Measurements of the selfcoupling of electroweak bosons at LEP II

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Humboldt Universität zu Berlin
& L3 Collaboration

Workshop on Physics and Detectors for Future
e^+e^- Linear Colliders
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Outline

The Triple-Gauge Boson Vertex

Coupling measurements in

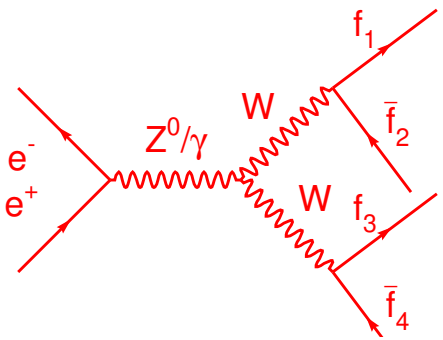
$e^+e^- \to \nu\nu\gamma$

$e^+e^- \to We\nu_e$

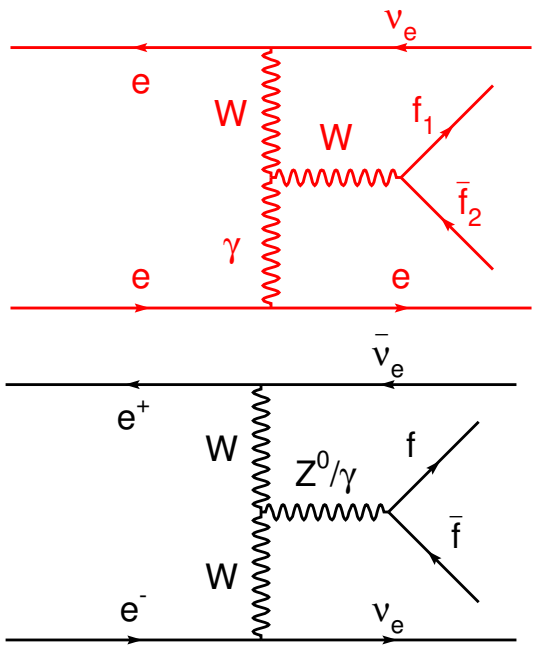
$e^+e^- \to W^+W^-$

Summary

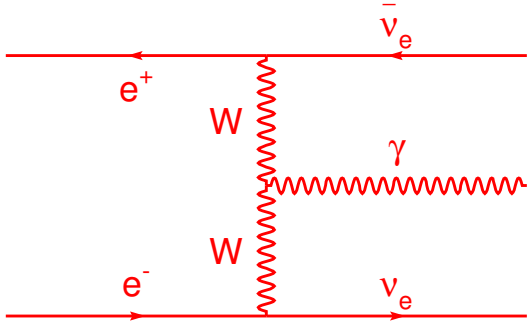
$e^+e^- \to W^+W^-$



$e^+e^- \to We\nu_e$

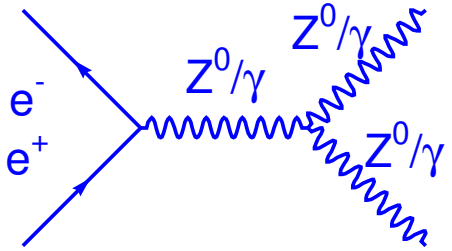


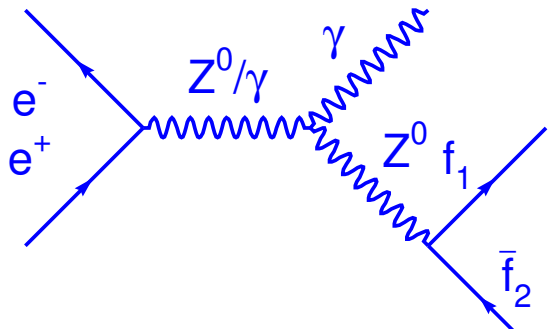
$e^+e^- \to \nu\nu\gamma$



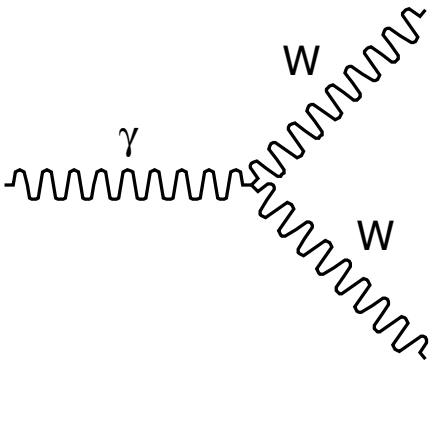
Not discussed :

Search :





The Three Boson Vertex

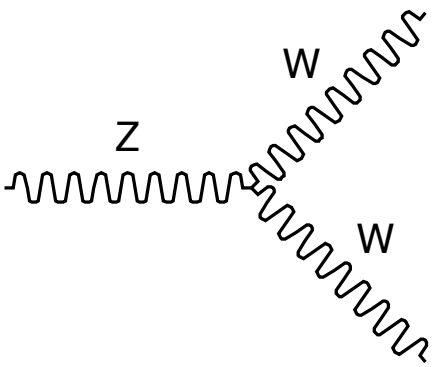


$$E1 = e g_1^\gamma$$

$$M2 = \frac{e}{2M_W}\left(g_1^\gamma + \kappa_\gamma + \lambda_\gamma\right) \overset{SM}{=} \frac{e}{M_W}$$

$$E4 = -\frac{e}{M_W^2}\left(\kappa_\gamma - \lambda_\gamma\right) \overset{SM}{=} -\frac{e}{M_W^2}$$

$$\text{SM} : g_\gamma^1 = 1, \kappa_\gamma = 1, \lambda_\gamma = 0$$



$$g_1^Z \overset{SM}{=} 1$$

$$\kappa_Z \overset{SM}{=} 1$$

$$\lambda_Z \overset{SM}{=} 0$$

The Three Boson Vertex

Extending the Lagrangian to an effective Lagrangian (purely phenomenological) including C/P and CP violating terms

$$\imath\frac{\mathcal{L}_{eff}^{WWV}}{g_{WWV}} = g_1^V V^\mu \left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right)$$

$$+ \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}$$

$$+ \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}$$

$$+ \imath g_5^V \epsilon_{\mu\nu\rho\sigma}\left(\left(\partial^\rho W^{-\mu}\right) W^{+\nu} - W^{-\mu}\left(\partial^\rho W^{+\nu}\right)\right) V^\sigma$$

$$+ \imath g_4^V W^-_\mu W^+_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right)$$

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

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

The Three Boson Vertex

$$\mathcal{L}^{\text{TGC}}_{d=6} = \imath g' \frac{\alpha_{B\phi}}{m_W^2} (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$
$$+ \imath g \frac{\alpha_{W\phi}}{m_W^2} (D_\mu \Phi)^\dagger \vec{\tau} \cdot \vec{\hat{W}}^{\mu\nu} (D_\nu \Phi)$$
$$+ g \frac{\alpha_W}{6 m_W^2} \vec{\hat{W}}^{\mu}_{\nu} \cdot (\vec{\hat{W}}^{\nu}_{\rho} \times \vec{\hat{W}}^{\rho}_{\mu})$$

$$\hat{W}_{\mu\nu} = W_{\mu\nu} - g W_\mu \times W_\nu$$

The Three Boson Vertex

constraints :

no C,CP violation $\tilde{\lambda}_V = \tilde{\kappa}_V = g_4^V = g_5^V = 0$

electromagnetic gauge invariance $g_1^\gamma = 1$

gauge invariance

$$\lambda_\gamma = \lambda_Z$$

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

remaining parameter set :

$$(\Delta g_1^Z, \Delta\kappa_\gamma, \lambda_\gamma)$$

observable consequences :

- total cross section is coupling dependent $\sigma = \sigma(TGC)$
- differential cross section is coupling dependent $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(TGC)$
- dependence on TGC constants is quadratic

The coupling measurement

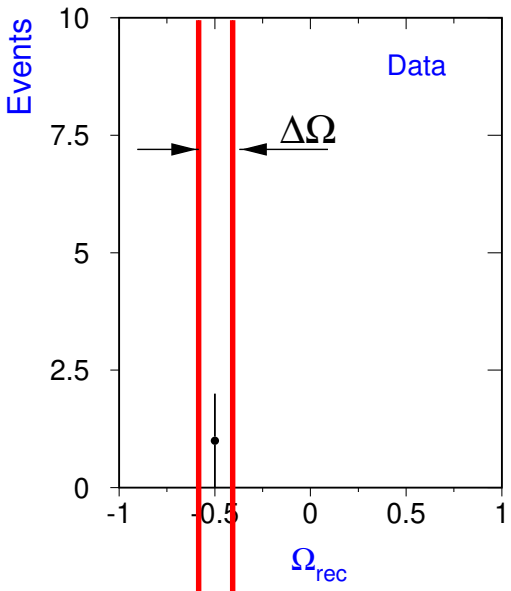
Fit of the total cross section

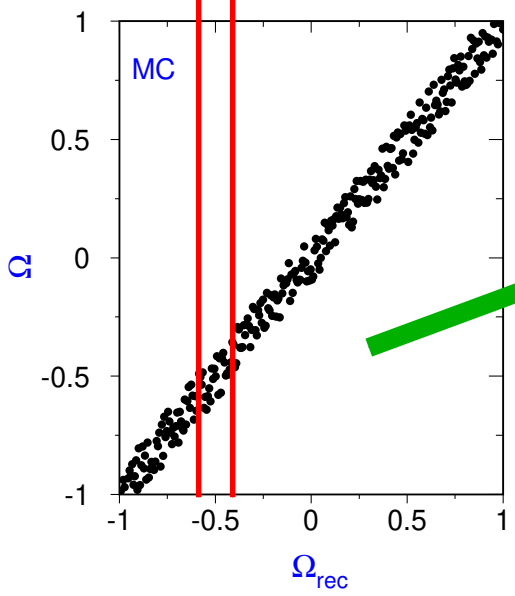
$$\ln \mathcal{L}_{\text{tot}} = \sum_{\text{channels}} \ln \left\{ \frac{\mu_i(\kappa_\gamma)^{N_i^{\text{data}}} e^{-\mu_i(\kappa_\gamma)}}{N_i^{\text{data}}!} \right\}$$

$$\mu_i(\kappa_\gamma) = L(\sigma(\kappa_\gamma)\epsilon(\kappa_\gamma) + \sigma_{\text{bckg}})$$

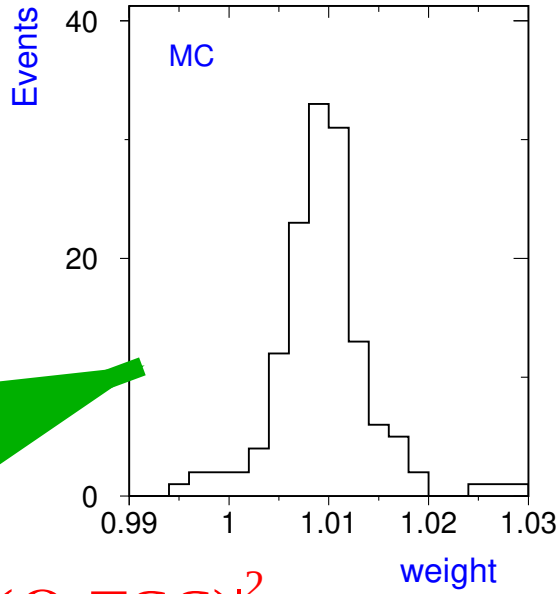
Fit of the differential cross section
(e.g. $e^+e^- \to \nu\nu\gamma$)

$$\ln \mathcal{L}_{\text{diff}} = \sum_{\text{events}} \ln \left\{ \frac{1}{\sigma(\kappa_\gamma)} \cdot \frac{d^2\sigma}{dE_\gamma d\cos\theta_\gamma}(\kappa_\gamma) \right\}$$





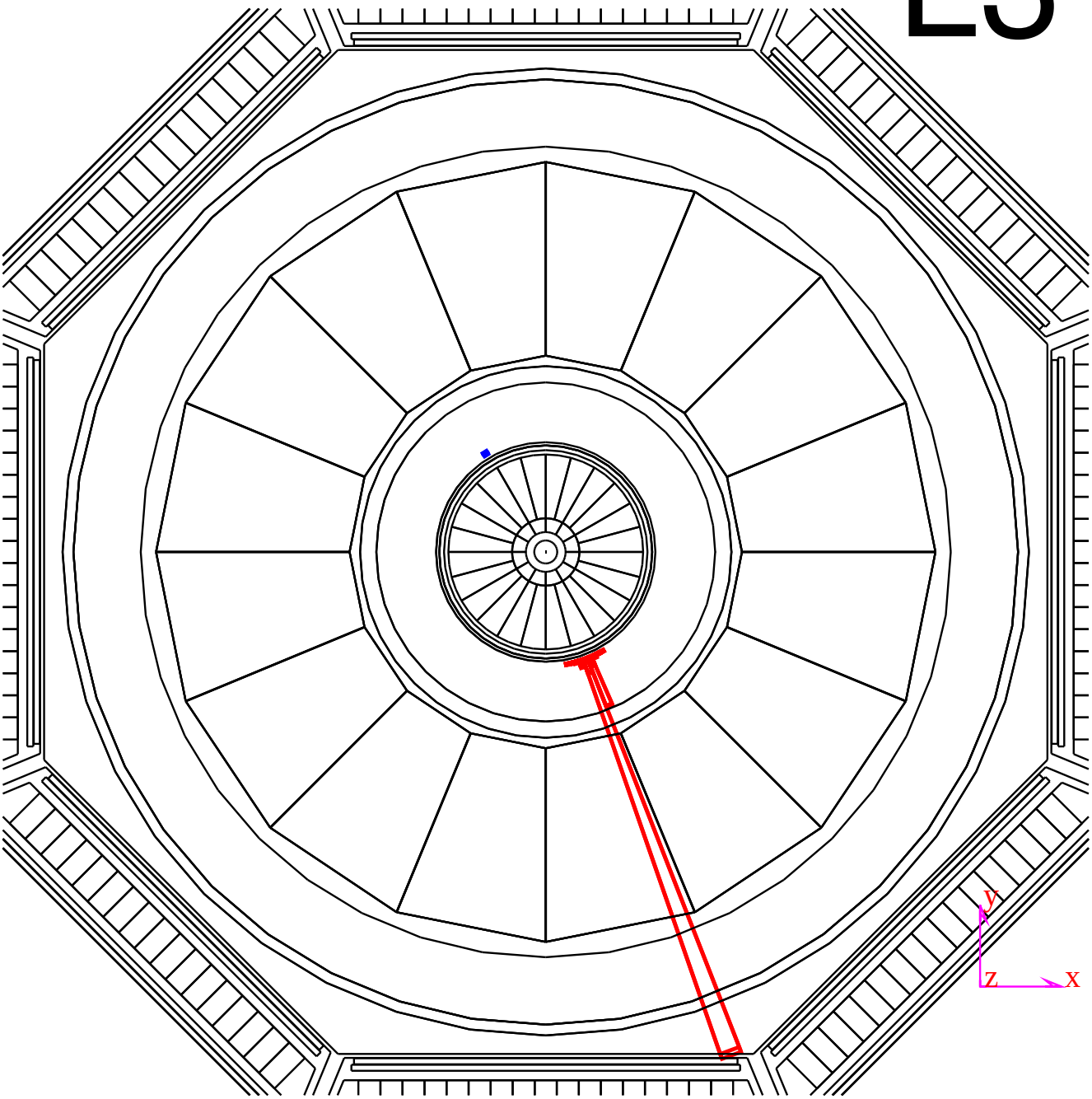
$$\frac{d\sigma}{d\Omega}(TGC) = \frac{\sigma^{MC}}{N_{MC}\Delta\Omega}\sum weight_j(TGC)$$



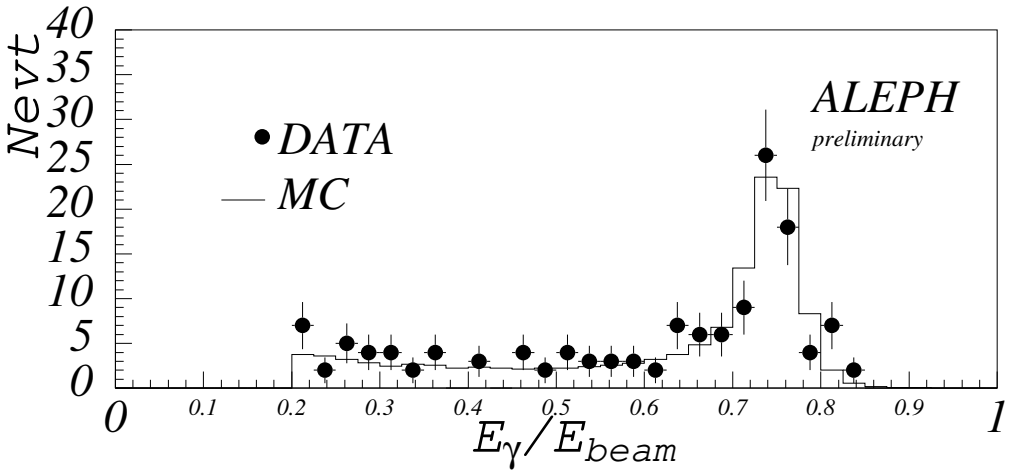
$$weight_j(TGC) = \frac{|M(\Omega, TGC)|^2}{|M(\Omega, SM)|^2}$$

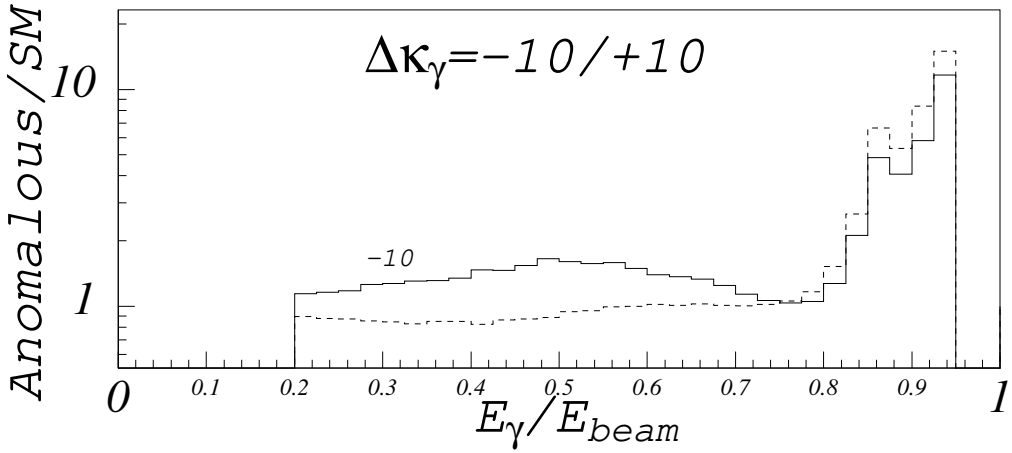
Run # 671913 Event # 731 Total Energy : 70.25 GeV

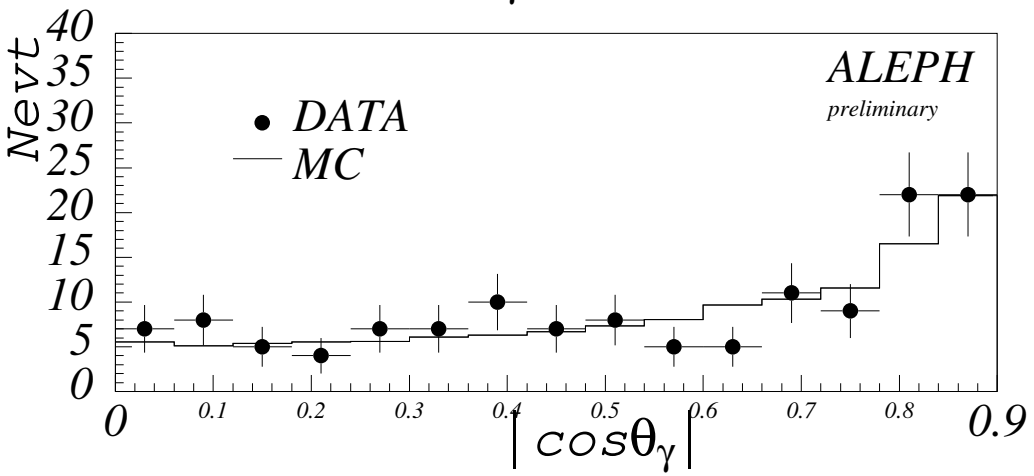
L3

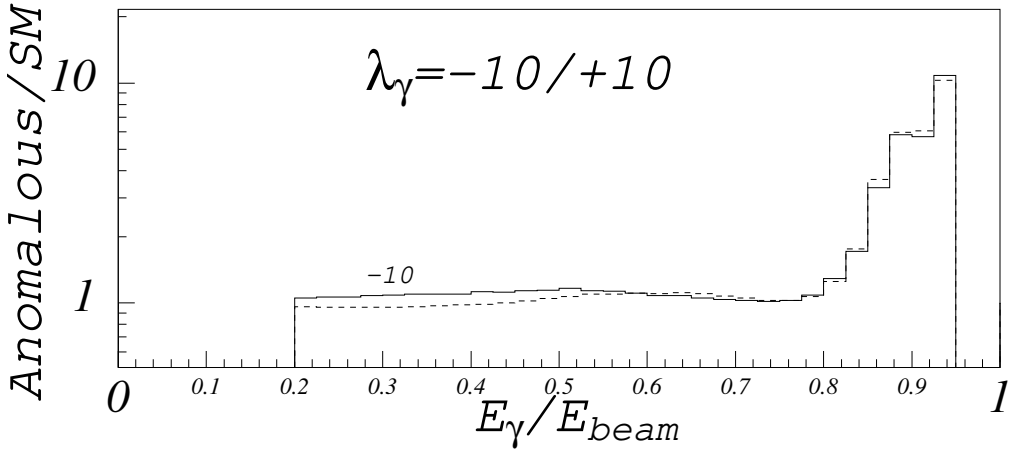


Transverse Imbalance : .9565 **Longitudinal Imbalance :** -.2568

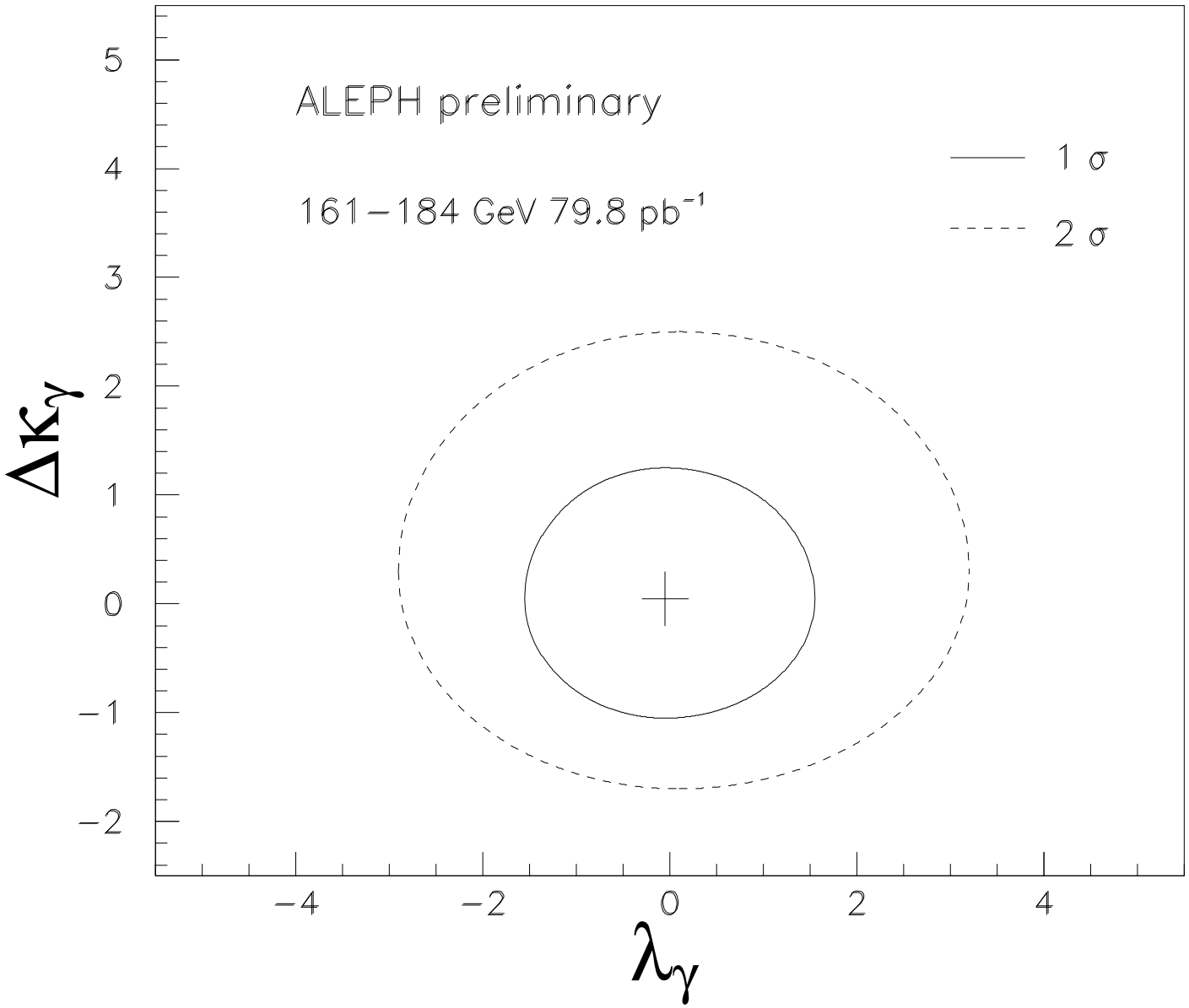

Nevt
ALEPH
preliminary
DATA
MC
E_γ/E_{beam}


Anomalous/SM
$\Delta\kappa_\gamma$=−10/+10
−10
E_γ/E_{beam}

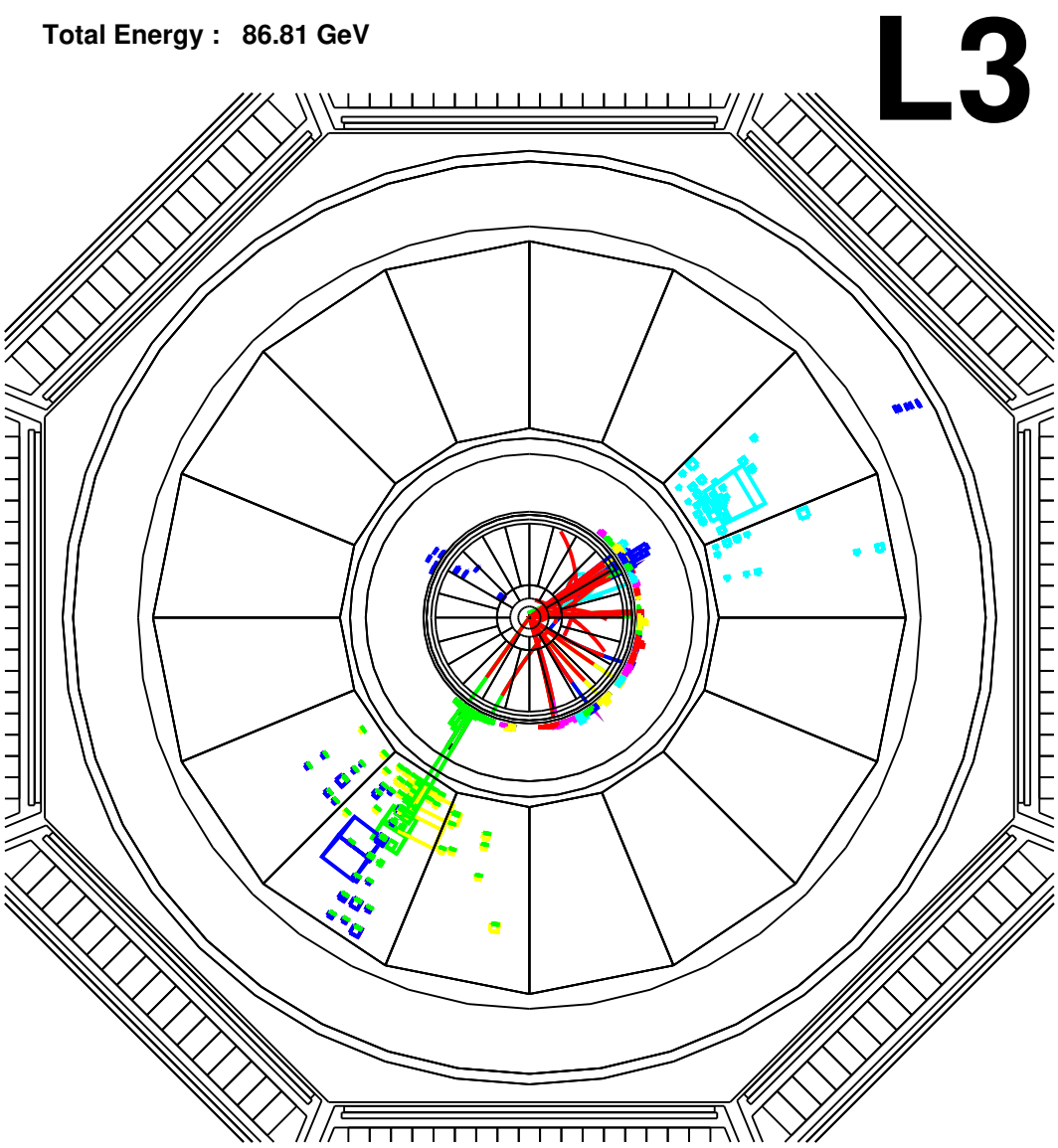

Nevt
ALEPH
preliminary
DATA
MC
$|\cos\theta_\gamma|$


Anomalous/SM
λ_γ=−10/+10
−10
E_γ/E_{beam}

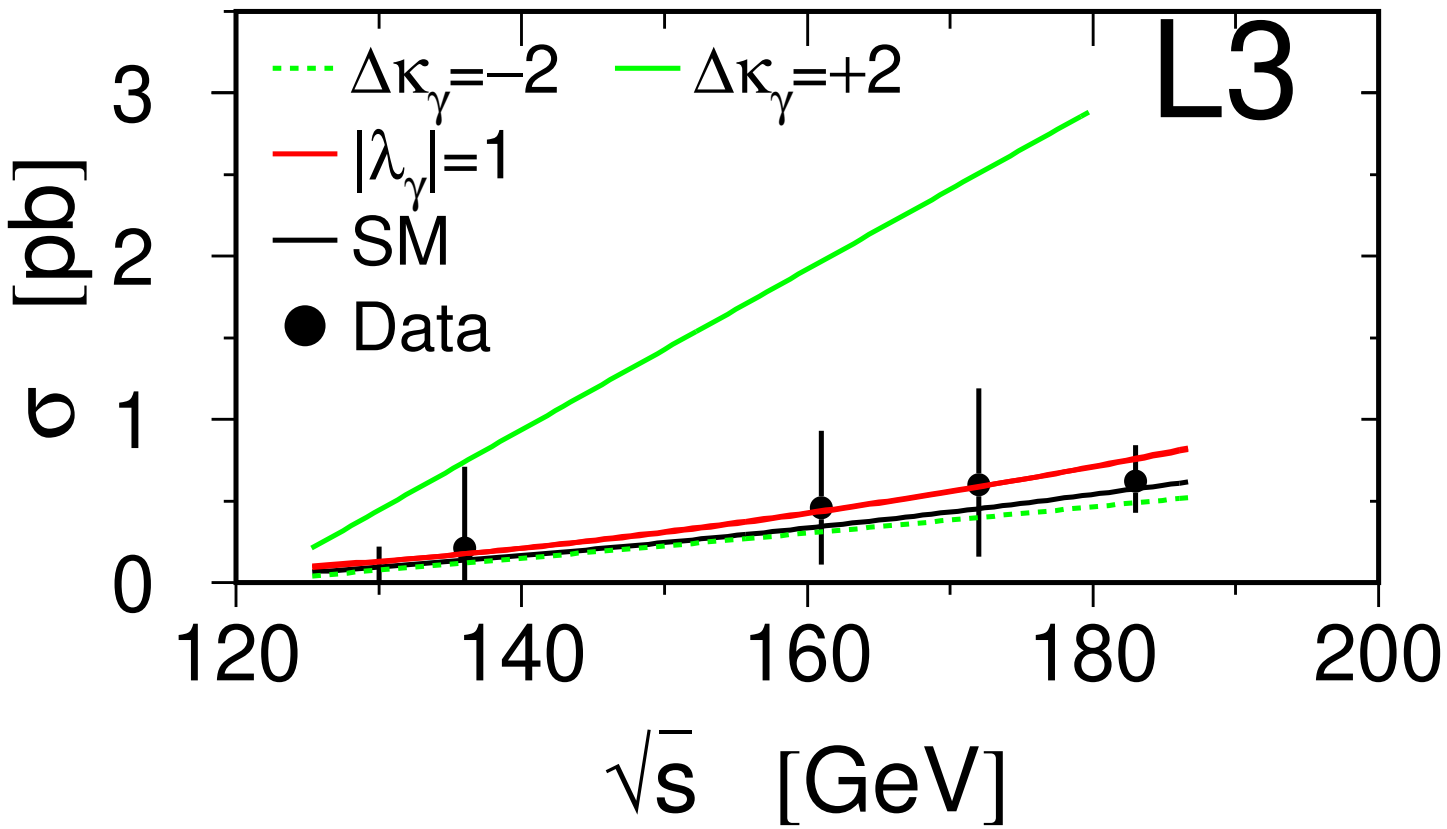
Fit of $\sigma(\nu\nu\gamma)$ and $\frac{1}{\sigma(\nu\nu\gamma)} \frac{d^2\sigma}{dE_\gamma d\cos\Theta_\gamma}$

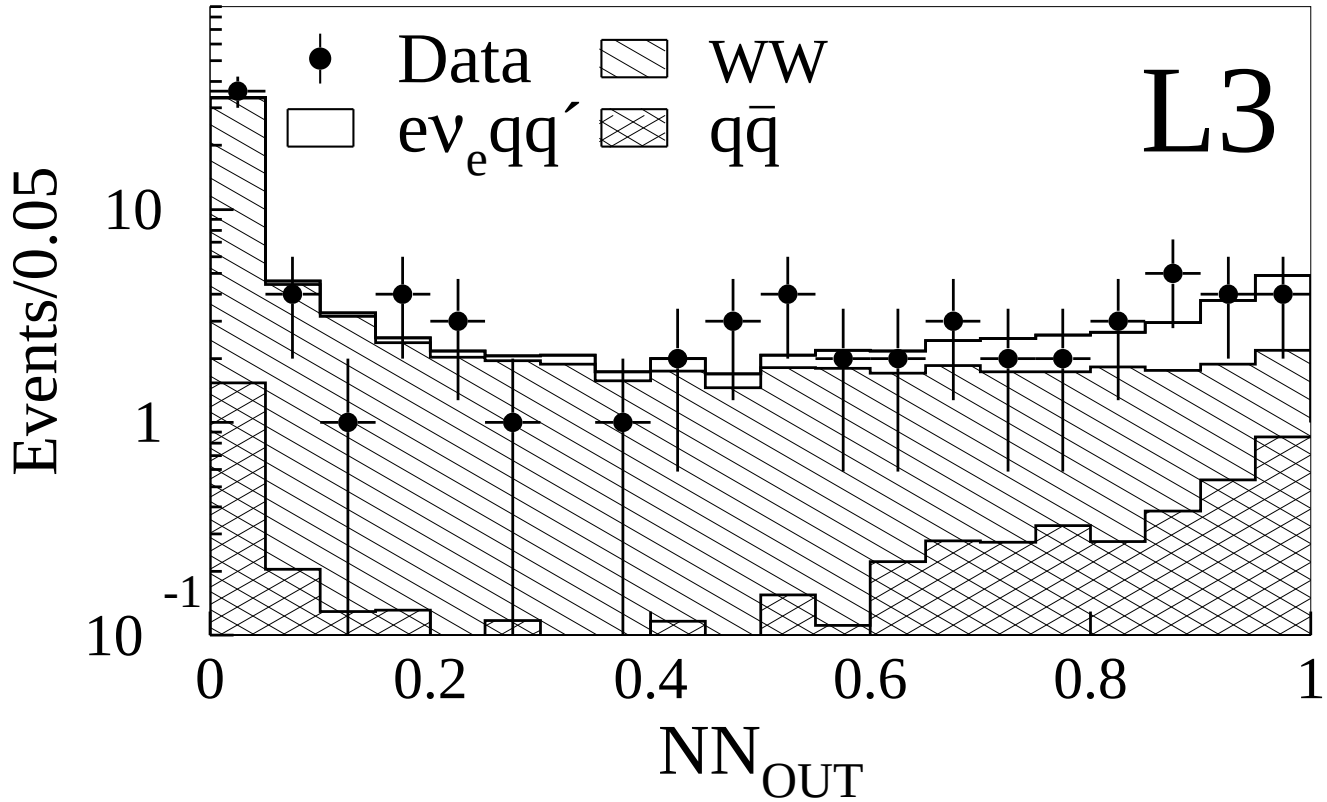


$e^+e^- \to We\nu$



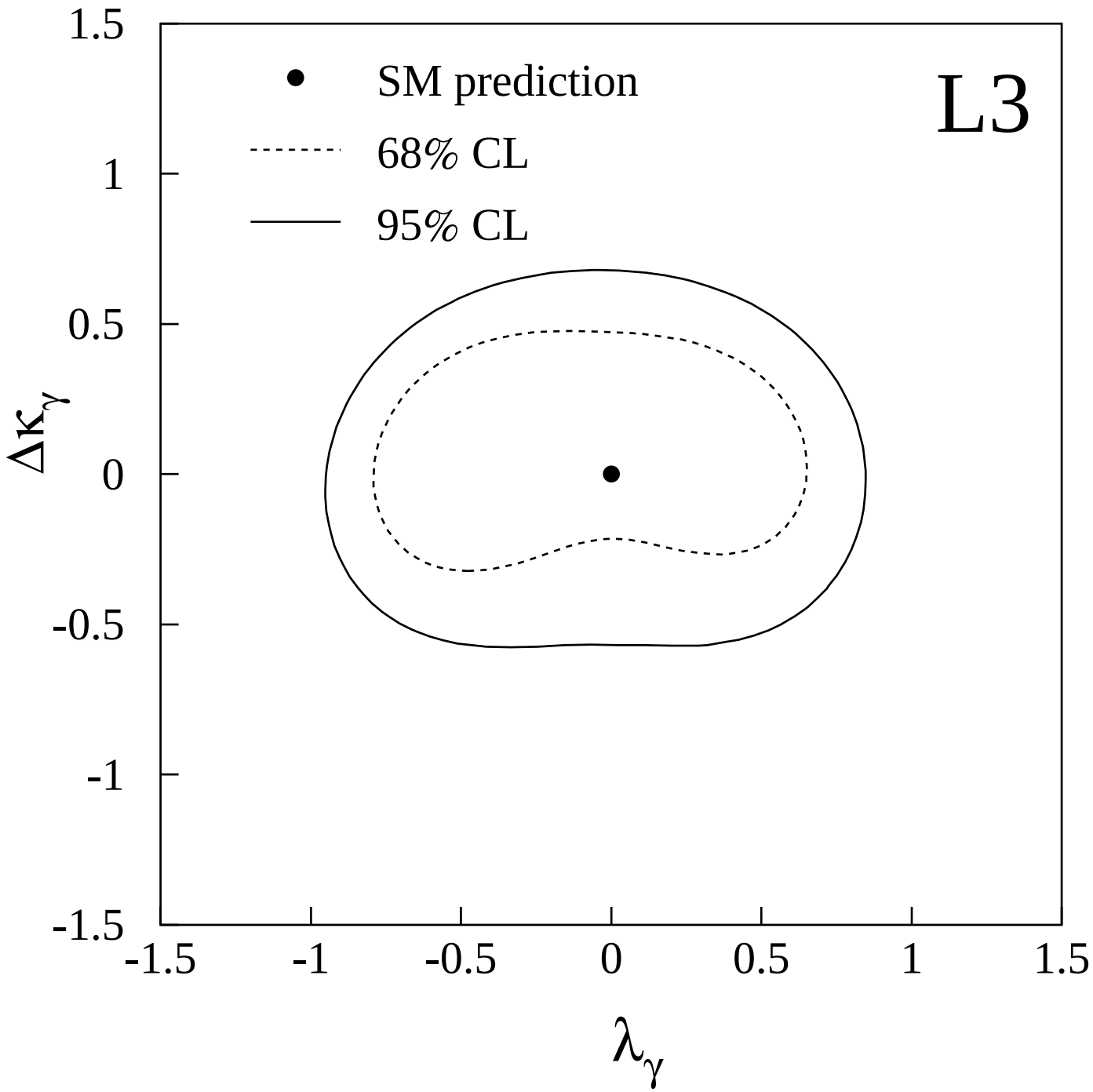
electron is lost in beam pipe →
single W seen in the detector


L3
$\Delta\kappa_\gamma$=−2
$\Delta\kappa_\gamma$=+2
$|\lambda_\gamma|$=1
SM
Data
σ [pb]
0
1
2
3
120
140
160
180
200
$\sqrt{s}$ [GeV]


L3
Data
WW
$e\nu_e qq'$
$q\bar{q}$
Events/0.05
10
1
10^{-1}
0
0.2
0.4
0.6
0.8
1
NN_{OUT}

Fit of

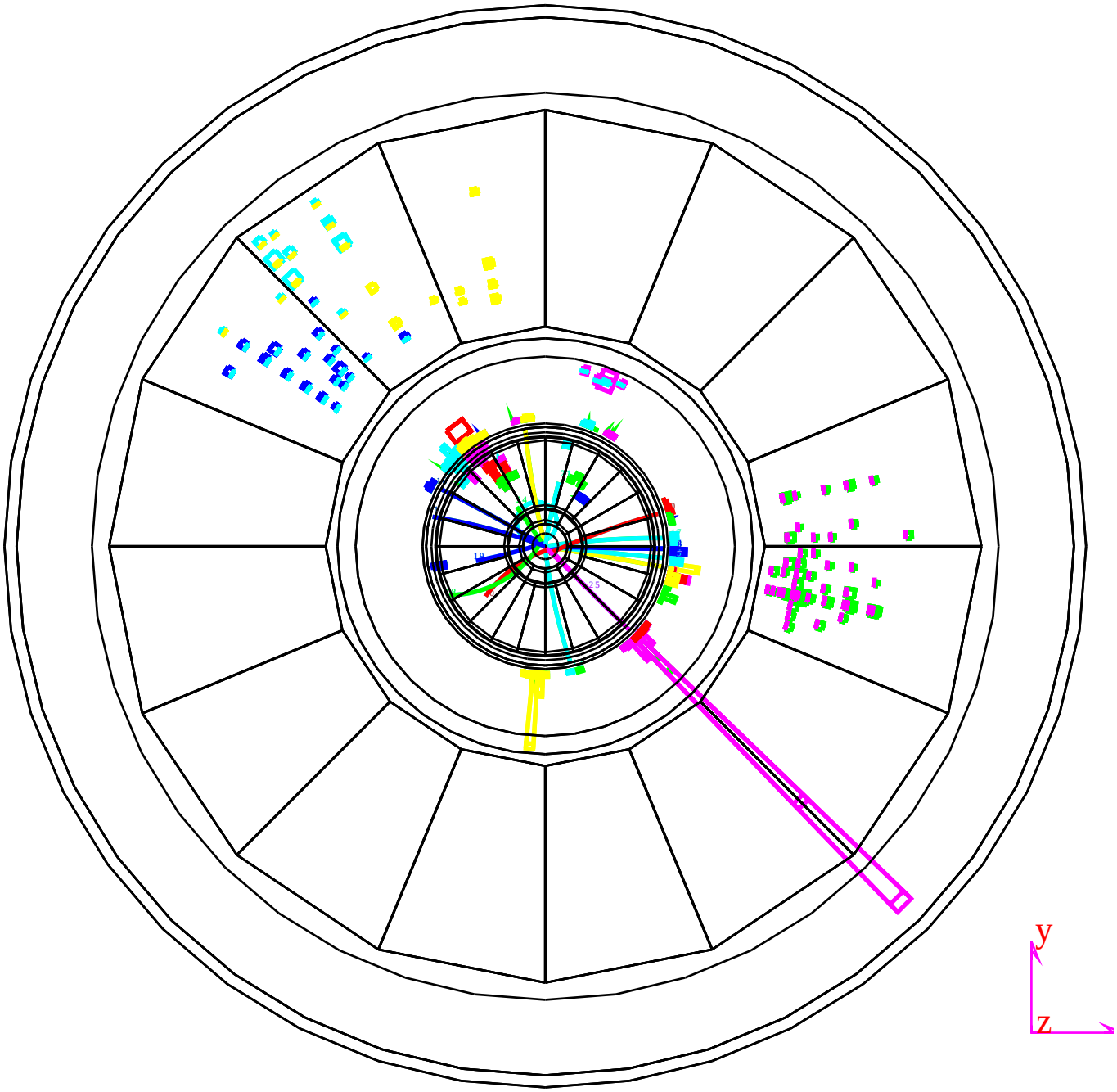
$\sigma(e\nu W \to l\nu, qq')$ and $\frac{1}{\sigma(e\nu W \to qq')} \frac{d\sigma(e\nu W \to qq')}{d(NN_{\text{out}})}$



$e^+e^- \to W^+W^- \to qqe\nu_e$

ın # 671603 Event # 3681 Total Energy : 132.88 GeV

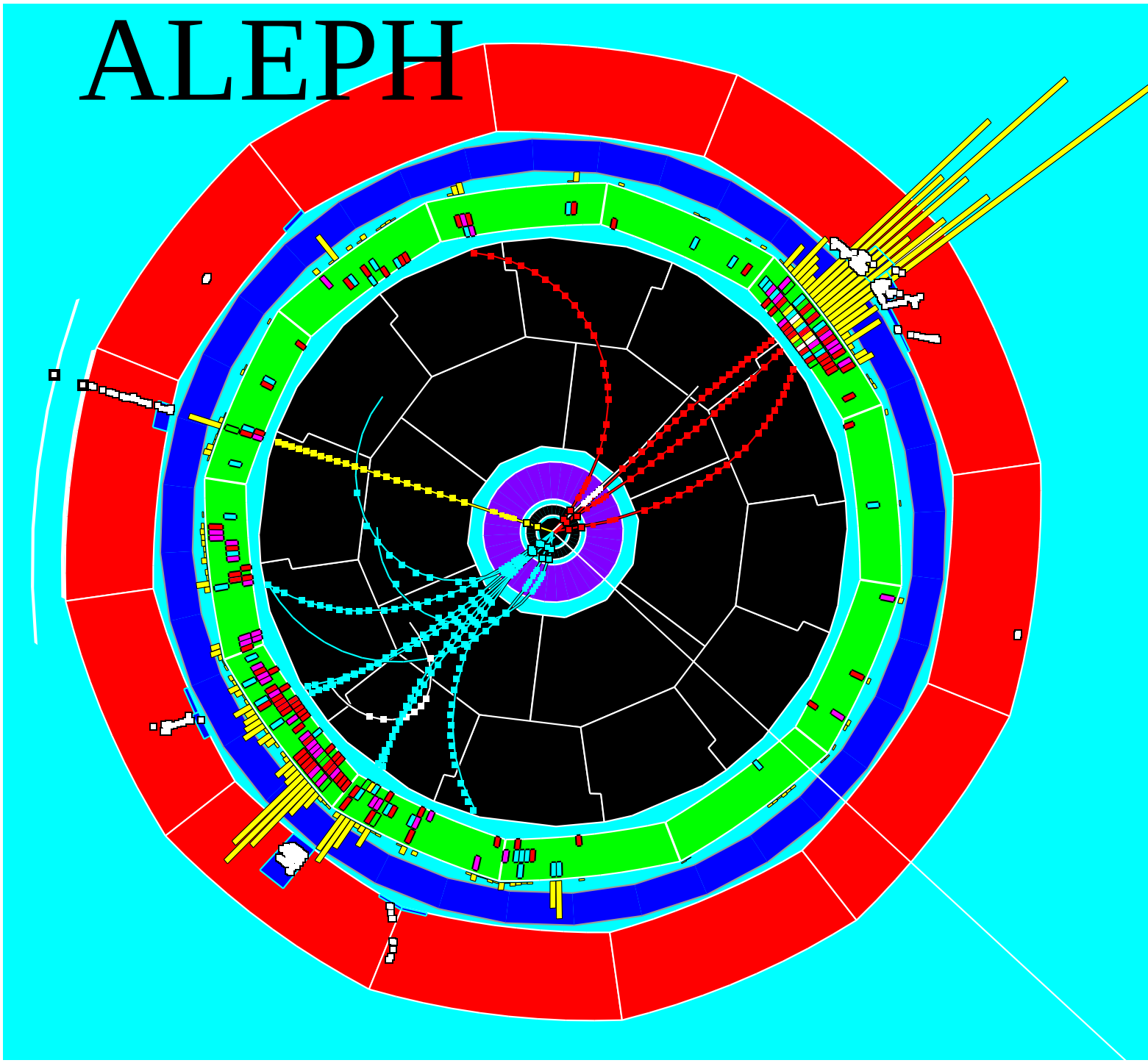
L3



Efficiency : 80% Purity : 90%

$N^{\text{LEP2}}_{\text{events}}(161 - 183\ \text{GeV}) = 550$

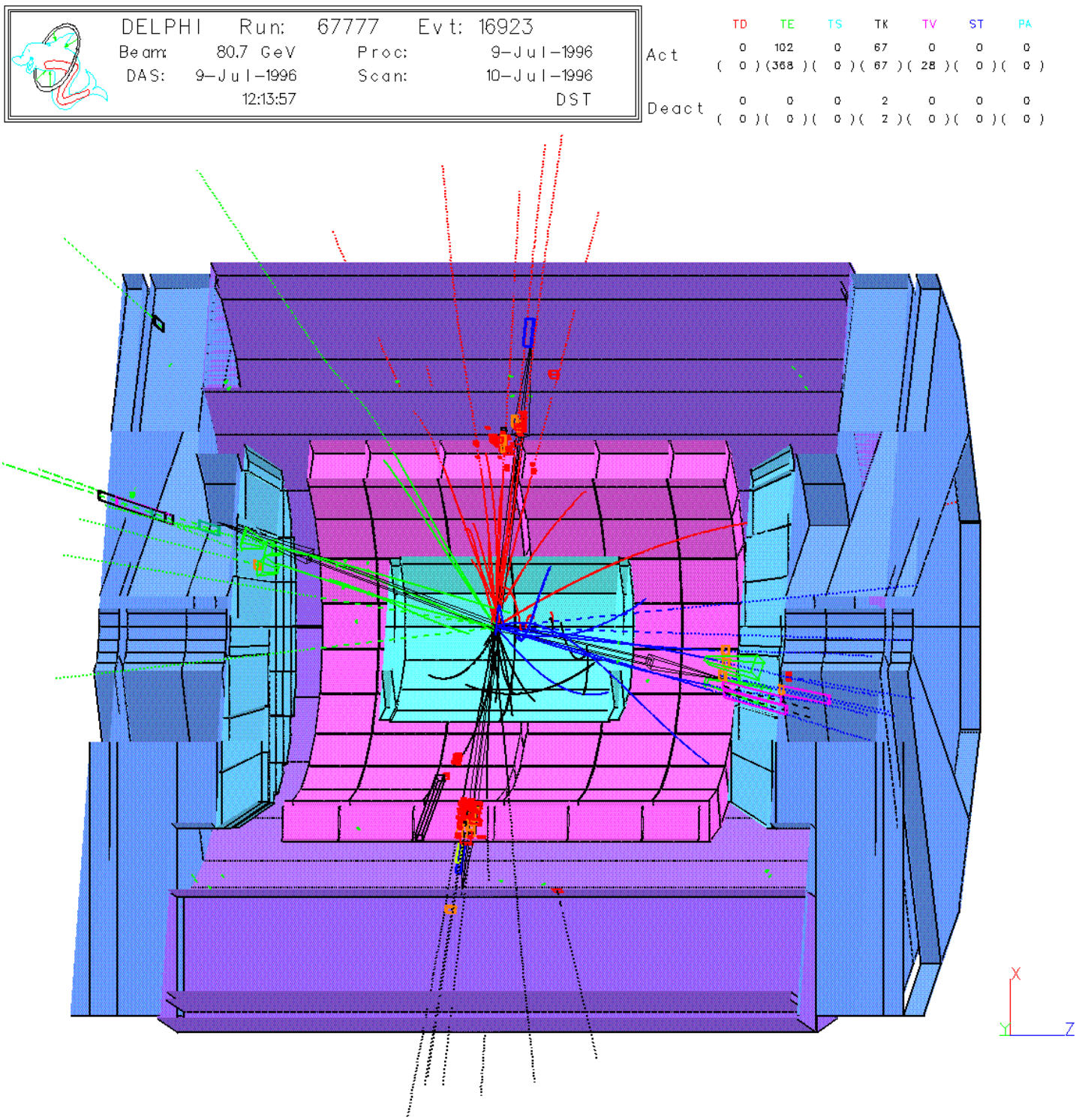
$e^+e^- \to W^+W^- \to qq\mu\nu_\mu$



Efficiency : 80% Purity : 90%

$N^{\text{LEP2}}_{\text{events}}(161 - 183\ \text{GeV}) = 550$

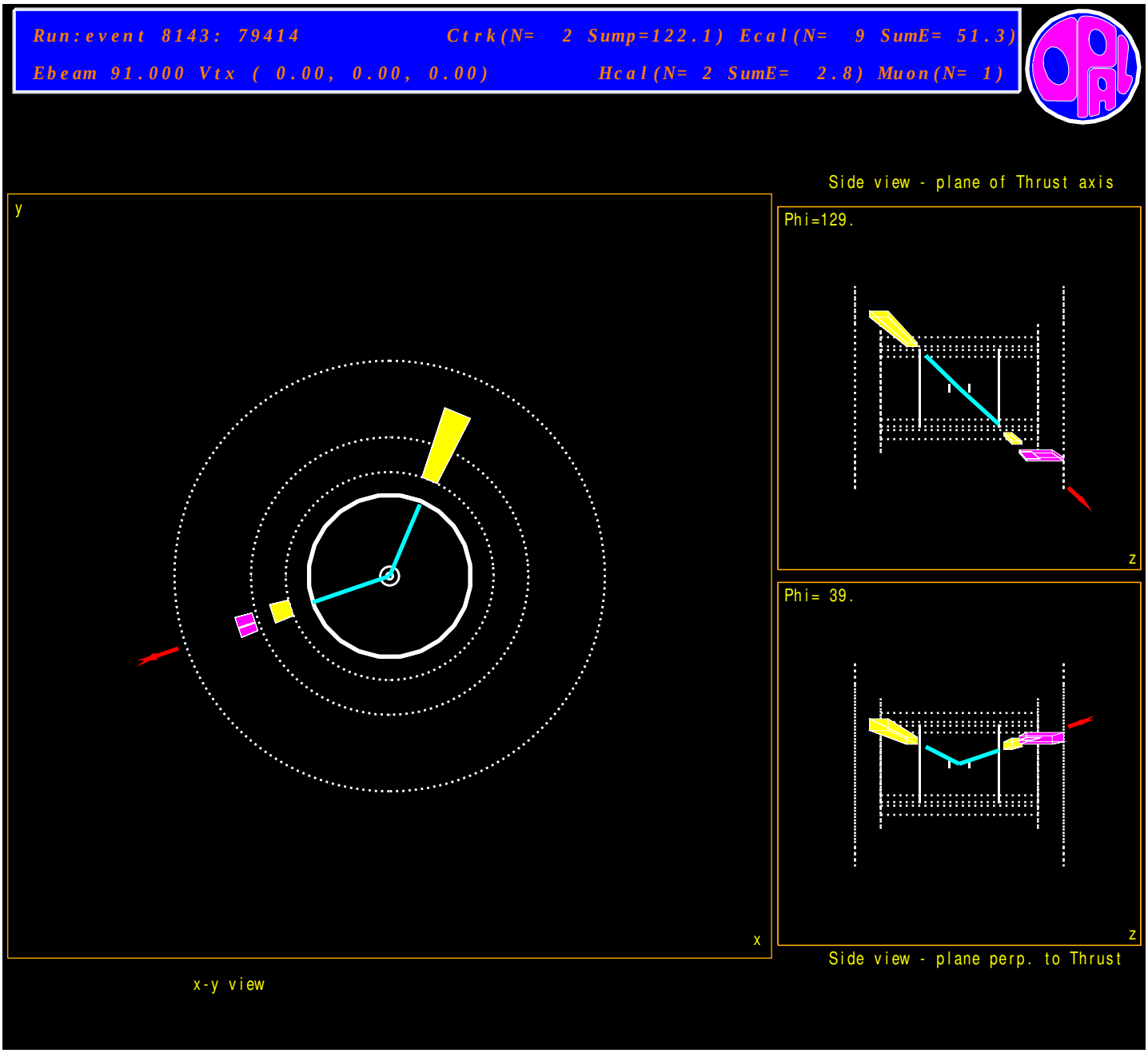
$e^+e^- \to W^+W^- \to qqqq$



Efficiency : 80% Purity : 80%

$N^{\text{LEP2}}_{\text{events}}(161 - 183\ \text{GeV}) = 2000$

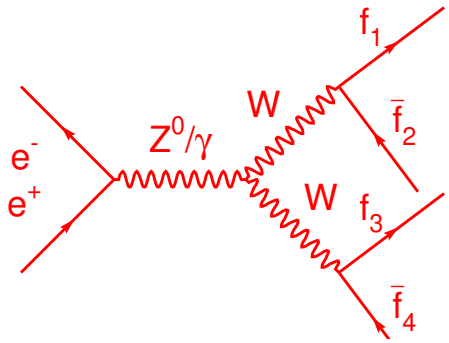
$e^+e^- \to W^+W^- \to l\nu l'\nu'$

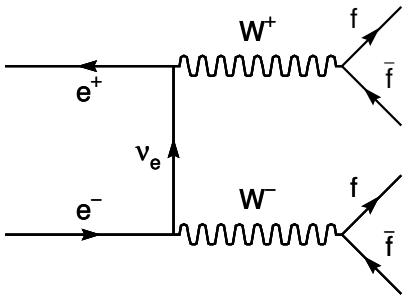


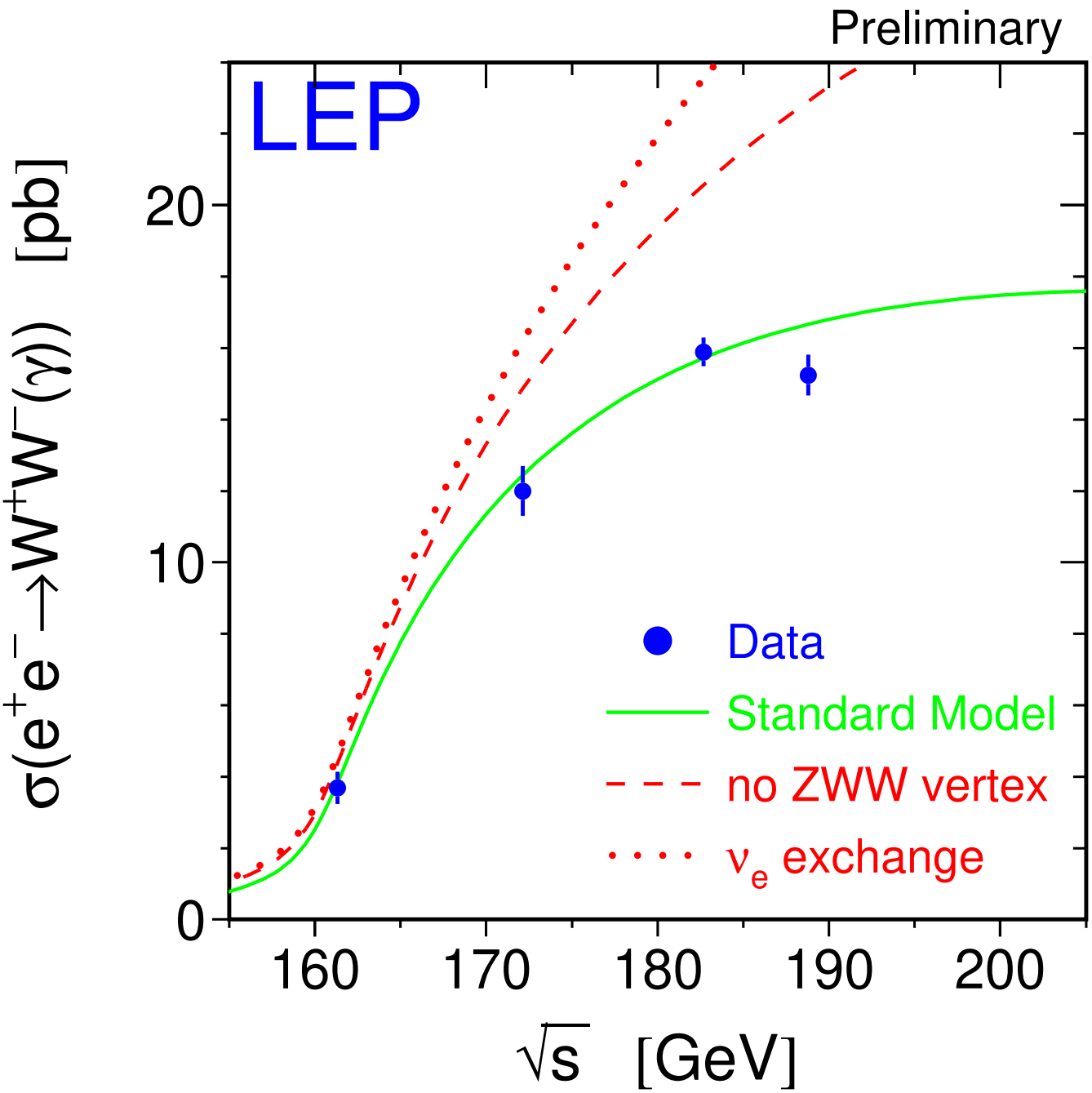
Efficiency : 50% Purity : 90%

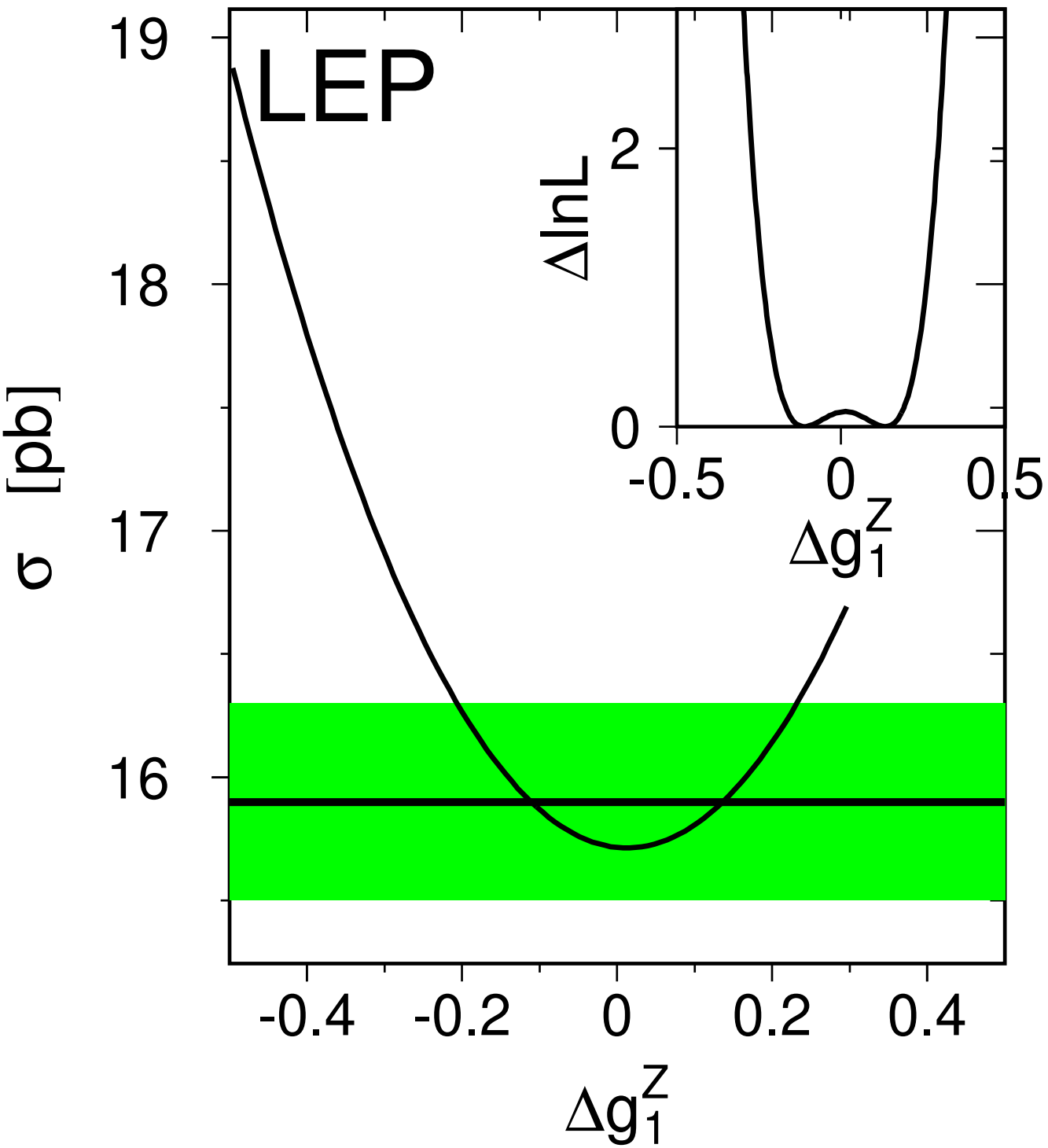
$N^{\text{LEP2}}_{\text{events}}(161 - 183\ \text{GeV}) = 300$

$e^+e^- \to W^+W^-$

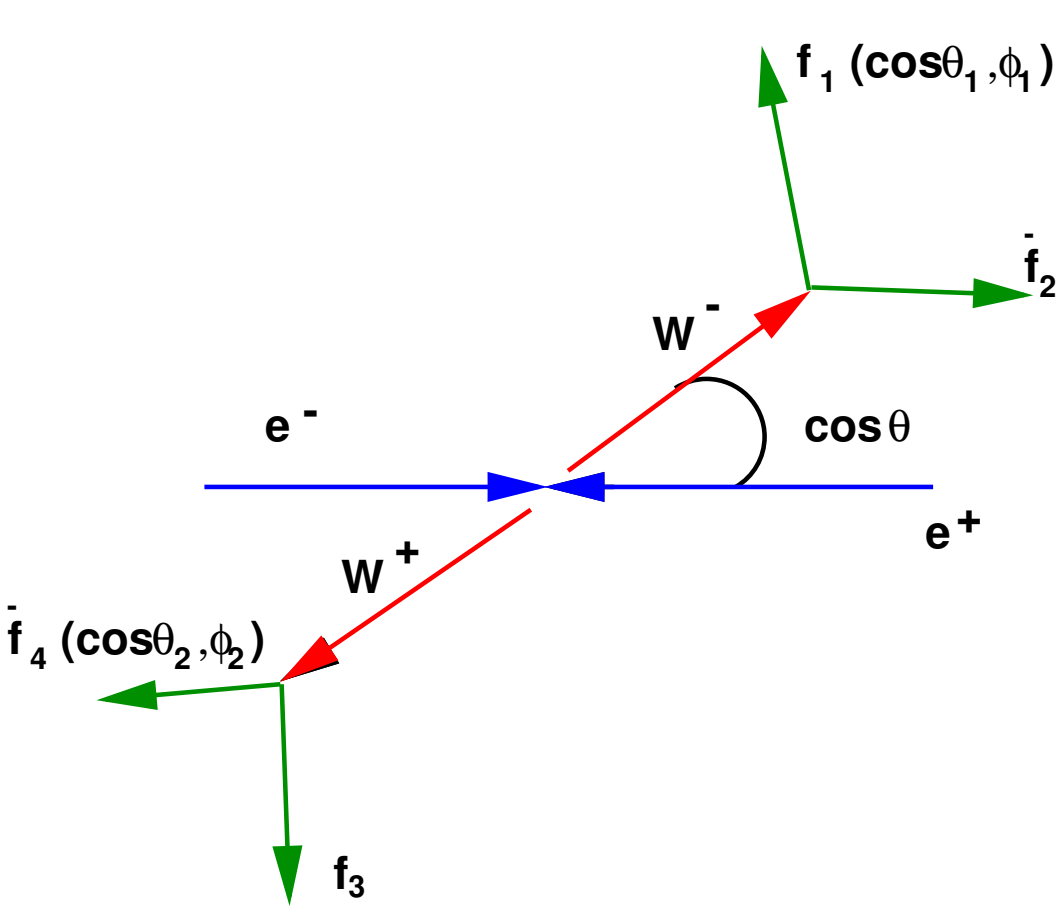

e-
e+
Z0/γ
W
W
f1
f̄2
f3
f̄4


e+
e−
νe
W+
W−
f
f̄
f
f̄


Preliminary
LEP
σ(e+e−→W+W−(γ)) [pb]
20
10
0
160
170
180
190
200
√s [GeV]
Data
Standard Model
no ZWW vertex
νe exchange


LEP
σ [pb]
19
18
17
16
-0.4
-0.2
0
0.2
0.4
Δg_1^Z
ΔlnL
2
0
-0.5
0
0.5
Δg_1^Z

Independent variables of WW-events



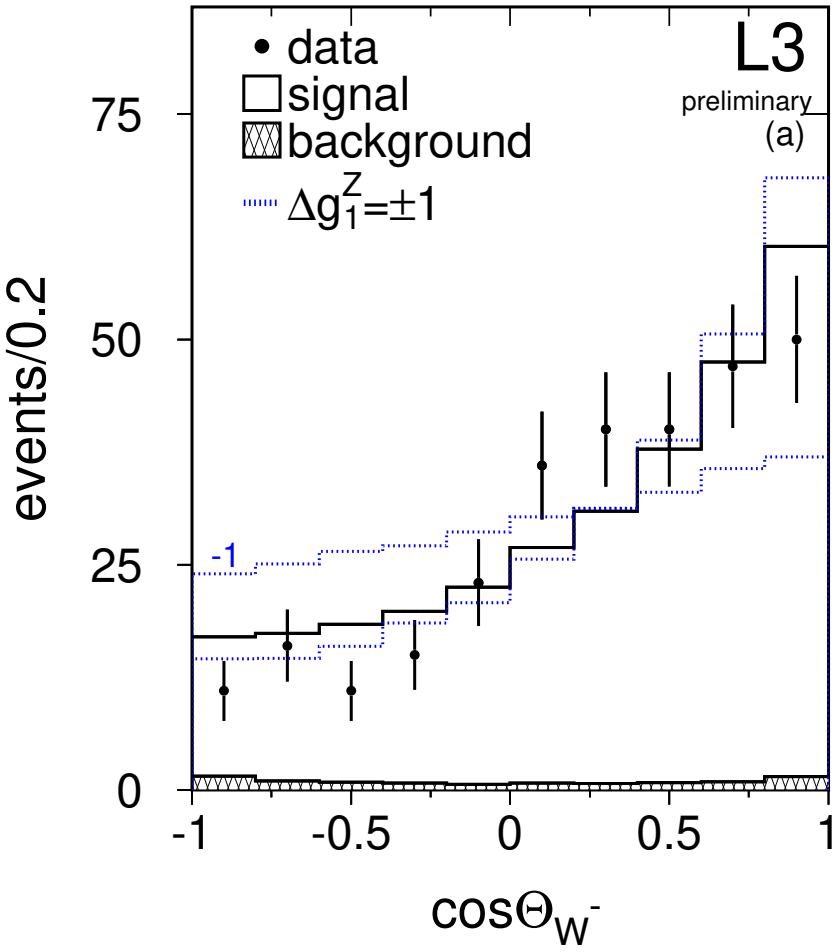
Number of independent variables :

four four-momentum vectors	4×4
four momentum conservation	- 4
masses of final state particles	- 4
W-masses	- 2
assume azimuthal independence	- 1
number of independent parameters	= 5

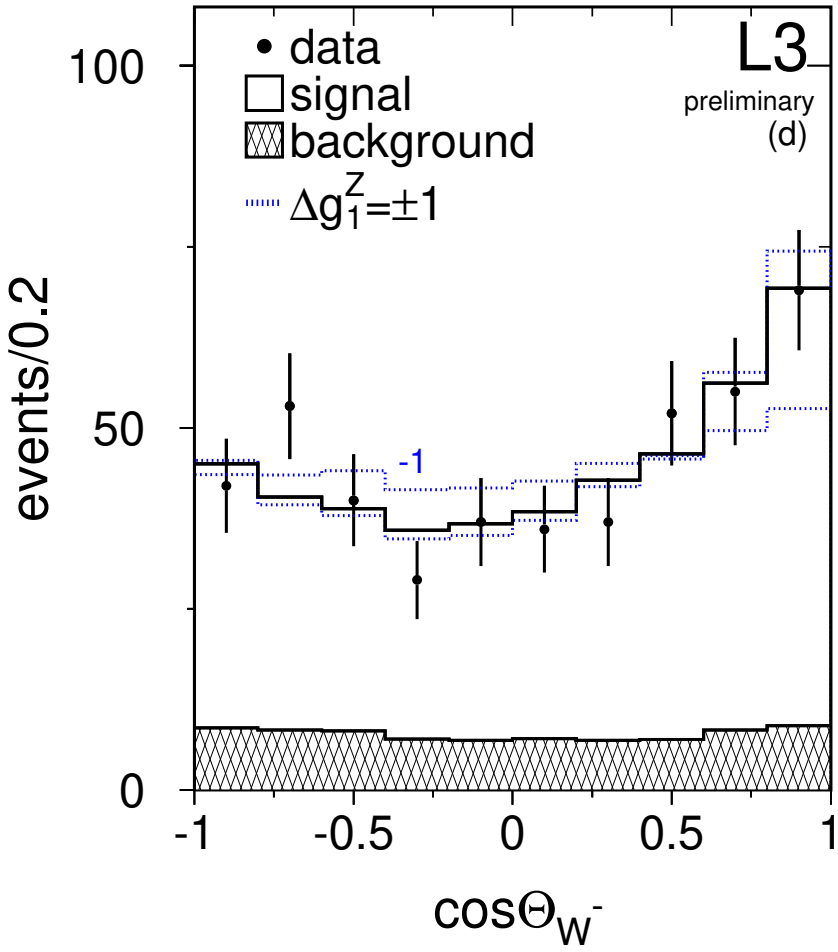
Set of independent variables :

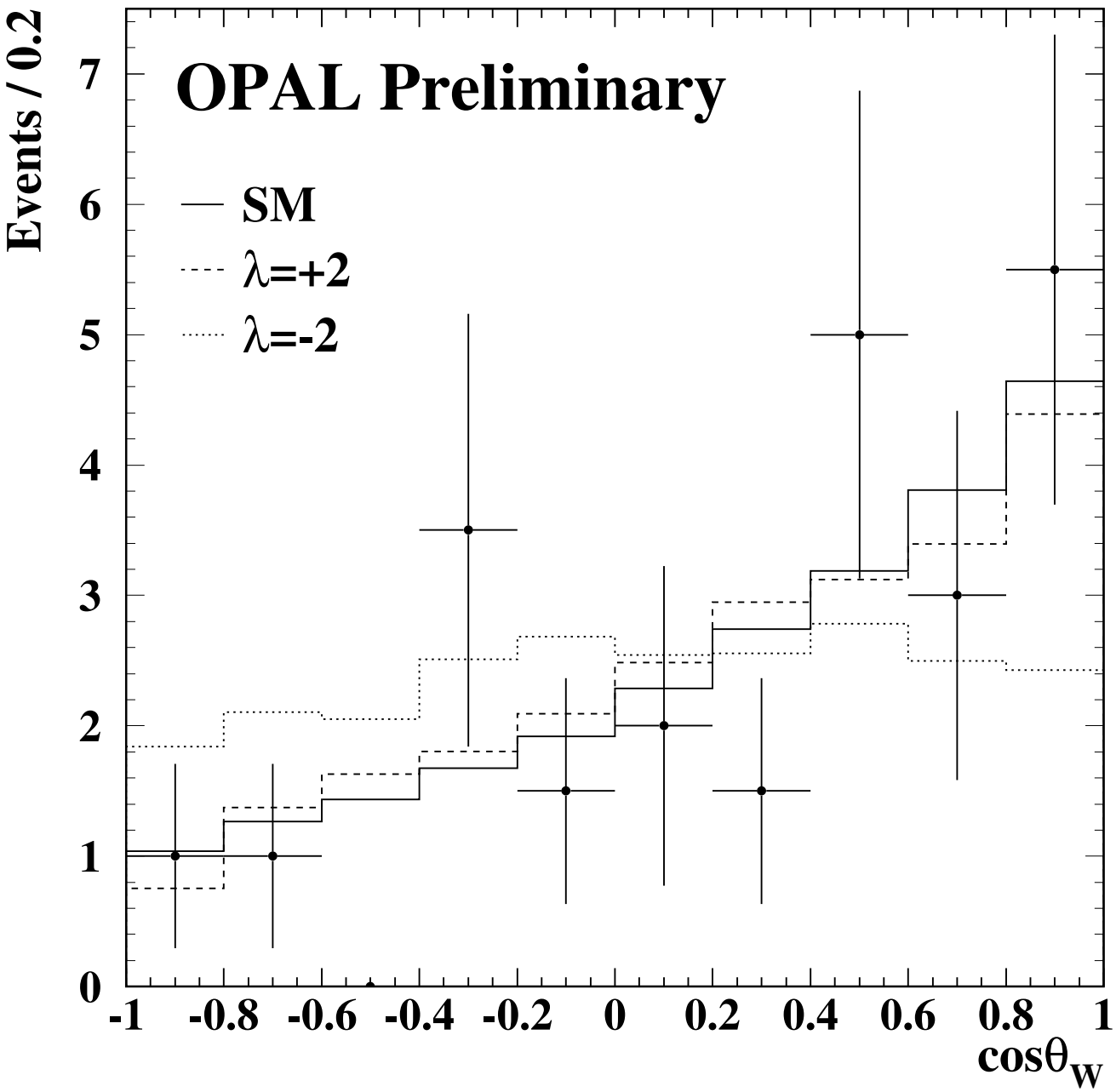
$$\Omega = \cos\theta_W, \cos\theta_1, \phi_1, \cos\theta_2, \phi_2$$

$qql\nu_l$


• data
signal
background
Δg_1^Z=±1
L3
preliminary
(a)
-1
events/0.2
75
50
25
0
-1
-0.5
0
0.5
1
cosΘ$_{W^-}$

$qqqq$


• data
signal
background
Δg_1^Z=±1
L3
preliminary
(d)
-1
events/0.2
100
50
0
-1
-0.5
0
0.5
1
cosΘ$_{W^-}$



twofold ambiguity

$\Rightarrow$ two entries with weight 0.5 per event

Optimal Observables

$$\frac{d\sigma(\Omega,\alpha)}{d\Omega} = \overbrace{\frac{d\sigma(\Omega,SM)}{d\Omega}}^{c_0} + \overbrace{\frac{d^2\sigma(\Omega,SM)}{d\Omega d\alpha}(\Omega)}^{c_1}\,\alpha + \overbrace{\frac{d^3\sigma(\Omega,SM)}{2d\Omega d\alpha^2}}^{c_2}\,\alpha^2$$

for TGC parameter α

$$O_1 = \frac{c_1}{c_0}(\Omega)$$

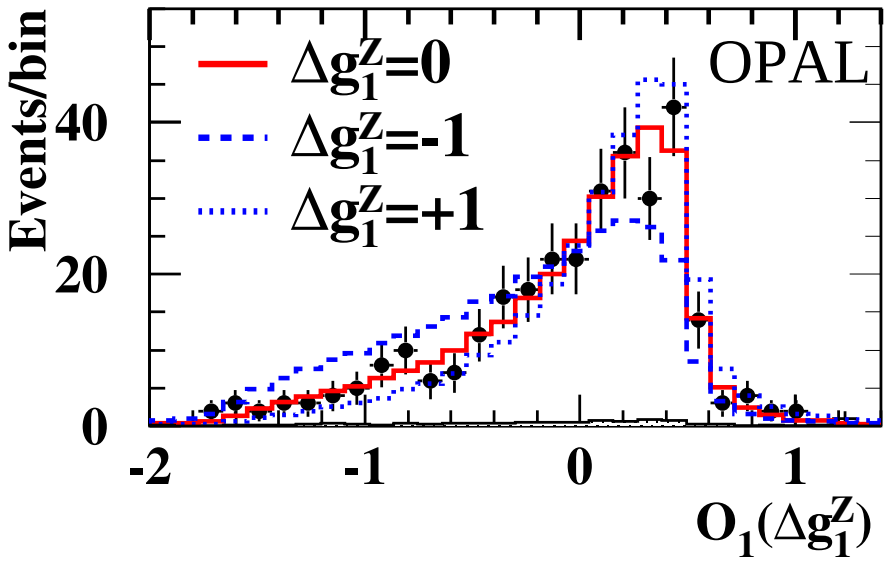
$$O_2 = \frac{c_2}{c_0}(\Omega)$$

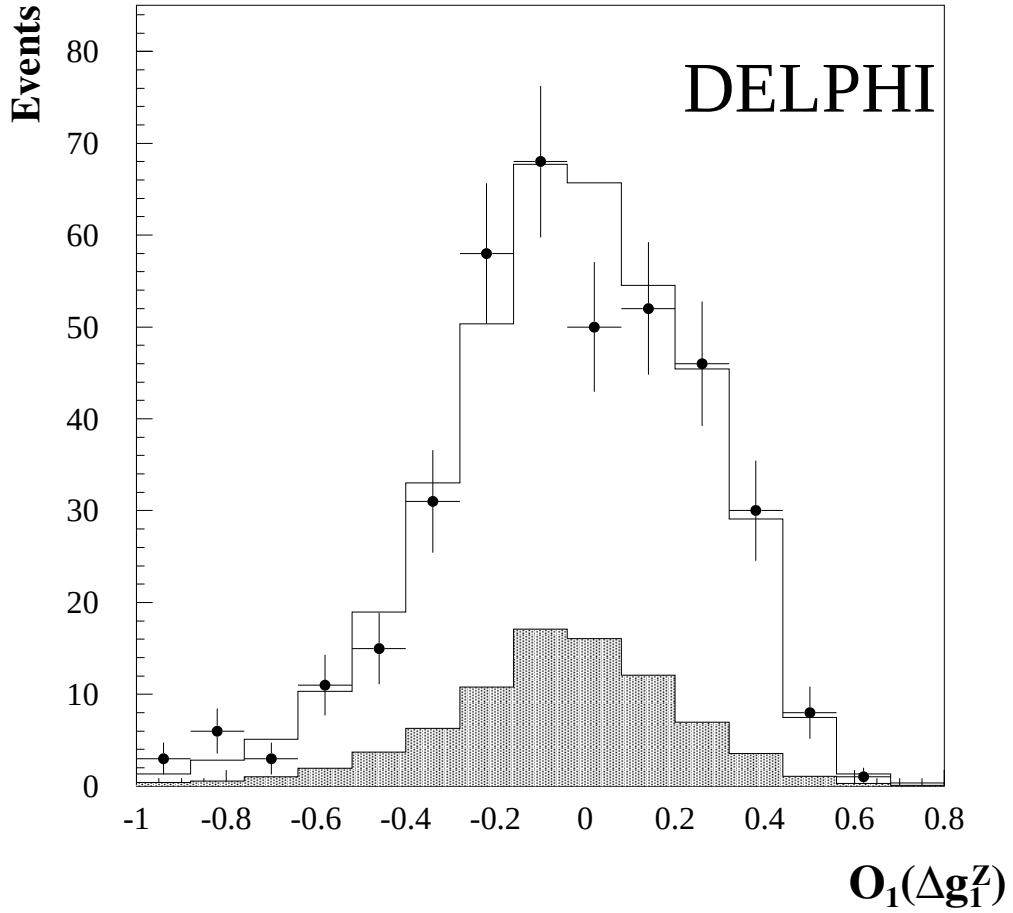
$\Omega_{\mathrm{DL}} \rightarrow \Omega_{GL}$ different strategies used :

1. OO computed from DL variables, OO distribution fitted with reweighting
2. folding of c_i with detector resolution; $c_i \rightarrow \int c_i(\Omega_{GL}) D(\Omega_{DL},\Omega_{GL}) d\Omega_{GL}$
3. OO computed from unfolded variables

method 1

method 2





Spin density matrices

+ visualization of W polarisation $\Rightarrow$
model independent TGC tests

$$\rho_{\tau_-\tau'_-}(\cos\theta_W) = \sum_{\tau_+\tau'_+} \frac{\mathcal{F}_{\tau_-\tau_+}(\mathcal{F}_{\tau'_-\tau'_+})^*}{\sum_{\tau_+\tau_-}|\mathcal{F}_{\tau_-\tau_+}|^2}$$

$\mathcal{F}_{\tau_-\tau_+}$ is helicity matrix for W^+W^- helicities $\tau_+\tau_-$

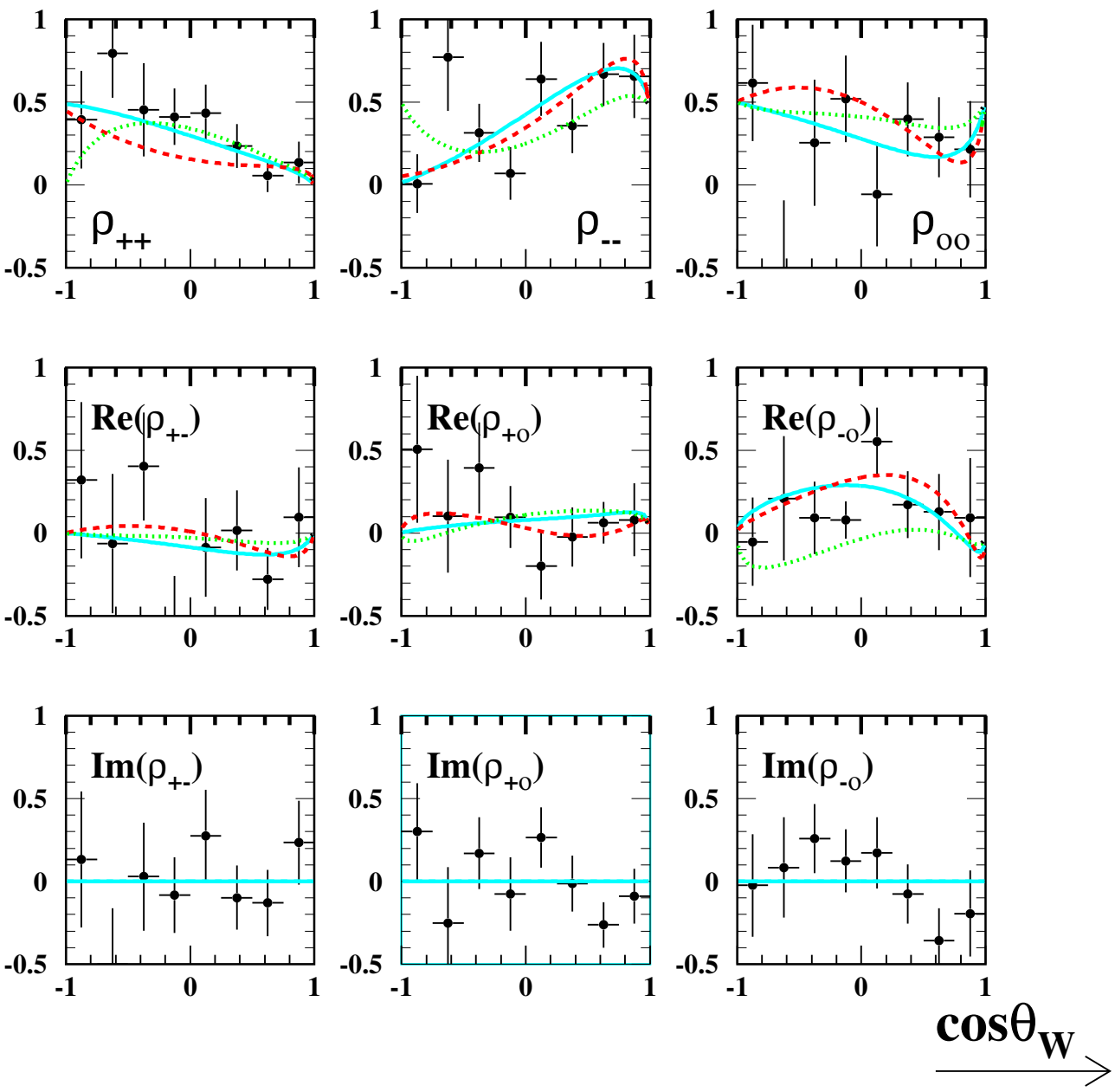
$$\Longleftrightarrow$$

$$\rho_{\tau\tau'}(\cos\theta_W) = \frac{1}{N}\sum_{i=1}^{N}\Lambda_{\tau\tau'}(cos\theta_l, \phi_l)$$

$\Lambda_{\tau\tau'}(cos\theta_l, \phi_l)$ is projector for $\rho_{\tau\tau'}$

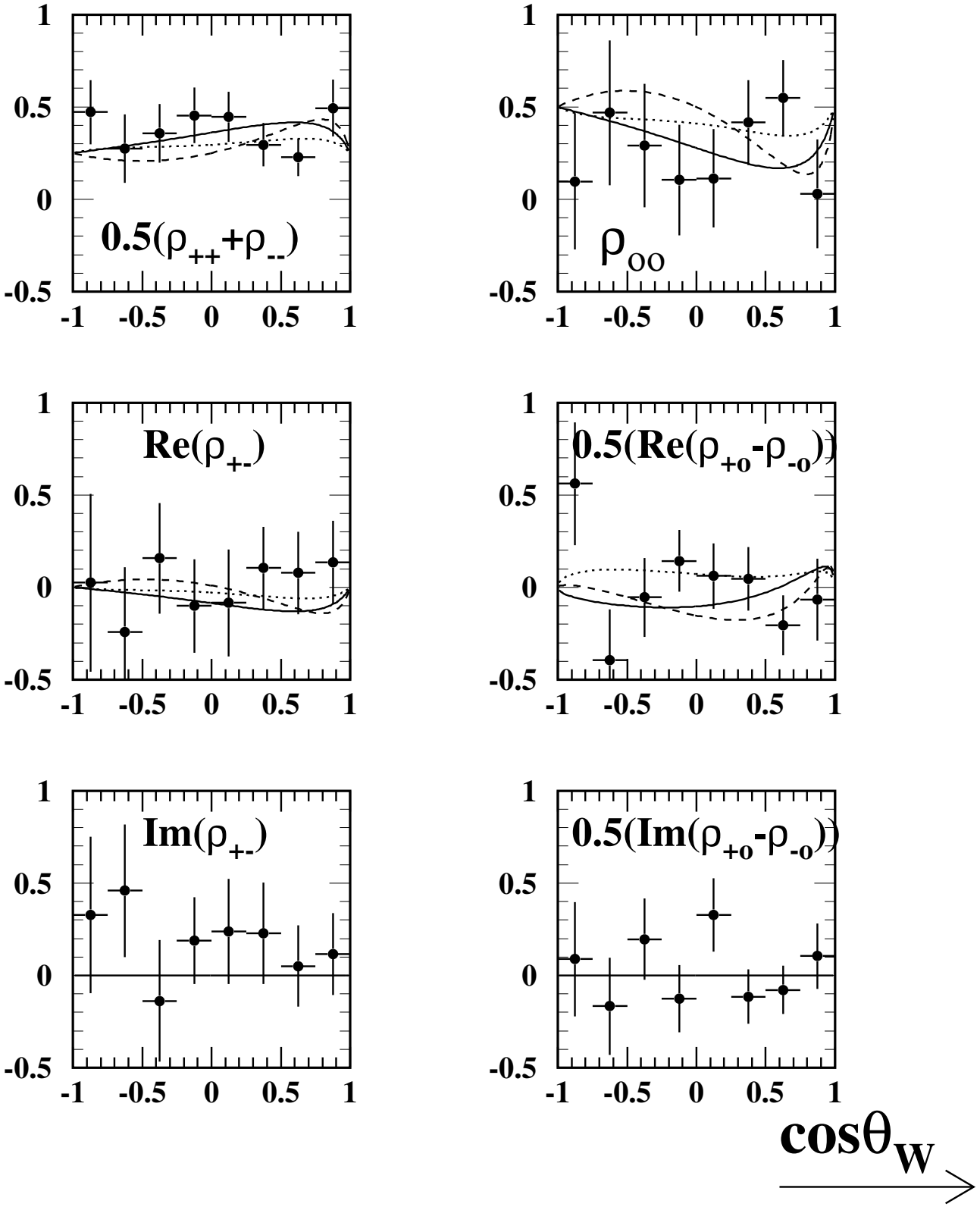
Detector level measurement$\rightarrow$
background subtraction
unfolding in the three variables $cos\theta_W$, $cos\theta_l$ and ϕ_l
$\rightarrow$ $\rho-$matrices

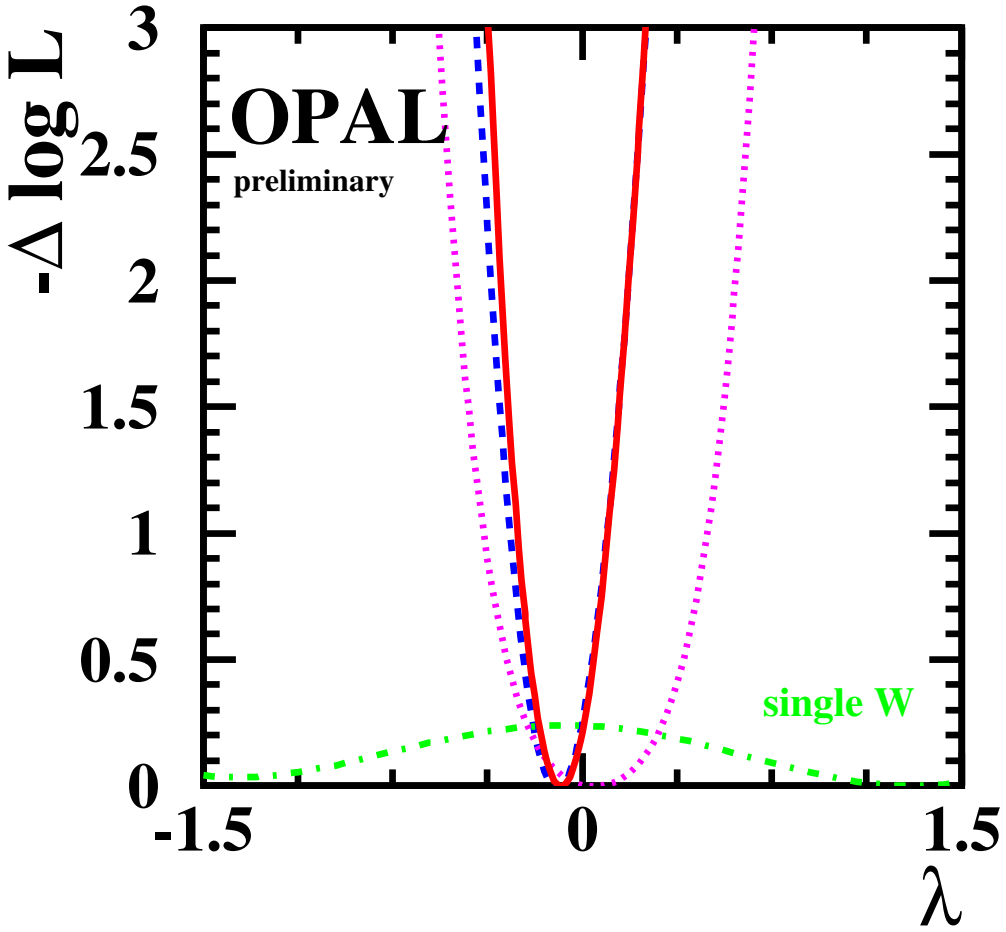
OPAL Preliminary

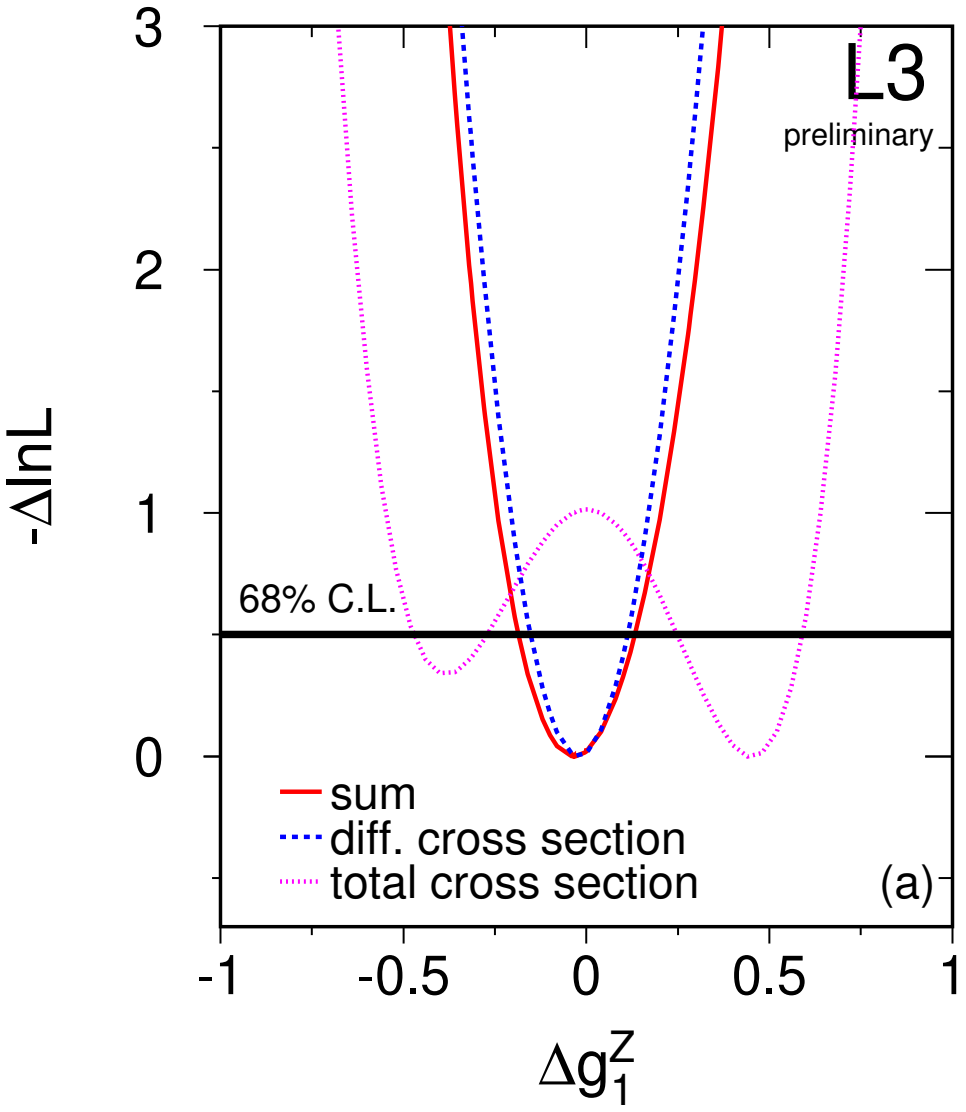


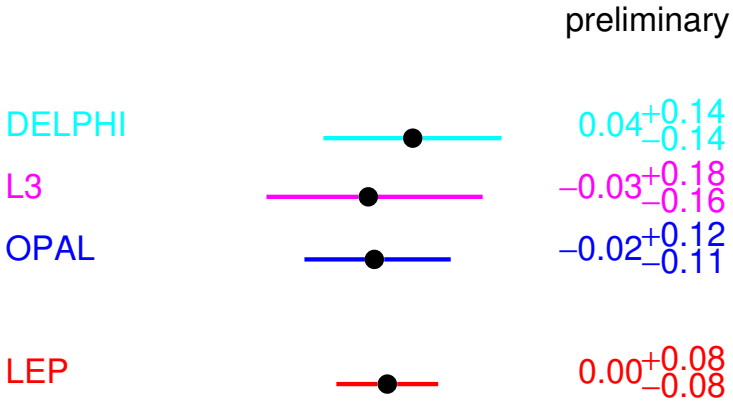
(solid/dashed/dotted) curves correspond to SM, Δg_1^Z=-1,1

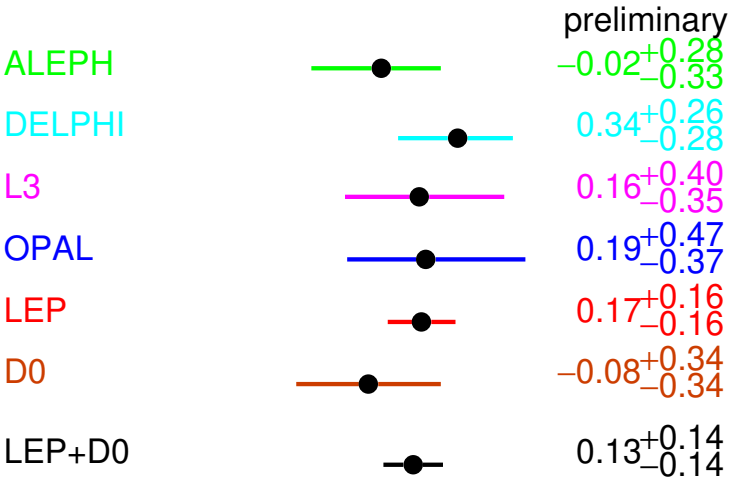
OPAL Preliminary

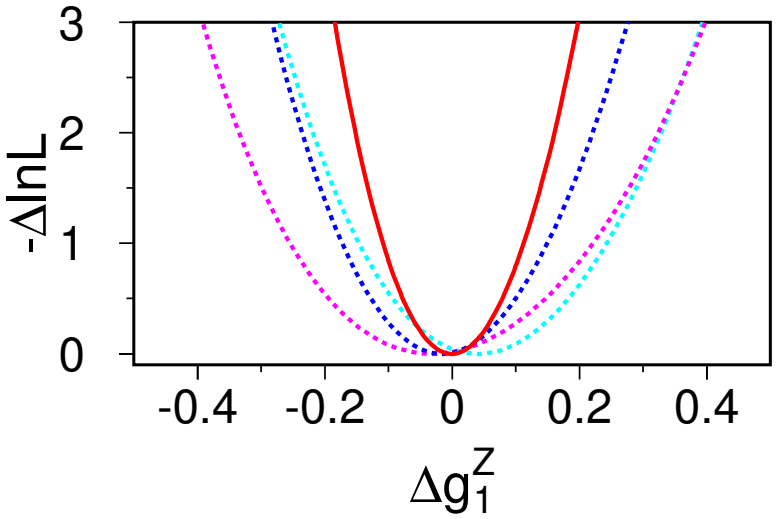


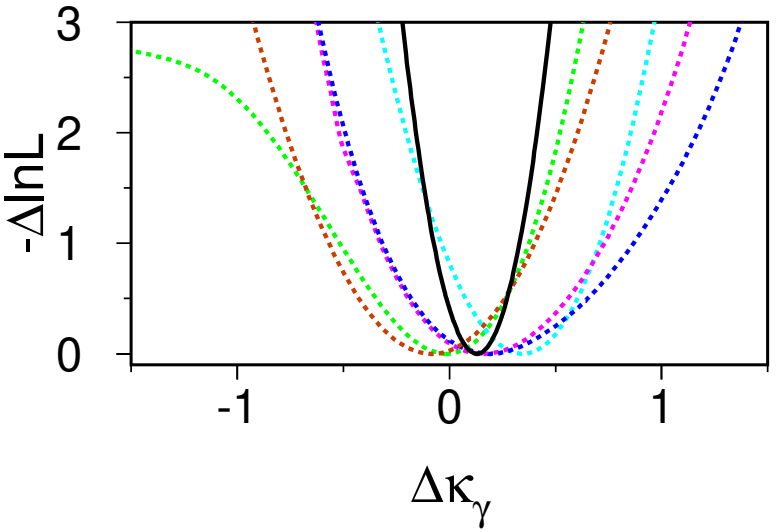

OPAL
preliminary
single W
-Δ log L
λ
3
2.5
2
1.5
1
0.5
0
-1.5
0
1.5

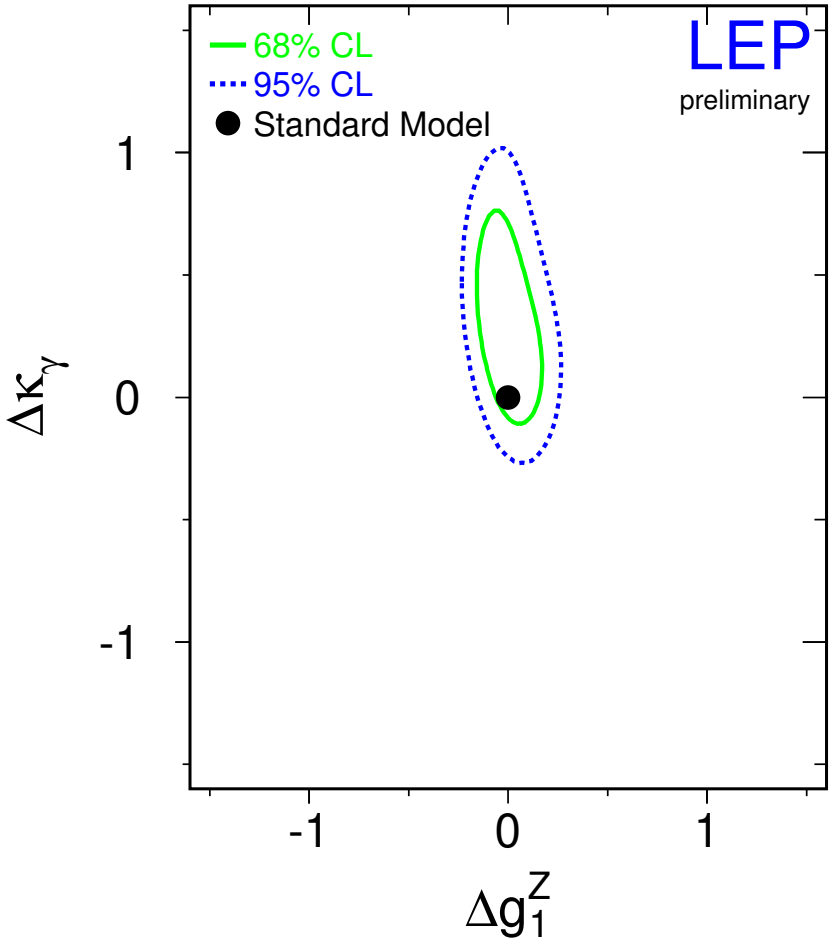

L3
preliminary
68% C.L.
sum
diff. cross section
total cross section
(a)
-ΔlnL
Δg_1^Z
3
2
1
0
-1
-0.5
0
0.5
1

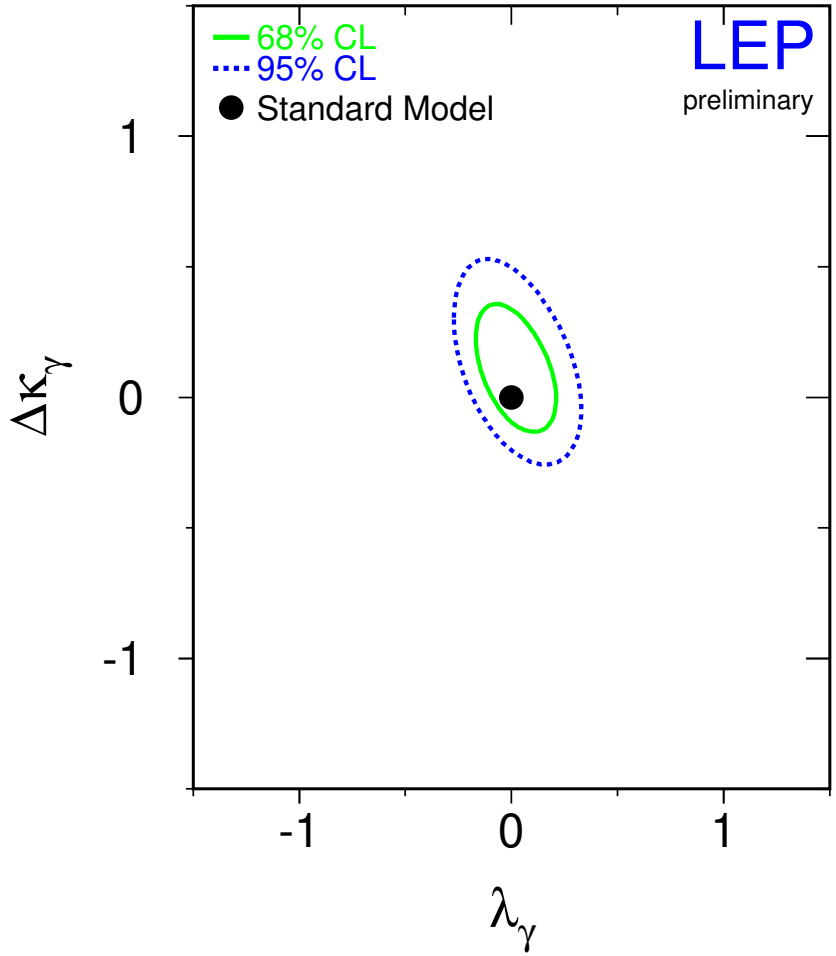

preliminary
DELPHI
$0.04^{+0.14}_{-0.14}$
L3
$-0.03^{+0.18}_{-0.16}$
OPAL
$-0.02^{+0.12}_{-0.11}$
LEP
$0.00^{+0.08}_{-0.08}$


preliminary
ALEPH
$-0.02^{+0.28}_{-0.33}$
DELPHI
$0.34^{+0.26}_{-0.28}$
L3
$0.16^{+0.40}_{-0.35}$
OPAL
$0.19^{+0.47}_{-0.37}$
LEP
$0.17^{+0.16}_{-0.16}$
D0
$-0.08^{+0.34}_{-0.34}$
LEP+D0
$0.13^{+0.14}_{-0.14}$


-ΔlnL
3
2
1
0
-0.4
-0.2
0
0.2
0.4
Δg_1^Z


-ΔlnL
3
2
1
0
-1
0
1
$\Delta\kappa_\gamma$


68% CL
95% CL
Standard Model
LEP
preliminary
1
0
-1
$\Delta\kappa_\gamma$
-1
0
1
Δg_1^Z


68% CL
95% CL
Standard Model
LEP
preliminary
1
0
-1
$\Delta\kappa_\gamma$
-1
0
1
λ_γ

Summary

Non abelian gauge theories require γ/Z-WW vertex

- experimental proof of the existence of the ZWW and the γWW vertex

- Measurement in three independent channels

  - single photon channel
  - single-W channel
  - W-pair production channel
  - $\Delta g_1^Z = 0.00 \pm 0.08$
  - $\Delta \kappa_\gamma = 0.13 \pm 0.14$
  - $\lambda_\gamma = -0.03 \pm 0.07$

- At the end of LEP II :

  error of Δg_1^Z, $\lambda_\gamma < 0.04$

Outlook

- short term : TEVATRON Run II

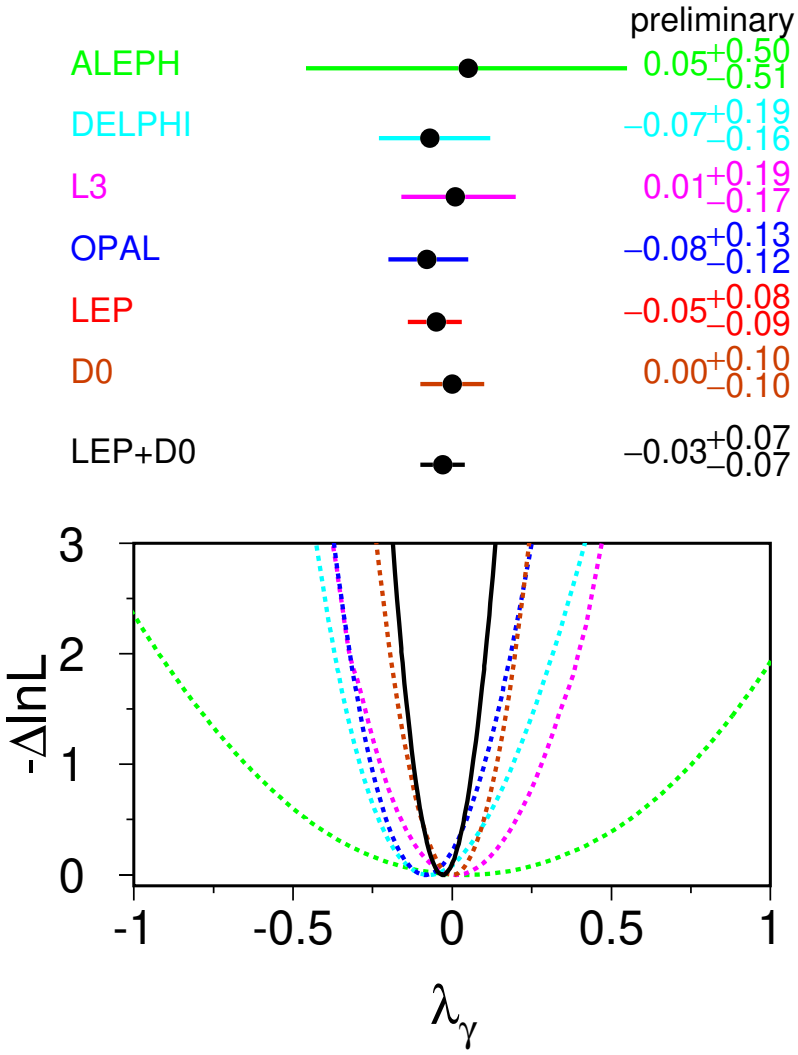
  $> 20\times$ luminosity $\Rightarrow$

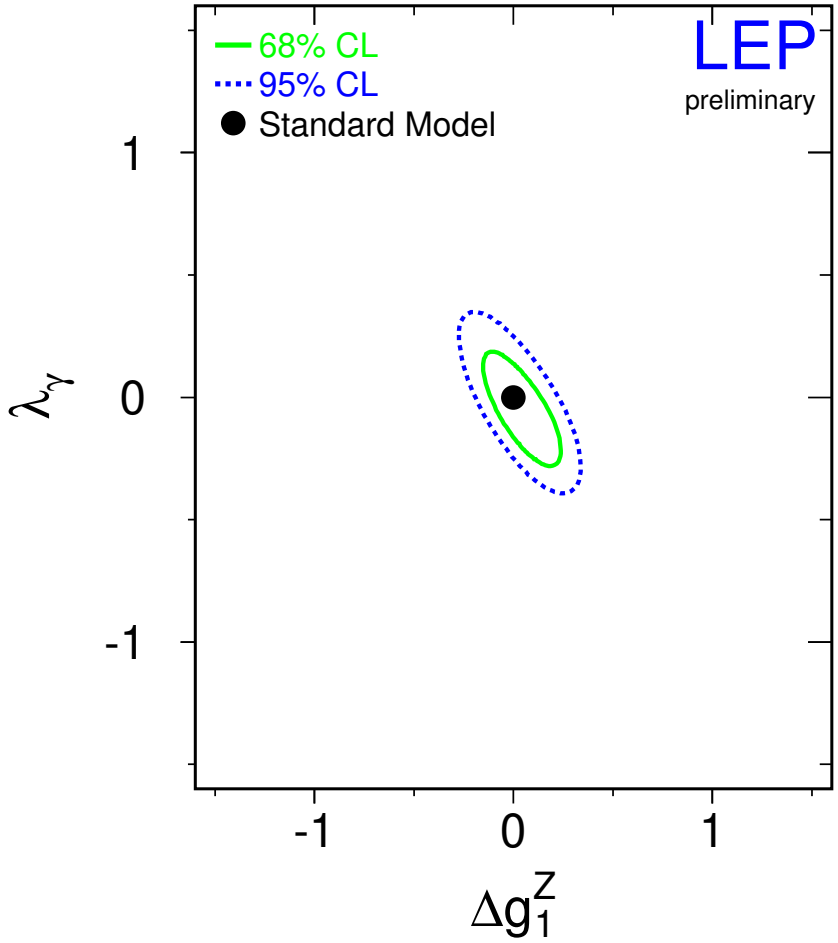
  $$|\Delta\kappa_\gamma| < 0.1,\ |\lambda_\gamma| < 0.03$$

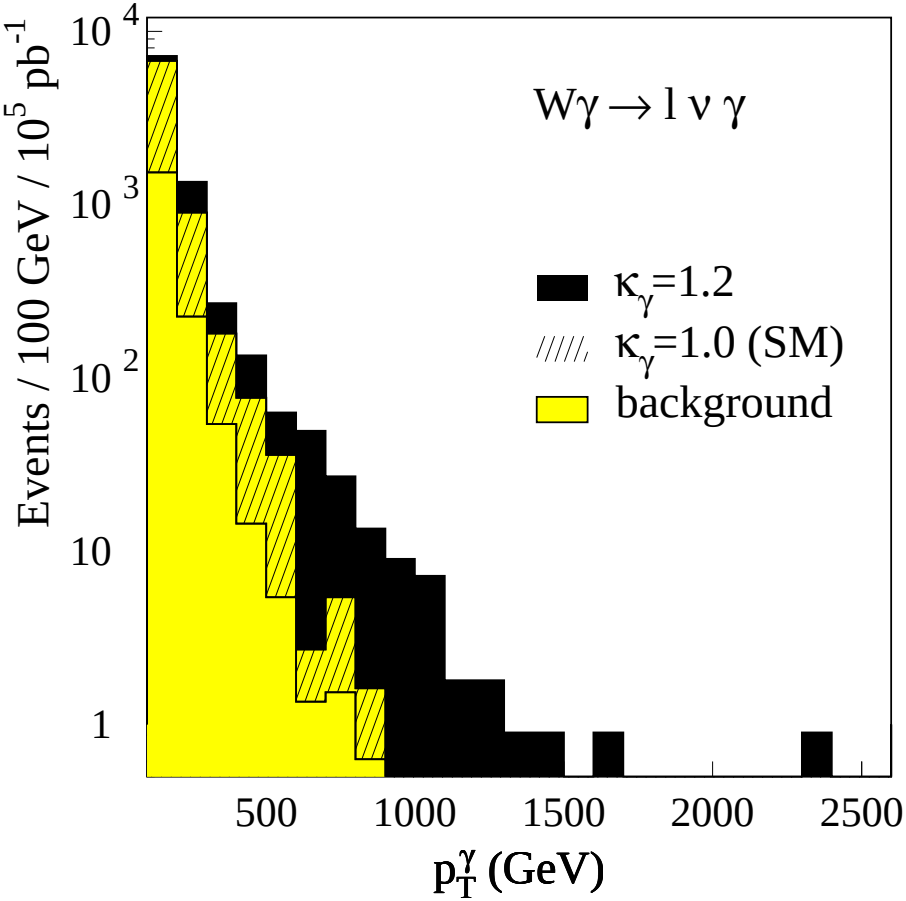
- long term :

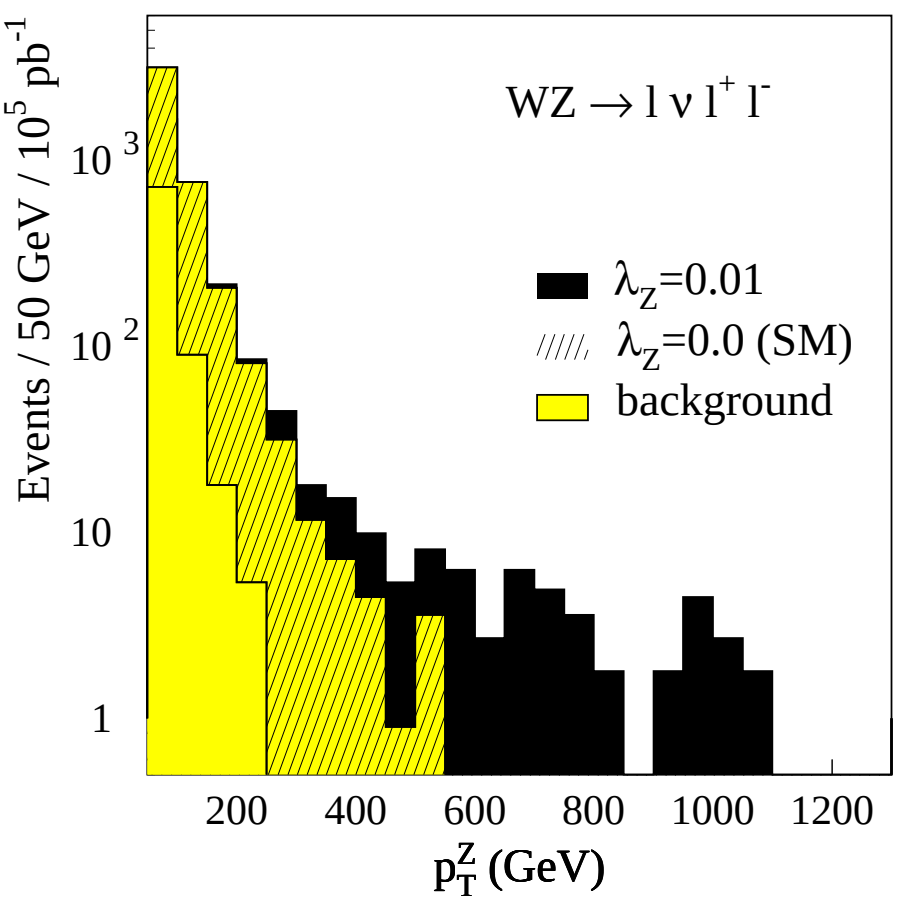
  – LHC $|\Delta\kappa_\gamma| < 0.04,\ |\Delta\kappa_Z| < 0.07,$
  $|\lambda_\gamma| < 0.0025,\ |\lambda_Z| < 0.005$

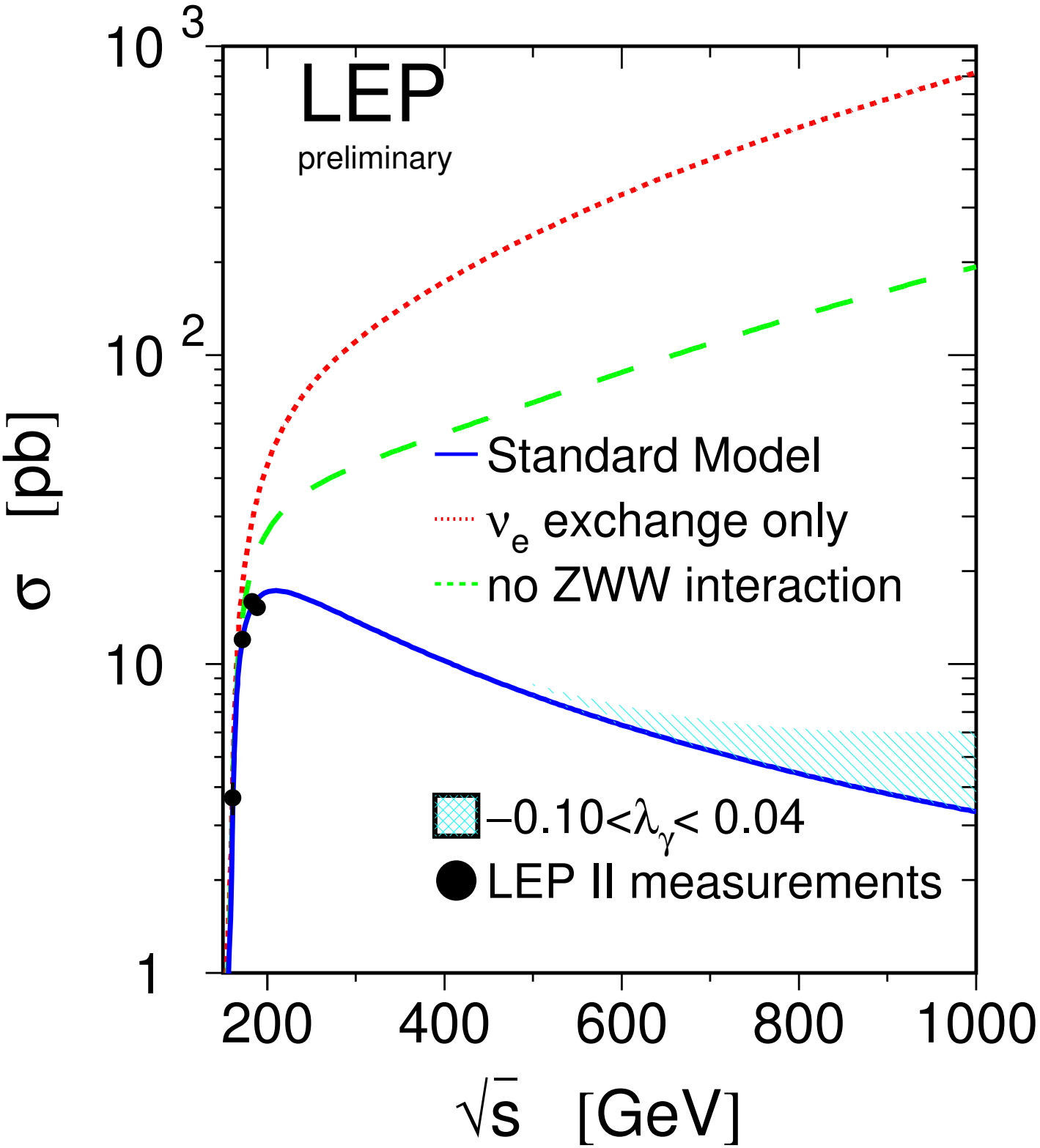
  – LC ?


preliminary
ALEPH
$0.05^{+0.50}_{-0.51}$
DELPHI
$-0.07^{+0.19}_{-0.16}$
L3
$0.01^{+0.19}_{-0.17}$
OPAL
$-0.08^{+0.13}_{-0.12}$
LEP
$-0.05^{+0.08}_{-0.09}$
D0
$0.00^{+0.10}_{-0.10}$
LEP+D0
$-0.03^{+0.07}_{-0.07}$
$-\Delta\ln L$
λ_γ

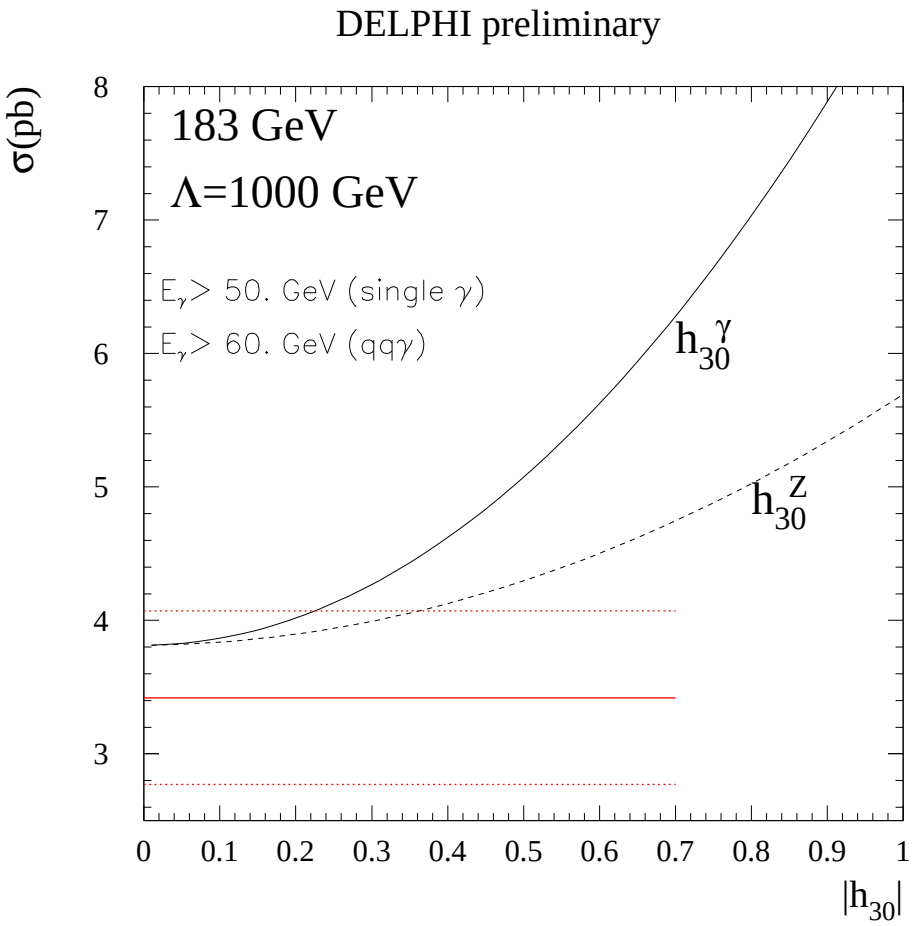

68% CL
95% CL
Standard Model
LEP
preliminary
λ_γ
Δg_1^Z

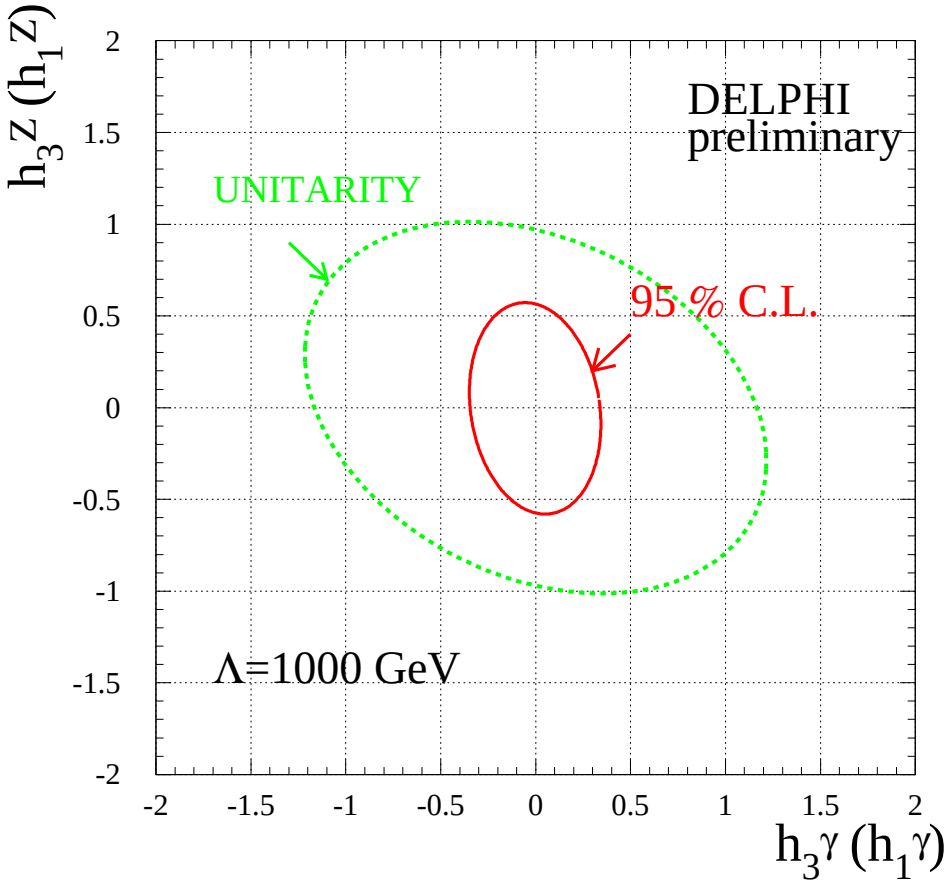
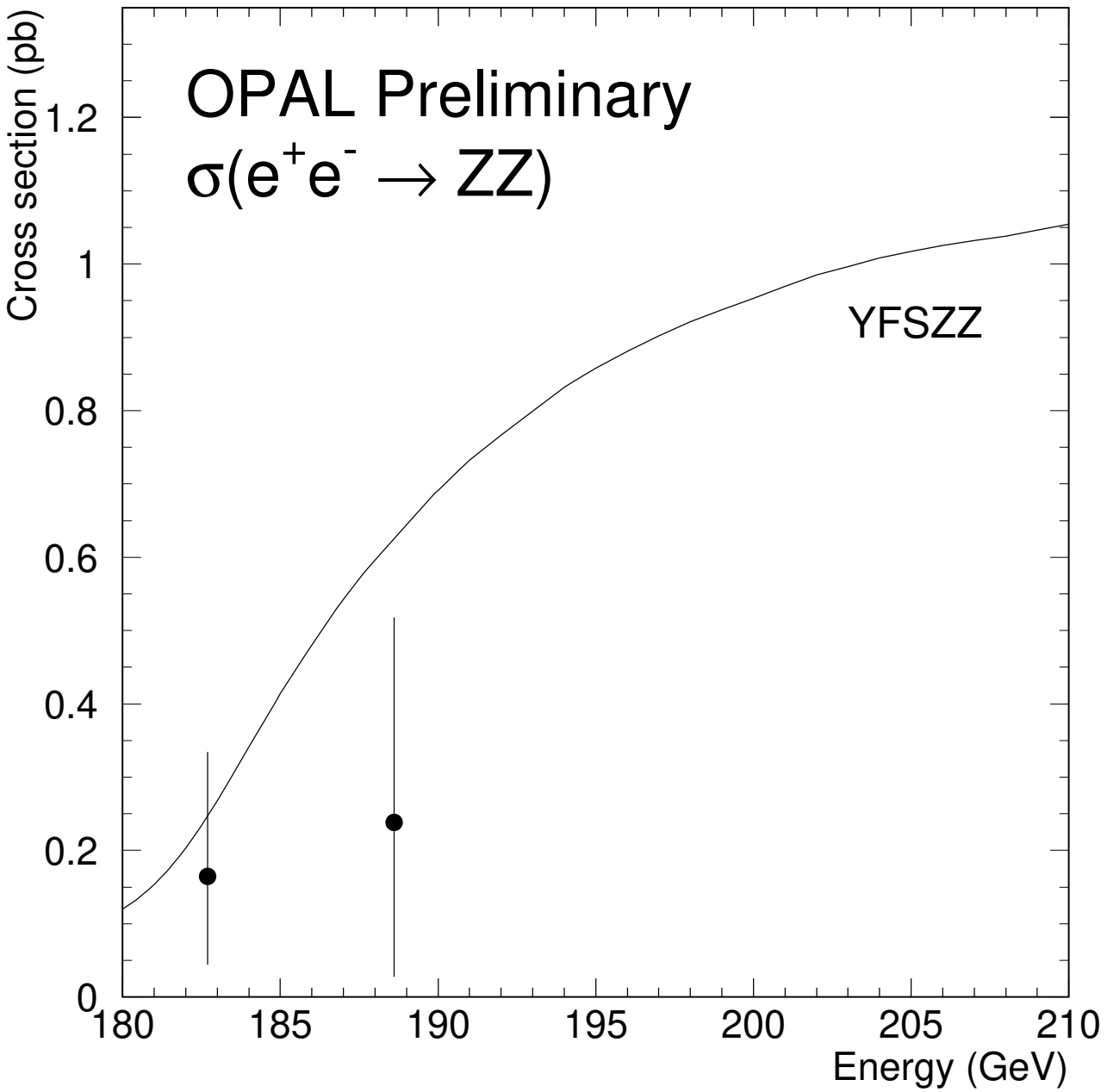

Wγ → l ν γ
κγ=1.2
κγ=1.0 (SM)
background
Events / 100 GeV / 10^5 pb^-1
p_T^γ (GeV)


WZ → l ν l+ l-
λZ=0.01
λZ=0.0 (SM)
background
Events / 50 GeV / 10^5 pb^-1
p_T^Z (GeV)


LEP
preliminary
Standard Model
ν_e exchange only
no ZWW interaction
$-0.10<\lambda_\gamma<0.04$
LEP II measurements
10^3
10^2
10
1
200
400
600
800
1000
σ [pb]
$\sqrt{s}$ [GeV]

Couplings at LC


DELPHI preliminary
σ(pb)
183 GeV
Λ=1000 GeV
E_γ> 50. GeV (single γ)
E_γ> 60. GeV (qqγ)
h30γ
h30Z
|h30|


h3Z (h1Z)
DELPHI
preliminary
UNITARITY
95 % C.L.
Λ=1000 GeV
h3γ (h1γ)

ZZ production