Searching for Dark Photons using Maverick Top Partners

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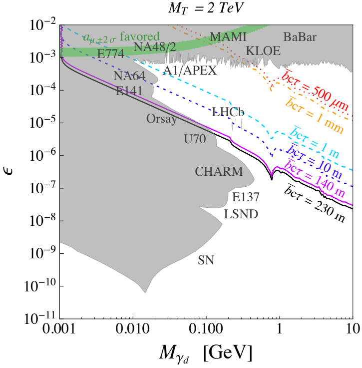
Based on arXiv:1904.05893



Outline

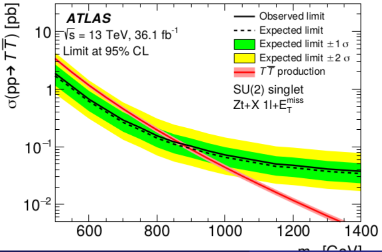
Motivation

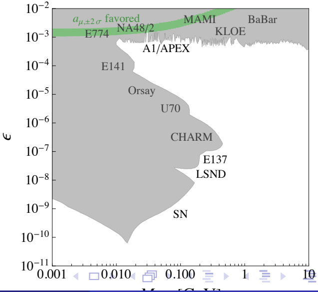
Why VLT?	Why Dark Photon?
• Vector like fermions dont introduce new anomalies. • Vector like top partners are found in Little and Composite Higgs Models, which address radiative corrections to the Higgs mass. • Accordingly there have been many searches for them but none have seen top partners.	• Given the rich structure of the SM the nature of a dark sector could be equally as complicated. • There could be many additional particles and forces. • The simplest possible extension of a dark force is the introduction of a dark photon.

Typical Searches

VLQ	Dark Photon
There have been many searches for VLQ's but no discovery. But normally assume $Br(VLQ \to SM) = 1$.	Dark photon searches typically rely on direct detection due to the small couplings (ϵ) making collider production difficult.

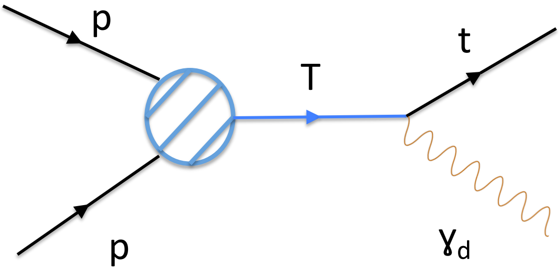
From arXiv 1705.10751





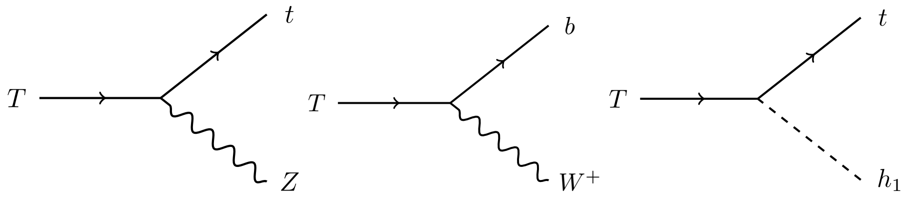
Motivation

- Branching ratio of top partner to SM $\ll 1$
- Dark photon production depends on QCD and not small parameter ϵ

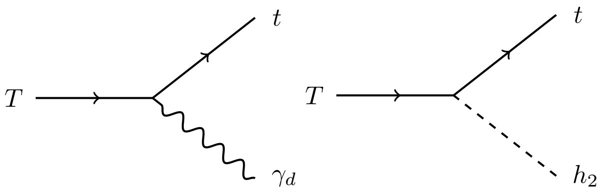


Maverick Tops

Typical top partner electroweak decay modes



Maverick top partners have additional decay modes



We thank KC Kong and Doug McKay for the term "Maverick top partner"

Goldstone Boson Equivalence (GBE)

From GBE, the partial width of T into fully SM final states is

$$\Gamma(T \to b/t + W/Z/h) \sim \sin^2\theta \, \frac{M_T^3}{v_{EW}^2},$$

where θ is a mixing angle between the SM top quark and T.
If we imagine a Higgs mechanism for the dark photons we can also use GBE to get

$$\Gamma(T \to t + \gamma_d/h_d) \sim \sin^2\theta \frac{M_T^3}{v_d^2}.$$

The ratio of the rates into γ_d/h_d and $W/Z/h$ is given by

$$\frac{\Gamma(T \to t + \gamma_d/h_d)}{\Gamma(T \to t/b + W/Z/h)} \sim \left(\frac{v_{EW}}{v_d}\right)^2 \gtrsim \mathcal{O}(100),$$

where for dark photon masses $M_{\gamma_d} \lesssim 10$ GeV, we generically expect that the vev $v_d \lesssim 10$ GeV. This ratio implies the VLT preferentially decays to these new non SM-states.

Model Overview

In order for the GBE argument to work to work we augment the standard model by adding three new fields:

- A gauge boson for a dark force, F_D
- A vector like quark, t_2, charged under this $U(1)_D$
- A new scalar particle, H_D, charged under this $U(1)_D$

Benefits of the Model:

- The SM branching ratios for top partner are significantly reduced
- Dark Photons are produced at QCD rates independent of ϵ

Additional Terms in Lagrangian

The allowed form of the scalar potential is

$$V(\Phi, H_d) = -\mu^2|\Phi|^2 + \lambda\,|\Phi|^4 - \mu_{h_d}^2|H_d|^2 + \lambda_{h_d}|H_d|^4 + \lambda_{hh_d}|\Phi|^2|H_d|^2.$$

We add the new gauge kinetic pieces for the $U(1)_D$

$$\mathcal{L}_{Gauge-NEW} = -\frac{1}{4}(-\frac{2\varepsilon'}{\cos(\theta_W)}F_Y^{\mu\nu}F_{D\mu\nu} + F_D^{\mu\nu}F_{D\mu\nu})$$

The fermion yukawa interactions and mass terms are given by

$$\mathcal{L}_{Yuk} = -y_b\overline{Q}_L\Phi b_R - y_t\overline{Q}_L\widetilde{\Phi}t_{1R} - y_{t_2}H_d\overline{t}_{2L}t_{1R} - M_{t_2}\overline{t}_{2L}t_{2R} + \mathrm{h.c.}$$

Small Mixing Interaction terms

In the small mixing angle limit, $M_t/M_T, |\theta_L^t|, |\varepsilon| \ll 1$ the relevant couplings are

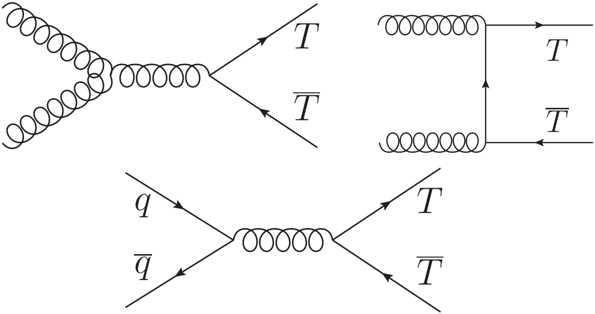
$$W - T - b \sim i\frac{g}{\sqrt{2}} \sin\theta_L^t \gamma^\mu P_L$$

$$Z - T - t \sim i\frac{g_Z^{SM}}{2} \sin\theta_L^t \gamma^\mu P_L + ig_d \frac{(M_T/M_t)\sin\theta_L^t}{1 + (M_T/M_t)^2 \sin^2\theta_L^t} \sin\theta_d \gamma^\mu P_R$$

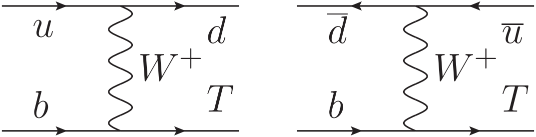
$$\gamma_d - T - t \sim -i\, g_d \sin\theta_L^t \gamma^\mu P_L - ig_d \frac{(M_T/M_t)\sin\theta_L^t}{1 + (M_T/M_t)^2 \sin^2\theta_L^t} \gamma^\mu P_R$$

Maverick Top Production Channels

Pair Production via QCD

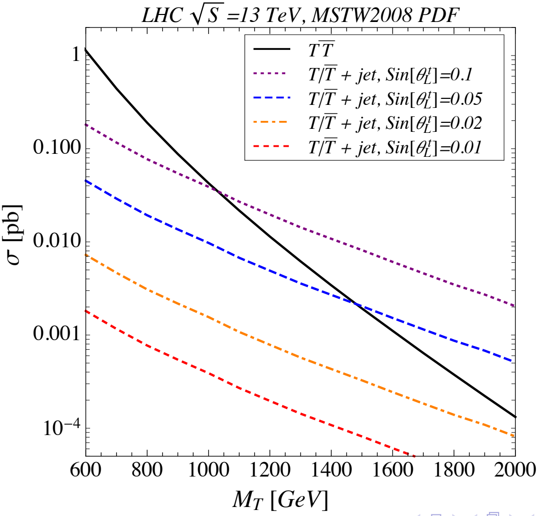


Single Production via W exchange



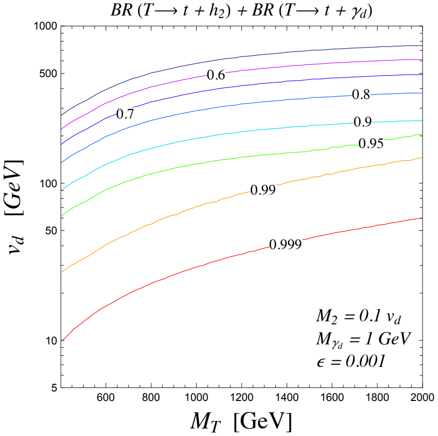
Maverick Top Production Rates

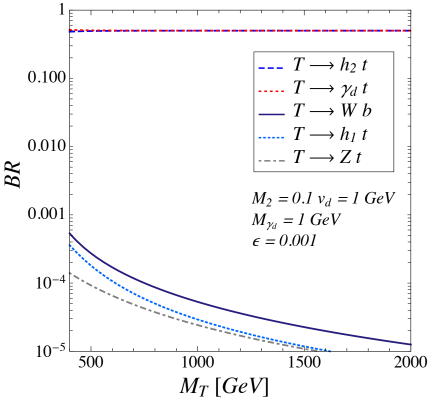
Maverick top production only depends on QCD structure



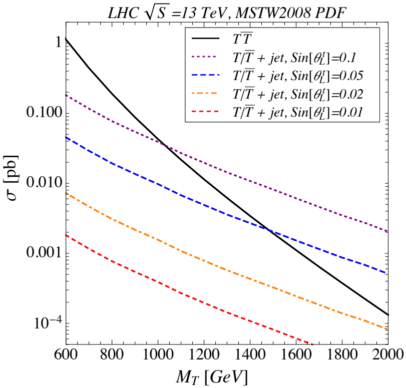
Full Branching ratio calculation

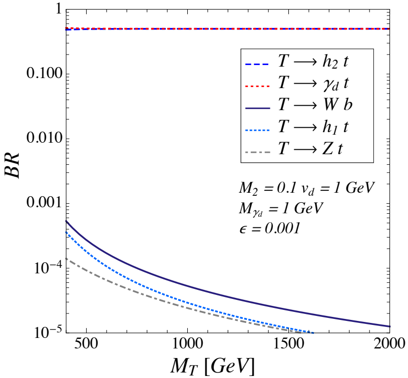
New non standard model decay modes dominate largely independent of model parameters.

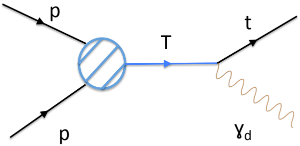




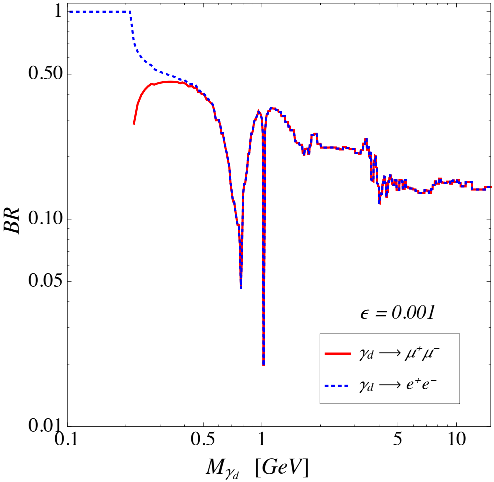
Dark Photon with QCD Production Rates







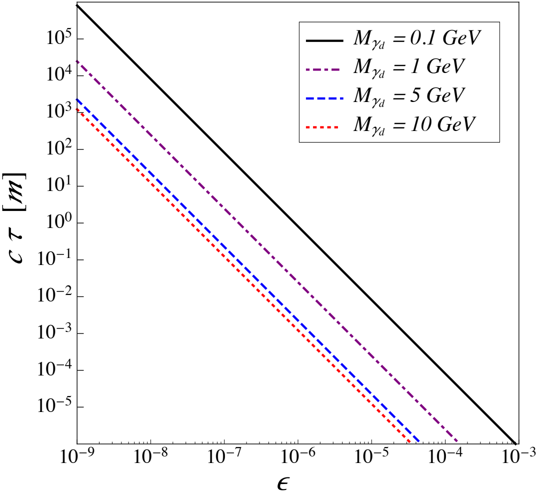
Dark Photon Branching Ratio



Curtin (2014) arXiv: **Curtin:2014cca**

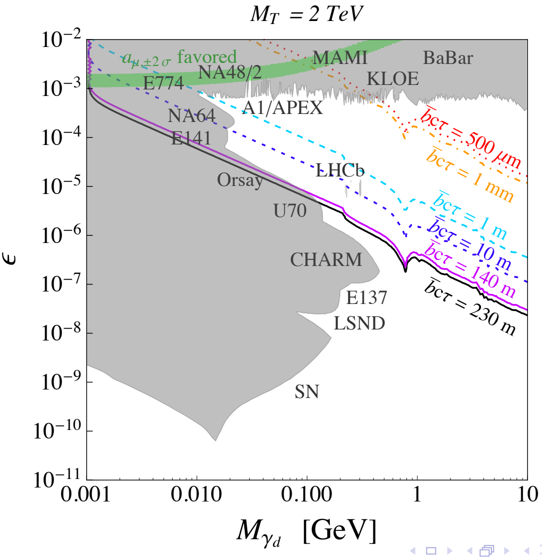
Dark Photon Decay Length

Lots of variability in the decay length depending on the model parameters.

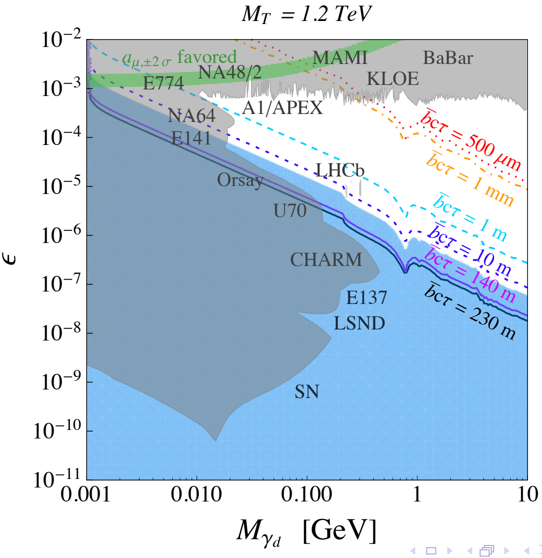


Dark Photon Collider Phenomenology

There is a rich decay phenomenology in the open parameter space.



Rule out longer decay lengths by recasting stop searches



Summary

Model Benefits:

- This model has vastly different top partner decay modes than the normal searches
- This model produces dark photons at QCD rates
- Some searches can be reinterpreted to exclude some regions of parameter space

Interpretation:

- A new particles phenomenology drastically depends on the structure of the model.
- We have a mechanism for searching for dark photons at colliders due to the large production rates and rich pheno.

Questions?

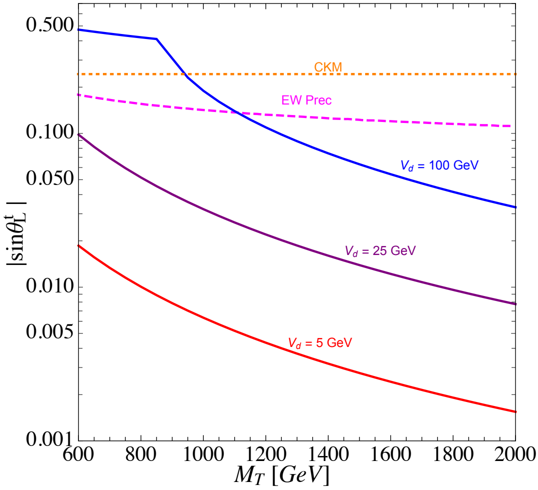
Particle Content

	$SU(3)$	$SU(2)_L$	Y	Y_d
t_{1R}	$\mathbf{3}$	$\mathbf{1}$	2/3	0
b_R	$\mathbf{3}$	$\mathbf{1}$	-1/3	0
$Q_L = \begin{pmatrix} t_{1L} \\ b_L \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	1/6	0
Φ	$\mathbf{1}$	$\mathbf{2}$	1/2	0
t_{2L}	$\mathbf{3}$	$\mathbf{1}$	2/3	1
t_{2R}	$\mathbf{3}$	$\mathbf{1}$	2/3	1
H_d	$\mathbf{1}$	$\mathbf{1}$	0	1

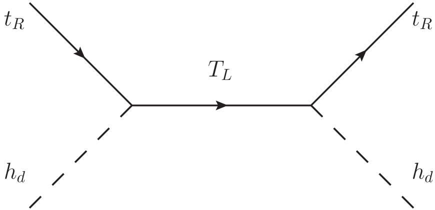
Table: Field content and their charges. t_{1R}, b_R, and Q_L are 3$^{\text{rd}}$ generation SM quarks, Φ is the SM Higgs doublet, t_2 is the $SU(2)_L$ singlet VLQ, and H_d is the $U(1)_d$ Higgs field. Y is the SM Hypercharge and Y_d is the $U(1)_d$ charge.

Oblique, CKM, and Perturbativity Constraints

Constraints from electroweak precision measurements and perturbativity strongly constrain the mixing angle.



Perturbativity Constraints



$$i\mathcal{M}(h_d t_R \to h_d t_R) = -i\frac{\lambda_t^2}{2}\cos\frac{\theta}{2} = i16\pi \sum_{j=1/2,3/2,\dots} (2j+1)a_j d^j_{1/2,1/2}(\theta),$$

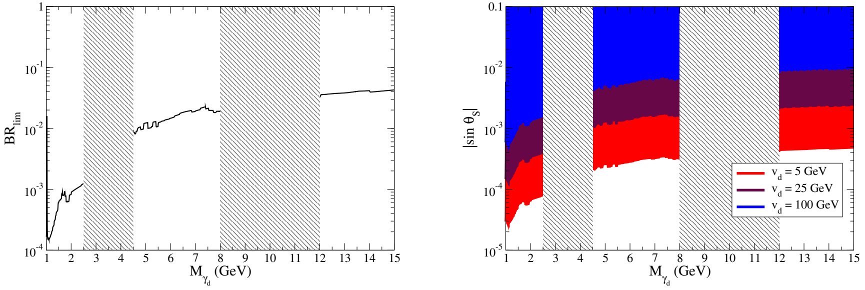
where θ is the scattering angle and $d^j_{m,m'}(\theta)$ are Wigner d-functions. There is only one relavant term

$$a_{1/2} = -\frac{\lambda_t^2}{64\pi}$$

$$|\mathrm{Re}\, a_{1/2}| \leq \frac{1}{2} \implies |\lambda_t| \leq 4\sqrt{2\pi}.$$

Higgs to $\gamma_d \gamma_d$ Constraints

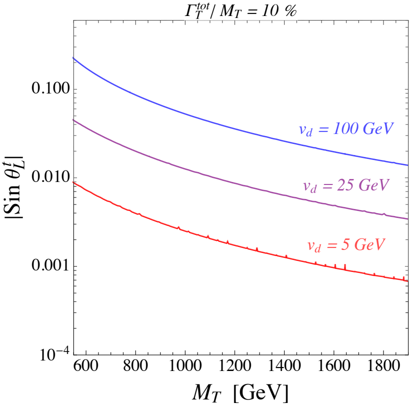
There have been searches at the LHC for $h_1 \to \gamma_d \gamma_d \to 4\ell$ where $\ell = e, \mu$ (Aboud *et al.* 2018). These searches place limits on the Higgs decay through dark photons in the mass range $1\ \mathrm{GeV} < M_{\gamma_d} < 60\ \mathrm{GeV}$.



Narrow Width Constraints

When $M_t \ll M_T$ and $v_d \ll v_{EW}$, the mixing angle $\sin\theta_L^t$ must be quite small for T to be narrow.

$$\frac{\Gamma_T^{tot}}{M_T} \approx \frac{1}{16\pi}\frac{M_T^4}{M_t^2\, v_d^2}\frac{\sin^2\theta_L^t}{1+(M_T/M_t)^2\sin^2\theta_L^t}.$$



Dark Photon Hadronic Decays

$$R(M_{\gamma_d}) \equiv \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$\begin{aligned}
\Gamma_{\gamma_d}^{tot} &= R(M_{\gamma_d})\Gamma(\gamma_d \to \mu^+\mu^-) + \sum_{f=e,\mu,\tau,\nu_e,\nu_\mu,\nu_\tau} \Gamma(\gamma_d \to f\bar{f}) \\
&\approx \frac{\varepsilon^2 e^2}{12\,\pi} M_{\gamma_d} \left[R(M_{\gamma_d}) + \sum_{\ell=e,\mu\tau} \theta(M_{\gamma_d} - 2\,M_\ell) \right]
\end{aligned}$$

M. Tanabashi et al. "Review of Particle Physics" , Phys. Rev. D98.3 (2018)

Boost Factor and Observed Decay Length

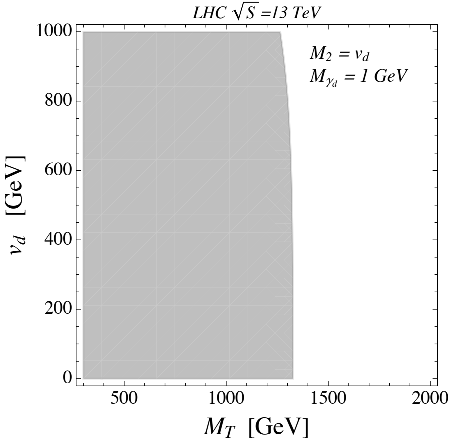
The decay length will be boosted based on the relative momentum coming from the VLQ decay

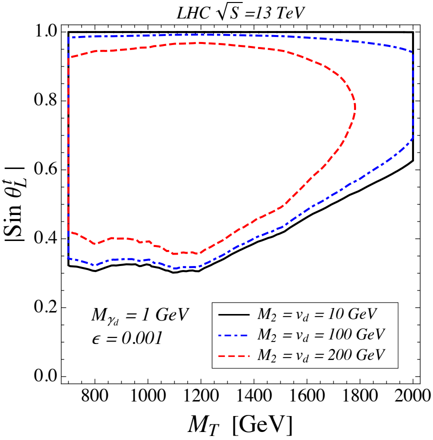
$$d = \bar{b} c \tau$$

$$\begin{aligned}\bar{b} &= \frac{|\overrightarrow{p}_{\gamma_d}|}{M_{\gamma_d}} = \frac{1}{2 M_{\gamma_d} M_T} \sqrt{(M_T^2 - M_{\gamma_d}^2 - M_t^2)^2 - 4 M_{\gamma_d}^2 M_t^2} \\ &\xrightarrow[M_T \gg M_{\gamma_d}, M_t]{} \frac{M_T}{2 M_{\gamma_d}} \approx \mathcal{O}(100),\end{aligned}$$

$$d = 580\ \mu\text{m} \times \frac{7}{R(M_{\gamma_d}) + \sum_{\ell=e,\mu\tau} \theta(M_{\gamma_d} - 2\, M_\ell)} \times \left(\frac{M_T}{1\ \text{TeV}}\right) \left(\frac{1\ \text{GeV}}{M_{\gamma_d}}\right)^2 \left(\frac{10^{-4}}{\varepsilon}\right)^2 .$$

Reinterpreting Stop Searches





CMS-PAS-SUS-19-005, Aaboud (2018) arXiv: **Aaboud:2018zpr**

Kinetic Mixing

- Normalize Gauge Kinetic Terms

$$F_{Y,\mu} = B_\mu + \frac{\varepsilon'}{\hat{c}_W\sqrt{1-\varepsilon'^2/\hat{c}_W^2}} B_{D,\mu}, \qquad F_{D,\mu} = \frac{1}{\sqrt{1-\varepsilon'^2/\hat{c}_W^2}} B_{D,\mu},$$

- Electroweak Rotation and Mass Diagonalization

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} = \hat{R}(\hat{\theta}_W) \begin{pmatrix} \hat{Z}_\mu \\ A_\mu \end{pmatrix}, \qquad \begin{pmatrix} \hat{Z}^\mu \\ B_D^\mu \end{pmatrix} = \hat{R}(\theta_D) \begin{pmatrix} Z^\mu \\ \gamma_d^\mu \end{pmatrix}.$$

- Covariant Derivative

$$\begin{aligned} D_\mu \;=\; & \partial_\mu - ig_S t^A G_\mu^A - ig^{SM} T^+ W^+ - ig^{SM} T^- W^- - ieQA_\mu \\ & -i\left[g_Z^{SM} Q_Z^{SM} - \varepsilon g_d\, Y_d \tan\theta_W^{SM}\right] Z_\mu - i\left[\varepsilon eQ + g_d Y_d\right]\gamma_{d,\mu} \\ & +\mathcal{O}(\varepsilon^2, M_{\gamma_d}^2/M_Z^2), \end{aligned}$$

Symmetry Breaking

The scalar potential is given by

$$\mathcal{V}(\Phi, S) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4 - \mu_s^2|S|^2 + \lambda_s|S|^4 + \lambda_{hs}|\Phi|^2|S|^2$$

with minimums occuring when

$$\frac{\partial \mathcal{V}}{\partial |\Phi|^2} = -\mu^2 + 2\lambda|\Phi_0|^2 + \lambda_{hs}|S_0|^2 = 0$$
$$\frac{\partial \mathcal{V}}{\partial |S|^2} = -\mu_s^2 + 2\lambda_s|S_0|^2 + \lambda_{hs}|\Phi_0|^2 = 0.$$

This system has solutions

$$|\Phi_0|^2 = \frac{2\lambda_s\mu^2 - \lambda_{hs}\mu_s^2}{4\lambda\lambda_s - \lambda_{hs}^2} = \frac{v^2}{2}, \text{ and } |S_0|^2 = \frac{2\lambda\mu_s^2 - \lambda_{hs}\mu^2}{4\lambda\lambda_s - \lambda_{hs}^2} = \frac{v_D^2}{2}$$