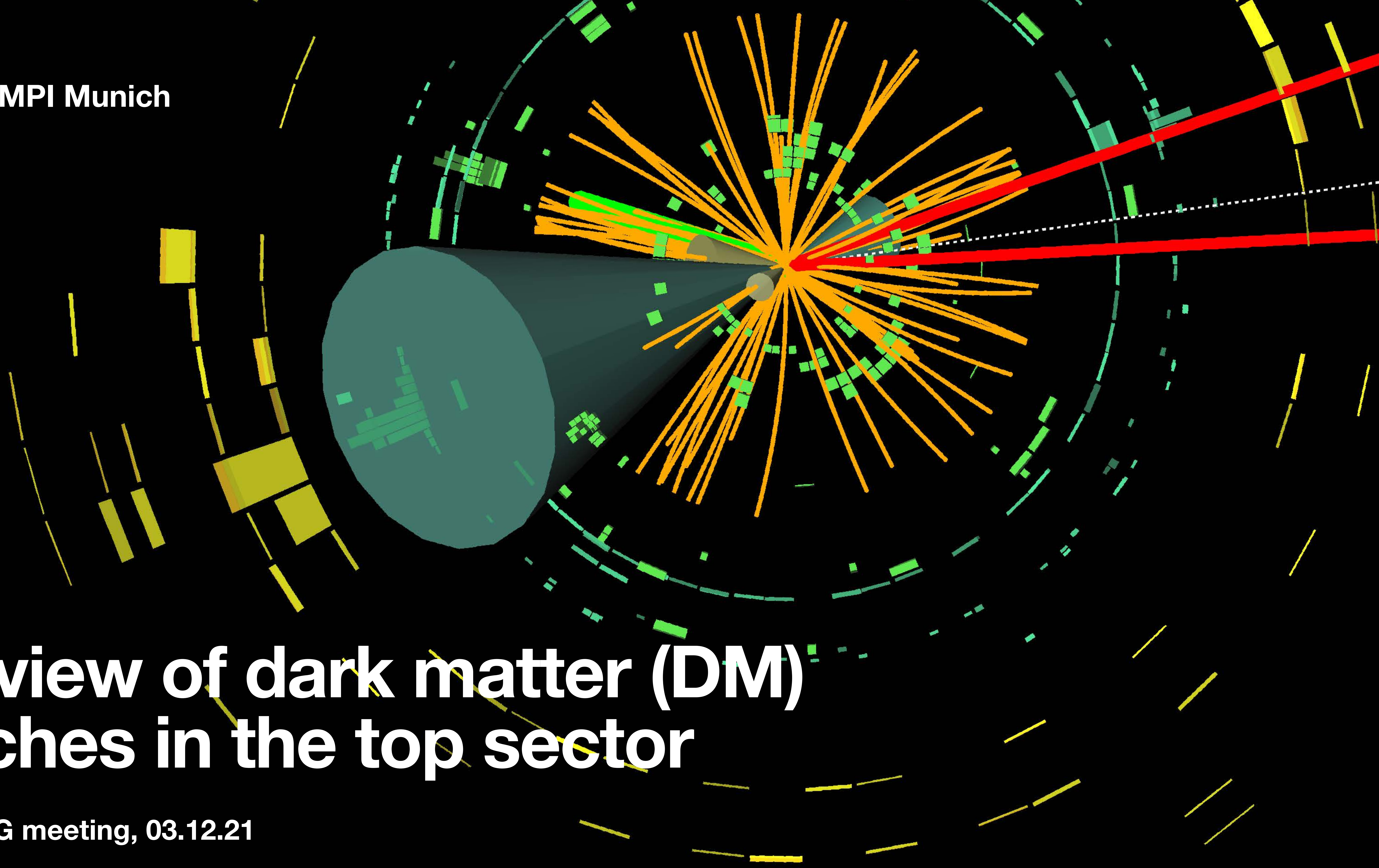
Uli Haisch, MPI Munich



Overview of dark matter (DM) searches in the top sector

LHC TOP WG meeting, 03.12.21

Fabio asked for the following

“[…] We also hold a “fun session” on topics that go beyond the core measurement activities. In this context, we thought it could be interesting to have a kind of “review” talk about $t\bar{t}$+DM searches. […]”

To have “fun”, I will interpret “review” & “DM” rather loosely focusing on interesting top signatures, giving examples of BSM physics that searches for them allow to test

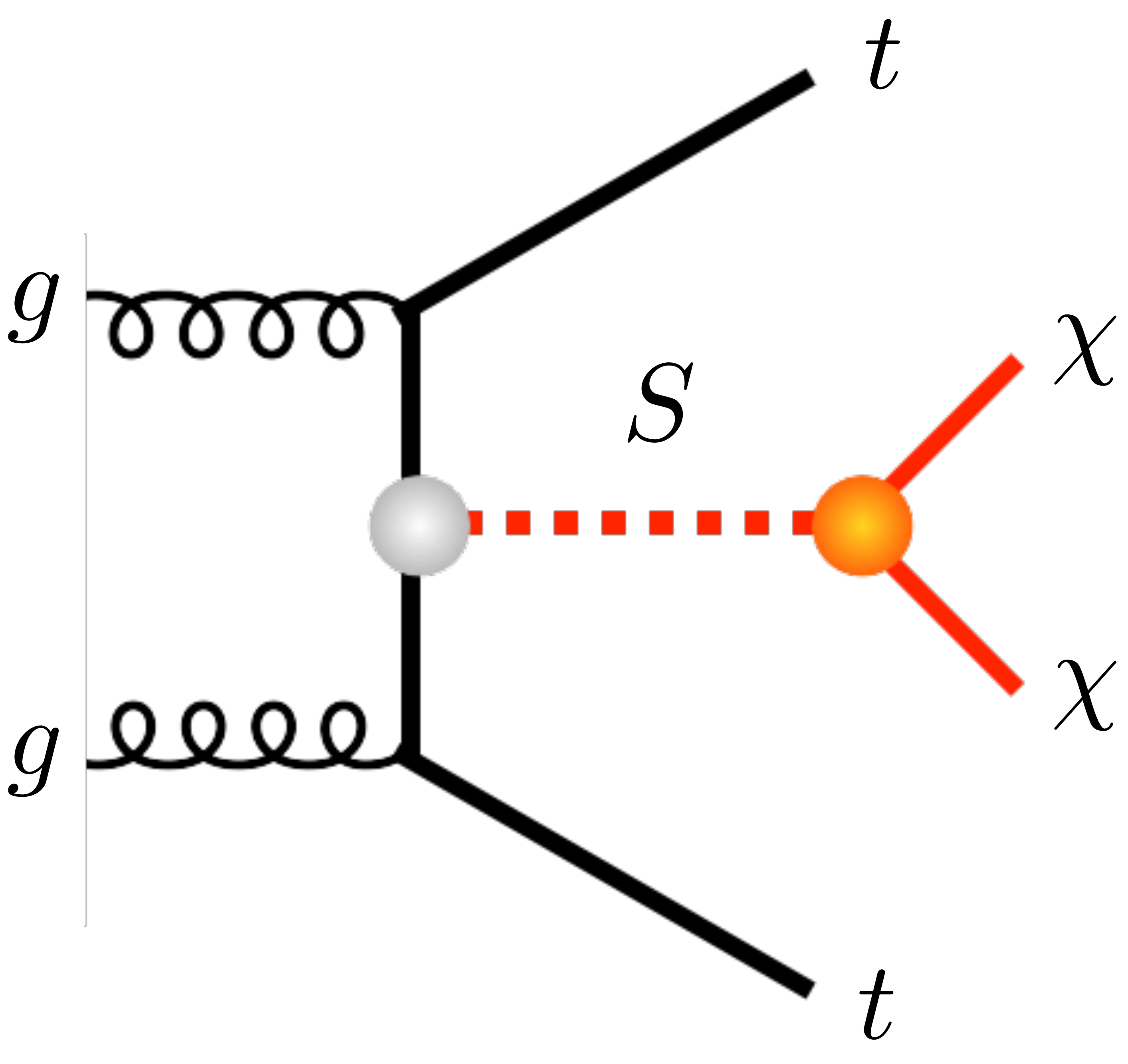
$t\bar{t}+E_{T,miss}$: simplified spin-0 DM model

SM Yukawa coupling

$$\mathcal{L}_S \supset g_{\rm SM} \sum_q \frac{y_q}{\sqrt{2}} \bar{q} q S + g_{\rm DM} \bar{\chi} \chi S$$

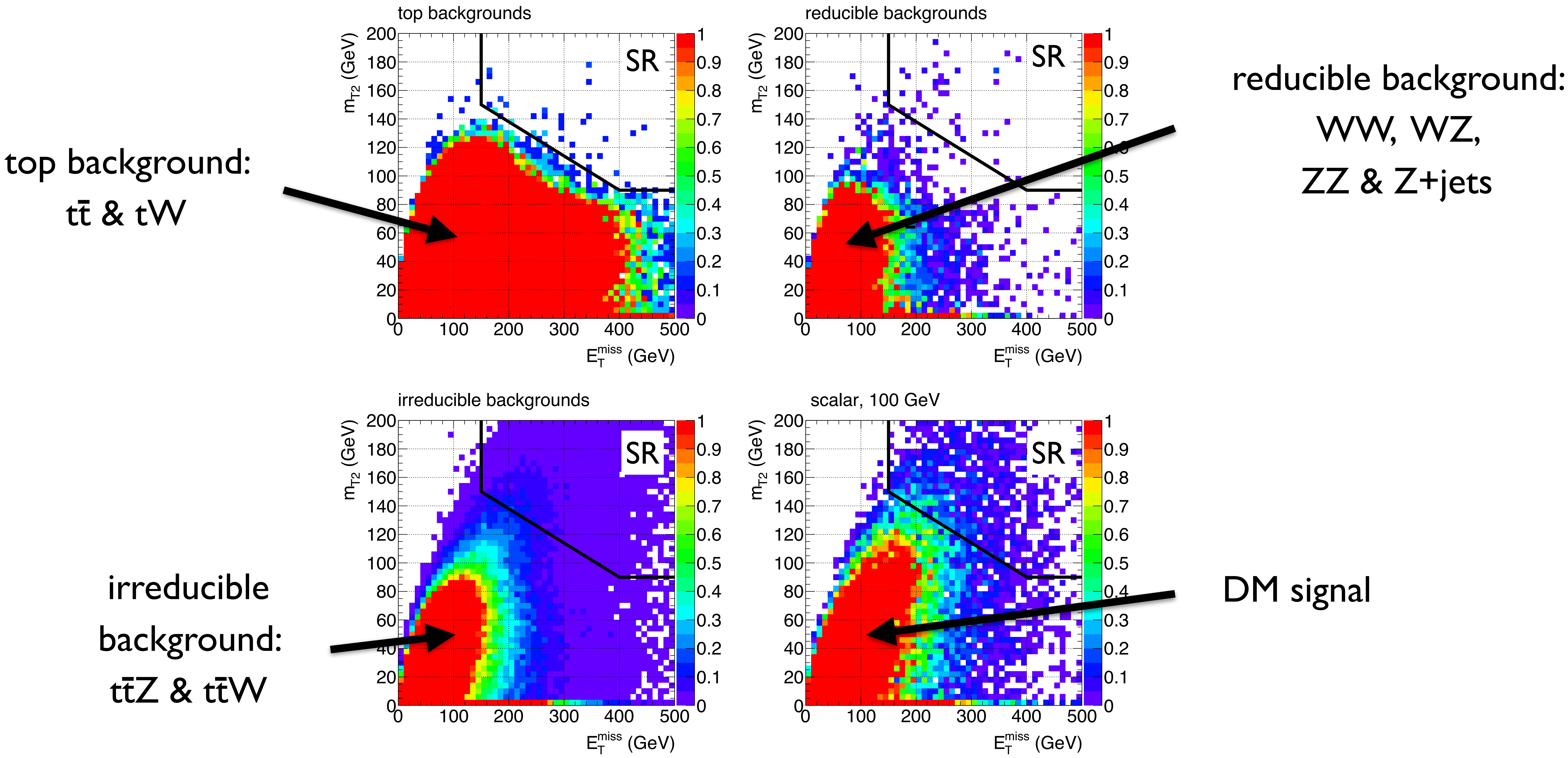
Dirac DM candidate

scalar (or pseudoscalar) mediator



[see for instance ATLAS/CMS DM Forum, 1507.00966]

$t\bar{t}+E_{T,miss}$: DM signal vs. background



[UH, Pani & Polesello, 1611.09841]

$t\bar{t}+E_{T,miss}$: background modelling

events/(300 fb^{-1})

	$t\bar{t}$	$t\bar{t}Z$
LO, narrow width approximation	0	47
LO, off-shell decays	17	49
NLO, narrow width approximation	0	47
NLO, off-shell decays	19	48

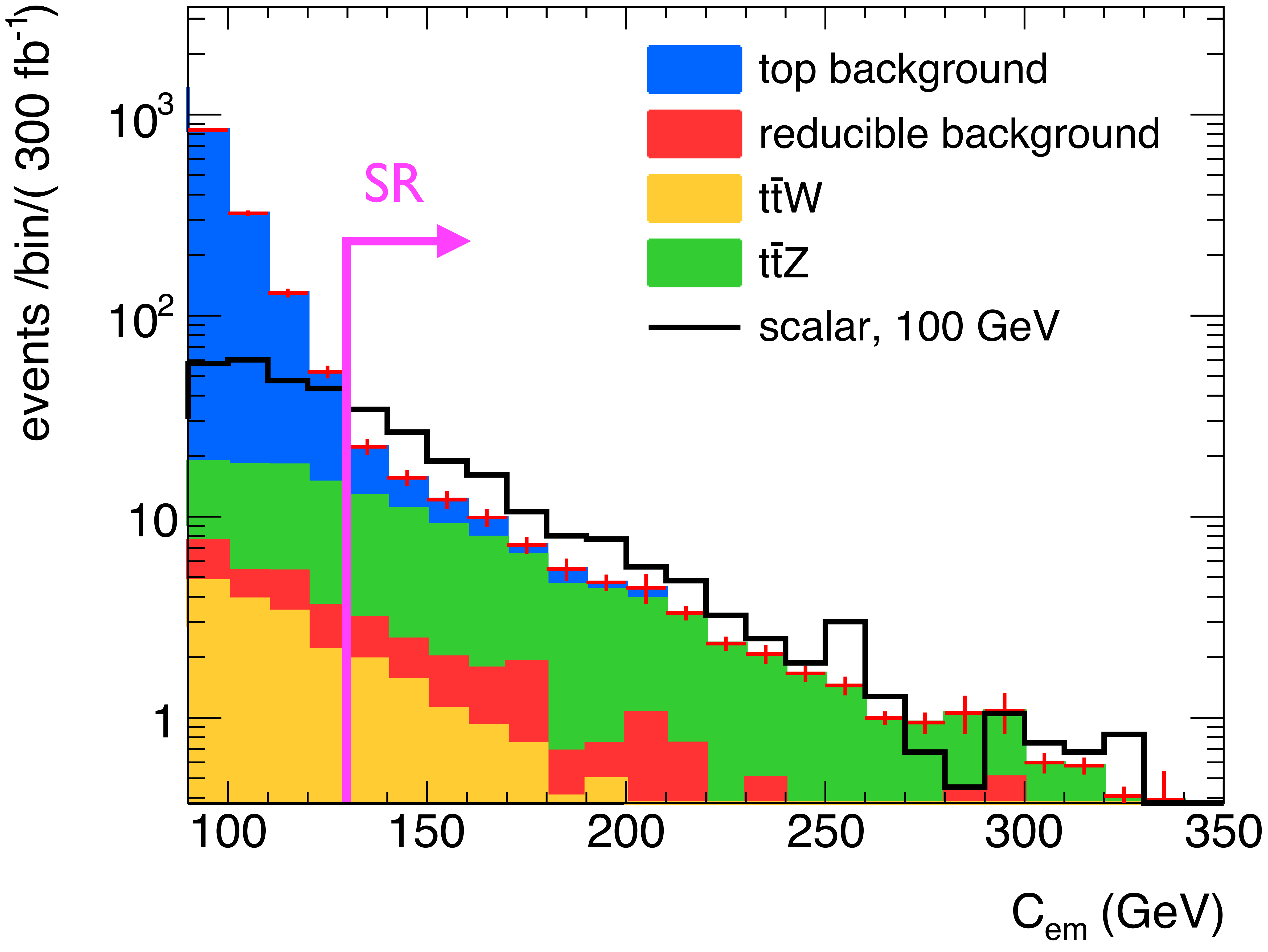
Off-shell & NLO QCD effects of O(few %) in case of leading SM background

To correctly model 2l events in exclusive fiducial region, very important to include off-shell effects in top decays. NLO QCD effects of O(10%)

[Hermann & Worek, 2108.01089]

$t\bar{t}+E_{T,miss}$: background suppression

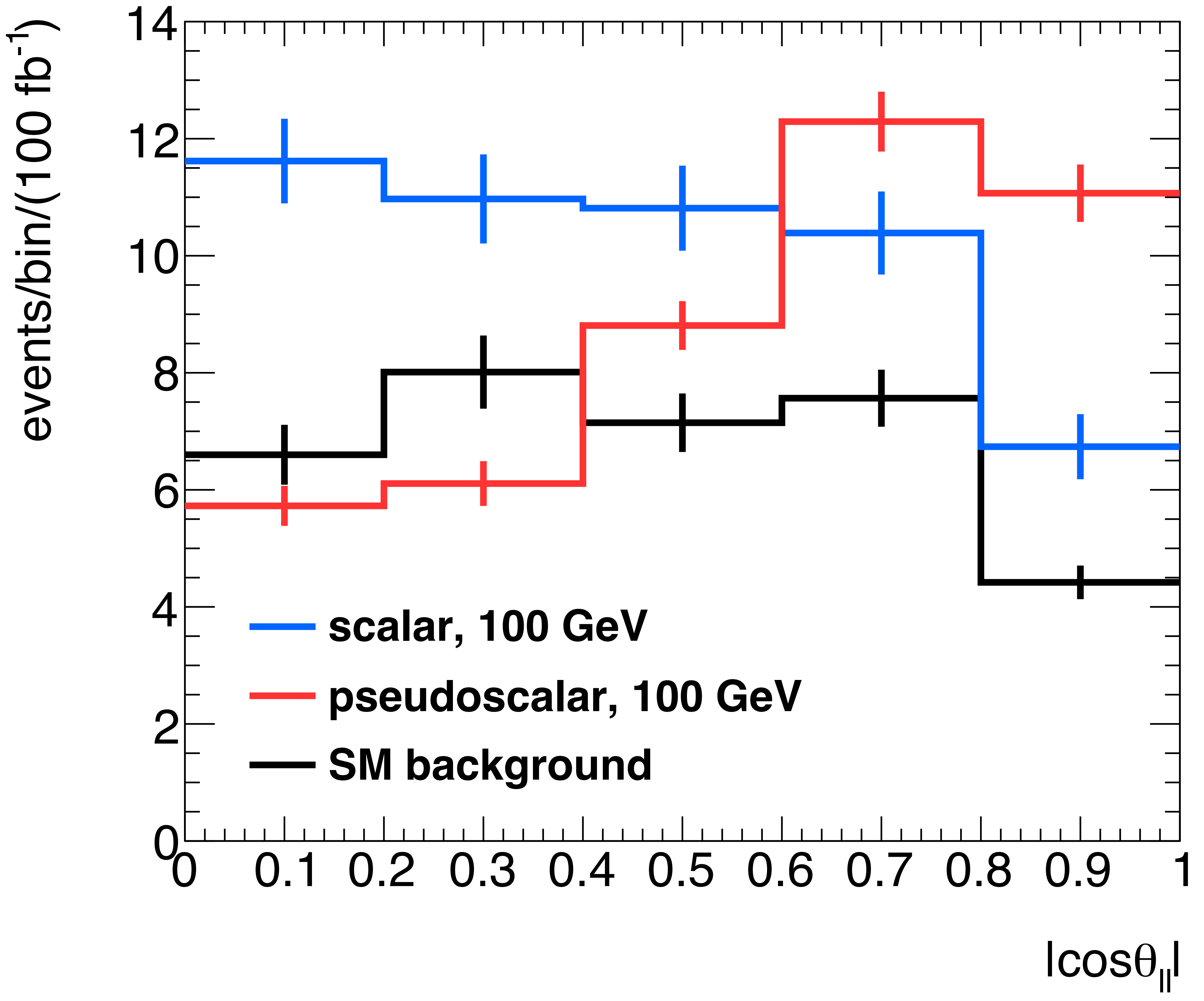
[UH, Pani & Polesello, 1611.09841]

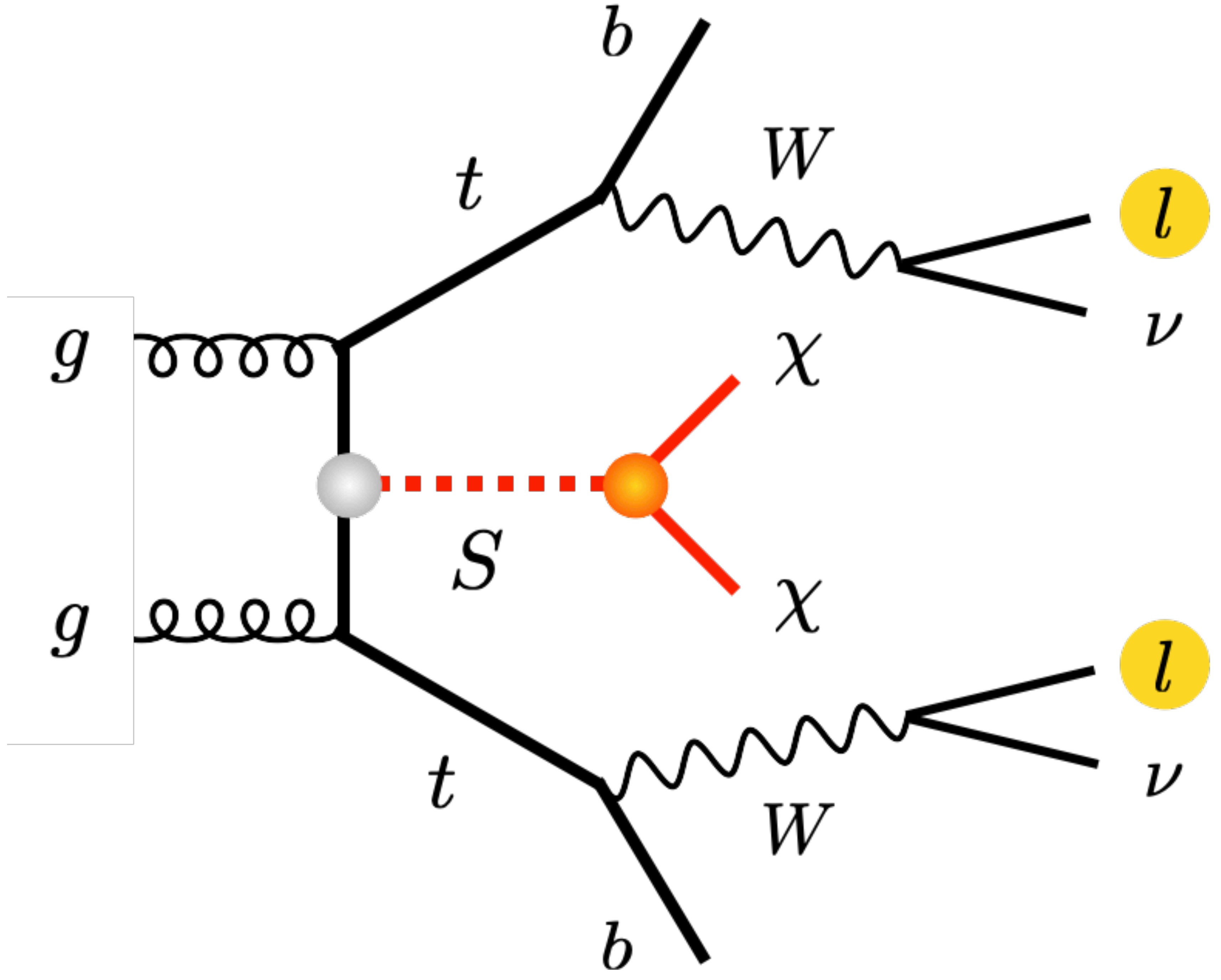


$$C_{\text{em}} = m_{T2} - 0.2\left(200\,\text{GeV} - E_T^{\text{miss}}\right)$$

One possible variable to suppress backgrounds. Latest ATLAS & CMS searches use, depending on final state, combinations of observables such as $E_{T,miss}$, $H_{T,sig,miss}$, m_T, topness, $m_{top,reclustered}$, …

$t\bar{t}+E_{T,miss}$: signal discrimination





Pseudorapidity difference of two leptons $\cos\theta_{ll} = \tanh(\Delta\eta_{ll}/2)$ allows to discriminate between signal hypotheses

[UH, Pani & Polesello, 1611.09841]

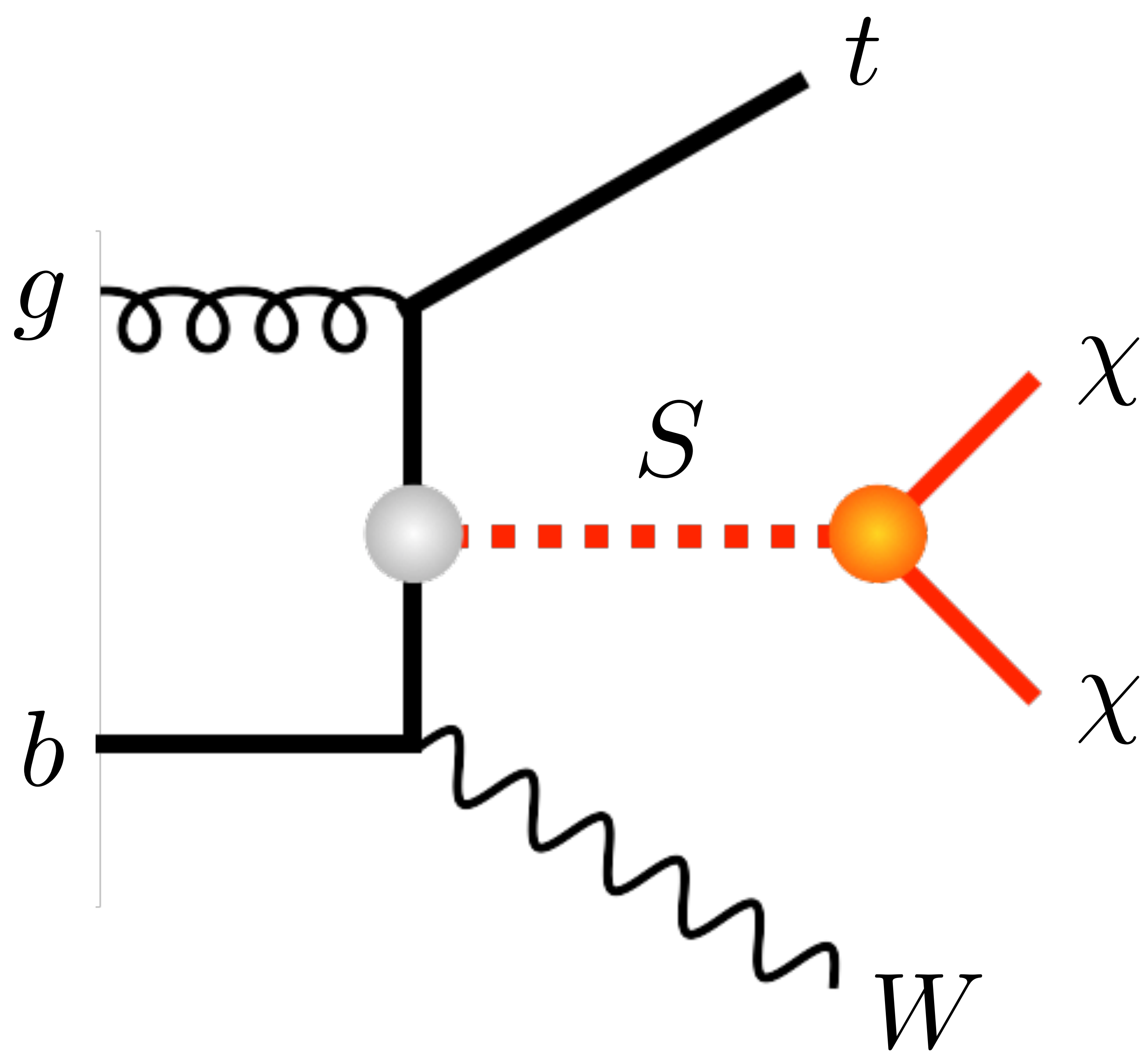
tW+$E_{T,\mathrm{miss}}$: simplified spin-0 DM model

SM Yukawa coupling

$$\mathcal{L}_S \supset g_{\mathrm{SM}} \sum_q \frac{y_q}{\sqrt{2}} \bar{q} q S + g_{\mathrm{DM}} \bar{\chi} \chi S$$

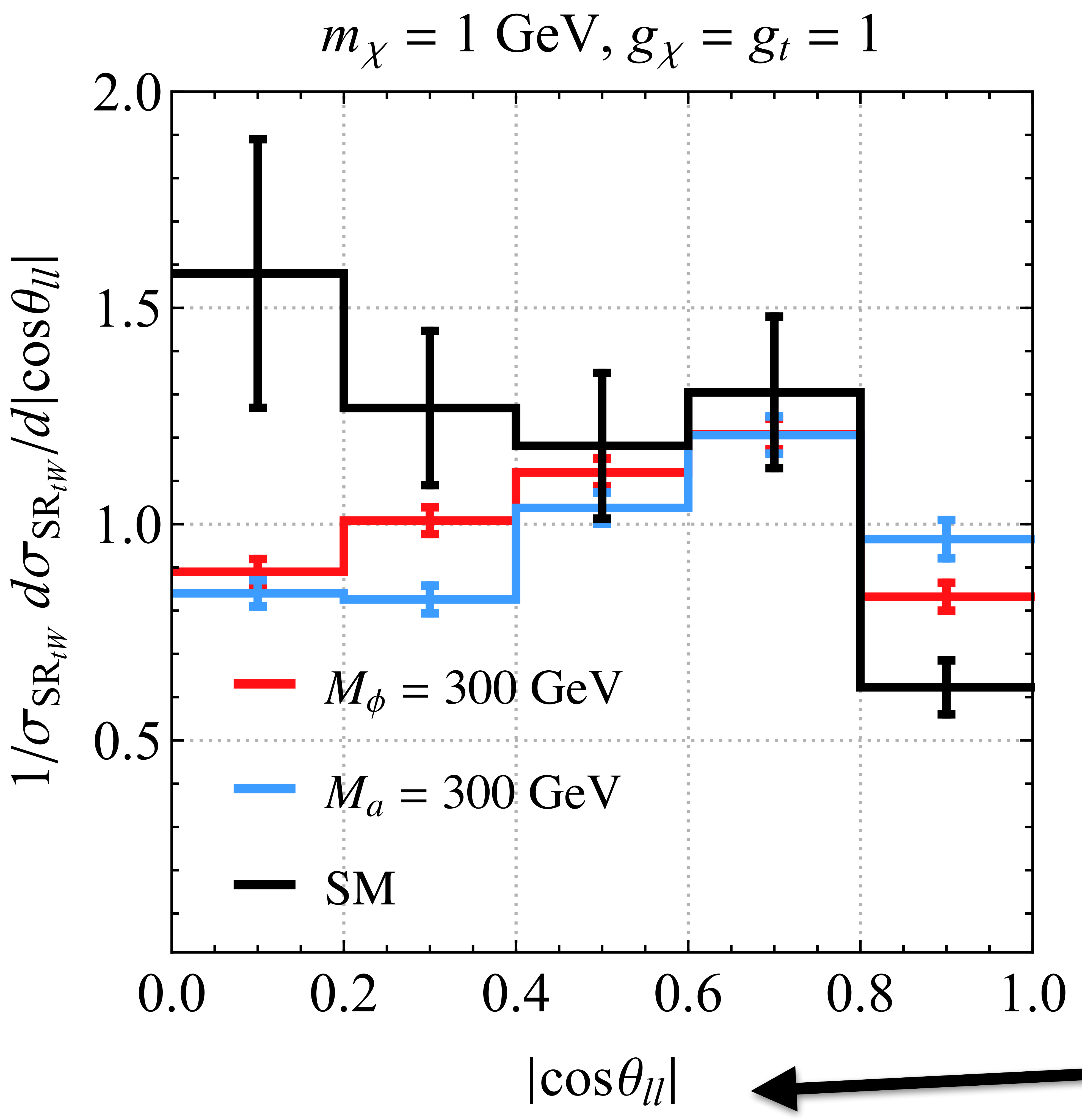
Dirac DM candidate

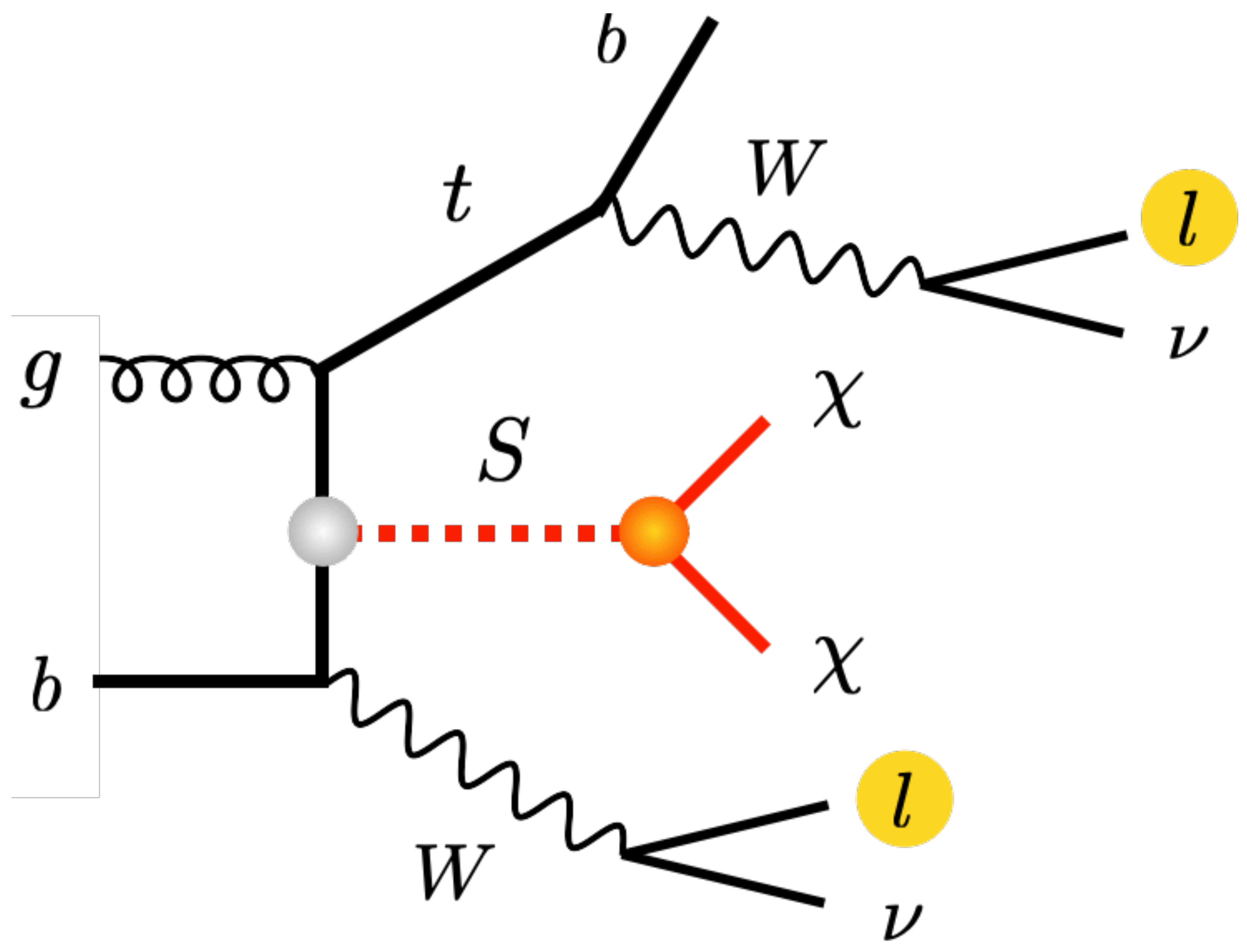
scalar (or pseudoscalar) mediator



[see Pinna et al., 1701.05195; Plehn, Thompson & Westhoff, 1712.08065 for first studies]

tW+$E_{T,miss}$: signal discrimination

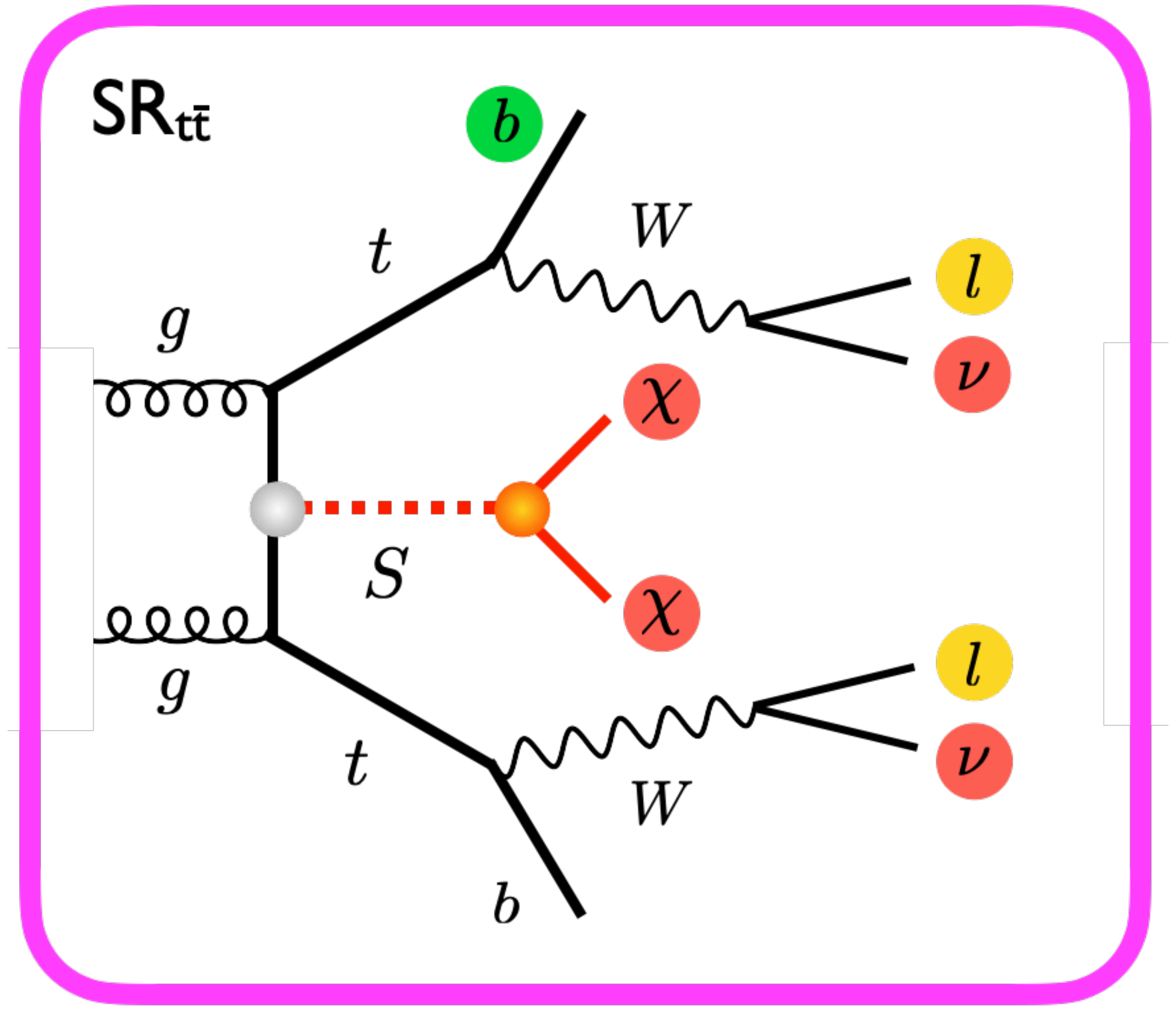


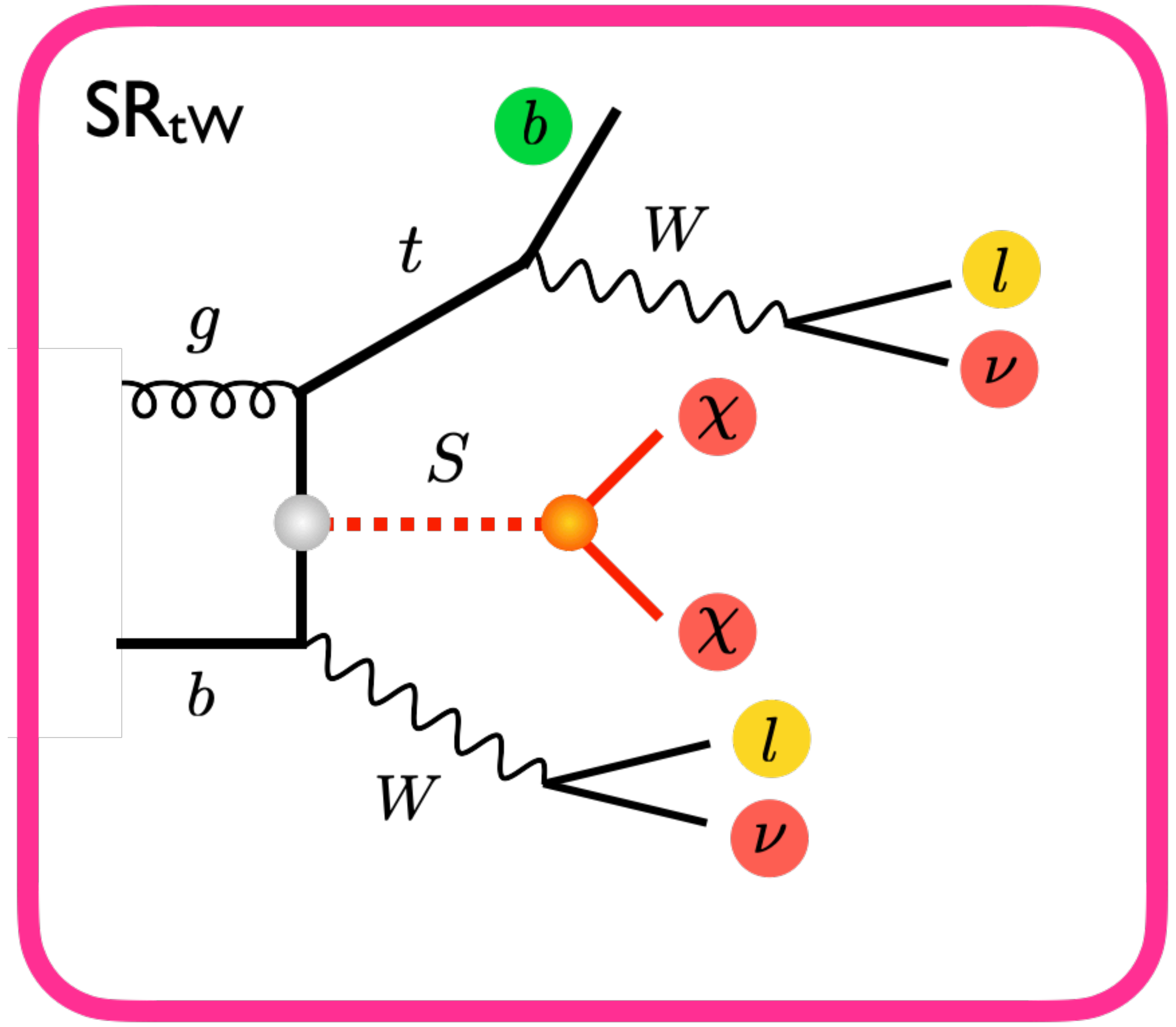


Angular correlations of leptons again allow to discriminate between signal hypotheses

[UH & Polesello, 1812.00694]

Combined tX+$E_{T,miss}$ search strategy





2lb+$E_{T,miss}$ final state receives contributions from $t\bar{t}$+$E_{T,miss}$ & tW+$E_{T,miss}$ channel.

To enhance sensitivity of search, design two signal regions $SR_{t\bar{t}}$ & SR_{tW} that target different production mechanisms

[UH & Polesello, 1812.00694]

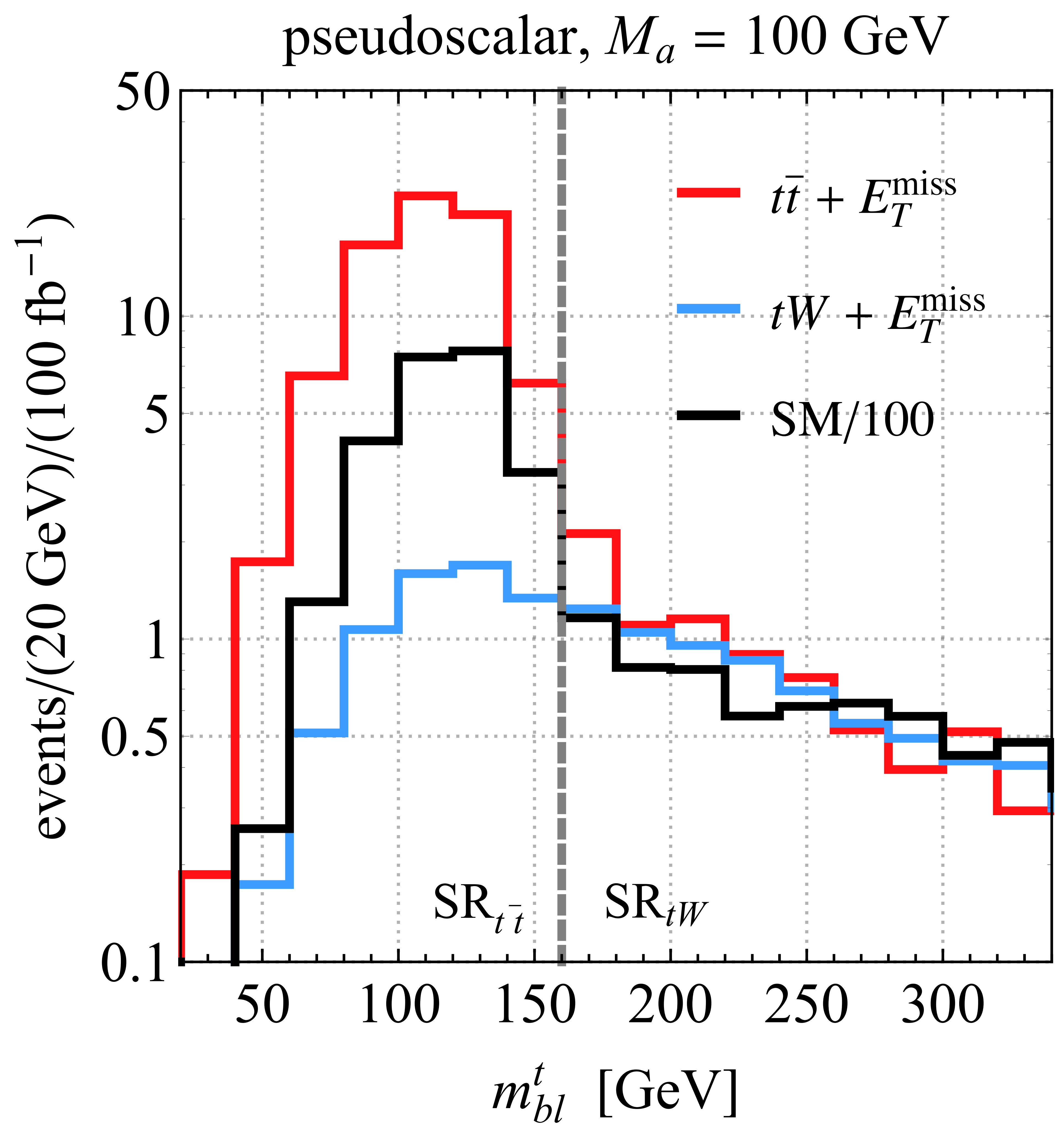
Combined tX+$E_{T,miss}$ search strategy

- Invariant mass of b-jet in semi-leptonic top decay bounded by:

$$\sqrt{m_t^2 - m_W^2} \simeq 153\,\mathrm{GeV}$$

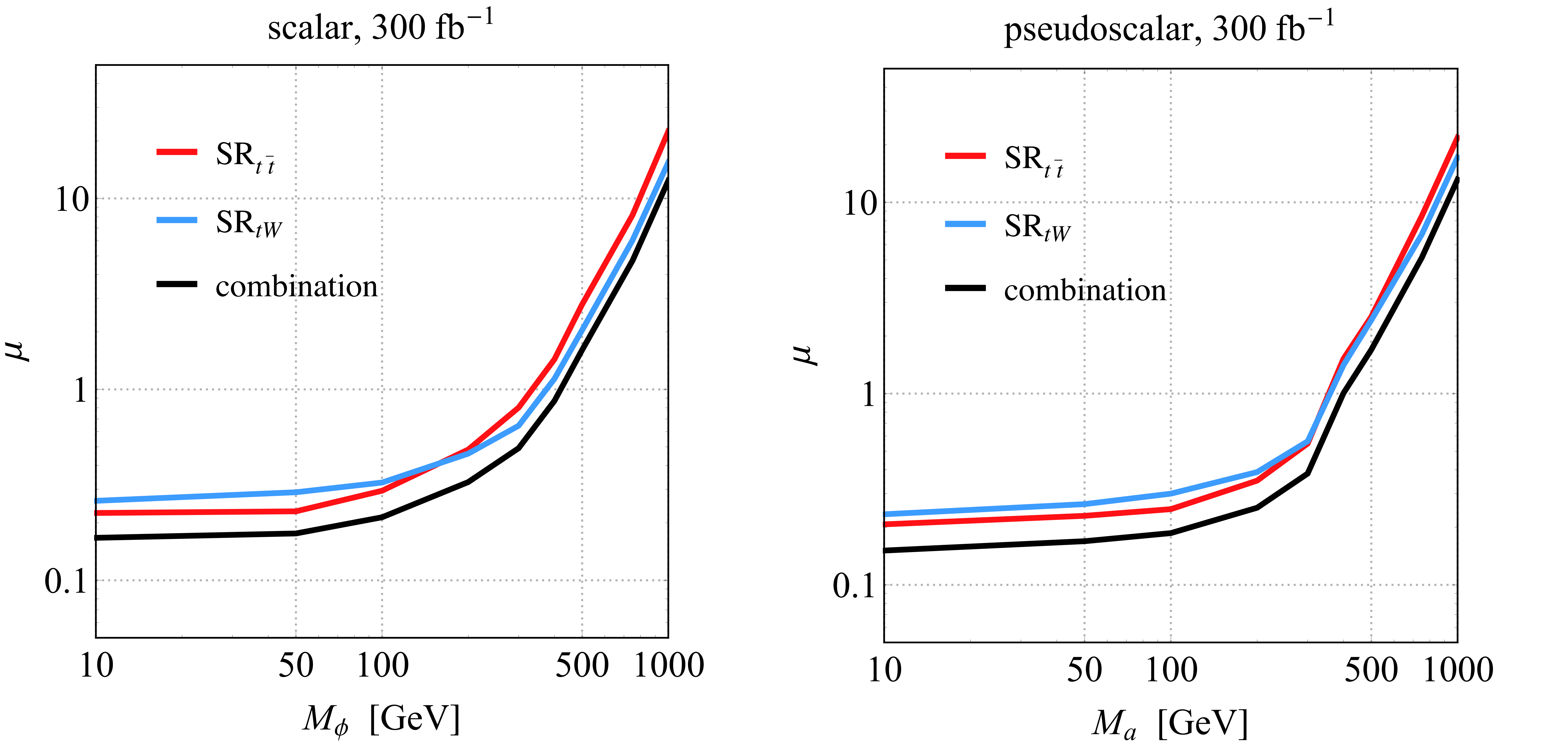
- Events compatible with two semi-leptonic top decays can hence be selected by using:

$$m_{bl}^t = \min\left(\max\left(m_{l_1 j_a}, m_{l_2 j_b}\right)\right)$$



[UH & Polesello, 1812.00694]

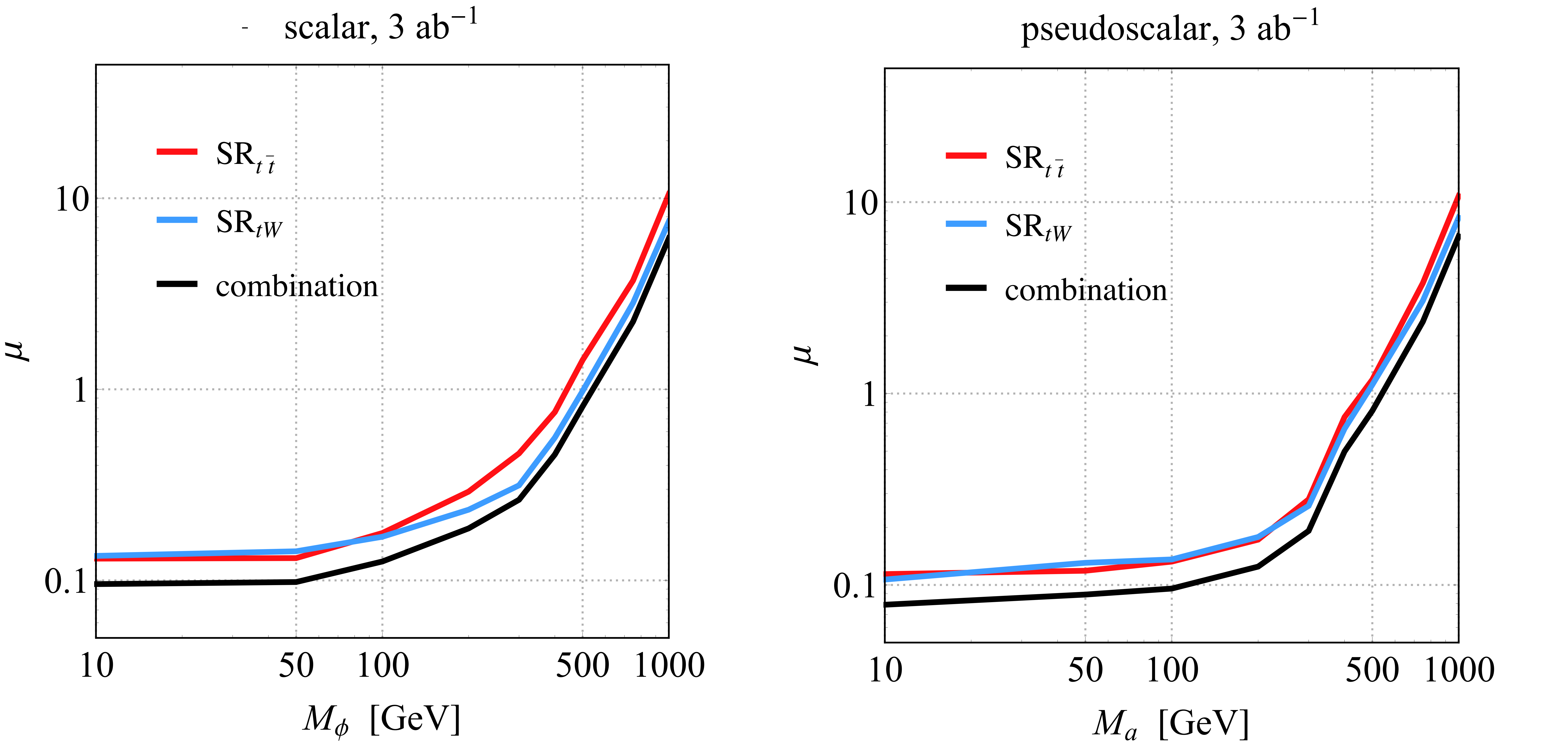
tX+$E_{T,miss}$ LHC Run 3 projections



Compared to standard SR$_{t\bar{t}}$ search, sensitivity of combined SR$_{t\bar{t}}$ & SR$_{tW}$ analysis higher by around 20% (80%) at low (high) mediator masses

[UH & Polesello, 1812.00694]

$tX+E_{T,miss}$ HL-LHC projections

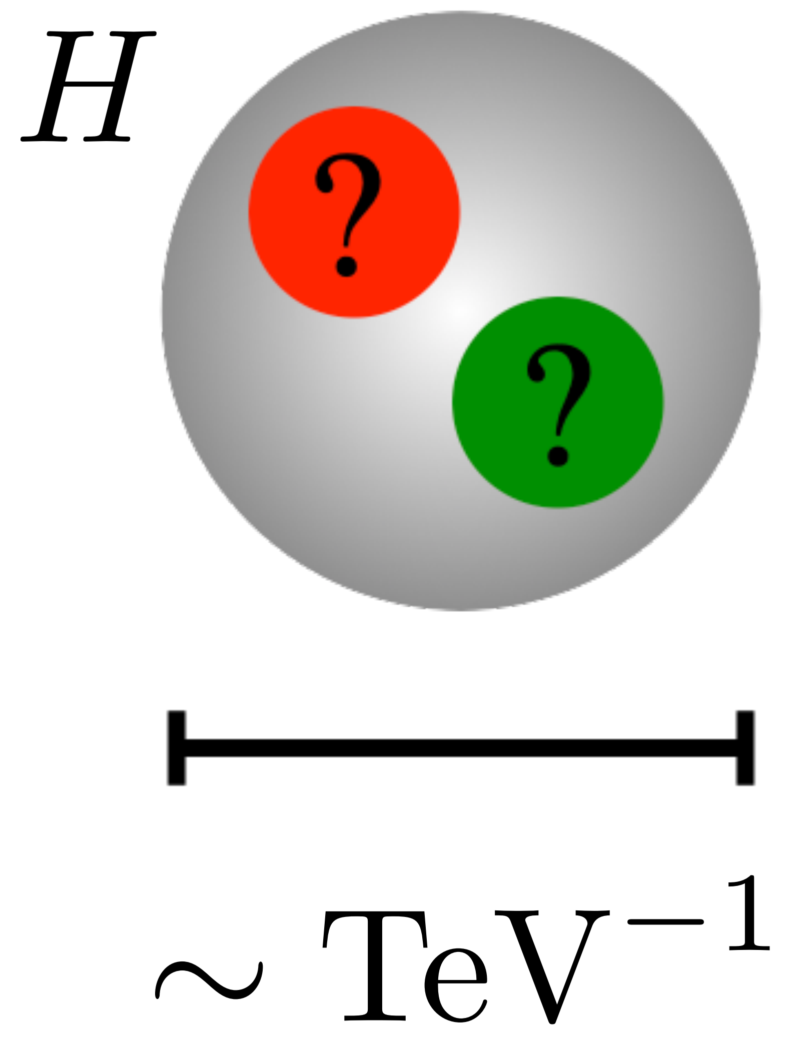


For m_χ = 1 GeV, $g_{SM} = g_{DM} = 1$ & assuming 3 ab^{-1} of 14 TeV LHC data, combined analysis leads to 95% CL limit of around 530 GeV on mediator mass

[UH & Polesello, 1812.00694]

Composite Higgs & DM

- A light elementary scalar is unnatural
- Possible solution is that Higgs is a bound state of a new strong sector. Description of theory changes above confinement scale of O(1 TeV) & Higgs mass is screened
- In analogy to QCD pions, Higgs arises as approximate Nambu-Goldstone boson (pNGB) & remains light
- No reason for Higgs to be alone. In fact, if stable, extra pNGB scalar χ makes attractive DM candidates since light & weakly coupled



[see for instance Agashe, Contino & Pomarol, hep-ph/0412089; Frigerio et al., 1204.2808]

pNGB DM models

Couplings of χ determined by global symmetry & explicit breaking, but at least two relevant interactions:

real scalar DM

SM Higgs doublet

$$Q_d = (\partial_\mu \chi^2)\,(\partial^\mu |H|^2)\ , \qquad Q_m = \chi^2 |H|^2$$

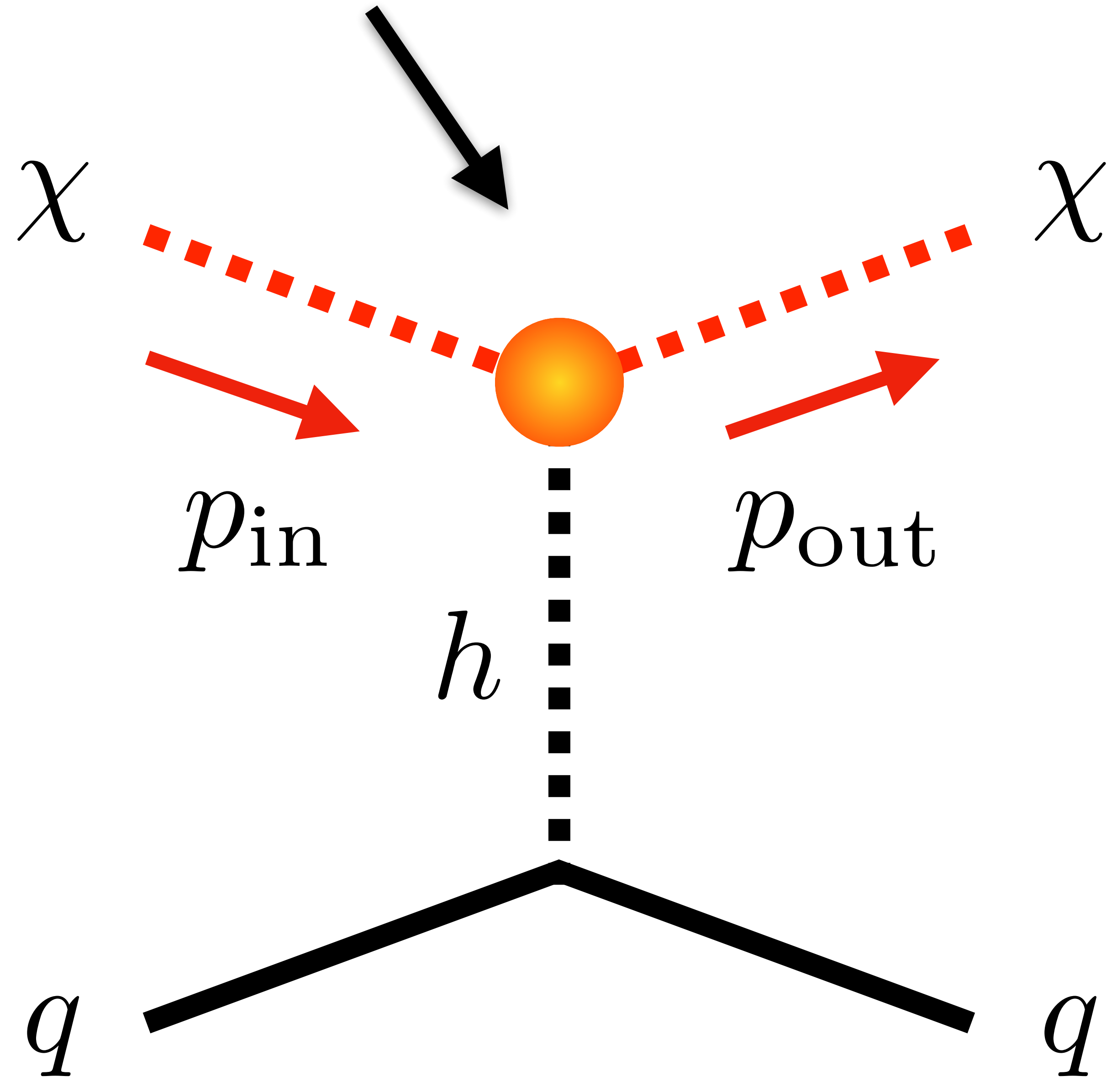
derivative operator:
DM shift symmetric

marginal operator:
breaks DM shift symmetry

[see for example Balkin, Ruhdorfer, Salvioni & Weiler, 1809.09106]

pNGB DM: direct detection bounds

$$\frac{c_d}{\Lambda^2}\left(\partial_\mu \chi^2\right)\left(\partial^\mu |H|^2\right)$$

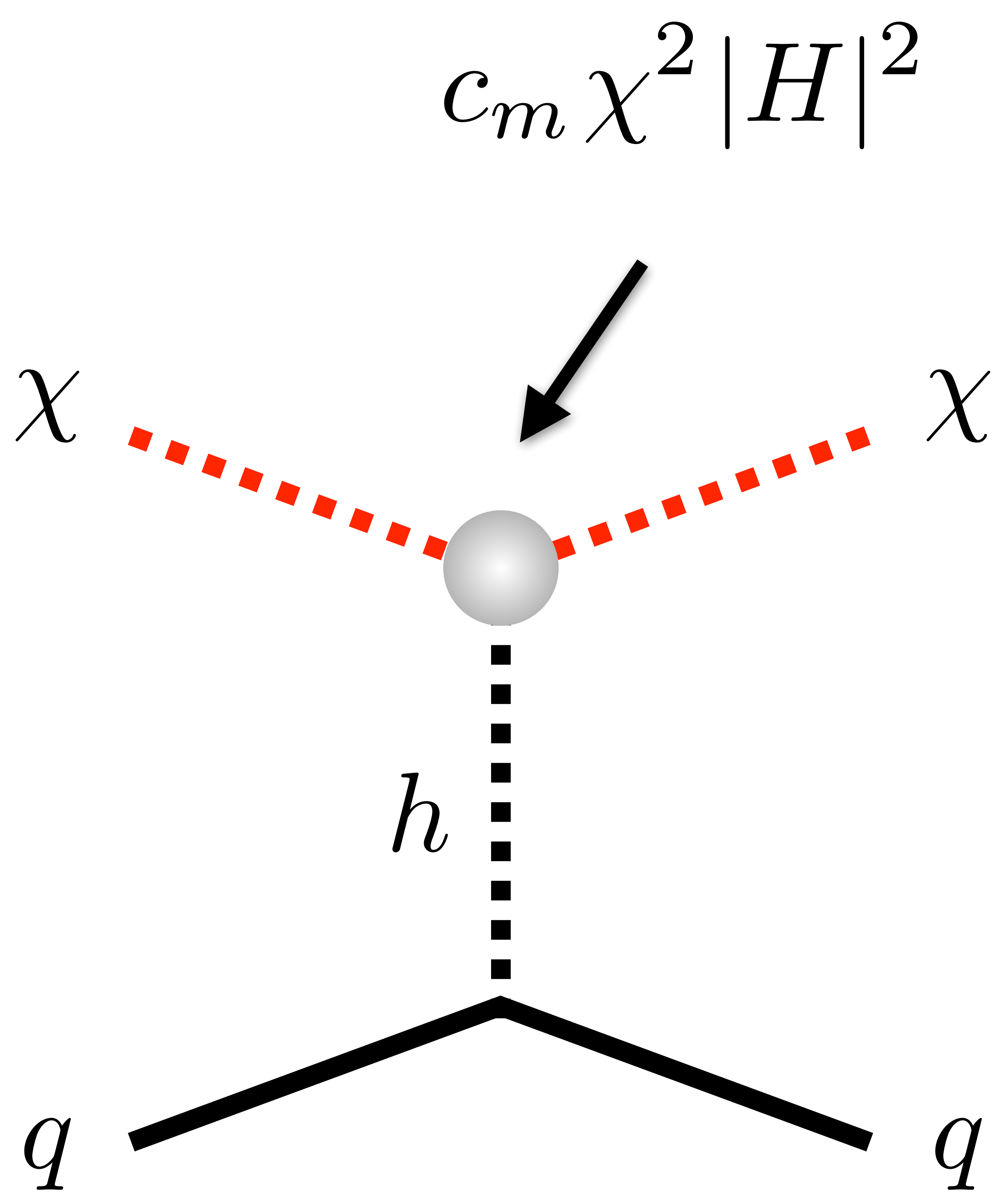


$$\propto \frac{(p_{\rm in} - p_{\rm out})^2}{\Lambda^2} \lesssim \frac{(100\,{\rm MeV})^2}{\Lambda^2}$$

Due to momentum suppression direct detection limits easily avoided for new-physics scales Λ of O(1 TeV)

[see for example Balkin, Ruhdorfer, Salvioni & Weiler, 1809.09106]

pNGB DM: direct detection bounds



$$\sigma_{\rm SI} = \frac{c_m^2 m_N^4 f_N^2}{\pi m_h^4 (m_\chi + m_N)^2}$$

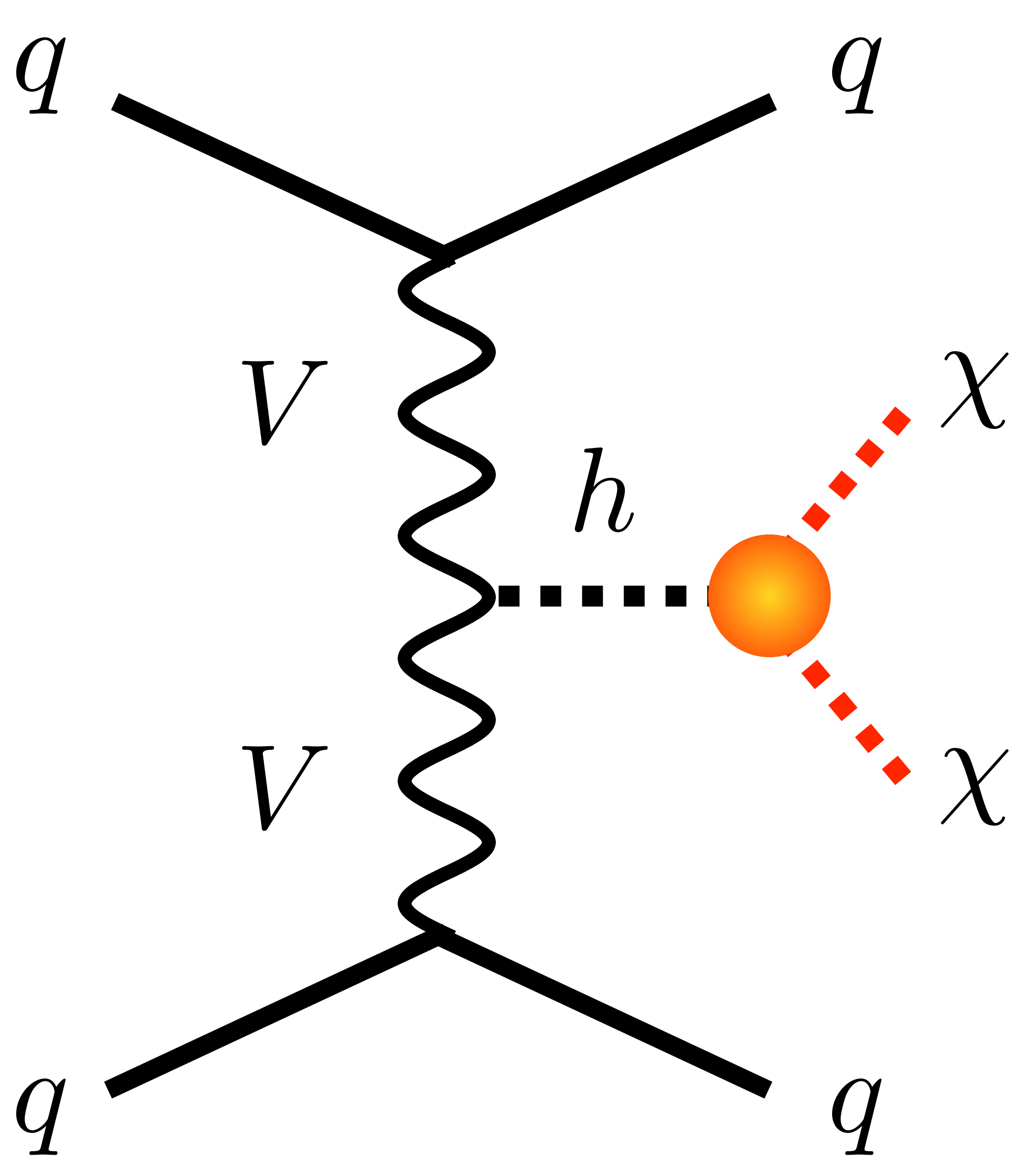
$$\sigma_{\rm SI} \lesssim 9 \cdot 10^{-47}\,{\rm cm}^2 \quad (m_\chi = 100\,{\rm GeV})$$

$$\Rightarrow \quad |c_m| \lesssim 5 \cdot 10^{-3}$$

Derivative portal is only scalar DM-Higgs operator that satisfies constraints from spin-independent (SI) DM-nucleon cross section $\sigma_{\rm SI}$ once loop effects are considered

[UH, Polesello & Schulte, 2107.12389]

pNGB DM: invisible Higgs decays



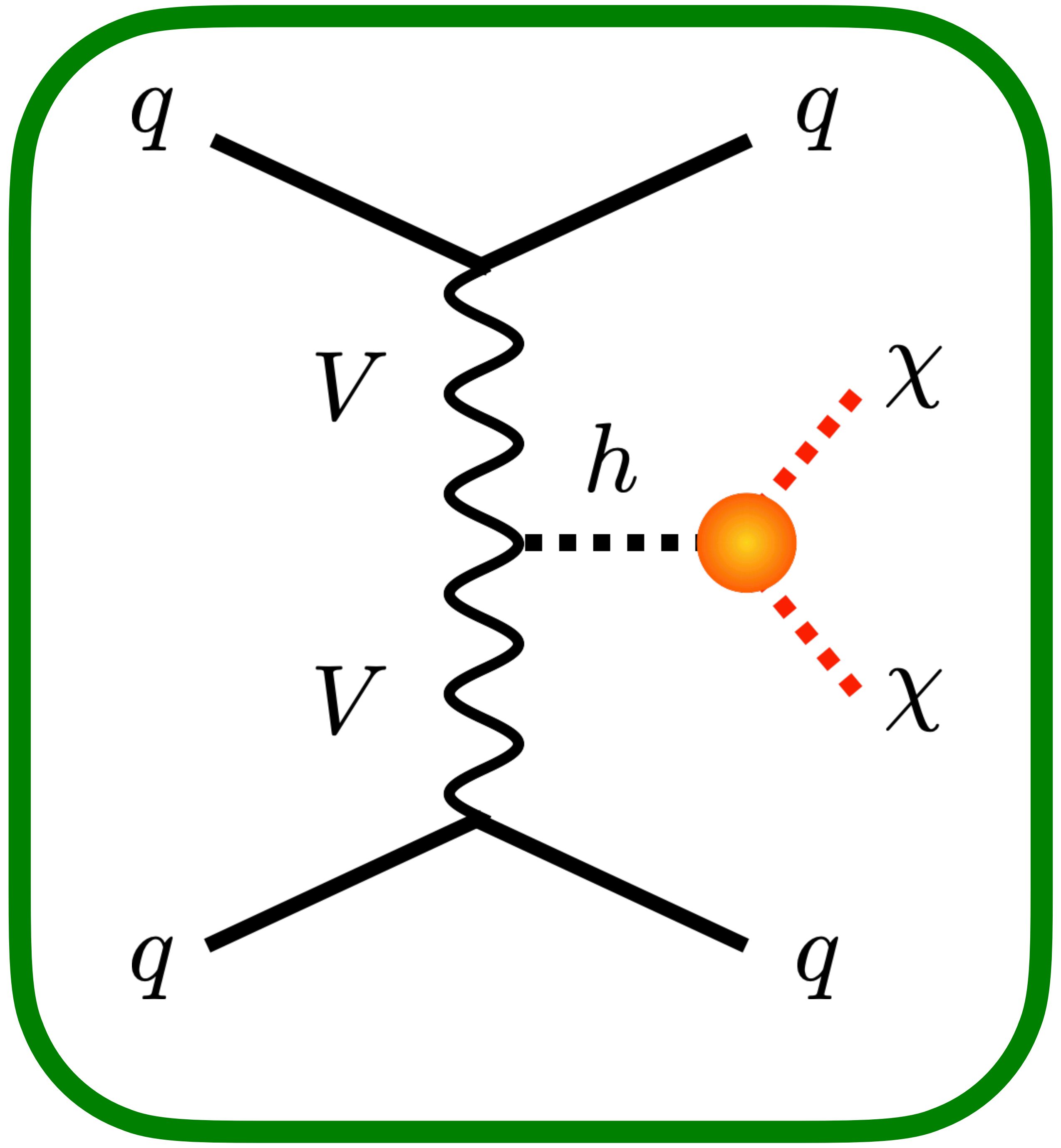
$$\Gamma(h \to \chi\chi) \simeq \frac{v^2}{8\pi m_h} \left(\frac{m_h^2 c_d}{\Lambda^2} + c_m \right)^2$$

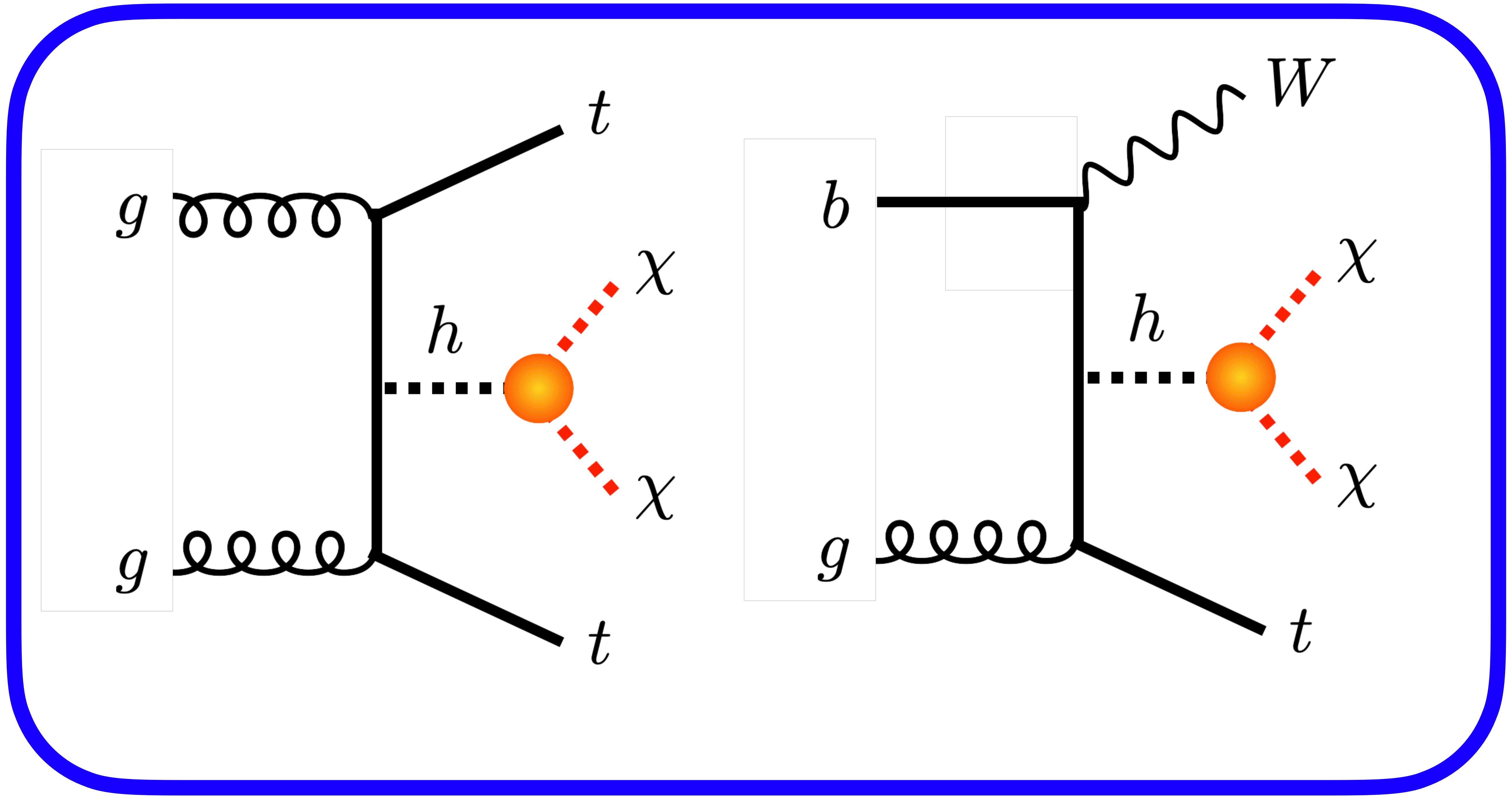
$$\mathrm{BR}\,(h \to \mathrm{inv}) \simeq \frac{\Gamma(h \to \chi\chi)}{4\,\mathrm{MeV}} < 0.11$$

$$\Rightarrow \quad \frac{\Lambda}{\sqrt{c_d}} \gtrsim 1.7\,\mathrm{TeV}\,, \quad |c_m| \lesssim 5 \cdot 10^{-3}$$

[UH, Polesello & Schulte, 2107.12389; ATLAS-CONF-2020-052]

pNGB DM: off-shell DM search strategies



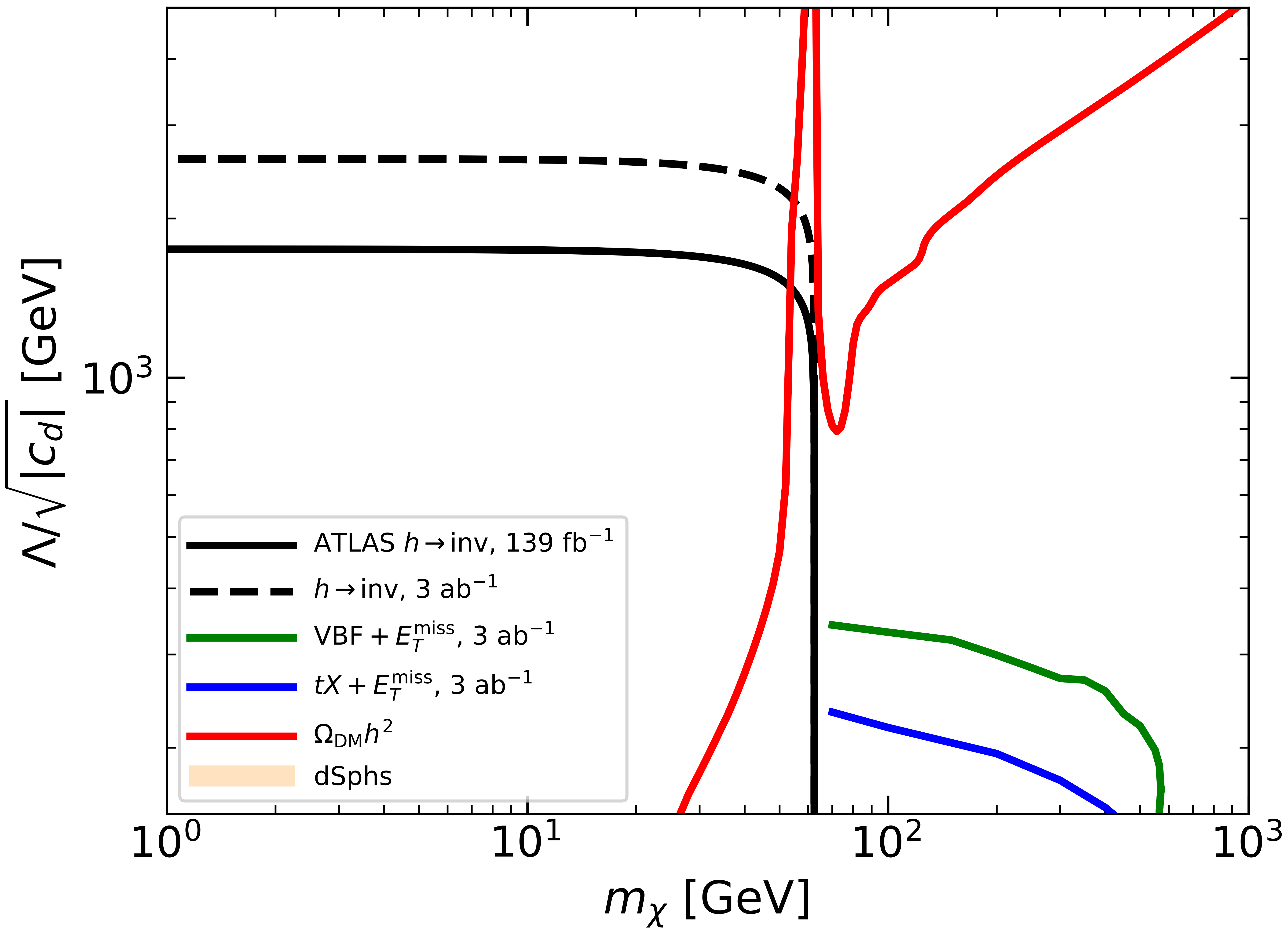


If DM is not kinematically accessible in Higgs decay, can test pNGB DM models in vector-boson fusion (VBF) Higgs production plus $E_{T,miss}$ & in tX+$E_{T,miss}$ channels

[Ruhdorfer, Salvioni & Weiler, 1910.04170; UH, Polesello & Schulte, 2107.12389]

Constraints on derivative operator

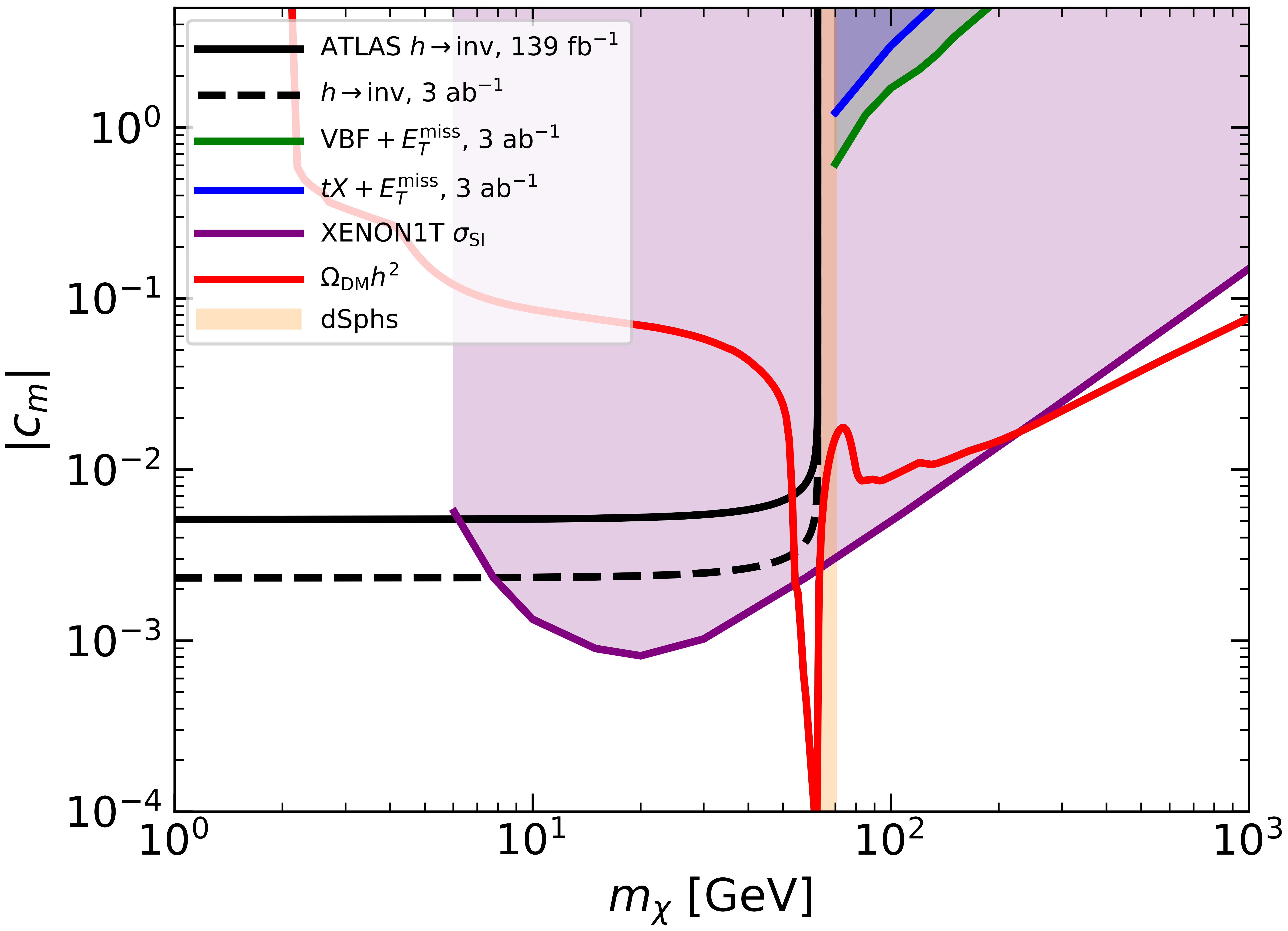
[Agryopoulos, Brandt & UH, 2109.13597]



[Higgs off-shell bounds from Ruhdorfer, Salvioni & Weiler, 1910.04170; UH, Polesello & Schulte, 2107.12389]

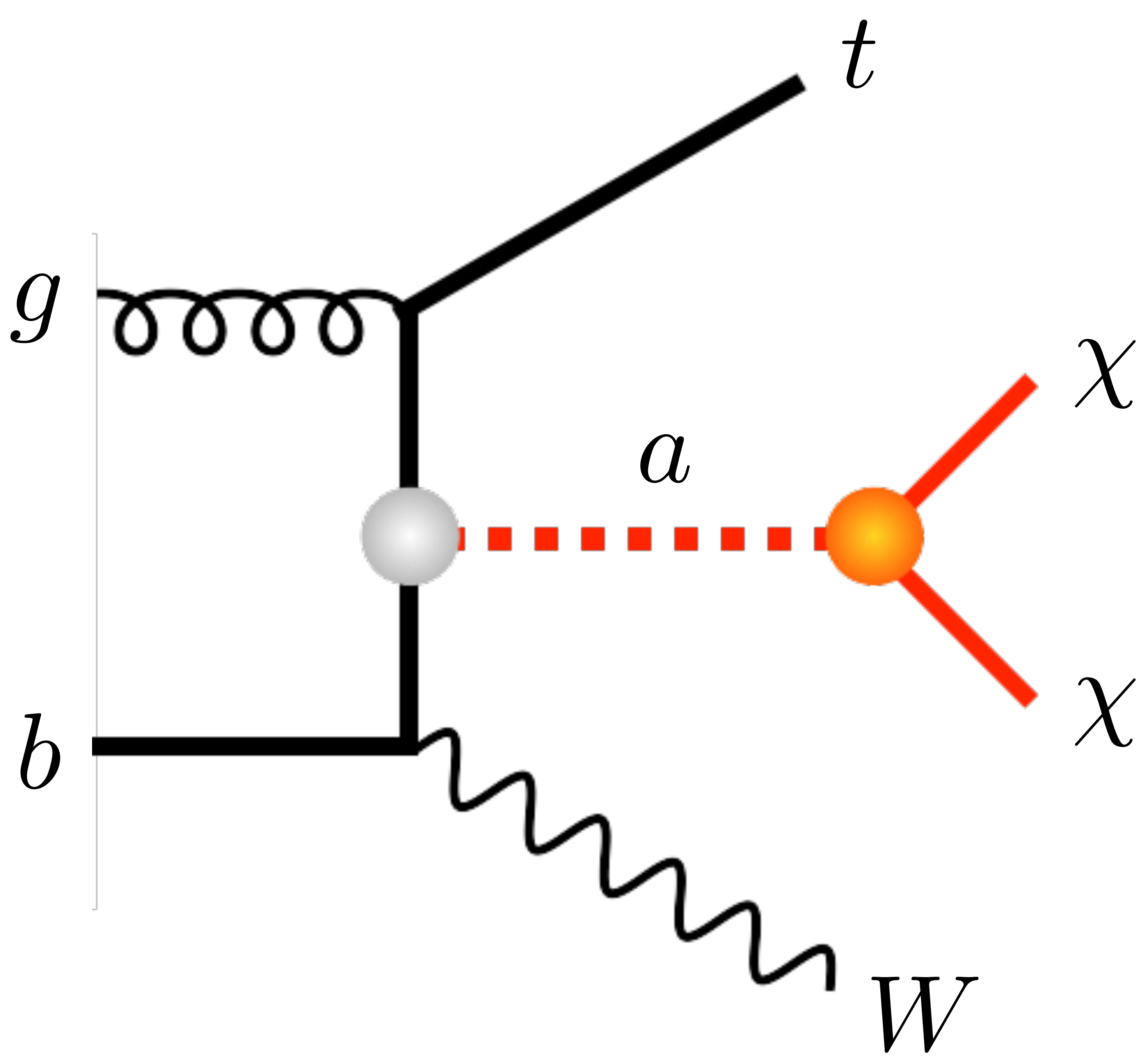
Constraints on marginal operator

[Agryopoulos, Brandt & UH, 2109.13597]



[Higgs off-shell bounds from Ruhdorfer, Salvioni & Weiler, 1910.04170; UH, Polesello & Schulte, 2107.12389]

Unitarity considerations

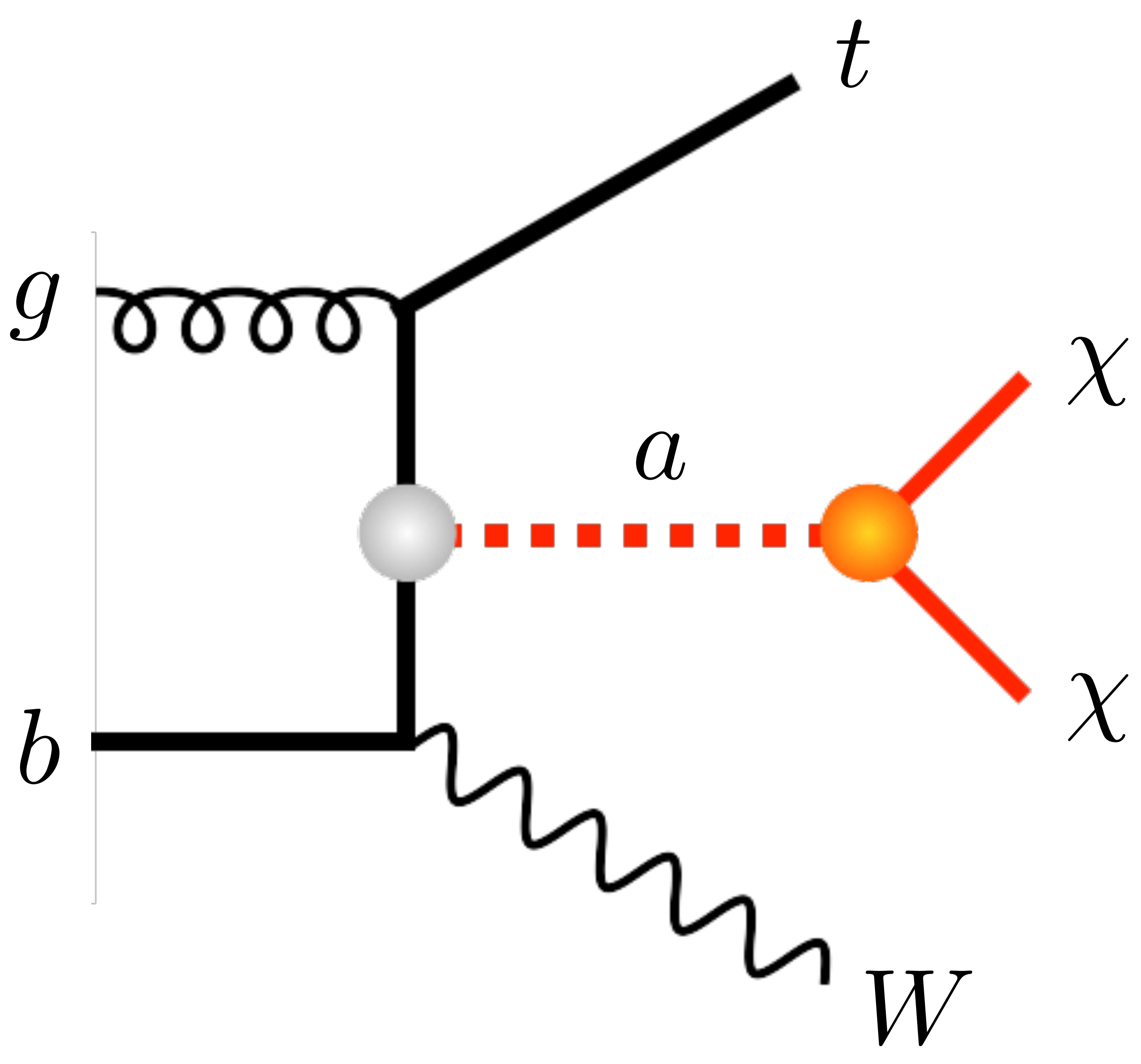


$$\sim \quad y_t \, g_{\rm SM} \, s^{1/2}$$

Unitarity violation small unless g_{SM} large and/or $s^{1/2} \gg 14$ TeV, but …

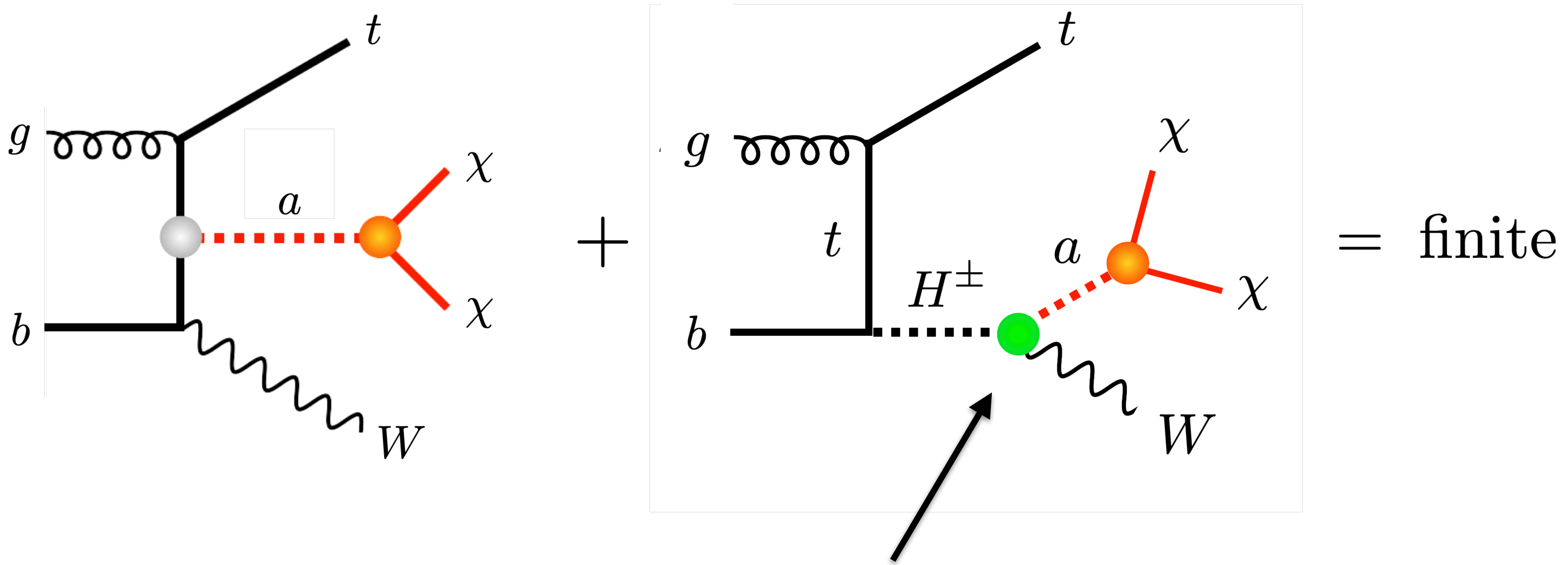
[see for instance Maltoni et al., hep-ph/0106293; Farina et al., 1211.3736; UH & Polesello, 1812.00694]

still can ask …



$$+\ ?\ =\ \text{finite}$$

One possible solution



A $aH^{\pm}W$ coupling only exists in models that feature an extended Higgs sector

2HDM+a model

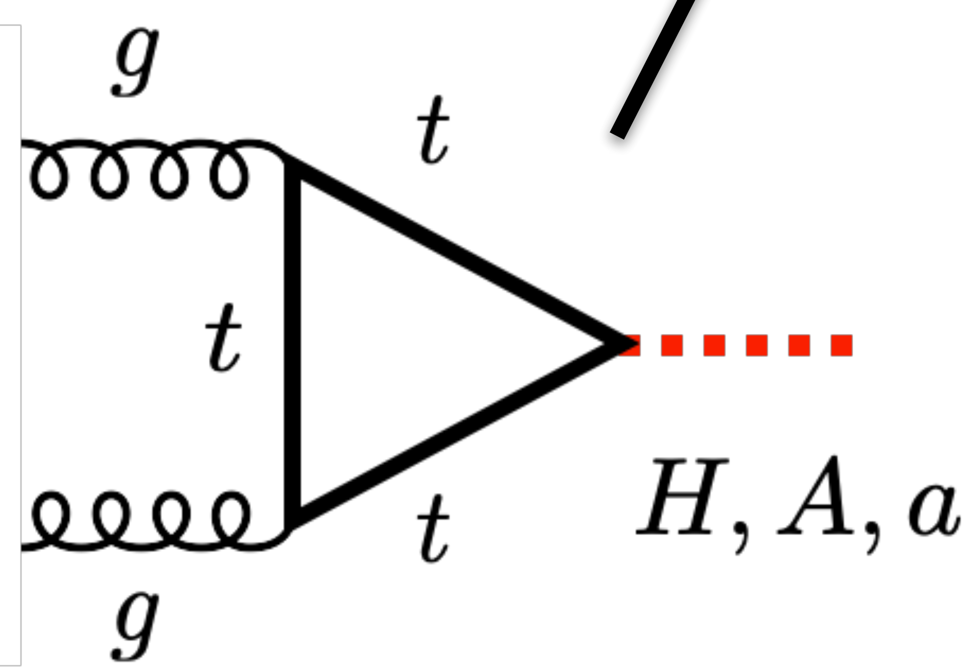
$$\mathcal{L} \supset -\bar{Q}Y_u\tilde{H}_2 d_R + \bar{Q}Y_d H_1 u_R - ib_P P H_1^\dagger H_2 - iy_\chi P\bar{\chi}\gamma_5\chi + \text{h.c.}$$

$$\text{states: } h, H, A, H^\pm, a$$

h is SM-like for cos(β-α) ≃ 0

mostly P for small θ

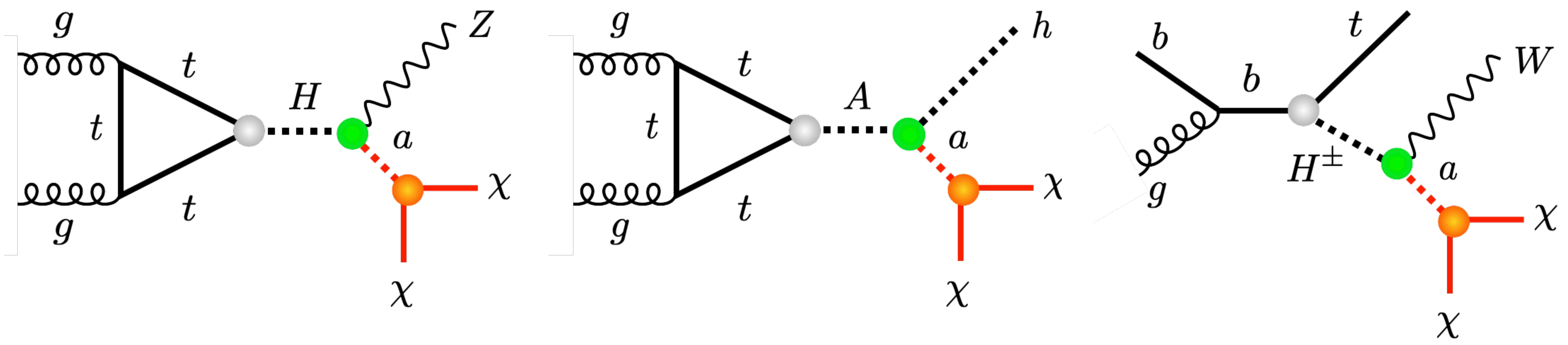
$$\text{angles: } \alpha, \beta, \theta$$



$$\propto \frac{1}{\tan\beta}$$

[Ipek et al. 1404.3716; No, 1509.01110; Goncalves et al., 1611.04593; Bauer et al., 1701.07427]

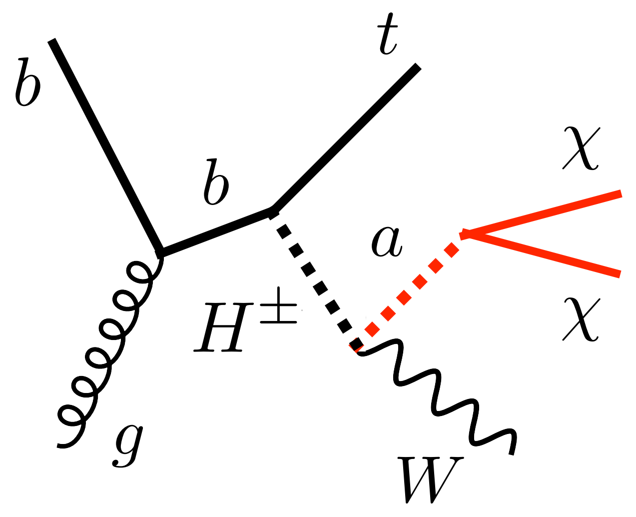
2HDM+a model: resonant $E_{T,miss}$ signatures

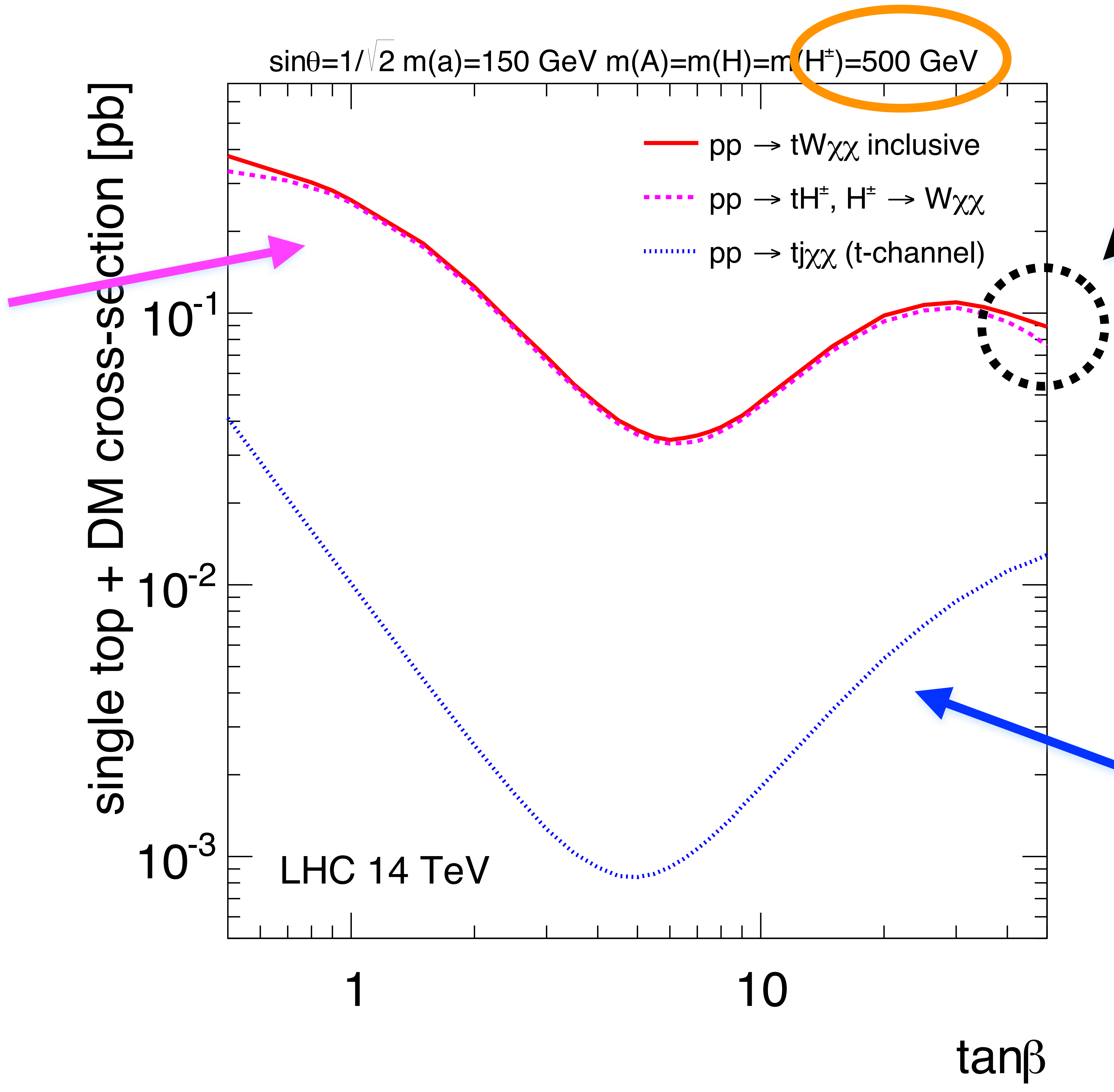


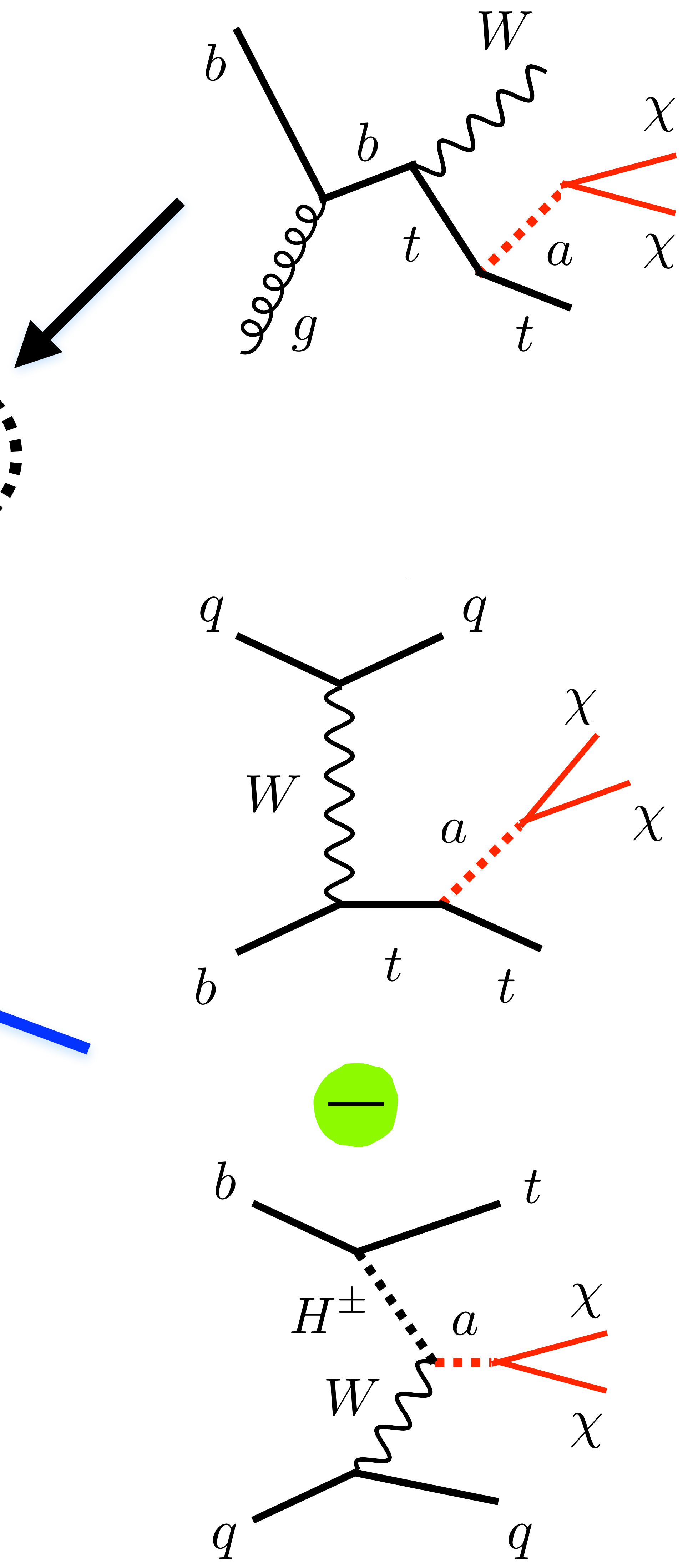
Mono-Z, mono-Higgs & tW+$E_{T,miss}$ channels are subleading in simplified spin-0 DM models. In 2HDM+a model, presence of H, A, & $H^{\pm}$ allows for resonant production of these mono-X signatures

[Goncalves et al., 1611.04593; Bauer et al., 1701.07427; Pani & Polesello, 1712.03874]

2HDM+a model: single-t plus $E_{T,miss}$

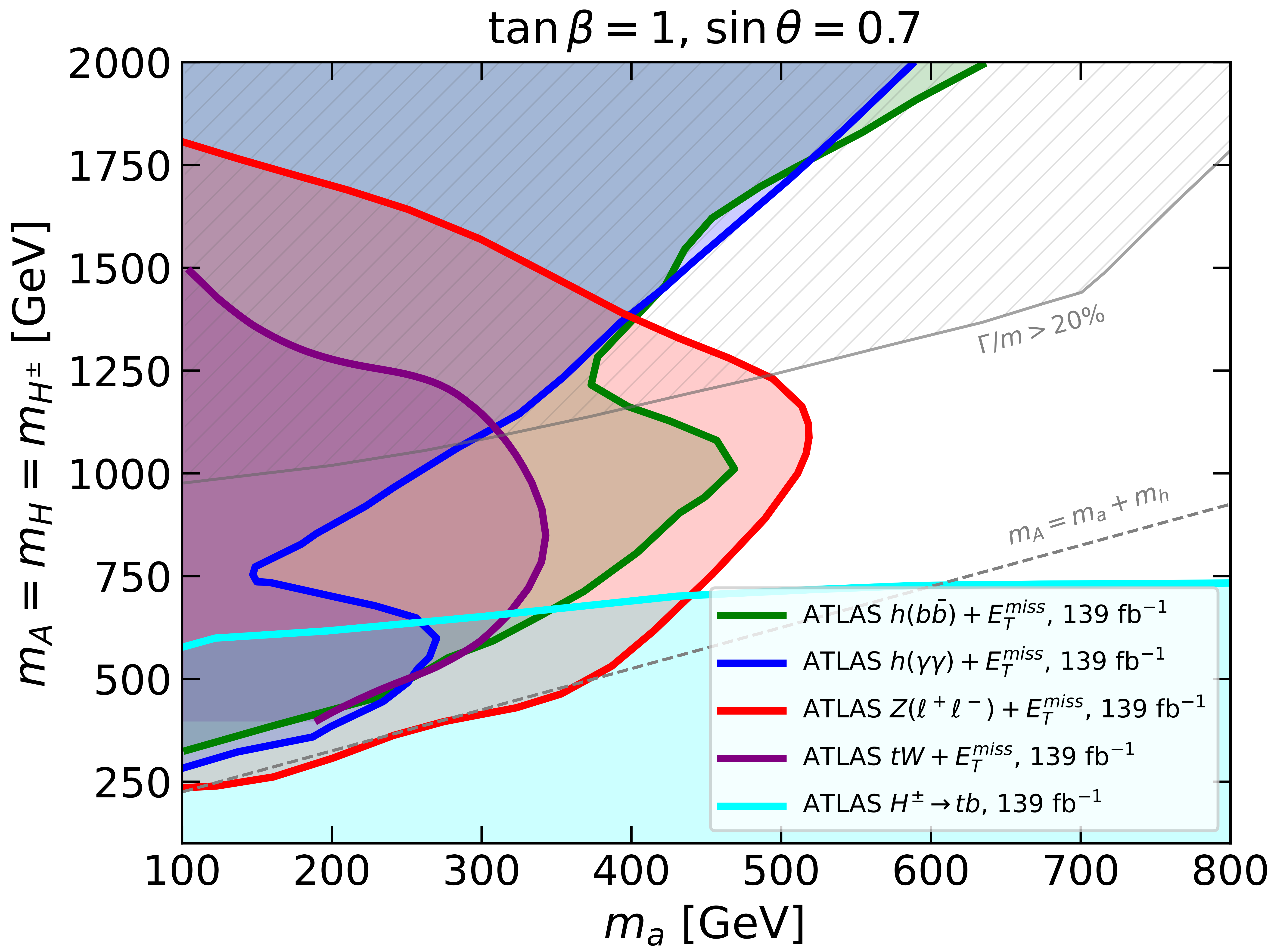






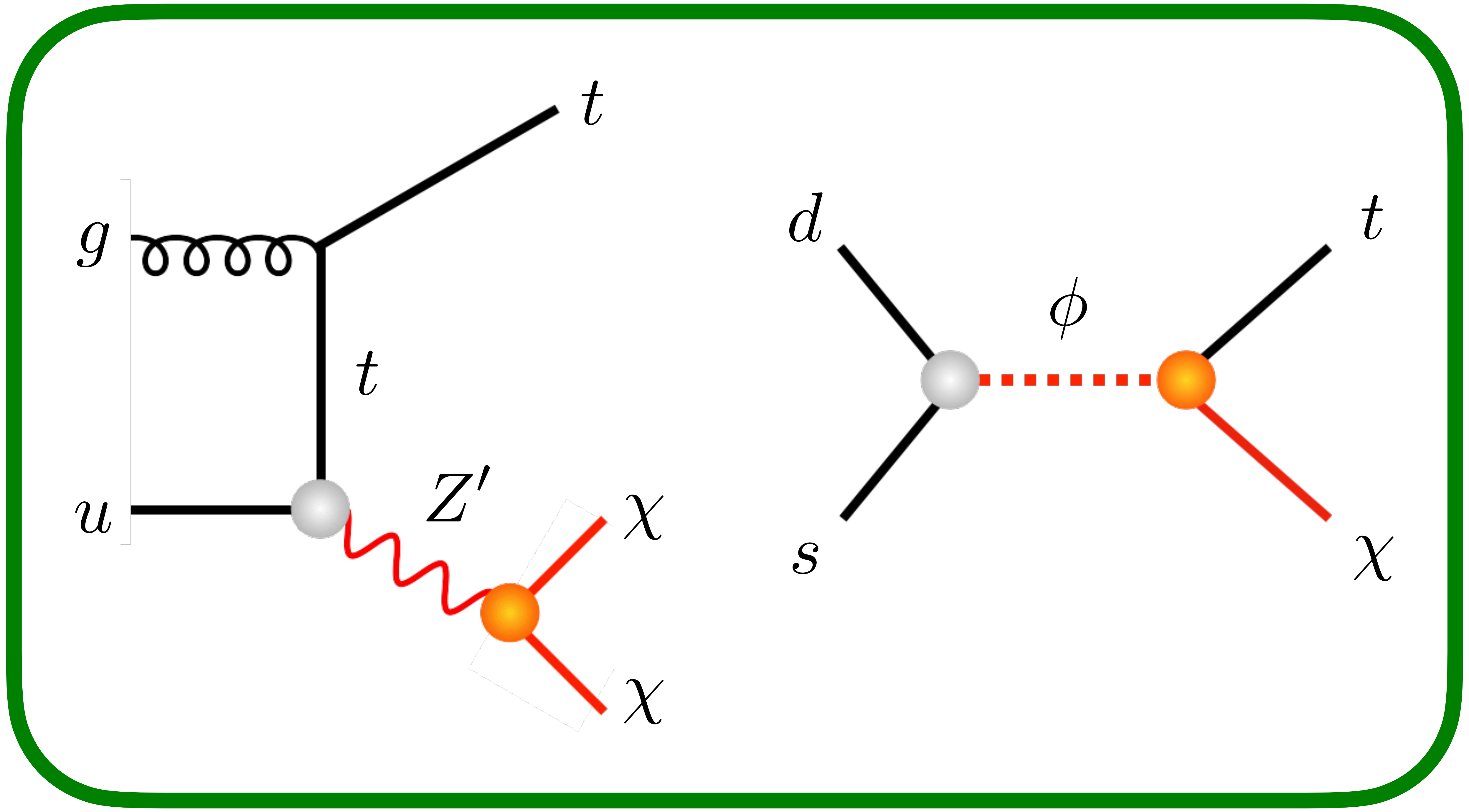
[Pani & Polesello, 1712.03874]

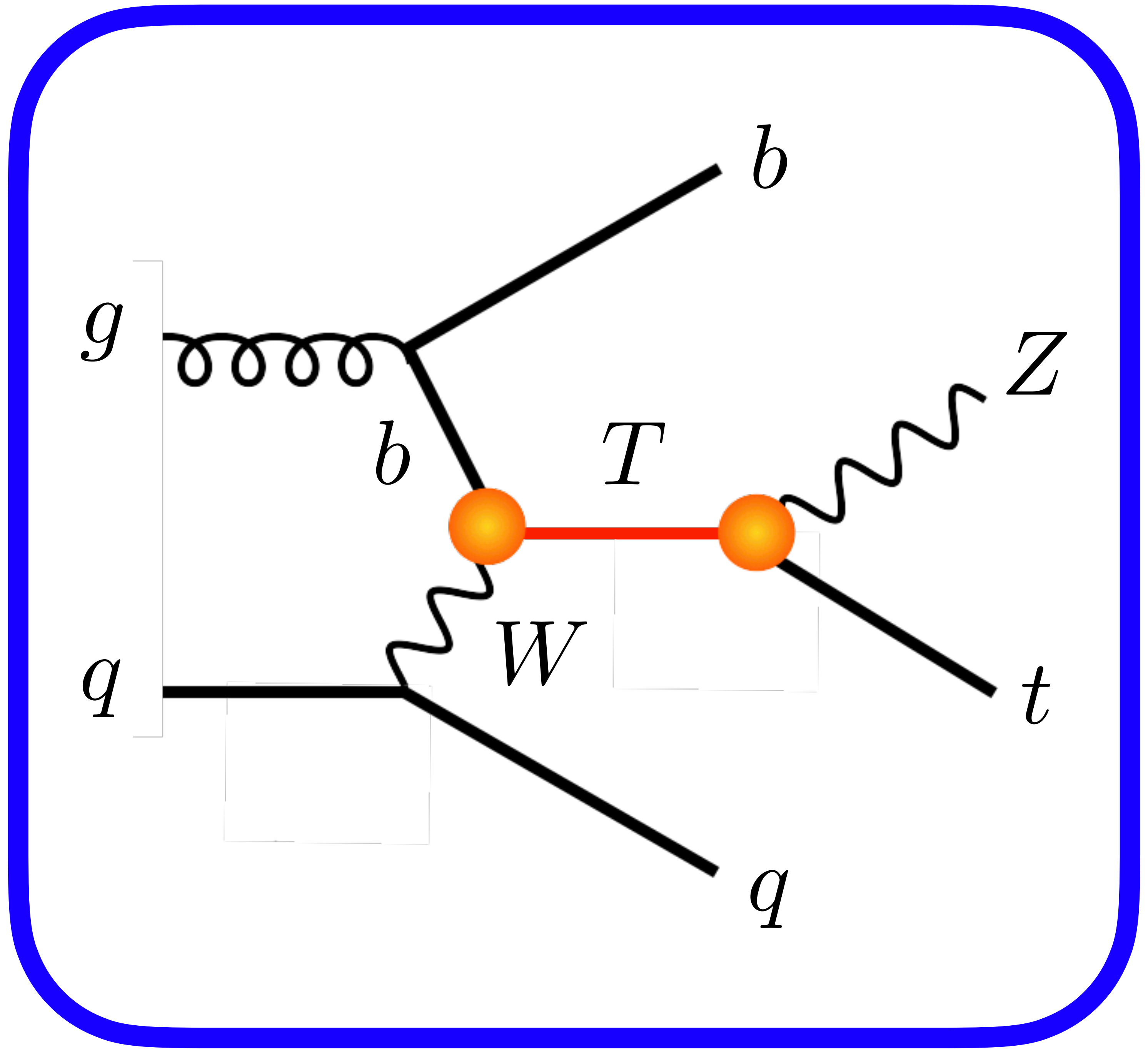
Constraints on 2HDM+a model



[Agryopoulos, Brandt & UH, 2109.13597]

Models with mono-top signatures





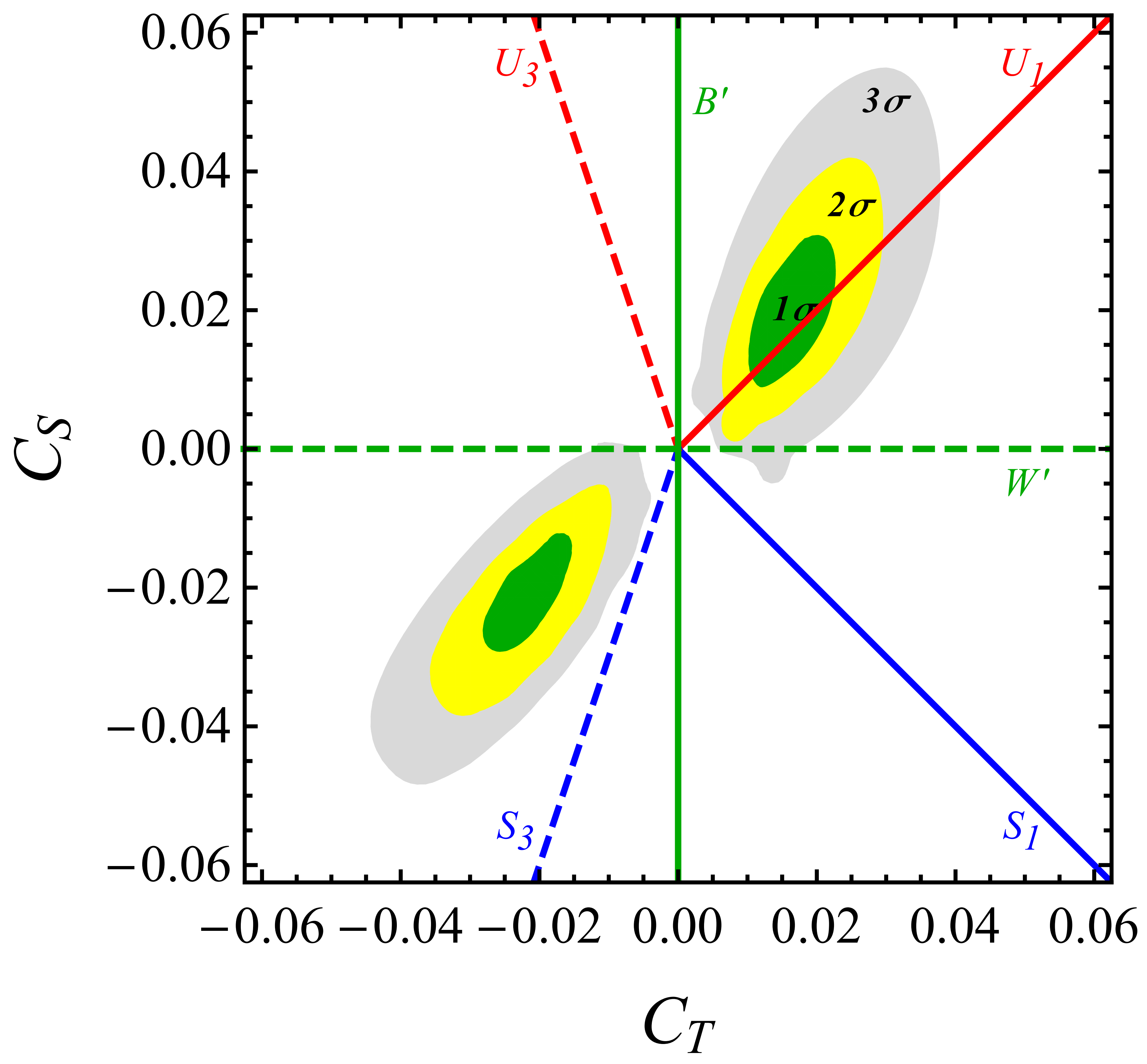
DM models with flavour-changing vector or scalar interactions

Models with vector-like top-quark partners without DM candidate

[see for example Andrea, Fuks & Maltoni, 1106.6199; Aguilar Saavedra et al., 1306.0572]

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



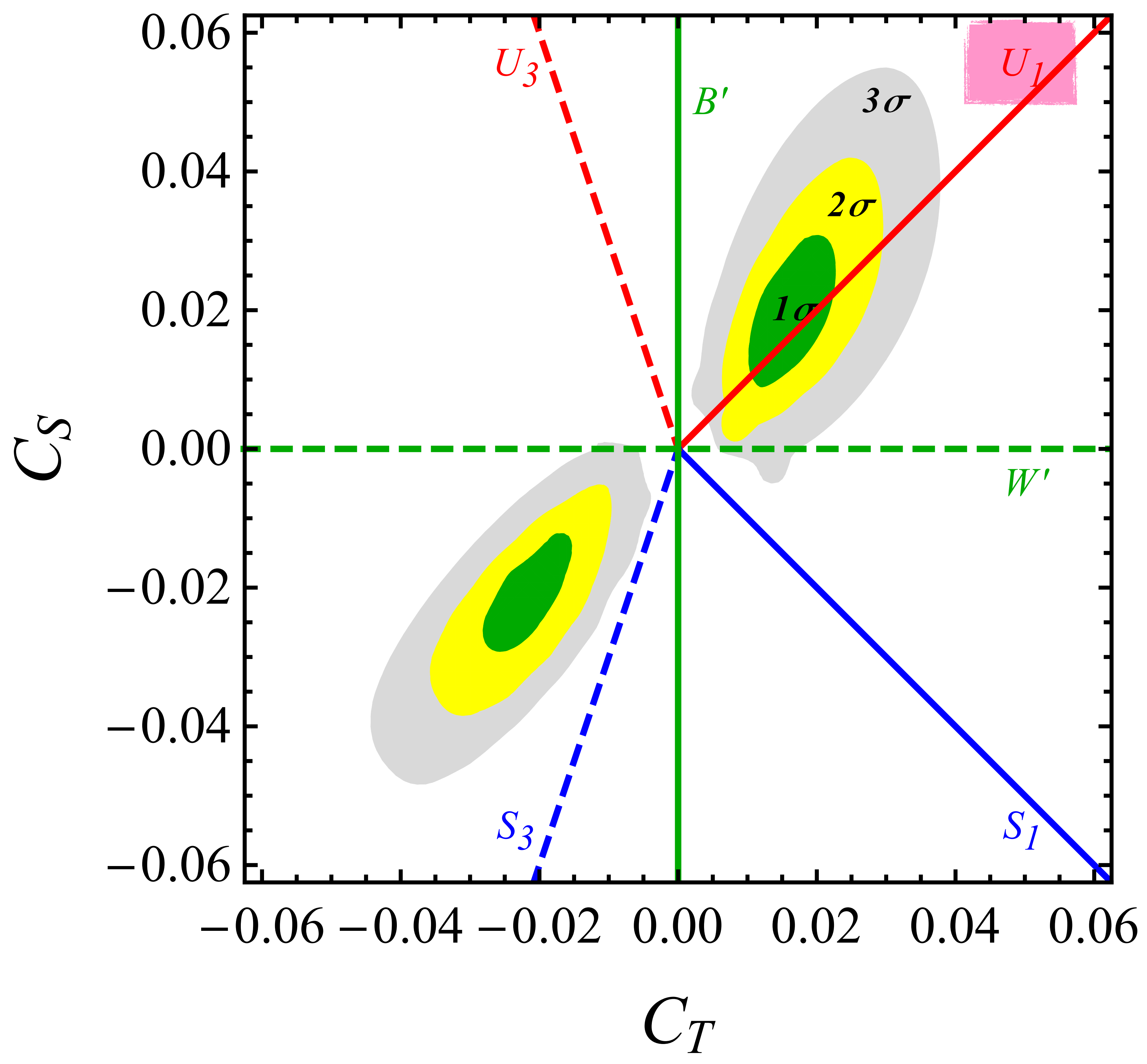
Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

b→s (b→c) anomalies alone can be accommodated by several simple single-mediator models

[see for instance Buttazzo, Greljo, Isidori & Marzocca, 1706.07808]

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

U1 singlet vector leptoquark (LQ) is only single-mediator model that can explain both sets of anomalies

[see for instance Buttazzo, Greljo, Isidori & Marzocca, 1706.07808]

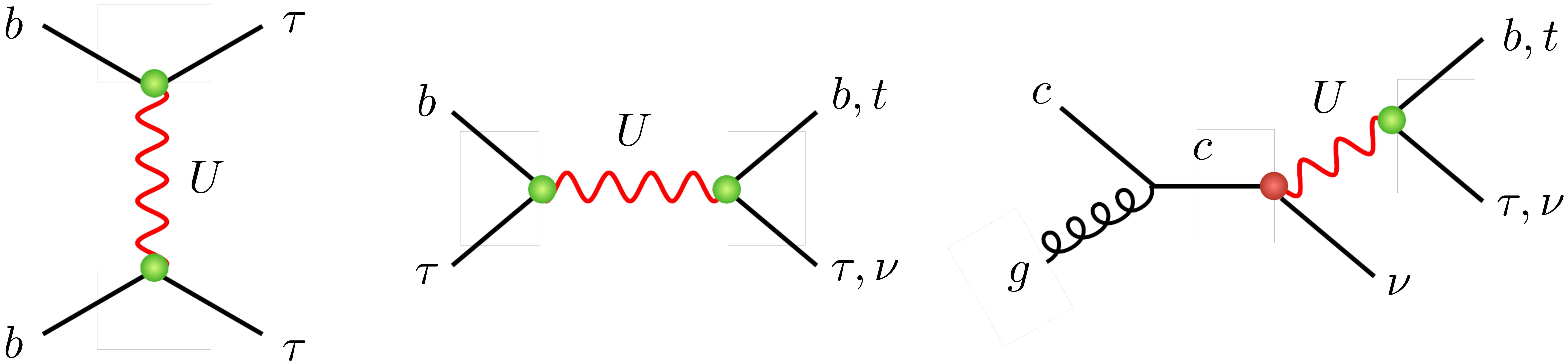
Vector leptoquark (LQ) model for B anomalies

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \left[\beta_L^{ij}\, \bar{Q}_L^{i,a} \gamma_\mu L_L^j + \beta_R^{ij}\, \bar{d}_R^{i,a} \gamma_\mu \ell_R^j \right] U^{\mu,a} + \text{h.c.}\,,$$

$$|\beta_L^{22}| \lesssim |\beta_L^{32}| \ll |\beta_L^{23}| \lesssim |\beta_L^{33}| = \mathcal{O}(1)$$

Parameters		Branching ratios			
β_L^{33}	β_L^{23}	$\text{BR}\,(U \to b\tau^+)$	$\text{BR}\,(U \to t\bar{\nu}_\tau)$	$\text{BR}\,(U \to s\tau^+)$	$\text{BR}\,(U \to c\bar{\nu}_\tau)$
1	0	51%	49%	0%	0%
1	1	25%	22%	25%	27%

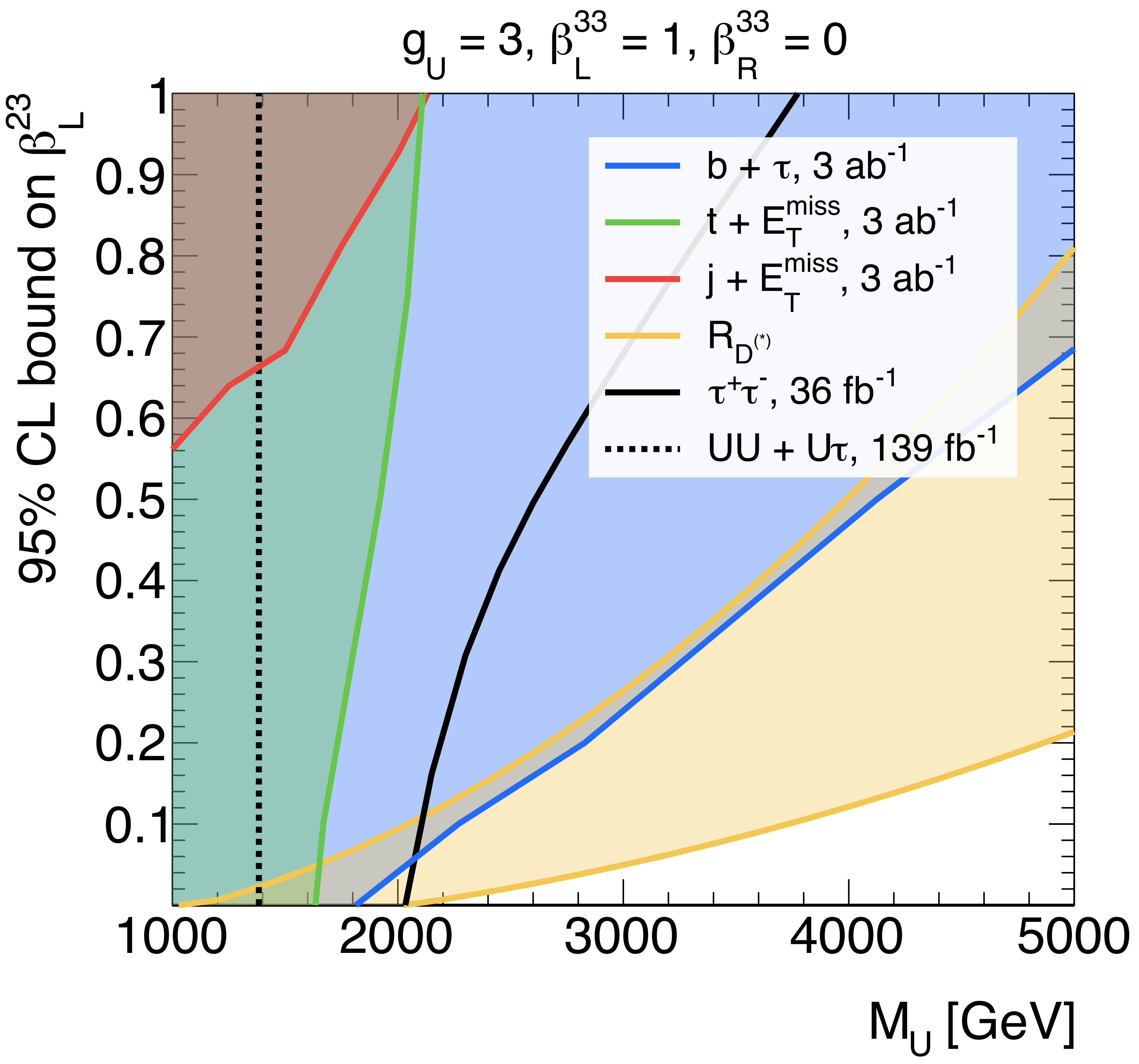
3rd generation vector LQ: LHC signatures

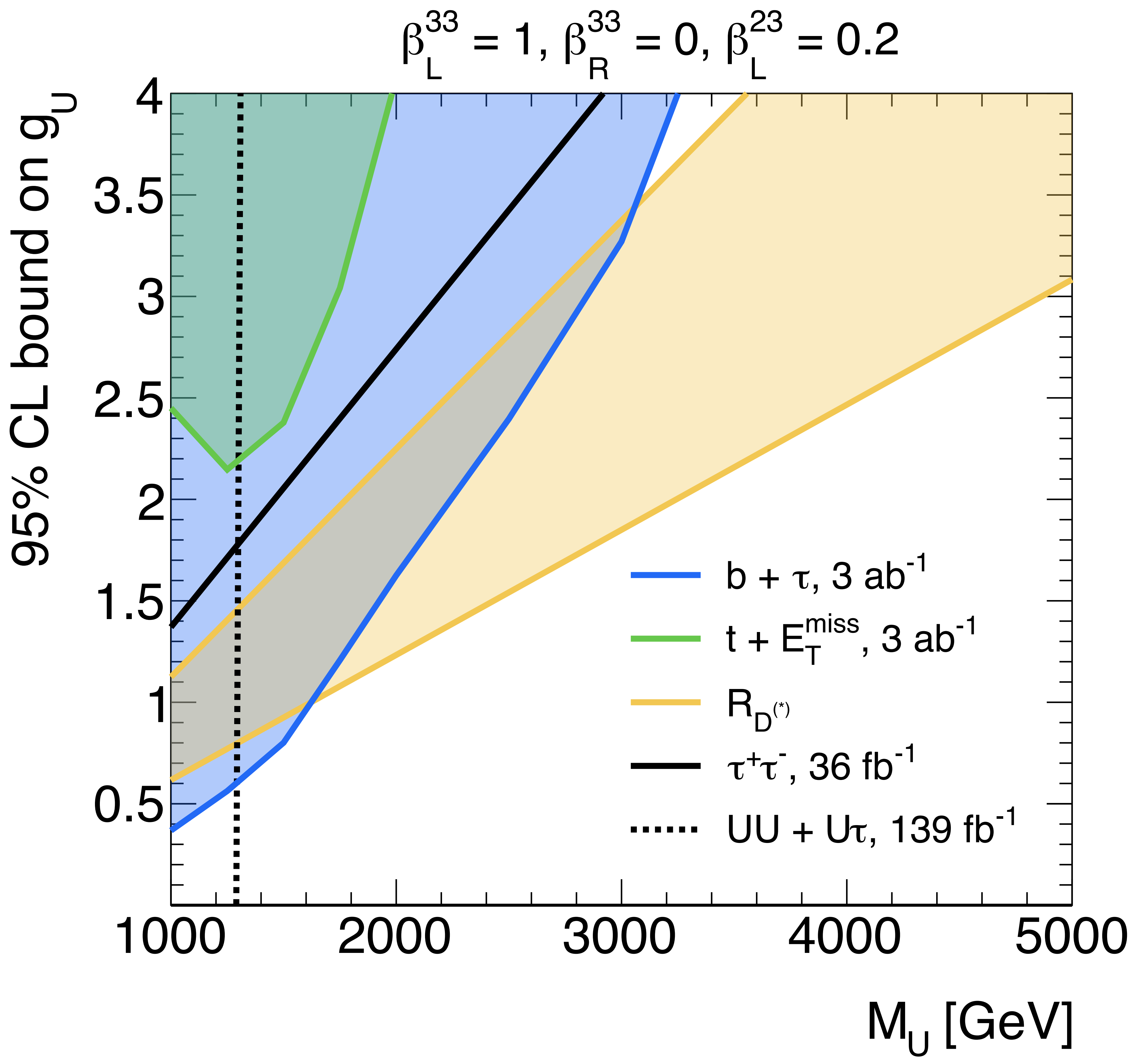


Flavour structure needed to explain b→c anomalies singles out pp→τ⁺τ⁻, pp→bτ & pp→tν as most interesting channels. In case of 33 & 23 mixing both 2→2 & 2→3 processes relevant. Because two topologies lead to final states with very different kinematic features, it is essential to develop two separate search strategies for them

[UH & Polesello, 2012.11474]

Comparison of LQ search strategies



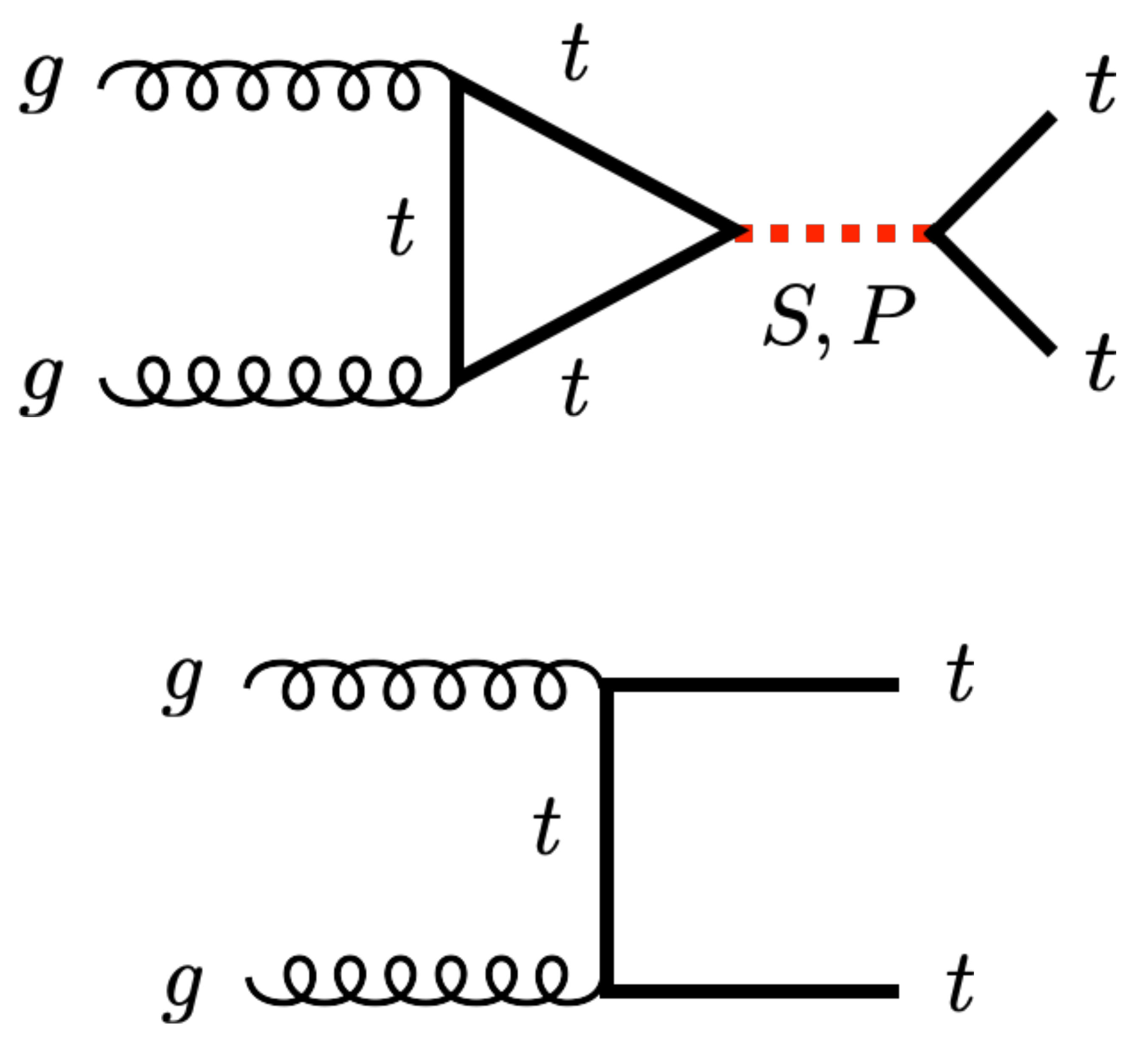


[UH & Polesello, 2012.11474]

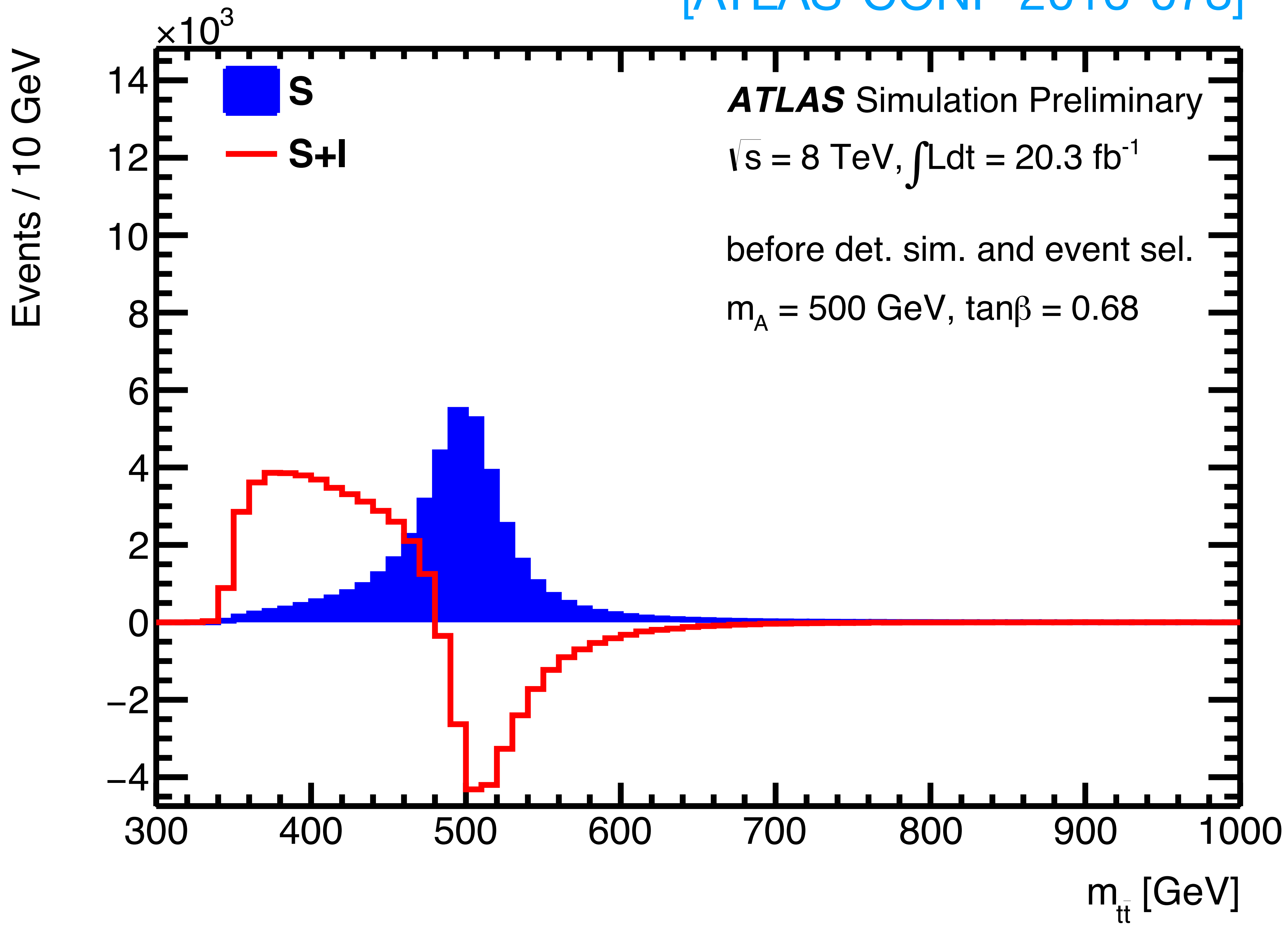
Summary

- Top physics offers a rich spectrum of processes such as top pair, single-top & mono-top production to look for DM. Searches for these final states allow to set relevant constraints for instance on simplified spin-0 DM models, pNGB DM & 2HDM+a model
- Channels like mono-top, $t\bar{t}Z$, $t\bar{t}$, four-top, etc. also provide test of other BSM scenarios such as vector-like fermions, leptoquarks, heavy Higgses, etc. that are not necessarily connected to DM — $t\bar{t}Z$ discussed in backup

Heavy Higgs effects in ditop production



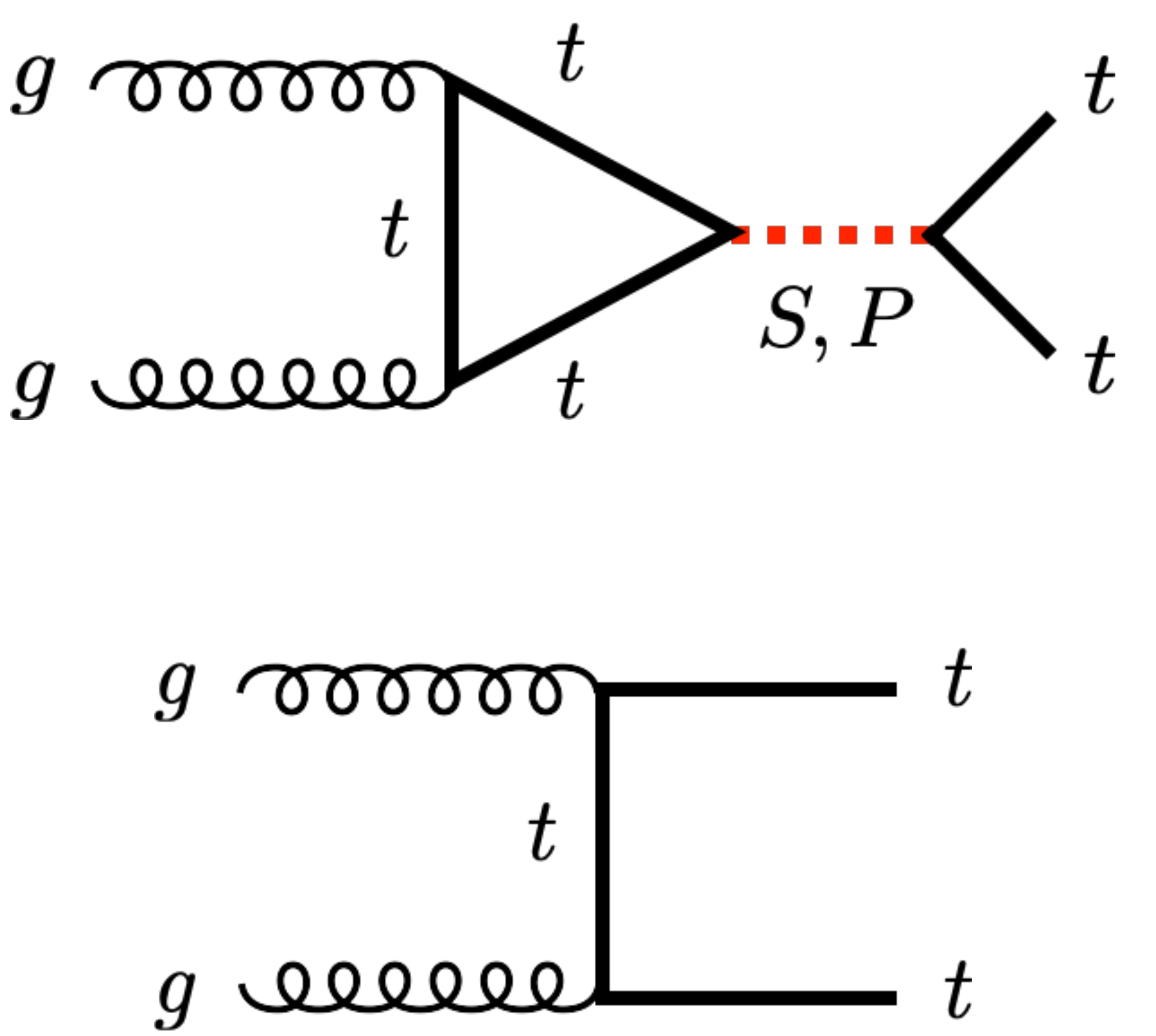
[ATLAS-CONF-2016-073]



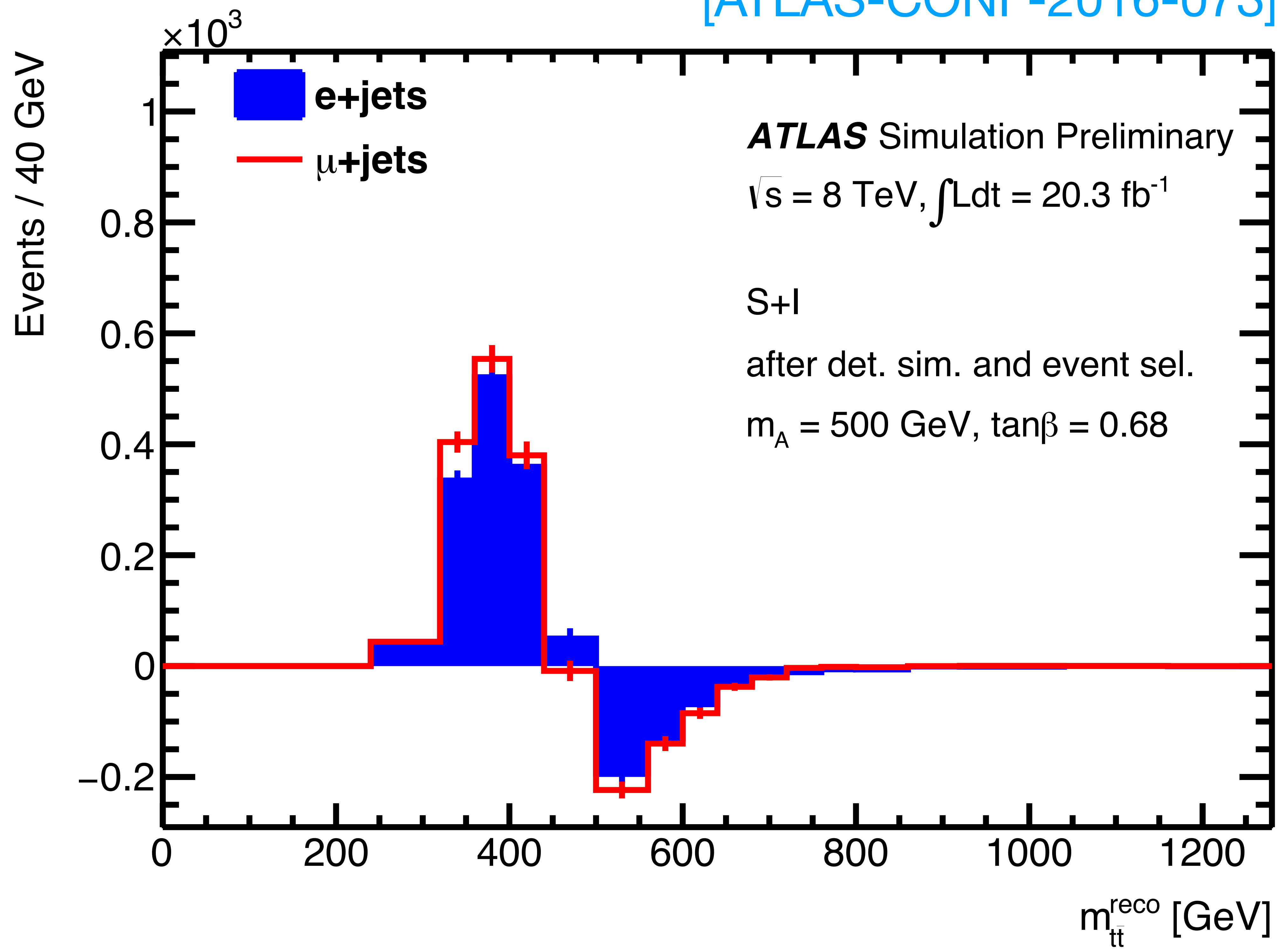
Spin-0 ditop resonances interfere maximal with SM background, which leads to a peak-dip structure in $m_{t\bar{t}}$ invariant mass spectrum

[see for instance Dicus et al., hep-ph/9404359; Frederix & Maltoni, 0712.2355; Craig et al., 1504.04630]

Heavy Higgs effects in ditop production

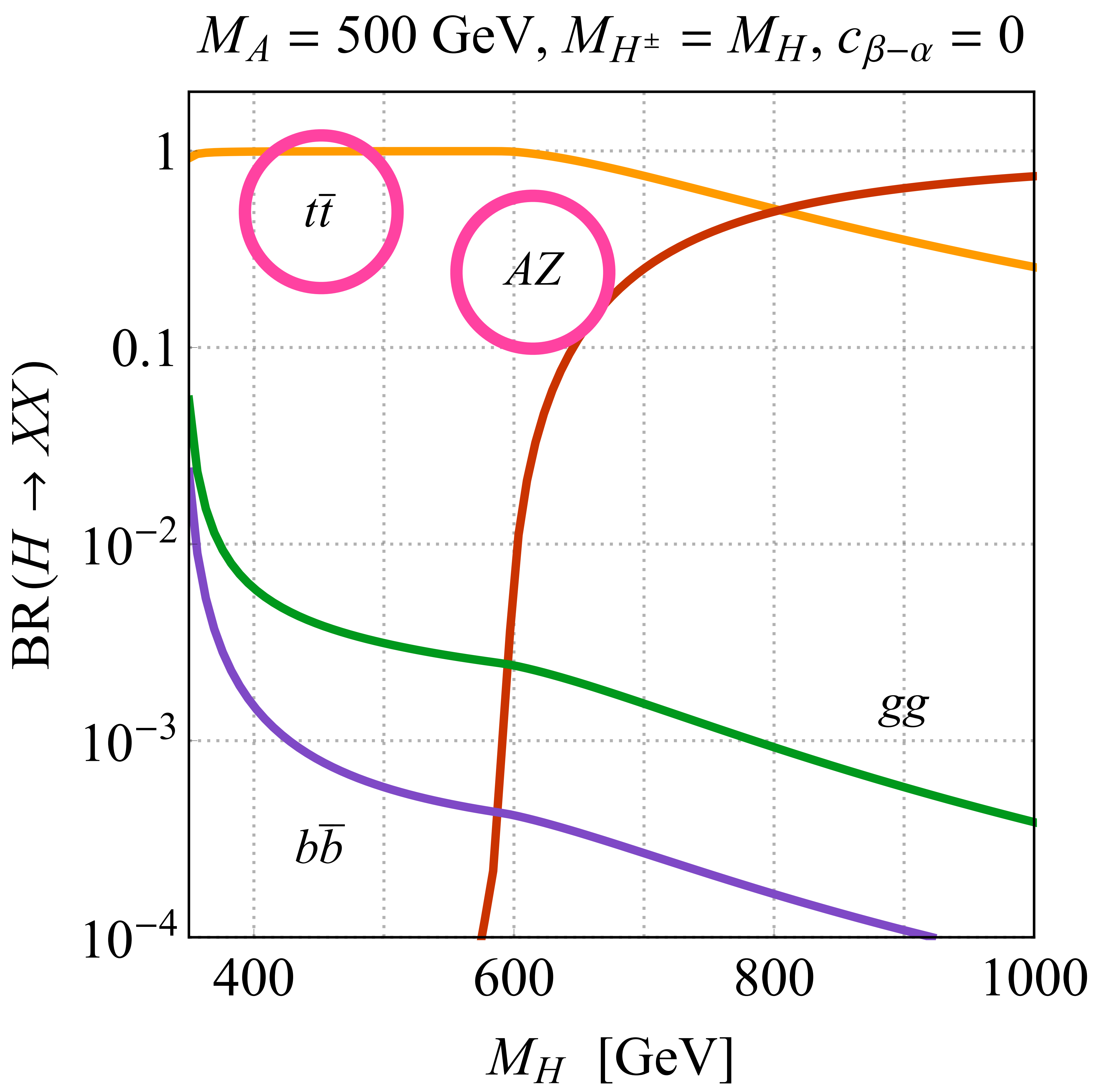


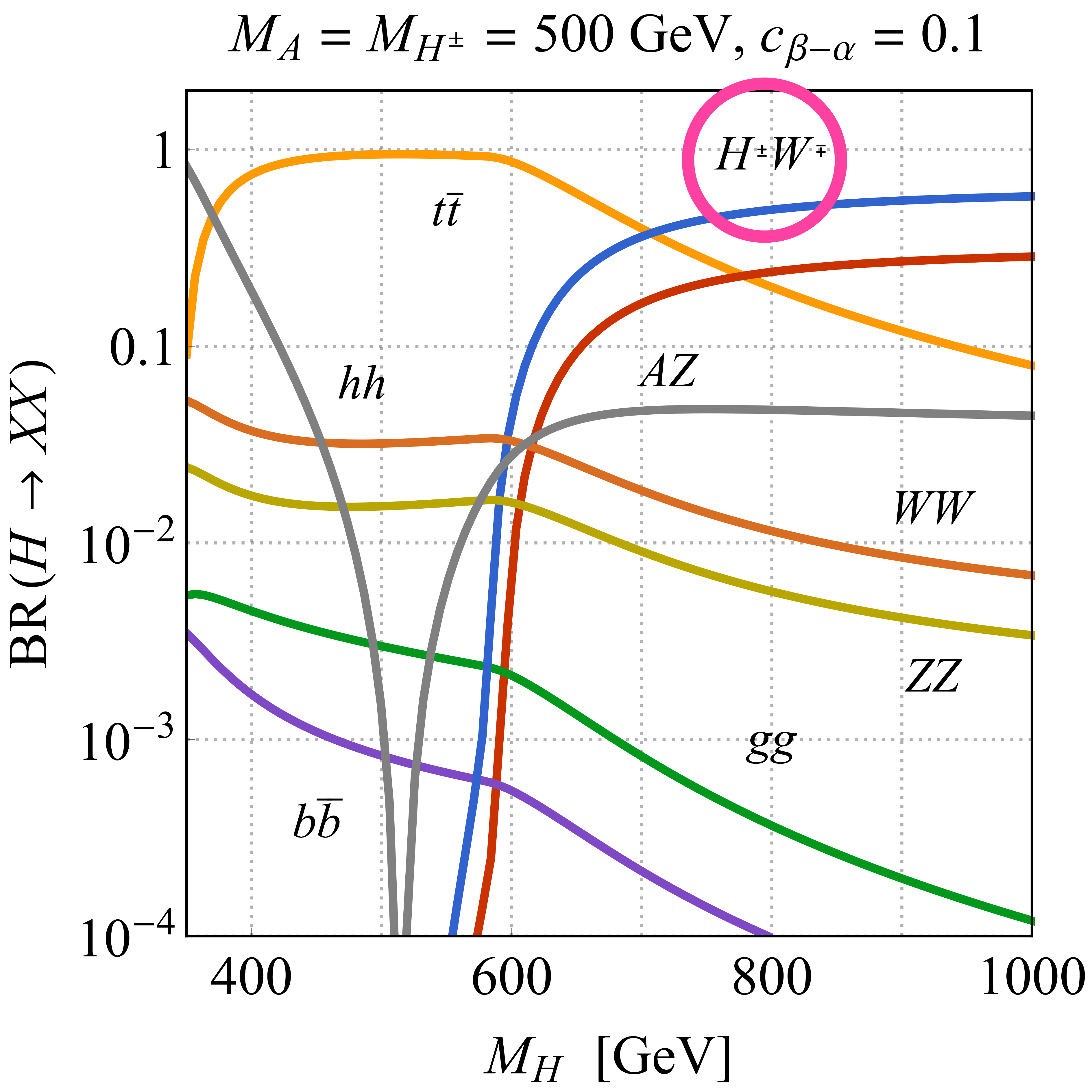
[ATLAS-CONF-2016-073]



Compared to parton-level spectra, reconstructed distributions are more strongly distorted due limits detector resolution. As a result, difficult to constrain spin-0 ditop resonances

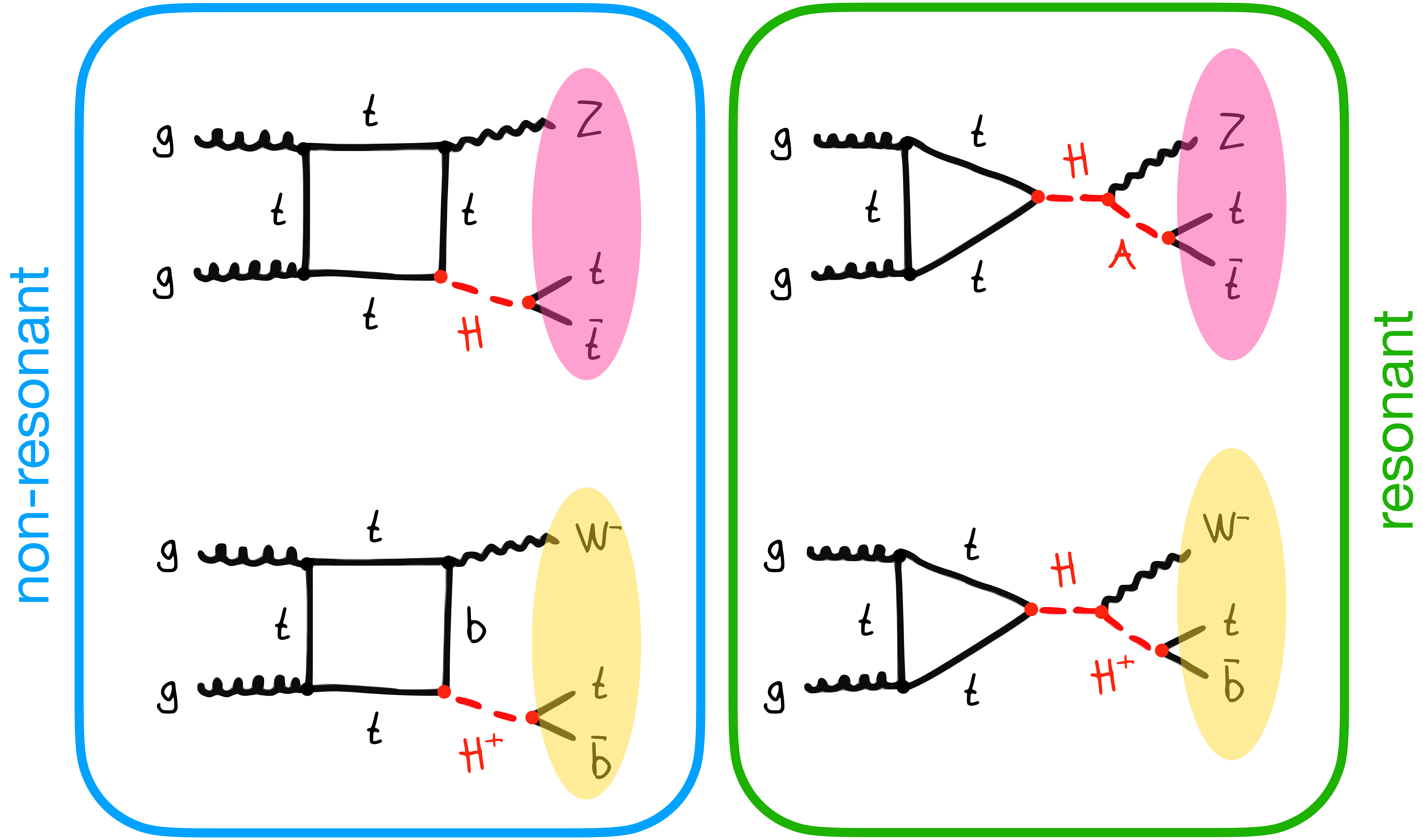
H decays in alignment limit of 2HDM





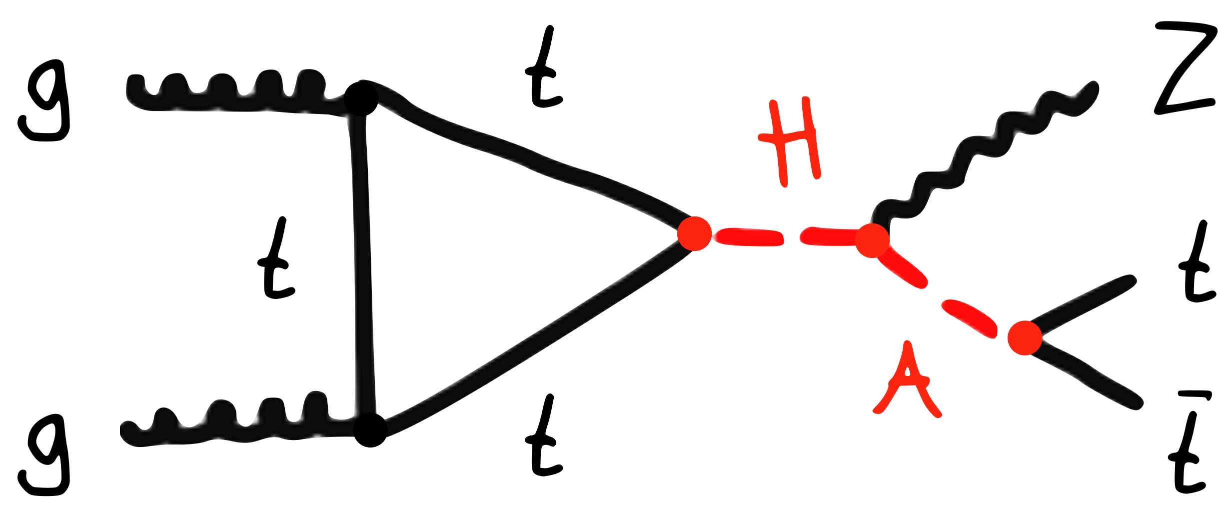
[UH & Polesello, 1807.07734]

Interesting/unexplored H, A search channels



[UH & Polesello, 1807.07734]

Kinematics of H, A contribution to tt̄Z



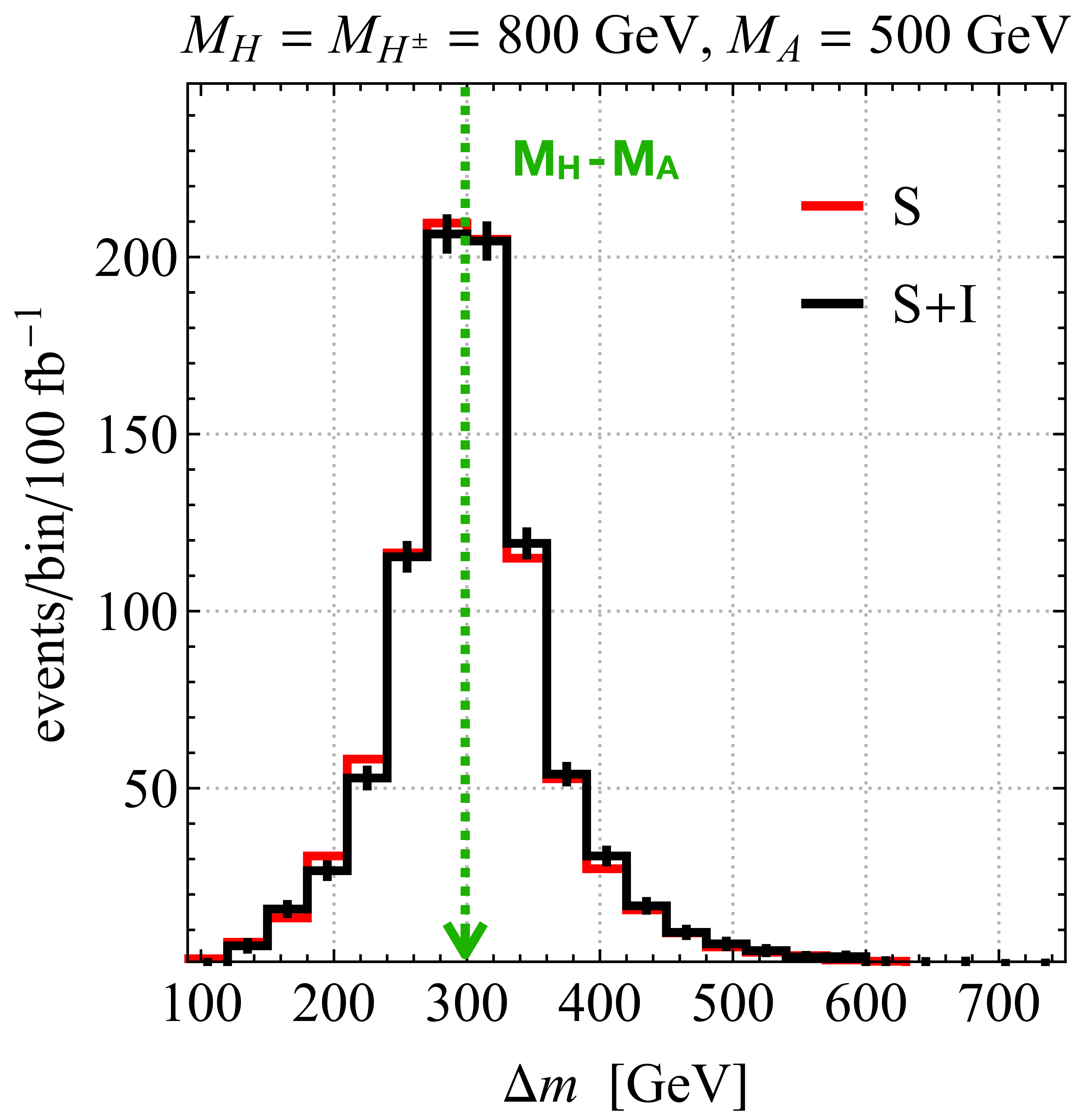
if kinematically allowed, H, A
are preferentially on-shell

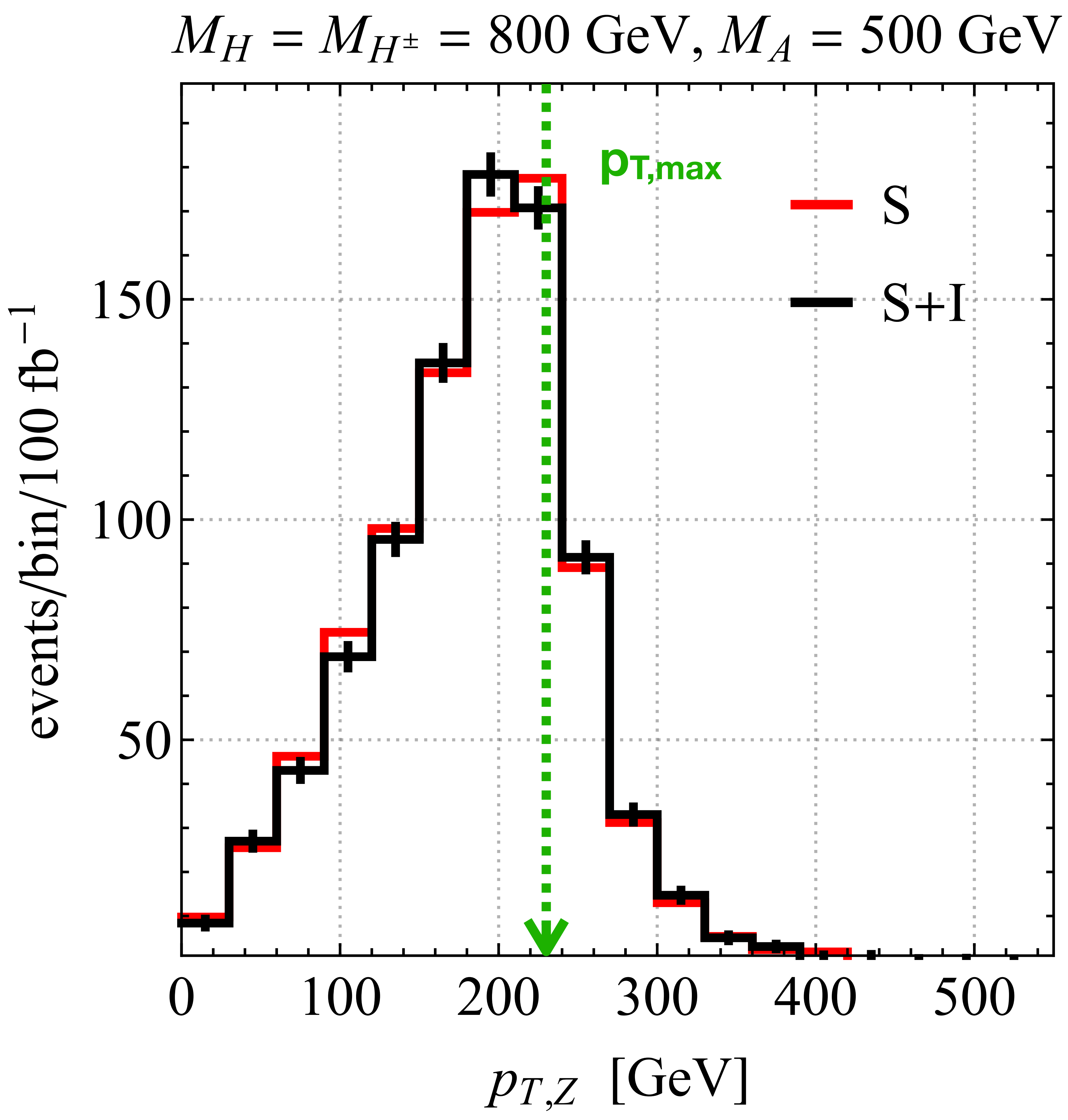
$$\Delta m = m_{t\bar{t}Z} - m_{t\bar{t}} \simeq M_H - M_A$$

$$p_{T,Z}^{\max} \simeq \frac{1}{2M_H}\sqrt{\left(M_H^2 - M_A^2 - M_Z^2\right)^2 - 4M_A^2 M_Z^2}$$

[UH & Polesello, 1807.07734]

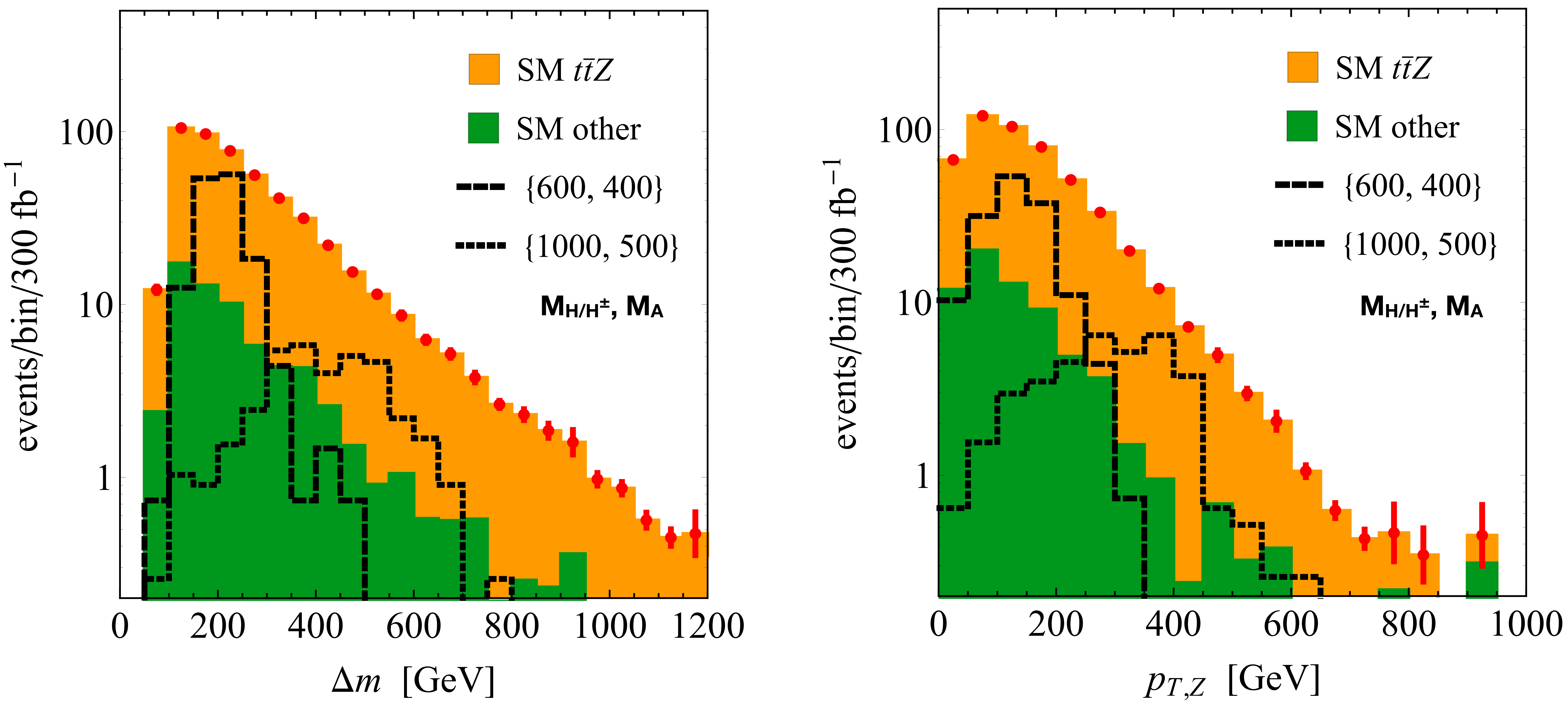
Kinematics of H, A contribution to $t\bar{t}Z$





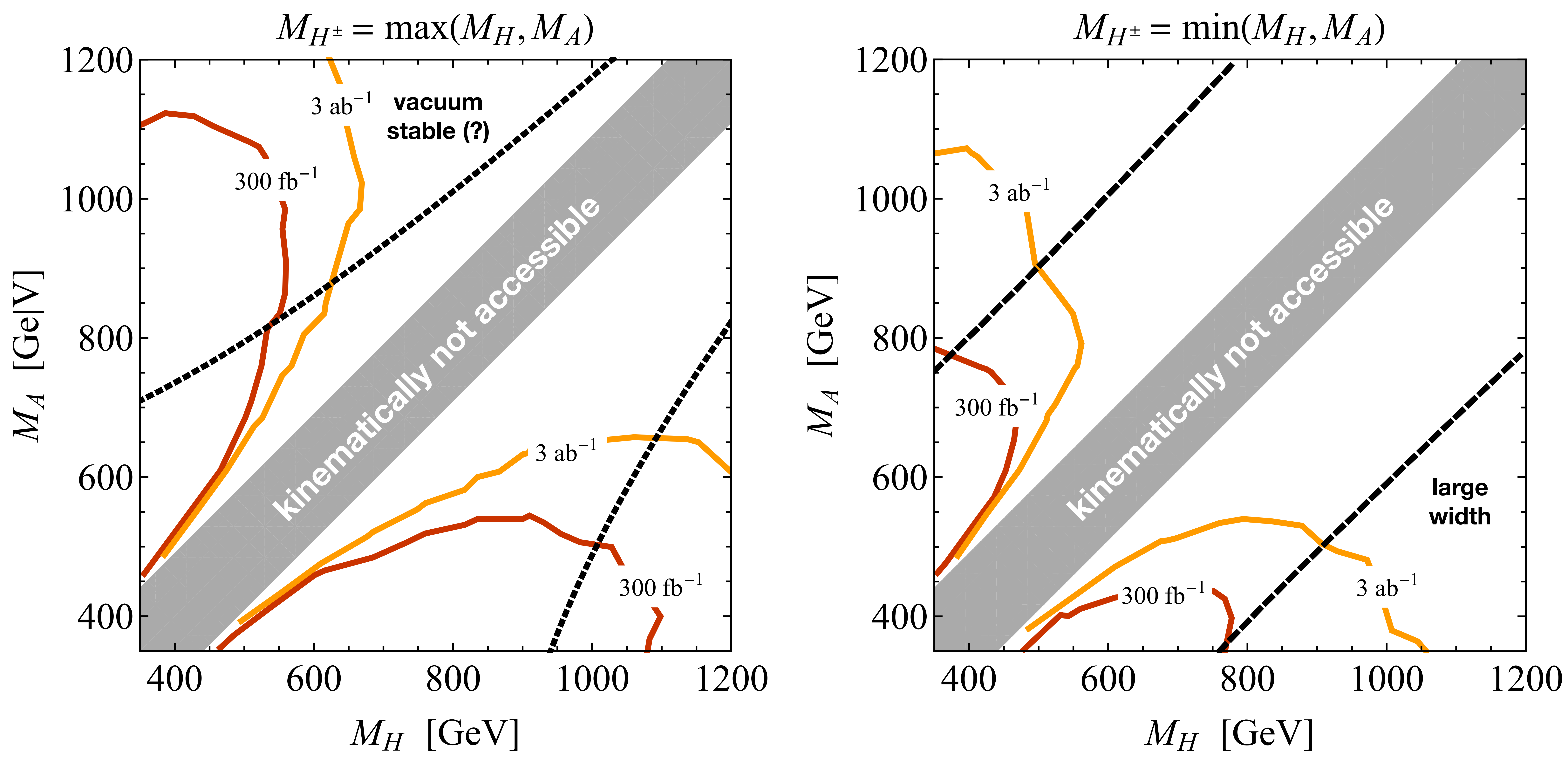
[UH & Polesello, 1807.07734]

$t\bar{t}Z$: signal vs. backgrounds



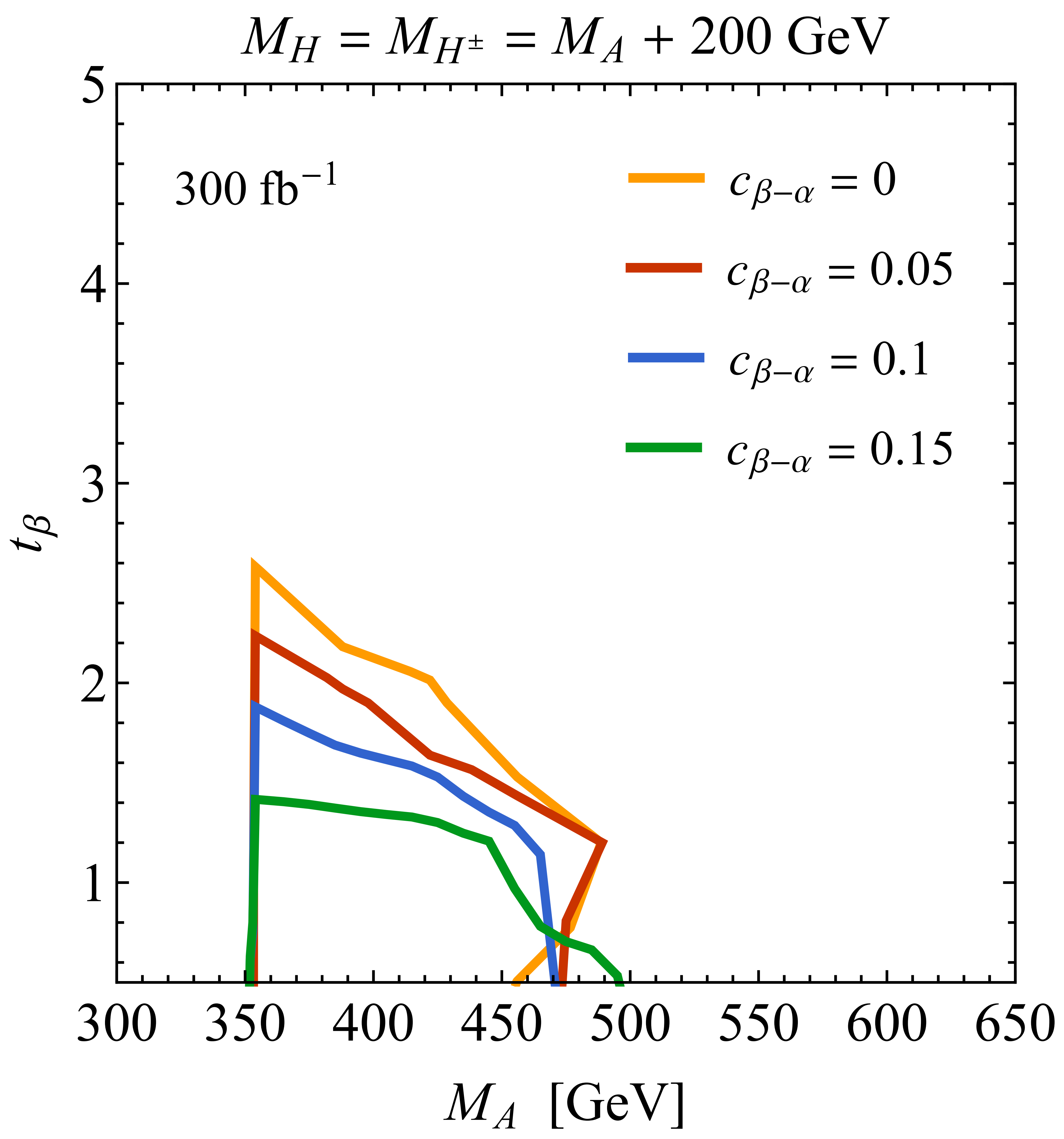
[UH & Polesello, 1807.07734]

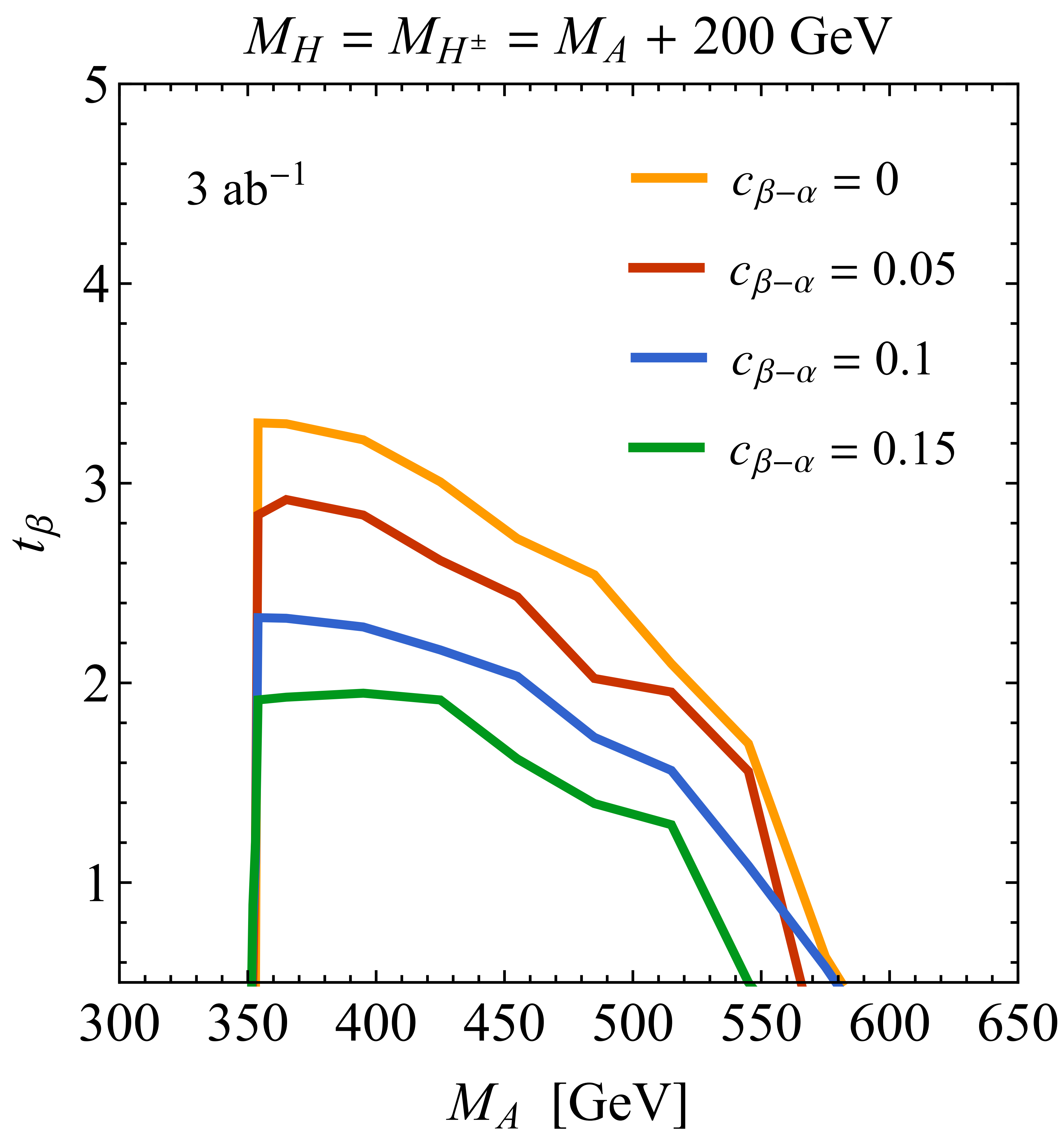
$t\bar{t}Z$: LHC exclusions in M_H-M_A plane



[UH & Polesello, 1807.07734]

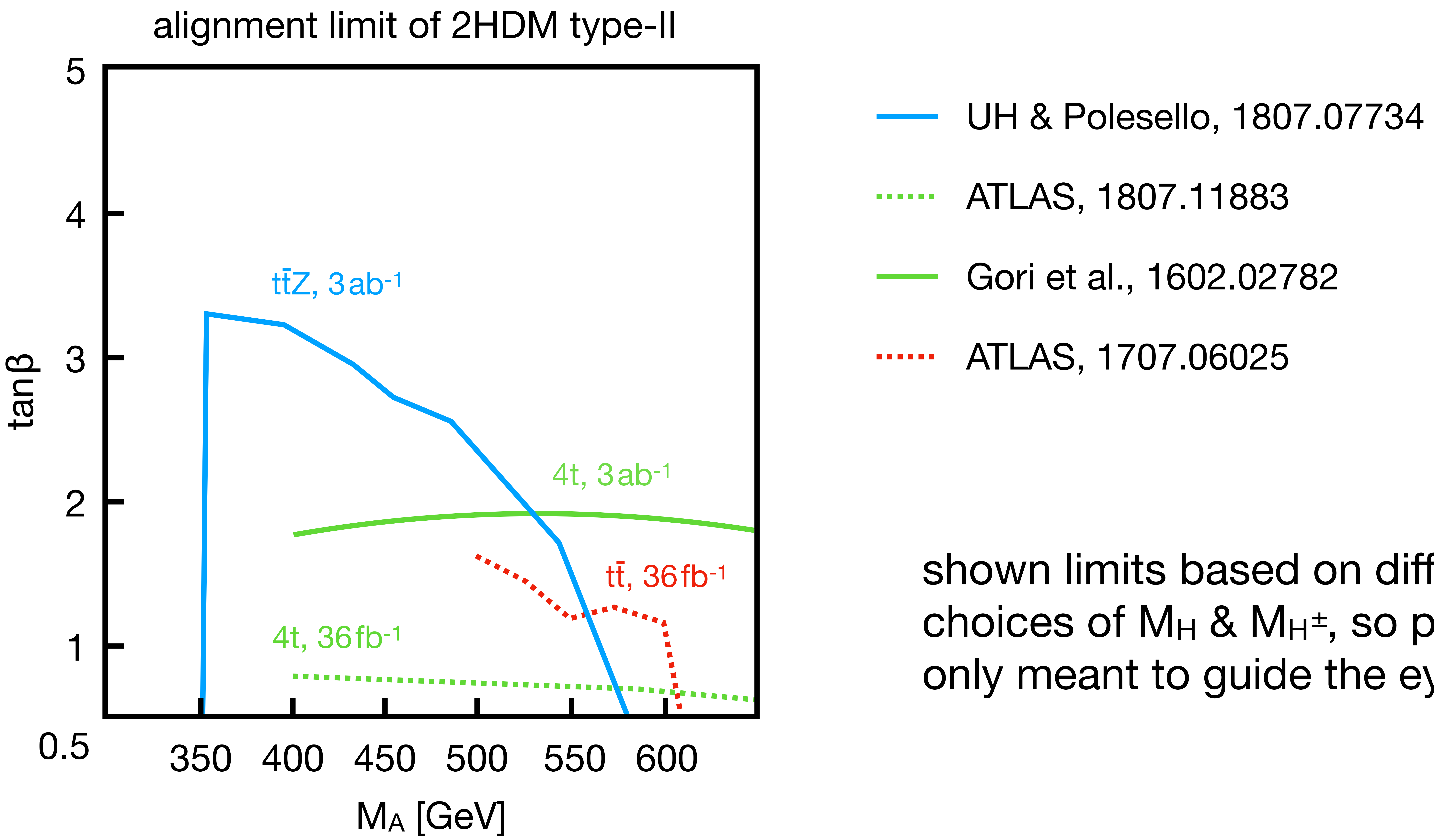
$t\bar{t}Z$: LHC exclusions in M_H-tanβ plane





[UH & Polesello, 1807.07734]

Comparison of bounds from top final states



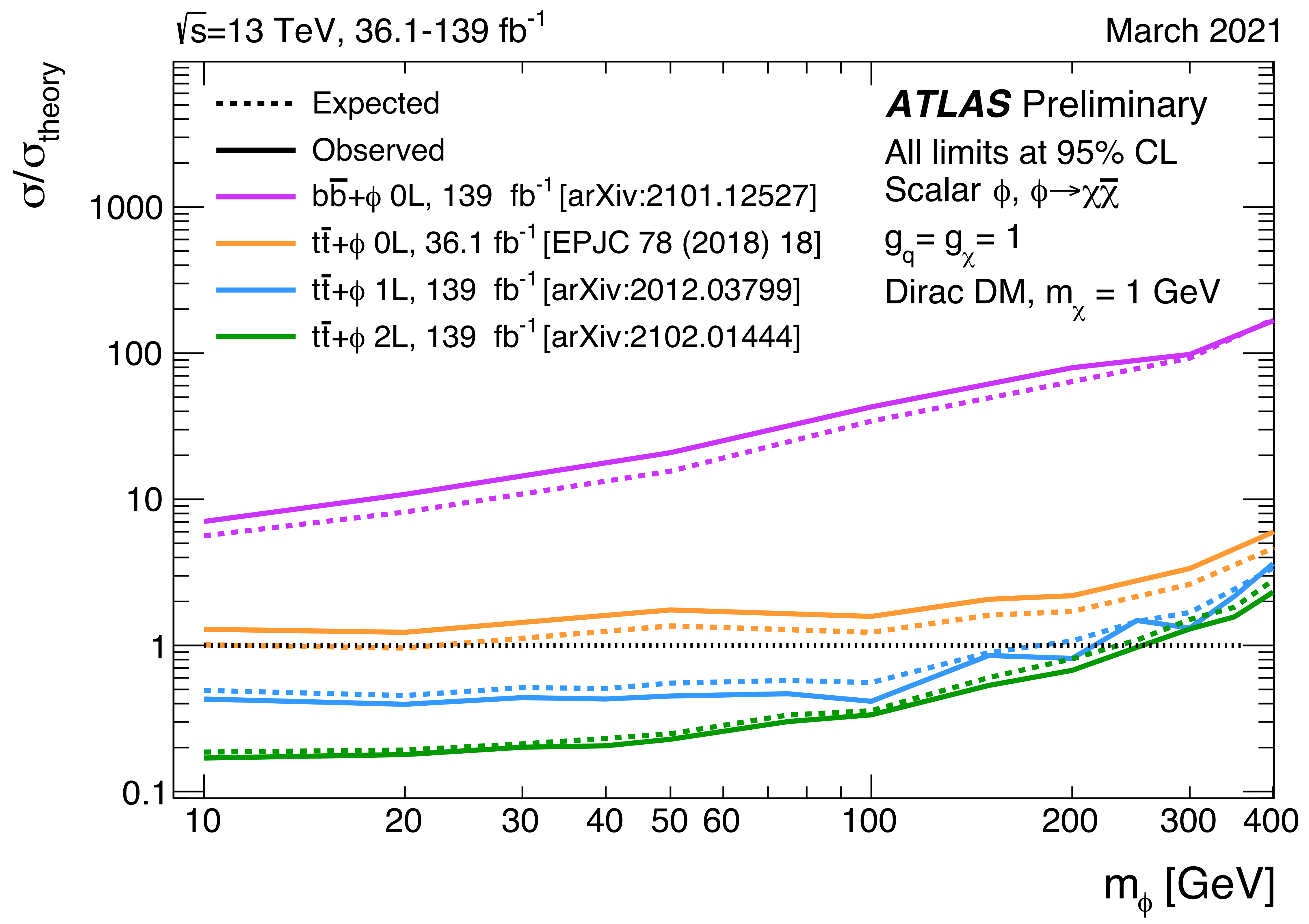
shown limits based on different choices of M_H & $M_{H^\pm}$, so plot is only meant to guide the eye

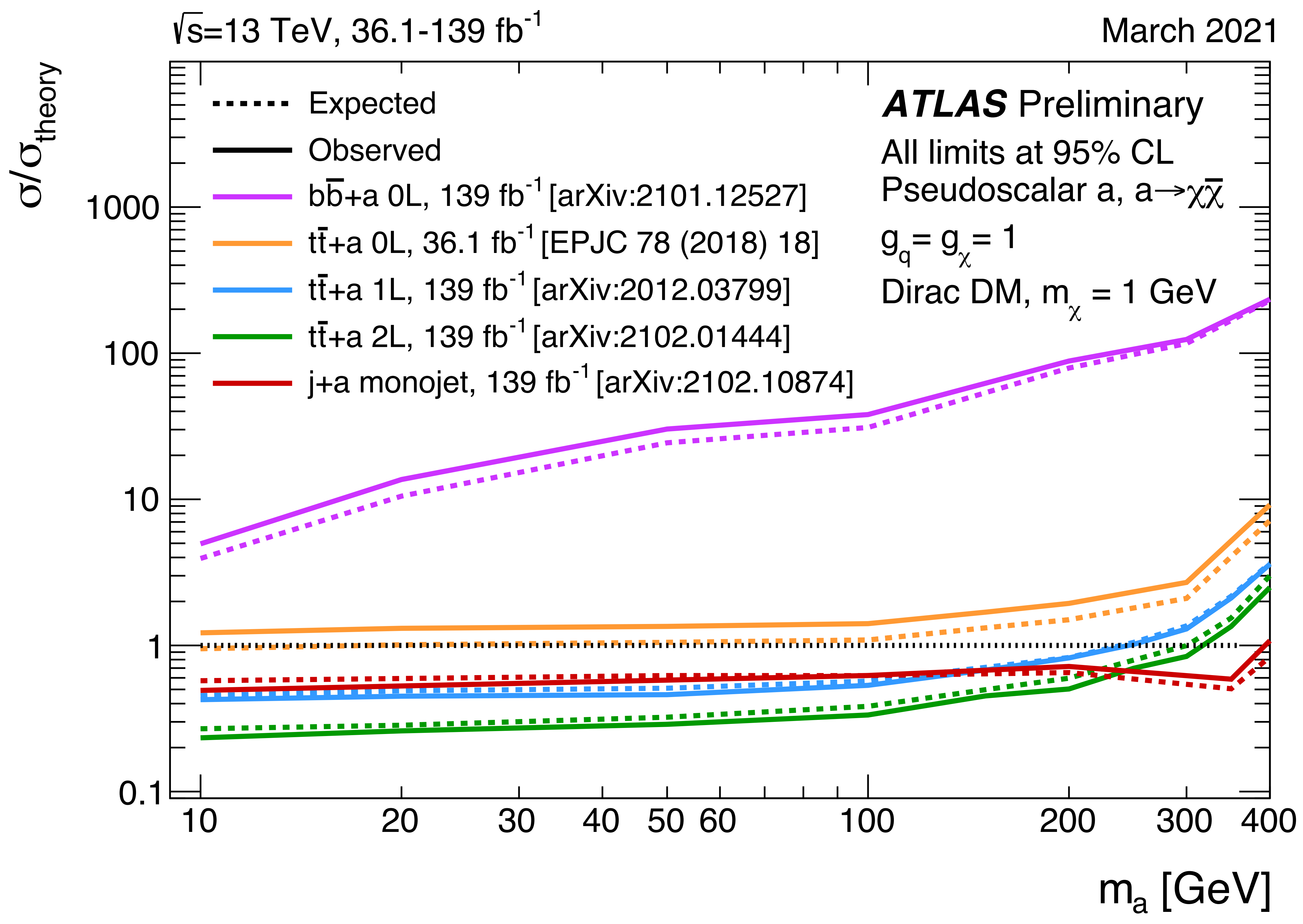
Combined tX+$E_{T,miss}$ search strategy

	$SR_{t\bar{t}}$	SR_{tW}
N_l	$= 2, \quad p_{T,l_1} > 25$ GeV, $\quad p_{T,l_2} > 20$ GeV, $\quad \lvert\eta_l\rvert < 2.5$	
m_{ll}	> 20 GeV, $\quad Z$-boson veto for opposite-sign leptons	
N_b	$> 0, \quad p_{T,b} > 30$ GeV, $\quad \lvert\eta_b\rvert < 2.5$	
m_{T2}	> 100 GeV	
m_{bl}^t	< 160 GeV	> 160 GeV $\quad \lvert\lvert \quad N_j = 1$
$\lvert\Delta\phi_{min}\rvert$	> 0.8	> 0.8
$\lvert\Delta\phi_{\mathrm{boost}}\rvert$	< 1.2	n/a
M_{scal}	n/a	< 500 GeV
C_{em}	> 200 GeV	> 200 GeV
$\lvert\cos\theta_{ll}\rvert$	shape fit	shape fit

[UH & Polesello, 1812.00694]

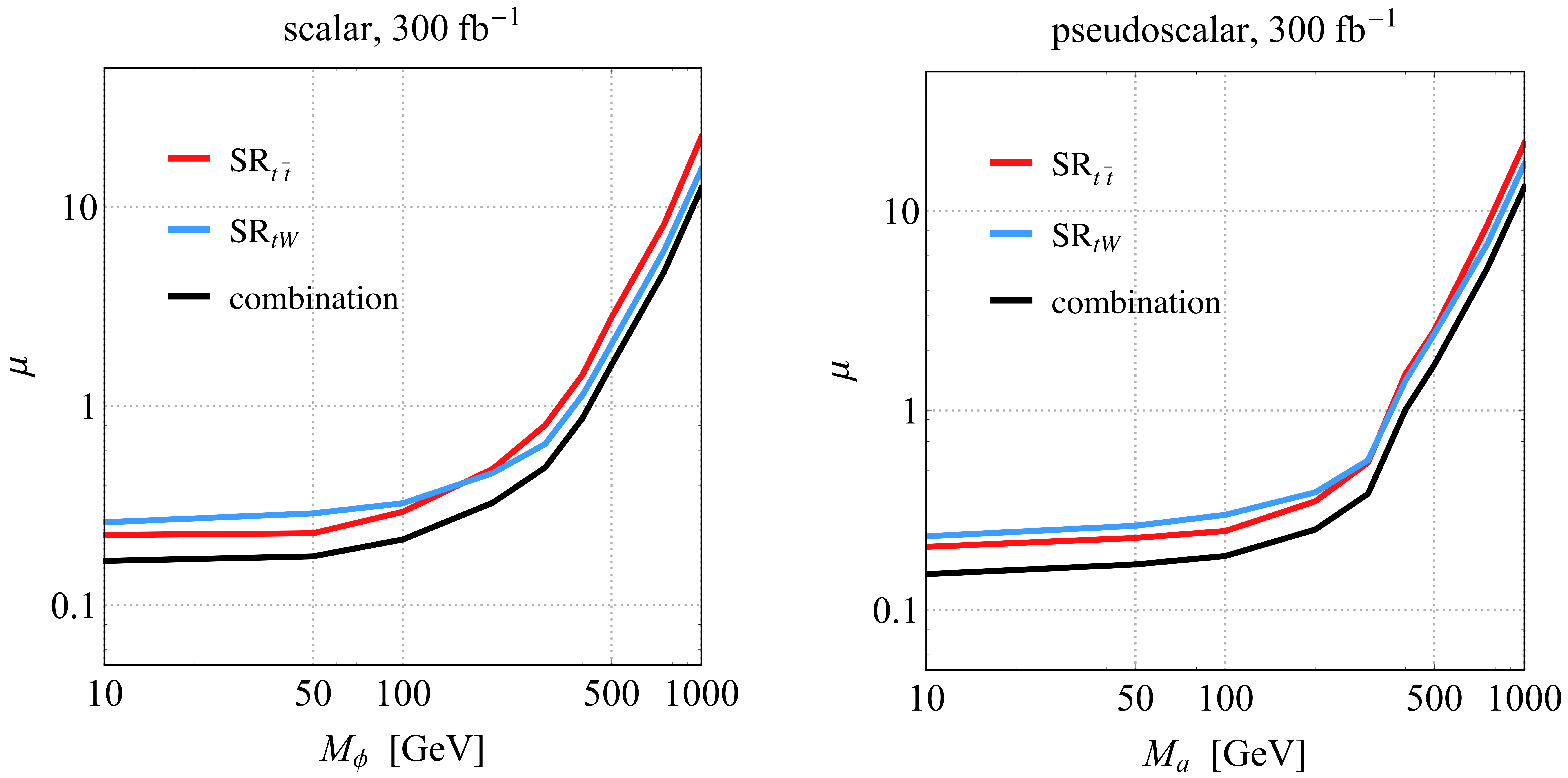
Existing spin-0 simplified DM bounds





[plots from ATL-PHYS-PUB-2021-006 & similar results by CMS]

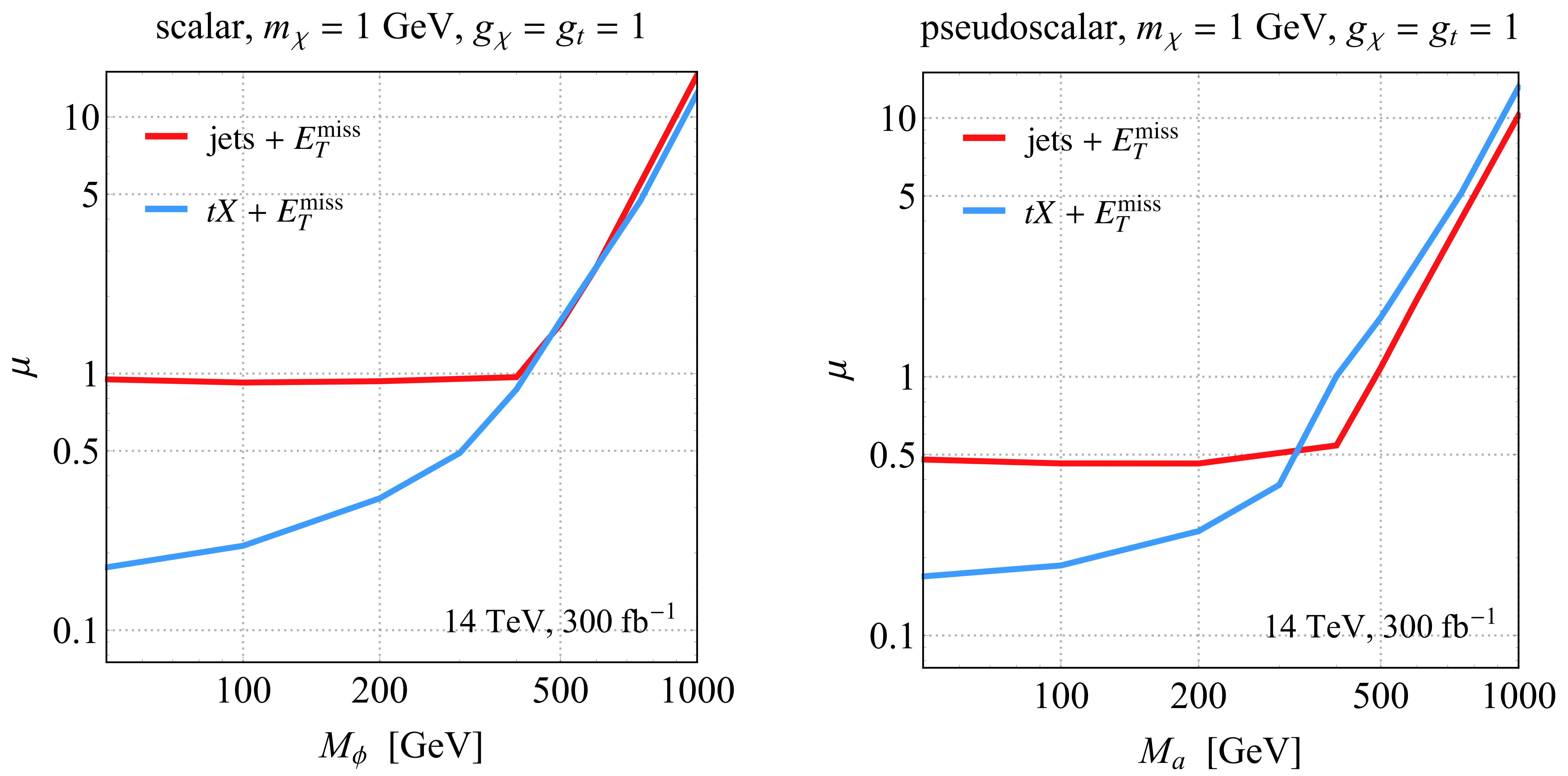
tX+E$_{T,miss}$ LHC Run 3 projections



For m_χ = 1 GeV, $g_{SM} = g_{DM}$ = 1 & assuming 300 fb^{-1} of 14 TeV LHC data, combined analysis leads to 95% CL limit of around 410 GeV on mediator mass

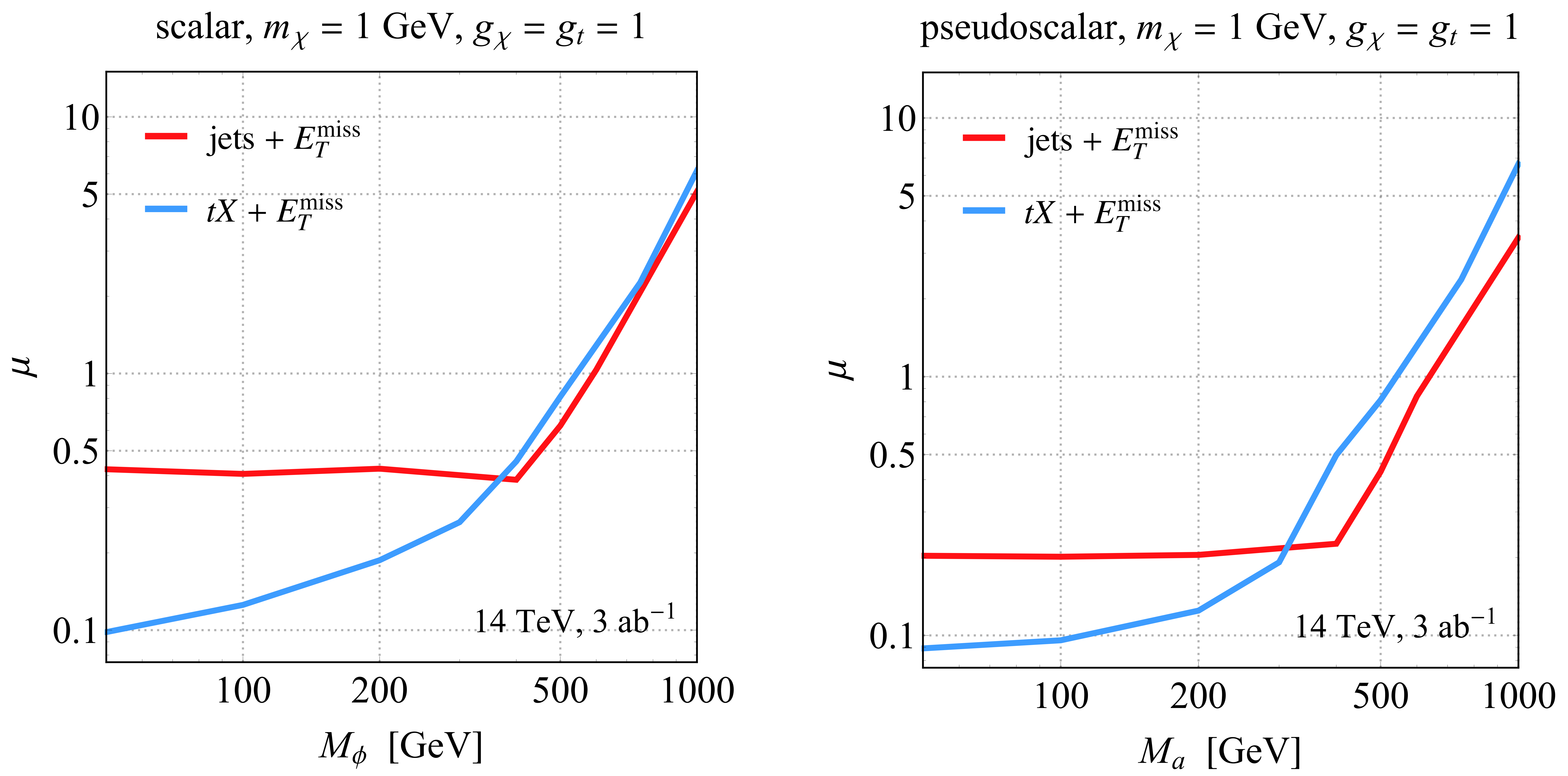
[UH & Polesello, 1812.00694]

Spin-0 simplified DM: tX+$E_{T,miss}$ vs. j+$E_{T,miss}$



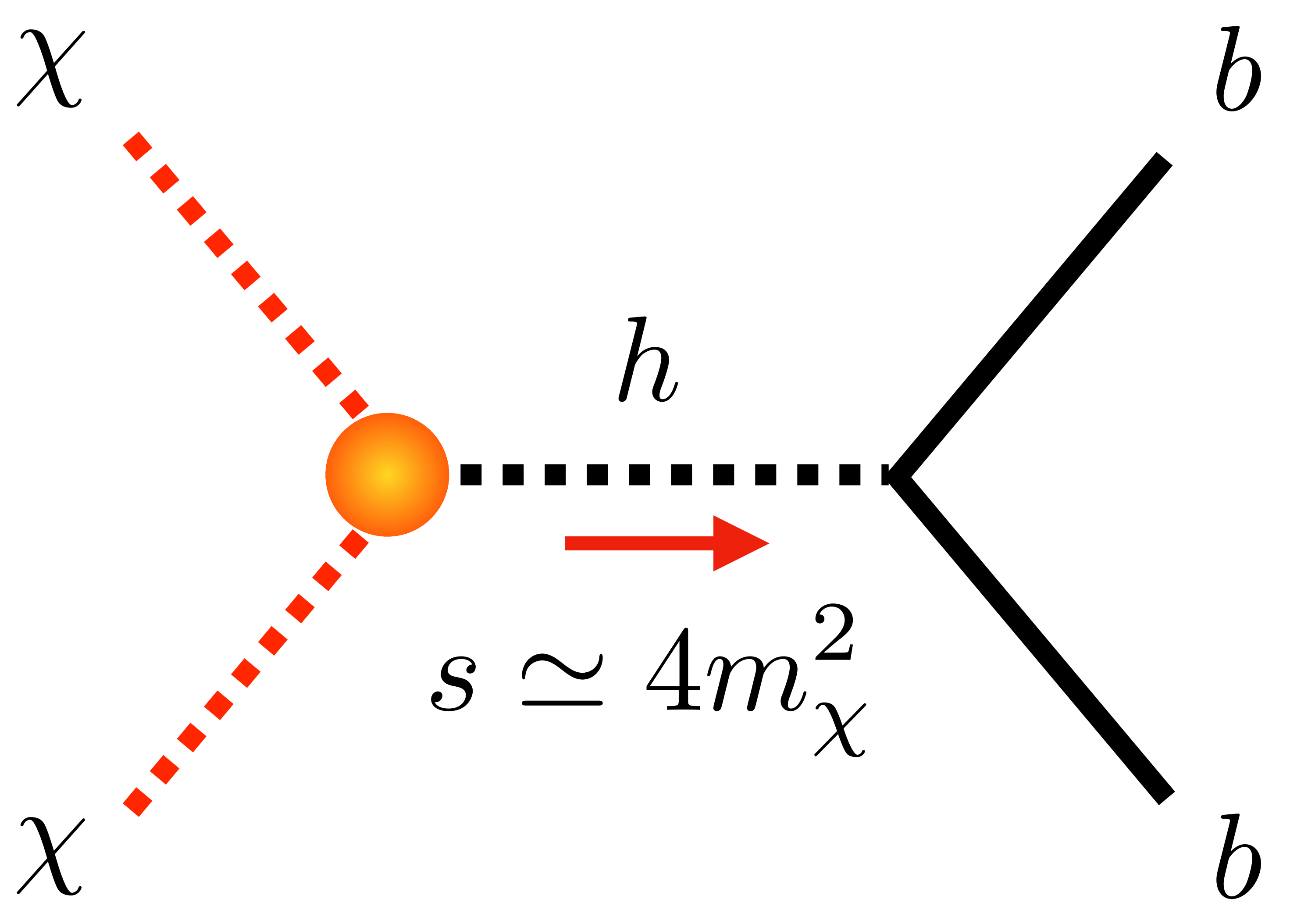
[based on UH & Polesello, 1812.00694 & 1812.08129]

Spin-0 simplified DM: tX+$E_{T,miss}$ vs. j+$E_{T,miss}$



[based on UH & Polesello, 1812.00694 & 1812.08129]

pNGB DM: indirect detection bounds

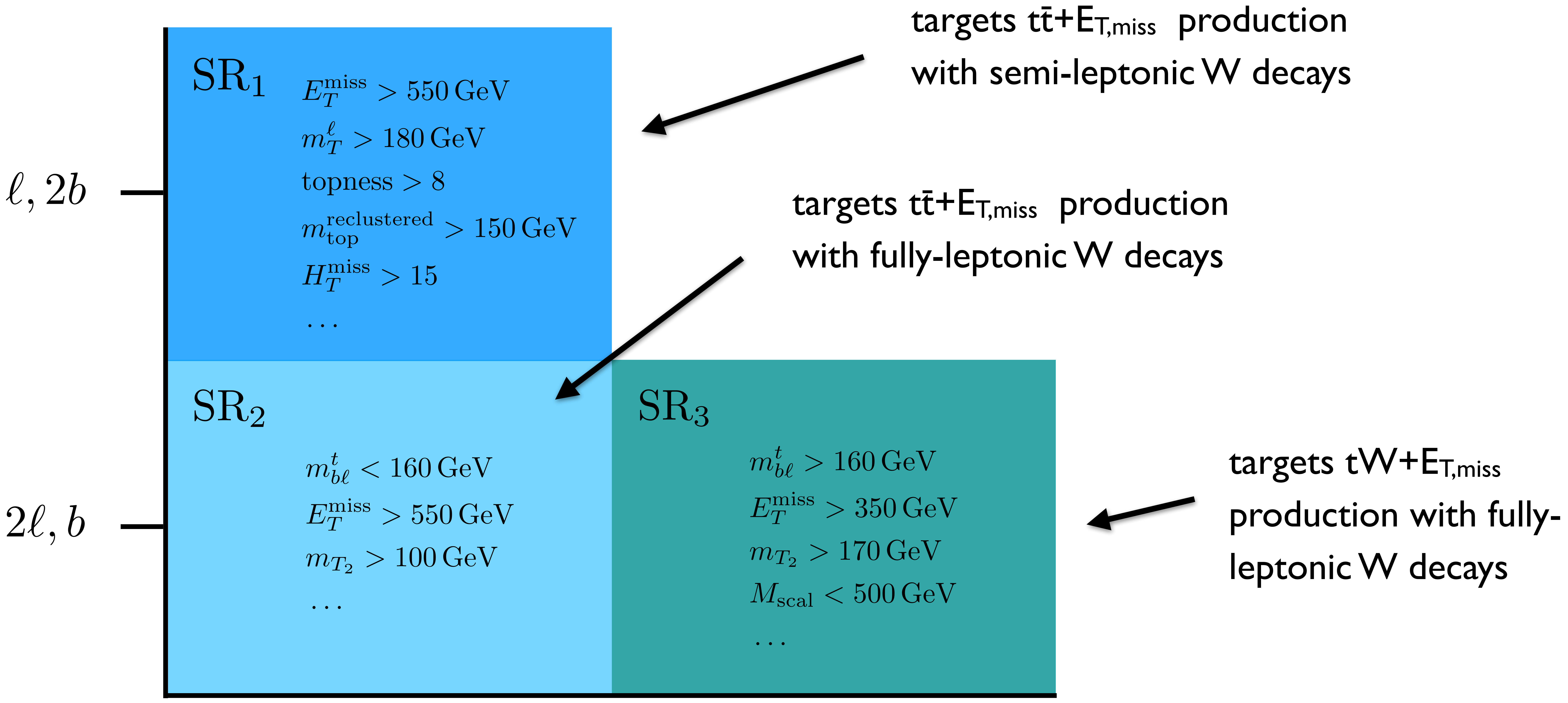


$$\langle \sigma v \rangle_b \propto \left| \frac{1}{4m_\chi^2 - m_h^2} \left(\frac{4m_\chi^2 c_d}{\Lambda^2} + c_m \right) \right|^2$$

$$\frac{\Omega_\chi h^2}{0.12} \simeq \frac{3 \cdot 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\sum_X \langle \sigma v \rangle_X}$$

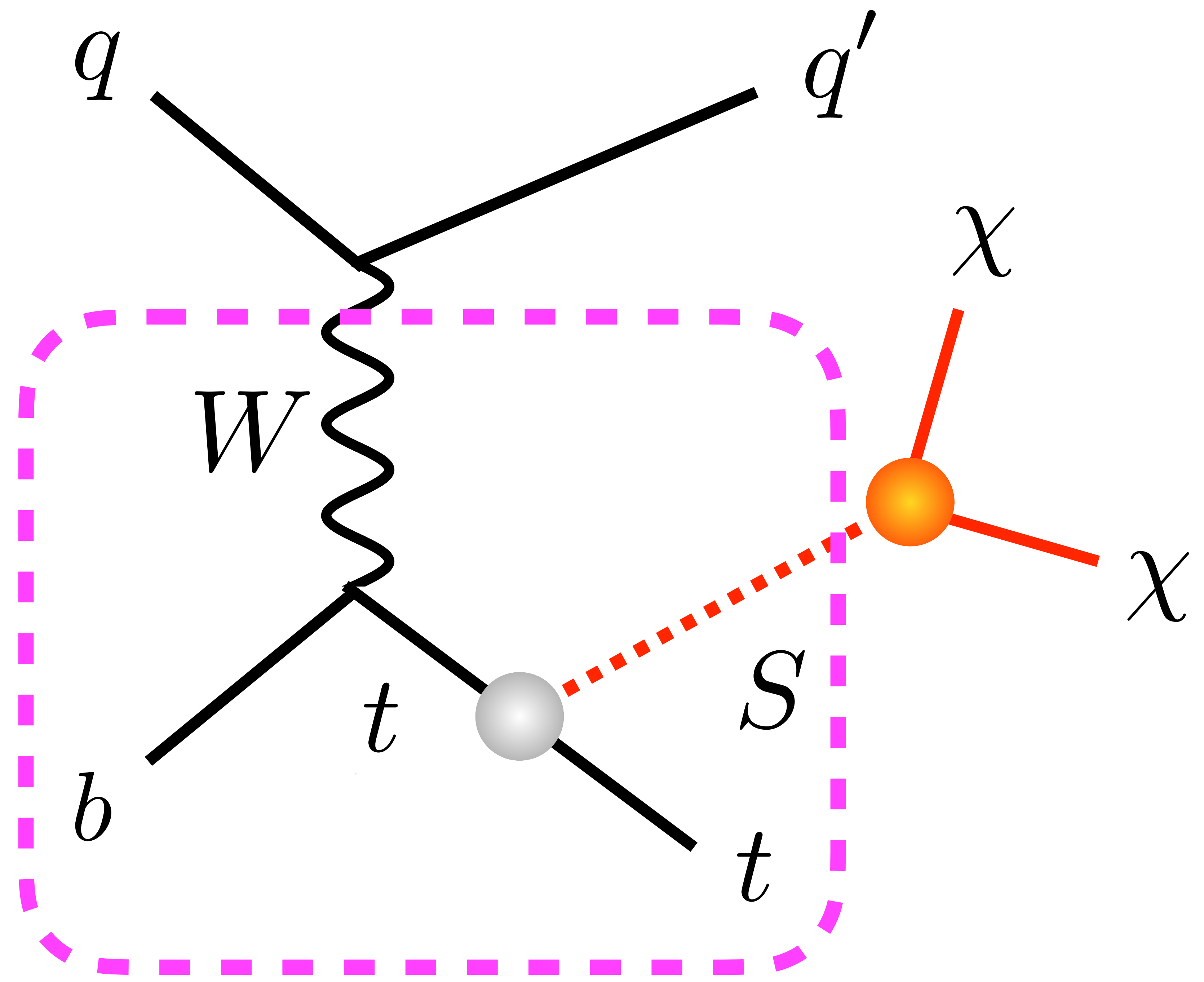
s-wave DM annihilation into SM particles. For light DM, resonant bottom contribution dominant. Above threshold, DM relic density $\Omega_\chi h^2$ set by annihilation to W, Z, h & t pairs

pNGB DM: tX+$E_{T,\mathrm{miss}}$ search strategy



[UH, Polesello & Schulte, 2107.12389]

Unitarity considerations



$$\Rightarrow \qquad |a_0| = \frac{|V_{tb}^*|}{24\pi}\,\frac{y_t}{v}\,g_{\rm SM}\,\hat{E}_{\rm CM}$$

All single-t plus $E_{T,\mathrm{miss}}$ signals involve b→tWS subprocess in simplified scalar DM models. Corresponding s-wave amplitude a_0 grows with partonic centre-of-mass (CM) energy $\hat{E}_{\rm CM}$

[see for instance Maltoni et al., hep-ph/0106293; Farina et al., 1211.3736; UH & Polesello, 1812.00694]

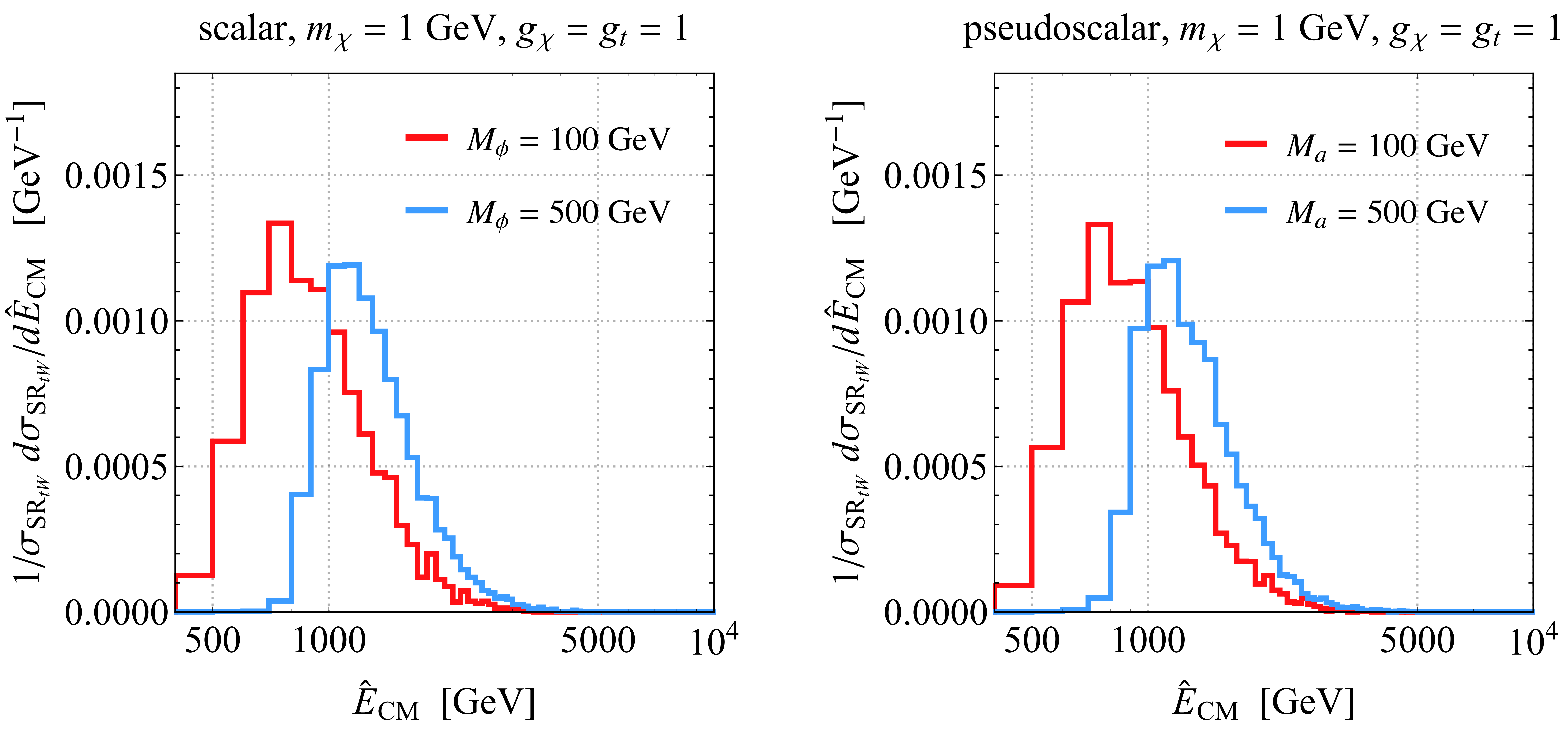
Unitarity considerations

$$|a_0| = \frac{|V_{tb}^*|}{24\pi} \frac{y_t}{v} g_{\text{SM}} \hat{E}_{\text{CM}} \quad \Rightarrow \quad \Lambda \simeq \frac{24\pi}{|V_{tb}^*|} \frac{v}{y_t} \frac{1}{g_{\text{SM}}} \simeq \frac{18.6\,\text{TeV}}{g_{\text{SM}}}$$

Imposing that $|a_0| < 1$ & identifying $\Lambda \simeq \hat{E}_{\text{CM}}$, one can estimate cut-off scale Λ where perturbative unitarity is lost. To make amplitude well-behaved additional particles/couplings have to appear at or before Λ

[UH & Polesello, 1812.00694]

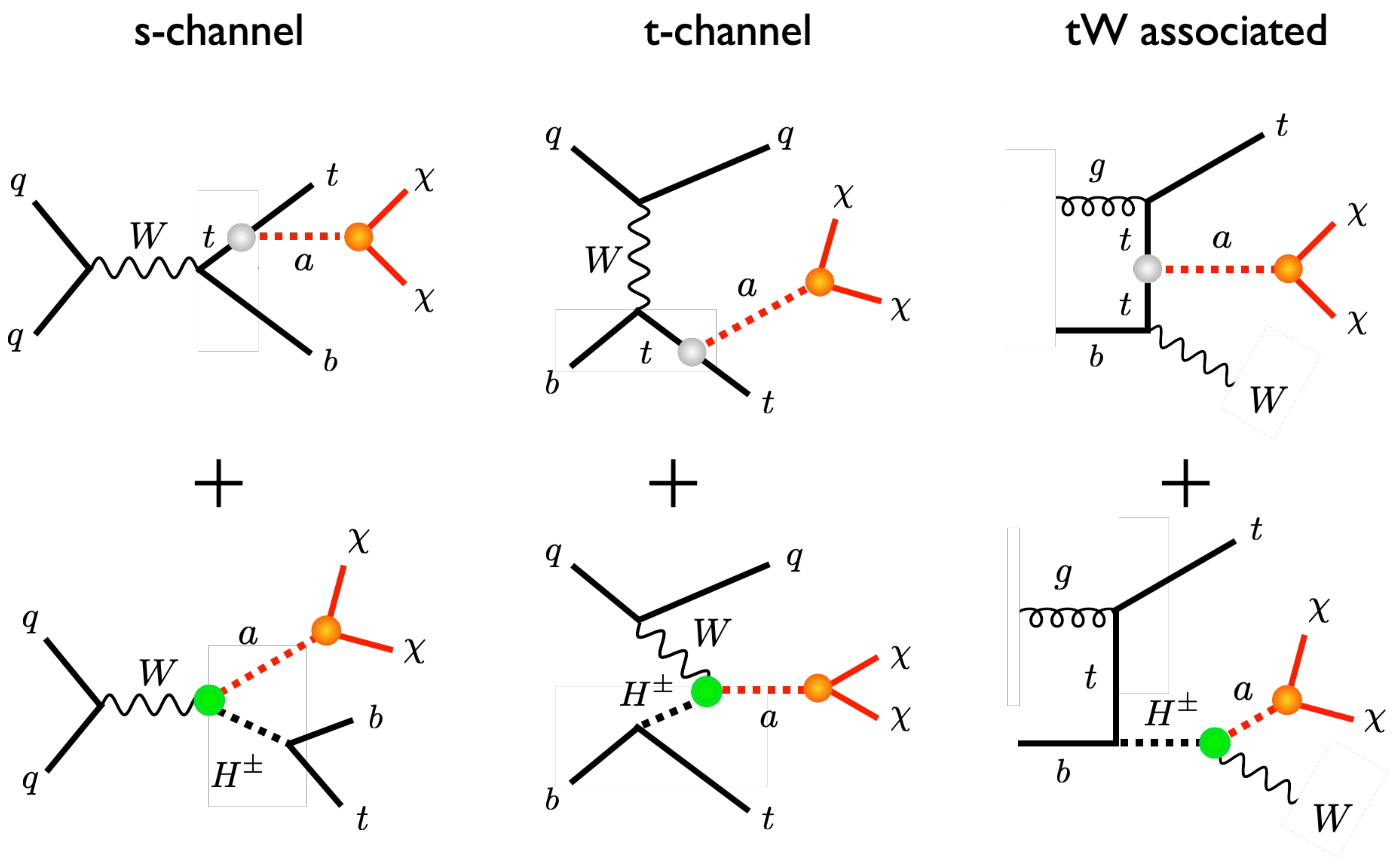
Unitarity considerations



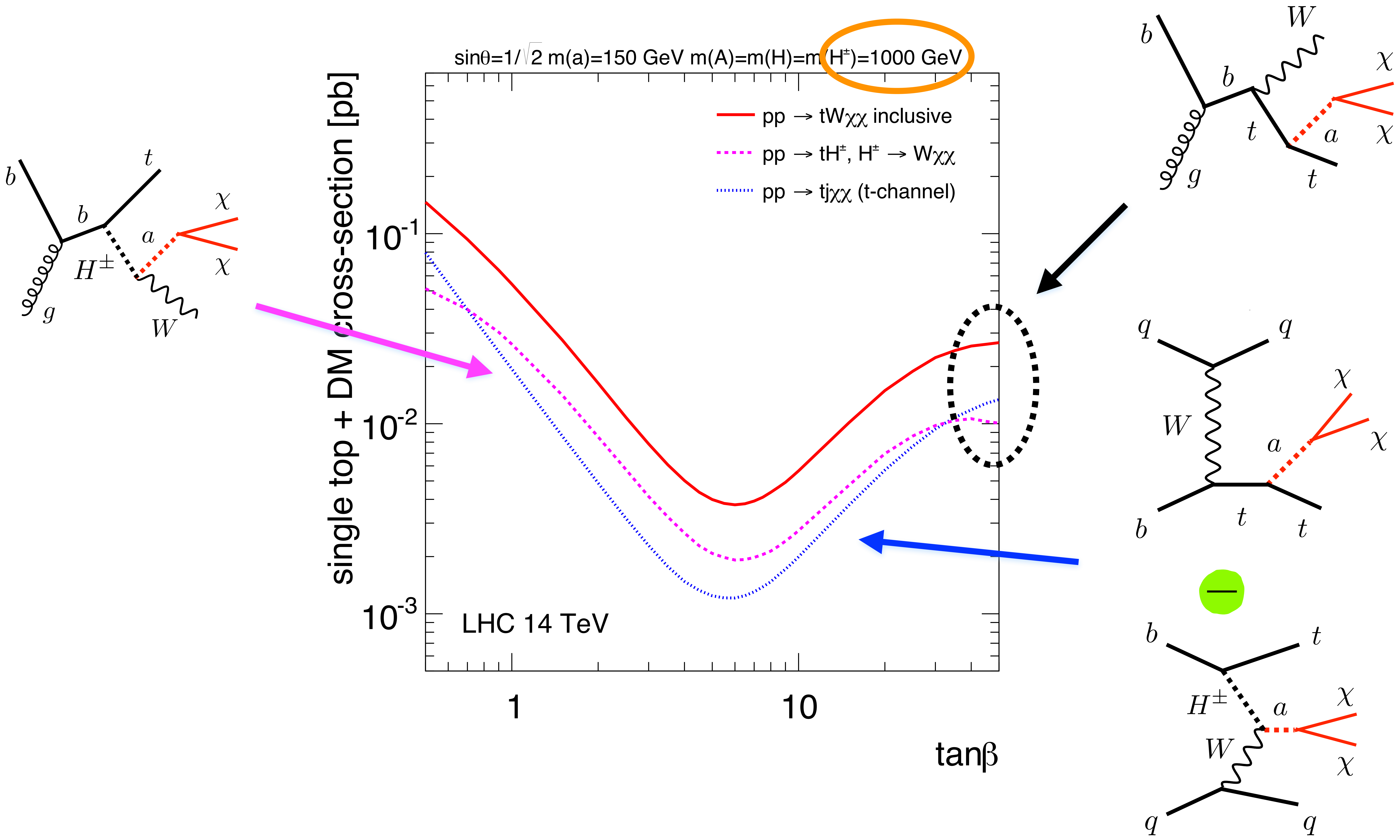
Fraction of single-t plus $E_{T,miss}$ events with $\hat{E}_{CM}$ in multi-TeV range negligible (i.e. far below 1%) at LHC energies. Predictions not plagued by artefacts due to unitarity violation in simplified spin-0 DM models

[UH & Polesello, 1812.00694]

UV finiteness channel by channel

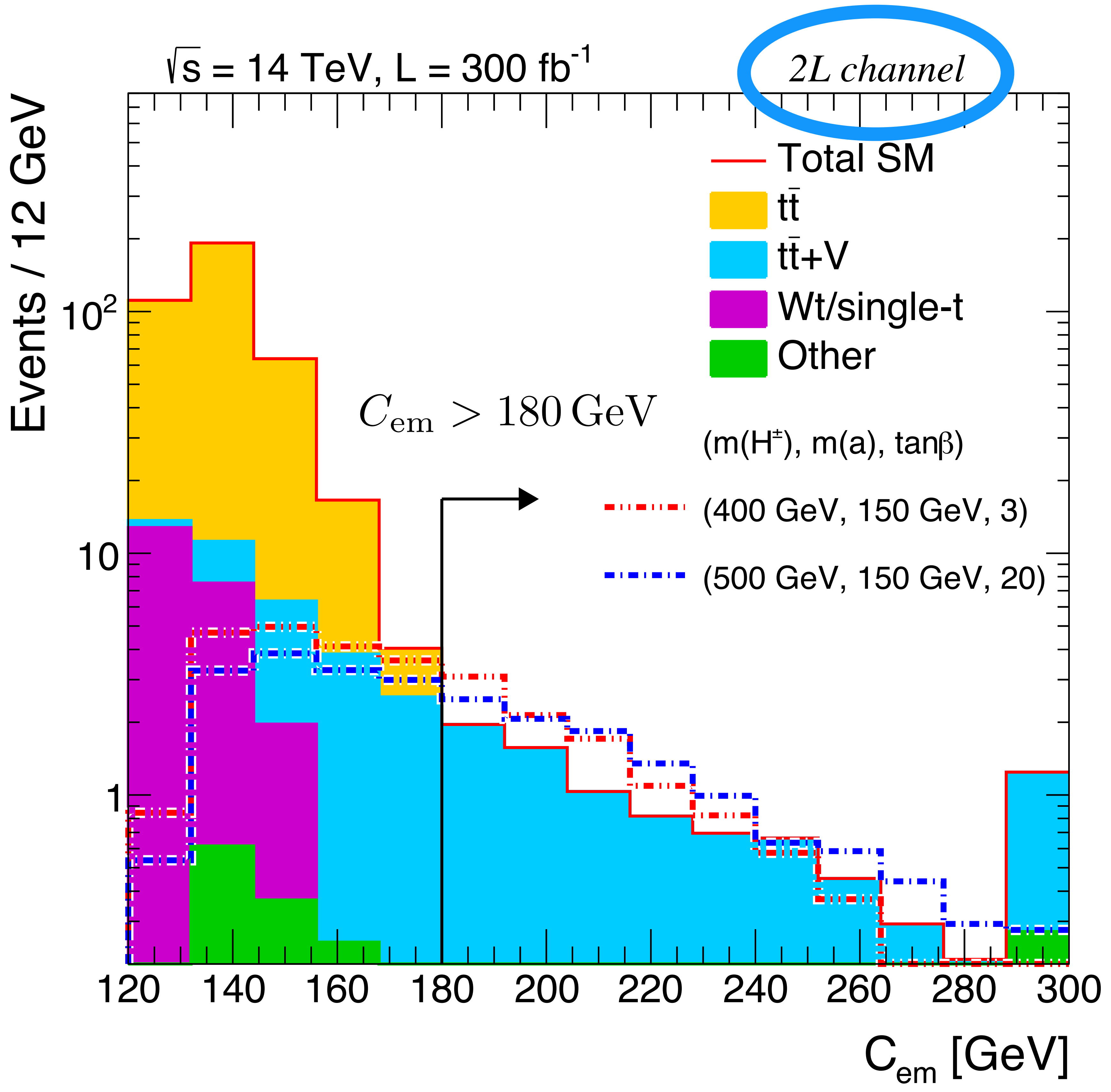


2HDM+a model: single-t plus $E_{T,miss}$

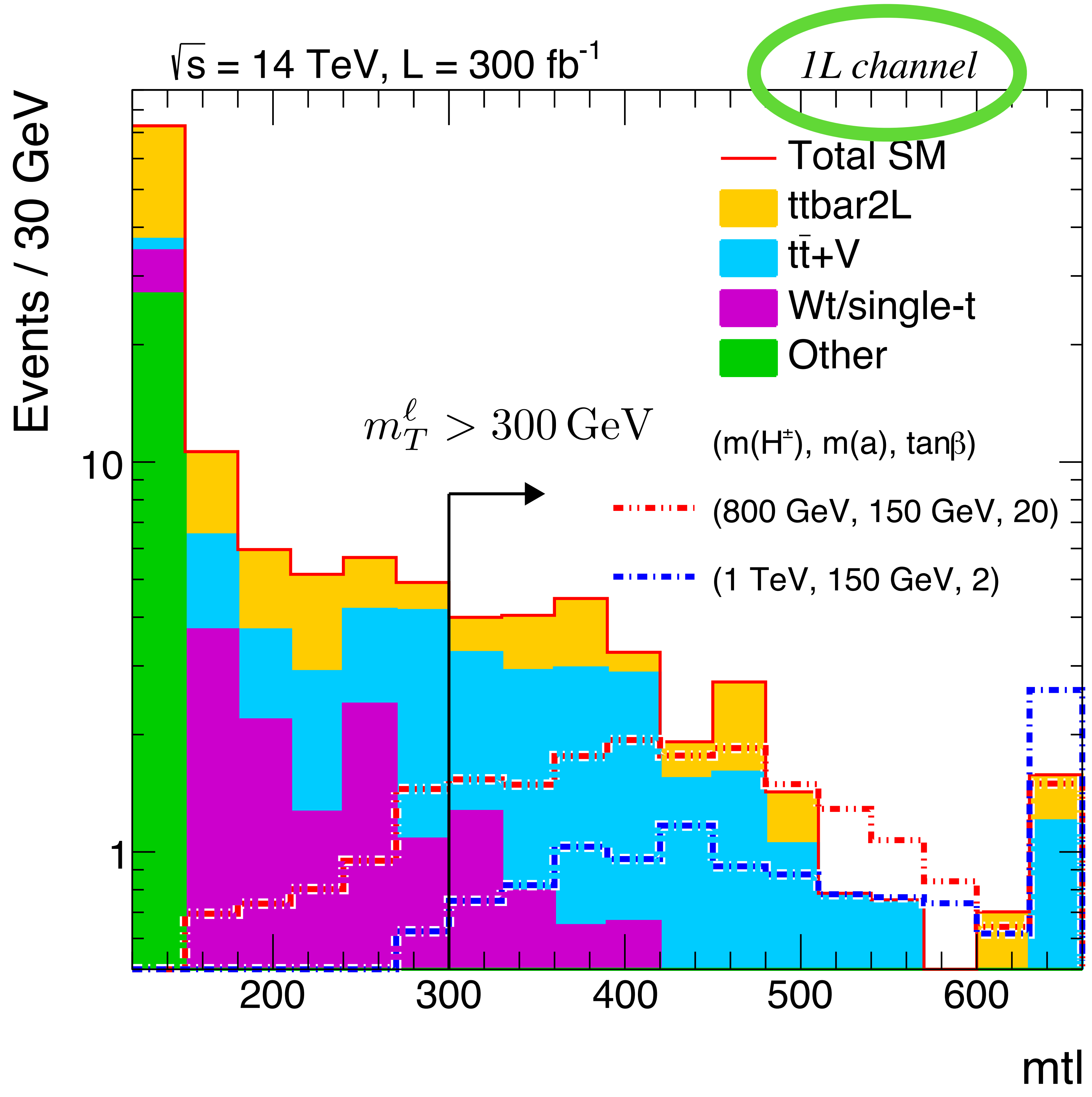


[Pani & Polesello, 1712.03874]

tW+$E_{T,miss}$ signal discriminants



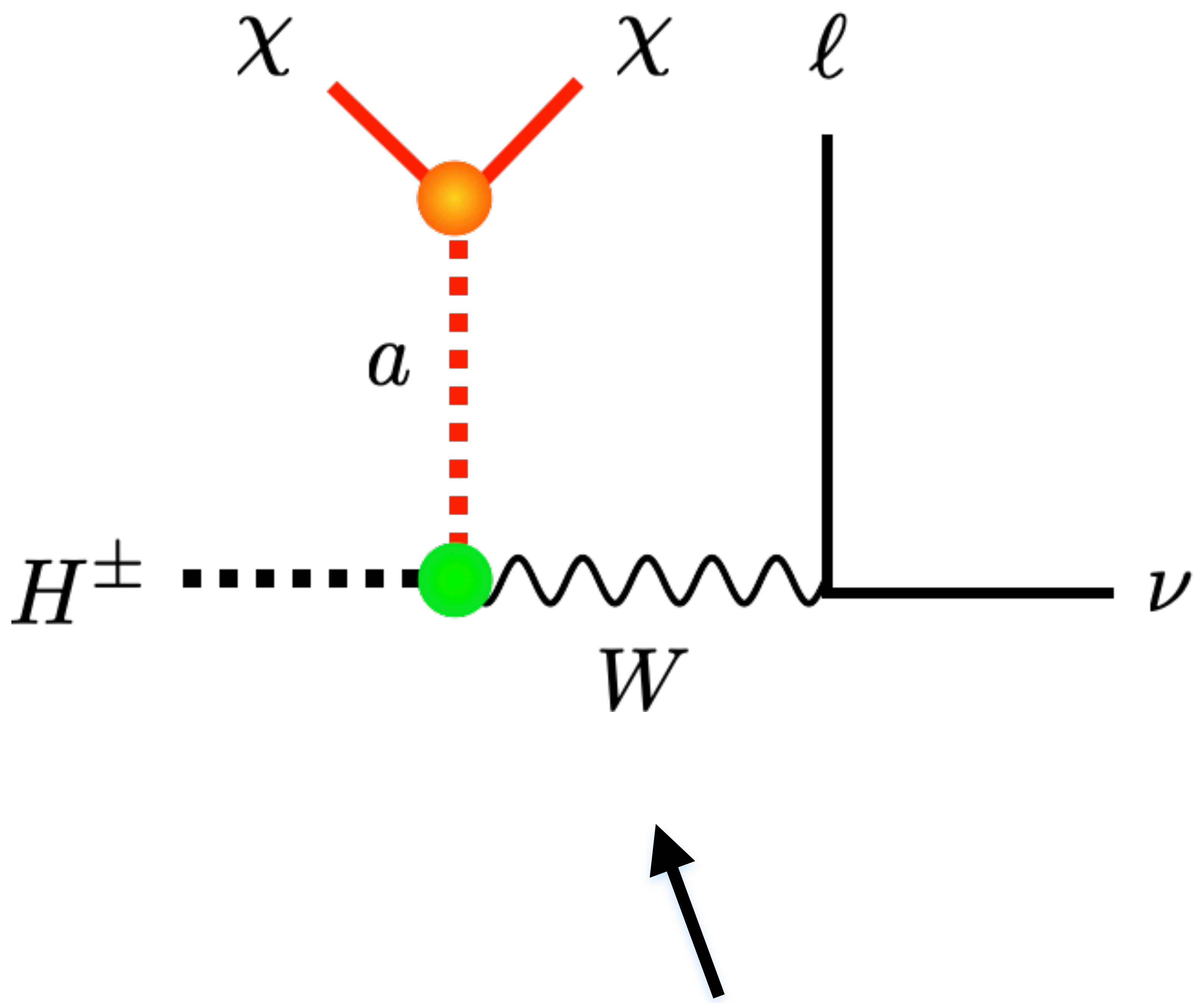
$$C_{em} = m_{T2} + 0.2\, E_T^{miss}$$



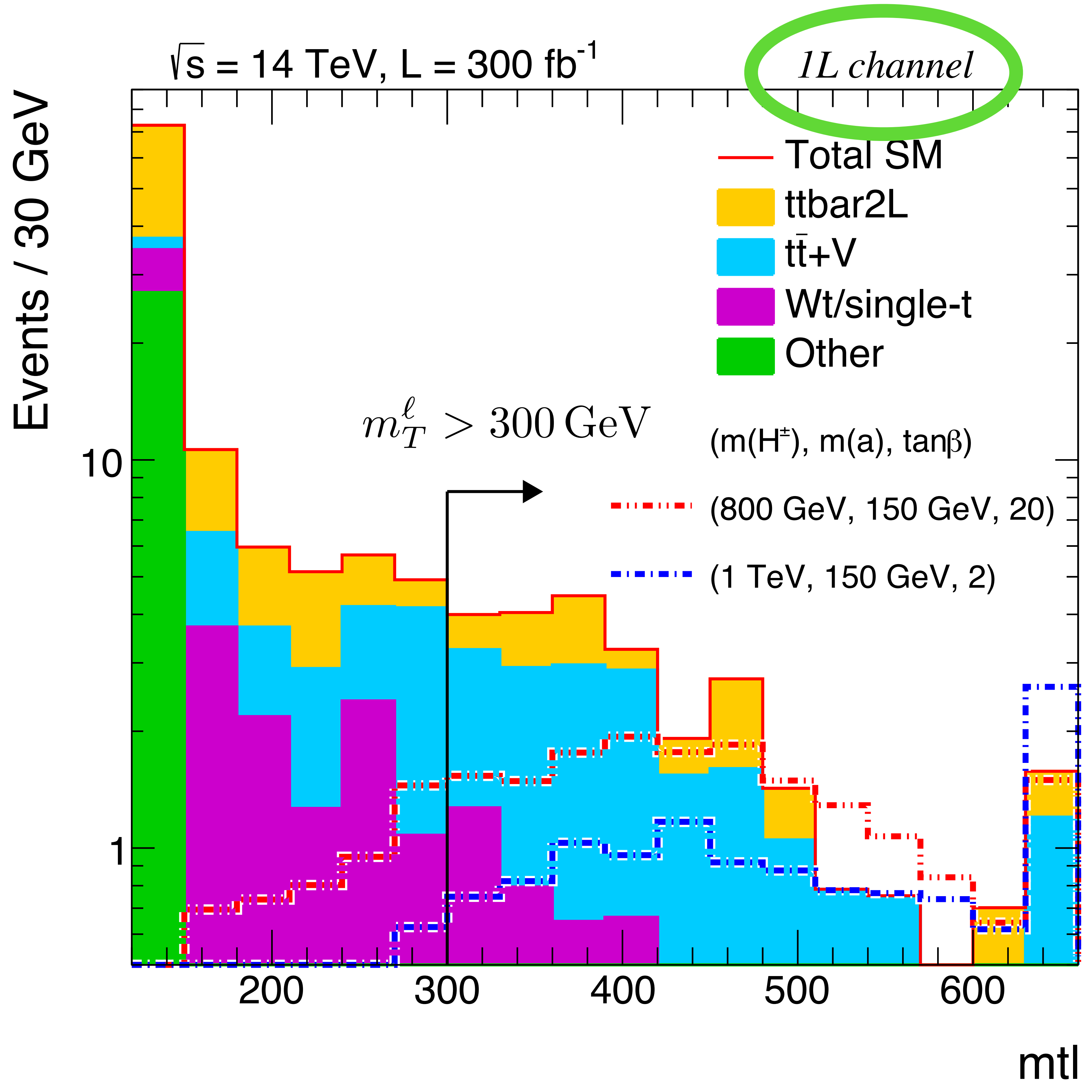
$$m_T^\ell = 2\,|\vec{p}_T^{\,\ell}|\,|\vec{p}_T^{\,miss}|\left(1 - \cos\Delta\phi_{\vec{p}_T^{\,\ell}\vec{p}_T^{\,miss}}\right)$$

[Pani & Polesello, 1712.03874]

tW+$E_{T,miss}$ signal discriminants



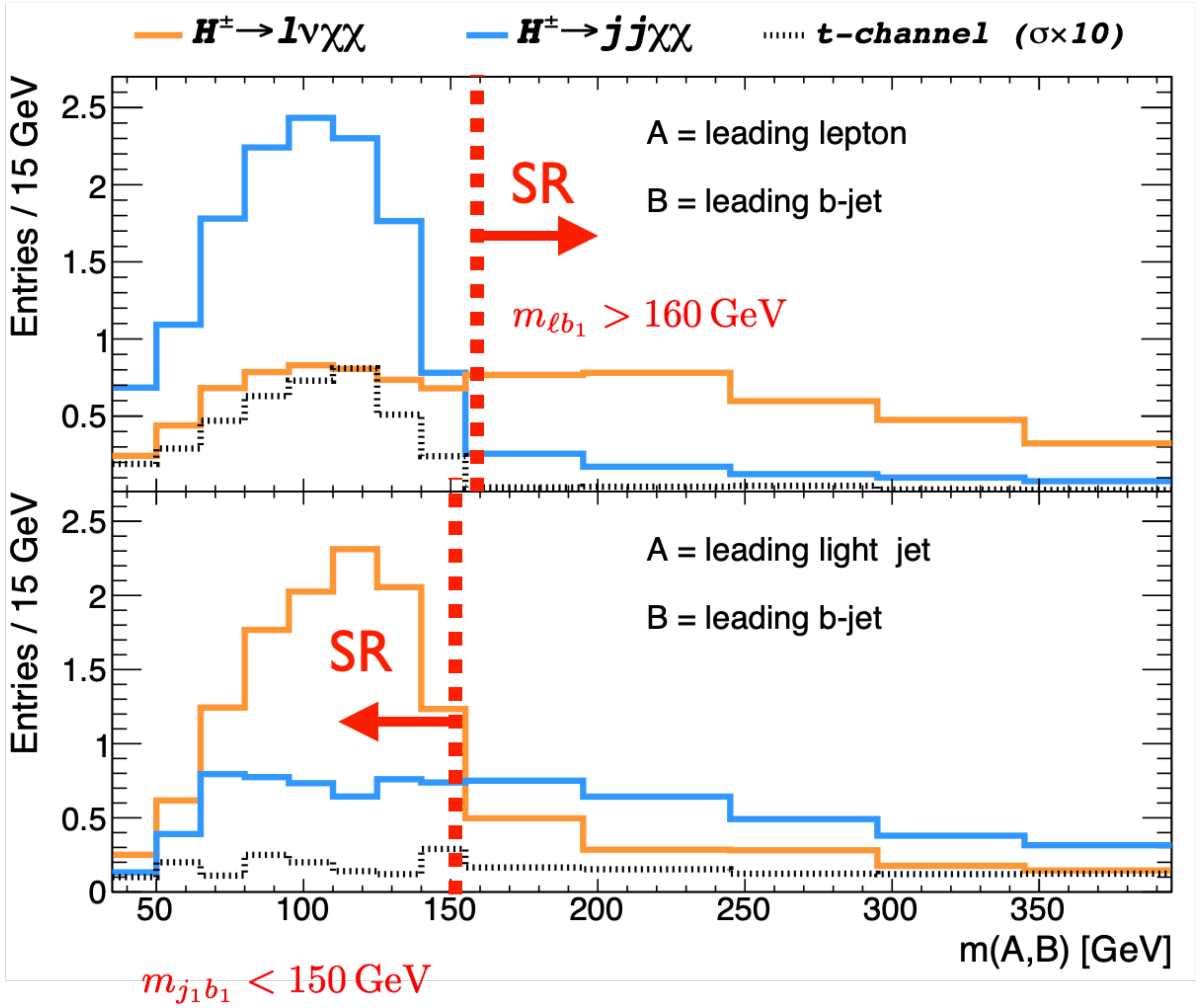
$H^{\pm}$ decay chain leads to endpoint in m_T^l spectrum of one-lepton signal



$$m_T^\ell = 2\,|\vec{p}_T^{\,\ell}|\,|\vec{p}_T^{\,\rm miss}|\,\left(1 - \cos\Delta\phi_{\vec{p}_T^{\,\ell}\vec{p}_T^{\,\rm miss}}\right)$$

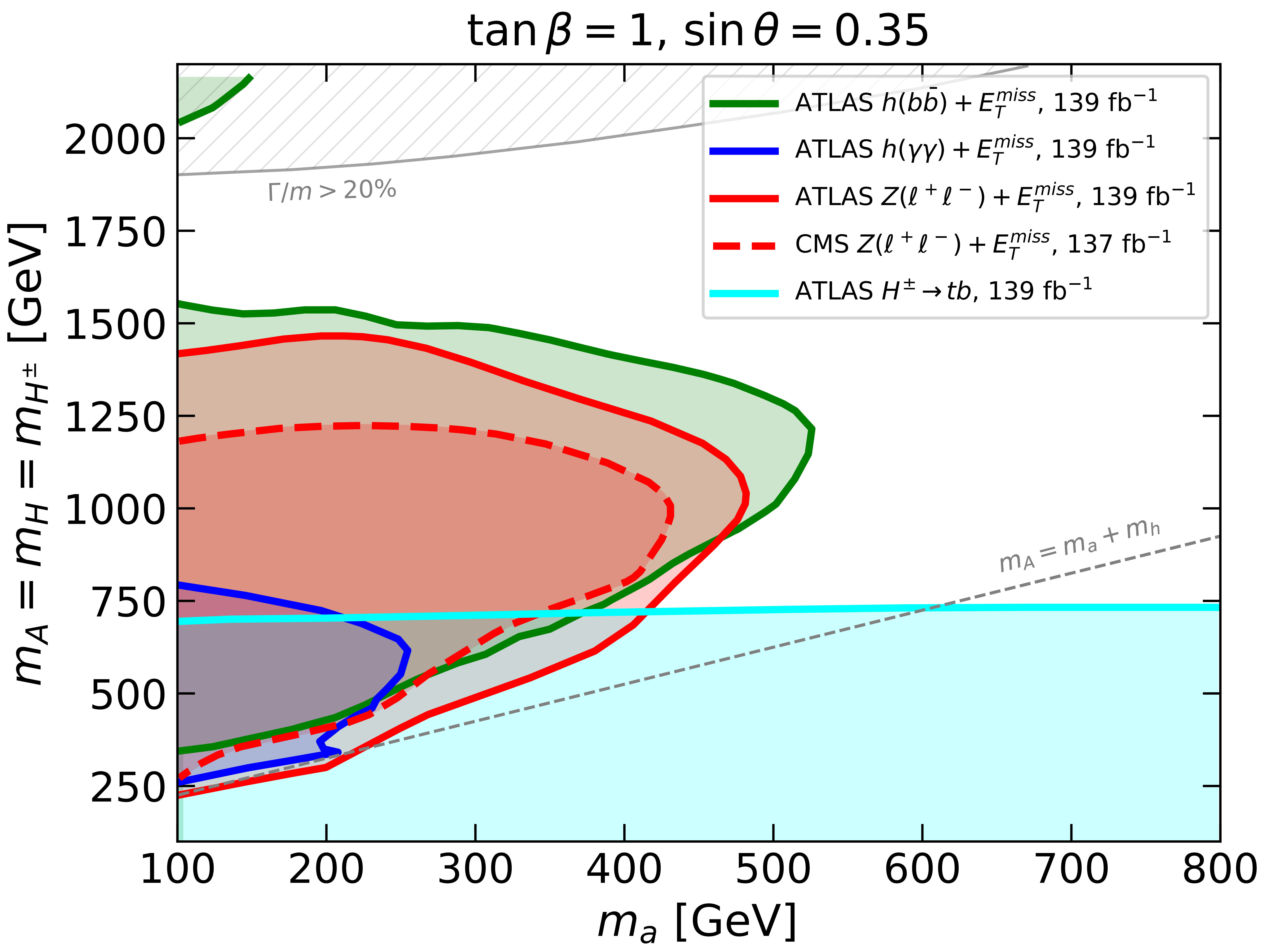
[Pani & Polesello, 1712.03874]

tW+$E_{T,miss}$ signal discriminants



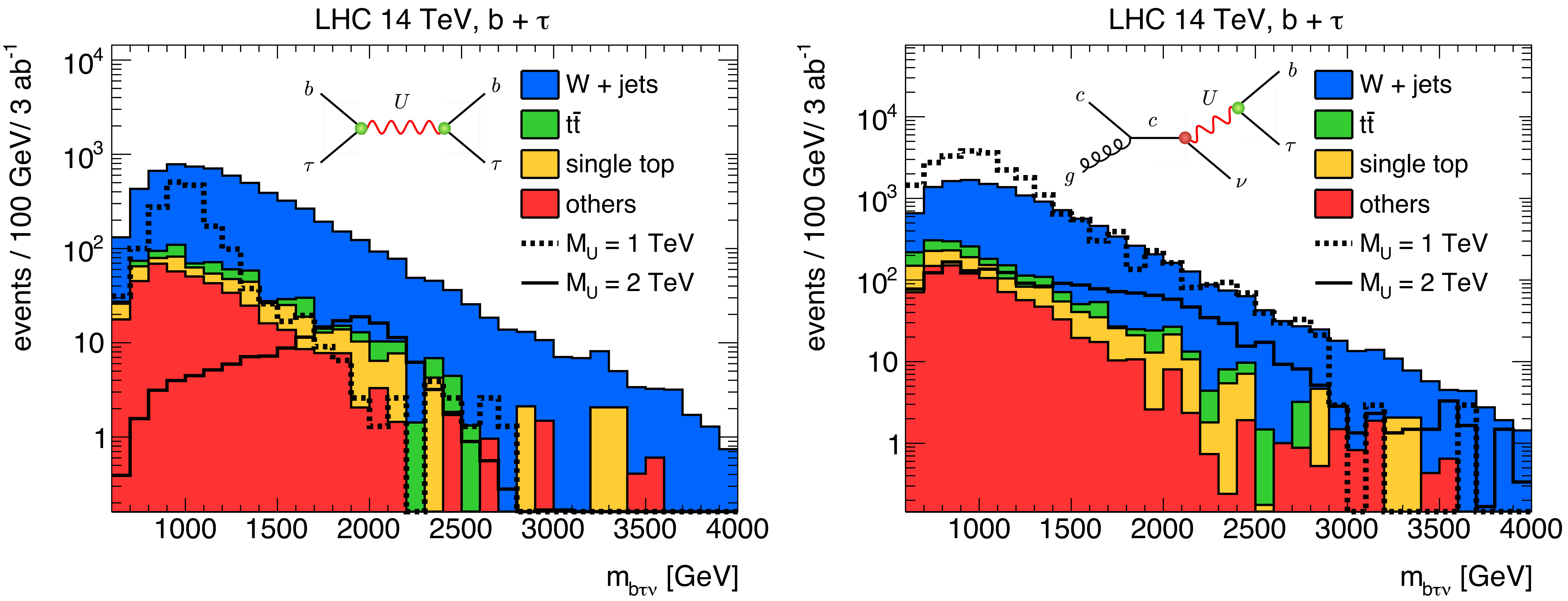
[Pani & Polesello, 1712.03874]

Constraints on 2HDM+a model



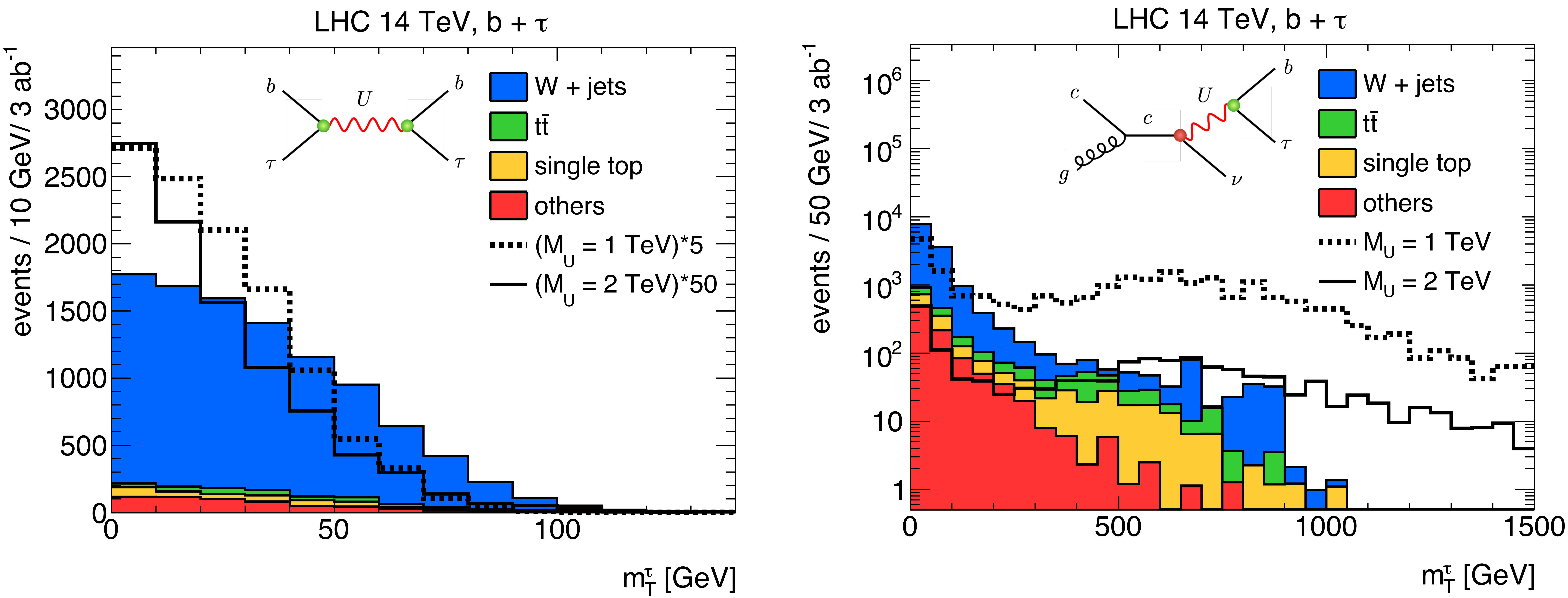
[Agryopoulos, Brandt & UH, 2109.13597]

Kinematic distributions of bτ signal



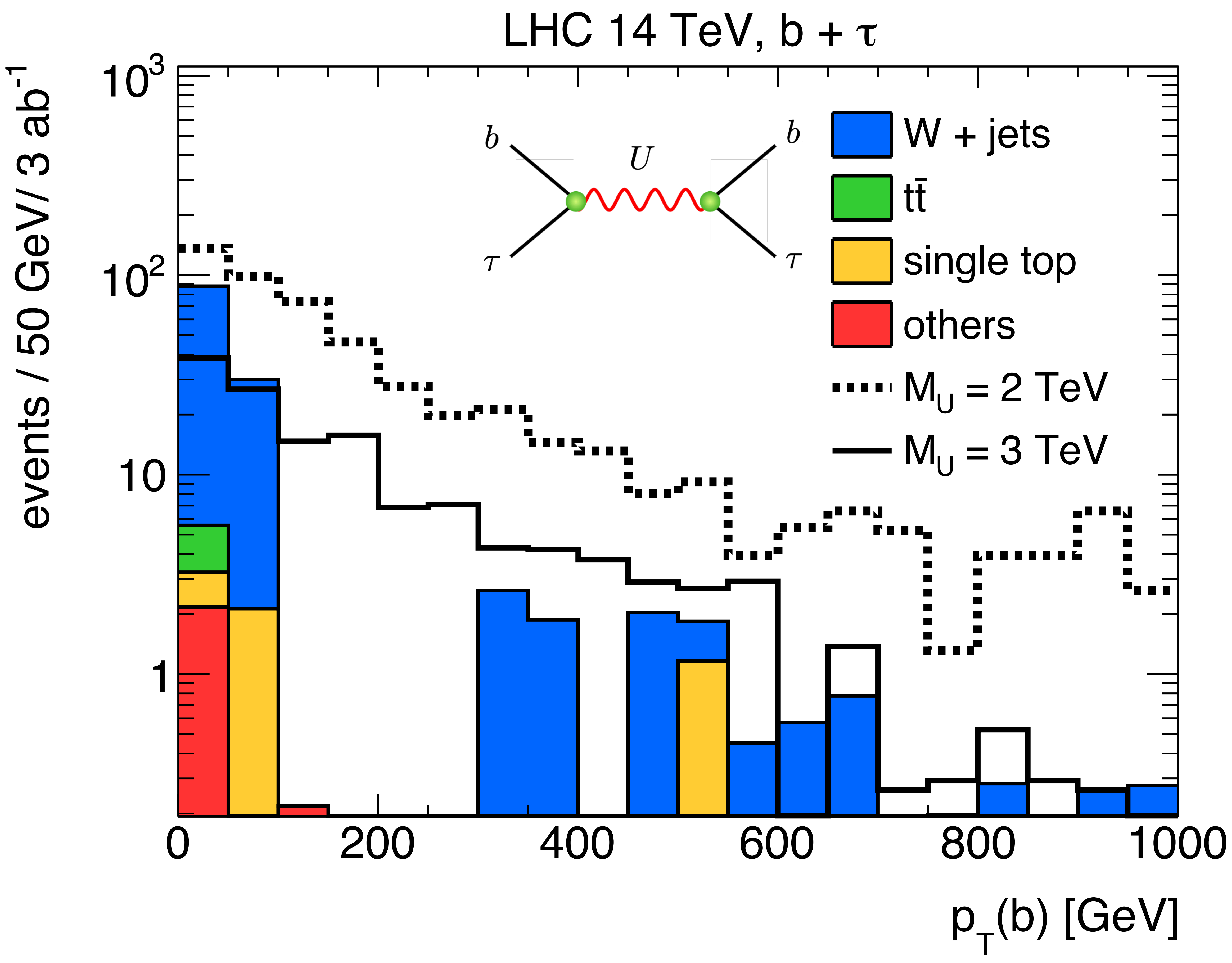
[UH & Polesello, 2012.11474]

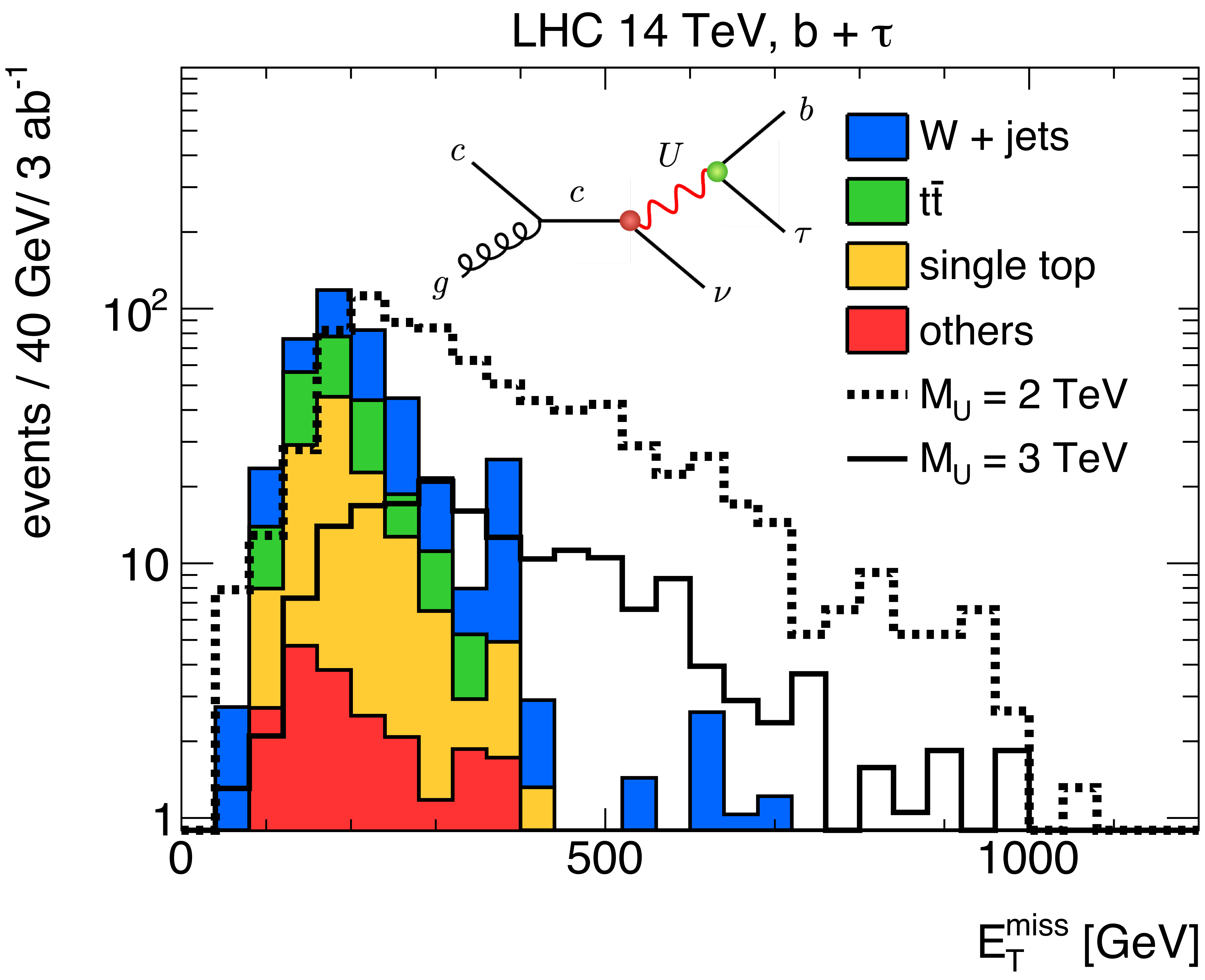
Kinematic distributions of bτ signal



[UH & Polesello, 2012.11474]

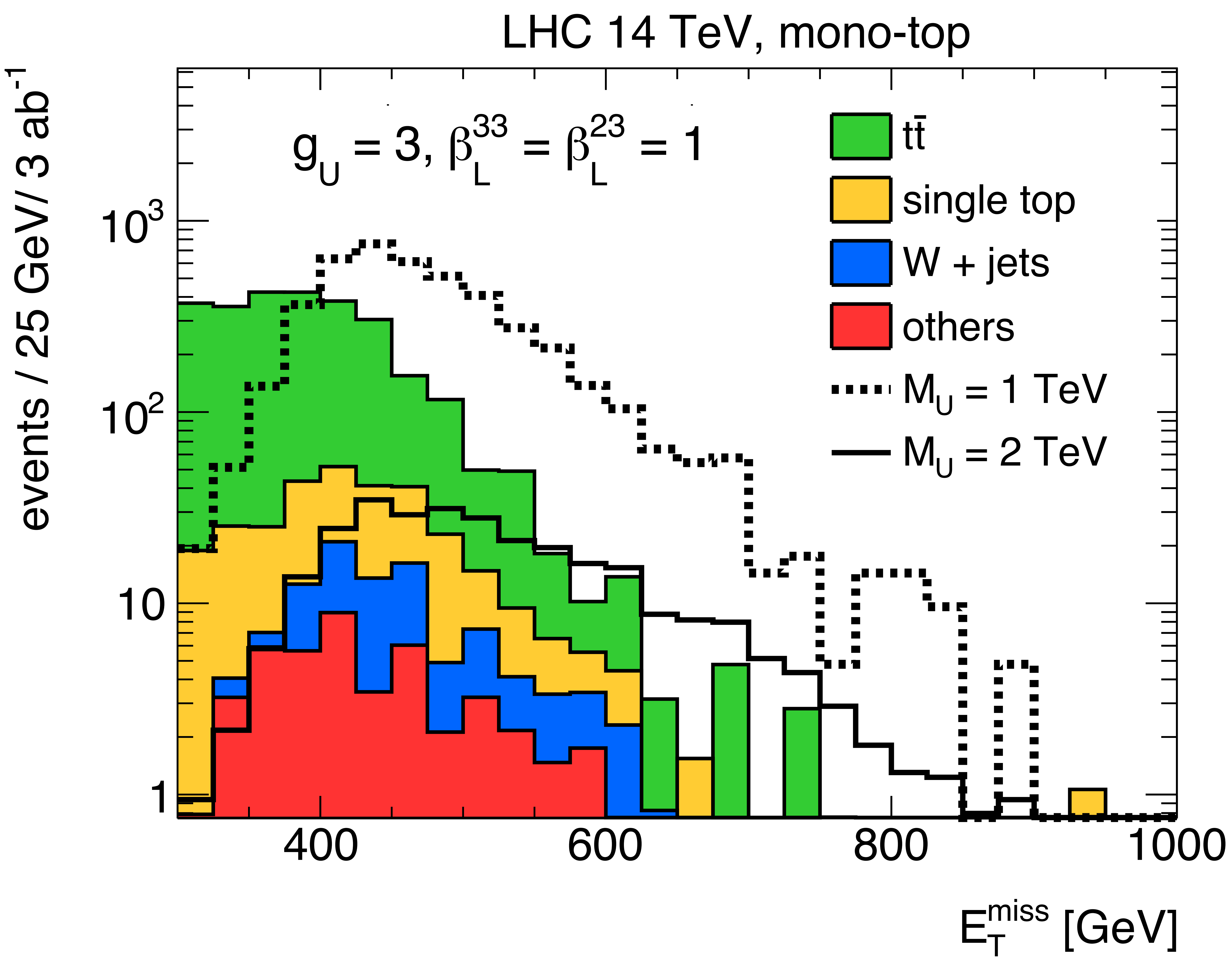
Kinematic distributions of bτ signal





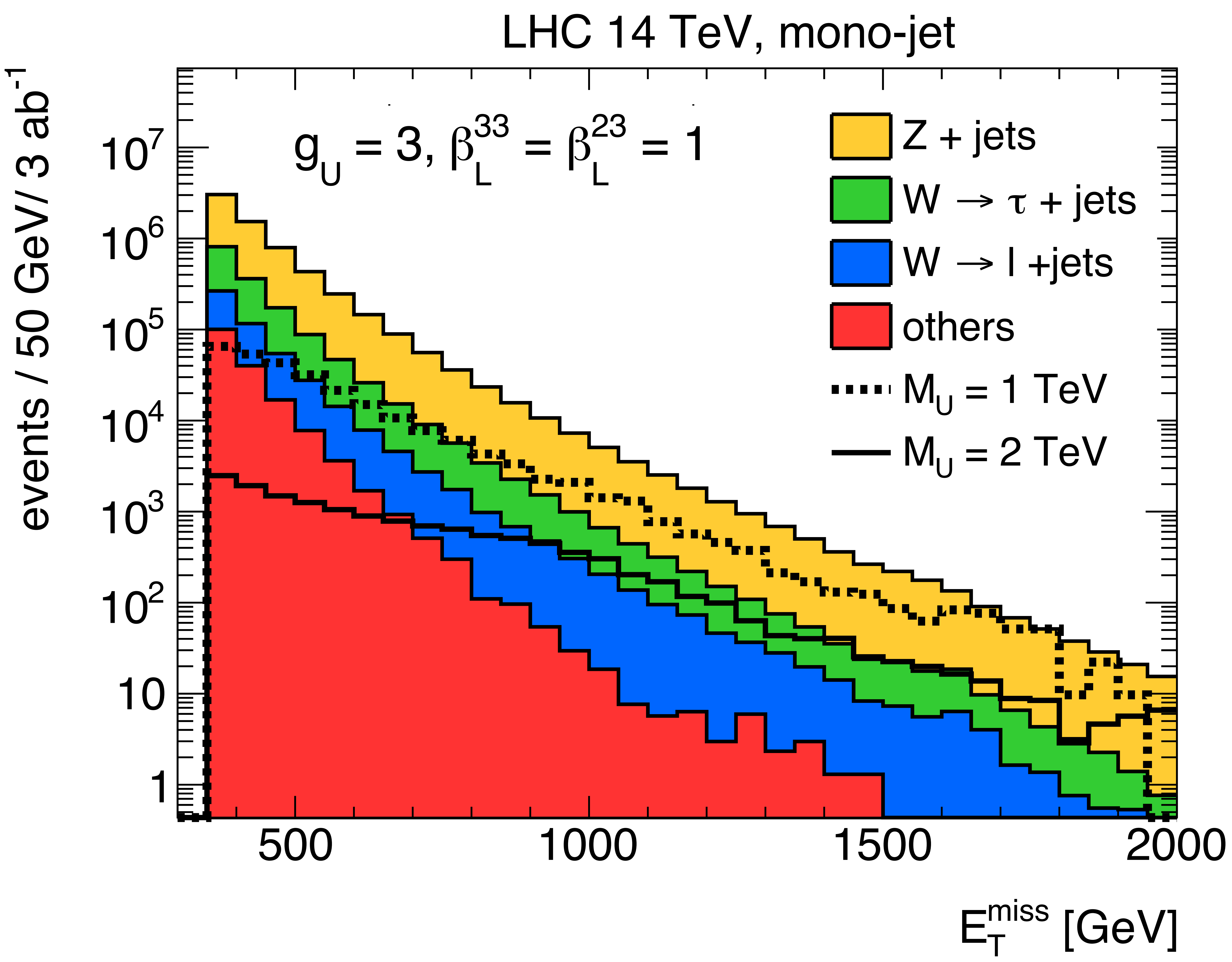
[UH & Polesello, 2012.11474]

Mono-top distributions



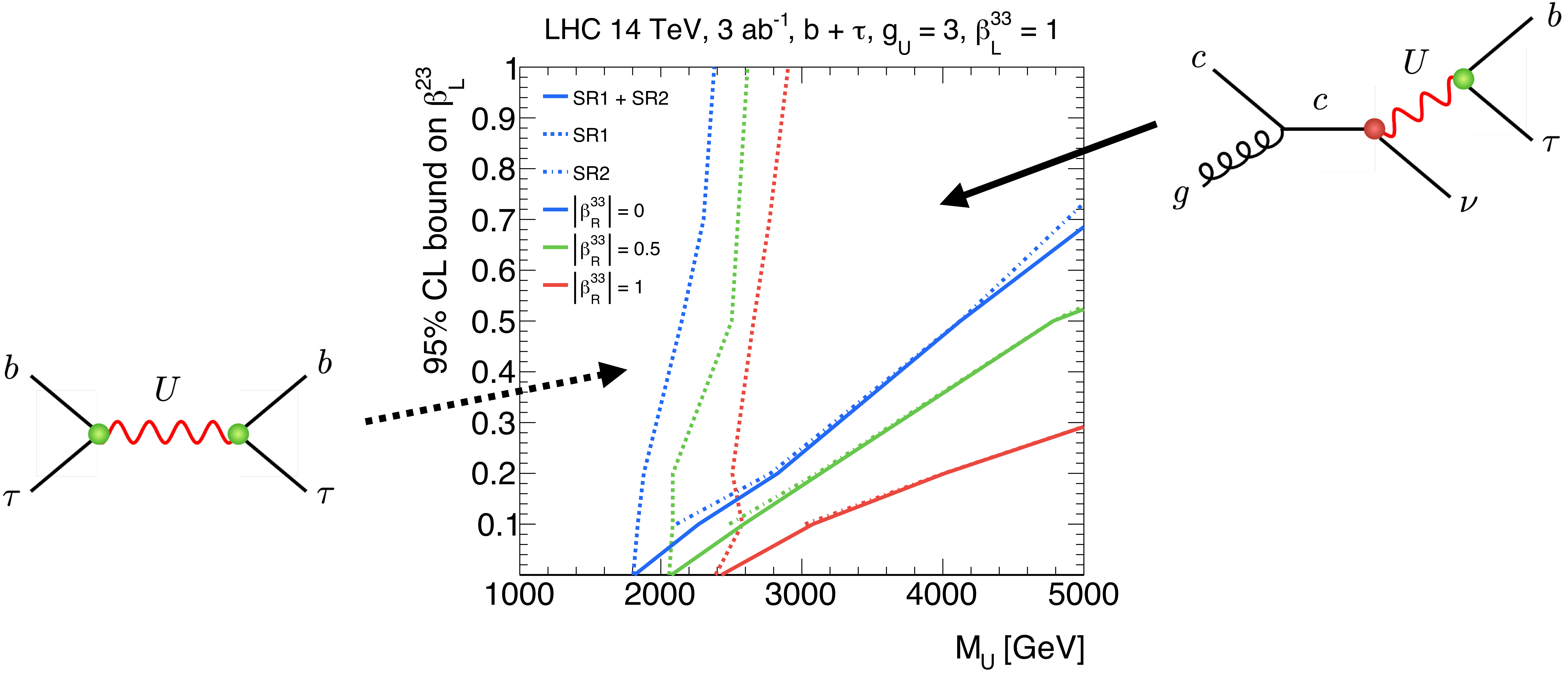
[UH & Polesello, 2012.11474]

Mono-jet distributions



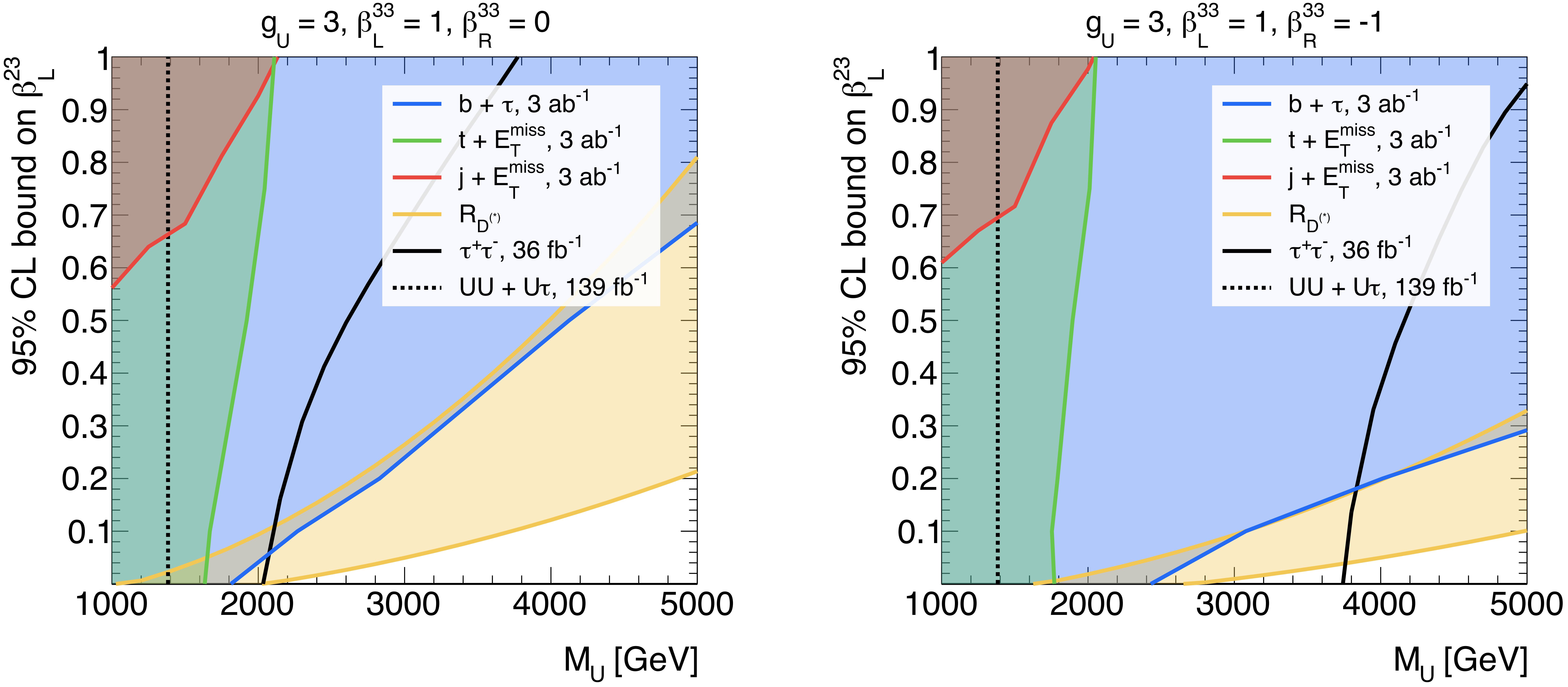
[UH & Polesello, 2012.11474]

bτ constraints from 2→2 & 2→3 processes



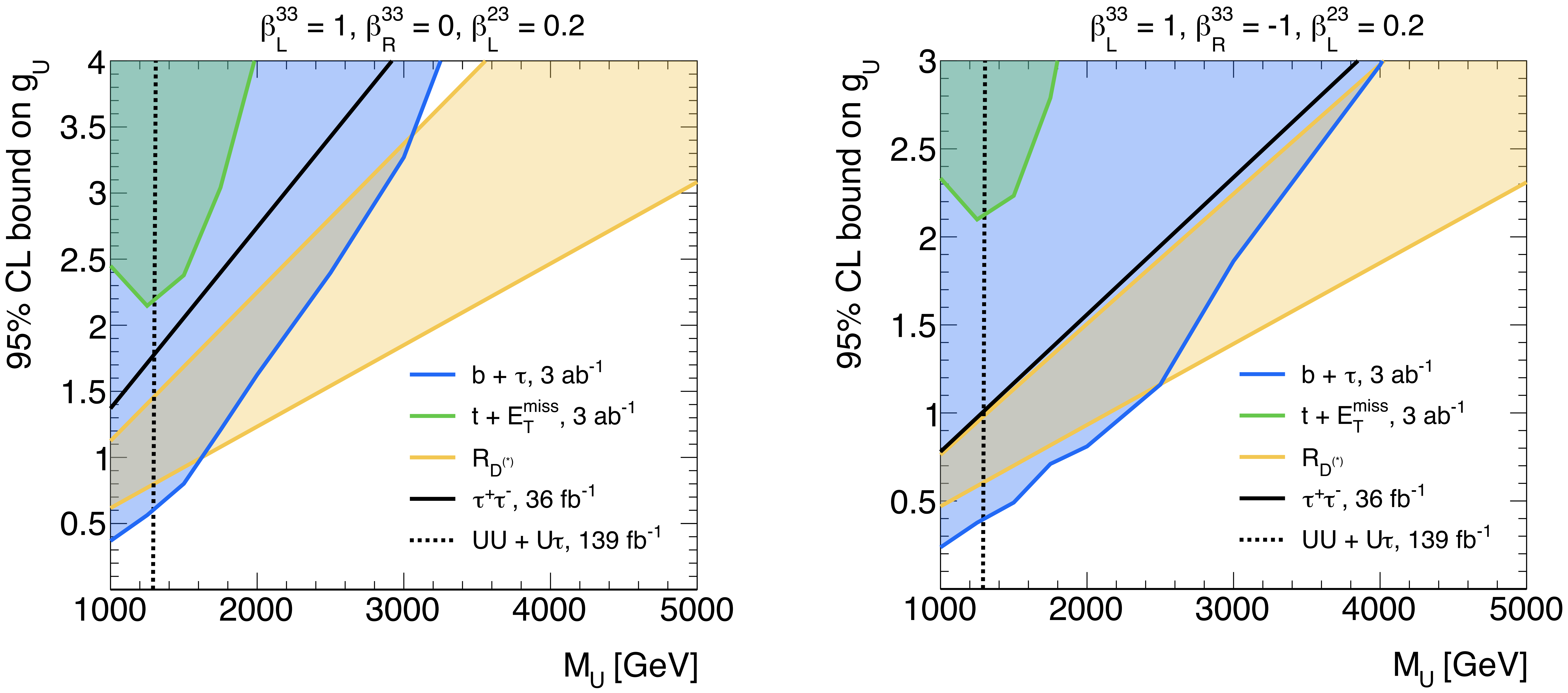
[UH & Polesello, 2012.11474]

Comparison of LQ search strategies



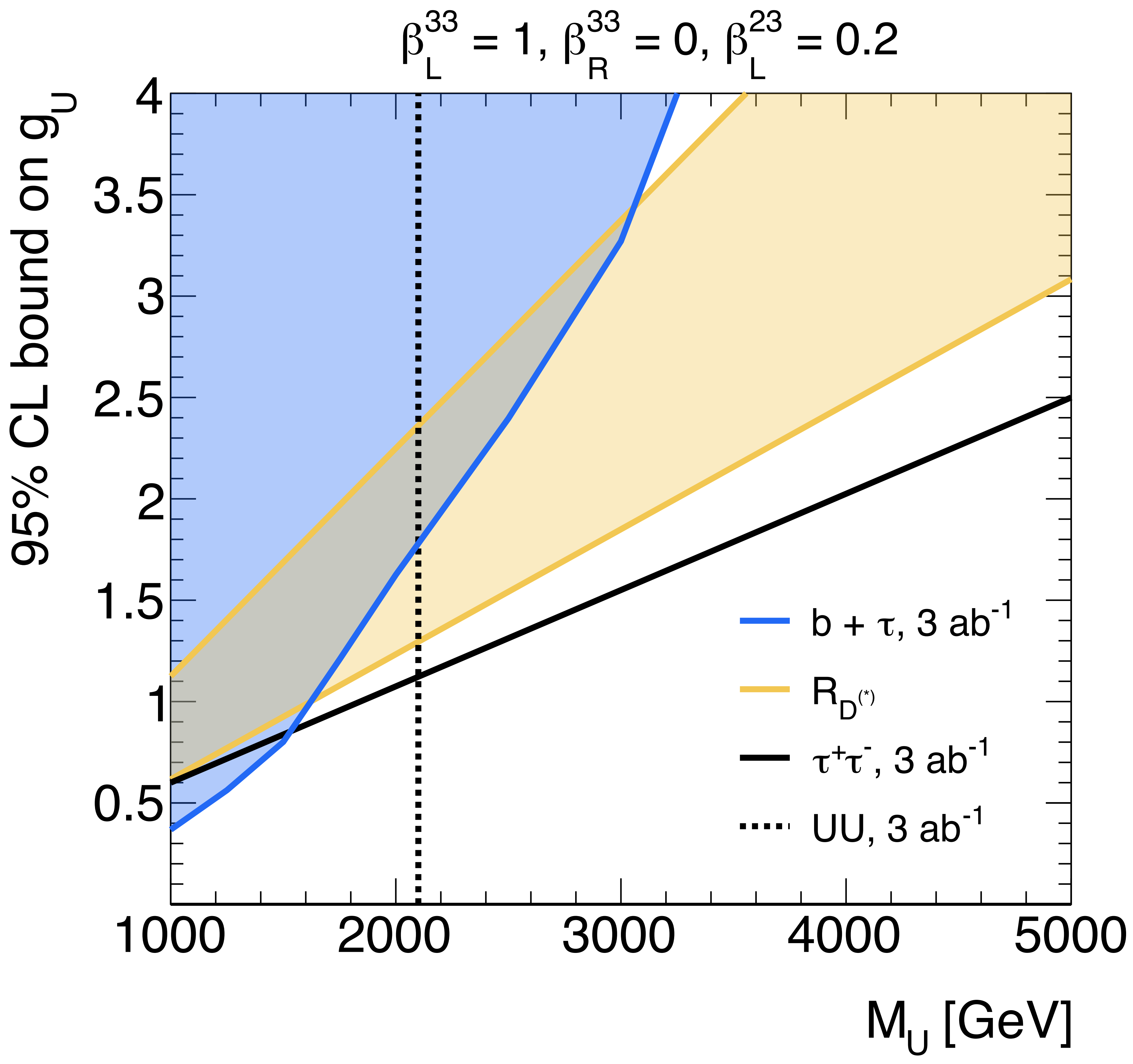
[UH & Polesello, 2012.11474]

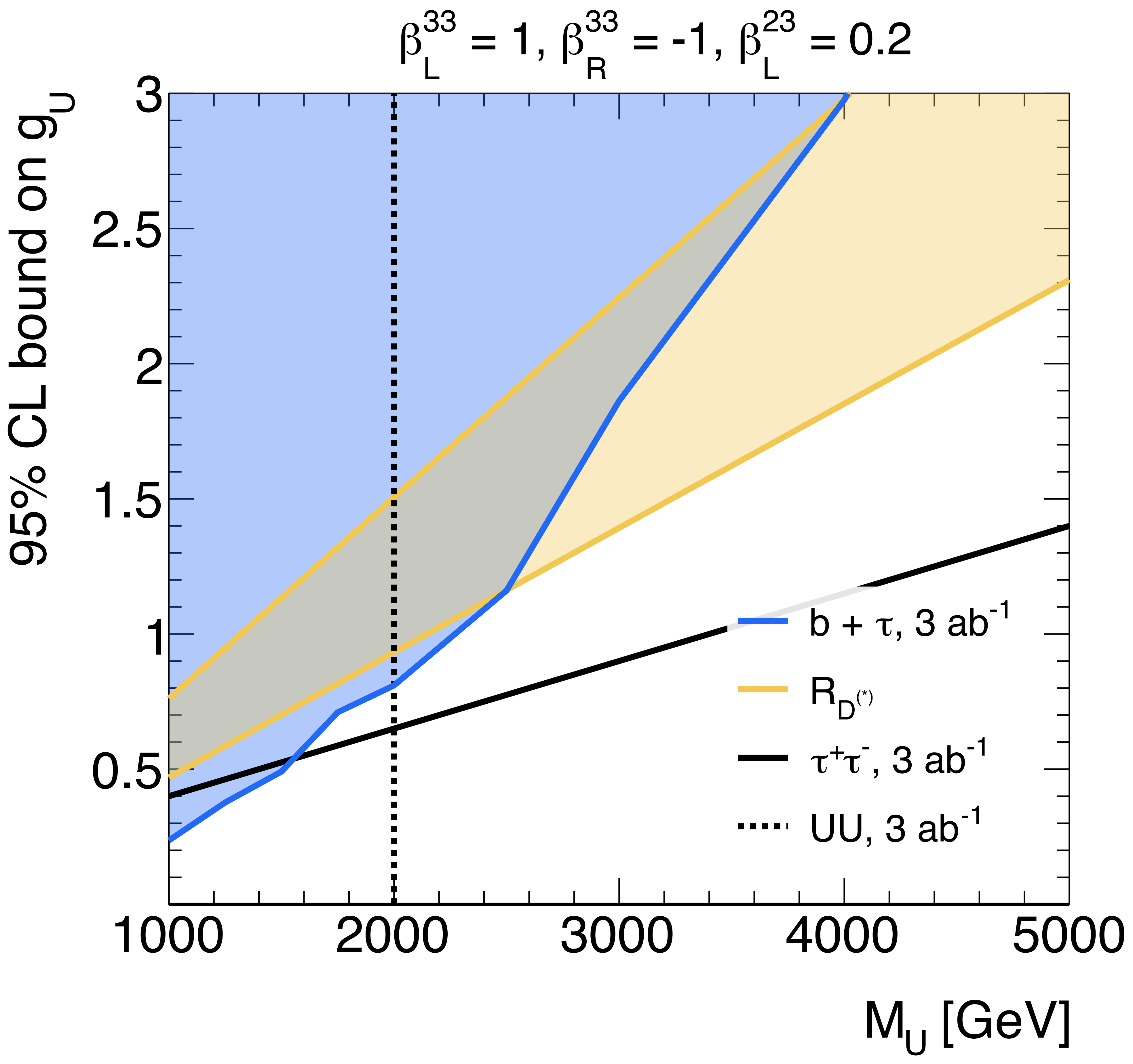
Comparison of LQ search strategies



[UH & Polesello, 2012.11474]

Prospects of LQ search strategies





[UH & Polesello, 2012.11474; Cornella et al., 2103.16558]