Higgs Physics, Dark Forces and the LHC

Ian Lewis

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

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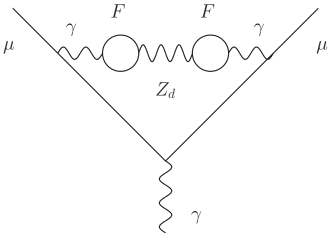
Motivation

- Observations indicate that a significant portion of the matter density of the Universe is dark matter (DM).
- May expect DM to be part of a larger sector.
- Dark sector may contain possible portal to Standard Model.
- In particular, this portal may be light.
- Been proposed as an explanation of positron excess observed by PAMELA/FERMI/AMS-02
- Independent DM, light new physics has also been proposed to eplain the $(g-2)_\mu$ excess Pospelov, arXiv:0811.1030. Although, in some tension now...



Kinetic Mixing

- Vector portal via kinetic mixing Holdom Phys.Lett. 166B:

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

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

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

- 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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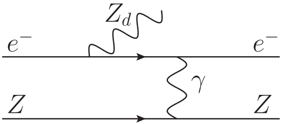
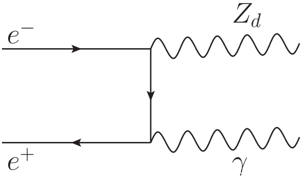
Low Energy Searches

- Robust program looking for light vector bosons weakly coupled to SM:

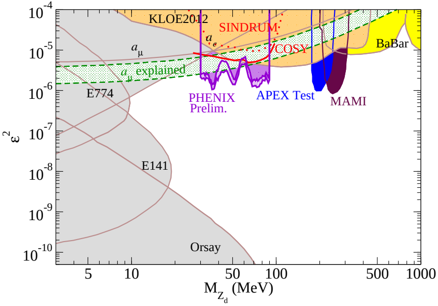


- Beam dump and fixed target experiments
  Bjorken, Essig, Schuster, Toro **PRD80** 075018; Andreas, Niebuhr, Ringwald **PRD86** 095019
  A1 Coll. **PRL106** 251802; APEX Coll. **PRL107** 191804

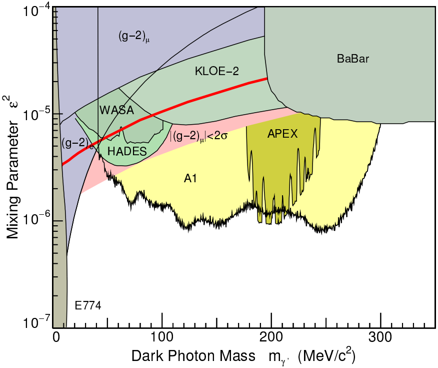


- Low energy e^+e^- eperiments.
  Reece, Wang **JHEP** 0907 051; Essig, Schuster, Toro **PRD80** 015003
  Batell, Pospelov, Ritz **PRD**79 115008, **PRD80** 095024
- Meson decays Fayet, hep-ph/0702176.

Current Constraints Low Energy Searches



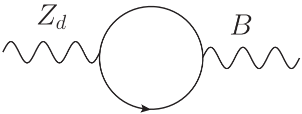
Davoudisl, IML PRD90 (2014) 033004



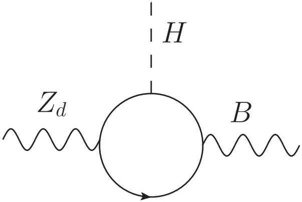
Merkel et al., PRL 112 (2014) 221802

- PHENIX and MAMI results exclude much of $(g-2)_\mu$ anomaly explanation.
- For LHC searches will focus on $M_{Z_d} \gtrsim 5$ GeV, complementary to previous low energy searches.

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:

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

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

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

Higgs Branching Ratios

- Assuming the kinetic mixing comes from heavy fermions with $m_F \sim$ few $\times$ 100 GeV, operator coefficients are
$$|c_{B,X}| \sim |\tilde{c}_{B,X}| \sim \frac{g_w g_d y_F}{16\pi^2 M_Z}$$
  - g_w generic weak coupling.
  - y_F fermion Yukawa coupling.
  - For $y_F \sim 1$ and $g_d \approx e$

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

Higgs Branching Ratios

- Assuming the kinetic mixing comes from heavy fermions with $m_F \sim \text{few} \times 100$ GeV, operator coefficients are
$$|c_{B,X}| \sim |\tilde{c}_{B,X}| \sim \frac{g_w g_d y_F}{16\pi^2 M_Z}$$
  - g_w generic weak coupling.
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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
  - Low energy parity violation $\delta^2 < \text{few} \times 10^{-4}$ 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 by mixing angle.
- Will focus on $H \to Z\, Z_d$ signals.

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.
- Focus on $H \to ZZ_d \to 4\ell$

Parameterization

- Mass mixing parameterization:

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

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

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

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

Parameterization

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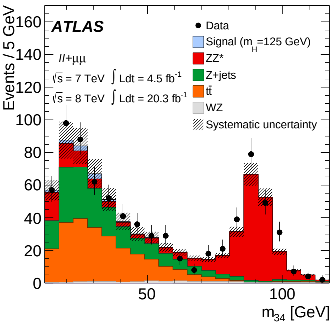
  - $c_{B,Z} = -\frac{g}{2\cos\theta_W}\frac{\kappa_Z}{M_Z}$
  - $\tilde{c}_{B,Z} = \frac{g}{2\cos\theta_W}\frac{\tilde{\kappa}_Z}{M_Z}$.
- For purposes of the collider search, will focus on mass mixing case.
- Will give results in terms of $\delta^2\ \mathrm{Br}(Z_d \to 2\ell)$
  - δ^2 is free parameter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

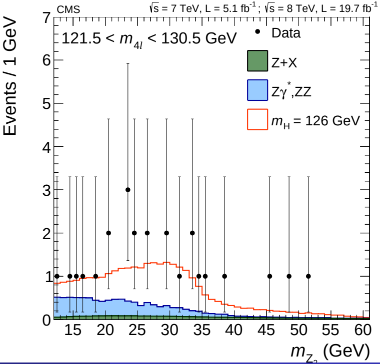
LHC Search

- 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.





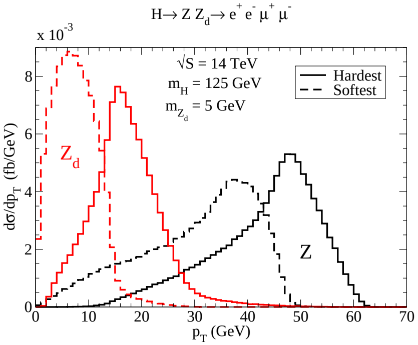
Benchmark Point and Event Reconstruction

- Benchmark point (no kinetic mixing):

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

- Want full reconstruction of signal to isolate from background.
  - 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:

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

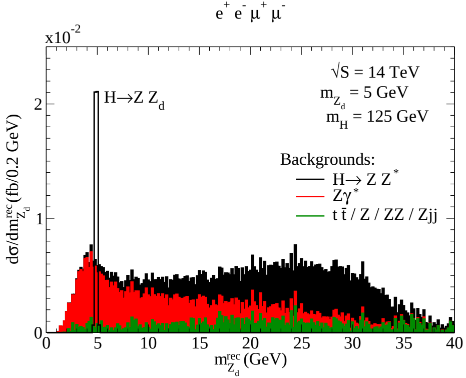
  - $\Delta\eta$ and $\Delta\phi$ difference in lepton rapidity and azimuthal angel, respectively.
- Originating from a Higgs resonance:

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

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

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

Z_d resonance peak



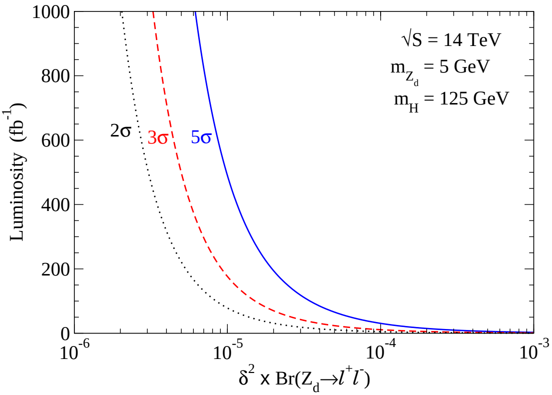
- After all previous cuts and energy smearing.
- Sharp drop-off in background below 4 – 5 GeV.
  - Invariant mass of two massless particles: $m_{12}^2 = 2E_1 E_2 (1 - \cos\theta_{12})$
  - Isolation cuts and p_T cuts effectively put lower bounds on invariant mass.
- Use peak to measure M_{Z_d} and place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

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

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 $\text{Br}(H \to ZZ_d)$ 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 $\text{Br}(H \to ZZ_d)$ 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.
  - $|M_{Z_d}^{\text{rec}} - M_{Z_d}| < 0.1 M_{Z_d}$ 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:

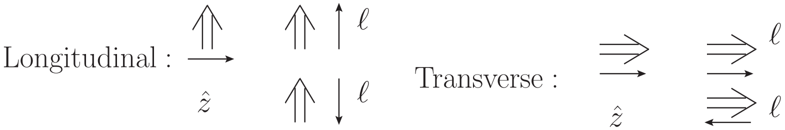
$$O_{B,Z} = c_{B,Z}\, H\, Z_{\mu\nu}\, Z_d^{\mu\nu}, \quad \tilde{O}_{B,Z} = \tilde{c}_{B,Z}\, H\, \tilde{Z}_{\mu\nu}\, Z_d^{\mu\nu}$$

  - 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

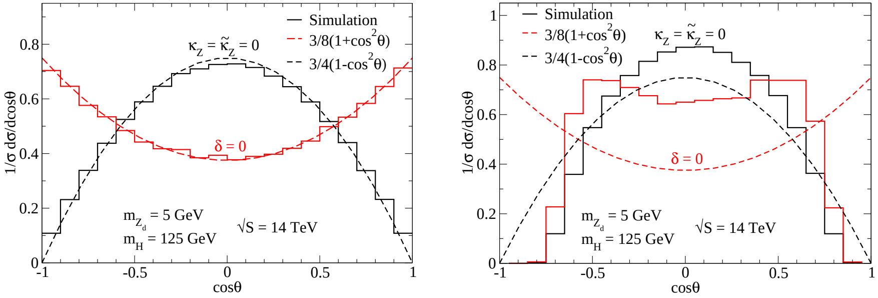


- $\hat{z}$ is Z_d moving direction.
  - Since Z_d highly boosted, $\hat{z}$ can be in CM or Lab frame.
- Lepton angular distribution with respect to $\hat{z}$:

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

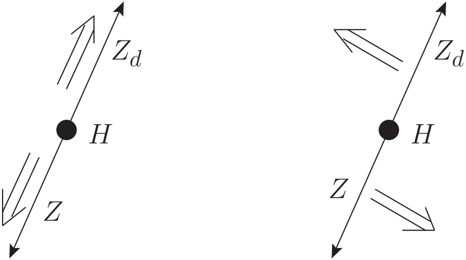
  - Upper sign for transverse polarizations.
  - Lower sign for Longitudinal

Distinguishing Operators



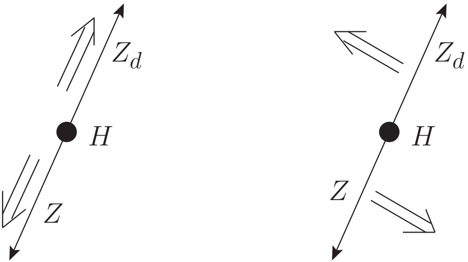
- After cuts cannot distinguish.
- Z_d is highly boosted and its decay products collimated.
  - For $\cos\theta_\ell = \pm 1$, one lepton moving in $-\hat{z}$-direction.
    - Boost into lab fame against direction of motion in Z_d-frame.
  - This configure results in softest leptons.
  - p_T^ℓ cuts kill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

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



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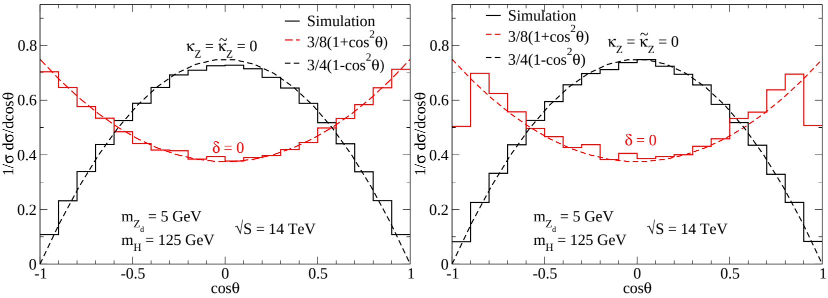
  - If Z_d is helicity state, Z is in same helicity state.
  - p_T of leptons from Z peaked in 30 – 50 GeV range, cut not as drastic.
- Use angular distributions of decay products of Z to probe coupling.
- Boost order:
  - Lab frame $\to$ Higgs rest frame
  - Higgs rest frame $\to$ Z rest frame.
  - Unlike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

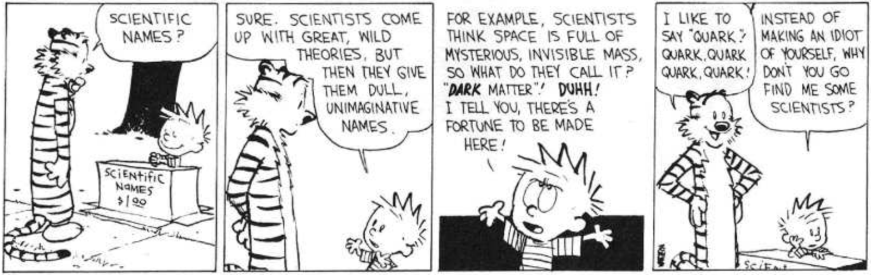
Distinguishing Operators



- Angular distribution stable against cuts.

Conclusions

- 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 $\sim 30-40\ \text{fb}^{-1}$
  - Discover Z_d with mass $5-10$ 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 polaized Z_d
    - Angular distribution of leptons from Z decay sensitive to this polarization, and stable against cuts.
- Could be interesting complementary search to low energy searches.
- May be able to distinguish mixing mechanisms with angular distributions.


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1.00
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.

BACKUP SLIDES

Event 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"

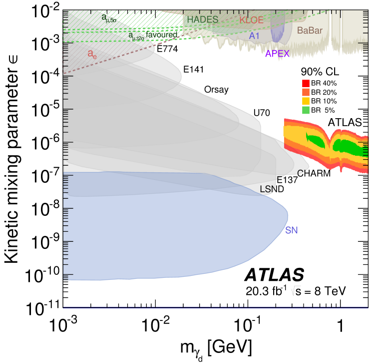
Signal and Background Rates

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^{rec} cuts dominate backgrounds are $Z\gamma^*$ and $H \to ZZ^*$



ATLAS arXiv:1409.0746

Search for $H \to \gamma_d \gamma_d + X$