Measuring the mass, width, and couplings of semi-invisible resonances with the matrix element method

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The problem

$W$ could be a charged Higgs scalar or a new $W'$ heavy gauge boson. To find: $M_W$, $M_\nu$, $\Gamma_W$, and the chirality of the couplings.

$$g^q = g^q_L P_L + g^q_R P_R \quad \quad g^l = g^l_L P_L + g^l_R P_R$$

where $P_{L,R} = (1 \mp \gamma_5)/2$

$$\tan(\varphi_q) \equiv \frac{g^q_R}{g^q_L} \quad \quad \tan(\varphi_l) \equiv \frac{g^l_R}{g^l_L}$$
The end point of the $P_{\ell T}$ distribution is given by

$$\mu = \frac{M_W^2 - M_\nu^2}{2M_W}$$
Matrix Element Method

Likelihood of an event $\{P_j^{\text{vis}}\}$ under a set of parameter values $\alpha$

$$
\mathcal{P}(\{P_j^{\text{vis}}\}|\alpha) = \frac{1}{\sigma_\alpha} \left( \prod_{j=1}^{N_f} \int \frac{d^3 p_j}{(2\pi^3 2E_j)} \right) W(\{P_j^{\text{vis}}\}, \{p_j^{\text{vis}}\}) \\
\times \sum_{a,b} \frac{f_a(x_1)f_b(x_2)}{2sx_1x_2} |\mathcal{M}_\alpha(\{p_i\}, \{p_j\})|^2 \\
\times (2\pi)^4 \delta^4 \left( \sum_{i=1}^{2} p_i - \sum_{i=1}^{N_f+2} p_j \right)
$$

Likelihood of set of $N$ events

$$
\mathcal{L}_\alpha = \prod_{n=1}^{N} \mathcal{P}(\{P_j^{\text{vis}}\}_n|\alpha)
$$
"Mass difference" $\mu$

\[ \mu = \frac{M_W^2 - M_\nu^2}{2M_W} \]
Mass scale $M_\nu$

\[
\frac{1}{\sigma} \frac{d\sigma}{dP_{lT}} = \frac{3}{4 + 3\rho} \frac{P_{lT}}{\mu \sqrt{\mu^2 - P_{lT}^2}} \left( 2 - \frac{P_{lT}^2}{\mu^2} + \rho \right)
\]

where $\rho = \frac{2M_\nu^2}{M_W^2 - M_\nu^2}$
Mass scale $M_\nu$

$\chi^2$ per d.o.f. fit from $P_{lz}$ templates

- $M_\nu = 0$ GeV, $M_W = 750$ GeV
- $M_\nu = 250$ GeV, $M_W = 826$ GeV
- $M_\nu = 500$ GeV, $M_W = 1000$ GeV
- $M_\nu = 1000$ GeV, $M_W = 1443$ GeV
- $M_\nu = 2000$ GeV, $M_W = 2410$ GeV
Width $\Gamma_W$

$\chi^2$ per d.o.f. fit from $P_{IT}$ templates (10000 events)

Flat direction

$$\frac{\Gamma_W}{\Gamma_{W}^{\text{true}}} = \frac{1 + (M_{\nu}^{\text{true}}/M_W^{\text{true}})^2}{1 + (M_{\nu}/M_W)^2}$$
Masses and width using MEM

Negative log likelihood fit for masses and width (1000 events)

Including both $P_{LT}$ and $P_{LZ}$ eliminates the flat direction
Chirality ($\varphi_l, \varphi_q$)

The dependence on ($\varphi_l, \varphi_q$) is through $\cos(2\varphi_l)\cos(2\varphi_q)$
Chirality \((\varphi_l, \varphi_q)\)

Dependence of matrix element on chirality has a degeneracy. Matrix element depends on

\[
\cos(2\varphi_l) \cos(2\varphi_q) = \cos^2(\varphi_l - \varphi_q) - \sin^2(\varphi_l + \varphi_q)
\]

Negative log likelihood fit for 1000 events assuming values of other parameters. True value: \(\varphi_q = \varphi_l = 0\)
Simultaneous measurement

Extent to which different components of the visible momenta are affected by the parameters

<table>
<thead>
<tr>
<th></th>
<th>$P_{\ell T}$</th>
<th>$P_{\ell z}$</th>
</tr>
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<tbody>
<tr>
<td>mass difference</td>
<td>✓</td>
<td>~</td>
</tr>
<tr>
<td>mass scale</td>
<td>~</td>
<td>✓</td>
</tr>
<tr>
<td>width</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>chirality</td>
<td>×</td>
<td>✓</td>
</tr>
</tbody>
</table>

For 100 events produced at $M_W = 1000$ GeV, $M_\nu = 500$ GeV, $\Gamma_W = 50$ GeV, $\phi_q = \phi_q = 45^\circ$, multivariate minimization of the log likelihood function yielded $M_W = 998$ GeV, $M_\nu = 502$ GeV, $\Gamma_W = 43$ GeV, $\phi_q = \phi_q = 46.5^\circ$.
Pair production of $W$ like resonances

Log likelihood minimization with 500 events
Thank You!