Minestrone: flavour cosmology, varying yukawas, flavour and DM.

I. Baldes 12.6.2018. DESY Workshop Seminar.

References:

1. Flavour and DM.

   1501.07268 + refs. therein.

   (Also see 1505.03862 for an alternative).

2. Flavour Cosmology / varying Yukawas

   hep-ph/0401012

   + DESY papers

   1604.04526 (PT)
   1608.03254 (FN)
   1612.02447 (RS)
   1706.08534 (CP)
   1803.08546 (CH)
   1804.07314 (CH)

Also see S.F. King et. al. for GUT flavour models and leptogenesis (e.g. 1710.03229).

1. Flavour Portal to DM

SM fermion mass:

FN model: $m_f = a_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{n_{ij}} \frac{v}{\sqrt{2}}$.

from $\mathcal{L} \supset a_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{n_{ij}} \bar{f}_L f_R \phi$.

Now make DM transform under G_{flav}. DM mass:

$$m_\chi = b_\chi \left(\frac{\langle\phi\rangle}{M}\right)^{n_\chi} \langle\phi\rangle$$

$$\text{from } \mathcal{L} \supset b_\chi \left(\frac{\phi}{M}\right)^{n_\chi} \phi \, \bar{\chi}_L \chi_R$$

$$\mathcal{L} \xrightarrow{SSB} \overbrace{n_f \frac{m_f}{\langle\phi\rangle}}^{\equiv \lambda_F} \bar{f}_L f_R \phi + \overbrace{(n_\chi + 1)\frac{m_\chi}{\langle\phi\rangle}}^{\equiv \lambda_\chi} \bar{\chi}_L \chi_R \phi.$$

Flavon talks to SM fermions and DM

Flavon mass arises from SSB of G_{flav}.

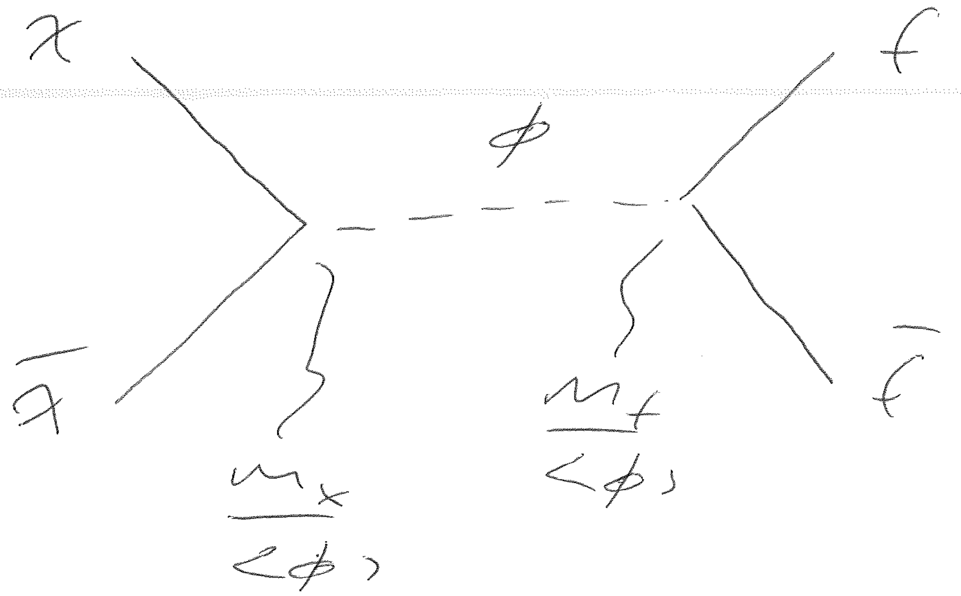
Parameterise: $m_\phi = k\langle\phi\rangle$.

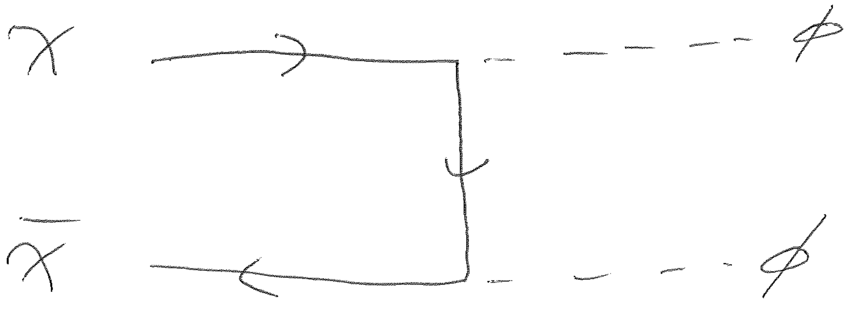
Some similarities to Higgs portal:

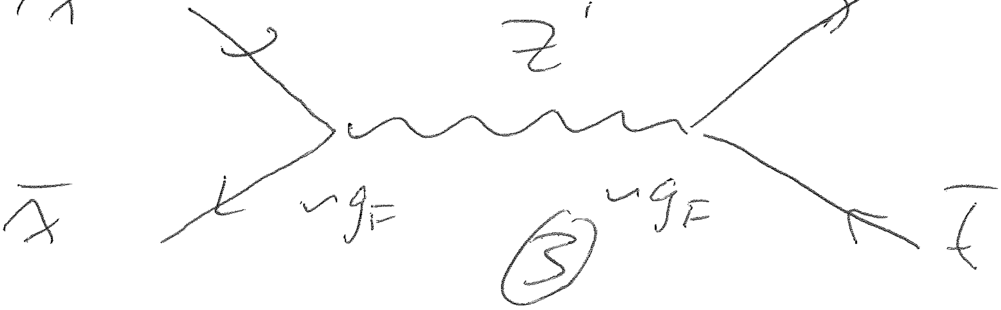
- Mediator couples preferentially to heavier flavours.

- Correlation b/w DM annihilation and scattering w/ Nuclei.

<u>Annihilation diagrams.</u>







if G_{flav} gauged.

$$\langle \sigma_\phi^T v \rangle \sim \frac{\lambda_\chi^4}{m_\chi^3} T$$

$$\langle \sigma_\phi^S v \rangle \sim \frac{\lambda_\chi^2 \lambda_t^2 m_\chi T}{(4m_\chi^2 - m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2}$$

$$\langle \sigma_{Z'} v \rangle \sim \frac{g_F^4 m_\chi^2}{(m_{Z'}^2 - 4m_\chi^2)^2 + \Gamma_{Z'}^2 m_{Z'}^2}$$

<u>DM + Nucleon SI scattering:</u>

$$\sigma_\phi^{SI} \sim \frac{\lambda_\chi^2 \lambda_{\phi N}^2}{m_\phi^4} \mu_{\chi N}^2, \quad \lambda_{\phi N} \propto \lambda_t$$

$$\sigma_{Z'}^{SI} \sim \frac{g_F^2 \lambda_{Z'N}^2}{m_{Z'}^4} \mu_{\chi N}^2, \quad \lambda_{Z'N} \propto g_F.$$

Explicit Model : $U(1)_F$ FN model

Charges: $(Q_{q_1}, Q_{q_2}, Q_{q_3}) = (3, 2, 0)$

$(Q_{u_1}, Q_{u_2}, Q_{u_3}) = (3, 2, 0)$

$(Q_{d_1}, Q_{d_2}, Q_{d_3}) = (4, 2, 2)$

Largest flavon coupling $\phi \, \bar{t}_{L,R} \, c_{R,L}$

" Z' couplings to lighter generations.

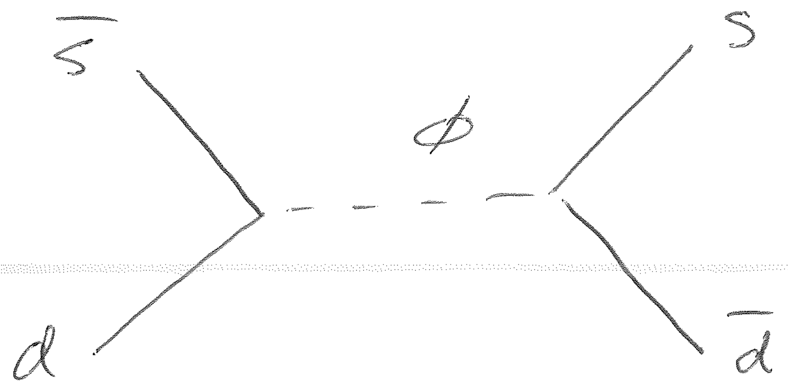
Assume anomalies are cancelled by unspecified field content in hidden and/or messenger sector.

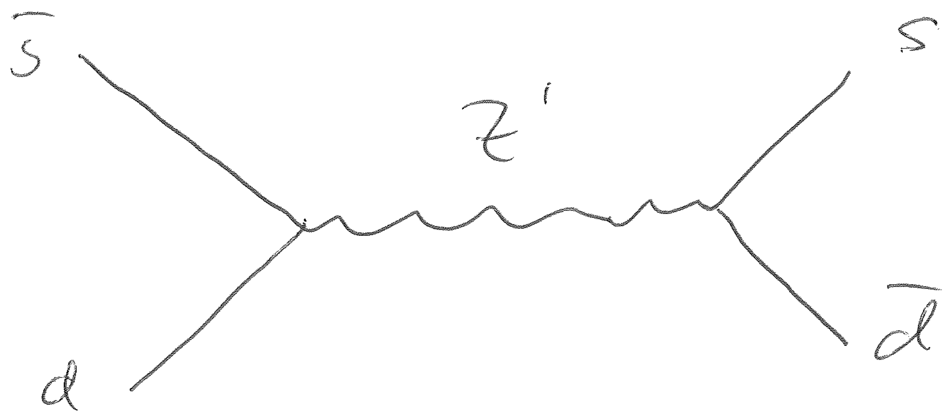
(e.g. Flavour messengers are vector-like quarks under SM gauge group – not necessarily vector-like under $G_{F\,em}$ – giving more freedom to cancel the anomalies).

Model is largely specified by the parameters

$$m_\phi, \; m_X, \; R \equiv \frac{m_\phi}{\langle\phi\rangle}.$$

Flavour constraints





ΔM_K

$m_\phi \gtrsim \sqrt{R} \times 580\,\mathrm{GeV}$

$m_{Z'} \gtrsim \left(\frac{g_F}{10^{-3}}\right) \times 210\,\mathrm{GeV}$

i.e. $\langle\phi\rangle \gtrsim 210\,\mathrm{TeV}$.

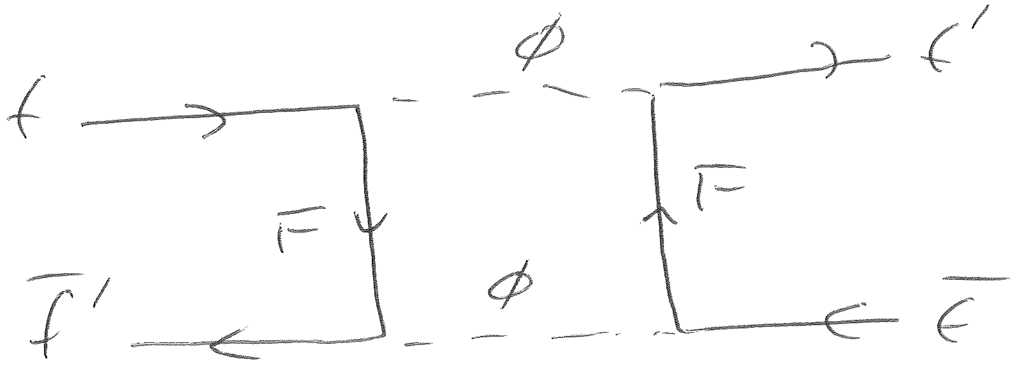
ε_K

$m_\phi \gtrsim \sqrt{R}\sqrt{\mathrm{avg}(\lambda^d_{12}\lambda^d_{21})} \times 2.3\,\mathrm{TeV}$

$m_{Z'} \gtrsim \left(\frac{g_F}{10^{-3}}\right)\sqrt{\mathrm{avg}(|V^d_{L12}||V^d_{R12}|)} \times 3.3\,\mathrm{TeV}$

UV Messenger fields

$\longrightarrow$ One-loop FCNC (1204.1275)



Limit from $D-\bar{D}$

$$m_\phi \gtrsim C_D \times k \times 2.3\,\mathrm{TeV}$$

from ε_K:

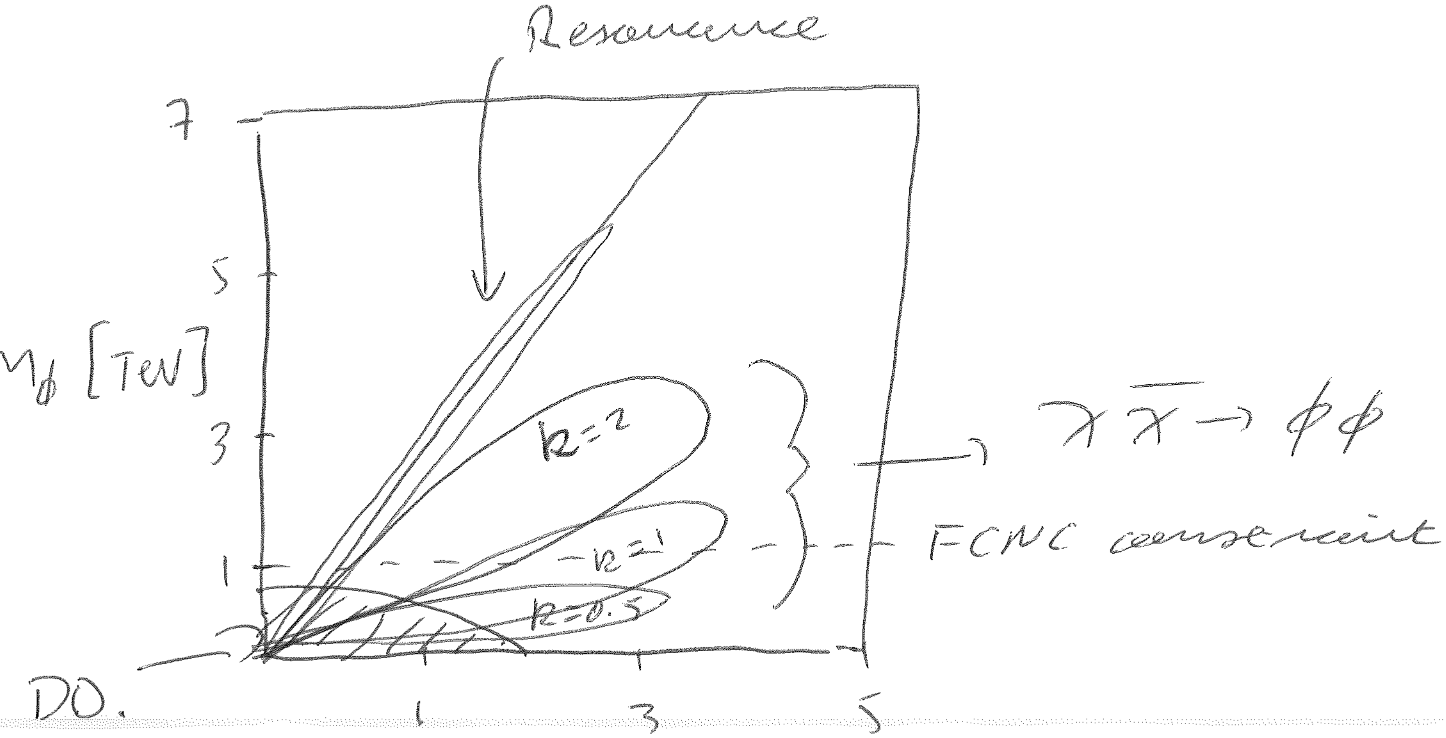
$$m_\phi \gtrsim C_K \times k \times 27\,\mathrm{TeV}.$$

C_D, C_K : product of unknown $O(1)$ coefficients.

For interesting pheno need $C_K \sim 0.1$.

Results

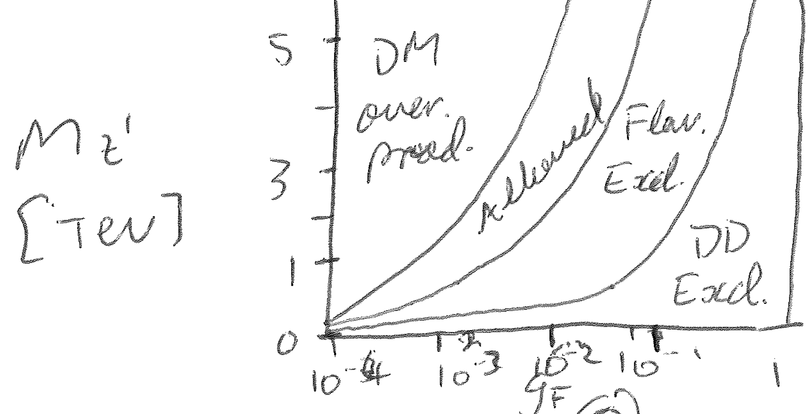
Global $U(1)_F$



DD can be under ν-floor.
(but many points above).

Gauged case $\langle\phi\rangle \gg v_{EW}$ due to Z' FCNC.

$\rightarrow$ have to be on resonance for DM.



(2) Flavour Cosmology

Motivation from EWBG. SM CP source

$$\epsilon_{CP} \sim \frac{1}{T_n^6 M_W^6} \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \times \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2)$$

$$\times J_{CP}$$

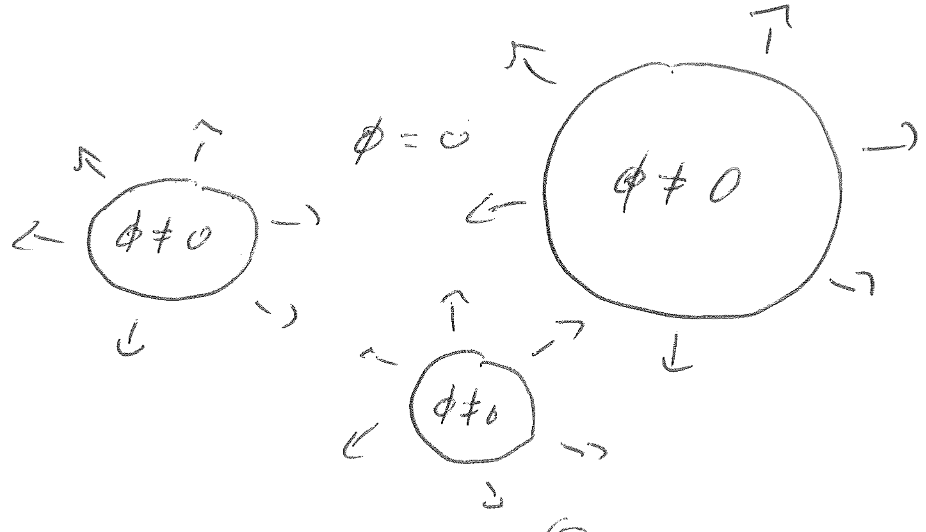
$$\hookrightarrow \sim s_{12} s_{23} s_{13} \sin\delta_{CKM}$$

$$\sim 10^{-19}$$

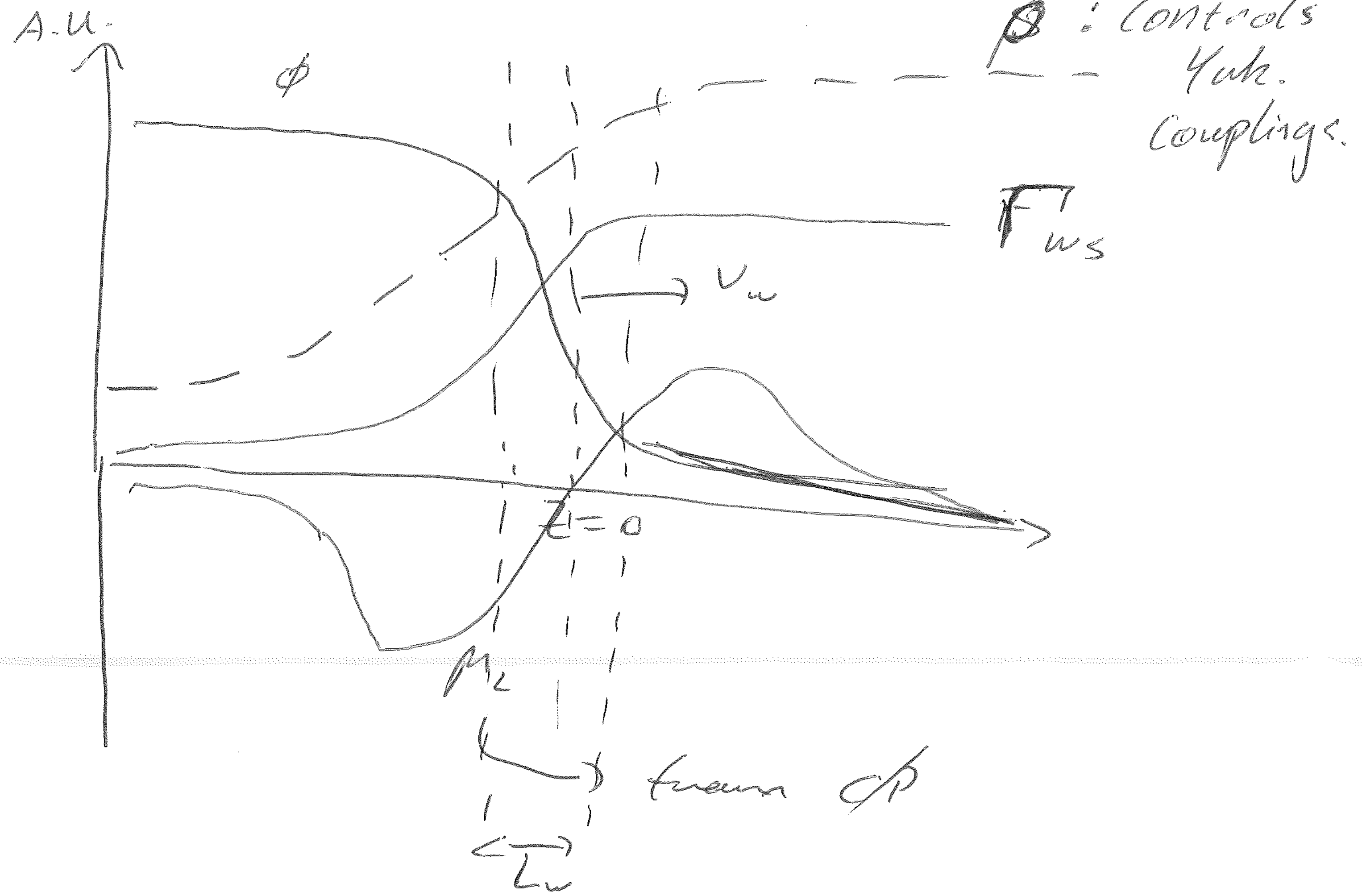
is too small.

Simple solution: increase Yukawas in the early universe!

The Yukawas today are set during the EWPT.



Varying Yukawas:



$$\partial_z n_B = \frac{3}{2} v_w^{-1} \Gamma_{ws} \left(N_c \mu_L T^2 - A n_B \right)$$

$$\Gamma_{ws} = 10^{-6} T e^{-a\phi(z)/T}$$

$$a \simeq 37 = \frac{E_{sph.}}{V_{EW}}$$

In SM $A = \frac{15}{2}$

$$\mu_L = \frac{\mu_{tL} + \mu_{bL} + \mu_{cL} + \mu_{sL} + \mu_{nL} + \mu_{dL}}{2}$$

To determine $\mu_L(z)$ solve

Transport Eq's.

$\not{CP}$ source

$$A(z) \cdot \Gamma'(z) + B(z) \cdot \Gamma(z) = \bar{S}(z)$$

Set by dynamics and interactions of the particles

$$\Gamma = (\mu_1, \ldots, \mu_N, u_1, \ldots, u_N)$$

chem. pot.

local vel. in plasma.

$$\eta_B = \frac{n_B(-\infty)}{s}$$

$$= \frac{135 N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{\infty} dz\, \Gamma_{ws} \mu_L \, \mathrm{Exp}\left[-\frac{3}{2}\frac{A}{v_w}\int_{-\infty}^{z} dz\, \Gamma_{ws}\right]$$

$$\sim \frac{\Gamma_{ws}\mu_L L_w}{g_* T} \sim 10^{-8}\frac{\mu_L}{T} \quad \text{for } L_w \sim \frac{1}{T}$$

It turns out dominant term w/ varying Yuk's is: $S \sim \mathrm{Im}\left[V^\dagger m^{\dagger\prime\prime} m V\right]_{ii}$.

FN – Froggatt – Nielsen.

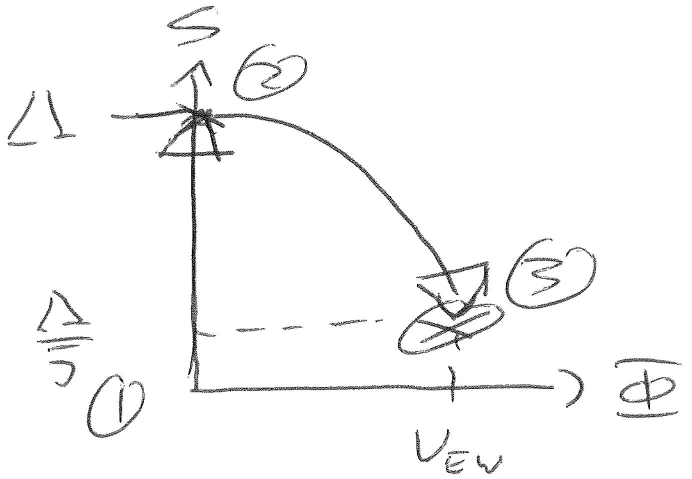
$$\mathcal{L} \supset y_{ij} \left(\frac{S}{\Lambda}\right)^{n_{ij}} \overline{Q_{iL} \Phi} \, q_R$$

$$\Rightarrow \quad y_{eff} \sim y_{ij} \left(\frac{\langle S \rangle}{\Lambda}\right)^{n_{ij}}$$

Need $\langle S \rangle \simeq \Lambda$ before EWPT

$$\langle S \rangle = \frac{\Lambda}{5} \text{ today}$$

(to fit quark masses / mixing).



① For $T \gg \Lambda$ in symmetric phase.

② At $T \sim \Lambda$ evolve to $\langle S \rangle \sim \Lambda$.

③ At EWPT

$$\langle S \rangle : \Lambda \to \frac{\Lambda}{5}$$

$$\langle \Phi \rangle : 0 \to v_{EW} = 246 \text{ GeV}.$$

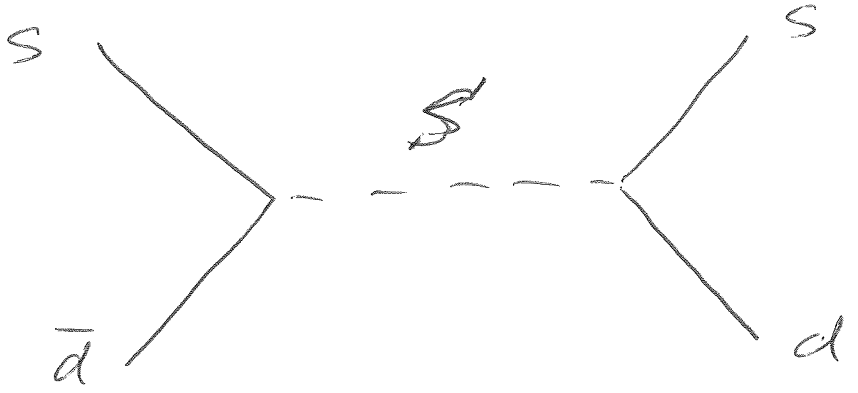
$$\left| V(\Phi = 0,\ S = \Lambda) - V(\Phi = v_{EW},\ S = \Lambda_s/5) \right|$$

$$\sim \mu_s^2 \Lambda_s^2 - \left(\mu_\phi^2 v_{EW}^2 + \mu_s^2 \Lambda_s^2 / 25 \right)$$

$$\Rightarrow \text{Need } \mu_s^2 \Lambda_s^2 \sim \mu_\phi^2 v_{EW}^2 \quad (*)$$

(for careful derivation see 1608.03254)

But $K - \bar{K}$



requires $m_s \Lambda_s \gtrsim (\text{few TeV})^2$

$\rightarrow$ incompatible with $(*)$.

Possible sol'n: multiple flavons.

~~One~~ control Yuk's today.

Other varies Yuk's during EWPT

but has negligible VEV ~~today~~ $\rightarrow$ FCNCs

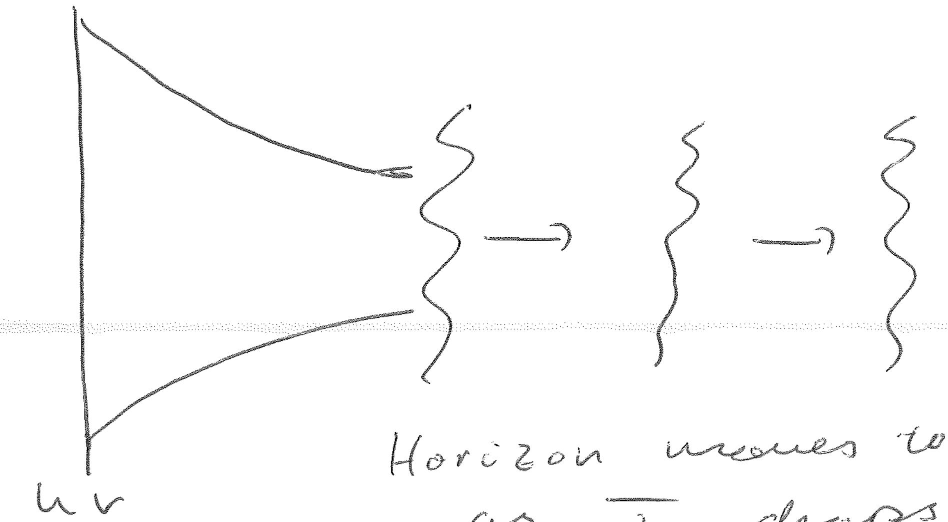
now loop process.

RS - Randall Sundrum

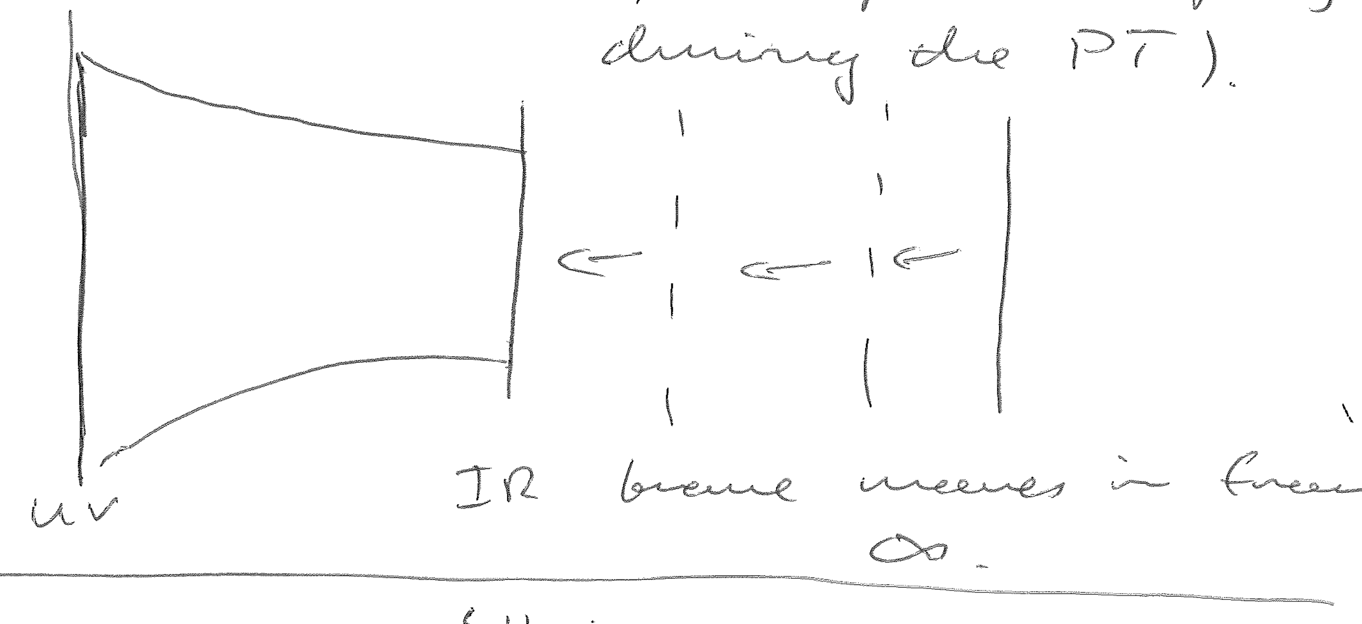
$$ds^2 = e^{-2ky}\eta_{\mu\nu}\,dx^\mu dx^\nu - dy^2$$

$$y \in [0, y_{IR}]$$

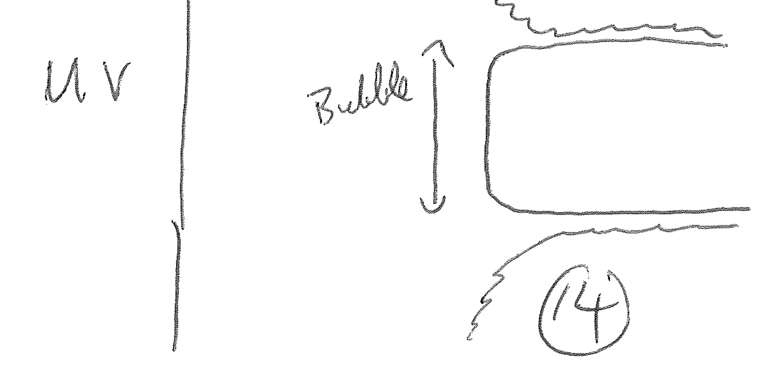
But at high T: AdS - Schwarzschild!



Horizon moves to ∞ as T drops (or rapidly during the PT).

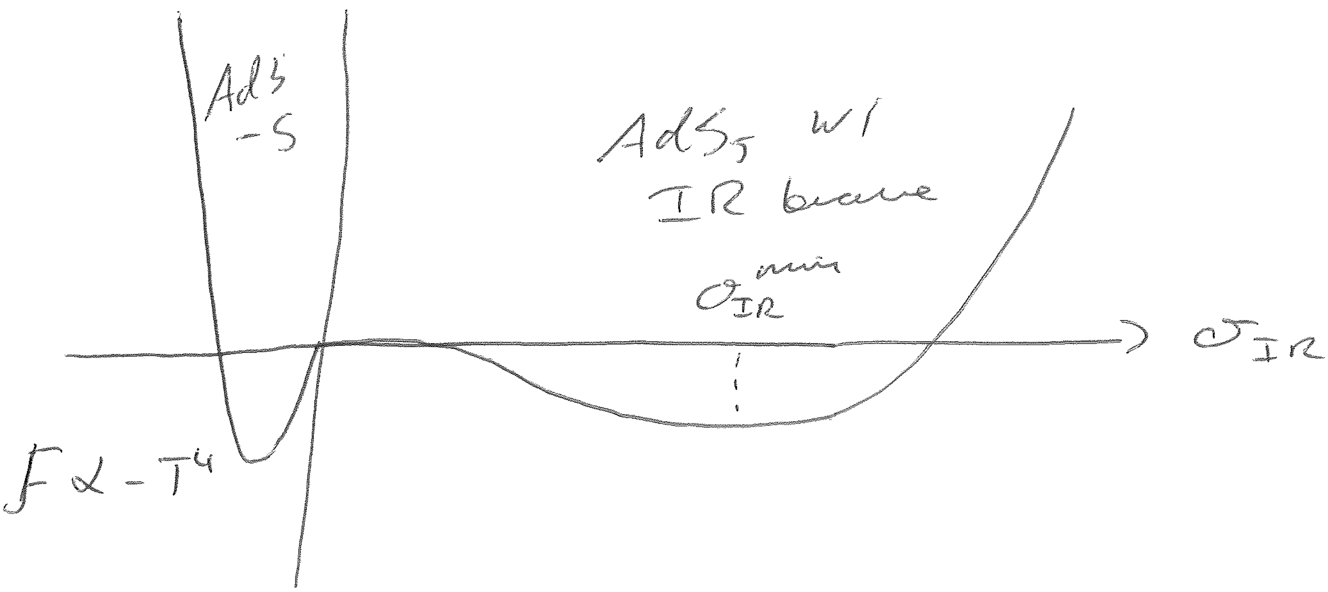


IR brane moves in from ∞.



Picture of the PT.

Use Goldberger – Wise mechanism to stabilise extra dimension.



$$\sigma_{IR} \equiv e^{-k y_{IR}}$$ position of

$$\sigma_{IR}^{min} * M_{pl} \sim \text{TeV}.$$

It turns out the potential is very shallow and slowly varying.

$$V(\sigma_{IR}) \sim \sigma_{IR}^4 \times f(\sigma_{IR}^{\varepsilon})$$

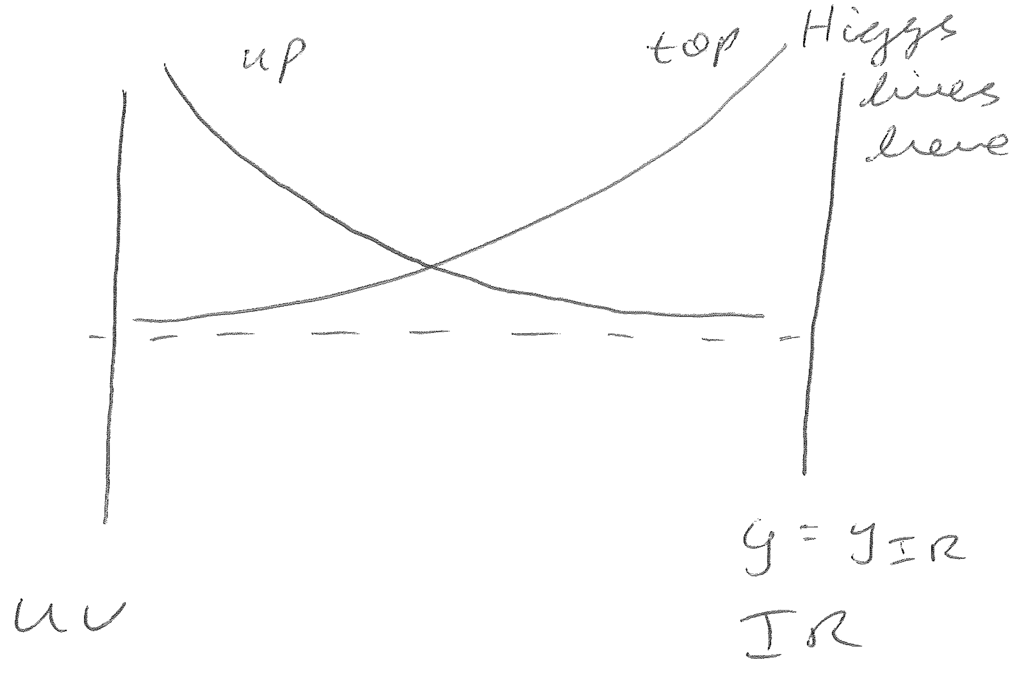
where $\varepsilon = \sqrt{4 + \frac{m_{GW}^2}{k^2}} - 2 \sim \frac{1}{20}$

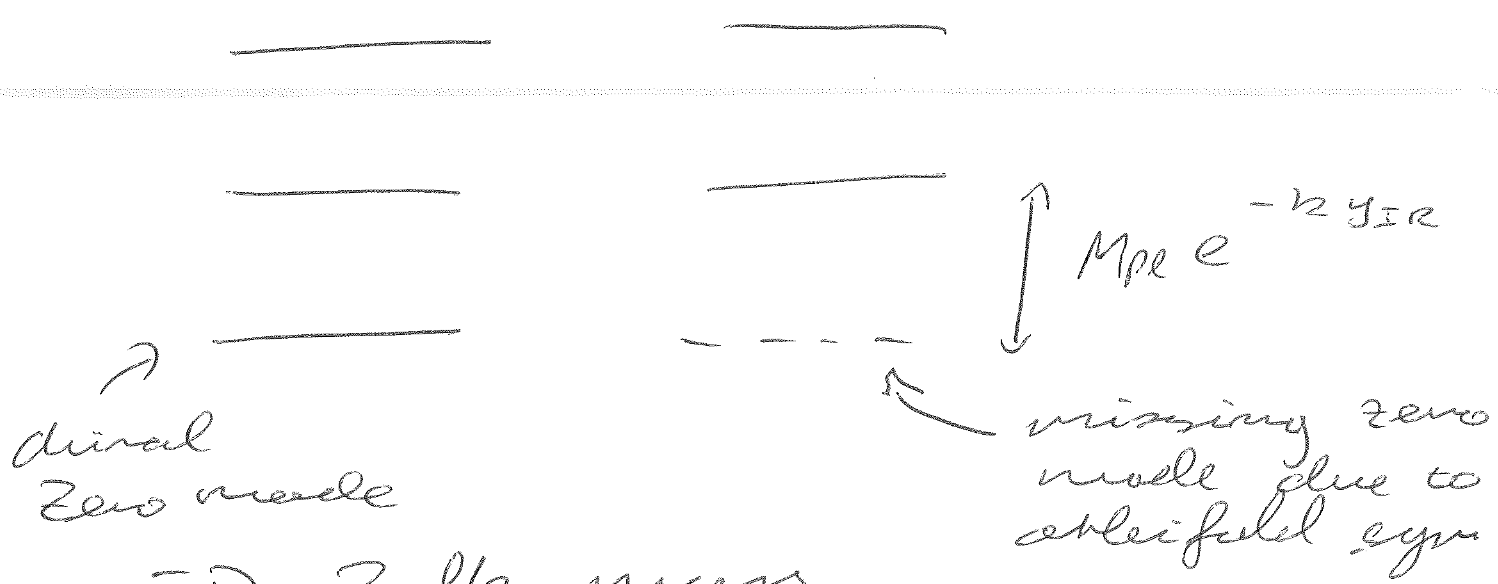
Higgs : $V(H) = \lambda(|H|^2 - v_p^2 \sigma_{IR}^2)^2$

$v_p \sim M_{pl}$

So $\langle H \rangle = v_{EW} \dfrac{\sigma_{IR}}{\sigma_{IR}^{min}}$ depends on the radion.

Fermions





5D Bulk mass

$$S \supset - \int d^5x \sqrt{g}\, c_Q k \bar{Q} Q$$

Profile $f^{(0)}(y) = N e^{(2-c_Q)ky}$

$c_Q > 1/2 \rightarrow$ UV localised

$c < 1/2 \rightarrow$ IR localised.

4D effective Yuk.

$$S \supset \int d^5x \sqrt{g}\, \delta(y - y_{IR})\, \lambda \tilde{H}\, \overline{Q_L^{(0)}} u_R$$

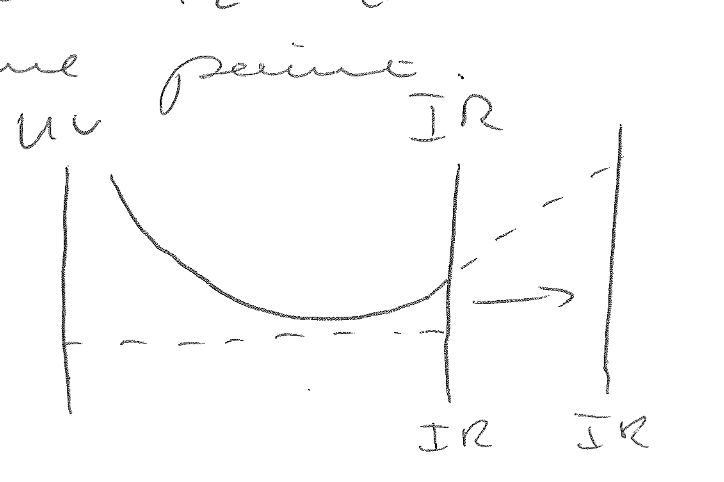
$$H = \sigma_{IR} \tilde{H}$$

But: overlap decreases as IR brane moves away.

One possibility: modify bulk mass term to depend on GW scalar

$$c_Q k \bar{Q} Q \rightarrow \rho_Q \Phi_{GW} \bar{Q} Q$$

Profile $f_L^{(0)}$ turns around at same point.



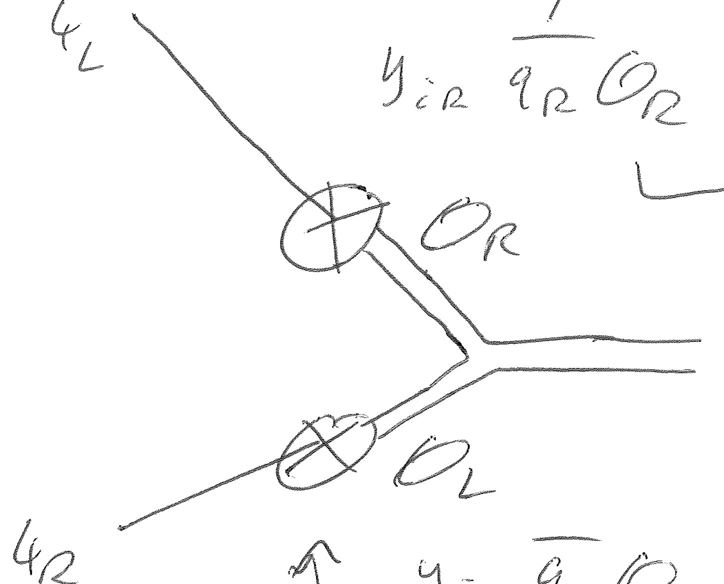
→ Larger Yuk's in sym. EW phase.

CH – Composite Higgs.

$\overline{} \rightarrow$ elementary fermion.

$y_{iR}\, \bar{q}_R\, \mathcal{O}_R$

$\rightarrow$ Composite sector operator.

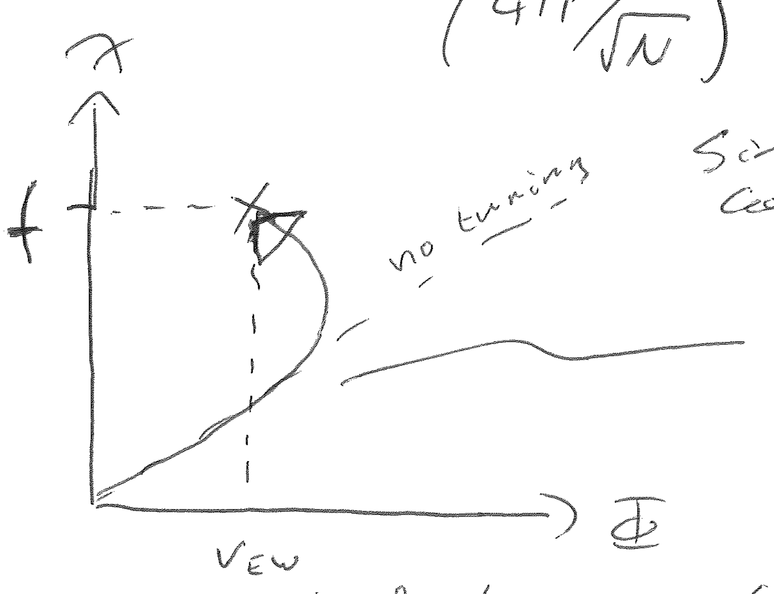


$\rightarrow$ Meson of theory.

$y_{iL}\, \bar{q}_L\, \mathcal{O}_L$

Mixing depends on dilaton $\chi \rightarrow$ meson or glueball. which sets confinement scale.

$$\lambda_q[\chi] \sim \frac{y_{q_L}(\chi)\, y_{q_R}(\chi)}{\left(4\pi/\sqrt{N}\right)}$$



Simultaneous confinement and EWSB non-trivial $\phi(\chi)$ ~~$\rightarrow$ helps~~ $\rightarrow$ required for BAU.

Some tuning required for $V_{EW} < f$.