# Exploring maverick top partner decays at the LHC

Sanjoy Biswas

*Ramakrishna Mission Vivekananda Educational and Research Institute, India*

Beyond Standard Model: From Theory to Experiment

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

# *What are vector-like quarks?*

Vector-like quarks are coloured, spin $\frac{1}{2}$ fermions with left and right-chiral components transforming in the same way under the SM gauge interactions

- **Extra dimension** (Randall and Sundrum, 1999; Carena et al., 2007)
- **Composite Higgs model** (Kaplan et al., 1984; Chivukula, 2000; Agashe et al., 2005)
- **Little Higgs model** (Arkani-Hamed et al., 2002)

# *Vector-like top partner*

- Top partner: VLQ with electric charge $+\frac{2}{3}$ and having mixing with the top-quark only

**VLQ**

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

$$\mathcal{L}_{\rm int} = -\left[y_t \left(\bar{Q}_L \tilde{H}\right) t_R + \omega_F \left(\bar{Q}_L \tilde{H}\right) T_R + \tilde{\omega}\left(\bar{T}_L t_R\right) + M_T \left(\bar{T}_L T_R\right) + h.c.\right]$$

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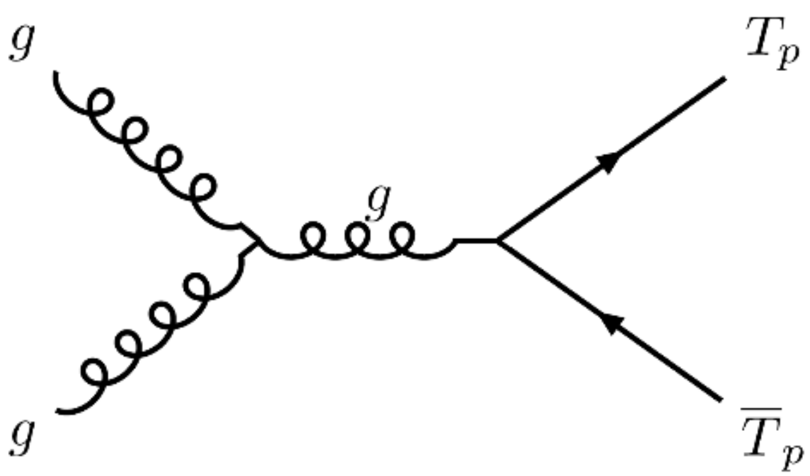
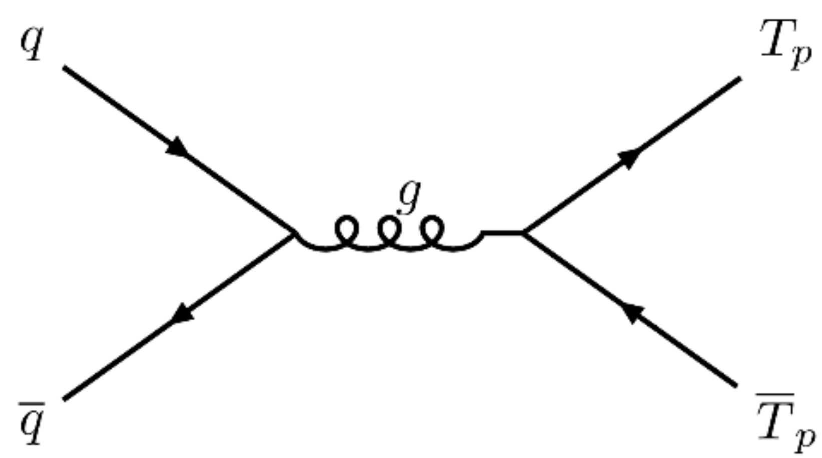
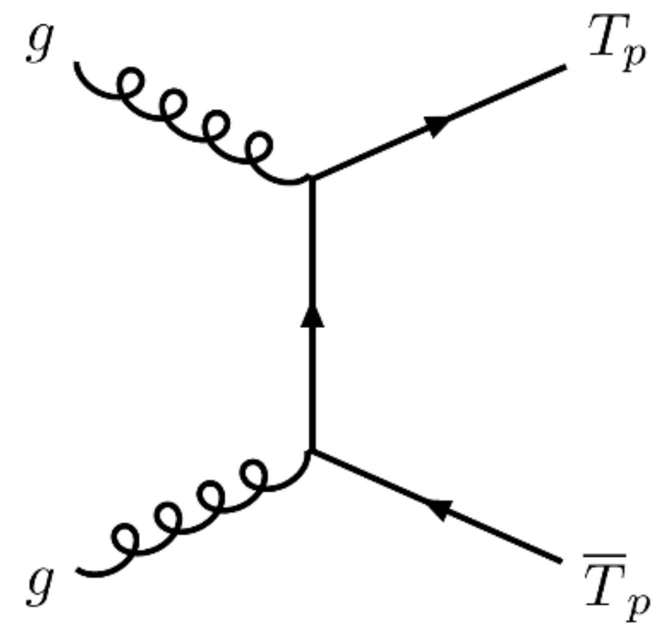
Relevant parameters:
mass of the top partner $m_{T_p}$ and mixing angle $\sin\theta_L$ (or $\sin\theta_R$)

# *Production@LHC*

**Pair production**

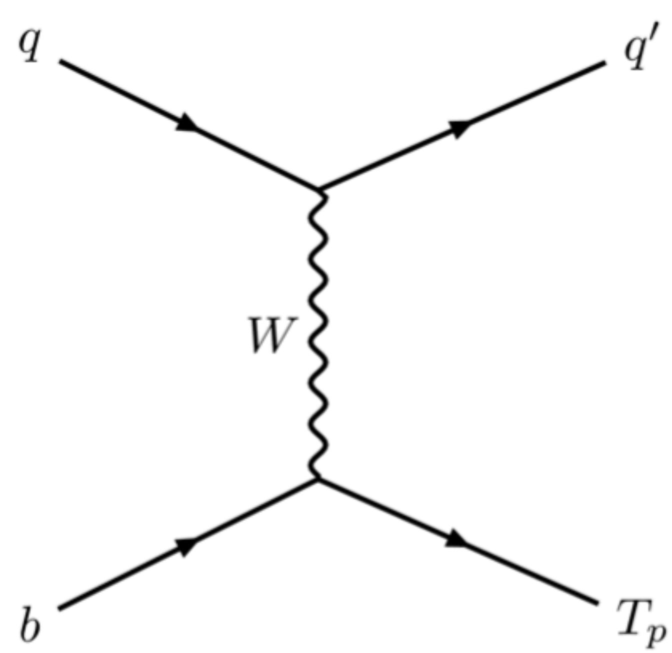


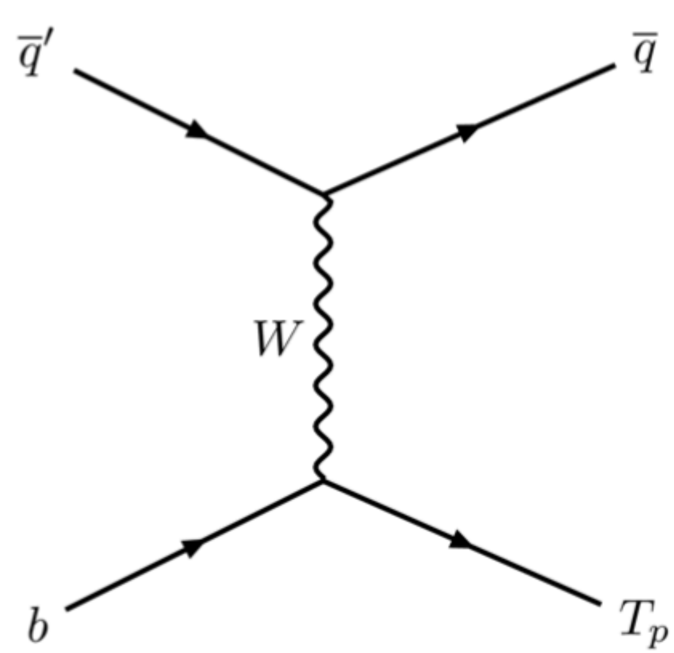




**Single production**

For higher masses single production channel gives dominant cross-section

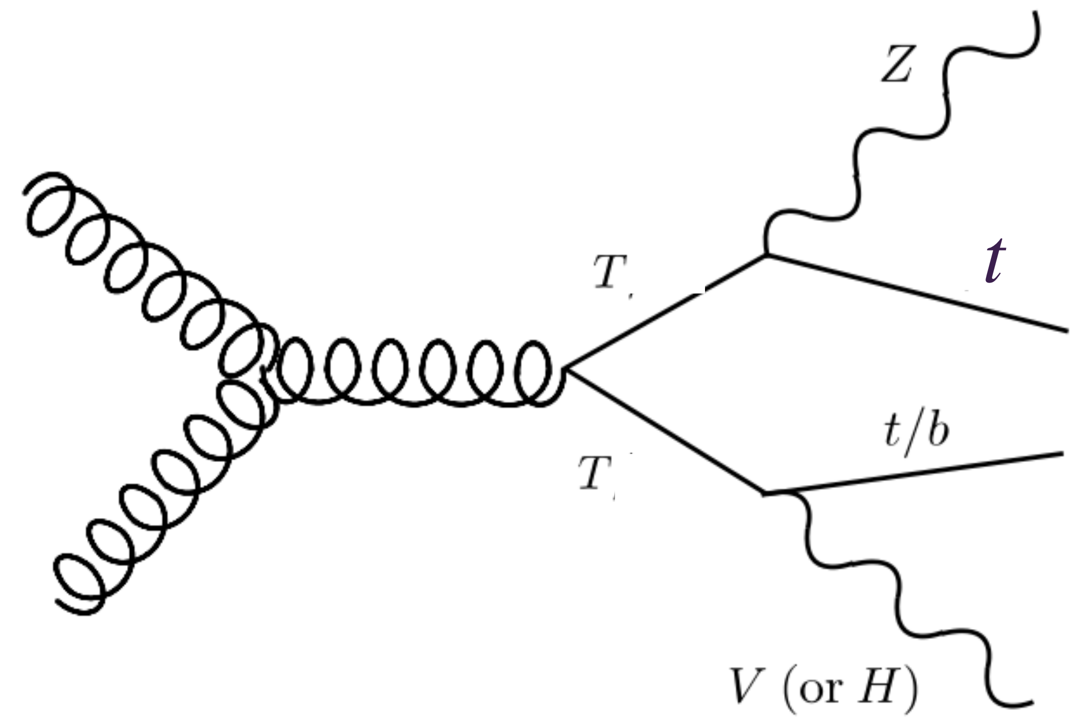


# *Search for Top-partner@LHC*

- Top partner: VLQ with electric charge $+\frac{2}{3}$ and having mixing with the top-quark only

- Traditional decay modes:
  - $\mathrm{T} \rightarrow \mathrm{bW}$
  - $\mathrm{T} \rightarrow \mathrm{tZ}$
  - $\mathrm{T} \rightarrow \mathrm{tH}$



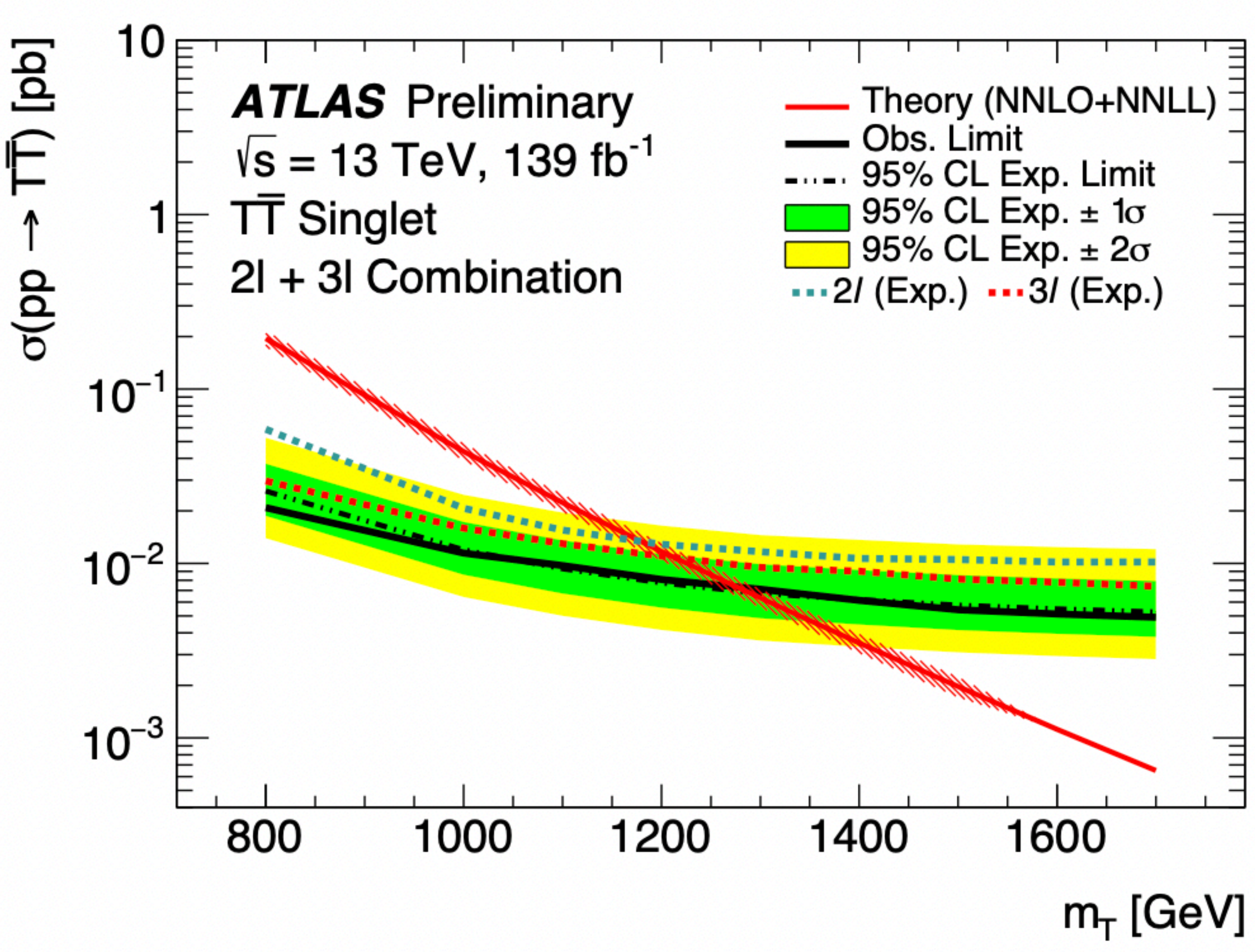

pair production cross-section
Only depend on the mass $m_{T_p}$

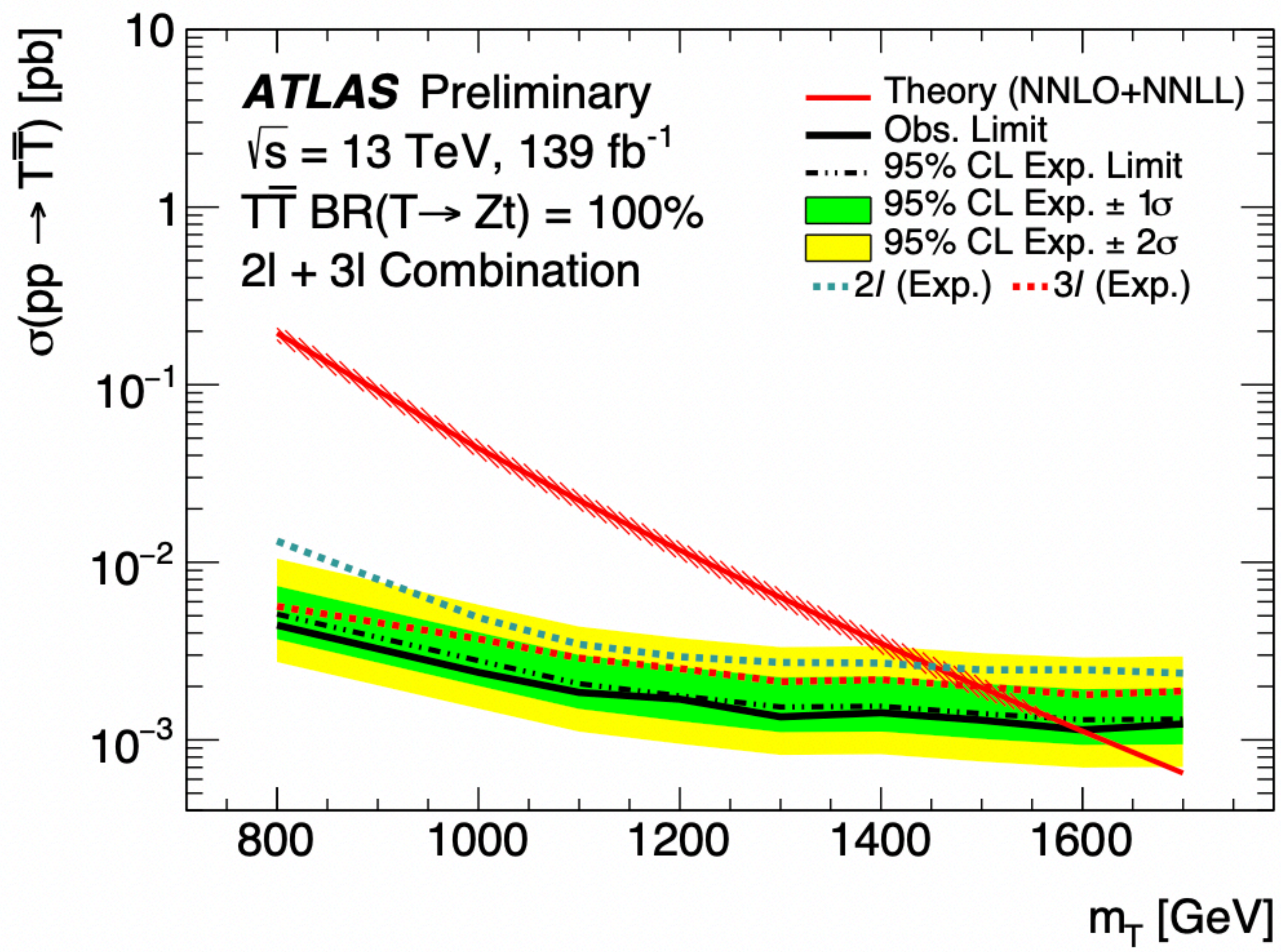
**ATLAS-CONF-2021-024**

$$\mathrm{BR}(bW) : \mathrm{BR}(tZ) : \mathrm{BR}(th)$$

$$= 50\,\% : 25\,\% : 25\,\% \qquad \text{(in large } m_T \text{ limit)}$$

# *Current LHC limits*




| **Model** | **Observed (Expected) Mass Limits [TeV]** $2\ell$ | $3\ell$ | **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%** $T \rightarrow Zt$ | 1.43 (1.43) | 1.54 (1.50) | 1.60 (1.57) |

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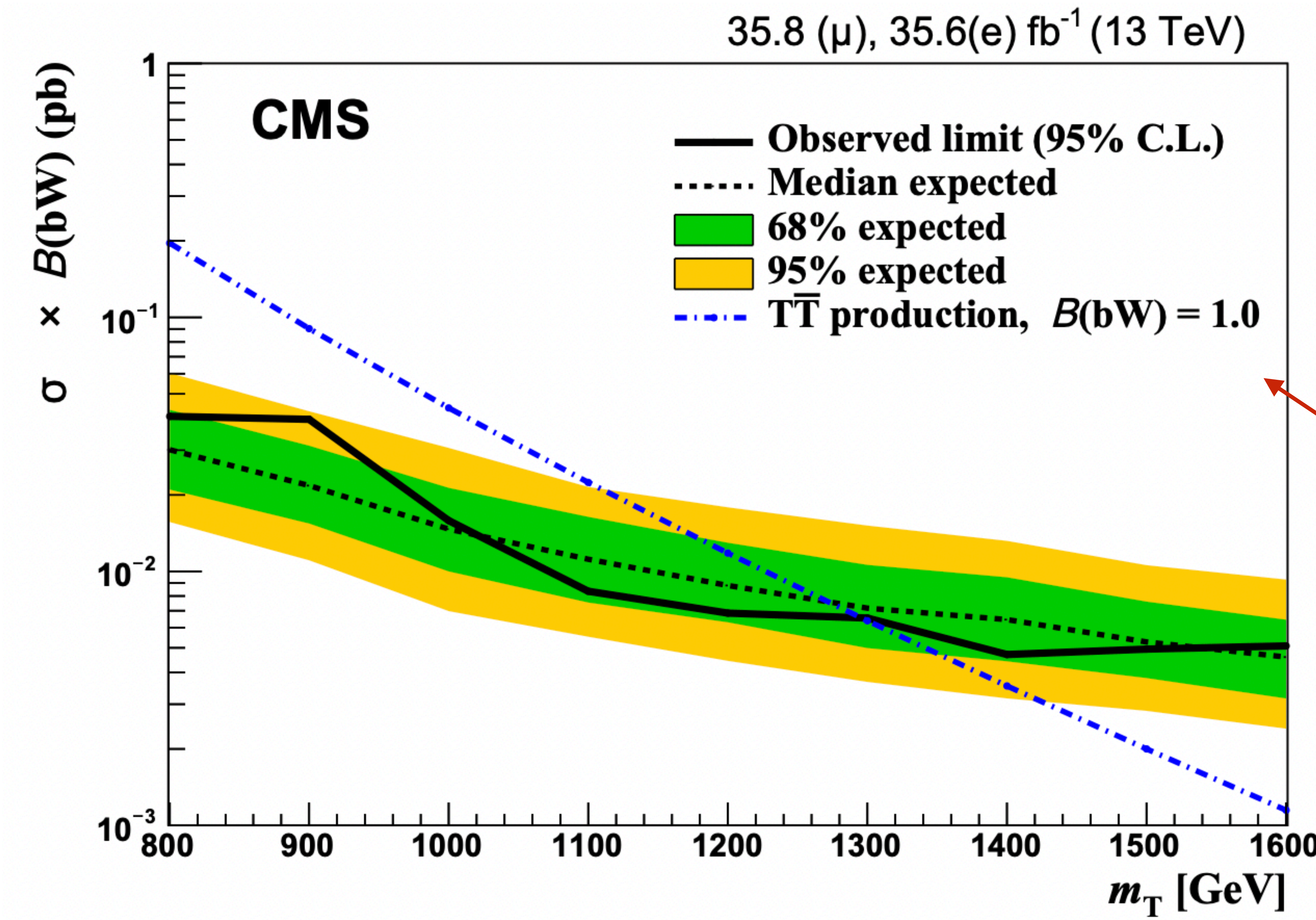
# *Current LHC limits*




***Rute Pedro's* talk for updated bound (2023)**

100% BR(bW) assumed

$$T\overline{T} \to bW\overline{b}W \to b\ell\nu\overline{b}q\overline{q}'$$

**CMS Collaboration, PLB 779 (2018)**

The observed limit on the top partner mass

$m_T \geq 1.3$ TeV

# *Non-standard modes*

- No evidence of vector-like top partner at the LHC in traditional search channels so far
- Search for top-partner in non-standard decay channels gaining strong interests

  - S. Banerjee et al., 2016
  - J. A. Aguilar-Saavedra et al., 2017
  - N. Bizot, G. Cacciapaglia and T. Flacke, 2018
  - K. Das et. al., 2019
  - R. Benbrik et al., 2020
  - A. Bhardwaj et al., 2022

# *Top partner + (singlet) scalar*

VLQ

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

$$\mathcal{L}_{\rm int} = -\Big[y_t\left(\bar{Q}_L\tilde{H}\right)t_R + \omega_F\left(\bar{Q}_L\tilde{H}\right)T_R + \tilde{\omega}\left(\bar{T}_L t_R\right) + M_T\left(\bar{T}_L T_R\right) + h.c.\Big]$$

$\Phi$ is a singlet under SM gauge group so we can write,

$$\Phi : (1,1,0)$$

$$\mathcal{L}_{\Phi\rm int.} = -\left[\lambda_1\left(\bar{T}_L t_R\right)\Phi + \lambda_2\left(\bar{T}_L T_R\right)\Phi\right] + \text{h.c.}$$

Important parameters: mass of the top partner $m_{T_p}$, mixing angle $\sin\theta_L$, mass of the scalar $m_S$ and scalar VEV.

**S. Banerjee et al. JHEP (2016); R. Benbrik et al. , JHEP (2020); A. Bhardwaj et al., 2022**

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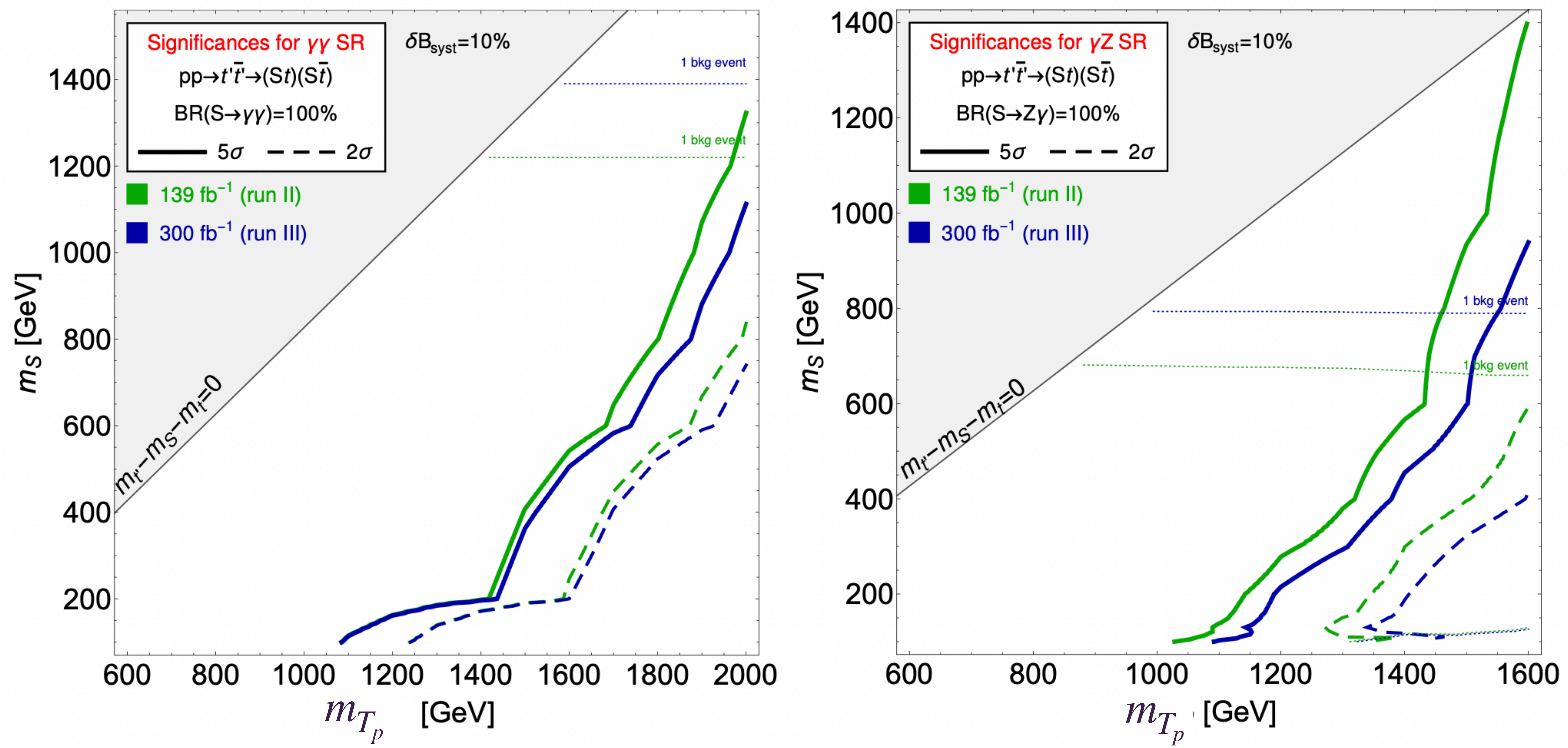
# *Non-standard decays: $T_p \to t\,S$*




$$pp \to T_p \bar{T}_p \to (tS)(\bar{t}S)$$

$$S \to \gamma\gamma, Z\gamma$$

**R. Benbrik et al. , JHEP (2020)**

# *Portal matter: top partner + local $U(1)_d$*

VLQ

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

$$\mathcal{L}_{\rm int} = -\Big[y_t\left(\bar{Q}_L\tilde{H}\right)t_R + \cancel{\omega_F\left(\bar{Q}_L\tilde{H}\right)T_R} + \cancel{\tilde{\omega}\left(\bar{T}_L t_R\right)} + M_T\left(\bar{T}_L T_R\right) + h.c.\Big]$$

$\Phi$ is a singlet under SM gauge group but charged under $U(1)_d$

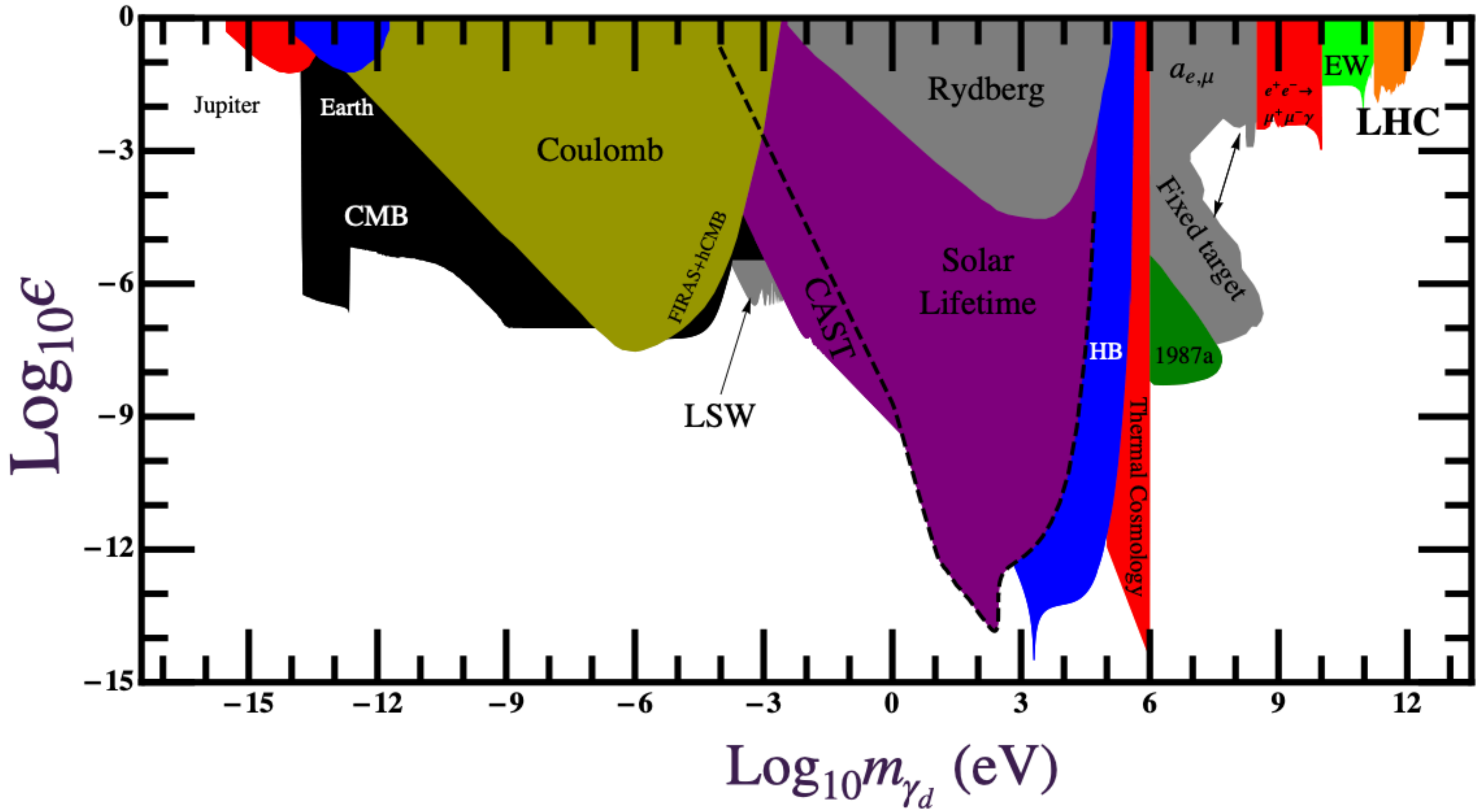
$$\Phi : (1, 1, 0, 1)$$

$$\mathcal{L}_{\Phi \rm int.} = -\left[\lambda_1\left(\bar{T}_L t_R\right)\Phi + \cancel{\lambda_2\left(\bar{T}_L T_R\right)\Phi}\right] + \text{h.c.}$$

Important parameters: mass of the top partner $m_{T_p}$, mixing angle $\sin\theta_L$, mass of the scalar $m_S$, scalar VEV, mass of the dark photon $m_{\gamma_d}$ and the dark gauge coupling $g_D$.

**J. H. Kim et al. (2020); S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023)**

# *Constraints:* $\epsilon$ vs $m_{\gamma_d}$



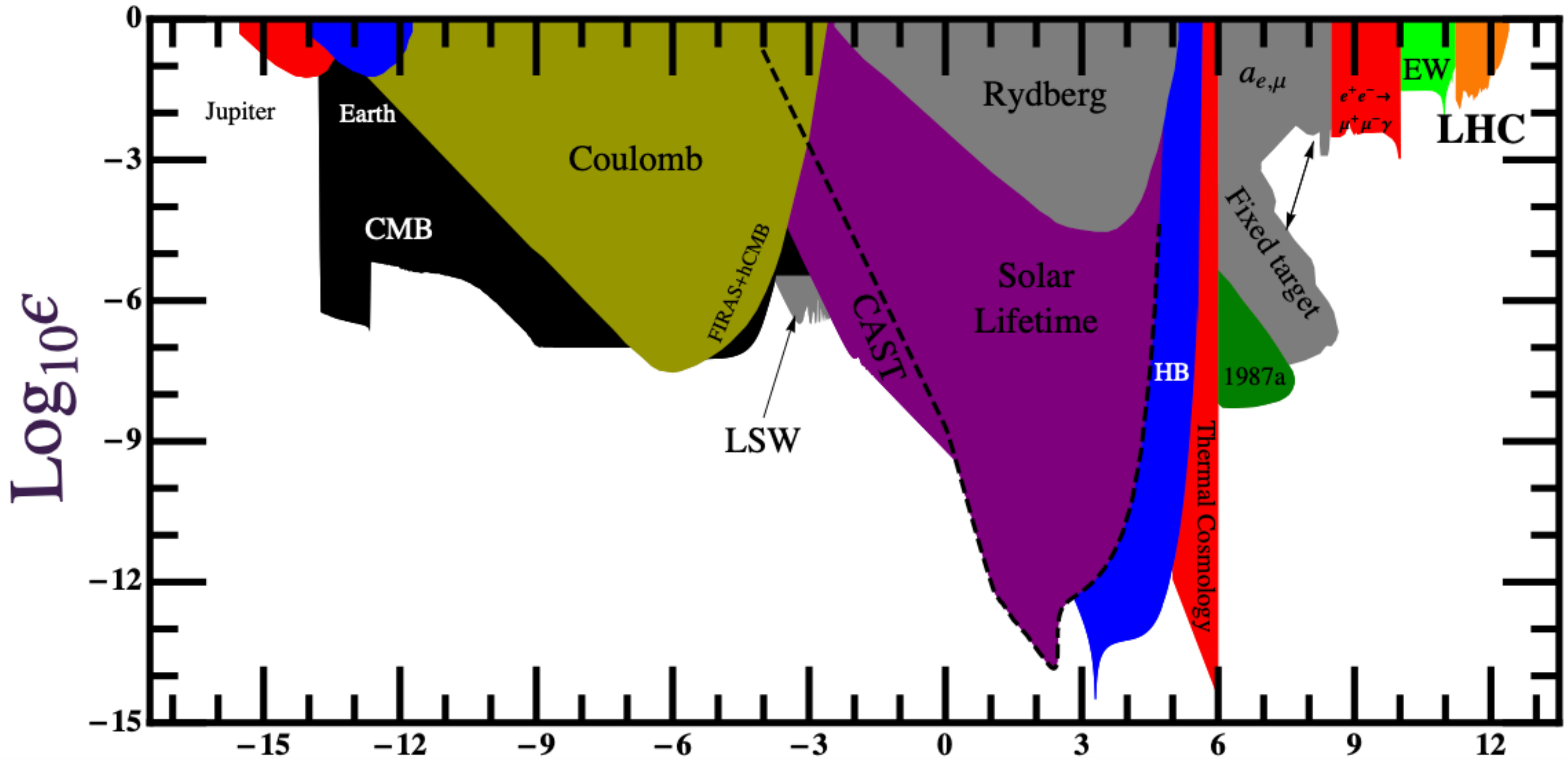

**Jaeckel, Ringwald; Ann. Rev. Nucl. 60 (2010)**

- The kinetic mixing is strongly constrained for massive dark photon

$$\epsilon = c_W \frac{g_D g_Y}{12\pi^2} \sum_i Q_{Y_i} Q_{D_i} \; ln \frac{m_i^2}{\mu^2} \qquad \mathscr{L}_{kin.\ mix} = \frac{\epsilon}{2} F_{\mu\nu} \bar{F}^{\mu\nu}$$

**Thomas Rizzo, PRD 99 (2019)**

# *Constraints:* $\epsilon$ vs $m_{\gamma_d}$




**Jaeckel, Ringwald; Ann. Rev. Nucl. 60 (2010)**

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

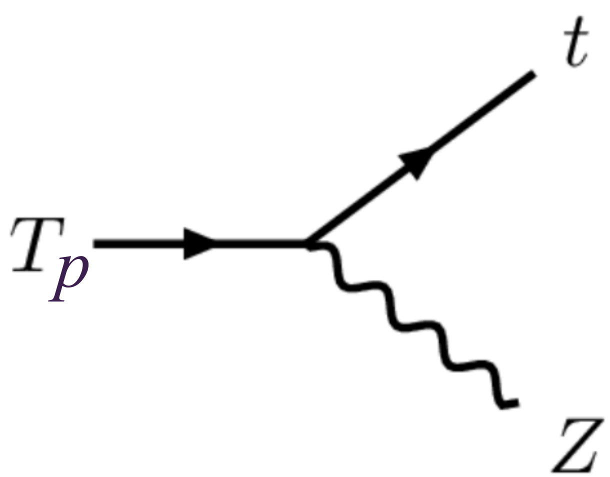
- The kinetic mixing is strongly constrained for massive dark photon

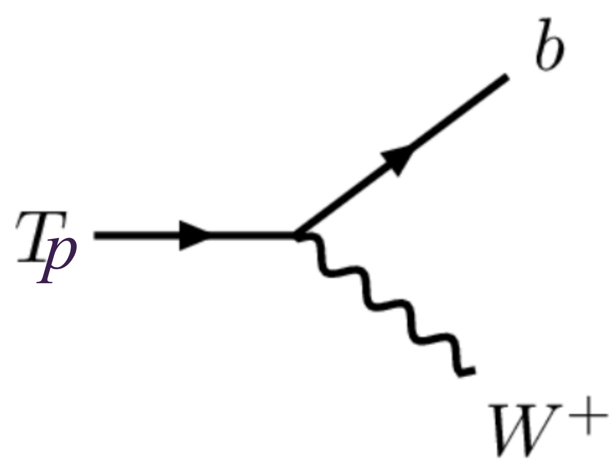
$$\epsilon = c_W \frac{g_D g_Y}{12\pi^2} \sum_i Q_{Y_i} Q_{D_i} \; ln \frac{m_i^2}{\mu^2} \qquad \mathscr{L}_{kin.\ mix} = \frac{\epsilon}{2} F_{\mu\nu} \bar{F}^{\mu\nu}$$

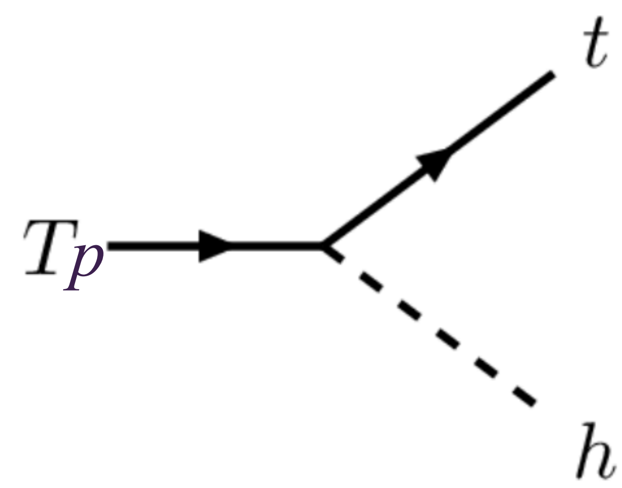
**Thomas Rizzo, PRD 99 (2019)**

# *Decay modes*

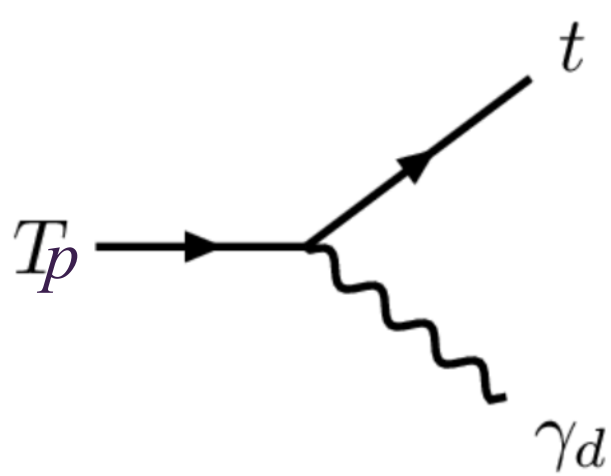
Traditional modes:

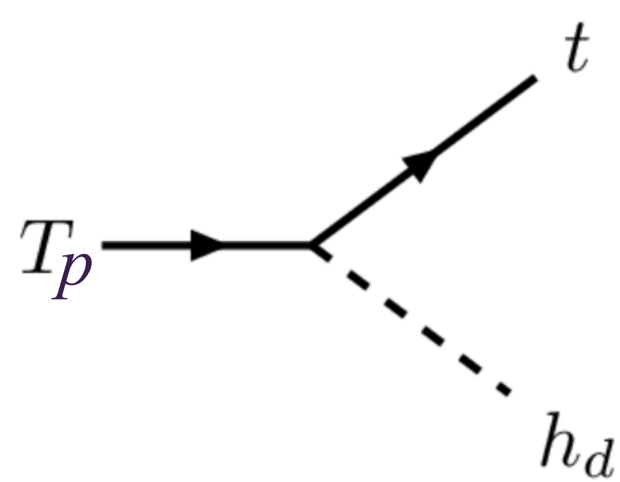



Non-standard modes:



# *Decay widths*

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

traditional modes

vs

non-standard modes

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

$D = m_t^2 \cos^2\theta_L + m^2_{T_p} \sin^2\theta_L$

**S. Verma, SB, A. Chatterjee, J. Ganguly (2022)**

# *Decay widths*

- $\Gamma(T_p \to bW) \approx \frac{1}{16\pi} \frac{m_{T_p}^3}{v^2} \sin^2\theta_L$

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

tional modes

vs

non-standard modes

- $\Gamma(T_p \to th) \approx \frac{1}{32\pi} \frac{m_{T_p}^3}{v^2} \sin^2\theta_L \cos^2\theta_L$

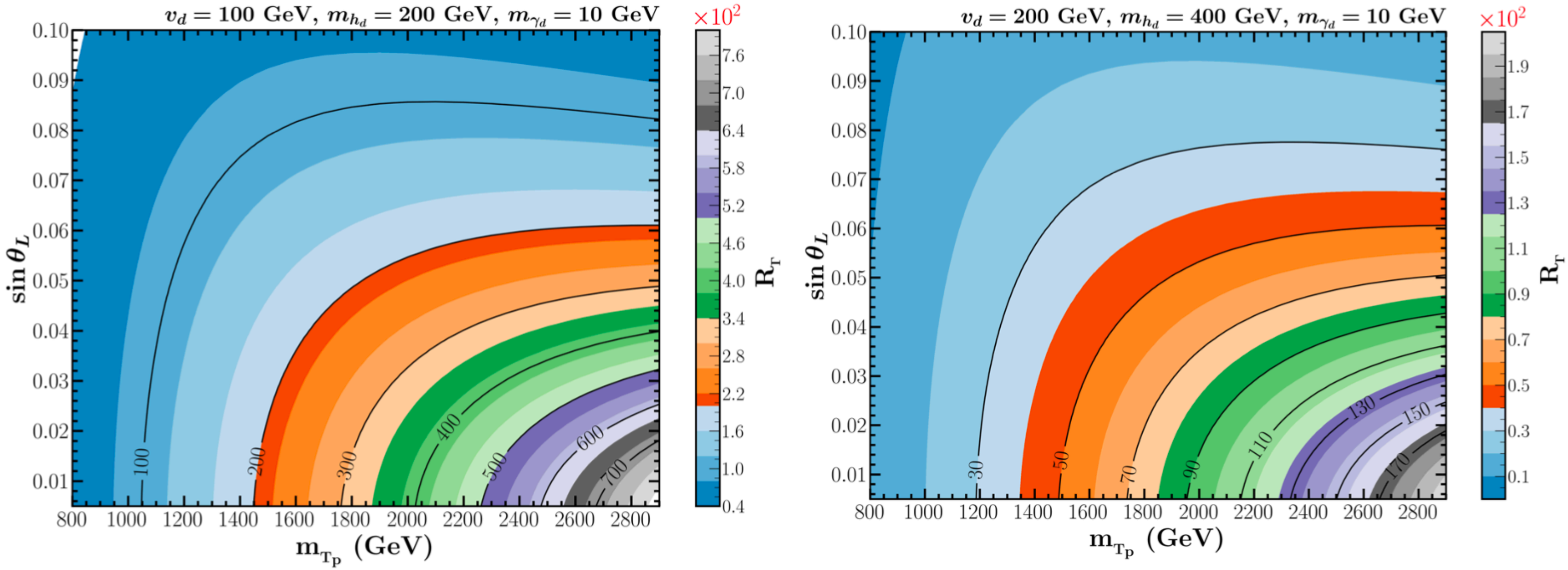
$$R_\Gamma \approx \frac{1}{2} \begin{cases} \left(\frac{m_{T_p}}{m_t}\right)^2 \left(\frac{v_{\mathrm{EW}}}{v_d}\right)^2 & \text{for, } |\sin\theta_L| \ll \frac{m_t}{m_{T_p}} \ll 1 \\ \left(\frac{m_t}{m_{T_p}\sin^2\theta_L}\right)^2 \left(\frac{v_{\mathrm{EW}}}{v_d}\right)^2 & \text{for, } \frac{m_t}{m_{T_p}}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

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

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

**S. Verma, SB, A. Chatterjee, J. Ganguly (2022)**

# *Traditional vs Non-standard modes*




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

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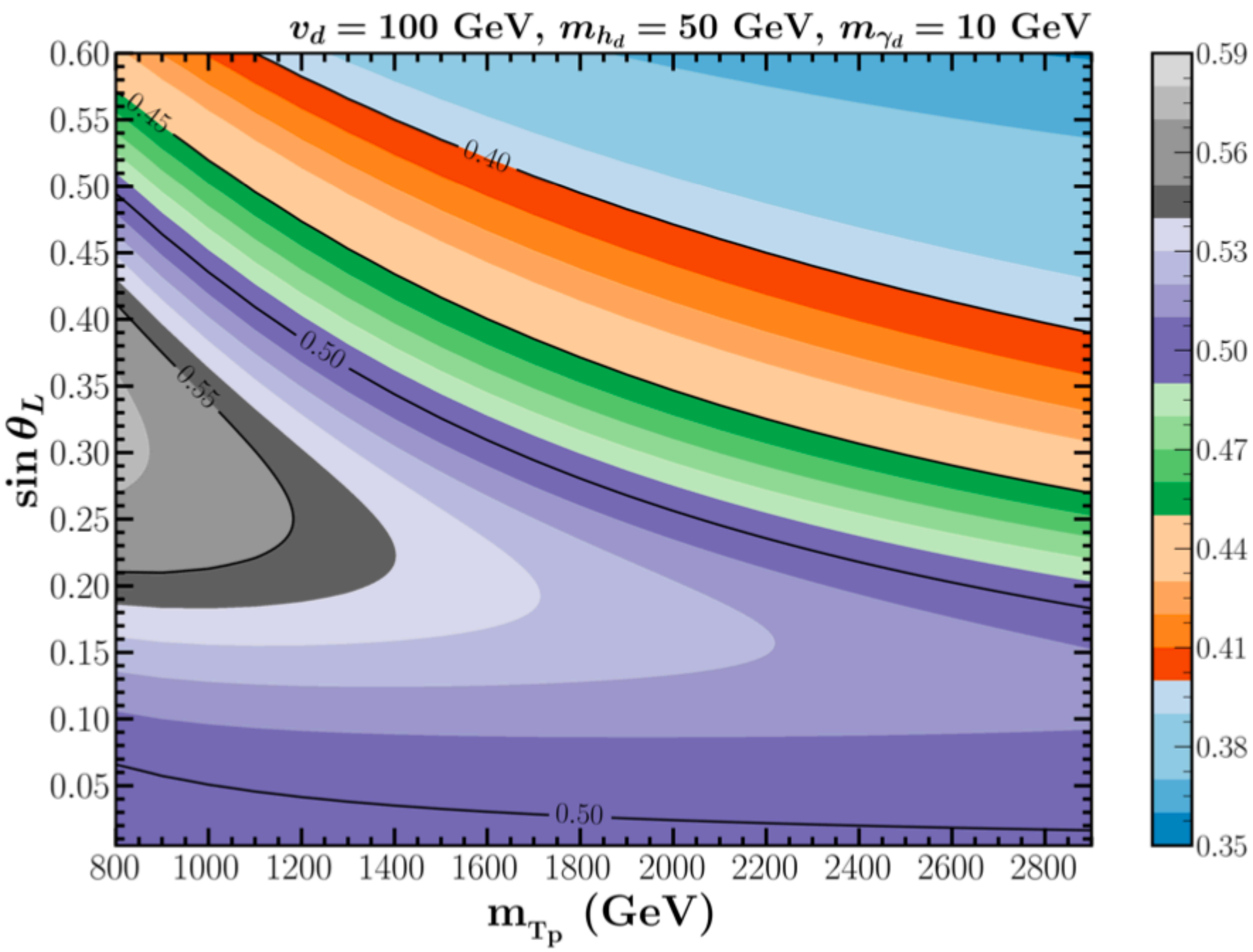
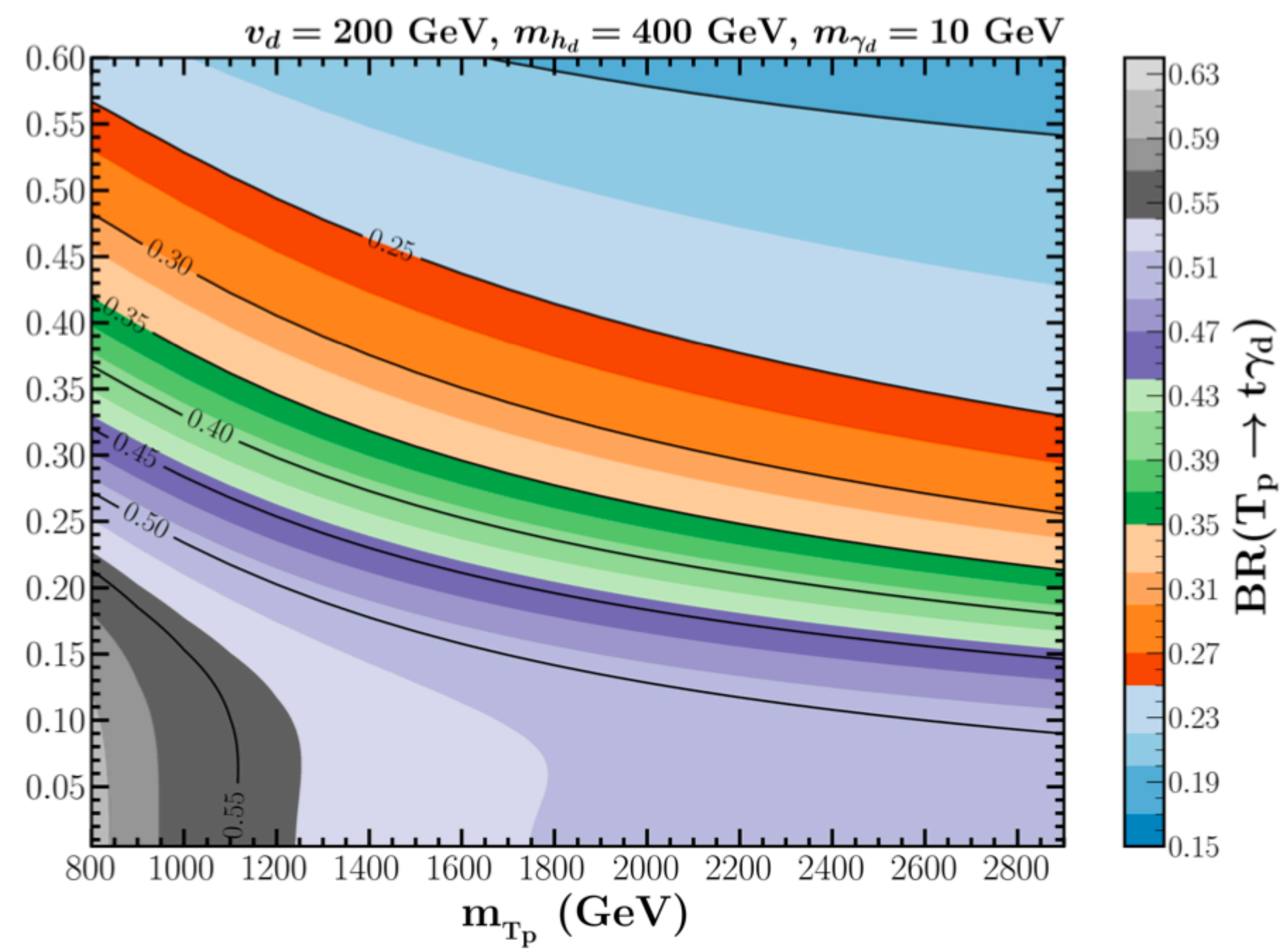
# *Branching Ratio:* $T_p \to t\ \gamma_d$




BR($T_p \to t\ \gamma_d$) can be as large as 65%

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

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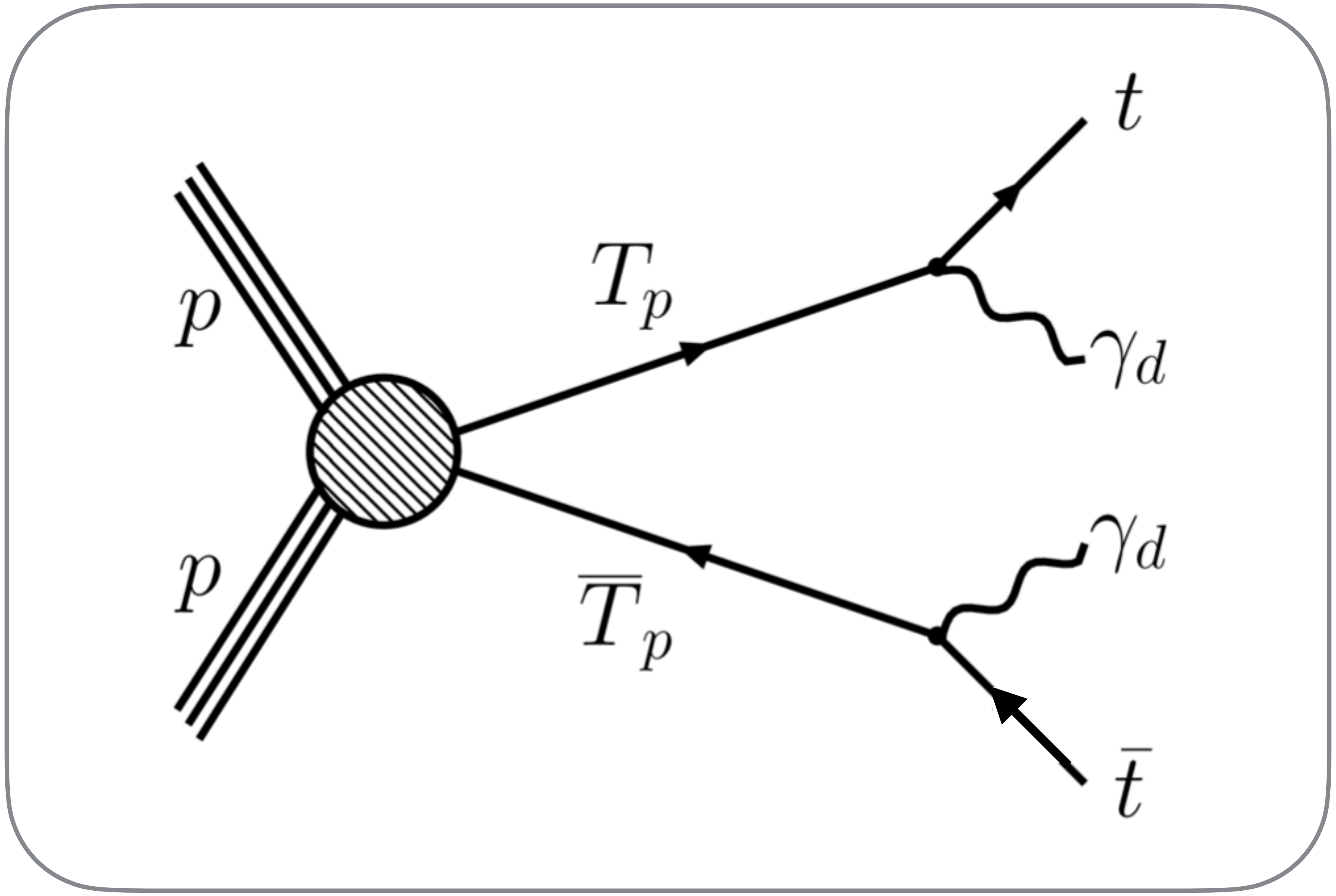
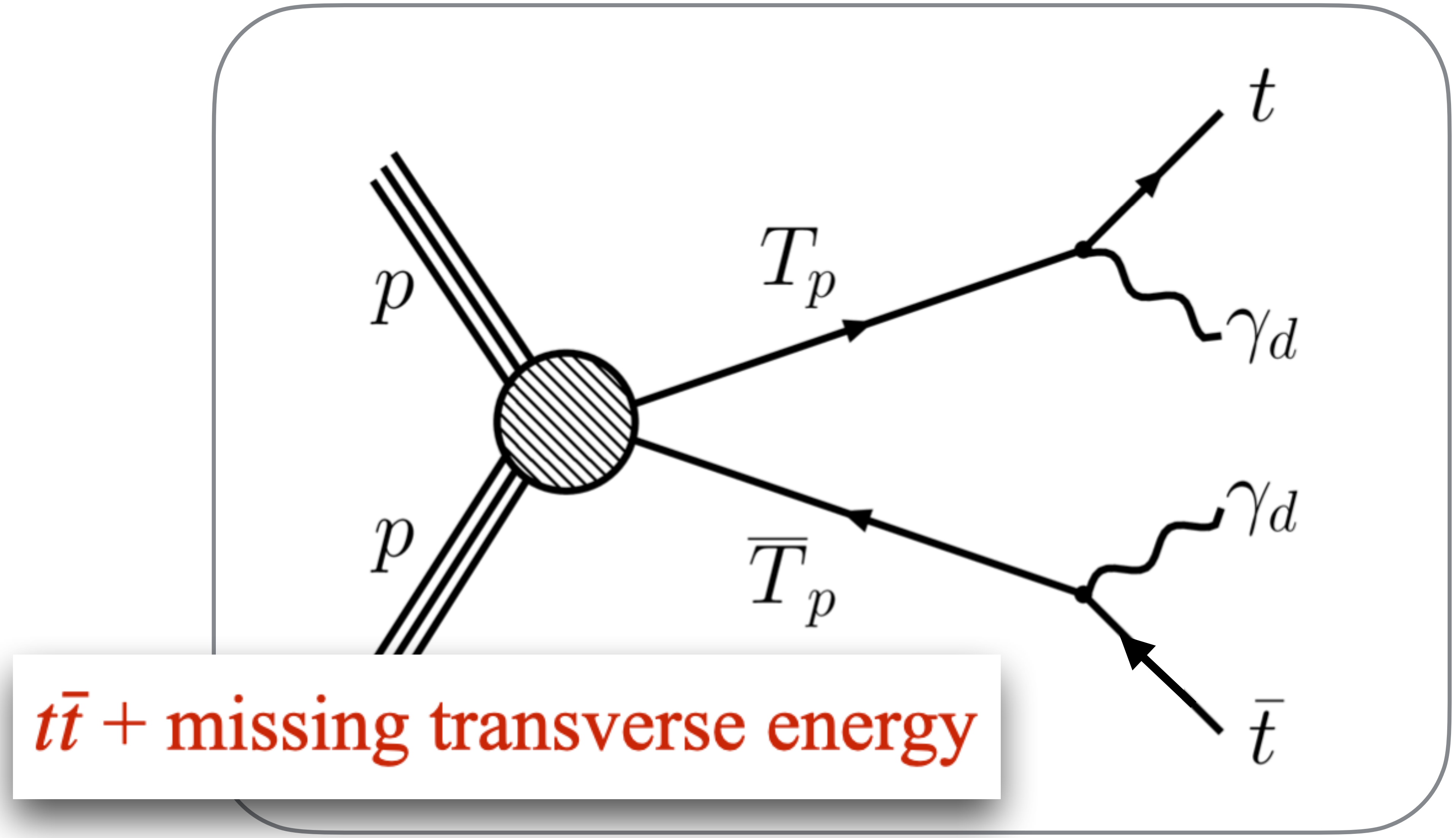
# *LHC searches: pair production*




- The top quarks produced are highly boosted in general
- Decay of the dark photon can give various possibilities

**Prompt lepton pair, lepton pair from displaced vertex, missing transverse energy**

# *LHC searches*

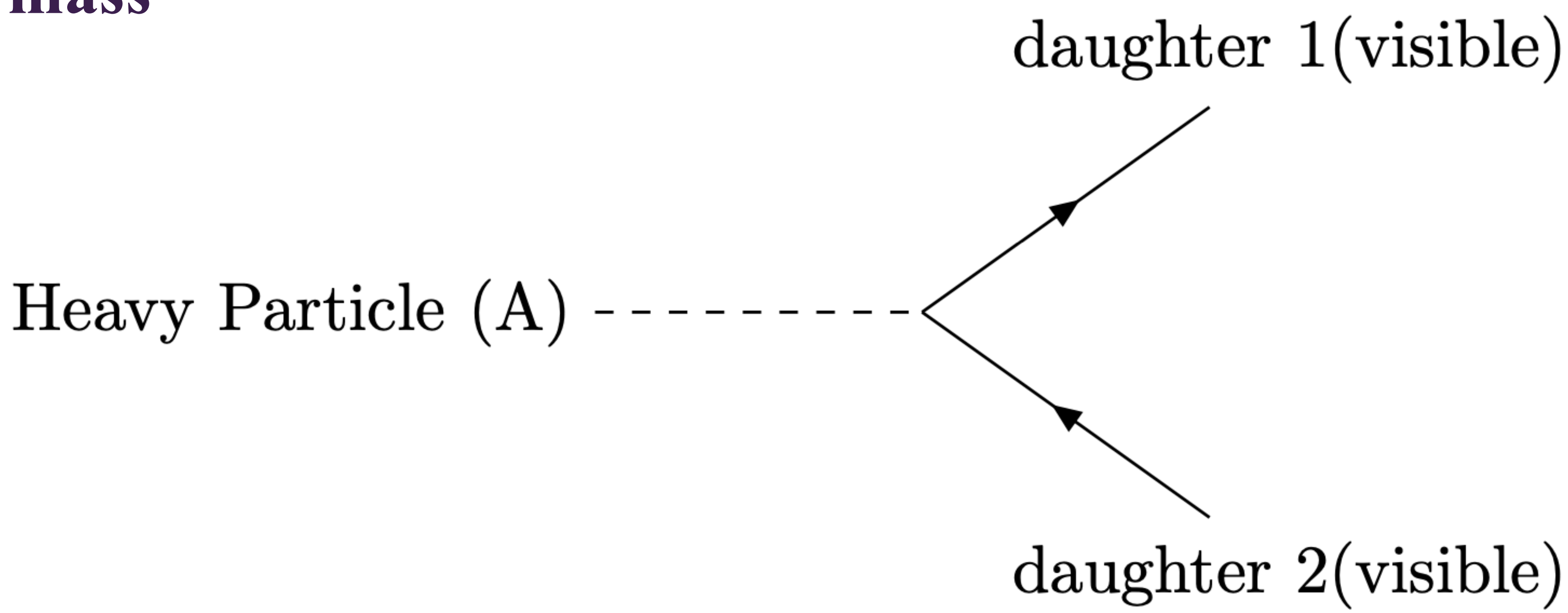



- The top quarks produced are highly boosted in general
- Decay of the dark photon can give various possibilities

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

# *Kinematic observables*

**Invariant mass**

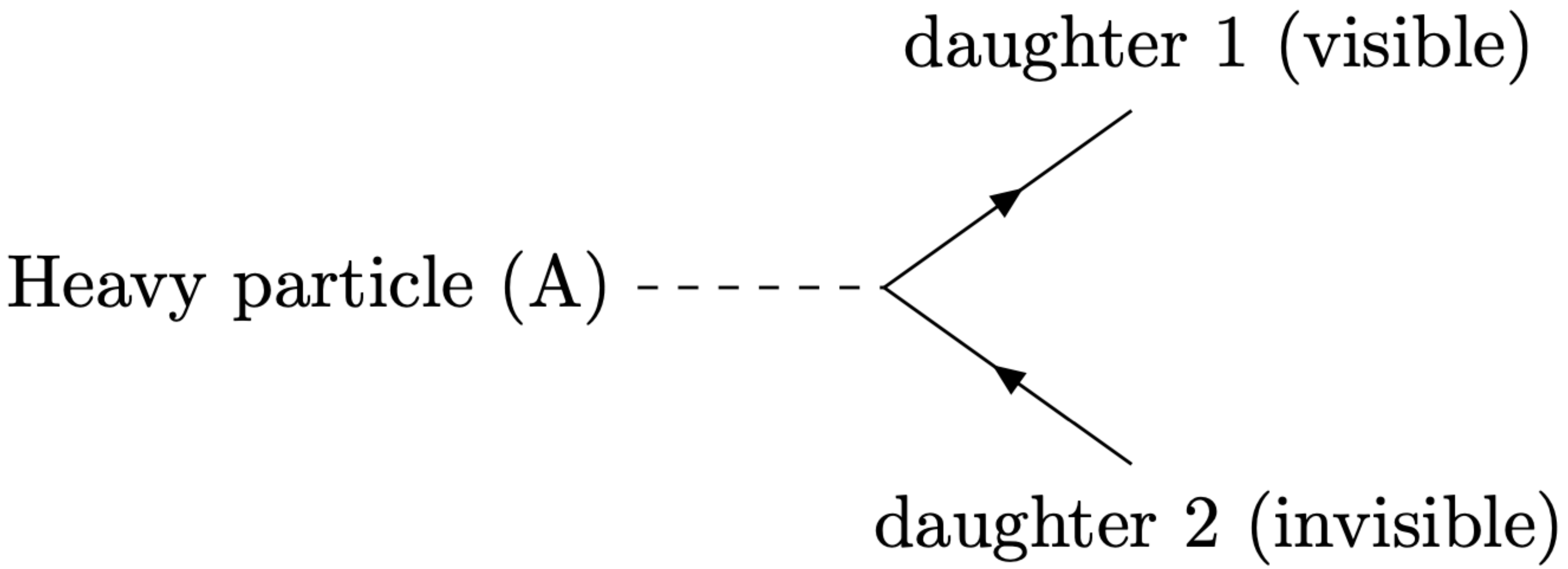



When a heavy particle decays into two constituents that are visible we can construct invariant mass of the particles as,

$$m_{12}^2 = (p_1 + p_2)^2 = M_A^2$$

# *Kinematic observables*

**Transverse mass**




If one of the decay product is not detected *missing transverse energy* might be helpful to define

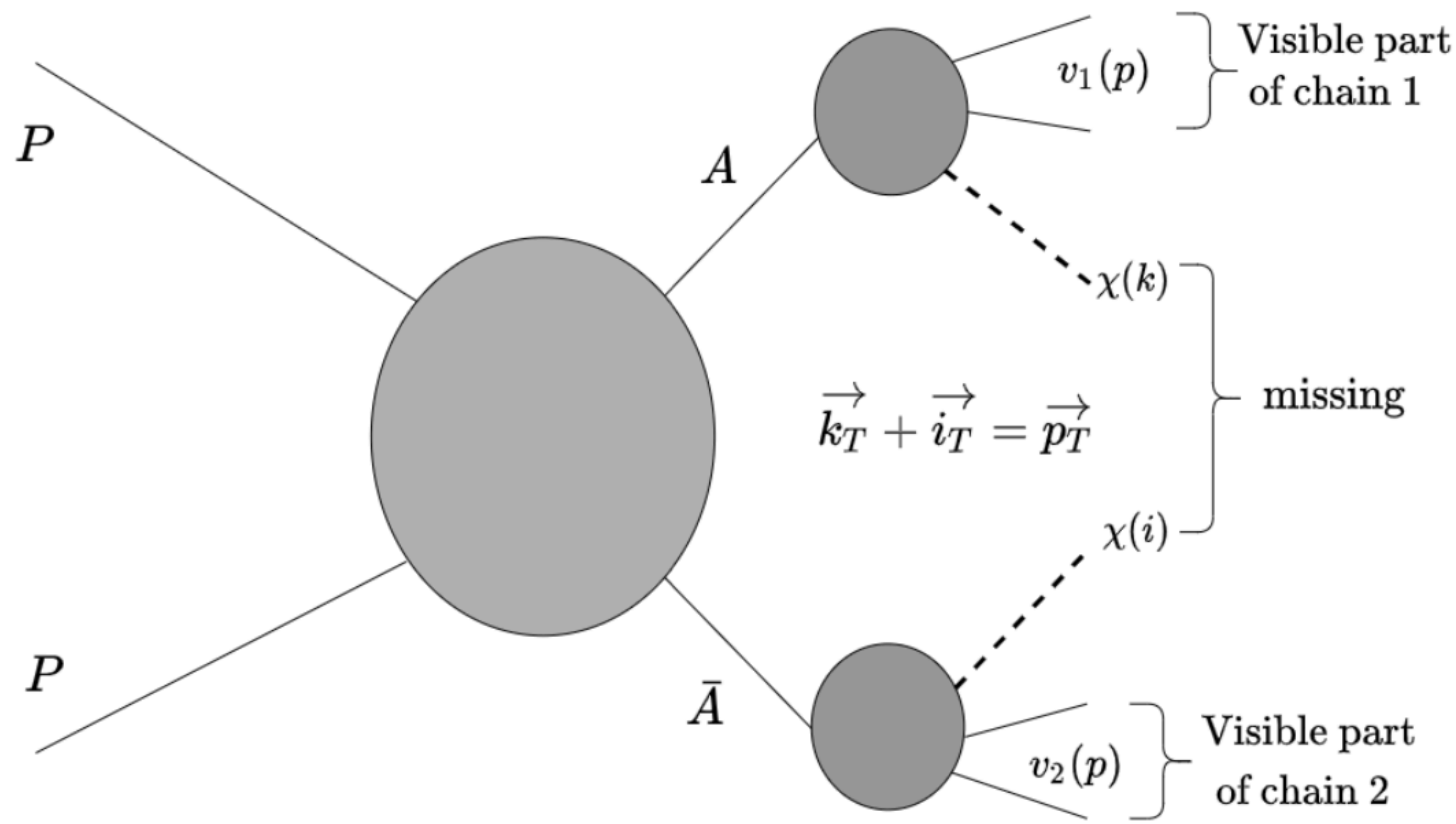
$$(M_T)^2 \quad = \quad (E_{T,1} + E_{T,2})^2 - (\vec{p}_{T,1} + \vec{p}_{T,2})^2 \leq M_A^2$$

*Applicable when single invisible particle is present in the final state

# *Kinematic observables*

**Stransverse mass**

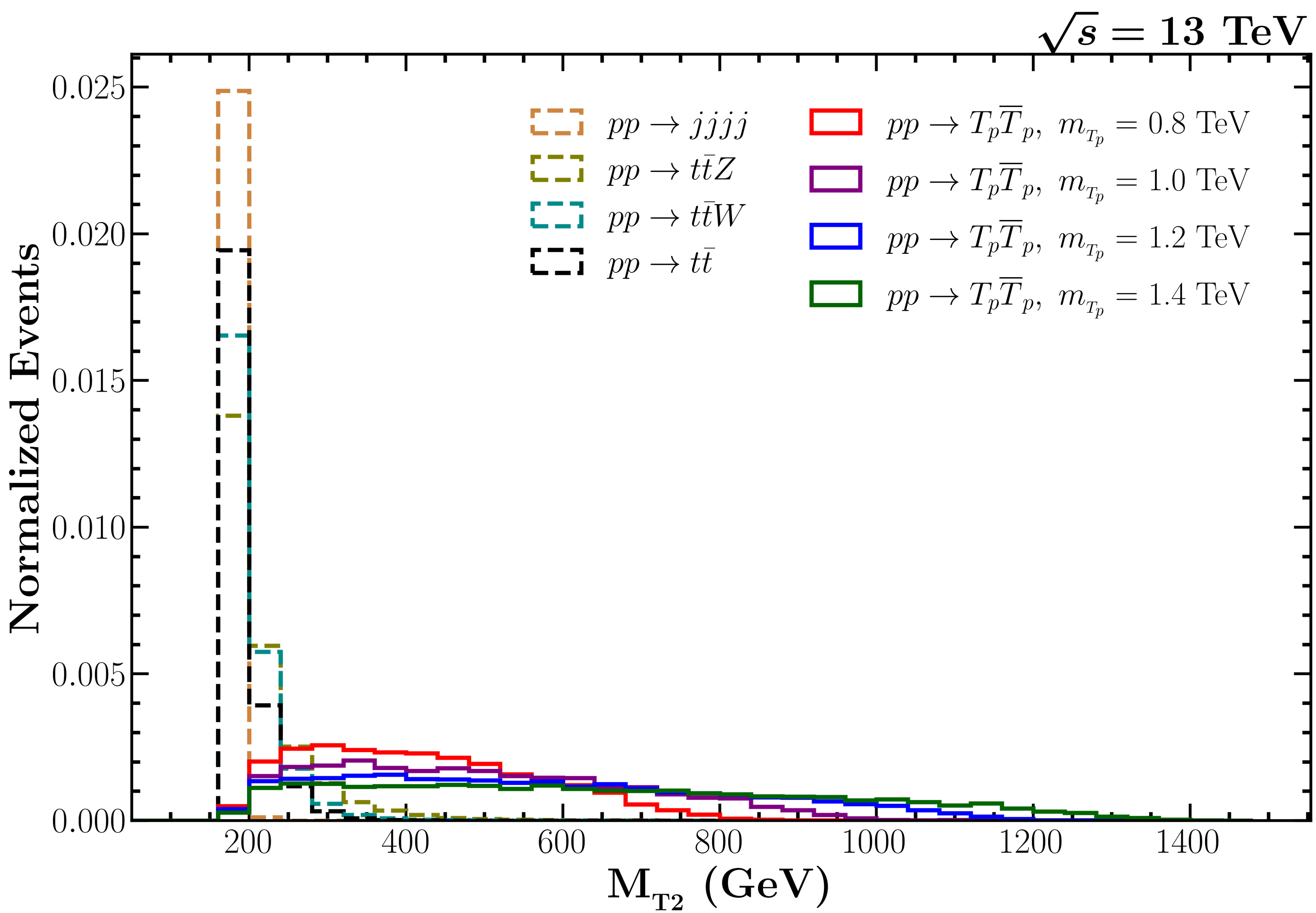
Lester and Summers, 1999




$$M_{T2}^2 \;=\; \min_{\vec{k_T}+\vec{i_T}=\text{tot. miss}\vec{p_T}} \left\{\max\left[M_T^2(\text{chain 1}), M_T^2(\text{chain 2})\right]\right\} < m_A^2$$

$M_{T2}$ is a function of the momenta of visible particles and the missing transverse momentum in an event.

# *Event kinematics: Stransverse mass*

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# *Exclusion limit*

**@LHC 13 TeV**

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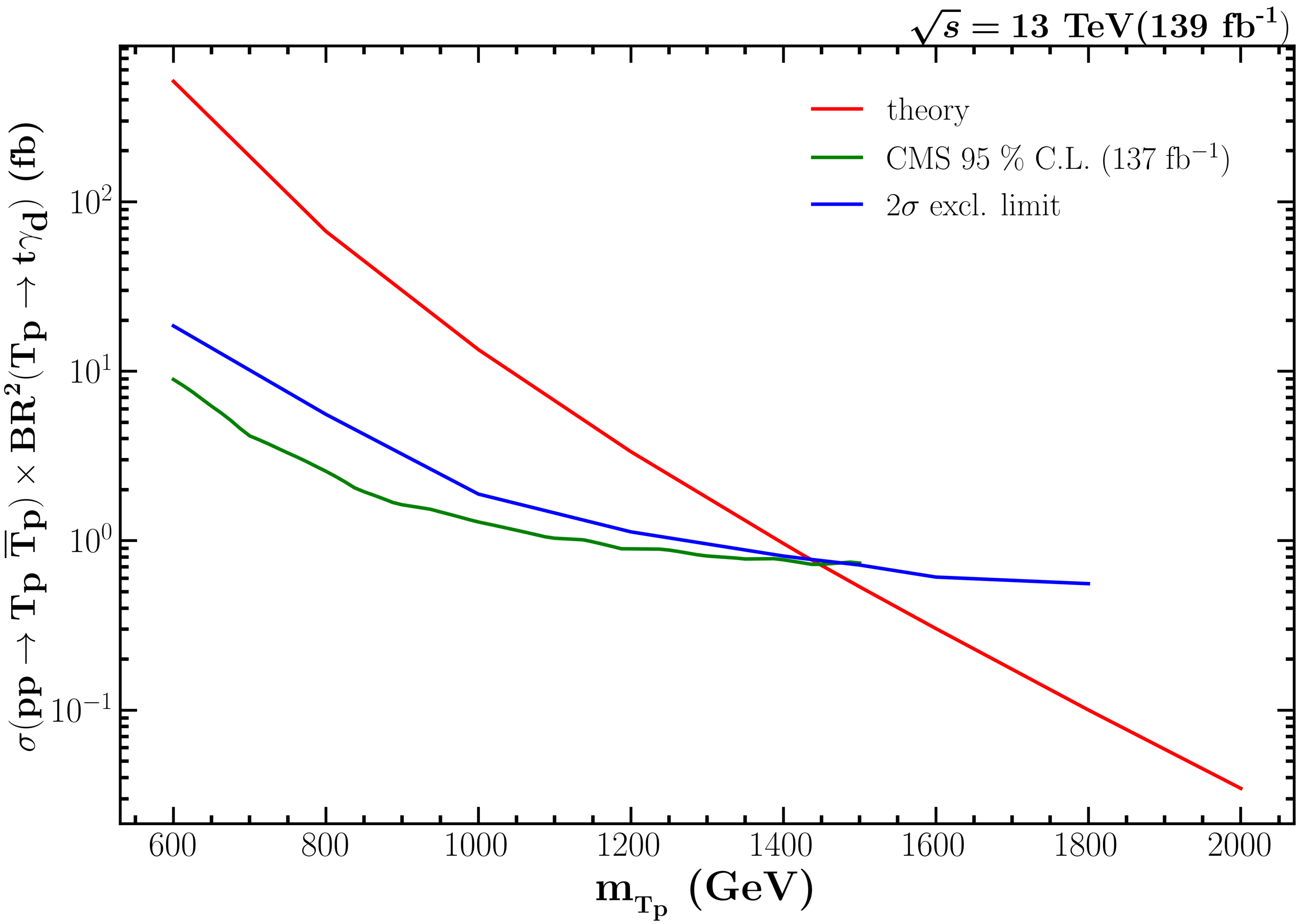


$\sigma \times \mathrm{BR}^2$
as low as
$\sim 1$ fb

$2\sigma$ exclusion limit
on $m_{T_p} > 1.4$ TeV
with present data

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.

# *Exclusion limit*

**@LHC 13 TeV**

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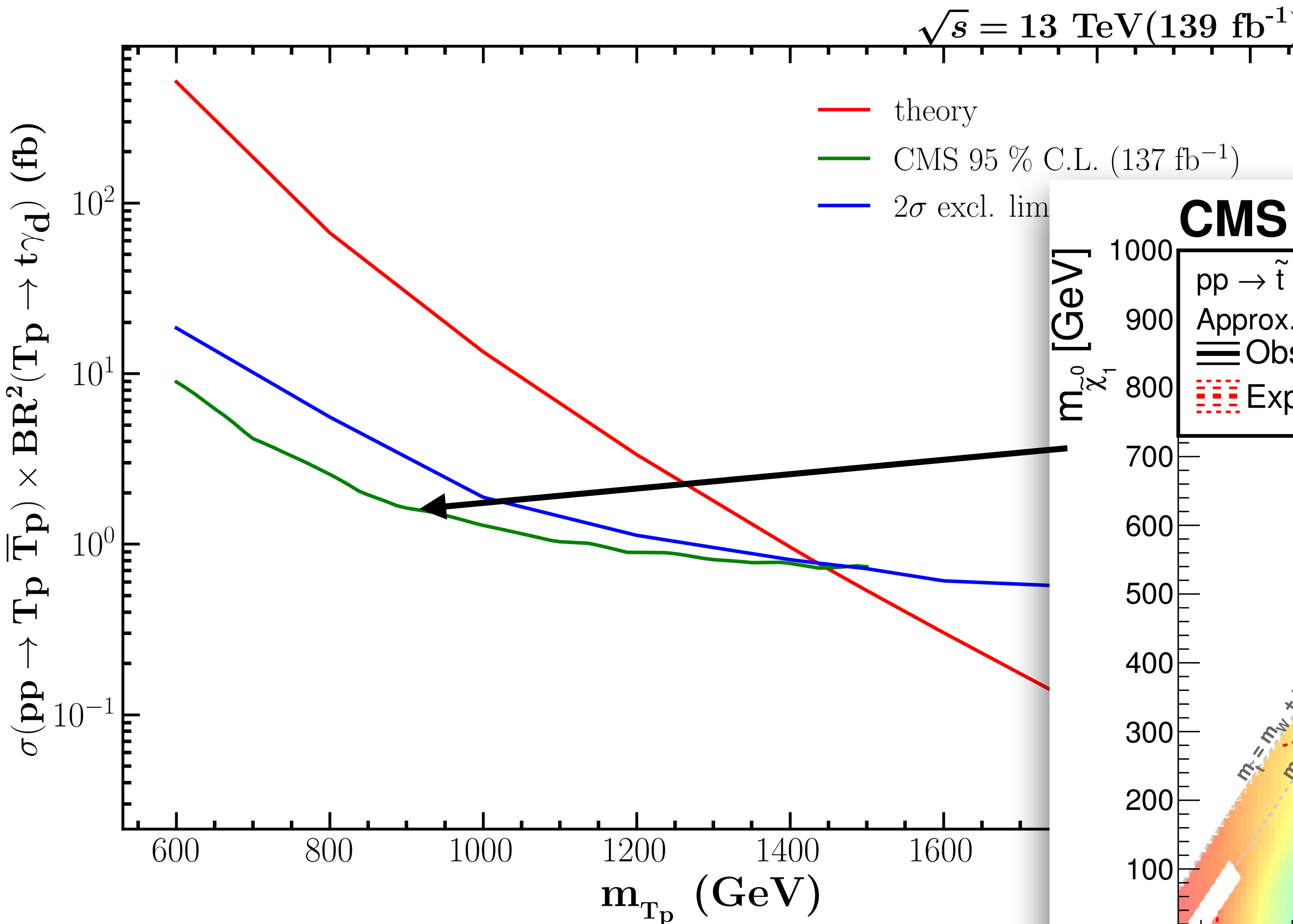
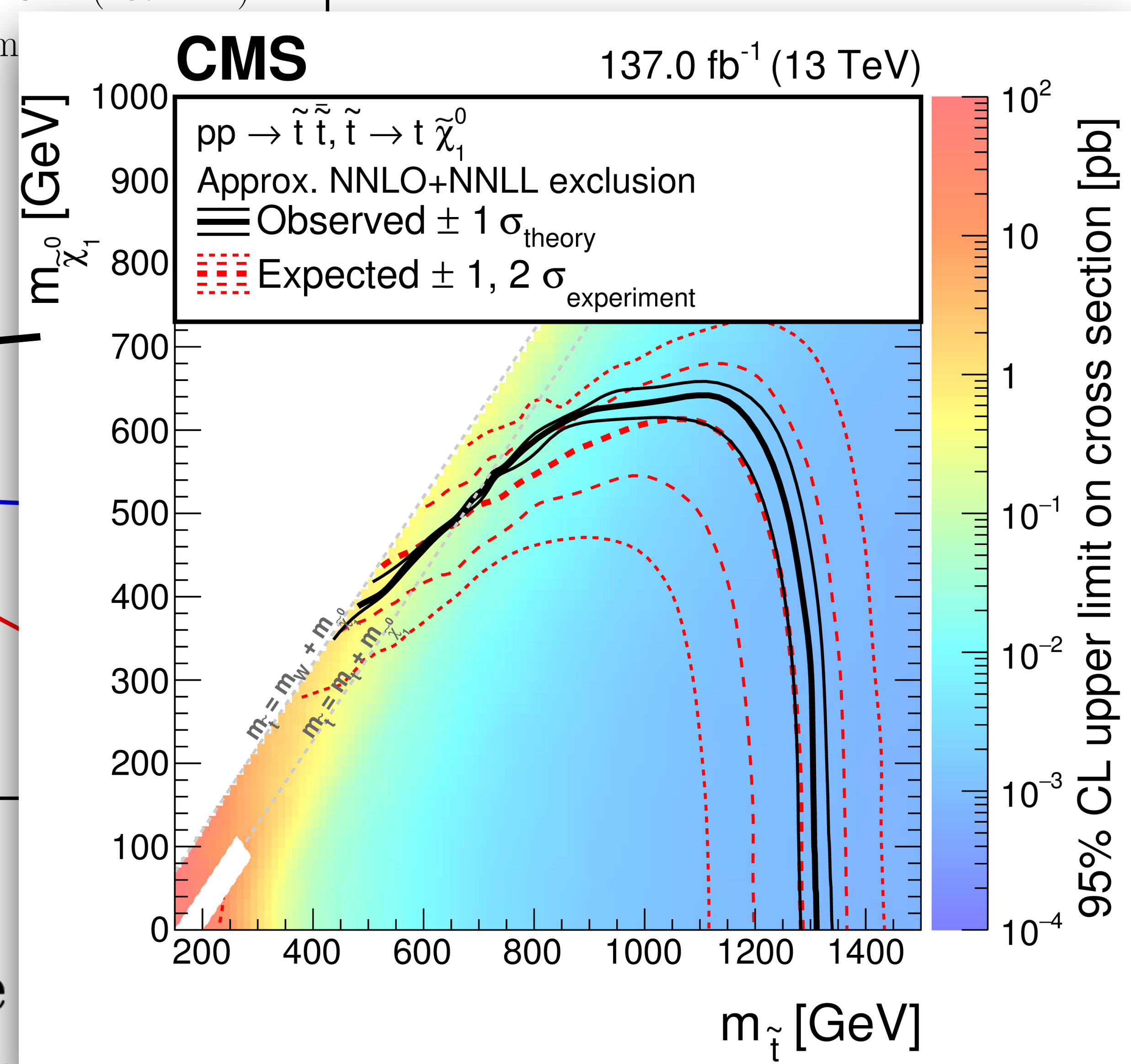
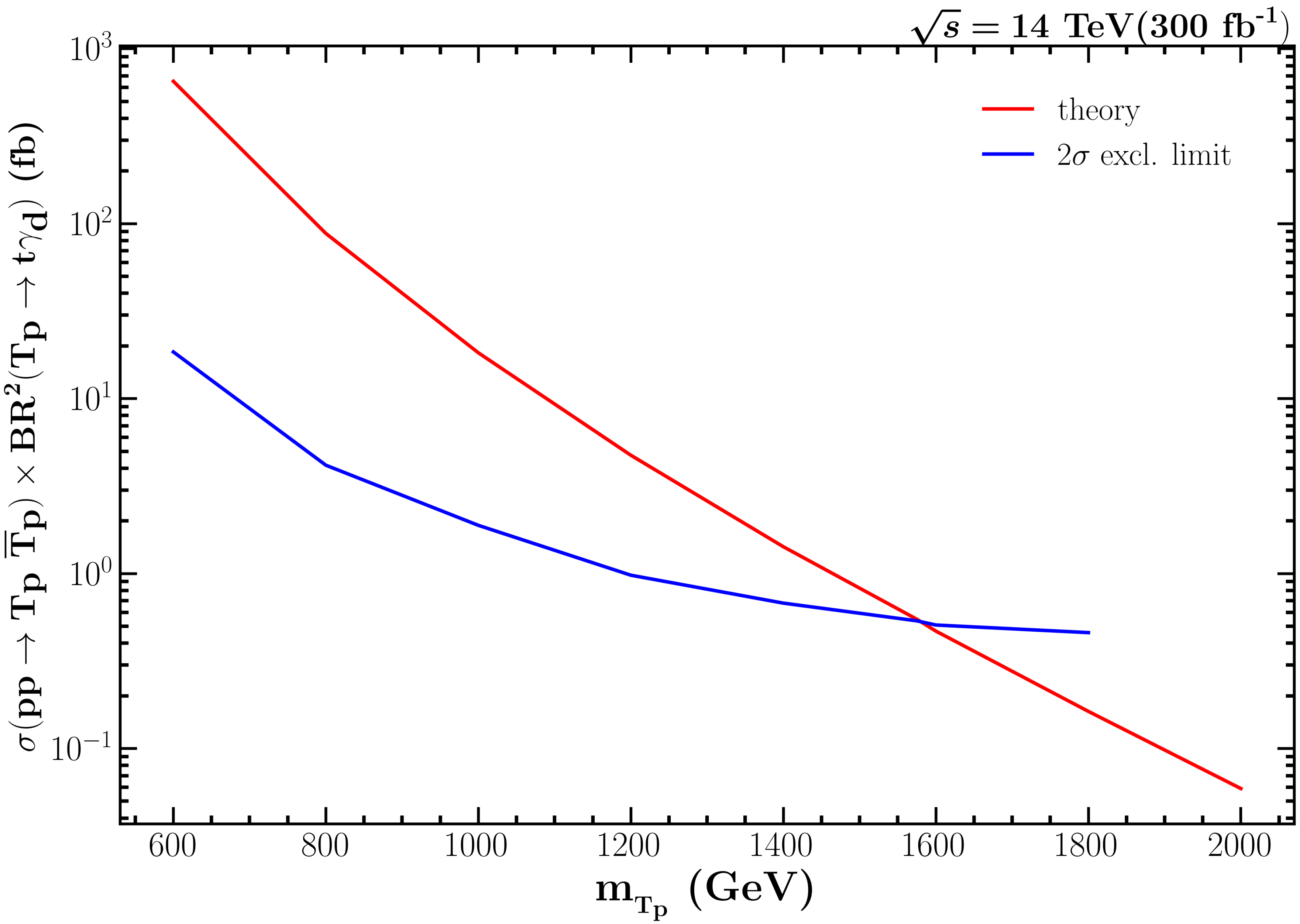



We depict the constraint coming from the ...
$\tilde{t} \to t\tilde{\chi}_1^0$) (Sirunyan et al., 2021) in the $t\bar{t}$+missing tranverse energy channel.

# *Exclusion limit*

**@LHC 14 TeV**

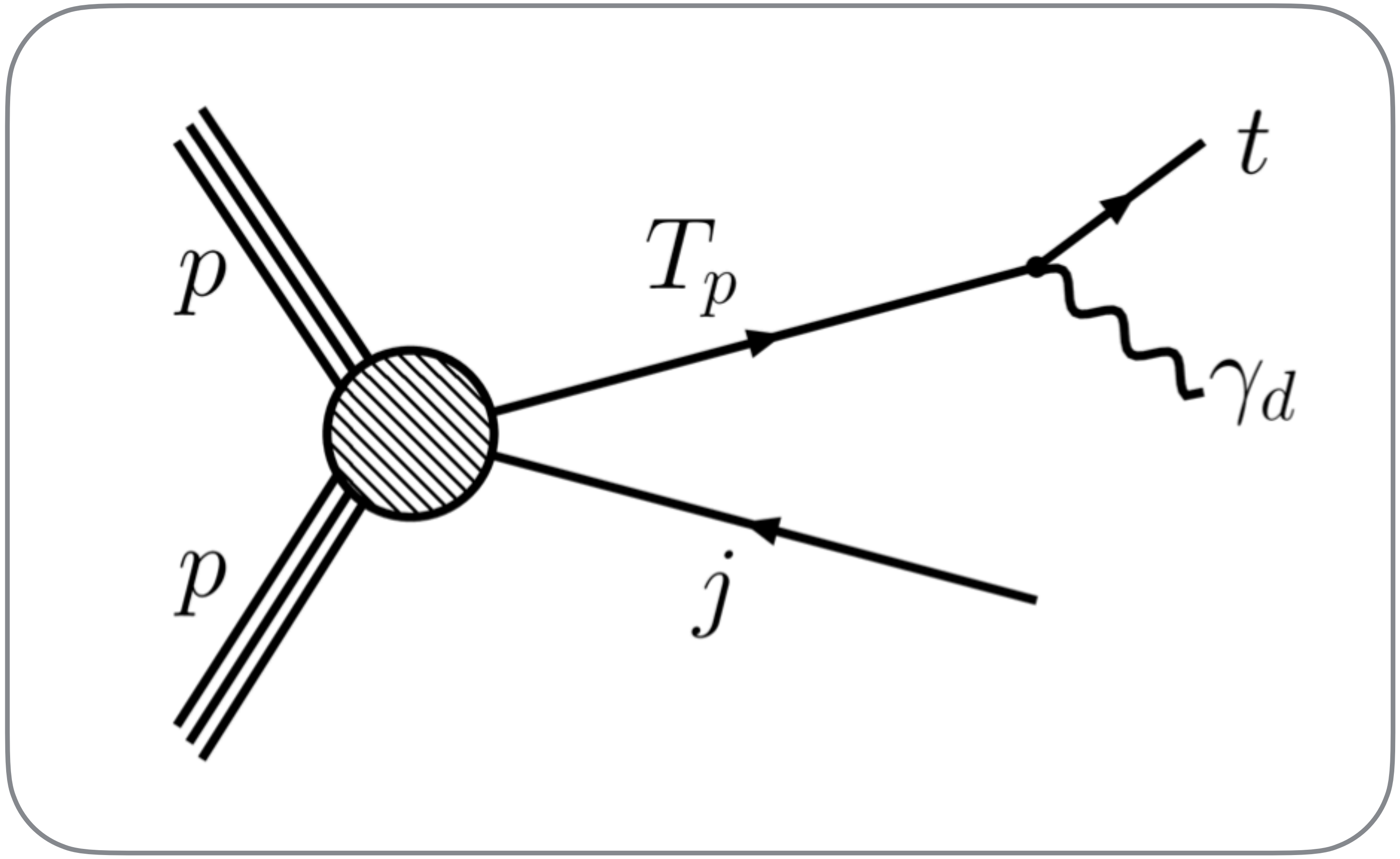



$\sigma \times BR^2$
as low as
$\sim 0.8$ fb

$2\sigma$ exclusion limit
on $m_{T_p} > 1600$ GeV
with present data

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

# *LHC searches: single production*



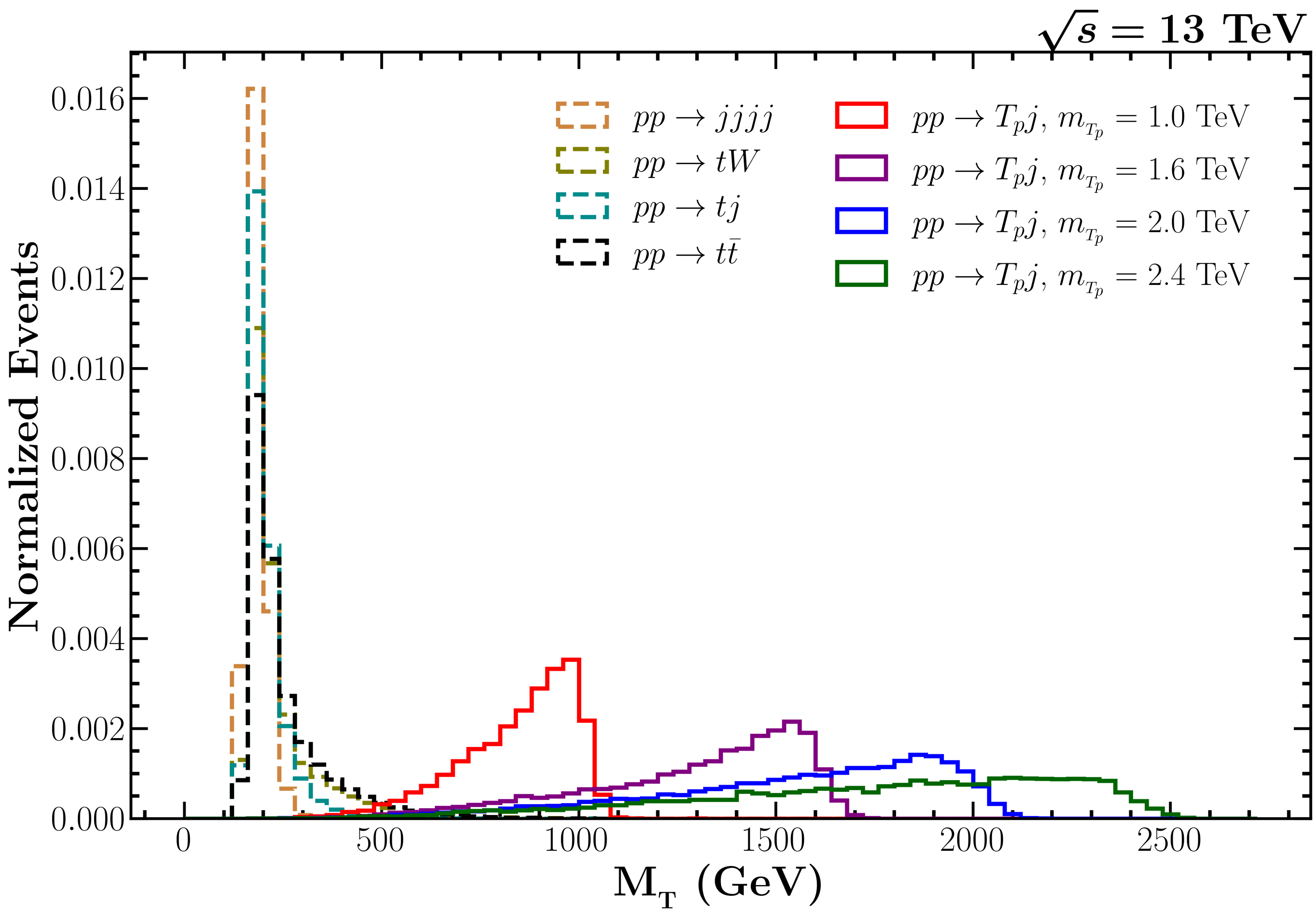

$t$ + missing transverse energy + forward jet

Make use of:

transverse mass, missing transverse energy and forward jet rapidity

# *Event kinematics: Transverse mass*

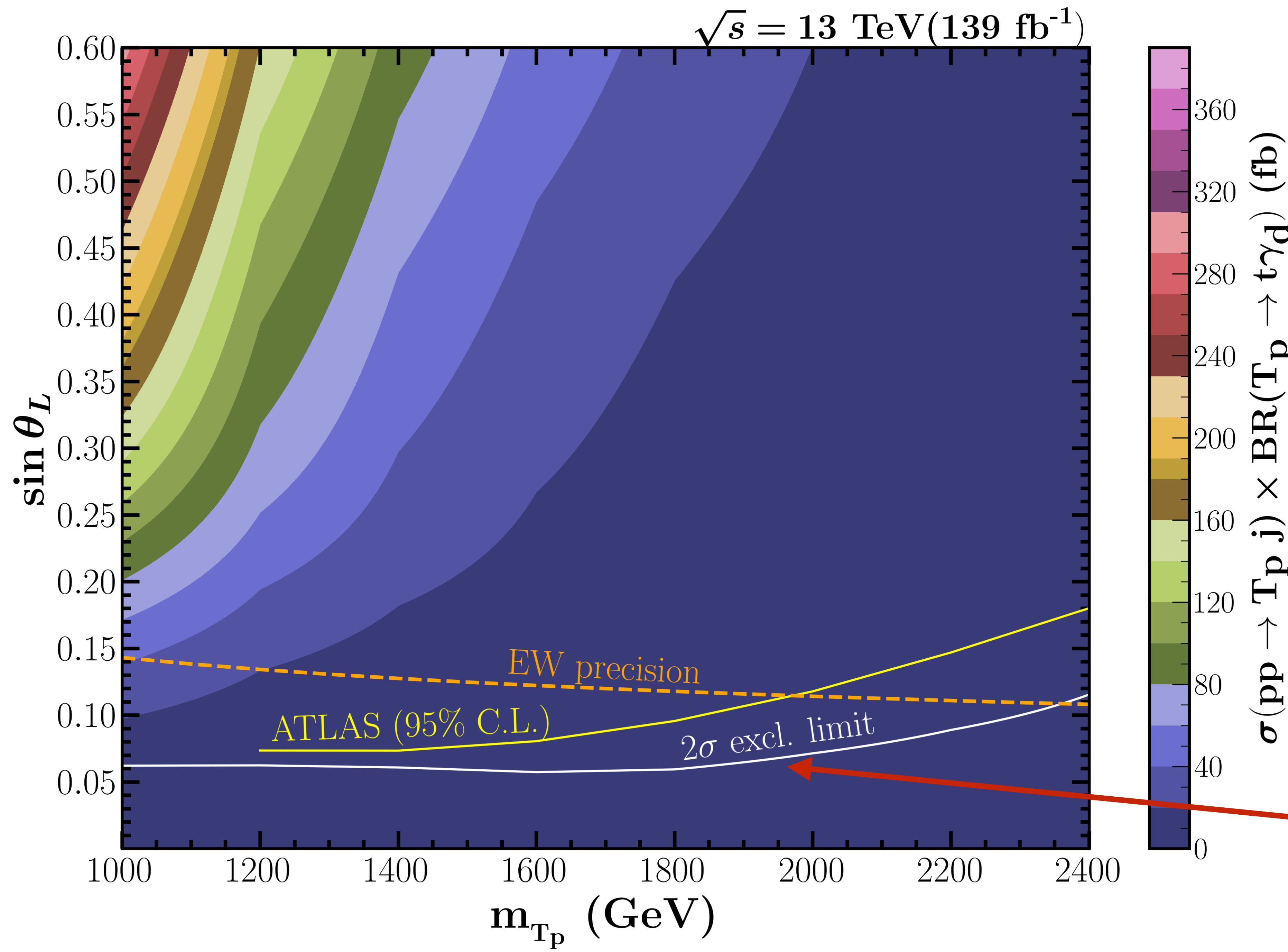
**S. Verma, SB, A. Chatterjee, J. Ganguly PRD (2023)**



# *Exclusion limit*

**@LHC 13 TeV**

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




$\sigma \times$ BR
as low as
$\sim$ 35 fb

$2\sigma$ exclusion limit
on $\sin\theta_L \sim 0.06$
for $m_{T_p} < 1.8$ TeV

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

# *Exclusion limit*

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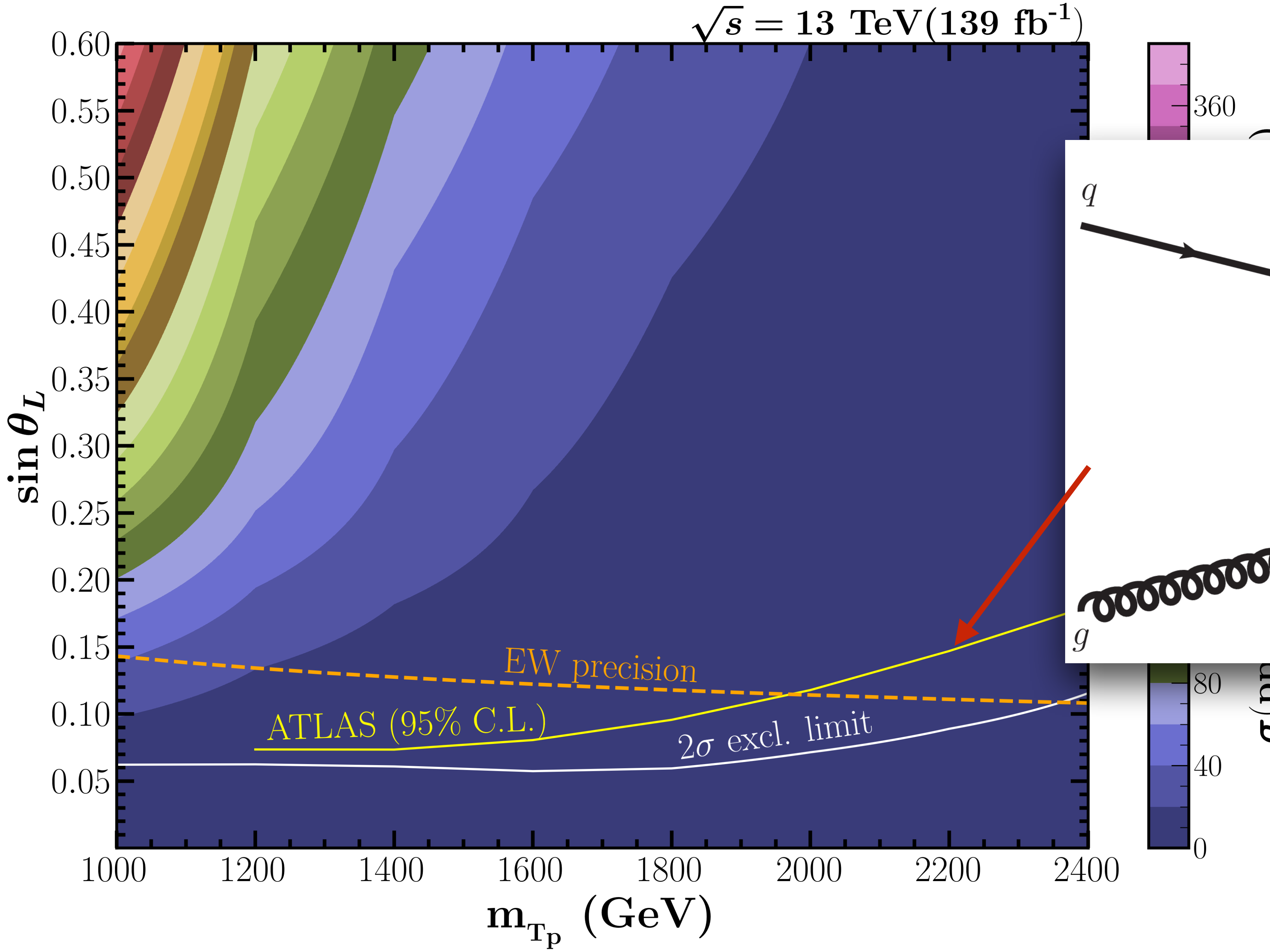


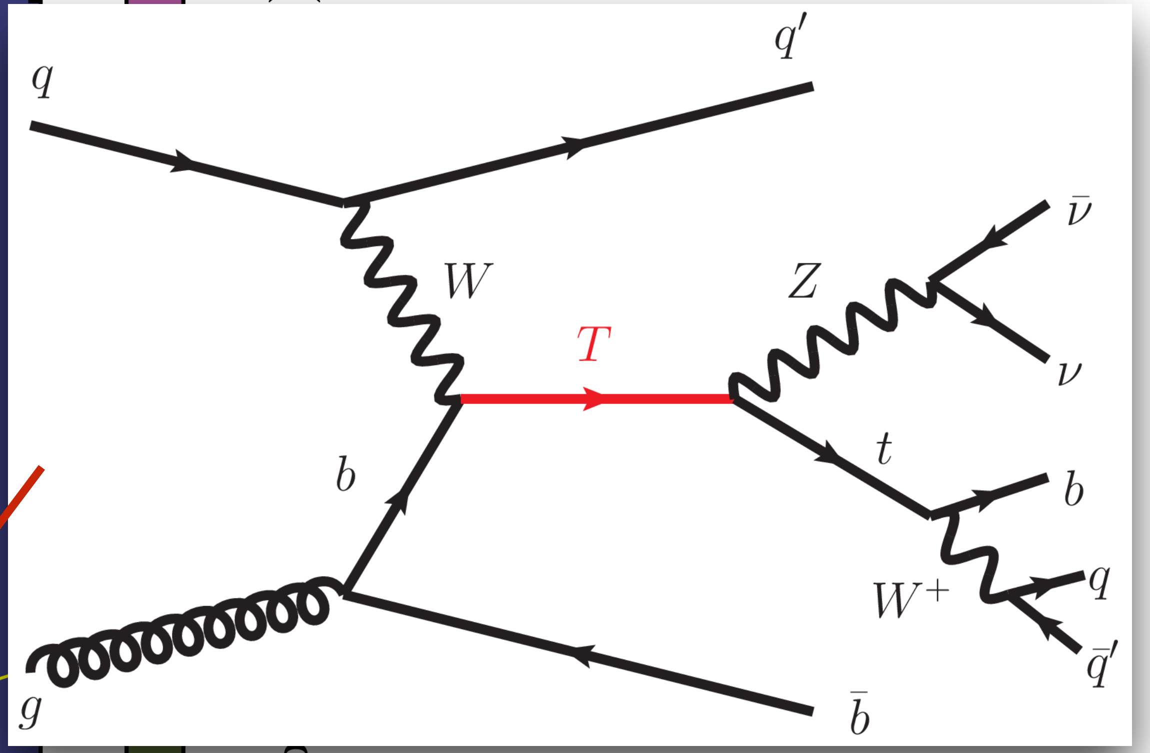


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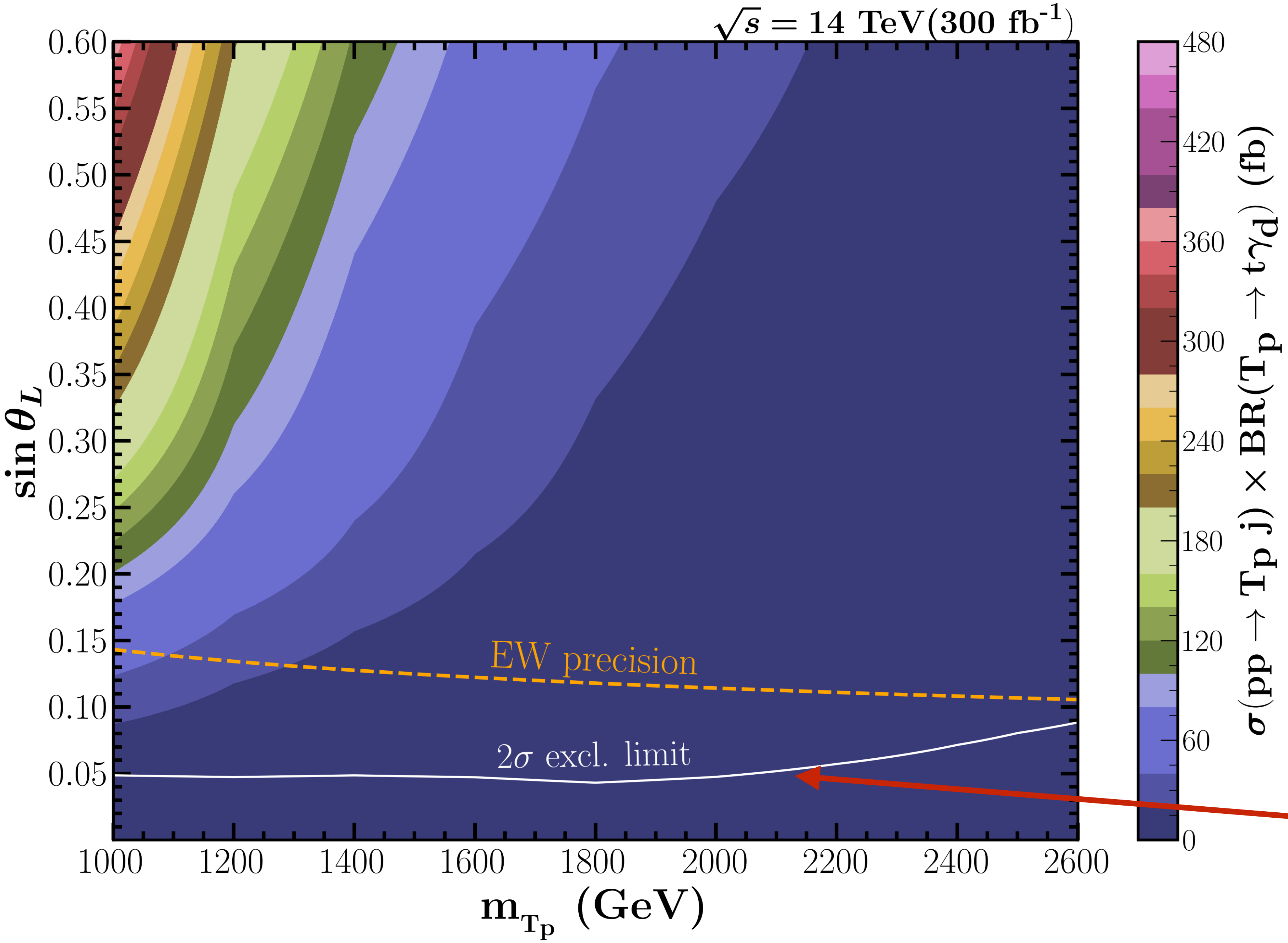
$$pp \to T_p j \to tZ(\to \nu\bar{\nu})$$

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

# *Exclusion limit*

**@LHC 14 TeV**

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




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

$\sigma \times$ BR as low as $\sim 20$ fb

$2\sigma$ exclusion limit on $\sin\theta_L \sim 0.05$ for $m_{T_p} < 2.0$ TeV

# *Conclusions*

- Vector-like top partners have been studied extensively at the LHC.
- However, LHC searches mostly focuses on the traditional decay modes (namely, $T_p \rightarrow tZ,\, bW, th$)
- Top partners decaying in the traditional channels have been already constrained by LHC data and the current limit is 1.3 TeV or higher.
- 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.
- In this work, we explored the the possibility of $T_p \rightarrow t\ \gamma_d$ decay at the LHC
- Study of maverick top partner or VLQ in general with non-standard interactions can shed some light on the physics of the *dark-sector* as well.

***Thank you!***