

Dark Matter, Dark Forces, and the LHC

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December 4, 2013

Outline

- 1 Motivation
- 2 Dark Matter Model
- 3 Coupling to Higgs
- 4 LHC Signals for $H \rightarrow ZZ_d$
- 5 Conclusion

Motivation

- Observations indicate that a significant portion of the matter density of the Universe is dark matter (DM).
- Current best measurements: [Planck, 1303.5076](#)
 - DM makes up $\sim 25\%$ of energy density.
 - Baryons makes up $\sim 5\%$ of energy density.

Motivation

- Observations indicate that a significant portion of the matter density of the Universe is dark matter (DM).
- Current best measurements: [Planck, 1303.5076](#)
 - DM makes up $\sim 25\%$ of energy density.
 - Baryons makes up $\sim 5\%$ of energy density.
- Much of the model building focused on the WIMP paradigm:
 - For thermal dark matter need cross section $\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \sim 0.1 \text{ pb}$.
 - For EW scale particle DM, corresponds to weak scale interactions.
- However, do not know much about DM.
- Lack of evidence at direct detection, indirect detection, and collider experiments motivates additional model building.
- Have been some signals for DM in the $\sim 10 \text{ GeV}$ range ... although LUX [LUX, arXiv:1310.8214](#)
[Belanger, Goudelis, Park, Pukhov arXiv:1311.0022](#); [Gresham, Zurek arXiv:1311.2082](#)
[Del Nobile, Gelmini, Gondolo, Huh arXiv:1311.4247](#); [Cirigliano, Graesser, Ovanessian, Shoemaker arXiv:1311.5886](#)
- Despite recent results, low-mass DM still an interesting and phenomenologically rich region to explore.

Viable Dark Matter Candidates

- Viable DM candidates need to meet several criteria:
 - Need to be stable on cosmological time scales.
 - Reproduce correct relic abundance.
 - Avoid direct and indirect searches.
 - If thermally produced, need to be in thermal equilibrium with SM at some time in the past.

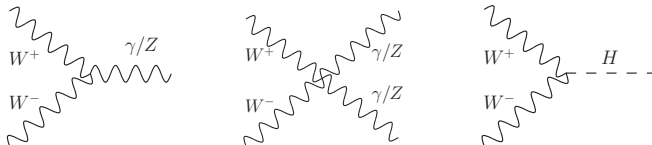
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 - If thermally produced, need to be in thermal equilibrium with SM at some time in the past.
- Stability of DM candidate often guaranteed by a discrete symmetry.
- As in SM, may expect stability to come from gauge, Lorentz or accidental symmetries.
- Postulate some gauge symmetry in the dark sector under which DM is charged.
- On general grounds may expect DM to be part of a larger sector.
- Also motivated by anomalies
 - Positron excesses in Fermi, PAMELA, AMS-02...
- Can organize symmetry breaking pattern such that stability is still guaranteed.

Dark Matter Stability

- Again, take the SM as a guide.

- Without the fermions, W^\pm interactions always involve two W 's

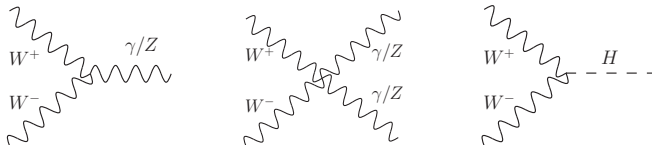


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- Even if electromagnetism broken by SU(2) singlet Higgs, would be stable.
- Stability guaranteed by residual symmetry.
- Postulate DM is gauge bosons of a broken non-abelian gauge symmetry
[Hambye 0811.0172](#); [Hambye, Tytgat arXiv:0907.1007](#); [Diaz-Cruz, Ma arXiv:1007.2631](#) ...
- Minimal dark matter sector: Gauge symmetries + Higgses.
- Vector DM also studied in context of
 - Extra-dimensions
[Cheng, Matchev, Schmaltz hep-ph/0204342](#); [Servant, Tait hep-ph/0206071](#); [Cheng, Feng, Matchev hep-ph/0207125](#) ...
 - Little Higgs Models
[Cheng, Low hep-ph/0308199](#) [hep-ph/0405243](#); [Birkedal, Noble, Perelstein, Spray hep-ph/0603077](#)

Portals

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- Need a portal between DM and SM
- Higgs portal:

$$\mathcal{L} \ni \lambda \phi^\dagger \phi H^\dagger H$$

- ϕ scalar of dark sector, H is SM Higgs doublet.
- Facilitates annihilation $\chi\chi \rightarrow \phi\phi \rightarrow \text{SM}$
- For gauge boson DM, ϕ can be Higgs that breaks the gauge symmetry.
- Most studied for this possibility.

Portals

- For thermally produced DM need to be in thermal equilibrium with SM at some point.
- To produce correct relic density need DM to annihilate into SM particles.
- Need some a portal between DM and SM
- Vector portal via kinetic mixing [Holdom Phys.Lett. 166B](#):

$$\mathcal{L}_{kin} = -\frac{1}{4} \left(B^{\mu\nu} B_{\mu\nu} - \frac{2\varepsilon}{\cos\theta_W} B_h^{\mu\nu} B_{\mu\nu} + B_h^{\mu\nu} B_{h,\mu\nu} \right)$$

- B_h is U(1) gauge boson of dark sector, B is SM hypercharge.
- After diagonalization into canonical normalization, B_h couples to SM E&M current:

$$\mathcal{L} \ni -e\varepsilon B_h^\mu J_\mu^{em}$$

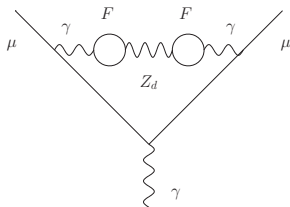
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Kinetic Mixing

- Kinetic mixing interesting in its own right.
- Many searches for light gauge boson in low energy fixed target, beam dump, e^+e^- experiments, and rare meson decays.
 - APEX, HPS, DarkLight at JLab
 - MAMI in Mainz.
 - Past experiments at CERN, KLOE, BaBar,...

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 - Past experiments at CERN, KLOE, BaBar,...
- Light vector boson can also explain muon $g_\mu - 2$ anomaly [Pospelov, arXiv:0811.1030](#)
- Imagine heavy fermions generate the kinetic mixing.



Dark Matter Model

- Combine non-abelian gauge boson DM with a vector portal.
- Postulate dark sector is composed of $SU(2)_h \times U(1)_h$ symmetry, with $U(1)_h$ kinetically mixed with hypercharge.
- As with Standard Model, introduce doublet Higgs Φ to break symmetry.
- Assume Φ has vev $(0, v_\Phi)^T / \sqrt{2}$

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 - Want to break $U(1)_{Q_h}$
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- Before symmetry breaking:
 - Φ : Higgs $SU(2)_h$ doublet with $U(1)_h$ charge 1/2
 - ϕ : Higgs $SU(2)_h$ singlet with $U(1)_h$ charge 1/2
 - $W_h^{1,2,3}$: Three gauge bosons of $SU(2)_h$ with gauge coupling g_h
 - B_h : Gauge boson of $U(1)_h$ with gauge coupling g'_h , kinetically mixed.

Dark Sector Content

- After symmetry breaking have 4 massive gauge boson fields:

“Hidden W ”:
$$W_h^\pm = \frac{1}{\sqrt{2}} (W_h^1 \pm iW_h^2)$$

“Hidden Z ”:
$$Z_h = \cos \theta_h W_h^3 - \sin \theta_h B_h.$$

“Hidden γ ”:
$$\gamma_h = \sin \theta_h W_h^3 + \cos \theta_h B_h.$$

Two Higgs bosons.

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Two Higgs bosons.

- W_h is our DM candidate.
 - Similar to SM example without fermions.
 - W_h only show up in pairs at vertices.
 - Stabilized by residual symmetry of broken gauge symmetry
- Z_h and γ_h obtain couplings to SM fermions via kinetic mixing.

Gauge Boson Masses

- Masses:
 - $M_{W_h} = \frac{1}{2}g_h v\Phi$
 - Identify Z_h, γ_h such that $M_{Z_h} > M_{\gamma_h}$.
 - Gauge boson masses obey the relation

$$\cos^2 \theta_h = \frac{M_{W_h}^2 - M_{\gamma_h}^2}{M_{Z_h}^2 - M_{\gamma_h}^2}$$

- Positivity of $\cos^2 \theta_h$ and $\sin^2 \theta_h$ enforces the hierarchy $M_{Z_h} \geq M_{W_h} \geq M_{\gamma_h}$.

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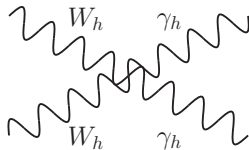
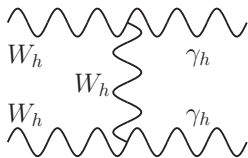
$$\cos^2 \theta_h = \frac{M_{W_h}^2 - M_{\gamma_h}^2}{M_{Z_h}^2 - M_{\gamma_h}^2}$$

- Positivity of $\cos^2 \theta_h$ and $\sin^2 \theta_h$ enforces the hierarchy $M_{Z_h} \geq M_{W_h} \geq M_{\gamma_h}$.
- In limit $M_{\gamma_h} \ll M_{W_h}$ and $v_\phi \ll v_\Phi$ recover relations:

$$M_{\gamma_h} \approx \frac{1}{2} \frac{g_h g'_h}{\sqrt{g_h^2 + g_h'^2}} v_\phi, \quad M_{W_h} \approx M_{Z_h} \cos \theta_h, \quad \tan \theta_h \approx g'_h / g_h$$

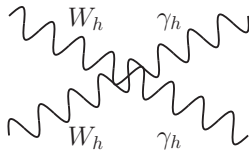
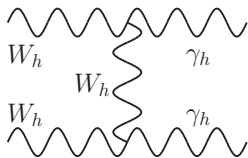
- For rest of talk will take simplifying assumption $M_{\gamma_h} \ll M_{W_h}$ and $v_\phi \ll v_\Phi$.

Relic Density



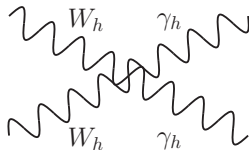
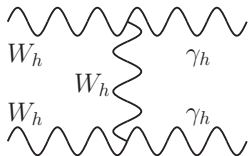
- Since $M_{W_h} \geq M_{\gamma_h}$, the annihilation channel $W_h W_h \rightarrow \gamma_h \gamma_h$ is always open.
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Relic Density



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- With the assumption $M_{\Phi_h}, M_{Z_h} \geq 2M_{W_h}$, this will be the dominant annihilation channel.
- Have tree level $W_h W_h \rightarrow \Phi_h \rightarrow \gamma_h \gamma_h$
 - $\Phi_h \gamma_h \gamma_h$ coupling is suppressed by v_ϕ^4/v_Φ^4
- Similarly, after Higgs mixing have $\phi W_h W_h$ tree-level coupling:
 - Scalar mixing from $\lambda \phi^\dagger \phi \Phi^\dagger \Phi$.
 - For perturbative self-couplings have $\mu_\phi \lesssim v_\phi$.
 - Scalar mixing will make a contribution to μ_ϕ^2 of λv_Φ^2 .
 - Hence, assuming little to no tuning, need $\lambda \lesssim v_\phi^2/v_\Phi^2$.

Relic Density



- Relic density given by

$$\Omega_h h^2 \simeq 1.04 \times 10^9 \frac{x_f \text{ GeV}^{-1}}{\sqrt{g_\star} M_{\text{Pl}} \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle}$$

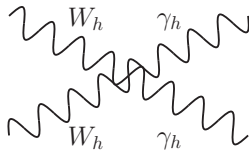
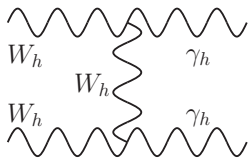
- Freeze out temperature set by ($\kappa = 3$ for gauge bosons)

$$\frac{M_{W_h}}{T_f} = x_f \simeq \ln[0.038(\kappa/\sqrt{x_f g_\star}) M_{\text{Pl}} M_{W_h} \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle] \simeq 20$$

- Lorentz structure of triple and quartic gauge couplings identical to SM, with coupling strength now set by $g_h \sin \theta_h$.
- The thermally averaged cross section for $M_{\gamma_h} \ll M_{W_h}$:

$$\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \simeq \frac{19 (g_h \sin \theta_h)^4}{72 \pi M_{W_h}^2}$$

Relic Density



- Assume QCD phase transition at $\Lambda_{QCD} = 200$ MeV.
 - $T_f < \Lambda_{QCD}$: e, ν, γ , and γ_h in thermal equilibrium: $g_\star = 13.75$
 - $T_f > \Lambda_{QCD}$: include μ, u, d, s and gluons: $g_\star = 64.75$
- Requiring that the relic density $\Omega_h h^2 = 0.12$ and using the typical value $x_f = 20$:

$$(g_h \sin \theta_h)^2 \simeq \frac{M_{W_h}}{10 \text{ GeV}} \begin{cases} 2.2 \times 10^{-3}; & T_f \lesssim \Lambda_{QCD} \\ 1.5 \times 10^{-3}; & T_f \gtrsim \Lambda_{QCD} \end{cases}$$

- Will be useful for direct detection calculation. First need coupling to SM fermions...

Couplings to SM

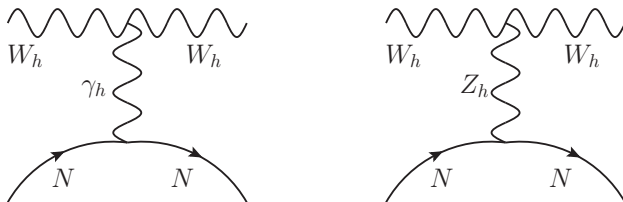
- In principle can have Higgs mixing in addition to vector portal.
- For simplicity and proof of principle, neglect possible Higgs mixing here.
- Couplings to SM Fermions:
 - As mentioned earlier, can write down a gauge invariant kinetic mixing:

$$\mathcal{L} \ni \frac{\varepsilon}{2 \cos \theta_W} B_h^{\mu\nu} B_{\mu\nu}$$

- Assuming $M_{Z_h}, M_{\gamma_h} \ll M_Z$, after diagonalizing the kinetic term, the “neutral” dark gauge bosons develop couplings to SM fermions:

$$\mathcal{L}_{\nu h} = -\varepsilon e [\cos \theta_h \gamma_{h,\mu} - \sin \theta_h Z_{h,\mu}] J_{em}^\mu$$

Direct Detection

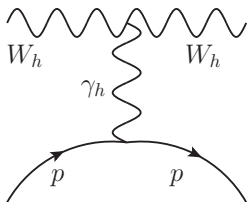


- Direct detection mediated via t -channel γ_h, Z_h exchange.
- Under our assumptions, $M_{\gamma_h} \ll M_{Z_h}$, γ_h exchange dominates.
- Elastic scattering cross section off a nucleon:

$$\sigma_{\text{el}} \simeq \frac{4Z^2 \alpha (\epsilon \cos \theta_h)^2 (g_h \sin \theta_h)^2 \mu_{\text{F}}^2(W_h, N)}{M_{\gamma_h}^4}$$

$\mu_r(X, Y) = M_X M_Y / (M_X + M_Y)$ is the reduced mass.

Direct Detection

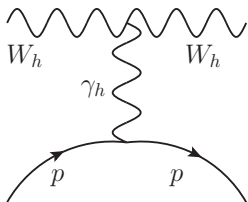


- Since γ_h couples to EM current, interacts with protons and not neutrons.
- Interested in scattering cross section with protons:

$$\sigma_p \simeq \frac{4\alpha (\epsilon \cos \theta_h)^2 (g_h \sin \theta_h)^2 \mu_{\text{F}}^2(W_h, n)}{M_{\gamma_h}^4}$$

- Obtain usual scattering cross section per nucleon: $\sigma_n = (Z^2/A^2)\sigma_p$.

Direct Detection



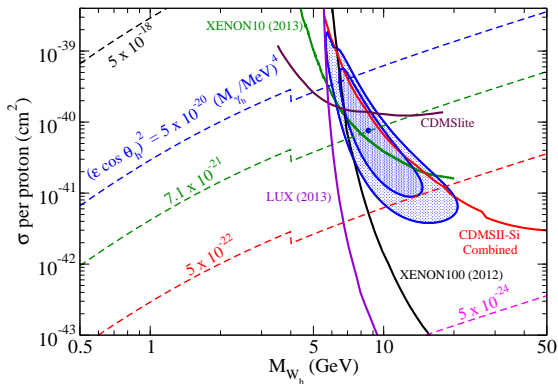
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- Obtain usual scattering cross section per nucleon: $\sigma_n = (Z^2/A^2)\sigma_p$.
- Can use relic density constraint to rewrite $(g_h \sin \theta_h)^2$ in terms of M_{W_h} .
- σ_p then depends on M_{W_h} and the ratio $(\epsilon \cos \theta_h)^2/M_{\gamma_h}^4$

Direct Detection

- σ_p as a function of M_{W_h} .
- Contours of $(\epsilon \cos \theta_h)^2 / M_{\gamma_h}^4$



$$\sigma_p = \frac{(\epsilon \cos \theta_h)^2}{5 \times 10^{-22}} \left(\frac{\text{MeV}}{M_{\gamma_h}} \right)^4 \left(\frac{\mu_r(W_h, n)}{\text{GeV}} \right)^2 \frac{M_{W_h}}{10 \text{ GeV}} \times \begin{cases} 1.2 \times 10^{-41} \text{ cm}^2; & T_f \lesssim \Lambda_{QCD} \\ 8.5 \times 10^{-42} \text{ cm}^2; & T_f \gtrsim \Lambda_{QCD} \end{cases}$$

Thermal Equilibrium

- Implicit assumption that DM in thermal equilibrium with SM.
- In our case, the hidden photon communicates with SM, so want γ_h in thermal equilibrium for $M_{\gamma_h} \leq T_f \approx M_{W_h}/20$
- So need dark photon decay rate to keep up with expansion rate at freeze-out of W_h :

$$\frac{M_{\gamma_h}}{T_f} \Gamma_{\gamma_h} \gtrsim H(T_f) = 1.7 g_*^{1/2} T_f^2 / M_{\text{Pl}}$$

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- For $M_{\gamma_h} \leq 1 \text{ GeV}$:

$$\Gamma_{\gamma_h} \lesssim \frac{4\alpha}{3} (\epsilon \cos \theta_h)^2 M_{\gamma_h}$$

- Get the condition:

$$(\epsilon \cos \theta_h)^2 \left(\frac{M_{\gamma_h}}{\text{MeV}} \right)^2 \gtrsim 10^{-12} g_*^{1/2} \left(\frac{M_{W_h}}{10 \text{ GeV}} \right)^3$$

Lower Bound on M_{γ_h}

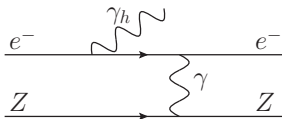
- As just seen, after relic density requirement, σ_p depends on M_{W_h} and the ratio $(\epsilon \cos \theta_h)^2 / M_{\gamma_h}^4$.
- Measurement of σ_p and M_{W_h} then fixes $(\epsilon \cos \theta_h)^2 / M_{\gamma_h}^4$.
- Can combine thermal equilibrium requirement with σ_p and M_{W_h} measurement to obtain a lower bound on M_{γ_h} :

$$\frac{M_{\gamma_h}}{40 \text{ MeV}} \gtrsim \left(\frac{M_{W_h}}{10 \text{ GeV}} \right)^{2/3} \left(\frac{\mu_r(W_h, n)}{1 \text{ GeV}} \right)^{1/3} \times \left(\frac{\sigma_p}{8 \times 10^{-41} \text{ cm}^2} \right)^{-1/6}.$$

- Limit depends on $M_{\gamma_h} < T_f$, consistent with bound for $M_{W_h} \gtrsim 1 \text{ GeV}$ and $\sigma_p \gtrsim 10^{-43} \text{ cm}^2$.
- Range of M_{γ_h} current low energy searches are exploring.

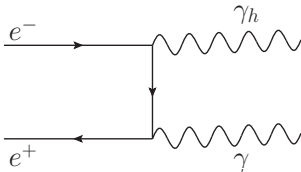
Low Energy Searches

- Dark matter searches not only place to search for this model, have a light “Dark photon”
- Robust program looking for light vector bosons weakly coupled to SM:



- **Beam dump and fixed target experiments**

Bjorken, Essig, Schuster, Toro [PRD80 075018](#); Andreas, Niebuhr, Ringwald [PRD86 095019](#)
 A1 Coll. [PRL106 251802](#); APEX Coll. [PRL107 191804](#)

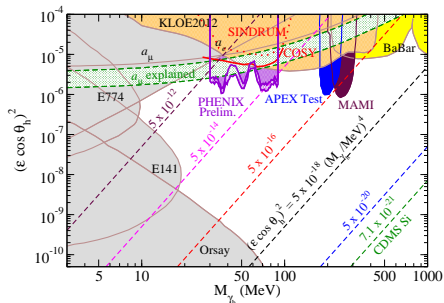


- **Low energy e^+e^- experiments.**

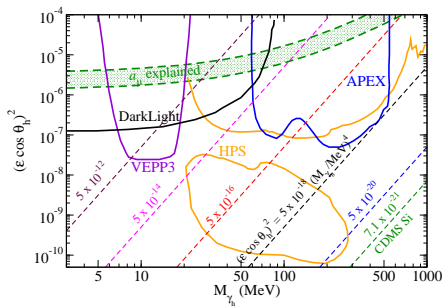
Reece, Wang [JHEP 0907 051](#); Essig, Schuster, Toro [PRD80 015003](#)
 Batell, Pospelov, Ritz [PRD79 115008](#), [PRD80 095024](#)

- **Meson decays** [Fayet, hep-ph/0702176](#).

Low Energy Searches



Current Constraints



Future Projections

- New preliminary PHENIX results from RHIC [Yorito Yamaguchi's talk at DNP](#)
- For $M_{W_h} \sim 1 - 5$ GeV and $\sigma_p \sim 10^{-43} - 10^{-38}$ cm²:

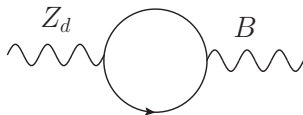
$$(\epsilon \cos \theta_h)^2 \sim 10^{-21} - 10^{-18} (M_{\gamma_h} / \text{MeV})^4$$

- Future experiments start probing this parameter region.

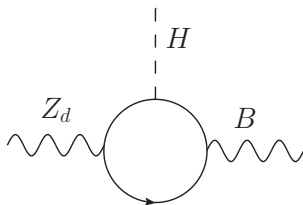
LHC Physics

- Have discussed how to search for these types of models at low energy and DM experiments.
- May also be able to search for light gauge bosons at the LHC.
- Specifically, will focus on Higgs physics in connection with a new dark gauge boson.
- Will neglect dark matter connection, and just assume a new $U(1)$ under which the SM is uncharged.
- Notation change: use Z_d for a generic dark $U(1)$.
- For LHC searches will focus on $M_{Z_d} \gtrsim 5$ GeV, complementary to previous low energy searches.
- In previous model, had $M_{\gamma_h} \lesssim M_{W_h} \lesssim M_{Z_h}$, so have for $M_{W_h} \sim O(\text{GeV})$ have “neutral” gauge bosons with masses in the sub-GeV range and in the multi-GeV range.

Couplings to Higgs



- Imagine kinetic mixing term originates from integrating out heavy fermions.



- If fermions have Higgs interactions, can induce the effective operators ($X = \gamma, Z, Z_d$):

$$O_{B,X} = c_{B,X} H X_{\mu\nu} Z_d^{\mu\nu}, \quad \tilde{O}_{B,X} = \tilde{c}_{B,X} H \tilde{X}_{\mu\nu} Z_d^{\mu\nu}$$

Mass Mixing

- Can also have direct mass mixing between Z and Z_d Davoudiasl, Lee, Marciano PRD85 115019:

$$O_{A,X} = c_{A,X} H X_\mu Z_d^\mu$$

- Here $X = Z, Z_d$
- For example, consider a two Higgs doublet model with extra SM singlet:

	$SU(2)_L$	$U(1)_Y$	$U(1)_d$
H_1	2	1/2	0
H_2	2	1/2	1
S_d	1	0	1

- The vev of H_2 induces a mass mixing between Z and Z_d :

$$\begin{aligned} \mathcal{L}_{Mass} &= \frac{1}{2} M_{Z^0}^2 Z^0 Z^0 - \Delta^2 Z^0 Z_d^0 + \frac{1}{2} M_{Z_d^0}^2 Z_d^0 Z_d^0 \\ \Delta^2 &= \frac{1}{2} g_d g_Z v_2^2 \end{aligned}$$

- $\langle H_{1,2} \rangle = v_{1,2}$

Mass Mixing

- This mass mixing induces off-diagonal Higgs couplings:

$$\mathcal{L}_{scalar} = \frac{1}{2} g_Z^2 v H \left(\frac{1}{2} Z Z + \Theta Z Z_d + \frac{1}{2} \Theta^2 Z_d Z_d \right)$$

- Assuming $|\Delta^2| \ll M_Z M_{Z_d}$ have:

$$\Theta \simeq \frac{\Delta^2}{M_Z^2} \approx \epsilon_Z \equiv \frac{M_{Z_d}}{M_Z} \delta$$

- $\delta = \sin \beta \sin \beta_d$ $\tan \beta = v_2/v_1$ $\tan \beta_d = v_2/v_d$

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- $\delta = \sin \beta \sin \beta_d$ $\tan \beta = v_2/v_1$ $\tan \beta_d = v_2/v_d$
- From this mixing the Z_d inherits a component of the SM Goldstone boson.
- For $M_{Z_d} \ll E_{Z_d}$, then Z_d in Higgs decays is longitudinally enhanced:

$$Z_d^\mu \rightarrow \partial^\mu \phi / M_{Z_d} + O(M_{Z_d} / E_{Z_d})$$

- Hence $\Theta Z_d^\mu \rightarrow \partial^\mu \phi / M_Z$:
 - $H \rightarrow Z Z_d$ no longer suppressed by M_{Z_d} .

Higgs Branching Ratios

- Assuming the kinetic mixing comes from heavy fermions with $m_F \sim \text{few} \times 100 \text{ GeV}$

$$|c_{B,X}| \sim |\tilde{c}_{B,X}| \sim \frac{g_w g_d y_F}{16\pi^2 M_Z}$$

- g_w generic weak coupling.
- y_F fermion Yukawa coupling.
- For $y_F \sim 1$ and $g_d \approx e$

$$0.1 \text{Br}(H \rightarrow \gamma\gamma) \approx \text{Br}(H \rightarrow \gamma Z_d) \approx 2 \text{Br}(H \rightarrow Z_d Z_d) \approx 10 \text{Br}(H \rightarrow ZZ_d)$$

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- Mass mixing:

$$\text{Br}(H \rightarrow ZZ_d) \approx 16\delta^2 \quad \text{Br}(H \rightarrow Z_d Z_d) \approx 80\delta^4$$

- $H \rightarrow Z_d Z_d$ is doubly suppressed by δ^4
- Rare B and K decays suggest $\delta^2 \lesssim 10^{-5}$ for $M_{Z_d} \ll 5 \text{ GeV}$
Davoudiasl, Lee, Marciano [PRD85 115019](#)
- Low energy parity violation $\delta^2 < \text{few} \times 10^{-4}$ for all M_{Z_d}
Davoudiasl, Lee, Marciano [PRD85 115019](#).
- So $\text{Br}(H \rightarrow ZZ_d)$ can be comparable to $\text{Br}(H \rightarrow \gamma\gamma) \simeq 2.3 \times 10^{-3}$

Higgs Decays

- Kinetic mixing motivated operators ($X_{\mu\nu} Z_d^{\mu\nu}$, $\tilde{X}_{\mu\nu} Z_d^{\mu\nu}$)

$$H \rightarrow ZZ_d, \quad \gamma Z_d, \quad Z_d Z_d$$

- Mass mixing motivated operators ($X_\mu Z_d^\mu$) do not have γ decays due to gauge invariance:

$$H \rightarrow ZZ_d, \quad Z_d Z_d$$

- $H \rightarrow Z_d Z_d$ doubly suppressed in mass mixing case.
- Will focus on $H \rightarrow ZZ_d$ signals.

Dark Z decays

- If kinetic mixing is dominant:
 - Z_d couples to SM E&M current.
 - $\text{Br}(Z_d \rightarrow 2\ell) > \text{Br}(Z \rightarrow 2\ell)$, since no neutrino coupling.
 - For $M_{Z_d} = 5 - 10$ GeV, can expect $\text{Br}(Z_d \rightarrow 2\ell) \simeq 0.3$
- If mass mixing dominates:
 - Z_d also couples to SM neutral current.
 - $\text{Br}(Z_d \rightarrow 2\ell)$ smaller than kinetic mixing case.
- Focus on $H \rightarrow ZZ_d \rightarrow 4\ell$

Parameterization

- Mass mixing parameterization:

$$O_{A,Z} = c_{A,Z} H Z_\mu Z_d^\mu$$

- Motivated by two Higgs doublet example: $c_{A,Z} = \frac{g}{\cos \theta_W} \epsilon_Z M_Z$
- $\epsilon_Z = M_{Z_d}/M_Z \delta$, with δ a free parameter.
- Kinetic mixing motivated:

$$O_{B,Z} = c_{B,Z} H Z_{\mu\nu} Z_d^{\mu\nu}, \quad \tilde{O}_{B,Z} = \tilde{c}_{B,X} H \tilde{Z}_{\mu\nu} Z_d^{\mu\nu}$$

- $c_{B,Z} = -\frac{g}{2 \cos \theta_W} \frac{\kappa_Z}{M_Z}$
- $\tilde{c}_{B,Z} = \frac{g}{2 \cos \theta_W} \frac{\tilde{\kappa}_Z}{M_Z}$.

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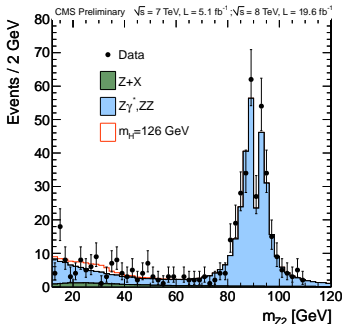
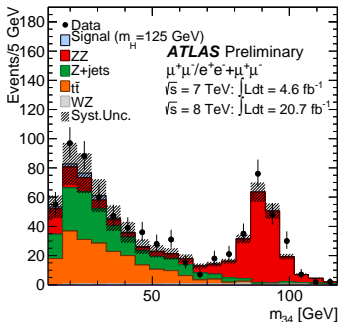
- $c_{B,Z} = -\frac{g}{2 \cos \theta_W} \frac{\kappa_Z}{M_Z}$
- $\tilde{c}_{B,Z} = \frac{g}{2 \cos \theta_W} \frac{\tilde{\kappa}_Z}{M_Z}$.
- For purposes of the collider search, will focus on mass mixing case.
- Will give results in terms of $\delta^2 \text{Br}(Z_d \rightarrow 2\ell)$
 - δ^2 is free parameter for $\text{Br}(H \rightarrow ZZ_d)$

LHC Search

- Work at $\sqrt{s} = 14$ TeV LHC and with the signal of two same flavor, opposite charge lepton pairs:

$$pp \rightarrow H \rightarrow ZZ_d \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$$

- Interested in mass range $M_{Z_d} \sim 5 - 10$ GeV.
- Complementary to previous low energy searches.
- May expect to appear in $H \rightarrow ZZ^*$ searches already.
 - ATLAS and CMS place lower bound $M_{Z^*} \geq 12$ GeV in published results.



Event and Detector Simulation

- Model implemented in MadGraph 5 using FeynRules.
- CTEQ6L pdfs used throughout.
- MadGraph 5 used to simulate both signal and background.
- Apply Gaussian smearing to all events:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$$

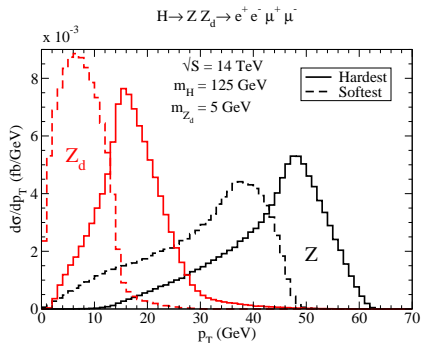
- Following ATLAS $a = 10\%$ (50%) and $b = 0.7\%$ (3%) for leptons (jets)
Voss, Breskin "The CERN Large Hadron Collider, accelerator and experiments"
- Benchmark point:

$$\begin{array}{ll}
 M_{Z_d} = 5 \text{ GeV} & M_H = 125 \text{ GeV} \\
 \delta^2 \text{Br}(Z_d \rightarrow 2\ell) = 10^{-5} & \kappa_z = \tilde{\kappa}_Z = 0
 \end{array}$$

Event Reconstruction

- Want full reconstruction of signal to isolate from background.
 - Need to identify which lepton pair originated from where.
 - Z_d mass not known *a priori*
 - Calculate invariant mass of all possible same flavor, opposite sign lepton pairs.
 - The lepton pair with mass closest to M_Z identified as originating from the Z
 - Identify other lepton pair with Z_d .

Transverse Momentum Distributions



- The momentum of Z and Z_d in Higgs rest frame: $|\mathbf{p}| \approx 30$ GeV.
- Energy of Z dominated by M_Z
 - p_T of Z decay products peak near $M_Z/2$
- Energy of Z_d dominated by $|\mathbf{p}|$
 - p_T of Z_d decay products peaked lower $\lesssim |\mathbf{p}|/2$
 - Not as sharp as Z_d since is not from a resonance.

Signal Isolation

- Require leptons with central rapidity:

$$p_T^\ell > 4 \text{ GeV} \quad |\eta^\ell| < 2.5$$

- Further triggers, following ATLAS [ATLAS-CONF-2013-012](#):

- One lepton with $p_T^\ell > 24 \text{ GeV}$, OR
 - Two leptons with $p_T^\ell > 13 \text{ GeV}$ each
- To trigger on four leptons, require isolation cut:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.3$$

- $\Delta\eta$ and $\Delta\phi$ difference in lepton rapidity and azimuthal angle, respectively.

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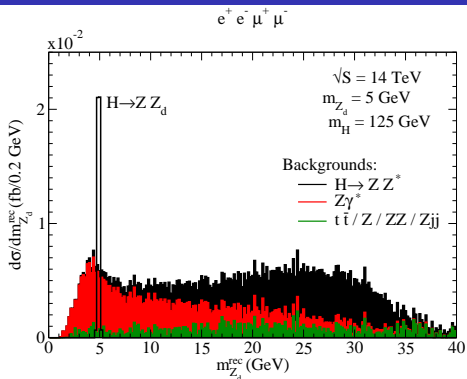
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.3$$

- $\Delta\eta$ and $\Delta\phi$ difference in lepton rapidity and azimuthal angle, respectively.
- Originating from a Higgs resonance:

$$|M_{4\ell} - M_H| < 2 \text{ GeV}$$

- $M_{4\ell}$ reconstructed four lepton invariant mass.
- Require the a Z is reconstructed:

$$|M_Z^{\text{rec}} - M_Z| < 15 \text{ GeV}$$

Z_d resonance peak

- After all previous cuts and energy smearing.
- Sharp drop-off in background below 4 – 5 GeV.
 - Invariant mass of two massless particles: $m_{12}^2 = 2E_1 E_2 (1 - \cos \theta_{12})$
 - Isolation cuts and p_T cuts effectively put lower bounds on invariant mass.
- Use peak to measure M_{Z_d} and place cut:

$$|M_{Z_d}^{\text{rec}} - M_{Z_d}| < 0.1 M_{Z_d}$$

Signal and Background Rates

Channel	$e^+e^-\mu^+\mu^-$		$2\mu^+2\mu^-$		$2e^+2e^-$	
	Sig.	Bkgrnd	Sig.	Bkgrnd	Sig.	Bkgrnd
σ (fb)						
No cuts and no energy smearing	0.10	.	0.051	.	0.051	.
Basic cuts + Trigger + Isol.	0.049	67	0.024	26	0.024	26
+ $M_{4\ell} + M_Z^{rec} + M_{Z_d}^{rec}$	0.043	0.030	0.022	0.017	0.022	0.014
S/B	1.5		1.3		1.5	

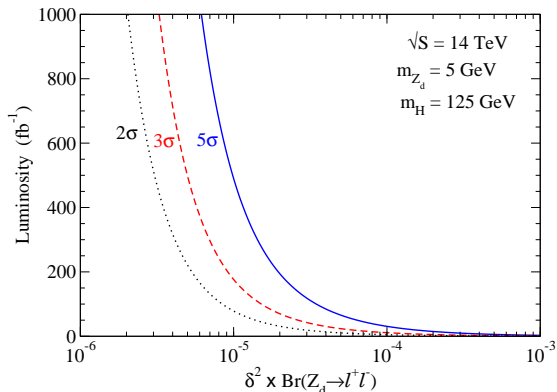
- Fraction of total background after basic cuts, trigger, and isolation:

$$2\mu^+\mu^- \text{ and } 2e^+e^-: \quad t\bar{t} \sim 32\% \quad Z \sim 38\% \quad ZZ \sim 26\%$$

$$e^+e^-\mu^+\mu^-: \quad t\bar{t} \sim 50\% \quad Z \sim 28\% \quad ZZ \sim 12\%$$

- After $M_{4\ell}$ and M_Z^{rec} cuts dominate backgrounds are $Z\gamma^*$ and $H \rightarrow ZZ^*$

Observability at Leading Order

300 fb⁻¹:Exclude $\delta^2 \gtrsim 4 \times 10^{-6}$ Observe $\delta^2 \gtrsim 7 \times 10^{-6}$ Discover $\delta^2 \gtrsim 1.5 \times 10^{-5}$ 

- Parity violation excluded $\delta^2 \gtrsim \text{few} \times 10^{-4}$
- For equal $\text{Br}(H \rightarrow ZZ_d)$ in kinetic and mass mixing case:

$$\kappa_Z^2 = \tilde{\kappa}_Z^2 = \delta^2 / 2$$

Observability

	$M_{Z_d} = 5 \text{ GeV}$		
	2σ (Excl.)	3σ (Obs.)	5σ (Disc.)
No K -factors	78 fb^{-1}	180 fb^{-1}	490 fb^{-1}
+ K -factors	33 fb^{-1}	75 fb^{-1}	210 fb^{-1}
	$M_{Z_d} = 10 \text{ GeV}$		
	2σ (Excl.)	3σ (Obs.)	5σ (Disc.)
No K -factors	100 fb^{-1}	230 fb^{-1}	640 fb^{-1}
+ K -factors	42 fb^{-1}	95 fb^{-1}	260 fb^{-1}

- For equal $\text{Br}(H \rightarrow ZZ_d)$ in kinetic and mass mixing case:

$$\kappa_Z^2 = \tilde{\kappa}_Z^2 = \delta^2/2$$

- $M_{Z_d} = 10 \text{ GeV}$:
 - For our parameterization, signal rate the same as 5 GeV.
 - $|M_{Z_d}^{\text{rec}} - M_{Z_d}| < 0.1 M_{Z_d}$ cut looser.
 - Background invariant mass distribution flat.
 - Accept more background and same amount of signal.

Distinguishing Operators

- Once discover such a signal, how can we determine what operator coupling is generated from?
- Kinetic mixing operators:

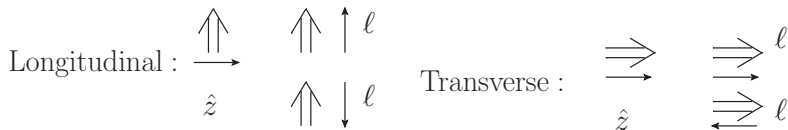
$$O_{B,Z} = c_{B,Z} H Z_{\mu\nu} Z_d^{\mu\nu}, \quad \tilde{O}_{B,Z} = \tilde{c}_{B,Z} H \tilde{Z}_{\mu\nu} Z_d^{\mu\nu}$$

- Z_d is typically transversely polarized.
- Mass mixing operators:

$$O_{A,Z} = c_{A,Z} H Z_\mu Z_d^\mu$$

- As discussed earlier, for $M_{Z_d} \ll M_H$, Z_d typically longitudinally polarized.

Distinguishing Operators

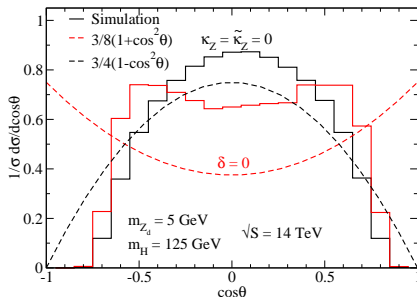
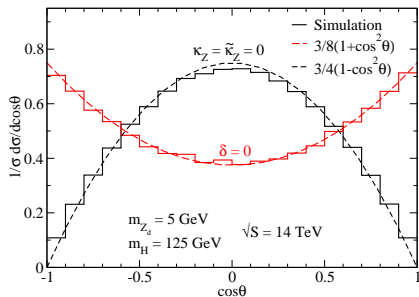


- \hat{z} is Z_d moving direction.
 - Since Z_d highly boosted, \hat{z} can be in CM or Lab frame.
- Lepton angular distribution with respect to \hat{z} :

$$\frac{d\Gamma(Z_d \rightarrow \ell^+ \ell^-)}{d\cos\theta} \sim (1 \pm \cos^2\theta)$$

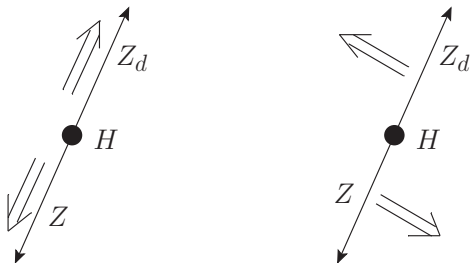
- Upper sign for transverse polarizations.
- Lower sign for Longitudinal

Distinguishing Operators



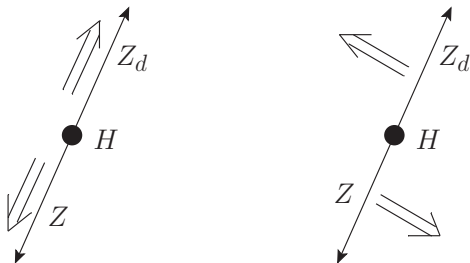
- After cuts cannot distinguish.
- Z_d is highly boosted and its decay products collimated.
 - For $\cos\theta_\ell = \pm 1$, one lepton moving in $-\hat{z}$ -direction.
 - Boost into lab frame against direction of motion in Z_d -frame.
 - This configure results in softest leptons.
 - p_T^ℓ cuts kill $\cos\theta_\ell = \pm 1$.

Distinguishing Operators



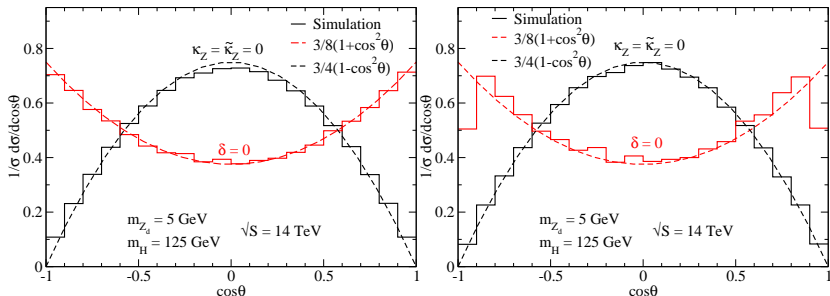
- Consider Higgs rest frame:
 - By conservation of momentum, Z and Z_d back-to-back.
 - By conservation of angular momentum, spins of Z and Z_d opposite directions.
 - If Z_d is helicity state, Z is in same helicity state.
 - p_T of leptons from Z peaked in 30 – 50 GeV range, cut not as drastic.

Distinguishing Operators



- Consider Higgs rest frame:
 - By conservation of momentum, Z and Z_d back-to-back.
 - By conservation of angular momentum, spins of Z and Z_d opposite directions.
 - If Z_d is helicity state, Z is in same helicity state.
 - p_T of leptons from Z peaked in 30 – 50 GeV range, cut not as drastic.
- Use angular distributions of decay products of Z to probe coupling.
- Boost order:
 - Lab frame \rightarrow Higgs rest frame
 - Higgs rest frame \rightarrow Z rest frame.
 - Unlike Z_d case, necessary to boost to Higgs frame first.

Distinguishing Operators



- Angular distribution stable against cuts.

Conclusions

- Presented a self-interacting DM model:
 - DM consisted of nonabelian gauge bosons.
 - Augmented with $U(1)$ that kinetically mixes with hypercharge.
 - DM stabilized via residual symmetry from the original gauge symmetries.
 - Setup produces a viable low-mass vector DM candidate.
 - Due to hierarchy of masses, can have a sub-GeV gauge boson coupling to SM E&M current.
 - This gauge boson can be searched for at low energy experiments.
 - Proposed low energy experiments will start probing interesting parameter regions for low mass DM.

Conclusions

- LHC study of $H \rightarrow ZZ_d$
 - Two classes of operators:
 - “Kinetic” mixing: $H Z_{\mu\nu} Z_d^{\mu\nu}$, $H \tilde{Z}_{\mu\nu} Z_d^{\mu\nu}$
 - “Mass” mixing: $H Z_\mu Z_d^\mu$
 - Focused on $H - Z - Z_d$ couplings from mass mixing.
 - Can probe mixing parameters down to $\delta^2 \gtrsim 4 \times 10^{-6}$ with 300 fb^{-1} and $M_{Z_d} = 5 \text{ GeV}$
 - With our benchmark points can exclude Z_d with mass $5 - 10 \text{ GeV}$ with $\sim 30 - 40 \text{ fb}^{-1}$
 - Discover Z_d with mass $5 - 10 \text{ GeV}$ with $\sim 200 - 250 \text{ fb}^{-1}$
 - Showed how to distinguish between two operators:
 - “Kinetic” mixing results in transversely polarized Z_d
 - “Mass” mixing in longitudinally polarized Z_d
 - Angular distribution of leptons from Z decay sensitive to this polarization, and stable against cuts.

