Measurement of the strong coupling $\alpha_s$ from the 3-jet rate in $e^+e^-$ annihilation using JADE data

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Introduction

- Why study 27+ year old $e^+e^- \rightarrow $ hadrons data?
  - Theory improvements: NLO > 3 jets, NNLO, ...
  - MC generators and hadronisation models
- Test QCD calculations for LHC
  - Techniques related, crossing relations
  - Precision tests independent of pp complications
- Because we can!
The JADE experiment

1979 to 1986 at PETRA (DESY)
e^+e^- annihilation to hadrons at 
\( \sqrt{s} = 14, 22, 34.6, 35, 38.3, 43.8 \) GeV
**JADE data**

Data samples:

- $O(10^3-10^4)$ events

Negligible backgrounds after selection

Event selection:

- momentum balance, visible energy, $N_{ch}$.
Durham jet clustering algorithm

JADE $\sqrt{s} = 44$ GeV

1. Phase space distances
   \[ y_{ij} = 2 \min(E_i, E_j)^2(1-\cos\theta_{ij})/s \]

2. Stop when all $y_{ij} > y_{\text{cut}}$

3. Combine pair with smallest $y_{ij}$
   \[ p_{ij} = p_i + p_j \]

4. Remove i and j, add ij, goto 1)

Observable:
\[ R_3(y_{\text{cut}}, Q) = N_{3\text{-jet}}(y_{\text{cut}}, Q) / N(Q) = \sigma_{3\text{-jet}} / \sigma_{\text{had}} \]
QCD predictions: fixed order

$$R_{3,\text{NNLO}}(y_{\text{cut}}, Q) = \frac{\sigma_{3\text{-jet}}}{\sigma_{0}} = A(y_{\text{cut}}) \alpha_s(Q) + B(y_{\text{cut}}) \alpha_s^2(Q) + C(y_{\text{cut}}) \alpha_s^3(Q)$$

$$\alpha_s = \frac{\alpha_s}{(2\pi)}; \sigma_0 = \sigma_{\text{had}} / (1 + 2\alpha_s + \ldots)$$

$A(y_{\text{cut}}), B(y_{\text{cut}}), C(y_{\text{cut}})$ by numerical integration of QCD ME

[Insert: rel. theory uncertainties NLO and NNLO]

QCD predictions: resummation

E.g. \(\alpha_S \log^2(1/0.01) \approx 0.4\)

\[ R_{3,\text{NLLA}} \text{ large for small } y_{\text{cut}} \]

Expand known \(R_{3,\text{NLLA}}\) to \(O(\alpha_S^3)\):

\[ L = \log(1/y_{\text{cut}}) \]

\[ R_{3,\text{NLLA,exp.}} = \sum_{i=1}^{3} \sum_{j=i}^{2i} \alpha_S^i L^j R_{ij} \]

“K-term”: partial subleading logs

R-matching:

\[ R_3 = R_{3,\text{NNLO}} + R_{3,\text{NNLA}} - R_{3,\text{NLLA,exp.}} \]

\(\alpha_S(M_Z) = 0.118\)

\(\sqrt{s} = 35 \text{ GeV}\)
Data vs MC

Data corrected to hadron-level, bb contribution subtracted

PYTHIA 5.7, HERWIG 6.2, ARIADNE 4.11

LL+LO, tuned to OPAL@LEP 1

Good description of low energy data with OPAL tune

MCs ok for experimental and hadronisation corrections

S. Kluth: alpha_S from 3-jet rate with NNLO+NLLA+K using JADE data
Hadronisation corrections

Compare MC parton-level (after parton shower) to hadron-level (particle level)

Check consistency MC LO+LL parton-level with theory NNLO+NLLA parton-level by OPAL:

Consistent within differences between MCs, covered by hadronisation correction systematic uncertainty

**R_3 fits**

**NNLO+NLLA+K**

**Fit ranges: exp. and had. corrections stable and “small”**

Incl. point-to-point correlations, $\chi^2$ from stat. errors only, $1.3 < \chi^2$/d.o.f. $< 3.8$ (except 14 GeV)

**Combine results 22 to 44 GeV:**

$\alpha_S(M_Z) = 0.1199 \pm 0.0010_{\text{stat.}} \pm 0.0021_{\text{exp.}} \pm 0.0054_{\text{had.}} \pm 0.0007_{\text{theo.}}$
Systematics

- **Experimental**
  - Vary event selection cuts
  - Tracks + ECAL clusters vs “energy flow”
  - PYTHIA vs HERWIG exp. corrections
  - JADE detector calibration versions
  - Vary $b\bar{b}$ subtraction
  - Vary fit range

- **Hadronisation**
  - PYTHIA vs HERWIG vs ARIADNE

- **Theory**
  - Renormalisation scale factor $0.5 < x_\mu < 2.0$
Cross checks

Renormalisation scale:
Fit with $x_\mu$ free: $x_\mu = O(1)$
Essentially same result for $\alpha_s(m_Z)$

NNLO only fit:
Slope not fully described
Sensitive to fit range
Scale uncertainty larger
DG$^3$HS/ALEPH Result

NNLO only, result at single point $y_{cut} = 0.02$

$\alpha_s(M_Z) = 0.1175 \pm 0.0004$ stat. $\pm 0.0019$ exp. $\pm 0.0006$ had. $\pm 0.0014$ theo.

Slope problem visible

Comparison to previous results

Result consistent with:

- previous JADE & OPAL
- DG$^{3}$HS/ALEPH
- PDG
Running coupling

Confirm QCD running coupling prediction

14 GeV analysis (not in average) still consistent

Prediction using PDG world average
JADE/OPAL Data preservation

Store data in computing centre (RZG)

Port software on modern platforms

Replace missing libraries

Cross check analyses against previous results

9 papers, two with 50+ citations, many conference contributions, PhD and diploma theses

Why? Physics objectives
How? Review analysis models
How? Soft- and hardware persistency
How? Common specifications
Who? Funding programs, initiatives
Summary

• First $\alpha_S$ from $R_3$ with NNLO+NLLA+K QCD
  
  \[
  \alpha_S(M_Z) = 0.1199 \pm 0.0010^{\text{stat.}} \pm 0.0021^{\text{exp.}} \pm 0.0054^{\text{had.}} \pm 0.0007^{\text{theo.}}
  \]

• Slope of $R_3(y_{\text{cut}})$ not fully described in NNLO

• Ok within errors with NNLO+NLLA

• Had. uncertainties dominate
  
  • LEP data
  • Better had. models (power corrections)?

• More new results from old data possible!