Recent results from the L3 experiment

A tale of many couplings

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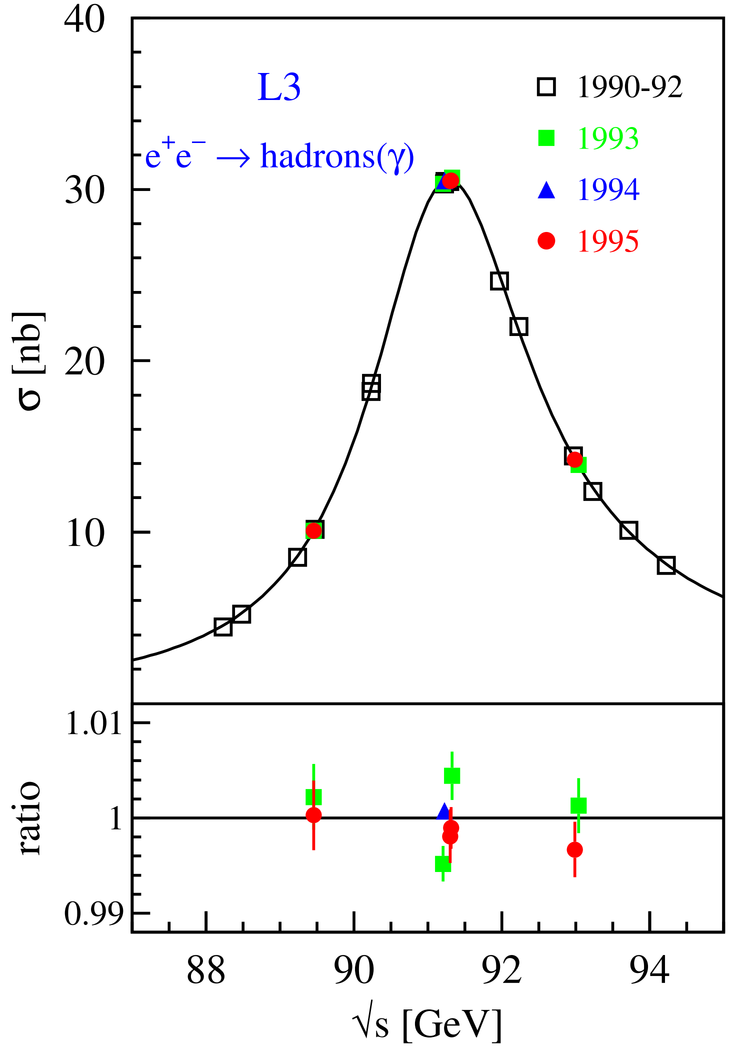
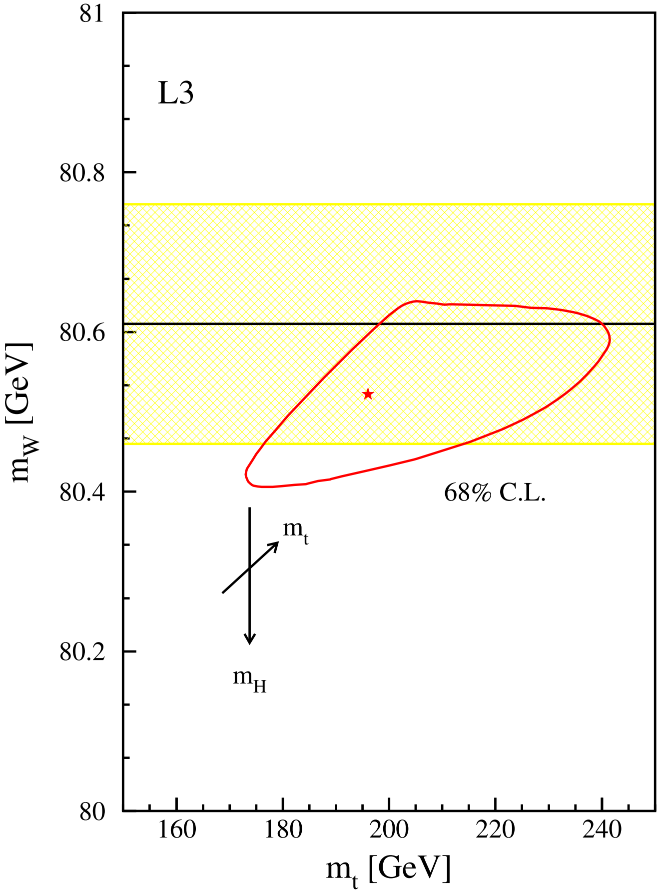
FNAL, March 17 2000

- Fermion-pair production
- Boson-pair production
- Extra dimensions?

Final Lineshape Results

$m_Z = 91189.8 \pm 3.1$ MeV
$\Gamma_Z = 2502.4 \pm 4.2$ MeV





using m_t; m_W from
$\sqrt{s} \leq 183$ GeV:
$m_H < 133$ GeV at 95% C.L.

Data collected

Integrated luminosity collected above the Z resonance:

$\sqrt{s}$ (GeV)	$\int \mathcal{L}dt$ (pb^{-1})	year
130.0	6.1	'95,'97
136.0	5.9	'95,'97
161.3	10.9	'96
172.1	10.3	'96
182.7	55.5	'97
188.7	176.8	'98
191.6	29.7	'99
195.5	83.7	'99
199.5	82.8	'99
201.7	37.0	'99
Total	499	

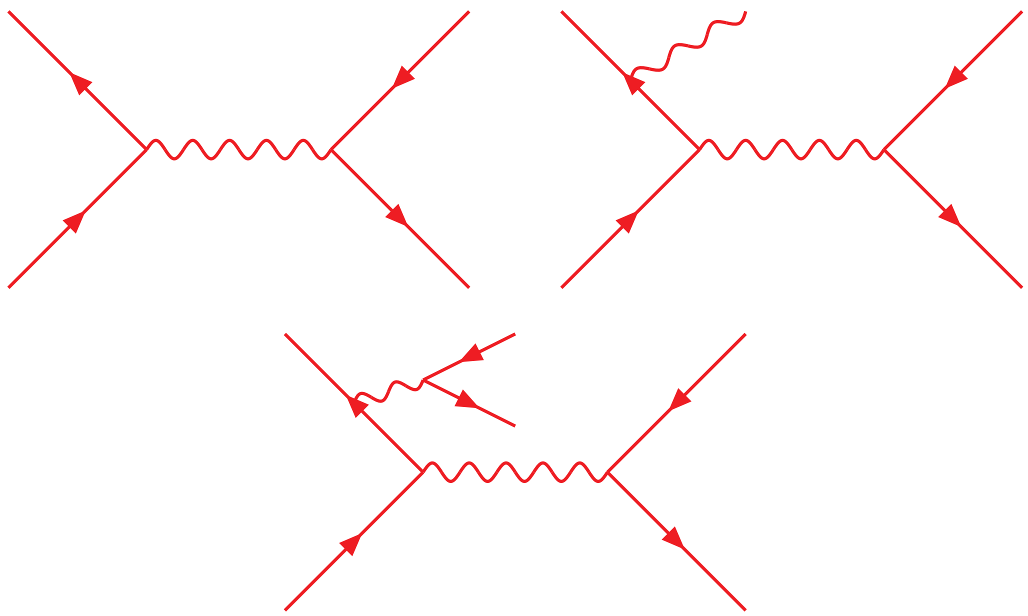
Exceeded expectations! LEP startup in a couple of weeks...

Status of most data analyses: as for Winter conferences

WWW: http://l3www.cern.ch/conferences/Moriond2000

Fermion-Pair Production

Fermion-pair production above the Z resonance:
'Lose' one order in rad. corrections ➡ need $\mathcal{O}(\alpha^2)$



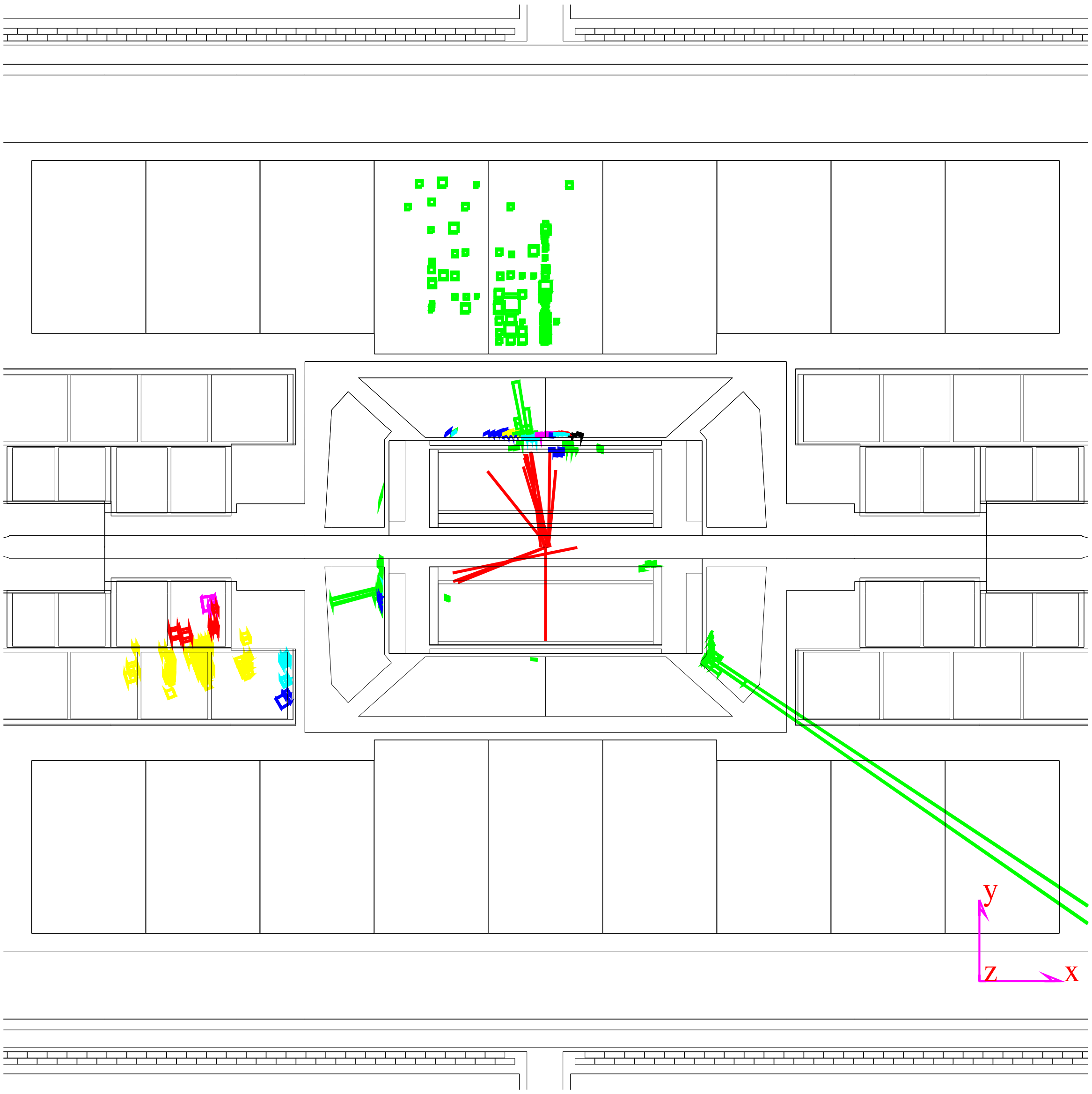
Separate interesting genuine 'high-energy' events from 'radiative returns' by means of cut on $\sqrt{s'}$ (*effective* CM energy of annihilation):

Channel	high-energy	inclusive
hadrons	$\sqrt{s'} > 0.85\sqrt{s}$	$\sqrt{s'} > 60$ GeV
$\mu^+\mu^-, \tau^+\tau^-$	$\sqrt{s'} > 0.85\sqrt{s}$	$\sqrt{s'} > 75$ GeV
e^+e^-	$\zeta < 25°$	$\zeta < 120°$

Main output: 'total' cross sections & forward-backward asymmetries

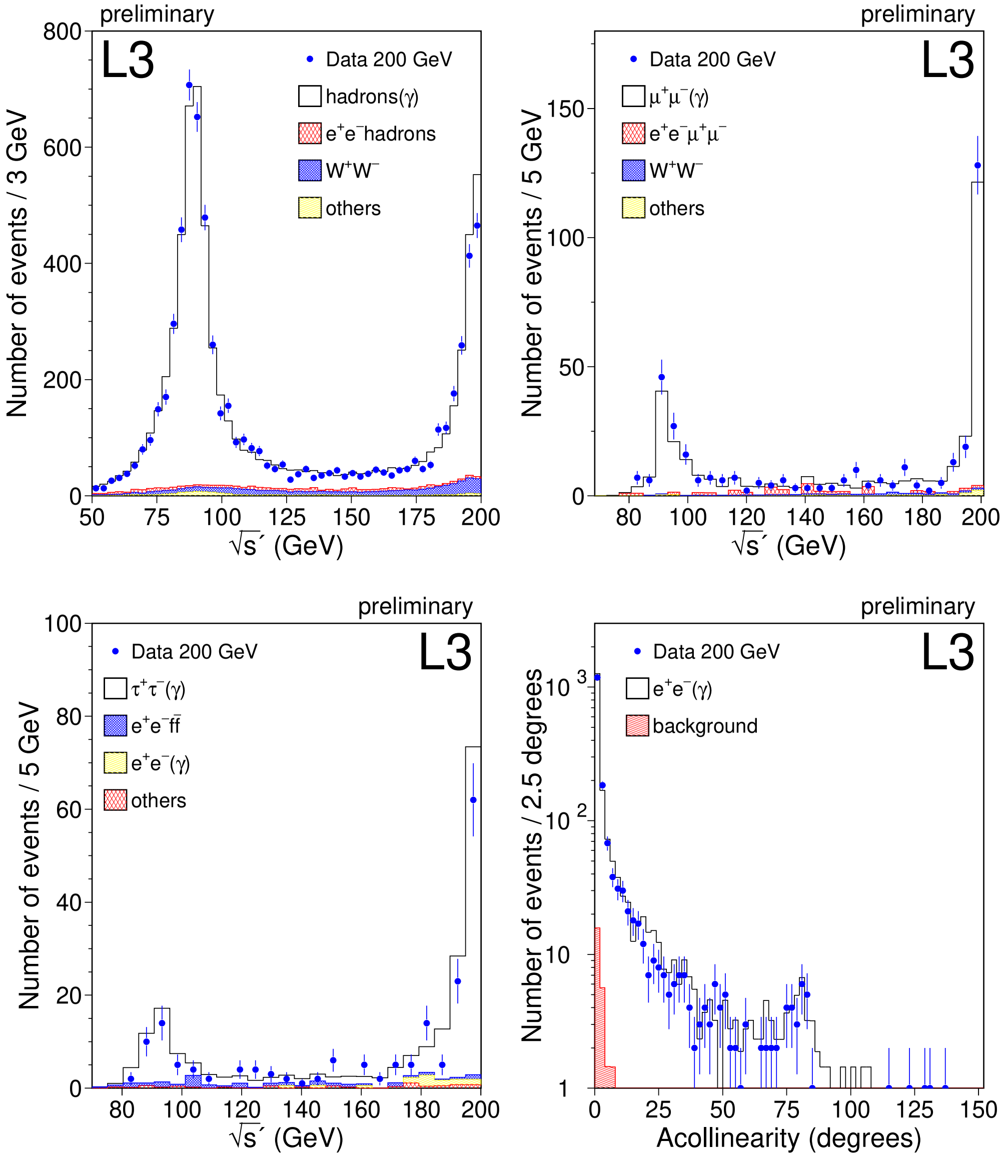
Fermion-pair production

Run # **765202** **Event #** **1940** Total Energy : 200.75 GeV



Transverse Imbalance : .0193		**Longitudinal Imbalance :** -.0374	
Thrust : .8052	**Major :** .4487	**Minor :** .0157	
Event DAQ Time :	*990803 11255*		

s' reconstruction

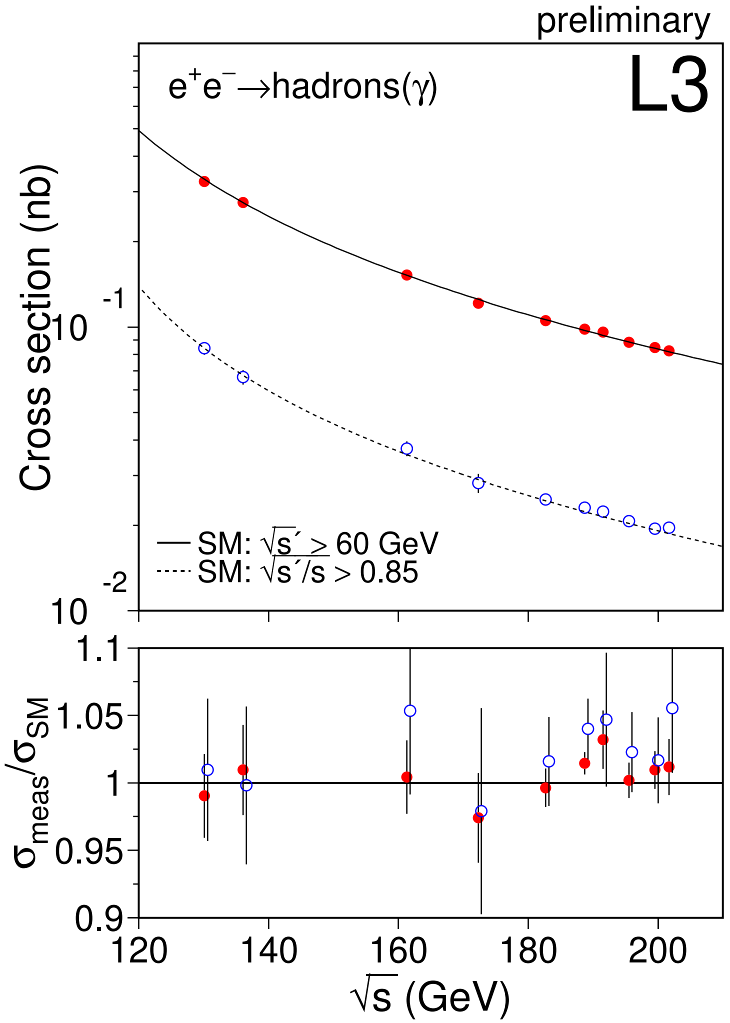


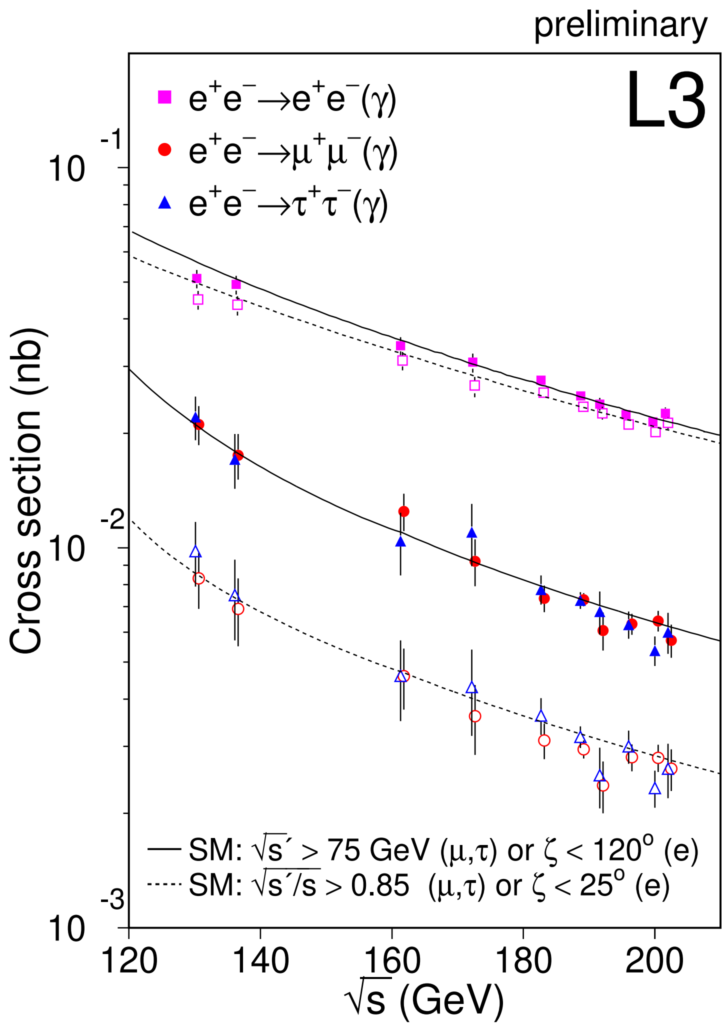
To find photons escaping along beam lines: kinematic fit or from polar angles of final-state f, $\bar{f}$

Initial-state radiation: at small angles w.r.t. beam direction and/or far away from final-state fermions

Correct to world w/o ISR-FSR interference (s' ill-defined otherwise): $\mathcal{O}(1\%)$. Include soft pair corrections.

Cross section measurements

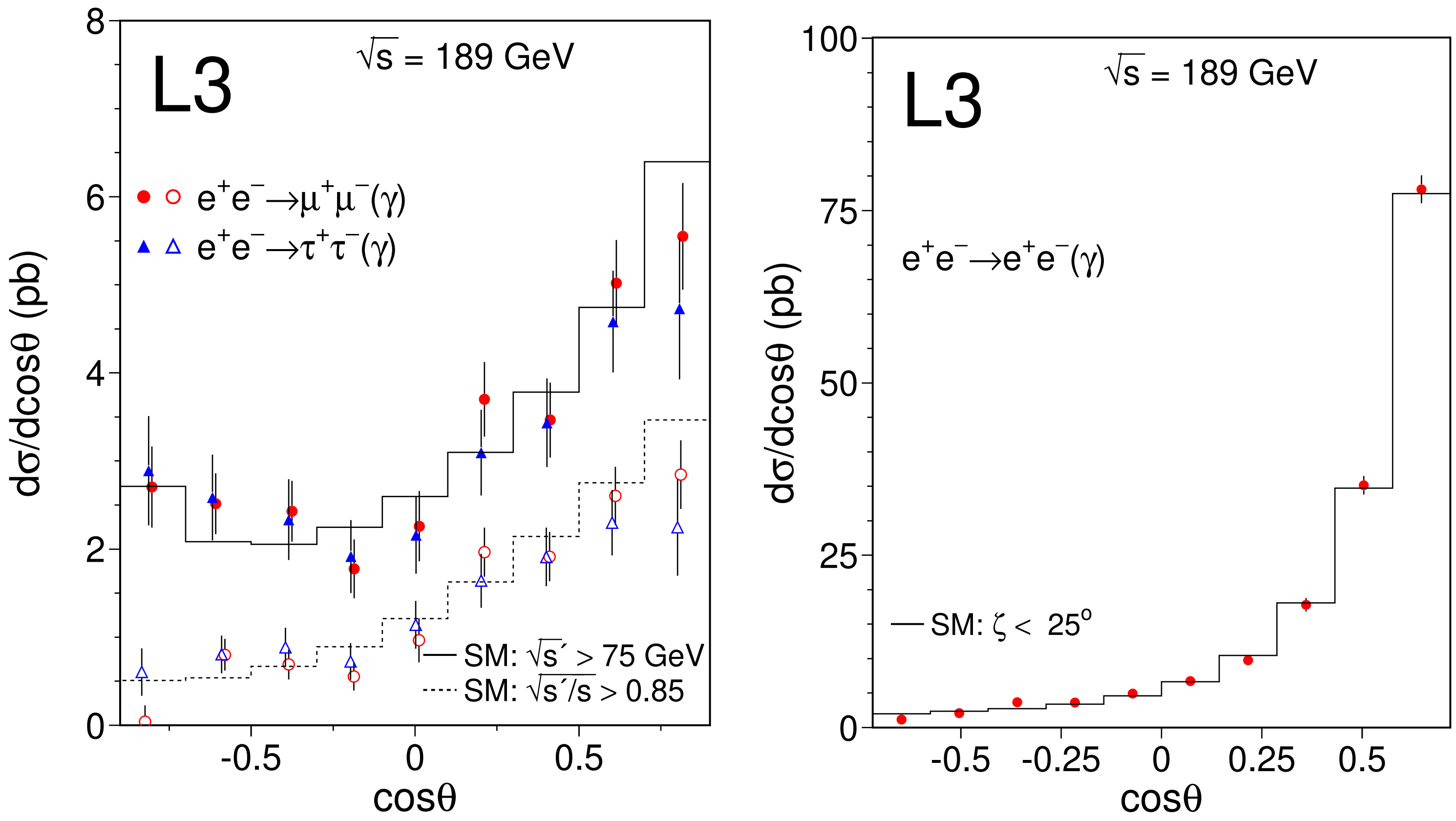




A_{FB} measurements

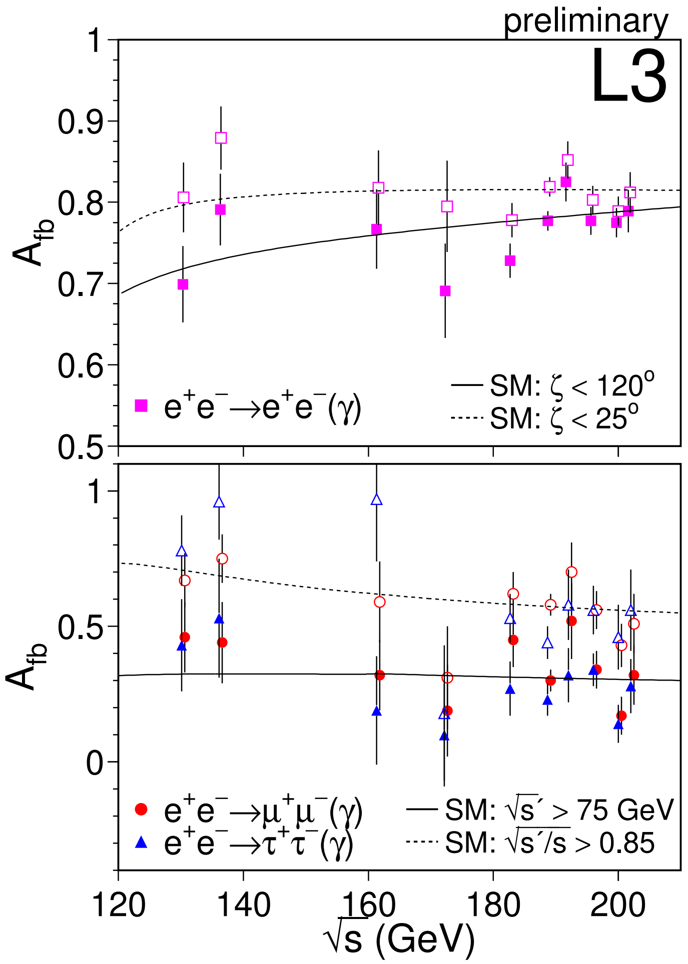
e^+e^- (and inclusive $\mu^+\mu^-$, $\tau^+\tau^-$) differential cross sections not described by

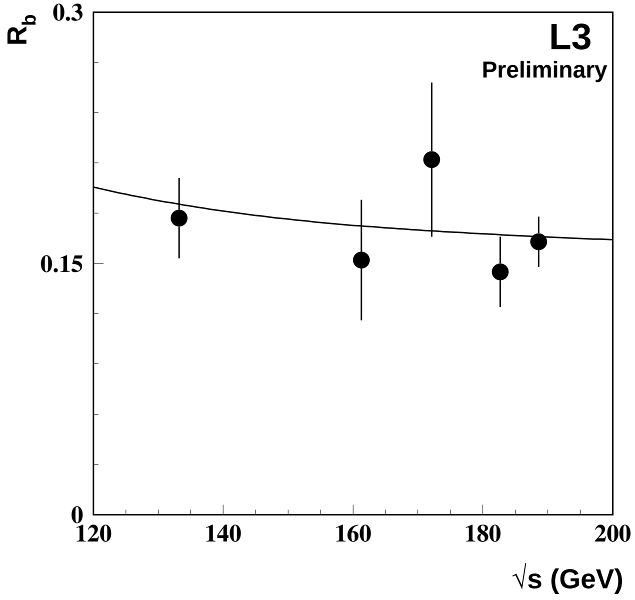
$$d\sigma/d\cos\theta \sim \frac{3}{8}(1+\cos^2\theta) + A_{FB}\cos\theta$$



added benefit: higher sensitivity to new-physics models

A_{FB}, R_b measurements





B-tag tuned on Z peak

Standard Model fits

S-Matrix framework:

$$\sigma_f^{0,a}(s) = \frac{4}{3}\pi\alpha^2 \left(\frac{g_f^a}{s} + \frac{j_f^a(s-\bar{m}_Z^2) + r_f^a}{(s-\bar{m}_Z^2)^2 + \bar{m}_Z^2\bar{\Gamma}_Z^2} \right), \qquad , a = \mathrm{tot}, \mathrm{FB}$$

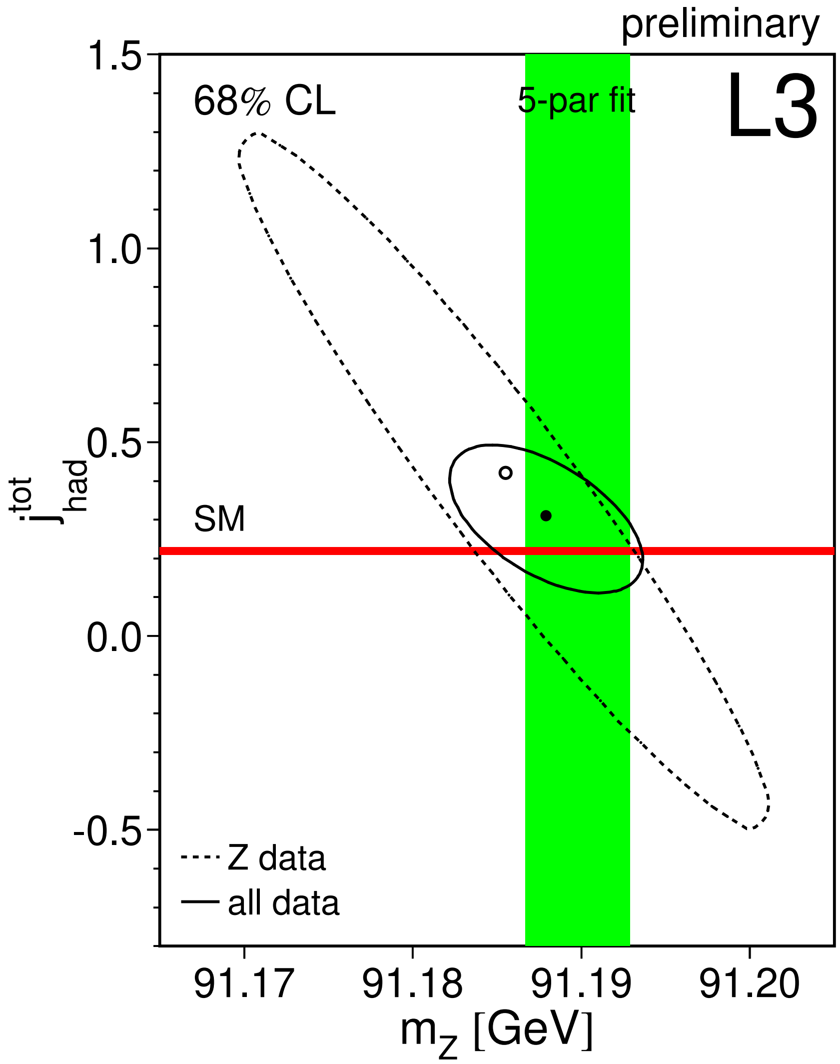
Connection with coupling constants:

$$\begin{aligned} g_f^{\mathrm{tot}} &\sim Q_e^2 Q_f^2, & g_f^{\mathrm{FB}} &= 0, \\ j_f^{\mathrm{tot}} &\sim g_{Ve} g_{Vf} Q_e Q_f, & j_f^{\mathrm{FB}} &\sim g_{Ae} g_{Af} Q_e Q_f, \\ r_f^{\mathrm{tot}} &\sim (g_{Ve}^2 + g_{Ae}^2)(g_{Vf}^2 + g_{Af}^2), & r_f^{\mathrm{FB}} &\sim g_{Ve} g_{Ae} g_{Vf} g_{Af} \end{aligned}$$

Plus. . .

- Allows fit without fixing γ/Z interference terms
- Small corrections to conform to LEP1-type definitions of m_Z, Γ_Z
- 'Usual' application of radiative corrections

Standard Model fits

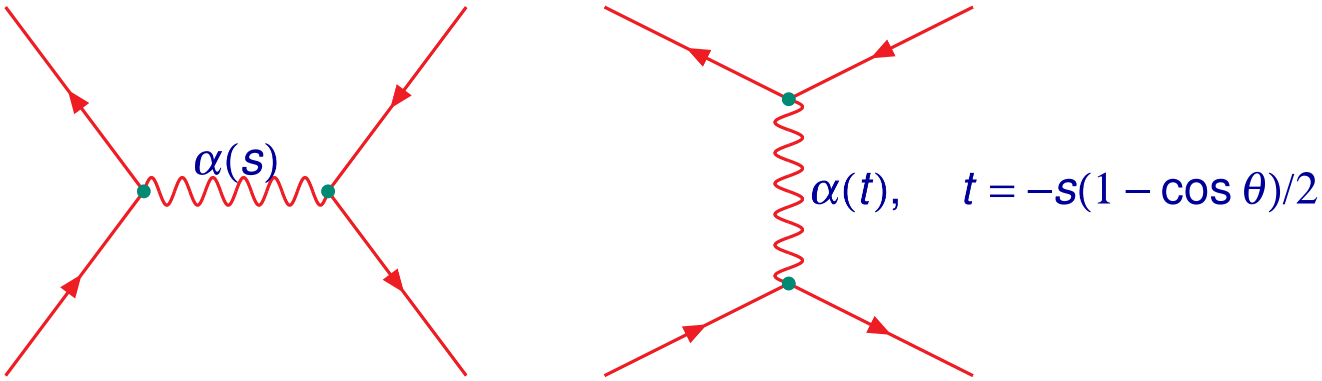


Data sample	m_Z(GeV)	j^{tot}_{had}
Z data	91185.2±10.3	0.44±0.59
all data	91187.9± 3.8	0.30±0.13

cf. 3.1 MeV uncertainty on m_Z in ‘standard’ fit

Fine structure constant

- $\alpha^{-1}_{\mathrm{QED}}(m^2_{\mathrm{Z}}) = 128.878 \pm 0.090$ limits sensitivity of Standard Model fits
- awaiting fundamental improvement by high-precision cross section measurement for low-energy $\mathrm{e^+e^-} \to$ hadrons



Usual parametrisation: $\alpha^{-1}_{\mathrm{QED}}(Q^2) = \alpha^{-1}(1 - \Delta\alpha(Q^2))$

When dominated by single QED diagram: clean extraction of $\alpha_{\mathrm{QED}}(Q^2)$.
First measurement by TOPAZ: compare $\mathrm{e^+e^-} \to \mu^+\mu^-$ and $\mathrm{e^+e^-} \to \mathrm{e^+e^-}\mu^+\mu^-$ scattering

$$\alpha^{-1}_{\mathrm{QED}}((57.77\ \mathrm{GeV})^2) = 128.6 \pm 1.6$$

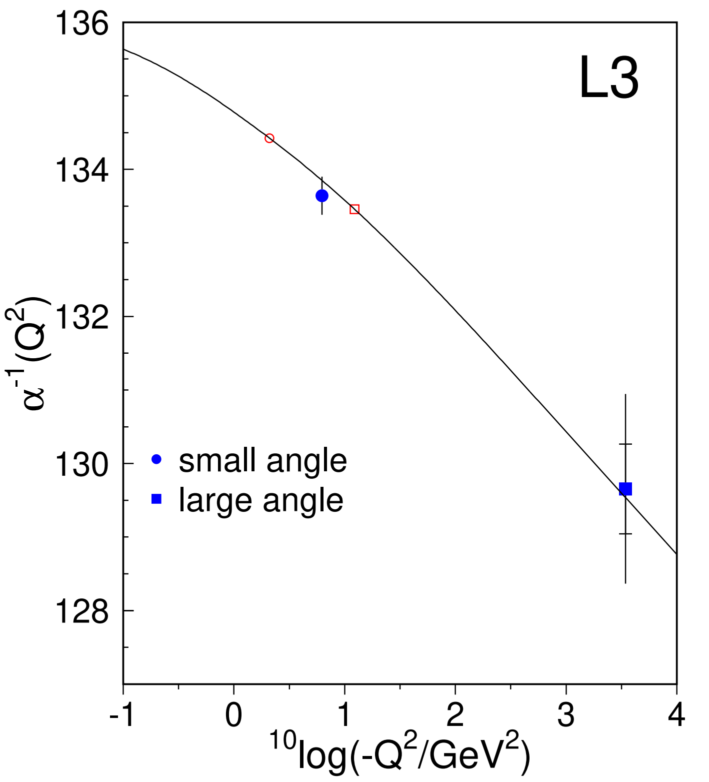
Measurement by VENUS using Bhabha scattering

Contribution by LEP?

Fine structure constant

Precise measurement of differential Bhabha scattering cross section:

- small-angle data (32–54 mrad) used for luminosity measurement at LEP1:
  no absolute cross section measurement (same data used for normalisation)
  ➡ measure only shape:
  - parametrise using add'l linear term in $\Delta\alpha_{\mathrm{QED}}(Q^2)$
  - binned ML fit comparing #events in 4 bins with predictions
- large-angle data (20–36°) at $\sqrt{s} = 189$ GeV: single cross-section measurement.
  - parametrise using constant multiplying $\Delta\alpha(Q^2)$



Measurements unfortunately systematics-limited. . .

New Physics searches

Sensitive searches for New Physics phenomena:
Possible because of smallness of SM cross sections!

General approach: *helicity* amplitudes

$$\frac{d\sigma}{d\Omega} = \sum_{i,j=L,R} \frac{d\sigma^{ij}}{d\Omega},$$

$$\frac{d\sigma^{ij}}{d\Omega} \sim \left| A^{ij}_{SM} + A^{ij}_{\text{new physics}} \right|^2$$

with L,R denoting fermion helicities
(helicity-conserving interactions only)

Analysis procedure:

- Use high-energy cross sections, asymmetries only
  Differential leptonic cross sections in most models add marginal sensitivity
- Add QED corrections as for SM terms
- Apply χ^2 or ML fit (correlated syst. uncertainties have small effect)
- Derive 95% C.L. limits from $\Delta\chi^2 = 3.84$

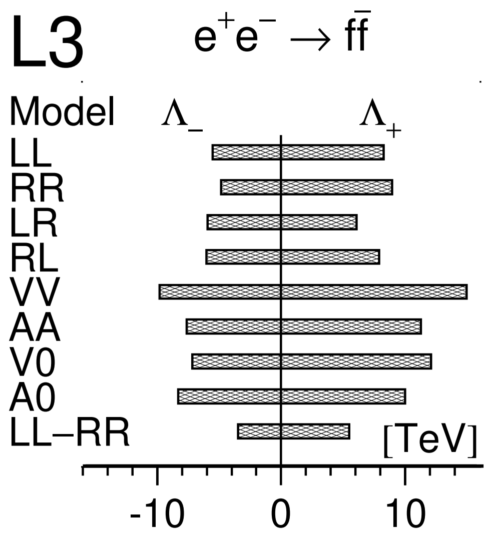
Contact Interactions

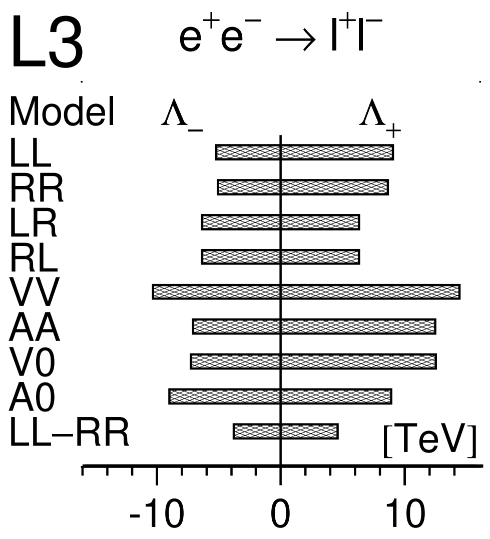
<u>Four-fermion interactions:</u>
Low-energy manifestation of heavy-particle exchange

$$\mathcal{L} = \frac{1}{1+\delta_{ef}} \sum_{i,j=\mathrm{L,R}} \eta_{ij} \frac{g^2}{\Lambda^2} (\bar{e}_i \gamma_\mu e_i)(\bar{f}_j \gamma^\mu f_j)$$

By convention: largest $|\eta_{ij}| = 1$, $g^2/4\pi = 1$
➡ Set limits on Λ

Assume contributions to various channels: e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $\ell^+\ell^-$, $u\bar{u}$,$d\bar{d}$, $q\bar{q}$, $b\bar{b}$
and according to various models: η_{ij}
Within each model: sign choice





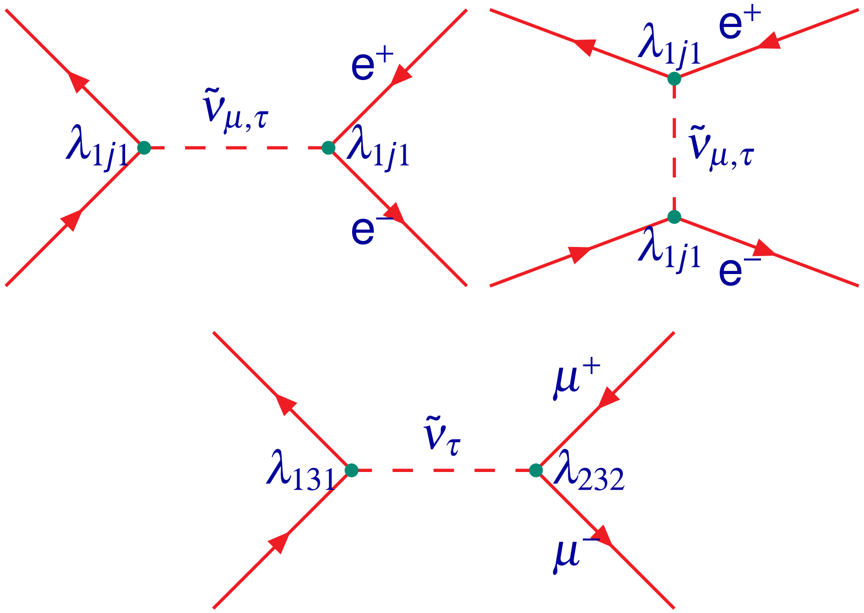
Squarks and Sneutrinos

Lepton terms in most general super-potential in R-parity violating SUSY:

$$W = \lambda_{ijk} L^i_L L^j_L \bar{E}^k_R + \lambda'_{ijk} L^i_L Q^j_L \bar{D}^k_R$$

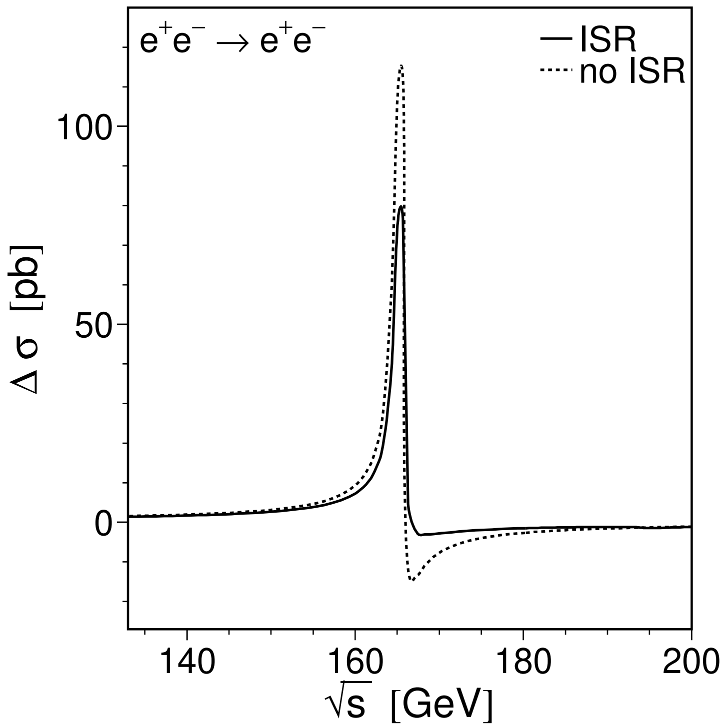
with $\lambda_{ijk} = -\lambda_{jik}$

giving rise to additional amplitudes in $e^+e^- \to \ell^+\ell^-$:



Resonant behaviour for s-channel $\tilde{\nu}$ exchange

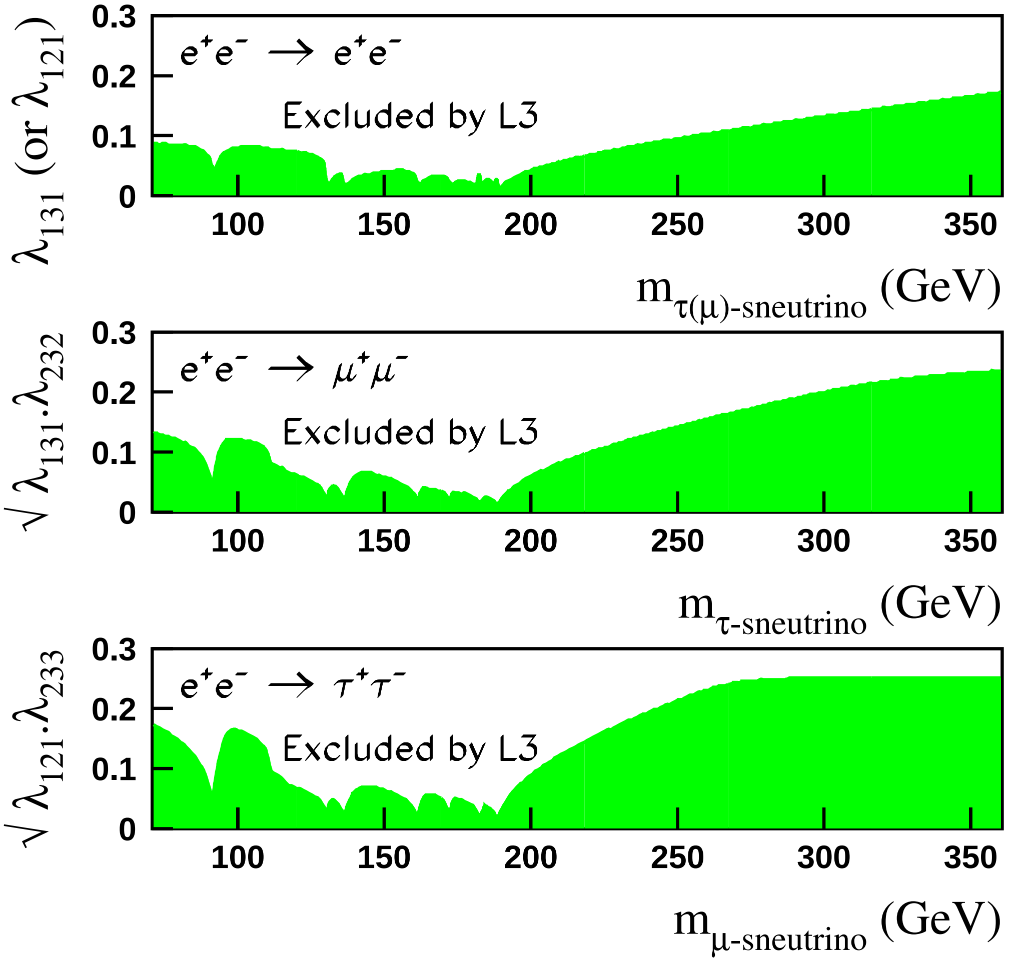
e.g. for $m_{\tilde{\nu}_\tau}, m_{\tilde{\nu}_\tau} = 165$ GeV:



$\tilde{q}$ exchange only in t, u channels
➡reduces to CI analysis
(similarly for leptoquarks)

Squarks and Sneutrinos

Derive limits on coupling constants as function of $\tilde{\nu}$ mass:

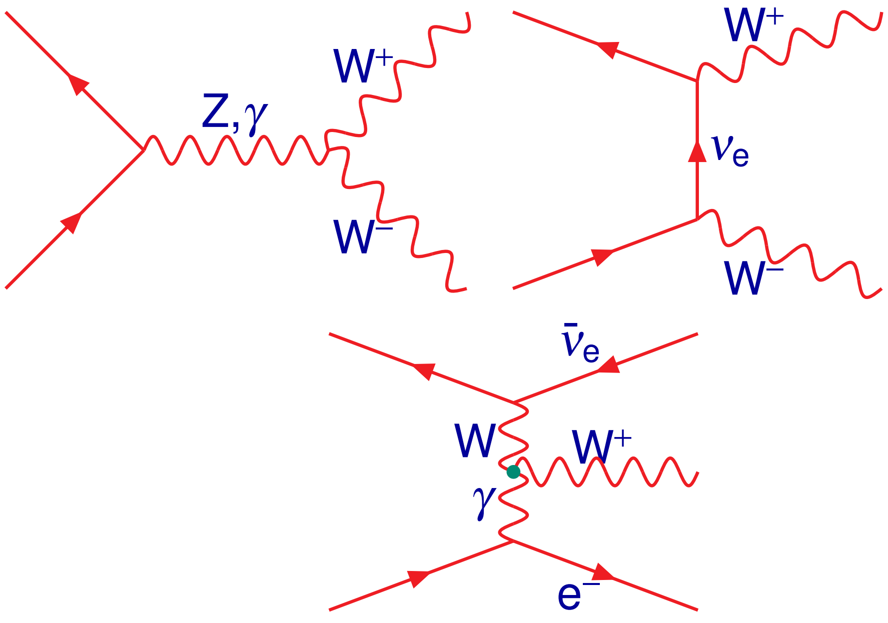


Also: Z', fermion radii

W-pair production

W⁺W⁻ reconstructed in all possible decay modes:

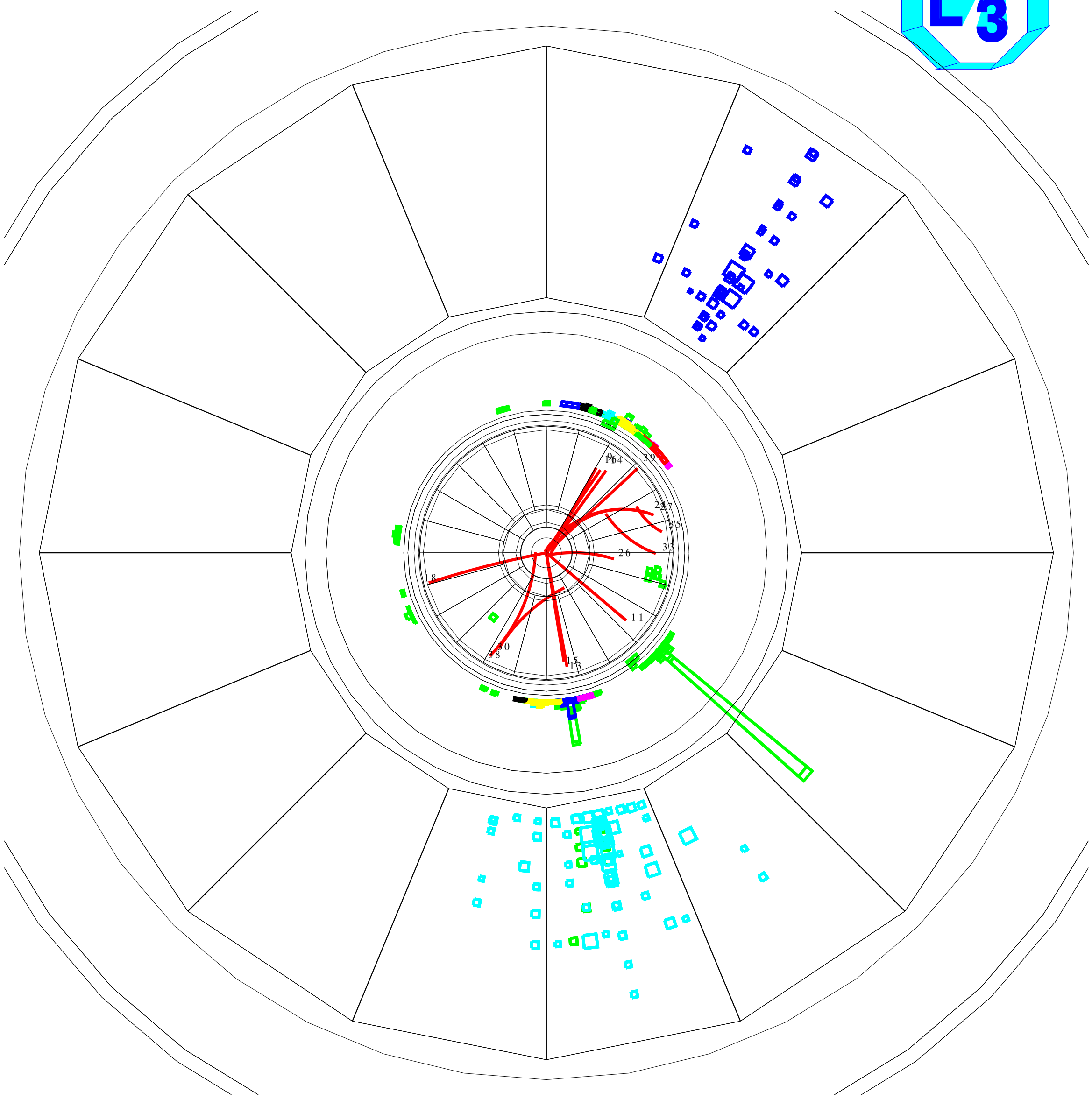
- **hadronic:**
  - clustered into 4 jets (Durham)
  - 4C kinematic fit
  - jet pairing: disregard combination yielding smallest mass sum, then take combination with smallest mass difference
- **semi-leptonic:**
  - $qqe\nu$: phase space cuts ($E_{e,\nu}$, $|\cos\theta_{e,\nu}|$, $m_{e\nu}$ to define signal region
  - mis-identification $\tau \leftrightarrow \mu, e$ ➡ coupled set of linear equations to extract individual cross-sections (correlations $\lesssim 15\%$)
  - convert to CC03 cross section using SM calculation ($1 \pm 10\%$)



- **leptonic:**
  - phase space cuts to define signal (CC56+NC56)
  - coupled equations

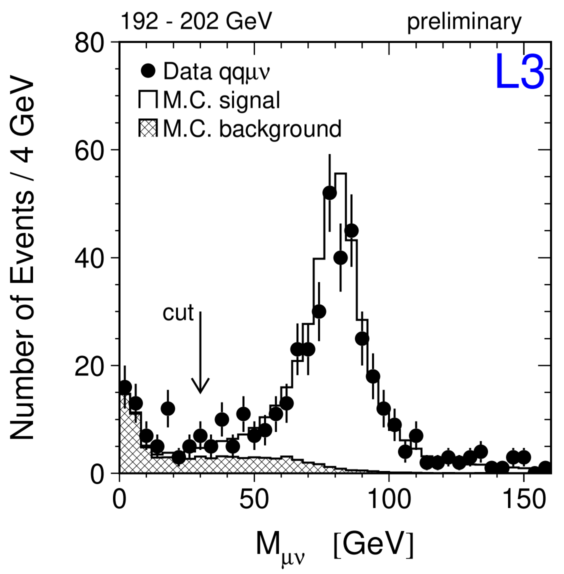
W-pair production

Run # 764803 Event # 3795

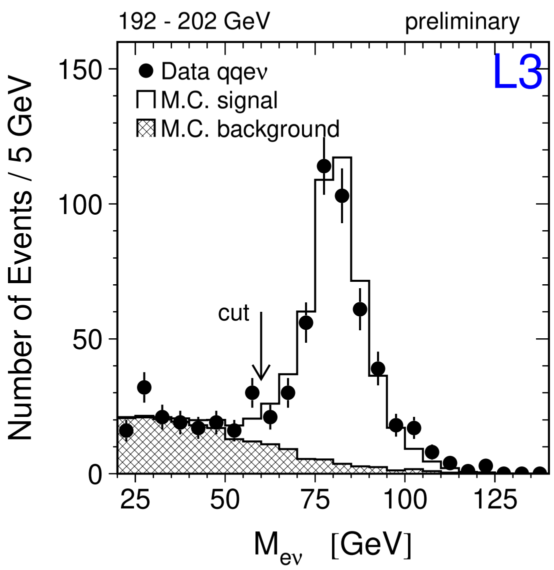


W-pair production

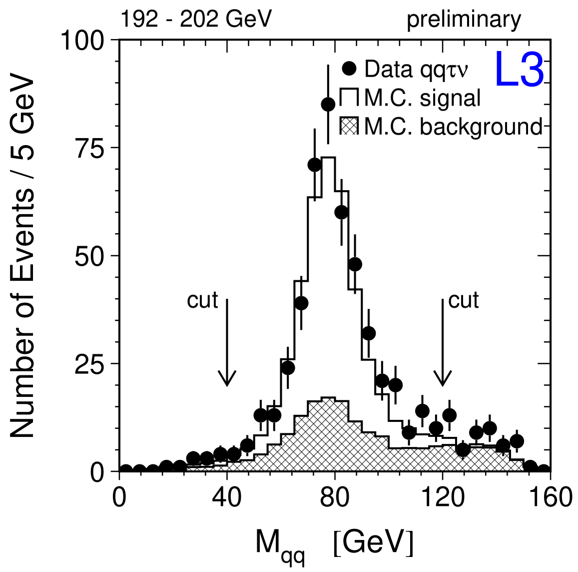
431 $q\bar{q}\mu\nu$ events



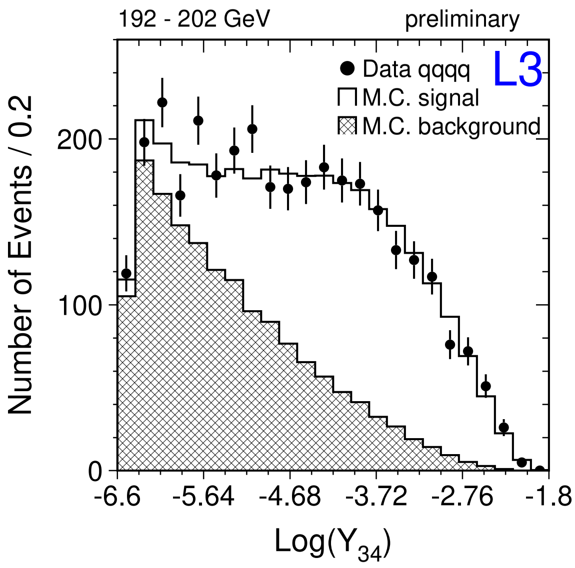
485 $q\bar{q}e\nu$ events



469 $q\bar{q}\tau\nu$ events



1861 $q\bar{q}e\nu$ events

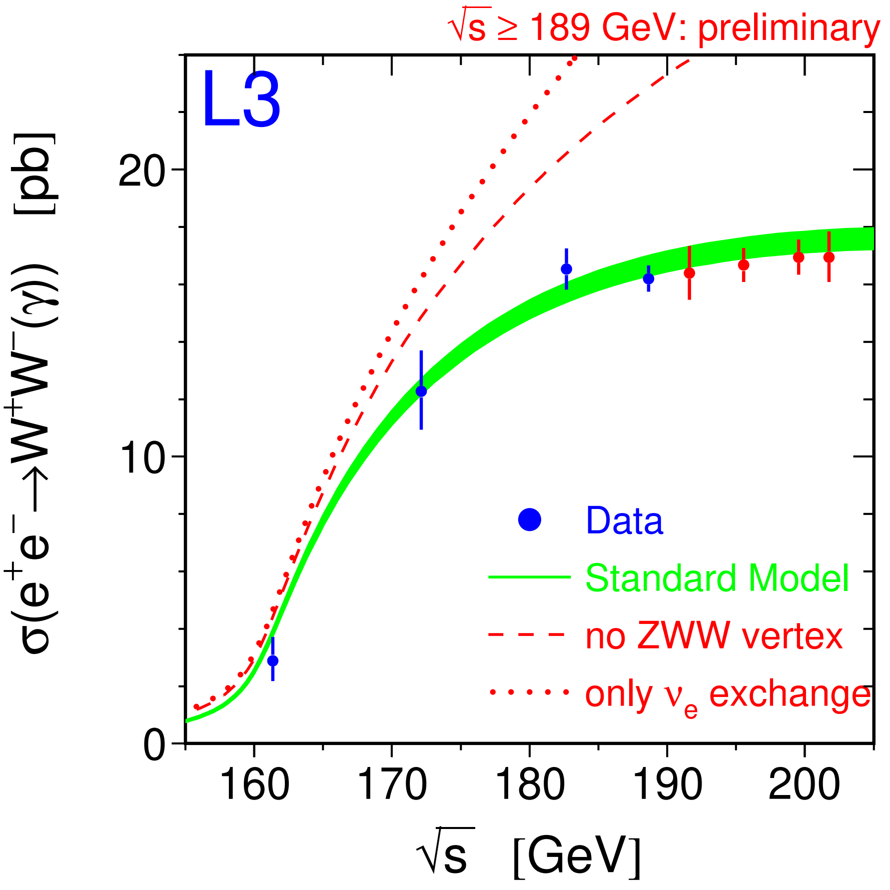


1999: 283 $\ell\nu\ell\nu$ events , 3529 events total

W-pair production

Branching ratios independent of $\sqrt{s}$

➡ use ML fit to $\sigma(e^+e^- \to W^+W^-)(\sqrt{s})$, BRs

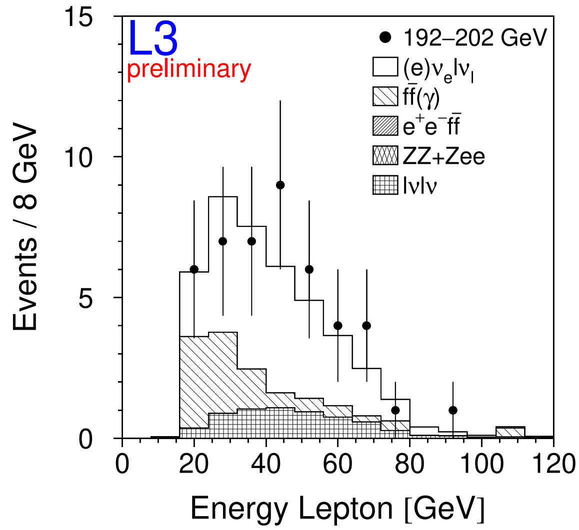


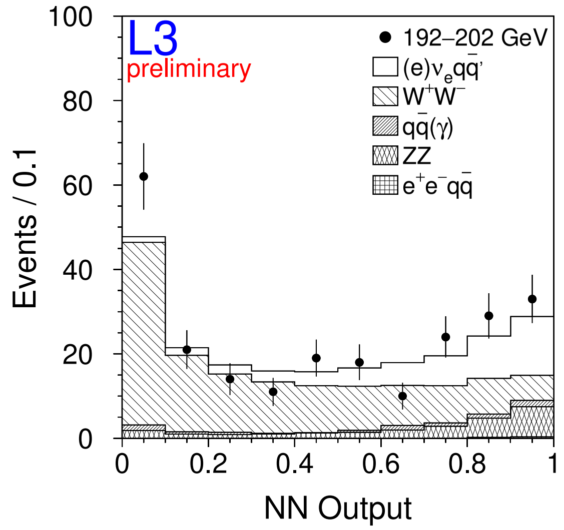
Channel	BR (%)	BR_{univ} (%)	BR_{SM} (%)
$W \to e\nu$	10.22±0.36		
$W \to \mu\nu$	9.87±0.38	10.51±0.19	10.83
$W \to \tau\nu$	11.64±0.51		
$W \to qq$	68.27±0.59	68.47±0.59	67.51

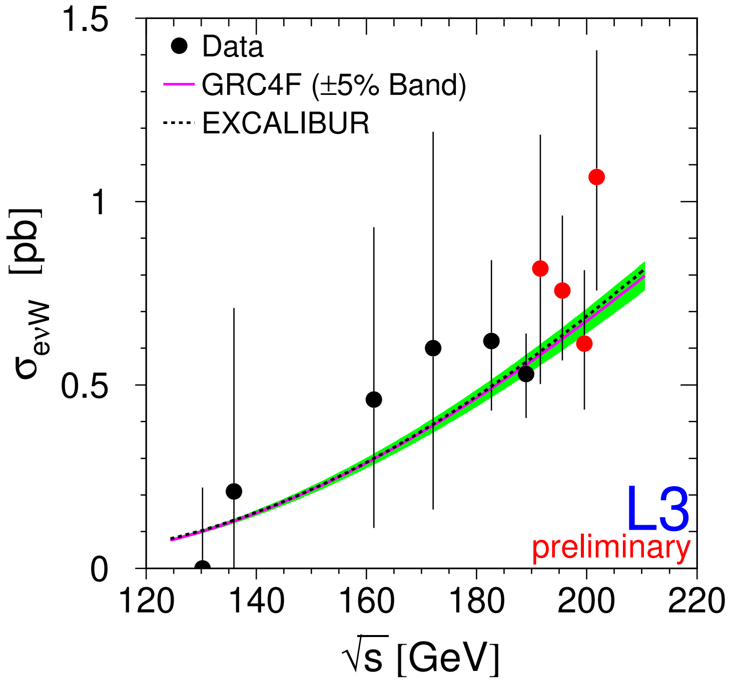
$|V_{cs}| = 1.021 \pm 0.023 \pm 0.015$

Single-W production

Again phase-space cuts for signal definition
($|\cos\theta_e| > 0.997$, $E_f, E_{\bar{f}} > 15$ GeV): 90% pure
Signature: acoplanar pair of jets or single lepton







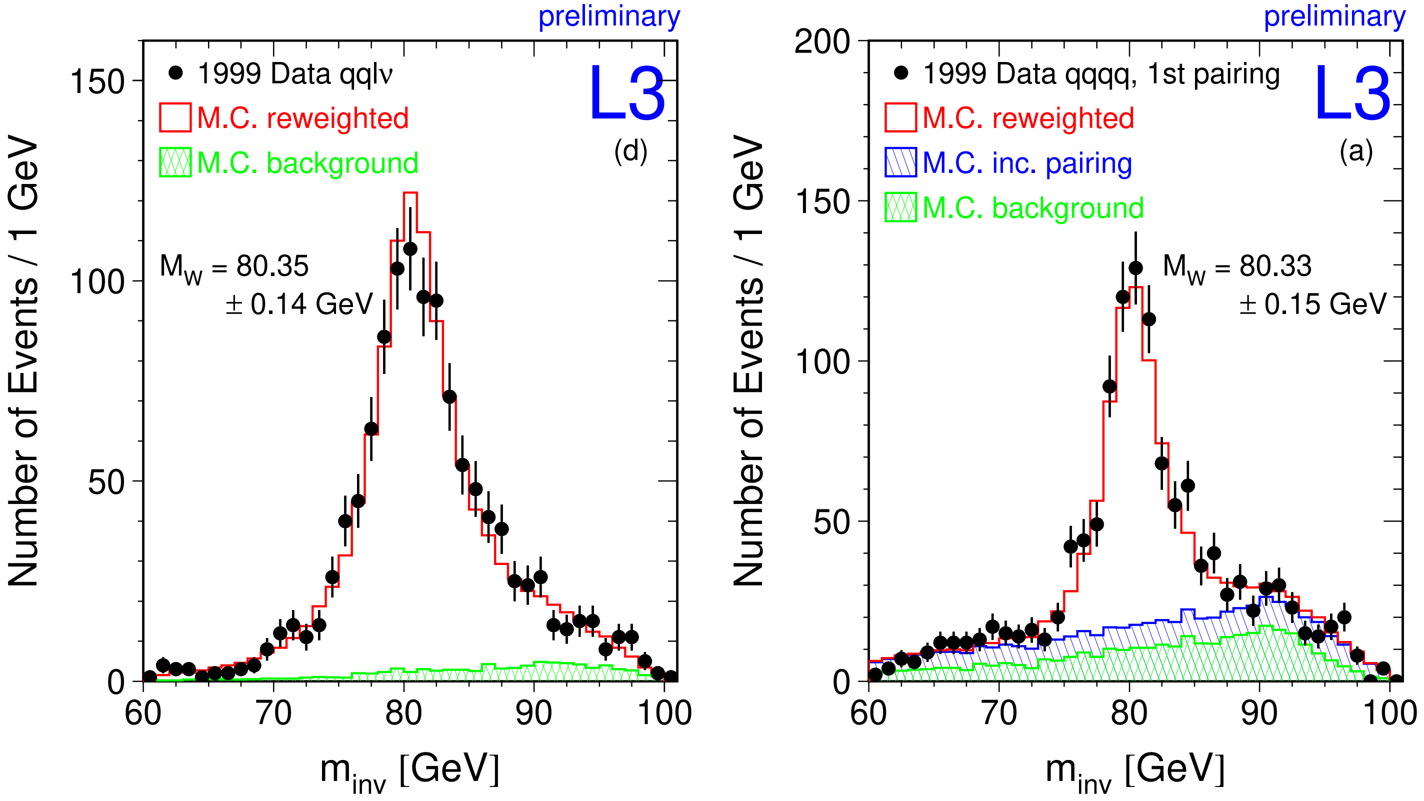
W boson mass

Use

- all final states with 0 ν (5C fit), 1 ν (2C fit)
- $qq\tau\nu$ (only m_{qq}; rescale jet energies to $\sqrt{s}/2$)

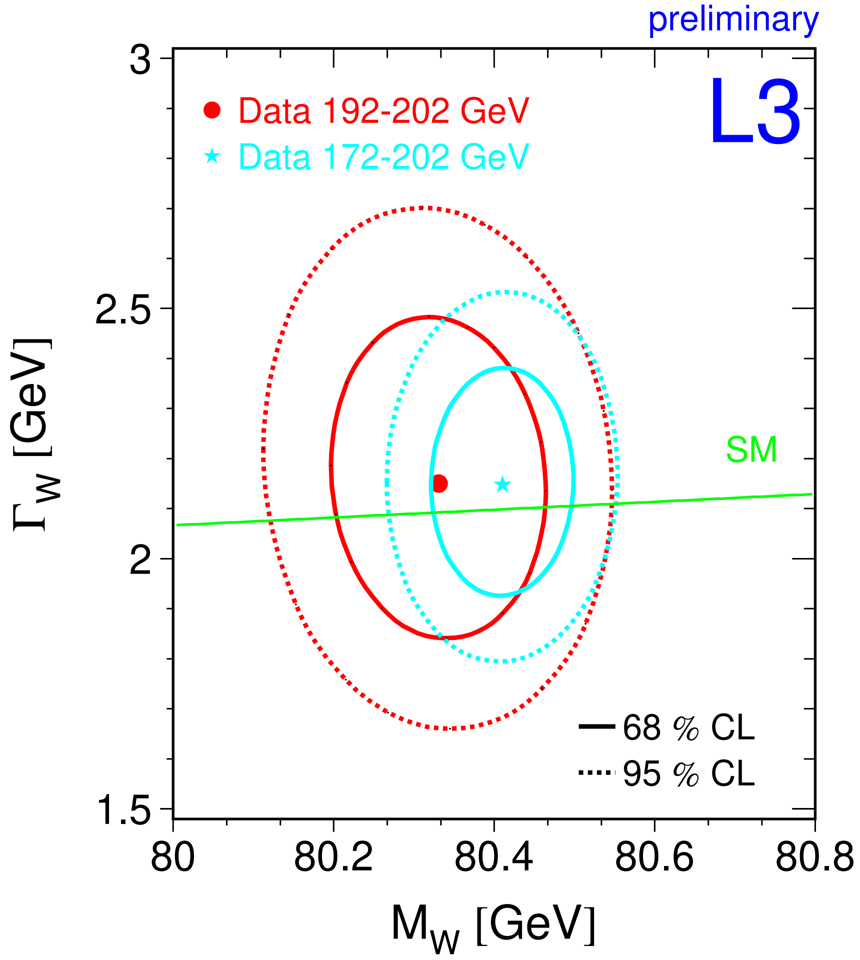
Unbinned ML fit of m_W, Γ_W to $m_{\ell\nu}$, m_{qq} distributions

$qqqq$: best, 2nd best pairing according to 5C fit likelihood



W boson mass

Using 172–202 GeV data:



$$m_W = 80.368 \pm 0.058 \pm 0.064 \text{ GeV}$$
$$\Gamma_W = 2.19 \pm 0.14 \pm 0.16 \text{ GeV}$$

Cross-check using $qq\gamma$ events at $\sqrt{s} = 183$ GeV:

$$m_Z = 91.172 \pm 0.098 \text{ GeV}$$

W boson mass

Systematics different for $qqqq$, $qq\ell\nu$ final states:

$$qq\ell\nu: \quad m_W = 80.28 \pm 0.09 \pm 0.05 \text{ GeV}$$
$$qqqq: \quad m_W = 80.49 \pm 0.08 \pm 0.11 \text{ GeV}$$

Systematics:

- LEP beam energy ~ 20 MeV (see E. Torrence talk)
- fragmentation ~ 60 (30) MeV $qqqq$ ($qq\ell\nu$)
- colour reconnection / Bose-Einstein correlation effects: $\sim 50 \oplus 50$ MeV ($qqqq$ only)

$qqqq$ special: $W^{\pm}$ decay well before being $\mathcal{O}(f\mathrm{m})$ apart
➡ soft QCD effects might introduce interference between two decaying systems?

Difference (BE/CR systematics not included):

$$\Delta m_W = 0.23 \pm 0.12 \pm 0.07 \text{ GeV}$$

Bose-Einstein correlations

Look for enhancement of two-particle density function

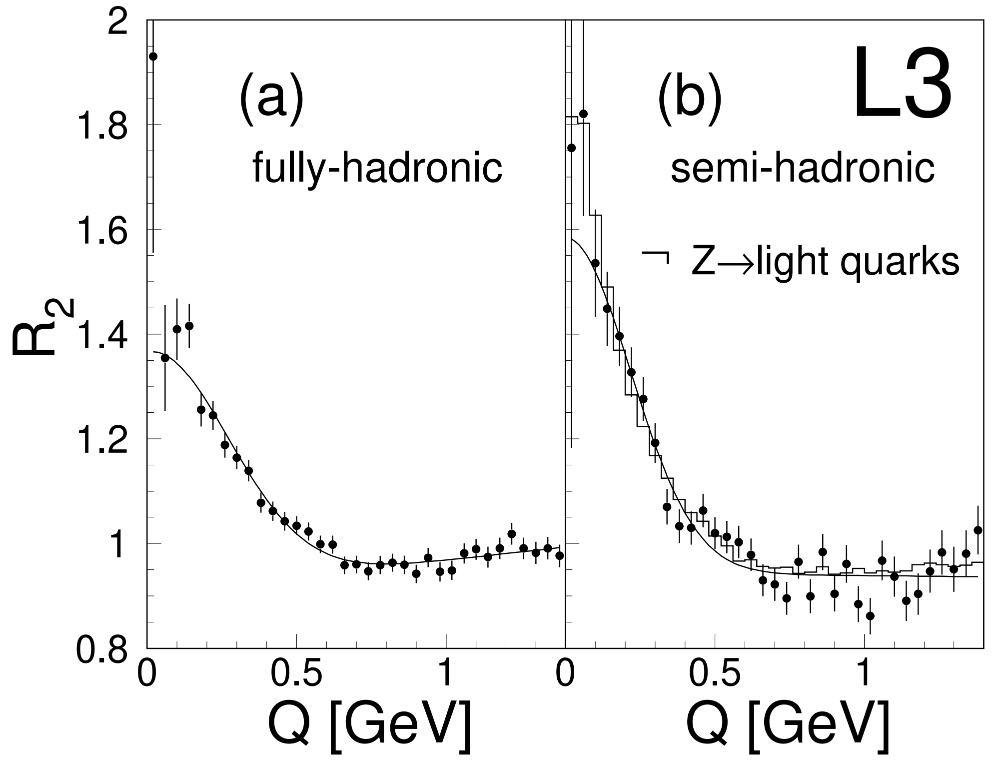
$$\rho \equiv \frac{1}{N_{\mathrm{evt}}} \frac{dn_{\mathrm{pair}}}{dQ}, \qquad Q^2 \equiv -(p_1 - p_2)^2 \quad (= m_{\mathrm{inv}}^2 - 2(m_1^2 + m_2^2))$$

at small Q:

$$R_2 = \left(\frac{\rho(\pm,\pm)}{\rho(+,-)}\right)_{\mathrm{data}} \cdot \left(\frac{\rho(+,-)}{\rho(\pm,\pm)}\right)^{\mathrm{gen}}_{\mathrm{MC,noBE}} \cdot \left(\frac{\rho(\pm,\pm)_{\mathrm{gen}}}{\rho(\pm,\pm)_{\mathrm{det}}} \frac{\rho(+,-)_{\mathrm{det}}}{\rho(+,-)_{\mathrm{gen}}}\right)_{\mathrm{MC}}$$

account for dynamical correlations (decays, four-momentum conservation)

account for detector effects (resolution, acceptance, particle mis-ID)



Bose-Einstein correlations

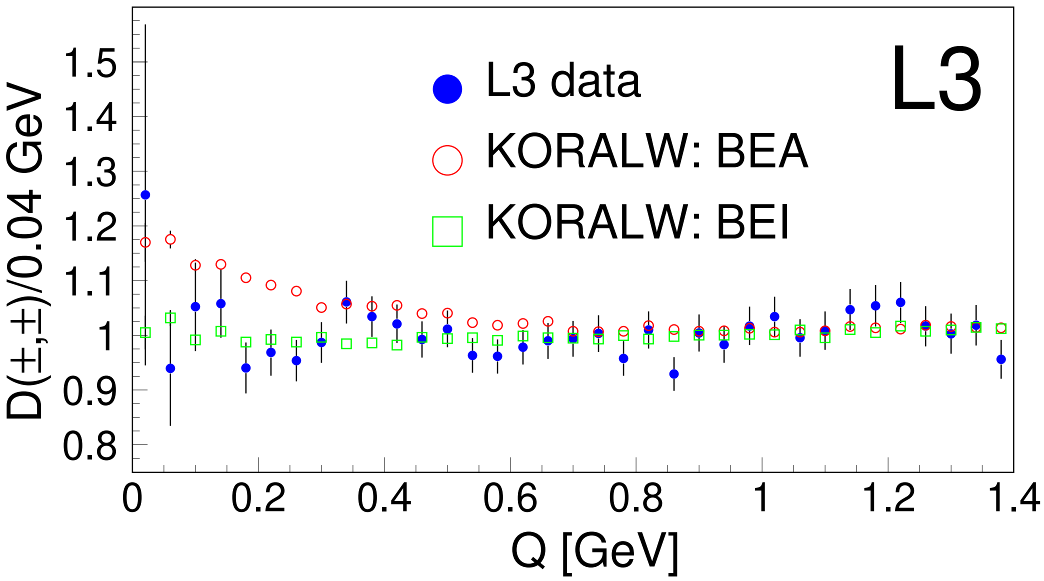
Study inter-W correlations: obtain reference sample by mixing $W \to qq$ jets from $qq\ell\nu$ events

In absence of BE correlations:

$$\rho(\pm,\pm)^{WW} = \rho(\pm,\pm)^{W^+} + \rho(\pm,\pm)^{W^-} + 2\rho(\pm,\pm)^{WW}_{mix}$$

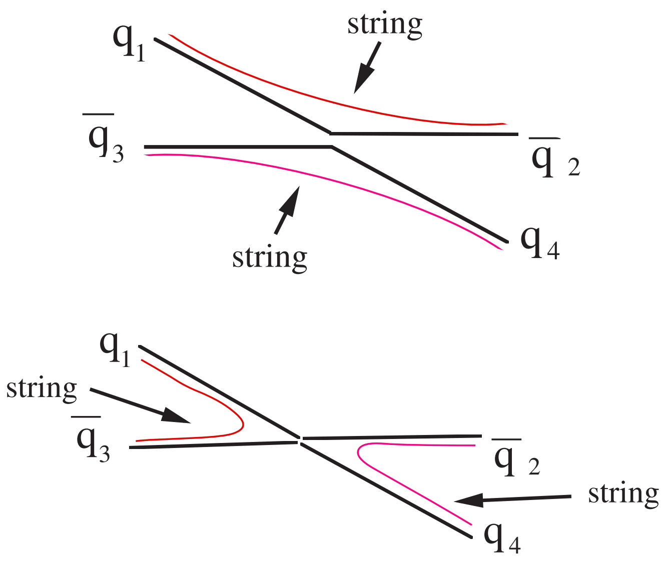
➡study ratio

$$D(\pm,\pm) = \frac{\rho(\pm,\pm)^{WW}}{2\rho(\pm,\pm)^{W} + 2\rho(\pm,\pm)^{WW}_{mix}}, \qquad D'(\pm,\pm) = \frac{D(\pm,\pm)}{D(\pm,\pm)_{MC,noBE}}$$

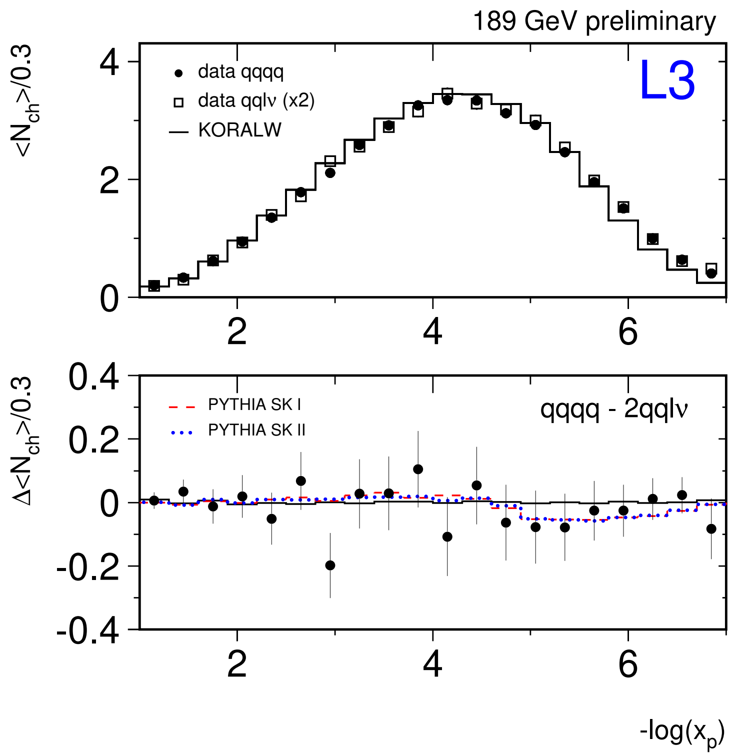


No significant effect found!

Colour reconnection



As a function of p/E_{beam}:



Simplest study: comparison charged-particle multiplicity in hadronic ↔ semileptonic WW decays (excluding lepton):

$$qqqq: \quad n_{\mathrm{ch}} = 37.14 \pm 0.22$$
$$qq\ell\nu: \quad n_{\mathrm{ch}} = 18.69 \pm 0.17$$
$$\Delta n_{\mathrm{ch}} = -0.24 \pm 0.40$$

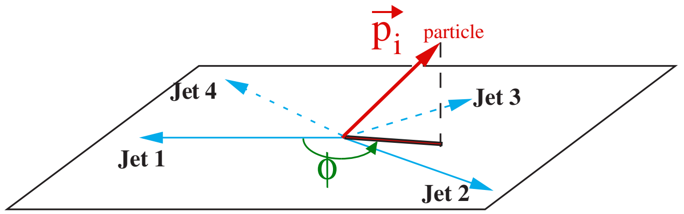
not very conclusive...

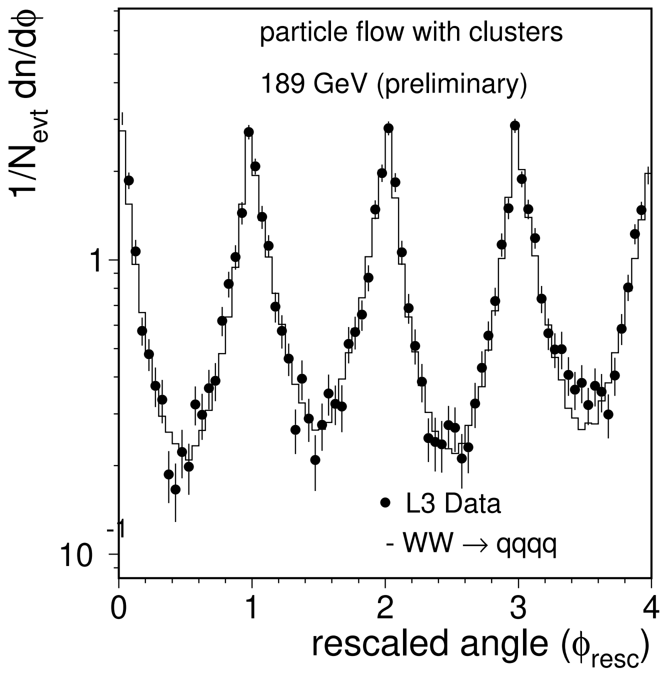
Colour reconnection

Alternative: consider explicitly inter-W (versus intra-W) activity

Select 'symmetric' WW hadronic decays:

- well-balanced
- two largest interjet angles: 100°–140°, not adjacent.
- other two jet angles $< 100^\circ$





Determine ratio of inter-W/intra-W particle/energy flow:

$$R_N = \frac{\int_{0.3}^{0.7} \frac{dn}{d\phi}(\text{inter-jet})\,d\phi / N_{evt}}{\int_{0.3}^{0.7} \frac{dn}{d\phi}(\text{intra-jet})\,d\phi / N_{evt}}$$

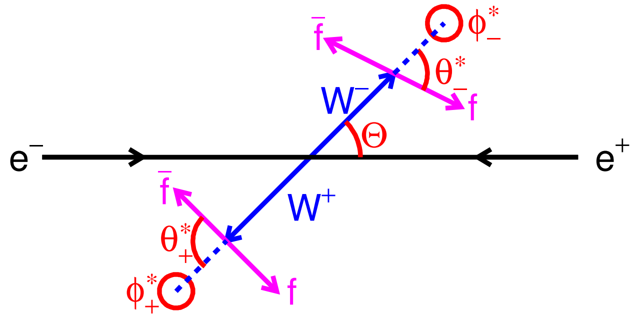
Model	R_N
No CR	0.889±0.007
SKII	0.875±0.007
SKI	0.855±0.007
GH	0.776±0.007
Data	0.76±0.05

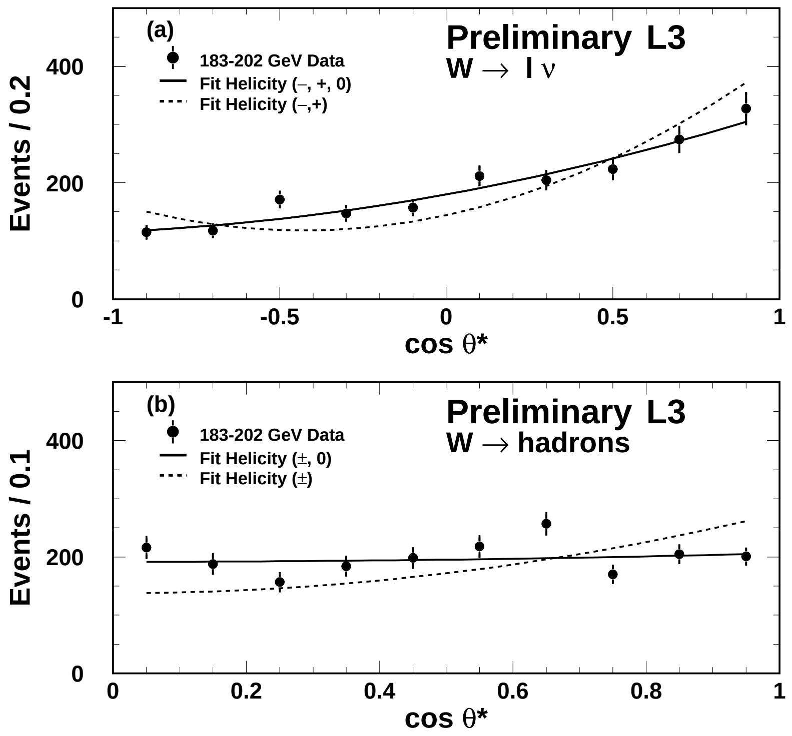
Errors statistical only! But first hint. . .

W polarisation

Use $qq\ell\nu$ events, both W decays:

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = f_-\frac{3}{8}(1+\cos\theta^*)^2 + f_+\frac{3}{8}(1-\cos\theta^*)^2 + f_0\frac{3}{4}\sin^2\theta^*$$





W $\to$ qq: only $|\cos\theta^*|$,
with $f_\pm \equiv f_- + f_+$

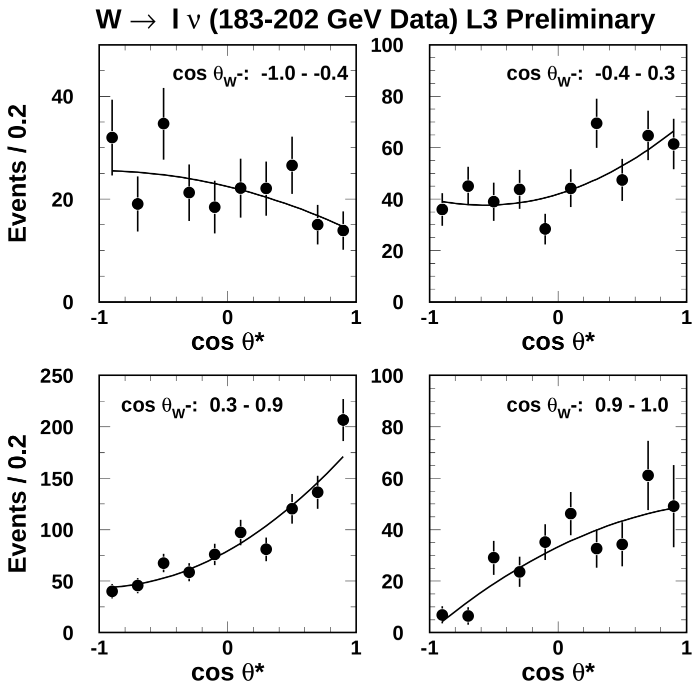
➡ need longitudinal polarisation:

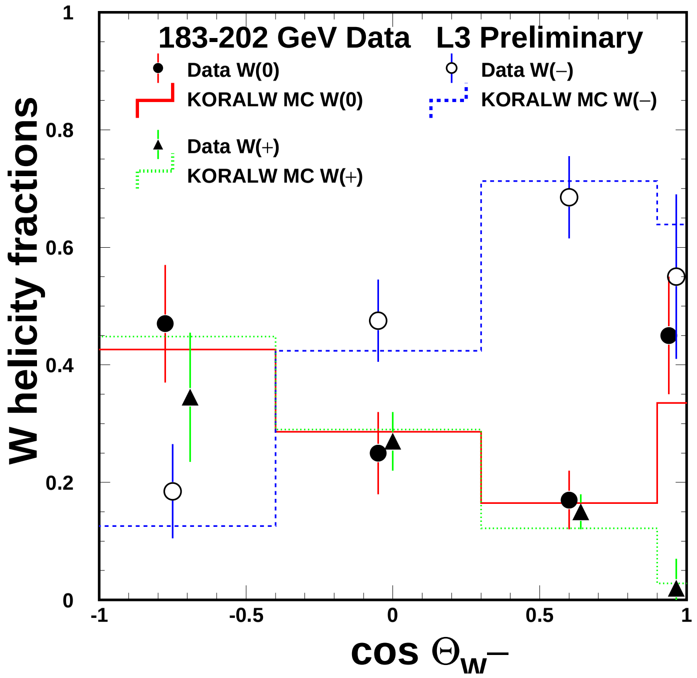
$$f_0 = 0.259 \pm 0.035 \pm 0.030$$

(SM: $f_0 = 0.248$)

W polarisation

In bins of cos θ_W:

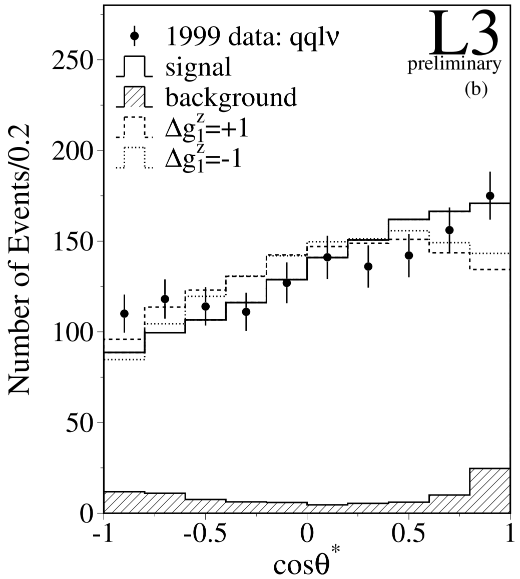


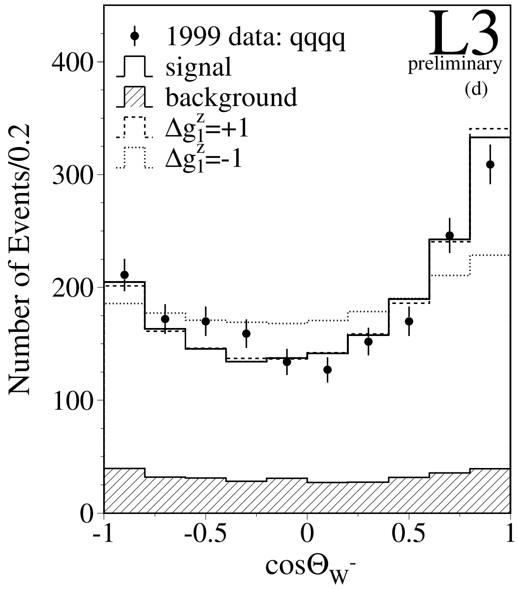


Triple Gauge Boson couplings

Anomalous couplings parametrised by 3 C,P-conserving (g_1^Z, κ_γ, λ_γ) and 1 CP-violating (g_5^Z) coupling

Use same data as for polarisation measurement, plus *qqqq* (jet charge measurement to distinguish $W^+ \leftrightarrow W^-$: ~ 70% pure)





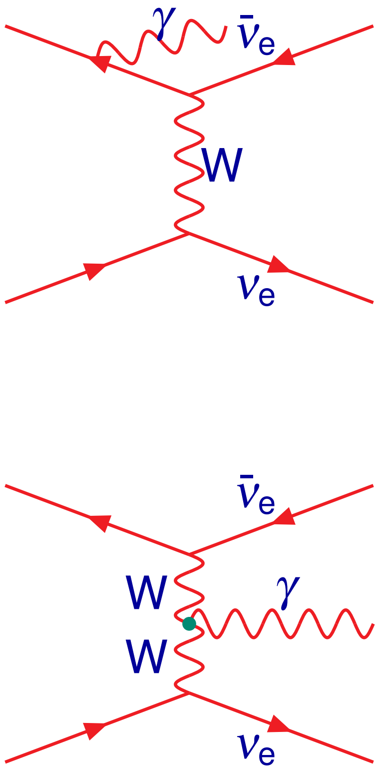
$$
\begin{aligned}
g_1^Z &= 0.93^{+0.05}_{-0.04} \pm 0.04 \pm 0.02 \\
\kappa_\gamma &= 0.80^{+0.09}_{-0.08} \pm 0.11 \pm 0.09 \\
\lambda_\gamma &= -0.08^{+0.05}_{-0.04} \pm 0.06 \pm 0.02 \\
g_5^Z &= -0.23^{+0.20}_{-0.19} \pm 0.16 \pm 0.08
\end{aligned}
$$

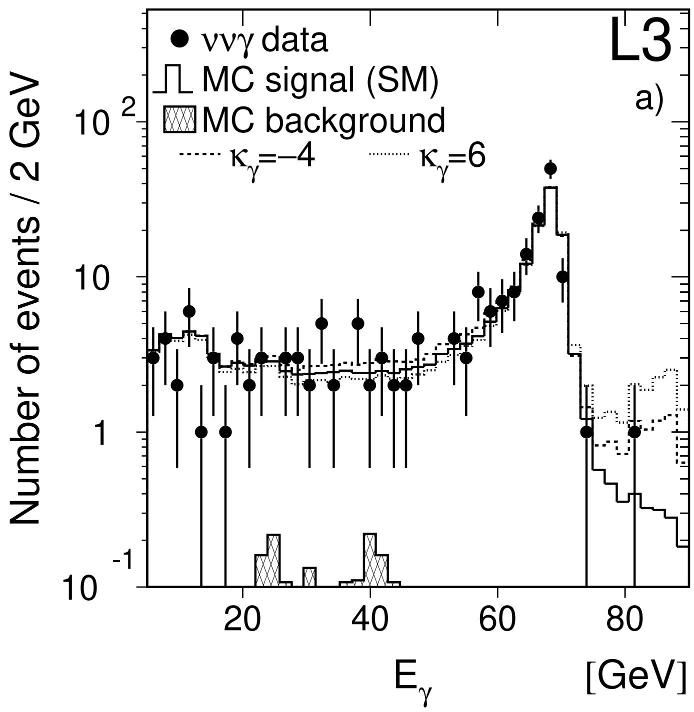
Triple Gauge boson Couplings

Independently: fits using single-W production:

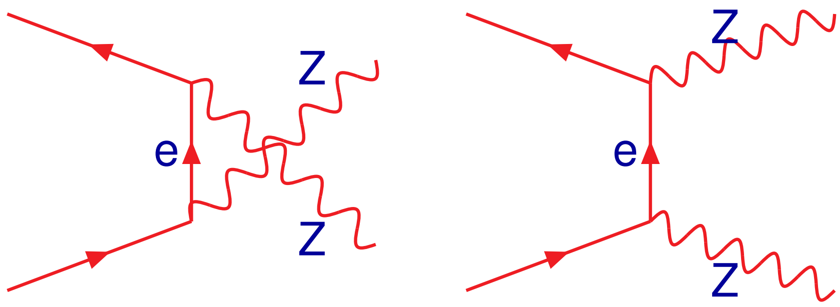
$$\kappa_\gamma = 1.10 \pm 0.10 \pm 0.08$$
$$\lambda_\gamma = -0.20^{+0.59}_{-0.16} \pm 0.11$$

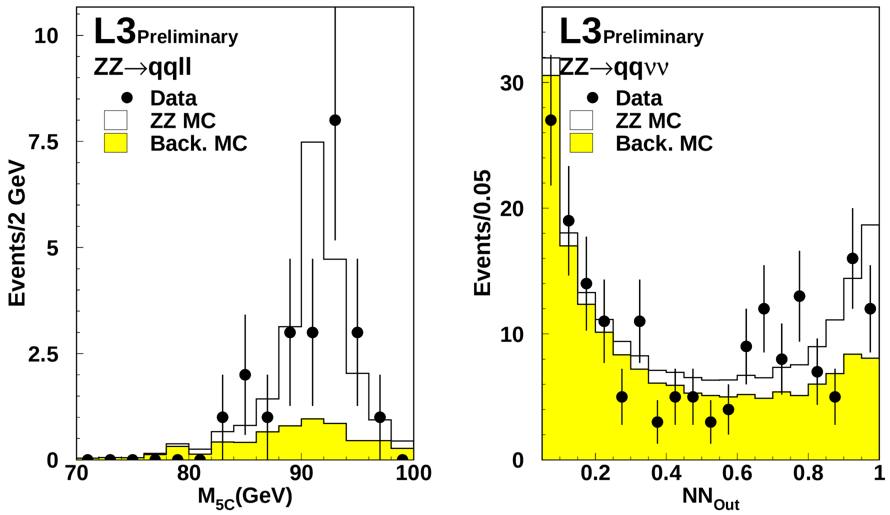
Foresee combination of data samples, including also single-γ production

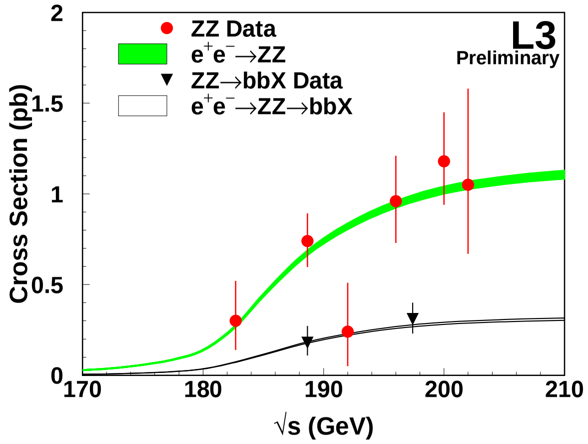




Z-pair production







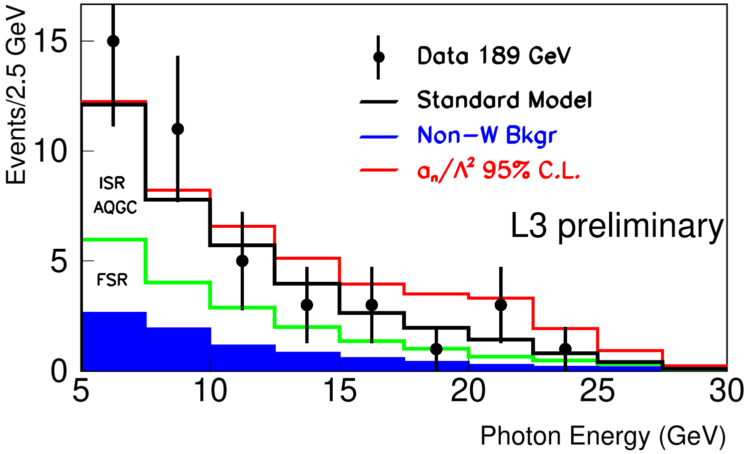
ZZ, Zγ final states:
ZZZ, ZZγ, Zγγ couplings

Quartic Gauge boson Couplings

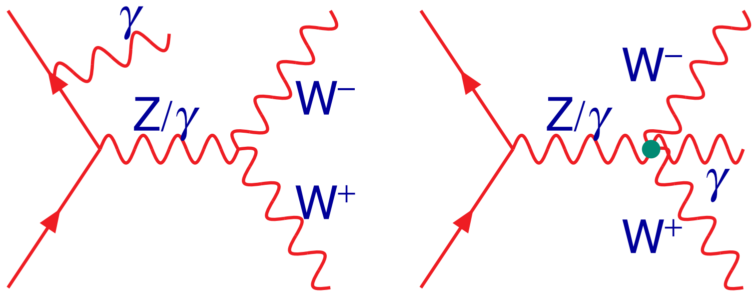
‘Genuine’ QGCs involving photons:

$$\vec{W}_\mu = \begin{pmatrix} (W^+_\mu + W^-_\mu)/\sqrt{2} \\ i(W^+_\mu - W^-_\mu)/\sqrt{2} \\ Z_\mu/\cos\theta_W \end{pmatrix}$$

➡ models $\mathcal{L}_0$, $\mathcal{L}_c$, $\mathcal{L}_n$



WWγ final states:

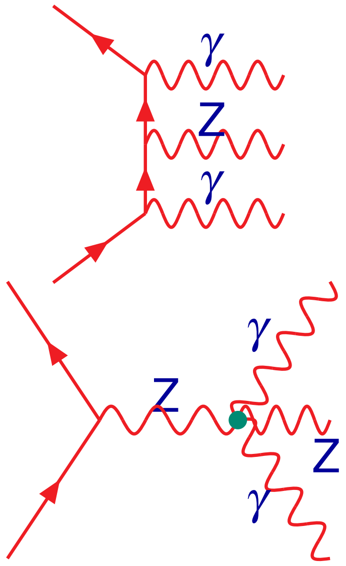


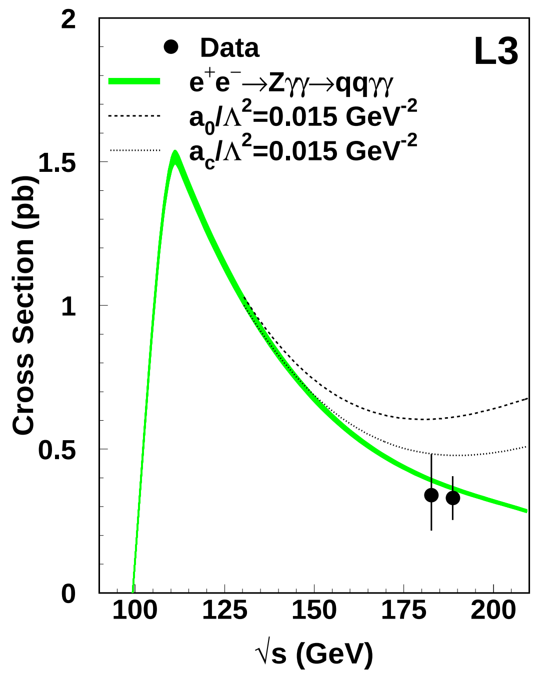
Phase space cuts to define signal ($E_\gamma > 5$ GeV; $\theta_\gamma, \theta_{\gamma W} > 20^\circ$)

$$a_0/\Lambda^2 = 0.017^{+0.018}_{-0.039} \pm 0.002 \text{ GeV}^{-2}$$
$$a_c/\Lambda^2 = 0.068^{+0.040}_{-0.095} \pm 0.009 \text{ GeV}^{-2}$$
$$a_n/\Lambda^2 = 0.012^{+0.150}_{-0.330} \pm 0.010 \text{ GeV}^{-2}$$

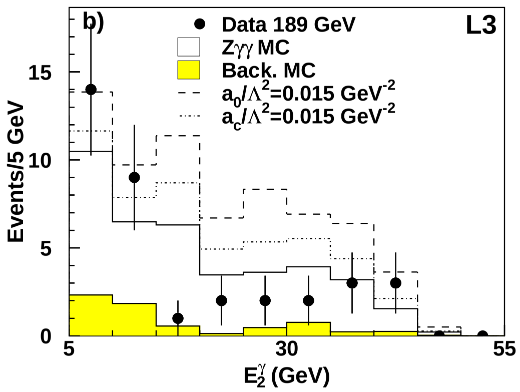
Quartic Gauge boson Couplings

Same interaction can be studied using $e^+e^- \to Z\gamma\gamma$ (only $Z \to qq$ considered):





Phase space cuts ($E_\gamma > 5$ GeV, $\theta_\gamma > 14°$, $|m_{qq} - m_Z| < 2\Gamma_Z$)



$$a_0/\Lambda^2 = 0.001 \pm 0.004 \text{ GeV}^{-2}$$
$$a_c/\Lambda^2 = 0.003 \pm 0.005 \text{ GeV}^{-2}$$

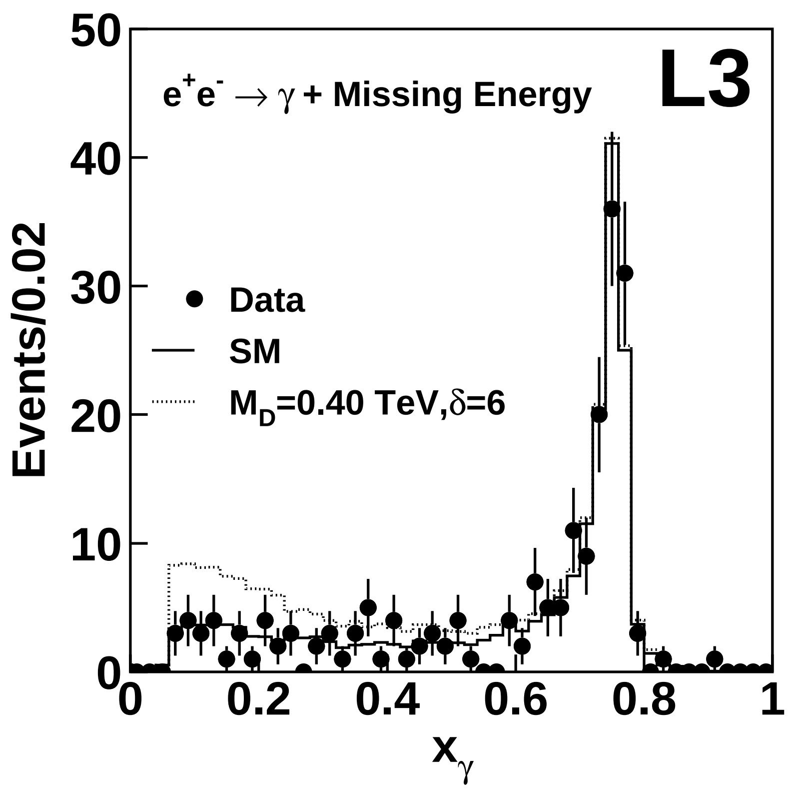
Extra dimensions?

'Generation' of M_{Pl} from M_{D} by compactified $\delta \geq 2$ extra dimensions with radius R?

$$M_{\mathrm{Pl}}^2 \sim R^\delta M_{\mathrm{D}}^{\delta+2}$$

Very predictive: M_{D}, δ only free parameters in effective theory

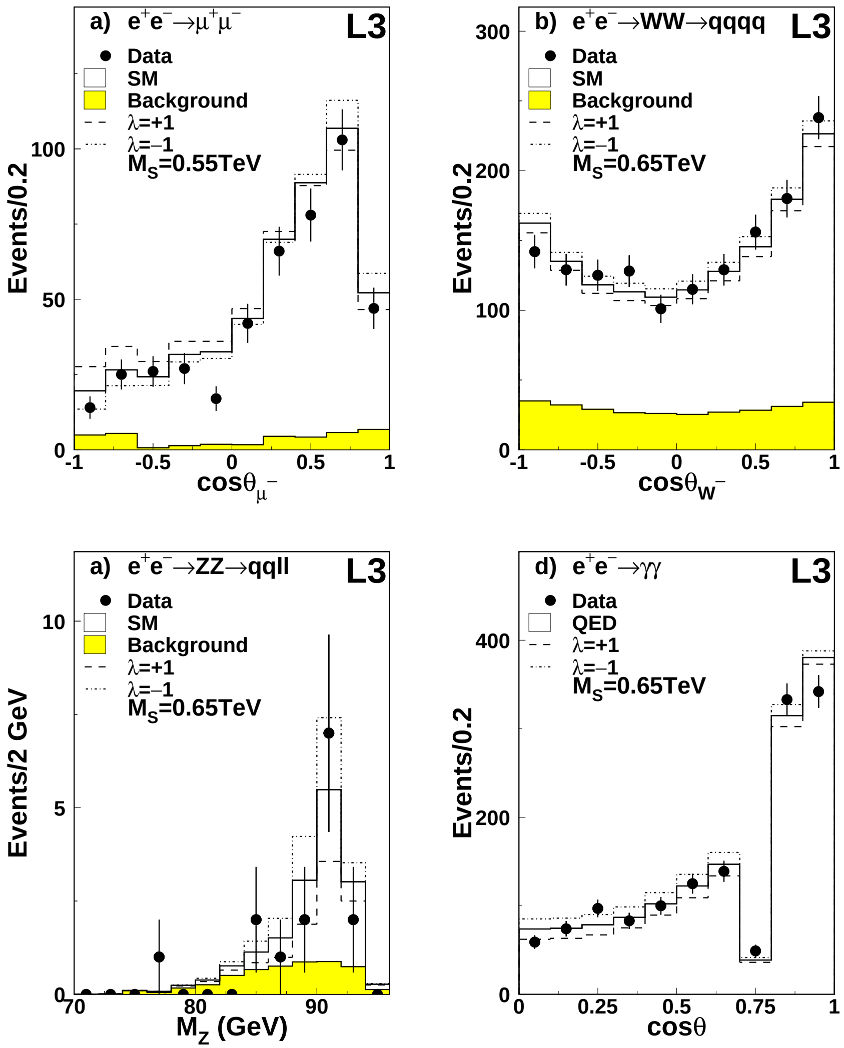
Real graviton production: $e^+e^- \to \gamma G$
dominated by high-E gravitons



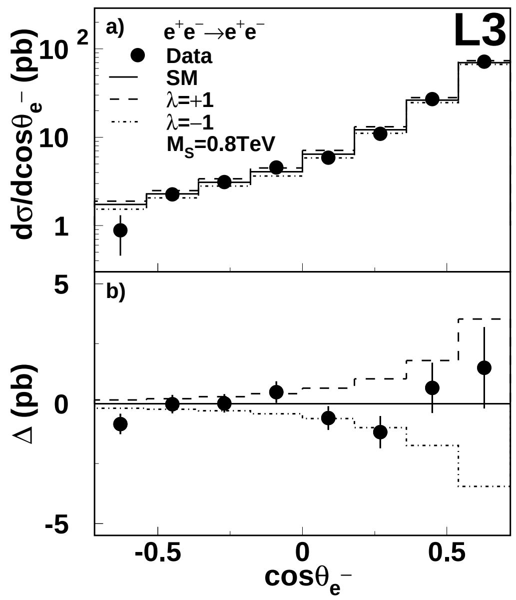
(also $e^+e^- \to ZG$: less sensitive)

Extra dimensions?

Virtual effects: replace actual mass scale M_D with ‘cutoff mass’ M_S



λ: sign of interference term



Extra dimensions?

All data with $\sqrt{s} \leq 190$ GeV:

Process	M_S (TeV) $\lambda = +1$	$\lambda = -1$
$e^+e^- \to ZZ$	0.77	0.76
$e^+e^- \to W^+W^-$	0.79	0.68
$e^+e^- \to \gamma\gamma$	0.79	0.80
Bosons Combined	0.89	0.82
$e^+e^- \to \mu^+\mu^-$	0.69	0.56
$e^+e^- \to \tau^+\tau^-$	0.54	0.58
$e^+e^- \to q\bar{q}$	0.49	0.49
$e^+e^- \to e^+e^-$	0.98	0.84
Fermions Combined	1.00	0.84
Bosons + Fermions	1.07	0.87

Conclusions

- LEP2 Standard Model physics results becoming quite precise
- No new physics found. . .
  in spite of sensitive searches!
- Wait for July LEPC