New QCD Studies with the Resurrected JADE Data

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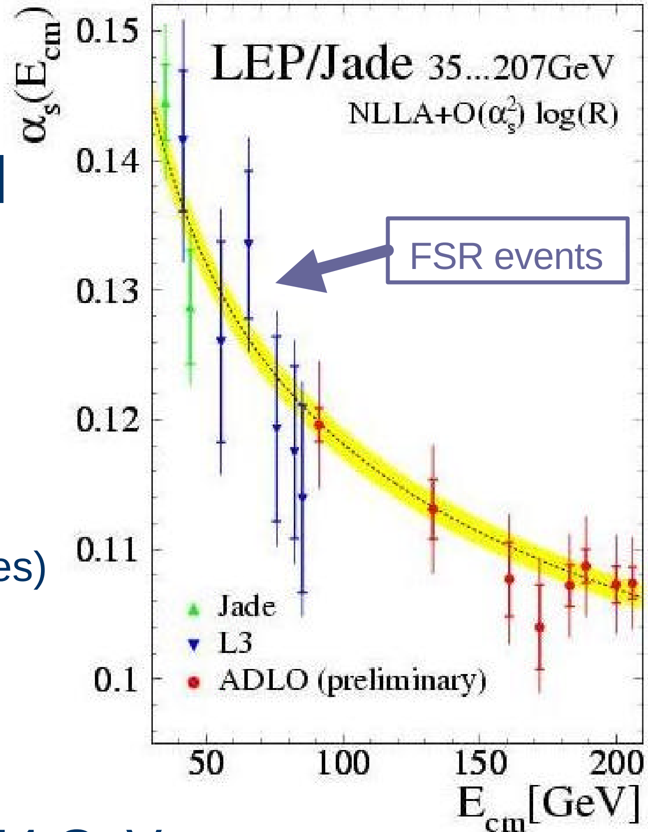
Outline

- 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 ∝ 1/log(Q)
    NP effects ∝ 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

a_s @ PETRA Times

1979 MARK-J Coll.:

- First direct measurement α_s based on LO for the Oblateness variable

1979+ a_s **= 0.15 … 0.23** @ $\sqrt{s}$ = 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

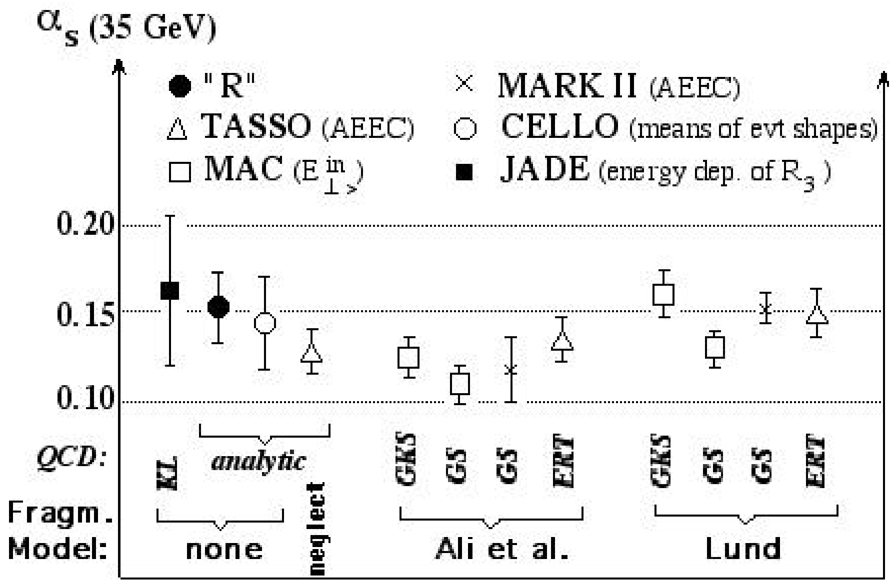
1982+ a_s **(35GeV) = 0.11… 0.19**

- based on NLO predictions

…inconsistent results due to

- incomplete QCD matrix elements
- fragmentation models

Status of α_s in 1989



Summary value 1989:

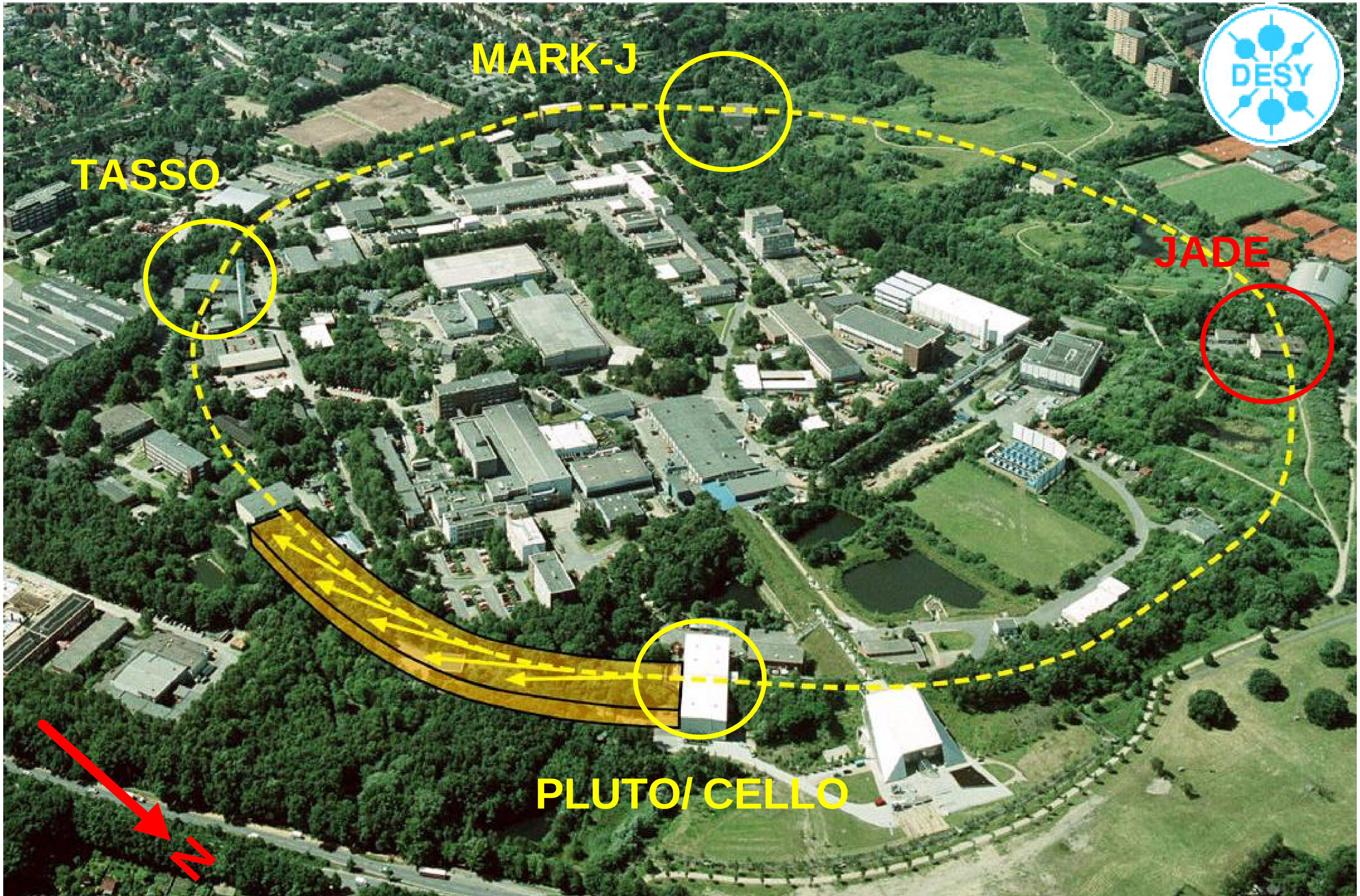
$\alpha_s(35\text{GeV}) = 0.14 \pm 0.02$

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

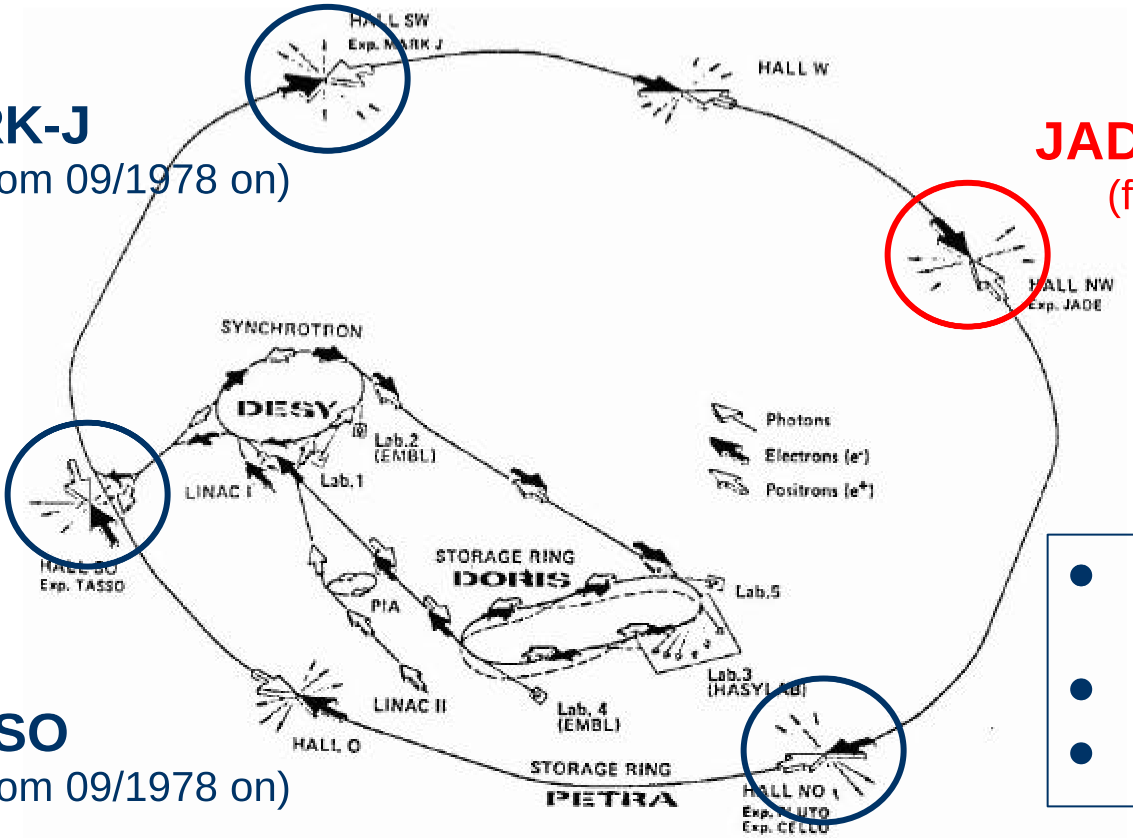


The PETRA e^+e^- Storage Ring

Operated 1978-1986 at DESY, Hamburg

MARK-J
(from 09/1978 on)

JADE
(from 02/1979 on)



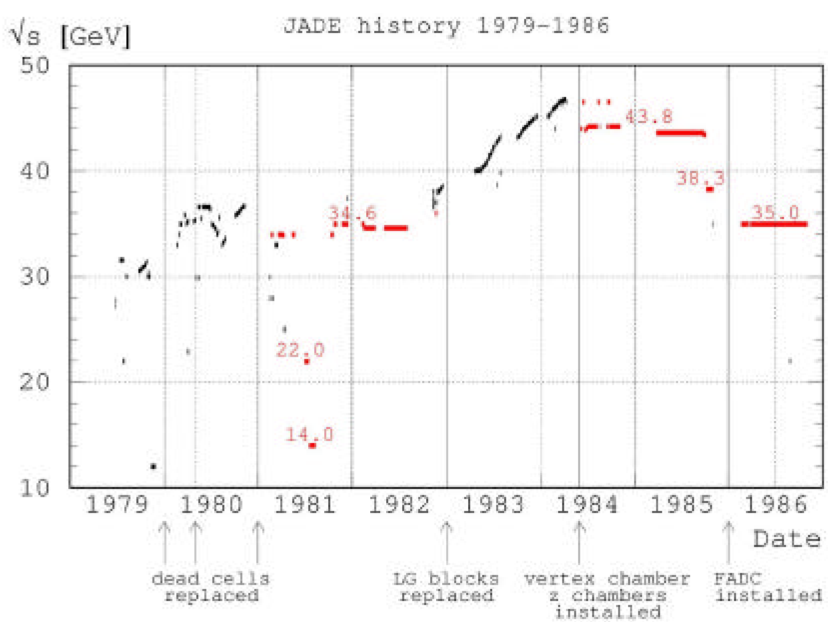
TASSO
(from 09/1978 on)

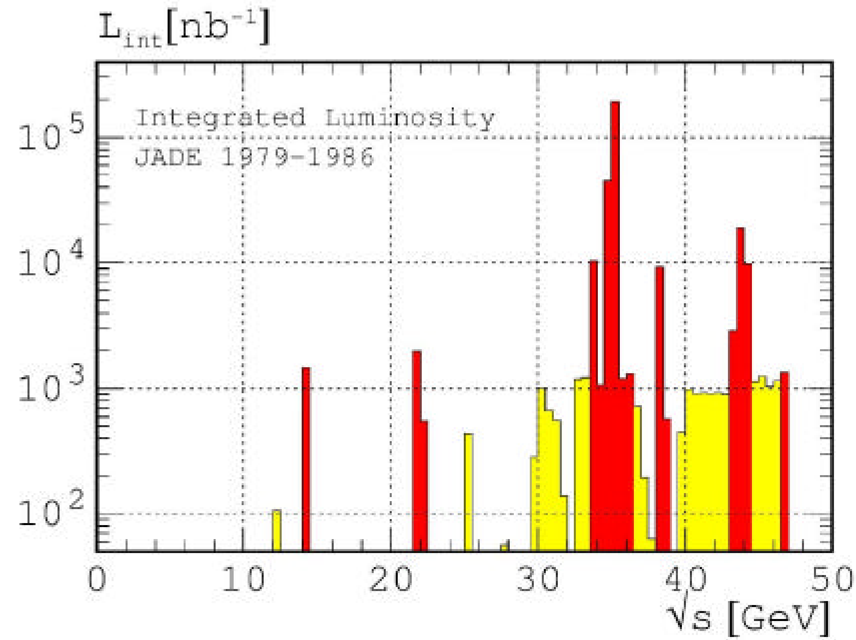
- largest storage ring at that time
- $\varnothing$ = 2.3 km
- $\sqrt{s}$ range 12–47 GeV

PLUTO (from 09/1978 on)

CELLO (replacing PLUTO from 08/1982 on)

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 pb^{-1}
- Peak lumi: 24 $\mu b^{-1}s^{-1}$

  $\Rightarrow$ 26 multihadrons per hour @ σ^{had}=0.3 nb
- Clean multihadrons: 43100

The JADE Experiment

- Participating states:

  JApan (Tokyo), **D**eutschland (DESY, Hamburg, Heidelberg),
  England (Lancaster, Manchester, RAL), USA (Maryland)

- ≈ 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 rφ
  $\sigma_{r\varphi}$=180µm (110µm), σ_z=16-32mm (OPAL: $\sigma_{r\varphi}$=135µm, σ_z=45-60mm)

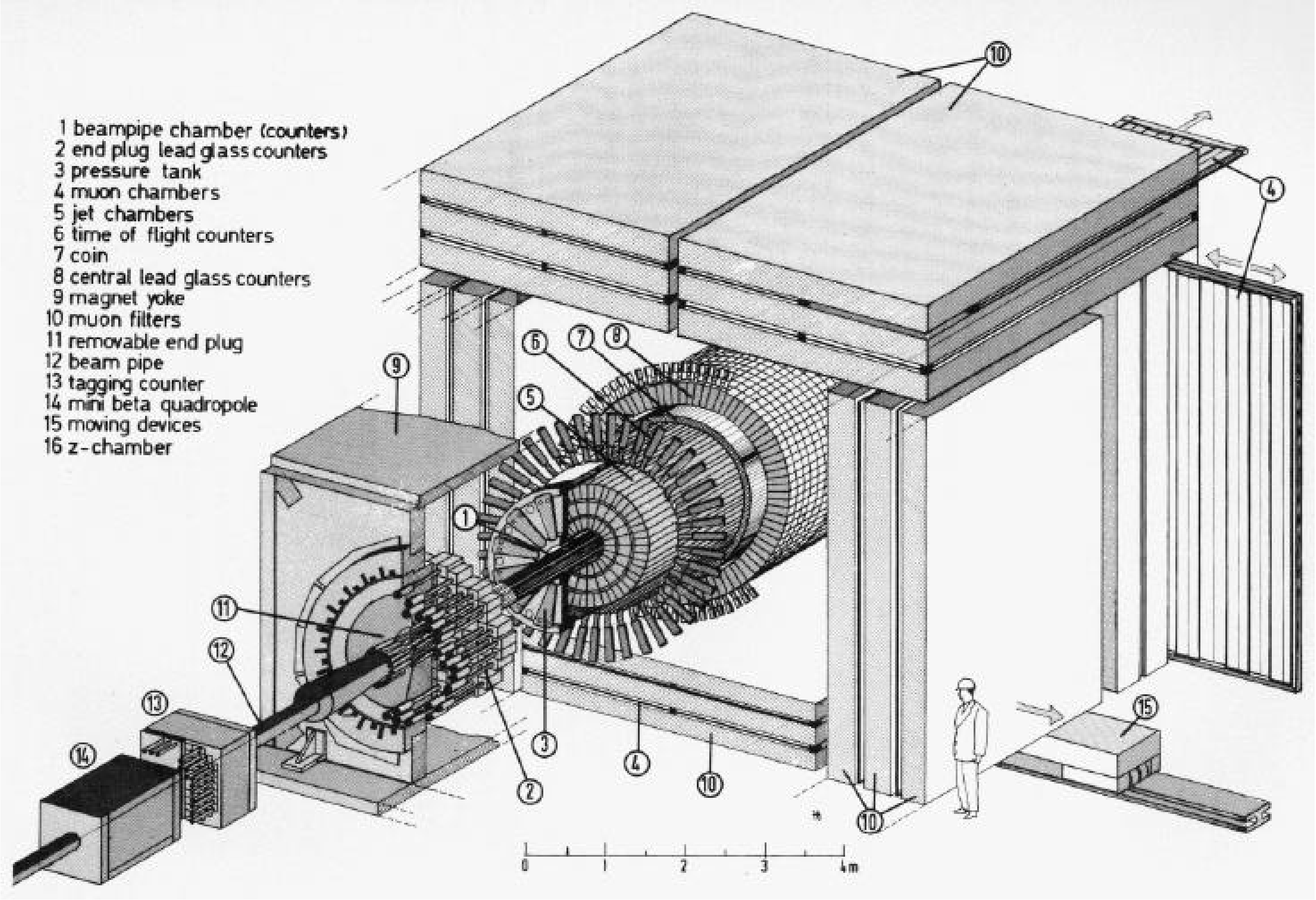
- E.M. Calorimeter

  ≈ 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

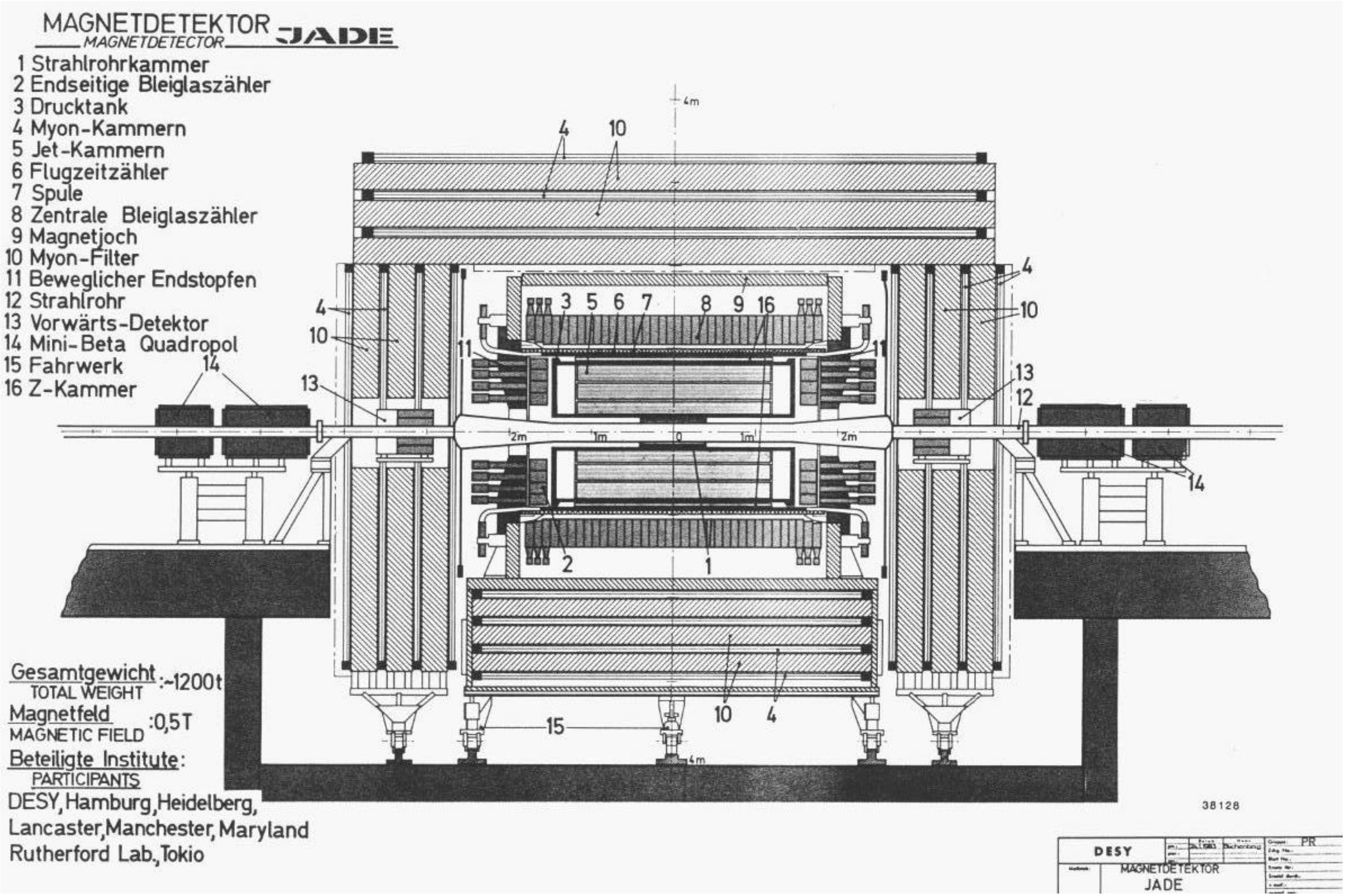
  up to 5 chamber layers / 3 absorber layers

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)
  - JADE Computer Notes
  - JADE Notes
  - JADE PhD theses
  - Manual fragments
  - Source code
  - …
- Code modification
- Emulation interfaces

  (missing libraries, IBM FORTRAN intrinsics …)

SHELTRAN, MORTRAN → FORTRAN 77

IBM Assembler, IBM FORTRAN, DESYLIB → CERNLIB

“PLOT-10” Terminal Control System → HIGZ

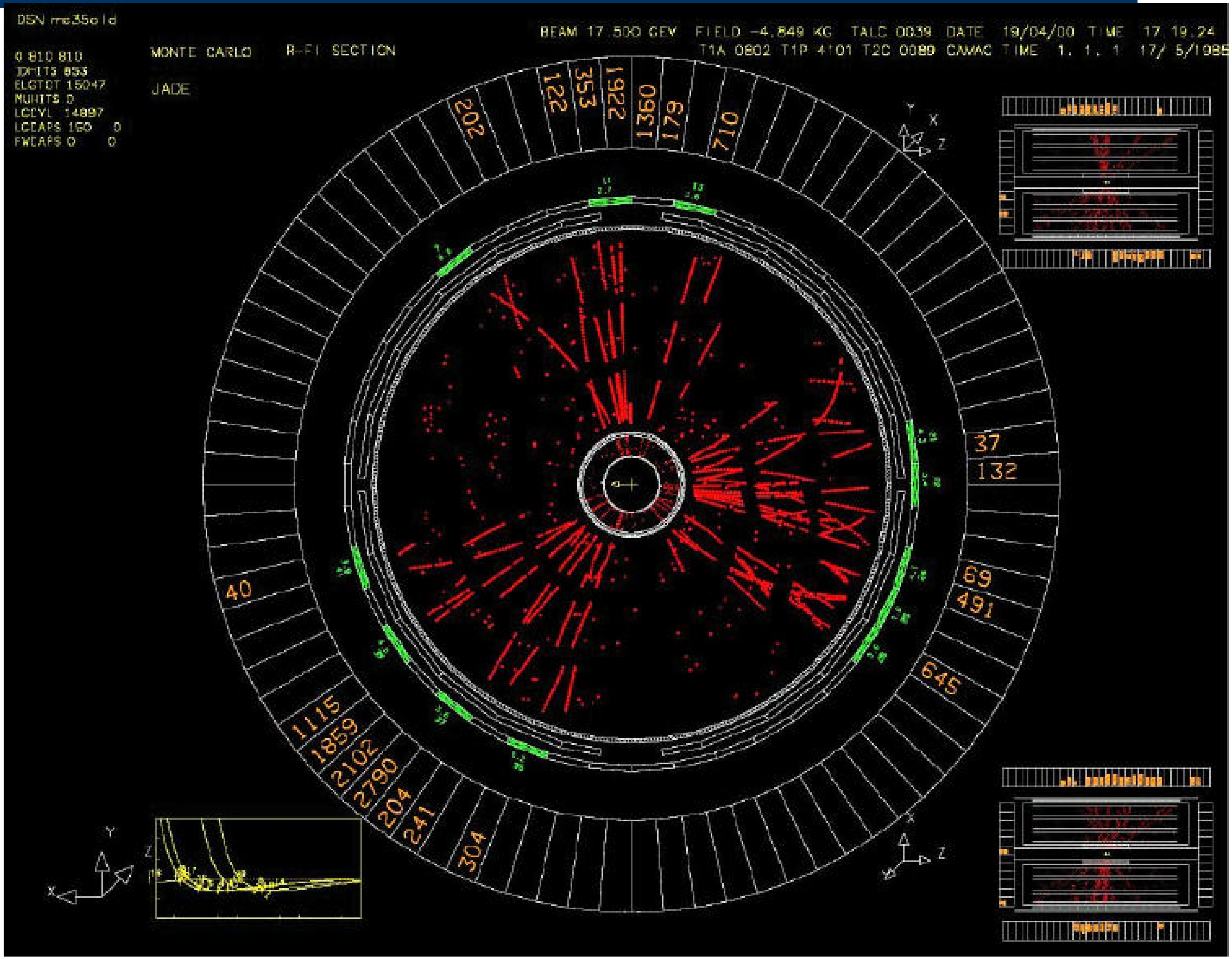
Platform dependent features extremely problematic!!!

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

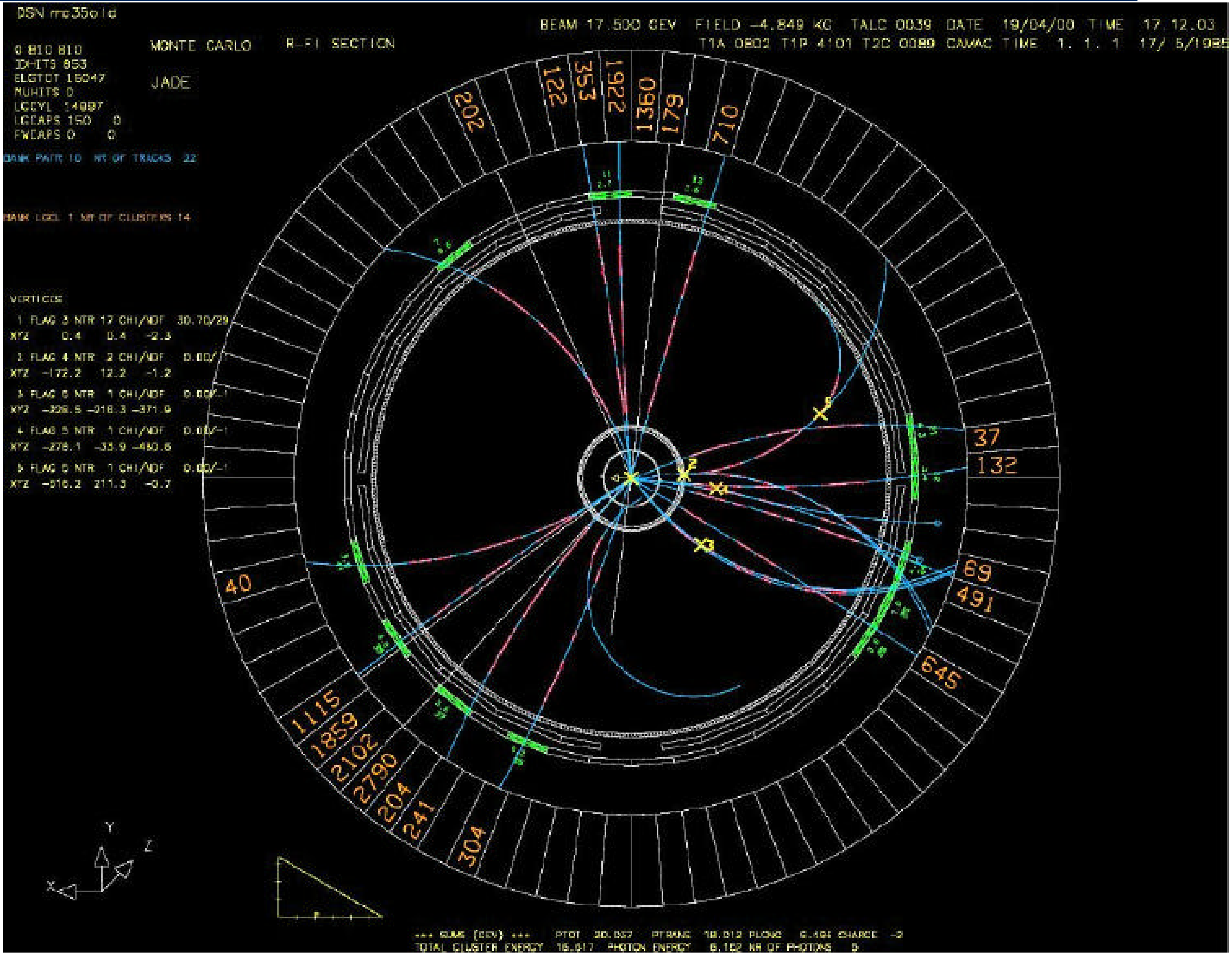
Complete installation succeeded on IBM RS/6000 AIX!

- XLF compiler advantageous
- same endian scheme as IBM/370

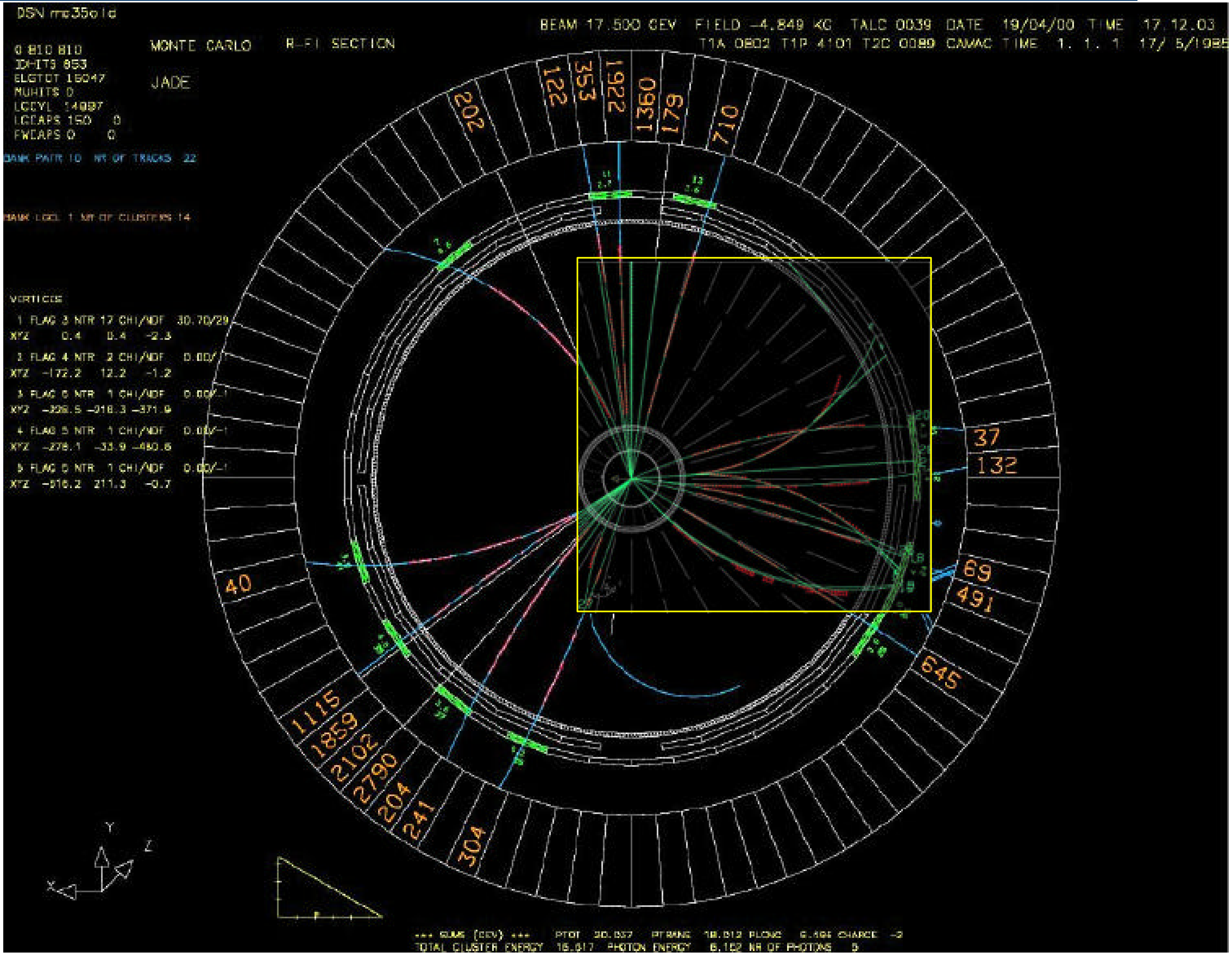
JADE Event Display



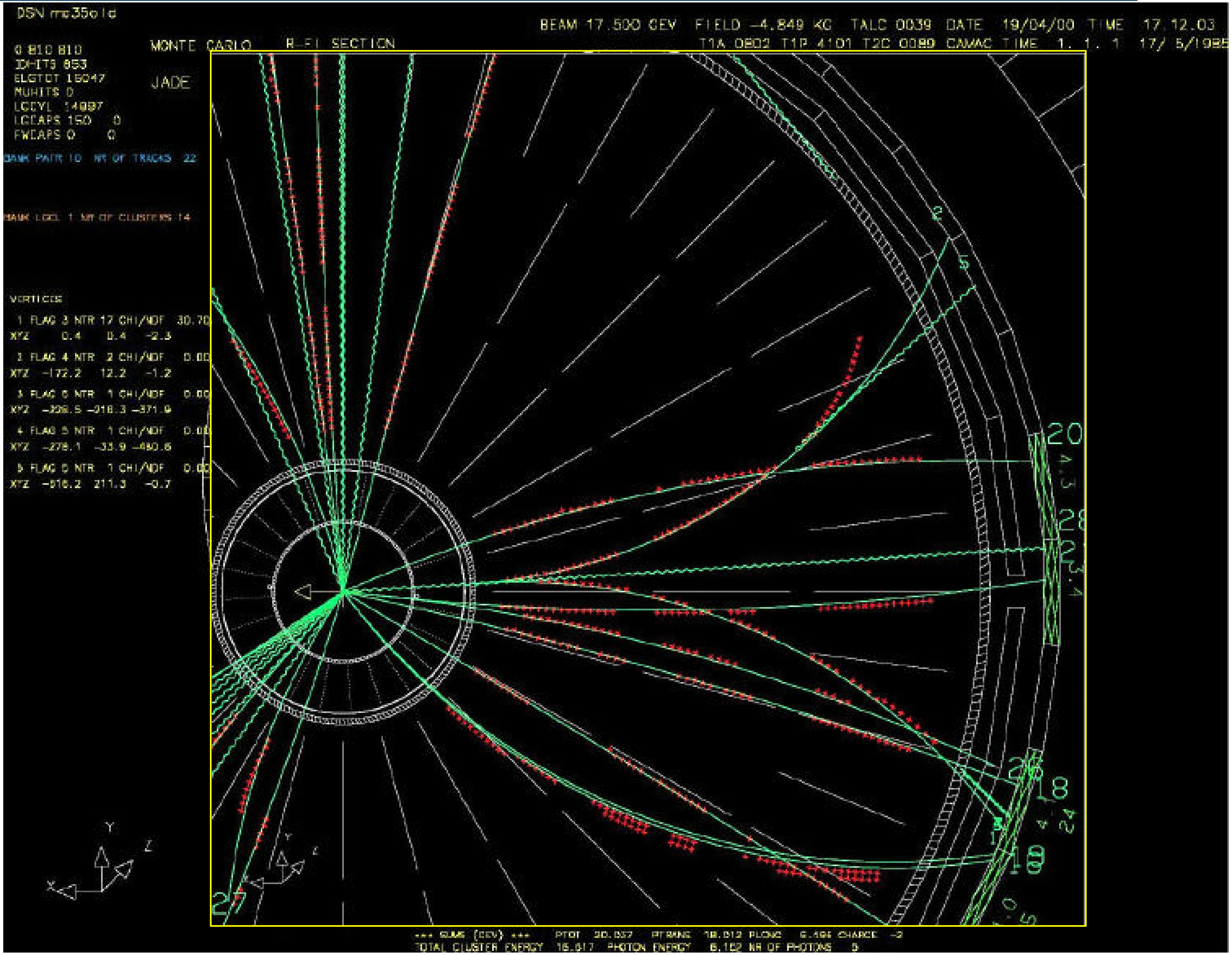
JADE Event Display



JADE Event Display



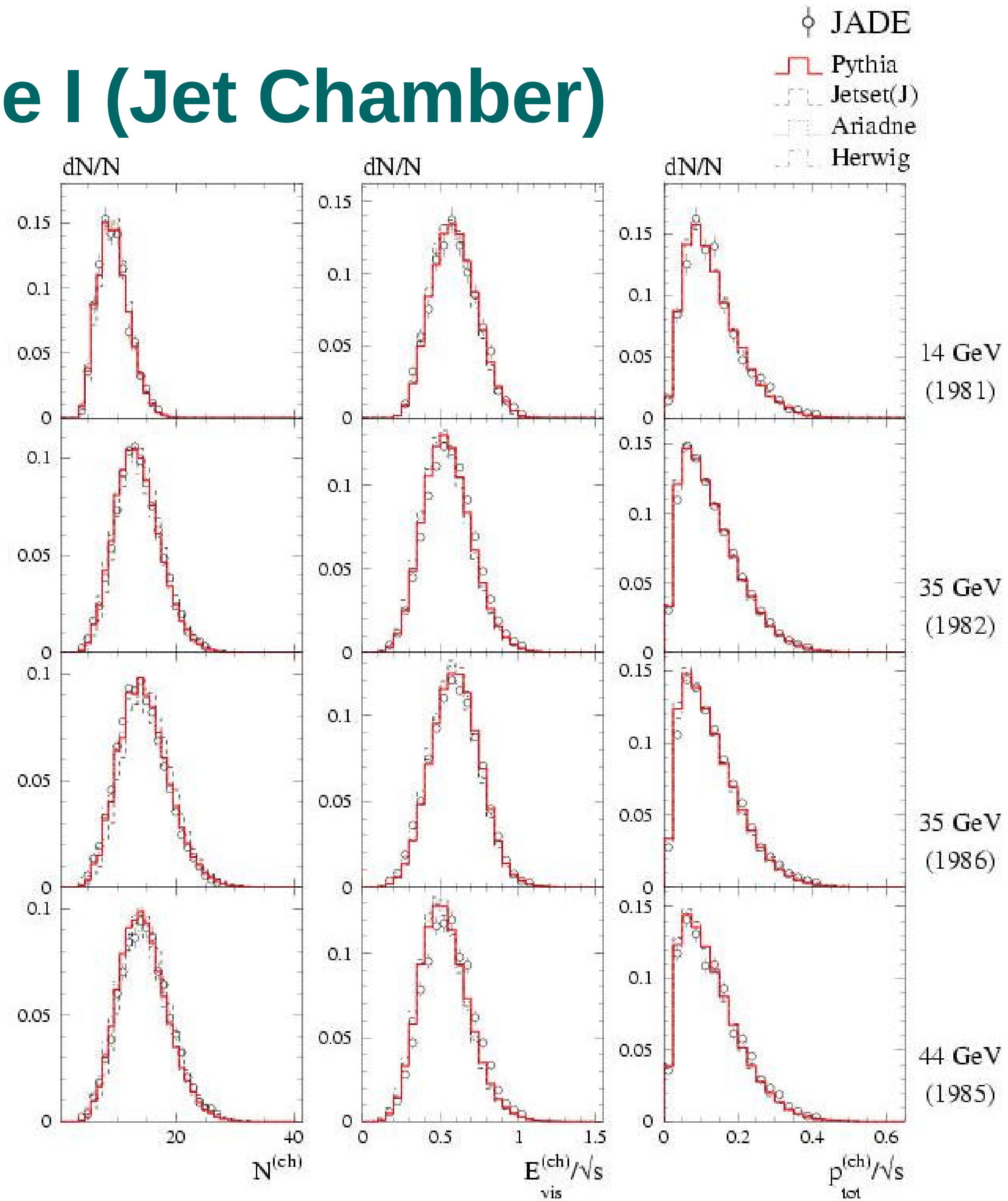
JADE Event Display



Performance I (Jet Chamber)

Integral quantities:

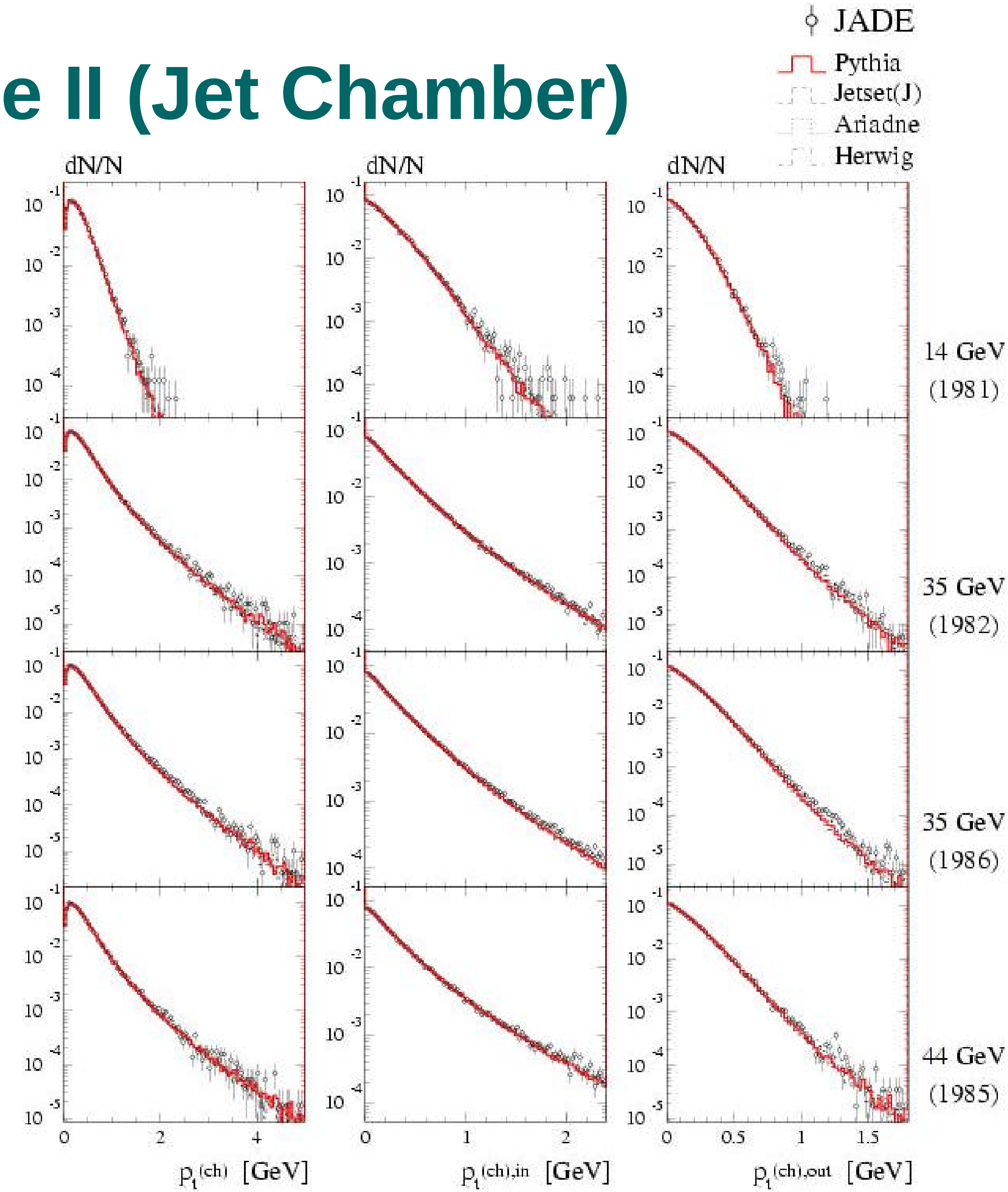
- $N^{(ch)}$,
- $E_{vis}^{(ch)}/\sqrt{s}$,
- $p_{tot}^{(ch)}/\sqrt{s}$,
- …



Performance II (Jet Chamber)

Particle spectra:

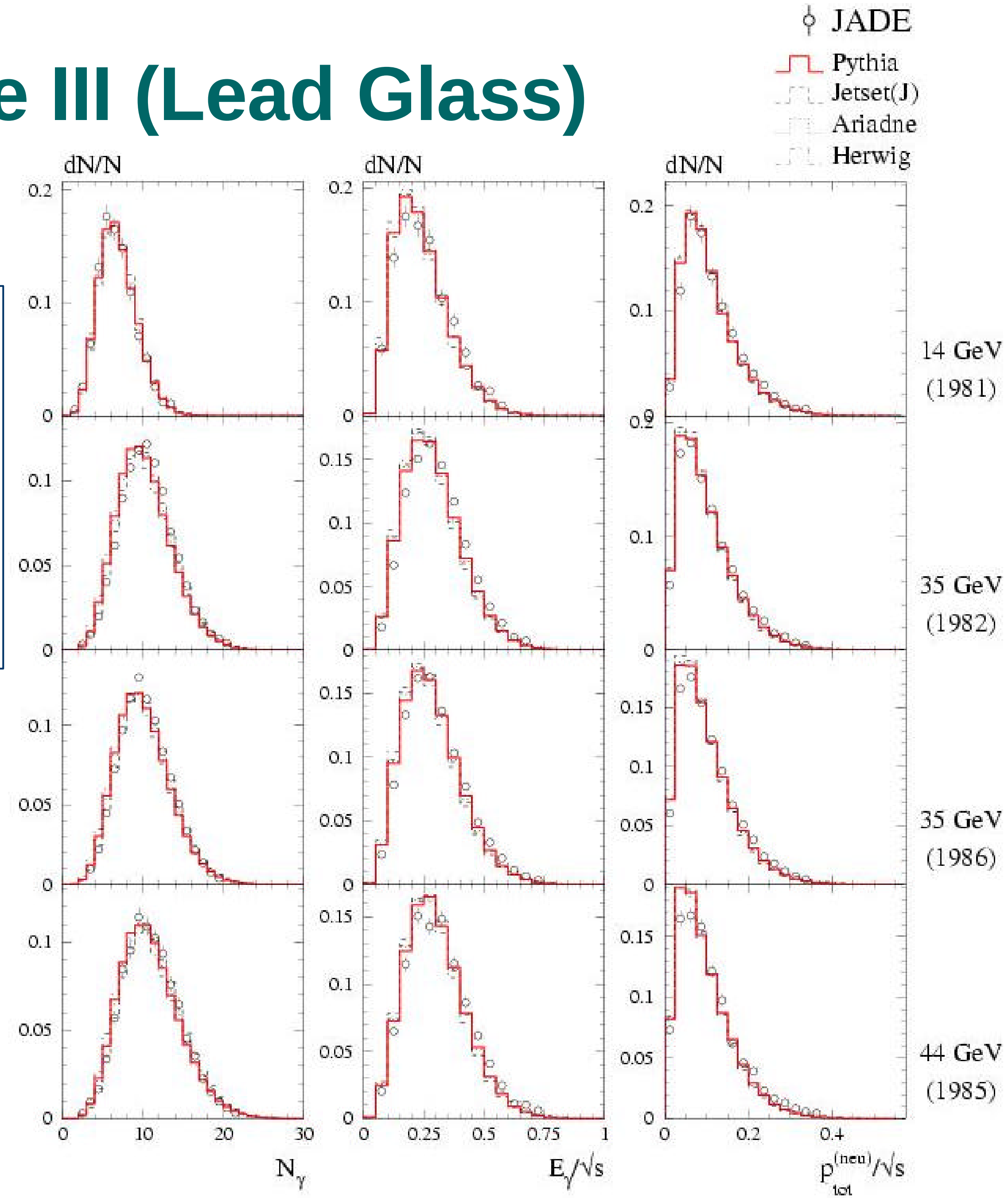
- $p_t^{(ch)}$,
- $p_t^{(ch), in}$,
- $p_t^{(ch), out}$,
- …



Performance III (Lead Glass)

Integral quantities:

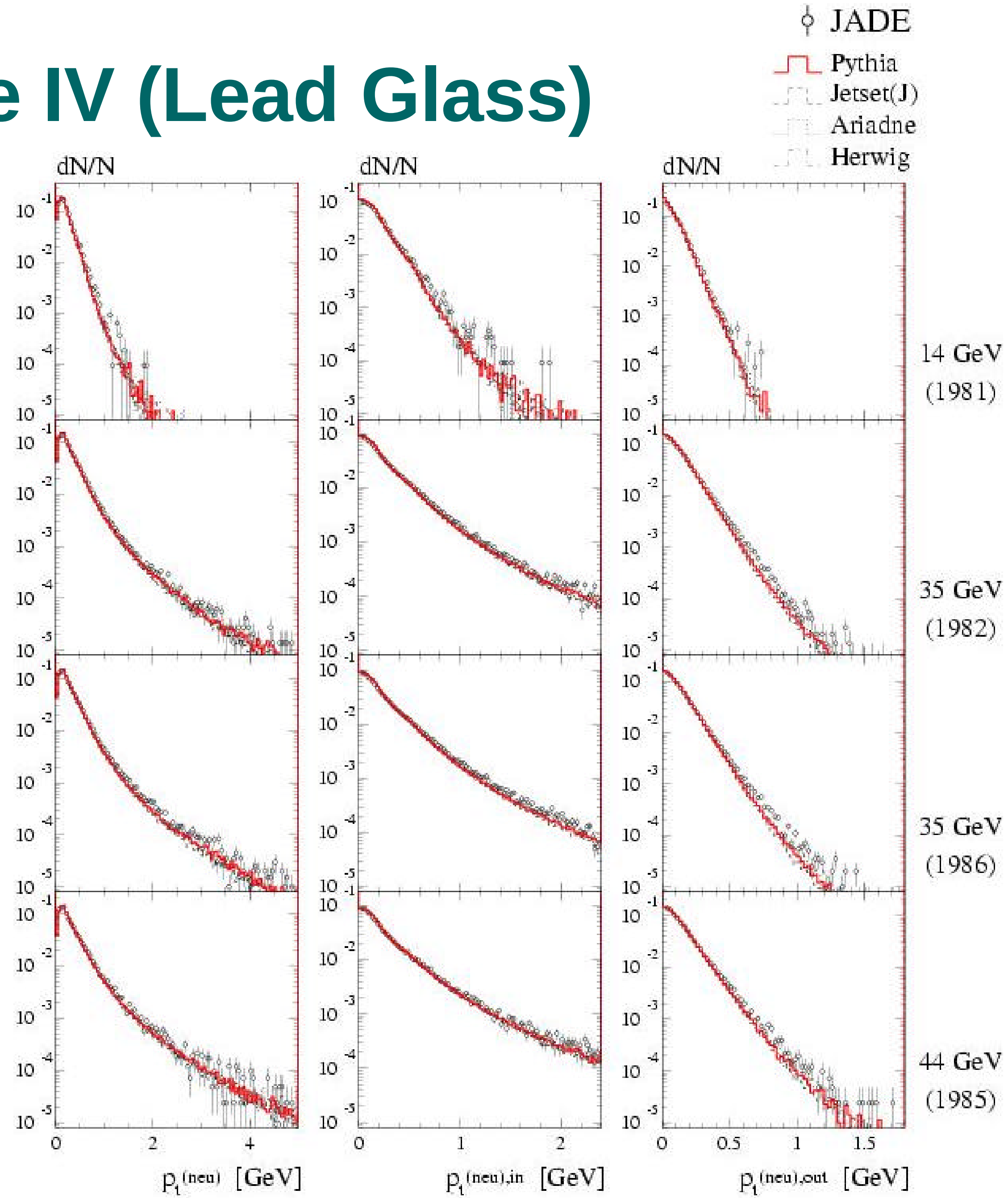
- N_γ ,
- $E_\gamma/\sqrt{s}$,
- $p_{tot}^{(neu)}/\sqrt{s}$,
- …



Performance IV (Lead Glass)

Particle spectra:

- $p_t^{(neu)}$,
- $p_t^{(neu), in}$,
- $p_t^{(neu), out}$,
- …

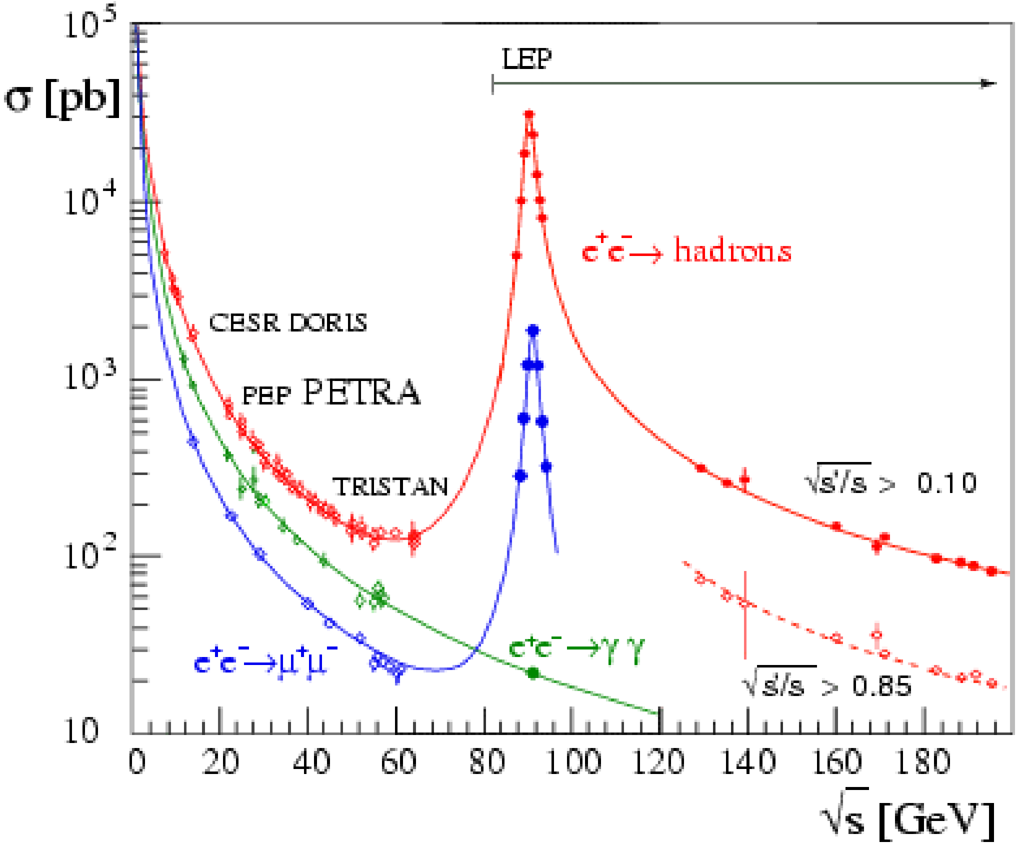


Revival Summary

- 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
  - …

QCD Studies

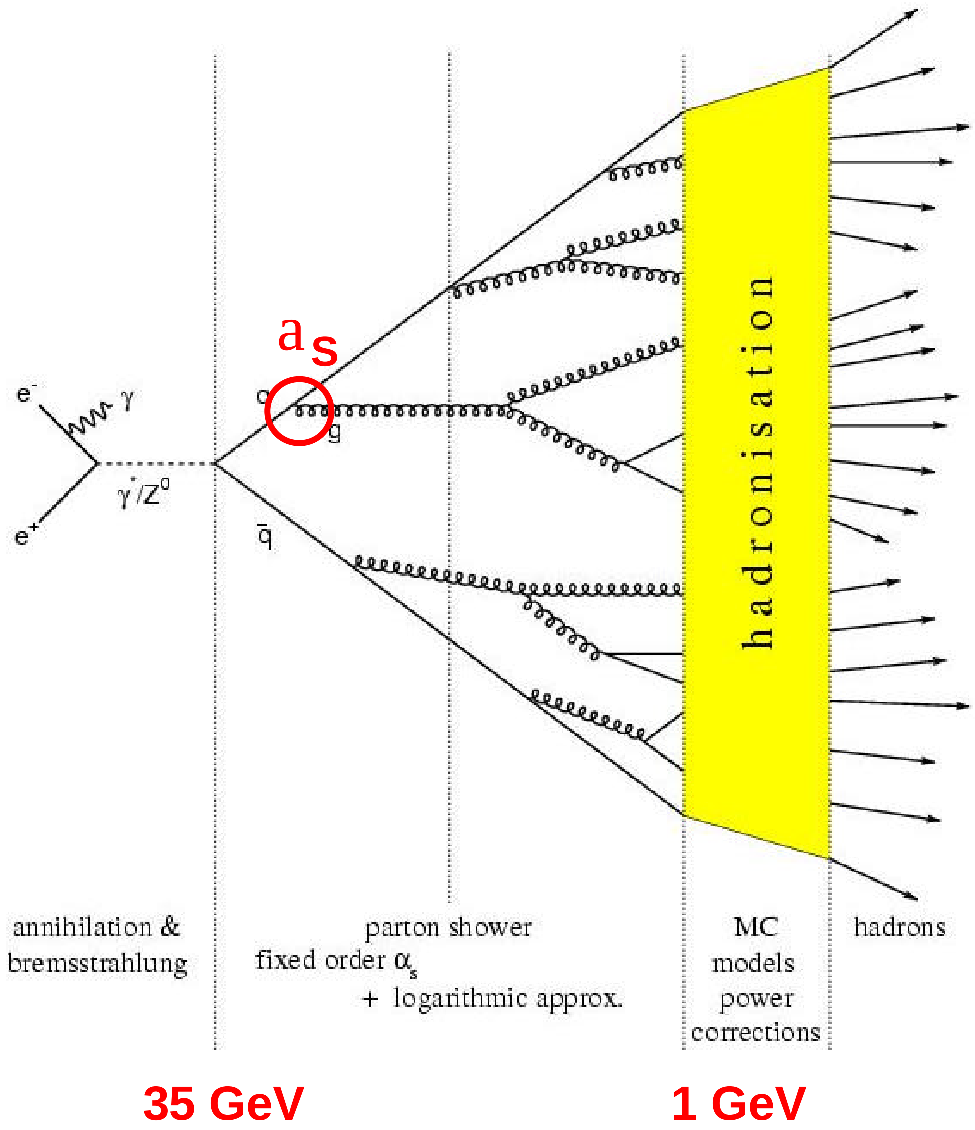
Hadronic Final States



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

- σ^{had} (PETRA) = 0.1…10nb ≈ $1/100\sigma^{had}$ (M_Z)
- Hadron production at PETRA energies mainly via γ^* exchange

QCD in e^+e^- Annihilation



PT QCD:

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

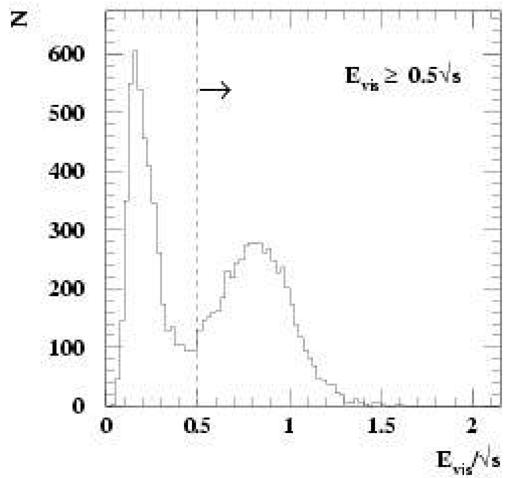
NP QCD:

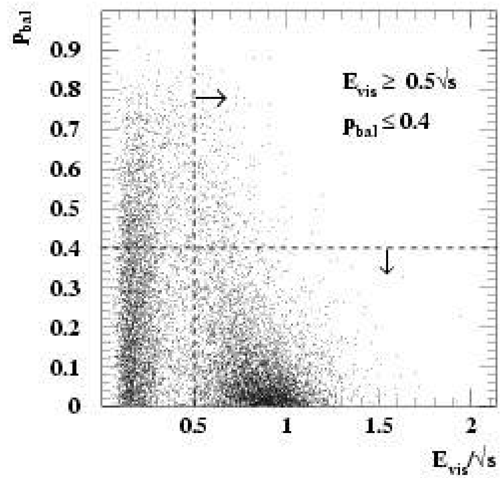
- Phenomenological hadronisation models
- Analytical power corrections

Multihadronic Selection

Main Selection Cuts:

- 4 tracks from vertex region
- 3 "long + good" tracks
- Visible Energy > $0.5\cdot\sqrt{s}$
- Momentum balance < 40%
- Missing Momentum < $0.3\cdot\sqrt{s}$
- $|\cos \Theta_T| < 0.8$





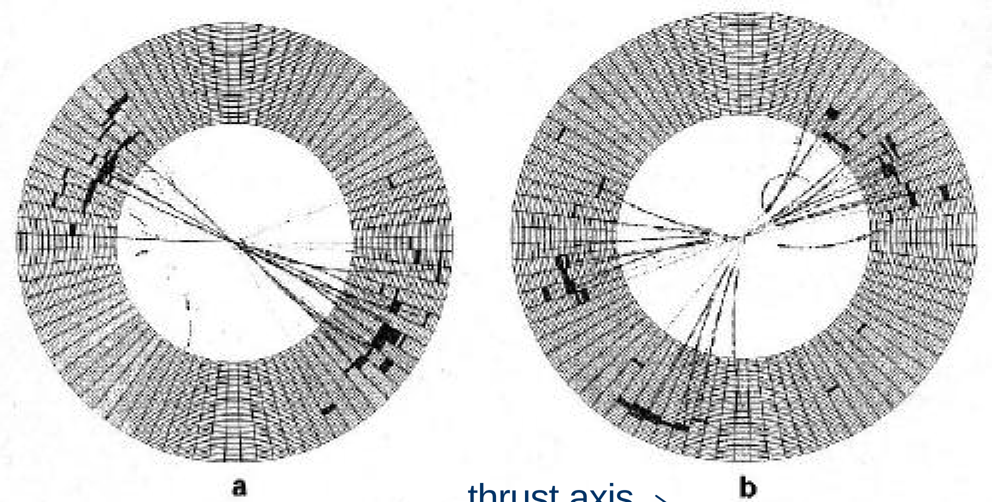
Residual background ≈ 1%

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

MH data samples for main analyses:

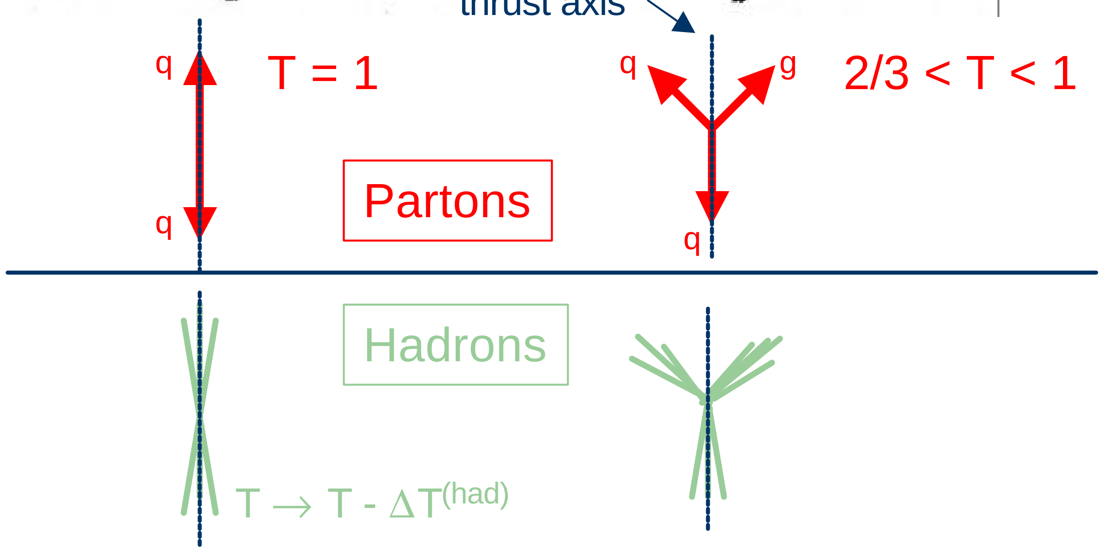
$\sqrt{s}$-range [GeV]	data taking period	$\mathcal{L}$ [pb^{-1}]	$\langle\sqrt{s}\rangle$ [GeV]	MH data
14.0	Jul.-Aug. 1981	1.46	14.0	1734
22.0	Jun.-Jul. 1981	2.41	22.0	1390
33.8 – 36.0	Feb. 1981 - Aug. 1982	61.7	34.6	14372
35.0	Feb.-Nov. 1986	92.3	35.0	20925
38.3	Oct.-Nov. 1981	8.28	38.3	1587
43.4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

Hadronic Event Shapes

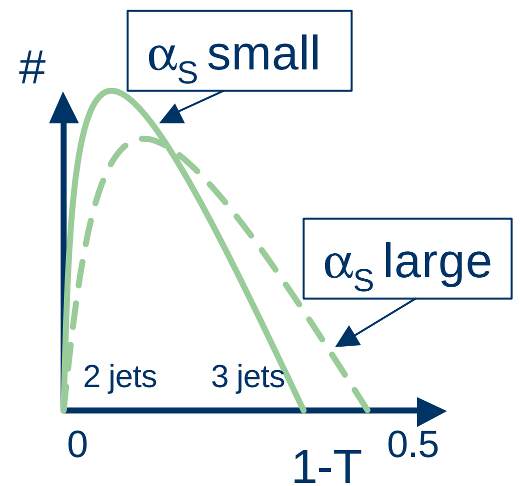


- Quantify the shape of an event by a single number.
- Example: "**Thrust**"

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

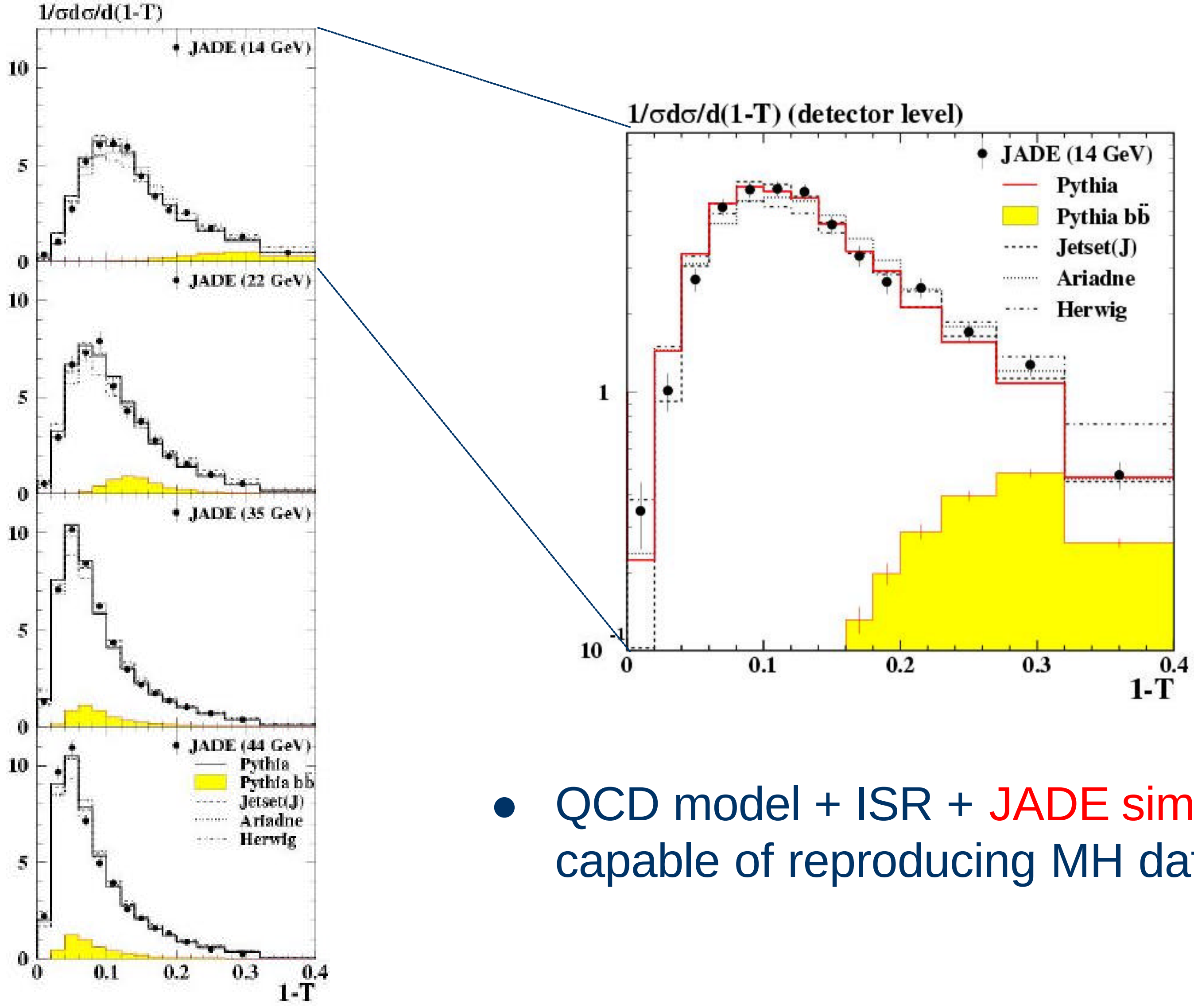


QCD expectation:



Event shape observables are sensitive to PT and NP effects!

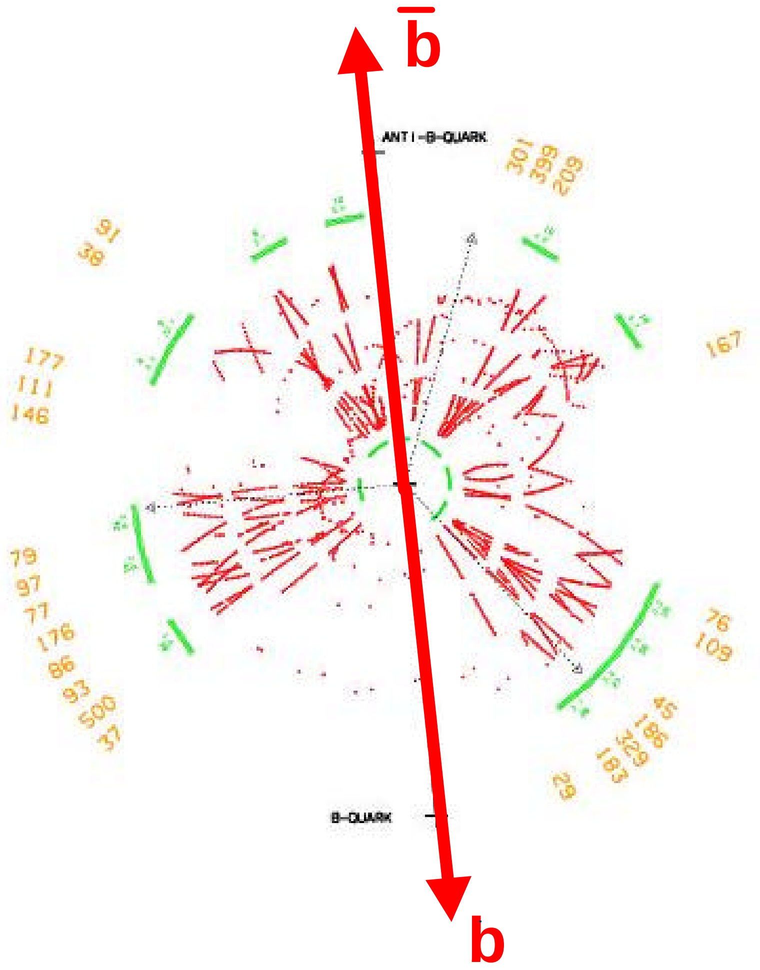
Detector Level Distributions



- QCD model + ISR + JADE simulation capable of reproducing MH data

$b\bar{b}$ Events

Pythia event @ 14 GeV



- 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

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

$\Rightarrow$ thrust axis $\vec{n}_T$
event hemispheres H_k $\Rightarrow$

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

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

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

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

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

- 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").

Measurement

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

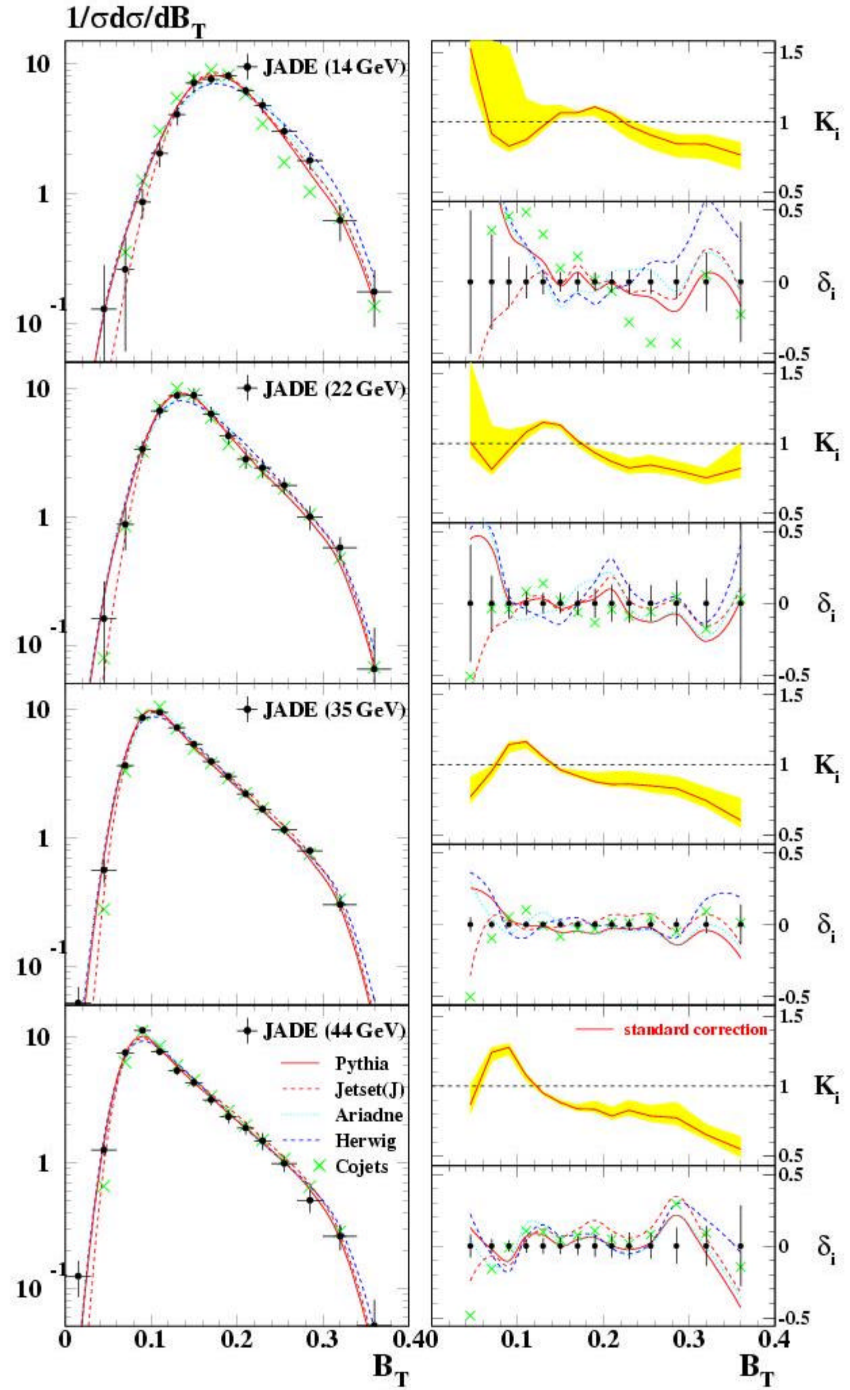
Try also former JADE optimisation for JETSET 6.3

Hadron Level

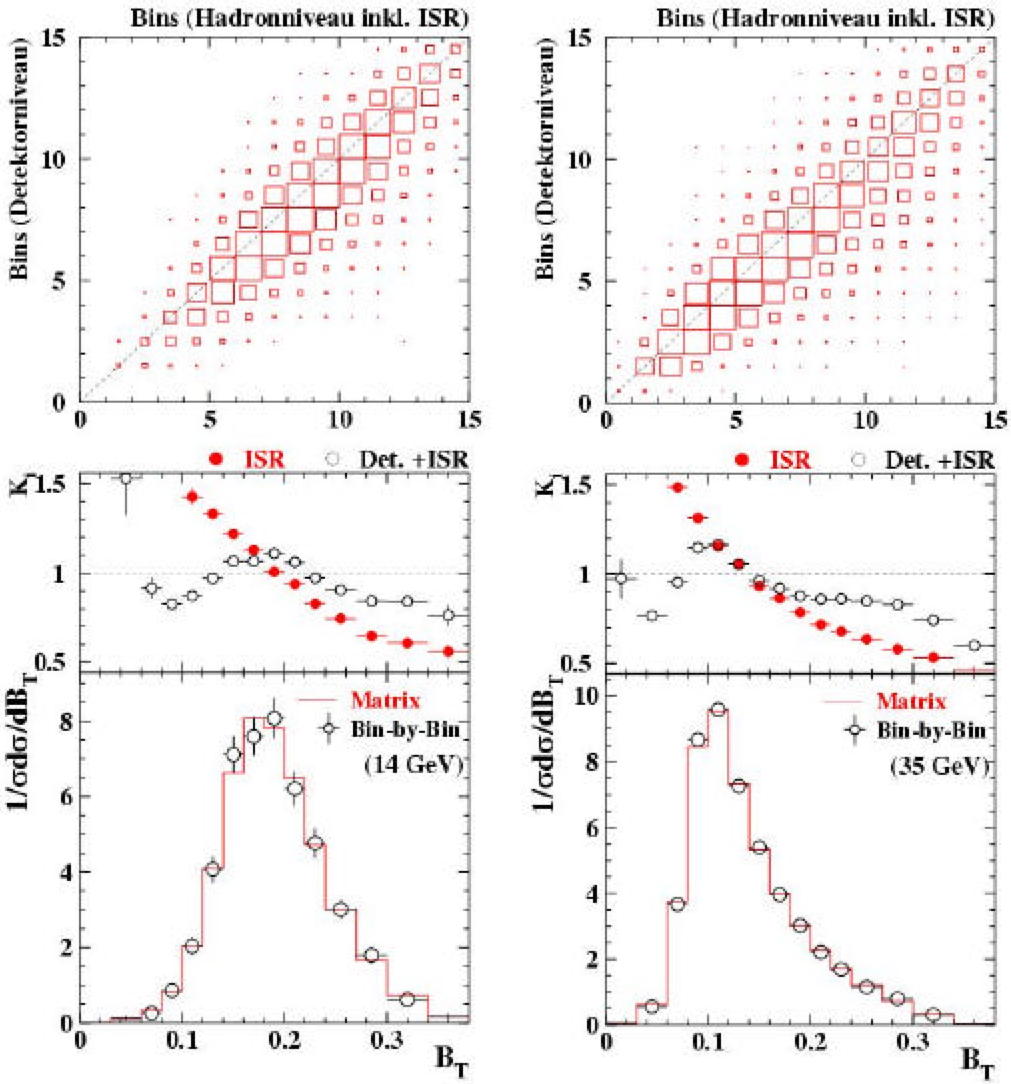
Bin-by-bin unfolding with correction factors $K_i = MC_i^{had}/MC_i^{det}$ based on udsc samples:

- PYTHIA
  - good overall consistency
- HERWIG/ARIADNE
  - moderate at 14+22 GeV, better at higher √s
- JETSET (JADE)
  - 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



Matrix vs. Bin-by-Bin Unfolding



- Consistent hadron levels
- Detector effects partially compensate ISR

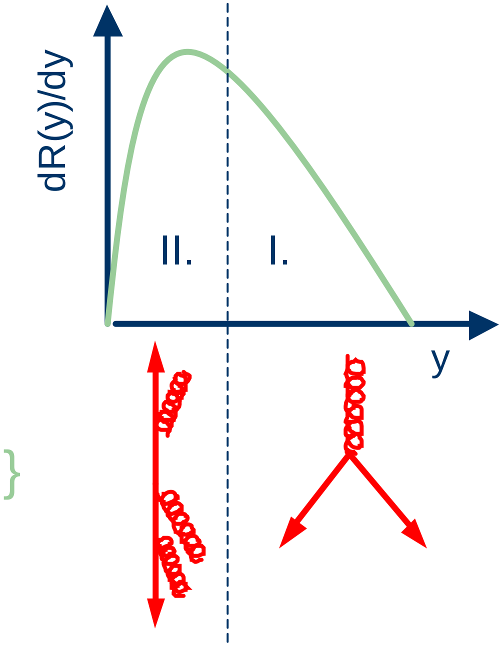
Determination of the α_S

- PT prediction for the cumulative cross section
  $R(y)=\int^{y} dy' 1/\sigma \cdot d\sigma/dy'$

I. NLO: describes "hard" gluon contribution
   $R(y)= 1 + A(y)\cdot\alpha_S + B(y)\cdot\alpha_S^2$

II. NLLA: describes "soft" gluon contribution
   $R(y)= (1+C_1\cdot\alpha_S + C_2\cdot\alpha_S^2) \exp\{ Lg_1(\alpha_S L)+g_2(\alpha_S L) \}$
   $L=\ln(1/y)$

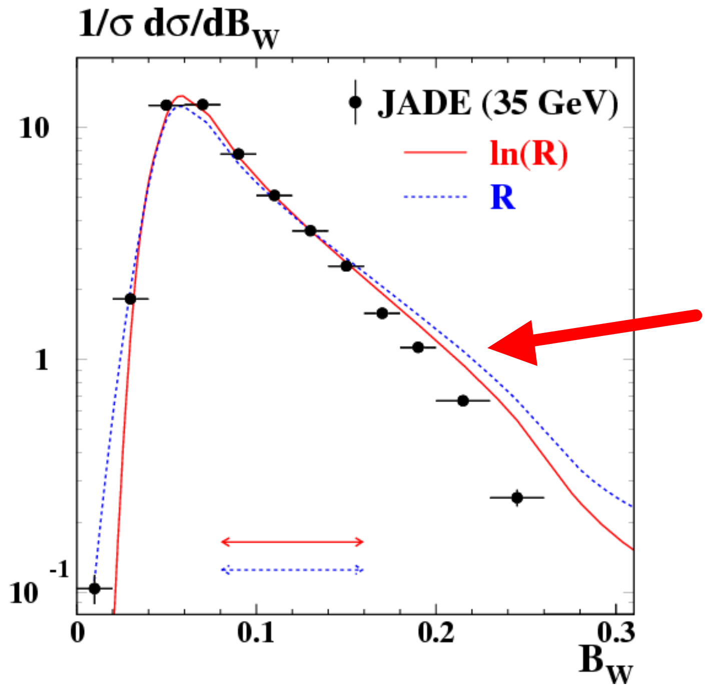
III. Combination of NLO+NLLA, e.g.: ln(R) matching
   $\ln(R) = Lg_1(\alpha_S L)+g_2(\alpha_S L)$
   $- (G_{11}L+G_{12}L^2)\cdot\alpha_S - (G_{22}L+G_{23}L^2)\cdot\alpha_S^2$
   $+A(y)\cdot\alpha_S + [B(y)- ½ A(y)^2]\cdot\alpha_S^2$

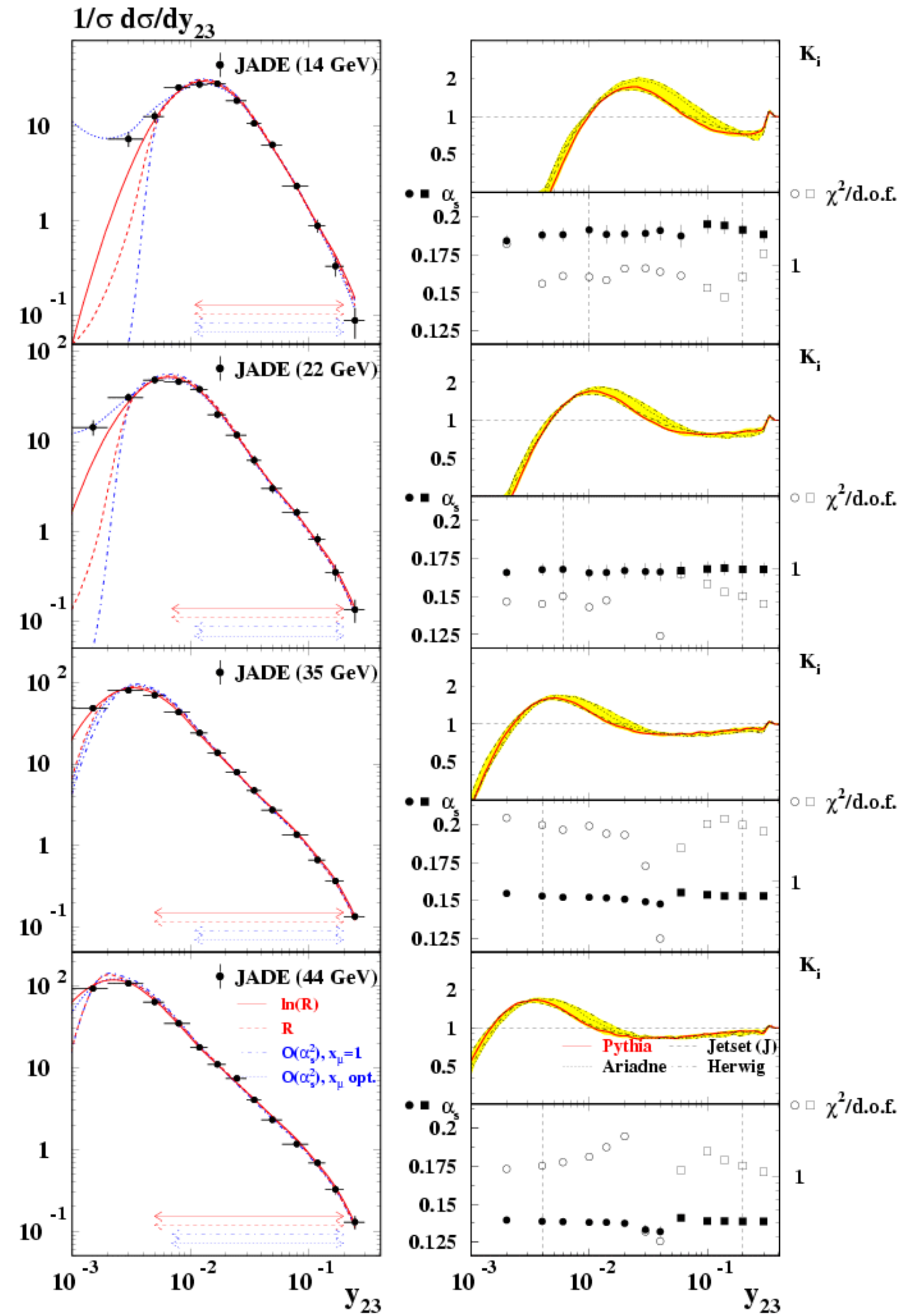


- NP effects: PYTHIA, JETSET(JADE), ARIADNE, HERWIG
- Fit α_S with renormalisation scale factor $x_\mu=\mu/\sqrt{s}=1$
  + bin-by-bin hadronisation correction of R(y) (standard=PYTHIA)

Fit Curves

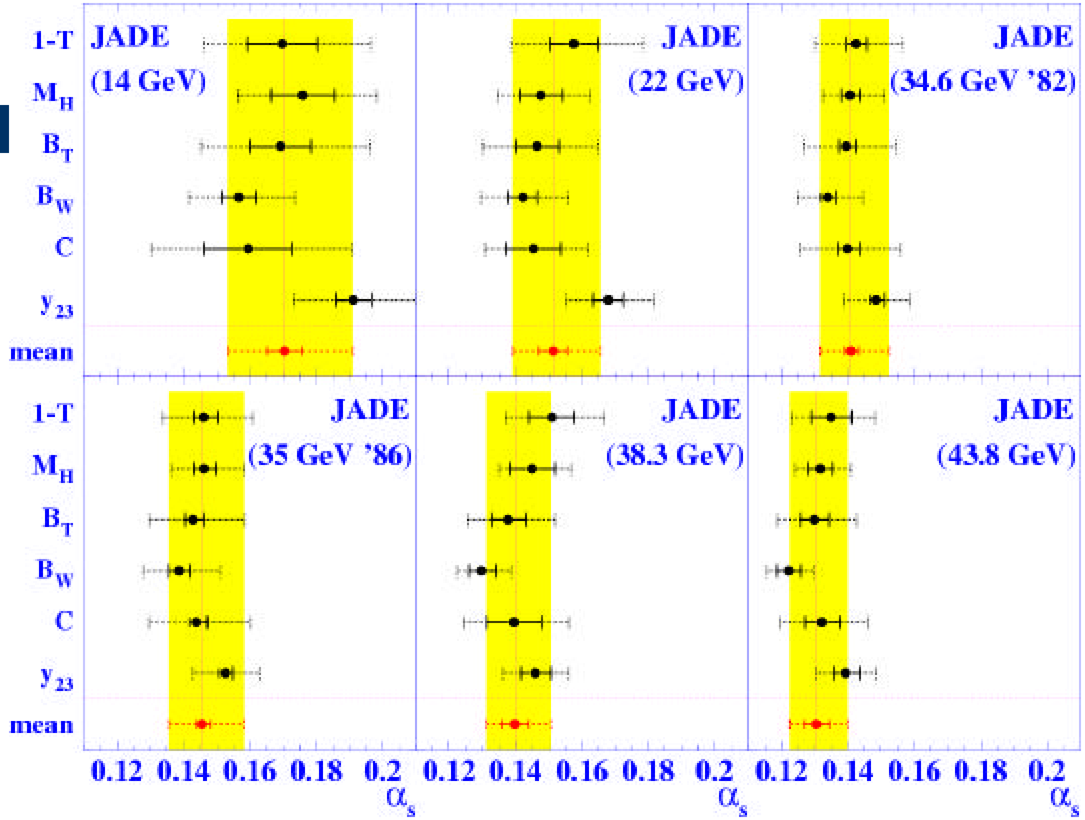
- Typically χ^2/d.o.f. =0.5…2.0
- Stable Fits
- Large hadronisation corrections at 14 GeV!
- Problems with B_W





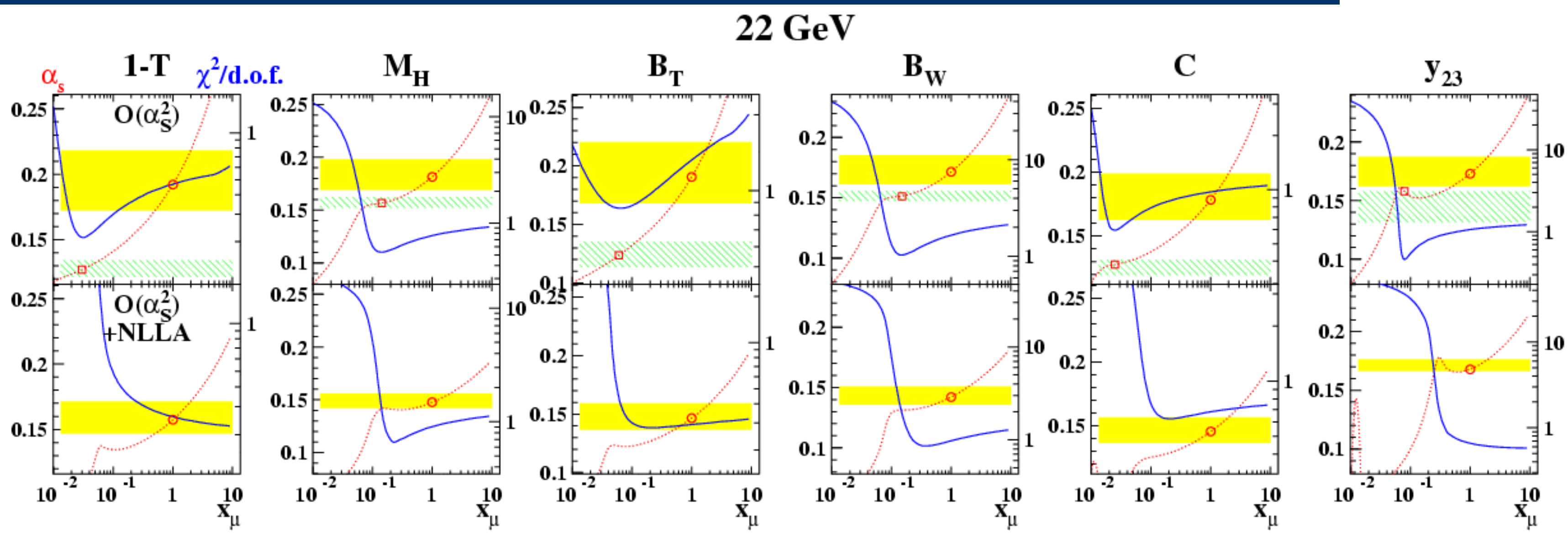
α_s Results

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



$\langle\sqrt{s}\rangle$ [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	$^{+0.0068}_{-0.0044}$	$^{+0.0096}_{-0.0080}$

Renormalisation Scale

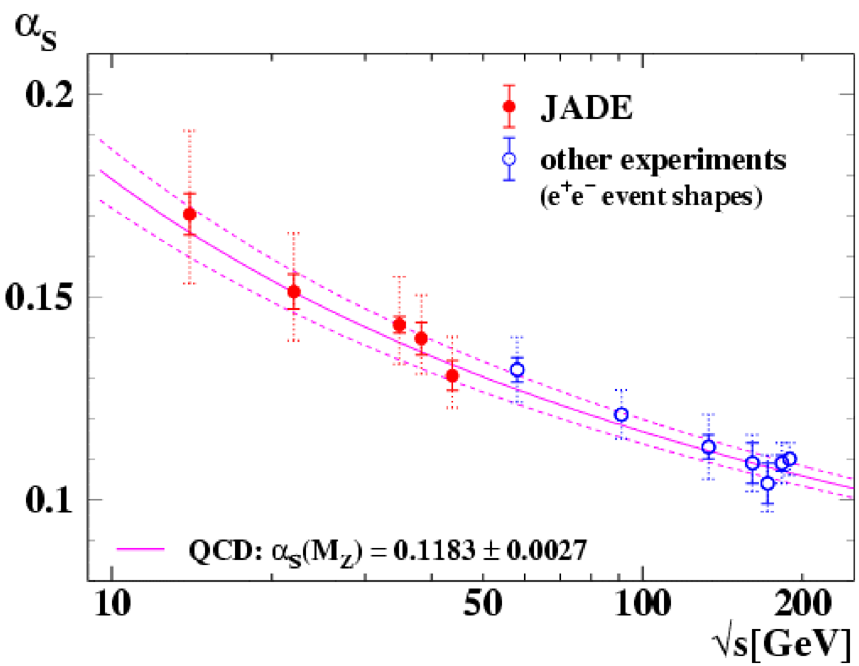


- NLO+NLLA: reduced x_μ dependence around x_μ=1 compared to NLO
  - $\alpha_S(\sqrt{s},x_\mu=1)$ more consistent than in NLO case
  - But: sizable α_S dependence around x_μ=1 still present
- Pure NLO: Preference for small $x_\mu^{(opt)}$ = O(0.01…0.5)
  - scale dependence around $x_\mu^{(opt)}$ sometimes 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

Test of the Running of α_S



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

- Now more values with higher accuracy available
- α_S of "homogeneously" determined from PETRA to LEP2 energies

QCD expectation:

$C_A=3$, $C_F=4/3$, $N_F=5$

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

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

$$\beta_0 = \frac{1}{12\pi}(33 - 2N_f)$$

$$\beta_1 = \frac{1}{24\pi^2}(153 - 19N_f)$$

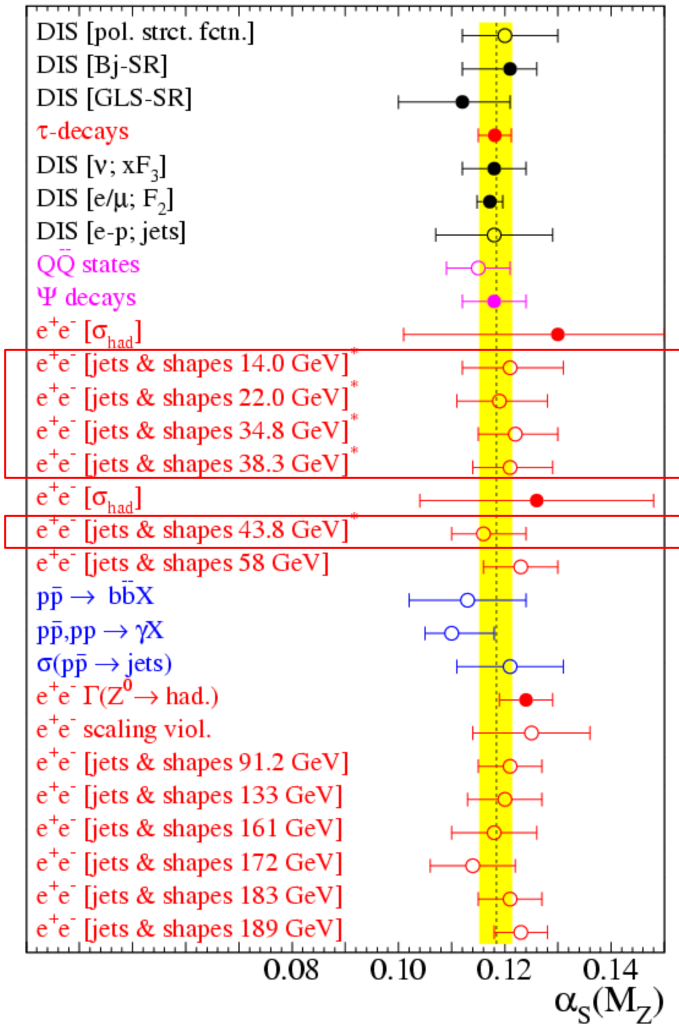
$$\beta_2 = \frac{1}{3456\pi^3}\left(77139 - 15099N_f + 325N_f^2\right)$$

Good agreement with world average based on NNLO QCD

α_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 α_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

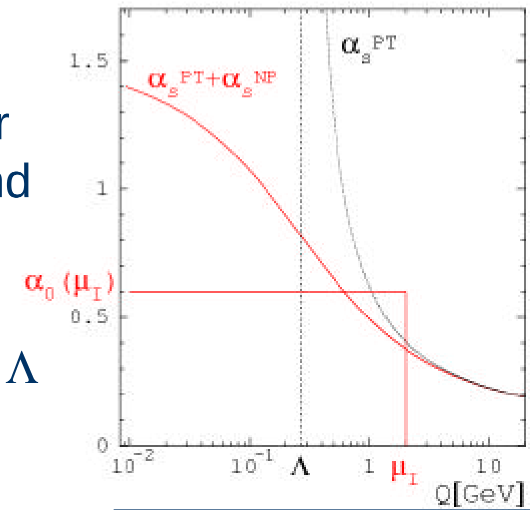
$$\alpha_S(M_{Z^0}) = 0.1194^{+0.0083}_{-0.0070} \quad \text{(PETRA)}$$
$$\alpha_S(M_{Z^0}) = 0.121 \pm 0.006 \quad \text{(LEP + SLC)}$$
$$\alpha_S(M_{Z^0}) = 0.120 \pm 0.007 \quad \text{(LEP2)}$$



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 Λ (0…2GeV)
  - Dokshitzer, Marchesini, Webber (DMW): NP structure due to soft gluon radiation at $\mu \approx \Lambda$



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

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

$$\alpha_0(\mu_\mathrm{I}) \equiv \frac{1}{\mu_\mathrm{I}} \int_0^{\mu_\mathrm{I}} \mathrm{d}\mu\, \alpha_\mathrm{S}(\mu)$$

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

- α_0 is the only NP parameter!
- α_0 is universal

Power Corrections to Distributions

- Observable specific part is D_y:
  $\Rightarrow$ T, M_H, C: shift
  $\Rightarrow$ B_T, B_W: shift+squeeze

  (y_{23} : no 1/Q contribution)

y	$\mathcal{D}_y = \mathcal{D}_y(\alpha_S, y)$
$1-T$	2
M_H^2	1
C	3π
B_T	$\ln(1/y) + D_T(y, \alpha_S(yQ))$
B_W	$\frac{1}{2}\ln(1/y) + D_1(y, \alpha_S(yQ))$

Test of DMW ansatz:

- Use mod. ln(R) matching for PT part
- Perform simultaneous (α_S, α_0) fits to all available event shape spectra

Available data sets:

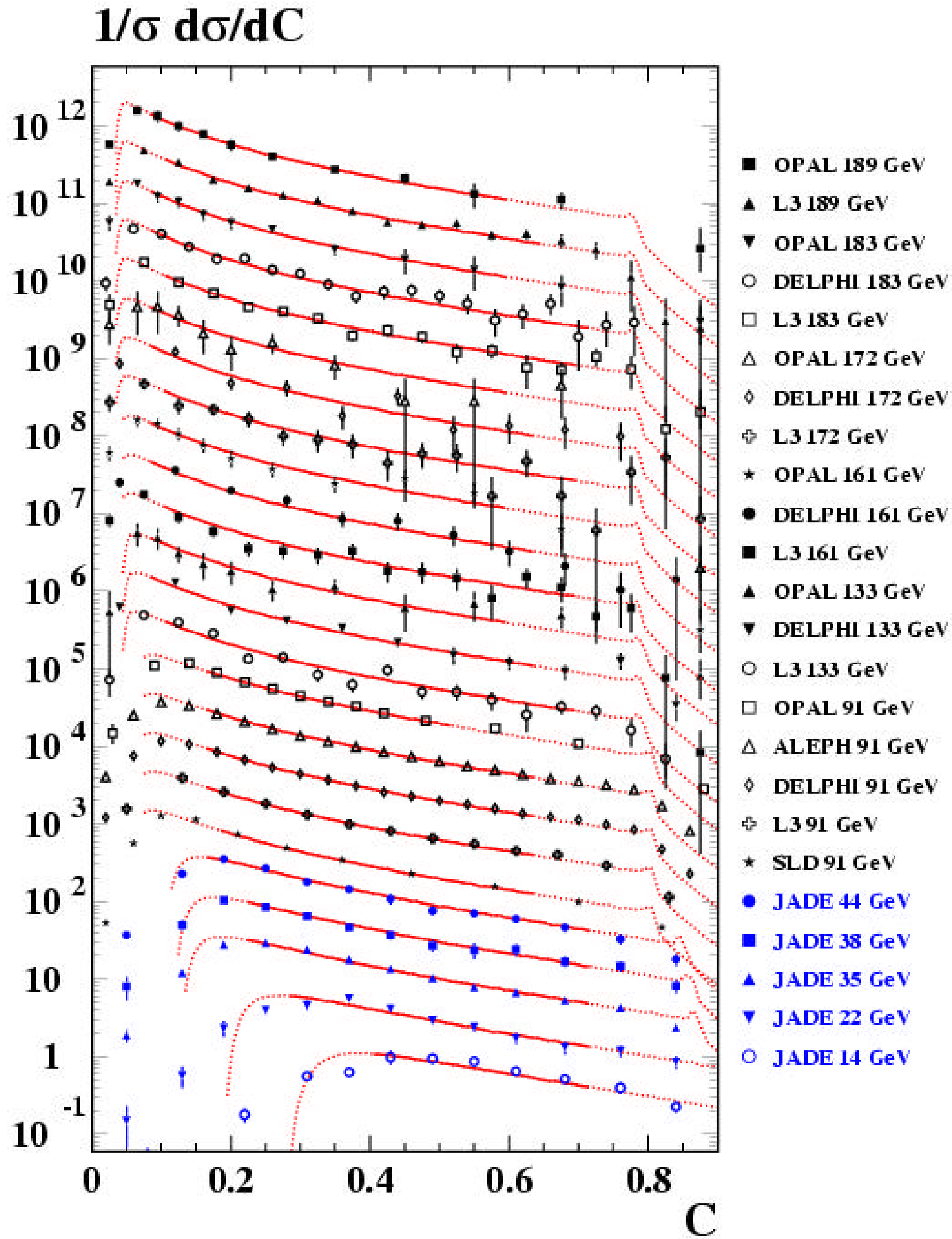
Accelerator	$\sqrt{s}$ [GeV]	$1-T$ M_H	B_T, B_W, C
PETRA (JADE, TASSO)	12-47	102000	43700
PEP (HRS, MARK II)	29	28300	
TRISTAN (AMY)	55-58	1900	
LEP I (ADLO*)	91	$\mathcal{O}(10^6)$	
SLC (SLD)	91	37200	
LEP II (ADLO*)	133-189	15600	

JADE is the only contribution for new observables below M_Z

… covering the energy range $\sqrt{s}$ = 14…189 GeV !!!

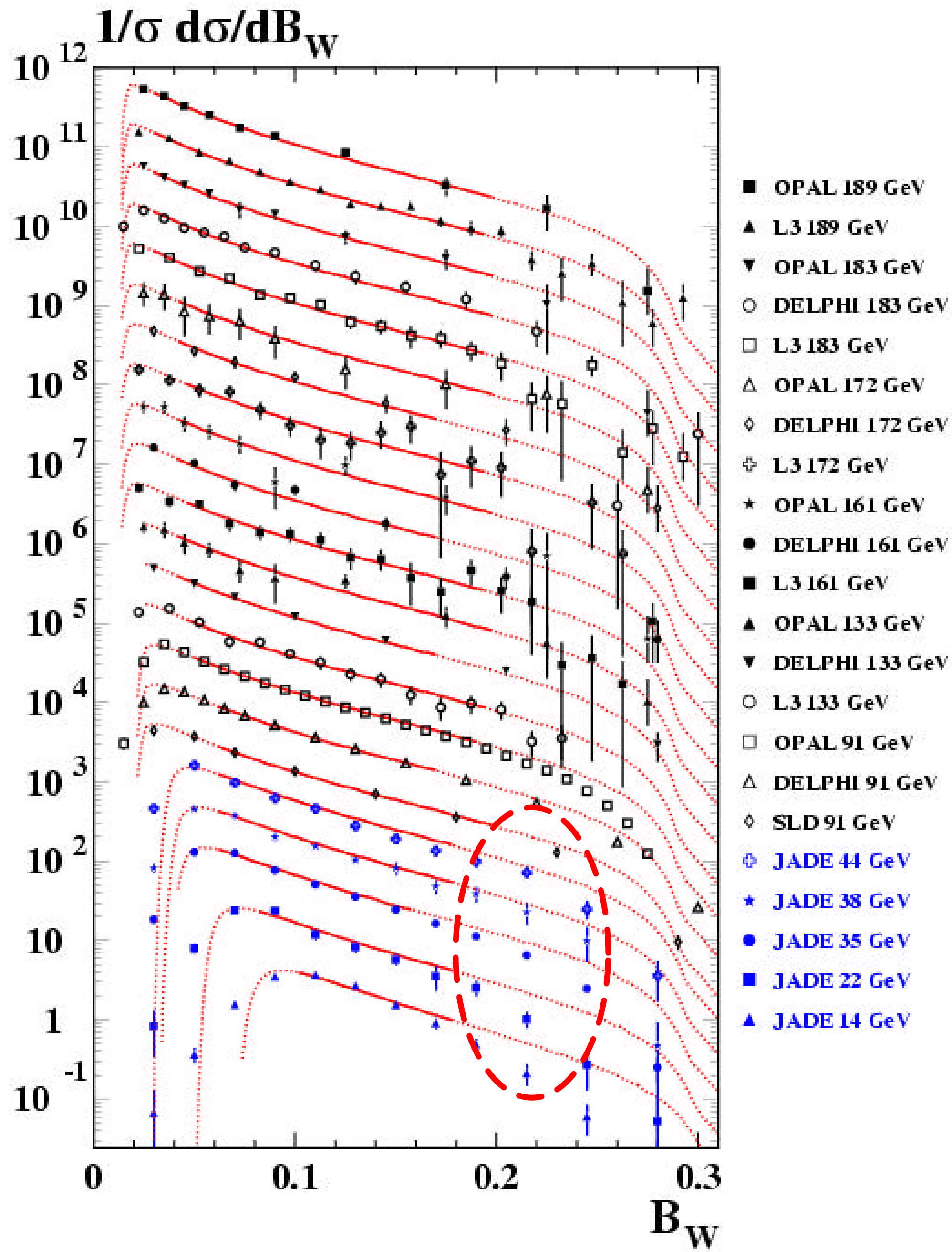
DMW Fits (I)

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

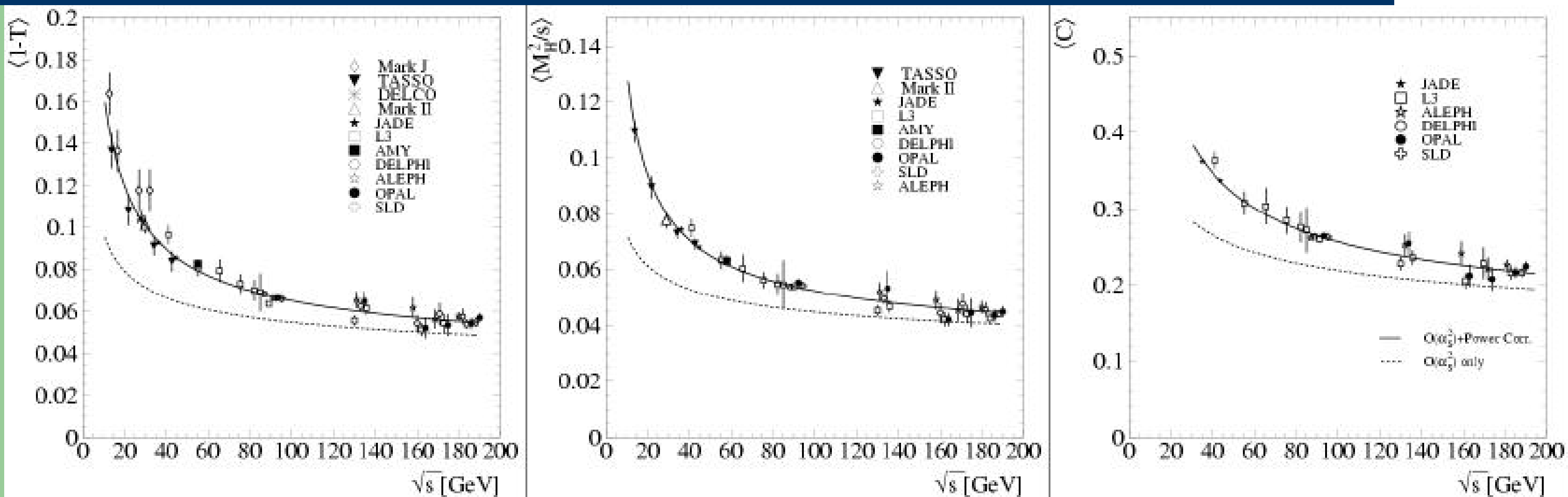


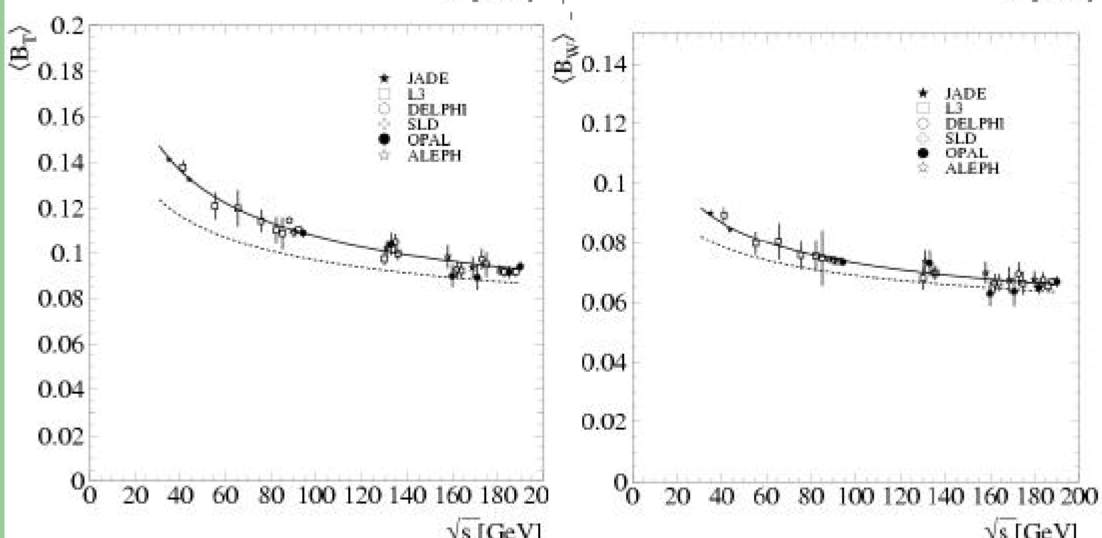
DMW Fits (II)

- 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

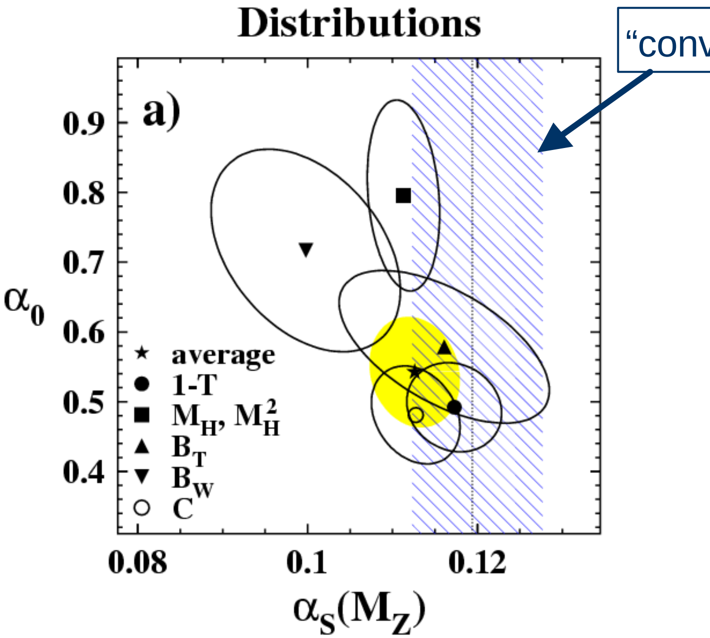


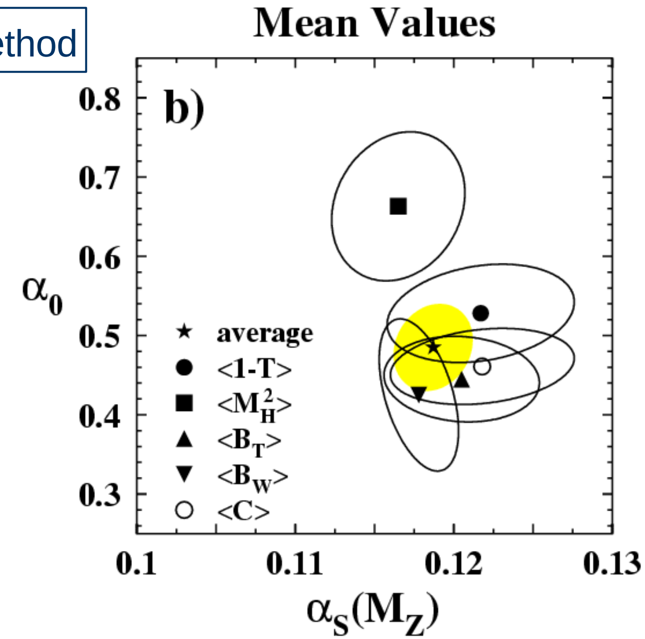


- NLO+DMW capable of describing measured mean values of all observables

[Does not include update at 14+22 GeV]

(α_S, α_0)-Results



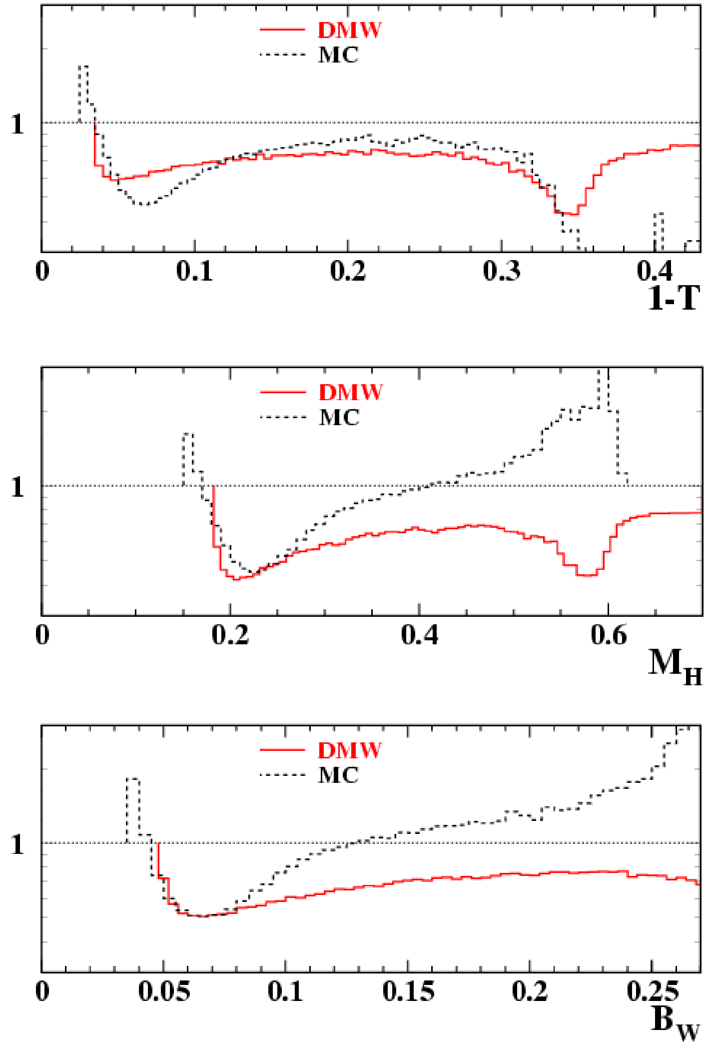


Distributions	fit	exp.	theo.
$\alpha_S(M_{Z^0})=$ 0.1126	± 0.0005	± 0.0037	$^{+0.0044}_{-0.0030}$
$\alpha_0(2\text{ GeV})=$ 0.542	± 0.005	± 0.032	$^{+0.084}_{-0.060}$

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

- Individual results consistent within 1-2σ of total errors
- α_0 universal within 20% uncertainty level of the Milan factor
  (stemming from $O(\alpha_S^2)$ evaluation of power corrections)
- But: $\alpha_S^{(pow.corr)} < \alpha_S^{(MC)}$ due to minor/missing squeeze of PT spectrum
  (fit chooses small α_S to compensate; big effect for jet broadening variables!!!)

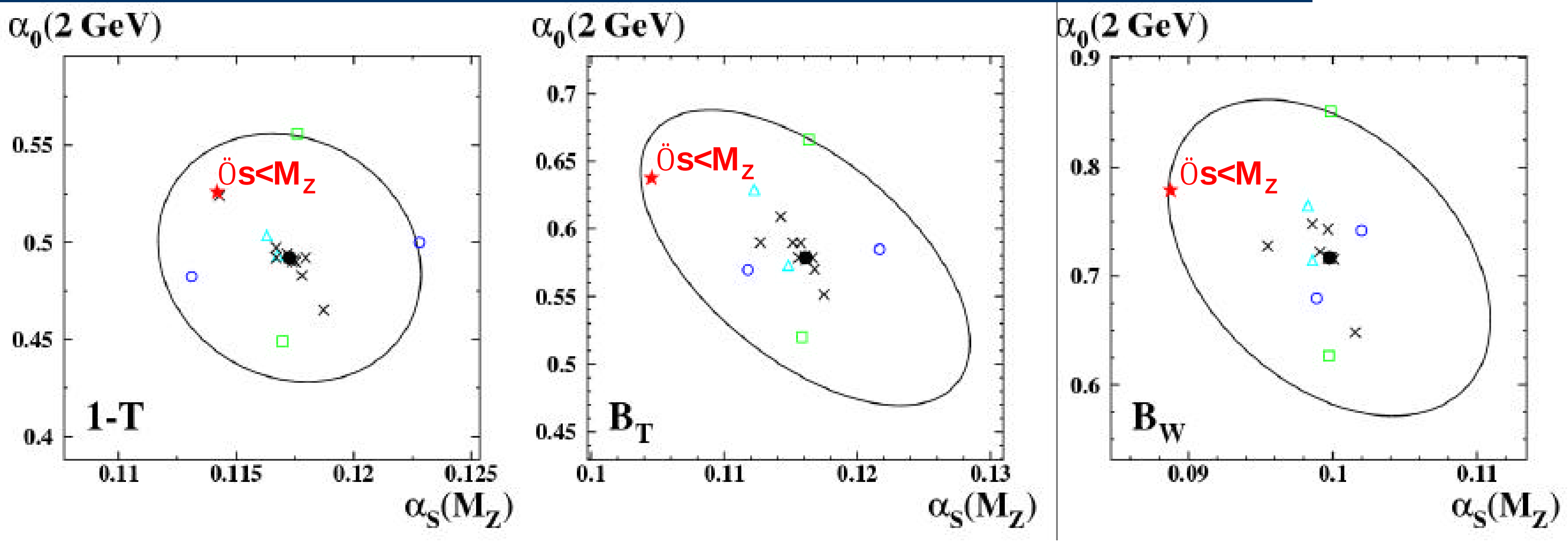
Power Corrections vs. MC Predictions



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 α_S values

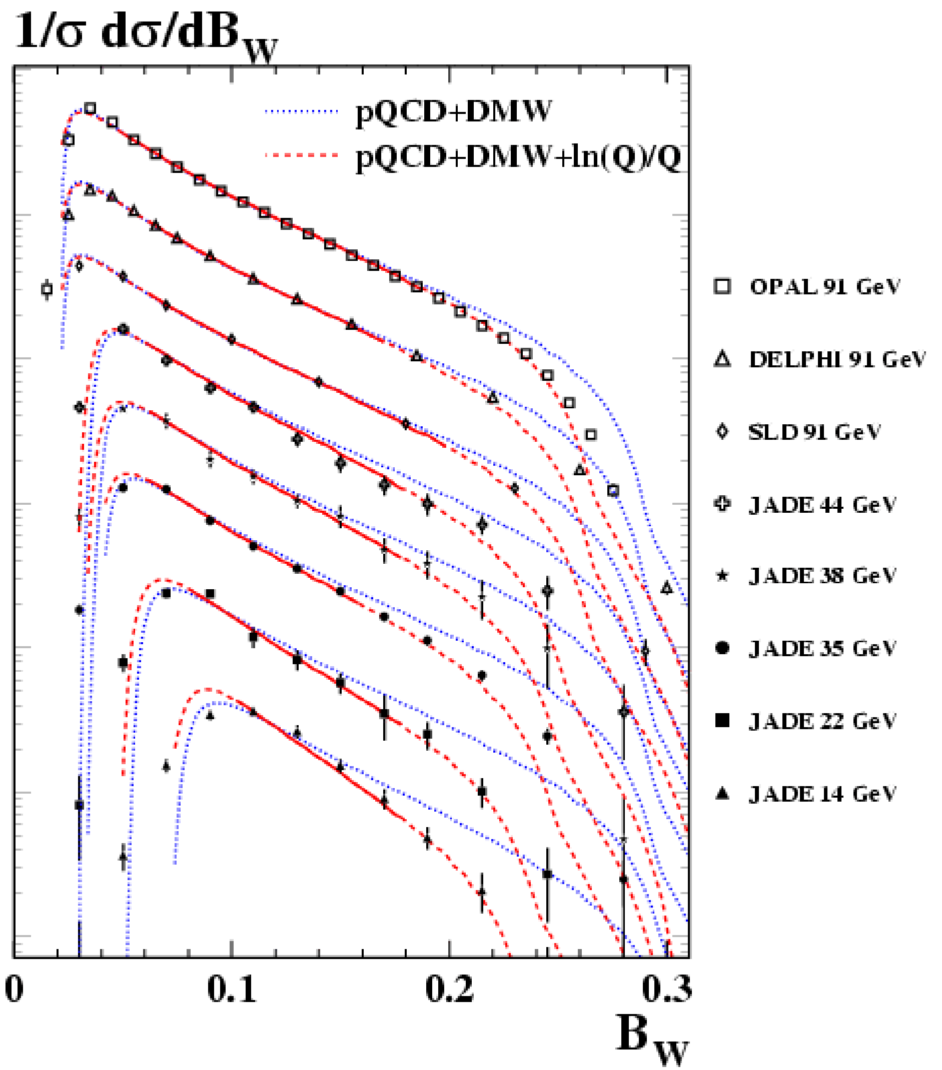
Missing NP Terms?



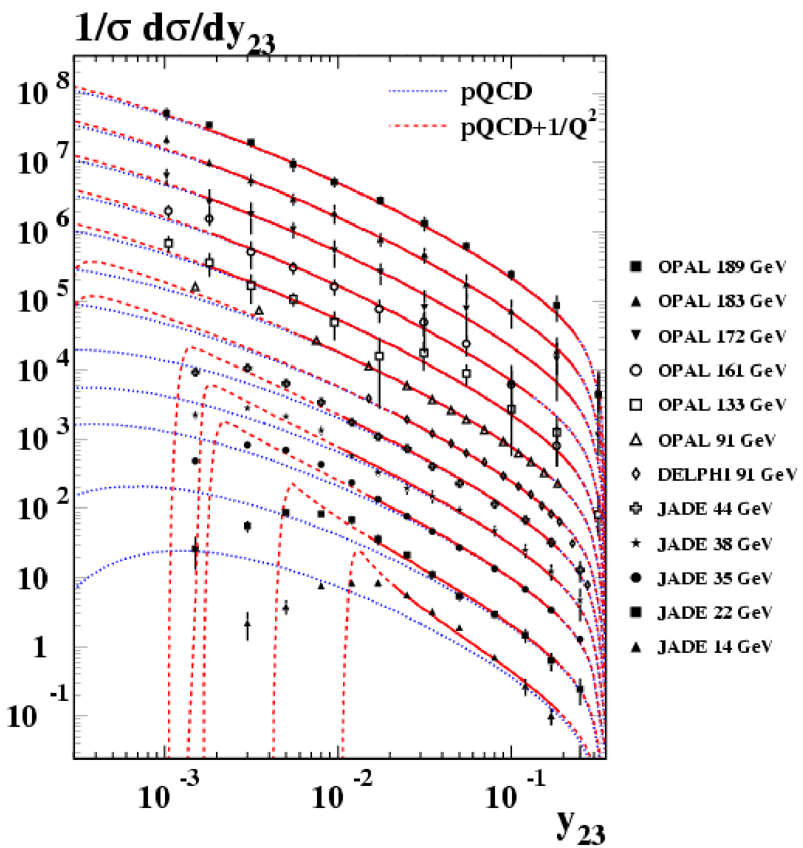
- Explore possible missing (higher order) terms by fits to separate data sets: $\sqrt{s}<M_Z$, $\sqrt{s}$ ³ M_Z , …
  - Large systematic effects for B_T, B_W

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_μ)
- 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!

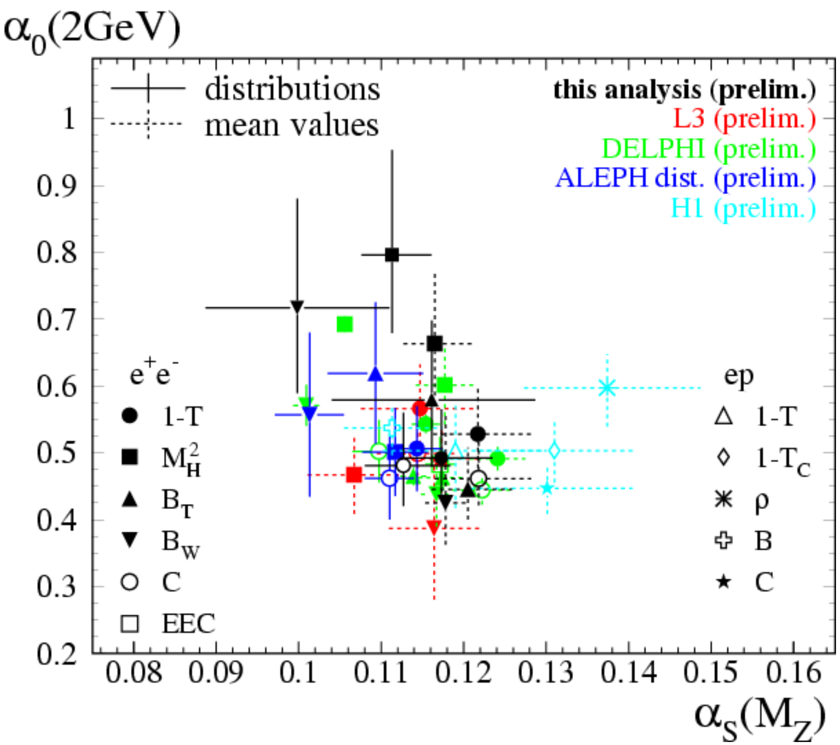
		$\alpha_S(M_{Z^0})$	$\mathcal{A}_{10}$[GeV]	$\mathcal{A}_{20}$[GeV^2]	χ^2/d.o.f.
I	pQCD	0.1147±0.0005	—	—	59.7/100
II	pQCD	0.1152±0.0005	—	—	151/107
	pQCD+$\mathcal{A}_{10}/Q$	0.1124±0.0006	0.062±0.008	—	98.2/106
	pQCD+$\mathcal{A}_{20}/Q^2$	0.1133±0.0005	—	2.25±0.18	71.2/106
	pQCD+$\mathcal{A}_{10}/Q$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

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)
- α_0 universal at 20% level
- DMW (for distributions) different from MC prediction
  $\rightarrow \alpha_S^{(pow.corr)} < \alpha_S^{(MC)}$
- Indication of higher order terms (B_W, y_{23}) may inspire theorists?
- Combined means+distributions:

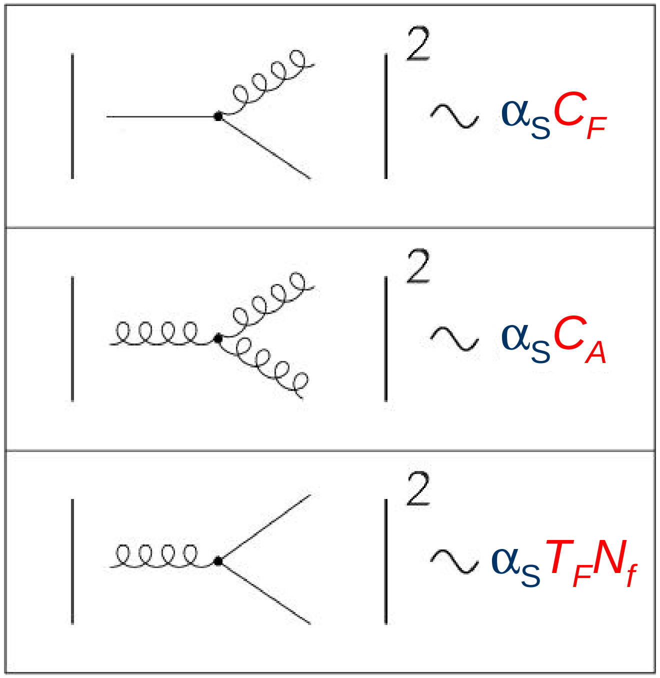
$$\alpha_S(M_{Z^0}) = 0.1175^{+0.0031}_{-0.0021}$$
$$\alpha_0(2\text{ GeV}) = 0.503^{+0.066}_{-0.045}$$

- Consistency with other measurements



More and improved PC calculations needed!

Colour Factors from Event Shapes



Relative weights of fundamental vertices determined by QCD gauge structure:

$C_F = 4/3$, $C_A = 3$, $T_f N_f = 1/2 N_f$

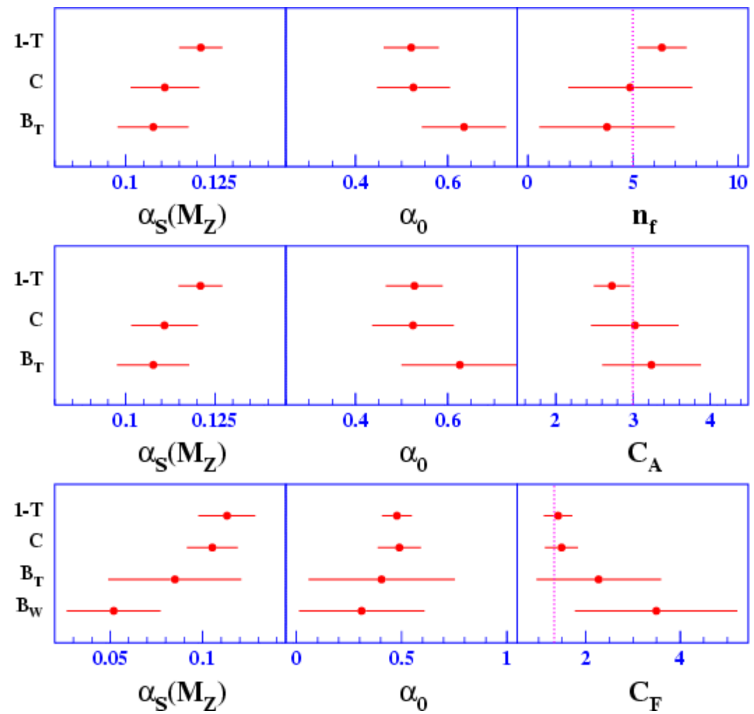
Colour structure known for event shape

- PT part
  - $A \propto C_F$, $B = B(C_A, C_F, N_F)$
  - $NLLA = NLLA\ (C_A, C_F, N_F)$
- Running α_S
  - $\beta_0 = \beta_0 (C_A, N_F)$, $\beta_1 = \beta_1 (C_A, C_F, N_F)$
- 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)

Results



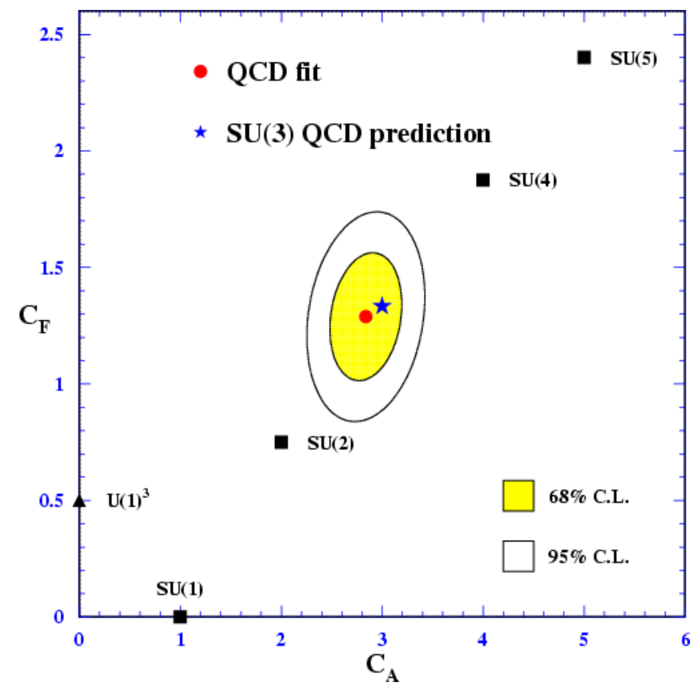
	Fit α_S and α_0 and (C_A or C_F or N_f)		Fix α_0 and N_f and fit α_S and C_A and C_F		
	$1-T$	C	$1-T$	C	QCD
C_A	2.7 ± 0.2	3.0 ± 0.6	2.7 ± 0.2	3.0 ± 0.5	3
C_F	1.4 ± 0.3	1.5 ± 0.4	1.3 ± 0.2	1.3 ± 0.5	4/3
N_f	6.4 ± 1.2	4.9 ± 3.0	—	—	5

- 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 s $_L$

Differential cross section for inclusive hadron production in **e⁺e⁻** ® g,**Z** ® **h+X**

contribution from gluon radiation in quark/anti-quark system

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

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

transverse… longitudinal… asymmetric…

…contribution to <u>fragmentation function *F*^{h}*(x)*</u>

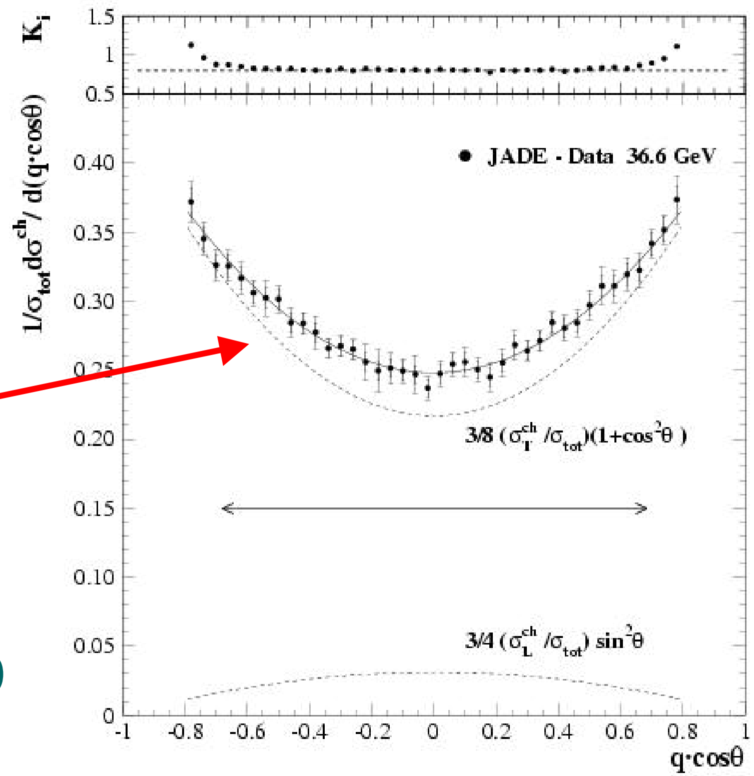
x = 2p/√s: fractional momentum of particle

Θ = ∠(incoming particle, outgoing hadron)

$$\frac{\sigma_{T,L}}{\sigma_{\mathrm{tot}}} \equiv \frac{1}{2}\sum_h \int \mathrm{d}x\ x\cdot\mathcal{F}_{T,L}^h(x)$$

⇩

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



- **measure cos(q) distribution of charged particles**
- **fit r$_L$/r$_{tot}$ and h^{ch} (corrects for neutral particles)**

Results

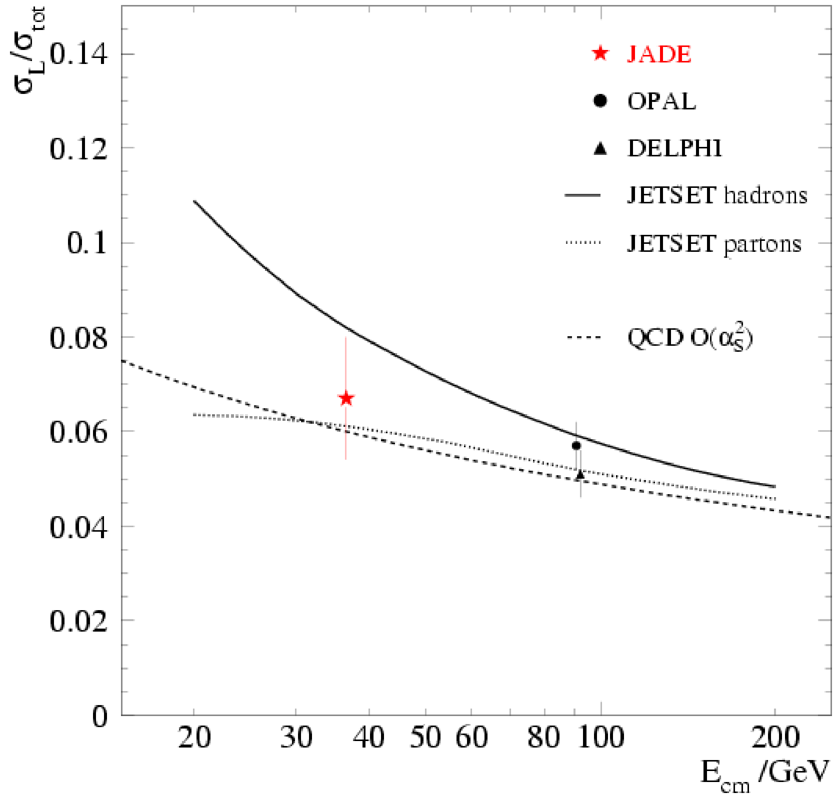
$\rho_L/\rho_{tot} = 0.067 \pm 0.011$

Dominant errors:

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

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

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



Power corrections:

$\alpha_S(M_Z) = 0.126 \pm 0.020$
$\alpha_0(2\text{GeV}) = 0.3 \pm 0.3$

… not fixed as yet due to low data+MC statistics

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

x Distribution

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

- MLLA calculation (Fong, Webber):

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

$$Y \equiv \ln\frac{\sqrt{s}}{2\Lambda_{\text{eff}}}$$

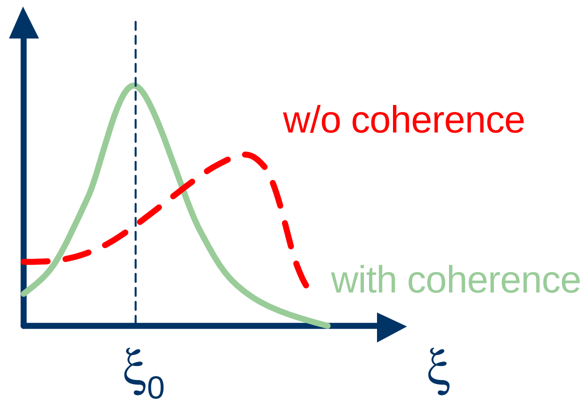
$$\delta \equiv \frac{\xi - \langle\xi\rangle}{\sigma}$$

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

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

with N, k, s, σ, β, ρ, ω known functions of Y, C_A, C_F, N_f

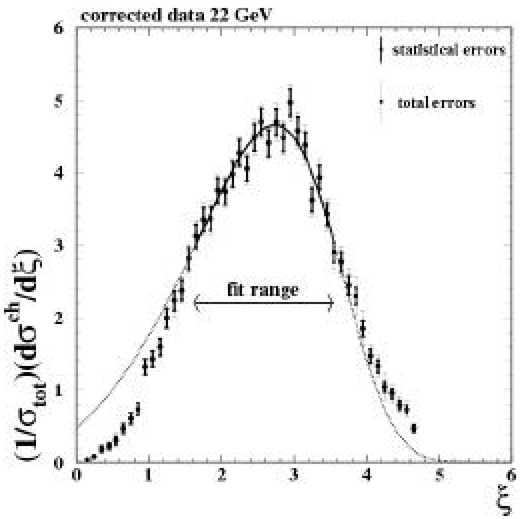
skewed Gaussian

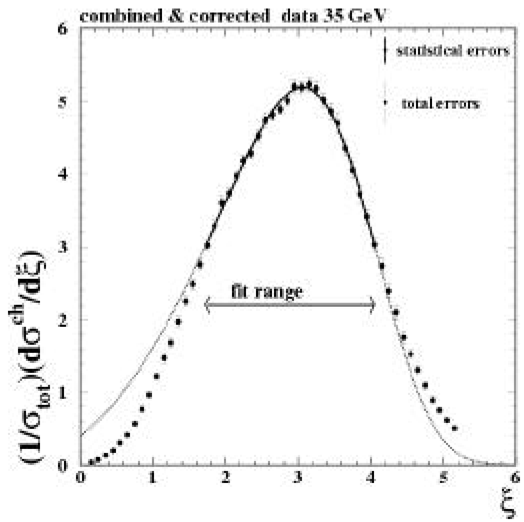


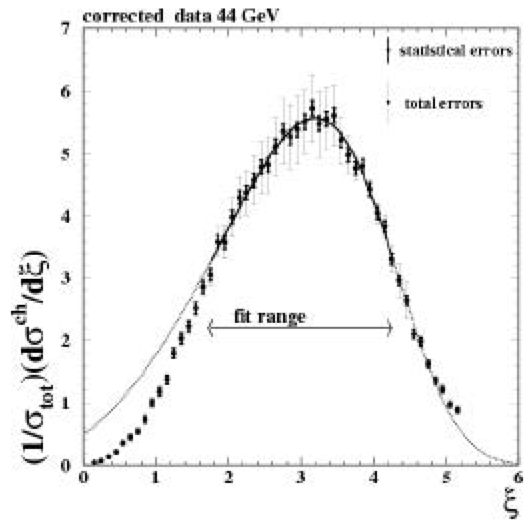
PT prediction
+
Assume LPHD
(affects mainly normalisation and not shape)
⇓
Hadron spectrum

- Test MLLA by fits to measured distributions @ 22, 35 and 44 GeV (theory only valid close to ξ_0)
- Free parameters: e.g. N, Λ_{eff}, ξ_0
- Explore the predicted scale dependence of ξ_0

Fits

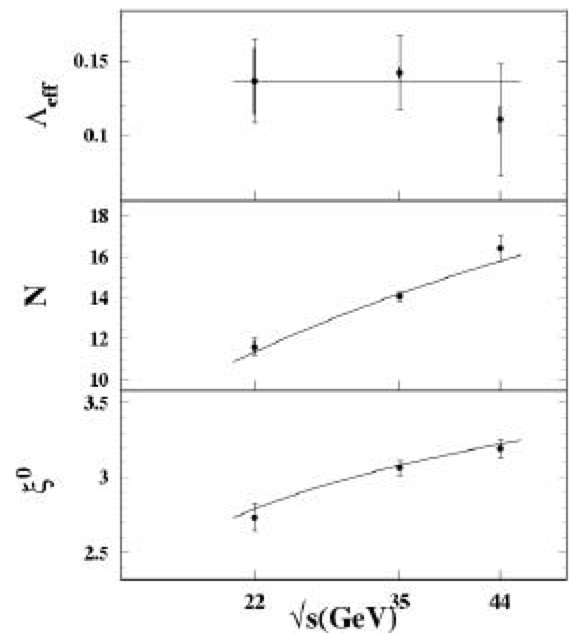




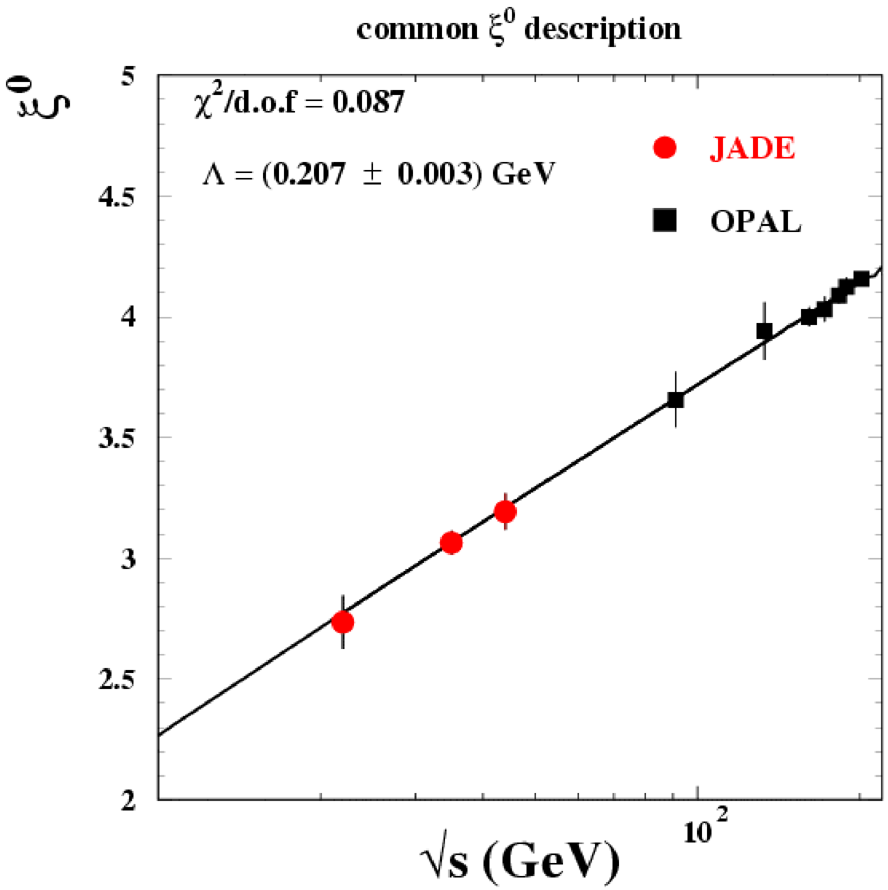


- Good description of data within the kinematic boundaries
- Energy evolution consistent with QCD expectation

	ξ_0	N	Λ_{eff}
22 GeV	2.74±0.09	11.6±0.4	136±28
35 GeV	3.06±0.05	14.1±0.2	142±25
44 GeV	3.19±0.06	16.4±0.6	110±38



Scale Dependence

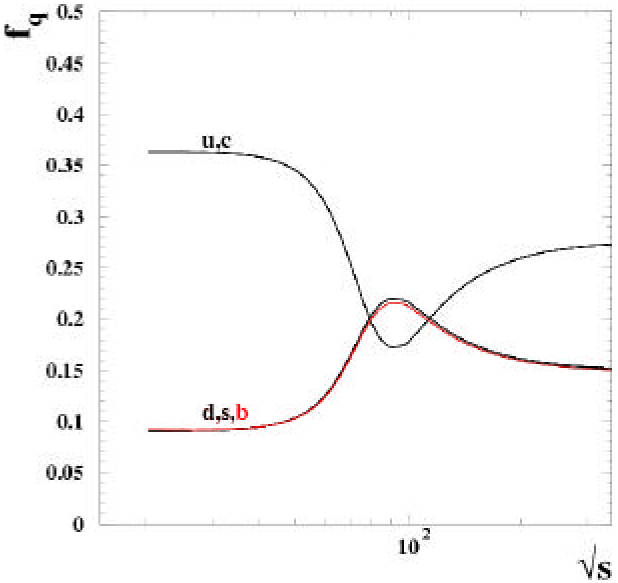


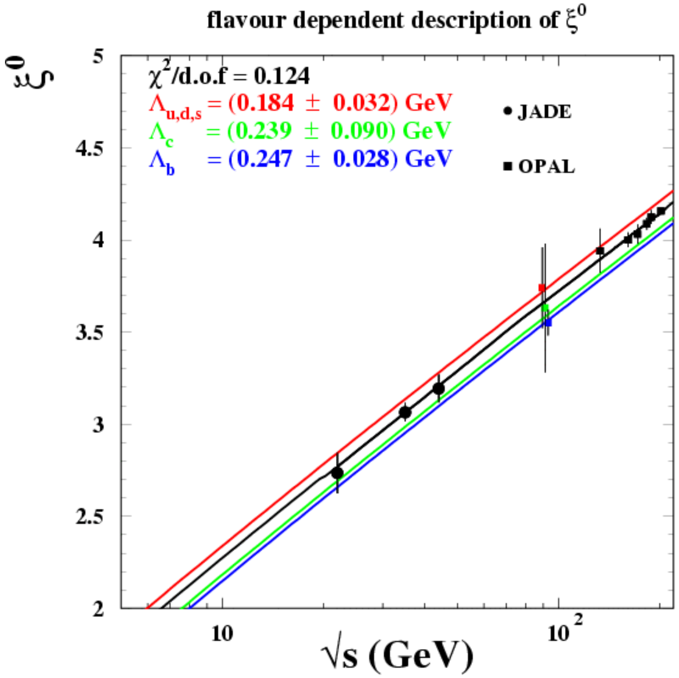
- $\xi_0(Y) = \frac{1}{2}Y + \sqrt{CY} + C$
  $Y = \ln(0.5\sqrt{s} / \Lambda_{eff})$
- Use JADE + OPAL data
  $\sqrt{s}$ = 22 … 202 GeV

Reasonable description of data:
Λ_{eff}=207±3 MeV

Flavour dependence

- write ξ_0 ($\sqrt{s}$) as linear combination of peak positions $\xi_0^{(q)}$ ($\sqrt{s}$) for flavour q, weighted with branching ratio $f_q(\sqrt{s})$
- $\xi_0^{(c,b)} - \xi_0^{(uds)} \propto 0.5 \ln(\Lambda^{(c,b)} / \Lambda^{(uds)})$
  $\Rightarrow$ 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%:

$\Lambda^{(uds)}$ = 184±32MeV

$\Lambda^{(c)}$ = 239±90MeV

$\Lambda^{(b)}$ = 247±28MeV

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!