Overview of WWV Program

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OUTLINE

Basic Goal of WWV Software

Identifying W Pairs / Classifying Decays

Reconstructing Production / Decay Angles

Parametrizing Angular Distributions

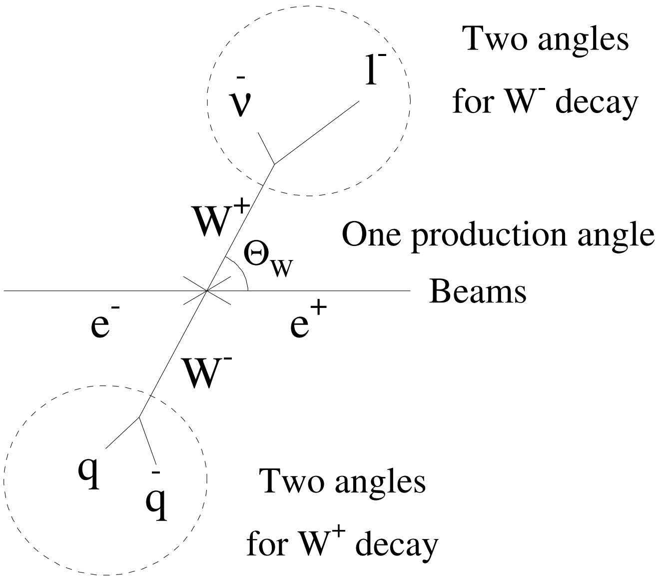
Parameter Fitting Algorithm

WWV Program

Basic Goal of WWV

Loop over events...

- Identify W pair candidate events and classify decays
- Reconstruct and store W production / decay angles:



End loop

Fit angular distribution(s) to extract couplings parameters

Identifying / Classifying Decays

For the moment, W pair identification is a cheat:

Real efficiency loss (via smearing, acceptance cuts),

But purity = 100%

Classification of W decays (first-guess cut values):

- $WW \to e\nu q\bar{q}'$, $WW \to \mu\nu q\bar{q}'$ Channels

  Identified isolated, energetic e or μ (see next page)

  \# charged tracks ≥ 3

  \# neutrals ≥ 3

  $E_{charged}, E_{neutral} > 0.05\, E_{\rm CM}$

  $E_{charged} + E_{neutral} > 0.20\, E_{\rm CM}$

- $WW \to q\bar{q}'q\bar{q}'$ Channel

  No identified e, μ

  \# charged tracks ≥ 6

  \# neutrals ≥ 6

  $E_{charged}, E_{neutral} > 0.10\, E_{\rm CM}$

  $E_{charged} + E_{neutral} > 0.40\, E_{\rm CM}$

Electron ID:

- Cheat: consider only true electrons
- $0.90 \times E_\ell^{\rm min} < E_e < 1.10 \times E_\ell^{\rm max}$ †
- $0.8 < E_e/p_e < 1.2$
- Electron isolated by 15^o from nearest charged track ($p_{trk} > 1$ GeV)

Muon ID:

- Cheat: consider only true muons
- $0.90 \times E_\ell^{\rm min} < E_\mu < 1.10 \times E_\ell^{\rm max}$ †
- Muon isolated by 15^o from nearest charged track ($p_{trk} > 1$ GeV)

† $E_\ell^{\rm min}$, $E_\ell^{\rm max} \equiv$ min / max allowed lepton energy (for no ISR, $\Gamma_W = 0$

Events passing $\ell \nu q \bar{q}'$ selection subjected to JADE-algorithm jet-finding until exactly two jets remaining (excluding lepton)

Reconstructing five production, decay angles

(Only $WW \to e\nu q\bar{q}'$, $WW \to \mu\nu q\bar{q}'$ channels considered)

Two approaches implemented: [`TLB` and `kinfit`(1-3)]

- `TLB` (Barklow algorithm):

  Assumes ideal resolution for e, μ energies / directions

  Assumes ideal measurement of jet speed ($|\vec{p}_{jet}/E_{jet}|$) (systematic errors partly cancel)

  E_ℓ defines allowed cone for parent W direction (assuming no ISR and $\Gamma_W = 0$)

  Take W direction to be vector on cone nearest to W defined by two jets

  Decay angles then determined

- `kinfit`(1-3) (Kinematic fits for three M_W cases):

  Allows for measurement error in lepton, jet energies, directions

  Customized least-square, constrained fit to determine "best" set of daughter directions

  Decay angles then determined

  Three different W mass assumptions:

  1. Both W masses free to float independently
  2. W masses float together ($M_{W^+} = M_{W^-}$)
  3. Both W masses fixed to nominal value (80.2 GeV)

Generic Parametrization:

(Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB 282: 253 (1987))

$$
\begin{aligned}
L_{WWV}/g_{WWV} \quad = \quad & i\, g_1^V (W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}) \\
+ \quad & i\, \kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} \\
+ \quad & \frac{i\, \lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda} \\
- \quad & g_4^V W_\mu^\dagger W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
+ \quad & g_5^V \epsilon^{\mu\nu\rho\sigma} (W_\mu^\dagger \overleftrightarrow{\partial}_\rho W_\nu) V_\sigma \\
+ \quad & \tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu} \\
+ \quad & \frac{i\, \tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu \tilde{V}^{\nu\lambda}
\end{aligned}
$$

where

$$W_{\mu\nu} \equiv \partial_\mu W_\nu - \partial_\nu W_\mu \qquad V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$$

$$V \equiv \gamma, Z \qquad (A \overleftrightarrow{\partial}_\mu B) \equiv A(\partial_\mu B) - (\partial_\mu A) B$$

$$\tilde{V}_{\mu\nu} \equiv \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$$

Normalization:

$$g_{WW\gamma} \quad \equiv \quad -e \qquad g_{WWZ} \quad \equiv \quad -e \cot\theta_W$$

Seven $\times$ two independent couplings

but

g_4^V, $\tilde{\kappa}_V$, $\tilde{\lambda}_V$ terms CP-violating

g_5^V term C, P violating

(these terms often ignored in studies)

Standard Model:

$$g_1^V = \kappa_V = 1 \qquad \lambda_V = g_4^V = g_5^V = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$$

Higher order operators with additional derivatives equivalent to momentum-dependent couplings:

$$\kappa_V \quad = \quad \kappa_V(q^2/\Lambda^2) \qquad \text{Form factor couplings}$$

$\Rightarrow$ Important at hadron colliders

In more familiar terminology ...

W magnetic dipole moment:

$$\mu_W \quad \equiv \quad \frac{e}{2\,M_W}(1+\kappa_\gamma+\lambda_\gamma)$$

W electric quadrupole moment:

$$Q_W \quad \equiv \quad -\frac{e}{M_W^2}(\kappa_\gamma-\lambda_\gamma)$$

W electric dipole moment:

$$d_W \quad \equiv \quad \frac{e}{2\,M_W}(\tilde{\kappa}_\gamma+\tilde{\lambda}_\gamma)$$

W magnetic quadrupole moment:

$$\tilde{Q}_W \quad \equiv \quad -\frac{e}{M_W^2}(\tilde{\kappa}_\gamma-\tilde{\lambda}_\gamma)$$

Deviations from SM:

$$\Delta g_1^Z \quad \equiv \quad g_1^Z - 1 \qquad\qquad \Delta\kappa_V \quad \equiv \quad \kappa_V - 1$$

$$g_1^\gamma(q^2 \to 0) \quad \equiv \quad 1 \qquad - \qquad \text{W electric charge}$$

In momentum space...

$$
\begin{aligned}
\Gamma_V^{\alpha\beta\mu}(q,\bar{q},P) \;=\;\; & f_1^V (q-\bar{q})^\mu \;-\; \frac{f_2^V}{M_W^2}(q-\bar{q})^\mu P^\alpha P^\beta \\
& + f_3^V (P^\alpha g^{\mu\beta} - P^\beta g^{\mu\alpha}) \;+\; i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) \\
& + i f_5^V \epsilon^{\mu\alpha\beta\rho}(q-\bar{q})_\rho \;-\; f_6^V \epsilon^{\mu\alpha\beta\rho} P_\rho \\
& - \frac{f_7^V}{M_W^2}(q-\bar{q})^\mu \epsilon^{\alpha\beta\rho\sigma} P_\rho (q-\bar{q})_\sigma
\end{aligned}
$$

where

$$
\begin{aligned}
f_1^V &= g_1^V + \frac{s}{2\,M_W^2}\lambda_V \\
f_2^V &= \lambda_V \\
f_3^V &= g_1^V + \kappa_V + \lambda_V \\
f_i^V &= g_i^V \qquad\qquad\qquad\qquad (\text{for } i = 4,5) \\
f_6^V &= \tilde{\kappa}_V - \tilde{\lambda}_V \\
f_7^V &= -\frac{1}{2}\,\tilde{\lambda}_V
\end{aligned}
$$

We need the matrix element amplitude for

$$e^-(k,\sigma) + e^+(\bar{k},\bar{\sigma}) \quad \rightarrow \quad W^-(q,\lambda) + W^+(\bar{q},\bar{\lambda})$$

where σ, λ, *etc.*, are initial and final state helicities

From Hagiwara *et al.*, define:

$$M_1 = M_{\sigma\bar{\sigma};\lambda\bar{\lambda}}(\Theta_W) = \sqrt{2}e^2\tilde{M}_{\sigma\bar{\sigma};\lambda\bar{\lambda}}(\Theta_W)\Delta\sigma(-1)^{\bar{\lambda}}d^{J_0}_{\Delta\sigma,\Delta\lambda}(\Theta_W)$$

where

$$\Delta\sigma = \frac{1}{2}(\sigma - \bar{\sigma}) \qquad \Delta\lambda = \lambda - \bar{\lambda} \qquad J^0 = \max(|\Delta\sigma|, |\Delta\lambda|)$$

and where

$$\tilde{M} = -\frac{\sqrt{2}}{\sin^2\theta_W}\frac{1}{1+\beta^2 - 2\,\beta\cos\Theta_W}\delta_{\Delta\sigma,-1} \qquad (|\Delta\lambda| = 2)$$

$$\tilde{M} = \tilde{M}^\gamma + \tilde{M}^Z + \tilde{M}^\nu \qquad (|\Delta\lambda| \leq 1)$$

The γ, Z, and ν contributions can be expressed in terms of certain $A^V_{\lambda\lambda}$, $B_{\lambda\lambda}$, and $C_{\lambda\lambda}$ coefficients related to the f_i parameters defined earlier:

$$\tilde{M}^\gamma = -\beta\delta_{|\Delta\sigma|,1}A^\gamma_{\lambda\lambda}$$

$$\tilde{M}^Z = \beta[\delta_{|\Delta\sigma|,1} - \frac{1}{2\,\sin^2\theta_W}\delta_{\Delta\sigma,-1}]\frac{s}{s-M_Z^2}A^Z_{\lambda\lambda}$$

$$\tilde{M}^\nu = \frac{1}{2\,\sin^2\theta_W\beta}\delta_{\Delta\sigma,-1}[B_{\lambda\lambda} - \frac{1}{1+\beta^2-2\,\beta\cos\Theta_W}C_{\lambda\lambda}]$$

Seven helicity coefficients $A^V_{\lambda\lambda}$ for WWV couplings:

$(\lambda,\bar\lambda)$	$A^V_{\lambda\lambda}$
$(+,0)$	$\gamma(f_3^V - i f_4^V + \beta f_5^V + i\beta^{-1} f_6^V)$
$(0,-)$	$\gamma(f_3^V + i f_4^V + \beta f_5^V - i\beta^{-1} f_6^V)$
$(0,+)$	$\gamma(f_3^V + i f_4^V - \beta f_5^V + i\beta^{-1} f_6^V)$
$(-,0)$	$\gamma(f_3^V - i f_4^V - \beta f_5^V - i\beta^{-1} f_6^V)$
$(+,+)$	$f_1^V + i\beta^{-1} f_6^V + 4\, i\gamma^2\beta f_7^V$
$(-,-)$	$f_1^V - i\beta^{-1} f_6^V - 4\, i\gamma^2\beta f_7^V$
$(0,0)$	$\gamma^2[-(1+\beta^2) f_1^V + 4\,\gamma^2\beta^2 f_2^V + 2\, f_3^V]$

And corresponding helicity coefficients $B_{\lambda\lambda}$, $C_{\lambda\lambda}$ for ν exchange (shown with S.M. $A^V_{\lambda\lambda}$ values):

$(\lambda,\bar\lambda)$	$A^V_{\lambda\lambda}$(S.M.)	$B_{\lambda\lambda}$	$C_{\lambda\lambda}$
$(+,0),(0,-)$	2γ	2γ	$2\,(1+\beta)/\gamma$
$(0,+),(-,0)$	2γ	2γ	$2\,(1-\beta)/\gamma$
$(+,+),(-,-)$	1	1	$1/\gamma^2$
$(0,0)$	$2\,\gamma^2+1$	$2\,\gamma^2$	$2/\gamma^2$

$$\beta = (1 - 4\, M_W^2/s)^{\frac{1}{2}} \qquad \gamma = \sqrt{s}/(2M_W)$$

The “d functions” $d^{J^0}_{\Delta\sigma,\Delta\lambda}(\theta)$ are defined:

$$
\begin{aligned}
d^2_{1,2} &= -d^2_{-1,-2} &&= +\frac{1}{2}(1+\cos\theta)\,\sin\theta \\
d^2_{1,-2} &= -d^2_{-1,2} &&= -\frac{1}{2}(1-\cos\theta)\,\sin\theta \\
d^1_{1,1} &= d^1_{-1,-1} &&= +\frac{1}{2}(1+\cos\theta) \\
d^1_{1,-1} &= d^1_{-1,1} &&= +\frac{1}{2}(1-\cos\theta) \\
d^1_{1,0} &= -d^1_{-1,0} &&= -\sqrt{\frac{1}{2}}\sin\theta
\end{aligned}
$$

Define the production tensor:

$$P^{\lambda\bar{\lambda}}_{\lambda'\bar{\lambda}'} \equiv \sum_{\sigma}\sum_{\bar{\sigma}} M_1(\sigma,\bar{\sigma},\lambda,\bar{\lambda};\Theta_W)M_1^*(\sigma,\bar{\sigma},\lambda',\bar{\lambda}';\Theta_W)$$

The differential cross section w.r.t. Θ_W is (unpolarized beams)

$$\frac{d\sigma}{d\cos\Theta_W} = \frac{\beta}{128\,\pi s}P^{\lambda\bar{\lambda}}_{\lambda\bar{\lambda}}$$

Generalization for polarized beams (Barklow notation):

$$\begin{aligned} Q^{\lambda\bar{\lambda}}_{\lambda'\bar{\lambda}'} \equiv\ & (1+P_e)\sum_{\bar{\sigma}} M_1(+,\bar{\sigma},\lambda,\bar{\lambda};\Theta_W)M_1^*(+,\bar{\sigma},\lambda',\bar{\lambda}';\Theta_W) \\ & (1-P_e)\sum_{\bar{\sigma}} M_1(-,\bar{\sigma},\lambda,\bar{\lambda};\Theta_W)M_1^*(-,\bar{\sigma},\lambda',\bar{\lambda}';\Theta_W) \end{aligned}$$

The differential cross section w.r.t. Θ_W is (polarized beams)

$$\frac{d\sigma}{d\cos\Theta_W} = \frac{\beta}{128\,\pi s}Q^{\lambda\bar{\lambda}}_{\lambda\bar{\lambda}}$$

Now consider the final state $WW \to \ell^- \bar{\nu}_\ell q \bar{q}'$, where we identify the charge of the lepton but not of the quarks

Differential cross section w.r.t. production / decay angles (Θ_W, θ, ϕ, $\bar{\theta}$, $\bar{\phi}$) for e^- beam polarization P_e (Barklow notation)

$$\frac{d\sigma}{d\cos\Theta_W \, d\cos\theta \, d\phi \, d\cos\bar{\theta} \, d\bar{\phi}} = \frac{9\beta B_{lh}}{8192\,\pi^3 s} \sum_{\lambda,\lambda',\bar{\lambda},\bar{\lambda}'} Q^{\lambda\bar{\lambda}}_{\lambda'\bar{\lambda}'}(\cos\Theta_W; P_e)$$
$$\times D^{\lambda}_{\lambda'}(\cos\theta, \phi) \, \bar{H}^{\bar{\lambda}}_{\bar{\lambda}'}(\cos\bar{\theta}, \bar{\phi})$$

Where

$$B_{lh} \equiv \mathrm{B}(W^- \to \ell^- \bar{\nu}_\ell) \times \mathrm{B}(W^+ \to q\bar{q}')$$

And where $D^{\lambda}_{\lambda'}$ and $\bar{H}^{\bar{\lambda}}_{\bar{\lambda}'}$ are the leptonic and hadronic decay tensors:

$$\bar{H}^{\bar{\lambda}}_{\bar{\lambda}'}(\cos\bar{\theta}, \bar{\phi}) \equiv \bar{D}^{\lambda}_{\lambda'}(\cos\bar{\theta}, \bar{\phi}) + \bar{D}^{\lambda}_{\lambda'}(-\cos\bar{\theta}, \bar{\phi} + \pi)$$

The leptonic decay tensor $D^{\lambda}_{\lambda'}(\cos\theta, \phi)$ is defined:

$$
\begin{aligned}
D^{+}_{+} &= \frac{1}{2}(1-\cos\theta)^2 \\
D^{-}_{-} &= \frac{1}{2}(1+\cos\theta)^2 \\
D^{0}_{0} &= \sin^2\theta \\
D^{+}_{0} &= +\frac{1}{\sqrt{2}}(1-\cos\theta)\sin\theta e^{i\phi} \\
D^{-}_{0} &= -\frac{1}{\sqrt{2}}(1+\cos\theta)\sin\theta e^{-i\phi} \\
D^{+}_{-} &= \frac{1}{2}\sin^2\theta e 2 i\phi
\end{aligned}
$$

Where

$$
D^{\lambda'}_{\lambda} = (D^{\lambda}_{\lambda'})^*
$$

Parameter Fitting Algorithm

Fitting technique is binned maximum likelihood using Minuit

- Only 1-d distribution in Θ_W now supported
- Efficiency correction handled via Monte-Carlo-derived migration matrix M_{ij}
  (true Θ_W bin $i \Rightarrow$ reconstructed Θ_W bin j)
- Expectation per true bin based on function value at center (Can think about crude integral over bin width at some penalty in cpu)
- Binning is in Θ_W, <u>not</u> $\cos\Theta_W$
- No background correction yet
- Only pure $WW \to \ell^- \bar{\nu}_\ell q \bar{q}'$ events now supported
  (not $WW \to \ell^+ \nu_\ell q \bar{q}'$)

Not clear whether above approach will be practical (cpu-wise) for full 5-dimensional simultaneous fit to (Θ_W, θ, ϕ, $\bar{\theta}$, $\bar{\phi}$)

WWV Program

- Written in Fortran 77
- Uses CERN Library extensively
  (Minuit, Hbook, matrix routines)
- All executable code / commons in one Patchy file
- Will provide utility for running Patchy processor, compiling, linking and running on HP Unix O.S.
- Will also provide fortran generated from Patchy
- Support for other systems will depend on demand
- Few programming bells / whistles
  (*e.g.*, produces histograms but no ntuple)
- Tested with only Pythia events so far
- Patchy source file contains small driver program for generating Pythia $e^+e^- \to W^+W^-$ events
  (includes options for turning off ISR, setting $\Gamma_W = 0$, forcing $WW \to \ell^-\bar{\nu}_\ell q\bar{q}'$)
- Future enhancements will depend on demand

Basic Structure

```
      call init
      do iev = 1, nev
        call read_evt
        call find_5ang_true
        call smear_particles
        call classify
        if(..lepton vs hadron..)then
          call find_jets
          call find_5ang_TLB
          call find_5ang_kinfit
        endif
        call fill_hists
      enddo
      call fit_1ang
*     call fit_5ang
      call hrput
```

Important Common Blocks

Global control commons

- `wwvctrl`
  Misc. control variables for analysis, binning, *etc.*
- `fit1ctrl`
  Determines which couplings are free to vary in fit

Event Information

- `wwvtrue`
  Information on true kinematics of W's and daughters
- `wwvdet`
  Information on "detected" particles
- `wwvclass`
  Classification of event
  (#leptons, event type, jet info, TLB angles)
- `wwvkinfit`
  Results of kinematic fits

Important Common Blocks

Accumulated info used for coupling parameters fitting

- `wwvcum`
  Accumulated values of five angles from all events
- `ang1raw`
  Raw distribution in $\cos\Theta_W$
  (can be chosen from among: true, TLB, or kinfit[1-3])
- `couplings`
  Current assumed coupling values
- `dis1info`
  Expected angular distribution for current couplings
- `fitio`
  Results of coupling fits

Input / Output

- Reads in 4-vector files in Lund `lujets` format
- Produces output file of sets of five angles (true, TLB, kinfit[1-3])
- Can read in angles file and skip directly to parameter extraction from cumulative angular distribution(s)
- Outputs histogram file containing ang. distributions for “data”, S.M. expectation, fitted curve (and $\pm\sigma$), slices of Θ_W migration matrix, resolutions for five reconstructed angles
- For now, 4-vector and angle files are free format (ascii, editable)
- May want to use compression techniques in future