α_S and Power Corrections from JADE Data

P.A. Movilla Fernández
Max-Planck-Institut für Physik, München

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2. e^+e^- Event Shapes at 14 – 44 GeV
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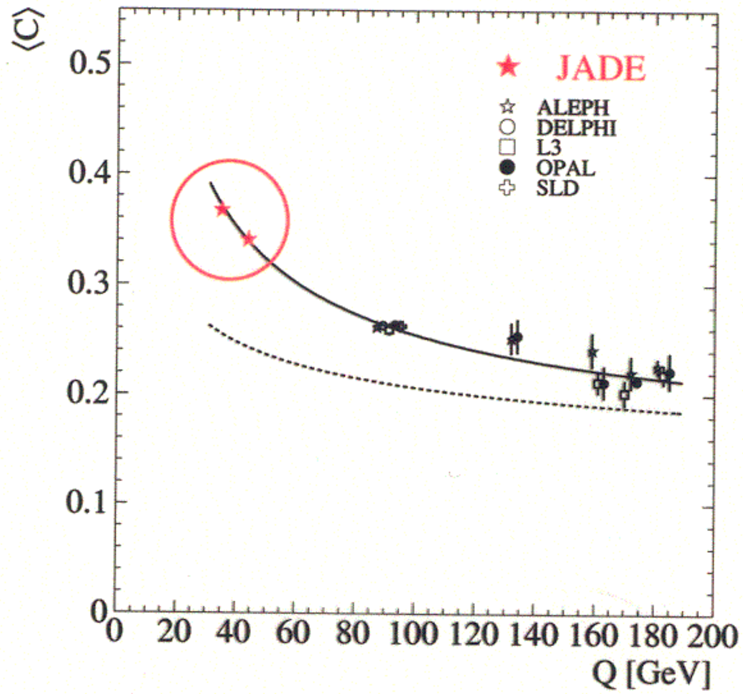
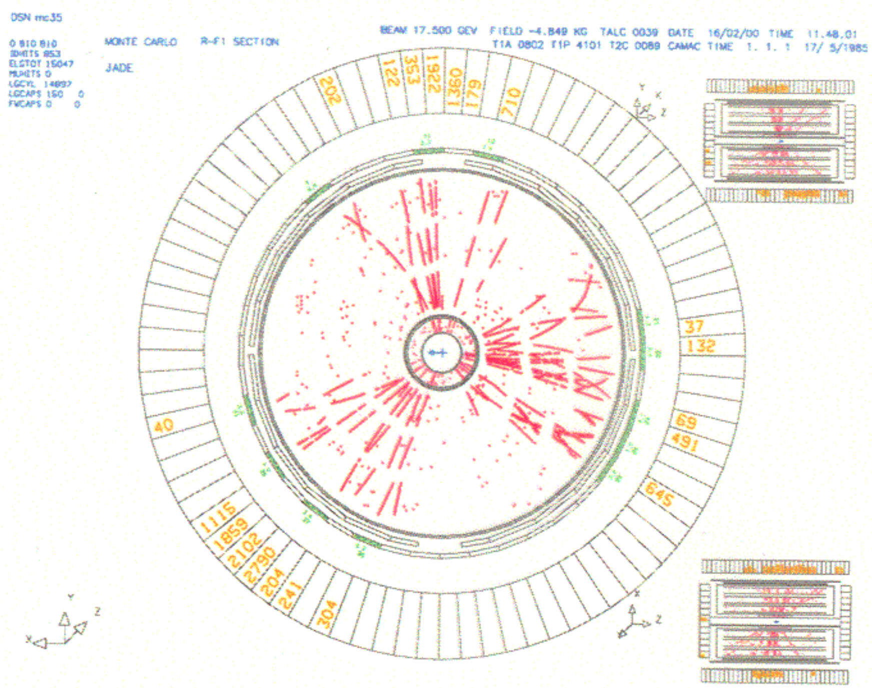
1 Motivation



e^+e^- **data at low $\sqrt{s}$ provide a large leverage for QCD tests:**

- PT effects $\propto 1/\ln Q$
- NP effects $\propto 1/Q$

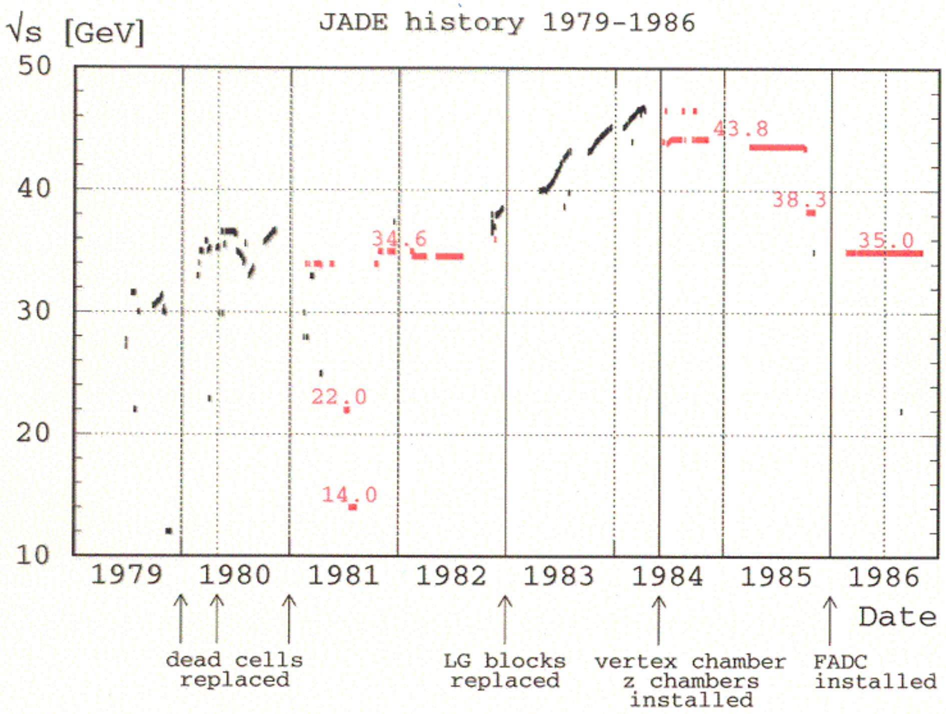
(typically for event shapes)

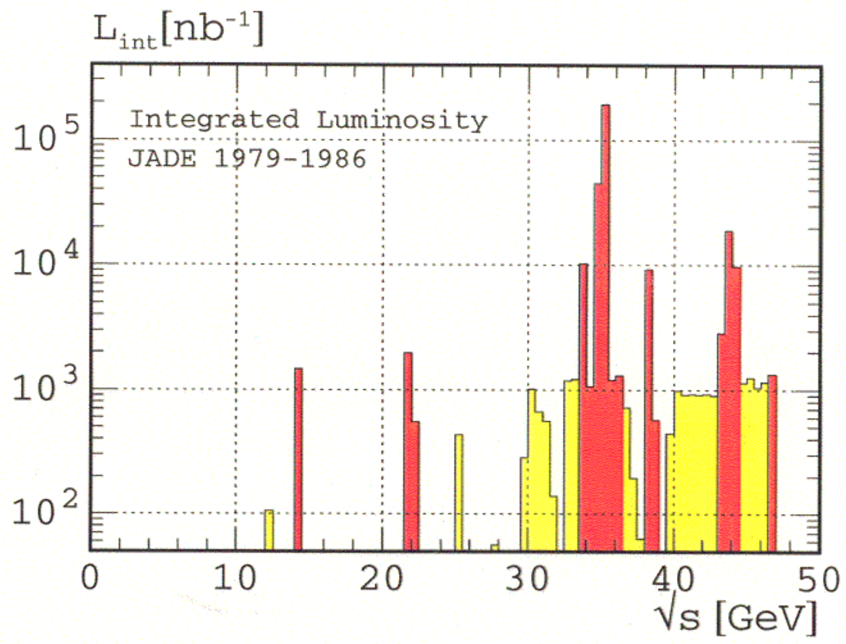


- JADE re-analysis: unique contribution for $M_{b\bar{b}} < \sqrt{s} < M_{Z^0}$
- Original JADE software reanimated successfully

JADE data ready for state-of-the-art studies at $\sqrt{s} = 14 - 44$ GeV.

1.1 JADE at PETRA (1979-1986)





$\sqrt{s}$-range [GeV]	data taking period	$\mathcal{L}$ [pb^{-1}]	$<\sqrt{s}>$ [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

- High multihadronic selection purity
- Residual background $\approx 1\%$:

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

  $e^+e^- \to e^+e^-$ hadrons

2 e^+e^- Event Shapes at 14 – 44 GeV

Observables commonly used for α_S studies:

- Thrust $(1-T)$, Heavy Jet Mass (M_H), 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 $\alpha_S \cdot \ln 1/\mathcal{F}$ $(\mathcal{F} = 1-T, B_T...)$

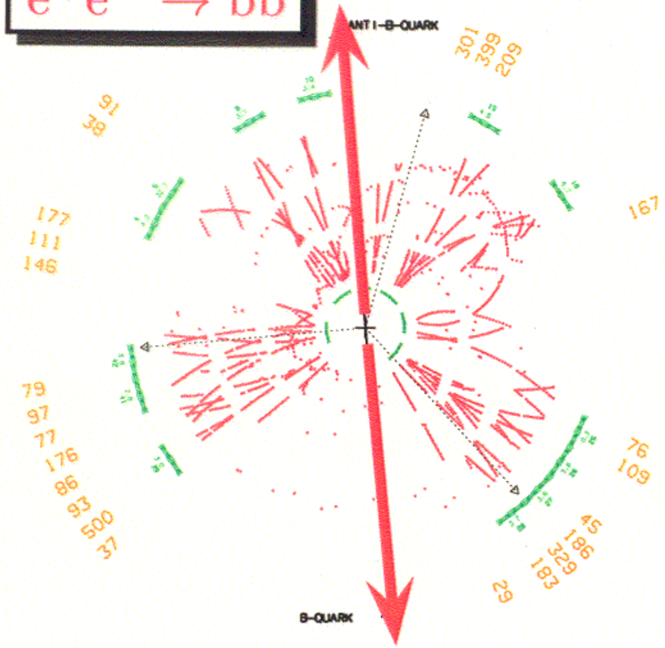
QCD models for describing e^+e^- event shapes:

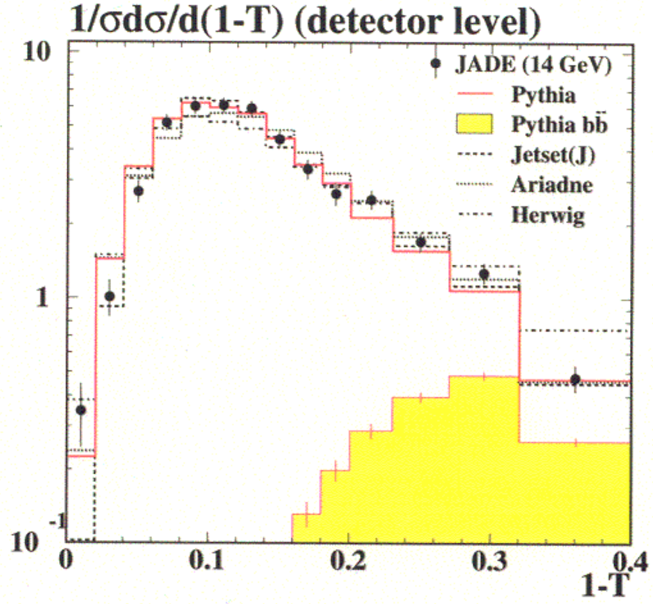
- PYTHIA/JETSET: LLA parton shower + string fragmentation
- ARIADNE: colour dipole + string fragmentation
- HERWIG: MLLA parton shower + cluster fragmentation
- COJETS: independent fragmentation

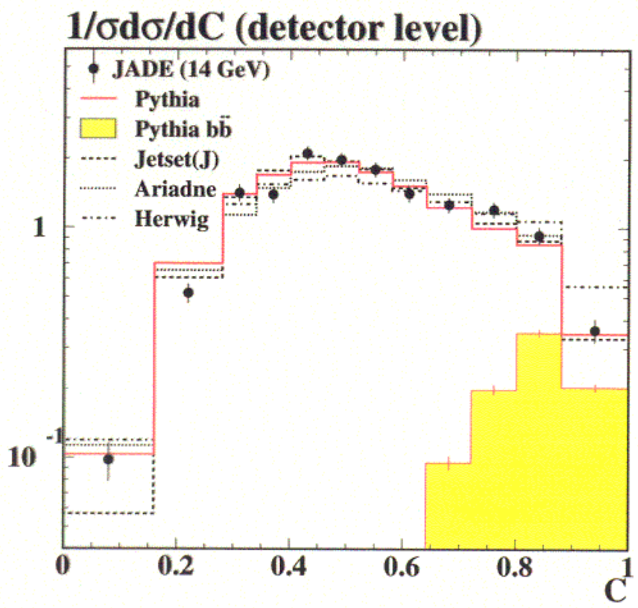
Use LEP tuned versions and try also former JADE optimisation of JETSET 6.3

2.1 Measurement

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

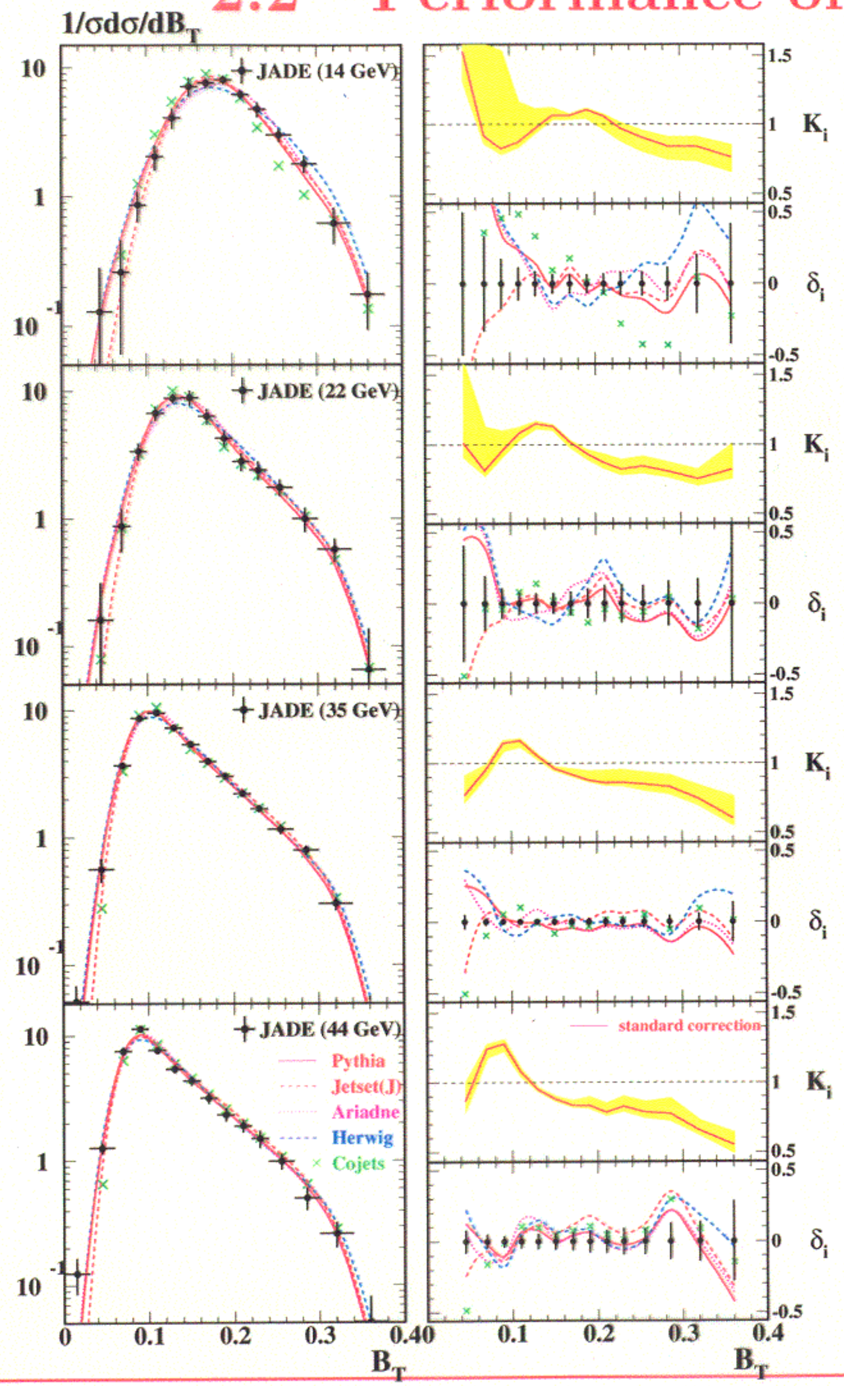






- $e^+e^- \to b\bar{b}$ distort event shape and fake hard gluon radiation due to electroweak decays
  $\Rightarrow$ subtract at detector level
- Bin-by-bin unfolding with correction factors $K_i = \mathrm{MC}_i^{\mathrm{had}}/\mathrm{MC}_i^{\mathrm{det}}$ based on udsc samples

2.2 Performance of Hadronisation Models



Comparison with hadron level data (excl. $e^+e^- \to b\bar{b}$):

- PYTHIA
  good overall consistency
- HERWIG/ARIADNE
  moderate at 14+22 GeV, better at higher $\sqrt{s}$
- JETSET 6.3(JADE)
  good at 14+22 GeV, slightly worse at higher $\sqrt{s}$
- COJETS
  disfavoured at 14+22 GeV, remains worse at higher $\sqrt{s}$

3 Determinations of α_S

- PT QCD predictions for event shape observable $\mathcal{F}$:

  $\mathcal{O}(\alpha_S^2)$: describes hard gluon contribution (3-jet region) ($\hat{\alpha}_S = \alpha_S/2\pi$)

$$\frac{dR}{d\mathcal{F}} = \frac{1}{\sigma_0}\frac{d\sigma}{d\mathcal{F}} = \frac{d\mathcal{A}(\mathcal{F})}{d\mathcal{F}}\hat{\alpha}_S + \left(\frac{d\mathcal{B}(\mathcal{F})}{d\mathcal{F}} - 2\frac{d\mathcal{A}(\mathcal{F})}{d\mathcal{F}}\right)\hat{\alpha}_S^2$$

  NLLA: resums soft gluon contribution (2-jet region) ($L = \ln(1/\mathcal{F})$)

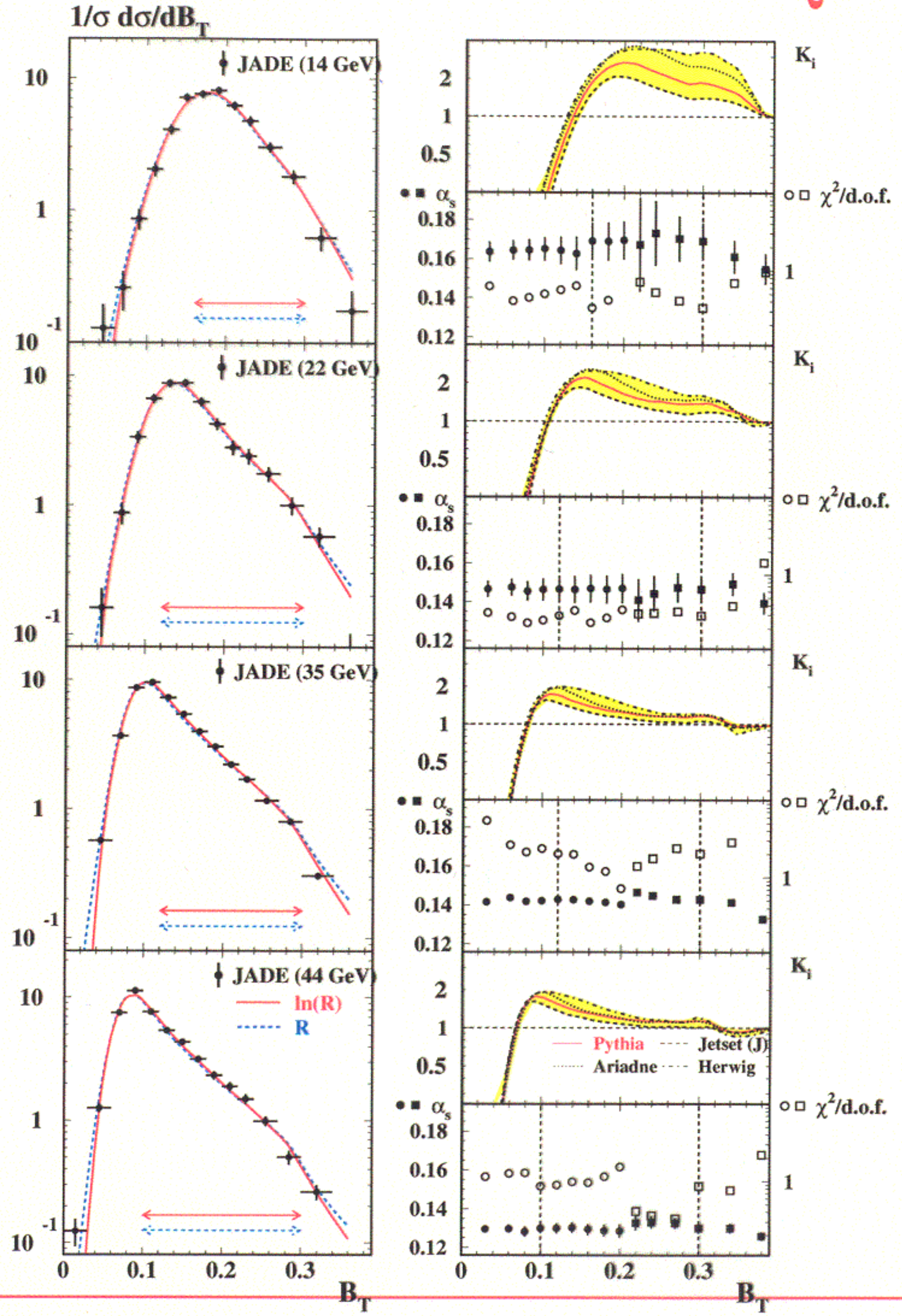
$$R(\mathcal{F}) = (1 + C_1\hat{\alpha}_S + C_2\hat{\alpha}_S^2)\exp\{Lg_1(\alpha_S L) + g_2(\alpha_S L)\}$$

  $\mathcal{O}(\alpha_S^2)$+NLLA: improved description of 2+3 jet region, e.g. $\ln(R)$ matching:

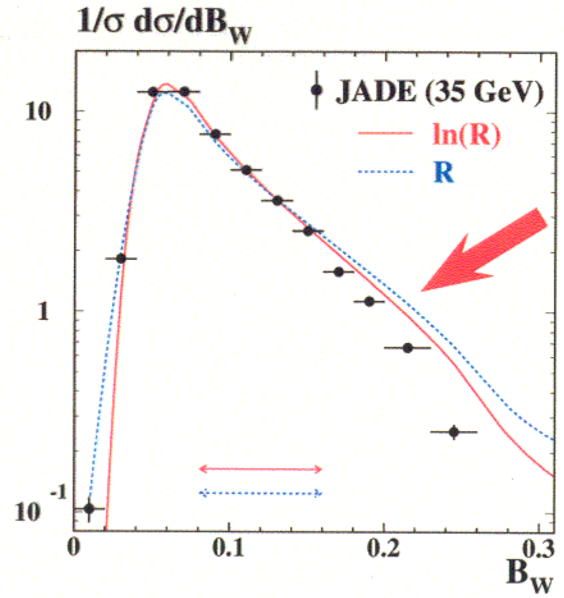
$$\ln R(\mathcal{F}) = Lg_1(\alpha_S L) + g_2(\alpha_S L) - (G_{11}L + G_{12}L^2)\hat{\alpha}_S - (G_{22}L^2 + G_{23}L^3)\hat{\alpha}_S^2 + \mathcal{A}(\mathcal{F})\hat{\alpha}_S + \left[\mathcal{B}(\mathcal{F}) - \frac{1}{2}\mathcal{A}(\mathcal{F})^2\right]\hat{\alpha}_S^2$$

- Estimate NP effects with PYTHIA, JETSET 6.3(JADE), ARIADNE, HERWIG
- Fit PT prediction with renormalisation scale factor $x_\mu = 1$
  + bin-by-bin hadronisation correction of $R(\mathcal{F}) = \int_0^{\mathcal{F}} d\mathcal{F}'(1/\sigma_0 d\sigma/d\mathcal{F}')$
  (Standard = PYTHIA)

3.1 QCD Fits

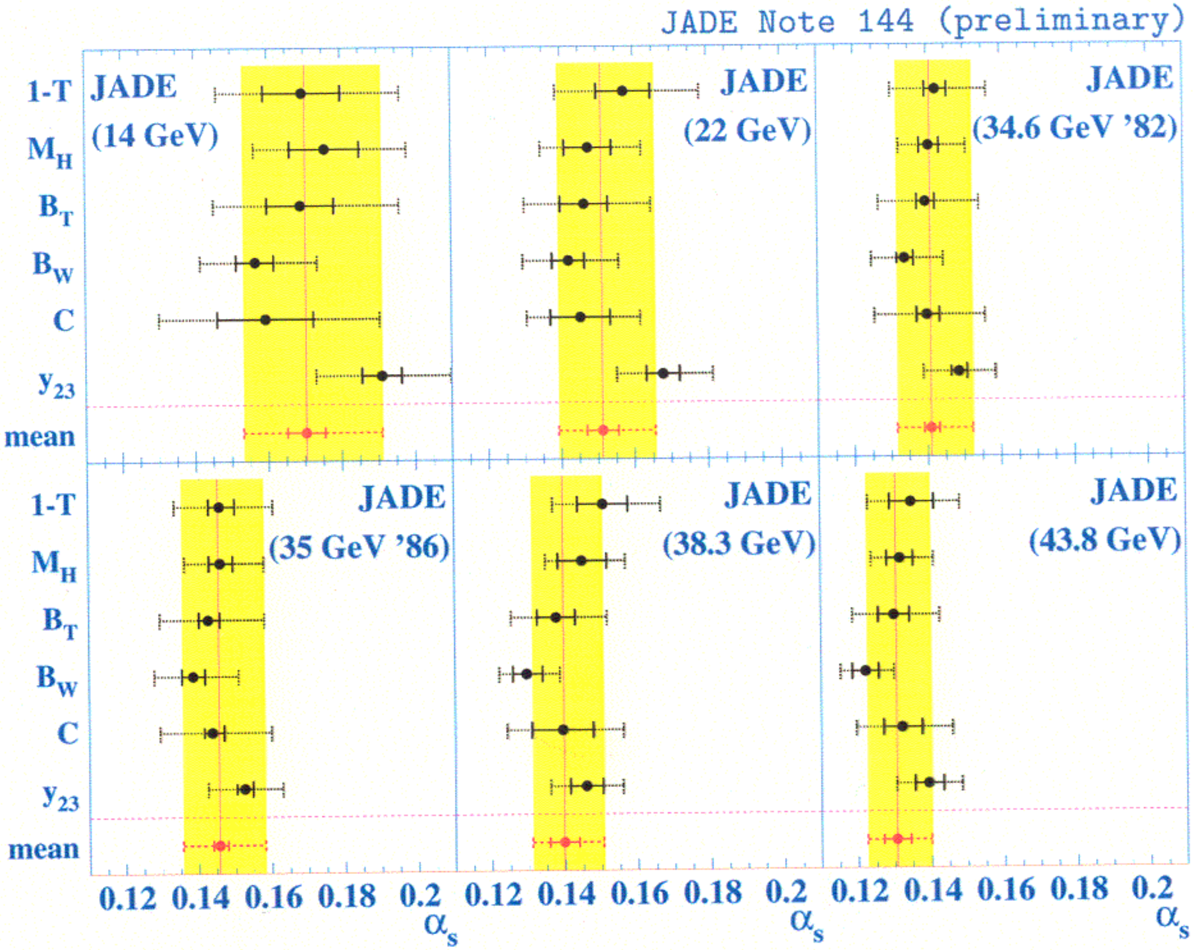


- Typically $\chi^2/\text{d.o.f.} = 0.5 \ldots 2.0$
- Stable fits
- Large hadronisation corrections at 14 GeV!
- Problems with B_W!



3.2 α_S Results

- Consistency within $1-2\sigma$ of experimental errors
- Significantly reduced x_μ-dependence w.r.t. $\mathcal{O}(\alpha_S^2)$
- Dominant errors:
  - ➳ renormalisation scale
  - ➳ hadronisation uncertainties



α_S decreases by $\approx 25\%$

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

3.3 Test of the Running of α_S

3-loop formula:

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

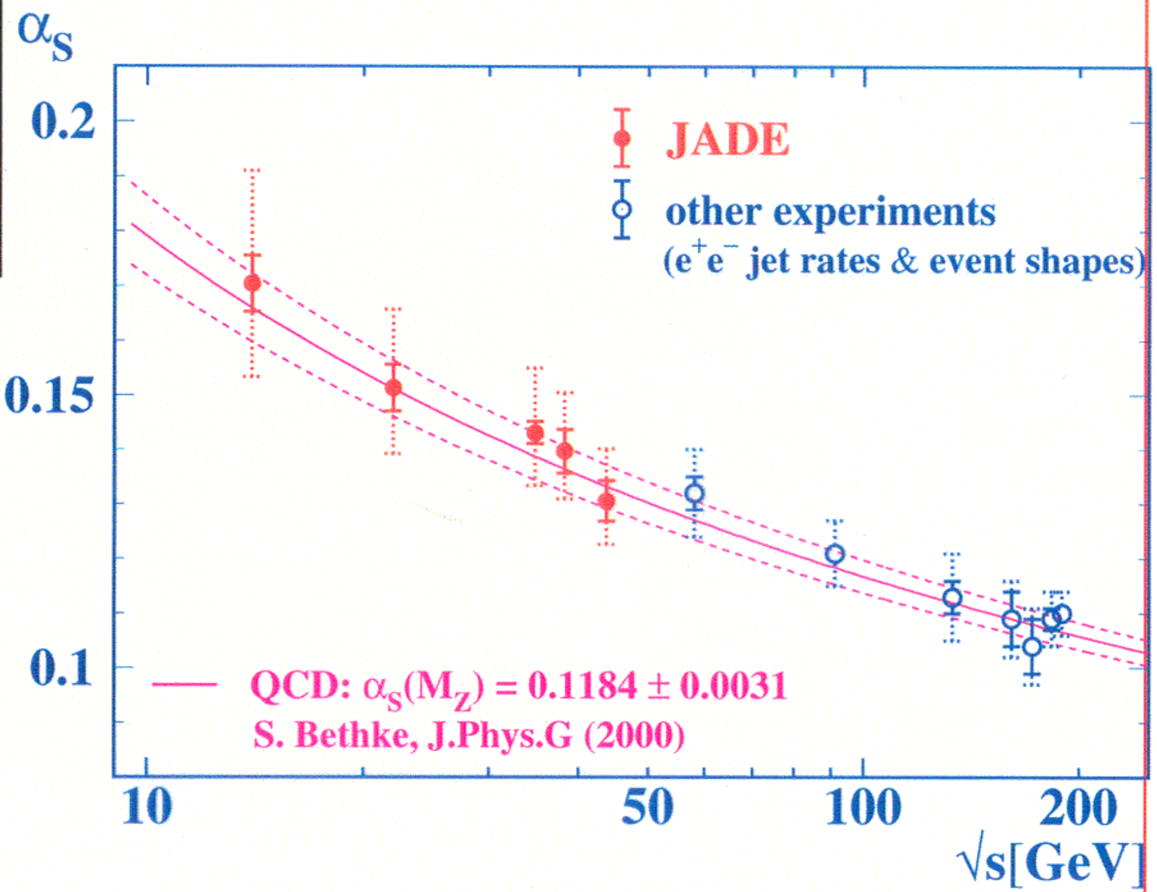
$l = \ln(\sqrt{s}/\Lambda_{\overline{MS}})^2$

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

$$\Lambda^{(5)}_{\overline{MS}} = 246 \pm 7\,\mathrm{MeV}$$
$$\alpha_S(M_{Z^0}) = 0.1210 \pm 0.0006$$
$$P(\chi^2) = 75\%$$

- α_S=const., total uncertainties (outer error bars):

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

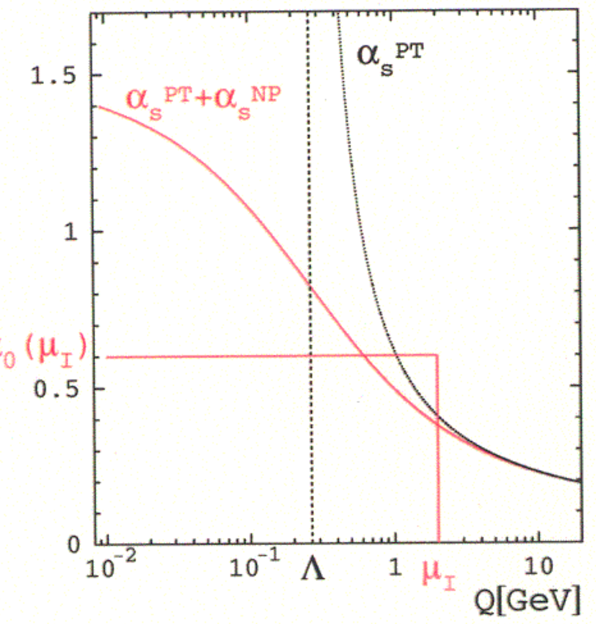


Good agreement with world average based on NNLO QCD!

4 Power Corrections

- Parametrise unknown but analytical behaviour of the physical strong coupling constant α_S.

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



- Dokshitzer-Marchesini-Webber (DMW): structure of power corrections from soft gluon radiation at $\mu \approx \mathcal{O}(\Lambda)$

$$\langle \mathcal{F} \rangle = \langle \mathcal{F} \rangle^{PT} + \mathcal{D}_\mathcal{F}\mathcal{P} \quad \text{(means)}$$

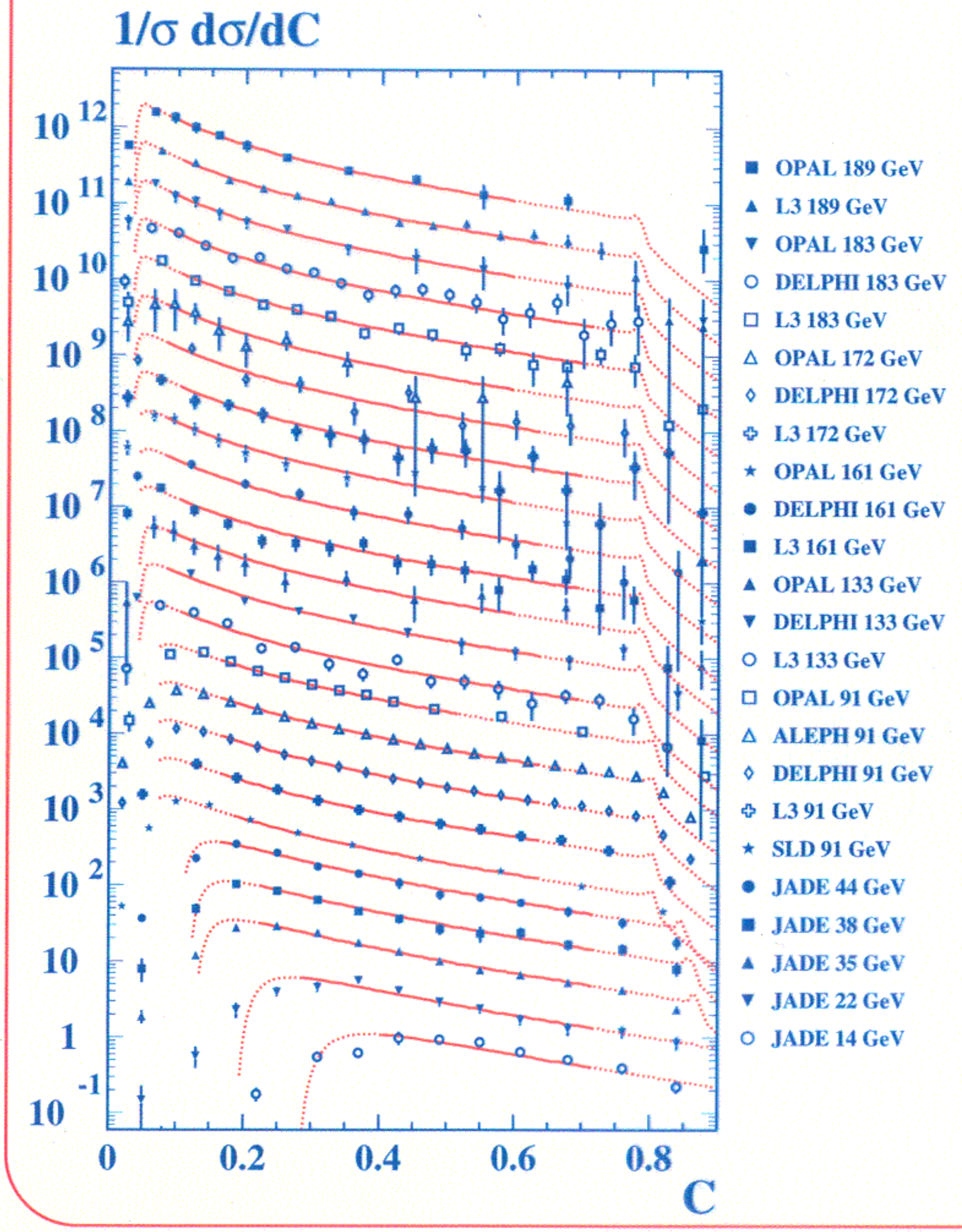
$$\frac{d\sigma(\mathcal{F})}{d\mathcal{F}} = \frac{d\sigma^{PT}(\mathcal{F} - \mathcal{D}_\mathcal{F}\mathcal{P})}{d\mathcal{F}} \quad \text{(distributions)}$$

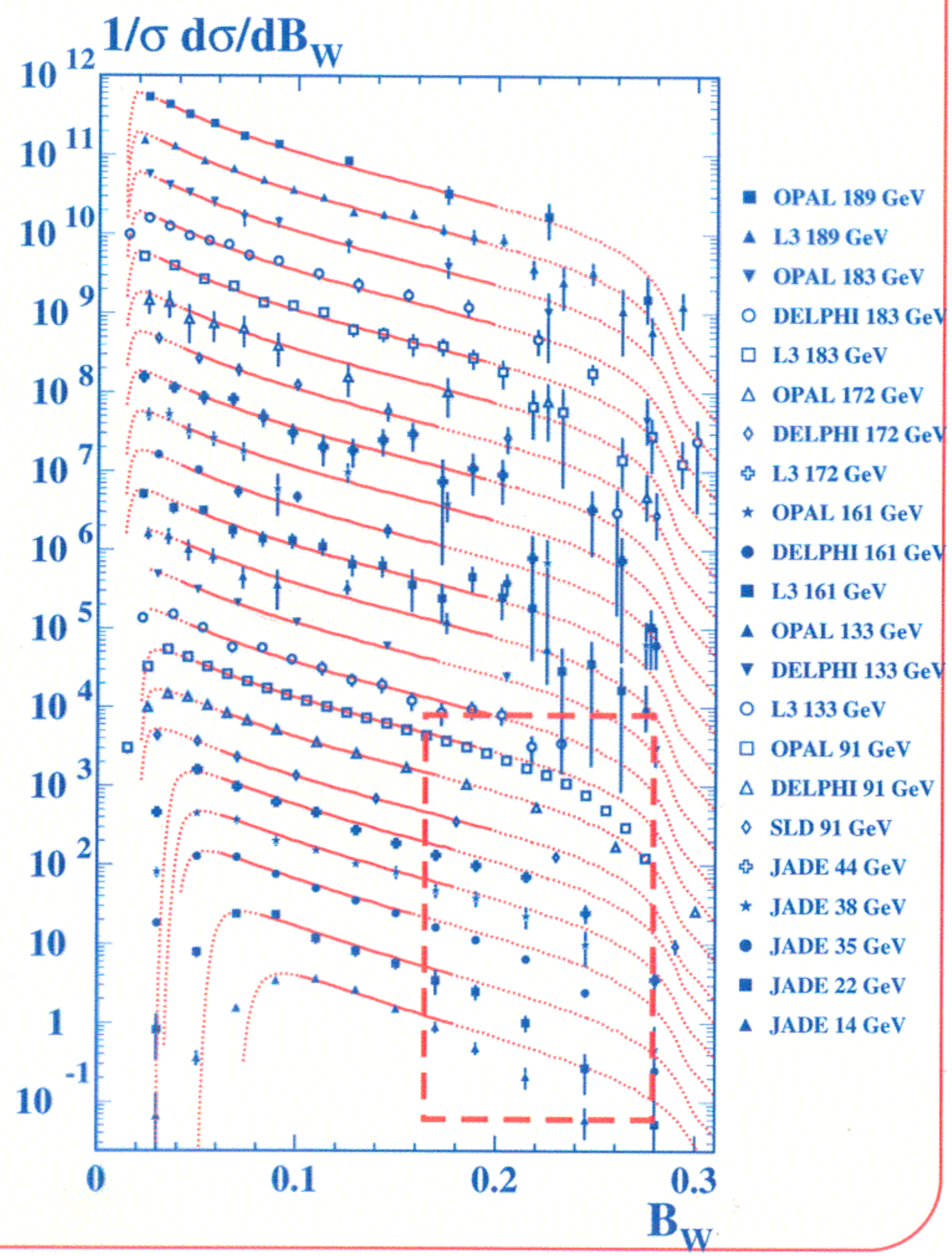
$$\mathcal{P} = \frac{4C_F}{\pi^2}\mathcal{M}\frac{\mu_I}{Q}\left[\alpha_0(\mu_I) - \alpha_S(\mu_R) - \beta_0\frac{\alpha_S^2(\mu_R)}{2\pi}\left(\ln\frac{\mu_R}{\mu_I} + \frac{K}{\beta_0} + 1\right)\right] \ \ldots\ \textbf{universal}$$

$$\mathcal{D}_\mathcal{F} = \begin{cases} \text{const.} & (\mathcal{F} = 1-T,\ M_H^2,\ C) \quad \Rightarrow \text{simple shift} \\ a_\mathcal{F}\cdot\ln(1/\mathcal{F}) + F_\mathcal{F} & (\mathcal{F} = B_T,\ B_W) \quad \Rightarrow \text{shift + squeeze} \end{cases}$$

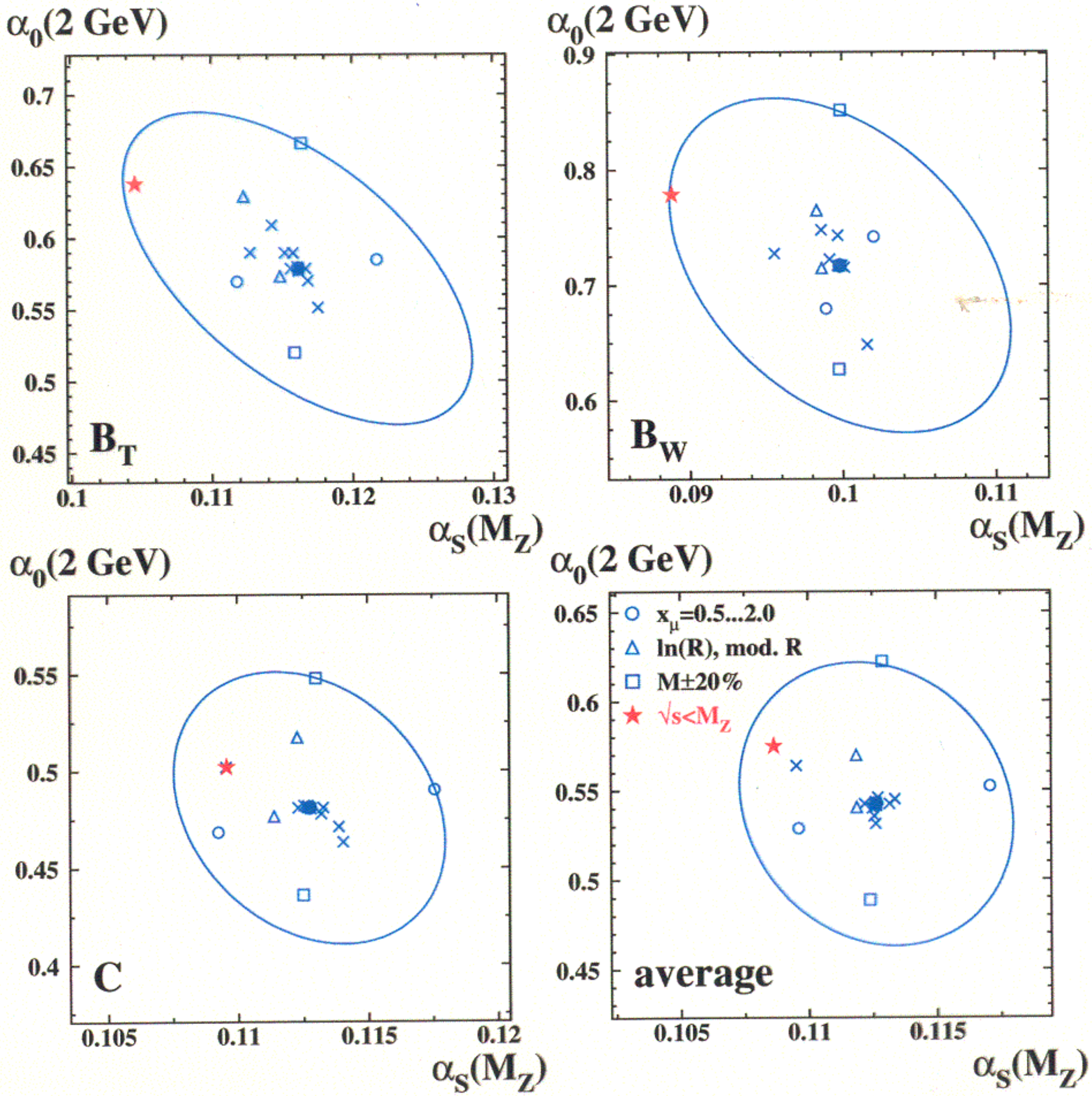
- **Universality of α_0 is an essential ingredient of the model !**
- Test ansatz by global (α_S,α_0) fits of pQCD+DMW to overall event shape data from PETRA/PEP/TRISTAN/SLC/LEP ($\sqrt{s}$ = 14–189 GeV)

4.1 Global (α_S,α_0) Fits to Distributions





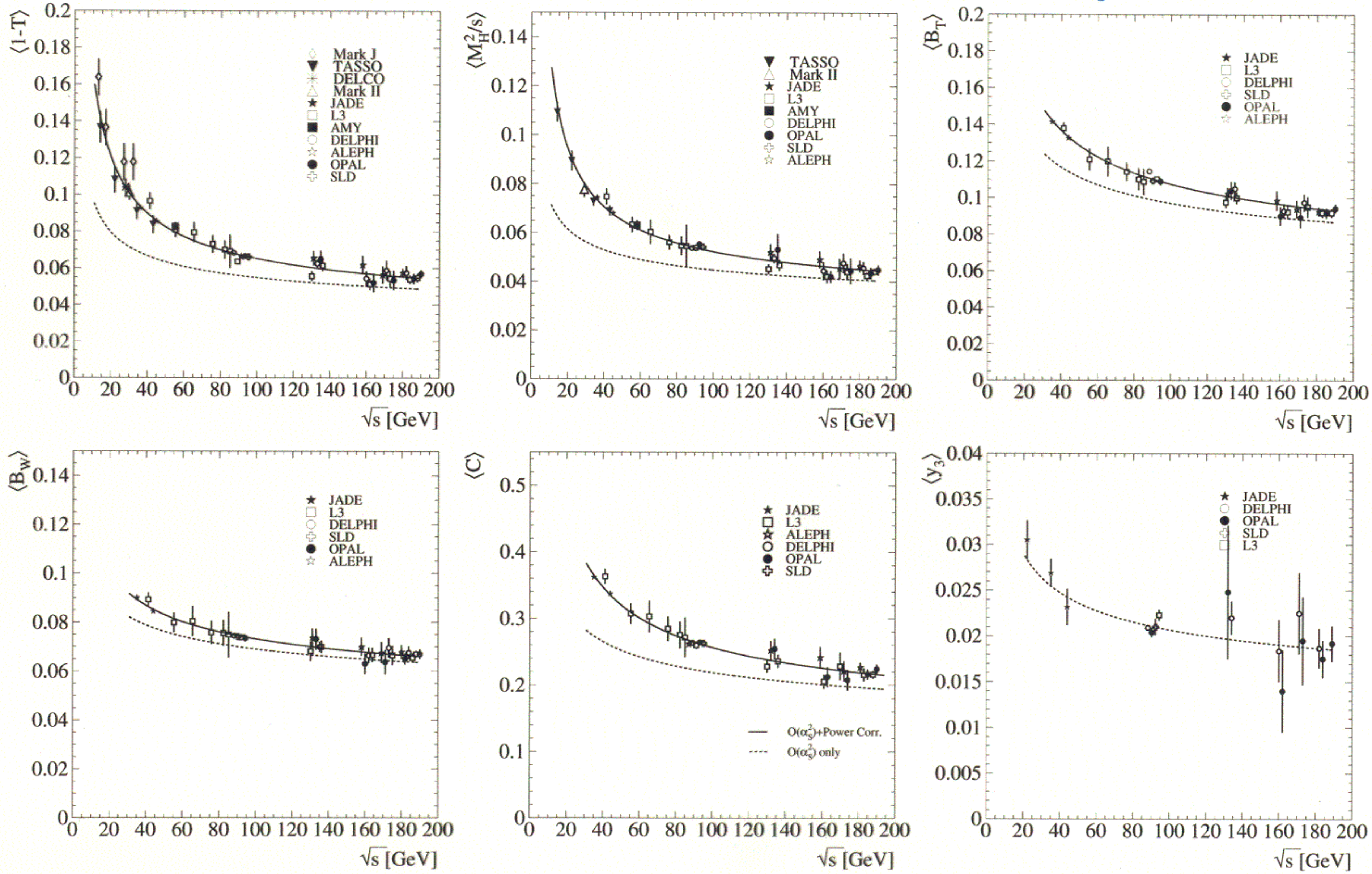
4.2 Systematics



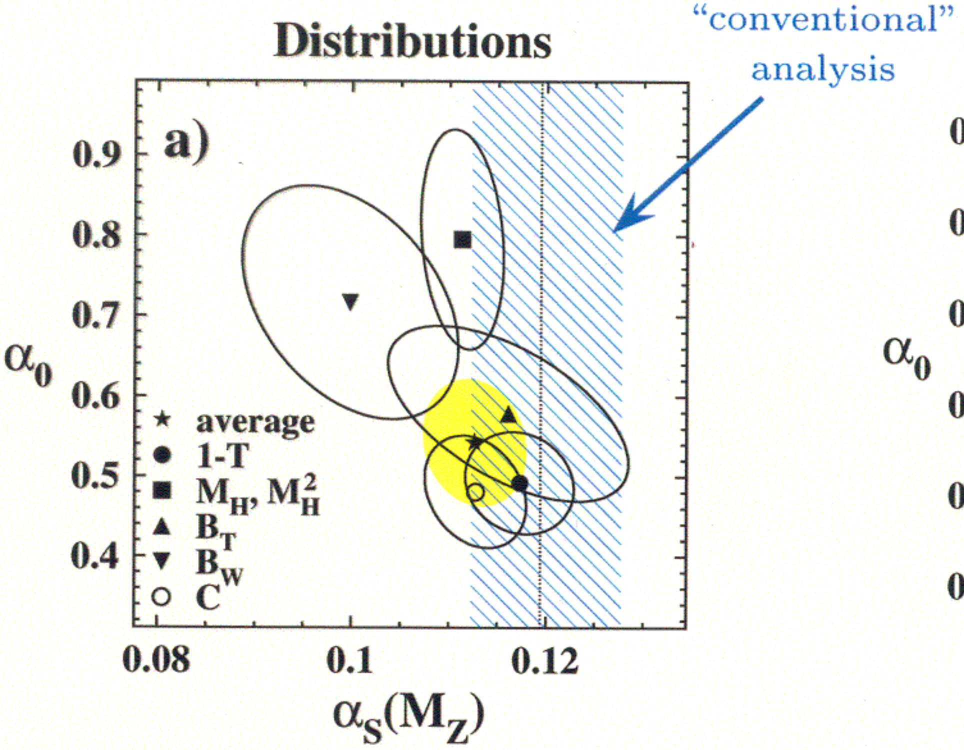
- Fit correlation $\rho_{\rm fit}^{(\alpha_S-\alpha_0)} \approx -80\%$
- Good description of $1-T$, C, (B_T)
- Excess in 3-jet region for B_W, M_H
- Systematic deviations from fits to separate data sets
  $\sqrt{s} < M_{Z^0}$: missing higher order contributions?
  (B_T, B_W)

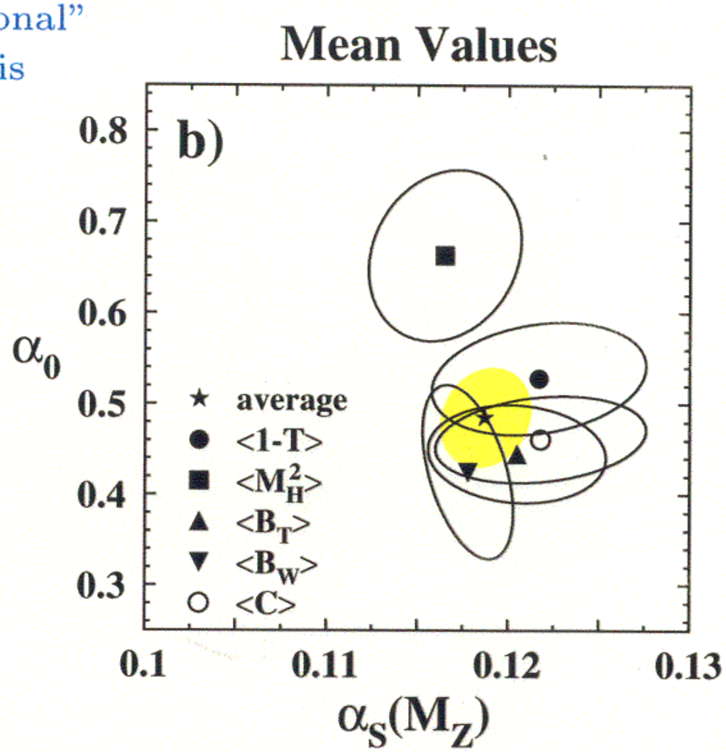
4.3 Global (α_S,α_0) Fits to Mean Values

Eur.Phys.J. C22 (2001) 1 (does not include update @ 14+22 GeV)



4.4 (α_S, α_0) Results



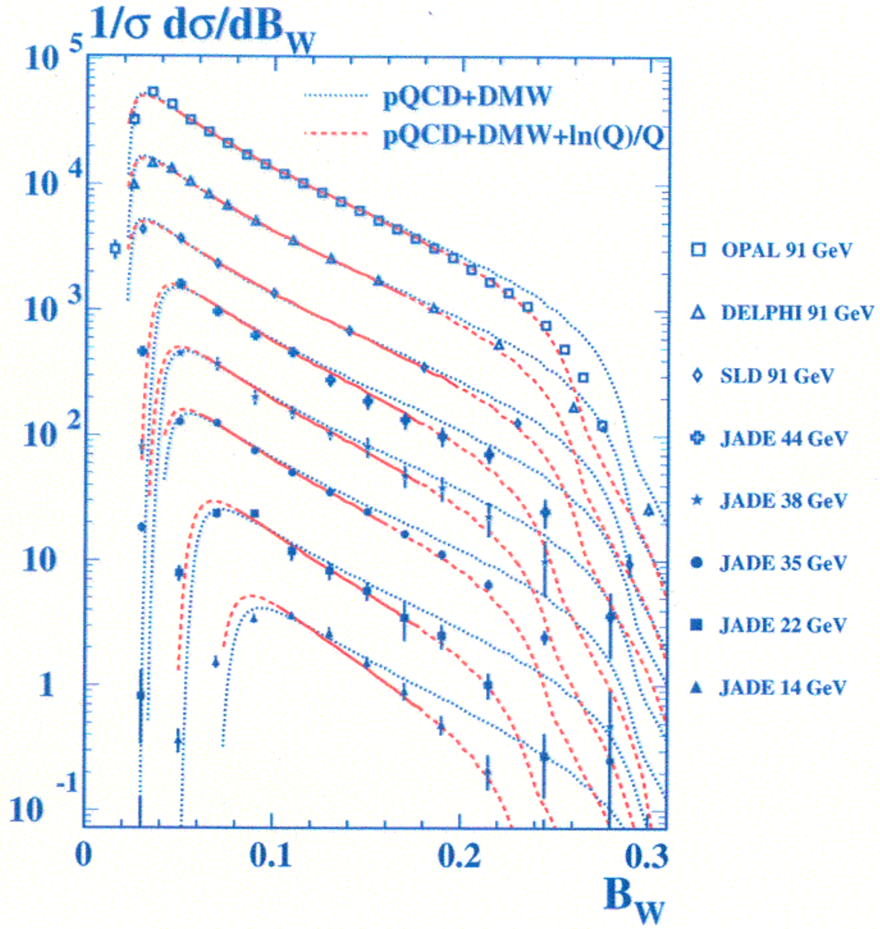


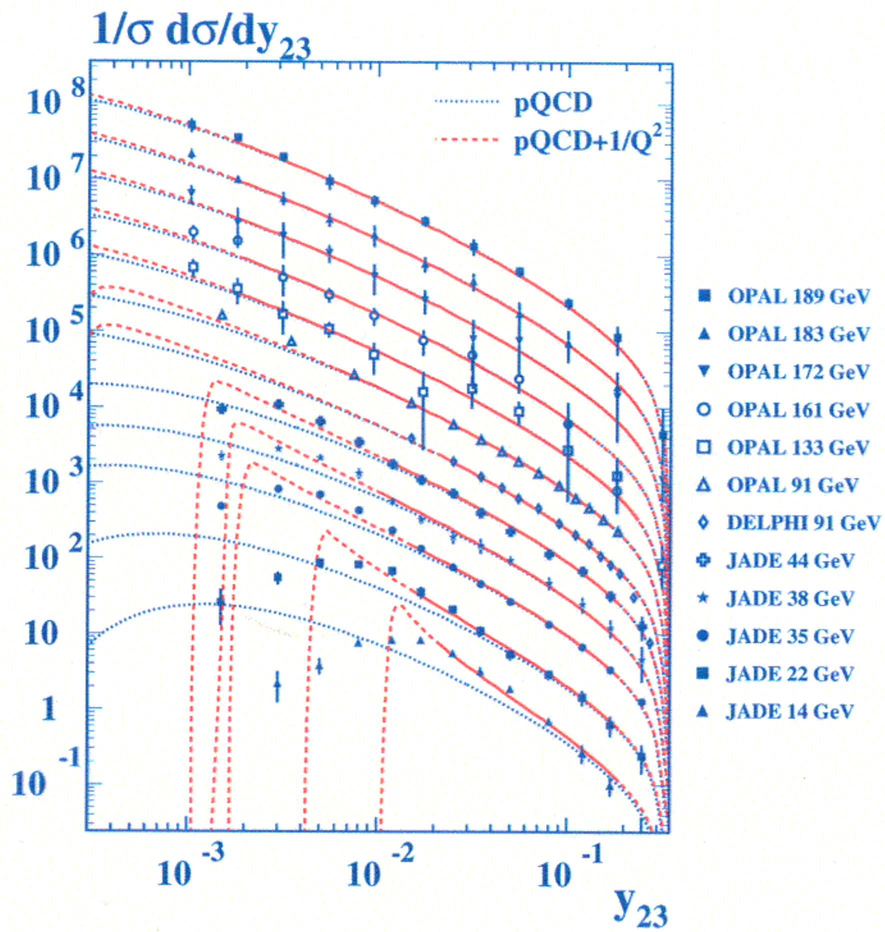
Distributions		fit	exp.	theo.
$\alpha_S(M_{Z^0})=$	0.1126	± 0.0005	± 0.0037	$^{+0.0044}_{-0.0030}$
$\alpha_0(2\text{ GeV})=$	0.542	± 0.005	± 0.032	$^{+0.084}_{-0.060}$

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	$^{+0.065}_{-0.043}$

- Consistency within $1 - 2\sigma$ of total errors
- α_0 universal within 20% uncertainty level of Milan factor $\mathcal{M}$
- $\alpha_S^{(PC)} < \alpha_S^{(MC)}$ from distributions due to minor/missing squeeze of PT spectrum

4.5 Higher Order Contributions?





Log. enhancement $\propto (\ln Q)/Q$ yields better description of data

(Disentangle PC from re-definition of x_μ)

$1/Q^2$ corrections for y_{23} seen in JADE data

Fit pQCD$+\mathcal{A}_{10}/Q + \mathcal{A}_{20}/Q^2$:

$$\alpha_S(M_{Z^0}) = 0.1128 \pm 0.0007\,(\mathrm{fit})\,^{+0.0059}_{-0.0060}\,(\mathrm{syst.})$$
$$\mathcal{A}_{10} = 0.018 \pm 0.014\,(\mathrm{fit})\,^{+0.024}_{-0.014}\,(\mathrm{syst.})\ \mathrm{GeV}$$
$$\mathcal{A}_{20} = 1.94 \pm 0.31\,(\mathrm{fit})\,^{+0.34}_{-0.24}\,(\mathrm{syst.})\ \mathrm{GeV}^2$$

4.6 Colour Structure from Event Shapes

Colour structure known for:

- PT predictions

  $\mathcal{A} \propto C_F$, $\mathcal{B} = \mathcal{B}(C_A, C_F, n_f)$

  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

  $\mathcal{P} = \mathcal{P}(C_A, C_F, n_f)$, $\mathcal{M} = \mathcal{M}(C_A, n_f)$,

  $\mathcal{D_F} = \mathcal{D_F}(C_A, C_F, n_f)$

$\Longrightarrow$ **Reduced model dependence**

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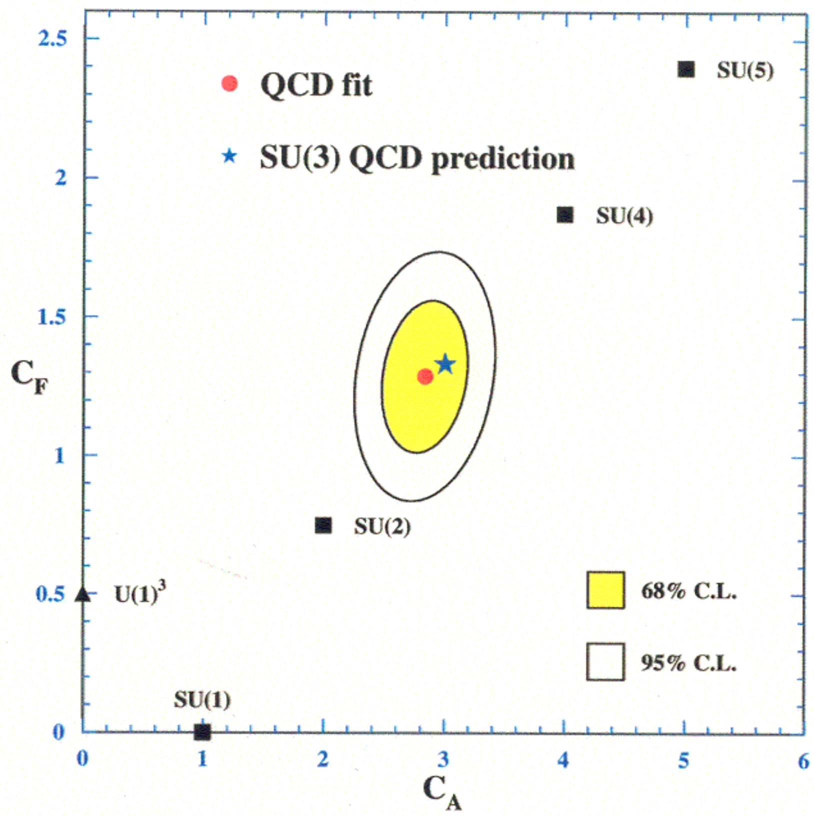


	Fit α_S and α_0 and (C_A or C_F or n_f)		Fix α_0 and n_f and fit α_S and C_A and C_F		
	$1-T$	C	$1-T$	C	QCD
C_A	2.7 ± 0.2	3.0 ± 0.6	2.7 ± 0.2	3.0 ± 0.5	3
C_F	1.4 ± 0.3	1.5 ± 0.4	1.3 ± 0.2	1.3 ± 0.5	4/3
n_f	6.4 ± 1.2	4.9 ± 3.0	—	—	5

$$C_A = 2.84 \pm 0.24$$
$$C_F = 1.29 \pm 0.18$$

Uncertainties competitive with other analyses

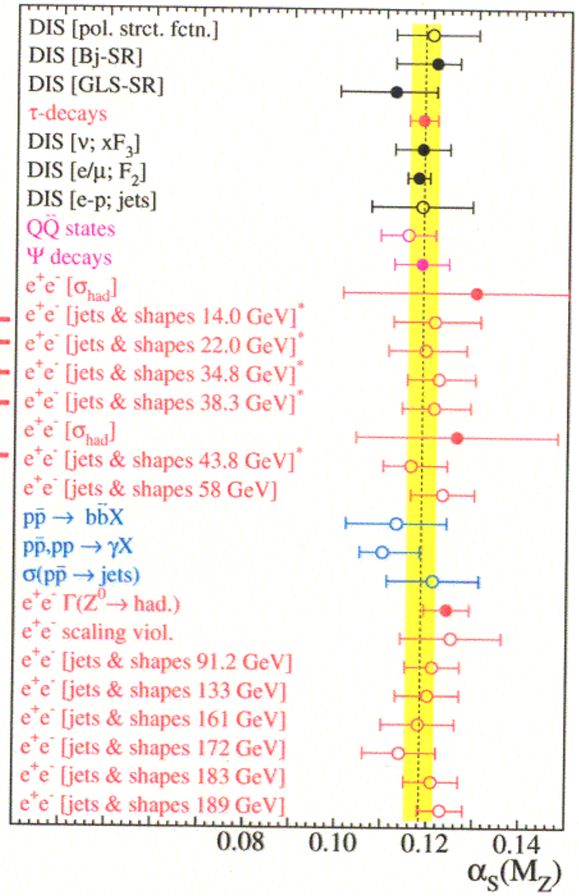
(e.g. 4-jet angular correlations)

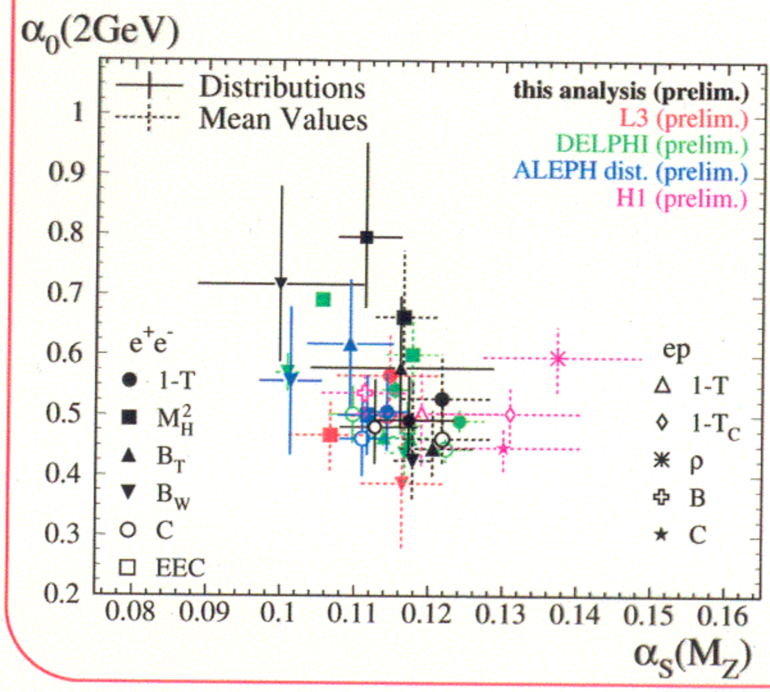
5 Summary

- $\mathcal{O}(\alpha_S^2)$+NLLA work well at PETRA energies
- Hadr. uncertainties at 14 GeV = $\mathcal{O}(\Delta\alpha_S^{(\text{ren.scale})})$

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

- Consistency with other measurements and methods





- PC competitive with MC method for some variables
- SU(3) structure of QCD confirmed
- Universality of α_0 established within $\pm 20\%$

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

- More and improved PC calculations needed!