

## LECTURE 17: Hadron Structure (Part 3) and QCD (Part 1)

### Overview:

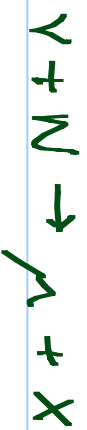
- Deep Inelastic Scattering (charged current)
- Deep Inelastic Scattering (neutral current)

(I used Quigg and Giffiths as references)

## Deep Inelastic scattering (charged current)

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In your first problem (in problem set #3), you calculate the cross section for the reaction:



→ lepton Tensor now has (V-A) structure

The result is:

$$\frac{d^2\sigma^\nu}{dq^2 dv} = \frac{G_F^2}{2\pi} \frac{E'}{E} \left[ 2W_1^\nu \sin^2\left(\frac{\theta}{2}\right) + W_2^\nu \cos^2\left(\frac{\theta}{2}\right) + W_3^\nu \frac{(E+E')}{M} \sin^2\left(\frac{\theta}{2}\right) \right]$$

In terms of  $x$  and  $y$ :

$$\frac{d^2\sigma^\nu}{dx dy} = \frac{G_F^2}{\pi} ME \left[ F_1(x) xy^2 + F_2(x)(1-y) \pm F_3 xy(1-y/2) \right]$$
$$F_3 \equiv \nu W_3^\nu(x)$$

Parton model prediction:

$$\sigma_{TOT}^{\nu N} \rightarrow R(x) \alpha E$$

# Deep Inelastic scattering (charged current)

$$\frac{\sigma}{E} (\nu N \rightarrow l) \approx 6 \times 10^{-34} \text{ cm}^{-2} / \text{GeV}$$

$$\frac{\sigma}{E} (\bar{\nu} N \rightarrow l) \approx 3 \times 10^{-34} \text{ cm}^{-2} / \text{GeV}$$

Also:

$$x \frac{F_3(x)}{F_2(x)} = \begin{matrix} +1 & \text{Fermion Target} \\ -1 & \text{anti-F Target} \end{matrix}$$

Combine with  $2 \times F_1(x) = F_2(x)$  for spin 1/2 partons

gives:

$$\frac{d^2\sigma}{dx dy} (\nu q) = \frac{G_F^2 M E}{\pi} F_2(x)$$

$$\frac{d^2\sigma}{dx dy} (\bar{\nu} q) = \frac{G_F^2 M E}{\pi} (1-y)^2 F_2(x)$$

why?

→ reproduces the form of previous sections with charged current interaction.

# Deep Inelastic scattering (charged current)

with the approx.:  $\cos \theta_c = 1$

$$F_2^{\nu}(x) = 2x (d(x) + \bar{u}(x))$$

$$F_3^{\nu}(x) = 2(d(x) - \bar{u}(x))$$

and  $F_2^{\bar{\nu}}(x) = 2x (u(x) + \bar{d}(x))$

$$F_3^{\bar{\nu}}(x) = 2(u(x) - \bar{d}(x))$$

Note That:

$$F_2^{\nu p} + F_2^{\nu n} = 2x (u(x) + \bar{u}(x) + d(x) + \bar{d}(x))$$

is proportional to:  $\frac{F_2^{\nu p} + F_2^{\nu n}}{F_2^{\nu p} + F_2^{\nu n}} = \frac{5}{18}$  (avg. 5 quarks)

→ ~ gluons carry ~50% of proton momentum which does not interact through weak and em forces

## Deep Inelastic scattering (charged current)

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→ also note that  $F_3^v$  measures the difference between quark and anti-quark contributions and  $F_3$  measures the sum.

$$F_3^{vp} + F_3^{vn} = 2(\nu - \bar{\nu} + d - \bar{d})$$

→ baryon number sum rule:  $\int_0^1 dx (F_3^{vp}(x) + F_3^{vn}(x)) = 6$

Consider a nucleus with  $N \equiv \frac{1}{2}(p+n)$

the charged xs are:

$$\frac{d\sigma^2}{dx dy}(\nu N \rightarrow \mu^+ X) = \frac{G_F^2 M E}{\bar{\nu}} \times [\nu(x) + \bar{d}(x) + (\bar{\nu}(x) + \bar{d}(x))(1-y)^2]$$

$$\frac{d\sigma^2}{dx dy}(\bar{\nu} N \rightarrow \mu^+ X) = \frac{G_F^2 M E}{\bar{\nu}} \times [\bar{\nu}(x) + \bar{d}(x) + (\nu(x) + d(x))(1-y)^2]$$

# Deep Inelastic scattering (neutral current) ⑥

For neutral currents:

$$\frac{d\sigma^2}{dx dy} (\nu N \rightarrow \nu X) = \frac{G_F^2 M E}{y_i} \times [L_\nu^2 + L_d^2] \left[ (|\nu(x) + d(x)| + |\bar{\nu}(x) + \bar{d}(x)|) + (1-y)^2 \right] + (R_\nu^2 + R_d^2) \left[ (|\nu(x) + d(x)|(1-y)^2 + |\bar{\nu}(x) + \bar{d}(x)|) \right]$$

except swap  $(1-y)^2$  Terms

if we neglect anti-quark Terms we obtain the ratios:

$$R_\nu \equiv \frac{\sigma(\nu N \rightarrow \nu X)}{\sigma(\bar{\nu} N \rightarrow \bar{\nu} X)} = \frac{1}{2} - x_w + \frac{20x_w^2}{27}$$

$$R_{\bar{\nu}} \equiv \frac{1}{2} - x_w + \frac{20x_w^2}{9}$$

$$x_w \approx 0.23$$

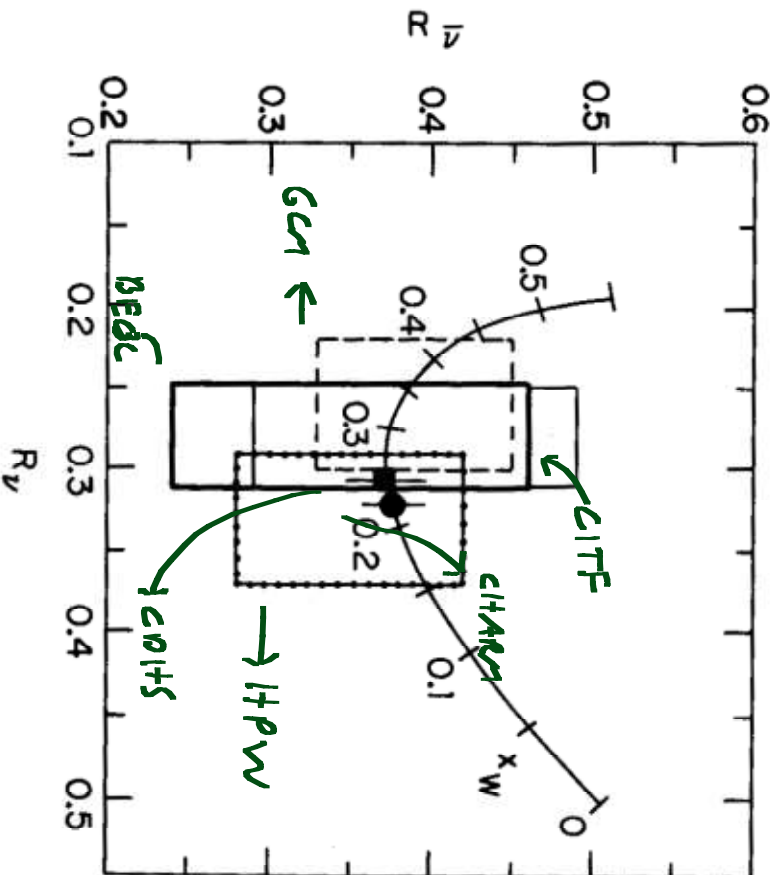
$$\rightarrow R_\nu = 0.31$$

$$R_{\bar{\nu}} = 0.39$$

# Deep Inelastic scattering (charged current)

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Ratios of  $R_V$  and  $R_V^i$  from various experiments:



We can also observe  $\gamma$ -Z interference effects in deep inelastic scattering.

$$\frac{d^2\sigma}{dx dy} (\text{ep} \rightarrow \text{ex}) = \text{em Term} + \text{weak Term} + \text{interference Term}$$

# Deep Inelastic scattering (neutral currents)

Asymmetry for  $Q^2 \ll M_Z^2$  :

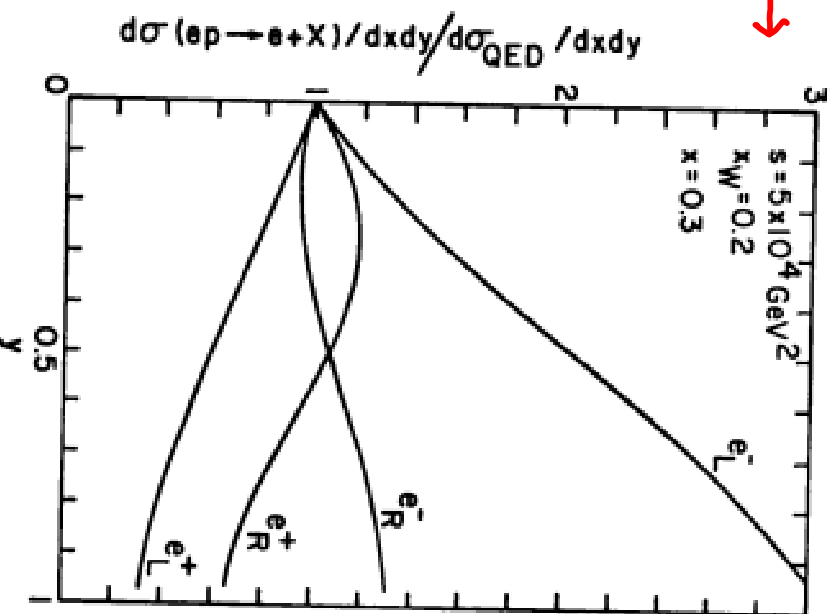
$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \cdot \frac{g}{5} \left(1 - \frac{20x_W}{9}\right)$$

$\frac{A}{Q^2} \approx -7 \times 10^{-5} \rightarrow$  small, observed by SLAC-YALE collaboration

AT higher energies →

effect becomes of order 1

Polarized at high energy beams were used at DESY.





# Hadron-Hadron Interactions

$$\sigma(a+b \rightarrow c+X) = \sum_{i,j} F_i^{(a)}(x_a) F_j^{(b)}(x_b) \hat{\sigma}(i+j \rightarrow c+X')$$

- Invariant mass of  $i, j$  system  $M = \sqrt{s}$   
 ↳ dimensionless parameter

$i, j$  system longitudinal momentum in hadron-hadron in c.m. :

$$p = x\sqrt{s}/2$$

$$- x_{a,b} = \frac{1}{2} [(x^2 + 4\eta^2)^{1/2} \pm x]$$

## Drell-Yan Production

$$a+b \rightarrow l+l' + X$$

$$q+\bar{q} \rightarrow \gamma \rightarrow l+l'$$

invariant mass  $M$

# HADRON-HADRON INTERACTIONS

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diff. cross section given by:

$$\frac{d\sigma}{d\Omega dx} = \left( \frac{4\pi\alpha^2}{3M^4} \right) F(\gamma, x)$$

↳ as in  $e^+e^- \rightarrow \mu^+\mu^-$

$$F(\gamma, x) = \frac{x_a x_b}{(x^2 + 4\gamma)^{1/2}} g(x_a, x_b)$$

$$\rightarrow g(x_a, x_b) = \frac{1}{3} \sum_i e_i^2 [q_i^a(x_a) \bar{q}_i^b(x_b) + \bar{q}_i^a(x_a) + q_i^b(x_b)]$$

