Particle Physics: The Standard Model

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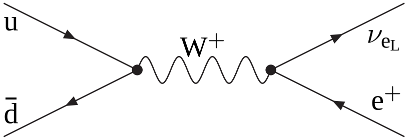
The Pion Decay

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



- $1-\gamma_5$ 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)

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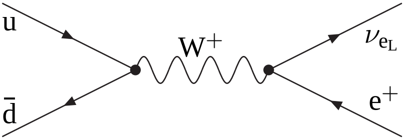

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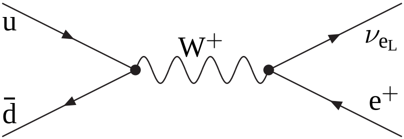

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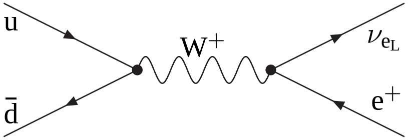

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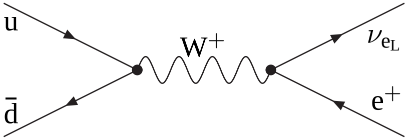

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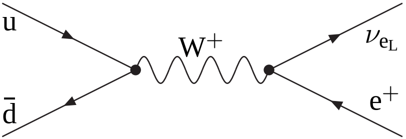

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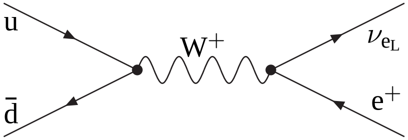

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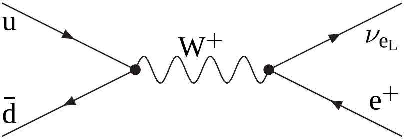

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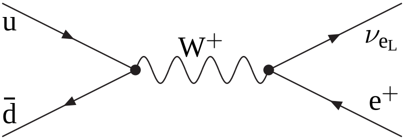

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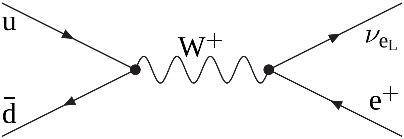

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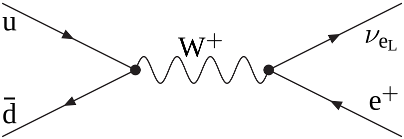

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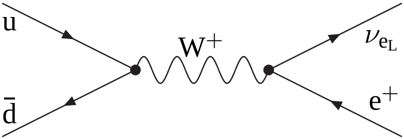

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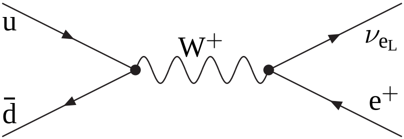

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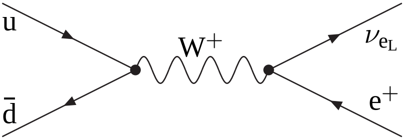

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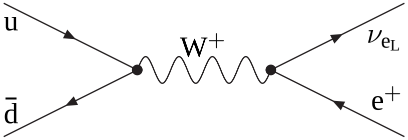

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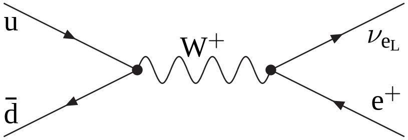

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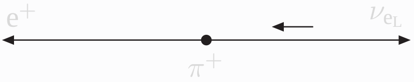
Branching Ration π^+

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

- $m_e \ll m_\mu$ 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!

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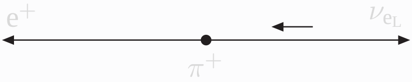

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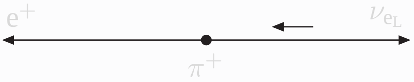

The pion is a scalar!

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

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

Branching Ration π^+

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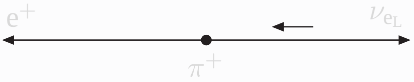

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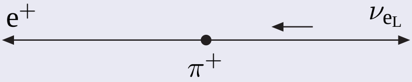

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Parity Tranformation

- $P(\vec{p}) \to -\vec{p}$
- 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

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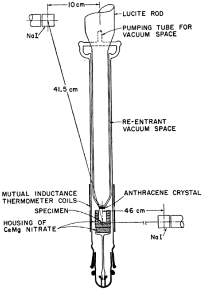
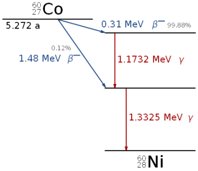
Wu 1957

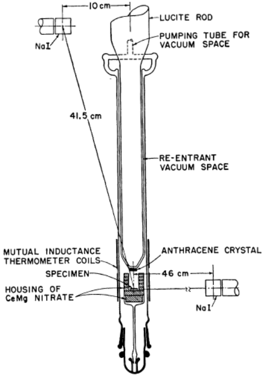




$$
\begin{aligned}
E_\beta &= 0.3 MeV \\
E_\gamma &= 1.2 MeV \\
E_\gamma &= 1.3 MeV
\end{aligned}
$$

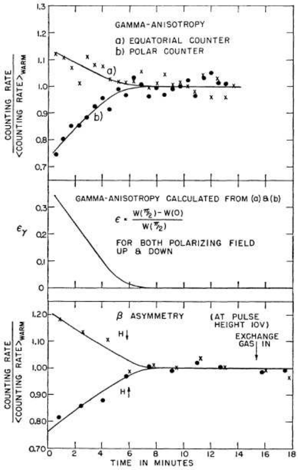
$$
\begin{aligned}
60Co &\rightarrow 60Ni^\star + \mathrm{e}^- + \bar{\nu}_{\mathrm{e_L}} \\
n &\rightarrow p + \mathrm{e}^- + \bar{\nu}_{\mathrm{e_L}} \\
60Ni^\star &\rightarrow 60Ni + \gamma + \gamma
\end{aligned}
$$

- β small free path
- γ larger free path



- Polarize Co with external field

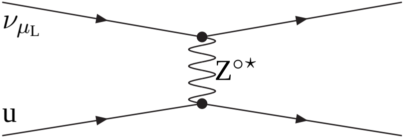
- Polarization: anisotropy of γ-rays (in-time) in two detectors (NaI)
- e detection in Antracene crystal (photons to PM)
- β: (de-)excitation after passage of particles (organic)
- γ: photo-electric effect, pair production ($\sim Z^5$, $\sim Z^2$, anorganic $Z(Na) = 11, Z(Na) = 53$)

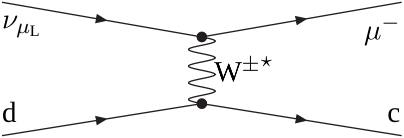


- γ anisotropy: large polarization
- use of two polarizations cancels systematics
- asymmetry opposite to spin direction
- parity violated maximally

Discussion of Garwin experiment on parity violation in Problem Solving session

Z° 1973



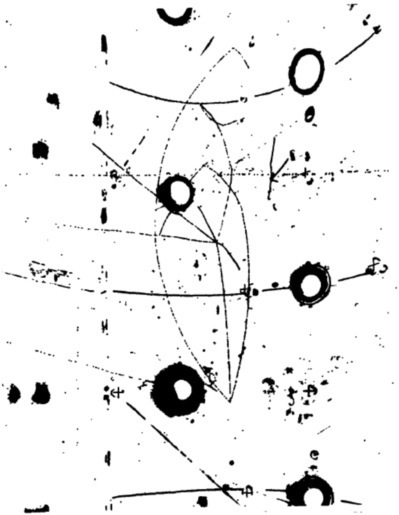


- impossible for photons
- no FCNC
- produce pion from protons
- pions decay to ν_{μ_L}
- detect hadronic final state from nothing

- (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 *rightarrow* bubbles
- ionizing particles leave bubble traces
- magnetic field for $\vec{p}$
- dE/dx
- picture with KODAK camera



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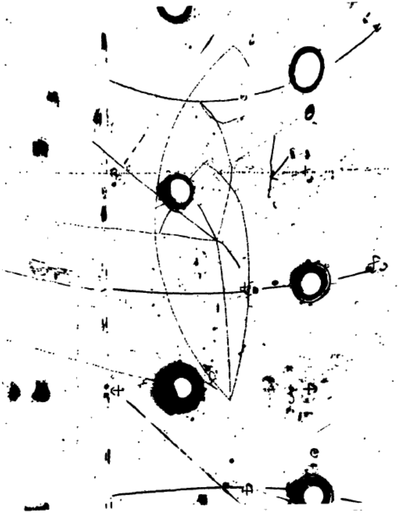

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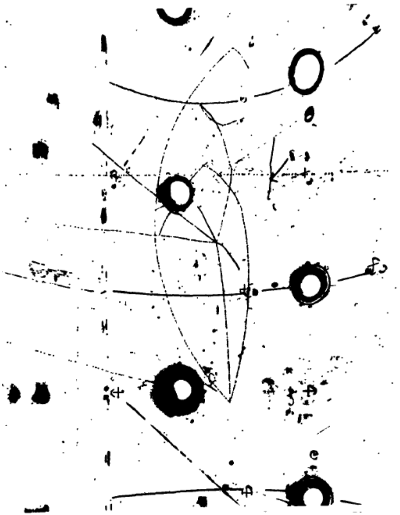

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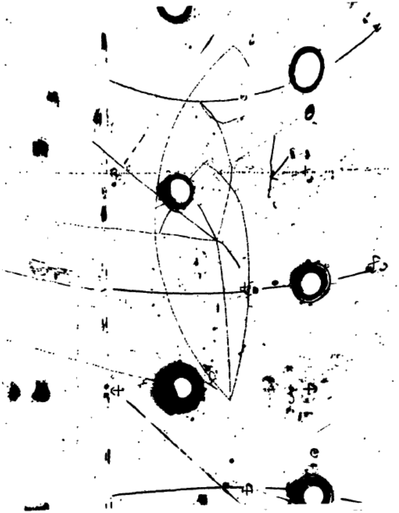

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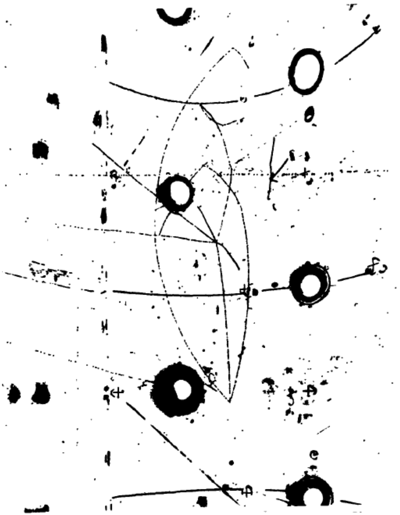

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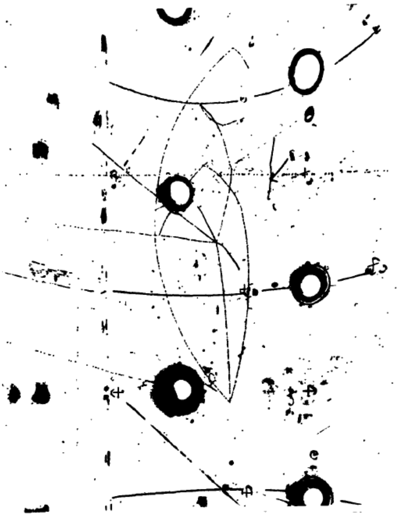
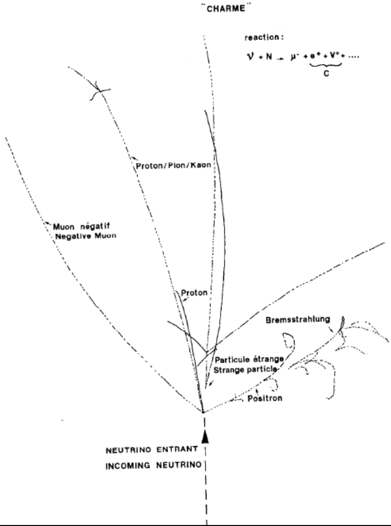
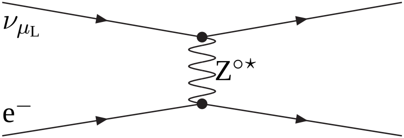
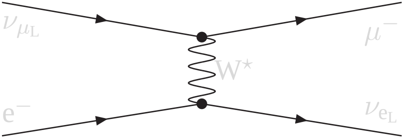


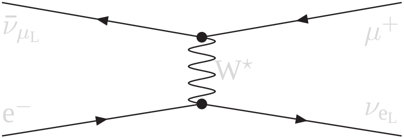

"CHARME"
reaction:
$\nu + N \to \mu^- + e^+ + V^\circ + \ldots$
C
Proton/Pion/Kaon
Muon négatif
Negative Muon
Proton
Bremsstrahlung
Particule étrange
Strange particle
Positron
NEUTRINO ENTRANT
INCOMING NEUTRINO



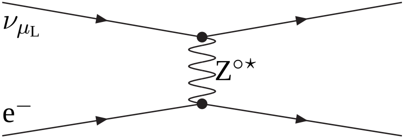


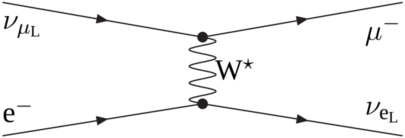
- $g_{eff}(\mathrm{Z^\circ ee}) \ll g_{eff}(\mathrm{Z^\circ}qq)$
- $N(q) \sim 3N(\mathrm{e})$
- detect electron at 2° beam axis
- signal: Anti-neutrino or neutrino beam
- background: Anti-neutrino beam

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



Charge Conservation!!





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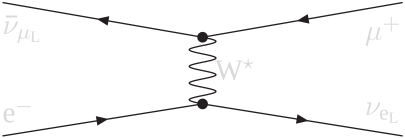

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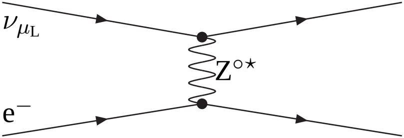

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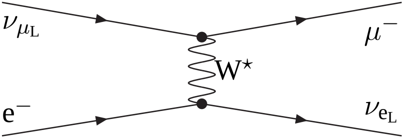

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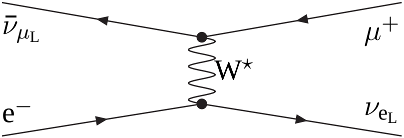
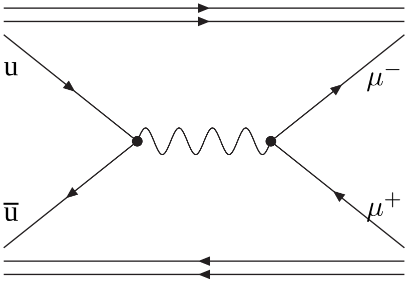


Charge Conservation!!

The Drell-Yan Process



Definition

$$h + h \rightarrow \mu^+\mu^- + X$$
$$\mathrm{q} + \bar{\mathrm{q}} \rightarrow \mu^+\mu^- + X$$

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

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

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)

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

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

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

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

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

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

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Drell-Yan

Add proton and anti-proton PDFs

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

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Drell-Yan

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

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

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Drell-Yan

Electric Charge initial state quark

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

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

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

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

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Drell-Yan

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

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Drell-Yan Scaling

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

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

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

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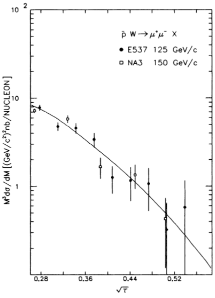

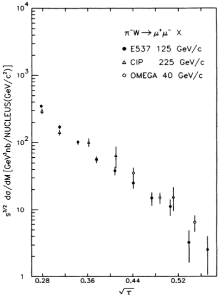

- anti-protons on target
- detect muon pairs $\rightarrow m^2$
- pions on target
- scaling observed

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