Hadronic Mono-$W'$ Probe of Dark Matter at Colliders

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Dark Matter search at Collider

Collider signal of DM: Visible + $E_T$ (Mono-$X$)

DM interact with SM particles via EFT operator:

\[
\begin{align*}
    g/q + E_T & : 1002.4137, 1108.1196, 1408.3583, 1502.01518 \ldots \\
    t/b + E_T & : 1303.6638, 1410.4031, 1503.00691 \ldots \\
    \gamma + E_T & : 1109.4398, 1410.8812, 1411.1559 \ldots \\
    W/Z + E_T & : 1309.4017, 1408.2745, 1404.005\ldots \\
    h + E_T & : 1312.2592, 1402.7074 \ldots 
\end{align*}
\]

When the NP particles are produced on-shell decay to SM particles

\[
\begin{align*}
    Z' + E_T & : 1504.01386 \\
    W' + E_T & : \text{This Work: } W' \rightarrow tb
\end{align*}
\]

$W'$: similar interaction with the SM $W$ boson:
- Resonant production
- Stringent Limits

Standard $W'$ search
Resonant production of $W'$ with a dark Higgs boson

Stringent trigger requirement

$p_T > 500 \text{ GeV}$

Mass region smaller than 1 TeV are not probed

$W' + \text{DM} \quad \text{The channel we are using:}$

$m_{W'} \quad \text{focus on} \quad 250 \sim 1750 \text{ GeV}$

A dark Higgs is emitted from $W'$

$E_T > 200 \text{ GeV}$

In addition to the DM search, this channel opens up the possibility to push $W'$ searches to lower masses
UV models with $W'$ commonly have a dark Higgs boson

- $W'$ comes from a new gauge symmetry that is broken before EWSB.
- There is new scalar responsible for the breaking: $\phi = h_D + v_\phi$
- The scalar gives $W'$ mass, and couples to $W'$:
  \[ \propto g_{new} W'^2 (h_D + v_\phi)^2 \]

Relavent Parameters
- **masses**: $m_{h_D}, m_{W'}$
- $W'$ - $t$ - $b$: new gauge coupling strength $g_{new}$
- $W'$ - $W'$ - $h_D$: new gauge coupling strength and $W'$ mass ($m_{W'} \propto v_\phi$)
Benchmark Model: Left-Right Symmetric Model (LRSM)

\[ \mathcal{L} = \frac{g_R}{\sqrt{2}} (\bar{u}_R \gamma^\mu d_R) W^\prime_\mu + h.c., \]

Kinetic terms of fermions

\[ Q_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i : (2, 1, \frac{1}{3}) , \quad Q_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i : (1, 2, \frac{1}{3}) , \]

Kinetic terms of scalars

\[ \mathcal{L}_{W' h_D} = g_R^2 v_R h_D (W'_\mu)^\dagger W'^\mu \]

\[ \Delta_R = \begin{pmatrix} \delta_R^+ / \sqrt{2} & \delta_R^{++} \\ \delta_R^{0} & -\delta_R^+ / \sqrt{2} \end{pmatrix} : (1, 3, 2) \]

\[ = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} + \begin{pmatrix} \vdots & \vdots \end{pmatrix} \]

| \[ g_R \] | \( > e/c_W(0.35) \) |
| \[ m_{W'} \] | \( \approx g_R v_R / \sqrt{2} \) |
| \[ m_{h_D} \] | Potential parameters |
### $W'$ Candidate Reconstruction

![Graph showing efficiency vs. $W'$ mass for different processes](image)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ [fb]</th>
<th>$\epsilon$ $\times 10^{-3}$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$6.74 \times 10^5$</td>
<td>$1.42 \times 10^{-3}$</td>
<td>2.89 $\times 10^5$</td>
</tr>
<tr>
<td>$Z + b\bar{b}$, $Z \rightarrow \nu\nu$</td>
<td>$2.47 \times 10^5$</td>
<td>$1.42 \times 10^{-4}$</td>
<td>10560</td>
</tr>
<tr>
<td>$t\bar{b} + \bar{t}b$</td>
<td>$1.00 \times 10^4$</td>
<td>$2.7 \times 10^{-4}$</td>
<td>820</td>
</tr>
<tr>
<td>$W^\pm + b\bar{b}$, $W^\pm \rightarrow \ell^\pm \nu$</td>
<td>$1.74 \times 10^5$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>620</td>
</tr>
<tr>
<td>$M_W = 300, M_{h_D} = 10$</td>
<td>2280</td>
<td>0.0016</td>
<td>1060</td>
</tr>
<tr>
<td>$M_W = 800, M_{h_D} = 100$</td>
<td>66</td>
<td>0.056</td>
<td>1120</td>
</tr>
<tr>
<td>$M_W = 1250, M_{h_D} = 250$</td>
<td>16.9</td>
<td>0.129</td>
<td>650</td>
</tr>
</tbody>
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2023 LHC DM WG Autumn Meeting  
Kun Cheng
Production cross section

The $W'$ can be on-shell before or after emitting a dark Higgs, and this two channel have comparable contribution

2-body: $pp \rightarrow W'h_D$ then $W' \rightarrow tb$

\[ \propto \left(g_R g_{W'W'h}\right)^2 \propto \text{constant} \]

3-body: $pp \rightarrow W'$ then $W' \rightarrow tbh_D$

\[ \propto g_R^2 \propto g_{W'W'h}^2 \]

We always have contribution from both channel. $\propto g_R^4$

Which cross section is larger? Only depends on the mass of $W'$ and $h_D$
Results and Discussion

Current LHC data is sensitive to $W' + h_D$ production in the range of 20 fb to 30 pb. The corresponding limit on $g_R$ can be as low as 0.6

We studied the $p_T^{\text{miss}}$ with hadronically-decaying $W'$, which:
- Describes a new search mode of DM
- Expand the $W'$ boson searches to small mass region
FIG. 3: Top (bottom): Distribution of the reconstructed $W'$ boson candidate mass in simulated events with $m'_W = 1000$ (1500) GeV, for each of the three reconstruction strategies (see Fig 2), where the selected objects are angled-matched ($\Delta R < 0.4$) and -unmatched ($\Delta R > 0.4$) to the correct parton-level objects.
Backup: backgrounds

FIG. 5: Top: Distribution of the missing transverse momentum ($p_T^{\text{miss}}$) for the expected background and selected signals normalized to an integrated luminosity of 300 fb$^{-1}$ after all requirements other than $p_T^{\text{miss}} > 200$ GeV are met. Bottom: Distribution of the reconstructed $W'$ boson 2-body candidate mass for the expected background and selected signals normalized to an integrated luminosity of 300 fb$^{-1}$ after the full selection.
FIG. 6: Distribution of the reconstructed $W'$ boson 3-body candidate mass for the expected background and selected signals normalized to an integrated luminosity of 300 fb$^{-1}$ after the full selection.
FIG. 7: Top: Summary of expected upper limits at 95% CL on the $h_D W'$ production cross section and the 2-body decay branching fraction of $W'$ as a function of the $W'$ boson mass normalized to an integrated luminosity of 300 fb$^{-1}$ for three choices of the $h_D$ boson mass. Also shown are expected theoretical cross sections and branching fractions at leading order for a coupling value of $g_R = 0.36$. Bottom: The same distributions as above except for the 3-body decay of the $W'$ boson.