# Higgs and New Physics

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Based on:

H.D., I. Lewis, and E. Pontón, arXiv:1211.3449 [hep-ph]

H.D., H.-S. Lee, and W. Marciano, PRD 86, (2012), [arXiv:1208.2973 [hep-ph]]

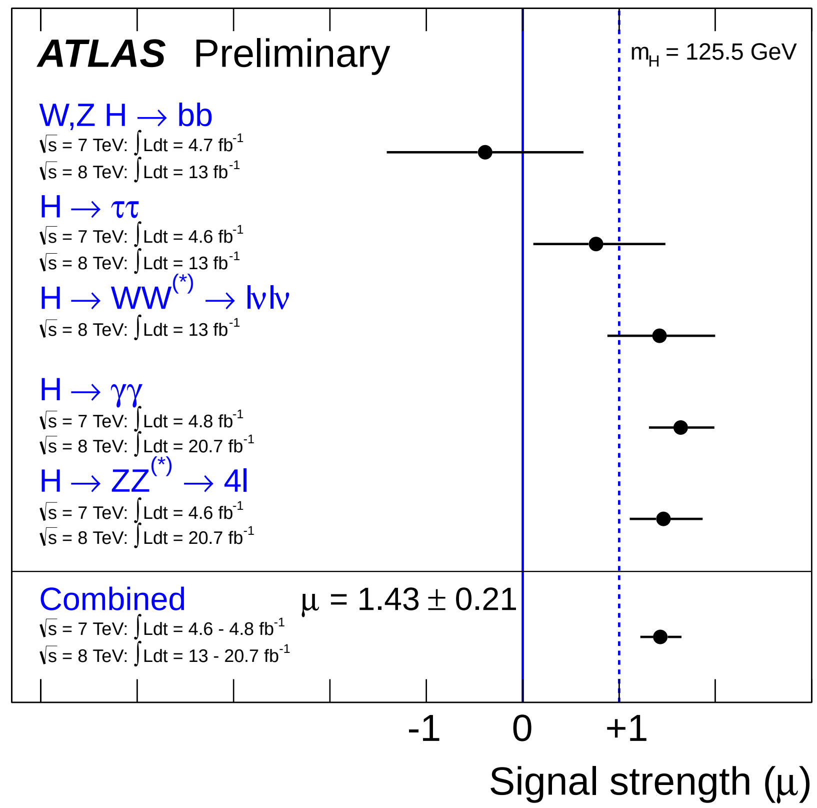
H.D., H.-S. Lee, I. Lewis, and W. Marciano, work in progress

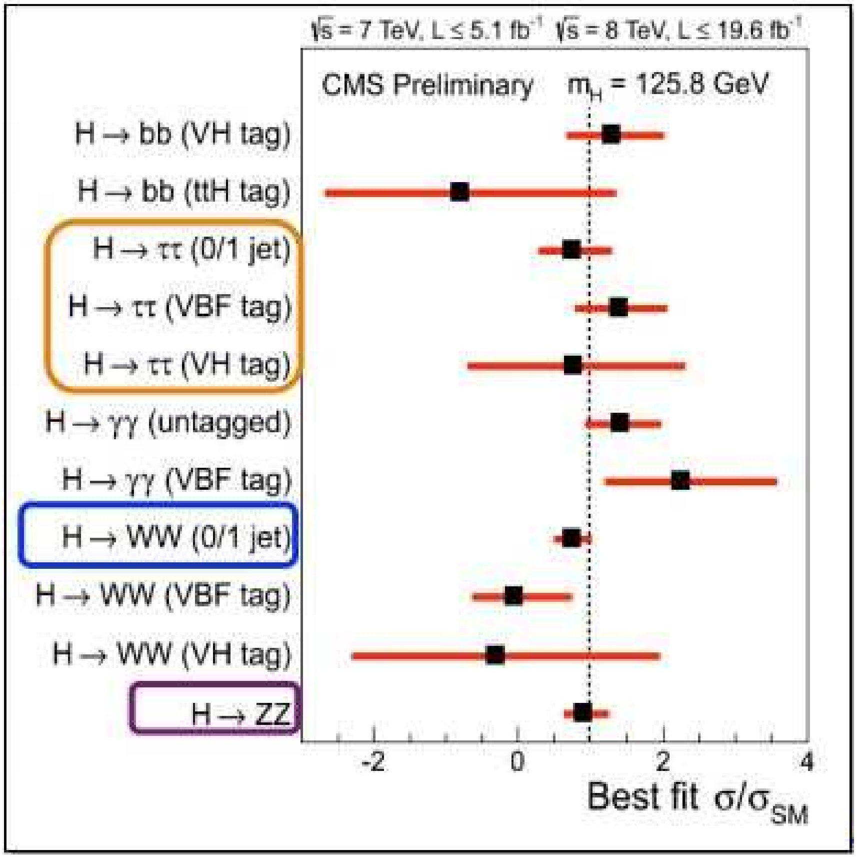
2013 Aspen Winter Conference

- Electroweak Symmetry Breaking (EWSB): A key question.

- The Standard Model (SM) Higgs mechanism, may be the answer:
- Consistency with precision measurements, simplicity,. . .

★ The state discovered in 2012 quite like the SM Higgs!





- Hints of a deviation? More statistics needed for a definitive answer.

## In this talk:

- Assume $H \to \gamma\gamma$ excess $\Rightarrow$ New fermions, $\mathcal{O}(1)$ coupling to Higgs.

- Question: *Can the new physics address other open questions?*

*Dark matter, baryon asymmetry, . . .*

- We focus on EW phase transition (EWPhT).

- EW baryogenesis: requires strongly 1$^{\text{st}}$ order EWPhT (SM: $m_H \lesssim 50$ GeV).

- New fermion interactions with Higgs can alter its potential.

See also M. S. Carena, A. Megevand, M. Quirós and C. E. M. Wagner, hep-ph/0410352 for a thermodynamic mechanism based on fermions.

- Connection to "dark sector" and $(g-2)_\mu$ deviation ($3.6\sigma$)

$\Rightarrow$ Potentially observable new Higgs decays into "dark" vectors:
$\boldsymbol{H \to X\, Z_d}$ with $\boldsymbol{X = \gamma, Z, Z_d}$.

# A Simple Extension for Enhanced $H \to \gamma\gamma$

- Weak scale vector-like (non-chiral) fermions*.
  - Could be naturally near the weak scale.

*See, for example: S. Dawson and E. Furlan, arXiv:1205.4733 [hep-ph]; M. Carena, I. Low and C. E. M. Wagner, arXiv:1206.1082 [hep-ph]; N. Bonne and G. Moreau, arXiv:1206.3360 [hep-ph]; H. An, T. Liu and L. -T. Wang, arXiv:1207.2473 [hep-ph]; A. Joglekar, P. Schwaller and C. E. M. Wagner, arXiv:1207.4235 [hep-ph]; N. Arkani-Hamed, K. Blum, R. T. D'Agnolo and J. Fan, arXiv:1207.4482 [hep-ph] L. G. Almeida, E. Bertuzzo, P. A. N. Machado and R. Z. Funchal, arXiv:1207.5254 [hep-ph]; J. Kearney, A. Pierce and N. Weiner, arXiv:1207.7062 [hep-ph]; H. D., H. -S. Lee and W. J. Marciano, arXiv:1208.2973 [hep-ph]; M. B. Voloshin, arXiv:1208.4303 [hep-ph]; W. -Z. Feng and P. Nath, arXiv:1303.0289 [hep-ph]; A. Joglekar, P. Schwaller and C. E. M. Wagner, arXiv:1303.2969 [hep-ph]

- Unchanged $ggH$ coupling $\Rightarrow$ vector-like **leptons** (no color charge).

- Minimal addition: one vector-like $SU(2)$ singlet $\chi$ at weak scale.

# Effective Theory

H.D., Lewis, Pontón, arXiv:1211.3449 [hep-ph]

$$\Delta\mathcal{L} = -m_\chi\,\chi\chi^c + 2G_m H^\dagger H\,\chi\chi^c + \text{h.c.} \qquad ([G_m] = -1)$$

- Charged state $L_1$ after EWSB; $m_1 \gtrsim 100$ GeV (LEP2).

$$\boxed{m_1(\phi) = m_\chi - G_m\phi^2}$$

$\langle H\rangle = \phi/\sqrt{2}$ and $\phi = v = 246$ GeV at $T = 0$

- Br$(H \to \gamma\gamma)$ enhanced if $G_m > 0$ so that $m_1 < m_\chi$:

$$R_{\gamma\gamma} \equiv \frac{\text{Br}(H \to \gamma\gamma)}{\text{Br}(H \to \gamma\gamma)_{\text{SM}}} \simeq \left| 1 - \frac{F_{1/2}(\tau_1)\,Q_1^2}{F_{\text{SM}}} \frac{\partial \ln m_1(v)}{\partial \ln v}\right|^2$$

$F_{\text{SM}} \simeq -6.49$, $\tau_1 = 4m_1^2/m_H^2$, and $F_{1/2}(\tau)$ the familiar loop function.

- $H\bar{L}_1 L_1$ Yukawa coupling: $\boxed{y_{\text{eff}} = -2G_m v}$

- A strongly first-order phase transition implies $y_{\text{eff}} \sim 1$.

- 1-loop potential in the EFT contains $\phi^6$ and $\phi^8$ divergences:

$$V_0(\phi) = -\tfrac{1}{2}\mu^2\,\phi^2 + \tfrac{1}{4}\lambda\,\phi^4 + \tfrac{1}{6}\bar{\gamma}\,\phi^6 + \tfrac{1}{8}\bar{\delta}\,\phi^8 \quad \text{(tree-level)}$$

- High-$T$ expansion, ignoring weak gauge bosons:

$$V(\phi) = \frac{1}{2}\mu_{\text{eff}}^2\phi^2 + \frac{1}{4}\lambda_{\text{eff}}\phi^4 + \frac{1}{6}\gamma_{\text{eff}}\phi^6 + \ldots$$

$$\begin{aligned} \lambda_{\text{eff}} &= \frac{m_H^2}{2v^2} + \beta - \frac{3y_t^4}{16\pi^2}\ln\left(\frac{2A_F T^2}{y_t^2 v^2}\right) + \frac{1}{3}G_m^2 T^2 - \frac{3G_m^2 m_\chi^2}{2\pi^2}\ln\left(\frac{A_F T^2}{\mu^2}\right) \\ \gamma_{\text{eff}} &= \bar{\gamma} + \frac{3G_m^3 m_\chi}{2\pi^2}\ln\left(\frac{A_F T^2}{\mu^2}\right) \end{aligned}$$

  - $\beta$ set by $T = 0$ renormalization conditions and $A_F = \pi^2 e^{-2\gamma_E}$ ; $\gamma_E \simeq 0.577$.

**Key feature: $\lambda_{\text{eff}}$ can become negative at finite temperature.**

- The mechanism mainly based on *fermionic*, $t$ and $\chi$, contributions.
  - Strongly first order EWPhT even without $W$ and $Z$ (cubic term not crucial).

# A Concrete UV Model

- Vector-like: $(\boldsymbol{\psi}, \boldsymbol{\psi^c}) \sim (\mathbf{1}, \mathbf{2})_{\pm\frac{1}{2}}$ , $\quad (\boldsymbol{\chi}, \boldsymbol{\chi^c}) \sim (\mathbf{1}, \mathbf{1})_{\mp 1}$

See, *e.g.*, Arkani-Hamed, Blum, D'Agnolo, Fan, 2012.

$$-\mathcal{L}_m = m_\psi \psi \psi^c + m_\chi \chi \chi^c + y H \psi \chi + y_c H^\dagger \psi^c \chi^c + \text{h.c.}$$

- We will set $y = y_c$ for simplicity.

- Two $|Q| = 1$ mass eigenstates $L_1$ and $L_2$

$$\boxed{m_{1,2}^2(\phi) = \frac{1}{2}\left(m_\psi^2 + m_\chi^2\right) + \frac{1}{2} y^2 \phi^2 \mp \frac{1}{2}(m_\psi + m_\chi)\sqrt{(m_\psi - m_\chi)^2 + 2y^2\phi^2}}$$

Also a neutral state $N$ with mass $m_N = m_\psi$.

- We consider $m_\psi \gg yv$:

Integrate out $L_2$ with $m_2 \approx m_\psi$ → EFT with only $L_1$ at weak scale.

# EFT Derived from the UV Model

- Match unknown EFT coefficients to the UV model at $m_\psi \gg 100$ GeV.

- Dim-5 operator coefficient: $G_m = \frac{Z_m y^2}{2(m_\psi - m_\chi)}$

- $\bar{\gamma} = \bar{\gamma}_{\text{th}} + \bar{\gamma}_{\text{RG}}$ and $\bar{\delta} = \bar{\delta}_{\text{th}} + \bar{\delta}_{\text{RG}}$:
  - Threshold contributions at $\mu = m_\psi$

$$\bar{\gamma}_{\text{th}} = \frac{Z_\gamma y^6}{16\pi^2} \frac{m_\psi(m_\psi^2 + 7m_\chi m_\psi - 2m_\chi^2)}{(m_\psi - m_\chi)^5} \quad ; \quad \bar{\delta}_{\text{th}} = -\frac{Z_\delta y^8}{48\pi^2} \frac{7m_\psi^3 + 27m_\chi m_\psi^2 - 4m_\chi^3}{(m_\psi - m_\chi)^7}$$

  - Running

$$\bar{\gamma}_{\text{RG}} \approx -\frac{3G_m^3 m_\chi}{2\pi^2} \ln\left(\frac{m_\psi^2}{\mu^2}\right) \quad ; \quad \bar{\delta}_{\text{RG}} \approx \frac{G_m^4}{2\pi^2} \ln\left(\frac{m_\psi^2}{\mu^2}\right)$$

- $Z_m, Z_\gamma, Z_\delta$ parameterize higher order effects at matching scale $m_\psi$.

- Full potential $V$ is $\mu$ (renormalization scale) independent.

# Results

- **Benchmark UV model:** $\boldsymbol{m_\chi = 300\ \mathrm{GeV},\ m_\psi = 4\ \mathrm{TeV},\ y = 4.}$

- Using the matched EFT with $Z_m = Z_\gamma = Z_\delta = 1$ (lowest order):

- $m_1(v) \approx 170$ GeV; $\phi_c \approx 140$ GeV; $T_c \approx 150$ GeV $\rightarrow$ $\phi_c/T_c \approx 0.93$

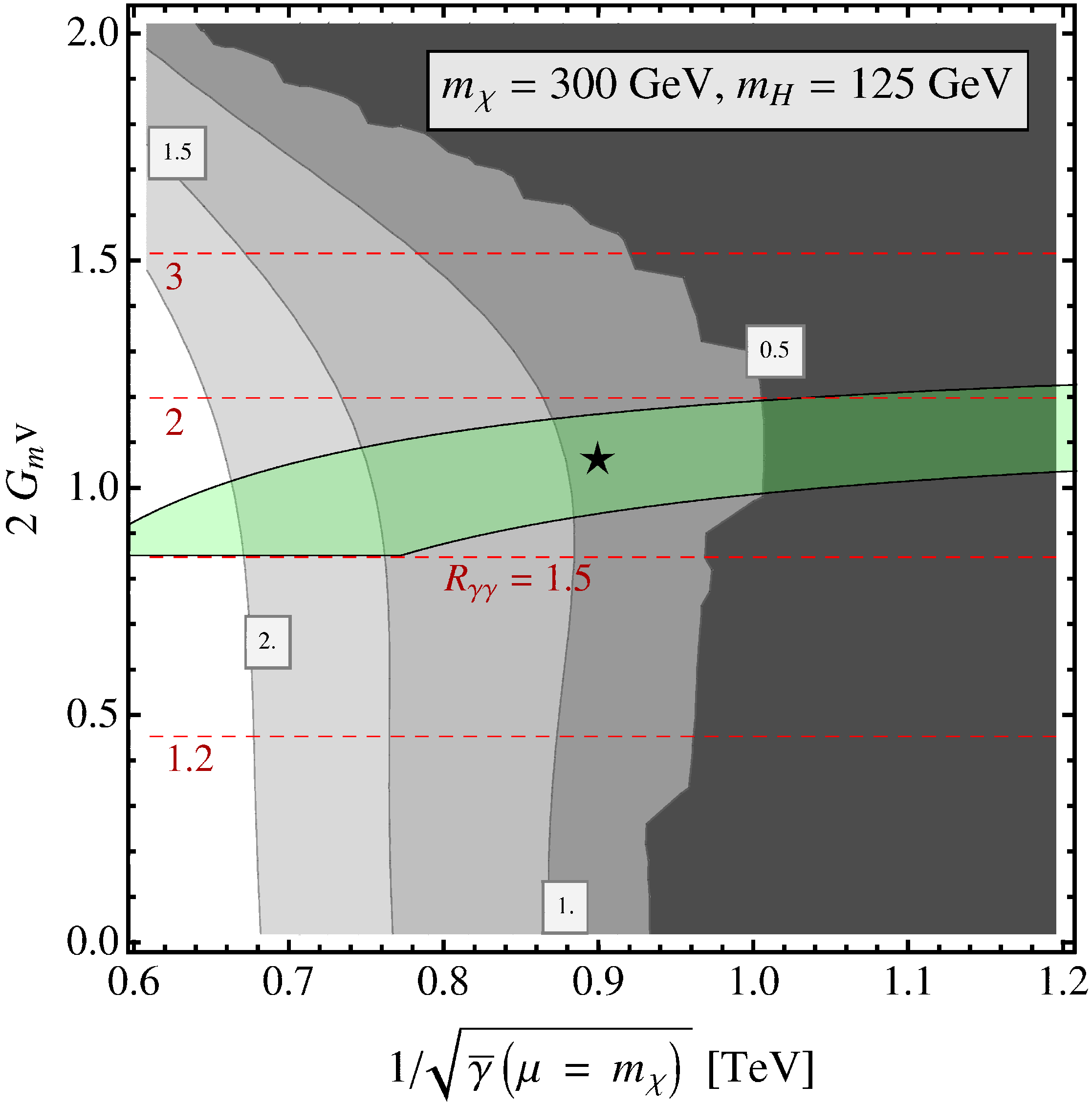
- Applying Coleman-Weinberg potential to the full UV model:

- $\phi_c \approx 128$ GeV; $T_c \approx 146$ GeV $\rightarrow$ $\phi_c/T_c \approx 0.88$

- UV model implies instability above $\sim 3.5$ TeV (just below $\sim m_\psi$)

- EFT not suitable at $\phi \gg 100$ GeV.

- $\phi_c/T_c \gtrsim 1$ and $m_1 \gtrsim 100$ GeV for $y \approx 2.5$, and (same sign) $m_\chi, m_\psi \sim$ few 100 GeV. However, this regime of parameters yields $R_{\gamma\gamma} < 1$.



- Higher loop effects (large Yukawa coupling in the UV model): $Z_m$ (vertical) and $Z_\gamma$ (horizontal) varied within 20% around benchmark point.
- $G_m v \ll 1 \to L_1$ decoupled, EFT with higher-dimension terms ($\phi^6, \phi^8$). Negative contributions to quartic dominated by $\bar{\gamma} > 0$.

Grojean, Servant, Wells, 2004

## Collider Phenomenology

- Higgs triple coupling $V'''(v) = 3m_H^2/v + 8\bar{\gamma}v^3$ (ignoring $\phi^8$ term).

- $1^{\text{st}}$ order EWPhT for $\bar{\gamma} \sim +(1\ \text{TeV})^{-2}$: $H^3$ coupling *enhanced*.

- However, $gg \to HH$ rate at LHC will be typically *reduced!*
  - Destructive interference: dominant top quark box and off-shell $s$-channel Higgs.
  - Modest increase in triple coupling suppresses the Higgs-pair production rate.

- $(600\ \text{GeV})^{-2} \gtrsim \bar{\gamma} \gtrsim (900\ \text{GeV})^{-2}$:

- Higgs pair production rate $40 - 60\%$ of the SM prediction.

- Several $\text{ab}^{-1}$ at 14 TeV LHC to exclude $V'''(v) = 0$ at 90% CL.

Baur, Plehn, Rainwater, 2003; Jakobs, 2009

- With 2 $\text{ab}^{-1}$, 500 GeV (1 TeV) ILC can measure Higgs self-coupling to $\sim 44\%$ ($\sim 17\%$). Baer et al., ILC DBD

# Connection with the “Dark Sector”

- $L_1$ decay possible with neutral $n, n^c$.

- After EWSB, $H\psi n$ couplings yield $n_1$.

- For $m_{n_1} < m_1$ we have $L_1 \to n_1 W^{(*)}$, can be prompt.

Arkani-Hamed, Blum, D’Agnolo, Fan, 2012.

- If all new fermions $\mathbb{Z}_2$ odd, $n_1$ stable, DM candidate.

Jogelkar, Schwaller, Wagner, 2012

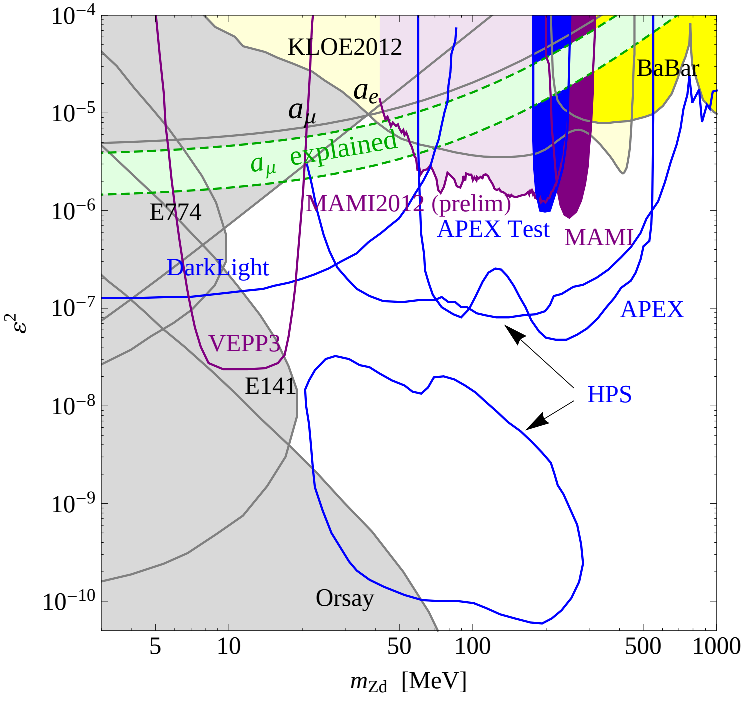
- Dark sector interactions mediated by a light vector boson $Z_d$.

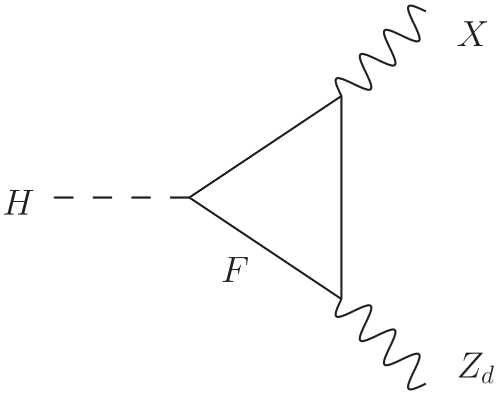
Motivated by astrophysical observations, $(g-2)_\mu$, . . .

- Consider $Z_d$ associated with $U(1)_d$, coupled to SM indirectly.

- Kinetic Mixing: loops of $\chi, \psi, \ldots$, charged under $U(1)_d$ and $U(1)_Y$.
  - Suppressed $Z_d$ coupling to EM charge: $\varepsilon \sim e g_d/(16\pi^2)$.
  - $(g-2)_\mu$: $m_{Z_d} \sim 20 - 50$ MeV and $g_d \sim e$ (such that $\varepsilon \sim 10^{-3}$).
  - $R_{\gamma\gamma} \sim 1.5 - 2$ from new fermion loops and $g_d \sim e$ suggest rates for loop-induced $H \to X\, Z_d$, with $X = \gamma, Z, Z_d$, not far below $H \to \gamma\gamma$.
  - $Z_d$ mostly transverse ($Z_d \to e^+e^-$ could mimic prompt $\gamma$ conversion).

HD, Lee, Marciano, 2012 [arXiv:1208.2973 [hep-ph]]





Plot courtesy of H.-S. Lee

- $Z$-$Z_d$ Mass Mixing (via a second Higgs doublet with $Q_d \neq 0$).
  - $Z_d$ coupling to neutral current parameterized by $\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta$.
  - Possibility of parity violation via $Z_d$.
  - Potential effects in flavor physics.
  - Can lead to $H \to ZZ_d$ with $Z_d$ dominantly longitudinal.

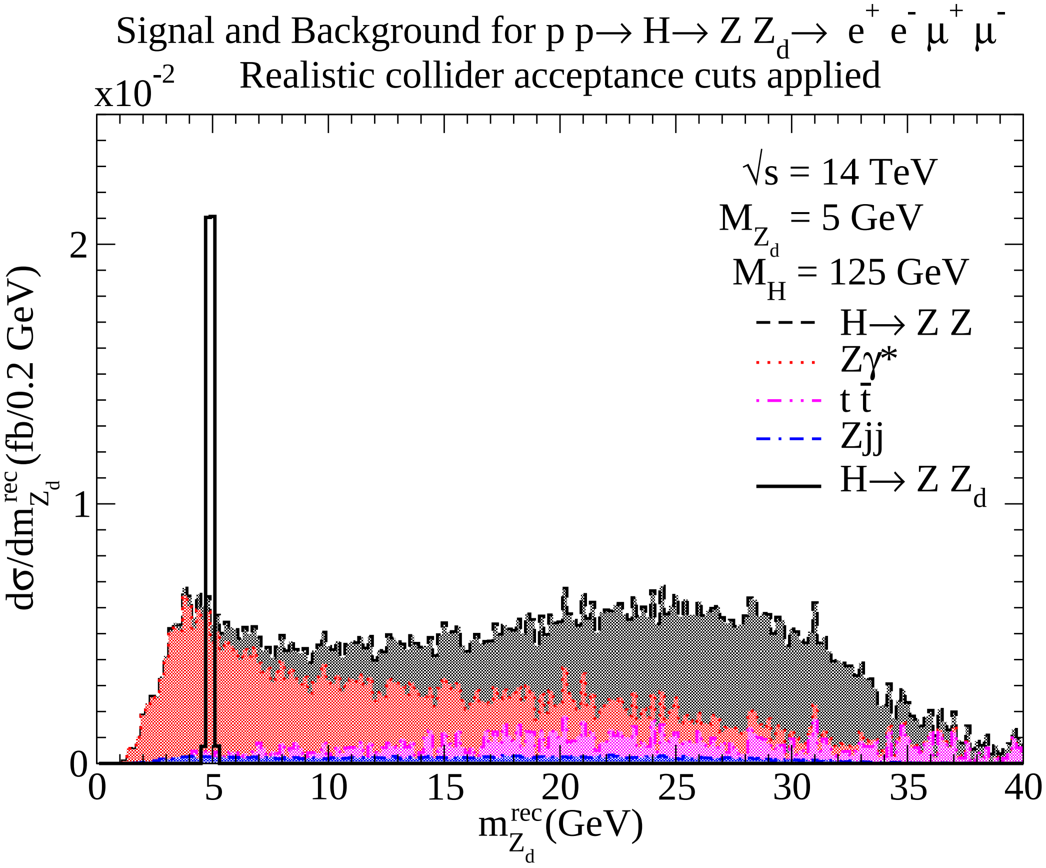
H.D., Lee, Marciano, arXiv:1203.2947 [hep-ph]; arXiv:1205.2709 [hep-ph]

Preliminary

H.D., H.-S. Lee, I. Lewis, W. Marciano,

work in progress

- Mass mixing with $\delta^2 = 10^{-5}$.
- $\text{Br}(Z_d \to \mu^+\mu^-) = \text{Br}(Z_d \to e^+e^-) = 0.5$
- Observation in run II of LHC with few hundred $\text{fb}^{-1}$ possible.



# Summary and Concluding Remarks

- The Higgs era has begun!
- Data still evolving, but possible hints of deviations from SM in $H \to \gamma\gamma$.
- EFT with a single weak scale vector-like "lepton" can lead to both enhanced $H \to \gamma\gamma$ and a strongly first order EWPhT (important for EW baryogenesis):
  - Here fermions, not bosons, crucial for enhancing EWPhT.
  - Predicted Higgs self-coupling modification may be observable (lepton collider).
- A UV model with a second fermion at $\sim 4$ TeV can lead to the EFT:
  - Reminiscent of warped hierarchy models with light and heavy KK fermions.
- Vector leptons with additional "dark interactions":
  - Possible connection to DM, $(g-2)_\mu$.
  - $\boldsymbol{H \to Z Z_d, \gamma Z_d, Z_d Z_d}$ could be within reach (2nd LHC run).
  - Mediated by mixing/loops: longitudinal/transverse $Z_d$ (diagnostic).