W and Z Pair Production at LEP2

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Outline:

- ✓ Data Sample
- ✓ WW Production (including *Branching Ratios, V_{cs}, Differential Cross Section*)
- ✓ WWγ Production
- ✓ ZZ Production
- ✓ Conclusions

Data Sample

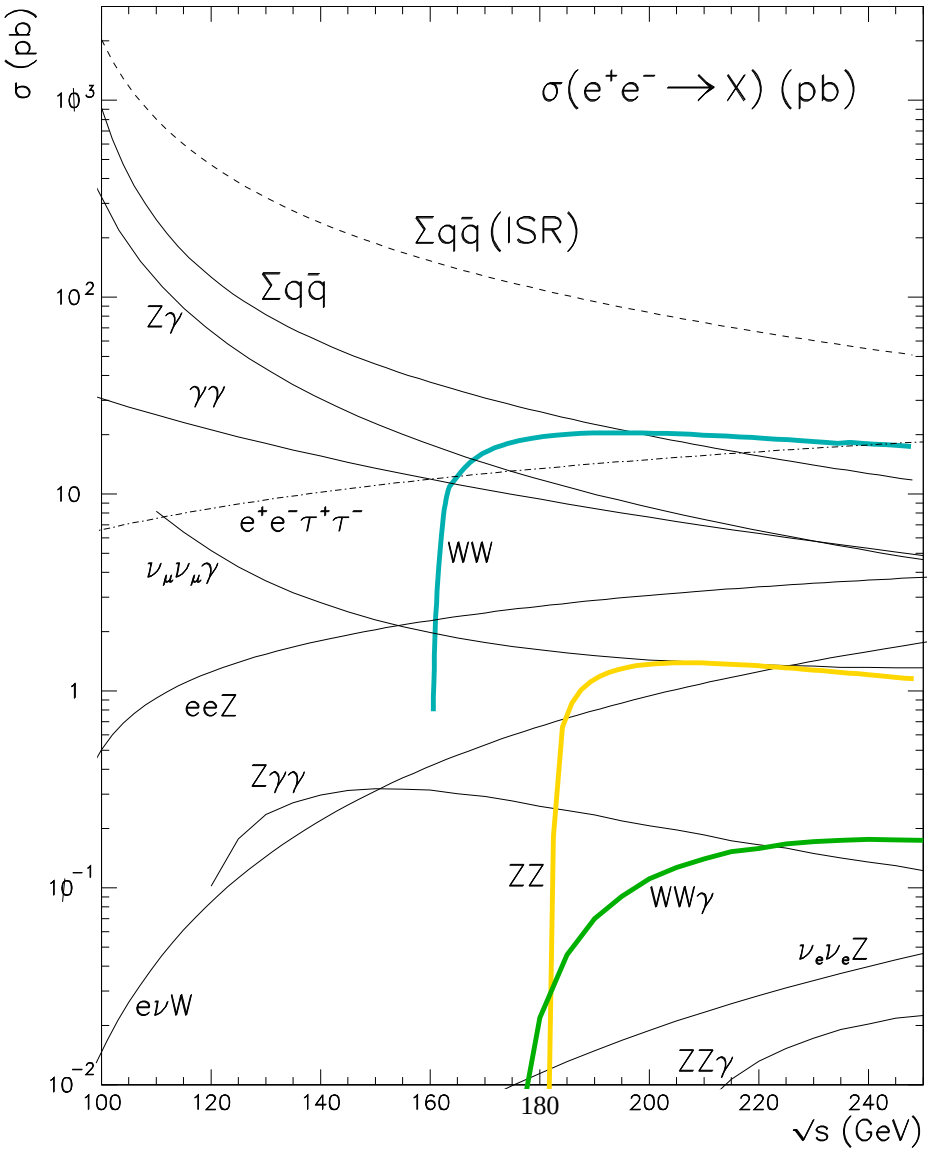
Year	$\sqrt{s}$ (GeV)	Luminosity ($\mathcal{L}$) (pb^{-1}/exp.)
1996	161	10
	172	10
1997	183	55
1998	189	160
1999	192	25
	196	75
	200	85
	202	40
2000	205	85
	207	140
Total		685

Total sample of selected events @ LEP:

$\sim$ 40000 WW

$\sim$ 400 WWγ

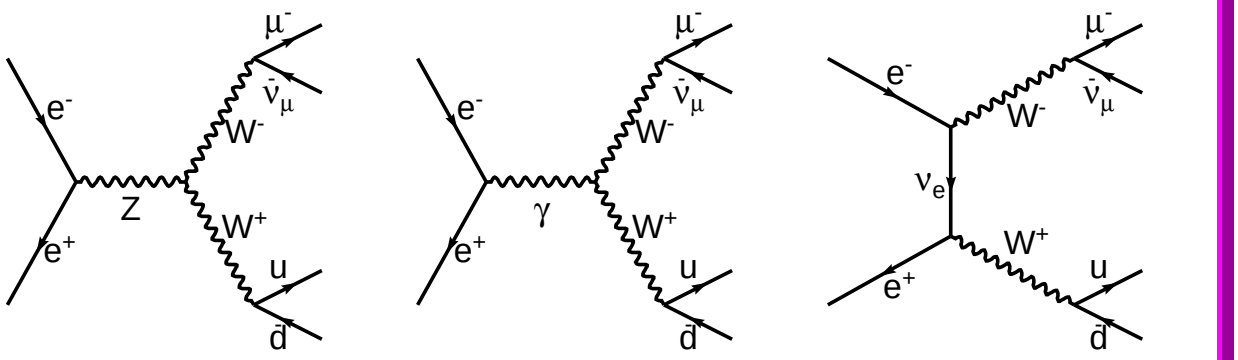
$\sim$ 1000 ZZ



WW Production

Born level diagrams for W pairs production @ LEP:

CC03 *diagrams*



Measured cross-sections are combined @ CC03 level including *Initial State radiation*.

Complete Electroweak theoretical $O(\alpha)$ corrections for $4f$ states is not available yet. Problem partially solved considering only

$O(\alpha)$ corrections affecting two resonant W bosons

$\longrightarrow$ *"Double Pole Approximation" (DPA)*

- ✓ Theoretical accuracy on $\sigma_{WW} \sim 0.5\%$.
- ✓ DPA effects: up to 1% on differential distributions.

WW: selections

Events are classified

in 10 different

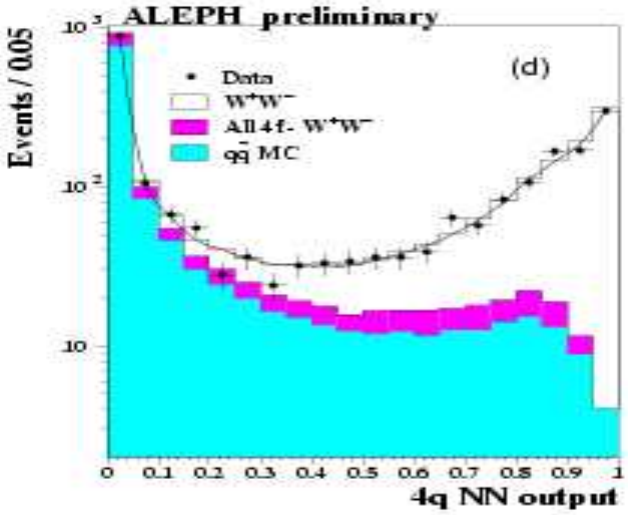
final states topologies:

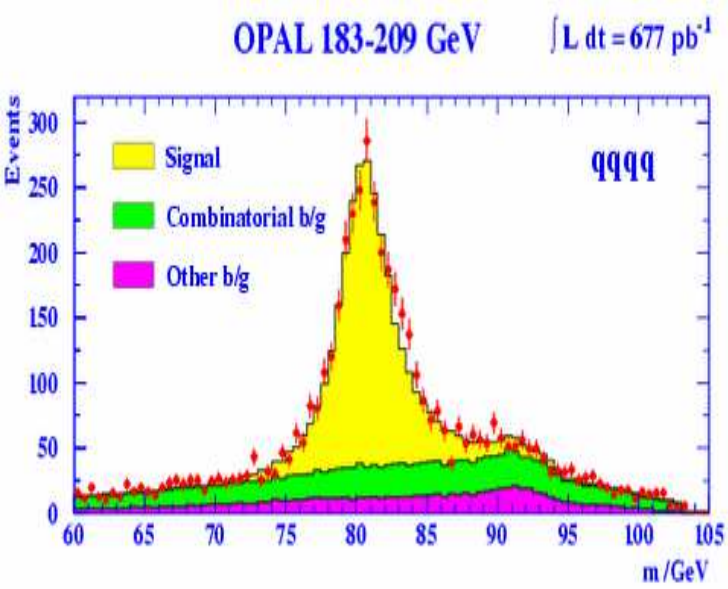
6-$\ell\nu\ell\nu(\gamma)$:	$e\nu e\nu(\gamma)$ $e\nu\mu\nu(\gamma)$ $e\nu\tau\nu(\gamma)$ $\mu\nu\mu\nu(\gamma)$ $\mu\nu\tau\nu(\gamma)$ $\tau\nu\tau\nu(\gamma)$	$\Longrightarrow$10.6%
3-$qq\ell\nu(\gamma)$:	$qqe\nu(\gamma)$ $qq\mu\nu(\gamma)$ $qq\tau\nu(\gamma)$	$\Longrightarrow$43.8%
1-$qqqq(\gamma)$:		$\Longrightarrow$45.6%

WARNING ! ! !

Measured cross-sections are extrapolated
to CC03 level.
In particularly, concerning $qqe\nu(\gamma)$ and $\ell\nu\ell\nu(\gamma)$ selections,
the correction to be applied is not
negligible (up to 10%).

WW: $qqqq(\gamma)$ selection





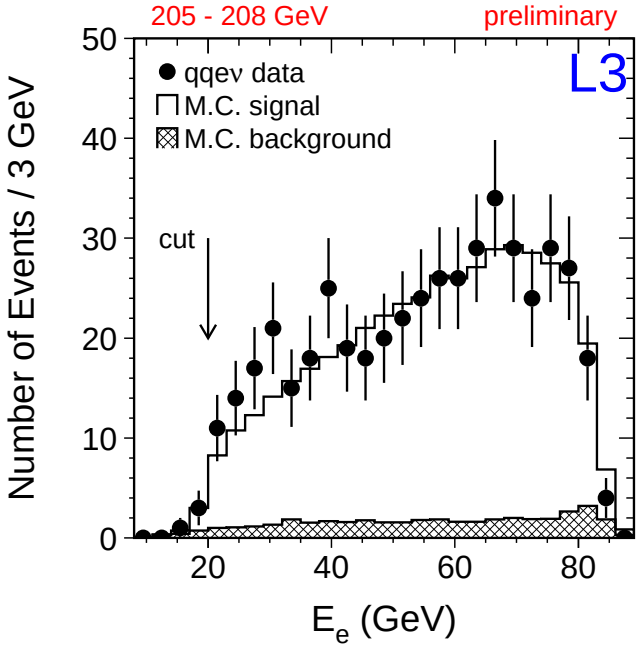
- ✓ 4 jets
- ✓ very low missing energy
- ✓ pairing
- ✓ major contamination comes from $q\bar{q}$ (γ) background

Due to the high background contamination, the so-called *cut-based* analyses have low efficiency:

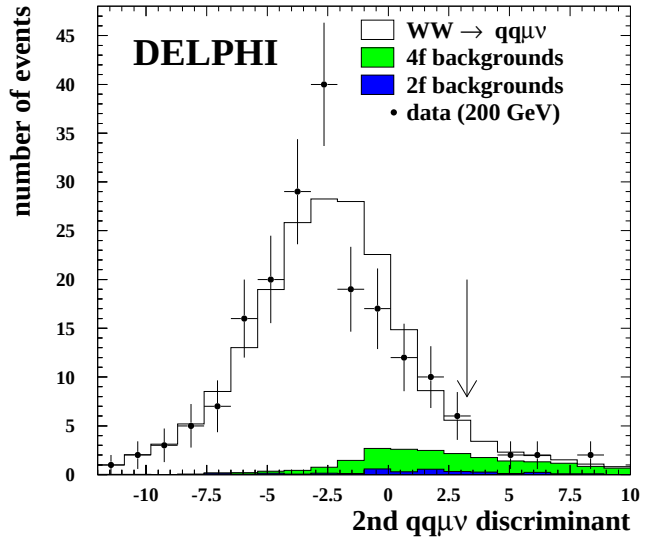
- ✓ neural network
- ✓ likelihood output

Typical efficiency	$\sim 85\%$
Typical accepted background	$\sim 1.5pb$
Typical # of sel. evt./exp.	~ 6000

WW: $qqe\nu(\gamma)$ *and* $qq\mu\nu(\gamma)$ *selections*



- ✓ 1 high energy lepton (e,μ)
- ✓ missing energy
- ✓ 2 jets
- ✓ constraint applied on invariant masses M_{qq},$M_{e\nu}$ ($M_{\mu\nu}$) $\sim M_W$
- ✓ major contamination comes from $q\bar{q}$ (γ) background

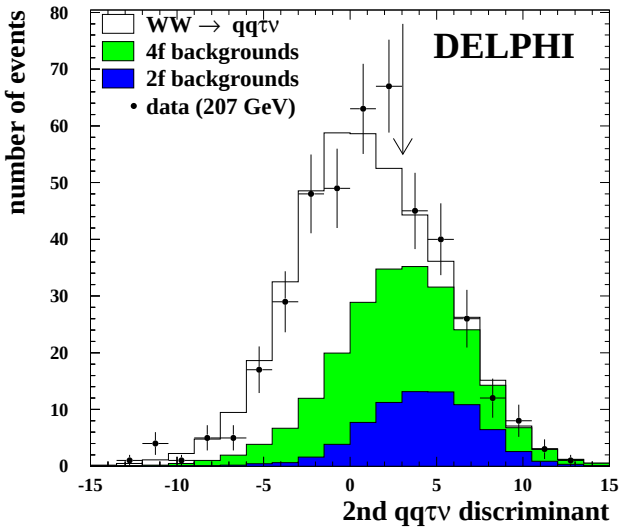


Typical efficiency $\sim 80\%$

Typical accepted background $\sim 150\,fb$

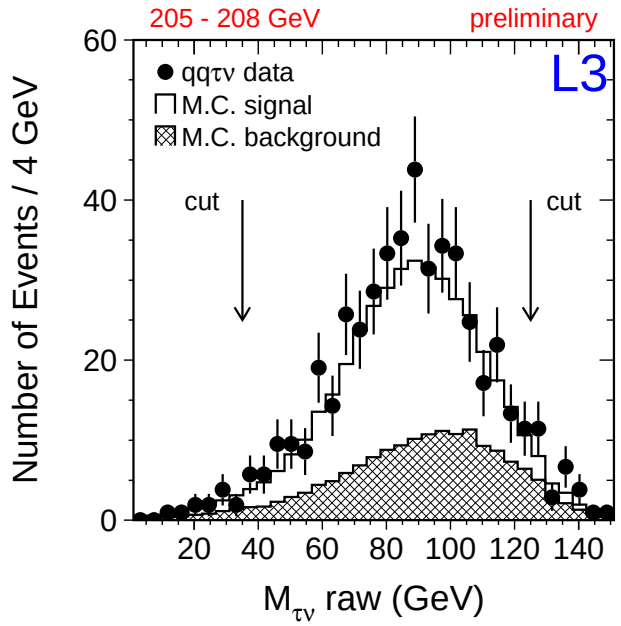
Typical # of sel. evt./exp. ~ 1500

WW: $qq\tau\nu(\gamma)$ selection



- ✓ 2 hadronic jets + 1 low-multiplicity jet or 1 lepton (e,μ)
- ✓ missing energy
- ✓ constraint on invariant masses M_{qq},$M_{\tau\nu} \sim M_W$
- ✓ major contamination comes from $q\bar{q}$ (γ) background

τ jet identification is crucial !

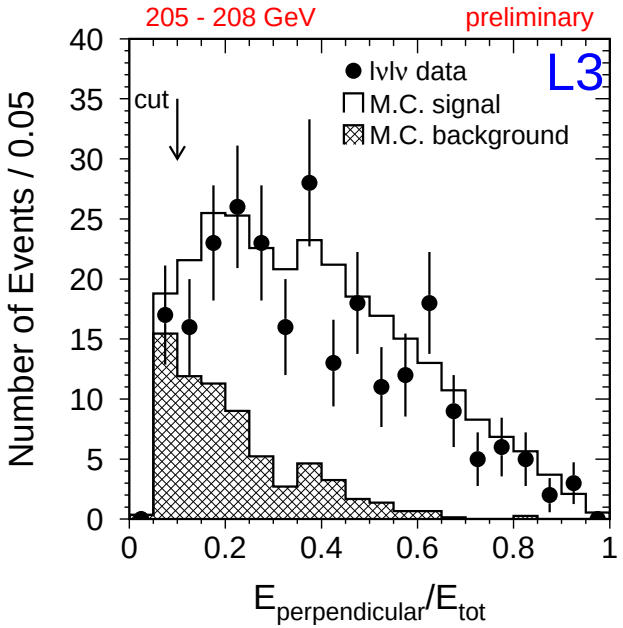


Typical efficiency $\sim 60\%$

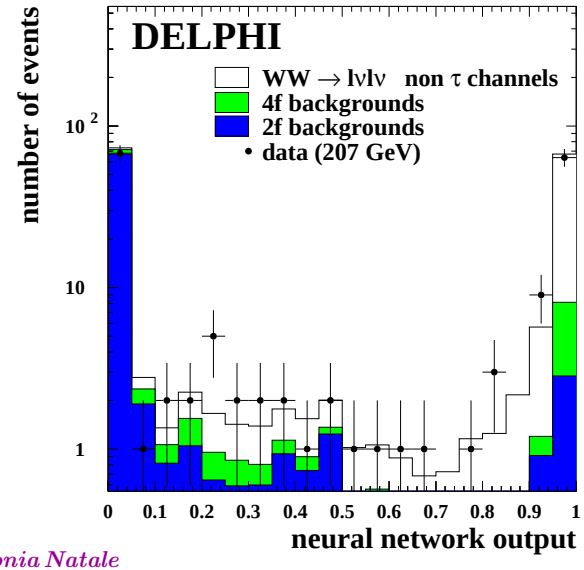
Typical accepted background $\sim 250 fb$

Typical # of sel. evt./exp. ~ 1500

WW: $\ell\nu\ell\nu(\gamma)$ selection



- ✓ 2 high energy and acoplanar leptons
- ✓ high missing energy
- ✓ 6 different topologies:
  ee, $e\mu$, $e\tau$, $\mu\mu$, $\mu\tau$, $\tau\tau$
- ✓ major contamination comes from:
  $e^+e^- \to e^+e^-\ell^+\ell^-\ (\gamma)$
  $e^+e^- \to \ell^+\ell^-\ (\gamma)$
  backgrounds



Typical efficiency $\sim 60 - 80\%$

Typical accepted backgr. $\sim 100 - 200\,fb$

Typical # of sel. evt./exp. ~ 800

Cross-section measurement

Combined fit (*likelihood*) *to all channels* $WW \rightarrow ffff$

$$\mathcal{L} = \prod_i \mathcal{P}(N_i, \mu_i)$$

	$\mathcal{P}$	Poissonian probability distribution
where:	N_i	number of observed events in channel i
	μ_i	number of expected events in channel i

$$\mu_i = \left(\sum_j \varepsilon_{ij}\sigma_j + \sigma_i^{bg} \right) \cdot \text{lumi}$$

	j	=	process
	ε_{ij}	=	efficiency matrix
where:	σ_j	=	cross-section of process j (to be measured)
	σ_i^{bg}	=	non–WW accepted background in process i
	lumi	=	integrated luminosity

✓ All known ***systematics*** effects are taken into account

✓ ***Double counting*** of selected events is avoided

✓ ***General method*** for WW, WWγ and ZZ cross-section

....more fits (only for W)

Fit to *Branching fraction* and to σ_{WW}:

replace σ_j with $r_i\sigma_{WW}$ where:

$$\begin{array}{rll} r_i= & BR(W\to qq)^2 & \text{for } i=qqqq \\ = & 2\cdot BR(W\to qq)BR(W\to \ell\nu) & \text{for } i=qq\ell\nu \\ = & BR(W\to \ell\nu)^2 & \text{for } i=\ell\nu\ell\nu \\ & 2\cdot BR(W\to \ell\nu)BR(W\to \ell'\nu') & \text{for } i=\ell\nu\ell'\nu' \end{array}$$

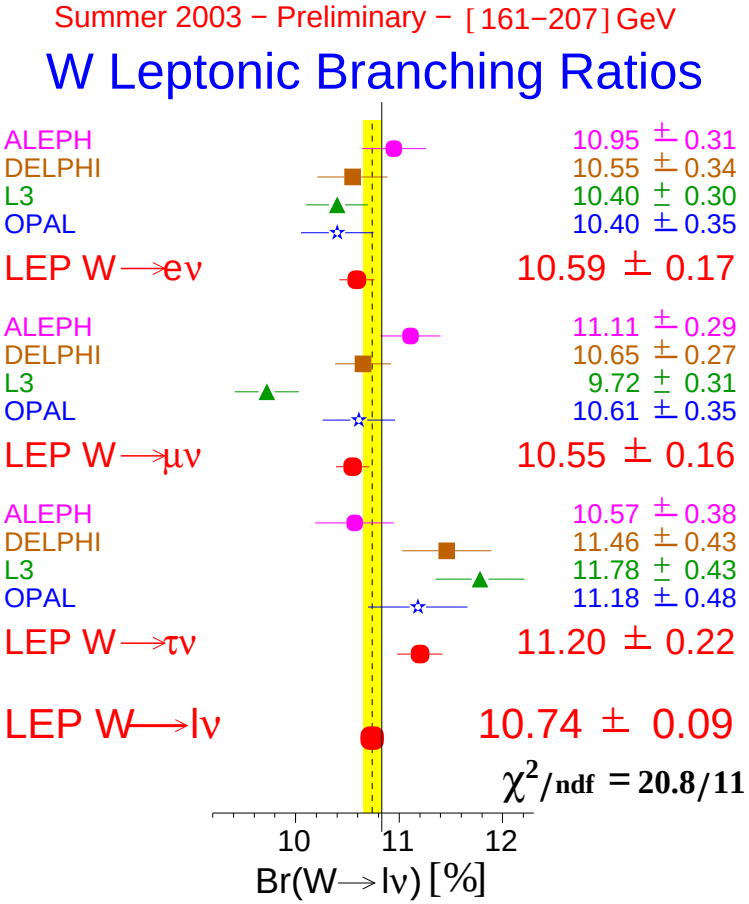
Fit imposing the *Lepton Universality*:

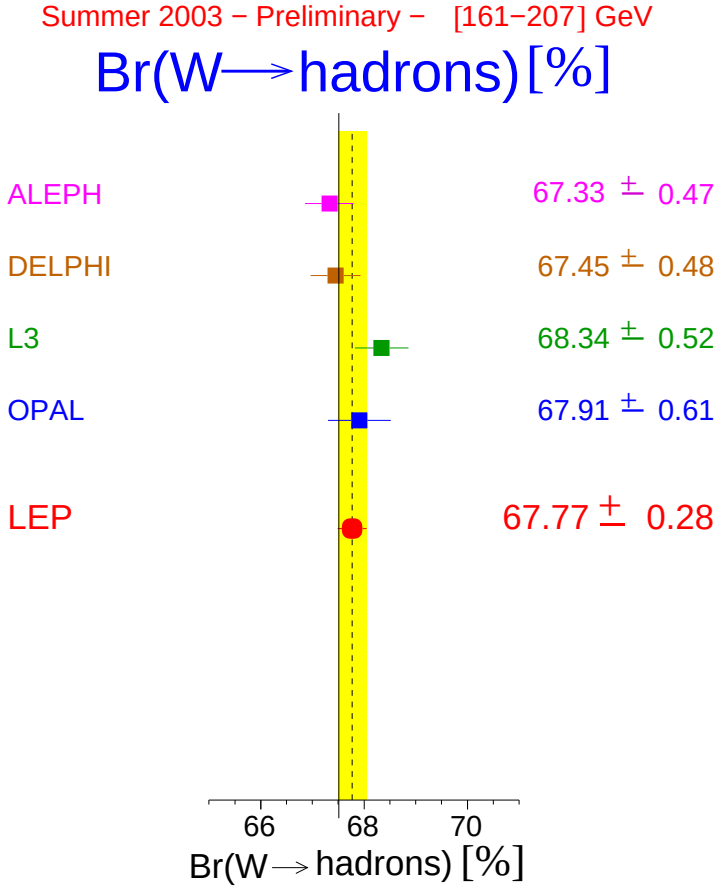
replacing $BR(W\to e\nu)$, $BR(W\to \mu\nu)$ and $BR(W\to \tau\nu)$ with a single $BR(W\to \ell\nu_\ell)$

Fit fixing BR's as from *Standard Model*:

replace r_i by correspondent ones from Standard Model and leave σ_{WW} as the only free parameter

WW: Branching Fraction Measurements





- ✓ Errors contain both ***statistical*** and ***systematic*** components.
- ✓ For hadronic BR's: $0.18(stat.)\% \oplus 0.22(syst.)\%$.
- ✓ An improved treatment of ***hadronization processes*** and ***comprehension of detector***, should reduce systematics up to 0.10% - 0.15%.

WW: $|V_{CS}|$ Measurement

Using the equation:

$$\frac{\mathrm{BR}(W \to qq)}{1 - \mathrm{BR}(W \to qq)} = \left(1 + \frac{\alpha_s(M_W^2)}{\pi}\right) \sum |\mathrm{V}_{ij}^{CKM}|^2$$

together with $\alpha_s = (0.119 \pm 0.002)$

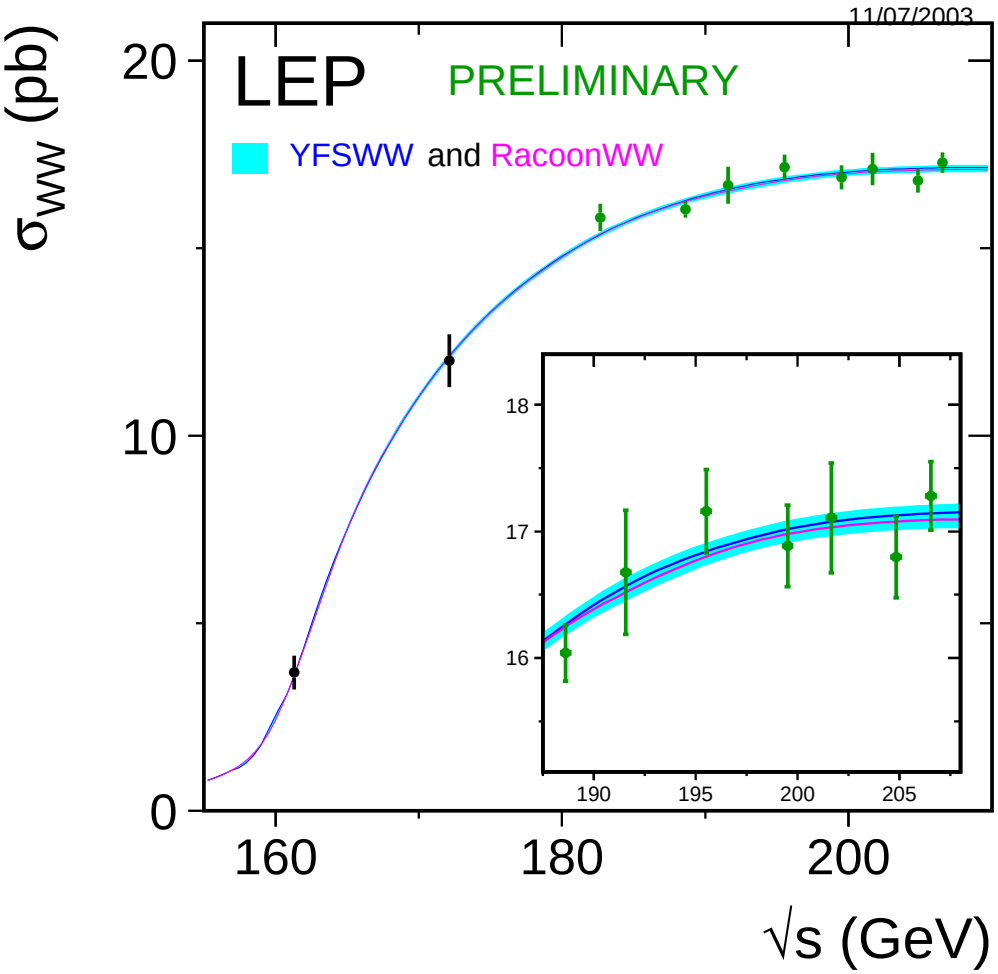
$$\sum |\mathrm{V}_{ij}^{CKM}|^2 = 2.026 \pm 0.026$$

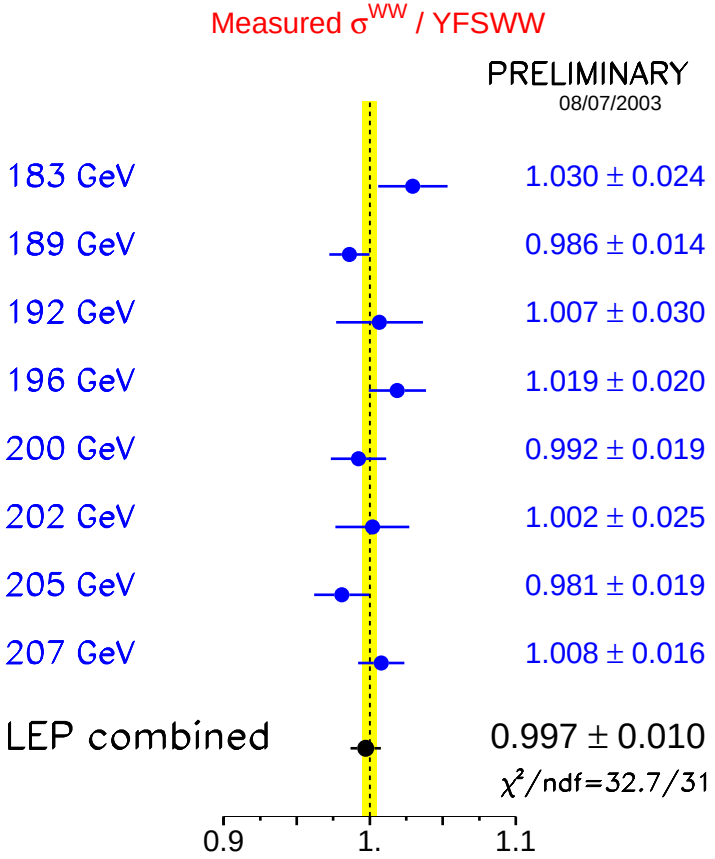
$|V_{CS}|$ is extracted fixing all the other ***CKM matrix*** elements to their measured values:

$$|V_{CS}| = 0.989 \pm 0.014$$

no assumption of Unitarity is required

WW Cross-Section

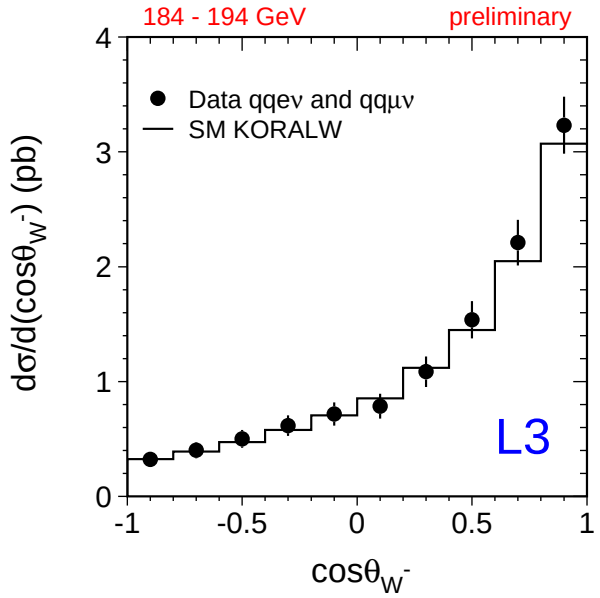


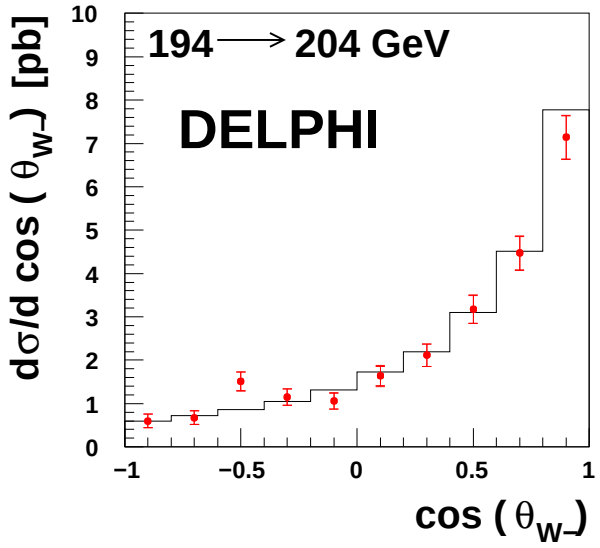


RacoonWW and YFSWW3 predictions are calculated using the Double Pole Approximation

Total systematical uncertainty ∼0.15% on R (mostly hadronization effects)

WW: $\cos(\theta_W)$ differential distribution





More information could be extracted from differential distributions.

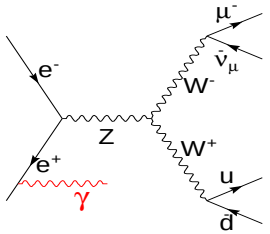
The signal definition, based on clean channels, is chosen as to minimize extrapolation in undetected phase space regions:

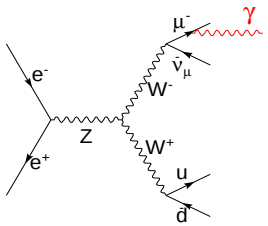
- ✓ Only $qq(e,\mu)\nu$ events are used
- ✓ $\theta_\ell > 20°$ w.r.t. beam axis
- ✓ Final state photons recombined with parent fermion
- ✓ No unfolding yet but bin-to-bin efficiency and background corrections

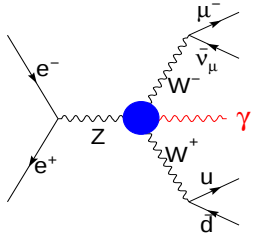
Combination will come soon!

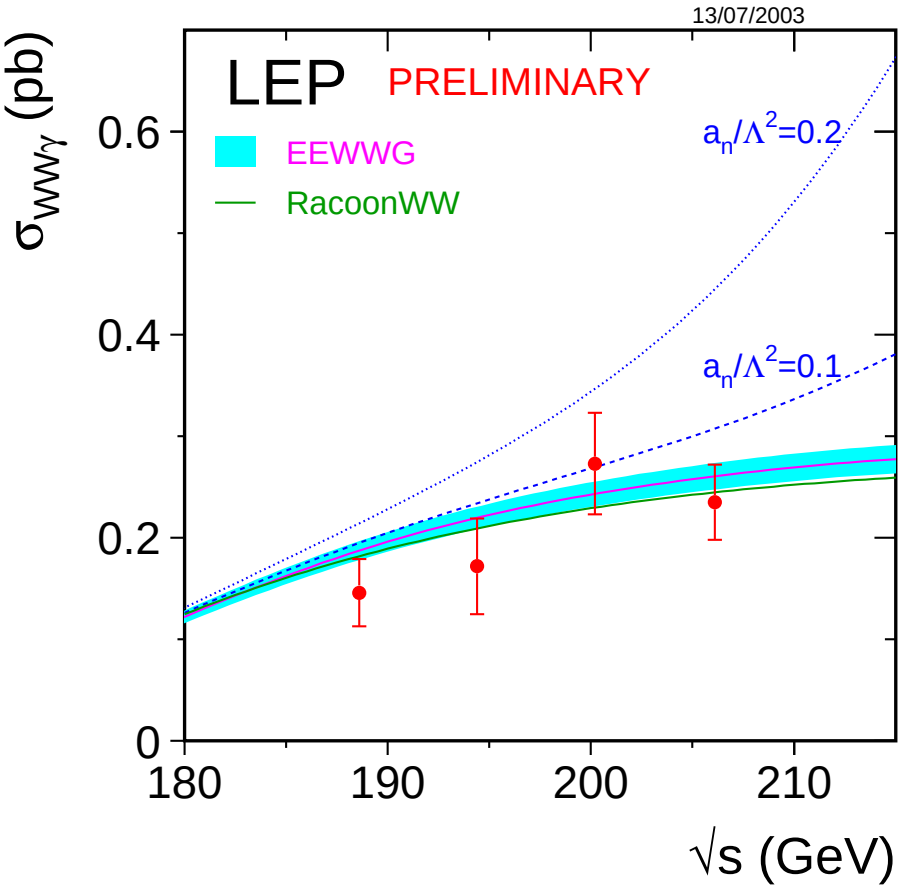
$WW\gamma$ Production

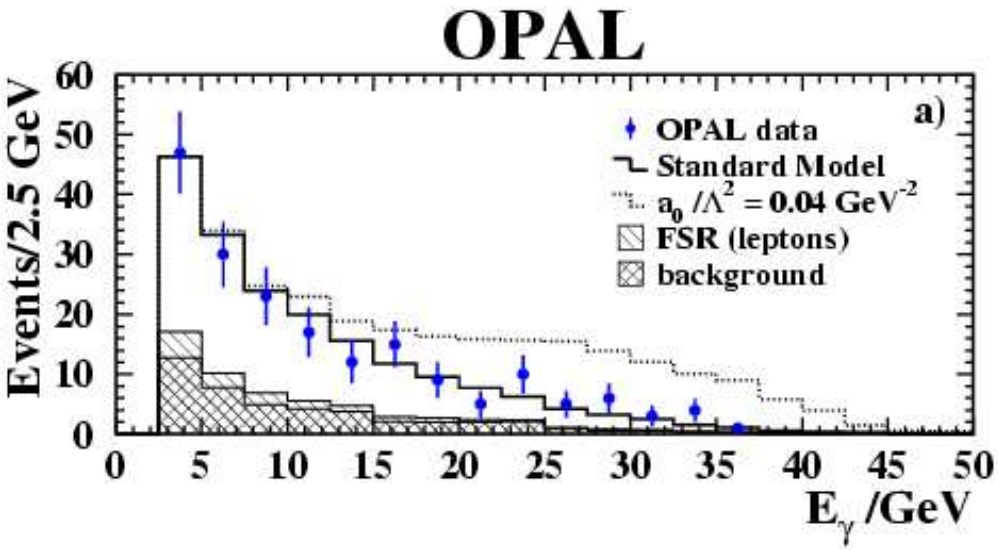
Detection of an additional final-state photon is required:

ISR: 

FSR: 

Quart. Gauge Coupl.: 



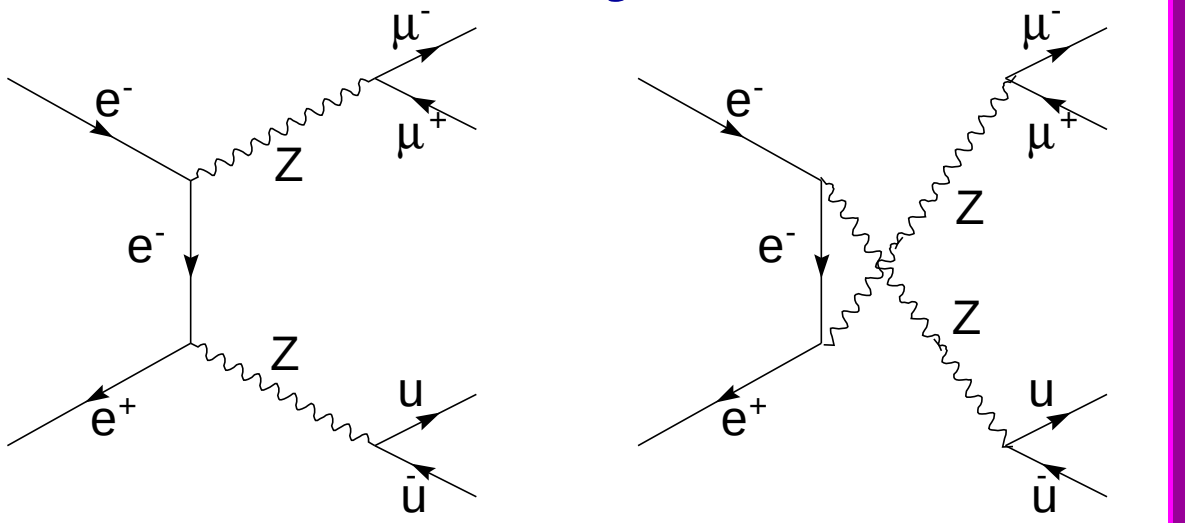


Only DELPHI, L3 and OPAL results are combined!

ZZ Production

Born level diagrams for Z pairs production @ LEP:

NC02 *diagrams*



Measured cross-sections are combined @ NC02 level including *Initial State radiation*.

✓ Theoretical accuracy $\sim 2\%$.

ZZ: selections

Events are classified in 12 different final states topologies:

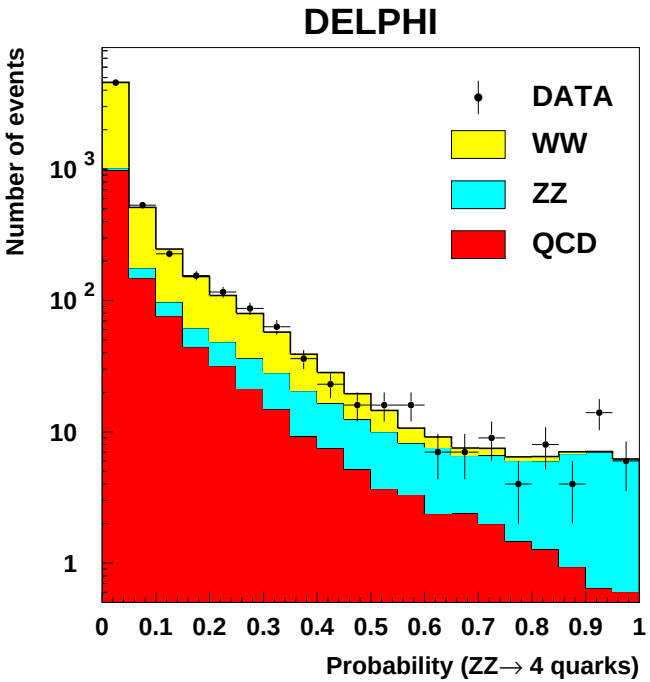
6-$\ell\ell\ell\ell(\gamma)$:	$eeee(\gamma)$ $ee\mu\mu(\gamma)$ $ee\tau\tau(\gamma)$ $\mu\mu\mu\mu(\gamma)$ $\mu\mu\tau\tau(\gamma)$ $\tau\tau\tau\tau(\gamma)$	$\Longrightarrow$1%
3-$\ell\ell\nu\nu(\gamma)$:	$ee\nu\nu(\gamma)$ $\mu\mu\nu\nu(\gamma)$ $\tau\tau\nu\nu(\gamma)$	$\Longrightarrow$4%
1-$q\bar{q}\ell\ell(\gamma)$:	$q\bar{q}ee(\gamma)$ $q\bar{q}\mu\mu(\gamma)$ $q\bar{q}\tau\tau(\gamma)$ where $Q = x, x, x$	$\Longrightarrow$14%
1-$q\bar{q}\nu\nu(\gamma)$:	$q\bar{q}\nu\nu(\gamma)$ where $Q = x, x$	$\Longrightarrow$28%
1-$q\bar{q}q\bar{q}(\gamma)$:	$q\bar{q}q\bar{q}(\gamma)$ where $Q = x, x$	$\Longrightarrow$49%

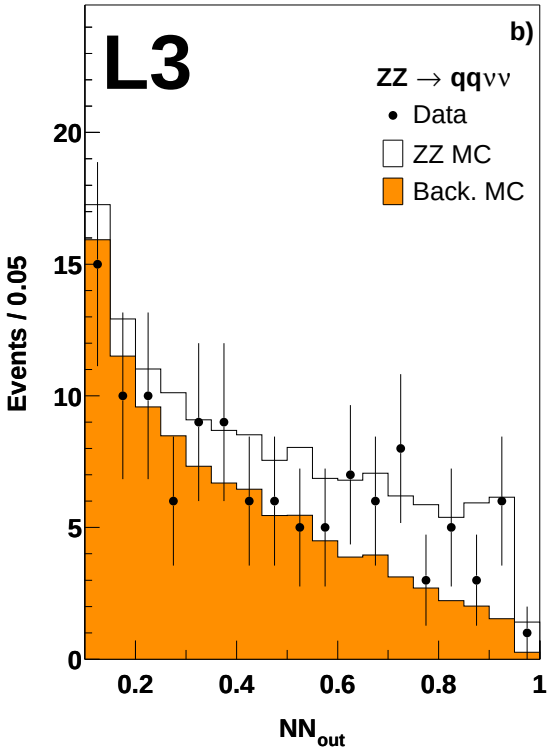
WARNING ! ! !

✓ Low signal cross-section w.r.t. the dominant background makes the selection not easy.

✓ In order to improve signal/background ratio multi-dimensional techniques are used.

ZZ: $q\bar{q}q\bar{q}(\gamma)$, $q\bar{q}\nu\nu(\gamma)$ selections





$q\bar{q}q\bar{q}(\gamma)$ Topology:

✓ 4 jets

Main Bkg:

✓ WW

✓ $q\bar{q}gg$

$q\bar{q}\nu\nu(\gamma)$ Topology:

✓ 2 jets

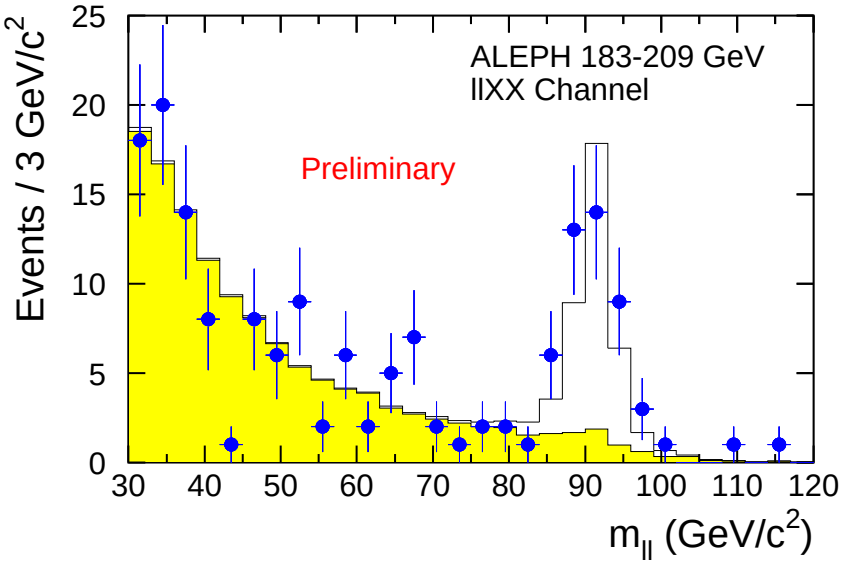
✓ missing energy

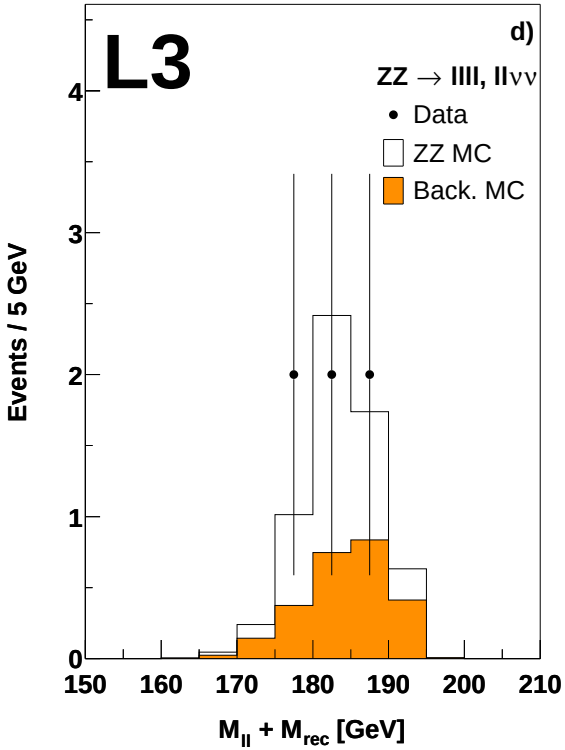
Main Bkg:

✓ $q\bar{q}(\gamma)$

✓ $q\bar{q}\ell\nu$

ZZ: $q\bar{q}\ell\ell(\gamma)$ and $\ell\ell\nu\nu(\gamma)$ + $\ell\ell\ell\ell(\gamma)$ selections





$q\bar{q}\ell\ell(\gamma)$ Topology:
- ✓ 2 jets
- ✓ 2 leptons

Main Bkg:
- ✓ $q\bar{q}\ell\nu$
- ✓ $Z\gamma$

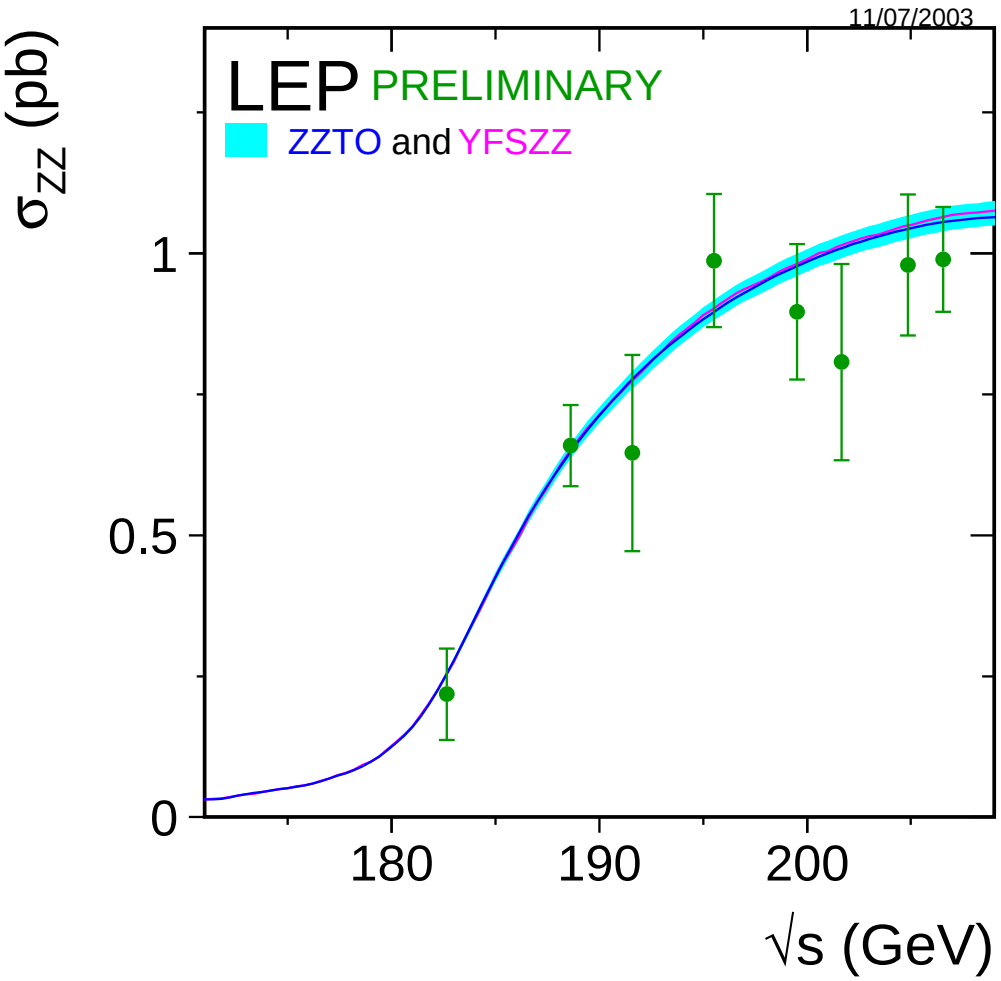
$\ell\ell\nu\nu(\gamma)$ Topology:
- ✓ 2 leptons
- ✓ missing energy

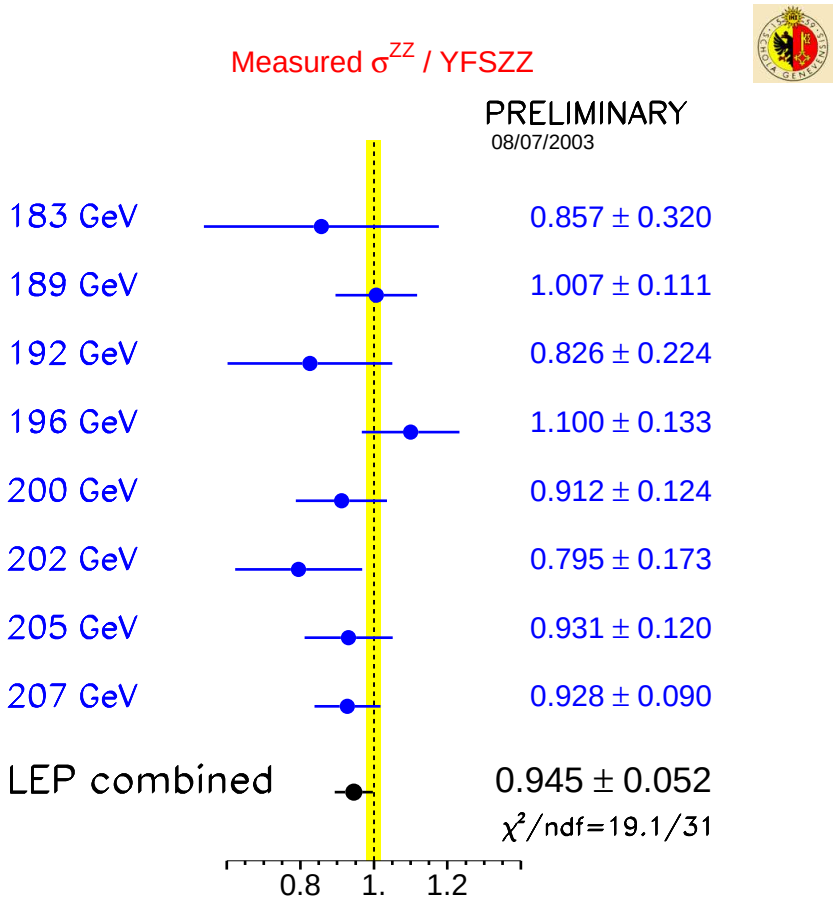
Main Bkg:
- ✓ $\ell\ell(\gamma)$

$\ell\ell\ell\ell(\gamma)$ Topology:
- ✓ 4 leptons

Main Bkg:
- ✓ $\ell\ell(\gamma)$
- ✓ $Z\gamma$

ZZ Cross-Section





ZZTO and YFSZZ are used to calculate cross-section predictions

Uncertainty is around 2%

LEP2 Analyses Status

	ALEPH	*DELPHI*	*L3*	*OPAL*
WW	preliminary	ready	preliminary	preliminary
$d\sigma/dcos\theta$	to be done	ready	preliminary	to be done
BR_W	preliminary	ready	preliminary	preliminary
$WW\gamma$	no	ready	ready	ready
ZZ	preliminary	ready	ready	ready

Conclusions

✓ **The full LEP2 *energy range* $\sqrt{s} = 161 - 209$ GeV has been analyzed.**

✓ ***WW*, *WW*γ and *ZZ* *cross sections* have been measured.**

✓ ***W* *Branching Fractions* measurement and V_{cs} extraction have also been performed.**

✓ **All *results* are in good agreement with the Standard Model predictions.**

✓ **Some *analyses* are still in progress.**

✓ **Final *combinations* are foreseen to come soon.**