Determination of α_s at LEP by L3 experiment

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QCD 02

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- Hadronic samples in e^+e^-collisions at $\sqrt{s}$ up to 208 GeV

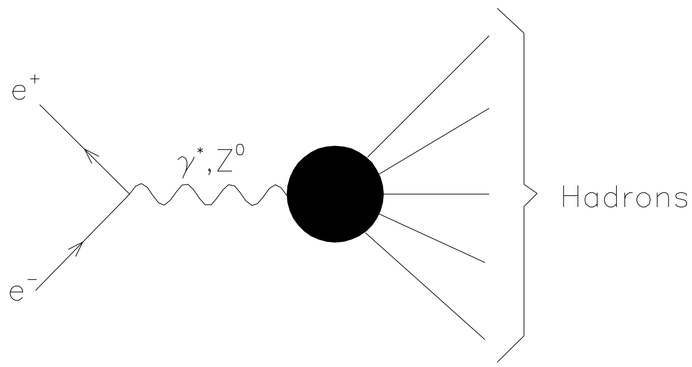
- Analysis Methods:
- Jet algorithm
- Event shape variables

- Experimental data and QCD tests:
- Distribution of event shape variables
- Energy evolution of event shape variables
- α_s at LEP
- Conclusions

Over a decade of LEP running:

- $3.5 \cdot 10^6$ Z hadronic decays recorded at $\sqrt{s} \sim m_Z$ (1989-1995)
- Target luminosity at $\sqrt{s} > m_Z$ 500 pb^{-1} /expt

  Delivered luminosity (1995-2000) $\approx$ 700 pb^{-1} / exp



Precise measurements of QCD at LEP:

- Clean initial state (e^+e^-)
- Small hadronization corrections ($\propto 1/E$)

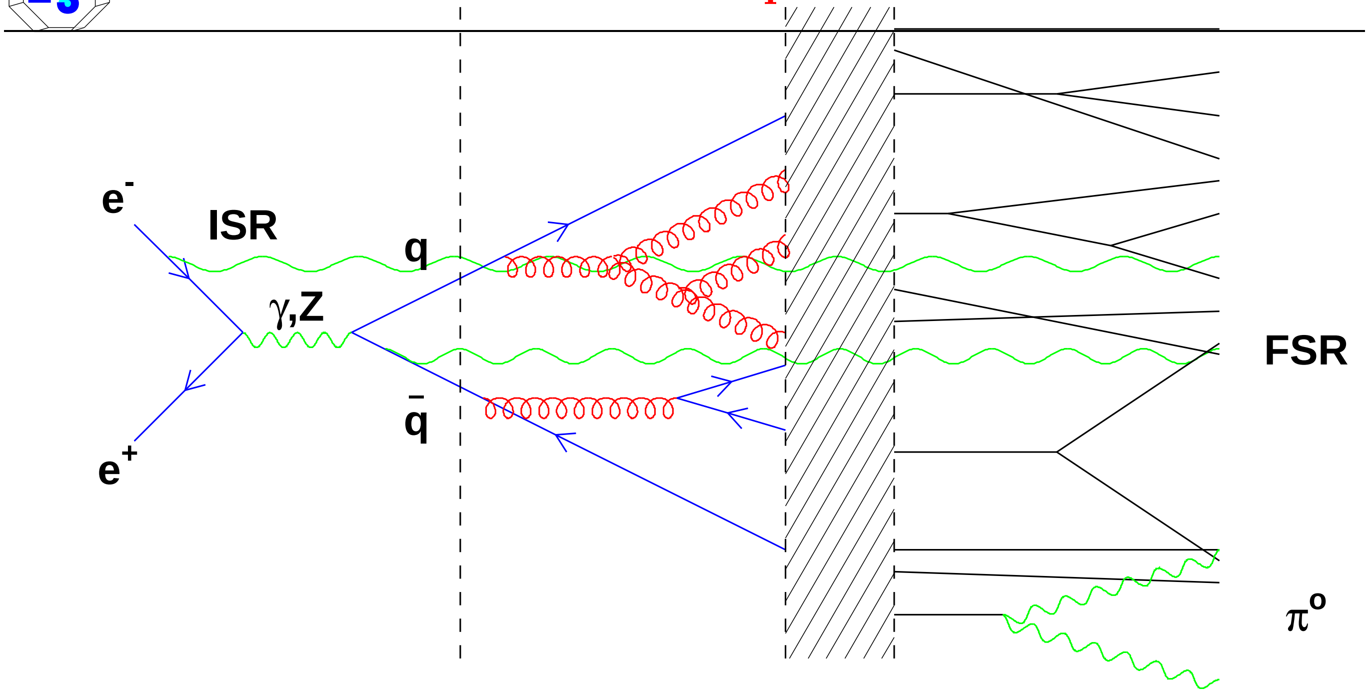
Study Hadronic events $30 \leq \sqrt{s} \leq 208$ GeV

- Hard Gluon Radiation:

Multi-jet topology, Event Shape Variables

Measurement of Strong coupling constant α_s

Event Samples



Electroweak pert.QCD Hadron Detector

- $\sqrt{s'} < m_Z$. Reduced $\sqrt{s'}$ from Z decay with isolated γ (FSR).

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

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

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

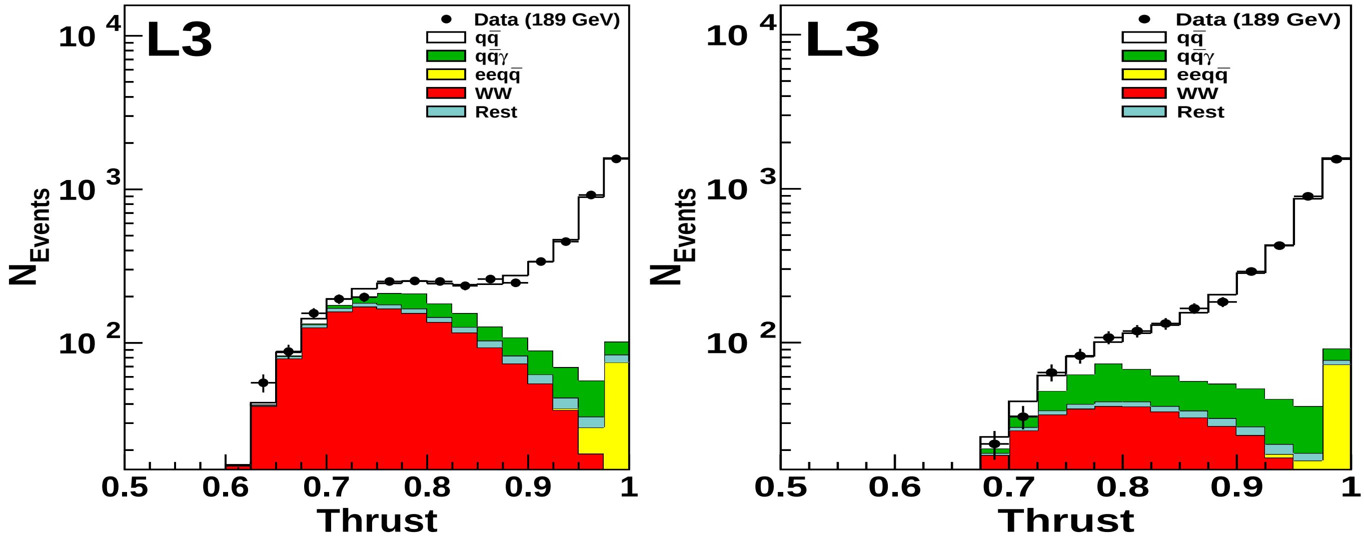
- $\sqrt{s} \sim m_Z$. Hadronic Z decays. Purity $\approx 99\%$

- $\sqrt{s} > m_Z$. Rejecting initial state radiation. Four fermion final state (WW,ZZ). Purity $\sim 78 - 90\%$:high selection efficiency $\sim 83 - 90\%$

Distribution of event shapes from total hadronic event sample → precise determination of α_s

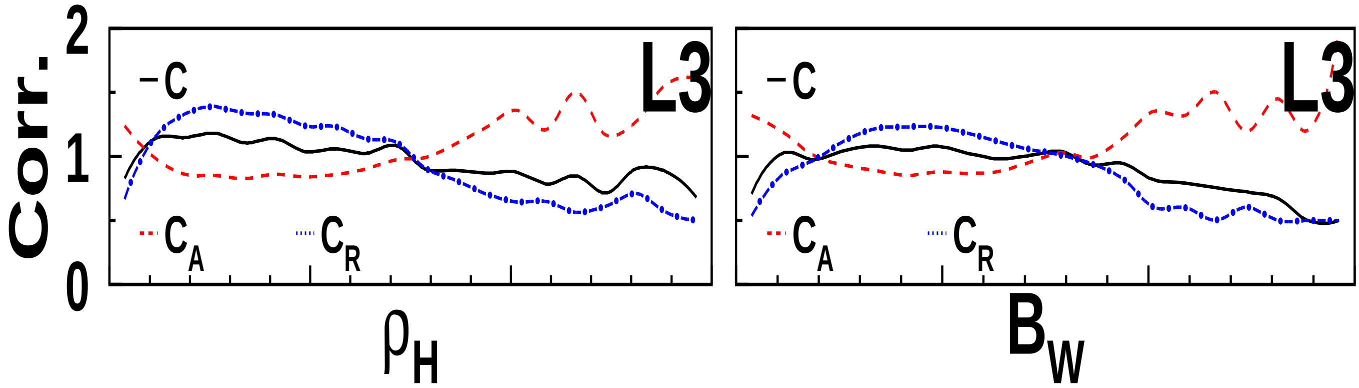
$\sqrt{s} > m_Z$: Large contamination from WW events

BEFORE WW rejection ATFER WW rejection



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

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



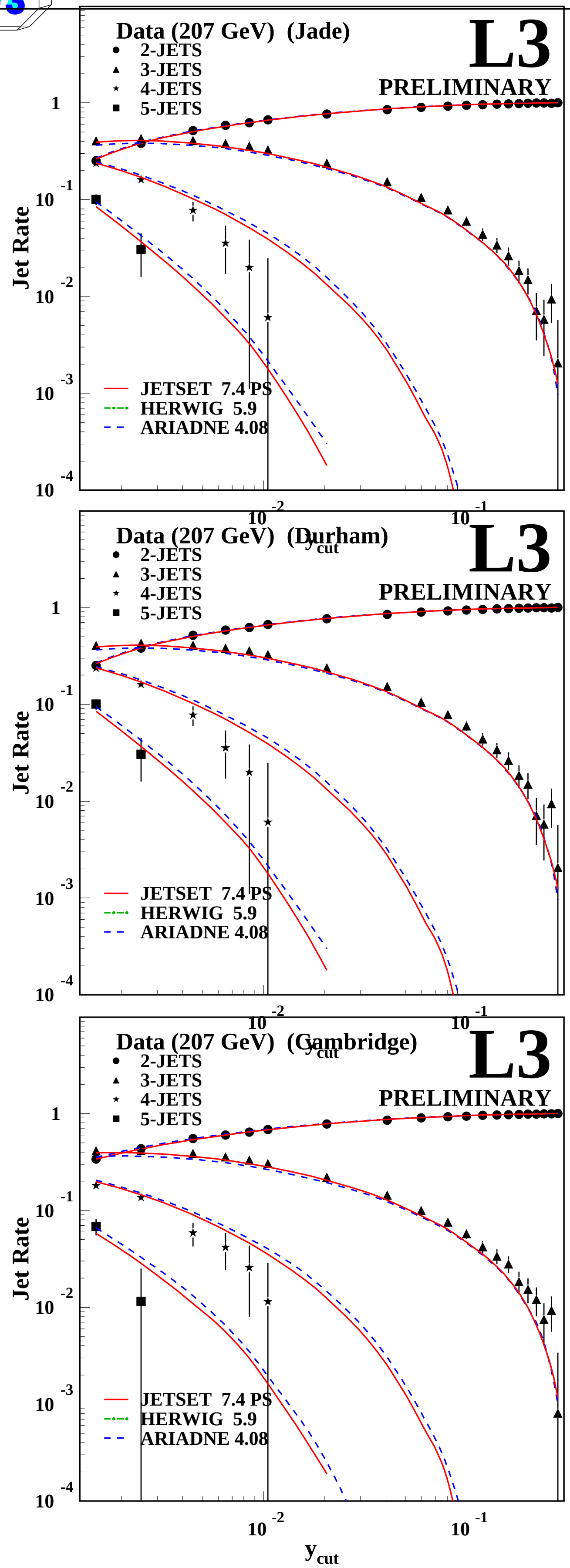
$\sqrt{s}$ (GeV)	$\int \mathcal{L}\,dt$ (pb^{-1})	Events
130	6.1	556
136	5.9	414
161	10.8	424
172	10.2	325
183	55.3	1500
189	176.8	4479
194.4	112.2	2403
200.2	117.0	2456
206.2	207.6	4146

- High energy sample. $192 \leq \sqrt{s} \leq 208$ 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

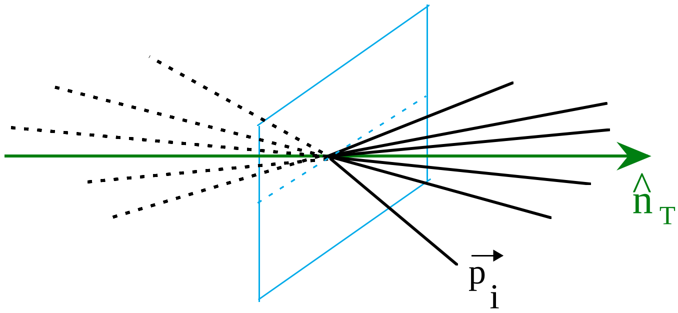


$$y_{ab}^{Jade} = \frac{2E_aE_b}{E_{vis}^2}(1-\cos\theta_{ab})$$

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

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

- Collinear and infrared safe variables analytically calculable.
- Perturbative calculations more complete than in jet rate.



Thrust

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

Heavy jet mass

$$\rho_H = (\Sigma_i p_i)^2_{max} / s$$

$$(i \text{ in } S_\pm)$$

Jet broadenings

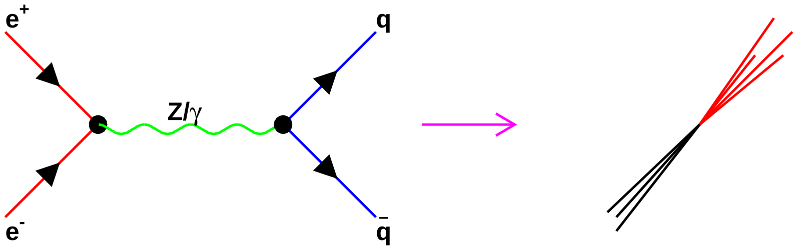
$$B_\pm = \left(\frac{\Sigma_i |\vec{p}_i \times \hat{n}_T|}{2\Sigma_i |\vec{p}_i|}\right)$$

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

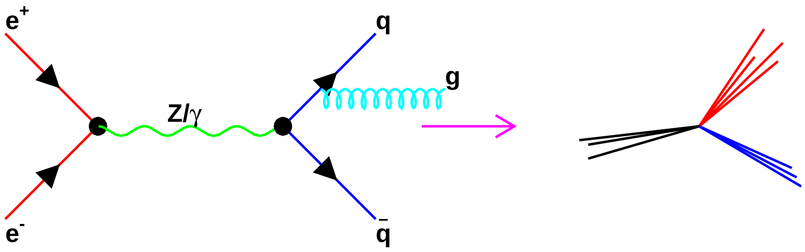
C-parameter

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

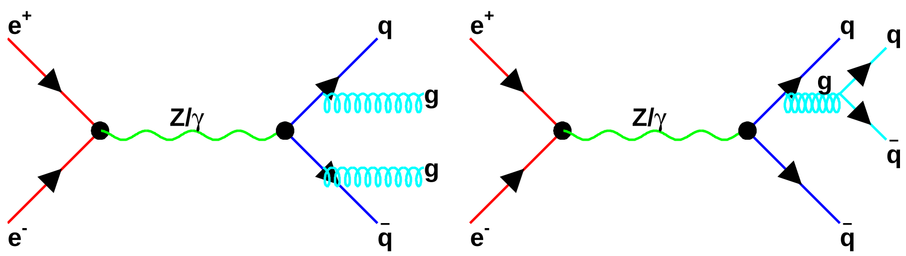
Event Shapes: relative contributions from n-jet configuration

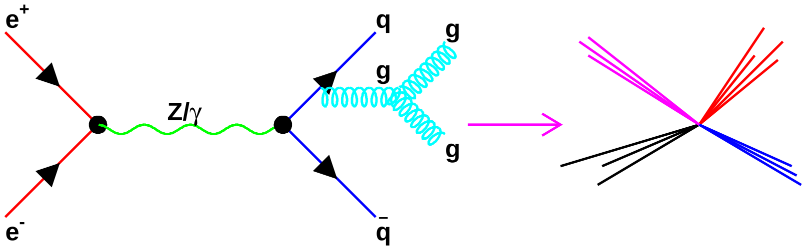


2 jets: $1 - T \simeq 0 \;\; \rho_H, \; B_T, \; B_W, \; C \simeq 0$



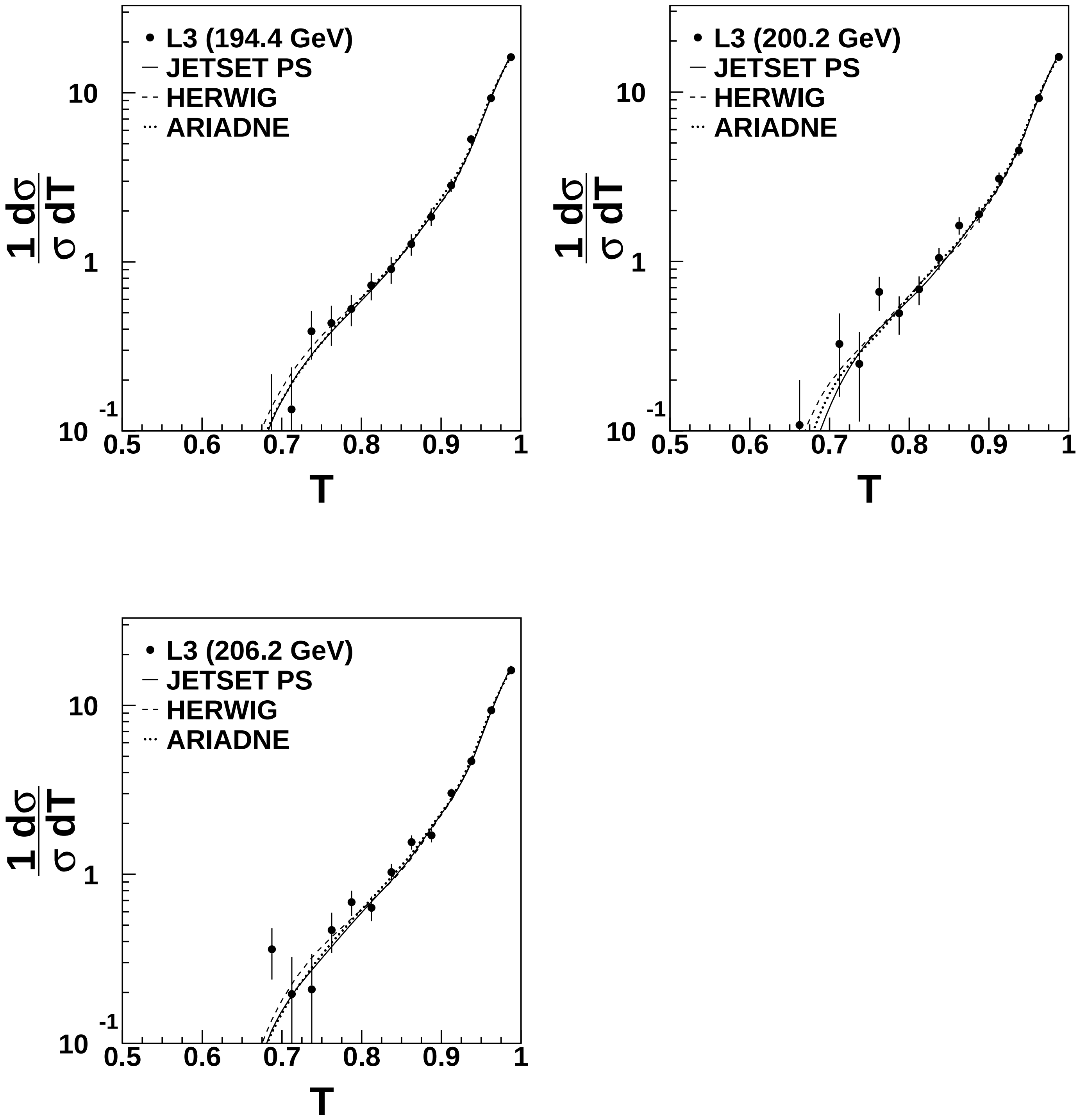
3 jets: $T \; [\frac{2}{3}, 1], \; \rho_H \approx 1 - T, \; B_T \; [0, \frac{1}{2\sqrt{3}}], \; C \; [0, \frac{3}{4}]$



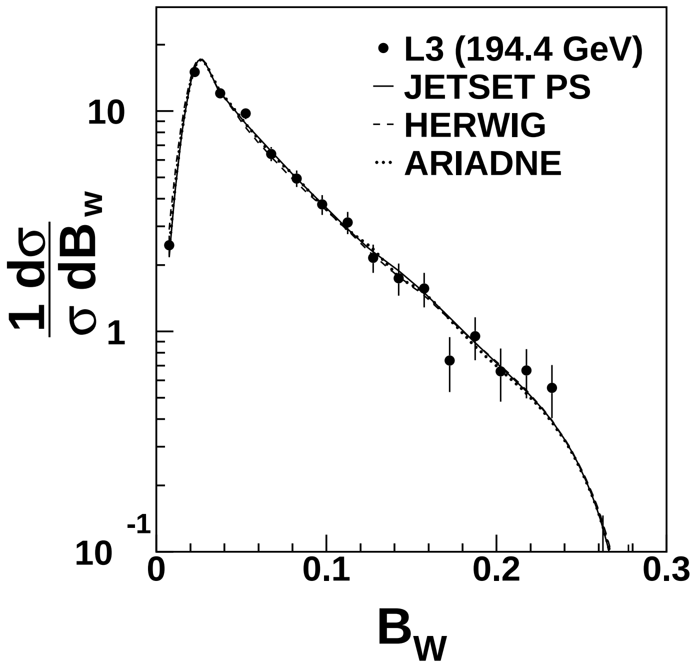


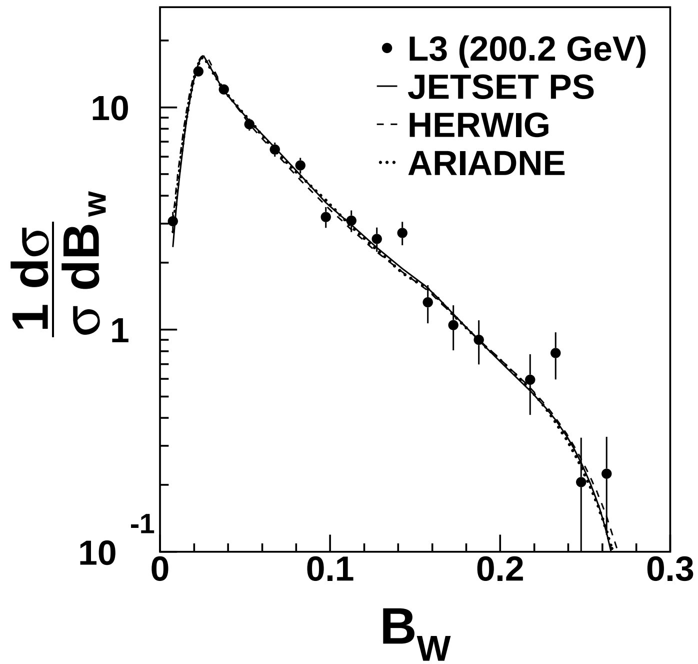
4 jets: $T \; [\frac{1}{\sqrt{3}}, 1]$, <u>Planar Topology</u> $(C)_{max} = 1.$
<u>Spherical Topology</u>, $(B_T)_{max} = \frac{\pi}{8}$, $(B_W)_{max} = \frac{\pi}{16}$

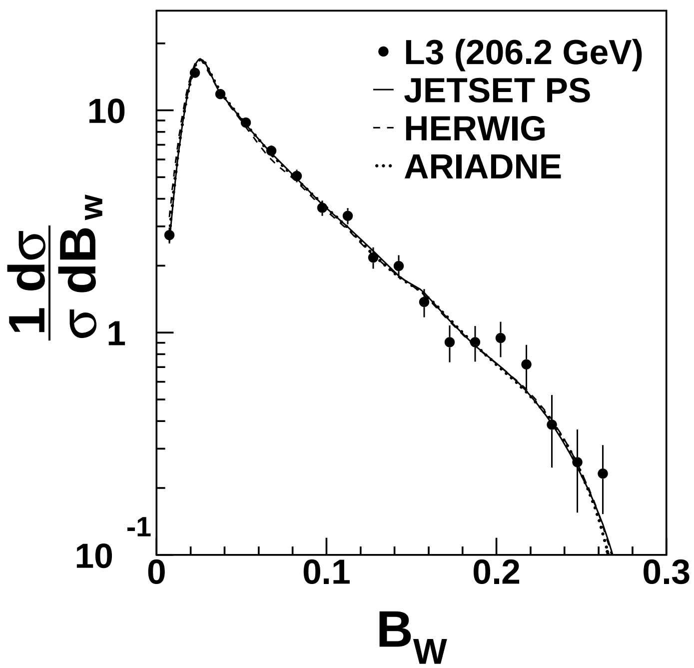
Distributions: Trust



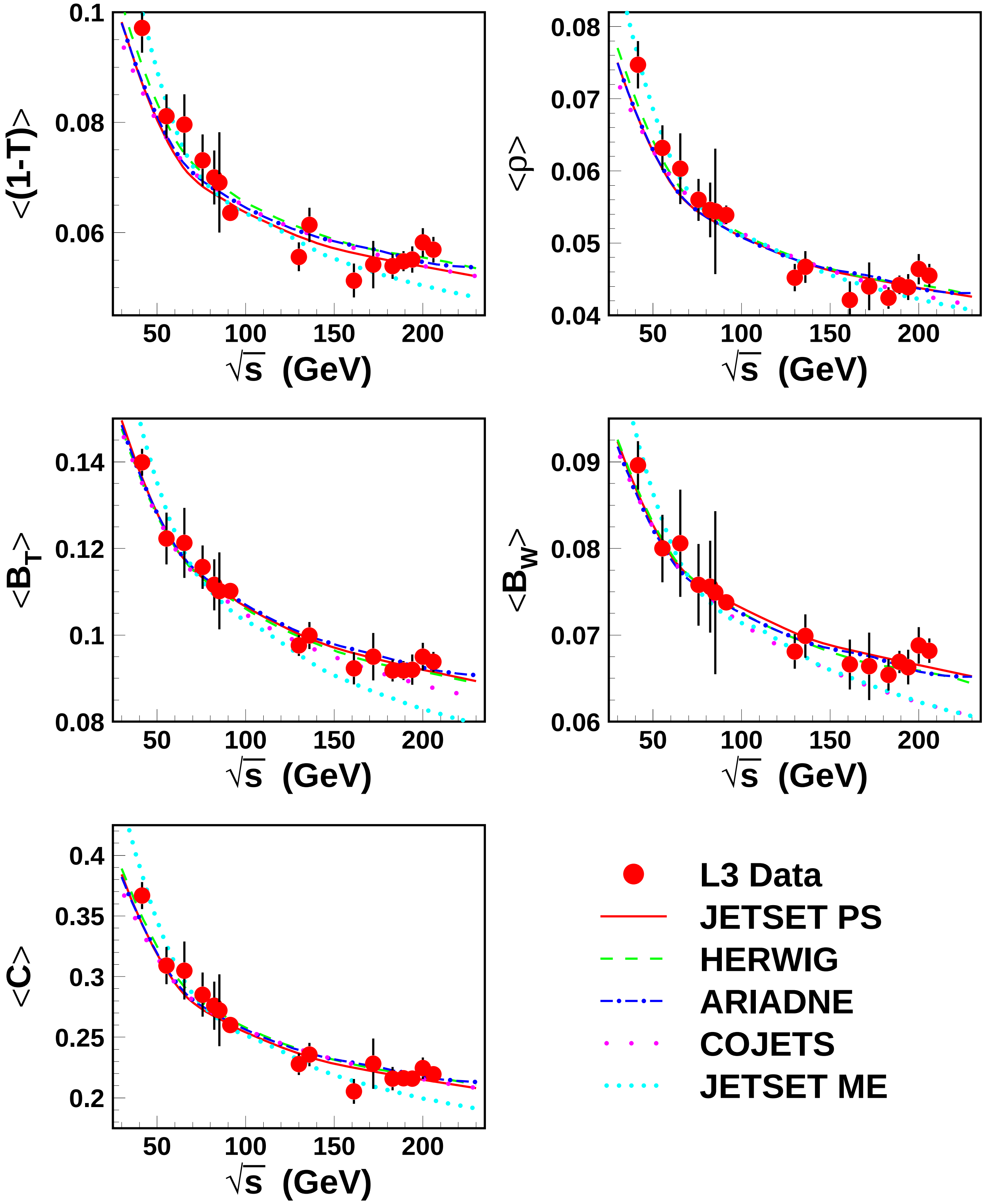
Distributions: Bw







Energy Evolutions



⇒ QCD Models with parton shower describe data well

Complete analytical QCD calculations are available for event shape variables up to second order and leading logharithmic terms have been resummed up all orders for certain variables:

• Complete calculation to $\mathcal{O}(\alpha_s^2)$ for the event shape variable y:

$$\frac{1}{\sigma}\frac{d\sigma}{dy} = A(y)\frac{\alpha_s(\mu)}{2\pi} + \left(B(y) + 2A(y)\beta_0 \ln\frac{\mu^2}{Q^2}\right)\left(\frac{\alpha_s(\mu)}{2\pi}\right)^2$$

μ is the renormalization scale used for α_s calculations. A(y), B(y) computed.

the event shape variables distributions $\propto \alpha_s$

$\Rightarrow$ great sensitivity to coupling constant.

• Resummation: Leading order terms $(\Sigma\overline{\alpha_s}^n L^{n+1})$ and next-to-leading logarithmic terms $(\Sigma\overline{\alpha_s}^n L^n)$, with $L = \ln(\frac{1}{y})$

	LL	NLL
$\mathcal{O}(\alpha_s)$	$\overline{\alpha_s}L^2$	$\overline{\alpha_s}L$
$\mathcal{O}(\alpha_s^2)$	$\overline{\alpha_s^2}L^3$	$\overline{\alpha_s^2}L^2$
$\mathcal{O}(\alpha_s^3)$	$\overline{\alpha_s^3}L^4$	$\overline{\alpha_s^3}L^3$
.	.	
.	.	

• Combination of fixed order calculations with resummed calculations (avoiding double counting of terms).
Modified Log R Replacing in the resummed terms by L' = ln $(y^{-1} - y_{max}^{-1} + 1)$, take log fixed order, expand in power series and match.
This calculations are performed at parton level and do not include heavy quarks mass effect.

• Compare the analytical calculations with the experimental distributions. The effect of hadronization and decays incorporated with MonteCarlo.
$p^{pert}(y')$ is convoluted with the probability of finding a value y after fragmentation and decays for a parton level y'.

$$f(y) = \int f^{pert} p^{non-pert}(y', y) dy$$

$p^{non-pert}$ is evaluted using Montecarlo: JETSET (as default), HERWIG/ARIADNE (for-cross-check).

Errors considered:

- Statistical
- Experimental systematics. Variation:

- Detector effect

- Background modelling

- Hadronization. Variation:

- Fragmentation models

- Fragmentation parameters

- Uncalculated High order. Variation:

- Matching schemes

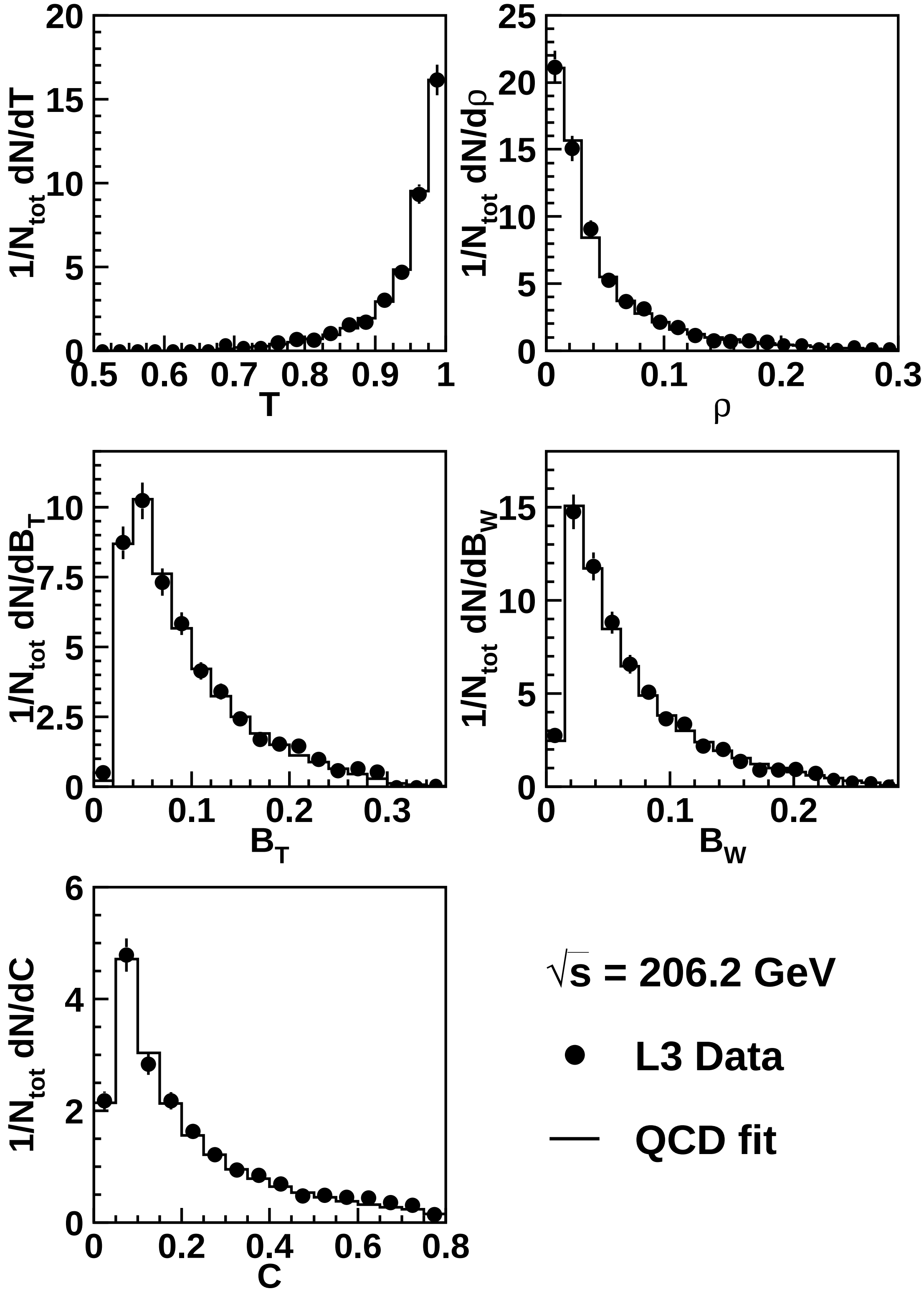
- Scale 0.5 $\sqrt{s}$ to 2 $\sqrt{s}$

α_s value at $\sqrt{s}$ = 206 GeV

$$\begin{aligned}
\alpha_s(\text{1-T}) &= 0.1173 \pm 0.0021\ (\text{exp}) \pm 0.0057\ (\text{theo}) \\
\alpha_s(\rho) &= 0.119 \pm 0.0019\ (\text{exp}) \pm 0.0034\ (\text{theo}) \\
\alpha_s(B_T) &= 0.1163 \pm 0.0021\ (\text{exp}) \pm 0.0065\ (\text{theo}) \\
\alpha_s(B_W) &= 0.1077 \pm 0.0019\ (\text{exp}) \pm 0.0062\ (\text{theo}) \\
\alpha_s(\text{C}\ ) &= 0.1077 \pm 0.0019\ (\text{exp}) \pm 0.0062\ (\text{theo})
\end{aligned}$$

- α_s is the average of α_s(1-T) $\alpha_s(\rho)$ $\alpha_s(B_T)$ $\alpha_s(B_W)$ α_s(C)

Measured distributions of event shape variables in comparison with QCD predictions.



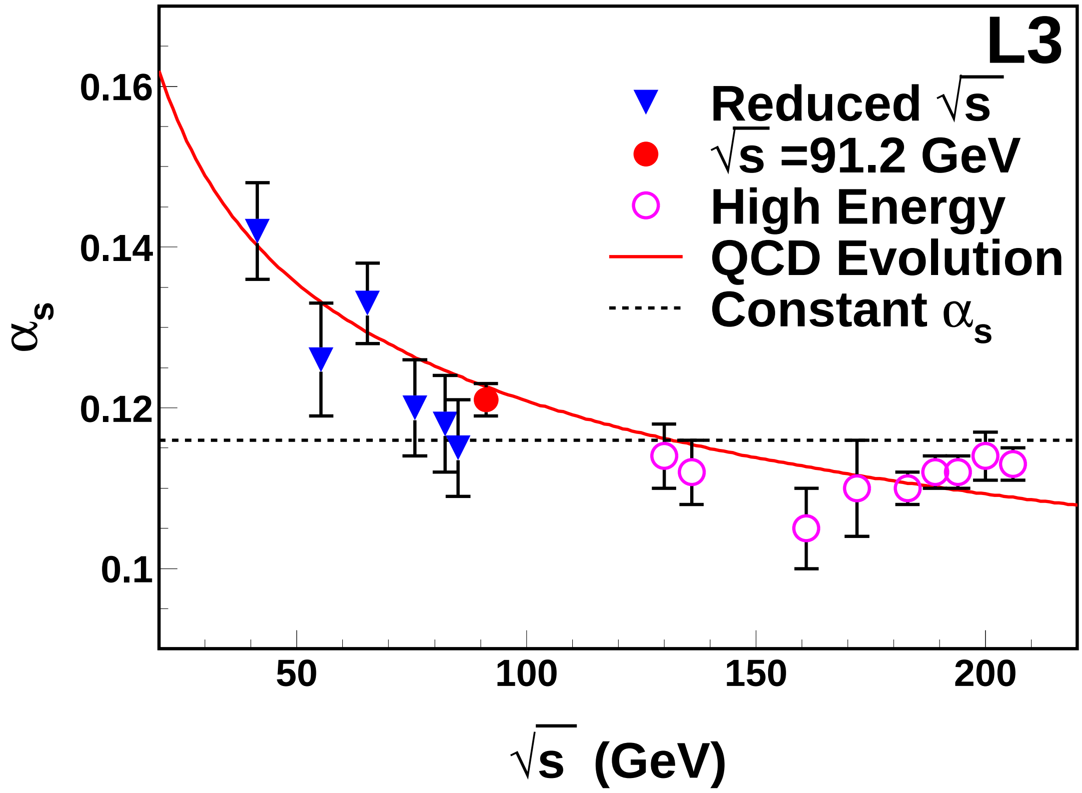
$\alpha_s(\text{thrust}) = 0.1173$, $\alpha_s(\rho) = 0.1119$, $\alpha_s(B_T) = 0.1163$,
$\alpha_s(B_W) = 0.1077$, $\alpha_s(B_W) = 0.1130$

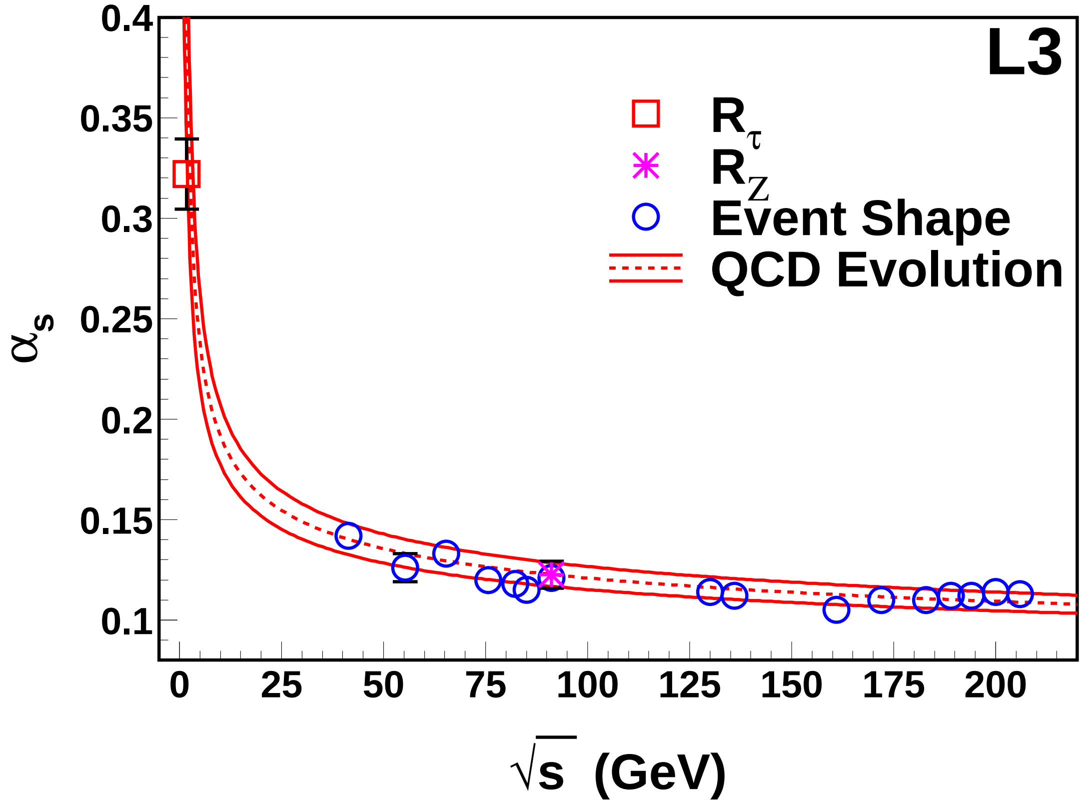
The α_s *running* is the solution of renormalization equation.
From the experimental data is possible to derive:

- **Energy dependence of α_s compared with QCD prediction.**
- **Fit to QCD evolution equation with $\alpha_s(m_Z)$ free parameter.**

Running α_s from 30 to 208 GeV

From event shape





α_s values

Combined α_s values from the five event shape variables.

$<\sqrt{s}>$ (GeV)	α_s measurement from T, ρ, B_T, B_w, C				
	α_s	stat	syst	hadr.	hi. order
41.4	0.1418	±0.0053	±0.0030	±0.0055	±0.0085
55.3	0.1260	±0.0047	±0.0056	±0.0066	±0.0062
65.4	0.1331	±0.0032	±0.0042	±0.0059	±0.0064
75.7	0.1204	±0.0024	±0.0059	±0.0060	±0.0053
82.3	0.1184	±0.0028	±0.0053	±0.0060	±0.0051
85.1	0.1152	±0.0037	±0.0051	±0.0060	±0.0055
91.2	0.1210	±0.0008	±0.0017	±0.0040	±0.0052
130.1	0.1138	±0.0033	±0.0021	±0.0031	±0.0046
136.1	0.1121	±0.0039	±0.0019	±0.0038	±0.0045
161.3	0.1051	±0.0048	±0.0026	±0.0026	±0.0044
172.3	0.1099	±0.0052	±0.0026	±0.0024	±0.0048
182.8	0.1096	±0.0022	±0.0010	±0.0023	±0.0044
188.6	0.1122	±0.0014	±0.0012	±0.0022	±0.0045
194.4	0.1123	±0.0018	±0.0016	±0.0020	±0.0047
200.2	0.1138	±0.0018	±0.0021	±0.0020	±0.0046
206.2	0.1132	±0.0014	±0.0016	±0.0019	±0.0047

α_s at m_Z

$$\alpha_s(m_Z) = 0.1227 \pm 0.0012 \text{ (exp)} \pm 0.0058 \text{ (theo)}$$

($\chi^2 = 17.9$ n.d.f $= 15$ c.l. $=0.27$)

Conclusions

- **Event shape variables have been studied over a large energy range: 30 to 208 GeV in e^+e^- collisions by L3 experiment. Good agreement is seen between data and coherent models tuned at $\sqrt{s} = m_Z$.**

- **Runinng of α_s is clearly demonstrated. In agreement with QCD predictions.**

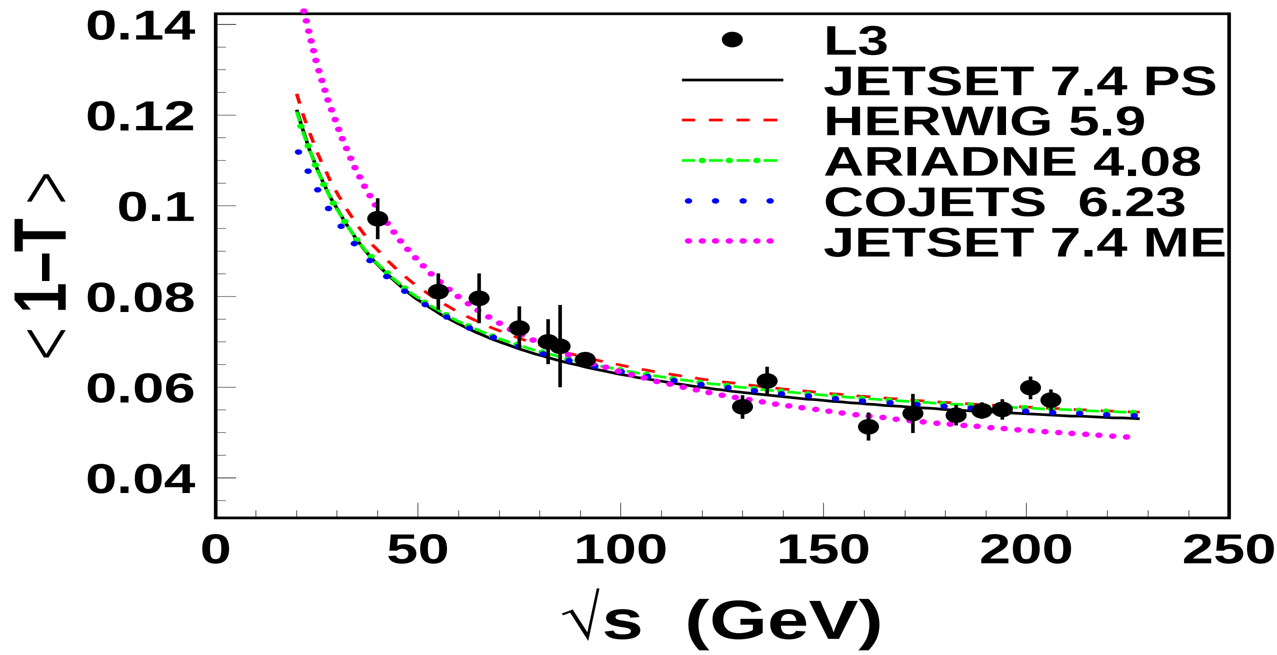
- **A fit to QCD evolutions gives:**

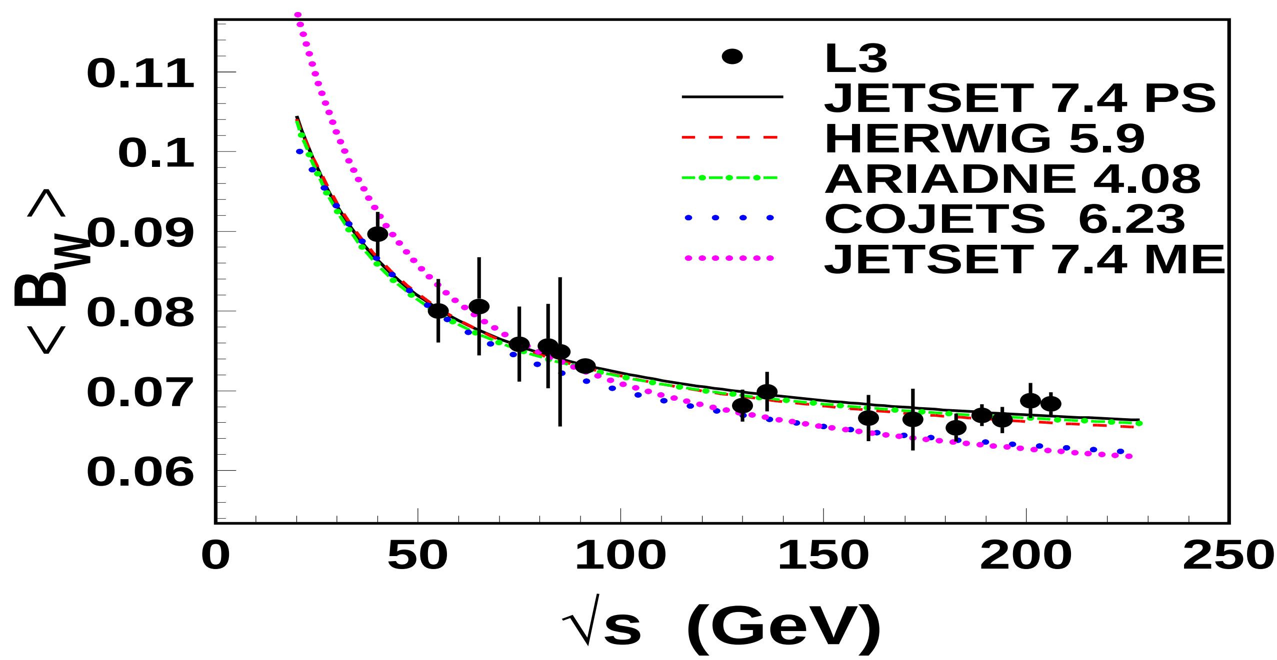
  $$\alpha_s(m_Z) = 0.1227 \pm 0.0012\ (\text{exp}) \pm 0.0058\ (\text{theo})$$

- **Theoretical uncertainty from unknown higher orders dominate.**

- **Very consistent result with other α_s measurements performed.**

Energy Evolutions





Error bars include experimental systematic uncertanties

spage Energy evolution of α_s

The *running* of α_s can be expressed as:

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_o)}{1 + \beta_o \alpha_s(\mu_o) ln \frac{(}{\mu^2} \mu_o^2)}$$

$$\beta_o = \frac{33 - 2n_f}{12\pi}$$

assumption: $\alpha_s(\mu_o) = \alpha_s(m_Z)$

- **Energy dependence of α_s compared with QCD prediction.**
- **Fit to QCD evolution equation with $\alpha_s(m_Z)$ free parameter.**