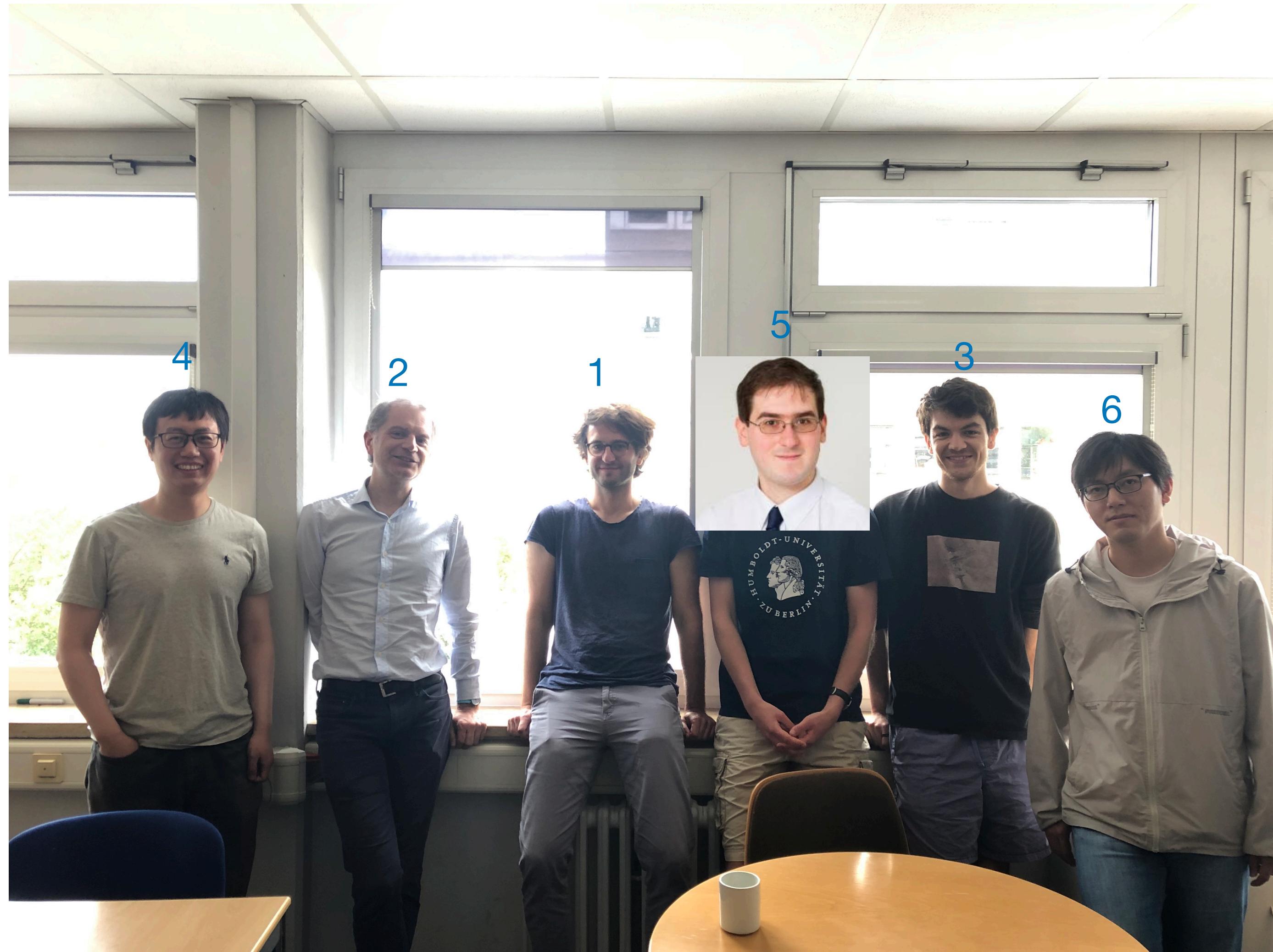


# Inverse Hierarchy MFV Quark Dipole

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# Outline

- Lightning review of MFV: A Loophole in a statement
- Light quark dipole: Chiral Enhancement and naturalness
- Low energy Flavor bounds: Neutral Kaon oscillation and Charged pion decay
- Signal in FCC-hh:  $pp \rightarrow Wh$ , profile over  $(c_{uW}, c_{\varphi q}^{(3)})$

# MFV

SM Lagrangian       $\mathcal{L} = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + \bar{L}_L Y_E E_R H + \text{h.c.} ,$

Flavor Symmetry       $G_F \equiv \text{SU}(3)_q^3 \otimes \text{SU}(3)_\ell^2 \otimes \text{U}(1)_B \otimes \text{U}(1)_L \otimes \text{U}(1)_Y \otimes \text{U}(1)_{\text{PQ}} \otimes \text{U}(1)_{E_R} ,$

Spurion:       $Y_U \sim (3, \bar{3}, 1)_{\text{SU}(3)_q^3} ,$

## Dim-6 Operators in SMEFT

$$\mathcal{O}_{\varphi q}^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L) \left( i H^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H \right)$$



$$\mathcal{O}_{uW} = W_{\mu\nu}^a \bar{Q}_L \tau^a \sigma^{\mu\nu} U_R \tilde{H}$$



In MFV SMEFT, the Yukawa couplings are the only source of the flavor violation.

# A Loophole in A Statement

Statement: The 1st family flavor violating Wilson coefficients are suppressed by light Yukawa coupling.

e.g.

$$C_{uW} \propto Y_u(Y_u Y_u^\dagger)^n \sim (3, \bar{3}, 1), \quad n = 1, 2, 3, \dots \quad \rightarrow \quad \left| \frac{C_{uW}^{11}}{C_{uW}^{33}} \right| \ll 1$$

However, this is not always true. If we define

$$\tilde{Y} = (Y^\dagger)^{-1}$$

We then find:

$$\tilde{Y}_u \sim (3, \bar{3}, 1), \quad \tilde{Y}_d \sim (3, 1, \bar{3}), \quad \dots$$

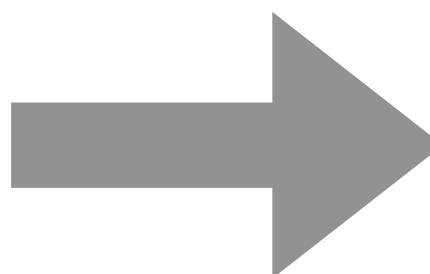
# Inverse Hierarchy

$\tilde{Y}$  and  $Y$  are simultaneously diagonal in the mass basis:

$$Y_u \propto \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

$$\tilde{Y}_u \propto \begin{pmatrix} \frac{1}{m_u} & 0 & 0 \\ 0 & \frac{1}{m_c} & 0 \\ 0 & 0 & \frac{1}{m_t} \end{pmatrix}$$

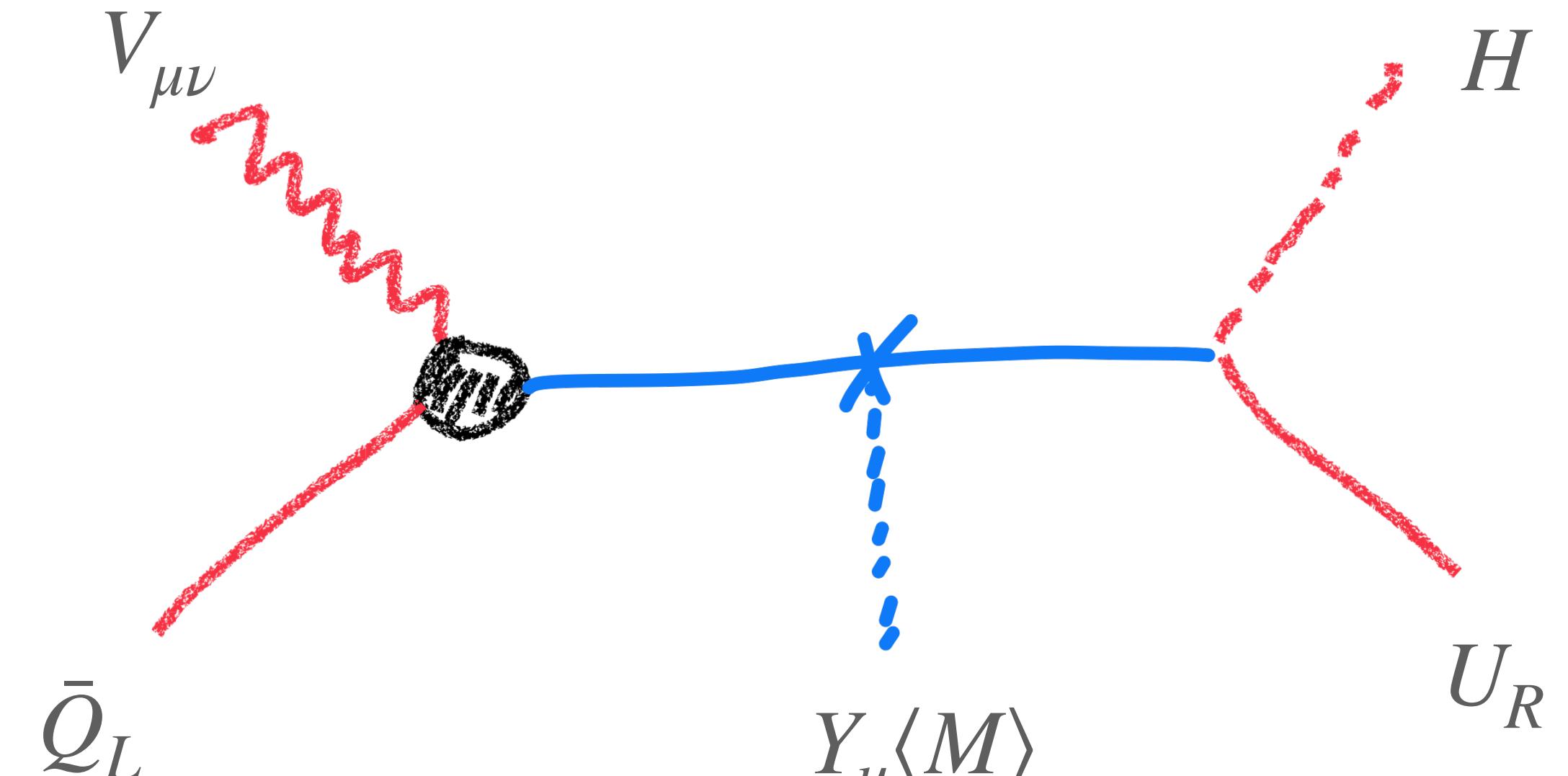
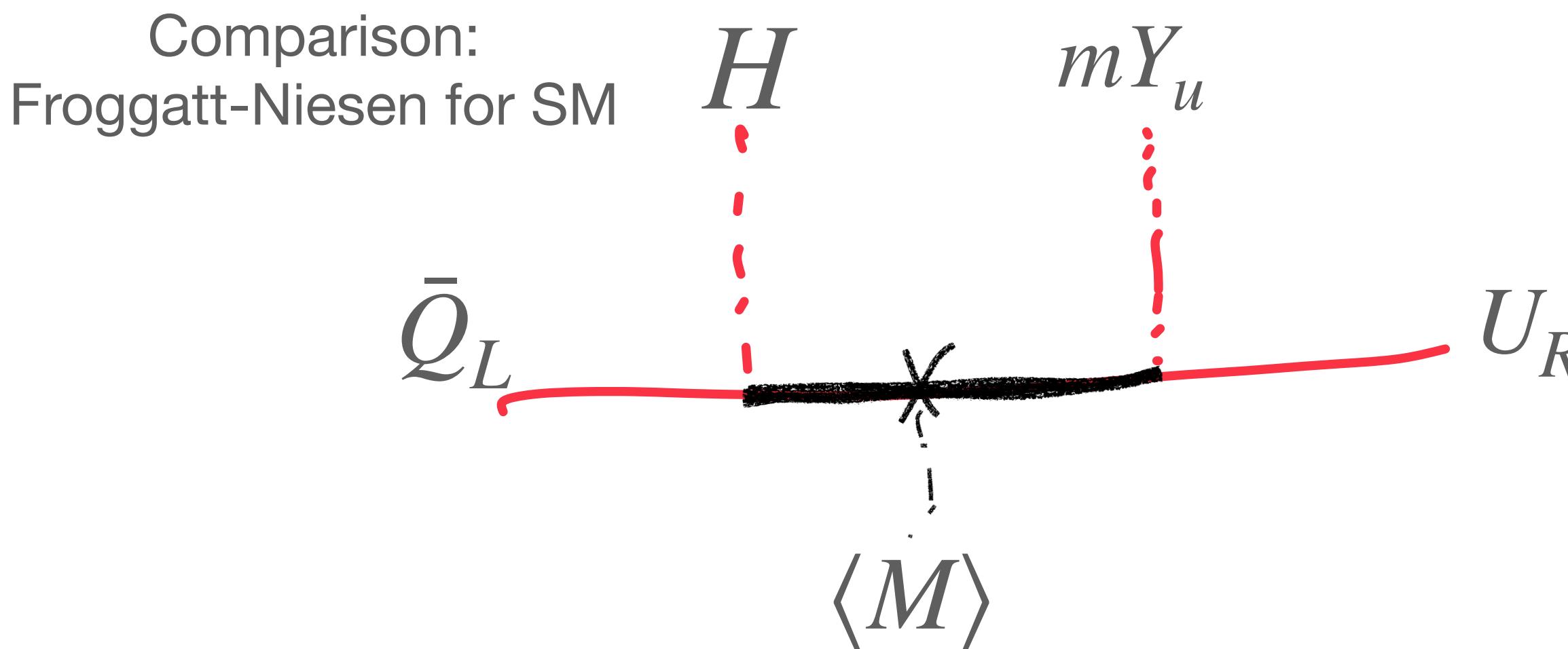
$$C_{uW} \propto \tilde{Y}_u$$



$$\left| \frac{C_{uW}^{11}}{C_{uW}^{33}} \right| \gg 1$$

# Inverse Hierarchy via Seesaw

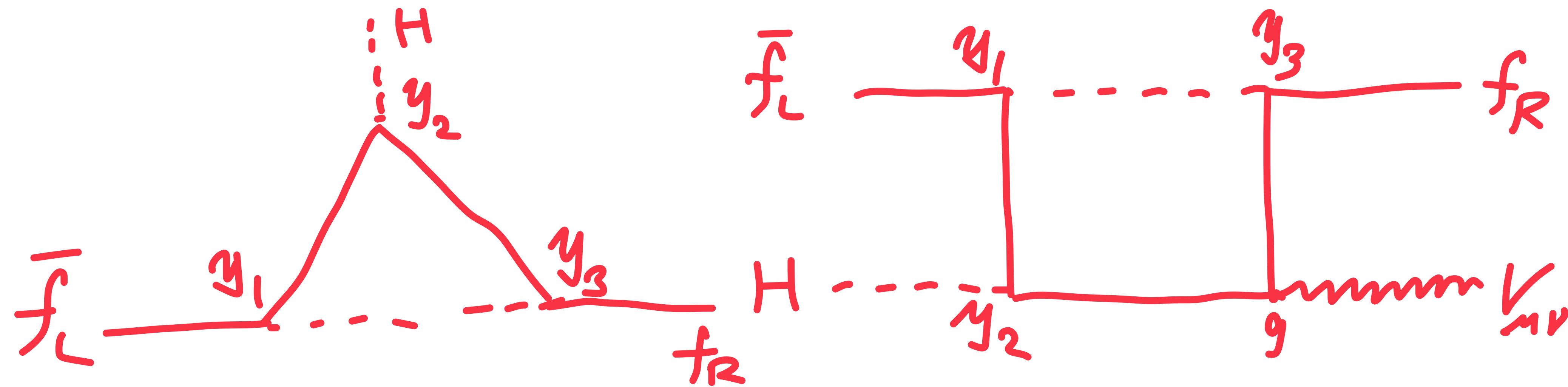
$$\mathcal{L} = \frac{1}{f} \bar{Q}_L \sigma^{\mu\nu} V_{\mu\nu} \bar{X}_L - X_R Y_u^\dagger M^\dagger \bar{X}_L + X_R \tilde{H} U_R + h.c.$$



$$\frac{1}{f} \bar{Q}_L \sigma^{\mu\nu} V_{\mu\nu} \left( \frac{1}{Y_u^\dagger M} \right) U_R \tilde{H}$$

# Correction to Yukawa Coupling

- $\delta Y_f H \bar{f}_L f_R$  and  $C_{fV} \bar{f}_L \sigma^{\mu\nu} V_{\mu\nu} f_R H$  flip the chirality.
- In most UV models the two operators come together



- $16\pi^2 \delta Y_f \sim y_1 y_2 y_3 \ln \left( \frac{M}{\mu} \right)$
- $16\pi^2 C_{fV} \sim \frac{g y_1 y_2 y_3}{M^2}$
- e.g. models for  $(g - 2)_\mu$  via the chiral enhancement.

# $Z_2$ Cancellation

$$\mathcal{L}_{\text{eff}} \supset \bar{Q}_L H_R \frac{1}{M} \left( F_X S_X^\dagger + F_Y S_Y^\dagger \right) + \left( \bar{F}_X S_X - \bar{F}_Y S_Y \right) \frac{C_R}{M} H_L Q_R + h.c.$$

$$SU(2)_R : \quad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \quad H_R = \begin{pmatrix} H_R^+ \\ H_R^0 \end{pmatrix} \quad Z_2 \text{ Symmetry: } X \leftrightarrow Y, \quad C_R \leftrightarrow -C_R$$

$H_R$



$$\begin{pmatrix} 0 \\ v_R \end{pmatrix}$$

**Yukawa**

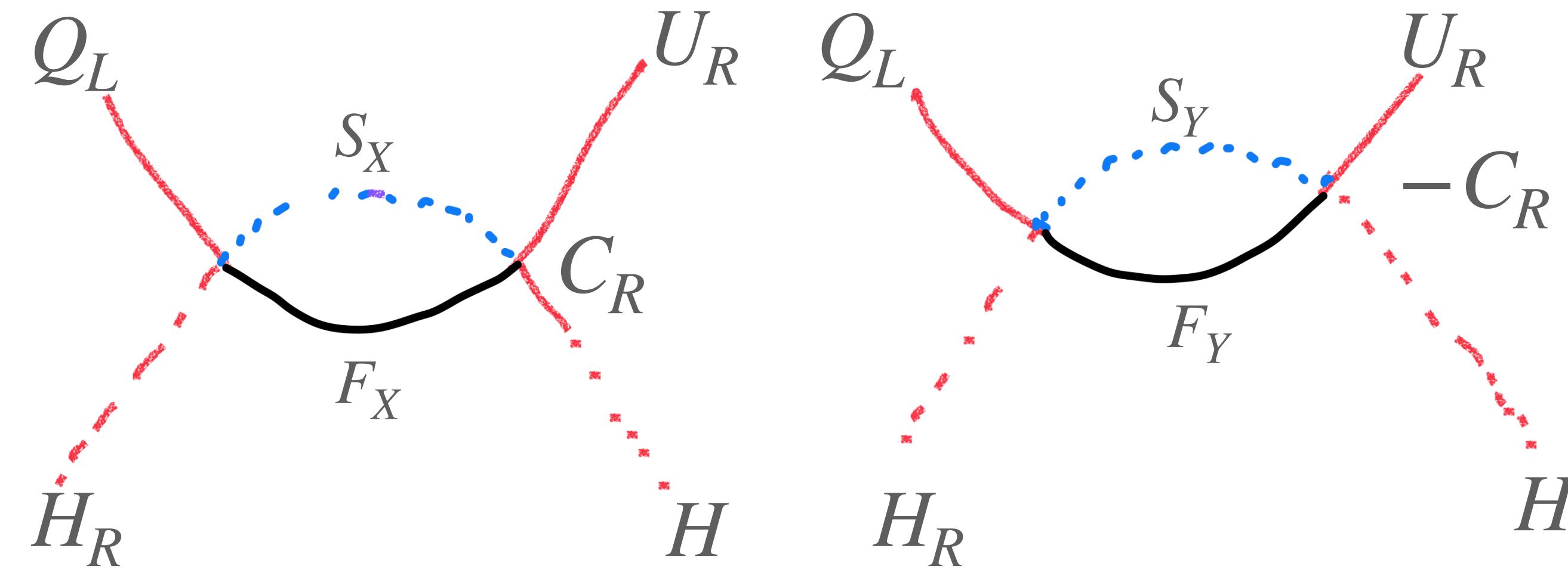
$SU(2)_R$  SSB

$$\frac{1}{M} \begin{pmatrix} \bar{Q}_L H_L H_R Q_R \\ \bar{Q}_L H_L \sigma^{\mu\nu} H_R Q_R F_{\mu\nu} \end{pmatrix}$$

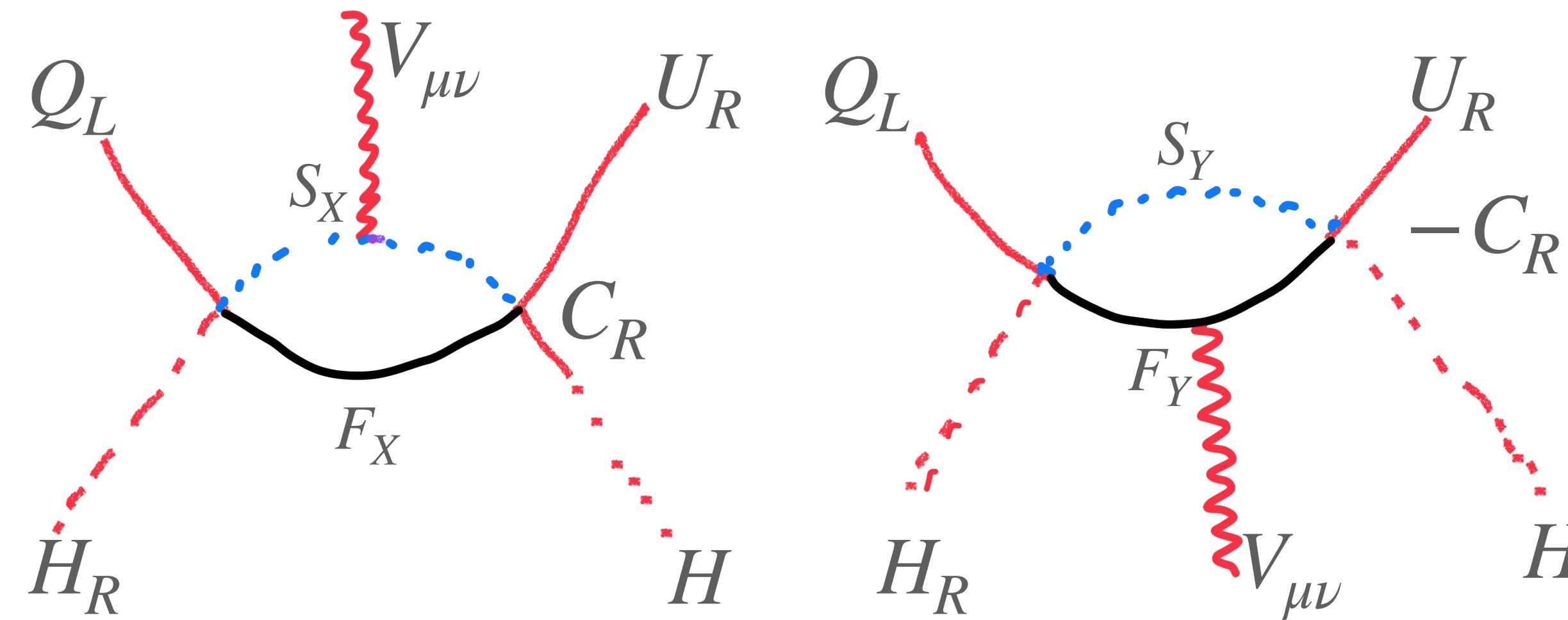


$$\frac{v_R}{M} \begin{pmatrix} \bar{Q}_L H_L u_R \\ \bar{Q}_L H_L \sigma^{\mu\nu} u_R F_{\mu\nu} \end{pmatrix}$$

**Dipole**



Yukawa correction,  $\delta Y_u \propto C_R$ , is forbidden by the  $Z_2$  symmetry

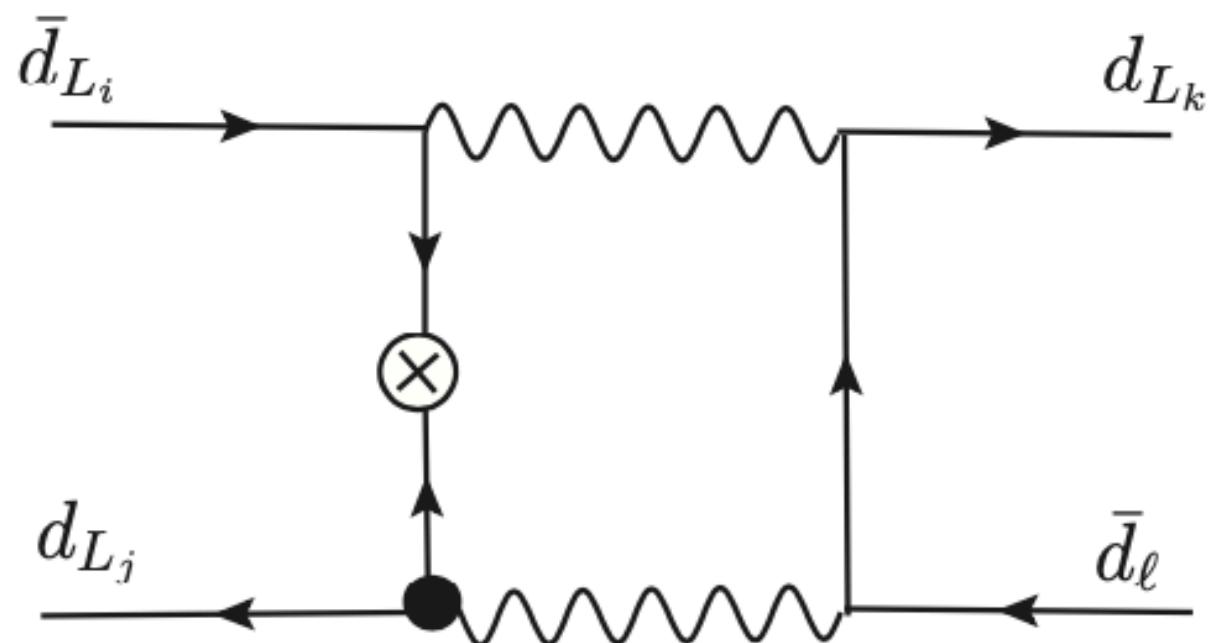


$Z_2$  is broken by gauge interaction, dipole operators,  $CuV \propto gC_R$  are no vanishing.

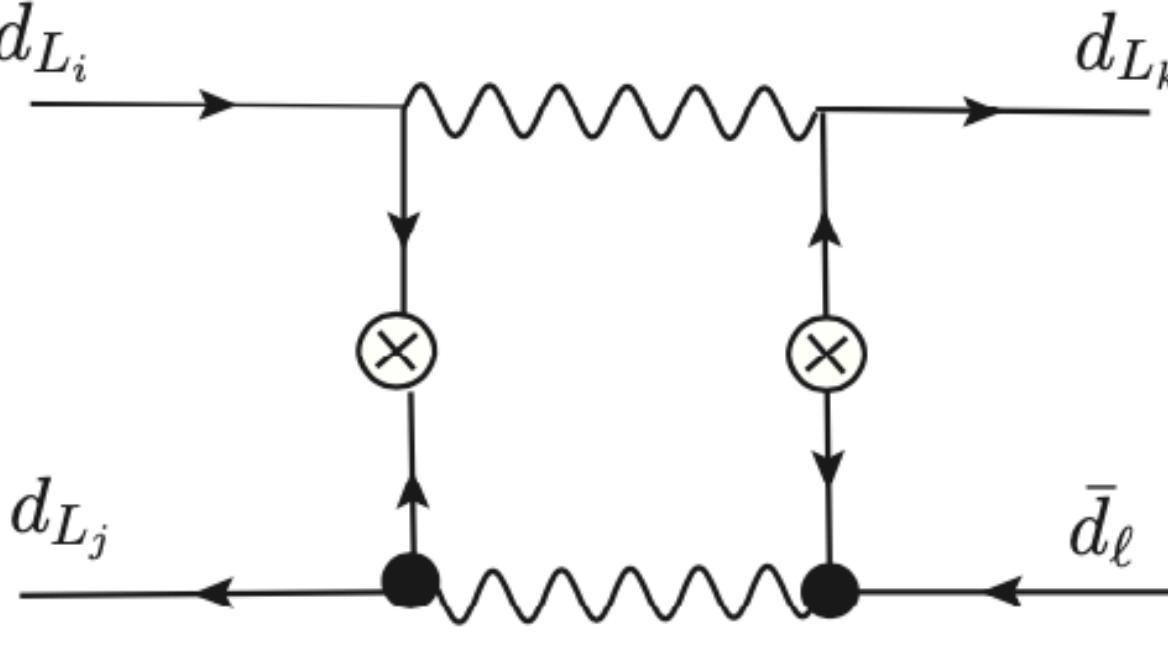
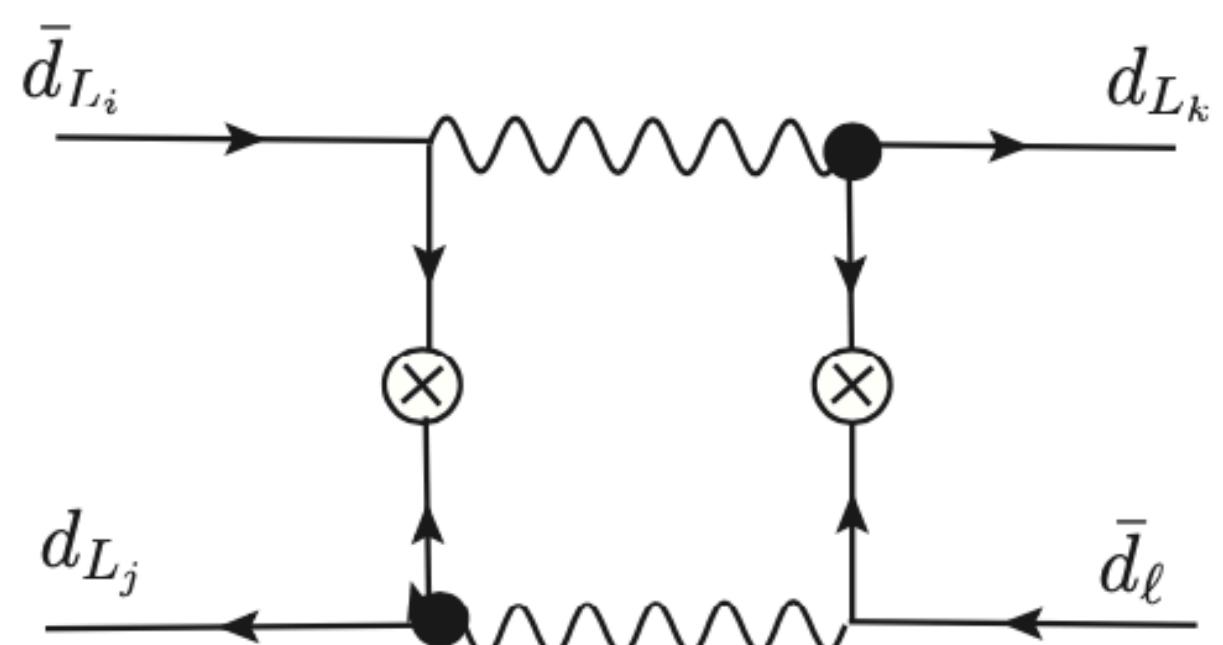
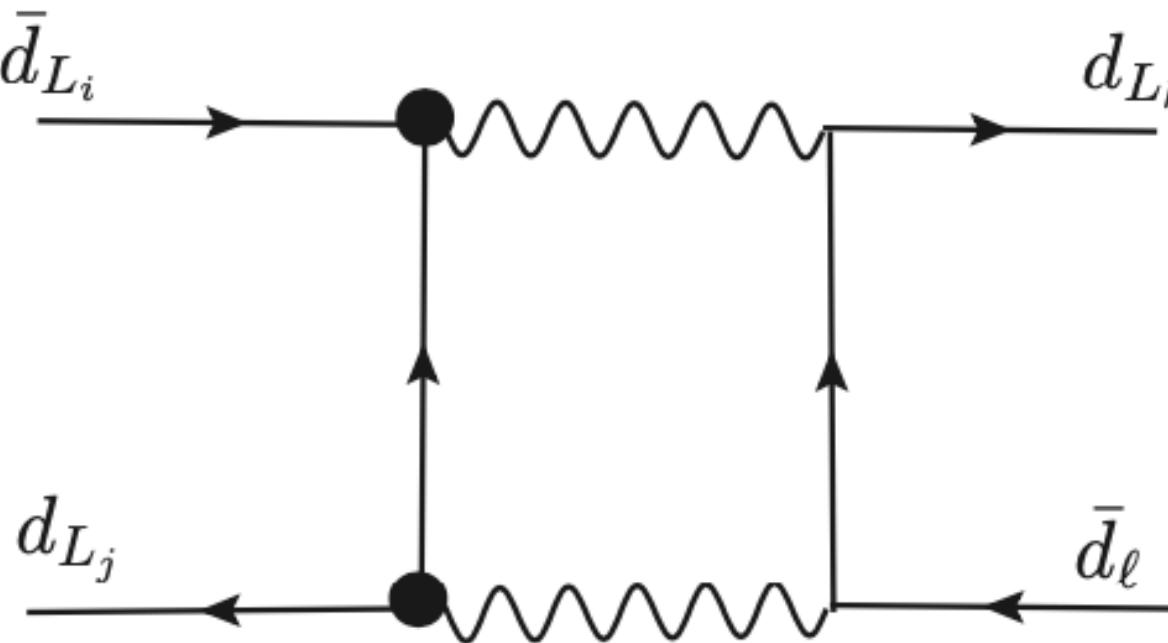
# Low Energy bounds

## 1) $\bar{K}^0 - K^0$ oscillation

$$y_u V_{\text{ckm}}^\dagger V_{\text{ckm}} C_{uW} \bar{d}_L d_L \bar{d}_L d_L$$



$$V_{\text{ckm}}^\dagger V_{\text{ckm}} C_{uW}^2 \bar{d}_L d_L \bar{d}_L d_L$$



$$y_u^2 \bar{d}_L d_L \bar{d}_L d_L$$

$$\left[ V_{\text{ckm}}^\dagger V_{\text{ckm}} \right]_{12} = 4.7 \times 10^{-4} \pm 4.6 \times 10^{-3}$$

$$y_u = 1.2 \times 10^{-5}$$

## 2) $\pi^+ \rightarrow e^+ \nu \gamma$ decay

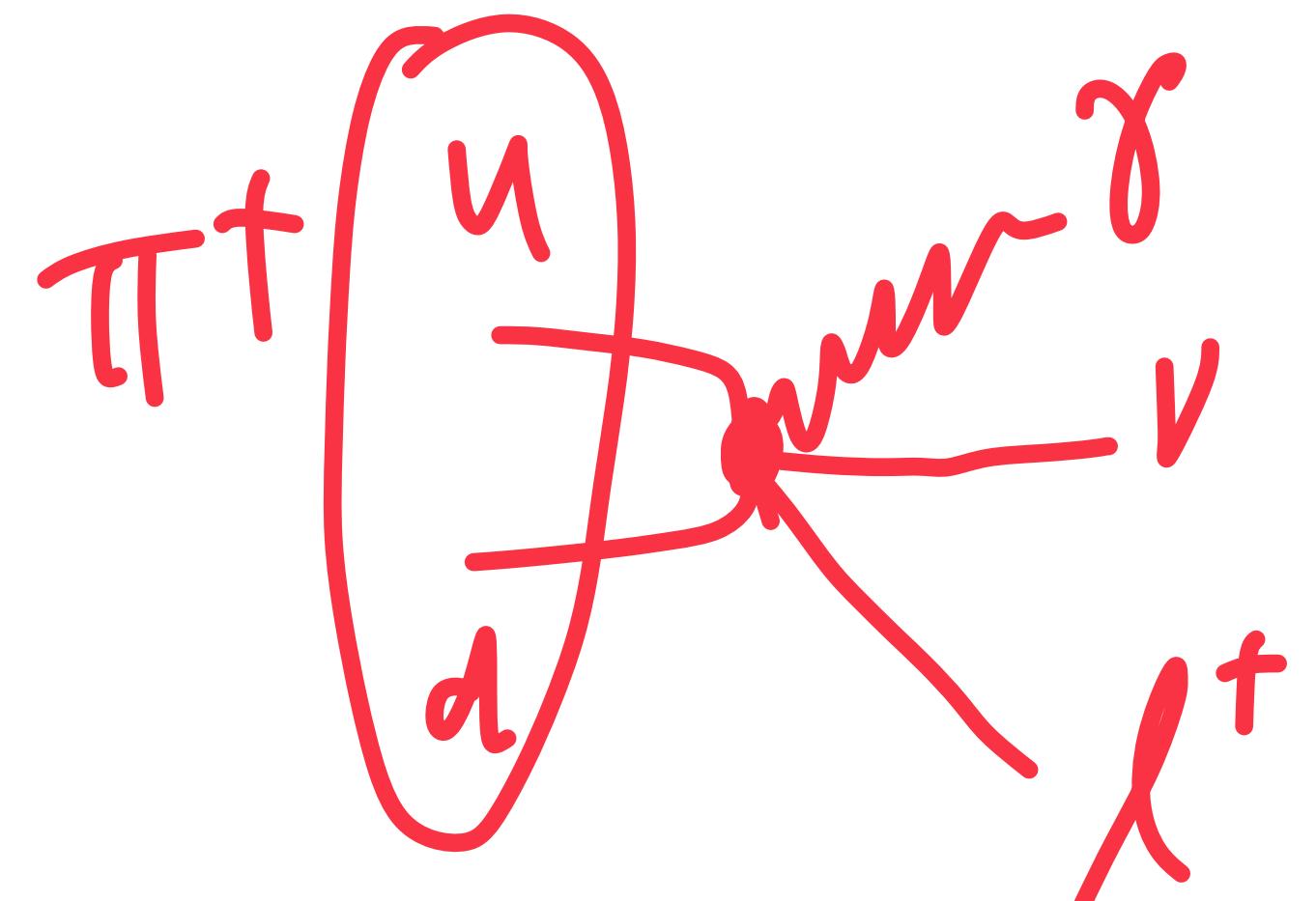
- Quark dipole may induce the charged meson decay.

$$\frac{1}{f} u_L^\dagger \sigma_{\mu\nu} d_R W^{\mu\nu} + W_\mu e \gamma^\mu \nu_e \xrightarrow{\text{Integrate out } W} \frac{G_F}{f} u_L^\dagger \sigma_{\mu\nu} d_R \partial^\mu e \gamma^\mu \nu_e$$

- From the current-algebra  $\langle \gamma | \bar{d} \sigma_{\mu\nu} \gamma^5 u | \pi^- \rangle = -\frac{e}{2} f_T (q_\mu \epsilon_\nu - q_\nu \epsilon_\mu)$

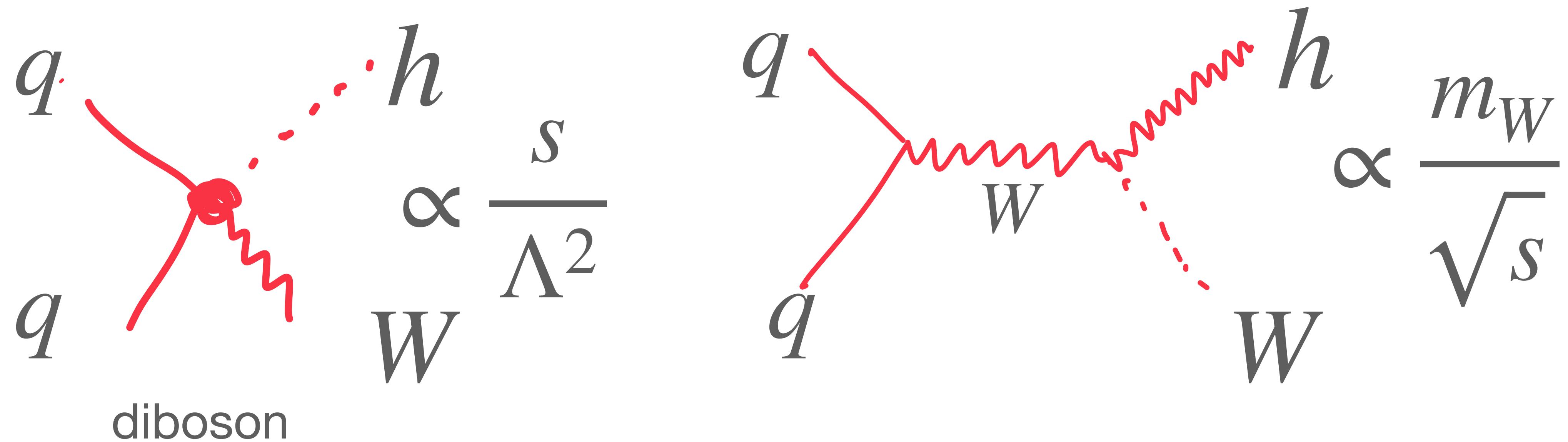
- we can derive the effective pion interaction  $\frac{C_{uW} G_F v_h}{\Lambda^2} \partial_\mu \pi^+ e^- \gamma_\nu \nu_e F^{\mu\nu}$

- The form factor bounds  $|C_{uW}| < 17.2 \left( \frac{\Lambda}{1 \text{TeV}} \right)^2$



# FCC-hh: $pp \rightarrow Wh \rightarrow \gamma\gamma\ell\nu$

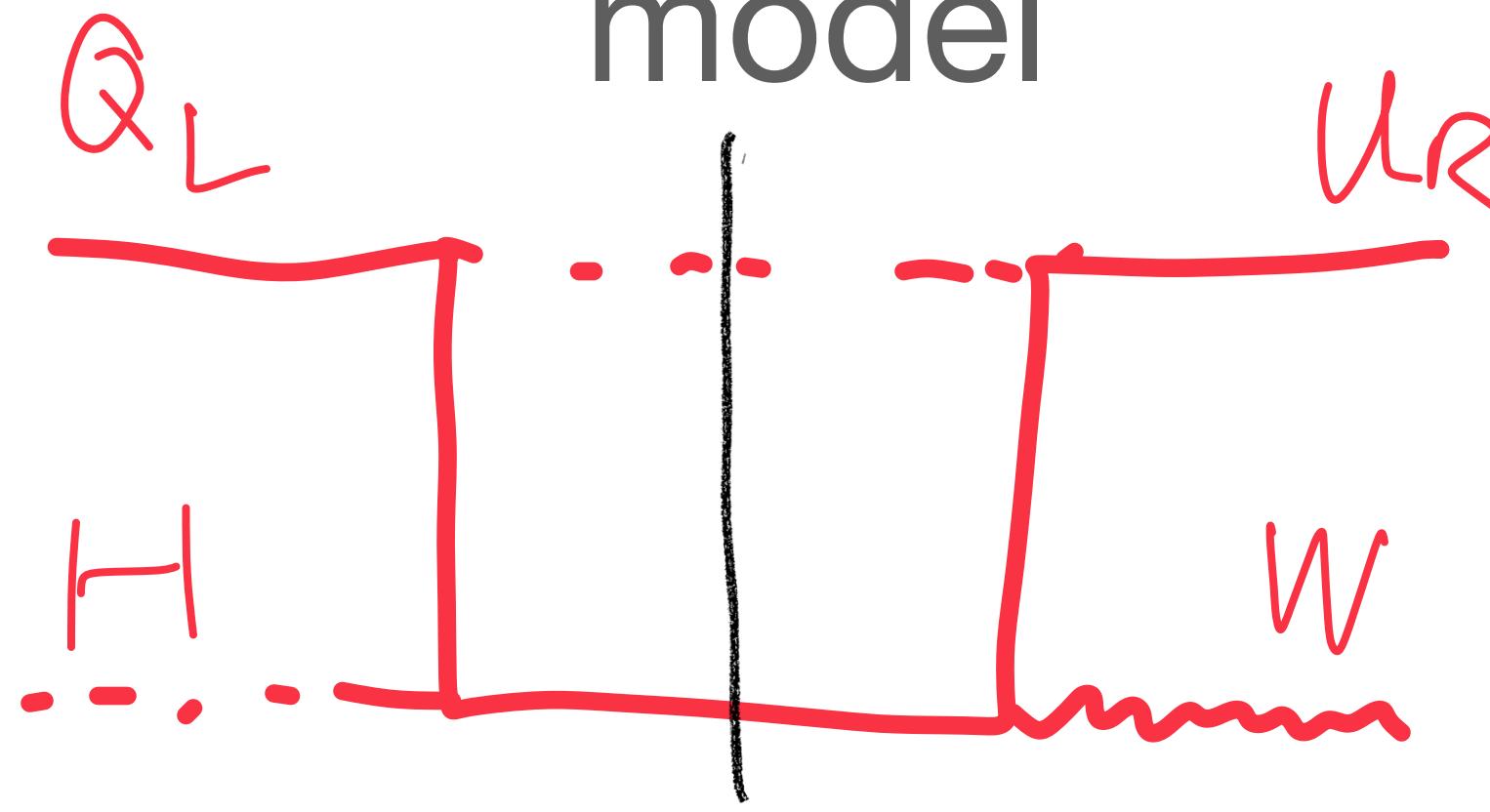
- Amplitudes grow with  $s$ : contact operator.



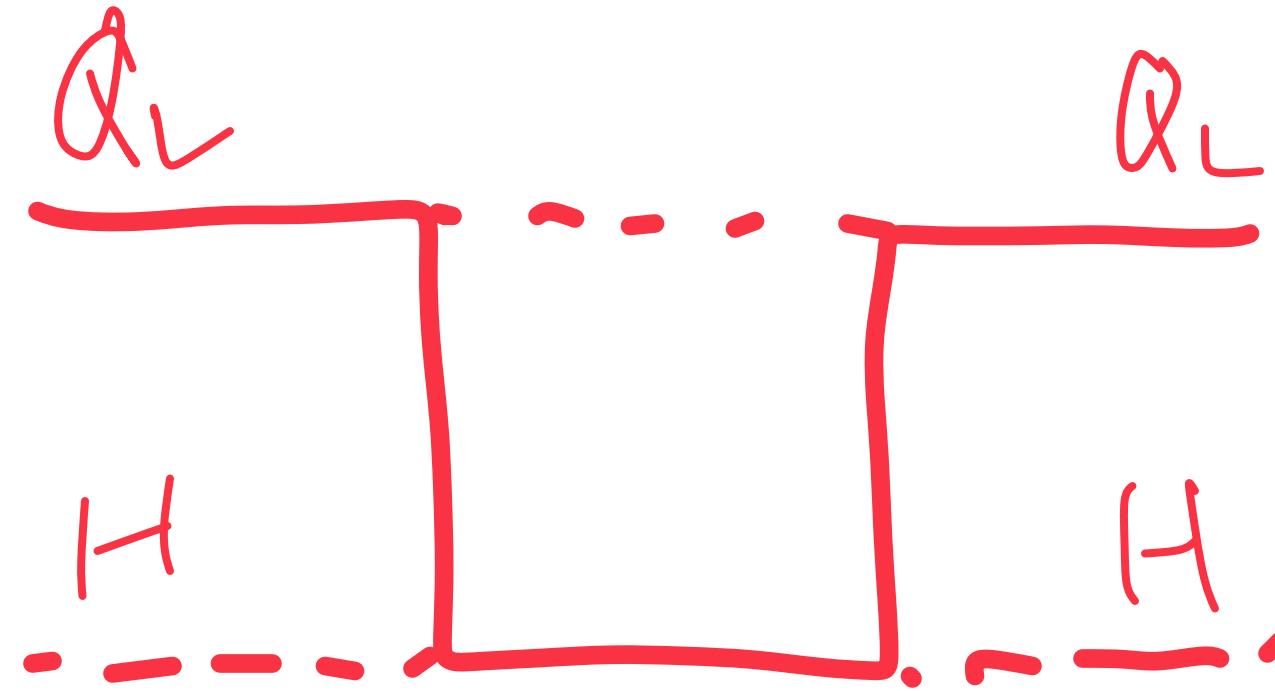
- Clean background: dilepton and diphoton

$\mathcal{O}_{uW}$  and  $\mathcal{O}_{\varphi q}^{(3)}$  same UV

model

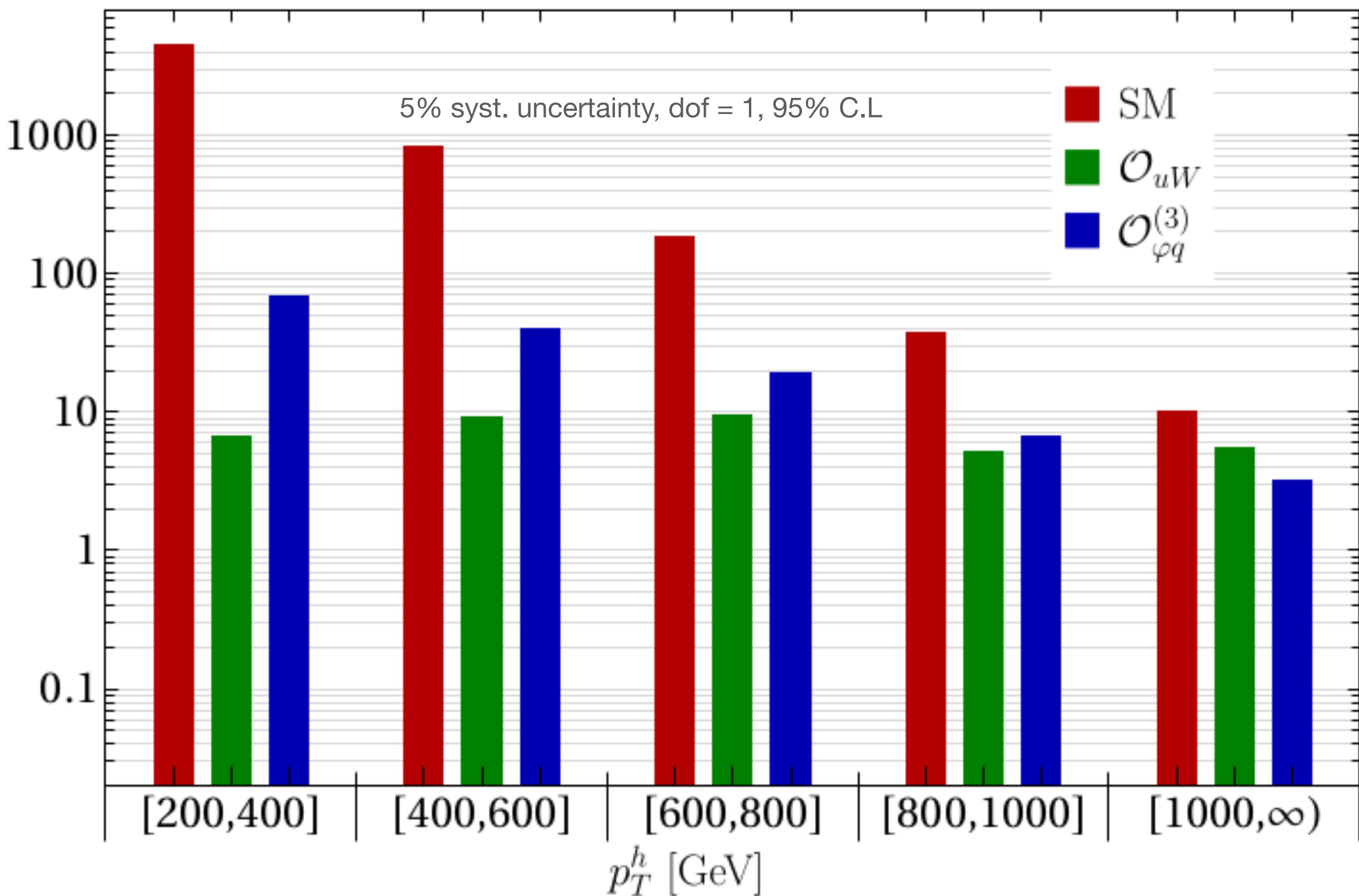


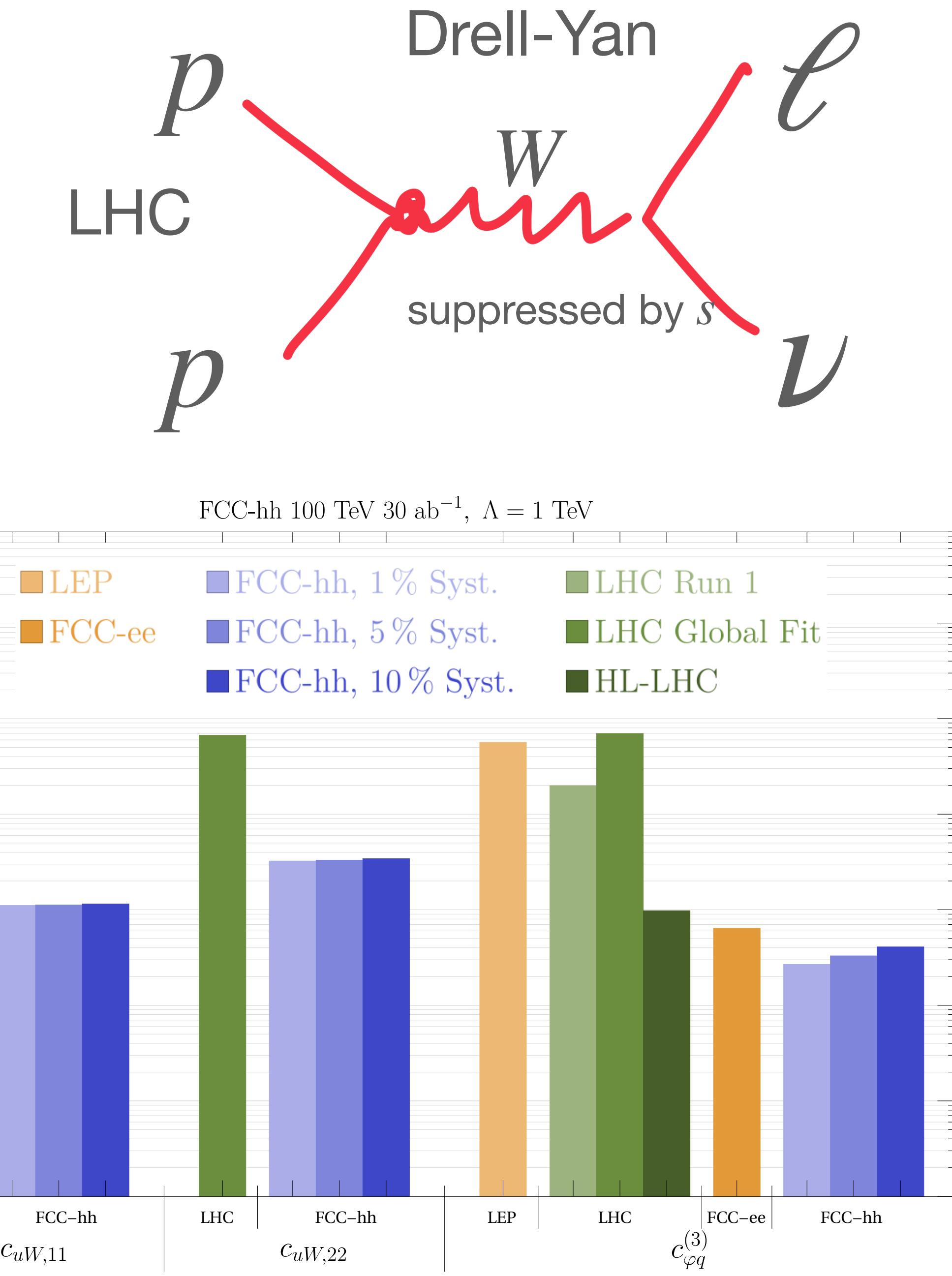
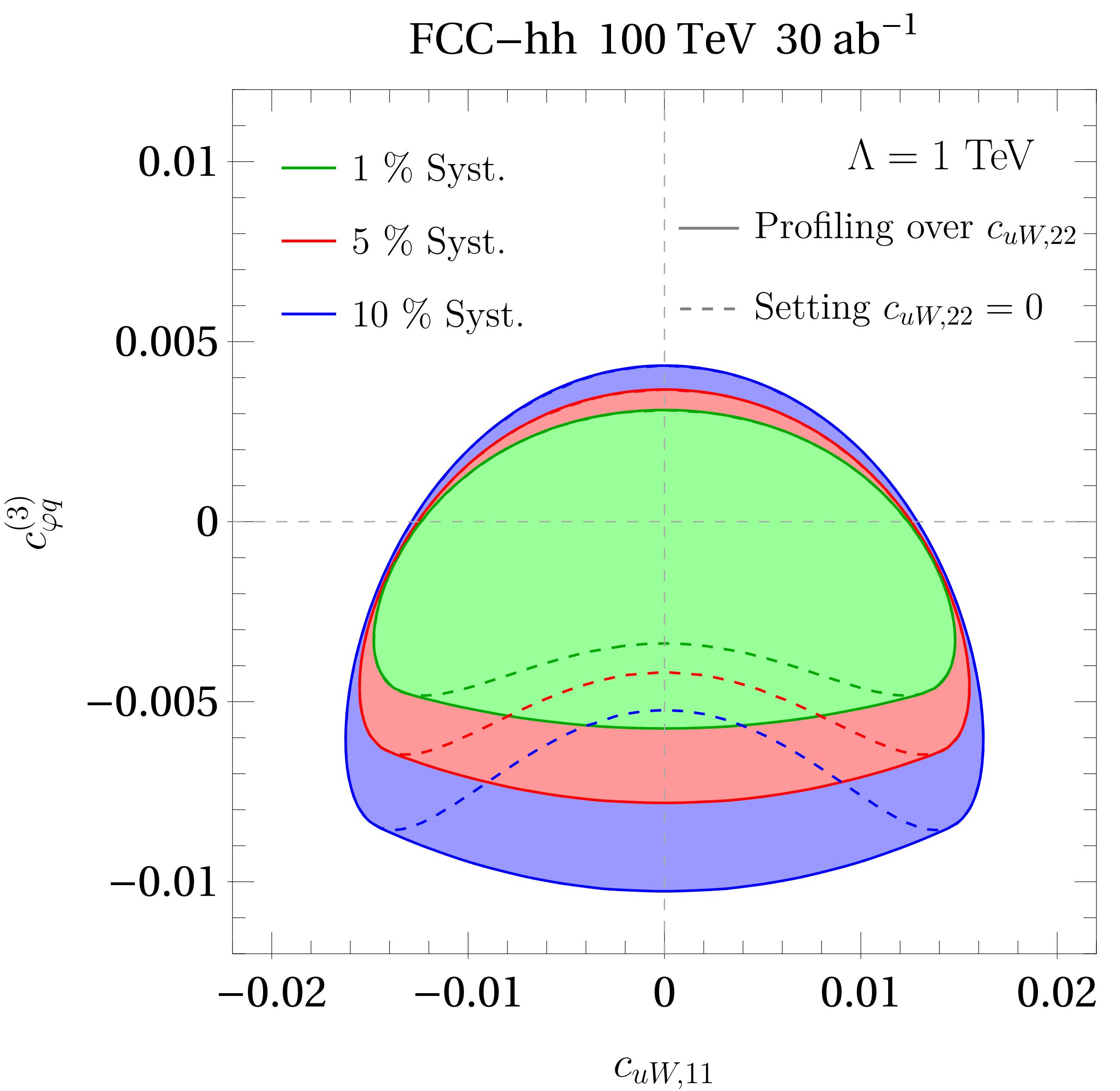
$$\mathcal{O}_{uW} = \bar{Q}_L \sigma^{\mu\nu} W_{\mu\nu} u_R H$$



$$\mathcal{O}_{\varphi q}^{(3)} = \bar{Q}_L \gamma^\mu \tau^a Q_L H^\dagger \overleftrightarrow{D}_\mu \tau^a H \supset \langle H \rangle \bar{q} \gamma^\mu q W_\mu h$$

FCC-hh 100 TeV 30 ab<sup>-1</sup>



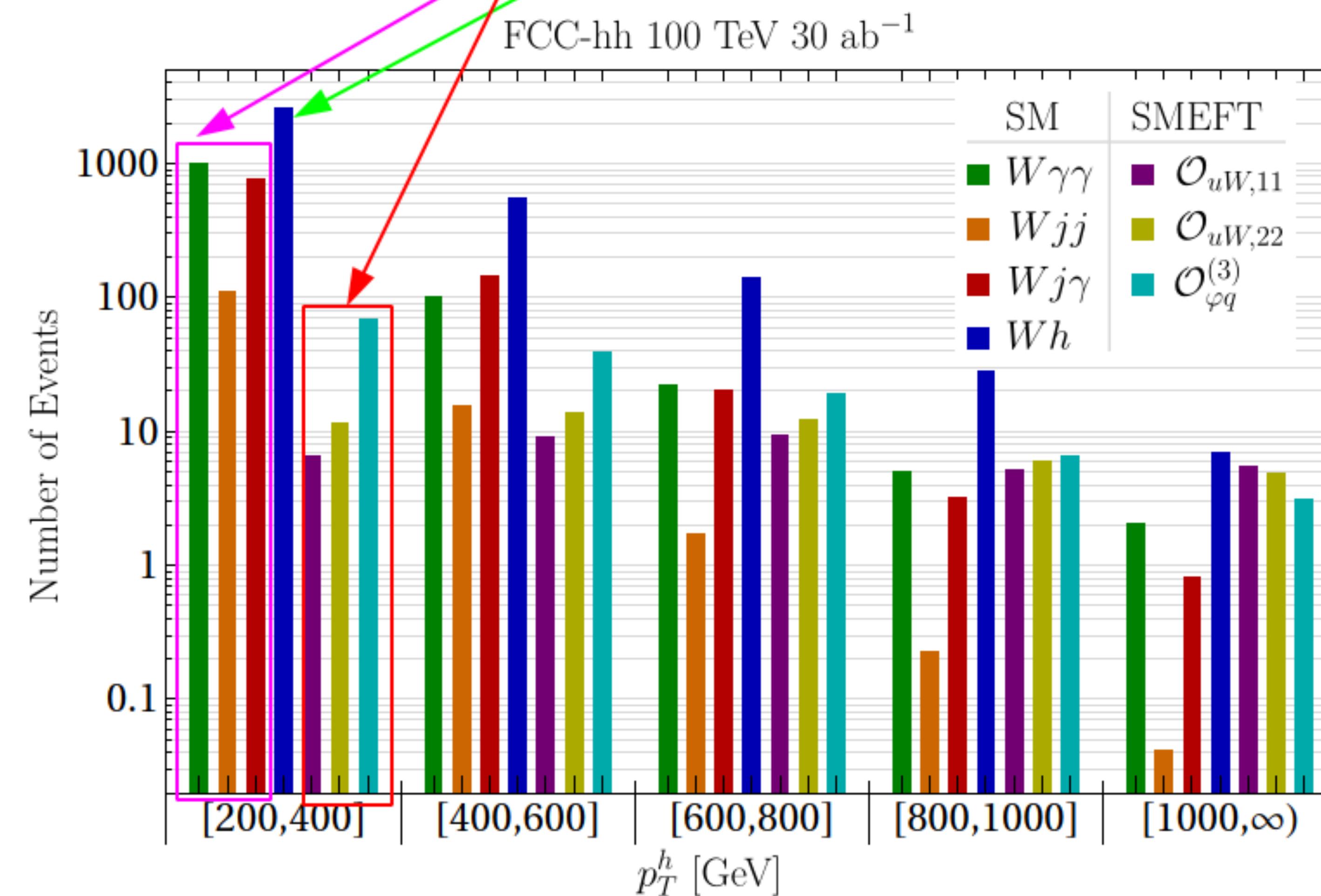


# Summary

- Inverse Hierarchy MFV Model
- Yukawa Naturalness Problem
- Flavor Bounds at low energy regime
- FCC-hh dilepton-diphoton simulation.

# Backup

$$\chi^2(c_i, \delta) = \sum_{k=1}^{N_{bins}} \frac{\left( n_{sig}^k(c_i) - n_{sig}^{k,SM} \right)^2}{\left( \sqrt{n_{sig}^{k,SM}} + n_{bkg}^k \right)^2 + \left( \delta \left( n_{sig}^{SM} + n_{bkg}^k \right) \right)^2},$$



$W$ polarization	SM	$\mathcal{O}_{\varphi q}^{(3)}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi \tilde{W}}$
$\lambda = 0$	1	$\frac{\hat{s}}{\Lambda^2}$	$\frac{M_W^2}{\Lambda^2}$	0
$\lambda = \pm$	$\frac{M_W}{\sqrt{\hat{s}}}$	$\frac{\sqrt{\hat{s}} M_W}{\Lambda^2}$	$\frac{\sqrt{\hat{s}} M_W}{\Lambda^2}$	$\frac{\sqrt{\hat{s}} M_W}{\Lambda^2}$

. High energy behavior of the SM and BSM helicity amplitudes for  $pp \rightarrow Wh$ .

$$\mathcal{M} = \mp \frac{e^{-i\theta}}{\sqrt{2}} \sin(\theta) (s - m_h^2 - m_V^2) \left( 1 \pm \sqrt{1 - \frac{4sm_V^2}{(s - m_h^2 + m_V^2)^2}} \right)$$

# Inverse Hierarchy

$\tilde{Y}$  and  $Y$  are simultaneously diagonal in the mass basis:

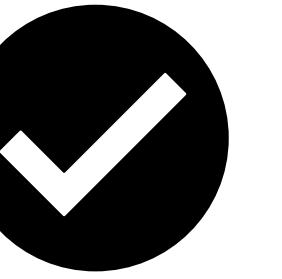
$$Y_u \propto \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

$$\tilde{Y}_u \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{m_u}{m_c} & 0 \\ 0 & 0 & \frac{1}{m_t} \end{pmatrix}$$

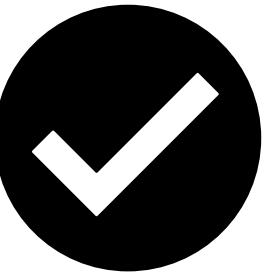
Another way to understand it:

$$Y_u(Y_u Y_u^\dagger)^n \sim (3, \bar{3}, 1) , \quad n = \pm 1, \pm 2, \pm 3 \dots$$

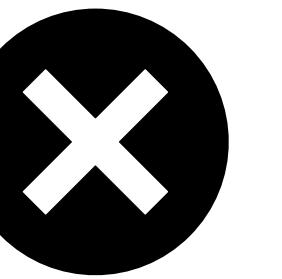
neutron MDM



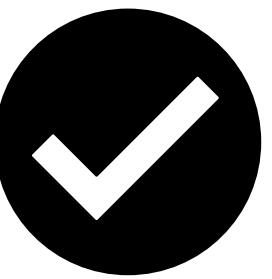
Collider



Lattice QCD



MadGraph



Low E

High E