Study of the structure of hadronic events at LEP with L3

- Introduction
- L3 Data at $\sqrt{\mathrm{s}} <$, equal to, $> \mathrm{M_Z}$
- Hadronic Event Selection
- Detector Corrected Distributions
- Comparison with QCD Predictions
- α_s determination

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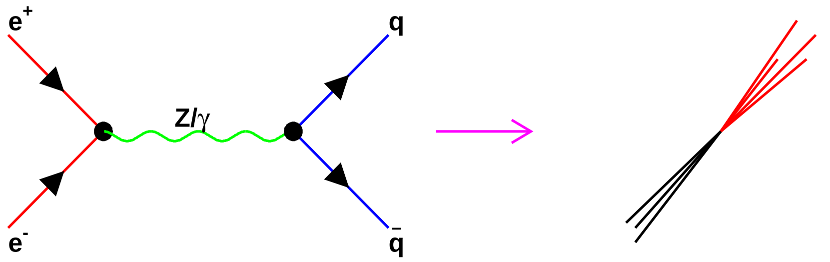
QCD '99, Montpellier
$7 - 13^{\mathrm{th}}$ July 1999

Event Shape Variables

$$T = \left(\frac{\sum_a |\vec{p}_a \cdot \hat{n}_T|}{\sum_a |\vec{p}_a|} \right)_{max} \qquad C = \left(\frac{3}{E_{vis}^2}\right) \sum_{i<j} |\vec{p}_i| * |\vec{p}_j| * \sin^2(\theta_{ij})$$

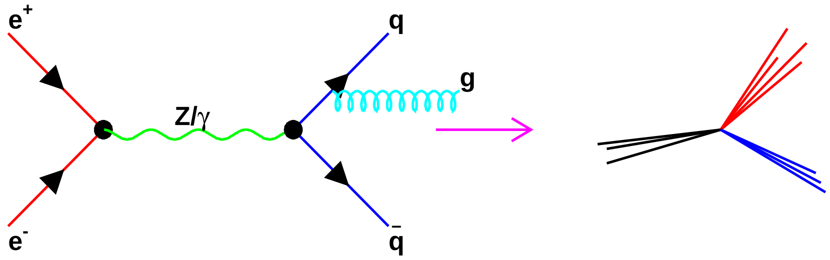
$$\rho_H = \left(\frac{\sum_{a \in S_\pm} p_a}{E_{vis}^2} \right)^2_{max} \qquad B_\pm = \left(\frac{\sum_{a \in S_\pm} |\vec{p}_a \times \hat{n}_T|}{2 \sum_a |\vec{p}_a|} \right) \qquad \begin{array}{l} B_T = B_+ + B_- \\ B_W = \max(B_+, B_-) \end{array}$$

Characteristic Hadronic Event Structures:



$T \approx 1$

$C, \rho_H, B_{T,W} \approx 0$

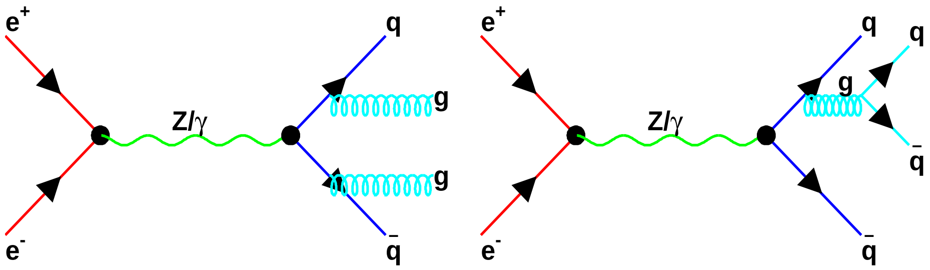


$(T)_{max} = \frac{2}{3}$

$(C)_{max} = \frac{3}{4}$

$\rho_H = 1 - T$

$(B_T)_{max} = \frac{1}{2\sqrt{3}}$



$(T)_{max} = \frac{1}{\sqrt{3}}$

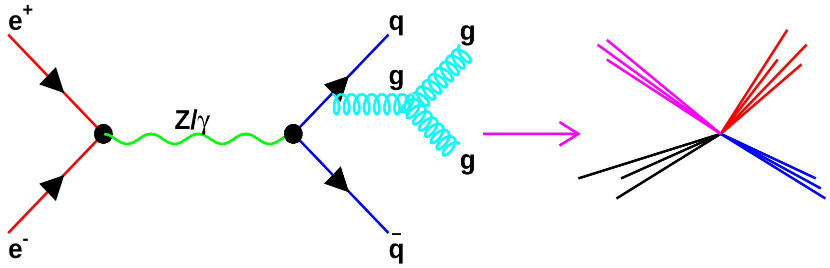
Planar Topology

$C \to 1$

Spherical Topology

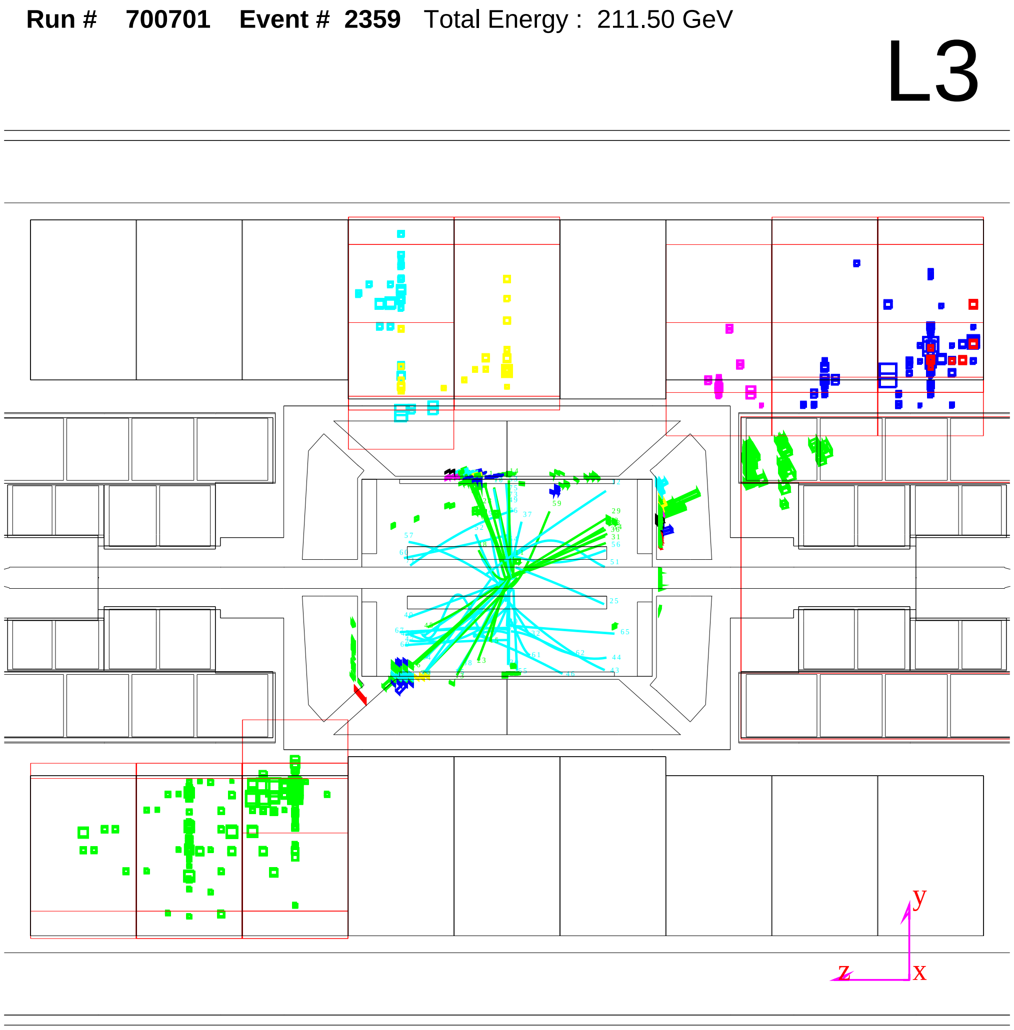
$B_T = \frac{\pi}{8}$

$B_W = \frac{\pi}{16}$



☞ Hadronic event characterized by:

- large visible energy observed in the detector
- large number of particles in the final state



✧ Resolutions (3.0 pb^{-1} calibration data @ 1998):

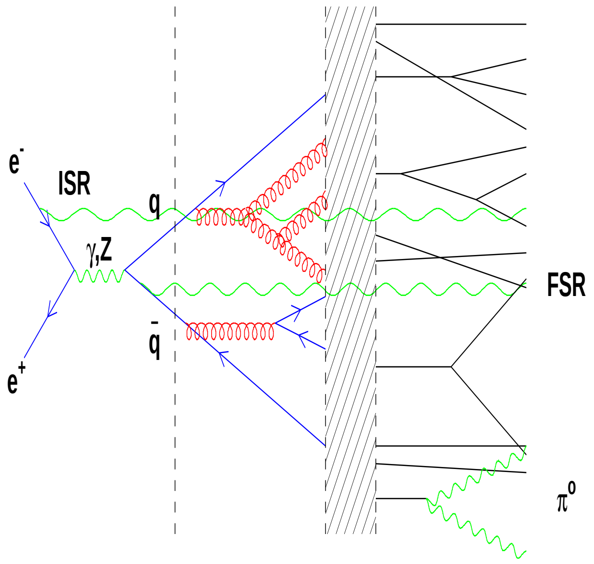
Energy	:	13.5%	-
Polar angle	:	44.3 mrad.	(2 jets)
Azimuthal angle	:	57.5 mrad.	(2 jets)

3 Event Samples:

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

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

$\sqrt{s'} = 40,\ 55,\ 65,\ 75,\ 82,\ 84$ GeV

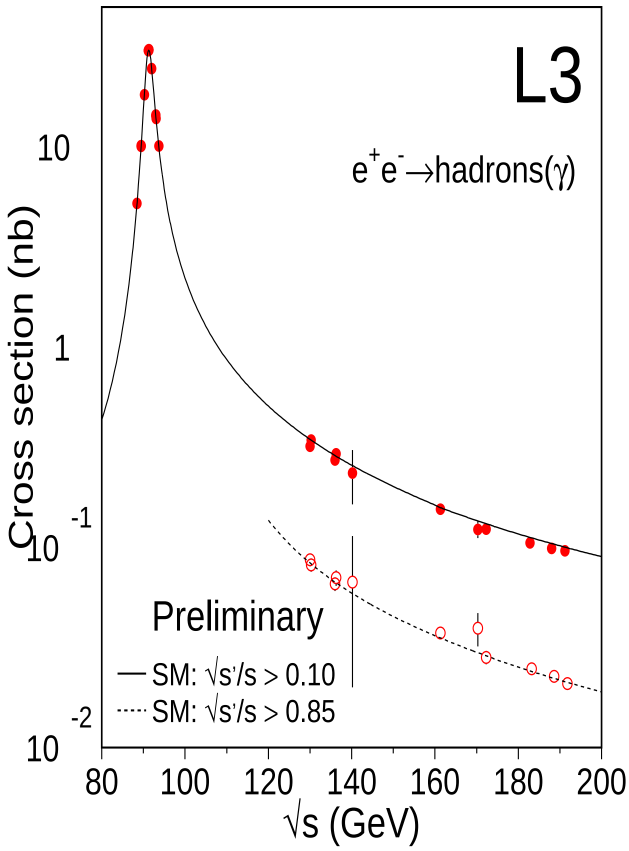


✪ Hadronic Z decays LEP1

$\sqrt{s} = M_Z$

★ LEP II Data rejecting "Radiative Return",WW

$\sqrt{s} = 130,\ 136,\ 161,\ 172,\ 183,\ 189$ GeV

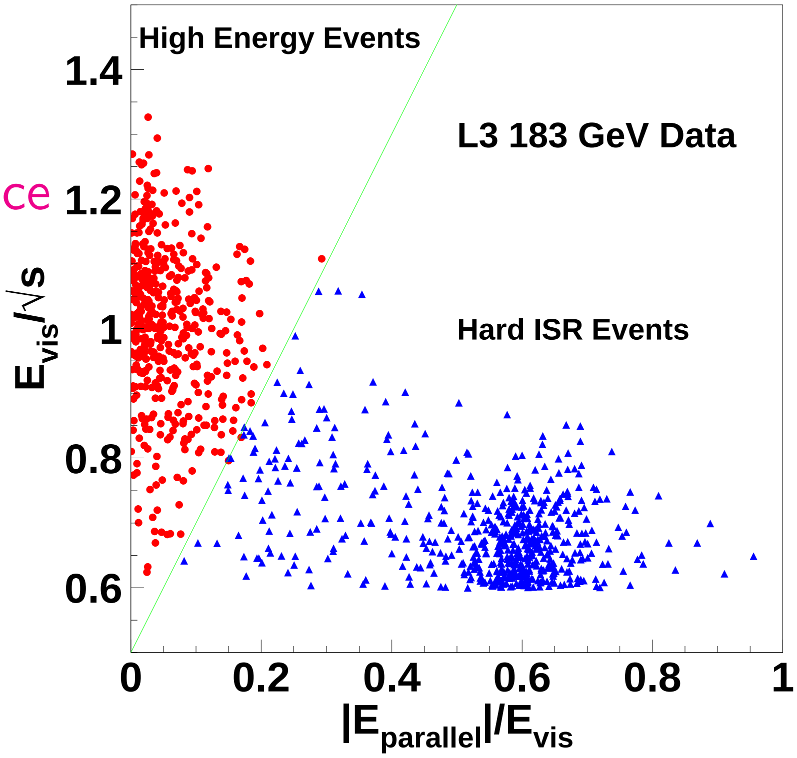


☞ $\underline{\sqrt{s} > M_Z}$: large contribution from ISR reducing $\sqrt{s'} \approx M_Z$

• If γ is lost in beam-pipe
$\Rightarrow$ parallel energy imbalance

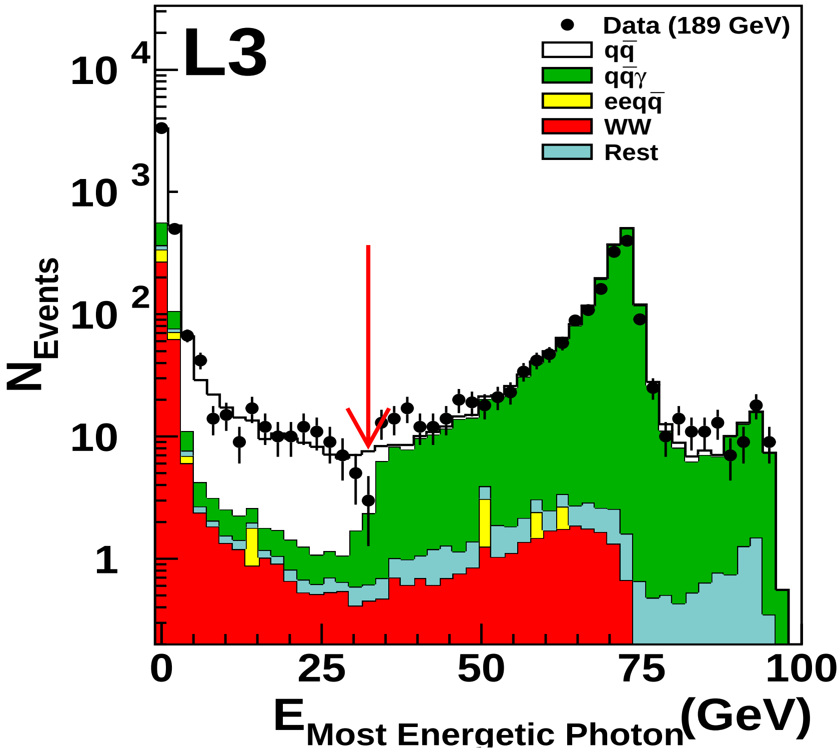
$$(E_{vis}/\sqrt{s}) \; > \; a(\mid E_{\parallel} \mid / E_{vis}) + b$$

Increase slope with $\sqrt{s}$



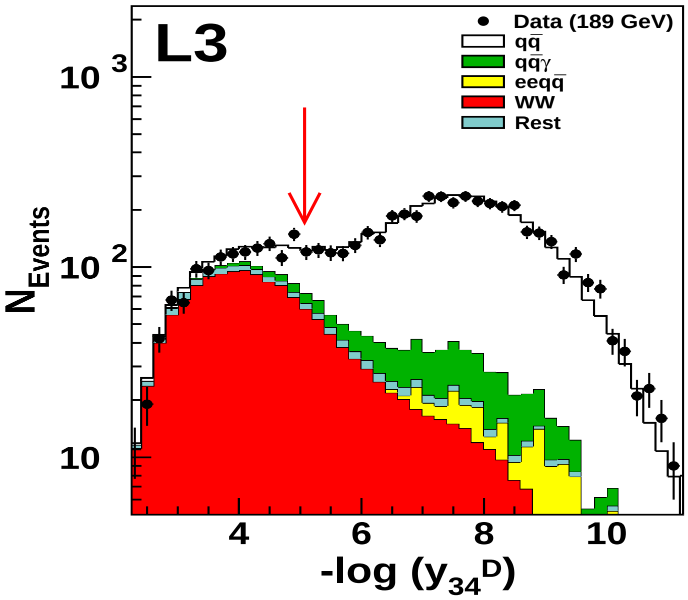
• If seen in the detector
reject isolated photons

$$(E_\gamma)_{\max} \le .18\sqrt{s}$$
$$(\approx 34 \text{ GeV})$$

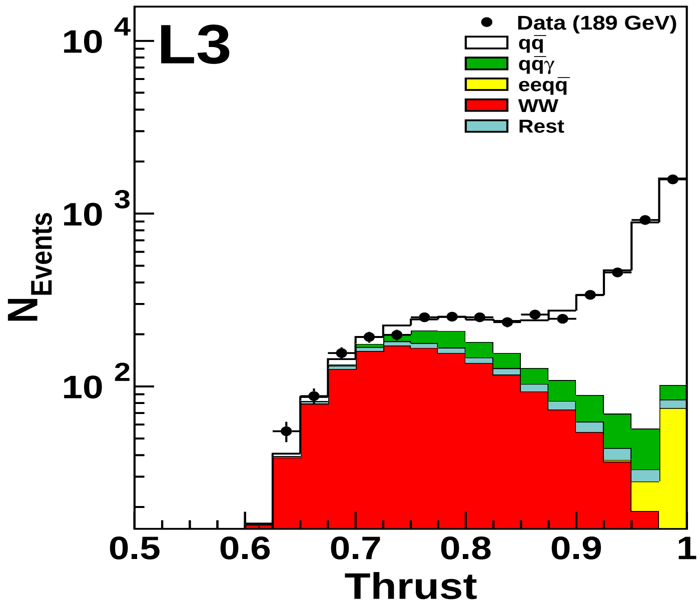


Above W^+W^- threshold, anti-select if :

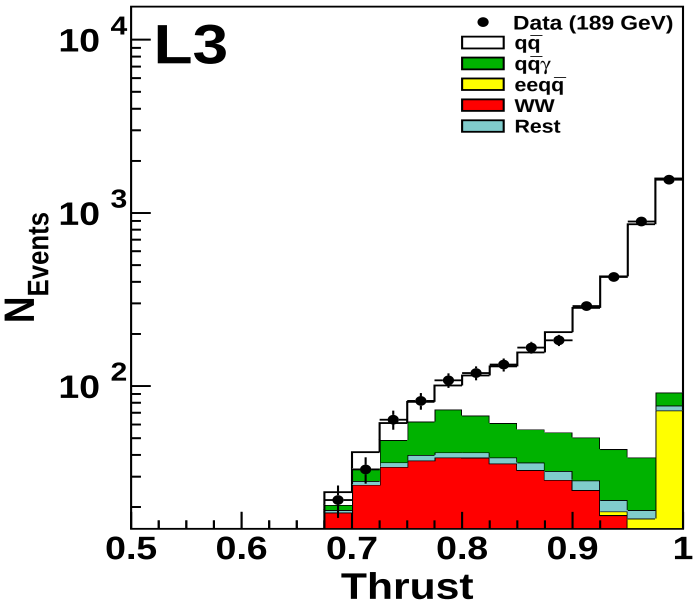
- Energetic electron/muon seen
- High multiplicity balanced 4jets compatible with W^+W^-



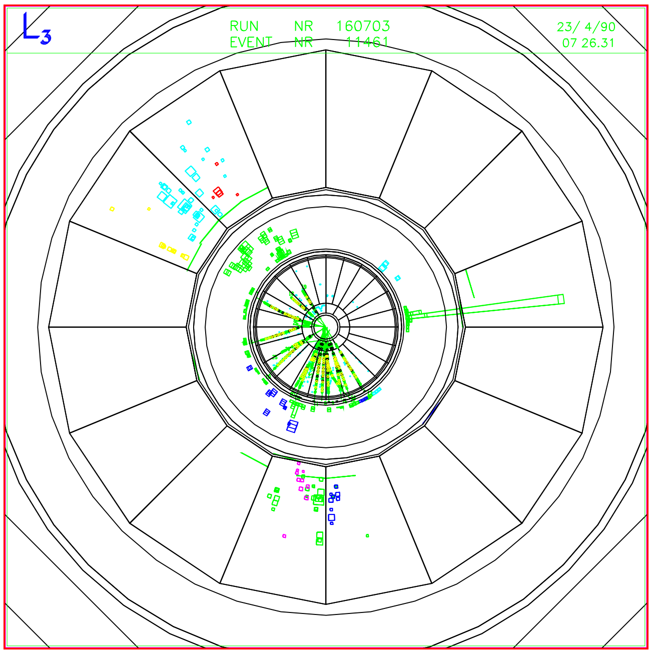
Before rejection



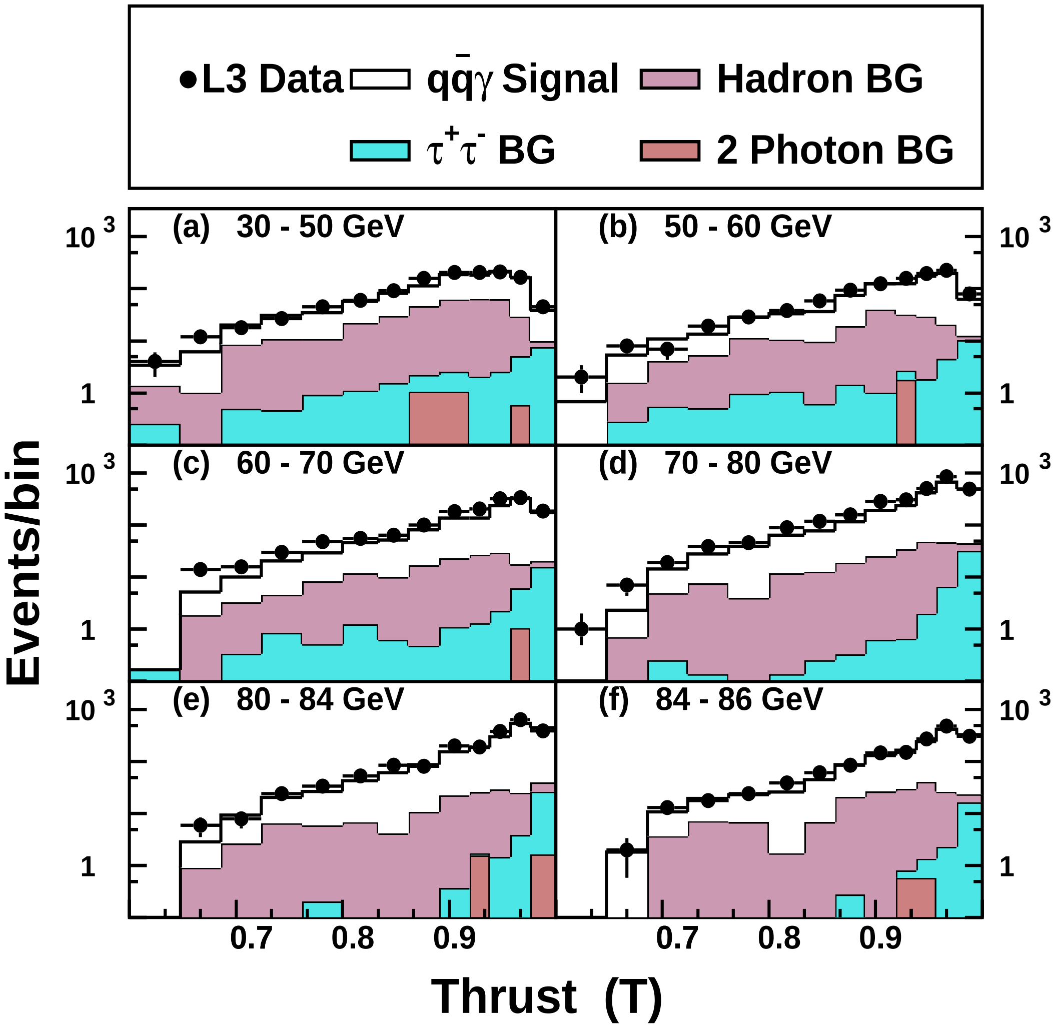
After rejection



➠ Substract remaining background *bin-by-bin*



- Select isolated energetic γ in hadronic events
- Remove γ from event
- Boost the event in CM of remaining hadronic system
- Hadronic background: mainly π^o and η decays
- Use a neural network to improve π^o/η rejection



Event Statistics

Energy (GeV)	$\int \mathcal{L}\,(\mathrm{pb}^{-1})$	$\sim$ Events
$\sqrt{\mathrm{s}'} < \mathrm{M_Z}$	142	1000-2000
Z peak	8.3	248 K
130 136	3+3 3+3	500 500
161 172	10 10	400 300
183	55	1500
189	176	3500

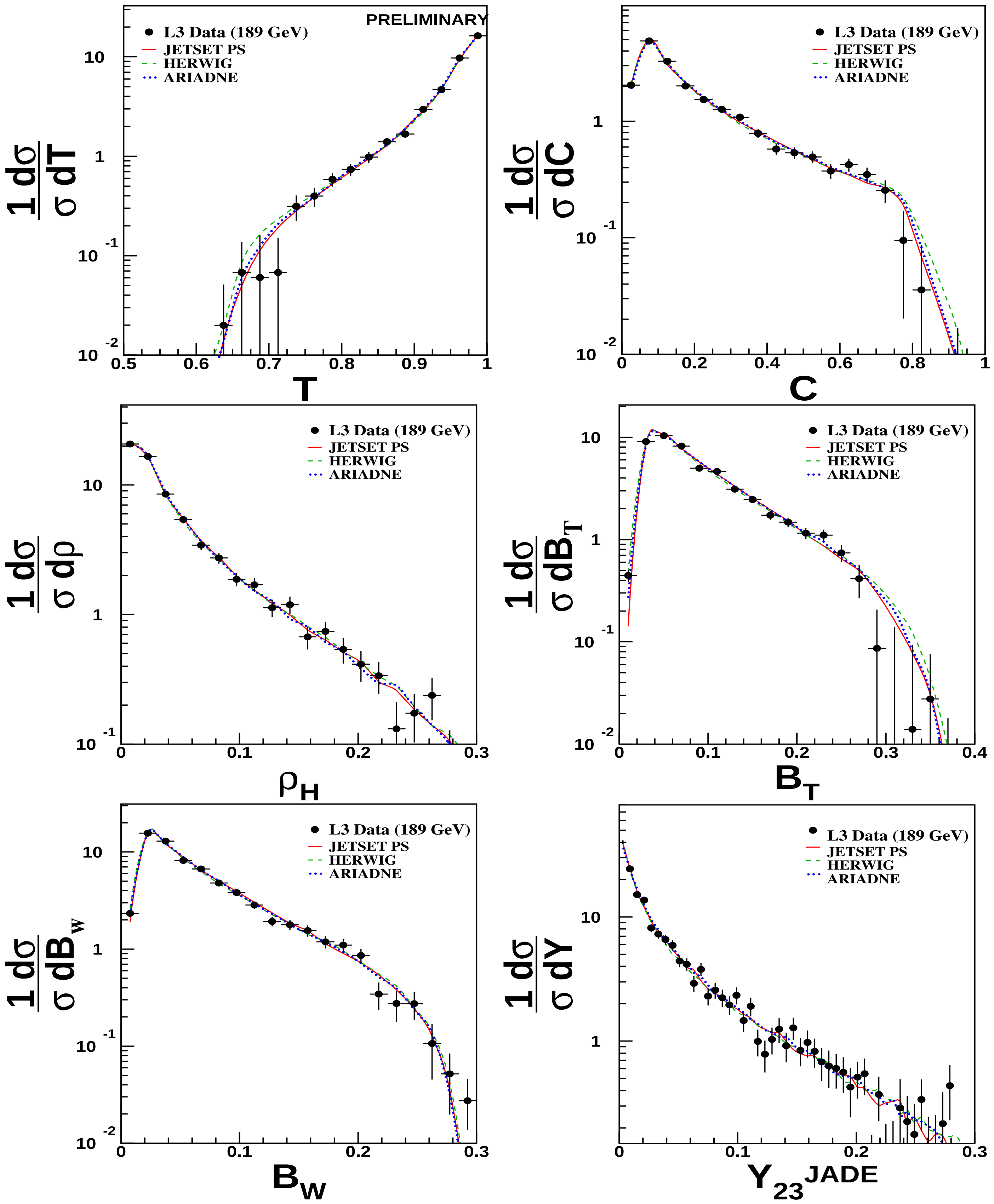
Backgrounds

☆ Hadronic Background: π°, η at $\sqrt{\mathrm{s}'} < \mathrm{M_Z}$
(ε = 50-30%, π = 70-90%)

✪ Negligible background at $\mathrm{M_Z}$
(ε = 98%, π = 99%)

★ ISR, WW backgrounds at $\sqrt{\mathrm{s}} > \mathrm{M_Z}$
(ε = 90-80%, π = 80-84%)

Event Shapes @ 189 GeV



Energy Evolution

Sources:

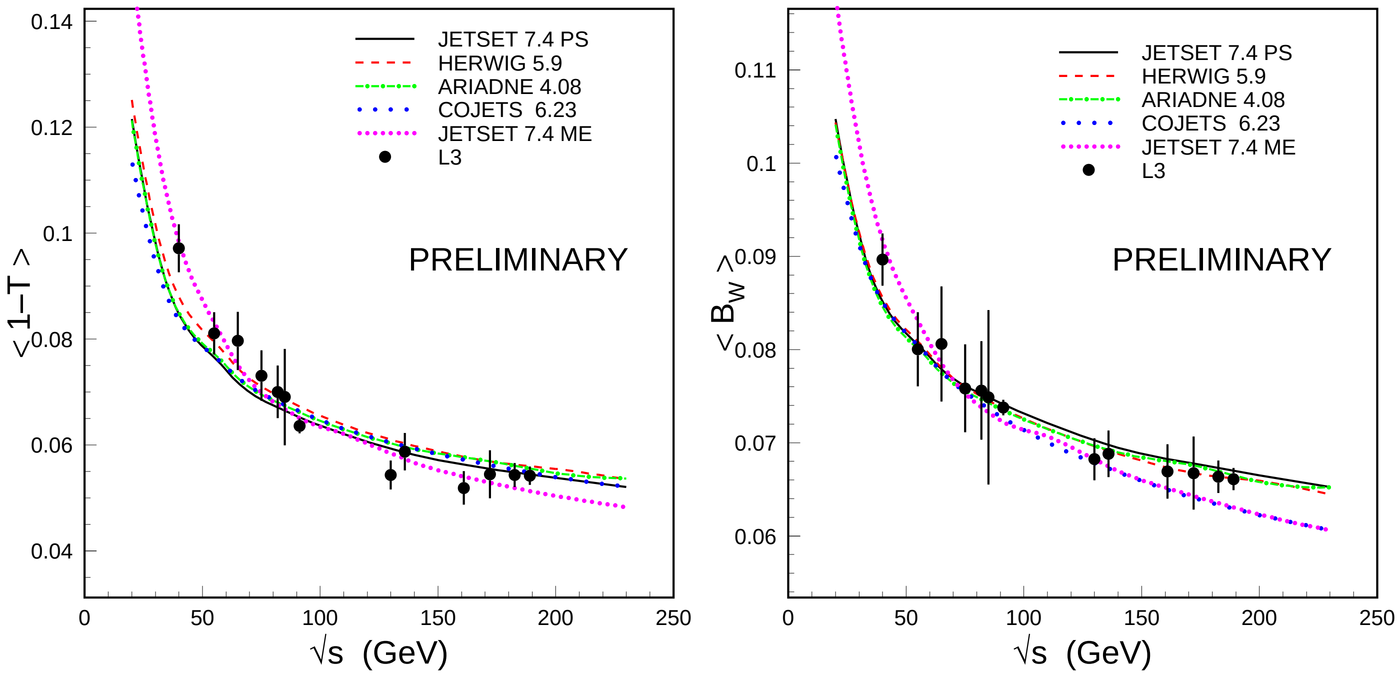
✶ Logarithmic dependence from α_s

✷ $1/Q^n$ dependence from non-perturbative effects

Comparison with QCD Event Generators:

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

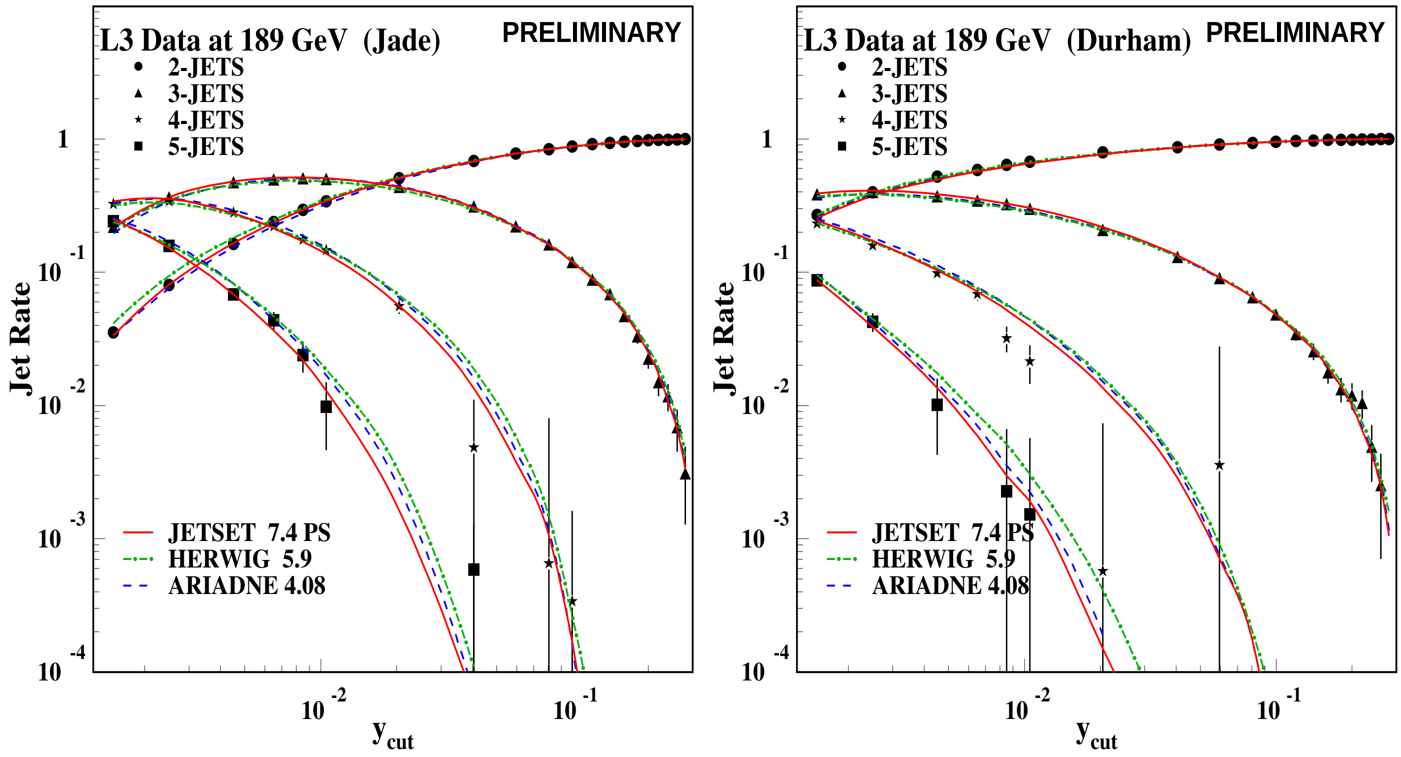
All models tuned at $\sqrt{s} = M_Z$ using LEP I data



⇒ QCD Models with coherent parton shower & string/cluster fragmentation describe data well

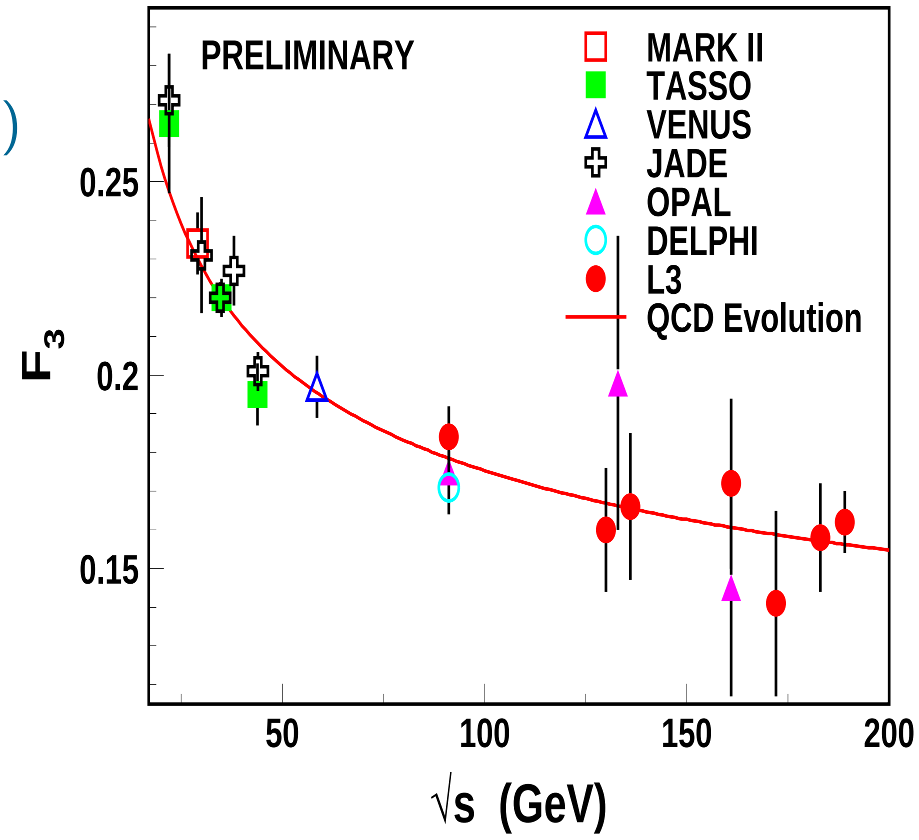
Jet Rates

♦ Cluster using JADE (E0) & DURHAM algorithms



✧ Energy evolution (JADE : ycut = 0.08)

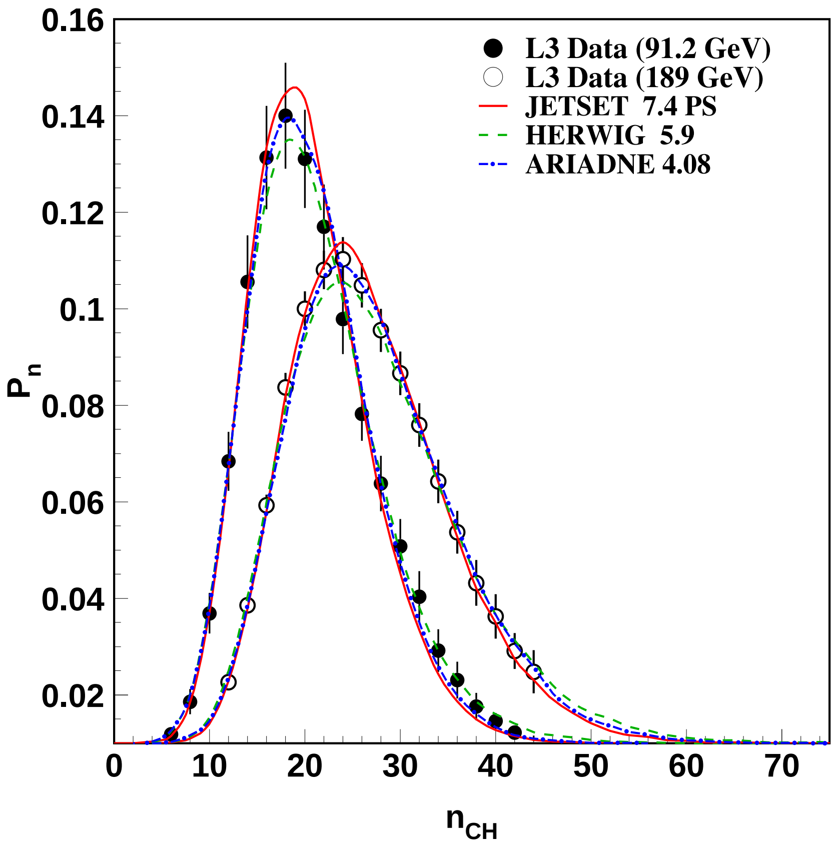
NLO Fit:
(with fixed $\mu = 1$)
$\alpha_s = .1198 \pm .0007$



Charged Particle Multiplicity

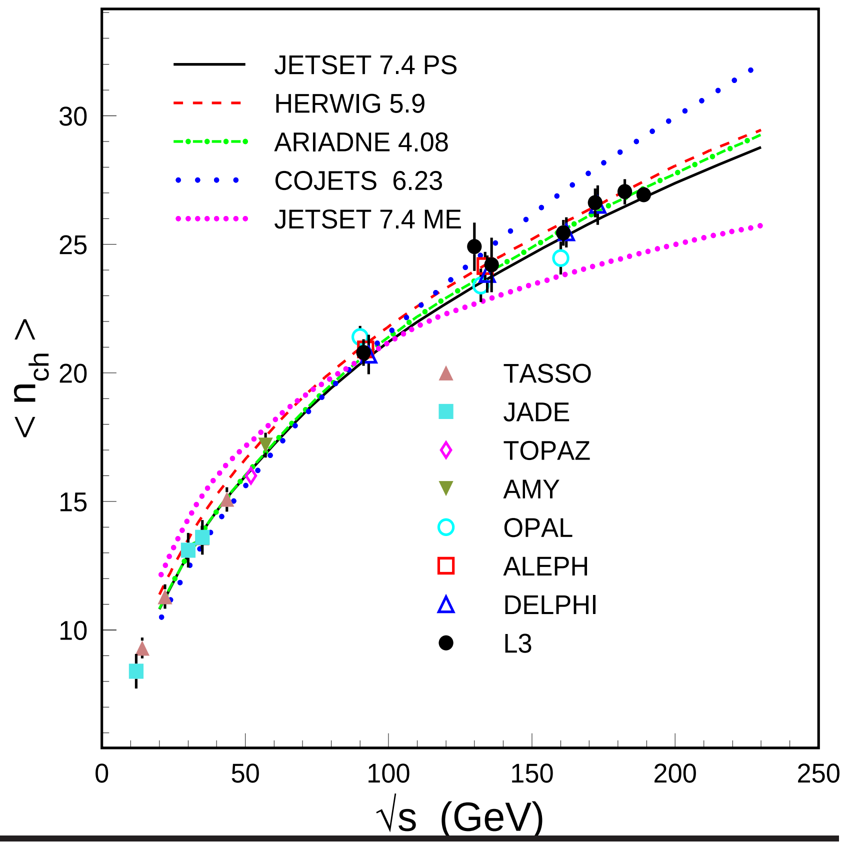
❄ Detector correction using unfolding

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



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

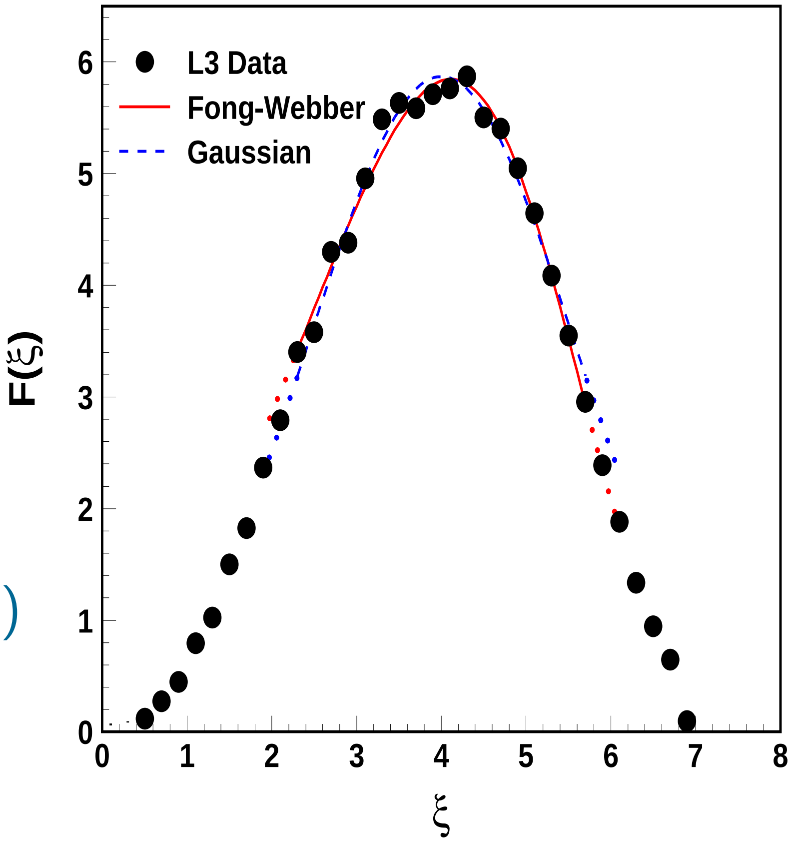
▼ Second order ME with a fixed number of partons cannot describe evolution



Destructive Interference
from soft gluon emissions

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

$\xi_\mathrm{p} = \ln(\frac{1}{\mathrm{x_p}})$ spectra:
- Gaussian (leading order)
- Skewed gaussian (MLLA)

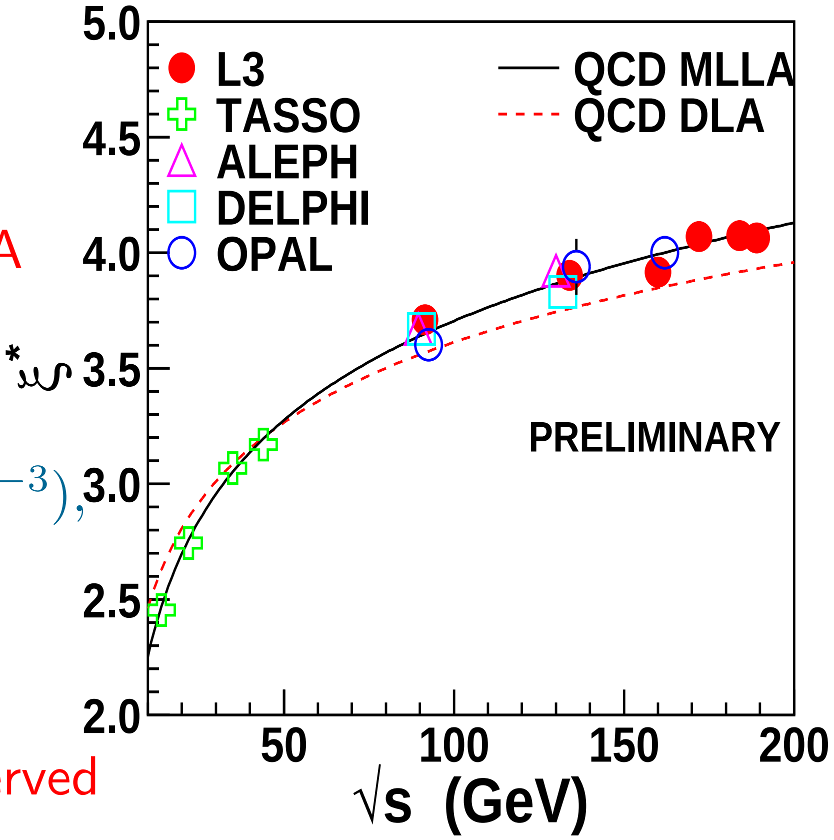


Peak position:
- evolves logarithmically
- infrared sensitive MLLA

QCD Predictions:

$$\xi^\star = \frac{1}{2}Y + \sqrt{C}\sqrt{Y} - C + \mathcal{O}(Y^{-3}),$$

where $Y = \ln(\mathrm{E}_{beam}/\Lambda)$



⇒ Gluon coherence observed

Determination of α_s

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

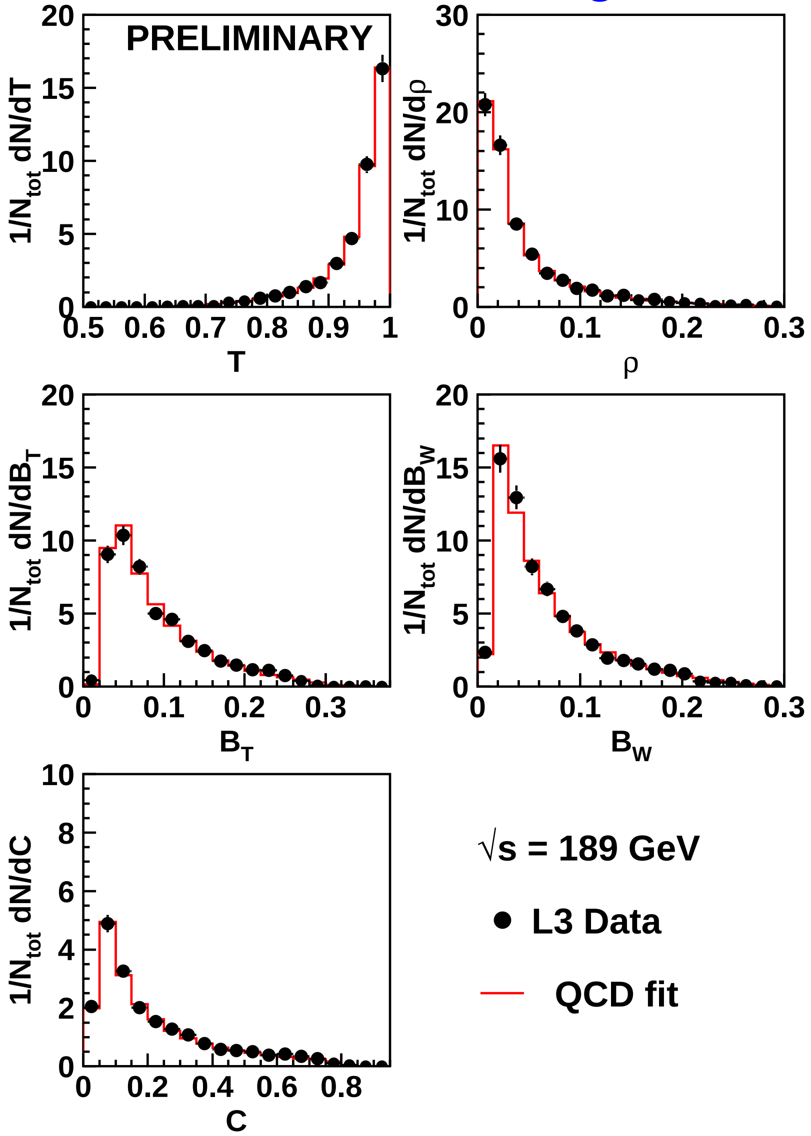
$$
\begin{aligned}
R(\alpha_s, y) &\equiv \int_0^y \frac{1}{\sigma}\frac{d\sigma}{dy} \\
&= \overline{\alpha}_s A(y) + \overline{\alpha}_s{}^2 \left[B(y) + 2\pi\beta_\circ \ln(\mu^2/s) A(y)\right]
\end{aligned}
$$

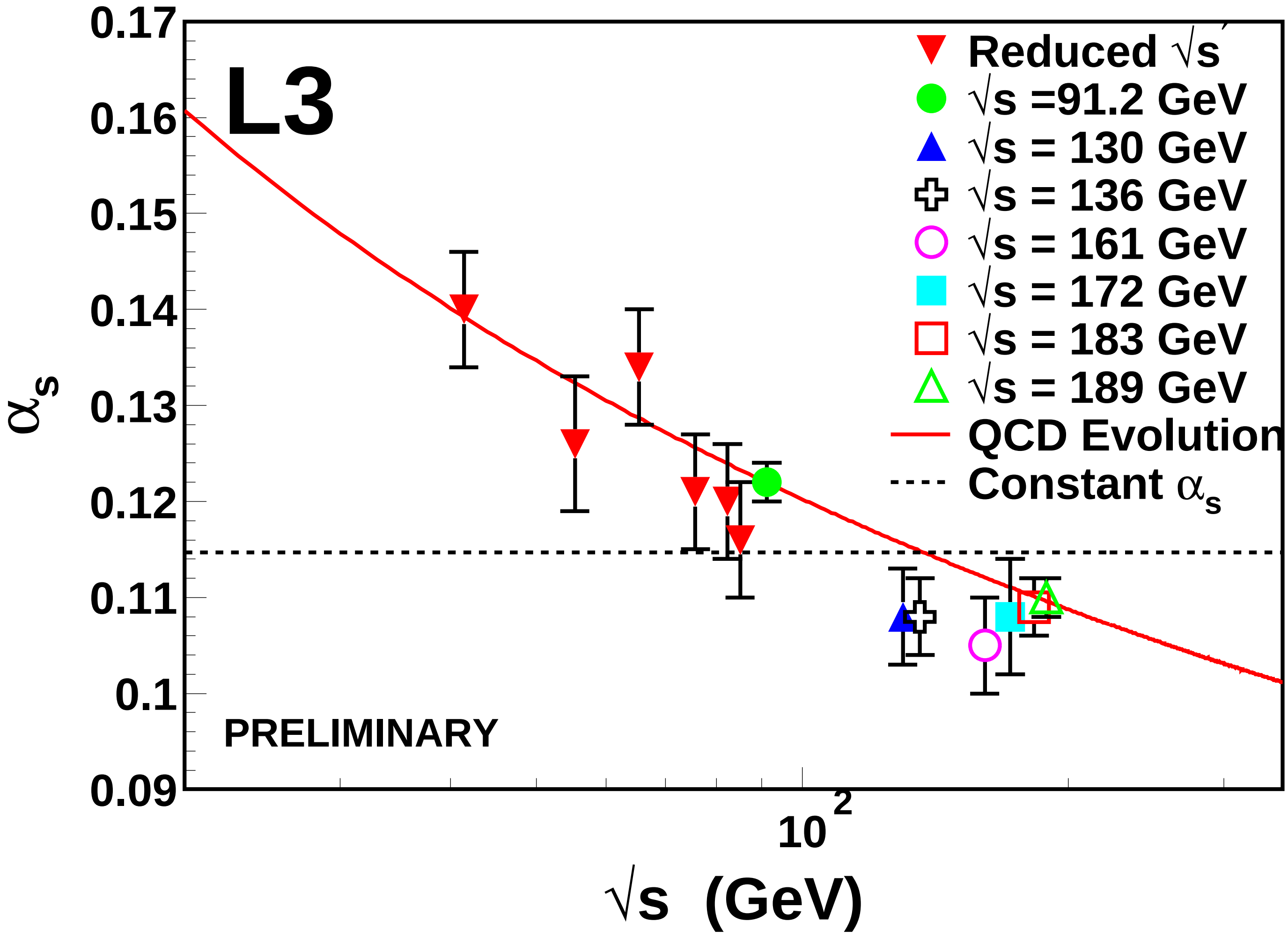
- Resummation:

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

Combining: Describe data over wide range

Hadronization effect folded in using PS Monte Carlo





Fitted:

$$\alpha_s(M_Z) = 0.1220 \pm 0.0015 \text{ (exp)} \pm 0.0060 \text{ (theo)}$$
$$\chi^2 = 15.4 \text{ for } 12 \text{ d.o.f}$$

Active no. of flavours: $N_f = 4.4 \pm 1.0 \pm 2.0$

Power correction

Assumption: Effective ("fake") gluon mass

$\Rightarrow$ freezes running of α_s in infrared region

Predictions: $\boxed{\langle V\rangle = \underbrace{\langle V\rangle_{\mathrm{PT}}}_{\mathcal{O}(\alpha_s{}^2)} + \underbrace{\langle V\rangle_{\mathrm{Non-PT}}}_{c_V * \mathcal{P}}}$

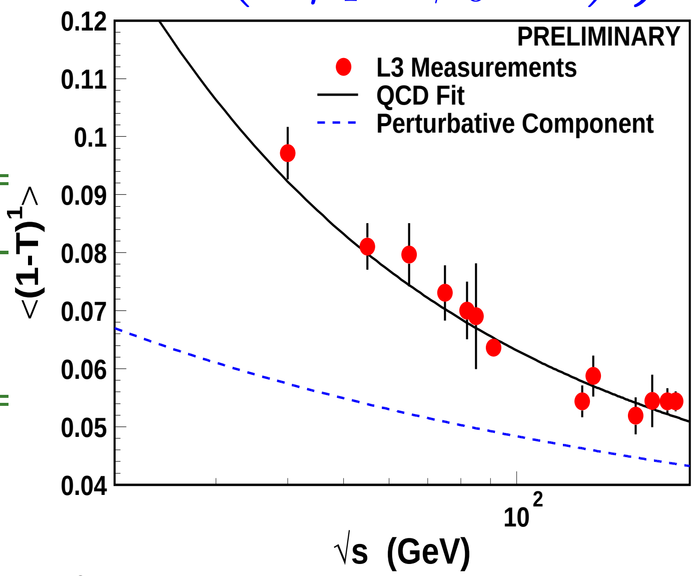
➪ For V = 1-T,C,ρ_{H} : "a shift $\propto$ 1/Q"

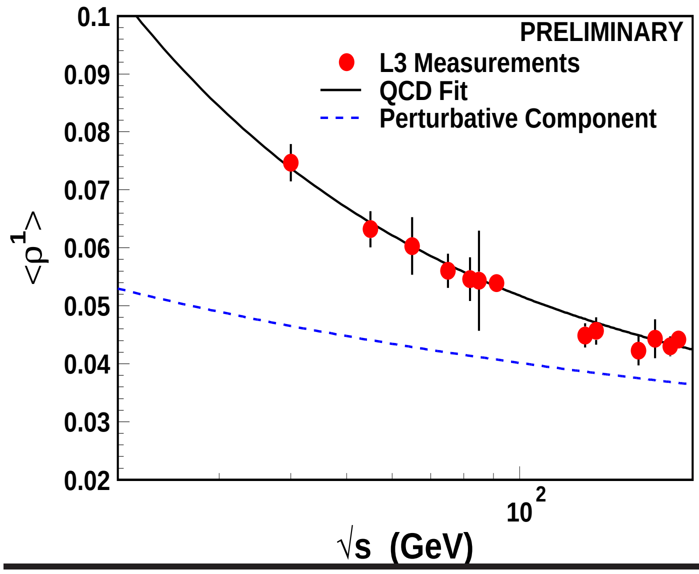
$$\mathcal{P} = \frac{4C_F}{\pi^2}\mathcal{M}\frac{\mu_{\mathrm{I}}}{Q}\left\{\alpha_0(\mu_{\mathrm{I}}) - \alpha_s - \beta_0\frac{\alpha_s{}^2}{2\pi}\left(\ln\frac{Q}{\mu_{\mathrm{I}}} + \frac{K}{\beta_0} + 1\right)\right\}$$

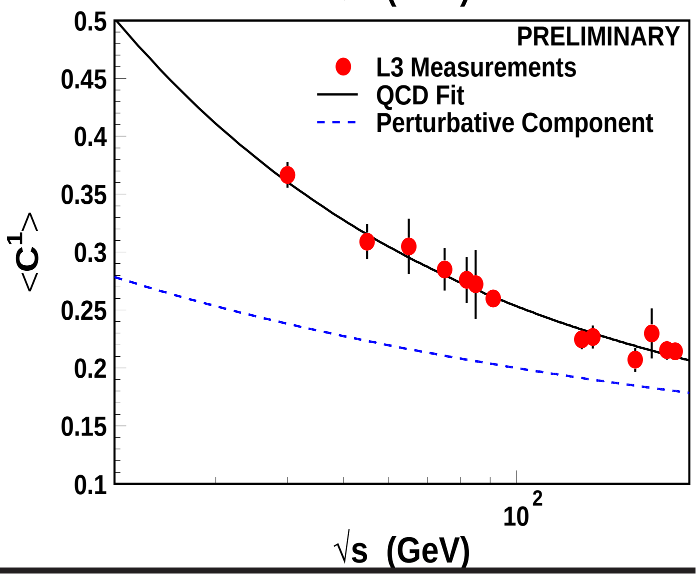
Free parameters:

❶ $\alpha_s(\mathrm{M_Z})$

❷ $\alpha_0(\mu_{\mathrm{I}}) = \frac{1}{\mu_{\mathrm{I}}}\int_0^{\mu_{\mathrm{I}}} dq\,\alpha_{\mathrm{eff}}(q)$



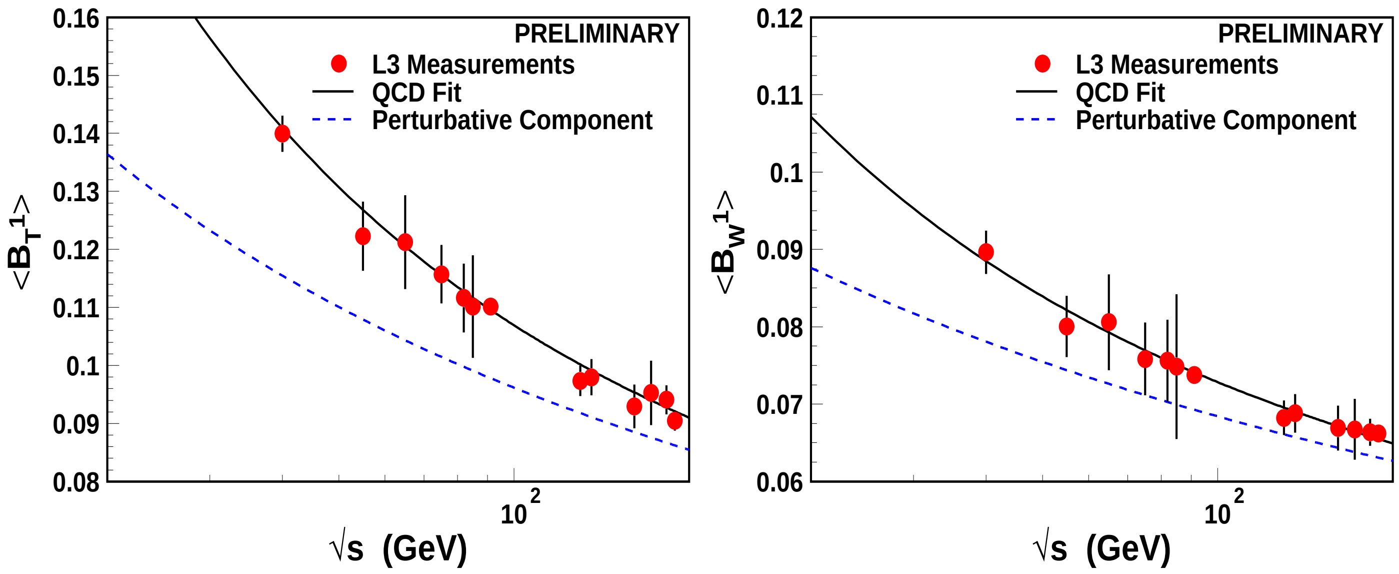




Power correction

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

$$\mathcal{P} * \delta_{\rm V} \left\{ \left(\alpha_{CMW}(\mathrm{Qe}^{-\frac{3}{4}}) \right)^{-\frac{1}{2}} + \mathrm{const_V} + \mathcal{O}(\sqrt{\alpha_s}) \right\}$$

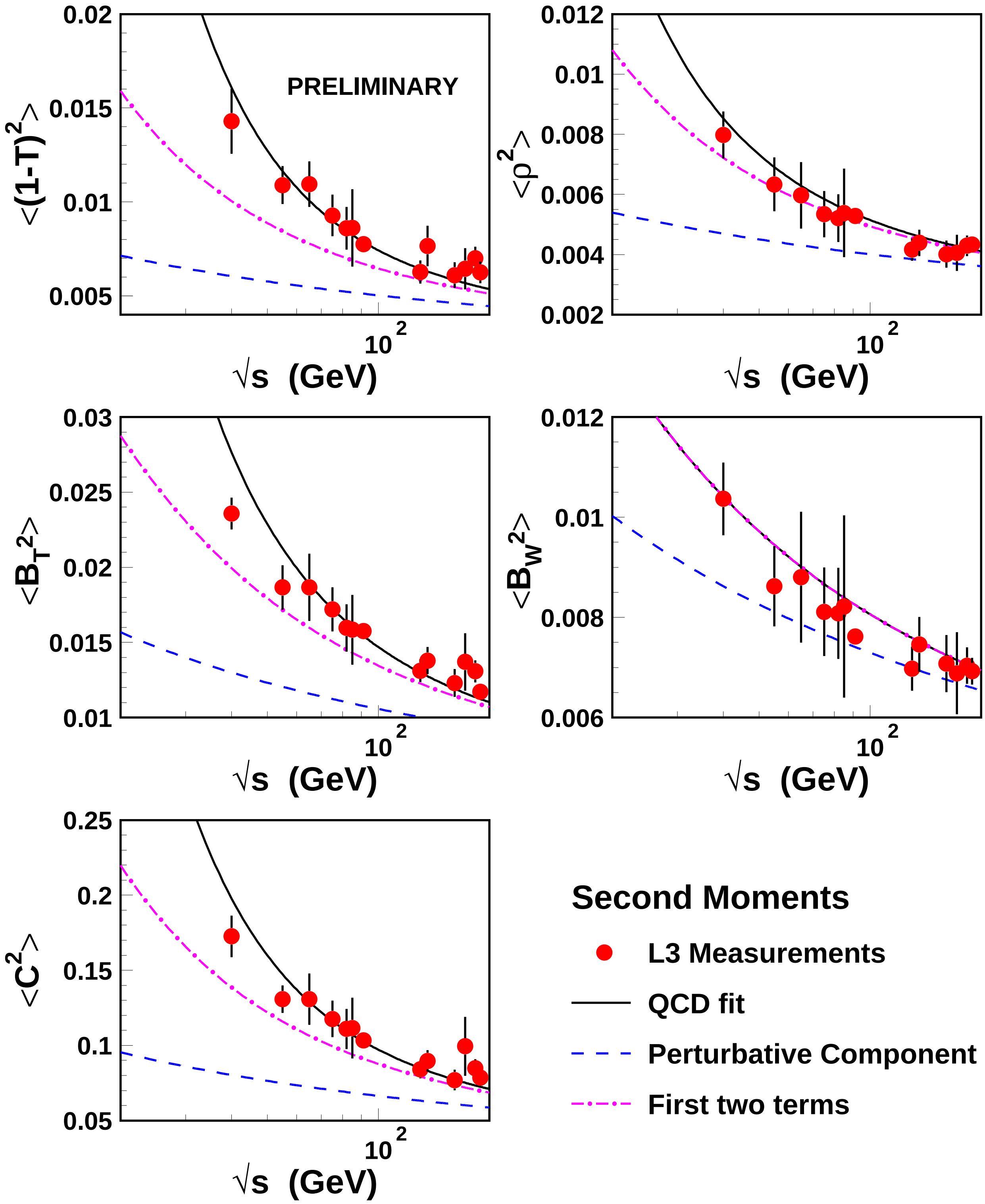


Model Independent α_s determination

Observable	α_0 (2 GeV)	$\alpha_s(\mathrm{M_Z})$	χ^2/d.o.f.
$\langle 1-T \rangle$	0.567 ± 0.054	0.1097 ± 0.0047	10.4/11
$\langle \rho_{\rm H} \rangle$	0.469 ± 0.041	0.1032 ± 0.0039	5.6/11
$\langle \mathrm{B_T} \rangle$	0.480 ± 0.034	0.1148 ± 0.0028	4.5/11
$\langle \mathrm{B_W} \rangle$	0.450 ± 0.069	0.1131 ± 0.0035	2.4/11
$\langle C \rangle$	0.482 ± 0.031	0.1120 ± 0.0033	6.2/11

Average: $\alpha_s(\mathrm{M_Z}) = 0.1106 \pm 0.0036 \pm 0.0040$

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



Summary

- Event Shape variables at L3 studied over a large energy range: 30 to 189 GeV
- Systematic errors taken to be correlated among the different energy points
- Good agreement seen between data and models with coherent parton shower tuned at $\sqrt{\mathrm{s}} = \mathrm{M_Z}$
- Jet Rates follow the expected QCD energy evolution
- Evidence of destructive interference from soft gluon emission between jets observed in charged particle inclusive momentum spectra
- Using $\mathcal{O}(\alpha_s{}^2)$+NLLA calculations:

$$\boxed{\alpha_s(\mathrm{M_Z}) = 0.1220 \pm 0.0015\ (\mathrm{exp}) \pm 0.0060\ (\mathrm{theo})}$$

Model independent α_s determination from 1^{st} moment

$$\boxed{\alpha_s(\mathrm{M_Z}) = 0.1106 \pm 0.0036\ (\mathrm{exp}) \pm 0.0040\ (\mathrm{theo})}$$

- Power law correction studies extended to 2^{nd} moment