CKM2014

Single top production

(direct measurements of V_{td}, V_{ts}, V_{tb} and new physics related to single top)

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Outline

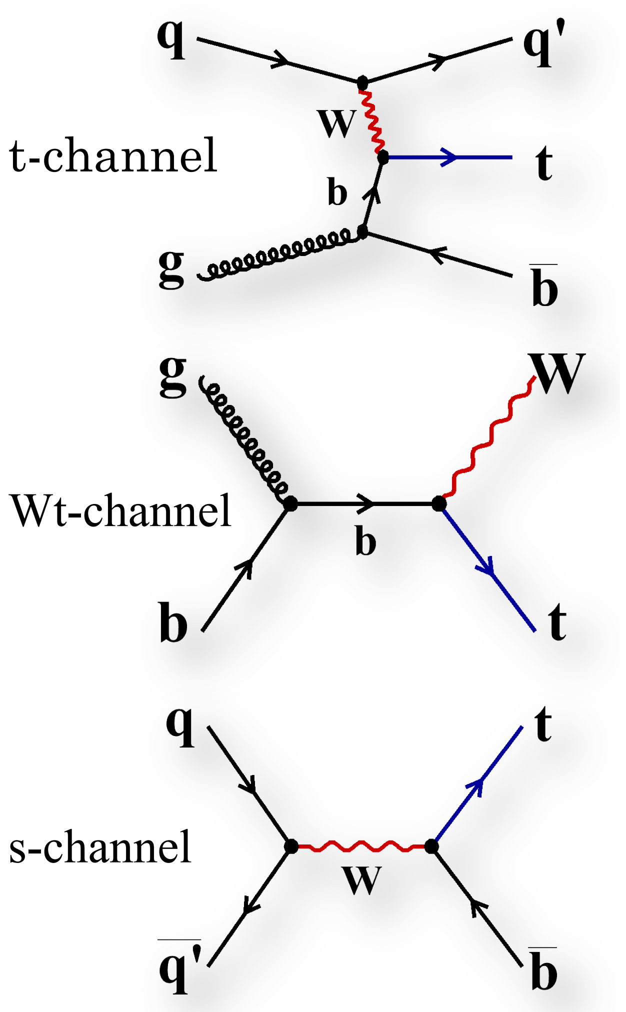
- Single top production within SM: V_{tb}, V_{ts} & V_{td} ?
- Single top production BSM: resonant NP vs EFT, monotops

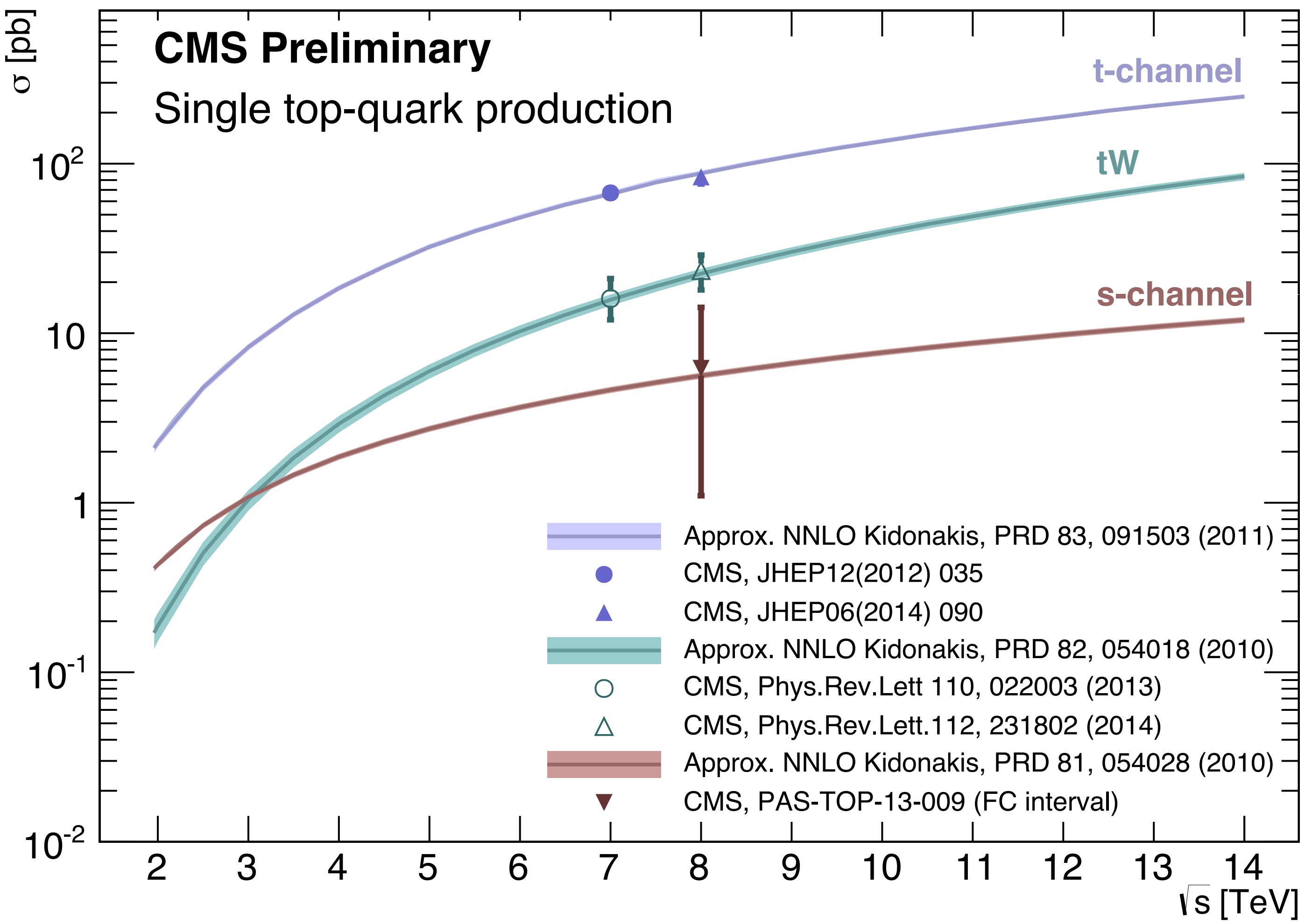
- Not covered in this talk: *th*, FCNC top production

(see talks by Brod, Mawatari, Sakurai)

- Disclaimer I: down with a virus infection the past few days
- Disclaimer II: have not travelled to west-central Africa recently

Single top production within SM





- Theoretical results for single top quark production are available at an ever increasing level of sophistication.

Single top production within SM

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G. Bordes and B. van Eijk, Nucl. Phys. B 435, 23 (1995).
T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D 56, 5919 (1997).
B.W. Harris et al., Phys. Rev. D 66, 054024 (2002).
M. Beccaria et al., Phys. Rev. D 77, 113018 (2008).
S. Heim et al., Phys. Rev. D 81, 034005 (2010).
J. M. Campbell, R.K. Ellis and F. Tramontano, Phys. Rev. D 70, 094012 (2004).
J. M. Campbell and F. Tramontano, Nucl. Phys. B 726, 109 (2005).
Q.-H. Cao, R. Schwienhorst and C. P. Yuan, Phys. Rev. D 71, 054023 (2005).
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A.S. Papanastasioiu et al., Phys. Lett. B 726, 223 (2013).
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R. Pittau, Phys. Lett. B 386, 397 (1996).
P. Falgari, P. Mellor and A. Signer, Phys. Rev. D 82, 054028 (2010).
P. Falgari et al., Phys. Rev. D 83, 094013 (2011).

  - NLO QCD & EW predictions

  - resummations

N. Kidonakis, Phys. Rev. D 83, 091503 (2011).
N. Kidonakis, Phys. Rev. D 81, 054028 (2010).
H. X. Zhu et al., JHEP 1102, 099 (2011).
J. Wang et al., arXiv:1010.4509 [hep-ph].

  - matching to parton showers

S. Frixione et al, JHEP 03, 092 (2006).
S. Frixione et al, JHEP 07, 029 (2013).
R. Frederix, E. Re and P. Torrielli, JHEP 1209, 130 (2012).
S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 0909, 111 (2009)

  - most recently: partial NNLO QCD prediction for *t*-channel

M. Brucherseifer, F. Caola and K. Melnikov, 1404.7116

8 TeV LHC	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
top	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
anti-top	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%

smallness of NLO effects appears accidental

V_{tx} from Single Top Production

- *t*-channel production @ LHC predicted at few % level!

$$\text{8 TeV LHC} \quad \sigma^{\text{NNLO}}_{t\,\&\,\bar{t}} = 83.9^{+0.8}_{-0.3}\text{pb}$$ (does not include ~2% PDF uncertainty)

- proportional to $|V_{tx}|^2$: $\sigma\,(\mathrm{pp} \rightarrow \mathrm{t/X}) = \mathrm{A_d}\,|\,\mathrm{Vtd}\,|^2 + \mathrm{A_s}\,|\,\mathrm{Vts}\,|^2 + \mathrm{A_b}\,|\,\mathrm{Vtb}\,|^2$

H. Lacker et al., 1202.4694

$$A_d : A_s : A_b = 5 : 1.8 : 1$$

in SM $|V_{td}|^2 : |V_{ts}|^2 : |V_{tb}|^2 = 6 \times 10^{-5} : 1.6 \times 10^{-3} : 1$

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in SM $\quad |V_{td}|^2 : |V_{ts}|^2 : |V_{tb}|^2 = 6 \times 10^{-5} : 1.6 \times 10^{-3} : 1$

- including top decay $\sigma(pp \to (t \to bW)/X) \simeq A_b|V_{tb}|^2 R$ J. Alwall et al., hep-ph/0607115

$$R \equiv \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2},$$ determined from $\mathcal{B}(t \to bW)/\mathcal{B}(t \to qW)$

- ~8% measurement of $\sigma(\mathrm{pp} \to \mathrm{t/X})$ can be translated into ~4% determination of $|V_{tb}|$ ⇒ theoretically $\delta|V_{tb}| < 1\%$ possible
- Access to V_{ts} & V_{td}?

V_{tx} from Single Top Production

- Access to V_{ts} & V_{td}?
  - In *t*-channel and tW production from initial *s*, *b* sea quarks,the events more central than those resulting from initial *d* quarks.

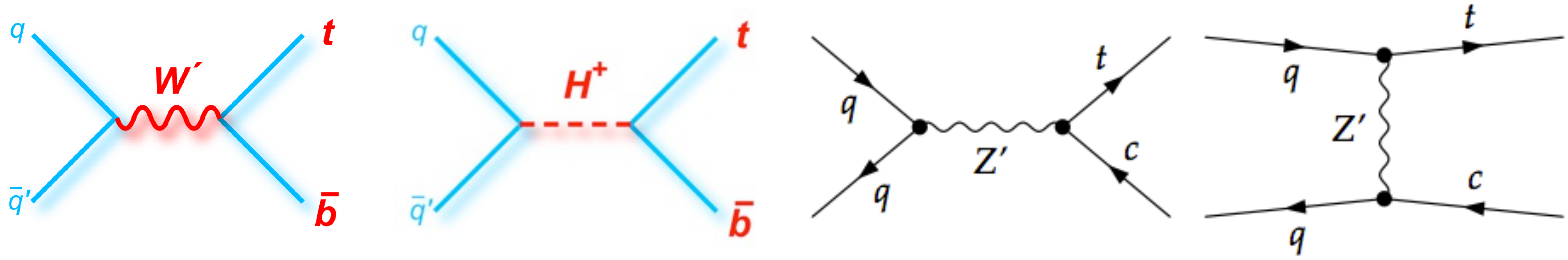
J. A. Aguilar-Saavedra and A. Onofre, 1002.4718

  - more pronounced for final state *t* quarks than for antiquarks.
  - Sensitivity far from expected value of $|V_{td}|$ (by two orders of magnitude)
  - Better prospects for $|V_{ts}|$ determination from *t* decays using characteristic differences in the *b*- and *s*-jet profiles

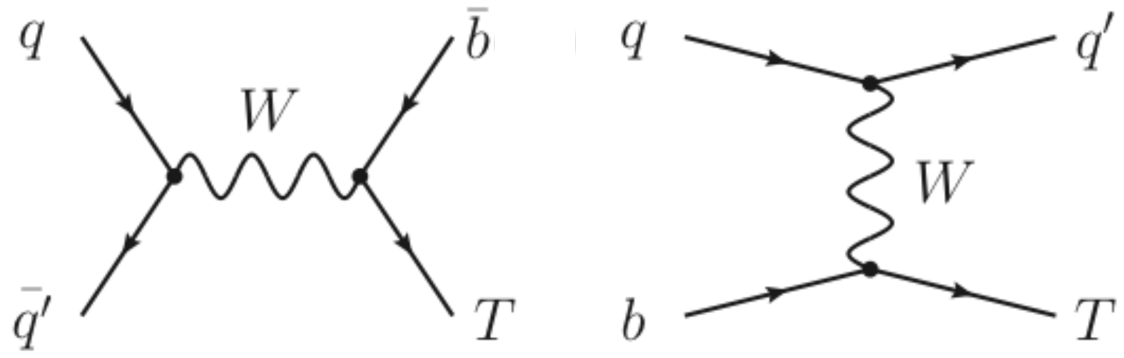
A. Ali, F. Barreiro and Th. Lagouri, (PLB 693(2010) 44-51).

Single top production beyond SM

- *s*- *t*- channel resonant production

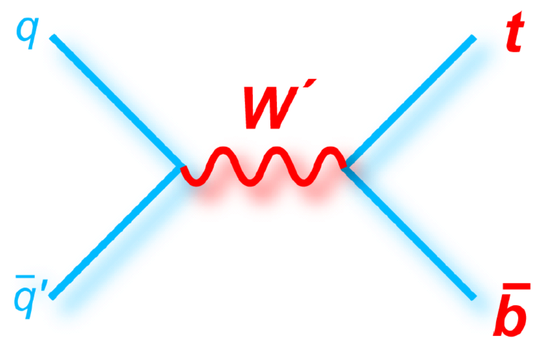


- single production of fermionic *t* & *b* partners

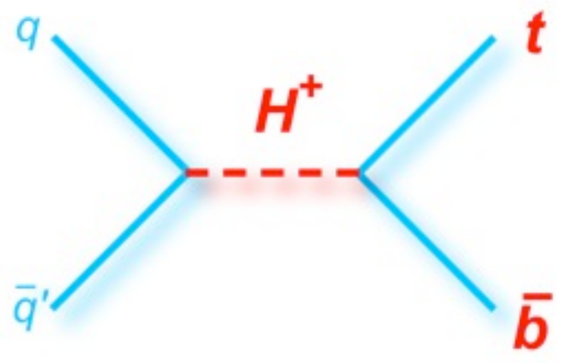


- EFT
    - anomalous *tWb* couplings & 4-quark operators

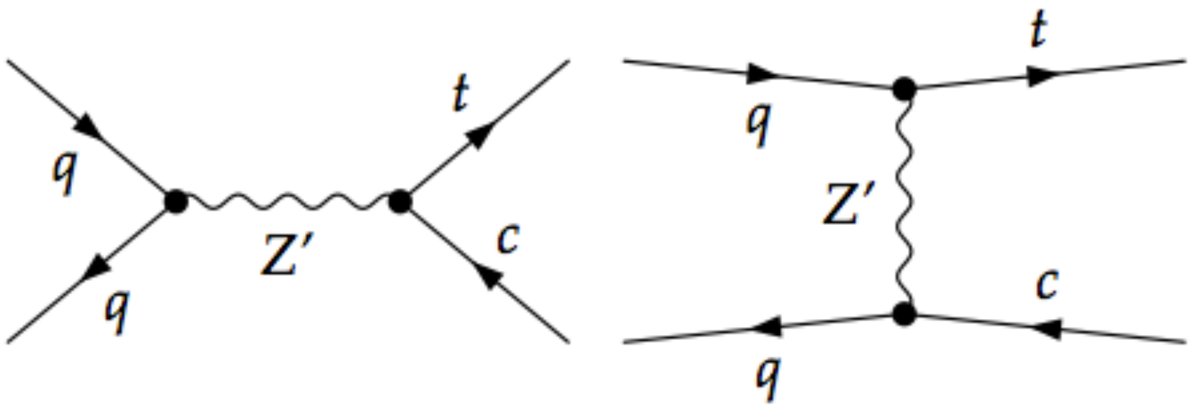
Resonant single top production



Leptophobic non-universal (Top flavor)



MFV-like multiple Higgs models

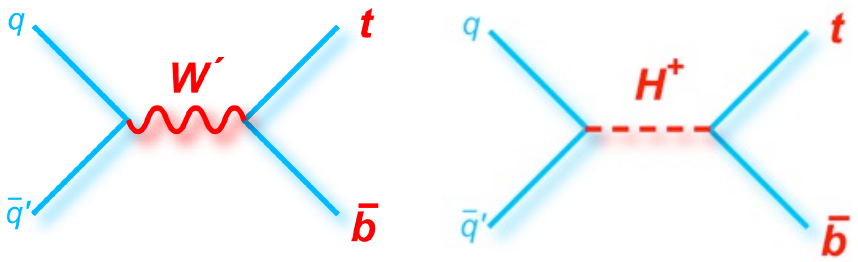


FCNC *Z’* models

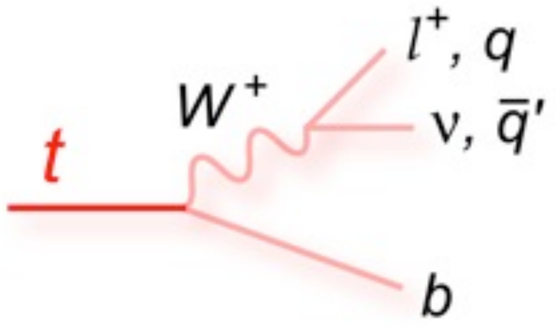
Generically severe constraints from D-$\underline{D}$ mixing

Ahrib et al., hep-ph/0602175

Resonant single top production



- The spin analyzing power of top decays can be used to probe resonance chirality



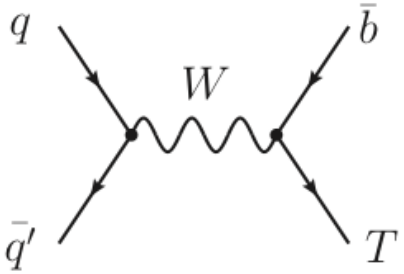
- distribution of charged lepton in *W* decay
    - In top rest frame, lepton always along top spin direction
    - In helicity basis $$\frac{d\Gamma}{\Gamma d\cos\theta_{\mathrm{hel}}} = \frac{1 + \lambda_t \cos\theta_{\mathrm{hel}}}{2}$$

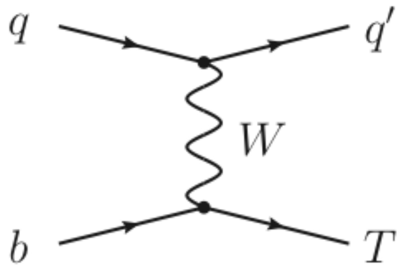
$\lambda_t = +1$ (right handed)

$\lambda_t = -1$ (left handed)

Kane, Ladinsky & Yuan, Phys.Rev. D45 (1992) 124-141

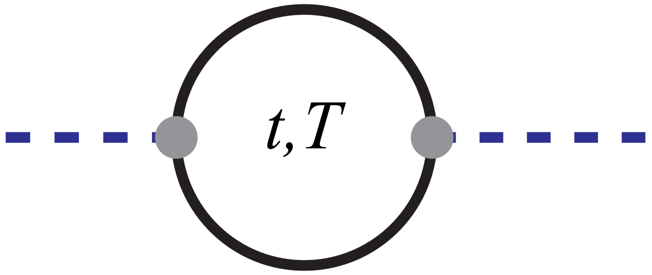
Resonant single top production

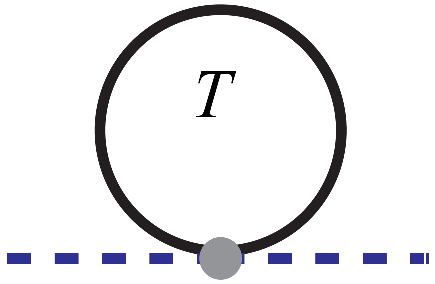




- Fermionic top partners below TeV ubiquitous in models of a light composite Higgs

$$\delta m_h^2 \sim \cancel{\frac{m_t^2}{v^2}\Lambda^2} + \frac{m_t^2}{v^2} m_T^2 \log \frac{\Lambda^2}{m_T^2} + \dots$$



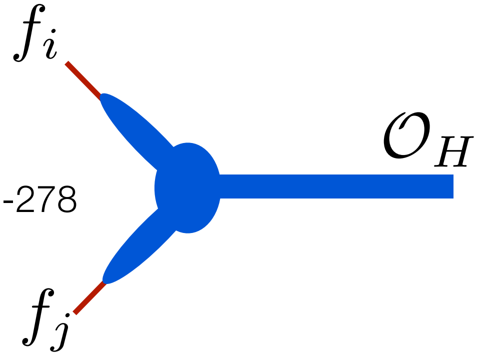


- top quark partial compositeness implies sizable *t*-*T* mixing

$$\mathcal{L} \ni m_L f_L \mathcal{O}_R + m_R f_R \mathcal{O}_L + \lambda \mathcal{O}_L \mathcal{O}_H \mathcal{O}_R \,, \quad \mathcal{O}_L \sim (3,2)_{1/6} \,, \dots$$

$$\Rightarrow \quad y_t \sim s_L s_R \lambda$$

Kaplan, Nucl.Phys. B365 (1991) 259-278

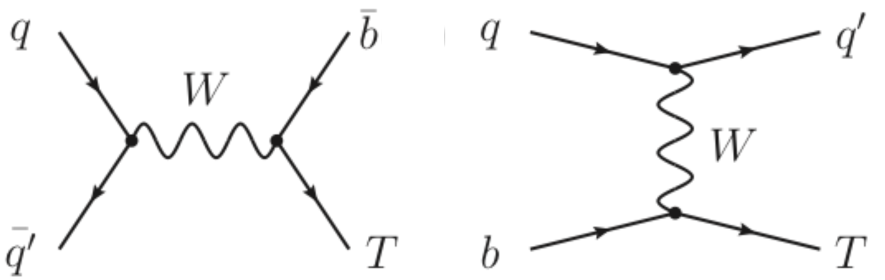


c.f. De Simone et al., 1211.5663

- single *T* production important search channel (especially for heavier *T* masses)

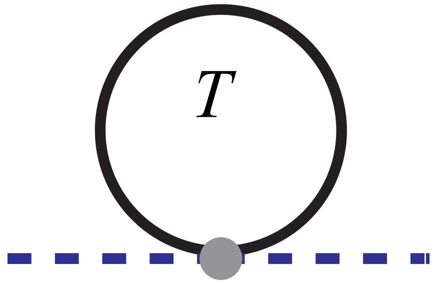
recent progress:
Azatov et al., 1308.6601
Gutierrez et al., 1403.7490
Gripaios et al., 1406.5957
Matsedonskyia, Panico & Wulzer, 1409.0100
Backovic et al., 1409.0409

Resonant single top production



- Fermionic top partners below TeV ubiquitous in models of a light composite Higgs

$\delta m_h^2 \sim \cancel{\frac{m^2}{2}}$



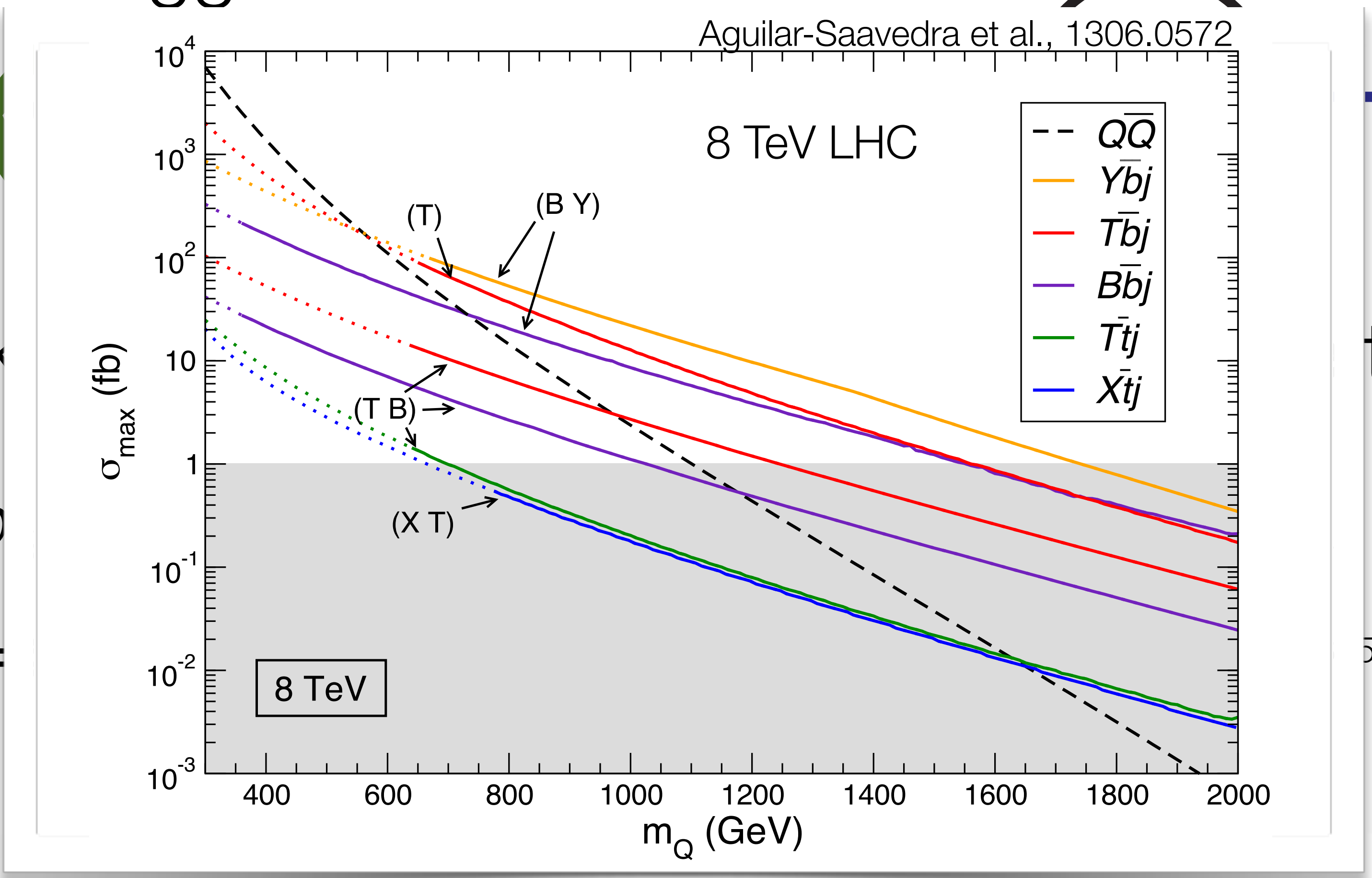
- top quark

t-T mixing

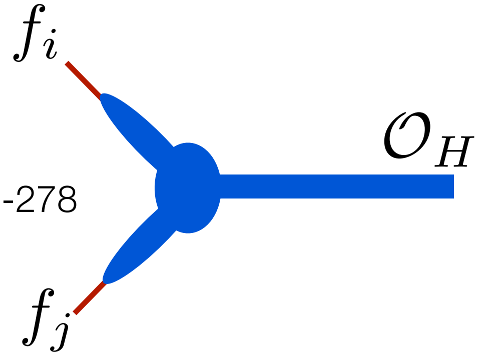
$\mathcal{L} \ni m_L f_L \mathcal{O}$

$=$

5 (1991) 259-278



Aguilar-Saavedra et al., 1306.0572



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Backovic et al., 1409.0409

BSM single top production in decoupling limit

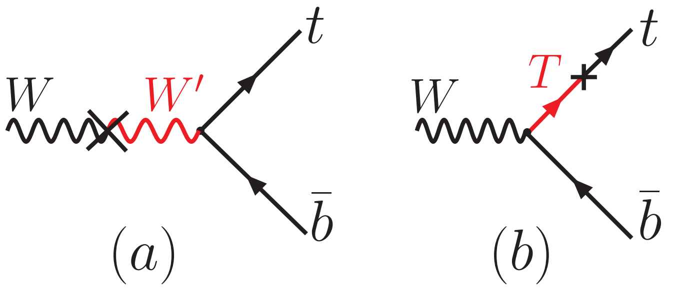
- If NP degrees of freedom kinematically inaccessible can describe BSM effects in single top production in terms of EFT

$$\mathcal{L}_{\rm int} = \sum_a \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a$$

- at lowest (n_a=2) order

Cao, Wudka & Yuan, 0704.2809

(1) anomalous *tWq*, (*tZq*) couplings



$$\begin{aligned}\hat{O}^{(3)}_{\varphi q} &= (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_L \sigma^I \gamma^\mu q_L) \\ \hat{O}_{\varphi tb} &= i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}_R \gamma^\mu b_R) \\ \hat{O}_{tW} &= \bar{q}_L \sigma^{\mu\nu} \sigma^I t_R \tilde{\varphi} W^I_{\mu\nu} \\ \hat{O}_{bW} &= \bar{q}_L \sigma^{\mu\nu} \sigma^I b_R \varphi W^I_{\mu\nu}\end{aligned}$$

$$\Rightarrow$$

$$\begin{aligned}\mathcal{L}_{Wtb} = &-\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu \\ &- \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W^-_\mu + \text{h.c.}\ ,\end{aligned}$$

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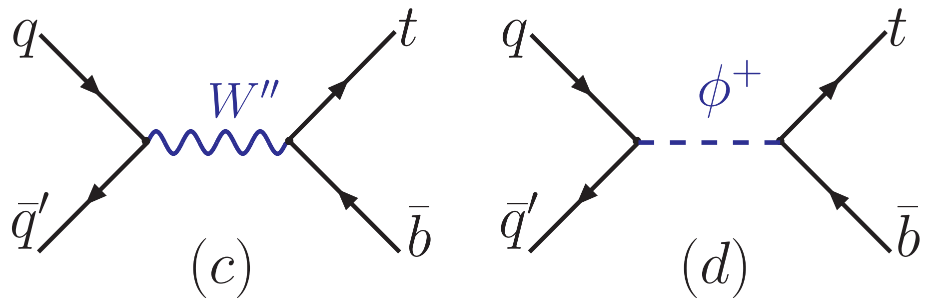
Cao, Wudka & Yuan, 0704.2809

(1) anomalous *tWq*, (*tZq*) couplings

(2) four quark operators



$$\begin{aligned}
\mathcal{O}_{qu}^{(1)} &= (\bar{q}_l t_R)\,(\bar{u}_R q_l)\,, \\
\mathcal{O}_{qq}^{(1)} &= \left(\bar{q}_l^i t_R\right)\left(\bar{q}_l^j b_R\right)\epsilon_{ij}, \\
\mathcal{O}_{qq}^{(3)} &= \frac{1}{2}\left(\bar{q}_l \gamma_\mu \tau^I q_l\right)\left(\bar{q}_h \gamma^\mu \tau^I q_h\right),
\end{aligned}$$

$$\Rightarrow$$

$$\begin{aligned}
\mathcal{O}_{4f} &= \mathcal{G}_{4f}\left[\frac{1}{v^2}\left(\bar{Q}'\gamma^\mu P_L Q\right)\left(\bar{b}\gamma_\mu P_L t\right)\right. \\
&\qquad \left. + \frac{1}{v^2}\left(\bar{Q}\gamma^\mu P_L Q'\right)(\bar{t}\gamma_\mu P_L b)\right], \\
&\qquad + \ldots
\end{aligned}$$

BSM single top production in decoupling limit

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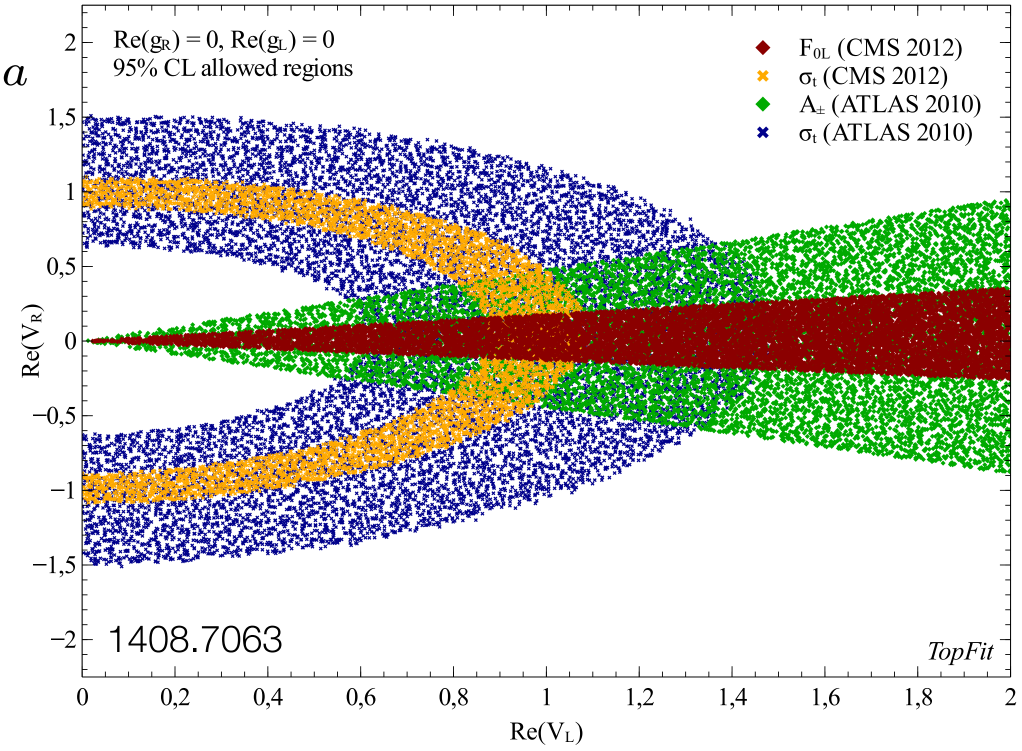


1408.7063

- at lowest (n_a=2) order

(1) anomalous *tWq*, (*tZq*) couplings

(2) four quark operators

Can be constrained with combination of single top production and decay observables:
- modified rates
- effects on top polarization

c.f.
Aguilar Saavedra, 0803.3810
Bach & Ohl, 1209.4564
Bernardo et al., 1408.7063

Monotop production

DM Pair Production at Hadron Colliders

- General discussion in terms of EFT

$$\mathcal{L}_{\rm int} = \sum_a \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a$$

- With *B* preservation, *O*a need to be bilinear in quark fields

$$\begin{aligned} \mathcal{O}^{ij}_{1a} =& (\bar{Q}^i_L \gamma_\mu Q^j_L) \mathcal{J}^\mu_a \,, \\ \mathcal{O}^{ij}_{2a} =& (\bar{u}^i_R \gamma_\mu u^j_R) \mathcal{J}^\mu_a , \qquad \mathcal{O}^{ij}_{3a} = (\bar{d}^i_R \gamma_\mu d^j_R) \mathcal{J}^\mu_a \,, \\ \mathcal{O}^{ij}_{4a} =& (\bar{Q}^i_L H u^j_R) \mathcal{J}_a \,, \qquad \mathcal{O}^{ij}_{5a} = (\bar{Q}^i_L \tilde{H} d^j_R) \mathcal{J}_a \,, \end{aligned}$$

- coupling to suitable dark sector currents, i.e.

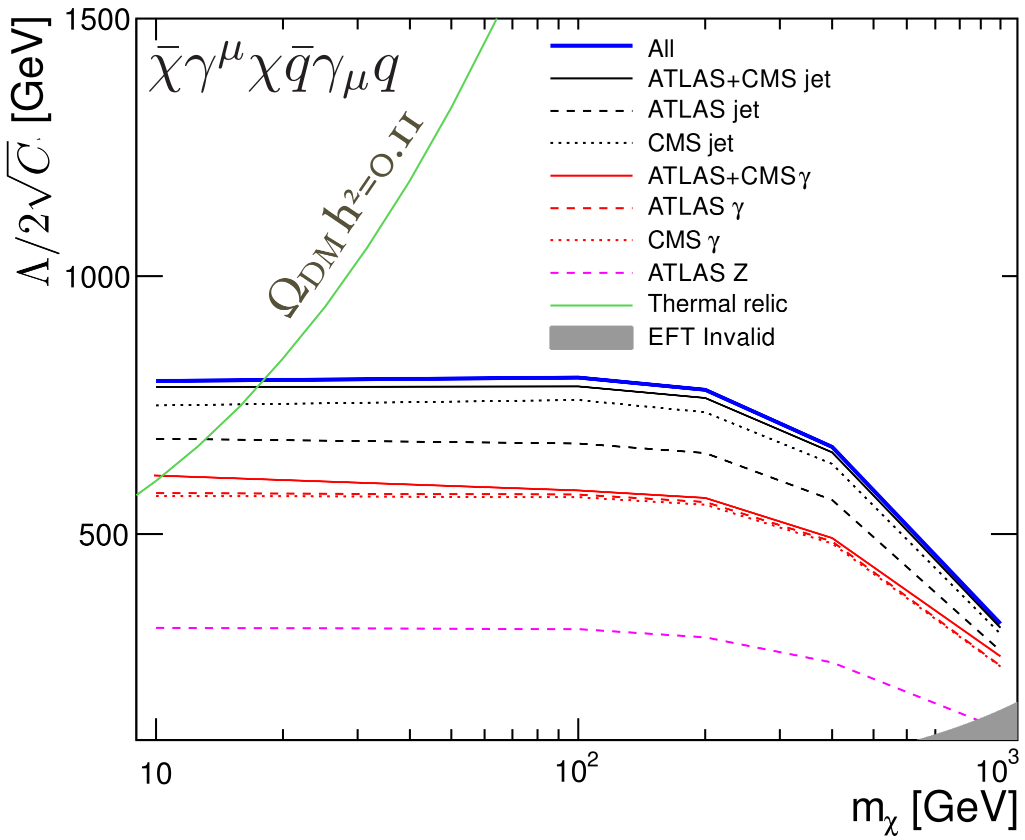
$$\mathcal{J}^\mu_{V,A} \ = \ \bar{\chi}\gamma^\mu\{1,\gamma_5\}\chi \quad \mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi \qquad \mathcal{J} = \chi^\dagger\chi, \ \mathcal{J}^\mu = \chi^\dagger\partial^\mu\chi$$

Fermionic

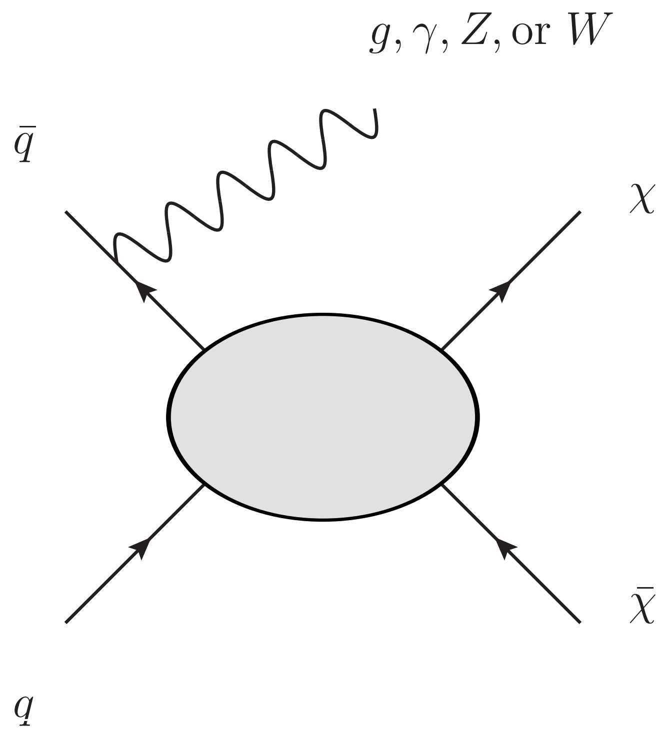
Scalar

DM Pair Production at Hadron Colliders

- Flavor universal contributions ($C_{ij} \sim \delta_{ij}$)
- mono[jet,γ] constraints using initial state radiation for tagging



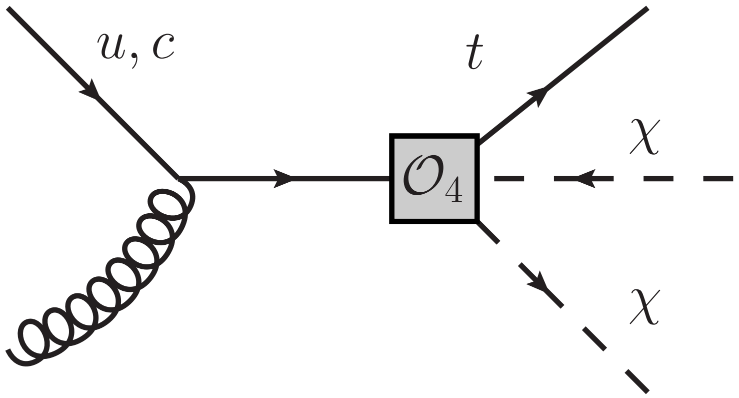
c.f. Zhou, Berge & Whiteson, 1302.3619



DM Pair Production at Hadron Colliders

- Can flavor violating interactions be competitive?
    - Constraints from Δ*F*=2 observables

Example: $\frac{C_{1a}^{13}}{\Lambda} \lesssim \frac{1}{2\ \mathrm{TeV}}, \quad \frac{C_{1a}^{23}}{\Lambda} \lesssim \frac{1}{0.3\ \mathrm{TeV}},$



    - effectively no bounds on $C_{2a,4a}^{13,23}$
- large monotop (t+E_{miss}) signals possible due to chirality flipping operators (also b+E_{miss}, but can be due to flavor conserving ops.)

J.F.K. & Zupan, 1107.0623
Boucheneb et al., 1407.7529

- reconstruction using $j_{(b)}jj$+E_{miss}, or $j_{(b)}l$+E_{miss} (M_T) (~ 1% signal eff.)

Andrea, Fuks & Maltoni, 1106.6199
Alvarez, Coluccio Leskow, Drobnak & J.F.K., 1310.7600
Agram et al., 1311.6478

Expectations in Models of Flavor

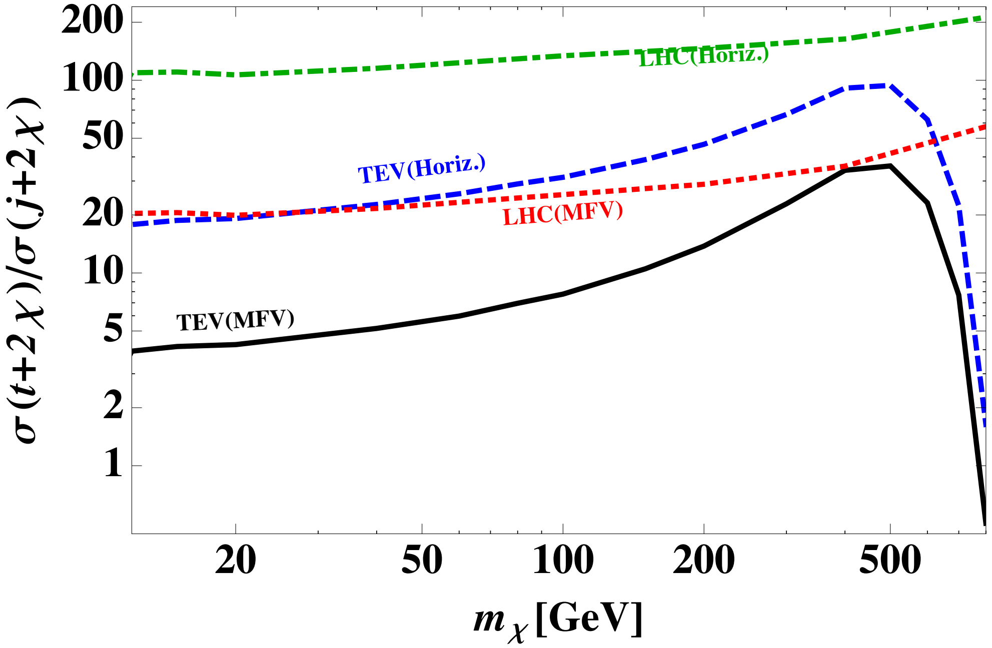
- Minimal Flavor Violation

$$C_{2a} = b_1^{(2a)} + b_2^{(2a)} Y_u^\dagger Y_u + b_3^{(2a)} Y_u^\dagger Y_d Y_d^\dagger Y_u + \cdots \,,$$
$$C_{4a} = \big(b_1^{(4a)} + b_2^{(4a)} Y_d Y_d^\dagger + \cdots \big) Y_u .$$

  - For $b_1^a \sim b_2^a \sim b_3^a$ C_{2a} almost flavor diagonal and universal

  - C_{4a} is highly hierarchical, can have large flavor violation if y_b~1

$$\frac{\hat\sigma(ug \to t + 2\chi)}{\hat\sigma(ug \to u + 2\chi)} \sim \left(\frac{y_t |V_{ub}| y_b^2}{y_u}\right)^2 \sim 5 \cdot 10^5\, y_b^4 ,$$
$$\frac{\hat\sigma(cg \to t + 2\chi)}{\hat\sigma(cg \to c + 2\chi)} \sim \left(\frac{y_t |V_{cb}| y_b^2}{y_c}\right)^2 \sim 50\, y_b^4 .$$



  - Larger effects expected with horizontal symmetries

Single X + t Production

- Corresponds to production of neutral mediators in DM models

- **Example:** Scalar DM (*S*) via (heavy *h*$_2$) Higgs portal in THDMIII

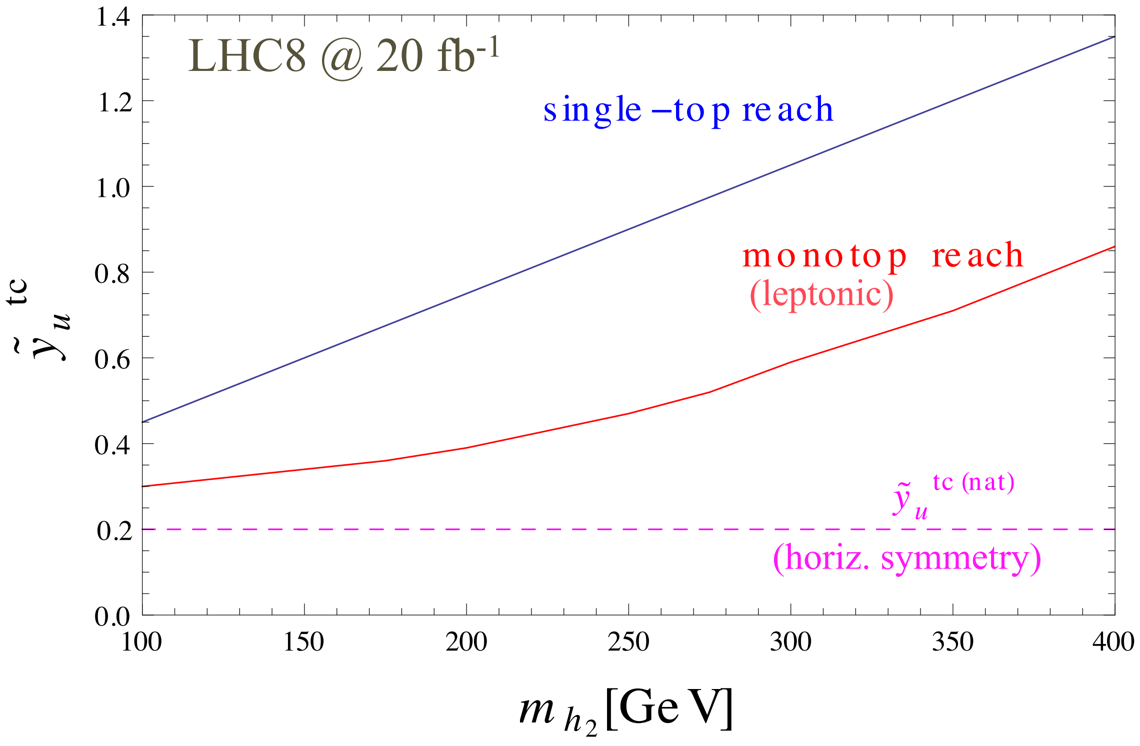
$$\mathcal{L}_{h_2}^{\tilde{y}} = \sum_{ij} \left(\tilde{y}_u^{ij} \bar{u}^i P_R u^j h_2 + \tilde{y}_d^{ij} \bar{d}^i P_R d^j h_2 \right) + \text{h.c.} + \lambda v_{\text{EW}} h_2 S S,$$

- *D*-$\underline{D}$ mixing

$$|\tilde{y}_u^{ut} \tilde{y}_u^{ct}|, |\tilde{y}_u^{tu} \tilde{y}_u^{tc}| < 0.030 \times \left(\frac{m_{h_2}}{250\text{GeV}} \right)^2 ,$$

$$|\tilde{y}_u^{tu} \tilde{y}_u^{ct}|, |\tilde{y}_u^{ut} \tilde{y}_u^{tc}| < 0.0088 \times \left(\frac{m_{h_2}}{250\text{GeV}} \right)^2 ,$$

$$\sqrt{|\tilde{y}_u^{ut} \tilde{y}_u^{tu} \tilde{y}_u^{ct} \tilde{y}_u^{tc}|} < 0.0036 \times \left(\frac{m_{h_2}}{250\text{GeV}} \right)^2 ,$$



Conclusions

- Single top quark production a key part of the top physics program at the LHC
  - fruitful laboratory of EW & QCD effects (e.g. PDF fits)
  - provides direct access to third row of CKM
- Rich BSM phenomenology, complementary to other searches
  - Example 1: single top partner production expected to become dominant discovery channel within composite scenarios
  - Example 2: monotop provides powerful probe of dark sectors coupling to quark flavor