Top quark FCNC in Leptoquark interpretations of $R_{D^{(*)}}$ anomaly

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Outline

- $R_{D^{(*)}}$ in rare B decays
- Leptoquark explanations of $R_{D^{(*)}}$
  - SU(2) singlet: $S_1, \quad U_1$
- Implications on top FCNC
  - Tree level
  - 1-loop level
- Collider prospects
- Summary

see more in talks of
N. Serra & J. Zupan

$R_{D^{(*)}}$ in rare B decays, lepton Non-universality

$$R_{D^{(*)}} = \left.\frac{Br(B \to D^{(*)}\tau\bar{\nu})}{Br(B \to D^{(*)}l\bar{\nu})}\right|_{l\in\{e,\mu\}}$$

$$R_D^{\rm SM} = 0.300(8)\,, \qquad R_{D^*}^{\rm SM} = 0.257(3).$$

2019 exp. world average

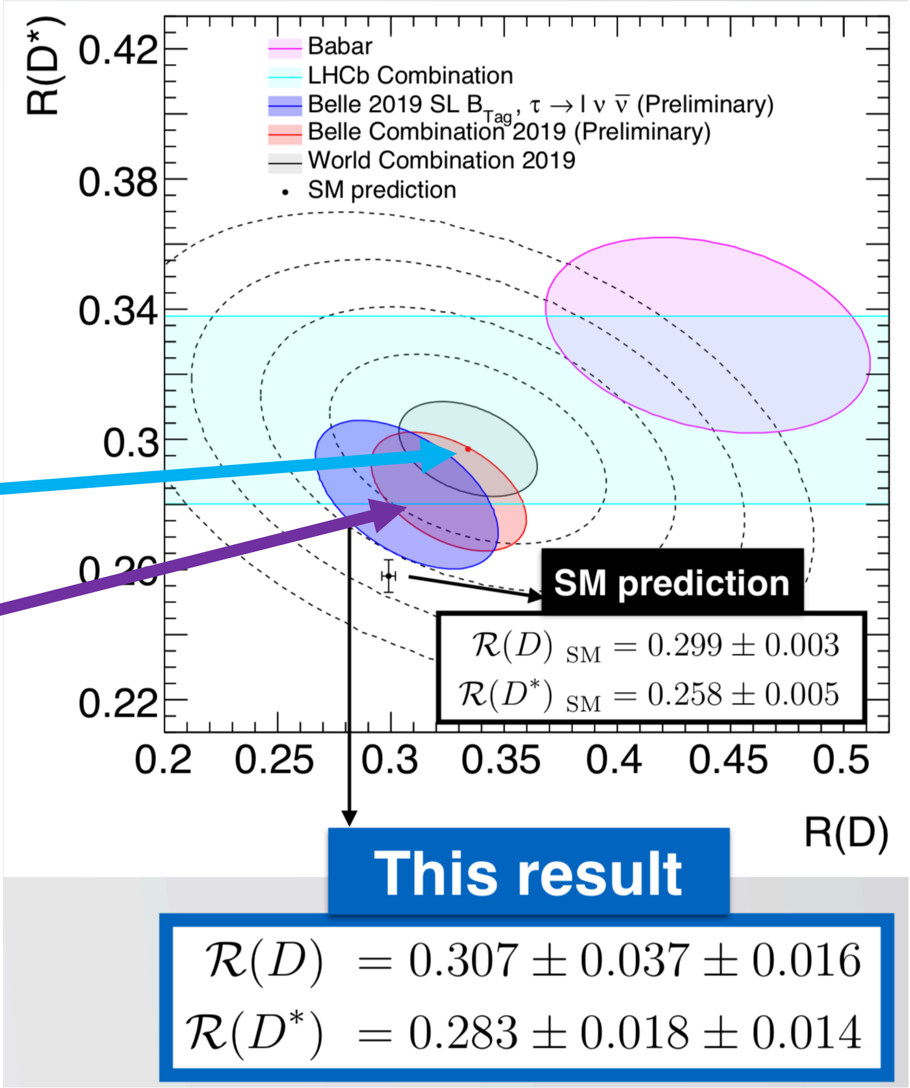
~ 3.1 σ deviation from SM

$$R_D \;= 0.334 \pm 0.031$$
$$R_{D^*} = 0.297 \pm 0.015$$

2019 Belle semi-lep. tau

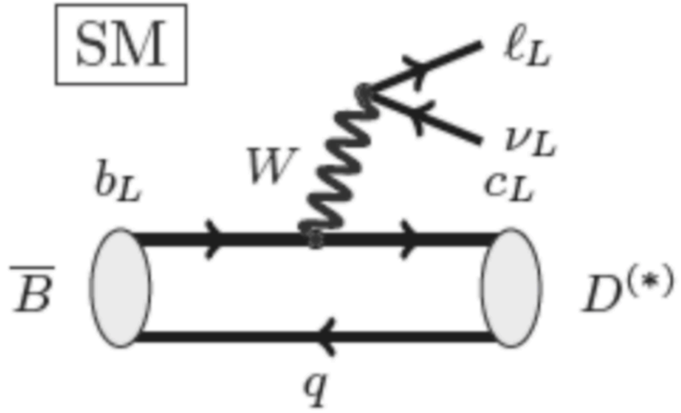
~ 1.2 σ consistent with SM

$$\mathcal{R}(D) \;= 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$



G. Caria
Moriond 2019

Low-energy EFT, $R_{D^{(*)}}$



$$-L_{\rm eff} = (C_{\rm SM}\delta_{l\tau} + C^l_{V_1})O^l_{V_1} + C^l_{V_2}O^l_{V_2} + C^l_{S_1}O^l_{S_1} + C^l_{S_2}O^l_{S_2} + C^l_T O^l_T$$

$l = 1,2,3$ being the neutrino generation index

$C_{\rm SM} = 2\sqrt{2}G_F V_{cb}$

$$O^l_{V_1} = (\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_{lL})\,, \quad O^l_{V_2} = (\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_{lL})$$
$$O^l_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R\nu_{lL})\,, \qquad O^l_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R\nu_{lL})\,,$$
$$O^l_T = (\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_{lL})\,.$$

LQ contributions

Dumont *et al*, 1603.05248

$$\mathcal{L}^{\rm LQ} = \mathcal{L}^{\rm LQ}_{F=0} + \mathcal{L}^{\rm LQ}_{F=-2}\,,$$

$$\mathcal{L}^{\rm LQ}_{F=0} = \left(h_{1L}^{ij}\,\bar{Q}_L^i\gamma_\mu L_L^j + h_{1R}^{ij}\,\bar{d}_R^i\gamma_\mu \ell_R^j\right)U_1^\mu + h_{3L}^{ij}\,\bar{Q}_L^i\boldsymbol{\sigma}\gamma_\mu L_L^j\boldsymbol{U}_3^\mu$$
$$+\left(h_{2L}^{ij}\,\bar{u}_R^i L_L^j + h_{2R}^{ij}\,\bar{Q}_L^i i\sigma_2 \ell_R^j\right)R_2 + \text{h.c.}\,,$$

$$\mathcal{L}^{\rm LQ}_{F=-2} = \left(g_{1L}^{ij}\,\bar{Q}_L^{c,j} i\sigma_2 L_L^j + g_{1R}^{ij}\,\bar{u}_R^{c,i}\ell_R^j\right)S_1 + g_{3L}^{ij}\,\bar{Q}_L^{c,i} i\sigma_2\boldsymbol{\sigma} L_L^j\boldsymbol{S}_3$$
$$+\left(g_{2L}^{ij}\,\bar{d}_R^{c,i}\gamma_\mu L_L^j + g_{2R}^{ij}\,\bar{Q}_L^{c,i}\gamma_\mu\ell_R^j\right)V_2^\mu + \text{h.c.}\,,$$

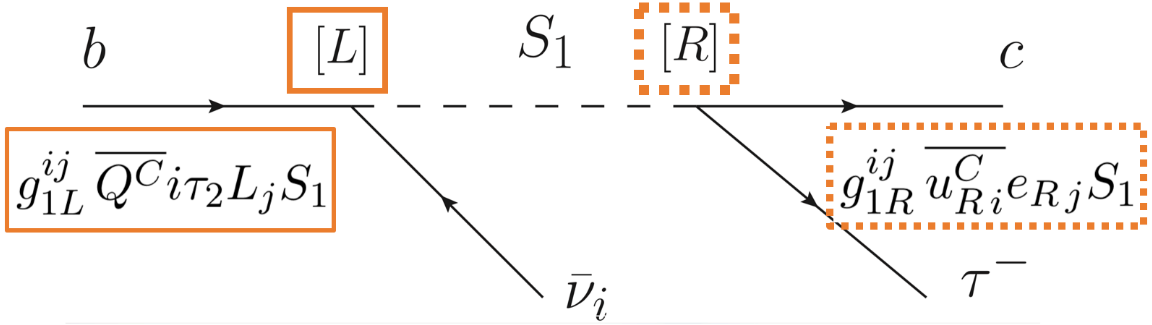
$$C^l_{\mathcal{V}_1} = \sum_{k=1}^{3} V_{k3}\left[\frac{g_{1L}^{kl}g_{1L}^{23*}}{2M_{S_1}^2} - \frac{g_{3L}^{kl}g_{3L}^{23*}}{2M_{\boldsymbol{S}_3}^2} + \frac{h_{1L}^{2l}h_{1L}^{k3*}}{M_{U_1}^2} - \frac{h_{3L}^{2l}h_{3L}^{k3*}}{M_{\boldsymbol{U}_3}^2}\right]$$

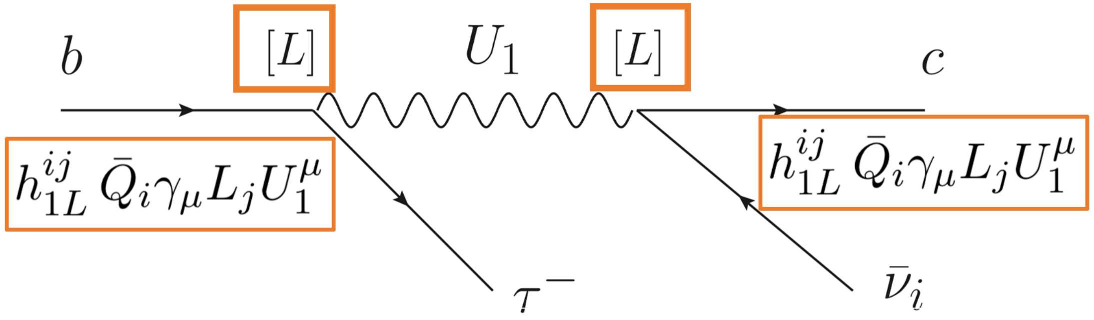
$$C^l_{\mathcal{V}_2} = 0\,,$$

$$C^l_{\mathcal{S}_1} = \sum_{k=1}^{3} V_{k3}\left[-\frac{2g_{2L}^{kl}g_{2R}^{23*}}{M_{V_2}^2} - \frac{2h_{1L}^{2l}h_{1R}^{k3*}}{M_{U_1}^2}\right],$$

$$C^l_{\mathcal{S}_2} = \sum_{k=1}^{3} V_{k3}\left[-\frac{g_{1L}^{kl}g_{1R}^{23*}}{2M_{S_1}^2} - \frac{h_{2L}^{2l}h_{2R}^{k3*}}{2M_{R_2}^2}\right],$$

$$C^l_{\mathcal{T}} = \sum_{k=1}^{3} V_{k3}\left[\frac{g_{1L}^{kl}g_{1R}^{23*}}{8M_{S_1}^2} - \frac{h_{2L}^{2l}h_{2R}^{k3*}}{8M_{R_2}^2}\right],$$





focus of this talk: $R_{D^{(*)}}$

LQ contributions

$$\mathcal{L}^{\rm LQ} = \mathcal{L}^{\rm LQ}_{F=0} + \mathcal{L}^{\rm LQ}_{F=-2}\,,$$

$$\mathcal{L}^{\rm LQ}_{F=0} = \left(h^{ij}_{1L}\,\bar{Q}^i_L\gamma_\mu L^j_L + h^{ij}_{1R}\,\bar{d}^i_R\gamma_\mu\ell^j_R\right) U^\mu_1 + h^{ij}_{3L}\,\bar{Q}^i_L\boldsymbol{\sigma}\gamma_\mu L^j_L \boldsymbol{U}^\mu_3 + \left(h^{ij}_{2L}\,\bar{u}^i_R L^j_L + h^{ij}_{2R}\,\bar{Q}^i_L i\sigma_2\ell^j_R\right) R_2 + \text{h.c.}\,,$$

$$\mathcal{L}^{\rm LQ}_{F=-2} = \left(g^{ij}_{1L}\,\bar{Q}^{c,j}_L i\sigma_2 L^j_L + g^{ij}_{1R}\,\bar{u}^{c,i}_R\ell^j_R\right) S_1 + g^{ij}_{3L}\,\bar{Q}^{c,i}_L i\sigma_2\boldsymbol{\sigma}L^j_L\boldsymbol{S}_3 + \left(g^{ij}_{2L}\,\bar{d}^{c,i}_R\gamma_\mu L^j_L + g^{ij}_{2R}\,\bar{Q}^{c,i}_L\gamma_\mu\ell^j_R\right) V^\mu_2 + \text{h.c.}\,,$$

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

Angelescu *et al*, 1808.08179

Numerical fit

$m_{LQ} = 1$ TeV

Dumont *et al*, 1603.05248

Leptoquark	$\bar{B} \to D^{(*)}\tau\bar{\nu}$	$\bar{B} \to X_s \nu\bar{\nu}$
S_1	$-0.87 < g_{1L}^{33} g_{1R}^{23*} < -0.54$ $1.64 < \lvert g_{1L}^{3i} g_{1R}^{23*}\rvert < 1.81 \quad (i=1,2)$ $0.19 < g_{1L}^{33} g_{1L}^{23*} < 0.48, \quad -5.59 < g_{1L}^{33} g_{1L}^{23*} < -5.87$ $1.04 < \lvert g_{1L}^{3i} g_{1L}^{23*}\rvert < 1.67 \quad (i=1,2)$	$\lvert g_{1L}^{3i} g_{1L}^{2j*}\rvert \lesssim 0.15$
$\boldsymbol{S}_3$	$0.19 < g_{3L}^{33} g_{3L}^{23*} < 0.48, \quad -5.59 < g_{3L}^{33} g_{3L}^{23*} < -5.87$ $1.04 < \lvert g_{3L}^{3i} g_{1L}^{23*}\rvert < 1.67 \quad (i=1,2)$	$\lvert g_{3L}^{3i} g_{3L}^{2j*}\rvert \lesssim 0.15$
R_2	$1.64 < \left\lvert \mathrm{Im}(h_{2L}^{2i} h_{2R}^{33*})\right\rvert < 1.81$	-
V_2	$g_{2L}^{3i} g_{2R}^{23*}$: no region within 2σ	$\lvert g_{2L}^{3i} g_{2L}^{2j*}\rvert \lesssim 0.07$
U_1	$0.10 < h_{1L}^{23} h_{1L}^{33*} < 0.24, \quad -2.94 < h_{1L}^{23} h_{1L}^{33*} < -2.80$ $0.52 < \lvert h_{1L}^{2i} h_{1L}^{33*}\rvert < 0.84 \quad (i=1,2)$ $h_{1L}^{2i} h_{1R}^{33*}$: no region within 2σ	-
$\boldsymbol{U}_3$	$0.10 < h_{3L}^{23} h_{3L}^{33*} < 0.24, \quad -2.94 < h_{3L}^{23} h_{3L}^{33*} < -2.80$ $0.52 < \lvert h_{3L}^{2i} h_{3L}^{33*}\rvert < 0.84 \quad (i=1,2)$	$\lvert h_{3L}^{2i} h_{3L}^{3j*}\rvert \lesssim 0.04$

Numerical fit

only two non-vanishing couplings

Leptoquark	2σ range for $\bar{B} \to D^{(*)}\tau\bar{\nu}$
S_1	$g_{1L}^{3l} g_{1R}^{23*} \in \left(\frac{M_{S_1}}{1\ \text{TeV}}\right)^2 \times \begin{cases} (1.64, 1.81) & l = 1,2 \\ (-0.87, -0.54) & l = 3 \end{cases}$
U_1	$h_{1L}^{2l} h_{1L}^{33*} \in \left(\frac{M_{U_1}}{1\ \text{TeV}}\right)^2 \times \begin{cases} (0.52, 0.84) & l = 1,2 \\ (-2.94, -2.80) & l = 3 \end{cases}$

$$g_{1L}^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \sim & \sim & g_{1L}^{3\ell} \end{pmatrix} \qquad g_{1R}^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{1R}^{23} \\ 0 & 0 & 0 \end{pmatrix}$$

$\ell = 1$ or 2 or 3

$$h_{1L}^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ \sim & \sim & h_{1L}^{2\ell} \\ 0 & 0 & h_{1L}^{33} \end{pmatrix} \qquad h_{1R}^{ij} = 0$$

$\ell = 1$ or 2 or 3

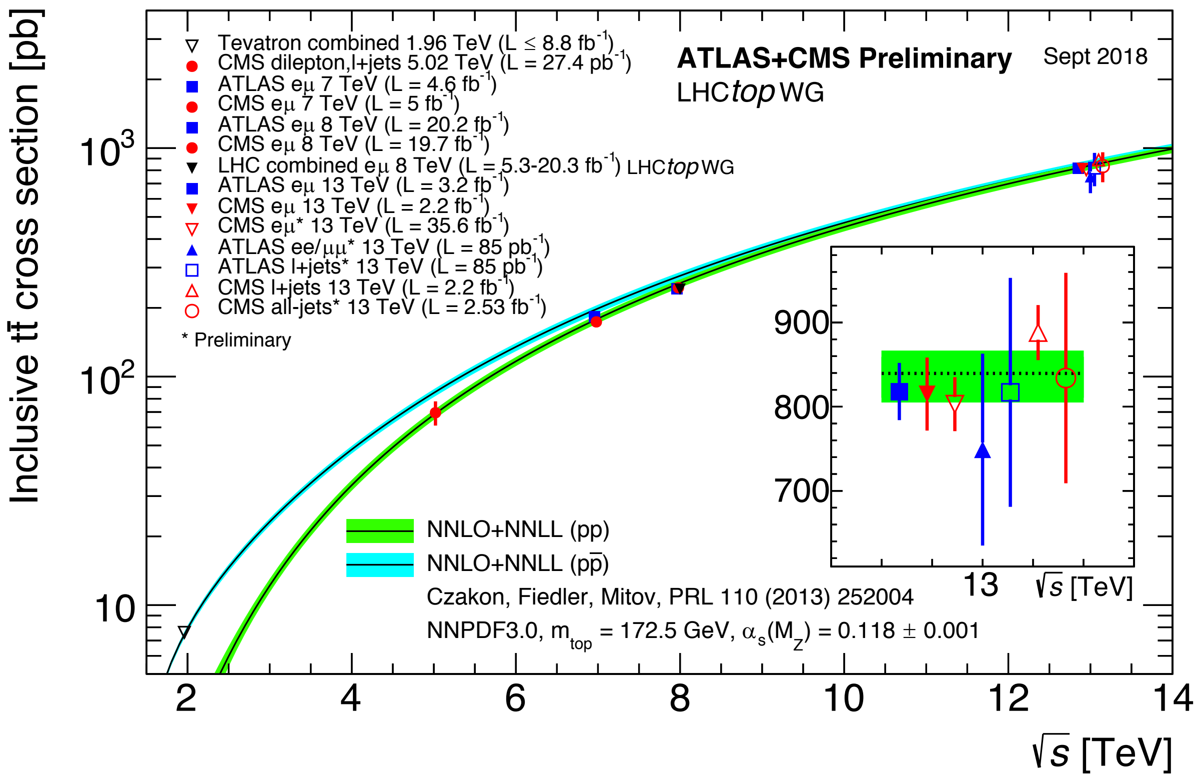
Sept. 2018 LHCTopWG Summary

Top quark at LHC

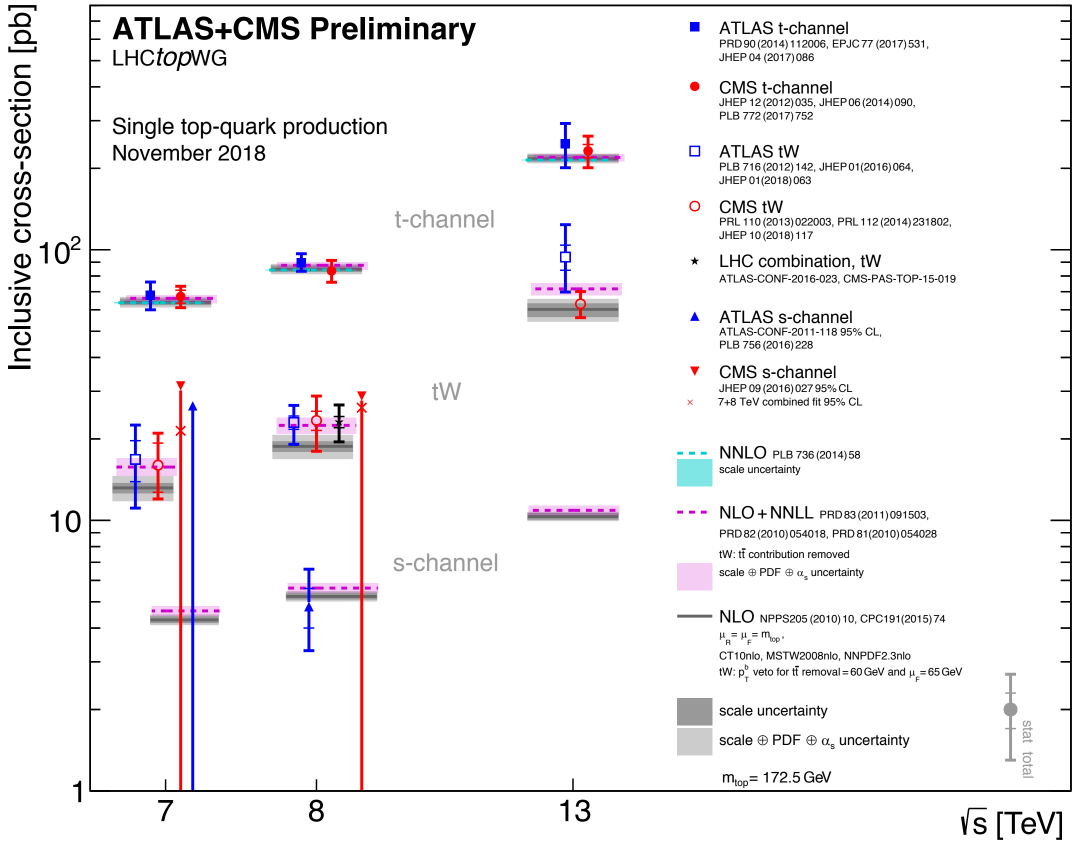
see more in talk of A. Gritsan

- fairly good agreements for cross section
- within theoretical uncertainties: scales of Ren. & Fact., PDF, α_S

$t\bar{t}$ cross section (pb)



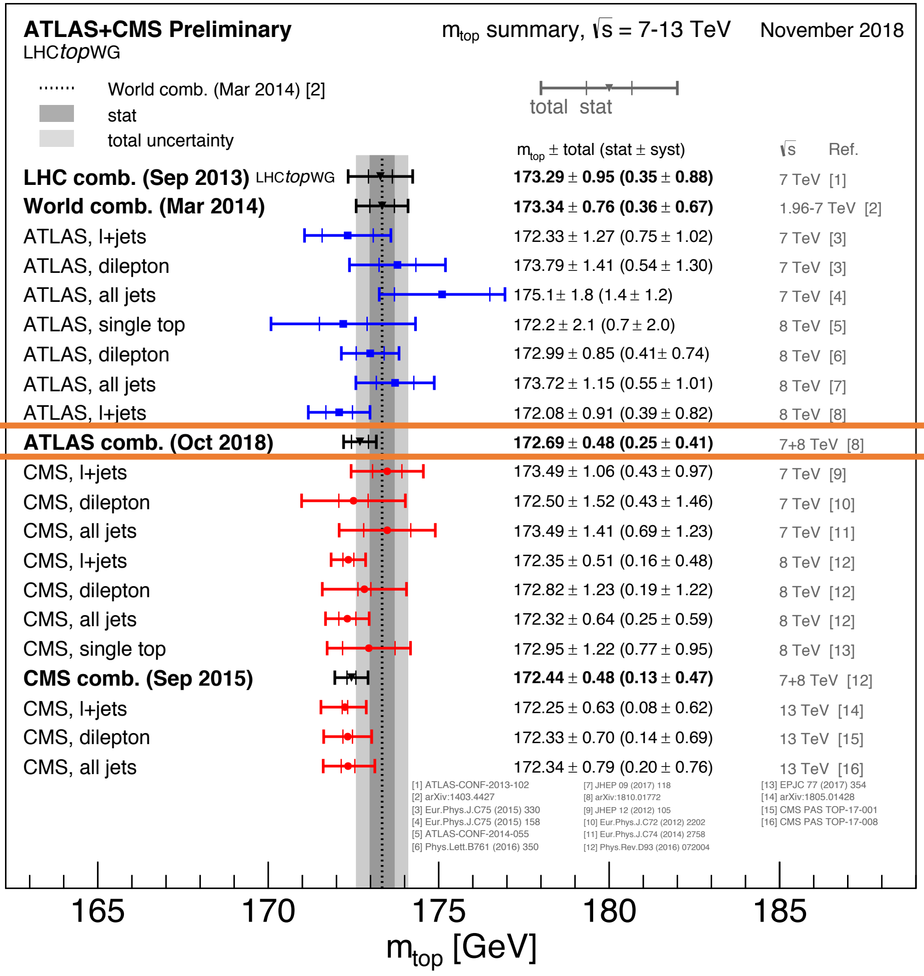
single t cross section (pb)



Sept. 2018 LHCTopWG Summary

Top quark at LHC

$$m_t = 172.69 \pm 0.48 \text{ GeV}$$

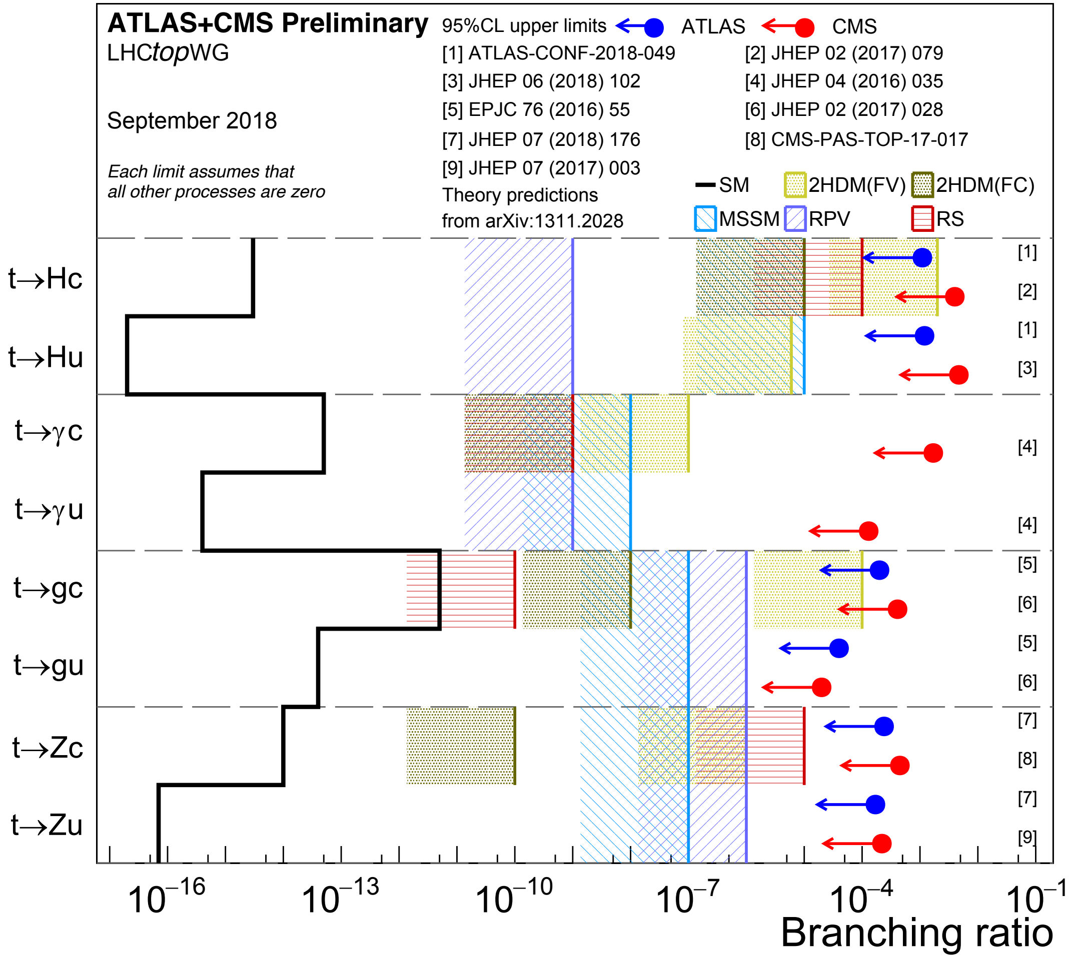


$$q = c$$

$$V = \{g, Z, \gamma, H\} \sim \{10^{-4}, 10^{-4}, 10^{-3}, 10^{-3}\}$$

$q = u$, slightly stronger limits, but same order

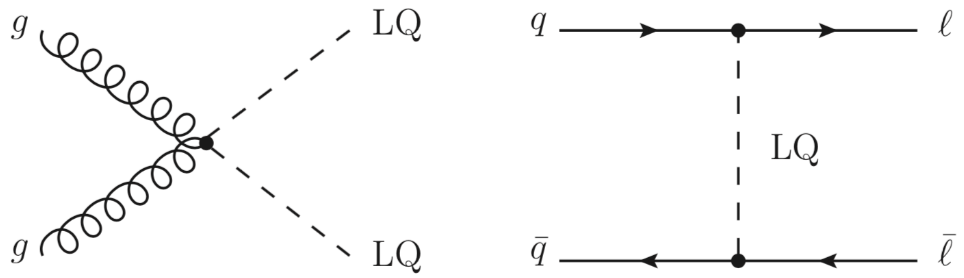
$$Br(t \to qV)$$



LQ limits at LHC

- to set limits, specific LQ decay modes are assumed
- currently, LQ mass bounds are 1 ~ 2 TeV, stronger for Vector LQ

Decays	LQs	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	S_1, R_2, S_3, U_1, U_3	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	R_2, S_3, U_1, U_3	850 (550) GeV	1550 (1290) GeV	12.9 fb^{-1} [52]
$t\bar{t}\,\tau\bar{\tau}$	S_1, R_2, S_3, U_3	900 (560) GeV	1440 (1220) GeV	35.9 fb^{-1} [53]
$jj\,\mu\bar{\mu}$	S_1, R_2, S_3, U_1, U_3	1530 (1275) GeV	2110 (1860) GeV	35.9 fb^{-1} [54]
$b\bar{b}\,\mu\bar{\mu}$	R_2, U_1, U_3	1400 (–) GeV	1900 (1700) GeV	36.1 fb^{-1} [55]
$t\bar{t}\,\mu\bar{\mu}$	S_1, R_2, S_3, U_3	1420 (950) GeV	1780 (1560) GeV	36.1 fb^{-1} [56, 57]
$jj\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	980 (640) GeV	1790 (1500) GeV	35.9 fb^{-1} [58]
$b\bar{b}\,\nu\bar{\nu}$	S_1, R_2, S_3, U_3	1100 (800) GeV	1810 (1540) GeV	35.9 fb^{-1} [58]
$t\bar{t}\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	1020 (820) GeV	1780 (1530) GeV	35.9 fb^{-1} [58]



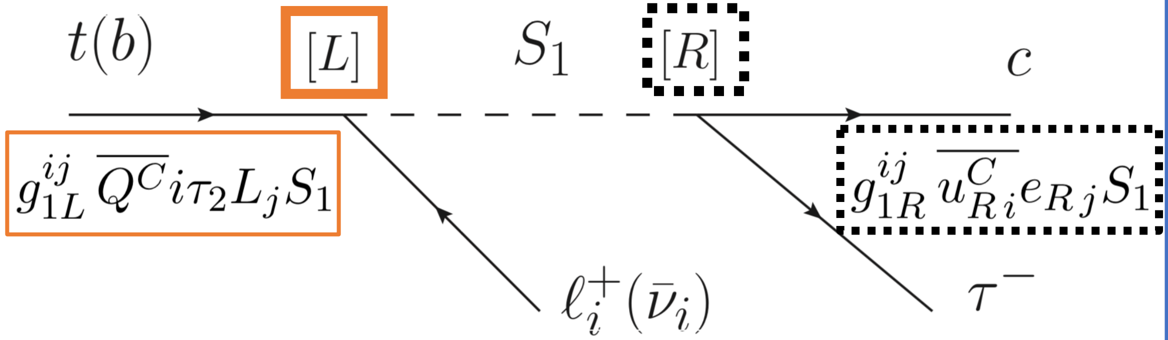
Angelescu *et al*, 1808.08179

Tree

Top FCNC at tree-level, 3-body

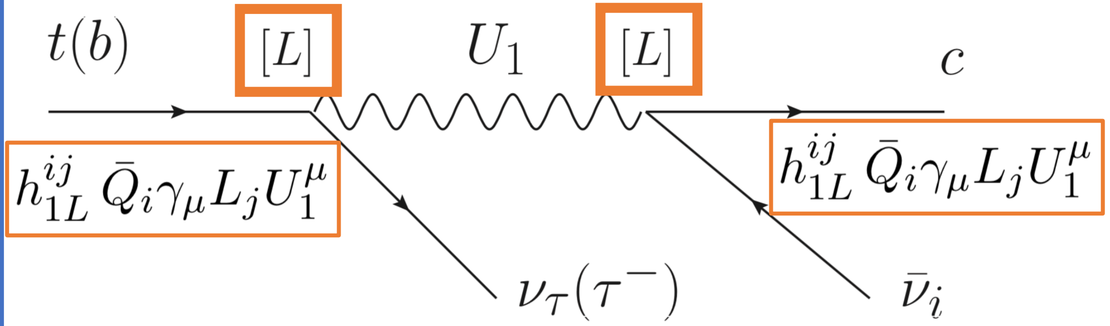
$$t \to c\tau^-\ell_i^+$$

scalar S_1



$$t \to c\nu_\tau\bar\nu_i$$

vector U_1



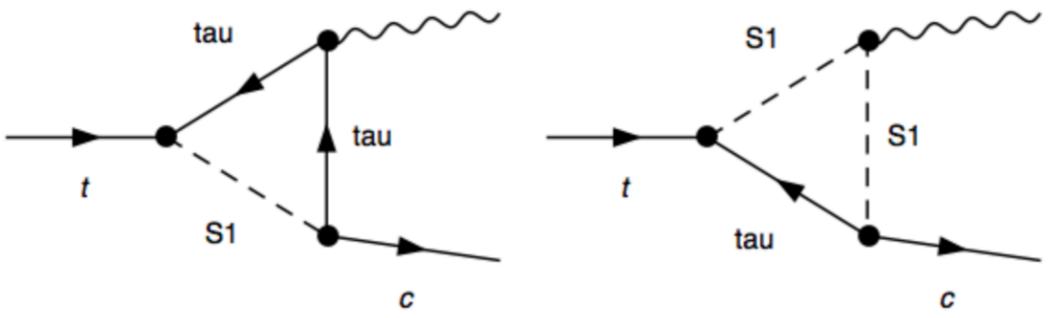
1-loop

Top FCNC at one-loop, 2-body

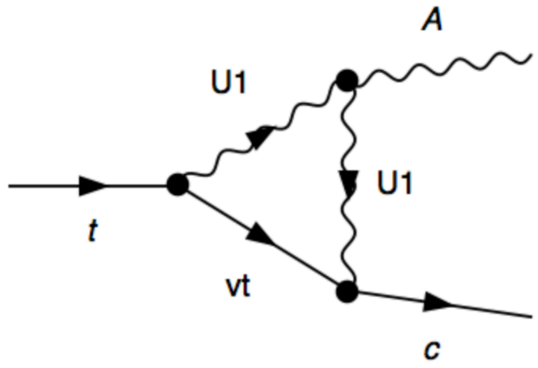
- we only consider loop for scalar S_1
- loop of vector U_1 needs UV-completion of m_{U_1} generation
  - SM-GIM-like mechanism needed to cancel divergence
  - more complete flavor structure needed

$t \to cV$

scalar S_1



vector U_1

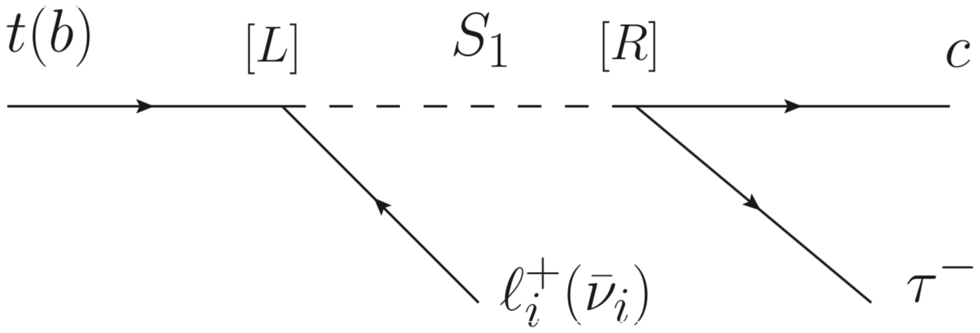


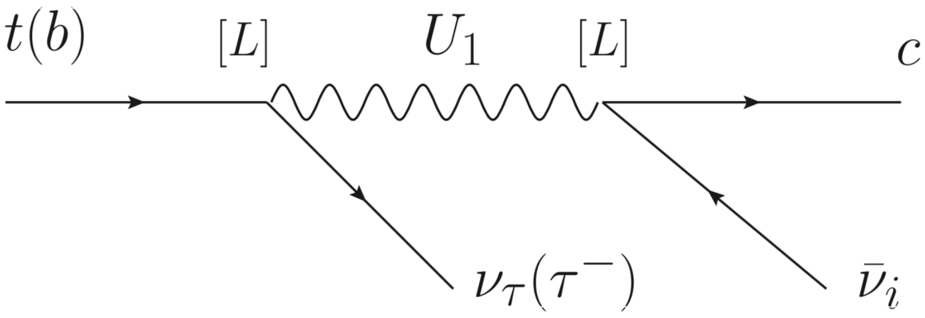
+ external leg diagrams

Tree-level: $R_{D^{(*)}}$ fit of $\frac{g_L g_R}{m_{LQ}^2}$ naturally implies Br_t^{FCNC}

scalar S_1 $\quad t \rightarrow c\tau^-\ell_i^+$

$t \rightarrow c\nu_\tau\bar{\nu}_i$ $\quad$ vector U_1

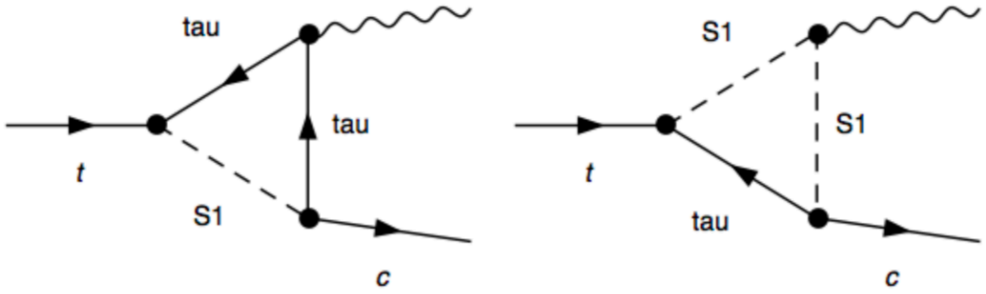




$$S_1 : Br(t \to c\tau^-\ell_l^+) \approx \frac{1}{\Gamma_{t,SM}}\left(\frac{m_t^5}{6144\pi^3}\right)\left|\frac{g_{1L}^{3l}g_{1R}^{23*}}{M_{S_1}^2}\right|^2 = 10^{-6} \times \begin{cases} 1.4 \sim 1.8 & l = 1,2 \\ 0.16 \sim 0.41 & l = 3 \end{cases}$$

$$U_1 : Br(t \to c\nu_\tau\bar{\nu}_l) \approx \frac{1}{\Gamma_{t,SM}}\left(\frac{m_t^5}{1536\pi^3}\right)\left|\frac{h_{1L}^{33}h_{1L}^{2l*}}{M_{U_1}^2}\right|^2 = 10^{-6} \times \begin{cases} 0.58 \sim 1.5 & l = 1,2 \\ 17 \sim 19 & l = 3 \end{cases}$$

Loop-level:



+ external leg corrections

Given the coupling chirality we choose, only left-handed part appears in dipole

$$f^g_{TR} = f^\gamma_{TR} = f^Z_{TR} = 0$$

$$x_\tau = \frac{m_\tau^2}{M_{S_1}^2}$$
$$x_t = \frac{m_t^2}{M_{S_1}^2}$$

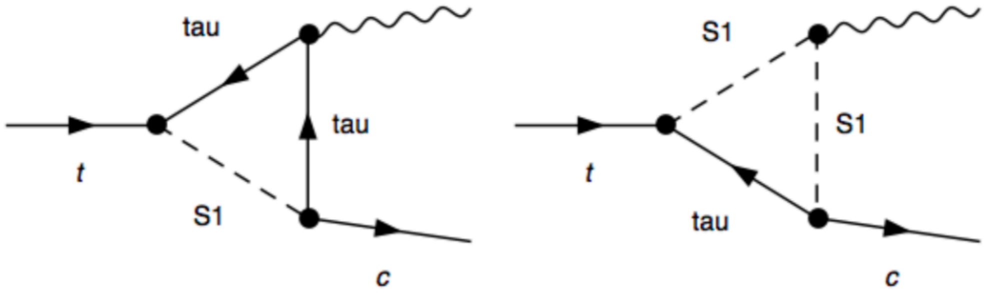
$$f^g_{TL} \simeq \frac{1}{16\pi^2} g_s m_\tau \frac{g_{1L}^{33} g_{1R}^{23*}}{M_{S_1}^2} \times \frac{1}{12}\Big(-6\,(22x_\tau x_t + 3x_t + 16x_\tau + 6)\log x_\tau - 49x_t - 48\Big)$$

$$f^\gamma_{TL} \simeq -\frac{1}{16\pi^2} e m_\tau \frac{g_{1L}^{33} g_{1R}^{23*}}{M_{S_1}^2} \times \frac{1}{3}\Big(\frac{1}{6}\,(14x_t x_\tau + x_t + 9x_\tau + 3) + (x_t + 1)\,x_\tau \log x_\tau\Big),$$

$$i\mathcal{M}_{tcV} = \bar{u}(p_2)\,\Gamma^\mu u(p_1)\,\epsilon_\mu(k,\lambda)$$

$$\Gamma^\mu_{tcZ} = \gamma^\mu(P_L f^Z_{VL} + P_R f^Z_{VR}) + i\sigma^{\mu\nu}k_\nu(P_L f^Z_{TL} + P_R f^Z_{TR}),$$
$$\Gamma^\mu_{tc\gamma} = i\sigma^{\mu\nu}k_\nu(P_L f^\gamma_{TL} + P_R f^\gamma_{TR}),$$
$$\Gamma^\mu_{tcg} = T^a i\sigma^{\mu\nu}k_\nu(P_L f^g_{TL} + P_R f^g_{TL}),$$

Loop-level:



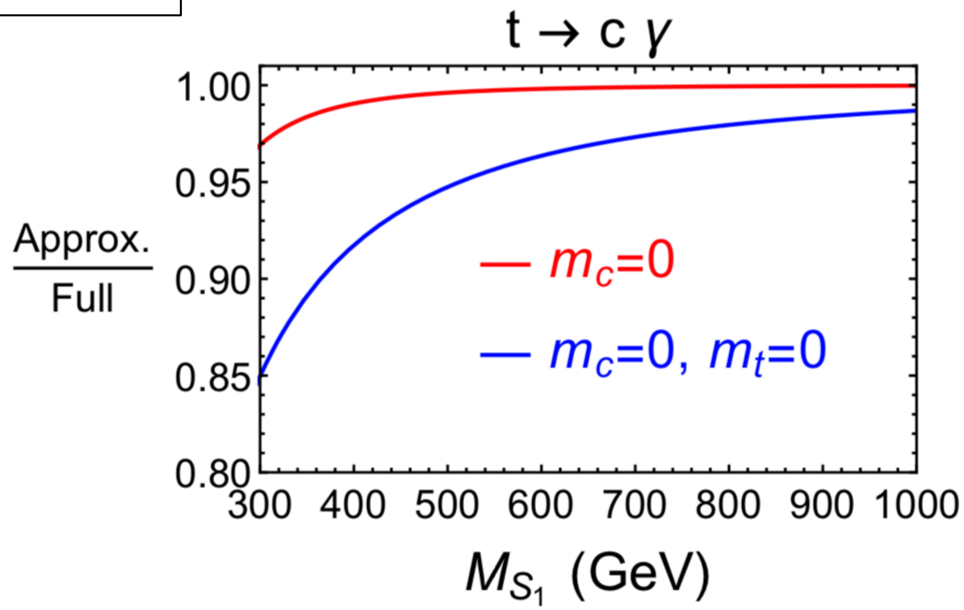
+ external leg corrections

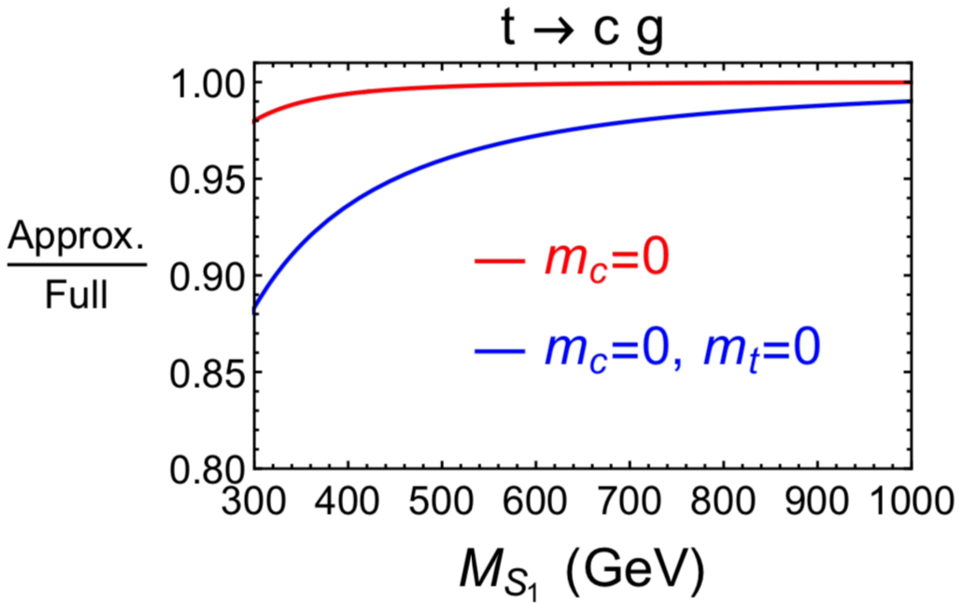
for $m_V = 0$ (γ, g)

- we kept $O(m_t^1)$ in loop function expansions
- unlike $b \to s\gamma$, $\mu \to e\gamma$ with m_b, m_μ being ignored

for $m_V \neq 0$ (Z)

- we keep the full expressions





For $M_{S_1} = [1,2]$ TeV

$Br(t \to c\gamma) \sim 10^{-10}$

$Br(t \to cg) \sim 10^{-11}$

$Br(t \to cZ) \sim 10^{-[11,12]}$

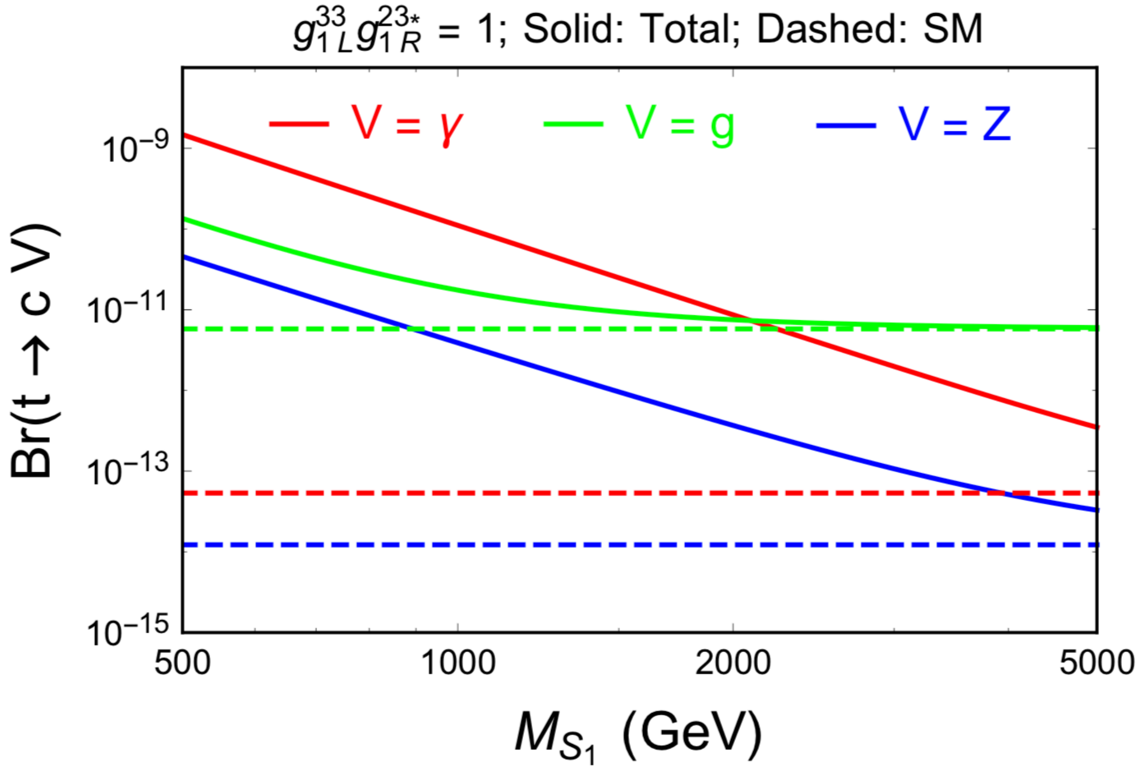
EFT fitting suggestion

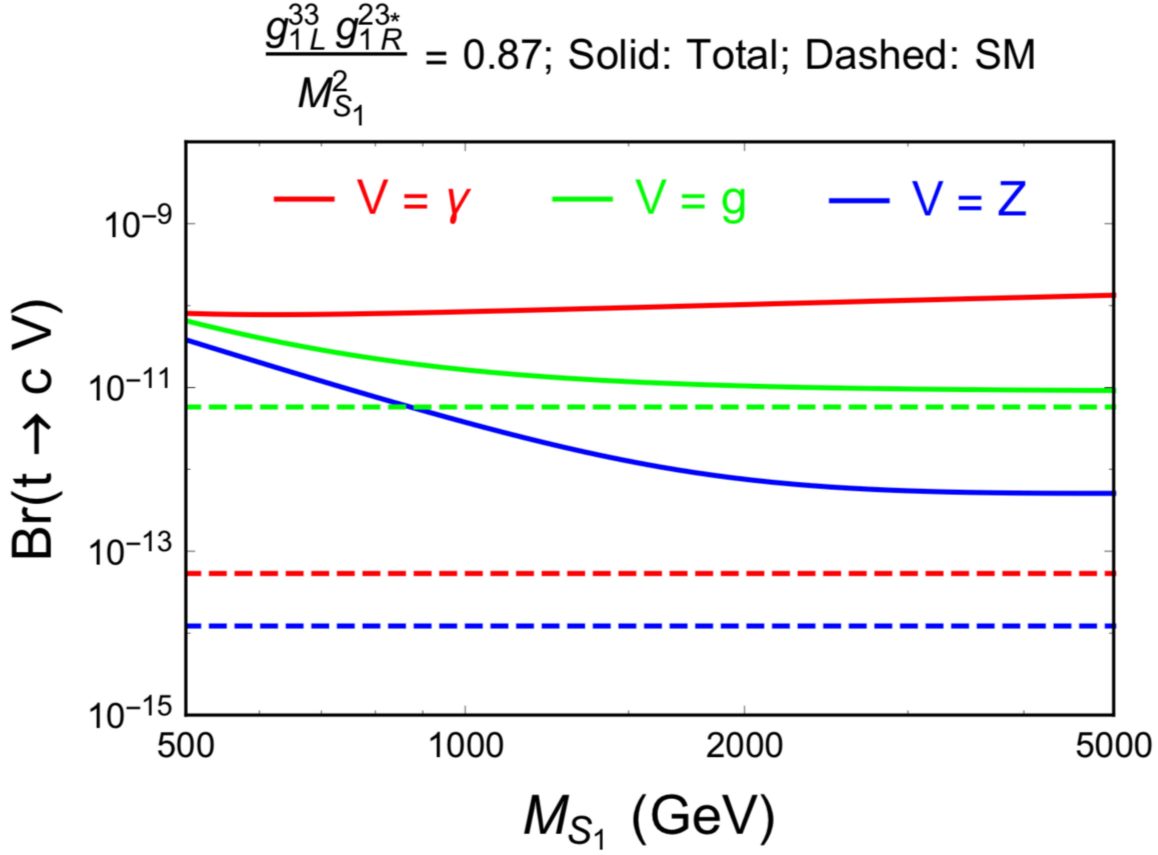
$$\frac{g_{1L}^{33} g_{1R}^{23*}}{M_{S_1}^2} = 0.87;$$

Loop-level:

decoupling to SM

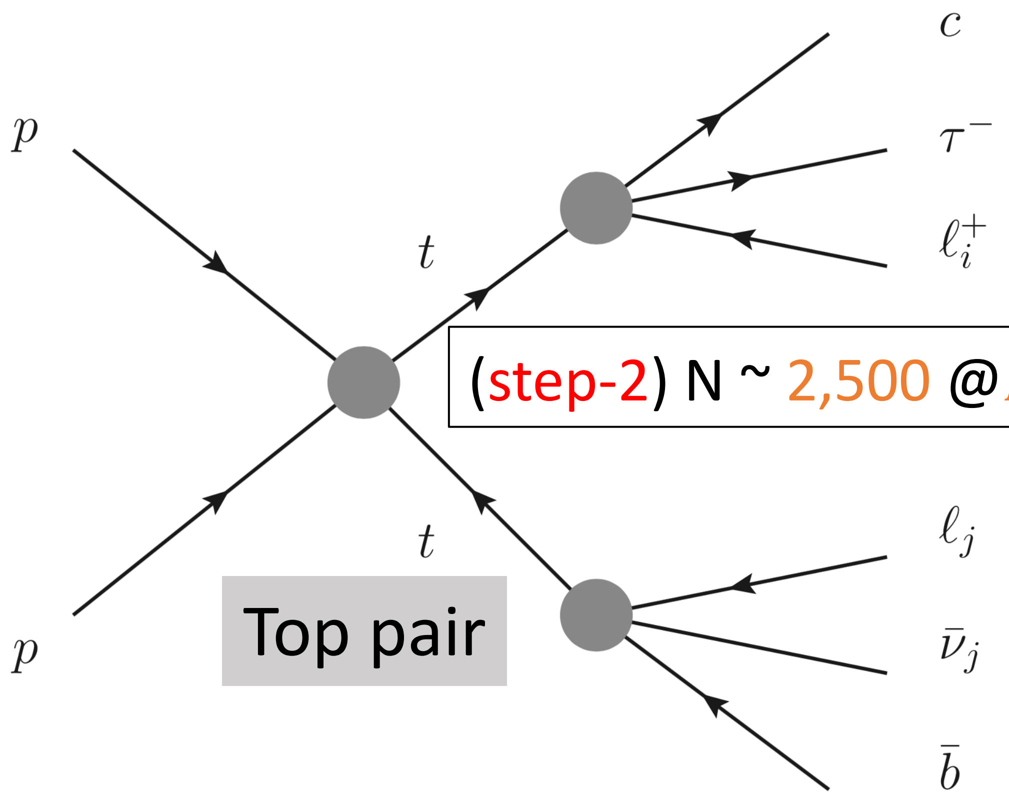
$$g_{1L}^{33} g_{1R}^{23*} = 1$$





S_1 collider prospects via $t\bar{t}$ production

(step-1) N ~ 2.5×10^9 @ $3\ \mathrm{ab}^{-1}$ LHC-13



$$t \to c\tau^-\ell_i^+$$

(step-2) N ~ 2,500 @$Br_t^{\mathrm{FCNC}}\sim10^{-6}$

(step-3) N ~ 500 @ leptonic top

Cut-and-count analysis

$1\,\ell, \qquad \geq 3\,j \ni \{1\,b, 2\,\tau\}$

- **Selection 1**: Exactly one lepton, at least three jets including exactly one b jet and two τ jets.

$2\,\ell \ni \{\mu, \ell\}, \qquad \geq 2\,j \ni \{1\,b, 1\,\tau\}$

- **Selection 2**: Exactly two leptons, at least one muon, at least 2 jets including exactly one b jet and one τ jet.

$1\,\ell, \qquad \geq 2\,j \ni \{1\,b\}$

- **Selection 3**: Exactly one lepton and more than two jets in the final state, where one of the jet is b-tagged, the missing transverse energy $E_T^{\text{miss}} > 80$ GeV.

	VV	DY	W+jet	$t\bar{t}$	$t \to c\mu\tau$	$t \to c\tau\tau$	$t \to c\nu\nu$
Selection 1	9559	108095	-	1189719	28	19	0.3
Selection 2	5433	54047	-	839651	39	5	0.0
Selection 3	296814	594522	16530371	64764862	140	94	102

@ 3 ab^{-1} LHC-13
one leptonic top

- simple cuts give signal/BG ~ 10^{-5}
- advanced techniques needed

Multi-variate analysis of BDT method

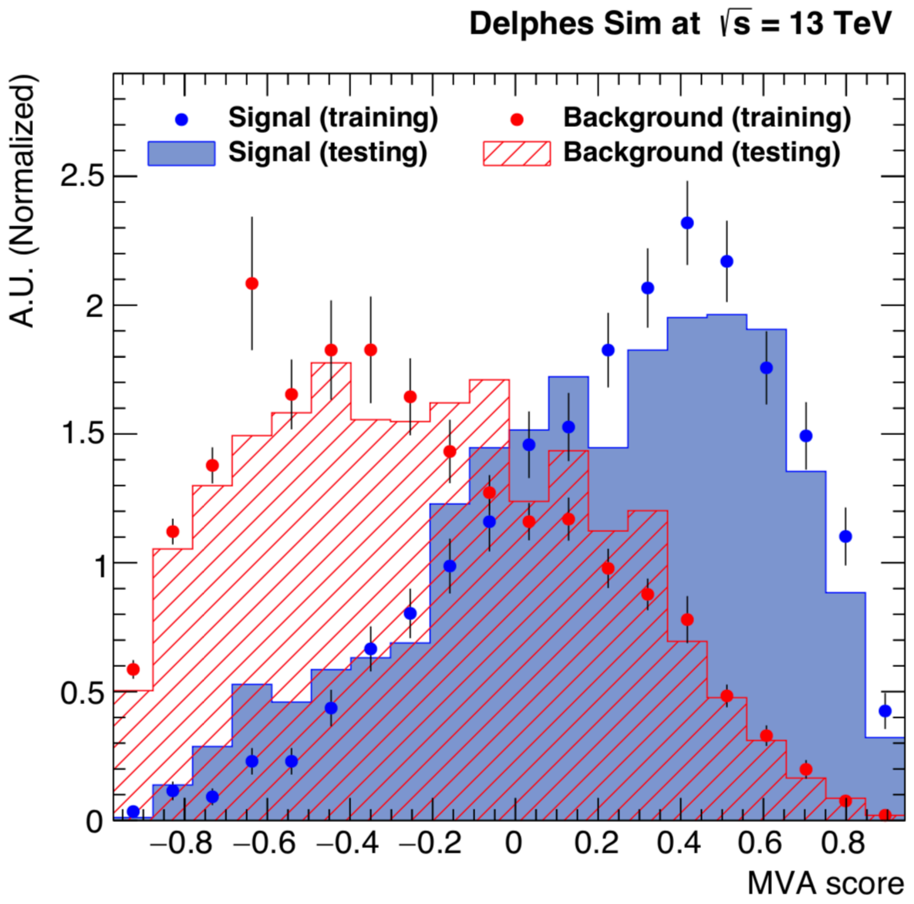
- Machine learning techniques based on
  - kinematic variables of the final objects
  - angle distances b.w. {leptons, MET}
  - ...

- multiplicity of jets, b jet, c jet and τ jet
- p_T, E_T^{miss} of the leading lepton
- p_T of the leading τ jet
- H_T which includes jets, leptons and E_T^{miss}
- p_T of leptons + E_T^{miss}, p_T of leptons + τ jet
- $\Delta R(\tau, \ell), \Delta\phi(\ell, E_T^{\text{miss}}), \Delta\phi(\tau, E_T^{\text{miss}})$
- $\Delta\phi(\tau + \ell, E_T^{\text{miss}})$
- $\Delta R(\ell, \text{leading } b \text{ jet})$

Multi-variate analysis of BDT method

- Increase of signal significance by O(30%) after using shape of final BDT distribution

- To further increase sensitivity
  - much larger event samples
  - more sophisticated statistical tools to perform shape analysis



Summary

- Anomalies in rare B decays have stimulated active discussions.
- LeptoQuark S_1, U_1 interpretations of $R_{D^{(*)}}$ naturally imply top FCNC
  - tree-level: $\sim 10^{-6}$ $\quad S_1 : Br(t \to c\tau^- \ell_l^+)$ $\quad U_1 : Br(t \to c\nu_\tau \bar{\nu}_l)$
  - loop-level: $\sim 10^{-10}$ $\quad S_1 : Br(t \to c\gamma)$
- Collider searches, $t\bar{t}$ events as an example
  - challenging for simple cut-and-count method
  - Multi-variate-analysis using BDT can improve the sensitivity

Thank you for listening

Back up

Moriond, 2019

$R_{K^{(*)}}$ in rare B decays, lepton Non-universality

$R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$ ~ 2.5 σ deviation from SM

$$R_{K^{(*)}}^{[q_1^2,q_2^2]} = \frac{\int_{q_1^2}^{q_2^2} dq^2 \frac{d}{dq^2} Br(B \to K^{(*)}\mu\mu)}{\int_{q_1^2}^{q_2^2} dq^2 \frac{d}{dq^2} Br(B \to K^{(*)}ee)}$$

$$q^2 = (p_{l^+} + p_{l^-})^2$$

SM ~ 1

$$R_K \equiv R_{K^+}^{[1,6]} = 0.846^{+0.060+0.016}_{-0.054-0.014} \text{ (LHCb)},$$

$$R_{K^*} \equiv R_{K^{*0}}^{[1.1,6]} = 0.96^{+0.45}_{-0.29} \pm 0.11 \text{ (Belle)}.$$

$$R_{K^{*0}}^{[0.045,1.1]} = 0.52^{+0.36}_{-0.26} \pm 0.05 \text{ (Belle)}$$