QCD at LEP

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event shapes α_s power corrections

color reconnection in Z decays

Event shapes

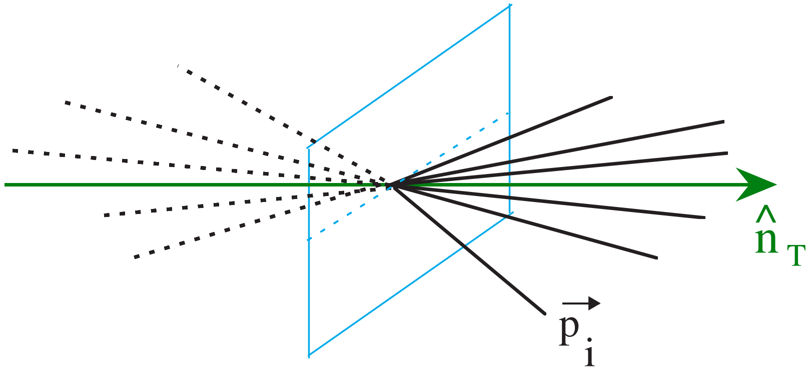
Event-shape variables are sensitive to rate of hard gluon emission and hence to α_s.

- Infrared safe
- Collinear safe
- insensitive to electroweak physics
- insensitive to non-perturbative effects (hadronization)

- 1 – Thrust:

$$1 - T = 1 - \max \frac{\sum |\vec{p} \cdot \vec{n}_T|}{\sum |\vec{p}|}$$

Divide event into hemispheres
by plane through origin $\perp \vec{n}_T$



Event shapes

hemispheres defined by $\vec{n}_\mathrm{T}$

- Scaled Heavy Jet Mass ρ:

$$M_\pm^2 = \left(\sum_{i \in \mathrm{hemi}\pm} p_i \right)^2$$
$$M_\mathrm{H} = \max\left(M_+, M_-\right)$$
$$\rho = M_\mathrm{H}/E_\mathrm{cms}$$

- Jet Broadening Variables:

$$B_\pm = \frac{\sum_{i \in \mathrm{hemi}\pm} |\vec{p}_i \times \vec{n}_\mathrm{T}|}{2 \sum_i |\vec{p}_i|}$$

Total Jet Broadening: $B_\mathrm{T} = B_+ + B_-$
Wide Jet Broadening: $B_\mathrm{W} = \max\left(B_+, B_-\right)$

- C-parameter, C: from eigenvalues, λ_i, of linearised momentum tensor, θ,

$$\theta_{ij} = \frac{\sum p_i p_j / |\vec{p}|}{\sum |\vec{p}|}, \quad i,j = 1,2,3$$
$$C = 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1)$$

- Jet resolution parameter, y_3: value of y_cut in $k_\perp$ algorithm at which event changes from 2-jet to 3-jet classification.

α_s from Event Shapes

The approach: For event shape variable y,

Experiment:

- Measure event shape distribution,

$$f(y) = \frac{1}{\sigma_{\text{tot}}} \frac{\mathrm{d}\sigma}{\mathrm{d}y}$$

- Correct for
  detector acceptance/resolution,
  background, ISR, ...

Theory:

- Calculate perturbative prediction of $f(y)$ at parton level

- Correct for hadronization using parton shower MC (JETSET, HERWIG, ARIADNE)

Compare:

- Fit corrected theory to corrected data $\longrightarrow \alpha_s$
- Determine experimental uncertainties
- Determine theoretical uncertainties

α_s from Event Shapes – Theory M.E.

To $\mathcal{O}(\alpha_s^2)$, (cumulative) dist. of shape variable y is given by

$$f_{\text{pert}}(\alpha_s, y) \equiv \frac{1}{\sigma_{\text{tot}}}\frac{d\sigma}{dy} = \frac{\alpha_s}{2\pi}A(y) + \left(\frac{\alpha_s}{2\pi}\right)^2 \left[B(y) + 2\pi\beta_0 \ln\left(\frac{\mu^2}{s}\right) A(y)\right]$$

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

where $\beta_0 = \frac{33-2n_f}{12\pi}$ and $\mu = x_\mu\sqrt{s}$ = renormalization scale, $x_\mu \approx 1$

$A(y)$, $B(y)$ computed by integrating ERT matrix elements.

Describes data well in multi-jet region,
but not in 2-jet (small y) region where softer gluons are important

α_s from Event Shapes – Theory NLLA

Leading and Next-to-Leading logs in perturbative expansion of $R(\alpha_s, y)$ summed to all orders of α_s.

$$\text{LL}: \qquad L\sum(\alpha_s L)^n \quad , \qquad L \equiv \ln\frac{1}{y}$$

$$\text{NLL}: \qquad \sum(\alpha_s L)^n$$

Most important in 2-jet region (small y), where L is large

NLLA calculations are available for $y = 1-T$, ρ, B_T, B_W, $C/6$, y_3

$\mathcal{O}(\alpha_s^2)$ M.E. and Resummed calculations can be combined, enabling larger fit range
Must avoid double counting ⇒ Matching Schemes: R or Log R
– some theoretical uncertainty in this

Modified Schemes include kinematic constraints: $\quad R|_{y=y_{max}} = 1, \quad \left.\frac{\mathrm{d}R}{\mathrm{d}y}\right|_{y=y_{max}} = 0$

for Log R: $\quad L \longrightarrow L' = \frac{1}{p}\ln\left[\left(\frac{1}{x_L y}\right)^p - \left(\frac{1}{x_L y_{max}}\right)^p + 1\right]$ with $x_L \approx 1$, $p \geq 1$

LEP QCD Working Group: α_s

- Combine α_s measurements by the 4 LEP experiments using Event Shapes – $\mathcal{O}(\alpha_s^2)$ M.E. + NLLA

- Particularly useful at LEP II where statistics is poor but theory uncertainties smaller

- common theory implementation: matching scheme
  modification for kinematic limits
  choice is: modified log R scheme with $x_\mu = x_\mathsf{L} = p = 1$

- consistent treatment of experimental systematic uncertainties

- consistent treatment of theoretical systematic uncertainties

All 4 experiments have recently released preliminary measurements.

α_s from Event Shapes – $\mathcal{O}(\alpha_s^2)$ M.E. + NLLA

Data samples:

- LEP I radiative events (L3, OPAL),
  $20 \lesssim \sqrt{s} \lesssim 85$ GeV
  OPAL not (yet) in combination
- LEP I, $\sqrt{s} \approx M_Z$
- LEP II, $133 \leq \sqrt{s} \leq 206$ GeV

Typical LEP II sample sizes (per experiment)
efficiency $\approx$ 80–90%   purity $\approx$ 80 %

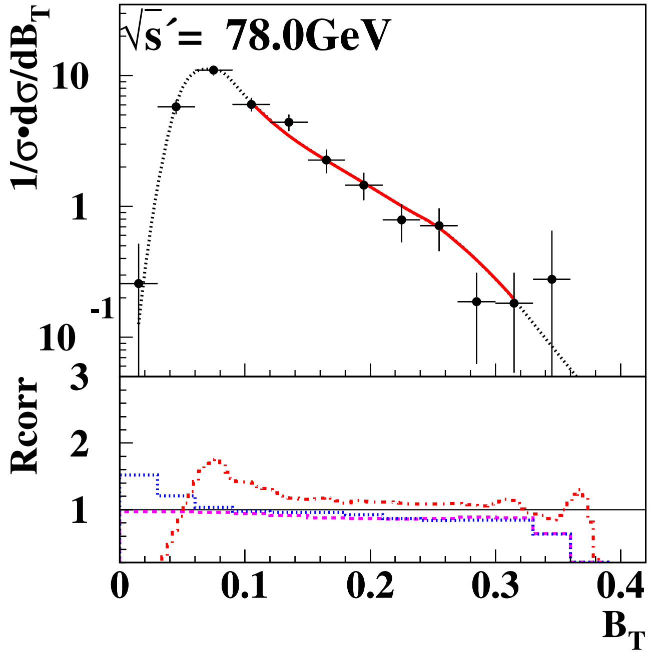
$\sqrt{s}$ (GeV)	Integrated Luminosity (pb^{-1})	Selected events
130.1	6.1	556
136.1	5.9	414
161.3	10.8	424
172.3	10.2	325
182.8	55.3	1500
188.6	176.8	4479
194.4	112.2	2403
200.2	117.0	2456
206.2	207.6	4146

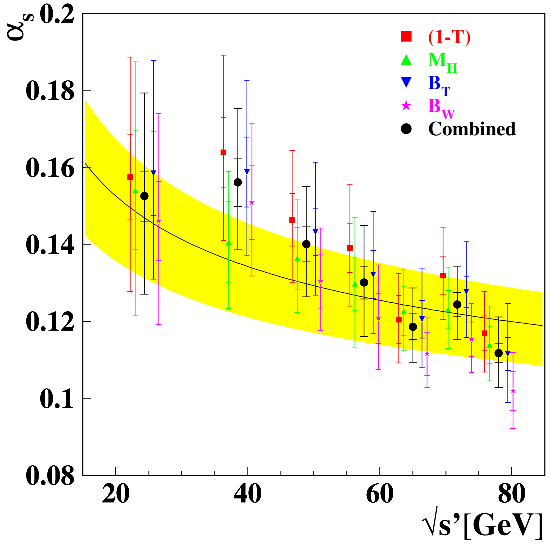
LEP I radiative events new preliminary OPAL results

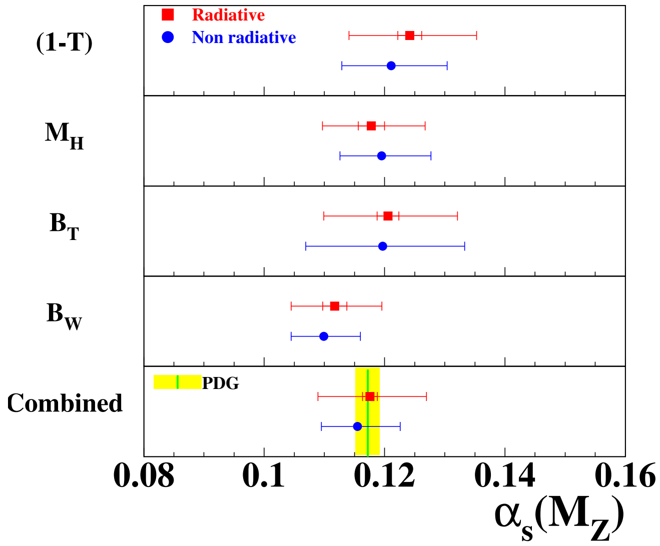
- From $\sqrt{s} = M_Z$ hadronic events,
  select those with at least 1 high-energy isolated photon candidate.

- Reject the photon, leaving hadronic system with $\sqrt{s'} = \sqrt{s}\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$

- background of π^0 misidentified as γ is about 7–16% for $E_\gamma = 10$–$45\,\mathrm{GeV}$.



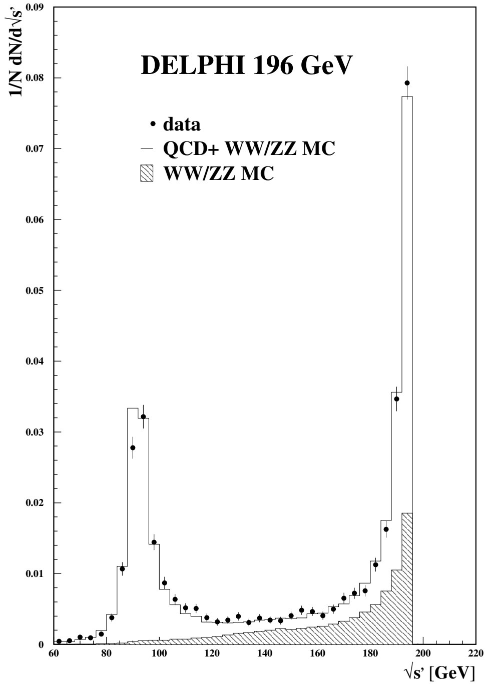




$\alpha_s(M_Z)$ of radiative/non-radiative events consistent

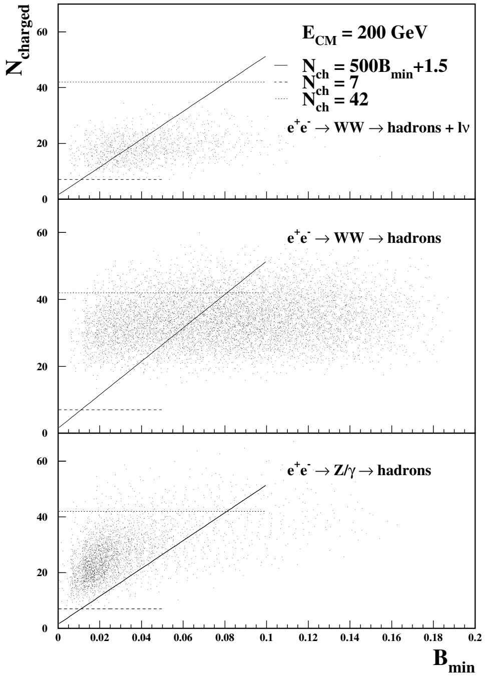
LEP II

Large backgrounds:
Radiative return to Z



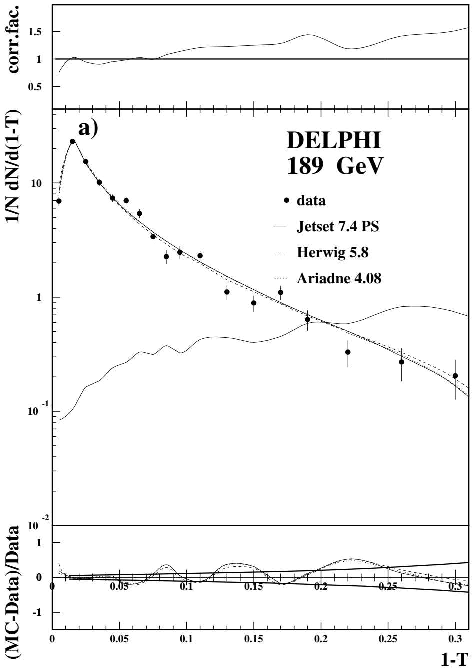
Cut on $\sqrt{s'}$

Four-fermion,
especially WW



Cut on N_{ch},
narrow jet broadening

Effect on $1 - T$

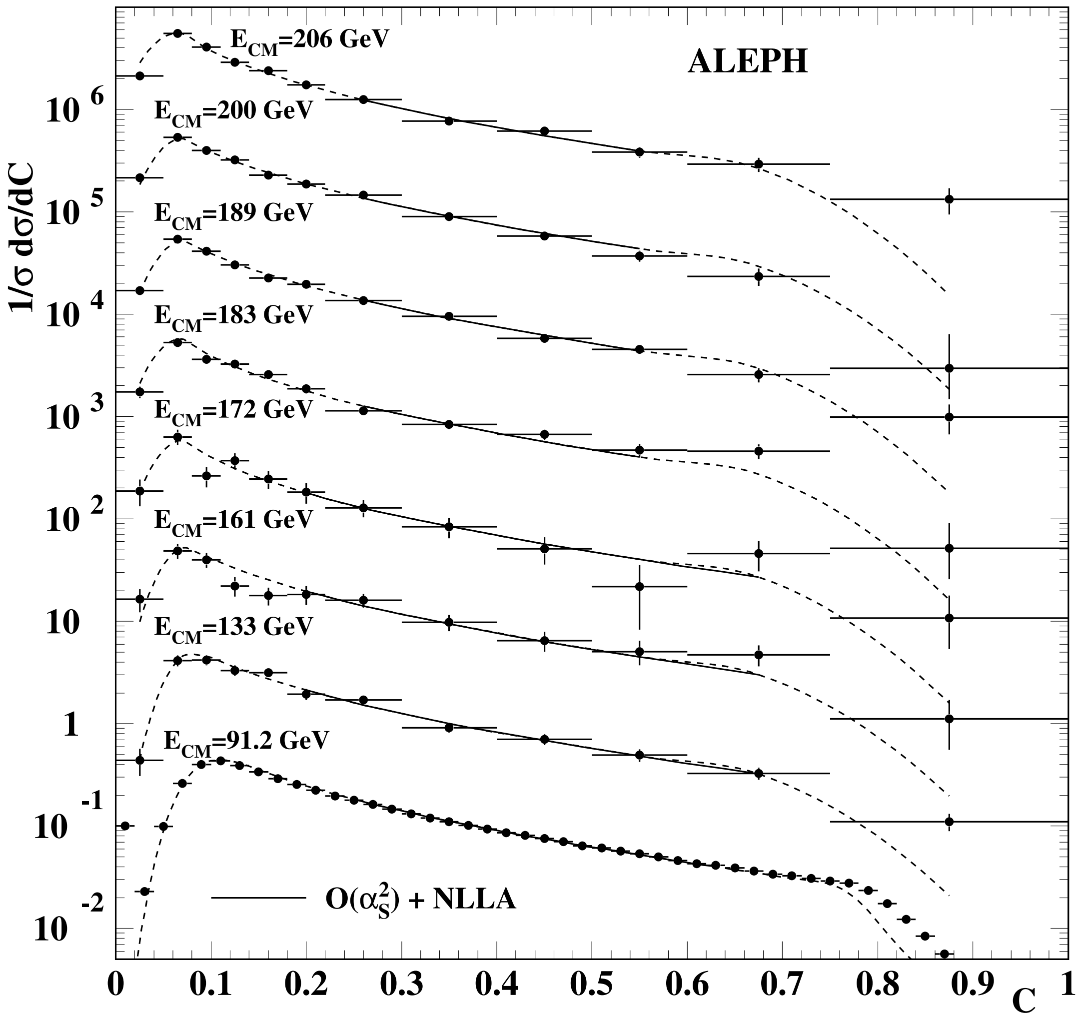


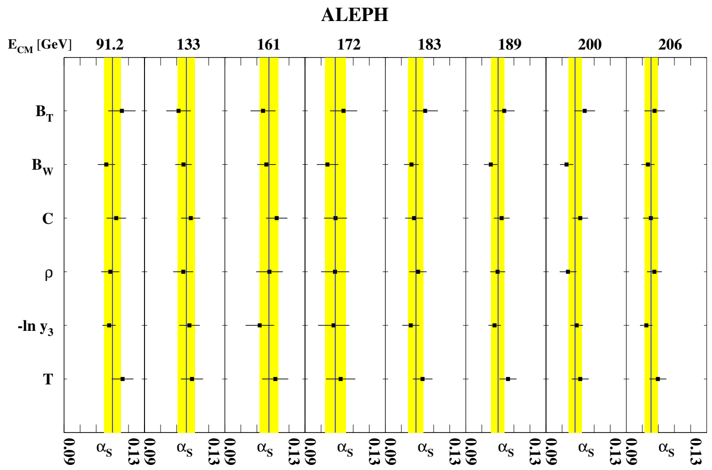
acceptance
correction

← subtracted
4-fermion
background

MC/data
comparison

LEP I, II – preliminary

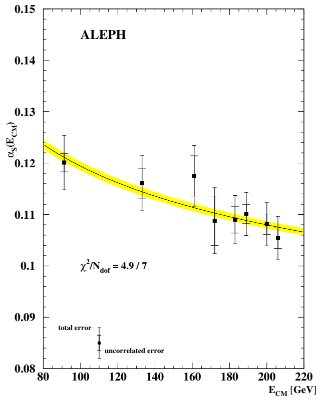




consistent α_s values
from different variables

Running

as
expected:



LEP QCD Working Group α_s combination – preliminary

At present 6 shape variables at 14 energies $\rightarrow$ 194 measurements of α_s

Convert α_s values to $\alpha_s(M_Z)$ – Renormalization Group Equation at 3 loops

Covariance matrix (194×194): $V_{ij} = V_{ij}^{\text{stat}} + V_{ij}^{\text{exp}} + V_{ij}^{\text{had}} + V_{ij}^{\text{theo}}$

V_{ij}^{stat} uncorrelated between expts., energies;
correlation between variables for same expt. and energy are calculated from MC

V_{ij}^{exp} uncorrelated between expts.; correlation between variables/energies from
'minimal overlap': $V_{ij}^{\text{exp}} = \min\left(V_{ii}^{\text{exp}}, V_{jj}^{\text{exp}}\right)$

V_{ij}^{had} correlation between experiments should be small (different generator tunings)
– correlations assumed zero – diagonal elements from
rms of PYTHIA, HERWIG, ARIADNE smoothed by fitting to $a/\sqrt{s} + b$

V_{ij}^{theo} certainly highly correlated, but difficult to assess – correlations assumed zero
diagonal elements from variation of x_μ, x_L, p, different matching scheme

If correlations not assumed zero, fits are very unstable
– problem is that these correlations are poorly known

LEP QCD Working Group α_s combination – preliminary

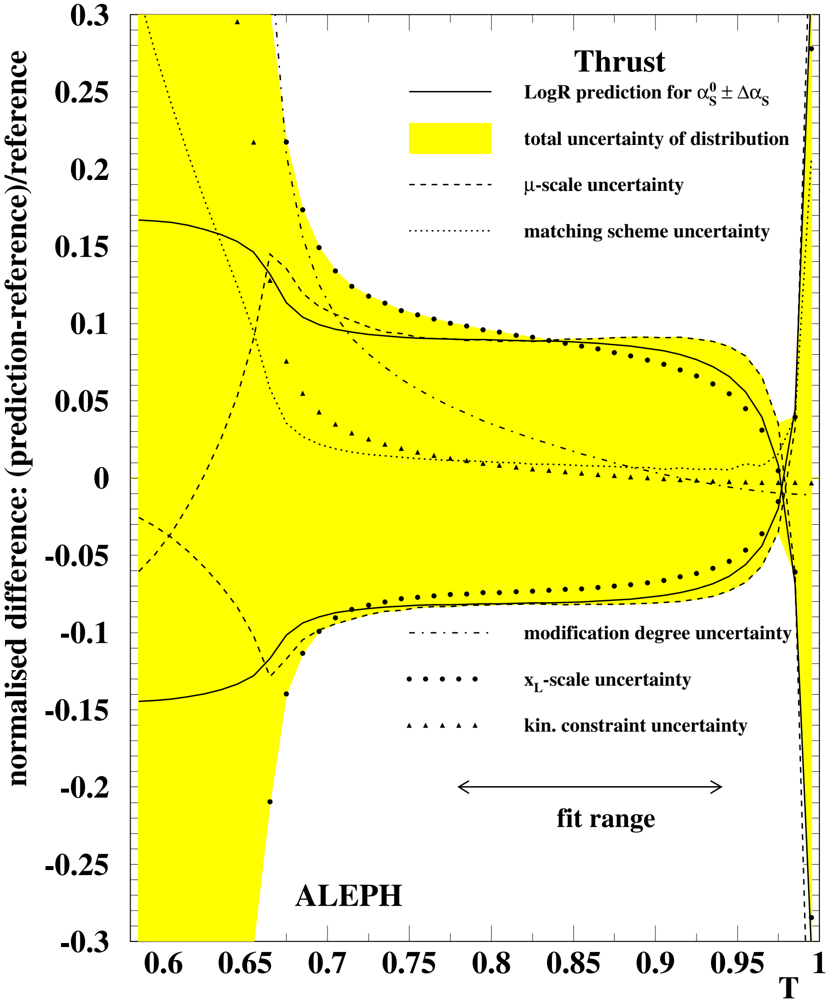
V_{ii}^{theo} diagonal elements:

1. Choose value of α_s

2. Calculate shape variable dist.
   in 'reference theory'
   (mod. log R, $x_\mu = x_L = p = 1$)

3. Vary matching scheme, x_μ, x_L, p
   and plot difference in predictions with
   reference theory $\longrightarrow \longrightarrow \Longrightarrow \Longrightarrow$

4. vary α_s in reference theory to find values giving prediction equal to largest/smallest prediction (3)
   in range of variable used in fit.
   These values are $\alpha_s \pm \sigma_{\pm}^{\text{theo}}$



LEP QCD Working Group α_s combination – preliminary

Find $\alpha_s(M_Z)$ by minimizing $\chi^2(\alpha_s) = \sum_{ij} \left(\alpha_s^i - \alpha_s\right) \left(V^{-1}\right)_{ij} \left(\alpha_s^j - \alpha_s\right)$

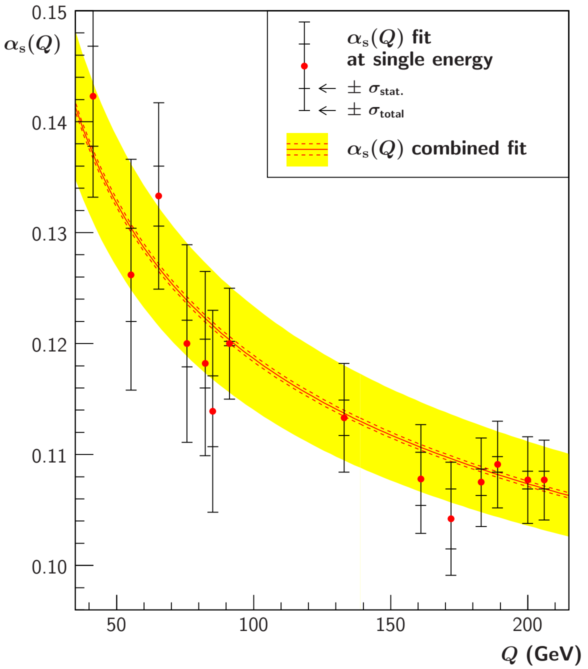
Value of α_s very robust to changes in procedure

But assumptions on correlations make hadronization and theory uncertaintites from χ^2 invalid.

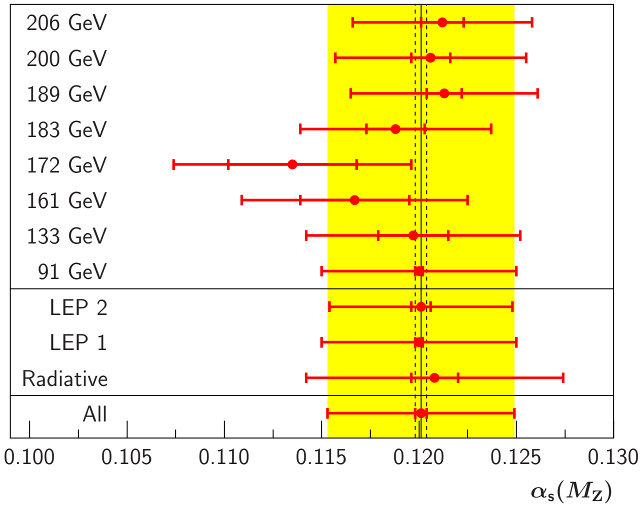
Hadronization: Combine 3 times using corrections from
PYTHIA, HERWIG, ARIADNE
Take α_s from PYTHIA; hadronization uncertainty as RMS.

Theory: Combine using $\alpha_{si} + \sigma_{ii}^{\text{theo}}$ values, $\alpha_{si} - \sigma_{ii}^{\text{theo}}$ values.
Take theory uncertainty as half the difference.

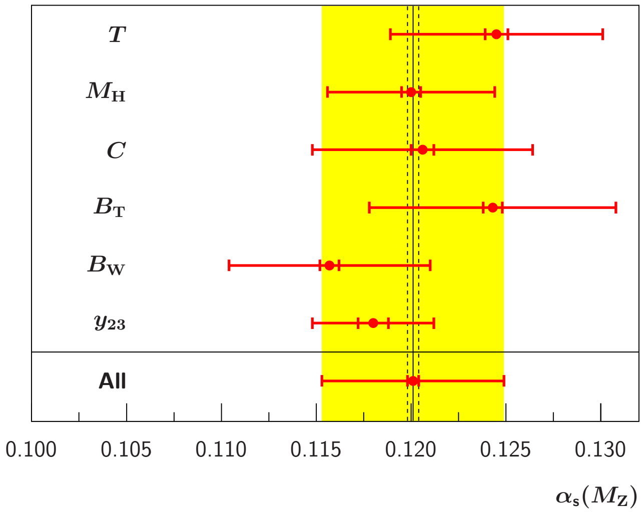
LEP QCD Working Group α_s combination – preliminary



Different energies are consistent



Different variables are consistent



LEP I:

$$\alpha_s(M_Z) = 0.1200 \pm 0.0002\ (\text{stat}) \pm 0.0008\ (\text{exp}) \pm 0.0010\ (\text{had}) \pm 0.0048\ (\text{theo})$$

LEP II:

$$\alpha_s(M_Z) = 0.1201 \pm 0.0005\ (\text{stat}) \pm 0.0010\ (\text{exp}) \pm 0.0007\ (\text{had}) \pm 0.0045\ (\text{theo})$$

LEP I radiative (L3) + LEP I + LEP II:

$$\alpha_s(M_Z) = 0.1201 \pm 0.0003\ (\text{stat}) \pm 0.0009\ (\text{exp}) \pm 0.0009\ (\text{had}) \pm 0.0047\ (\text{theo})$$

Power Corrections

Instead of hadronization corrections of shape variable distributions by MC model, could use power corrections

Parametrize unknown behavior of α_s below a IR matching scale, μ_I,
by average: $\alpha_0 = \frac{1}{\mu_\mathrm{I}} \int_0^{\mu_\mathrm{I}} \alpha_\mathrm{s}(k)\,\mathrm{d}k$ (Dokshitzer, Webber)

Leads to a power term, $P \propto 1/\sqrt{s}$ which

– shifts distributions:

$$f(y) = f_\mathrm{pert}(y - c_y P)$$

– increases moments:

$$\langle y \rangle = \langle y \rangle_\mathrm{pert} + c_y P$$

$$\langle y^2 \rangle = \langle y^2 \rangle_\mathrm{pert} + 2\langle y \rangle_\mathrm{pert}\, c_y P + \mathcal{O}\left(\frac{1}{s}\right)$$

where $\langle y^n \rangle_\mathrm{pert} = \int y^n\, f_\mathrm{pert}(\alpha_\mathrm{s}, y)\ \mathrm{d}y$

c_y is a known factor different for each shape variable – for B_T, B_W depends on α_s
P is supposed to be universal

Power Corrections

$$P = \frac{4C_\mathsf{F}}{\pi^2}\mathcal{M}\frac{\mu_\mathsf{I}}{\sqrt{s}}\left[\alpha_0(\mu_\mathsf{I}^2) - \alpha_\mathsf{s}(\mu^2) - \frac{\beta_0}{2\pi}\alpha_\mathsf{s}^2(\mu^2)\left(\ln\frac{\mu}{\mu_\mathsf{I}} + \frac{K}{\beta_0} + 1\right)\right]$$

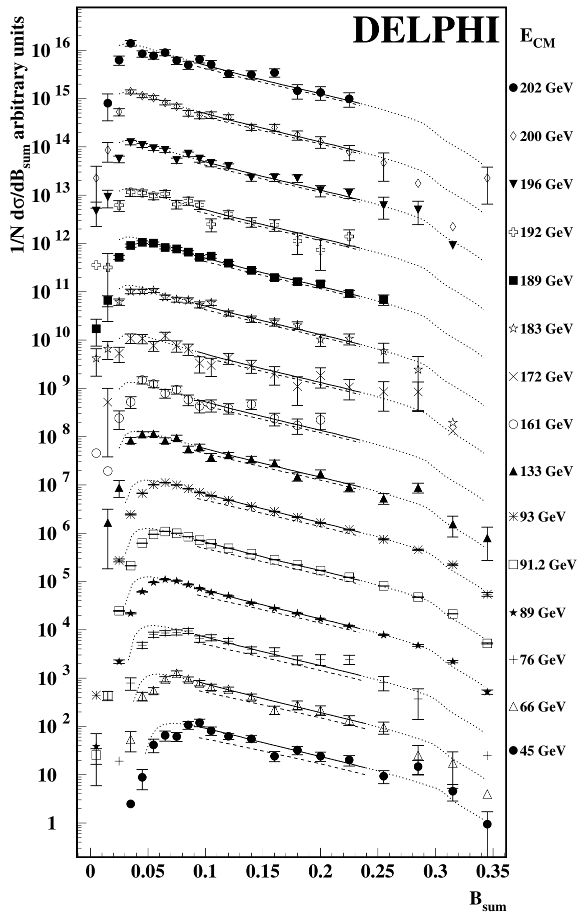
where $K = \left(\frac{67}{18} - \frac{\pi^2}{6}\right) C_\mathsf{A} - \frac{5}{9} n_\mathsf{f}$

P contains 3 new quantities – same for all y

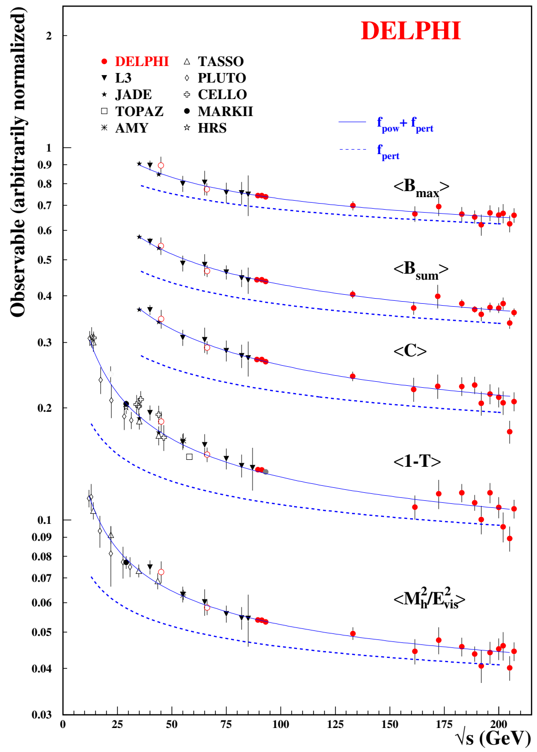
1. $\mathcal{M}$ – the 'Milan' factor – accounts for two-loop effects
   $\mathcal{M} = 1.49$ for all y (3 active flavors in non-pert. region) (Dokshitzer *et al.*)
2. μ_I – infra-red matching scale ≈ 2 GeV
3. $\alpha_0(\mu_\mathsf{I}^2) = \frac{1}{\mu_\mathsf{I}}\int_0^{\mu_\mathsf{I}} \alpha_\mathsf{s}(k)\,\mathrm{d}k$ – contribution from below μ_I

α_s from shape variables, power corrections

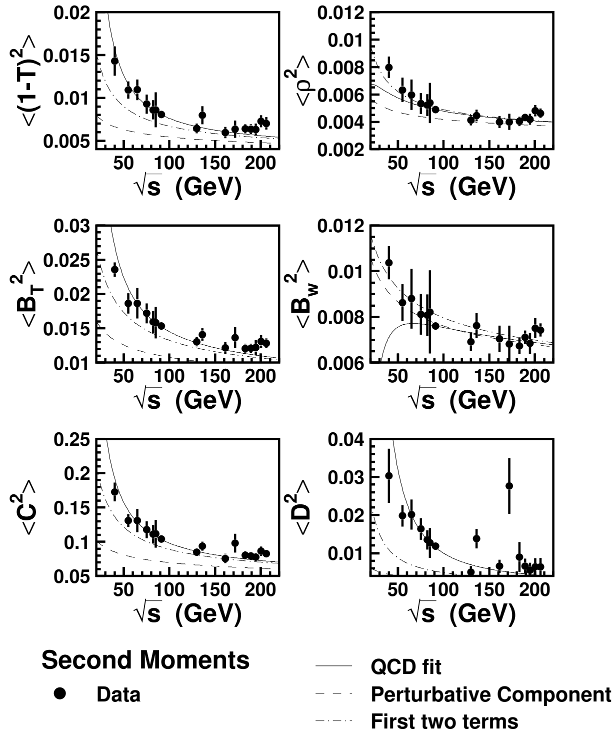
fit $f(y)$



fit $\langle y \rangle$ $vs.$ $\sqrt{s}$



L3 fit $\langle y^2 \rangle$ $vs.$ $\sqrt{s}$



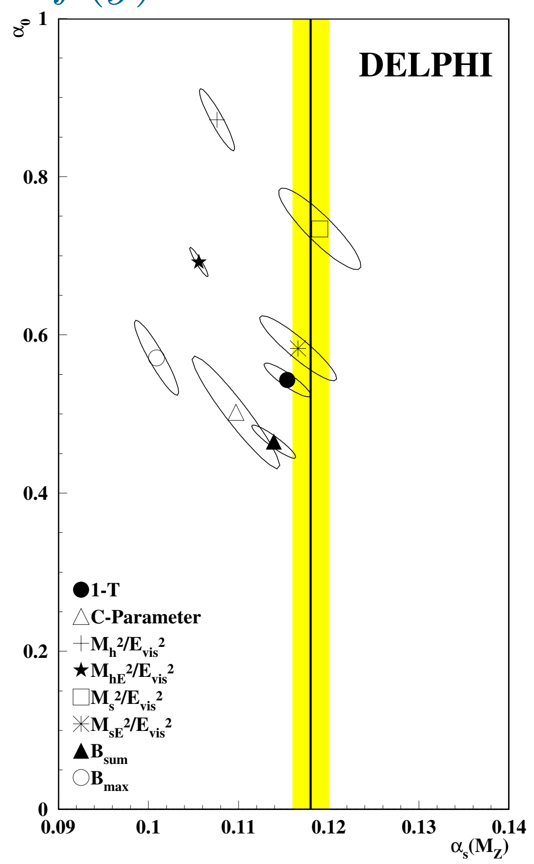
$\alpha_0(\mu_I^2)$, α_s fixed to results of $\langle y \rangle$ fit

$\mathcal{O}\left(\frac{1}{s}\right)$ term in $\langle y^2 \rangle$ replaced by parameter, A_y

α_s from shape variables, power corrections

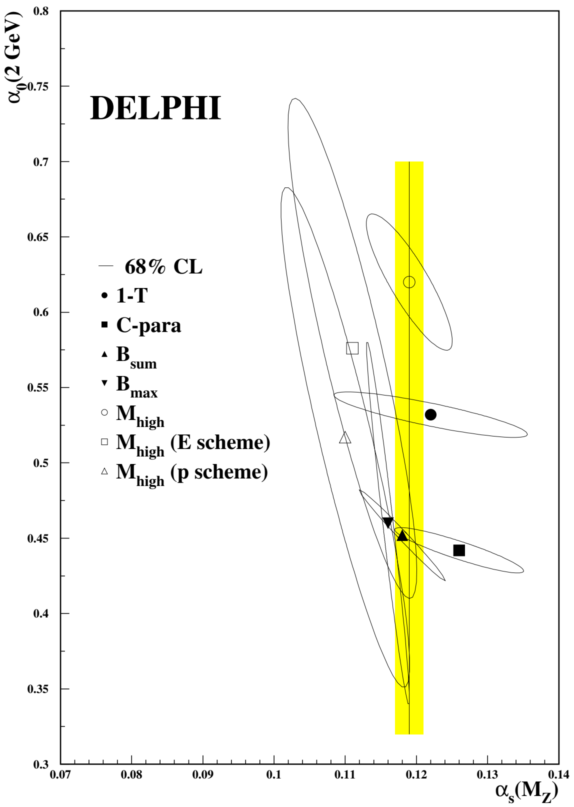
$\Leftarrow$ ellipses $=$ stat. $+$ syst. errors

fit $f(y)$



$\alpha_s(M_Z)$ values LOW

fit $\langle y \rangle$ *vs.* $\sqrt{s}$



$$\alpha_s(M_Z) = 0.1207 \pm 0.0048 \pm 0.0026$$

α_0, and hence P, not universal

L3 fit $\langle y^2 \rangle$ *vs.* $\sqrt{s}$

$\mathcal{O}\left(\frac{1}{s}\right)$ term in $\langle y^2 \rangle$ replaced by parameter A_y

A_y is very different for different y:

$$A_{B_T} = +15.0 \pm 0.5$$
$$A_{B_W} = -10.1 \pm 0.3$$

in L3 $\langle y \rangle$ fits:

$\alpha_0 \approx 0.32 – 0.64$

Rapidity Gaps (or Color Reconnection) – the L3 way

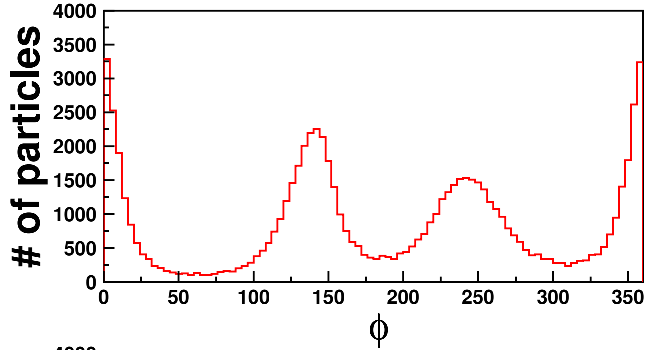
Rapidity gaps, as well as
Various models of Color Reconnection - ARIADNE, HERWIG, GAL (Rathsman) -
alter the color flow from that normally expected in 3-jet Z decays.

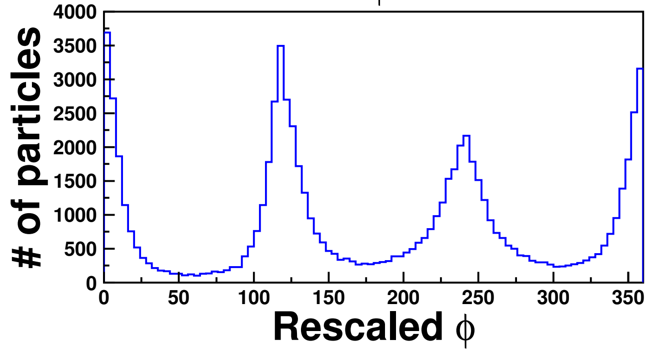
OPAL, ALEPH look at rapidity gaps in the gluon jet — Bill Gary's talk

L3 looks at particle flow in "Mercedes" events,

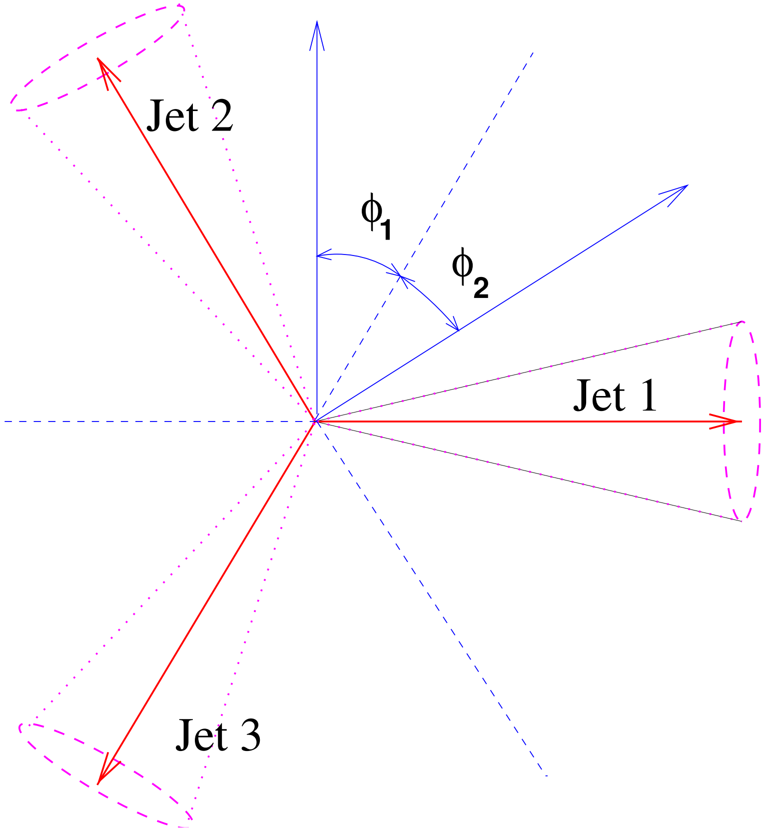
JADE, $y_{\text{cut}} = 0.05$, and inter-jet angles $= 120 \pm 30$ deg
$\longrightarrow$ 70k events

Order the jets by energy, $E_1 > E_2 > E_3$
Require b-tag for jets 1, 2 and anti-b-tag for jet 3
2668 events, gluon purity of jet 3 $= 78\%$





Sensitive Variables



Define a $\pm 15^\circ$ cone about each jet

Min. angle from bisector in Region ij,

$$B_{ij} = \min(\phi_1, \phi_2, \phi_3, \ldots)$$

Angular Asymmetry in Region 12:

$$A_{12}^{\mathsf{B}} = \frac{-B_{12} + B_{23} + B_{31}}{B_{12} + B_{23} + B_{31}}$$

Similarly, A_{23}^{B}, A_{13}^{B},

Alternative Angle definition for Region ij,

Max. angular separation between adjacent particles, S_{ij}

with asymmetries A_{12}^{S}, A_{23}^{S}, A_{13}^{S}

Assuming jet 3 is g, $A_{\mathsf{q\bar{q}}} = A_{12}$ $A_{\mathsf{qg}} = \frac{1}{2}(A_{13} + A_{23})$

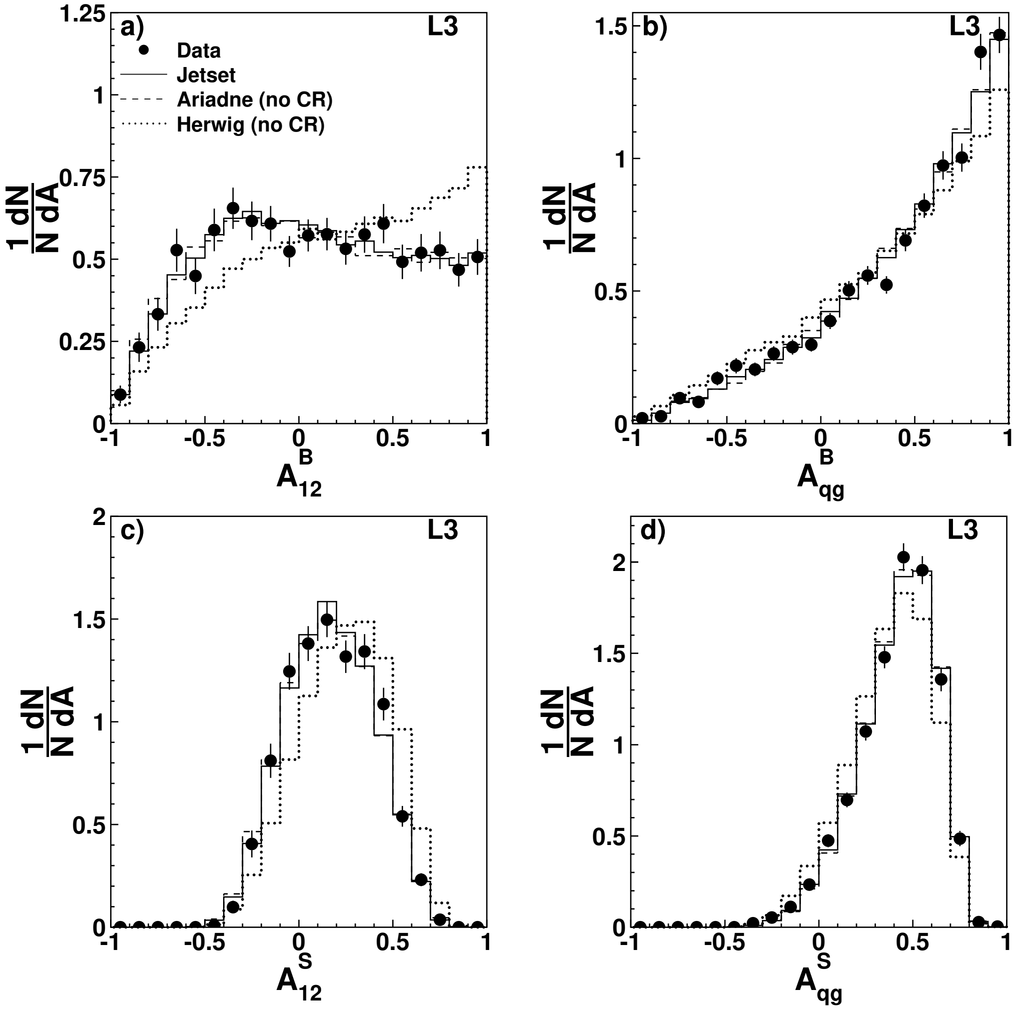
Sensitive Variables

In region of color flow,

- More particles (N)
- Smaller angular separation (B_{ij}, S_{ij})

So, altering the color flow should change the asymmetries

Comparison with Models



Models with no Color Reconnection

JETSET	agrees well
ARIADNE	agrees well
HERWIG	??

Comparison with Models

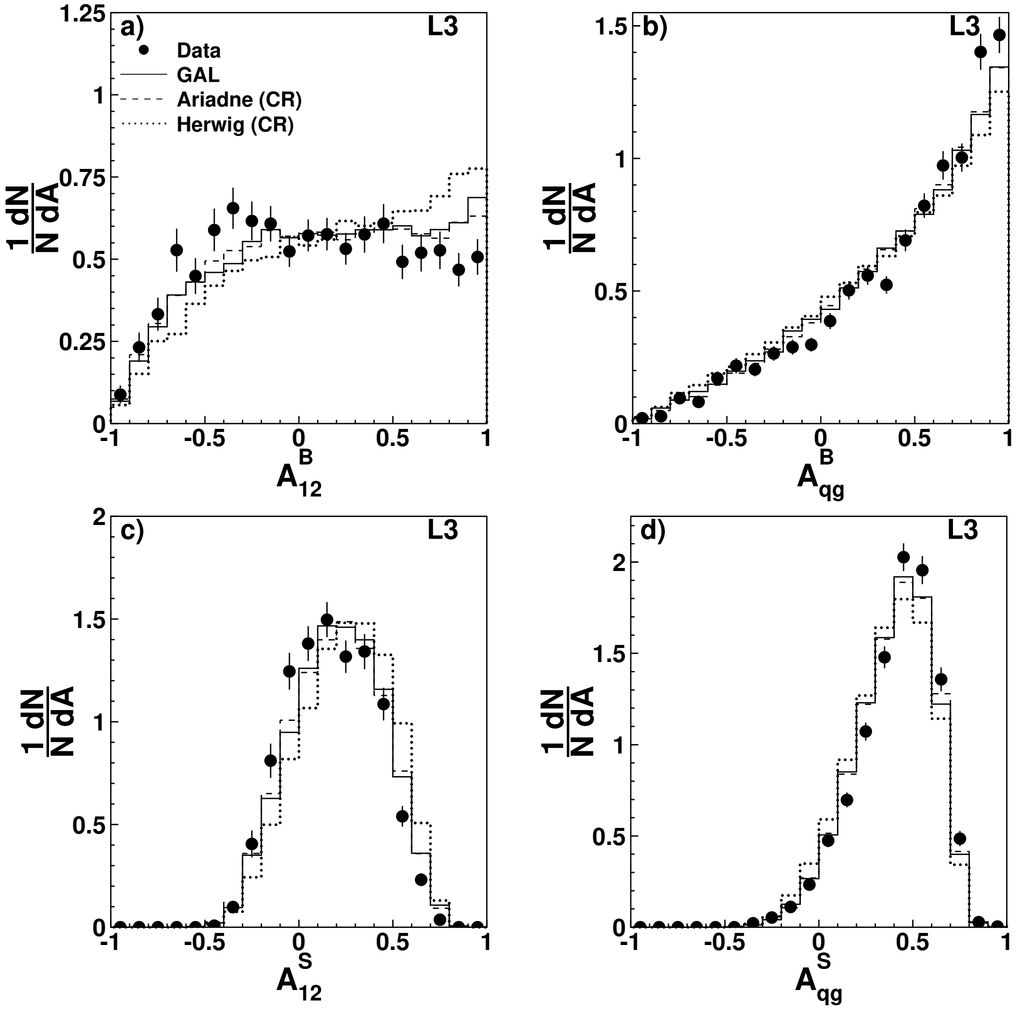
Models with Color Reconnection

In all cases, fragmentation parameters are retuned on Z shape variables

GAL	$R_0 = 0.1$	poor
ARIADNE-I	$E_{\text{gluon}}^{\text{min}} = 0\,\text{GeV}$	poor
HERWIG	Prob(CR) $= 1/9$	bad

Attempt to fit parameter R_0 in GAL (Rathsman) model:

$R < 0.025$ at 95% CL



Conclusions - Color Reconnection

CL:

Variable	No CR			CR		
	JETSET	ARIADNE	HERWIG	GAL	ARIADNE	HERWIG
A^{B}_{12}	0.99	0.94	10^{-8}	0.05	0.30	10^{-10}
$A^{\mathrm{B}}_{\mathrm{qg}}$	0.53	0.09	10^{-9}	10^{-4}	0.01	10^{-9}
A^{S}_{12}	0.95	0.80	10^{-23}	10^{-8}	10^{-6}	10^{-30}
$A^{\mathrm{S}}_{\mathrm{qg}}$	0.89	0.79	10^{-8}	0.03	0.09	10^{-11}

- With default CR parameters, GAL and ARIADNE do not describe the data.
- HERWIG with or without CR does not describe the data.

Summary

- New measurements of α_s

- α_s measurements from 4 LEP experiments treated consistently,,
  using $\mathcal{O}(\alpha_s^2)$ M.E. + NLLA resummed logs,
  are consistent for different shape variables and different energies
  $\alpha_s(M_Z) = 0.1201 \pm 0.0003$ (stat) ± 0.0009 (exp) ± 0.0009 (had) ± 0.0047 (theo)

- Power corrections are applied to shape distributions and their moments $\langle y \rangle$, $\langle y^2 \rangle$
  Unfortunately, α_0 is not universal, and α_s values obtained are inconsistent

- Color Reconnection models applicable to Z decay disagree with data