Tests of the QCD Sector of the Standard Model

- Structure functions and $\alpha_s$ in DIS
- Spin physics
- Jets and $\alpha_s$
- Event shapes
- Fragmentation
- Heavy flavours
- Summary

Tim Greenshaw, Liverpool University.
Introduction

- Progress on many fronts in QCD in last few years.
- Nobel prize in physics awarded to Gross, Politzer and Wilczek...
  
  “...for the discovery of asymptotic freedom in the theory of the strong interaction...”

- It is now official: QCD is the theory of the strong interactions!

- Why then “Tests of the QCD sector of the Standard Model”?

- Because we do not understand how partons are put together to make hadrons...

- ...or how those partons conspire to ensure the proton’s spin is ½.

- Because we need to understand future high energy experiments at the LHC...
Introduction

- ...and because $\alpha_s$ is the least well known of the fundamental constants of nature.
- Increased precision needed to determine if running electromagnetic, weak and strong couplings...
- ...unify at $\sim 10^{16}$ GeV.

\[ \alpha_s = 0.1186 \pm 0.003 \]
Structure functions and $\alpha_s$

- Measure structure of hadrons in deep-inelastic lepton-nucleon scattering.
- Neutral current DIS:
  - HERA is most important source of data on proton structure.
  - $0 < Q^2 < 10^5 \text{ GeV}^2$ i.e. sensitive to structure down to $\sim 10^{-18}$ m.
  - $10^{-6} < x < 1$.

Describe in terms of:

\[
Q^2 = -q^2, \quad x = \frac{Q^2}{2p \cdot q} \quad \text{and} \quad y = \frac{p \cdot q}{p \cdot k}
\]
Timescales in DIS

- Time scale for soft interactions
  \[ \Delta T_{\text{SOFT}} \approx \frac{E}{m} \frac{1}{\Lambda_{\text{QCD}}} \]

- For DIS
  \[ \Delta T_{\text{DIS}} \approx \frac{1}{\sqrt{Q^2}} \]

- \( \Delta T_{\text{SOFT}} \gg \Delta T_{\text{DIS}} \) so DIS takes snapshot of proton structure.
Neutral current cross section for DIS

\[ \frac{d^2 \sigma_{NC}(e^\pm)}{dx \, dQ^2} \sim Y_+ F_2 \mp Y_- x F_3 + y^2 F_L. \]

\[ Y_\pm = 1 \pm (1 - y)^2. \]

\[ F_2 \sim \sum_q x \left( q(x, Q^2) + \bar{q}(x, Q^2) \right), \]

\[ x F_3 \sim \sum_q x \left( q(x, Q^2) - \bar{q}(x, Q^2) \right), \]

\[ F_L \sim \alpha_s (Q^2) x g(x, Q^2). \]

- F$_2$ dominant for Q$^2 < m_Z^2$.
- xF$_3$ measurements require large luminosities.
- Precise F$_L$ measurement needs HERA running with lower proton beam energies.
Parton distribution functions

- NLO QCD fits to $F_2$, $x F_3$, and CC data allow extraction of the PDFs.
- ...and of $\alpha_s$.
- E.g. for ZEUS fit:
  $\alpha_s(m_Z) = 0.1166 \pm 0.0008\text{(unc)} \pm 0.0032\text{(corr)}$
  $\pm 0.0036\text{(norm)} \pm 0.0018\text{(mod)}$
- Gluon distribution determined from evolution with $Q^2$: uncertainties large and gluon distribution correlated with $\alpha_s(Q^2)$. 
Recent improvements in theoretical understanding

- NNLO DGLAP splitting functions and DIS coefficient functions recently calculated (Moch, Vermaseren, Vogt).
- Will lead to improved precision of PDFs and $\alpha_s$ – progress shown by Guffanti (Blümlein, Böttcher) and by Alekhin on incorporating DIS and E605 DY data.
- Splitting functions also crucial to extrapolation of PDFs from HERA to TeVatron and the LHC.
- DGLAP appropriate at low x?
- NLO MC developments also underway.
Experimental progress

- Data taking at high luminosity ongoing (HERA II)
- Techniques for combination of H1 and ZEUS data being studied (HERA-LHC workshop), cross calibration will lead to reduced systematic errors.
Add jet data to PDF determinations

- ZEUS exploit additional constraints provided by DIS and $\gamma p$ jet data.
- Boson gluon fusion sensitive to gluon distribution.
- Contributions from other diagrams break correlations with $\alpha_s$.

- Dijet cross section, photoproduction:

![Diagram showing dijet cross section](image)
Using jet data in PDF determinations

\[ \alpha_s(m_Z) = 0.1183 \pm 0.0028 \text{ (exp.)} \]
\[\pm 0.0008 \text{ (mod.)} \pm 0.005 \text{ (scale)}.\]

Resulting PDFs:
- Improved precision for gluon at medium and high \( x \).
Charm and beauty in the proton

- Charm and beauty identified using H1 central silicon tracker to measure impact parameter $\delta$ and its error $\sigma_\delta$.
- Flavour discrimination using $S = \delta/\sigma_\delta$ of tracks with largest significance, $S_1$, $S_2$...

![Graph showing significance $S_1$.](image)
Charm in proton

- Proportion of c events determined as function of x and $Q^2$, $\sim 24\%$ decreasing slightly with x.
- Hence extract $F_2^{cc}$.
- Good agreement between “lifetime” and “D* based” measurements.
- Positive scaling violations increase as x decreases.
- Well described by higher order QCD calculations.
Beauty in proton

- Proportion of b events found to be 0.3 to 3%, inc. with $Q^2$.
- Hence obtain first ever measurements of $F_2^{b\bar{b}}$.
- Well described by higher order QCD calculations.
- Of interest to LHC, e.g. $b\bar{b} \rightarrow H$.
- $b\bar{b}$ contributes ~ 5% to $pp \rightarrow ZX$.
- Need better than 20% accuracy on b distribution for 1% Z cross sections at the LHC.
Two scale problems in QCD and b production

- For $Q^2 >> m_Q^2$, treat $Q$ like uds, i.e. part of structure of proton.

- If $Q^2 \sim m_Q^2$, to LO $Q$ produced via boson gluon fusion.

- Careful matching needed to cover entire $Q^2$ range, “variable flavour number scheme” (ACOT, MRST).

- MRST04 and CTEQ6HQ VFNS, CCFM “massive” calculation.

- More HERA data needed here!
Contribution of photon to proton structure

- Include photons in evolution.

- $u$ quarks radiate more than $d$, so fewer $u$ quarks in proton at high $x$ than $d$ quarks in neutron.

- Isospin asymmetry: $d^p \neq u^n$, $u^p \neq d^n$.

- Effect is small, but influences NuTeV determination of $\sin^2 \theta_W$:

  $$\frac{\sigma_{NC}^v - \sigma_{NC}^\nu}{\sigma_{CC}^v - \sigma_{CC}^\nu} = \frac{1}{2} - \sin^2 \theta_W + \text{isospin viol. term.}$$

- $\sin^2 \theta_W = 0.2277 \pm 0.0013 \pm 0.0009$

  $\sim -0.002$

- C.f. world average $\sin^2 \theta_W = 0.2227 \pm 0.0004$. 

![Graph showing $x(d^p-u^n)$ and $x(u^p-d^n)$](image.png)
Spin structure measurements

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

Meas. with pol. target and pol. beam.

\[ \sigma_{\frac{1}{2}} \sim \sum_q e_q^2 q^+ (x) \quad \sigma_{\frac{3}{2}} \sim \sum_q e_q^2 q^- (x) \]

\[ A = \left( \sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}} \right) / \left( \sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}} \right) \]

\[ \sim \frac{\sum e_q^2 (q_+ - q_-)}{\sum e_q^2 (q_+ + q_-)} \sim g_1 (x) \]

\[ \sum F_1 (x) \]

New data from COMPASS.

\[ \Delta \Sigma = 0.202^{+0.042}_{-0.077} \rightarrow 0.237^{+0.024}_{-0.029} \]
Spin structure measurements

- Extract contributions of different flavours by measuring semi-inclusive asymmetries.

- $\Delta q = q_+ - q_-$
- $\Delta u > 0$ (u spin parallel to p spin)
- $\Delta d < 0$ (d spin anti-parallel to p spin)
- $\Delta \bar{u}$, $\Delta \bar{d}$ and $\Delta \bar{s}$ all $\sim 0$. 

Graphs showing data for $x\Delta u$, $x\Delta d$, etc. with Q$^2 = 2.5$ GeV$^2$. 

Legend: h, π$^-$
Spin structure measurements

- Probe gluon spin using photon gluon fusion
- Demand two high p_T hadrons in final state.
- Background from QCDC and resolved photon events (at low Q^2).
- A - A_{BG} \sim \Delta G/G

Resulting measurements

\[ \frac{\Delta G}{G} = 0.024 \pm 0.089 \pm 0.057 \]

\[ \Delta G = \int \Delta G(x) \, dx = 0.2, 0.6, 2.5 \text{ using GRSV min. standard and max. curves.} \]
Jets at the TeVatron

- TeVatron jets test of pQCD over ~8 orders of magnitude in $E_T$.
- Probe distances down to ~$10^{-19}$ m.
- Excitement when excess observed in Run I jet data.

- Can be explained by increasing gluon distribution at large $x$.

- Various problems addressed in Run II jet analyses:
  - JetClu algorithm not IR or collinear safe.
  - “Fudge factor” $R_{\text{sep}}$ introduced to mimic effects of jet algorithm in calculations.
- Move to using “safe” inclusive $k_T$ and midpoint algorithms.

**Run I CDF Inclusive Jet Data**

- Statistical Errors Only
- $R_{\text{CONE}}=0.7$, $0.1<|\eta|<0.7$
- $\mu_R=\mu_F=E_T/2$, $R_{\text{sep}}=1.3$

![Graph showing the relative difference between data and NLO QCD](image-url)
Jets at the TeVatron

- At Run II, reach in $p_T$ extended by $\sim 150$ GeV compared to Run I.
- Experimental uncertainty dominated by energy scale (luminosity uncertainty of 6% not shown on plots).
- NLO QCD corrected to hadron level using Pythia tune A ($\sim 20\%$ decreasing to $\sim 0\%$ with $p_T$).
- Theoretical error dominated by uncertainty in gluon at large $x$.
- Caution: Moretti, Nolton and Ross recently determined weak corrections to the theory: $\sim -30\%$ at the highest jet $E_T$ and $\sim -12\%$ at $p_T = 450$ GeV, consequences not yet fully explored.
Dijet azimuthal separation at the TeVatron

- Two jets back to back in $\phi$ if only little additional soft radiation.

- If hard radiation, $\Delta \phi$ can be large.

- $\Delta \phi < 2\pi/3$, four jet region.

- Small and large $\Delta \phi$ regions poorly described by LO calc, NLO better.
Dijet azimuthal separation at HERA

- Study frac. of dijets with $\Delta\phi^* < 2\pi/3$.

\[
S = \frac{\int_0^{2\pi/3} N_{\text{dijet}} (\Delta\phi^*) \, d\Delta\phi^*}{\int_0^{\pi} N_{\text{dijet}} (\Delta\phi^*) \, d\Delta\phi^*}
\]

- LO calc [$O(\alpha_s)$], at most 2 jets, fails to describe data.

- NLO calc [$O(\alpha_s^3)$], up to 4 jets, OK at high $x$, $Q^2$, but fails at low $x$ and $Q^2$!
Evolution schemes

- Look again at multiple parton emissions in evolution of $p$ structure.
- QCD interference effects give rise to angular ordering of partons.
- DGLAP approximation, large $Q^2$: $\theta_1 < \theta_2 < \theta_3 \ldots \rightarrow k_{T1} < k_{T2} < k_{T3} \ldots$
- In small $x$ regime inappropriate: ignores terms $\sim \ln(1/x)$.
- BFKL evolution equation, small $x$: $\theta_1 < \theta_2 < \theta_3 \ldots \rightarrow x_1 > x_2 > x_3 \ldots$ $k_T$ not ordered, sums $\ln(1/x)$ terms.
- CCFM equation implements angular ordering, applicable at all $x$ and $Q^2$.
- Do multiple emissions give measured separation at low $x$ and $Q^2$?
- Check using CASCADE Monte Carlo, based on CCFM equations.
Jet separation and CCFM evolution

- CASCADE describes data well, using unintegrated PDF.
- J2003 inc. full splitting function much better than JS2001 (singular terms only).
- ARIADNE ($k_T$ not ordered) also describes data in low $x$ and $Q^2$ regime, but fails at high $x$ and $Q^2$. 
Jet production and $\alpha_s$ measurements

- Complementary measurements of $\alpha_s$ to inclusive fits possible using jets.
- Use longitudinally invariant $k_T$ jet algorithm in the Breit Frame:
  - Iterative clustering
    $$d_{i,j} = \min(E_{T,i}^2, E_{T,j}^2) \times \left( (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \right)$$
  - Gives $n$ jets with $d_{i,j} > R_0 = 1$.
  - Collinear and IR safe.
- Comparison with DISENT.
Jet production and $\alpha_s$ measurements

- $\alpha_s$ from inclusive jet cross section.
- $\alpha_s(m_Z) = 0.1196 \pm 0.0011^{(\text{stat})}$
  $+0.0019 -0.0025^{(\text{exp})} +0.0029 -0.0017^{(\text{theory})}$
- Dominant experimental systematic error hadronic energy scale.
- Theory error largely due to renormalisation and factorisation scale uncertainties.
Jet production and $\alpha_s$ measurements

- Ratio of cross sections for 2 and 3 jet production also sensitive to $\alpha_s$.
- Good agreement with NLOJET calculations ($\gamma$ exchange) except where EW effects significant.

$$\alpha_s(m_Z) = 0.1175 \pm 0.0017 \text{ (stat.)}$$
$$\pm 0.0050 \text{ (exp.)} + 0.0054 \text{ (th.)}$$

Resulting $\alpha_s$ measurement:

- H1 Preliminary 99-00
  - $\alpha_s(Q^2)$
  - Averaged $\alpha_s(M_Z)$
  - World Average (PDG):
    - $\alpha_s(M_Z) = 0.1187 \pm 0.0020$
Event shapes

- Study of event shapes allows tests of pQCD and ideas beyond pQCD.
- E.g. thrust, \( T_T = \max \left( \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|} \right) \).
- Describe \( \langle 1 - T_T \rangle \) using pQCD plus “power corrections” (Dokshitzer, Webber...) which decrease with \( 1/Q \)
  \[ \langle 1 - T_T \rangle = \langle 1 - T_T \rangle_{PC} + \langle 1 - T_T \rangle_{pQCD} \]
- Introduces universal parameter \( \bar{\alpha}_0 \).
- Fit also \( T \) distributions; “pQCD” then re-summed NLL calculations matched to NLO (Dasgupta, Salam) as convergence of pert. series poor for small \( T \).

- Measurements in Breit Frame.

- Obtain values of \( \bar{\alpha}_0 \) and \( \alpha_s(M_Z) \). from event shape means and distributions.
Event shapes

- From means:

- Results from distributions qualitatively similar.

- $\bar{\alpha}_0 = 0.45 \pm 10\%$ for all variables except $T_g$ and $C$.

- Values of $\alpha_s(m_Z)$ extracted from means consistent within 5%.

- $\alpha_s(m_Z)$ from distributions consistent with world average.

- Dispersion of $(\alpha_s(m_Z), \bar{\alpha}_0)$ values indicative of need for higher order calculations?
HERA $\alpha_s$ summary

- C.f. HERA $\alpha_s$ measurements and world average:
  - Jet shapes in NC DIS
  - Multi-jets in NC DIS
  - ZEUS (DESY 05-019 - hep-ex/0502007)
  - Inclusive jet cross sections in $\gamma p$
  - Subjet multiplicity in CC DIS
  - ZEUS (Eur Phys Jour C 31 (2003) 149)
  - Subjet multiplicity in NC DIS
  - NLO QCD fit
  - NLO QCD fit
  - ZEUS (DESY 05-050 - hep-ex/0503274)
  - NLO QCD fit
  - Inclusive jet cross sections in NC DIS
  - Inclusive jet cross sections in NC DIS
  - Dijet cross sections in NC DIS
  - ZEUS (Phys Lett B 507 (2001) 70)
  - World average
    - S. Bethke, hep-ex/0407021

- $\alpha_s$ measurements from jets:

- Preliminary HERA average:
  - $\alpha_s(m_Z^2) = 0.1186 \pm 0.0011$(exp.)
  - $\pm 0.0050$(th.)
Back to PETRA where the gluon was discovered
Reanalysis of JADE data

- Study 4 jet rate using modern Monte Carlos to make hadronisation and detector corrections, c.f. NLO + NLL calculations.
- Significant progress in determination of $\alpha_s(m_Z)$ in last ~15 years!
Hadron production in $\gamma\gamma$ collisions

- Large disagreement with NLO QCD observed by L3 in $\gamma^*\gamma^* \rightarrow hX$
- New measurements by DELPHI show significantly better agreement.

DELPHI report using L3 cuts allows $e^+e^- \rightarrow q\bar{q}$ background into event sample at large $p_T$. 
Charm fragmentation

- Inclusive cross sections for D*...
- ... D⁺, D⁰...
- ... Ds⁺ and Λc measured by HERA experiments.
Charm fragmentation

- Hence fragmentation fractions determined:

- All fragmentation fractions are consistent with world average and support assumption of universality.
Beauty in DIS events

- Main production mechanism in DIS
- Identify semi-muonic beauty decays via $p_{T_{\text{rel}}}$ and impact parameter $\delta$ of muon (H1) or $\delta$ (ZEUS).
- Measure cross section for $e^+ p \rightarrow e^+ b \bar{b} Y \rightarrow e^+ \text{jet} \mu X$
- NLO QCD below both H1 and ZEUS data at small $p_T^\mu$ and in $p$ direction.
Summary of beauty measurements at HERA.

- Many measurements of beauty production now available.
- “Massive” NLO calcs tend to lie somewhat below the data (FMNR in photoproduction, HVQDIS for higher $Q^2$).
- Evidence that shapes of distributions poorly described in some places (e.g. in $e\mu X$ at low muon $p_T$ and in proton direction).
- “Double tag” analyses with no jet requirement started, aim is to study production of $b\bar{b}$ with low $p_T$. 
Recent measurements of heavy flavour production by L3 show good agreement with NLO QCD for c, but lie above expectations for b.
Top quark production at the TeVatron

- Production mechanism:
  - (15% \( gg \) and 85% \( q\bar{q} \))
  - Dominant theory errors are renormalisation and factorisation scale dependence (5%) and PDFs (7%).
  - Study all hadronic, lepton + jets, tau + jets (CDF) and dilepton decay modes of Ws.

- Decays of Ws in top pair events, BR ~ area:
Top quark production at the TeVatron

- Combined CDF measurement.
- So far ~ 300 pb\(^{-1}\) analysed. Experiments have ~ 1 fb\(^{-1}\) on tape.
- No evidence yet for single top production.

Summary of D0 results.

![Graph showing D0 Run II Preliminary results for top quark production](image)
Summary

QCD is the theory of strong interactions, but developing a complete understanding of its implications remains a challenge.

Theoretical progress is being made, e.g. in the area of NNLO calculations and in the development of NLO Monte Carlo programs.

Experiments are increasing the precision and range of data used in structure function and $\alpha_s$ determinations.

Further increasing the precision of nucleon PDFs requires more data, new data, and good ideas; some of which are available, or will be soon.

Surprises continue to appear, such as the effect of the photonic component of proton structure and the size of weak corrections at the TeVatron.

New and improved jet results coming from the TeVatron and a new round of jet measurements from HERA., studying both jet structure and jet rates.

Some areas where need for more than DGLAP apparent.

Inclusive heavy flavour production measurements well described, but still some areas where specific cross sections poorly described.

Thanks to all the speakers in the Hard QCD session, and apologies to those whose work could not be mentioned in this summary!