New QCD Studies with the Resurrected JADE Data

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Outline

- Motivation
- The Experiment
- Revival of Data and Software
- QCD studies
  - Hadronic Event Shapes in $e^+e^-$ Annihilation
  - Strong Coupling Constant
  - Power Corrections
  - QCD Colour Factors
  - Longitudinal Cross Section
  - Momentum Spectra
- Conclusions
Motivation

- Explore perturbative and non-perturbative QCD effects at low energy scales $Q$
  - large leverage for predictions:
    - PT effects $\propto 1/\log(Q)$
    - NP effects $\propto 1/Q$ (typically for event shapes)
  - interplay between hard and soft QCD best studied at “medium” energies

- JADE data: unique contribution for @ 14-44 GeV
- Test improved/new calculations from the LEP era at PETRA energies
  - New hadronic observables
  - New perturbative calculations
  - New MC models
  - New non-perturbative analytical approaches
α_S @ PETRA Times

1979  MARK-J Coll.:
   - First direct measurement α_S based on LO for the Oblateness variable

1979+  α_S = 0.15 ... 0.23 @ √s = 30 GeV
   - based on LO predictions

1982  CELLO Coll., JADE Coll.:
   - first significant measurements of α_S NLO for Thrust and Differential 3 Jet Cross Section

1982+  α_S (35GeV) = 0.11 ... 0.19
   - based on NLO predictions

...inconsistent results due to
• incomplete QCD matrix elements
• fragmentation models
Status of $\alpha_S$ in 1989

Summary value 1989:

$\alpha_S (35\text{GeV}) = 0.14 \pm 0.02$

Use LEP techniques at PETRA energies
- to increase the precision
- to allow better comparison of results (values+systematics) over a wide range of $e^+e^-$ annihilation energies
The Experiment
The PETRA e⁺e⁻ Storage Ring
The PETRA $e^+e^-$ Storage Ring

Operated 1978-1986 at DESY, Hamburg

- **MARK-J** (from 09/1978 on)
- **JADE** (from 02/1979 on)
- **TASSO** (from 09/1978 on)
- **PLUTO** (from 09/1978 on)
- **CELLO** (replacing PLUTO from 08/1982 on)

- largest storage ring at that time
- $\varnothing = 2.3$ km
- $\sqrt{s}$ range 12–47 GeV
C.M.S. Energies and Luminosities

- Fixed energy runs
- Scan periods (Top quark search)
- By far most data accumulated at $\sqrt{s} = 35$ GeV

- Total integrated lumi: $216 \text{ pb}^{-1}$
- Peak lumi: $24 \mu\text{b}^{-1}\text{s}^{-1}$
  $\Rightarrow 26$ multihadrons per hour
  @ $\sigma_{\text{had}} = 0.3 \text{ nb}$
- Clean multihadrons: 43100
The JADE Experiment

- Participating states:
  - JApan (Tokyo), DDeutschland (DESY, Hamburg, Heidelberg), EEngland (Lancaster, Manchester, RAL), USA (Maryland)
- \( \approx 120 \) collaborators in total

JADE is a magnetic, hermetic multipurpose detector:

- **Jet Chamber**
  - Track curvature + dE/dx measurement, \( B = 0.48T \)
  - 48 wire layers in \( r\phi \)
  - \( \sigma_{r\phi} = 180\mu m \) (110\mu m), \( \sigma_z = 16-32\text{mm} \) (OPAL: \( \sigma_{r\phi} = 135\mu m \), \( \sigma_z = 45-60\text{mm} \))

- **E.M. Calorimeter**
  - \( \approx 2700 \) Lead Glass blocks (individually calibrated)
  - \( \sigma_{E/E} = 4%/\sqrt{E}+1.5\% \) (OPAL: \( \sigma_{E/E} = 6.3%/\sqrt{E}+0.2\% \))

- **Muon System**
  - up to 5 chamber layers / 3 absorber layers
The Detector

Overall length/height: 8m/7m

(OPAL: 12m/12m)
The Detector
Revival of Data and Software
The JADE Revival Group

- RWTH Aachen, MPI Munich, DESY
  S. Bethke, O. Biebel, M. Blumenstengel, S. Kluth,
  P.A.M.F., C. Pahl, P. Pfeifenschneider,
  and J.E. Olsson

- Since 1998: 20+ publications/conference contributions based on/involving the reanalysed JADE data

- New JADE results considered in numerous publications from LEP collaborations / QCD theory groups

- Inspires a LEP working group to address the difficult question of keeping data and software of LEP collaborations alive
Resurrection of the JADE Data ...

- Original data were located on
  - IBM mainframe at the DESY computer centre
  - IBM tapes at DESY/Heidelberg U.
- DESY IBM completely closed July 1997
  - Last-Minute transfer to “modern” data carriers
    (IBM/EXABYTE cartridges) and computer platforms
- Now: data partially reside on CERN Castor tapes, DVDs ...
- Data organisation mainly based on the data management system
  BOS (version 1979)
  - Raw Data (REDUC1/REDUC2): BOS banks converted into FPACK
    (platform independent, still need to reconvert)
  - MH data sets (ZE4V) converted into ASCII
    (used for reanalyses)
... and of the JADE Software

- Detector simulation
  - detailed particle tracking, detector response, inefficiencies, resolution
- Event analysis software
  - pattern recognition, cluster analysis …
- JADE interactive graphics
  - event display, event analysis, event editing
- MH filtering and packing software

Source Code
- Code fragments date from 1974 on
- Mixture of different FORTRAN standards (FORTRAN IV, FORTRAN 77)
- “Illegal” IBM extensions
- Ancient pre-compiler languages (SHELTRAN, MORTRAN)
- IBM/370 assembler code

Big parts are extremely unstructured “spaghetti” code, badly documented!
Tasks

- Extract knowledge and information from incoherently spread sources (nontrivial “archaeological” challenge)
- Code modification
- Emulation interfaces (missing libraries, IBM FORTRAN intrinsics …)

<table>
<thead>
<tr>
<th>SHELTRAN</th>
<th>FORTRAN 77</th>
</tr>
</thead>
<tbody>
<tr>
<td>MORTRAN</td>
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<tr>
<td>IBM Assembler</td>
<td>CERNLIB</td>
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<tr>
<td>IBM FORTRAN</td>
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<tr>
<td>DESYLIB</td>
<td></td>
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<tr>
<td>“PLOT-10” Terminal</td>
<td>HIGZ</td>
</tr>
<tr>
<td>Control System</td>
<td></td>
</tr>
</tbody>
</table>

Platform dependent features extremely problematic!!!

- Bit&Byte manipulation
- Endian convention (byte storage order)

Complete installation succeeded on IBM RS/6000 AIX!
- XLF compiler advantageous
- same endian scheme as IBM/370
JADE Event Display
JADE Event Display
JADE Event Display
JADE Event Display
Performance I (Jet Chamber)

Integral quantities:

- $N^{(ch)}$
- $E_{\text{vis}}^{(ch)}/\sqrt{s}$
- $p_{\text{tot}}^{(ch)}/\sqrt{s}$
- …
Performance II (Jet Chamber)

Particle spectra:

\[ p_t^{(ch)}, \]
\[ p_t^{(ch)}, \text{in}, \]
\[ p_t^{(ch)}, \text{out}, \]
\[ \ldots \]
Performance III (Lead Glass)

Integral quantities:
- $N_γ$
- $E_γ/\sqrt{s}$
- $p_{tot}^{(neu)}/\sqrt{s}$
- ...
Particle spectra:
\[ p_t^{(\text{neu})}, \]
\[ p_t^{(\text{neu}), \text{in}}, \]
\[ p_t^{(\text{neu}), \text{out}}, \]
\[ ... \]
Revival Summary

- JADE software works reliably
- JADE simulation capable of reproducing most integral observables and particle spectra measured with the real detector
- JADE simulation usable for the correction of physical quantities, e.g.:
  - Event shape observables
  - Momentum spectra
  - ...

MPI Colloquium “QCD Studies with the Resurrected JADE Data”
Pedro A. Movilla Fernandez June 17th, 2003
QCD Studies
Hadronic Final States

Cross section for $e^+e^- \rightarrow \text{hadrons}$:

- $\sigma^{\text{had}}\,(\text{PETRA}) = 0.1...10\text{nb} \approx 1/100\sigma^{\text{had}}\,(M_Z)$
- Hadron production at PETRA energies mainly via $\gamma^*$ exchange
QCD in $e^+e^-$ Annihilation

PT QCD:
- $O(\alpha_S^2)$, NLLA, …
- Parton shower MC

NP QCD:
- Phenomenological hadronisation models
- Analytical power corrections

35 GeV  1 GeV
Multihadronic Selection

Main Selection Cuts:
- 4 tracks from vertex region
- 3 “long + good” tracks
- Visible Energy > 0.5\sqrt{s}
- Momentum balance < 40%
- Missing Momentum < 0.3\sqrt{s}
- |cos Θ_T|< 0.8

Residual background ≈ 1%
- e^+e^- → e^+e^- γγ
- e^+e^- → τ^+ τ^-

MH data samples for main analyses:
Hadronic Event Shapes

- Quantify the shape of an event by a single number.
- Example: "Thrust"

\[ T = \max \left( \frac{\sum_i |\vec{p}_i|}{\sum_i |\vec{p}_i|} \right) \]

QCD expectation:

Event shape observables are sensitive to PT and NP effects!
Detector Level Distributions

- QCD model + ISR + JADE simulation capable of reproducing MH data
$\bar{b}b$ Events

- 9% fraction
- fake hard gluon radiation due to electroweak decays + mass effects
- 14 GeV: up to 50% contamination in extreme 3 jet region

Treat as “background” in view of later comparison with massless QCD calculations!
More Event Shapes

**Thrust $T$**

$$T = \max_{\pi} \left( \frac{\sum_i |\vec{p}_i \hat{\pi}|}{\sum_i |\vec{p}_i|} \right)$$

⇒ thrust axis $\vec{n}_T$

event hemispheres $H_k$ ⇒

$$M_k^2 = \left\{ \left( \sum_i E_i \right)^2 - \left( \sum_i \vec{p}_i \right)^2 \right\}_{i \in H_k}$$

$$B_k = \frac{\sum_{i \in H_k} |\vec{p}_i \times \vec{n}_T|}{2 \sum_i |\vec{p}_i|}, \quad k = 1, 2$$

**Heavy Jet Mass $M_H$**

$$M_H^2 = \frac{\max(M_1^2, M_2^2)}{(\sum_i E_i)^2}$$

**Total/Wide Jet Broadening $B_T, B_W$**

$$B_T = B_1 + B_2$$

$$B_W = \max(B_1, B_2)$$

**$C$ Parameter**

$$C = 3(\lambda_1 \lambda_2 + \lambda_2 \lambda_3 + \lambda_3 \lambda_1)$$

- Calculate eigenvalues $\lambda_i$ from linearised momentum tensor.

**Differential 2 Jet Rate $y_{23}$ (Durham Scheme)**

$$y_{ij} = \frac{2 \min(E_i^2, E_j^2)(1 - \cos \theta_{ij})}{(\sum_k E_k)^2}$$

$$\frac{dR_2(y_{cut})}{dy_{cut}} = \frac{1}{\sigma} \frac{d\sigma(y_{23})}{dy_{23}}.$$

- Define jet resolution parameter $y_{ij}$.

- Combine particles $i, j$ with smallest $y_{ij}$ into pseudo particles and proceed until $y_{ij} > y_{cut}$ for 2 remaining pseudo particles ("jets").
Observables: $y=1-T$, $M_H$, $B_T$, $B_W$, $C$, $y_{23}$

- Infrared and collinear safe quantities
- Resumable in all orders $\alpha_S \log (1/y)$ (important in 2 jet region)

Perform MC based corrections to measured distributions

- $b\bar{b}$-fraction on detector level
  - reduces mass effects
- Detector effects
  - Resolution, acceptance, secondary processes
- MH selection
  - acceptance
- Photon ISR

Hadron level distributions comparable with QCD predictions
QCD Models

- **PYTHIA/JETSET:**
  - LLA parton shower + string fragmentation

- **ARIADNE:**
  - colour dipole scheme + string fragmentation

- **HERWIG:**
  - MLLA parton shower + cluster fragmentation

- **COJETS:**
  - LLA parton shower + independent fragmentation

Use LEP versions **tuned to OPAL data**
Try also former JADE optimisation for JETSET 6.3
Hadron Level

Bin-by-bin unfolding with correction factors $K_i = \frac{MC_{i\text{had}}}{MC_{i\text{det}}}$ based on udsc samples:

- **PYTHIA**
  - good overall consistency
- **HERWIG/ARIADNE**
  - moderate at 14+22 GeV, better at higher $\sqrt{s}$
- **JETSET (JADE)**
  - good at 14+22 GeV, slightly worse at higher $\sqrt{s}$
- **COJETS**
  - disfavoured at 14+22 GeV, remains worse at higher $\sqrt{s}$

Event shape become more and more 2 jet like at higher energies
Matrix vs. Bin-by-Bin Unfolding

- Consistent hadron levels
- Detector effects partially compensate ISR
Determinación del \( \alpha_S \)

- PT predicción para la sección de sección acumulada
  \[ R(y) = \int\limits_y^1 dy' \frac{1}{1 \sigma \cdot d\sigma/dy'} \]

I. NLO: describe “hard” contribución de glúon
  \[ R(y) = 1 + A(y) \cdot \alpha_S + B(y) \cdot \alpha_S^2 \]

II. NLLA: describe “soft” contribución de glúon
  \[ R(y) = (1 + C_1 \cdot \alpha_S + C_2 \cdot \alpha_S^2) \exp\{ Lg_1(\alpha_S L) + g_2(\alpha_S L) \} \]
  \[ L = \ln(1/y) \]

III. Combinación de NLO+NLLA, e.g.: \( \ln(R) \) matching
  \[ \ln(R) = Lg_1(\alpha_S L) + g_2(\alpha_S L) \]
  \[ - (G_{11} L + G_{12} L^2) \cdot \alpha_S - (G_{22} L + G_{23} L^2) \cdot \alpha_S^2 \]
  \[ + A(y) \cdot \alpha_S + [B(y) - \frac{1}{2} A(y)^2] \cdot \alpha_S^2 \]

- Efectos NP: PYTHIA, JETSET(JADE), ARIADNE, HERWIG
- Fit \( \alpha_S \) con factor de escala renormalización \( \chi_\mu = \mu/\sqrt{s} = 1 \)
  + corrección bin-by-bin de hadronización de \( R(y) \) (estándar=PYTHIA)
Fit Curves

- Typically $\chi^2$/d.o.f. = 0.5…2.0
- Stable Fits
- Large hadronisation corrections at 14 GeV!

Problems with $B_W$

$1/\sigma \frac{d\sigma}{dB_W}$

$\chi^2$/d.o.f.
**$\alpha_s$ Results**

- Similar scattering of individual results due to missing higher order terms, but...
- ...results consistent within 1-2\(\sigma\) of experimental errors
- $x_\mu$ dependence significantly smaller w.r.t. pure NLO results!
- Dominant errors:
  - Renormalisation scale
  - Hadronisation (14+22GeV!)
  - Mass effects (14+22GeV!)

<table>
<thead>
<tr>
<th>$\langle \sqrt{s} \rangle$ [GeV]</th>
<th>$\alpha_s(\sqrt{s})$</th>
<th>fit error</th>
<th>exp.</th>
<th>hadr.</th>
<th>higher ord.</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.0</td>
<td>0.1704</td>
<td>±0.0051*</td>
<td>±0.0017</td>
<td>±0.0071</td>
<td>+0.0141</td>
<td>+0.0206</td>
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<tr>
<td>22.0</td>
<td>0.1513</td>
<td>±0.0043*</td>
<td>±0.0011</td>
<td>±0.0086</td>
<td>+0.0101</td>
<td>+0.0144</td>
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<tr>
<td>34.6 ('82)</td>
<td>0.1409</td>
<td>±0.0012</td>
<td>±0.0020</td>
<td>±0.0064</td>
<td>+0.0096</td>
<td>+0.0125</td>
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<tr>
<td>35.0 ('86)</td>
<td>0.1457</td>
<td>±0.0011</td>
<td>±0.0026</td>
<td>±0.0056</td>
<td>+0.0056</td>
<td>+0.0099</td>
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<tr>
<td>38.3</td>
<td>0.1397</td>
<td>±0.0031</td>
<td>±0.0032</td>
<td>±0.0044</td>
<td>+0.0068</td>
<td>+0.0096</td>
</tr>
<tr>
<td>43.8</td>
<td>0.1306</td>
<td>±0.0019</td>
<td>±0.0032</td>
<td>±0.0056</td>
<td>+0.0044</td>
<td>-0.0080</td>
</tr>
</tbody>
</table>
Renormalisation Scale

- NLO+NLLA: reduced $x_\mu$ dependence around $x_\mu=1$ compared to NLO
  - $\alpha_S(\sqrt{s},x_\mu=1)$ more consistent than in NLO case
  - But: sizable $\alpha_S$ dependence around $x_\mu=1$ still present
- Pure NLO: Preference for small $x_\mu^{\text{(opt)}} = O(0.01…0.5)$
  - scale dependence around $x_\mu^{\text{(opt)}}$ sometimes smaller, but...
  - less consistent individual results
  - $(\alpha_S,x_\mu)$ fits not always stable, large statistical errors
  - no strong theoretical arguments for the choice $x_\mu = x_\mu^{\text{(opt)}}$
⇒ have to consider both $\alpha_S(\sqrt{s}, x_\mu=x_\mu^{\text{(opt)}})$ and $\alpha_S(\sqrt{s}, x_\mu=1)$

NLO+NLLA @ $x_\mu=1$ seems to be the “natural” choice
Test of the Running of $\alpha_s$

- QCD fit, exp.+stat. uncertainties (inner error bars):
  \[ \Lambda_{\text{MS}}^{(5)} = 246 \pm 7 \text{ MeV} \]
  \[ \alpha_s(M_Z) = 0.1210 \pm 0.0006 \]
  \[ P(\chi^2) = 75\% \]

- $\alpha_s = \text{const.}$, total errors (outer error bars):
  \[ P(\chi^2) = 1.1 \cdot 10^{-5} \]

- Now more values with higher accuracy available
- $\alpha_s$ of “homogeneously” determined from PETRA to LEP2 energies

**QCD expectation:**
\[ C_A=3, \ C_F=4/3, \ N_F=5 \]

\[ \alpha_s(\sqrt{s}) = \frac{1}{\beta_0 l} - \frac{\beta_1 \ln l}{\beta_0^3 l^2} + \frac{1}{\beta_0^3 l^3} \left[ \frac{\beta_2^2}{\beta_0} (\ln^2 l - \ln l - 1) + \frac{\beta_2}{\beta_0} \right] \]

\[ l = \ln(\sqrt{s}/\Lambda_{\text{MS}})^2 \]

\[ \beta_0 = \frac{1}{12\pi} (33 - 2N_f) \]
\[ \beta_1 = \frac{1}{24\pi^2} (153 - 19N_f) \]
\[ \beta_2 = \frac{1}{3456\pi^3} (77139 - 15099N_f + 325N_f^2) \]

Good agreement with world average based on NNLO QCD
\( \alpha_s \) Summary

- LEP established resummed calc for event shape work well at PETRA energies
- LEP tuned MC models (PYTHIA) capable of describing data down to 14 GeV
- Consistent picture of individual \( \alpha_s \) results
- Hadronisation uncertainties at 14 GeV as large as renormalisation scale ambiguity
- New PETRA results now better comparable with LEP (values+systematics)
- Results consistent with other measurements and methods

\[ \alpha_s(M_{Z^0}) = 0.1194^{+0.0083}_{-0.0070} \ \text{(PETRA)} \]
\[ \alpha_s(M_{Z^0}) = 0.121 \pm 0.006 \ \text{(LEP + SLC)} \]
\[ \alpha_s(M_{Z^0}) = 0.120 \pm 0.007 \ \text{(LEP2)} \]

But: Method is model dependent!
Power Corrections

- Classical method to estimate NP effects: MC models
  - PYTHIA, HERWIG, ARIADNE …
  - numerous parton shower + fragmentation parameters
- Promising alternative: “power corrections”
  - Parametrise unknown but analytical behaviour of the physical strong coupling constant around the Landau pole $\Lambda$ (0…2GeV)
  - Dokshitzer, Marchesini, Webber (DMW): NP structure due to soft gluon radiation at $\mu \approx \Lambda$

\[
\langle y \rangle = \langle y \rangle_{PT} + D_y \mathcal{P} \quad \text{(means)}
\]
\[
\frac{d\sigma}{dy}(y) = \frac{d\sigma_{PT}}{dy}(y - D_y \mathcal{P}) \quad \text{(distributions)}
\]
\[
\mathcal{P} = \frac{4C_F}{\pi^2} \mathcal{M} \frac{\mu_1}{Q} \left[ \alpha_0(\mu_1) - \alpha_S(\mu_R) - \beta_0 \frac{\alpha_S^2(\mu_R)}{2\pi} \left( \ln \frac{\mu_R}{\mu_1} + \frac{K}{\beta_0} + 1 \right) \right]
\]

- $\alpha_0$ is the only NP parameter!
- $\alpha_0$ is universal
Power Corrections to Distributions

- Observable specific part is $D_y$:
  - $T, M_H, C$: shift
  - $B_T, B_W$: shift+squeeze
  - $(y_{23} : \text{no } 1/Q \text{ contribution})$

Test of DMW ansatz:
- Use mod. ln(R) matching for PT part
- Perform simultaneous $(\alpha_s, \alpha_0)$ fits to all available event shape spectra

Available data sets:

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>$1 - T$</th>
<th>$M_H$</th>
<th>$B_T, B_W, C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETRA (JADE, TASSO)</td>
<td>12-47</td>
<td>102000</td>
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<tr>
<td>PEP (HRS, MARK II)</td>
<td>29</td>
<td>28300</td>
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<tr>
<td>TRISTAN (AMY)</td>
<td>55-58</td>
<td>1900</td>
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<tr>
<td>LEP I (ADLO*)</td>
<td>91</td>
<td>$\mathcal{O}(10^6)$</td>
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<tr>
<td>SLC (SLD)</td>
<td>91</td>
<td>37200</td>
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<tr>
<td>LEP II (ADLO*)</td>
<td>133-189</td>
<td>15600</td>
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</tr>
</tbody>
</table>

JADE is the only contribution for new observables below $M_Z$

... covering the energy range $\sqrt{s} = 14...189$ GeV !!!
DMW Fits (I)

- Good description of the data \((T, C, B_T)\) within the kinematical limit of the predictions
DMW Fits (II)

- Excess in 3 jet region for less inclusive observables \((M_H, B_W)\) at PETRA energies!
- NB: also problems with PT prediction for \(B_W\)
DMW Fits to Mean Values

- NLO+DMW capable of describing measured mean values of all observables

[Does not include update at 14+22 GeV]
**($\alpha_S, \alpha_0$)-Results**

- Individual results consistent within 1-2\(\sigma\) of total errors
- $\alpha_0$ universal within 20% uncertainty level of the Milan factor (stemming from $O(\alpha_S^2)$ evaluation of power corrections)
- But: $\alpha_S^{(\text{pow.corr})} < \alpha_S^{(MC)}$ due to minor/missing squeeze of PT spectrum (fit chooses small $\alpha_S$ to compensate; big effect for jet broadening variables!!)

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**Distributions**

- $\alpha_S(M_{Z^0}) = 0.1126 \pm 0.0005 \pm 0.0037 \pm 0.0044 \pm 0.0030$
- $\alpha_0(2 \text{ GeV}) = 0.542 \pm 0.005 \pm 0.032 \pm 0.084 \pm 0.060$

**Mean Values**

- $\alpha_S(M_{Z^0}) = 0.1187 \pm 0.0014 \pm 0.0001 \pm 0.0028 \pm 0.0015$
- $\alpha_0(2 \text{ GeV}) = 0.485 \pm 0.013 \pm 0.001 \pm 0.065 \pm 0.043$

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**MPI Colloquium “QCD Studies with the Resurrected JADE Data”**

Pedro A. Movilla Fernandez       June 17th, 2003
Power Corrections vs. MC Predictions

PC/MC corrections expressed by means of corrections factors:

- $T$, $C$, $B_T$ with “similar” corrections
- $M_H$, $B_W$ with strongly deviating corrections
- “Missing squeeze” (w.r.t. MC prediction) is compensated by small $\alpha_S$ values
Missing NP Terms?

- Explore possible missing (higher order) terms by fits to separate data sets: $\sqrt{s} < M_Z$, $\sqrt{s} \geq M_Z$, ...
  - Large systematic effects for $B_T$, $B_W$
Extended Power Corrections

- Evidence for additional terms probably behaving $\propto \ln(Q)/Q$
  - Extended power corrections?
  - Missing PT terms? (effect partially reproduced by redefining $x_\mu$)

- Log enhanced power corrections expected due to mass effects (but expected effect for $B_W$ not as large)
Power Corrections to $y_{23}$

- **DMW**: $1/Q$ coefficient = 0 …confirmed by fit
- Evidence for additional terms probably behaving $\propto 1/Q^2$
- Need 14+22 GeV data to see the effect!

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_s(M_{Z^0})$</th>
<th>$A_{10}$ [GeV]</th>
<th>$A_{20}$ [GeV$^2$]</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>pQCD</td>
<td>0.1147±0.0005</td>
<td>—</td>
<td>59.7/100</td>
</tr>
<tr>
<td></td>
<td>pQCD</td>
<td>0.1152±0.0005</td>
<td>—</td>
<td>151/107</td>
</tr>
<tr>
<td>II</td>
<td>pQCD+$A_{10}/Q$</td>
<td>0.1124±0.0006</td>
<td>0.062±0.008</td>
<td>98.2/106</td>
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<tr>
<td></td>
<td>pQCD+$A_{20}/Q^2$</td>
<td>0.1133±0.0005</td>
<td>—</td>
<td>2.25±0.18</td>
</tr>
<tr>
<td></td>
<td>pQCD+$A_{10}/Q + A_{20}/Q^2$</td>
<td>0.1128±0.0007</td>
<td>0.018±0.014</td>
<td>1.94±0.32</td>
</tr>
</tbody>
</table>

MPI Colloquium “QCD Studies with the Resurrected JADE Data”

Pedro A. Movilla Fernandez  June 17th, 2003
Power Corrections Summary

- PETRA data discriminate between “good” (T, C, B_T) and “bad” (M_H, B_W) observables (w.r.t. of DMW model)
- $\alpha_0$ universal at 20% level
- DMW (for distributions) different from MC prediction
  $\rightarrow \alpha_S^{(\text{pow.corr})} < \alpha_S^{(\text{MC})}$
- Indication of higher order terms (B_W, y_{23}) may inspire theorists?
- Combined means+distributions:
  
  $$\alpha_S(M_{Z0}) = 0.1175^{+0.0031}_{-0.0021}$$
  $$\alpha_0(2\text{ GeV}) = 0.503^{+0.066}_{-0.045}$$

- Consistency with other measurements

More and improved PC calculations needed!
Colour Factors from Event Shapes

Colour structure known for event shape

- PT part
  \[ A \propto C_F, \quad B = B(C_A, C_F, N_f) \]
  \[ \text{NLLA} = \text{NLLA} (C_A, C_F, N_f) \]

- Running \( \alpha_S \)
  \[ \beta_0 = \beta_0 (C_A, N_f), \quad \beta_1 = \beta_1 (C_A, C_F, N_f) \]

- Power Corrections
  \[ P = P(C_A, C_F, N_f) \]
  \[ M = M(C_A, N_f) \]
  \[ D_y = D_y(C_A, C_F, N_f) \]

Reduced model dependence!
(i.e. no bias from colour structure of MC)

Relative weights of fundamental vertices determined by QCD gauge structure:
\[ C_F = 4/3, \quad C_A = 3, \quad T_F N_f = 1/2 N_f \]
Results

- Combined results:
  \[ C_F = 2.84 \pm 0.24 \]
  \[ C_A = 1.29 \pm 0.18 \]
  competitive with 4 jet angular correlation analyses

- Need JADE data to constrain the fit
Longitudinal Cross Section $\sigma_L$

Differential cross section for inclusive hadron production in $e^+e^- \rightarrow \gamma,Z \rightarrow h+X$

$$\frac{1}{\sigma_{tot}} \cdot \frac{d^2\sigma^h}{dx \ d(cos\theta)} = \frac{3}{8} (1 + \cos^2\theta) \cdot F_T^h(x) + \frac{3}{4} (\sin^2\theta) \cdot F_L^h(x) + \frac{3}{4} (\cos\theta) \cdot F_A^h(x)$$

...contribution to fragmentation function $F^h(x)$

$x = 2p/\sqrt{s}$: fractional momentum of particle

$\Theta = \angle$(incoming particle, outgoing hadron)

$$\frac{\sigma_{T,L}}{\sigma_{tot}} = \frac{1}{2} \sum_h \int dx \ x \cdot F_{T,L}^h(x)$$

$$\frac{1}{\sigma_{tot}} \cdot \frac{d\sigma^{ch}}{d(q \cdot \cos\theta)} = \frac{3}{8} \eta^{ch} \left[ \frac{\sigma_L}{\sigma_{tot}} (1 - 3\cos^2\theta) + (1 + \cos^2\theta) \right]$$

- measure $\cos(\theta)$ distribution of charged particles
- fit $\rho_L/\rho_{tot}$ and $\eta^{ch}$ (corrects for neutral particles)

contribution from gluon radiation in quark/anti-quark system

not considered because no experimental distinction between quark/anti-quark
Results

\[ \frac{\rho_L}{\rho_{\text{tot}}} = 0.067 \pm 0.011 \]

Dominant errors:
- limited data statistics (combined 35+44 GeV analysis)
- limited MC statistics (preprocessed samples)

\[
\left( \frac{\sigma_L}{\sigma_{\text{tot}}} \right)_{\text{PT}} = \frac{\alpha_S}{\pi} + 8.444 \left( \frac{\alpha_S}{\pi} \right)^2
\]

\[ \alpha_S(36.6 \text{ GeV}) = 0.150 \pm 0.020 \]

Power corrections:
- \[ \alpha_S(M_Z) = 0.126 \pm 0.020 \]
- \[ \alpha_0(2 \text{ GeV}) = 0.3 \pm 0.3 \]

\[ \frac{\sigma_L}{\sigma_{\text{tot}}} = \left( \frac{\sigma_L}{\sigma_{\text{tot}}} \right)_{\text{PT}} + a_{\sigma_L} \cdot \frac{16 M \mu_I}{3 \pi^2 \sqrt{s}} \cdot (\alpha_0(\mu_I) - \alpha_S(\mu) + \mathcal{O}(\alpha_S^2)) \]
**$\xi$ Distribution**

Momentum spectrum: $\xi \equiv -\ln(x)$

- MLLA calculation (Fong, Webber):

\[
F_q(\xi, Y) = \frac{N(Y)}{\sigma \sqrt{2\pi}} \cdot \exp\left(\frac{k}{8} - \frac{s\delta}{2} - \frac{(2 + k)\delta^2}{4} + \frac{s\delta^3}{6} + \frac{k\delta^4}{24}\right)
\]

\[Y \equiv \ln \left(\frac{\sqrt{\rho}}{2\Lambda_{\text{eff}}}\right)\]

\[\delta = \frac{\xi - \langle \xi \rangle}{\sigma}\]

\[\langle \xi \rangle = \langle \xi(Y) \rangle = \frac{Y}{2} \left(1 + \frac{\rho}{24} \sqrt{Y} \beta\right) \cdot \left[1 - \frac{\omega}{6Y}\right] + O(1)\]

$\xi_0 - \langle \xi \rangle \approx \frac{3\rho}{32C_A} \approx 0.35$

with $N, k, s, \sigma, \beta, \rho, \omega$ known functions of $Y, C_A, C_F, N_f$

- Test MLLA by fits to measured distributions @ 22, 35 and 44 GeV (theory only valid close to $\xi_0$)

- Free parameters: e.g. $N, \Lambda_{\text{eff}}, \xi_0$

- Explore the predicted scale dependence of $\xi_0$

---

**MPI Colloquium “QCD Studies with the Resurrected JADE Data”**

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Fits

- Good description of data within the kinematic boundaries
- Energy evolution consistent with QCD expectation

<table>
<thead>
<tr>
<th></th>
<th>(\xi_0)</th>
<th>N</th>
<th>(\Lambda_{\text{eff}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 GeV</td>
<td>2.74±0.09</td>
<td>11.6±0.4</td>
<td>136±28</td>
</tr>
<tr>
<td>35 GeV</td>
<td>3.06±0.05</td>
<td>14.1±0.2</td>
<td>142±25</td>
</tr>
<tr>
<td>44 GeV</td>
<td>3.19±0.06</td>
<td>16.4±0.6</td>
<td>110±38</td>
</tr>
</tbody>
</table>
Scale Dependence

\[ \xi_0(Y) = \frac{1}{2} Y + \sqrt{CY + C} \]

\[ Y = \ln \left( 0.5 \sqrt{s} / \Lambda_{\text{eff}} \right) \]

- Use JADE + OPAL data
  \[ \sqrt{s} = 22 \ldots 202 \text{ GeV} \]

Reasonable description of data:
\[ \Lambda_{\text{eff}} = 207 \pm 3 \text{ MeV} \]
Flavour dependence

- write $\xi_0 (\sqrt{s})$ as linear combination of peak positions $\xi_0^{(q)} (\sqrt{s})$ for flavour q, weighted with branching ratio $f_q(\sqrt{s})$
- $\xi_0^{(c,b)} - \xi_0^{(uds)} \propto 0.5 \ln \left( \frac{\Lambda^{(c,b)}}{\Lambda^{(uds)}} \right)$
  $\Rightarrow$ flavour dependence of energy evolution
- fix $\xi_0^{(uds)}, \xi_0^{(c)}, \xi_0^{(b)}$ with OPAL data @ $\sqrt{s} = M_Z$
- fit $\Lambda^{(uds)}, \Lambda^{(c)}, \Lambda^{(b)}$

Mass effects about 20-30%:

\[
\begin{align*}
\Lambda^{(uds)} &= 184\pm32\text{MeV} \\
\Lambda^{(c)} &= 239\pm90\text{MeV} \\
\Lambda^{(b)} &= 247\pm28\text{MeV}
\end{align*}
\]
Conclusions

Reanalysis of JADE data…

- complements state-of-the-art studies from LEP in the lower energy part of the $e^+e^-$ continuum
- provides stringent tests of perturbative and non-perturbative aspects of QCD
- is needed for constraining (future!) QCD predictions

Keep the data and the software alive since QCD is still in progress!