THE GLUON DENSITY

EXTREMELY IMPORTANT

FOR THEORY: QUANTITATIVE EVIDENCE FOR GLUONS
QUARKS → HADRONS
GLUONS → NO GLUE-BALLS!
LATTICE (1.4-1.5 GeV)

TO BE ADDED TO "GLUON AS JET"
e+e− → 3 Jets, γ → ggg,
pp → W + jet + X; W/2 pt DISTRIB.

FOR PRACTICE: MANY PROCESSES GO BY
GLUON-GLUON OR
GLUON-QUARK FUSION

gg → gg, gg → QQ, gg → H

... HEAVY QUARK

gg → qg, ...

ALSO NEW PHYSICS e.g. gg → g g

UNFORTUNATELY GLUONS ARE ONLY
INDIRECTLY SEEN IN D. I. S.
GLUONS NECESSARY

NO GLUONS

Fitting scaling violations leads to $\Lambda$ and $g(x, Q^2)$ (correlated)
$\bar{p}p \rightarrow \text{jet + jet}$ at large $p_T$ also needs gluons:

$$F(x) = G(x) + \frac{4}{D F_2(x)}$$

Fig. 5.8
NEW CDF DATA

- Inclusive Jet $E_T$ distribution

![Graph showing inclusive jet $E_T$ distribution](image)

$E_T$(GeV)

WHEN SO MANY ORDERS OF MAGNITUDE ARE INVOLVED EVEN PREDICTION "WITHIN A FACTOR OF 2" BECOMES EXTREMELY SELECTIVE

NON LEADING CALCULATION (K. ELLIS, SATON) AWAITS FOR "JET DRESSING" (CHIAPPETTA, GRECO...)
Jet Angular distribution at $\sqrt{s} = 1.8$ TeV

CDF Preliminary

- $M_{jj} > 104$ GeV (normalized to QCD)
- $M_{jj} > 140$ GeV (normalized to $x$)
- $M_{jj} > 164$ GeV (normalized to $\sigma$)

$Q^2 = 2 - P_T^2$, $D = 0.1$, Lambda = 0.29

$(\sin\theta)^{-4}$ singularity typical of vector gluons

$q\bar{q}' \rightarrow q\bar{q}'$

$qq \rightarrow gq$

$gg \rightarrow gg$
IN PRINCIPLE IS A GOOD GLUON-METER

COMPLETE NON-LEADING CALCULATIONS
Aurenche, Bain, Fontanner, Schiff ...

\[ \sqrt{s} = 630 \text{GeV} \quad \eta = 0 \]

- Jet (UA1)
- 1 \( \gamma \) (UA1)
- 2 \( \gamma \) (UA1)
- 1 \( \gamma \) (UA2)

STIRLING \((x \times 1.5)\)

23\% Syst. Error

70\% Syst. Error

Fig. 6
UA6 \( \bar{p}p \) at \( \sqrt{s} = 24 \text{ GeV} \)

PRELIMINARY

CERN - LAUSANNE - MICHIGAN - ROCKEFELLER
$\pi^{-} - \pi^{+}$

$E d^3 \sigma / d^3 p [\text{pbarn GeV}^{-2}]$

$P_T$ (GeV/c)

$\Lambda_{MS} = 200$ MeV
WA70

\[ p p \rightarrow \gamma \]
\[ \text{ALL } |x_F| < 0.45 \]

\[ \frac{E_\gamma^3}{d \sigma^3} \text{ (pbarn.GeV)} \]

\[ p' \text{ (GeV/c)} \]

Similar data also from NA-24
\[ Q^2 = \frac{4}{3} P_T^2 \]

\[ (Q^2) = 40 \text{ GeV}^2/c^2 \]

This exp.

--- CDHS [1]
The old model is now obsolete.

More recent data support a softer gluon.

Sets of structure functions based on CDHS gluon to be revised [DO, EHLG, ...]

DFLM based on charm data.

\[ G(x) \text{ at } Q^2 = 10 \text{ GeV}^2 \]

\[ \begin{align*}
\text{CDHS} & \quad \text{---} \\
\text{CHARM} & \quad \text{----} \\
\end{align*} \]

MRS based on J/\Psi production \( \gamma \) at large \( p_T \).
The shape of $\frac{d\sigma}{dx}$ for $\gamma$ production confirms that gluon is softer than old "CDHS."
CHARM GLUON PARAMETRIZATION
CENTRAL, HARD AND SOFT LIMITS
COMPATIBLE WITH ALL EXP. UNCERTAINTIES
\( \int G \, dx = 0.52 \)

\[ G(x) \]

\( \Lambda = 260 \, \text{MeV} \)
\( \Lambda = 260 \, \text{MeV} \)
\( \Lambda = 360 \, \text{MeV} \)

Variation of charm quark fit for different values of \( \Lambda \)
BCDMS is now starting to produce gluons (with no \((1-x)^A\) bias).

N.L.O. BCDMS $H_2$ $Q_0^2 = 5.$

(Errors are correlated!)

Consistent with CHARM supports soft gluons.
CHARM

$Q^2 = 5.0 \text{GeV}^2$

$Q^2 = 4.3 \text{GeV}^2$

$Q^2 = 5 \text{GeV}^2$
BCDMS: Assume \( g(x) = (n + 1)(1-x)^n \) at \( Q^2 = 5 \text{ GeV}^2 \)

Determine \( n \) from best fit to the slopes.
DEEP INELASTIC SCATTERING ON POLARIZED PROTONS

VERY INTERESTING EMC RESULT:

\[ g_1^p(x, Q^2) \sim \frac{\sigma_{\uparrow} - \sigma_\downarrow}{\sigma_{\uparrow} + \sigma_\downarrow} \]

\[ \int_0^1 dx \, g_1^p(x, Q^2) = 0.114 \pm 0.012 \pm 0.026 \]

\[ \approx 0.114 \pm 0.029 \quad \text{ERRORS IN QUADRATURE} \]

\[ \langle Q^2 \rangle \approx 12.7 \text{ GeV}^2 \]

INTRIGUING BECAUSE IT IMPLIES THAT THE TOTAL HELICITY CARRIED BY \( q \) AND \( \bar{q} \) IN THE PROTON IS ZERO!

\[ S_p = \frac{1}{2} q + G + L_z \]

PROBABLY DUE TO \( L_z \)
NAIVE PARTON MODEL:
\[
\begin{align*}
\Delta q_i^p &= \frac{1}{2} \sum_i e_i^2 (q_i^+ - q_i^-) = \Delta q_i \\
\int dx \, \Delta q_i^p &= \frac{1}{2} \sum_i e_i^2 \int dx (q_i^+ - q_i^-) \\
&= \frac{1}{2} \sum_i e_i^2 \left( \text{number} \ q_i^+ - \text{number} \ q_i^- \right) \\
&= \sum_i e_i^2 \langle p, s \mid \bar{q}_i(0) \gamma_5 q_i(0) \mid p, s \rangle
\end{align*}
\]


Thus:
\[
\begin{align*}
\int_0^1 dx \, \Delta q_i^p &= \frac{1}{2} \left[ \frac{4}{3} \Delta u + \frac{1}{3} \Delta d + \frac{1}{3} \Delta s \right] \\
\int_0^1 dx \, \Delta q_i^m &= \frac{1}{2} \left[ \frac{4}{3} \Delta d + \frac{1}{3} \Delta u + \frac{1}{3} \Delta s \right]
\end{align*}
\]

\[
\Delta u = \int dx \left( u_+ + \bar{u}_+ - u_- - \bar{u}_- \right)
\]

\[
\frac{1}{2} \Delta u = \langle p, s \mid \bar{u} \gamma_\mu \gamma_5 u \mid p, s \rangle
\]

Bjorken Sum Rule:
\[
\int_0^1 dx (\Delta q_i^p - \Delta q_i^m) = \frac{1}{6} (\Delta u - \Delta d) = \frac{1}{6} \frac{g_A}{g_V}
\]
\[ S \Delta x g_1^A = \frac{1}{2} \left( \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right) = \]
\[ = \frac{1}{12} \left[ (\Delta u - \Delta d) + \frac{1}{3} (\Delta u + \Delta d - 2\Delta s) + \right. \]
\[ \left. + \frac{4}{3} (\Delta u + \Delta d + \Delta s) \right] \]

\[ \Delta u - \Delta d = \frac{g_A}{g_V} = F + D \Rightarrow \bar{q} \gamma_{\mu} X_5 \lambda^3 q \]

\[ \Delta u + \Delta d - 2\Delta s = 3F - D \Rightarrow \bar{q} \gamma_{\mu} X_5 \lambda^8 q \]

\[ \Delta u + \Delta d + \Delta s = \text{fit from ENC} \Rightarrow \bar{q} \gamma_{\mu} X_5 \lambda^0 q \]

\[ \lambda^i \ (i=1...8) \text{ are Gell-Mann SU(3)} \text{ flavour matrix} \]

\[ \lambda^0 \text{ is the identity in SU(3) space} \]

\[ \text{fit to hyperon decays:} \]

\[ F = 0.477 \pm 0.011 \]

\[ D = 0.755 \pm 0.011 \]

\[ \left( \frac{g_A}{g_V} \approx 1.232 \right) \]

\[ \text{(Actually } \frac{g_A}{g_V} \text{ is a bit larger)} \]
\[ \text{SU}(6) \text{ LIMIT:} \]

\[ \Delta u = \frac{4}{3} \]
\[ \Delta d = -\frac{1}{3} \]
\[ \Delta s = 0 \quad (\text{Jaffe, Jaffe, 1974}) \]

\[ \implies \Delta u - \Delta d = 9a / g_u = F + D = \frac{5}{3} \]
\[ \Delta u + \Delta d = 3F - D = 1 \quad \left\{ \begin{array}{l} F = \frac{2}{3} \\ D = 1 \end{array} \right. \]

AND THE SPIN OF THE PROTON IS:

\[ s = \frac{1}{2} = \frac{1}{2} (\Delta u + \Delta d) \]

ALL THE PROTON SPIN IS CARRIED BY U AND D

SU(6) IS NOT SO GREAT

(EVEN WORSE IN A MOMENT)
QCD EFFECTS.

GLUON RADIATION DOES NOT ALTER THE QUARK HELICITY $q_L^q q_R^q q_L^q q_R^q$

NOT POLARIZED

$\Delta u, \Delta d, \Delta s$ DO NOT VARY WITH $Q^2$!

[AT $\mathcal{O}(\alpha_s)$]

THE ONLY SMALL QCD EFFECT AT $\mathcal{O}(\alpha_s)$ IS A
NON LOG. DISTORTION OF COEFFICIENTS

\[
\frac{1}{12} \left\{ \left[ \frac{\Delta u - \Delta d}{3} \right] + \frac{4}{3} \left( \frac{\Delta u + \Delta d - 2\Delta s}{3} \right) \right\} \cdot \left( 1 - \frac{\alpha_s(Q^2)}{\pi} \right) + \frac{4}{3} \left( \frac{\Delta u + \Delta d + \Delta s}{2} \right) \left( 1 - \frac{\alpha_s(Q^2)}{\pi} \right)
\]

FOR EXAMPLE: Bjorken Sum Rule:

\[
\frac{1}{12} \int_0^1 dx \, g_1^A(x, Q^2) = \frac{1}{6} \frac{g_A^P}{g_V^*} \left( 1 - \frac{\alpha_s(Q^2)}{\pi} + \ldots \right)
\]

ONE FINDS

$\Delta u = 0.74 \pm 0.08$
$\Delta d = -0.51 \pm 0.08$
$\Delta s = -0.23 \pm 0.08$

$\Delta u + \Delta d + \Delta s = 0.00 \pm 0.24$

BINGO!
ELASTIC $^3\text{He} + p \rightarrow ^3\text{He} + p$ SCATTERING IS ALSO SENSITIVE TO $\Delta S$. WOHLFENSTEIN, GEORGI, ET AL., AND J. ELLIS, KARLINER MEASURES THE MATRIX ELEMENT OF THE AXIAL $Z$ CURRENT

$$Z : \chi [T^3(1-\delta s) - \frac{2}{3} \sin^2\theta W] \Rightarrow$$

F THE WEAK ISOSPIN

$$(p, s) \rightarrow (p, s)$$

$$\Rightarrow \Delta u - \Delta d - \Delta s$$

Ahrens et al. FIND

$$\Delta s = \frac{\delta a}{\sqrt{\delta v}} (0.12 \pm 0.07) = -0.15 \pm 0.09$$

CFR EMC: $-0.23 \pm 0.08$

BRODSKY, J. ELLIS, KARLINER

CHIRAL LIMIT ($m_q = 0$)

LEADING ORDER IN $1/\Lambda_c$

JAFFE RAPID DECREASE OF $A_0$ WITH $Q^2$ DUE TO NON-CONSERV. BY ANOMALY.
CONCLUSION

EMC DIS ON POL. P IMPLIES

\[ \Delta u + \Delta d + \Delta S = 0.00 \pm 0.24 \]

THE TOTAL AMOUNT OF PROTON HELICITY CARRIED BY \( q \) AND \( \bar{q} \)

\[ \leq 35\% \] 90 c.e.

THE MATRIX ELEMENT OF THE SU(3) SINGLET AXIAL CURRENT IS COMPATIBLE WITH ZERO

\[ \langle \psi \bar{\psi} \sum \frac{1}{i} q_i \gamma_\mu \gamma_5 q_i \mid p.s. \rangle = 0. \]

\( \Delta u, \Delta d, \Delta S \) CONSERVED BY \( 0(\alpha_s) \) QCD EVOLUTION ARE SEPARATELY LARGE, BUT CANCEL.

ELASTIC \( \bar{u}p \) SCATTERING SUPPORT EMC AN OPEN PROBLEM!
W/Z Production

CDF MEASURED $\sigma^W B(W \rightarrow \nu \overline{\nu})$ AT $\sqrt{s} = 1.8$ TeV:

$$\sigma^W B = 2.57 \pm 0.56 \pm 0.46 \text{ nb}$$

$$= 2.57 \pm 0.73 \text{ nb}$$

QCD PREDICTS [ $\sin^2 \theta_W = 0.23$, $M_W = 80.8$ GeV, $M_Z = 92$ GeV ]

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma^W (\text{nb})$</th>
<th>$\sigma^Z (\text{nb})$</th>
<th>$M_t$</th>
<th>$B^W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.54</td>
<td>4.3 $\pm$ 1.3</td>
<td>1.4 $\pm$ 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.63</td>
<td>5.4 $\pm$ 1.6</td>
<td>1.7 $\pm$ 0.5</td>
<td>40</td>
<td>0.089</td>
</tr>
<tr>
<td>1.6</td>
<td>17 $\pm$ 2.5</td>
<td>5.1 $\pm$ 1.2</td>
<td>60</td>
<td>0.100</td>
</tr>
<tr>
<td>1.7</td>
<td>19 $\pm$ 2.6</td>
<td>5.8 $\pm$ 1.6</td>
<td>$\geq 80$</td>
<td>0.109</td>
</tr>
<tr>
<td>1.6</td>
<td>21 $\pm$ 4.0</td>
<td>6.4 $\pm$ 1.9</td>
<td>IF $m_t \uparrow$</td>
<td>$\sigma^W \uparrow$</td>
</tr>
</tbody>
</table>

THUS

$M_t = 60 \text{ GeV}$

$\sqrt{s} = 1.8$ TeV

$\sigma^W B = 2.57 \pm 0.73 \text{ nb}$

THE "CENTRAL" VALUES HERE ARE OBTAINED BY DIEMEZ ET AL STRUCTURE FUNCTIONS

NOTE: BCDSM DATA (ON H) FAVOUR UPPER EDGE OF ERROR BAND.
\[ \sqrt{s} \]

Note: $\sigma$ not $\sigma_\pi$

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma^+\sigma^-$ ($M_\pi = 83$ GeV) (nb)</th>
<th>$\sigma^\pi$ ($M_\pi = 94$ GeV) (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.54</td>
<td>4.2$^+\ _{-1.3}$ 1.3$^+\ _{-0.6}$</td>
<td>1.3$^+\ _{-0.4}$ 0.2</td>
</tr>
<tr>
<td>0.63</td>
<td>5.3$^+\ _{-1.6}$ 1.6$^+\ _{-0.9}$</td>
<td>1.6$^+\ _{-0.5}$ 0.3</td>
</tr>
<tr>
<td>1.6</td>
<td>16.0$^+\ _{-4.0}$ 4.0$^+\ _{-2.5}$</td>
<td>4.9$^+\ _{-1.2}$ 0.8</td>
</tr>
<tr>
<td>2.0</td>
<td>20.0$^+\ _{-6.0}$ 6.0$^+\ _{-4.0}$</td>
<td>6.2$^+\ _{-1.9}$ 1.2</td>
</tr>
<tr>
<td>10.0</td>
<td>75.0$^+\ _{-35.0}$ 27.0$^+\ _{-25.0}$</td>
<td>27.0$^+\ _{-20.0}$ 9.0</td>
</tr>
<tr>
<td>20.0</td>
<td>130.0$^+\ _{-70.0}$ 46.0$^+\ _{-55.0}$</td>
<td>46.0$^+\ _{-20.0}$ 24.0</td>
</tr>
<tr>
<td>40.0</td>
<td>190.0$^+\ _{-108.0}$ 70.0$^+\ _{-120.0}$</td>
<td>70.0$^+\ _{-30.0}$ 12.0</td>
</tr>
</tbody>
</table>

\[ \frac{\text{TeV}}{\gamma} \sim 3 \pm 4 \]

Fig. 6: Centre point

In this production antiparticle the cross-section varies in such a way that a double fixed target production Fig. 7.

Fig. 5: Total-cross-sections for the production of $W^+ + W^-$ ($M_\pi = 83$) and hypothetical $W$s of heavier mass vs. centre of mass energy. The solid line is for proton-antiproton collisions and the dashed line for proton-proton collisions. (Distributions DOI, $A = 0.2$ GeV)
There is disagreement between BCDMS and EMC in $H$ (i.e. beyond the declared systematics).
Fig. 11. BCDMS data on the structure function $F_2^p$ compared to the parametrizations of GHR, DO1, EHLQ1; only statistical errors are indicated, the systematics are ±3% at low $x$. 
IT IS INTERESTING TO OBSERVE THAT
BCDMS ALSO FITS DRELL-YAN BETTER²

![Graph showing data points for different experiments including CFS, NA3, and pp at two different energies.](Image)

Fig. 5
Measuring $\alpha_s(M_W)$ from $W^+W^-/W+0\mu^+$

UA2 has found (Thesis by V. Ruhmann)

$$\alpha_s(M_W) = 0.12 \pm 0.03 \pm 0.03$$

(We expect $0.11 \pm 0.01$)

Method limited by

- Incomplete calculation of $k$ factors (need $O(\alpha_s^2)$ to $O(\alpha_s^4)$)

- Need of Monte Carlo simulation to complete missing $k$-factors to implement "jet dressing"

To make detector simulation

However, promising for the future

$$\alpha_s = \text{value} \pm 0.006 \pm 0.02$$
THE OBSERVED RATIO \(( UA1/UA2) \)

\[ R = \frac{\sigma_B(W \rightarrow e\nu)}{\sigma_Z(Z \rightarrow e\nu)} \]

depends on \( m_L \) and \( N_{\nu} \) through 
\[ 3(W \rightarrow e\nu) \quad \text{and} \quad B(Z \rightarrow e\nu). \]

\[ R_{\text{Exp}} = \frac{\sigma_W \Gamma(W \rightarrow e\nu)}{\sigma_Z \Gamma(Z \rightarrow e\nu)} \frac{\Gamma_Z}{\Gamma_W}. \]

COMPUTED

(NO NEW CHARGED LEPTON
\( 41 \text{GeV} < m_L < 110 \text{GeV} \))

\[ R_{\sigma}(QCD) = 3.28 \pm 0.15 \quad \text{DFLM} \]

CONCLUSION:

\begin{itemize}
  \item \( N_{\nu} \leq 5 \) \quad (90\% \text{ c.e.})
  \item NO SIGNIFICANT UPPER LIMIT ON \( m_L \)
  \item CORRELATION:
    \begin{align*}
      \text{IF} \quad N_{\nu} \uparrow, \quad m_L & \downarrow \\
    \end{align*}
\end{itemize}

COMPARABLE LIMITS ON \( N_{\nu} \) FROM \( e^+e^- \), NUCLEOSYNTHESIS.
Fig. 5. Comparison of EMC and BCDMS (preliminary) data on $F_2^u/F_2^p$ with predictions from various sets of structure functions at appropriate $Q^2$. 
The determination of $R_0$ is clearly crucial for this purpose.

![Graph showing the dependence of $R_0$, the ratio of W to Z production cross sections, on $\sin^2 \theta_W$ for various choices of structure functions: Duke and Owens sets 1 and 2; Glück, Hoffman and Reya; Eichten, Hinchliffe, Lane and Quigg sets 1 and 2; Diemoz, Ferroni, Longo, Martinelli.](graph.png)

Fig. 4. Dependence of $R_0$, the ratio of W to Z production cross sections, on $\sin^2 \theta_W$ for various choices of structure functions: Duke and Owens sets 1 and 2; Glück, Hoffman and Reya; Eichten, Hinchliffe, Lane and Quigg sets 1 and 2; Diemoz, Ferroni, Longo, Martinelli.
Fig. 7. Compilation of the results on $R_\sigma = \sigma_W/\sigma_Z$. (*) these results have been rescaled to $\sin^2 \theta_W = 0.230$, the present world average. (**) values neglect systematic uncertainties and do not include the BCDMS data.
Empirical by this measurement.

Combined measurement of $R$ and the hatched lines are the 90% and 95% C.L. upper limits.

Fig 1.a. The curves are the predictions for the ratio $R$ as a function of $m_{\text{W}^0}$ with the theoretical

\[
\text{R}_{\text{CENTRAL}} = \frac{R_{\Omega}}{R_{\odot}}
\]

For $\frac{R_{\Omega}}{R_{\odot}} = 3.25$.

$\text{N} = 3$.

90% C.L. upper limit (VLA + VLS).

55% C.L. upper limit (VLA + VLS).

ENRON.

STUBERNAUER

CALS (GENIE),
NEW DEVELOPMENTS ON HEAVY QUARK PRODUCTION

NON LEADING CORRECTIONS FINALLY COMPLETELY COMPUTED
NASON, DAWSON, K. ELLIS

RESULTS ALREADY AVAILABLE FOR TOTAL CROSS-SECTIONS.
PT AND Y DISTRIBUTIONS PUBLISHED SHORTLY
PHOTOPRODUCTION ALSO IN PREPARATION

PHYSICAL IMPLICATIONS
THEORETICAL ERRORS
COMPARISON WITH EXPERIMENTS ON B AND C PRODUCTION
LE HADRON LOWER LIMIT
G.A. DIEMEZ, MARTINELLI, NASON

GIVES PRECISE STATUS OF FLAVOUR EXCITATION
GWON SPLITTING, DIFFRACTION PRODUCTION
BASIC FORMULAE

\[ \sigma(S) = \sum_{ij} \int \frac{dx_1 dx_2}{S} \hat{\sigma}(x_1, x_2, S, m^2, \mu^2) \frac{F_i^A(x_1, \mu^2) F_j^B(x_2, \mu^2)}{\text{PARTON DENSITIES}} \]

\[ \hat{\sigma}(S, m^2, \mu^2) = \frac{\alpha_s^2(m^2)}{m^2} \left[ f_{ij}^0(p) + \frac{4\pi \alpha_s(m^2)}{m^2} \left( f_{ij}^1(p) + f_{ij}^1(p) \ln \frac{\mu^2}{m^2} \right) + o(\alpha_s^2) \right] \]

\[ \mathcal{F} = \frac{4 m^2}{\hat{S}} \quad \text{SCALE CHANGE COMPENSATOR} \]

\[ f^0 : \{ \begin{array}{c} q\bar{q} \rightarrow Q\bar{Q} \\ gg \rightarrow Q\bar{Q} \end{array} \]

\[ f^1 : \{ \begin{array}{c} q\bar{q} \rightarrow Q\bar{Q}, g \\ gg \rightarrow Q\bar{Q}, g \end{array} \]
\[ \hat{\sigma} = \frac{\alpha_s^2(m^2)}{m^4} \left[ \mathcal{F}^0 + 4\pi\alpha_s \left( \mathcal{F}^1 + \frac{\alpha_s'}{\hat{s}^2} \frac{m^2}{m^2} \right) \right] \]

2.3 for \( 0.2 < \hat{s} < 0.195 \)

Nason, Dawson, R.K. Ellis = NDE

**Figure 3**

\[ \frac{1}{\rho} = \frac{\hat{s}}{4m^2} \]

Note: \( \mathcal{F}^1 \) not zero at threshold, Coulomb singularity.
Figure 4

\[
\frac{1}{\rho} = \frac{\hat{S}}{4m^2} \left( \text{SUB ENERGY} \right)^2
\]

Drop with x of parton densities
cuts away large \( \hat{S} \) values

(Fast enough?)
Gluon Quark

\[ f_{gq}^{(1)} \quad \overline{f}_{gq}^{(1)} \]

![Graph showing the relationship between \( f(\rho) \) and \( 1/\rho \)]

Figure 5
Gluon Gluon, $p_T > 2 \text{ m}$

$\frac{f_{gg}^{(0)}}{f_{gg}}$

$\frac{f_{gg}^{(1)}}{f_{gg}}$

$\frac{f_{gg}^{(1)}}{f_{gg}}$

Figure 19
SOURCES OF ERROR:

● INTRINSIC
  - SCALE DEPENDENCE
  - $O(\alpha_s^4)$ TERMS
  - EXACT VALUE OF $m$
    e.g. $m_b = 4.5$ to $5$ GeV
    $m_c = 1.2$ to $1.5$ GeV
    $m_t = \ldots$

● DUE TO IGNORANCE ON INPUT DATA
  - VALUE OF $\Lambda_{QCD}$
    - VALUE OF $\Lambda$ ($\Lambda = \Lambda_{QCD}$)
      ~EQUIVALENT TO $\Lambda_{QCD} = 260 \pm 100$ MeV
  - GLUON DENSITY

WE USE:

$\Lambda_5 = 170 \pm 80$ MeV ($\Lambda = \Lambda_{QCD}$)

DFLM STRUCTURE FUNCTIONS

FOR ERROR EVALUATION:

RECENT DATA ON $g$

VARY $\Lambda_5$ IN $90 \pm 250$ MeV

N.L. QCD EVOLUTION

$\Lambda$ & $g$ - DENSITY CORRELATED VARIABLE $\Lambda$

NEW $\Lambda$ → NEW INPUT GLUON → NLL QCD EVOLUTION

NEW EXPRESSLY DERIVED RESULTS
Scale Dependence: \[ \alpha_s = (\alpha_s)_{\overline{MS}} \]

\[ \sigma \approx \alpha_s^2(m) f^1 + \alpha_s^3(m) f^1 + 0(\alpha_s^4) \]

When are we very happy?

Naive: When \( f^1 \) is very small

But it depends on choice of \( m \):

\[ \sigma \approx \alpha_s^2(m) f^0 + \alpha_s^3(m) \left( f^1 + \ln \frac{\mu^2}{m^2} \right) \]

More reasonable: When the scale \( \mu \), \( m_0 \) is nearby the physical scale \( \sim m \)

When this is true, the corrections around the "physical region"

\[ m \sim \frac{m}{2} \div 2m \]

Are as small as possible \[ \left( \alpha_s(m) \right) \]

[Not necessarily so small:

\[ \frac{\alpha_s^2(m/2)}{\alpha_s^2(2m)} = 2.2 \quad m = 5 \text{ GeV} \]

\[ \frac{\alpha_s^2(m/2)}{\alpha_s^2(2m)} = 1.6 \quad m = 40 \text{ GeV} \]
$\phi \bar{\phi}: \sqrt{s} = 630 \text{ GeV}$

$M_t = 40 \text{ GeV}$

$\bar{\Lambda}_5 = 200 \text{ MeV}$

---

**Theoretical Errors**

---

\[ \mathcal{O} \sim \chi^2(\mu) \mathcal{O}^0 + \chi^3(\mu) \left[ \mathcal{O}^1 + \ln \frac{m}{m^2} \mathcal{O}^1 \right] \]

\[ \Rightarrow \text{Physically} \quad m \sim o(m) \]
THE AMBIGUITY DUE TO $\mu$ IN $\frac{m_t}{2}$ TO $2m_b$ IS $\sim 30\%$

$\sim 23\%$
CONCLUSION

TOP IS VERY GOOD AT SPS
AND (FOR $m_t \geq 80 \text{GeV}$) AT TEVATRON

$m$ LARGE, $m/\sqrt{s}$ NOT TOO SMALL.
DFLM
\[ \Lambda_5 = 170 \text{ MeV} \]
\[ p\bar{p} \sqrt{s} = 630 \text{ GeV} \]

Upper \( \mu = m/2 \)
Middle \( \mu = m \)
Lower \( \mu = 2m \)

\( \sigma \) (mb)

\( m \) (GeV)
The uncertainty from ignorance of \( \Lambda \) is comparable to that from scale depending on the graph.

DFLM

- \( \bar{p}p \) $\sqrt{s} = 630$ GeV
- $\mu = m$
- Upper $\Lambda_3 = 250$ MeV
- Middle $\Lambda_3 = 170$ MeV
- Lower $\Lambda_3 = 90$ MeV

\( \sigma \) (mb)

\( m \) (GeV)
INFORMATION ON THE TOP QUARK MASS

A  LOWER LIMITS

- e+e-  $m_t > 2.3\div 2.5$ GeV  COMPLETELY SOLID

- UA1  $m_t > 44$ GeV

QCD + MAIN ASSUMPTION  $B(t \to (e or \mu)+X) \sim 11\%$

ALTERNATIVE:  $t \to H^+ + b$ (Glashow et al.)

$\sim 35$ GeV  $\pm 30$ GeV  UNLIKELY

- ARGUS  $B_d - \bar{B}_d$ MIXING  $m_t > 45$ GeV

ASSUMPTIONS:

- ONLY 3 FAMILIES
- $BF_{B}^{1/2} \sim 140 \pm 60$ MeV

B  UPPER LIMITS

(No Limit from $\frac{0.8 (WZ e
\nu)}{0.8 (Z \gamma ee)}$)

ELECTRO-WEAK RADIATIVE CORRECTIONS

- $S_{\text{neutral currents}}$
- $(\sin^2 \theta_W)_{\text{V}V} = (\sin^2 \theta_W)_{\text{EW}}$

$m_t < 190 \div 200 \div 220$ GeV

(Costa et al.  Amaldi et al.  my estimate)
**THE UA1 LIMIT ON \( m_{top} \)**

\[ m_{top} > 44 \text{ GeV} \]  
(95% EXP + ?? THEORY)

\[ p\bar{p} \rightarrow W + X \]  
\[ \rightarrow \ell \bar{\nu} \]  
OR  
\[ p\bar{p} \rightarrow \ell \bar{\nu} + X \]  

\( \sigma \) WELL KNOWN

ALSO \( m_{b'} > 32 \text{ GeV} \)  
(No \( W \rightarrow \ell b' \))

BIG PROGRESS  
RECENTLY THE \( o(\alpha_s^3) \) TERMS IN \( \sigma(p\bar{p} \rightarrow q\bar{q}X) \) WERE COMPUTED!!  
NASON, DAWSON, K. ELLIS

A BETTER ESTIMATE OF THE LIMIT IS NOW POSSIBLE

\[ \Rightarrow \]
LIMIT ON $m_b, m_{b'}$ FROM UA1

$p\bar{p}$ $\sqrt{s} = 630$ GeV

ADMN

INCLUDING $O(\alpha_s^3)$

DFLM STR. FUNCT'S

90 MeV $\lesssim \Lambda_5 \lesssim 250$ MeV

$\frac{m}{2} \leq \mu \leq 2m$

$\sigma$(nb)

$M_{b'} > 34$ GeV

$M_t > 41$ GeV

UA1: $t\bar{t}$ (95% c.l.)

UA1: $b\bar{b}'$ (95% c.l.)
Lower edge of EHLQ band
$90 \text{ MeV} \leq \Lambda_5 \leq 250 \text{ MeV}$; \( \frac{m_b}{2} \leq \mu \leq 2m_b \)

\[
\begin{array}{c}
\text{ADMN} \\
\sqrt{s} = 2 \text{ TeV} \\
\sqrt{s} = 1.8 \text{ TeV} \\
\sqrt{s} = 630 \text{ GeV}
\end{array}
\]

\( \ell \ell \) PAIRS/$10^{10}$ pb

\[
\begin{array}{c}
10^2 \\
10^1 \\
10^0 \\
0(\text{nb})
\end{array}
\]

\[
\begin{array}{c}
40 \\
50 \\
60 \\
70 \\
80 \\
90
\end{array}
\]

\[
\begin{array}{c}
m(\text{GeV})
\end{array}
\]
PROBABLY $Z \rightarrow \ell^+ \ell^-$: BAD NEWS FOR LEP. (S.L.C.)

SEARCHING FOR $\ell$ EVEN MORE IMPORTANT GOAL FOR $p\bar{p}$ COLLIDERS.

ESTIMATED DISCOVERY RANGES

- HERA
- LEP II
- LEPI
- UA1 (Argus)
- TEVATRON
- ACOL
- SLC

$M_{\text{top}}$(GeV)

20 40 60 80 100 120 140 160

$5 \text{ pb}^{-1}$, $20 \text{ pb}^{-1}$, $1.9 \text{ TeV}$
b PRODUCTION

FOR \( \sqrt{s} = 52 \text{ GeV} \) (ACADEMIC CASE)

\[ \frac{5}{62} \sim \frac{50}{630} \]

BALANCE OF \( m \) AND \( \sqrt{s} \)

AS FOR TOP AT 5 TeV

HOWEVER, LARGER ERRORS

BECAUSE \( \alpha_s(m_b) > \alpha_s(m) \)

THE SCALE AMBIGUITY BETWEEN \( \frac{m_b}{2} \) AND \( 2m_b \)

AMOUNTS TO A FACTOR OF 2
The $b$ production in $pp$ is worse than in $p\bar{p}$ at $\sqrt{s} = 62$ GeV (ISR) because relative weight of gluons is larger.

![Graph showing production cross-section as a function of $\mu$ (GeV)]

*Fig. 15*

Scale ambiguity: a factor of 3
b production at $\sqrt{s}$:

CLEAR PROBLEMS

\[ \sigma (\mu b) \]

\[ \mu \text{ (GeV)} \]

DFLM

$\Lambda_s = 200 \text{ MeV}$

$p\bar{p}$ $\sqrt{s} = 630 \text{ GeV}$

$m = 5 \text{ GeV}$

- $L + NL$
- $L$

---

---
\[ \phi(\gamma, \mu) = \gamma \int dx_1 dx_2 F_i^A(x_1, \mu) F_j^B(x_2, \mu) \delta(x_1 x_2 - \tau) \]
pp. EHLQ, set 1 $\Lambda=0.2$ GeV

$m=\mu=5$ GeV $\sqrt{s}=0.63$ TeV

$O(a_s^2)$

$S_{pp\bar{s}}$

$\phi(\tau, \lambda) \phi^*(\tau, \lambda)$

$10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $1$

$10^{-3}$ $10^{-4}$ $10^{-5}$ $1$

$\tau = x, x_s$

$\phi(\tau, \lambda) \phi^*(\tau, \lambda)$

$pp. EHLQ, set 1 \Lambda=0.2$ GeV

$m=\mu=5$ GeV, $\sqrt{s}=1.8$ TeV

$O(a_s^2)$

$O(a_s^2)$

tevatron
The theory of \( \bar{q}q \) production at \( \frac{m}{\sqrt{s}} \ll 1 \) needs further work.

In particular, \( \bar{b} \) at LHC, SSC
\[ b \text{ at SPS, teVatron.} \]
\[ c \text{ at } II II \]

However we find:

SPS: \( \sqrt{s} = 0.63 \text{ TeV} \)

\[ m_b = 4.5 \text{ GeV} \rightarrow \sigma = 19 \pm 10 \mu b \]

\[ = 5 \text{ GeV} \rightarrow \sigma = 12 \pm 7 \mu b \]

Extrapolation of UA1 outside their acceptance by QCD
(at \( c(\alpha_s^3) \)) \( p_T \) and \( y \) distributions:

\[ \sigma_{UA1} \sim 16 \pm 5 \mu b \]

The calculation is not reliable but it works.
\[ \sigma \cdot B(\Lambda_b \rightarrow \rho D^0 \pi^-) = \left( \frac{150}{500} \right) \times \sigma \]  
\[ \sqrt{s} = 63 \text{ GeV} \]

\[ y > 1.4, \ x_p > 0.3 \]  

BSF
CHARM PRODUCTION

REALLY MARGINAL
EVEN AT MODERATE $\sqrt{s}$

---

**Fig. 17**

\[ \text{DFLM} \]
\[ \Lambda_3 = 170 \text{ MeV} \]
\[ pp \sqrt{s} = 30 \text{ GeV} \]
\[ m_c = 1.5 \text{ GeV} \]

---

**Legend:**
- **L+N:**
- **L:**
CHARM REDUCTION

pp DFLM

$1 \text{ GeV} \leq \mu \leq 2m$
$90 \text{ MeV} \leq \Lambda_s \leq 250 \text{ MeV}$

$m = 1.2 \text{ GeV}$
$m = 1.5 \text{ GeV}$

$\sigma (\mu b)$

$\sqrt{s} (\text{GeV})$

DATA FROM TAVERNIER

$m_c \approx 1.2 \text{ GeV}$

$m_c \approx 1.5 \text{ GeV}$
**Conclusion**

**Total X-ctions**

• A certain balance in $m$ vs $\sqrt{s}$ needed:

\[
\frac{2m}{\sqrt{s}} \ll 1 \quad \text{BAD}
\]

\[e.g., \] at $5\text{ppps}$, tension

\[
G_{\text{jet}} \lesssim 40 \div 200 \text{ GeV} \quad \text{GOOD}
\]

b at $\sqrt{s} \leq 1\text{SR}$ \quad \text{GOOD}

\[c \text{ at fixed target} \quad \text{GOOD} \]

• Corrections, taken at face value, tend to improve agreement with fit.

**Next:** $p_t$ and $y$ distributions

Location in phase space of large corrections

Further theoretical insight needed
OVERALL CONCLUSION

• IT IS FAIR TO STATE THAT QCD WORKS VERY WELL IN THE PERTURBATIVE REGIME.

• THE THEORY IS VERY PREDICTIVE.

• THERE ARE A NUMBER OF COMPLETELY QUANTITATIVE TESTS:
  - e.g. $\chi^2$ FROM $T$.
  - [Also W2 production, jet-jet at large $p_T$, $\gamma$ at large $p_T$, Drell-Yan, $\gamma-Z$,...]

• THERE ARE PROBLEMS (WITH EXPERIMENT):
  - e.g. EMC $g_1$
  - NALC ANG, DIST OF $MU$.
  - PP ELASTIC SCAT.

... BUT THEY APPEAR TO BE DETAILS.