**Exploring Drell-Yan Processes at the LHC**

In this project we will investigate various Drell-Yan (DY) processes at the LHC. Let us consider three resonant particles: spin-0, spin-1 and spin-2 (See Ref. [1] for other $Z'$ models).

- **Spin-0 states:** We begin with the neutral scalar boson $S$ which can have the following Lagrangian

$$ \mathcal{L}_S = \overline{f_i} \left( g_{S}^{ij} + ig_{P}^{ij} \gamma_5 \right) f_j S, \tag{1} $$

where $f$ can be either a quark or a lepton. The indices $i$ and $j$ run over generations, and the generation matrices $g_{S}^{ij} = (g_{S}^{ij})_{ij}$ and $g_{P}^{ij} = (g_{P}^{ij})_{ij}$ are required to be Hermitian by the Hermiticity of the Lagrangian. While a specific model predicts what these coefficients are, we will take a model-independent approach and consider them as free parameters. They are only constrained by experiments. For simplicity, let us consider these matrices are flavor-diagonal and universal for both quark and lepton sector. Therefore there are only four parameters: $\{g_S, g_P, MS, WS\}$, where MS and WS are the mass and the width of the scalar particle, $S$.

- **Spin-1 states:** Using the same notation, the most general Lagrangian for the neutral vector boson $V_\mu$ is

$$ \mathcal{L}_V = \overline{f_i} \gamma^\mu \left( g_{V}^{ij} + g_{A}^{ij} \gamma_5 \right) f_j V_\mu, \tag{2} $$

where $g_{V}^{ij} = (g_{V}^{ij})_{ij}$ and $g_{A}^{ij} = (g_{A}^{ij})_{ij}$ are required to be Hermitian matrices. Again, we will restrict ourselves to the case with two couplings, $g_{V}$ and $g_{A}$.

- **Spin-2 states:** The neutral tensor Lagrangian is given by

$$ \mathcal{L}_T = \frac{i}{\Lambda} \left[ \overline{f_i} \left( g_{T}^{ij} - g_{AT}^{ij} \gamma_5 \right) \left( \gamma^\mu \partial^\nu f_j + \gamma^\nu \partial^\mu f_j \right) - \left( \partial^\mu \overline{f_i} \gamma^\nu + \partial^\nu \overline{f_i} \gamma^\mu \right) \left( g_{T}^{ij} + g_{AT}^{ij} \gamma_5 \right) f_j \right] T_{\mu\nu} \tag{3} $$

where the couplings $g_{T}^{ij} = (g_{T}^{ij})_{ij}$ and $g_{AT}^{ij} = (g_{AT}^{ij})_{ij}$ are general $3 \times 3$ complex matrices. Here $\Lambda$ denotes the cutoff scale of the effective interactions, which should be at least at the order of the resonance mass or higher. Note that a dimension-4 operator between SM fermions and neutral tensor particle is not allowed since it would be proportional to the trace of the tensor which we have assumed to be traceless. As before, two free couplings are $g_{T}$ and $g_{AT}$.

1. The most general interaction for above resonances are presented in Ref. [2]. As discussed, we are interested in a simpler case with two couplings. Take the FeynRules model file described in Ref. [2], and redefine couplings for our purpose. Set couplings to $g_S = 1 = g_V = g_T$ and $g_P = 0 = g_A = g_{AT}$. Set masses to 1 TeV and their width to $\Gamma = 0.03 M$. Generate UFO files using FeynRules package and copy them under models directory of MadGrapg5. The names of the particles along with their charge, mass and width are listed in Table I.

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>$SV$</td>
<td>$MSV$</td>
</tr>
<tr>
<td>$V_\mu$</td>
<td>$VV$</td>
<td>$MVV$</td>
</tr>
<tr>
<td>$T_{\mu\nu}$</td>
<td>$TV$</td>
<td>$MTV$</td>
</tr>
</tbody>
</table>

**TABLE I:** Particles implemented in DY-FeynRules. In the first column is the symbol we use for the particle in this article. In the last 3 columns are the ASCII names we use for these particles, their masses and widths in FeynRules. These are the names that would be used in a simulation. The masses are set to 1 TeV by default while the widths are set to 20 GeV by default, but both of these parameters are free and can be set by the user. Make sure to change the width.

2. Generate DY event samples for three different spin scenarios with default settings, turning on PYTHIA and PGS/DELPHES, *i.e.*, $pp \rightarrow S \rightarrow e^+e^-$ and $pp \rightarrow S \rightarrow \mu^+\mu^-$, similarly for $V_\mu$ and $T_{\mu\nu}$.

3. Count the number of PGS/DELPHES events in the electron final state, and compare with that of the muon final state. Which final states give you more events? Take a look PGS/DELPHES. Can you explain why?
4. Reconstruct and plot the dilepton invariant mass. Are two distributions with $e^+e^-$ and $\mu^+\mu^-$ are the same? If you are not sure, repeat the same exercise with $M = 3$ TeV.

5. One of the main advantages of the present process is the feasibility to fully reconstruct the CM system of the two charged leptons that is the rest frame of the new boson. Although we do not know the direction of the quark on an event-by-event basis, it is strongly correlated with the direction of the CM frame of the charged lepton pair due to the parton distribution functions of the quark versus the anti-quark in a proton. Calculate this angle by first boosting into the CM frame of the charged leptons, and then taking the angle between the moving direction of the negatively charged lepton and the direction of the boost. Repeat the same procedure for all three spin-scenarios and compare three distributions. Perform the same exercise with all cuts removed this time, run_card.dat. Compare distributions as shown in Fig. 1. If distributions are slightly distorted, try to generate more events.

6. For Fig. 1, we have assumed $g_S = 1 = g_V = g_T$ and $g_P = 0 = g_A = g_{AT}$. Try to plot angular distributions of various models described in the project by Prof. Seong Chan Park.

7. We have set pseudo scalar coupling and axial coupling to zero and fixed the width to be 0.03$M$, which leave us two free parameters, mass and vector (scalar) coupling. Compute DY production cross sections in the two dimensional parameter space, $(M, g)$. You only need to scan over the mass parameter, since total cross section is proportional to $g^4$. Set factorization and renormalization scale to the mass of the resonance, which effectively reduces cross section (to be conservative). Map current LHC limits in this plot. Use results in Ref. [3]. As a naive estimate, you only needs to read off observed limits for $Z'^{SSM}$ (the sequential standard model) in Fig. 5 in the ATLAS paper. (Do not take this analysis seriously, as it is meant to give you a rough idea.)

8. Now suppose you run DY production with both scalar and vector resonance with $MS = 1$ TeV and $MV = 1.1$ TeV. Plot dimuon invariant mass distribution including an irreducible background of $pp \to \mu^+\mu^-$. Since the resonances masses are at 1 TeV and the widths are narrow, it is perfectly fine to impose minimum invariant mass cut when generating events. Say we impose $m_{\mu^+\mu^-} > 700$ GeV. Use 0.1 for couplings. Discuss whether you can resolve two broad (large width) resonances nearby.

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[1] Z’ Hunter’s guide: https://sites.google.com/site/zprimeguide/