Measurement of the W Boson Mass at LEP

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Overview:

❶ **The Standard Model**

❷ **The LEP Project**

❸ **The OPAL experiment**

❹ **W-Physics at LEP**

❺ **Measurement of the W-boson Mass**

❻ **Outlook and Conclusions**

❶ Standard Model

FERMIONS : spin $\frac{1}{2}$

leptons — **Charge**

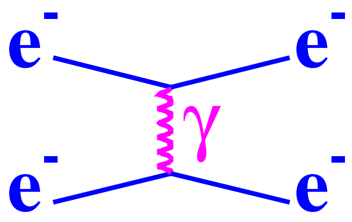
$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \qquad \begin{matrix} -1 \\ 0 \end{matrix}$$

quarks — e.g. proton (uud)

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{matrix} +\frac{2}{3} \\ -\frac{1}{3} \end{matrix}$$

+ anti-particles

Fermion interactions = exchange of spin 1 bosons



BOSONS : spin 1

		Mass	Force
Photon	γ	0	Electromagnetic
W-boson	$W^{\pm}$	91.2 GeV	Weak (CC)
Z-boson	Z^0	80.3 GeV	Weak (NC)
Gluon	g	0	Strong (QCD)

Electroweak Unification

Unification of electro-magnetic and weak forces

SU$(2)_L \otimes$U(1) Symmetry (local gauge invariance)

$$\begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix} B \rightarrow \begin{pmatrix} W^+ \\ Z^0 \\ W^- \end{pmatrix} \gamma$$

Physical Fields : Z^0, A (photon)

$$\begin{aligned} \mathrm{Z}^0{}_\mu &= W^0_\mu \cos\theta_W - B_\mu \sin\theta_W \\ A_\mu &= W^0_\mu \sin\theta_W + B_\mu \cos\theta_W \end{aligned}$$

θ_W : weak mixing angle

Massive Particles !

★ Experiment: $\mathrm{W}^\pm$, Z^0 are massive

★ Theory : 'Basic' SU$(2)_L \otimes$U(1) ➜ zero mass

Higgs mechanism: Fundamental Scalar Field

➜ Mass to $\mathrm{W}^\pm$, Z^0 preserving SU$(2)_L \otimes$U(1)

➜ + lepton, quark masses.

★ Holy Grail : Discovery of the Higgs Boson

Precision tests of the SM

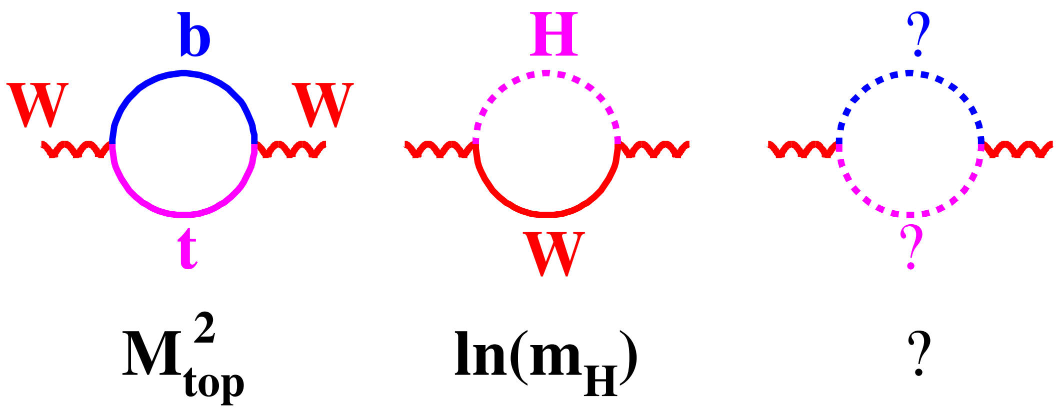
Tree Level :

$$G_\mu = \frac{\pi \alpha_{em}}{\sqrt{2}\sin^2\theta_W}\frac{1}{M_{\mathrm{W}}{}^2}$$

$$\sin^2\theta_W = 1 - \frac{M_{\mathrm{W}}{}^2}{M_{\mathrm{Z^0}}{}^2}$$

→ $M_{\mathrm{W}} = 80.937\ \mathrm{GeV}$ **(13σ from WA !)**

→ **Need Radiative Corrections**



$$M_{\mathrm{W}}{}^2\sin^2\theta_W = \frac{\pi\alpha_{em}}{\sqrt{2}G_\mu}(1+\Delta r)$$

WHY MEASURE M_{W} ?

★ **Test the self-consistency of SM**

★ **Sensitive to m_{H} : $\Delta r(M_{\mathrm{top}}, m_{\mathrm{H}}, ..)$**

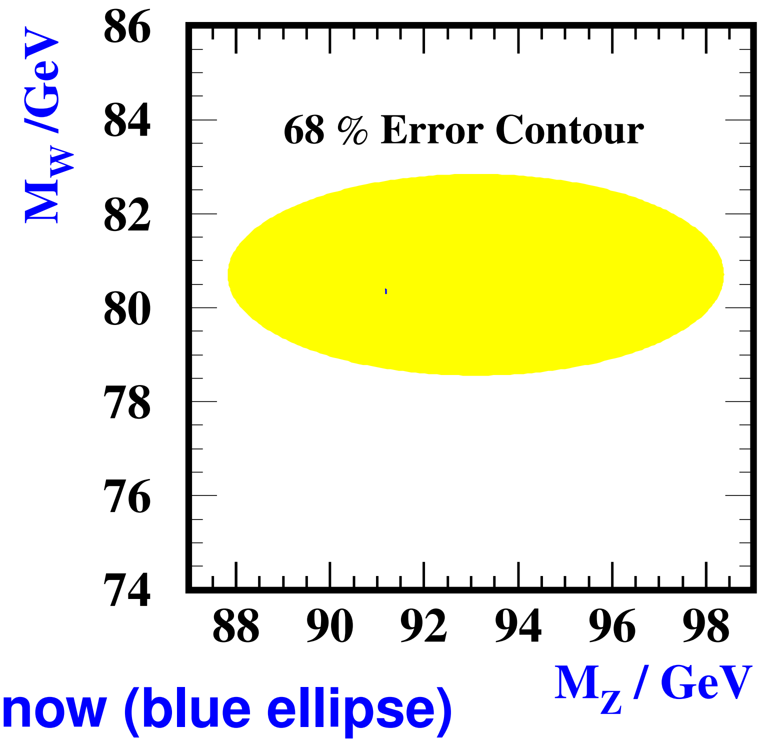
LEP Physics

★ (In the absence of a discovery) LEP physics will be summarised as:

"…. precise measurements of the mass and couplings of the Z^0 and $W^{\pm}$ …"

PERKINS V^{th} EDITION (2007)

The situation in 1989 (yellow ellipse)….



….and now (blue ellipse)

The on-going effort to measure M_W is the main topic of this talk

❷ LEP

The
Large Electron Positron
Collider

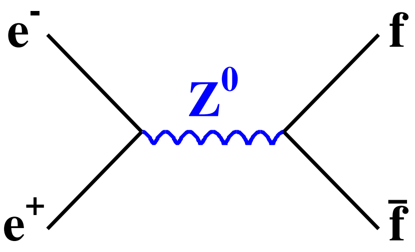
★ Large = 26 km circumference

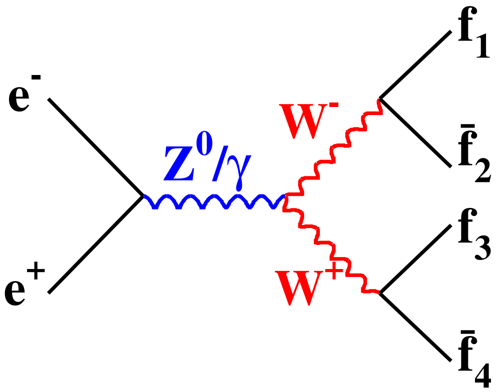
★ Highest energy $\mathrm{e^+e^-}$ machine ever built

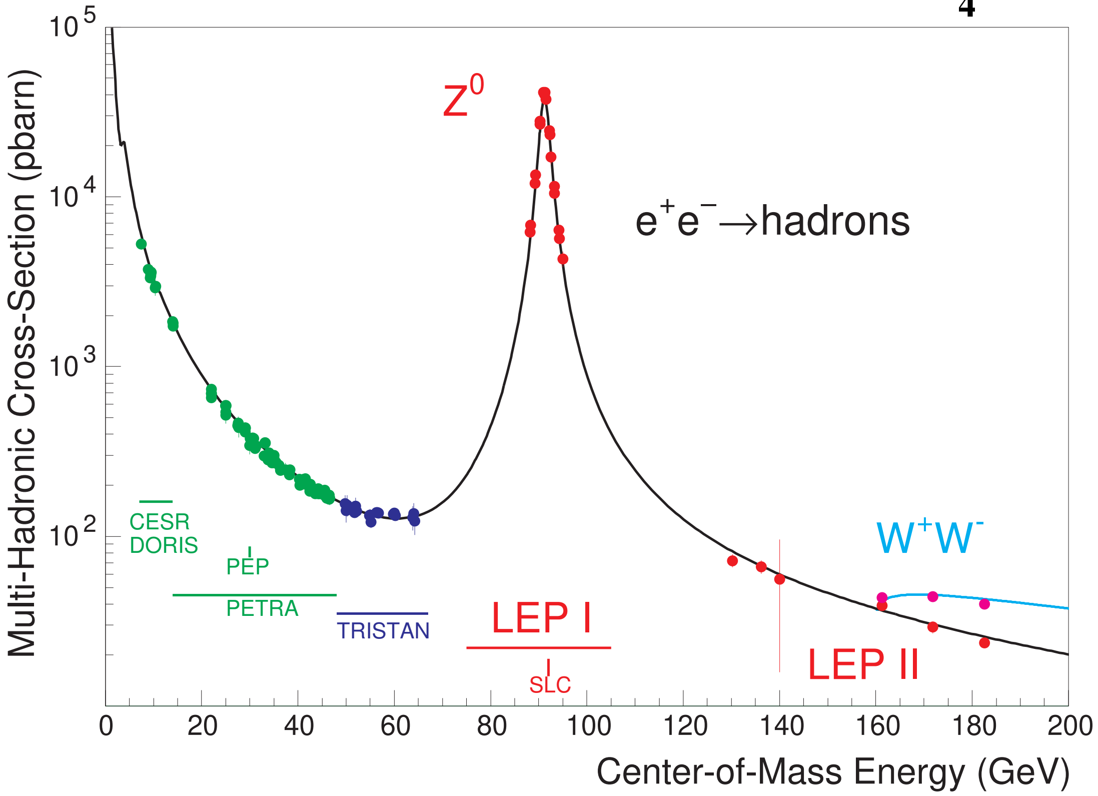
★ Accelerates e^- and e^+ to 99.999999999 % c

★ $\mathrm{Z^0}$ and $\mathrm{W^\pm}$ Boson Factory

Precision Measurements at LEP







LEP (four experiments) Combined:

★ **LEP 1 : 16,000,000 Z^0**

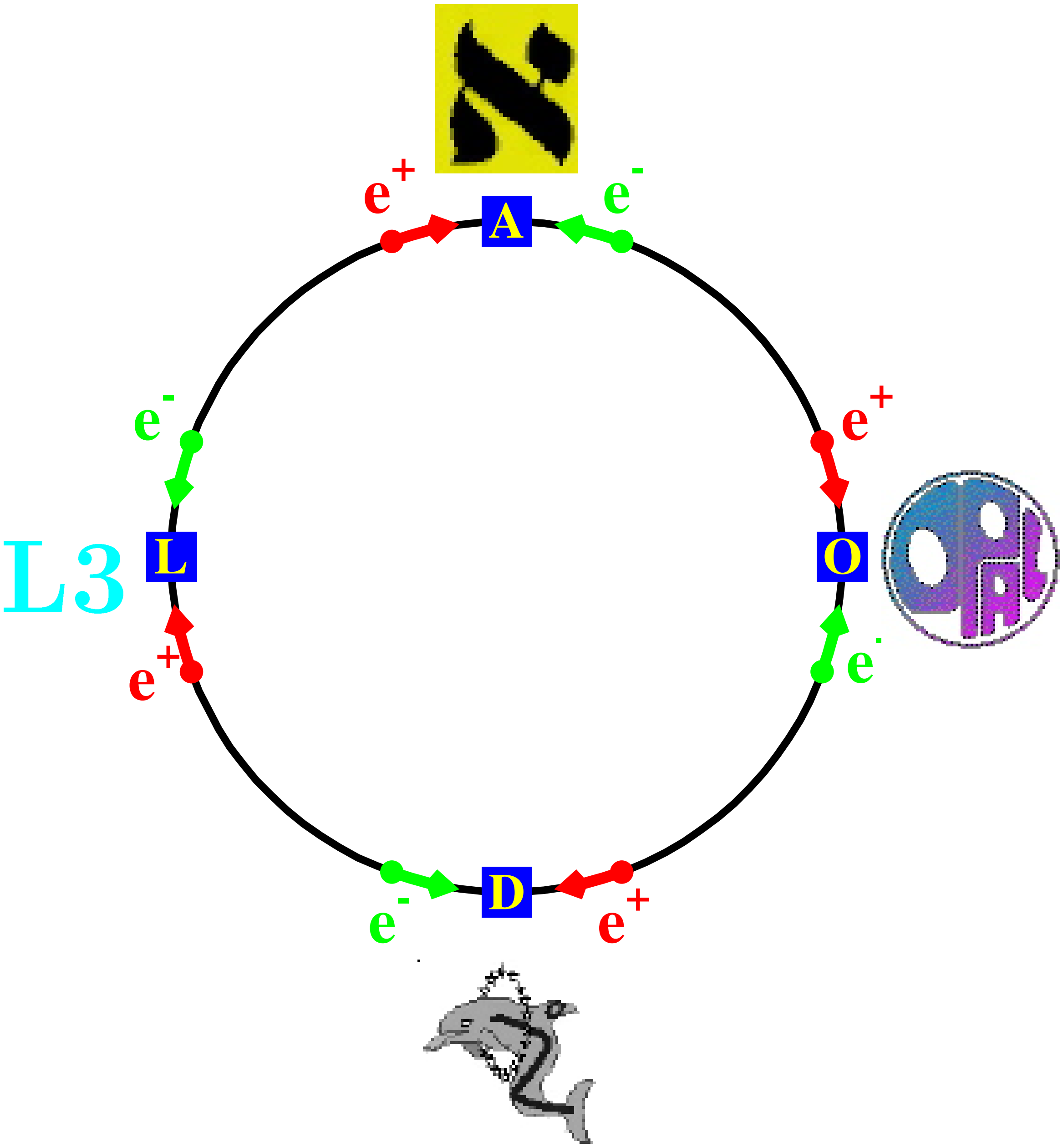
★ **LEP 2 : 30,000 W^+W^-**

Large data samples $\longrightarrow$ test SM !

★ **LEP 1 : $M_{Z^0}, \sin^2\theta_W$**

★ **LEP 2 : M_W**

4 LEP Experiments

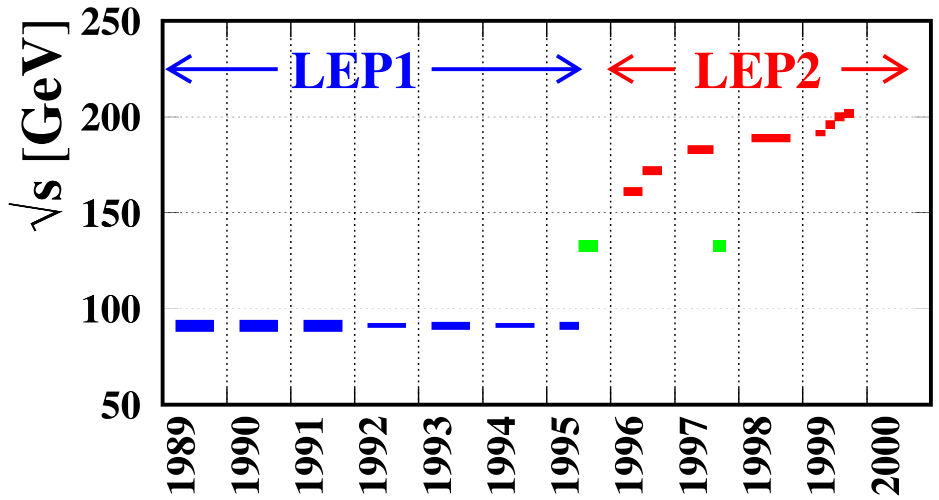


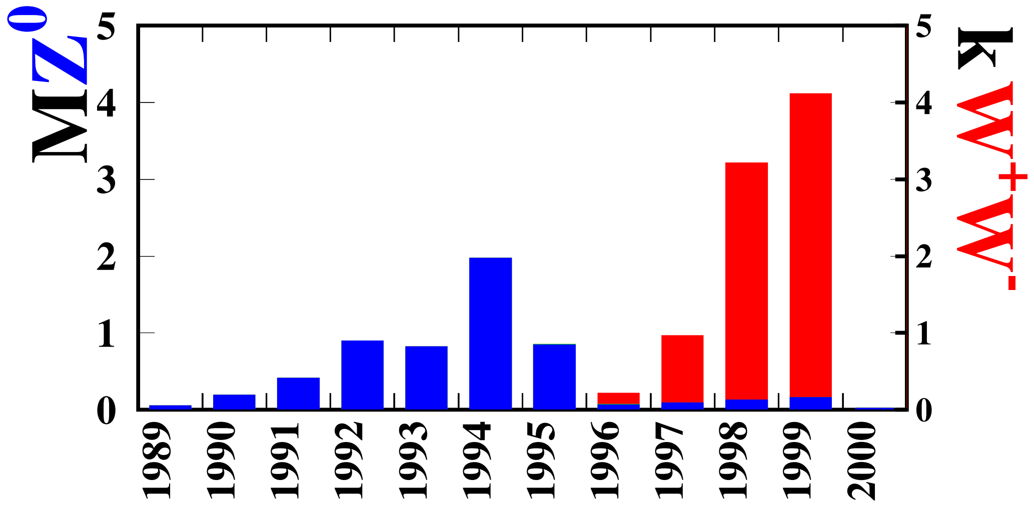
- ★ 4 bunches of e^-, 4 bunches of e^+
- ★ Total current $\sim$8 mA
- ★ Collisions at 4 Interaction Points
- ★ Four experiments Aleph, Delphi, L3 and Opal
- ★ approx. 1600 physicists

A Brief History of LEP: 1989-2000

★ born.. Autumn 1989

★ R.I.P. Autumn 2000



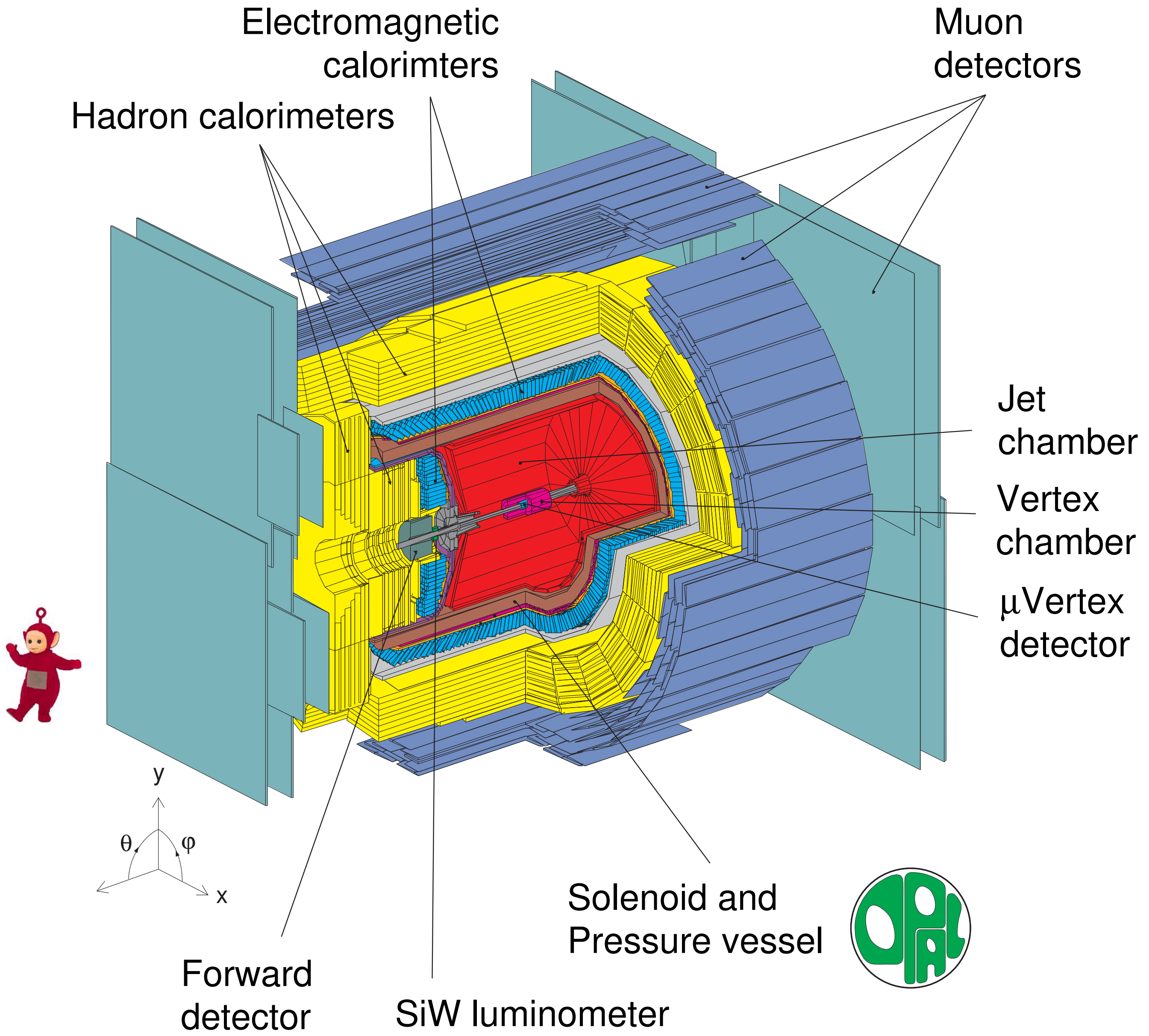


★ Results use 260 pb^{-1} of data at $\sqrt{s} = 161 - 189$ GeV

★ Final LEP 2 total 550-600 pb^{-1} at $\sqrt{s} = 161 - 205$ GeV

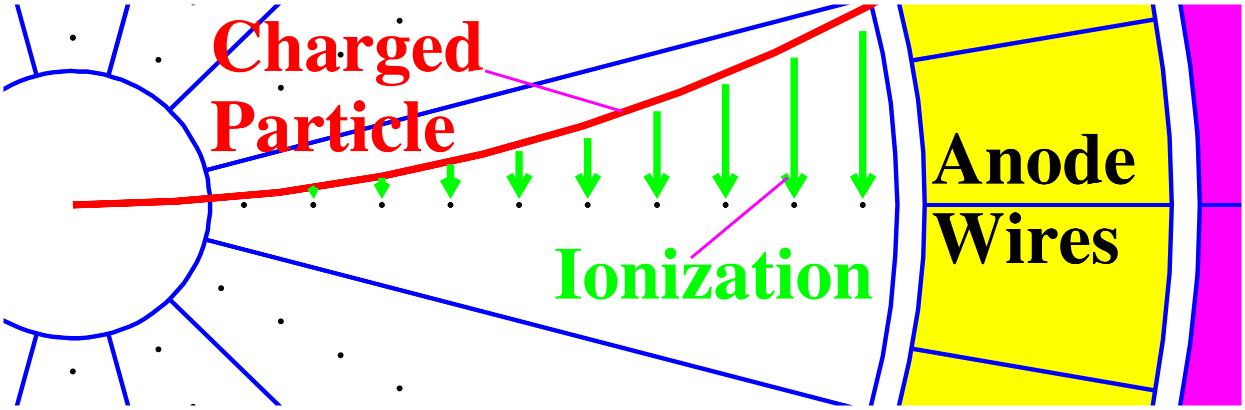
★ The results are preliminary

❸ The Opal Detector



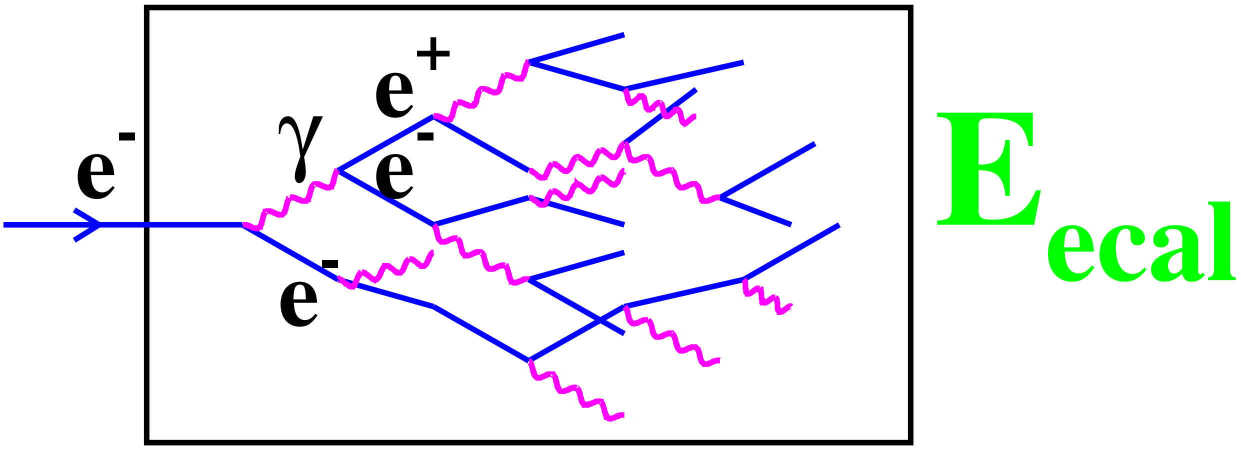
Particle Detection

TRACKING



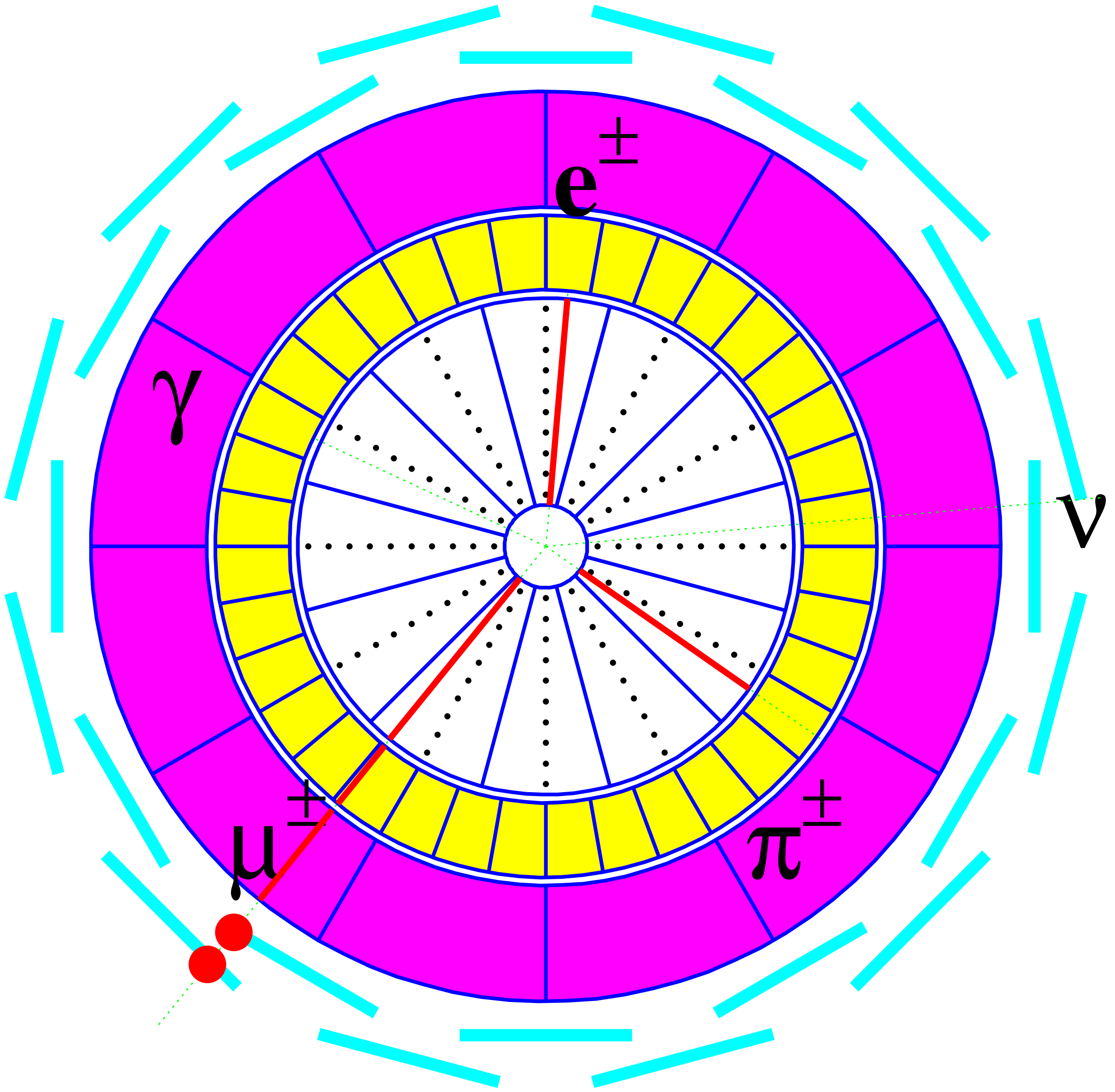
- 0.437 T Axial Magnetic Field
- Track curvature $\propto 1/p_{\perp}$
- $(\sigma_{p_{\perp}}/p_{\perp})^2 = 0.02^2 + 0.0015^2.(p_{\perp}/GeV)^2$

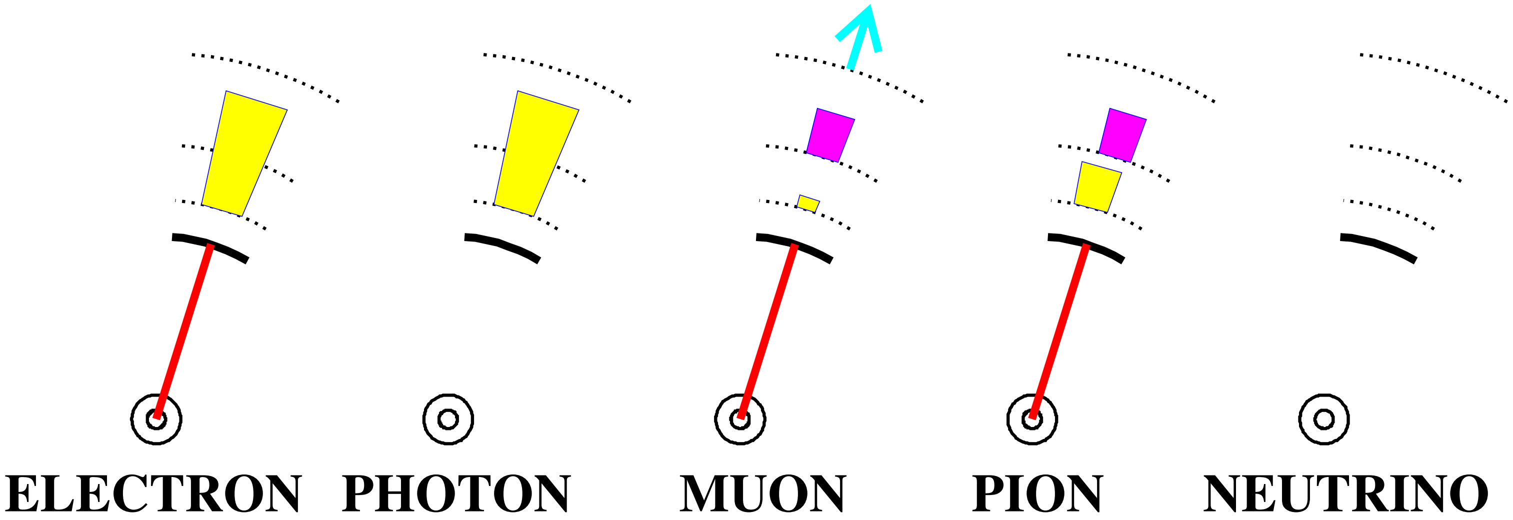
ELECTRO-MAGNETIC CALORIMETRY



- ECAL = 11705 pb-Glass blocks
- ECAL coverage $\sim 98\ \%\ 4\pi$
- ECAL Energy Resolution ~ 3 % at 45 GeV

Particle Identification





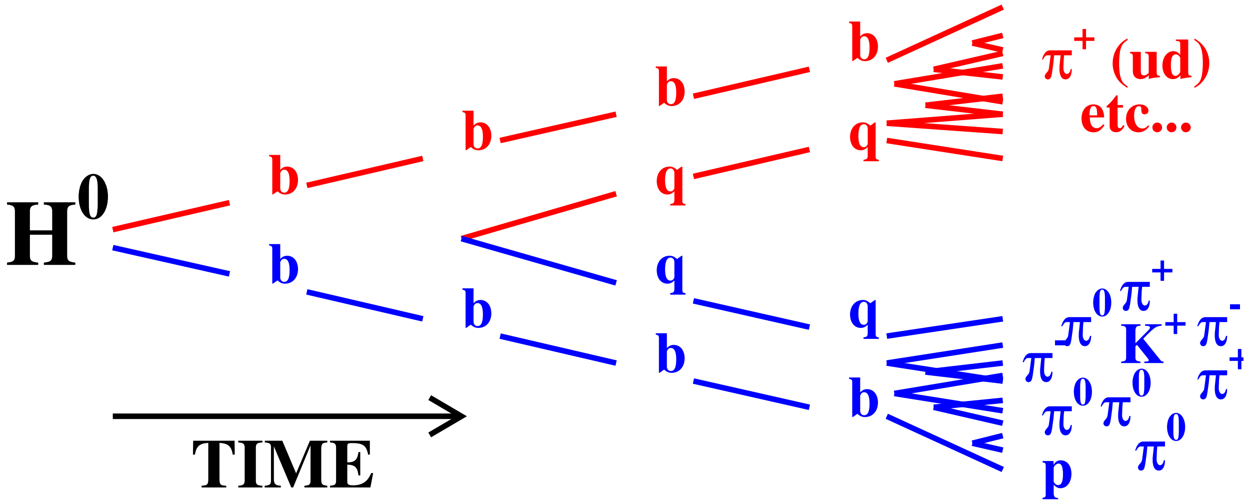
Quarks vs. Jets

Higgs bosons decay mainly to bottom quarks :

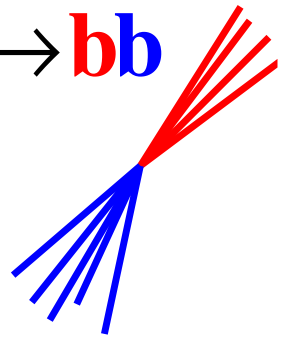
- $\mathrm{H}^0 \rightarrow \mathrm{b}\overline{\mathrm{b}}$

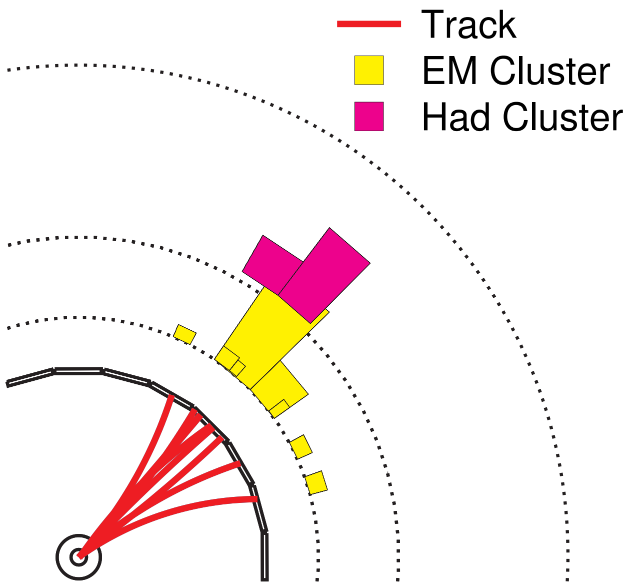
Colour field between two free quarks :

$$V(r) \propto r$$



$\mathrm{H}^0 \rightarrow \mathrm{bb}$

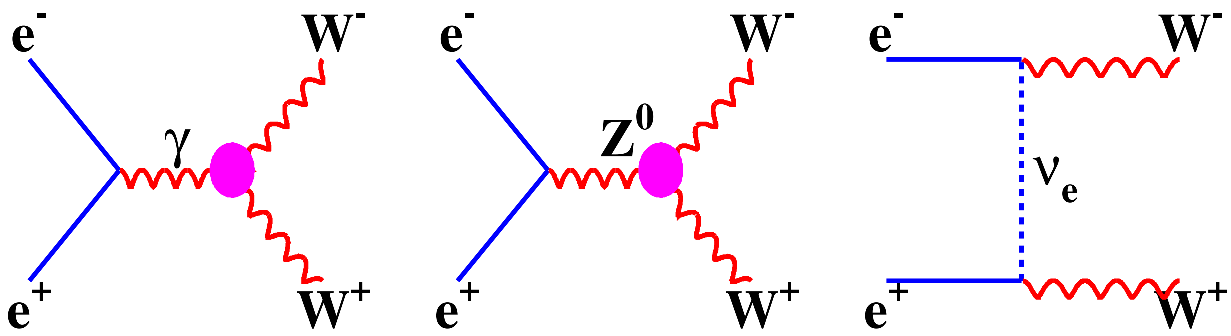




❹ W^+W^- Physics at LEP

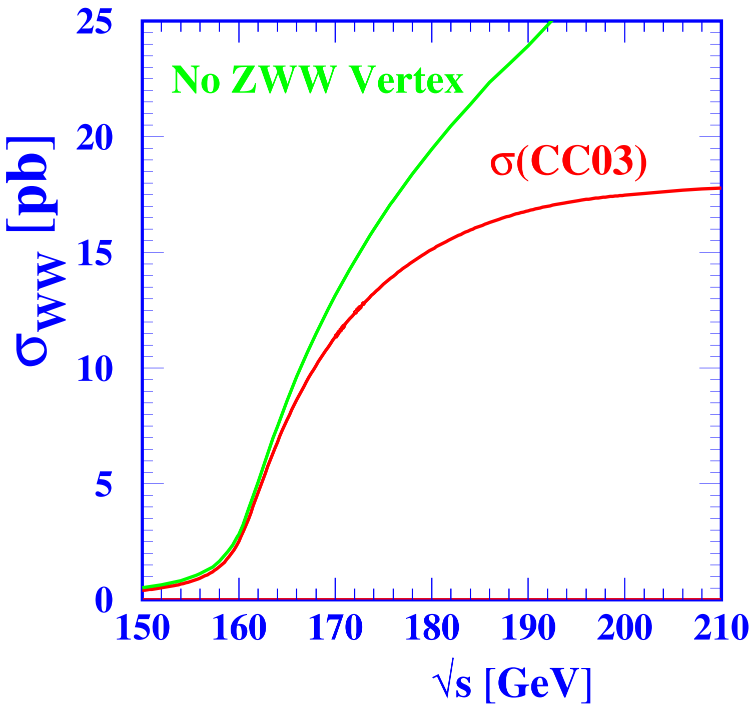
Three Diagrams (CC03):

- t-channel ν exchange
- s-channel Z^0 exchange
- s-channel γ exchange



★ t-channel dominates - W^- produced preferentially in direction of e^-

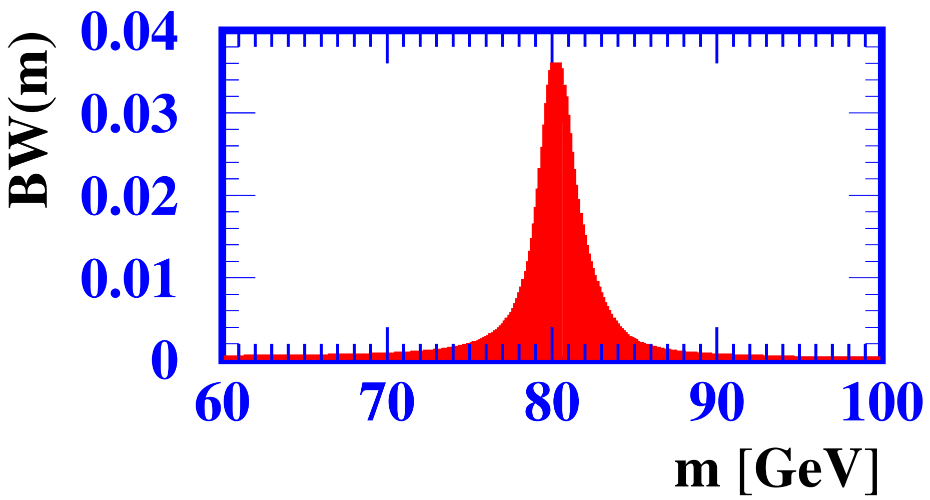
★ Main effect of s-channel is -ve interference



Mass Distribution

- ★ **W-bosons are unstable, finite width** $\Gamma_W \sim 2$ **GeV**
- ★ **Mass distribution** $\rho(m)$ **= relativistic Breit-Wigner (BW)**

$$\rho(m) = \frac{m^2}{(m^2 - M_W{}^2)^2 + m^2\Gamma_W{}^2}$$



In Practice Reconstruct :
$m_{avr} = (m_1 + m_2)/2$

W^+W^- Decay at LEP

In SM: $W^\pm \ell\nu$ and $W^\pm q\bar{q}$ couplings are equal.

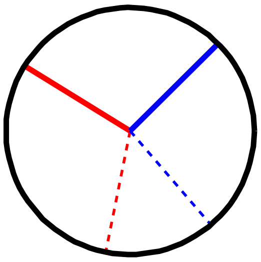
			3 TIMES		
e	μ	τ	u	c	$\cancel{t}$
ν_e	ν_μ	ν_τ	d	s	$\cancel{b}$

★ Br($W^\pm \rightarrow q\bar{q}$) = $\frac{2}{3}$

★ Br($W^\pm \rightarrow \ell\nu$) = $\frac{1}{3}$

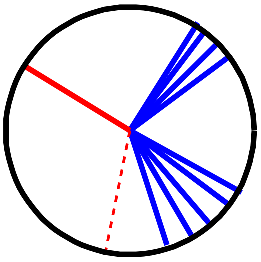
QCD corrections $\sim (1 + \alpha_s/\pi)$ ➡
Br($W^\pm \rightarrow q\bar{q}$) = 0.675

$WW \rightarrow l\nu l\nu$



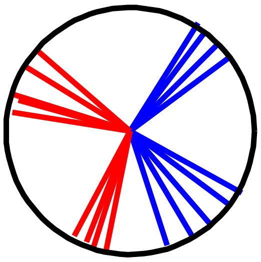
10.5 %

$WW \rightarrow qql\nu$



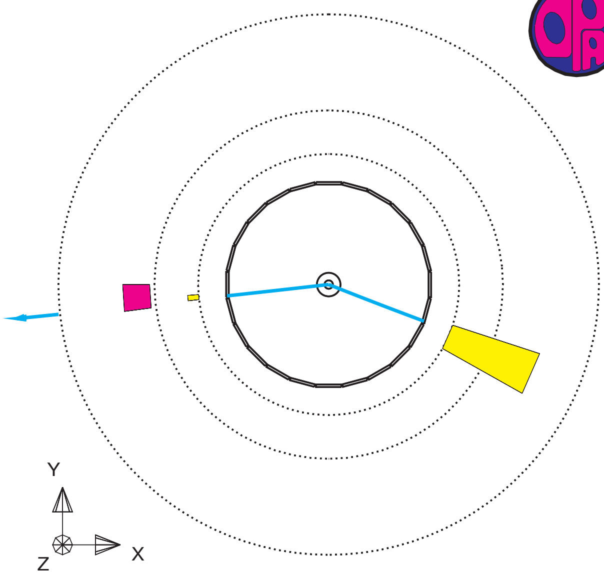
43.9 %

$WW \rightarrow qqqq$

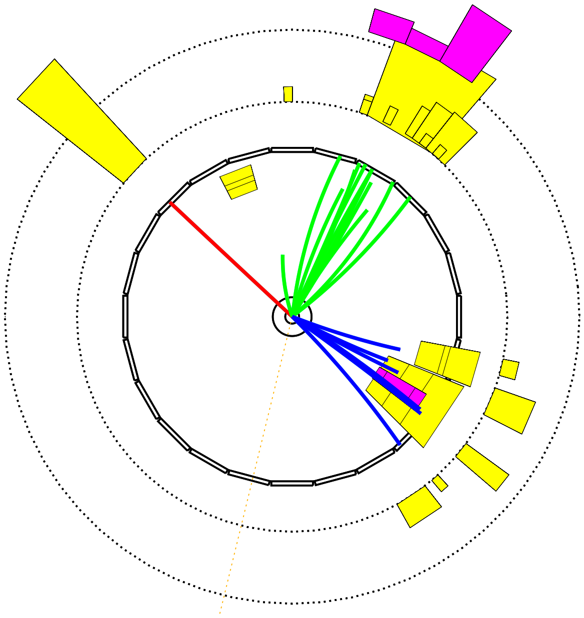


45.6 %

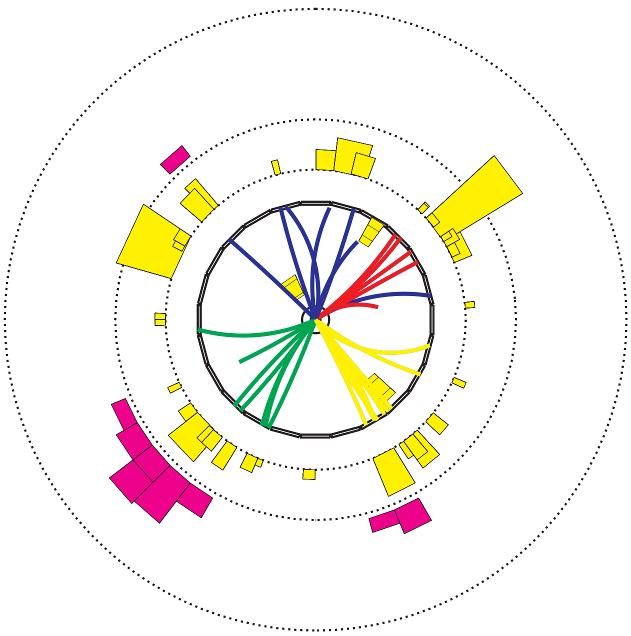
W^+W^- Events in OPAL



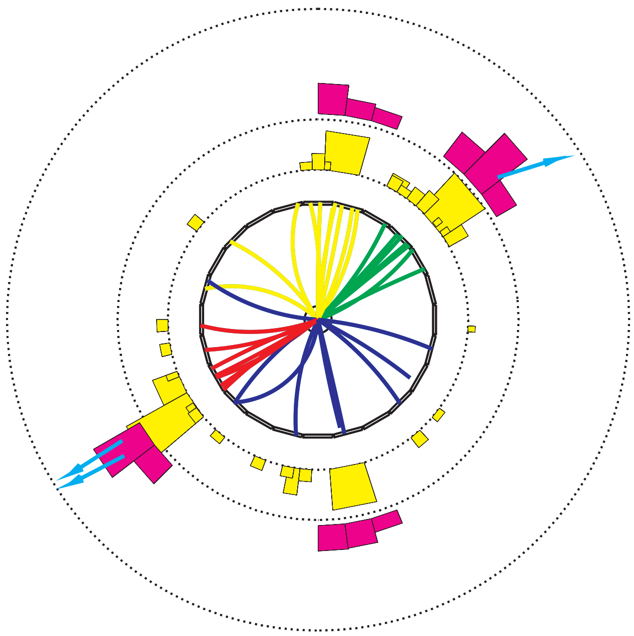
$W^+W^- \rightarrow e\nu\mu\nu$



$W^+W^- \rightarrow qqe\nu$



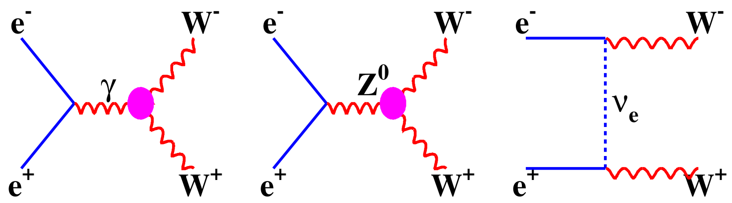
$W^+W^- \rightarrow q\bar{q}q\bar{q}$



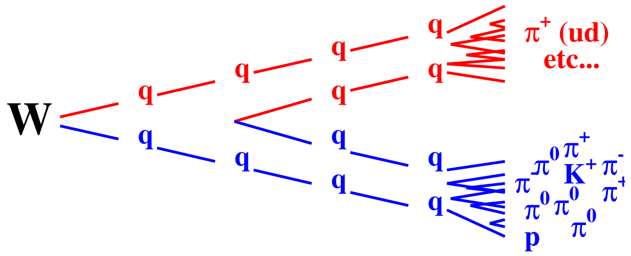
$W^+W^- \rightarrow q\bar{q}q\bar{q}$

Monte Carlo Simulation

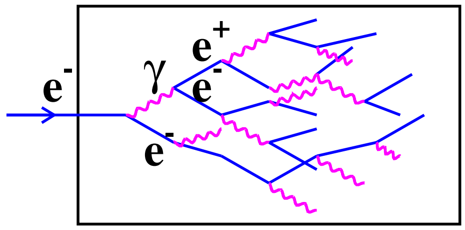
Physical process



+ Hadronization (q → jets)

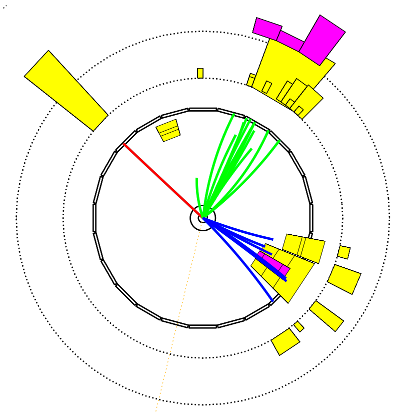


+ Detector Simulation



+ Many random numbers...

= SIMULATED EVENT



★ **MC events treated just like real data**

★ **Determine "expected" results for**

BACKGROUND i.e. no Higgs

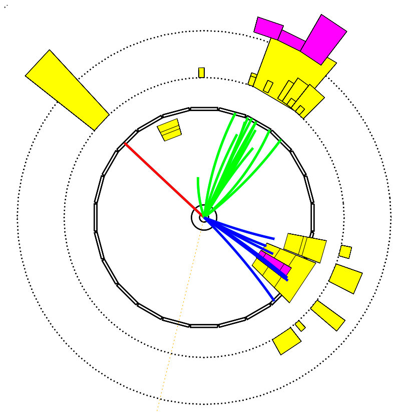
BACKGROUND + SIGNAL vs. m_{H}

Event Reconstruction: Data and MC

- ★ Large amount of information in each event :

  0.25 Mbytes(raw) 40 kbytes (compressed)

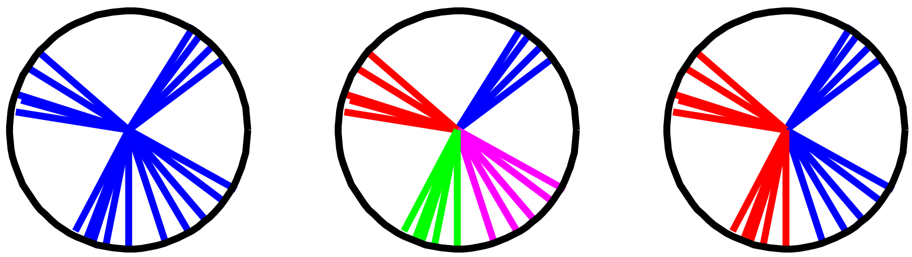
- ★ FOR M_{W} : most information is redundant...
- ★ Want momenta of the four fermions



➡ $\vec{p}_{q_1}, \vec{p}_{q_2}, \vec{p}_e, \vec{p}_\nu$

For $e^{\pm}$ ($\mu^{\pm}$): use $\mathrm{E_{ECAL}}$ ($\mathrm{p_{TRACK}}$)

For Quarks:

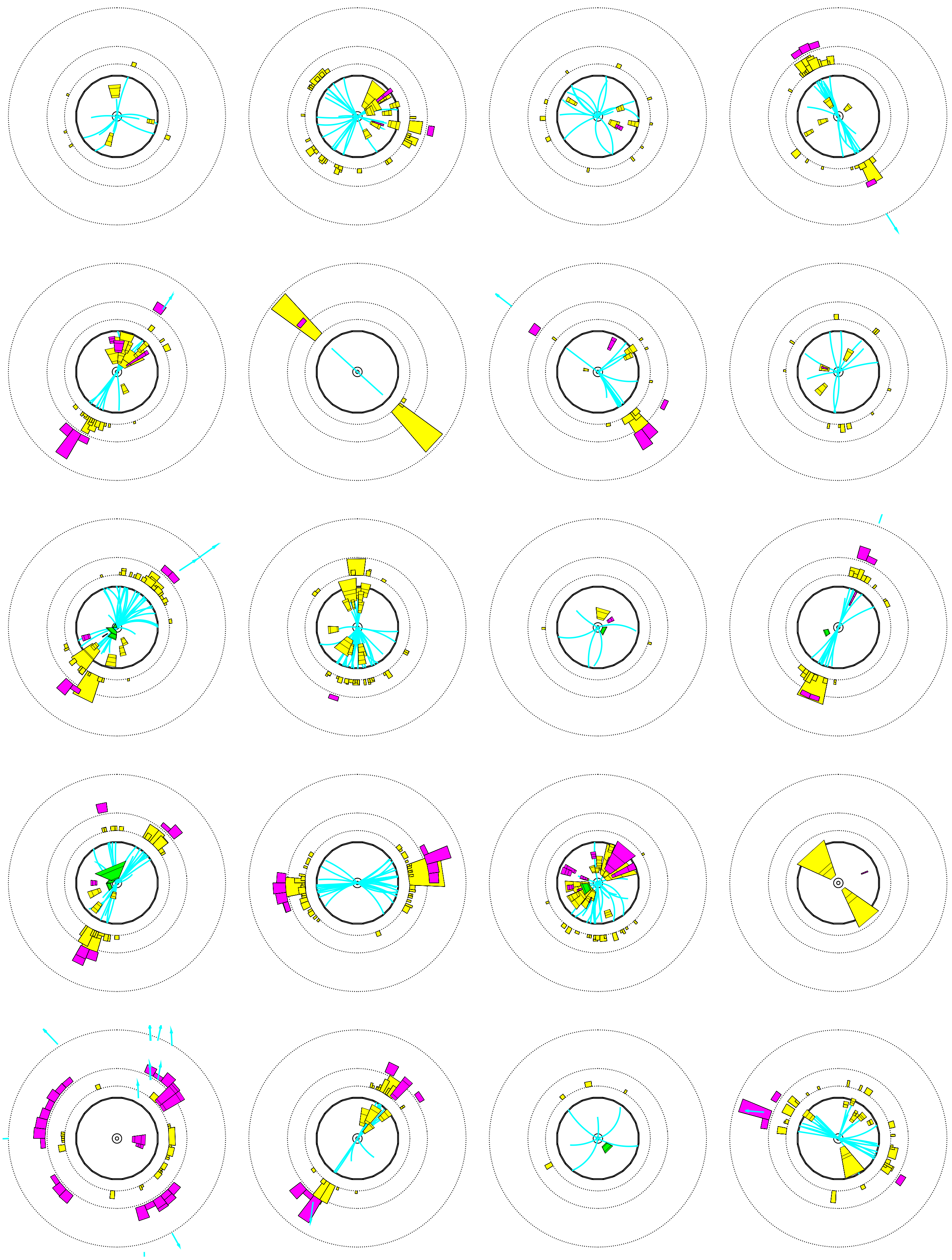


- ★ Force event into 2/4 Jets : Durham Algorithm

  (minimise transverse momentum)

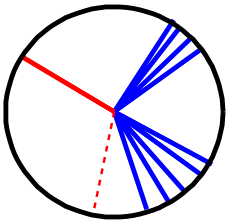
- ★ Add track momenta and ECAL/HCAL energies
- ★ Empirical corrections
- ★ Jets (quarks) : $\sigma_{E_{\mathrm{JET}}}/E_{\mathrm{JET}} = 20\ \%$

Spot the $e^+e^- \rightarrow W^+W^-$



Event Selection : e.g. $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$

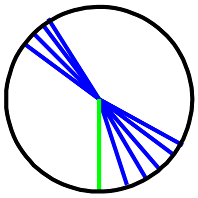
$WW \rightarrow qq l\nu$



$\sigma \sim 7$ pb

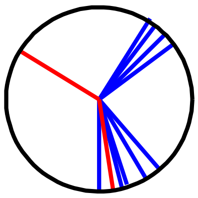
MAIN BACKGROUNDS :

$e^+e^- \rightarrow qq$
(+fragmentation track)



$\sigma \sim 100$ pb

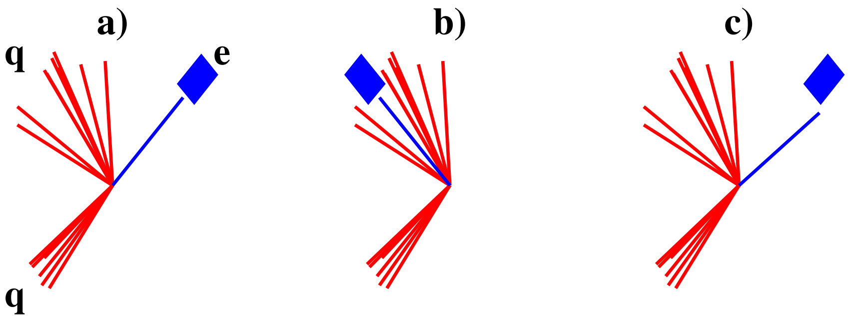
$ZZ \rightarrow qqll$



$\sigma \sim 140$ fb

Selection: Find most probable lepton candidate

No explicit lepton ID/lepton isolation cuts



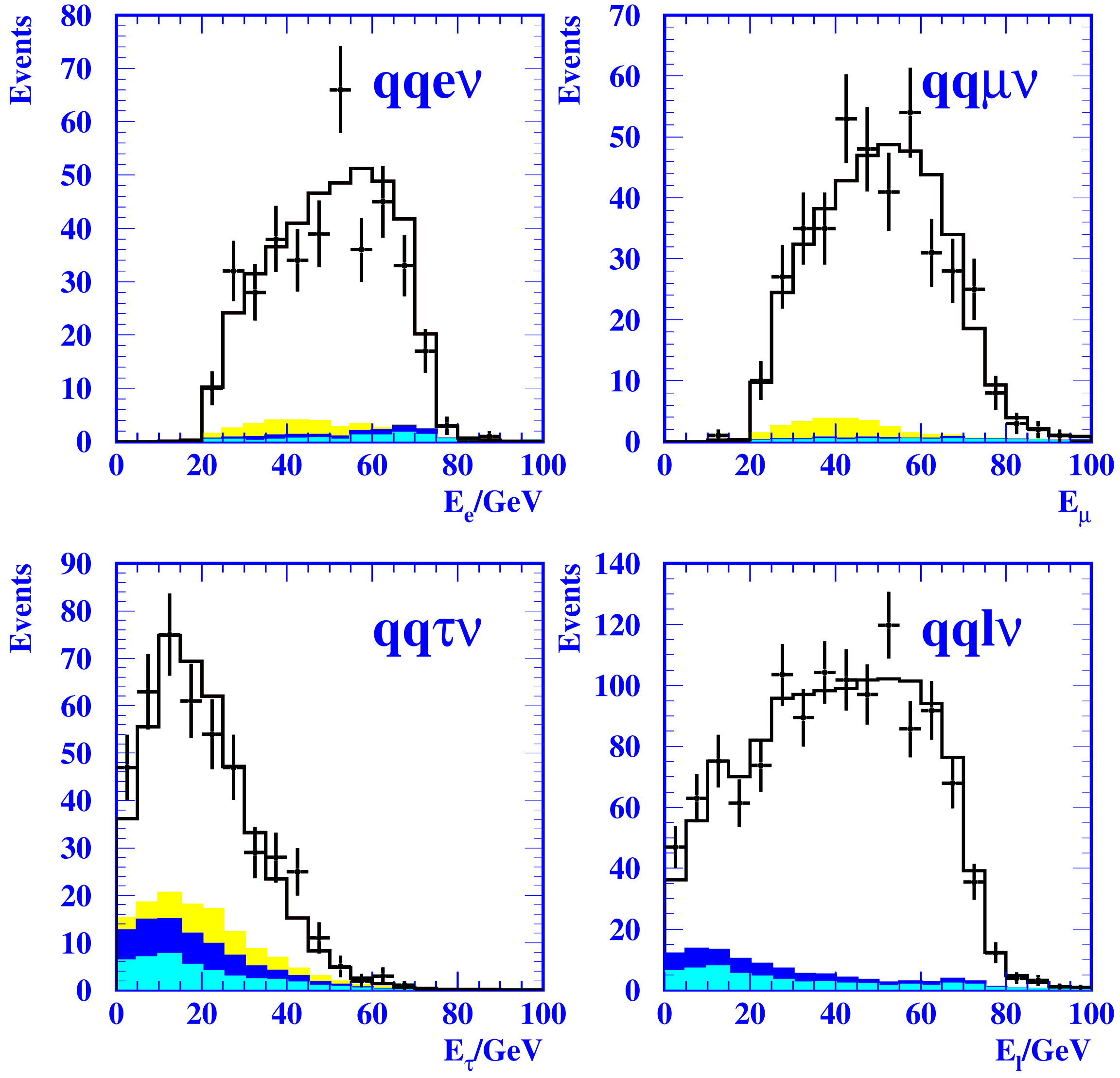
Followed by multivariate likelihood

	Efficiency	Purity
OPAL	87%	90%

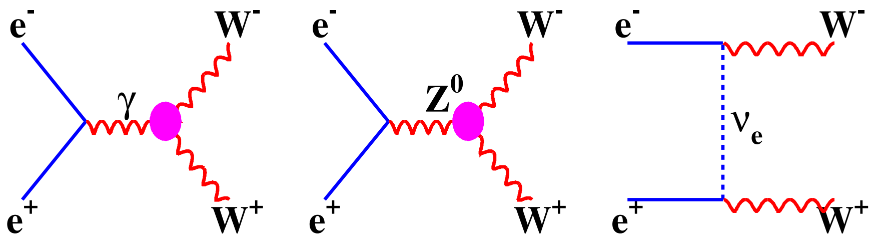
OPAL at 189 GeV

Selection	Effic.	Purity	Expect	Observe
$W^+W^- \to \ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$	82%	90%	290.0	278
$W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$	87%	90%	1287.2	1252
$W^+W^- \to q\overline{q}q\overline{q}$	86%	79%	1511.1	1546
Combined	87%	85%	3088.3	3076

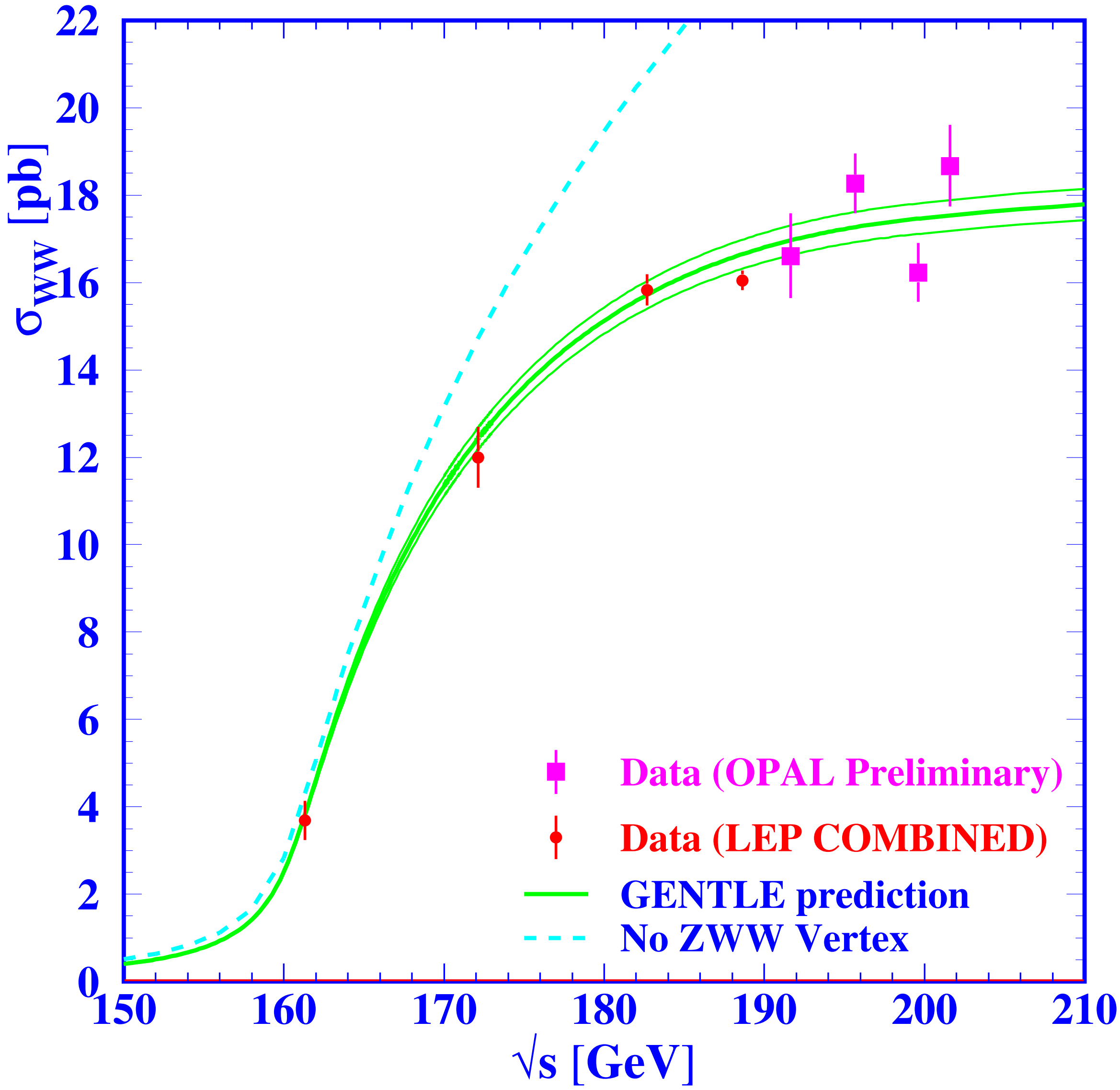
- **Good agreement between data and MC....e.g.**



W^+W^- Cross Section Results



LEP COMBINED CC03 Cross Section



Expt. Error $\sim 1.0\ \%$ vs Theory Error $2.0\ \%$

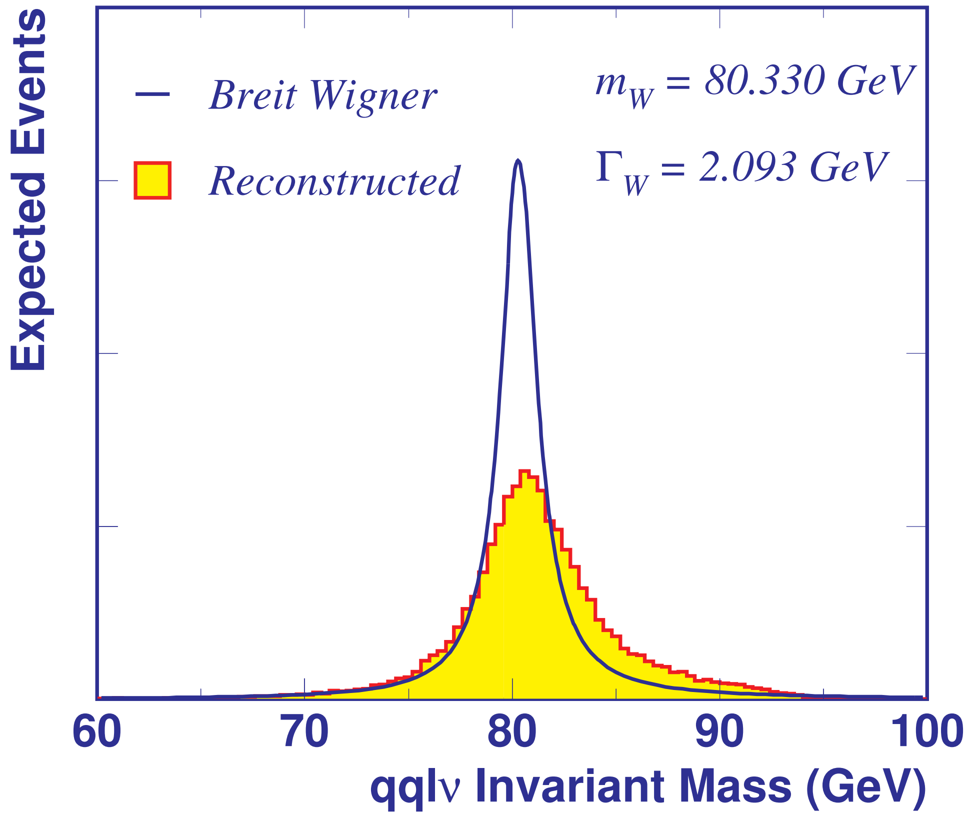
RacoonWW: $\sim 2.5\ \%$ lower than GENTLE

❺ W MASS

M_W determined from the kinematic reconstruction of the invariant mass of the $\mathrm{W^+W^-}$ decay products

Two Distinct Stages:

- ★ Reconstruct Mass Distribution
- ★ Fit M_W



Mass Distribution Distorted by

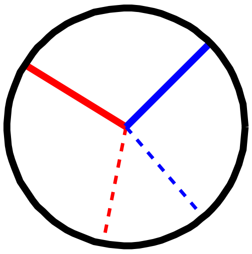
- ★ Experimental Resolution
- ★ Event Selection
- ★ ISR, etc...

Kinematic Fitting

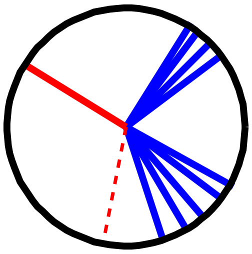
Mass resolution improved using a kinematic fit

5 Constraints:

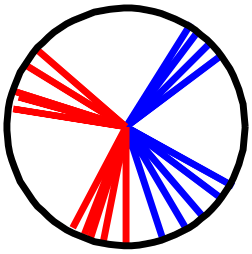
- ★ **Energy/momentum conservation :**
  $$(E, \vec{p}) = (E_{LEP}, \vec{0})$$
- ★ **Neglect Γ_W : $m_1 = m_2$**



$\ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$ **: 6 unknowns ($\vec{p^1}_\nu, \vec{p^2}_\nu$)**
Under-constrained : not used



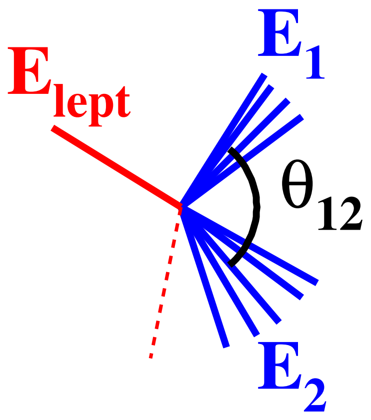
$q\overline{q}\ell\overline{\nu}_\ell$ **: 3 unknowns ($\vec{p}_\nu$)**
Over-constrained : use kinematic fit



$q\overline{q}q\overline{q}$ **: 0 unknowns**

- ★ **Constraints : Lagrange multipliers**
- ★ **Iterative χ^2 minimisation**

Mass Reconstruction : $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$



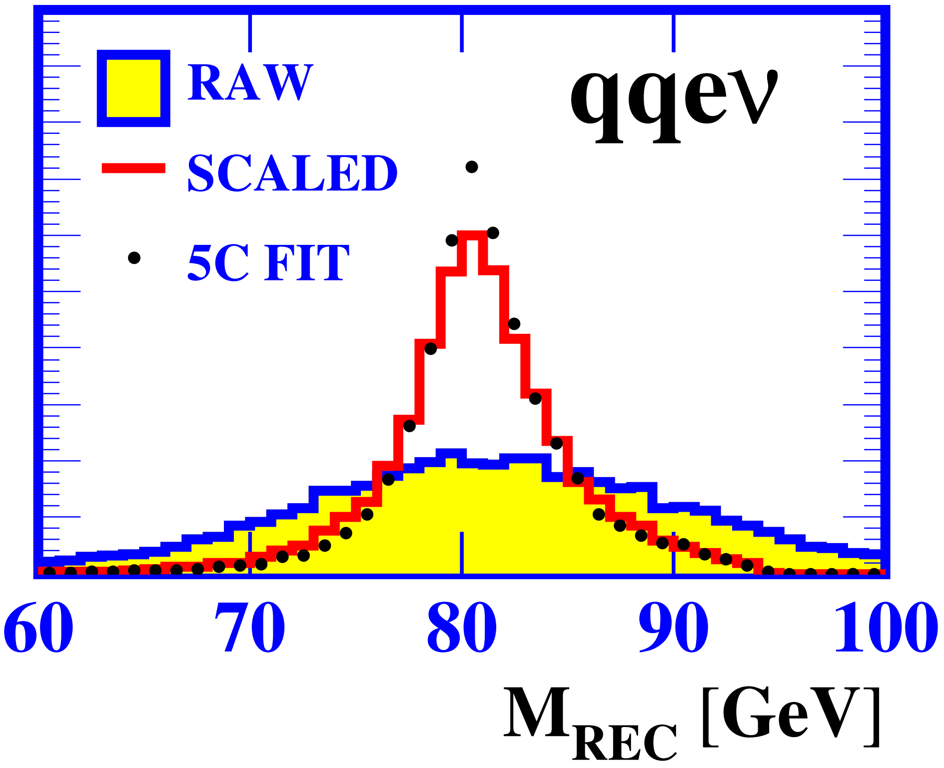
★ **Jet angles better measured than energies.**

Mass Reconstruction:

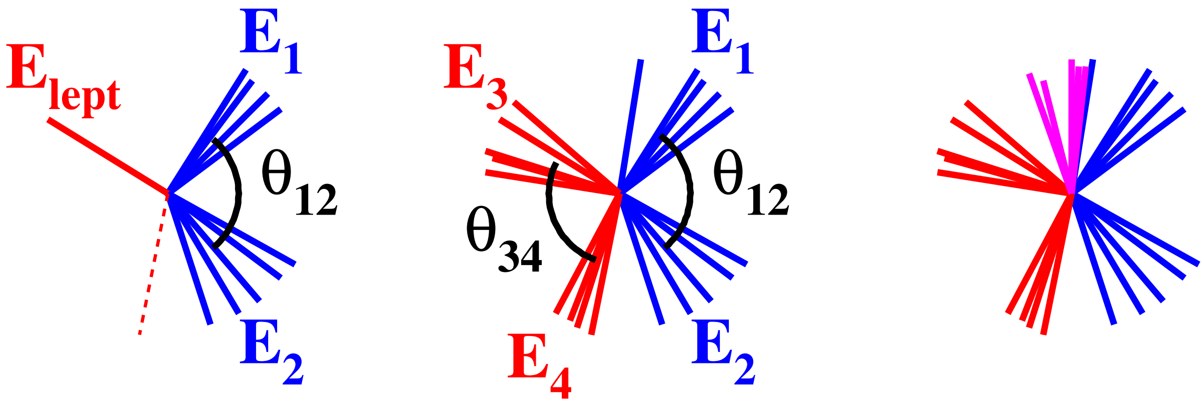
❶ **Raw :** $M_{q\overline{q}} = \sqrt{2E_1E_2}(1 - \cos\theta_{12})$

❷ **Scaled :** $M'_{q\overline{q}} = M_{q\overline{q}}\frac{E_{beam}}{(E_1+E_2)}$

❸ **Kinematic fit (5C)**



Mass Reconstruction : $W^+W^- \rightarrow q\bar{q}q\bar{q}$

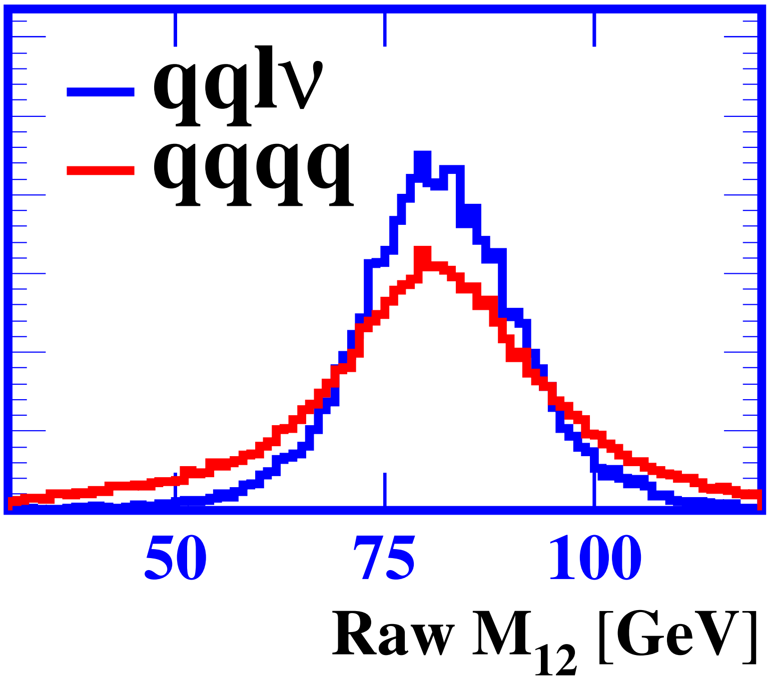


Detect all fermions ➠ Better Resolution ?

★ **But some hadrons assigned to wrong jet**

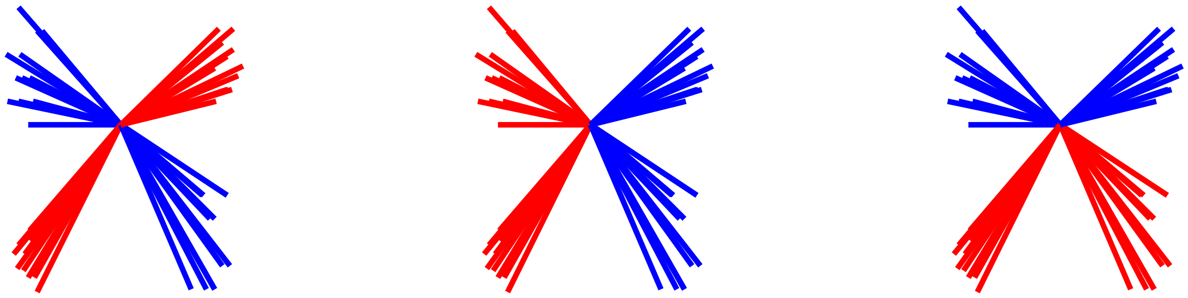
★ $\alpha_s(M_W) \sim 0.12$: **Gluon radiation**

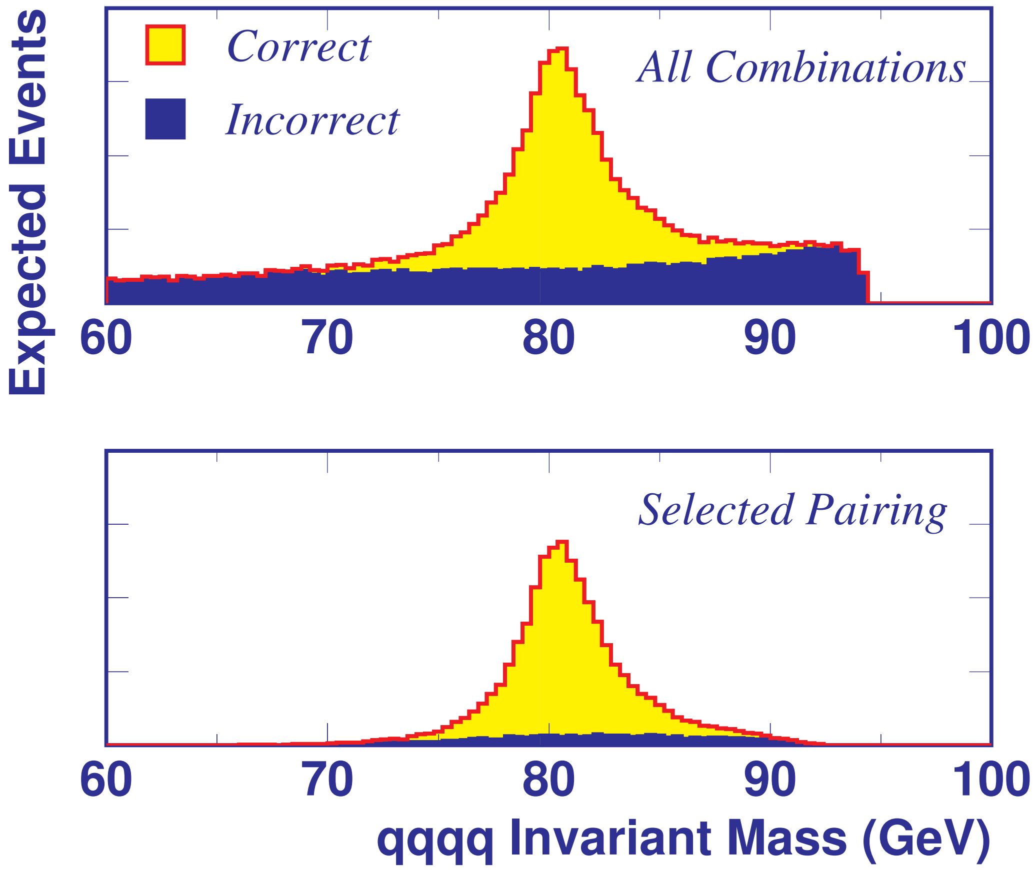
➠ **both effects degrade resolution**



$W^+W^- \rightarrow q\bar{q}q\bar{q}$ Jet Pairing

★ 3 pairings of jets to $W^{\pm}W^{\mp}$





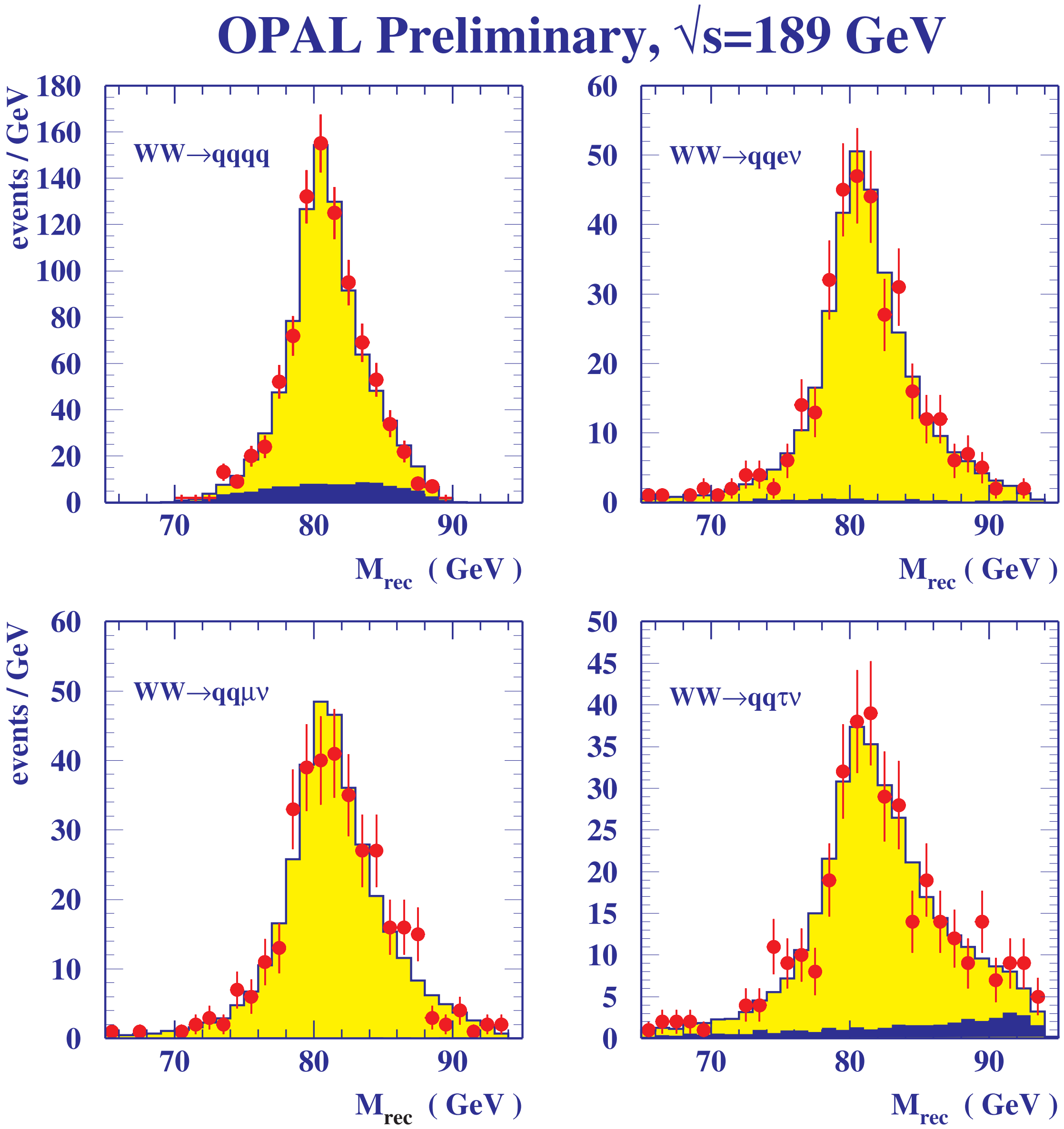
★ Incorrect pairings $\Rightarrow$ Combinatorial BGD.

★ Only correct pairing $\Rightarrow$ M_{W} info

★ Correct pairing chosen using Likelihood discriminant $\mathcal{L}(P_{FIT}, m_1 - m_2)$

Mass Distributions

5C fit masses:



Time to extract M_W....

THREE METHODS :

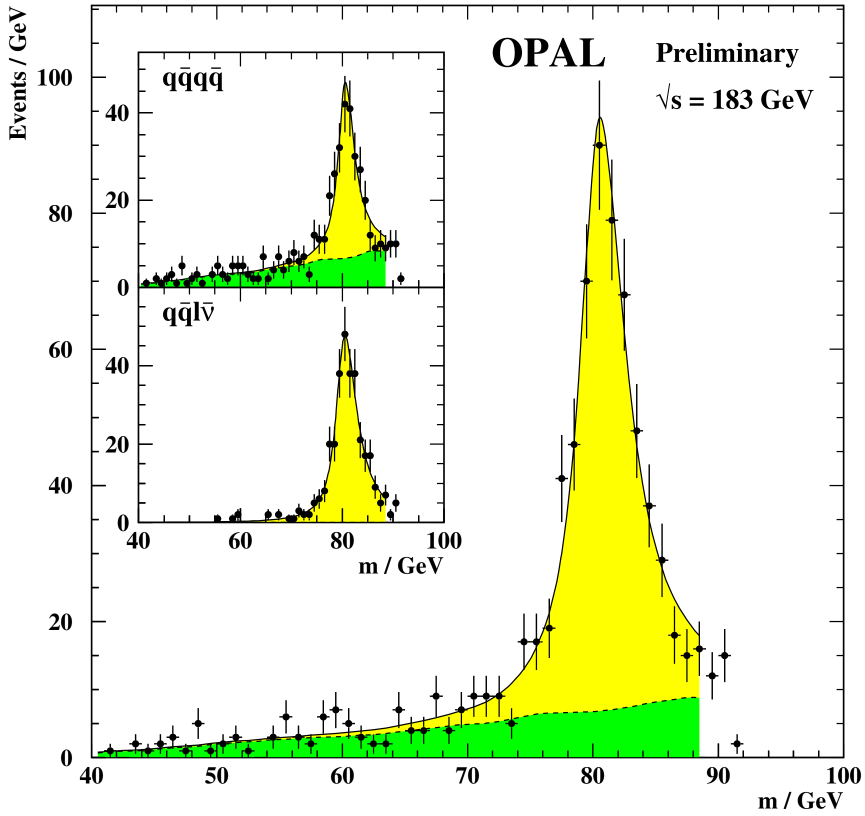
① **Breit-Wigner Fit (ADLO)**

② **Monte Carlo Reweighting (ALO)**

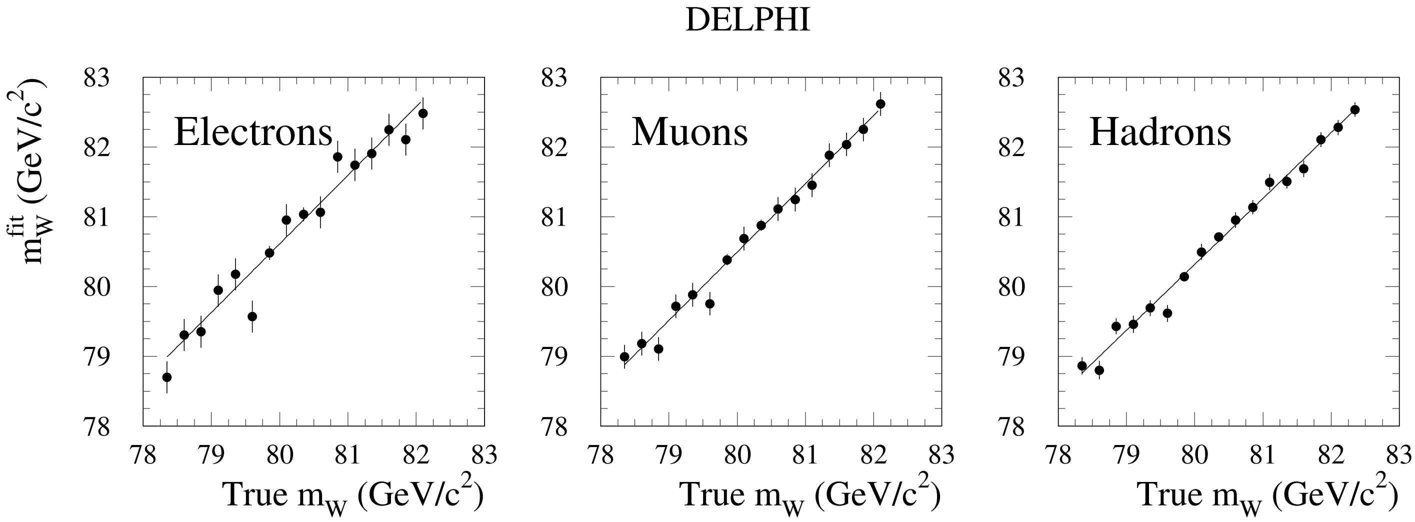
③ **Convolution (D O)**

① Breit-Wigner Fit

★ **Parameterise using function based on BW**



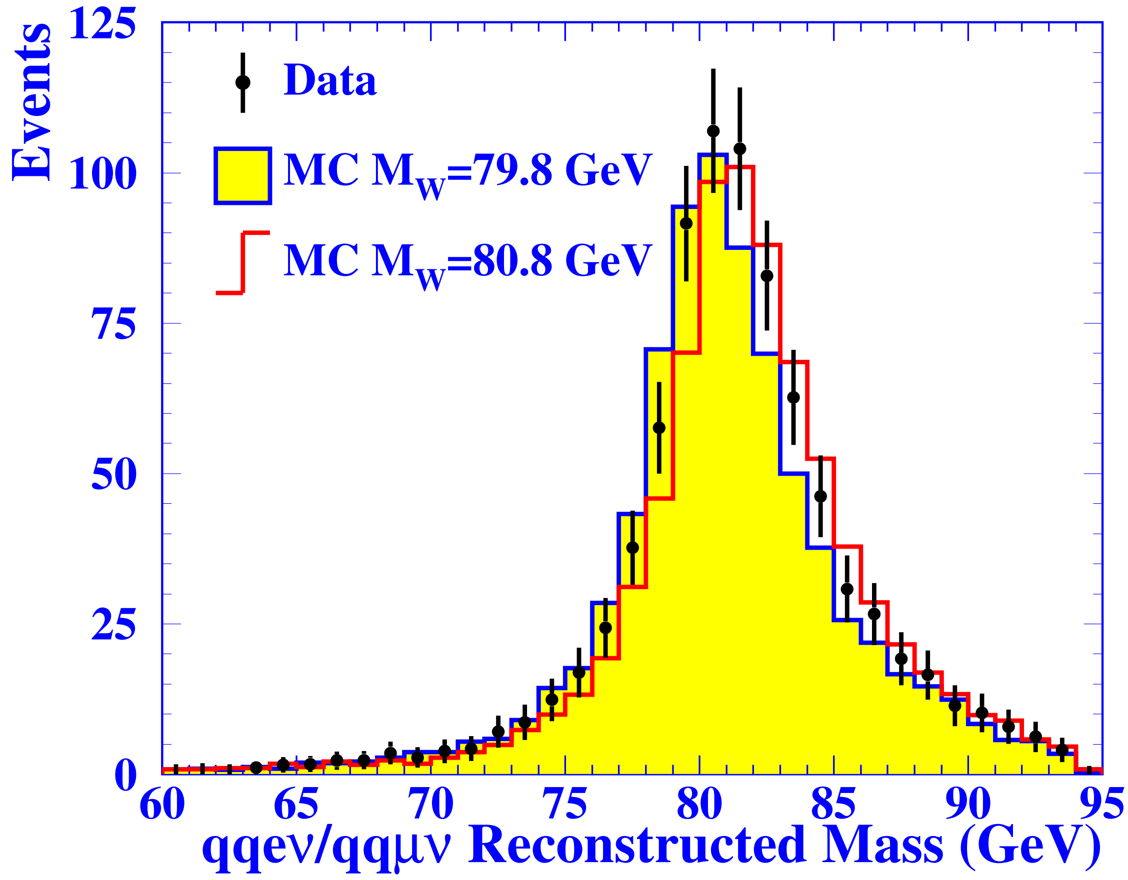
★ **Use MC to calibrate fitted mass**



★ **SIMPLE/ROBUST : used by ADLO as cross-check**

② Reweighting Fit ALO

★ Compare Data to MC ➡ $\chi^2(M_{\mathrm{W}})$



★ Could generate many MC samples

★ Generate one large sample $(M_{\mathrm{W}}, \Gamma_{\mathrm{W}})$ and **REWEIGHT** to $(M_{\mathrm{W}}{}', \Gamma_{\mathrm{W}}{}')$

For event i with generated masses (m_1, m_2)

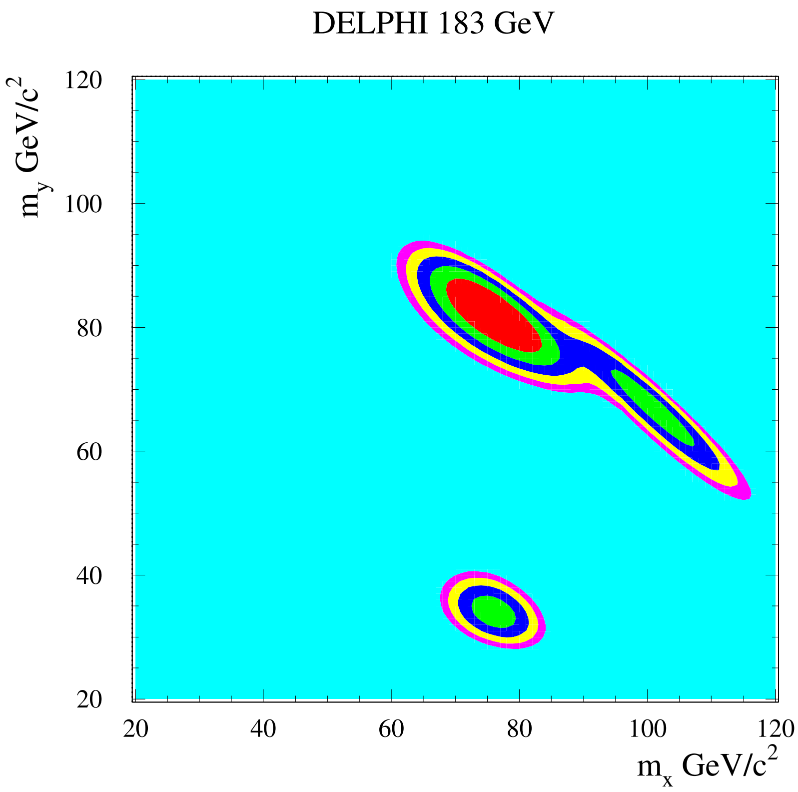
$$w^i = \frac{BW(m_1, m_2 : M_{\mathrm{W}}{}', \Gamma_{\mathrm{W}}{}')}{BW(m_1, m_2 : M_{\mathrm{W}}, \Gamma_{\mathrm{W}})}$$

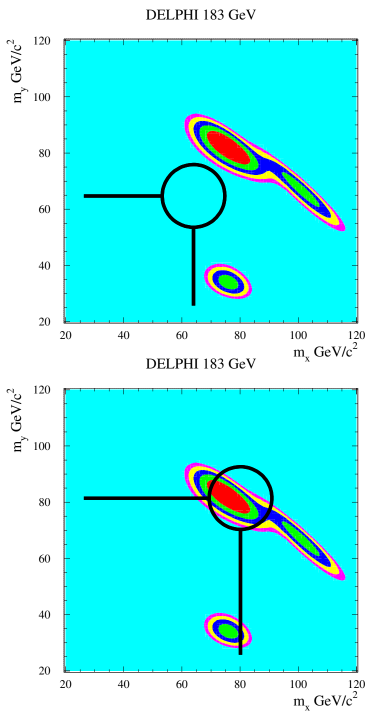
③ Convolution Fit : DELPHI

★ Use 4C fit $\Rightarrow$ 2 masses for each jet pairing

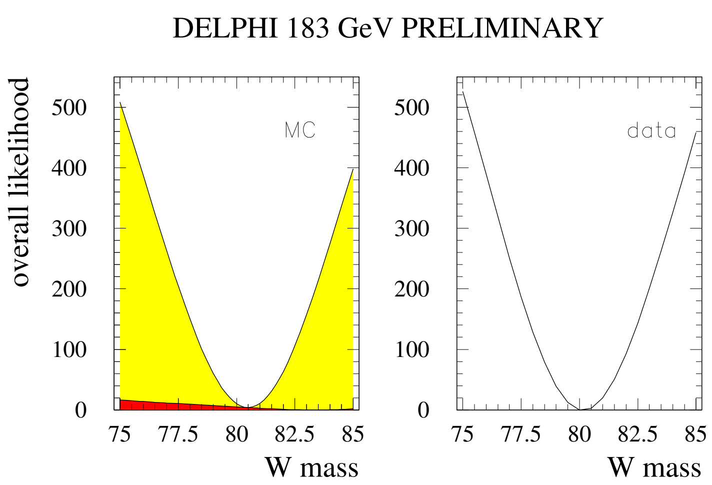
★ $\Rightarrow$ event PDF (all jet pairings used !)

★ calculate overlap integral of event PDF with a 2D Breit-Wigner, $\mathcal{BW}(M_W)$ $\Rightarrow$ event likelihood, $\mathcal{L}^i(M_W)$





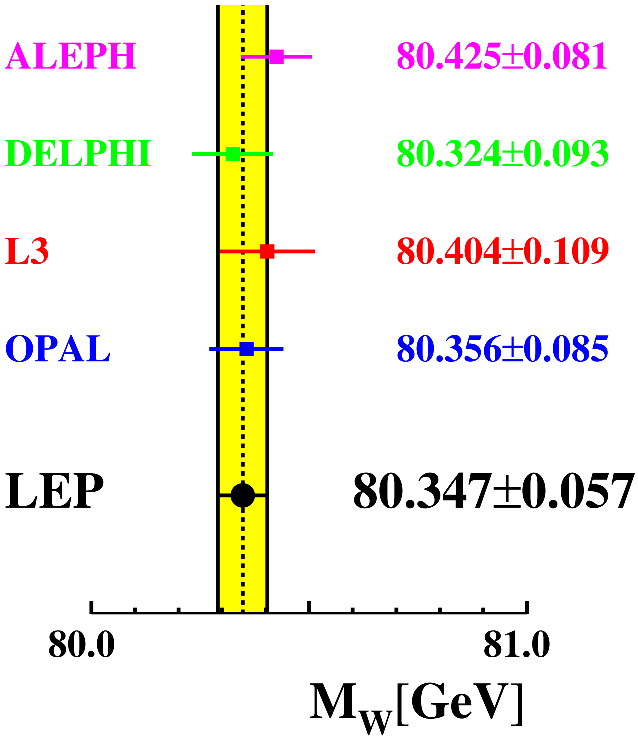
★ $\mathcal{L}(M_W) = \sum_i \mathrm{PDF}_i \otimes \mathcal{BW}(M_W)$



Results (172-189 GeV)

(189 GeV results all preliminary)

Combining $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$:



LEP COMBINED:

$q\overline{q}\ell\overline{\nu}_\ell$	: 80.313 $\pm$ 0.052 $\pm$ 0.036 GeV
$q\overline{q}q\overline{q}$	: 80.429 $\pm$ 0.049 $\pm$ 0.074 GeV

M_W from $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$:

- ★ **Similar statistical errors**
- ★ **Systematic much larger in $q\overline{q}q\overline{q}$**
- ★ **Weight of $q\overline{q}q\overline{q}$ in combination $\sim \frac{1}{3}$!**

Systematic Uncertainties

Typical Systematic Errors:

Source	ΔM_W (MeV) $q\bar{q}\ell\bar{\nu}_\ell$	ΔM_W (MeV) $q\bar{q}q\bar{q}$
Detector calibration	15	5
non-WW background	5	5
MC statistics	10	10
Hadronization	25	25
Initial state radiation	5	5
Beam energy	15	15
Final State Interactions (FSI)	0	70
Total Systematic	35	80
Statistical (LEP 600 pb^{-1})	30	30

Systematic errors reflect POSSIBLE inadequacies of MC simulation

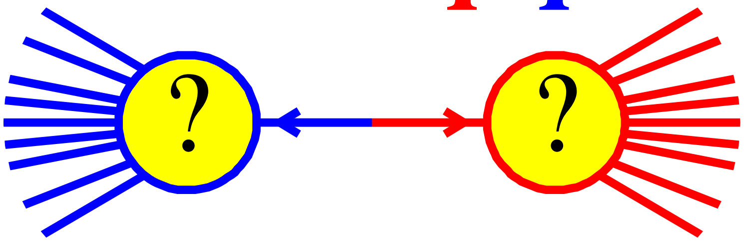
Most Worrying Systematics (my biased view)

- ★ F.S.I.
- ★ Hadronization (detector response to quarks)

Correlated between 4 experiments !

Hadronization Systematics

$\mathbf{W \rightarrow q\ q}$



- ★ Process of $q \longrightarrow$ hadrons
- ★ Compare JETSET string model with HERWIG cluster model
- ★ Both models tuned at Z^0
- ★ $\sim$ 25 MeV systematic uncertainty

Final State Interactions (FSI)

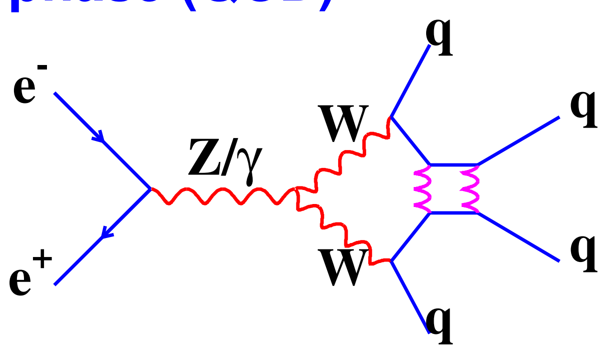
Largest systematic: FSI

- ★ Only affects $\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}q\bar{q}}$
- ★ Standard MCs assume independent fragmentation for the two W bosons
- ★ W-decay length $\sim$0.1 fm
- ★ Hadronization scale $\sim$1 fm
- ★ Interactions between W-decay products during fragmentation process ➡ Mass shifts.

Final State Interactions

Colour Reconnection

Perturbative phase (QCD)



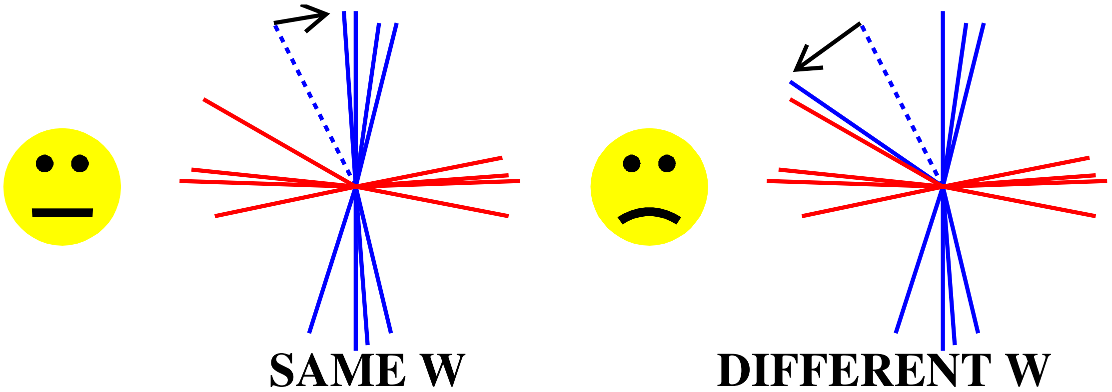
- Suppressed by 2 gluon exchange + colour
- Negligible mass shifts < 10 MeV

Hadronization phase (non-perturbative)

- Rely on models (string, cluster...)
- Mass bias ? : Predictions from 0-100 MeV

Bose-Einstein Correlations

- BEC - Quantum mechanical effect
- Like-sign pions closer in phase space
- BEC between pions from different Ws ?



Systematic Error from FSI

Sys. Errors estimated by comparing Models

Some typical values:

Model	Effect	Mass shift
Herwig	CR	$\sim$ 10-30 MeV
Pythia	CR	$\sim$ 20-50 MeV
Ariadne	CR	$\sim$ 50-100 MeV
Pythia	BE	$\sim$ 20-50 MeV
KoralW	BE	$\sim$ 20-50 MeV

Tests of CR

- ★ **Would like to test above models**
- ★ **For CR most sensitive observable is M_{W} ?**

LEP COMBINED

$$M_{\mathrm{W}}^{\mathrm{q\overline{q}q\overline{q}}} - M_{\mathrm{W}}^{\mathrm{q\overline{q}}\ell\overline{\nu}_\ell} = 152 \pm 74 \text{ MeV}$$

- ★ **Not a useful test !**

Tests of BEC

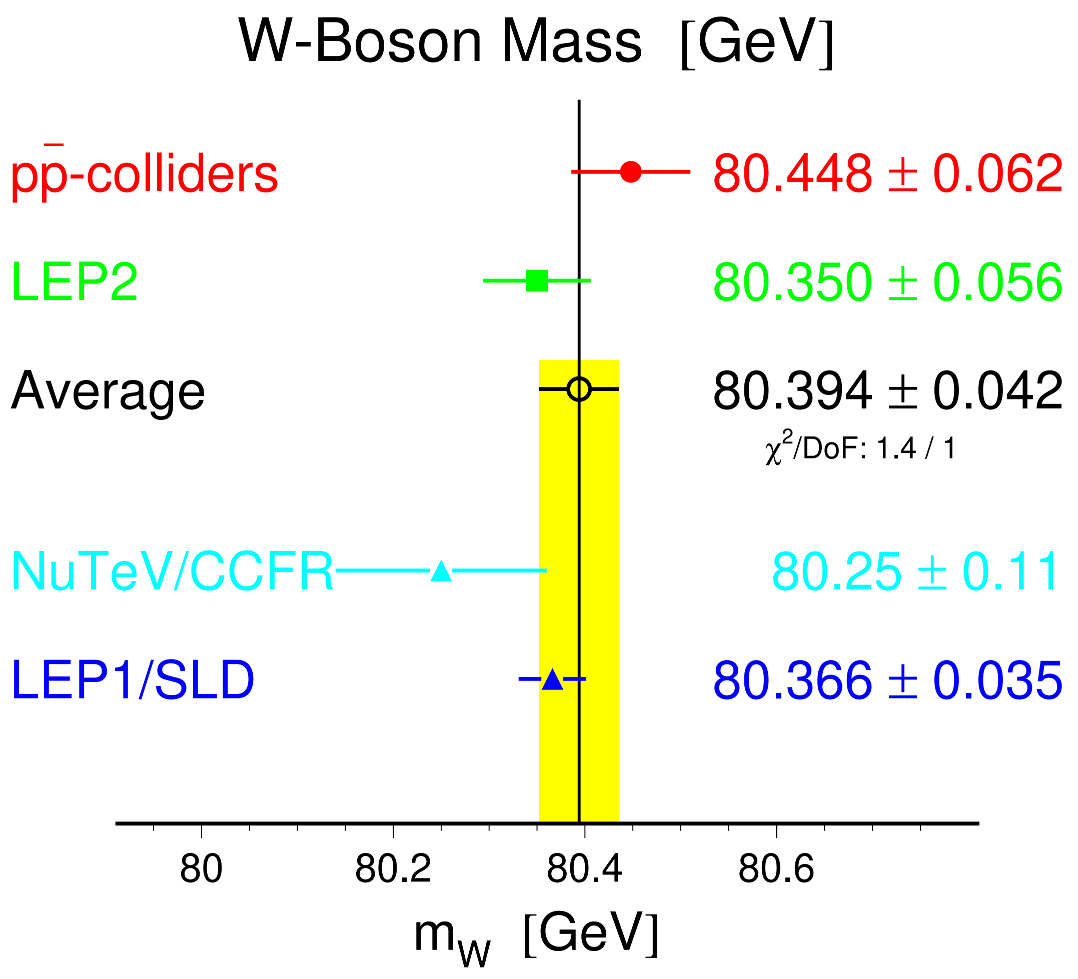
- ★ **More promising....**
- ★ **....but for now not clear**

Combined M_W Result

LEP Combined M_W including M_W from cross section at 161 GeV : 80.40$\pm$0.22 GeV

M_W(LEP) = 80.350 $\pm$0.056 GeV

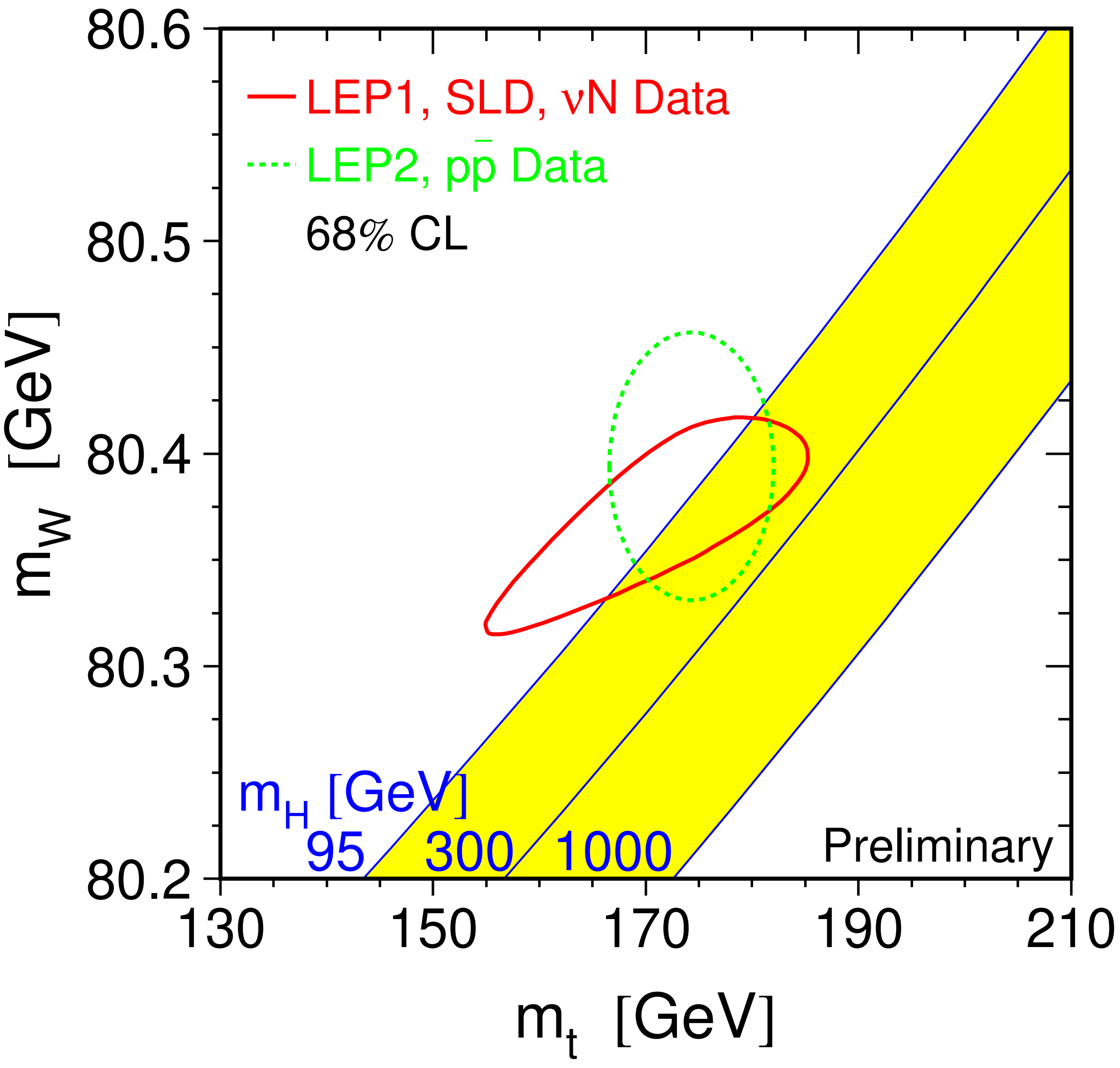
CURRENT WORLD AVERAGE



- ★ **Direct measurements consistent with SM theoretical prediction using LEP1/SLD measurements of M_{Z^0}, etc.**
- ★ **Powerful test of the theory**

Direct vs. Indirect

- **DIRECT : measurements of $M_{\mathbf{W}}$ and $M_{\mathbf{top}}$ from TeVatron and LEP**
- **INDIRECT : Electroweak data *excluding* direct measurements of $M_{\mathbf{W}}$ and $M_{\mathbf{top}}$**



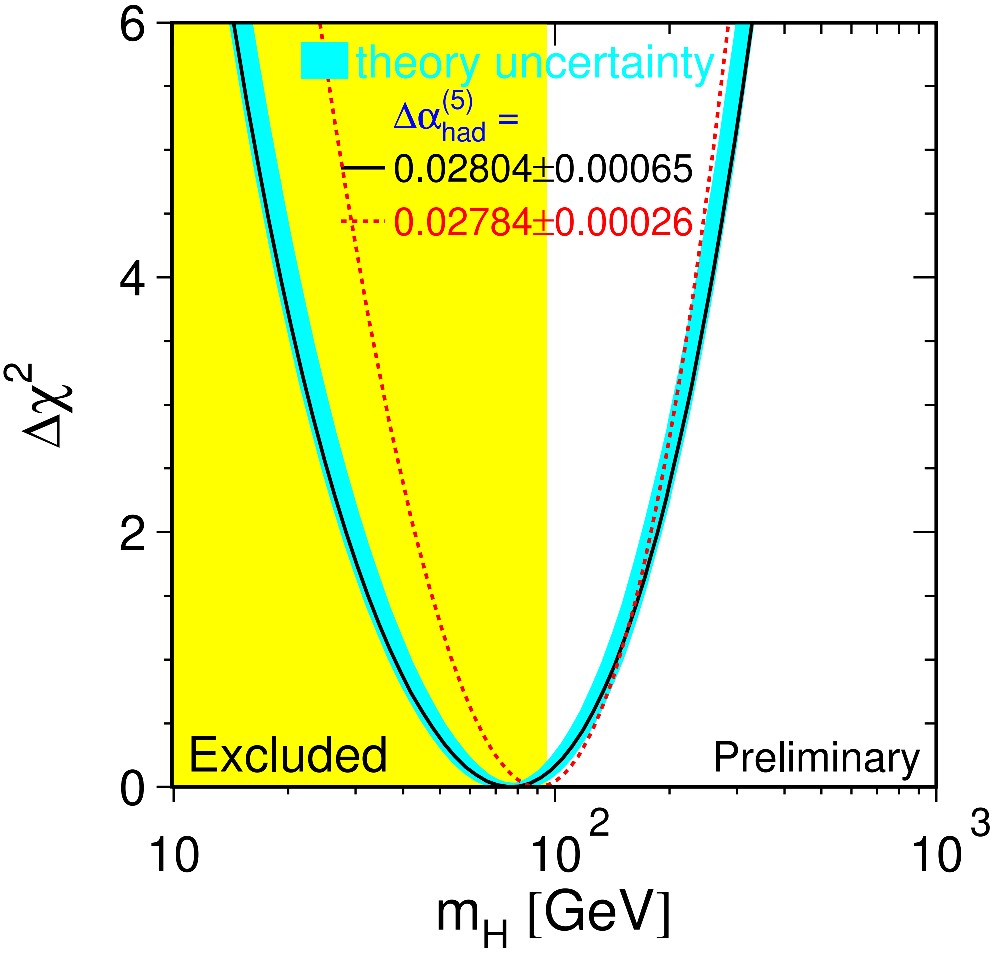
Direct measurements of $(M_{\mathbf{W}}, M_{\mathbf{top}})$ + $(\mathrm{M_Z}, \mathrm{G}_\mu, \alpha_{\mathrm{em}})$:

- $\mathbf{m_{Higgs} = 74^{+106}_{-55} GeV}$

Electroweak Fit Results

Direct + Indirect

- $m_{\mathrm{Higgs}} = 76^{+68}_{-38}$ GeV



$m_{\mathrm{Higgs}} < 215$ GeV (95 % C.L.)

- ★ **Measurements favour a light Higgs !**
- ★ **Hope for LEP, TeVatron, LHC**
- ★ **(IF it exists...)**

❺ Outlook and Conclusions

Ultimate LEP M_{W}

★ **Assume 600 pb^{-1}/expt.**

★ **My guestimates are not pessimistic !**

Source	ΔM_{W} (MeV)		
	$\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$	$\mathrm{q\overline{q}q\overline{q}}$	Comb
Detector calibration	5	5	5
non-WW background	5	5	
Hadronization	10	5	5
$O(\alpha_{em})$ + ISR	5	5	5
Beam energy	12	12	12
FSI	0	0-100	0-10
Statistical	30	30	20-30
Systematic	20	15-100	15-20
Total	35	35-105	25-35

★ **Final LEP M_{W} Error $25 - 35$ MeV**

★ **Depends on FSI error**

Conclusions

eM_W at LEP :

★ M_W to ± 56 MeV (0.07 %)

★ Ultimate LEP stat. precision $\sim$20 MeV

★ Important test of SM

★ Provide info on m_{Higgs}

BUT

★ FSI could kill $W^+W^- \to q\bar{q}q\bar{q}$ channel

★ Vital to understand these effects

➠ 4 LEP experiments share knowledge

➠ Experimentalists $\leftrightarrow$ Theorists

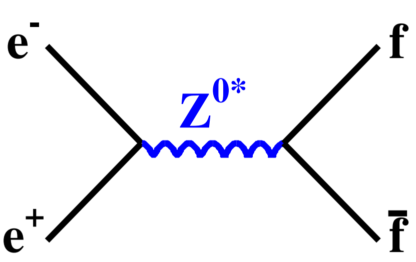
Inter-collaboration collaboration has started

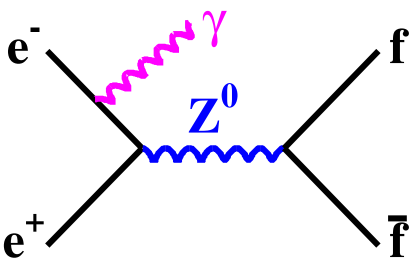
★ First LEP W-Workshop : WW'99 (Crete)

★ Continuing Effort.... WW'00 (???)

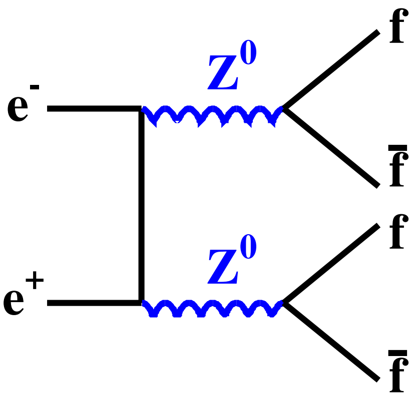
Backgrounds to W^+W^-

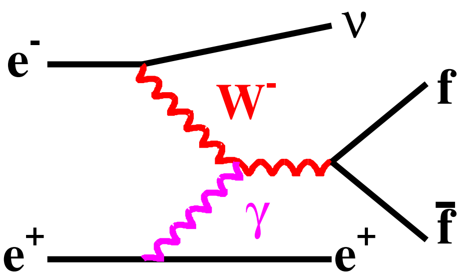
2F



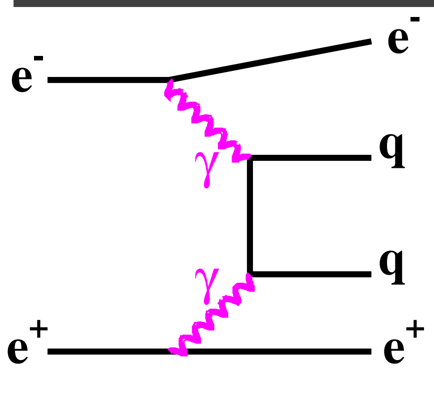


4F



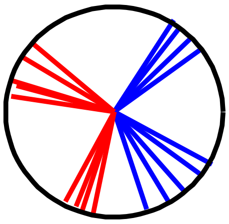


TWO-PHOTON



Selections : $W^+W^- \to q\bar{q}q\bar{q}$

$WW \to qqqq$

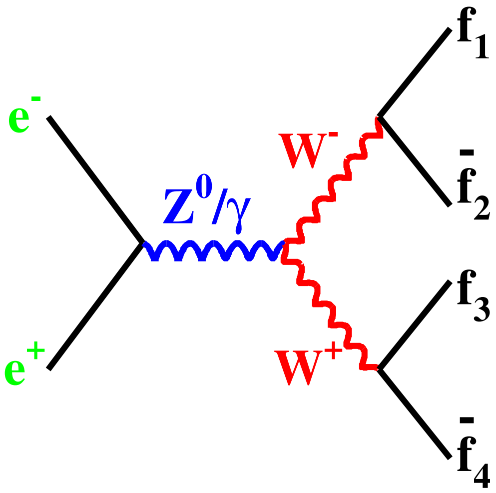


- **Multivariate analysis to separate**
  $W^+W^- \to q\bar{q}q\bar{q}$ and
  $Z^0/\gamma \to q\bar{q} \to$ 4 jets

SIGNAL:

$WW \to qqqq$

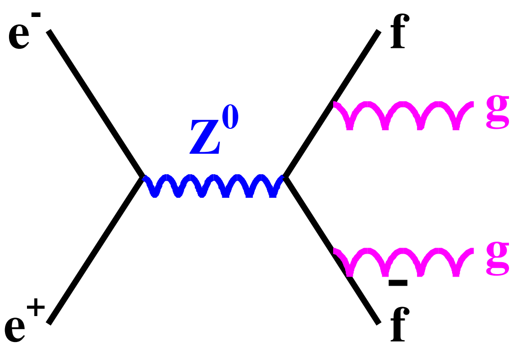
$\sigma \sim 8$ pb



BACKGROUND

$Z \to qq\,gg$

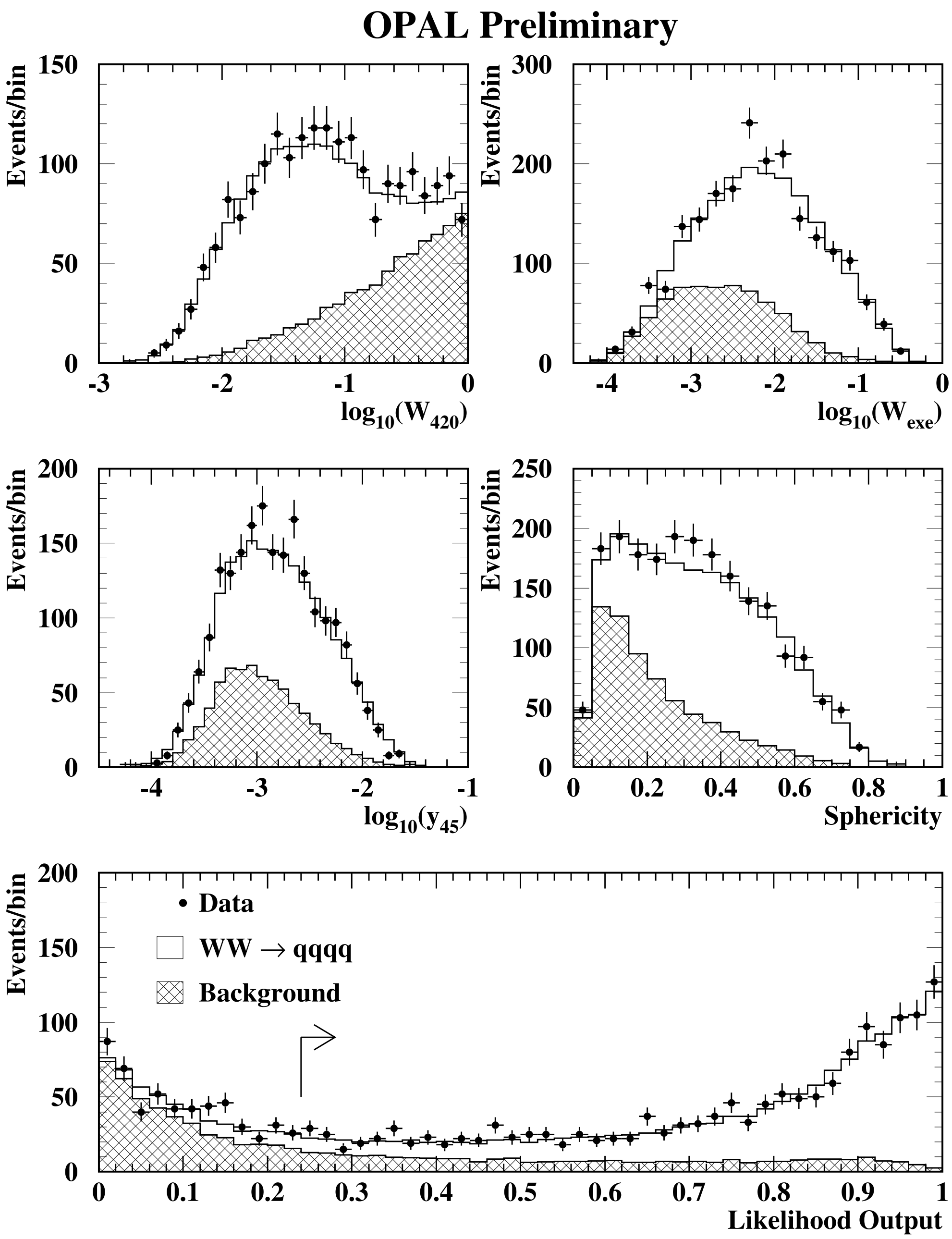
$\sigma_{qq(gg)} \sim 100$ pb



SELECTION:

Loose Cuts to select 4-jet events

Likelihood Using 4 variables



For $\sqrt{s} = 189$ GeV:

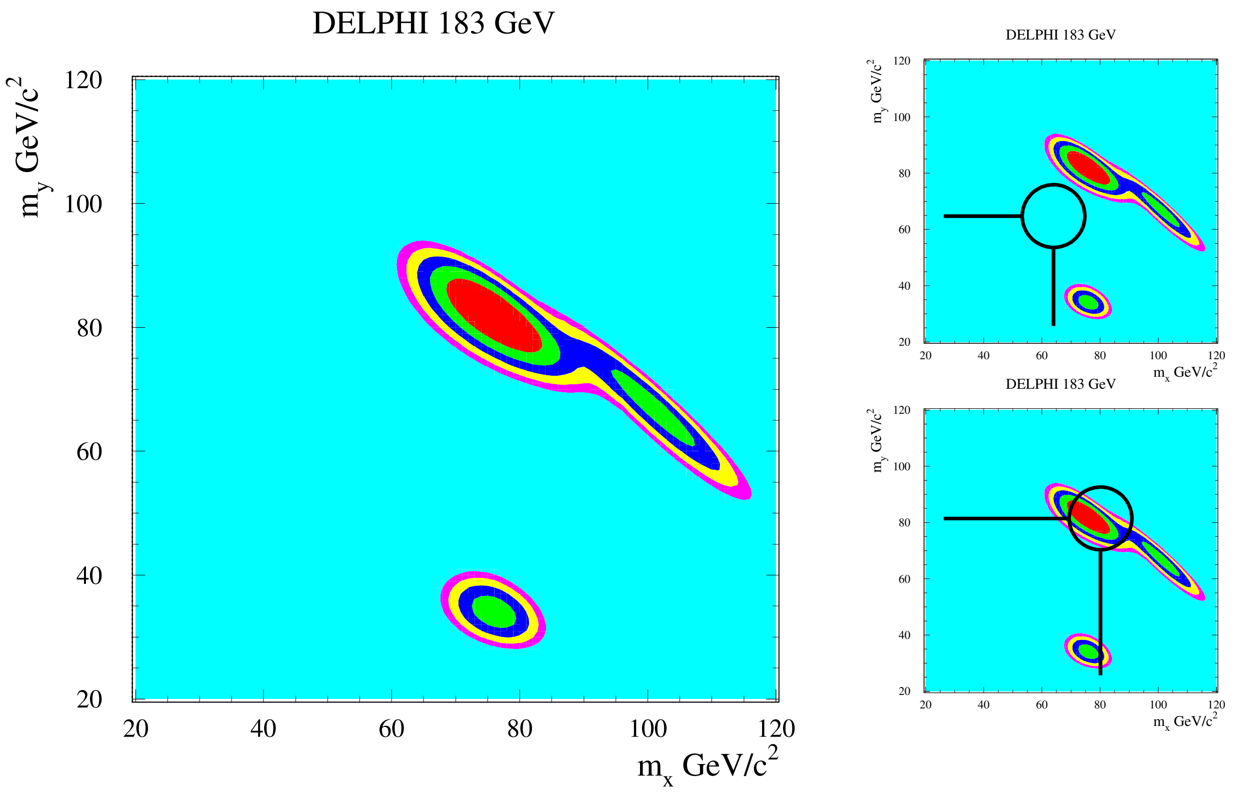
	Efficiency	Purity
OPAL	$\sim 86\%$	$\sim 79\%$

③ Convolution Fit : DELPHI

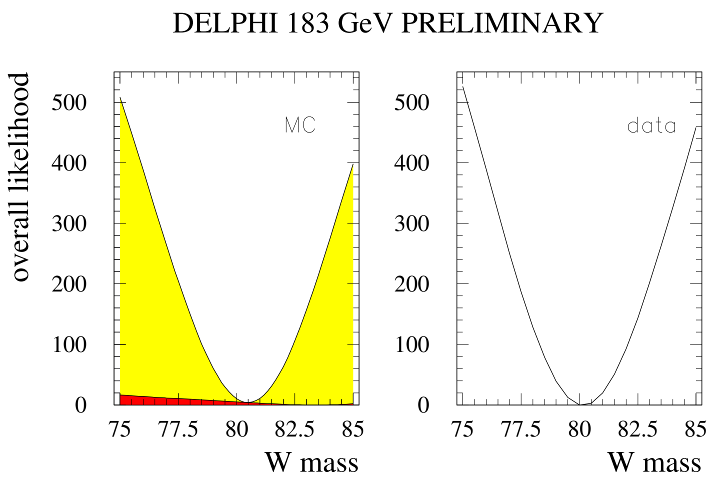
★ Use 4C fit $\Rightarrow$ 2 masses for each jet pairing

★ $\Rightarrow$ event PDF (all jet pairings used !)

★ calculate overlap integral of event PDF with a 2D Breit-Wigner, $\mathcal{BW}(M_{\mathrm{W}}) \Rightarrow$ event likelihood, $\mathcal{L}^{i}(M_{\mathrm{W}})$



★ $\mathcal{L}(M_{\mathrm{W}}) = \sum_i \mathrm{PDF}_i \otimes \mathcal{BW}(M_{\mathrm{W}})$



Advantages/Disadvantages

Which Method is best ?

At WW'99 Crete : all methods have similar inherent statistical sensitivity $\pm 5\ \%$

Breit-Wigner

- ✔ **Simple/Robust**
- ✘ **Needs Monte Carlo calibration: $\mathrm{M}_{fit} \longrightarrow \mathrm{M}_{true}$**
- ✘ **Arbitrary Fit function**
- ✘ **Least statistical power**

Reweighting

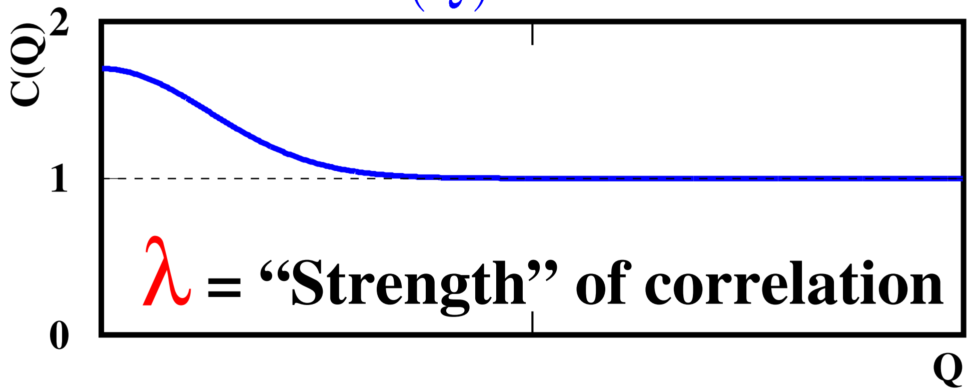
- ✔ **Simple/Unbiased**
- ✔ **No calibration**
- ✘ **Still requires MC describes data**
- ✘ **Requires lots of MC**

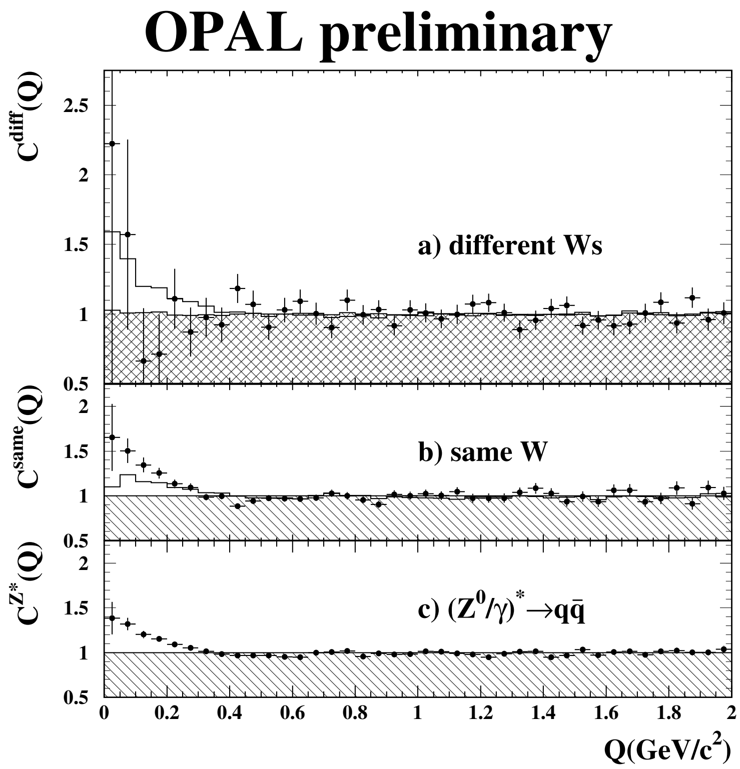
Convolution

- ✔ **Statistical power**
- ✔ **Elegant...**
- ✘ **Requires bias correction**
- ✘ **Slow: computationally intensive**

Experimental Status of BEC in WW

$$C(Q) = \frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}; \quad Q^2 = M^2(\pi\pi) - 4m_\pi^2$$





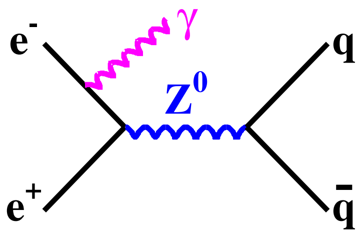
$$\lambda^{same} = 0.69 \pm 0.12 \pm 0.06$$

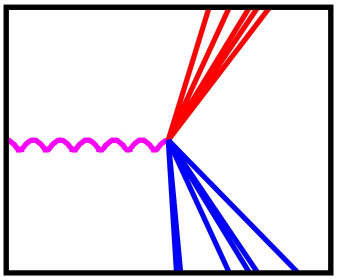
$$\lambda^{diff} = 0.05 \pm 0.67 \pm 0.35$$

- ★ **Current situation unclear**
- ★ **But by end of LEP ...**

Detector/Hadronization Systematics

Many Cross-Checks e.g. Radiative Z^0

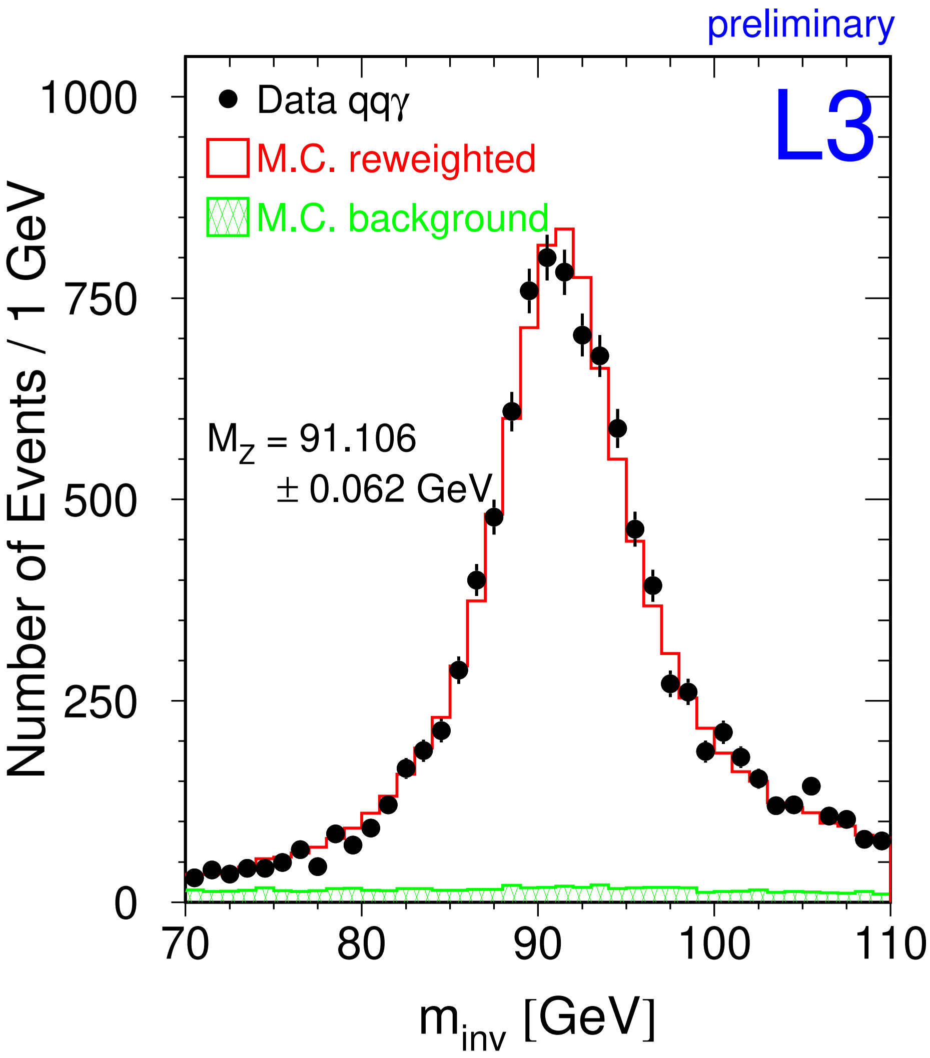




$$\mathrm{M}_{\mathbf{q\bar{q}}} = M_{\mathbf{Z^0}}$$

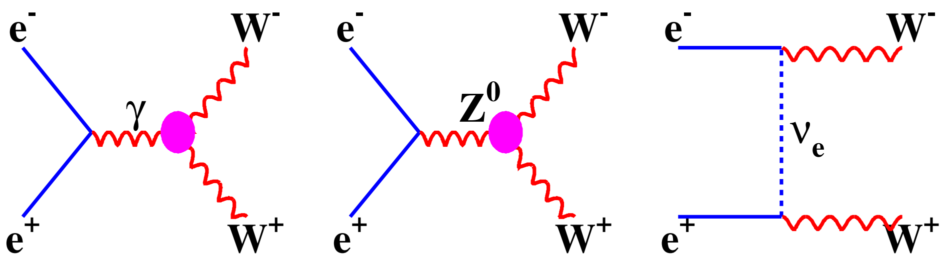
★ **Reconstruct $\mathrm{M}_{\mathbf{q\bar{q}}}$ using kinematic fit.**

★ **Fit by reweighting MC**

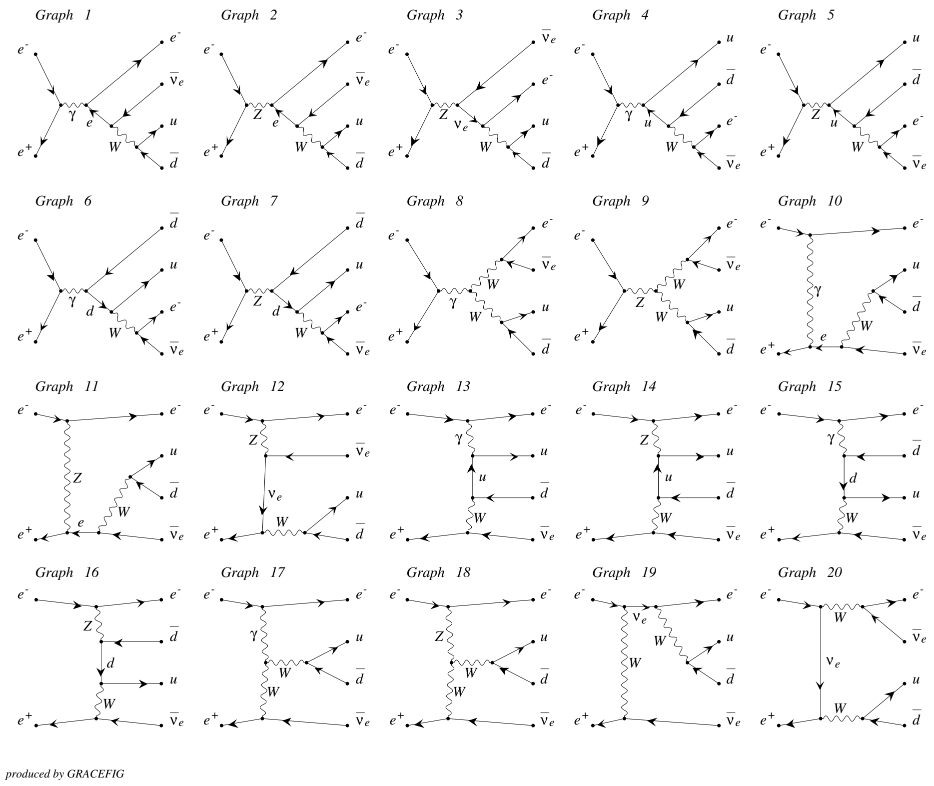


W^+W^- Cross Section

Want measure W^+W^- Cross section (CC03)



Correct for background and interference from other four-fermion diagrams, e.g. $\mathrm{q\overline{q}e\overline{\nu}_e}$



★ **Effective 4f background:**

$$\sigma(4f)^{ACC} - \sigma(CC03)^{ACC}$$

'CC03' Cross-section not Gauge Invariant

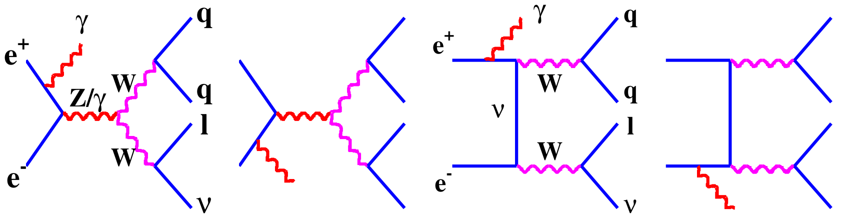
It could be worse....

144 diagrams for $e^+e^- \rightarrow e^+e^-e^+e^-$

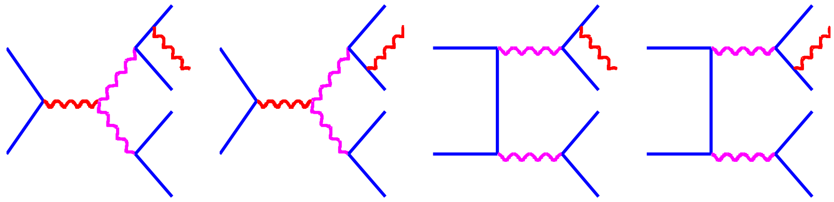
★ **Wait until 500 GeV linear collider:**
$e^+e^- \rightarrow 6$ **fermions**

$O(\alpha_{em})$ Corrections

ISR

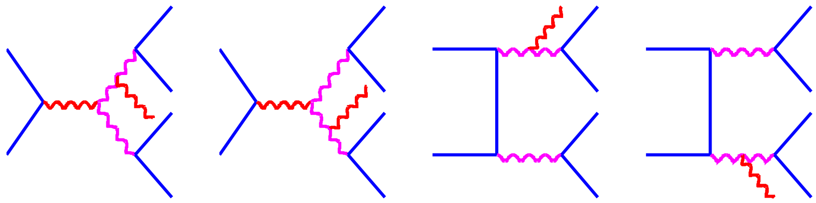


FSR
(quark)



FSR
(lepton)

WSR



QGC