Salvatore Mele

CERN/EP INFN/Napoli

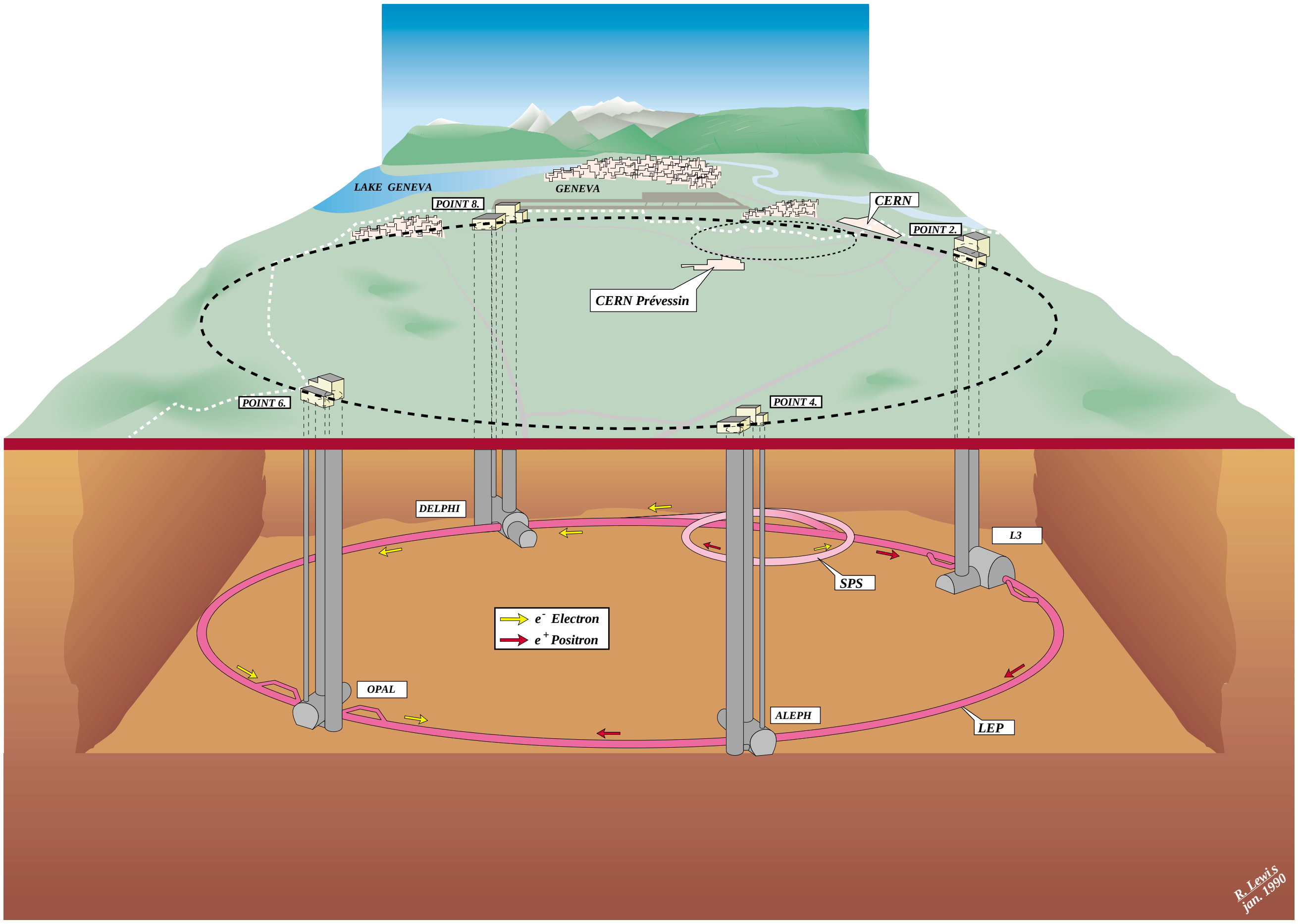
Couplings at LEP

- Lep & the data set
- Boson-fermion couplings
- Charged triple gauge boson couplings
- Neutral triple gauge boson couplings
- Anomalous Higgs couplings
- Quartic gauge boson couplings
- Conclusions

Summarising the ongoing efforts and the imagination of $\mathcal{O}(100)$ experimental and theory colleagues.

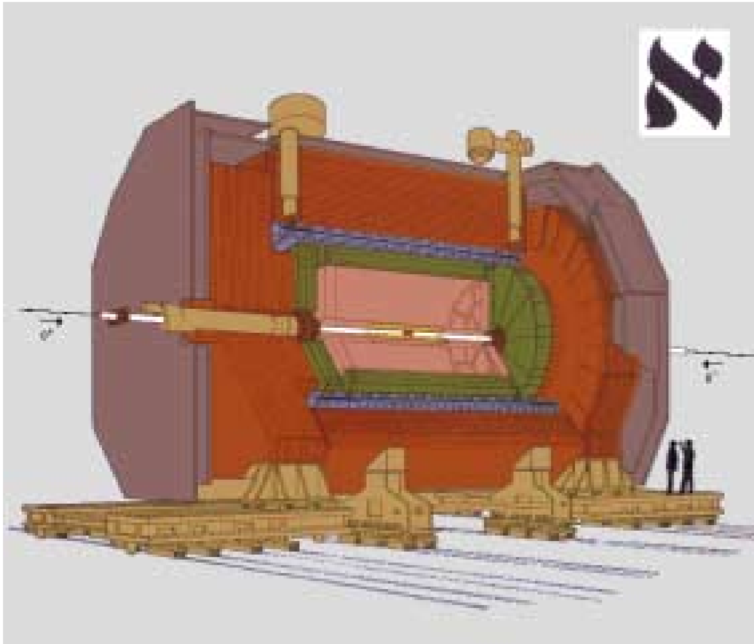
Results are preliminary, unless otherwise stated. Updates at:

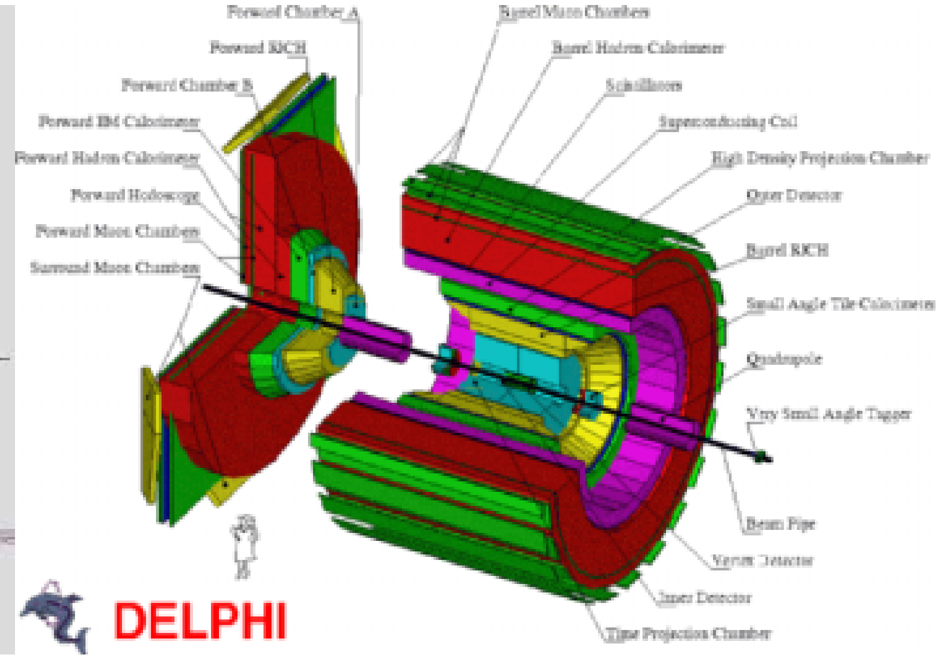
http://cern.ch/LEPEWWG	(Z properties)
http://cern.ch/LEPHFS	(b physics)
http://cern.ch/LEPEWWG/lepww/tgc/	(TGC & QGC)

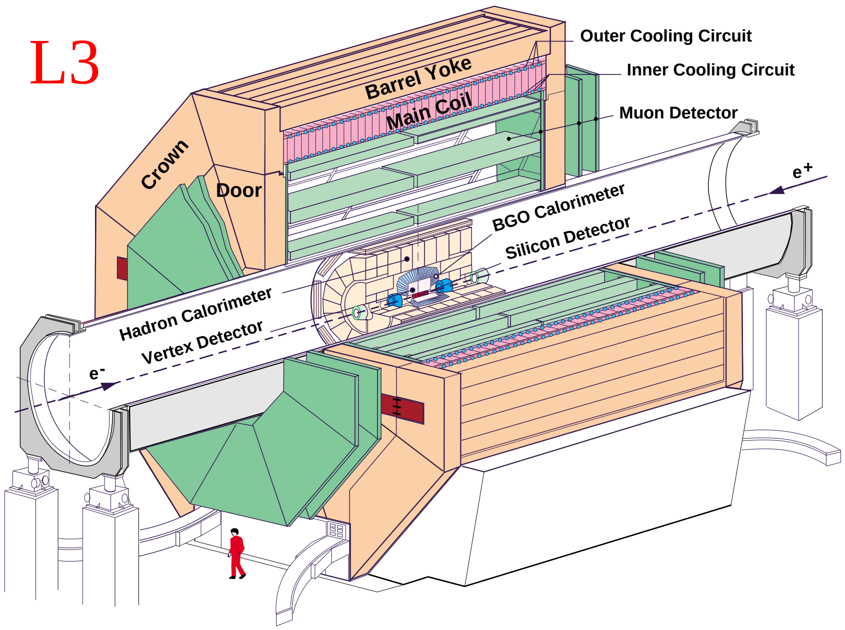


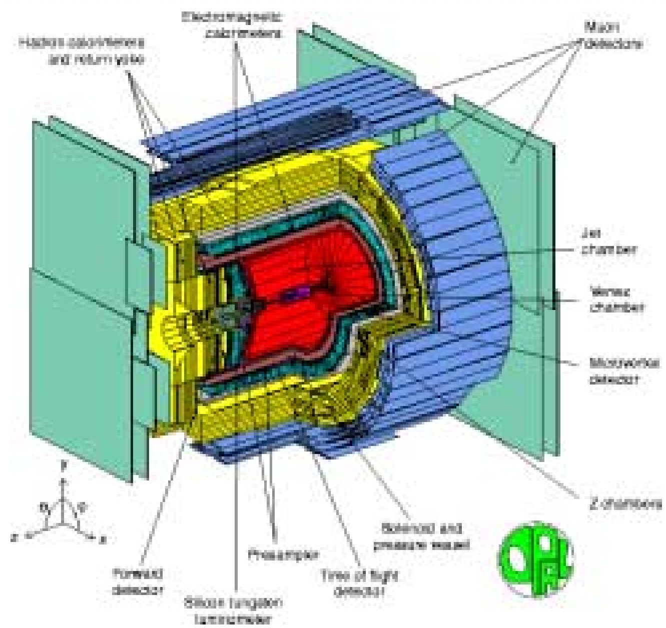
- The largest scientific instrument built so far (27 km circumference)
- High precision 1989–1995 (1–2 MeV)
- High energy 1995–2000 (Above 209 GeV)

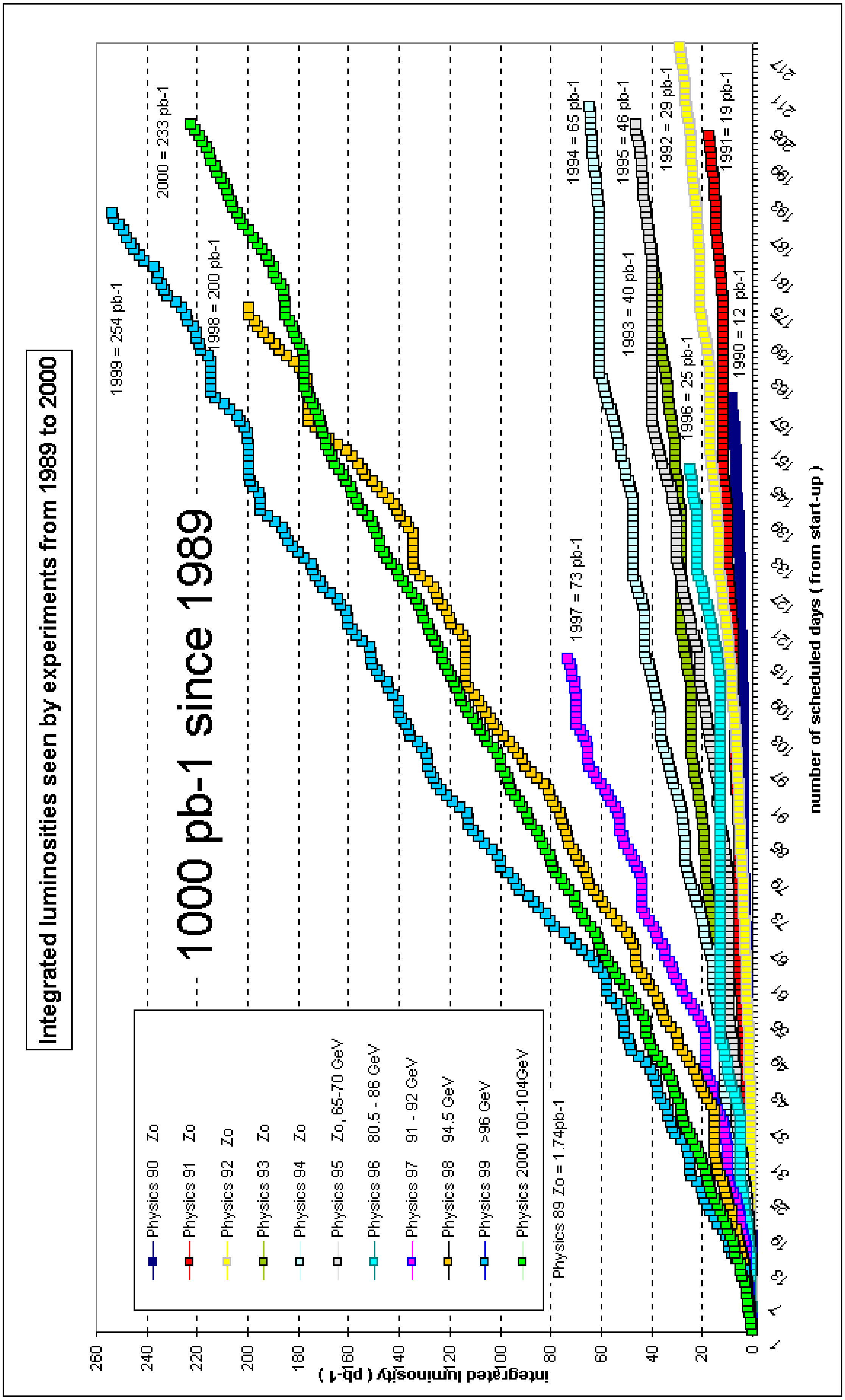
The Detectors









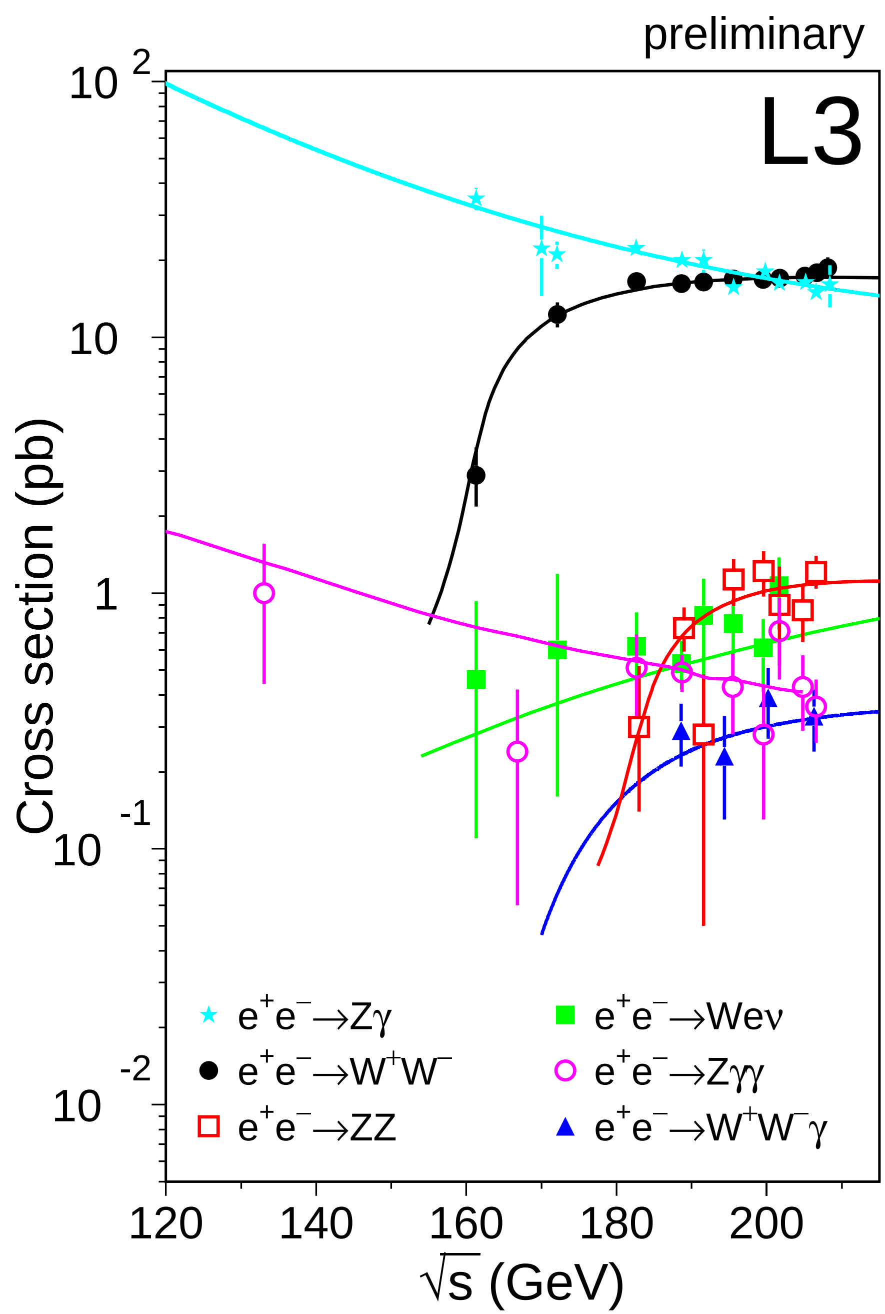


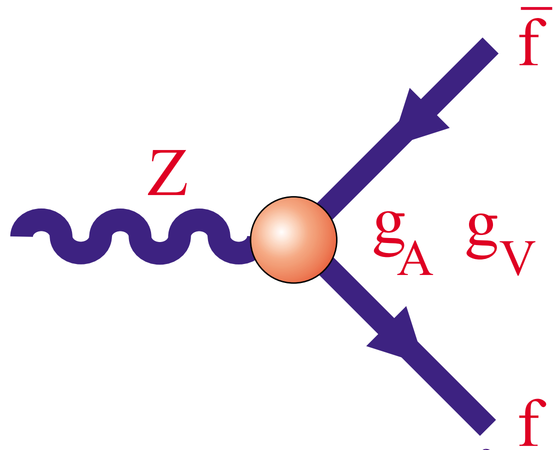
Integrated luminosities seen by experiments from 1989 to 2000
1000 pb-1 since 1989
Physics 90 Zo
Physics 91 Zo
Physics 92 Zo
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 >96 GeV
Physics 2000 100-104GeV
Physics 89 Zo = 1.74pb-1
1999 = 254 pb-1
2000 = 233 pb-1
1998 = 200 pb-1
1997 = 73 pb-1
1994 = 65 pb-1
1995 = 46 pb-1
1993 = 40 pb-1
1992 = 29 pb-1
1996 = 25 pb-1
1991 = 19 pb-1
1990 = 12 pb-1
integrated luminosity (pb-1)
number of scheduled days (from start-up)

Collected luminosities

At the Z peak:
5 million Z/exp
7 million B-hadrons in total
Above the W-pair threshold:

Year	$\sqrt{s}$	Lumi/exp
1996	161GeV	10 pb^{-1}
1996	172GeV	10 pb^{-1}
1997	183GeV	55 pb^{-1}
1998	189GeV	180 pb^{-1}
1999	192GeV	30 pb^{-1}
1999	196GeV	80 pb^{-1}
1999	200GeV	85 pb^{-1}
1999	202GeV	40 pb^{-1}
2000	200-209GeV	230 pb^{-1}
		720 pb^{-1}





At the tree level: $\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$

$$g_V = \sqrt{\rho}(T_3 - 2Q\sin^2\theta_W), \quad g_A = \sqrt{\rho}T_3$$

After radiative corrections:

$$g_V = \mathcal{R}\left[\mathcal{G}_V\right] = \mathcal{R}\left[\sqrt{1+\Delta\rho}\left(T_3 - 2Q(1+\Delta\kappa)\sin^2\theta_W\right)\right]$$
$$g_A = \mathcal{R}\left[\mathcal{G}_A\right] = \mathcal{R}\left[\sqrt{1+\Delta\rho}T_3\right]$$

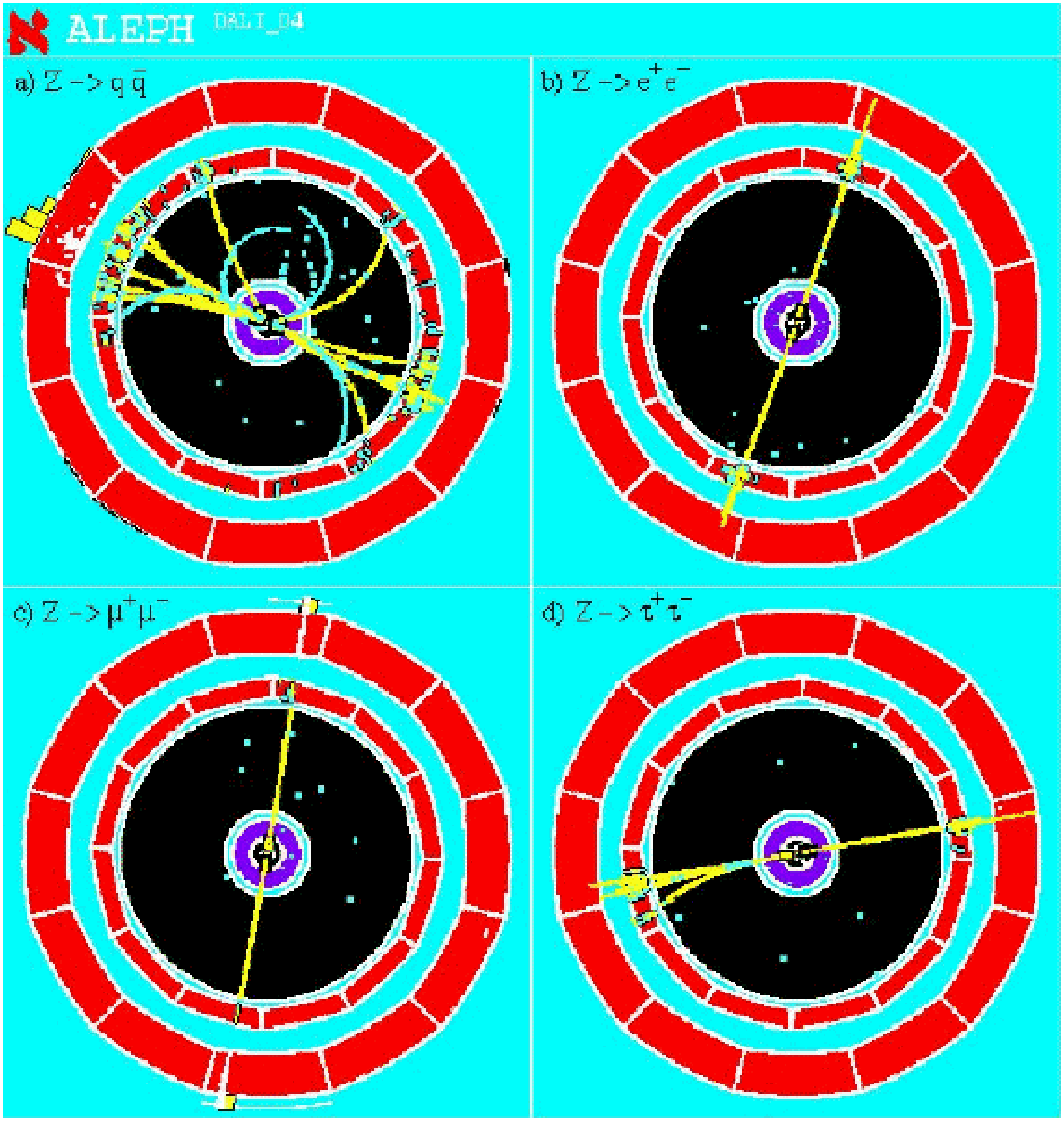
Asymmetry parameter:

$$\mathcal{A}_f = \frac{2g_A g_V}{g_A^2 + g_V^2}$$

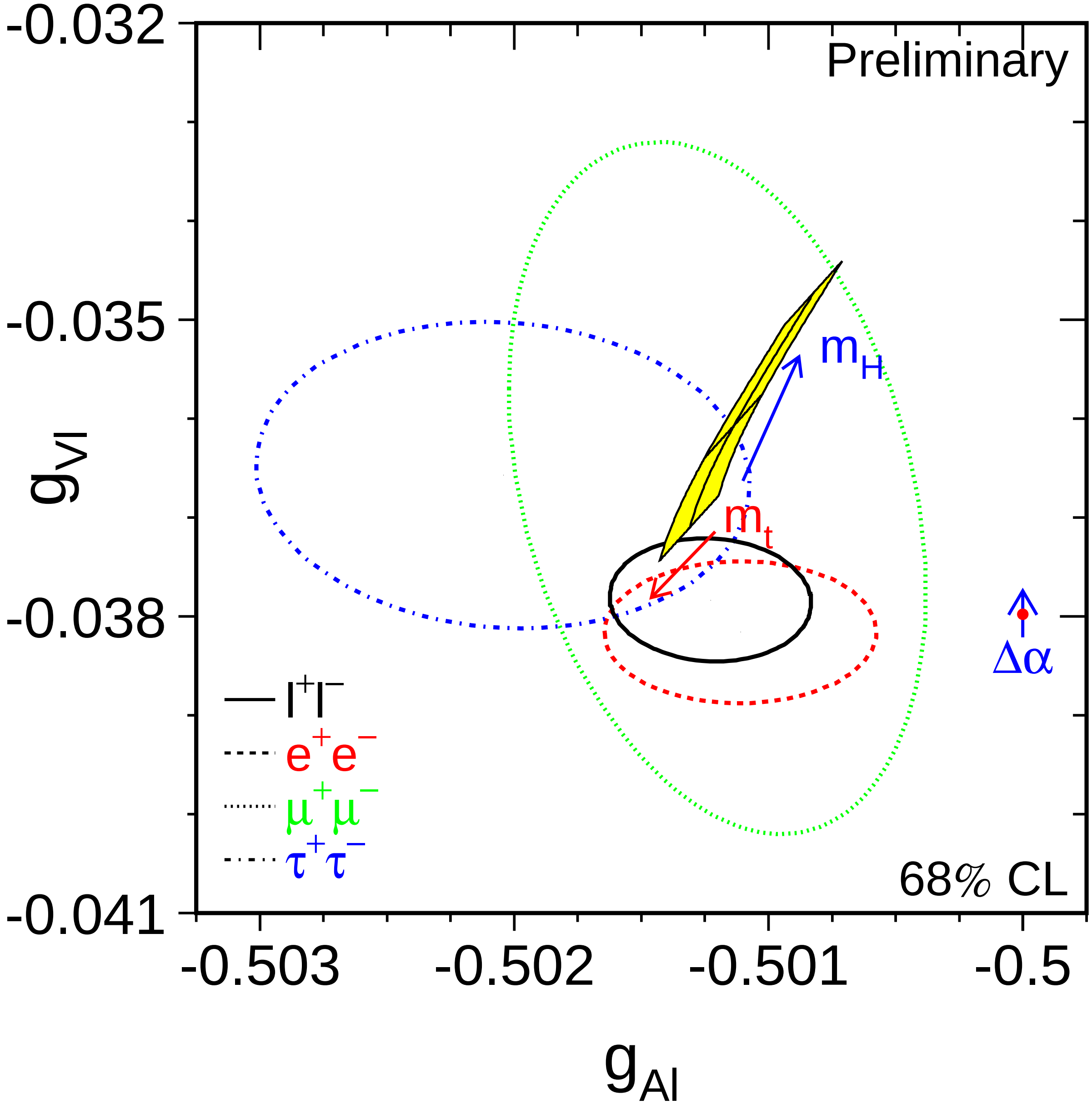
Measurements - Parameters

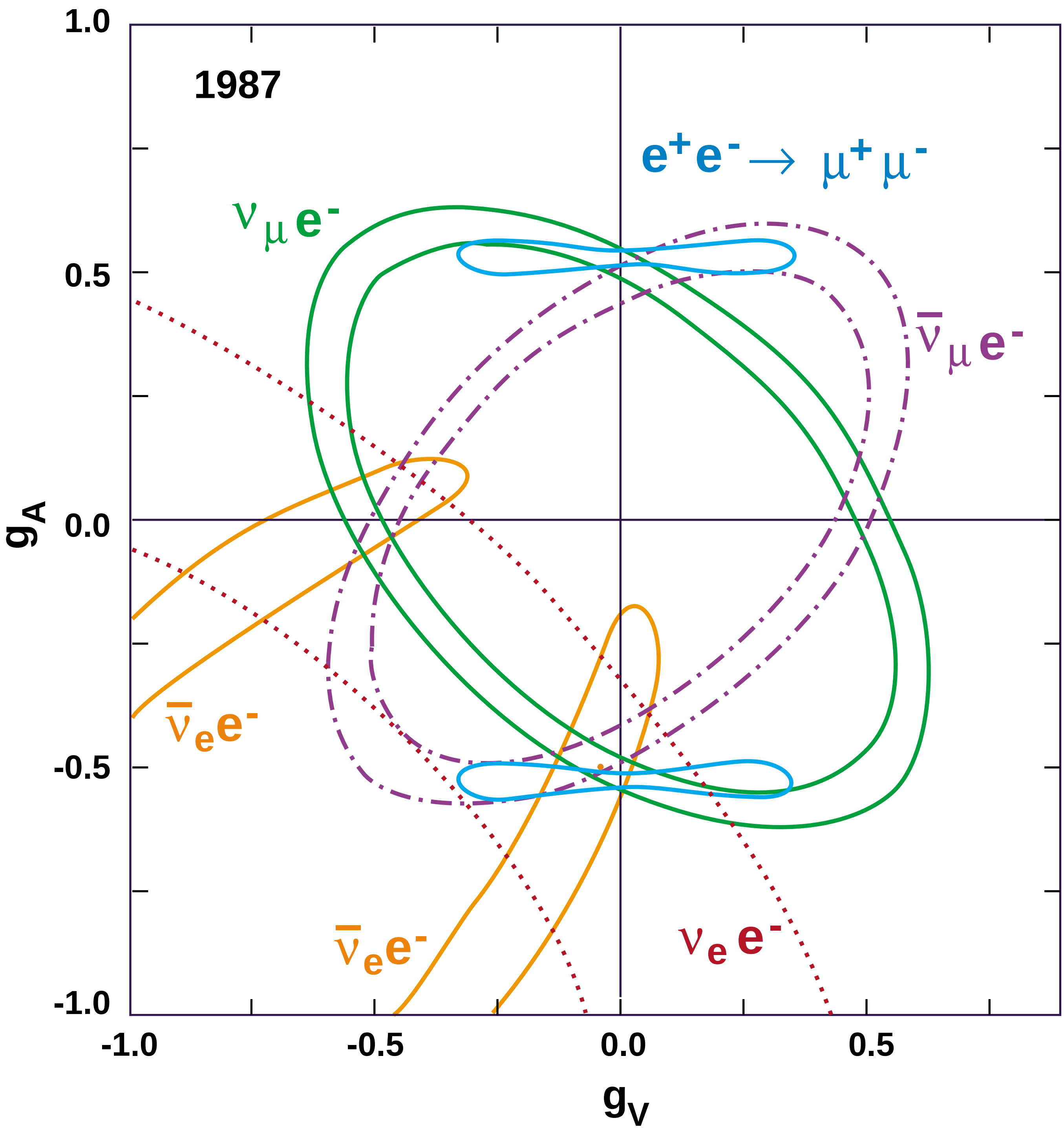
$$\frac{\mathcal{N}_F - \mathcal{N}_B}{\mathcal{N}_F + \mathcal{N}_B} = A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{(LEP, SLD)}$$
$$\frac{\mathcal{N}_L - \mathcal{N}_R}{\mathcal{N}_L + \mathcal{N}_R}\frac{1}{<\mathcal{P}_f>} = A_{LR} = \mathcal{A}_e \quad \text{(SLD)}$$
$$\frac{\mathcal{N}_{Pol}}{\mathcal{N}_{tot}} = -\mathcal{P}_f = \mathcal{A}_f \quad \text{(SLD, LEP } \tau\text{)}$$
$$\Gamma(Z \to f\bar{f}) = N_c^f \frac{G_F m_Z^3}{6\sqrt{2}\pi}\left(|\mathcal{G}_A|^2 R_{Af} + |\mathcal{G}_V|^2 R_{Vf}\right) + \Delta_{EW/QCD}$$

Z decays into hadrons and lepton are identified with high efficiency and precision



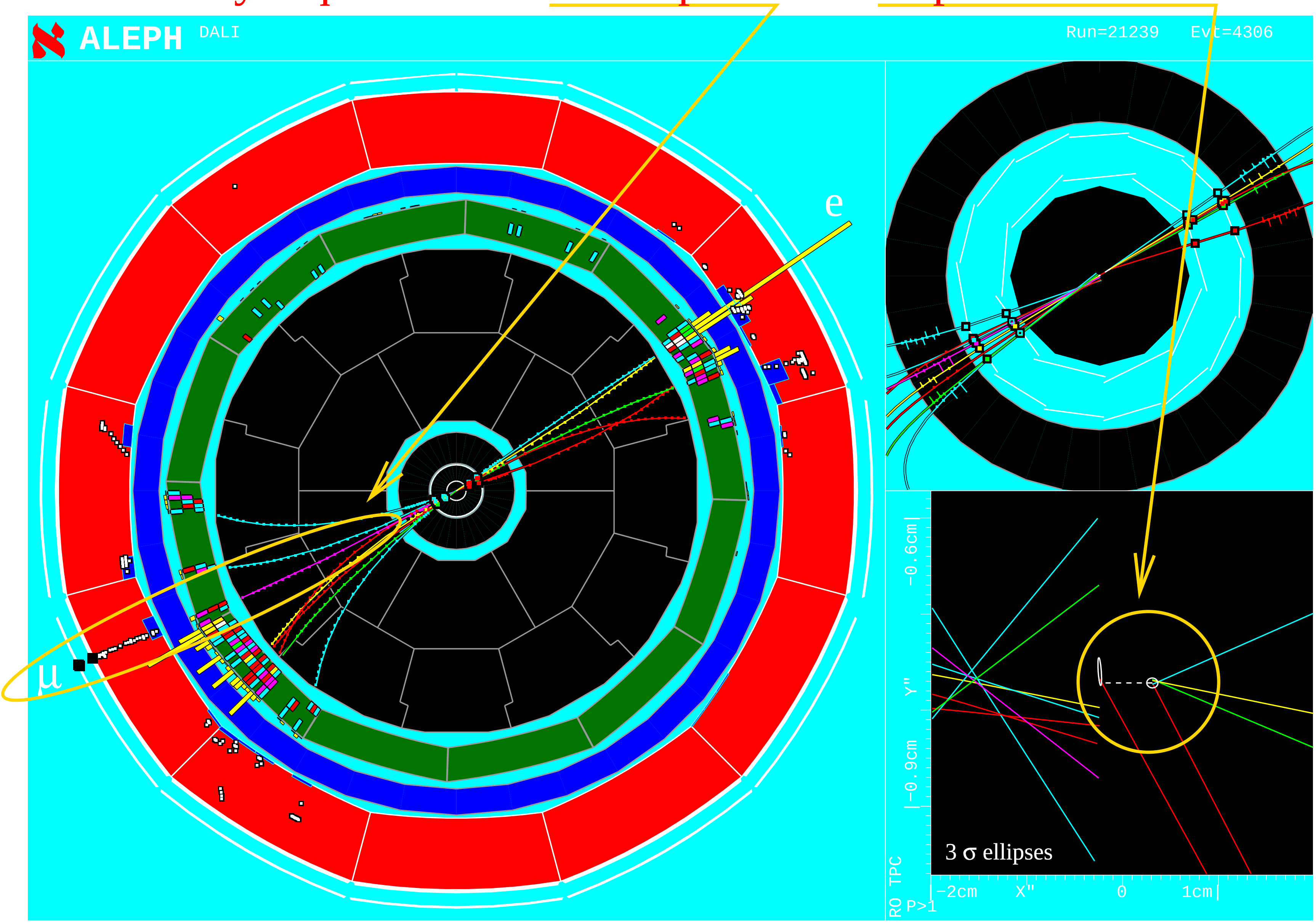
Standard Model predictions from:
$m_{\rm t} = 174.3 \pm 5.1$, $m_{\rm H} = [114.1, 1000]$

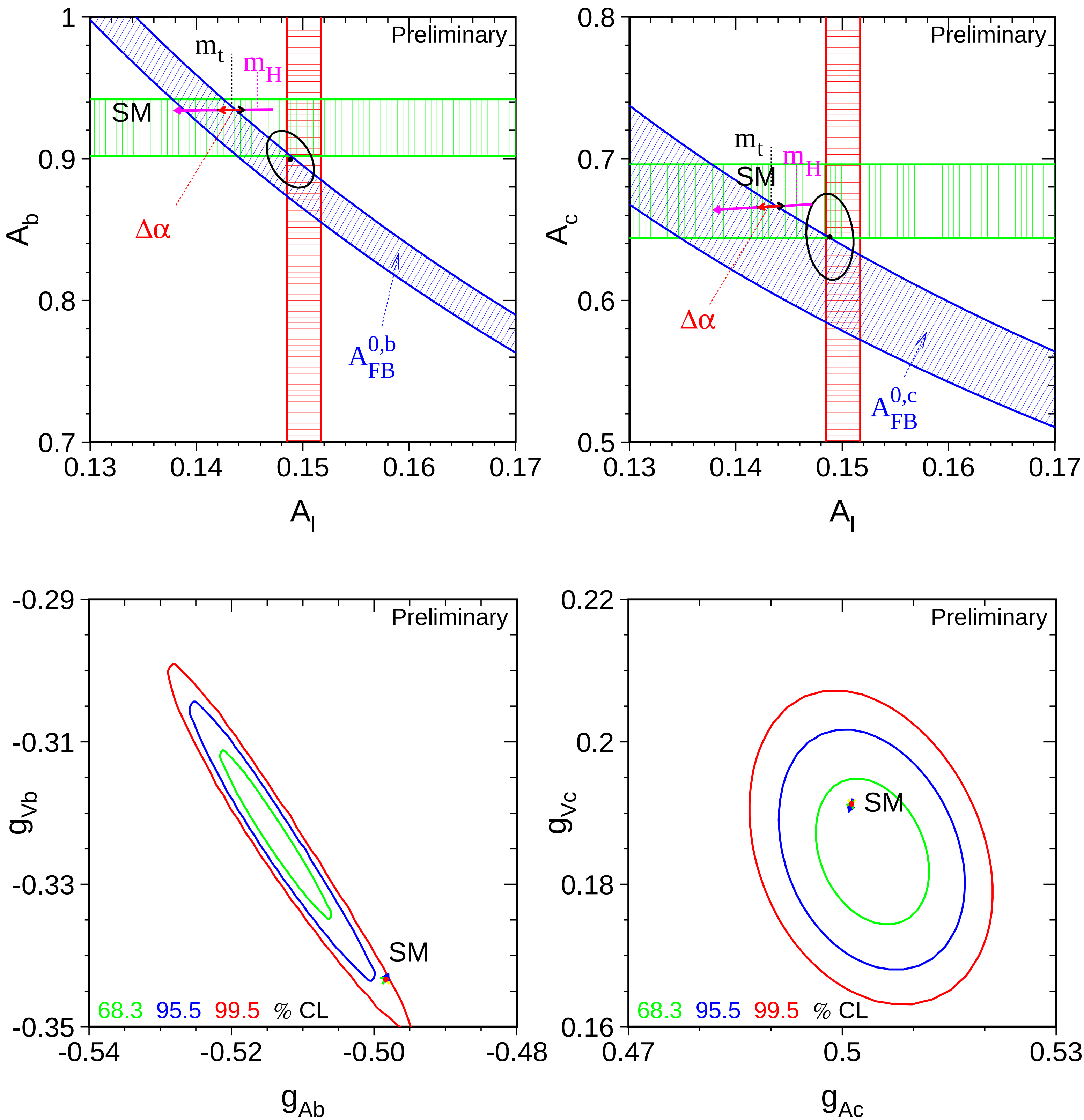



1987
$e^+e^- \to \mu^+\mu^-$
$\nu_\mu e^-$
$\bar{\nu}_\mu e^-$
$\bar{\nu}_e e^-$
$\bar{\nu}_e e^-$
$\nu_e e^-$
1.0
0.5
0.0
-0.5
-1.0
g_A
-1.0
-0.5
0.0
0.5
g_V

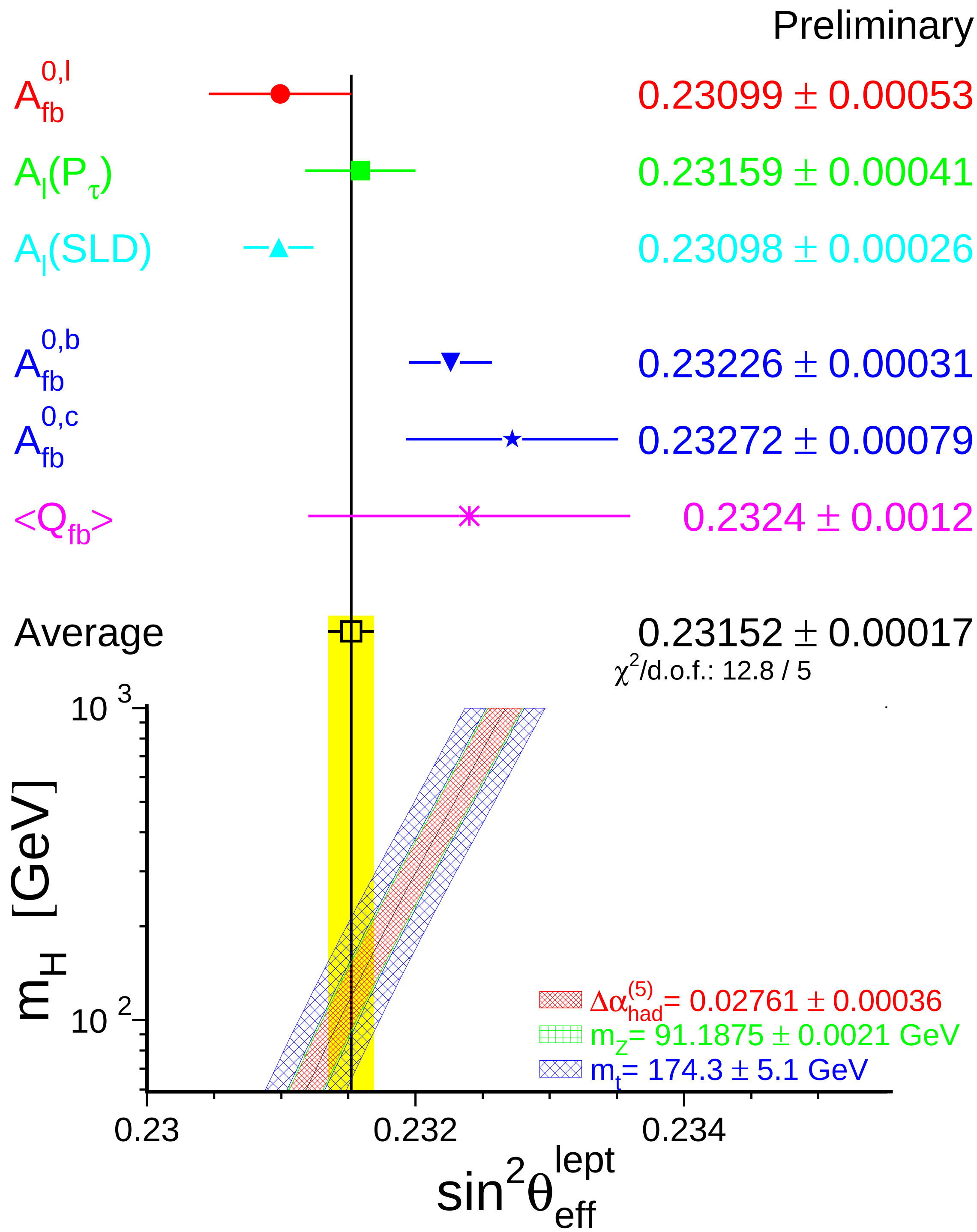
b quark identification at LEP

Identify b quarks with hard leptons and displaced vertices



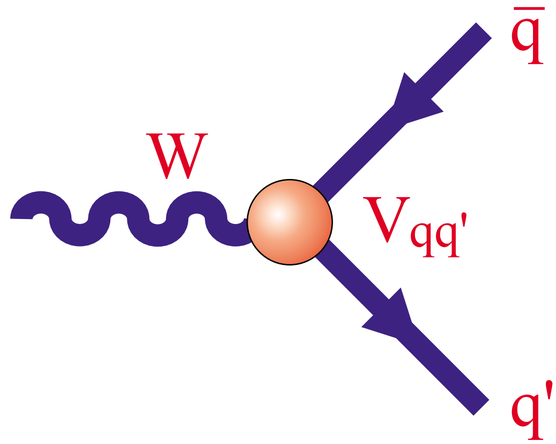


Some deviations for b quarks (with leptons)



$$\chi^2(\text{leptons})/d.o.f. = 1.6/2\ (44.3\%)$$
$$\chi^2(\text{hadrons})/d.o.f. = 0.3/2\ (84.6\%)$$
$$\chi^2(\text{total})/d.o.f. = 12.8/5\ \ (2.5\%)$$

Difference of 3.3σ between hadrons and leptons

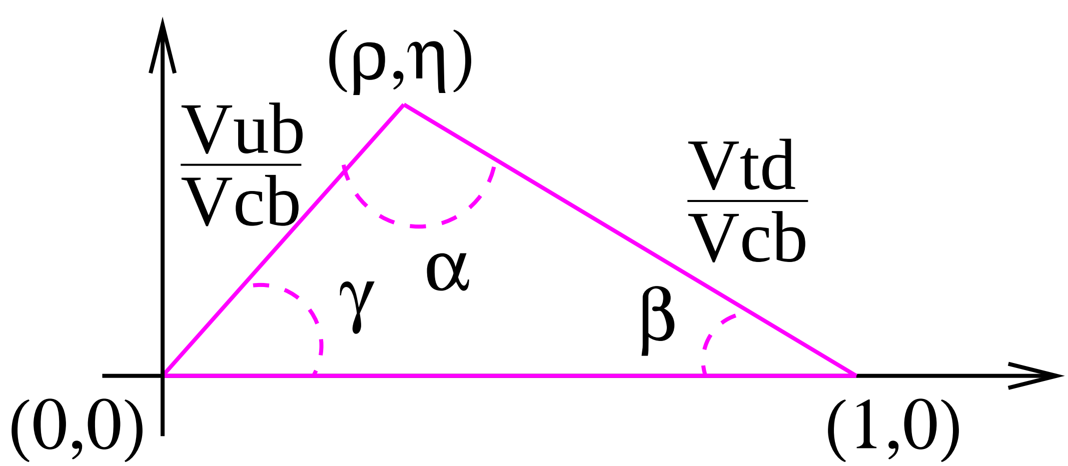


Described by the Cabibbo-Kobayashi-Maskawa matrix

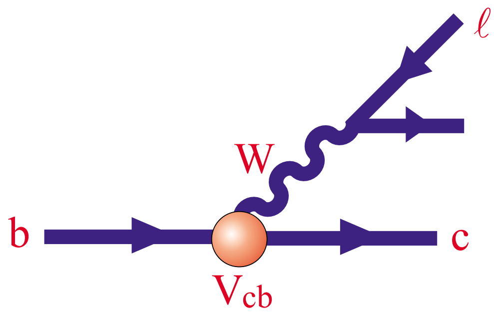
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq$$

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Free parameters of the Standard Model!
Summarised by the unitarity triangle:

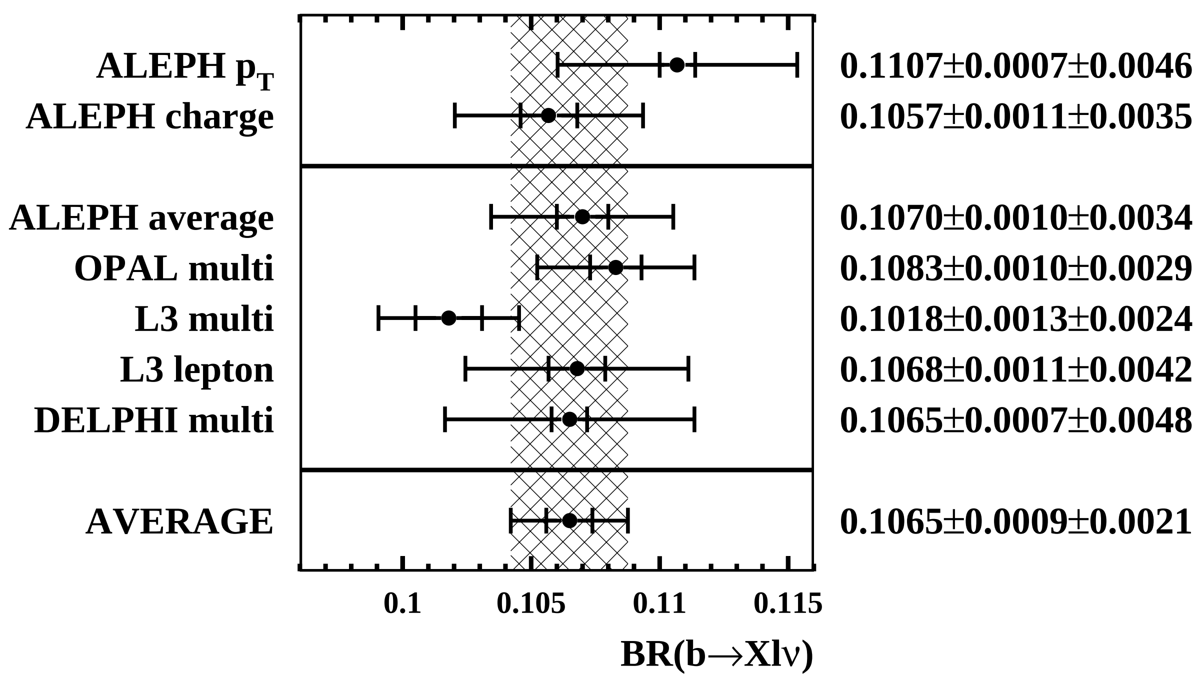


The semileptonic $b \to c\ell\nu$ decay gives access to V_{cb}



$$|V_{cb}| = 0.0411 \times \sqrt{\frac{Br(B \to X_c \ell\nu)}{0.105}} \times \sqrt{\frac{1.55\,\text{ps}}{\tau_B}} \pm 5\%_{\text{theory}}$$

I. I. Bigi *et al.*, Ann. Rev. Nucl. Part. Sci. **47** (1997) 591



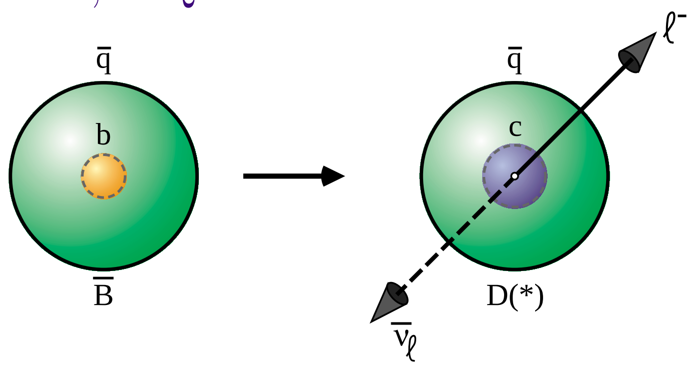
$$V_{cb} = (40.7 \pm 0.5 \pm 2.0) \times 10^{-3}$$

V_{cb} from Exclusive decays

$$\frac{d\Gamma}{d\omega}\left(\overline{B^0} \to D^{\star +}\ell\nu\right) = K(\omega)F^2(\omega)|V_{cb}|^2$$

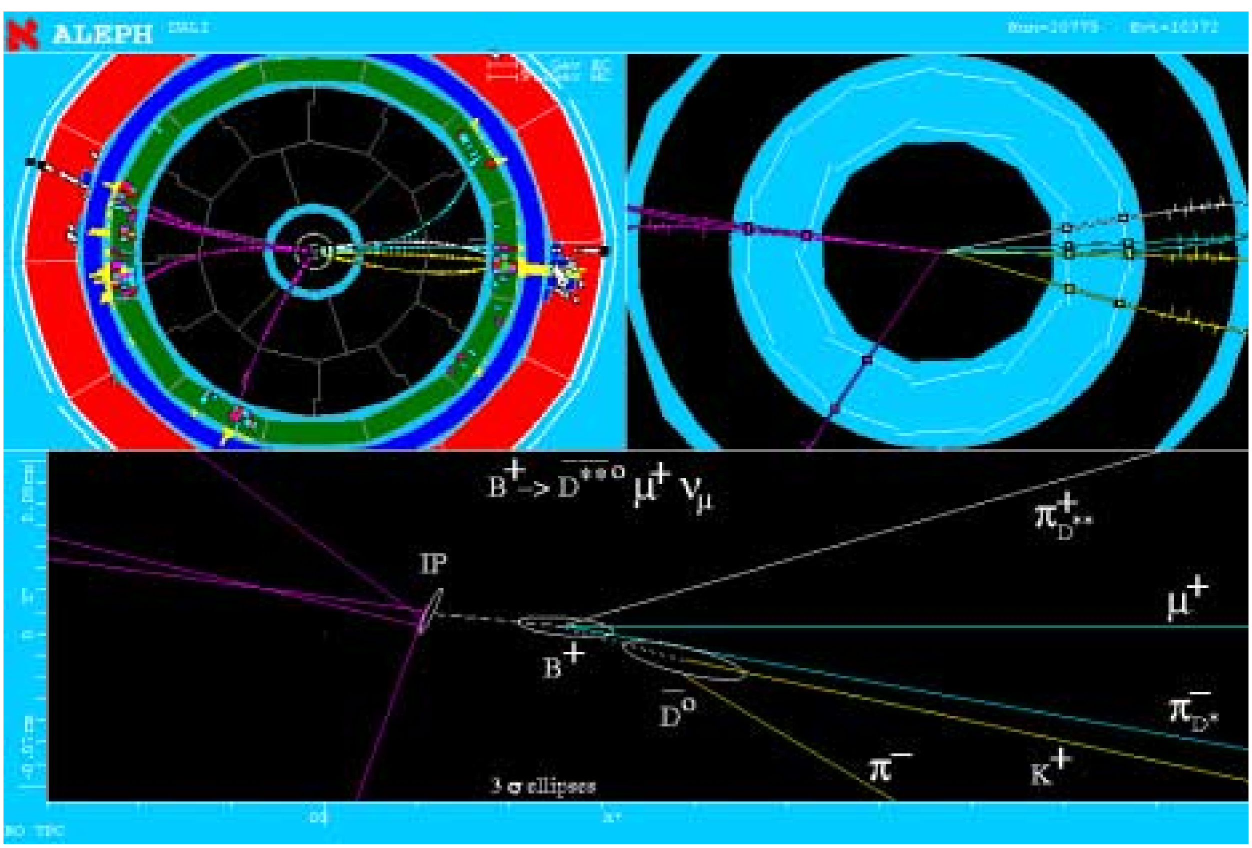
$$\begin{aligned} \omega &= v_{\overline{B}^0} \cdot v_{D^{\star+}} & [\omega = 1 \Rightarrow \text{HQET}] \\ K(\omega) &= \text{Phase space} & [\text{Known Function}] \\ F(\omega) &= \text{Form factor} & [\text{HQET}] \end{aligned}$$

At rest, $\omega = 1$, HQET has with a lower uncertainty.

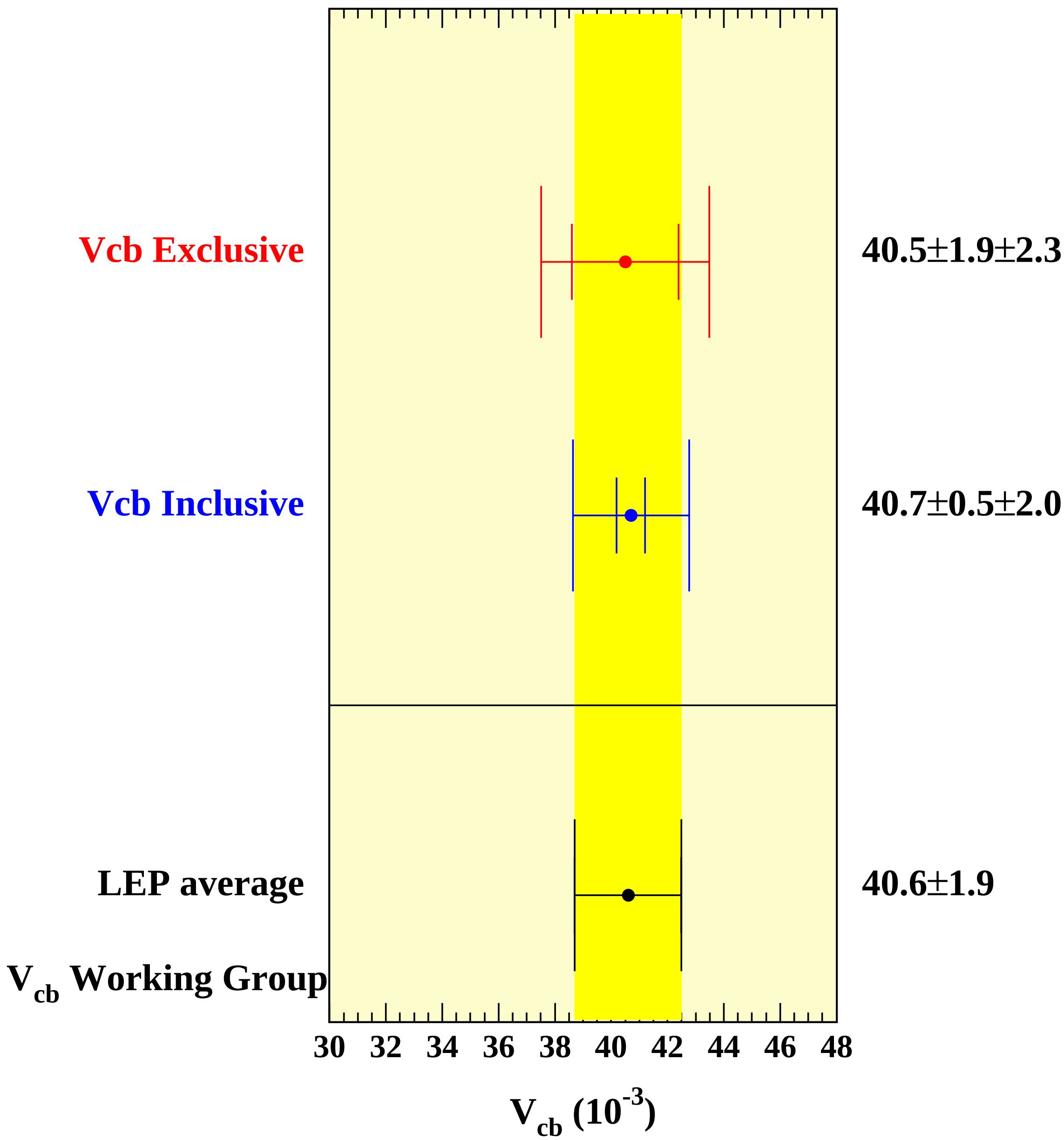


M. Luke, Phys. Lett. **B 252** (1990) 447

I. Caprini *et al.* Nucl. Phys. **B 530** (1998) 153

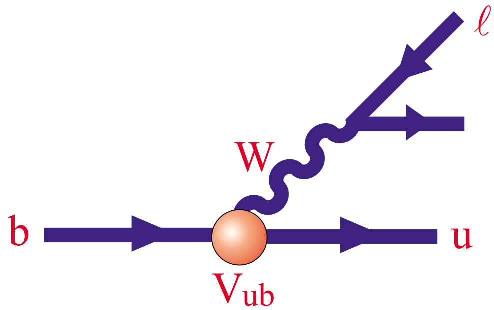


Combine the LEP inclusive and exclusive measurements of V_{cb}



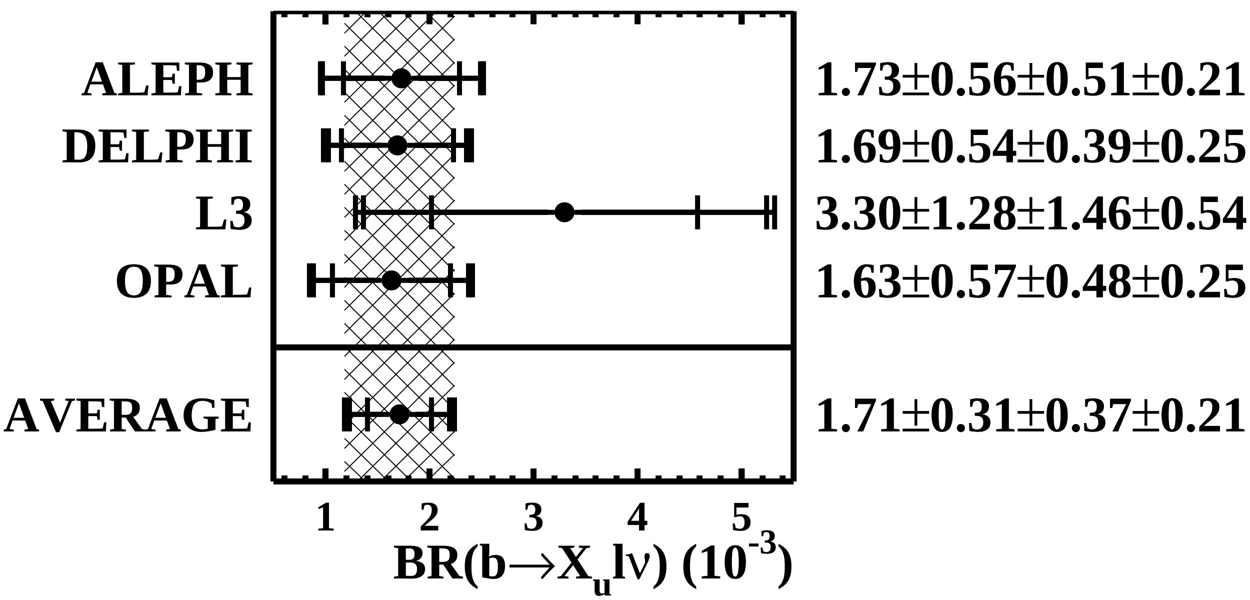
Competitive with the B-factories result

The semileptonic $b \to u\ell\nu$ decay gives access to V_{ub}



$$|V_{ub}| = 0.00458 \times \sqrt{\frac{Br(B \to X_u \ell \nu)}{0.002}} \times \sqrt{\frac{1.6\,\mathrm{ps}}{\tau_B}} \pm 4\%_{\mathrm{theory}}$$

I. I. Bigi, `hep-ph/9907270`
N. Uraltsev, Int. J. Mod. Phys. **A 14** (1999) 4641

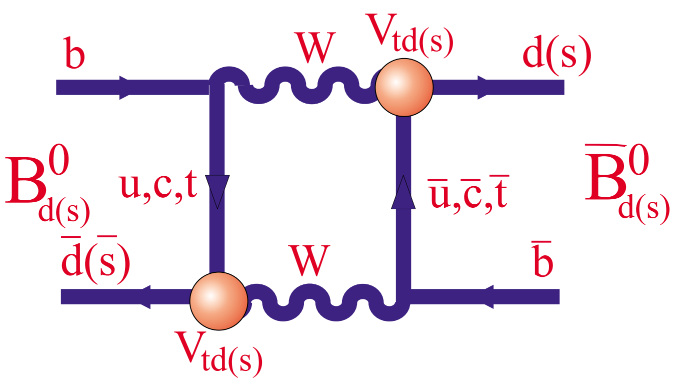


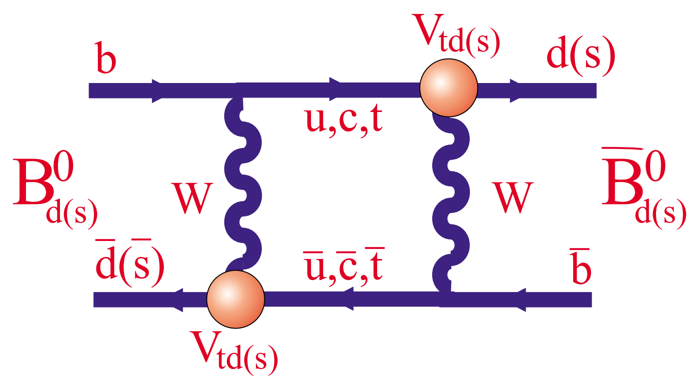
$$V_{ub} = (4.09^{+0.59}_{-0.69}) \times 10^{-3}$$

Competitive with the B factories result

$$|B_L\rangle = p|B^0_{d,s}\rangle + q|\bar{B}^0_{d,s}\rangle \qquad |B_H\rangle = p|B^0_{d,s}\rangle - q|\bar{B}^0_{d,s}\rangle$$

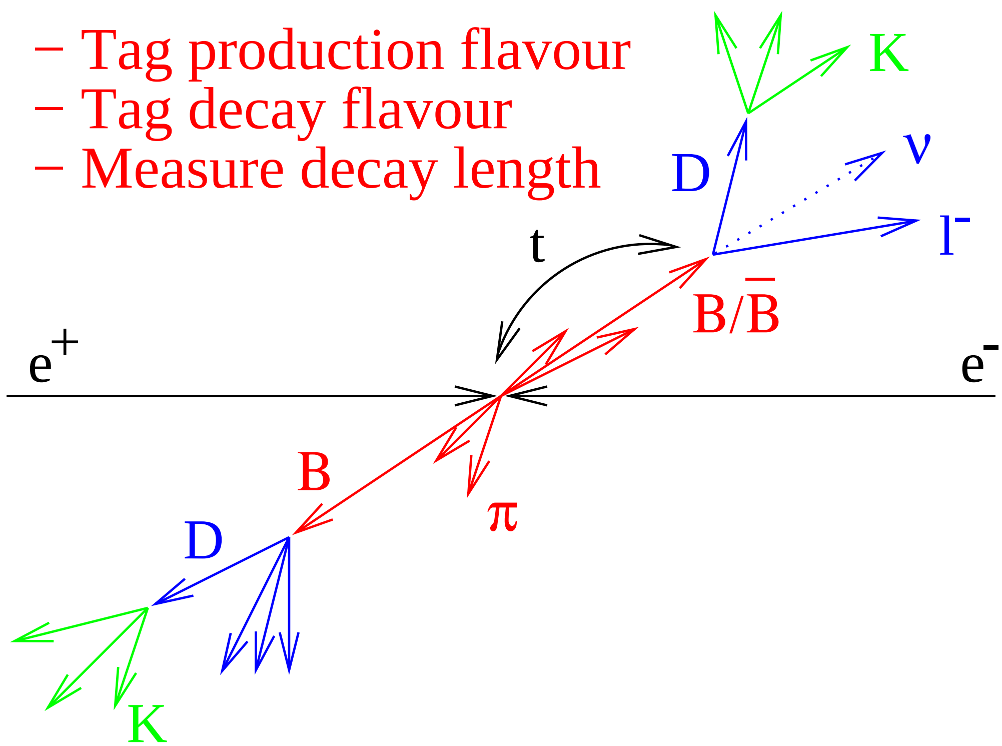
$$\Delta m_{d,s} = m_{B_H} - m_{B_L}$$



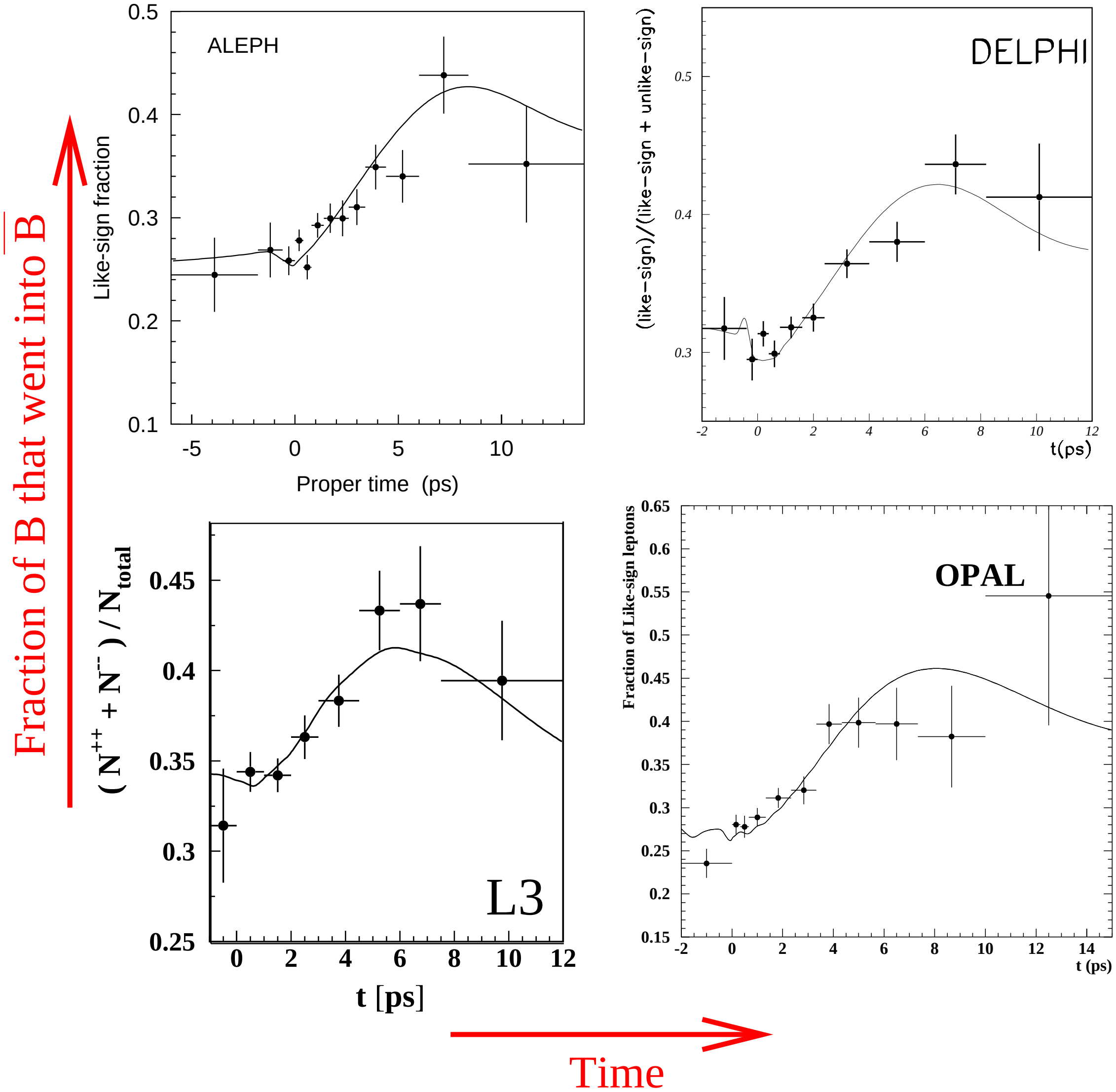


$$P\left[B^0_{d,s} \rightarrow (B^0_{d,s}\bar{B}^0_{d,s})\right] = \frac{1}{2\tau}e^{-t/\tau}\left(1 \pm \cos \Delta m_{d,s} t\right)$$

– Tag production flavour
– Tag decay flavour
– Measure decay length



Textbook evidence of B_d^0 Oscillations



$\Delta m_d = 0.494 \pm 0.007\,\mathrm{ps}^{-1}$ World average

$\Delta m_d = 0.484 \pm 0.015\,\mathrm{ps}^{-1}$ LEP only

(Before LEP 0.5 ± 0.1 from ARGUS and a signal from UA1)

The Δm_d measurement constrains $|\mathrm{V_{td}}|/|\mathrm{V_{cb}}|$

$\Delta m_s > 14.6\,\mathrm{ps}^{-1}$ 95% C.L. World average

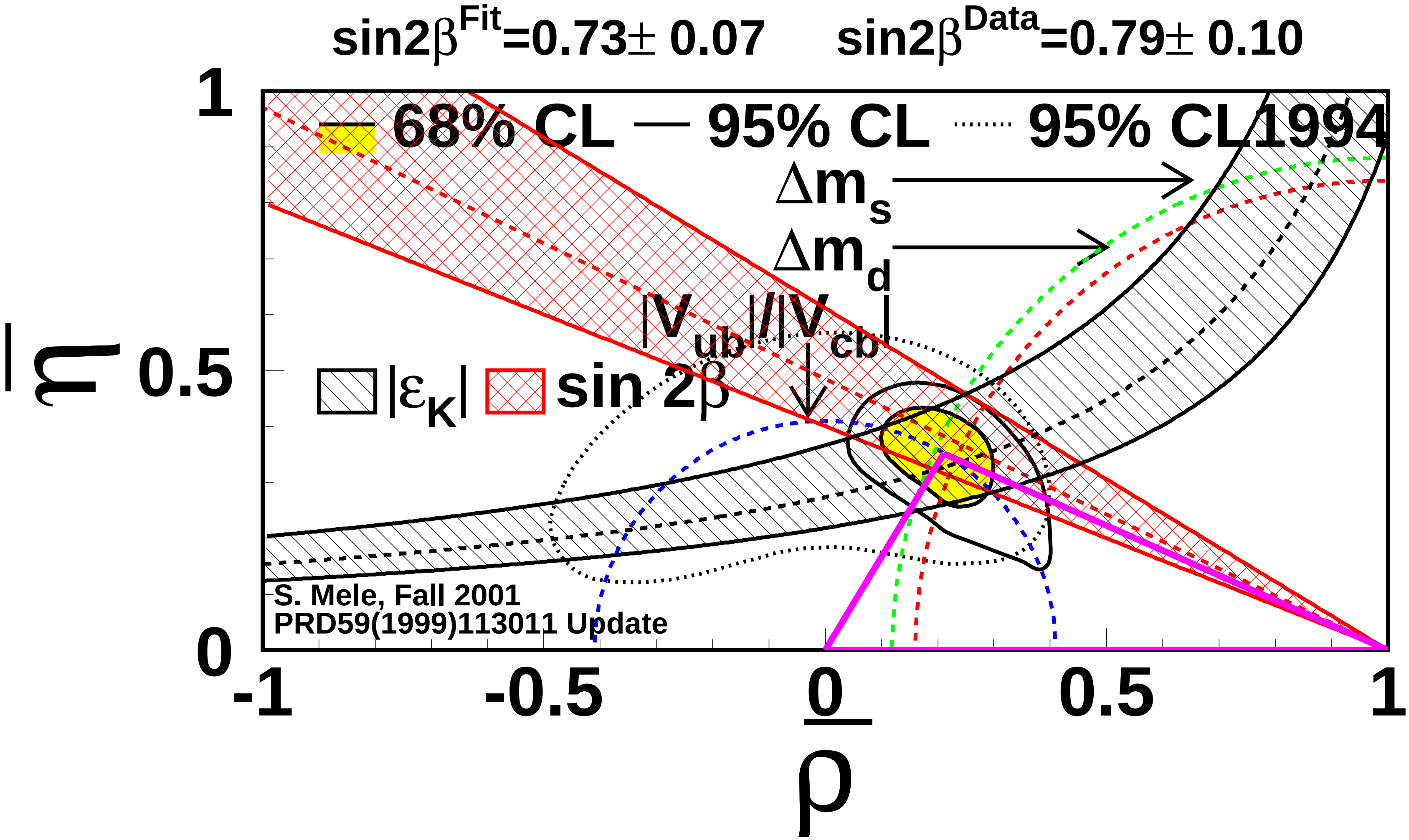
$\Delta m_s > 14.3\,\mathrm{ps}^{-1}$ 95% C.L. LEP only

There is a 2.5σ signal around 17 ps^{-1}

(No studies before LEP)

The Δm_s limit constrains $|\mathrm{V_{ts}}|/|\mathrm{V_{cb}}|$

The unitarity triangle



$$\bar{\rho} = 0.22 \pm 0.06, \quad \bar{\eta} = 0.34 \pm 0.05$$

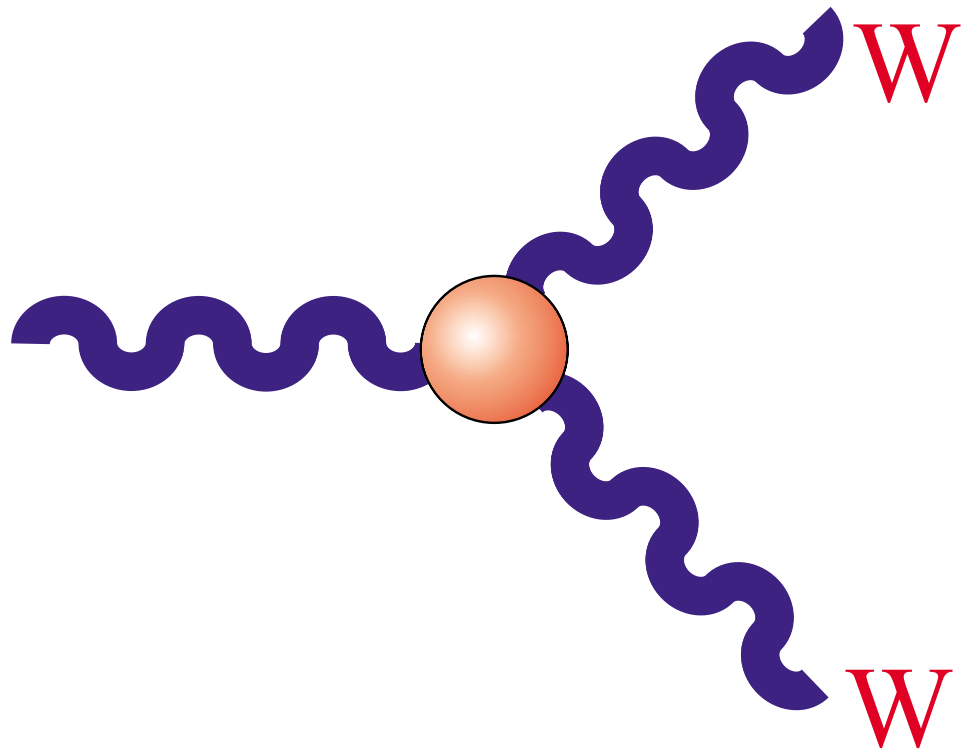
See also:

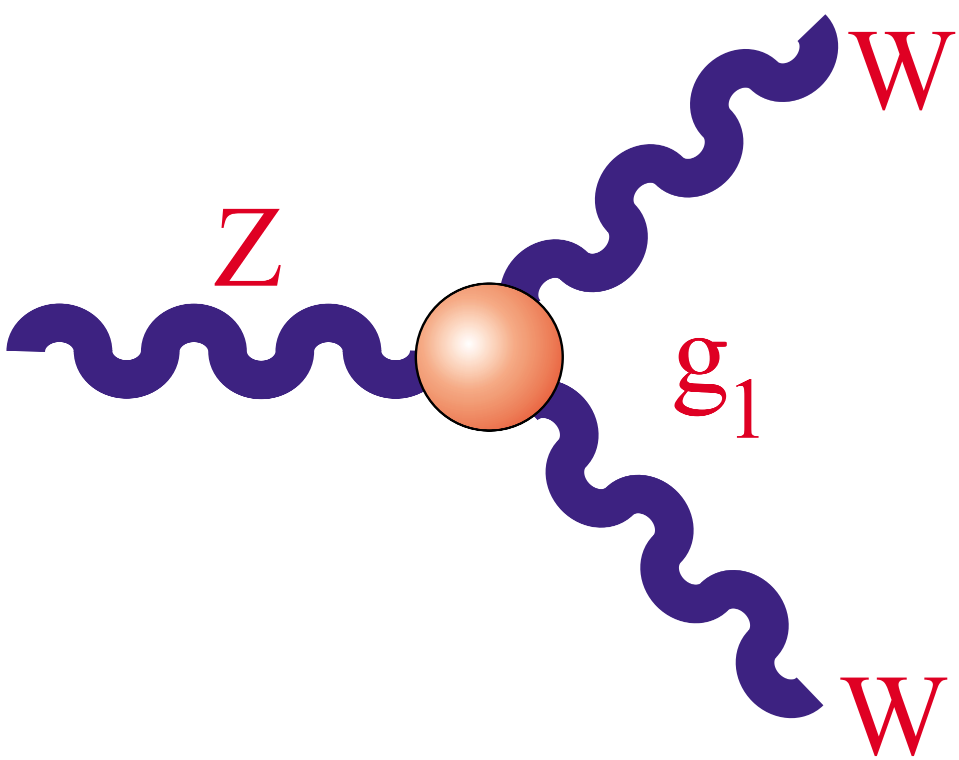
A. Ali and D. London, Eur. Phys. Jour. **C9** (1999) 687

M. Ciuchini *et al.*, JHEP **0107** (2001) 013

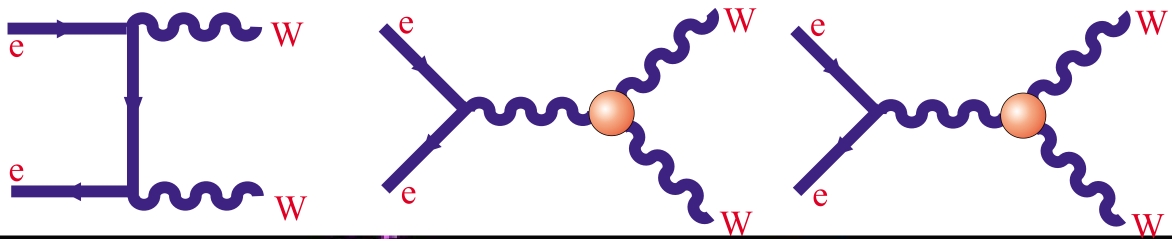
A. Hocker *et al.*, Eur. Phys. J. **C 21** (2001) 225

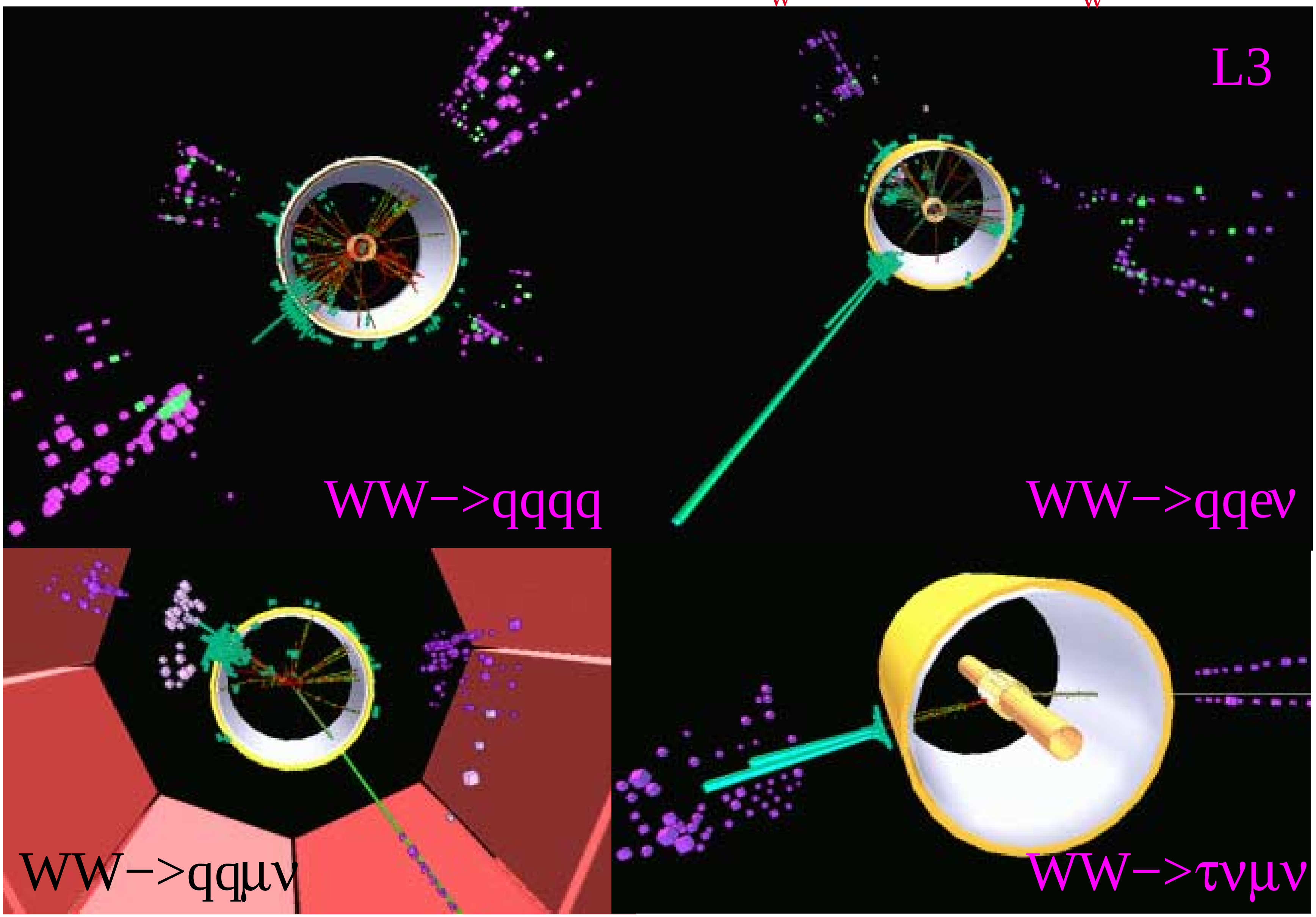
A. Buras, `hep-ph/0109197`

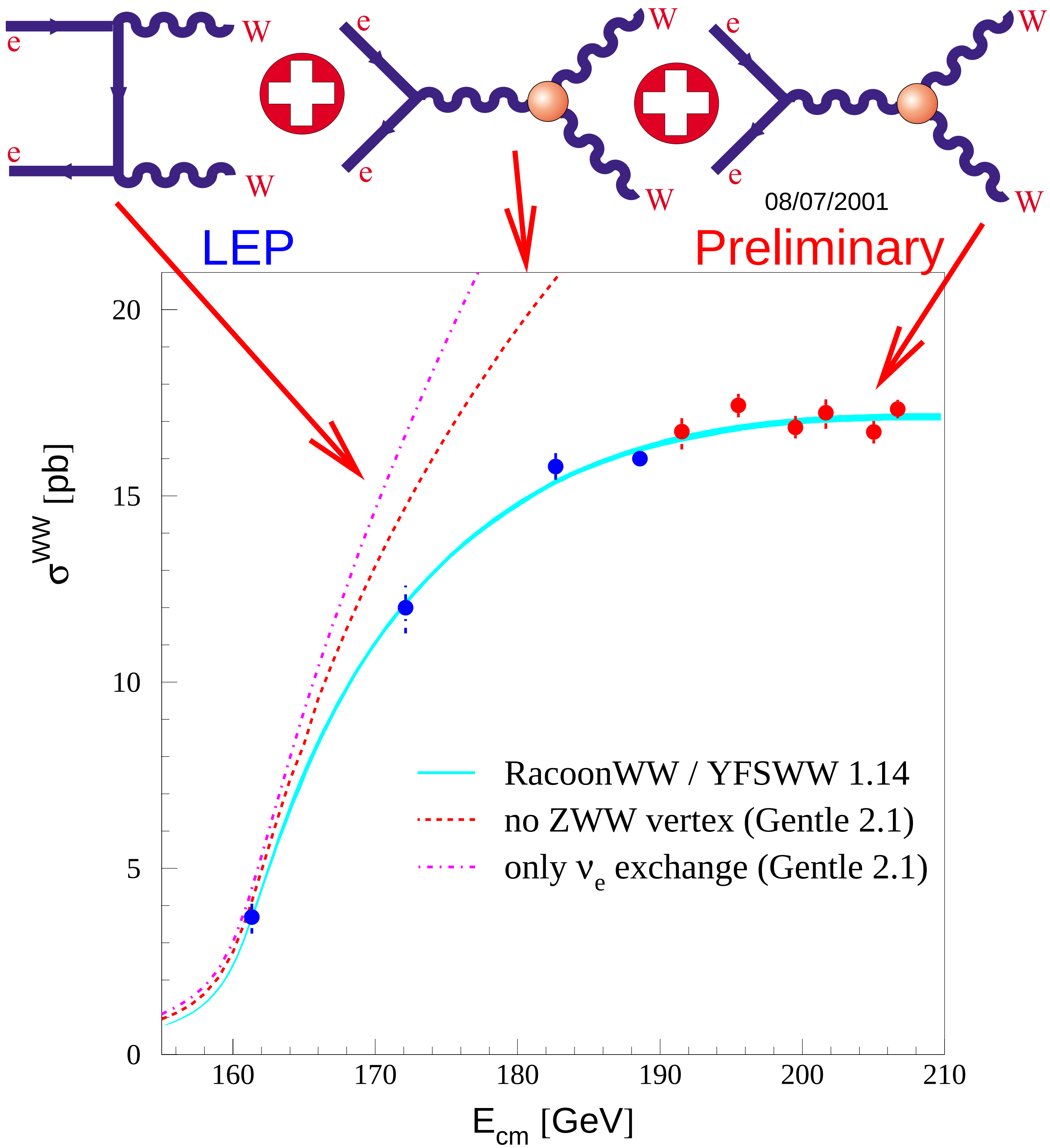

W
W


W
Z
g
1
W

W pair production







Impressive evidence of the non-Abelian structure of the Standard Model

$$
\begin{aligned}
i\mathcal{L}^{WWV} = \\
g_{WWV}[\quad & g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) + \\
& \kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^\dagger_{\rho\nu} W^\mu_\nu V^{\rho\nu} + \\
& \not{C} + \not{P} + \not{C}\not{P} + dim > 6]
\end{aligned}
$$

$$V = \gamma, Z, \quad W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu, \quad V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

In the Standard Model:

$$g_1^Z = g_1^\gamma = \kappa_Z = \kappa_\gamma = 1; \quad \lambda_\gamma = \lambda_Z = 0$$

$$g_{WWZ} = e \cot\theta_W; \quad g_{WW\gamma} = e$$

Multipole expansion of the W-γ interaction:

$Q_W = e g_1^\gamma$	Charge
$\mu_W = \frac{e}{2m_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$	Magnetic dipole
$q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$	Electric quadrupole

Five parameters to study deviations:

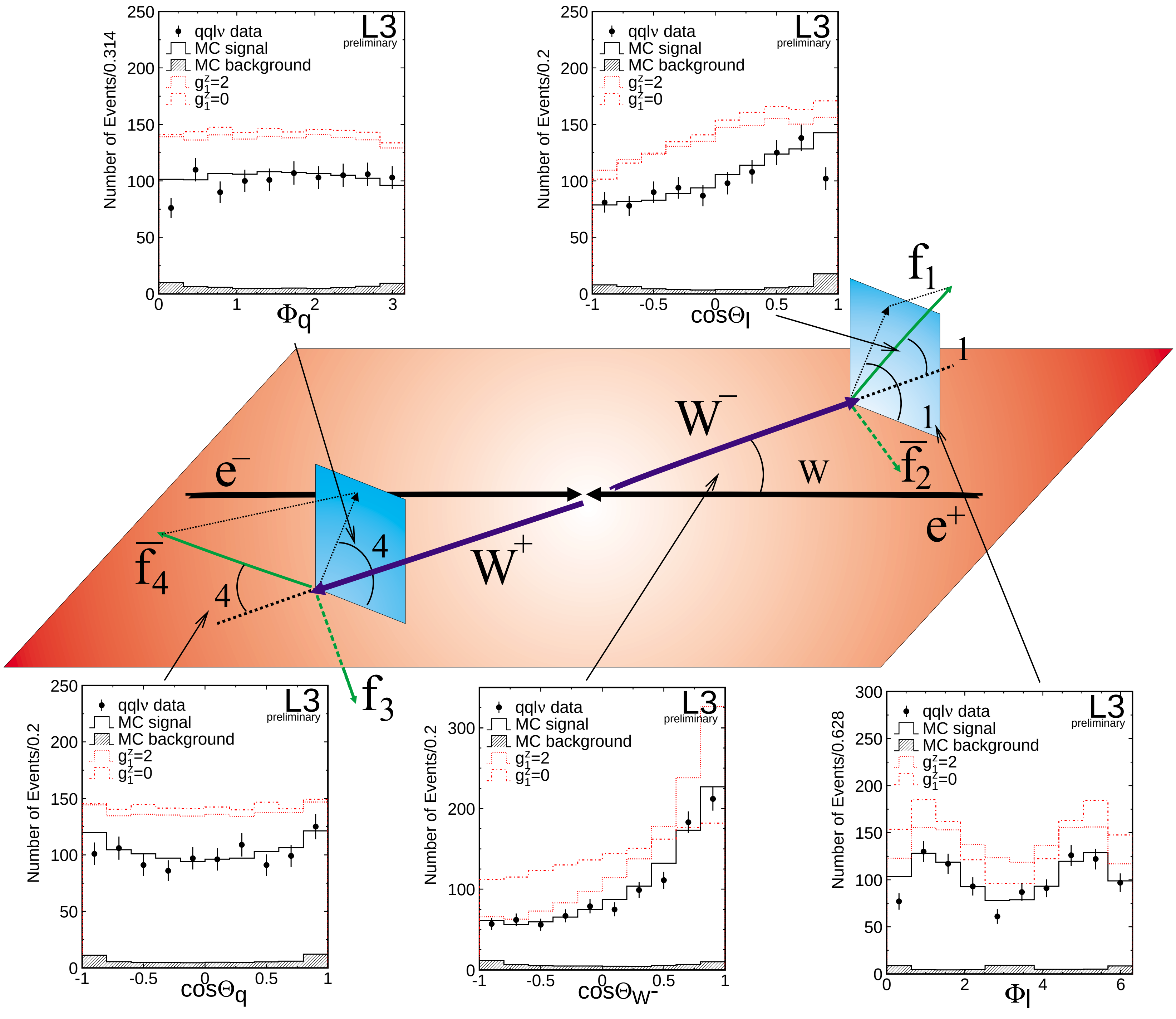
$$\boxed{\Delta g_1^Z \equiv (g_1^Z - 1), \;\; \Delta\kappa_\gamma \equiv (\kappa_\gamma - 1), \;\; \Delta\kappa_Z \equiv (\kappa_Z - 1), \lambda_\gamma, \;\; \lambda_Z}$$

Reduced to three by gauge invariance:

$$\lambda_Z = \lambda_\gamma \quad \Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$$

K. Gaemers and G. Gounaris, Z. Phys. **C 1** (1979) 259
K. Hagiwara *et al.*, Nucl. Phys. **B 282** (1987) 253
M. Bilenky *et al.*, Nucl. Phys. **B 409** (1993) 22
I. Kuss and D. Schildknecht, Phys. Lett. **B 383** (1996) 470
Physics at LEP 2 CERN 96-01 (1996), eds. G. Altarelli *et al.*

TGC measurement



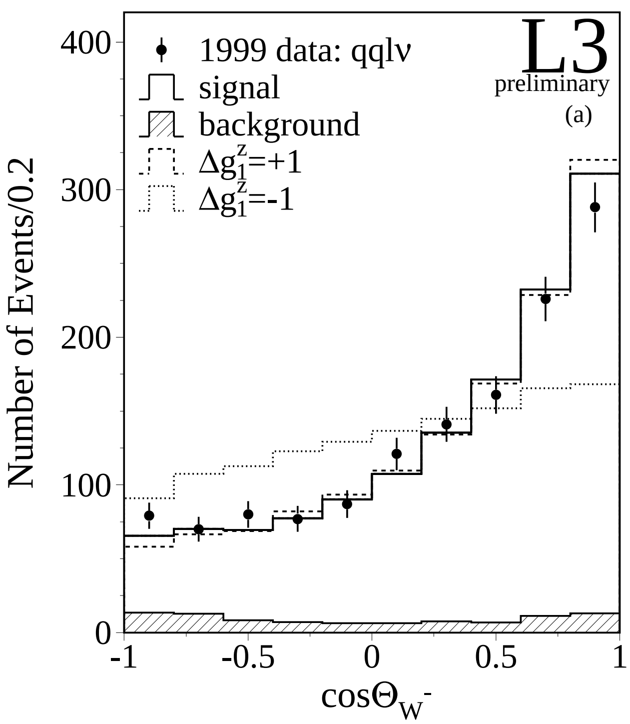
Given the couplings α_i and the phase space Ω:

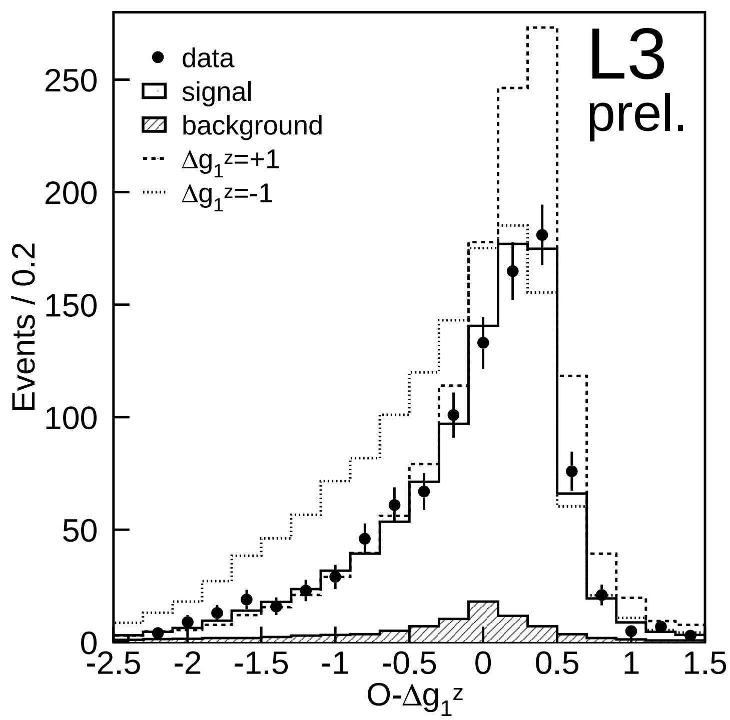
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = c_0(\Omega) + \Sigma_i c_1^i(\Omega)\alpha_i + \Sigma_{i\leq j} c_2^{ij}(\Omega)\alpha_i\alpha_j$$

Define the Optimal Observables:

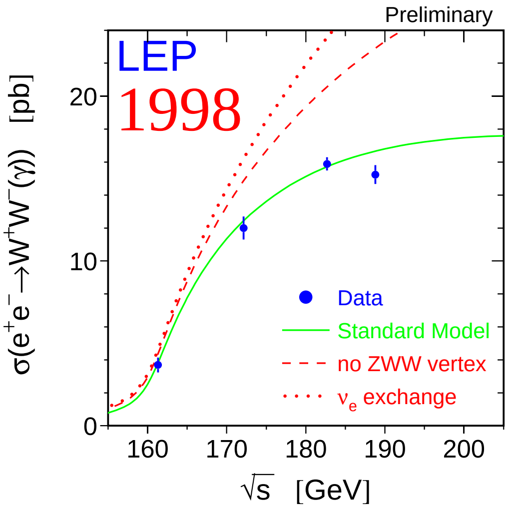
$$\mathcal{O}_i^1 = \frac{c_1^i(\Omega)}{c_0(\Omega)} \quad \mathcal{O}_{ij}^2 = \frac{c_2^{ij}(\Omega)}{c_0(\Omega)}$$

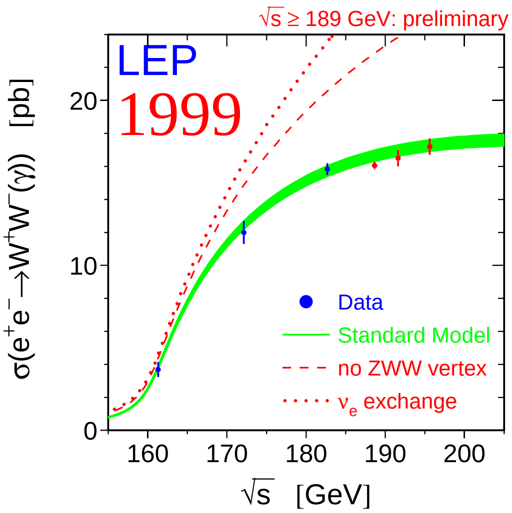
The Optimal Observables contain the same information of the phase space angles but for $\alpha \longrightarrow 0$ all the information is in $< \mathcal{O}_i^1 >$: single variable fit!

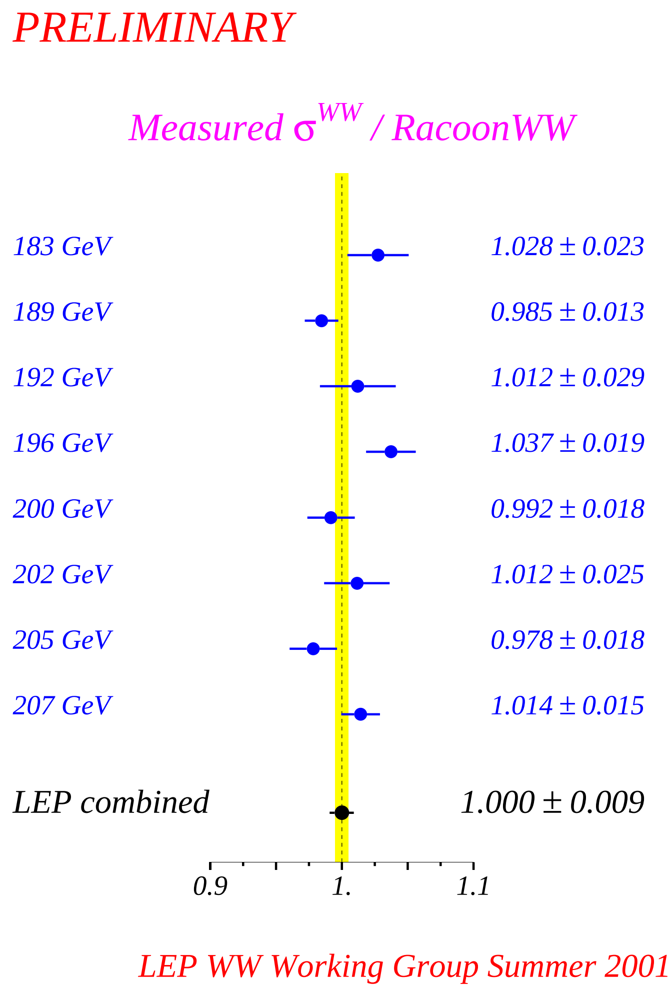


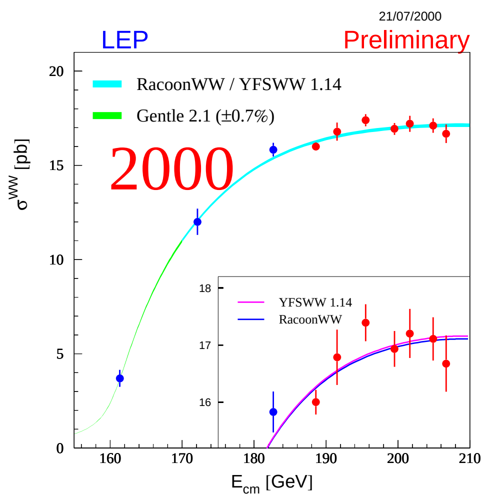


Results... no, not yet!





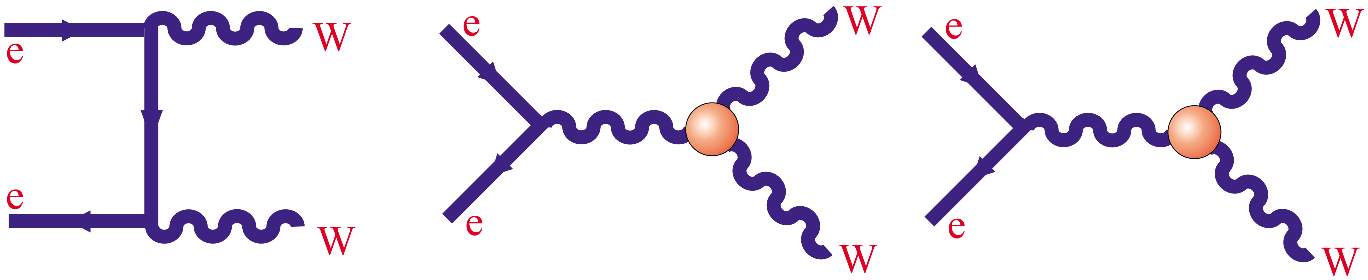




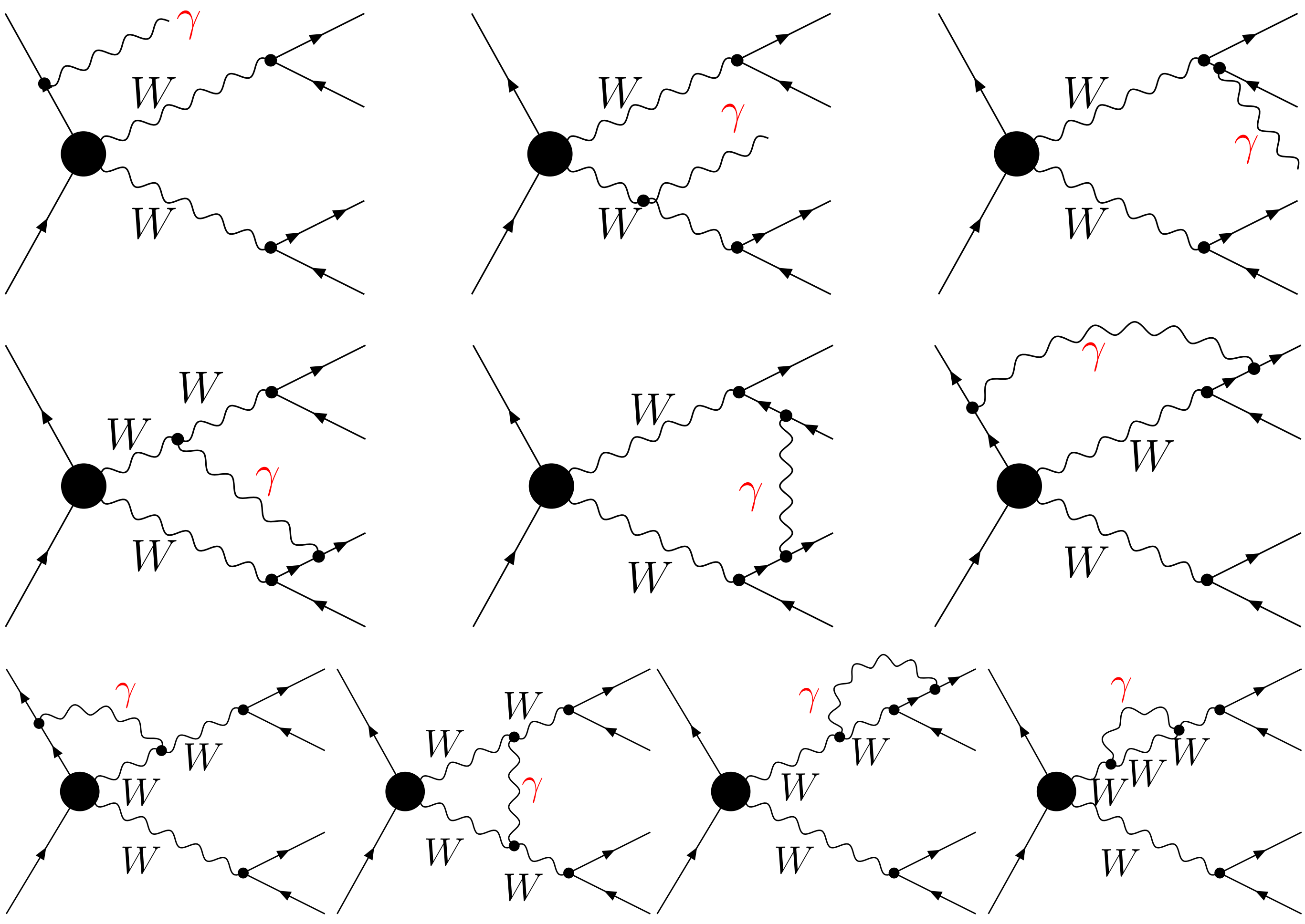
O(α) virtual corrections
O(α) real corrections
Leading Pole Approximation
Double Pole Approximation
Improved Born Approximation
Coulomb screening
YFS exponentiation

Lep-2 Monte Carlo Workshop, M. Grünewald *et al.*, hep-ph/0005309
GENTLE, D. Bardin *et al.*, Comp. Phys. Comm. **104** (1996) 161
KORALW, S. Jadach *et al.*, Comp. Phys. Comm. **119** (1999) 272
RacoonWW, A. Denner *et al.*, Nucl. Phys. **B 560** (1999) 33
YFSWW, S. Jadach *et al.*, Comp. Phys. Comm. **140** (2001) 432

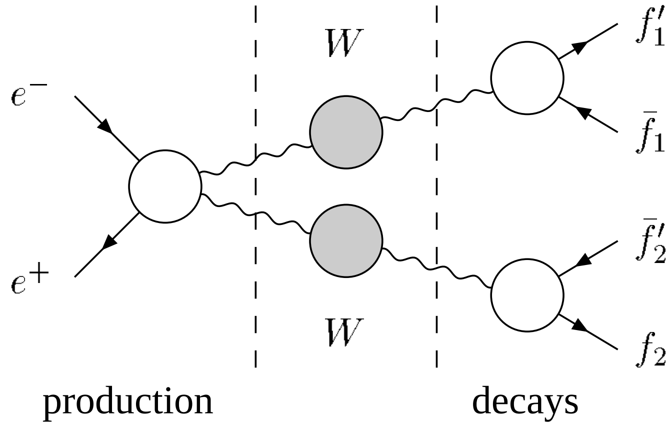
The radiative corrections



When a photon is added [= $\mathcal{O}(\alpha)$corrections],
things are more complex than described so far...

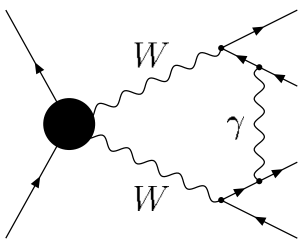


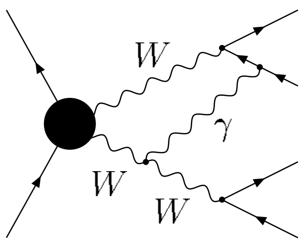
The Double Pole Approximation

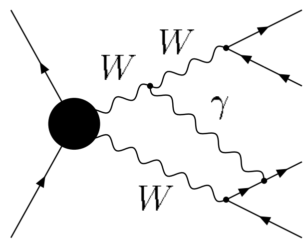


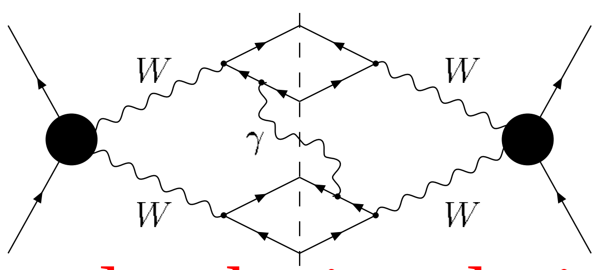
Consider the corrections enhanced by the W poles

+ non factorisable contributions

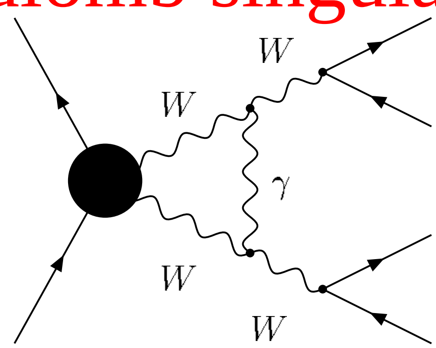


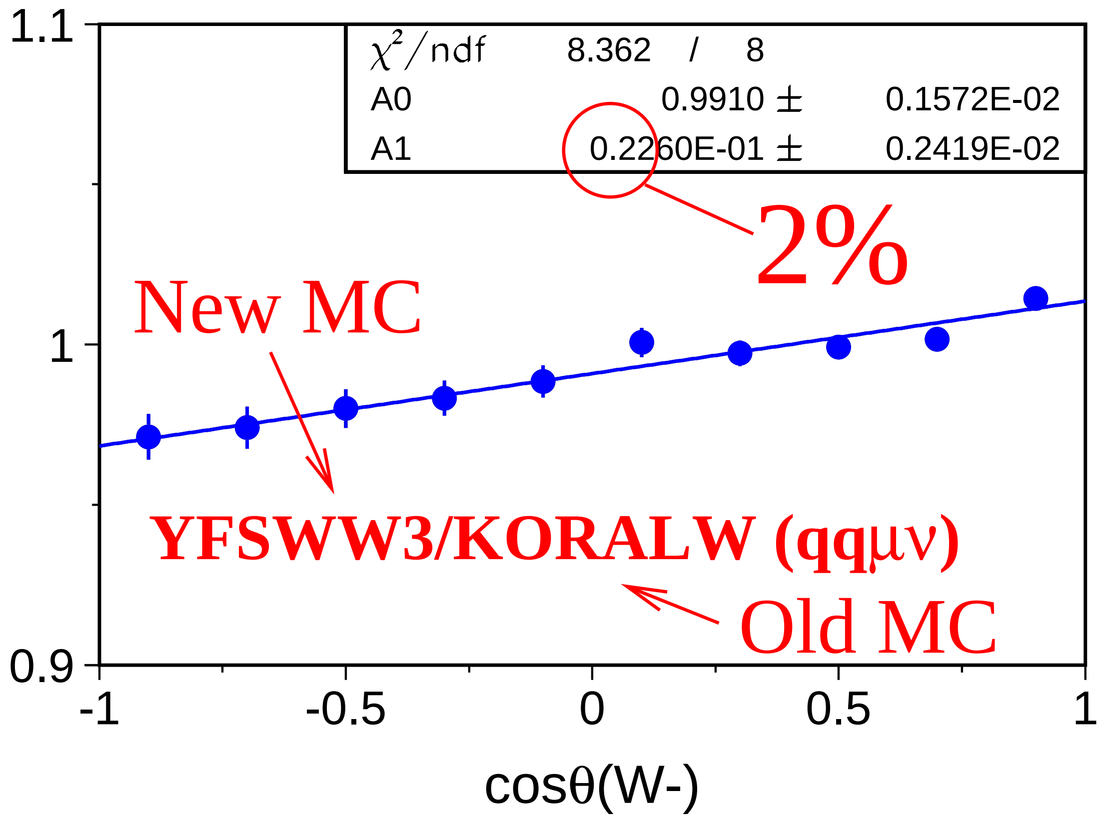






+ coulomb singularity

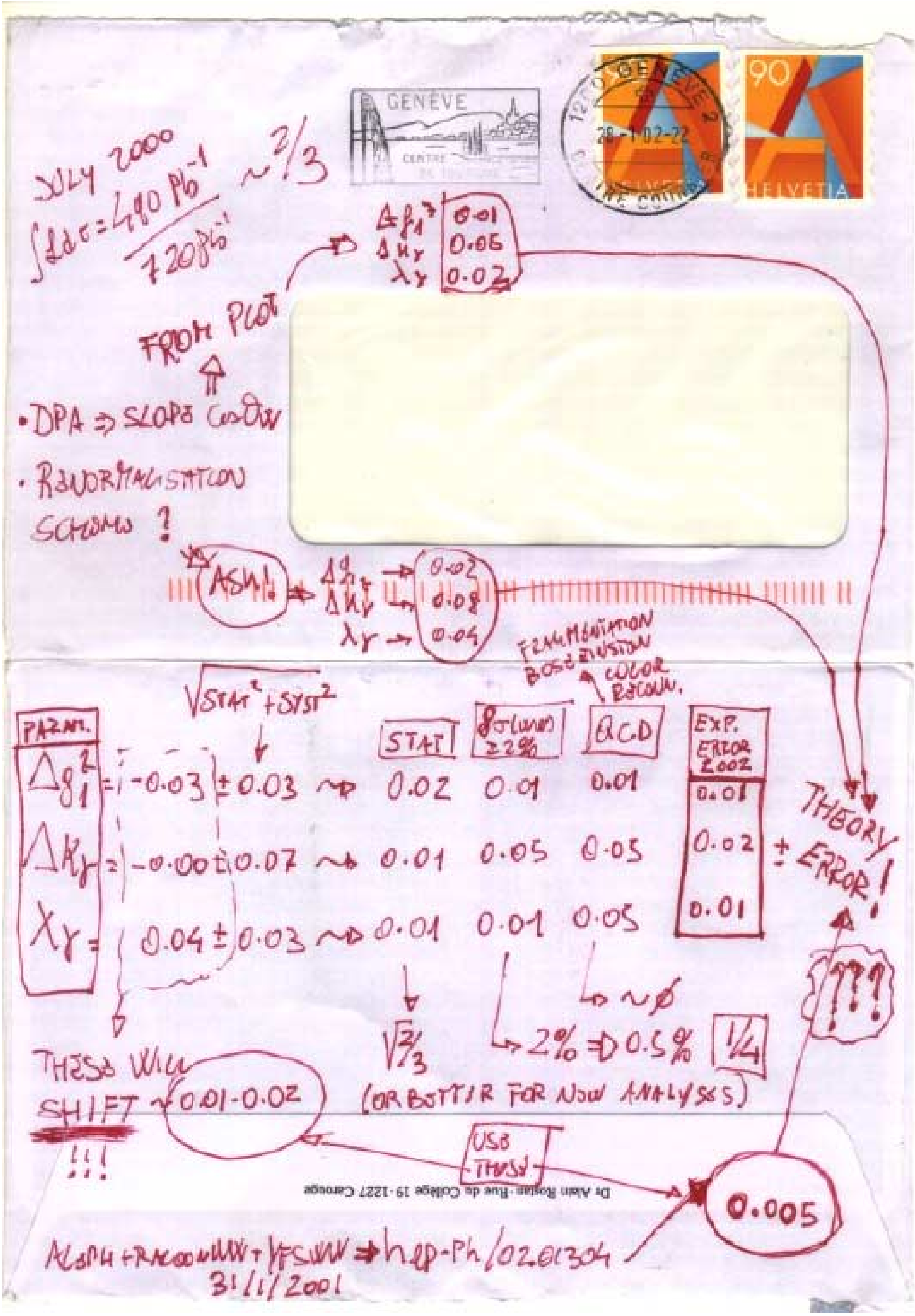




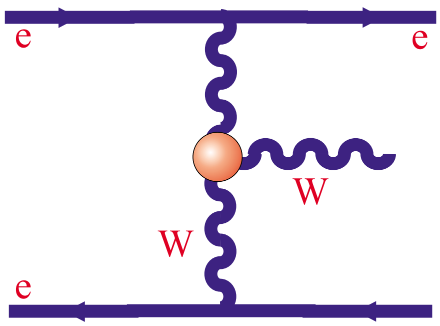
The experiments need:

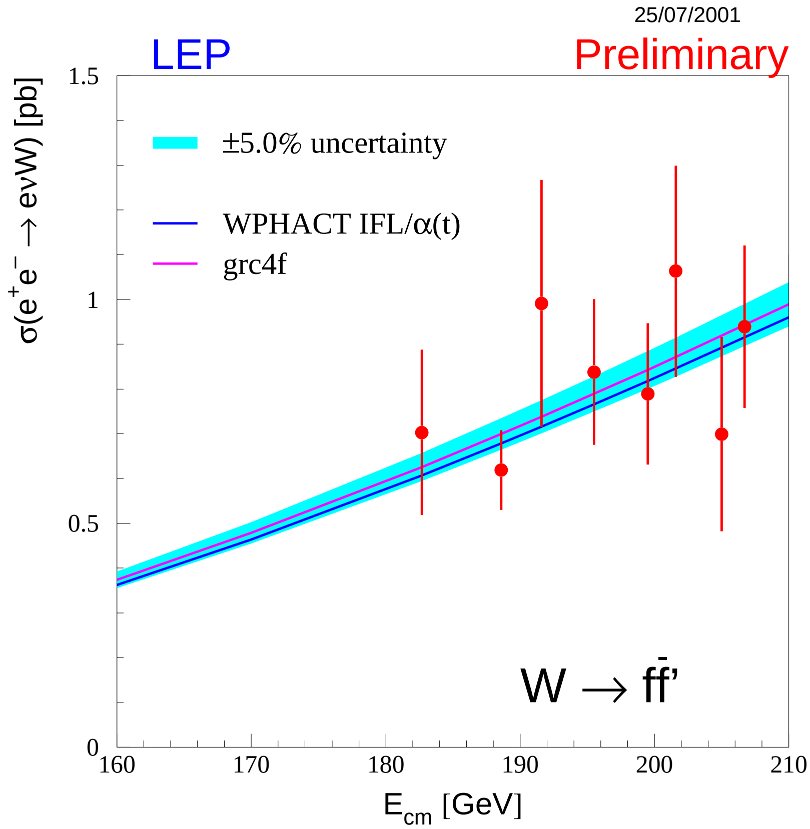
- to understand the new Monte Carlo program(s)
- to install and test them
- to produce million of events (months of CPU)
- to know a theoretical uncertainty

Which precision will we achieve?



The WWγ vertex can also be accessed through "single W" production

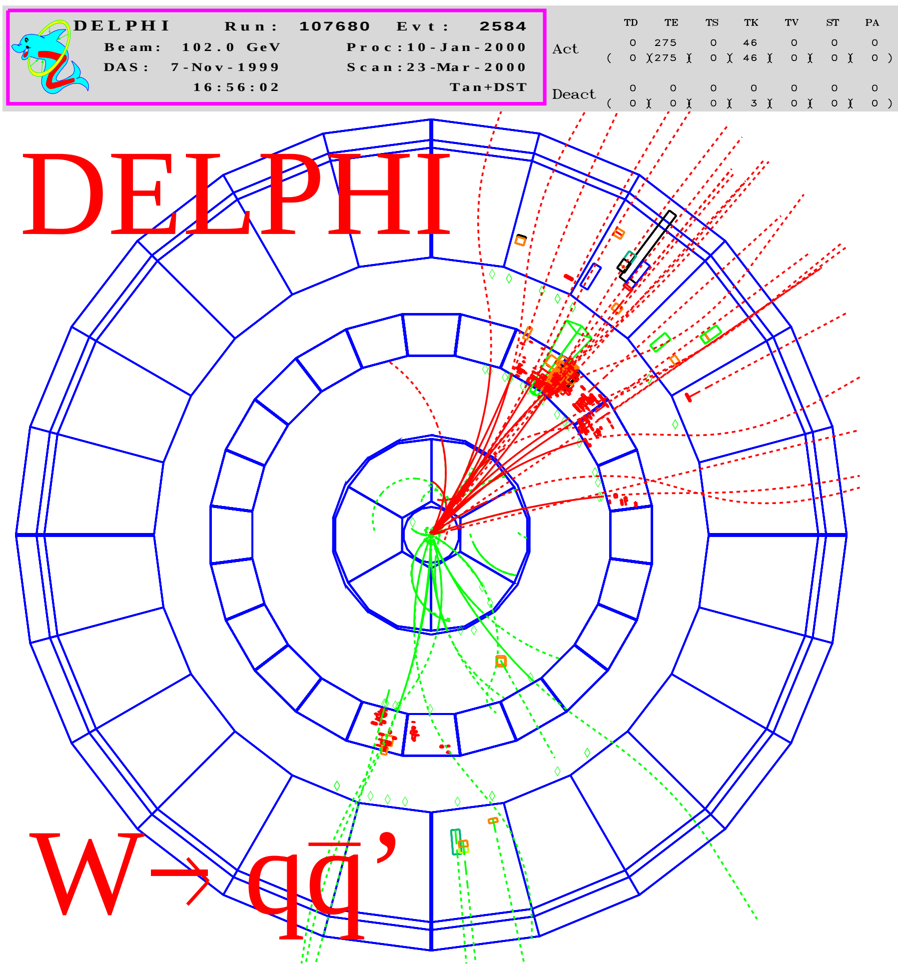


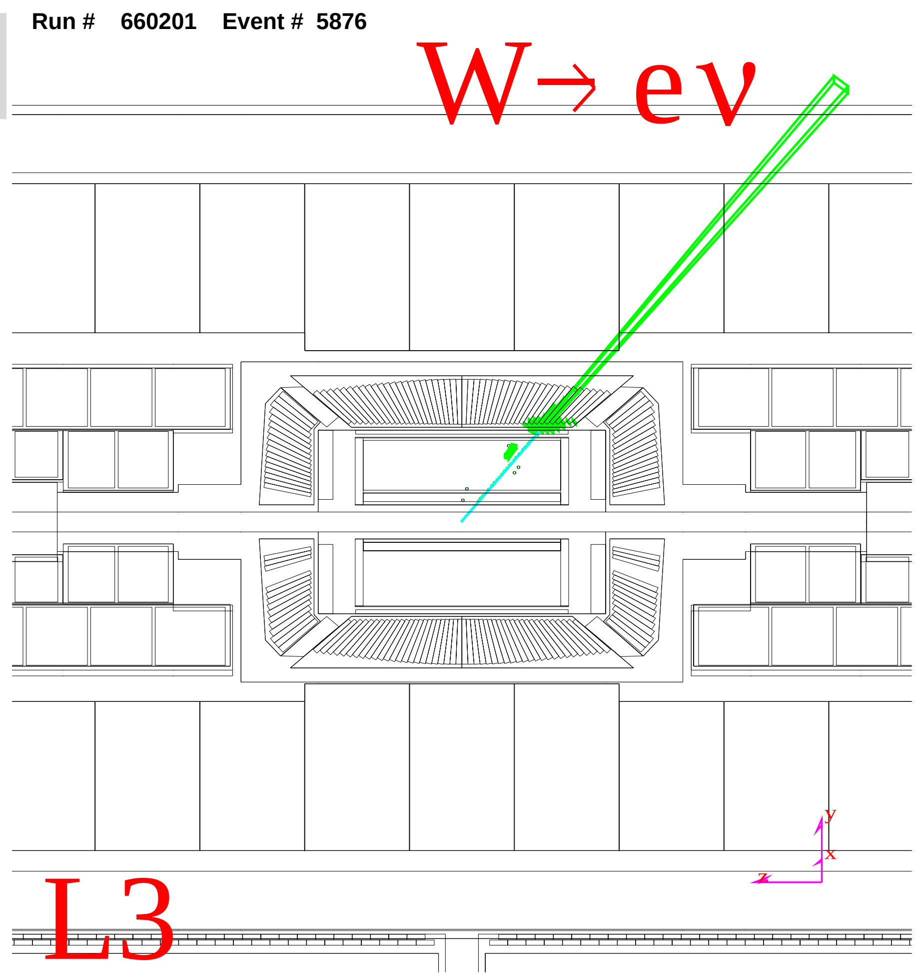


		λ_γ	$\Delta\kappa_\gamma$	
ALEPH	$490\,\text{pb}^{-1}$	[-0.57,0.44].	[-0.54,0.15]	95% C.L.
DELPHI	$180\,\text{pb}^{-1}$	$0.4^{+0.4}_{-1.2}$	$0.2^{+0.4}_{-0.6}$	
L3	$490\,\text{pb}^{-1}$	$-0.2^{+0.6}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	
OPAL	$180\,\text{pb}^{-1}$	$-0.4^{+0.4}_{-0.2}$	$0.0^{+0.2}_{-0.2}$	

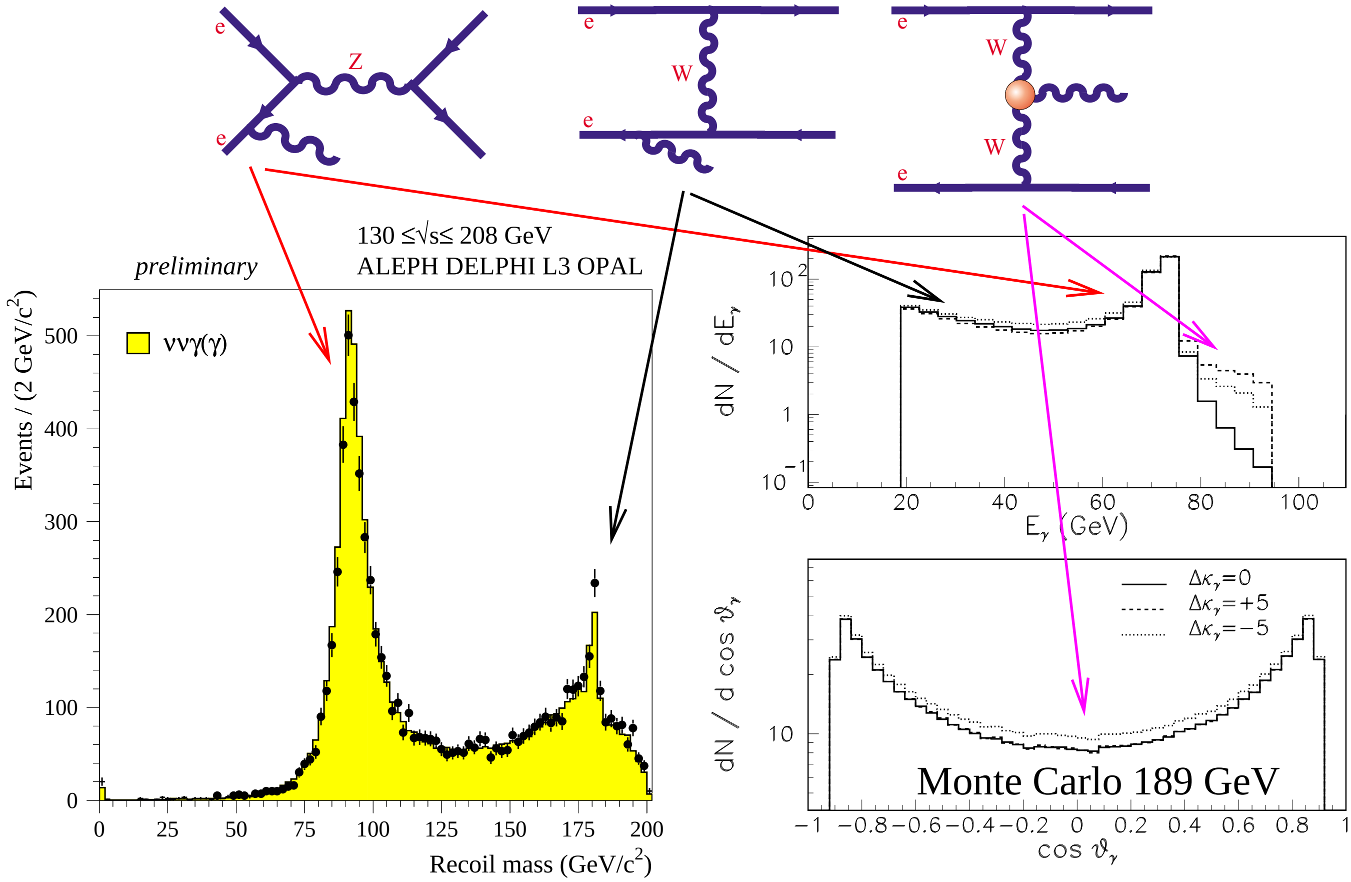
Sensitivity smaller than with W pair production.
Will be included in the global combination.

Single W events



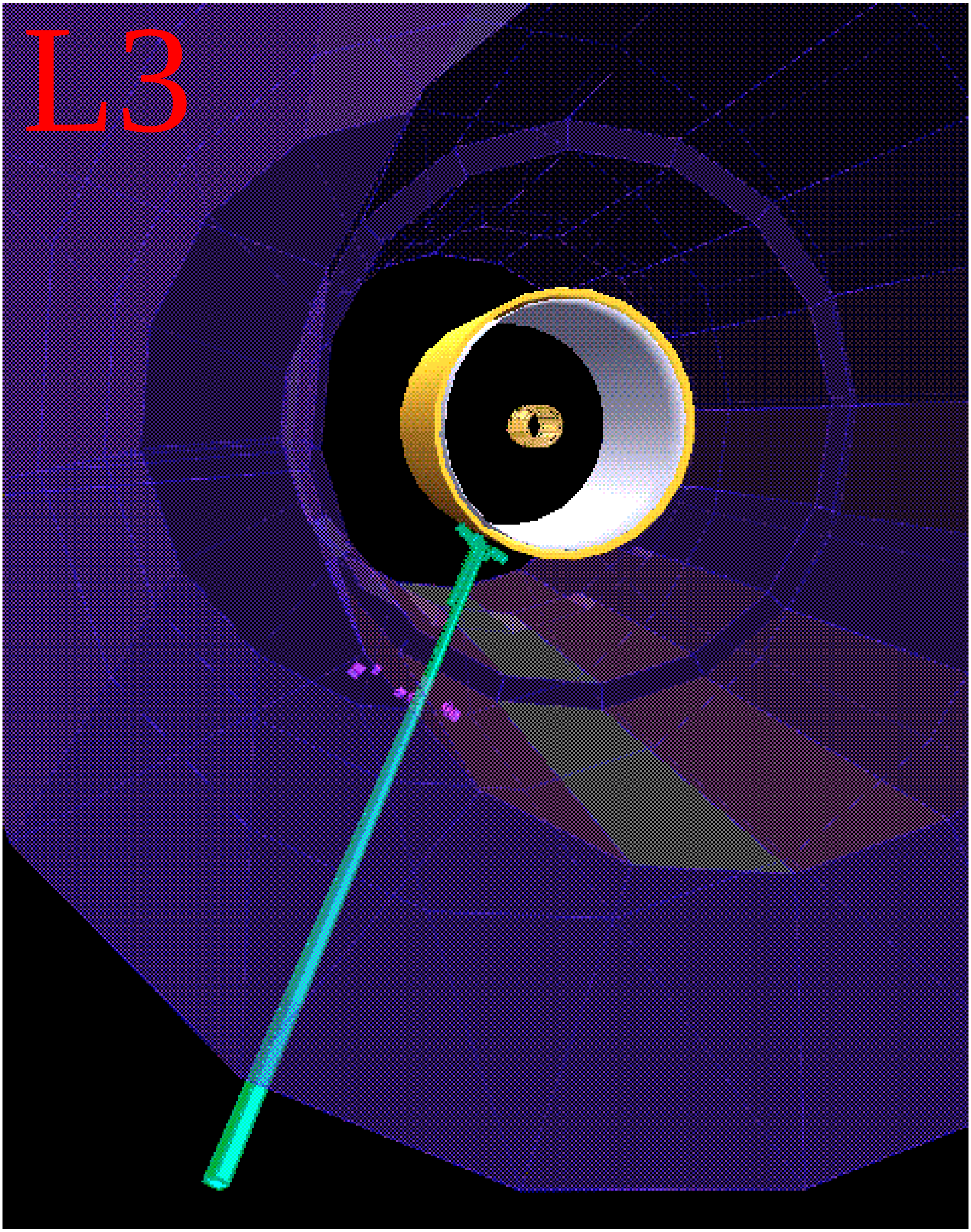


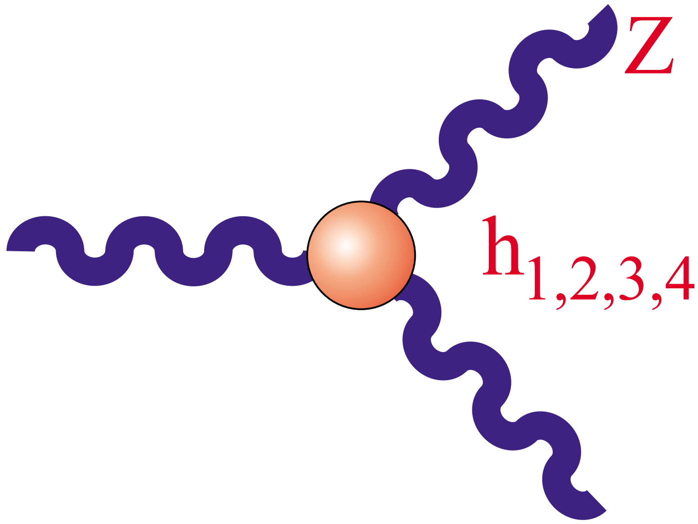
The WWγ vertex can also be accessed through single photon production

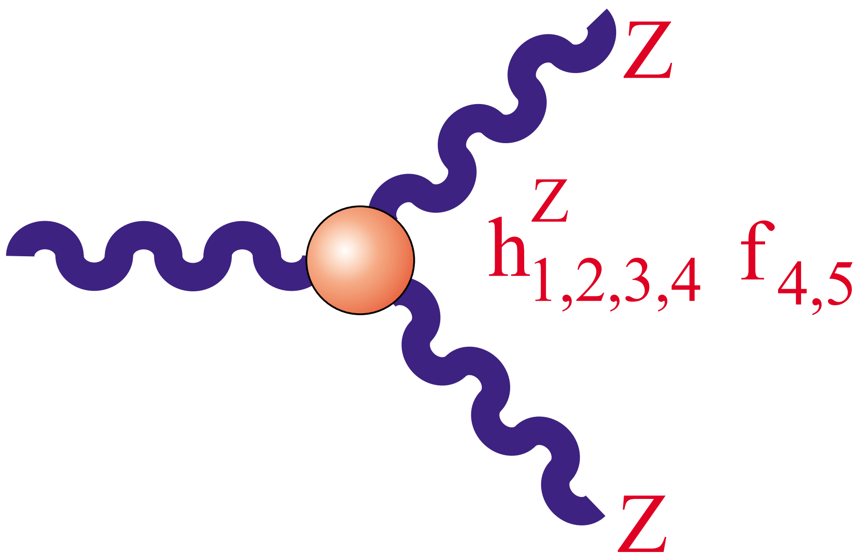


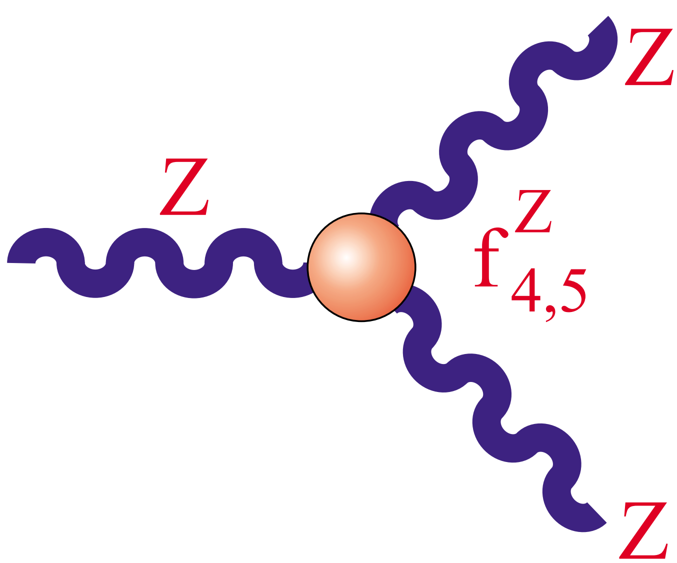
		λ_γ	$\Delta\kappa_\gamma$
ALEPH	$720\,\mathrm{pb}^{-1}$	$0.1^{+0.4}_{-0.4}$	$0.0^{+0.3}_{-0.3}$
DELPHI	$180\,\mathrm{pb}^{-1}$	$0.6^{+1.0}_{-1.8}$	$0.7^{+0.8}_{-1.0}$
L3	$430\,\mathrm{pb}^{-1}$	$0.6^{+1.0}_{-1.8}$	$0.7^{+0.8}_{-1.0}$
OPAL	$430\,\mathrm{pb}^{-1}$	$-0.2^{+1.4}_{-1.3}$	$-0.1^{+1.1}_{-1.0}$

Sensitivity smaller than single W and W pair production, will also be included in the global combination.


L3

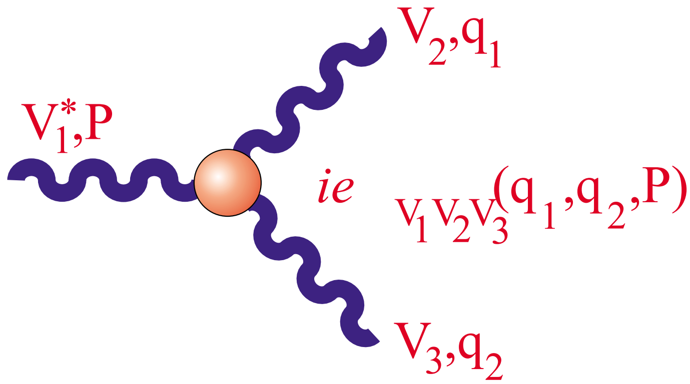

Z
h1,2,3,4


Z
hZ1,2,3,4 f4,5
Z


Z
Z
fZ4,5
Z

Parametrisation of the nTGC

These couplings are forbidden at tree level in the Standard Model



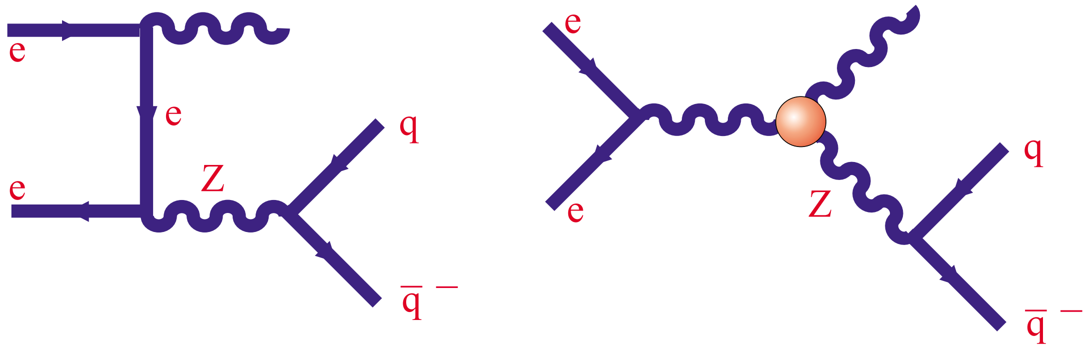
$$\Gamma^{\alpha\beta\mu}_{VZ\gamma}(q_1, q_2, P) = i\frac{s-m_V^2}{m_Z^2}\times$$
$$[h_1^V(q_2^\mu g^{\alpha\beta}) - q_2^\alpha g^{\mu\beta} + \frac{h_2^V}{m_Z^2}P^\alpha(P\cdot q_2\, g^{\mu\beta} - q_2^\mu P^\beta)$$
$$+h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}]$$

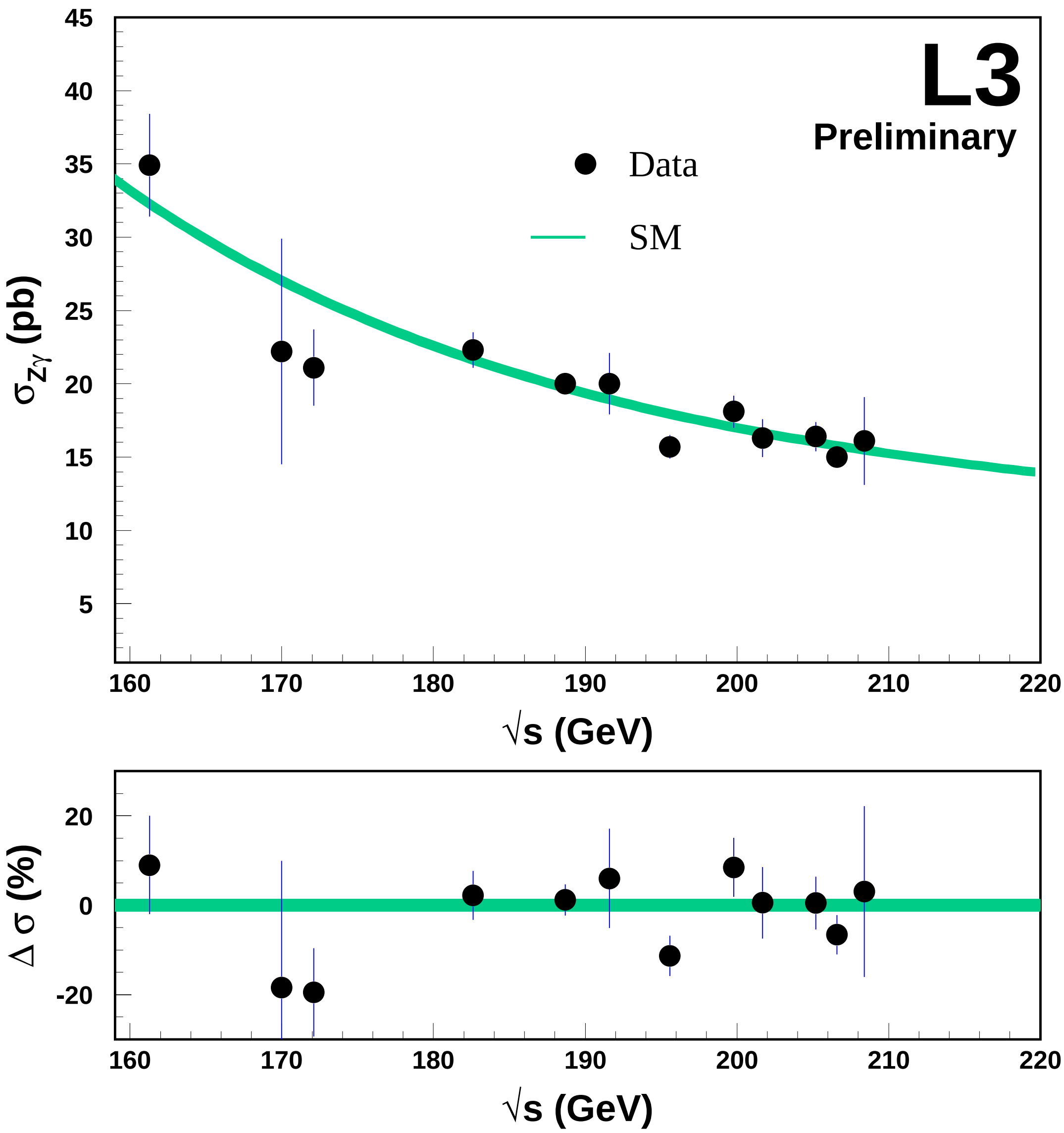
$$\Gamma^{\alpha\beta\mu}_{VZZ}(q_1, q_2, P) = i\frac{s-m_V^2}{m_Z^2}\times$$
$$[f_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho]$$

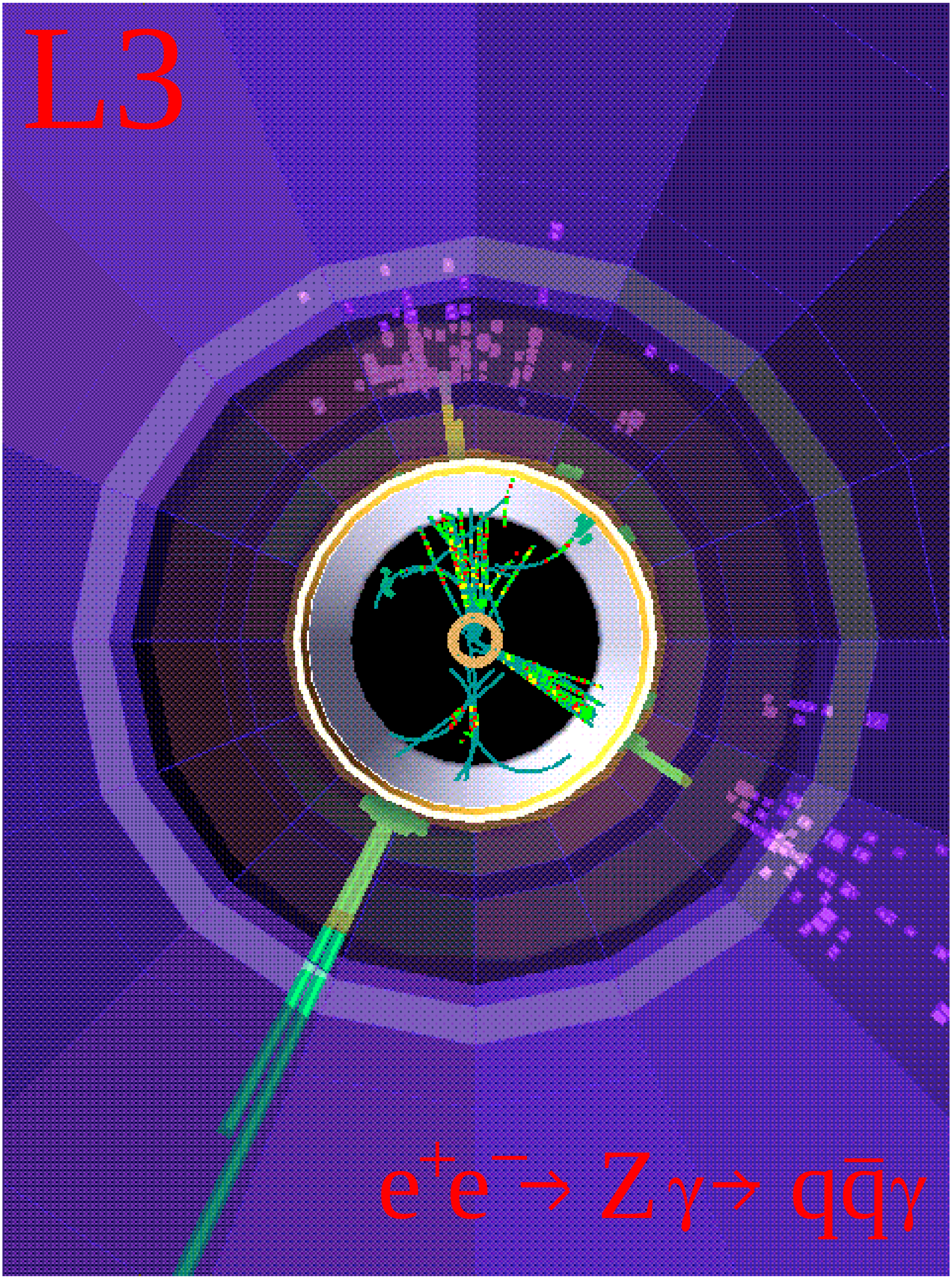
h_1^V, h_2^V and f_4^V violate CP; h_3^V, h_4^V and f_5^V conserve CP

K. Hagiwara *et al.*, Nucl. Phys. **B 282** (1987) 253
G. Gounaris *et al.*, Phys. Rev. **D 62** (2000) 073012
J. Alcaraz *et al.*, Phys. Rev. **D 61** (2000) 075006
J. Alcaraz `hep-ph/0111283`

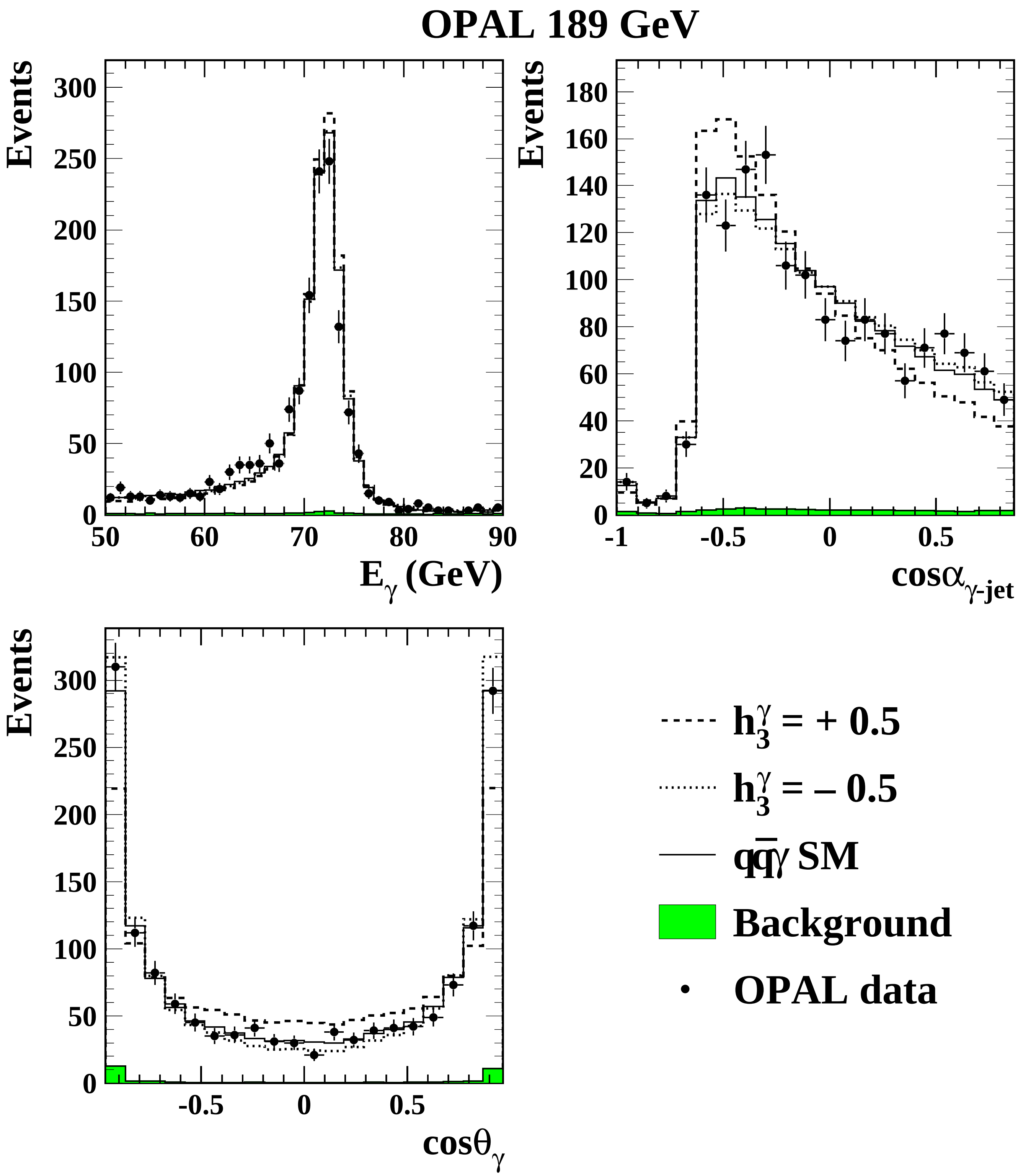
Use the Zγ production as a probe

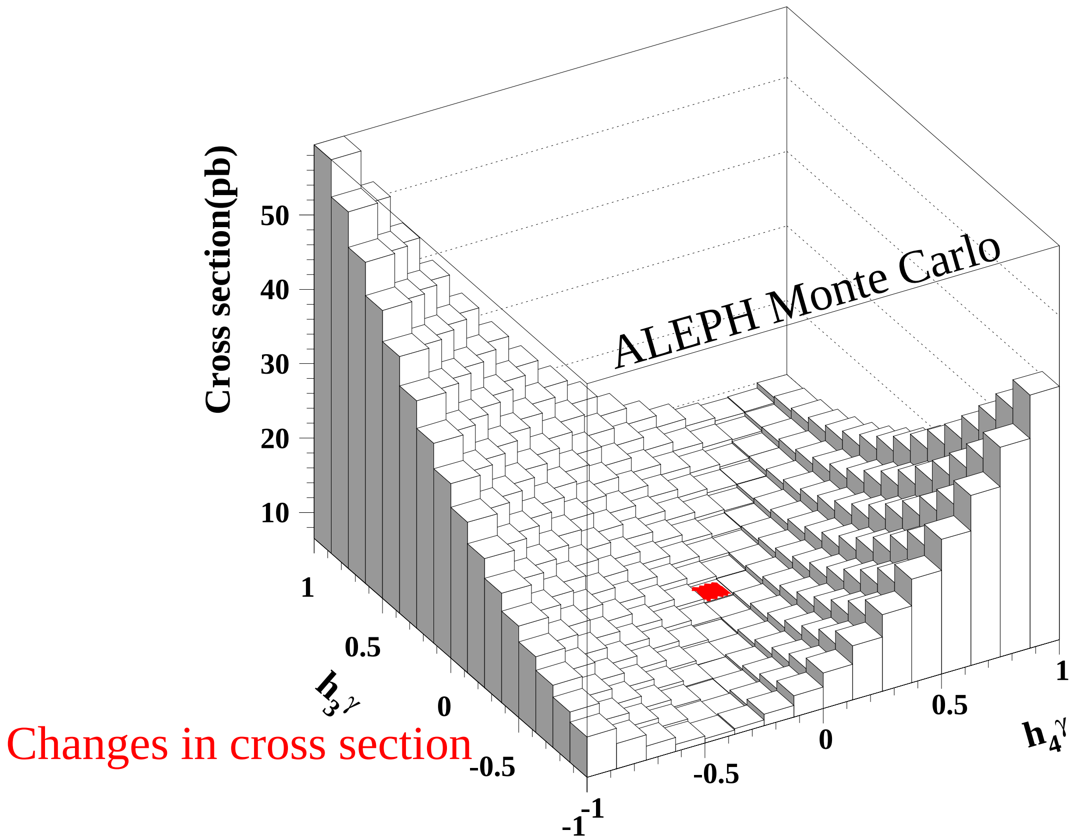




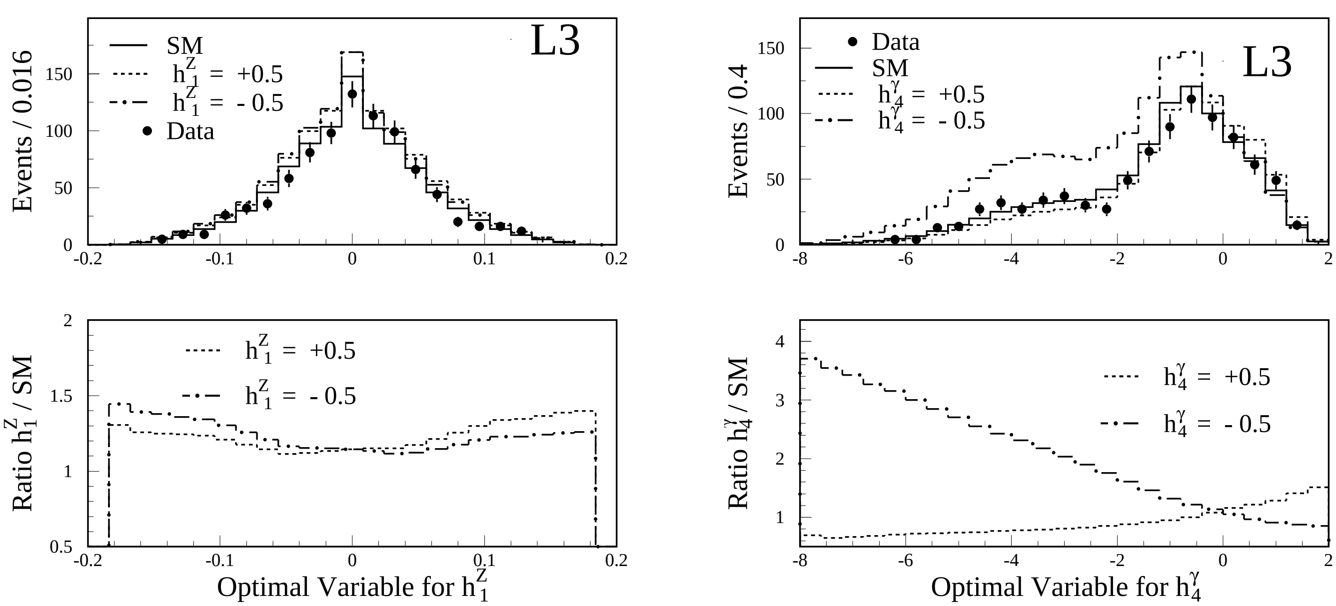

L3
$e^+e^- \to Z\gamma \to q\bar{q}\gamma$

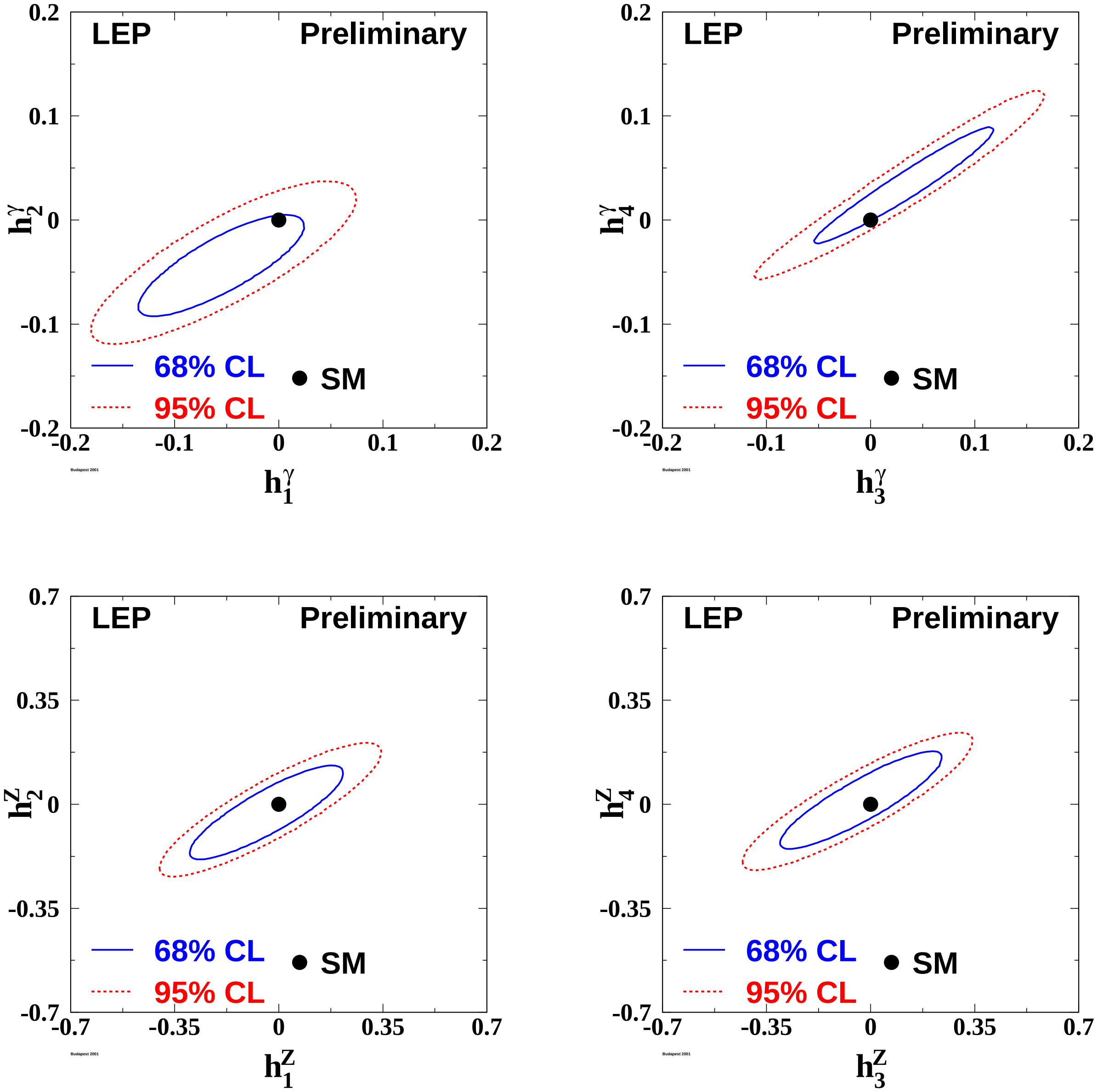
Changes in the $e^+e^- \to Z\gamma$ kinematics.





Fit the shape variables or build Optimal Observables

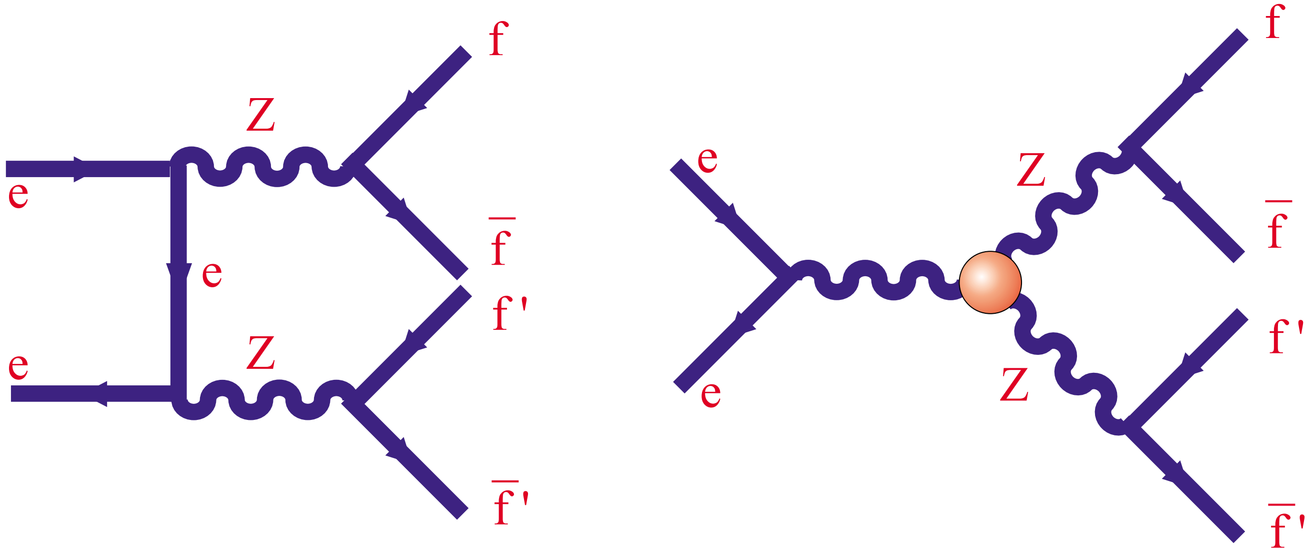


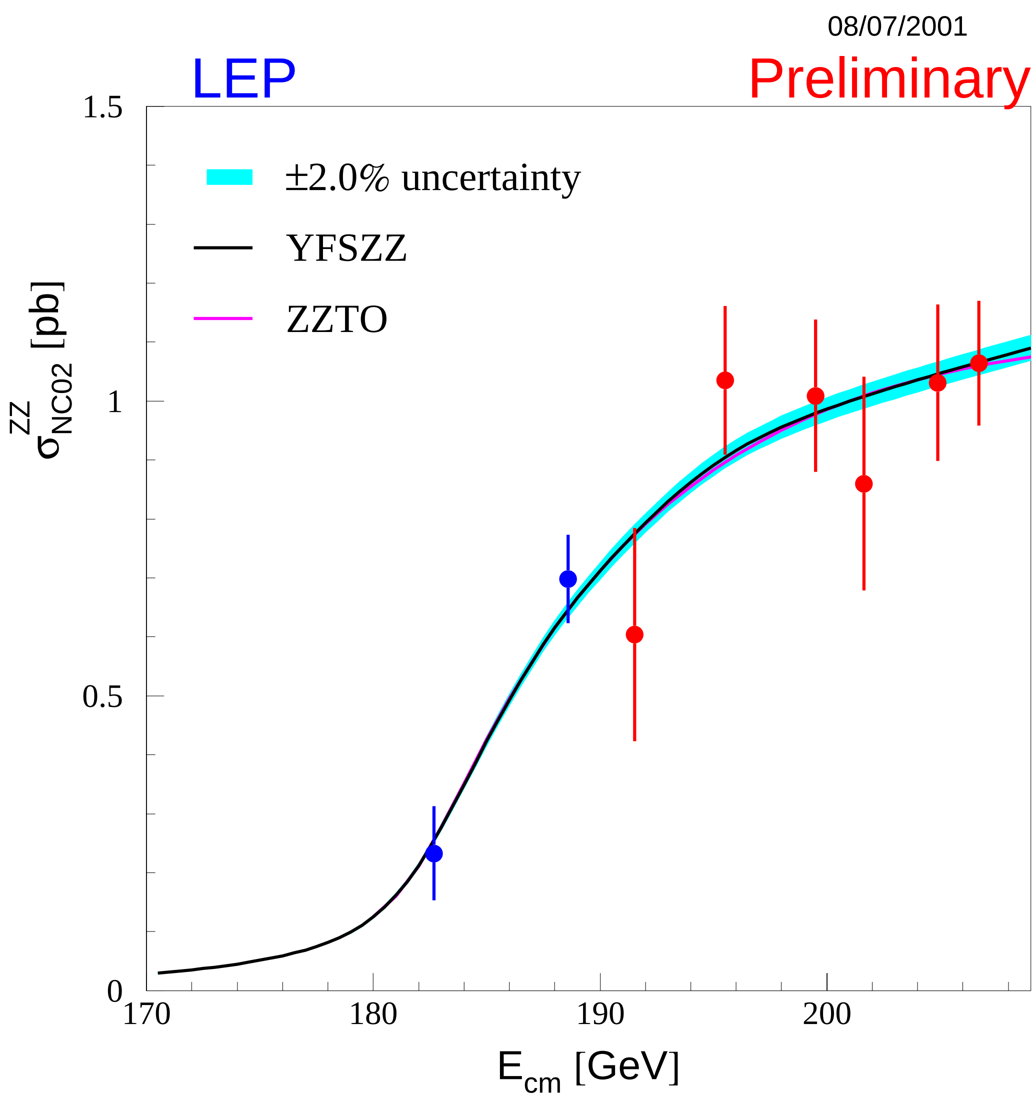


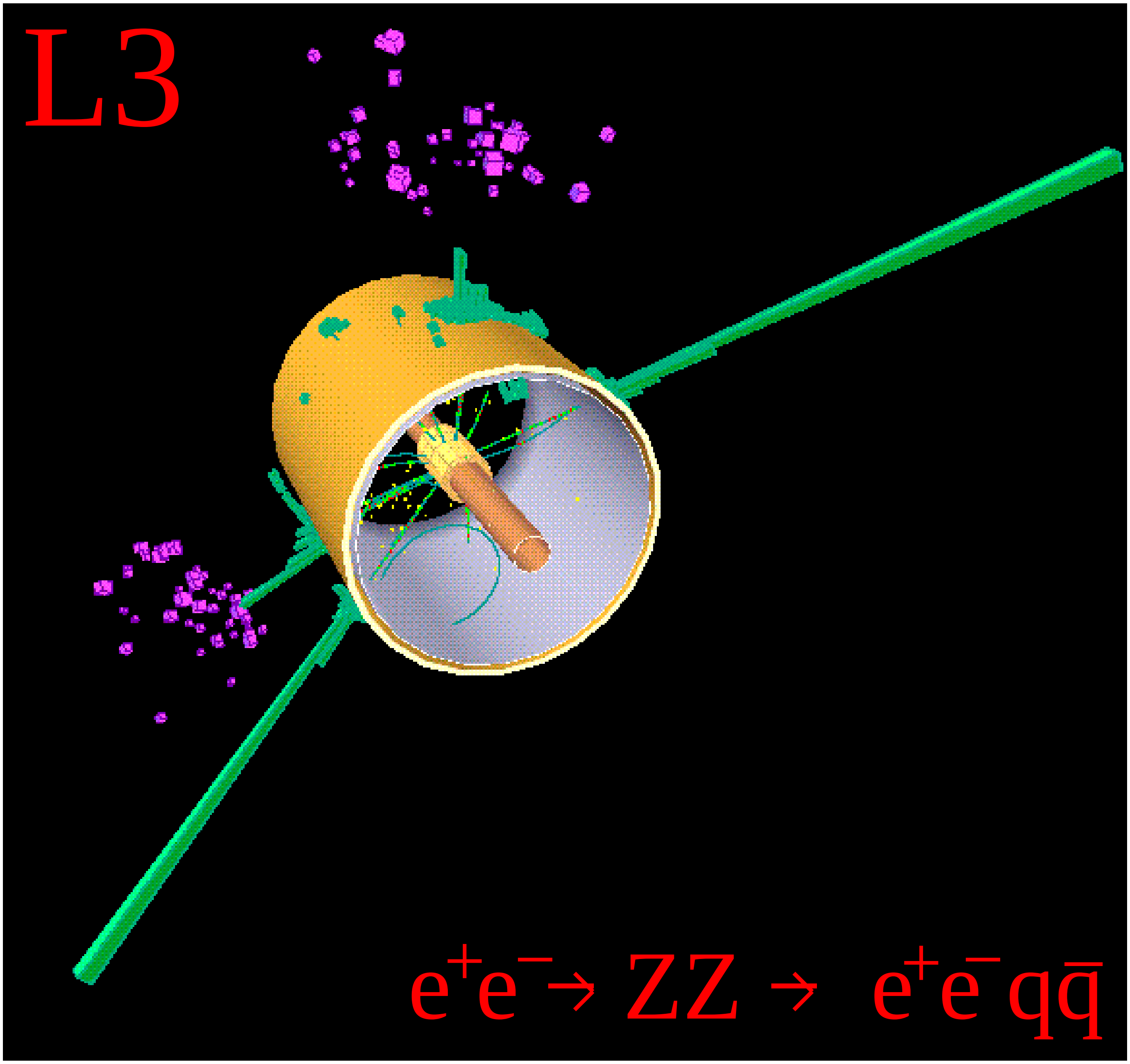
Limits at 95% C.L.

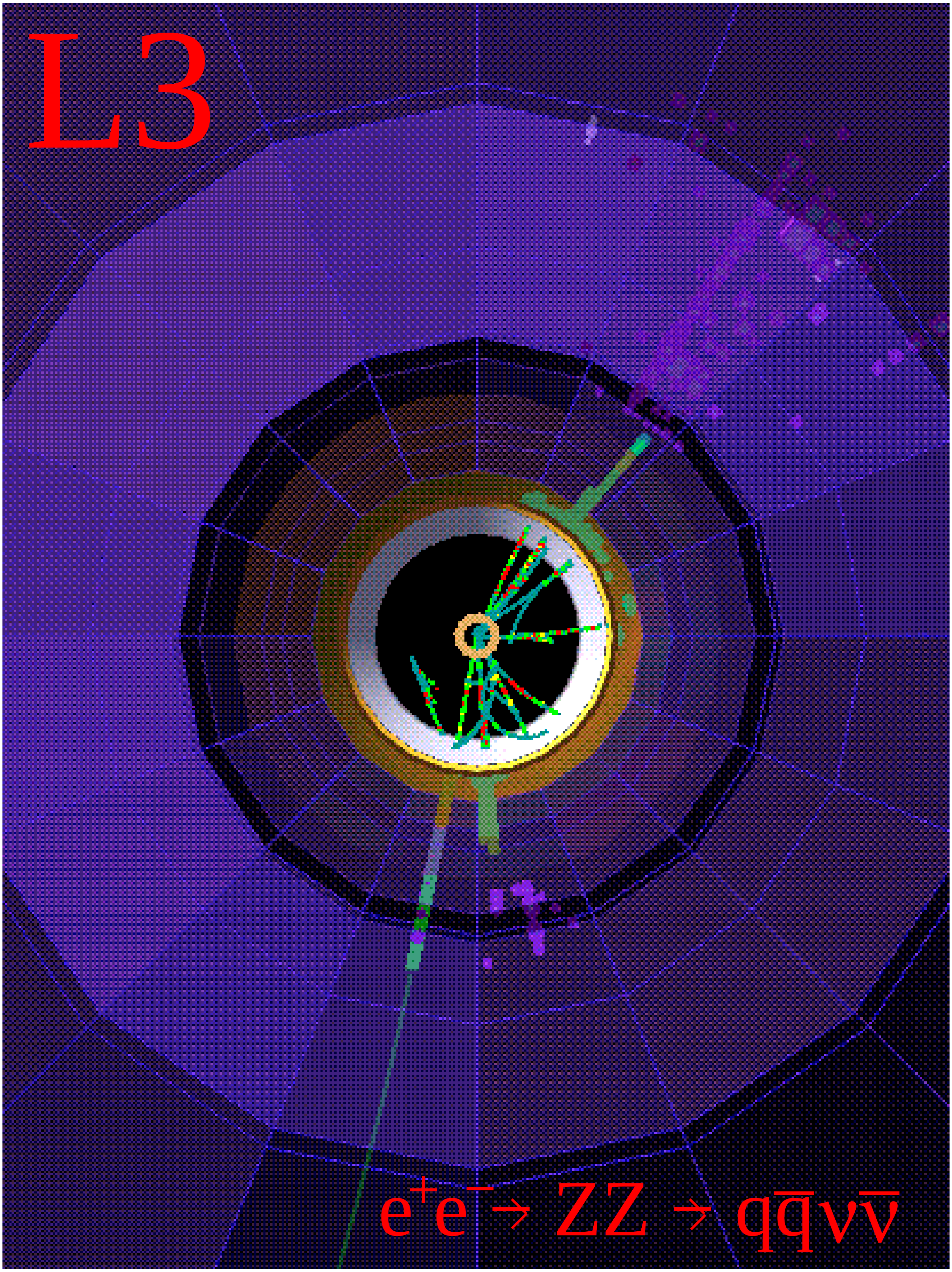
CP Violating		CP Conserving	
h_1^γ	[-0.056, 0.055]	h_3^γ	[-0.049, 0.008]
h_2^γ	[-0.045, 0.025]	h_4^γ	[-0.002, 0.034]
h_1^Z	[-0.13, 0.13]	h_3^Z	[-0.20, 0.07]
h_2^Z	[-0.08, 0.07]	h_4^Z	[-0.05, 0.12]

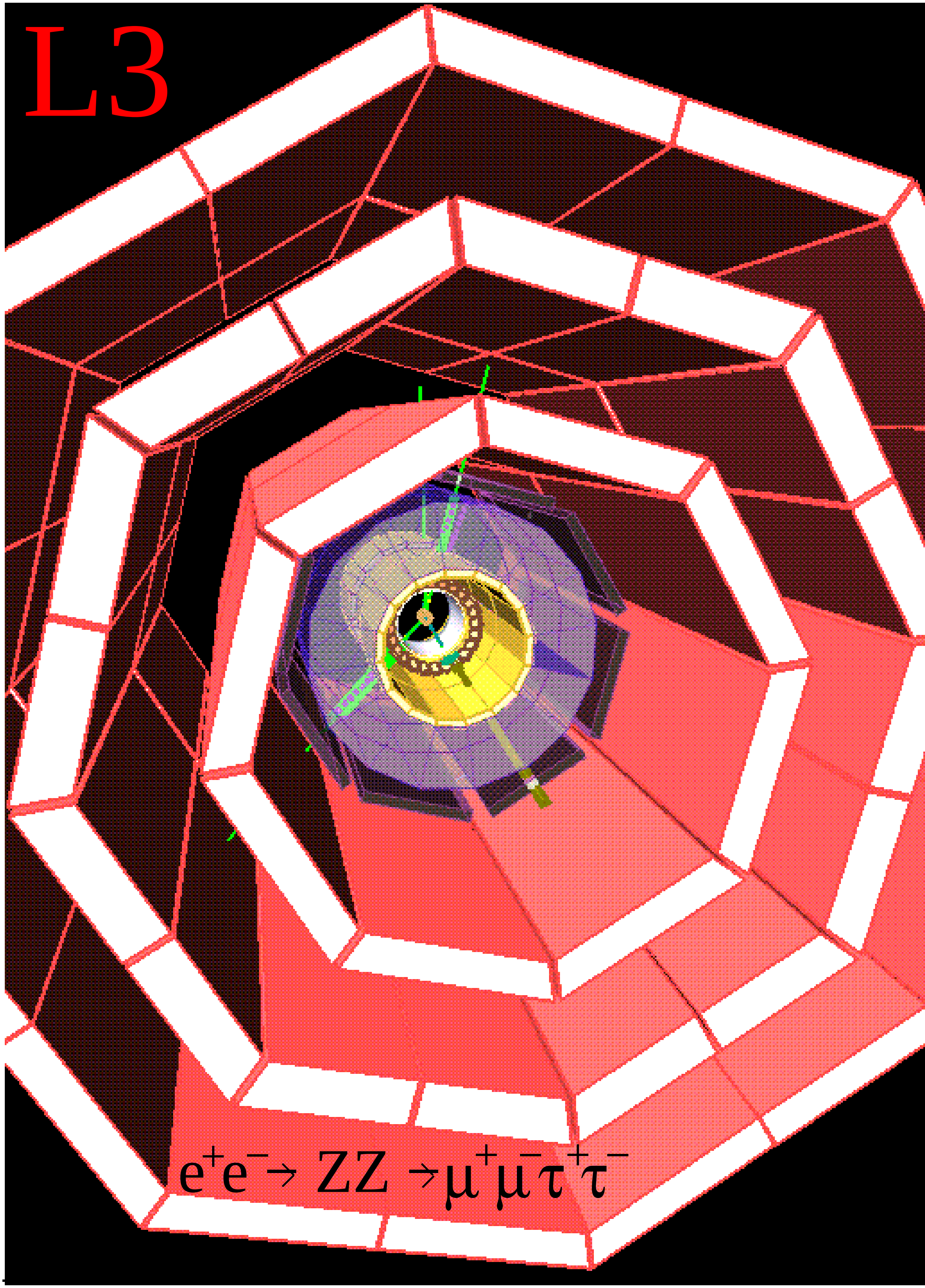
Accessible through ZZ production



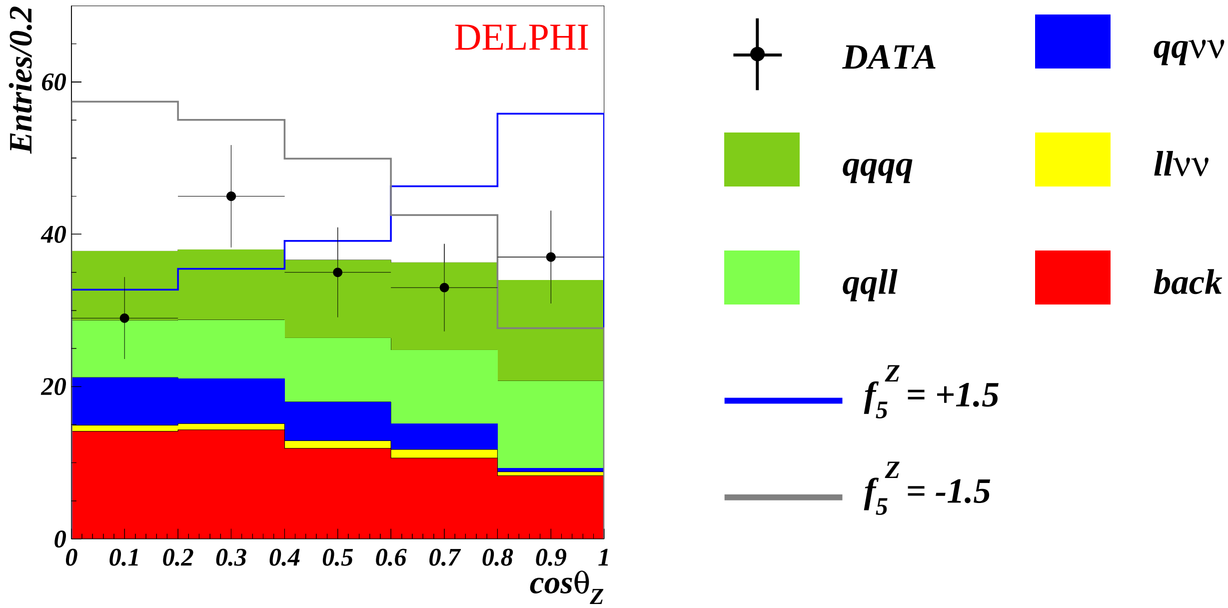


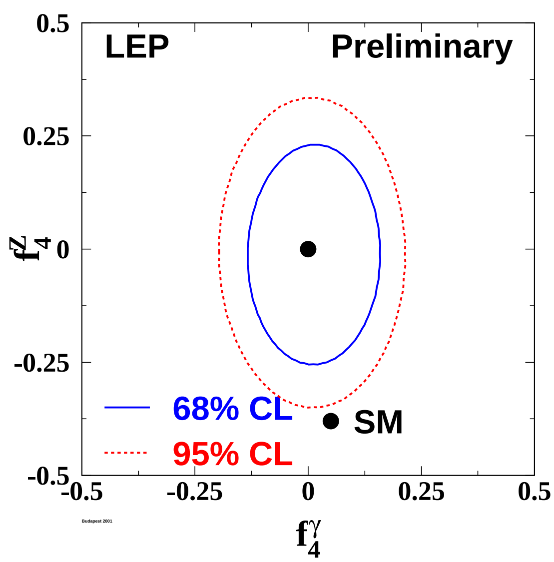

L3
e+e- → ZZ → e+e-qq̄

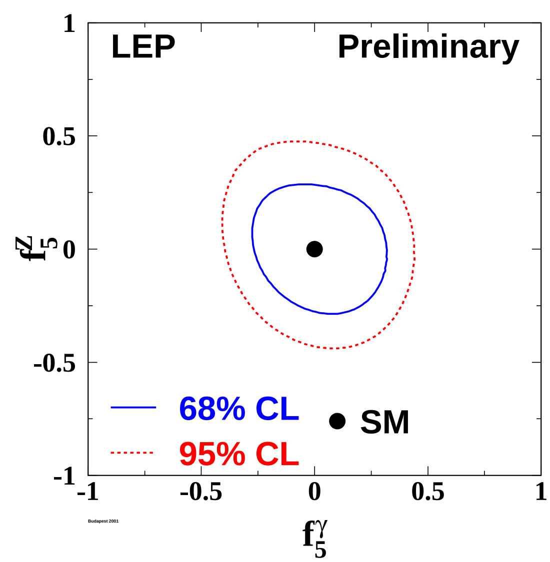

L3
e+e- → ZZ → qq̄νν̄


L3
$e^+e^- \rightarrow ZZ \rightarrow \mu^+\mu^-\tau^+\tau^-$

Cross section and scattering angle of $e^+e^- \rightarrow ZZ$

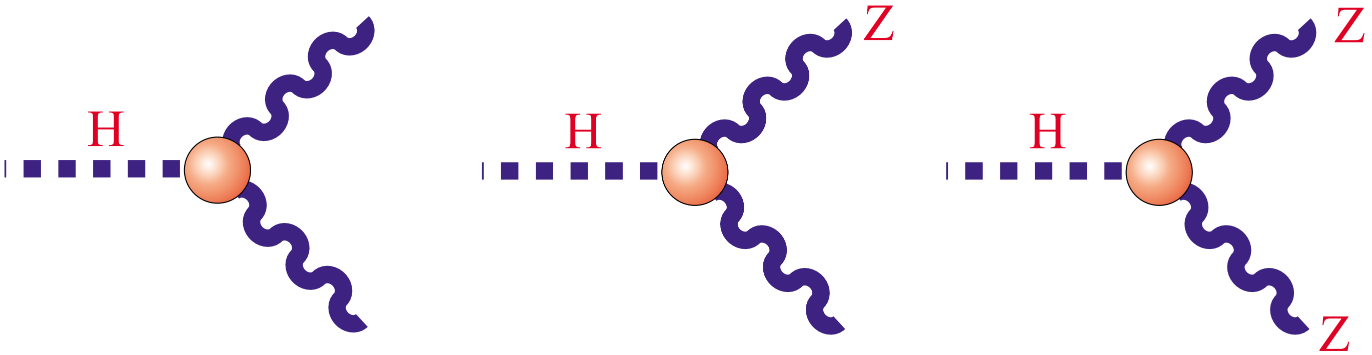






Limits at 95% C.L.

CP Violating		CP Conserving	
f_4^γ	[-0.17, 0.19]	f_5^γ	[-0.34, 0.38]
f_4^Z	[-0.30, 0.28]	f_5^Z	[-0.36, 0.38]



$$\mathcal{L}_{eff} = g_{\mathrm{H}\gamma\gamma}\mathrm{HA}_{\mu\nu}\mathrm{A}^{\mu\nu} + g^{(1)}_{\mathrm{HZ}\gamma}\mathrm{A}_{\mu\nu}\mathrm{Z}^{\mu}\partial^{\nu}\mathrm{H} + g^{(2)}_{\mathrm{HZ}\gamma}\mathrm{HA}_{\mu\nu}\mathrm{Z}^{\mu\nu}$$
$$+ g^{(1)}_{\mathrm{HZZ}}\mathrm{Z}_{\mu\nu}\mathrm{Z}^{\mu}\partial^{\nu}\mathrm{H} + g^{(2)}_{\mathrm{HZZ}}\mathrm{HZ}_{\mu\nu}\mathrm{Z}^{\mu\nu} + g^{(3)}_{\mathrm{HZZ}}\mathrm{HZ}_{\mu}\mathrm{Z}^{\mu}$$

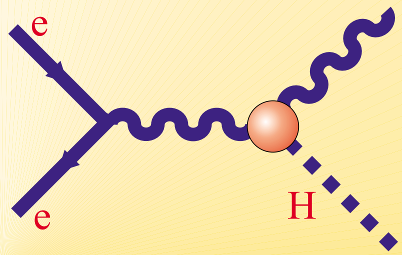
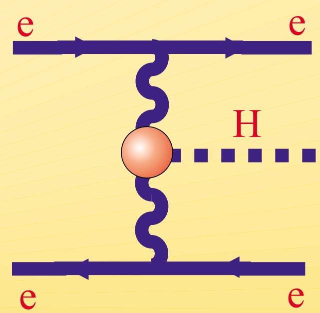
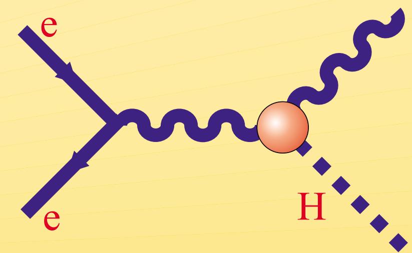
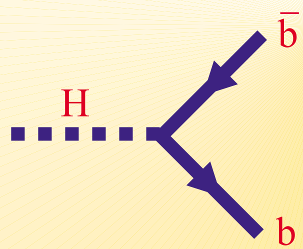
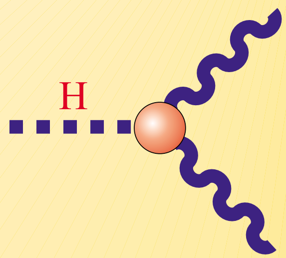
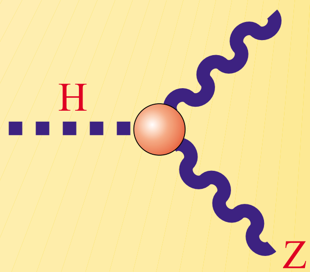
These six CP-conserving couplings reduce to five:

$$\begin{aligned}
g_{\mathrm{H}\gamma\gamma} &= \frac{g}{2\mathrm{m_W}}\left(d\sin^2\theta_\mathrm{W} + d_B\cos^2\theta_\mathrm{W}\right)\\
g^{(1)}_{\mathrm{HZ}\gamma} &= \frac{g}{\mathrm{m_W}}\left(\Delta g_1^\mathrm{Z}\sin 2\theta_\mathrm{W} - \Delta\kappa_\gamma\tan\theta_\mathrm{W}\right)\\
g^{(2)}_{\mathrm{HZ}\gamma} &= \frac{g}{2\mathrm{m_W}}\sin 2\theta_\mathrm{W}(d - d_B)\\
g^{(1)}_{\mathrm{HZZ}} &= \frac{g}{\mathrm{m_W}}\left(\Delta g_1^\mathrm{Z}\cos 2\theta_\mathrm{W} + \Delta\kappa_\gamma\tan^2\theta_\mathrm{W}\right)\\
g^{(2)}_{\mathrm{HZZ}} &= \frac{g}{2\mathrm{m_W}}\left(d\cos^2\theta_\mathrm{W} + d_B\sin^2\theta_\mathrm{W}\right)\\
g^{(3)}_{\mathrm{HZZ}} &= \frac{g}{2\mathrm{m_W}\cos^2\theta_\mathrm{W}}\delta_\mathrm{Z}
\end{aligned}$$

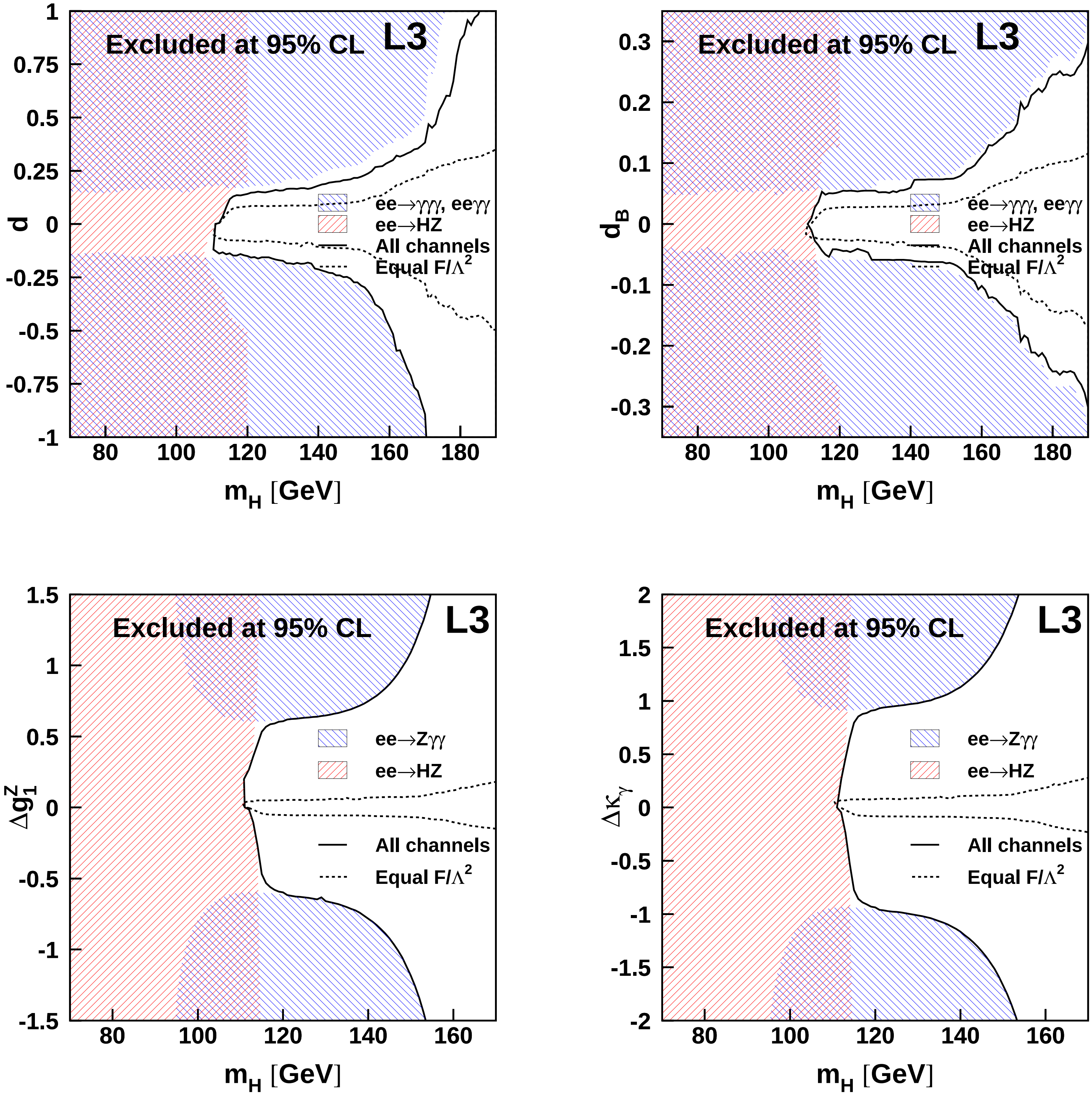
δ_Z, d and d_B are new, Δg_1^Z and $\Delta\kappa_\gamma$ are the WWV couplings!

K. Hagiwara *et al.*, Nucl. Phys. **B 282** (1987) 253
B. Grzadkowski and J. Wudka, Phys. Lett. **B 364** (1995) 49
G. Gounaris *et. al*, Nucl. Phys. **B 459** (1996) 51
O. Eboli *et. al*, Phys. Lett. **B 434** (1998) 340

Experimental technique

			
	$e^+e^-\to b\bar{b}$ Isolated photon b-tag	$e^+e^-\to e^+e^-b\bar{b}$ Missing energy b-tag	$e^+e^-\to b\bar{b}f\bar{f}$ Two b's recoiling a Z SM Higgs signature
	$e^+e^-\to$ Three photons	$e^+e^-\to e^+e^-$ Two photons Missing energy	$e^+e^-\to Z$ Two photons Two fermions at Mz
	$e^+e^-\to Z$ Two photons Two jets at Mz		

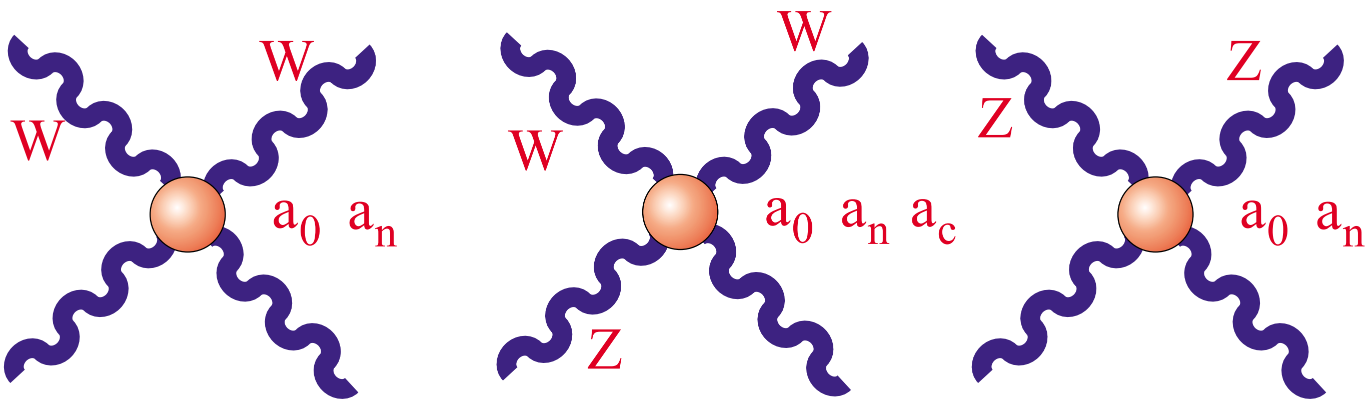
Results



Additional limit for the common coupling F at the scale Λ:

$$m_{\mathrm{W}}^2 F/\Lambda^2 = \Delta\kappa_\gamma = -d = -d_B/\tan^2\theta_{\mathrm{W}} = 2\cos^2\theta_{\mathrm{W}}\Delta g_1^{\mathrm{Z}}$$

Limits on δ_{Z} from model independent Higgs searches



$$\mathcal{L}_6^0 = -\frac{\pi\alpha}{4}\frac{a_0}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}\vec{W}_\rho\cdot\vec{W}^\rho$$

$$\mathcal{L}_6^c = -\frac{\pi\alpha}{4}\frac{a_c}{\Lambda^2}F_{\mu\rho}F^{\mu\sigma}\vec{W}^\rho\cdot\vec{W}_\sigma$$

$$\mathcal{L}_6^n = -\frac{\pi\alpha}{4}\frac{a_n}{\Lambda^2}\epsilon_{ijk}W^i_{\mu\alpha}W^j_\nu W^{k\alpha}F^{\mu\nu}$$

$\frac{a_0}{\Lambda^2}$ and $\frac{a_c}{\Lambda^2}$ conserve CP; $\frac{a_n}{\Lambda^2}$ violates CP.

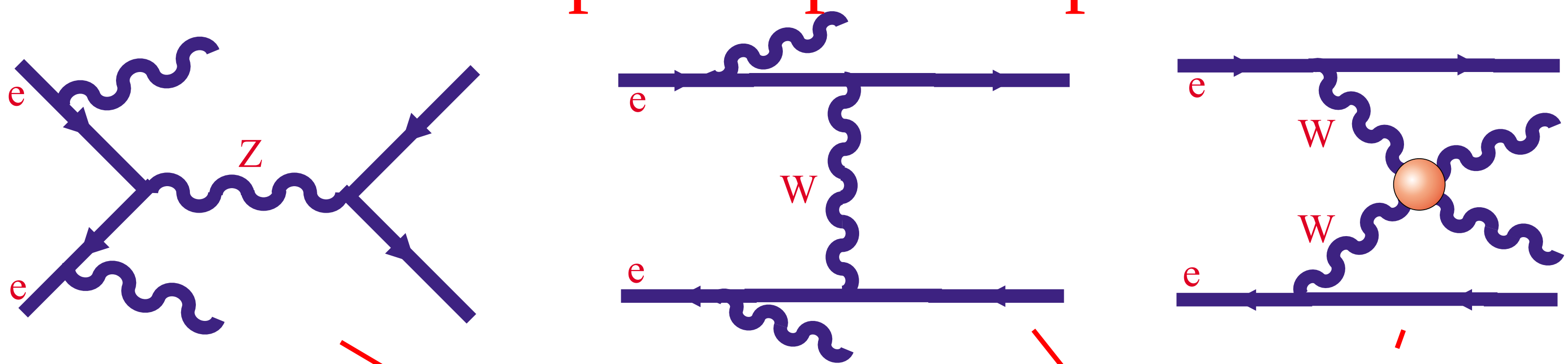
G. Bélanger and F. Boudjema Phys. Lett. **B 288** (1992) 201.
W. J. Stirling and Abu Leil J. Phys. **G 21** (1995) 517
W. J. Stirling and A. Werthenbach Phys. Lett. **B 466** (1999) 369.
W. J. Stirling and A. Werthenbach Eur. Phys. J. **C 14** (2000) 103.

New parametrisations with additional couplings are not (yet) considered.

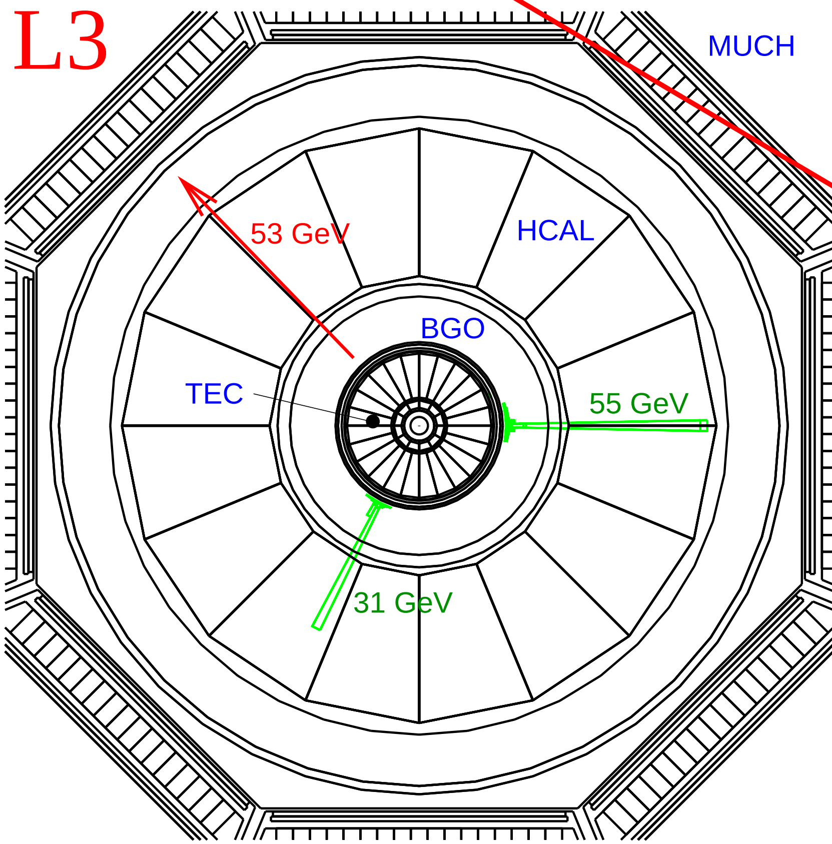
G. Bélanger *et al.* Eur. Phys. J. **C 13** (2000) 283.
A. Denner *et al.* Eur. Phys. J. **C 20** (2001) 201.

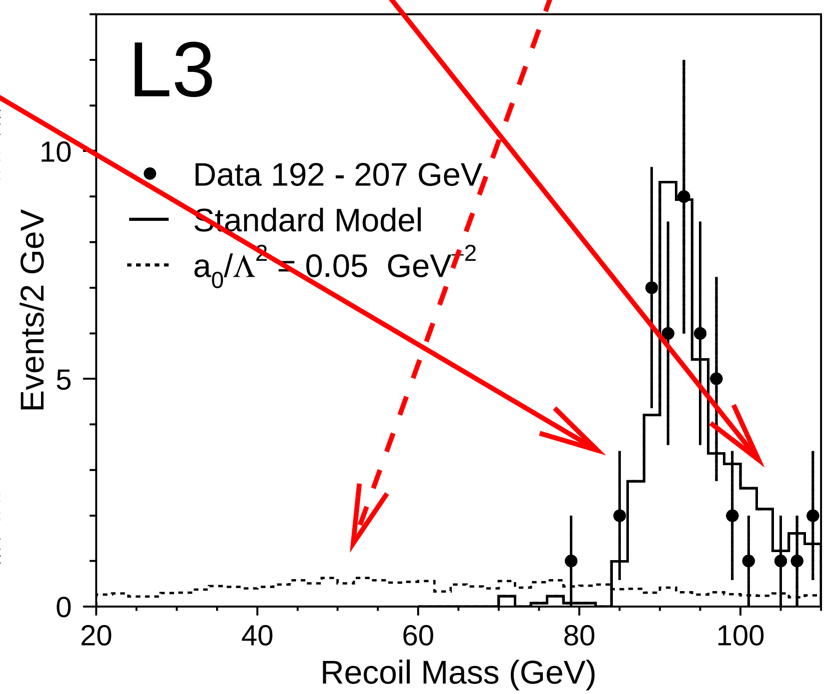
In principle, couplings with W's might be different from those with Z's

Acoplanar photon pairs

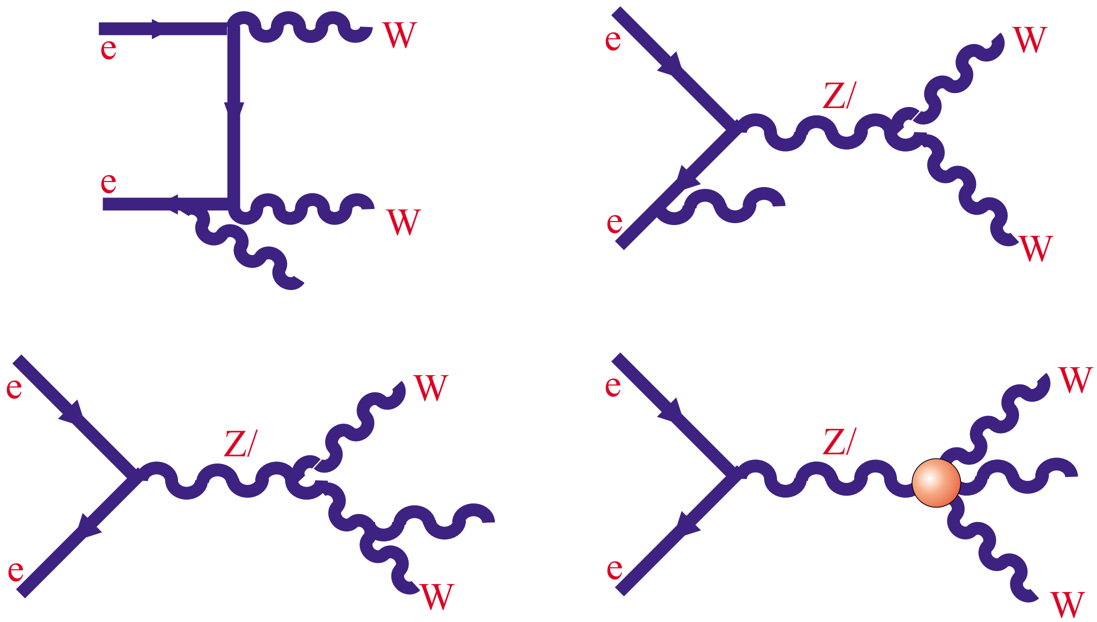


L3

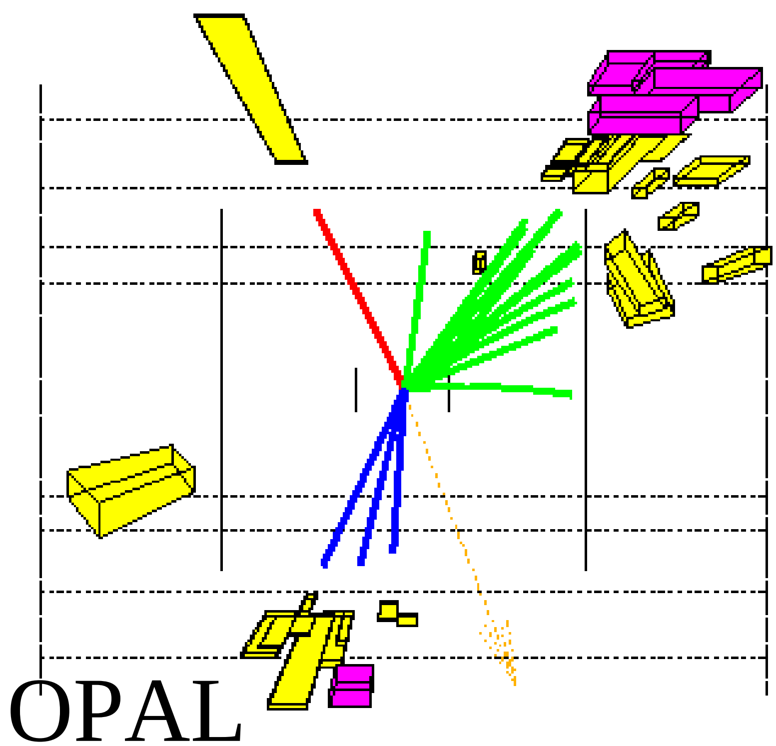




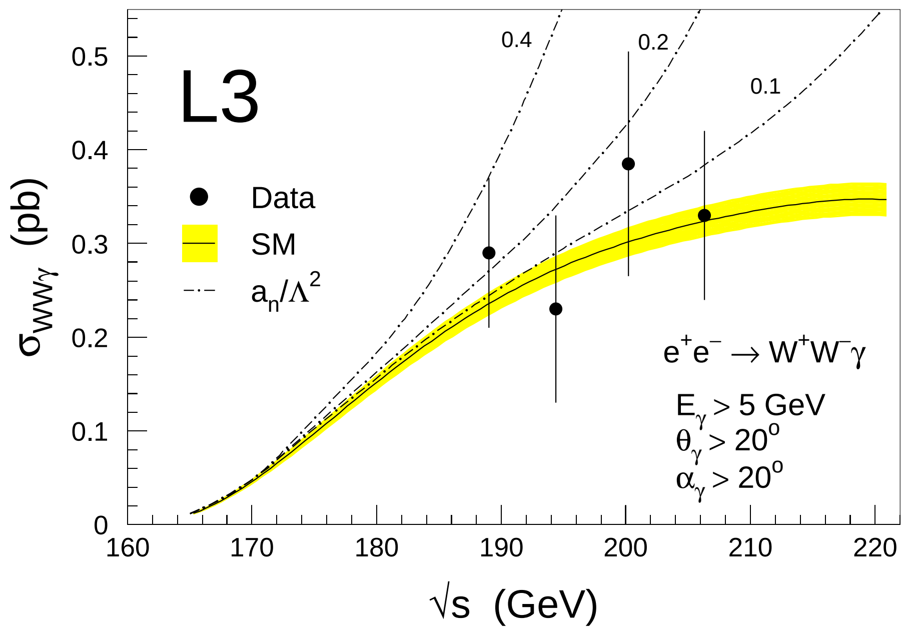
Standard Model QGC contribution negligible.

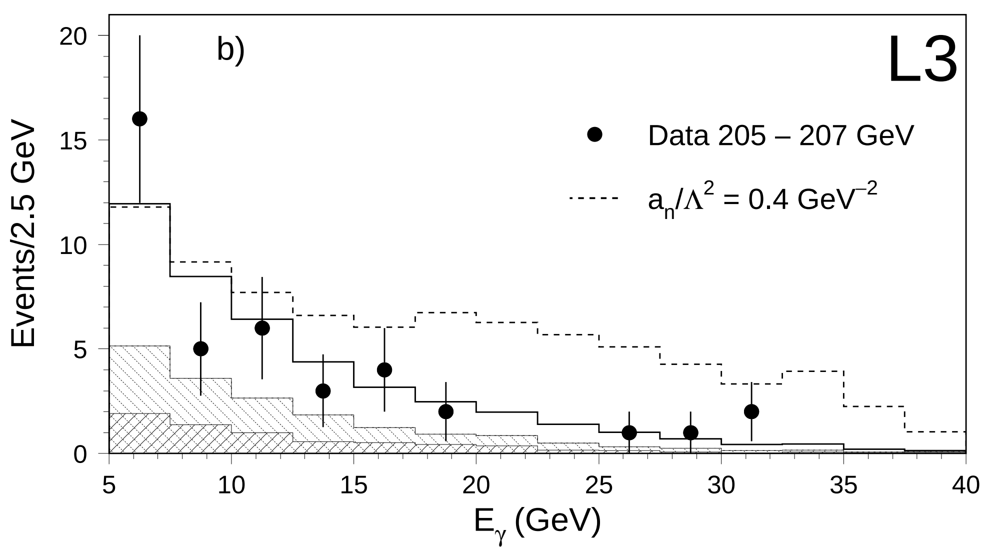


Select W pairs with an additional isolated photon.



Larger cross section and harder photons





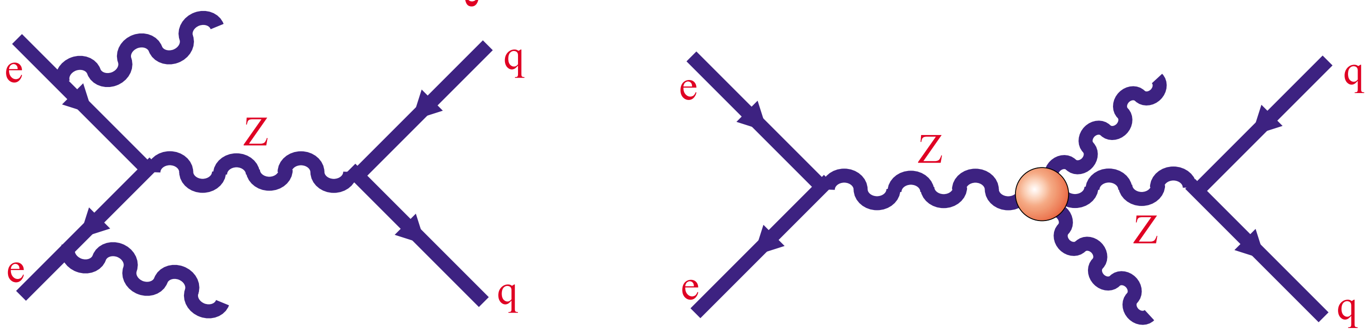
Limits at 95% C.L. from $e^+e^- \rightarrow WW\gamma$ and $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$

a_0/Λ^2 [-0.049, 0.008]

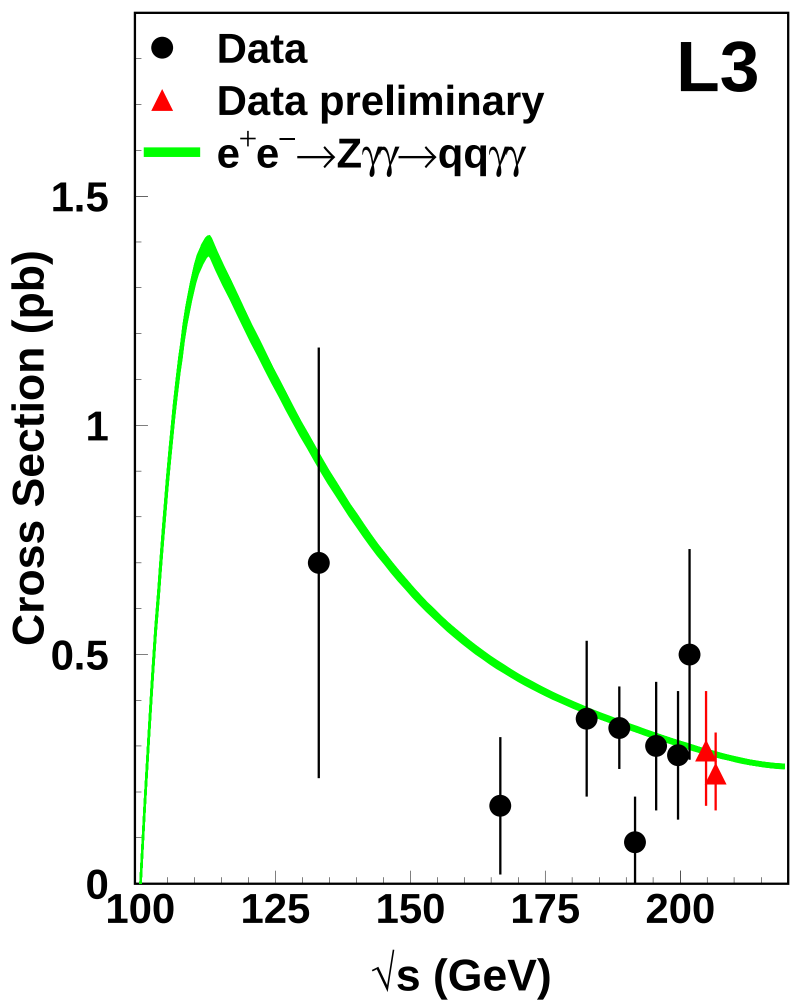
a_c/Λ^2 [-0.002, 0.034]

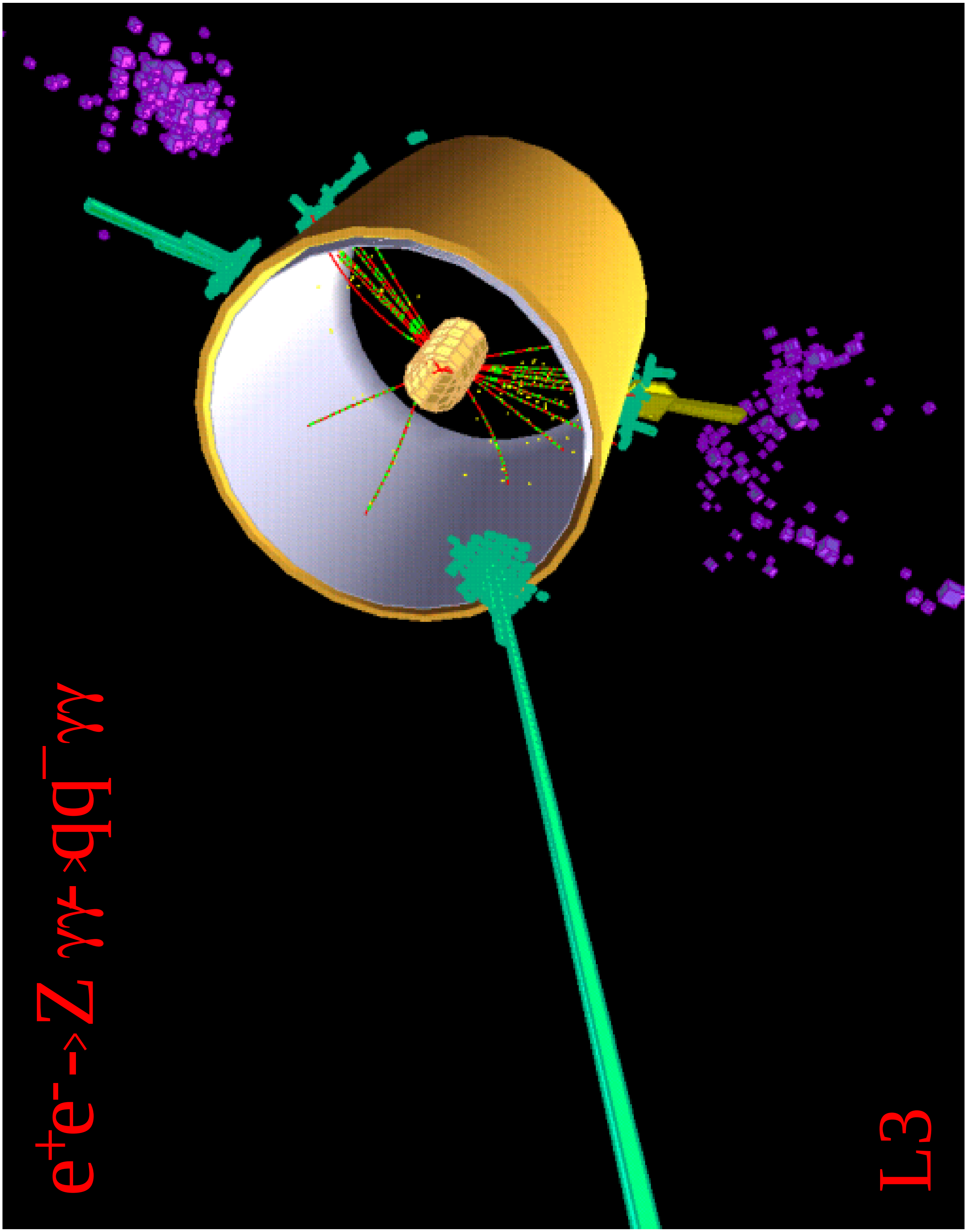
a_n/Λ^2 [-0.20, 0.07]

The $e^+e^- \to Z\gamma\gamma$ process has no Standard Model QGC contribution.

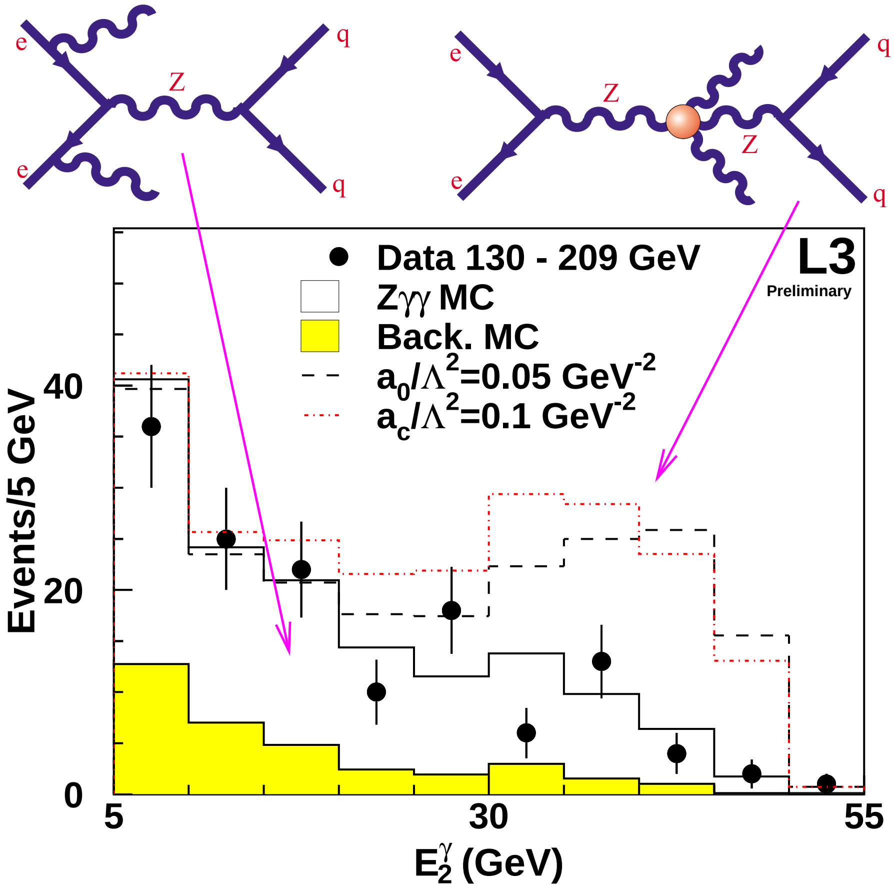


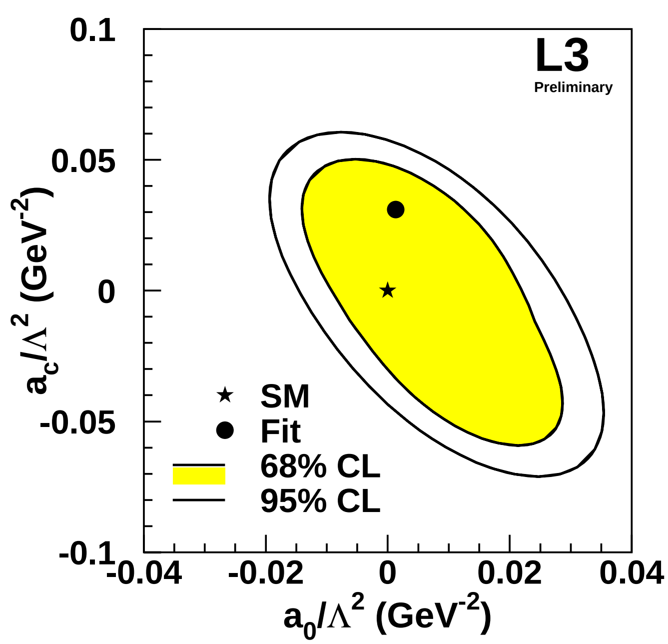
Select events with two jets and two photons.




e+e- ->Z γγ->q q̄ γγ
L3

Effects and results





a_0/Λ^2 [-0.007, 0.014] 95% C.L.

a_c/Λ^2 [-0.052, 0.037] 95% C.L.

WRAP, G. Montagna *et al.*, Phys. Lett. **B 515** (2001) 197

Conclusions

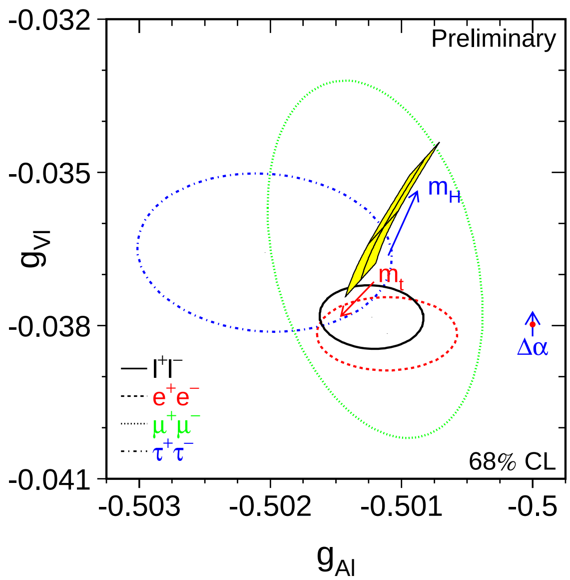
- More precision (and more couplings!) than expected at the start of this adventure.

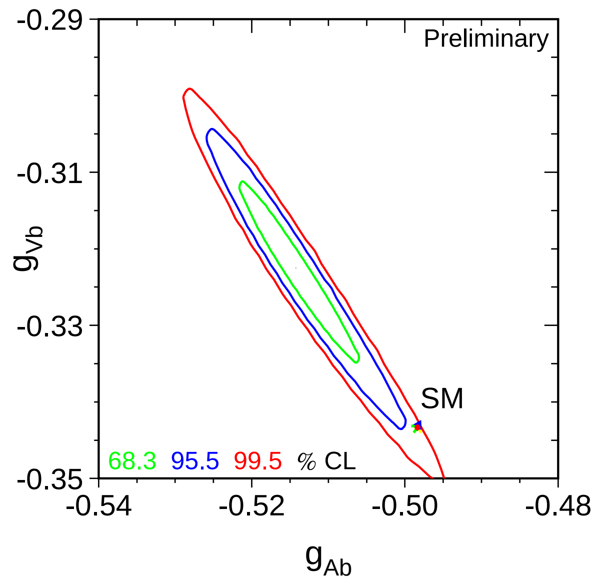
- Excellent collaboration between the experiments: understanding of the problems and combination techniques
- Close contact with the theory community

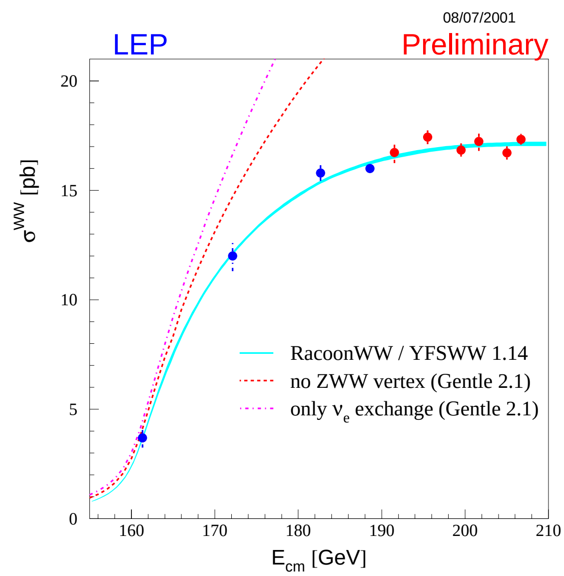
- The analyses are still in progress within severe person-power constraints.

- Final results by this (or the next) summer conference

LEP, the last "lord of the (e^+e^-) rings", unveiled much of our knowledge on couplings:







$\Delta\kappa_\gamma \; \Delta g_Z^1 \;\; \lambda_\gamma$

$f_4^\gamma \; f_5^\gamma \; f_4^Z \; f_5^Z$

$h_1^\gamma \; h_2^\gamma \; h_3^\gamma \; h_4^\gamma \; h_1^Z \; h_2^Z \; h_3^Z \; h_4^Z$

$d \;\; d_B$

$a_0 \; a_c \; a_n$

Agree with the Standard Model

The next frontier of couplings in the Standard Model and beyond awaits a huge luminosity at the Z again, or higher energy e^+e^- collisions!