CP and flavor violation in top physics

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OUTLINE

- CP violation
  - some quick basics
  - top system in collisions
- indirect constraints
  - can you even discover CPV at LHC?
- flavor violation
  - searching for dark matter using monotops

CP violation

CP violation basics

- CP violated ⇔ (weak) phases in Lagrangian
  - CPV measured from interference
  - at least two amplitudes needed
  - have to have different weak phases
- the simplest example
  - also take $a_2 << a_1$

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)}$$
$$\bar{A} = a_1 e^{i(-\delta_1+\phi_1)} + a_2 e^{i(-\delta_2+\phi_2)}$$
$$A_{\rm CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \frac{a_2}{a_1} \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

  - nonzero only if strong phase difference nonzero

CP violation basics

- whether or not one needs nonzero strong phases matters
  - they are perturbative = small
- can use weighted cross sections instead

$$\langle O_a \rangle = \int_{\substack{i \to f \\ \bar{i} \to \bar{f}}} dp.s.\, |A|^2 O_a(\{p_k\})$$

  - free to choose the observable O_a
- useful to categorize them according to T_N
  - T_N = naive time inversal: **p→-p**, **s→-s**, but not |*f*>→|*i*>
  - the transf. prop. under T_N tells whether strong phases are needed

CP violation basics

$\langle O_i \rangle \neq 0$ if	O_i T_N-odd	O_i T_N-even
O_i CP-odd	$\Delta\delta_w \neq 0$, $\Delta\phi_s$ may $=0$	$\Delta\delta_w \neq 0$, $\Delta\phi_s \neq 0$
O_i CP-even	$\Delta\delta_w$ may $=0$, $\Delta\phi_s \neq 0$	$\Delta\delta_w$ may $=0$, $\Delta\phi_s$ may $=0$

- Note: $\langle O_i \rangle \neq 0$ signals CPV only, if O_i is CP-odd
- preferred if also T_N-odd, since then strong phases can be small
- a number of observables, here just two examples

Atwood, Bar-Shalom, Eilam, Soni, hep-ph/0006032 Antipin, Valencia, 0807.1295

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$O_i = \pm 1 \Rightarrow A_{CP}$

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O_i CP-even	$\Delta\delta_w$ m… $\Delta\phi_s \neq 0$	…, $\Delta\phi_s$ may $=0$

$\epsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}})$

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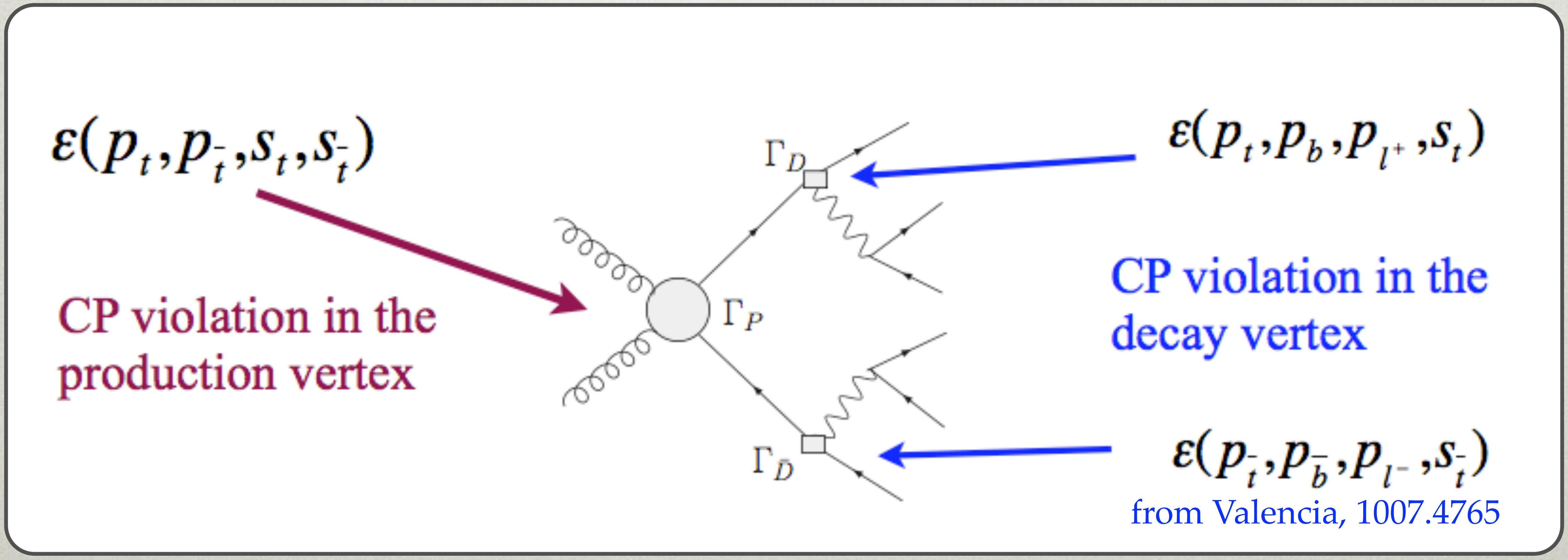
CPV in ttbar

- focus on ttbar production at LHC
  - CPV in production
  - CPV in decay
- the initial state basically *gg* or *qqbar*



CPV in production

- EDM and CEDM are CP violating

$$\mathcal{H}_{\text{eff}} = -\frac{1}{2}\bar{\psi}_q\left[(F_{\mu\nu}\sigma^{\mu\nu})(\mu_q + i\gamma_5 d_q)\right.$$
$$\left. + g_s\,(G^a_{\mu\nu}t^a\sigma^{\mu\nu})(\tilde{\mu}_q + i\gamma_5\tilde{d}_q)\right]\psi_q$$
$$-\frac{1}{6}w f^{abc}\varepsilon^{\mu\nu\lambda\rho}\,G^a_{\mu\sigma}G^{b\sigma}_{\nu}G^c_{\lambda\rho}\,,$$

- CEDM would contribute to CPV observables in ttbar production
  - can be enhanced from BSM
- bounds from LHC and tevatron from σ_{tt} and $d\sigma_{tt}/dm_{tt}$

Kamenik, Papucci, Weiler, 1107.3143

$$|\tilde{d}_t|m_t < 0.16 \quad (95\%\,\text{C.L.})\,,$$

- could reach 0.05 with 10 fb^{-1} from T_N-odd correlators Gupta, Mete, Valencia, 0905.1074
- but stringent constraints from neutron EDM

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  - top CEDM introduces finite threshold corrections to Weinberg op.

$$|\tilde{d}_t|m_t < 2.0\times 10^{-3}(95\%\text{CL})$$

- Note: assumes that $q^2\to 0$ limit OK at LHC (i.e. EFT valid)
  - probably hard to loosen bounds in realistic (on-shell) models

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CPV in decays

- indirect bounds on CC
  - anomalous $t \to bW$ couplings

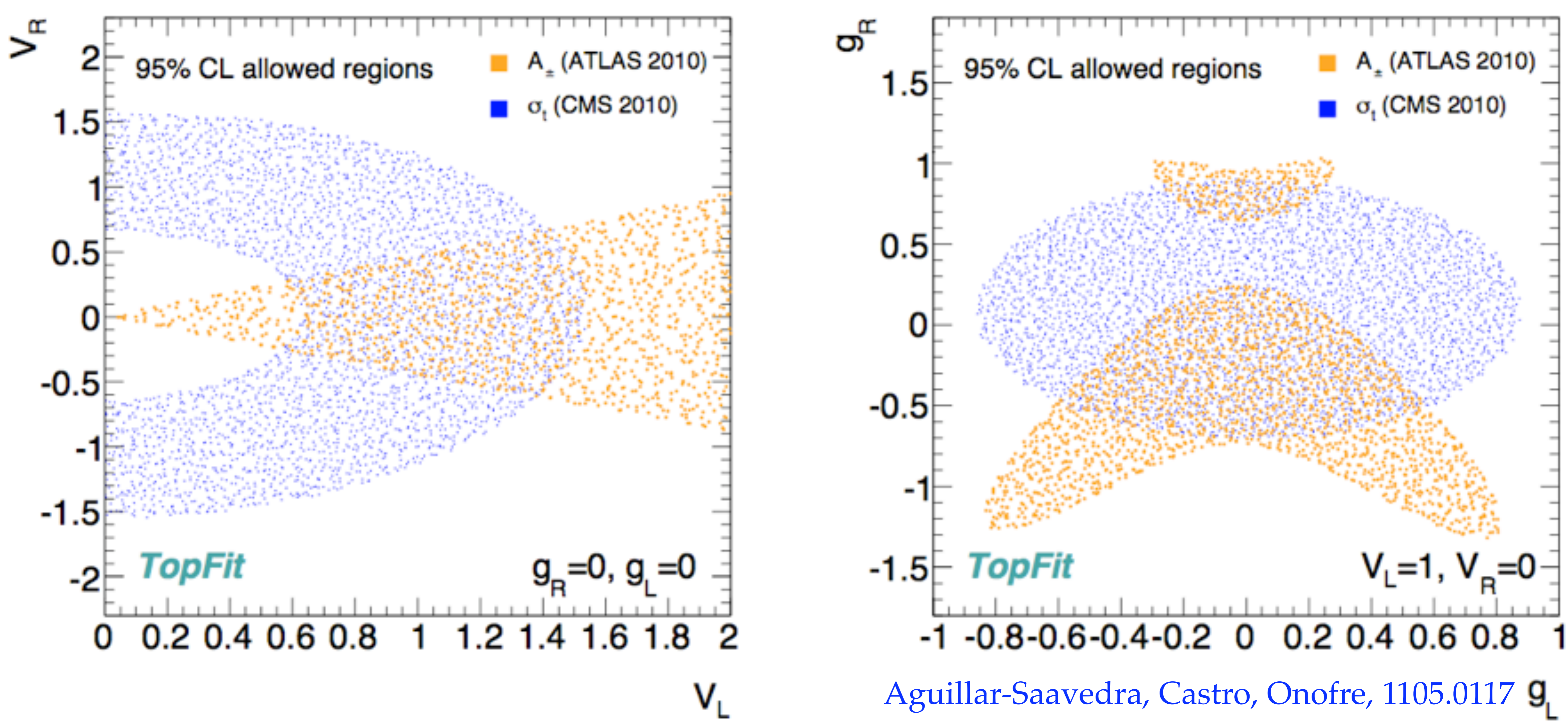
$$\mathcal{L}_{tWb} = \mathcal{L}_{tWb}^{\rm SM} - \frac{g}{\sqrt{2}}\bar{b}\Big[(V_L P_L + V_R P_R)\gamma^\mu + \frac{i\sigma^{\mu\nu}q_\nu}{m_W}(G_L P_L + G_R P_R)\Big] t W_\mu$$

- indirect bounds from B mixing and B decays

Drobnak, Fajfer, Kamenik, 1109.2357; 102.4347

  - in general much better than direct bounds
  - in addition also constrain imaginary parts
  - but $Im[V_L]$ and $Im[G_R]$ unconstrained
- G_R the only one that can give T_N-odd contrib. from interference with SM
  - an opportunity for LHC to be best/discover something?

CPV in decays



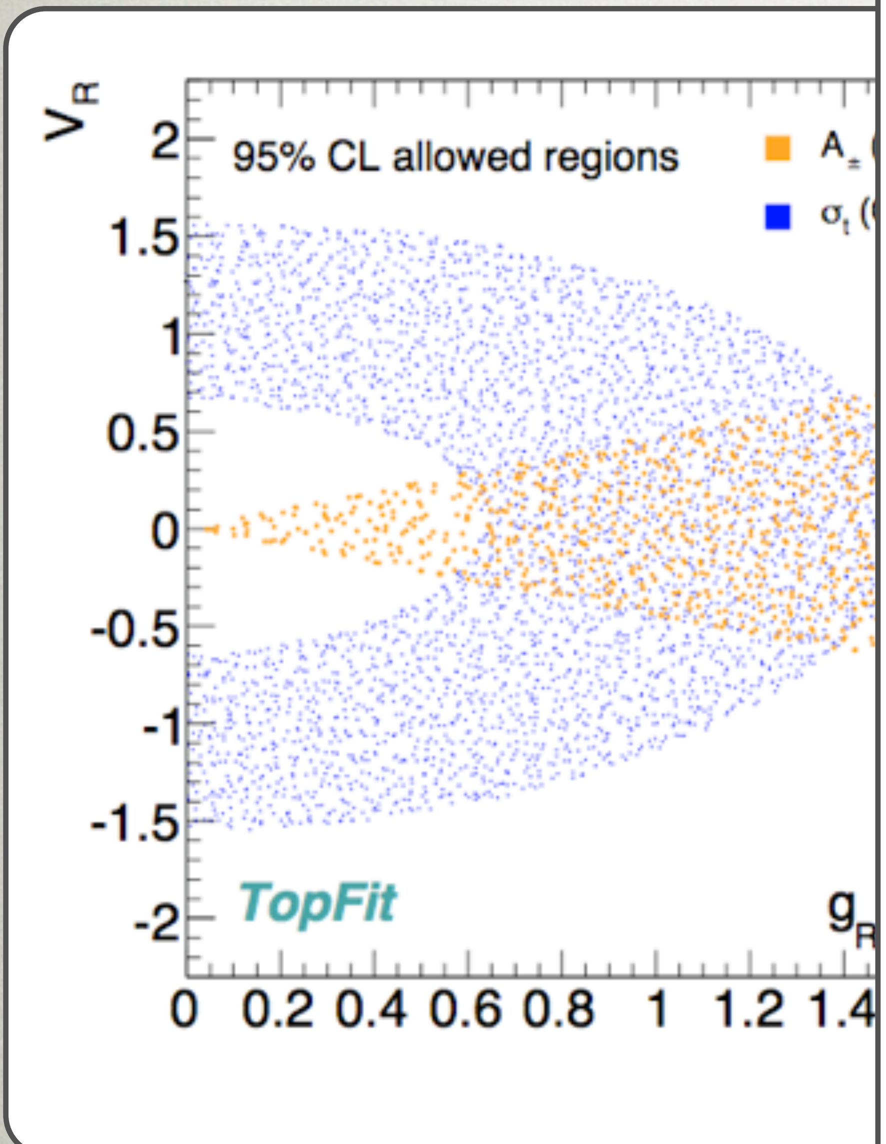
Aguillar-Saavedra, Castro, Onofre, 1105.0117

tW_μ

interference with SM

- an opportunity for LHC to be best/discover something?

CP



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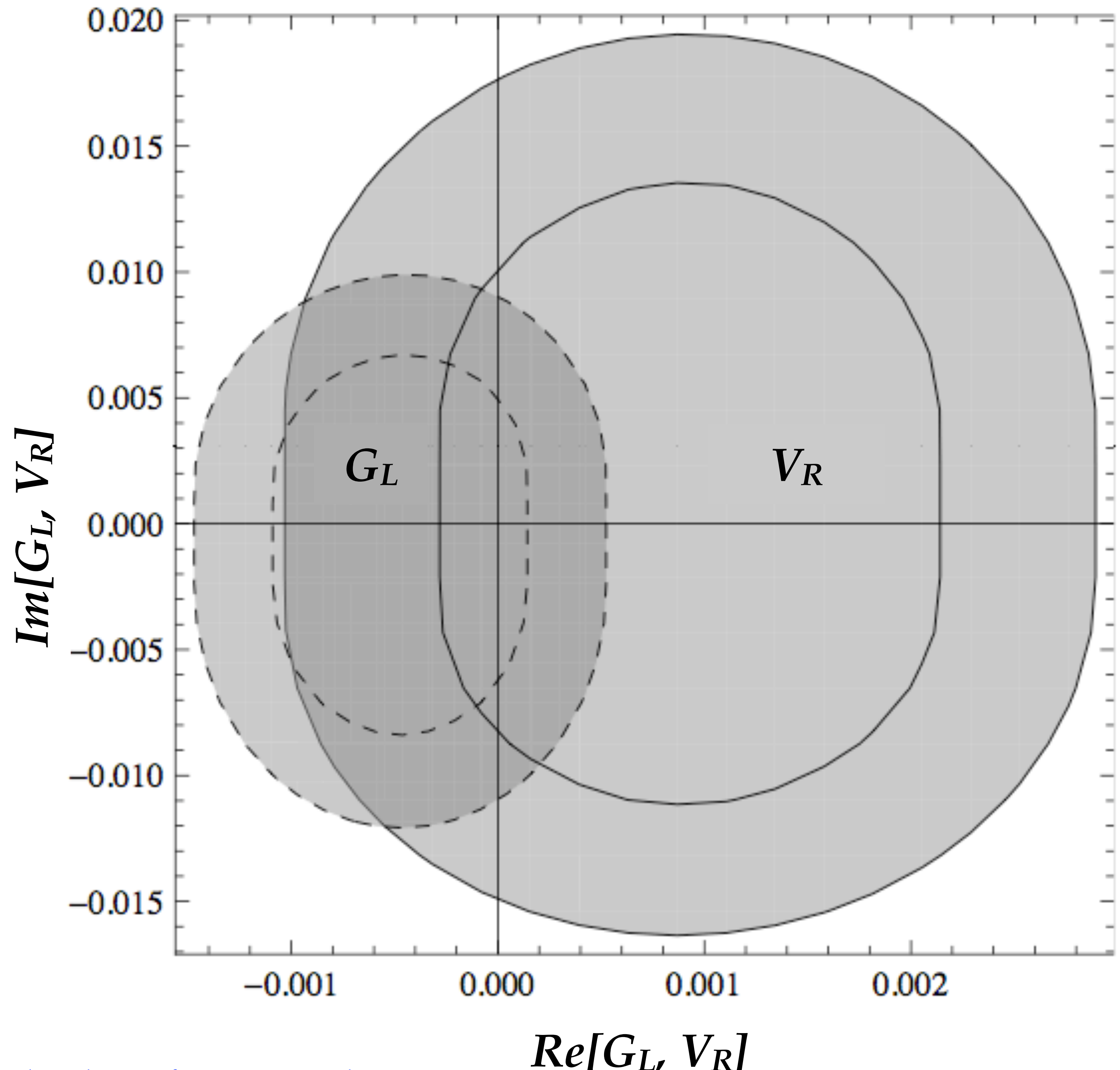

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Flavor violation

FLAVOR VIOLATION

- FCNC decays $t\to q\gamma, qZ, qg$ see talks by Wicke, Mc Carn
- FCNC single top production $gq\to t$
  - EFT basis in Aguilar-Saavedra 0811.3842
  - QCD corrections in Drobnak et al. 1007.2551
- will focus instead on a different topic
  - dark matter and top production through flavor violation

THE BIG PICTURE

- monojets searches are a standard DM search channel
- will show that the monotops can be the dominant signal

Kamenik, JZ, 1107.0623

  - somewhat surprising since it comes from flavor violation
  - Note: flavor symm. violated in the SM
    - inevitable that also violated in the presence of NP

WHAT WILL BE DONE

- interested in LHC
  - so focus only on DM-quark couplings
- take a few examples of flavor breaking
  - Minimal Flavor Violation
  - horizontal symmetries
- start with EFT
  - then also on-shell resonance production

DIRECT PRODUCTION

- use EFT for DM interactions with quarks

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

- only interested in interactions with quarks

$$\mathcal{J}^\mu_{V,A} = \bar\chi \gamma^\mu \{1, \gamma_5\} \chi$$

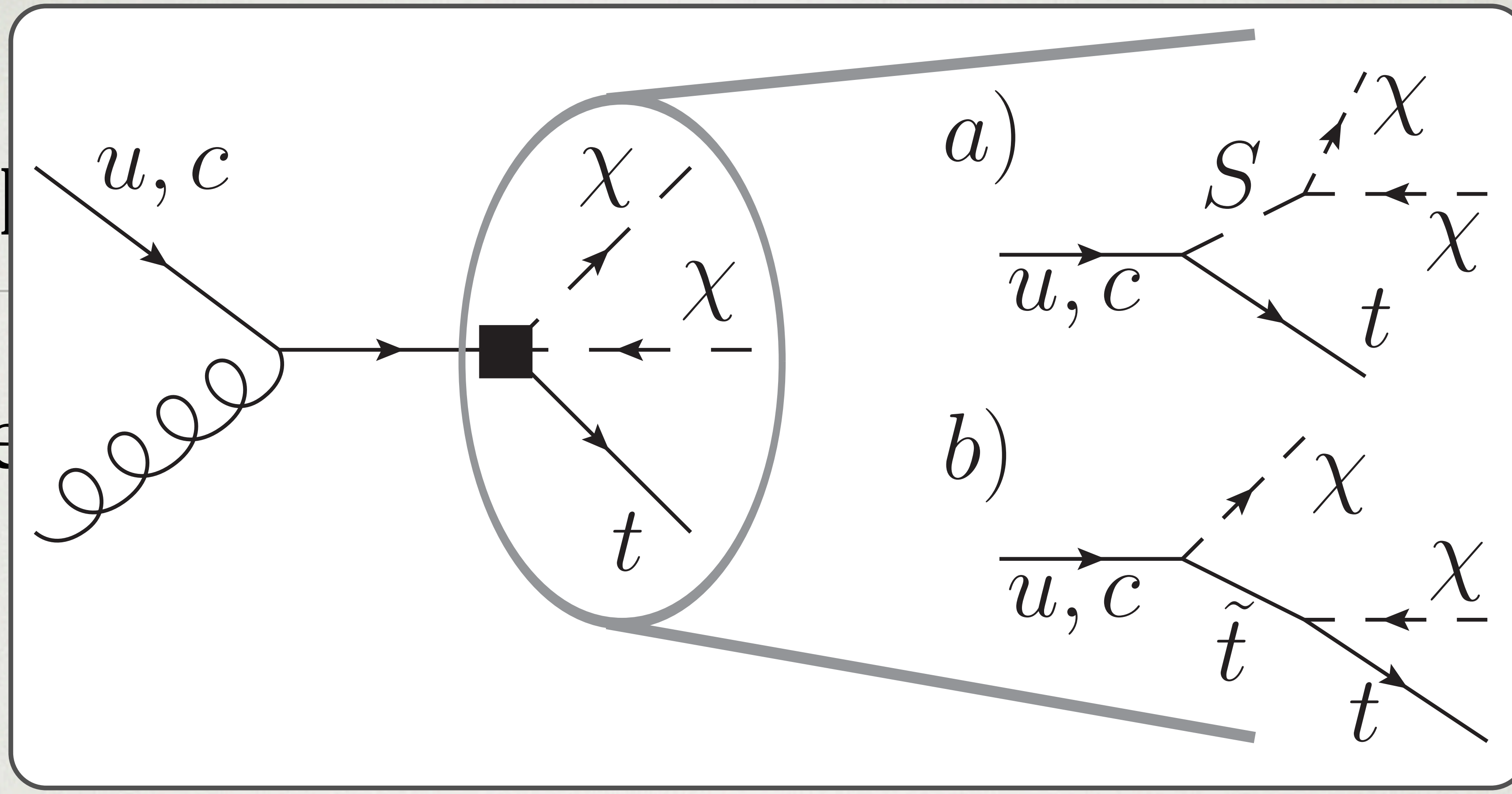
$$\mathcal{O}^{ij}_{1a} = (\bar{Q}^i_L \gamma_\mu Q^j_L) \mathcal{J}^\mu_a ,$$

$$\mathcal{O}^{ij}_{2a} = (\bar{u}^i_R \gamma_\mu u^j_R) \mathcal{J}^\mu_a , \qquad \mathcal{O}^{ij}_{3a} = (\bar{d}^i_R \gamma_\mu d^j_R) \mathcal{J}^\mu_a ,$$

$$\mathcal{O}^{ij}_{4a} = (\bar{Q}^i_L H u^j_R) \mathcal{J}_a , \qquad \mathcal{O}^{ij}_{5a} = (\bar{Q}^i_L \tilde{H} d^j_R) \mathcal{J}_a ,$$

- full set includes other ops.

$$\mathcal{J}_{S,P} = \bar\chi \{1, \gamma_5\} \chi$$



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\end{aligned}$$

- full set includes other ops.

$$\mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi$$

MINIMAL FLAVOR VIOLATION

- as a start look at MFV
  - the Wilson coefficients have the form

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

- in up-quark mass basis $Y_d = V_{\rm CKM} {\rm diag}(y_d, y_s, y_b)$, $Y_u = {\rm diag}(y_u, y_c, y_t)$
- assume $b_1^a \sim b_2^a \sim b_3^a$ then $C_{2a} \sim \mathbb{1}$
- the chirality flipping C_{4a} different, proportional to Yu
  - off-diagonal elements more important
- the FV $qg \to t\chi\chi$ is enhanced compared to $qg \to q\chi\chi$

MONOTOPS

- monotops the leading signal despite coming from FV

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

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

- what have we learned?
  - t+MET can be >> monojet signal even in MFV
  - y_b needs to be large ~*O(1)*
  - DM needs to couple to quarks through scalar int.
- if only through Higgs no FV, need other scalars
- incidentally, this needed for isospin viol. DM models proposed to explain CoGeNT and DAMA

BEYOND MFV

- this quite generic for any model of flavor
- an example: abelian horizontal symm.

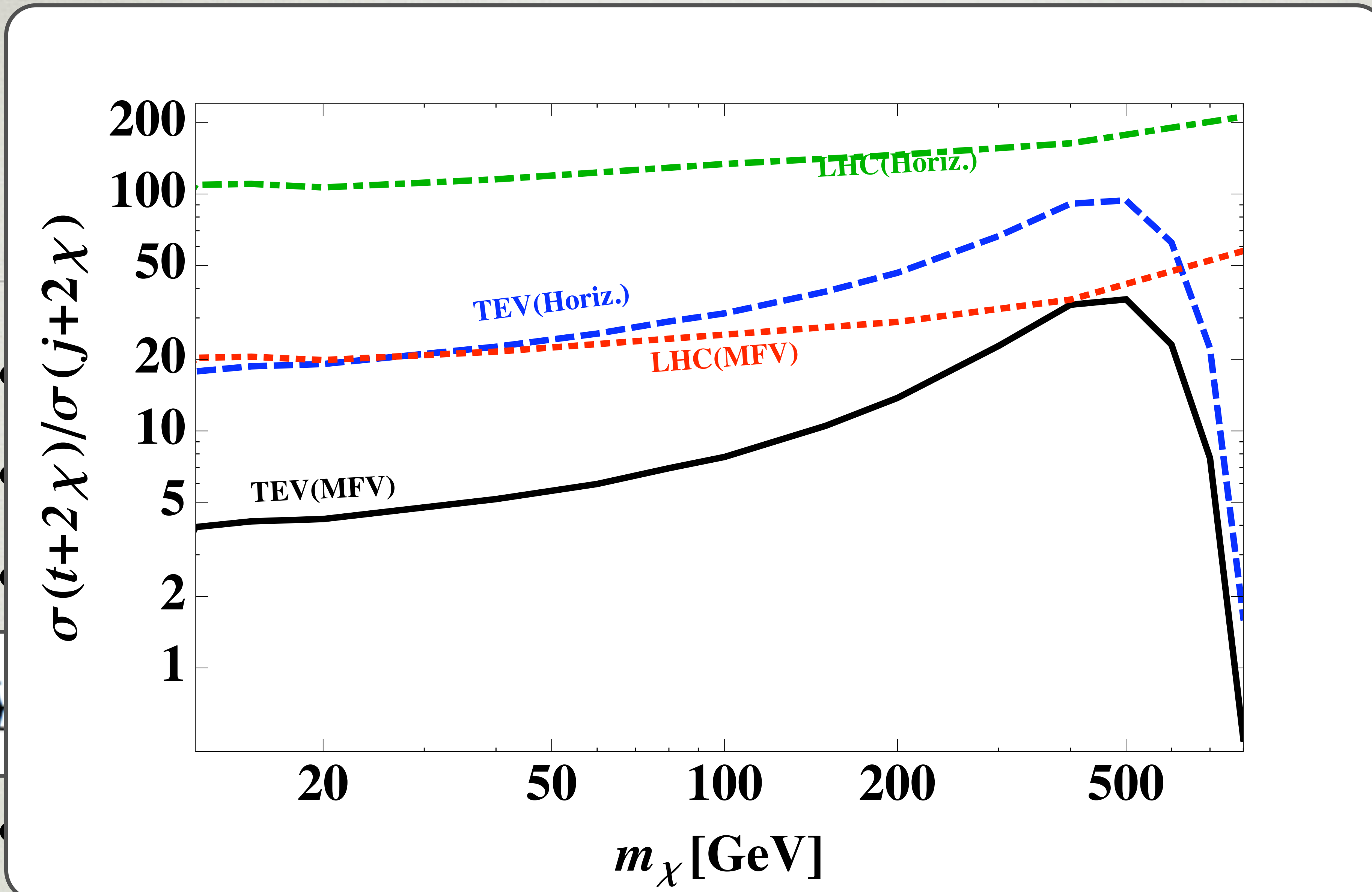
  Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320
- the yukawas are given by

$$(Y_u)_{ij} \sim \lambda^{|H(\bar{u}_R^j)+H(Q^i)|}, \quad (Y_d)_{ij} \sim \lambda^{|H(\bar{d}_R^j)+H(Q^i)|}$$

- in the same way the couplings to DM

$$C_2 \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}, \quad C_4 \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

- note: *c*-*t*-DM coupling parametrically larger
- even larger effects if DM charged under flavor



9310320

$(Y \ldots Q^i)|$

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ON-SHELL PRODUCTION

- largest cross sections expected if mediators on-shell
- two classes of models
  - DM from decay of singlet S
  - exchange of mediator in t-channel
- will give an example for each of them

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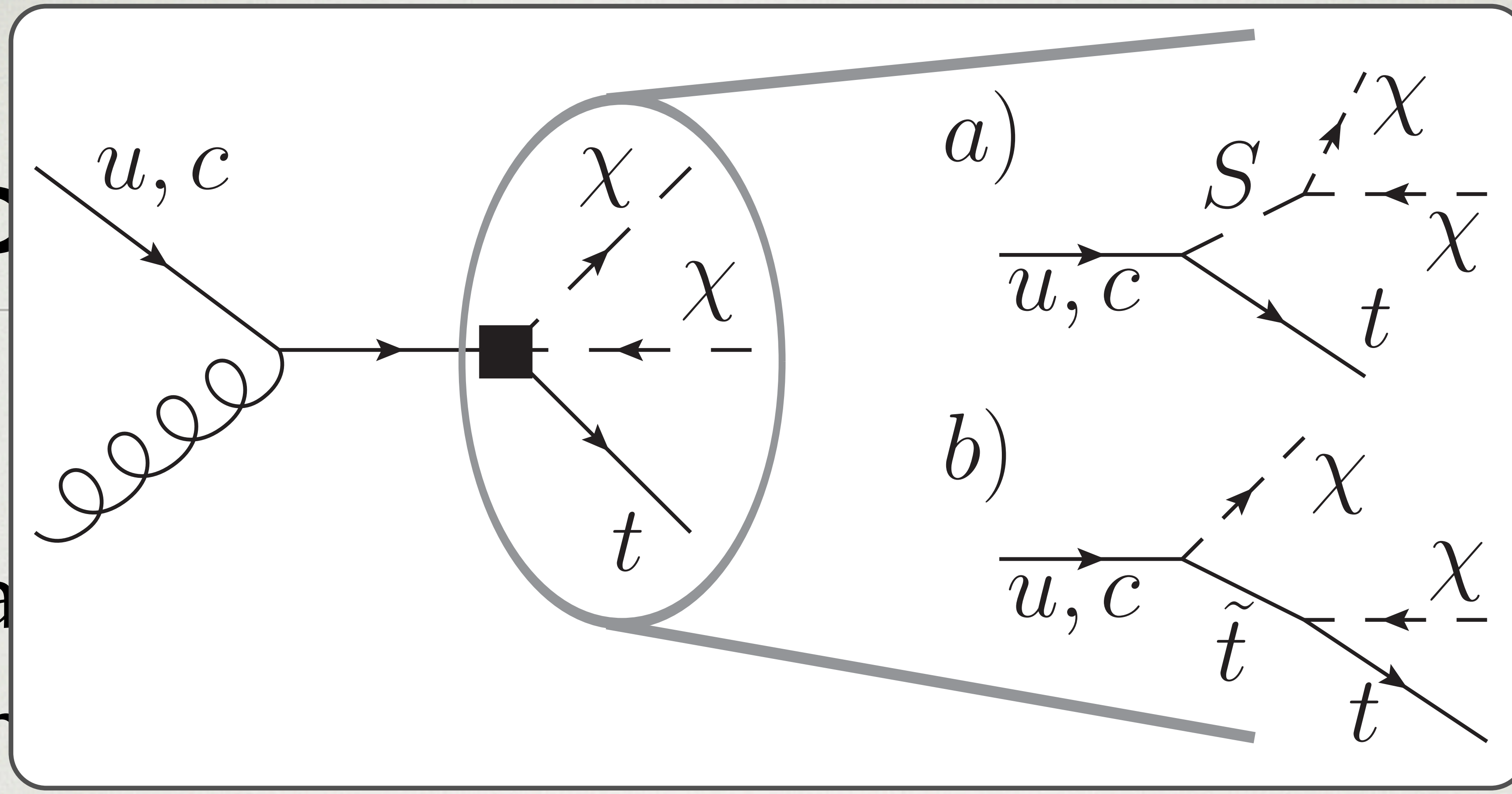

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  m

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EXAMPLE FROM THE FIRST CLASS

- take S and χ to both be scalars
- horizontal symmetries scaling
- with 5 fb^{-1} 7 TeV LHC, significance of 5σ (3σ) for m_S=*200* GeV (*400* GeV)

EXAMPLE FROM THE SECOND CLASS

- a toy example equiv. to MSSM keeping only
  - the lightest stop and a neutralino
  - χ_0 has large higgsino component
- ttbar+MET production is O(10) larger than monotops
- t+MET can compete if Br($t_1 \to t + \chi$)<<100%

CONCLUSIONS

- CPV in top production well constrained from EDMs
- CPV in top decays not fully constrained by indirect searches in *B* physics
- monotops can be an interesting search signal for DM production at the LHC

EXTRA SLIDES

EXAMPLE OF THE FIRST CLASS

- take S and χ to be both scalars
- after EWSB the relevant part of Lagr.

$$\mathcal{L}_{\rm int} = g_L^u \bar{u}_R t_L S + g_L^c \bar{c}_R t_L S + g_R^u \bar{t}_R u_L S + g_R^c \bar{t}_R c_L S + \lambda v S \chi\chi + h.c.,$$

- in our hor. symm. example: $g_L{}^u \sim \lambda^3$, $g_L{}^c \sim \lambda$
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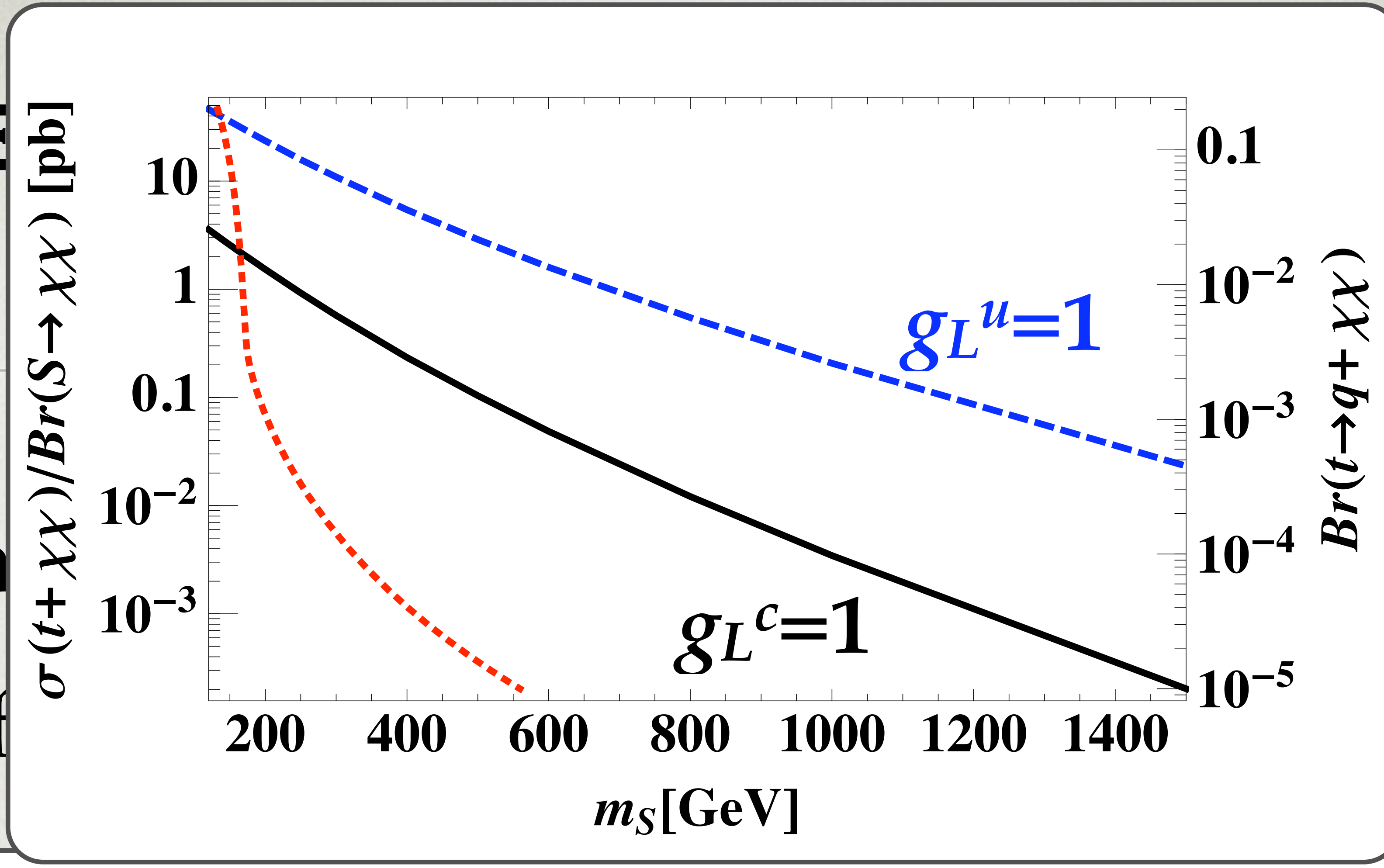
E ... ST



- ta...
- af... gr.

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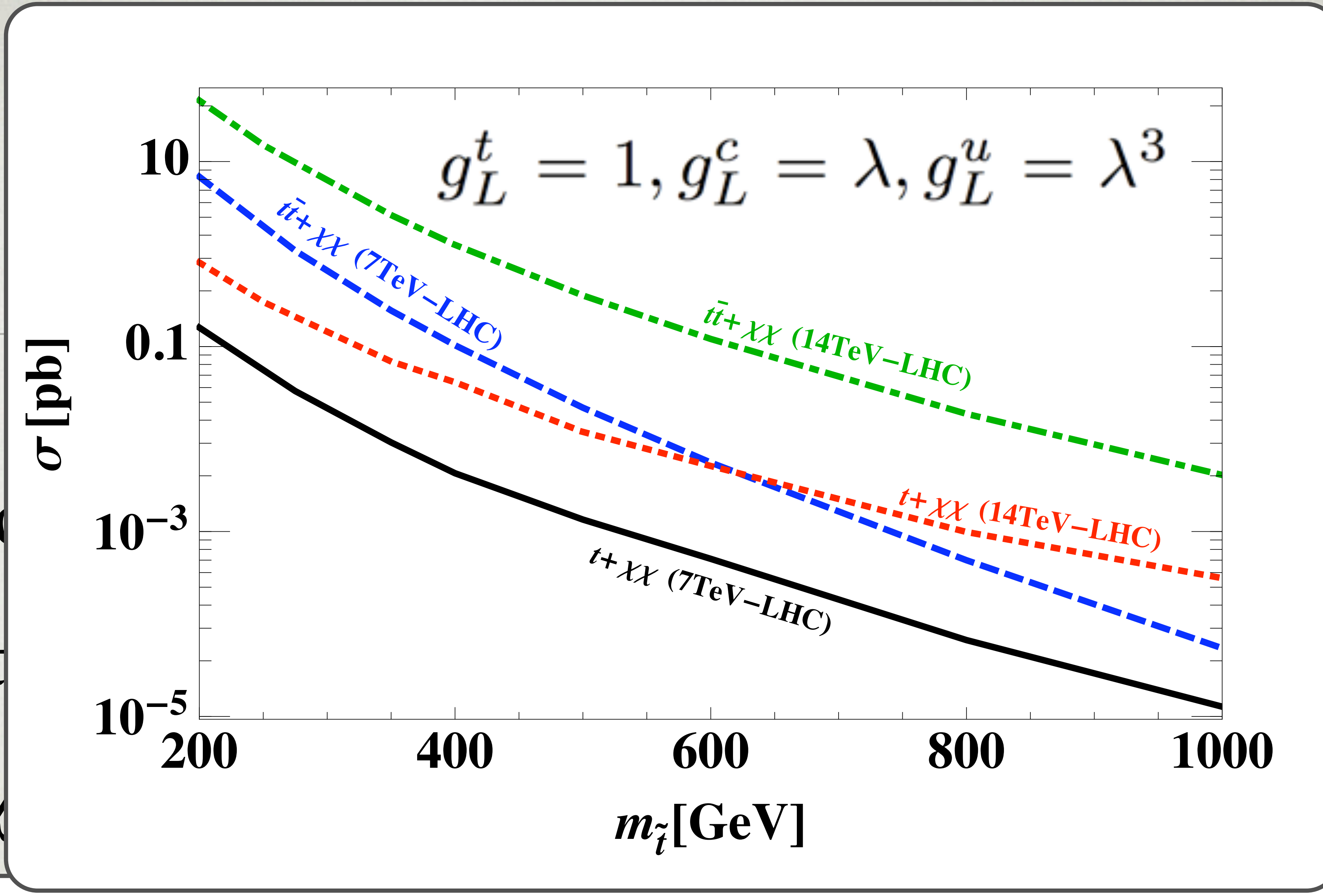
- a t... only
  - t
  - χ



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