Dark Matter, Dark Forces, and the LHC

Ian Lewis

Brookhaven National Laboratory

Hooman Davoudiasl, 1309.6640
Hooman Davoudiasl, Hye-Sung Lee, Bill Marciano, PRD88 (2013) 015022

University of California-Irvine

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Outline

Motivation

- Observational indications are that 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.

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- Observational indications are that 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 $\langle \sigma_{\rm ann} v_{\rm rel} \rangle \sim 0.1$ pb.
  - For EW scale particle DM, corresponds 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 ~ 10 GeV range ... although LUX LUX, arXiv:1310.8214
- 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:
  - Needs to be stable on cosmological time scales.
  - Reproduce correct relic abundance.
  - Avoid direct and indirect searches.
  - If thermally produced, needs to be in thermal equilibrium with SM at some time in the past.

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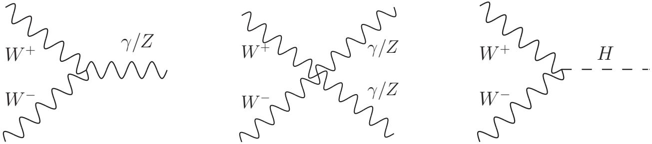
  - If thermally produced, needs to be in thermal equilibrium with SM at some time in the past.
- Stability of DM candidate often gauranteed by a discrete symmetry.
- As in SM, may expect stability to come from gauge, Lorentz or accidental symmetries.
- Postulate some gauge symmetry in the dark sector 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 gauranteed.

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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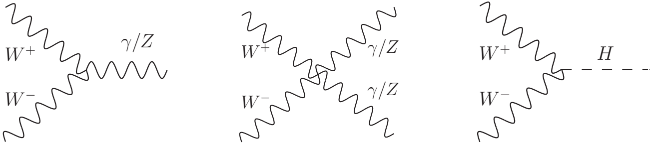

  - Even if electromagnetism broken by SU(2) singlet Higgs, would be stable.
  - Stability gauranteed by residual symmetry.
- Postulate DM is gauge bosons of a broken non-abelian gauge symmetry
  Hambye 0811.0172; Hamybe, Tytgat arXiv:0907.1007; Diaz-Cruz, Ma arXiv:1007.2631 ...
- Minimal dark matter sector: 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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- Higgs portal:

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

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

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- To produce correct relic density need DM to annihilate into SM particles.
- Need some sort of portal between DM and SM
- Vector portal 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:

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

  - Facilitates annihilation $\chi\chi \to B_h B_h \to$ SM

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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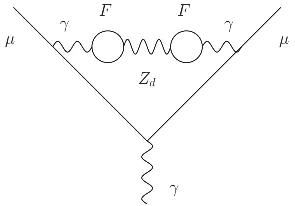

- Light vector boson can also explain muon $g_\mu - 2$ anomaly Pospelov, arXiv:0811.1030
- Imagine heavy fermions generate the kinetic mixing.

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.
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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": $W_h^{\pm} = \frac{1}{\sqrt{2}}\left(W_h^1 \pm i W_h^2\right)$

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

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

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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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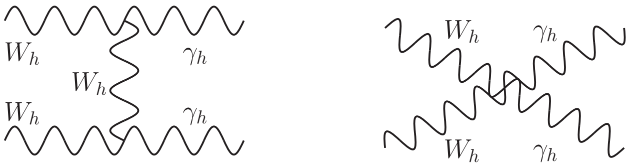
  - In limit $M_{\gamma_h} \ll M_{W_h}$ and $v_\phi \ll v_\Phi$ recover relations:

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

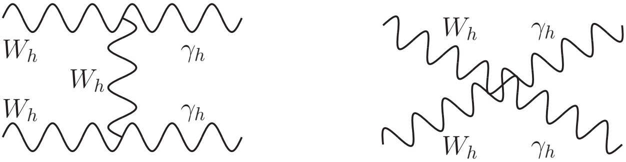
- For rest of talk will take simplifying assumption $M_{\gamma_h} \ll M_{W_h}$ and $v_\phi \ll v_\Phi$.

Relic Density



- Since $M_{\gamma_h} \leq M_{W_h}$, the annihilation channel $W_h W_h \to \gamma_h \gamma_h$ is always open.
- With the assumption $M_{\Phi_h}, M_{\phi_h}, M_{Z_h} \geq 2M_{W_h}$, this will be the dominant annihilation channel.

Relic Density



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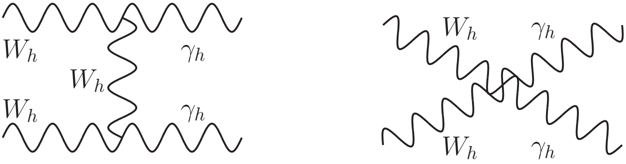
- With the assumption $M_{\Phi_h}, M_{\phi_h}, M_{Z_h} \geq 2M_{W_h}$, this will be the dominant annihilation channel.
- Have tree level $W_h W_h \to \Phi_h \to \gamma_h \gamma_h$
  - $\Phi_h \gamma_h \gamma_h$ coupling is suppressed by v_ϕ^4 / v_Φ^4
- Similarly, after Higgs mixing have $\phi W_h W_h$ 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 contributin 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



- 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 $M_{\gamma_h} \ll M_{W_h}$:

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

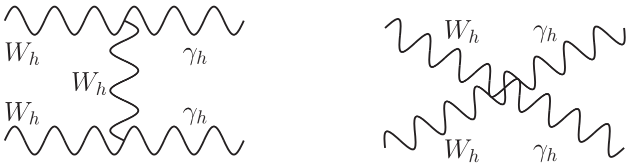
- Relic density given by

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

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

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

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

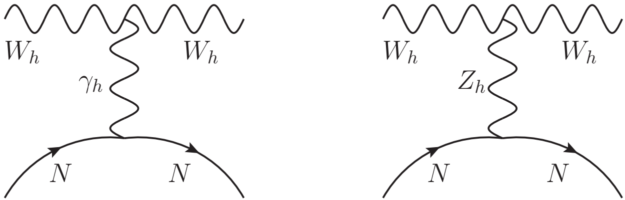
- In principle can have Higgs mixing in addition to vector portal.
- For simplicity and proof of principle, neglect possible Higgs mixing here.
- Couplings to SM Fermions:
  - As mentioned earlier, can write down a gauge invariant kinetic mixing:

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

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

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

Direct Detection

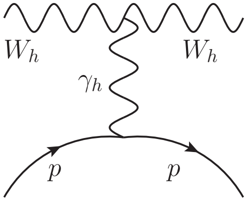


- Direct detection mediated via t-channel γ_h, Z_h exchange.
- Under our assumptions, $M_{\gamma_h} \ll M_{Z_h}$, γ_h exchange dominates.
- Elastic scattering cross section off a nucleon:

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

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

Direct Detection

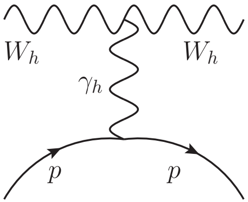


- Since γ_h couples to EM current, interacts with protons and not neutrons.
- Interested in scattering cross section with protons:

$$\sigma_p \simeq \frac{4\alpha\,(\varepsilon\cos\theta_h)^2\,(g_h\sin\theta_h)^2\,\mu_r^2(W_h,n)}{M_{\gamma_h}^4}$$

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

Direct Detection



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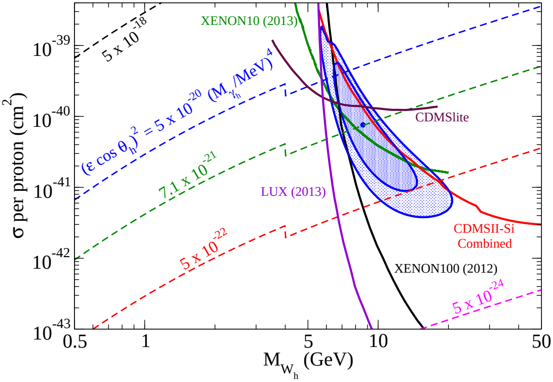
- Obtain usual scattering cross section per nucleon: $\sigma_n = (Z^2/A^2)\sigma_p$.
- Can use relic density constraint to rewrite $(g_h\sin\theta_h)^2$ in terms of M_{W_h}.
- σ_p then depends on M_{W_h} and the ratio $(\varepsilon\cos\theta_h)^2/M_{\gamma_h}^4$

Direct Detection

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



$$\sigma_p = \frac{(\varepsilon\cos\theta_h)^2}{5\times10^{-22}}\left(\frac{\text{MeV}}{M_{\gamma_h}}\right)^4\left(\frac{\mu_r(W_h,n)}{\text{GeV}}\right)^2\frac{M_{W_h}}{10\text{ GeV}}\times\begin{cases}1.2\times10^{-41}\text{ cm}^2; & T_f\lesssim\Lambda_{QCD}\\ 8.5\times10^{-42}\text{ cm}^2; & T_f\gtrsim\Lambda_{QCD}\end{cases}$$

Thermal Equlibrium

- 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:

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

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

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

- Get the condition:

$$(\varepsilon\cos\theta_h)^2\left(\frac{M_{\gamma_h}}{\rm MeV}\right)^2 \gtrsim 10^{-12} g_\star^{1/2}\left(\frac{M_{W_h}}{10~{\rm GeV}}\right)^3$$

Lower Bound on M_{γ_h}

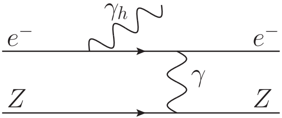
- As just seen, after relic density requirement, σ_p depends on M_{W_h} and the ratio $(\varepsilon\cos\theta_h)^2/M_{\gamma_h}^4$.
- Measurement of σ_p and M_{W_h} then fixes $(\varepsilon\cos\theta_h)^2/M_{\gamma_h}^4$.
- Can combine thermal equilibrium requirement with σ_p and M_{W_h} measurement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

$$\frac{M_{\gamma_h}}{40\ \mathrm{MeV}} \gtrsim \left(\frac{M_{W_h}}{10\ \mathrm{GeV}}\right)^{2/3}\left(\frac{\mu_r(W_h,n)}{1\ \mathrm{GeV}}\right)^{1/3}\times\left(\frac{\sigma_p}{8\times10^{-41}\ \mathrm{cm}^2}\right)^{-1/6}.$$

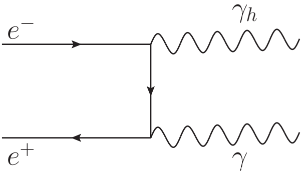
- Limit depends on $M_{\gamma_h} < T_f$, consistent with bound for $M_{W_h} \gtrsim 1$ GeV and $\sigma_p \gtrsim 10^{-43}$ cm^2.
- Range of M_{γ_h} current low energy searches are exploring.

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:

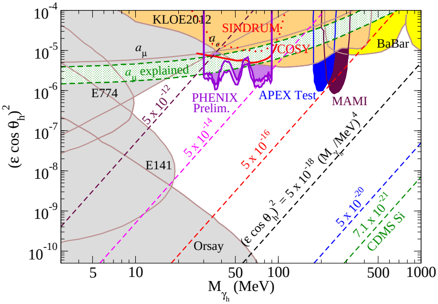


- Beam dump and fixed target experiments
  Bjorken, Essig, Schuster, Toro **PRD80** 075018; Andreas, Niebuhr, Ringwald **PRD86** 095019
  A1 Coll. **PRL106** 251802; APEX Coll. **PRL107** 191804

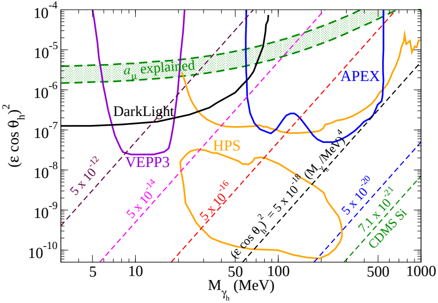


- Low energy e^+e^- eperiments.
  Reece, Wang **JHEP** 0907 051; Essig, Schuster, Toro **PRD80** 015003
  Batell, Pospelov, Ritz **PRD**79 115008, **PRD80** 095024
- Meson decays Fayet, hep-ph/0702176.

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 $\sigma_p \sim 10^{-43} - 10^{-38}$ cm^2:

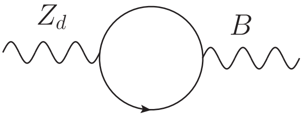
$$(\varepsilon \cos\theta_h)^2 \sim 10^{-21} - 10^{-18} (M_{\gamma_h}/\text{MeV})^4$$

- Future experiments start probing this parameter region.

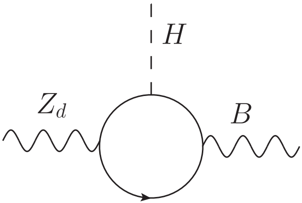
LHC Physics

- 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 in 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 originate 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 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 betwwen Z and Z_d:

$$\mathcal{L}_{Mass} = \frac{1}{2}M_{Z^0}^2 Z^0 Z^0 - \Delta^2 Z^0 Z_d^0 + \frac{1}{2}M_{Z_d^0}^2 Z_d^0 Z_d^0$$

$$\Delta^2 = \frac{1}{2} g_d g_Z v_2^2$$

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

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:

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

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

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

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

- Hence $\Theta Z_d^\mu \to \partial^\mu \phi / M_Z$, no longer suppressed by M_{Z_d}.

Higgs Branching Ratios

- Assuming the kinetic mixing comes from heavy fermions with $m_F \sim$ few $\times$ 100 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 $g_d \approx e$

$$0.1\mathrm{Br}(H \to \gamma\gamma) \approx \mathrm{Br}(H \to \gamma Z_d) \approx 2\,\mathrm{Br}(H \to Z_d Z_d) \approx 10\,\mathrm{Br}(H \to Z Z_d)$$

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- Mass mixing:

$$\mathrm{Br}(H \to Z Z_d) \approx 16\,\delta^2 \qquad \mathrm{Br}(H \to Z_d Z_d) \approx 80\,\delta^4$$

  - $H \to Z_d Z_d$ is doubly suppressed by δ^4
  - Rare B and K decays suggest $\delta^2 \lesssim 10^{-5}$ for $M_{Z_d} \ll 5$ GeV
    Davoudiasl, Lee, Marciano **PRD85** 115019
  - Precision Z poles measurements suggest $\delta^2 <$ few $\times 10^{-4}$ for all M_{Z_d}
    Davoudiasl, Lee, Marciano **PRD85** 115019.
  - So $\mathrm{Br}(H \to Z Z_d)$ can be comparable to $\mathrm{Br}(H \to \gamma\gamma) \simeq 2.3 \times 10^{-3}$

Higgs Decays

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

$$H \to Z Z_d, \quad \gamma Z_d, \quad Z_d Z_d$$

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

$$H \to Z Z_d, \quad Z_d Z_d$$

  - $H \to Z_d Z_d$ doubly suppressed in mass mixing case.
- Will focus on $H \to Z Z_d \to 4\ell$ signals.

Parameterization

- Mass mixing parameterization:

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

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

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

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

Dark Z decays

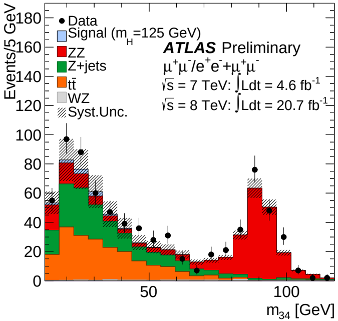
- If kinetic mixing is dominant:
  - Z_d couples to SM E&M current.
  - $\text{Br}(Z_d \to 2\ell) > \text{Br}(Z \to 2\ell)$, since no neutrino coupling.
  - For $M_{Z_d} = 5 - 10$ GeV, can expect $\text{Br}(Z_d \to 2\ell) \simeq 0.3$
- If mass mixing dominates:
  - Z_d also couples to SM neutral current.
  - $\text{Br}(Z_d \to 2\ell)$ smaller than kinetic mixing case.
- For purposes of the collider search, will focus on mass mixing case.
- Will give results in terms of $\delta^2\ \text{Br}(Z_d \to 2\ell)$

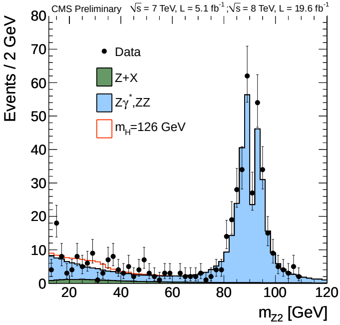
LHC Search

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

$$pp \to H \to Z Z_d \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$$

- Interested in mass range $M_{Z_d} \sim 5 - 10$ GeV.
- Complementary to previous low energy searches.
- May expect to appear in $H \to ZZ^*$ 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"

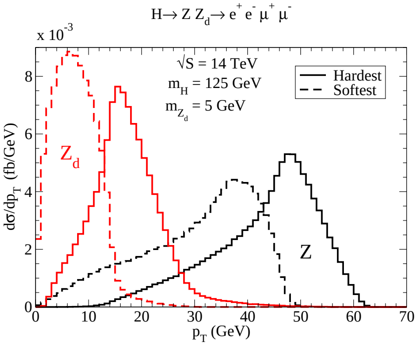
- Benchmark point:

$$M_{Z_d} = 5 \text{ GeV} \qquad M_H = 125 \text{ GeV}$$
$$\delta^2 \text{Br}(Z_d \to 2\ell) = 10^{-5} \qquad \kappa_z = \tilde{\kappa}_Z = 0$$

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



(No smearing or cuts)

- 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:

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

- Further triggers, following ATLAS ATLAS-CONF-2013-012:
  - One leton with $p_T^\ell > 24$ GeV, OR
  - Two leptons with $p_T^\ell > 13$ 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 angel, respectively.

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

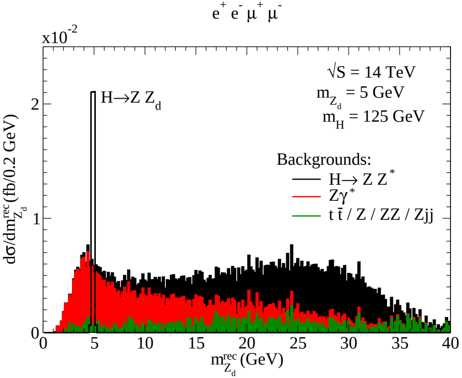
  - $\Delta\eta$ and $\Delta\phi$ difference in lepton rapidity and azimuthal angel, respectively.
- Originating from a Higgs resonance:

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

  - $M_{4\ell}$ 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: $m_{12}^2 = 2E_1E_2(1-\cos\theta_{12})$
  - Isolation cuts and p_T cuts effectively put lower bounds on invariant mass.
- Use peak to measure M_{Z_d} and place cut:

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

Signal and Background Rates

Channel	$e^+e^-\mu^+\mu^-$		$2\mu^+2\mu^-$		$2e^+2e^-$	
σ (fb)	Sig.	Bkgrnd	Sig.	Bkgrnd	Sig.	Bkgrnd
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:

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

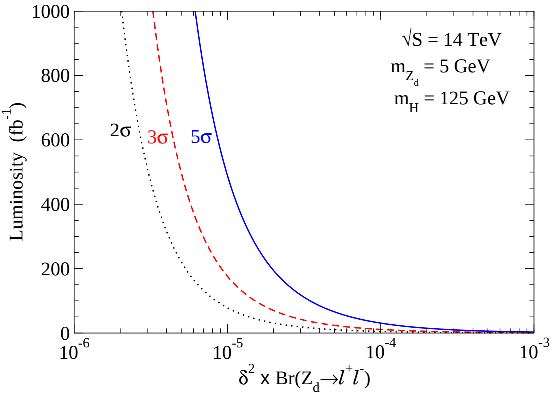
  $e^+e^-\mu^+\mu^-$: $t\bar{t} \sim 50\%$ $Z \sim 28\%$ $ZZ \sim 12\%$

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

Observability

300 fb^{-1}:

Exclude	$\delta^2 \gtrsim 4 \times 10^{-6}$
Observe	$\delta^2 \gtrsim 7 \times 10^{-6}$
Discover	$\delta^2 \gtrsim 1.5 \times 10^{-5}$



- Exclusion from precision Z-pole was $\delta^2 \gtrsim \text{few} \times 10^{-4}$
- For equal $\text{Br}(H \to ZZ_d)$ in kinetic and mass mixing case:

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

Observability

	$M_{Z_d} = 5$ 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}

	$M_{Z_d} = 10$ 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 $\mathrm{Br}(H \to ZZ_d)$ in kinetic and mass mixing case:

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

- $M_{Z_d} = 10$ GeV:
  - For our parameterization, signal rate the same as 5 GeV.
  - $|M_{Z_d}^{\rm rec} - M_{Z_d}| < 0.1 M_{Z_d}$ 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:

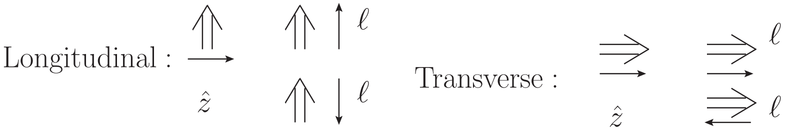
$$O_{B,Z} = c_{B,Z}\, H\, Z_{\mu\nu}\, Z_d^{\mu\nu}, \quad \tilde{O}_{B,Z} = \tilde{c}_{B,Z}\, H\, \tilde{Z}_{\mu\nu}\, Z_d^{\mu\nu}$$

  - 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

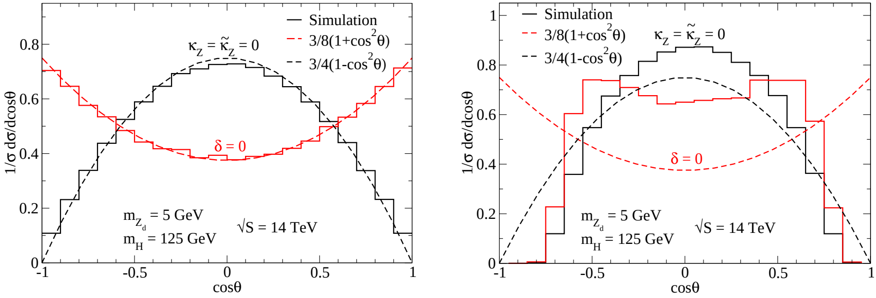


- $\hat{z}$ is Z_d moving direction.
  - Since Z_d highly boosted, $\hat{z}$ can be in CM or Lab frame.
- Lepton angular distribution with respect to $\hat{z}$:

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

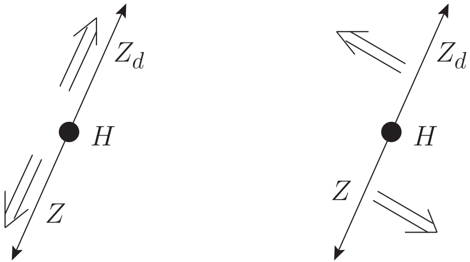
  - Upper sign for transverse polarizations.
  - Lower sign for Longitudinal

Distinguishing Operators



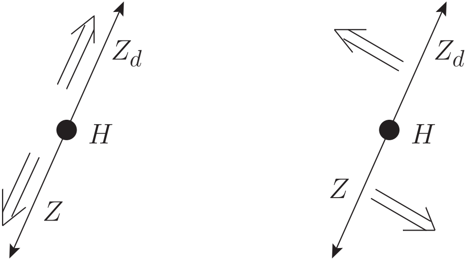
- After cuts cannot distinguish.
- Z_d is highly boosted and its decay products collimated.
  - For $\cos\theta_\ell = \pm 1$, one lepton moving in $-\hat{z}$-direction.
    - Boost into lab fame against direction of motion in Z_d-frame.
  - This configure results in softest leptons.
  - p_T^ℓ cuts kill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

Distinguishing Operators



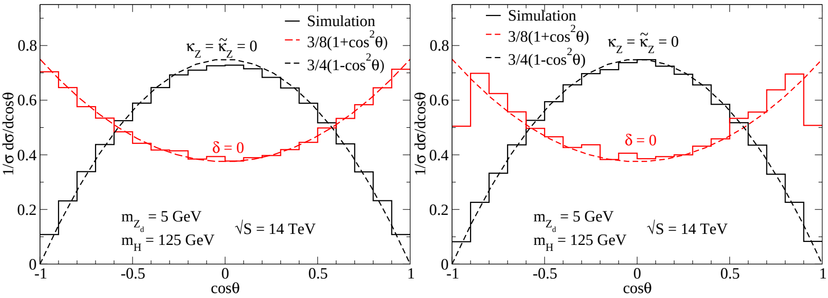
- Consider Higgs rest frame:
  - By conservation of momentum, Z and Z_d back-to-back.
  - By conservation of angular momentum, spins of Z and Z_d opposite directions.
  - If Z_d is helicity state, Z is in same helicity state.
  - p_T of leptons from Z peaked in 30 – 50 GeV range, cut not as drastic.

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 $\to$ Higgs rest frame
  - Higgs rest frame $\to$ Z rest frame.
  - Unlike Z_d case, necessary to boost to Higgs frame first.

Distinguishing Operators



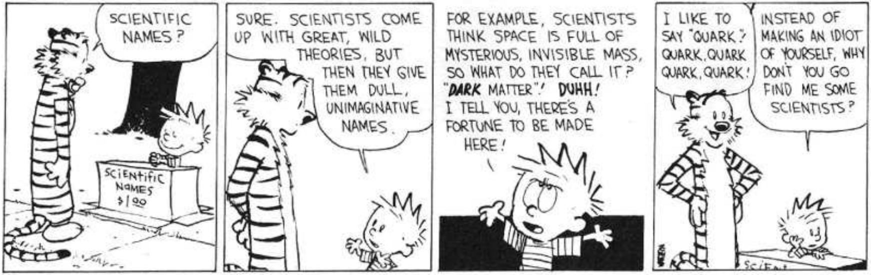
- Angular distribution stable against cuts.

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 $H \to ZZ_d$
  - 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: $HZ_\mu Z_d^\mu$
  - 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 $M_{Z_d} = 5$ GeV
  - With our benchmark points can exclude Z_d with mass $5-10$ GeV with $\sim 30-40$ fb^{-1}
  - Discover Z_d with mass $5-10$ GeV with $\sim 200-250$ fb^{-1}
  - Showed how to distinguish between two operators:
    - “Kinetic" mixing results in transversely polarized Z_d
    - “Mass" mixing in longitudinally polaized Z_d
    - Angular distribution of leptons from Z decay sensitive to this polarization, and stable against cuts.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SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS. SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
I LIKE TO SAY "QUARK." QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?


1. Explain Newton's First Law of Motion in your own words.
!
Yakka Foob Mog. Grug Pubbawup Zink wattoom Gazork. Chumble Spuzz.
I LOVE LOOPHOLES.