Precise Standard Model Measurements at LEP-2

LEPC – 29 May 1997

D.G. Charlton
University of Birmingham

- Energy/Luminosity Scenarios
- W mass
- Vector Boson Self-Interactions
- Fermion-Pair Production
- Higgs Search

"YB" = Yellow Book = *Physics at LEP2*, CERN 96-01

Energy/Luminosity Scenarios

Year	E_{CM} (GeV)	$\mathcal{L}_{int}$ (pb^{-1})	
1997	184	100	now 50 pb^{-1}?
1998	188-192	200	
For 1999+2000, I consider:			
either	190-192	200	
or	200	150	needs 7 MV/m

Note that:

- 188 GeV (for 1998) makes cautious assumptions about machine performance in order to guarantee high luminosity
- A play-off is possible between energy and luminosity, particularly in 1999-2000 when more experience with RF system, and more cryo power

I consider the accumulation of:

- $\sim$ 500 pb^{-1} total luminosity
- $\sim$ 250pb^{-1} around 190 GeV **plus** $\sim$ 150 pb^{-1} at 200 GeV

and address:

- What is the interest of EW measurements with high luminosity?
- How does the precision evolve with luminosity?
- How does the precision change with energy?
- Mass reach for Standard Model Higgs

W Mass Reconstruction from Decay Products

Idea:

- reconstruct W mass from observed decay products in the experiment
- use energy-momentum constraints to improve resolution

$\longrightarrow$ the “direct reconstruction” method

Studied at length in LEP-2 yellow book:

- statistical and systematic error estimates
- estimate of E_{CM} dependence

For 10 pb^{-1} per experiment at 172 GeV:

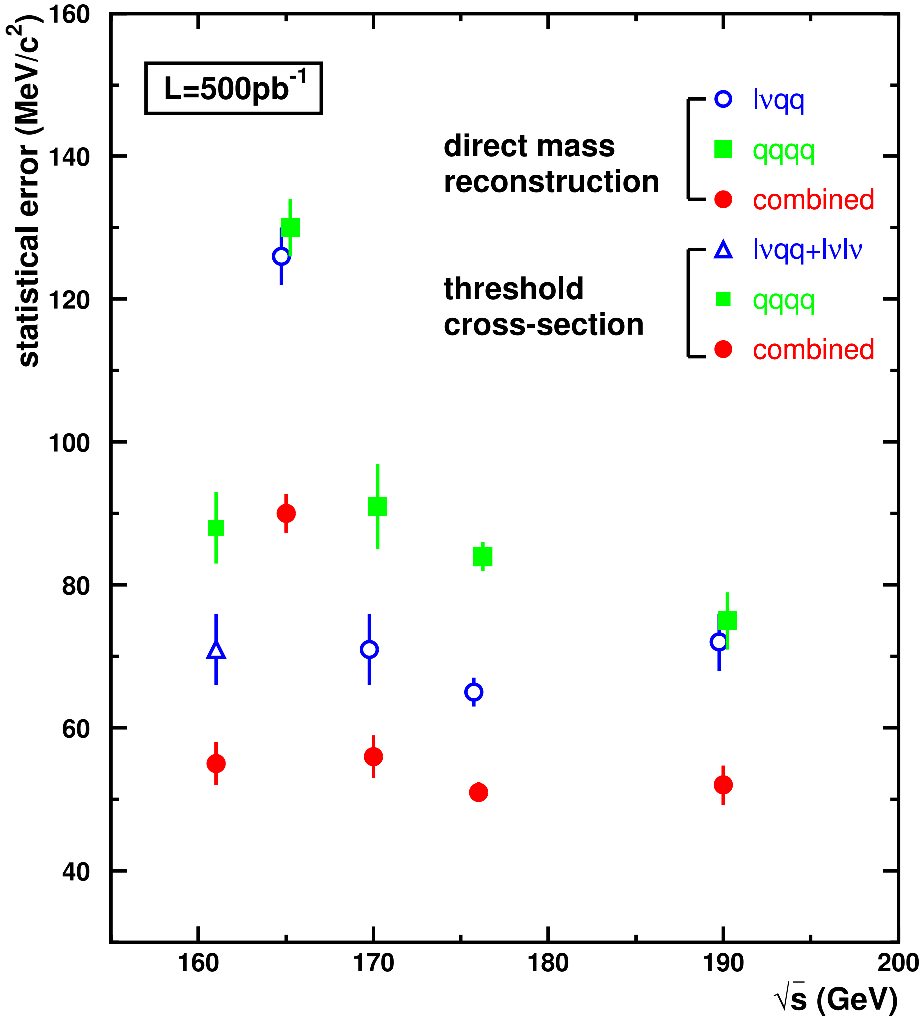
Yellow book	**180 MeV**	
LEP average	**180 MeV**	**(excluding FSI)**

Caveats:

- preliminary – stat. precision may yet improve a little
- statistics dominate

E_{CM} Dependence of m_W Precision

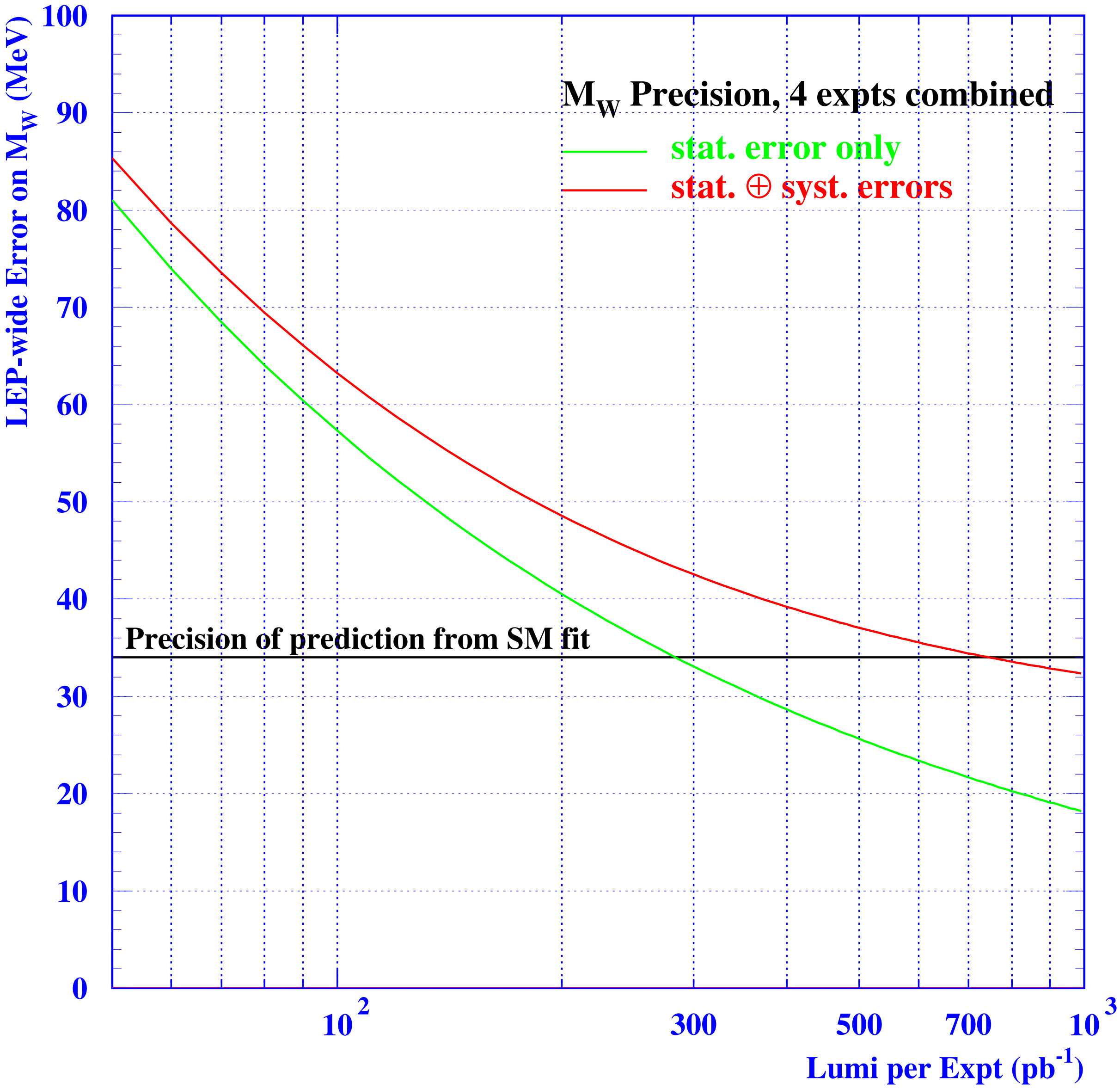
Single experiment statistical errors:



- $q\bar{q}\ell\nu$ and $q\bar{q}q\bar{q}$ have similar statistical power ($E_{CM} \lesssim 190$ GeV)
- No strong dependence of statistical error on E_{CM}, at least up to 190 GeV
- Systematic errors also not expected to depend strongly on E_{CM}

Luminosity Evolution of m_{W} Error

Luminosity is per experiment, m_{W} error is LEP-combined:



- Statistical errors are typical for current analyses
- Yellow book systematic errors
- Extrapolation for $E_{CM} \simeq 190$ GeV, but no strong E_{CM} dependence

Systematic Errors on m_{W}

How do we compare with the yellow book estimates?

Error	Yellow book	10pb^{-1} at 172 GeV (preliminary)
E_{beam}	12	30
ISR	10	$\lesssim 30$
fragmentation	16	$\lesssim 50$
backgrounds	6-12	$\lesssim 25$
detector	10	~ 50
fitting/MC stats	14	~ 50
"F.S.I."	–	~ 50
Total	~ 30	~ 100

(all in MeV)

Many errors limited by statistics in data and Monte Carlo

Much work remains to bring systematics to yellow book level, particularly for:

- Beam energy calibration
- Detector calibration (lepton momentum scale)
- Four-jet QCD backgrounds
- Fitting techniques
- Final-State Interactions: colour reconnection and Bose-Einstein

With work, we can still expect to reach yellow book errors...

Final-State Interaction Effects

Effects which may distort W decay product distributions, and so reconstructed W mass spectrum in $\mathrm{q\overline{q}q\overline{q}}$ events

Colour Reconnection

$\mathrm{W^+}$–$\mathrm{W^-}$ decay separation $\ll$ typical hadronisation scales

Many phenomenological studies of this effect:

- Mass shifts: 0-100 MeV in either direction
- Effects on soft particles might be measurable (y, N_{chg},...)
  $\longrightarrow$ possible experimental tests of models
- Models of event selections of varying realism
- No use of real experimental mass fits

More "experimental" work is needed and in progress

Bose-Einstein Effects

Symmetrisation of identical particle wavefunctions affects soft particle distributions

Could affect W mass spectrum

- First studies indicated possible shift $\mathcal{O}(100)$ MeV
  (Lönnblad & Sjöstrand)
- More recent reweighting studies indicate smaller effects $\mathcal{O}(20)$ MeV
  (Jadach & Zalewski, Kartvelishvili et al.)
- No conclusions yet

Potential to probe BE effects using data $\longrightarrow$

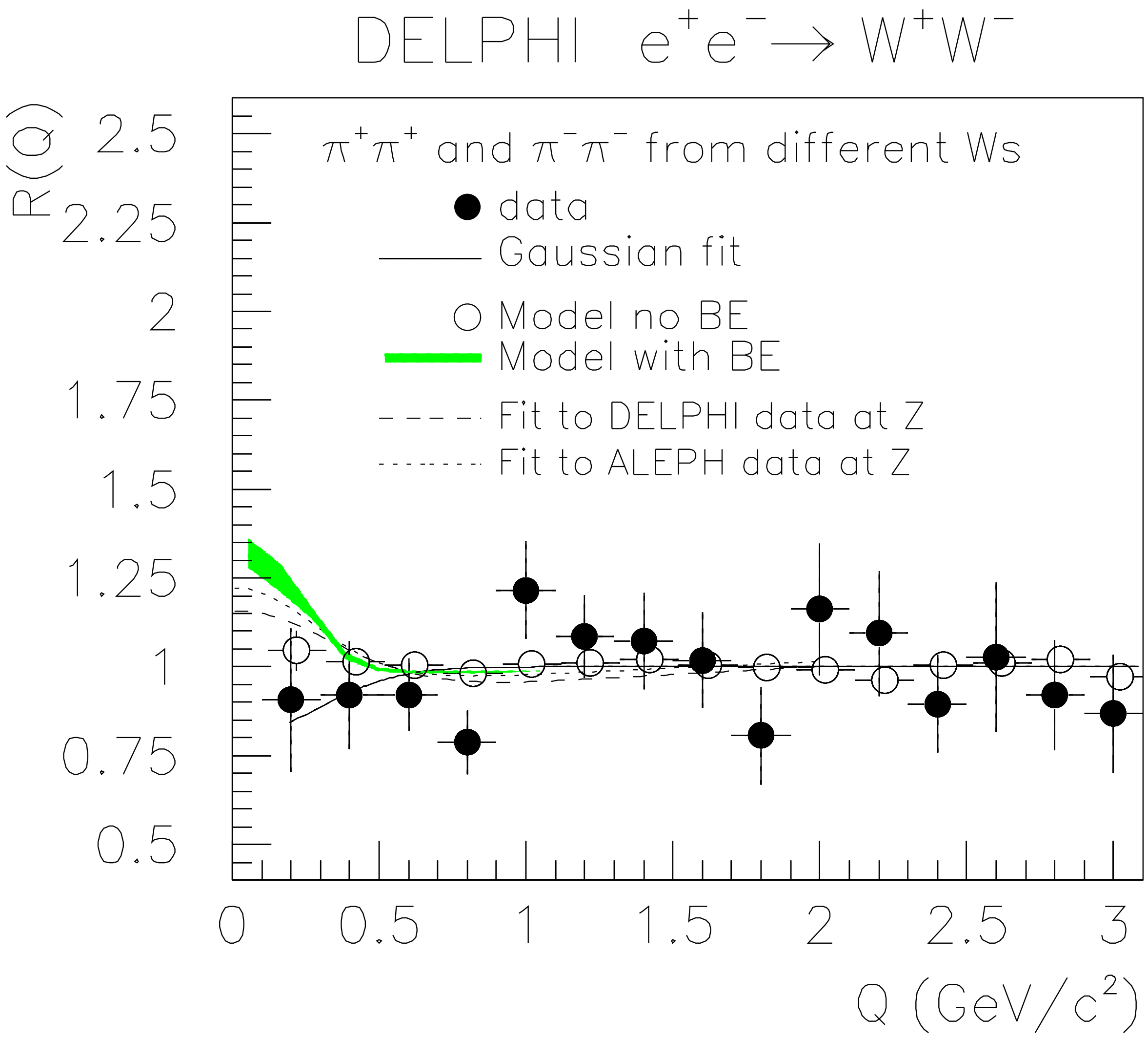
Bose-Einstein Correlations from Data?

(DELPHI: CERN-PPE/97-30)

Correlation function

$$R = \frac{N(\pi^+\pi^+ + \pi^-\pi^-)}{N(\pi^+\pi^-)}$$

where N's obtained by subtracting distribution for $\mathrm{q\overline{q}}\ell\nu$ events from that for $\mathrm{q\overline{q}q\overline{q}}$ events

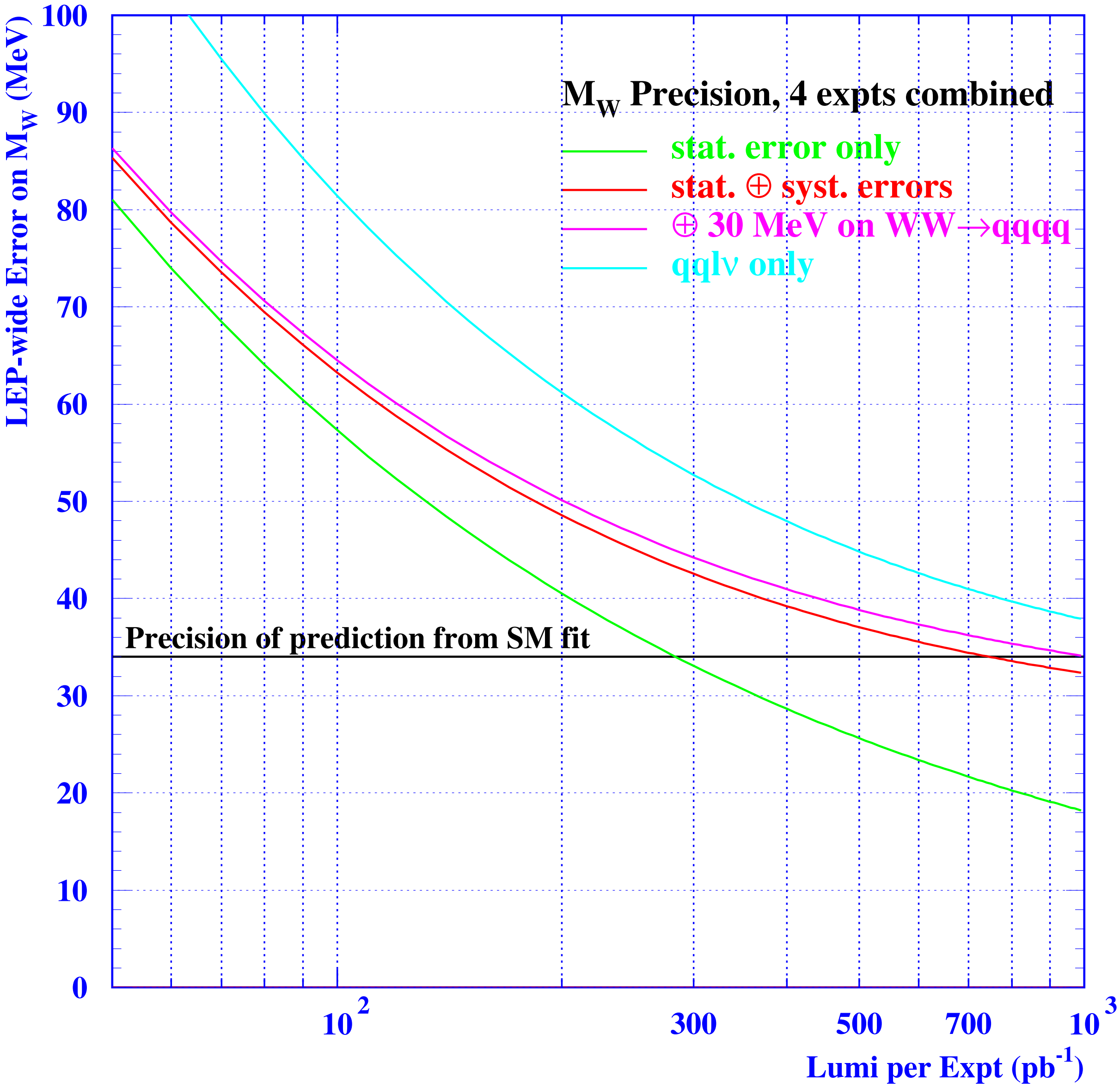


Present sensitivity is insufficient to distinguish models

promising technique for future

As illustration, add 30 MeV for final-state interaction effects:

(again luminosity is per experiment, m_W error is LEP-combined)



Summary of Measurements of m_{W}

Projected error on m_{W} in MeV for 4 experiments combined:

$\mathcal{L}$ per experiment	stat. only	YB errors	YB plus 30 on $\mathrm{q\bar{q}q\bar{q}}$	$\mathrm{q\bar{q}}\ell\nu$ alone
100 pb^{-1}	57	63	65	81
300 pb^{-1}	33	43	44	53
500 pb^{-1}	26	37	39	45

(all in MeV)

Error on *indirect* Standard Model prediction from EW measurements (including m_{top}):

$$\Delta m_{\mathrm{W}} \simeq \textbf{34 MeV}$$

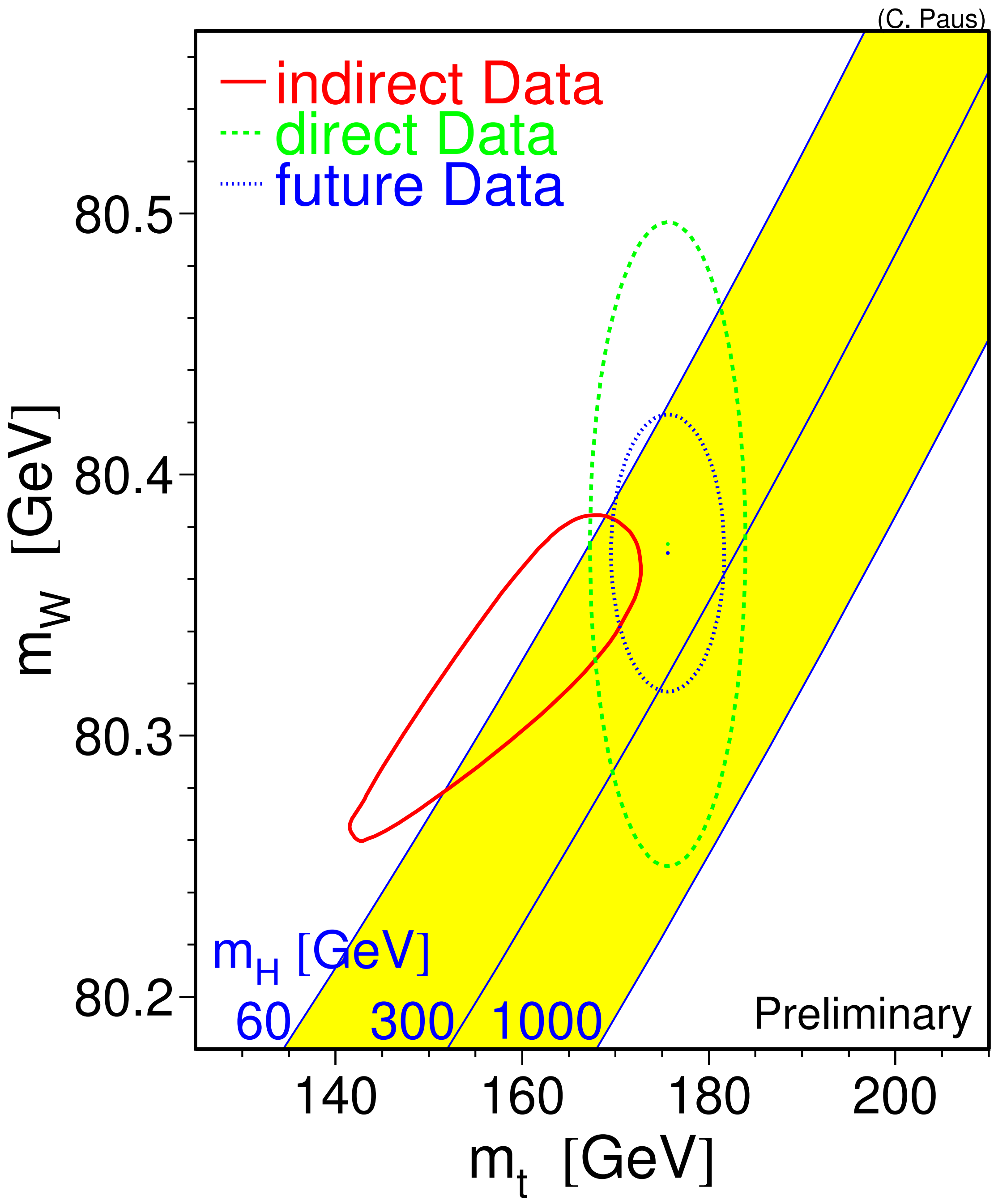
Current error from Tevatron of 100 MeV, which should drop to $\sim$ 80 MeV this year with full run-1 analyses

From threshold measurement, could obtain

+40 pb^{-1}	90 MeV
+90 pb^{-1}	70 MeV

Testing the Standard Model with m_W

If Δm_W=35 MeV and Δm_{top}=4 GeV (68% CL contours):



Vector Boson Self Interactions

Effective lagrangian for ZWW vertex (similar for γ):

$$e\cot\theta_W \quad [\quad (1+\Delta g_1^Z)Z^\mu(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + $$
$$(1+\Delta\kappa_Z)W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} Z^{\mu\nu}W^{+\rho}_\nu W^-_{\rho\mu} + \ldots \ ]$$

Anomalous coupling parameters **"TGC's"**, all 0 in SM:

$$\Delta g_1^Z, \Delta\kappa_\gamma, \Delta\kappa_Z, \lambda_\gamma, \lambda_Z$$

plus additional C,P,CP violating terms

Static electromagnetic properties of W:

- Electric charge: $Q_W = e$
- Magnetic dipole moment: $\mu_W = \frac{e}{2m_{\mathrm{W}}}(2+\Delta\kappa_\gamma+\lambda_\gamma)$
- Electric quadrupole moment: $q_W = \frac{-e}{m_{\mathrm{W}}^2}(1+\Delta\kappa_\gamma-\lambda_\gamma)$

Common LEP-2 parameterisation, motivated by operators not already constrained by LEP-1:

- $\alpha_{W\phi} = \Delta g_1^Z \cos^2\theta_W$
- $\alpha_{B\phi} = \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$
- $\alpha_W = \lambda_\gamma = \lambda_Z$

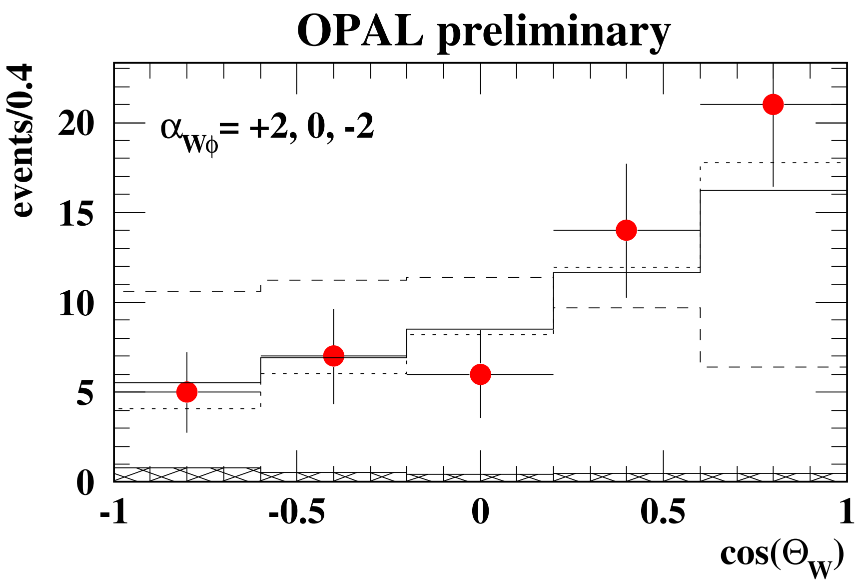
with $\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_1^Z$

Measuring the Triple Gauge Couplings

Fit to total WW cross-section and W production, decay angles:

- Needs W charge identification: main analysing power from $\mathrm{q\overline{q}}\ell\nu$
- Experimental challenges reconstructing W decay angles

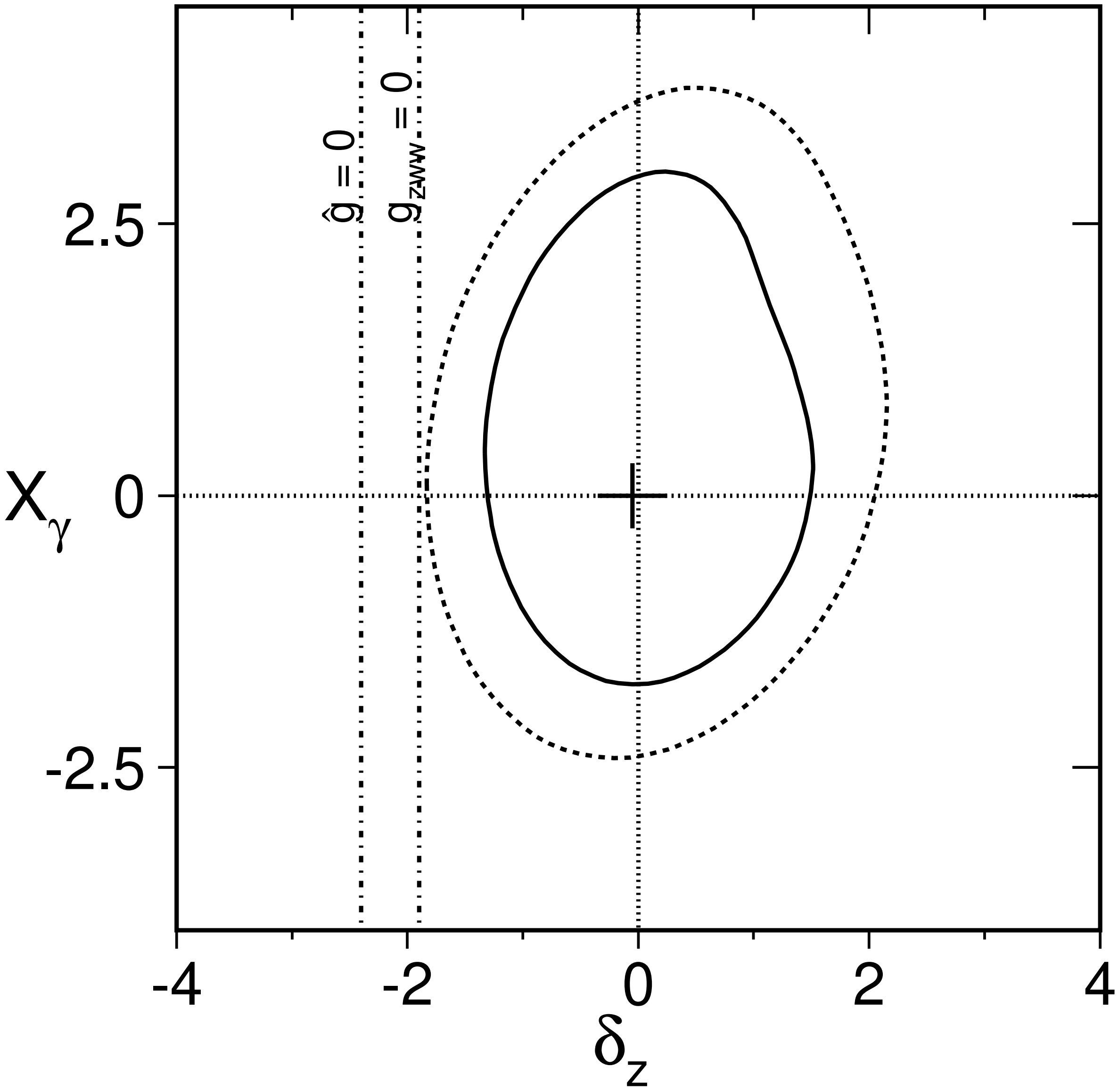
W production angular distribution:



- Simplest fits so far allow just 1 TGC to vary
- 2 (and 3) parameter fits also possible $\longrightarrow$

Systematic uncertainties dominated by detector effects: hard to predict, but reasonable to assume they can be kept below or at level of statistical precision

Example fit to two TGC's (from L3):



$$\delta_Z \equiv \Delta g_1^Z \,/\, \tan\theta_W$$

Precisions on α Parameters

- No detailed study of experimental attainable accuracy in yellow book: sensitivity studies performed for “ideal detector”
- Now first measurements with real detectors, backgrounds etc
  $\longrightarrow$ can calibrate degradation ideal$\rightarrow$real
- Find typical $\sim (20 \pm 20)\%$ degradation from ideal case

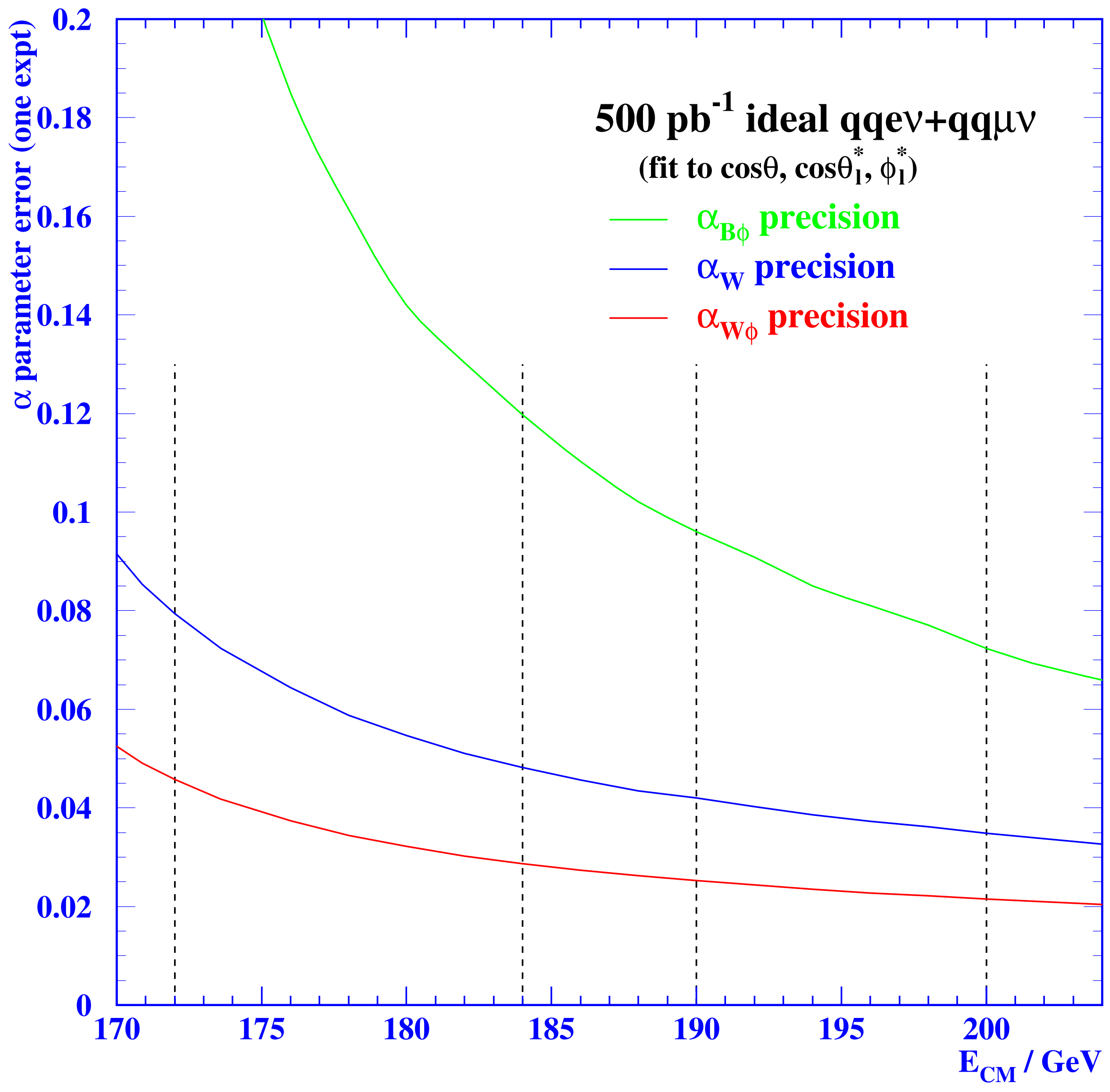
Statistical precisions attainable in 1-parameter fits (**ideal** case) per experiment:

	Sample	$\Delta\alpha_{W\phi}$	$\Delta\alpha_{B\phi}$	$\Delta\alpha_{W}$
I	50 pb^{-1} at 184 GeV	0.09	0.38	0.15
II	200 pb^{-1} at 190 GeV	0.040	0.15	0.067
III	150 pb^{-1} at 200 GeV	0.039	0.13	0.064
IV	I+2$\times$II	0.027	0.10	0.045
V	I+II+III	0.027	0.10	0.044

$\longrightarrow$

For TGC: 150 pb^{-1} at 200 GeV $\simeq$ 210-270 pb^{-1} at 190 GeV

E_{CM} Dependence of TGC Precision



TGC Comparisons

Comparison with Tevatron requires care: different parameters fitted

However:

- $\alpha_W = \lambda$ if $\alpha_{W\phi} = \alpha_{B\phi} = 0$
- Compare LEP sensitivity to $\Delta\kappa$ as fitted by CDF/D0, constraining $\delta g_1^Z = \lambda = 0$

Approximate comparison:

	κ	λ
D0 1997 (WW production)	0.2-0.3	0.2
LEP-2 (one expt)	0.04	0.04

Other Tevatron limits from $\mathrm{W}\gamma$ production:
similar sensitivity as new D0 result to λ, lower to κ

Other vector-boson self-coupling analyses at LEP-2:

- Sensitivity to $\mathrm{ZZ}\gamma$, $\mathrm{Z}\gamma\gamma$ couplings
- Sensitivity to C,P and CP-violating couplings
- Single-W production $\longrightarrow$ $\mathrm{WW}\gamma$-couplings

Fermion Pair Production

With 500pb^{-1} expect $\mathcal{O}$(10000) non-radiative $q\bar{q}$ events per expt. $\longrightarrow$

$$\frac{\Delta^{\rm stat}\sigma_{\rm non-rad}(q\bar{q})}{\sigma_{\rm non-rad}(q\bar{q})} \simeq 0.5\% \qquad \frac{\Delta^{\rm stat}\sigma_{\rm non-rad}(\mu^+\mu^-)}{\sigma_{\rm non-rad}(\mu^+\mu^-)} \simeq 1.5\%$$

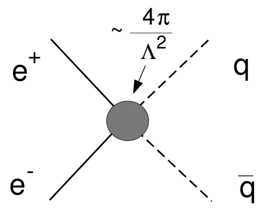
from 4 experiments combined – with work to keep systematics low

Examples of impact:

- S-matrix formalism: γZ interference term floats

	Δm_Z (MeV)
LEP-1 alone **SM fit**	1.9
LEP-1 + current data **S-matrix**	3.3
LEP-1 + 0.5% $\sigma(q\bar{q})$ at 190 GeV **S-matrix**	2.0

- Contact interactions



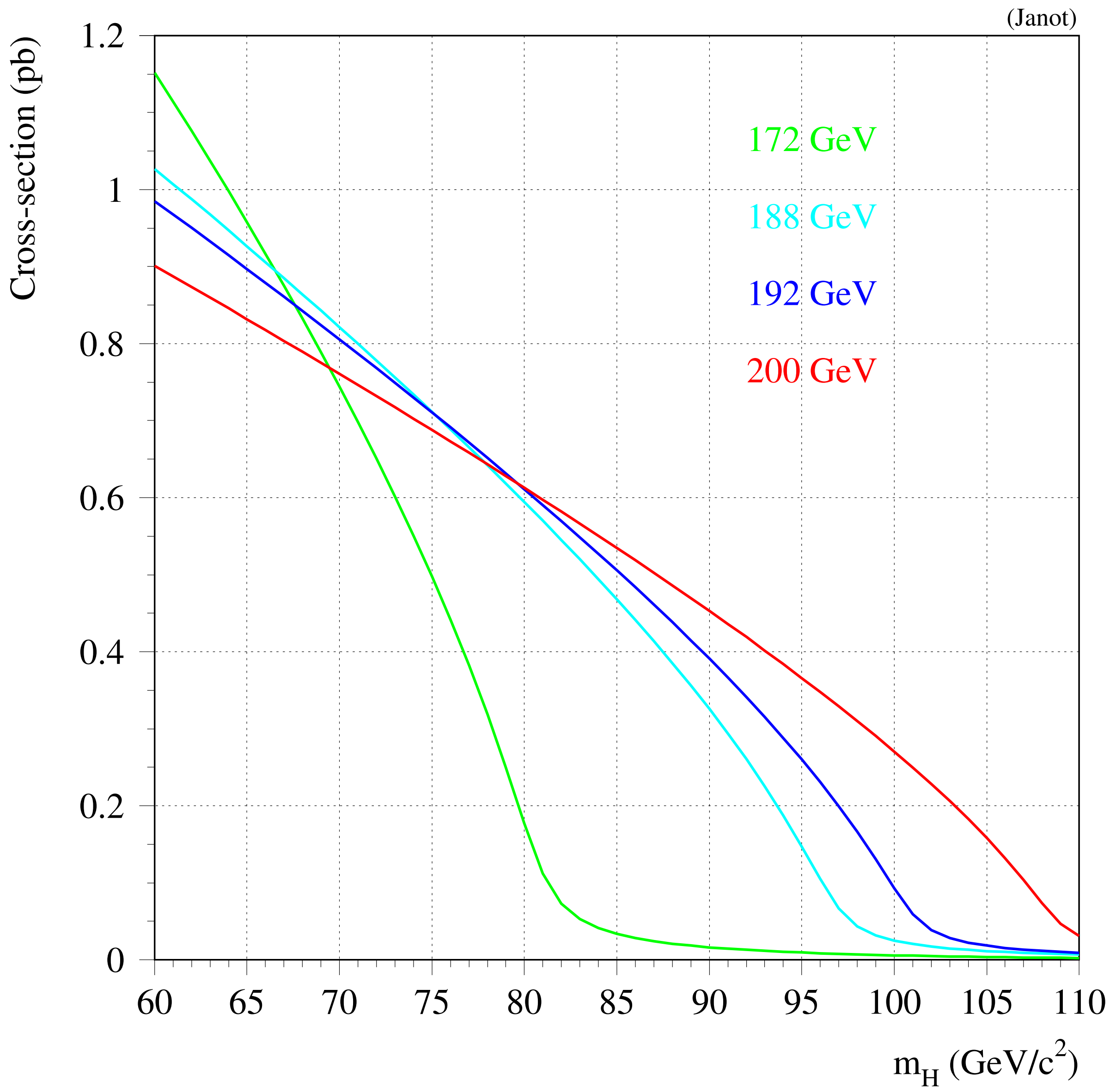
$$\mathcal{L}_{\rm contact} = \frac{4\pi}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij} [\bar{e}_i \gamma^\mu e_i][\bar{f}_j \gamma_\mu f_j]$$

95% CL Λ limits (TeV)	$q\bar{q}$ contact interaction			
i, j $(\eta = +1, -1)$	LL	RR	LR	RL
LEP-1.5+1996 data (OPAL prel.)	2.8,2.1	2.3,2.5	2.4,2.4	2.0,2.9
+ 100 pb^{-1} at 184 + 400 pb^{-1} at 188	7.3,3.3	3.8,6.3	4.4,5.3	2.7,8.6
+ 100 pb^{-1} at 200	7.6,3.3	3.8,6.5	4.5,5.5	2.8,9.0

(limits are for one experiment, stat. errors only for extrapolations)

Higgs Search

Expected H production cross-section (ZH plus boson fusion):

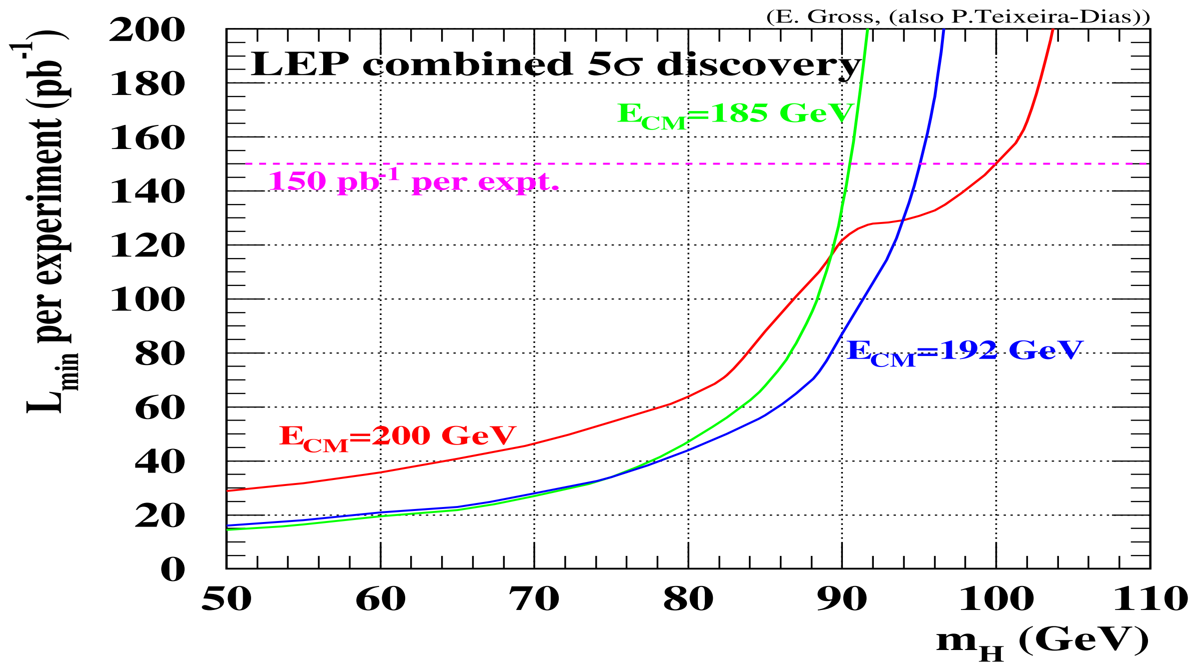


- ZH production dominates over boson fusion process at LEP-2 energies
- ZZ background becomes significant at high E_{CM}, $m_{\rm H} \simeq m_{\rm Z}$:
  $\sigma({\rm e^+e^-} \rightarrow {\rm ZZ} \rightarrow {\rm b\bar{b}}X) \simeq 0.24$ pb at 200 GeV

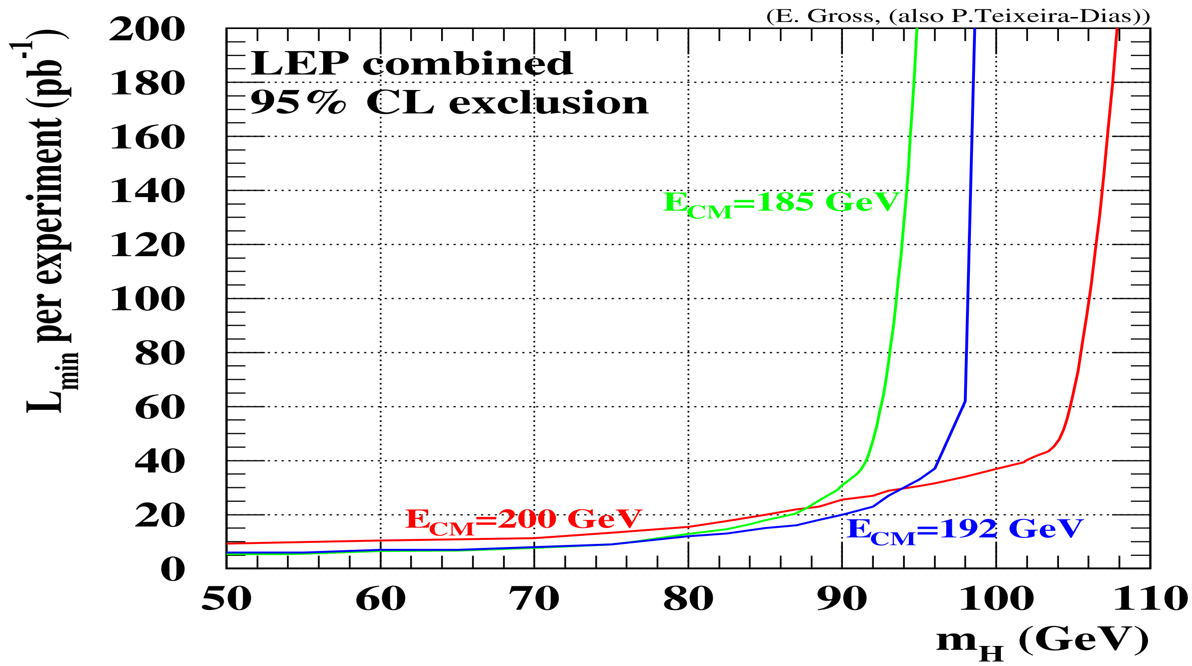
Standard Model Higgs Mass Reach

Sensitivity studied during the LEP workshop, as reported in the yellow book

5σ case : "Solid" discovery potential



95% CL limit case : relatively weak exclusion potential



Caveat:

Sensitivity at 200 GeV has not been studied in detail: limits here rely on extrapolation from 205 GeV

SM Higgs Mass Reach: Summary

Mass reaches for LEP combined, integrated luminosity per expt:

Sample	95% CL exclusion	5σ discovery
50 pb^{-1} at 184 GeV	91 GeV	80 GeV
200 pb^{-1} at 192 GeV	99 GeV	96 GeV
100 pb^{-1} at 200 GeV	106 GeV	87 GeV
150 pb^{-1} at 200 GeV	106 GeV	100 GeV

- For 95% CL exclusion, 50-70 pb^{-1} per experiment is enough for limit close to sensitivity “wall”
- This level of sensitivity could also give a first hint if there is a signal
- But, for 5σ discovery at high energy, need substantial ($\gtrsim$ 150 pb^{-1}) luminosity

Summary

With 500 pb^{-1} at $\gtrsim$184 GeV:

- $\Delta m_{\mathrm{W}} \simeq$ 30-40 MeV – precision close to that of other precise electroweak observables for SM fits
- Non-Abelian gauge structure (TGC) tested at level of 0.02-0.1
- Contact interaction sensitivity to Λ $\sim$3-7 TeV
- SM Higgs mass reach depends critically on E_{CM}
  $\sim$96 GeV for 200 pb^{-1} at E_{CM} =192 GeV
  $\sim$100 GeV for 150 pb^{-1} at E_{CM} =200 GeV

W mass	$\mathcal{L} \gtrsim$ 500 pb^{-1} to match predicted m_{W}
TGC	$\mathcal{L}$ and E_{CM} both matter
Contact Int.	$\mathcal{L}$ and E_{CM} both matter
Higgs	E_{CM} crucial, provided $\mathcal{L} \simeq$ 150 pb^{-1}

With 150 pb^{-1} at a highest energy of $E_{CM} \simeq$ 200 GeV:

- SM Higgs 5σ discovery mass reach should extend to 100 GeV
- SM Higgs 95% CL exclusion mass reach should extend to 106 GeV