QCD at high energy

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QCD at high energy

- very lively and active field: 60 abstracts submitted to the conference
- QCD at end of LEP hera: emphasis shifts from testing the theory to pushing its precision
- Theory Standard: NLO.
- Tackle the study of power suppressed effects

Status of phenomenology

- Large body of tests in many different areas
- Overall agreement with theory
- Some minor discrepancies (need for better calculations)
- Some major discrepancies (interesting puzzles)
PLAN OF THE TALK

- Few examples of current results in $e^+e^-$, $ep$ and $p\bar{p}$ physics
- Power suppressed effects
- Towards NNLO
- Some puzzling results
QCD in $e^+e^- \rightarrow$ hadrons:

- QCD studies at highest available energies
- 4-jets NLO studies
- Fits to QCD color factors and $\alpha_s$
- Charge multiplicity studies
- Bose-Einstein correlations, color reconnection
- Power corrections, energy evolution of shape variables distributions
- Heavy quark mass effects
- Fragmentation function studies
- $\gamma\gamma$ collision studies
Theoretical basis

NLO formulae for 3–jets

\[ \alpha_S(\mu^2)A + \alpha_S^2(\mu^2)B(\mu^2/Q^2) + \ldots \]

K. Ellis, Ross, Terrano

and 4–jets, infrared safe quantities

\[ \alpha_S^2(\mu^2)C + \alpha_S^3(\mu^2)D(\mu^2/Q^2) + \ldots \]

Signer, Dixon; Nagy, Trocsanyi; Campbell, Cullen, Glover; Weinzierl, Kosower

Heavy quark mass effects included in the 3–jets result

Bernreuther, Brandenburg, Uwer; Rodrigo, Santamaria, Bilenky; P.N., Oleari
Resummation of Sudakov effects at NLL level: needed in the limit of thin jets

\[ R(y) = F(\alpha_S) e^{Lg_1(\alpha_S L) + g_2(\alpha_S L)} \]

where \( R \) is a jet rate, \( y \) the jet thickness, \( L = -\log y \).

**Hadronization and power corrections:** suppressed as \( 1/Q \), but still important at LEP energies. Estimated using *Montecarlo hadronization models*.

**Renormalon** inspired models provide an alternative

Dokshitzer, Marchesini, Webber
**Shape variables at highest energy**

**L3:** thrust, heavy jet mass, total jet broadening, wide jet broadening and $C$ parameter measured at different energies.

From fit:

$$\alpha_s(M_Z) = 0.1220 \pm 0.0011\text{(exp.)} \pm 0.0061\text{(th.)}$$
Fits to QCD color factors (OPAL, ALEPH)

- Jet resolution \( y_{ij} = 2 \min(E_i^2, E_j^2)(1 - \cos \theta_{ij})/E_{\text{vis}}^2 \)
- Differential 2-jet rate \( D_2(y_{23}) = \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dy_{23}} \) (OPAL)
- 4-jet rate \( R_4(y_{\text{cut}}) \)
- 4-jet, \( y_{\text{cut}} = 0.008, \ E_1 > E_2 > E_3 > E_4 \)
  - \( \chi_{\text{BZ}} = \angle[(\vec{p}_1 \wedge \vec{p}_2), (\vec{p}_3 \wedge \vec{p}_4)] \)
  - \( \Theta_{\text{NR}} = \angle[((\vec{p}_1 - \vec{p}_2), (\vec{p}_3 - \vec{p}_4)] \)
  - \( \Phi_{\text{KSW}} = \langle \angle[(\vec{p}_1 \wedge \vec{p}_4), (\vec{p}_2 \wedge \vec{p}_3)] \rangle_{3 \leftrightarrow 4} \)
  - \( \cos(\alpha_{34}) = \cos(\angle[(\vec{p}_3, \vec{p}_4)]) \) (ALEPH)
- Color dependence
  \[
  D_2 = \alpha_S C_F \ldots + \alpha_S^2 C_F (C_F \ldots + C_A \ldots + T_F n_f \ldots) \\
  R_4 = \alpha_S^2 C_F (C_F \ldots + C_A \ldots + T_F n_f \ldots) + \alpha_S^3 \ldots
  \]
• $Z$ peak data (1991/1995)
• hadronization corrections:
  Montecarlo models
  (fixed color factors?)

**OPAL:**

$C_A = 3.02 \pm 0.25 \pm 0.49$

$C_F = 1.34 \pm 0.13 \pm 0.22$

$\alpha_S(M_Z) = 0.120 \pm 0.011 \pm 0.020$

**ALEPH:**

$C_A = 2.93 \pm 0.14 \pm 0.49$

$C_F = 1.35 \pm 0.07 \pm 0.22$

$\alpha_S(M_Z) = 0.119 \pm 0.006 \pm 0.022$

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Heavy Quark mass effects

comparison of light and heavy quark hadronic events exposes the effects of the heavy quark mass.

Two kind of analysis:

- Fit the $b$ quark mass from the ratio of 3-jet rates in $b$-quark jets and light quark jets

$$B_3 = \frac{R^b_3}{R^dusc_3}$$

(which can be computed at NLO including mass effects)

- Compare the $\alpha_S$ determination in light quark events and $b$, $c$ quark events (tests of flavour independence of $\alpha_S$)
Results from $b$-mass fits to $B_3$, called (improperly?) a test of the running of the $b$-quark mass, from various experiments.

DELPHI has new results:

\[
\bar{m}_b(M_Z) \text{ (in GeV)} = \\
\text{Duhram: } 2.67 \pm 0.25\text{(stat.)} \\
\pm 0.34\text{(had.)} \pm 0.27\text{(th)} \\
\text{Cambridge: } 2.61 \pm 0.18\text{(stat.)} \\
\pm 0.47\text{(had.)} \pm 0.18\text{(tag)} \\
\pm 0.12\text{(th)}
\]

Measurement of the $b$ mass in high energy processes
Flavour independence of the strong coupling: \( \alpha_s^{(b/c)}/\alpha_s^{(uds)} \) is much more consistent with 1 if heavy flavour mass effects are included.
HERA

- Structure function studies
- Jet studies in DIS
- Jet studies in photoproduction
- Shape variable and power correction studies
- Production of Heavy flavours
Zeus: $\alpha_s(M_Z) = 0.1166$
$\pm 0.0019$ (stat.) $\pm 0.0024$ (exp.)
$+0.0057$ (th. + pdf) $-0.0044$ (th. + pdf)
3 jet study from H1

- Recent NLO Calculation by Nagy and Trocsanyi
- Jets defined with $k_T$ cluster algorithm
- $E_T > 5$ GeV, $M_{3\text{jet}} > 25$ GeV
3-jet CM
1+2 → 3+4+5
E_3>E_4>E_5

$\frac{1}{\sigma_{3\text{jet}}} \frac{d\sigma_{3\text{jet}}}{d\cos \theta_3}$

- H1 data $150 < Q^2 < 5000 \text{ GeV}^2$
- QCD NLO
- QCD LO
- Phase Space

$1/\sigma_{3\text{jet}} d\sigma_{3\text{jet}}/d\psi_3$

- H1 data $150 < Q^2 < 5000 \text{ GeV}^2$
- QCD NLO
- QCD LO
- Phase Space
TEVATRON

- Inclusive jet versus $E_t$ and pseudorapidities
- Jets with cluster ($k_T$) algorithms
- Jet structure
- $W/Z$ and $\gamma$ production
D0 jet analysis at large rapidity extends sensitivity to PDF’s at small $x$ and large $Q^2$. Impressive agreement with NLO theoretical calculations.
D0 data, JETRAD ($\mathcal{O}(\alpha_S^3)$)

CTEQ4HJ (○) and CTEQ4M (●)  
MRSTg↑ (○) and MRST (●)

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CDF dijet study: look at $E_T$ of one central jet ($0.1 < \eta_1 < 0.7$) where the other jet lies in several different pseudorapidity intervals.
Sensitivity to PDF at large $x$ enhanced;
Qualitatively good description of data,
quantitative problems

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{CDF_dijet_study.png}
\caption{CDF dijet study graph showing sensitivity to PDF at large $x$.}
\end{figure}
No PDF set is found that fits the data satisfactorily.

Other problematic areas:

- Direct photon at low transverse momenta
- $b$ production

In all these cases discrepancies could be attributed to unknown higher order effects.
Power Corrections

(Movilla Fernández, Bethke, Biebel, Kluth)

- $\sqrt{S} = 14$ to $189$ GeV
- several shape variables considered
- fit to $\alpha_S$ and to the parameter $\alpha_0$ in the power correction model of Dockshitzer, Marchesini and Webber
\( \alpha_s(M_Z) = 0.1187^{+0.0014}_{-0.0001} \pm 0.0028 \pm 0.0015 \),
\( \alpha_0(2 \text{ GeV}) = 0.485^{+0.013}_{-0.001} \pm 0.065 \pm 0.043 \) (fit + syst. + theo. errors)

\( \alpha_s(M_{Z0}) = 0.1171^{+0.0032}_{-0.0020} \), \( \alpha_0(2 \text{ GeV}) = 0.513^{+0.066}_{-0.045} \)
Power corrections studies at HERA

Power Correction Fits (stat. and exp. syst. uncertainties)

ZEUS Preliminary 1995–97

- All data Q > 9 GeV
- Lower x-bins excluded
  ($\chi^2 = \chi^2_{\text{nuis}} + 4$ contours)

$\alpha_s(M_Z)$

$\bar{\alpha}_0(\mu_I = 2 \text{ GeV})$

$\alpha_s(M_Z)$

$\tau$

$B_c$

$\rho$

$\tau_c$

$C$

$C_0$

$\rho_0$

$\tau_m$

$\alpha_s$ World Average

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What we know about power corrections

- In $R_{e^+e^-}$, $1/Q^4$ (from O.P.E.)
  (why $\tau$ hadronic physics works so well)
- In DIS, $1/Q^2$ (from O.P.E.)
  (why scaling sets in early in $Q^2$)
- In Jets, $1/Q$ (from many points of view...)
  (why Jet physics is so hard)

Can we understand Jets better?
Power Correction Model

Basic idea: from QED analogy, fluctuations of gluons into virtual and real states cause $\alpha_s$ running. Physical quantities written as:

$$ F(Q^2) = \int dk^2 F(Q^2, k^2) \alpha_s(k^2). $$

(Unknown) low energy behaviour of $\alpha_s$ determines power corrections. Power correction law determined by low $k^2$ behaviour of $F(Q^2, k^2)$

$$ F(Q^2) \propto \frac{1}{k} \rightarrow 1/Q \text{ correction} $$

$F(Q^2, k^2)$: physical quantity computed with a gluon of mass $k^2$.

Scheme by Dockshitzer, Marchesini, Webber.
Several similar suggestions: Akhoury and Zakharov, Sterman and Korchemsky, etc.
Cannot work as is for shape variables (Seymour, P.N.)

Shape variables “know” what is inside the blob.

Thrust: decreases for a generic blob, does not change in some kinematic configurations

\[ 1 - t \approx \frac{|k|}{Q} \]

Dokshitzer, Lucenti, Marchesini and Salam have examined these effects at the two-loop level.

The effect amounts to a factor of order unity (Milan factor) in front of the 1-loop (naive) formula.

This factor has the same value for several common shape variables

If 2-loop same as 1-loop, what about higher loops?
On the bright side:

- One parameter model of power corrections
- Also power suppressed effects depend upon color factors: Kluth et al. have used it to fit QCD color factors without relying on Montecarlo hadronization models.
- Some support from data
- Alternative model to estimate power corrections: low $\alpha_s$ values from distributions.

Study using DELPHI data: PMS type of data analysis (RGI) gives very good fit to data without power corrections

So: Power corrections or NNLO?
Remarkable progress in NNLO calculations

Current goal: jet production in hadronic collisions.

- Double soft limit (Berends and Giele, 1989)
- Double collinear and soft-collinear (Campbell and Glover, 1998; Catani and Grazzini, 1999; Del Duca, Frizzo and Maltoni, 2000)
- $2\rightarrow 3$ amplitude at one loop level (Bern, Dixon and Kosower, 1993; Kunszt, Signer and Trócsányi, 1994).
- Collinear limit of one loop amplitudes (Bern, Dixon, Dunbar and Kosower, 1994; Kosower, 1999; Kosower and Uwer, 1999)
- Soft limit of one loop amplitudes (Bern, Del Duca, Schmidt, 1998; Bern, Del Duca, Kilgore and Schmidt 1999; Catani and Grazzini, 2000)
- Some analytic phase space integrals (Gehrman, Glover; Catani, de Florian, Grazzini)
The two loop 2→2 contribution recently computed (Anastasiou, Glover, Oleari, Tejeda-Yeomans; 2001).

Recursion relations among Feynman integrals reduce the problem to the computation of a small number of master integrals. The hardest of those (double box, planar and crossed) only recently solved (Smirnov, 1999; Tausk, 1999).

All ingredients needed for a full NLO computation of jet cross sections in hadronic collisions are in place now.

The implementation into a useful result is still a formidable task. But it does not look far...
Puzzle in $b$ production
\[ e^+ e^- \rightarrow e^+ e^- b \bar{b} \]

- At LEP, direct and single resolved comparable
- L3 uses the electrons or muons from semileptonic \( b \) decays.
- The \( P_t \) of the lepton (relative to closest jet) fitted to extract the \( c, b \) and light quark fraction:
  \[
  \sigma(e^+ e^- \rightarrow e^+ e^- b \bar{b}X)_{\mu} = 14.9 \pm 2.8 \pm 2.6 \text{ pb}, \\
  \sigma(e^+ e^- \rightarrow e^+ e^- b \bar{b}X)e = 10.9 \pm 2.9 \pm 2.0 \text{ pb}
  \]
- OPAL (\( \mu \) only) gets comparable results
- \( c \) cross section in agreement with calculations, excess of \( b \) production
\[ \sigma(e^+e^- \to e^+e^-cc\bar{c}, bb\bar{b}) \text{ (pb)} \]

\[ \sqrt{s} \text{ (GeV)} \]

- \( m_c = 1.3 \text{ GeV} \)
- \( m_c = 1.7 \text{ GeV} \)
- \( m_b = 4.5 \text{ GeV} \)
- \( m_b = 5.0 \text{ GeV} \)

- OPAL \((\mu, \sqrt{s}=189-202 \text{ GeV, prel.})\)
- L3 \((\mu, e, \sqrt{s}=189-202 \text{ GeV, prel.})\)

- NLO (direct+resolved, GRV)
- NLO (direct only)

 Bands: \( m_b = 4.5 \text{ GeV}, \mu = m_b/2 \)
\( m_b = 5.2 \text{ GeV}, \mu = 2m_b \)
**b excess at HERA**

New H1 results confirm previous findings:
- $\sigma(b)$ from impact parameter fit in photoproduction
- $\sigma(b)$ in DIS both in excess over QCD calculations.

Theoretical uncertainties are small. In DIS production, no resolved contribution. Similarities with $\gamma\gamma$ result.

Very difficult to justify!
Conclusions and outlook

- Convincing tests of PQCD
- Few problematic areas, some serious puzzles
- NLO calculations are the standard now
- True progress can only come going from NLO to NNLO
- Hadron colliders are the near future: we need a quality jump in QCD.
EXTRA SLIDES
$R_4$ vs $\log(y_{\text{cut}})$

- OPAL data
- NLO
- R-matched
- fitted R-matched

$C_{\text{tot}}$ vs $\log(y_{\text{cut}})$

Fit range indicated on the graph.
D0, jet cross sections with $k_T$ cluster algorithm.

Resolution parameter:

$$d_{ij} = \min(p_{t_i}^2, p_{t_j}^2) \frac{\Delta R_{ij}^2}{D^2},$$

$$\Delta R_{ij}^2 = \Delta \Phi_{ij}^2 + \Delta \eta_{ij}^2.$$

Merge $ij$ if $d_{ij}$ is the smallest of all $p_{t_i}^2$ and $d_{kl}$.

Choosing $D = 1$ roughly corresponds to $R = 0.7$ in standard jet definition.
Running of $\alpha_S$: a 3-jet rate goes like

$$R_3 = C \times \alpha_S(\mu^2) \left[ 1 + \frac{\alpha_S}{\pi} \left(A + b_0 \log \frac{\mu^2}{Q^2}\right) \right]$$

$\alpha_S$ goes like

$$\alpha_S(Q^2) = \alpha_S(\mu^2) \left[ 1 + \frac{\alpha_S}{\pi} \left(b_0 \log \frac{\mu^2}{Q^2}\right) \right]$$

You measure $R_3$, you prove the running.

For the running mass, the commonly used quantity goes like

$$R_{3d}^{bd} - 1 = -18.62 \frac{m_b^2}{Q^2} \left[ 1 + \frac{\alpha_S}{\pi} \left(-6.1955 - 0.483 \log \frac{m_b^2}{Q^2}\right) \right]$$

while the running mass goes like

$$\bar{m}^2(Q^2) = m^2 \left[ 1 + \frac{\alpha_S}{\pi} \left(-\frac{8}{3} + 2 \log \frac{m_b^2}{Q^2}\right) \right]$$

Thus: find a quantity that runs like a mass to prove the running.