The phenomenology of the $U(1)$ Phantom Sector of the Standard Model

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JHEP **0811** (2008) 036 [arXiv:0807.4666 [hep-ph]].

Outline

1. $U(1)$ Phantom Model

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2. The LEP search

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2. The LEP search
3. The LHC search

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Motivation

- Minimal Lepton Number Conserving Phantom Sector

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- "Phantom" $\longrightarrow$ singlet under the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$

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- Minimal Lepton Number Conserving Phantom Sector
- "Phantom" $\longrightarrow$ singlet under the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Simple model leading to interesting phenomenology
  - Small neutrino masses
  - Leptogenesis
  - Invisible Higgs boson decays

The "Phantom" Sector

- Just 2 openings in the SM for renormalisable operators coupling $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge singlet to SM fields [1]

- Higgs mass term: $H^\dagger H$
- Lepton-Higgs Yukawa interaction: $\bar{L}\tilde{H}$

- What would happen if we filled in the gaps?
- But, no evidence for $B - L$ violation yet, so could try to build a $B - L$ conserving model
- Will try to be "natural" in the 't Hooft and the aesthetic sense - couplings either $\mathcal{O}(1)$ or strictly forbidden

[1] B. Patt and F. Wilczek, hep-ph/0605188

- Augment the SM with two $SU(3)_c \times SU(2)_L \times U(1)_Y$ singlet fields
  - a complex scalar Φ
  - a Weyl fermion s_R

$$-\mathcal{L}_{link} = \left(h_\nu \bar{l}_L \cdot \tilde{H} s_R + \mathrm{H.c.} \right) - \eta H^\dagger H \Phi^* \Phi$$

$\tilde{H} = i\sigma_2 H^*$, h_ν and η will be $\mathcal{O}(1)$, s_R carries lepton number $L = 1$.

- But, this model is no good – neutrinos would have large, electroweak scale masses

- Solution: Postulate the existence of a purely gauge singlet sector; add ν_R and s_L [2]

$$-\mathcal{L}_p = h_p \Phi \bar{s}_L \nu_R + M \bar{s}_L s_R + \mathrm{H.c.}$$

- Forbid other terms by imposing a phantom sector global $U(1)_D$ symmetry, such that

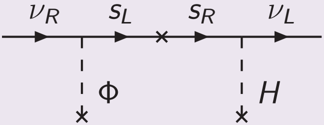
$$\nu_R \rightarrow e^{i\alpha}\nu_R \quad , \quad \Phi \rightarrow e^{-i\alpha}\Phi$$

  transform non-trivially
- If we require small Dirac neutrino masses this is the simplest choice for the phantom sector

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{link} + \mathcal{L}_p$$

[2] D. G. Cerdeno, A. Dedes and T. E. J. Underwood, JHEP **0609** (2006) 067 [arXiv:hep-ph/0607157]; M. Roncadelli and D. Wyler, PLB133(1983)325

Small effective Dirac neutrino masses –Dirac See-Saw



- Low energies:

$$\mathcal{L}_\nu = \frac{(\bar{L} \cdot \tilde{H})(\Phi \cdot \nu_R)}{\Lambda}$$

Essentially the Froggatt-Nielsen mechanism! [3]

[3] C. D. Froggatt and H. B. Nielsen, NPB147(1979)277

The Potential

$$V(H,\Phi) = \mu_H^2 H^* H + \mu_\Phi \Phi^* \Phi + \lambda_H (H^* H)^2 + \lambda_\Phi (\Phi^* \Phi)^2 - \eta H^* H \Phi^* \Phi$$

- After spontateous symmetry breaking of $U(1)_D$, the field Φ develops a vev, which through the link η-term, forces the Higgs field H to develop a vev, triggering $SU(2)_L \times U(1)_Y$ symmetry breaking.
- Expanding around the minima

$$H = v + \frac{1}{\sqrt{2}}(h + iG)\,, \quad \Phi = \sigma + \frac{1}{\sqrt{2}}(\phi + iJ)$$

- We have
  - the Goldstone bosons: G (eaten as usual) and J
  - h and ϕ mix (due to the η term) and become two massive Higgs bosons H_1 and H_2

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = O \begin{pmatrix} h \\ \phi \end{pmatrix} \text{ with } O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \text{ and the mixing angle}$$

$$\tan 2\theta = \frac{\eta v \sigma}{\lambda_\Phi \sigma^2 - \lambda_H v^2}$$

- The limits $v \ll \sigma$ and $\sigma \ll v$ both lead to the SM with an isolated hidden sector
- These limits need an unnaturally small η, and would present problems with baryogenesis and small neutrino masses.
- A 'natural' choice of parameters (with e.g. $\eta \sim 1$) would lead to

$$\tan\theta \sim 1 \quad , \quad \tan\beta \equiv v/\sigma \sim 1$$

Stability and Triviality Bounds

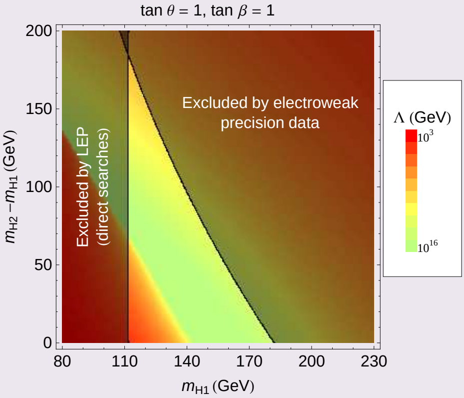
- Triviality: Parameters λ_H, λ_Φ and η are required to be perturbative up to a certain scale $\Lambda_T \gg v$.
- Vacuum Stability: Potential is bound from below up to a scale $\Lambda_V \gg v$.
- After solving 1–loop RGEs, we can plot the maximum scale up to which our effective theory satisfies the above constraints.

$$\Lambda_T \, , \Lambda_V \lesssim 10^{16}\mathrm{GeV}$$

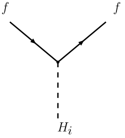
$$4\lambda_H(Q)\lambda_\Phi(Q) > \eta(Q)^2$$

for all $Q \lesssim \Lambda_V$.

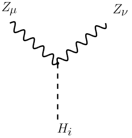
Stability and Triviality Bounds



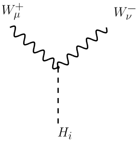
Feynman Rules: Trilinear Couplings



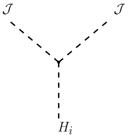
: $-i\frac{m_f}{v}\; O_{i1}$



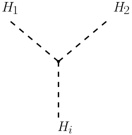
: $i\frac{g_2 M_Z}{\cos\theta_W}\; O_{i1}\, g_{\mu\nu}$



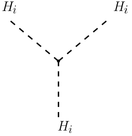
: $ig_2 M_W\; O_{i1}\, g_{\mu\nu}$



: $-i\frac{m_{H_i}^2}{v}\; \tan\beta\; O_{i2}$



: $\frac{i}{v}\left(m_{H_1}^2 + m_{H_2}^2 + m_{H_i}^2\right) \cdot O_{i1} O_{i2}\left(O_{1i} + O_{2i}\; \tan\beta\right)$



: $-3i\frac{m_{H_i}^2}{v}\; \left(O_{i1}^3 + O_{i2}^3\; \tan\beta\right)$

LEP searches

Look at the number of visible events ($H \to YY$) compared to the number expected in the SM

$$\mathcal{R}_i^2 \equiv \frac{\sigma(e^+e^- \to H_i\, X)\,\mathrm{Br}(H_i \to YY)}{\sigma(e^+e^- \to h\, X)\,\mathrm{Br}(h \to YY)}$$

Define a similiar parameter for invisible events

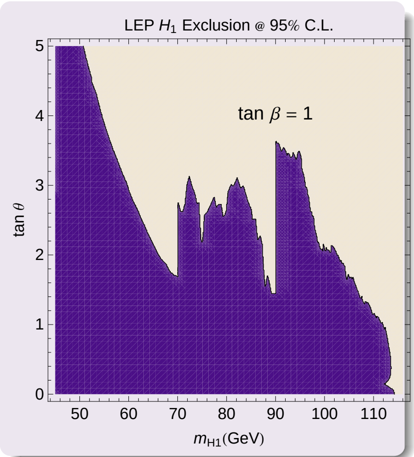
$$\mathcal{T}_i^2 \equiv \frac{\sigma(e^+e^- \to H_i\, X)}{\sigma(e^+e^- \to h\, X)}\,\mathrm{Br}(H_i \to \mathcal{J}\mathcal{J})$$

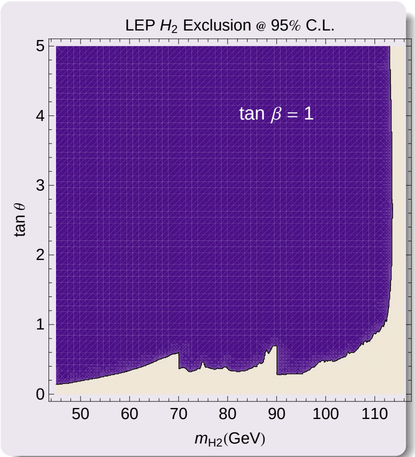
$$\mathcal{T}_1^2 = \cos^2\theta - \mathcal{R}_1^2 \,,$$
$$\mathcal{T}_2^2 = \sin^2\theta - \mathcal{R}_2^2 \,.$$

In the LEP search region, $m_{H_2} < m_{H_1} \lesssim 115$ GeV

$$\mathcal{R}_1^2 \simeq \left[(1+\tan^2\theta)\left(1+\frac{1}{12}\frac{m_{H_1}^2}{m_b^2}\tan^2\theta\tan^2\beta\right)\right]^{-1} ,$$

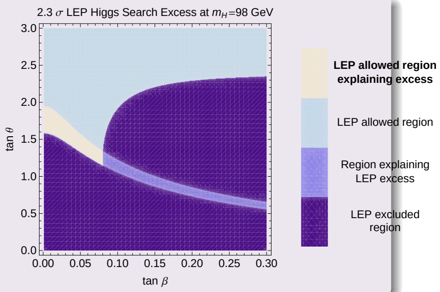
$$\mathcal{R}_2^2 \simeq \left[(1+\cot^2\theta)\left(1+\frac{1}{12}\frac{m_{H_2}^2}{m_b^2}\cot^2\theta\tan^2\beta\right)\right]^{-1} .$$



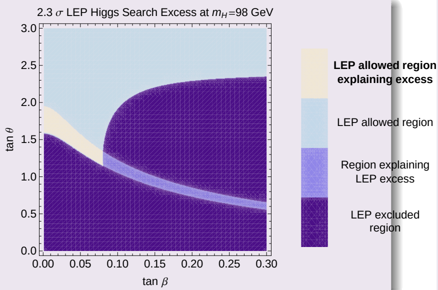


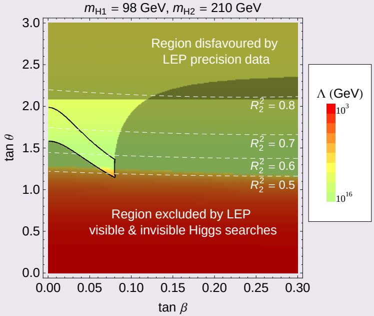
LEP could have missed a partially invisible Higgs boson

2.3σ LEP Higgs search excess



2.3σ LEP Higgs search excess





Expectation for the LHC

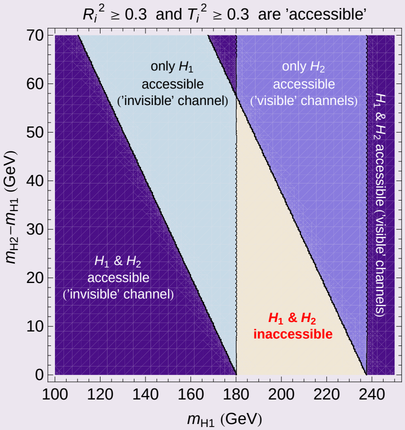
Visible events

$$\mathcal{R}_i^2 \equiv \frac{\sigma(pp \to H_i\, X)\, \mathrm{Br}(H_i \to YY)}{\sigma(pp \to h\, X)\, \mathrm{Br}(h \to YY)}$$

Invisible events

$$\mathcal{T}_i^2 \equiv \frac{\sigma(pp \to H_i\, X)}{\sigma(pp \to h\, X)}\, \mathrm{Br}(H_i \to \mathcal{J}\mathcal{J})$$

Expectations for the LHC



- Potential nightmare scenario
- No-lose theorem: If experiments can discover a Higgs boson over the whole range of $\mathcal{R}_i^2$ down to 0.25 or over the whole range of $\mathcal{T}_i^2$ down to 0.25 then at least one Higgs boson should be found.

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Benchmark Scenarios

$$\text{B1}: \quad m_{H_1} = 68 \text{ GeV} \quad , \quad m_{H_2} = 114 \text{ GeV} \quad ,$$

$$\tan\theta = 2 \quad , \quad \tan\beta = 1 \, .$$

$\tan\theta = 1$ $\tan\beta = 1$

Benchmark	m_{H_1}(GeV)	m_{H_2}(GeV)
B2	112	130
B3	140	165
B4	160	190
B5	185	190

The implementation of the $U(1)$ Phantom Model into SHERPA

- Both trilinear and quadrilinear couplings have been implemented into the MC SHERPA [4]
- Model parameters: $\tan\theta$, $\tan\beta$, m_{H_1}, and m_{H_2}
- Higgs effective couplings (e.g. $H_i gg$)
- 2 body decays of the Higgs bosons H_i are generated automatically

[4] T. Gleisberg, S. Hoche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert and J. Winter, JHEP **0902** (2009) 007 [arXiv:0811.4622 [hep-ph]]

ZH production

$pp \longrightarrow \ell^+\ell^- + \not{E}_T$

- Signal: $pp \rightarrow ZH \rightarrow \ell^+\ell^-\mathcal{J}\mathcal{J}$
- Backgounds: ZZ, WW, WZ, and Z

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ZH production

Selection cuts

- one lepton pair of the same kind with opposite charges, where each lepton individually satifies $p_{T,\ell} > 15\ \mathrm{GeV}$ and $|\eta_\ell| < 2.5$;
- $|M_{\ell\bar{\ell}} - M_Z| \leqslant 10\ \mathrm{GeV}$;
- $\not{E}_T > 100\ \mathrm{GeV}$;
- a veto on jets with $p_T > 20\ \mathrm{GeV}$, $|\eta| < 4.9$;
- a veto on b–jets with $p_T > 15\ \mathrm{GeV}$, $|\eta| < 4.9$;
- $m_T > 200\ \mathrm{GeV}$, where $m_T = \sqrt{2 p_T^{\ell\bar{\ell}} \not{p}_T (1 - \cos\phi)}$;
- $\Delta R_{\ell\bar{\ell}} < 1.75$;
- $p_T(\ell\bar{\ell}\not{E}_T) < 60\ \mathrm{GeV}$

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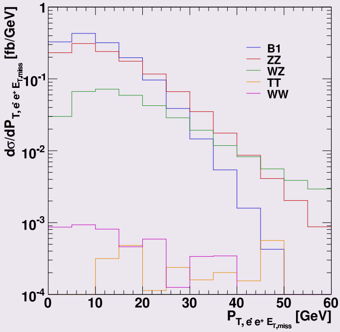
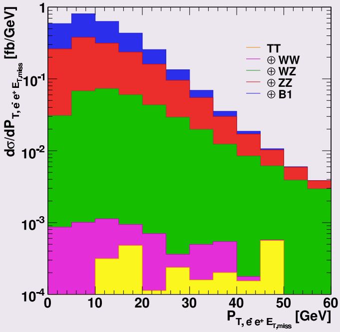
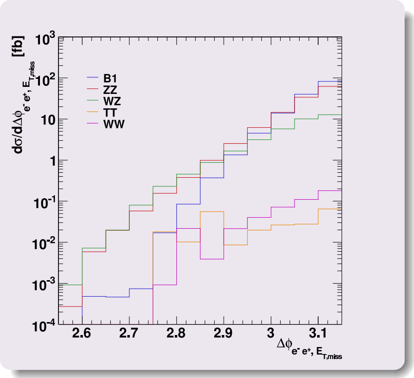
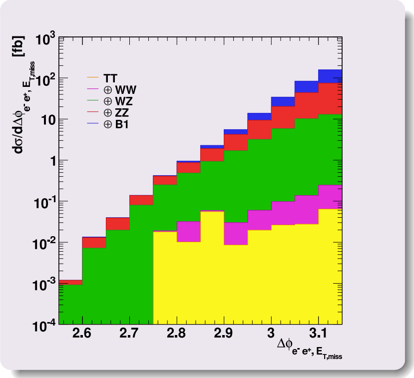
ZH production





ZH production





ZH production

Signal and Background Cross sections

	ZZ	$W^{\pm}Z$	W^+W^-	$t\bar{t}$	Z
$\sigma_{\text{tot}}^{\text{gen}}$ [fb]	164	$1.17{\cdot}10^3$	$1.01{\cdot}10^4$	$7.44{\cdot}10^4$	$1.81{\cdot}10^6$
σ_{eff} [fb]	2.02	1.75	$2.25{\cdot}10^{-5}$	$1.15{\cdot}10^{-5}$	-

	B_1	B_2	B_3	B_4	B_5
σ_{tot} [fb]	280	114.6	53.0	29.0	13.6
σ_{eff} [fb]	7.15	5.65	3.68	2.42	1.34

- The most dangerous backgrounds are ZZ and WZ production.
- After cuts, $S/B \approx 1/8$ up to 1

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Vector Boson Fusion

$pp \longrightarrow jj + \not{E}_T$

- Signal: $pp \rightarrow Hjj \rightarrow \mathcal{J}\mathcal{J}jj$
- Backgrounds: Zjj,Wjj,$t\bar{t}$

Vector Boson Fusion

Selection cuts

- Two tagging jets with
  - $p_{T,j} > 40$ GeV, $|\eta_j| < 5$,
  - $|\eta_{j_1} - \eta_{j_2}| > 5$, $\eta_{j_1} \cdot \eta_{j_2} < 0$,
  - $m_{j_1 j_2} > 1700$ GeV ,
  - $\Delta\phi_{j_1 j_2} = |\phi_{j_1} - \phi_{j_2}| < 1$,
- missing transverse momentum, $\not{p}_T > 100$ GeV;
- no identified lepton, i.e. no lepton with $p_T^{e,\mu} > 5\,,6$ GeV in $|\eta_l| < 2.5$,
- a central jet veto, i.e. no jets with $p_T > 20$ GeV, $\min\{\eta_{j_1}, \eta_{j_2}\} < \eta < \max\{\eta_{j_1}, \eta_{j_2}\}$.

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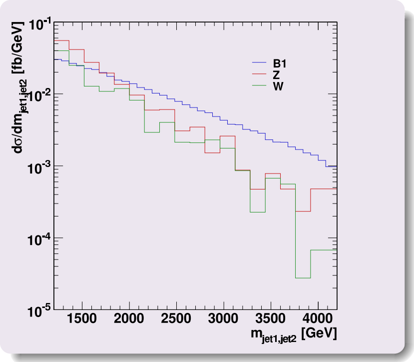
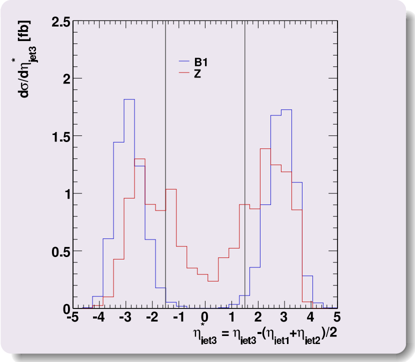
Vector Boson Fusion

Additional Selection cuts

- $|\eta_3^*| = \left|\eta_{j_3} - \frac{1}{2}\left(\eta_{j_1} + \eta_{j_2}\right)\right| > 1.5,$
- $\Delta\phi_{j_1,j_3},\ \Delta\phi_{j_2,j_3}\ < 1.25.$

Vector Boson Fusion





Vector Boson Fusion

Signal and Background Cross sections

	Z+jets (QCD+EW)	W+jets (QCD+EW)	$t\bar{t}$
$\sigma_{\rm tot}^{\rm gen}$ [nb]	9.41	51.8	0.145
$\sigma_{\rm eff}$ [fb]	10.7	7.45	0.0621

	B_1	B_2	B_3	B_4	B_5
$\sigma_{\rm tot}^{\rm gen}$ [pb]	5.46	4.46	2.99	2.06	1.32
$\sigma_{\rm eff}$ [fb]	17.0	17.5	14.4	11.2	7.9

- $S/B \approx 1/3$ up to 1

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Conclusions

- NGBs lead to the dilution and potential invisibility of the expected SM signal.
- LEP excludes the minimal phantom sector case where both Higgs bosons have masses $m_H \lesssim 85$ GeV irrespective of their decay modes.
- Experimentally allowed regions exist where one Higgs boson is much lower than the SM Higgs boson exclusion limit $m_{H_1} = 68$ GeV, and the other just at the limit, $m_{H_2} = 114$ GeV.
- In each of the 5 benchmark scenarios, fairly good S/B ratios are found for the LHC.