Higgs Decays as a Window into the Dark Sector

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Based on:

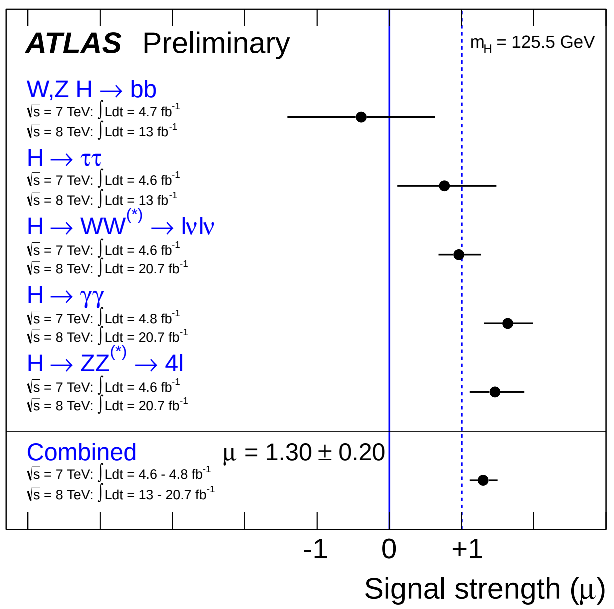
HD, H.-S. Lee, I. Lewis, W. Marciano, arXiv:1304.4935 [hep-ph] (to be published in PRD)

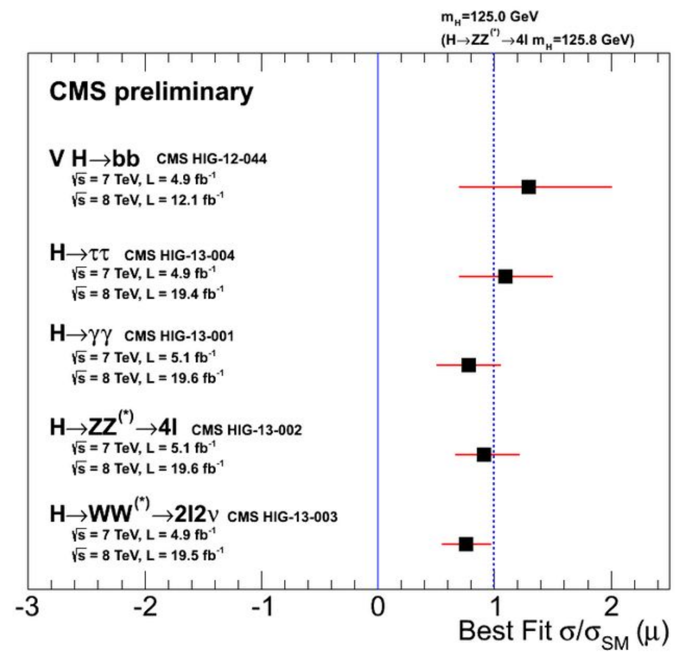
Fermilab, June 19, 2013

Introduction

- A Higgs at $\sim$ 125 GeV

- Largely appears to be that of the Standard Model (SM), now seemingly complete.
- Higgs properties may show deviations from SM, *e.g.* diphotons.
- Too early to draw firm conclusions.





- Strong evidence new physics is needed: Dark Matter.

- Also, neutrino masses, baryogenesis, . . .

- Other hints: $g_\mu - 2$ discrepancy at 3.6σ, . . .

Potential Hints, Speculations

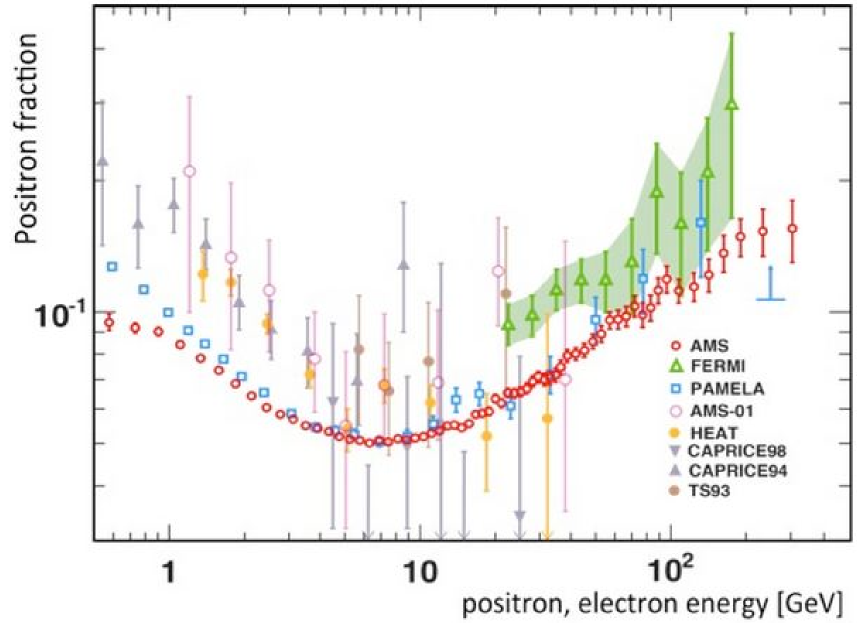
- Heavy DM annihilation signals
- New interactions in the dark sector

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

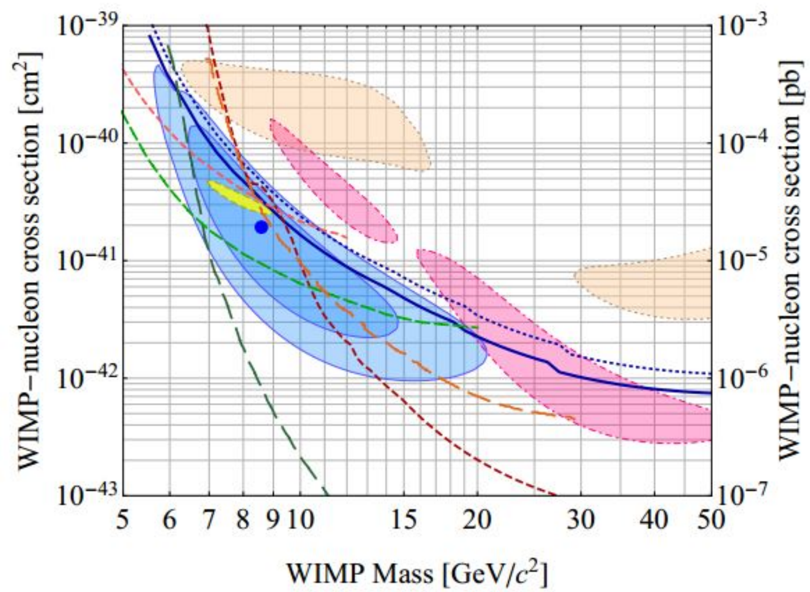
- Dark matter stability
- Gauge charges, analogous to $e^{\pm}$.
- Multi-component dark sector (like SM)
- Perhaps DM extending to the GeV sector
- $g_\mu - 2$: a new photon-like contribution
- "Dark photon," kinetic mixing

Fayet, 2007; Pospelov, 2008

- New vector bosons, scalars, ...
- Masses $\sim 0.1 - 10$ GeV
- Weak couplings to the SM



AMS Collaboration, 2013



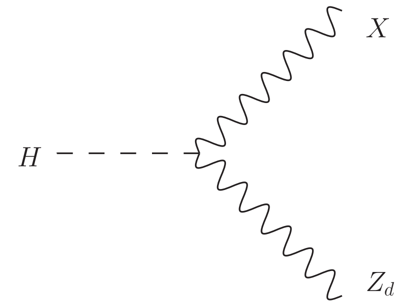
CDMS Collaboration, 2013

Outline:

- We assume a dark (hidden) sector endowed with a $U(1)_d$ gauge interaction.
- $U(1)_d$ is broken, associated vector boson Z_d with $m_{Z_d} \lesssim 10$ GeV.
- SM particles not charged under $U(1)_d$.
- Z_d coupling to SM only through mixing or loops.
- Suppressed couplings: no large deviations from the SM.
- Rare Higgs decays could shed light on the "dark sector."
- Consider $H \to X Z_d$, with $X = Z, Z_d, \gamma$, at the LHC (focus on $X = Z$).
- Two types of operators: (A) dim-3 and (B) dim-5

Formalism and Notation

(A): $O_{A,X} = c_{A,X} H X_\mu Z_d^\mu$ (dim-3)



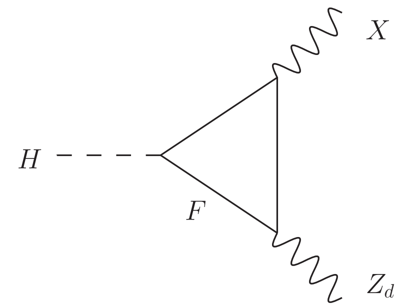
- $X \neq \gamma$ (gauge invariance), $[c_{A,X}] = 1$.
- Focus on $X = Z$, for example via Z-Z_d mixing from $\varepsilon_Z m_Z^2 Z Z_d$ with

$$\boldsymbol{\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta}$$

- Z_d in this case dominantly *longitudinal* in $H \to Z Z_d$.
- Couplings of Z_d: SM Z couplings suppressed by ε_Z
- Z_d as "dark" Z (in principle different from a "dark" photon coupled to electric charge)
- New source of parity violation (atomic PV, e scattering,...) HD, Lee, Marciano, 2012
- **For $m_{Z_d} \ll m_B$ rare meson decays $\Rightarrow \delta^2 \lesssim 10^{-5}$**
- Precision EW (Z-pole), early H decay data: $\delta^2 \lesssim 10^{-4}$
- Parametrization: $\boldsymbol{c_{A,X} = \frac{g}{\cos\theta_W}\varepsilon_Z m_Z}$ g is the $SU(2)_L$ coupling constant

($X = Z_d$ from Higgs-scalar mixing Gopalakrishna, Jung, Well, 2008)

(B): Generically from loop processes (dim-5)



CP even: $O_{B,X} = c_{B,X} H X_{\mu\nu} Z_d^{\mu\nu}$

CP odd: $\tilde{O}_{B,X} = \frac{\tilde{c}_{B,X}}{2} \varepsilon_{\mu\nu\rho\sigma} H X^{\mu\nu} {Z_d}^{\rho\sigma}$

- $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ and $[c_{B,X}] = [\tilde{c}_{B,X}] = -1$
- Vector-like fermions F charged under $SU(2) \times U(1)_Y \times U(1)_d$.

HD, Lee, Marciano, 2012

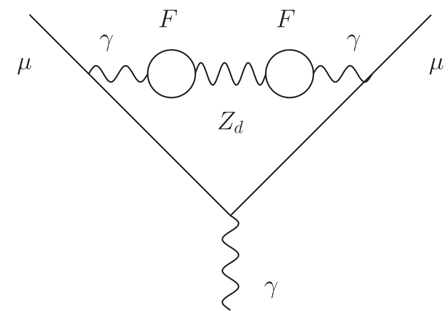
- F has EW preserving mass m_F.
- Z_d in the Higgs decay dominantly *transverse* in this case.
- Angular distribution of final state fermions can distinguish $O_{B,X}$ from $\tilde{O}_{B,X}$.

Voloshin, 2012 (for $H \to \gamma\gamma$)

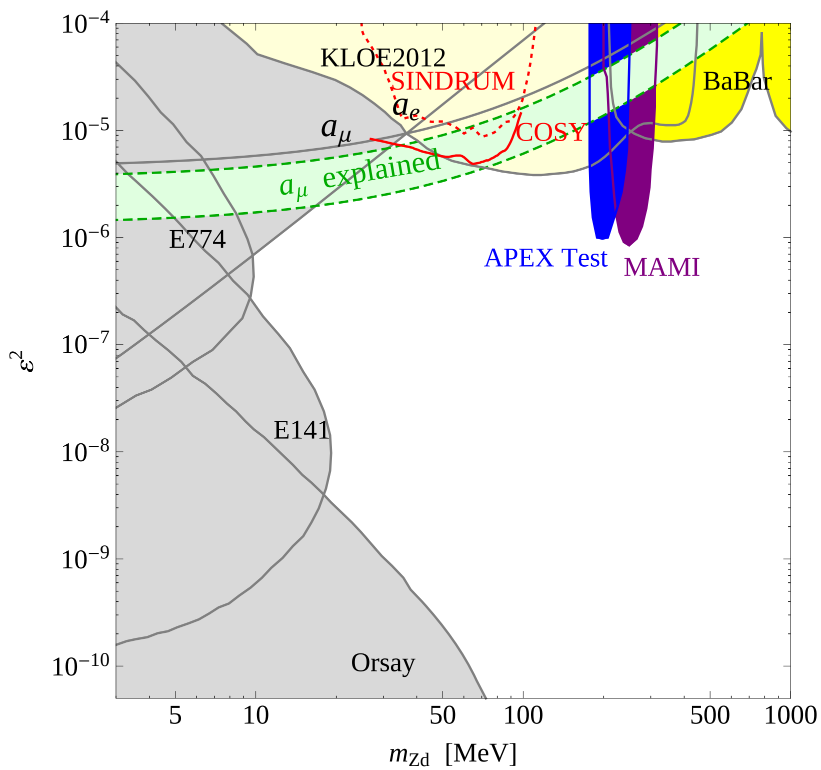
- Expect $c_{B,X}$, $\tilde{c}_{B,X} \to 0$ as $m_F \to \infty$.
- Weak scale F could affect Higgs decays into di-bosons, *e.g.* $H \to \gamma\gamma$
- Parametrization: $\boldsymbol{c_{B,X} = -\frac{g}{2\cos\theta_W}(\kappa_X/m_Z)}$ and $\boldsymbol{\tilde{c}_{B,X} = \frac{g}{2\cos\theta_W}(\tilde{\kappa}_X/m_Z)}$
- $[\kappa_X] = [\tilde{\kappa}_X] = 0$, model dependent

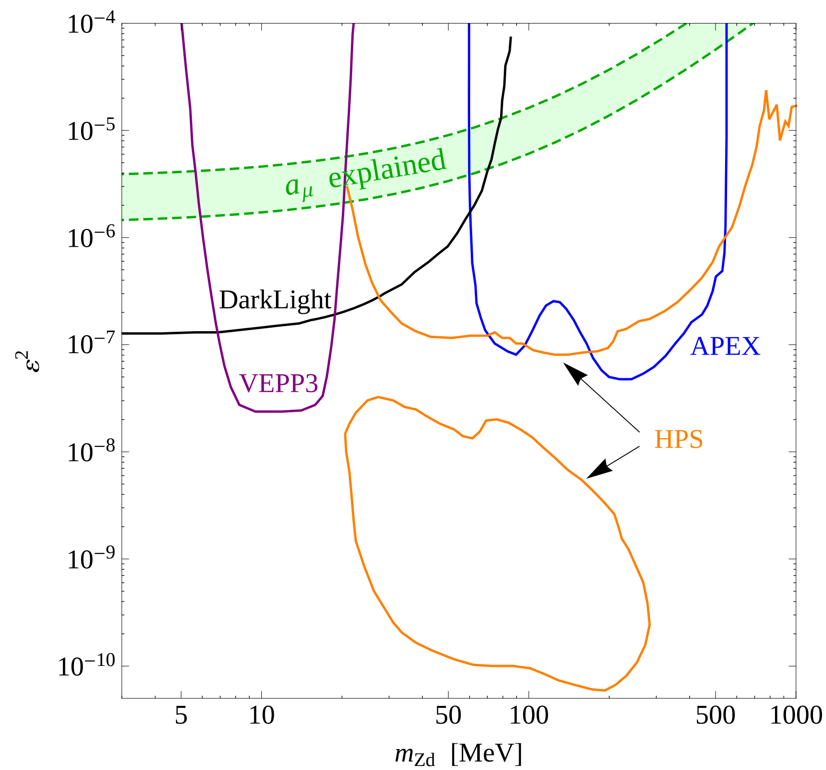
Aside:

- Fermions with $SU(2) \times U(1)_Y \times U(1)_d$ charges induce *kinetic mixing*: $\frac{\varepsilon}{2\cos\theta_W} \boldsymbol{B_{\mu\nu} Z_d^{\mu\nu}}$
  Holdom, 1986
- Z_d couples to J_μ^{EM} suppressed by ε (dark photon).
- Loops: $\varepsilon \sim e g_d/(16\pi^2) \sim \mathcal{O}(10^{-3})$ $\quad (g_d \approx e)$
- $m_{Z_d} \sim 20 - 50$ MeV can explain $g_\mu - 2$ anomaly.



- Our focus on $m_{Z_d} \gtrsim 1$ GeV complementary to low energy experiments.





$H \to ZZ_d$ at the LHC

- $H \to ZZ_d$: can originate from both (A) and (B) operators
  - γZ_d not relevant for (A) and $Z_d Z_d$ doubly suppressed in Z-Z_d mass mixing.
- Examine $pp \to H \to ZZ_d \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$ (S, B: MadGraph 5 and CTEQ6L pdf set)
  - $\sqrt{s} = 14$ TeV LHC and $\ell_i = e, \mu$
- $\boxed{m_{Z_d} = 5\,\text{GeV}}$ and $m_H = 125$ GeV
- Focus on class (A) for now:

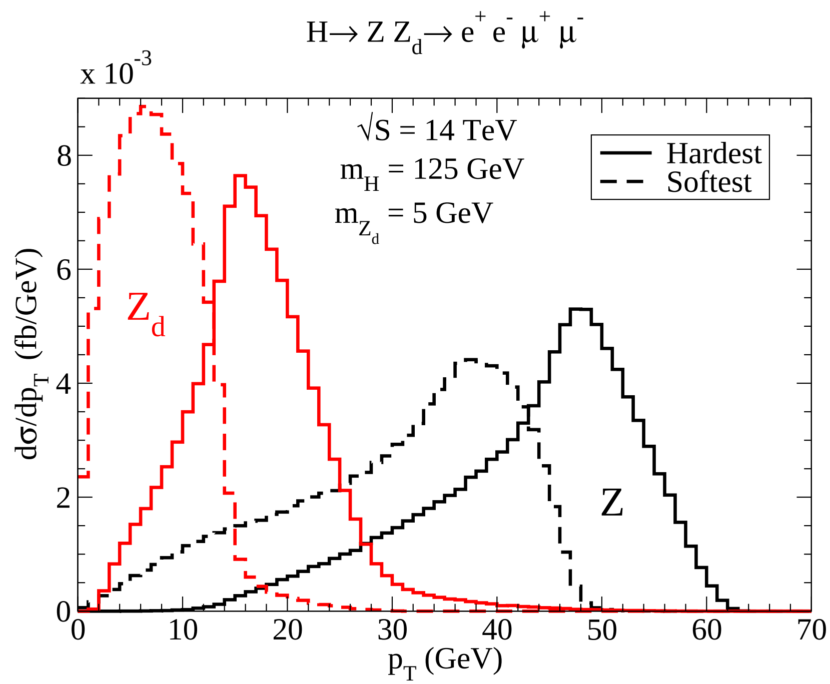
$$\boxed{\delta^2 \times \texttt{Br}(Z_d \to \ell^+\ell^-) = 10^{-5} \text{ and } \kappa_Z = \tilde{\kappa}_Z = 0}$$

  - Kinetic mixing dominance: $\texttt{Br}(Z_d \to \ell^+\ell^-) \simeq 0.3$ for $m_{Z_d} \sim 5 - 10$ GeV
  - Smaller $\texttt{Br}(Z_d \to \ell^+\ell^-)$ if Z-Z_d mass mixing dominates.
  - Above choices: $\texttt{Br}(H \to ZZ_d \to 4\ell) \approx 0.1 \times \texttt{Br}(H \to ZZ^* \to 4\ell)$. HD, Lee, Marciano, 2012
  - $\texttt{Br}(H \to ZZ^* \to 4\ell) \approx 10^{-4}$ (SM). $[\texttt{Br}(H \to ZZ_d) \approx 2 \times 10^{-4} / \texttt{Br}(Z_d \to \ell^+\ell^-)]$
- $m_{\ell\ell} \lesssim 15$ GeV not covered in early searches.

Analysis

- Detector resolution: Gaussian energy smearing with $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$ (E in GeV)
  - Leptons (jets): $a = 10\%$ (50%) and $b = 0.7\%$ (3%) (ATLAS).

- Cuts:
  - $p_T^\ell > 4$ GeV and $|\eta^\ell| < 2.5$
  - $\exists\, \ell\, (\vee\, 2\ell)$, $p_T^\ell > 24(13)$ GeV (ATLAS trigger)
  - $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.3$
  - $|m_{4\ell} - m_H| < 2$ GeV
  - $|m_Z^{rec} - m_Z| < 15$ GeV



- Backgrounds:
  - Irreducible: $H \to ZZ^*$, $Z\gamma^*$, ZZ, $Z(\to 4\ell)$
  - Reducible: Zjj (jet fakes); $t\bar{t} \to (b \to c\ell^-)(\bar{b} \to \bar{c}\ell^+)\ell^+\ell^- + \not{p}_T$ (4 lpetons)
  - Jet fake rate $\sim 10^{-3}$ and $\mathtt{Br}(b \to c\ \ell\bar{\nu}) \simeq \mathtt{Br}(B^0 \to \ell\bar{\nu} + \text{anything}) = 0.10$

Z_d Resonance Signal

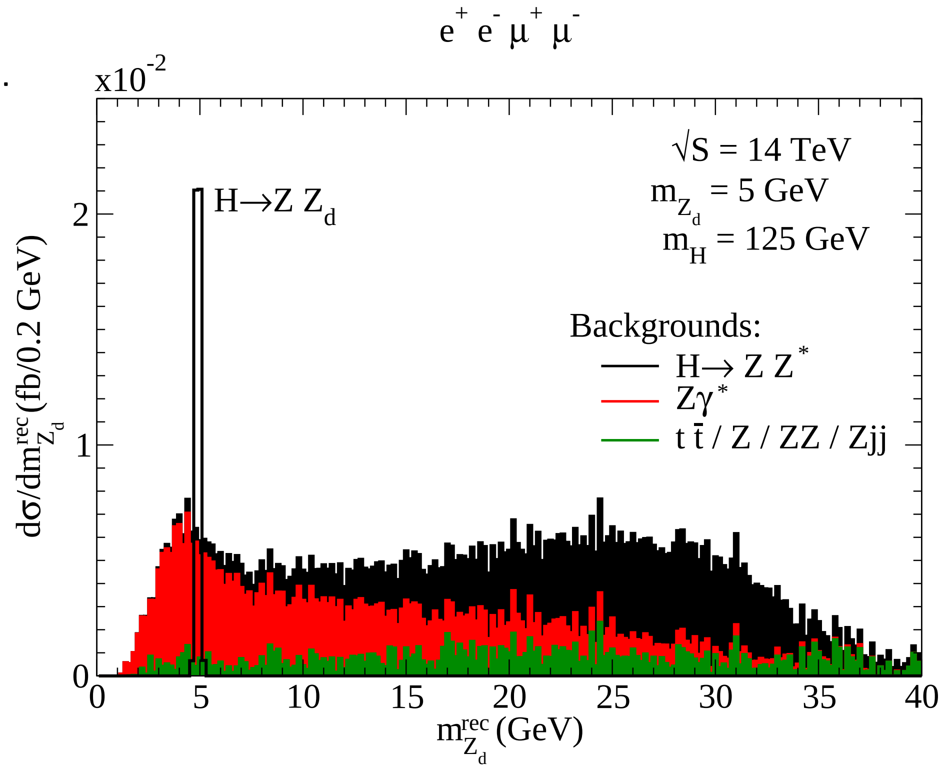
- Drop in B below 5 GeV: p_T^ℓ, η^ℓ, and ΔR cuts: $m_{12}^2 = 2E_1E_2\,(1 - \cos\theta_{12})$

- $m_{Z_d} \lesssim 5$ GeV at LHC: relax isolation or p_T cuts.

- Clear signal: also use $|m_{Z_d}^{rec} - m_{Z_d}| < 0.1\, m_{Z_d}$.

* S largely unchanged, B suppressed.

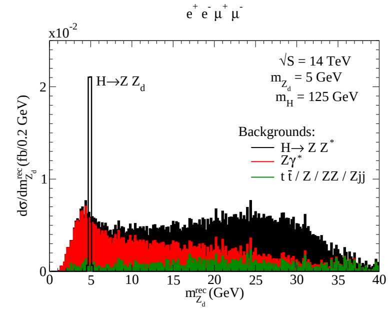
* Good S/B

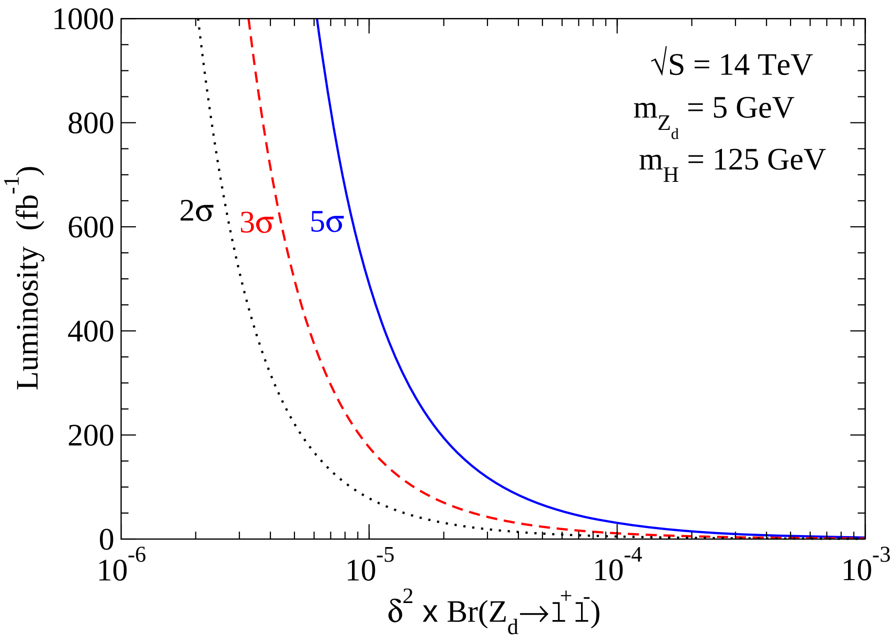


Channel	$e^+e^-\mu^+\mu^-$		$2\mu^+2\mu^-$		$2e^+2e^-$	
σ (fb)	Signal	Back-ground	Signal	Back-ground	Signal	Back-ground
No cuts and no energy smearing	0.10	·	0.051	·	0.051	·
Basic cuts + Trigger + Isol.	0.049	67	0.024	26	0.024	26
$+\, m_{4\ell}\ +\, m_Z^{rec}\ +\, m_{Z_d}^{rec}$	0.043	0.030	0.022	0.017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

LHC Reach

- Significance using $S/\sqrt{S+B}$
- Roughly flat B: $|m_{Z_d}^{rec} - m_{Z_d}| < 0.1\, m_{Z_d}$ less efficient at larger m_{Z_d}
- Reach for larger m_{Z_d} would be improved for models with $\delta \propto m_{Z_d}$
- With $\sim$ few $\times$ 100 fb^{-1} LHC (14 TeV) can probe $\delta^2 \times \mathrm{Br}(Z_d \to \ell^+\ell^-) \gtrsim 10^{-5}$.





	$m_{Z_d} = 5$ 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}

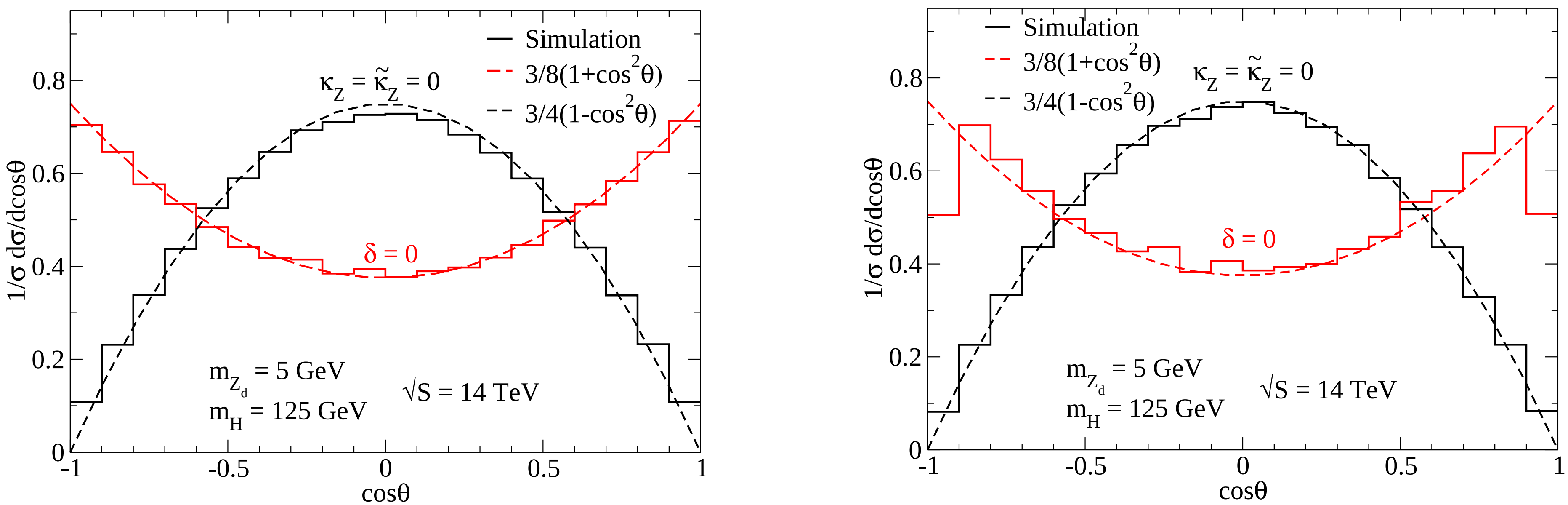
$K \sim 2$ for $gg \to H$ at NNLO-NNLL in α_s, $K = 1.4$ for $t\bar{t}$ at NNLO-NNLL, and $K = 1.19$ for Z at NNLO, $K = 1.18$ for $Z\gamma$ at NLO in α_s, $K = 1.62$ for ZZ at NLO, $K = 0.9$ for Zjj at NLO.

Angular Diagnostics

- Class (A)/(B) interactions: dominantly longitudinal/transverse Z_d
- Angular distribution: $\frac{d\Gamma(Z_d \to \ell^+\ell^-)}{d\cos\theta_\ell} \sim (1 \pm \cos^2\theta_\ell)$
  - θ_ℓ: ℓ^- angle with respect to the Z_d spin-quantization axis
  - $\pm \to$ transversely/longitudinally polarized Z_d
  - Z_d helicity eigenstate for $m_{Z_d} \ll m_H - m_Z$.
- Consider Z_d direction of motion for measuring θ_ℓ.
- For $\cos\theta_\ell \sim \pm 1$ one lepton moves in the opposite direction of $Z_d \Rightarrow$ soft lab frame ℓ.
- The p_T^ℓ cut then removes events with $\cos\theta_\ell \sim \pm 1 \Rightarrow$ less efficient discrimination.

Alternative Distribution

- In partonic CM frame: Z and Z_d momentum and spin anti-aligned.
- Z and Z_d have the same helicity in this frame.
- Measure θ_ℓ in the Z rest frame with respect to the Z momentum in partonic CM frame.
- Z decay products harder, less affected by p_T^ℓ cuts $\Rightarrow$ distribution a better discriminant.



Simulation using (A)/(B) operators (solid) and longitudinal/transverse distributions (dashed)

Left (Right): Without (with) cuts or energy smearing

- Suppression at $\cos\theta_\ell \sim \pm 1$ from isolation cut: a lepton from Z moving along the direction of Z_d.
- $\kappa_Z \neq 0$, $\tilde{\kappa}_Z = 0$ or $\kappa_Z = 0$, $\tilde{\kappa}_Z \neq 0$ yield the same results.
- CP violation would arise if both κ and $\tilde{\kappa}$ are non-zero.

Extension to Other Cases

- $H \to Z Z_d$

$m^2_{Z_d} \ll D^2$ (with $D^2 \equiv m^2_H - m^2_Z$)

$$\Gamma(H \to Z Z_d) \simeq \frac{D^4}{16\pi m_H^3 m_Z^2} \left(\mathcal{C}^{\rm SM}_{HZZ}\right)^2 \left[\varepsilon_Z^2 \frac{D^2}{4m^2_{Z_d}} + 3\varepsilon_Z \kappa_Z + \left(\kappa_Z^2 + \tilde{\kappa}_Z^2\right) \frac{D^2}{2m_Z^2}\right]$$

$\mathcal{C}^{\rm SM}_{HZZ} \equiv g m_Z / \cos\theta_W$ (SM HZZ coupling)

- $H \to Z_d Z_d$

$m^2_{Z_d} \ll m^2_H$

(Extra factor of 1/2 in operator definition to cancel factor of 2 from Feynman rules)

$$\Gamma(H \to Z_d Z_d) \simeq \frac{m_H}{32\pi} \left(\mathcal{C}^{\rm SM}_{HZZ}\right)^2 \left[\varepsilon_Z^4 \frac{m_H^2}{4m^4_{Z_d}} + 3\varepsilon_Z^2 \kappa_{Z_d} \frac{1}{m_Z^2} + \left(\kappa_{Z_d}^2 + \tilde{\kappa}_{Z_d}^2\right) \frac{m_H^2}{2m_Z^4}\right].$$

- $H \to \gamma Z_d$

$m^2_{Z_d} \ll m^2_H$

$$\Gamma(H \to \gamma Z_d) \simeq \frac{1}{32\pi} \left(\mathcal{C}^{\rm SM}_{HZZ}\right)^2 \frac{m_H^3}{m_Z^4} \left(\kappa_\gamma^2 + \tilde{\kappa}_\gamma^2\right)$$

- Class (B) operators (dim-5) from vector-like lepton loops
- Mediate kinetic mixing.
- If $m_{Z_d} \sim 20 - 50$ MeV, Z_d could account for $g_\mu - 2$ with $g_d \approx e$.
- These vector-like leptons can enhance Higgs diphoton rate.
- $R_{\gamma\gamma} \sim 1.5 \rightarrow 10\,\mathrm{Br}(H \rightarrow ZZ_d) \approx 2\,\mathrm{Br}(H \rightarrow Z_d Z_d) \approx \mathrm{Br}(H \rightarrow \gamma Z_d) \approx 0.1\,\mathrm{Br}(H \rightarrow \gamma\gamma)$

HD, Lee, Marciano, arXiv:1208.2973 [hep-ph]

- W loops do not contribute to $O_{B,X}$ and $\tilde{O}_{B,X}$, but dominate SM $H \rightarrow \gamma\gamma$, $Z\gamma$

$\Rightarrow H \rightarrow XZ_d$ relatively suppressed

- Z_d could mimic promptly converted γ, but may be distinguished by $m_{Z_d} \neq 0$, vertex near beam.

- p_T cuts eliminate more signal from class (B) processes than class (A) processes.
- The implemented cuts and triggers decrease signals from (A) by $\sim 50\%$ and (B) by $\sim 65\%$.
- Our results can be easily rescaled to account for different values of Z_d leptonic branching fractions.

Concluding Remarks

- Dark matter requires physics beyond SM.
- The "dark sector" may have its own forces.
  - Hints from astrophysical observations
  - General considerations
  - May explain other hints, *e.g.* $g_\mu - 2$ with $m_{Z_d} \lesssim 100$ MeV.
- We considered Z_d, a "dark Z" from a $U(1)_d$, $m_{Z_d} = 5 - 10$ GeV.
  - Z_d coupled to SM indirectly: via mixing or loops.
  - Mass-mixing with Z: "dark" Z, new source of parity violation.
  - Kinetic mixing with hypercharge: "dark" photon.
- Possible dark sector signals at LHC in $H \to X Z_d$, with $X = Z, \gamma, Z_d$.
  - (A) dim-3 (mixing) or (B) dim-5 (loop) operators.
  - Classes (A) and (B) dominated by longitudinal and transverse Z_d, respectively.
- We focused on $H \to Z Z_d \to 4\ell$ through mixing
  - 14 TeV LHC reach with few $\times$ 100 fb^{-1} complements low energy searches with $m_{Z_d} \ll 5$ GeV.
  - Lepton angular distributions as a diagnostic of underlying physics: (A) or (B) operators.