united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR.1317 - 5

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

STANDARD MODEL AND HIGGS PHYSICS

Lecture III

J. ELLIS
CERN, Geneva, SWITZERLAND

Please note: These are preliminary notes intended for internal distribution only.

3 – W physics

3.1 – Cross section for $e^+e^- \to W^+W^-$

3.2 – Methods to measure m_W

3.3 – Electroweak gauge boson couplings

3.4 – QCD tests

Cross Section for $e^+e^- \to W^+W^-$

W^+W^- must be considered together with (indistinguishable) 4-fermion final states

(distinction not gauge invariant, ...)

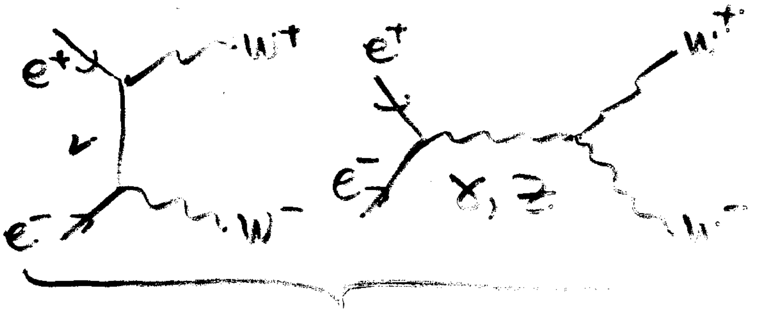
$$\sigma = \sigma_{WW} + \sigma_{bkd}$$

where $\sigma_{WW} = \sigma_0^{WW}(1 + \delta_{EW} + \delta_{QCD})$

(not all $O(\alpha)$ corrections to σ_{bkd} known)

and σ_0^{WW} is Born cross section due to 3 "classic" diagrams for off-shell $W^\pm$

(finite width!)



"CC3"

$$\sigma_0(s) = \int_0^s ds_1 \int_0^{(\sqrt{s}-\sqrt{s_1})^2} ds_2\, \rho(s_1)\rho(s_2)\sigma_0(s, s_1, s_2)$$

where
$$\rho(s) = \frac{1}{\pi}\frac{\Gamma_W}{M_W}\frac{s}{(s-M_W^2)^2 + s^2\Gamma_W^2/M_W^2}$$
Breit-Wigner

conventionally: s-dependent width $\Gamma_W(s) = \frac{s\Gamma_W}{M_W^2}$

and δ_{EW} electroweak corrections

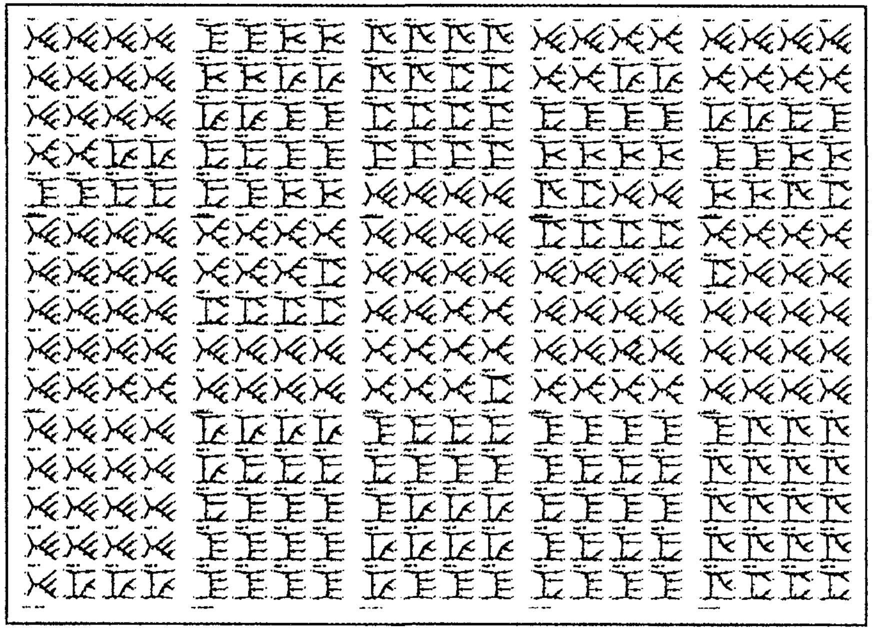
δ_{QCD} QCD

Four-fermion final states

Conceptually simple:

$$\boxed{e^+e^- \rightarrow ffff}$$

In practice:



$\times\ 10 = 3000$ diagrams

On-shell Cross Section

to be integrated with Breit-Wigner weight

$$\sigma^{on} = \sigma_0(s, m_W^2, m_W^2)$$

obtained from Born matrix elements

$$\mathcal{M}_B = \underbrace{\frac{e^2}{2s_W^2}\frac{1}{t}\mathcal{M}_1\delta_L}_{\nu\ \text{exchange}} + e^2 \underbrace{\left(\frac{1}{s} - \frac{c_W}{s_W} g_{eeZ}\frac{1}{s-m_Z^2}\right)}_{\gamma,\, Z} 2\underbrace{(\mathcal{M}_3 - \mathcal{M}_1}_{\text{fermion traces}}$$

where $\delta_L = 1$ for e_L , 0 for e_R

$$g_{eeZ} = \frac{s_W}{c_W} - \delta_L\frac{1}{2s_Wc_W}$$

dominated close to threshold by ν exchange

$$\mathcal{M}_1 \sim 1 \quad , \quad \mathcal{M}_{2,3} \sim \beta$$

$$\frac{d\sigma^{on}}{d\Omega} \simeq \frac{\alpha^2}{s}\frac{1}{4s_W^4}\beta\left[1 + 4\beta\cos\theta\frac{3c_W^2-1}{4c_W^2-1} + O(\beta^2)\right]$$

$$\sigma^{on} \simeq \frac{\pi\alpha^2}{s}\frac{1}{4s_W^4}4\beta + O(\beta^3)$$

- sharp threshold rise
- not very sensitive to triple-gauge couplings

Electroweak Corrections

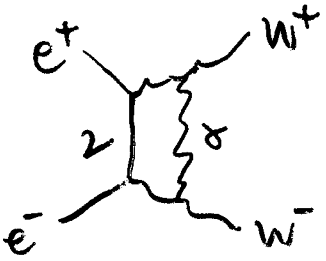
known completely for on-shell $W^\pm$

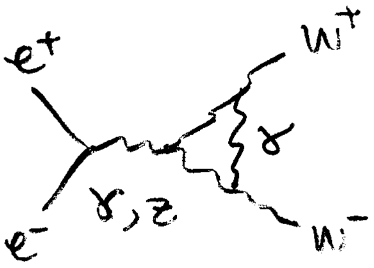
leading contributions known

$$\sim \ln(s/m_e^2),\ \sqrt{m_W/\Gamma_W},\ m_t^2/m_W^2, \ldots$$

assume residual error $\delta_{th}\sigma/\sigma \lesssim 2\%$

Coulomb corrections





usual result for stable particles (on-shell $W^\pm$) : $\sim \frac{\alpha\pi}{v_0}$: $v_0 = 2\sqrt{1-\frac{4m_W^2}{s}}$

$\uparrow$ velocity

blows up at threshold : BUT cut off by finite lifetime of $W^\pm$: $\frac{\alpha\pi}{v_0} \rightarrow \alpha\pi\sqrt{\frac{m_W}{\Gamma_W}}$

net correction : $+6\%$ in threshold region

corresponds to shift $\delta m_W \sim 100$ MeV

will not discuss here

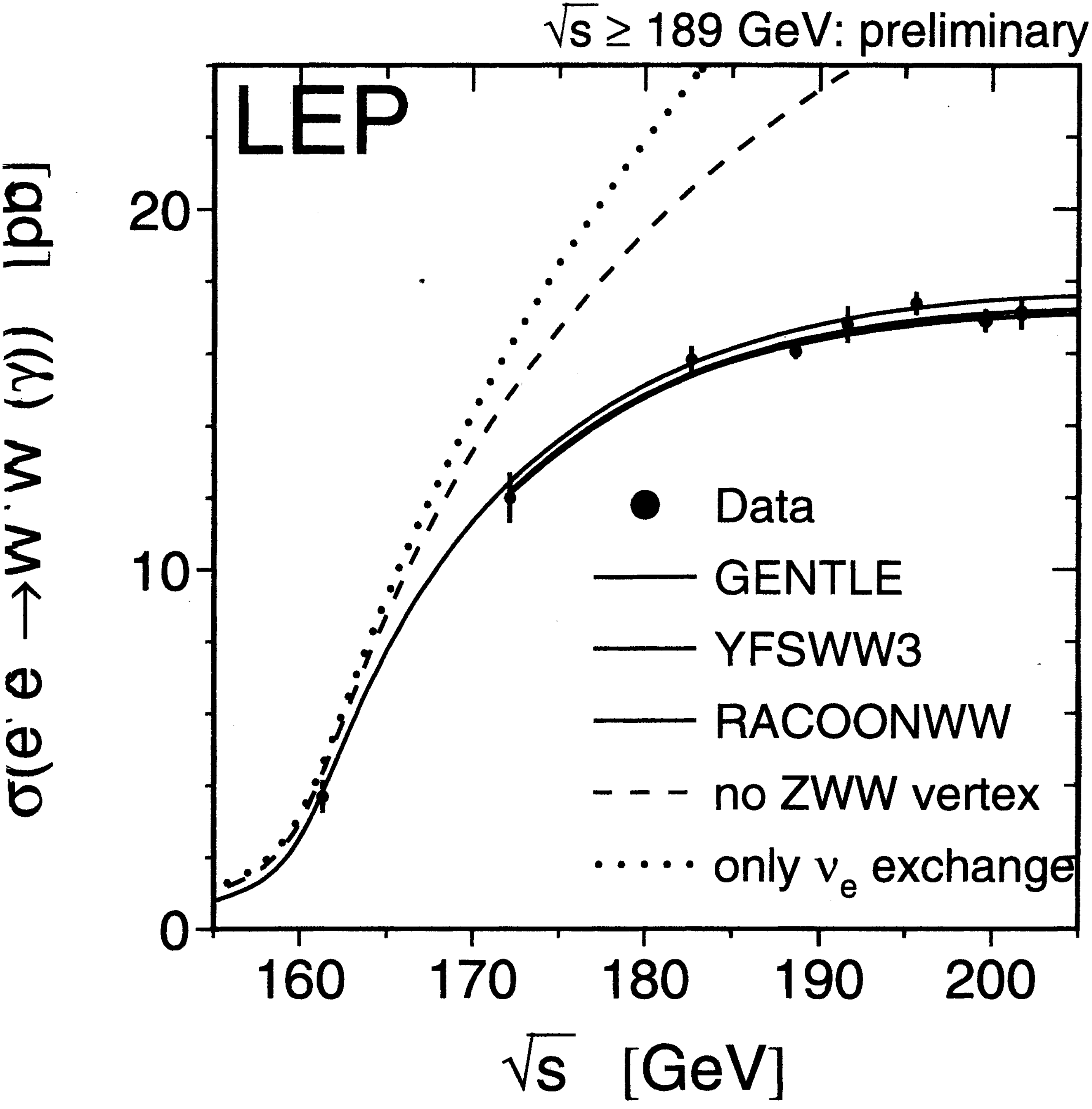
Initial-State radiation, improved Born approximation

CC11 vs CC3, ...

WW Production Cross Section

triple gauge couplings exist

have (close to) SM values



Double-Pole Approximation

(CERN 2000-009
ed. Pittau

for W^+W^- (ZZ) production ← modern approach

- go to poles at complex mass^2 ← unstable particles
- isolate gauge-invariant residues
- project on to physical phase space

$$\uparrow \quad \text{ambiguity} = O\left(\frac{\alpha}{\pi}\frac{\Gamma_W}{m_W}\right) \sim \frac{1}{2}\%$$

consider single unstable particle ← e.g. Z^0

$$\mathcal{M} = \frac{W(p^2,\omega)}{\underset{\nearrow}{p^2-\tilde{M}^2}} \sum_{n=0}^{\infty}\left(\frac{-\tilde{\Sigma}(p^2)}{p^2-\tilde{M}^2}\right)^n = \frac{W(p^2,\omega)}{p^2-\tilde{M}^2+\tilde{\Sigma}(p^2)}$$

bare mass

$$= \frac{W(M^2,\omega)}{p^2-M^2}\frac{1}{Z(M^2)} + \left[\frac{W(p^2,\omega)}{p^2-\tilde{M}^2+\tilde{\Sigma}(p^2)} - \frac{W(M^2,\omega)}{p^2-M^2}\frac{1}{Z(M^2)}\right]$$

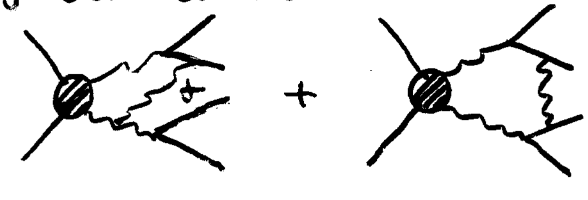
complex mass pole ↗ wave-function ren^n ↖ no pole ↖

$$M^2-\tilde{M}^2+\tilde{\Sigma}(M^2)=0 \qquad Z(M^2)=1+\tilde{\Sigma}'(M^2) \qquad \sum_n (p^2-M^2)^n c_n$$

application to W^+W^- production:

- consider only double-pole residues
- calculate one-loop electroweak corrections

factorizable ↙ ↘ non-factorizable



2-Methods to Measure m_W

- Threshold cross-section measurement

$$\Delta m_W \underset{\nearrow}{\geqslant} 91\text{ MeV}\sqrt{\frac{100\text{pb}^{-1}}{\mathcal{L}}}$$

reached @ 161 GeV, assuming 100% efficiency, no background.

- Direct reconstruction of W decays

$$\Delta m_W \underset{\nearrow}{\geqslant} \frac{\Gamma_W}{\sqrt{N}} \simeq 50\text{ MeV}\sqrt{\frac{100\text{pb}^{-1}}{\mathcal{L}}}$$

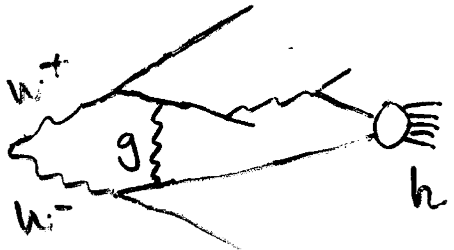
valid @ any energy ≳ 170 GeV, again assuming 100% efficiency, no background ⊕ perfect resolution

can use $(W^\pm \Rightarrow \bar{q}q)(W^\mp \Rightarrow l^\mp \nu)$ 2 constraints

how about $(W^\pm \Rightarrow \bar{q}q)(W^\mp \Rightarrow \bar{q}q)$?

Problem of colour reconnection

Bose-Einstein effect



- Lepton end-point energy

$$\Delta m_W = \frac{\sqrt{s-4m_W^2}}{m_W}\,\Delta E_\pm$$

smeared by finite-width effects, ISR, ...: not useful.

Threshold Behaviour

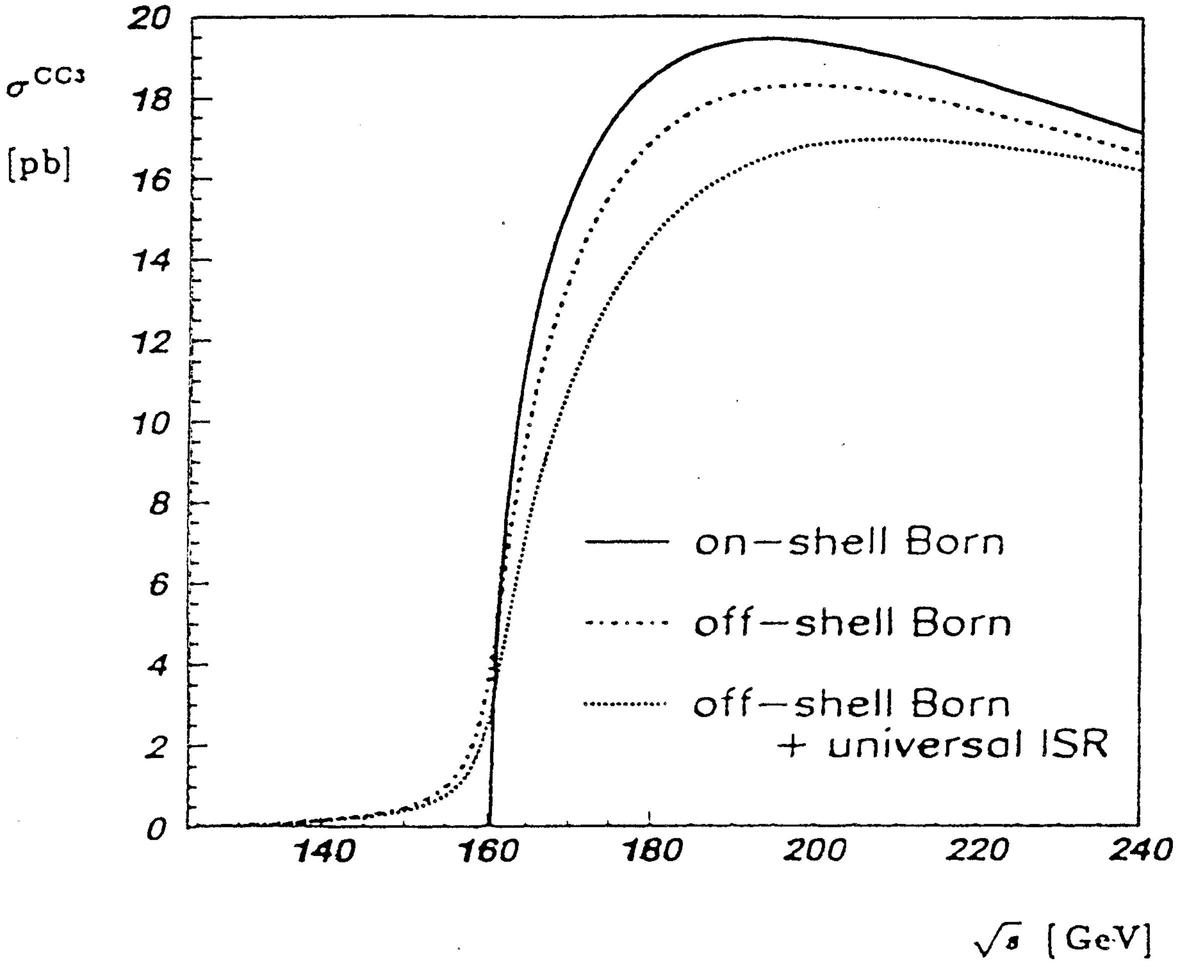
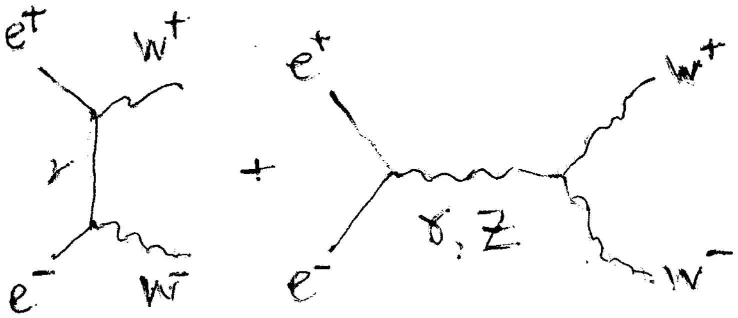


Figure 7: The inclusive CC3 cross-section.

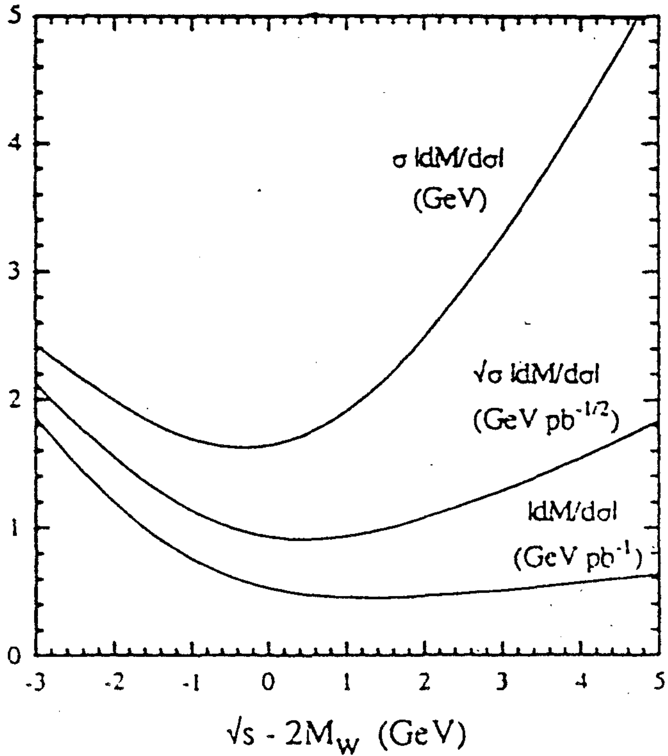


(LEP 2 YB)

B diagrams

Sensitivity to $W^{\pm}$ mass

in threshold region



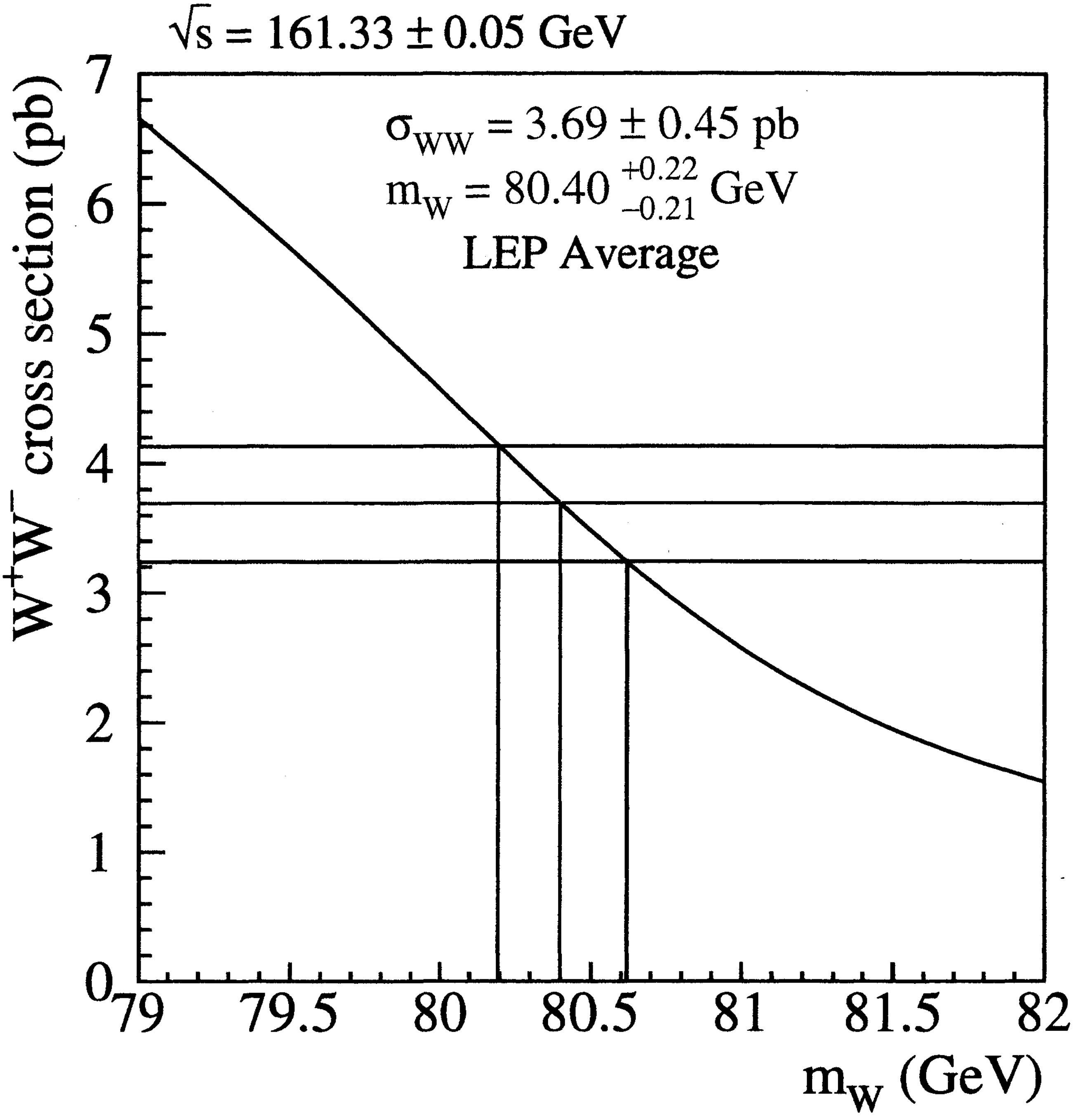
↑ chosen energy: $E_{cm} = 161.3$ GeV

Figure 7: *The sensitivity of the* W^+W^- *cross-section to the W mass, plotted as a function of* $\sqrt{s} - 2M_W$. *The significance of the three curves to the W mass measurement is discussed in the text. A value of* $M_W = 80.26$ GeV *has been used in the calculations.*

(LEP 2 YB)

Threshold Measurement of m_W

m_W from σ_{WW} at 161 GeV



Final LEP 161 GeV W mass
LEP EW Working Group

Extraction of m_W from direct reconstruction

- improves as $\sqrt{N}$, limited by exp$^{\text{tal}}$ resolutions
- can be improved by kinematic fits
- calibrate extraction using MC

ALEPH, L3 ≤ 207 GeV, DELPHI, OPAL ≤ 202 GeV

$$m_W = 80.447 \underset{\text{(stat.)}}{\pm 0.026} \underset{\text{(syst.)}}{\pm 0.030}\ \text{GeV}$$

marginal decrease with full data

main systematics: LEP energy 17 MeV

hadronization 18 MeV

fragmentation models

final-state interactions in $(\bar{q}q)(\bar{q}q)$ not $(\bar{q}q)(l\nu$

colour reconnection Bose-Einstein

$$\underbrace{\pm 40\,\text{MeV} \qquad\qquad\qquad \pm 25\,\text{MeV}}$$

±13 MeV in full data set

mass difference: $m_W(\bar{q}q\bar{q}q) - m_W(\bar{q}q l\nu) = 18 \pm 46$ MeV

projected final precision: ± 30 to 35 MeV

LEP II Energy Tools

Resonant Depolarization

High Precision technique used extensively at LEP I

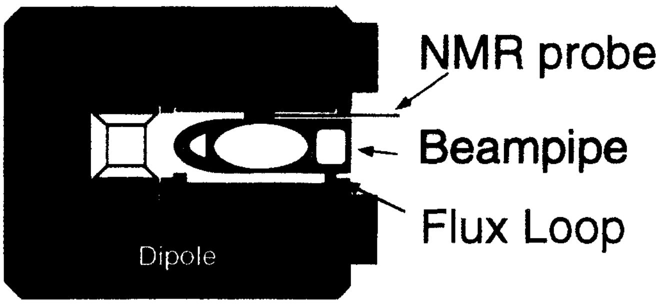
Spin Precession Frequency: $\nu_s = \frac{g_e - 2}{2m_e c^2}\langle E_{Beam}\rangle$

Intrinsic Resolution: $\delta E_{Beam} \approx 200 keV$

$\Rrightarrow$ Only works up to $E_{Beam} \sim 60$ GeV

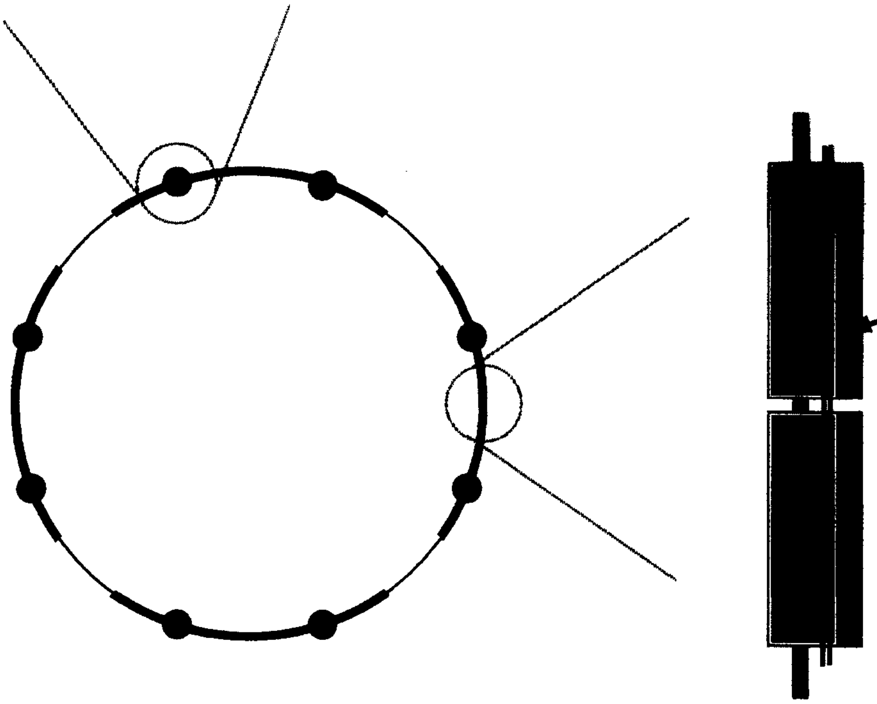
Total Bending Field

$E_{Beam} \propto \oint B_{\perp} dl$



16 Probes $\frac{\delta B}{B} \sim 10^{-6}$

Continuous Readout



Flux Loop

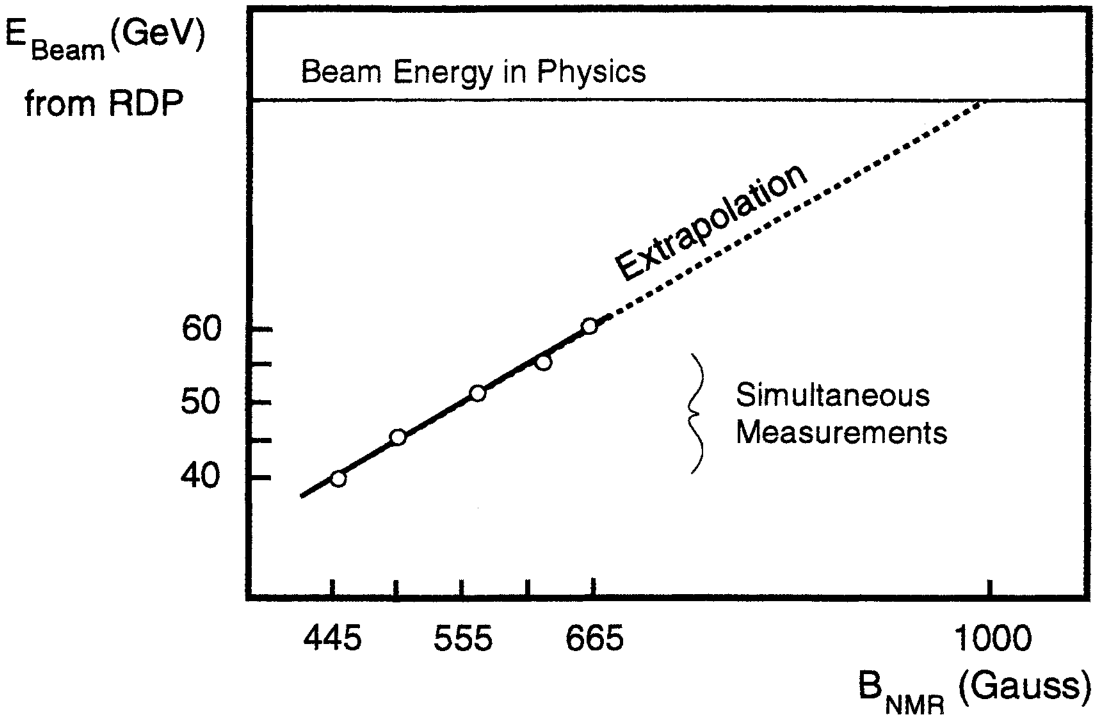
96.5% of Total Field

$\frac{\delta B}{B} \sim 10^{-4}$

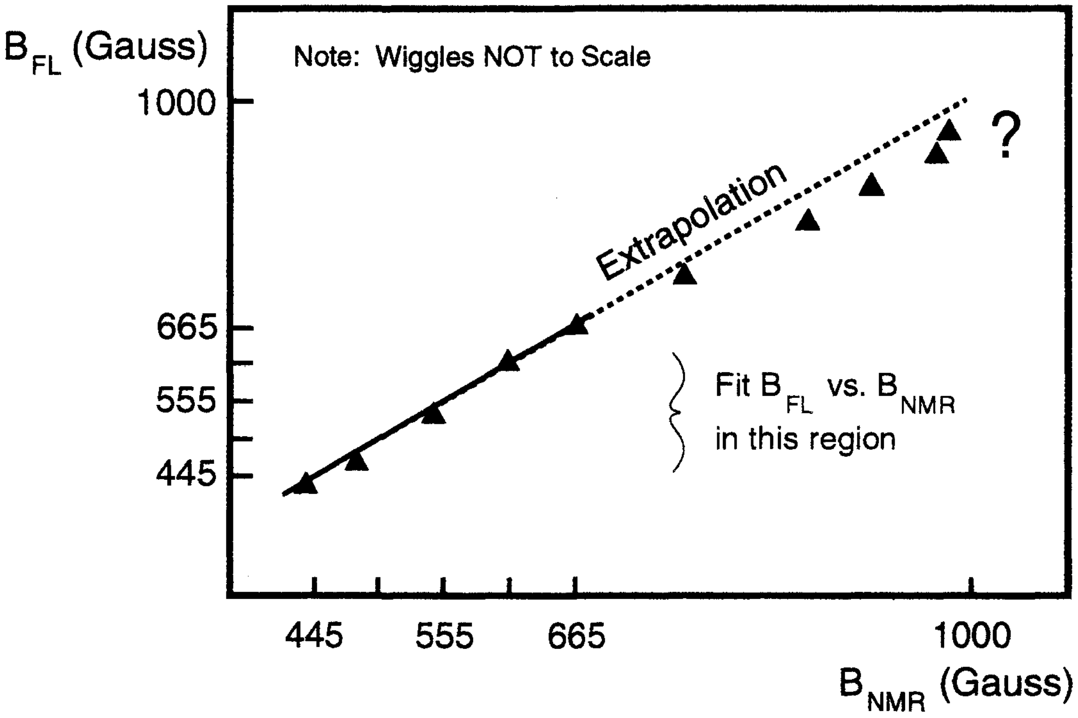
Occasional Readout

Magnetic Extrapolation

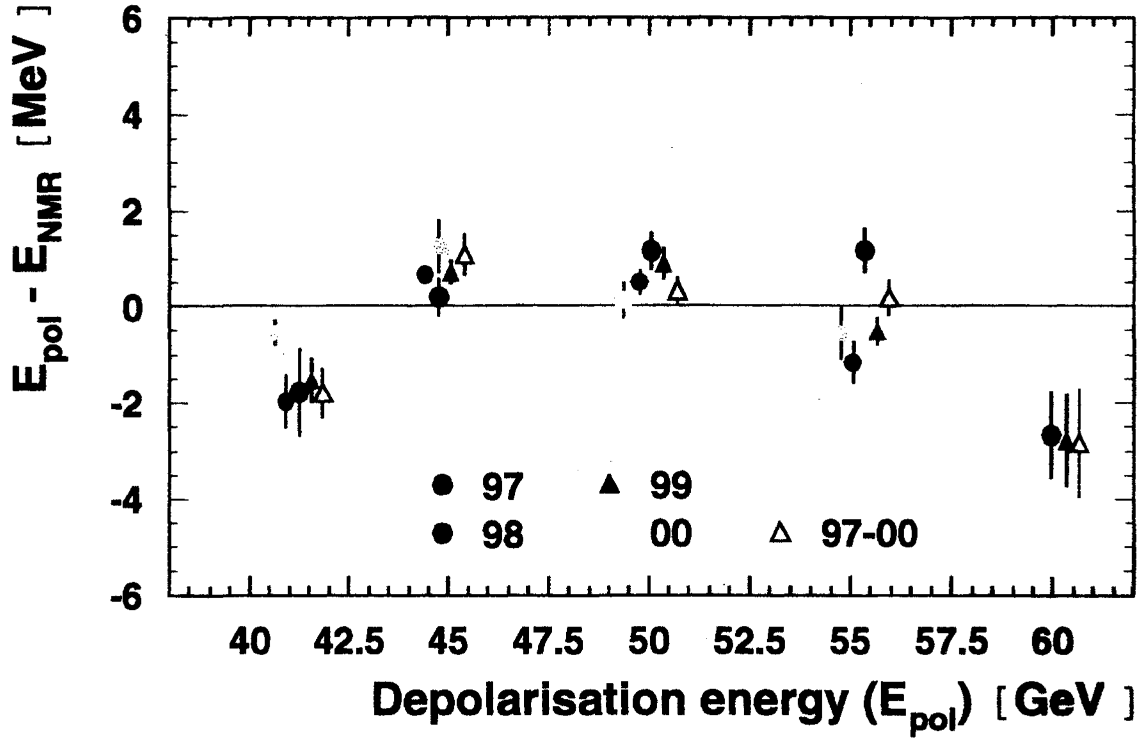
Step 1: Calibrate NMRs with RDP

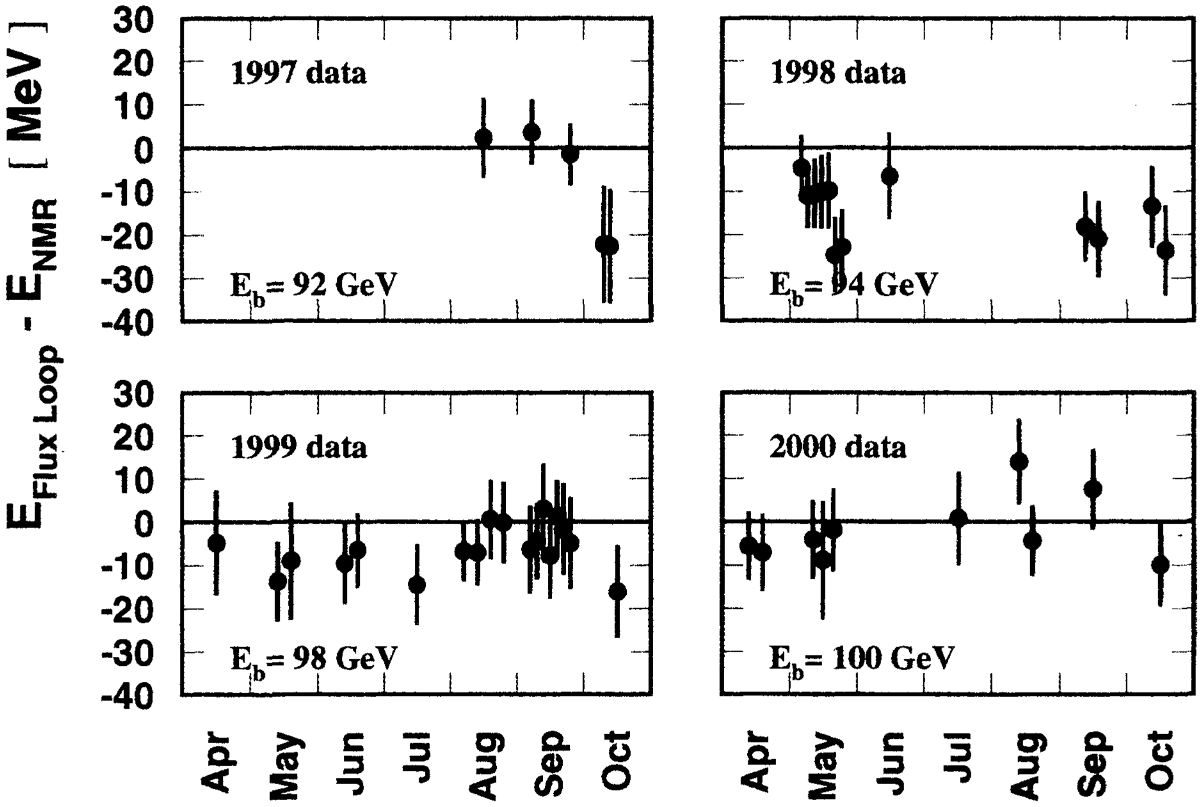


Step 2: Cross Check Linearity with Flux Loop



Extrapolation Data

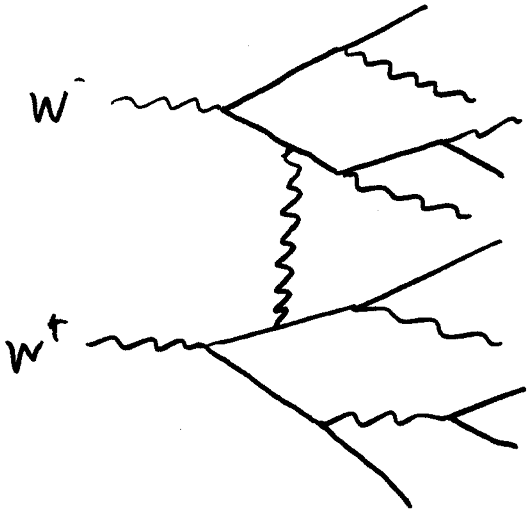




Issues in m_W Measurement

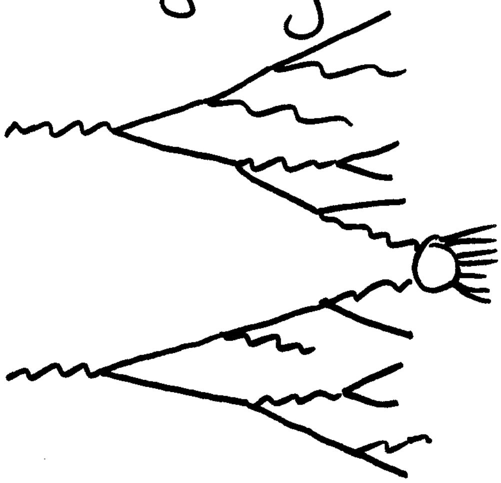
in $(W^+ \to \bar{q}q)(W^- \to \bar{q}q)$ states

- Colour reconnection?



g exchange redistributes colour, $E, p, \delta m_W$?

- Parton exogamy?



joint hadronization of partons from diffrent $W^\pm$?

- Bose-Einstein Correlations

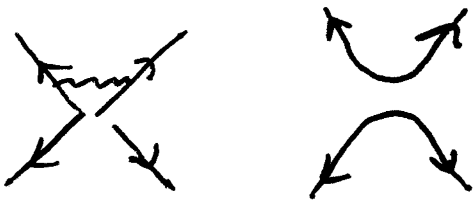
interference between hadrons from $W^\pm$?

Hope for clarification from combination of data

Colour reconnection

- interaction between $W^\pm$ decay products
  @ parton level
- final hadrons (colour singlets) may not correspond
  to initial $W^\pm$
- 'exogamous' hadronization
- change jet shape, reconstructed W mass

phenomenological models ← no real calculation



- overlap of strings
- 'shorter' strings
- reduced sizes of hadronization clusters

possible effects:

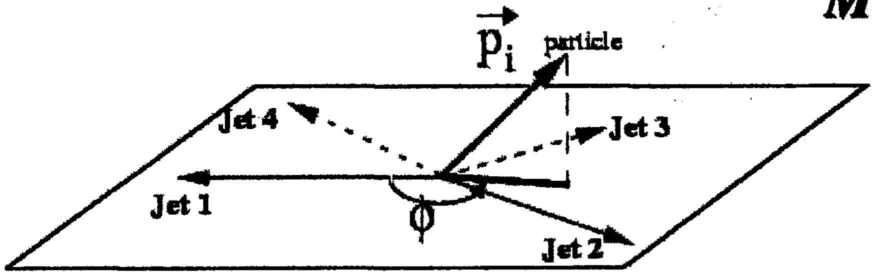
- lower multiplicity
- modified particle flow

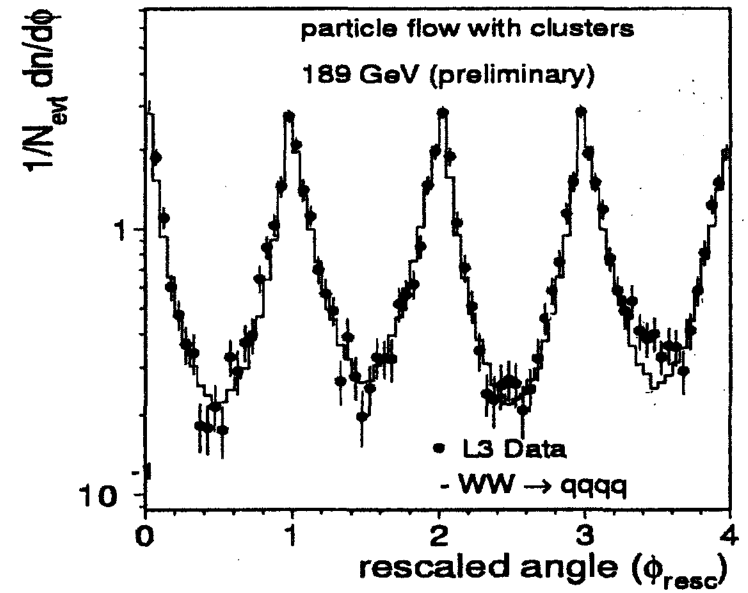
extract reconnection probability from measurements

2 or 3 σ/experiment?

estimate systematic effect on m_W from models

Search for modified particle flow in 4-jet events at LEP2





Method:

Preselection:

- depends on experiment

L3 algorithm:

- ***2 angles < 100°***
- ***2 angles > 100°, < 140°***

=> low efficiency (~ 15 % only) !

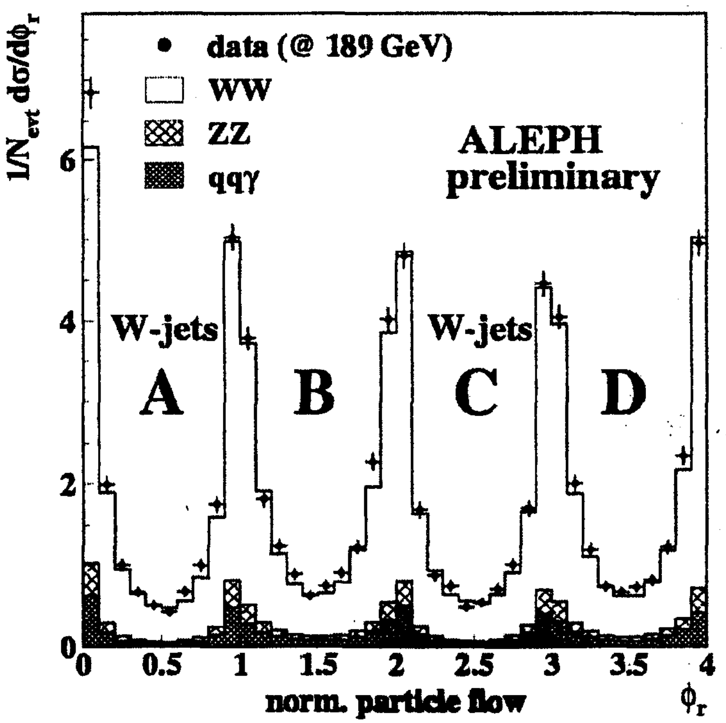
Combination of jet ordering in energy and adjacent interjet angles allows to associate dijets with Ws (here 1+2, 3+4)

- particle momenta projected onto plane 12

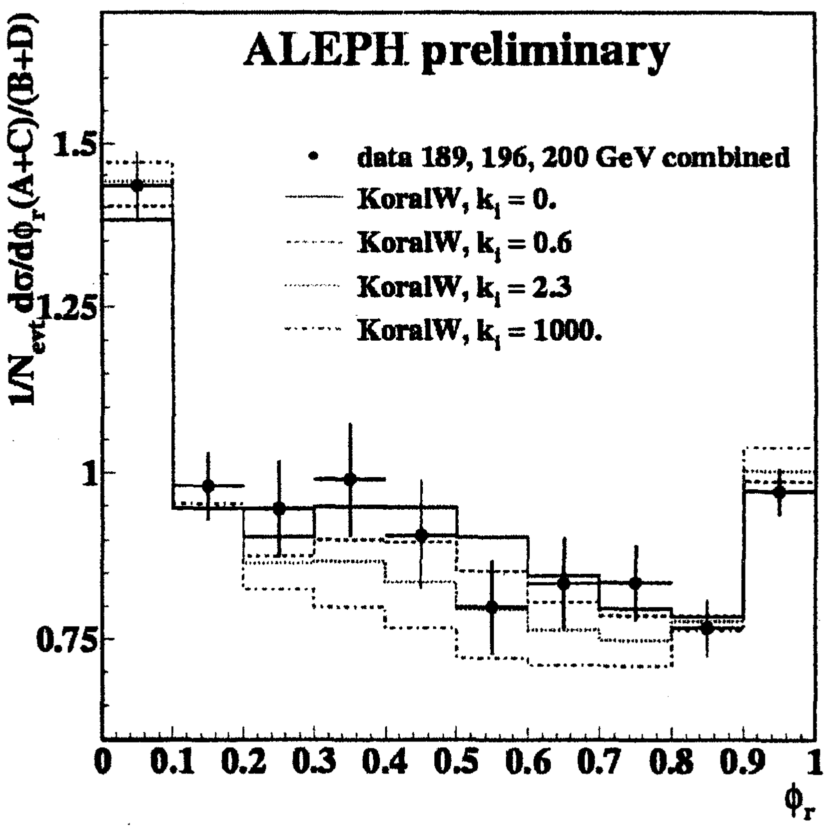
- interjet angles rescaled to 1

Search for modified particle flow in 4-jet events at LEP2

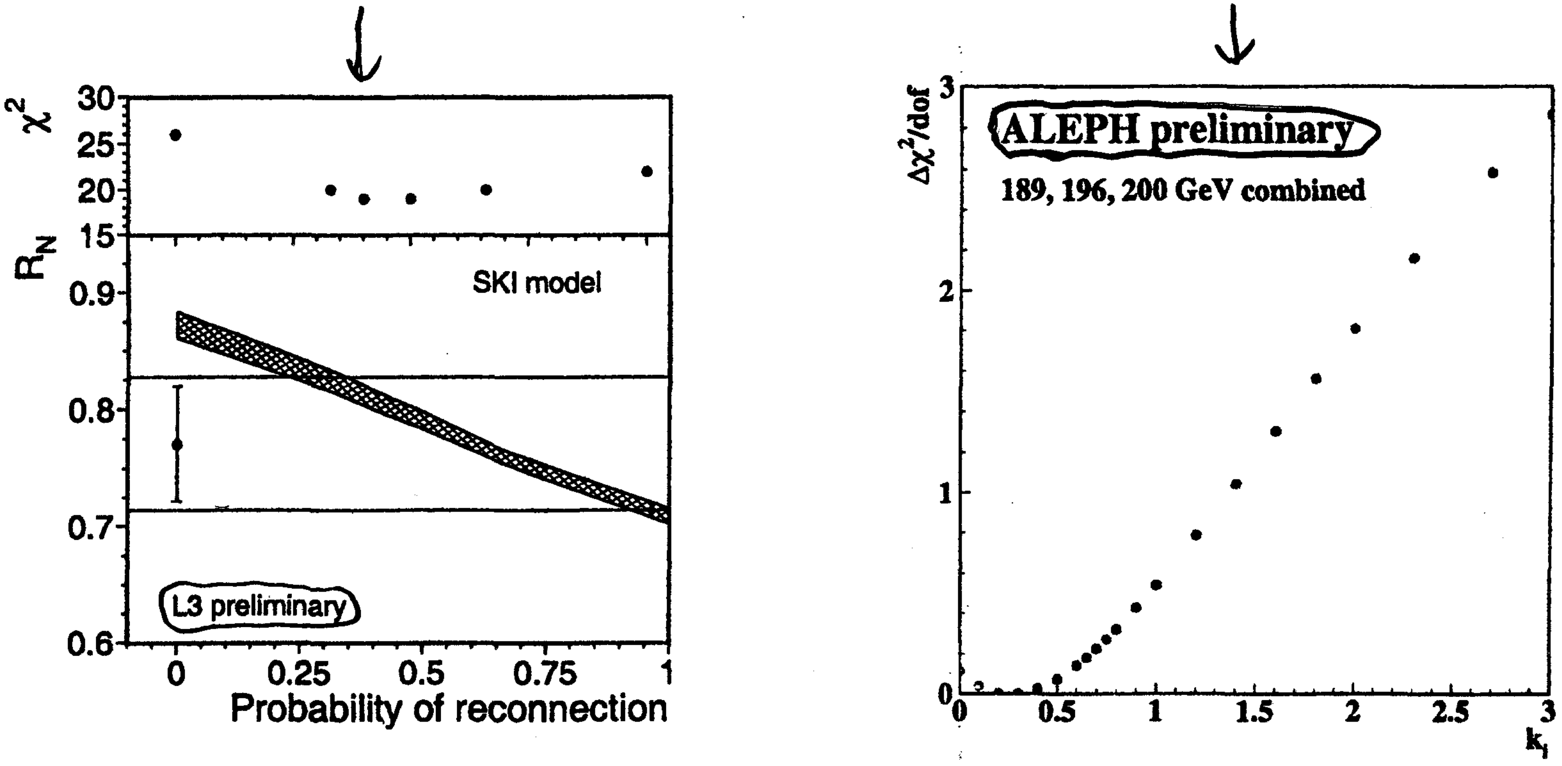
- look at the ratio (A+C)/(B+D)



- compare with models



Constraints on reconnection probability



favours non-zero reconnection

favours no reconnection

Figure 4: χ^2 between data and SK CR model as a function of reconnection probability.

Bose-Einstein effect

quantum-mechanical interference in particle prod^n

seen in Z^0 and individual $W^\pm$ decays

is there interference between $\pi^\pm$ from different $W^\pm$?

measure
$$\rho(Q) \equiv \frac{1}{N}\frac{dN}{dQ} \quad : \; Q = \sqrt{(p_1 - p_2)^2}$$
$$R_2(Q) = \rho(\text{data}) / \rho(\text{MC})_{\text{noBE}}$$

mixed reference sample : hadrons from different

$(W \to \bar{q}q)(W \to l\nu)$

no correlations between different $W^\pm$ yet observed

systematic effect on m_W?

- current estimate : ± 25 MeV
- probably overestimated :

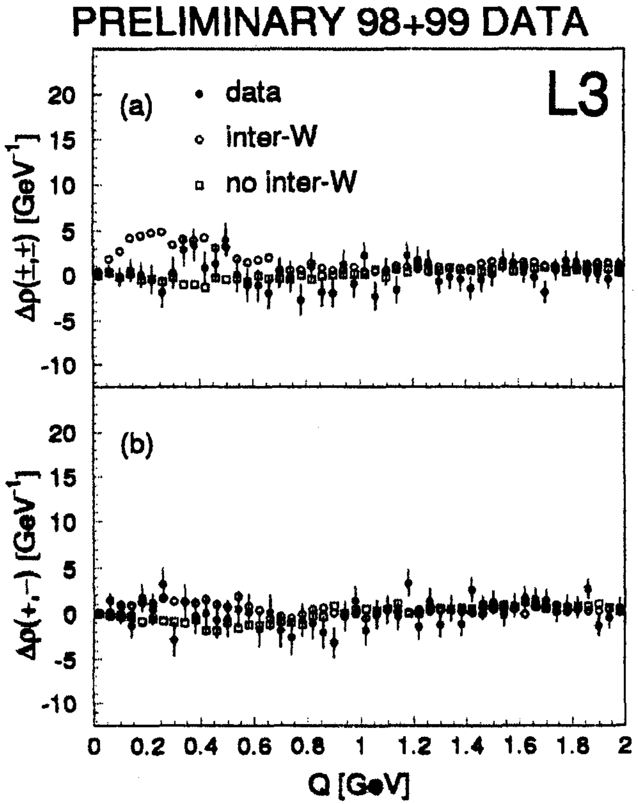
  some MC introduce artificial correlations

  reshuffle momenta ⇒ Δp between $W^\pm$

  reweighting better
- using mixing technique
- combine data from different experiments

Measurement of inter-W particle correlations at LEP2

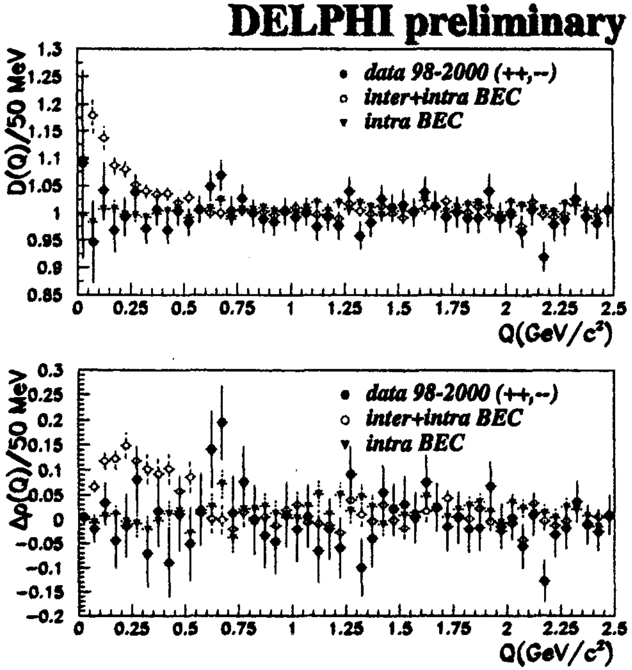
Comparing 2-particle densities in hadronic and 'mixed' WW events:



$$\Delta\rho = \rho^{WW}(hadr.) - \rho^{WW}(mixed)$$

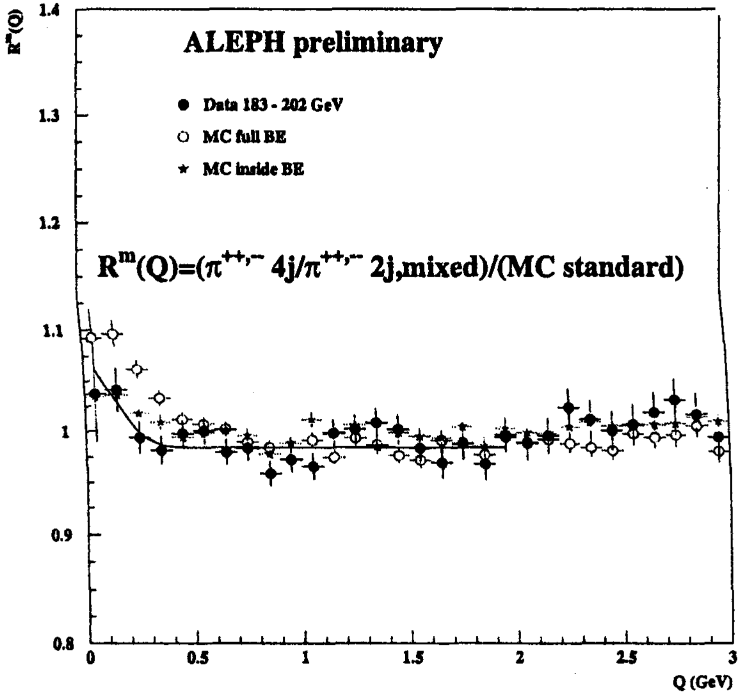
$$D = \rho^{WW}(hadr.) / \rho^{WW}(mixed)$$

NO correlations between different Ws observed !



Measurement of inter-W particle correlations at LEP2

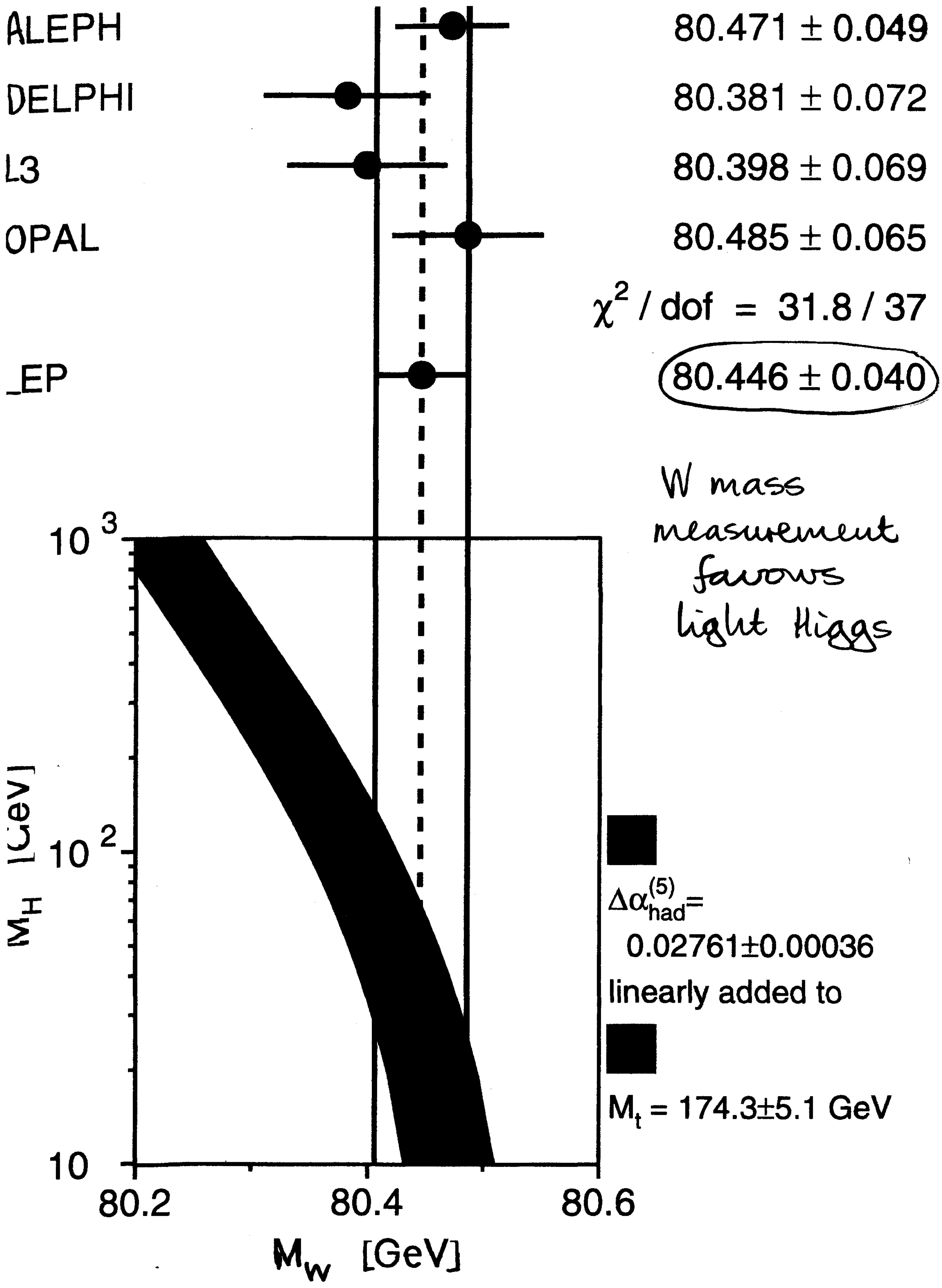
LEP results compatible (data agree with 'correlations within W only' scenario)



<u>Future (experimental) plans</u> :

<u>Mixing technique</u> considered the best choice for the combined LEP analysis:

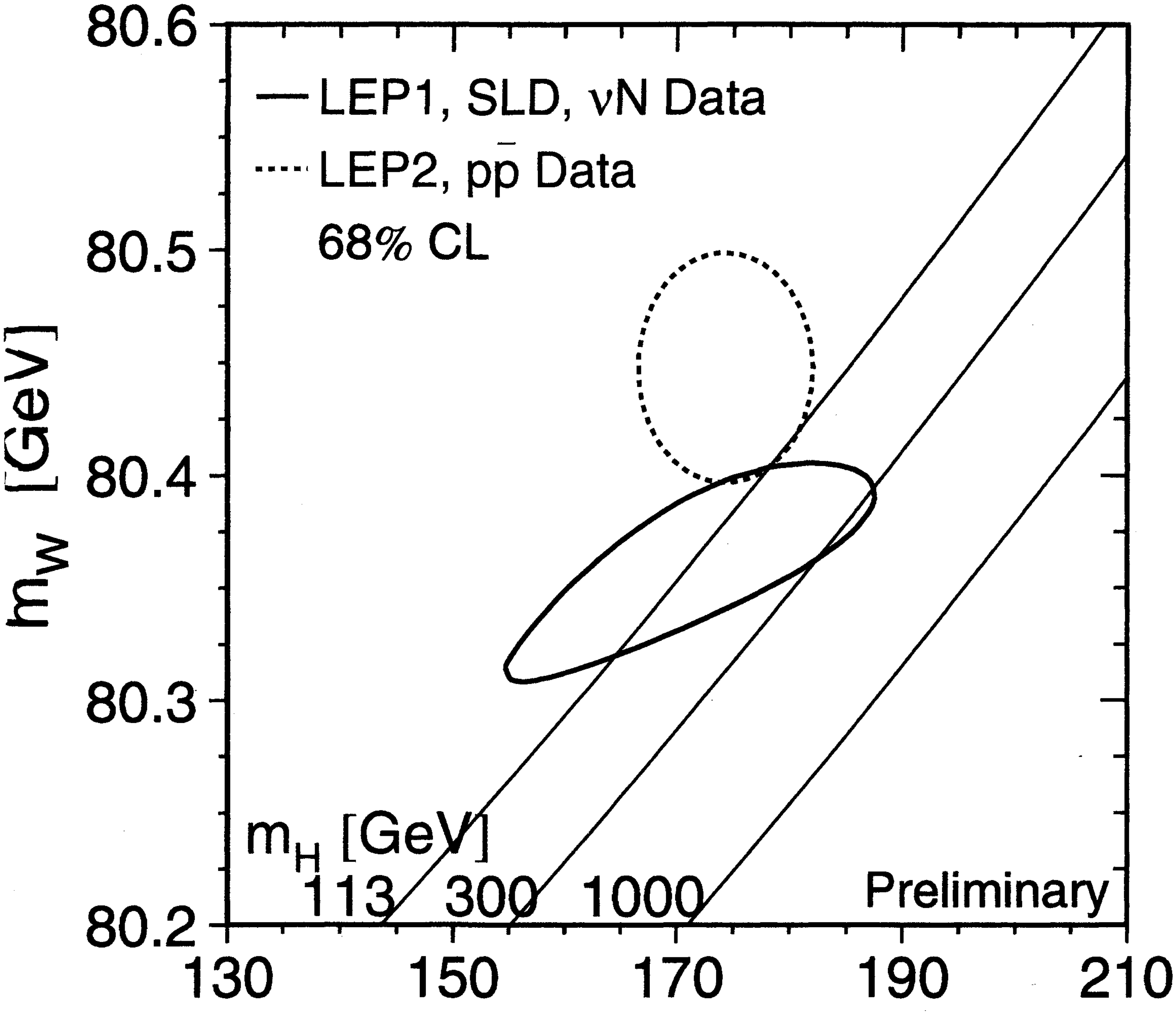
- ***worked out in all collaborations***
- ***OPAL data expected for summer 2001***
- ***first ADLO (?) combinations in late summer (ISMD 2001) ?***



W mass
measurement
favours
light Higgs

Measurements of m_t, m_W

favour light Higgs boson



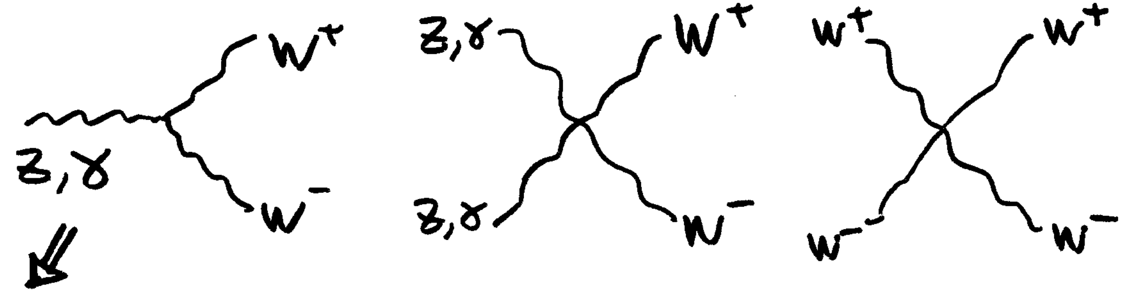
predict $\boxed{m_t = 168^{+12}_{-9} \text{ GeV}}$

33- Electroweak Gauge Boson Couplings

key feature of Standard Model

essential for renormalizability

expect:



⇙

general parametrization of triple gauge couplings:

$$i\mathcal{L}_{WWV} = g_1^V V^\mu (W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}$$

$\overset{\prime\prime}{Z,\gamma}$

$$+ \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} \leftarrow \text{conserve } P, C$$

$$+ i g_5^V \epsilon_{\mu\nu\rho\sigma} [(\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})] V^\sigma \leftarrow \text{violates } P, C$$

$$+ i g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \leftarrow \text{violates } C$$

$$- \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \epsilon^{\mu\nu\alpha\beta} V_{\alpha\beta}$$

$\leftarrow$ violate P

total:

$2 \times 7 = 14$ parameters

in Standard Model:

$$\kappa_\gamma = \kappa_Z = g_1^Z = g_1^\gamma = 1, \quad \text{others} = 0$$

Manageable parametrization

P, C invariance

SU(2) × U(1) invariance

no effect on tree-level propagators

three free parameters

$$\boxed{\kappa_\gamma\,,\ g_1^Z\,,\ \lambda_\gamma}$$

$$g_1^\gamma = e$$

$$\lambda_Z = \lambda_\gamma \equiv \lambda$$

$$\kappa_Z = -(\kappa_\gamma - 1)\tan^2\theta_W + g_1^Z$$

in Standard Model: $\kappa_\gamma = g_1^Z = 1\,,\ \lambda = 0$

generally: deviations $\Delta\kappa_\gamma\,,\ \Delta g_1^Z\,,\ \lambda$

magnetic dipole moment: $\mu_W = \frac{e}{2M_W}(1 + \kappa_\gamma + \lambda_\gamma)$

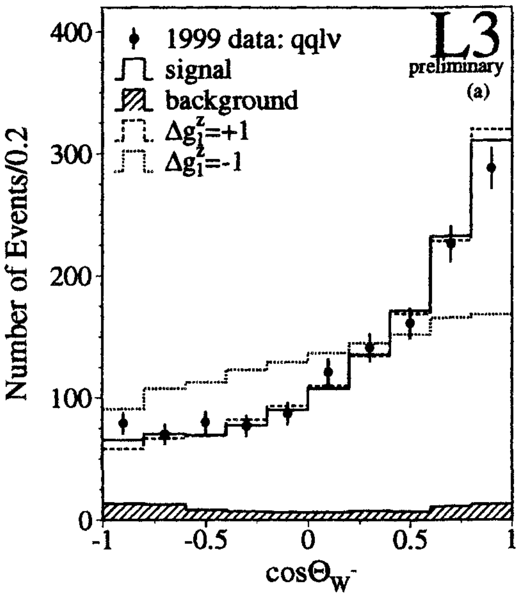
electric quadrupole: $Q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$

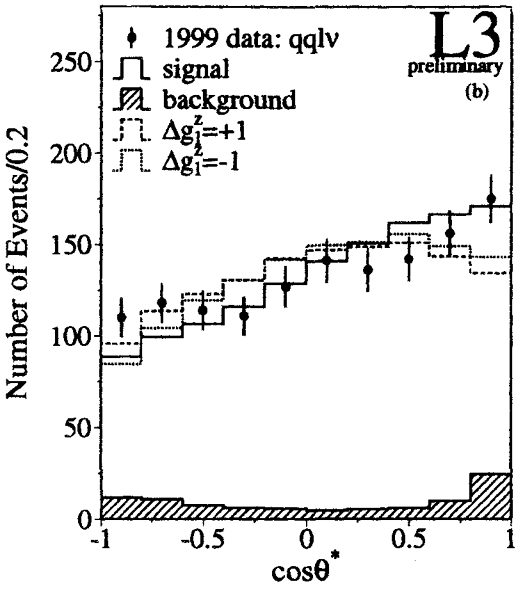
effects of anomalous TGCs on:

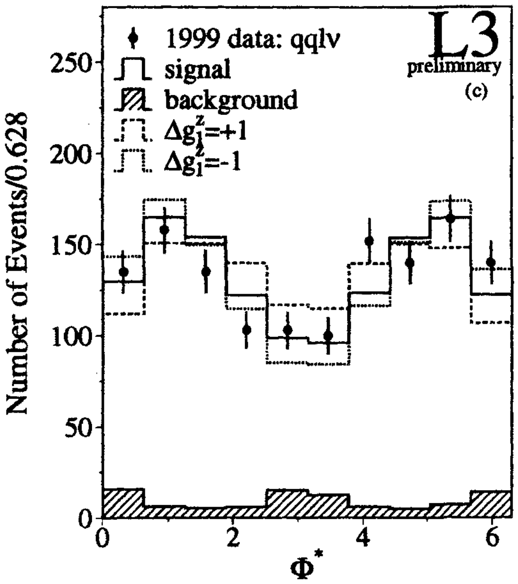
$\sigma(e^+e^- \to W^+W^-)$, W production angles, helicit

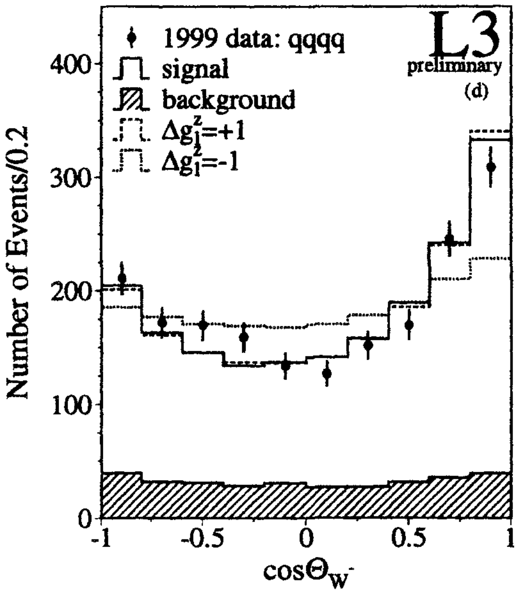
Charged TGCs in WW-Production

- **angular distributions:**



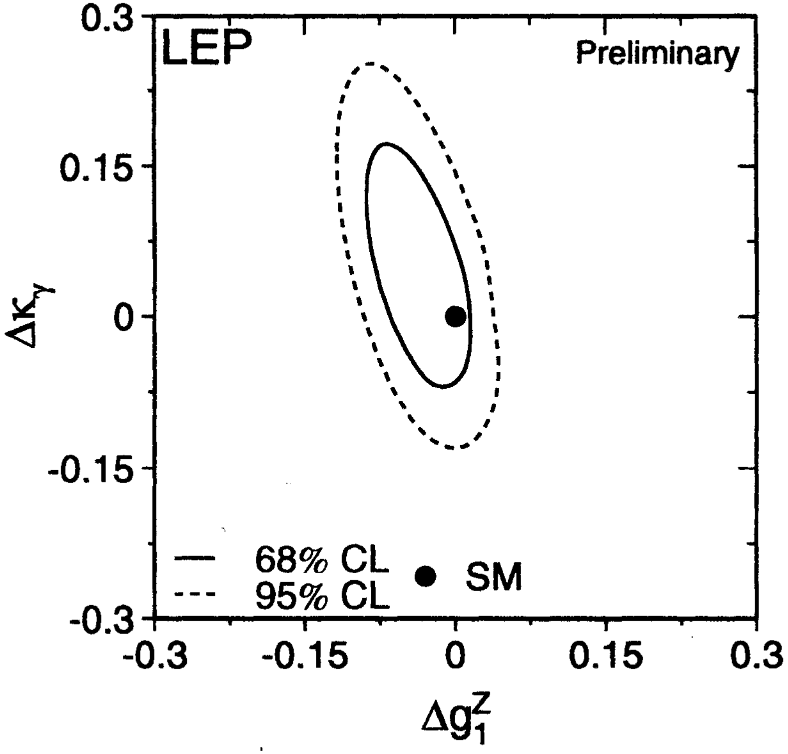


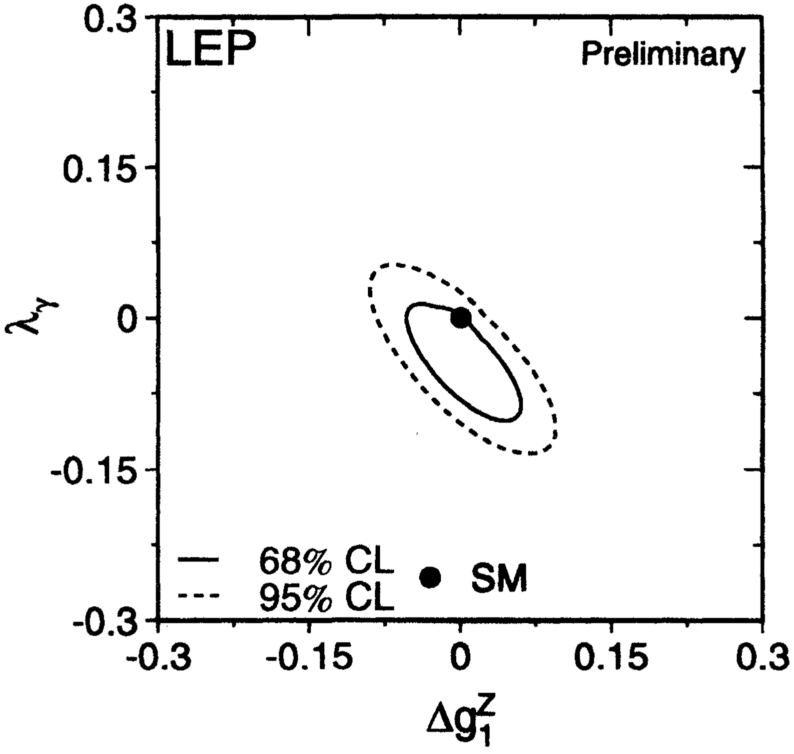




LEP Combined Charged TGCs

- **combination: $\Rightarrow$ adding $\log L$-curves from ADLO**
- **2 parameter fits: status from OSAKA 2000**





Combined results (Osaka 2000

systematic errors:

- fragmentation mainly $\bar{q}q\bar{q}q$: jet pairing, charg
- Bose-Einstein, colour reconnection smaller
- detectors

correlated systematic ~ (0·3 to 1·3) x uncorrelated

$O(\alpha)$ corrections:

- decrease σ_{tot} by ~ 2·5% $\Delta\sigma \to 0{\cdot}5\%$
- change angular distributions

(1 to 2)% difference in slope

- shift comparable to LEP combined error

$\Delta\kappa_\gamma = \pm 0{\cdot}066$, $\Delta g_1^z = \pm 0{\cdot}026$, $\Delta\lambda_\gamma = \pm 0{\cdot}028$

example of ALEPH analysis:

	$-0{\cdot}021^{+0{\cdot}079}_{-0{\cdot}073}$	$+0{\cdot}015^{+0{\cdot}035}_{-0{\cdot}032}$	$+0{\cdot}001^{+0{\cdot}034}_{-0{\cdot}031}$
$O(\alpha)$:	0·037	0·013	0·015

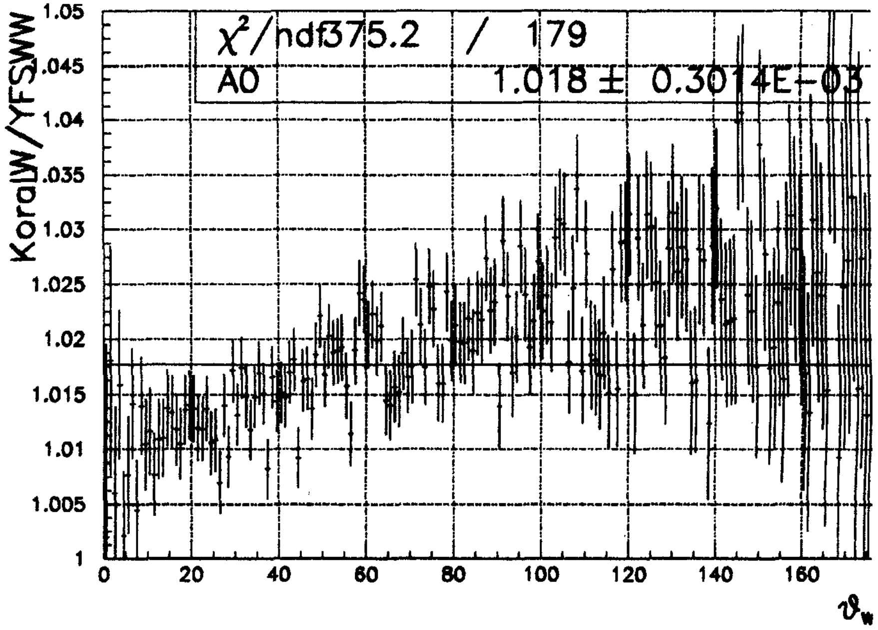
treated as systematic

$\mathcal{O}(\alpha)$ Corrections

- $\mathcal{O}(\alpha)$ corrections to W-pair production in double pole approximation (DPA).

  YFSWW, RacoonWW

relative change in W-productio angular distr. due to DPA



relevance for TGC measurements:

- decreases total cross section by $\simeq$ 2.5% ($\Delta\sigma_{theo}$: 2% ⟶ 0.5%)
- changes shape of $\cos\theta_{\mathrm{W}}$ distr.

Other couplings

neutral TGCs

- absent in Standard Model
- consider ZZZ, $ZZ\gamma$, $Z\gamma\gamma$
- two sets of anomalous couplings:

$ZZ(\gamma, Z)$ $\qquad\qquad$ $Z\gamma(\gamma, Z)$

$f_5^V \leftarrow$ CP conserving $\rightarrow h_3^V, h_4^V$

$f_4^V \leftarrow$ CP violating $\rightarrow h_1^V, h_2^V$

- affect σ_{tot}, polarization of Z

quatic couplings

- Standard Model couplings too small for LEP
- parametrization not affecting charged TGCs

$$\mathcal{L} = -\frac{e^2}{16\Lambda^2}\left(a_0 F_{\mu\nu}F^{\mu\nu}\vec{W}_\alpha\vec{W}^\alpha + a_c F_{\mu\alpha}F^{\mu\beta}\vec{W}^\beta\vec{W}_\alpha + a_n \epsilon_{ijk} W^i_{\mu\alpha} W^j_\nu W^{k\alpha} F^{\mu\nu} \right)$$

conserve C,P ↗ →

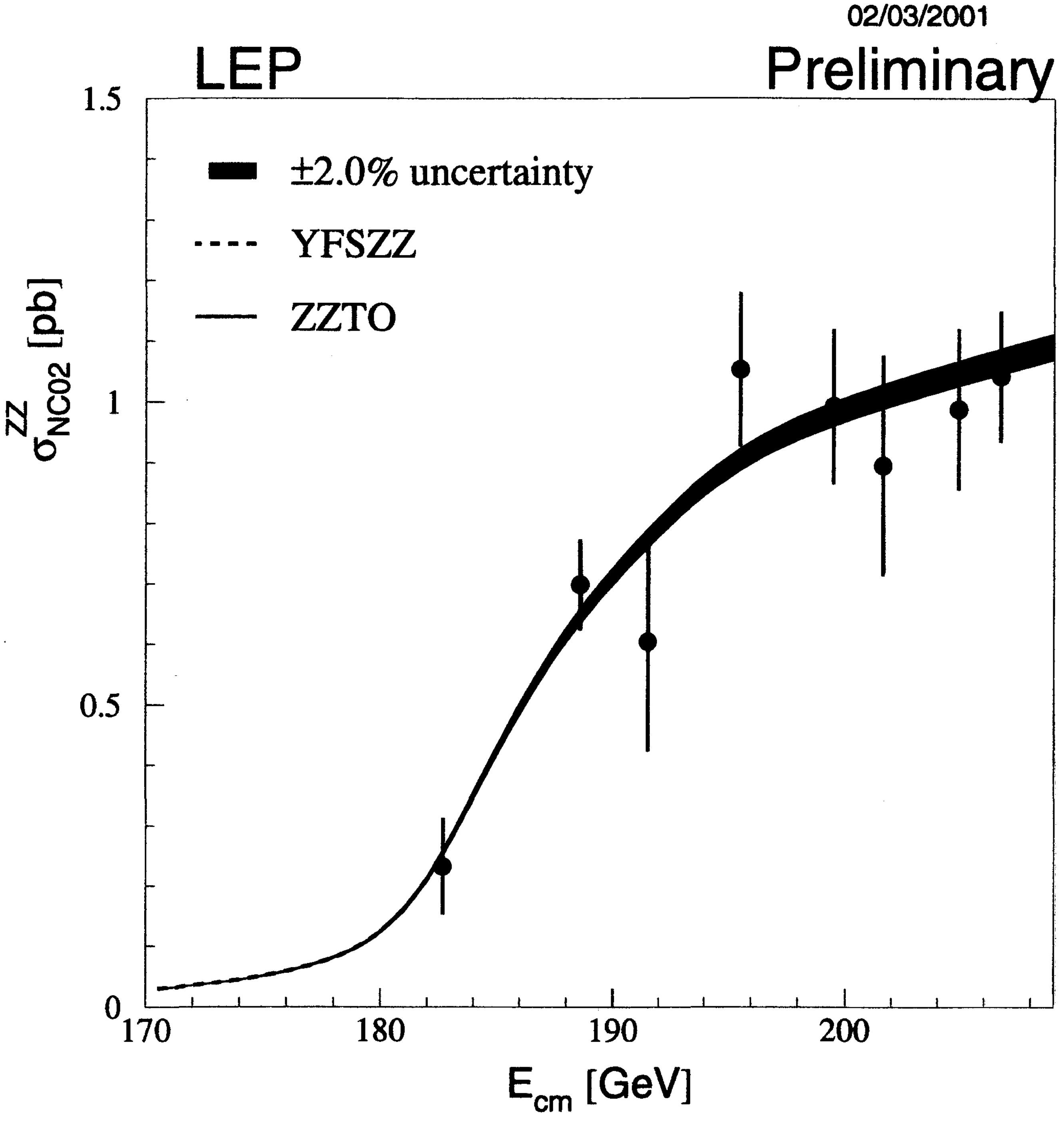
WWVV, $ZZ\gamma\gamma$

↑ violates CP : $WWZ\gamma$

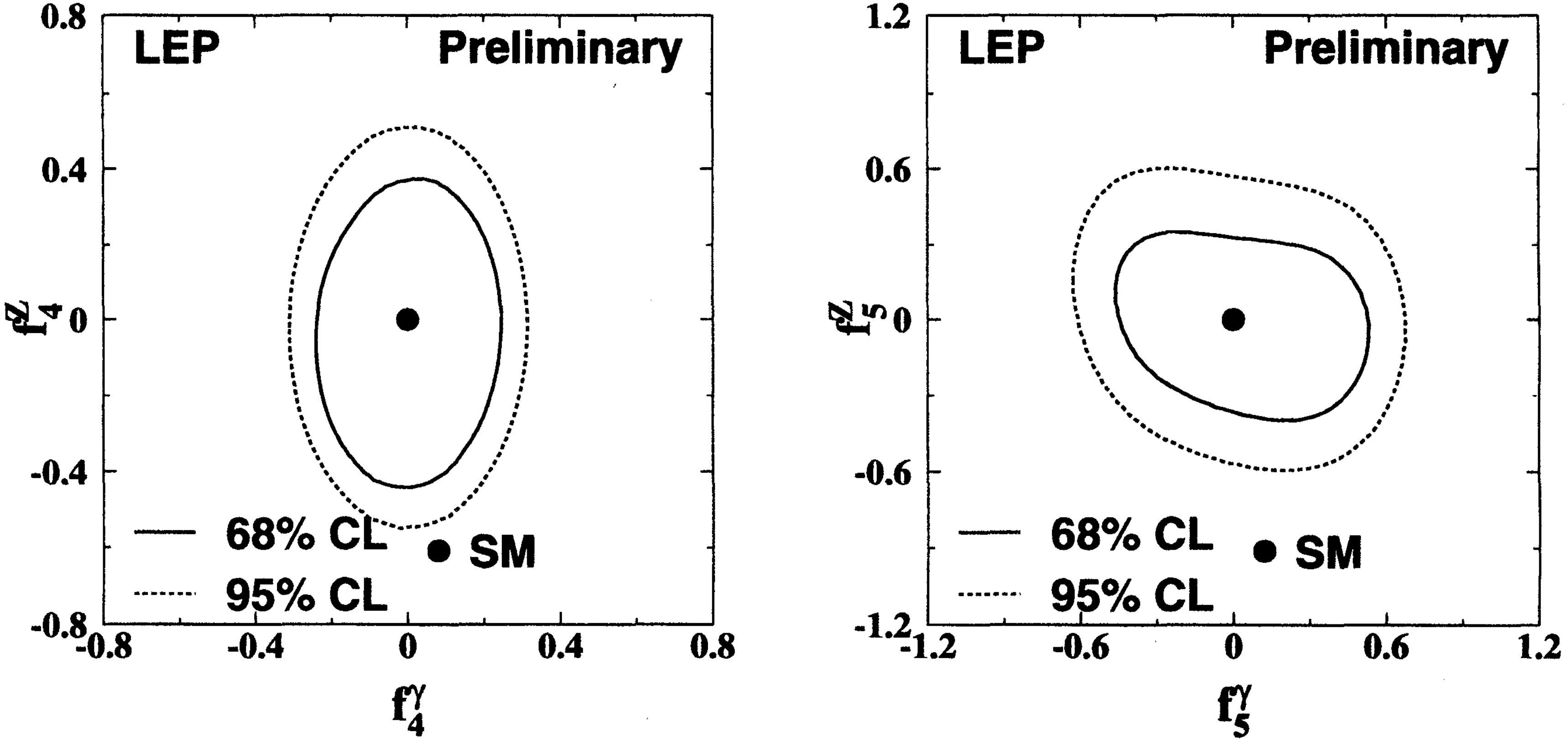
- now first direct limits from LEP

$e^+e^- \Rightarrow Z^0Z^0$ production

background to $e^+e^- \rightarrow Z^0 + H$



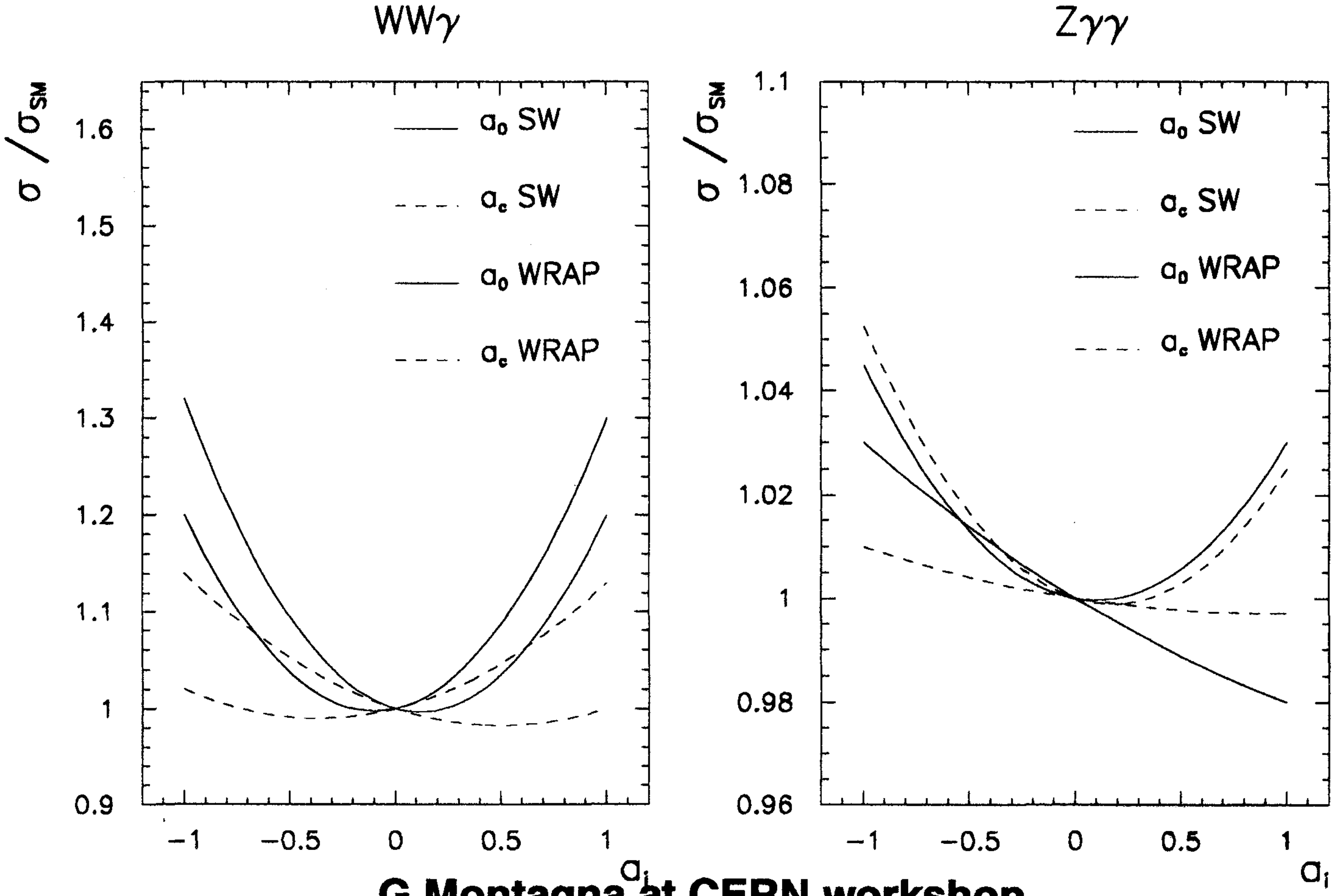
f-Couplings in ZZ Production



Quartic Gauge Couplings

- **theoretical input needed:**

comparison: Stirling/Werthenbach with G.Montagna *et al.*



G.Montagna at CERN workshop

3.4-QCD Tests

running of α_s

$$\mu^2 \frac{\partial \alpha_s}{\partial \mu^2} = \beta(\alpha_s) \simeq -\beta_0 \alpha_s^2 - \beta_1 \alpha_s^3$$

where $\beta_0 = \frac{11 C_A - 2 n_f}{12\pi}$, $\beta_1 = \frac{17 C_A^2 - 5 C_A n_f - 3 C_F n_f}{24\pi^2}$

experimental objectives:

- verify running
- measure coefficients to test QCD values

$$C_A, n_f, N_c, C_F, \ln^n, \ldots$$

observables:

- total cross section: $R = 3 \sum_q Q_q^2 \left(1 + \frac{\alpha_s}{\pi} + 1.441 \left(\frac{\alpha_s}{\pi}\right)^2 - 12.8 \left(\frac{\alpha_s}{\pi}\right)^3 + \ldots\right.$

(cf R_V, R_A @ Z^0) low E ↗

- τ decay: $R_\tau = 3.058 \left(1.001 + \delta_{pert} + \overset{?}{\delta_{nonpert}}\right)$:

$$\delta_{pert} = \frac{\alpha_s(m_\tau)}{\pi} + 5.20 \left(\frac{\alpha_s}{\pi}\right)^2 + 26.37 \left(\frac{\alpha_s}{\pi}\right)^3$$

- event shapes, jet rates, energy correlations
- scaling violations in jet fragmentation

Running of α_s

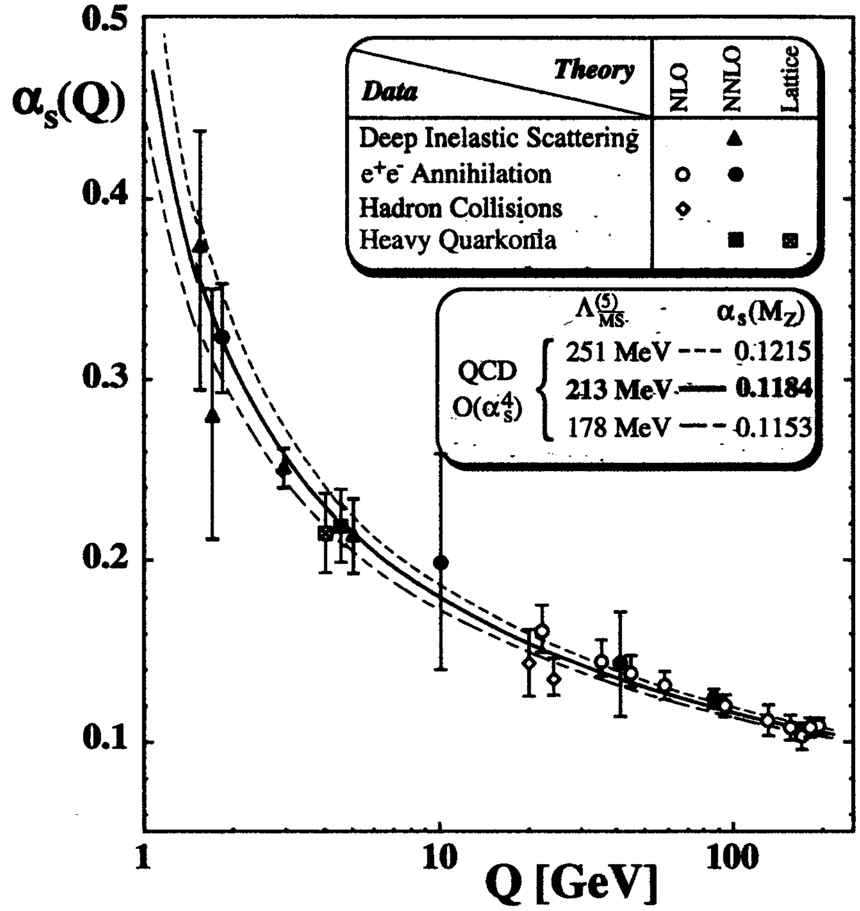


Figure 10: Summary of $\alpha_s(Q)$.

Total cross section @ Z peak

reduce systematics by comparing to leptons

$$R_l = \frac{\Gamma_l}{\Gamma_h} = 20.767 \pm 0.025 \pm 0.007$$

cf Standard Model fit 20.740

corresponds to $\alpha_s(m_Z) = 0.124 \pm 0.004$

errors :	Δm_Z	Δm_t	Δm_H	$\frac{m_Z}{2} < \mu < 2M_Z$	ren^{n} schem
	0.00003	0.0002	0.0017	$+0.0028$ -0.0004	0.0002

combined: $\alpha_s(m_Z) = 0.124 \pm 0.004 \pm 0.002 \; (m_t, m_H)$

$$\begin{matrix} + \\ - \end{matrix} \begin{matrix} 0.003 \\ 0.001 \end{matrix} \quad (\mathrm{QCD})$$

global fit reduces central value (within errors)

$$\boxed{\alpha_s(m_Z) = 0.121 \pm 0.003}$$

τ decay rate

Large $\alpha_s(m_\tau)$, low mass ⇒ new problems:

- treatment of higher orders in pert^n theory
  - work to fixed order?
  - improve by contour integration?
  - improve by summing renormalon chain?
- evaluation/estimate of non-pert^ive cont^n
  - ↖ constrained by moments of decay dist^ns

recent compilation:

$$\alpha_s(m_\tau) = 0{\cdot}323 \underset{(\text{exp})}{\pm 0{\cdot}005} \underset{(\text{theory})}{\pm 0{\cdot}030}$$

run up to M_Z, assuming QCD, using 4-loop β function, 3-loop matching @ m_b

$$\boxed{\alpha_s(M_Z) = 0{\cdot}1181 \pm 0{\cdot}0007 \pm 0{\cdot}0030}$$

$$\qquad\qquad\qquad\qquad (\text{exp}) \qquad (\text{theory})$$

Event shapes, jet rates, energy correlations

vast topic: set of lectures by themselves

many observables:

Thrust : $T \equiv \max \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|} \right)$,

major, minor, oblateness,

jet pair masses: $y_{ij} = M_{ij}^2 / E_{vis}^2$ (JADE, Durham

jet broadening, energy correlations, ...

issues:

- theory: $\frac{1}{\sigma_0} \frac{d\sigma}{dy} = R_1(y) \alpha_s(\mu^2) + R_2(y, Q^2/\mu^2) \alpha_s^2(\mu^2) + \underset{\uparrow}{\cdots}$

(LO) (NLO) no NNLO

for some observables, known resummation of leading, next-to-leading logarithms (NLLA)

$\Rightarrow$ resummed NLO

- hadronization $\leftarrow$ non-perturbative QCD: $(1/Q)^n$

- detector acceptance, resolution $\nwarrow$ models

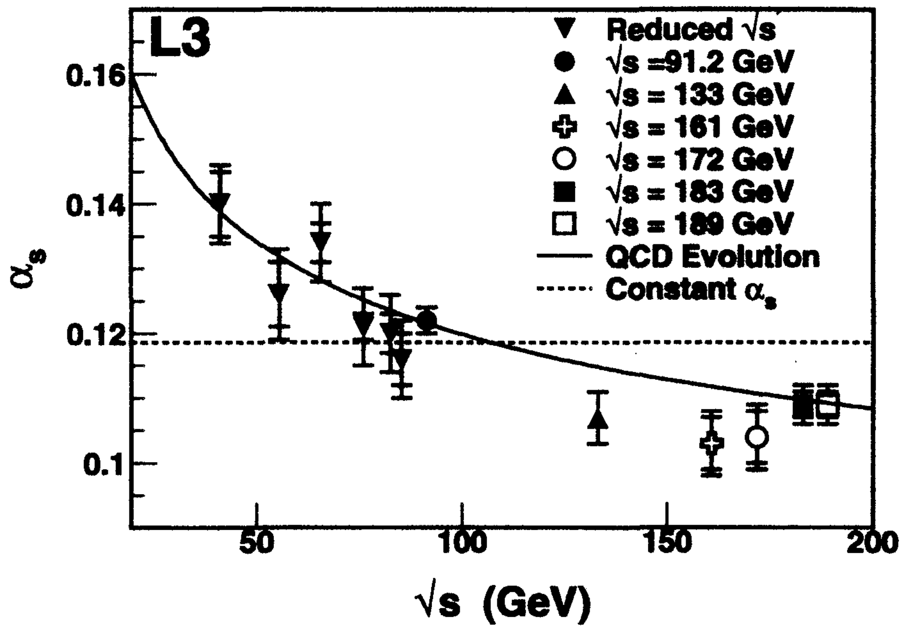


Figure 8: Running of α_s from hadronic event shapes at LEP, measured by L3. The results at energies below 91 GeV are from radiative events at $2E_{beam} \approx M_{Z^0}$ (figure from reference [81]).

Quantifying the running of α_s

- energy dependence:

τ decay, (deep inelastic), Γ_Z, event shapes @ LEP2

assuming $n_f = 5$: $N_c = 3{\cdot}03 \pm 0{\cdot}12$

- event shape variables:

$n_f = 5{\cdot}64 \pm 1{\cdot}35$ (vs 5)

$C_F = 1{\cdot}45 \pm 0{\cdot}27$ (vs 4/3)

$C_A = 2{\cdot}88 \pm 0{\cdot}27$ (vs 3)

$T_F/C_F = 0{\cdot}29 \pm 0{\cdot}05 \pm 0{\cdot}06$ (vs 3/8)

unique contribution of LEP (?)

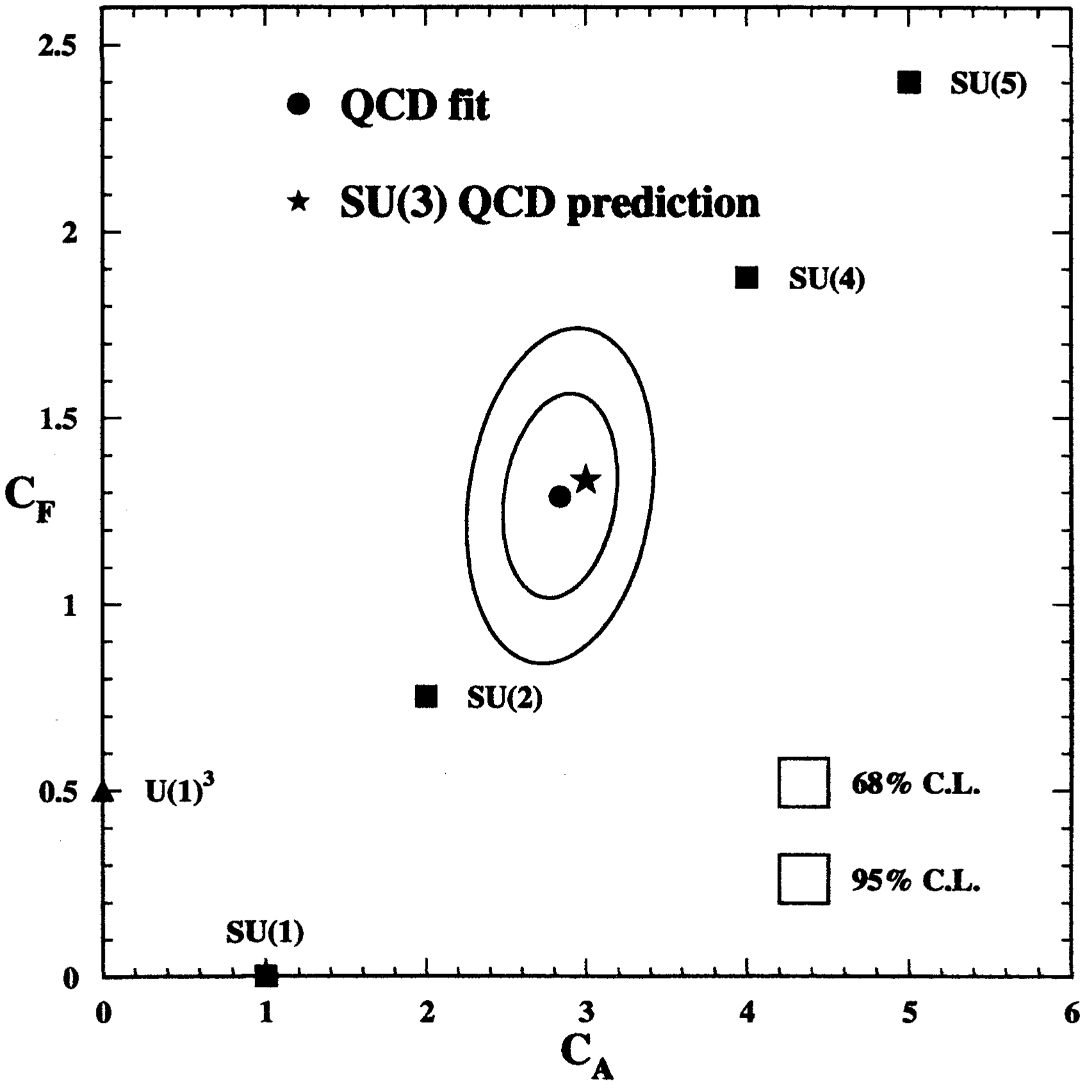
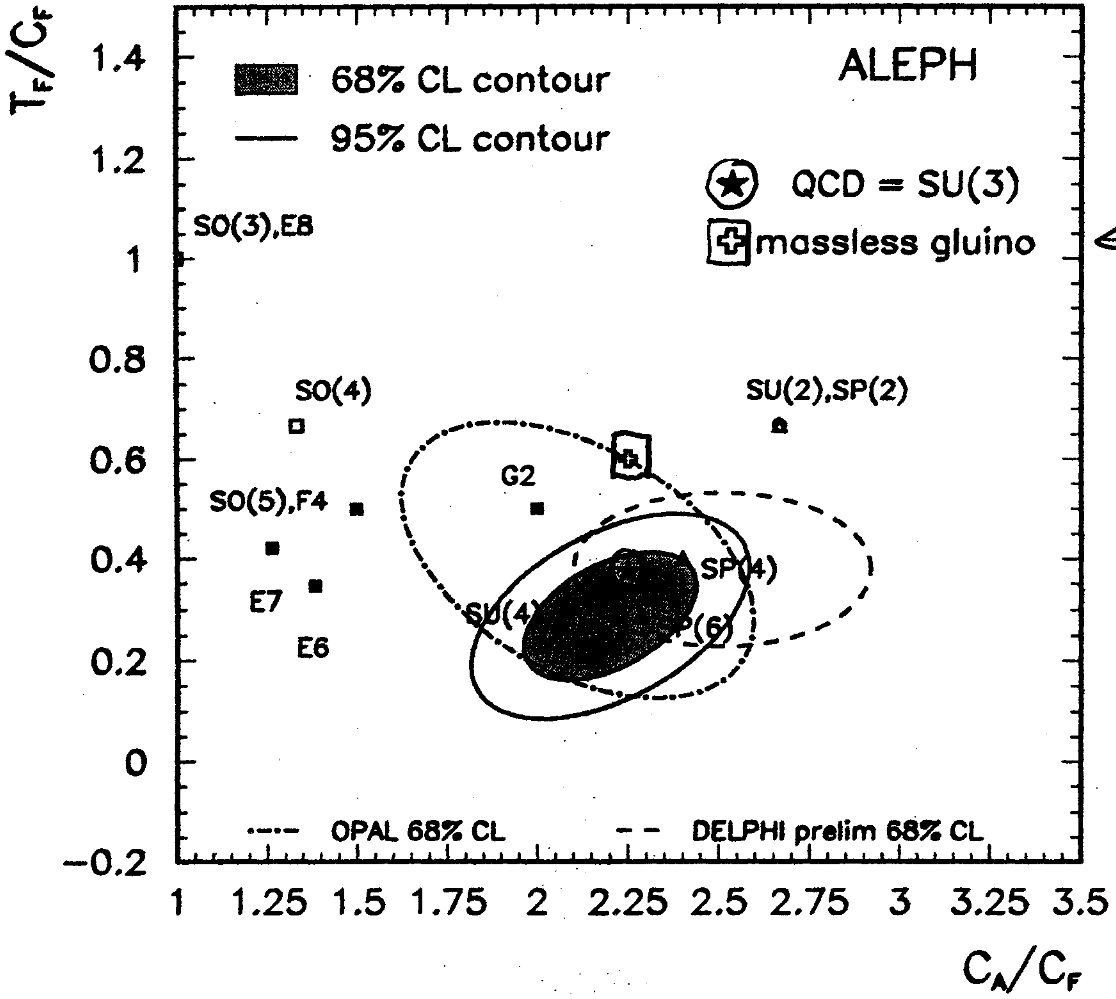


Figure 4: The figure presents the combined results for the colour factors C_A and C_F from fits to $\alpha_s(M_{Z^0})$, C_A and C_F based on the observables $1-T$ and C. The square and triangle symbols indicate the expectations for C_A and C_F for different symmetry groups.

LEP vs different gauge groups



← disfavoured

Figure 5: Results of the colour factor measurement by ALEPH, compared to measurements of OPAL and DELPHI. Also indicated are the expectations from SU(3) and other gauge groups .