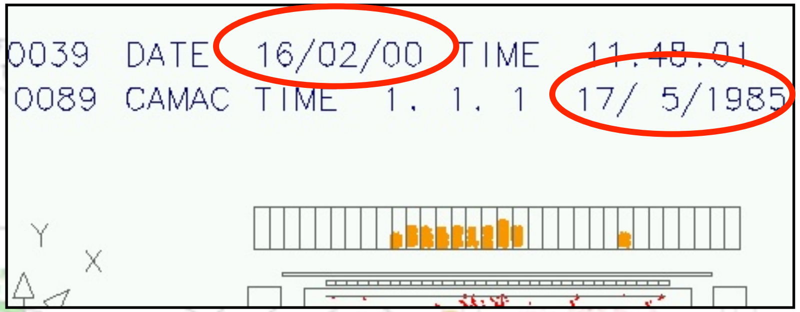


α_S Determination with e^+e^- (JADE-) Data

Jochen Schieck

Ludwig-Maximilians-Universität München and

Excellence Cluster Universe

Phys.Lett.B517(2001)37
Eur.Phys.J.C21(2001)199
Eur.Phys.J.C22(2001)1
Eur.Phys.J.C17(2000)19
Eur.Phys.J.C1(1998)461

Eur.Phys.J.C64(2009)533
Eur.Phys.J.C64(2009)351
Eur.Phys.J.C60(2009)181
Eur.Phys.J.C48(2006)3

http://wwwjade.mppmu.mpg.de

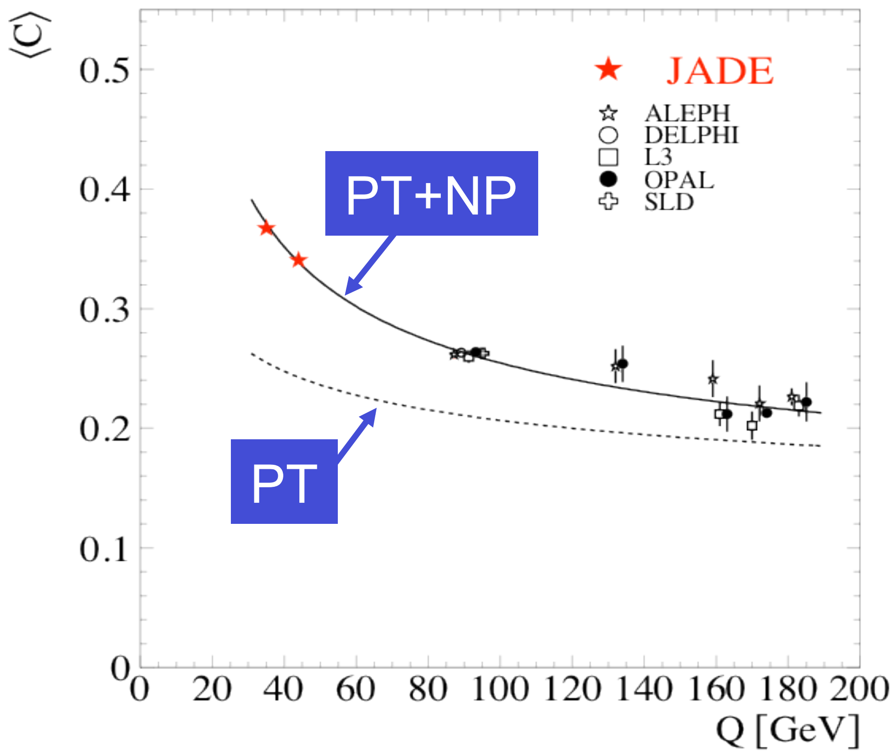
Motivation for Reanalysis

analysis of JADE data provides access to QCD effects at low energy scales

large leverage for QCD measurements at small √s

PT effects ~ 1/log(Q)

NP effects ~ 1/Q



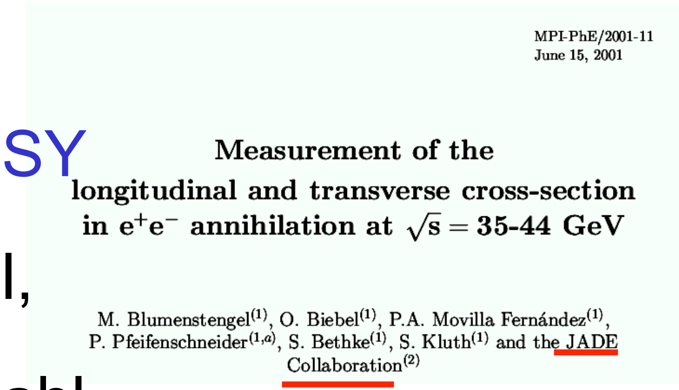
•JADE provides unique contribution for the energy range between 14 and 44 GeV!

•analysis using FSR-Z^0 events O(500) / energy point (final state radiation)

Outline of the Talk

- the JADE experiment at PETRA
- resurrection of data and software
- status of QCD at the end of PETRA
- latest results from QCD analysis with JADE-Data
  - measurement of α_s with event shapes using NNLO resummed calculations
  - measurement of α_s using the four-jet rate
  - moments of event shapes
  - power corrections and hadronization

The JADE Revival Group


MPI-PhE/2001-11
June 15, 2001

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

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

- RWTH Aachen, MPI München, LMU, DESY

    S.Bethke, O.Biebel, M. Blumenstengel,

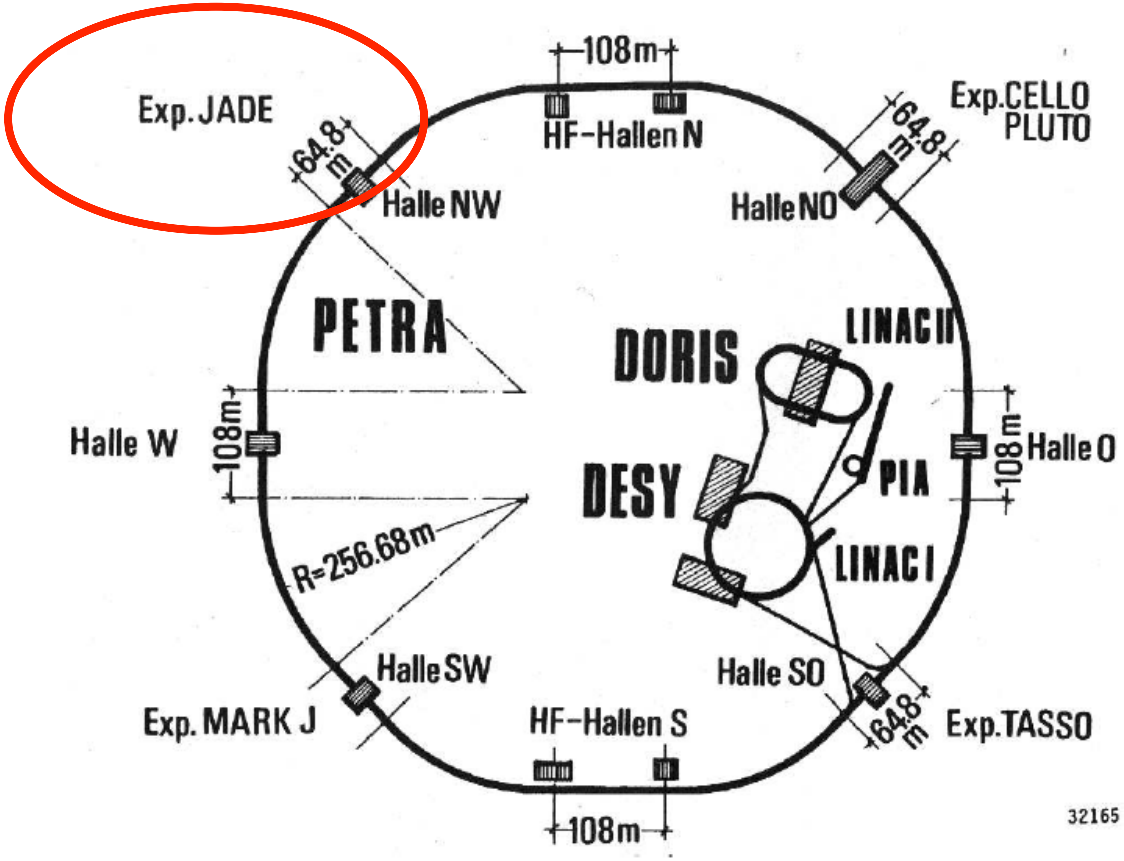
    S. Kluth, P.A. Movilla Fernandez, C. Pahl,

    P. Pfeifenschneider, J.E. Olsson and JS

- since 1998 more than 20 publications and conference contributions based on/involving re-analyzed JADE data
- new JADE results have been considered by various QCD theory groups and publications from LEP collaborations

The PETRA e^+e^- Storage Ring

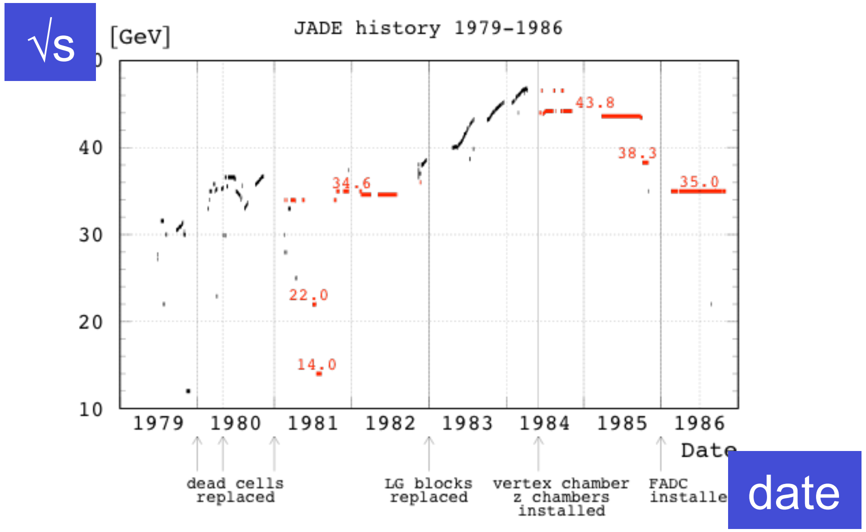
Physics at PETRA from 1979-1986

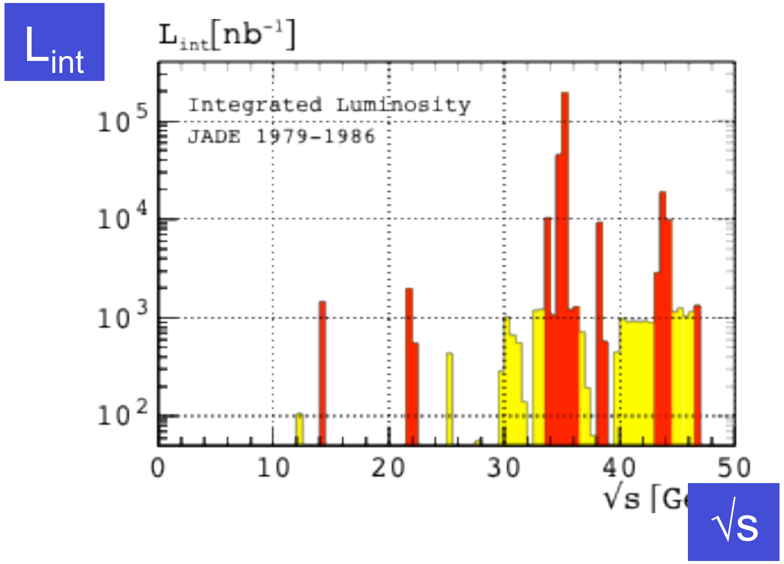


- largest e^+e^- accelerator at that time
- Luminosity $\sim 24\text{x}\ 10^{30}\ /\text{cm}^2\ \text{s}^1$ (= 26 hadronic events/hour)

(hadronic cross section ~ 0.3 nb)

Data Collected at JADE





fixed energy runs and scan periods for t-quark search

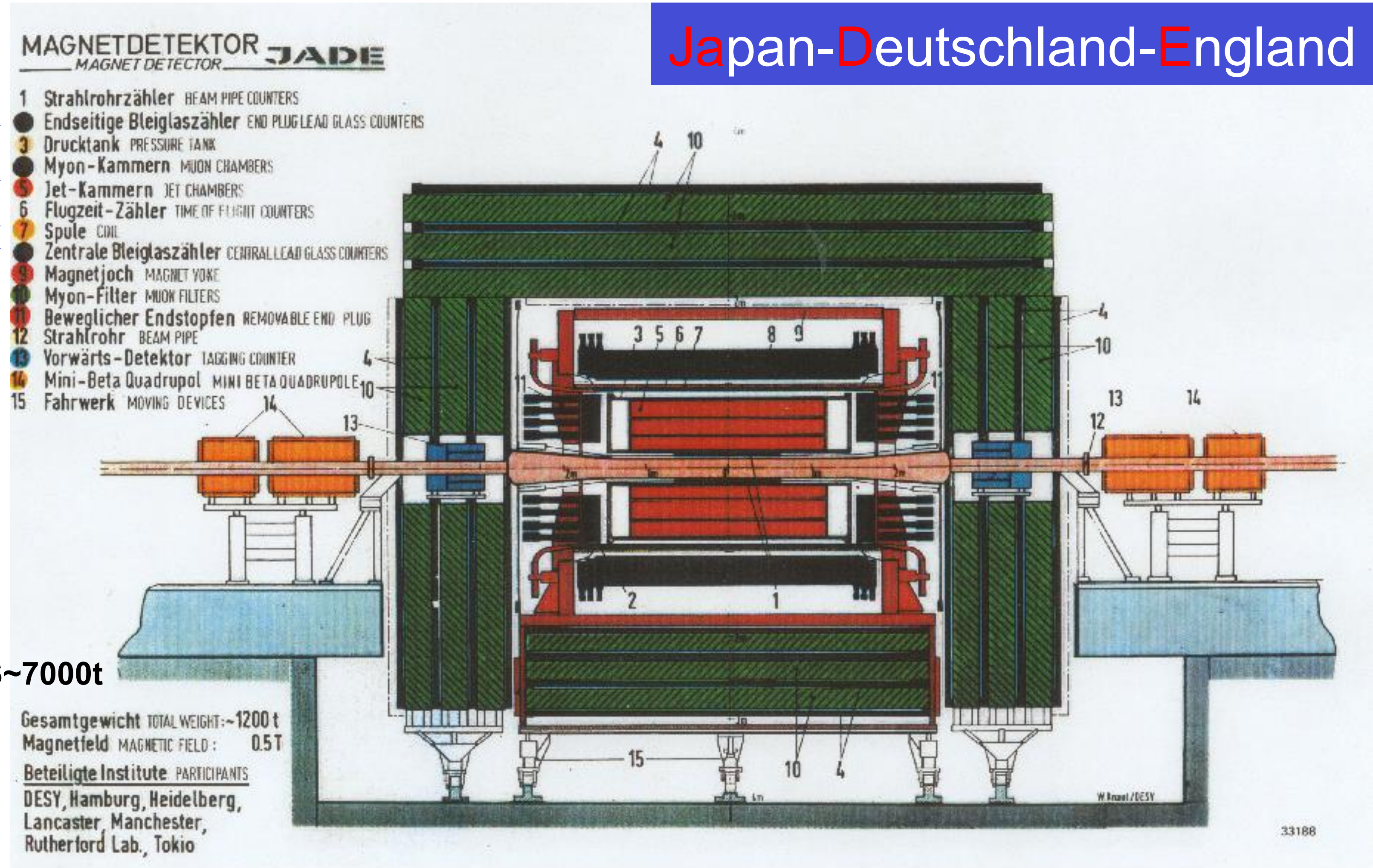
CME range (GeV)	Data taking period	Luminosity (pb^{-1})	√s (GeV)	MH events
14.0	07-08/1981	1.46	14.0	1734
22.0	06-07/1981	2.41	22.0	1390
33.8-36.0	02/1981-08/1982	61.7	34.6	14372
35.0	02-06/1986	92.3	35.0	20925
38.3	10-11/1981	8.28	38.3	1587
43.4-46.6	06/1984-10/1985	28.8	43.8	3940

LEP (OPAL): 330000
Zeit. fur Phys.C 59 (1993) 1-19

- 216 pb-1
- 43100 multihadrons

The JADE Experiment

Japan-Deutschland-England



ATLAS~7000t

concept similar to the OPAL detector

Resurrection of Data and Software

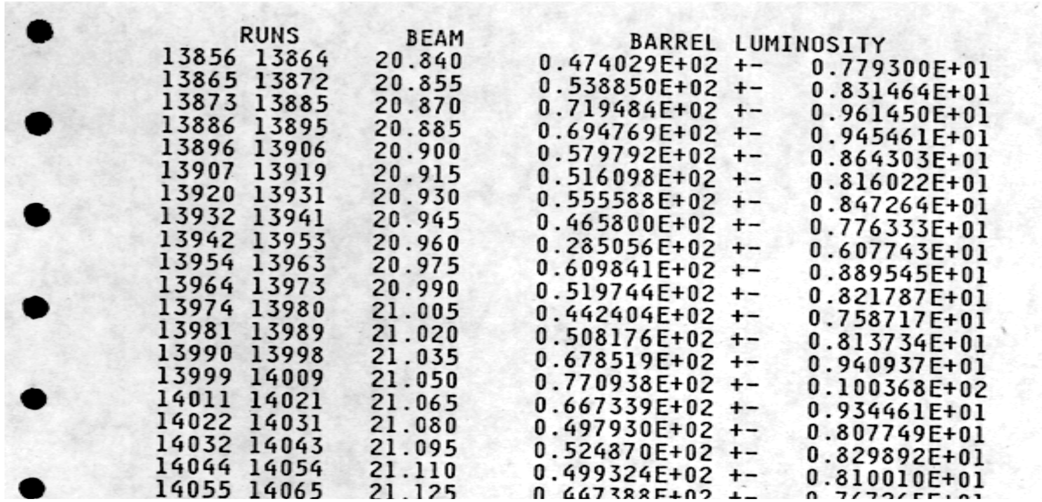
the JADE data:

- original data were located at
  - IBM mainframe at the DESY computer center
  - IBM tapes at DESY/University of Heidelberg
- DESY IBM closed completely in 1997
  - transfer of data to ‘modern’ data carriers (IBM /EXABYTE cartridges) and computer platforms
- ‘raw’ data converted into FPACK format (J. Olsson)
- multihadronic event sets are available in platform independent ZE4V-ASCII-files (‘mini-DST’) (E. Elsen)
  - ➢ **used for the current analysis**

The Recovery of JADE Data

•however, not all information were available in electronic format…

convert it to electronic version ‘the hard way’…



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	+-	[illegible]

JADE luminosity files

•Monte Carlo events only available for $\sqrt{s}$= 35 and 44 GeV
(also ZE4V – ASCII format)

•for more MC events the revival of the JADE software necessary

The Revival of the JADE Software

to generate new Monte Carlo Events requires:

a) detector simulation

b) event analysis software (reconstruction)

c) (JADE event display)

d) multihadronic filtering and packing

Source code:

- code fragments from 1974 (!)
- mixture of different FORTRAN standards/extensions
- IBM specific extensions
- IBM/370 assembler code

The Revival of the JADE Software

•historic research work using old JADE notes/PhDs/ publications necessary

•move to FORTRAN77, CERNLIB and HIGZ

•platform dependence extremely difficult

IBM: big-endian (most significant byte stored in lowest address)

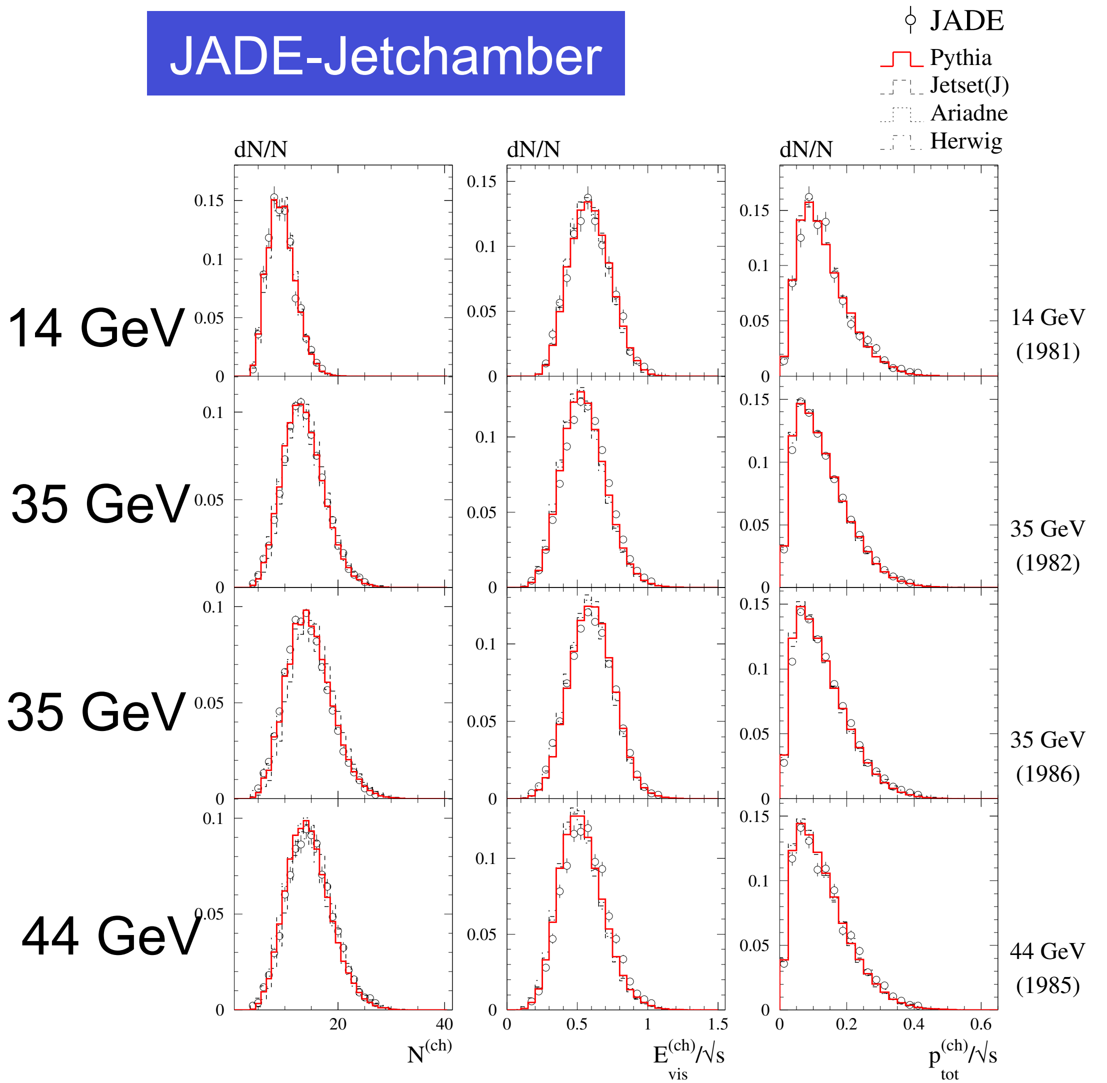
PCs: little-endian (vice versa)

➢JADE software accesses BOS-banks not in units of of words (4 Bytes)

•complete installation successful on IBM RS/6000 AIX machine (with XLF compiler)

The Revival of the JADE Software

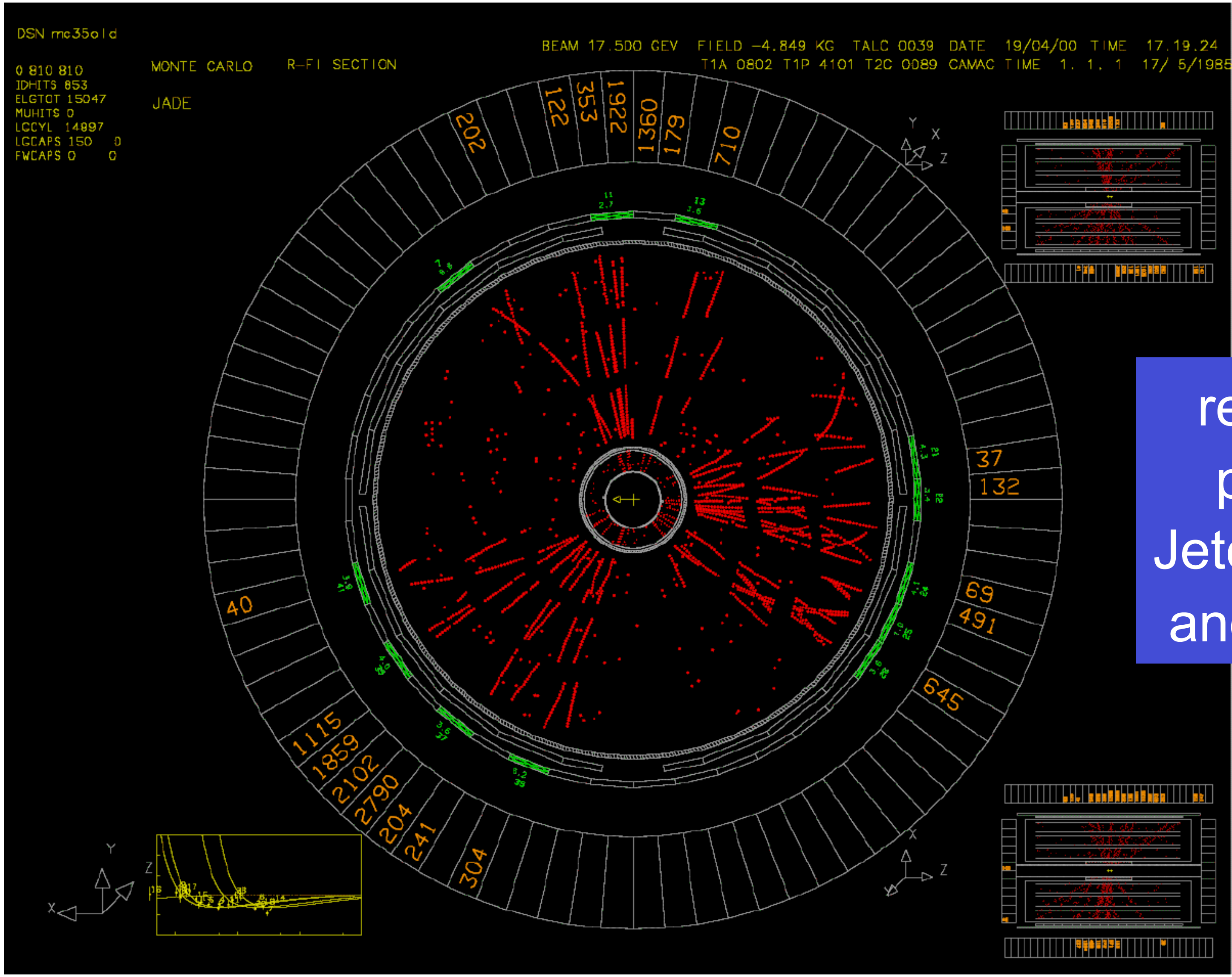
JADE-Jetchamber



- Monte Carlo with OPAL LEP-I tune
- good description of data from 14-44 GeV

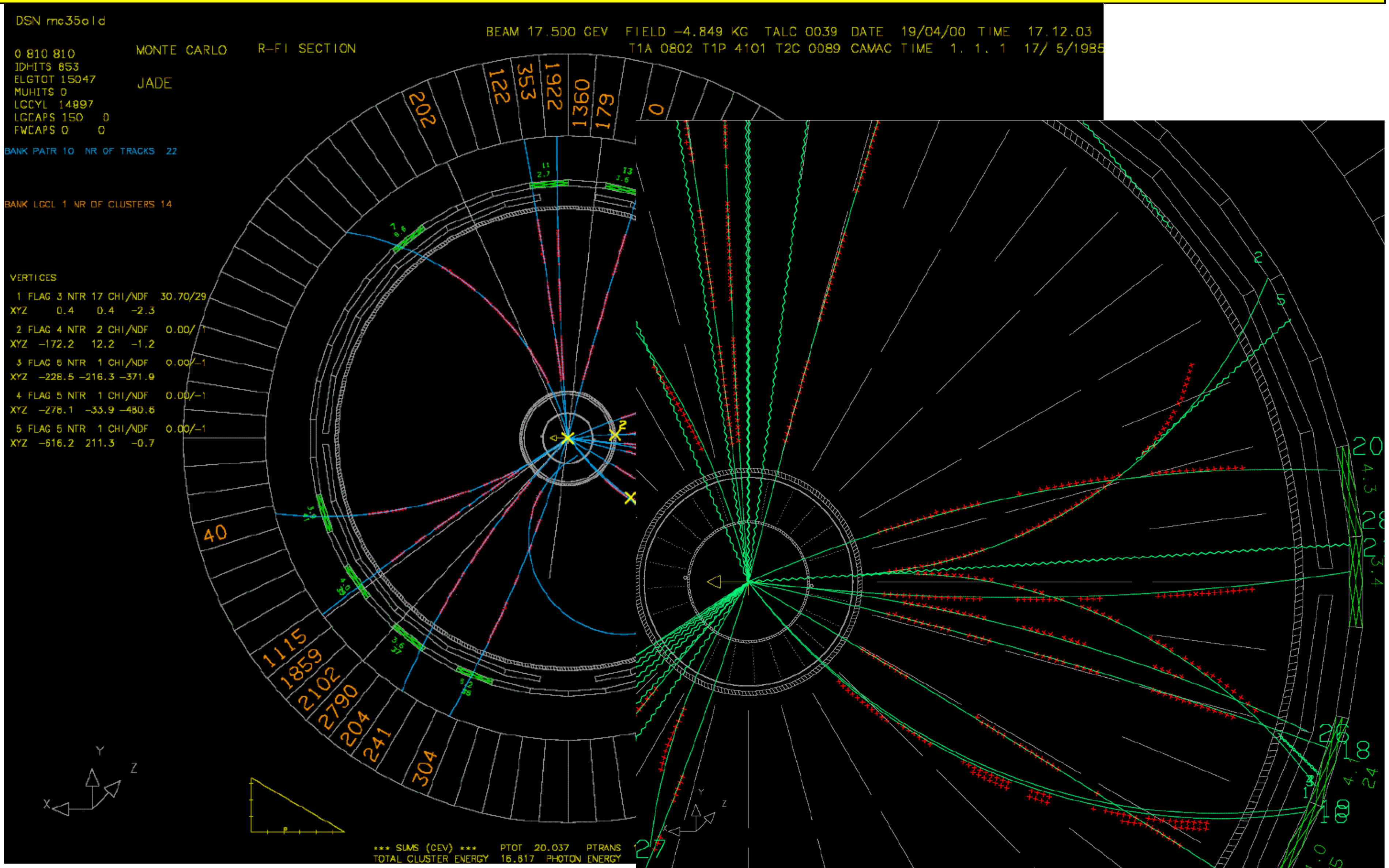
(PhD thesis P. Movilla Fernandez, 2003)

Event Display

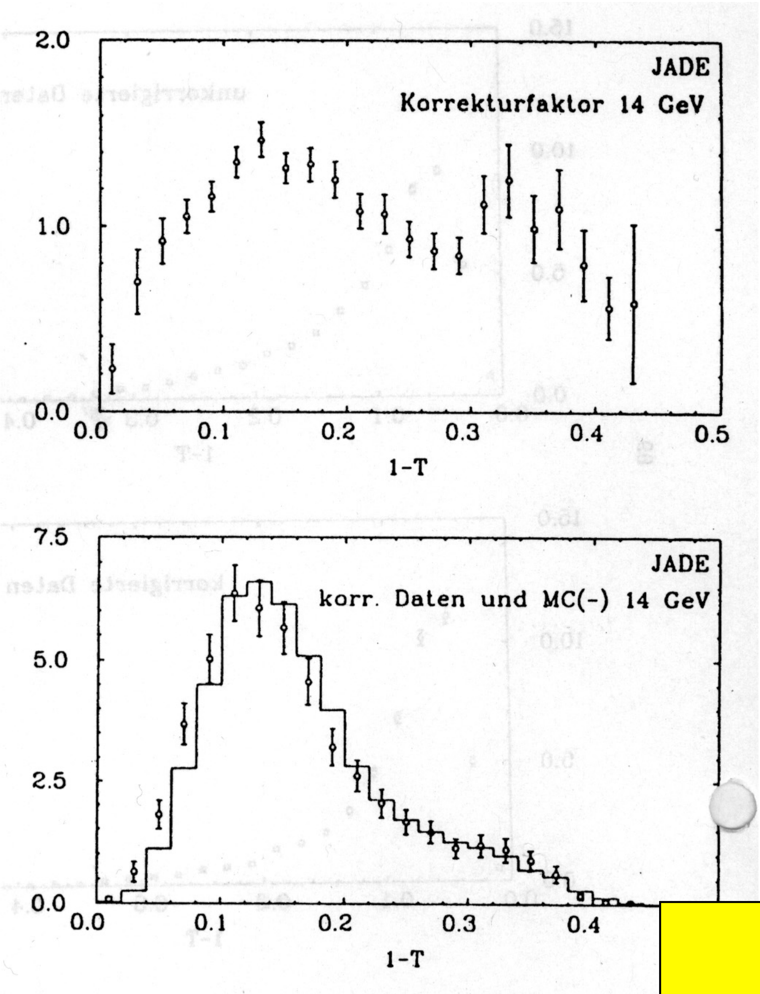


reconstructed points in the Jetchamber, TOF and Calorimeter

Event Display

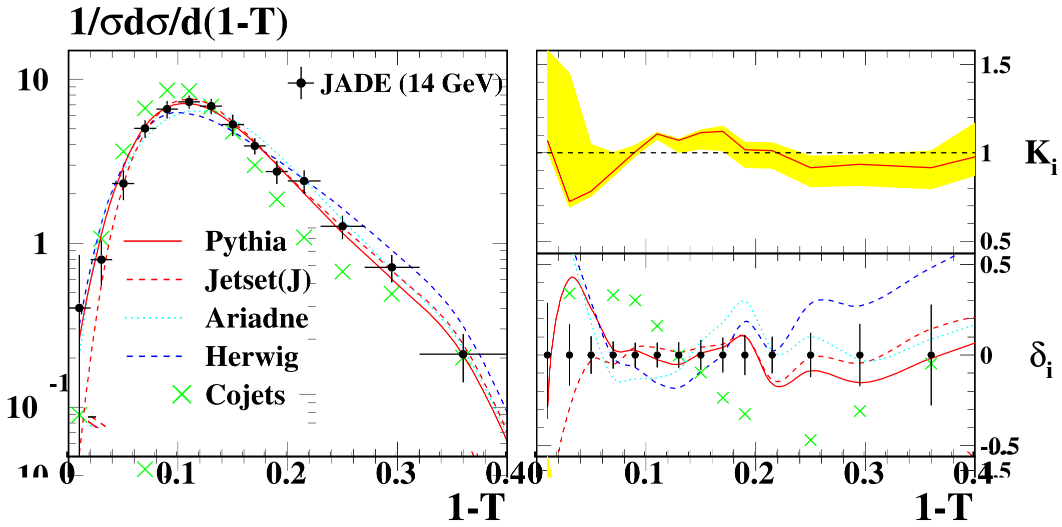


Data versus Monte Carlo



(PhD thesis Andreas Dieckmann, 1987)

detector correction

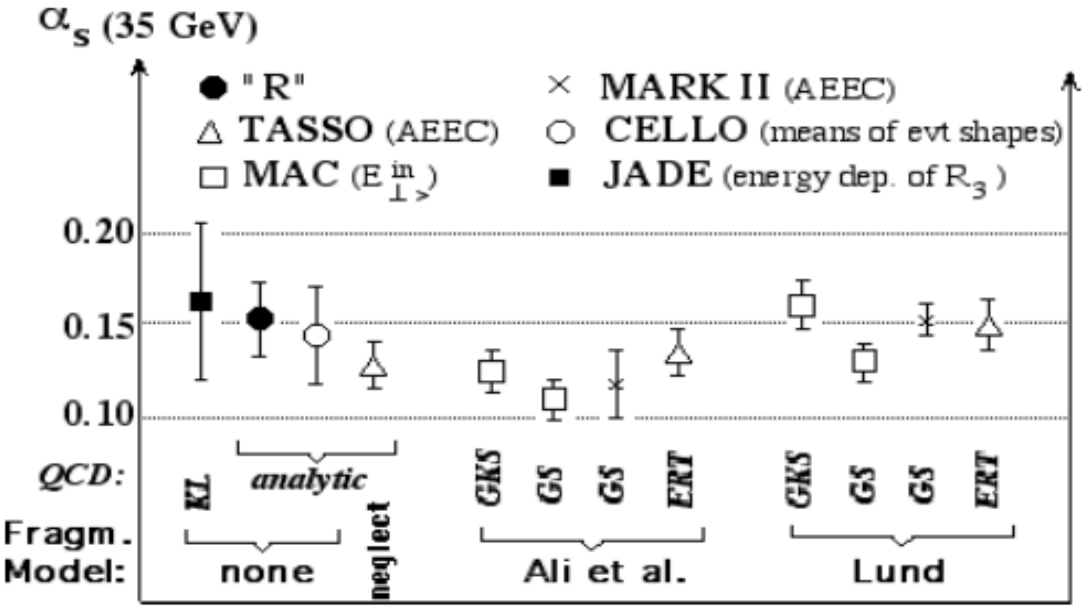


normalized deviation from data

(PhD thesis P. Movilla Fernandez, 2003)

significant improvement of data description by Monte Carlo (LEP tune)

Status of the QCD before LEP



S.Bethke, LBL-28112 (1989)

summary value 1989:

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

$$\Rightarrow \alpha_s(M_Z) = 0.119 \pm 0.016$$

(1973: concept of asymptotic freedom
1979: discovery of gluons
2004: Nobel Prize for asymptotic freedom)

- very large dependence on Monte Carlo model
- dependence on matrix element calculation
- no renormalization scale variation

What's happened since PETRA

LEP learned a lot from the QCD experience at PETRA, now PETRA profits from LEP

PETRA 80's

↓ important QCD input for LEP

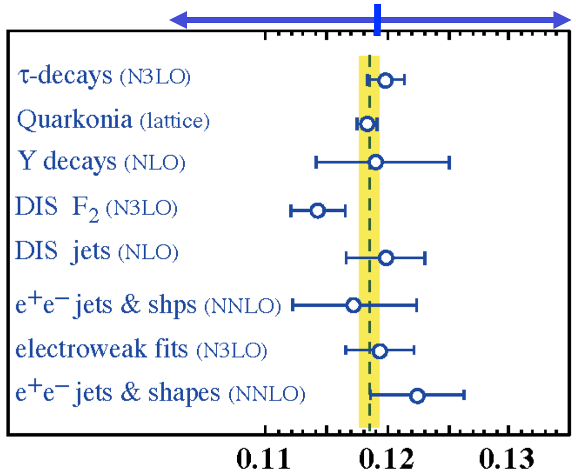
LEP

↓ feedback for PETRA

PETRA 2K

- improved theoretical predictions
  - (NNLO predictions, resummed calculations for event shapes,…)
- development of new event-shape variables
- new jet finders (Durham, Cambridge)
- improved Monte-Carlo models
- power corrections

α_s 1989

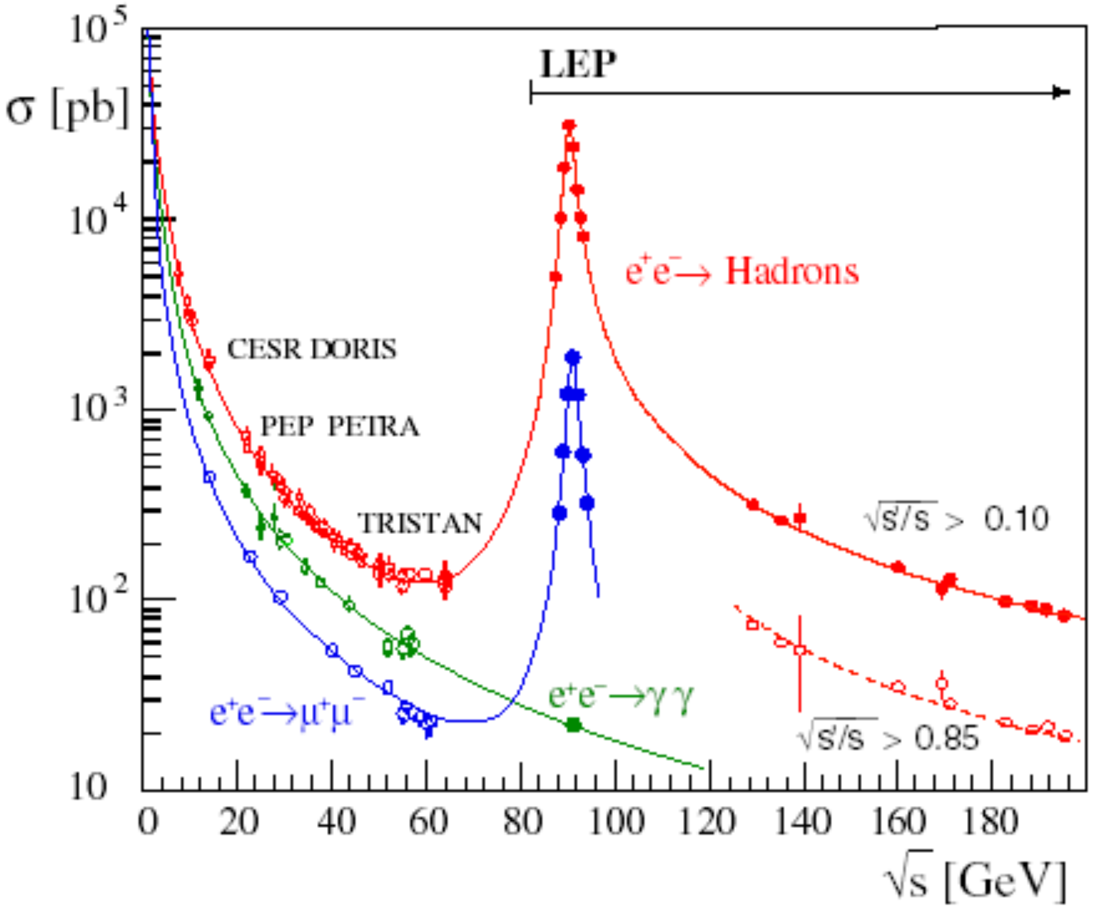


$\alpha_s(M_Z)$

S.Bethke,hep-ph/0908.1135

Hadronic Final States

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



- σ^{had}(PETRA) = 0.1…10nb ≈ 1/100 $\sigma^{had}(M_Z)$

Event Shapes

Event Shapes

- Thrust $(1-T)$
- Heavy Jet Mass (M_H^2)
- Jet Broadening $(B_T,B_W)^*$
- C Parameter*
- Differential 2-jet rate y_{23}^* (Durham scheme)

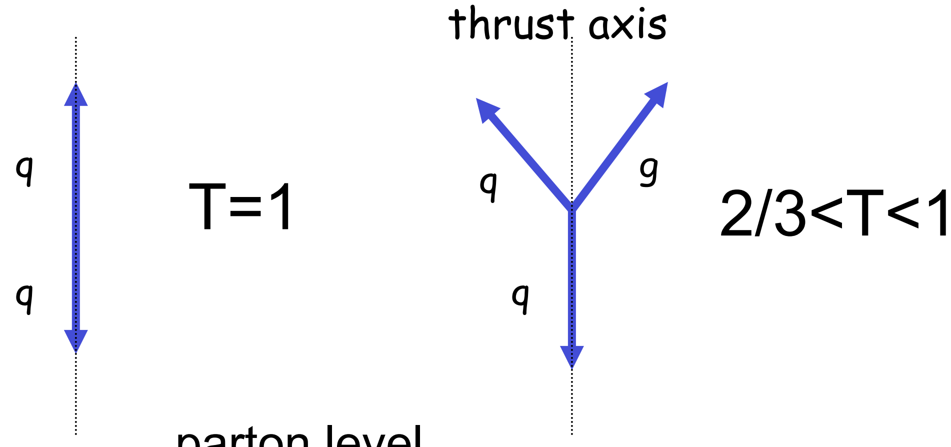
- infrared and collinear safe quantities
- resummable in all orders $\alpha_s \ln(1/F)$

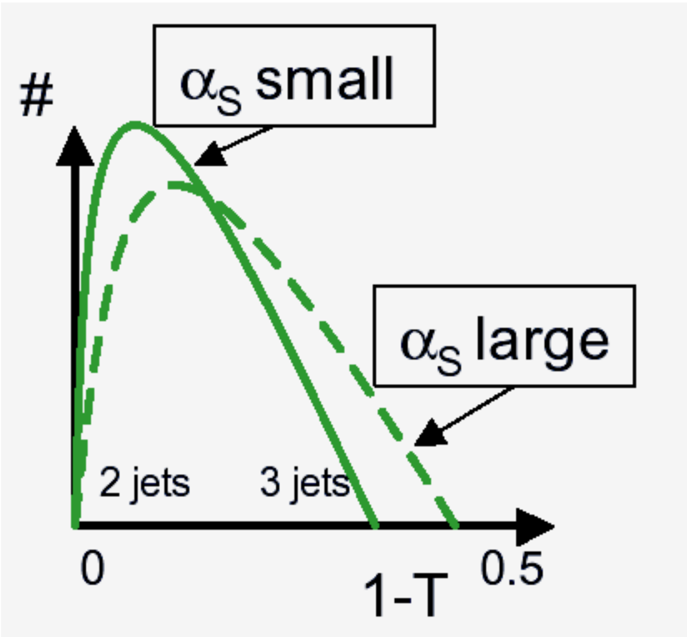
$F=1-T,C,M_H^2,\ldots$

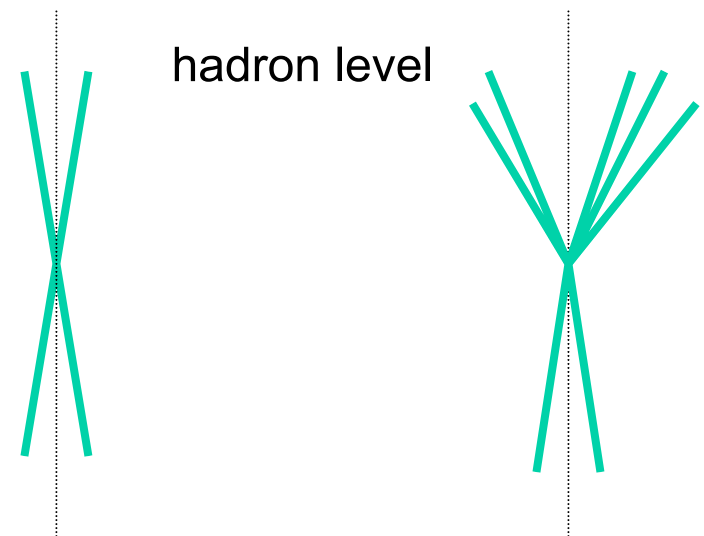
*) Event Shape variables only used after shutdown of PETRA

Event Shape: Thrust

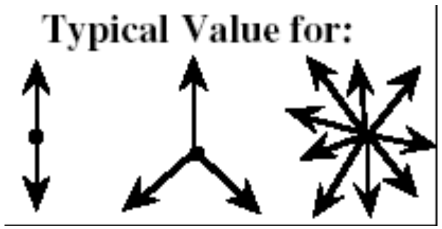
$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p}_i \vec{n}|}{\sum_i |\vec{p}_i|} \right)$$







Event Shapes



•Heavy Jet Mass $(M_H)^2$

event divided in two hemispheres using thrust axis

M_H= max (inv. mass of hemisphere) $_{l=1,2}$

0 ≤1/3 ≤1/2

•Jet Broadening (B_T, B_W)

momentum of hadrons in one Hemisphere perpendicular to thrust axis

maximum (B_W) and total (B_T)

B_T: 0 ≤1/(2√3) ≤1/(2√2)

B_W: 0 ≤1/(2√3) ≤1/(2√3)

• C Parameter

average angle between hadron pairs weighted with momentum

(eigenvalues of linearised momentum tensor)

0 ≤3/4 ≤1

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

y_{cut} value, when an event switches from 2-Jet type to 3-Jet type

Jetfinder: JADE → Durham!

QCD Predictions

•O(α_s^2) calculations, (3 jet region):

(used for PETRA QCD analysis in the 80's)

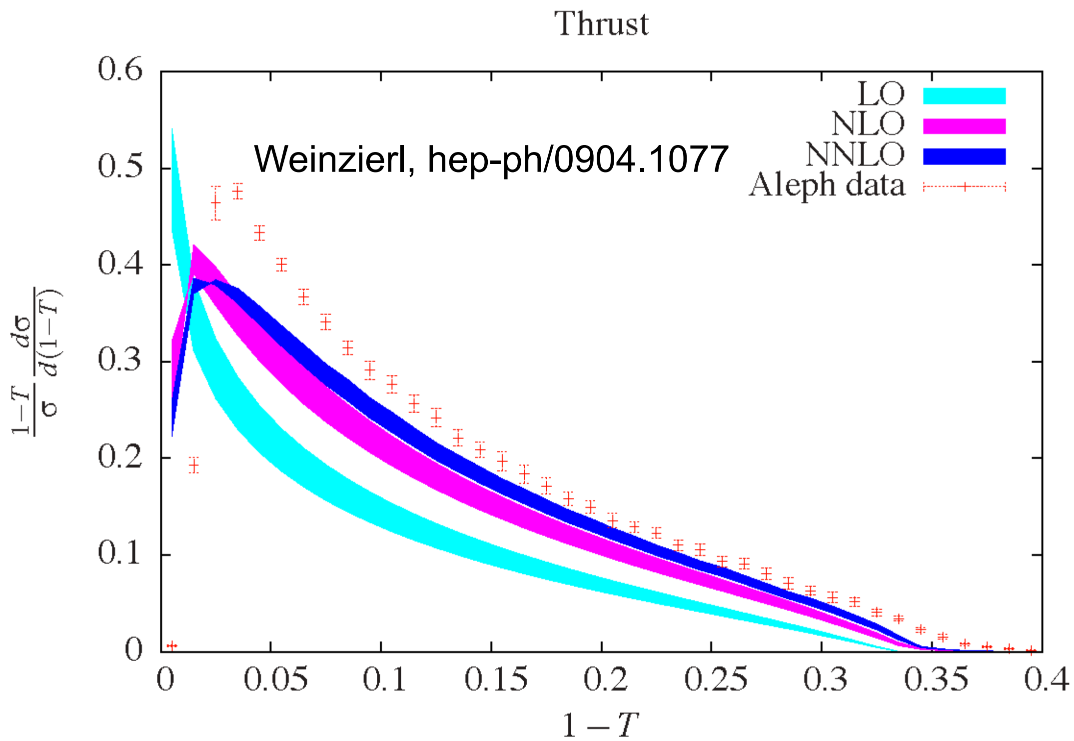
$$\frac{dR}{dF} = \frac{1}{\sigma_0}\frac{d\sigma}{dF} = \frac{dA(F)}{dF}\frac{\alpha_s(\mu)}{2\pi} + \frac{dB(F)}{dF}\left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 + O\left(\left(\frac{\alpha_s(\mu)}{2\pi}\right)^3\right)$$

Gehrmann–De Ridder et al.;
Weinzierl

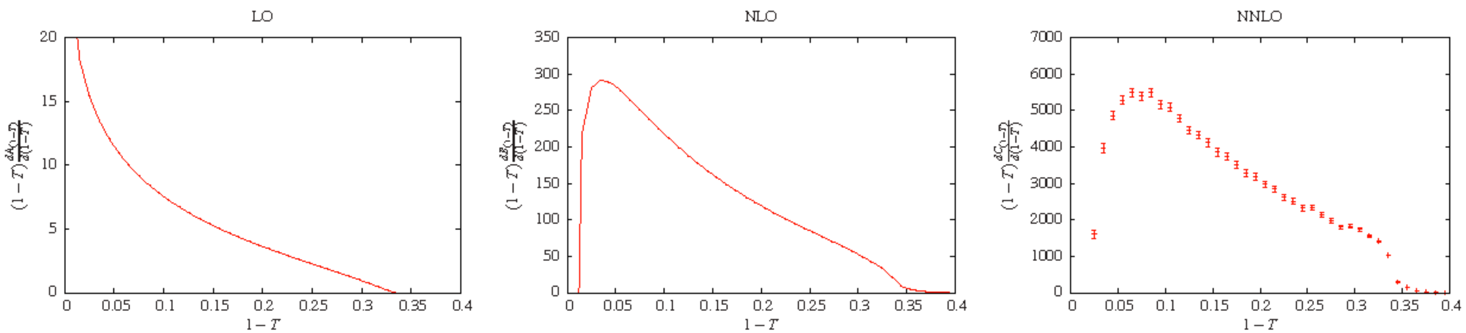
Since 2007 available
•O(α_s^3) calculations

$$\frac{dR}{dF} = \frac{1}{\sigma_0}\frac{dR}{dF} = \frac{dA(F)}{dF}\frac{\alpha_s(\mu)}{2\pi} + \frac{dB(F)}{dF}\left(\frac{\alpha_S(\mu)}{2\pi}\right)^2 + \frac{dC(F)}{dF}\left(\frac{\alpha_S(\mu)}{2\pi}\right)^3 + O\left(\left(\frac{\alpha_S(\mu)}{2\pi}\right)^4\right)$$

QCD Predictions



- significant improvement of QCD predictions
  - reduced dependency on higher order missing terms (x_μ-dependency)
- difference to observed data from missing non-perturbative corrections (‘hadronization’)



QCD Predictions

•Problem:

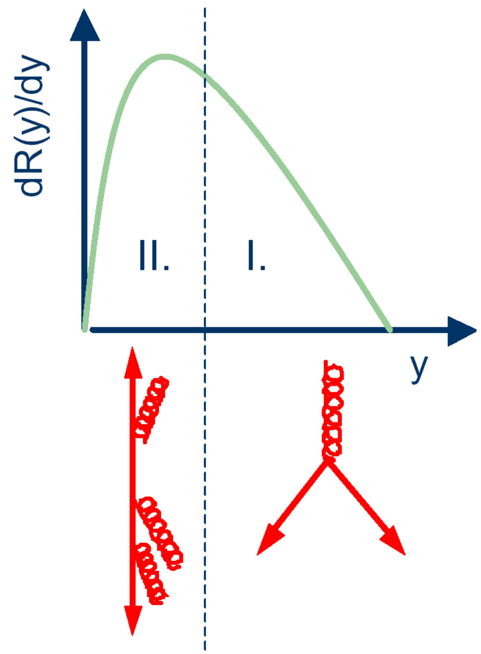
no good description for F →0 (divergent)

•take large logarithmic L=ln(1/F) contribution into account (NLLA)

$$R(F) = \int_0^F dF' \frac{1}{\sigma_0} \frac{d\sigma(F')}{dF'} = C(\alpha_s) e^{G(\alpha_s, L)} + D(\alpha_s, L)$$

$$R(F) = (1 + C_1\alpha_s + C_2\alpha_s^2) e^{Lg_1(\alpha_s L) + g_2(\alpha_s L)}$$

with $L = \ln(1/F)$



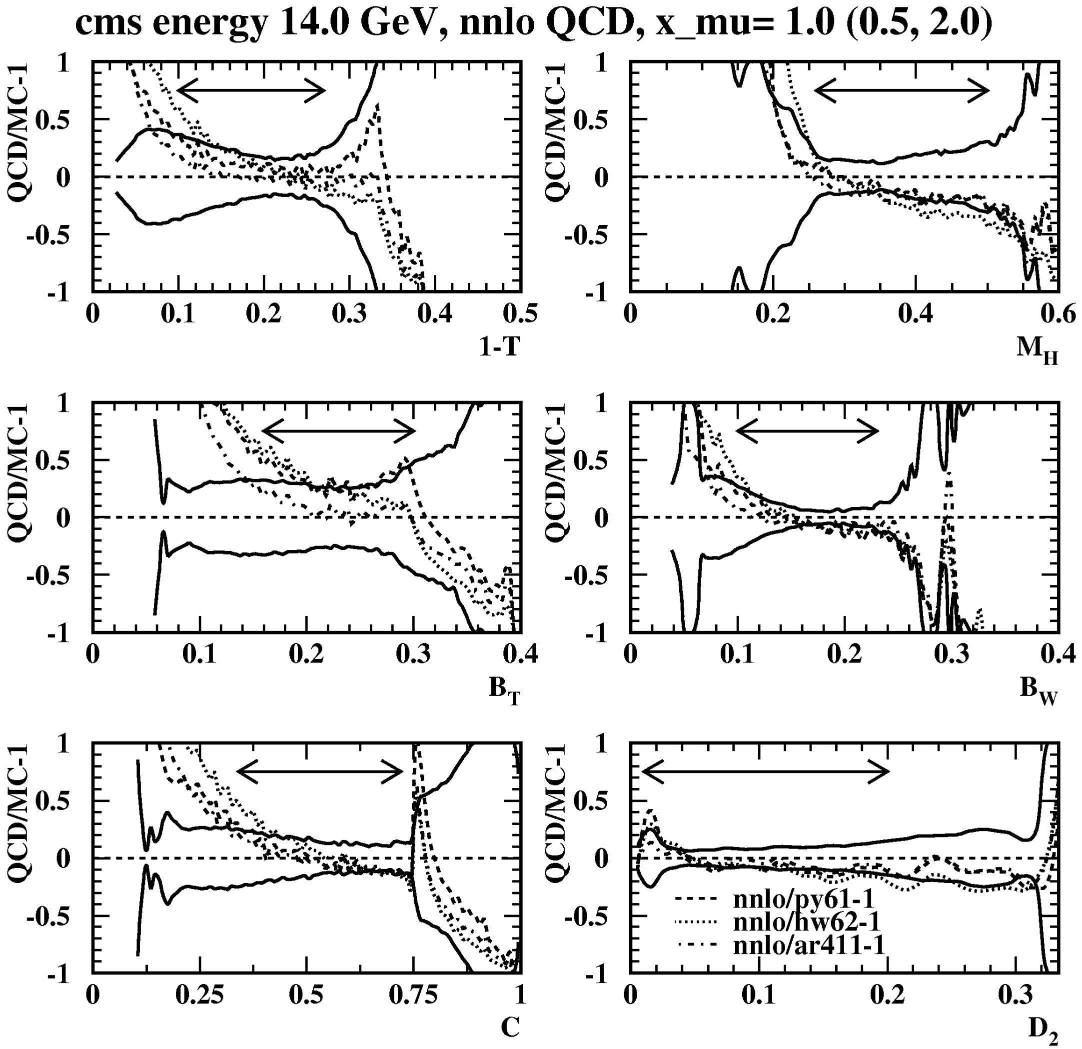
•match both calculations $O(\alpha_s^3)$ + NLLA:

•dependent from renormalization scale μ

•fit perturbative predictions with scale factor $x_\mu = \mu/\sqrt{s} = 1$

• α_s as the only free parameter

QCD Prediction vs MC Parton Shower



- envelope corresponds to hadronization uncertainty + scale error (x_μ=.5…2)
- bias on α_S covered by systematic uncertainty

Correction Procedure

•measured distribution needs to be corrected for imperfect detector ('detector correction')

- •subtract $b\bar{b}$-background on detector level ➢see following slide
- •resolution, acceptance and secondary processes
- •photon initial state radiation (ISR)

•QCD calculations describe parton level of event shape distribution

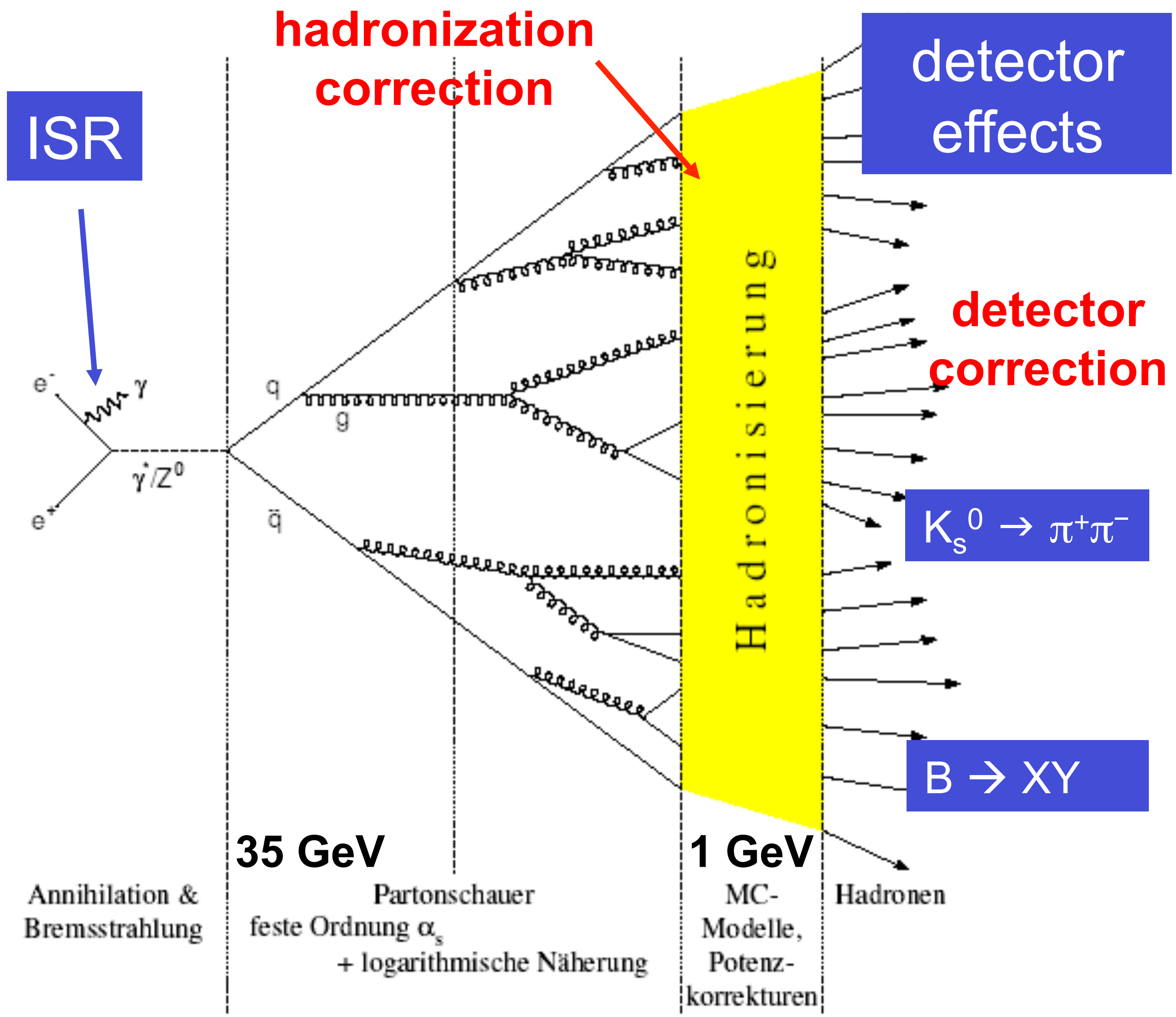
- • correction for hadronization effects ('hadronization correction')

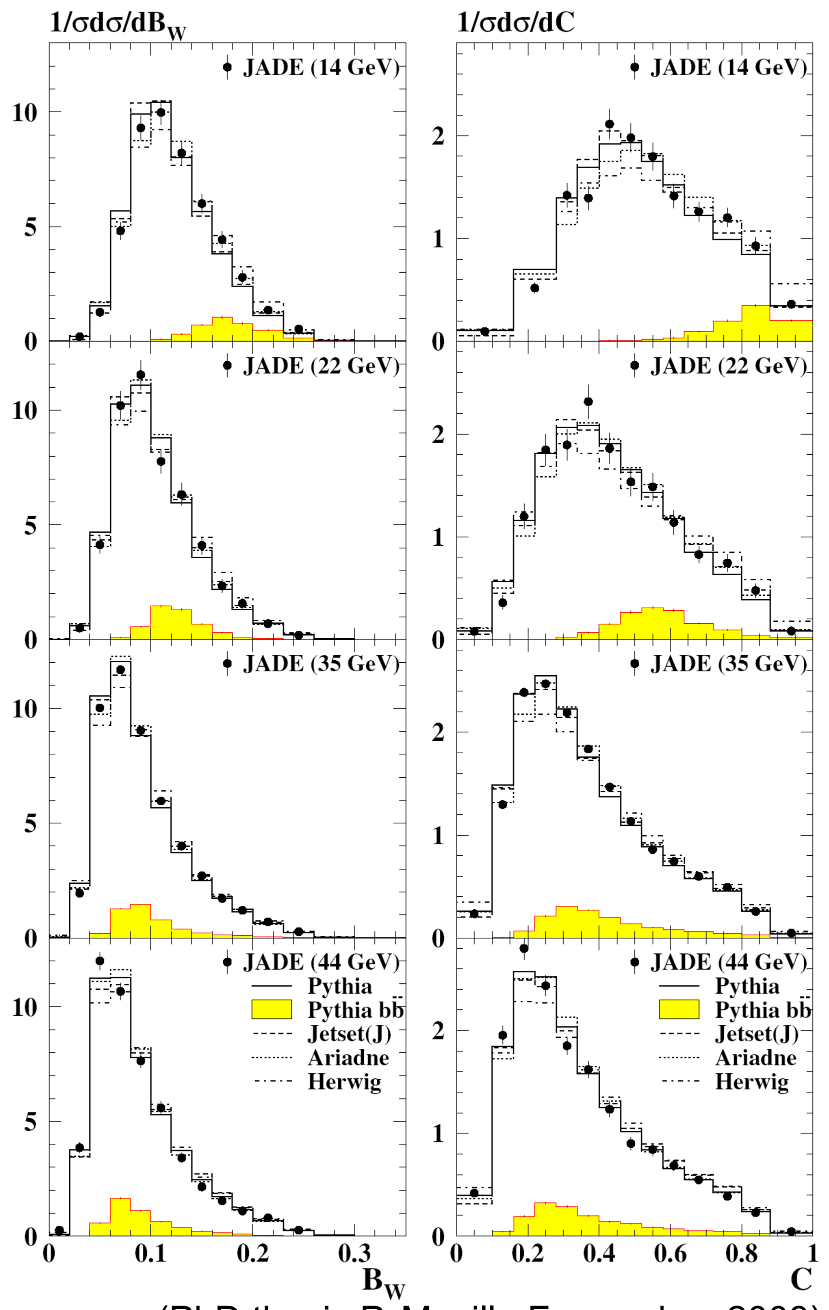
Monte Carlo Models

PT QCD:

- $O(\alpha_s^3)$+NLLA
- parton shower

- **NP QCD:**
- models (string, cluster,…)
- analytic power corrections





(PhD thesis P. Movilla Fernandez, 2003)

Detector Level Distributions

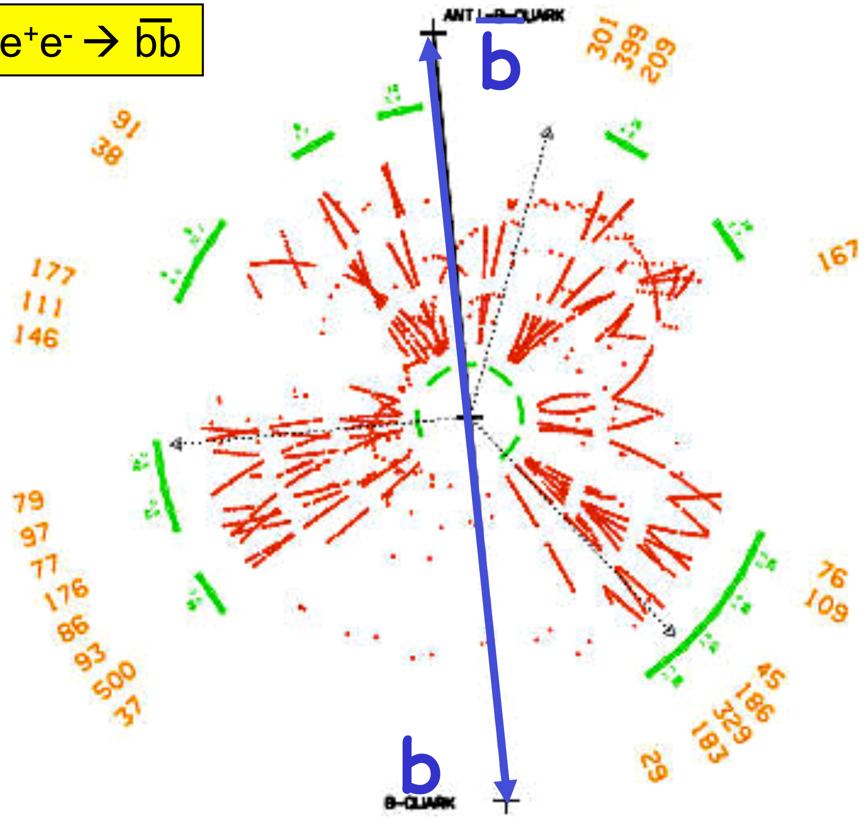
Monte Carlo + JADE simulation reproduces multihadronic events

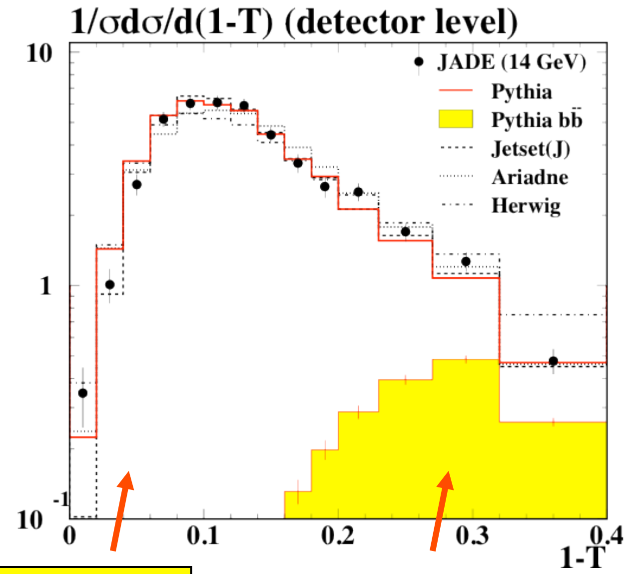
Monte Carlo models:

- PYTHIA/JETSET
  - LLA parton shower + string
- ARIADNE
  - color dipole + string
- HERWIG
  - MLLA parton shower + cluster
- COJETS
  - LLA parton shower + independent

Correction for $b\bar{b}$-Events

$e^+e^- \rightarrow b\bar{b}$





2-jet region

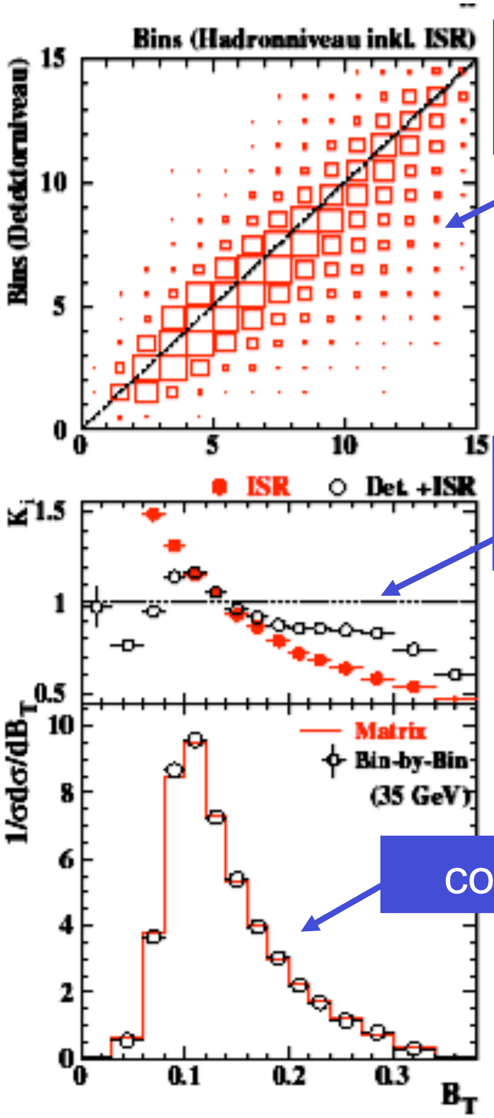
bb events

~about 9% $b\bar{b}$-events

- $b\bar{b}$ events fake events with gluon radiation (electro weak decay)
  - ➢subtraction at detector level

Correction Method

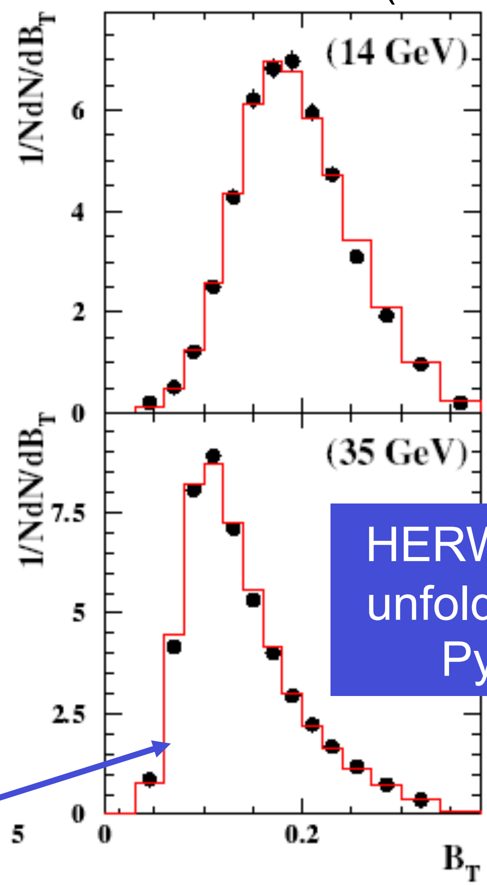
(bin-by-bin)



bin-by-bin corrections for 'resolution' effects

detector effects partially compensated by ISR

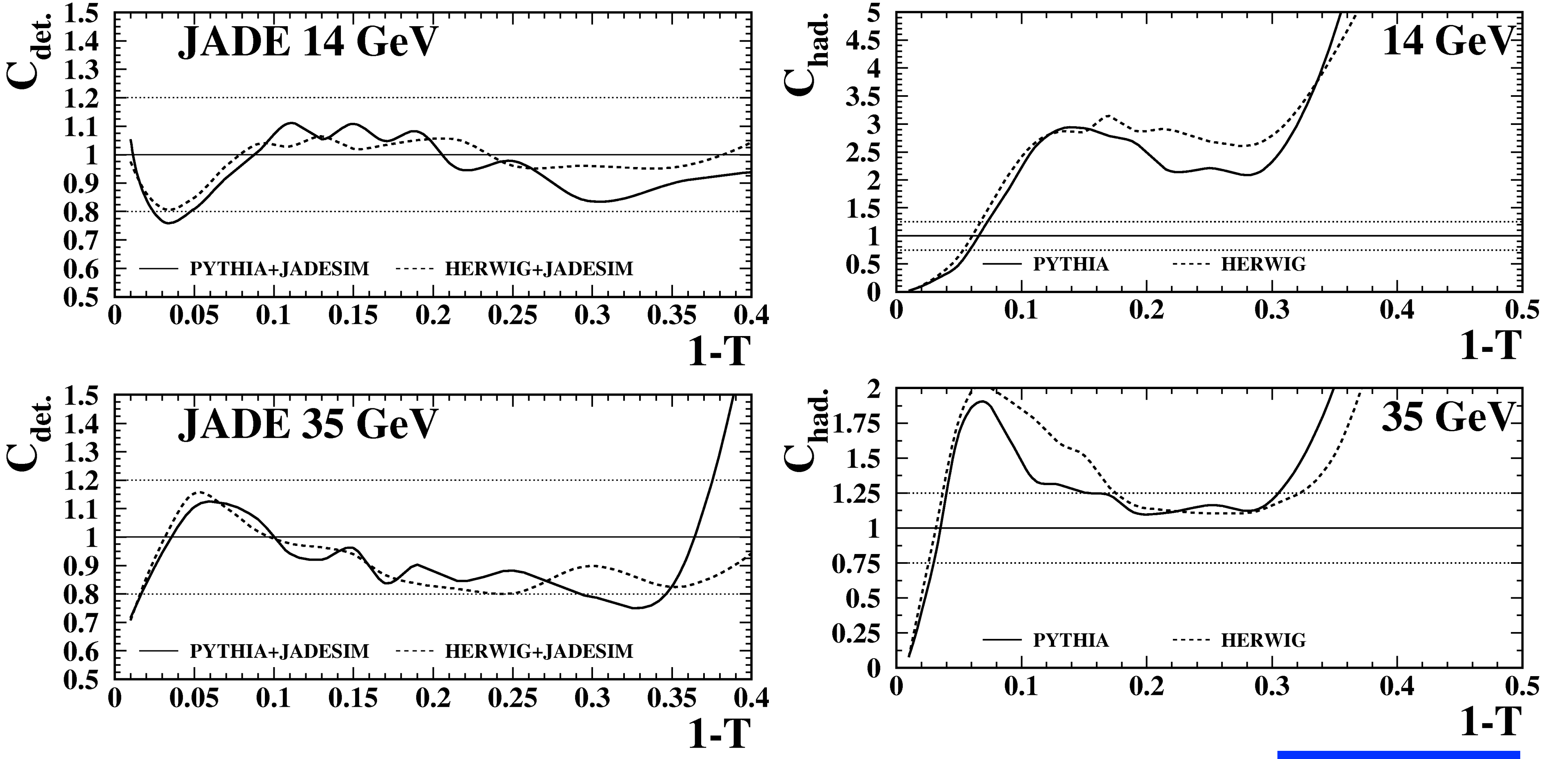
consistent hadron levels



HERWIG MC unfolded with Pythia

'detector correction' done bin-by-bin

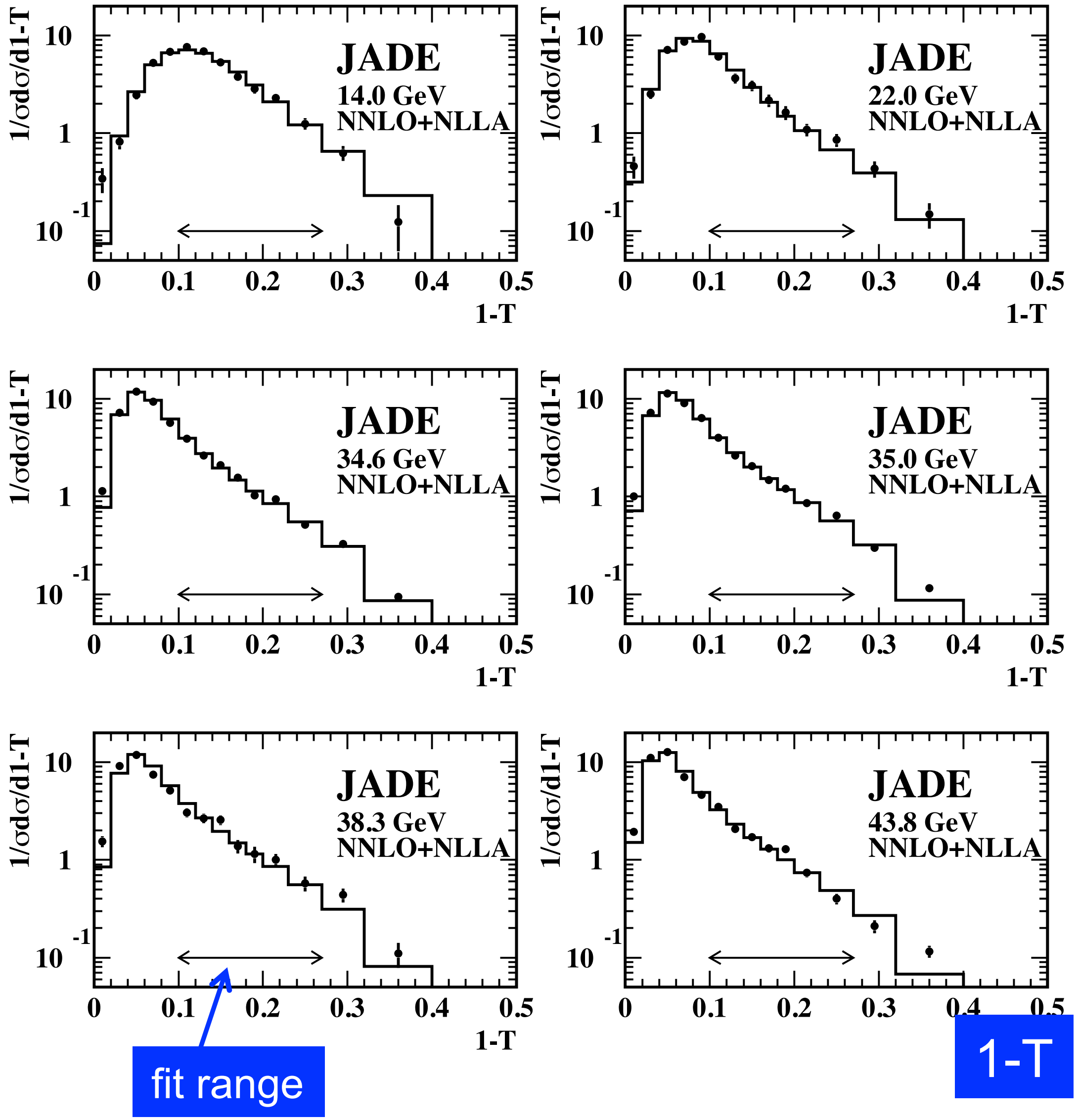
Data Correction



detector effects

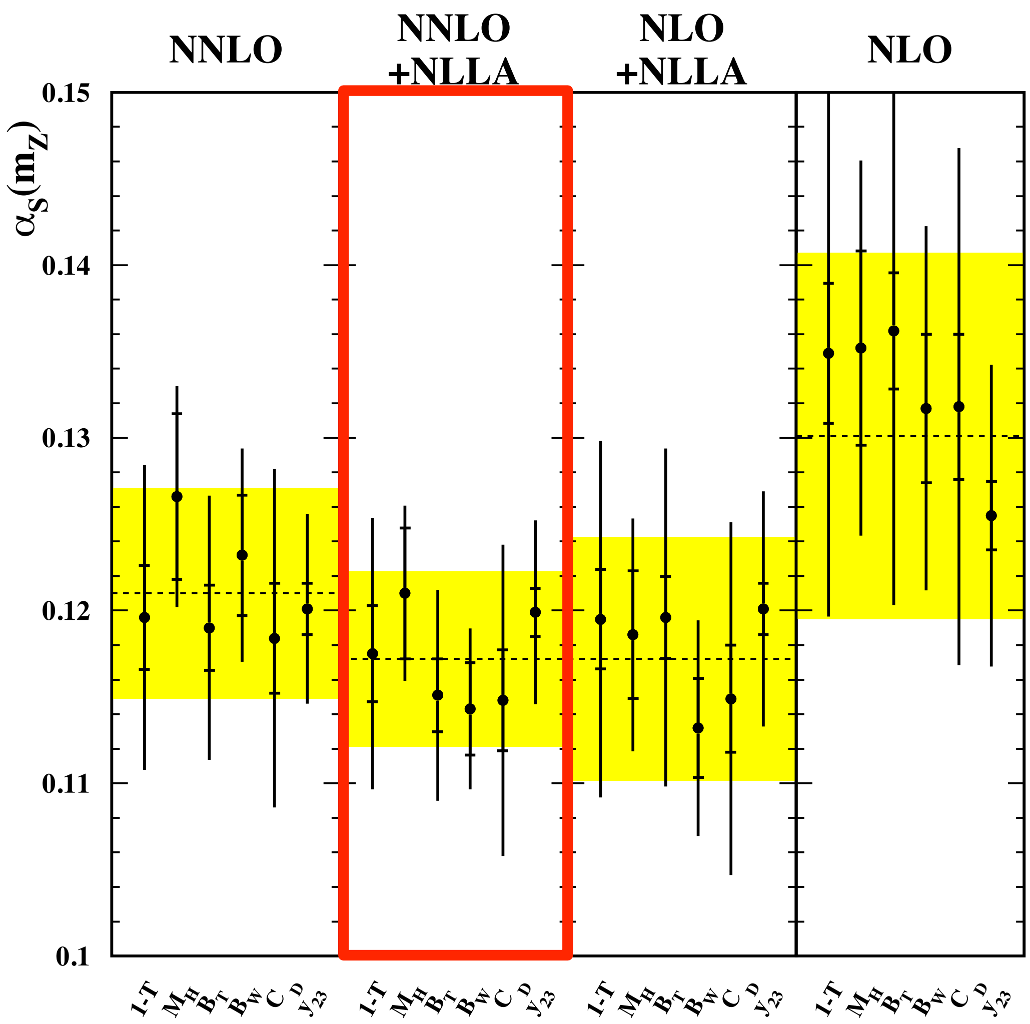
hadronization

Fit to Distribution



- χ^2 /d.o.f. between 3 and 2.3 (use statistical error only for fit)
- fit range determined by $\alpha_S$lny/y < 1 and all orders of NNLO calculation contribute

α_s Results



α_s (34.6) = 0.12±0.01±0.01
Phys.Rep.**148**(1987)67

α_s (34.6)$^{NNLO+NLLA}$ = 0.1367±0.0067

~50% smaller error with new theoretical calculations

dominant errors:

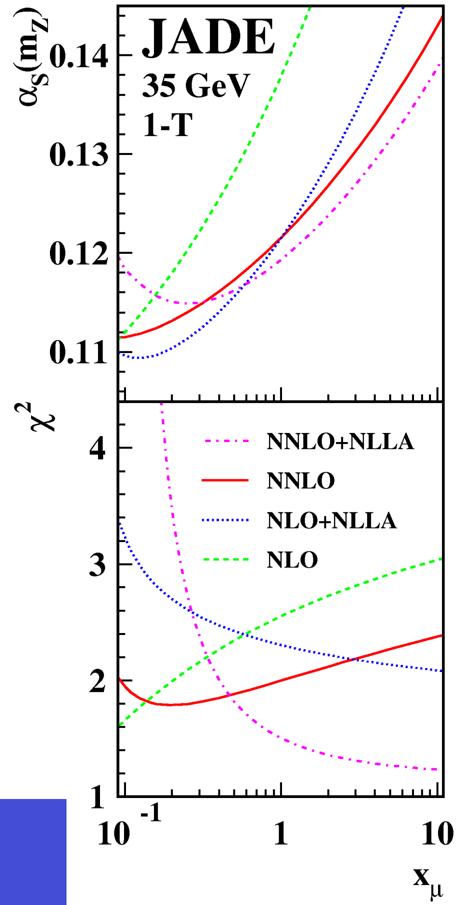
- renormalisation scale
- hadronization uncertainties

x_μ dependence significantly reduced w.r.t $O(\alpha_S^2)$ calculations

α_s Result (NNLO+NLLA)

√s (GeV)	$a_s(\sqrt{s})$	Stat.	Hadr.	Higher order
14.0	0.1605	0.0044	0.0148	0.0073
22.0	0.1456	0.0036	0.0077	0.0048
34.6('82)	0.1367	0.0011	0.0046	0.0040
35.0('86)	0.1412	0.0009	0.0049	0.0047
38.3	0.1388	0.0030	0.0042	0.0048
43.8	0.1296	0.0019	0.0033	0.0034

scale uncertainty



$\alpha_s(M_z)^{JADE}=0.1172\pm0.0006\pm0.0050$

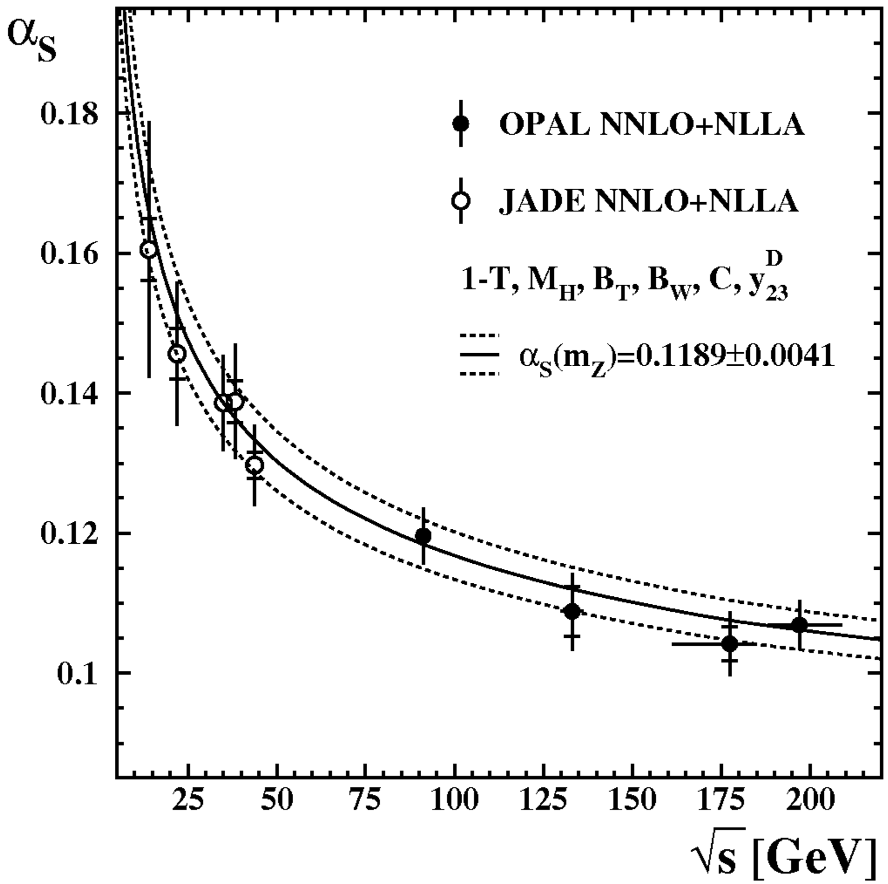
$\alpha_s(M_z)^{Lep1}=0.1224\pm0.0009\pm 0.0038$

ALEPH
hep-ph/0906.3436

Combined α_s Result

$$\alpha_s(Q) = \frac{1}{\beta_0 L} - \frac{\beta_1 \ln L}{\beta_0^3 L^2} + \frac{1}{\beta_0^3 L^3}\left[\frac{\beta_1^2}{\beta_0}(\ln^2 L - \ln L - 1) + \frac{\beta_2}{\beta_0}\right]$$

$$L = \ln(Q/\Lambda_{\overline{MS}})^2$$



$\alpha_s(M_z)^{NNLO}$=

0.1210±0.0007(stat.)±0.0021 (exp.)±0.0044(had.)±0.0036 (theo.)

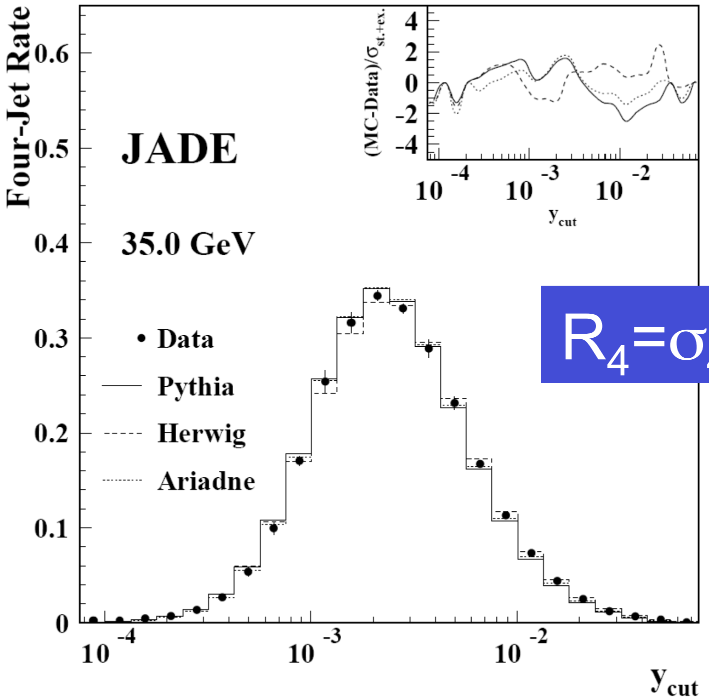
$\alpha_s(M_z)^{NNLO+NLLA}$=
0.1172±0.0006(stat.)±0.0020 (exp.)±0.0035(had.)±0.0030 (theo.)

Measurement using Jet Rates

- NLO+NLLA calculations available for 3- and 4-Jet Rate:

α_S from 3-jet rate:

$$\alpha_s(M_{Z^0}) = 0.1206 \pm 0.0031(\text{stat.}+\exp) \pm 0.0038(\text{theo})$$



•similar theoretical uncertainty as event shape analysis

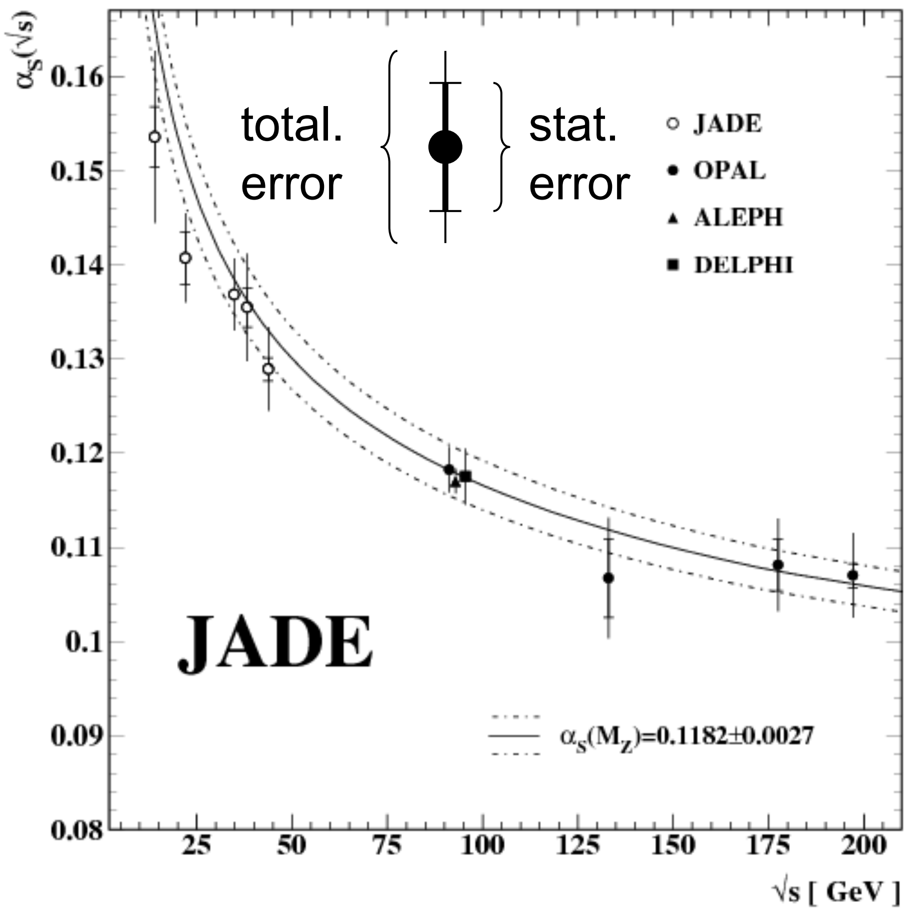
$R_4=\sigma_{4\text{-Jet}}/\sigma_{tot}=\alpha_s^2 B(y_{cut})+\alpha_s^3 C(y_{cut})$+NLLA

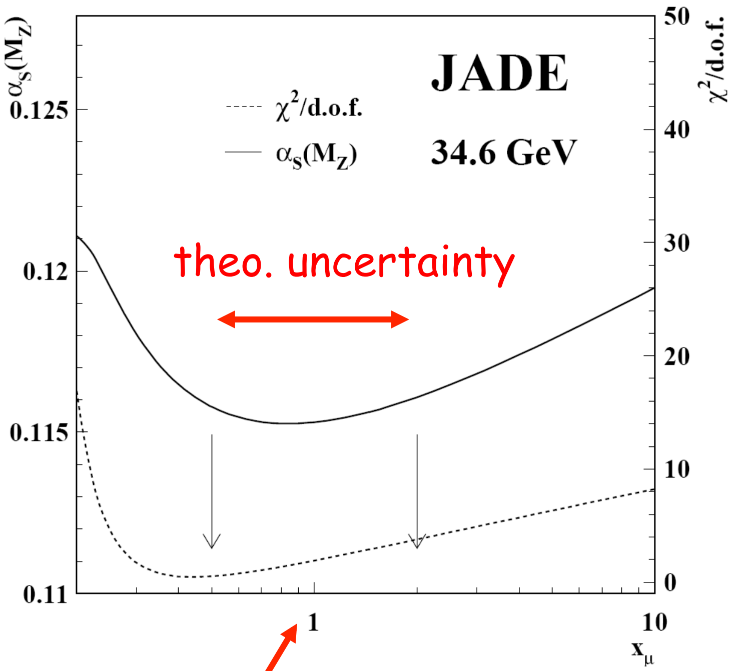
•reduced scale sensitivity:

(smaller theoretical uncertainty)

$$\Delta R_4(x_\mu) \propto \alpha_S^3 \cdot \ln x_\mu$$

Measurement using 4-Jet Rate





reduced scale (theo.) uncertainty
(variation x_μ=.5…2.)

α_s= 0.1159±0.0004±0.0012±0.0024±0.0007

(stat±exp±had±theo)

result close to α_S with least sensitivity to x_μ

‘Running’ of α_S

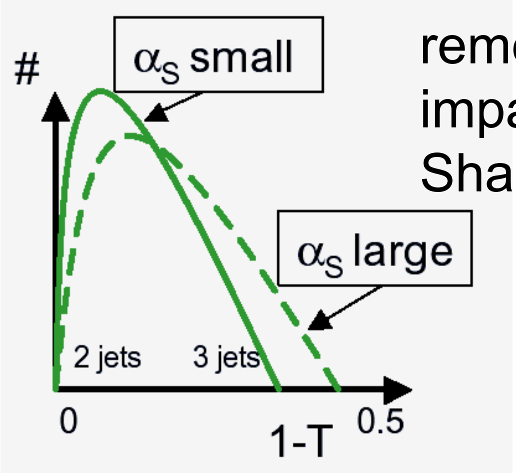
	running α_S χ^2/d.o.f. χ^2 probability	constant α_S χ^2/d.o.f. χ^2 probability
JADE 14-44 GeV	3.9/5 57%	7.0/5 22%
OPAL 91-209 GeV	6.4/12 90%	12.4/12 42%
JADE+OPAL 14-209 GeV	12.0/18 85%	149.5/18 0.0%

combination of α_S values:

- JADE data alone return no significant proof for running of α_S
- LEP alone consistent with being constant

►combination of LEP and JADE date excludes constant value of α_S

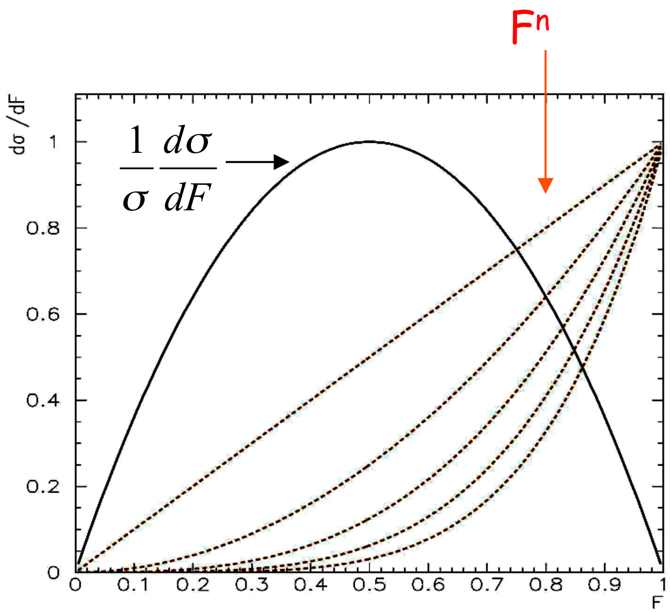
Moments of Event Shapes



remember:
impact of α_S on Event Shape Distributions

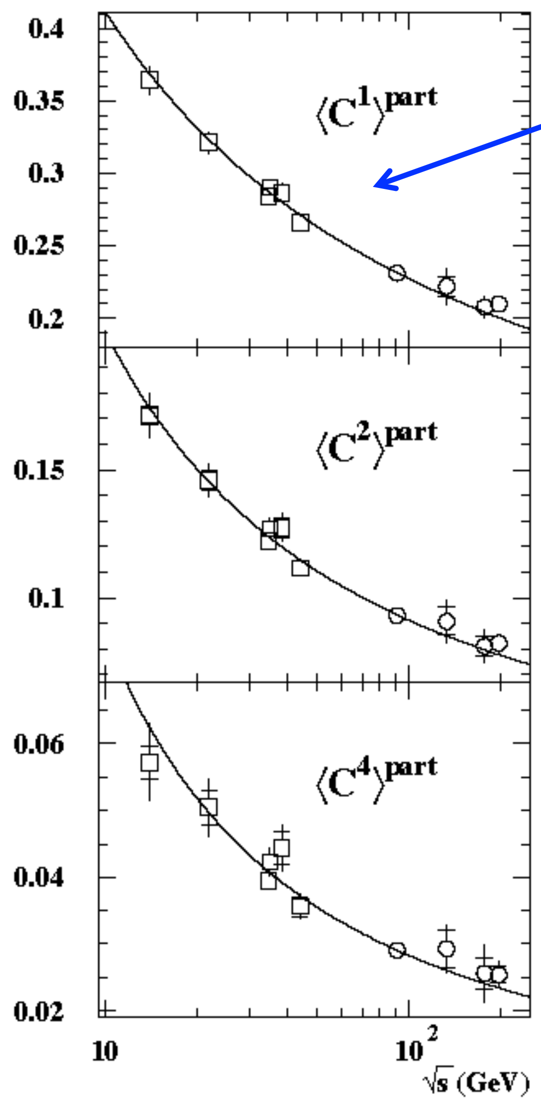
n^{th} moment:

$$\langle F^n \rangle = \int F^n \frac{1}{\sigma} \frac{d\sigma}{dF} dF$$



- fit range for α_S measurments using event shape distribution restricted
- fit to moments probe complete available phase space

Moments of Event Shapes

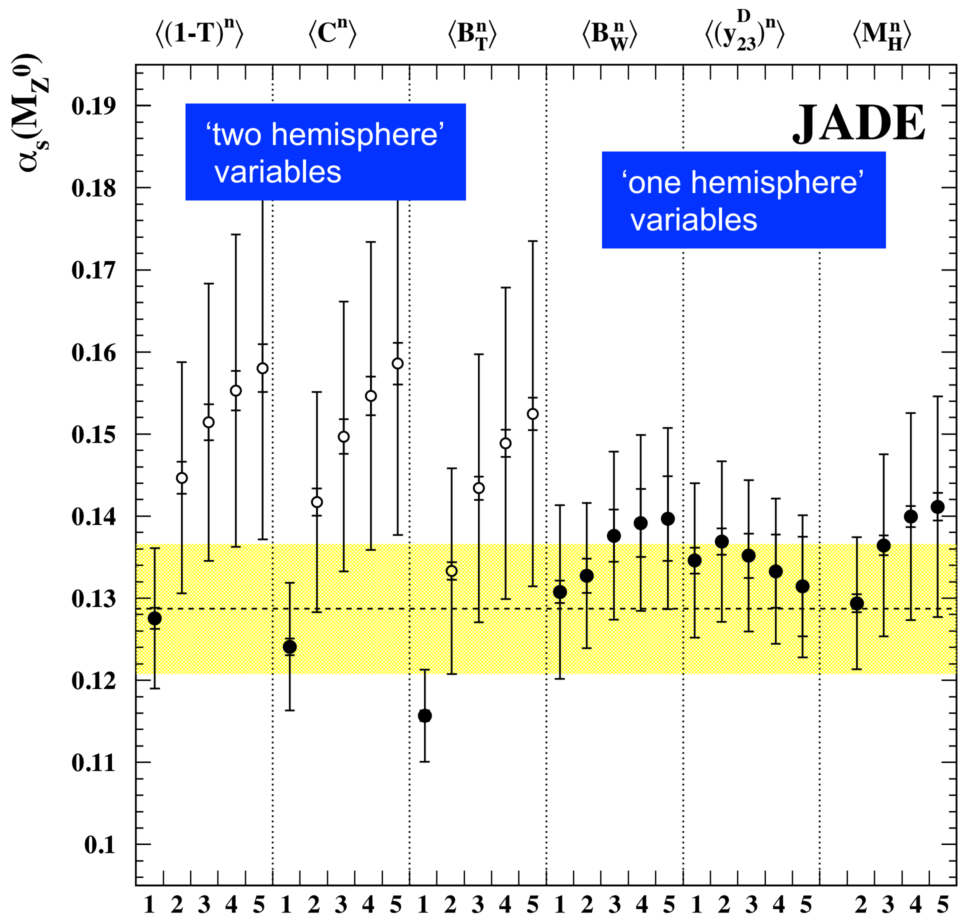


direct evidence for change of of α with √s

- use perturbative NLO predictions
- correction for hadronization effects with Monte Carlo

Moments of Event Shapes

$\frac{B_n}{A_n}$ increase for $i = 1 \ldots 5$



result consistent with fit to distribution

Require:

$$\frac{B_n}{A_n} \cdot \frac{\alpha_S}{2\pi} < 0.5$$

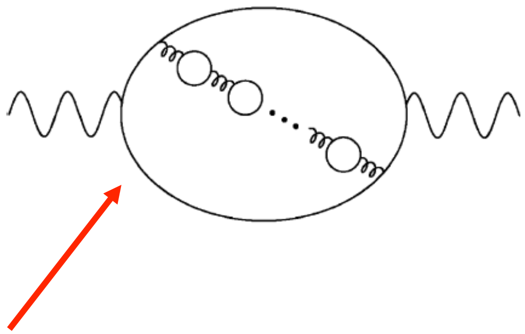
combined result: (filled circles)

$$\alpha_s(M_{Z^0}) = 0.1287 \pm 0.0007(\text{stat.}) \pm 0.0011(\text{exp.}) \pm 0.0022(\text{had.}) \pm 0.0075(\text{theo.})$$
$$= 0.1287 \pm 0.0079$$

Power Corrections

remember: QCD calculations predict only distribution on parton level

- large uncertainties due to hadronization modeled with Monte Carlo with quite a few free parameters



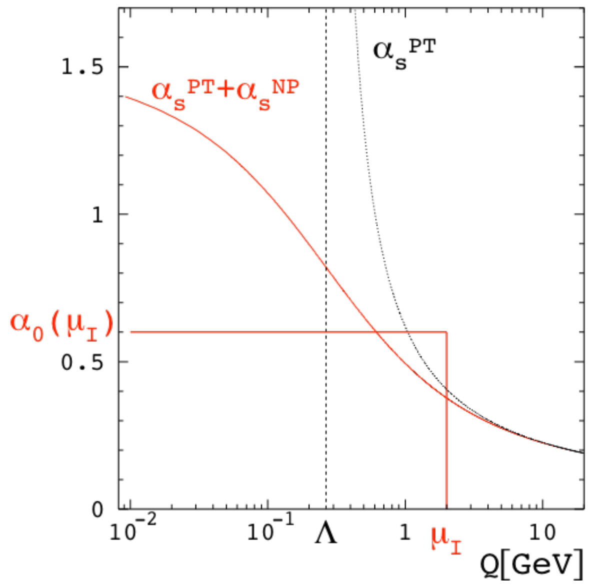
Power Corrections:

- perturbative treatment of hadronization leads to divergences
- separate effects at large Scale (PT) and small scale (PC)

Power Corrections

μ_I : separation between PT and NP

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



$$\langle F\rangle = \langle F\rangle^{PT} + D_F P$$

$$\frac{d\sigma(F)}{dF} = \frac{d\sigma^{PT}(F - D_F P)}{dF}$$

$$D_F = a_F \cdot \ln(1/F) + F_F \qquad F=B_T,B_W$$

$$D_F = const. \qquad F=1-T,M_H^2,C$$

universal parameter

$$P = \frac{4C_F}{\pi^2} M \frac{\mu_I}{Q}\left[\alpha_0(\mu_I) - \alpha_s(\mu_R) - \beta_0 \frac{\alpha_s^2}{2\pi}\left(\ln(\frac{\mu_R}{\mu_I}) + \frac{K}{\beta_0} + 1\right)\right]$$

Dokshitzer-Marchesini-Webber (DMW) structure of power corrections (1996)

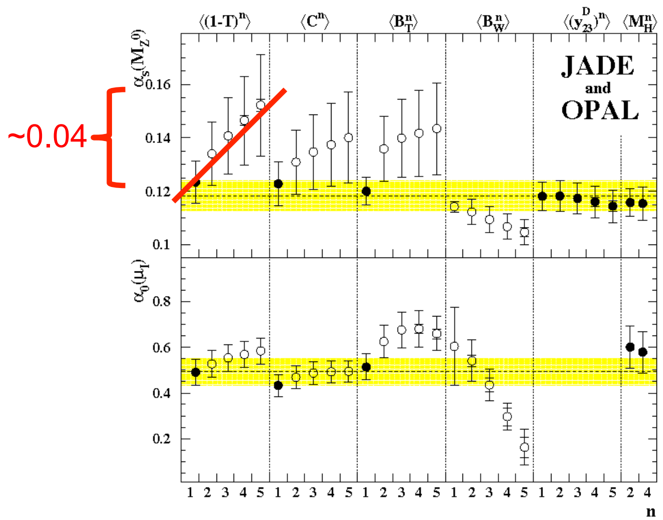
Moments of Event Shapes

- OPAL and JADE data:
- use NLO and hadronization correction using power corrections

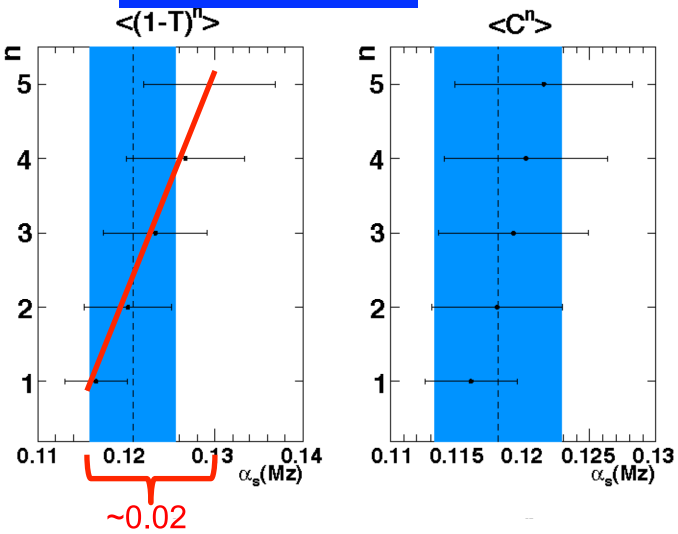
$$\alpha_s(M_{Z^0}) = 0.1183 \pm 0.0007(\text{stat.}) \pm 0.0016(\text{exp.}) \pm 0.0011(\text{had.}) \pm 0.0052(\text{theo.})$$

- use NNLO for perturbative predictions:

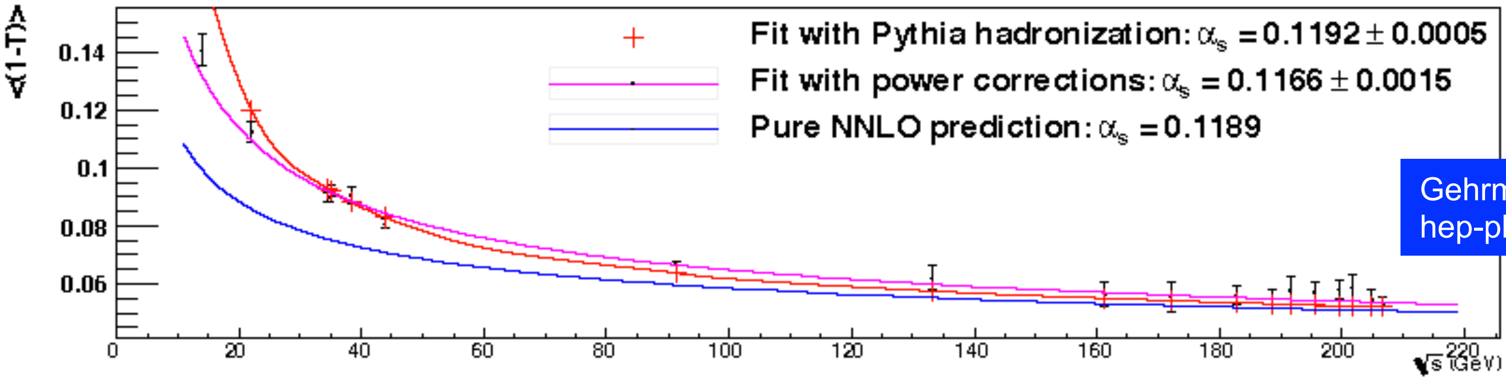
$$\alpha_s(M_{Z^0}) = 0.1153 \pm 0.0017(\text{exp.}) \pm 0.0023(\text{theo.})$$



Gehrmann et al.
hep-ph/0911.2422

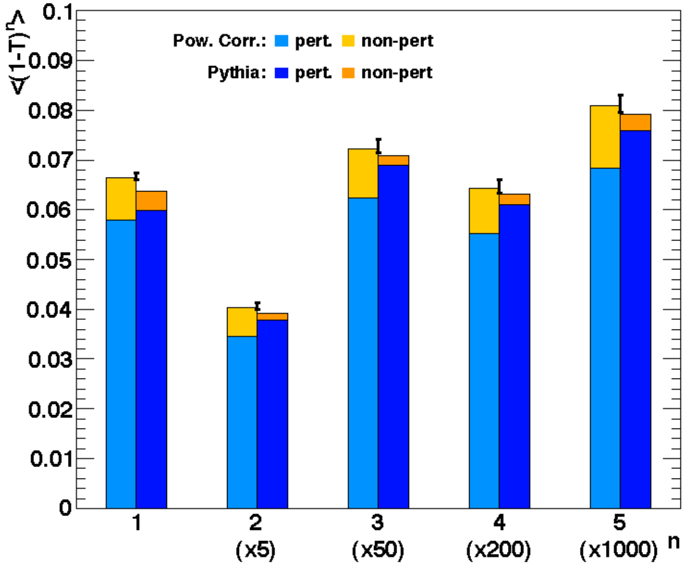


Moments of Event Shapes



Gehrmann et al.
hep-ph/0911.2422

- compare hadronization correction from MC and power correction
- both approaches describe data well
- MC hadronization correction considerably smaller
- α_0(2 GeV)=0.5132±0.0115(fit)±0.0381(theo)

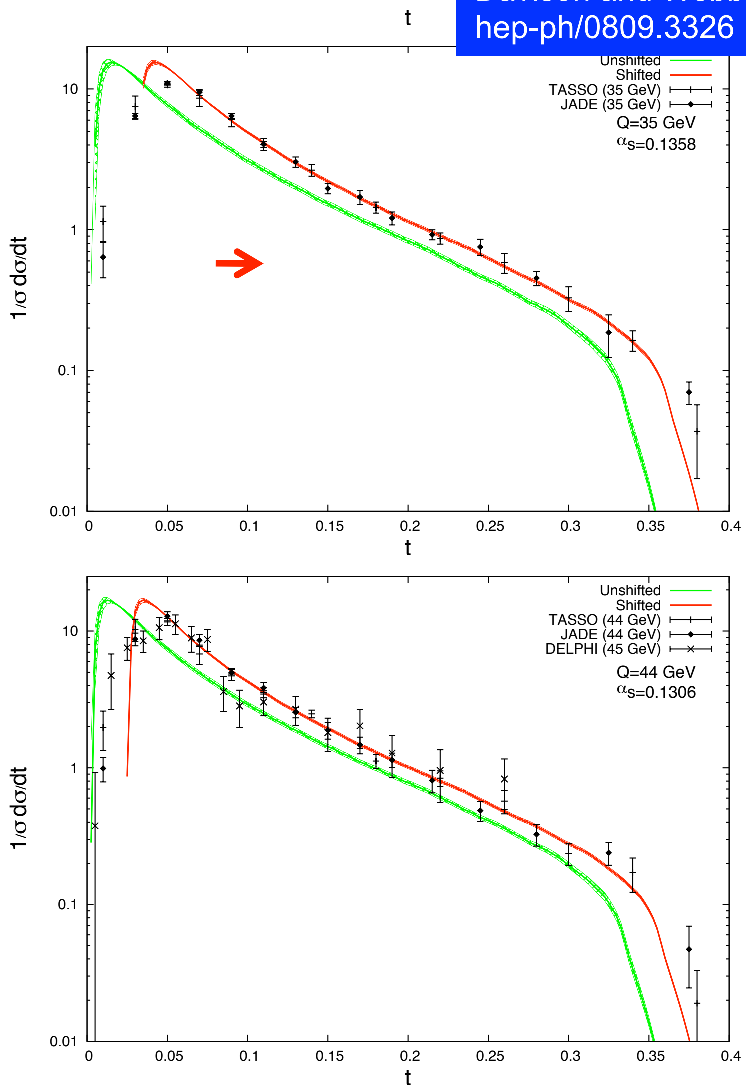


Pythia Pow.Corr

Power Correction for Distribution

Davison and Webber
hep-ph/0809.3326

- use NNLO perturbative calculation
- expect shift of event shape distribution due to hadronization effects
- power corrections for event shape distributions together with NNLO perturbative predictions only for Thrust available
- fit to LEP, Petra and Amy

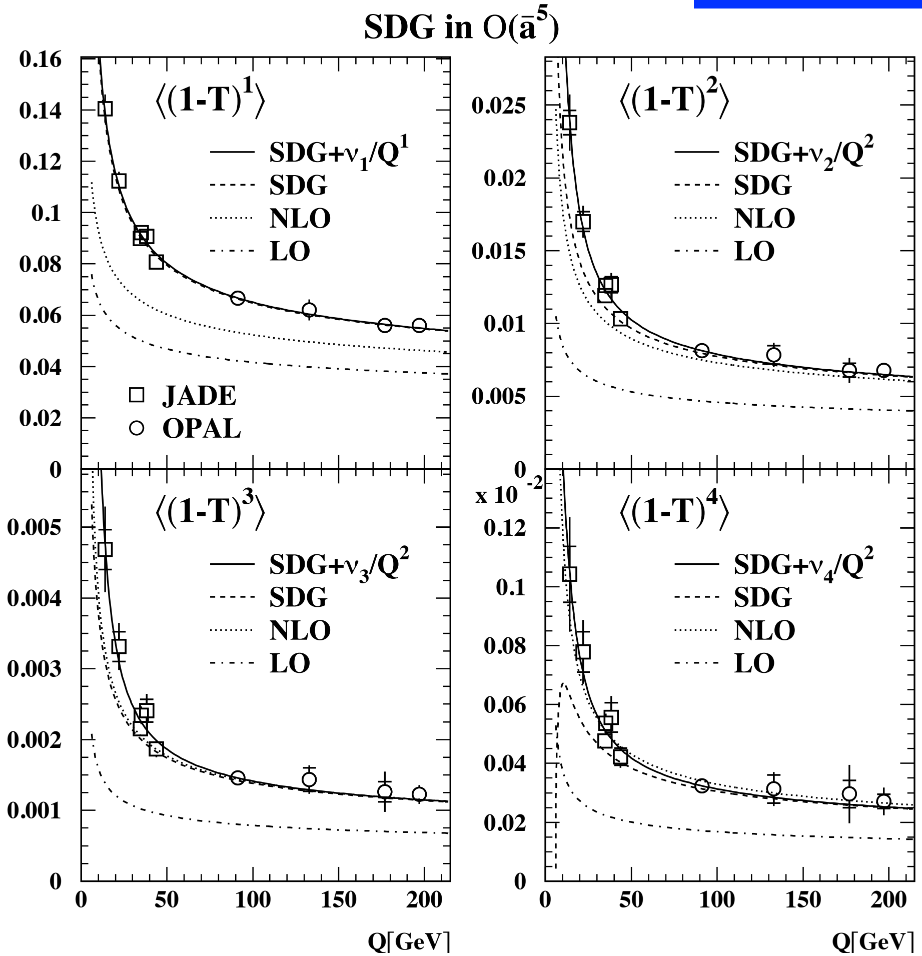


$$\alpha_s(M_{Z^0}) = 0.1164 \pm 0.0028$$
$$\alpha_0(2GeV) = 0.59 \pm 0.03$$

Single Dressed Gluon Approximation

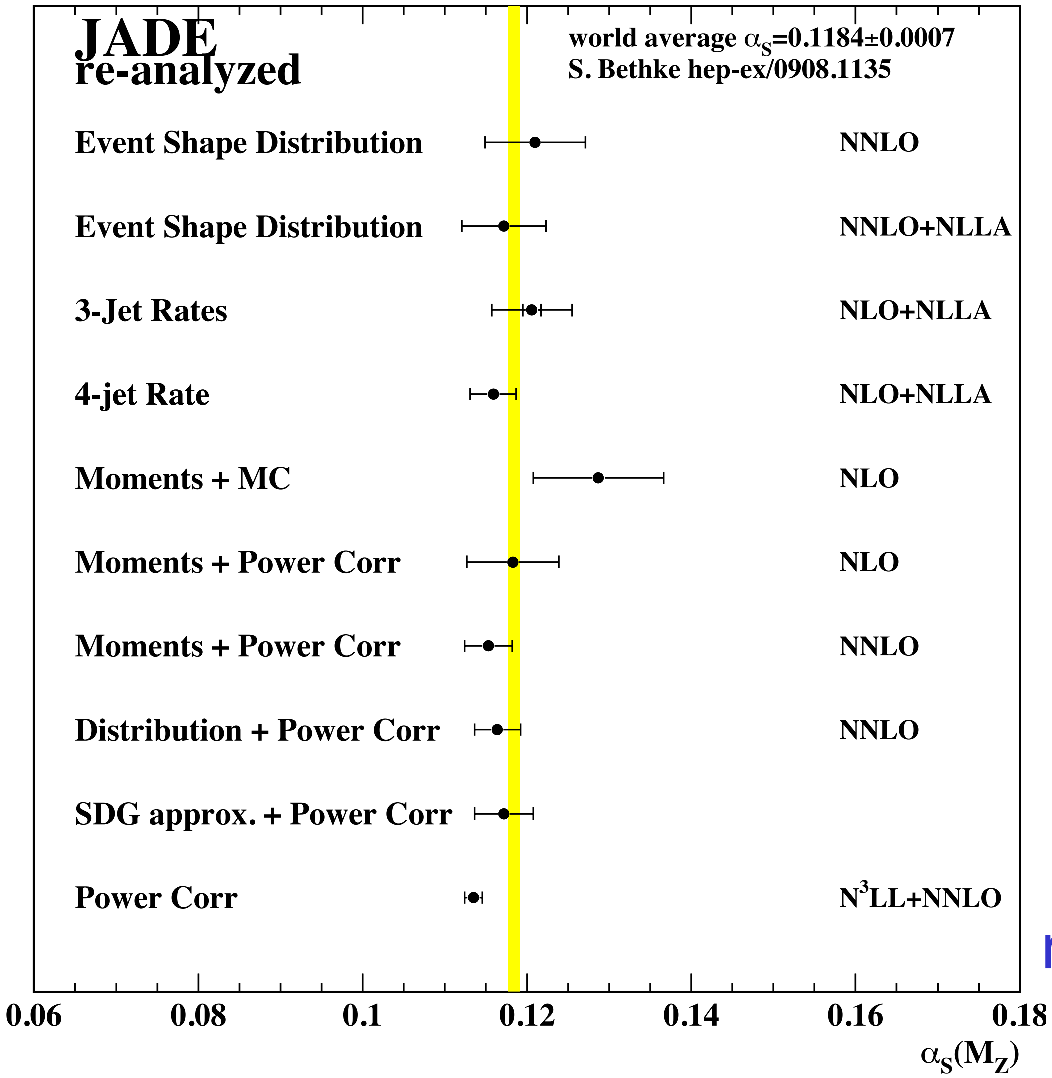
Gardi and Grunberg
hep-ph/99084582

- reorder perturbative series (*skeleton expansion*)
  - first contribution single dressed gluon (QED: single photon dressed with all possible vacuum polarization insertions)
  - existence only proven for abelian field theory



$$\alpha_s(M_{Z^0}) = 0.1172 \pm 0.0036(tot.)$$

Conclusion (I)



$O(\alpha_s^3)$ + NLLA calculation first time applied to PETRA data

$a_s(M_{Z°})$=0.1172±0.0051 (JADE)

$a_s(M_{Z°})$=0.1224±0.0039 (LEP)

consistent with other measurements and methods

Conclusion (II)

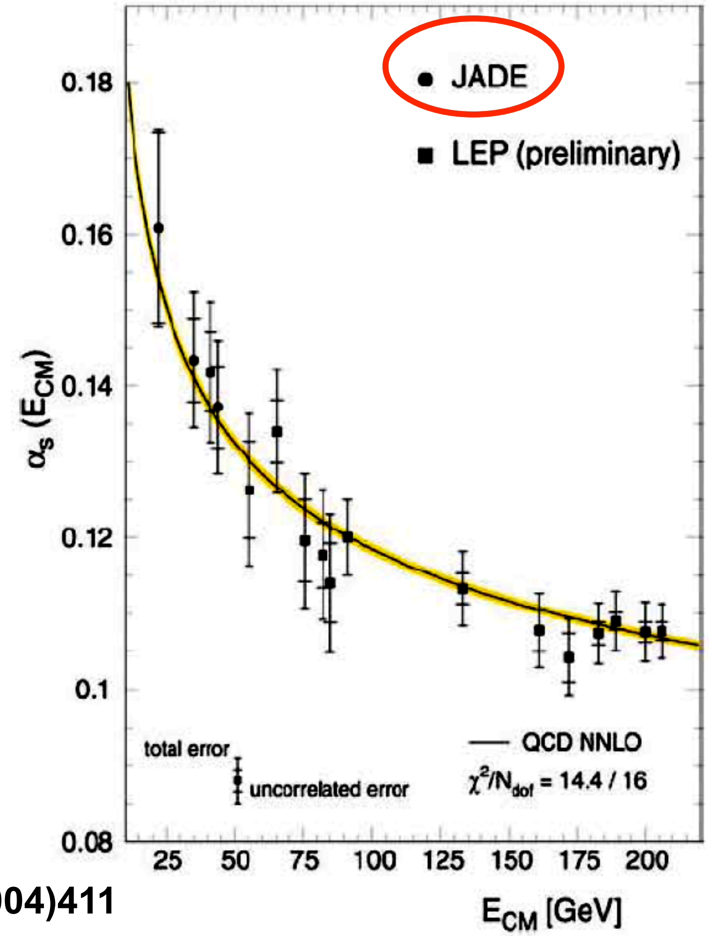
- data and software from the JADE experiment were successfully resurrected
- data was used to perform state-of-the-art QCD studies at $\sqrt{s} < M_{Z0}$
- results provide stringent tests of perturbative and non-perturbative aspects of QCD
- keep the data and software alive, it’s worth it

A Comment on archiving…

- archived data of finished experiments can provide valuable sources for future analysis
  - apply new theoretical calculations
  - use new Monte Carlos methods to analyze data
- no analysis without reconstruction software and the corresponding documentation (!)
- platform independent software simplifies running the code in the future
  - enforce the compilation and running of the software on several different machines

Nobel prize 2004

- Advanced Information on the Nobel Prize in Physics 2004:



P. Zerwas: Eur.Phys.J.C36(2004)411