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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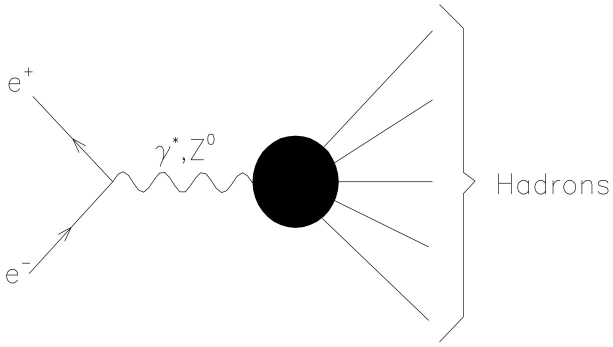
ANNECY lapp

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 ($\sqrt{\mathrm{s}} > \mathrm{M_Z}$) : 500 pb^{-1} /expt
  Delivered luminosity (1995-2000) $> 637\ \mathrm{pb}^{-1}$ /expt



Precise measurements of QCD at LEP:

★ *Clean* initial state ($\mathrm{e^-e^+}$)

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

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

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

  Measurement of Strong coupling constant α_s

  Measurement of Active # of quark flavours $\mathrm{n_f}$

- *Soft Gluon Radiation:*

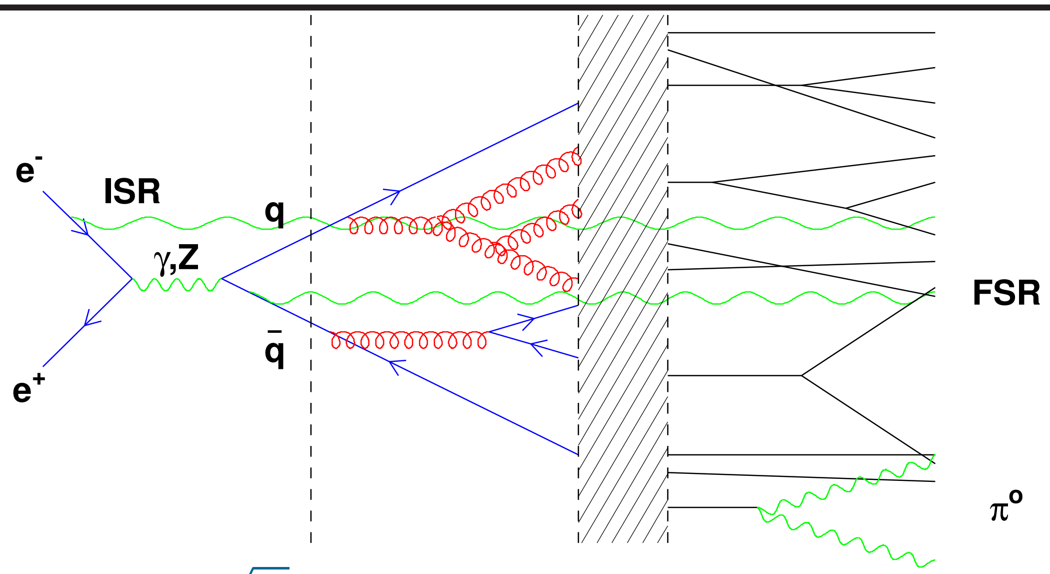
  Evidence of Intrajet Color coherence

  (inclusive charged particle spectra)

- *Quark and gluon multiplicity*:

  Measurement of QCD color factors $\mathrm{C_A/C_F}$

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 %

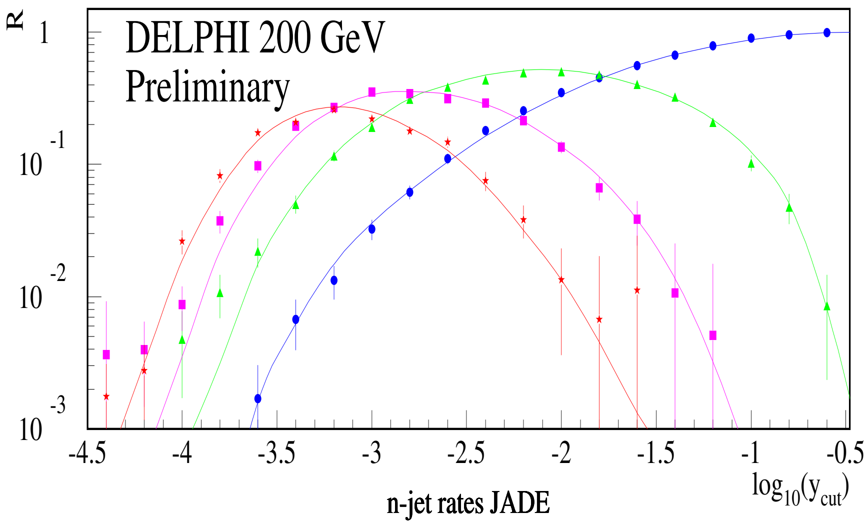
★ LEP 2 Data rejecting ISR, 4 fermion (WW,ZZ)

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

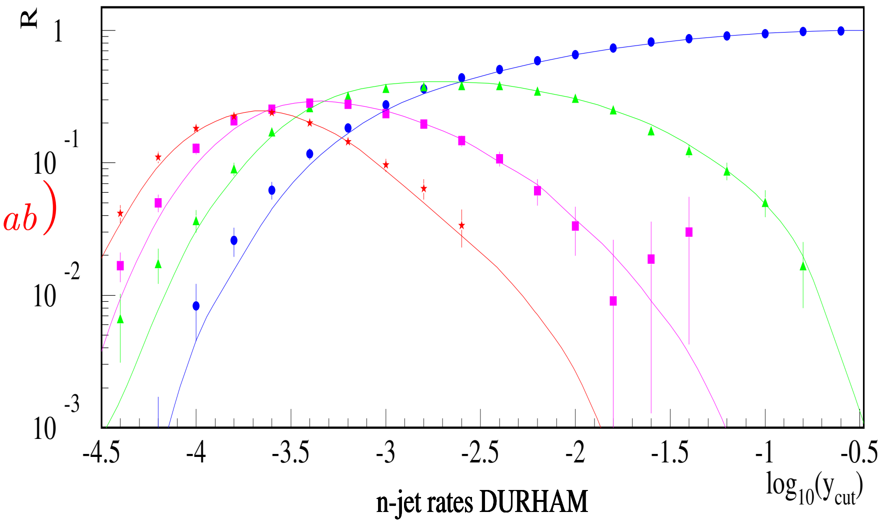
ALEPH, DELPHI, L3, OPAL: Purity ∼ 78-90%

Jet Rates

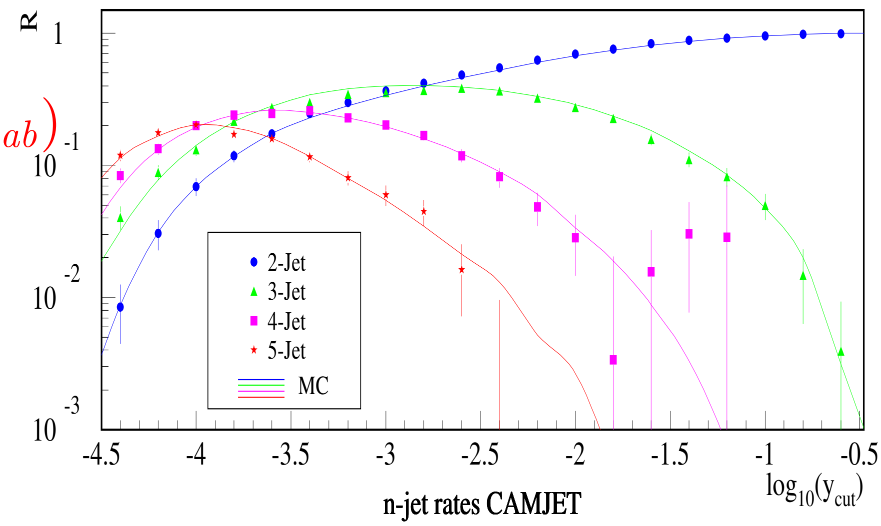
$$y_{ab}^{\text{JADE}} = \frac{2E_aE_b}{{E_{vis}}^2}(1-\cos\theta_{ab})$$



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



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



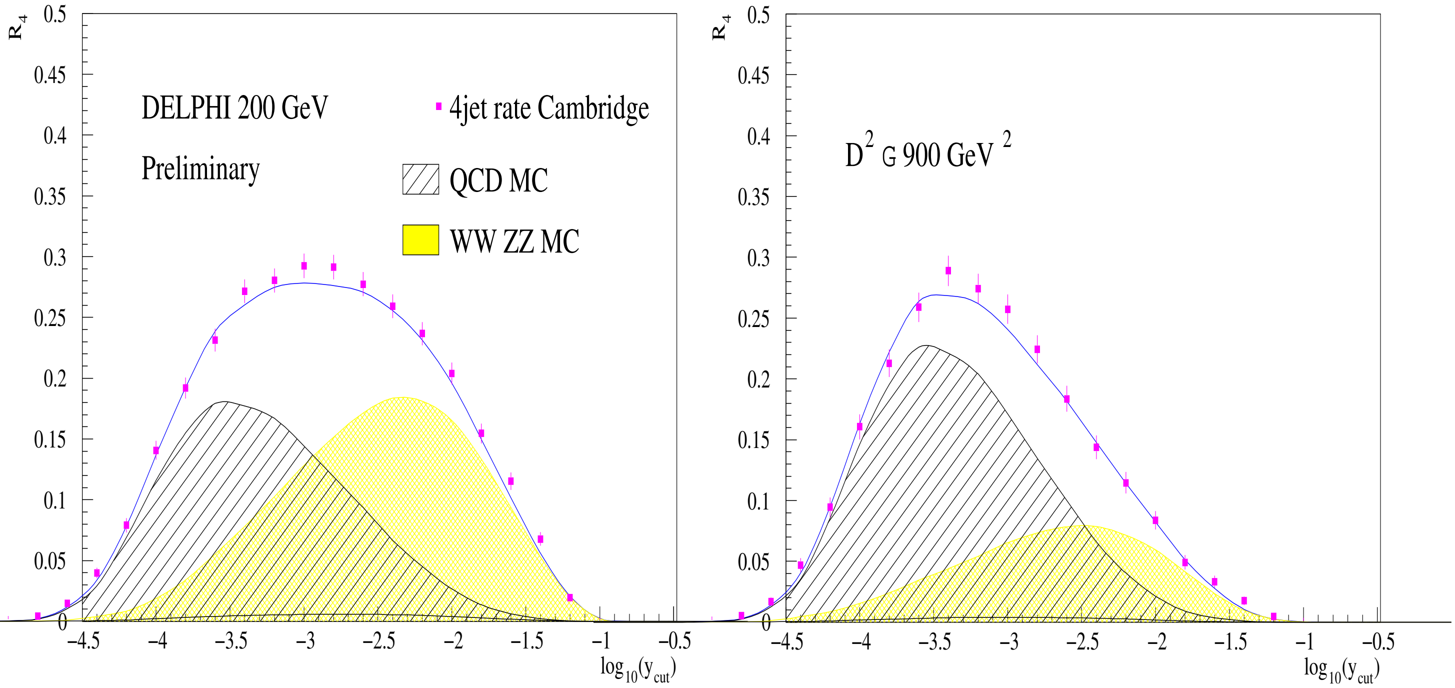
☞ Angular Ordering

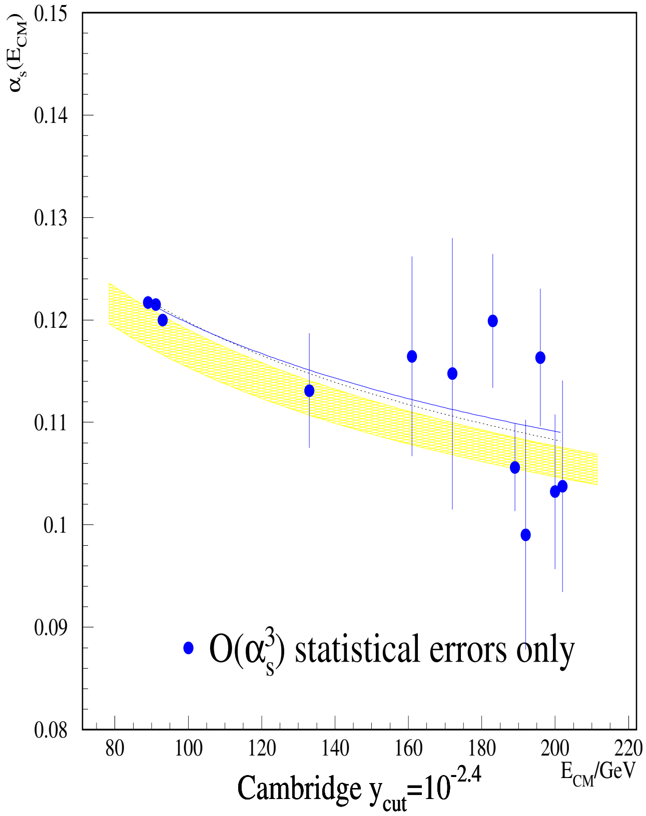
$$v_{ab} = (1-\cos\theta_{ab})$$

☞ 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)

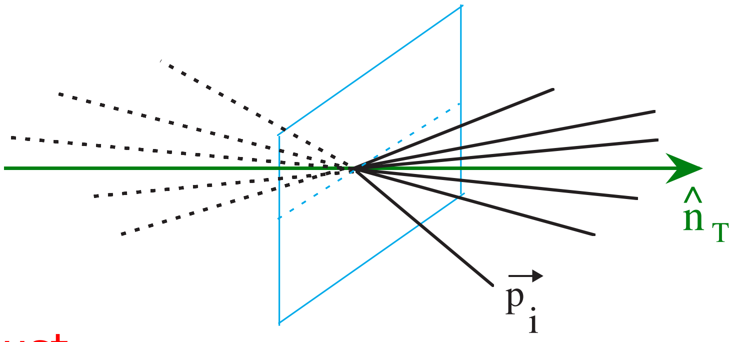
$$\frac{d\alpha_s{}^{-1}}{d \log E_{cm}} = 2b_0(1 + b_1\alpha_s + \ldots)$$

Fit R_4: $\boxed{1.17 \pm 0.28}$

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

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

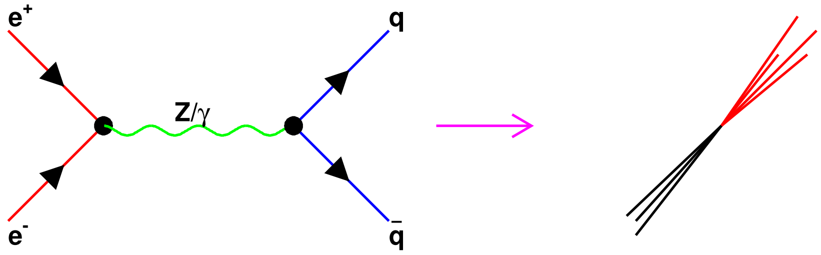
$$B_T = B_+ + B_-, \quad B_W = \max(B_+, B_-)$$

C-parameter

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

Jets & Shapes

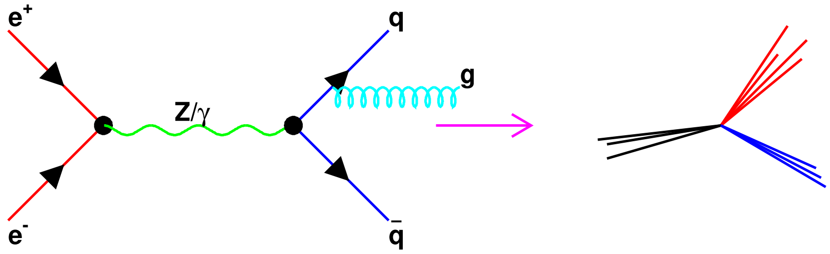
Event Shapes: relative contributions from n-jet configurations



2 jets

$1 - T \simeq 0$

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



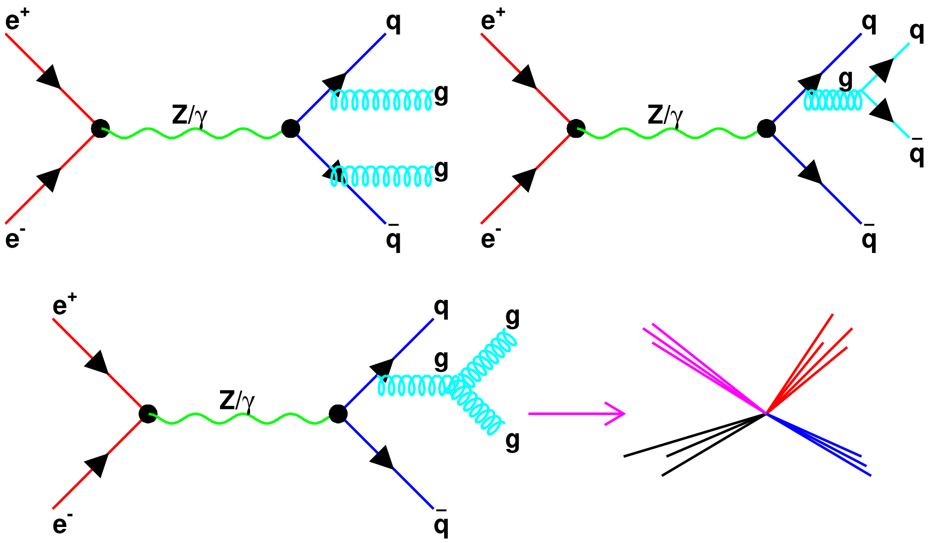
3 jets

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

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

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

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



4 jets

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

<u>Planar Topology</u>

$(C)_{max} = 1$

<u>Spherical Topology</u>

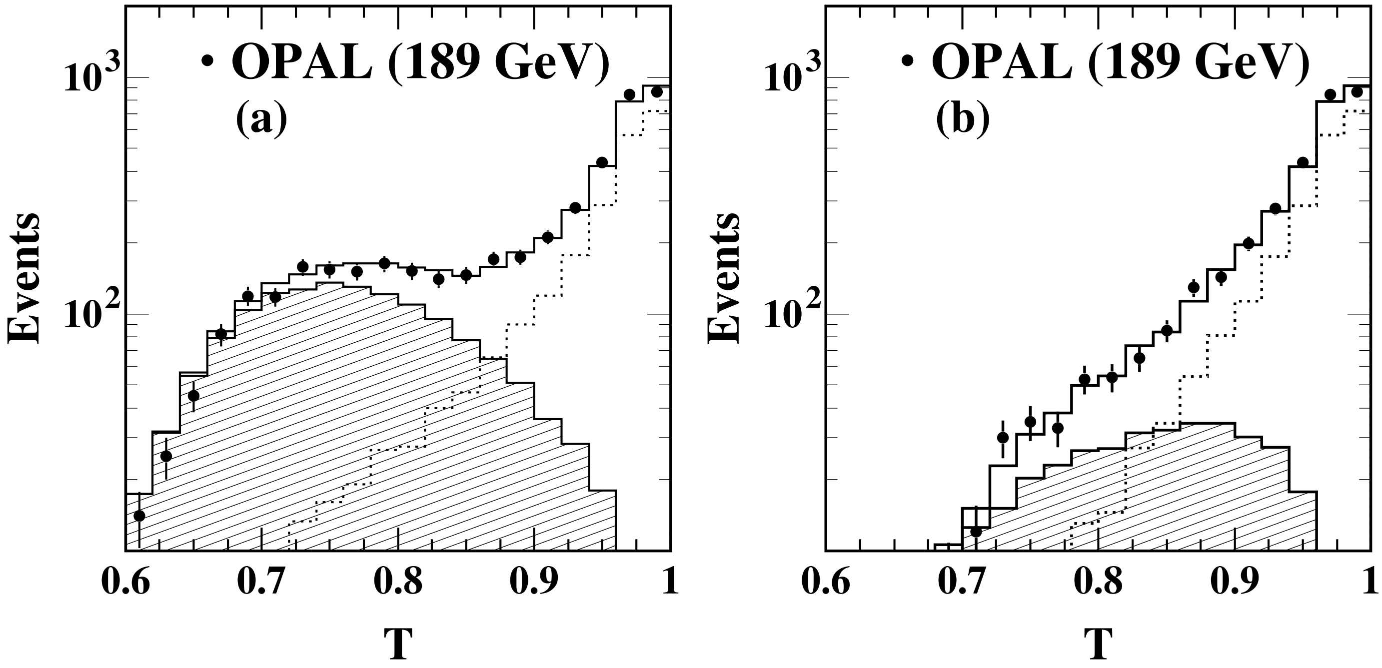
$(\mathrm{B_T})_{max} = \frac{\pi}{8}$

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

Distributions and moments of event shapes
from *total* hadronic event sample
➠ precise determination of α_{s}
(smaller theoretical and statistical errors than from $\mathrm{R}^{\mathrm{n}}_{jet}$)

Event Shape Corrections

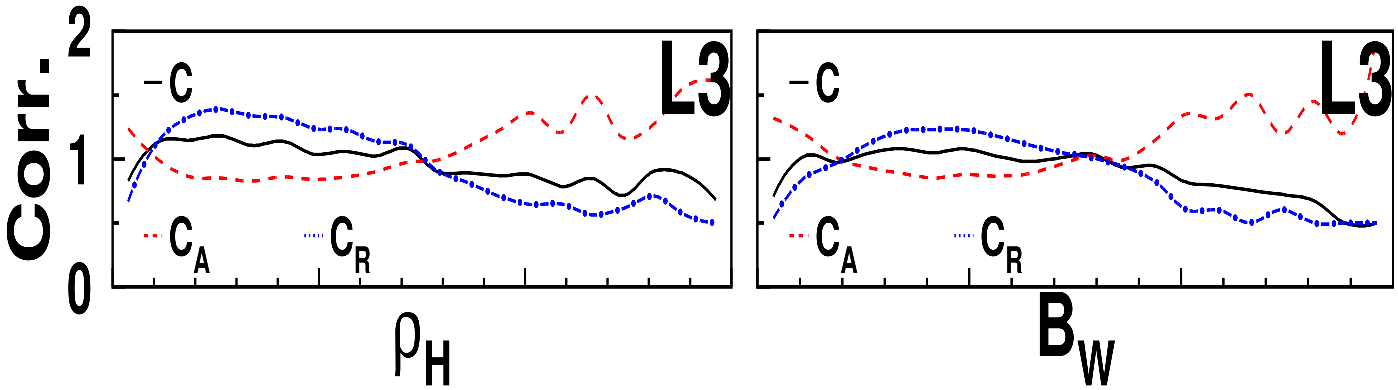
Before WW rejection	After WW rejection



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

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

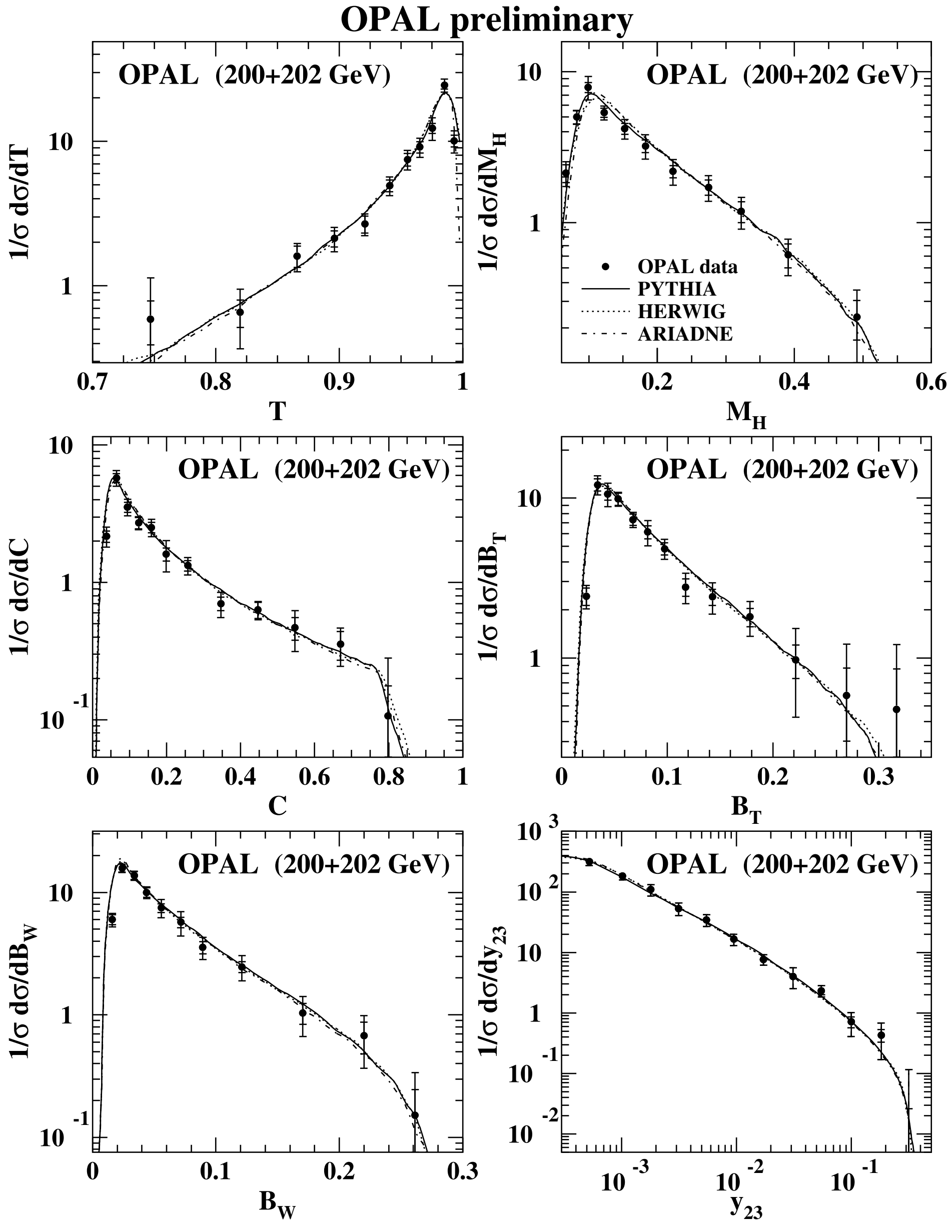
Correction Factors at $\sqrt{s} = 189$ GeV:



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

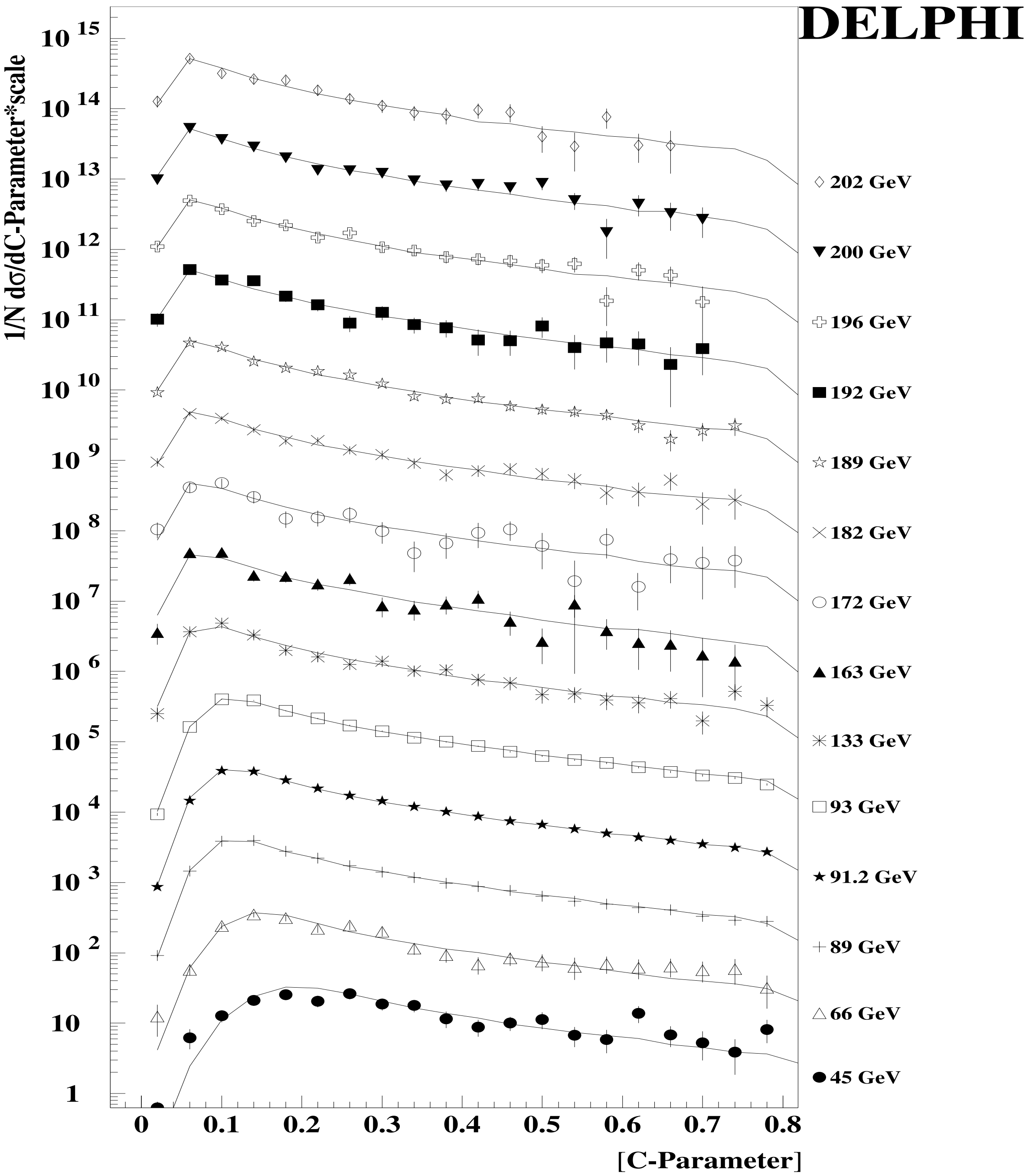
All models tuned at $\sqrt{s} = M_Z$ using LEP I data



Energy Evolution

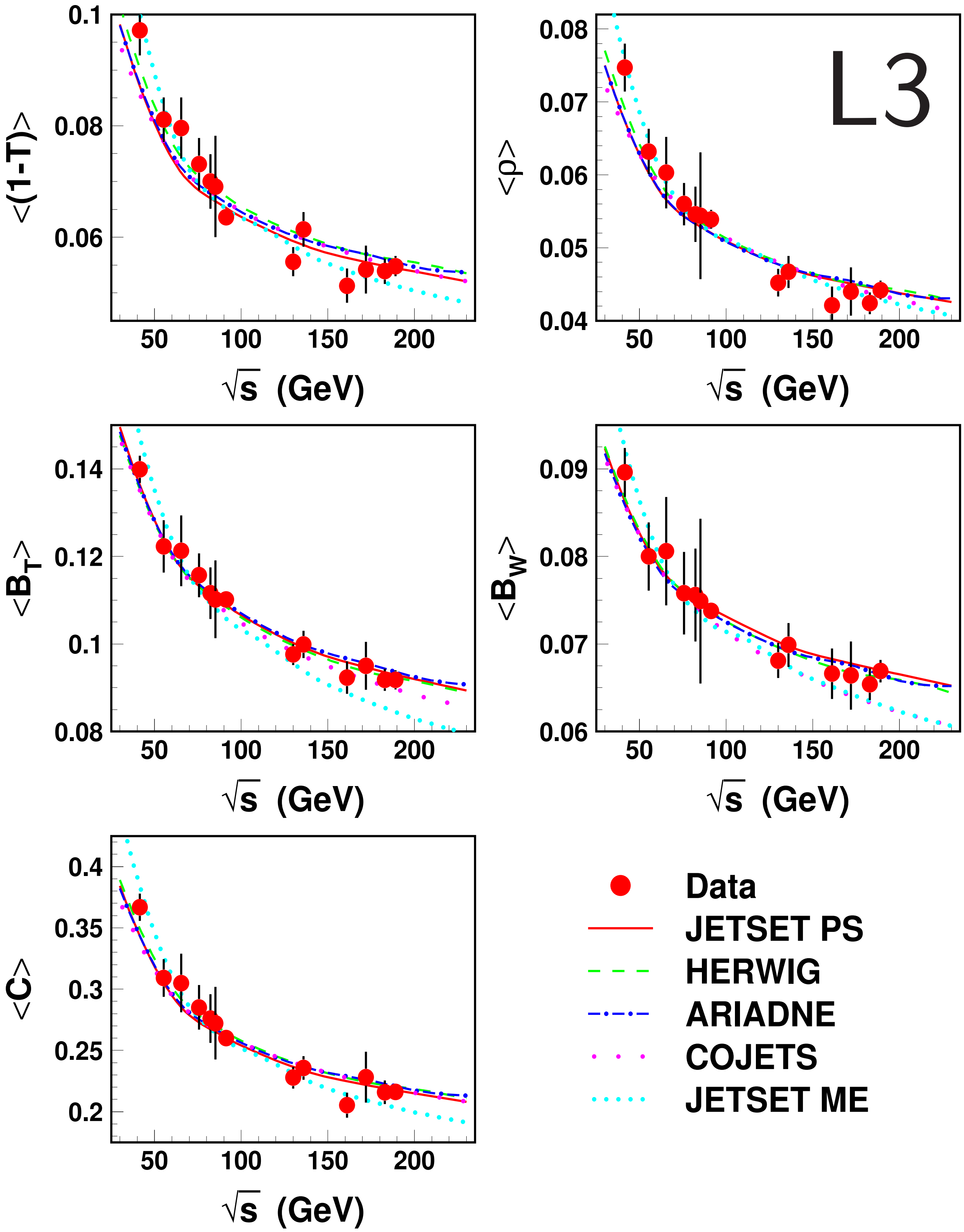
Sources:

- ✶ 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* α_{eff}, *different from* α_s *only in infrared region*

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

Free parameters:

1. $\alpha_s(\text{M}_\text{Z})$
2. $\alpha_0(\mu_\text{I}) = \frac{1}{\mu_\text{I}} \int_0^{\mu_\text{I}} dq \alpha_{\text{eff}}(q)$

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

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

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

☞ For V = $\text{B}_\text{T}, \text{B}_\text{W}$: "a shift $\propto$ 1/Q" + "logarithmic-skew"

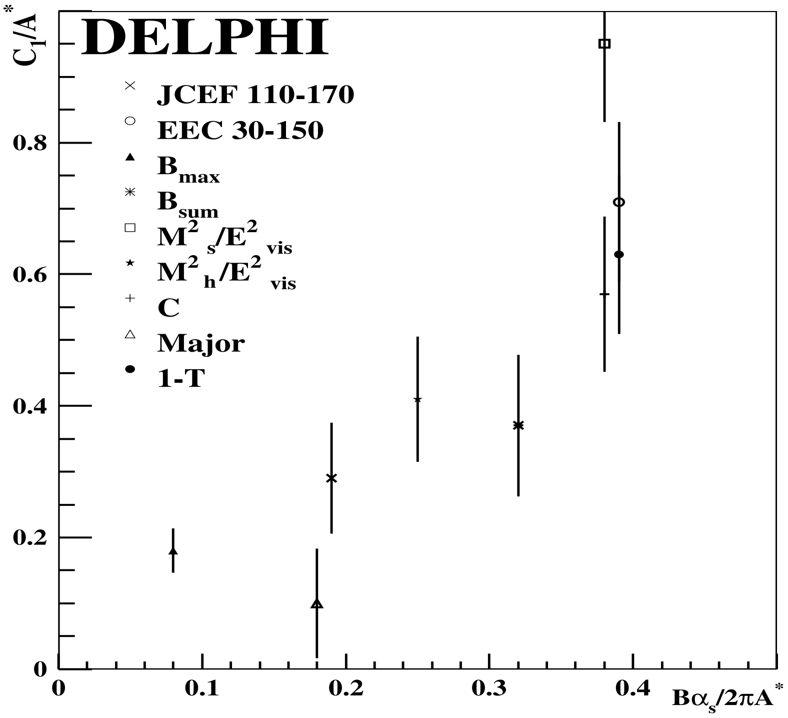
$$\mathcal{P} * \delta_\text{V}\left\{\left(\alpha_{CMW}(\text{Q}e^{-\frac{3}{4}})\right)^{-\frac{1}{2}} + \text{const}_\text{V} + \mathcal{O}(\sqrt{\alpha_s})\right\}$$

Correlation between relative size of the power contribution $(\frac{\text{C}_1}{\text{A}^\star})$

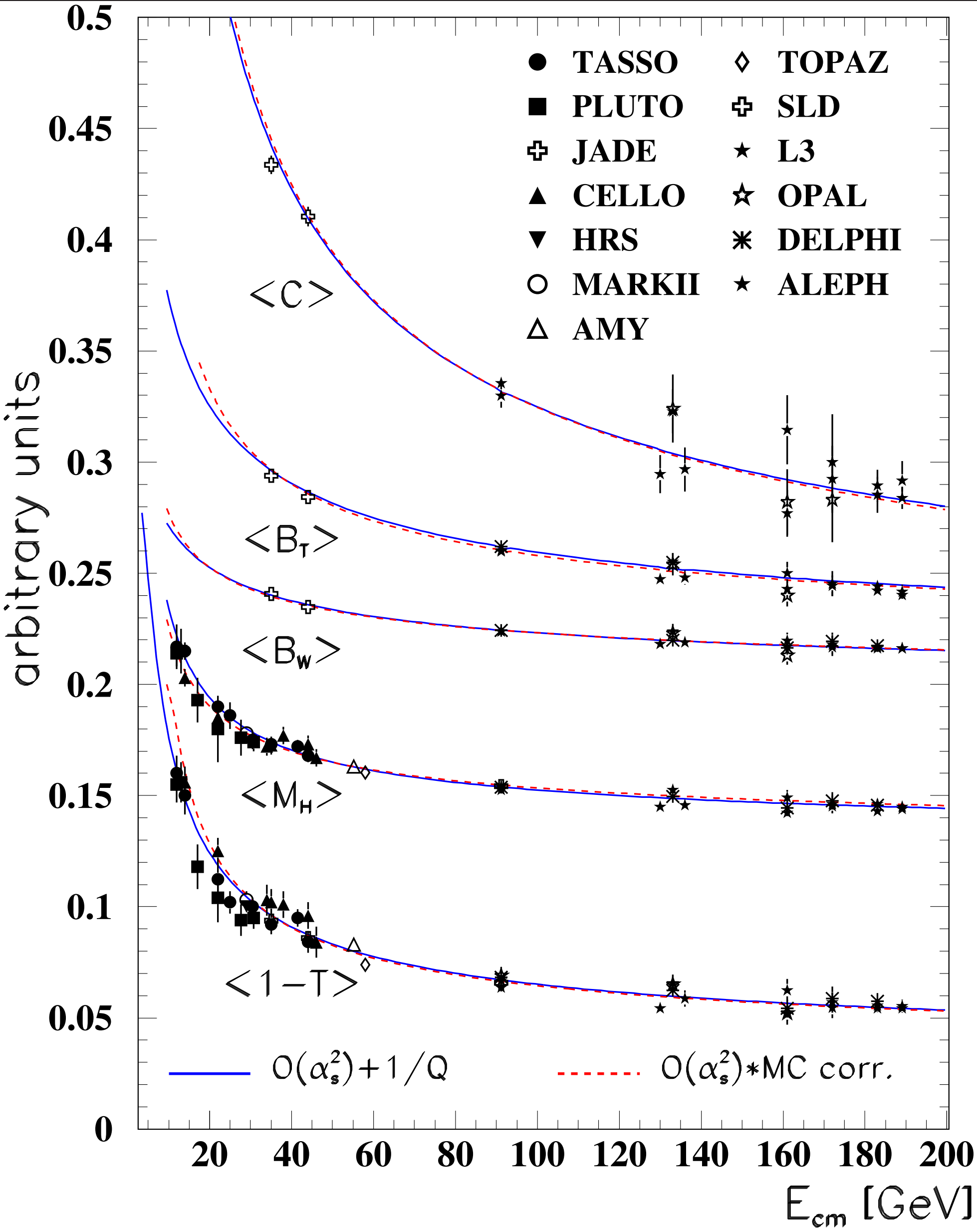
Versus

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

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



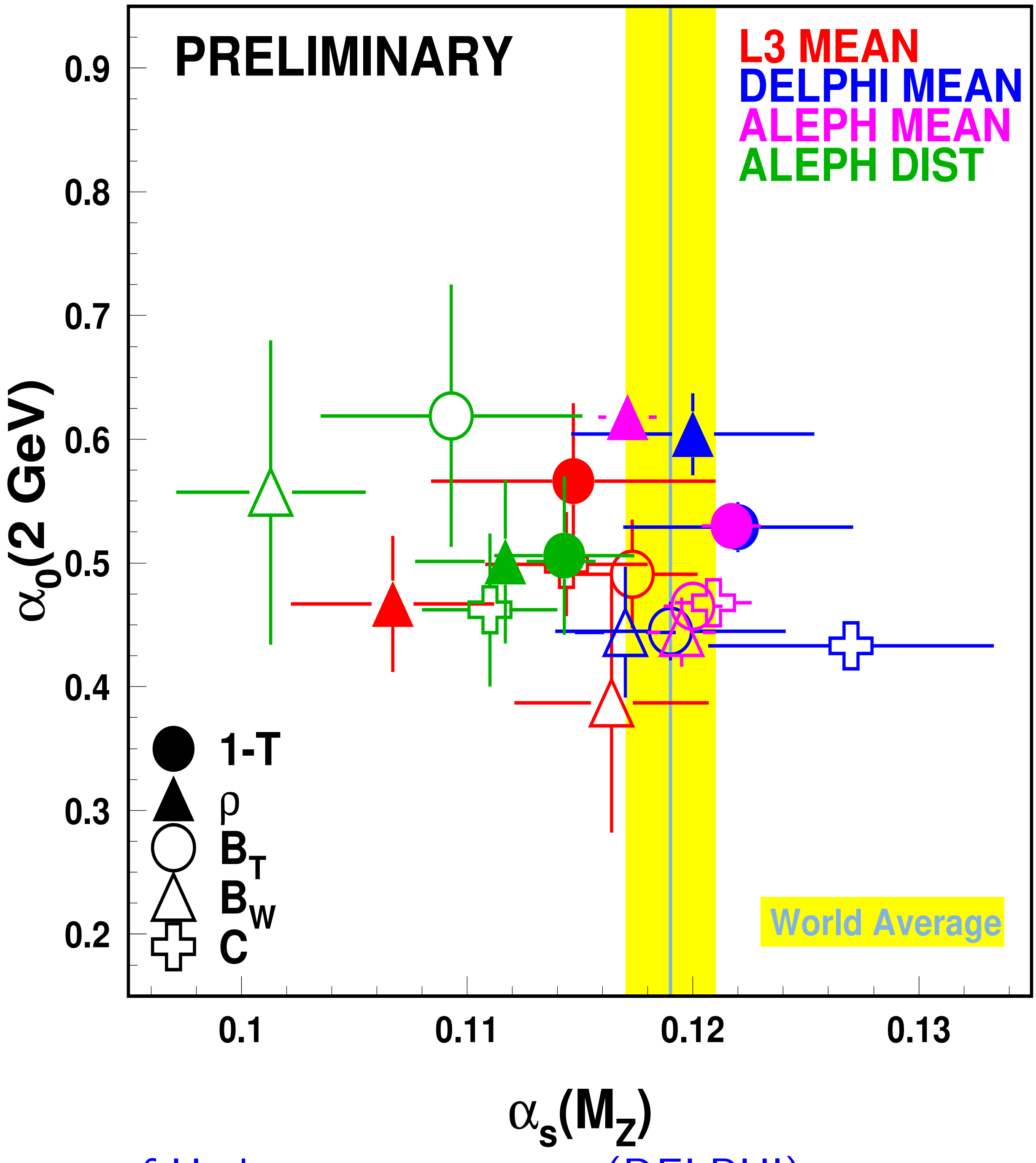
Power law behaviour



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:

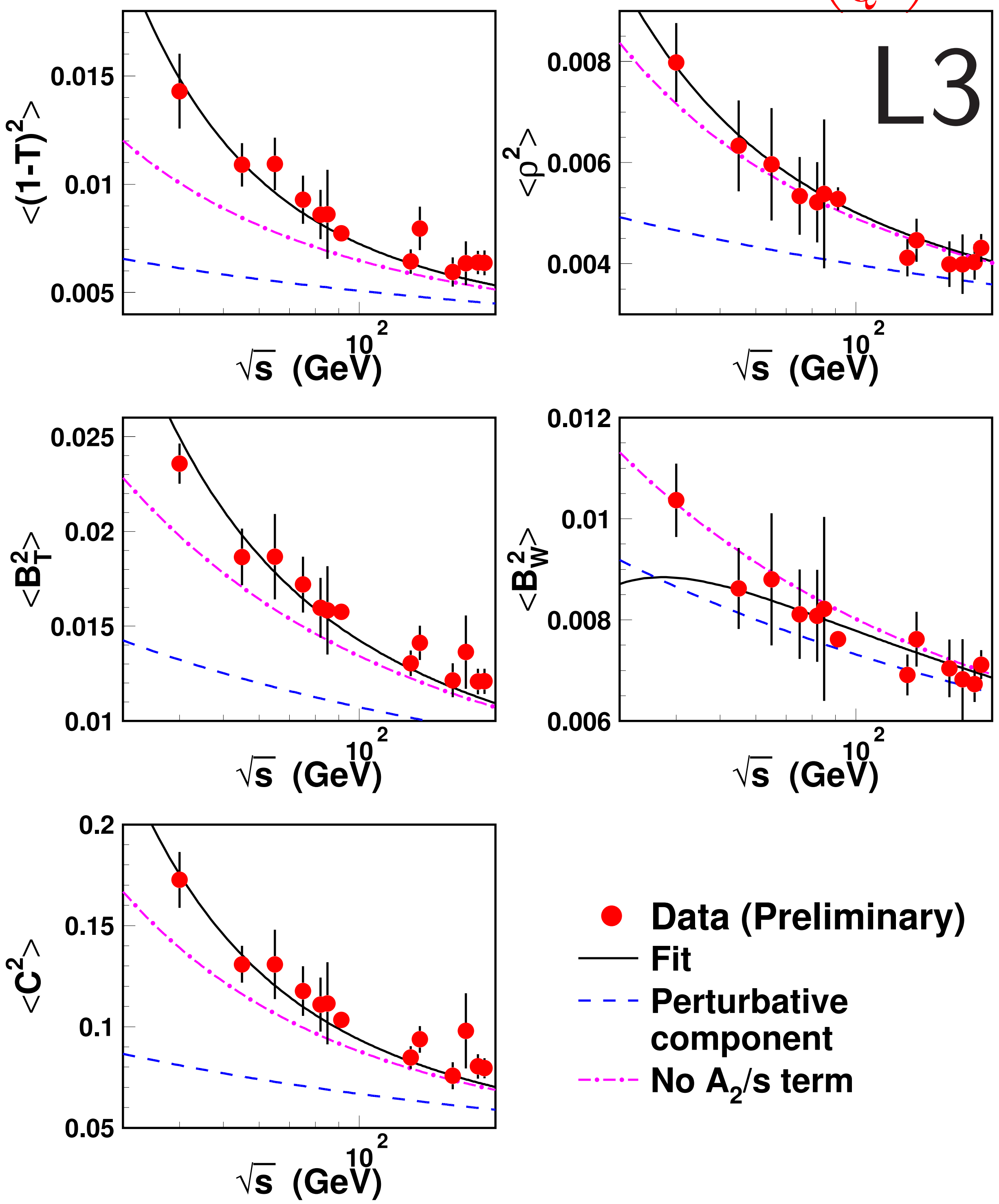


Influence of Hadron masses on α_0 (DELPHI):

	$(\vec{p}$,E)	$(\vec{p}, \vert\vec{p}\vert)$	$(\hat{p}$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

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



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

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

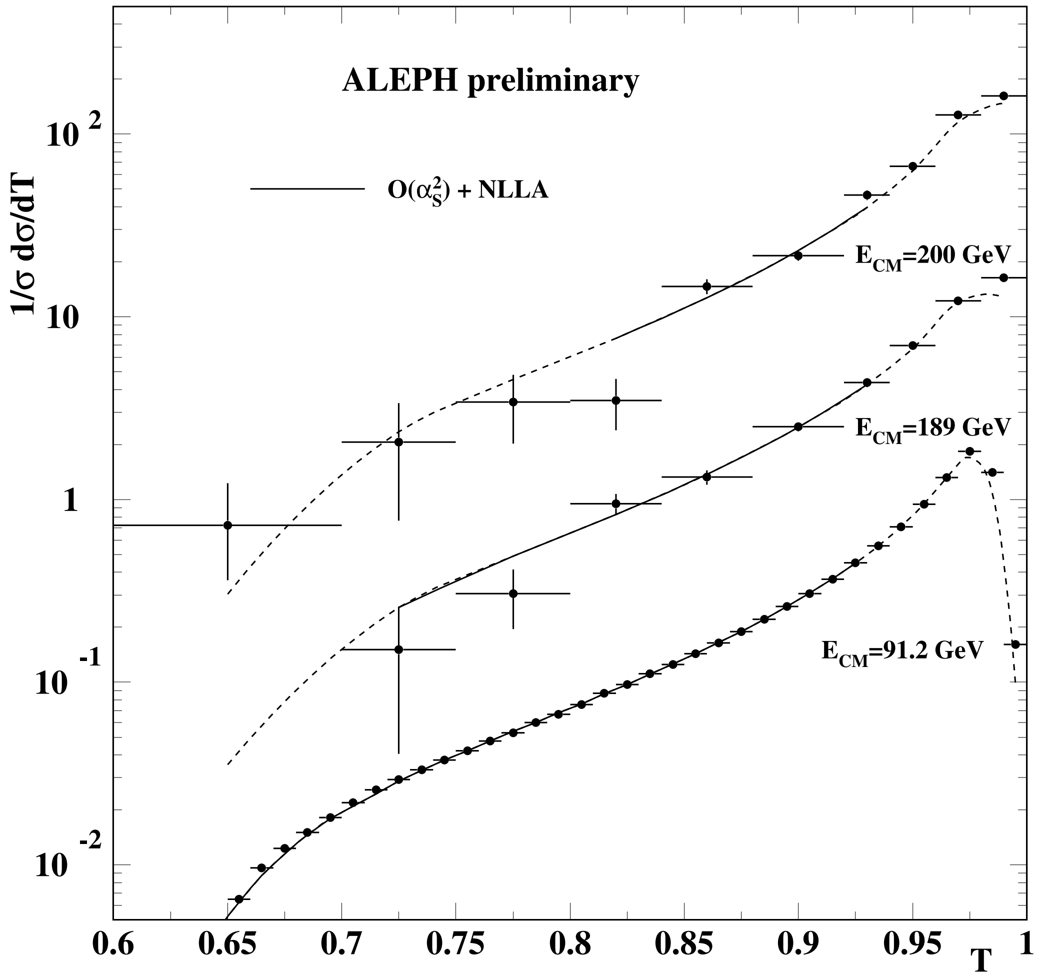
☞ Complete Calculations to $\mathcal{O}({\alpha_s}^2)$:

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

☞ Resummation:

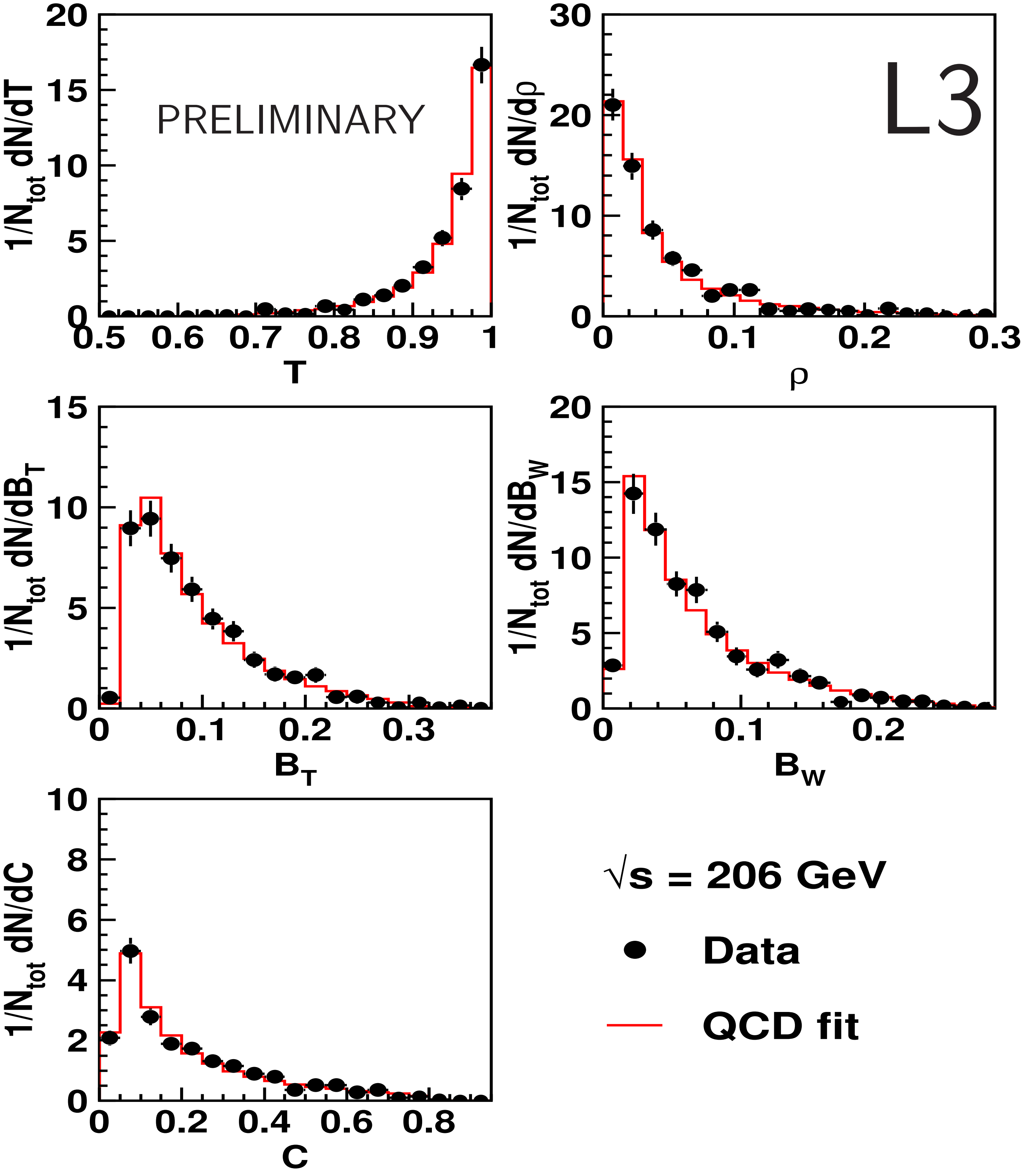
Leading-Log	$\sum(\alpha_s L^2)^n$
Next-to-Leading-Log	$\sum({\alpha_s}^n L^{2n-1})$

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



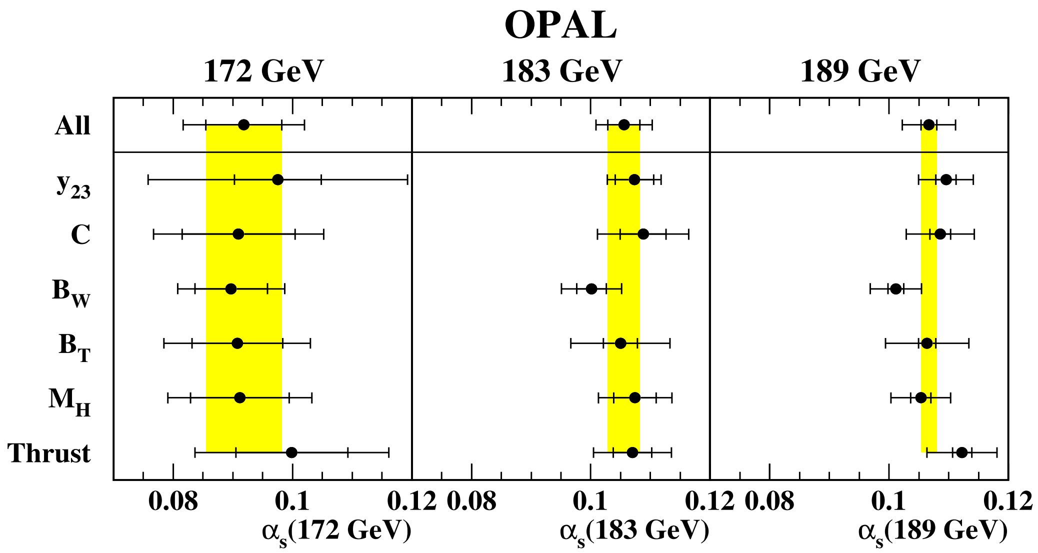
☞ Quark Mass Effects : 1% at M_Z, 0.2-0.3% at 200 GeV
$\mathcal{O}\ ({\alpha_s}^2)$ calculations (P.Nason and C. Oleari '98)

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

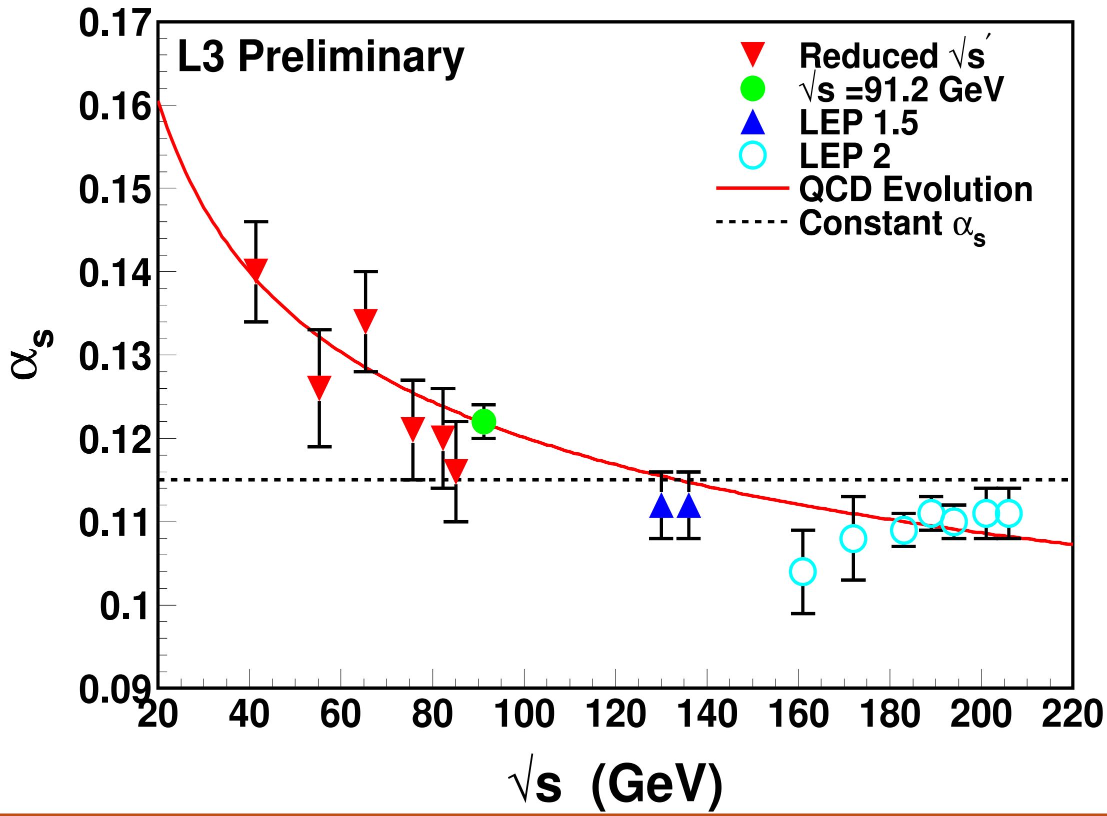


☞ L3 probes smaller values of y by using wider fit range

Combining the measurements



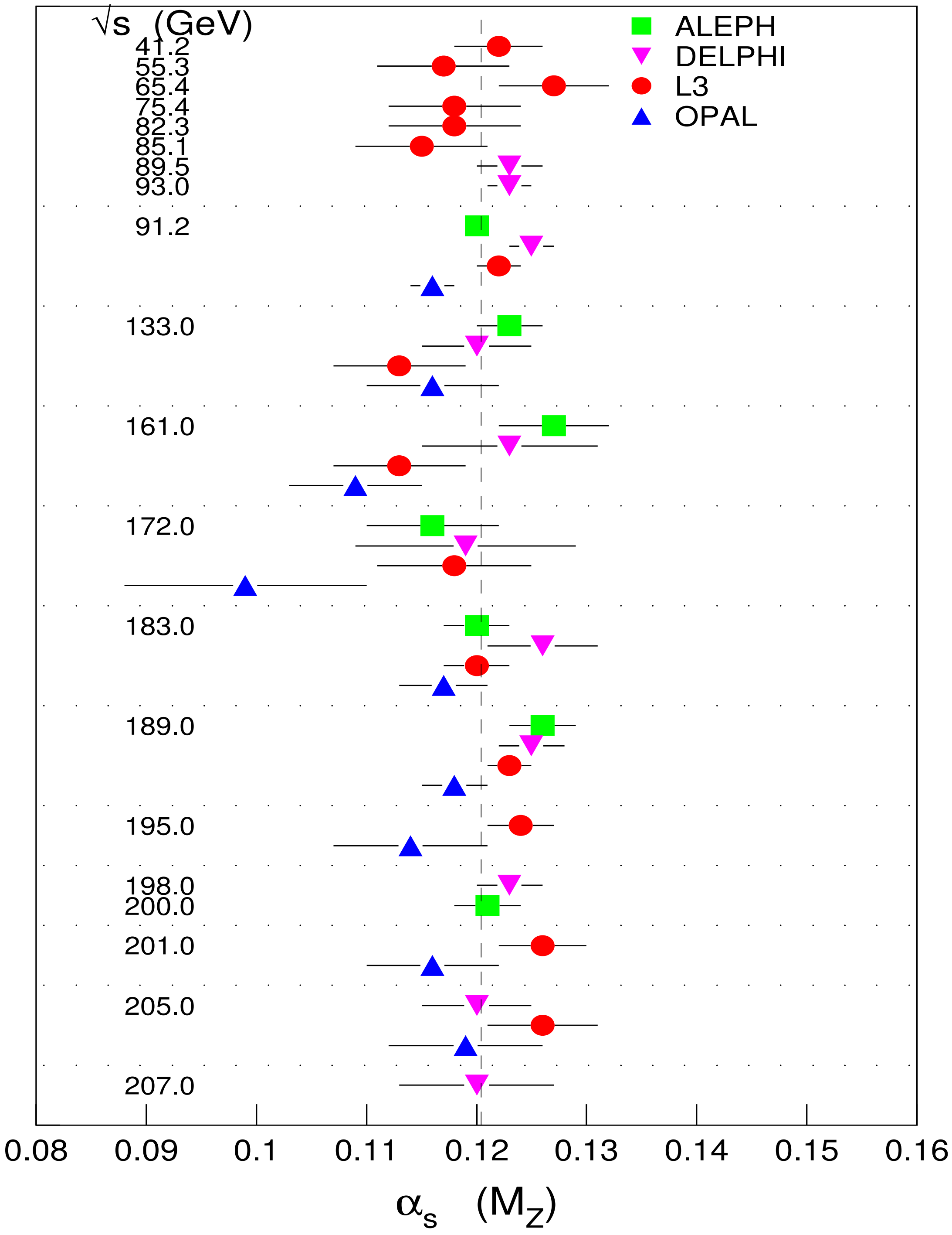
Running of α_s from 30 to 206 GeV from L3 Data:



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

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

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



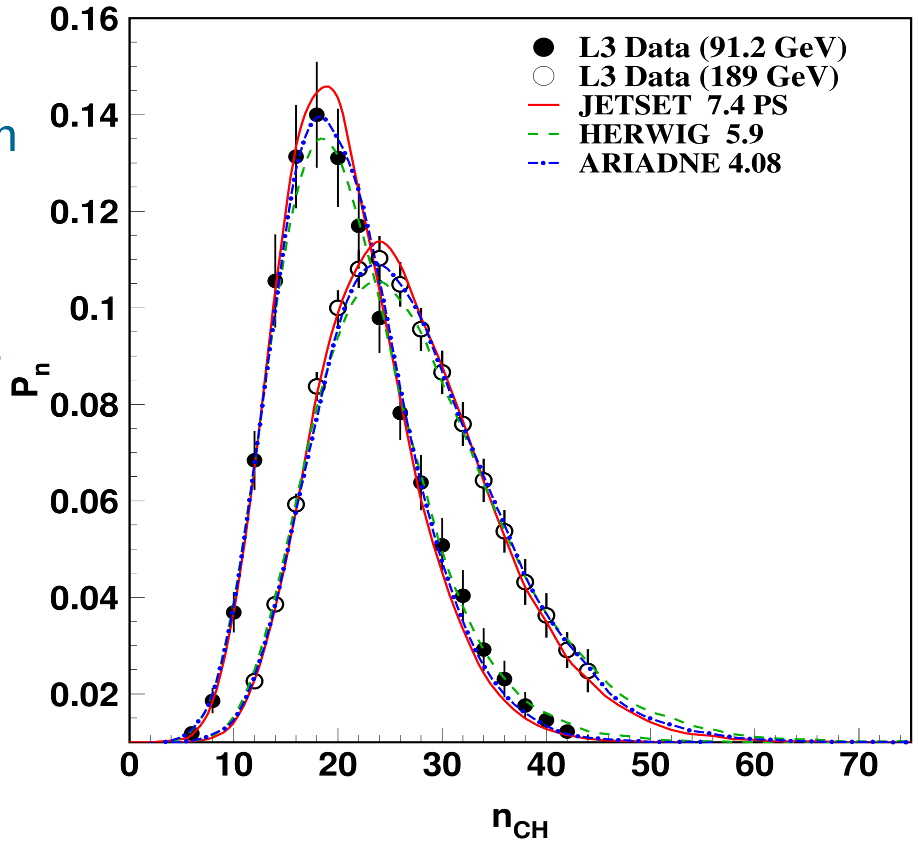
$\underbrace{T, -\ln y_3, m_H^2, \mathrm{B_W}, C}_{\text{ALEPH}}$ $\underbrace{T, \rho}_{\text{DELPHI}}$ $\underbrace{T, \rho, \mathrm{B_T}, \mathrm{B_W}, C}_{\text{L3}}$ $\underbrace{T, y_3, \rho, \mathrm{B_T}, \mathrm{B_W}, C}_{\text{OPAL}}$

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

Charged Particle Multiplicity

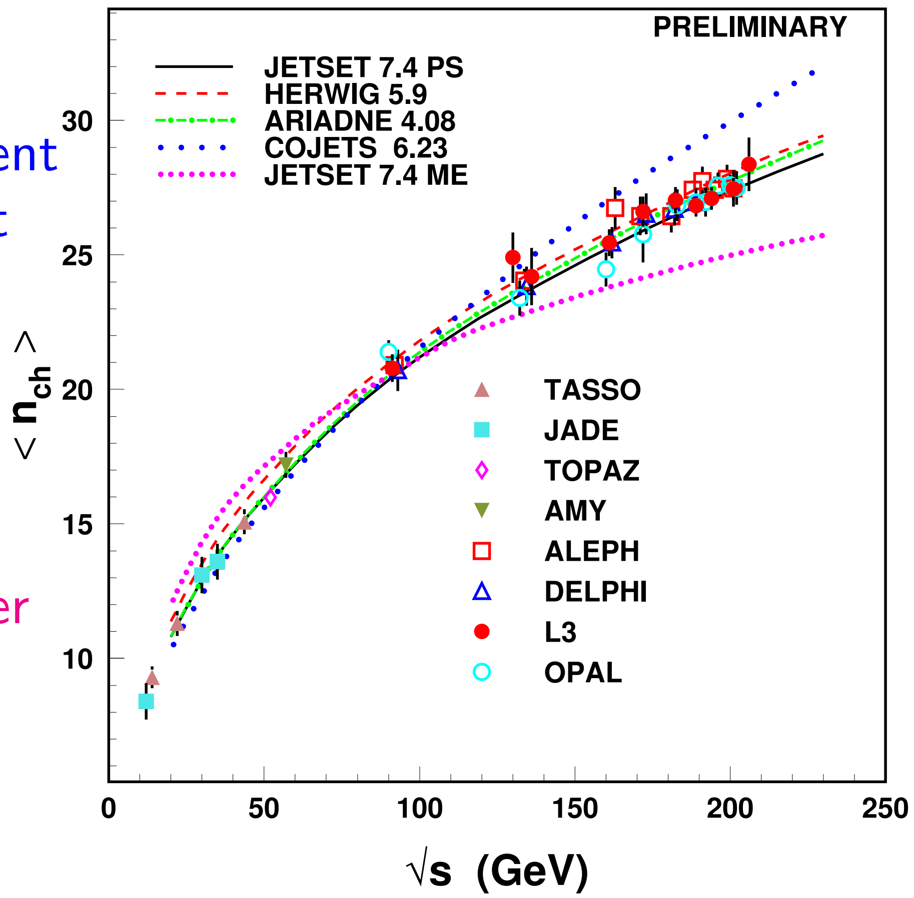
❇ Detector correction using unfolding

❑ Spectra "shifts" & "broadens" with increasing $\sqrt{s}$

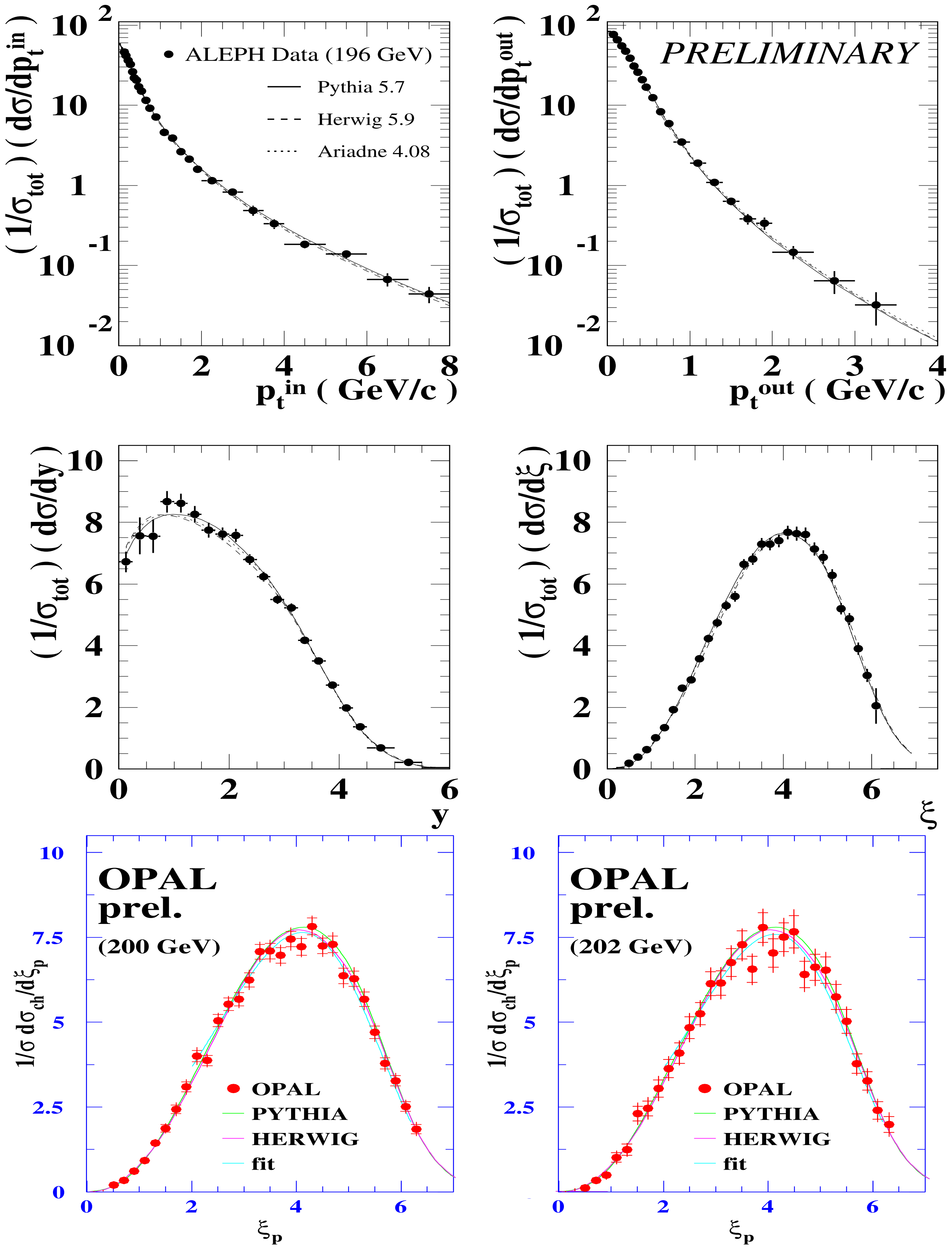


▲ COJETS (incoherent PS & independent fragmentation)
⇒ higher multiplicity at high energies

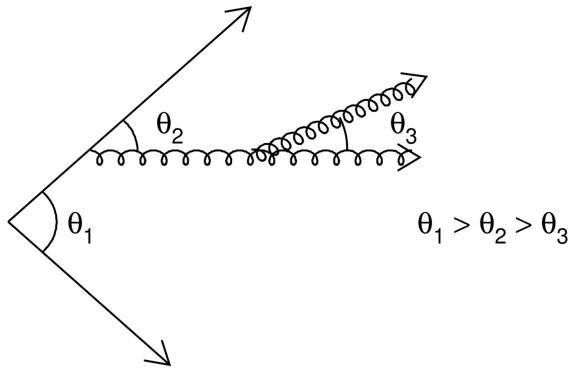
▼ Second order ME with a fixed number of partons cannot describe evolution



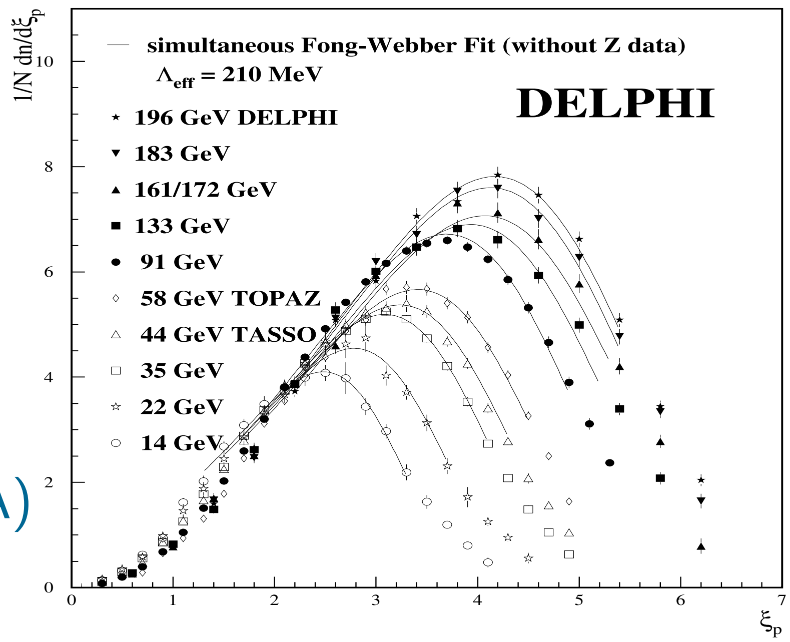
Inclusive Charged Particle Spectra



Gluon Coherence



Angular Ordering of successive soft gluon radiation reduces phase space available

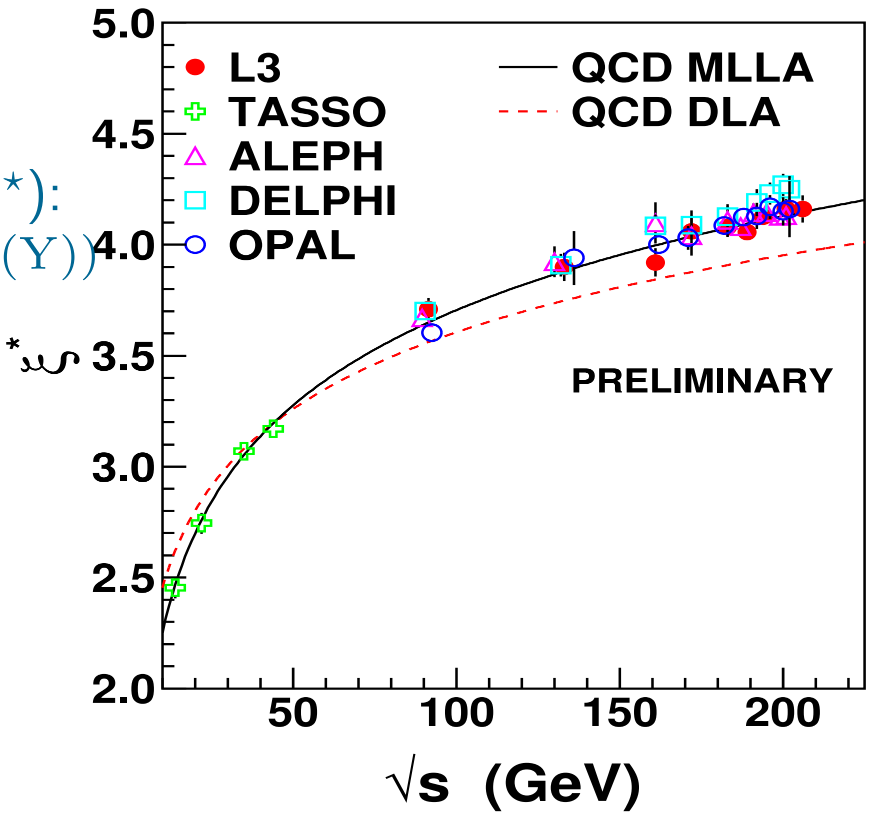


$\Rightarrow$ Dip at low momentum
$(x_p = 2\,|\vec{p}|\,/\sqrt{s})$

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

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

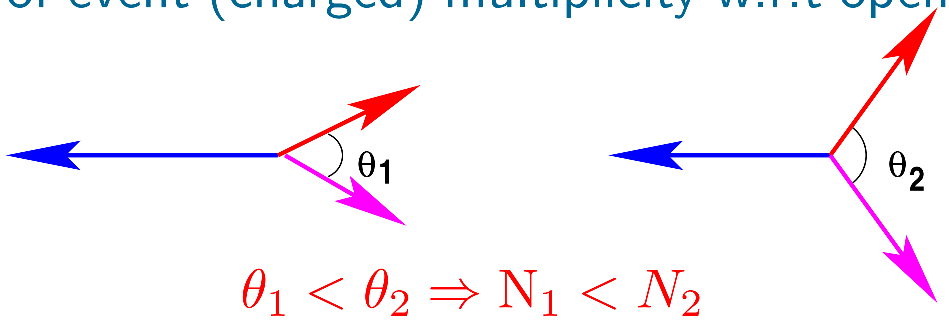
Predictions for peak ($\xi^\star$):
$Y(\frac{1}{2} + \sqrt{C\alpha_s(Y)} - C\alpha_s(Y))$
where $Y = \ln(E_{beam}/\Lambda)$



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:



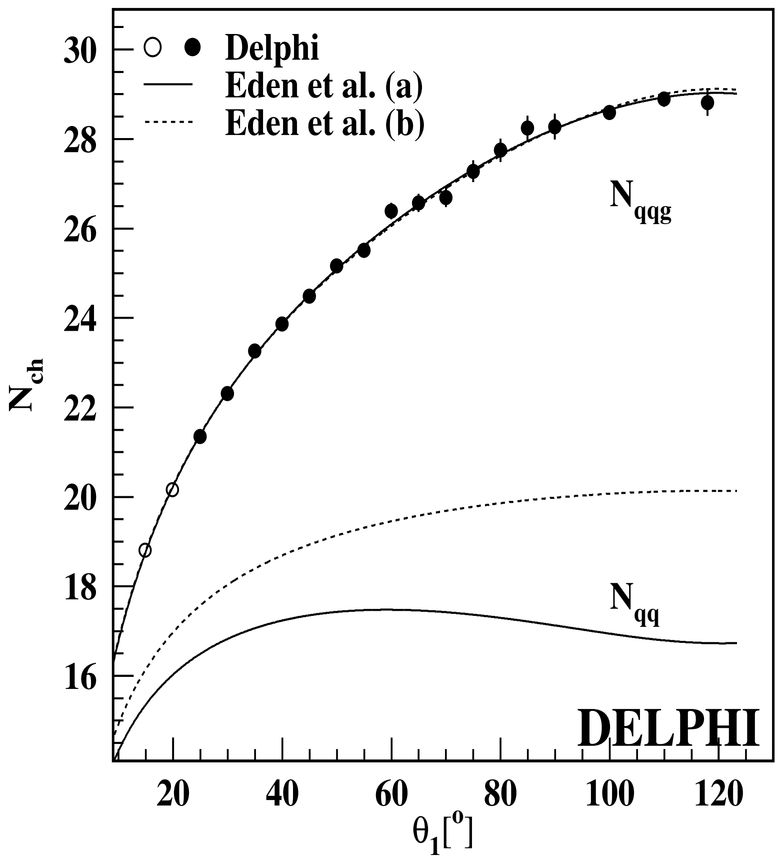
$$\theta_1 < \theta_2 \Rightarrow \mathrm{N}_1 < N_2$$

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

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

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

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



$\Rightarrow$ New measurements of Color factors:

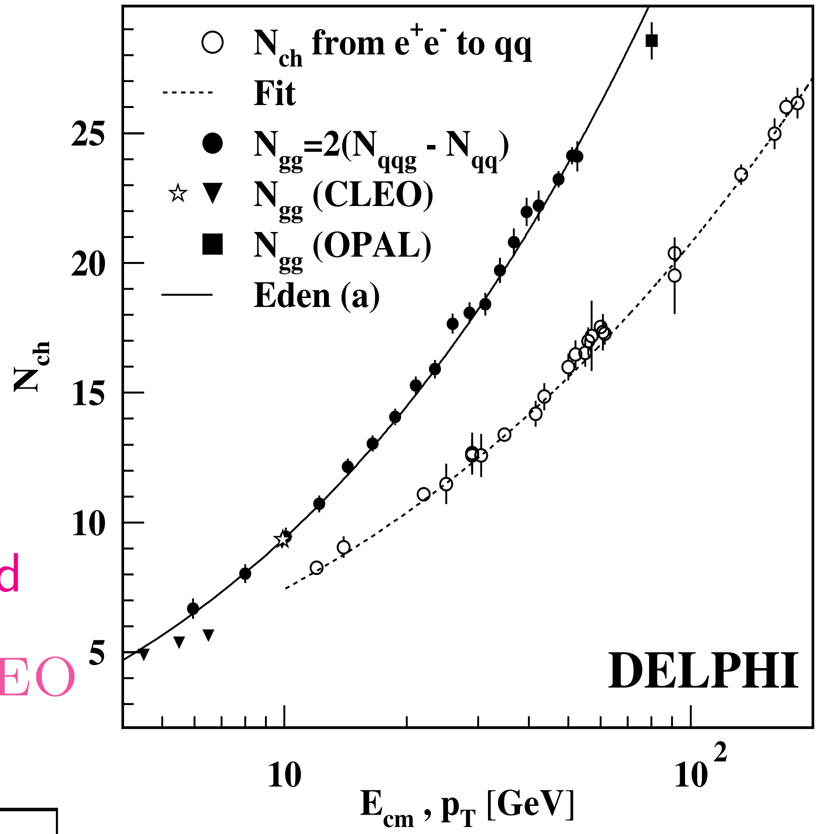
$\mathrm{C_A/C_F}$ = 2.221
± 0.047 (exp)
± 0.058 (had)
± 0.075 (theo)

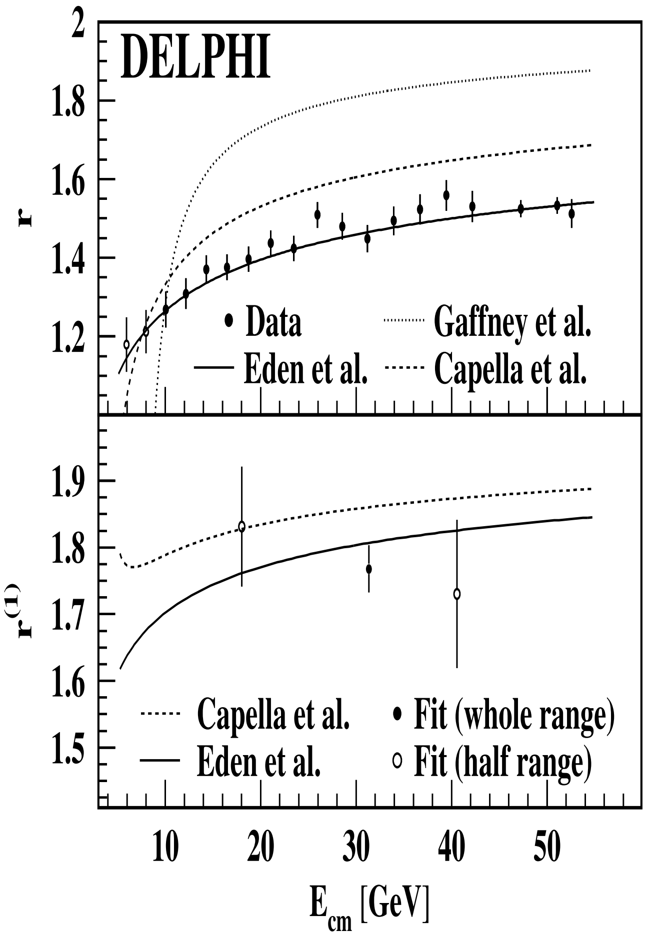
$q\bar{q}$ and gg multiplicities

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 $\sqrt{\mathrm{s}} = \mathrm{M_Z}$.
- Jet Rates follow the expected QCD energy evolution. New $\mathcal{O}({\alpha_\mathrm{s}}^3)$ calculations have become available.
- LEP Average of α_s measurements using $\mathcal{O}({\alpha_\mathrm{s}}^2)$+NLLA calculations from event shapes:

$$\boxed{\alpha_\mathrm{s}(\mathrm{M_Z}) = 0.1204 \pm 0.0007\ (\text{exp}) \pm .0034\ (\text{theo})}$$

- 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.