# Top FCNC in RS

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# FCNC at $t\bar{t}$ Threshold

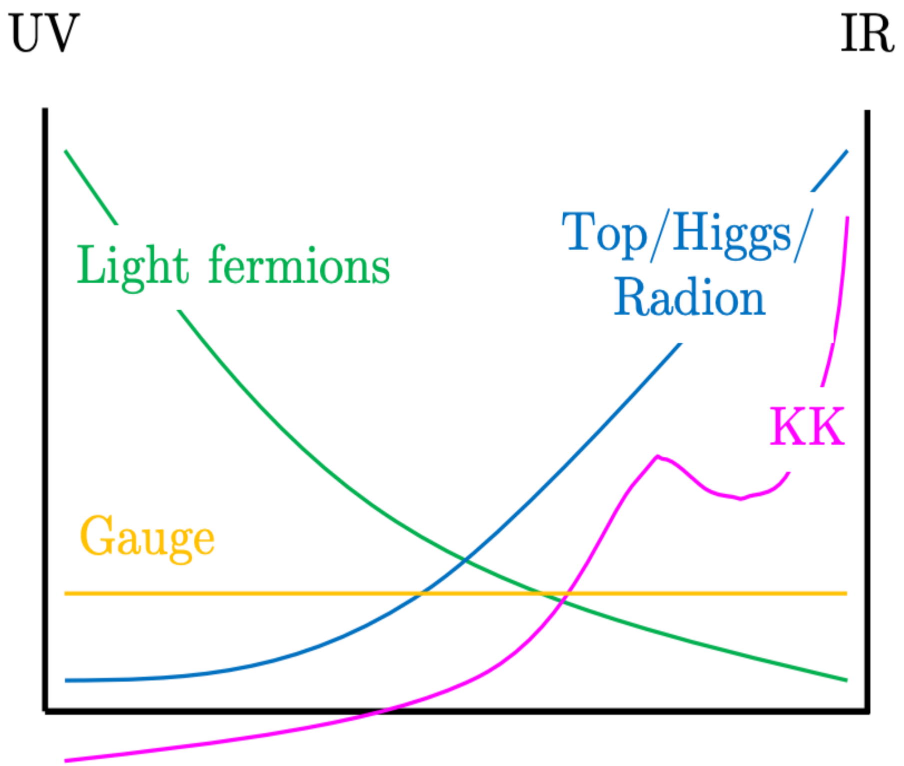
- In SM, flavor violating couplings induced at loop level are very small suppressed by light quark masses $m_b(m_t)^4/m_t^4$
- BSM models explaining the origin of EWSB often lead to level sizable FCNC couplings of top quark

| Process | SM | 2HDM(FV) | 2HDM(FC) | MSSM | RPV | RS |
|---|---|---|---|---|---|---|
| $t \to Zu$ | $7 \times 10^{-17}$ | – | – | $\leq 10^{-7}$ | $\leq 10^{-6}$ | – |
| $t \to Zc$ | $1 \times 10^{-14}$ | $\leq 10^{-6}$ | $\leq 10^{-10}$ | $\leq 10^{-7}$ | $\leq 10^{-6}$ | $\leq 10^{-5}$ |
| $t \to gu$ | $4 \times 10^{-14}$ | – | – | $\leq 10^{-7}$ | $\leq 10^{-6}$ | – |
| $t \to gc$ | $5 \times 10^{-12}$ | $\leq 10^{-4}$ | $\leq 10^{-8}$ | $\leq 10^{-7}$ | $\leq 10^{-6}$ | $\leq 10^{-10}$ |
| $t \to \gamma u$ | $4 \times 10^{-16}$ | – | – | $\leq 10^{-8}$ | $\leq 10^{-9}$ | – |
| $t \to \gamma c$ | $5 \times 10^{-14}$ | $\leq 10^{-7}$ | $\leq 10^{-9}$ | $\leq 10^{-8}$ | $\leq 10^{-9}$ | $\leq 10^{-9}$ |
| $t \to hu$ | $2 \times 10^{-17}$ | $6 \times 10^{-6}$ | – | $\leq 10^{-5}$ | $\leq 10^{-9}$ | – |
| $t \to hc$ | $3 \times 10^{-15}$ | $2 \times 10^{-3}$ | $\leq 10^{-5}$ | $\leq 10^{-5}$ | $\leq 10^{-9}$ | $\leq 10^{-4}$ |

Snowmass 2013 Top quark working group report

# Top FCNC RS

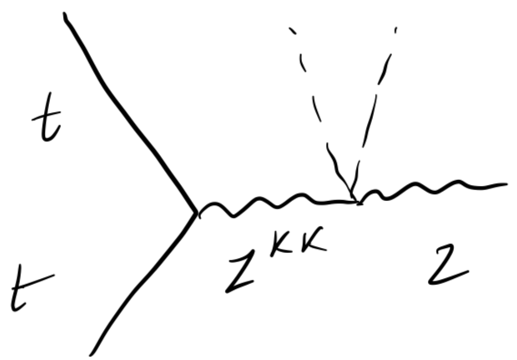
- All SM particles are “zero” modes of 5D fields
- All the KK modes appear roughly at the same scale
- In the flavor basis, KK gauge bosons have non-universal couplings to SM fermions
- $Z_{KK}$ mixes with SM Z through Higgs
- Leads to flavor violating coupling of SM Z in the mass basis

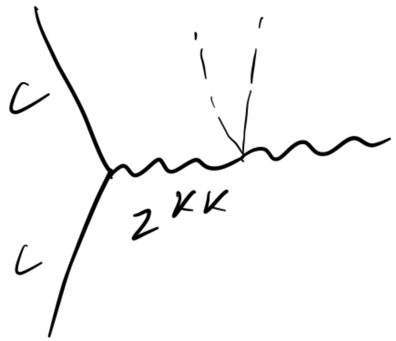


# RS Feynman Diagrams

- Diagrammatically this is $t \to Z c$

$$g_Z Z^{(n)}_{\mu} \left(\bar{t}_{L\,weak}\ \ \bar{c}_{L\,weak}\right) \begin{pmatrix} a_t & 0 \\ 0 & a_c \end{pmatrix} \begin{pmatrix} t_{L\,weak} \\ c_{L\,weak} \end{pmatrix}$$

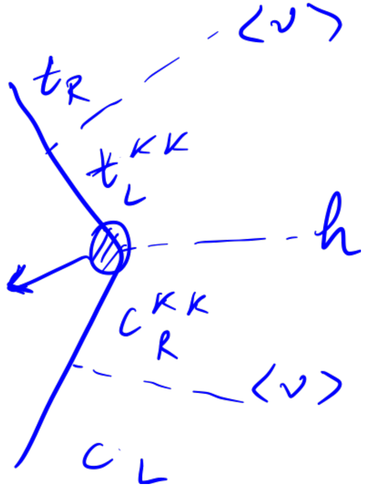



$$\longrightarrow\ g_Z Z^{(n)} \left(\bar{t}_{L\,mass}\ \ \bar{c}_{L\,mass}\right) U_L^{\dagger} \begin{pmatrix} a_t & 0 \\ 0 & a_c \end{pmatrix} U_L \times \begin{pmatrix} t_{L\,mass} \\ c_{L\,mass} \end{pmatrix}$$

For $t \to h c$

$$\lambda_{5D}^{R} \sim g_4 \sqrt{k \pi r}$$



# Top FCNC RS

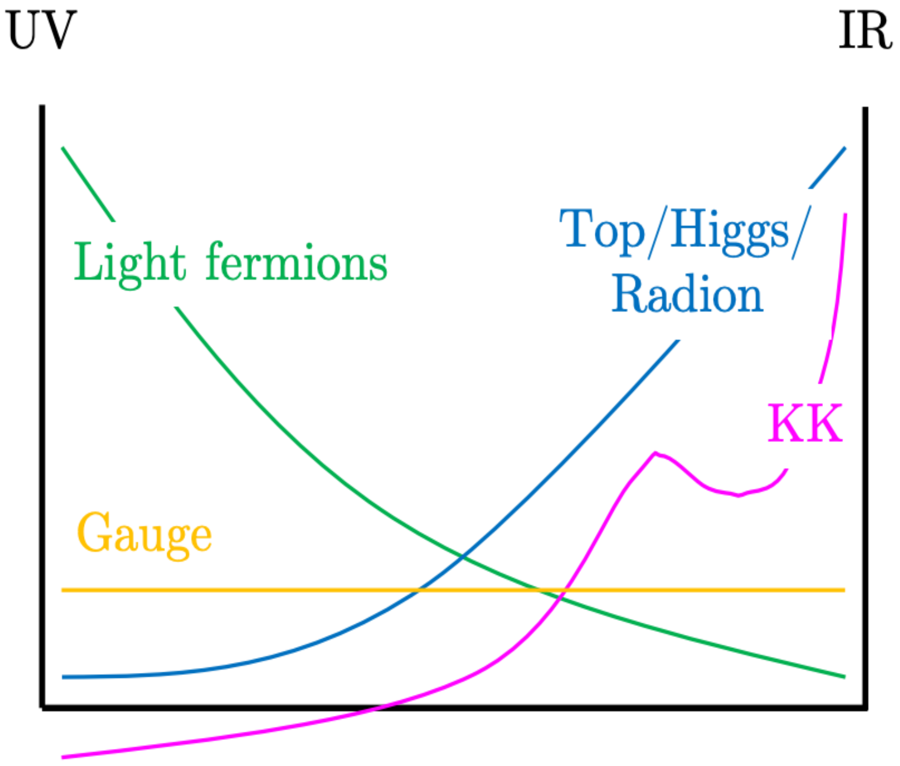
- $Z_{KK}$ mixes with SM Z through Higgs
- flavor violating coupling of SM Z in the mass basis

$$\mathcal{L}^t_{\rm FC} \ni \left(g_1 \bar{t}_R \gamma_\mu c_R + g_2 \bar{t}_L \gamma_\mu c_L\right) Z^\mu g_Z \,,$$

with

$$g_{1,2} \sim \left[5\cdot 10^{-3}\frac{(U_R)_{23}}{0.1}, 4\cdot 10^{-4}\frac{(U_L)_{23}}{0.04}\right]\left(\frac{3\ \rm TeV}{m_{KK}}\right)^2$$

$$\mathrm{BR}\left(t\to cZ\right) \sim 10^{-5}\left(\frac{3\ \ \rm TeV}{m_{KK}}\right)^4\left(\frac{(U_R)_{23}}{0.1}\right)^2 .$$




***Agashe, Kaustubh and Perez, Gilad and Soni, Amarjit, arxiv:0606293***

# Top FCNC RS

$$\mathrm{BR}\,(t \to cZ) \sim 10^{-5} \left(\frac{3\ \text{TeV}}{m_{KK}}\right)^4 \left(\frac{(U_R)_{23}}{0.1}\right)^2 .$$

$$U_R^{23} \sim \frac{m_c}{m_t \lambda_{CKM}^2}$$

- $m_{KK}$ is a crucial input
- $(U_R)_{23}$ cannot be moved easily
- Previously, strongest constraints on $m_{KK}$ came from EWPT (LEP)
- But LHC has been collecting a lot of data
- ATLAS/CMS use simplified models

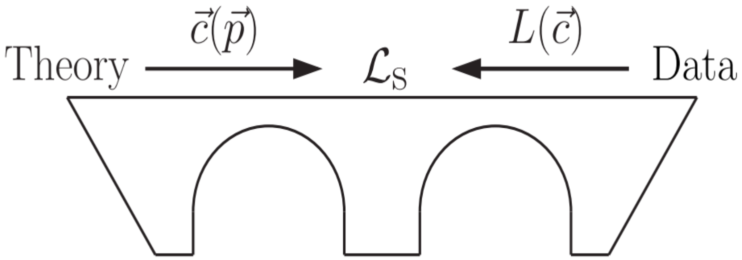



Figure 1.1: Pictorial view of the Bridge Method.

| Channel | HVT-A Exclusion Limit Observed [TeV] | HVT-A Exclusion Limit Expected [TeV] | HVT-B Exclusion Limit Observed [TeV] | HVT-B Exclusion Limit Expected [TeV] |
|---|---|---|---|---|
| $VV$ | 4.2 | 4.0 | 4.3 | 4.2 |
| $VH$ | 3.6 | 3.6 | 3.9 | 3.9 |
| $VV + VH$ | 4.2 | 4.2 | 4.5 | 4.4 |
| $\ell\ell + \ell\nu + \tau\nu$ | 5.8 | 5.6 | 3.2 | 2.7 |
| $VV + VH + \ell\ell + \ell\nu + \tau\nu$ | 5.8 | 5.6 | 4.5 | 4.4 |

Table 2: 95% C.L. lower observed and expected mass limits on the HVT-A and HVT-B benchmark for the $q\bar{q}$ production mode. Limits are quoted to the nearest 100 GeV.

**Pappadopulo et. al. arXiv:1402.4431v2**

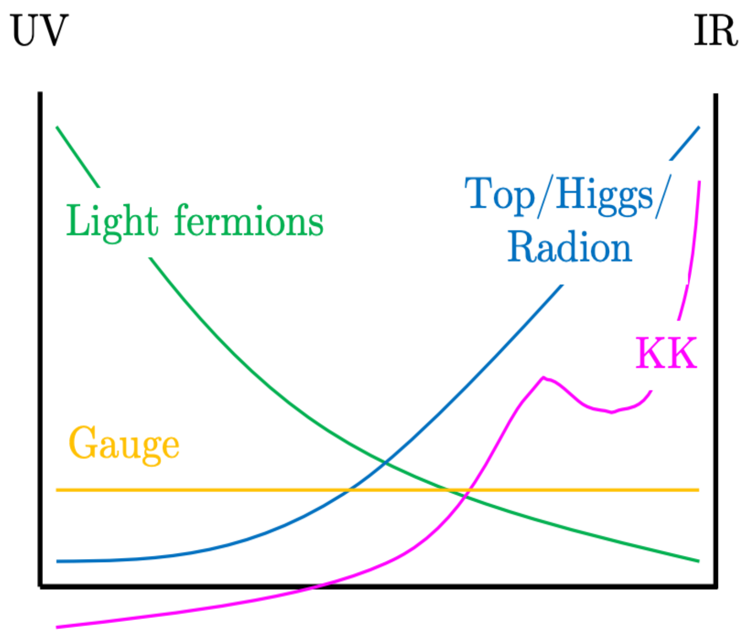
**ATLAS-CONF-2022-028**

# Top FCNC RS

- HVT model –

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left( \mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right),$$

- Very much like RS $W_{KK}/Z_{KK}$ when $g_H \gtrsim 1$ and $g_{q,l} \ll 1$ (HVT-B)

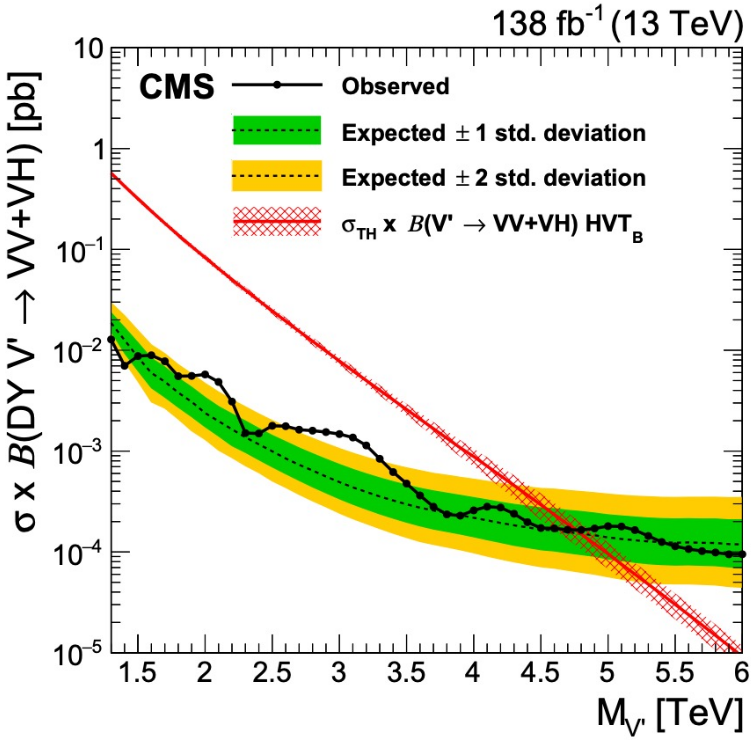


# Top FCNC RS

- HVT model –

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left( \mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right),$$

- Very much like RS $W_{KK}/Z_{KK}$ when $g_H \gtrsim 1$ and $g_{q,l} \ll 1$ (HVT-B)
- Recast needs to be done because of slightly different couplings, hence different production rates and branching ratios

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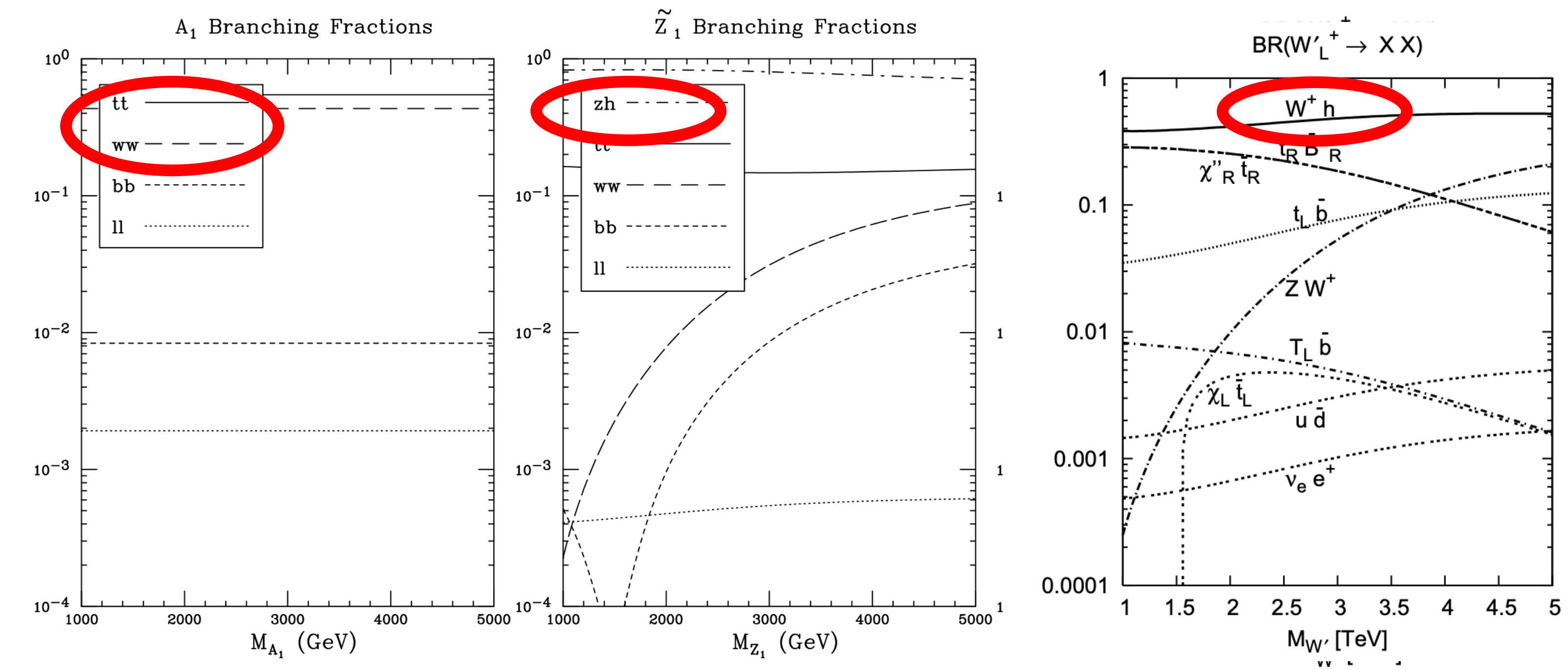
# Top FCNC RS

- HVT- B vs RS couplings

$$\frac{g^2}{2g_V}\bar{q}\gamma^{\mu}(1-\gamma^5)\sigma^a q W_{a,\mu} \quad \text{v.s.} \quad \frac{g_Z}{\sqrt{k\pi r_c}}\bar{q}\gamma^{\mu}(t^3L\ - Q\sin^2\theta)\, q\, Z_{KK,\mu}$$

- Branching Ratios
  - HVT-B VV(VH) ≈50%
  - RS less trivial

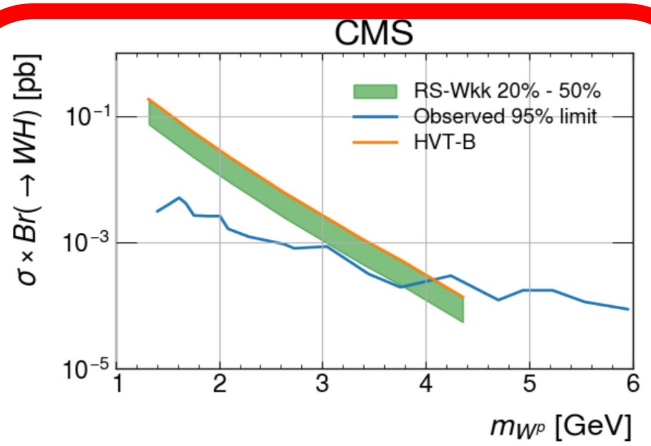


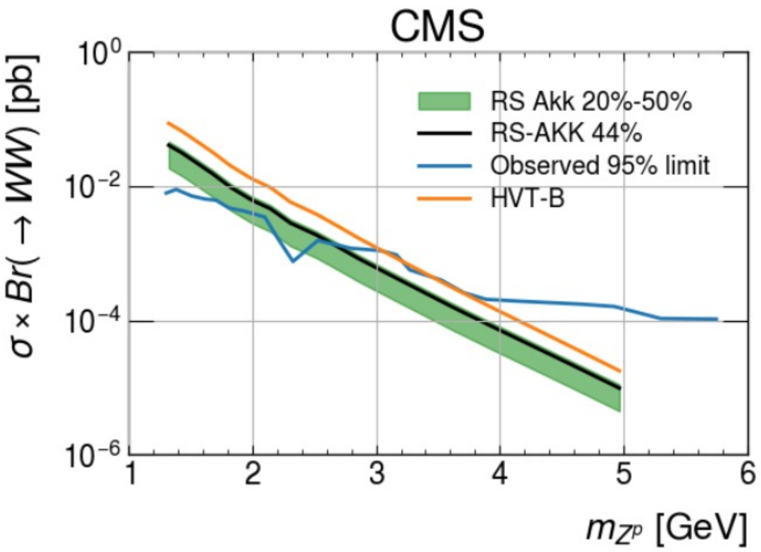

- $t\bar{t}$ final state also relevant for $A_{KK}$

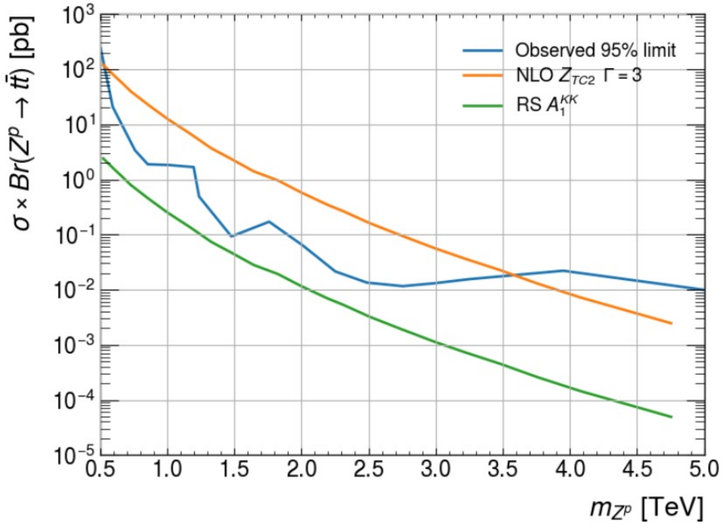
Agashe et. al. arXiv:0810.1497, arXiv:0709.0007

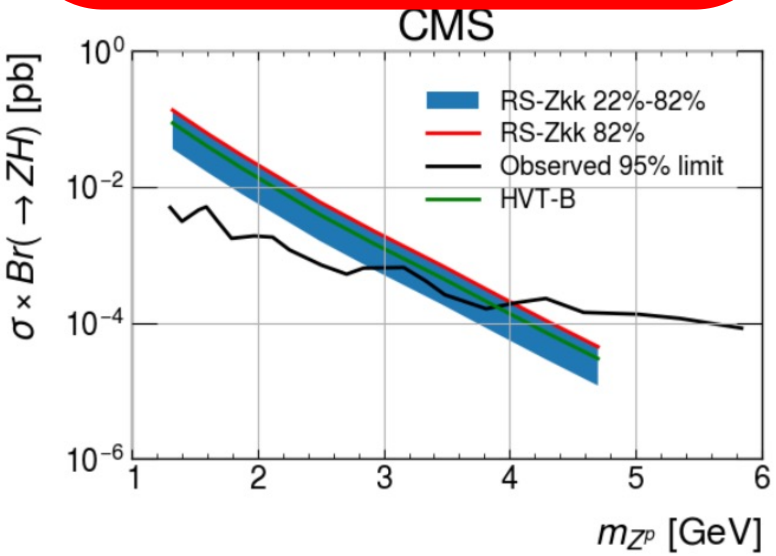
# Top FCNC RS

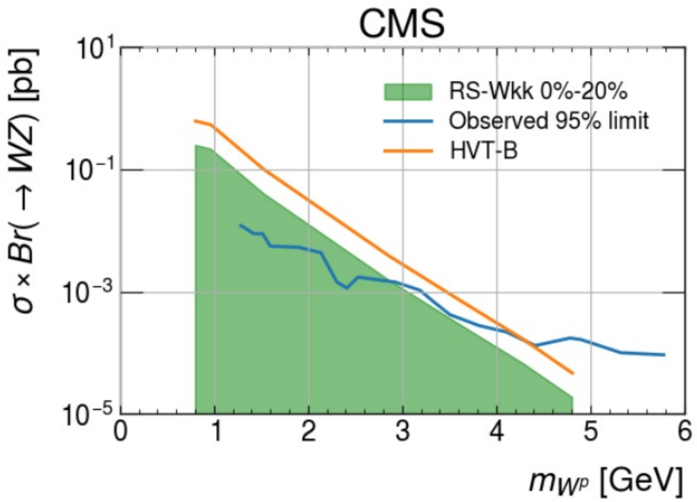
- Recast $m_{EW_{KK}} > 3.7\ TeV$ with $138\ fb^{-1}$ 13 TeV data
- Channels ZH, WW, WH, ZW, ttbar



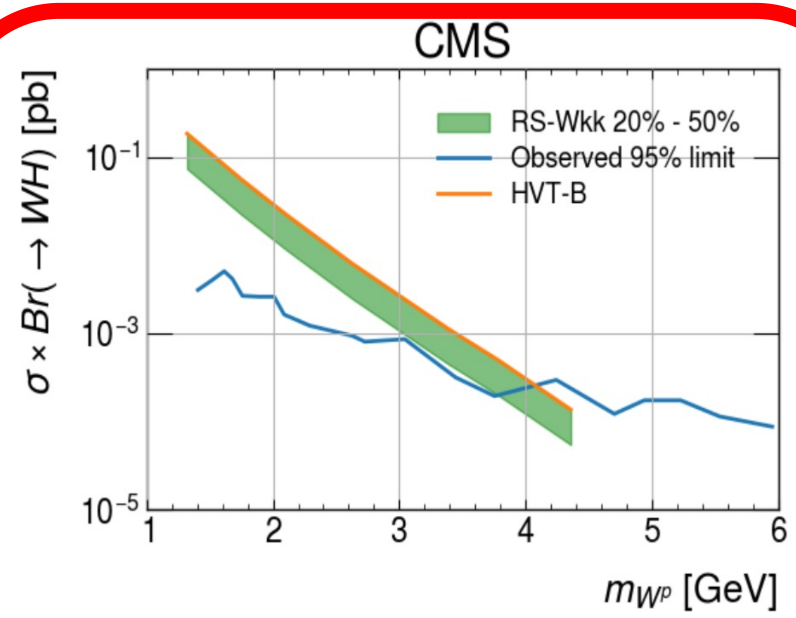



# Top FCNC RS

- Recast 138 $fb^{-1}$ 13 TeV CMS and ATLAS data
- Channels ZH, WW, WH, ZW, ttbar
- Current bound $m_{KK} > 3.7\ TeV$
- At HL-LHC 3 $ab^{-1}$ we expect it to go to roughly 5 $TeV. \Rightarrow Br(t \to cZ) \approx 1.2 \times 10^{-6}$



# Single Top Production

- How does single top production at Higgs Factory perform in comparison to the ttbar threshold run?
- EFT parametrization of FCNC

$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j),$$

$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j),$$

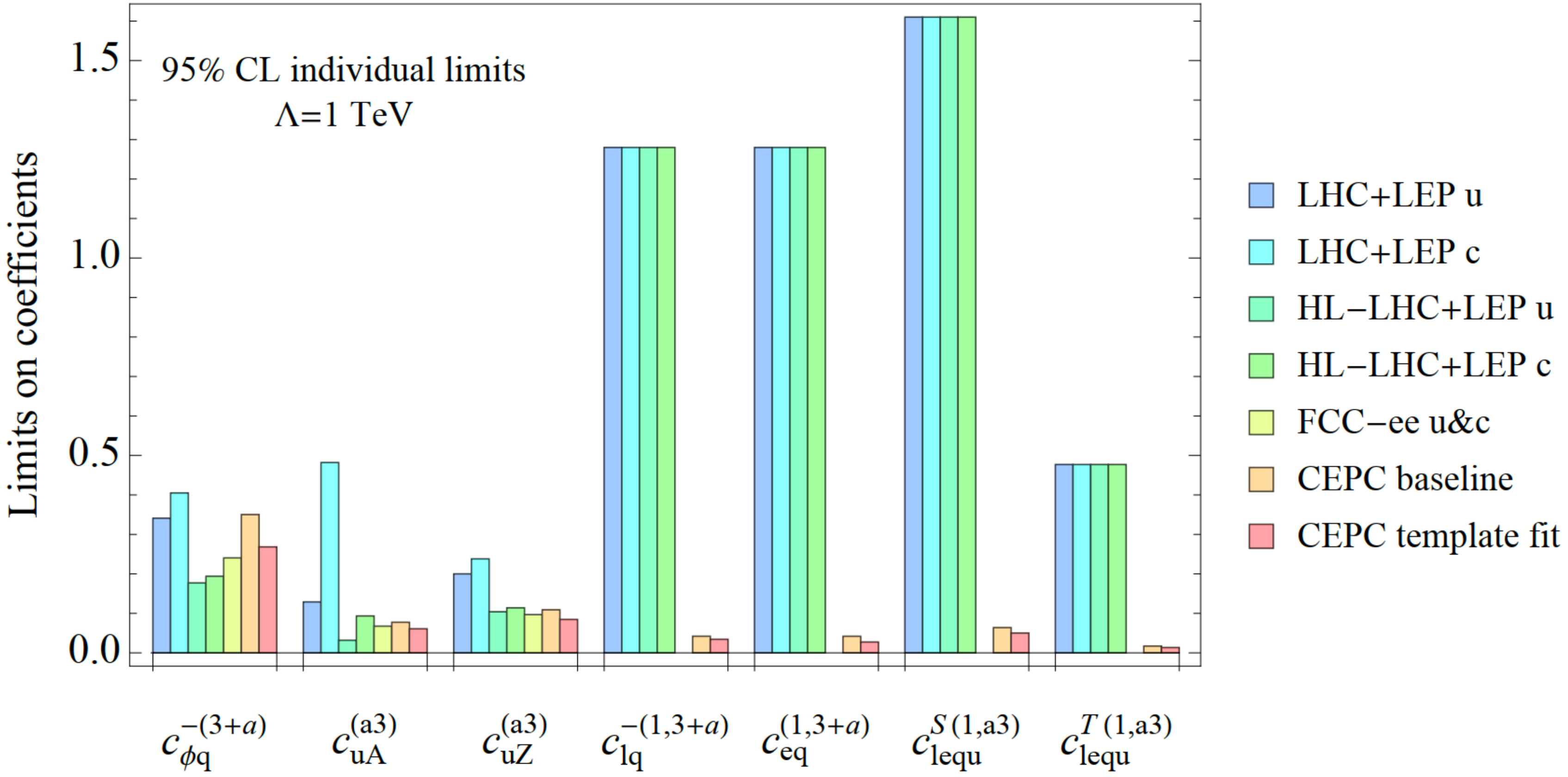
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j),$$

$$O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\,\tilde{\varphi} W^I_{\mu\nu},$$

$$O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j)\,\tilde{\varphi} B_{\mu\nu},$$

# Single Top Production

- These expected bounds roughly translate to ~ few $\times 10^{-6}$ top quark
- We verified the results using MadGraph (dim6top) simulations and implementing crucial detector effects manually for FCC-ee




J. A. Aguilar Saavedra et. al. arXiv:1802.07237

Liaoshan Shi, Cen Zhang 2019

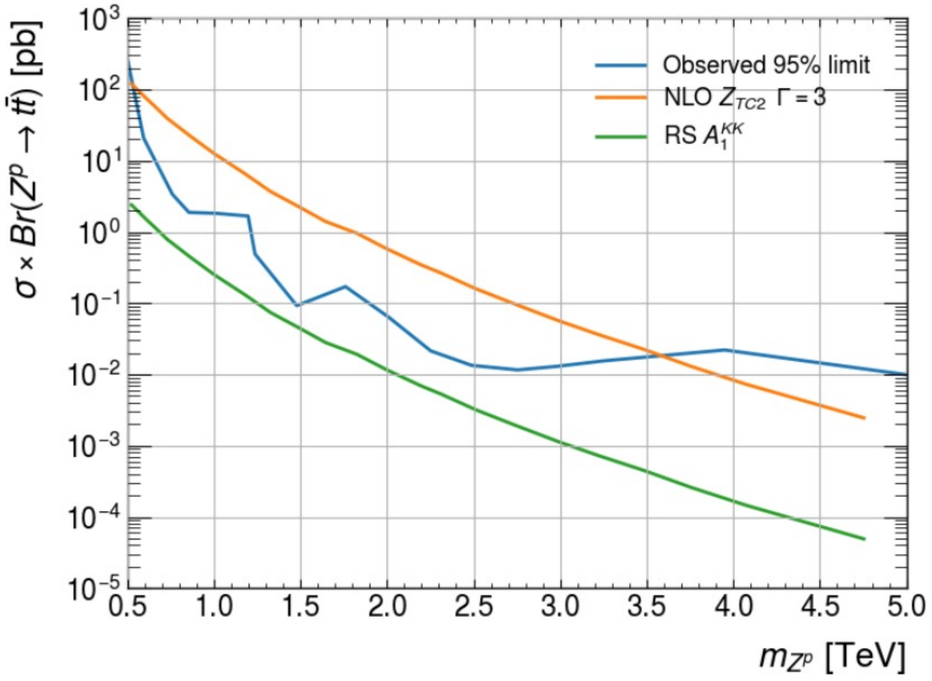
# Takeaways

- Constraint from direct searches will bring down $t \to c\, Z$ decay in RS model to branching fractions close to $\sim 10^{-6}$
- FCC-ee Z pole will maybe also push the kk scale to at least 10 TeV
- Single top is not too bad either for $t \to c\, Z$ decays

# Backup

# $t\bar{t}$ final state RS FCNC

- ATLAS puts a constraint on $Z_{TC2}$ model
- $\frac{\sigma_{RS}}{\sigma_{TC2}} \approx 1/75$ and $\frac{BR^{RS}}{BR^{TC2}} \approx \frac{3}{2}$



# RS Flavor

$$m_{u^i,d^i} \sim \frac{2v\lambda_{5D}k}{f_{Q^i}f_{u^i,d^i}},$$

$$\left|(D_L)_{ij}\right| \sim \left|(U_L)_{ij}\right| \sim \left|(V_{\mathrm{CKM}})_{ij}\right| \sim \frac{f_{Q^i}}{f_{Q^j}} \quad \text{for} \quad j \leq i\,,$$

$$\left|(U_R, D_R)_{ij}\right| \sim \frac{f_{u^i,d^i}}{f_{u^j,d^j}} \quad \text{for} \quad j \leq i\,,$$

**Agashe et.al. : arXiv 040813**