Measurement of R_c^W at LEP2 with the OPAL Detector

Alain Bellerive
Enrico Fermi Institute

July 1st 1999
XIth Rencontre de Blois

Outline:

- Introduction: $R_c^W = \frac{\Gamma(W \to cX)}{\Gamma(W \to \text{hadrons})}$
- Motivation and Strategy
- Vertex and Lepton Tags
- Results
- Systematic Uncertainties
- Summary
- Conclusion

Introduction

In 1997 and 1998 the LEP e^+e^- collider was operated at energies well above the threshold for 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.

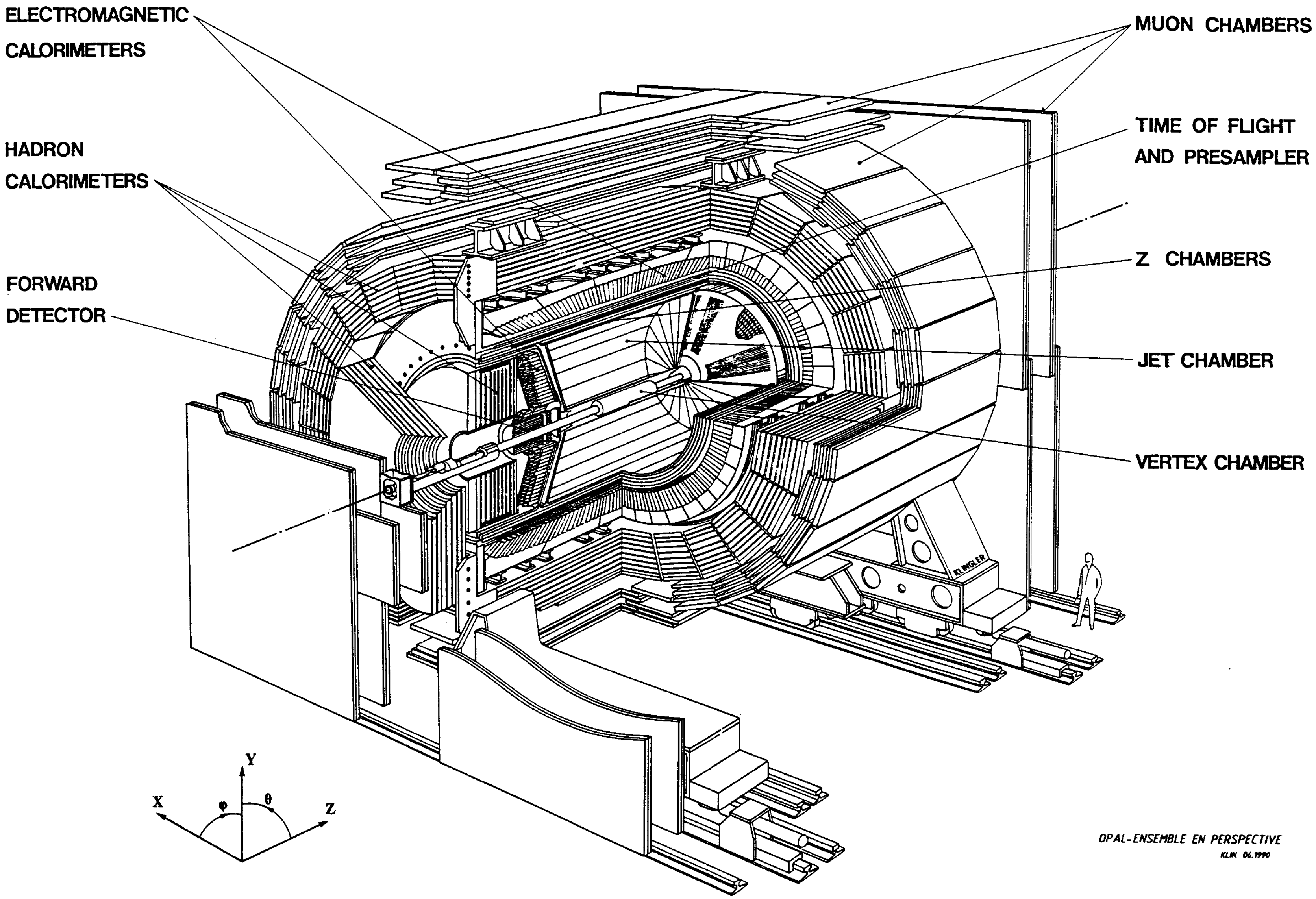
$$J_\mu^+ = (\bar{u}, \bar{c}, \bar{t})\,\frac{1}{2}\,\gamma_\mu\,(1-\gamma^5)\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

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

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

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

Experimental Apparatus: OPAL



Motivation

Measure the partial decay width:
$R_c^W = \Gamma(W \to cX)/\Gamma(W \to \text{hadrons})$.
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.

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

$\Longrightarrow$ Lead to an indirect measurement of $|V_{cs}|$ using the measured values of the other CKM matrix elements.

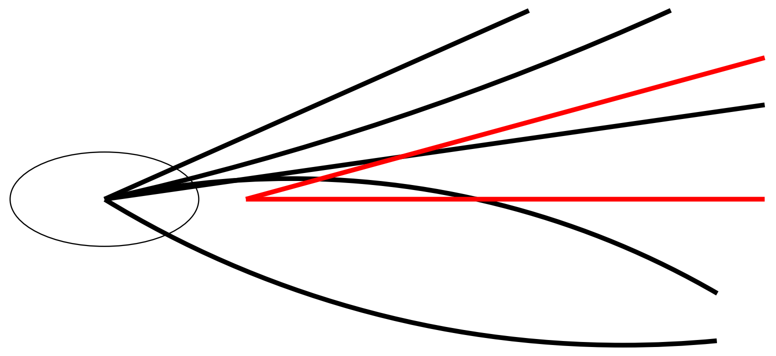
At LEP2, the determination of $|V_{cs}|$ from R_c^W with the OPAL data at $\sqrt{s} \simeq 183$ GeV and 189 GeV will be as accurate as the current best direct measurement of $|V_{cs}| = 1.04 \pm 0.16$.

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).

MC Samples: The main WW MC samples are generated with KoralW. Further samples generated with other generators were used to modeled (and study) the background and to determine the model dependencies of the measurement.

Strategy

Reconstruction of the Sub-Jet



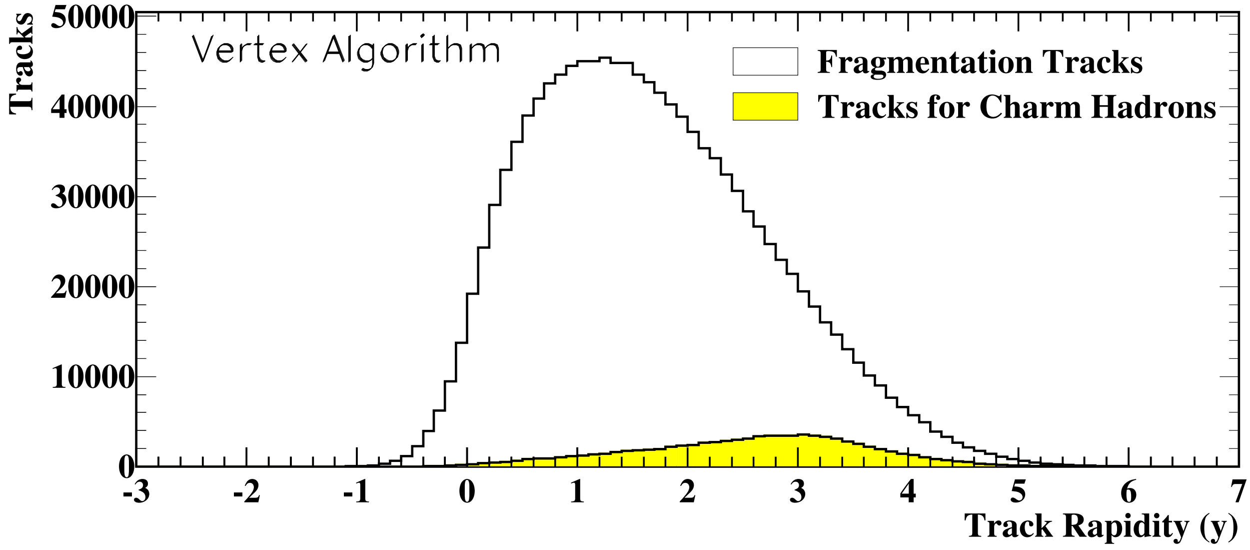
Tag the charm flavour with
- lifetime information
- lepton ID
- jet properties

- 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
- $|V_{ub}|$ and $|V_{cb}|$ are small

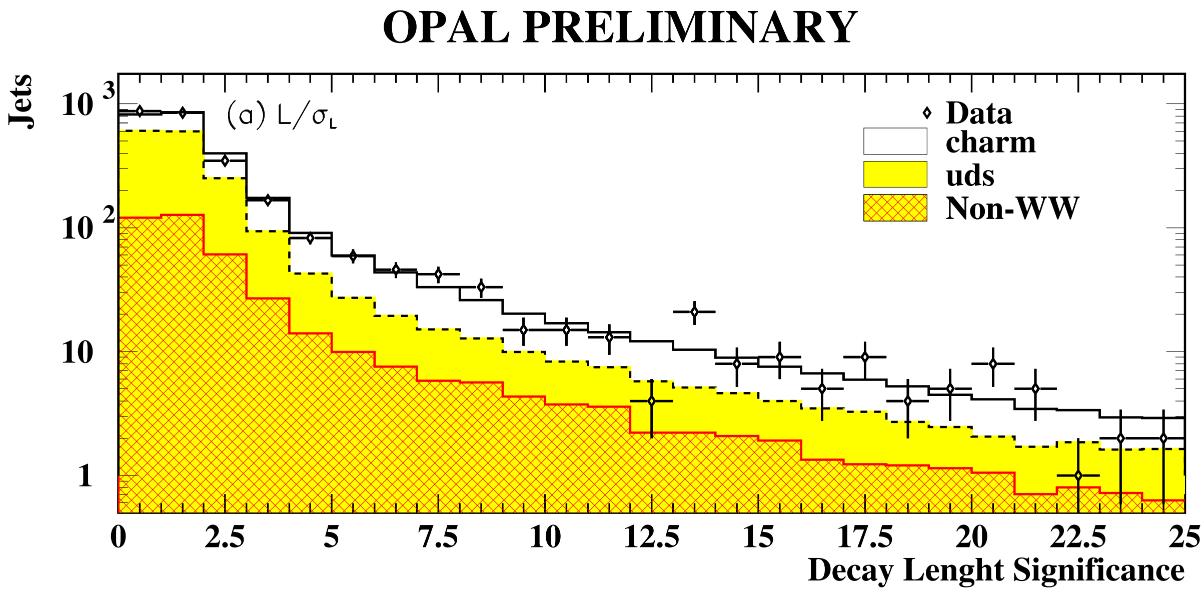
Vertex Tag: Selection

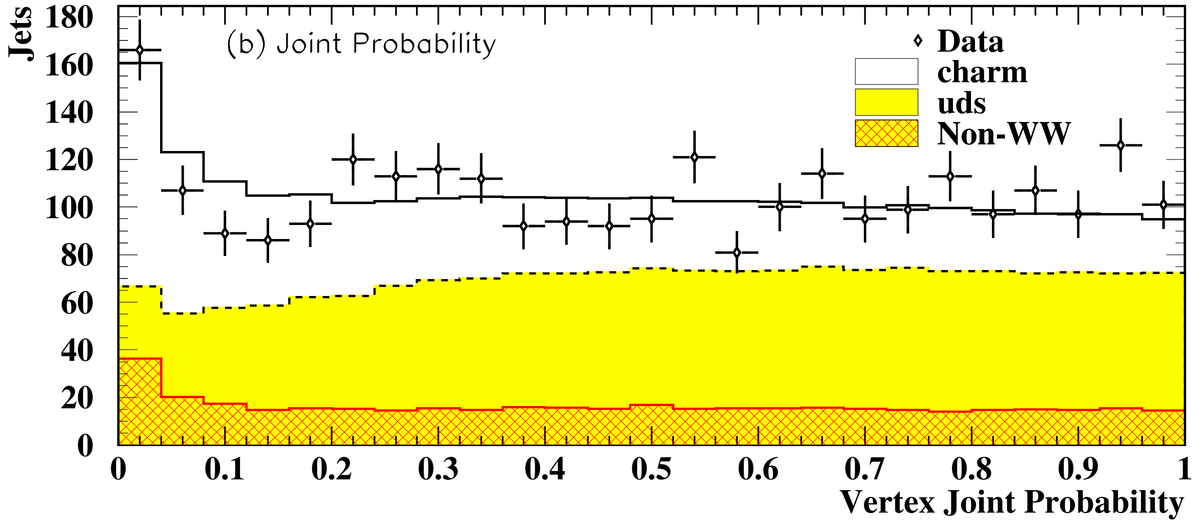
Charm Vertex Finding:

- 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

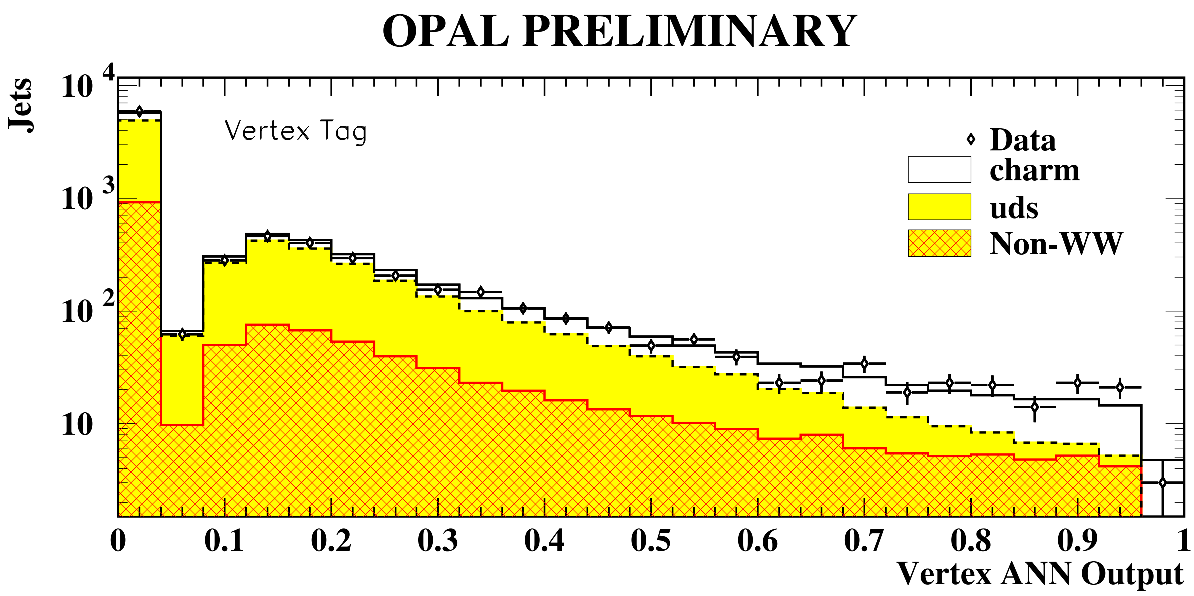


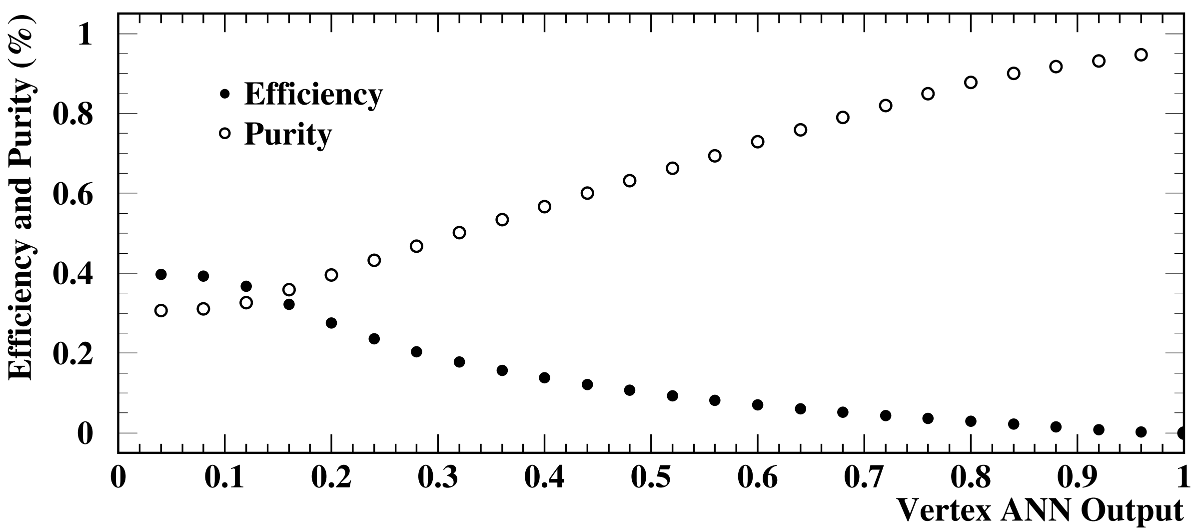


Inputs to the ANN:

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

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

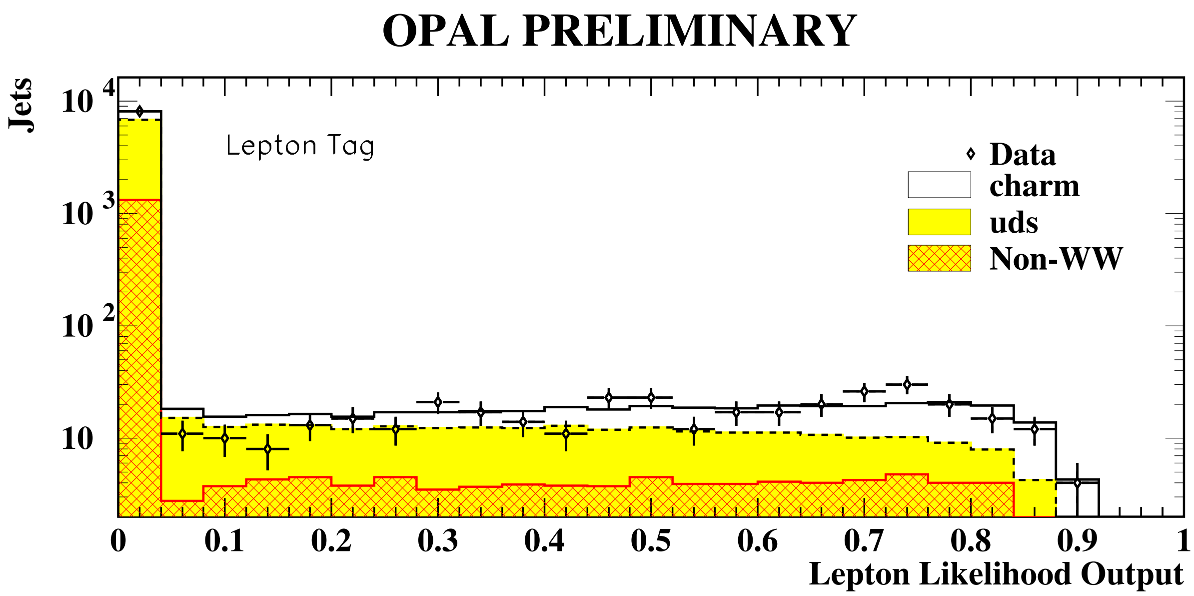
In $\mathrm{W^+W^-} \to \mathrm{q\bar{q}}\ell\bar{\nu}_\ell$ selected events:

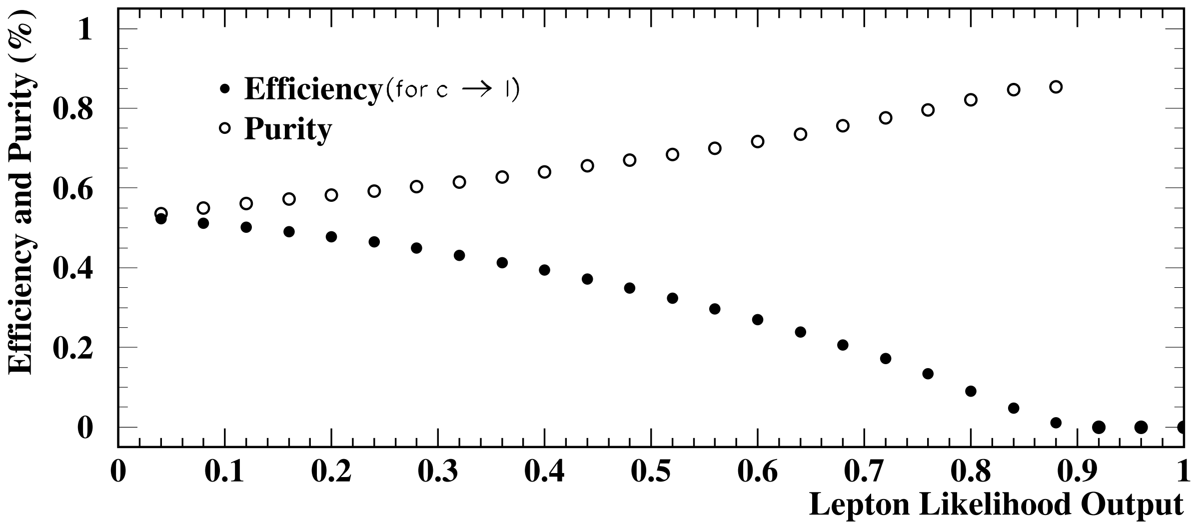
- $Q_\ell \cdot Q_{\mathrm{W}\to\ell\bar{\nu}_\ell}$

For electron only:

- OPAL conversion finder ANN output

Lepton Tag: Performance

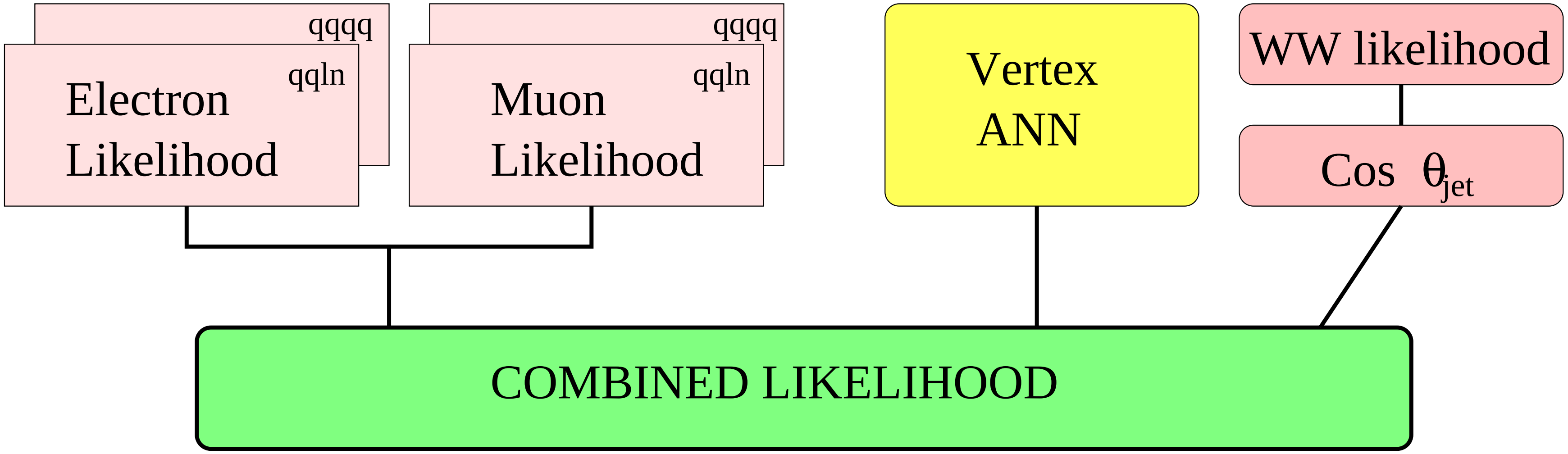




Strategy: Using the fact that BR$(c \to \ell) \simeq 20\%$ with $\ell = e$ or μ: Tag charm hadron jets with the identification of prompt leptons.

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:

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

with $R_c^W = 2\,F_c$ and

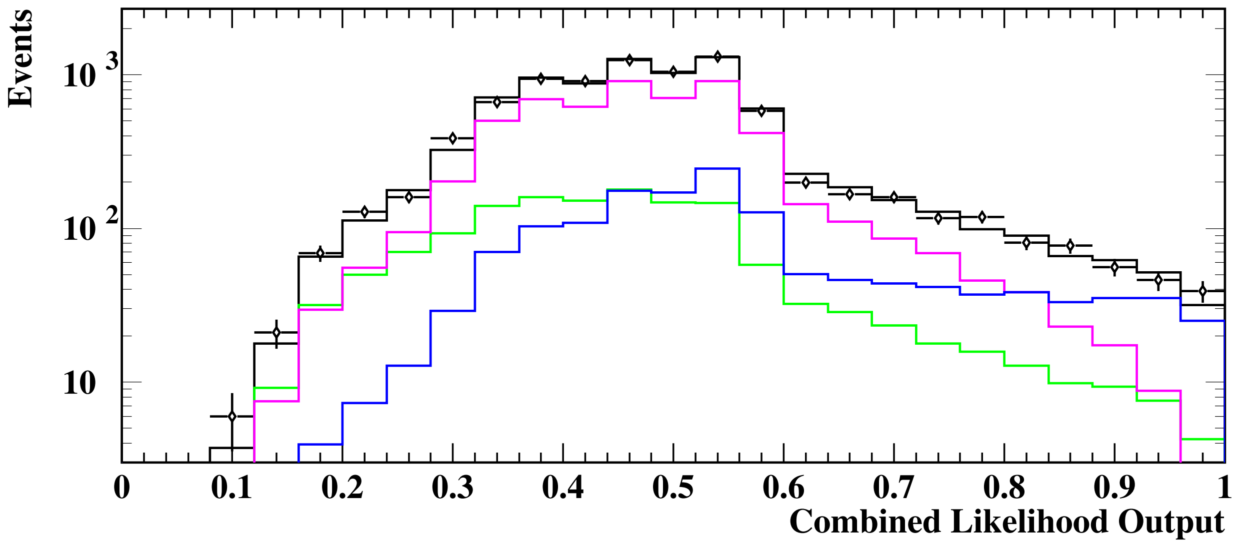
F_c: Fraction of charm jets (float)

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

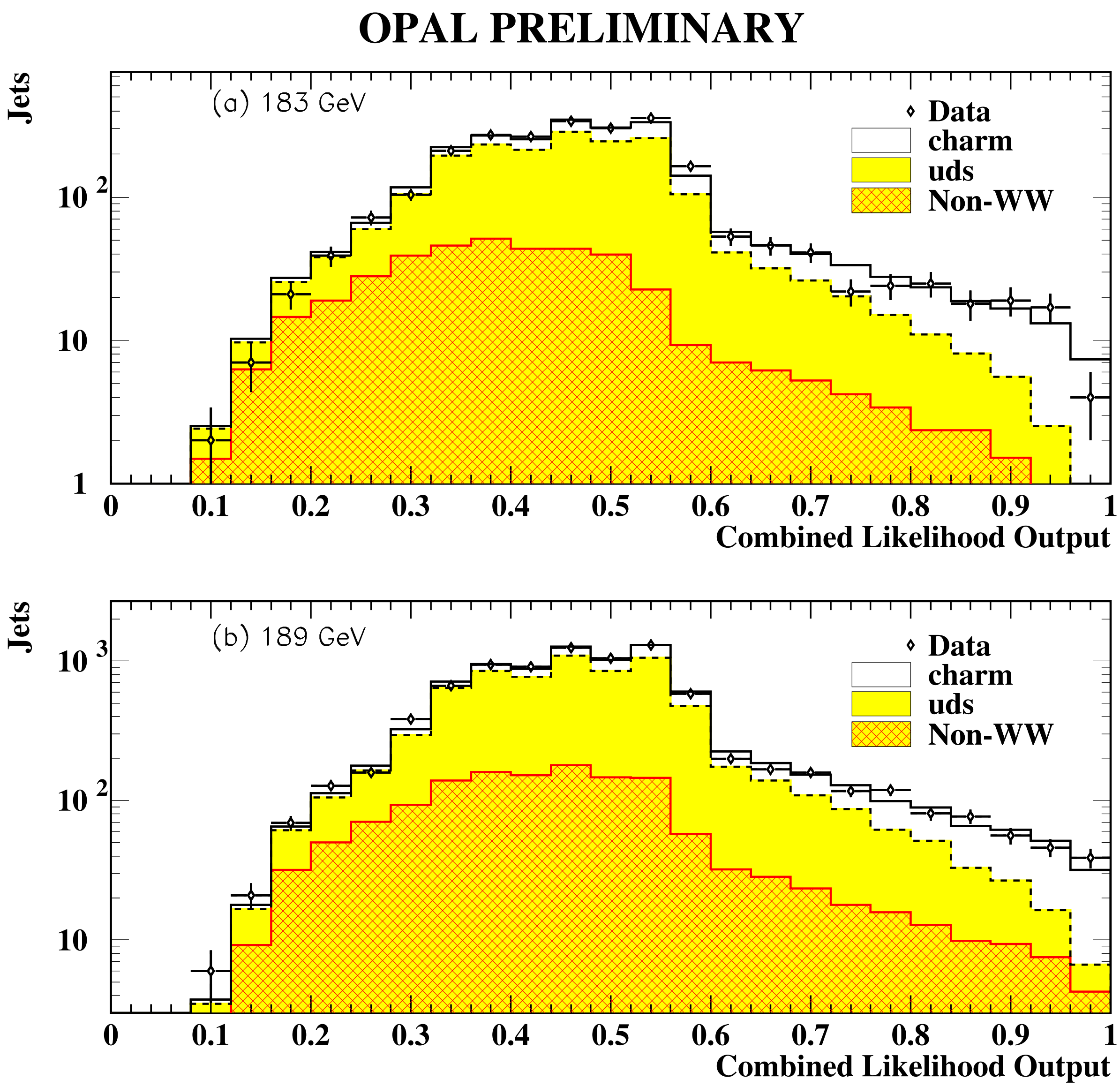
$\mathcal{P}_{uds}^i$: Probability to tag uds in $i^{\rm th}$ bin

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

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



Fit Results for R_c^W



$$R_c^W = 0.48 \pm 0.08 \quad \text{at 183 GeV}$$

and

$$R_c^W = 0.46 \pm 0.05 \quad \text{at 189 GeV.}$$

Systematic Uncertainties

Source of Systematic Error	$\Delta\ R_c^W$ 183 GeV	189 GeV
Hadronisation Model	0.020	0.022
Centre–of–mass Energy	0.009	0.012
Mass of the W Boson	0.008	0.010
Charm Frag. Function	0.008	0.008
Background Cross-Section	0.010	0.007
Background Composition	0.015	0.012
Charm Hadron Fractions	0.016	0.018
Light Quark Composition	0.015	0.015
Vertex Reconstruction	0.031	0.035
Charm Hadron Lifetimes	0.003	0.003
Charm Decay Multiplicity	0.012	0.012
Lepton Identification	0.027	0.025
Lepton Energy Spectrum	0.006	0.006
Branching ratio BR(c$\rightarrow \ell$)	0.011	0.010
Total systematic error	0.06	0.06
Statistical error	0.08	0.05
Value of R_c^W	0.48	0.46

Systematic Error: Details

- *Hadronisation model:* The Pythia MC sample, which uses the Lund string fragmentation as implemented in Jetset, is compared to a sample generated with Herwig, which uses cluster fragmentation.

- *W mass and centre–of–mass energy:* The analysis is repeated with different W masses and at different centre–of–mass energies.

- *Charm fragmentation function:* The fragmentation of heavy flavours in the Jetset simulation is parametrised according to the model of Peterson *et al*. The mean scaled energy of charmed hadrons in W decays is varied around its MC value by twice the LEP1 experimental uncertainty ($x_D = 0.484 \pm 0.008(\times 2)$).

- *Background cross–section:* Fraction F_{bkg} can float in the fit for F_c. As a check the expected number of background jets is fixed and varied within the error on the non-WW background.

- *Background composition:* The various background sources have different probabilities to fake a charm jet. The background composition is varied within the range prescribed in the OPAL cross-section paper (check the shape).

Systematic Error: Details

- *Flavour composition of down–type quark jets:* The small difference in the shape of the template histograms for d and s jets can bias the measurement. Check the effects of varying $|V_{ud}|, |V_{cs}|, |V_{us}|$, and $|V_{cd}|$.

- *Vertex reconstruction:* Change the detector resolution by smearing $(\pm 10\%)$ the track parameter errors and the track multiplicity.

- *Lifetime and Fractions of charmed hadrons:* The lifetimes and fractions of the weakly decaying charmed hadrons are varied within their experimental errors.

- *Charm decay multiplicity:* The relative abundance of 2, 3, and 4 prong charm decays has been changed in the MC within their experimental errors.

- *Lepton identification:* The error of the lepton detection efficiency and the error on the fake rate are increased by 50 % with respect to the values obtained at LEP1.

- *Lepton energy spectrum:* The lepton spectrum is reweighted from the spectrum implemented in Jetset to the ACCMM model.

- *Semileptonic BR of charm quarks:* Br (c$\rightarrow \ell) = 0.098 \pm 0.005$ is varied within its experimental error.

Results (OPAL Preliminary)

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

$$R_c^W = 0.48 \pm 0.08(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

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

$$R_c^W = 0.46 \pm 0.05(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

Combined value:

$$R_c^W = 0.47 \pm 0.04(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

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

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

$$|V_{cs}| = 0.91 \pm 0.07(\mathrm{stat}) \pm 0.11(\mathrm{syst}) \pm 0.004(\mathrm{ckm})$$

Summary

Measurement of R_c^W

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

$$R_c^W = 0.47 \pm 0.04(\text{stat}) \pm 0.06(\text{syst})$$

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

$$|V_{cs}| = 0.91 \pm 0.07(\text{stat}) \pm 0.11(\text{syst}) \pm 0.004(\text{ckm})$$

D semileptonic decays (MARKIII & CLEO):

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

Neutrino experiments (CCFR):

$$|V_{cs}| = 1.05 \pm 0.10\,(\text{stat.})^{+0.07}_{-0.11}\,(\text{syst.})$$

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

Experiment	R_c^W
ALEPH	$0.51^{+0.05}_{-0.05}\,(\mathrm{stat.}) \pm 0.030\,(\mathrm{syst.})$
DELPHI	$0.52^{+0.07}_{-0.05}\,(\mathrm{stat.}) \pm 0.050\,(\mathrm{syst.})$
L3	$0.50^{+0.11}_{-0.11}\,(\mathrm{stat.}) \pm 0.035\,(\mathrm{syst.})$
OPAL	$0.46^{+0.10}_{-0.10}\,(\mathrm{stat.}) \pm 0.080\,(\mathrm{syst.})$
LEP	$0.506 \pm 0.035\,(\mathrm{stat.}) \pm 0.05\,(\mathrm{syst.})$

Extraction of $|V_{cs}|$ from R_c^W with the direct measurements of the other CKM matrix elements:

Experiment	$\lvert V_{cs}\rvert$
ALEPH	$1.00^{+0.10}_{-0.10}\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.})$
DELPHI	$1.01^{+0.12}_{-0.10}\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.})$
L3	$0.98^{+0.22}_{-0.22}\,(\mathrm{stat.}) \pm 0.08\,(\mathrm{syst.})$
OPAL	$0.89^{+0.18}_{-0.18}\,(\mathrm{stat.}) \pm 0.15\,(\mathrm{syst.})$
LEP	$0.987 \pm 0.07\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.})$

Source: V.Obraztsov (ICHEP98 Vancouver)

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

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

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

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

under the assumption that the W couples with equal strength to quarks and leptons.

Experiment	$\lvert V_{cs}\rvert$
ALEPH	$1.05 \pm 0.06\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})$
DELPHI	$0.98 \pm 0.07\,(\mathrm{stat.}) \pm 0.04\,(\mathrm{syst.})$
L3	$1.10 \pm 0.06\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.})$
OPAL	$0.99 \pm 0.06\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})$
LEP	$1.03 \pm 0.03\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})$

Source: V.Obraztsov (ICHEP98 Vancouver)

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

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

Conclusion

OPAL Update of R_c^W

Analysing the data collected at $\sqrt{s} = 183$ GeV and 189 GeV with an improved charm tagger compared to ICHEP98:

$$R_c^W = 0.47 \pm 0.04(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

$$|V_{cs}| = 0.91 \pm 0.07(\mathrm{stat}) \pm 0.11(\mathrm{syst}) \pm 0.004(\mathrm{ckm})$$

- LEP2 provides a clean environment to investigate the coupling strength of the W boson to the charm quark.
- The extraction of $|V_{cs}|$ from R_c^W with the direct measurements of the other CKM matrix elements is more accurate that the current(PDG98) best measurement.
- Future: New result from NuTeV and more data for the LEP experiments.