Exploring dark photon production via maverick top partner decays at the LHC

Shivam Verma

Ramakrishna Mission Vivekananda Educational and Research Institute, India

Higgs 2023, IHEP, Beijing
1st December 2023

Based on: **Phys. Rev. D 107, 115024 (2023)** [2209.13888]
SV, Sanjoy Biswas, Anirban Chatterjee and Joy Ganguly

What are vector-like quarks?

- Spin 1/2 fermion
- Color triplet
- L and R components of field transforms similarly under SM gauge group.

VLQs are ubiqutous

VLQs are omnipresent in many extensions of the SM addresing the quadratic divergence of higgs mass such as

1. **SM with extra dimension** (Randall and Sundrum, 1999; Carena et al., 2007),
2. **Composite higgs model** (Kaplan et al., 1984; Chivukula, 2000; Agashe et al., 2005),
3. **Little higgs model** (Arkani-Hamed et al., 2002b; Arkani-Hamed et al., 2002a)

Top partner

Top partner: VLQ with $+2/3$ electric charge and mixing with only top-quark.

Top partner

Top partner
$T_{L/R}:\ (3,1,2/3)$

there can also be a Bottom partner,
$B_{L/R}:\ (3,1,-1/3)$

Top and bottom quark
$Q_L = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$: (3, 2, 1/6)
t_R: (3,1,2/3), b_R: (3, 1, -1/3)

$$\begin{aligned} \mathcal{L}_{\text{int}} &= -\Big[y_t\left(\bar{Q}_L\tilde{H}\right)t_R + \omega_F\left(\bar{Q}_L\tilde{H}\right)T_R + \tilde{\omega}\left(\bar{T}_L t_R\right) \\ &\quad + M_T\left(\bar{T}_L T_R\right) + h.c.\Big] \end{aligned} \tag{1}$$

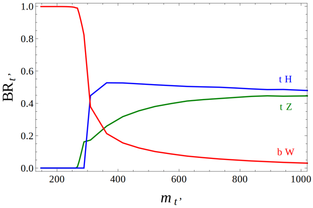
LHC Searches in traditional channels

For top partner with {3, 1, +2/3} charge under SM gauge group,

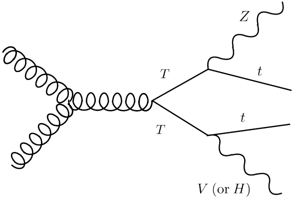
Top partner has 3 traditional decay channels,

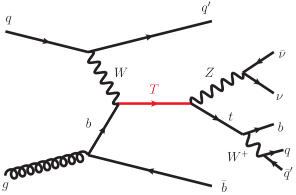
- T $\rightarrow$ bW
- T $\rightarrow$ tZ
- T$\rightarrow$ tH

$\mathrm{BR}(bW) : \mathrm{BR}(tZ) : \mathrm{BR}(tH)$
$= 50\% : 25\% : 25\%$



Source: (Okada and Panizzi, 2013)



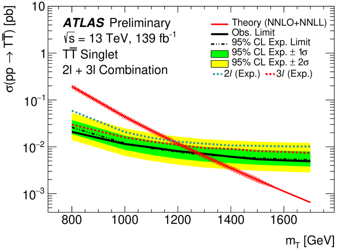


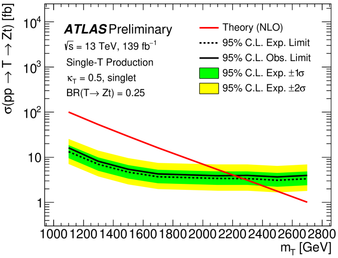
Source:ATLAS-CONF-2021-024 (pair),

ATLAS-CONF-2022-036 (single)

Search for Top partner LHC

Recent result in search of top partner in $T \to tZ$.

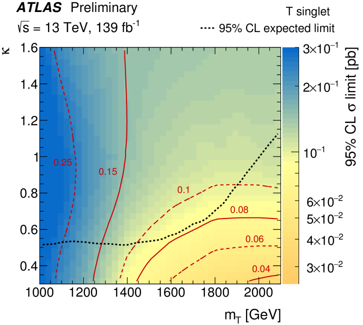




Source: ATLAS-CONF-2021-024

Model	Observed (Expected) Mass Limits [TeV] 2ℓ	3ℓ	Combination
$T\bar{T}$ Singlet	1.14 (1.16)	1.22 (1.21)	1.27 (1.29)
$T\bar{T}$ Doublet	1.34 (1.32)	1.38 (1.37)	1.46 (1.44)
100% $T \to Zt$	1.43 (1.43)	1.54 (1.50)	1.60 (1.57)

Source: ATLAS-CONF-2022-036



Motivation of present work

- No evidence for a top partner that has yet been found at the LHC in the traditional channels ($T \rightarrow bW/tZ/tH$).
- Search for top-partner in non-standard decay channels gaining strong interests.
  - Banerjee et al., 2016
  - Chala, 2017; Aguilar-Saavedra et al.,2017
  - Das et al., 2019,
  - Bizot et al., 2018,
  - Xie et al., 2019,
  - Cacciapaglia et al., 2019,
  - Benbrik et al., 2020,
  - Bhardwaj et al., 2022,
  - Banerjee et al.,2022b,
  - Banerjee et al., 2022a.

Model

Fields	$SU(3)_C$	$SU(2)_L$	Y	Y_d
$t_R^{'}$	3	1	2/3	0
b_R	3	1	-1/3	0
$Q_L = \begin{pmatrix} t_L^{'} \\ b_L \end{pmatrix}$	3	2	1/6	0
Φ	1	2	1/2	0
$T_L^{'}$	3	1	2/3	1
$T_R^{'}$	3	1	2/3	1
Φ_d	1	1	0	1

(J. H. Kim et al. (2020))

$U(1)_D$ gauge boson $\rightarrow$ dark photon(γ_d).

For simplicity, we will only consider mixing between top partner and 3rd generation SM quarks.

Lagrangian of various sectors

Gauge sector

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i,\mu\nu} - \frac{1}{4}B'_{\mu\nu}B'^{,\mu\nu} + \frac{\varepsilon'}{2\cos\theta_W}B'_{d,\mu\nu}B'^{\mu\nu} - \frac{1}{4}B'_{d,\mu\nu}B'^{,\mu\nu}_d \quad (2)$$

Scalar sector

$$\mathcal{L}_{\text{Scalar}} = |D_\mu\Phi|^2 + |D_\mu\Phi_d|^2 - V(\Phi,\Phi_d)$$

$$V(\Phi,\Phi_d) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4 - \mu^2_{h_d}|\Phi_d|^2 + \lambda_{h_d}|\Phi_d|^4 + \lambda_{hh_d}|\Phi|^2|\Phi_d|^2 \quad (3)$$

Fermion Sector

Fermion lagrangian

$$\mathcal{L}_{\text{u3}-\text{quark}} = \bar{Q}_L i\not{D} Q_L + \bar{t'}_R i\not{D} t'_R + \overline{T}' i\not{D} T' - m_T \overline{T}'_L T'_R + \mathcal{L}_{\text{Yuk}} \quad (4)$$

$$\mathcal{L}_{\text{Yuk}} = -y_t \bar{Q}_L \tilde{\Phi} t'_R - \lambda_T \Phi_d \overline{T}'_L t'_R + h.c. \quad (5)$$

Fermion Sector

After SSB the mass matrix in t' and T' basis can be written in a form as,

$$\mathcal{L}_{u3-\text{mass}} = -\overline{\chi}_L \mathcal{M} \chi_R + h.c., \tag{6}$$

where,

$$\chi_{L/R} = \begin{pmatrix} t'_{L/R} \\ T'_{L/R} \end{pmatrix}, \quad \mathcal{M} = \begin{pmatrix} \frac{y_t\, v_{\text{EW}}}{\sqrt{2}} & 0 \\ \frac{\lambda_T\, v_d}{\sqrt{2}} & m_T \end{pmatrix}, \tag{7}$$

One requires the bi-unitary transformation of the following kind in order to diagonalize the above mass matrix

$$\begin{pmatrix} t_{L/R} \\ T_{p_{L/R}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{L/R} & -\sin\theta_{L/R} \\ \sin\theta_{L/R} & \cos\theta_{L/R} \end{pmatrix} \begin{pmatrix} t'_{L/R} \\ T'_{L/R} \end{pmatrix} \tag{8}$$

We have three free parameters here but since we know top mass we are left with 3 i.e.

$$m_t = 173 \text{ GeV}, \;\; m_{T_p}, \;\; \theta_L$$

Constraints on the model

- **Kinetic mixing**: $|\varepsilon| \lesssim 10^{-3}$ for $M_{\gamma_d} = 0.1 - 10$ GeV
- **Perturbativity bound:**

$$|\lambda_T| \leq 4\sqrt{2\pi} \tag{9}$$

$$|\sin\theta_L| = \frac{1}{2}\sqrt{\frac{2m_{T_p}^2 - 2m_t^2 - \lambda_T^2 v_d^2}{m_{T_p}^2 - m_t^2}\left(1 - \sqrt{1 - \frac{8\lambda_T^2 v_d^2 m_t^2}{\left(2m_{T_p}^2 - 2m_t^2 - \lambda_T^2 v_d^2\right)^2}}\right)} \tag{10}$$

Reality condition alongwith the perturbative unitarity limit gives us,

$$|\lambda_T| \quad \leq \quad \sqrt{2}\,\min\left[\frac{m_{T_p} - m_t}{v_d}, 4\sqrt{\pi}\right] \tag{11}$$

- **Scalar mixing angle**: The constraint on the scalar mixing angle is $|\sin\theta_S| \lesssim 0.21$–$0.22$ for $m_t < m_{T_p} < 1$TeV (Robens and Stefaniak, 2015).
- **EW precision**: Using formula from (Chen et al., 2017), we obtain the limits on EWPO in this framework. $m_{T_p} \leq 2.6$ TeV is ruled out for $\sin\theta_L \sim 0.10$ at 14 TeV(3 ab^{-1}).

Top partner decay

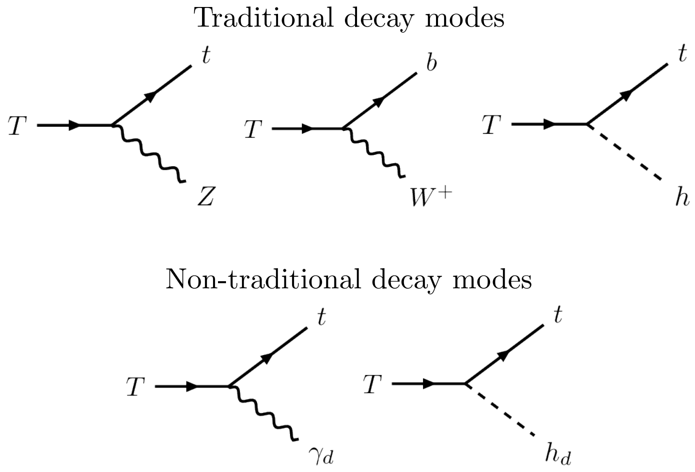


Figure: Feynman Diagrams top partner decay modes at the LHC.

Decay widths

Traditional modes:

- $\Gamma(T_p \to bW) \approx \frac{1}{16\pi} \frac{m_{T_p}^3}{v_{EW}^2} \sin^2\theta_L$
- $\Gamma(T_p \to tZ) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v_{EW}^2} \sin^2\theta_L \cos^2\theta_L$
- $\Gamma(T_p \to th) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v_{EW}^2} \sin^2\theta_L \cos^2\theta_L$

Approximation limit

$|\sin\theta_d|,\ |\sin\theta_s|,\ \varepsilon,\ m_t/m_{T_p} \ll 1$

Non-traditional modes:

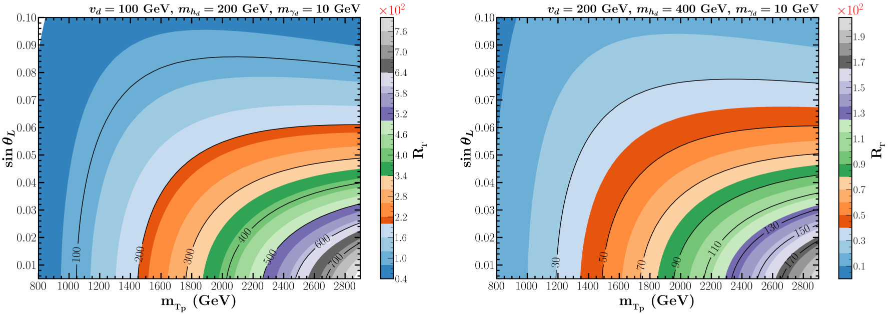
- $\Gamma(T_p \to th_d) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v_d^2} \sin^2\theta_L \cos^2\theta_L \frac{m_{T_p}^4}{D^2} \left(\sin^4\theta_L + \frac{m_t^2}{m_{T_p}^2} \cos^4\theta_L + 4\frac{m_t^2}{m_{T_p}^2} \sin^2\theta_L \cos^2\theta_L \right)$
- $\Gamma(T_p \to t\gamma_d) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v_d^2} \sin^2\theta_L \cos^2\theta_L \left(1 + \frac{m_{T_p}^2 m_t^2}{D^2} \right)$

where, $D = m_t^2 \cos^2\theta_L + m_{T_p}^2 \sin^2\theta_L$.

$$R_\Gamma = \frac{\Gamma(T_p \to t + h_d/\gamma_d)}{\Gamma(T_p \to b/t + W/Z/h)}$$

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Variation of R_Γ



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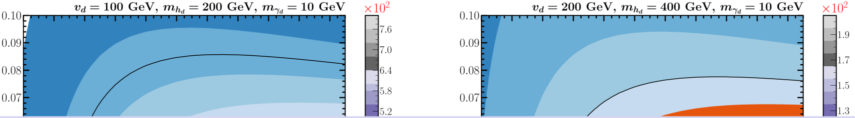


R_Γ: limiting cases

$$\mathrm{R}_\Gamma \approx \frac{1}{2}\begin{cases} \left(\frac{m_{T_p}}{m_t}\right)^2 \left(\frac{v_{\mathrm{EW}}}{v_d}\right)^2 & \text{for, } |\sin\theta_L| \ll \frac{m_t}{m_{T_p}} \ll 1 \\ \left(\frac{m_t}{m_{T_p}\sin^2\theta_L}\right)^2 \left(\frac{v_{\mathrm{EW}}}{v_d}\right)^2 & \text{for, } \frac{m_t}{m_{T_p}} \ll |\sin\theta_L| \ll 1 \end{cases}$$

$$\mathrm{R}_\Gamma = \frac{\Gamma(T_p \to t + h_d/\gamma_d)}{\Gamma(T_p \to b/t + W/Z/h)}$$

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

BR($T_p \to t\gamma_d$) variation

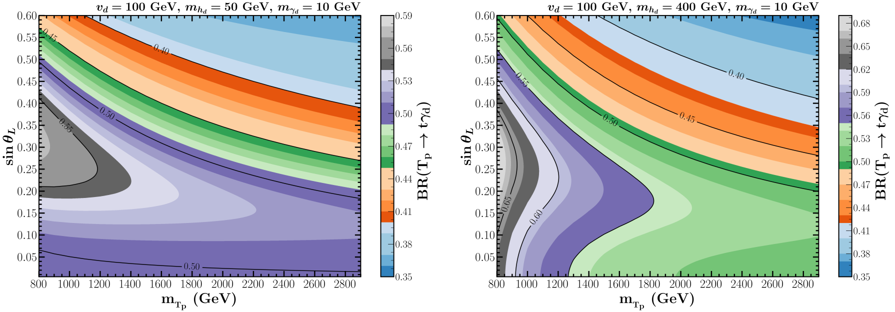
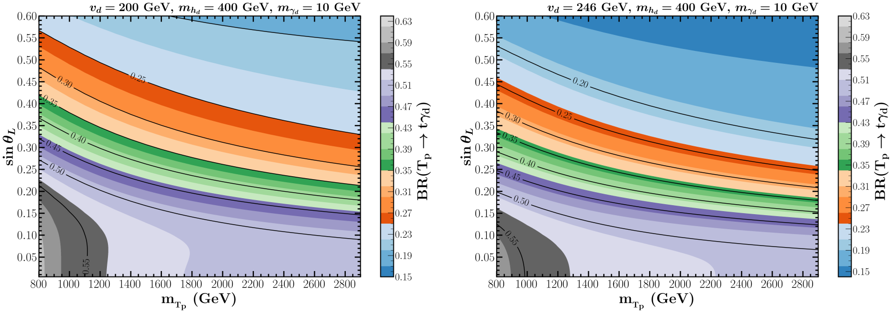


Figure: Variation of the branching ratio of $T_p \to t\gamma_d$ in the $\sin\theta_L - m_{T_p}$ plane for several choices of v_d, m_{γ_d} and m_{h_d}.

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))



$BR(T_p \to t\gamma_d)$ can be as large as 65%
$BR(T_p \to t\gamma_d\ ) + BR(T_p \to th_d\ )$ can be as large as 99%.

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Top partner @ LHC

Feynman diagrams

Pair production

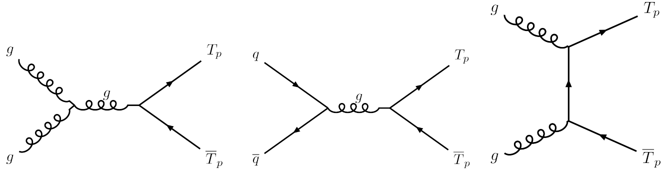


Figure: Feynman diagrams for the pair production of top partner at the LHC.

Single production

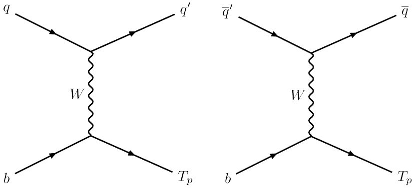
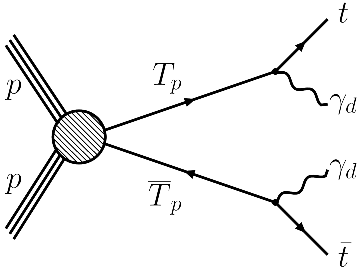


Figure: Feynman diagrams for the single production of top partner at the LHC.

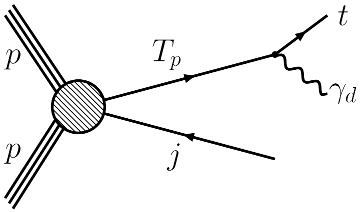
Final State

Pair production



$t\bar{t} + missing\ transverse\ energy$

Single production



$t + missing\ transverse\ energy + jet$

Top tagger

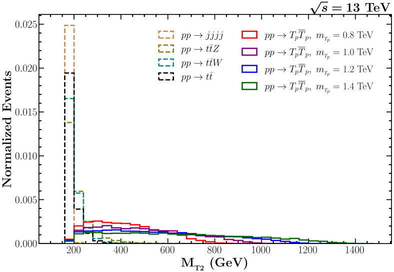
We consider the top partner in the mass range **1TeV (800GeV)** $\leq m_{T_p} \leq$ **2.6 (1.6) TeV** for the single (pair) production of top partner at the LHC. The top-quarks thus produced in the decay of the top partners are **highly boosted** for most of the ranges of top partner mass which motivates us to use **Johns Hopkins top tagger** (Kaplan et al., 2008) in identification and reconstruction of top quark.

Kinematic variable distribution

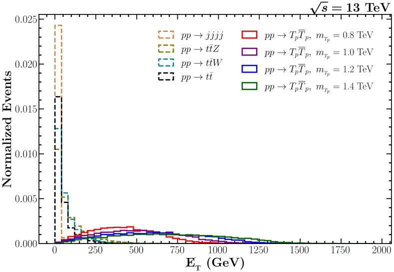
Pair production

KV used: Transverse momentum, missing transverse energy, STransverse mass.

Stransverse mass



Missing transverse energy



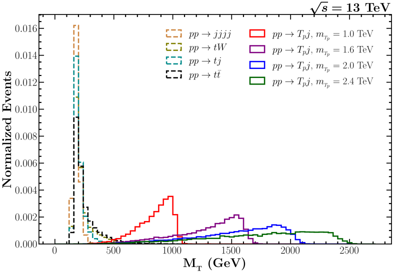
(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Kinematic variable distribution

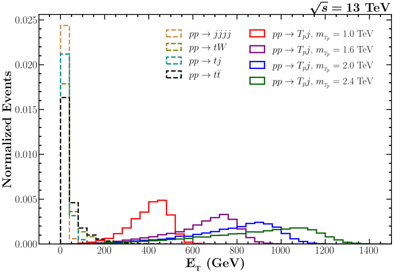
Single production

KV used: Transverse momentum, missing transverse energy, Transverse mass, Forward jet rapidity.

Transverse mass



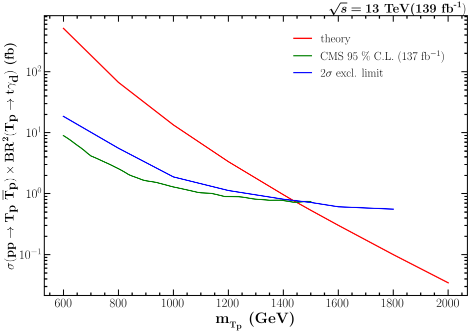
Missing transverse energy



(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Results

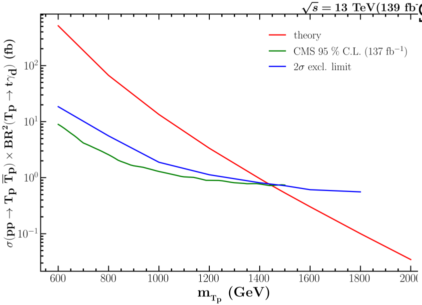
Pair production: Exclusion limit @LHC (13 TeV)

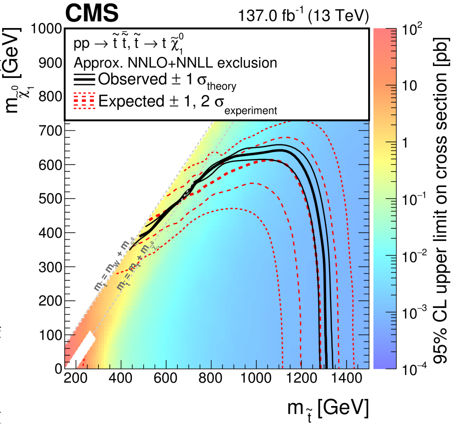


We depict the constraint coming from the CMS stop searches ($pp \to \tilde{t}\tilde{t}^*$, $\tilde{t} \to t\tilde{\chi}_1^0$) (Sirunyan et al., 2021) in the $t\bar{t}$+*missing tranverse energy* channel. (S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Results

Pair production: Exclusion limit @LHC (13 TeV)





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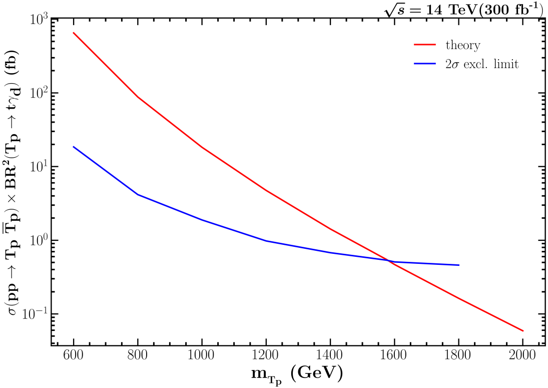
$t\tilde{\chi}_1^0$) (Sirunyan et al., 2021) in the $t\bar{t}$+*missing tranverse energy* channel.

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Results

Pair production: Exclusion limit @LHC (14 TeV)

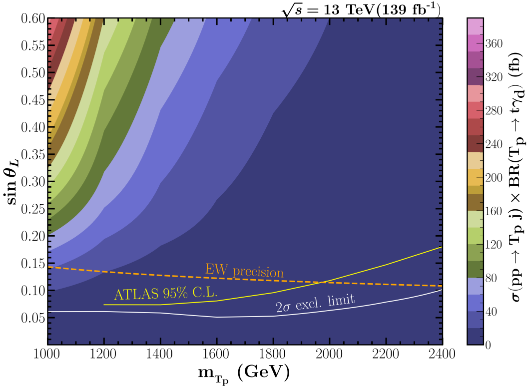


$$\sigma \times \mathrm{BR}^2 \sim 0.8\mathrm{fb}.$$
$$2\sigma \text{ exclusion limit on } m_{T_p} > 1600 \text{ GeV}.$$

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Results

Single production: Exclusion limit @LHC (13 TeV)

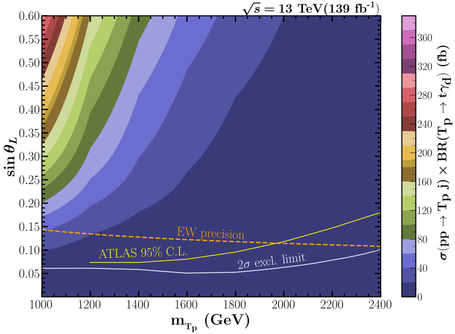


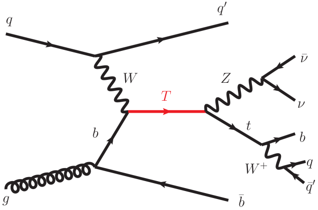
$[v_d = 200$ GeV, $m_{\gamma_d} = 10$ GeV and $m_{h_d} = 400$ GeV $]$

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Results

Single production: Exclusion @LHC (13 TeV)





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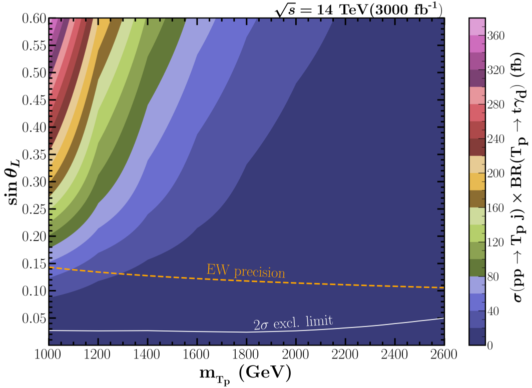
$$[v_d = 200 \text{ GeV}, \; m_{\gamma_d} = 10 \text{ GeV and } m_{h_d} = 400 \text{ GeV.}]$$

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Results

Single production: Exclusion limit



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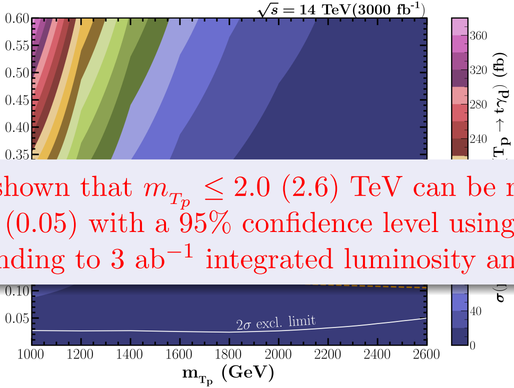
(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Results

Single production: Exclusion limit



We have shown that $m_{T_p} \leq 2.0$ (2.6) TeV can be ruled out for $\sin\theta_L \sim 0.025$ (0.05) with a 95% confidence level using the future LHC data corresponding to 3 ab^{-1} integrated luminosity and $\sqrt{s} = 14$ TeV.

[$v_d = 200$ GeV, $m_{\gamma_d} = 10$ GeV and $m_{h_d} = 400$ GeV.]

(S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023))

Conclusions

1. VLQs are ubiquitous.
2. Vector like top partners decaying in the traditional channels have been already constrained by LHC data and the current limit is 1.3 TeV or higher.
3. Vector-like top partner carrying additional charge under the local symmetry group of the dark sector (portal matters) can give rise to rich collider phenomenology and opens up new avenue for the LHC searches.
4. We have explored the phenomenology of a vector-like top partner (3, 1, 2/3, 1) in non-standard decay modes.
5. We have shown that top partner mass up to 1.6 TeV can be exclude with more than 2σ significance using the top-pair production channel at 14 TeV(3 ab^{-1}).
6. For single top partner production case, we have shown that $\sin\theta_L \sim 0.025$ (0.05) can be ruled out for $m_{T_p} \leq 2.0$ (2.6) TeV at a 95% confidence level using the future LHC data corresponding to 3 ab^{-1} integrated luminosity and $\sqrt{s} = 14$ TeV center of mass energy.

thank you!