Measurement of $|V_{cs}|$ with the OPAL Detector

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Outline:

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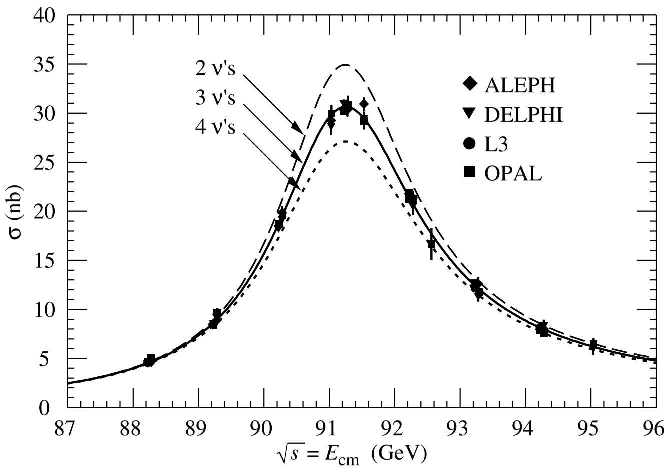
Testing the Standard Model

- Success of the Standard Model over the last two decades has (perhaps) obscured the importance of thoroughly investigating the weak interaction.
- The situation 15 years ago looked like this[a]:
  - $\sin^2\theta_W = 0.217 \pm 0.014$
  - $M_W(\text{indirect}) = 83.0 \pm 2.8$ GeV
  - $M_Z(\text{indirect}) = 93.8 \pm 2.3$ GeV
- Today, we have *measured* $\Delta\sin^2\theta_W = 0.0002$, $\Delta M_Z = 0.002$ GeV, and $\Delta M_W = 0.06$ GeV !
  $\longrightarrow$ the SM success is so thorough, can only be wrong at the quantum loop level... and even then beyond leading order.

Nevertheless, measuring fundamental parameters of the SM and comparing them with the theoretical expectations is no less important today than it was 20 years ago. SM success just makes it more difficult.



[a] W.J.Marciano and A.Sirlin, Phys.Rev. **D29** (1984) 945.

W Mass at LEP2

All LEP experiments with data collected at $\sqrt{s} = 172 - 183 - 189$ GeV:

$\Delta\ M_W$(MeV)	$q\bar{q}q\bar{q}$	$q\bar{q}\ell\bar{\nu}_\ell$
Stat. Error	49	52
Exp. Systematic	43	32
FSI	58	0
LEP Energy	17	17

LEP Preliminary (Fall 99)

$$M_W = (80.350 \pm 0.056)\ \text{GeV}$$

Remark: Final results for Moriond/Summer 2000.

FUTURE: At the end of the LEP2 program with $\int \mathcal{L}\, dt \approx 500\text{pb}^{-1}$.

$\Delta\ M_W$(MeV)	$q\bar{q}q\bar{q}$	$q\bar{q}\ell\bar{\nu}_\ell$	Total
Stat. Error	35	35	25
Total Systematic	74	35	40

SM Higgs Search

PRELIMINARY Limit on the SM Higgs mass with data collected at $\sqrt{s} = 161 - 202$ GeV:

At the end of 99 run experiments reported preliminary limits up to:

$$m_H > 106 \text{ GeV } (95\% \text{ CL})$$

FUTURE: LEP coordinator proposed a total of 200 pb^{-1} at high energy, of which about 40^{-1} will be devoted to achieve the very highest possible energy.

Expected limit for stable running at 206 GeV:

$$m_H > 114 \text{ GeV } (95\% \text{ CL})$$

Introduction: Why $|V_{\mathrm{cs}}|$?

Today, the SM provides a general description of the physics currently accessible with modern particle accelerators. However, many predictions of the SM still have to be verified:

- We are still searching for the Higgs boson.
- We are still seeking a better understanding of the electroweak properties of the neutral and charged mediators of the weak interaction.

The first concerns the origin of mass generation in the electroweak sector via the Higgs mechanism. The other deals with the origin of quark mixing and CP violation.

Quark Mixing

$$J_\mu^+ = (\bar{u}, \bar{c}, \bar{t})\,\frac{1}{2}\,\gamma_\mu\,(1-\gamma^5)\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM Matrix

CKM matrix element	Value(PDG98)
$\lvert V_{ud}\rvert$	0.9740 ± 0.0010
$\lvert V_{us}\rvert$	0.2196 ± 0.0023
$\lvert V_{cd}\rvert$	0.224 ± 0.016
$\lvert V_{cs}\rvert$	1.04 ± 0.16
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	0.08 ± 0.02
$\lvert V_{cb}\rvert$	0.0395 ± 0.0017

⇒So far direct measurements of $|V_{cs}|$ have limited precision compared to its CKM partners $|V_{ud}|$, $|V_{us}|$, and $|V_{cd}|$.

$$V \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

with the Cabibbo angle $\lambda \simeq 0.22$.

Using the measured values of the CKM matrix elements together with unitarity, and assuming ONLY 3 generations, the 90% CL on $|V_{ij}|$ are:

$$\begin{pmatrix} 0.9742-0.9757 & 0.219-0.226 & 0.002-0.005 \\ 0.219-0.225 & 0.9734-0.9749 & 0.037-0.043 \\ 0.004-0.014 & 0.035-0.043 & 0.9990-0.9993 \end{pmatrix}$$

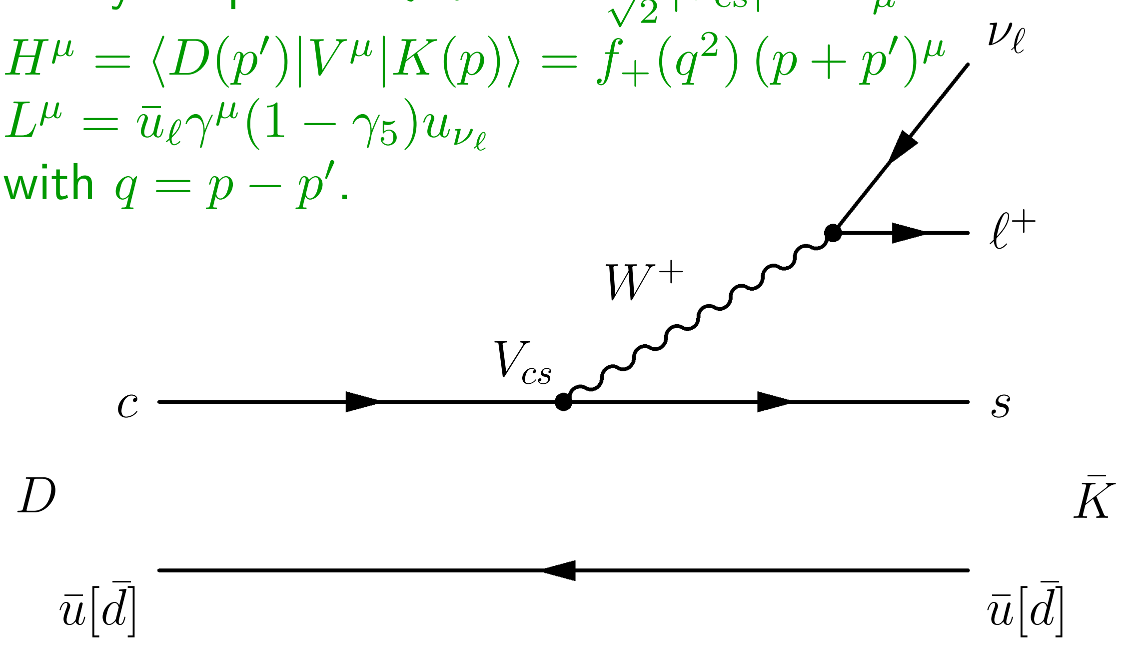
$|V_{cs}|$: $D \rightarrow \bar{K}\ell^+\nu_\ell$

Decay Amplitude: $\mathcal{M} = -i\frac{G_F}{\sqrt{2}}|V_{cs}|L^\mu H_\mu$ where

$H^\mu = \langle D(p')|V^\mu|K(p)\rangle = f_+(q^2)\,(p+p')^\mu$

$L^\mu = \bar{u}_\ell\gamma^\mu(1-\gamma_5)u_{\nu_\ell}$

with $q = p - p'$.



Most commonly assumed *forms* for the form factor are:

$f_+(q^2) = f_+(0)\,e^{\alpha q^2}$ and $f_+(q^2) = \frac{f_+(0)}{(1-q^2/M^2_{\rm pole})}$

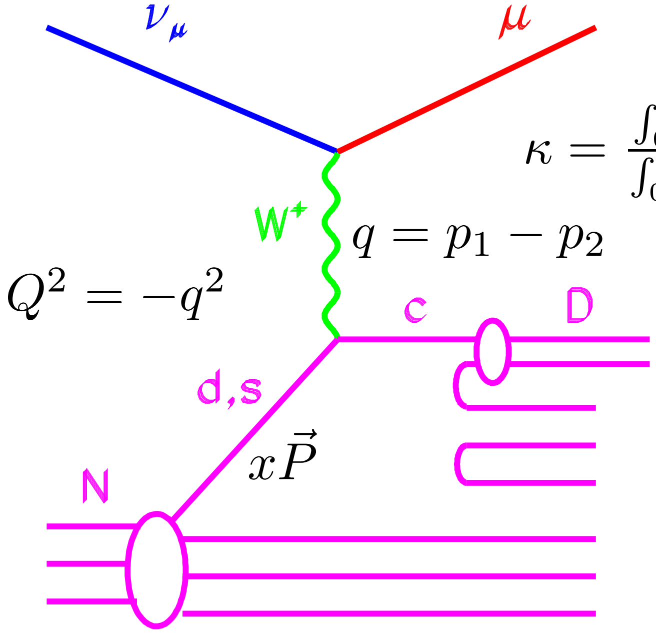
Normally $M_{\rm pole} = 2.1$ GeV is used. Then

$$\frac{d\,\Gamma(D\rightarrow\bar{K}\ell\nu_\ell)}{d\,q^2} = \frac{G_F^2\,|V_{cs}|^2\,p_D^3}{24\,\pi^3}\,|f_+(q^2)|^2$$

$\Gamma(D\rightarrow\bar{K}\ell\nu_\ell) = |f_+(0)|^2|V_{cs}|^2\,(1.54\times 10^{11}\ s^{-1})$.

$$\boxed{|V_{cs}| = 1.04 \pm 0.16}$$

$|V_{cs}|$: NuTeV



$$\kappa = \frac{\int_0^1 [xs(x,Q^2)+x\bar{s}(x,Q^2)]\,dx}{\int_0^1 [x\bar{u}(x,Q^2)+x\bar{d}(x,Q^2)]\,dx}$$

Value of $|V_{cs}|$ from neutrino beam depends on the strange quark density in the parton sea.

From di-muon sample: $\nu_\mu + N \to c + \mu^- + X$
$\quad \hookrightarrow s + \mu^- + \nu_\mu$

$$\Rightarrow \frac{\kappa}{\kappa+2}|V_{cs}|^2 = 0.200 \pm 0.015$$

from CCFR using runs E744 and E770 collected in 1985 and 1987, respectively.

Recently, inclusive $\nu - N$ interaction studies provide and independent measurement of kappa:

$$\kappa = 0.453 \pm 0.106^{+0.028}_{-0.096}$$

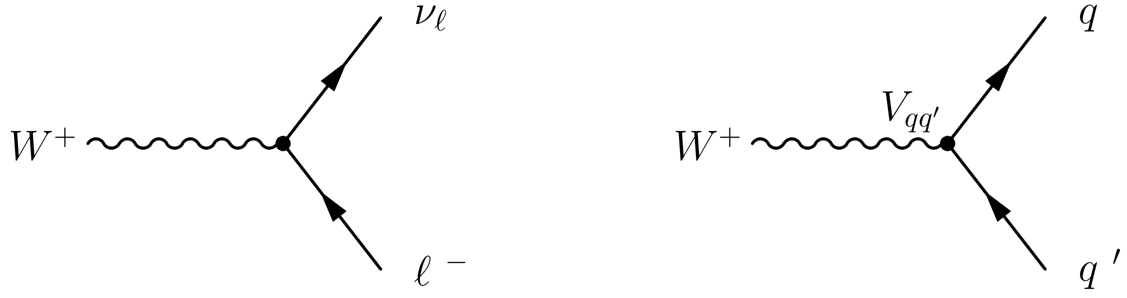
Leading to a preliminary result of

$$\boxed{|V_{cs}| = 1.05 \pm 0.10^{+0.07}_{-0.11}}$$

$|V_{cs}|$: OPAL at LEP

In 1997 and 1998 the LEP e^+e^- collider was operated at energies well above the threshold for on-shell W pair production. This offers a unique opportunity to study the hadronic decays of W bosons in a clean environment and to investigate the coupling strength of W bosons to different quark flavours.

Direct Production of W's



Data Samples: The data used for this analysis was recorded by OPAL. The integrated luminosity used for the analysis amounts to $180.2\,\mathrm{pb}^{-1}$($56.5\,\mathrm{pb}^{-1}$) at a luminosity-weighted mean energy of 188.6 GeV(182.7 GeV).

Motivation

WW Production rate: $\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})$

$$\frac{\mathrm{Br}(\mathrm{q\bar{q}})}{(1-\mathrm{Br}(\mathrm{q\bar{q}}))} = \left(1+\frac{\alpha_s(M_\mathrm{W})}{\pi}\right) \sum_{i=\mathrm{u,c};\, j=\mathrm{d,s,b}} |\mathrm{V}_{ij}|^2$$

Charm Tagging:

$R_\mathrm{c}^\mathrm{W} \equiv \Gamma(\mathrm{W} \to cX)/\Gamma(\mathrm{W} \to \mathrm{q\bar{q}})$

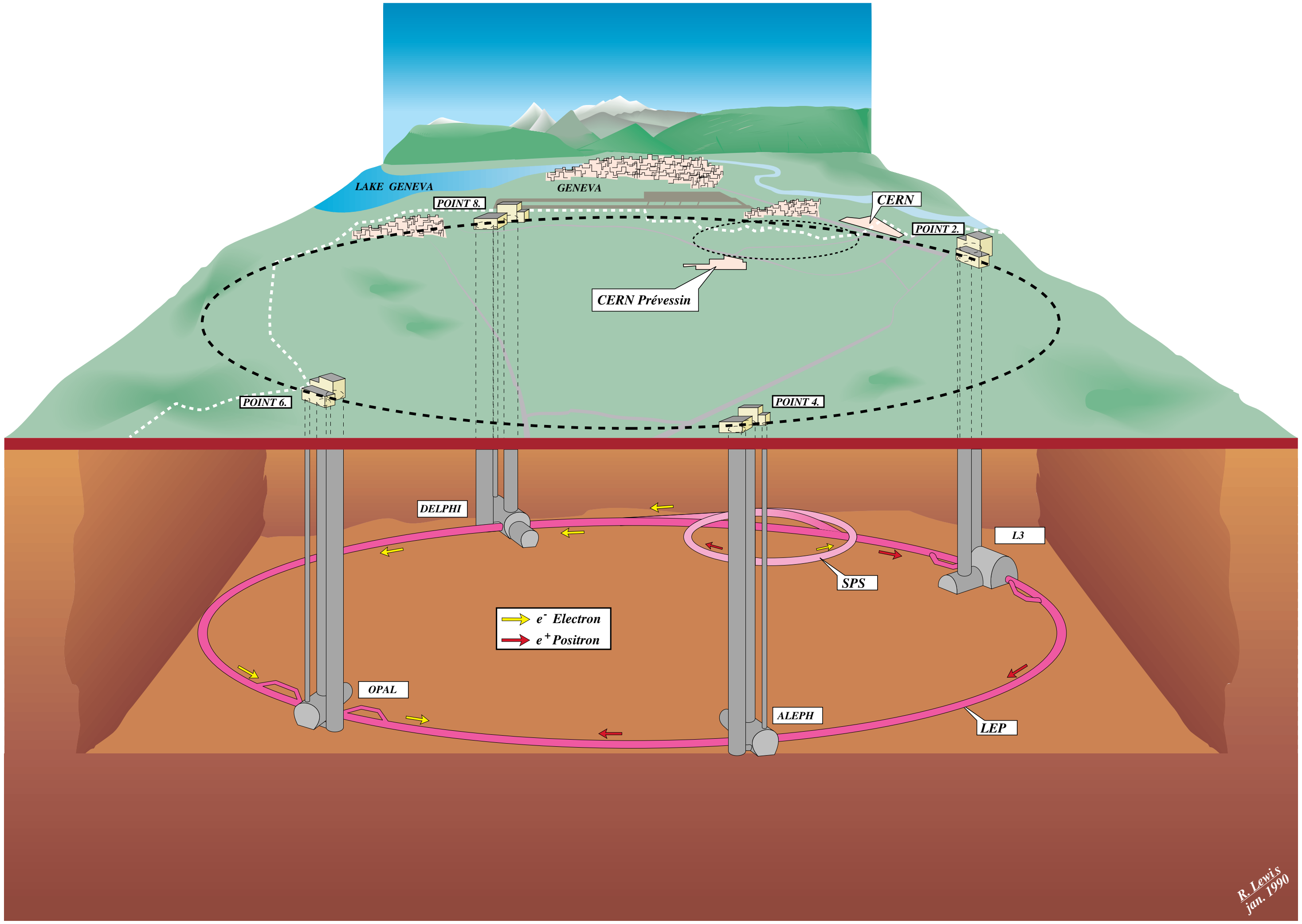
$$R_\mathrm{c}^\mathrm{W} = \frac{|V_\mathrm{cd}|^2+|V_\mathrm{cs}|^2+|V_\mathrm{cb}|^2}{|V_\mathrm{ud}|^2+|V_\mathrm{us}|^2+|V_\mathrm{ub}|^2+|V_\mathrm{cd}|^2+|V_\mathrm{cs}|^2+|V_\mathrm{cb}|^2}$$

$\Longrightarrow$ A measurement of R_c^W allows a direct **test of unitarity** of the CKM matrix in three generations within the framework of the Standard Model.

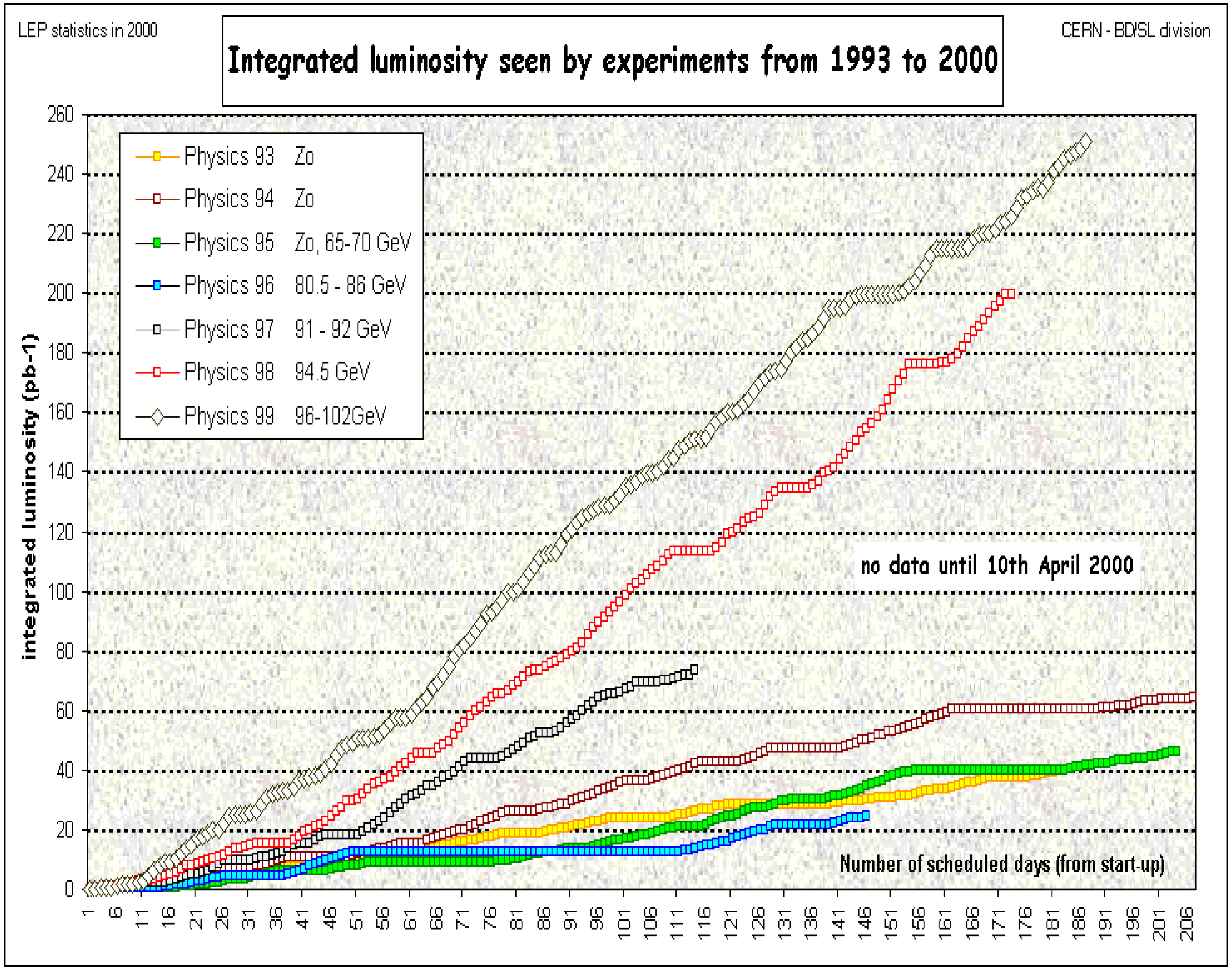
$\Longrightarrow$ $\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})$ and R_c^W lead to a measurement of $|V_\mathrm{cs}|$ using the measured values of the other CKM matrix elements.

At LEP2, the determination of $|V_\mathrm{cs}|$ with the OPAL data at $\sqrt{s} \simeq 183$ GeV and 189 GeV will be more accurate than the current world average.

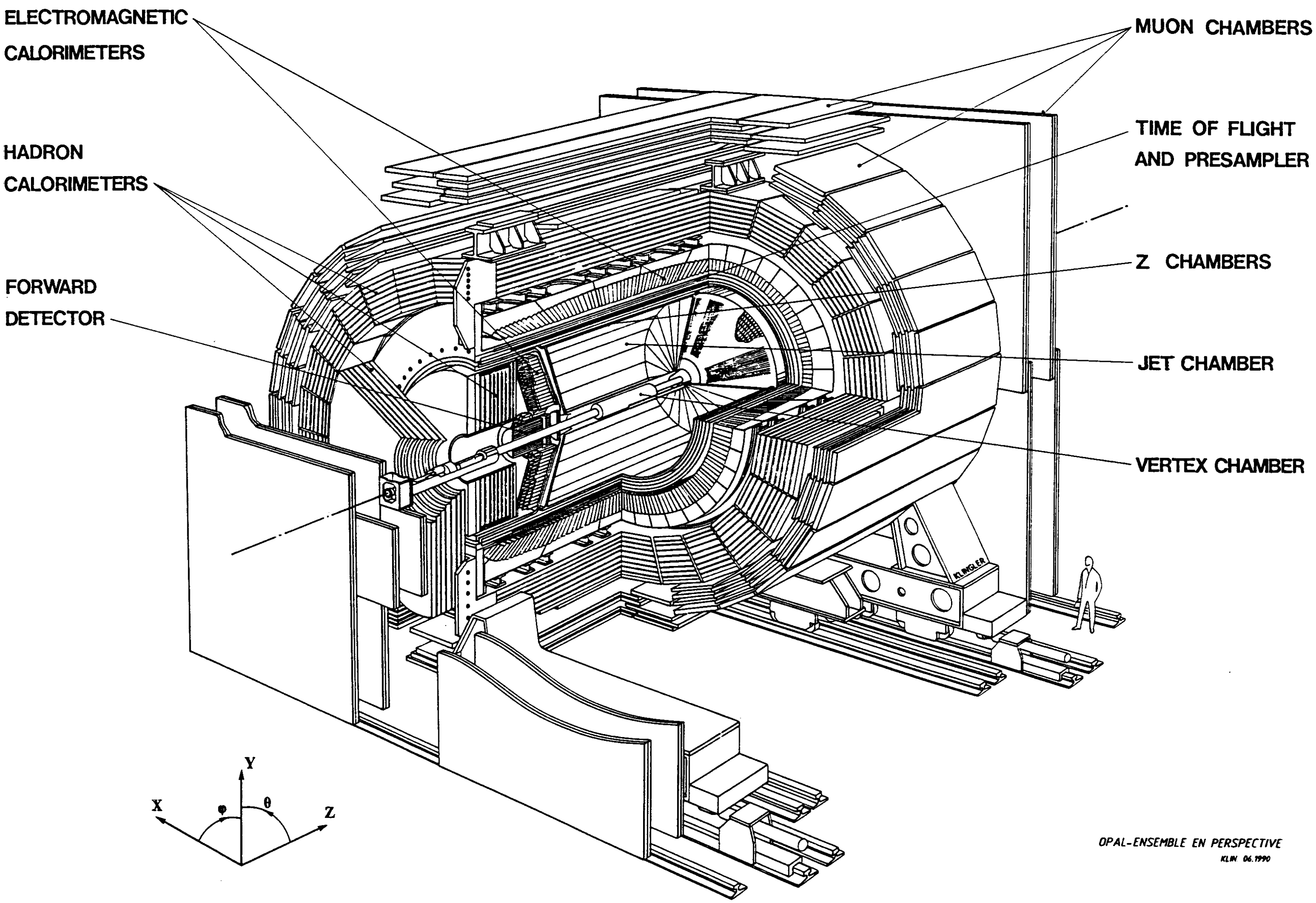
Experimental Apparatus: LEP



LEP Performance



Experimental Apparatus: OPAL

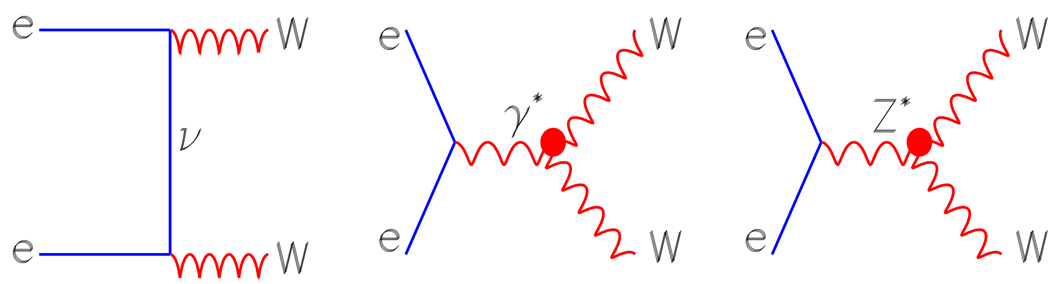


W Bosons Properties

WW Cross–Section and BR(W $\rightarrow q\bar{q}$)

Signal Process

$e^+e^- \rightarrow W^+W^-$ dominated by:



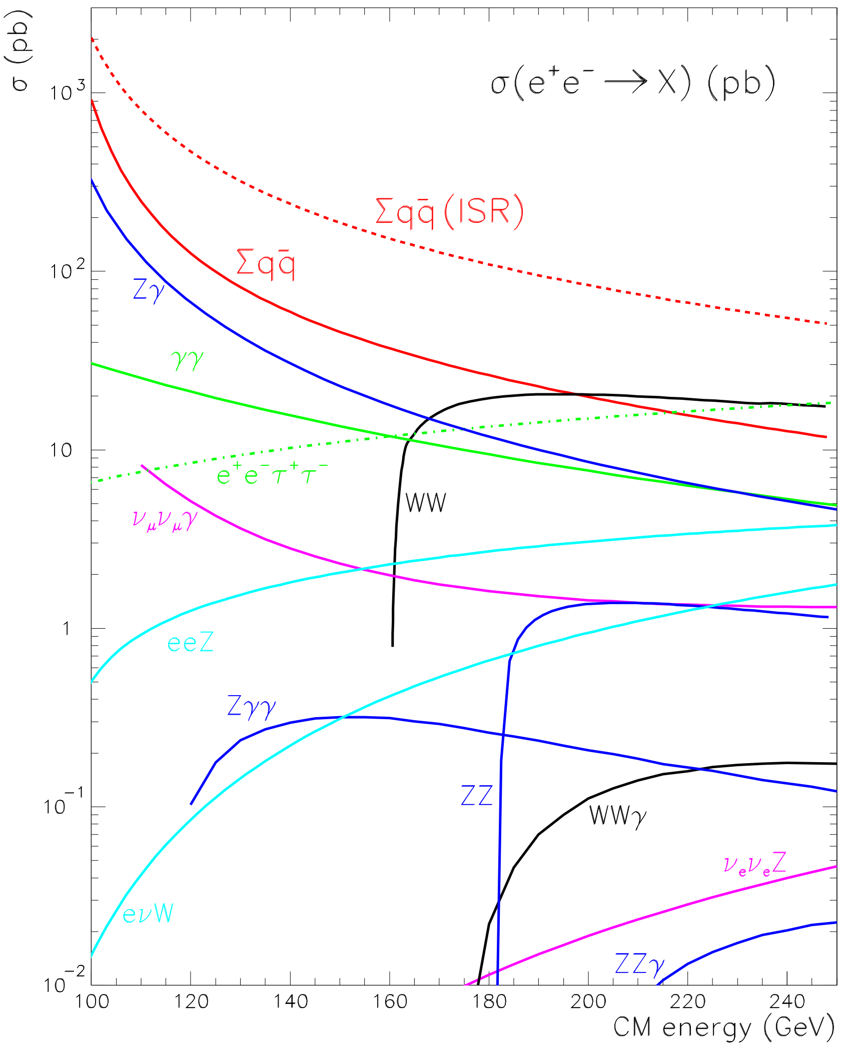
Each $W^{\pm}$ decays to $f\bar{f}$ pair. The $f\bar{f}f\bar{f}$ final states:

final state	BR
$q\bar{q}q\bar{q}$	45%
$q\bar{q}\ell\bar{\nu}_\ell$	44%
$\ell\bar{\nu}_\ell\ell\bar{\nu}_\ell$	11%

The expected production cross–sections are:

$\sqrt{s}$	$\sigma(e^+e^- \rightarrow WW)$
161 GeV	3.6 pb
172 GeV	12.4 pb
183 GeV	15.7 pb
189 GeV	16.7 pb

Background Processes



background	$\sigma(\sqrt{s}=183)$
$e^+e^- \longrightarrow Z/\gamma \longrightarrow q\overline{q}$	107 pb
$e^+e^- \longrightarrow Ze^+e^-$	2.8 pb
$e^+e^- \longrightarrow (Z/\gamma)^*(Z/\gamma)^*$	0.6 pb
$e^+e^- \longrightarrow We\nu$	0.6 pb

Remark: The background $e^+e^- \longrightarrow Z/\gamma \longrightarrow q\overline{q}$ is labelled "QCD" background and the rest "4-fermion" background.

$\mathrm{W^+W^-}$ Events

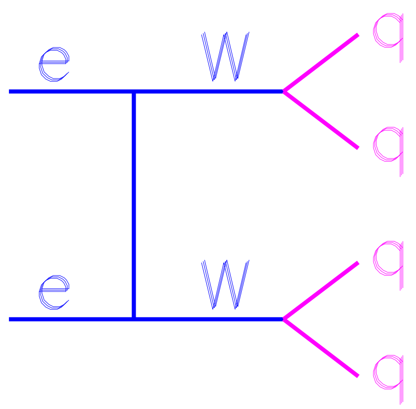
Event Characteristics:

- $\mathrm{W^+W^-} \rightarrow \ell^- \overline{\nu}_\ell \ell'^+ \nu_{\ell'}$
  - Two acoplanar and energetic leptons.
  - A lot of missing energy
- $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}}\ell\bar{\nu}_\ell$
  - Two hadronic jets.
  - One isolated and energetic lepton.
  - Missing energy.
- $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$
  - Four Hadronic jets.
  - No missing energy.
  - Large QCD background.

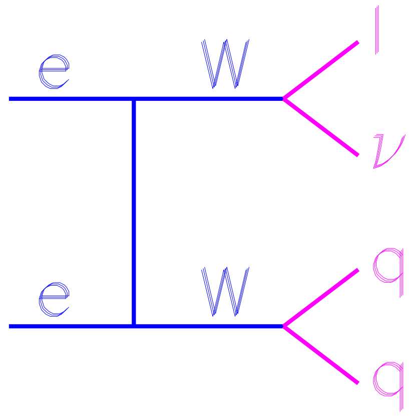
Events not selected as $\mathrm{W^+W^-} \rightarrow \ell^- \overline{\nu}_\ell \ell'^+ \nu_{\ell'}$ are passed to the $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}}\ell\bar{\nu}_\ell$ selection procedure and may be classified as $\mathrm{q\overline{q}e}\overline{\nu}$, $\mathrm{q\overline{q}}\mu\overline{\nu}$, or $\mathrm{q\overline{q}}\tau\overline{\nu}$. The $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$ selection is applied to events that fail the preceding selections.

Event Selection

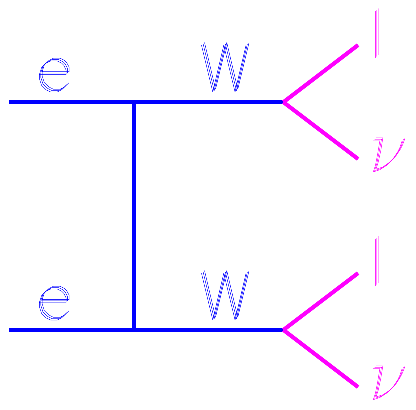
- Expected stat error: $\sim \frac{1}{\sqrt{\mathrm{N_{WW}}}} \cdot \frac{1}{\sqrt{\mathrm{Purity}}}$



$\mathrm{BR} \approx \mathbf{45\%}$
$\varepsilon = \mathbf{86\%}$
$\mathbf{P} = \mathbf{79\%}$



$\mathrm{BR} \approx \mathbf{44\%}$
$\varepsilon = \mathbf{87\%}$
$\mathbf{P} = \mathbf{90\%}$



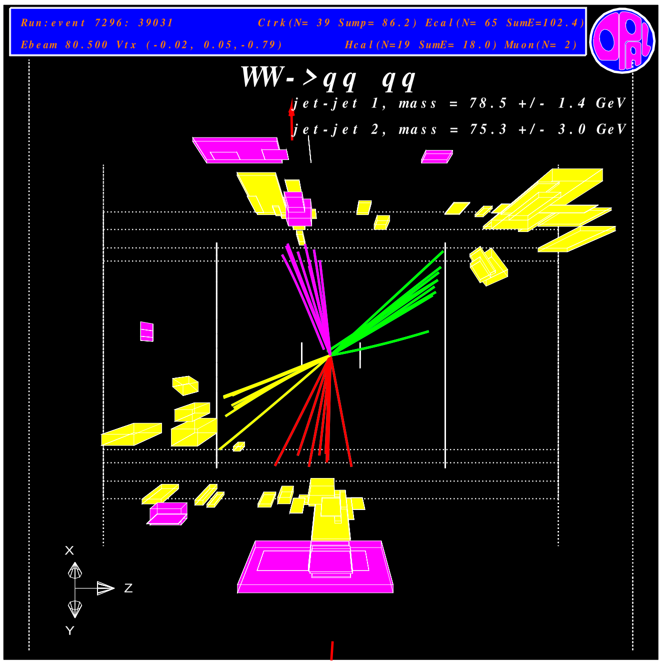
$\mathrm{BR} \approx \mathbf{11\%}$
$\varepsilon = \mathbf{82\%}$
$\mathbf{P} = \mathbf{90\%}$

For 1998 @ $\sqrt{s} = 189\,\mathrm{GeV}$ this gives (excl. $\ell\bar{\nu}_\ell\ell\bar{\nu}_\ell$):

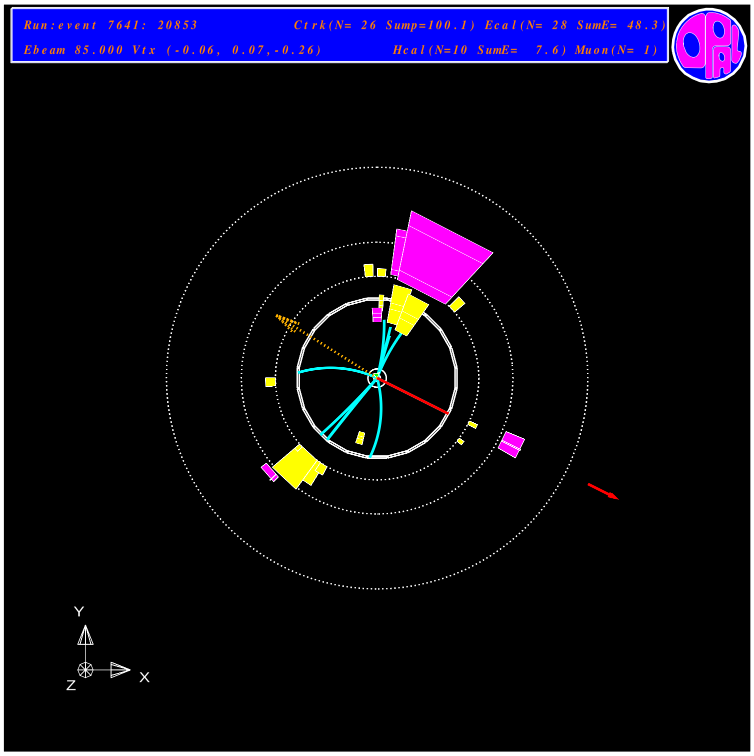
$\mathrm{N_{WW}} \approx 2000 \quad \mathrm{N_{bgd}} \approx 350$

Some Selected Events:

$WW \rightarrow q\bar{q}q\bar{q}$

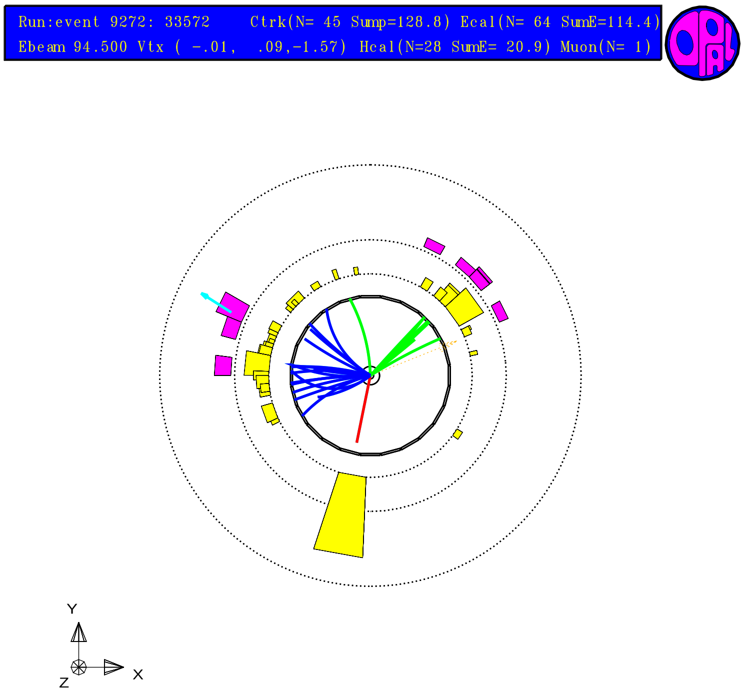


$WW \rightarrow q\bar{q}\mu\bar{\nu}$

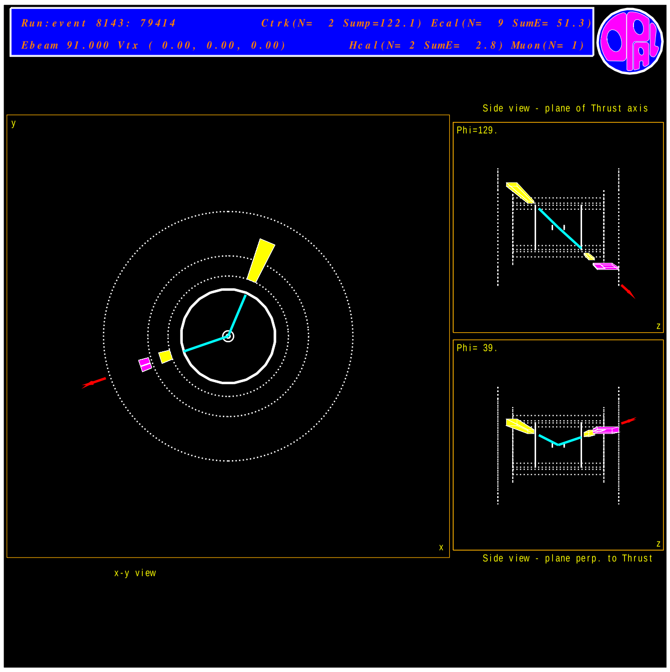


Some Selected Events:

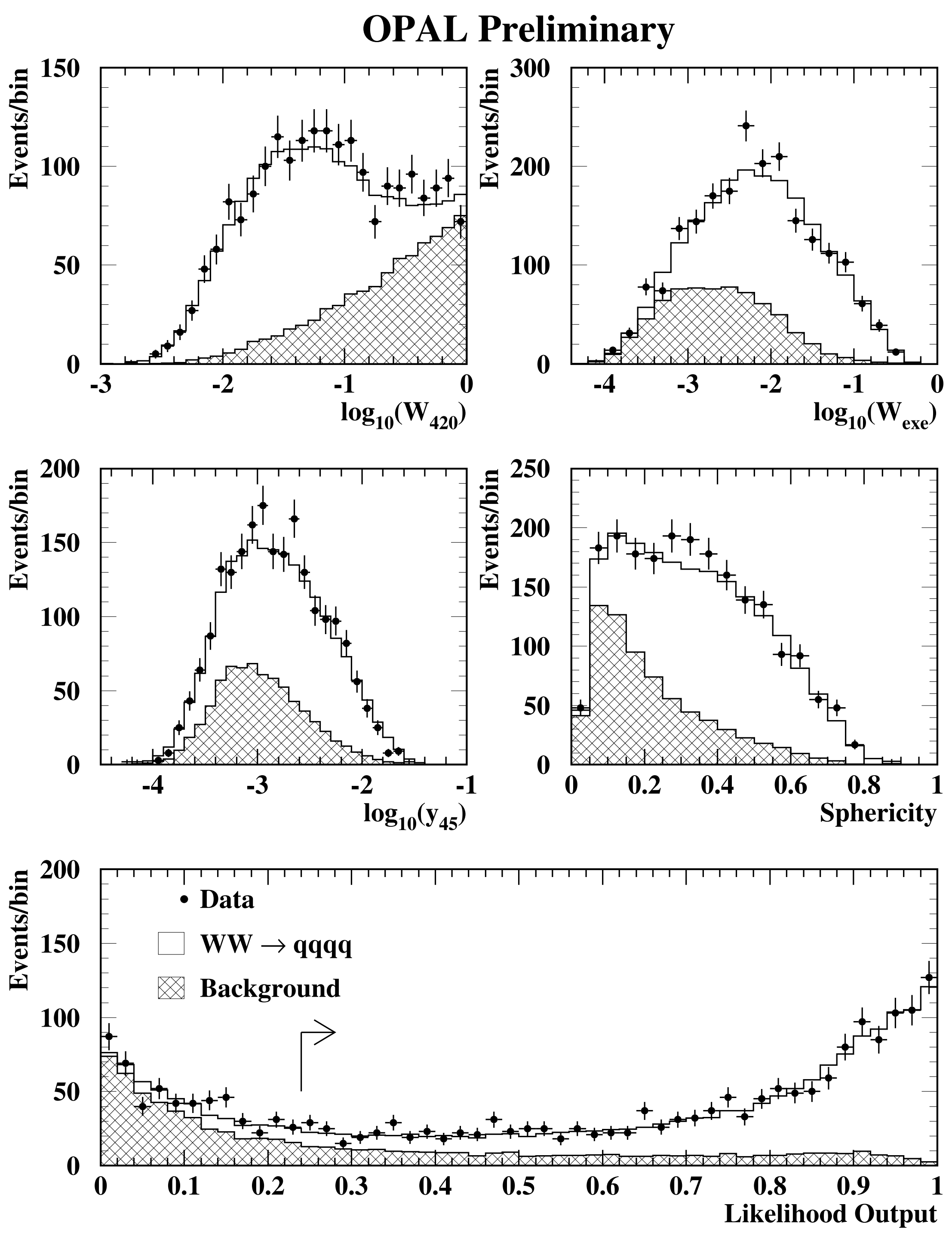
$$WW \rightarrow q\bar{q}e\bar{\nu}$$



$$WW \rightarrow \ell\bar{\nu}_\ell\ell\bar{\nu}_\ell$$



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



Likelihood Input Variables:

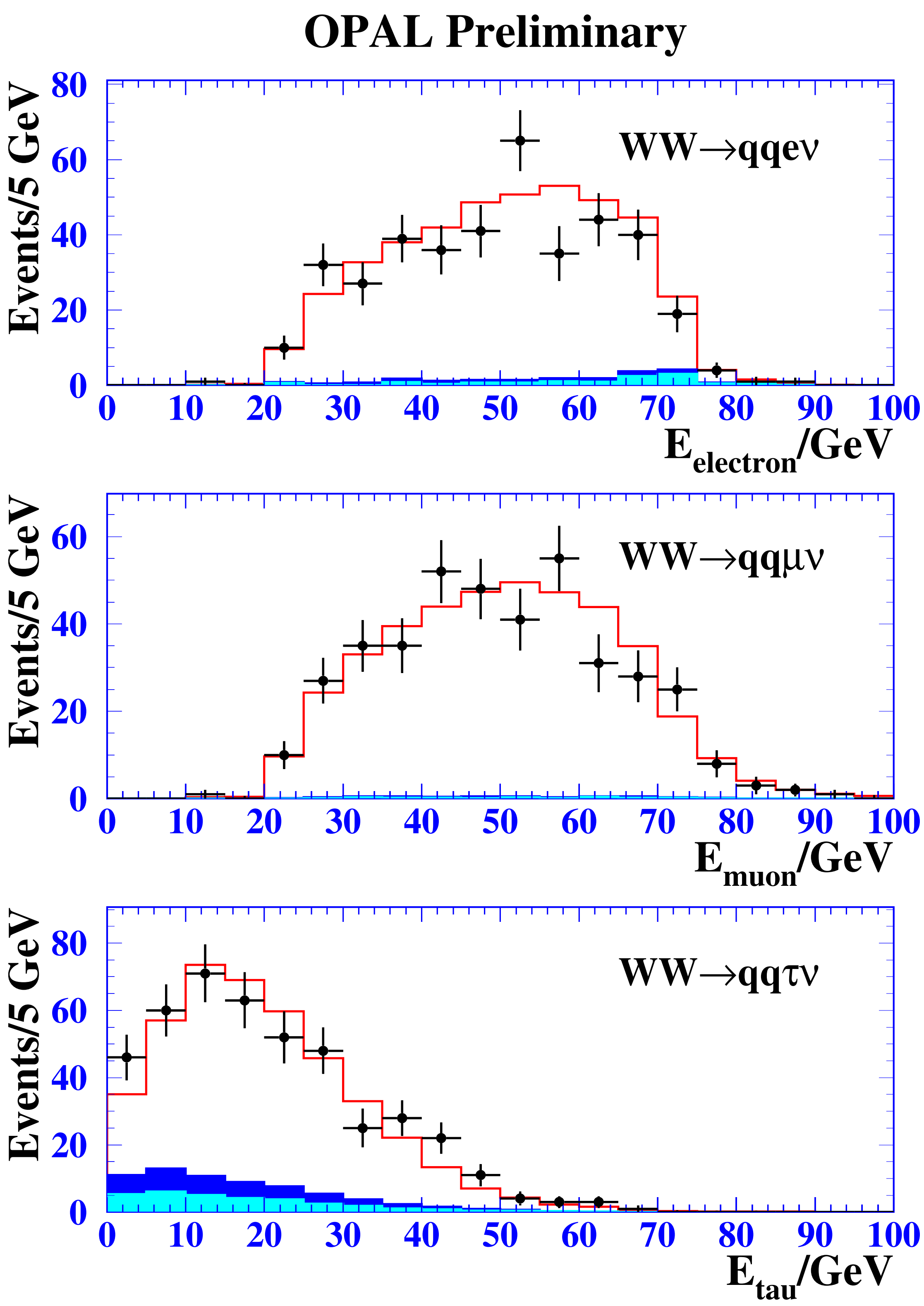
W_{420}: The QCD $\mathcal{M}$

W_{exe}: The CC03 $\mathcal{M}$

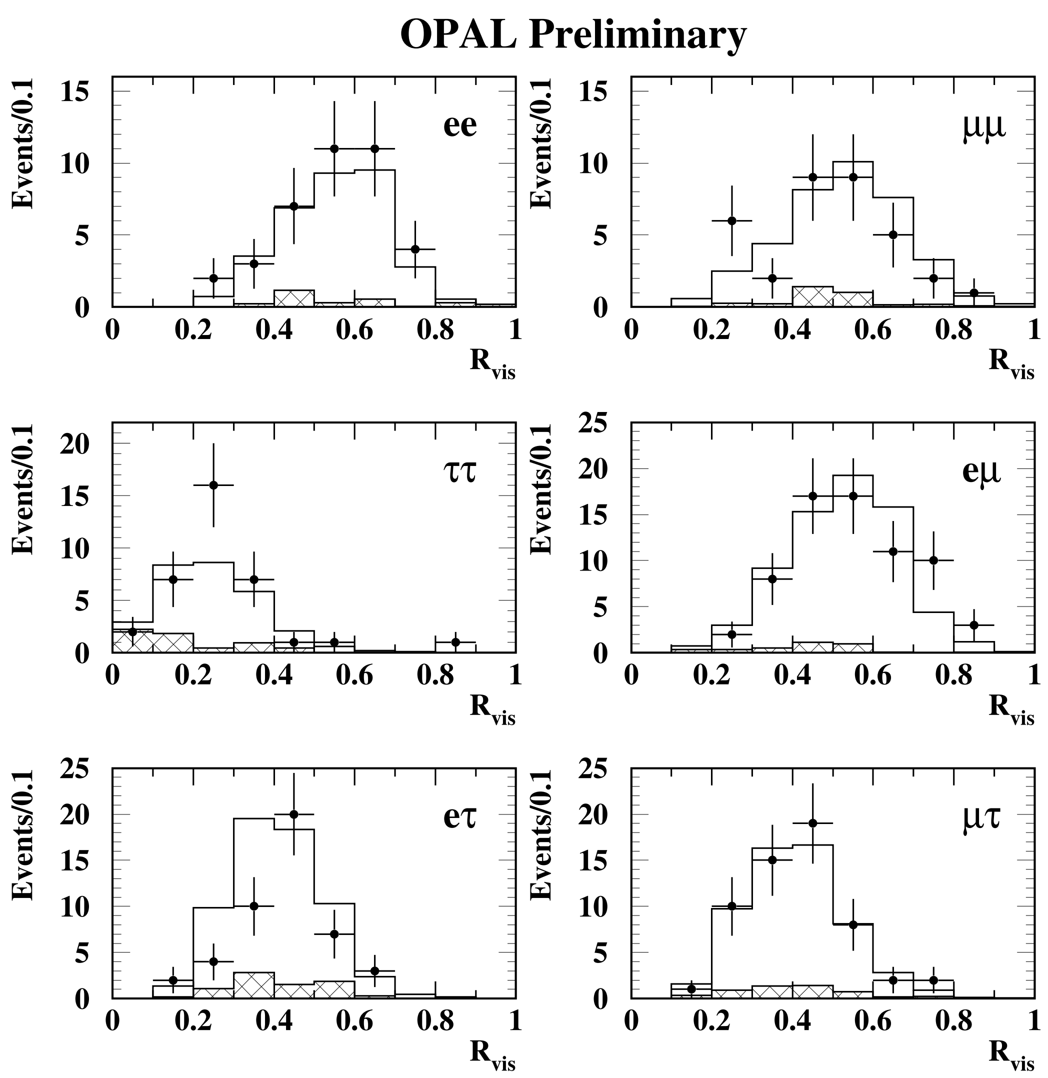
y_{45}: Durham 4 jets $\rightarrow$ 5 jets

Sphericity

$W^+W^- \rightarrow q\bar{q}\ell\bar{\nu}_\ell$ Candidates:



$W^+W^- \rightarrow \ell^- \overline{\nu}_\ell \ell'^+ \nu_{\ell'}$ Candidates:

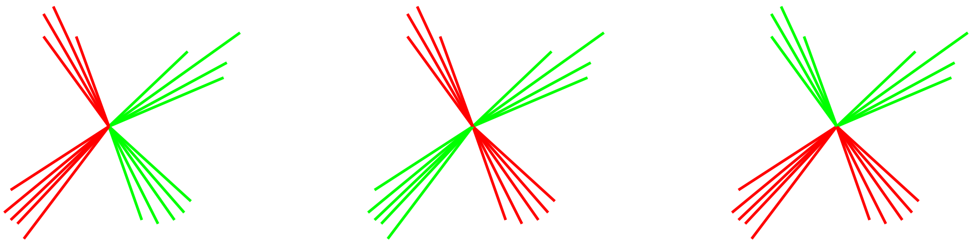


$$R_{vis} = E_{vis}/\sqrt{s}$$

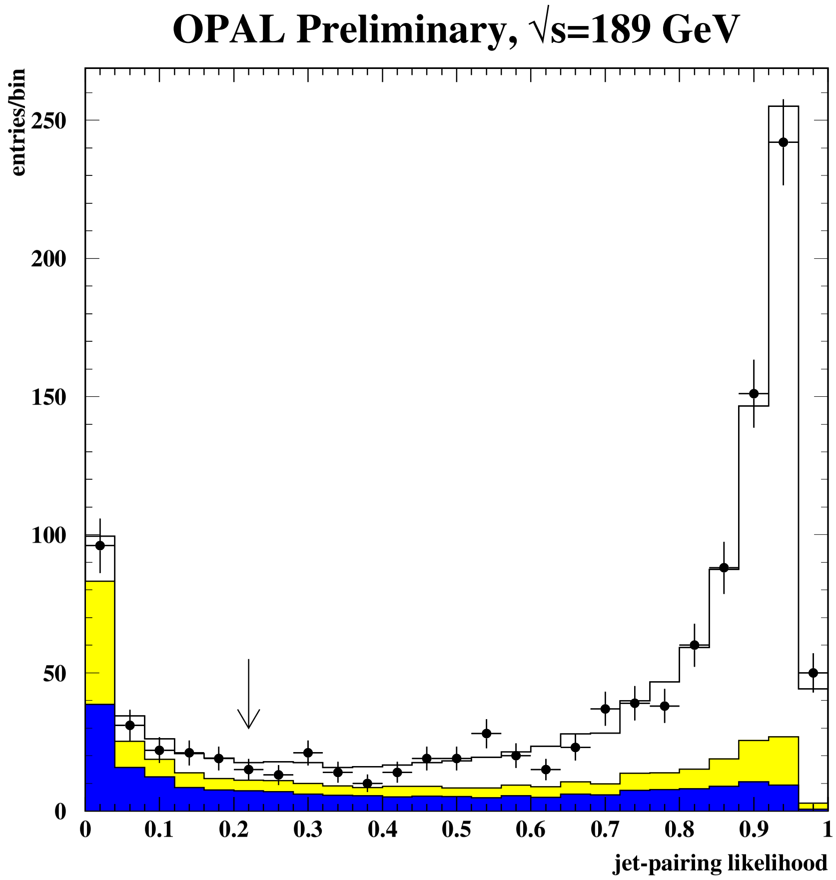
⇒ Data Quality is very good

$WW \rightarrow q\bar{q}q\bar{q}$ Combinatorics

- 4-jets: jet pairing ambiguity yields 3 combinations:



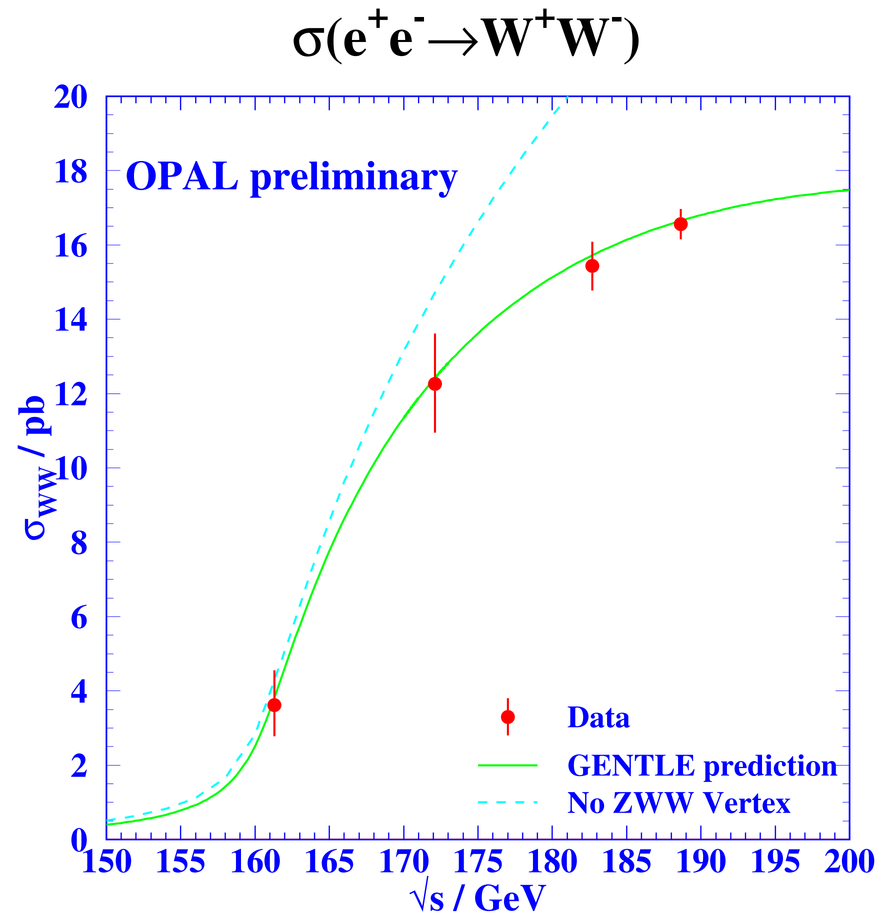
- only correct combination contains angular information
- use Δm_{rec}, $\sum \theta_{jj}$ and information from kinematic fit to choose best combination:



- choose correctly $\approx 87\%$

Cross–Section:

Final state	N_{exp}	N_{obs}
$W^+W^- \to \ell^- \overline{\nu}_\ell \ell'^+ \nu_{\ell'}$	290.0 ± 8.9	278
$W^+W^- \to q\overline{q}\ell\bar{\nu}_\ell$	1287.2 ± 29.5	1252
$W^+W^- \to q\overline{q}q\overline{q}$	1511.1 ± 34.9	1546
Combined	3088.3 ± 62.0	3076



Assuming SM branching fractions:

$\sigma_{WW}(189) = 16.55 \pm 0.35(\text{sta}) \pm 0.20(\text{sys})$ pb

Assuming lepton universality:

$\text{BR}(W \to q\bar{q}) = 68.5 \pm 0.7(\text{sta}) \pm 0.4(\text{sys})\%$

Selection Uncertainties

Systematics of selection efficiency (%)

Source of uncertainty	Event Selection WW $\rightarrow$ $q\bar{q}e\bar{\nu}$	$q\bar{q}\mu\bar{\nu}$	$q\bar{q}\tau\bar{\nu}$	$q\bar{q}q\bar{q}$
Statistical	0.17	0.14	0.26	0.12
Comp. MC models	0.35	0.44	0.73	0.22
M_W dependence	0.03	0.03	0.05	0.06
ΔE_{beam}	0.01	0.02	0.02	0.01
Fragmentation	0.40	0.40	0.60	0.68
Tracking Losses	0.40	0.10	0.40	0.22
Data/MC Preselection	0.25	0.25	0.30	0.18
Data/MC Likelihood	0.50	0.30	0.50	0.30
4-Fermion Rejection	0.30	0.10	0.30	–
Total	0.94	0.74	1.25	0.84

$\rightarrow$ Dominant systematic uncertainty on selection efficiency from MC modelling.

Accepted background cross-sections (fb)

Source	Event Selection WW $\rightarrow$ $q\bar{q}e\bar{\nu}$	$q\bar{q}\mu\bar{\nu}$	$q\bar{q}\tau\bar{\nu}$	$q\bar{q}q\bar{q}$
$q\bar{q}q\bar{q}$	0 ± 1	1 ± 2	12 ± 5	330 ± 40
$q\bar{q}e\bar{\nu}$	35 ± 29	2 ± 2	80 ± 12	0 ± 0
$q\bar{q}\ell\ell$	33 ± 15	31 ± 4	99 ± 24	38 ± 19
$q\bar{q}\nu\nu$	0 ± 0	0 ± 0	33 ± 5	0 ± 0
$Z \rightarrow q\bar{q}$	69 ± 14	22 ± 3	199 ± 27	1310 ± 110
$Z \rightarrow \ell\ell$	2 ± 1	1 ± 1	5 ± 1	0 ± 0
$\gamma\gamma$	4 ± 4	2 ± 2	0 ± 2	2 ± 2
Total	143 ± 36	59 ± 7	429 ± 39	1680 ± 120

$\rightarrow$ Dominant systematic uncertainty on accepted background from fragmentation uncertainties.

$|V_{cs}|$ from $\mathrm{BR}(\mathrm{W} \to \mathrm{q\bar{q}})$

The hadronic branching fraction $\mathrm{BR}(\mathrm{W} \to \mathrm{q\bar{q}})$ can be interpreted as a measurement of $|V_{cs}|$ since:

$$\frac{\mathrm{Br}(\mathrm{q\bar{q}})}{(1-\mathrm{Br}(\mathrm{q\bar{q}}))} = \left(1 + \frac{\alpha_s(M_\mathrm{W})}{\pi}\right) \sum_{i=\mathrm{u,c};\, j=\mathrm{d,s,b}} |\mathrm{V}_{ij}|^2$$

- Under the assumption that the W couples with equal strength to quarks and leptons:
  $\mathrm{BR}(\mathrm{W} \to \mathrm{q\bar{q}}) = [68.5 \pm 0.7(\mathrm{sta}) \pm 0.4(\mathrm{sys})]\%$
- Using PDG98 for other $|\mathrm{V}_{ij}|$.
- And $\alpha_s(M_\mathrm{W}) = 0.121 \pm 0.002$.
- Without assuming unitarity of the CKM matrix.

OPAL Preliminary Update with $\sqrt{s}$=189 GeV data:

$$\boxed{|V_{cs}| = 1.015 \pm 0.029(\mathrm{stat}) \pm 0.015(\mathrm{syst})}$$

Remark: PDG98 from charm semielectronic decays is

$$|V_{cs}| = 1.04 \pm 0.16.$$

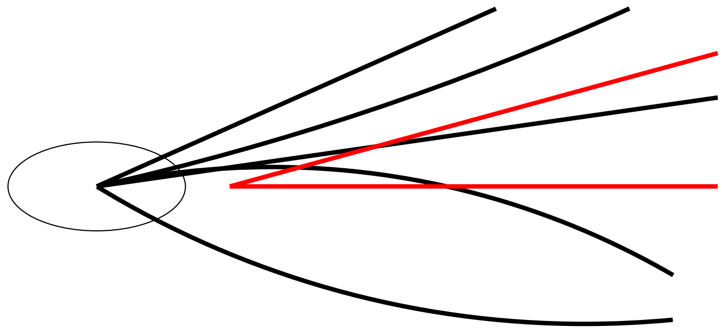
Charm Production in W Decays

Charm Tags and Direct Measurement of

$$R_c^W = \frac{\Gamma(W \to cX)}{\Gamma(W \to q\bar{q})}$$

Strategy

Reconstruction of the Sub-Jet



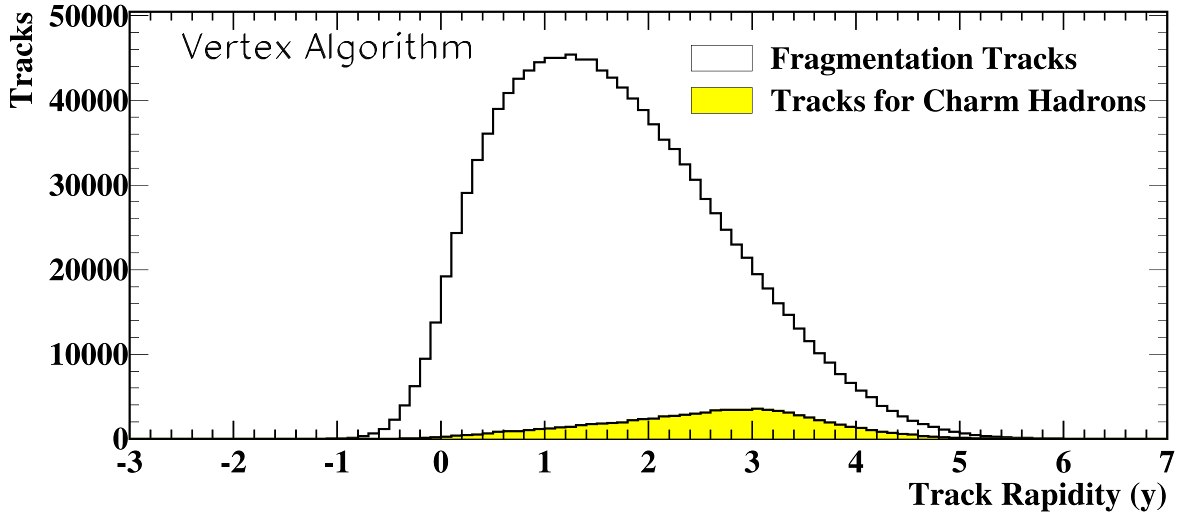
Tag the charm flavour with
- lifetime information
- lepton ID
- jet properties

- Inclusive JET BASED charm tag for a better statistical power
- Average charged multiplicity for charm hadron decays: 2-3
- $\tau_{\mathrm{charm}} \sim 1$ ps: large flight distance of about 1-2 mm
- Charm hadrons are a source of prompt leptons
- Charm quark heavier than uds-quarks: specific momentum distribution within the jet
- $|V_{\mathrm{ub}}|$ and $|V_{\mathrm{cb}}|$ are small

Vertex Tag: Selection

Charm Vertex Finding:

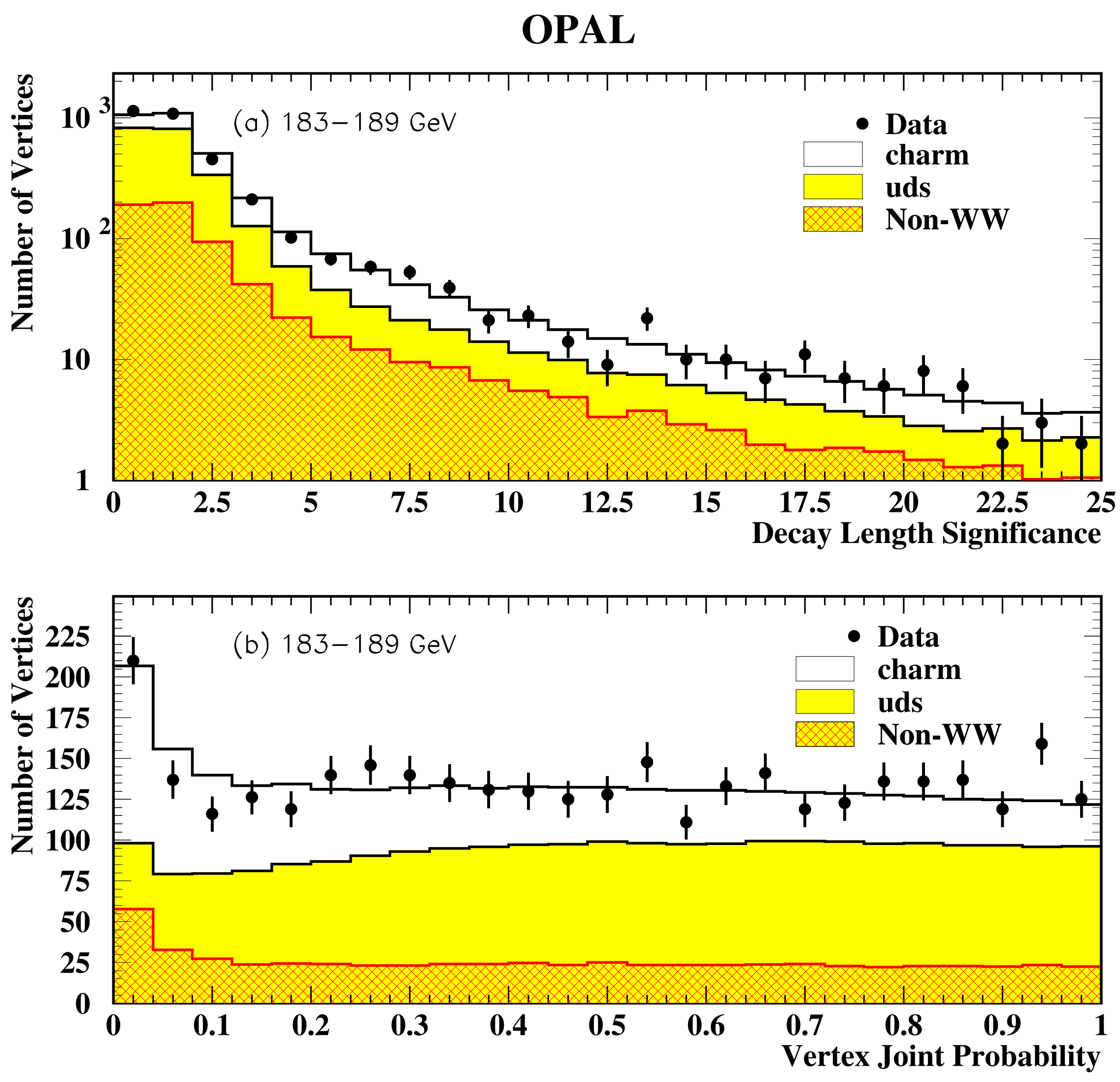
- Track preselections: $d_0 < 0.3\,\text{cm}$, $\sigma_{d_0} < 0.1\,\text{cm}$, $d_0/\sigma_{d_0} > 0$, and $p > 0.75\,\text{GeV}$.
- In Each Jet: the tracks or clusters with the lowest rapidity are removed until the charm mass is reached: $y = \frac{1}{2}\ln(\frac{E+p_\parallel}{E-p_\parallel})$.
- All tracks selected are fitted to a common vertex.
- Tracks which contribute more than 4 to the χ^2 of this fit are removed and the fit is repeated.



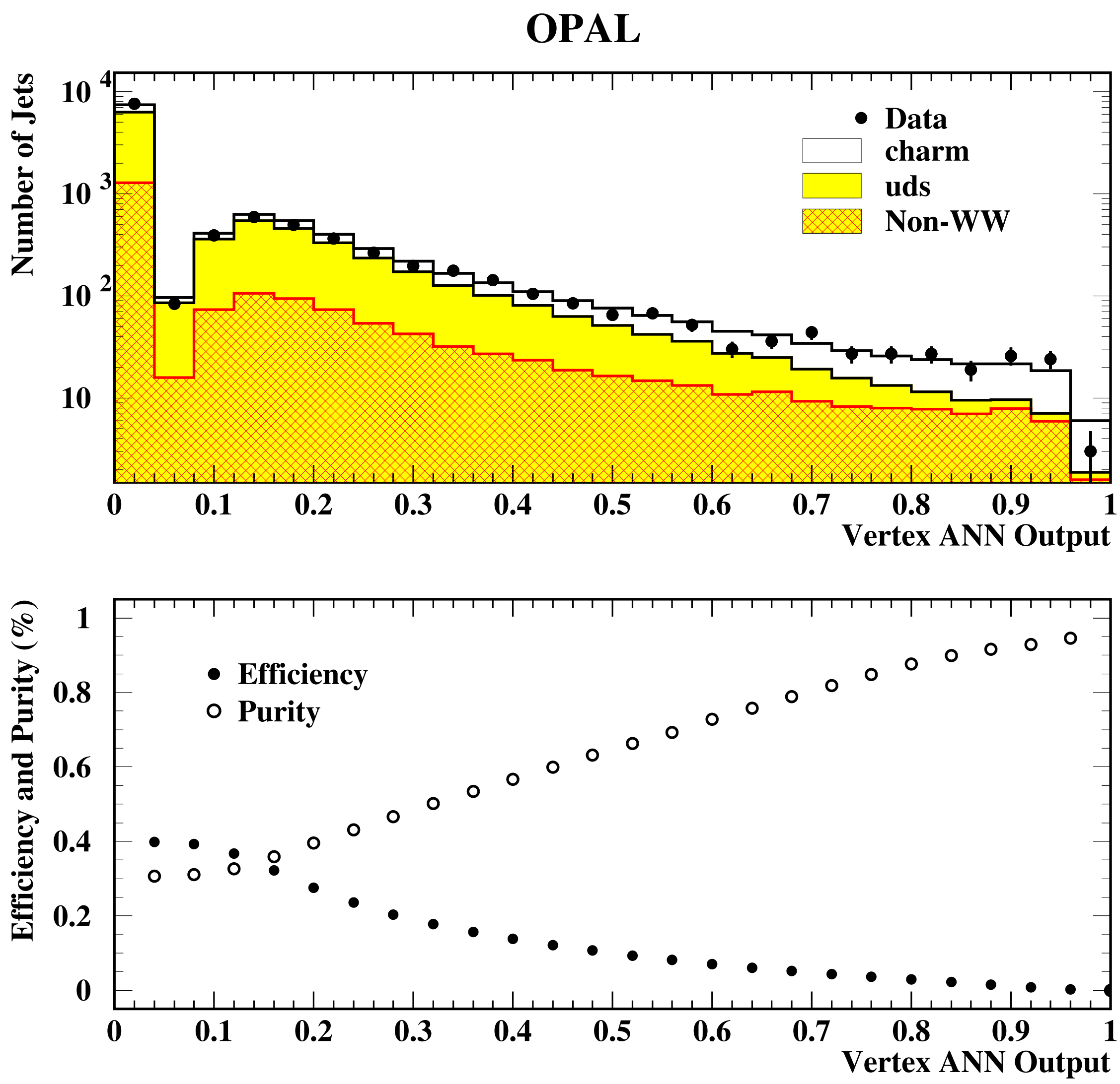
Vertex Tag: Inputs

Inputs to the ANN:

- L/σ_L and Vertex joint probability
- $E_{\mathrm{vertex}}/E_{\mathrm{beam}}$ and M_{vertex}
- DCA_{vertex} and $\frac{\sum_{\mathrm{tracks}} d_0/\sigma_{d_0}^2}{\sum_{\mathrm{tracks}} 1/\sigma_{d_0}^2}$
- $Max(p_{\mathrm{track}})$
- Largest and second largest track d_0



Vertex Tag: Performance



Strategy: Tag charm hadron jets with the reconstruction of secondary vertices with respect to the primary vertices.

Goal: Discriminate charm and light flavoured jets!

Lepton Tag: Selection

Lepton Selection:

- $|\cos\theta_\ell| < 0.9$ and $p_\ell > 2.0$ GeV
- Electron: ID mainly based on E/p and dE/dx
- Muon: Match between tracking system, hadronic calorimeter, and the muon chambers
- Of these lepton candidates, the most energetic lepton of each jet, if any, is selected.

Lepton From Charm: Construction of a likelihood function to separate charm and uds jets.

Both for electrons and for muons:

- OPAL lepton ID ANN output
- $\cos\theta_\ell$
- $|p_\ell|$

In $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ selected events:

- $Q_\ell \cdot \cos\theta_\mathrm{W}$

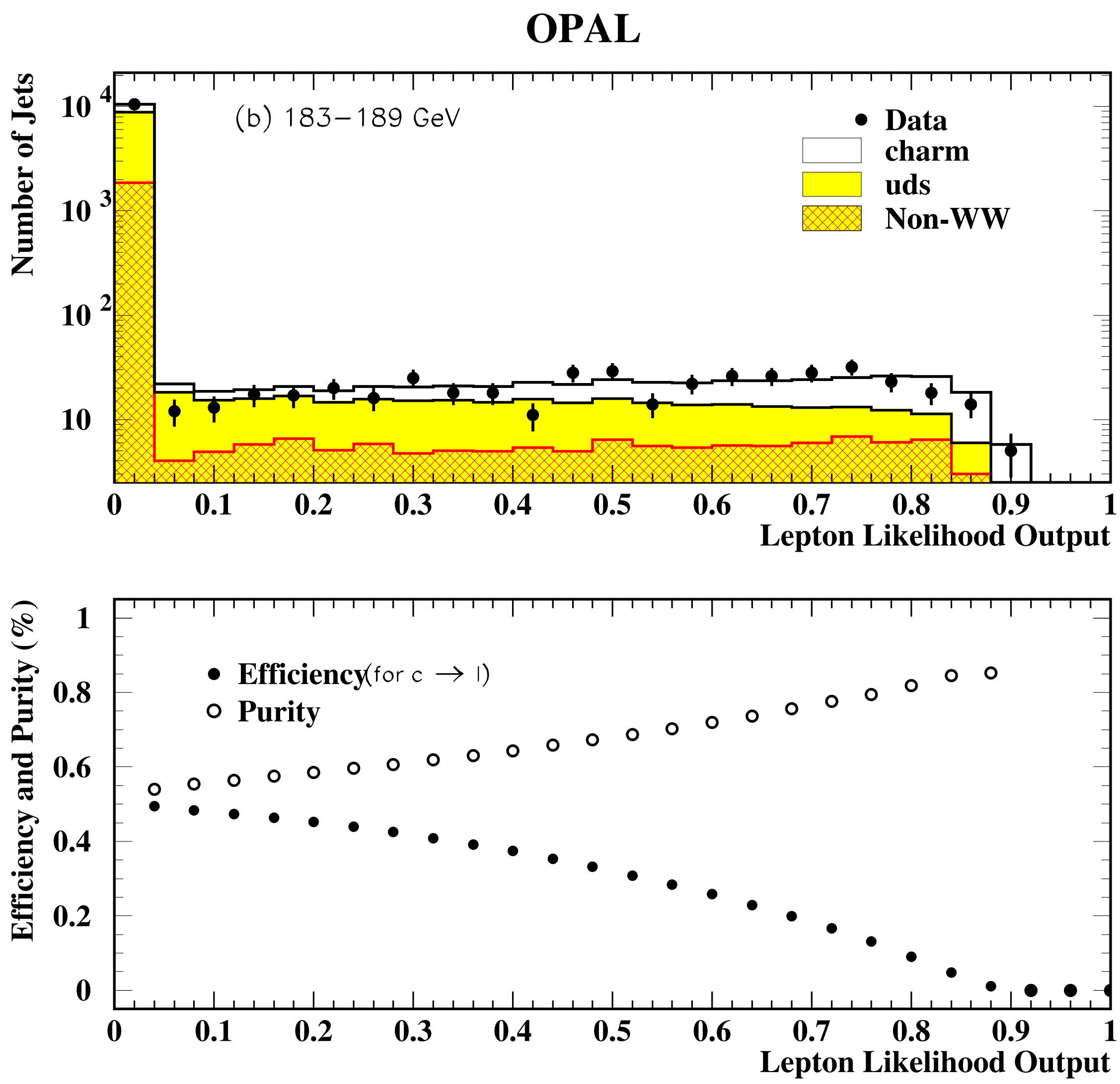
In $\mathrm{W^+W^-} \to \mathrm{q\bar{q}}\ell\bar{\nu}_\ell$ selected events:

- $Q_\ell \cdot Q_{\mathrm{W}\to\ell\bar{\nu}_\ell}$

For electron only:

- OPAL conversion finder ANN output

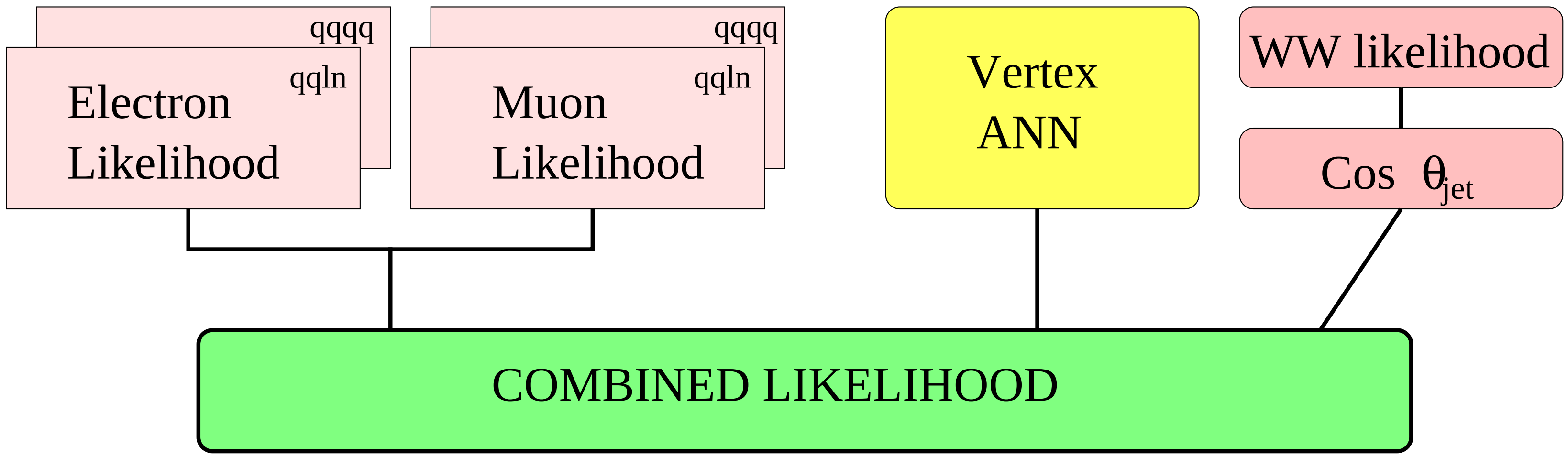
Lepton Tag: Performance



Strategy: Using the fact that BR$(c \to \ell) \simeq 20\%$ with $\ell = e$ or μ: Tag charm hadron jets with the identification of prompt leptons.

Goal: Separation of charm jets from other jets!

Combined Tag



- The jet angle in the W (*i.e.* di-jet) rest frame helps to discriminate jets originating from up–type quarks from down–type quarks due to the $V - A$ nature of the weak interaction.
- The likelihood output of the WW event selection suppresses false tags from background events, especially from $\mathrm{Z}^0/\gamma \rightarrow \mathrm{b\bar{b}}$ events.

Fit for R_c^{W}

Binned Maximum Likelihood Fit:

$$-\ln\mathcal{L} = -\sum_{i=1}^{N} n_i \ln\{(1-F_{\mathrm{bkg}})[F_c\mathcal{P}_c^i + (1-F_c)\mathcal{P}_{uds}^i] + F_{\mathrm{bkg}}\mathcal{P}_{\mathrm{bkg}}^i\}$$

with $R_c^{\mathrm{W}} = 2\,F_c$ and

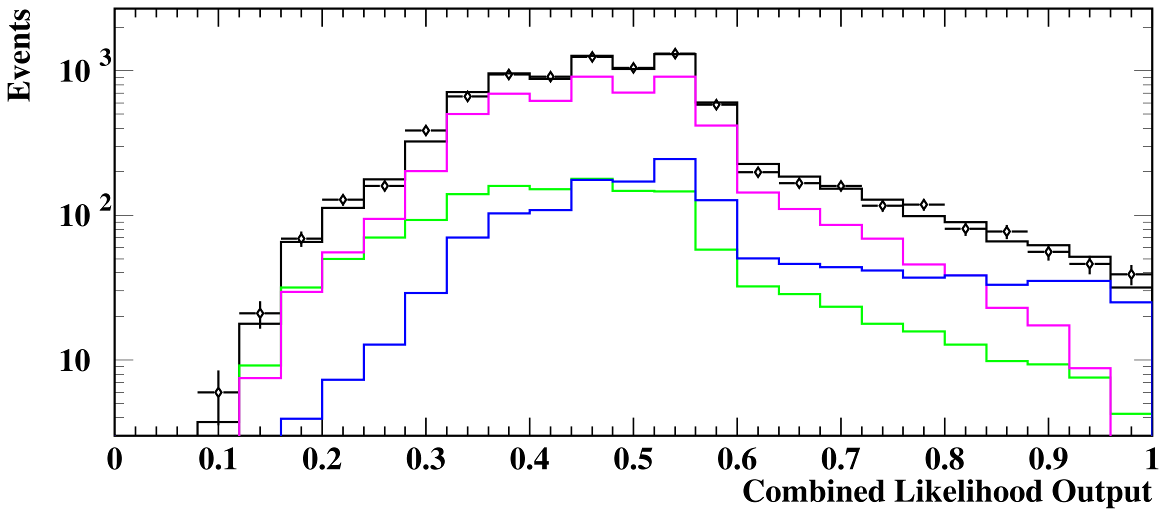
F_c: Fraction of charm jets (float)

$\mathcal{P}_c^i$: Probability to tag Charm in i^{th} bin

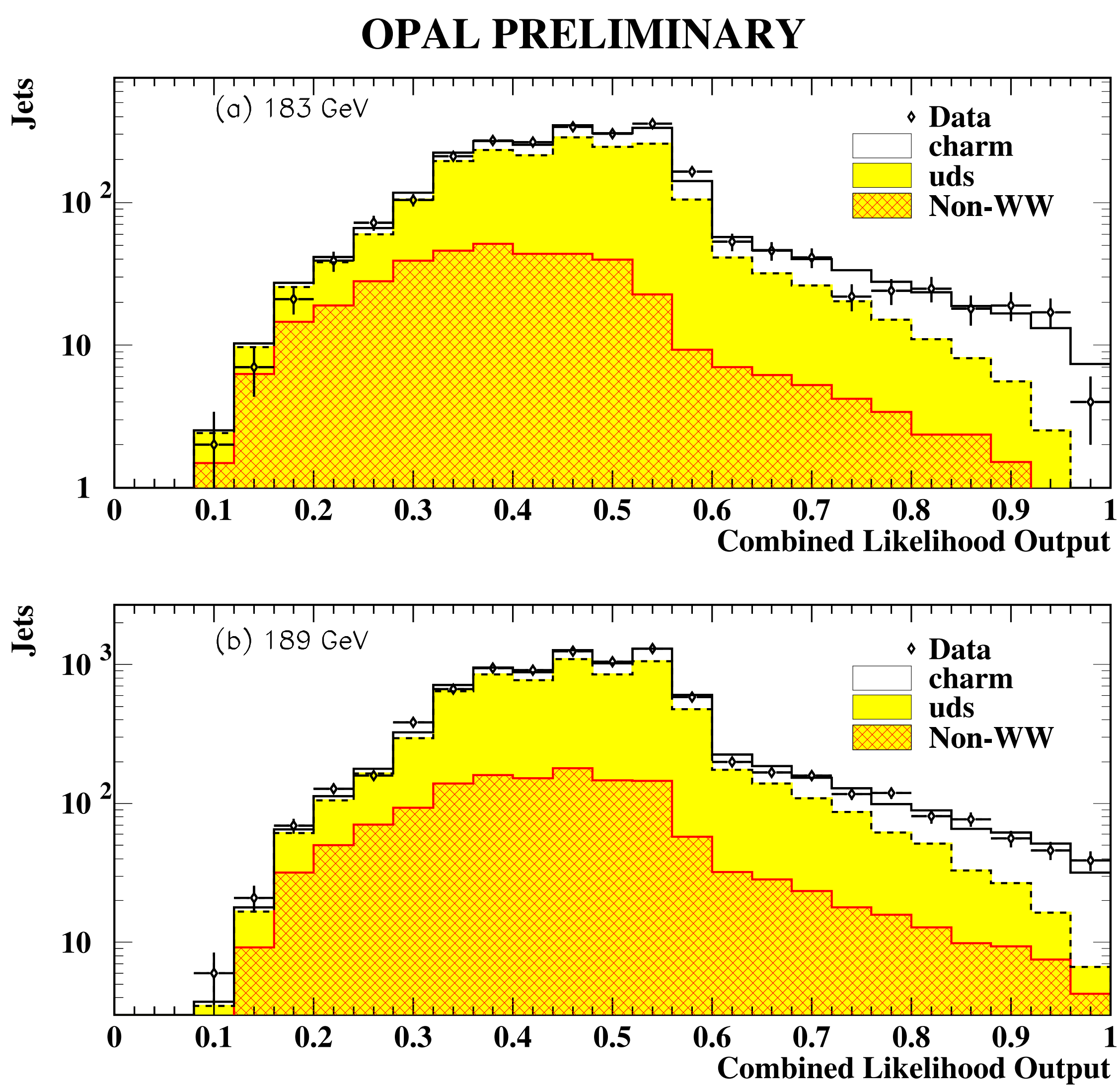
$\mathcal{P}_{uds}^i$: Probability to tag uds in i^{th} bin

F_{bkg}: Fraction of background jets (float or fixed)

$\mathcal{P}_{\mathrm{bkg}}^i$: Probability to tag non-WW bkg in i^{th} bin



Fit Results for R_c^W



$\mathbf{R_c^W} = \mathbf{0.493 \pm 0.090}$ at 183 GeV $(\chi^2\mathrm{pdf} = 17.2/24)$

and

$\mathbf{R_c^W} = \mathbf{0.478 \pm 0.047}$ at 189 GeV $(\chi^2\mathrm{pdf} = 35.4/24)$

Systematic Uncertainties

Source of Systematic Error	$\Delta\ R_c^W$ 183 GeV	$\Delta\ R_c^W$ 189 GeV
Hadronisation Model	0.011	0.012
Centre–of–mass Energy	0.007	0.005
Mass of the W Boson	0.004	0.003
Charm Frag. Function	0.007	0.007
Back. Cross–Section	0.006	0.006
Back. Composition	0.010	0.009
Charm Hadron Fractions	0.006	0.007
Light Quark Composition	0.007	0.005
Vertex Reconstruction	0.016	0.017
Charm Hadron Lifetimes	0.003	0.002
Charm Decay Multiplicity	0.010	0.010
Lepton Identification	0.012	0.014
Lepton Spectrum	0.003	0.003
$\mathrm{Br}(c \rightarrow \ell)$	0.006	0.006
Total systematic error	0.032	0.032
Statistical error	0.090	0.047
Value of R_c^W	0.493	0.478

Systematic Error: Details

- *Hadronisation model:* The PYTHIA MC sample, which uses the Lund string fragmentation, is compared to a sample generated with HERWIG, which uses cluster fragmentation.
- W *mass and centre–of–mass energy:* The W mass is varied by 100 MeV and $\sqrt{s}$ is varied by the diff. between the centre–of–mass energies in data and MC.
- *Charm fragmentation:* At $\sqrt{s} = M_{\mathrm{Z}^0}$, the mean scaled energy of weakly decaying charm hadrons is found to be $\langle x_{\mathrm{D}}(\mathrm{M_Z})\rangle = 0.484 \pm 0.008$. No measurements of this quantity exist for W decays, but it is expected to be similar to that in Z decays. To assess the systematic uncertainty, $\langle x_{\mathrm{D}}(\mathrm{M_W})\rangle$ is varied by the experimental uncertainty obtained on $\langle x_{\mathrm{D}}(\mathrm{M_Z})\rangle$, *i.e.* 0.008. The fragmentation schemes of Peterson, Collins and Spiller, Kartvelishvili and the Lund group were used to attribute a possible discrepancy on the shape of the fragmentation function.
- *Background cross–section:* In the fit for extracting $R_{\mathrm{c}}^{\mathrm{W}}$, the fraction of background was varied according to the error on the expected fraction of background events.
- *Background composition:* The various background sources have different probabilities to fake a charm jet. The background composition is varied within its uncertainty.

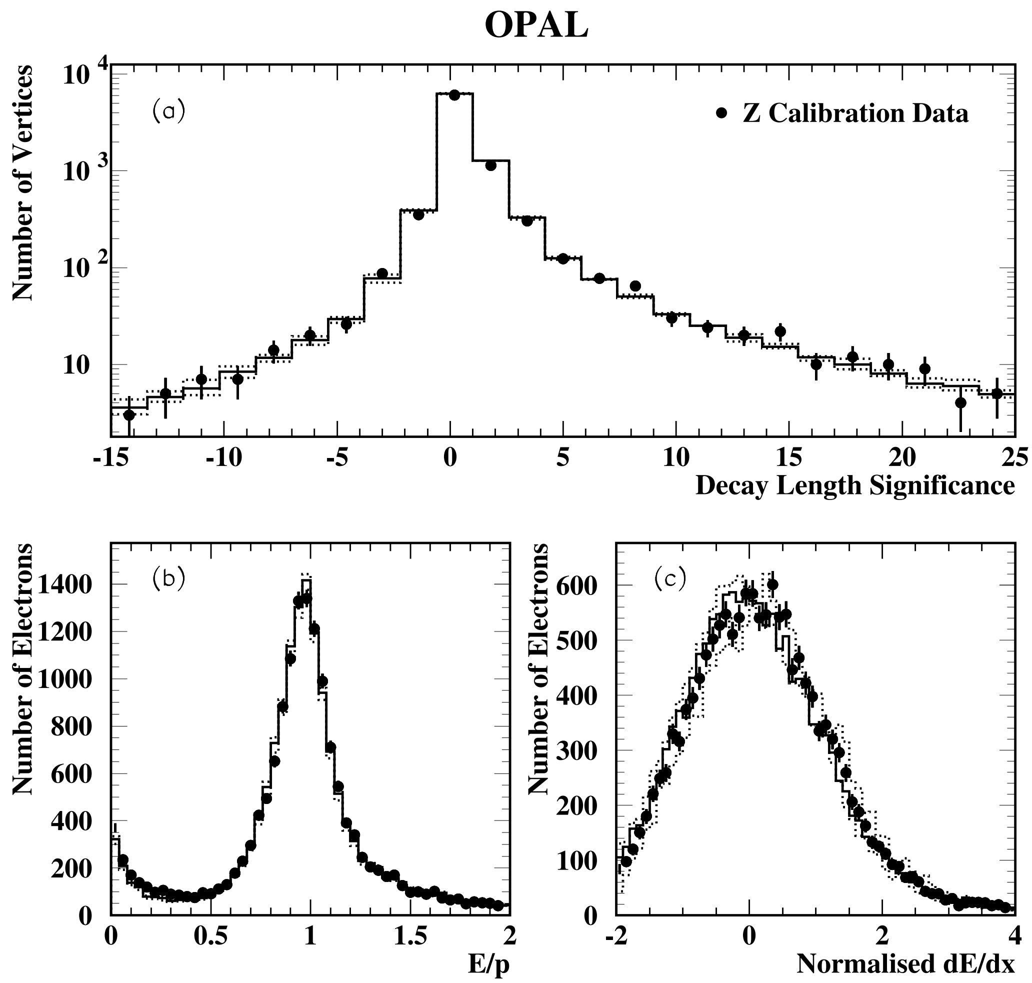
Systematic Error: Details

- *Charm hadron fractions:* The fractions of the weakly decaying charm hadrons are varied within their experimental errors.
- *Light quark composition:* The quark flavour fractions were varied according to the actual errors on the CKM matrix so that the error covers the effect of assumptions concerning the CKM matrix elements on the uds template histogram. The number of bottom hadrons from W bosons was also doubled to ensure that the measured $R_{\mathrm{c}}^{\mathrm{W}}$ is insensitive to the bottom fraction in W decays.
- *Vertex reconstruction:* This is checked by comparing the track parameters between calibration data collected at $\sqrt{s} \sim M_{\mathrm{Z}^0}$ and MC simulation. The sensitivity to the vertex reconstruction was assessed by degrading or improving the tracking resolution in the MC.
- *Charm hadron lifetimes:* The lifetimes of the weakly decaying charm hadrons are varied within their experimental errors.
- *Charm decay multiplicity:* The relative abundance of 1, 2, 3, 4, 5, and 6 prong charm decays has been changed in the MC within their experimental errors. Similarly, the relative abundance of neutral pions has been varied in the MC within the experimental errors.

Systematic Error: Details

- *Lepton identification:* The relative error of the efficiency to identify a genuine electron (muon) has been estimated to be 4 % (3 %), and the relative error on the probability to wrongly identify a hadron as a lepton had been evaluated to be around 16 % (10 %) for electrons (muons). By studying the $\mathrm{d}E/\mathrm{d}x$ for electron candidates in calibration data taken at the Z^0 mass in 1997 and 1998, it was found that a shift of the mean $\mathrm{d}E/\mathrm{d}x$ of 0.04 keV/cm (0.3%) and a scaling by 1% of the $\mathrm{d}E/\mathrm{d}x$ resolution in data was needed to correct a slight discrepancy between MC and data. This effect is also taken into account in the assignment of the uncertainty on the electron tagging efficiency.
- *Lepton energy spectrum:* The energy spectrum of the lepton in the rest frame of the weakly decaying charm hadron is reweighted from the spectrum implemented in JETSET to the ISGW and ACCMM models.
- *Branching ratio $\mathrm{Br}(\mathrm{c} \to \ell)$:* The branching fraction for inclusive charm decays to leptons was varied within the range $\mathrm{Br}(\mathrm{c} \to \ell) = 0.098 \pm 0.005$ by reweighting the MC events.

Main Systematic Errors

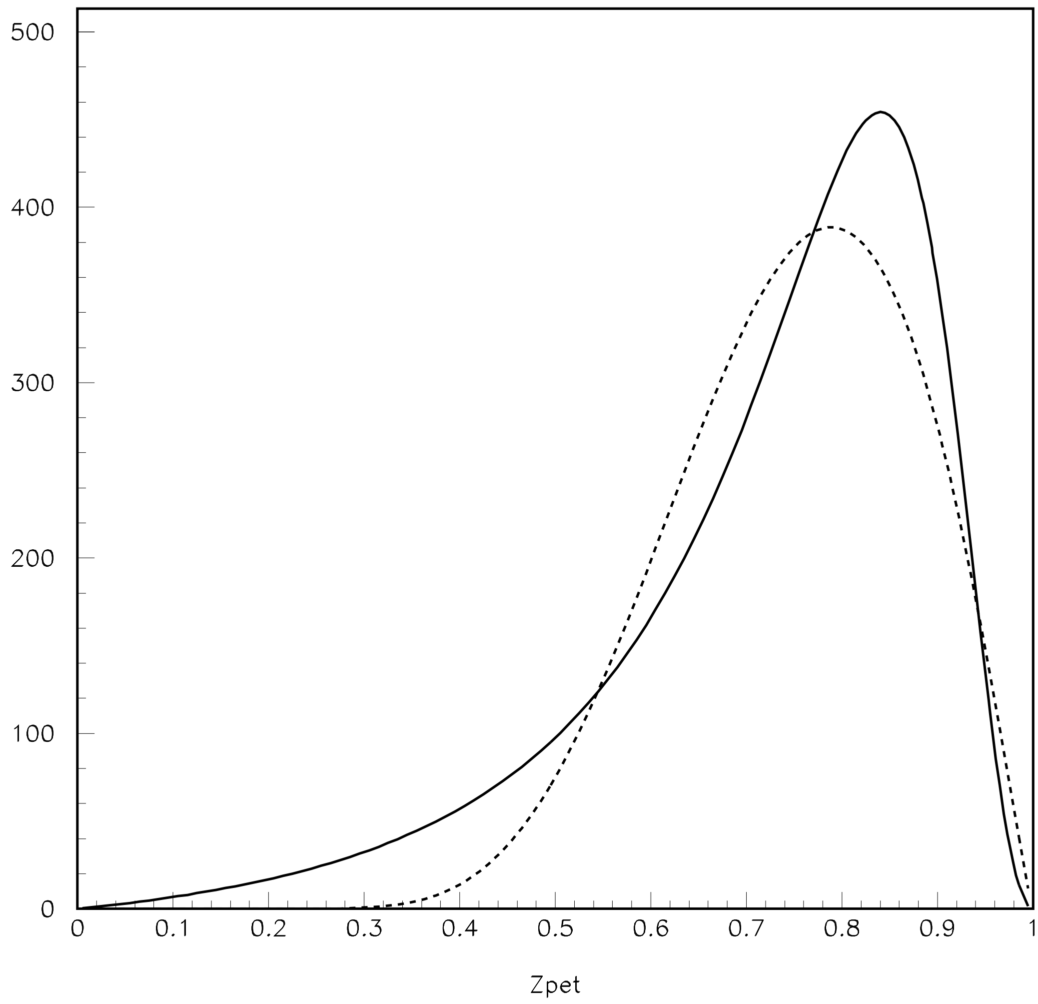


$\Rightarrow$ The dominant systematic errors are those associated with the vertex reconstruction and lepton identification (*i.e.* detector response).

(a) The decay length significance L/σ_{L} for data and MC. The dotted line shows the effect of the $\pm 5\,\%$ variation on the tracking resolution used to assess the systematic uncertainty on the vertex tag.

(b-c) E/p and the norm. $\mathrm{d}E/\mathrm{d}x$ for electron candidates from data and MC. The dotted lines show how the variation of the detection (mis)identification and resolution.

Fragmentation Function



$$z = \frac{(E + p_{\|})_{\text{hadron}}}{(E + p_{\|})_{\text{available}}}$$

$$Peterson : f(z) = \frac{1}{z[1 - (1/z) - \epsilon_c/(1-z)]^2}$$

$$Lund : f(z) = \frac{(1-z)^a}{z} e^{-b\, m_T^2/z}$$

Systematic Uncertainties

Check List:

Charm Charged Multiplicity: OK

D Hadron	Mark III	MC
D^0	2.38 ± 0.064	2.43 ± 0.06
D^+	2.56 ± 0.050	2.53 ± 0.09
D_s	2.69 ± 0.330	2.58 ± 0.12
Λ_c	2.90 ± 0.120	2.83 ± 0.15

Charm Hadrons Lifetime: OK

D Hadron	PDG	MC
D^0	0.415 ± 0.004	0.412 ± 0.002
D^+	1.057 ± 0.015	1.056 ± 0.011
D_s	0.467 ± 0.017	0.461 ± 0.007
Λ_c	0.206 ± 0.012	0.201 ± 0.003

Beauty Charged Multiplicity: OK

B Hadron	Recommended	MC
All B's	4.95 ± 0.06	4.96 ± 0.02

Reweighting Lifetime

$$p(t) = \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right).$$

Get a different lifetime τ':

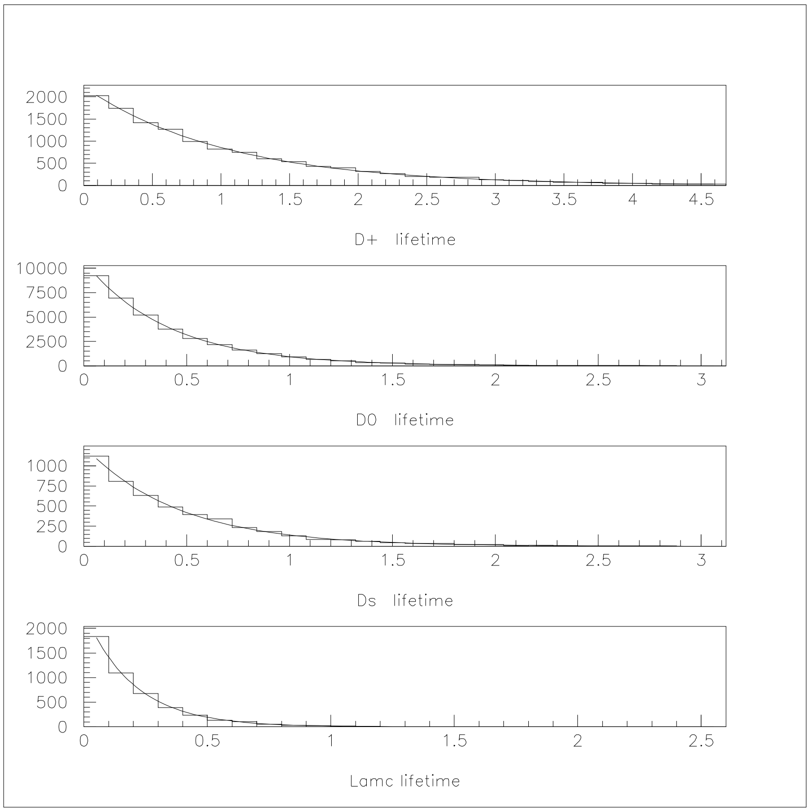
$$p'(t) = \frac{1}{\tau'} \exp\left(-\frac{t}{\tau'}\right).$$

Then,

$$w(t)\frac{p'(t)}{p(t)} = \frac{\tau}{\tau'} \exp\left(\frac{t}{\tau} - \frac{t}{\tau'}\right),$$

with the constraint:

$$\langle w \rangle = \int_0^\infty p(t) \cdot w(t)\, \mathrm{d}\,t = 1$$



Results (OPAL Preliminary)

At $\sqrt{s} \simeq 183$ GeV:

$$R_c^W = 0.493 \pm 0.090(\mathrm{stat}) \pm 0.032(\mathrm{syst})$$

At $\sqrt{s} \simeq 189$ GeV:

$$R_c^W = 0.478 \pm 0.047(\mathrm{stat}) \pm 0.032(\mathrm{syst})$$

Combined value:

$$\boldsymbol{R_c^W = 0.481 \pm 0.042(\mathrm{stat}) \pm 0.032(\mathrm{syst})}$$

CKM matrix element	Value(PDG98)
$\lvert V_{ud}\rvert$	0.9740 ± 0.0010
$\lvert V_{us}\rvert$	0.2196 ± 0.0023
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	0.08 ± 0.02
$\lvert V_{cd}\rvert$	0.224 ± 0.016
$\lvert V_{cb}\rvert$	0.0395 ± 0.0017

$$|V_{cs}| = \sqrt{\frac{R_c^W(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)}{1 - R_c^W} - |V_{cd}|^2 - |V_{cb}|^2}$$

$$|V_{cs}| = 0.93 \pm 0.08(\mathrm{stat}) \pm 0.06(\mathrm{syst}) \pm 0.004(\mathrm{ckm})$$

Results (OPAL Preliminary)

Based on a new and original idea, one can extract $|V_{\mathrm{cs}}|$ from $\mathrm{Br}\,(\mathrm{W} \to \mathrm{hadrons})$ and $\Gamma^{\mathrm{W}}_{\mathrm{tot}}$. In the SM,

$$\Gamma\,(\mathrm{W} \to \mathrm{c\,X}) = \frac{C G_{\mathrm{F}} {M_{\mathrm{W}}}^3}{6\sqrt{2}\pi}\left(|V_{\mathrm{cd}}|^2 + |V_{\mathrm{cs}}|^2 + |V_{\mathrm{cb}}|^2\right)$$

with $$\frac{C G_{\mathrm{F}} {M_{\mathrm{W}}}^3}{6\sqrt{2}\pi} = (707 \pm 1)\mathrm{MeV}$$

Thus:

$$\boldsymbol{\Gamma\,(\mathrm{W} \to \mathrm{c\,X}) = R^{\mathrm{W}}_{\mathrm{c}}\,\mathrm{Br}\,(\mathrm{W} \to \mathrm{q\bar{q}})\,\Gamma^{\mathrm{W}}_{\mathrm{tot}}}$$

$\mathrm{BR}\,(\mathrm{W} \to \mathrm{q\bar{q}})$	$\Gamma^{\mathrm{W}}_{\mathrm{tot}}$ (GeV)
0.6873 ± 0.0089	2.06 ± 0.05

$$\boldsymbol{|V_{\mathrm{cs}}| = 0.955 \pm 0.044 \pm 0.033 \pm 0.014 \pm 0.004}$$

- 1^{st} Error: Statistical,
- 2^{nd} Error: Experimental Systematic,
- 3^{rd} Error: External from $\mathrm{BR}\,(\mathrm{W} \to \mathrm{q\bar{q}})$ and $\Gamma^{\mathrm{W}}_{\mathrm{tot}}$,
- 4^{th} Error: Uncertainties on the other $|\mathrm{V}_{ij}|$ used.

Summary: OPAL Charm Tag

Measurement of R_c^W

Data Collected at $\sqrt{s}$= 183 GeV and 189 GeV with the OPAL detector:

$$\boldsymbol{R_c^W = 0.481 \pm 0.042(\mathrm{stat}) \pm 0.032(\mathrm{syst})}$$

It leads to an indirect measurement of $|V_{cs}|$:

$$\boldsymbol{|V_{cs}| = 0.955 \pm 0.057}$$

D semileptonic decays (MARKIII & CLEO):

$$|V_{cs}| = 1.04 \pm 0.16$$

Neutrino experiments (CCFR):

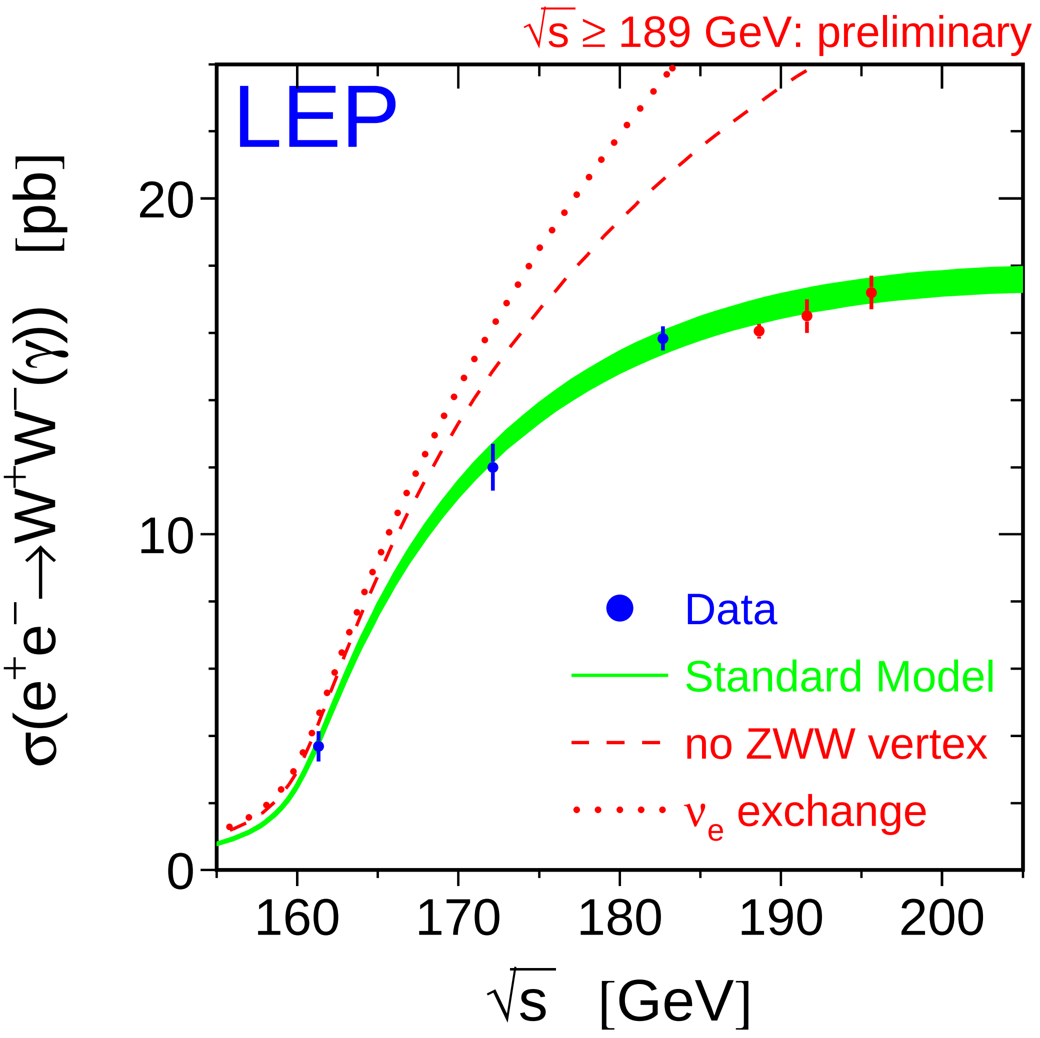
$$|V_{cs}| = 1.05^{+0.12}_{-0.15}$$

SUMMARY

$|V_{cs}|$ at LEP2

ALEPH DELPHI L3 OPAL

WW Cross–Section



Assuming SM branching fractions (at 189 GeV):

$$\sigma_{\mathrm{WW}} = (16.05 \pm 0.22)\mathrm{pb}$$

Assuming lepton universality (data up to 189 GeV):

$$\mathrm{BR}(\mathrm{W} \rightarrow \mathrm{q\bar{q}}) = (67.96 \pm 0.41)\%$$

$$\boxed{|V_{cs}| = \mathbf{0.997 \pm 0.016(stat)0.012(syst)}}$$

R_c^W and $|V_{cs}|$ at LEP2

Exp.	R_c^W
ALEPH	$0.510^{+0.050}_{-0.050}(\mathrm{stat}) \pm 0.030(\mathrm{syst})$
DELPHI	$0.520^{+0.070}_{-0.050}(\mathrm{stat}) \pm 0.050(\mathrm{syst})$
L3	$0.502^{+0.110}_{-0.110}(\mathrm{stat}) \pm 0.035(\mathrm{syst})$
OPAL	$0.481^{+0.042}_{-0.042}(\mathrm{stat}) \pm 0.032(\mathrm{syst})$
LEP	$\mathbf{0.499 \pm 0.027(stat) \pm 0.037(syst)}$

Data Samples:

- ALEPH: $\sqrt{s}$ = 172 GeV & 183 GeV
- DELPHI: $\sqrt{s}$ = 161 GeV, 172 GeV & 183 GeV
- L3: $\sqrt{s}$ = 183 GeV
- OPAL: $\sqrt{s}$ = 183 GeV & 189 GeV

Preliminary update of $|V_{cs}|$ from R_c^W at LEP2:

$$\boxed{|V_{cs}| = 0.974 \pm 0.050}$$

DELPHI provides a measurement of:

$$R_{cs} = \frac{\Gamma(W \rightarrow c\bar{s})}{\Gamma(W \rightarrow q\bar{q})} = 0.46^{+0.18}_{-0.14}(\mathrm{stat}) \pm 0.07(\mathrm{syst}),$$

which leads to

$$|V_{cs}| = 0.94^{+0.32}_{-0.26}(\mathrm{stat}) \pm 0.13(\mathrm{syst}).$$

Summary: OPAL and LEP2

OPAL $|V_{cs}|$ from the WW Cross-Section:

Preliminary update with $\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})$ obtained from data up to $\sqrt{s}$= 189 GeV:

$$|V_{cs}| = 1.015 \pm 0.029(\mathrm{stat}) \pm 0.015(\mathrm{syst})$$

OPAL R_c^W and $|V_{cs}|$:

Analysing the data collected at $\sqrt{s}$= 183 GeV and 189 GeV:

$$R_c^W = 0.481 \pm 0.042(\mathrm{stat}) \pm 0.032(\mathrm{syst})$$

$$|V_{cs}| = 0.955 \pm 0.057$$

LEP $|V_{cs}|$ from the WW Cross-Section:

Preliminary update with $\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})$ obtained from data up to $\sqrt{s}$= 189 GeV:

$$|V_{cs}| = 0.997 \pm 0.016(\mathrm{stat})0.012(\mathrm{syst})$$

LEP R_c^W and $|V_{cs}|$: Preliminary update of $|V_{cs}|$ from R_c^W

$$R_c^W = 0.499 \pm 0.027(\mathrm{stat}) \pm 0.037(\mathrm{syst})$$

$$|V_{cs}| = 0.974 \pm 0.050$$

Conclusions

- LEP2 provides a clean environment to investigate the coupling strength of the W boson to the charm quark.
- The extraction of $|V_{\rm cs}|$ from $\rm Br(W \rightarrow q\overline{q})$ and the direct measurements of the other CKM matrix elements is more accurate that the current best measurement.
- The direct measurement of $R_{\rm c}^{\rm W}$ assume neither $\rm Br(W \rightarrow q\overline{q})$+$\rm Br(W \rightarrow \ell\bar{\nu}_\ell)$=1 nor lepton universality.
- Moreover, the extraction of $|V_{\rm cs}|$ from $R_{\rm c}^{\rm W}$ with the direct measurements of $|V_{\rm cd}|$, $|V_{\rm cb}|$, $\rm Br(W \rightarrow q\overline{q})$, and $\Gamma_{\rm tot}^{\rm W}$ is more accurate that the current(PDG98) best measurement.
- The LEP(2) experiments offer a great variety of experimental probes for the study of the weak properties of the neutral AND charged mediators of the weak interaction.
- New result from NuTeV soon.
- Future: More data for the LEP experiments (at higher energies!).

Last Slide

LEP $|V_{cs}|$ from the WW Cross-Section:

$$\mathrm{BR}(W \to q\bar{q}) = (67.96 \pm 0.41)\%$$
$$|V_{cs}| = 0.997 \pm 0.016(\mathrm{stat})0.012(\mathrm{syst})$$

LEP R_c^W and $|V_{cs}|$:

$$R_c^W = 0.499 \pm 0.027(\mathrm{stat}) \pm 0.037(\mathrm{syst})$$
$$|V_{cs}| = 0.974 \pm 0.050$$

Standard Model expectation:

$$R_c^W = 0.5$$
$$\mathrm{BR}(W \to q\bar{q}) = 67.5\%$$

Consistent with a 3×3 Unitarity CKM Matrix