JADE Analysis in the New Millennium

Pedro A. Movilla Fernández
Lawrence Berkeley National Laboratory

UCLA Experimental Particle and Nuclear Physics Seminar, Feb 16th 2005

Advanced information on the Nobel Prize in Physics, 5 October 2004

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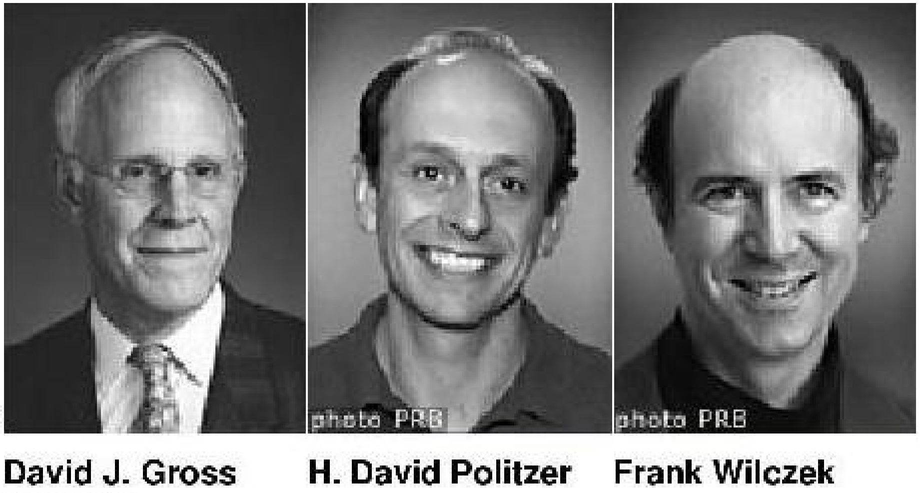
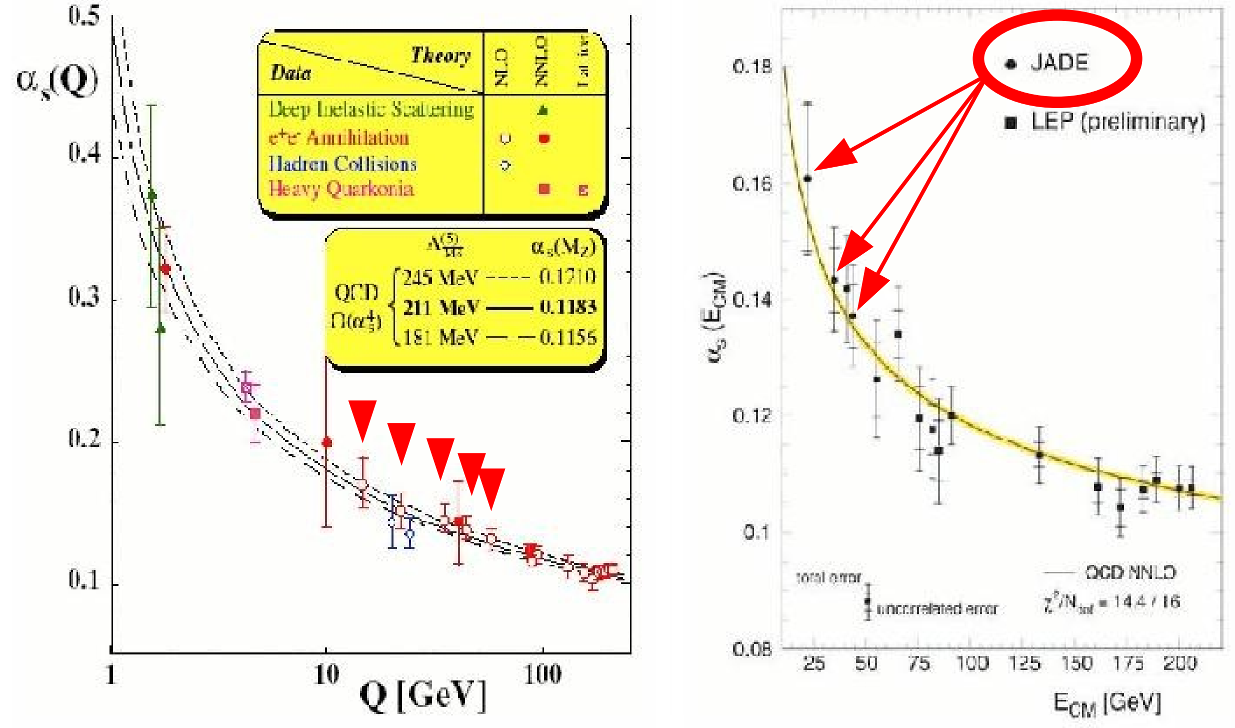


David J. Gross **H. David Politzer** **Frank Wilczek**

Asymptotic Freedom and Quantum ChromoDynamics: the Key to the Understanding of the Strong Nuclear Forces



...taken from the Physics Nobel Prize press release (Oct 5, 2004)

The left-hand panel shows a collection of different measurements by S. Bethke from High-Energy International Conference in Quantum Chromodynamics, Montpellier 2002 (hep-ex/0211012). The right-hand panel shows a collection by P. Zerwas, Eur. Phys. J. C34(2004)41. JADE was one of the experiments at PETRA at DESY. NNLO means Next-to-Next-to-Leading Order computation in QCD.

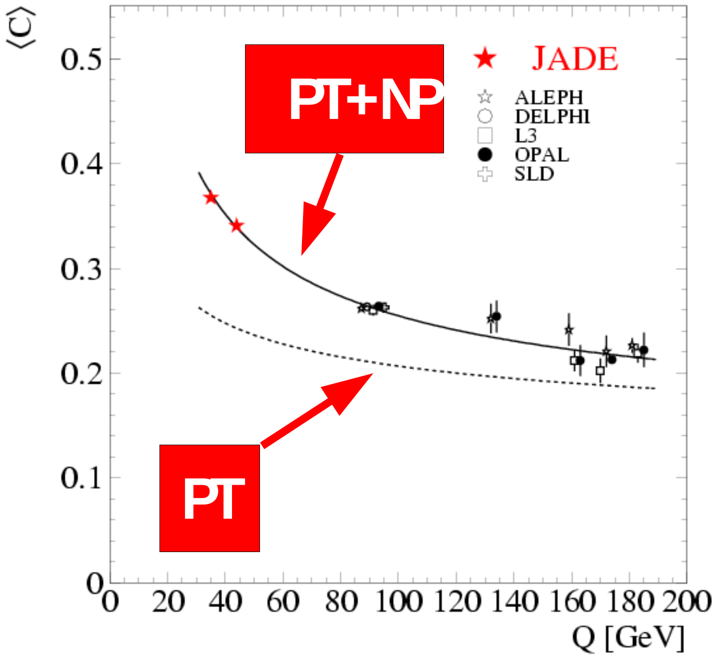
http://nobelprize.org/physics/laureates/2004/press.html

Outline

- Motivation
- The Experiment
- Resurrection of Data and Software
- Recent QCD results
  - α_s from event topologies and jet rates (includes recent OPAL results)
  - Power corrections
  - QCD color structure
- Summary and Conclusions

Motivation

JADE analysis probes QCD at low energy scales Q with state-of-the-art techniques



- large leverage for predictions:

PT effects ∝ 1/log(Q)
NP effects ∝ 1/Q (event shapes)

- interplay between hard and soft QCD best studied at “medium” energies
- JADE provides unique contribution for the energy range 14-44 GeV
  - ~1500 ... 35000 multihadronic events/energy point, precise energy bins
- LEP FSR-Z^0 analysis technique
  - O(500-1000) events/energy point down to <√s>=40 GeV, coarse energy bins

α_s at PETRA Times

1973 Concept of asympotic freedom

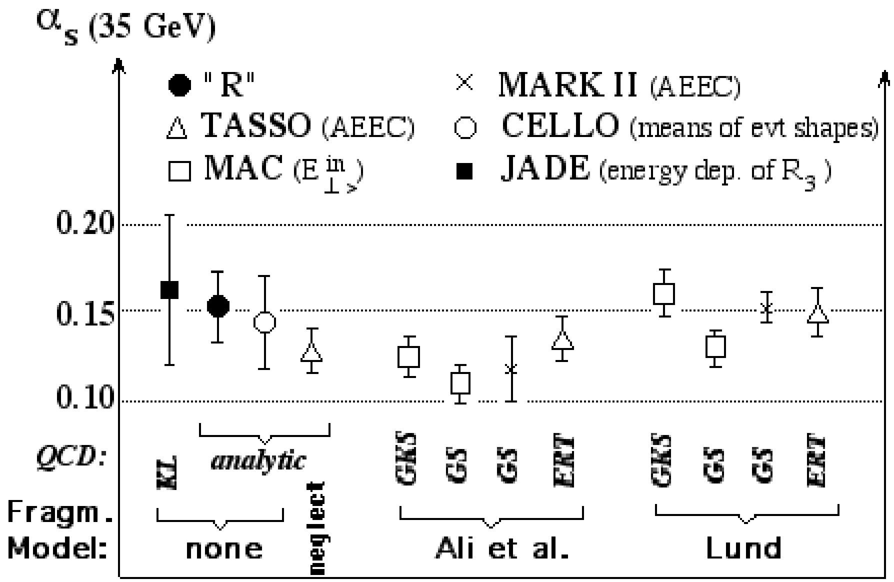
1979 Discovery of the gluon at PETRA

1979 MARK-J Coll.: First direct measurement α_S using LO for oblateness

1979+ $\alpha_S = 0.15 \ldots 0.23$ @ $\sqrt{s} = 30$ GeV based on LO predictions

1982 CELLO Coll., JADE Coll.: First "significant" measurements of α_S based on NLO for thrust and differential 3-jet cross section

1982+ $\alpha_S(35\text{GeV}) = 0.11 \ldots 0.19$ based on NLO predictions



S. Bethke, LBL-28112 (1989)

…inconsistent results due to

- **incomplete NLO matrix elements**
- **obsolete MC models**

Summary value 1989:
$\alpha_s(35\text{GeV}) = 0.14 \pm 0.02$

What's happened since PETRA

- LEP/SLC learned from QCD PETRA/PEP experiences, now PETRA in turn profits form LEP
- QCD predictions have drastically improved since PETRA shutdown
  - Development of new event shape variables with better theoretical properties (e.g. infrared safe), also new jet finders
  - New theoretical perturbative predictions, e.g. resummed NLO calculations for event shapes
  - New/improved hadronization models (Pythia, Herwig, Ariadne)
  - Novel analytical approach to describe hadronization (power corrections)
  - ...

PETRA/PEP 1980's

↓

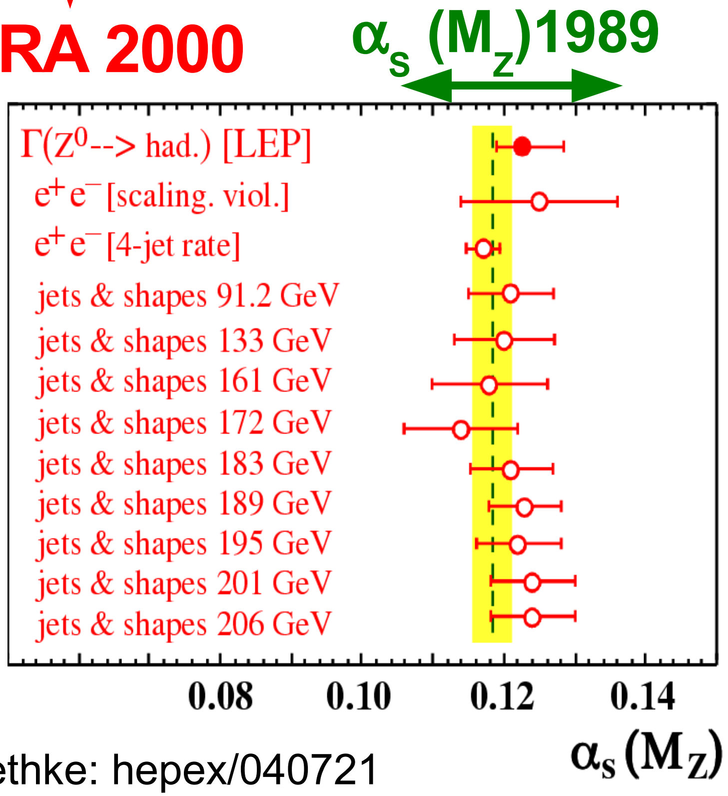
LEP/SLC

↓

PETRA 2000

QCD input for LEP/SLC

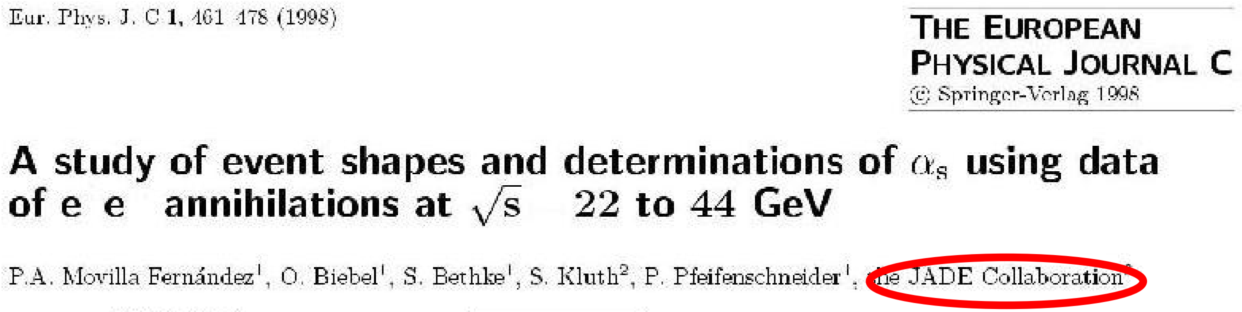
feedback for PETRA



S.Bethke: hepex/040721
Nucl.Phys.Proc.Suppl.135 (2004) 345

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, J. Schieck and J.E. Olsson
- Since 1998: 25+ publications/conference contributions based on/involving the reanalysed JADE data
- New JADE results have been considered in numerous publications from LEP collaborations / QCD theory groups

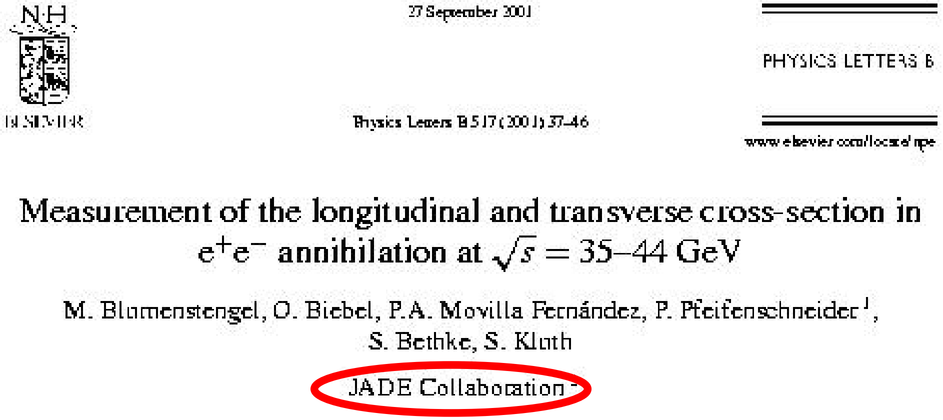


Eur. Phys. J. C 1, 461 478 (1998)

THE EUROPEAN
PHYSICAL JOURNAL C
© Springer-Verlag 1998

A study of event shapes and determinations of α_s using data of e e annihilations at $\sqrt{s}$ 22 to 44 GeV

P.A. Movilla Fernández[1], O. Biebel[1], S. Bethke[1], S. Kluth[2], P. Pfeifenschneider[1], the JADE Collaboration



N·H
ELSEVIER

27 September 2001

PHYSICS LETTERS B

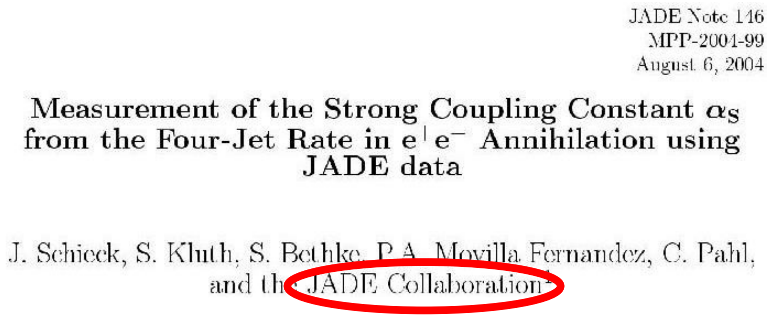
Physics Letters B 517 (2001) 37–46

www.elsevier.com/locate/npe

Measurement of the longitudinal and transverse cross-section in e^+e^- annihilation at $\sqrt{s} = 35$–44 GeV

M. Blumenstengel, O. Biebel, P.A. Movilla Fernández, P. Pfeifenschneider[1],
S. Bethke, S. Kluth

JADE Collaboration



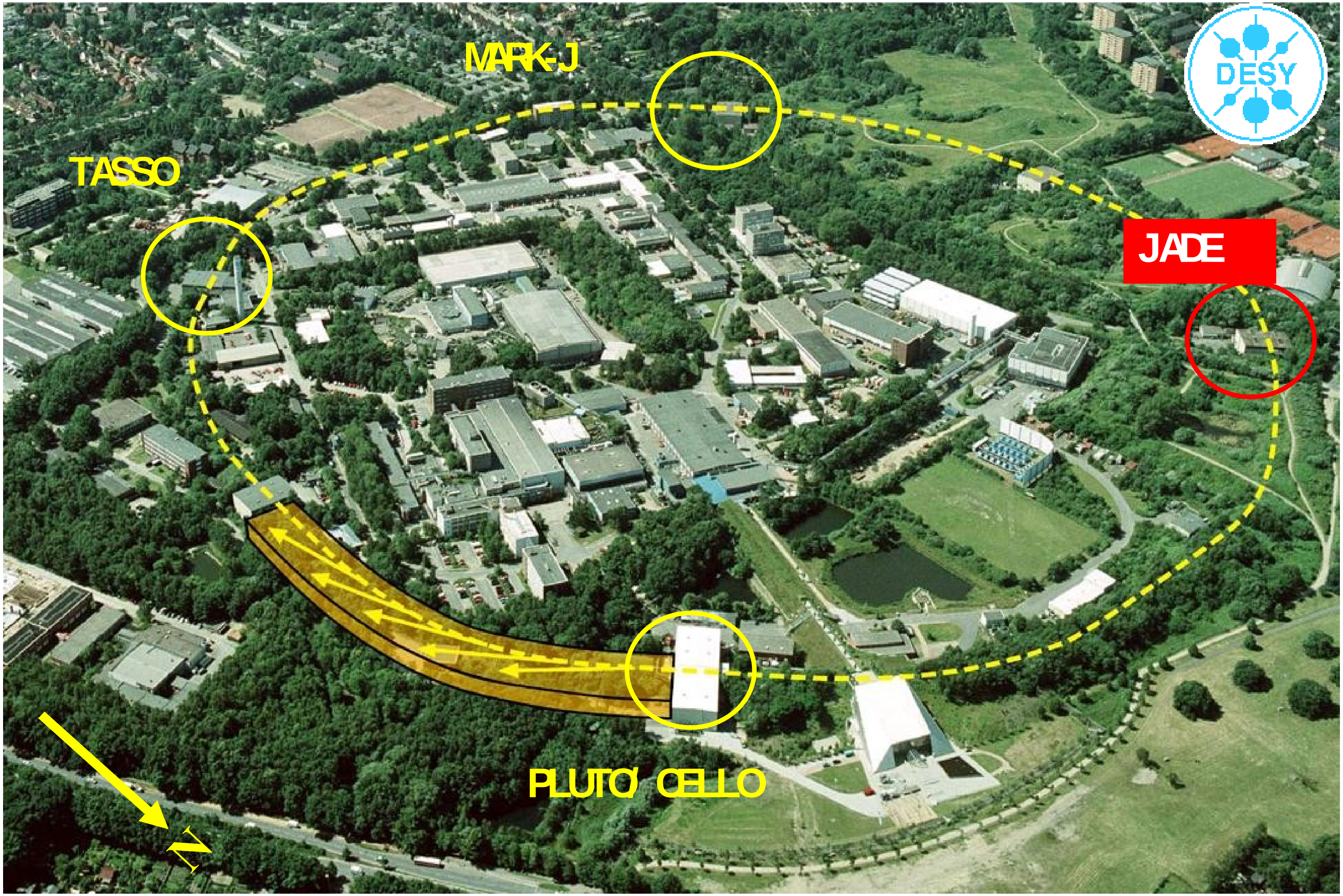
JADE Note 146
MPP-2004-99
August 6, 2004

Measurement of the Strong Coupling Constant α_S from the Four-Jet Rate in e^+e^- Annihilation using JADE data

J. Schieck, S. Kluth, S. Bethke, P.A. Movilla Fernandez, C. Pahl,
and the JADE Collaboration

The Experiment

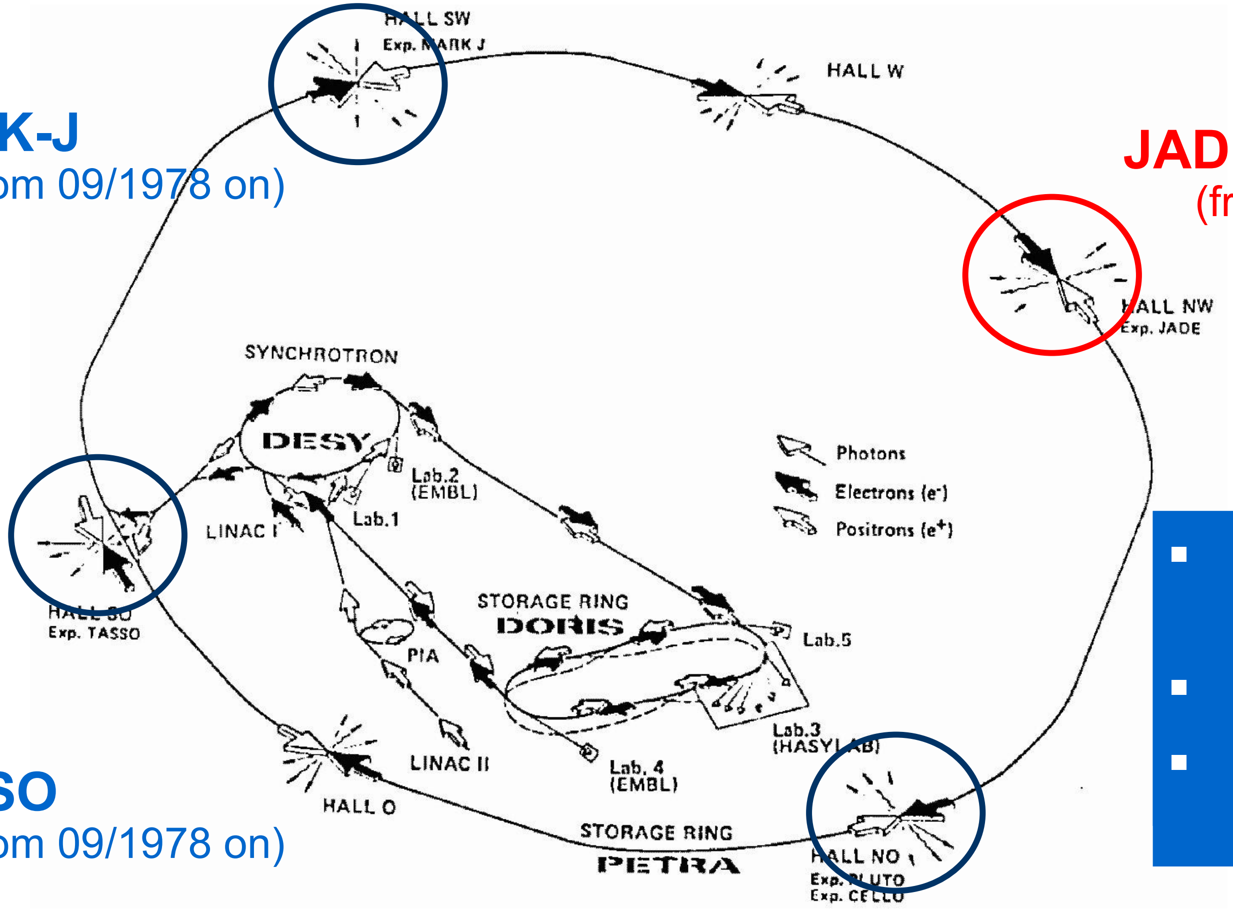
The PETRA e^+e^- Storage Ring



DESY, Hamburg

The PETRA e^+e^- Storage Ring

Operated 1978-1986 at DESY, Hamburg



MARK-J
(from 09/1978 on)

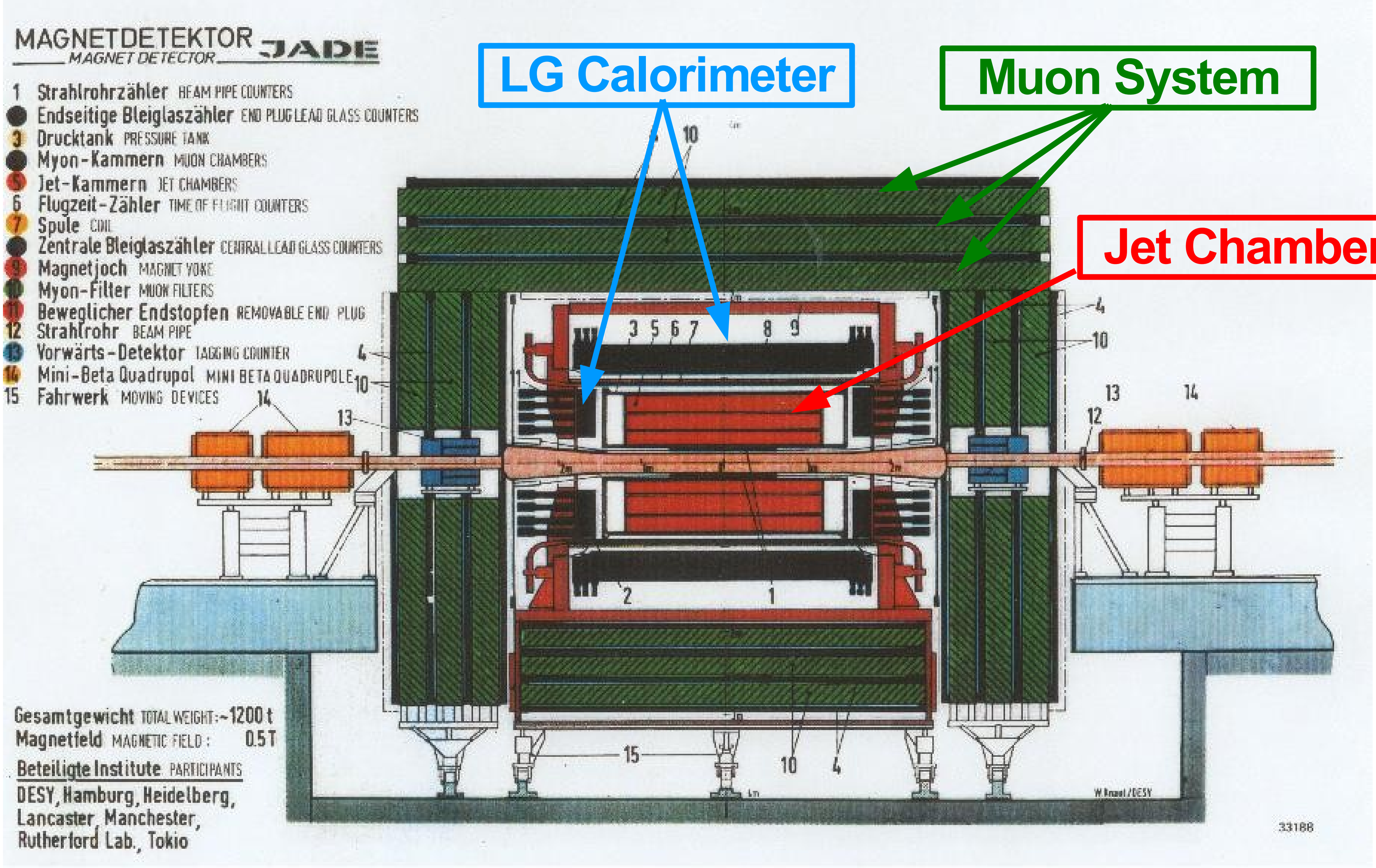
JADE
(from 02/1979 on)

TASSO
(from 09/1978 on)

PLUTO (from 09/1978 on)
CELLO (replacing PLUTO from 08/1982 on)

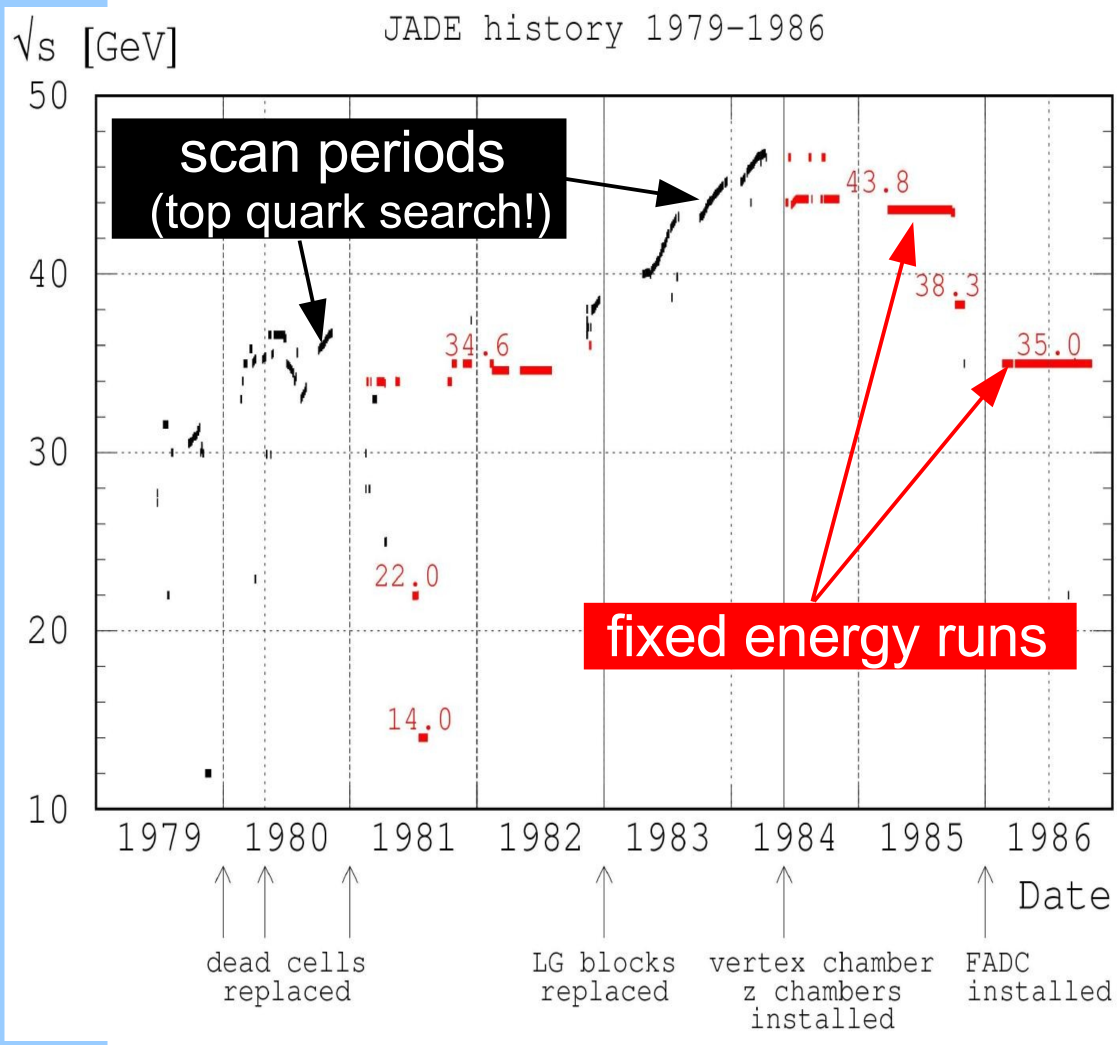
- largest storage ring at that time
- ∅ = 2.3 km
- $\sqrt{s}$ range 12–47 GeV

The JADE Detector



120 collaborators from **JA**pan (Tokyo), **D**eutschland (DESY, Hamburg, Heidelberg), **E**ngland (Lancaster, Manchester, RAL), USA (Maryland)

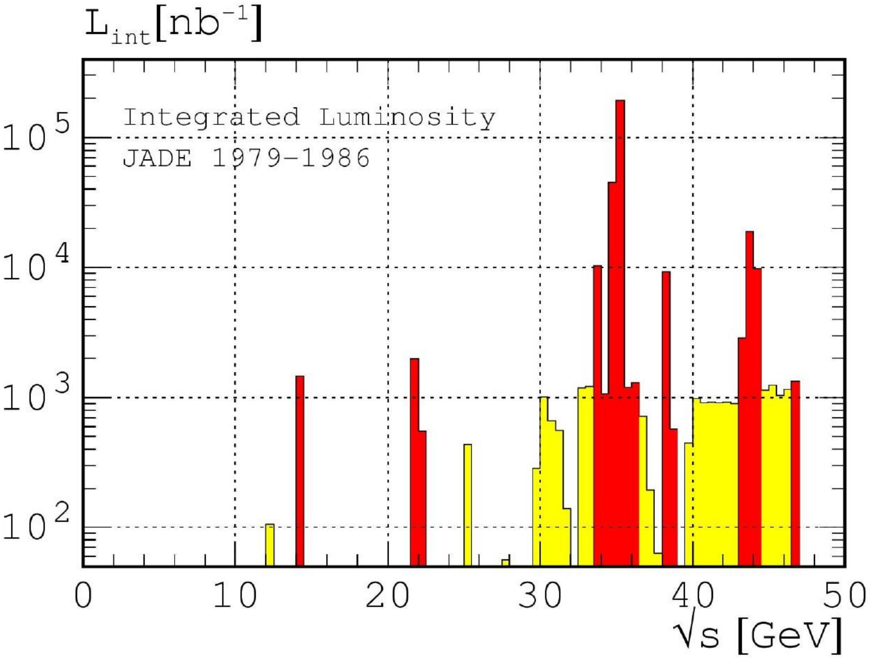
C.M.S. Energies and Luminosities



scan periods (top quark search!)

fixed energy runs

various detector upgrades

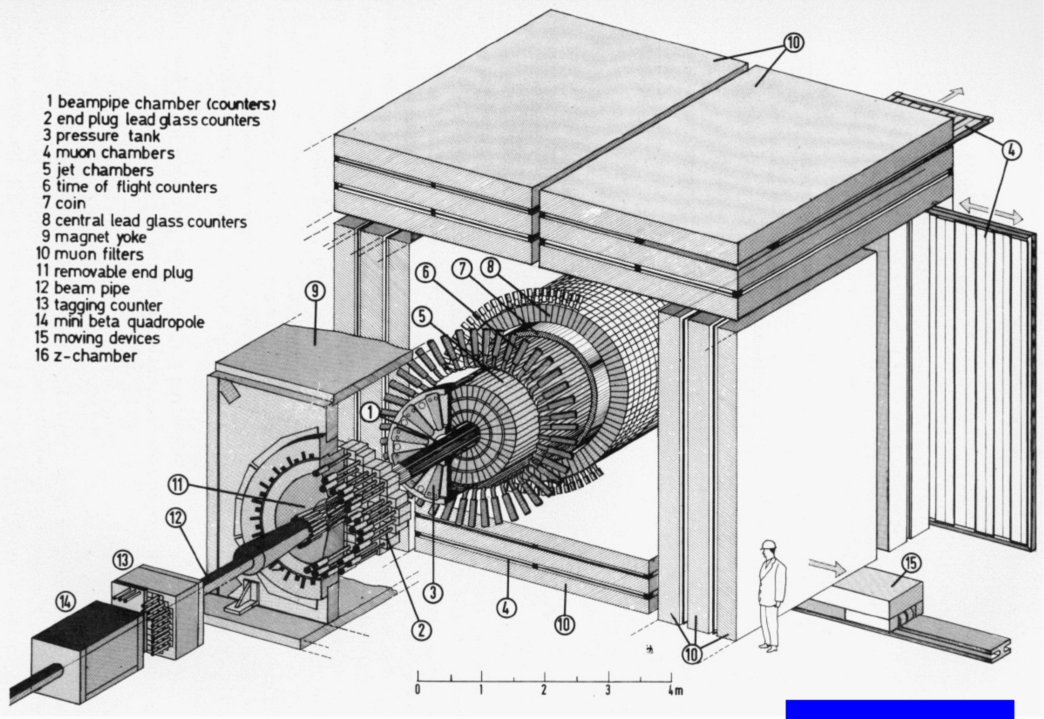


- $216\ \mathrm{pb}^{-1}$ total integrated luminosity collected by JADE
- Peak luminosity: $24\ \mu b^{-1}s^{-1}$

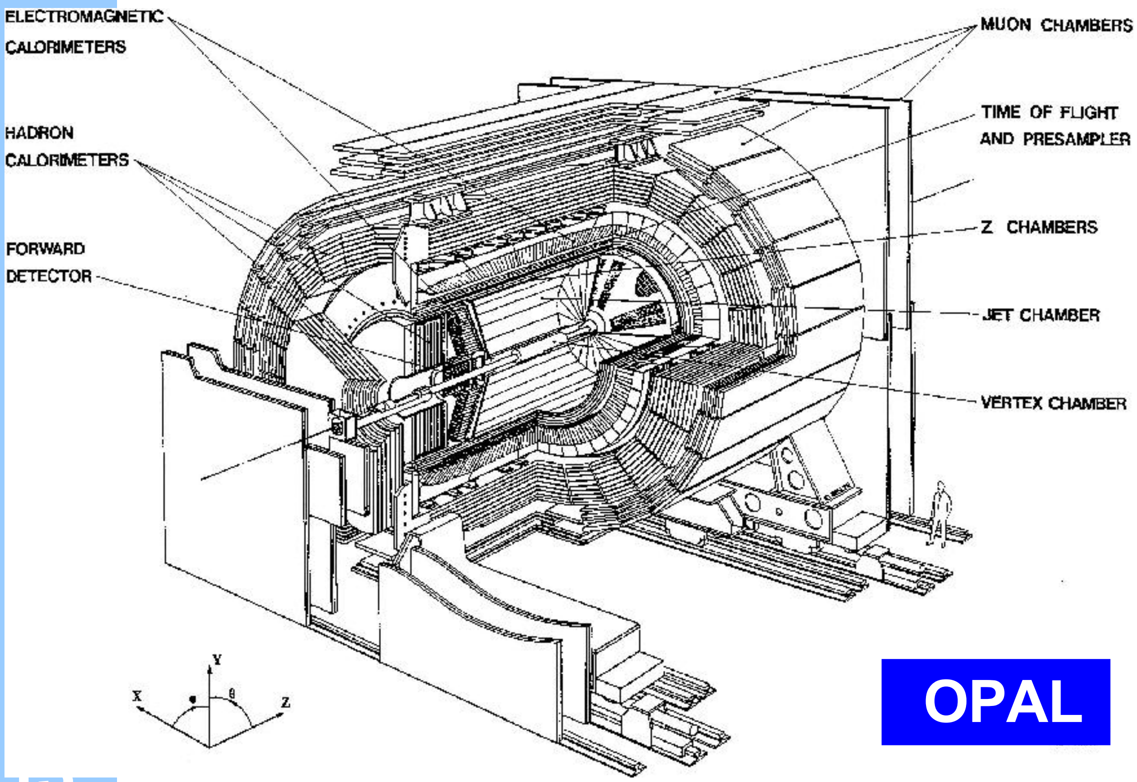
  $\Rightarrow$ 26 multihadrons per hour @ $\sigma^{had}=0.3$ nb
- ≈ 43000 “clean” multihadrons

JADE ...

- **Inner Detector:** Magnetic field (~0.5T), pictorial drift chamber, vertex chamber, Z chamber, TOF
- **EM Calorimeter:** lead glass blocks, barrel+endcaps
- **Muon Detector:** drift chamber / absorber layers
- No hadron calorimeter



JADE



OPAL

... & OPAL

Concept very similar
(Jet Chamber, LG Calorimeter)

OPAL detector at LEP:

- operated 1989 – 2000
- $\sqrt{s}$ = 91...209 GeV
- collected O(1M) multihadronic events

JADE Resurrection

Recovery of JADE Data …

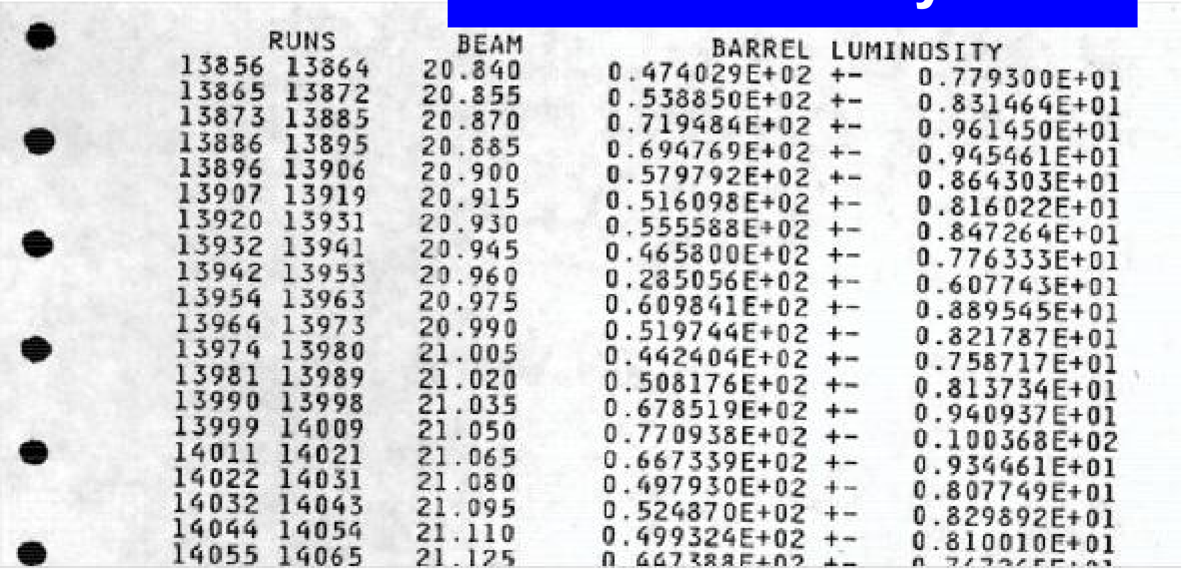
- Original data were located at
  - IBM mainframe at the DESY computer center
  - IBM tapes at DESY and Heidelberg U.
- DESY IBM closed completely in July 1997
  - last-minute transfer to “modern” data carriers (IBM/EXABYTE cartridges) and computer platforms
- Data organized by “antique” data management system **BOS** (version 1979)
- Raw data (REDUC1/REDUC2) converted into FPACK format (platform independent)
- Multihadronic data sets (ZE4V ~ ”mini-DST”) converted into ASCII format → used for current analyses

Recovery of the JADE Data

However, not all information were available in electronic format ...

...convert it to electronic version by hand

JADE luminosity files



```
      RUNS          BEAM            BARREL  LUMINOSITY
13856 13864        20.840    0.474029E+02 +-    0.779300E+01
13865 13872        20.855    0.538850E+02 +-    0.831464E+01
13873 13885        20.870    0.719484E+02 +-    0.961450E+01
13886 13895        20.885    0.694769E+02 +-    0.945461E+01
13896 13906        20.900    0.579792E+02 +-    0.864303E+01
13907 13919        20.915    0.516098E+02 +-    0.816022E+01
13920 13931        20.930    0.555588E+02 +-    0.847264E+01
13932 13941        20.945    0.465800E+02 +-    0.776333E+01
13942 13953        20.960    0.285056E+02 +-    0.607743E+01
13954 13963        20.975    0.609841E+02 +-    0.889545E+01
13964 13973        20.990    0.519744E+02 +-    0.821787E+01
13974 13980        21.005    0.442404E+02 +-    0.758717E+01
13981 13989        21.020    0.508176E+02 +-    0.813734E+01
13990 13998        21.035    0.678519E+02 +-    0.940937E+01
13999 14009        21.050    0.770938E+02 +-    0.100368E+02
14011 14021        21.065    0.667339E+02 +-    0.934461E+01
14022 14031        21.080    0.497930E+02 +-    0.807749E+01
14032 14043        21.095    0.524870E+02 +-    0.829892E+01
14044 14054        21.110    0.499324E+02 +-    0.810010E+01
14055 14065        21.125    0.667388E+02 +-
```

- Also <u>preprocessed</u> JADE detector simulation samples (ZE4V) available, but:
  - not for all relevant energy points (only 35 and 44 GeV)
  - older generators
  - simulation parameters not well documented
- For more/better MC samples reactivation of JADE software necessary!

Revival of the JADE Software

Programs:

- 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
- Multihadronic event filtering and packing software

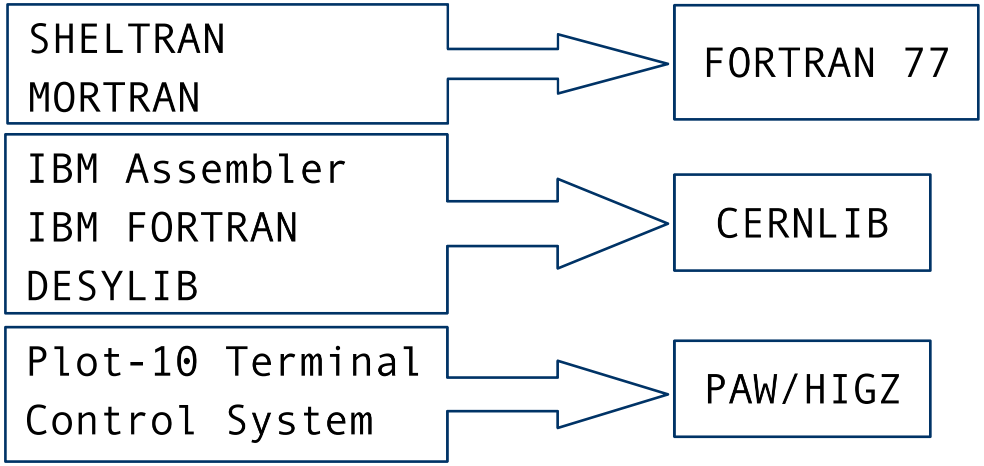
Source code:

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

...extremely unstructured, badly documented “spaghetti” code

Revival of the JADE Software

- “Historical/archaeological” research work using old JADE notes, PhD theses, manual fragments, source code comments.
- Code modification, emulation interfaces for missing libraries (e.g. graphics), obsolete FORTRAN dialects, etc.



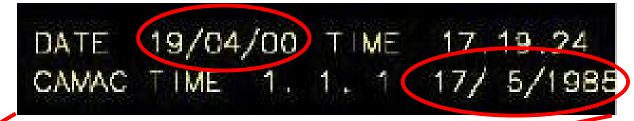
SHELTRAN
MORTRAN
→ FORTRAN 77

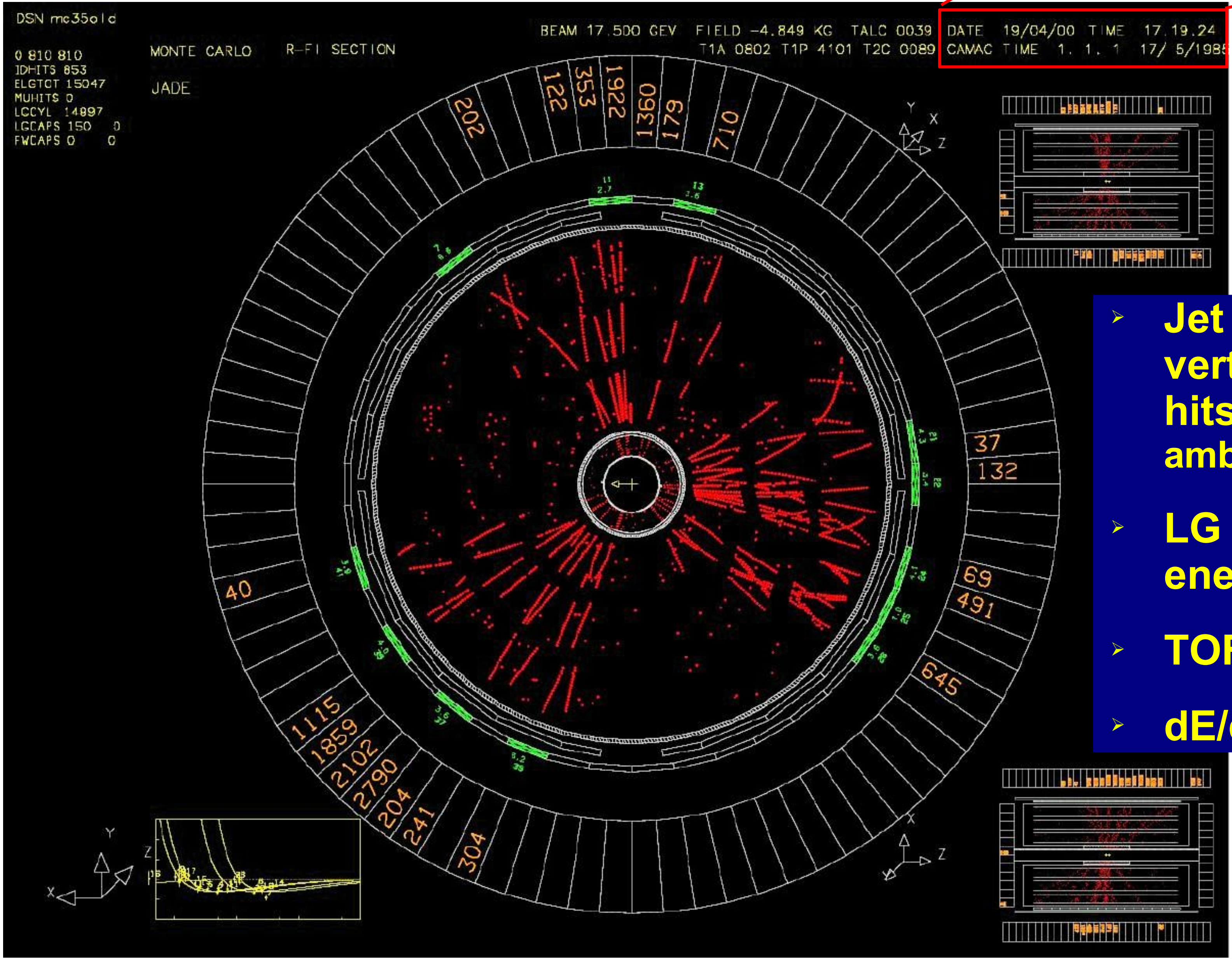
IBM Assembler
IBM FORTRAN
DESYLIB
→ CERNLIB

Plot-10 Terminal Control System
→ PAW/HIGZ

- Platform dependencies extremely problematical
  - Bit/byte manipulation of data words
  - Access to BOS banks not in units of a fixed word length (4 bytes)
  - Byte storage order (IBM is big endian, PC is little endian)
- Complete installation successful on IBM RS/6000 AIX (same endian scheme as IBM/370) with XLF compiler.

JADE Event Display

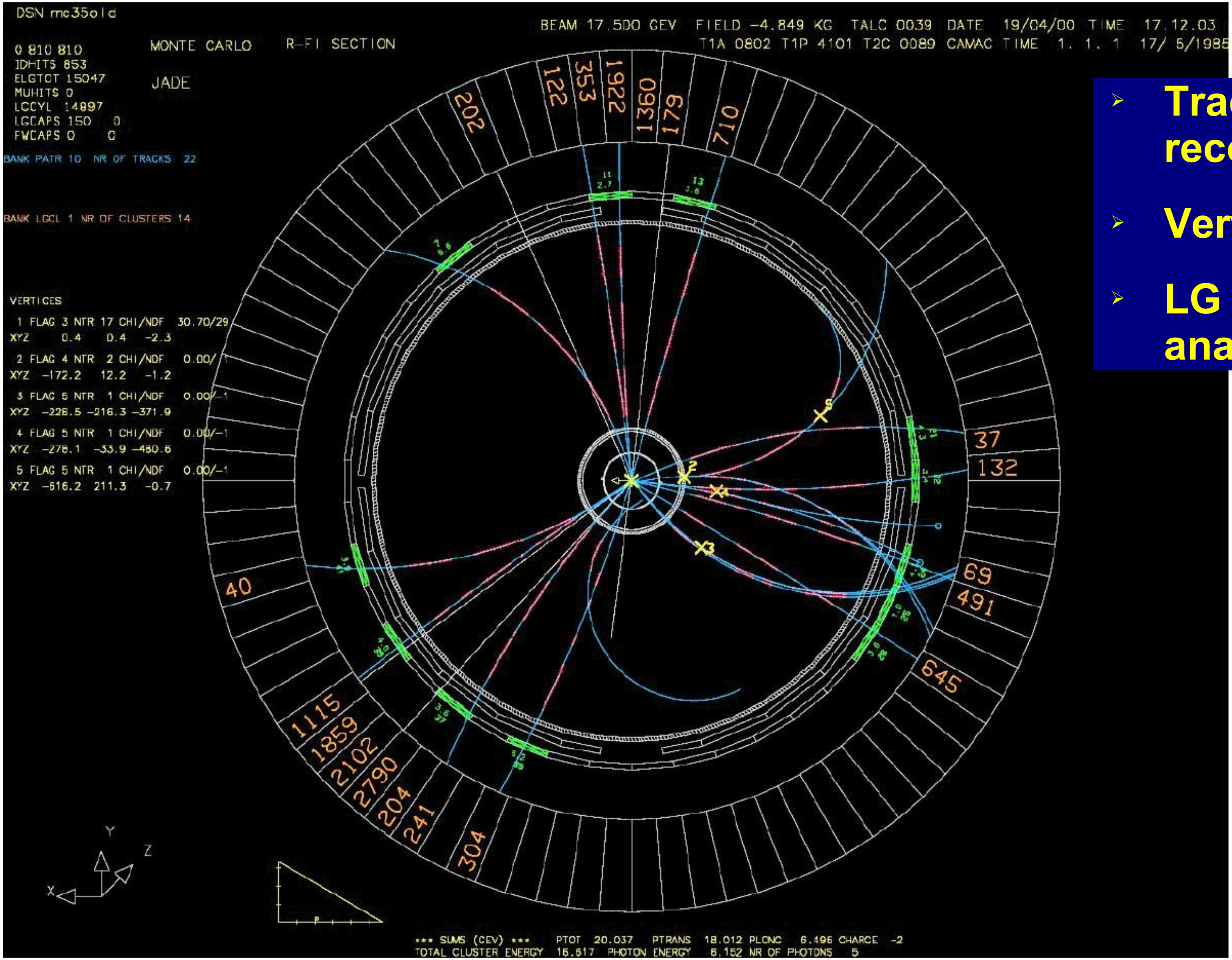




- **Jet chamber / vertex chamber hits (incl. R/L ambiguities)**
- **LG calorimeter energies**
- **TOF hits**
- **dE/dx meas.**

Simulated JADE event, Pythia $e^+e^-\to q\bar{q}g$ @ $\sqrt{s}$ = 35 GeV

JADE Event Display



```
DSN mc35old

0 810 810          MONTE  CARLO     R-FI  SECTION
IDHITS 853
ELGTOT 15047       JADE
MUHITS 0
LCCYL  14897
LGCAPS 150    0
FWCAPS 0      0
BANK PATR 10  NR OF TRACKS  22

BANK LGCL 1 NR OF CLUSTERS 14

VERTICES
 1 FLAG 3 NTR 17 CHI/NDF  30.70/29
XYZ     0.4    0.4   -2.3
 2 FLAG 4 NTR  2 CHI/NDF   0.00/ 1
XYZ  -172.2   12.2   -1.2
 3 FLAG 5 NTR  1 CHI/NDF   0.00/-1
XYZ  -228.5 -216.3 -371.9
 4 FLAG 5 NTR  1 CHI/NDF   0.00/-1
XYZ  -278.1  -33.9 -480.6
 5 FLAG 5 NTR  1 CHI/NDF   0.00/-1
XYZ  -616.2  211.3   -0.7
```

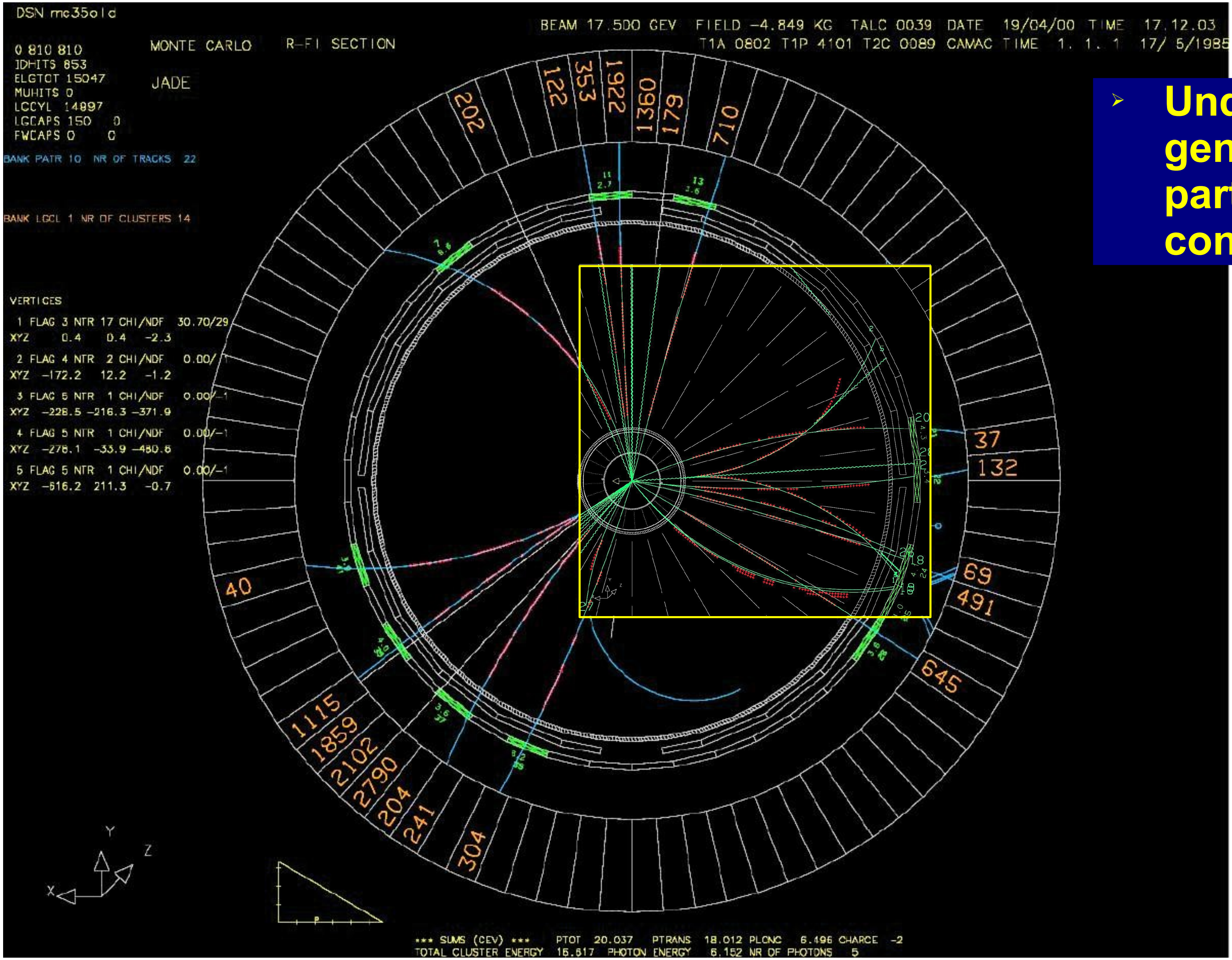
```
BEAM 17.500 GEV  FIELD -4.849 KG  TALC 0039  DATE  19/04/00  TIME  17.12.03
        T1A 0802  T1P 4101  T2C 0089  CAMAC TIME  1. 1. 1  17/ 5/1985
```

```
*** SUMS (GEV) ***    PTOT  20.037   PTRANS  18.012 PLONG   6.496 CHARGE  -2
TOTAL CLUSTER ENERGY  16.617  PHOTON ENERGY   6.152 NR OF PHOTONS   5
```

- **Track reconstruction**
- **Vertex finding**
- **LG cluster analysis**

Original display was monochromatic!

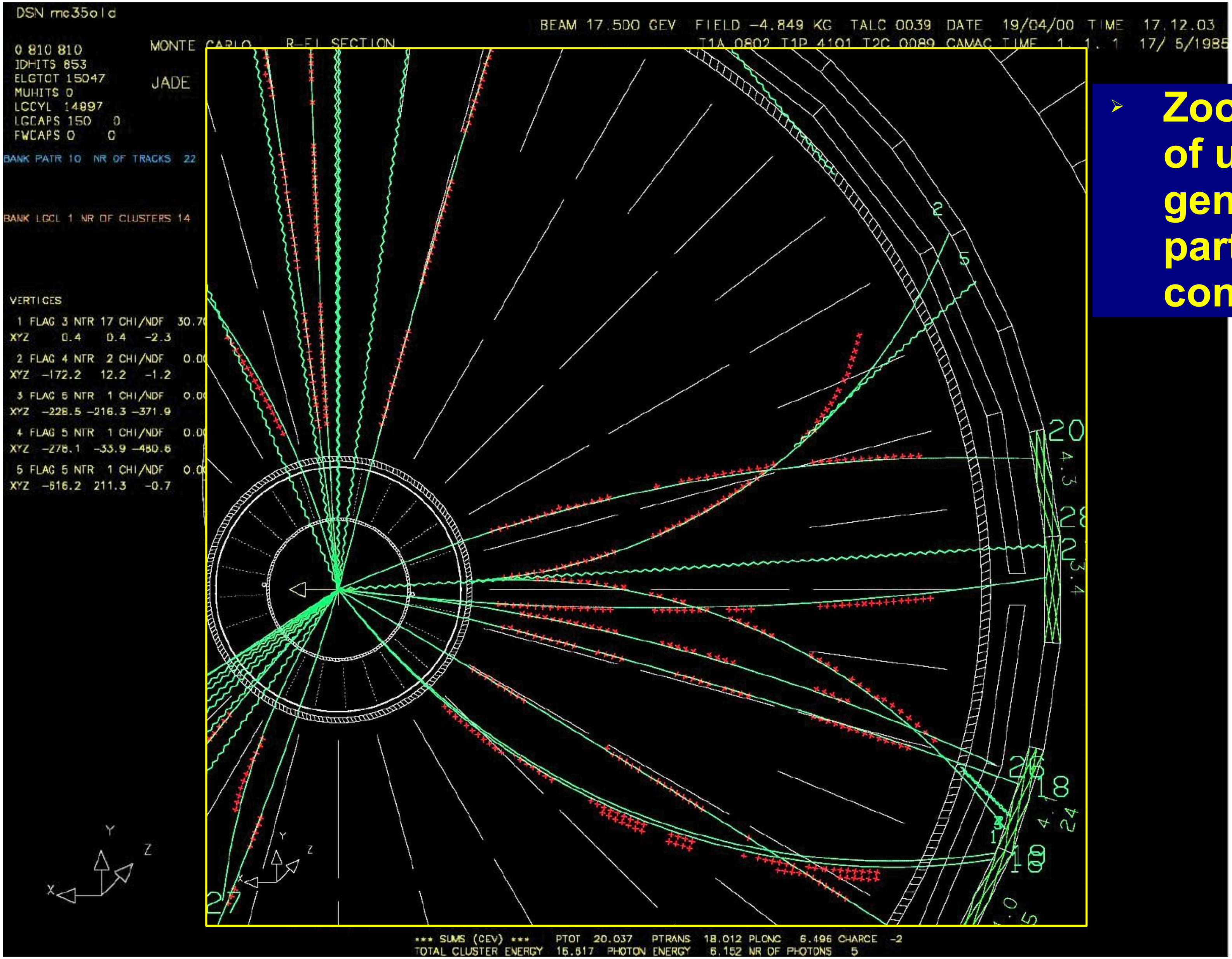
JADE Event Display



```
DSN mc35old

0 810 810              MONTE CARLO     R-FI SECTION
IDHITS 853
ELGTOT 15047           JADE
MUHITS 0
LCCYL  14897
LGCAPS 150    0
FWCAPS 0      0
BANK PATR 10  NR OF TRACKS  22

BANK LGCL 1 NR OF CLUSTERS 14

VERTICES
 1 FLAG 3 NTR 17 CHI/NDF  30.70/29
XYZ     0.4    0.4   -2.3
 2 FLAG 4 NTR  2 CHI/NDF   0.00/ 1
XYZ  -172.2   12.2   -1.2
 3 FLAG 5 NTR  1 CHI/NDF   0.00/-1
XYZ  -228.5 -216.3 -371.9
 4 FLAG 5 NTR  1 CHI/NDF   0.00/-1
XYZ  -278.1  -33.9 -480.6
 5 FLAG 5 NTR  1 CHI/NDF   0.00/-1
XYZ  -616.2  211.3   -0.7

BEAM 17.500 GEV  FIELD -4.849 KG  TALC 0039  DATE  19/04/00  TIME  17.12.03
             T1A 0802 T1P 4101 T2C 0089 CAMAC TIME  1. 1. 1  17/ 5/1985

*** SUMS (CEV) ***   PTOT  20.037   PTRANS  18.012 PLONC   6.496 CHARCE  -2
TOTAL CLUSTER ENERGY  16.617  PHOTON ENERGY   6.152 NR OF PHOTONS   5
```

- **Underlying generated particle configuration**

JADE Event Display



```
DSN mc35old
                                        BEAM 17.500 GEV  FIELD -4.849 KG  TALC 0039  DATE  19/04/00  TIME  17.12.03
0 810 810        MONTE CARLO   R-FI SECTION   T1A 0802 T1P 4101 T2C 0089 CAMAC TIME  1. 1. 1  17/ 5/1985
IDHITS 853
ELGTOT 15047     JADE
MUHITS 0
LCCYL  14897
LGCAPS 150    0
FWCAPS 0      0
BANK PATR 10  NR OF TRACKS  22

BANK LGCL  1  NR OF CLUSTERS 14

VERTICES
 1 FLAG 3 NTR 17 CHI/NDF  30.7
XYZ     0.4    0.4   -2.3
 2 FLAG 4 NTR  2 CHI/NDF   0.0
XYZ  -172.2   12.2   -1.2
 3 FLAG 5 NTR  1 CHI/NDF   0.0
XYZ  -228.5 -216.3 -371.9
 4 FLAG 5 NTR  1 CHI/NDF   0.0
XYZ  -276.1  -33.9 -480.6
 5 FLAG 5 NTR  1 CHI/NDF   0.0
XYZ  -616.2  211.3   -0.7

*** SUMS (GEV) ***    PTOT   20.037   PTRANS   18.012 PLONG   6.496 CHARGE  -2
TOTAL CLUSTER ENERGY  15.617  PHOTON ENERGY   6.152 NR OF PHOTONS   5
```

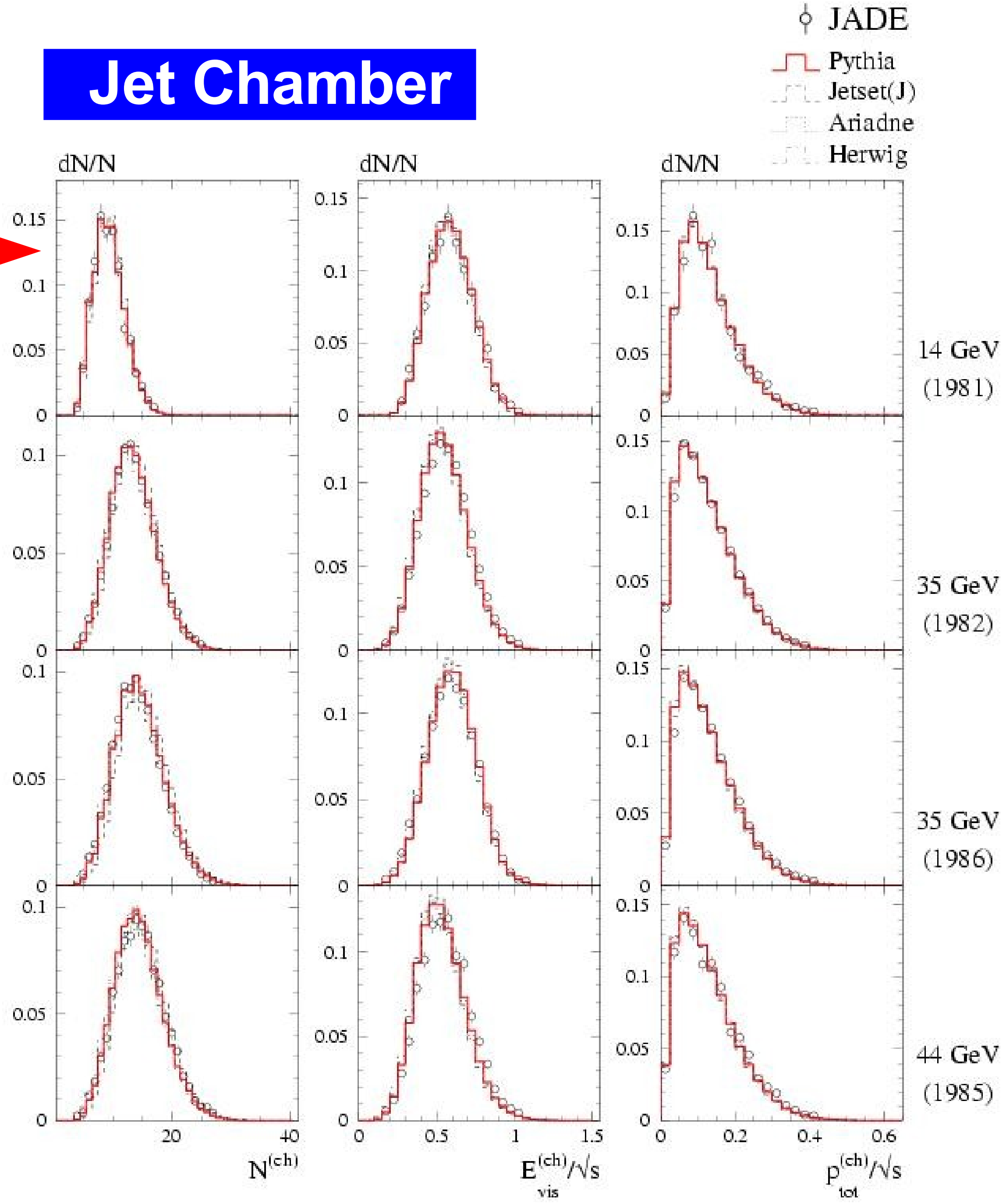
- **Zoomed section of underlying generated particle configuration**

Performance

Jet Chamber

Example:

$N^{(ch)}$, $E_{vis}^{(ch)}/\sqrt{s}$, $p_{tot}^{(ch)}/\sqrt{s}$

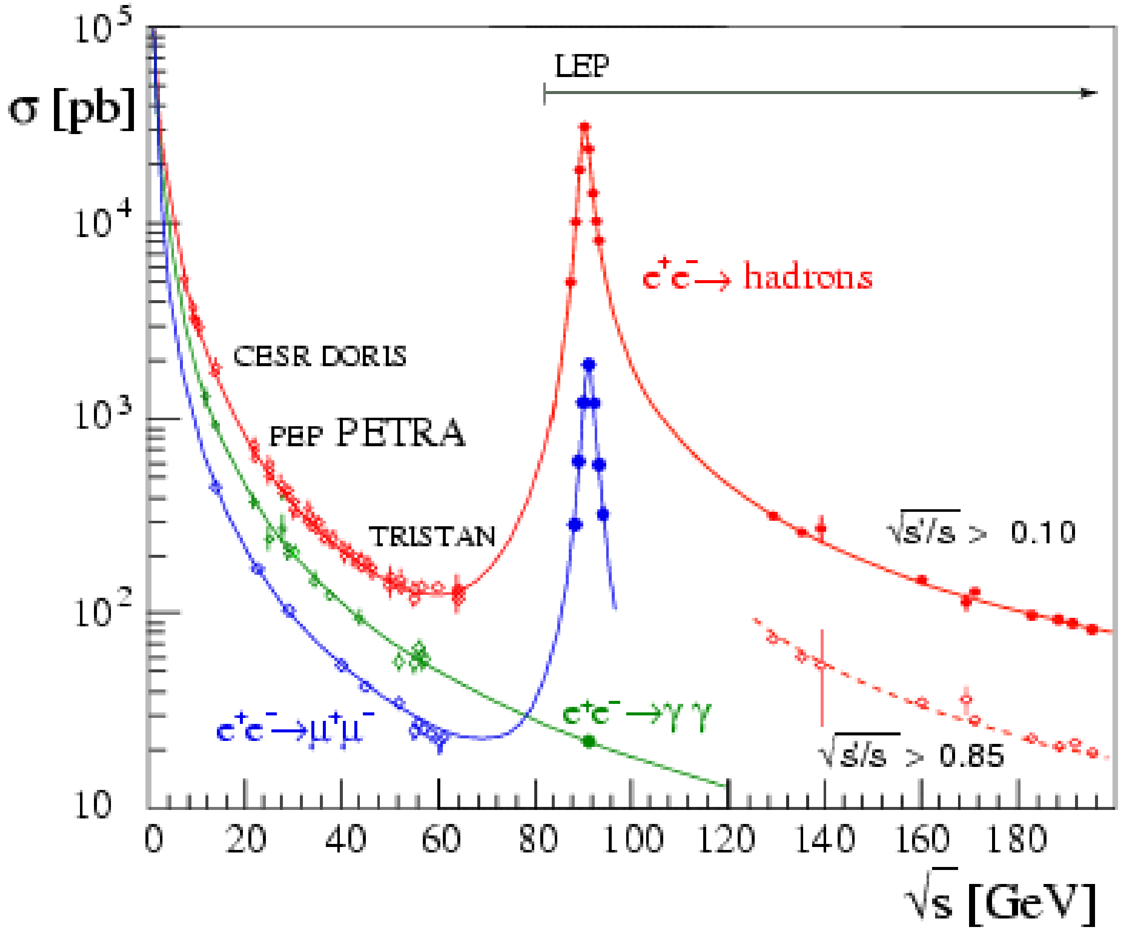


- JADE simulation with OPAL LEP-I tune
- generally good description of data from 14-44 GeV

Event Shapes in e^+e^- Annihilation

Hadronic Final States

Cross section for $e^+e^- \rightarrow$ hadrons

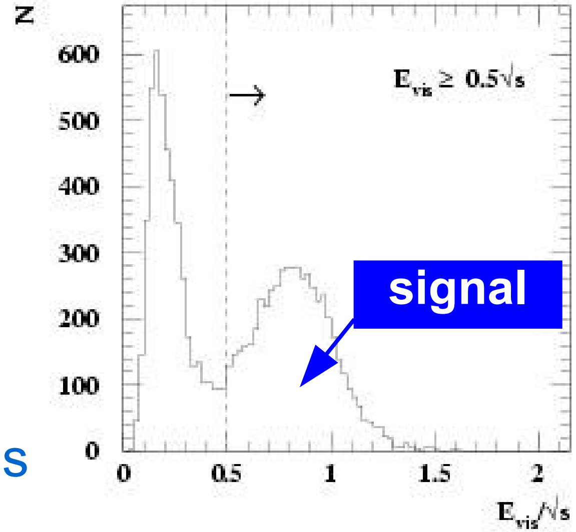


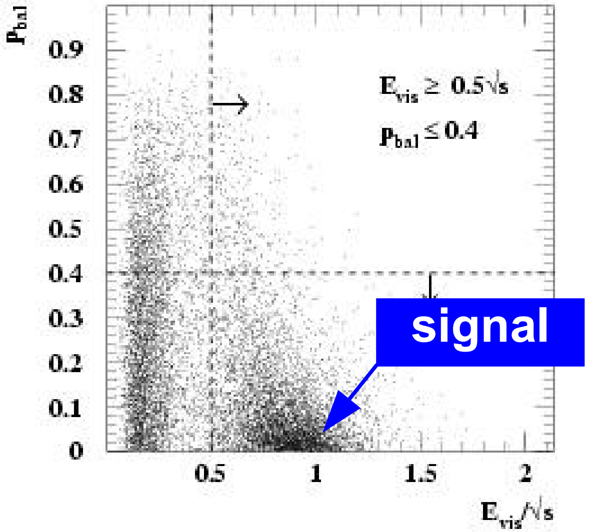
- σ^{had} (PETRA) = 0.2 ... 3nb ≈ 1/10 ... 1/100 σ^{had} (LEP I)
- Hadron production at PETRA energies mainly via $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}(g)$

Multihadronic Data Sets

Main selection cuts:

- 4 tracks from vertex region
- 3 “long + good” tracks
- visible energy > $0.5\cdot\sqrt{s}$
- momentum balance $|\Sigma p_z|/E_{vis} < 0.4$
- missing momentum < $0.3\cdot\sqrt{s}$
- $|\cos\Theta_{Thrust}| < 0.8$

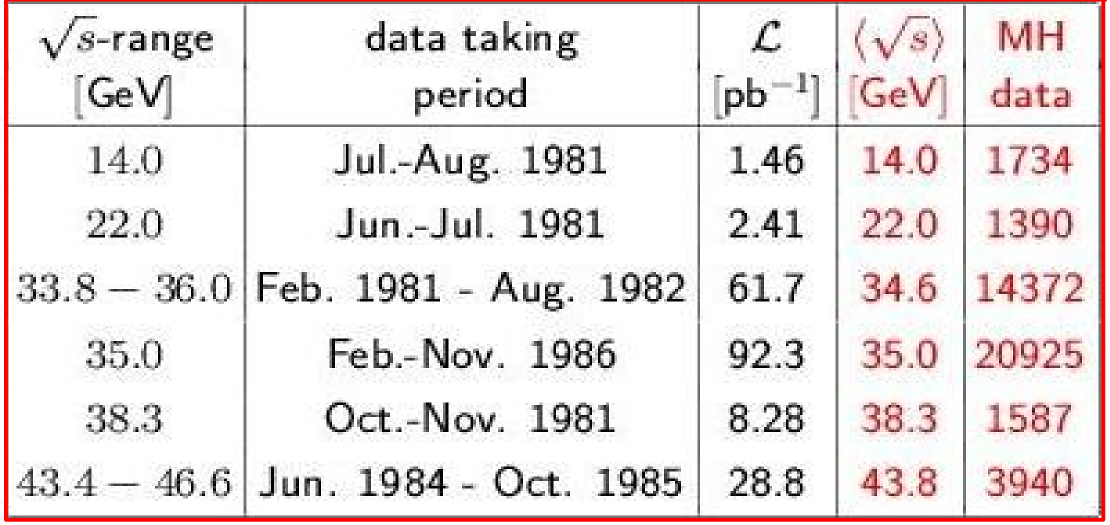




Very clean samples, residual background ≈ 1%:

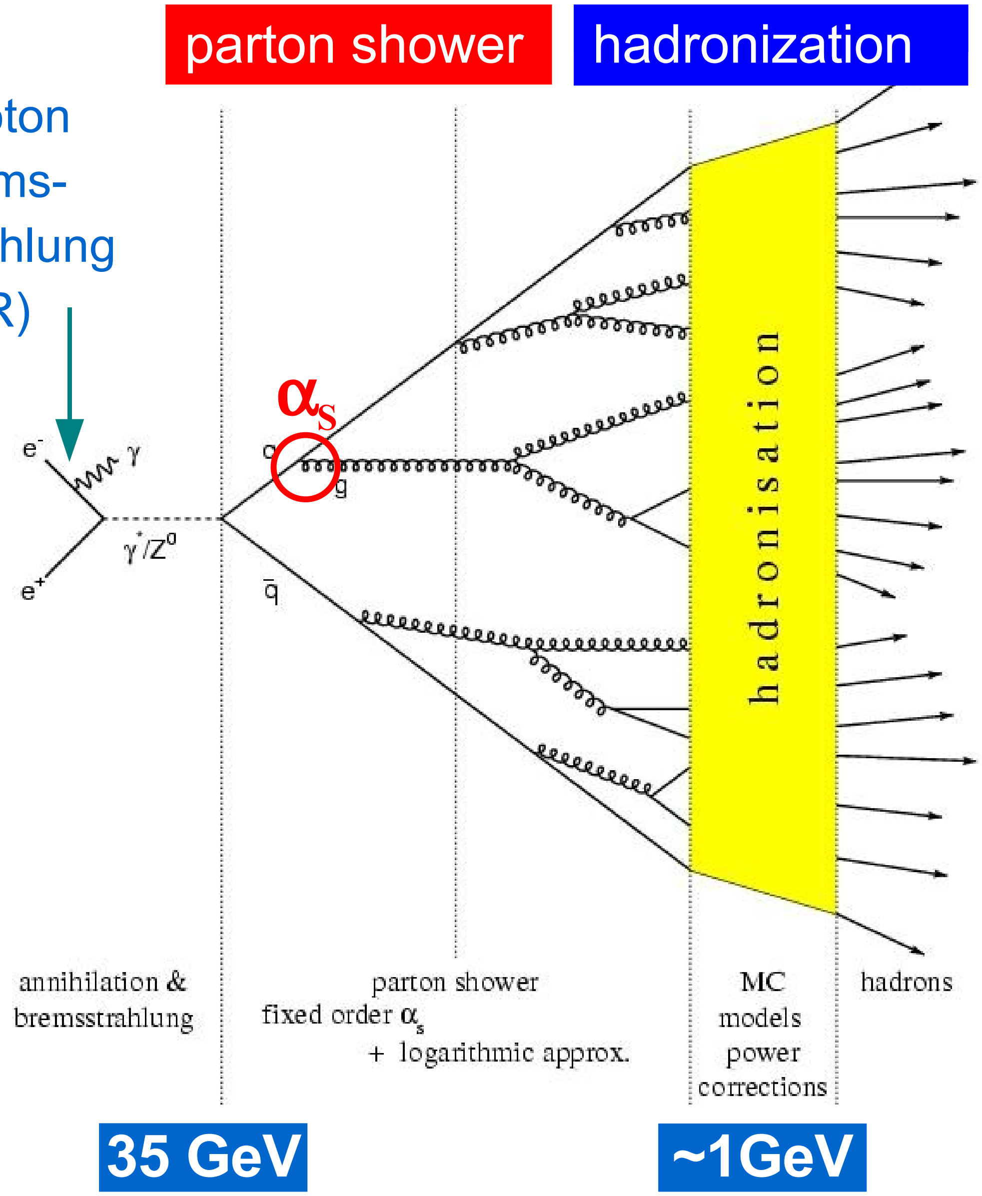
- $e^+e^- \to e^+e^-\gamma\gamma$
- $e^+e^- \to \tau^+\tau^-$

MH data samples



$\sqrt{s}$-range [GeV]	data taking period	$\mathcal{L}$ [pb^{-1}]	$\langle\sqrt{s}\rangle$ [GeV]	MH data
14.0	Jul.-Aug. 1981	1.46	14.0	1734
22.0	Jun.-Jul. 1981	2.41	22.0	1390
33.8 – 36.0	Feb. 1981 - Aug. 1982	61.7	34.6	14372
35.0	Feb.-Nov. 1986	92.3	35.0	20925
38.3	Oct.-Nov. 1981	8.28	38.3	1587
43.4 – 46.6	Jun. 1984 - Oct. 1985	28.8	43.8	3940

QCD in e^+e^- Annihilation



Photon brems-strahlung (ISR)

Various theoretical approaches to describe parts of the process:

PT QCD:

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

NP QCD:

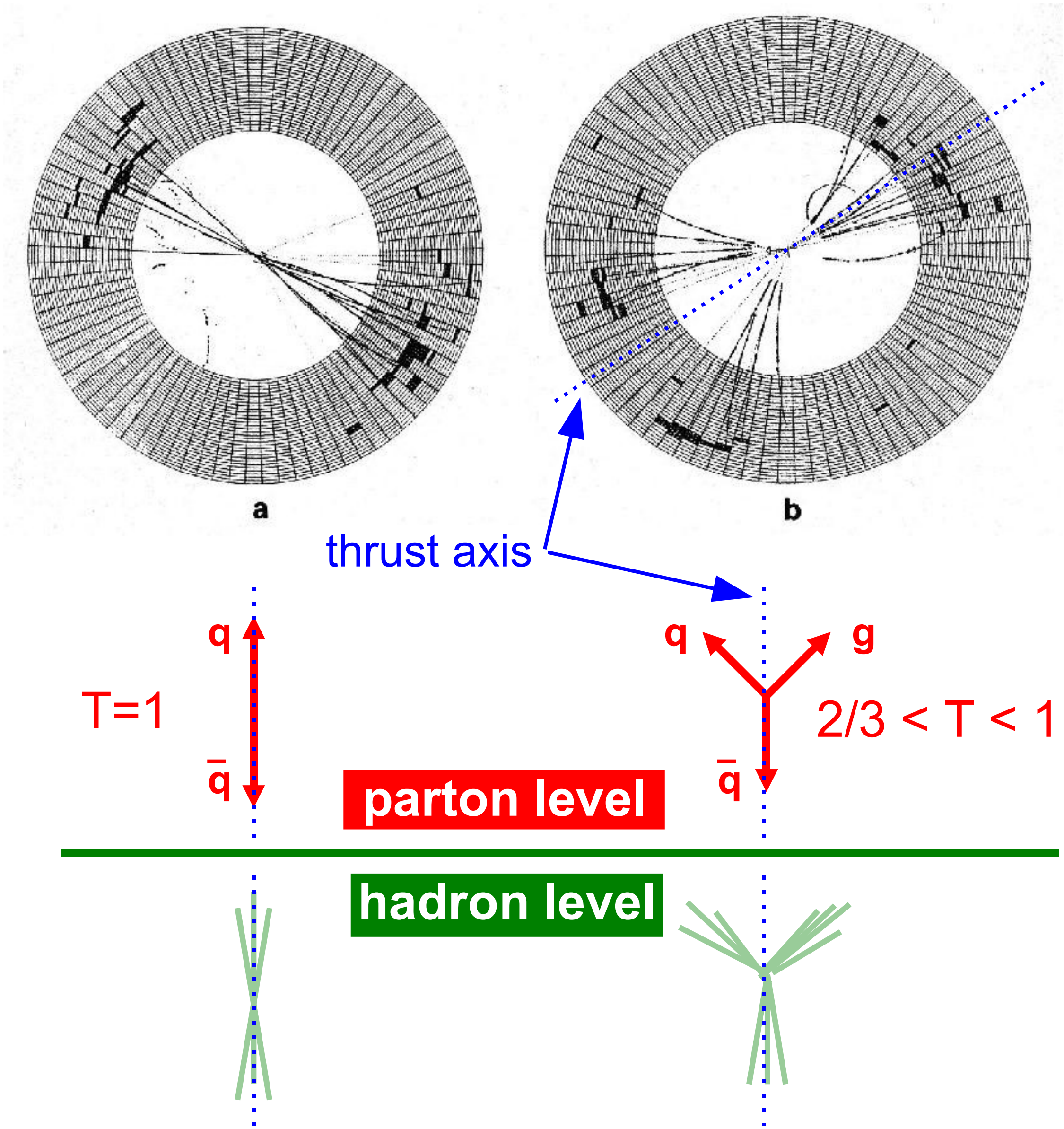
- Phenomenological hadronization models: **string fragmentation, cluster model**
- Analytical power corrections

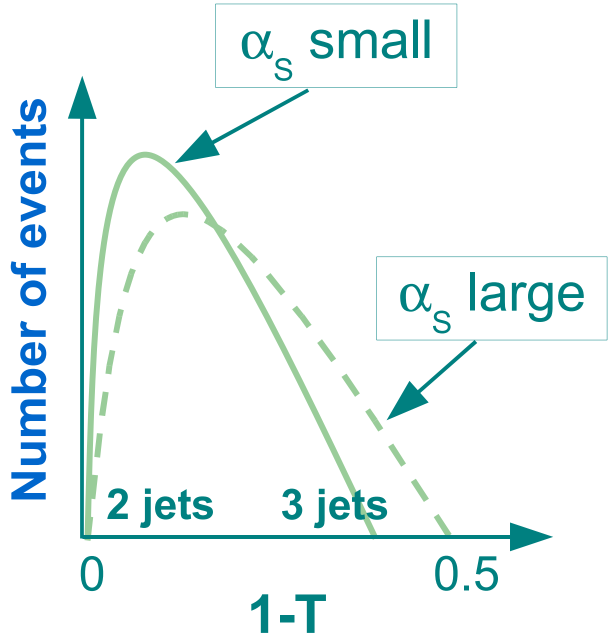
Hadronic Event Shapes

Quantify the event topology by a single number.

Example: “**Thrust**”

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





Event shape variables are important tools to probe PT and NP effects.

More Event Shapes ...

Thrust *T*

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

$\Rightarrow$ ....defines two hemispheres H_k $\Rightarrow$

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

hemisphere masses

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

hemisphere p_T

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

$$\begin{aligned} B_T &= B_1 + B_2 \\ B_W &= \max(B_1, B_2) \end{aligned}$$

***C* Parameter**

$$\Theta^{\alpha\beta} = \frac{\sum_i (p_i^\alpha p_i^\beta) / |\vec{p}_i|}{\sum_i |\vec{p}_i|}, \quad \alpha, \beta = 1, 2, 3$$

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

= 3 $<\sin\theta^2 ij>$: average of the momentum weighted angle between pairs of particles

- Calculate eigenvalues λ_i from linearised momentum tensor.

Differential 2-jet rate y_{23} (Durham scheme)

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

$$\frac{\mathrm{d}R_2(y_{\mathrm{cut}})}{\mathrm{d}y_{\mathrm{cut}}} = \frac{1}{\sigma}\frac{\mathrm{d}\sigma(y_{23})}{\mathrm{d}y_{23}}.$$

- Define jet resolution parameter y_{ij}.
- Combine particles i, j with smallest y_{ij} into pseudo particles and proceed until $y_{ij} > y_{\mathrm{cut}}$ for 2 remaining pseudo particles ("jets").

y_{23} is value of y_{cut} for which event switches from 3 jet to 2 jet type

MC Models

- PYTHIA/JETSET

  LLA parton shower +
  string fragmentation

- ARIADNE

  colour dipole scheme +
  string fragmentation

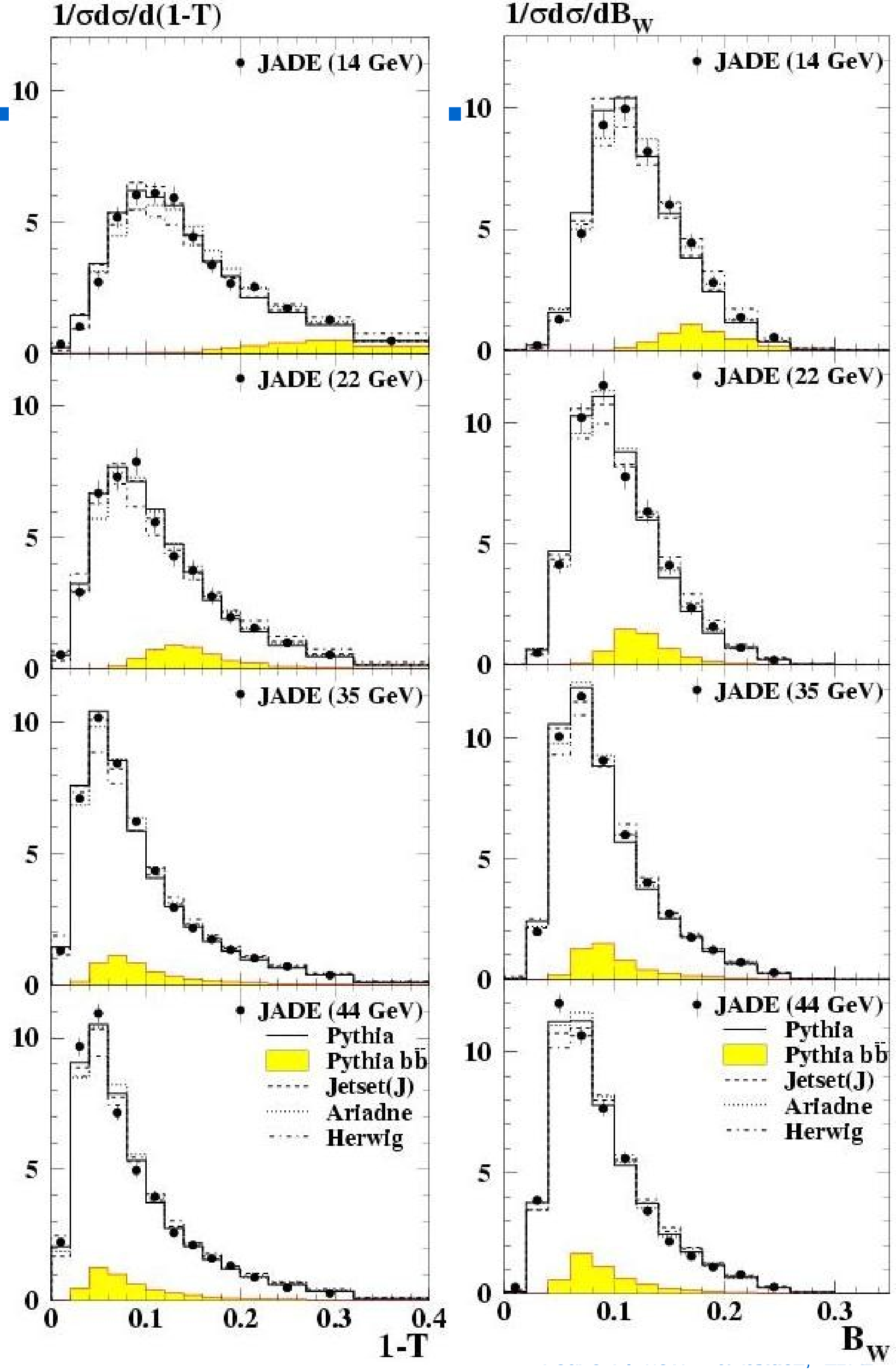
- HERWIG

  MLLA parton shower +
  cluster fragmentation

- COJETS

  LLA parton shower +
  independent fragmentation

**Monte Carlo +
JADE simulation reproduce
multihadronic data!**



detector level

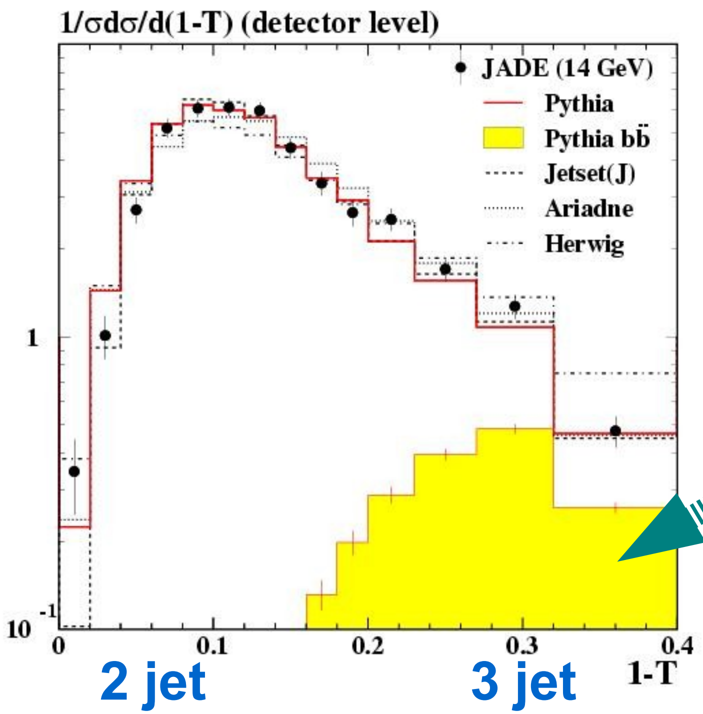
Correction Procedure (1)

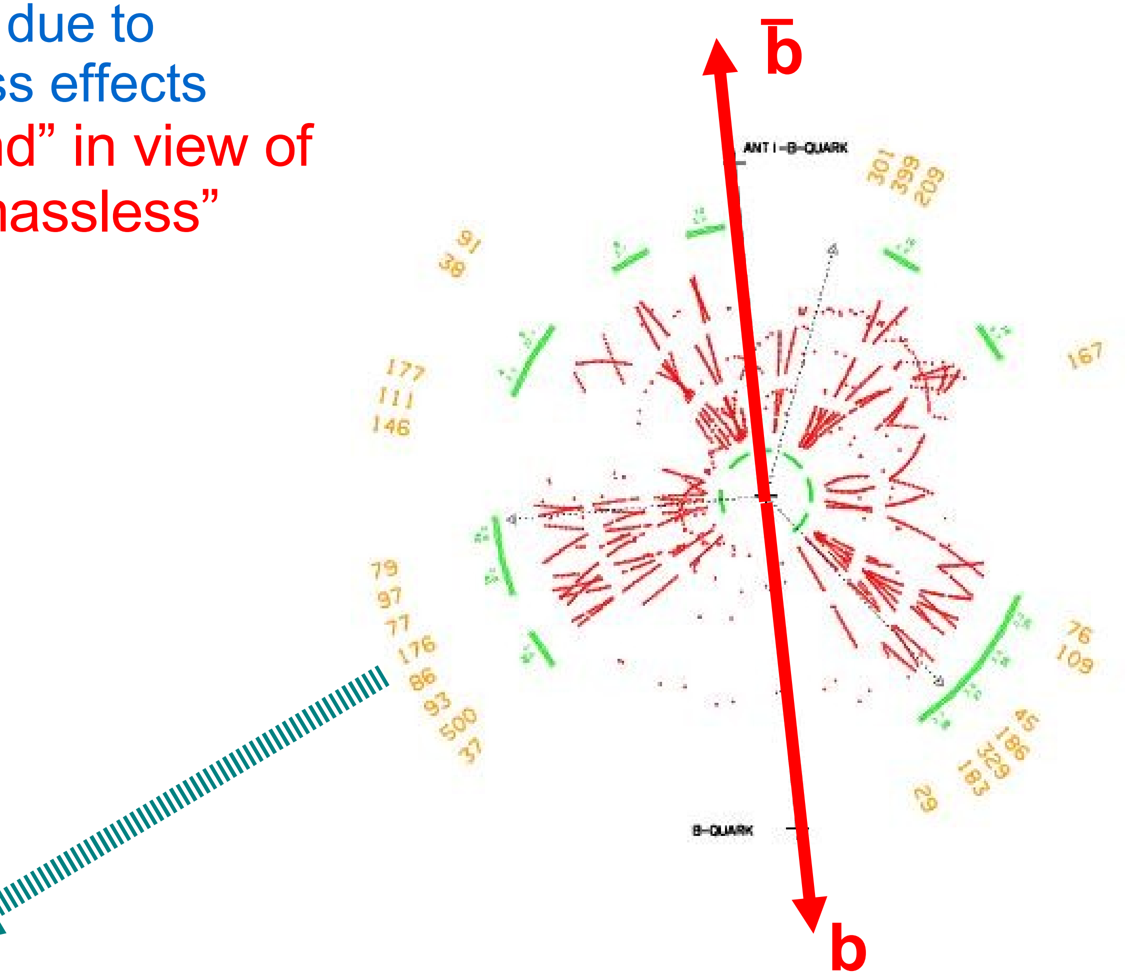
$b\bar{b}$ subtraction at detector level

- about 9% fraction of hadronic final states
- fakes hard gluon radiation due to electroweak decays + mass effects

  ... treated as “background” in view of later comparison with “massless” QCD calculations

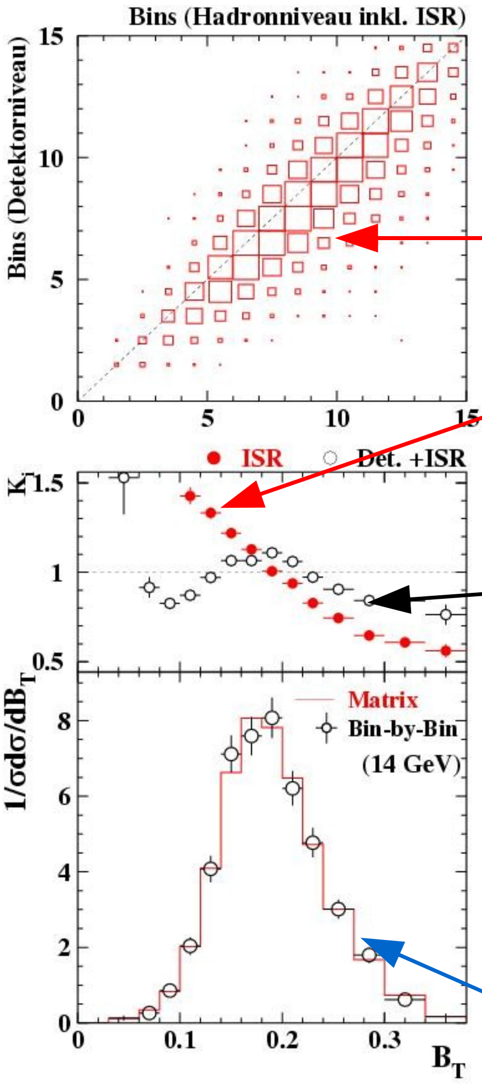
Pythia e+e- →$b\bar{b}$, 14 GeV





Correction Procedure (2)

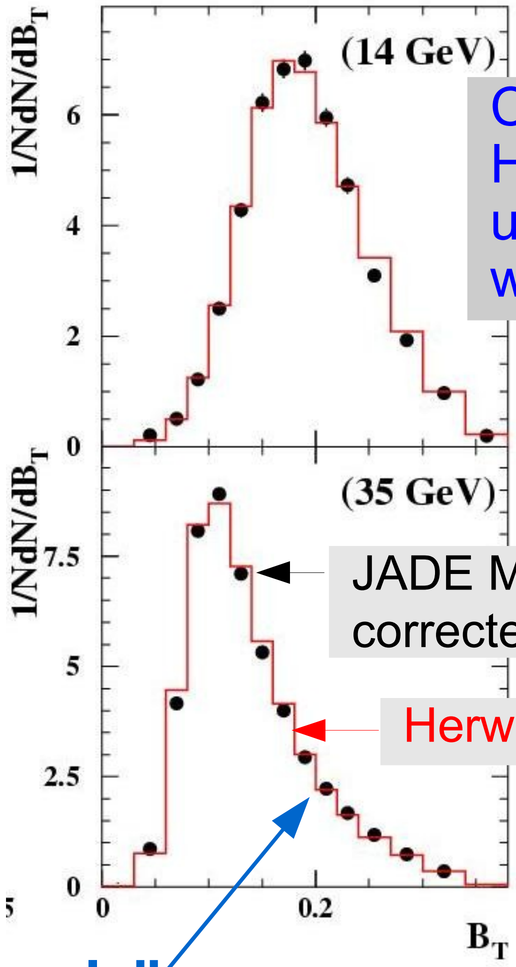
- Detector effects, MH selection
  limited resolution, acceptance effects, secondary processes
- Photon ISR



pure detector effects
(matrix correction)

ISR correction
(partially compensated by
detector effects)

total bin-by-bin
correction



Check:
Herwig MC
unfolded
with Pythia

JADE MC (Herwig)
corrected

Herwig hadrons

consistent "hadron levels"

“Physics” Data

Comparison with MC models:

PYTHIA (LEP I tune)

- good overall consistency

HERWIG/ARIADNE

- moderate at 14+22 GeV, better at higher √s

JETSET (JADE optimization)

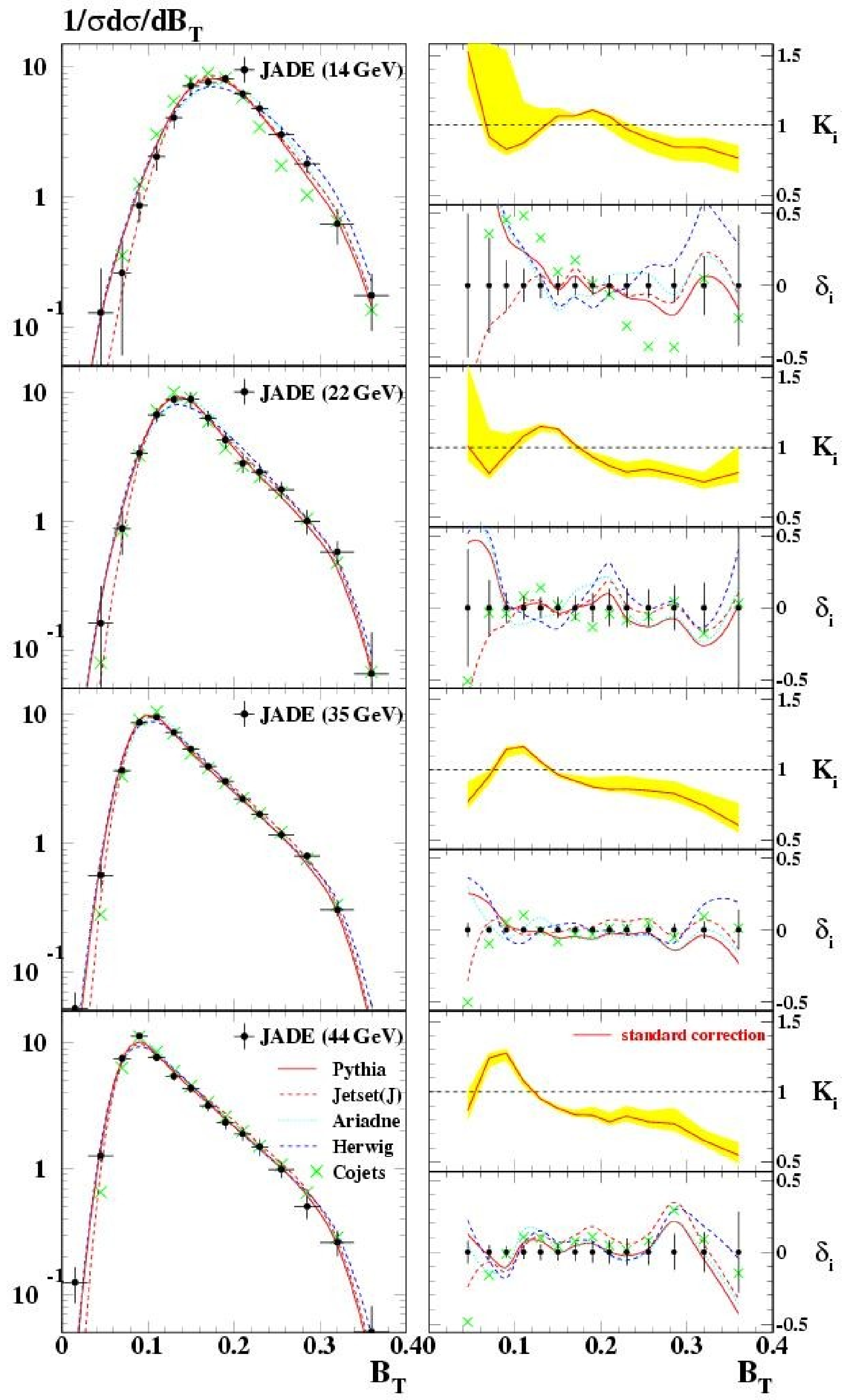
- good at 14+22 GeV, slightly worse at higher √s

COJETS

- disfavoured at 14+22 GeV, remains worse at higher √s

Event shape become more and more “2-jet like” at higher energies:

- **running of α_s**
- **hadronization effects**

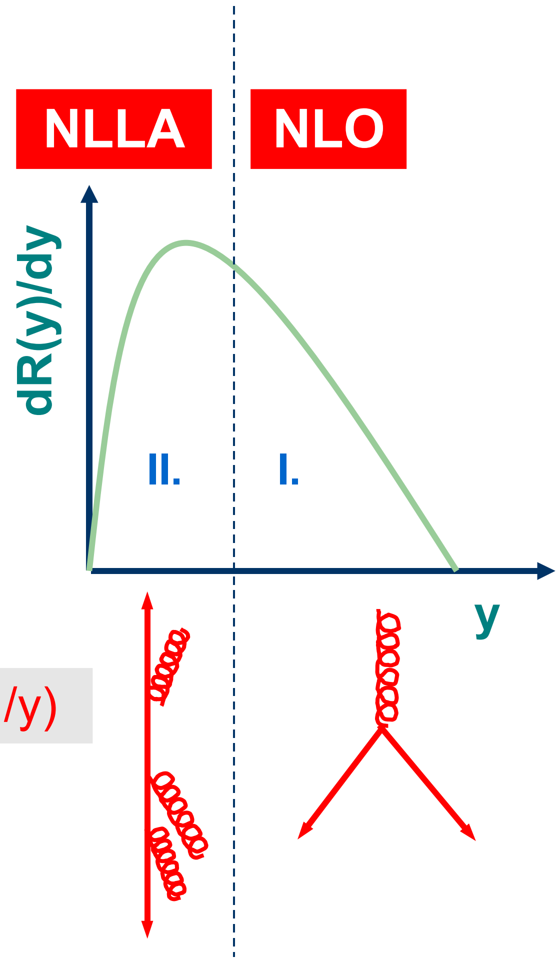


Determinations of α_s

QCD Predictions

$y=1-T$, M_H, B_T, B_W, C, y_{23} ... infrared and collinear safe

Cumulative predictions $R(y)=\int^{y} dy' \, 1/\sigma \cdot d\sigma/dy'$:



I. **NLO:** describes “hard” gluon contribution

$$R(y)= 1 + A(y)\cdot\alpha_S + B(y)\cdot\alpha_S^2$$

Problem: divergent for y→0 (2 jet region)

II. **NLLA:** describes “soft” gluon contribution

$$R(y)= (1+C_1\cdot\alpha_S + C_2\cdot\alpha_S^2) \exp\{ Lg_1(\alpha_S L)+g_2(\alpha_S L) \}$$

$L=\log(1/y)$

...collects large logarithmic contributions $\alpha_S L$

⇒ much better convergence for y→0

Problem: not designed for 3 jet region

III. **Matching:** NLO + NLLA, e.g.: ln(R)-matching

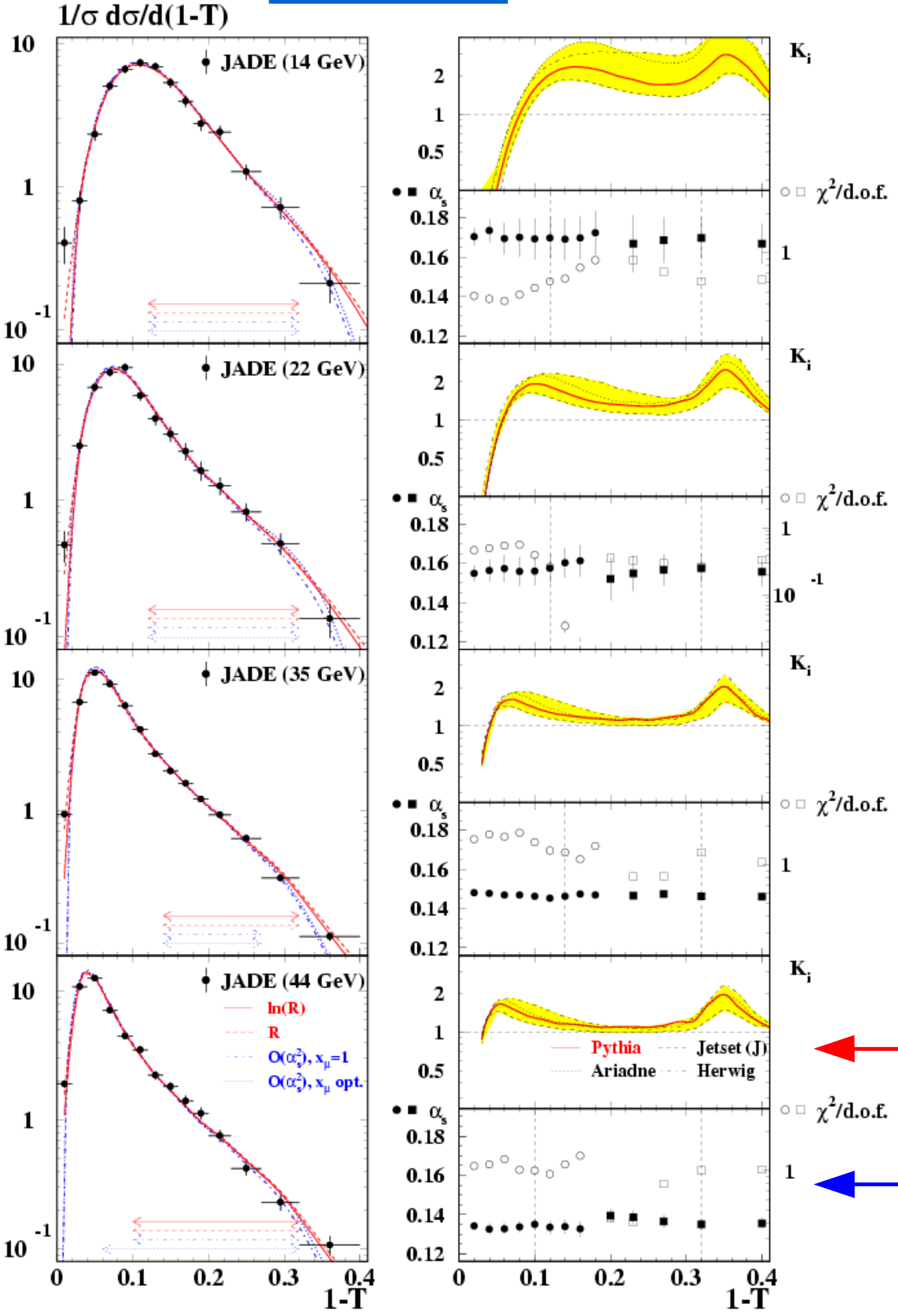
$$\begin{aligned}\ln(R(y)) = {} & Lg_1(\alpha_S L)+g_2(\alpha_S L) \\ & - (G_{11}L+G_{12}L^2)\cdot\alpha_S - (G_{22}L+G_{23}L^2)\cdot\alpha_S^2 \\ & + A(y)\cdot\alpha_S + [B(y) - \tfrac{1}{2} A(y)^2]\cdot\alpha_S^2\end{aligned}$$

subtract incomplete 2nd order contribution

replace by complete NLO

...avoids double counting

Thrust



α_s-Fits

- α_s is only free parameter

  renormalization scale factor fixed:

  $x_\mu=\mu/\sqrt{s}=1$
- Perform hadronization correction of cumulative predictions R(y)

Fit curves:

- Typically: χ^2/d.o.f. =0.5...2.0
- Stable fits
- Hadronization correction increases drastically for $\sqrt{s} \rightarrow 14$ GeV

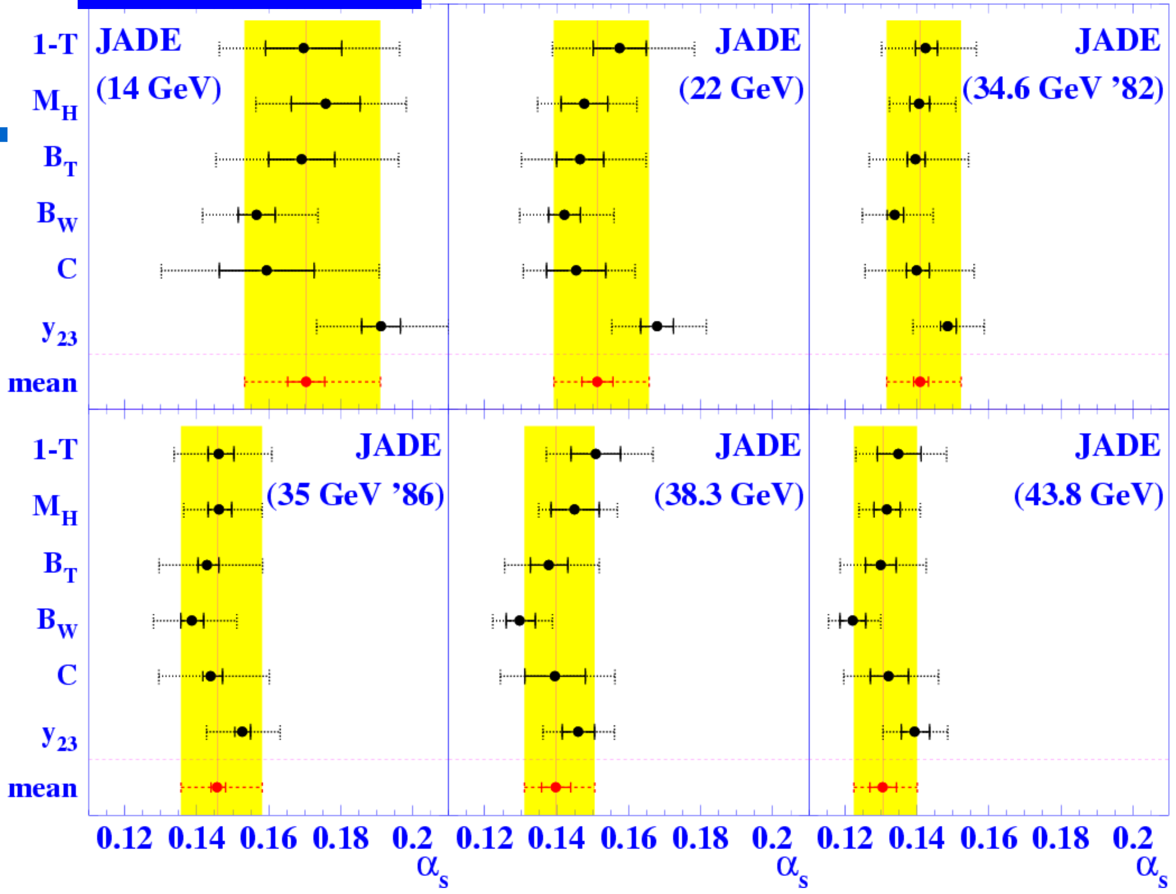
hadronization correction

α_s and χ^2 dependence of fit range

α_S Results

- Similar scattering of individual results (missing higher order terms), but…
- Results consistent within 1-2σ of experimental errors
  ...much better consistency than old PETRA values
- Dominant errors:
  - Renormalization scale (x_μ=0.5...2.0)
    ...significantly reduced w.r.t. NLO caluclations
  - 14+22 GeV: hadronisation, mass effects

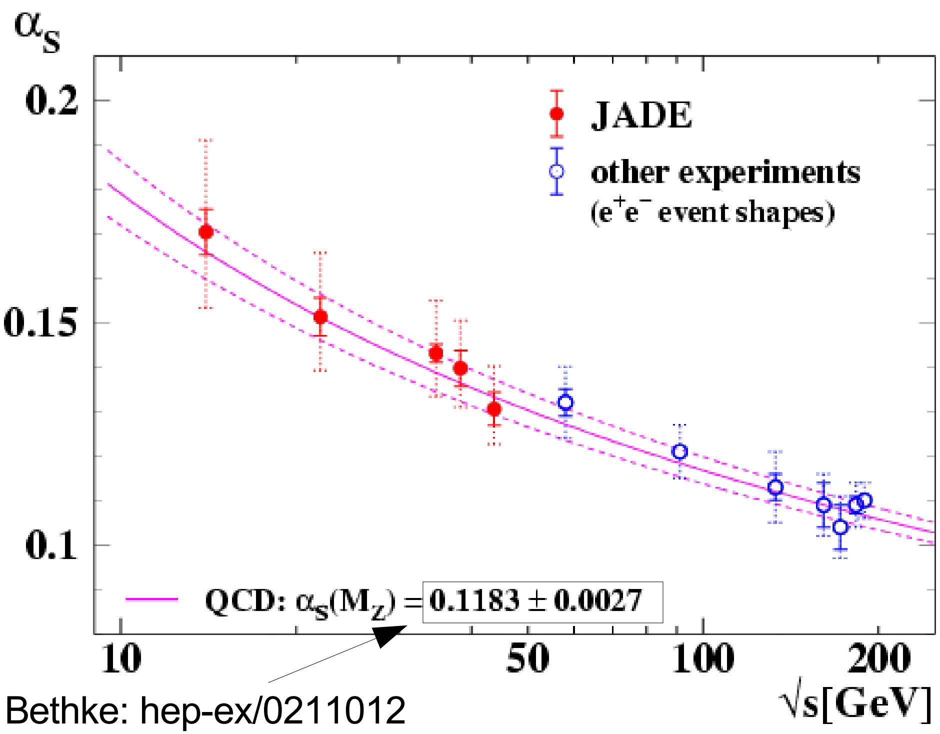
preliminary



$\langle\sqrt{s}\rangle$ [GeV]	$\alpha_S(\sqrt{s})$	fit error	exp.	hadr.	higher ord.	total
14.0	0.1704	±0.0051*		$^{+0.0141}_{-0.0136}$	$^{+0.0143}_{-0.0091}$	$^{+0.0206}_{-0.0171}$
22.0	0.1513	±0.0043*		±0.0101	$^{+0.0101}_{-0.0065}$	$^{+0.0144}_{-0.0121}$
34.6 ('82)	0.1409	±0.0012	±0.0017	±0.0071	$^{+0.0086}_{-0.0057}$	$^{+0.0114}_{-0.0093}$
35.0 ('86)	0.1457	±0.0011	±0.0020	±0.0076	$^{+0.0096}_{-0.0064}$	$^{+0.0125}_{-0.0101}$
38.3	0.1397	±0.0031	±0.0026	±0.0054	$^{+0.0084}_{-0.0056}$	$^{+0.0108}_{-0.0087}$
43.8	0.1306	±0.0019	±0.0032	±0.0056	$^{+0.0068}_{-0.0044}$	$^{+0.0096}_{-0.0080}$

$\alpha_S(M_Z)$= 0.1194± 0.0020(exp+stat)± 0.0051(had) $^{+0.0061}_{-0.0041}$ theo)

Test of the Asymptotic Freedom



Bethke: hep-ex/0211012

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

$$l = \ln(\sqrt{s}/\Lambda_{\overline{\mathrm{MS}}})^2$$

$$\begin{aligned} \beta_0 &= \frac{1}{12\pi}(33 - 2N_f) \\ \beta_1 &= \frac{1}{24\pi^2}(153 - 19N_f) \\ \beta_2 &= \frac{1}{3456\pi^3}\left(77139 - 15099N_f + 325N_f^2\right) \end{aligned}$$

- α_S has been "homogeneously" determined from LEP 2 energies down to lowest PETRA energies
- This is the first measurement at 14 and 22 GeV
- PETRA points increase significance of QCD test substantially

QCD fit, exp.+stat. uncertainties
(inner error bars):

$\Lambda_{MS}^{(5)}$ = 246 ± 7 MeV
$\alpha_S(M_Z)$ = 0.1210 ±0.0006
$P(\chi^2)$ = 75%

"α_S = const.", total errors
(outer error bars):

$P(\chi^2)$ = $1.1 \cdot 10^{-5}$

Excellent agreement with

- ✓ **QCD expectation for running of α_S**
- ✓ **world average value (NNLO)**

Moments and 4-Jet Rates (JADE & OPAL)

Common JADE/OPAL Analysis

- JADE and OPAL are similar detectors, thus many systematics in QCD analyses are expected to be “similar” and can be studied more consistently:
  - MH selection cuts, track/cluster matching, ...
- JADE Revival Group has established a “homogeneous” technical framework to analyse multihadronic final states measured in both experiments:
  - Data/MC reside in almost identical ntuples
  - A master analysis program reads JADE and OPAL ntuples and generates all histograms needed (performs event selection, correction of detector effects, etc)
- Goal:
  - Consider correlations of experimental uncertainties as much as possible
  - Use LEP-QCD working group methods to combine results

Moments of Event Shapes

- α_s analyses of differential distributions compares theory with data only in restricted kinematical regions.
- Complementary approach: Moment analysis
  ...probes all available phase space

nth moment of event shape distribution:

$$\langle y^n \rangle = \int_0^{y_{max}} y^n \frac{1}{\sigma} \frac{d\sigma}{dy} dy$$

- QCD expectation obtained by full numerical integration of NLO ME over phase space: $\langle y^n \rangle = A_n \alpha_s + B_n \alpha_s^2$

JADE and **OPAL**
have analyzed 1st ... 5th moments

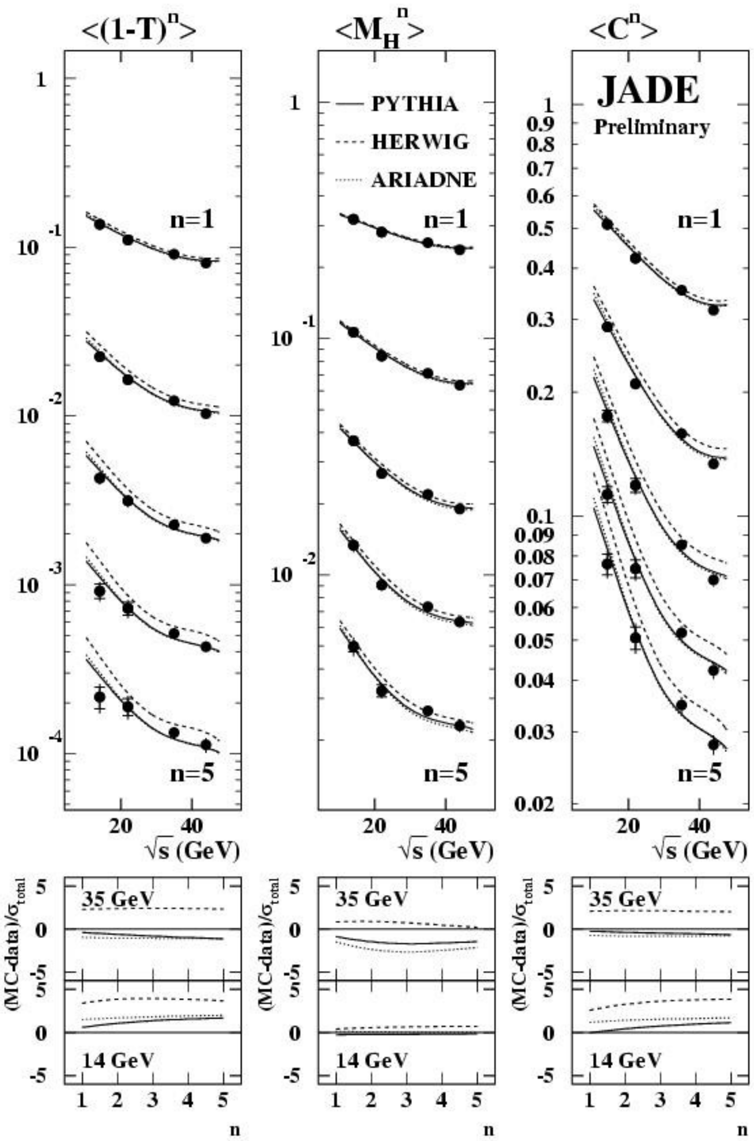
14-44 GeV
ICHEP '04 #5-0502
hep-ex/0408123

91-209 GeV
ICHEP '04 #5-0527
CERN-EP 04-044

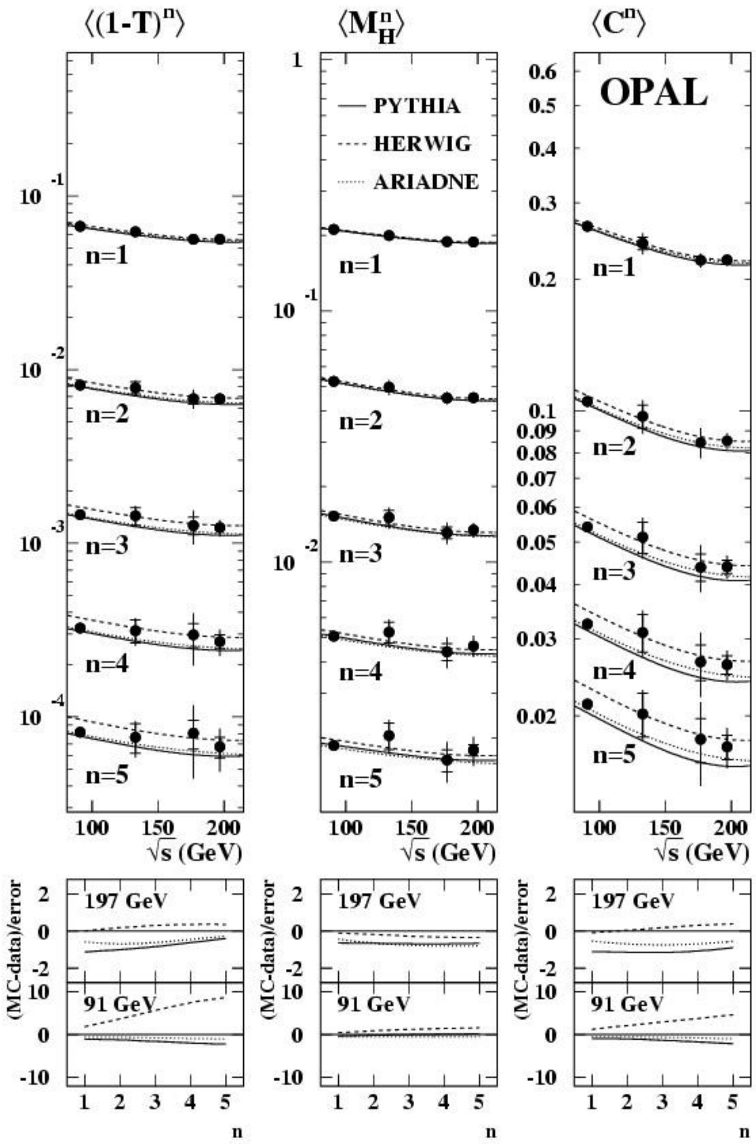
Data vs MC Models

preliminary

JADE



OPAL



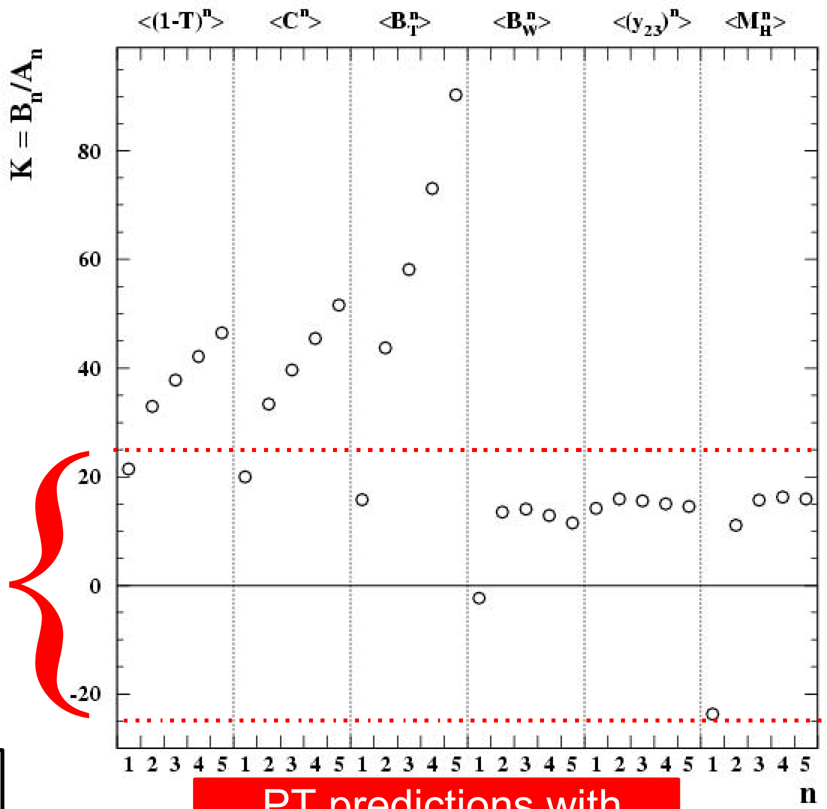
Generally good agreement with MC predictions (PYTHIA, Ariadne)

α_s from Moments

- QCD expectation fitted individually to √s evolution of the moments
  - α_s increases with order n
  - n dependence of α_s is correlated with size of NLO correction $K=B_n/A_n$
- α_s combination (JADE and OPAL separately as yet):
  - consider only converging fits of those predictions with NLO term $|K\,\alpha_s/2\pi| < 0.5 \rightarrow$ 17 observables
  - calculate weighted mean:

$$\alpha_S(M_Z)=\sum w_i\,\alpha_{S,i} \qquad w_i=\frac{\sum_j (V'^{-1})_{ij}}{\sum_{j,k}(V'^{-1})_{jk}}$$

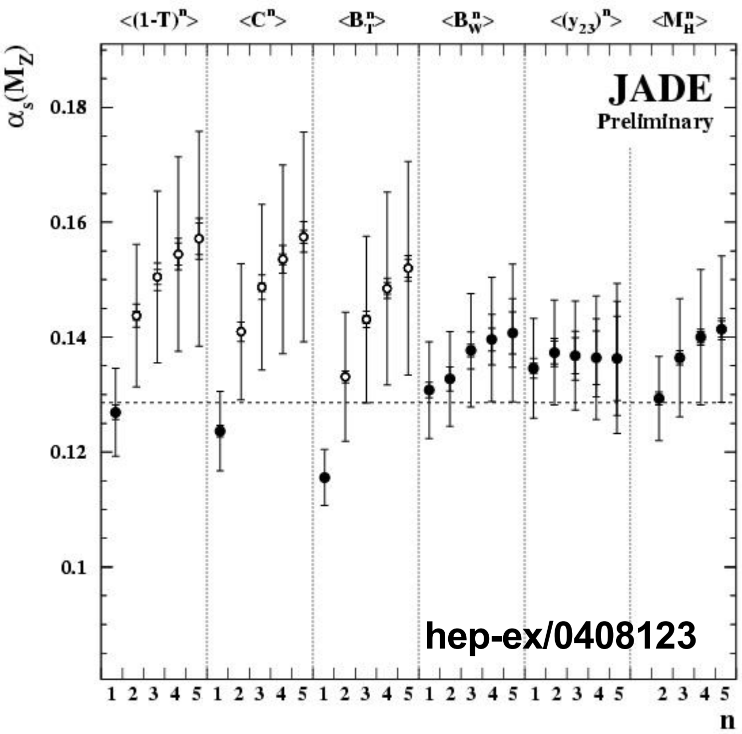
$$V'_{ij}=V'^{(stat)}_{ij}+V'^{(exp)}_{ij}+V'^{(had)}_{ij}+V'^{(theo)}_{ij}$$



PT predictions with "good" convergence

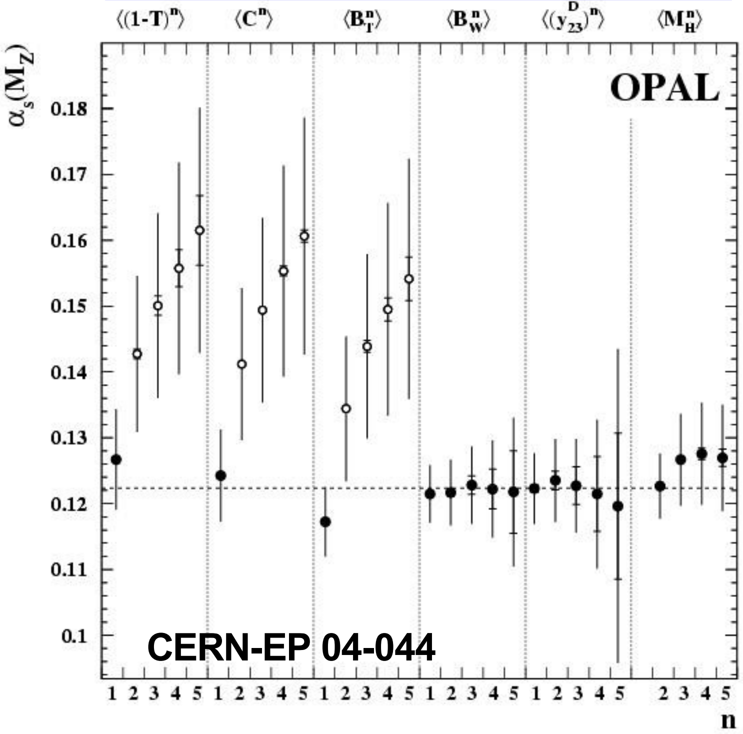
α_s from Moments

JADE (preliminary)



hep-ex/0408123

OPAL (preliminary)



CERN-EP 04-044

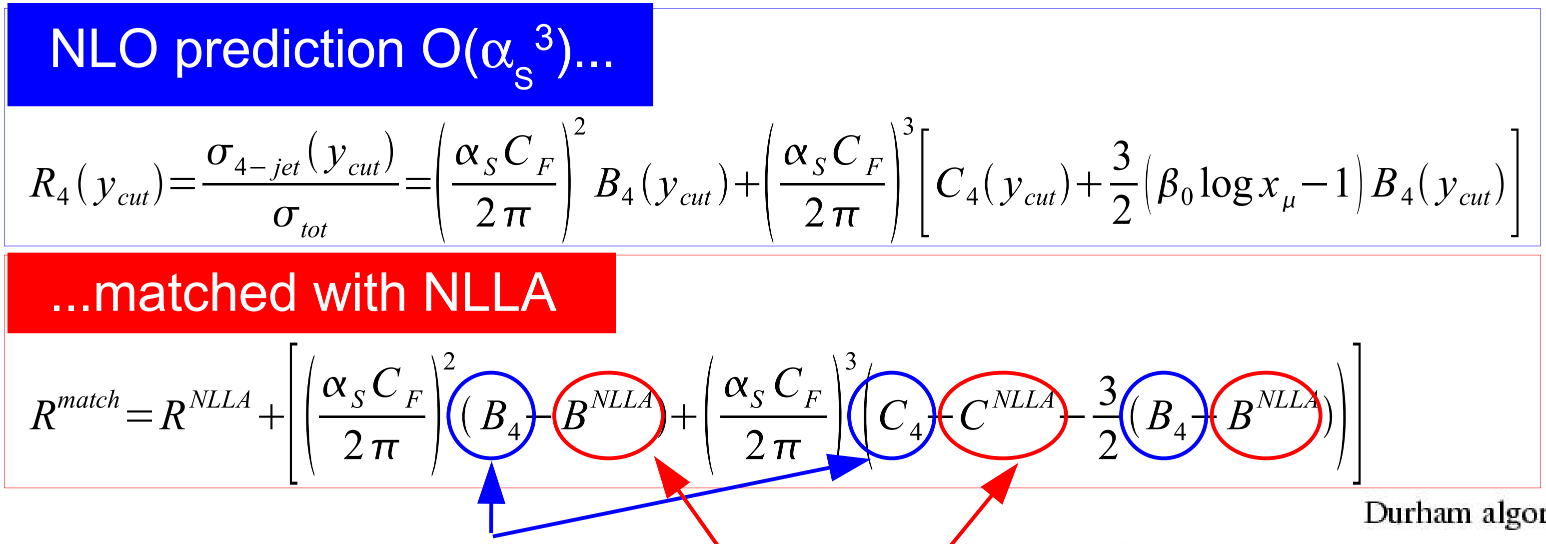
$$\alpha_s(M_Z) = 0.1286 \pm 0.0007^{stat} \pm 0.0011^{exp} \pm 0.0022^{had} \pm 0.0068^{theo}$$

$$\alpha_s(M_Z) = 0.1223 \pm 0.0005^{stat} \pm 0.0014^{exp} \pm 0.0016^{had} \, {}^{+0.0054}_{-0.0036} \, \text{theo}$$

- consistent with world average
- α_s from fits of NLO (with $\mu=\sqrt{s}$) to distributions tend to be large as well
- remarkable: “theoretical” uncertainties only slightly higher than from resummed NLO

α_S from 4-Jet Rate

- Measure number of event with 4 jets as a function of a jet resolution parameter y_{cut} using the Durham scheme



NLO prediction $O(\alpha_S^3)$...

$$R_4(y_{cut}) = \frac{\sigma_{4-jet}(y_{cut})}{\sigma_{tot}} = \left(\frac{\alpha_S C_F}{2\pi}\right)^2 B_4(y_{cut}) + \left(\frac{\alpha_S C_F}{2\pi}\right)^3 \left[C_4(y_{cut}) + \frac{3}{2}\left(\beta_0 \log x_\mu - 1\right) B_4(y_{cut})\right]$$

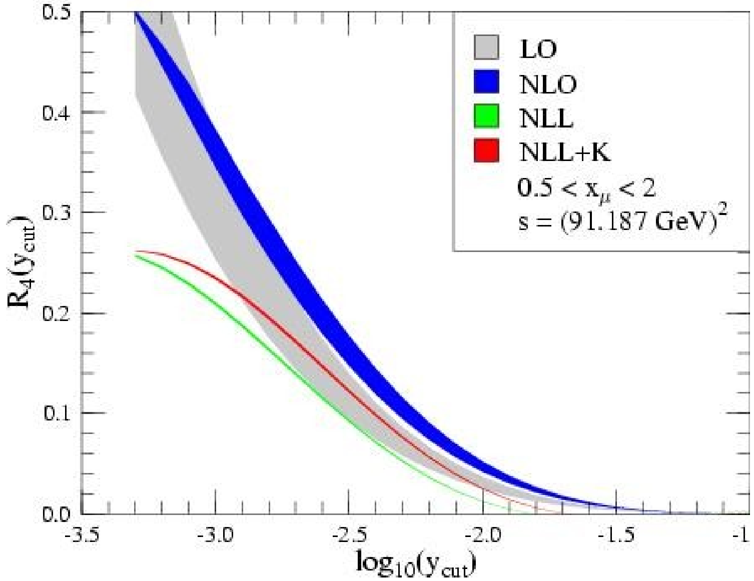
...matched with NLLA

$$R^{match} = R^{NLLA} + \left[\left(\frac{\alpha_S C_F}{2\pi}\right)^2 \left(B_4 - B^{NLLA}\right) + \left(\frac{\alpha_S C_F}{2\pi}\right)^3 \left(C_4 - C^{NLLA} - \frac{3}{2}\left(B_4 - B^{NLLA}\right)\right)\right]$$

LO/NLO coefficients from integration of ME for $e^+e^- \to q\bar{q}gg,\ q\bar{q}q'\bar{q}'$

LO/NLO coefficients of NLLA prediction

Durham algorithm



- Scale uncertainty
  $\Delta R_4(x_\mu) \propto \alpha_S^3 \log x_\mu$

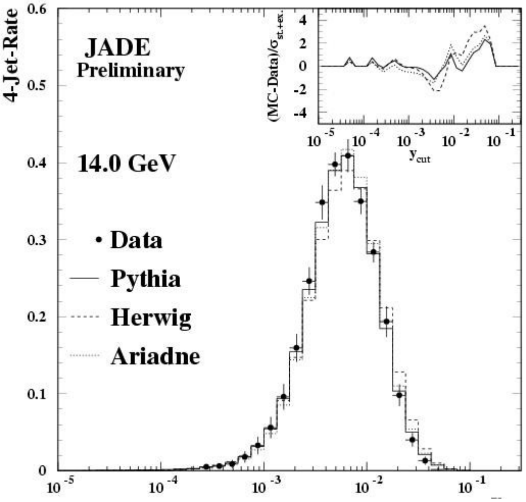
Data vs MC Model

JADE
14-44 GeV

ICHEP '04 #5-0498
hep-ex/0408122

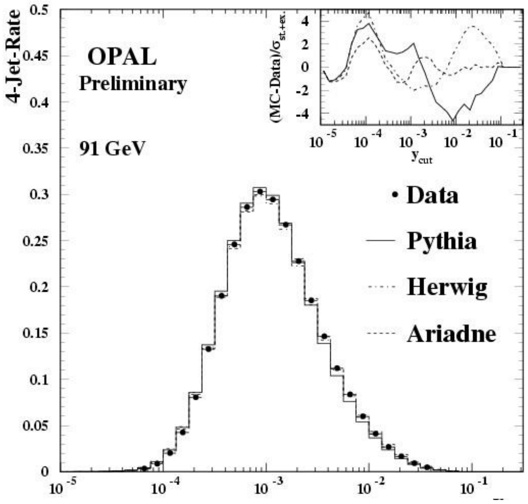
ICHEP '04 #6-0600

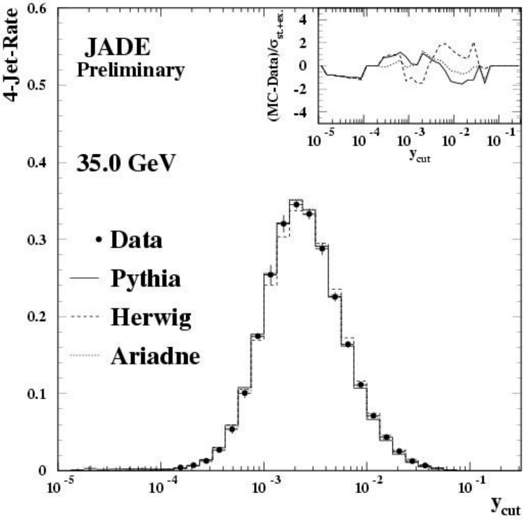
OPAL
91-209 GeV



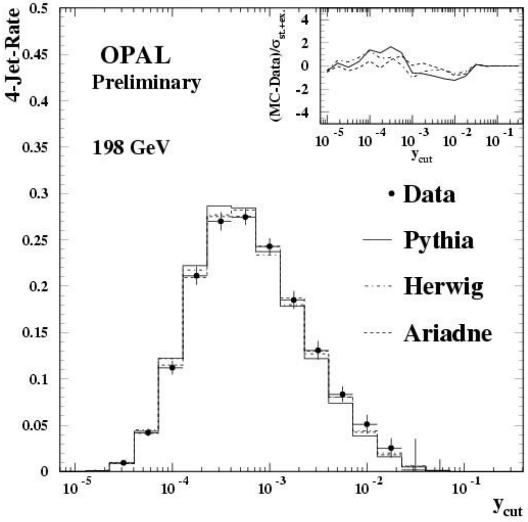
- Single event can contribute to several bins
- Complete covariance matrix needed for α_s fits

Hadron level data
vs.
MC predictions



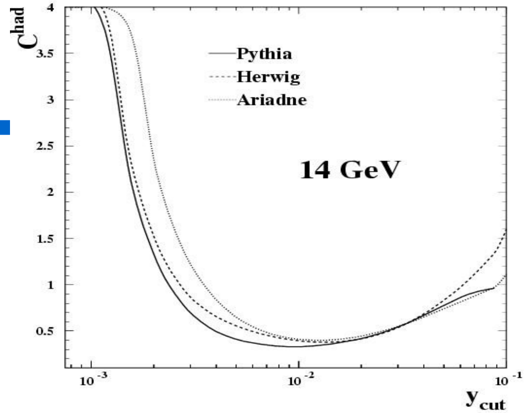


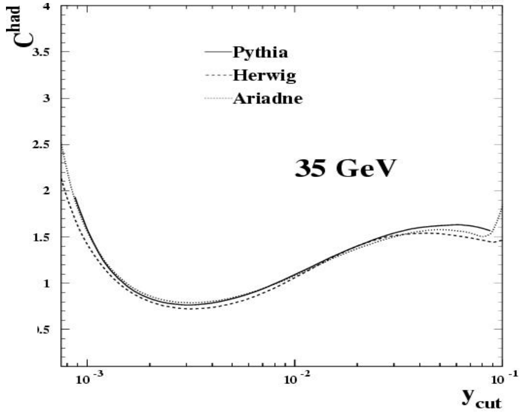
- Good agreement between data and MC model



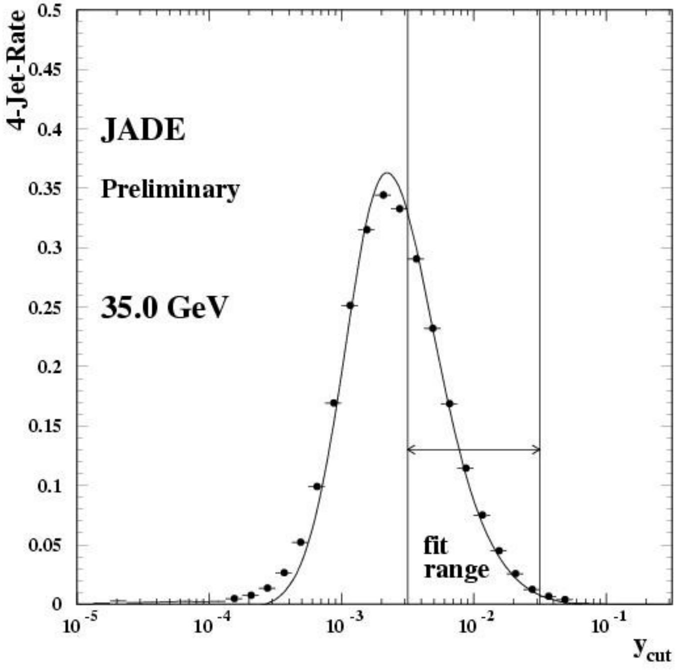
α_s from 4-Jet Rate

- Hadronization correction to parton level
- Fit with α_s as only free parameter
- Fit ranges:
  - region with moderate hadronization uncertainties
  - stay away from too low y_{cut} values (region dominated by events with more than 4 jets)

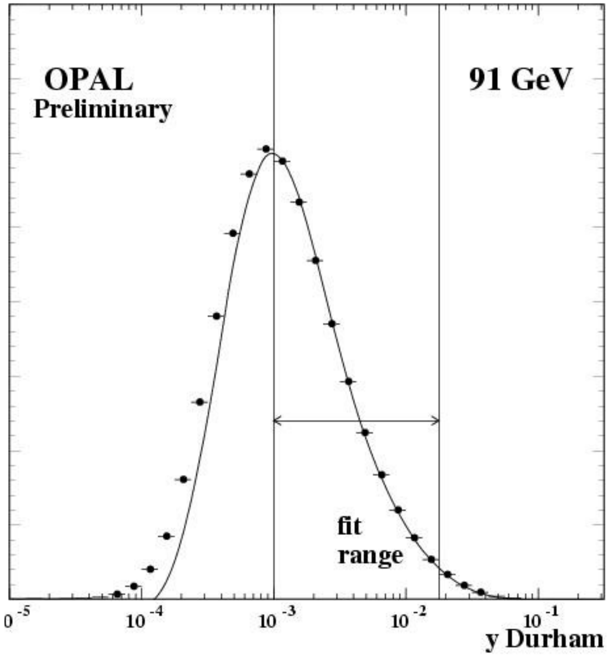




JADE



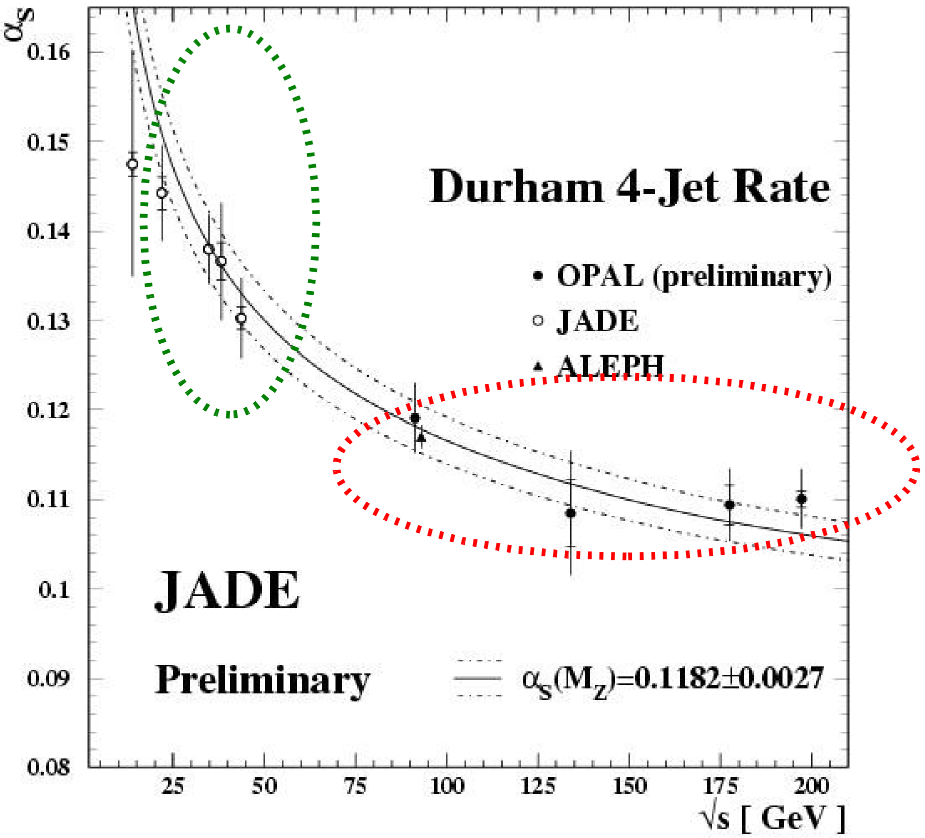
OPAL



α_s from 4-Jet Rate

hep-ex/0408122

- Combine results using weighted mean method (JADE and OPAL separately as yet)
- Skip JADE point at 14 GeV because of hadronization uncertainties



JADE (preliminary):

$$\alpha_s(M_Z)= 0.1169 \pm 0.0004^{stat} \pm 0.0012^{exp} \pm 0.0021^{had} \pm 0.0007^{theo}$$

OPAL (preliminary):

$$\alpha_s(M_Z)= 0.1208 \pm 0.0006^{stat} \pm 0.0021^{exp} \pm 0.0019^{had} \pm 0.0024^{theo}$$

- Small renormalization scale uncertainties indicate “small” missing higher order contributions
  (...estimate might depend on fit range)
- in excellent agreement with world average

Power Corrections

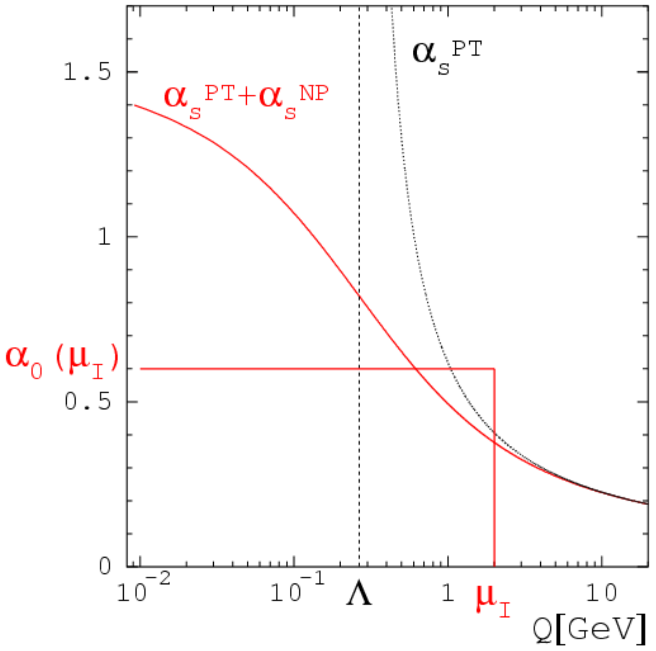
Power Corrections a la DMW

- Classical method to estimate NP effects: MC models

  Problem: numerous parameters (parton shower, string fragmentation)

- Promising alternative: **Power Corrections (PC)**

  I. Parametrize unknown but analytical behaviour of the strong coupling constant around the Landau pole Λ (0…2GeV)



$$\alpha_0(\mu_I)=\frac{1}{\mu_I}\int_0^{\mu_I}\alpha_S(\mu)\,d\mu$$

  - integrates over all NP details
  - μ_I separates PT and NP region (usually μ_I=2GeV)

  II. Dokshitzer, Marchesini, Webber (**DMW**):

  NP structure due to soft gluon radiation at $\mu \approx \Lambda$

DMW Predictions for Event Shapes

NP: general structure

$$\langle y \rangle = \langle y \rangle^{\mathrm{PT}} + \mathcal{D}_y \mathcal{P} \qquad \text{(means)}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(y) = \frac{\mathrm{d}\sigma^{\mathrm{PT}}}{\mathrm{d}y}(y - \mathcal{D}_y \mathcal{P}) \quad \text{(distributions)}$$

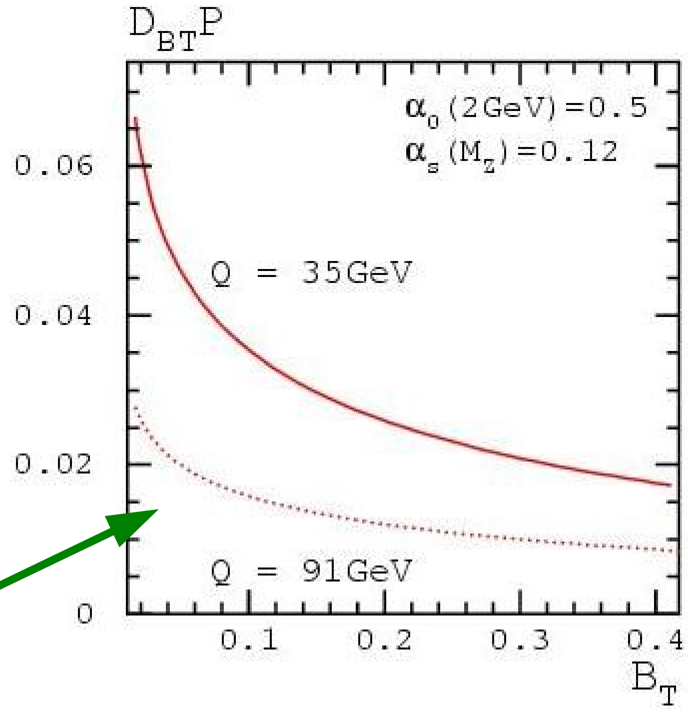
$$\mathcal{P} = \frac{4C_F}{\pi^2} \mathcal{M} \frac{\mu_{\mathrm{I}}}{Q} \left[\alpha_0(\mu_{\mathrm{I}}) - \alpha_{\mathrm{S}}(\mu_{\mathrm{R}}) - \beta_0 \frac{\alpha_{\mathrm{S}}^2(\mu_{\mathrm{R}})}{2\pi} \left(\ln \frac{\mu_{\mathrm{R}}}{\mu_{\mathrm{I}}} + \frac{K}{\beta_0} + 1 \right) \right]$$

NP: observable specific part

y	$\mathcal{D}_y = \mathcal{D}_y(\alpha_{\mathrm{S}}, y)$
$1-T$	2
M_{H}^2	1
C	3π
B_{T}	$\ln(1/y) + D_T(y, \alpha_{\mathrm{S}}(yQ))$
B_{W}	$\frac{1}{2}\ln(1/y) + D_1(y, \alpha_{\mathrm{S}}(yQ))$

shift

shift+squeeze



y_{23}: no 1/Q contribution expected

PT:

NLO+ NLLA, different matching schemes

- α_0 is the only NP parameter
- α_0 is “universal”

Tests of the DMW Model

- Global fit of PT+PC to overall event shape data from JADE and measurements published by other experiments at PETRA, LEP, SLC, PEP, TRISTAN
- 2 free parameters:

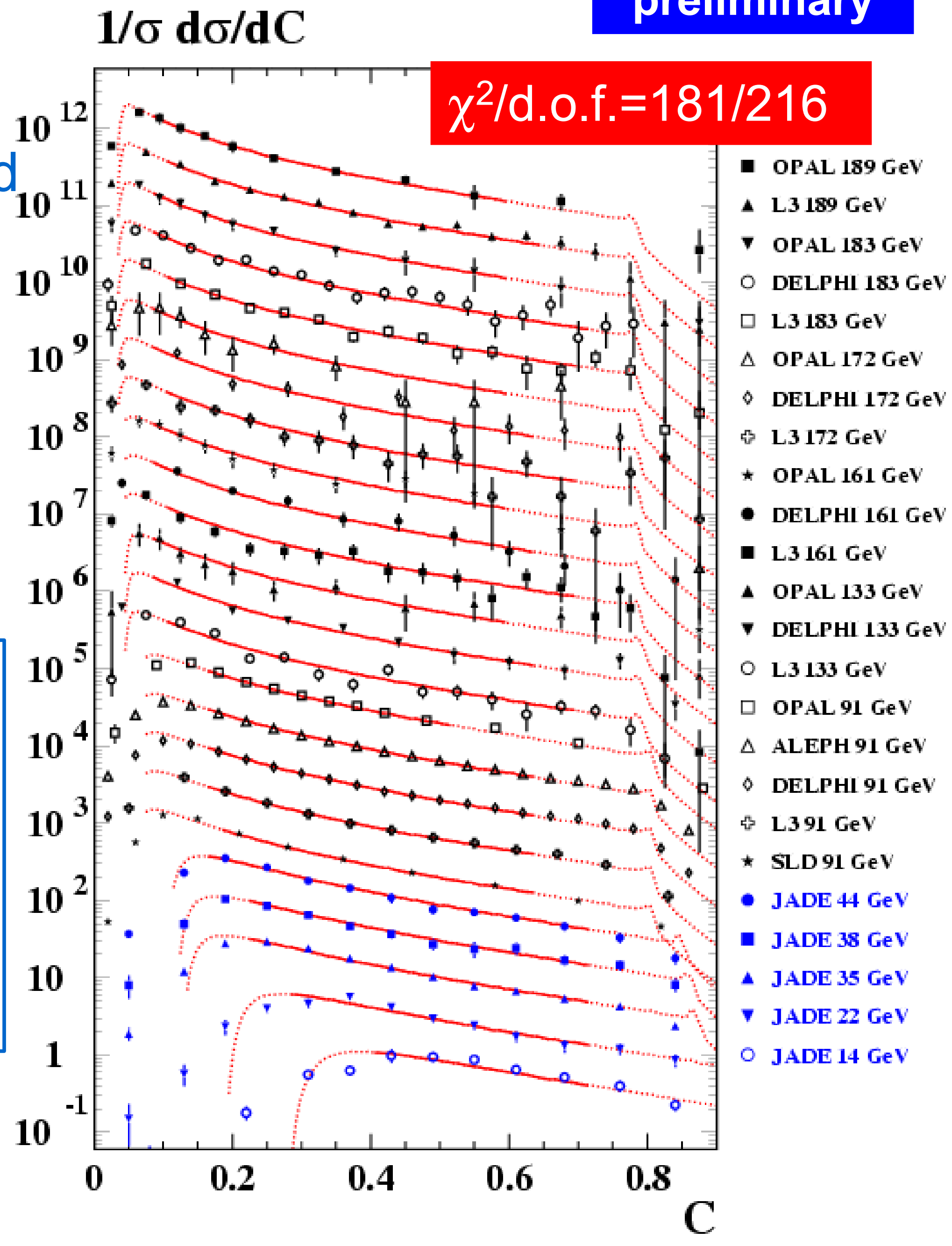
  $\alpha_s(M_Z)$, $\alpha_0(\mu_I)$

Data sets

Accelerator	$\sqrt{s}$ [GeV]	$1-T$	M_H	B_T, B_W, C
PETRA (JADE, TASSO)	12-47	102000		43700
PEP (HRS, MARK II)	29	28300		
TRISTAN (AMY)	55-58	1900		
LEP I (ADLO*)	91	$\mathcal{O}(10^6)$		
SLC (SLD)	91	37200		
LEP II (ADLO*)	133-189	15600		

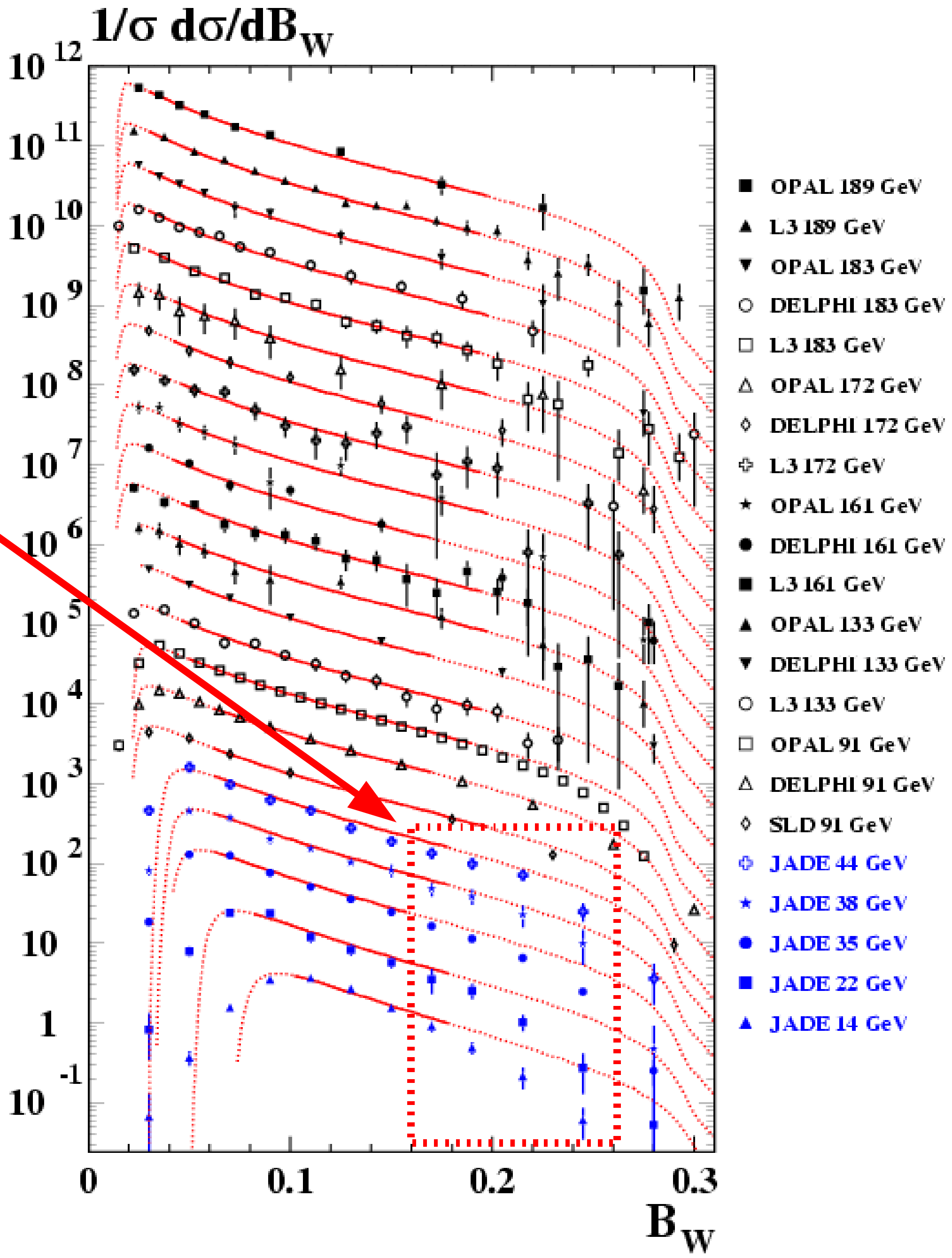
analysis covers the energy range 14-189 GeV

preliminary



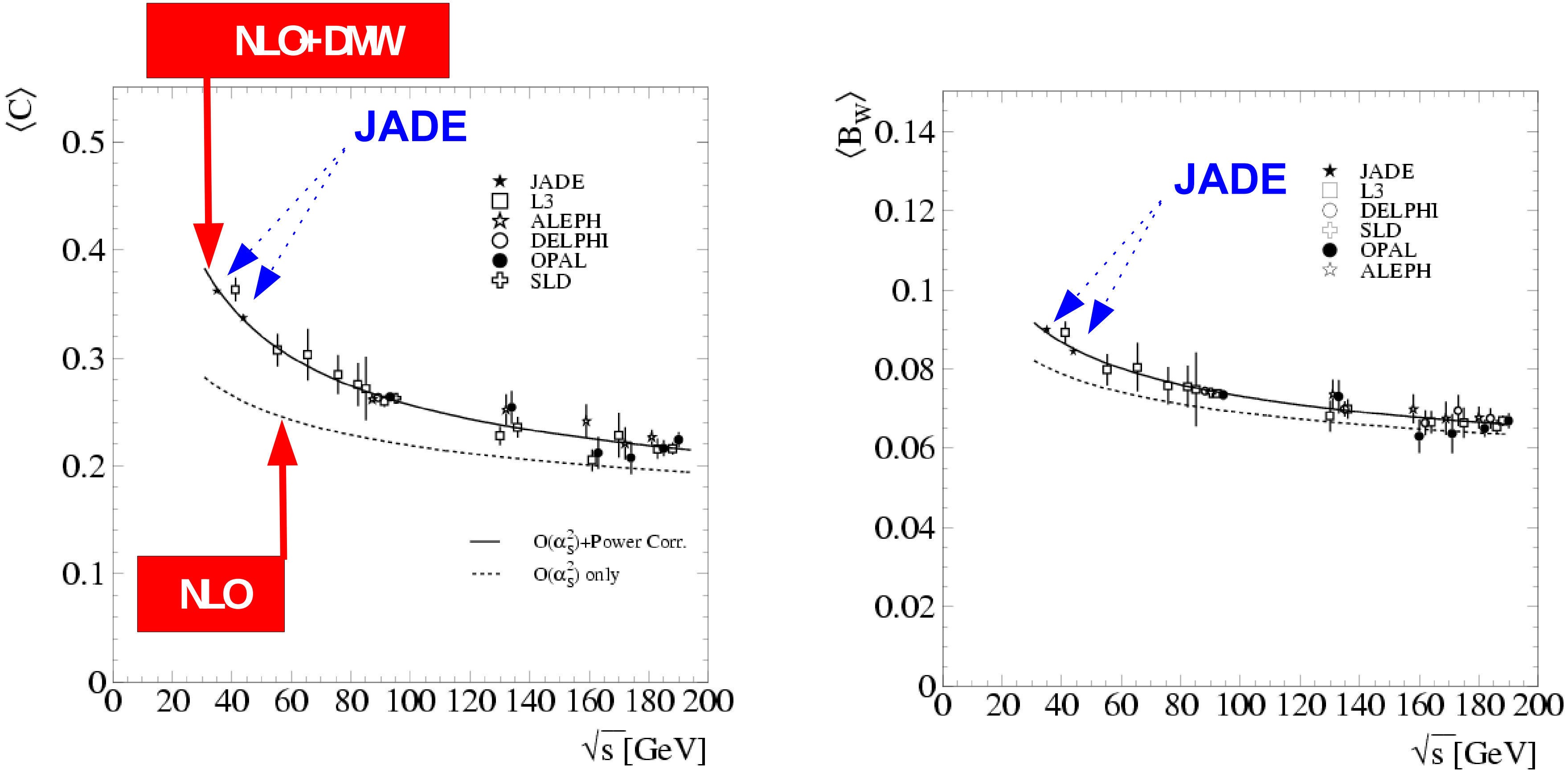
Tests of the DMW Model

- Model works well for T, C, B_T
- DMW predictions for the <u>less inclusive variables</u> M_H, B_W have problems at PETRA energies: significant excess in 3 jet region (but: also problems with PT part of B_W)



Tests of the DMW Model

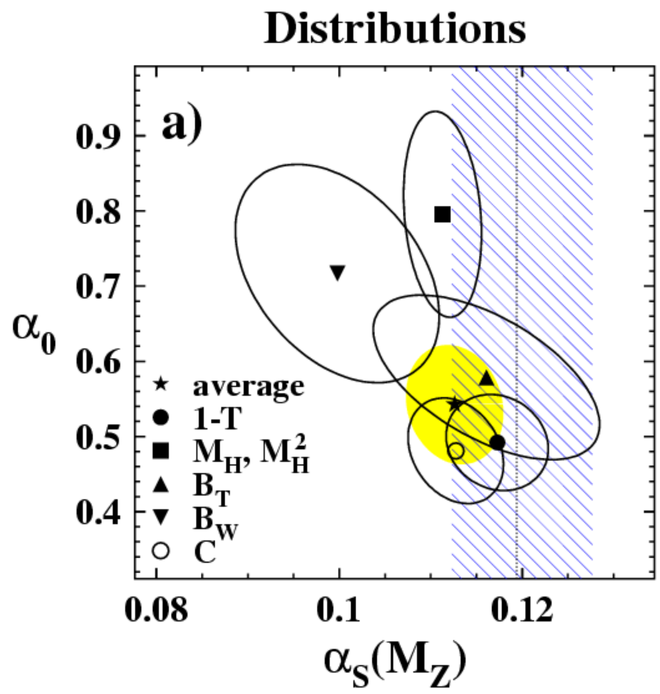
- DMW predictions for mean values of event shapes:



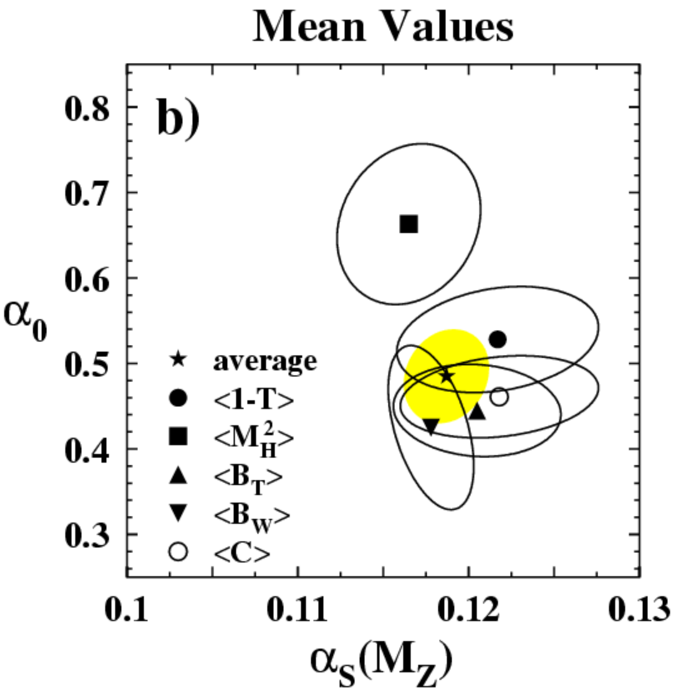
[These plots do not include JADE update at 14+22 GeV]

- Fits mainly constrained by JADE and LEP-I data points
- Model works here well for all variables

α_s and α_0 from DMW Fits



Distributions	fit	exp.	theo.
$\alpha_S(M_{Z^0})=$ 0.1126	±0.0005	±0.0037	$^{+0.0044}_{-0.0030}$
$\alpha_0(2\ \mathrm{GeV})=$ 0.542	±0.005	±0.032	$^{+0.084}_{-0.060}$

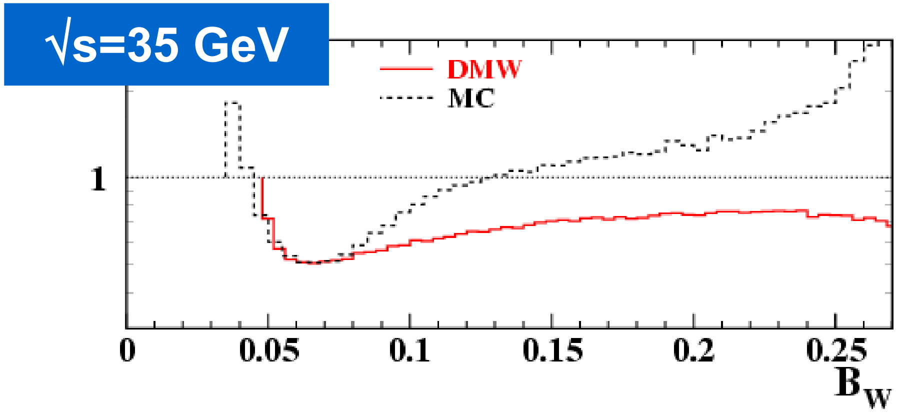


Mean Values	fit	exp.	theo.
$\alpha_S(M_{Z^0})=$ 0.1187	±0.0014	±0.0001	$^{+0.0028}_{-0.0015}$
$\alpha_0(2\ \mathrm{GeV})=$ 0.485	±0.013	±0.001	$^{+0.065}_{-0.043}$

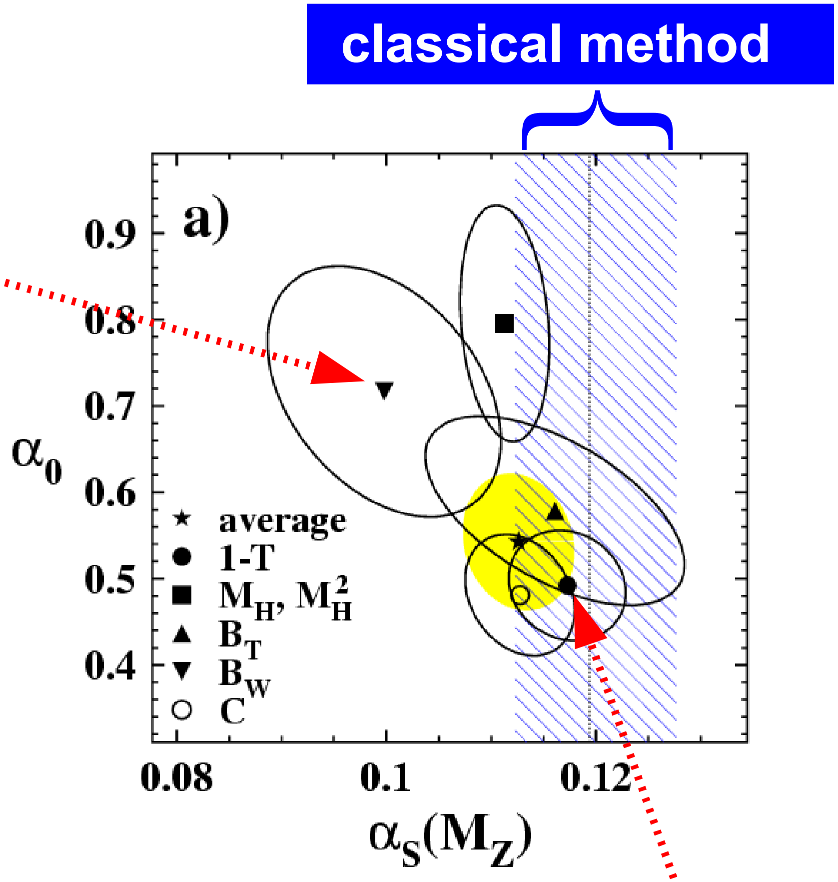
- Individual results consistent within 1-2σ of total errors
- α_0 universal at 20% level

  ...corresponds to uncertainty of $O(\alpha_s^2)$ evaluation of power corrections ("Milan factor")

DMW vs. MC

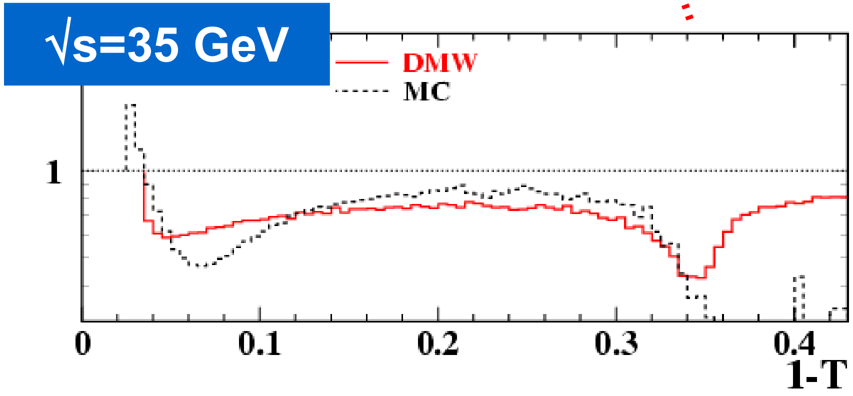


√s=35 GeV



classical method

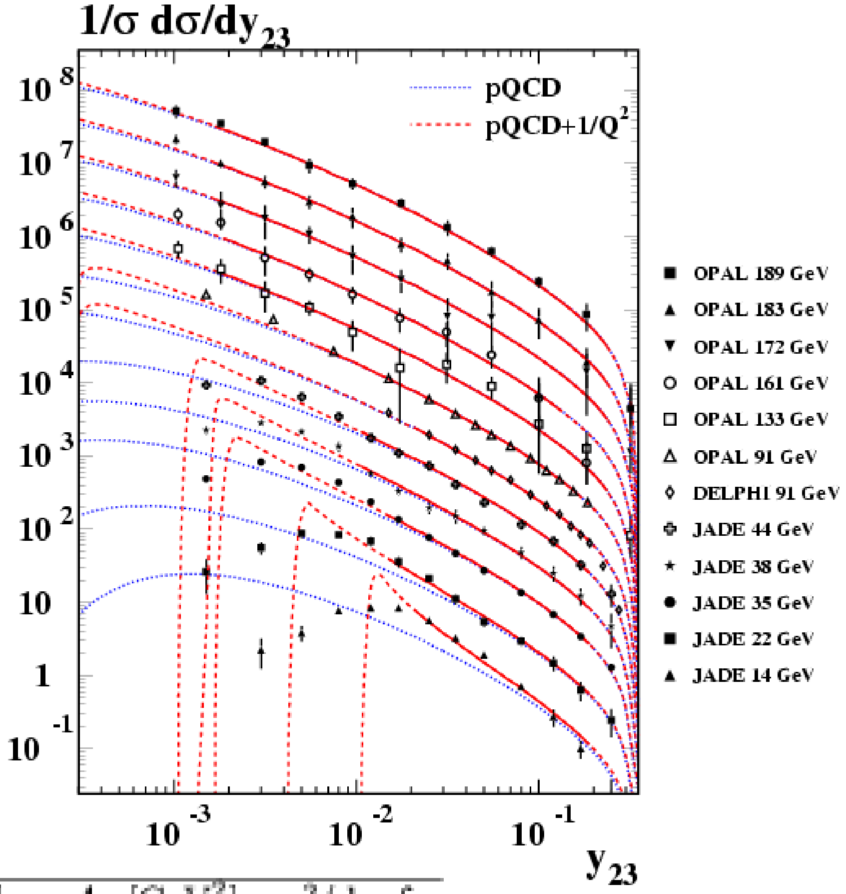
- PT spectrum of B_W, M_H much less squeezed by DMW model than by classical hadronization models
  - Interplay between α_S and α_0 allows fit to compensate for "missing squeeze" by choosing small α_S values
- systematically lower α_S results from power corrections for differential distributions



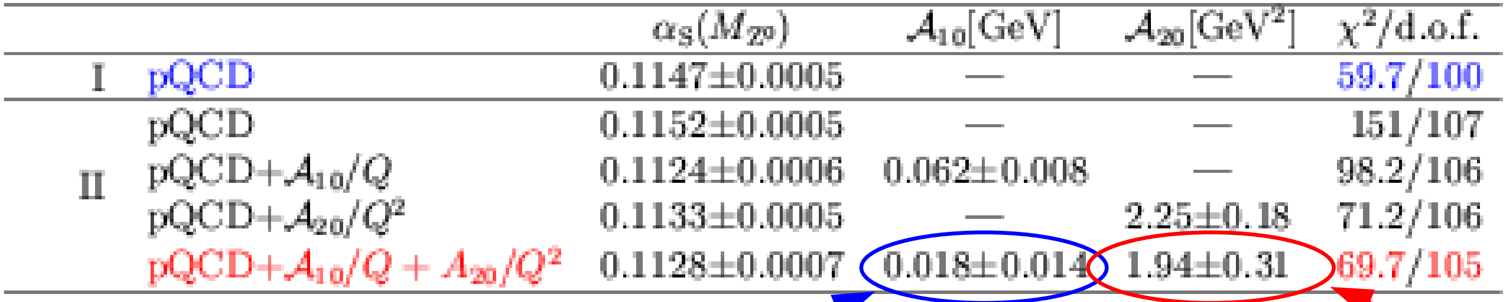
√s=35 GeV

Power Corrections to y_{23}?

- DMW: 1/Q coefficient = 0
- Corrections of type $1/Q^2$, $\ln Q/Q^2$ expected, but no detailed prediction exist.
- JADE data at 14+22 GeV would probably help to detect higher order terms more easily.



- Example: <u>assume</u> same NP structure but $A_{10}/Q+A_{20}/Q^2$ dependence:



		$\alpha_S(M_{Z^0})$	A_{10}[GeV]	A_{20}[GeV^2]	χ^2/d.o.f.
I	pQCD	0.1147±0.0005	—	—	59.7/100
II	pQCD	0.1152±0.0005	—	—	151/107
	pQCD+A_{10}/Q	0.1124±0.0006	0.062±0.008	—	98.2/106
	pQCD+A_{20}/Q^2	0.1133±0.0005	—	2.25±0.18	71.2/106
	pQCD+$A_{10}/Q+A_{20}/Q^2$	0.1128±0.0007	0.018±0.014	1.94±0.31	69.7/105

1/Q

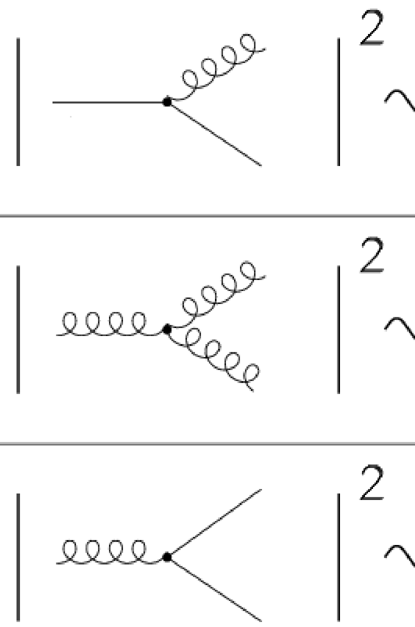
compatible with 0

$1/Q^2$

6σ effect

Color Factors from Event Shapes

QCD color factors



$\left| \cdots \right|^2 \sim \alpha_S C_F$

$\left| \cdots \right|^2 \sim \alpha_S C_A$

$\left| \cdots \right|^2 \sim \alpha_S T_F N_f$

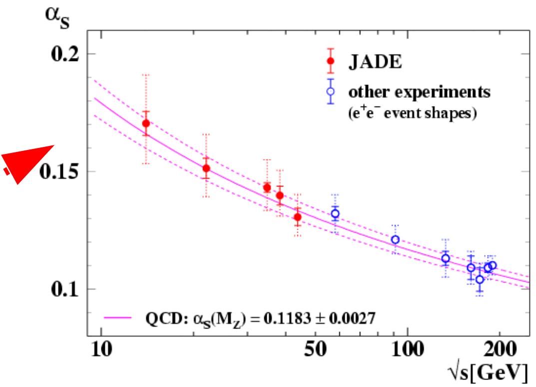
...relative weights of the fundamental vertices are determined by SU(3):

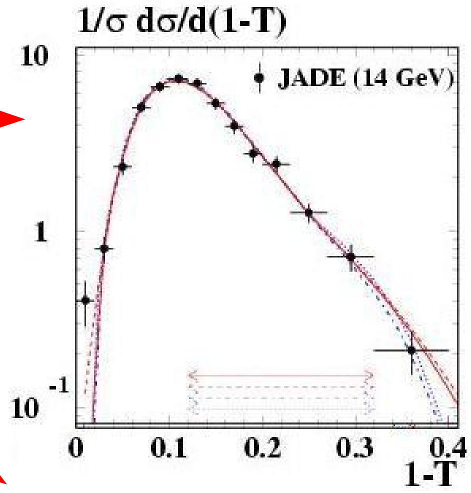
- $C_F = 4/3$
- $C_A = 3$
- $T_F N_f = 1/2 N_f$

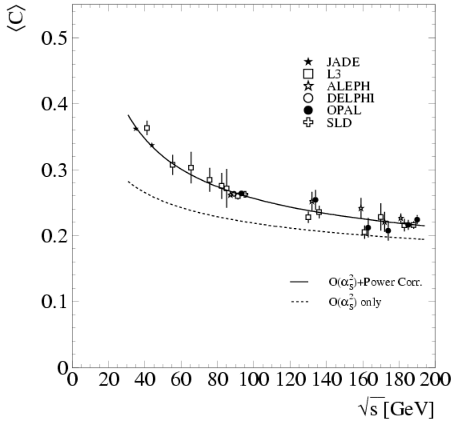
Shape variables have known color structure:

- Running of α_S
  - $\beta_0 = \beta_0 (C_A, N_F)$,
  - $\beta_1 = \beta_1 (C_A, C_F, N_F)$
- PT prediction
  - $A \propto C_F$,
  - $B = B(C_A, C_F, N_F)$
  - $\text{NLLA} = \text{NLLA}\ (C_A, C_F, N_F)$
- Power Corrections
  - $P = P(C_A, C_F, N_F)$
  - $M = M(C_A, N_F)$
  - $D_y = D_y(C_A, C_F, N_F)$

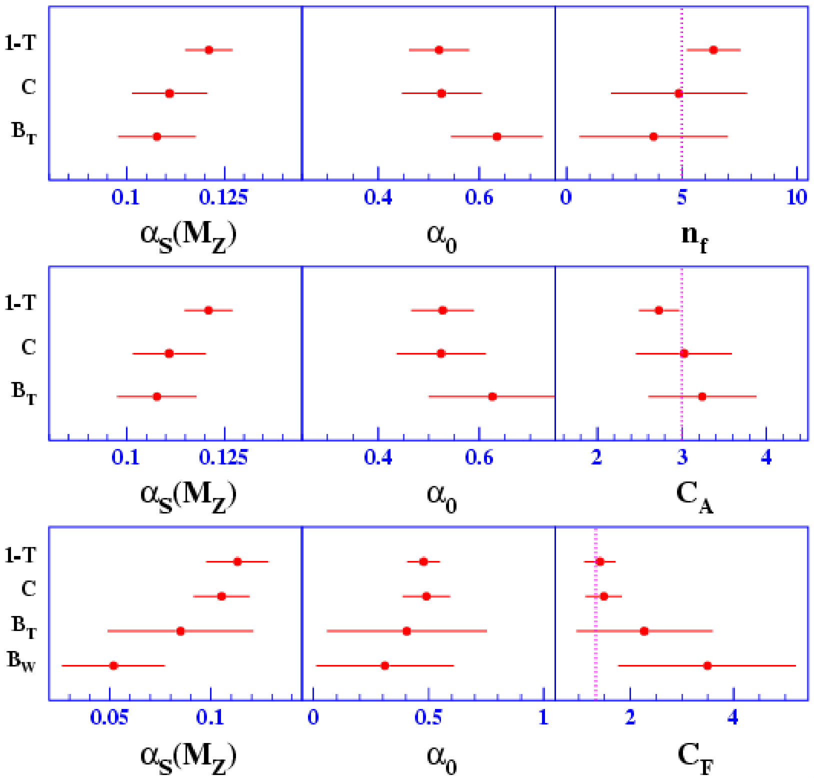
DMW allows measurement w/o bias from color structure of MC models



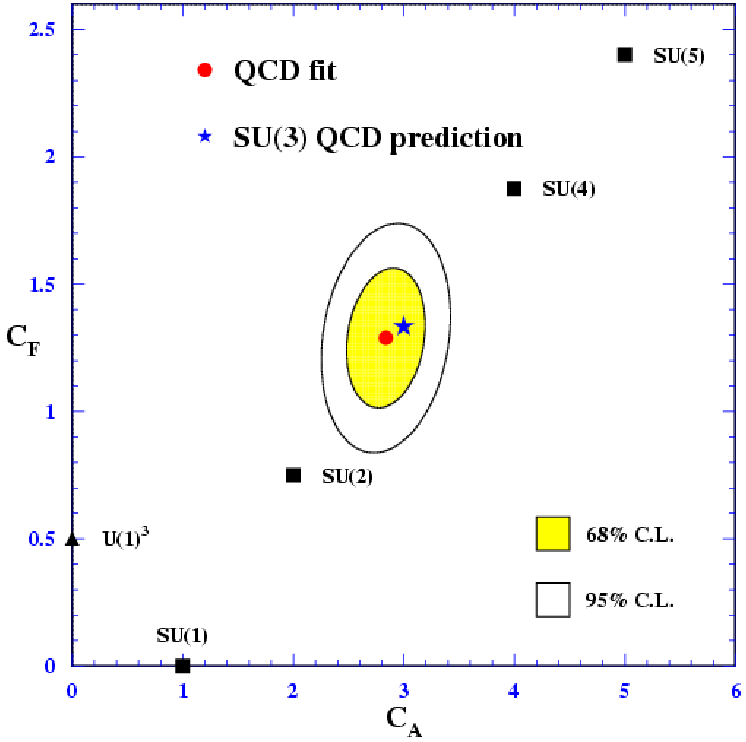




Color Factors from Event Shapes (2)



	Fit α_S and α_0 and (C_A or C_F or N_f)		Fix α_0 and N_f and fit α_S and C_A and C_F		
	$1-T$	C	$1-T$	C	QCD
C_A	2.7 ± 0.2	3.0 ± 0.6	2.7 ± 0.2	3.0 ± 0.5	3
C_F	1.4 ± 0.3	1.5 ± 0.4	1.3 ± 0.2	1.3 ± 0.5	4/3
N_f	6.4 ± 1.2	4.9 ± 3.0	—	—	5



$C_F = 2.84 \pm 0.24$ (QCD:3)

$C_A = 1.29 \pm 0.18$ (QCD:4/3)

- errors competitive with classical 4-jet angular correlation analyses
- need JADE data to constrain the fit

Summary and Conclusions

Summary I

- NLO+NLLA calculations for event shapes first time applied to PETRA data
- Better calculations gives now a consistent picture of individual α_s at PETRA energies

recent JADE results

- Differential event shapes:

  JADE: $\alpha_s(M_z)=0.1194^{+0.0082}_{-0.0068}$

  LEP+SLC: $\alpha_s(M_z)=0.121 \pm 0.006$

  LEP2: $\alpha_s(M_z)=0.120 \pm 0.007$

- Moments:

  JADE: $\alpha_s(M_z)=0.1286 \pm 0.0072$ (prel.)

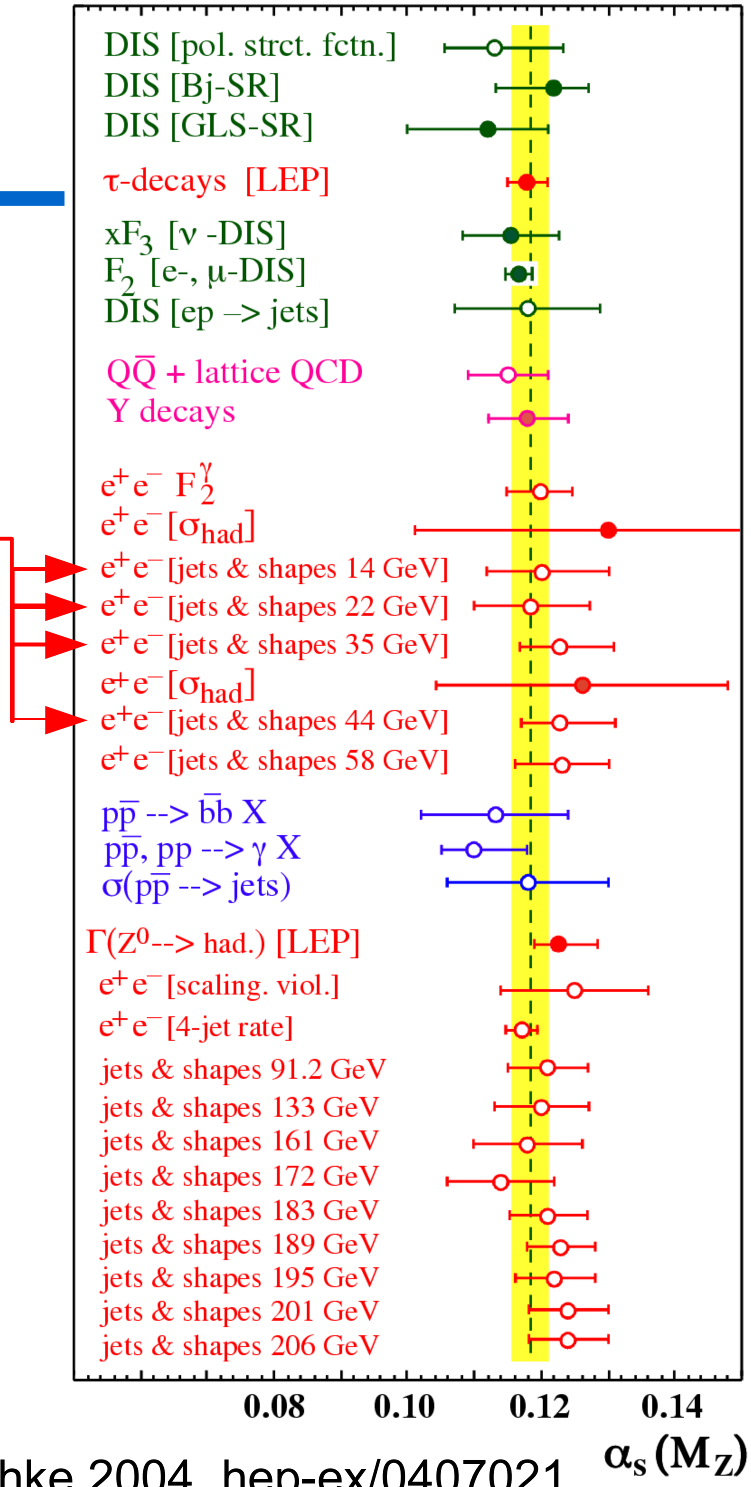
  OPAL: $\alpha_s(M_z)=0.1223 \pm 0.0059$ (prel.)

- 4-jet rate:

  JADE: $\alpha_s(M_z)=0.1169 \pm 0.0026$ (prel.)

  OPAL: $\alpha_s(M_z)=0.1208 \pm 0.0038$ (prel.)

- **Overall consistent picture of results from different experiments and methods!**



Bethke 2004, hep-ex/0407021

Summary II

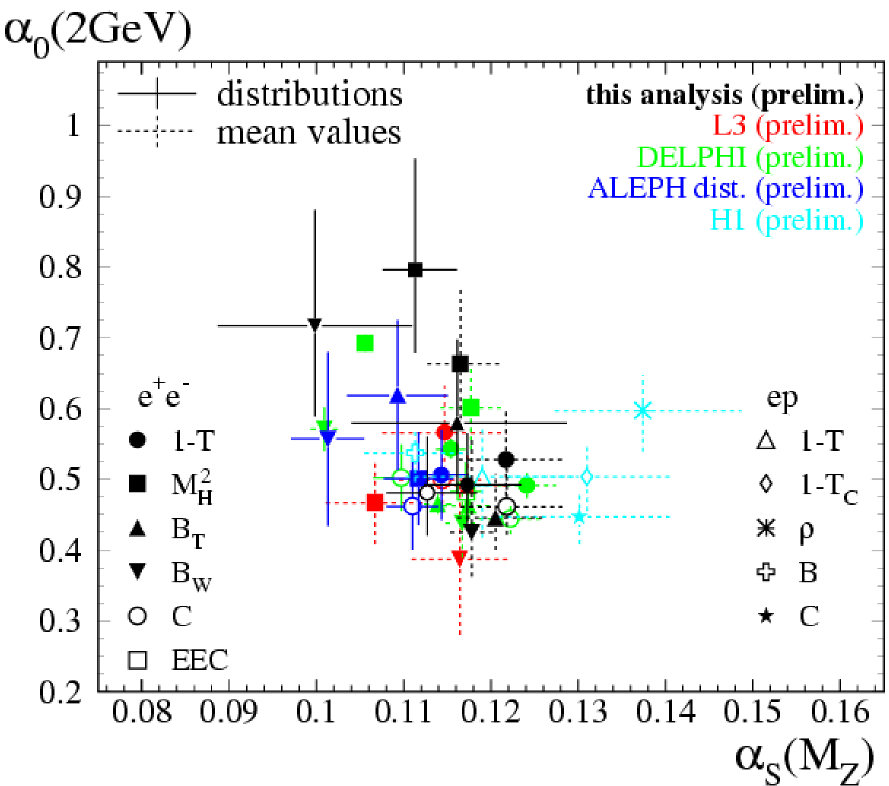
- Power corrections useful to describe event shape data from PETRA to LEP2 energies
- NP parameter α_0 is universal at a level of 20%

Distributions:

$\alpha_s(M_Z)=0.113^{+0.006}_{-0.005}$ $\alpha_0(2\text{GeV})=0.54^{+0.09}_{-0.07}$

Mean values:

$\alpha_s(M_Z)=0.119^{+0.003}_{-0.002}$ $\alpha_0(2\text{GeV})=0.49^{+0.07}_{-0.05}$



- Nice agreement also with other measurements, but clearly improved calculation for more observables needed
- SU(3) structure confirmed in a complementary way

A Comment on Archiving...

- Archived data of finished experiments might be valuable sources for future analyses:
  - Was the pentaquark already visible at LEP?
  - Where was the $D_s^+\pi^0$ resonance before BaBar?
- Long-term maintenance of data+software of an experiment after shutdown is a highly non-trivial task! Things to consider:
  - Keep software platform independent. At least test on different machines using different compilers.
  - Provide detailed documentation.
  - Which data carrier has the longest lifetime?
    Are there devices available in future which can read 10 years old data carriers? (Commercial products?)
    (...recall JADE data rescue drama 1997, i.e. ~10 years after PETRA shutdown)

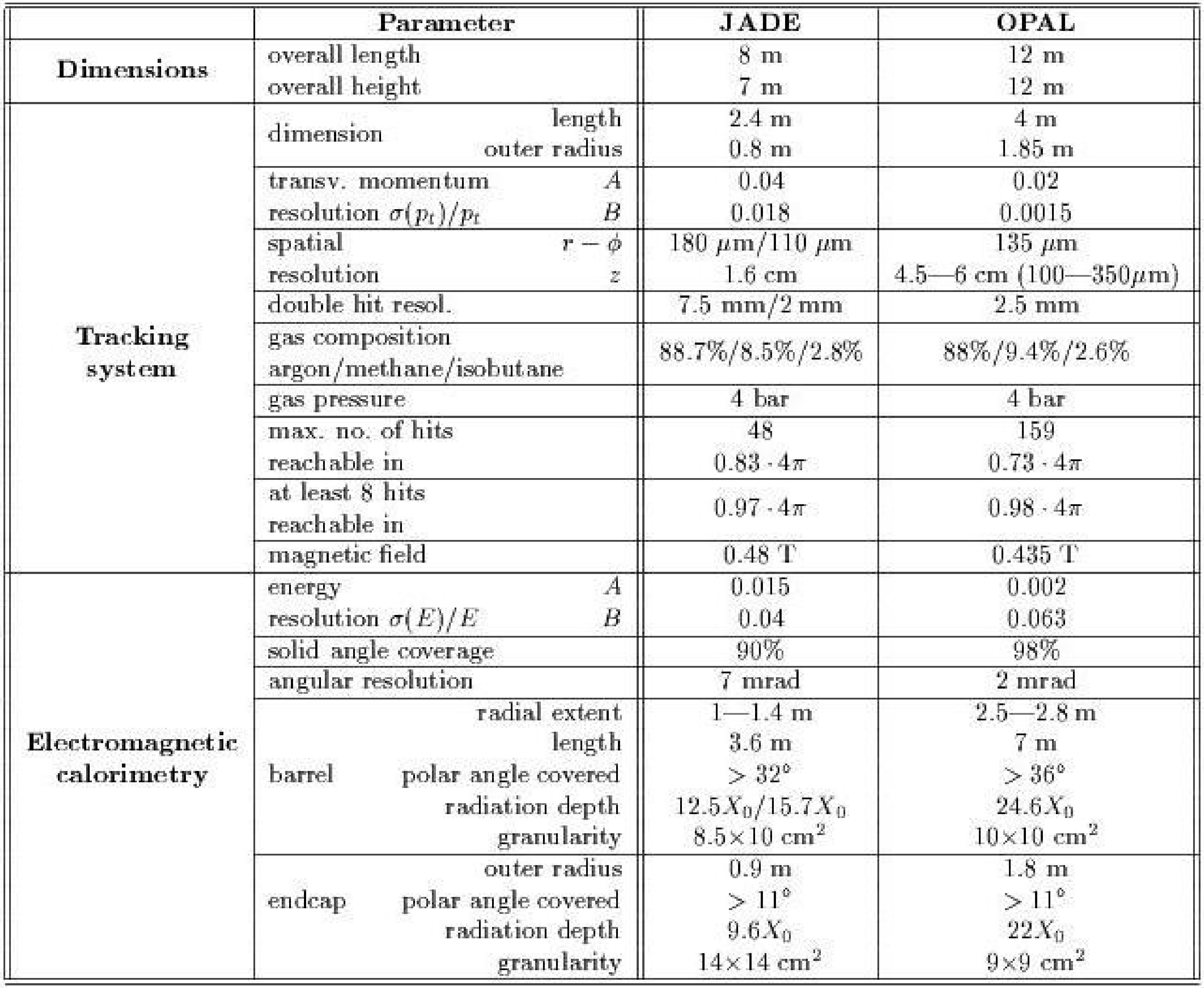
Conclusions

- JADE revival and reanalysis project established in HEP community.
- Data and software from the JADE experiment were successfully resurrected.
- Recent state-of-the-art analyses with JADE data proves to be a valuable counterpart to LEP.
- Results provide new stringent test of perturbative and non-pertrubative aspects
  of Quantum Chromodynamics.

Keep the data and software alive,
it's worth it!!!

Backup Slides

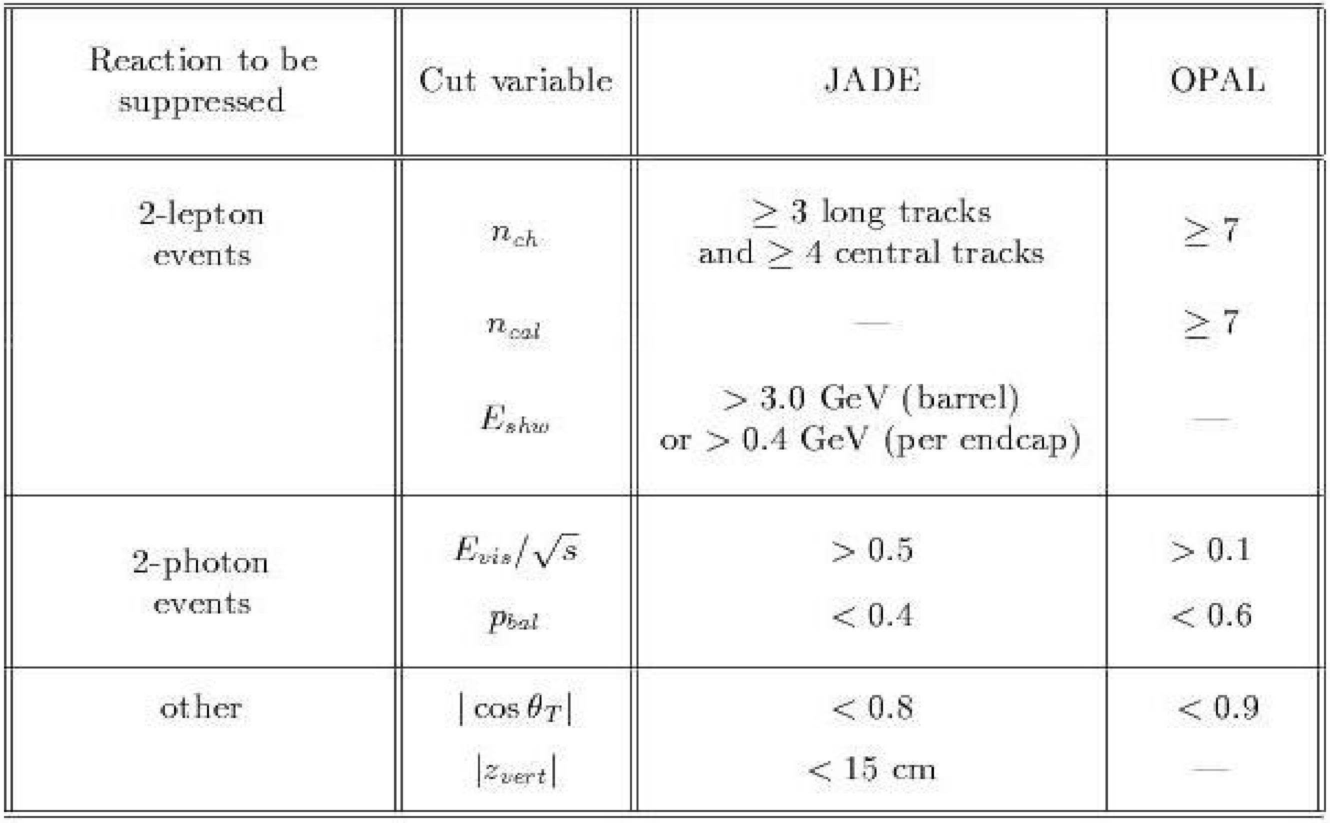
Tracking/Calorimetry: JADE vs OPAL



	Parameter		JADE	OPAL
Dimensions	overall length		8 m	12 m
	overall height		7 m	12 m
Tracking system	dimension	length	2.4 m	4 m
		outer radius	0.8 m	1.85 m
	transv. momentum resolution $\sigma(p_t)/p_t$	A	0.04	0.02
		B	0.018	0.0015
	spatial resolution	$r-\phi$	180 μm/110 μm	135 μm
		z	1.6 cm	4.5—6 cm (100—350μm)
	double hit resol.		7.5 mm/2 mm	2.5 mm
	gas composition argon/methane/isobutane		88.7%/8.5%/2.8%	88%/9.4%/2.6%
	gas pressure		4 bar	4 bar
	max. no. of hits		48	159
	reachable in		$0.83 \cdot 4\pi$	$0.73 \cdot 4\pi$
	at least 8 hits reachable in		$0.97 \cdot 4\pi$	$0.98 \cdot 4\pi$
	magnetic field		0.48 T	0.435 T
Electromagnetic calorimetry	energy resolution $\sigma(E)/E$	A	0.015	0.002
		B	0.04	0.063
	solid angle coverage		90%	98%
	angular resolution		7 mrad	2 mrad
	barrel	radial extent	1—1.4 m	2.5—2.8 m
		length	3.6 m	7 m
		polar angle covered	$> 32°$	$> 36°$
		radiation depth	$12.5X_0/15.7X_0$	$24.6X_0$
		granularity	8.5×10 cm^2	10×10 cm^2
	endcap	outer radius	0.9 m	1.8 m
		polar angle covered	$> 11°$	$> 11°$
		radiation depth	$9.6X_0$	$22X_0$
		granularity	14×14 cm^2	9×9 cm^2

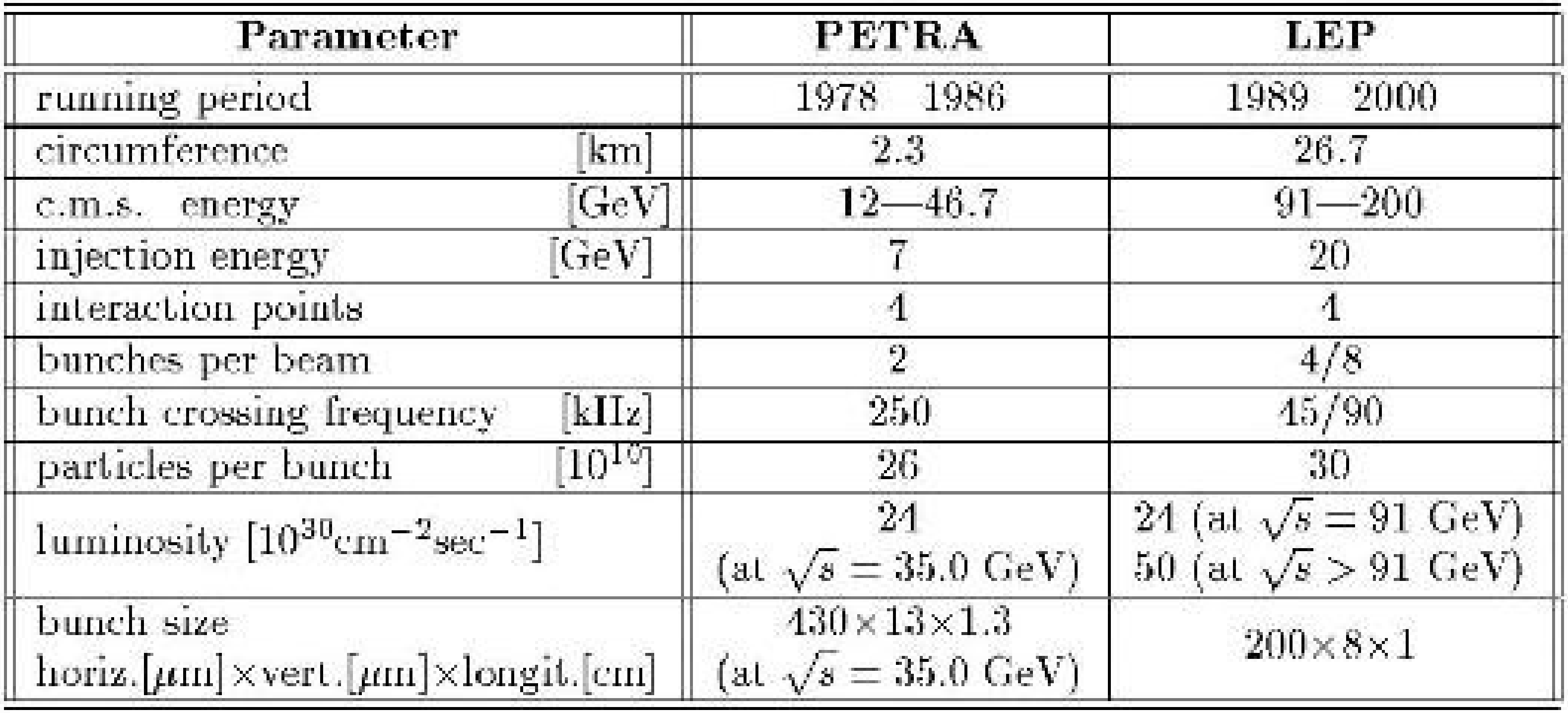
MH Selection JADE vs OPAL

- Main cuts:



Reaction to be suppressed	Cut variable	JADE	OPAL
2-lepton events	n_{ch}	≥ 3 long tracks and ≥ 4 central tracks	≥ 7
	n_{cal}	—	≥ 7
	E_{shw}	> 3.0 GeV (barrel) or > 0.4 GeV (per endcap)	—
2-photon events	$E_{vis}/\sqrt{s}$	> 0.5	> 0.1
	p_{bal}	< 0.4	< 0.6
other	$\lvert \cos\theta_T \rvert$	< 0.8	< 0.9
	$\lvert z_{vert} \rvert$	< 15 cm	—

PETRA versus LEP



Parameter	PETRA	LEP
running period	1978 1986	1989 2000
circumference [km]	2.3	26.7
c.m.s. energy [GeV]	12—46.7	91—200
injection energy [GeV]	7	20
interaction points	4	4
bunches per beam	2	4/8
bunch crossing frequency [kHz]	250	45/90
particles per bunch [10^{10}]	26	30
luminosity [$10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	24 (at $\sqrt{s} = 35.0$ GeV)	24 (at $\sqrt{s} = 91$ GeV) 50 (at $\sqrt{s} > 91$ GeV)
bunch size horiz.[μm]×vert.[μm]×longit.[cm]	430×13×1.3 (at $\sqrt{s} = 35.0$ GeV)	200×8×1

Longitudinal Cross Section σ_L

Differential cross section for inclusive hadron production:

$$\frac{1}{\sigma_{\rm tot}}\cdot\frac{d^2\sigma^h}{dx\,d(\cos\theta)} = \frac{3}{8}(1+\cos^2\theta)\cdot\boxed{\mathcal{F}_T^h(x)} + \frac{3}{4}(\sin^2\theta)\cdot\boxed{\mathcal{F}_L^h(x)} + \frac{3}{4}(\cos\theta)\cdot\boxed{\mathcal{F}_A^h(x)}$$

transverse **longitudinal** **asymmetric**

fragmentation functions

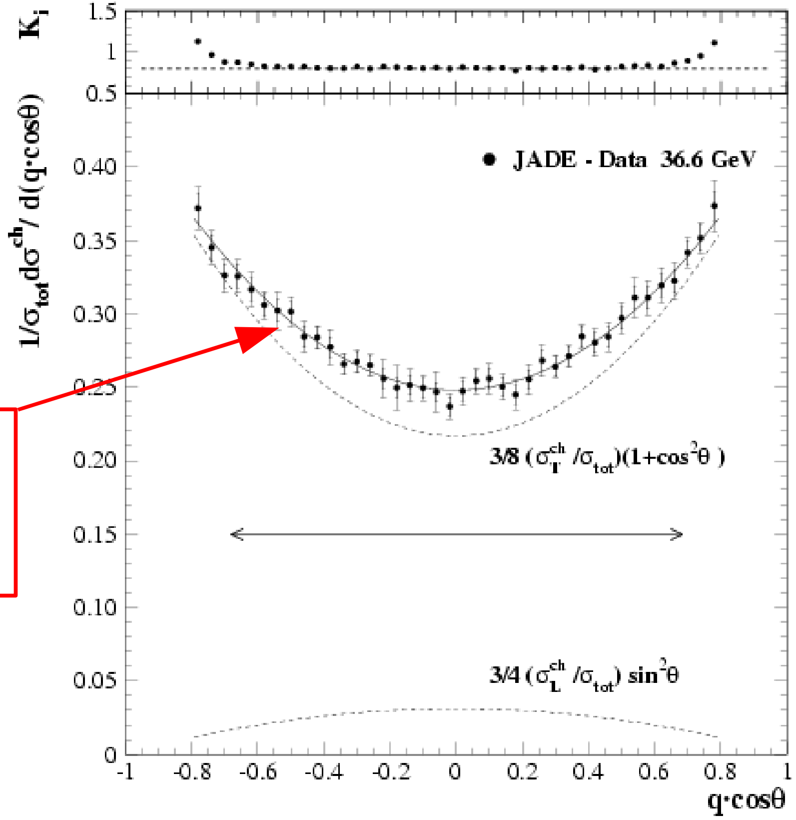
x= fractional particle momentum

Θ= ∠(incoming particle, outgoing hadron)

- Longitudinal part comes from gluon radiation in quark/anti-quark system
- Asymmetric part not considered because no exp. distinction between quark and anti-quark

$$\frac{\sigma_{T,L}}{\sigma_{\rm tot}} \equiv \frac{1}{2}\sum_h \int dx\, x\cdot\mathcal{F}^h_{T,L}(x)$$

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



- measure cos(θ) distribution (chrgd particles)
- fit ρ_L/ρ_{tot} and η^{ch} (corrects for neutral particles)

Measurement of σ_L/σ_{tot}

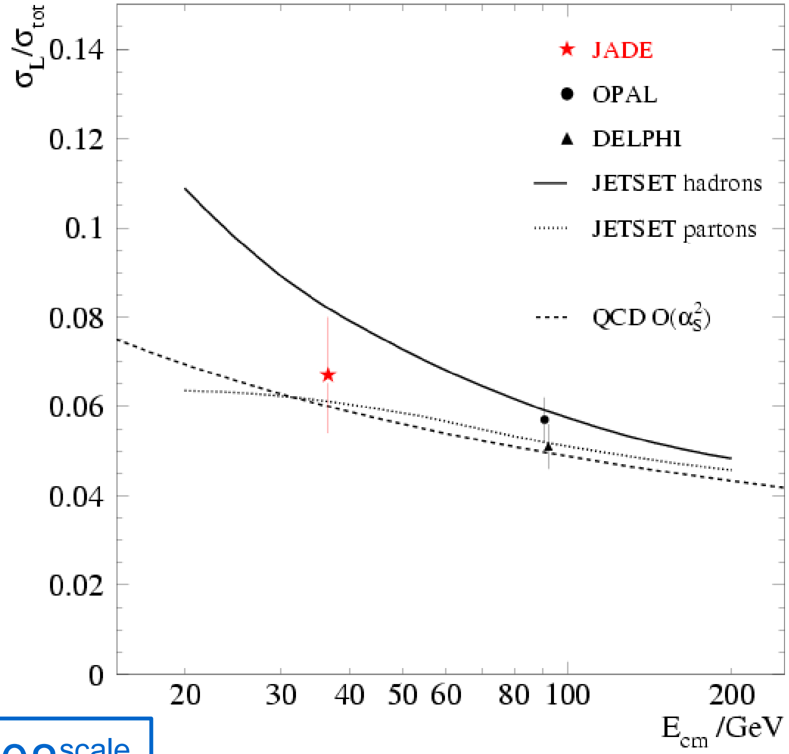
Result:

$\rho_L/\rho_{tot} = 0.067 \pm 0.011^{stat} \pm 0.007^{sys}$

- combined 35+44 GeV analysis
- precision is limited by statistics of data and old JADE MC samples
- only measurement below Z peak

⇓

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



α_s (36.6 GeV) = $0.150 \pm 0.020^{stat} \pm 0.013^{sys} \pm 0.008^{scale}$

- Power corrections:
  $\alpha_s(M_Z) = 0.126 \pm 0.025$
  α_0 (2 GeV) = 0.3 ± 0.3
- Uncertainty can be significantly reduced by considering newly generated JADE MC samples

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

Particle Momentum Spectra

Test (soft) QCD predictions for hadron momentum spectra **$x=2p/\sqrt{s}$, $\xi \equiv -\ln(x)$**

Theoretical input

Next-to-Leading-Log Approximation (NLLA)
(coherence effects, angular ordering)

+

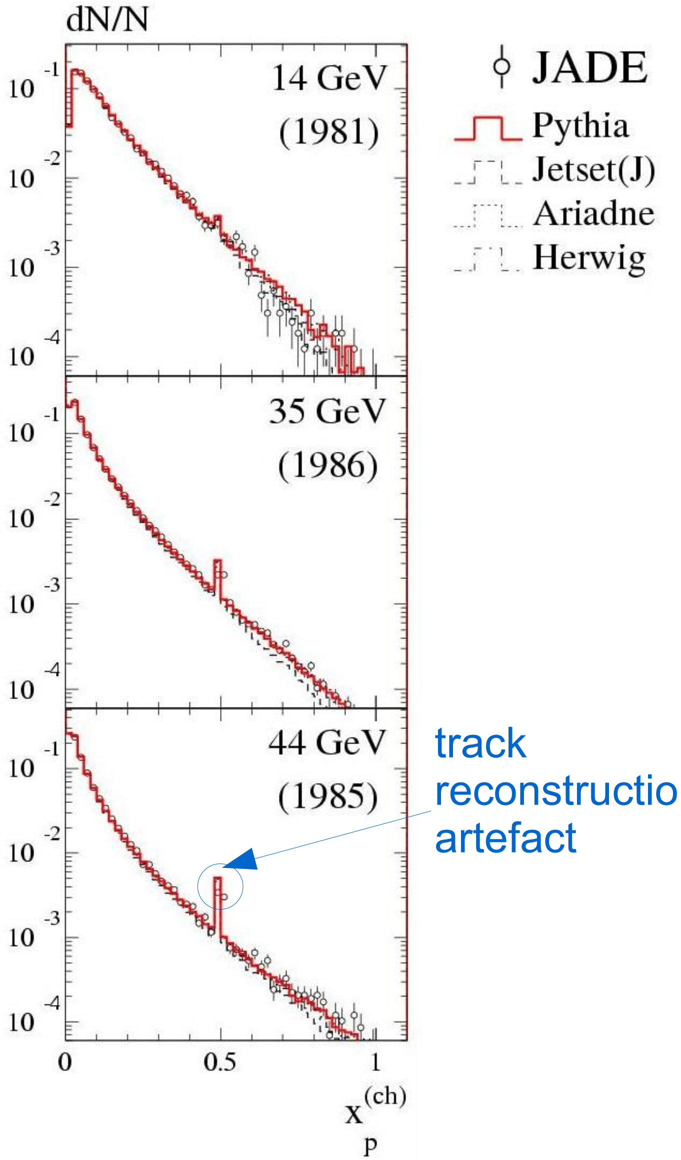
Local Parton Hadron Duality (LPHD)

- properties of partons at the end of parton shower similar to those of hadrons
- hadronization **affects only normalization but not shape** of the spectra

Prediction

- shape around peak of ξ distribution
- √s dependence
- effects of heavy quarks

Uncorrected x spectra
(data vs. and detector MC)



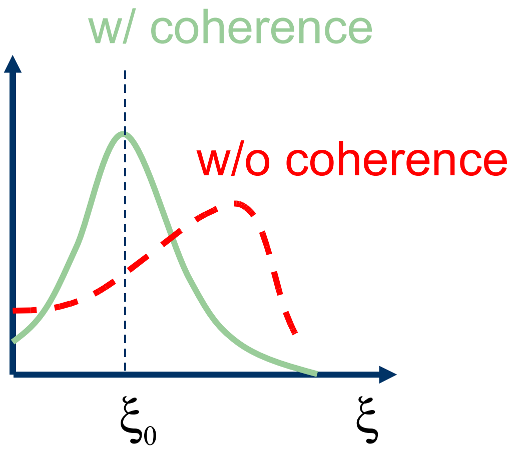
track reconstruction artefact

Prediction for ln(1/x)

Fong-Webber parametrization: skewed Gaussian

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

- includes soft gluon coherence effects
- spectrum is softer w/o coherence



$\delta=(\xi-\langle\xi\rangle)/\sigma$

$\xi-\xi_0\approx(11+2N_f)/(32*9C_A)$

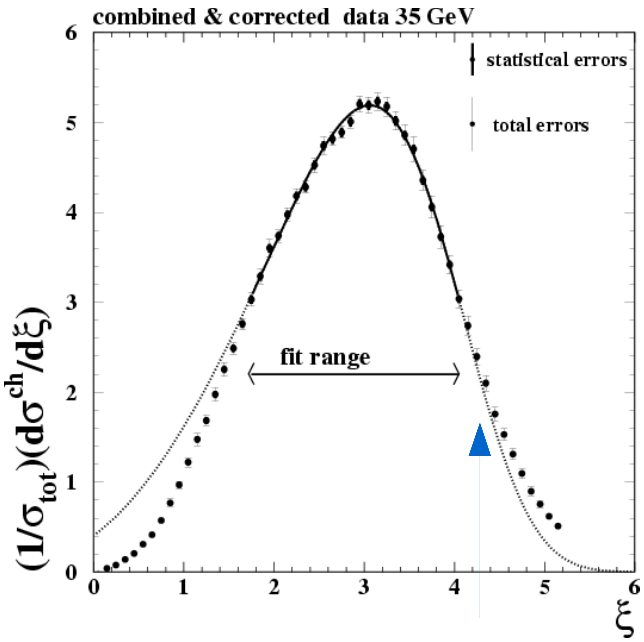
$Y=\ln(\sqrt{s}/2\Lambda_{eff})$

N= normalization factor related to chrgd multiplicity

$\langle\xi\rangle$: mean value
ξ_0: peak position
σ : width
s : skewness
k : kurtosis

dependent on Y and QCD color factors

$$\langle\xi\rangle \equiv \langle\xi(Y)\rangle = \frac{Y}{2}\left(1+\frac{\rho}{24}\sqrt{\frac{48}{\beta Y}}\right)\cdot\left[1-\frac{\omega}{6Y}\right]+\mathcal{O}(1)$$



soft region

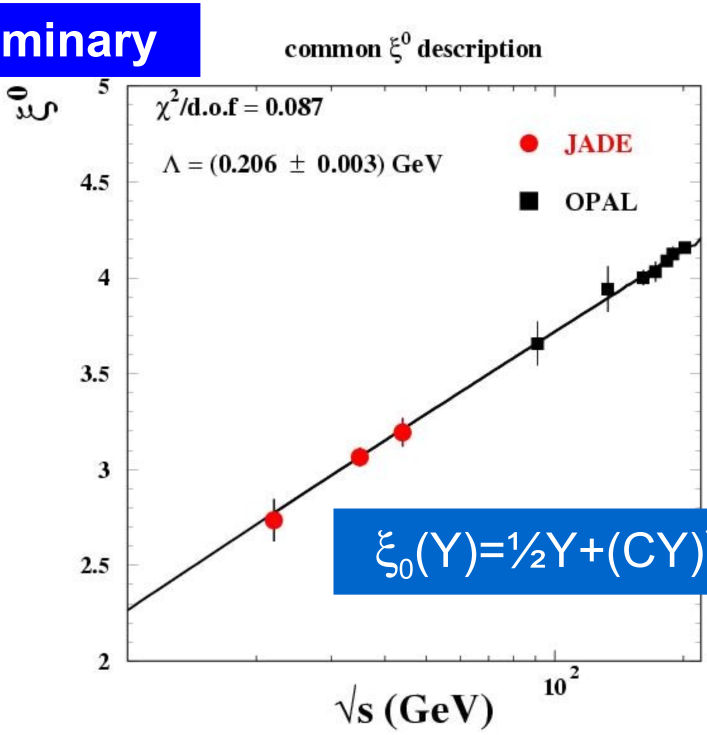
Test of Fong-Webber Predictions

3 simultaneous fit variables:

$$\Lambda_{eff}, \text{ N and } \left\{ \begin{array}{l} \langle\xi\rangle \\ \text{or } \xi_0 \\ \text{or } O(1) \end{array} \right.$$

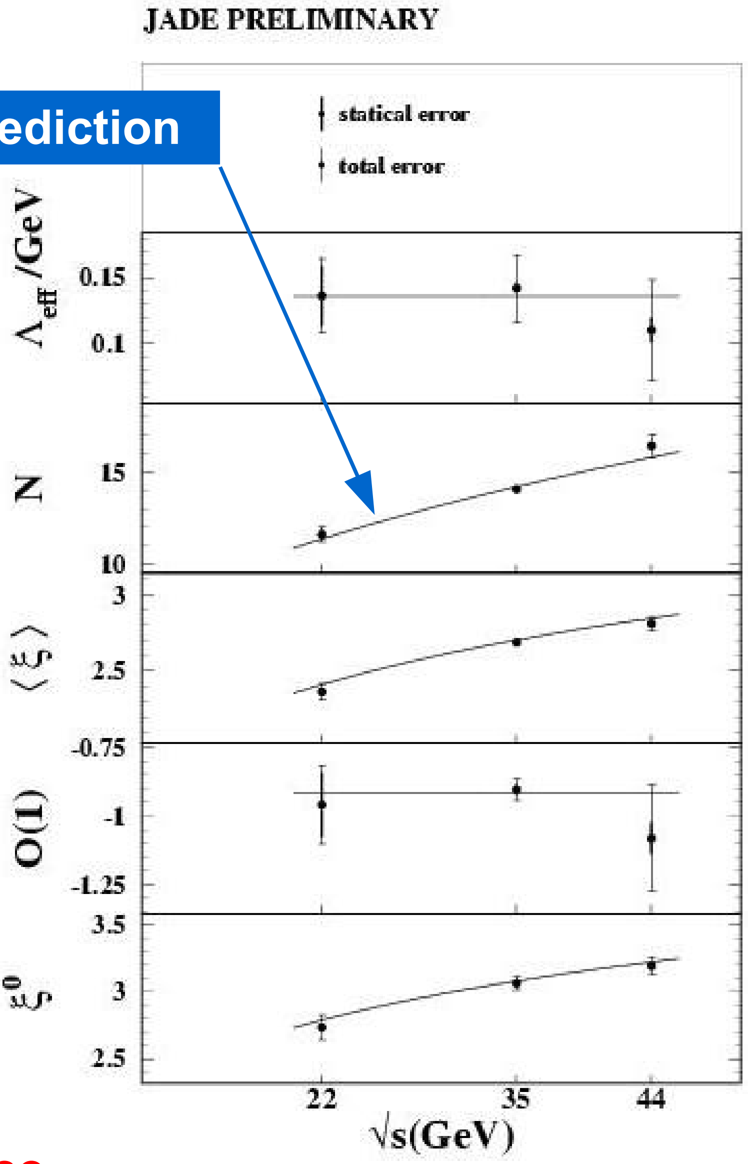
$\langle\xi\rangle$, ξ_0 and N depend on $\sqrt{s}$, Λ_{eff}, and O(1) constant

preliminary



$$\xi_0(Y)=\tfrac{1}{2}Y+(CY)^{1/2}+C+O(Y^{-1/2})$$

Fong-Webber prediction

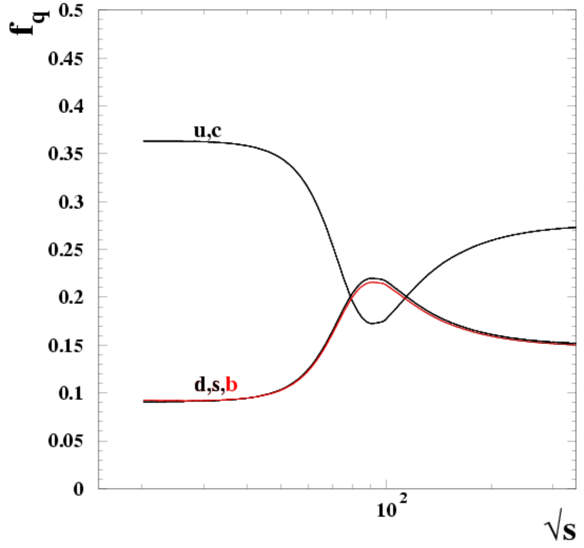


Good description of spectra & energy dependence

$\Lambda_{eff}=206\pm1^{stat}\pm3^{sys}$ MeV

Flavor Dependence

- write ξ_0 ($\sqrt{s}$) as linear combination of peak positions $\xi_0^{(q)}$ ($\sqrt{s}$) for flavour q, weighted with branching ratio $f_q(\sqrt{s})$
- $\xi_0^{(c,b)} - \xi_0^{(uds)} \propto 0.5 \ln(\Lambda^{(c,b)} / \Lambda^{(uds)})$
  $\Rightarrow$ energy evolution is flavor dependent
- fix $\xi_0^{(uds)}, \xi_0^{(c)}, \xi_0^{(b)}$ with OPAL data @ $\sqrt{s} = M_Z$
- fit $\Lambda^{(uds)}$, $\Lambda^{(c)}$, $\Lambda^{(b)}$

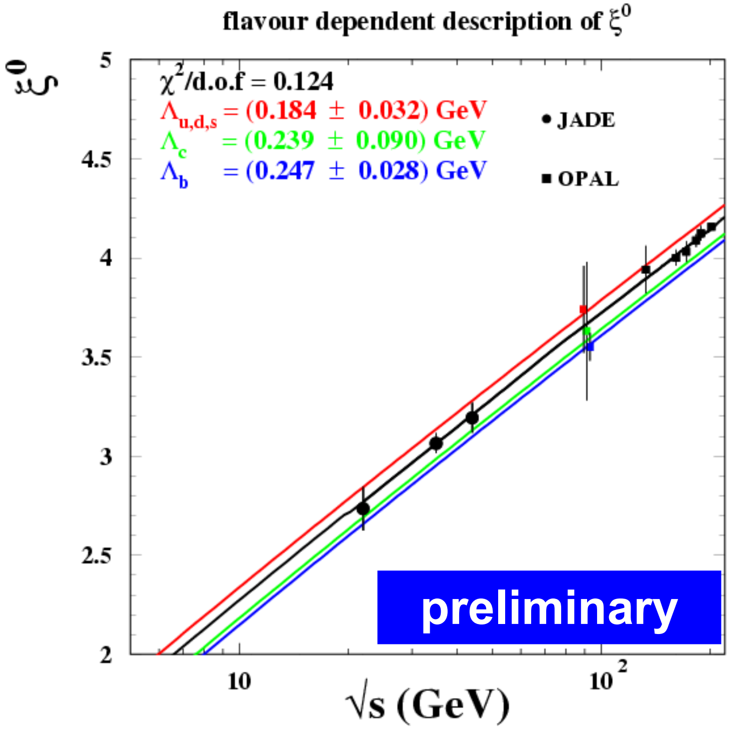


Mass effects about 20-30%

$\Lambda^{(uds)}$ = 184±32 MeV

$\Lambda^{(c)}$ = 239±90 MeV

$\Lambda^{(b)}$ = 247±28 MeV

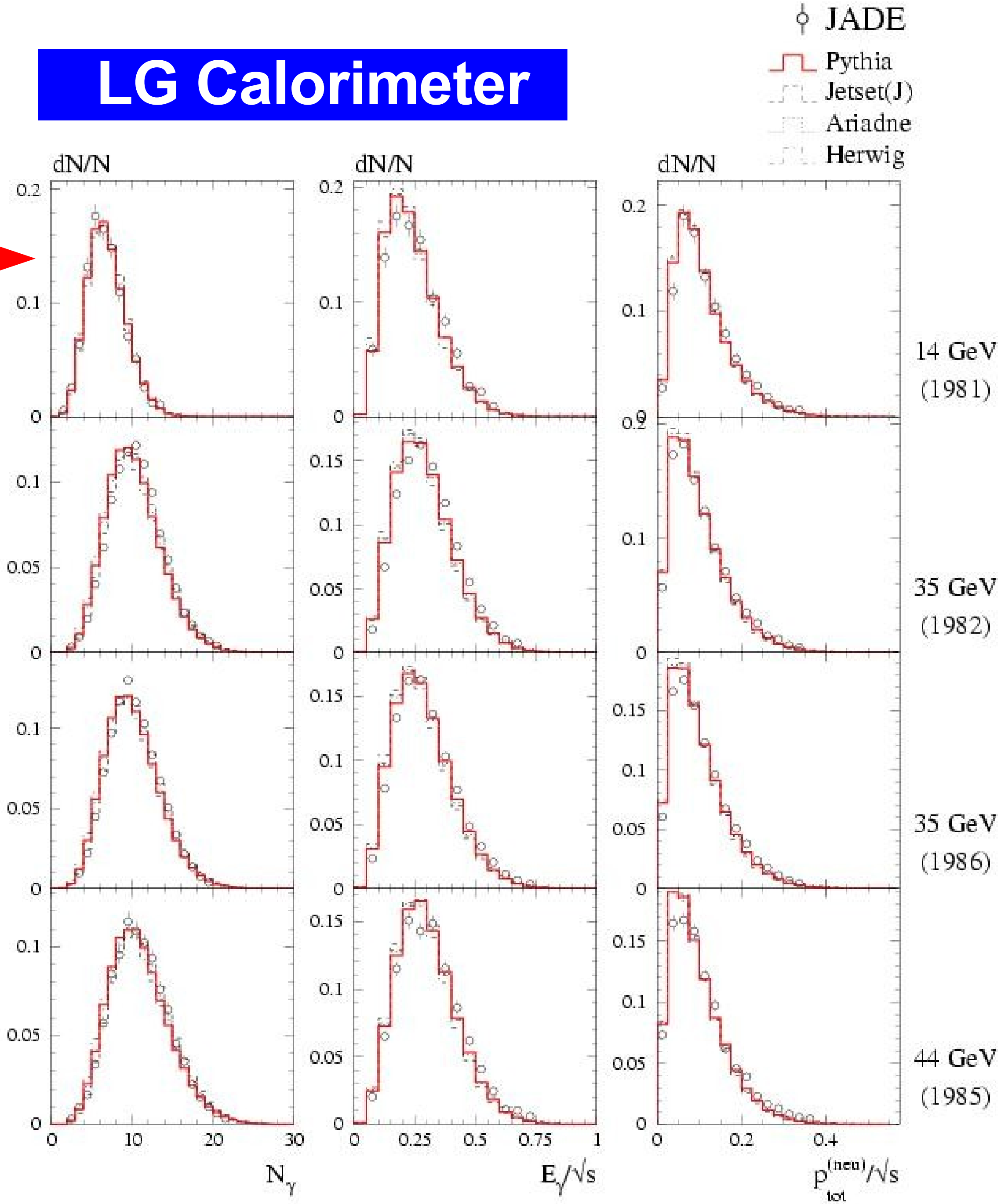


Performance

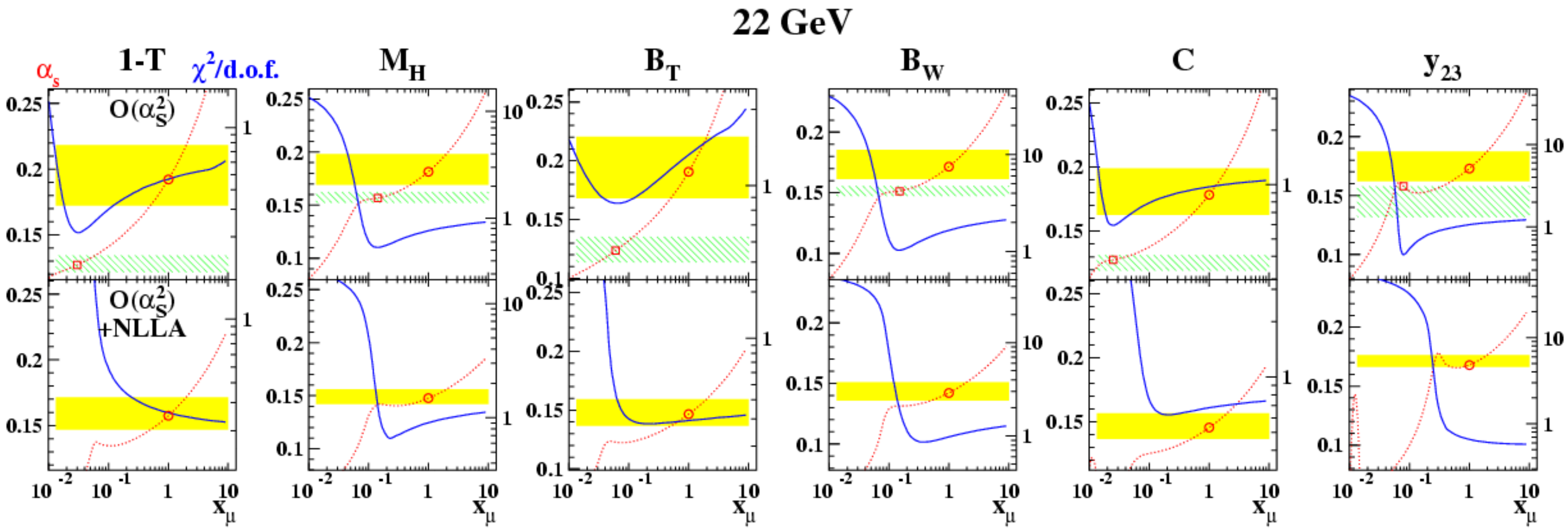
LG Calorimeter

Example:

N_γ, $E_\gamma/\sqrt{s}$, $p_{tot}^{(neu)}/\sqrt{s}$



Renormalization Scale Dependence



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

$\Rightarrow$ have to consider **both** $\alpha_S(\sqrt{s}, x_\mu=x_\mu^{(opt)})$ **and** $\alpha_S(\sqrt{s}, x_\mu=1)$

NLO+NLLA @ x_μ=1 seems to be the “natural” choice