# Hidden $U(1)$ at the Electroweak Scale

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# Outline

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# Introduction
## Why consider an extra $U(1)$?

- Many models have an extra $U(1)$

| | |
|---|---|
| Left-Right | Leptophobic $U(1)$ |
| $SO(10)$ GUT | Hadrophobic $U(1)$ |
| Supersting $E_6$ | $3^{\text{rd}}$ generation $U(1)$ |
| Topflavor | ...etc... |

- Common feature: SM fermions couple to the $U(1)$
- LHC can explore an extra $U(1)$ beyond the EW scale

# Introduction

## What are some features of this extra $U(1)$?

- SM particles don't couple to this symmetry (Unlike most extra $U(1)$ symmetries)
- Broken at the EW scale
- Exotic quarks and singlet Higgs
  - Messengers between SM sector and extra $U(1)$ sector

$$\underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{\text{Standard Model Gauge Group}} \times U(1)'$$

# Model
## Particle content

### Fermions

- SM fermions: $q_L^i$, $l_L^i$, $u_R^i$, $d_R^i$, $e_R^i$
- New Weak singlet quarks: $D = D_L + D_R$

### Scalar bosons

- SM EW doublet Higgs: $H$
- New EW singlet Higgs: $S$

### Gauge bosons

- SM gluons and EW bosons: $G_\mu$, $W_\mu$, $B_\mu$
- New gauge boson: $Z'_\mu$

## Quantum numbers

| | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)'$ |
|---|---|---|---|---|
| $b_R$ | 3 | 1 | $-\frac{1}{3}$ | 0 |
| $D_L$, $D_R$ | 3 | 1 | $-\frac{1}{3}$ | $-1$ |
| $S$ | 1 | 1 | 0 | 1 |

- SM particles are neutral under $U(1)'$

- Higgs potential

$$V(H,S) = -\mu_H^2(H^\dagger H) - \mu_S^2(S^\dagger S) + \lambda_H(H^\dagger H)^2 + \lambda_{HS}(H^\dagger H)(S^\dagger S) + \lambda_S(S^\dagger S)^2$$

- Vacuum expectation values and mass matrix

$$S \to \frac{1}{\sqrt{2}}(v_S + S^0) \qquad H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + H^0 \end{pmatrix}$$

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H\, v_H^2 & \lambda_{HS}\, v_H\, v_S \\ \lambda_{HS}\, v_H\, v_S & 2\lambda_S\, v_S^2 \end{pmatrix}$$

- The mass eigenstates are $\phi_H$ and $\phi_S$ with a mixing angle $\beta$

# Model

## Yukawa interactions, mass terms, and mixing

- Mixing between the SM and the $U(1)'$ sector occurs through the Yukawa and mass terms

$$\mathcal{L}_{(\text{Yuk H})} = y^d_{jk}\overline{q}^j_L d^k_R H + \overbrace{y^u_{jk}\overline{q}^j_L u^k_R \widetilde{H} + y^e_{jk}\overline{l}^j_L e^k_R H}^{\text{Not relevant for } D \text{ mixing}} + h.c.$$

$$\mathcal{L}_{(\text{Yuk S})} = y_{Dd^k}\overline{D}_L d^k_R S + h.c.$$

$$\mathcal{L}_{(\text{mass})} = M_D \overline{D}_L D_R + h.c.$$

- $\mathcal{L}_{(\text{Yuk H})}$ is the SM Yukawa couplings
- $\mathcal{L}_{(\text{Yuk S})}$ only has down-type couplings
- $\mathcal{L}_{(\text{mass})}$ allowed
  - $D_L$ and $D_R$ have same quantum numbers

# Model

## Yukawa interactions, mass terms, and mixing

- Let $y_{Dd}$, $y_{Ds} \approx 0$
- Mass matrix in gauge basis of $(b, D)$ is not symmetric

$$M = \begin{pmatrix} y_b \, v_H/\sqrt{2} & 0 \\ y_{Db} \, v_S/\sqrt{2} & M_D \end{pmatrix}$$

- Diagonalize with a bi-unitary transformation: $R_L M R_R^\dagger$

$$R_i = \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix} \qquad i = L, R$$

- $(b_L, D_L)$ mixing is different from $(b_R, D_R)$

- Kinetic Lagrangian terms contain a new interaction for the $D$

$$\mathcal{L} \ni \overline{D} i\gamma^\mu D_\mu D$$

- The covariant derivative (ignoring color interactions)

$$D_\mu = \partial_\mu - ig' Y B_\mu - ig'' Y_q Z'_\mu$$

- Mixings of $b$ and $D$ creates new effective gauge couplings

- Effective couplings with gauge bosons:
  - $\psi_i \in \{D, b, t\}$ and $V_\mu \in \{Z_\mu, Z'_\mu, W^\pm_\mu\}$

$$\overline{\psi}_i K \gamma^\mu (c_V - c_A \gamma^5) V_\mu \psi_j$$

- Effective couplings with Higgs bosons:
  - $\psi_i \in \{D, b\}$ and $\phi \in \{\phi_H, \phi_S\}$

$$\overline{\psi}_i K (c_S - c_P \gamma^5) \phi \psi_j$$

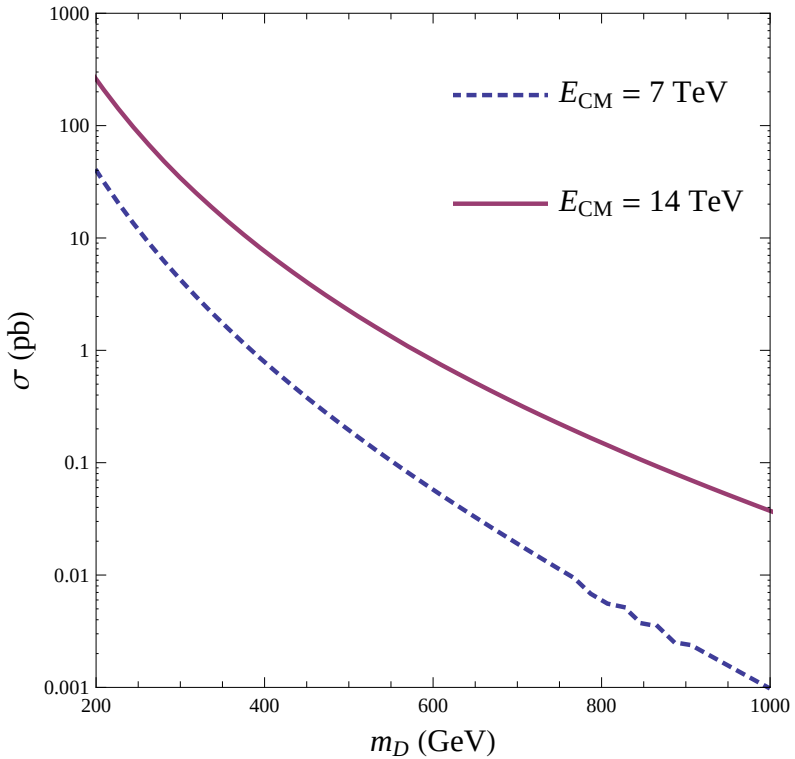
- $K$, $c_V$, $c_A$, $c_S$, $c_P$ are in terms of mixing angles, Yukawa couplings, and gauge couplings

# Phenomenology
## Production of $D$

- Pair production: $pp \to \overline{D}D$
- Large production cross section

### Production cross sections (pb)

| $m_D$ (GeV) | $\sqrt{s}$ 7 TeV | $\sqrt{s}$ 14 TeV |
|---|---|---|
| 300 | 4.265 | 34.368 |
| 500 | 0.194 | 2.270 |



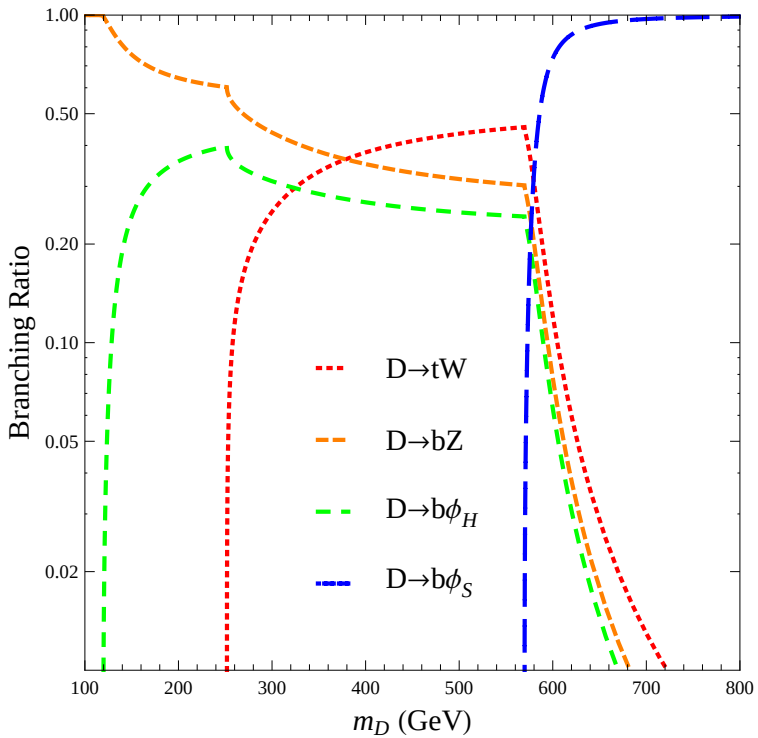
- Two parameter points chosen for examining decays

## Parameters

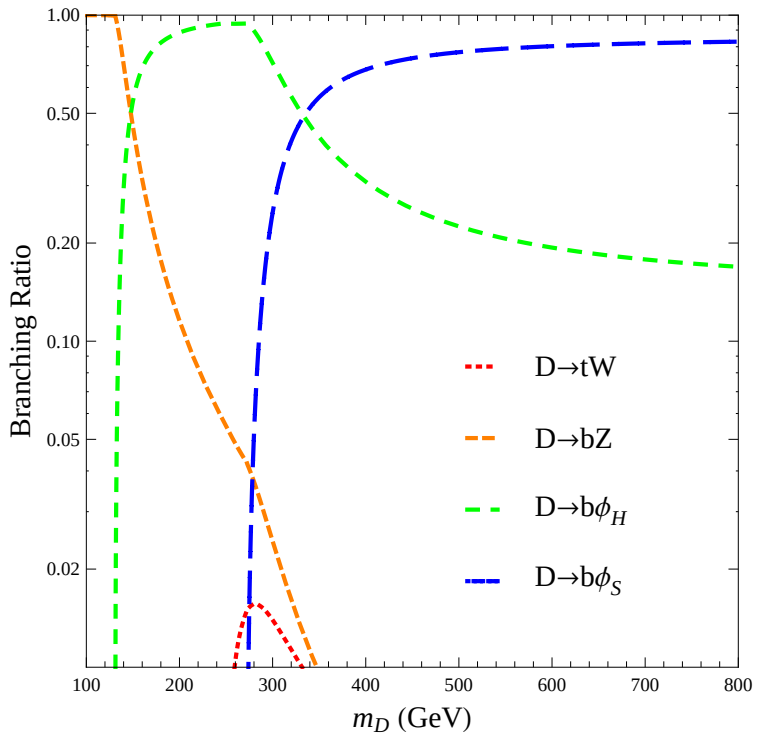
| | Point I | Point II |
|---|---|---|
| $(\lambda_H, \lambda_S, \lambda_{HS})$ | $(0.11, 0.16, 0.005)$ | $(0.2, 0.05, 0.1)$ |
| $v_S$ | 1000 GeV | 800 GeV |
| $y_{Db}$ | 0.15 | 0.05 |
| $m_{\phi_H}$ | 115 GeV | 127 GeV |
| $m_{\phi_S}$ | 566 GeV | 268 GeV |
| $m_{Z'}$ | 1000 GeV | 800 GeV |
| $\sin\beta$ | 0.004 | 0.380 |

# Phenomenology
## Branching ratios of $D$

Point I




Point II



- Interesting final states

$$\overline{D}D \to \begin{cases} 6b + X \\ 4b + 2l + X \\ 2b + 2l + X \\ nb + l + X \qquad (n \geq 3) \end{cases}$$

- Kinematic selection cuts

$$p_T^b > 20 \text{ GeV} \qquad |\eta^b| < 3.0 \qquad \Delta R_{bb} > 0.7$$
$$p_T^l > 20 \text{ GeV} \qquad |\eta^l| < 2.5 \qquad \Delta R_{lb} > 0.4$$
$$\Delta R_{ll} > 0.2$$

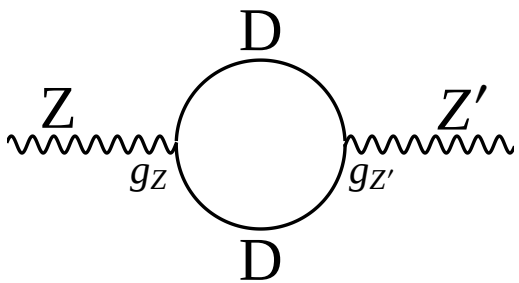
## Final state cross sections (fb)

| | SM background | $m_D = 300$ GeV I | $m_D = 300$ GeV II | $m_D = 500$ GeV I | $m_D = 500$ GeV II |
|---|---|---|---|---|---|
| $\sqrt{s} = 14$ TeV | | | | | |
| $6b + X$ | $\sim 70$ | 1394 | 5521 | 531 | 115 |
| $4b + 2l + X$ | $< 10$ | 384 | 184 | 20 | 22 |
| $\sqrt{s} = 7$ TeV | | | | | |
| $6b + X$ | $< 10$ | 182 | 719 | 5 | 115 |
| $4b + 2l + X$ | $< 1$ | 51 | 24 | 1.8 | 2.1 |

- Some final states have large signal, small SM background
  - $6b + X$ really stands out

# Phenomenology
## What about $Z - Z'$ mixing?

- Kinetic mixing assumed to be zero
- $\theta$-mixing will occur at the one-loop level




- $\theta_{Z-Z'} < 10^{-3}$
  - LEP bound $m_{Z'} > 1$ TeV does not apply

# Summary

- Extra gauge symmetry: $U(1)'$
  - Exotic quarks $D_L$, $D_R$ and Higgs singlet $S$
    - Charged under $U(1)'$
    - Communicate $U(1')$ to the SM sector
  - SM particles neutral under $U(1)'$
- Large production of $\overline{D}D$ at LHC
- Decay signals above the SM background
  - $6b + X$ stands out