$

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\pi^+ \rightarrow e^+ \nu_{e_L}$$
$$-\bar{d}(\mathbf{p}')u(\mathbf{p}) \rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})$$



- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

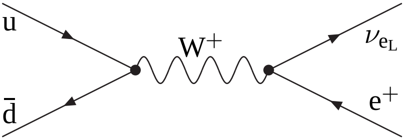
$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu \frac{1-\gamma_5}{2} u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu \frac{1-\gamma_5}{2} v(\mathbf{k}')$$

- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\begin{aligned}\pi^+ &\rightarrow e^+\nu_{e_L}\\ -\bar{\mathrm{d}}(\mathbf{p}')\mathrm{u}(\mathbf{p}) &\rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})\end{aligned}$$



- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

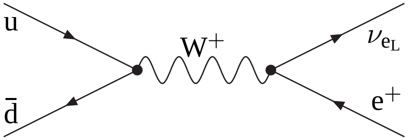
$$T_{fi} = \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \frac{g^{\mu\nu}}{q^2-m_W^2} \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')$$

- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

$$\frac{G_F}{\sqrt{2}} = \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} = \frac{e^2}{8\sin^2\theta_W m_W^2}$$

The Pion Decay

$$\begin{aligned}\pi^+ &\to e^+\nu_{e_L}\\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\to e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})\end{aligned}$$



- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

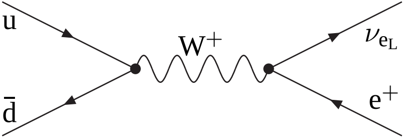
- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$\begin{aligned}T_{fi} &= \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \\ &\quad \frac{g^{\mu\nu}}{q^2-m_W^2} \\ &\quad \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}')\end{aligned}$$

$$\begin{aligned}\frac{G_F}{\sqrt{2}} &= \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} \\ &= \frac{e^2}{8\sin^2\theta_W m_W^2}\end{aligned}$$

The Pion Decay

$$
\begin{aligned}
\pi^+ &\rightarrow e^+\nu_{e_L} \\
-\bar{d}(\mathbf{p}')u(\mathbf{p}) &\rightarrow e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k})
\end{aligned}
$$



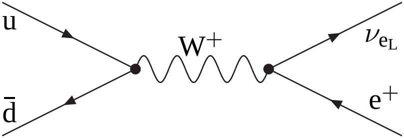
- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$
\begin{aligned}
T_{fi} &= \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \\
&\quad \frac{g^{\mu\nu}}{q^2-m_W^2} \\
&\quad \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}') \\
\frac{G_F}{\sqrt{2}} &= \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} \\
&= \frac{e^2}{8\sin^2\theta_W m_W^2}
\end{aligned}
$$

The Pion Decay

$$\begin{aligned} \pi^+ &\to e^+\nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\to e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



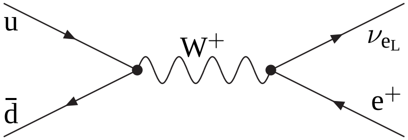
- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

$$\begin{aligned} T_{fi} &= \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \\ &\quad \frac{g^{\mu\nu}}{q^2-m_W^2} \\ &\quad \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}') \\ \frac{G_F}{\sqrt{2}} &= \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} \\ &= \frac{e^2}{8\sin^2\theta_W m_W^2} \end{aligned}$$

The Pion Decay

$$\begin{aligned} \pi^+ &\to e^+\nu_{e_L} \\ -\bar{d}(\mathbf{p}')u(\mathbf{p}) &\to e^+(\mathbf{k}')\nu_{e_L}(\mathbf{k}) \end{aligned}$$



- $1-\gamma_5$ ensures left-handed
- $q^2 = s = m_\pi^2$
- $m_\pi \ll m_W$ Fermi-contact interaction

- initial state fermions
- final state fermions
- massive propagator
- vertex (incoming)
- vertex (outgoing)

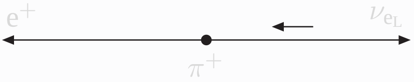
$$\begin{aligned} T_{fi} &= \bar{v}(\mathbf{p}')\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\mu\frac{1-\gamma_5}{2}u(\mathbf{p}) \\ &\quad \frac{g^{\mu\nu}}{q^2-m_W^2} \\ &\quad \bar{u}(\mathbf{k})\frac{e}{\sqrt{2}\sin\theta_W}\gamma_\nu\frac{1-\gamma_5}{2}v(\mathbf{k}') \\ \frac{G_F}{\sqrt{2}} &= \frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2}\frac{1}{m_W^2}\frac{e}{\sqrt{2}\sin\theta_W}\frac{1}{2} \\ &= \frac{e^2}{8\sin^2\theta_W m_W^2} \end{aligned}$$

Branching Ration π^+

$$\begin{aligned}\mathcal{B}(\pi^+ \rightarrow \mu^+\nu_{\mu_L}) &= 0.9999 \\ \mathcal{B}(\pi^+ \rightarrow e^+\nu_{e_L}) &= 0.0001\end{aligned}$$

- $m_e \ll m_\mu$ phase space!
- theory is chiral not helicity!
- mass breaks helicity=chirality
- $m_e \ll m_\mu \rightarrow$ muons break easier!

Helicity picture



The pion is a scalar!

$$\begin{aligned}\frac{\mathcal{B}(e^+\nu_{e_L})}{\mathcal{B}(\mu^+\nu_{\mu_L})} &= \frac{\frac{\Gamma(\pi^+\rightarrow e^+\nu_{e_L})}{\Gamma}}{\frac{\Gamma(\pi^+\rightarrow\mu^+\nu_{\mu_L})}{\Gamma}} \\ &= \left(\frac{m_e}{m_\mu}\right)^2\left(\frac{m_\pi^2-m_e^2}{m_\pi^2-m_\mu^2}\right) \\ &\sim 1\cdot 10^{-4}\end{aligned}$$

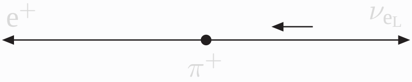
Pion decay understood from left-right structure of the Standard Model!

Branching Ration π^+

$$\mathcal{B}(\pi^+ \to \mu^+ \nu_{\mu_L}) = 0.9999$$
$$\mathcal{B}(\pi^+ \to e^+ \nu_{e_L}) = 0.0001$$

- $m_e \ll m_\mu$ phase space!
- theory is chiral not helicity!
- mass breaks helicity=chirality
- $m_e \ll m_\mu \to$ muons break easier!

Helicity picture



The pion is a scalar!

$$\frac{\mathcal{B}(e^+\nu_{e_L})}{\mathcal{B}(\mu^+\nu_{\mu_L})} = \frac{\frac{\Gamma(\pi^+\to e^+\nu_{e_L})}{\Gamma}}{\frac{\Gamma(\pi^+\to\mu^+\nu_{\mu_L})}{\Gamma}} = \left(\frac{m_e}{m_\mu}\right)^2\left(\frac{m_\pi^2-m_e^2}{m_\pi^2-m_\mu^2}\right) \sim 1\cdot 10^{-4}$$

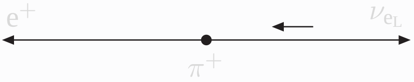
Pion decay understood from left-right structure of the Standard Model!

Branching Ration π^+

$$\mathcal{B}(\pi^+ \to \mu^+ \nu_{\mu_L}) = 0.9999$$
$$\mathcal{B}(\pi^+ \to e^+ \nu_{e_L}) = 0.0001$$

- $m_e \ll m_\mu$ phase space!
- theory is chiral not helicity!
- mass breaks helicity=chirality
- $m_e \ll m_\mu \to$ muons break easier!

Helicity picture



The pion is a scalar!

$$\frac{\mathcal{B}(e^+\nu_{e_L})}{\mathcal{B}(\mu^+\nu_{\mu_L})} = \frac{\frac{\Gamma(\pi^+\to e^+\nu_{e_L})}{\Gamma}}{\frac{\Gamma(\pi^+\to\mu^+\nu_{\mu_L})}{\Gamma}} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right) \sim 1 \cdot 10^{-4}$$

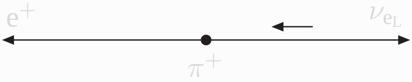
Pion decay understood from left-right structure of the Standard Model!

Branching Ration π^+

$$\begin{aligned} \mathcal{B}(\pi^+ \to \mu^+ \nu_{\mu_L}) &= 0.9999 \\ \mathcal{B}(\pi^+ \to e^+ \nu_{e_L}) &= 0.0001 \end{aligned}$$

- $m_e \ll m_\mu$ phase space!
- theory is chiral not helicity!
- mass breaks helicity=chirality
- $m_e \ll m_\mu \to$ muons break easier!

Helicity picture



The pion is a scalar!

$$\begin{aligned} \frac{\mathcal{B}(e^+\nu_{e_L})}{\mathcal{B}(\mu^+\nu_{\mu_L})} &= \frac{\frac{\Gamma(\pi^+ \to e^+ \nu_{e_L})}{\Gamma}}{\frac{\Gamma(\pi^+ \to \mu^+ \nu_{\mu_L})}{\Gamma}} \\ &= \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right) \\ &\sim 1 \cdot 10^{-4} \end{aligned}$$

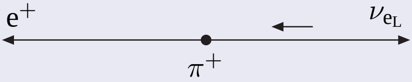
Pion decay understood from left-right structure of the Standard Model!

Branching Ration π^+

$$\mathcal{B}(\pi^+ \to \mu^+ \nu_{\mu_L}) = 0.9999$$
$$\mathcal{B}(\pi^+ \to e^+ \nu_{e_L}) = 0.0001$$

- $m_e \ll m_\mu$ phase space!
- theory is chiral not helicity!
- mass breaks helicity=chirality
- $m_e \ll m_\mu \to$ muons break easier!

Helicity picture



The pion is a scalar!

$$\frac{\mathcal{B}(e^+ \nu_{e_L})}{\mathcal{B}(\mu^+ \nu_{\mu_L})} = \frac{\frac{\Gamma(\pi^+ \to e^+ \nu_{e_L})}{\Gamma}}{\frac{\Gamma(\pi^+ \to \mu^+ \nu_{\mu_L})}{\Gamma}} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right) \sim 1 \cdot 10^{-4}$$

Pion decay understood from left-right structure of the Standard Model!

Parity Tranformation

- $P(\vec{p}) \rightarrow -\vec{p}$
- Spin is unchanged
- Helicity changes sign

Electroweak Interaction

- $\bar{\psi}\gamma^{\mu}\psi$ perfectly symmetric for left- and right-handed particles

Lee and Yang 1957, Heintze/Jensen

Electroweak Interaction

- violates parity maximally
- has $V - A$ structure
- left-handed behaves differently than right-handed

- left- and right? Spin
- Polarization: average orientation of spin
- Invert polarization and measure at the same location

Parity Tranformation

- $P(\vec{p}) \to -\vec{p}$
- Spin is unchanged
- Helicity changes sign

Electroweak Interaction

- $\bar{\psi}\gamma^{\mu}\psi$ perfectly symmetric for left- and right-handed particles

Lee and Yang 1957, Heintze/Jensen

Electroweak Interaction

- violates parity maximally
- has $V - A$ structure
- left-handed behaves differently than right-handed

- left- and right? Spin
- Polarization: average orientation of spin
- Invert polarization and measure at the same location

Parity Tranformation

- $P(\vec{p}) \rightarrow -\vec{p}$
- Spin is unchanged
- Helicity changes sign

Electroweak Interaction

- $\bar{\psi}\gamma^{\mu}\psi$ perfectly symmetric for left- and right-handed particles

Lee and Yang 1957, Heintze/Jensen

Electroweak Interaction

- violates parity maximally
- has $V - A$ structure
- left-handed behaves differently than right-handed

- left- and right? Spin
- Polarization: average orientation of spin
- Invert polarization and measure at the same location

Parity Tranformation

- $P(\vec{p}) \rightarrow -\vec{p}$
- Spin is unchanged
- Helicity changes sign

Electroweak Interaction

- $\bar{\psi}\gamma^{\mu}\psi$ perfectly symmetric for left- and right-handed particles

Lee and Yang 1957, Heintze/Jensen

Electroweak Interaction

- violates parity maximally
- has $V - A$ structure
- left-handed behaves differently than right-handed

- left- and right? Spin
- Polarization: average orientation of spin
- Invert polarization and measure at the same location

Parity Tranformation

- $P(\vec{p}) \to -\vec{p}$
- Spin is unchanged
- Helicity changes sign

Electroweak Interaction

- $\bar{\psi}\gamma^{\mu}\psi$ perfectly symmetric for left- and right-handed particles

Lee and Yang 1957, Heintze/Jensen

Electroweak Interaction

- violates parity maximally
- has $V - A$ structure
- left-handed behaves differently than right-handed

- left- and right? Spin
- Polarization: average orientation of spin
- Invert polarization and measure at the same location

Parity Tranformation

- $P(\vec{p}) \to -\vec{p}$
- Spin is unchanged
- Helicity changes sign

Electroweak Interaction

- $\bar{\psi}\gamma^\mu\psi$ perfectly symmetric for left- and right-handed particles

Lee and Yang 1957,
Heintze/Jensen

Electroweak Interaction

- violates parity maximally
- has $V - A$ structure
- left-handed behaves differently than right-handed

- left- and right? Spin
- Polarization: average orientation of spin
- Invert polarization and measure at the same location

Parity Tranformation

- $P(\vec{p}) \rightarrow -\vec{p}$
- Spin is unchanged
- Helicity changes sign

Electroweak Interaction

- $\bar{\psi}\gamma^\mu\psi$ perfectly symmetric for left- and right-handed particles

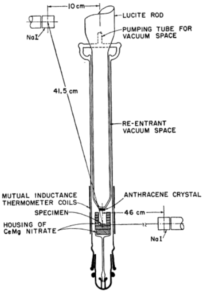
Lee and Yang 1957,
Heintze/Jensen

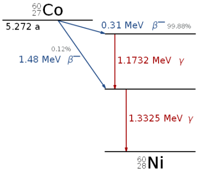
Electroweak Interaction

- violates parity maximally
- has $V - A$ structure
- left-handed behaves differently than right-handed

- left- and right? Spin
- Polarization: average orientation of spin
- Invert polarization and measure at the same location

Wu 1957

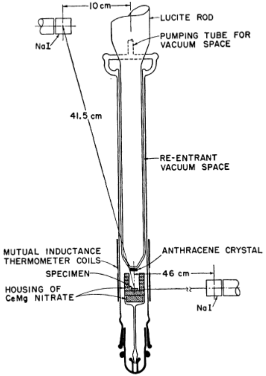




$$\begin{aligned} E_\beta &= 0.3 MeV \\ E_\gamma &= 1.2 MeV \\ E_\gamma &= 1.3 MeV \end{aligned}$$

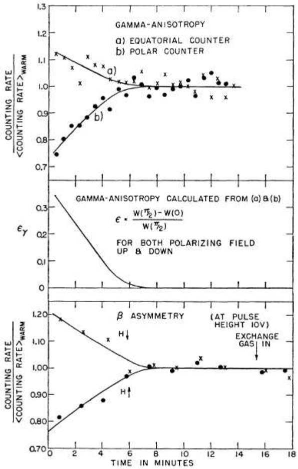
$$\begin{aligned} 60Co &\rightarrow 60Ni^\star + \mathrm{e}^- + \bar{\nu}_{\mathrm{e_L}} \\ n &\rightarrow p + \mathrm{e}^- + \bar{\nu}_{\mathrm{e_L}} \\ 60Ni^\star &\rightarrow 60Ni + \gamma + \gamma \end{aligned}$$

- β small free path
- γ larger free path



- Polarize Co with external field

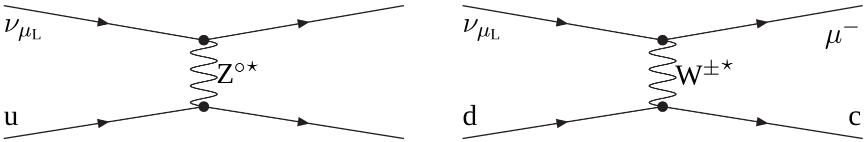
- Polarization: anisotropy of γ-rays (in-time) in two detectors (NaI)
- e detection in Antracene crystal (photons to PM)
- β: (de-)excitation after passage of particles (organic)
- γ: photo-electric effect, pair production ($\sim Z^5$, $\sim Z^2$, anorganic $Z(Na) = 11$, $Z(I) = 53$)



- γ anisotropy: large polarization
- use of two polarizations cancels systematics
- asymmetry opposite to spin direction
- parity violated maximally

Discussion of Garwin experiment on parity violation in Problem Solving session

Z° 1973

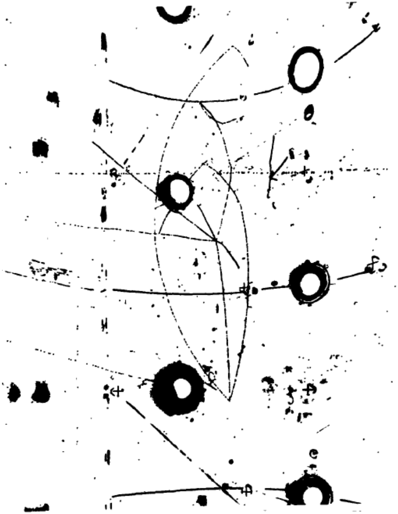


- impossible for photons
- no FCNC
- produce pion from protons
- pions decay to ν_{μ_L}
- detect hadronic final state from nothing

- (CC) charm: charged lepton plus strange
- strange liftime visible (V°)
- vertex: 2 OS leptons
- displaced hadronic vertex

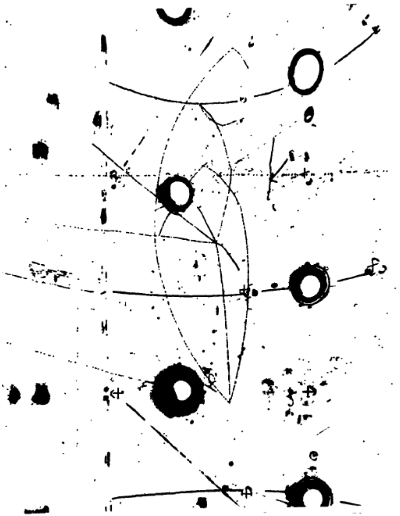
Gargamelle

- Liquid gas (Freon) close to bubbling
- reduce pressure, augment volume $\longrightarrow$ bubbles
- ionizing particles leave bubble traces
- magnetic field for $\vec{p}$
- dE/dx
- picture with KODAK camera



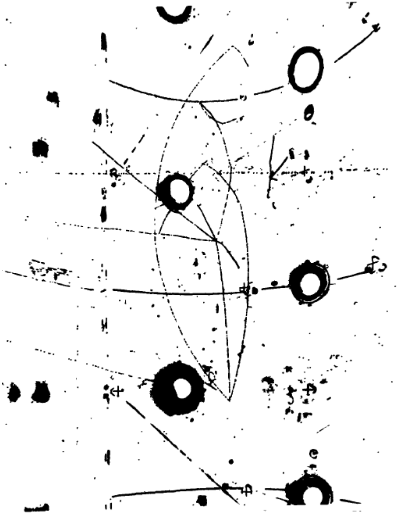
Gargamelle

- Liquid gas (Freon) close to bubbling
- reduce pressure, augment volume → bubbles
- ionizing particles leave bubble traces
- magnetic field for $\vec{p}$
- dE/dx
- picture with KODAK camera



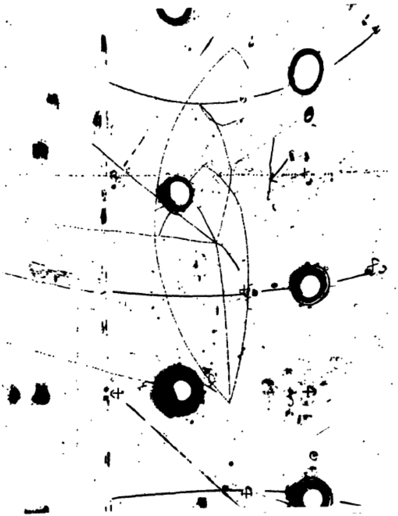
Gargamelle

- Liquid gas (Freon) close to bubbling
- reduce pressure, augment volume $\rightarrow$ bubbles
- ionizing particles leave bubble traces
- magnetic field for $\vec{p}$
- dE/dx
- picture with KODAK camera



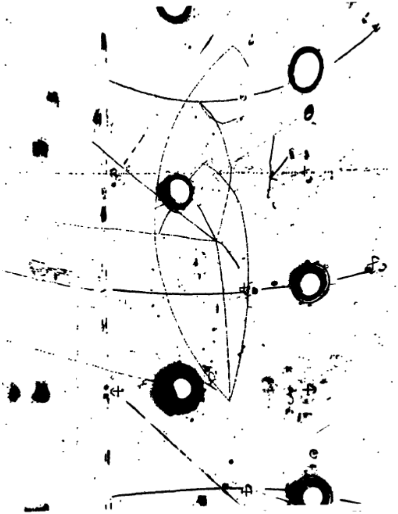
Gargamelle

- Liquid gas (Freon) close to bubbling
- reduce pressure, augment volume $\longrightarrow$ bubbles
- ionizing particles leave bubble traces
- magnetic field for $\vec{p}$
- dE/dx
- picture with KODAK camera



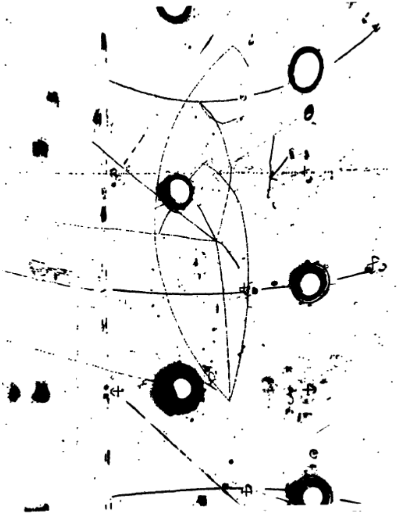
Gargamelle

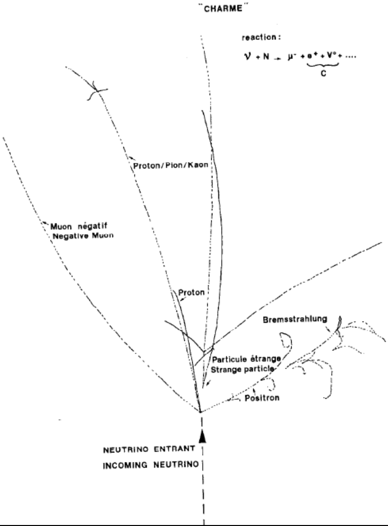
- Liquid gas (Freon) close to bubbling
- reduce pressure, augment volume $\rightarrow$ bubbles
- ionizing particles leave bubble traces
- magnetic field for $\vec{p}$
- dE/dx
- picture with KODAK camera

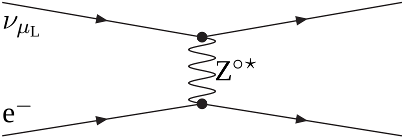


Gargamelle

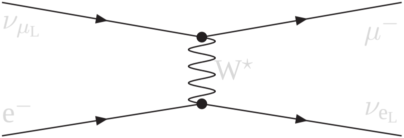
- Liquid gas (Freon) close to bubbling
- reduce pressure, augment volume $\rightarrow$ bubbles
- ionizing particles leave bubble traces
- magnetic field for $\vec{p}$
- dE/dx
- picture with KODAK camera



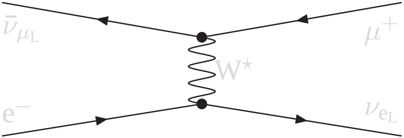

"CHARME"
reaction:
$\nu + N \rightarrow \mu^- + e^+ + V^\circ + ...$
C
Proton/Pion/Kaon
Muon négatif
Negative Muon
Proton
Bremsstrahlung
Particule étrange
Strange particle
Positron
NEUTRINO ENTRANT
INCOMING NEUTRINO



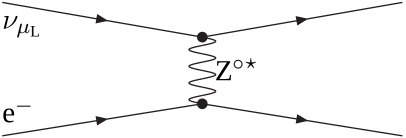
- $g_{eff}(Z^\circ ee) \ll g_{eff}(Z^\circ qq)$
- $N(q) \sim 3N(e)$
- detect electron at 2° beam axis
- signal: Anti-neutrino or neutrino beam
- background: Anti-neutrino beam

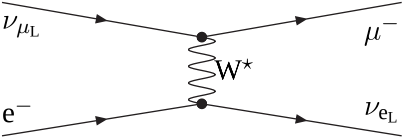


Charged current (CC) background for ν_{μ_L} (PID)



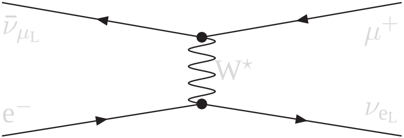
Charge Conservation!!



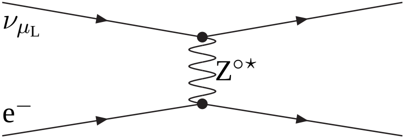


- $g_{eff}(Z^\circ ee) \ll g_{eff}(Z^\circ qq)$
- $N(q) \sim 3N(e)$
- detect electron at 2° beam axis
- signal: Anti-neutrino or neutrino beam
- background: Anti-neutrino beam

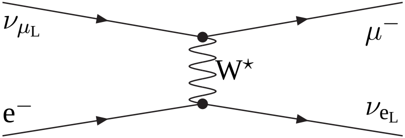
Charged current (CC) background for ν_{μ_L} (PID)



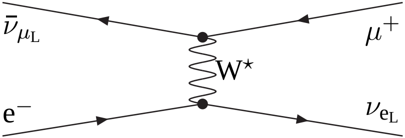
Charge Conservation!!



- $g_{eff}(Z^\circ ee) \ll g_{eff}(Z^\circ qq)$
- $N(q) \sim 3N(e)$
- detect electron at 2° beam axis
- signal: Anti-neutrino or neutrino beam
- background: Anti-neutrino beam

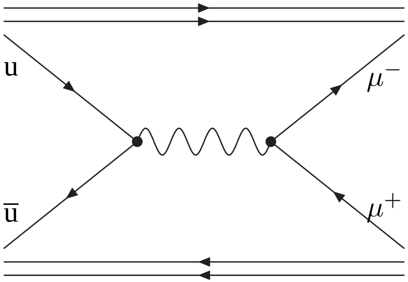


Charged current (CC) background for ν_{μ_L} (PID)



Charge Conservation!!

The Drell-Yan Process



Definition

$$\begin{aligned} h + h &\rightarrow \mu^+\mu^- + X \\ q + \bar{q} &\rightarrow \mu^+\mu^- + X \end{aligned}$$

h: hadrons
X: remnants
neglect fermion masses!
$\mathbf{P_q} = x \cdot \mathbf{P_h}$
$s = (\mathbf{P_q} + \mathbf{P_{\bar{q}}})^2$

$$\sigma(\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

Kinematics

Enter the QPM: $M^2 = \hat{s}$ is CM energy of the partonic system

$$\begin{aligned}
(\mathbf{p_1} + \mathbf{p_2})^2 &= 2 \cdot \mathbf{p_1} \cdot \mathbf{p_2} \\
&= 2 \cdot x_1 x_2 E_1 \cdot E_2 (1 - \cos(\pi)) \\
&= 4 \cdot x_1 x_2 E_1 \cdot E_2 \\
&= 4 \cdot x_1 x_2 \frac{\sqrt{s}}{2} \cdot \frac{\sqrt{s}}{2} \\
&= x_1 x_2 s \\
\frac{1}{s} &= \frac{x_1 x_2}{M^2}
\end{aligned}$$

Drell-Yan

Kinematics and integration $d\Omega$ (same as electron)

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan

Add proton and anti-proton PDFs

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan

Colour Factor Initial state: $\frac{3}{9} = \frac{1}{3}$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan

Electric Charge initial state quark

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan

Differential cross section $d\sigma/d\hat{s}$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\mathrm{q}}^{\bar{p}}(x_2) + f_{\mathrm{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}$$

$$\sigma = \frac{4\pi\alpha^2}{3\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$\sigma = \frac{4\pi\alpha^2}{9\hat{s}}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]$$

$$d\sigma = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(M^2 - \hat{s})dM^2$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(s(\frac{M^2}{s} - x_1x_2))$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{1}{s}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2}Q_q^2\frac{x_1x_2}{M^2}[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)]\delta(\frac{M^2}{s} - x_1x_2)$$

Drell-Yan Scaling

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^4}\sum_q Q_q^2 \int_0^1\int_0^1 x_1x_2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)] \delta(\frac{M^2}{s} - x_1x_2)dx_1dx_2$$

$$M^3\frac{d\sigma}{dM} = 2\frac{4\pi\alpha^2}{9}\sum_q Q_q^2 \int_0^1\int_0^1 x_1x_2[f_q^p(x_1)f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1)f_q^{\bar{p}}(x_2)] \delta(\frac{M^2}{s} - x_1x_2)dx_1dx_2$$

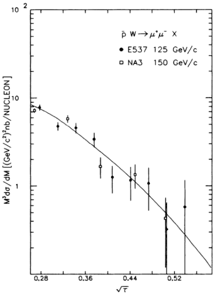
Compare different experiments with $\tau = m/\sqrt{s}$

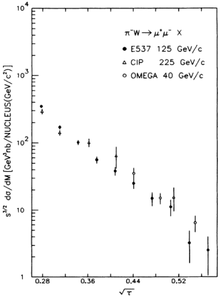
Drell-Yan Scaling

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^4} \sum_q Q_q^2 \int_0^1 \int_0^1 x_1 x_2 [f_q^p(x_1) f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1) f_q^{\bar{p}}(x_2)] \delta(\frac{M^2}{s} - x_1 x_2) dx_1 dx_2$$

$$M^3 \frac{d\sigma}{dM} = 2\frac{4\pi\alpha^2}{9} \sum_q Q_q^2 \int_0^1 \int_0^1 x_1 x_2 [f_q^p(x_1) f_{\bar{q}}^{\bar{p}}(x_2) + f_{\bar{q}}^p(x_1) f_q^{\bar{p}}(x_2)] \delta(\frac{M^2}{s} - x_1 x_2) dx_1 dx_2$$

Compare different experiments with $\tau = m/\sqrt{s}$





- anti-protons on target
- detect muon pairs $\rightarrow m^2$

- pions on target
- scaling observed

Predicted LO: $\frac{1}{3}$, observed $\sim 2 - 3$LO, NLO ~ 3LO :)