Four-Lepton Signatures

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The 4l Channel

What can we learn from on-shell 4l decay?

\[ N_S = 20000 \]
The 4l Channel

What can we learn from on-shell 4l decay?

(Other than mass)

4 leptons
12 degrees of freedom
8 if we look in CM frame and focus on decay
Experimental Advantage

Leptons are clean and well-measured

We have analytical differential cross section

Possible to build full detector-level likelihood without the need of huge simulation samples

Many well-established analysis techniques
Many studies available

<table>
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<tr>
<th>Authors</th>
<th>ArXiv Number</th>
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<tbody>
<tr>
<td>Godbole, Miller, Muhlleitner</td>
<td>0708.0458</td>
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<tr>
<td>Cao, Jackson, Keung, Low</td>
<td>0911.3398</td>
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<td>De Rujula, Lykken, Pierini, Rogan, Spiropulu</td>
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<td>Bordone, Greljo, Isidori, Marzocca, Pattori</td>
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As well as many other studies, including studies from the LHC experiments.
Intermediate Boson

The intermediate boson can be Z or photon in SM

How sensitive are we to (effective) coupling involving photons?
Intermediate Boson

Parameterization used in this talk:

\[ L \supset \frac{h}{4\nu} \left( 2A_1^{ZZ} m_Z^2 Z^\mu Z_\mu + A_2^{ZZ} Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} Z^{\mu\nu} \tilde{Z}_{\mu\nu} \right. \]
\[ \left. + A_2^{Z\gamma} Z^{\mu\nu} F_{\mu\nu} + A_3^{Z\gamma} Z^{\mu\nu} \tilde{F}_{\mu\nu} + A_2^{\gamma\gamma} F^{\mu\nu} F_{\mu\nu} + A_3^{\gamma\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu} \right) \]
Interference Sizes

Differential Cross Section

\[ \frac{d\Gamma}{d\Omega} \sim \sum A_n^i A_m^j A_n^{*i} A_m^{*j} \times \frac{d\Gamma_{nm}^{ij}}{d\Omega} \]

Integrated Magnitude

\[ \Pi_{nm}^{ij} = \int \left| \frac{d\Gamma_{nm}^{ij}}{d\Omega} \right| d\Omega \]

O(1) coupling

\[
\begin{array}{cccccccc}
\text{A1ZZ} & A2ZZ & A3ZZ & A2ZA & A3ZA & A2AA & A3AA \\
1 & 0.28 & 0.027 & 0.66 & 0.32 & 1.2 & 0.76 \\
A2ZZ & 0.025 & 0.0051 & 0.091 & 0.023 & 0.15 & 0.035 \\
A3ZZ & 0.0092 & 0.023 & 0.034 & 0.035 & 0.07 & 0.023 \\
A2ZA & 9.6 & 2.9 & 0.31 & 0.51 & 0.22 & 0.01 \times 10^{-1} \\
A3ZA & 5.4 & 0.51 & 0.023 & 0.035 & 0.22 & 0.07 \times 10^{-1} \\
A2AA & 2.5 & 0.11 & 0.023 & 0.035 & 0.22 & 0.07 \times 10^{-1} \\
A3AA & 3 & 0.51 & 0.22 & 0.07 & 0.01 \times 10^{-1} & 0.07 \times 10^{-2} \\
\end{array}
\]
Interference Sizes

Differential Cross Section

\[
\frac{d\Gamma}{d\Omega} \sim \sum A_n^i A_m^{j*} \times \frac{d\Gamma_{nm}^{ij}}{d\Omega}
\]

Integrated Magnitude

\[
\Pi_{nm}^{ij} = \int \left| \frac{d\Gamma_{nm}^{ij}}{d\Omega} \right| d\Omega
\]

SM-like coupling O(\%)
Sensitivity

Parameter extraction with pseudo-experiments

Perform a fit to the differential cross section

Background assumed to be dominated by $qq\rightarrow 4l$

CMS Run I like cut
Sensitivity

Most sensitive to diphoton

Reaches SM prediction with O(1000) signal events

Can be improved by lowering di-lepton mass cut

ZA is hard (beyond 3ab\(^{-1}\))

ZZ is hard\(^2\) (beyond 3ab\(^{-1}\))
Projection to a few ab$^{-1}$

68% contour

Different selections investigated:
- CMS Run I-like
- Relaxed $M_\parallel$ cut ($M_\parallel > 4$ GeV, and not close to $M_\gamma$)
Projection to a few ab$^{-1}$

68% contour

Direct measurement size of coupling better

4-lepton channel can obtain sign and CP properties
Resolving 1-Loop

When $V/V'$ contains photon, there are two major contributions to the loop: $W$ and top quark.

Loops containing Higgs contribute to ZZ case.
We can write

\[ A_i^{VV'} = A_i^{VV'}(y_t, \tilde{y}_t, g_{WW}, ...) \]

Htt coupling  CP-odd version  HWW coupling

Substitute them into the differential cross section, and try to estimate the sensitivity
Here we investigate two different models to demonstrate the sensitivity to sign of the $g_{WW}$ (relative to $g_{ZZ}$)

$$\lambda_{WZ} = \frac{g_{WW}}{g_{ZZ}} = +1 \text{ (SM), } -1/2 \text{ (5plet)}$$

We consider two cases: fixing top Yukawa coupling to the SM value, or integrate it out during the model comparison.
For each model, we generate pseudo-data and evaluate the likelihood of having a negative $\lambda_{WZ}$. 

\[ \lambda_{WZ} \]
Custodial Symmetry

...and express the p-value in terms of effective sigma
Custodial Symmetry

Assuming true model is SM, sensitivity on ratio between W and Z

Prior on $y_t \sim$ restricting range between -3 – 3, free floating within 2

Restricting range on $y_t$ helps the sensitivity a lot
Here we investigate sensitivity to $y_t$

We only reach 1 sigma with a few $ab^{-1}$ assuming true model is SM
Top Coupling

Projection to end of HL-HLC

Direct measurement can pin down the value quite well

4l channel would be independent confirmation
Concluding Remarks

- The 4l channel provides a unique opportunity to measure the sign of couplings due to interference effects.
- It complements direct cross section measurement from other channels.
Backup Slides Ahead
$y_t$ prior in $\lambda_{WZ}$ analysis