Event shapes and other QCD studies at LEP

Abstracts submitted to ICHEP 2000, Osaka:

#	Experiment
164	ALEPH
638, 640	DELPHI
626, 630	L3
113, 252	OPAL

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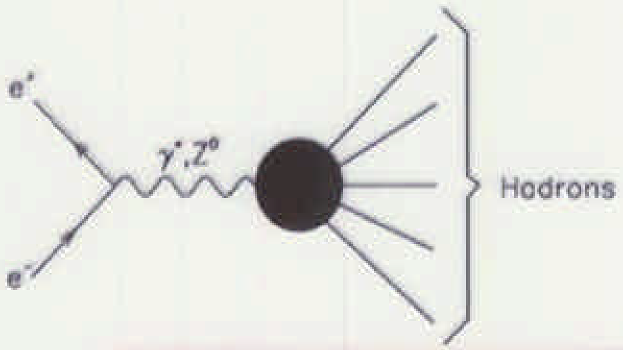
Introduction

Over a decade of LEP running:

- $17 \cdot 10^6$ Z decays recorded at LEP 1 (4 expts, 1989-1995)
- Target luminosity at LEP 2 ($\sqrt{s} > M_Z$) : 500 pb^{-1} /expt
  Delivered luminosity (1995-2000) > 637 pb^{-1} /expt



Precise measurements of QCD at LEP:

★ *Clean* initial state ($e^- e^+$)

★ *Small* hadronization corrections ($\propto 1/E$)

☞ Study Hadronic events $30 \leq \sqrt{s} \leq 208$ GeV

- *Hard Gluon Radiation:*
  Multi-jet topology, Event Shape Variables

  Measurement of Strong coupling constant α_s

  Measurement of Active # of quark flavours n_f

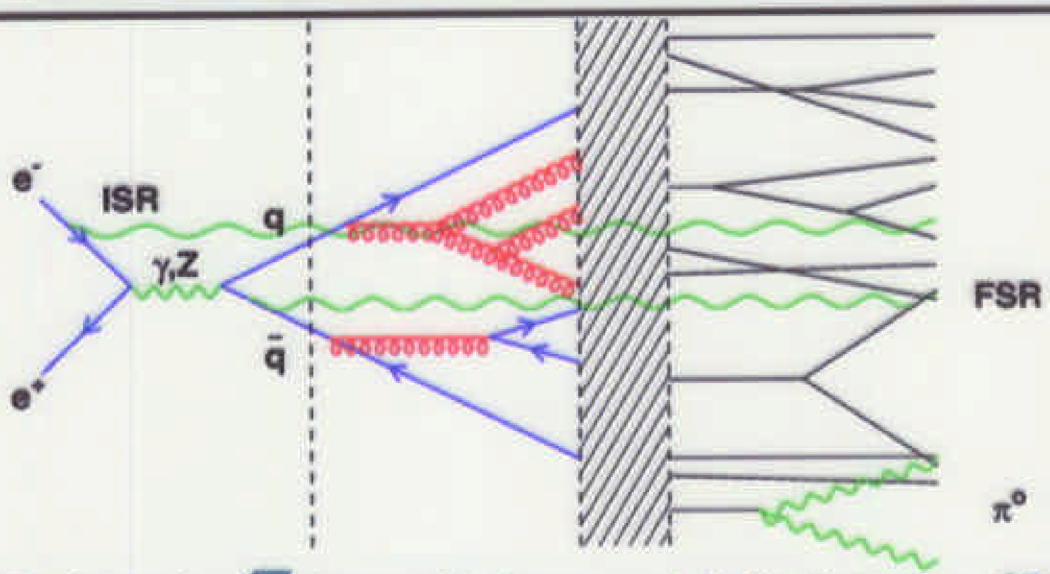
- *Soft Gluon Radiation:*

  Evidence of Intrajet Color coherence
  (inclusive charged particle spectra)

- *Quark and gluon multiplicity*:

  Measurement of QCD color factors C_A/C_F

LEP DATA: 3 Event Samples



☆ Reduced $\sqrt{s'}$ from Z decay with isolated γ (FSR)

$$\sqrt{s'} = \sqrt{s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)}$$

$$\sqrt{s'}(\mathrm{GeV}) = \underbrace{40, 55, 65, 75, 82, 84}_{\mathrm{L3}}, \underbrace{45, 66}_{\mathrm{DELPHI}}$$

$\mathcal{O}(1000)$ events with purity 70 – 90 %

✪ Hadronic Z decays LEP1 with $\sqrt{s} \sim M_Z$
ALEPH, DELPHI, L3, OPAL: purity ≈ 99 %

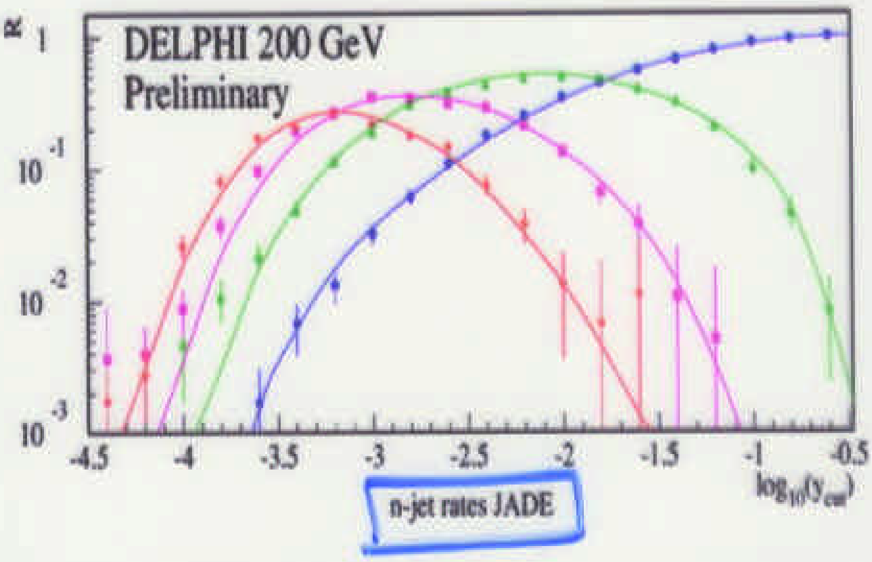
★ LEP 2 Data rejecting ISR, 4 fermion (WW,ZZ)

'95-'98	$\sqrt{s}$(GeV)	130	136	161	172	183	189
	Events	500	400	400	300	1.5K	4.2K
'99-'00	$\sqrt{s}$(GeV)	192	196	200	202	205	207
	Events	400	1.5K	1.5K	400	1.1K	500

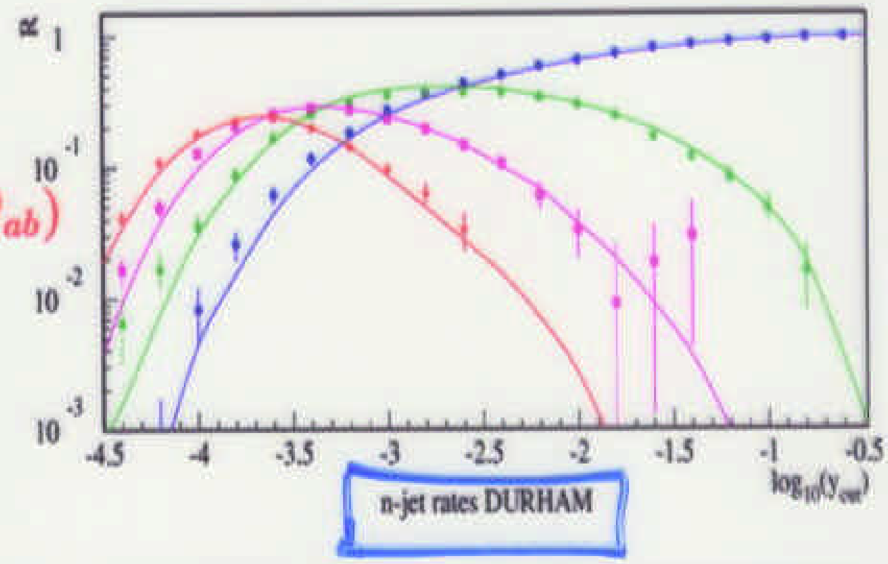
ALEPH, DELPHI, L3, OPAL: Purity ~ 78-90%

Jet Rates

$$y_{ab}^{\text{JADE}} = \frac{2E_aE_b}{{E_{vis}}^2}(1 - \cos\theta_{ab})$$

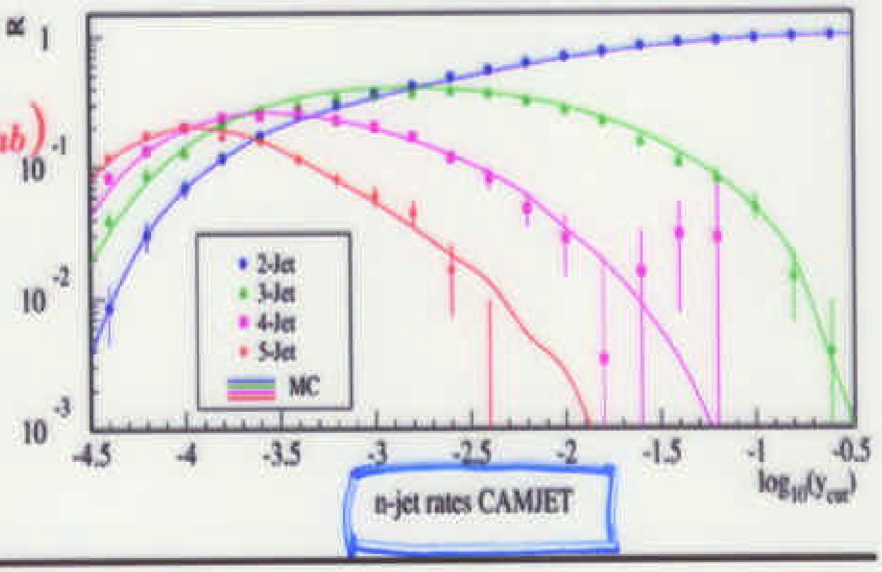


$$y_{ab}^{\text{DURHAM}} = 2\frac{(E_a^2, E_b^2)_{\min}}{{E_{vis}}^2}(1 - \cos\theta_{ab})$$



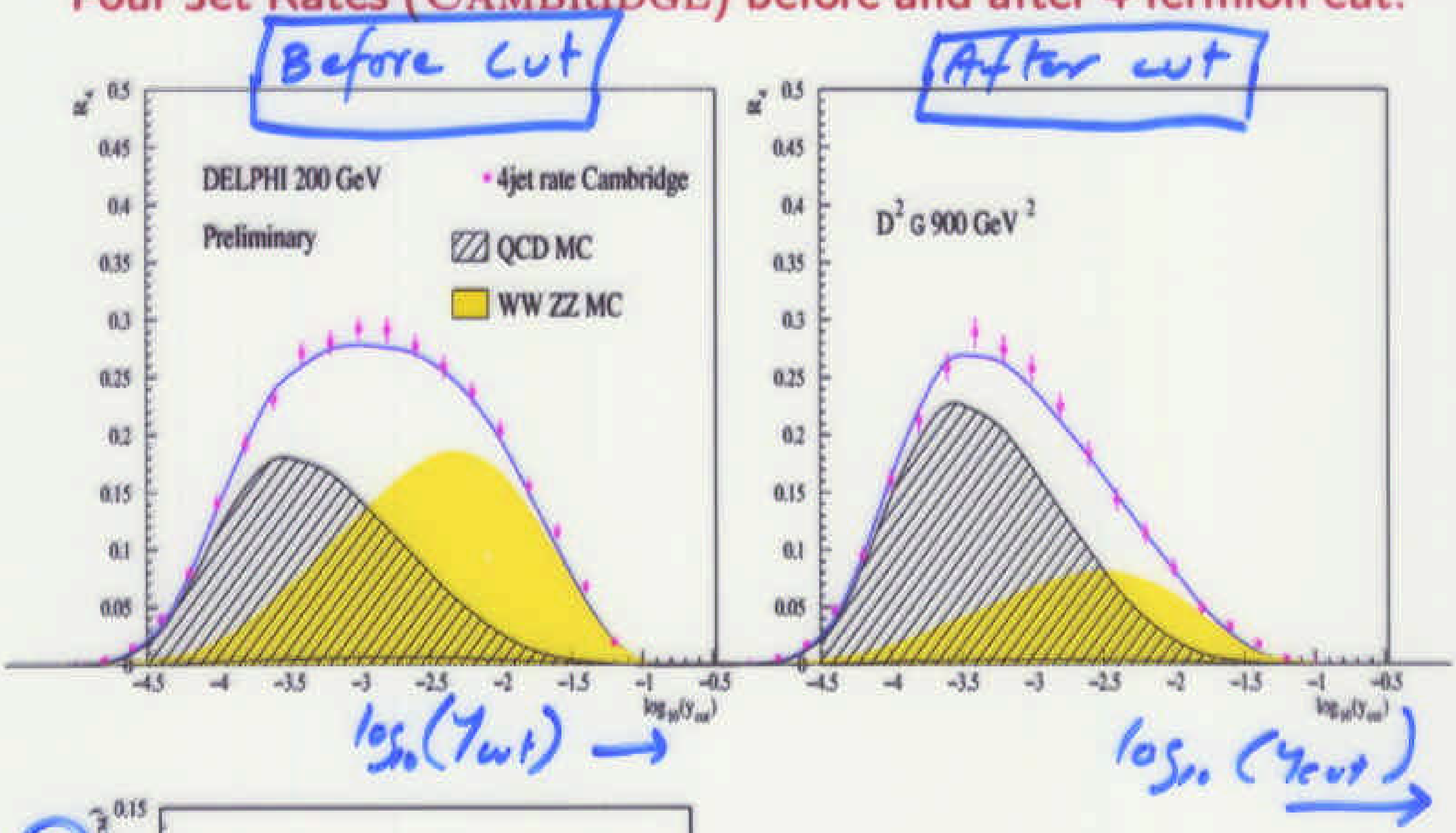
$$y_{ab}^{\text{CAMBRIDGE}} = 2\frac{(E_a^2, E_b^2)_{\min}}{{E_{vis}}^2}(1 - \cos\theta_{ab})$$

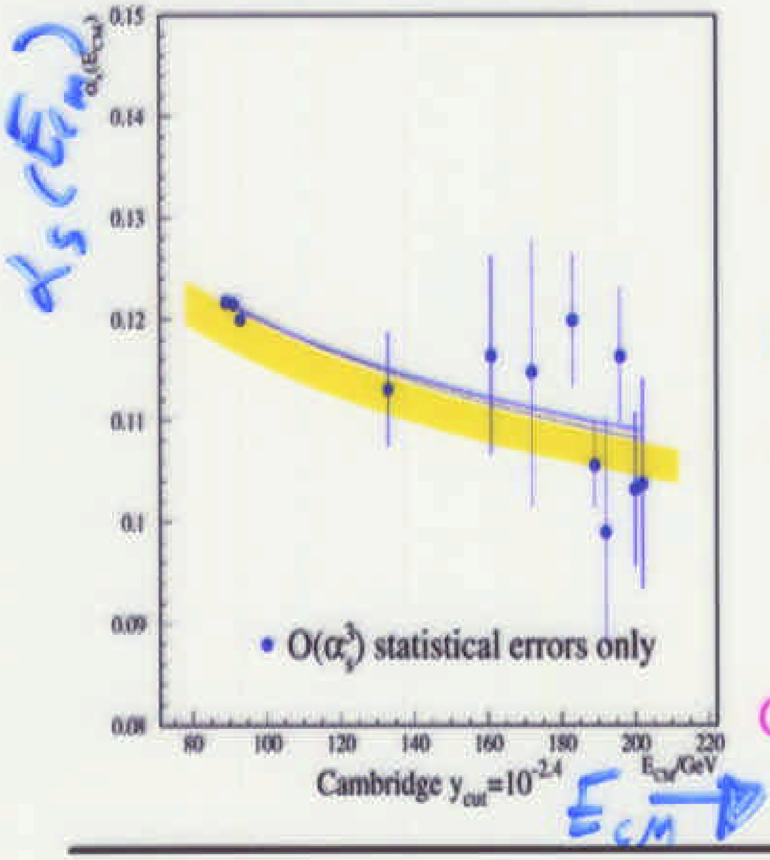
- Angular Ordering $v_{ab} = (1 - \cos\theta_{ab})$
- Soft Freezing



α_s from 4 Jet Rate

Four Jet Rates (CAMBRIDGE) before and after 4 fermion cut:





NLO predictions:

$$R_4 = B \cdot \alpha_s^2 + C \cdot \alpha_s^3 + \ldots$$

(DEBRECEN1.0)

slope :

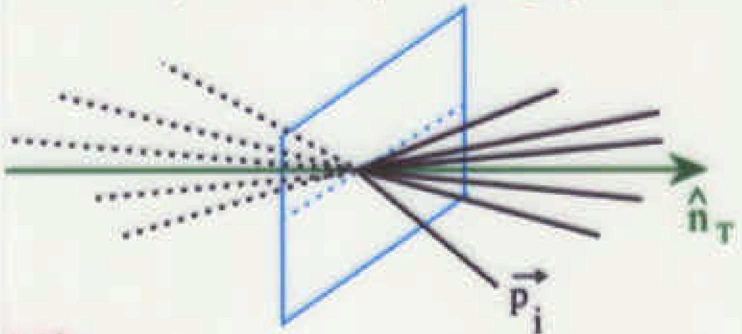
$$\frac{d\alpha_s^{-1}}{d \log E_{cm}} = 2b_0(1 + b_1\alpha_s + \ldots)$$

Fit R_4: **1.17 ± 0.28**

QCD prediction ($n_f = 5$): 1.27

Global event shape variables

- Energy Flow in hadronic events conveniently studied
- Collinear and infrared safe variables analytically calculable
- Perturbative calculations more complete than R^n_{jet}
- Hadronization: independent / string / cluster / power



Thrust

$$T = \left(\frac{\sum_i |\vec{p}_i \cdot \hat{n}_T|}{\sum_i |\vec{p}_i|} \right)_{max}$$

Heavy jet mass

$$\rho_H = \left(\sum_{i \in S_\pm} p_i \right)^2_{max} / s$$

Jet broadenings

$$B_\pm = \left(\frac{\sum_{i \in S_\pm} |\vec{p}_i \times \hat{n}_T|}{2 \sum_i |\vec{p}_i|} \right)$$

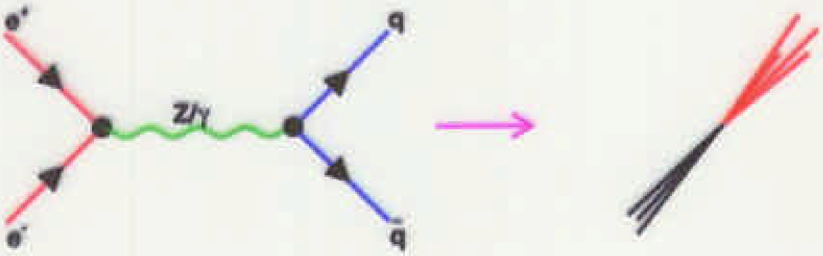
$$B_T = B_+ + B_-, \quad B_W = \max(B_+, B_-)$$

C-parameter

$$C = (\tfrac{3}{s}) \sum_{i<j} |\vec{p}_i| * |\vec{p}_j| * \sin^2(\theta_{ij})$$

Jets & Shapes

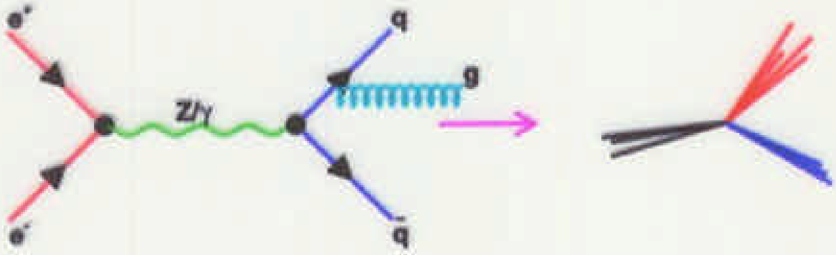
Event Shapes: relative contributions from n-jet configurations



2 jets

$1 - \mathrm{T} \simeq 0$

$\rho_{\mathrm{H}}, \mathrm{B_T}, \mathrm{B_W}, \mathrm{C} \simeq 0$



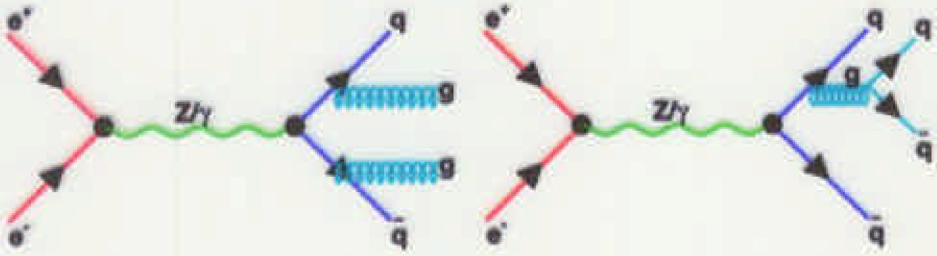
3 jets

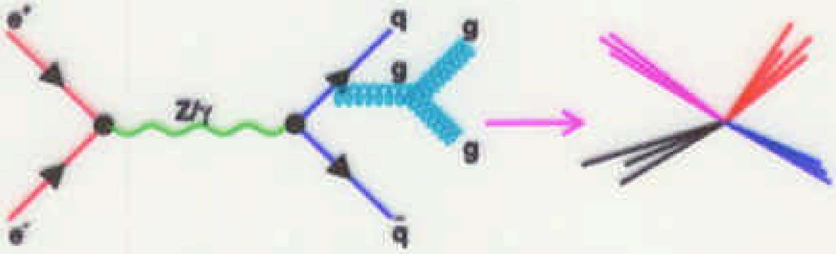
$\mathrm{T} \in [\frac{2}{3}, 1]$

$\rho_{\mathrm{H}} \approx 1 - \mathrm{T}$

$\mathrm{B_T} \in [0, \frac{1}{2\sqrt{3}}]$

$\mathrm{C} \in [0, \frac{3}{4}]$





4 jets

$\mathrm{T} \in [\frac{1}{\sqrt{3}}, 1]$

Planar Topology

$(\mathrm{C})_{max} = 1$

Spherical Topology

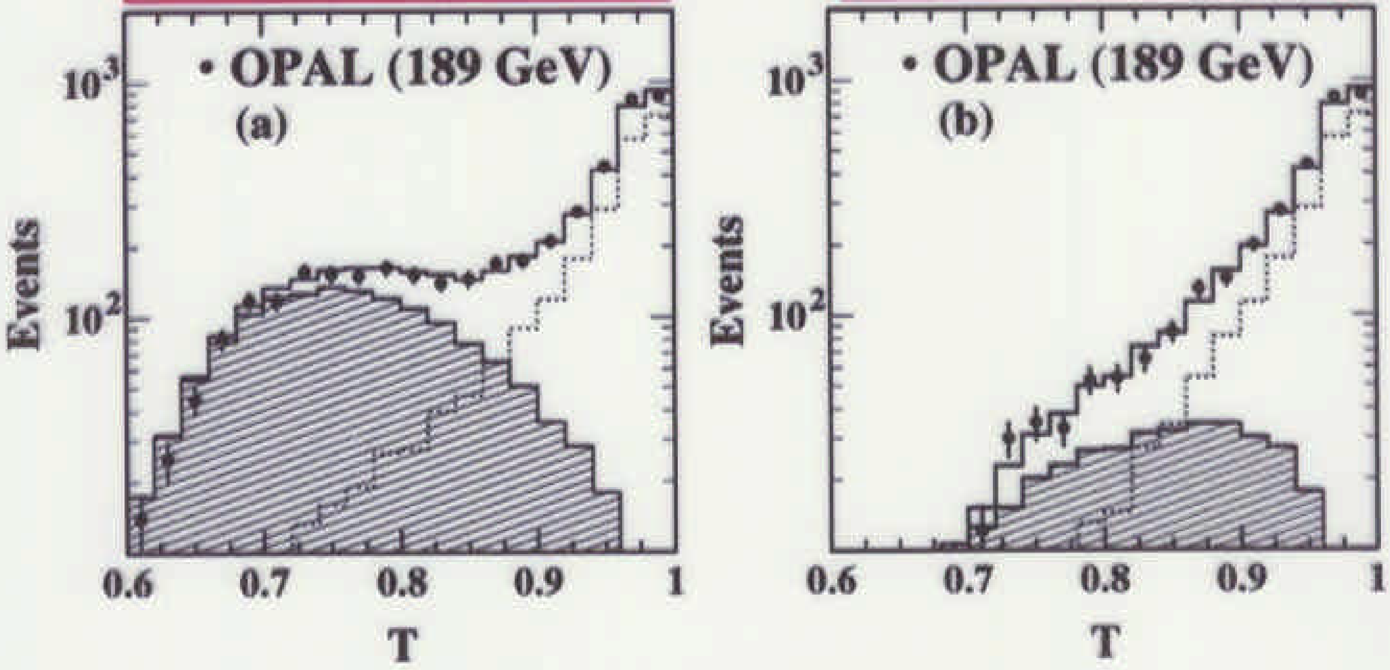
$(\mathrm{B_T})_{max} = \frac{\pi}{8}$

$(\mathrm{B_W})_{max} = \frac{\pi}{16}$

Distributions and moments of event shapes
from *total* hadronic event sample
➡ precise determination of α_s
(smaller theoretical and statistical errors than from R^{n}_{jet})

Event Shape Corrections

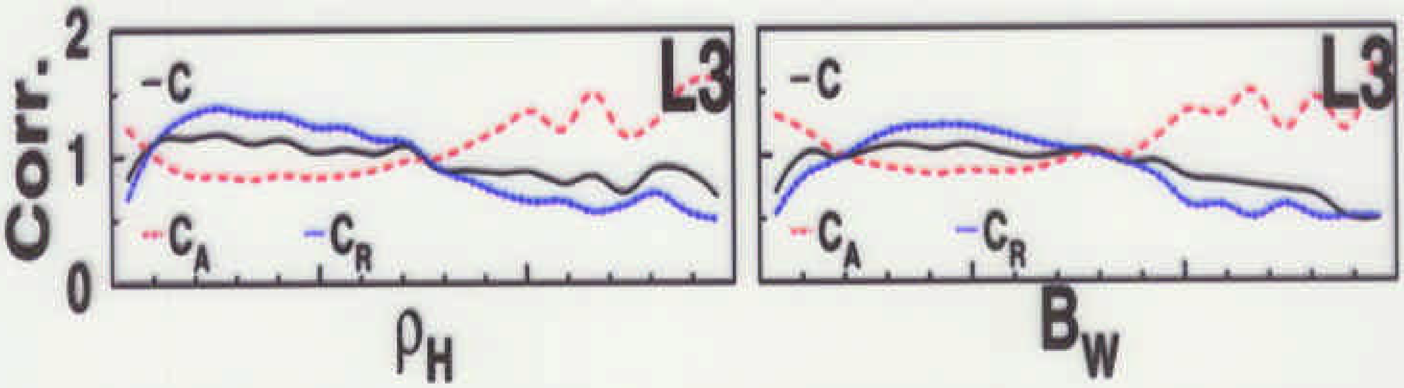
Before WW rejection | **After WW rejection**



Detector level distributions corrected *bin-by-bin* for:

- Remaining Background
- Detector Resolution
- Acceptance
- Initial/Final State Radiation

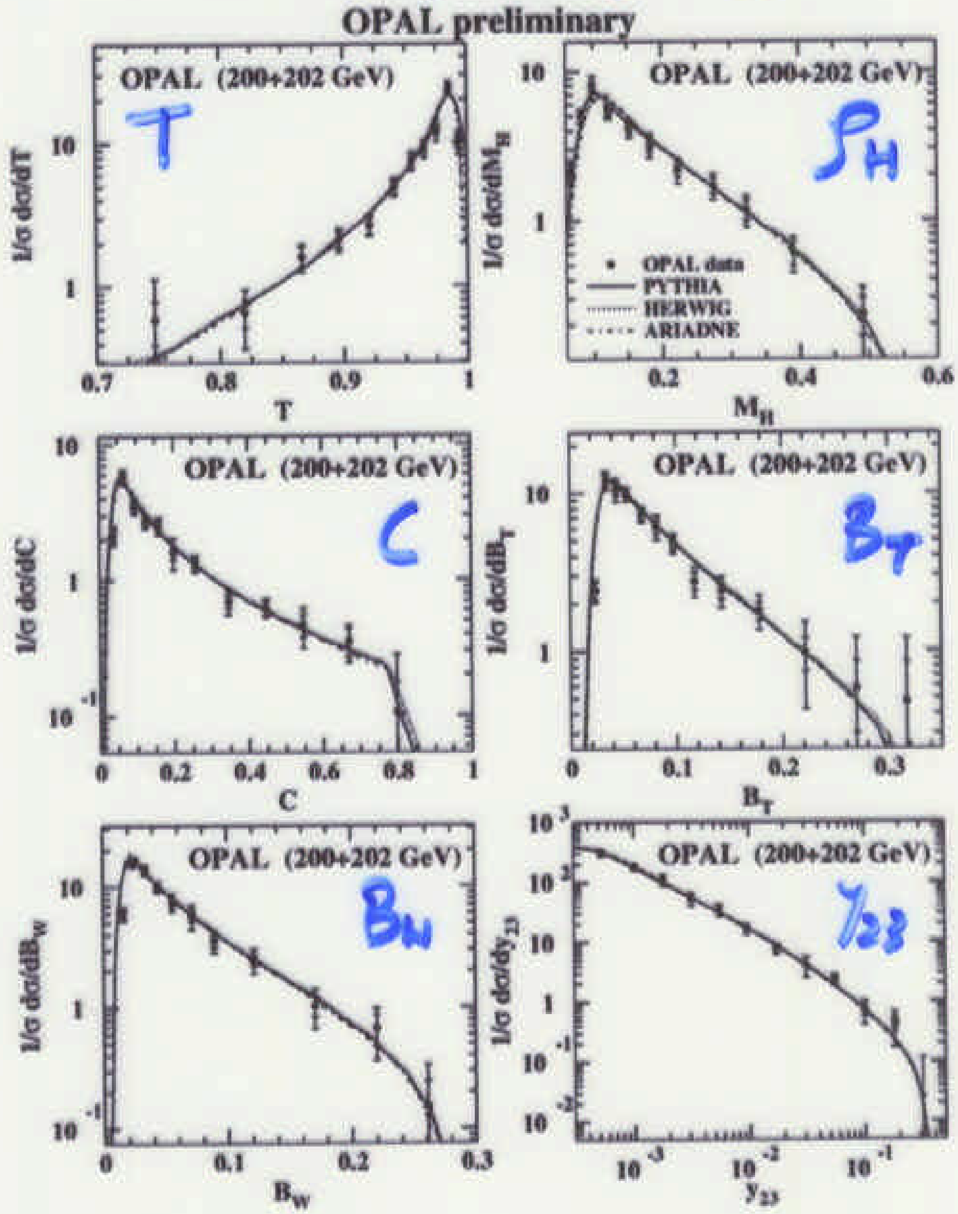
Correction Factors at $\sqrt{s} = 189$ GeV:



Comparison with QCD Event Generators

QCD Model	Shower Development	Fragmentation
JETSET/PYTHIA	Parton Shower	String
HERWIG	Parton Shower	Cluster
ARIADNE	Color Dipole	String
COJETS	Incoherent	Independent

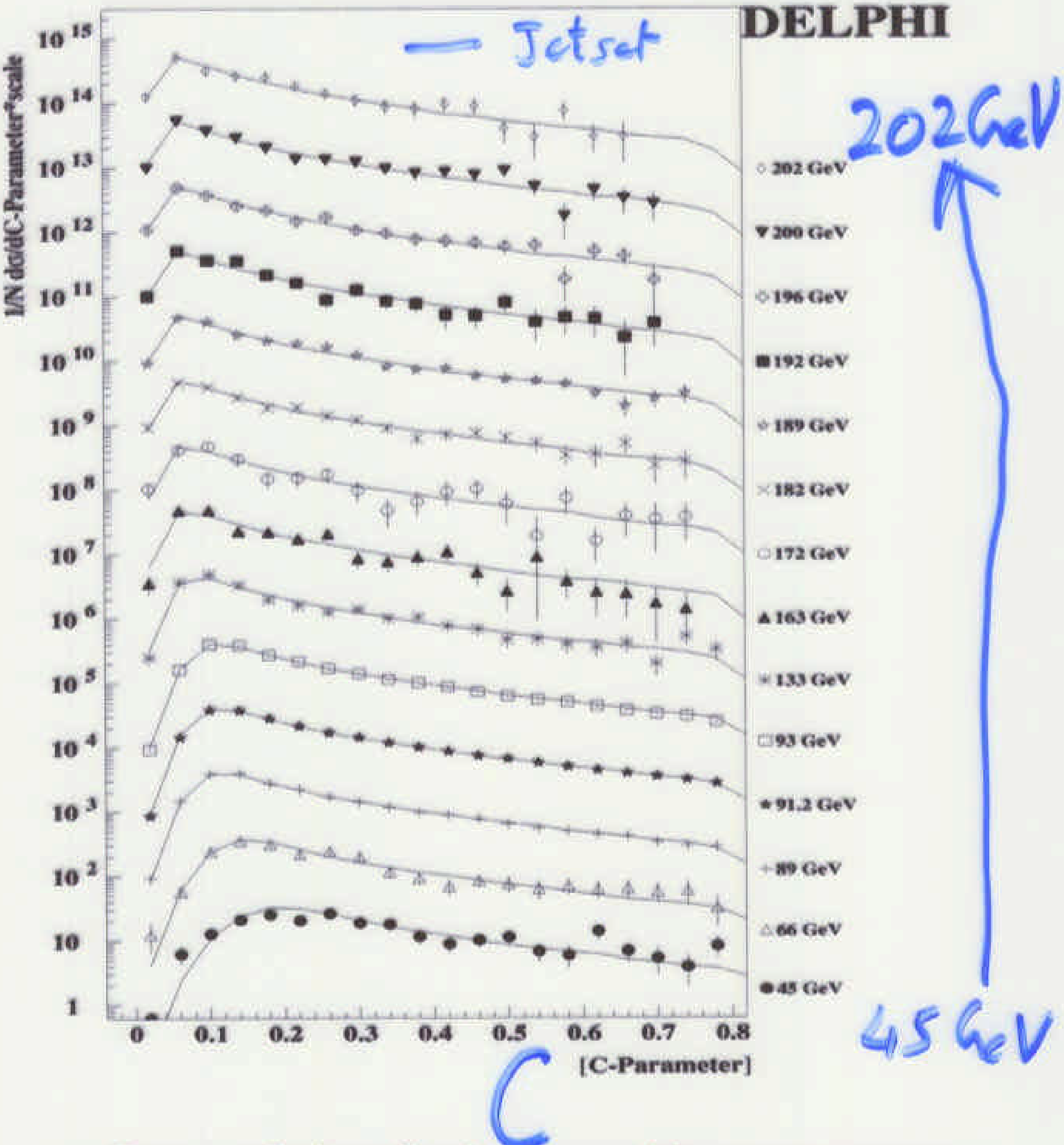
All models tuned at $\sqrt{s} = M_Z$ using LEP I data



Energy Evolution

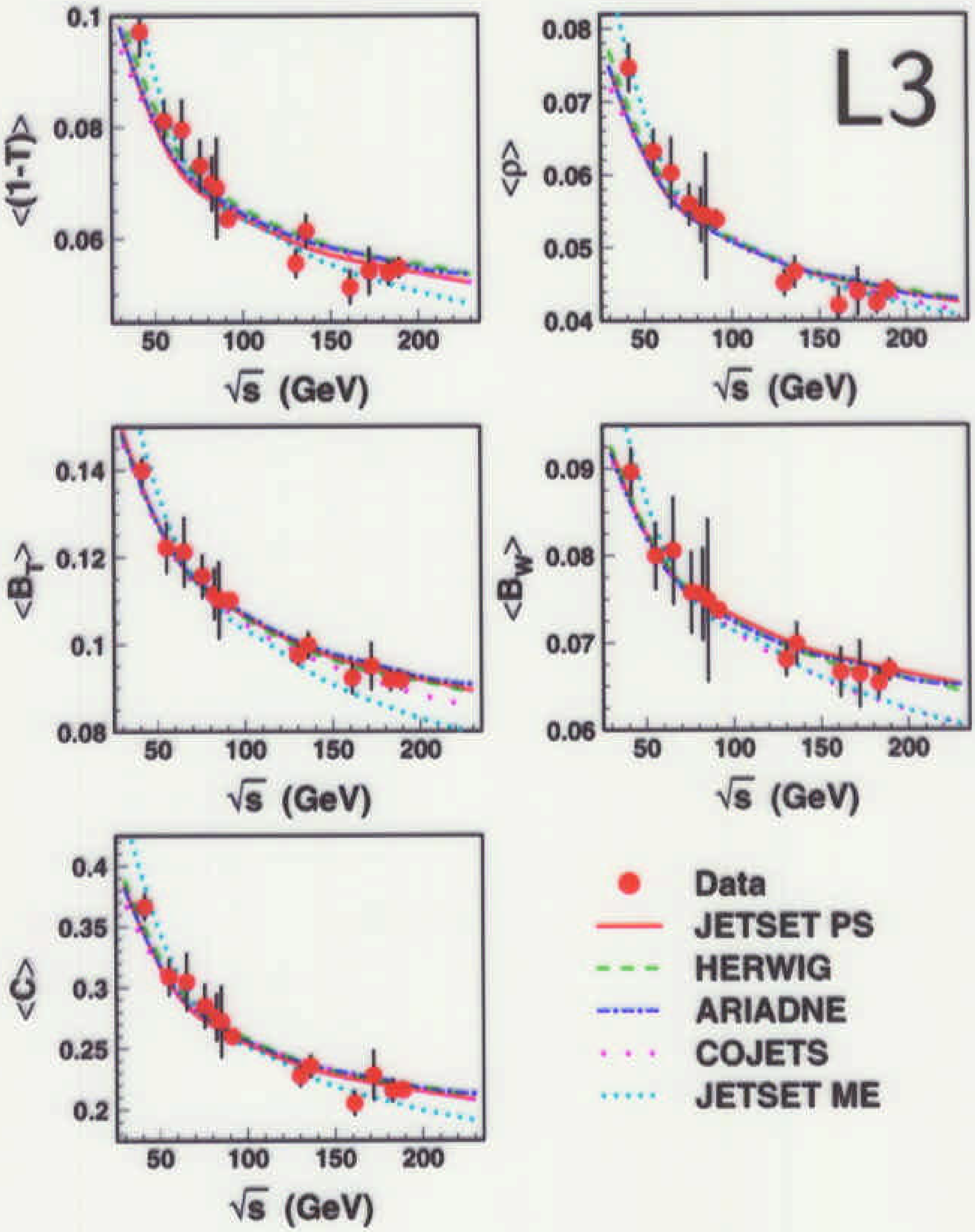
Sources:

- ★ Logarithmic dependence from α_s
- ✸ $1/Q^n$ dependence from non-perturbative effects



⇒ Data well described over a wide energy range

Mean Values



⇒ QCD Models with parton shower describe data well

Power law behaviour

Assumption: Soft gluon emission controlled by *effective* $\alpha_{\rm eff}$, *different from* α_s *only in infrared region*

$$\langle V\rangle = \underbrace{\langle V\rangle_{\rm PT}}_{\mathcal{O}(\alpha_s^2)} + \underbrace{\langle V\rangle_{\rm NPT}}_{c_V * \mathcal{P}}$$

Free parameters:

1. $\alpha_s(M_Z)$
2. $\alpha_0(\mu_I) = \frac{1}{\mu_I}\int_0^{\mu_I} dq\,\alpha_{\rm eff}(q)$

$$\mathcal{O}(\alpha_s^2) : \langle V\rangle_{\rm PT} = A\frac{\alpha_s(Q)}{2\pi} + \left(B + 2A\beta_0 \ln\frac{\mu^2}{Q^2}\right)\left(\frac{\alpha_s(Q)}{2\pi}\right)^2$$

☞ For V = 1-T,C,ρ_H : "a shift $\propto$ 1/Q"

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

☞ For V = B_T, B_W : "a shift $\propto$ 1/Q" + "logarithmic-skew"

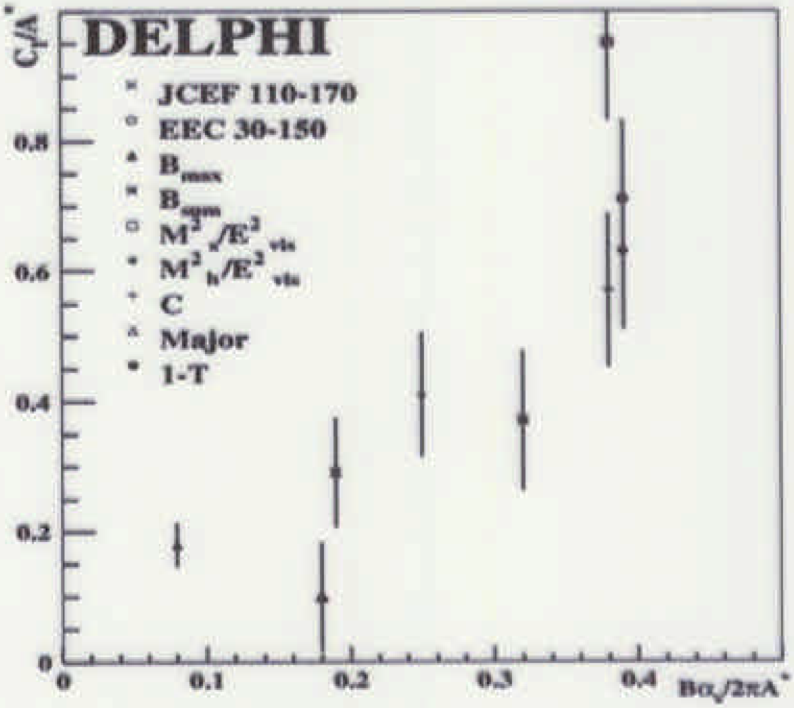
$$\mathcal{P} * \delta_V \left\{ \left(\alpha_{CMW}(Qe^{-\frac{3}{4}})\right)^{-\frac{1}{2}} + {\rm const}_V + \mathcal{O}(\sqrt{\alpha_s}) \right\}$$

Correlation between relative size of the power contribution $(\frac{C_1}{A^*})$

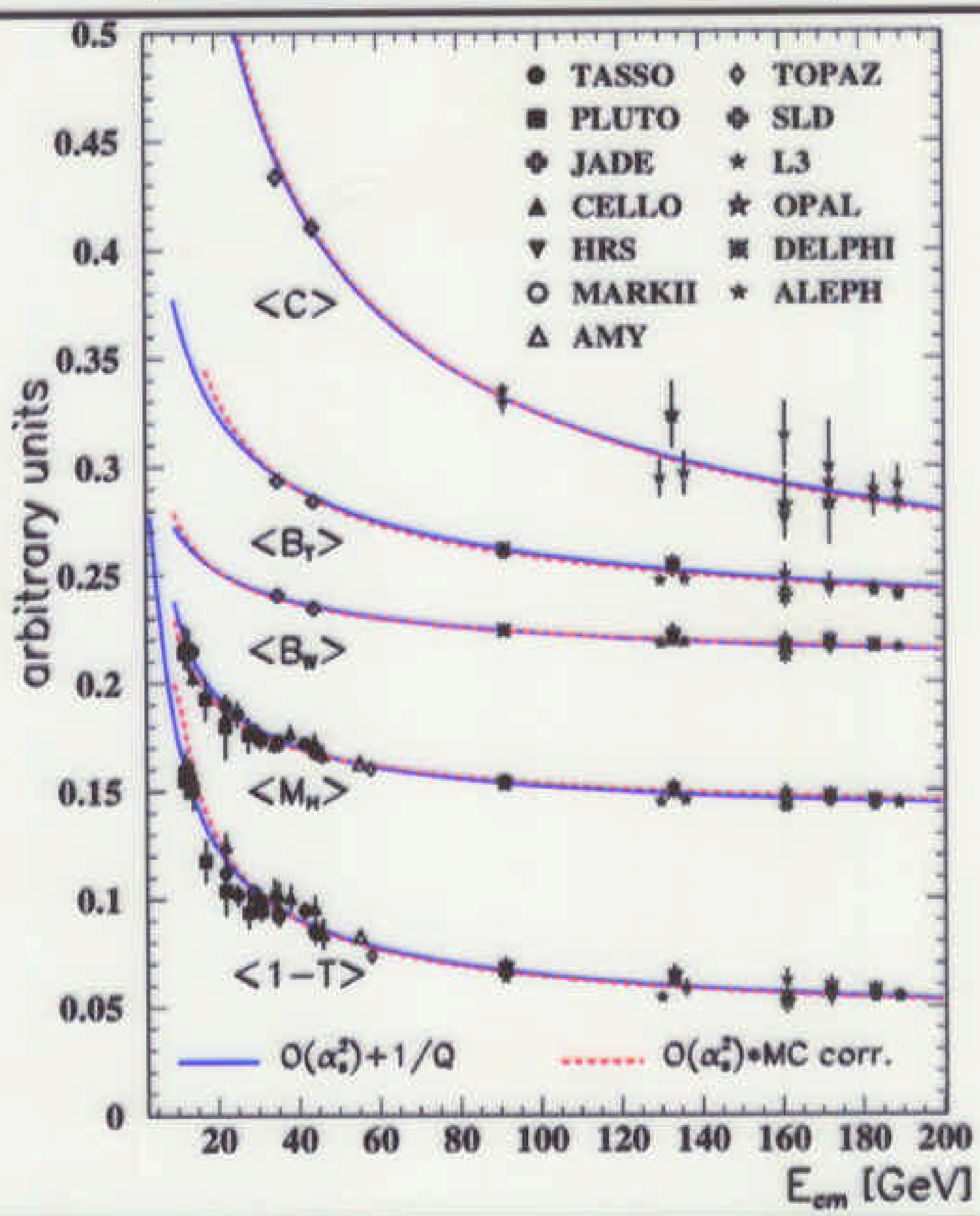
Versus

relative size of the second order term $(\frac{B\alpha_s}{2\pi A^*})$:

$$(A^* = A + \frac{\alpha_s}{2\pi}\cdot B)$$



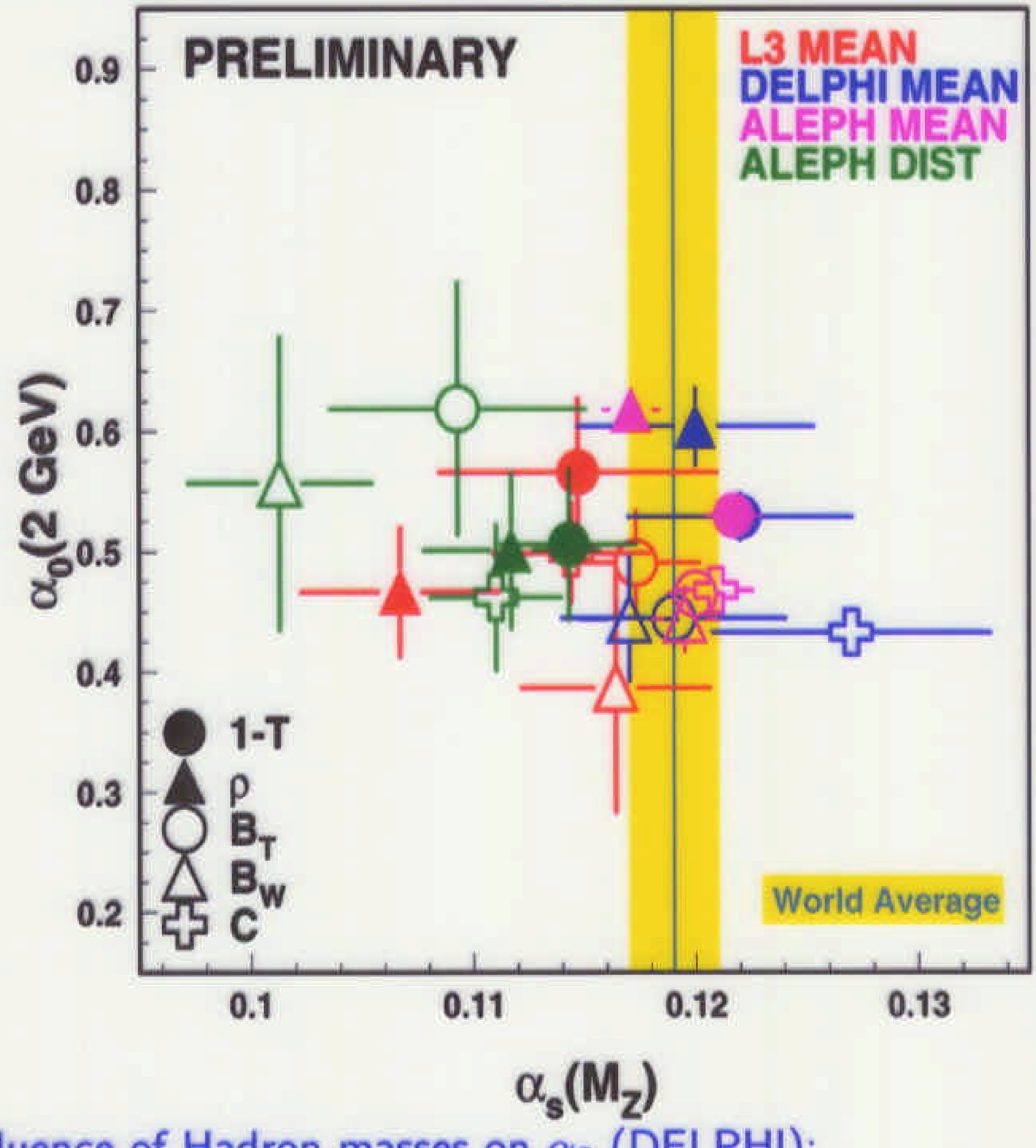
Power law behaviour



Variable	$\mathcal{O}({\alpha_s}^2) + 1/Q$		$\mathcal{O}({\alpha_s}^2) \star \mathrm{MC}$
	$\alpha_0(2\mathrm{GeV})$	$\alpha_s(\mathrm{M_Z})$	$\alpha_s(\mathrm{M_Z})$
T	.530 ± .010	.1217 ± .0013	.1289 ± .0004
ρ	.618 ± .018	.1171 ± .0013	.1266 ± .0006
$\mathrm{B_T}$	.465 ± .018	.1200 ± .0013	.1217 ± .0004
$\mathrm{B_W}$	.444 ± .028	.1195 ± .0015	.1266 ± .0005
C	.468 ± .013	.1209 ± .0017	.1270 ± .0005

Power law behaviour

Predictions for mean AS WELL AS differential distributions:

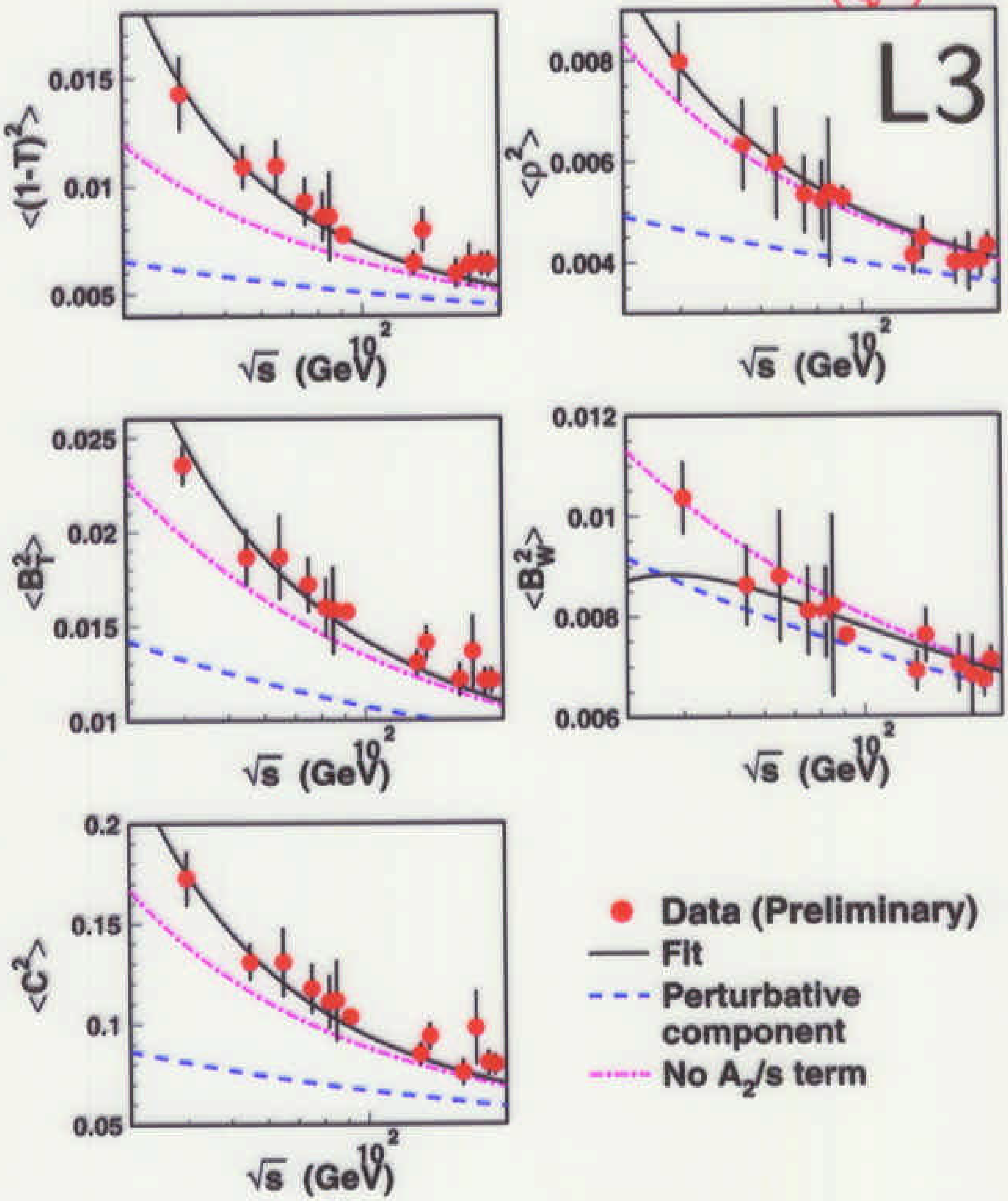


Influence of Hadron masses on α_0 (DELPHI):

	$(\vec{p}$,E)	$(\vec{p},\|\vec{p}\|)$	$(\hat{p}$E,E)
α_0 (from M_h^2)	0.69 ± 0.04	0.46 ± 0.03	0.49 ± 0.03
α_0 (from M_s^2)	0.66 ± 0.04	0.45 ± 0.04	0.50 ± 0.03

Second Moments

$$\langle f^2 \rangle = \langle f^2_{\rm pert} \rangle + 2\langle f_{\rm pert} \rangle \cdot c_f \mathcal{P} + \mathcal{O}\left(\frac{1}{Q^2}\right)$$



$\mathcal{O}(\frac{1}{Q^2})$ term small for ρ, negative for $\mathrm{B_W}$

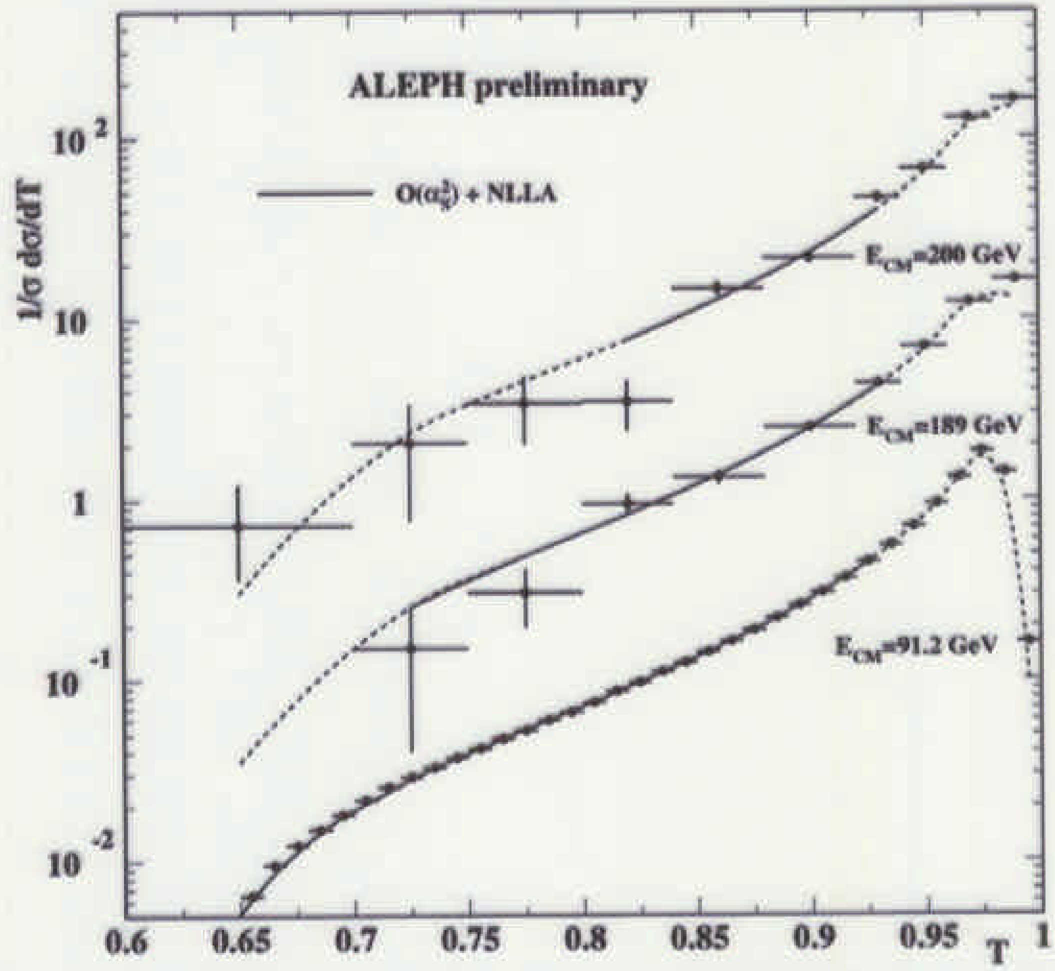
Resummed LL & NLL + $\mathcal{O}(\alpha_s^2)$

- Complete Calculations to $\mathcal{O}(\alpha_s^2)$: $y = 1-T, \rho_H, B_T, B_W, C, y_{23}$

$$R(\alpha_s, y) \equiv \int_0^y \frac{1}{\sigma}\frac{d\sigma}{dy} = \overline{\alpha}_s A(y) + \overline{\alpha}_s^2 \left[B(y) + 2\pi\beta_0 \ln(\mu^2/s) A(y)\right]$$

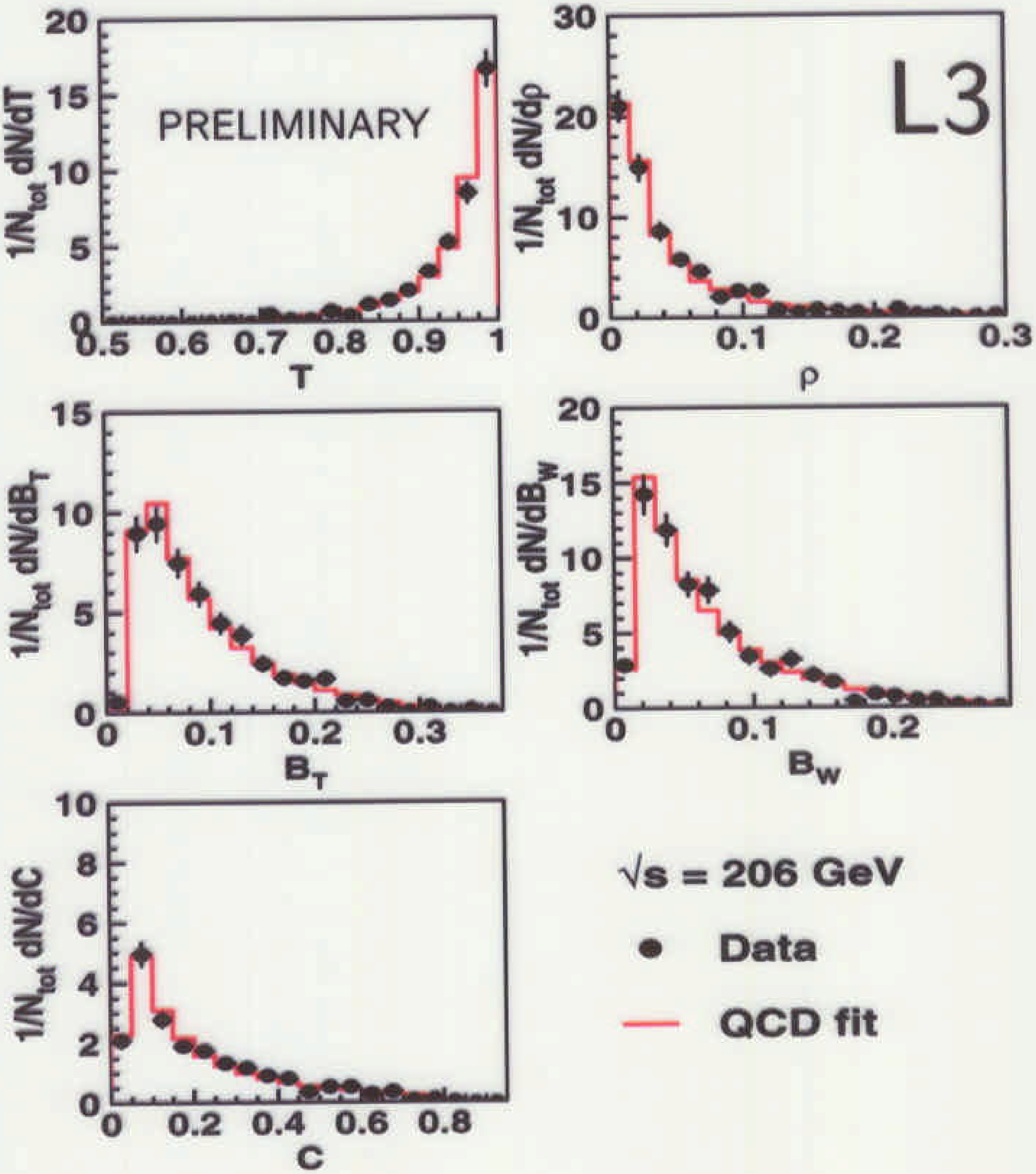
- Resummation: Leading-Log $\sum(\alpha_s L^2)^n$; Next-to-Leading-Log $\sum(\alpha_s^n L^{2n-1})$, $L = \log(y)$

$\mathcal{O}(\alpha_s^2)$ multi-jet region, NLL semi-inclusive region



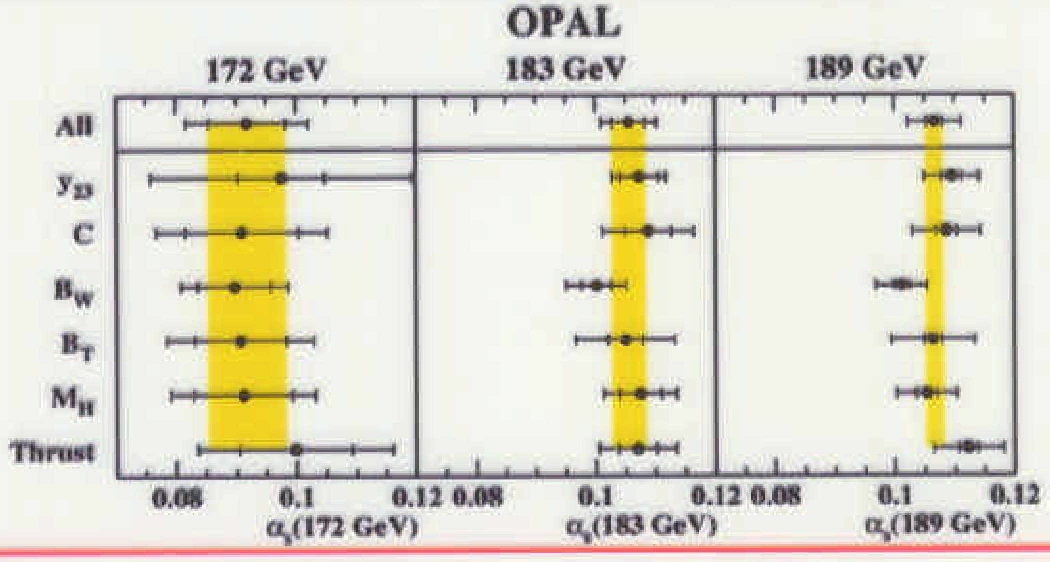
- Quark Mass Effects : 1% at M_Z, 0.2-0.3% at 200 GeV
  $\mathcal{O}(\alpha_s^2)$ calculations (P.Nason and C. Oleari '98)

Resummed LL & NLL + $\mathcal{O}(\alpha_s^2)$

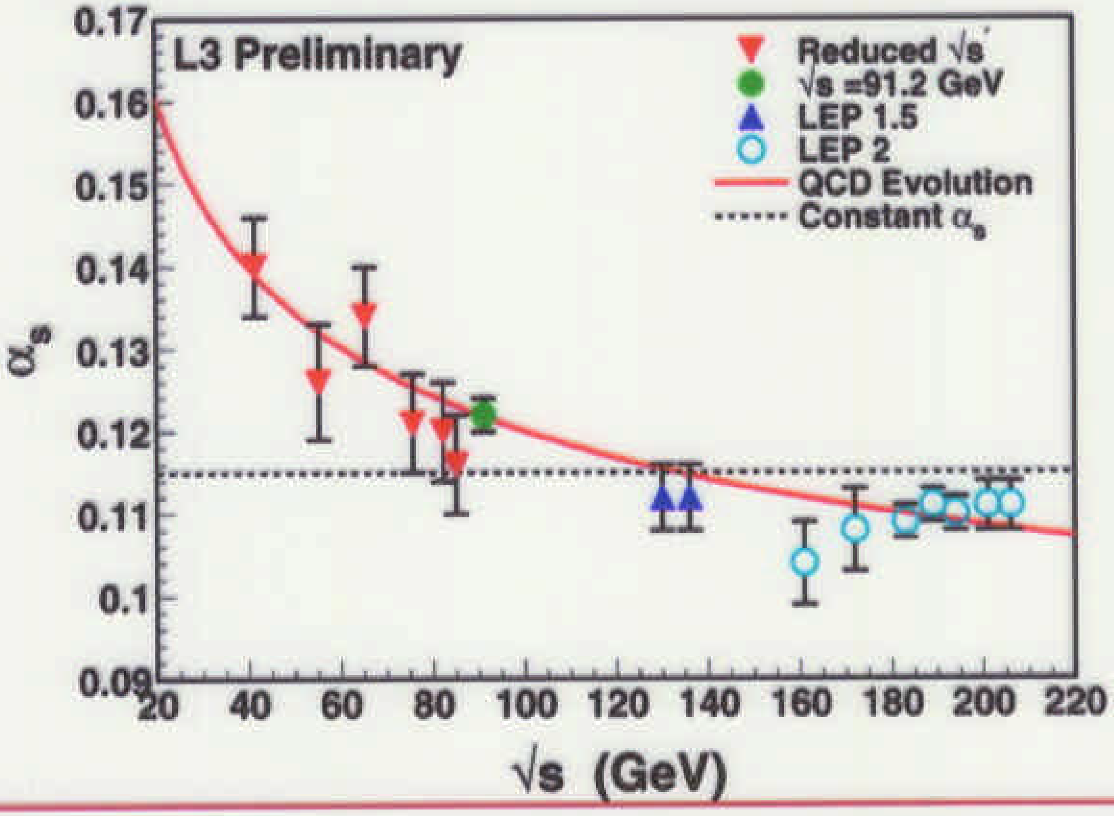


☞ L3 probes smaller values of y by using wider fit range

Combining the measurements



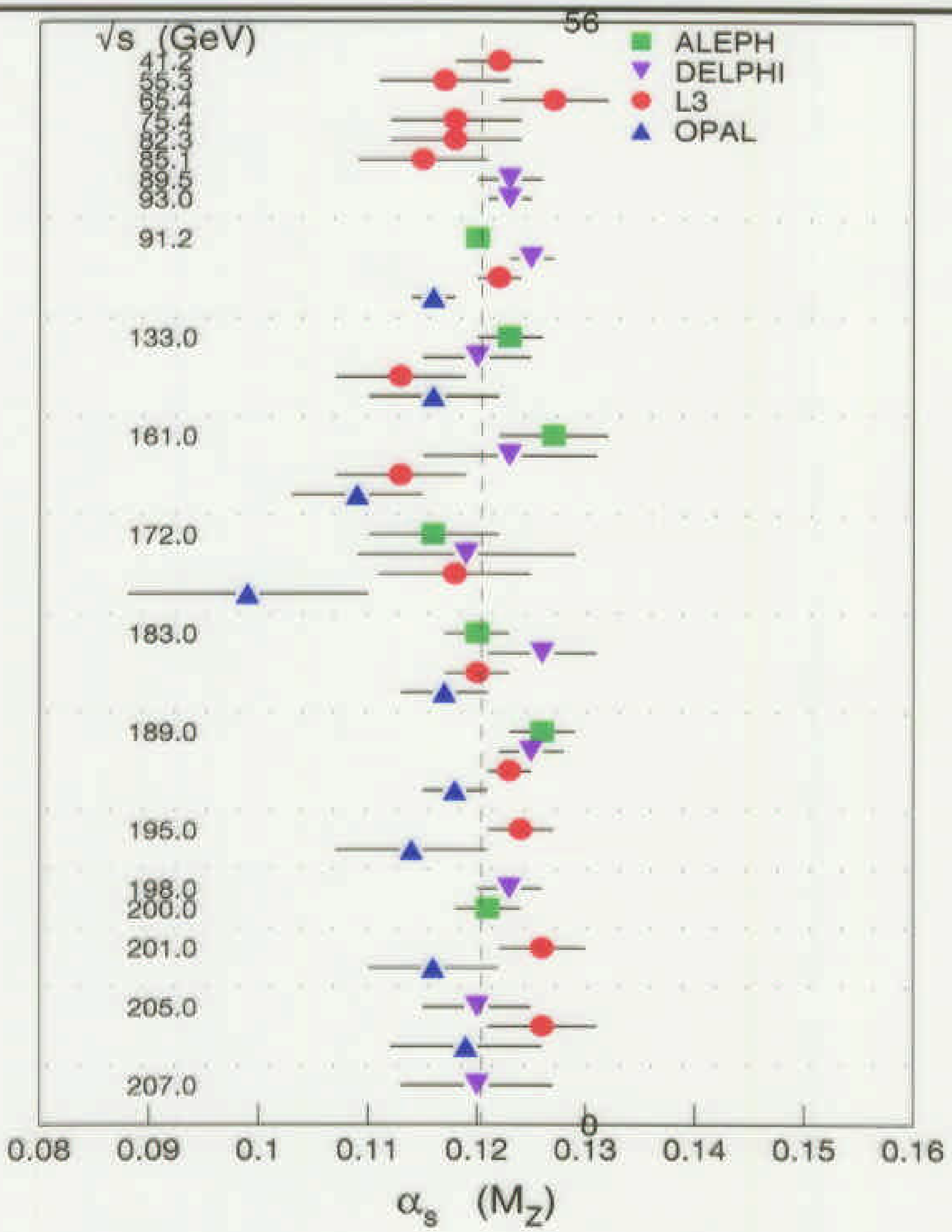
Running of α_s from 30 to 206 GeV from L3 Data:



$$\alpha_s(M_Z) = 0.1218 \pm 0.0012\ (\text{exp}) \pm 0.0061\ (\text{theo})$$

$$N_f = 5.1 \pm 1.3\ (\text{exp}) \pm 1.9\ (\text{theo})$$

LEP Average of NLL + $\mathcal{O}(\alpha_s^2)$ fits

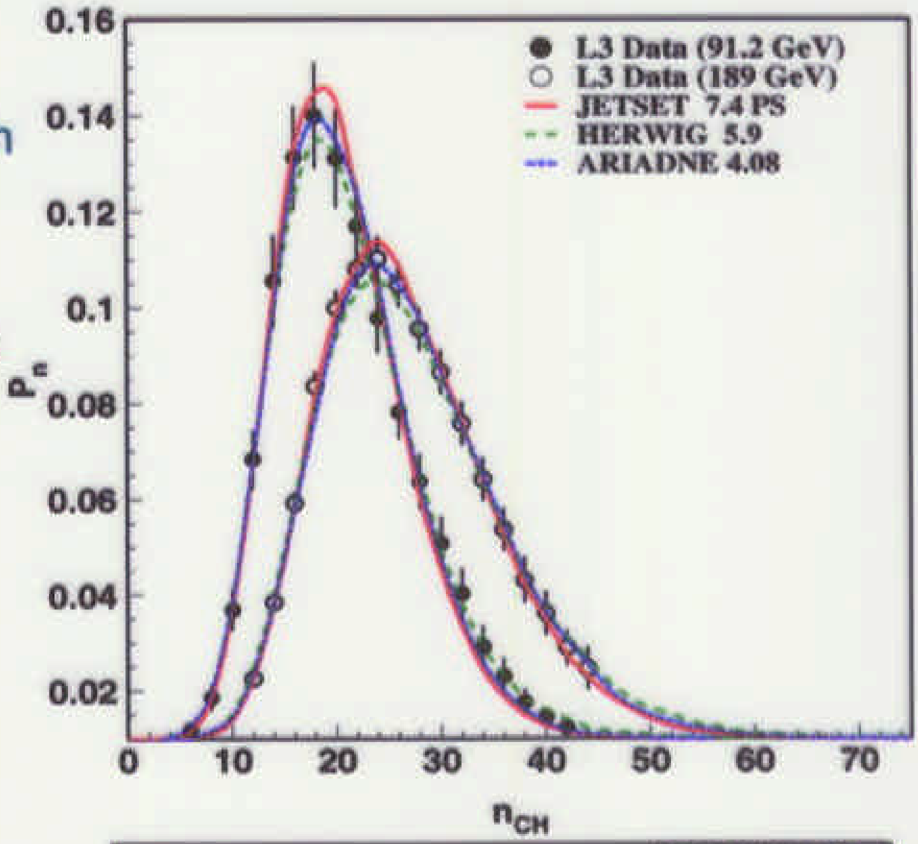


ALEPH	DELPHI	L3	OPAL
$T, -\ln y_3, m_H^2, B_W, C$	T, ρ	T, ρ, B_T, B_W, C	$T, y_3, \rho, B_T, B_W, C$

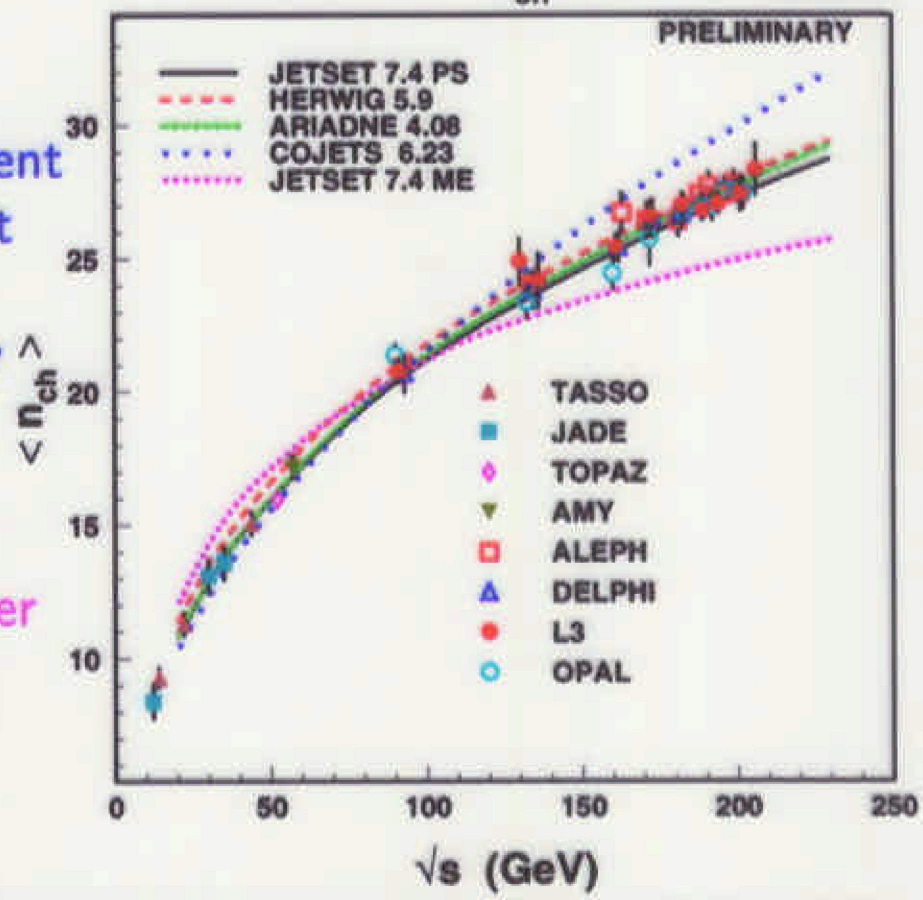
$$\alpha_s(M_Z) = 0.1204 \pm 0.0007(\text{exp}) \pm .0034(\text{theo})$$

Charged Particle Multiplicity

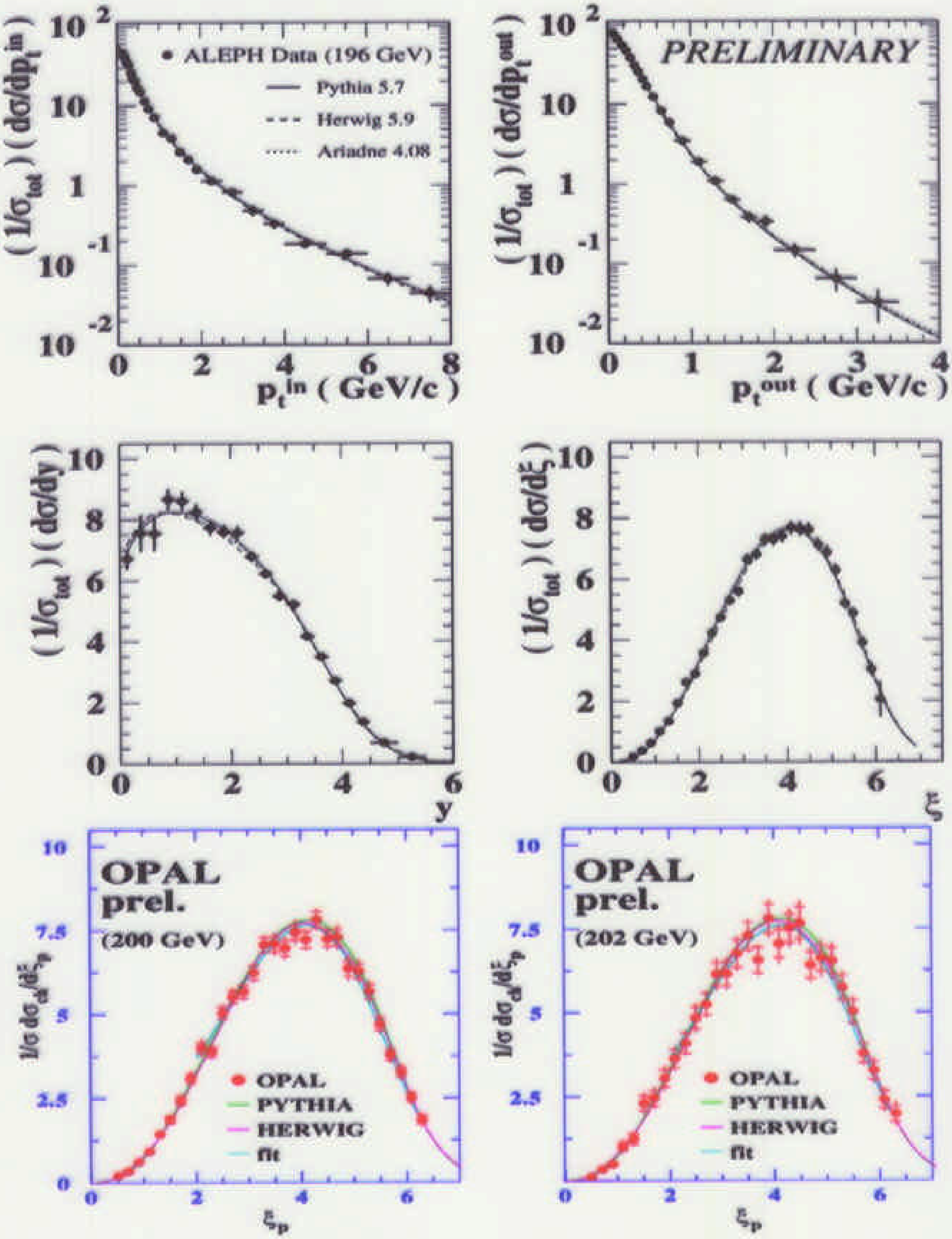
- ✳ Detector correction using unfolding
- ❑ Spectra "shifts" & "broadens" with increasing $\sqrt{s}$



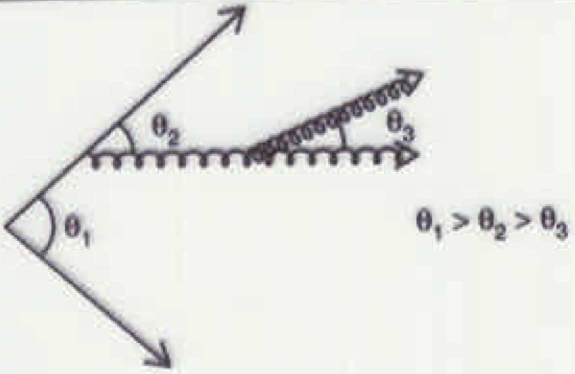
- ▲ COJETS (incoherent PS & independent fragmentation) ⇒ higher multiplicity at high energies
- ▼ Second order ME with a fixed number of partons cannot describe evolution



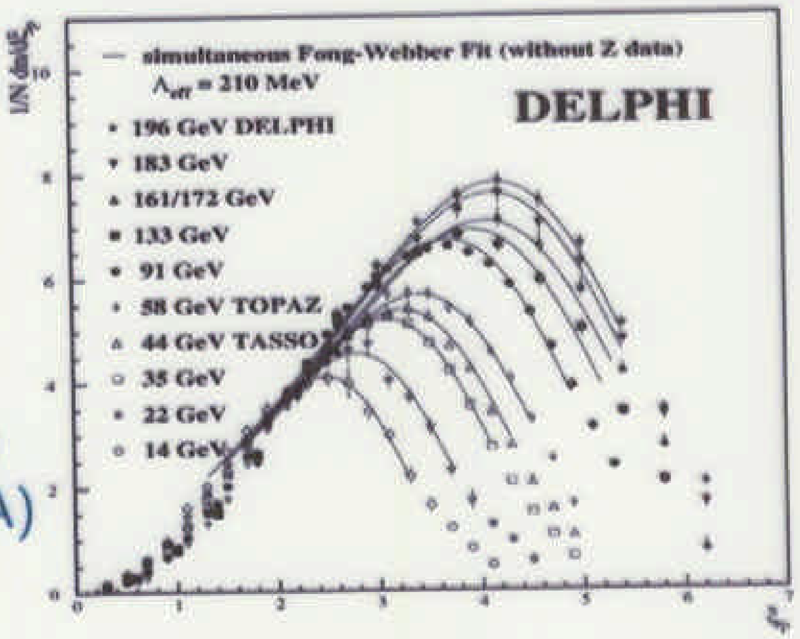
Inclusive Charged Particle Spectra



Gluon Coherence



Angular Ordering of successive soft gluon radiation reduces phase space available

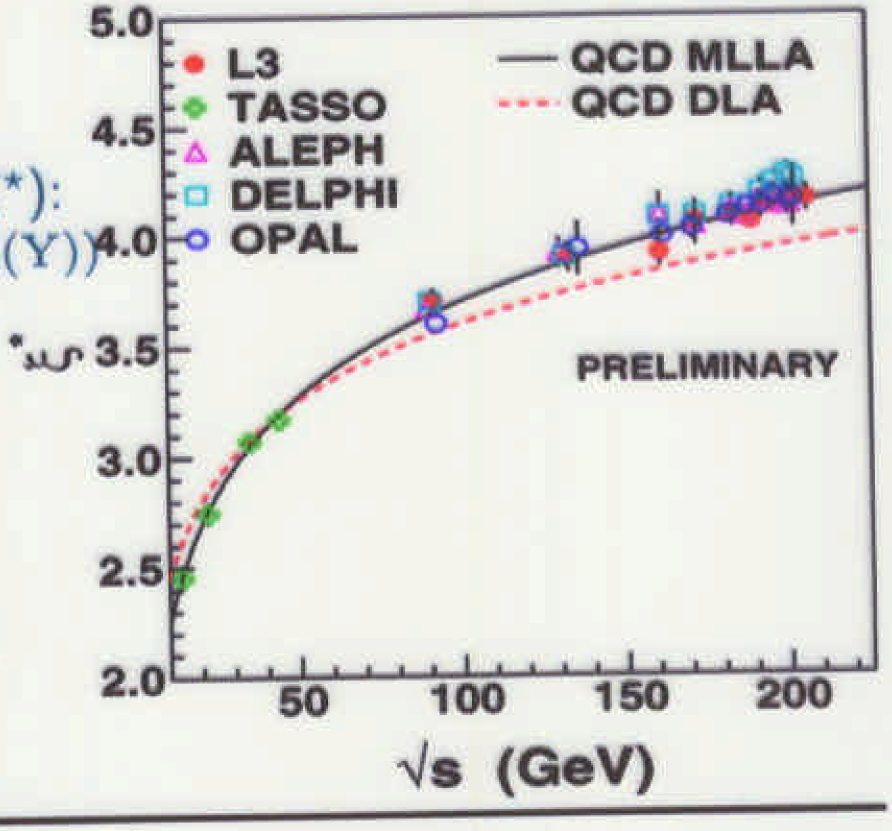


⇒ Dip at low momentum
$(x_p = 2\,|\vec{p}|\,/\sqrt{s})$

$\xi_p = \ln(\frac{1}{x_p})$ spectra:

- Gaussian (leading order)
- Skewed Gaussian (MLLA)

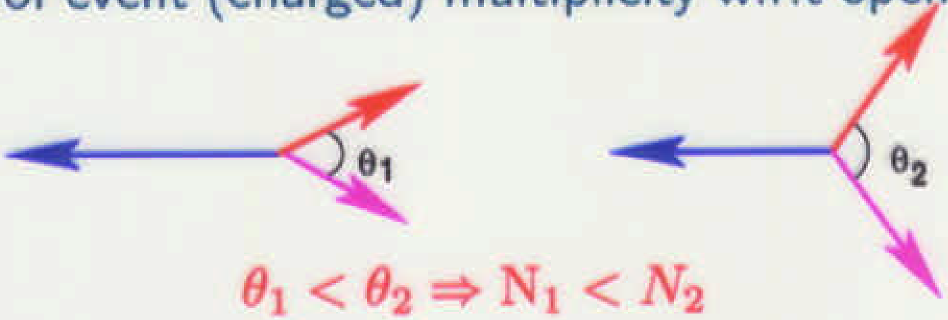
Predictions for peak ($\xi^\star$):
$Y(\frac{1}{2} + \sqrt{C\alpha_s(Y)} - C\alpha_s(Y))$
where $Y = \ln(E_{beam}/\Lambda)$



Fit to L3 + TASSO:
χ^2/d.o.f =
56.3/12 for DLA
12.2/12 for MLLA

Symmetric 3 jet events

Evolution of event (charged) multiplicity w.r.t opening angle:



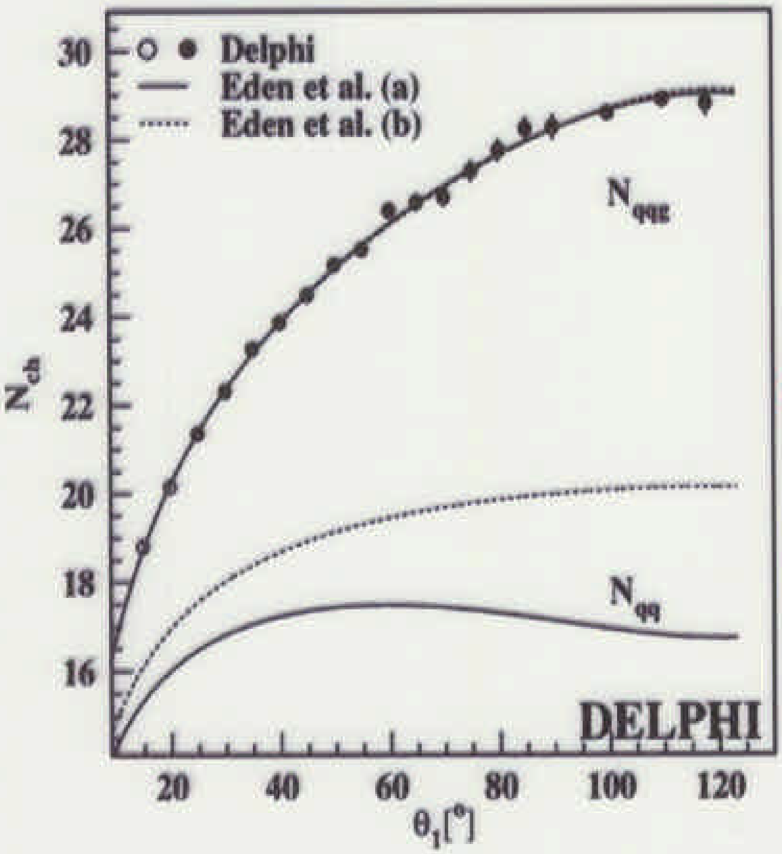
$$\theta_1 < \theta_2 \Rightarrow \mathrm{N}_1 < N_2$$

Recent theoretical calculations: (P.Eden et.al. '98,'99)

$$\mathrm{N}_{q\bar{q}g} = \mathrm{N}_{q\bar{q}}(\mathrm{L}_{q\bar{q}}, \kappa_{\mathrm{Lu}}) + \frac{1}{2}\mathrm{N}_{gg}(\kappa_{\mathrm{Le}}) \quad ...(a)$$

$$\mathrm{N}_{q\bar{q}g} = \mathrm{N}_{q\bar{q}}(\mathrm{L}, \kappa_{\mathrm{Lu}}) + \frac{1}{2}\mathrm{N}_{gg}(\kappa_{\mathrm{Lu}}) \quad ...(b)$$

$$\mathrm{k}_{\perp\mathrm{Lu}}^{2} = \frac{s_{qg}s_{\bar{q}g}}{s} \qquad \mathrm{k}_{\perp\mathrm{Le}}^{2} = \frac{s_{qg}s_{\bar{q}g}}{s_{q\bar{q}}} \qquad s_{\mathrm{ij}} = (p_{\mathrm{i}} + p_{\mathrm{j}})^2$$



⇒ New measurements of Color factors:

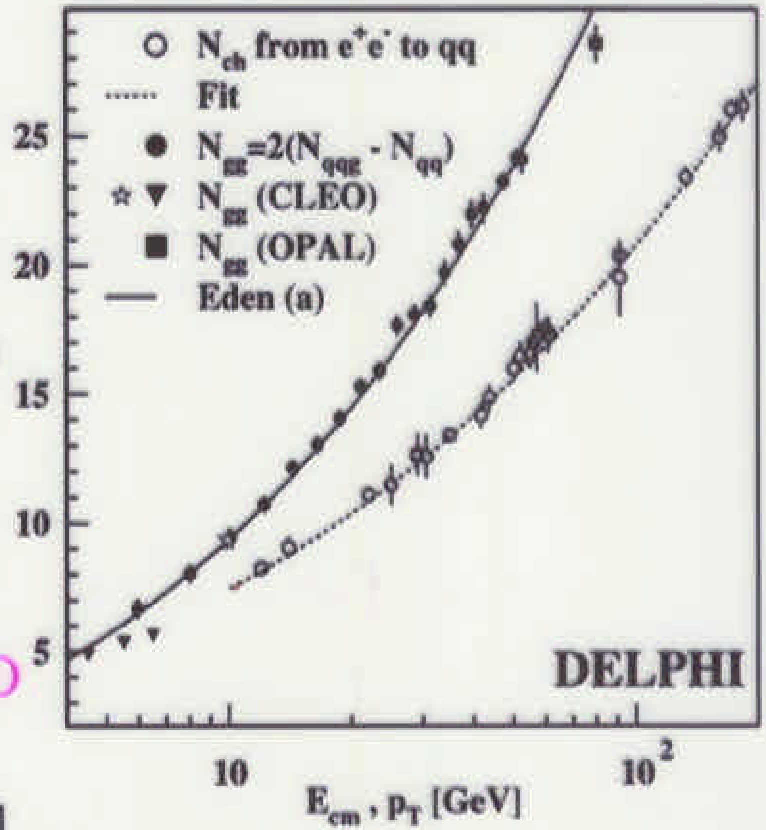
$$\mathrm{C_A/C_F} = 2.221 \pm 0.047\ (\mathrm{exp}) \pm 0.058\ (\mathrm{had}) \pm 0.075\ (\mathrm{theo})$$

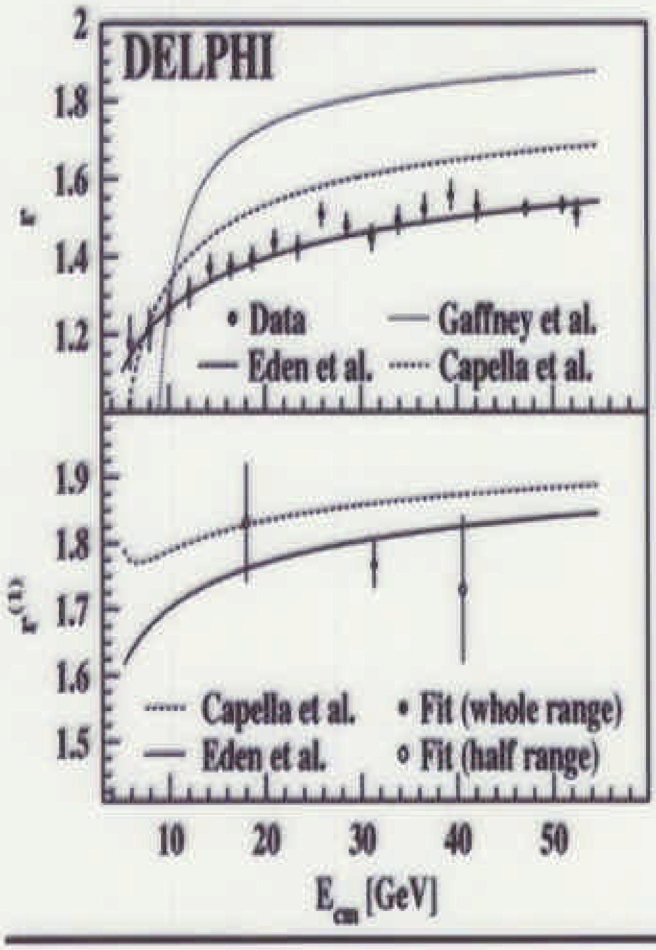
$q\bar{q}$ and gg multiplicities

Gluon-gluon Multiplicity extracted at scales given by C.M. energy and $k_\perp$:

$$N_{gg} = 2[N_{q\bar{q}g}(\theta) - N(L_{q\bar{q}}, \kappa_{Lu}) - N_0]$$

- $C_A/C_F = 2.25$ assumed
- N_0 estimated from CLEO





$$\frac{dN_{gg}/dy}{dN_{q\bar{q}}/dy} = r^{(1)} = 1.77 \pm 0.03$$

Evidence of:
- ☞ triple gluon vertex
- ☞ higher gluon color charge

Summary

- Event Shape variables have been studied over a large energy range: 30 to 208 GeV from LEP data. Good agreement seen between data and coherent models tuned at $\sqrt{s} = M_Z$.

- Jet Rates follow the expected QCD energy evolution. New $\mathcal{O}({\alpha_s}^3)$ calculations have become available.

- LEP Average of α_s measurements using $\mathcal{O}({\alpha_s}^2)$+NLLA calculations from event shapes:

$$\alpha_s(M_Z) = 0.1204 \pm 0.0007\ (\text{exp}) \pm .0034\ (\text{theo})$$

- From Power law parametrization α_s is measured to be lower. Universality of α_0 have been tested within 20%, and power law studies have been extended to 2^{nd} moment.

- Evidence of gluon coherence have been observed in charged particle inclusive spectra.

- Evidence of triple gluon vertex and higher gluon color charge has been observed. Color factor measurement is in agreement with QCD expectation. Gluon-gluon multiplicity has been measured.