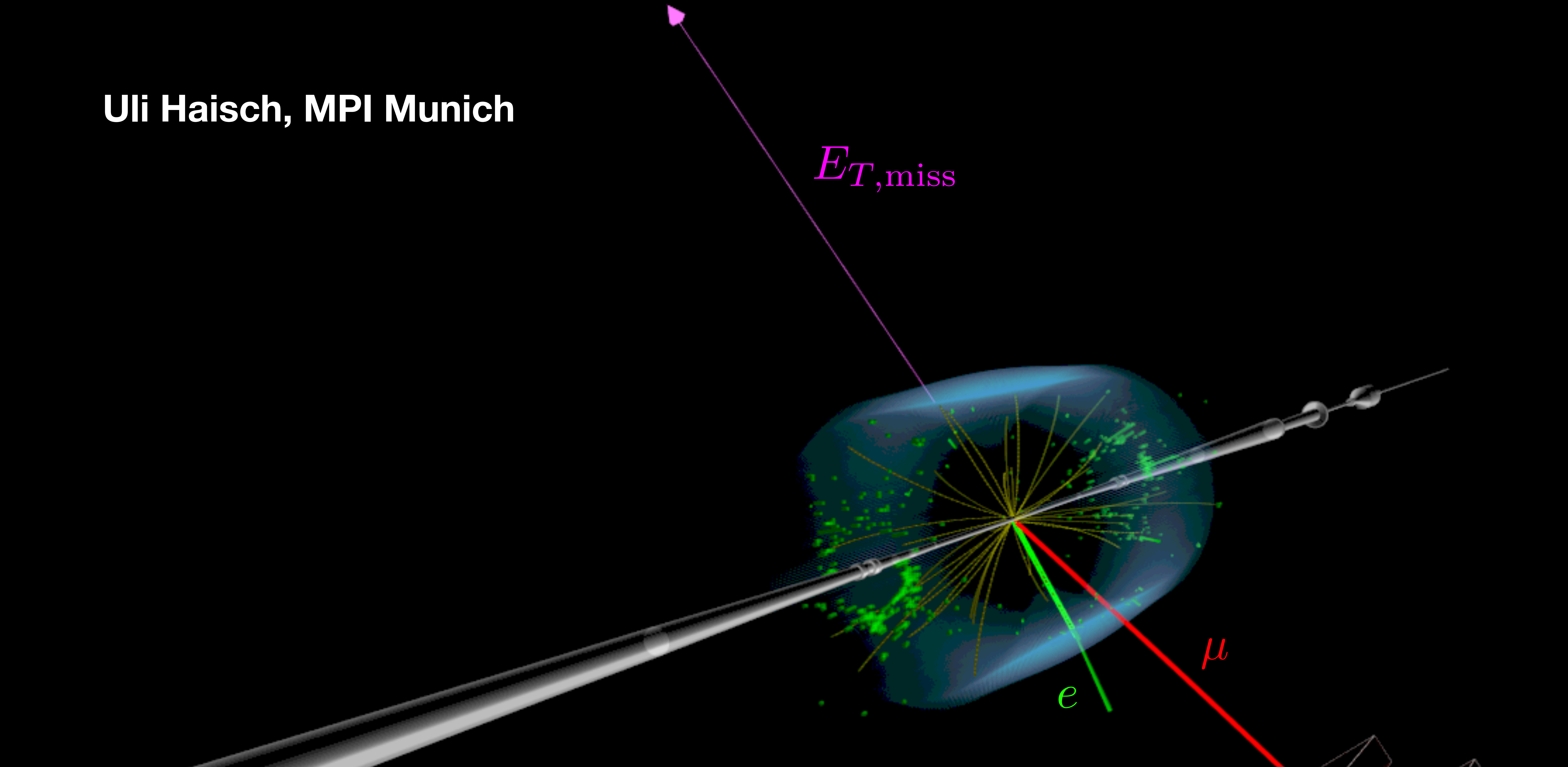
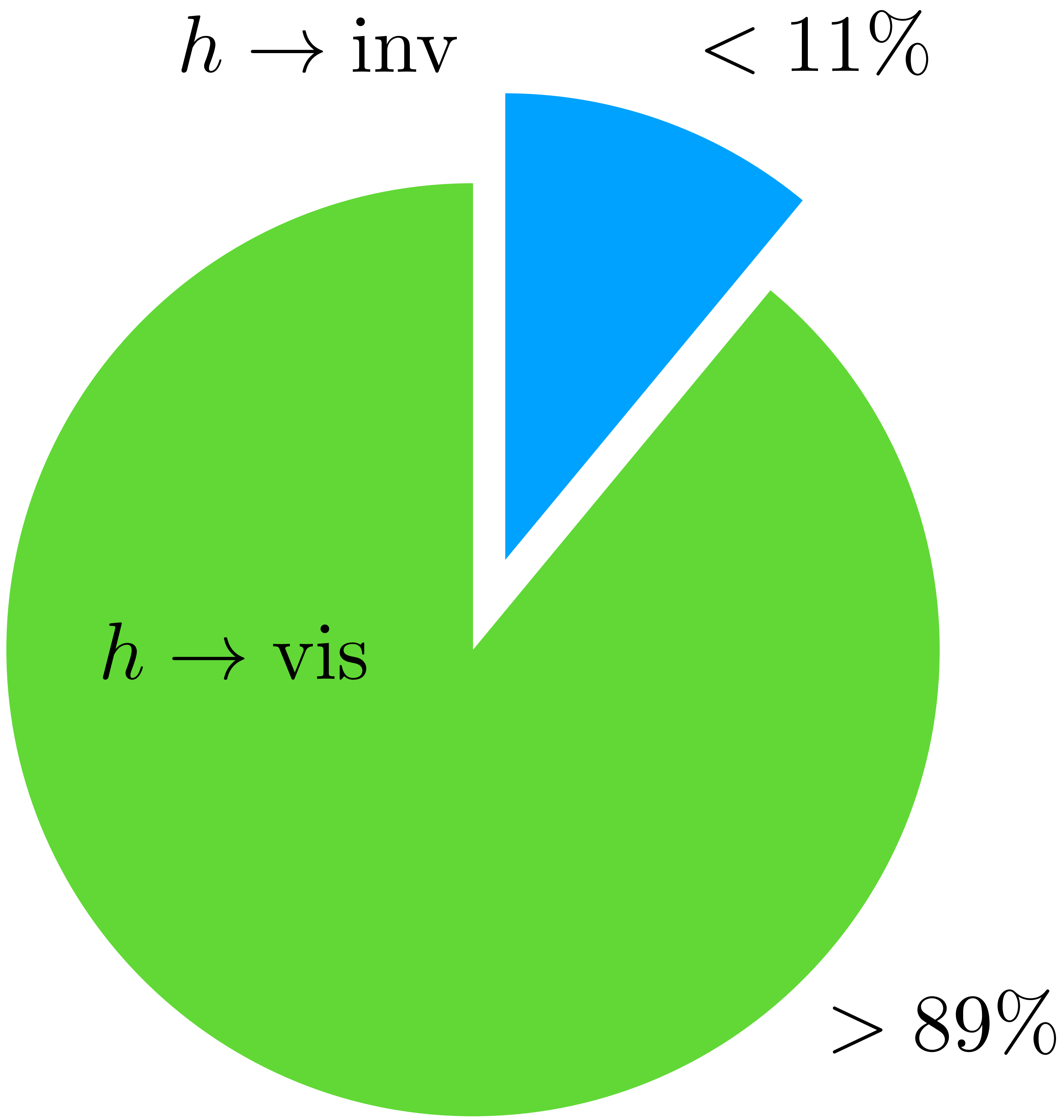
Uli Haisch, MPI Munich

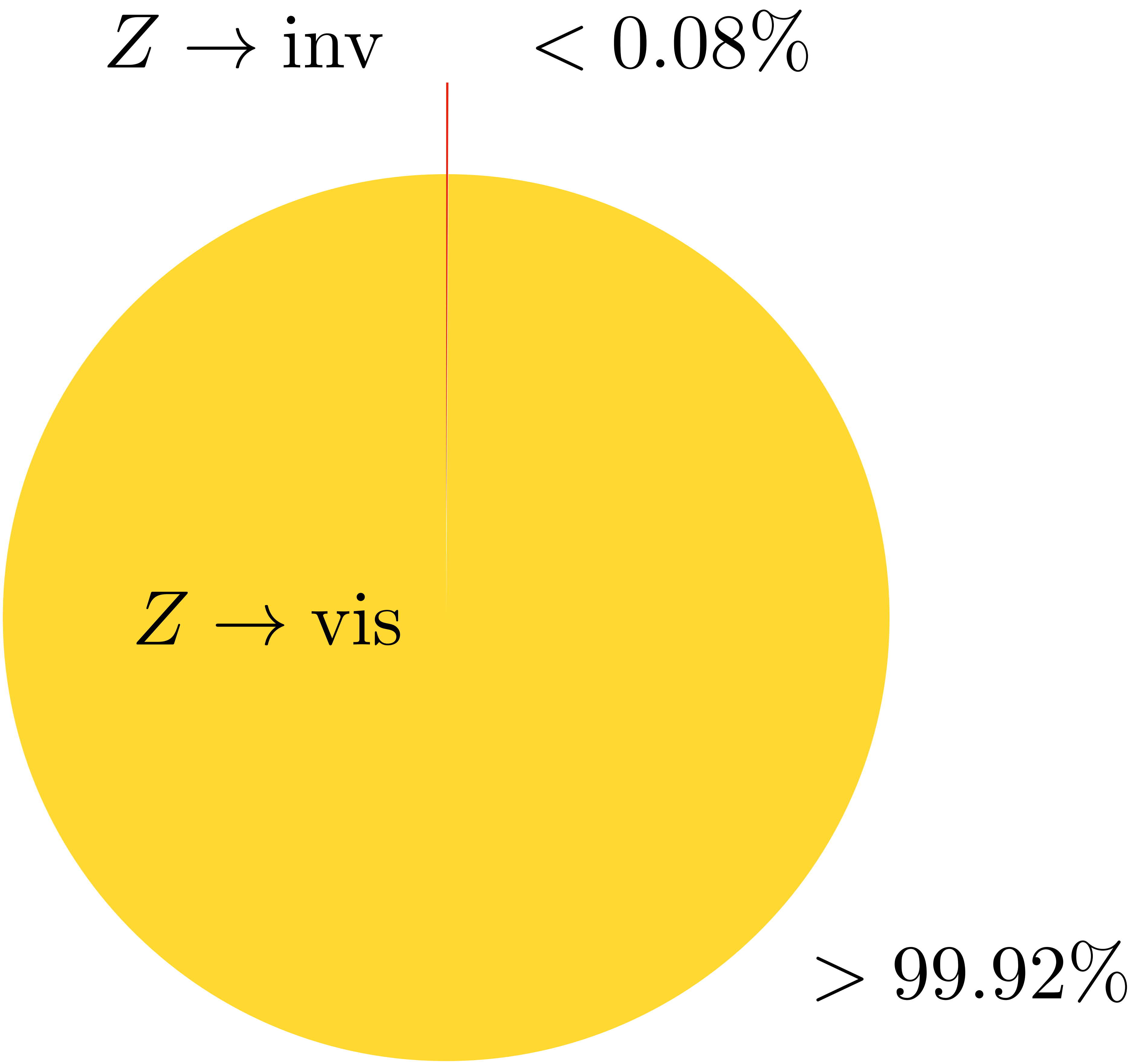


Collider searches for dark matter (DM) through the Higgs lens

Particle and Astroparticle Theory Seminar, MPIK Heidelberg, 16.1.23

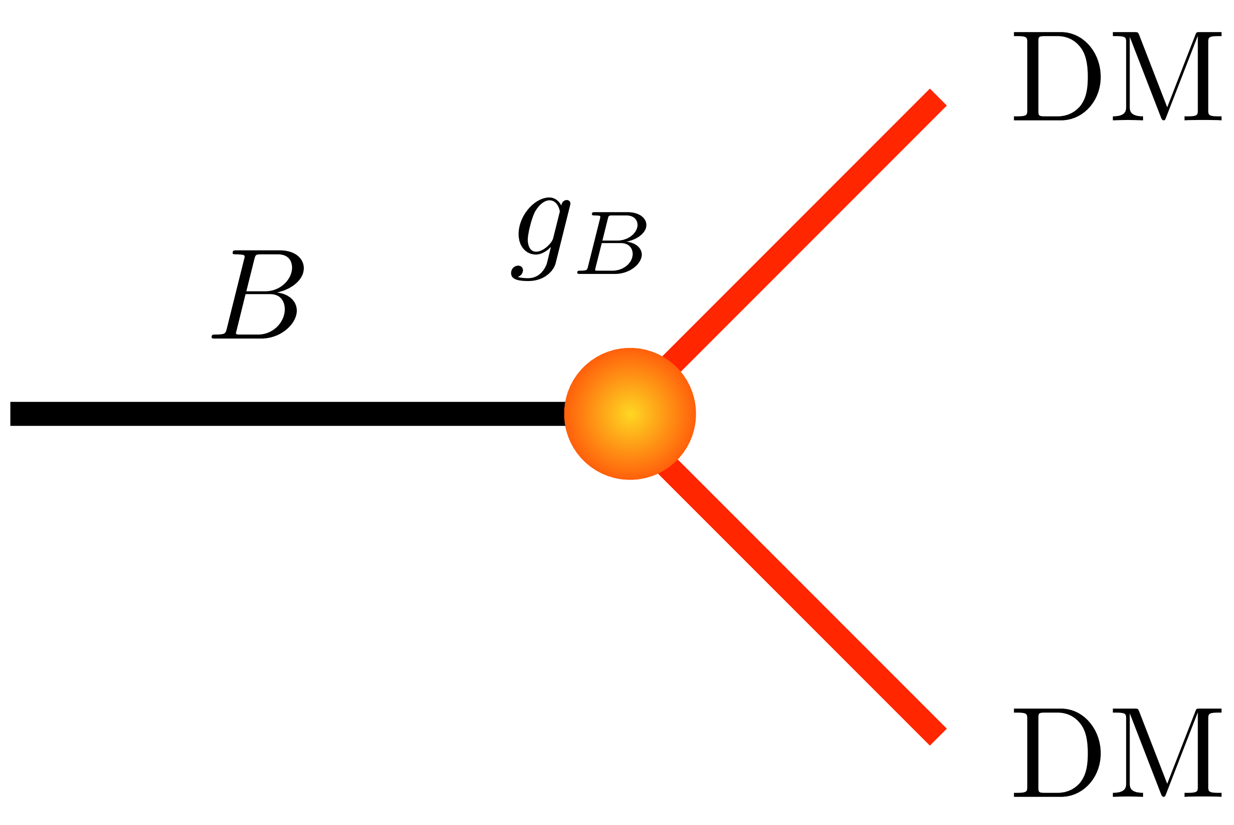
Invisible decays of neutral gauge bosons





[quoted number of Z→inv branching ratio (BR) includes only additional invisible contribution but not decays to neutrinos]

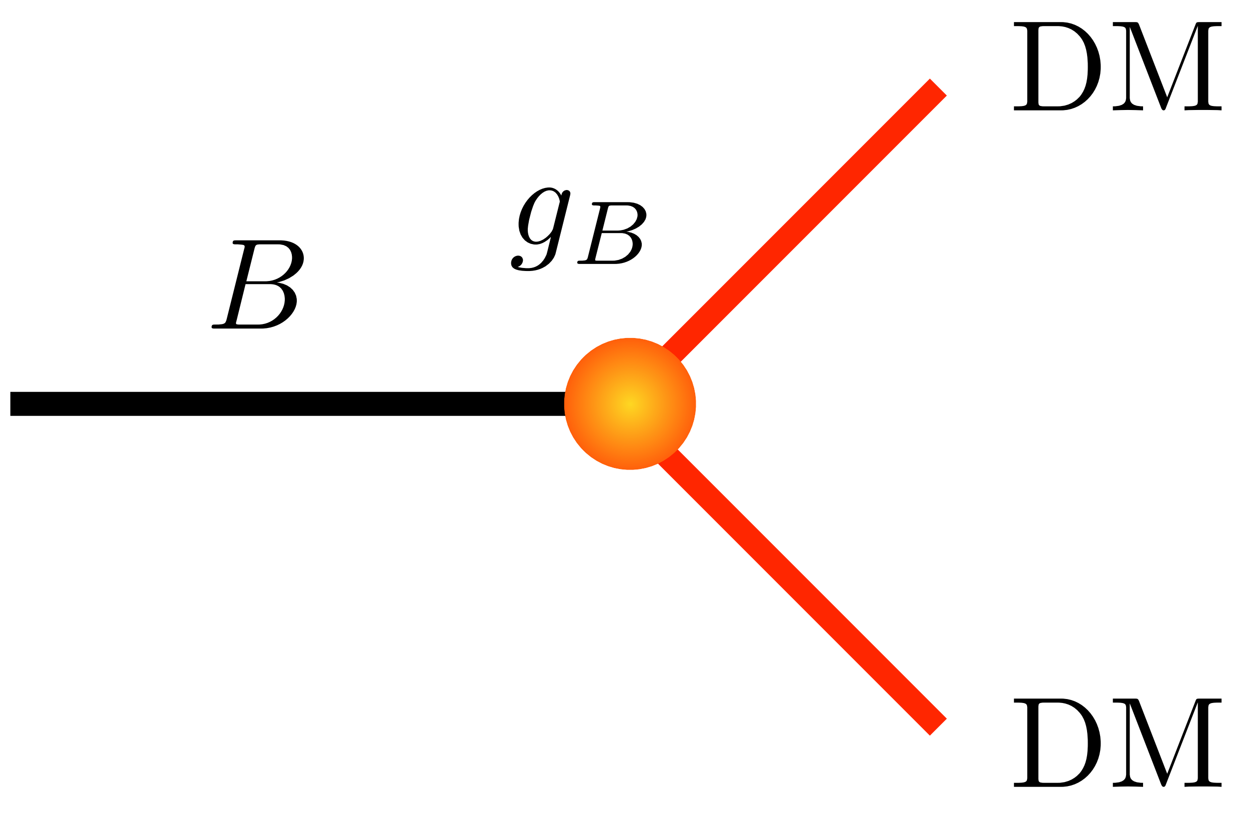
So why Higgs lens & not Z lens?



$$\Rightarrow \qquad \Gamma(B \to \mathrm{DM\,DM}) \simeq \frac{g_B^2}{16\pi} m_B$$

$$\mathrm{BR}(B \to \mathrm{DM\,DM}) \simeq \frac{\Gamma(B \to \mathrm{DM\,DM})}{\Gamma_B^{\mathrm{SM}}}$$

So why Higgs lens & not Z lens?

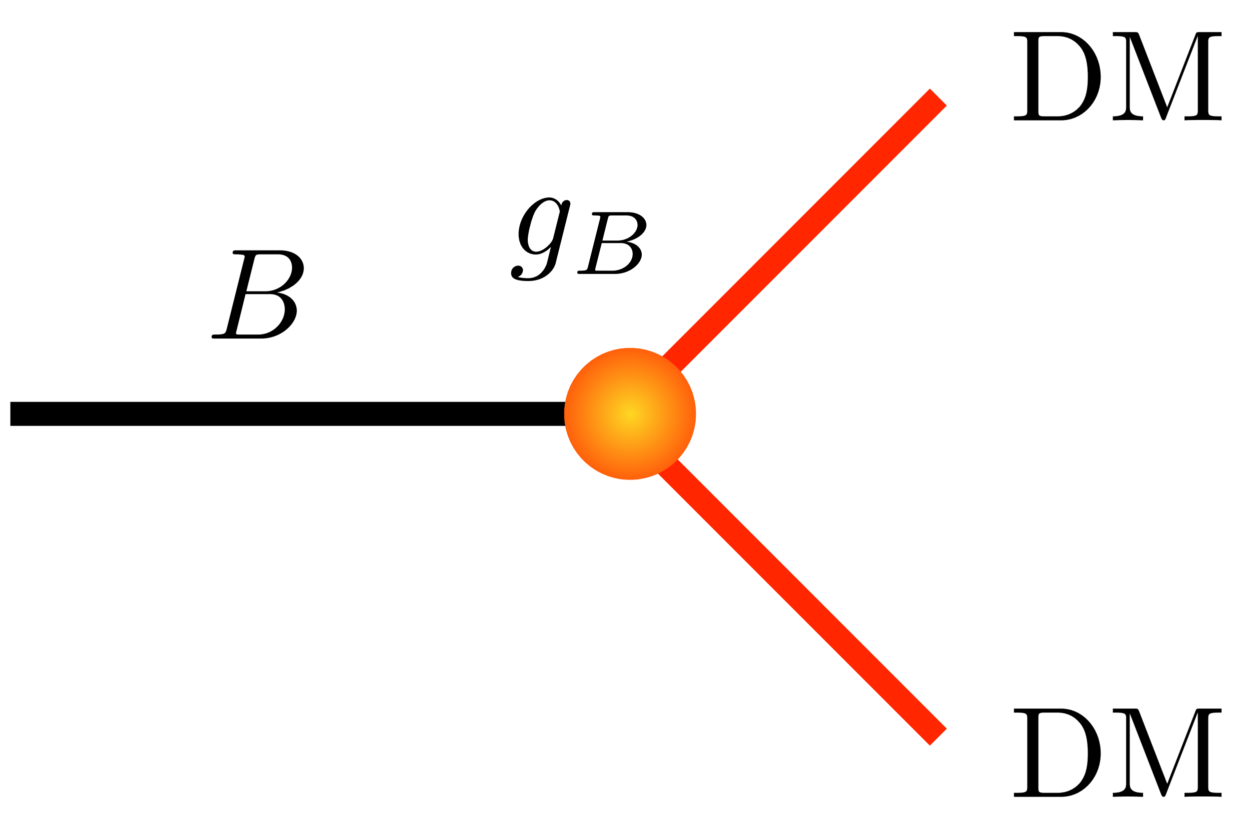


$$\Rightarrow \quad \Gamma(B \to \mathrm{DM\,DM}) \simeq \frac{g_B^2}{16\pi} m_B$$

$$\mathrm{BR}(B \to \mathrm{DM\,DM}) \simeq \frac{\Gamma(B \to \mathrm{DM\,DM})}{\Gamma_B^{\mathrm{SM}}}$$

$$\Gamma_Z^{\mathrm{SM}} \simeq 2.5\,\mathrm{GeV}\,, \quad \Gamma(Z \to \mathrm{DM\,DM}) \lesssim 2\,\mathrm{MeV} \quad \Rightarrow \quad g_Z \lesssim 0.03$$

So why Higgs lens & not Z lens?



$$\Rightarrow \qquad \Gamma(B \to \mathrm{DM}\,\mathrm{DM}) \simeq \frac{g_B^2}{16\pi} m_B$$

$$\mathrm{BR}(B \to \mathrm{DM}\,\mathrm{DM}) \simeq \frac{\Gamma(B \to \mathrm{DM}\,\mathrm{DM})}{\Gamma_B^{\mathrm{SM}}}$$

$$\Gamma_Z^{\mathrm{SM}} \simeq 2.5\,\mathrm{GeV}\,, \quad \Gamma(Z \to \mathrm{DM}\,\mathrm{DM}) \lesssim 2\,\mathrm{MeV} \qquad \Rightarrow \qquad g_Z \lesssim 0.03$$

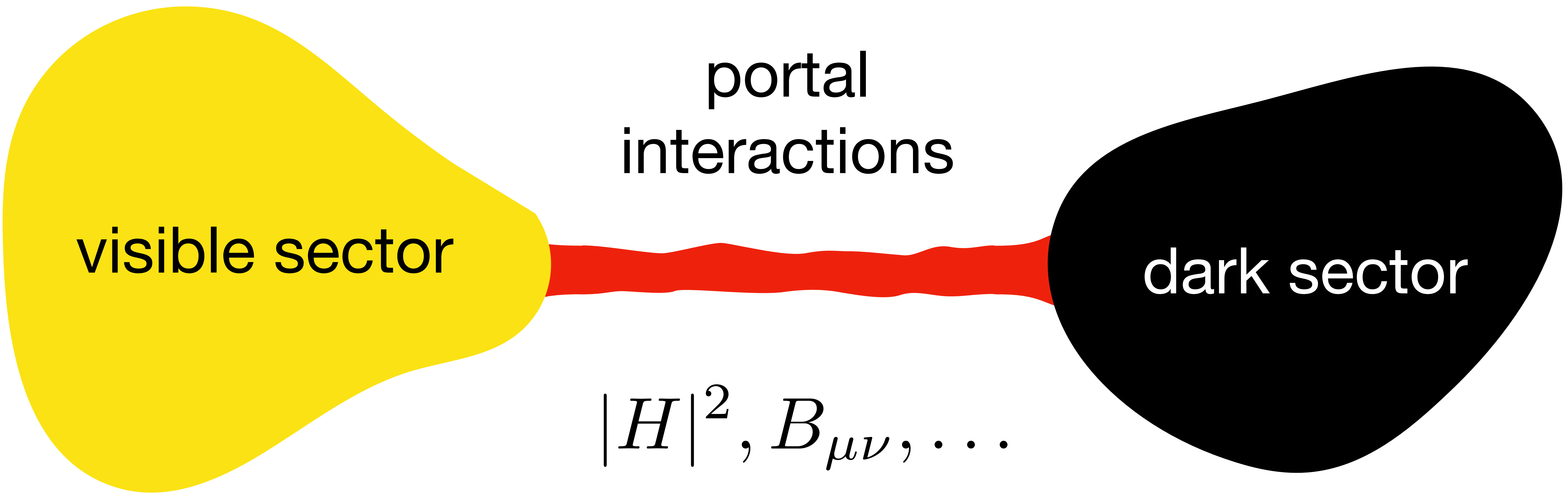
$$\Gamma_h^{\mathrm{SM}} \simeq 4.1\,\mathrm{MeV}\,, \quad \Gamma(h \to \mathrm{DM}\,\mathrm{DM}) \lesssim 0.5\,\mathrm{MeV} \qquad \Rightarrow \qquad g_h \lesssim 0.01$$

Because …

due to small Standard Model (SM) Higgs decay width, current LHC sensitivity to strength of Higgs-DM interactions already on par/exceeds LEP sensitivity to size of Z-DM coupling

Besides this largely empirical argument there are also theoretical reasons why Higgs sector could play an important role in mediation between visible & invisible sectors. IMHO most convincing theoretical argument is based on following effective field theory (EFT) reasoning — often heard argument that links mass generation in SM via Higgs mechanism to mass generation of DM is generically problematic in view of LHC Higgs precision measurements

Because …



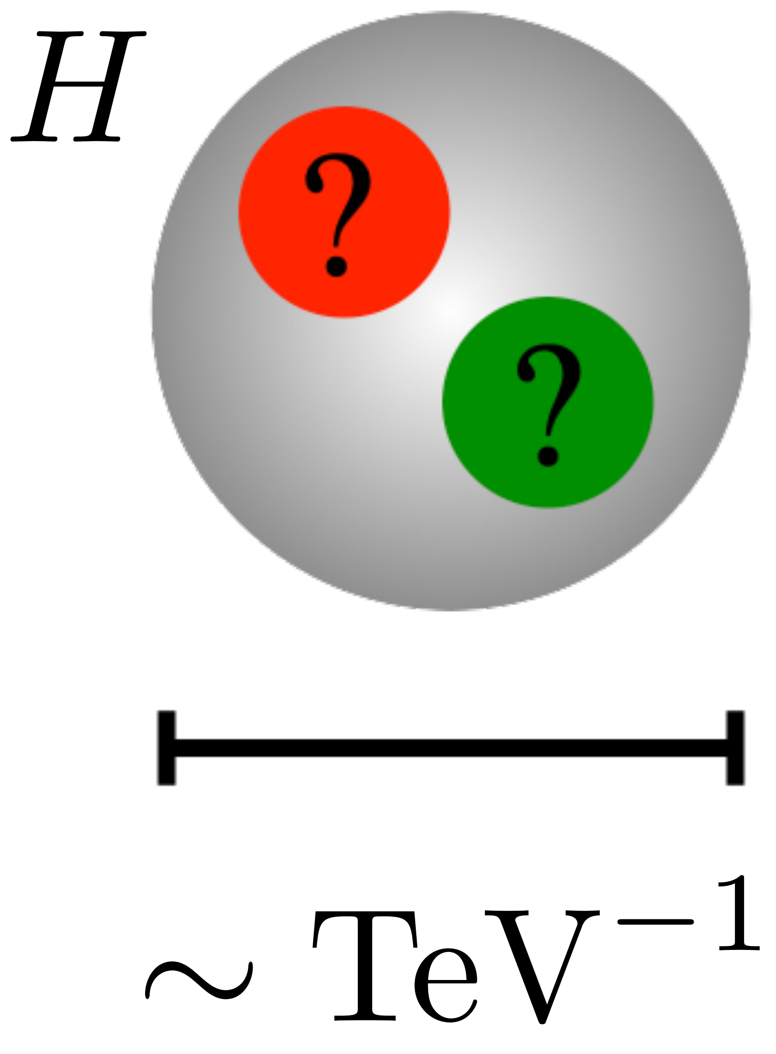
$|H|^2$ is one of two lowest dimensional operators that is allowed by SM gauge invariance — second possibility is hypercharge gauge field strength $B_{\mu\nu}$. From an EFT point of view, this so-called Higgs portal could be most relevant link between visible & dark sector. Also vector portal interesting but in this case DM cannot be a pure SM singlet

In this talk, …

I will sketch several theoretical ideas in which Higgs(es) play a crucial role in mediation between visible & dark sectors & discuss in each case experimental consequences with a focus on LHC physics. Discussion follows closely recent review article by Argyropoulos, Brandt & UH, 2109.13597

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

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

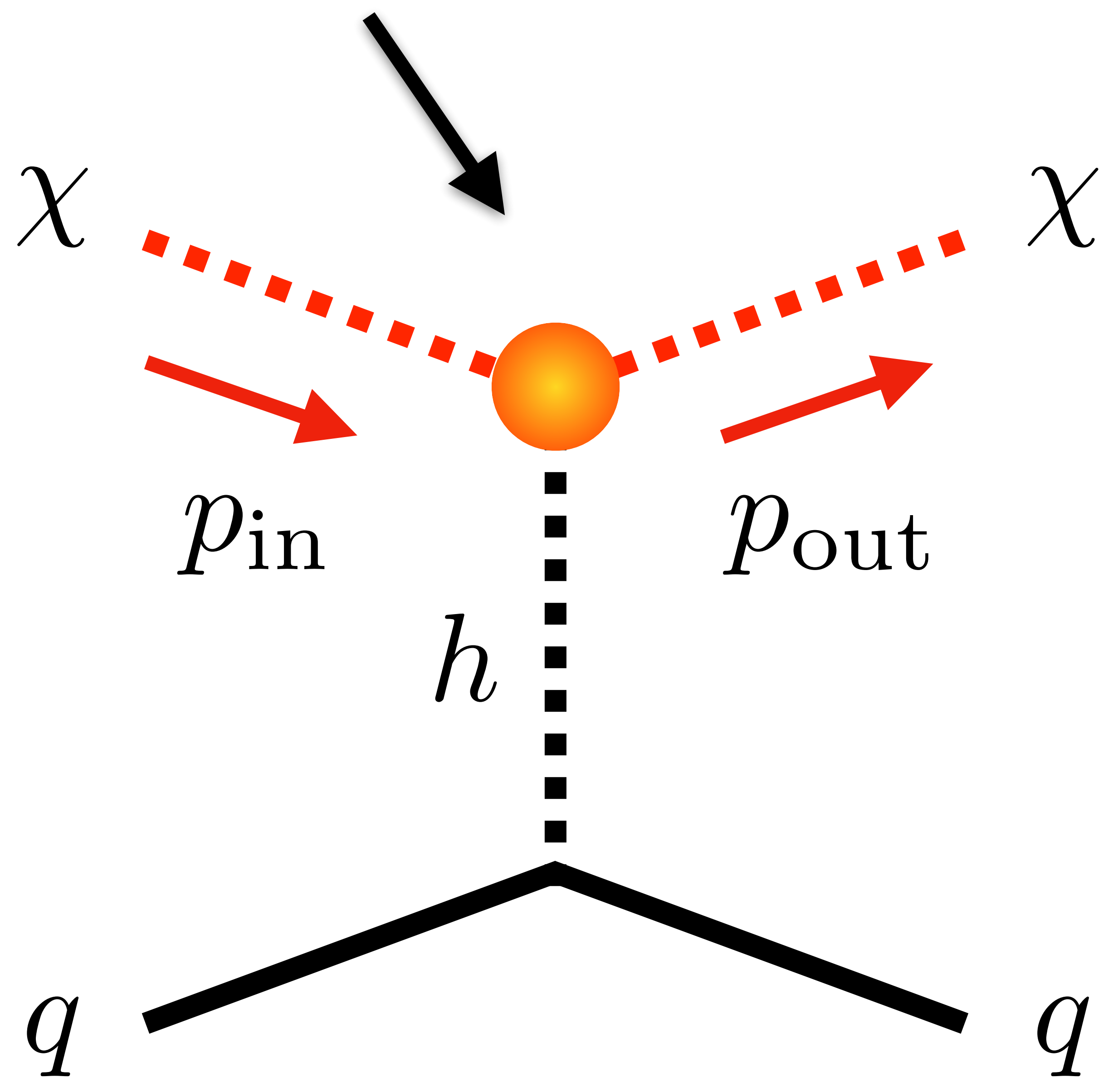
derivative operator:
DM shift symmetric

marginal operator:
breaks DM shift symmetry

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

pNGB DM: direct detection bounds

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

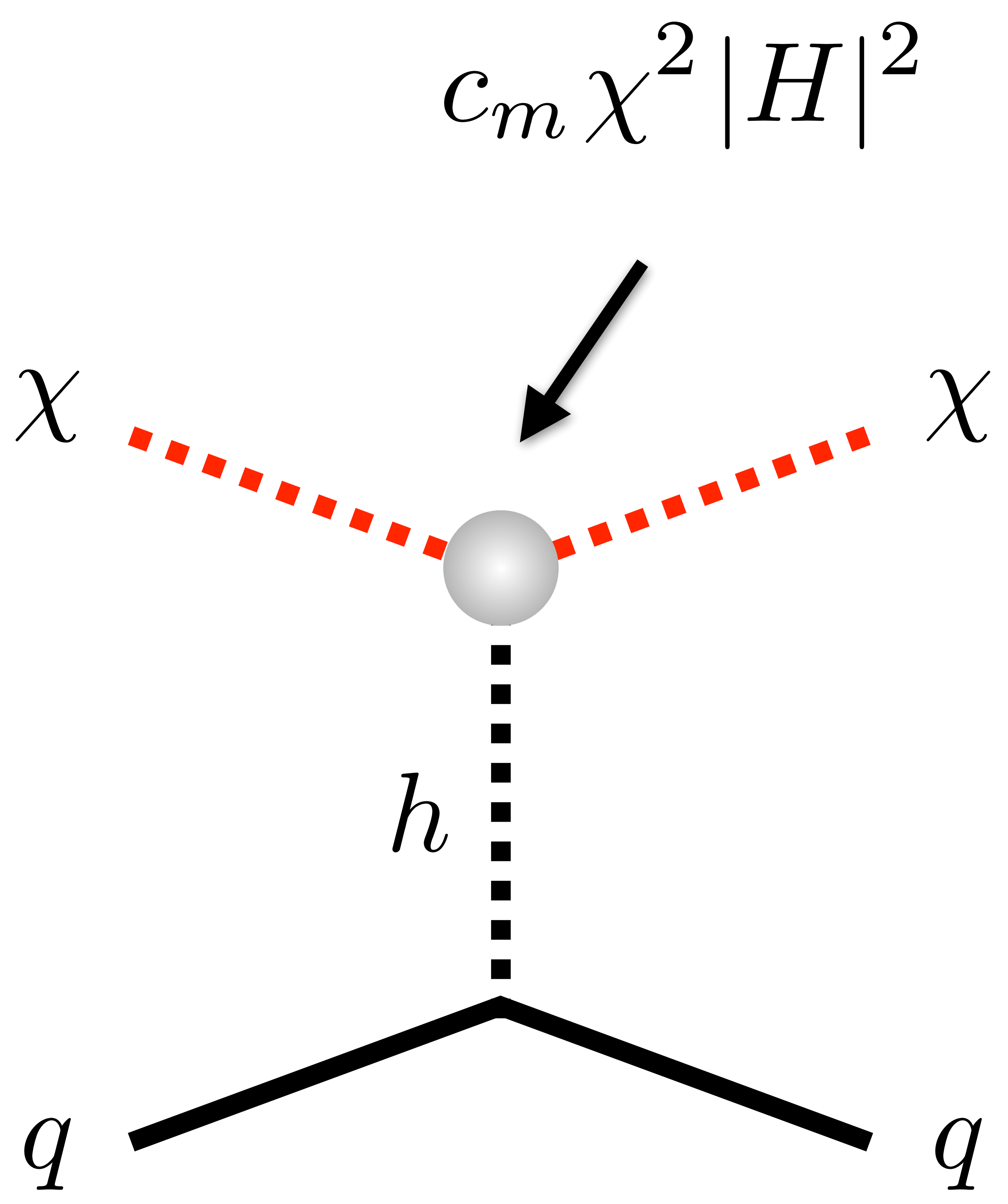


$$\propto \frac{\left(p_{\rm in}-p_{\rm out}\right)^2}{\Lambda^2} \lesssim \frac{(100\,\mathrm{MeV})^2}{\Lambda^2}$$

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



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

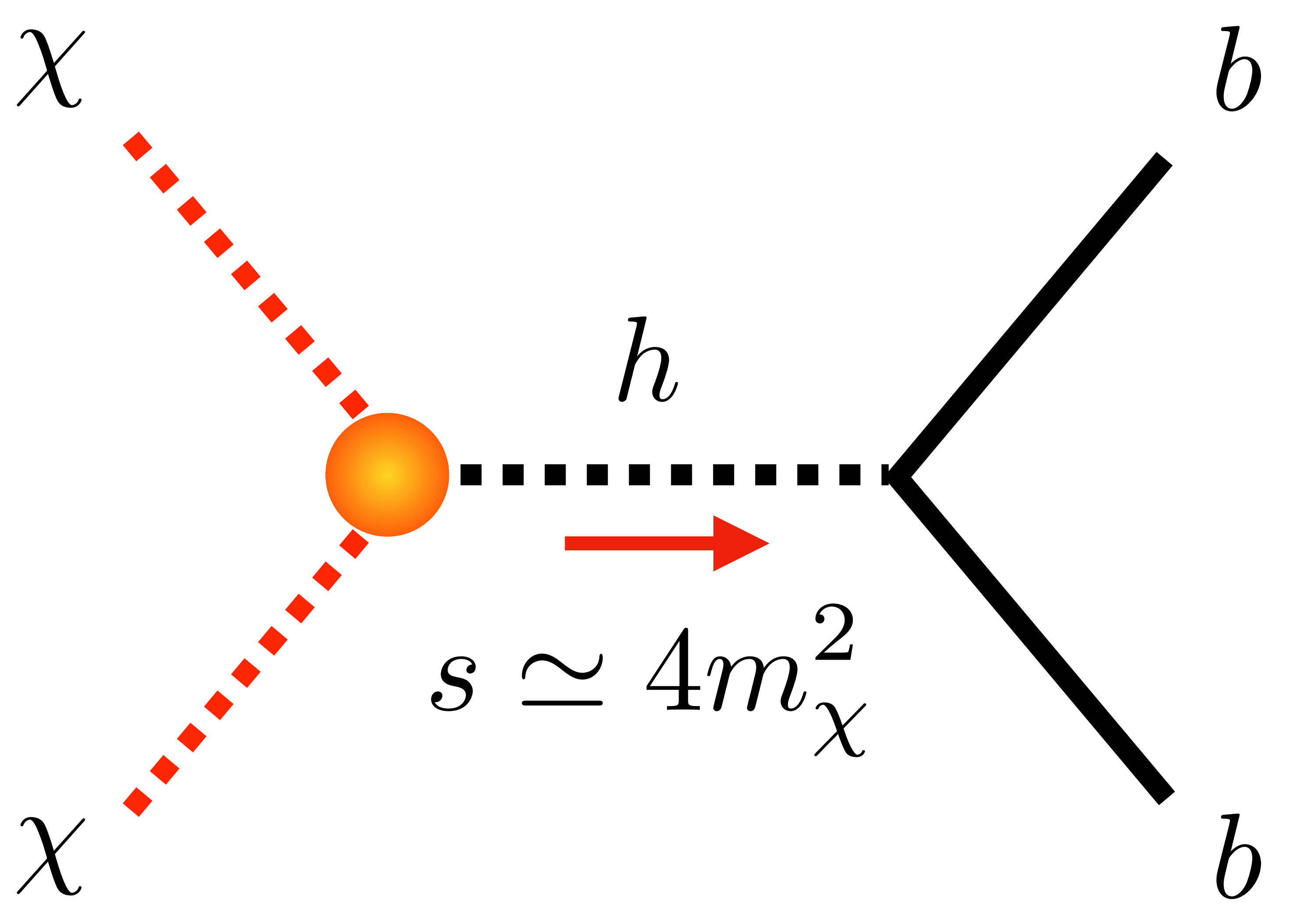
$$\sigma_{\rm SI} \lesssim 9 \cdot 10^{-47}\,{\rm cm}^2 \quad (m_\chi = 100\,{\rm GeV})$$

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

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: indirect detection bounds

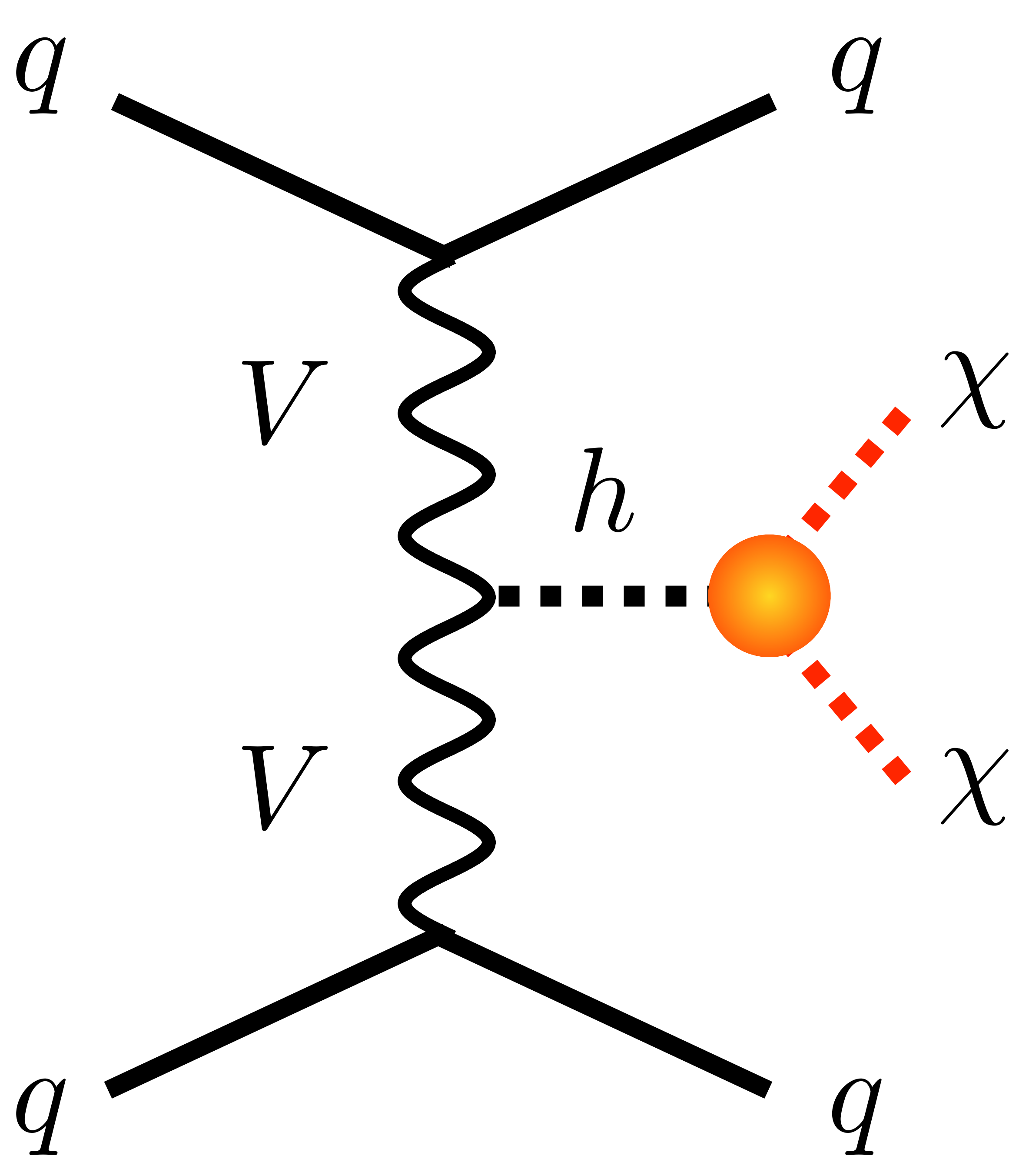


$$\langle \sigma v \rangle_b \propto \left| \frac{1}{4m_\chi^2 - m_h^2} \left(\frac{4m_\chi^2 c_d}{\Lambda^2} + c_m \right) \right|^2$$

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

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 & top-quark pairs

pNGB DM: invisible Higgs decays



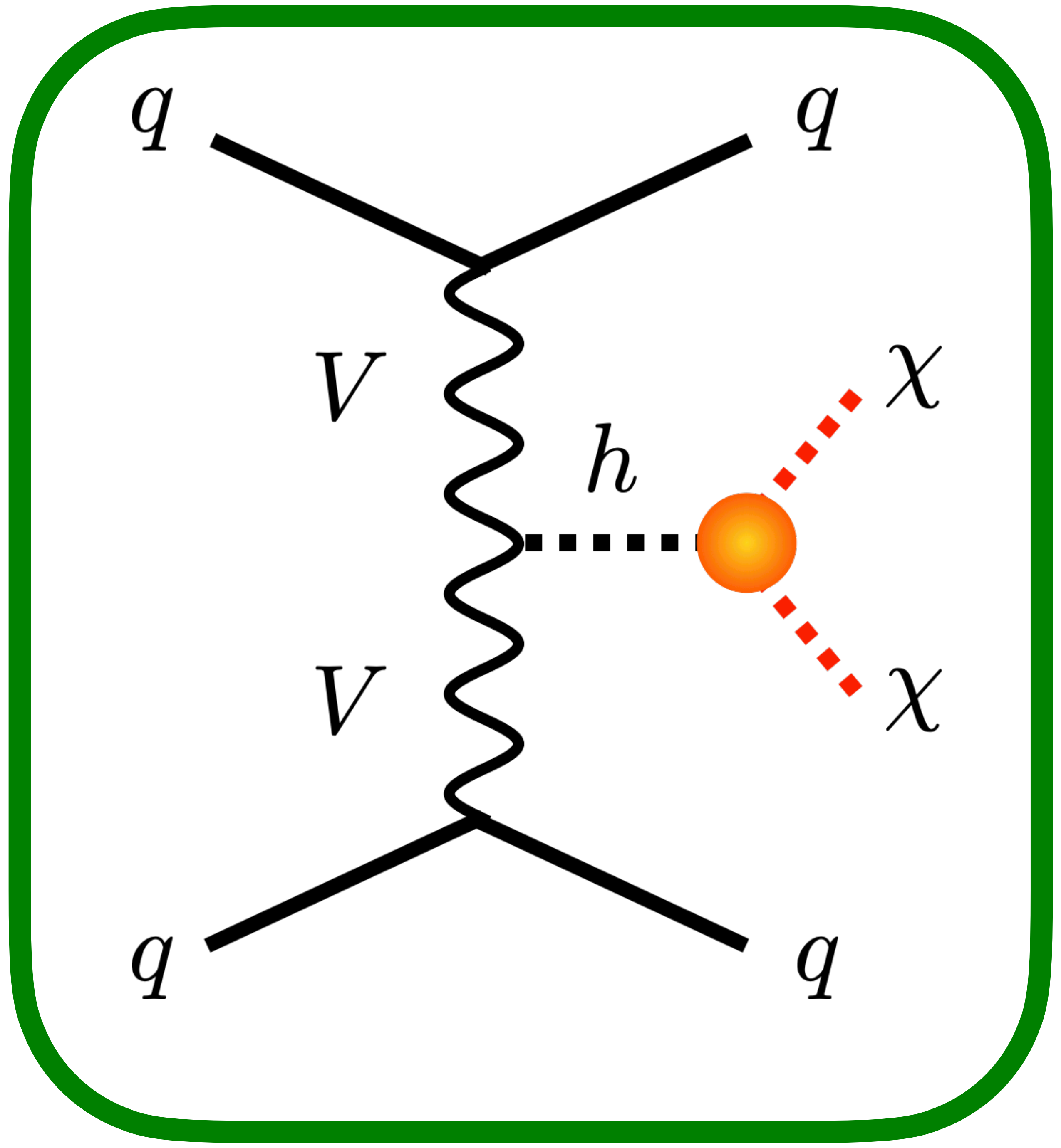
$$\Gamma(h \to \chi\chi) \simeq \frac{v^2}{8\pi m_h}\left(\frac{m_h^2 c_d}{\Lambda^2} + c_m\right)^2$$

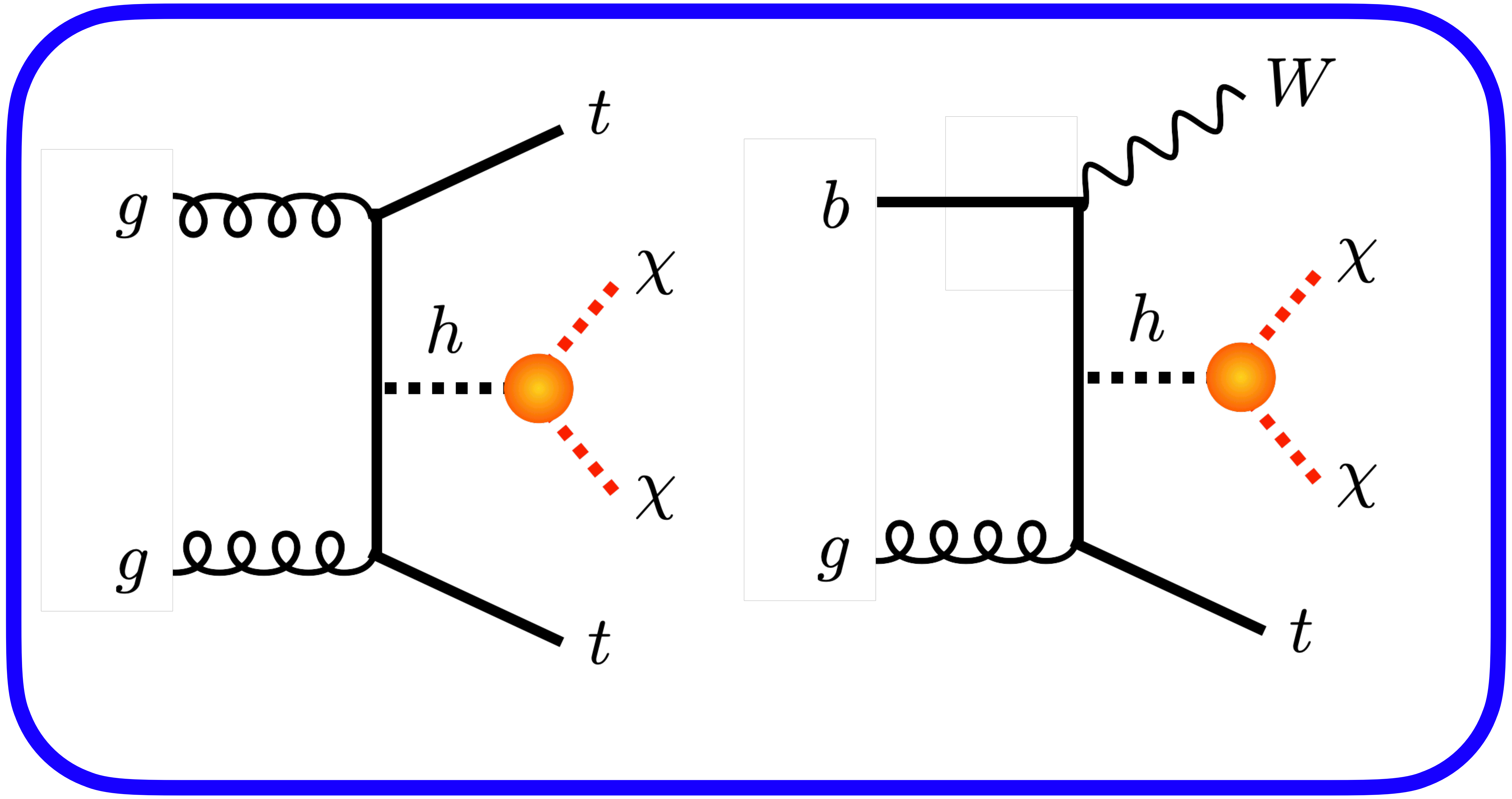
$$\mathrm{BR}\,(h \to \mathrm{inv}) \simeq \frac{\Gamma(h \to \chi\chi)}{4\,\mathrm{MeV}} < 0.11$$

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

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

pNGB DM: off-shell DM search strategies



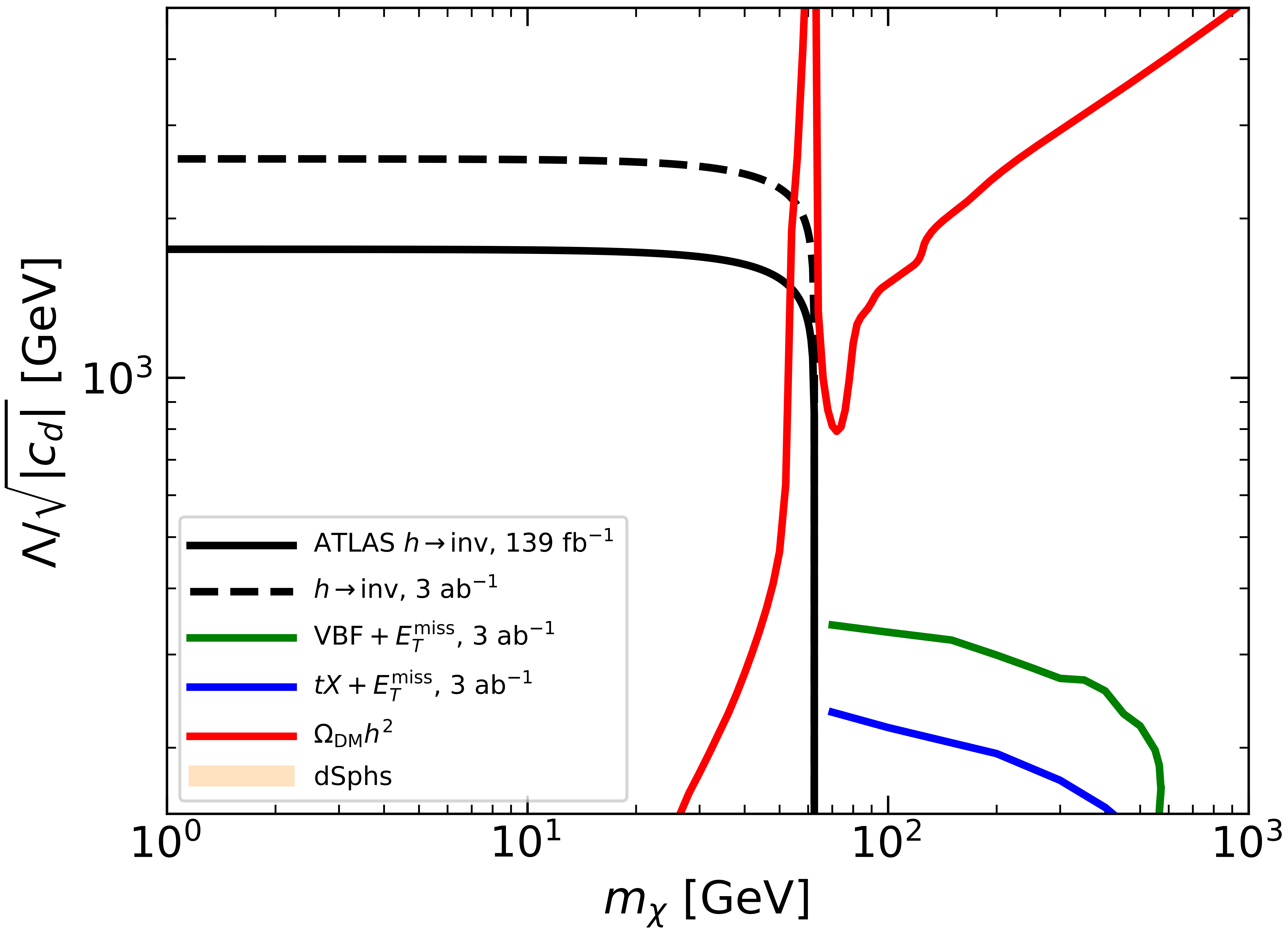


If DM is not kinematically accessible in Higgs decay, can test pNGB DM models in vector-boson fusion (VBF) Higgs production plus $E_{T,miss}$ & in tX+$E_{T,miss}$ channels

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

Constraints on derivative operator

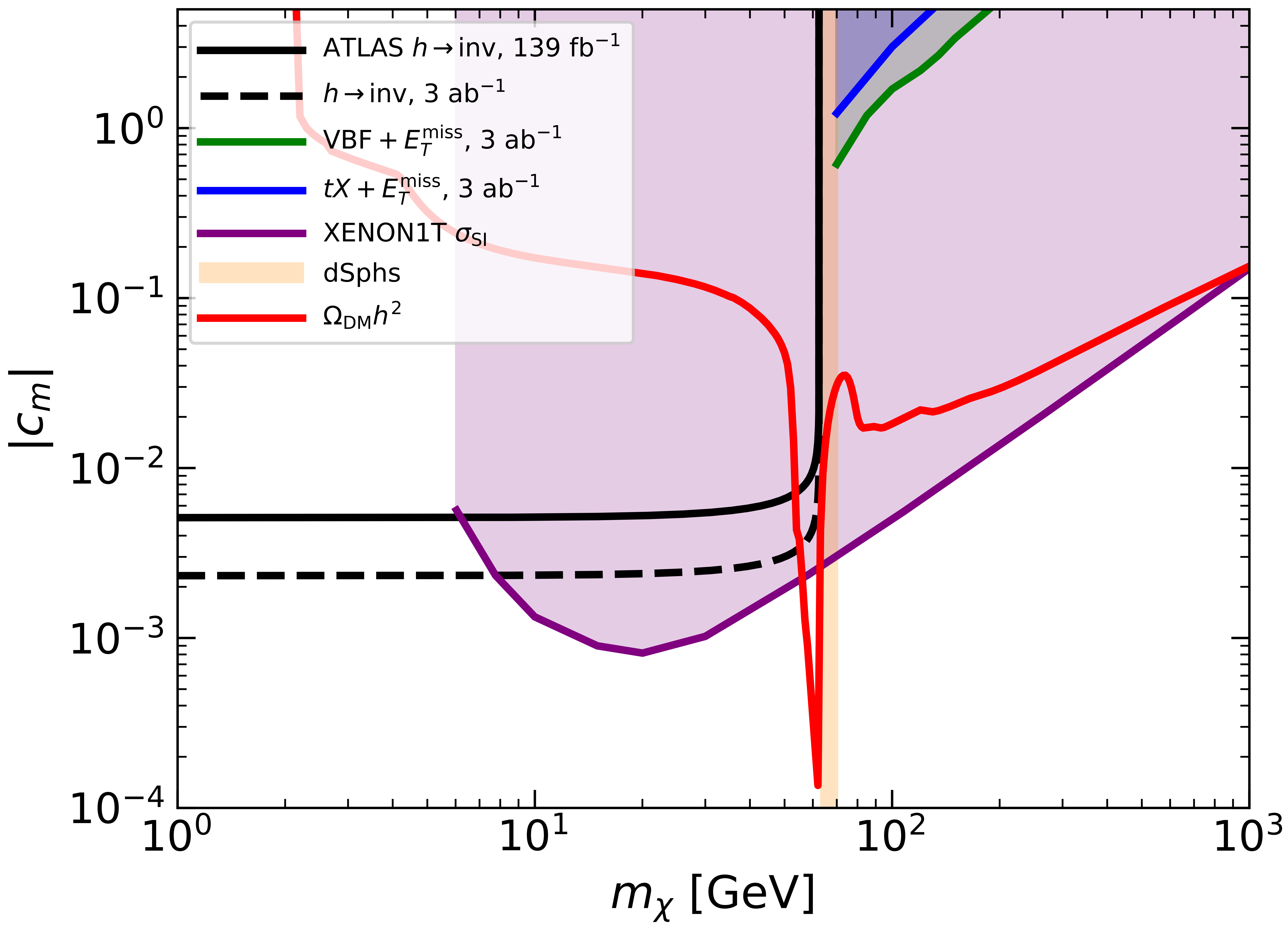
[Agryopoulos, Brandt & UH, 2109.13597]



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

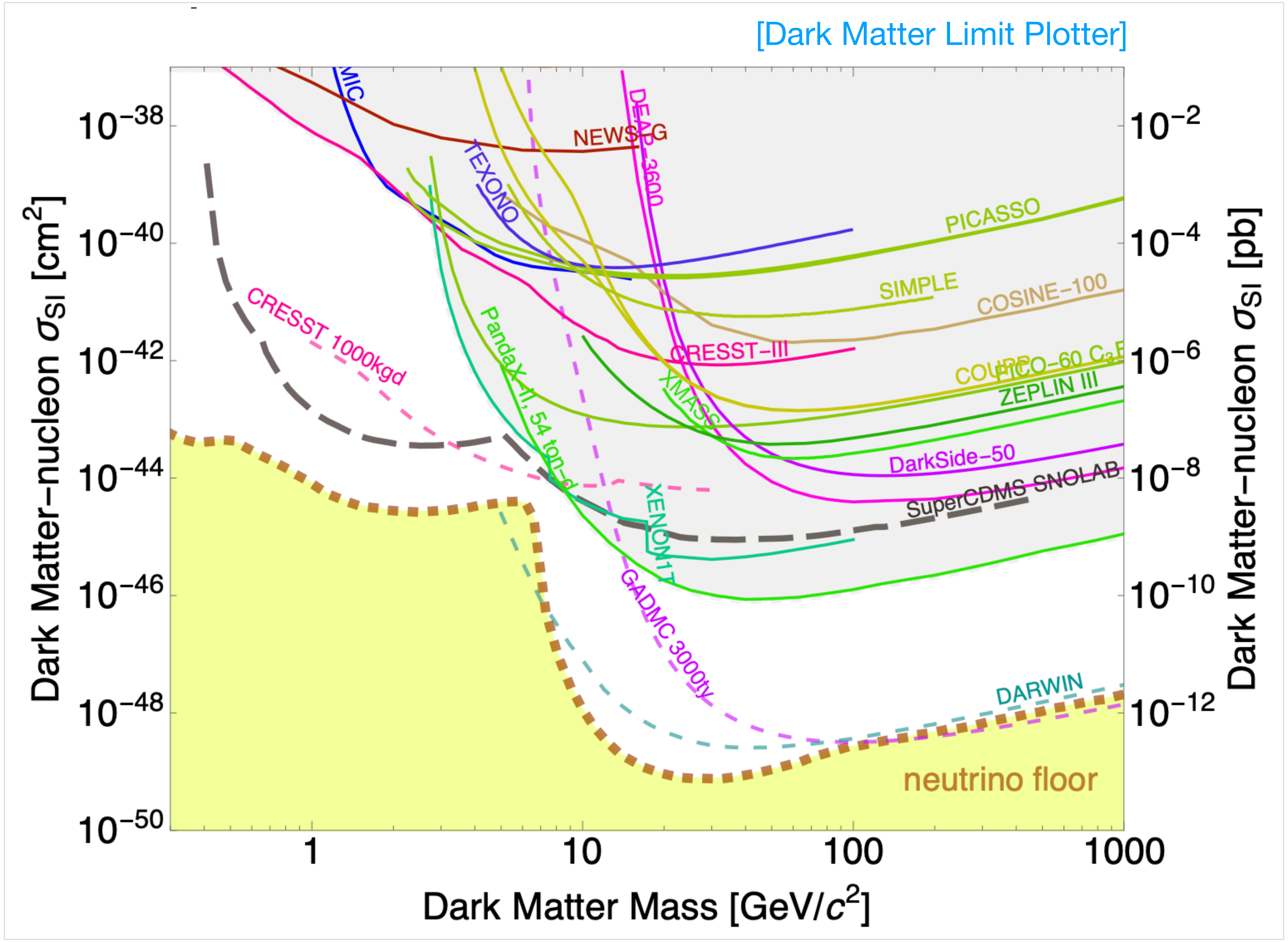
Constraints on marginal operator

[Agryopoulos, Brandt & UH, 2109.13597]



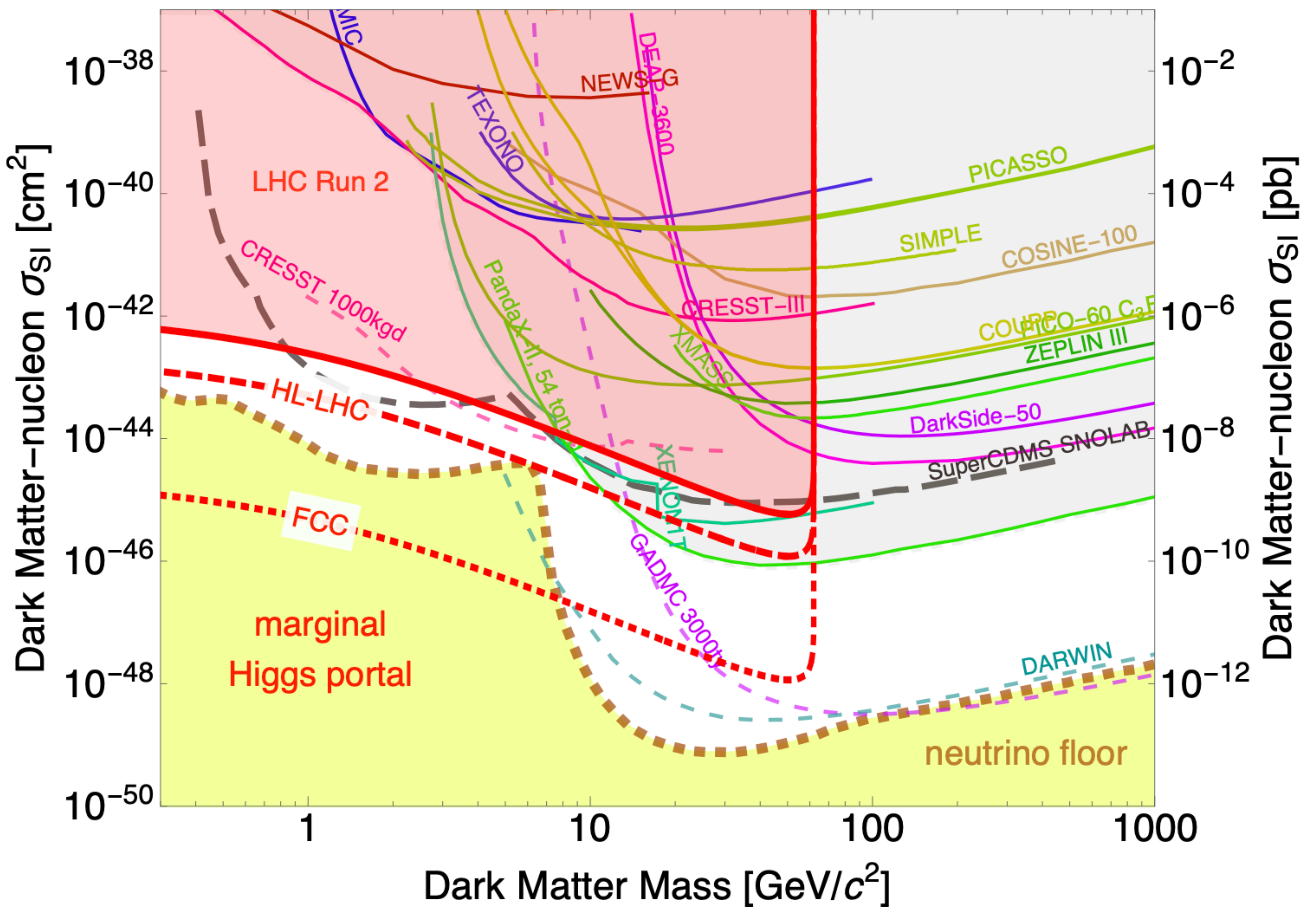
[Higgs off-shell bounds from Ruhdorfer, Salvioni & Weiler, 1910.04170; UH, Polesello & Schulte, 2107.12389]

Future probes of neutrino floor



Future probes of neutrino floor

[Dark Matter Limit Plotter; de Blas et al., 1905.03764]



Simplified spin-0 DM model

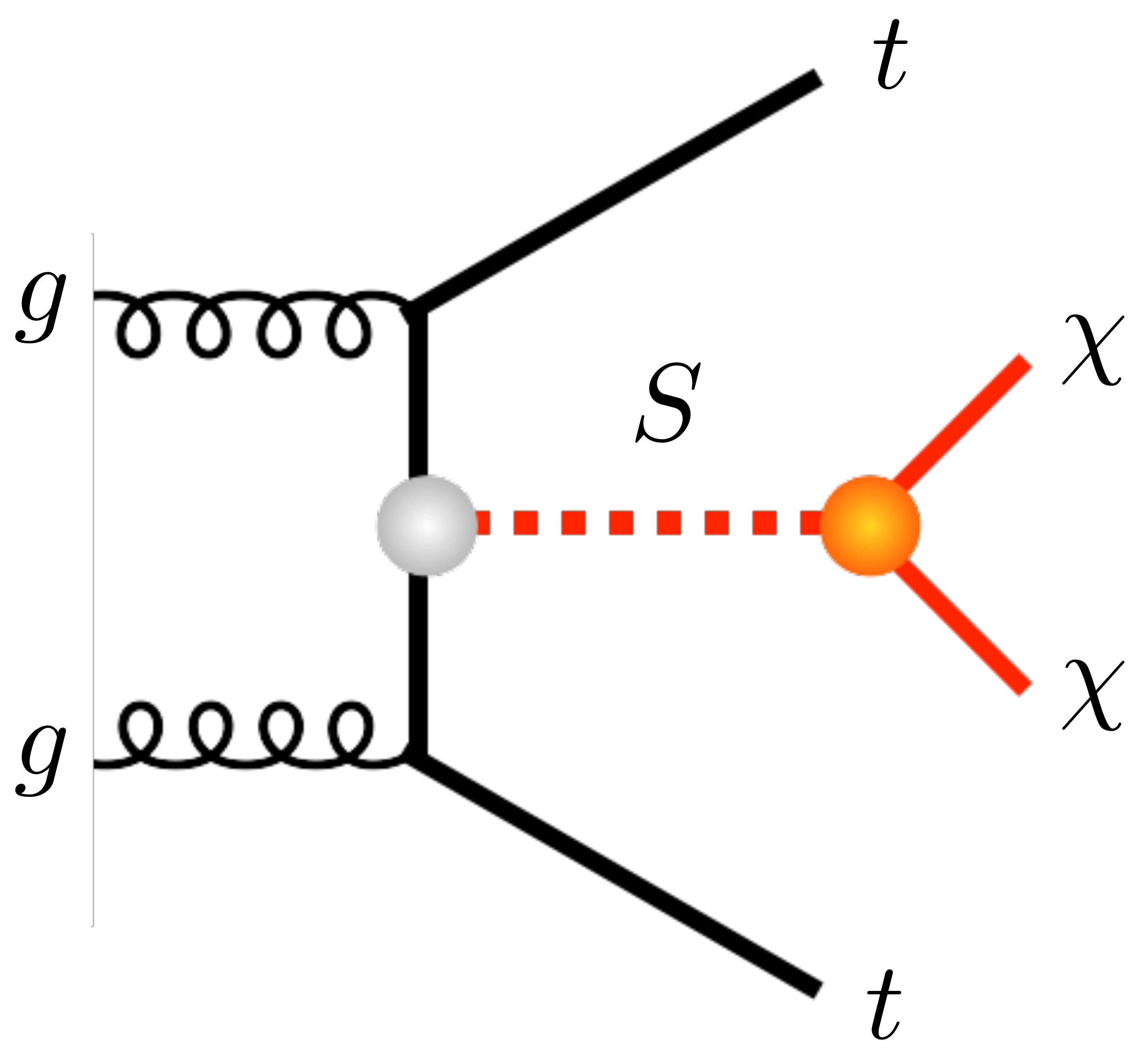
SM Yukawa coupling

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

$$+\, g_{\rm DM} \bar{\chi} \chi S$$

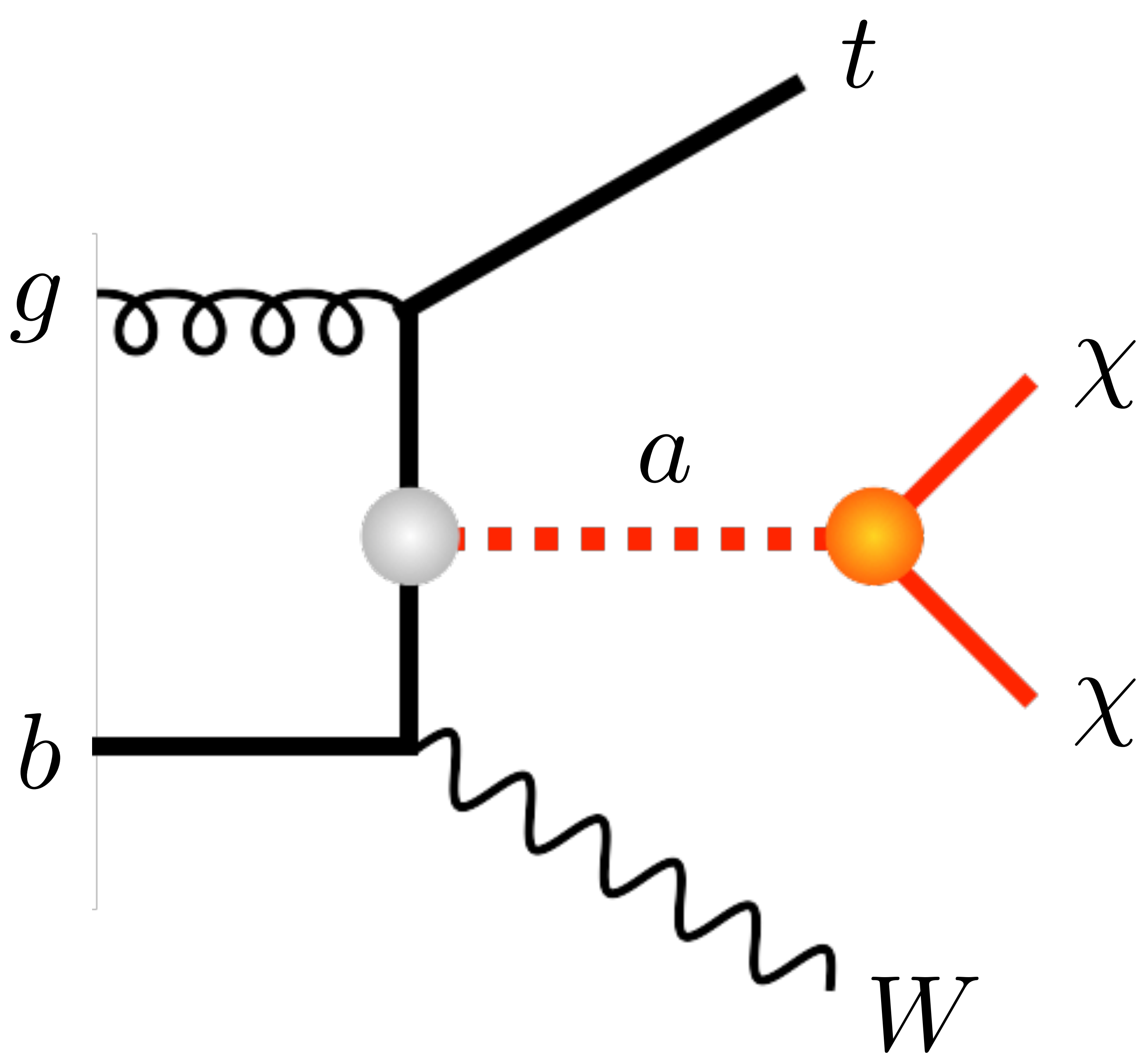
Dirac DM candidate

scalar (or pseudoscalar) mediator



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

Unitarity considerations

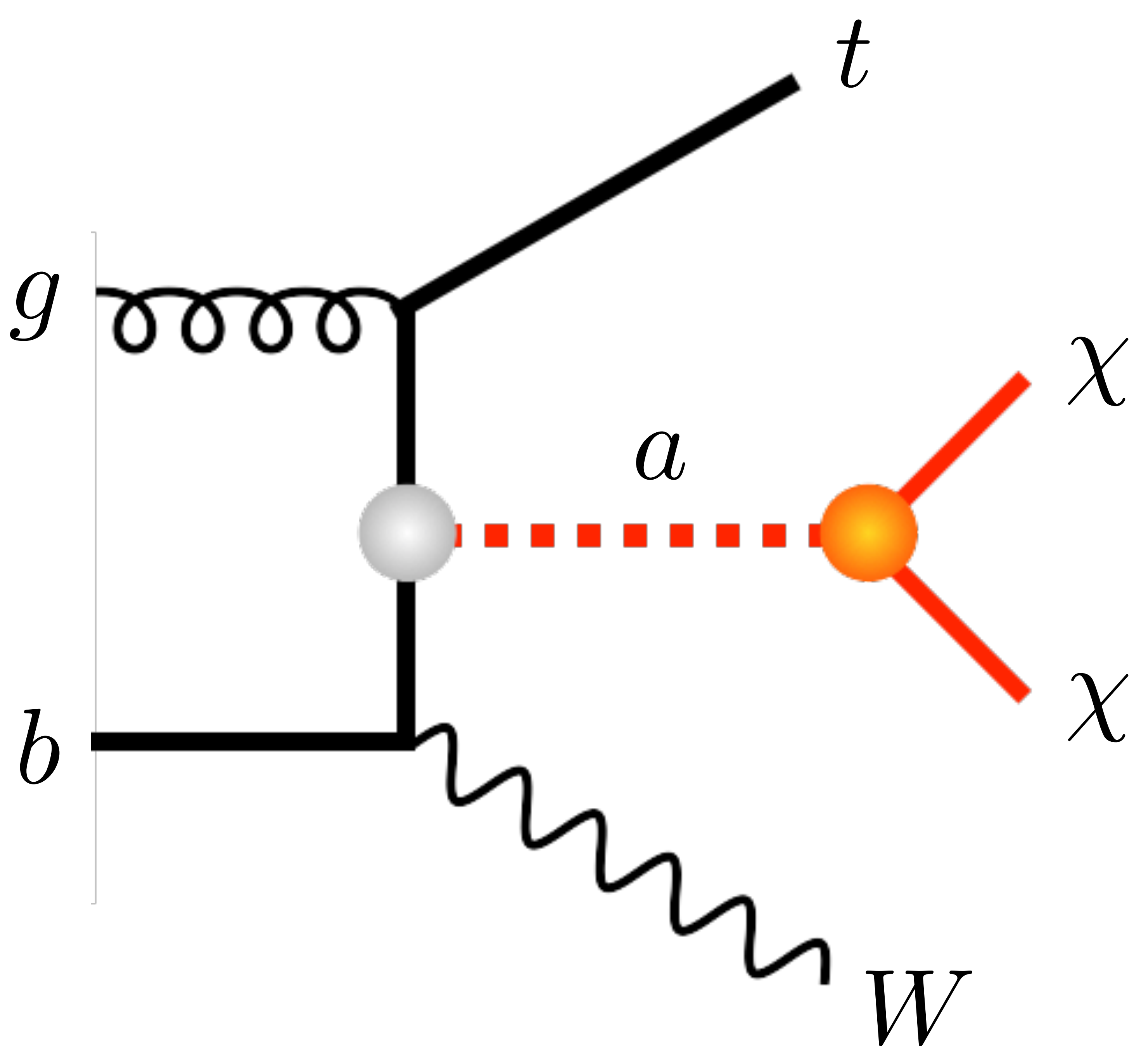


$$\sim \quad y_t \, g_{\rm SM} \, s^{1/2}$$

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

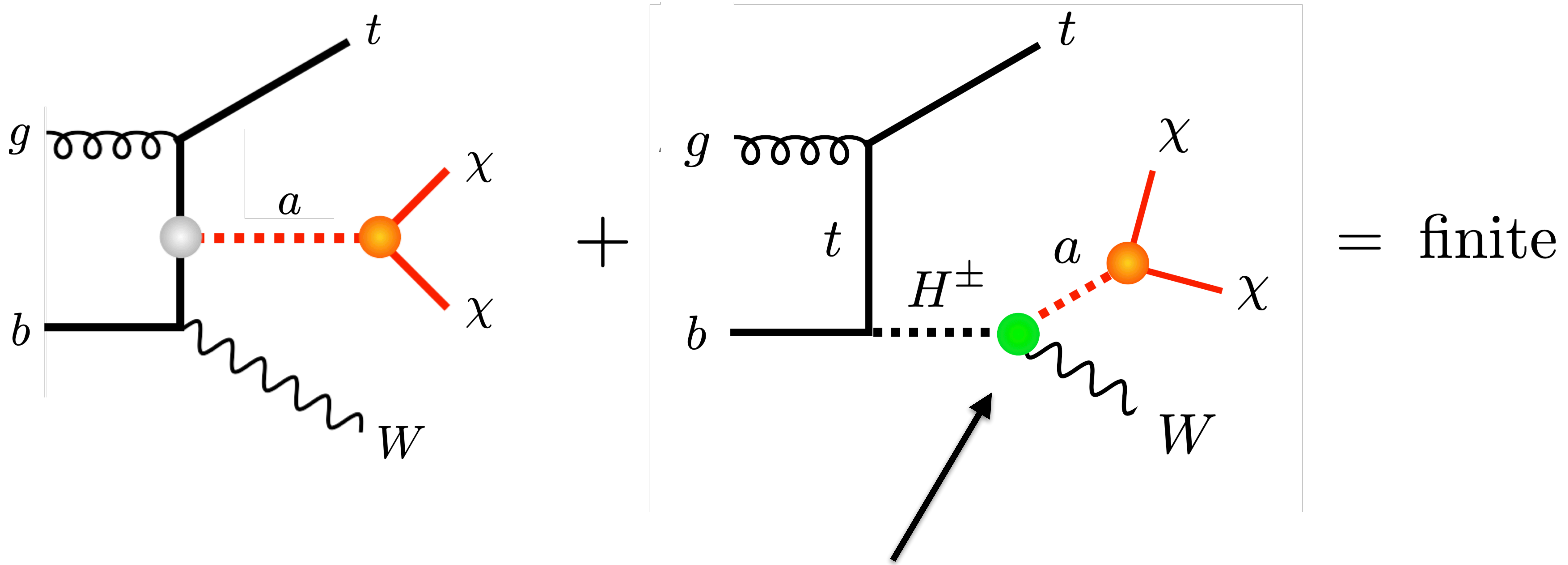
[see for instance Maltoni et al., hep-ph/0106293; Farina et al., 1211.3736; UH & Polesello, 1812.00694]

still can ask …



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

One possible solution



A aH±W coupling only exists in models that feature an extended Higgs sector

2HDM+a model

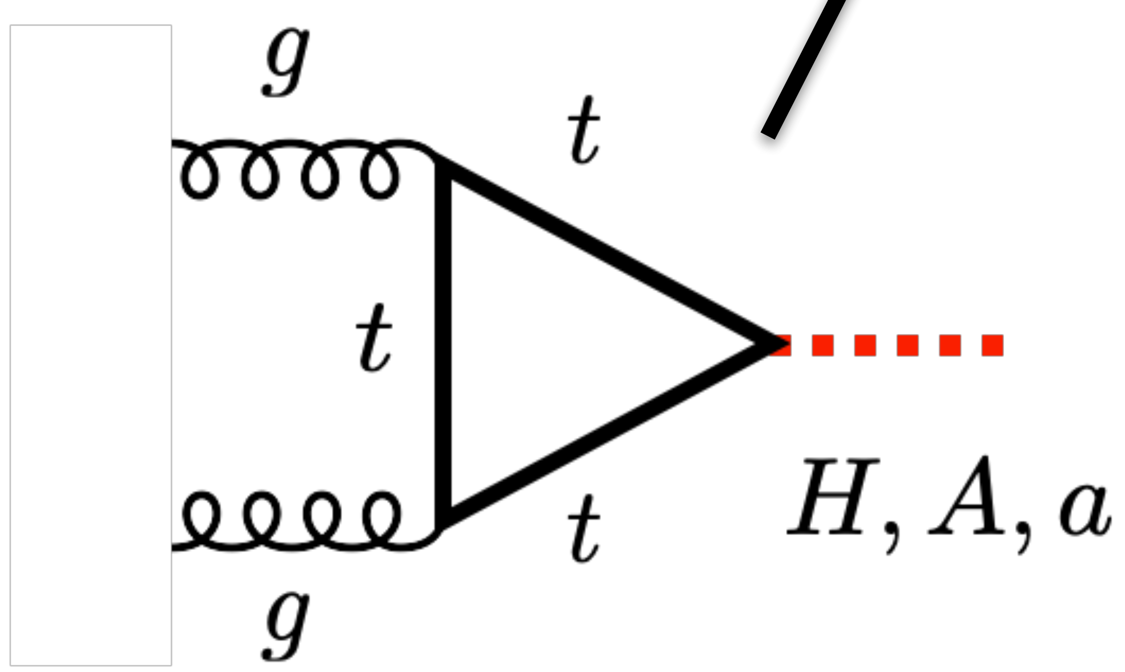
$$\mathcal{L} \supset -\bar{Q}Y_u\tilde{H}_2 d_R + \bar{Q}Y_d H_1 u_R - i b_P P H_1^\dagger H_2 - i y_\chi P \bar{\chi}\gamma_5\chi + \text{h.c.}$$

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

h is SM-like
for cos(β-α) ≃ 0

mostly P
for small θ

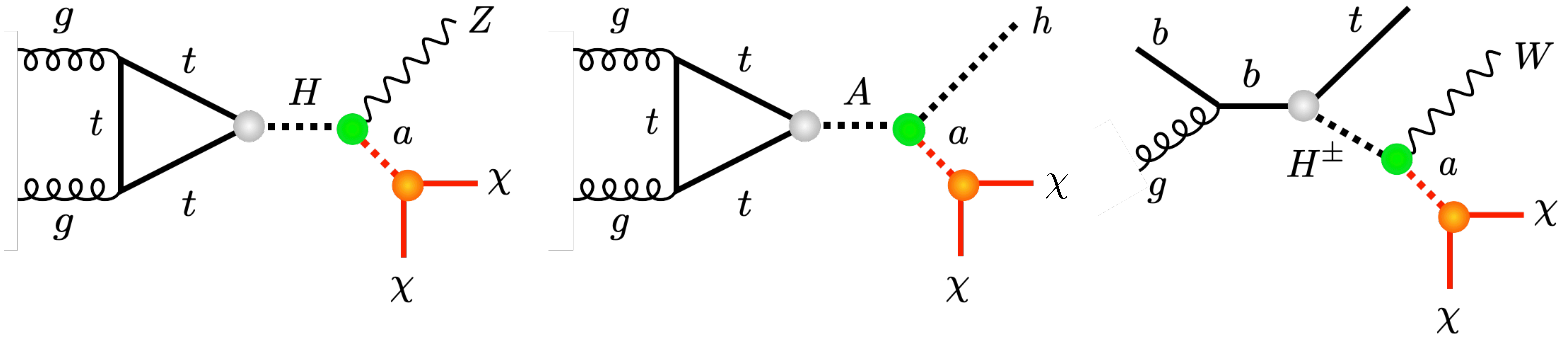
$$\text{angles: } \alpha, \beta, \theta$$



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

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

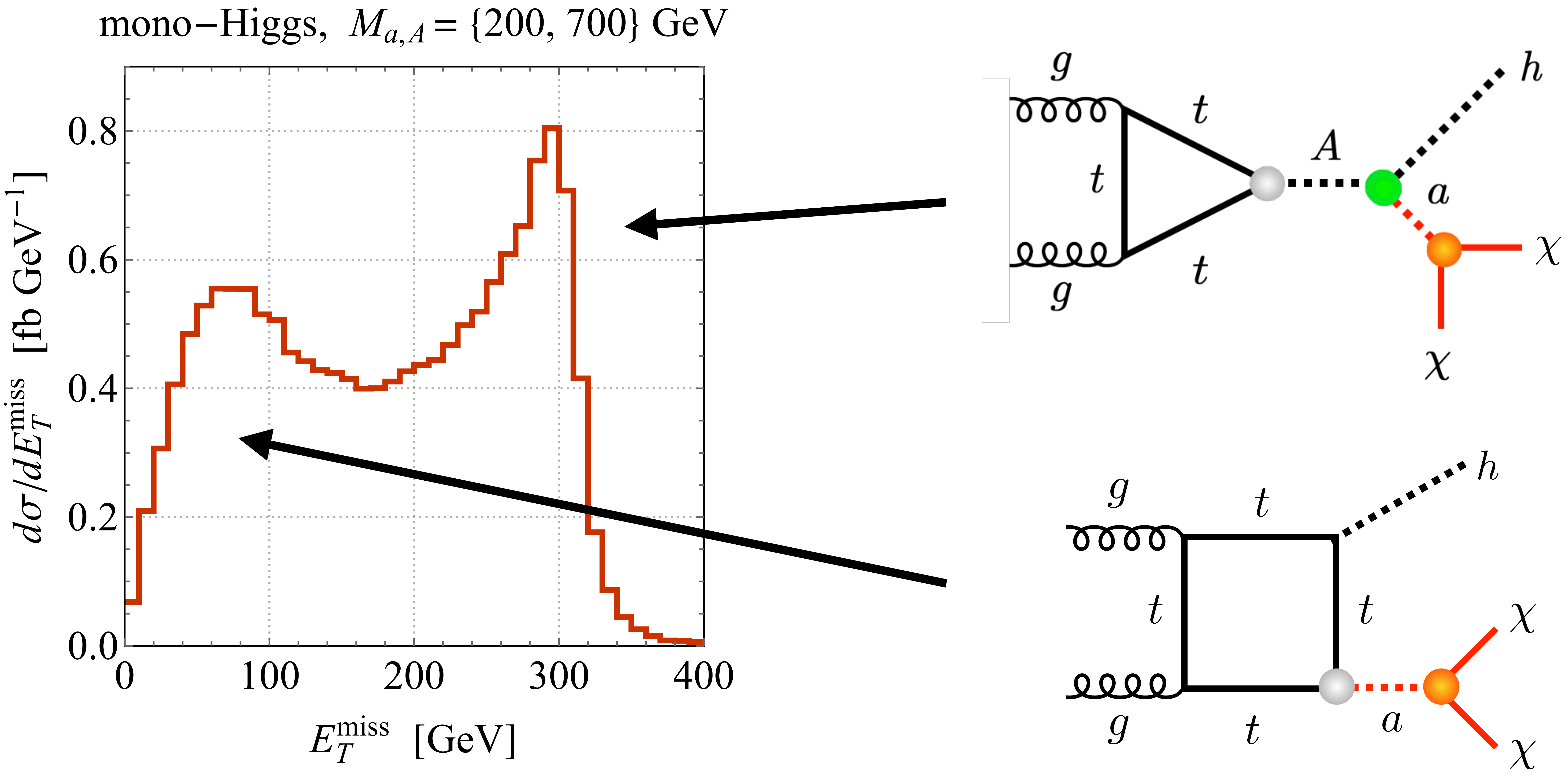
2HDM+a model: resonant $E_{T,miss}$ signatures



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

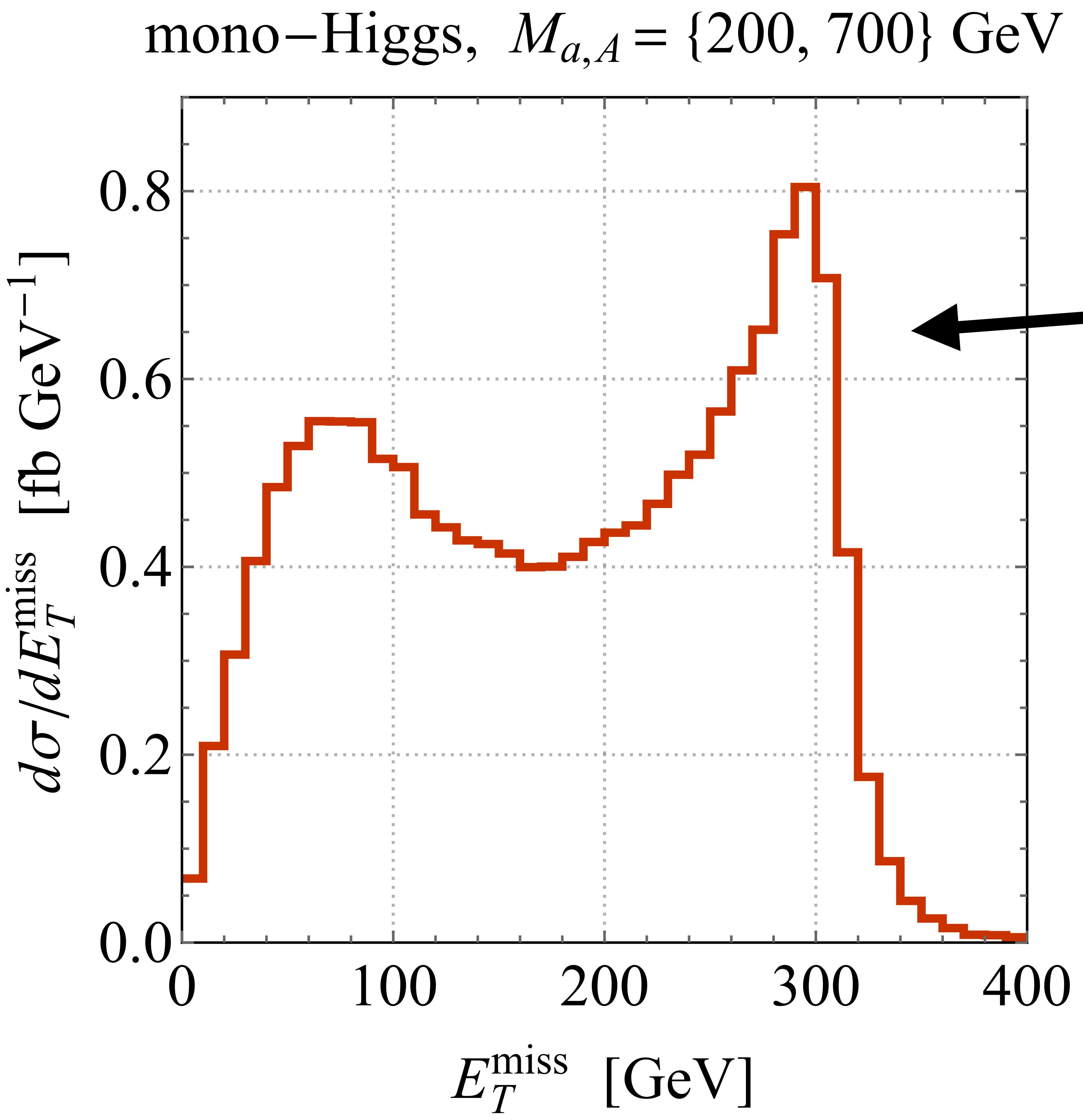
[Goncalves et al., 1611.04593; Bauer et al., 1701.07427; Pani & Polesello, 1712.03874]

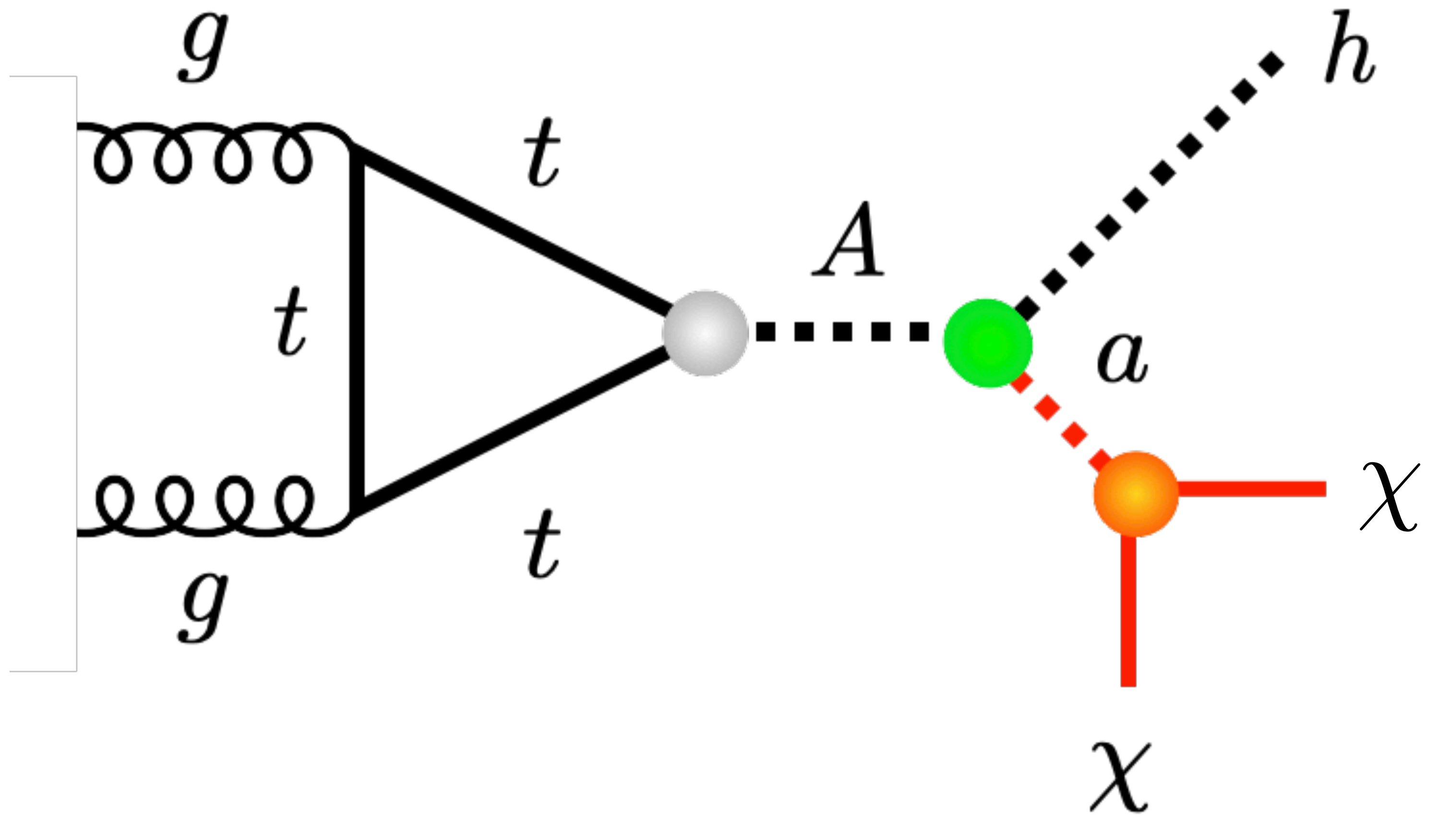
2HDM+a model: mono-Higgs



[Goncalves et al., 1611.04593; Bauer et al., 1701.07427; LHCDMWG, 1810.09420]

2HDM+a model: mono-Higgs

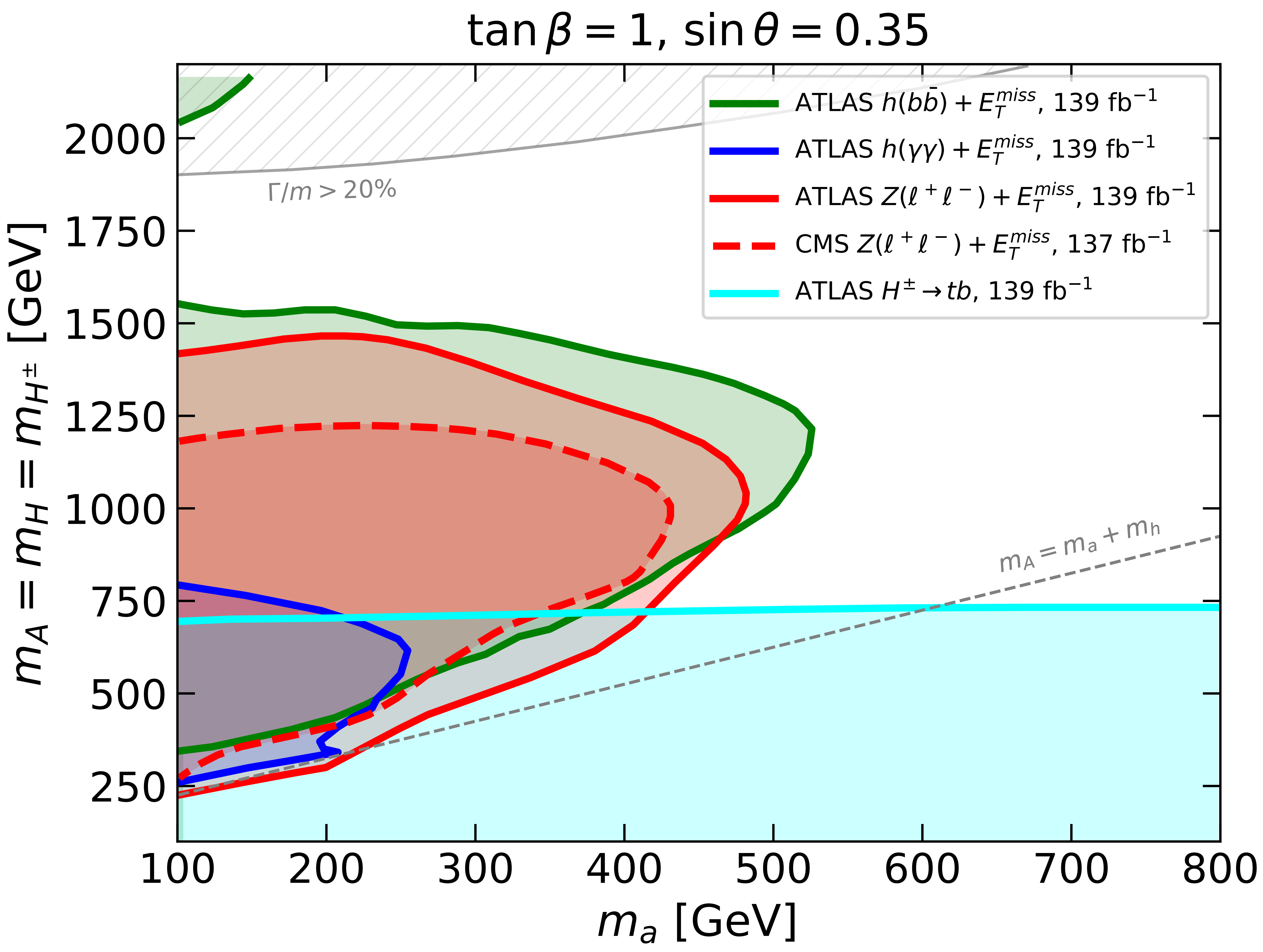




Harder $E_{T,miss}$ spectrum due to resonant contribution, leading to better signal-to-background ratio

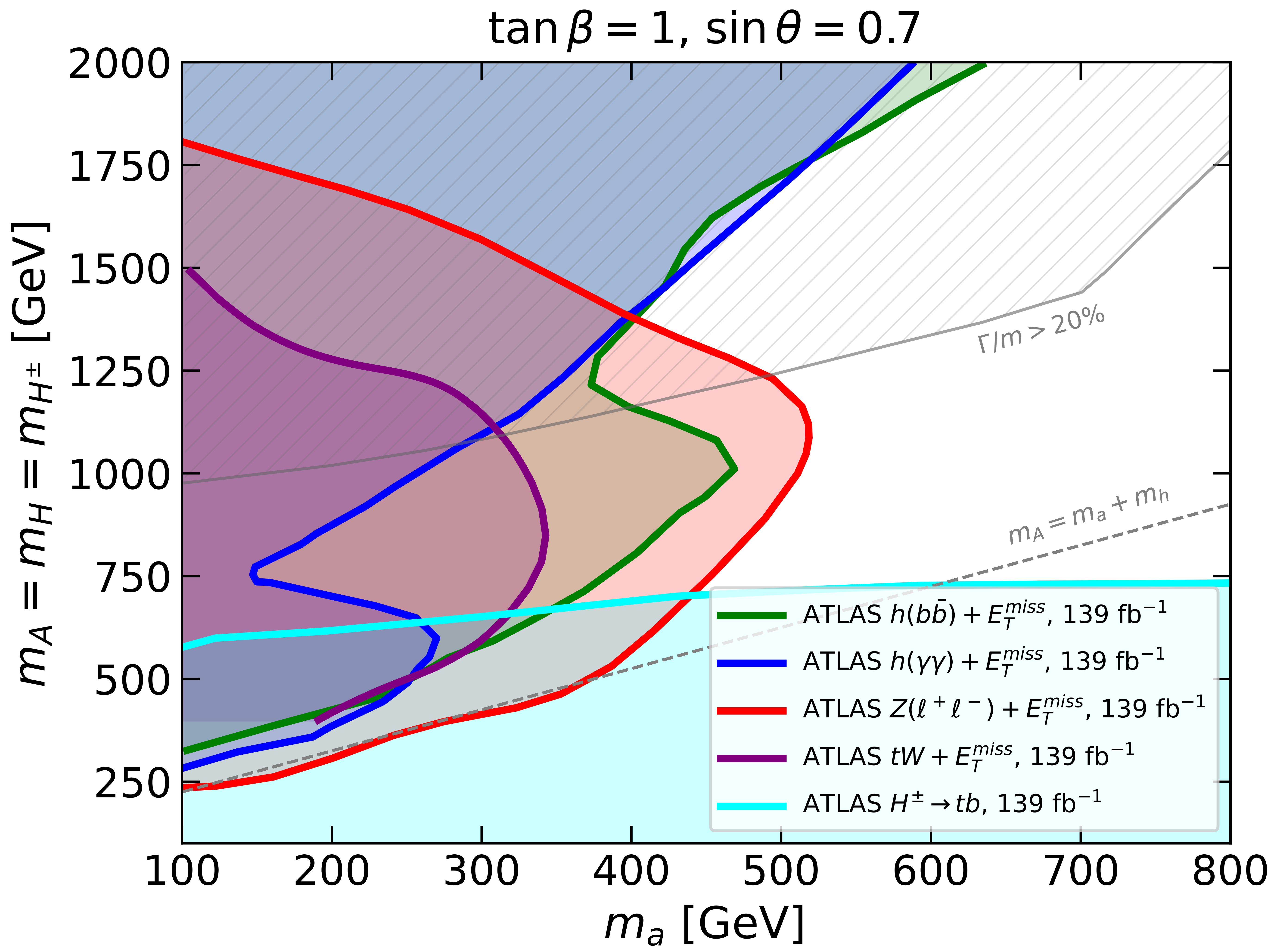
[Goncalves et al., 1611.04593; Bauer et al., 1701.07427; LHCDMWG, 1810.09420]

Constraints on 2HDM+a model



[Agryopoulos, Brandt & UH, 2109.13597]

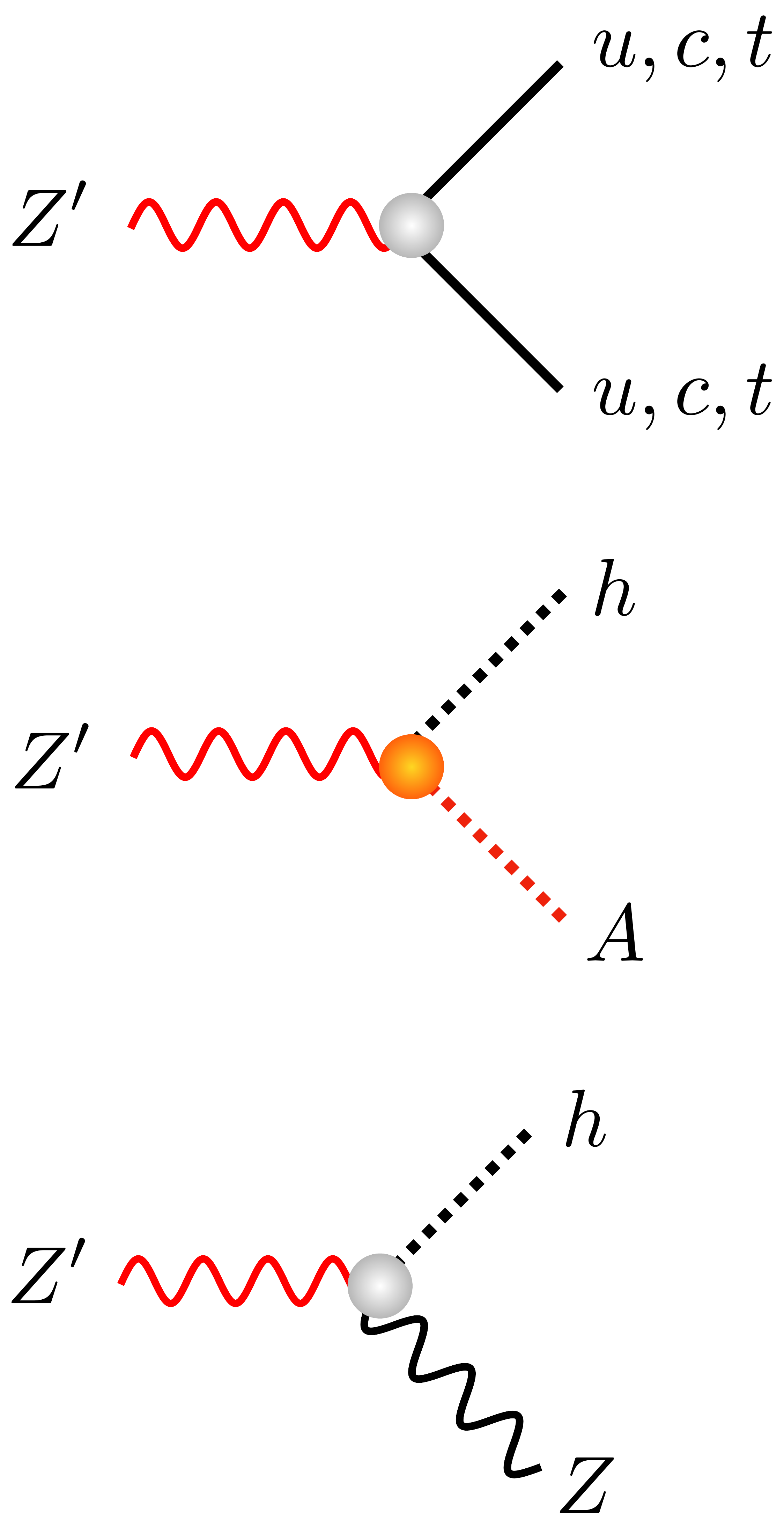
Constraints on 2HDM+a model



[Agryopoulos, Brandt & UH, 2109.13597]

2HDM+Z′ model

	$U(1)_{Z'}$
H_1	0
H_2	$1/2$
Q, L, d, l	0
u	$1/2$



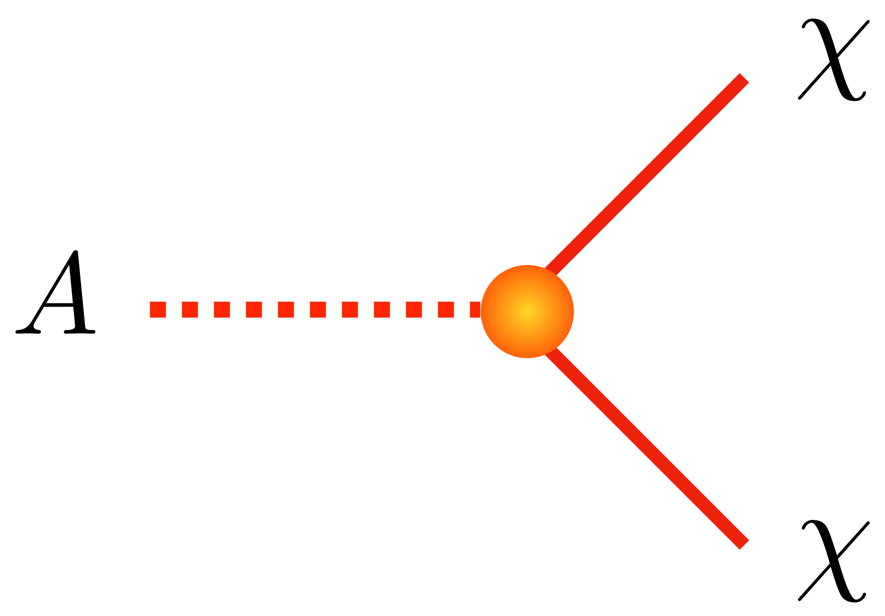
$\propto \; g_{Z'}$

$\propto \; g_{Z'} \dfrac{\tan\beta}{1+\tan^2\beta}$

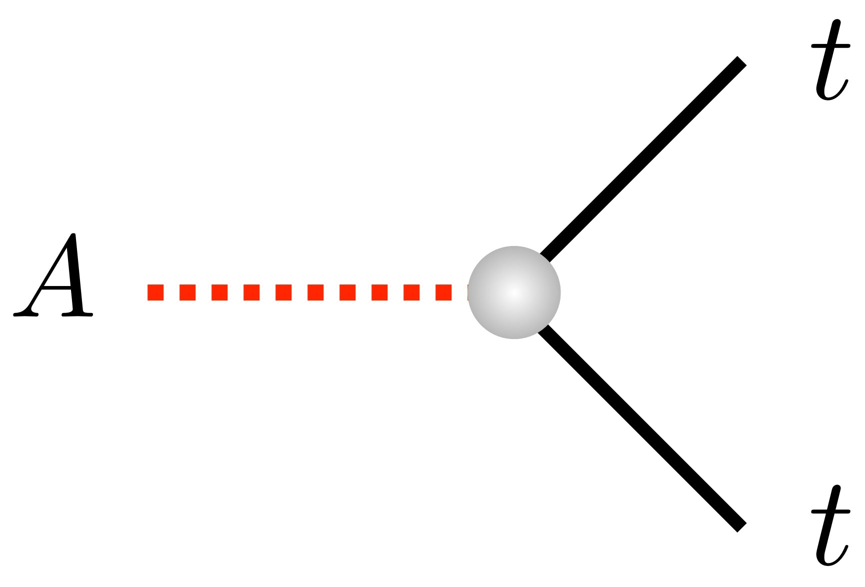
$\propto \; g_{Z'} \dfrac{\tan^2\beta}{1+\tan^2\beta}$

[Berlin, Lin & Wang, 1402.7074]

2HDM+Z′ model



$\propto \; g_\chi$

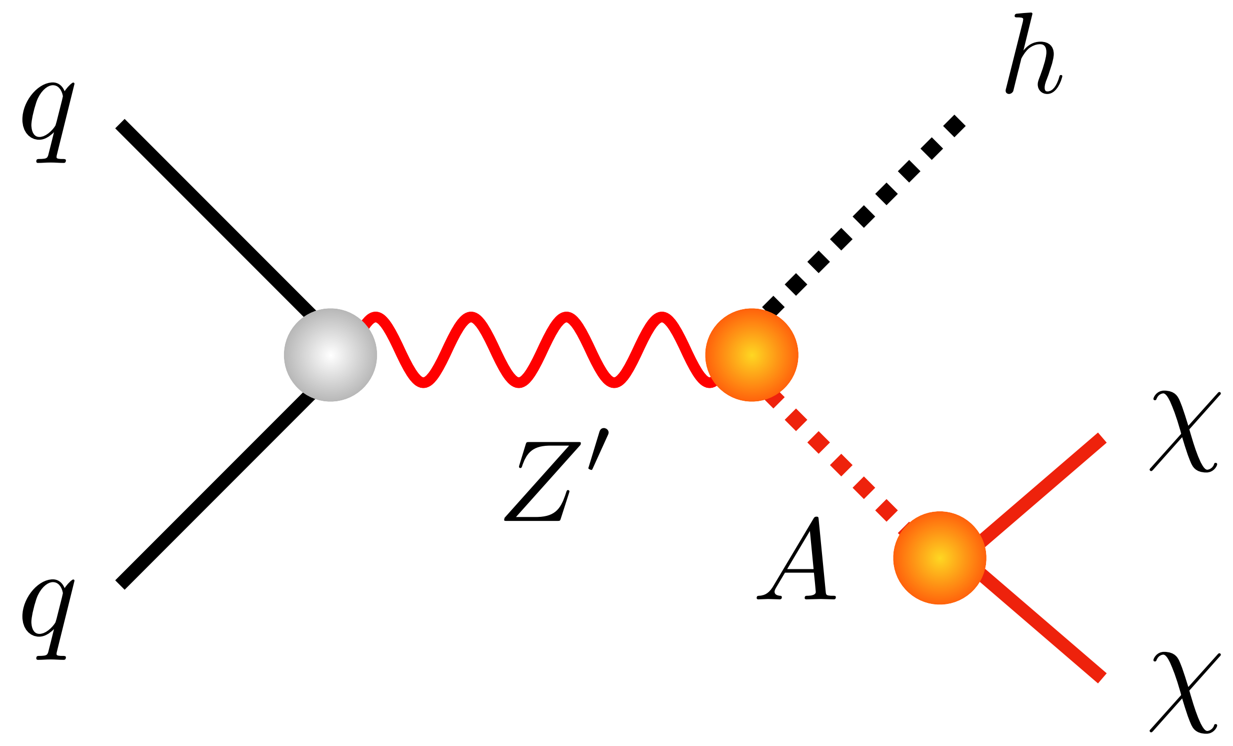


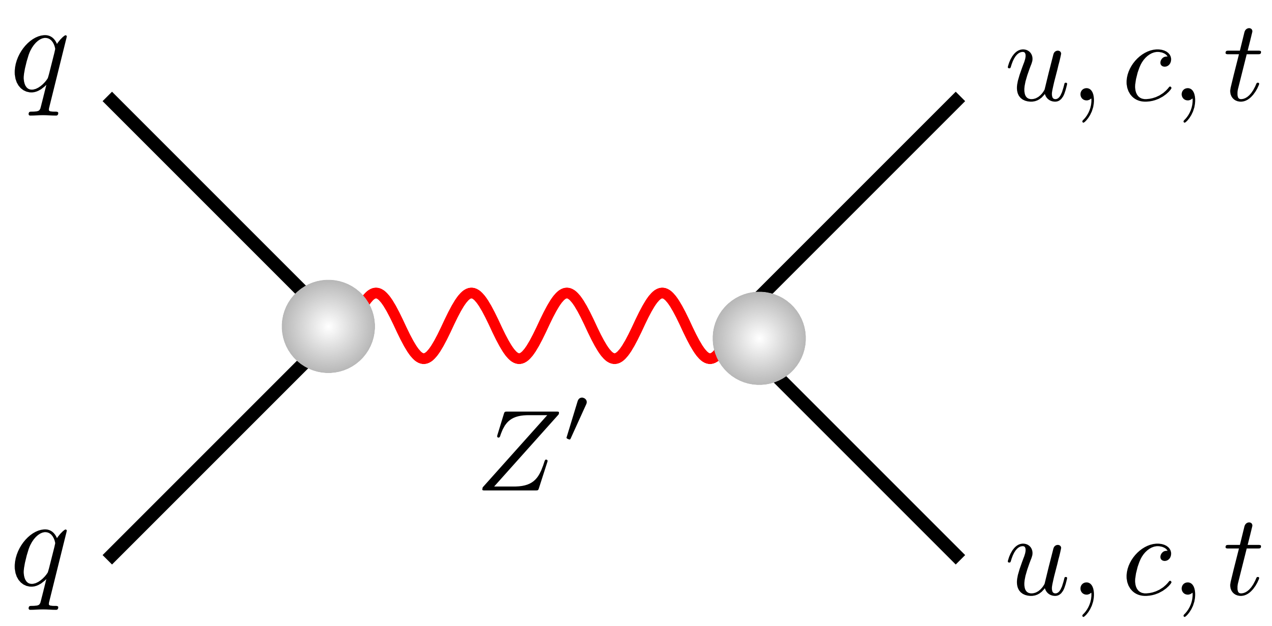
$\propto \; \frac{y_t}{\tan\beta}$

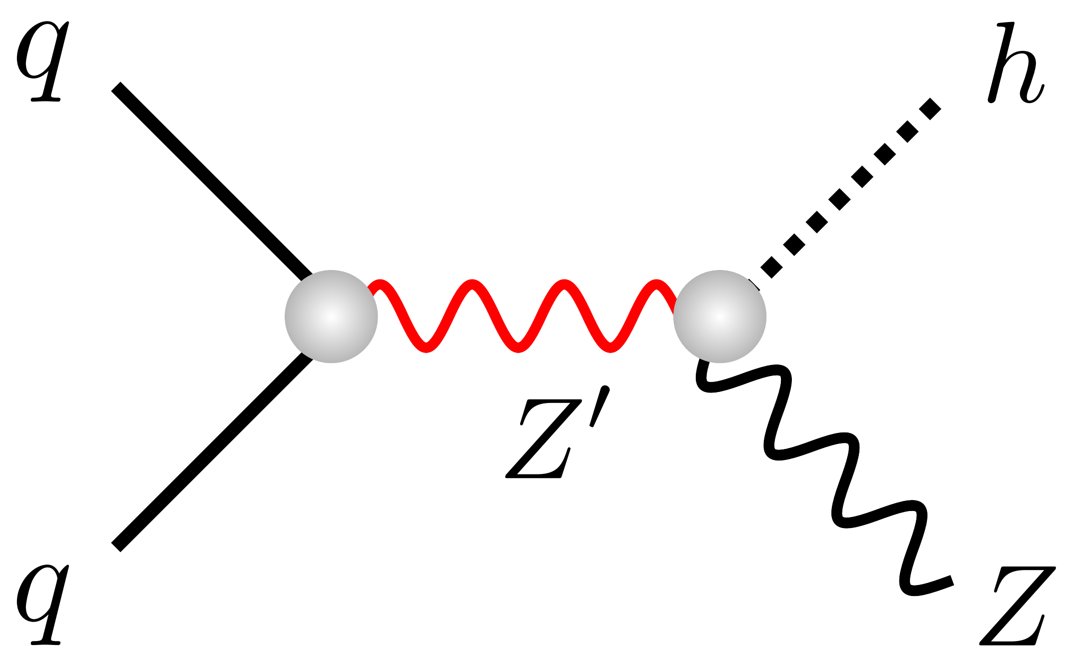
DM candidate taken to be a Majorana fermion
arising from a singlet-doublet DM model

[Berlin, Lin & Wang, 1402.7074; Mahbubani & Senatore, hep-ph/0510064]

2HDM+Z′ model: LHC signatures

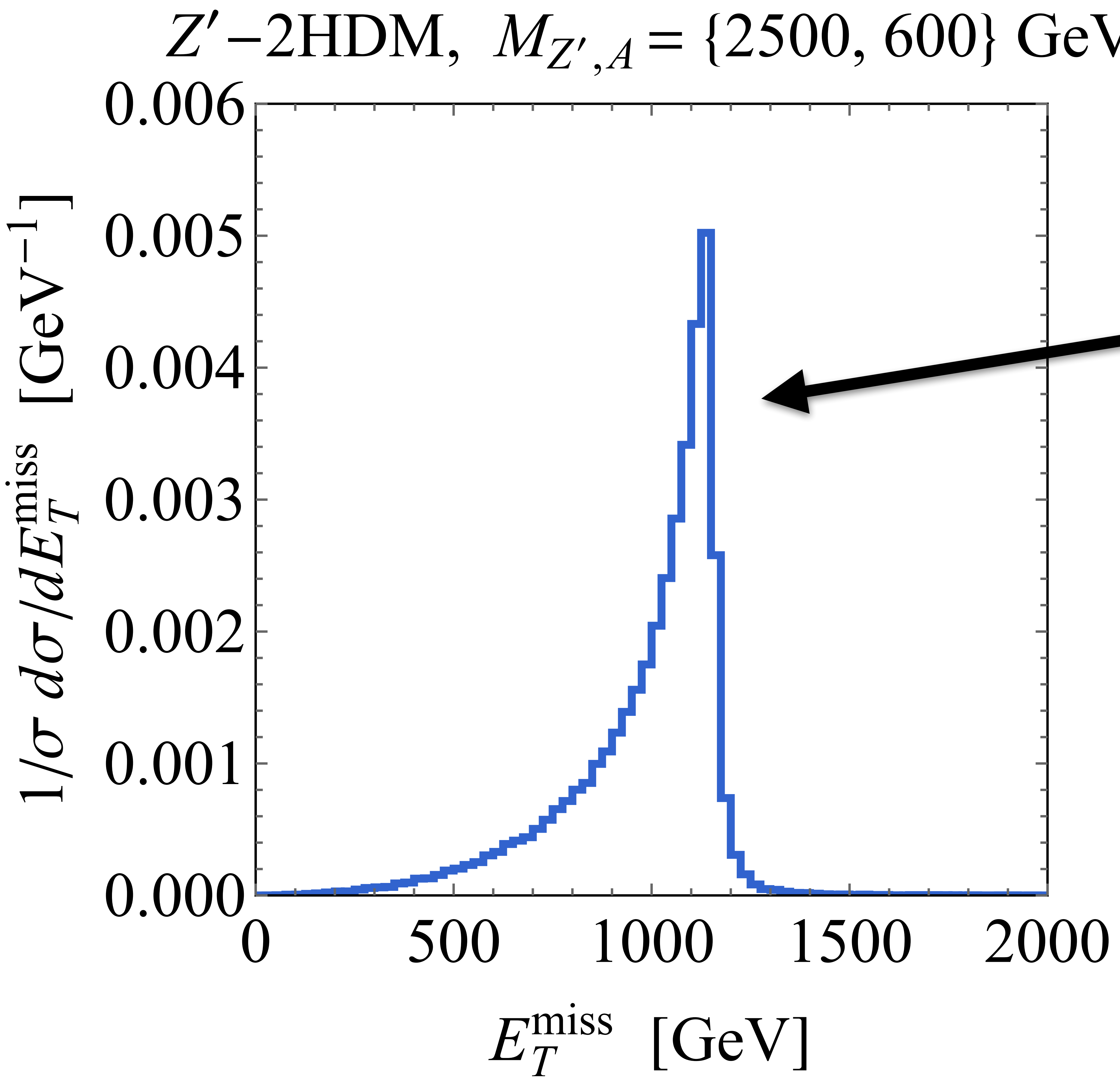


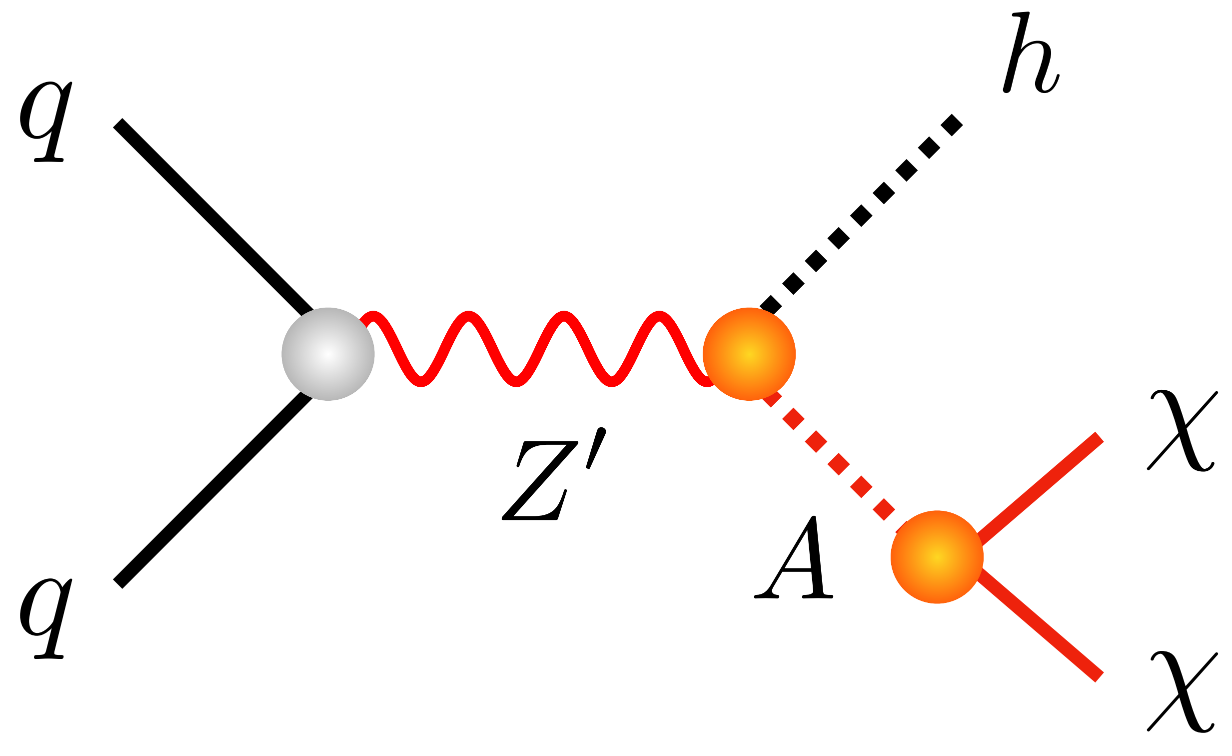




Dominant LHC signatures in 2HDM+Z′ model are mono-Higgs, dijet & ditop as well as Zh production. ATLAS & CMS have focused mostly on $E_{T,miss}$ signal while largely ignoring Z′ resonance searches in SM final states

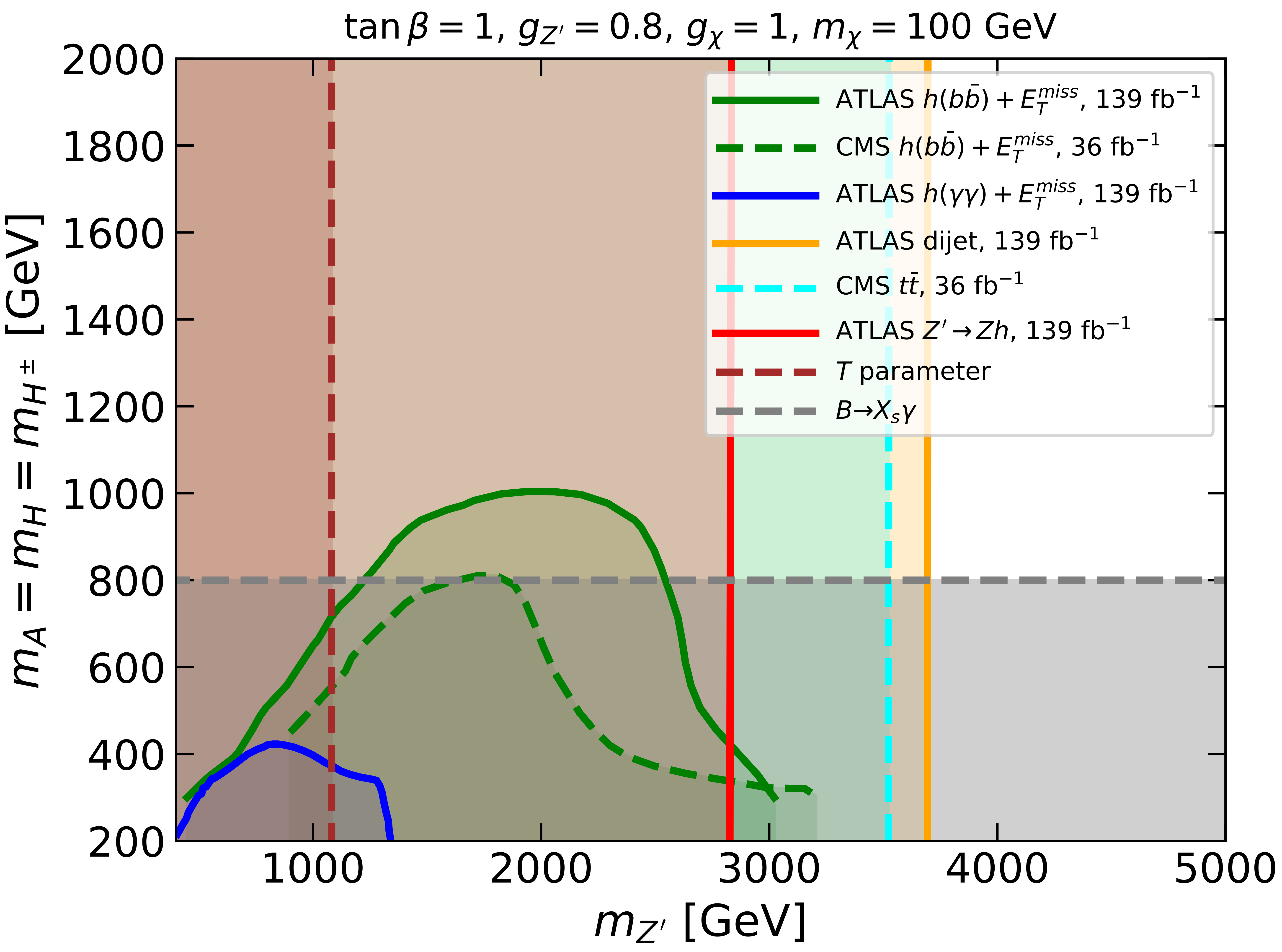
2HDM+Z′ model: mono-Higgs signal





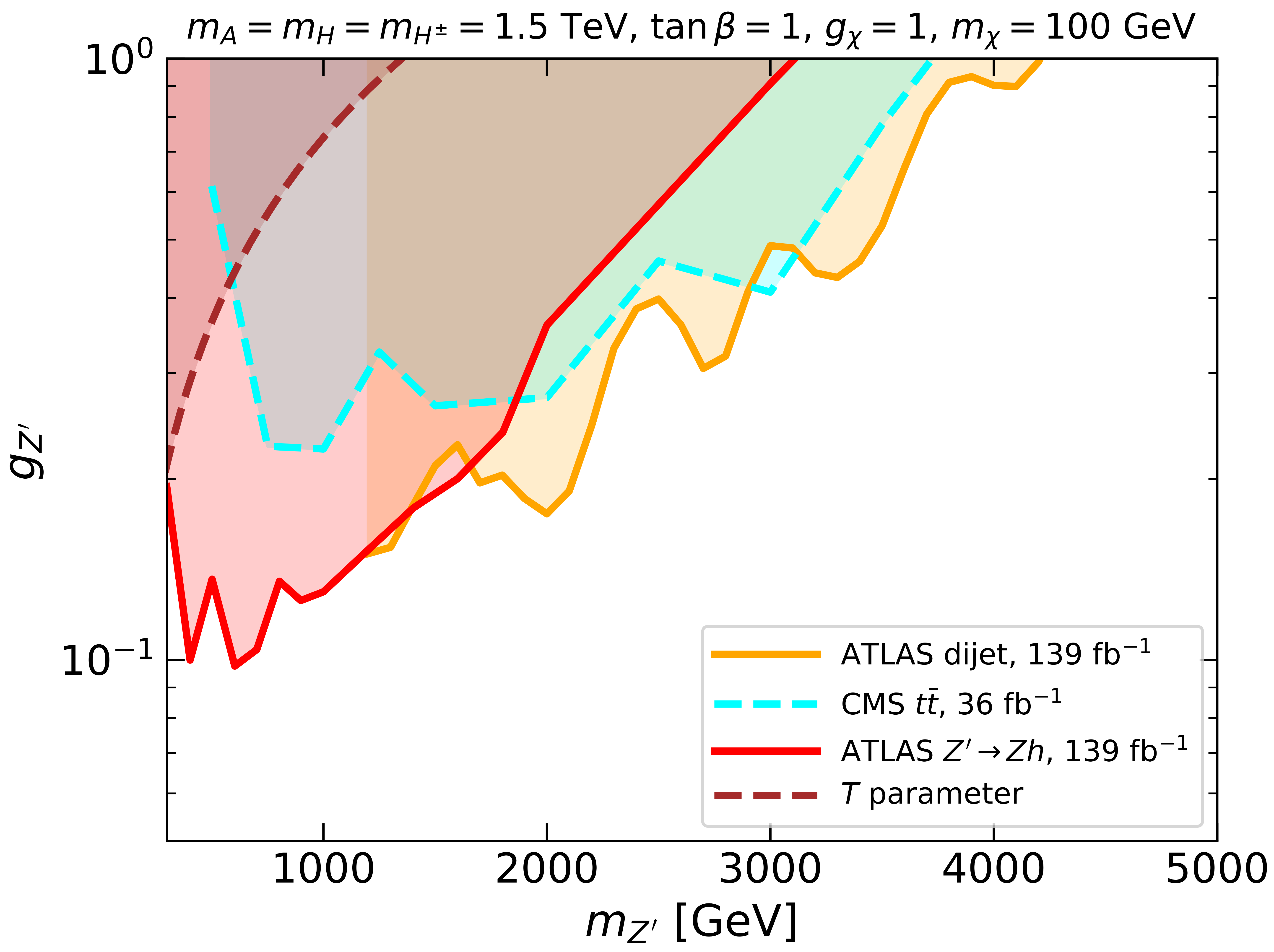
Jacobian peak in $E_{T,miss}$ spectrum
due to resonant Z′ contribution

Constraints on 2HDM+Z′ model



[Agryopoulos, Brandt & UH, 2109.13597]

Constraints on 2HDM+Z′ model



[Agryopoulos, Brandt & UH, 2109.13597]

Two mediator DM (2MDM) model

	H	S	q	l	χ
$U(1)_{Z'}$	0	$q_S = -2q_\chi$	q_q	0	q_χ

SM Higgs doublet uncharged to avoid Z-Z′ mixing. Also forbids tree-level ZZ′h vertex

Majorana DM to avoid direct detection

$$\mathcal{L} = -\frac{g'}{2} q_\chi Z'^\mu \bar{\chi}\gamma_\mu\gamma_5\chi - \frac{y_\chi}{2}\bar{\chi}\left(P_L S + P_R S^*\right)\chi$$

$$+ 4g'^2 q_\chi^2 Z'^\mu Z'_\mu S^\dagger S - g' q_q Z'^\mu \sum_q \bar{q}\gamma_\mu q$$

complex dark Higgs

[Duerr, Kahlhoefer, Schmidt-Hoberg, Schwetz & Vogl, 1606.07609]

Two mediator DM (2MDM) model

$$\langle S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ w \end{pmatrix} \implies m_{Z'} = 2g' q_\chi \,, \quad m_\chi = \frac{y_\chi w}{\sqrt{2}}$$

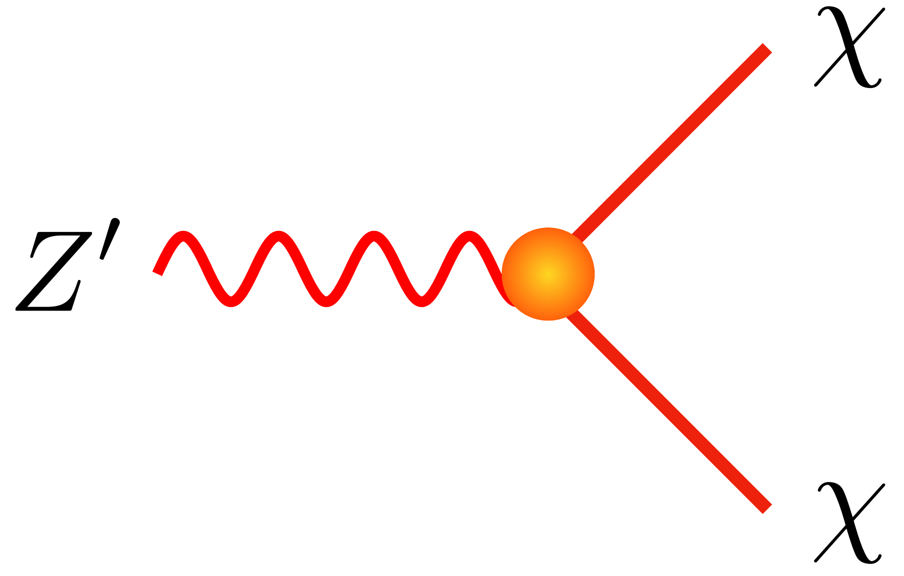
$$\Downarrow$$

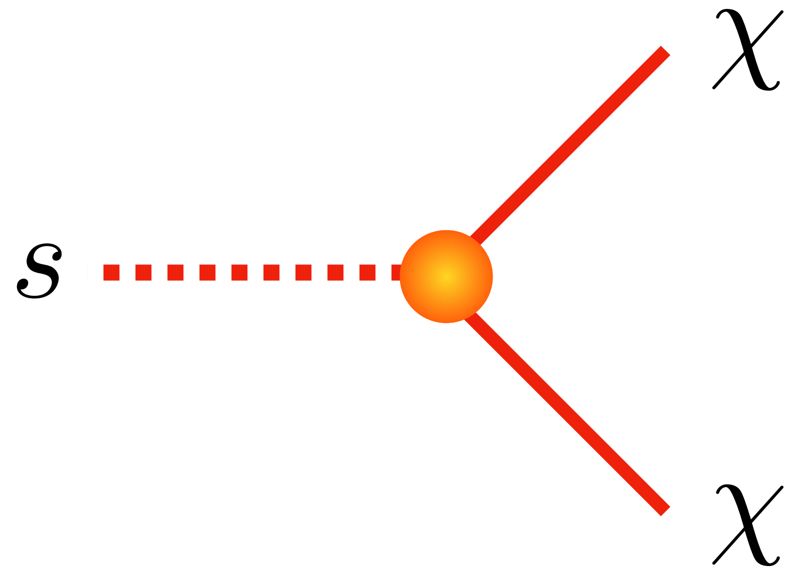
$$\mathcal{L} = -\frac{g_\chi}{2} Z'^\mu \bar{\chi}\gamma_\mu\gamma_5\chi - \frac{g_\chi m_\chi}{m_{Z'}} s\chi\bar{\chi}$$

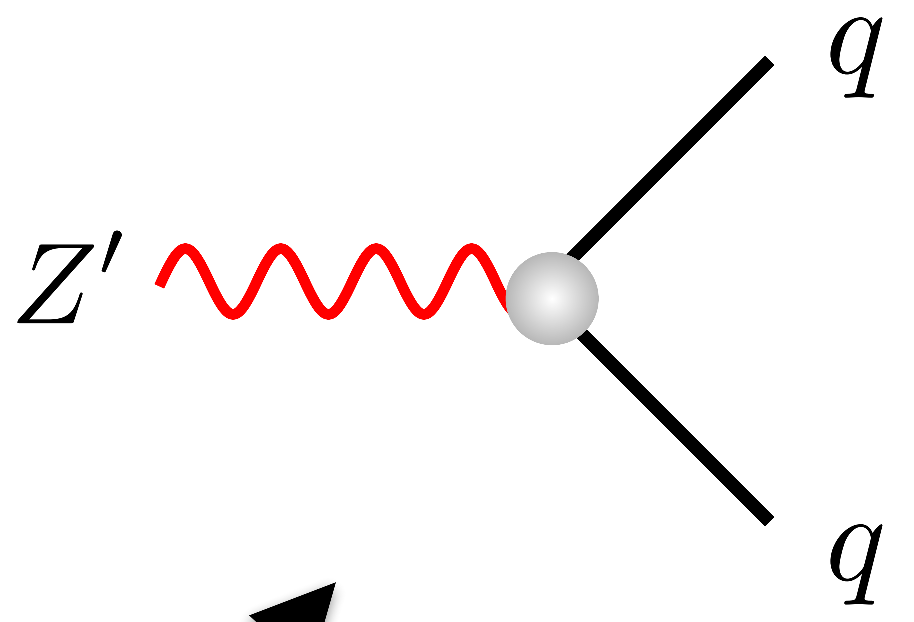
$$+ 2g_\chi^2 Z'^\mu Z'_\mu \left(\frac{m_{Z'}}{g_\chi} s + s^2 \right) - g_q Z'^\mu \sum_q \bar{q}\gamma_\mu q$$

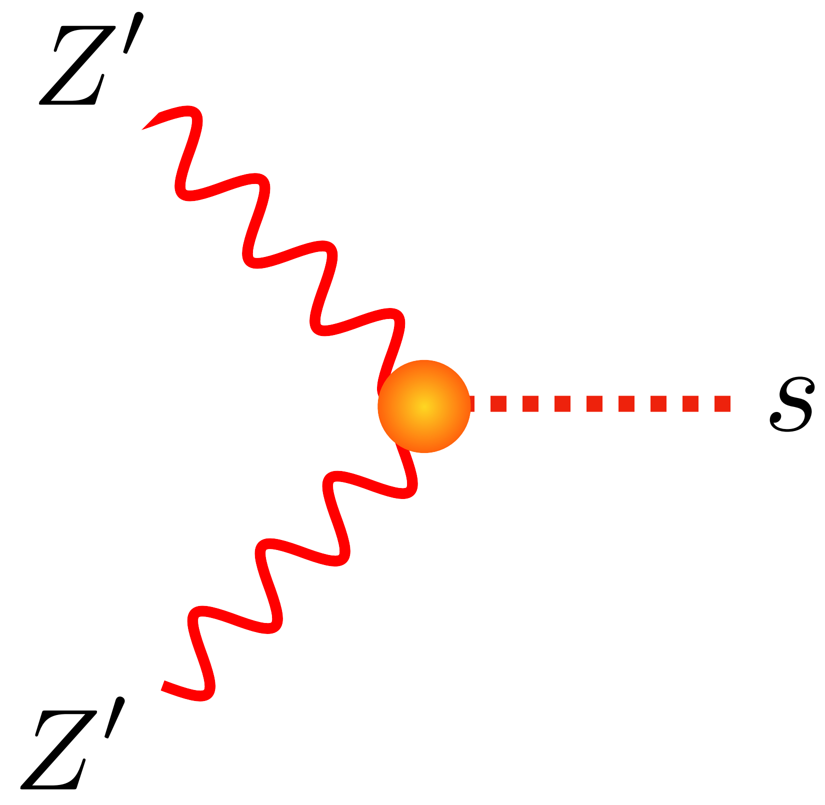
[Duerr, Kahlhoefer, Schmidt-Hoberg, Schwetz & Vogl, 1606.07609]

Two mediator DM (2MDM) model





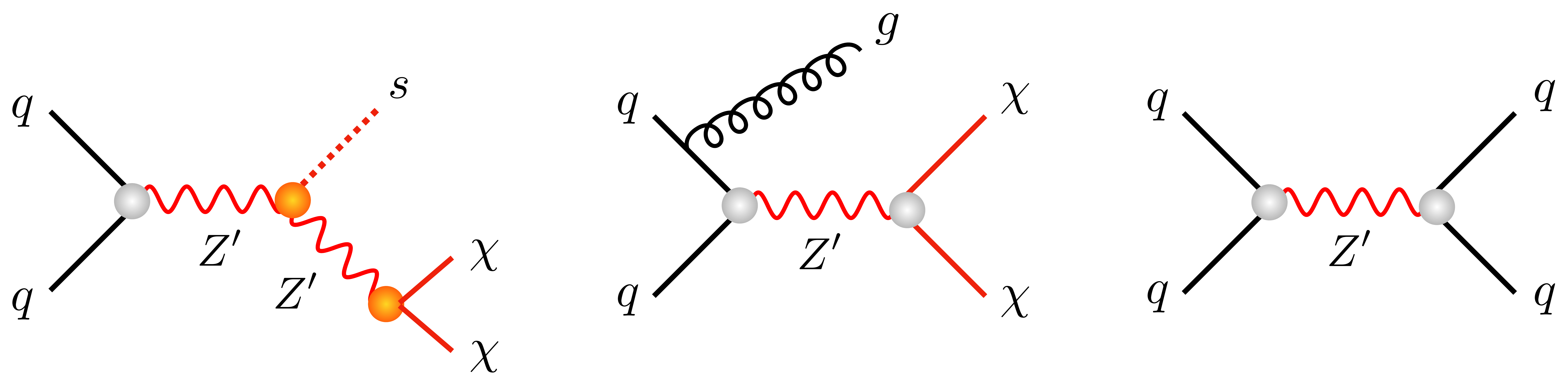




$$\mathcal{L} = -\frac{g_\chi}{2} Z'^\mu \bar{\chi}\gamma_\mu\gamma_5\chi - \frac{g_\chi m_\chi}{m_{Z'}} s\chi\bar{\chi} + 2g_\chi^2 Z'^\mu Z'_\mu \left(\frac{m_{Z'}}{g_\chi} s + s^2\right) - g_q Z'^\mu \sum_q \bar{q}\gamma_\mu q$$

[Duerr, Kahlhoefer, Schmidt-Hoberg, Schwetz & Vogl, 1606.07609]

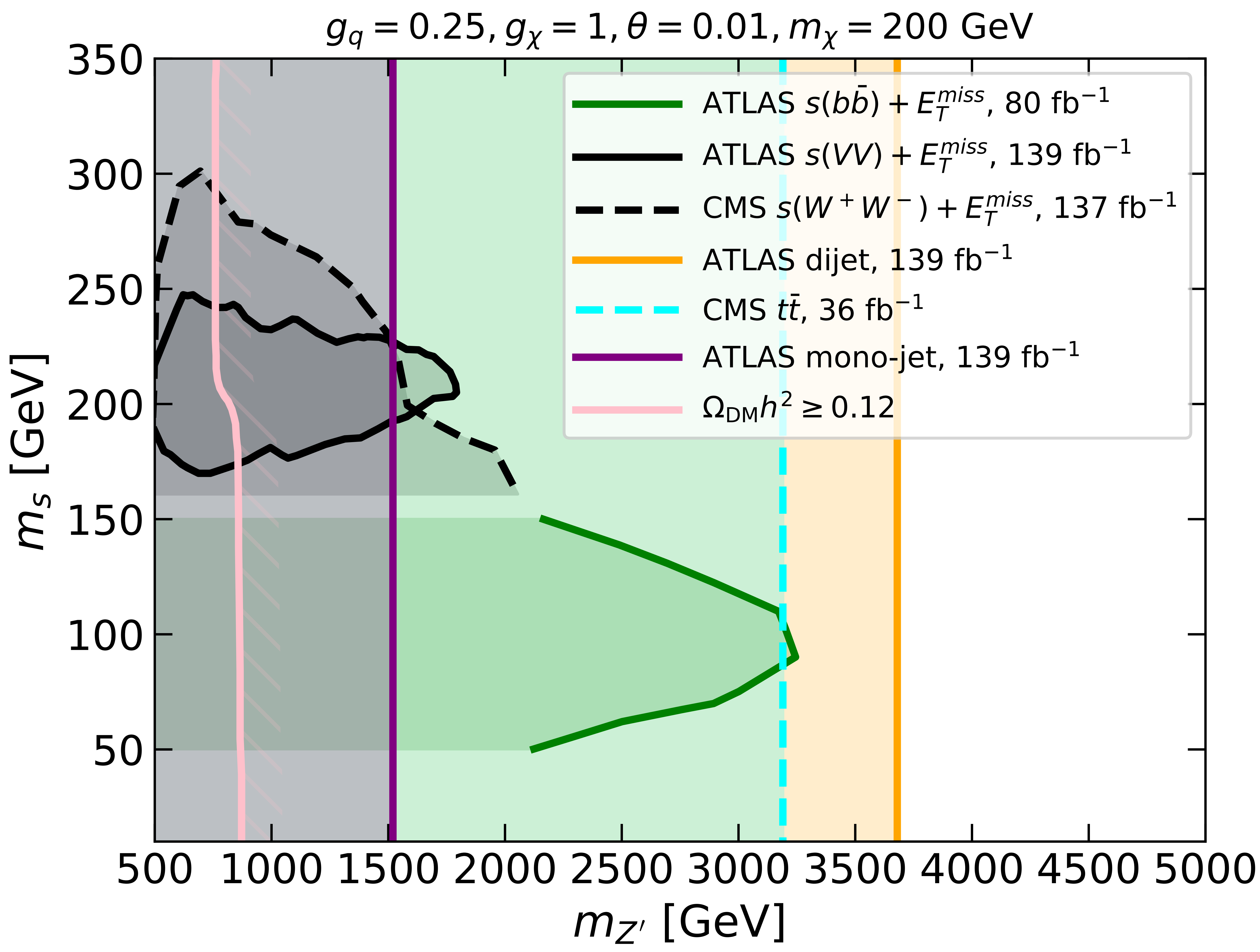
2MDM model: LHC signatures



ATLAS & CMS have recently studied mono-s production in s→bb̄ & s→VV channel. Mono-jet signal & searches for Z′ resonance in dijet & ditop production so far not studied by LHC experiments

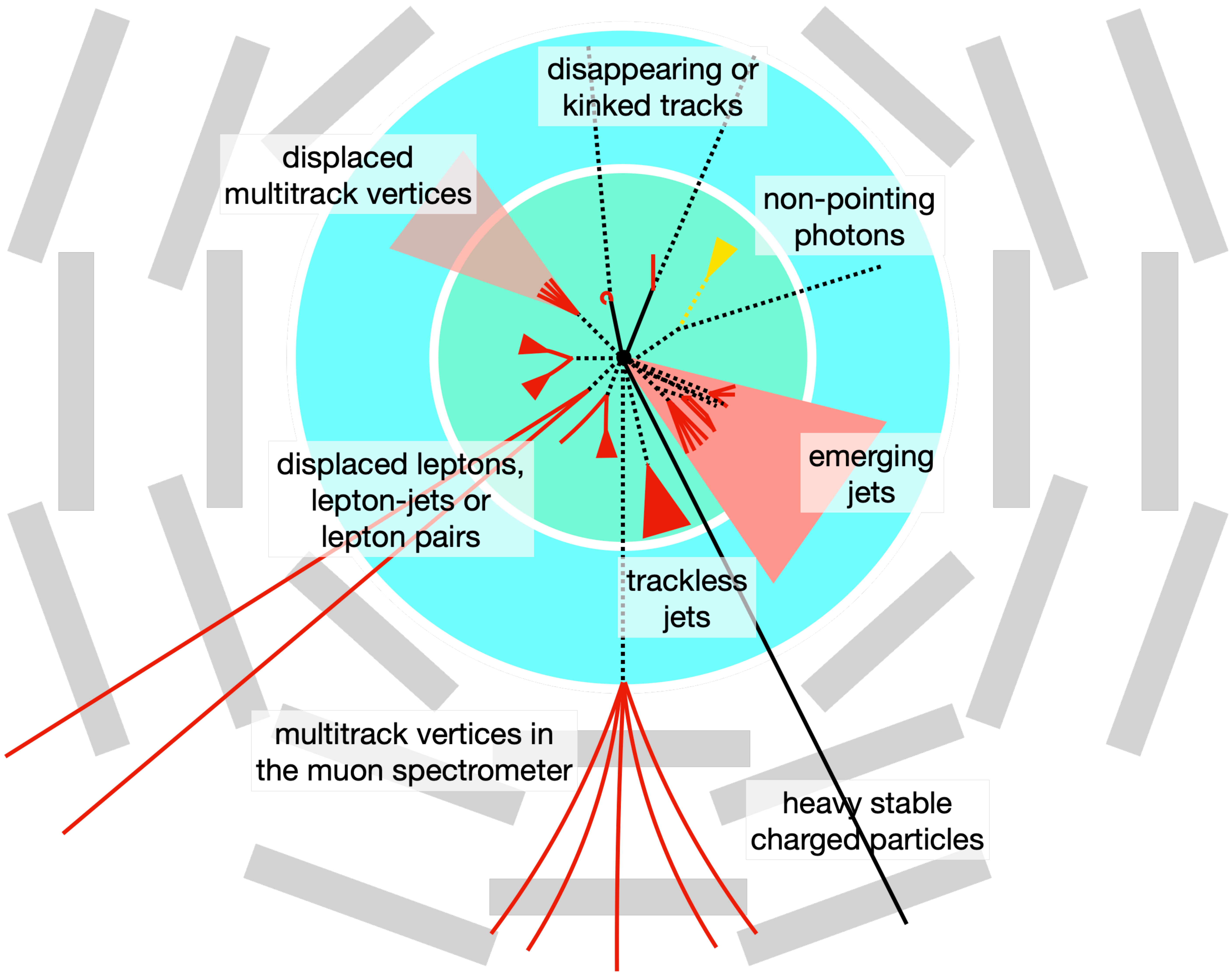

CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-29 15:50:37.950272 GMT
Run / Event / LS: 305840 / 53780077 / 30
$E_{T,\mathrm{miss}}$
ν
μ
W
ν
e
q
Z'
s
W
χ
q
Z'
χ
μ
e

Constraints on 2MDM model

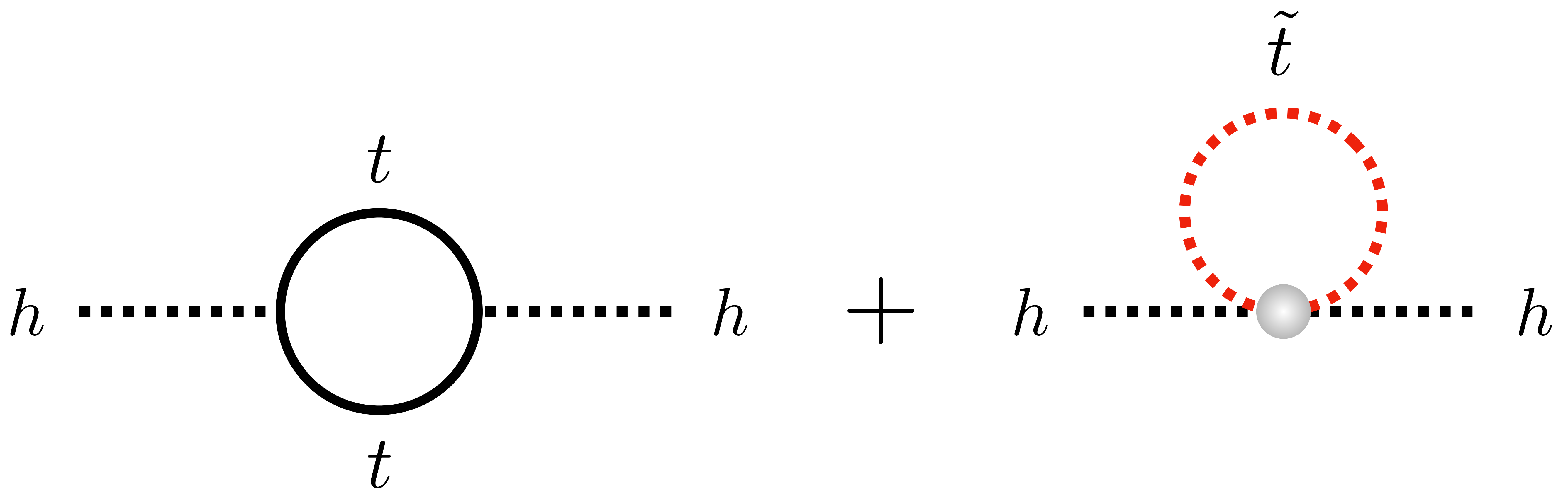


[Agryopoulos, Brandt & UH, 2109.13597]

Long-lived particle (LLP) searches @ LHC



Neutral naturalness

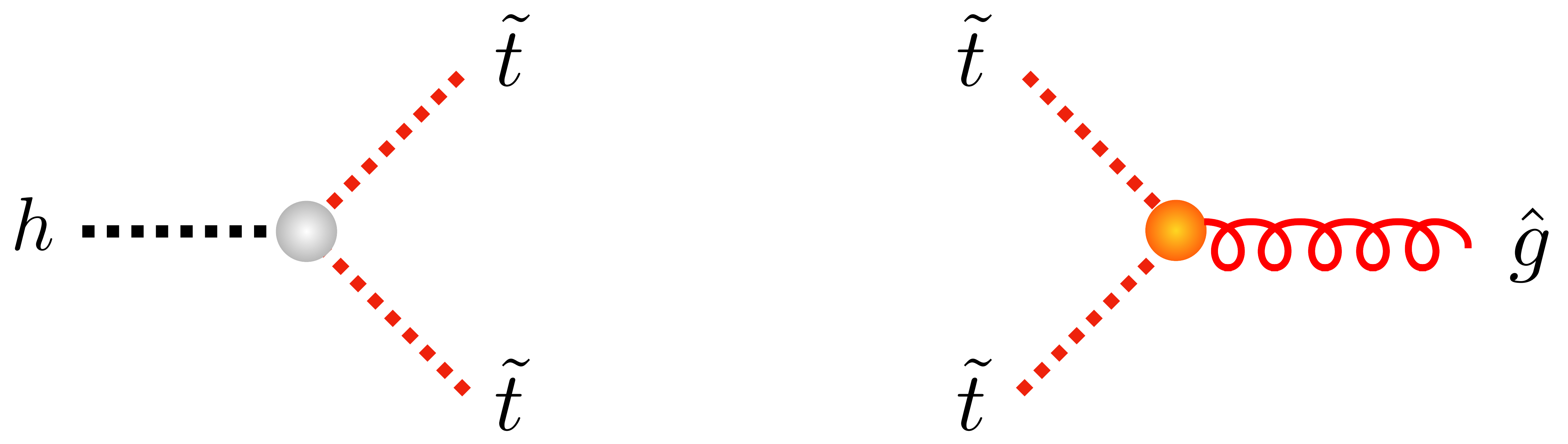


$$\propto \frac{y_t^2}{(4\pi)^2} m_{\tilde{t}}^2 \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

In models of neutral naturalness such as twin Higgs, folded supersymmetry, quirky little Higgs & orbifold Higgs, large top corrections to Higgs mass are cancelled by uncoloured top partners. This relaxes harsh LHC constraints from QCD production

[Chacko et al., hep-ph/0506256; Burdman et al., hep-ph/0609152; Cai et al., 0812.0843; Craig et al., 1410.6808]

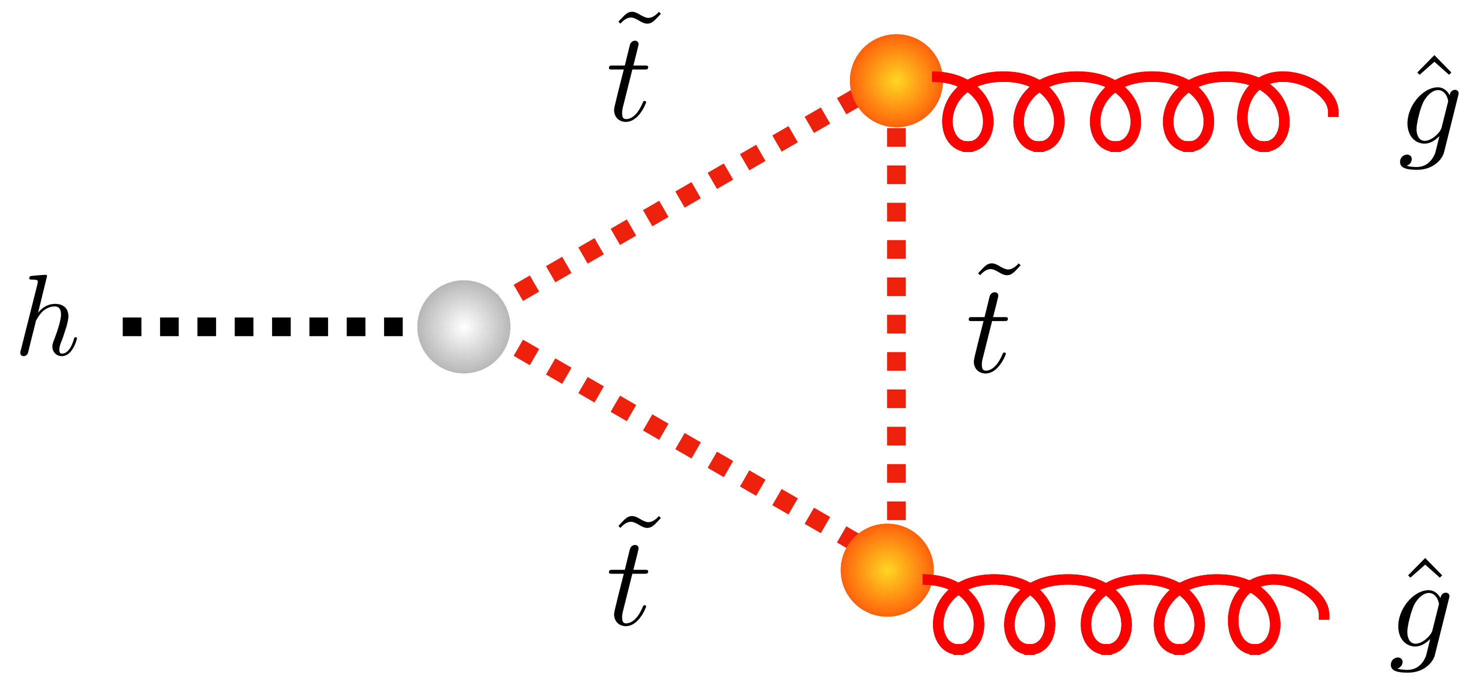
Neutral naturalness



Cancellation is achieved with discrete symmetries that must be nearly exact in top sector. Since QCD coupling drives renormalisation group running of top Yukawa y_t, viable theories of neutral naturalness contain at least a new QCD-like hidden gauge group with a coupling $\hat{\alpha}_s$ with a strength similar to α_s

[Chacko et al., hep-ph/0506256; Burdman et al., hep-ph/0609152; Cai et al., 0812.0843; Craig et al., 1410.6808]

Neutral naturalness



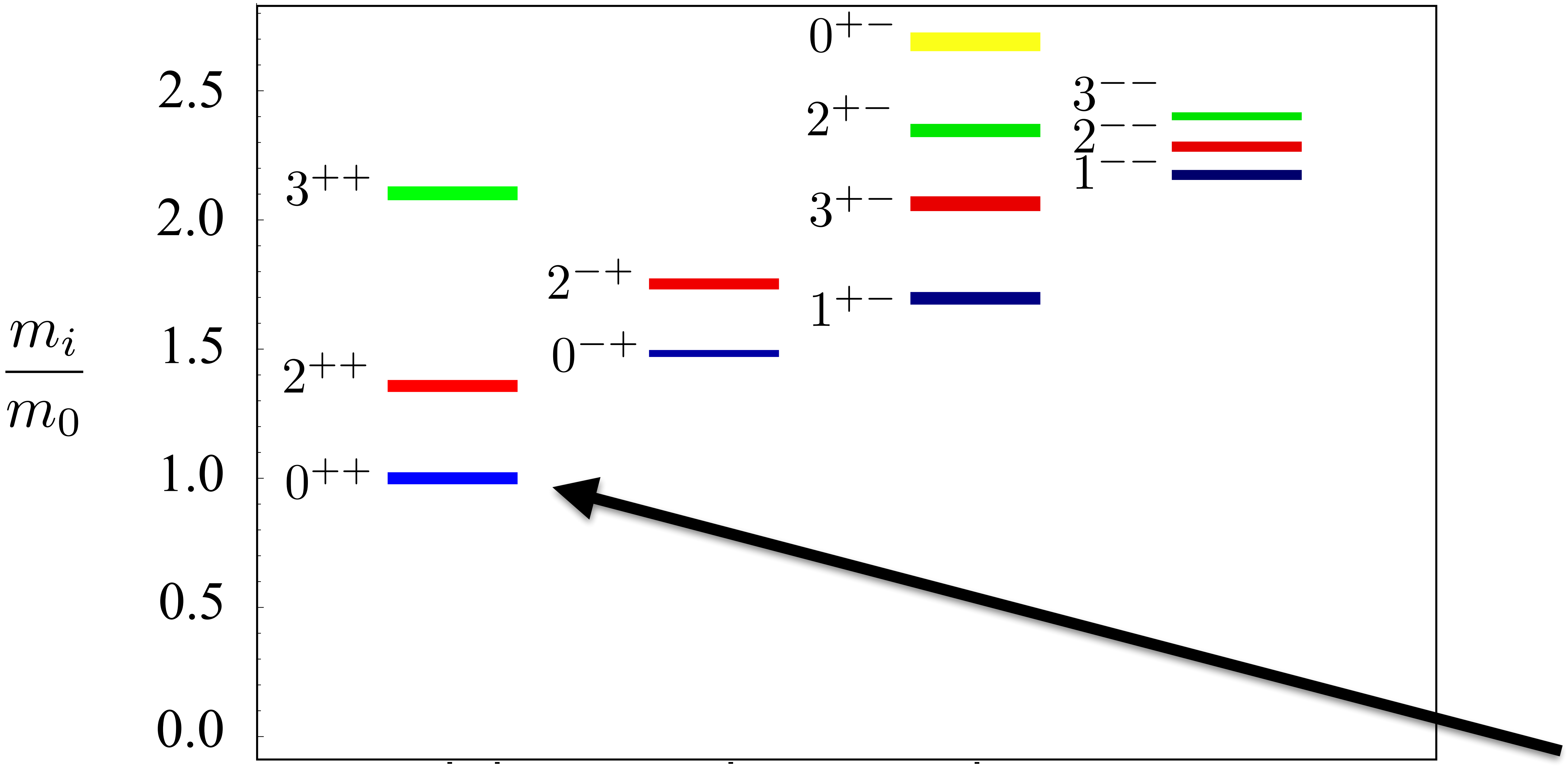
$$\Longrightarrow \qquad \mathcal{L} \simeq \frac{\hat{\alpha}_s}{12\pi} \frac{h}{v} \hat{G}^a_{\mu\nu} \hat{G}^{a,\mu\nu} \frac{v^2}{m^2_{\tilde{t}}}$$

In full analogy to SM where top loops generate an effective *hgg* coupling, in theories of neutral naturalness interactions of Higgs & top partners gives rise to an effective *h*$\hat{g}\hat{g}$ coupling at one-loop level

[Chacko et al., hep-ph/0506256; Burdman et al., hep-ph/0609152; Cai et al., 0812.0843; Craig et al., 1410.6808]

Hidden glueballs

$$m_0 \simeq 7\Lambda_{QCD} \simeq 1.7\,\text{GeV}$$



In pure SU(3) theories $J^{CP} = 0^{++}$ glueball is lightest bound state

[Morningstar & Peardon, hep-lat/9901004; Juknevich et al., 0903.0883, 0911.5616]

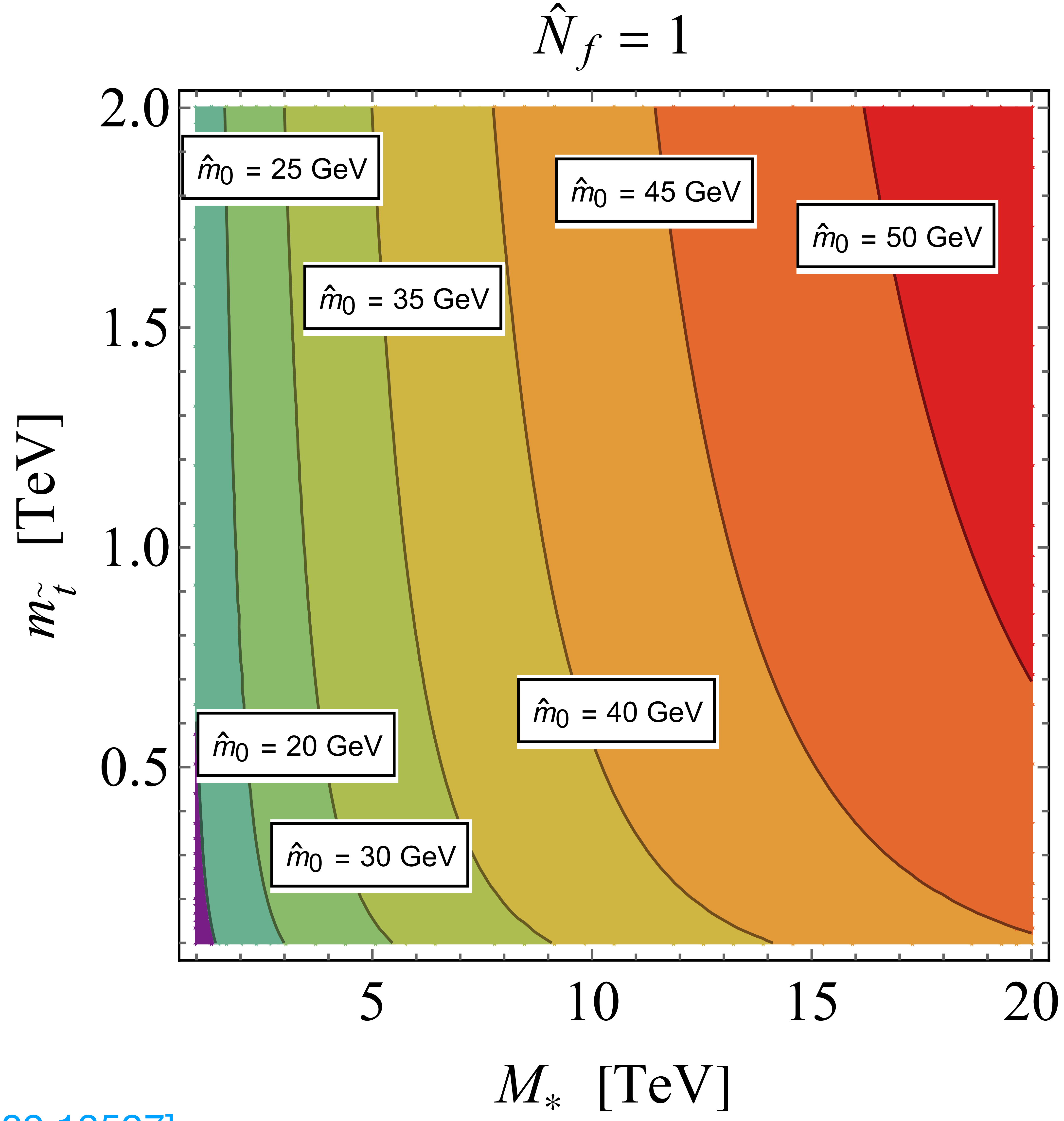
Hidden glueballs

$$\hat{m}_0 = \frac{\hat{\Lambda}_{\text{Landau}}}{\Lambda_{\text{Landau}}} m_0 \simeq 11\,\hat{\Lambda}_{\text{Landau}}$$

$$\hat{\alpha}_s(M_*) = \alpha_s(M_*)$$

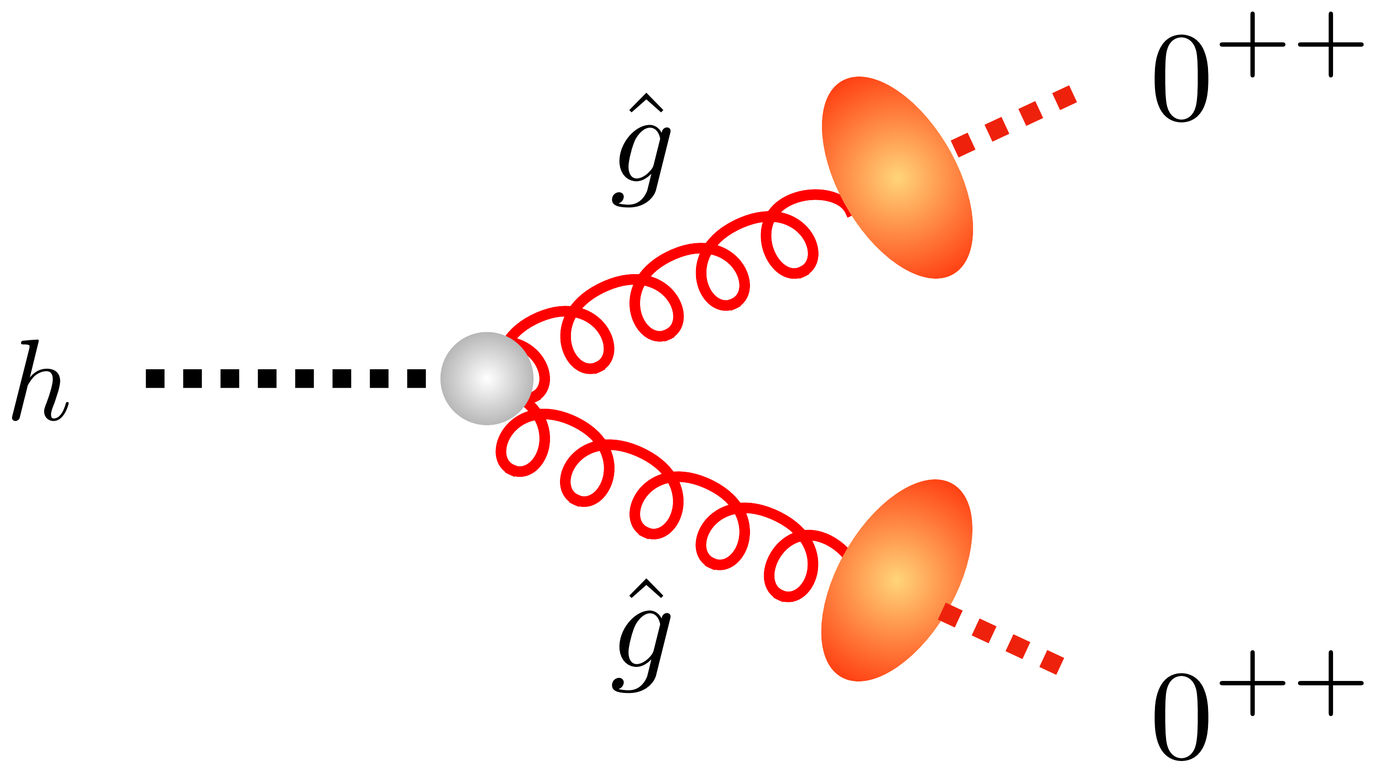
$$\hat{\beta} = \begin{cases} 11 - \frac{2}{3}\hat{N}_f\,, & m_{\tilde{t}} < \mu < M_* \\ 11\,, & m_{\tilde{t}} < M \end{cases}$$

$$\frac{1}{\hat{\alpha}_s(\hat{\Lambda}_{\text{Landau}})} = 0$$

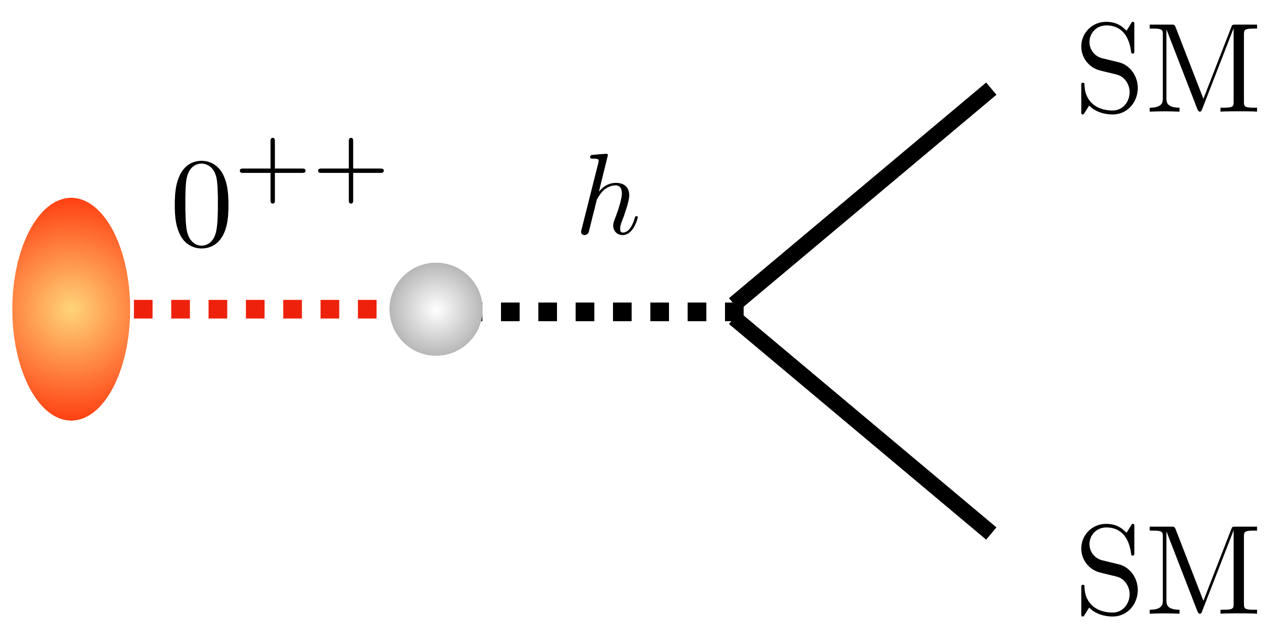


[Craig, Knapen & Longhi, 1410.6808; Agryopoulos, Brandt & UH, 2109.13597]

Hidden glueballs



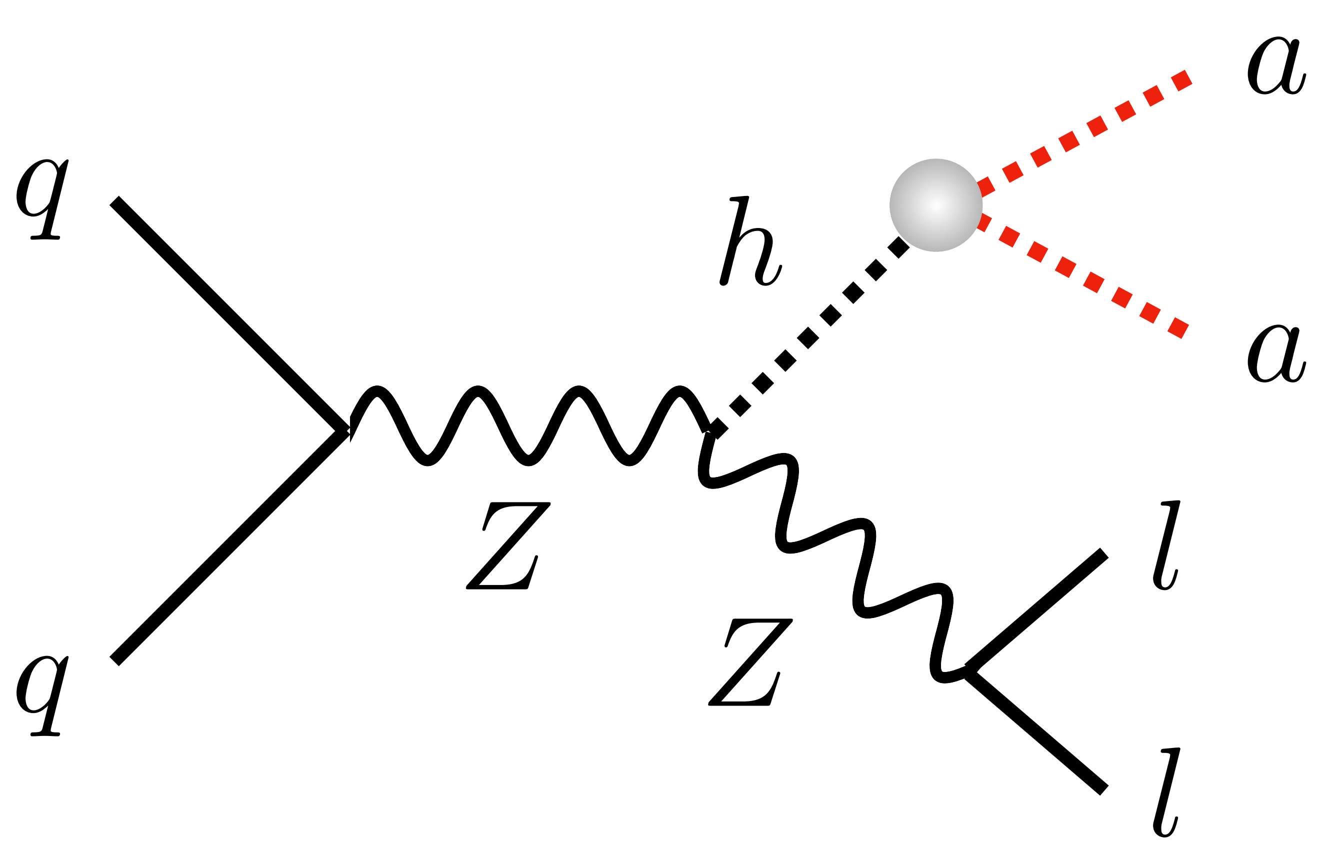
$$2 \cdot 10^{-5} \lesssim \mathrm{BR}\left(h \to 0^{++}0^{++}\right) \lesssim 1 \cdot 10^{-2}$$

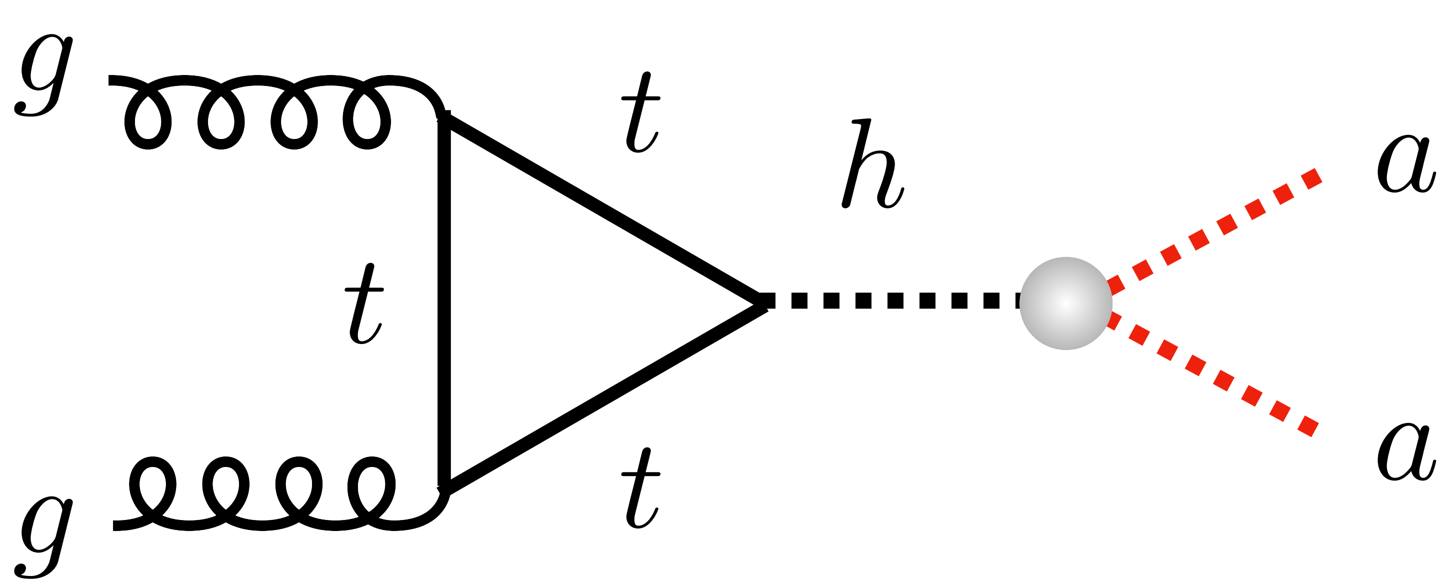


$$c\tau_{0^{++}} \simeq 2\,\mathrm{m} \cdot \left(\frac{15\,\mathrm{GeV}}{\hat{m}_0}\right)^7 \left(\frac{m_{\tilde{t}}}{1\,\mathrm{TeV}}\right)^4$$

[Curtin & Verhaaren, 1506.06141; Juknevich, 0911.5616]

Neutral naturalness: LHC signatures

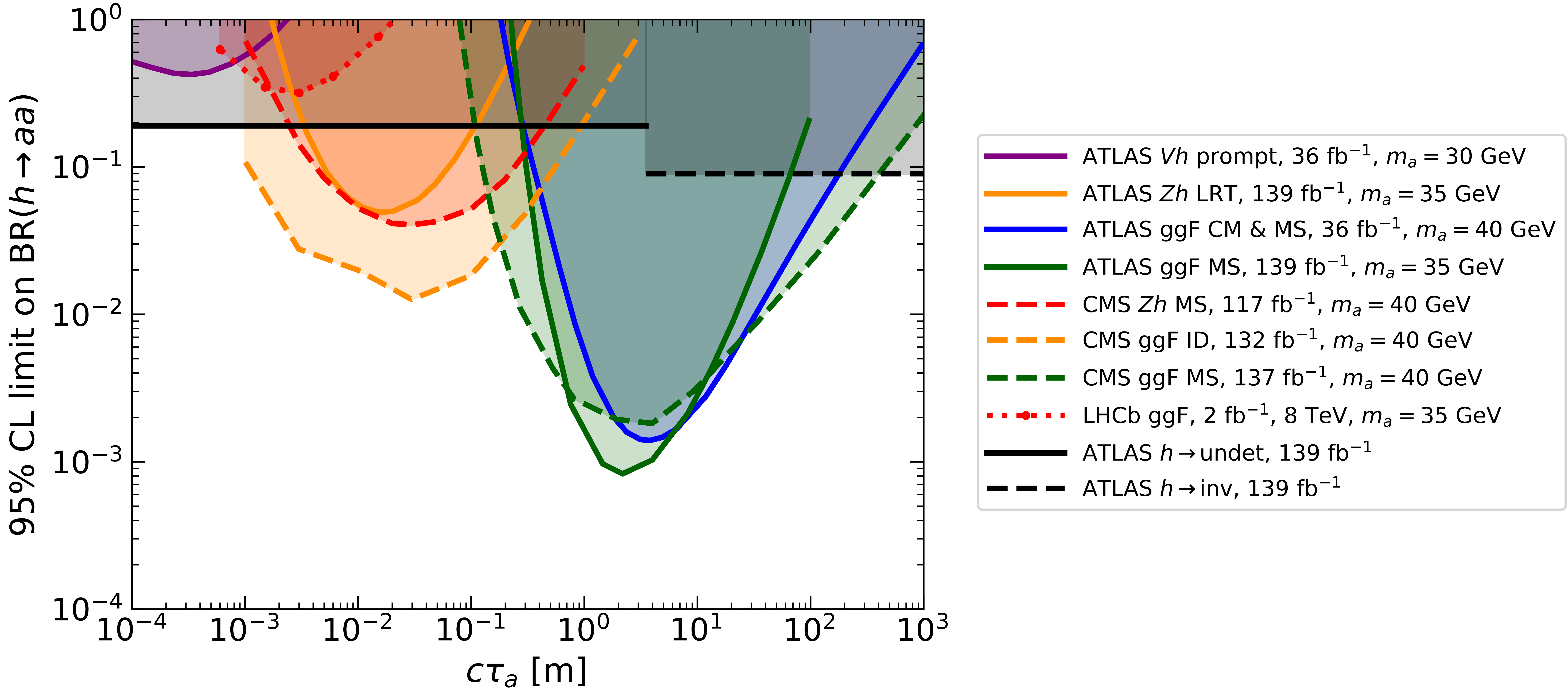




LLP signatures from neutral naturalness have been tested by ATLAS, CMS & LHCb in Zh or gluon-gluon-fusion (ggF) Higgs production. Phenomenology very similar to hidden valleys with role of hidden glueballes (0^{++}, s) played by hidden pions (π_h, a)

[Strassler & Zurek, hep-ph/0604261, hep-ph/0605193; Han et al., 0712.2041]

Constraints on neutral naturalness



[Agryopoulos, Brandt & UH, 2109.13597]

Dark photons

hypercharge portal

Higgs portal

$$\mathcal{L} = \frac{\epsilon}{2\cos\theta_w} B_{\mu\nu} X^{\mu\nu} - \kappa (H^\dagger H) S^2$$

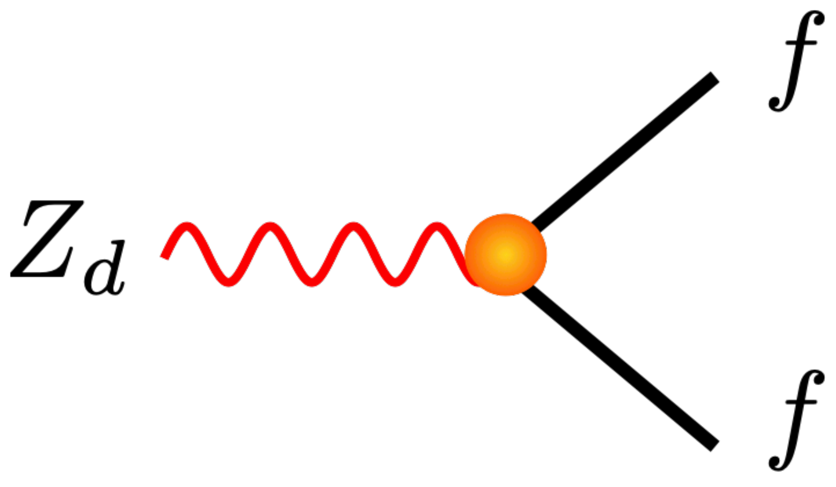
$\langle H \rangle, \langle S \rangle$

γ, Z, Z_d ← dark photon

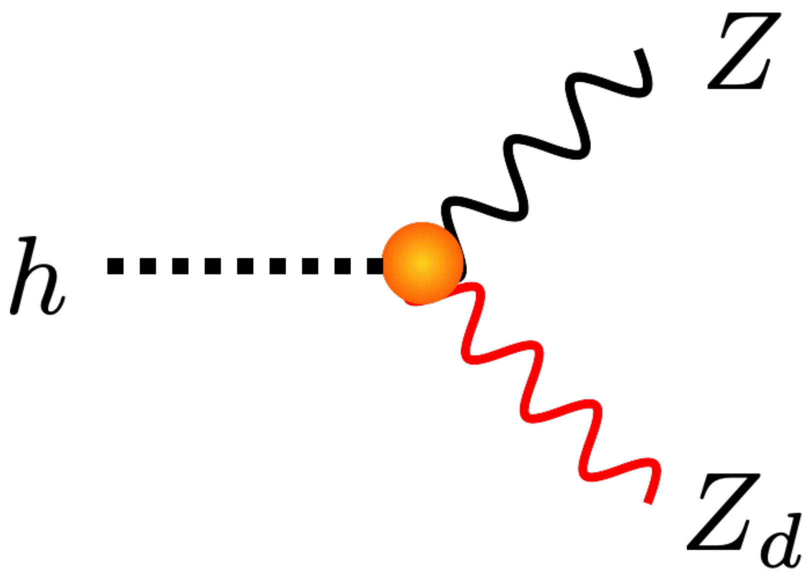
h, h_d ← dark Higgs

[see for instance Curtin et al., 1312.4992, 1412.0018]

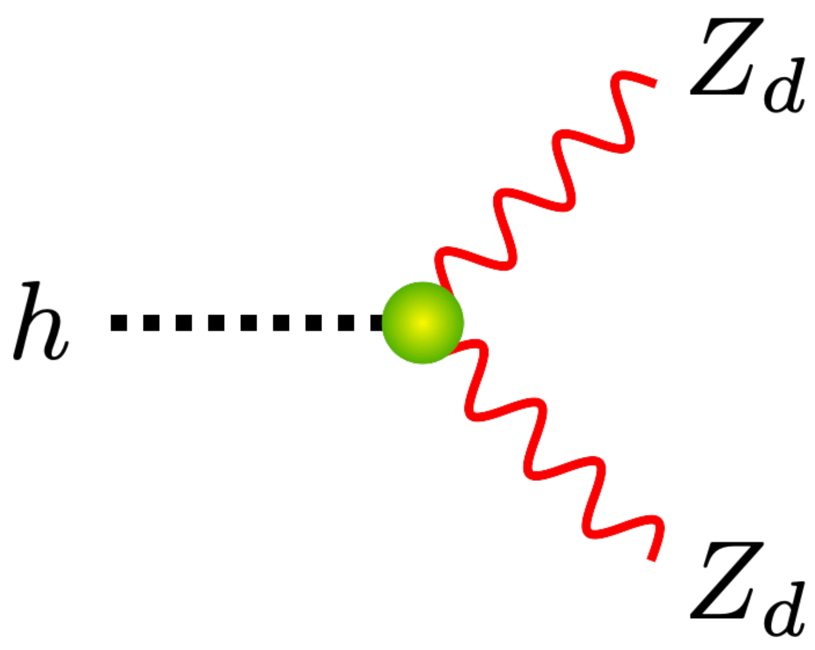
Dark photons



$$g_{Z_d f \bar{f}} = \epsilon e \left[Q_f + \left(Q_f - \frac{Y_f}{\cos^2 \theta_w} \right) \frac{m_{Z_d}^2}{m_Z^2} \right]$$



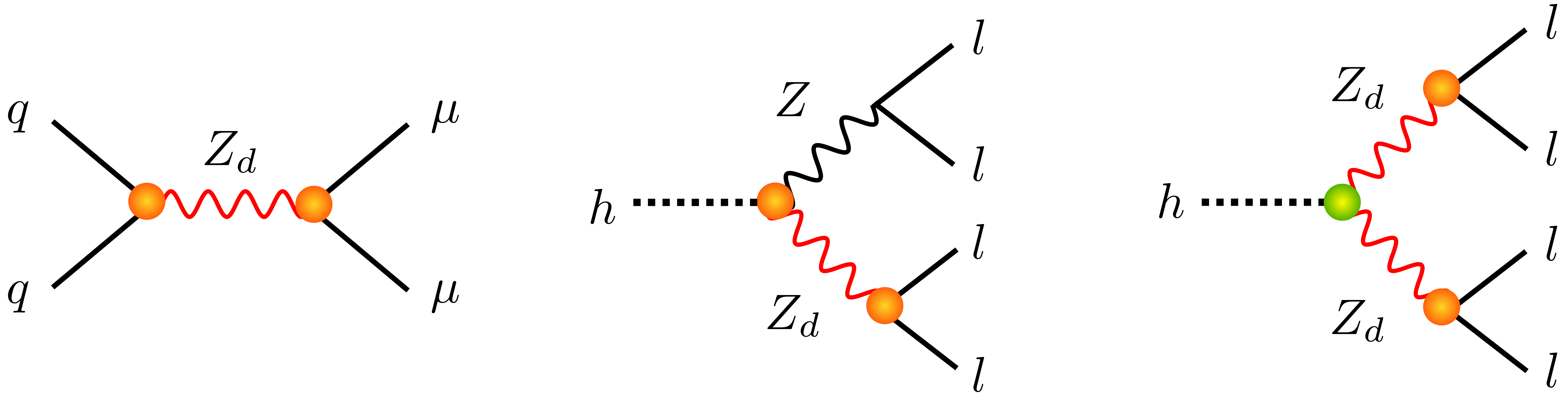
$$g_{hZZ_d} = \frac{2\epsilon \tan \theta_w}{v} \frac{m_{Z_d}^2 m_Z^2}{m_Z^2 - m_{Z_d}^2}$$



$$g_{hZ_dZ_d} = \frac{2\kappa v m_{Z_d}^2}{m_{h_d}^2 - m_h^2}$$

[see for instance Curtin et al., 1312.4992, 1412.0018]

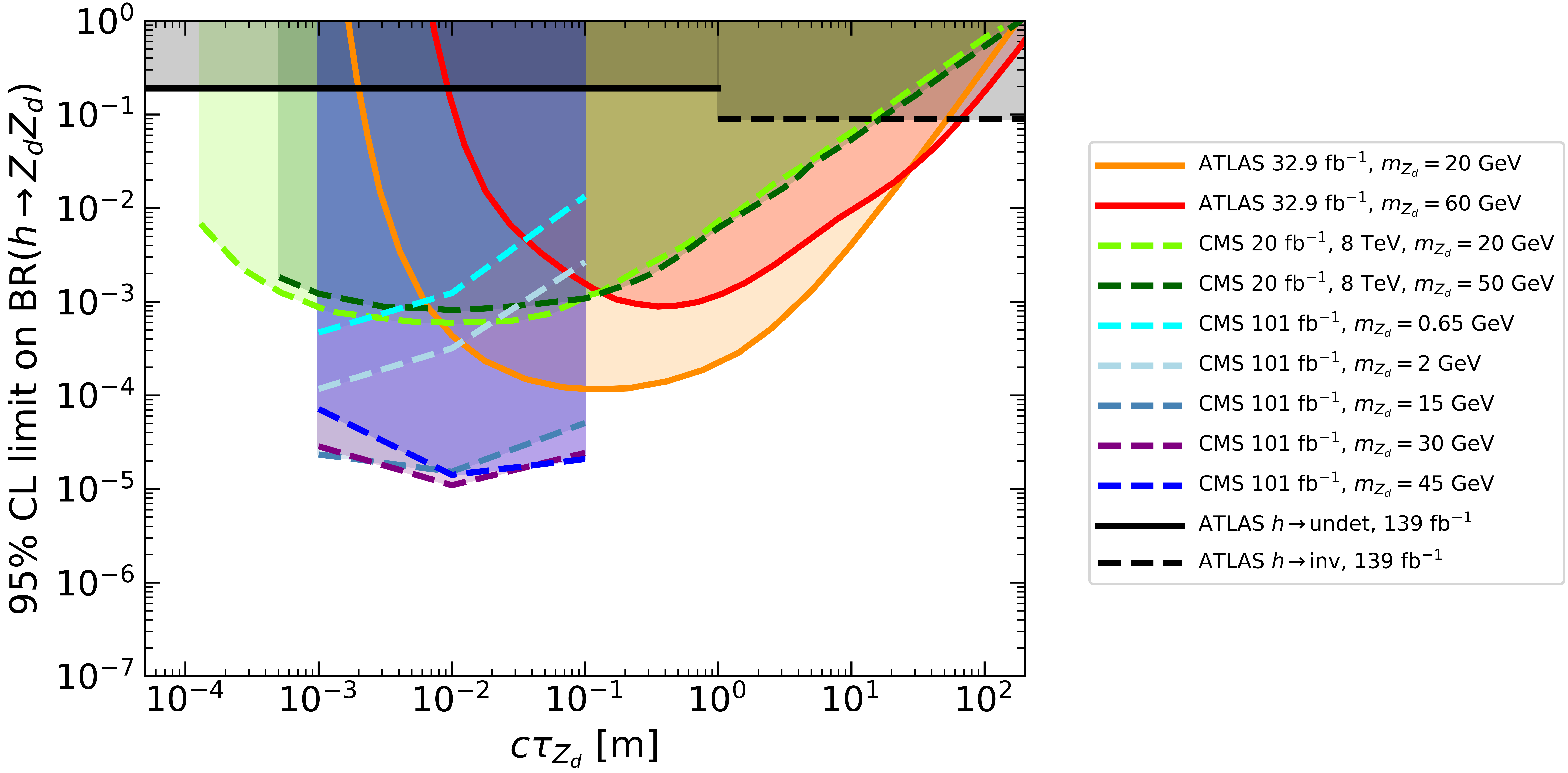
Dark photons



Dark photons can be looked for in dimuon Drell-Yan production & also exotic Higgs decays to 4l. For $\varepsilon \gtrsim O(10^{-4})$ dark photon decays prompt but for $O(10^{-8}) \lesssim \varepsilon \lesssim O(10^{-4})$, Z_d decays are displaced with a large fraction ending up in LHC detectors

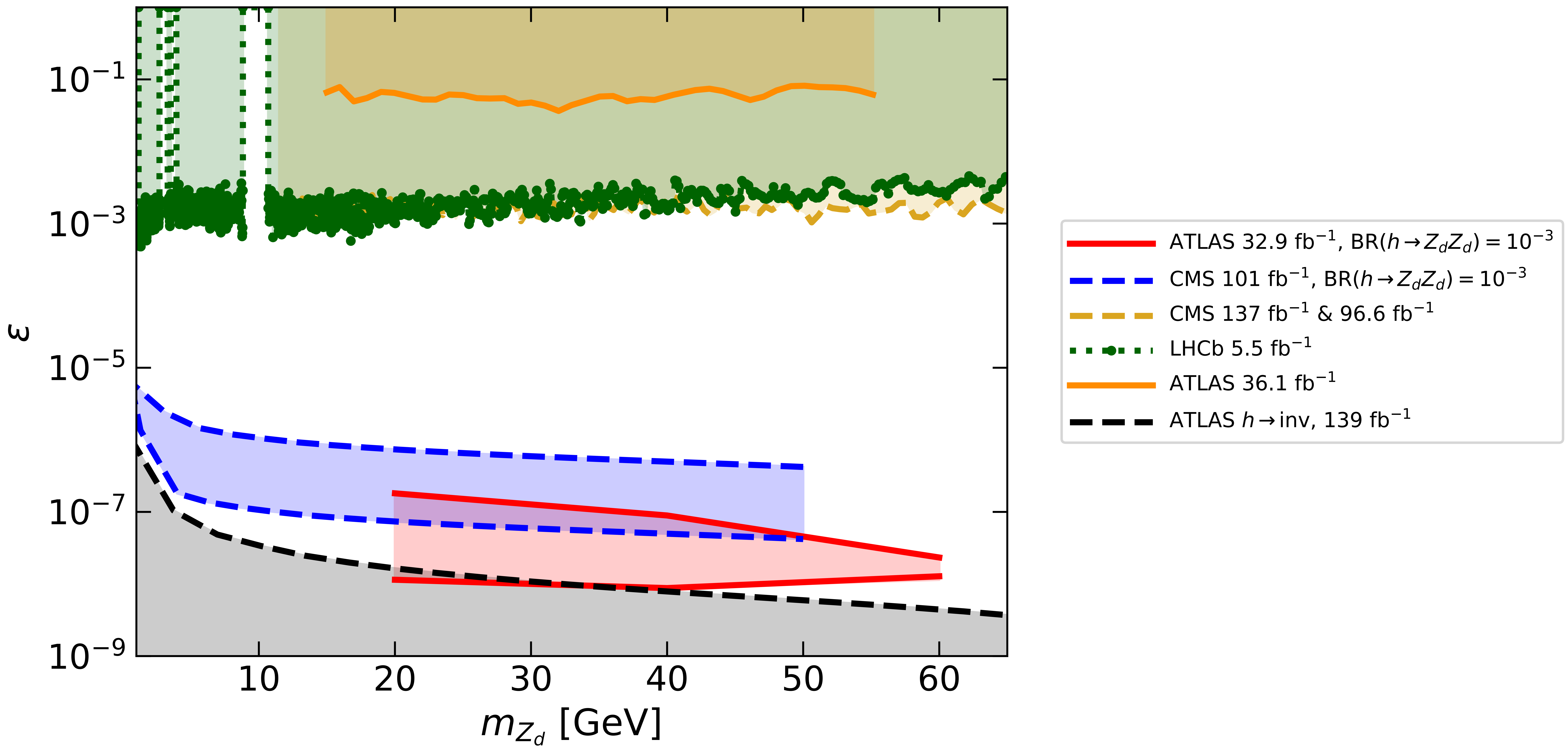
[see for instance Curtin et al., 1312.4992, 1412.0018]

Constraints on dark photons



[Agryopoulos, Brandt & UH, 2109.13597]

Constraints on dark photons

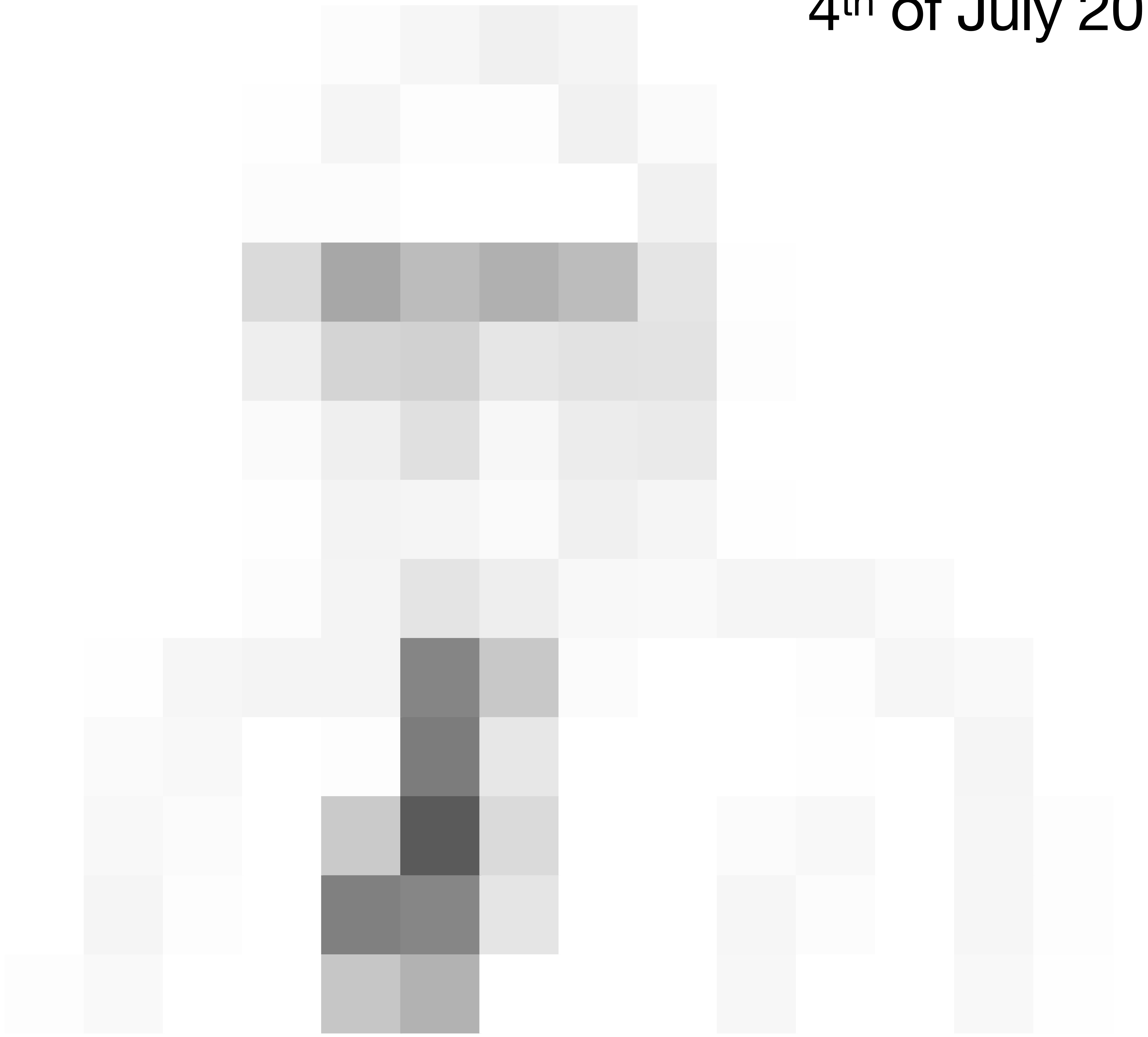


[Agryopoulos, Brandt & UH, 2109.13597]

Whether or not …

there is a connection between Higgs & DM or dark sector can only be figured out by experiments. LHC can play an important role in this context

4th of July 2012



Higgs in ATLAS & CMS

Whether or not …

In 2022

there is a connection between Higgs & DM or dark sector can only be figured out by experiments. LHC can play an important role in this context

Higgs in ATLAS & CMS

Whether or not …

Maybe in 2032

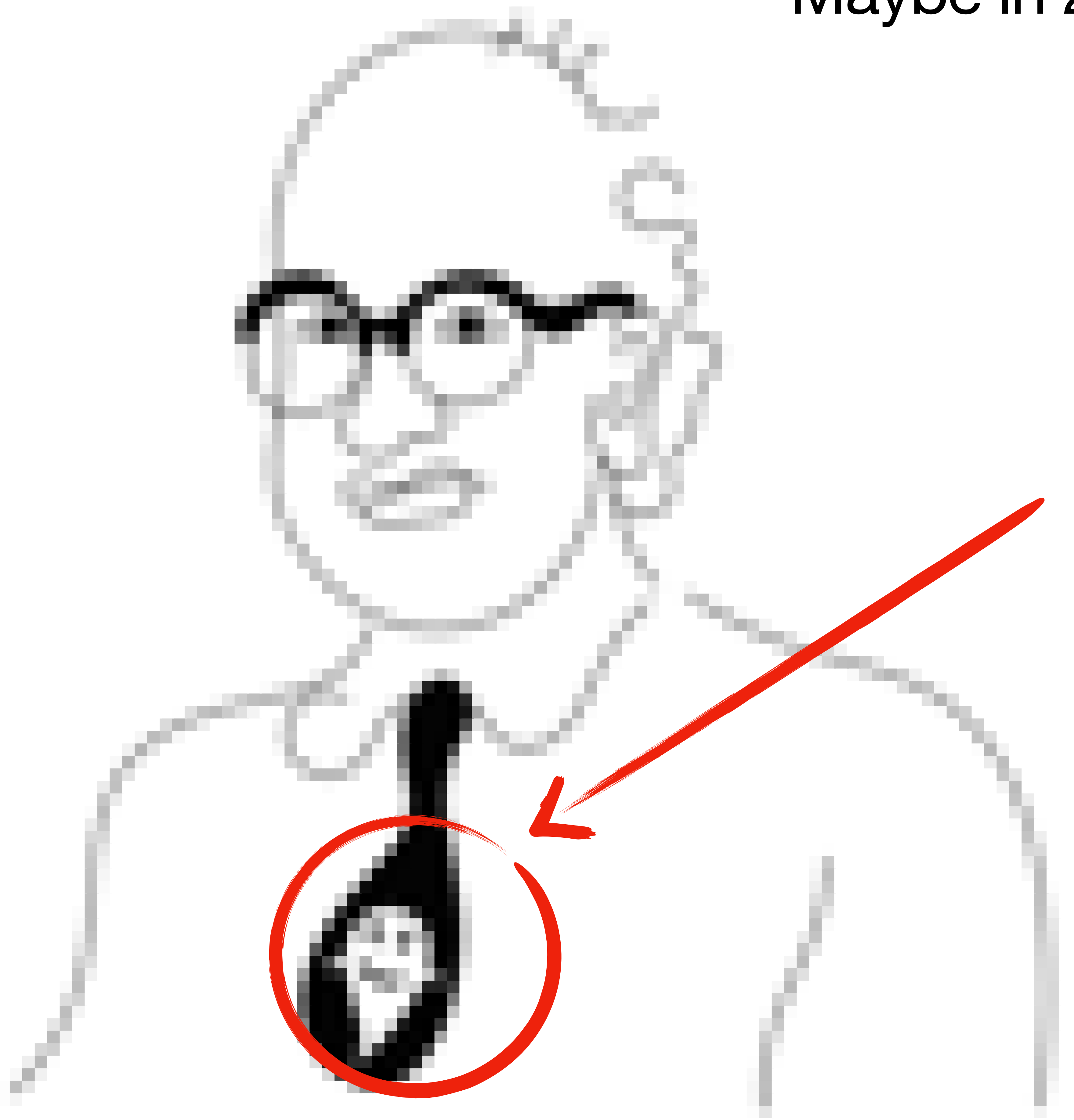
there is a connection between Higgs & DM or dark sector can only be figured out by experiments. LHC can play an important role in this context

Higgs in ATLAS & CMS

Whether or not …

there is a connection between Higgs & DM or dark sector can only be figured out by experiments. LHC can play an important role in this context

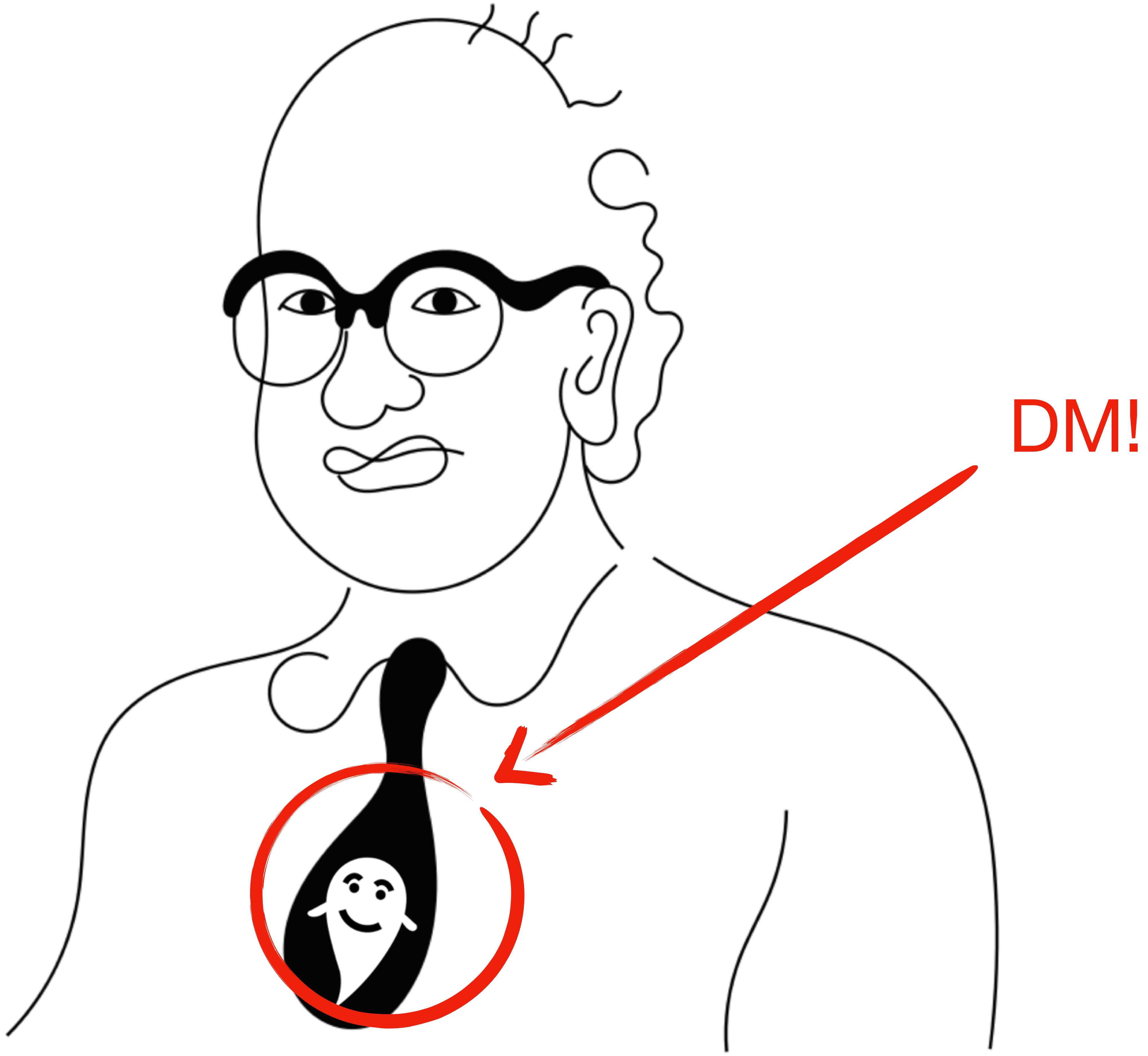
Maybe in 2032



Higgs in ATLAS & CMS

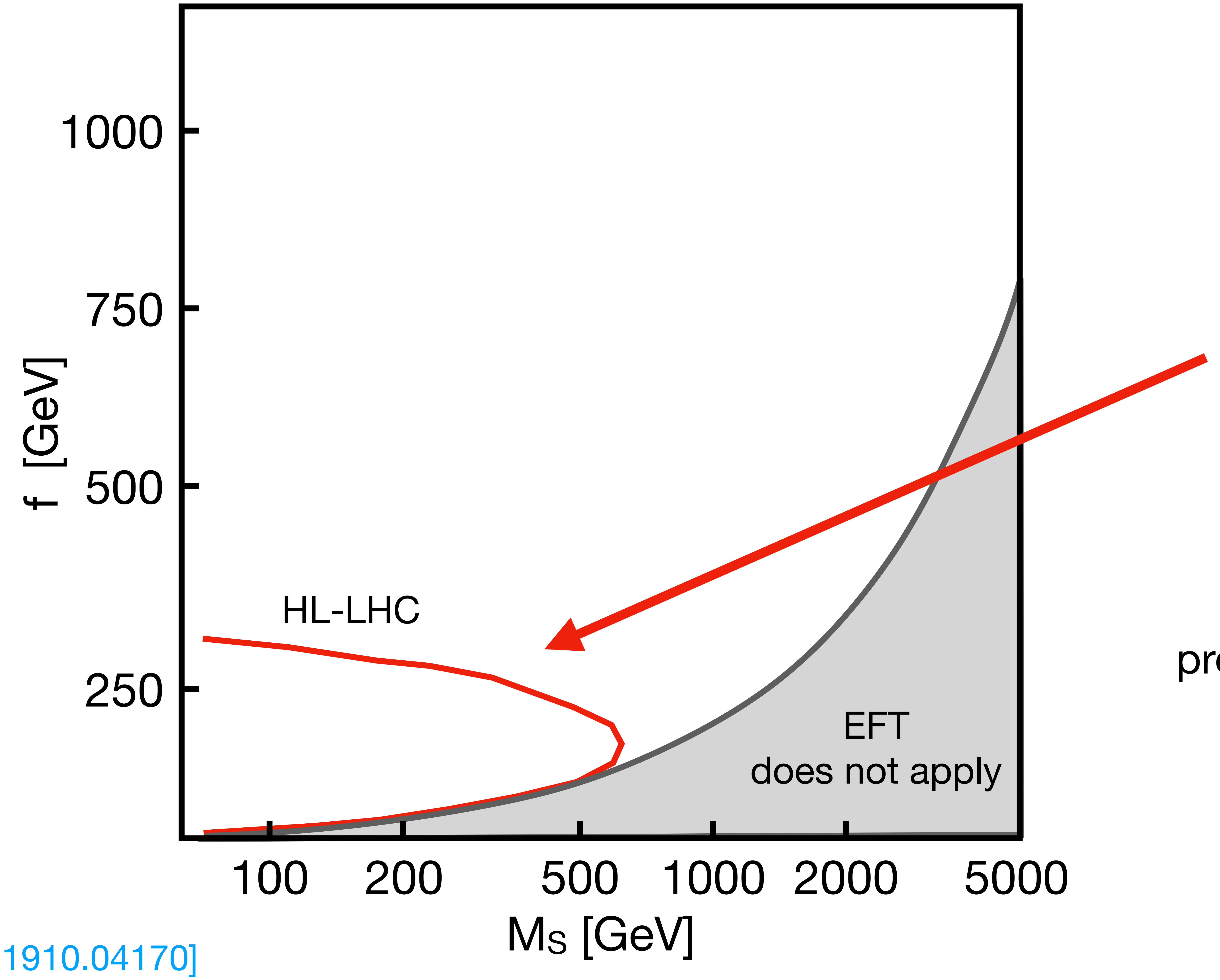
Whether or not …

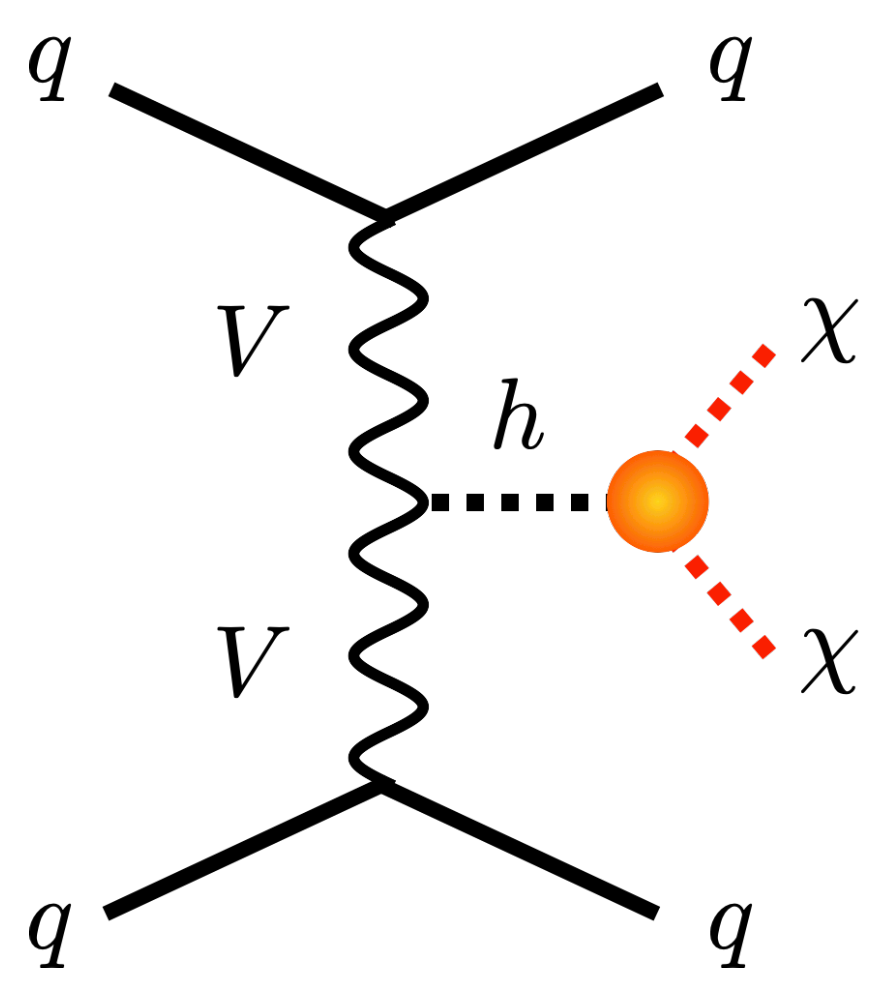
there is a connection between Higgs & DM or dark sector can only be figured out by experiments. LHC can play an important role in this context



Beyond SM Higgs

Derivative Higgs portal @ LHC

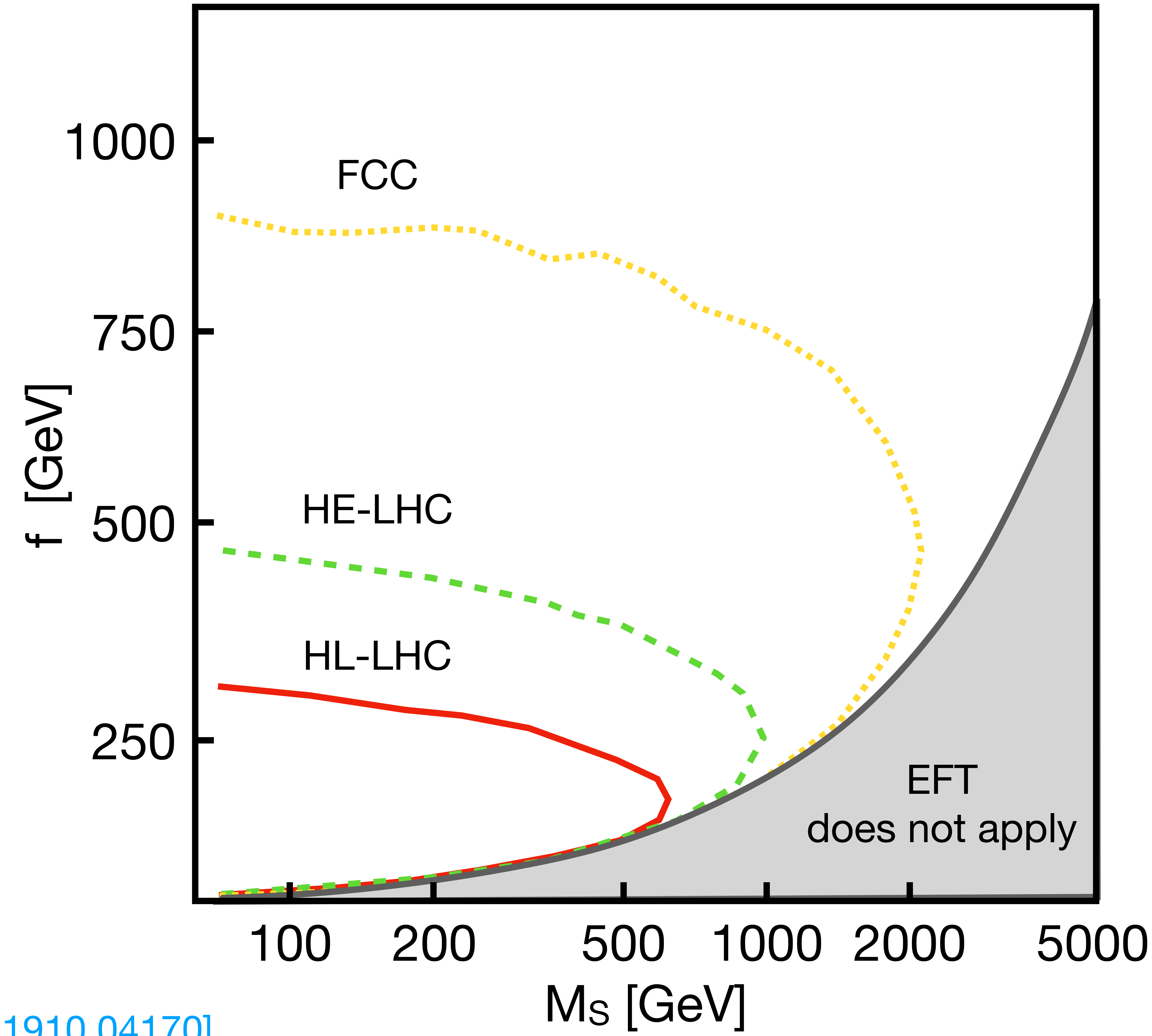




Off-shell Higgs boson production in VBF channel

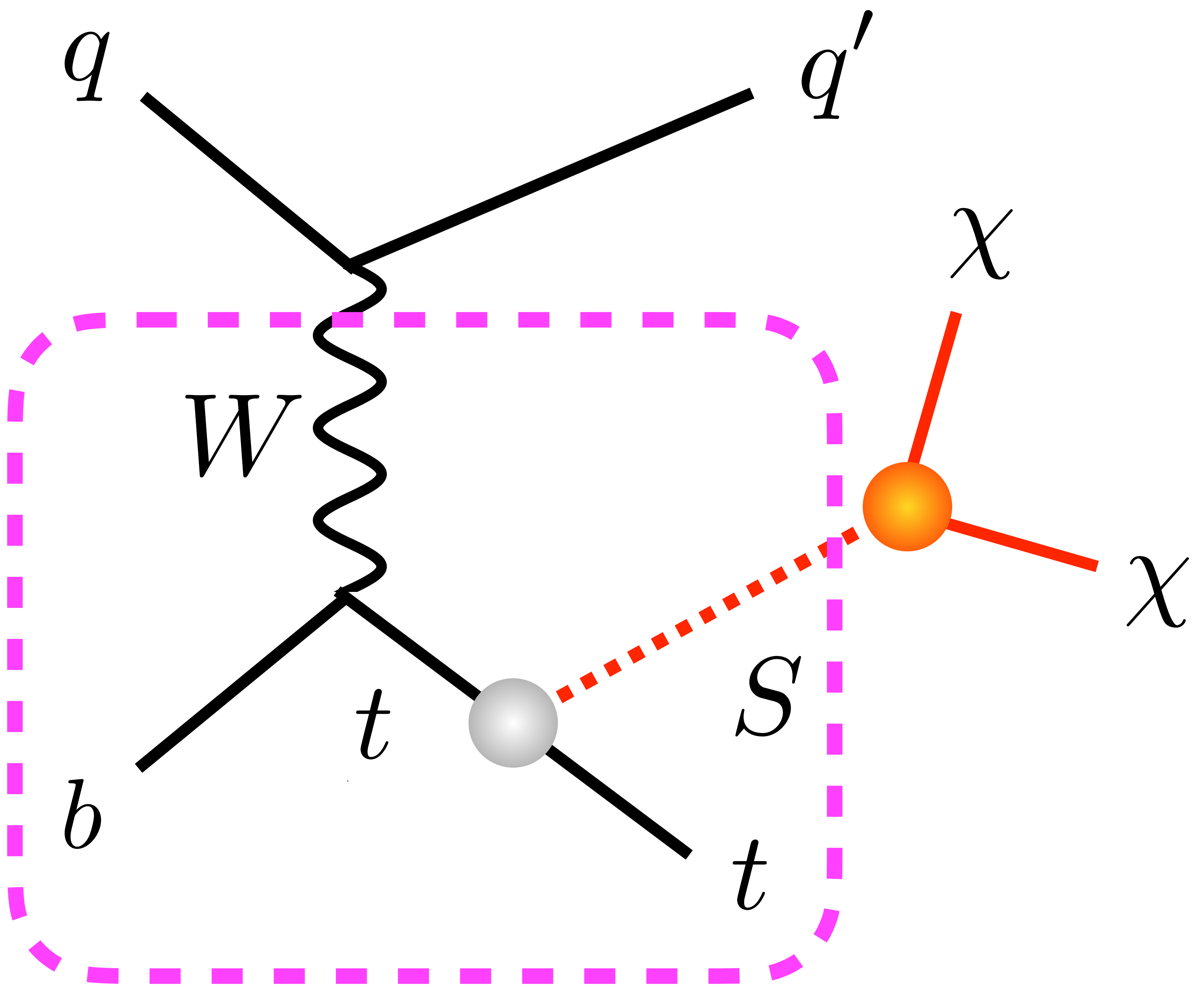
[Ruhdorfer, Salvioni & Weiler, 1910.04170]

Derivative Higgs portal @ future collider



[Ruhdorfer, Salvioni & Weiler, 1910.04170]

Unitarity considerations



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

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

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

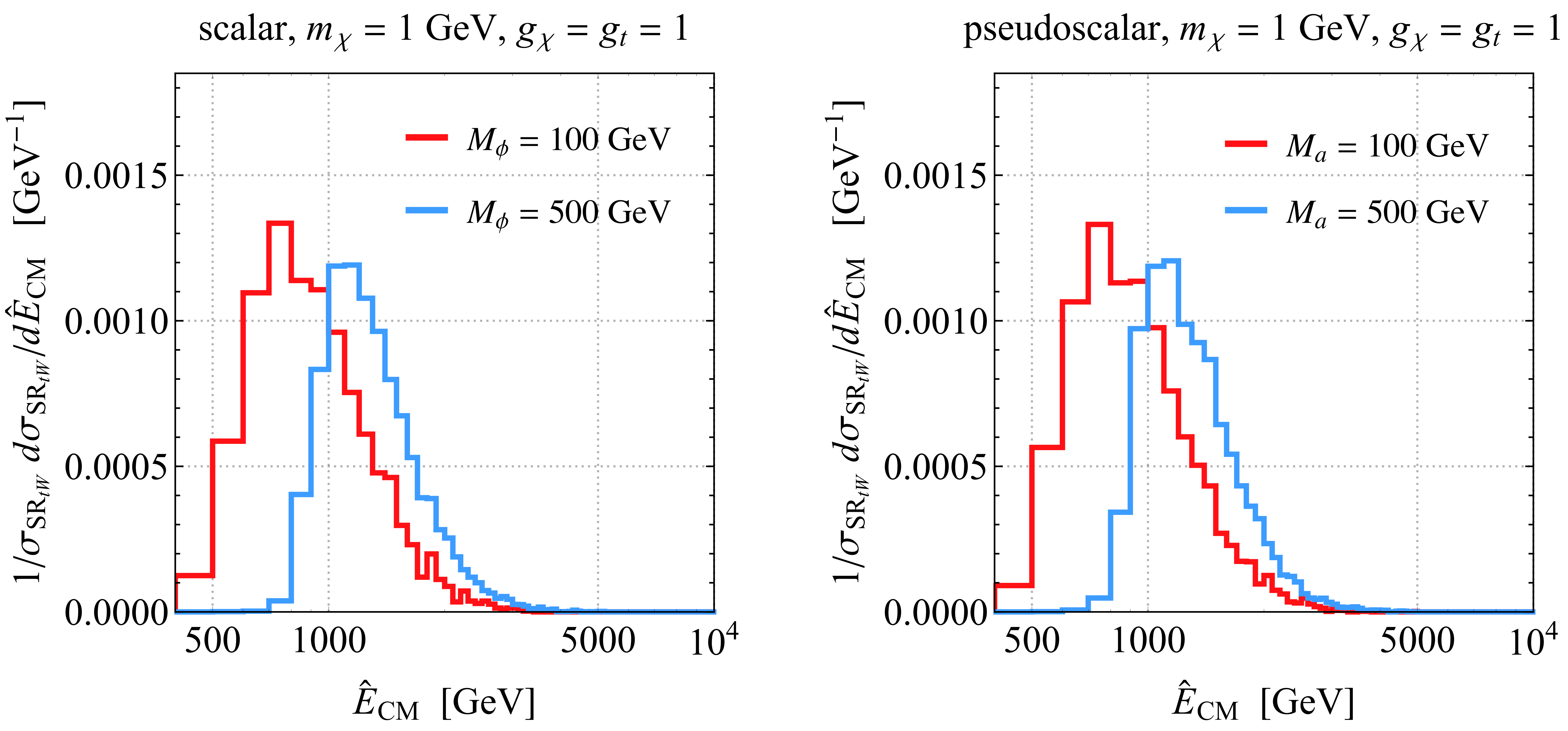
Unitarity considerations

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

Imposing that $|a_0| < 1$ & identifying $\Lambda \simeq \hat{E}_{CM}$, 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

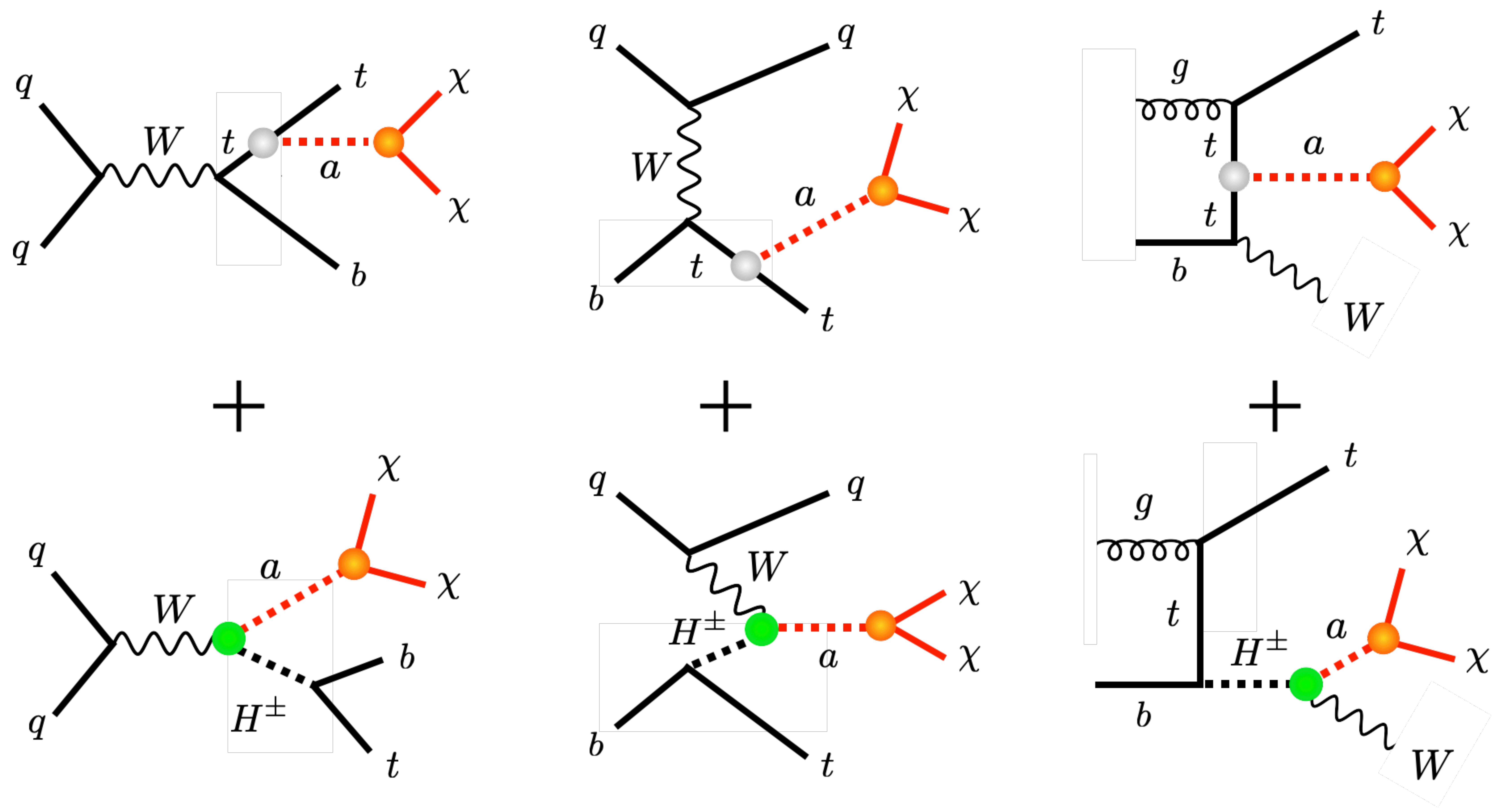


Fraction of single-t plus $E_{T,\mathrm{miss}}$ events with $\hat{E}_{\mathrm{CM}}$ in multi-TeV range negligible (i.e. far below 1%) at LHC energies. Predictions not plagued by artefacts due to unitarity violation in simplified spin-0 DM models

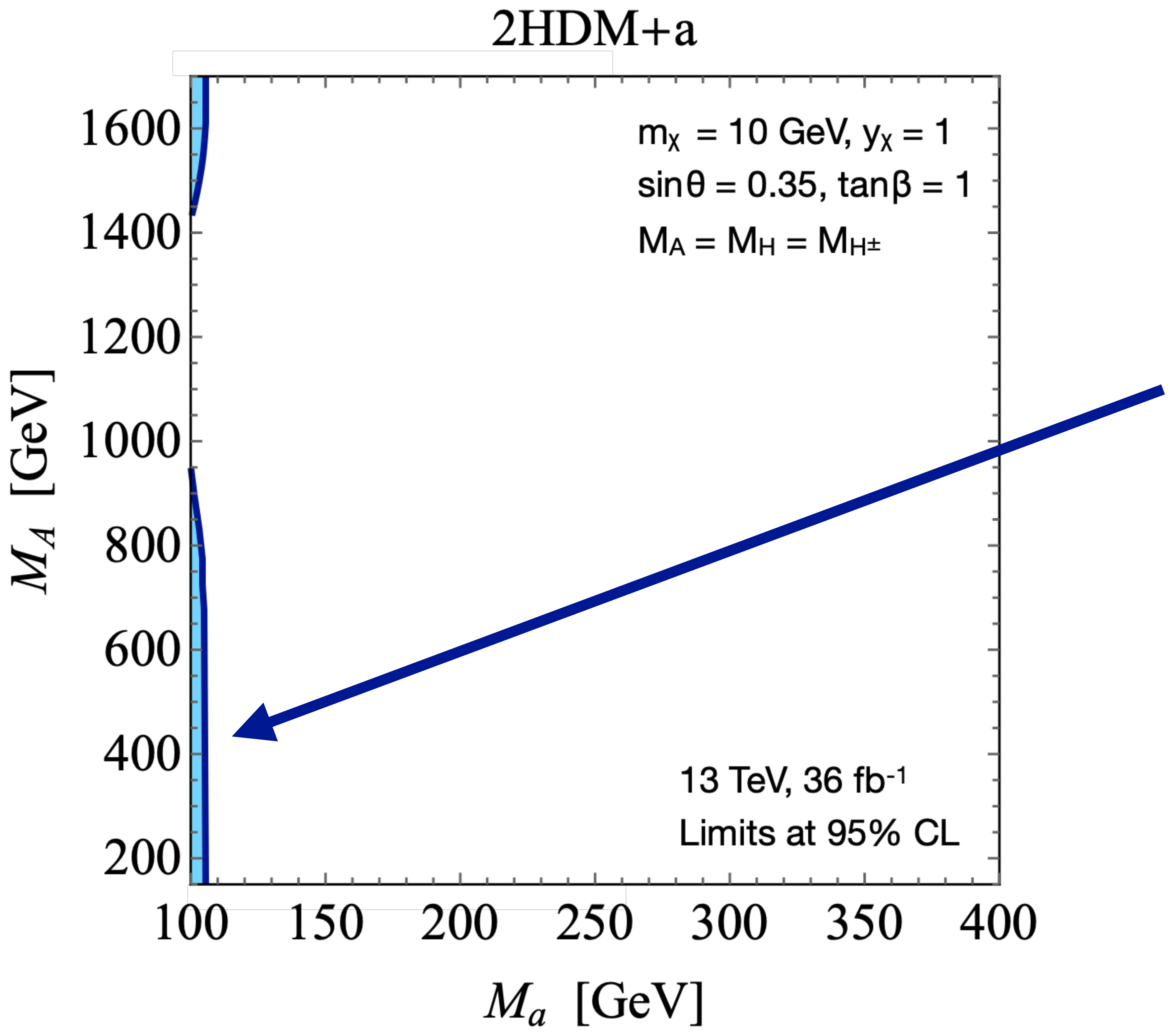
[UH & Polesello, 1812.00694]

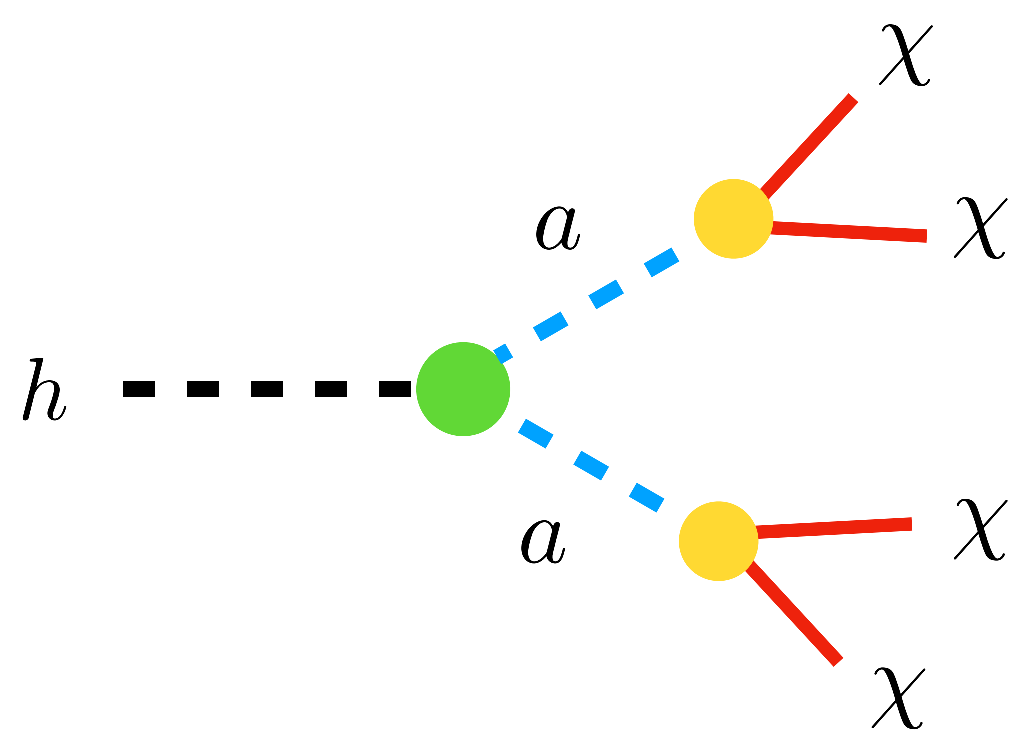
Unitarity restoration channel by channel

s-channel | t-channel | tW associated



2HDM+a model: LHC constraints

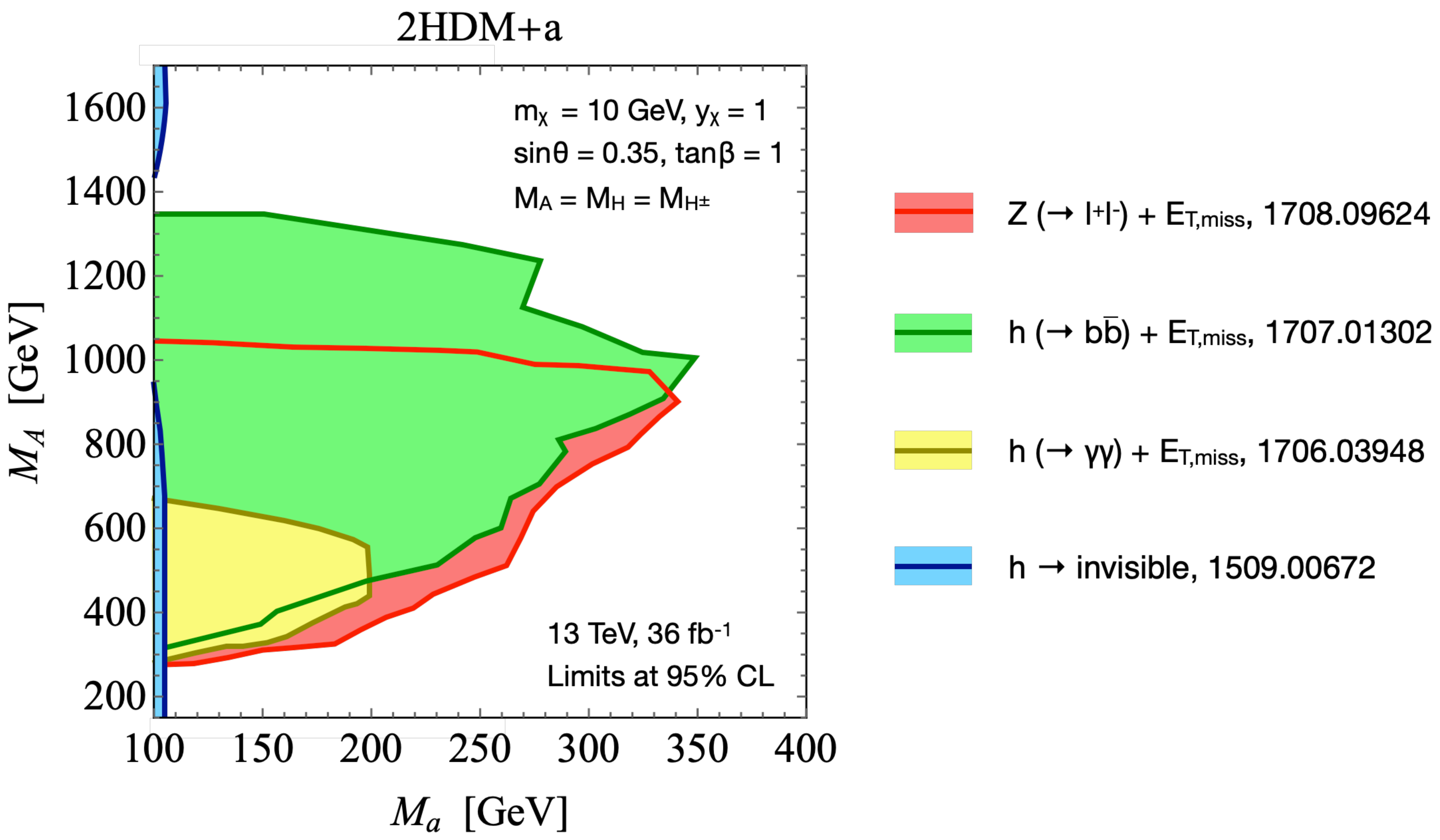




Due to off-shell contribution, invisible Higgs bound extends beyond $M_h/2$ = 62.5 GeV

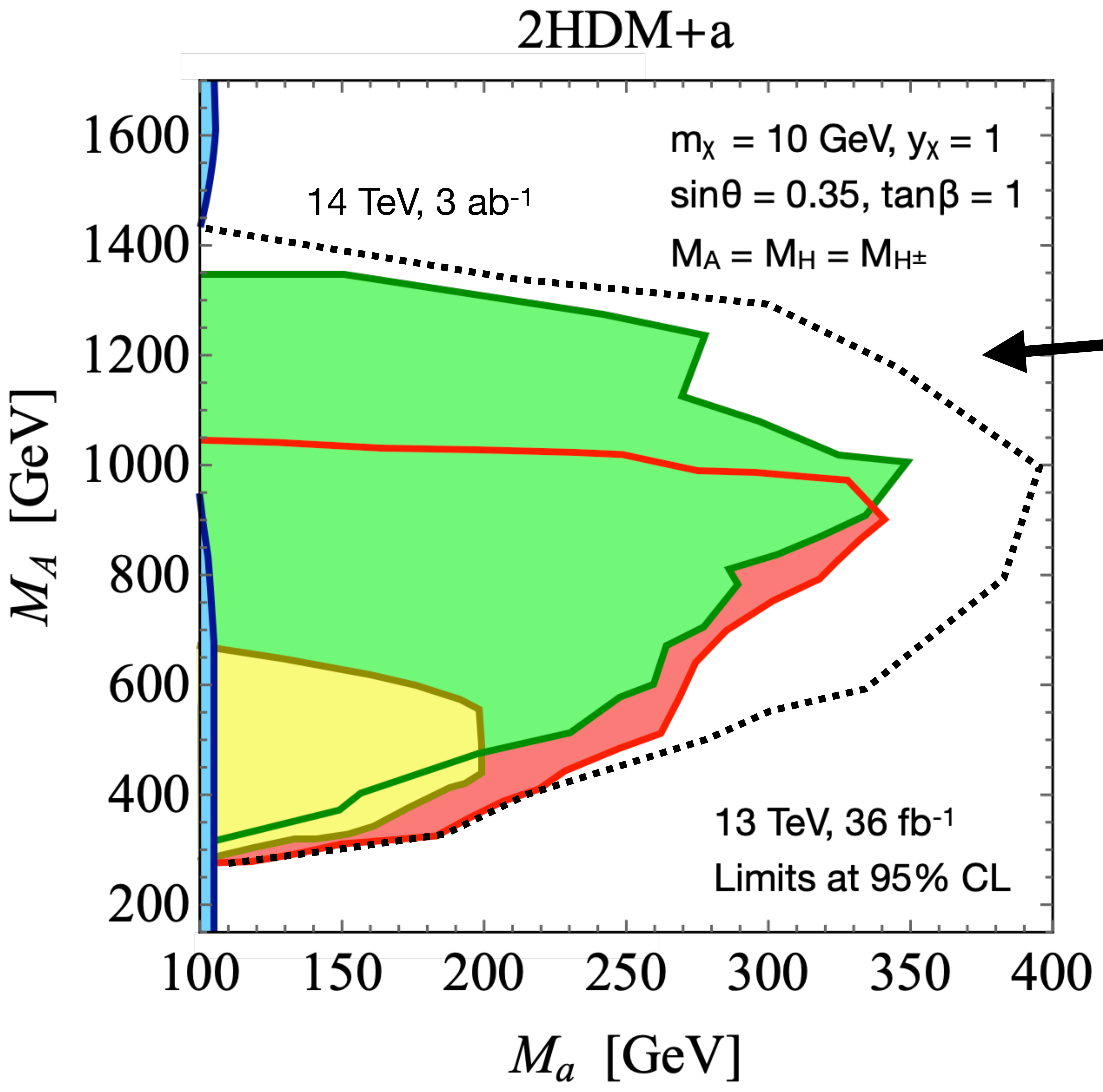
[based on ATLAS, 1903.01400]

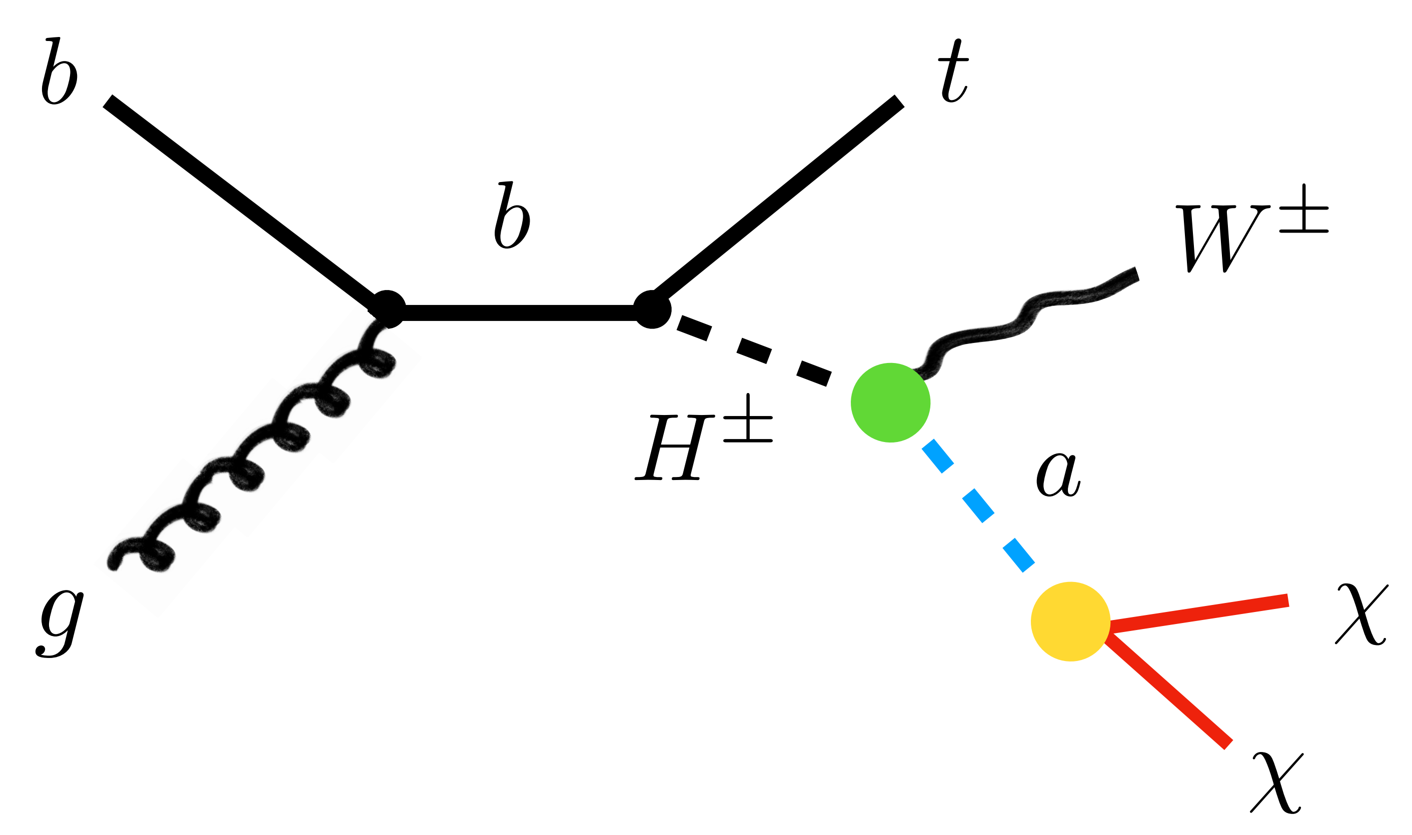
2HDM+a model: LHC constraints



[based on ATLAS, 1903.01400]

2HDM+a model: LHC constraints

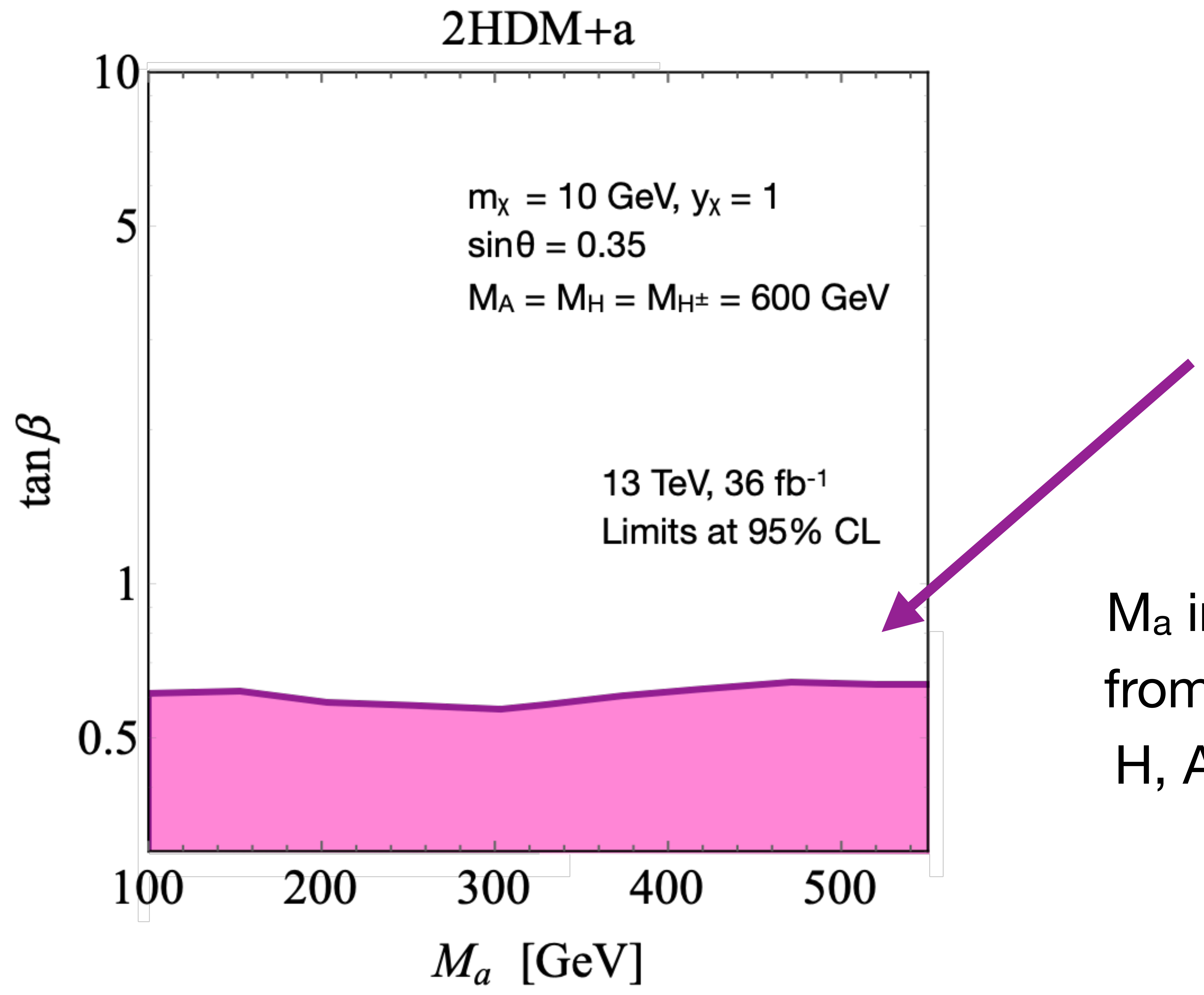


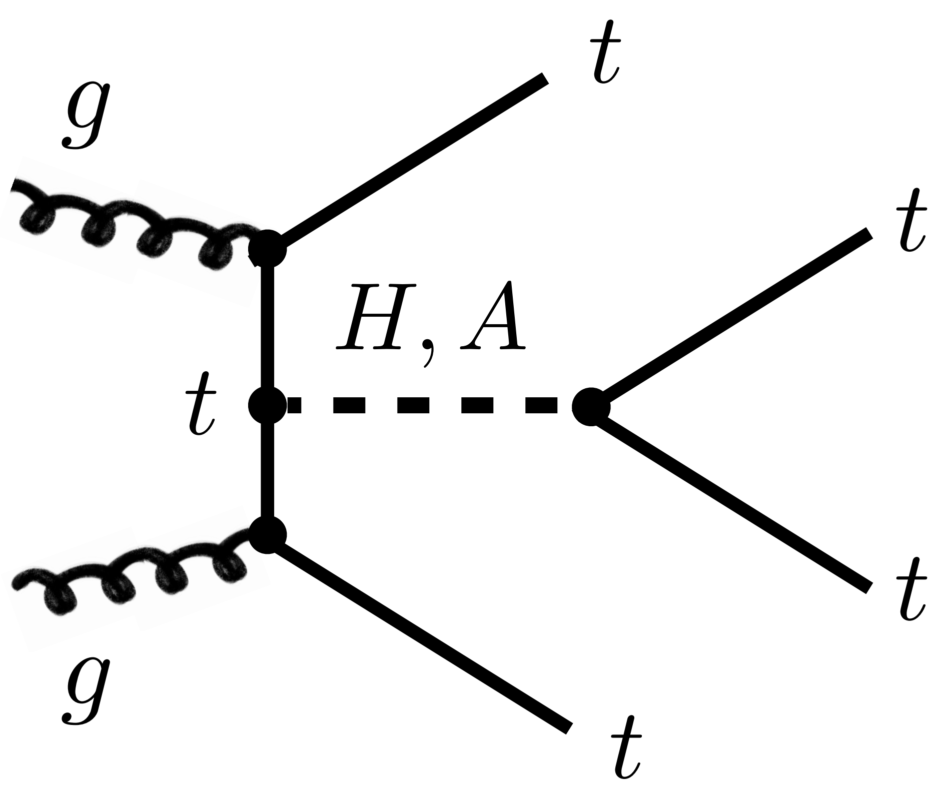


tW+$E_{T, miss}$ channel has great potential at LHC Run 3 & HL-LHC

[based on ATLAS, 1903.01400; Pani & Polesello, 1712.03874]

2HDM+a model: LHC constraints

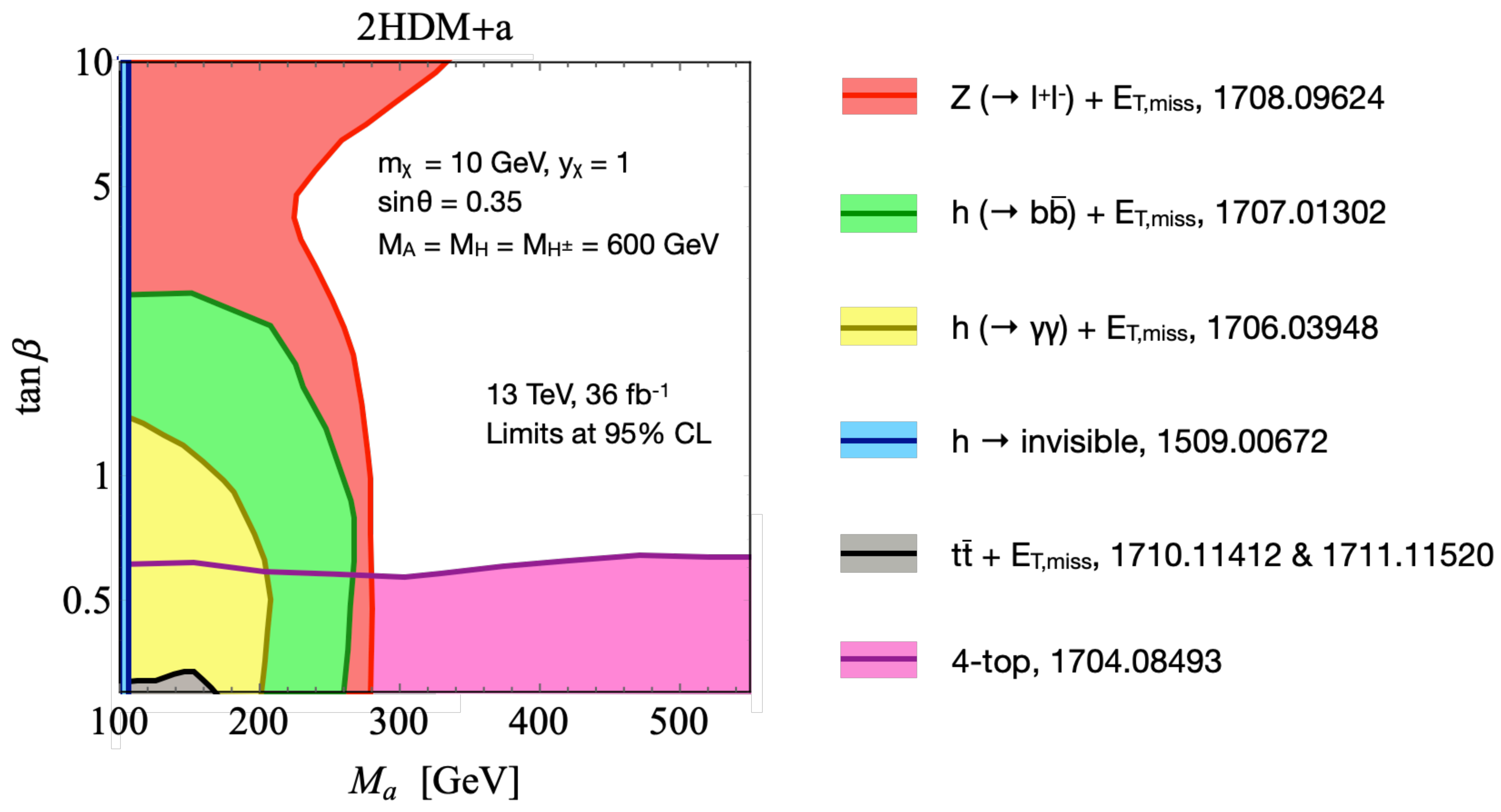




M_a independent bound on tan β from 4-top diagrams with virtual H, A producing top-quark pairs

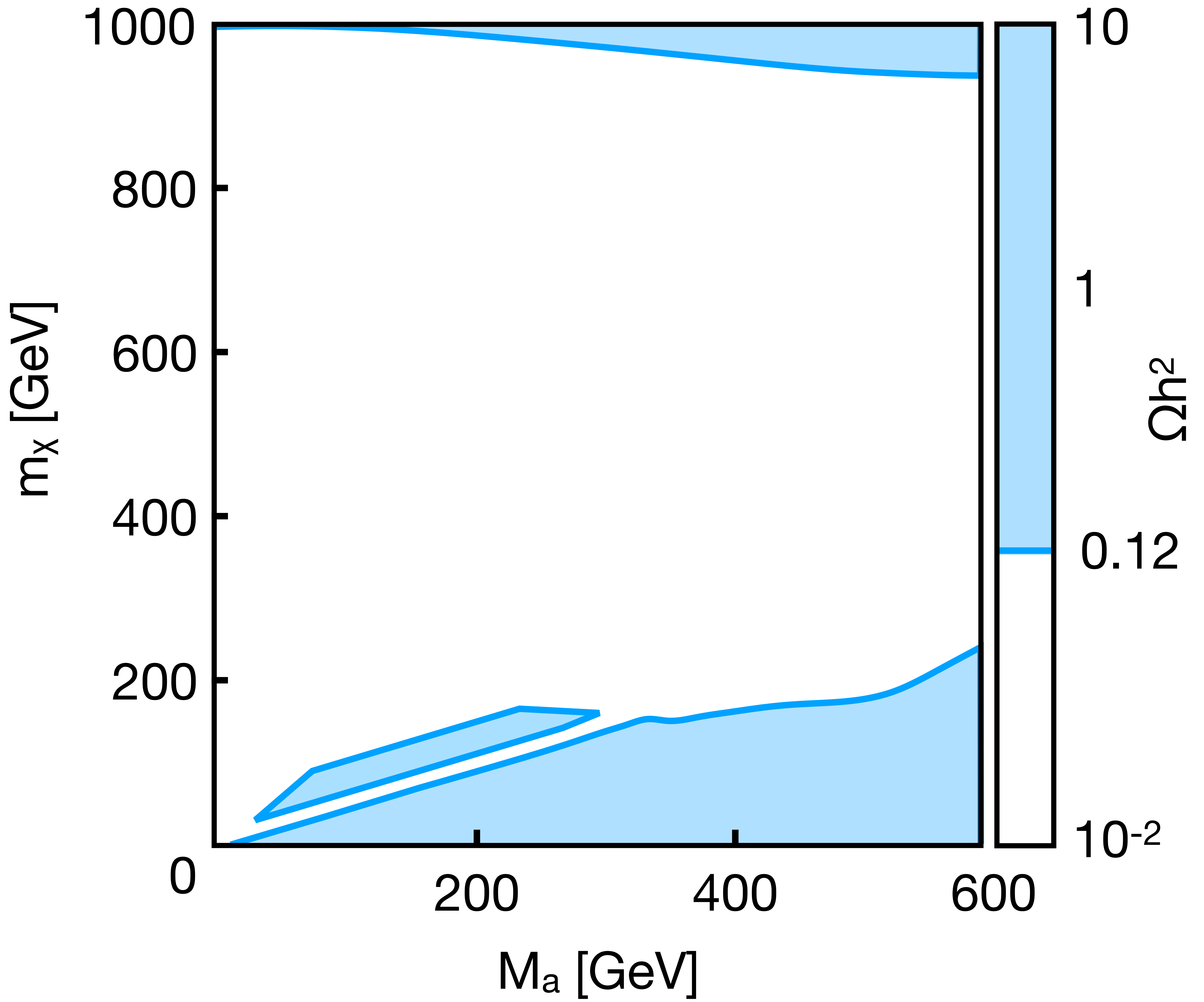
[based on ATLAS, 1903.01400]

2HDM+a model: LHC constraints



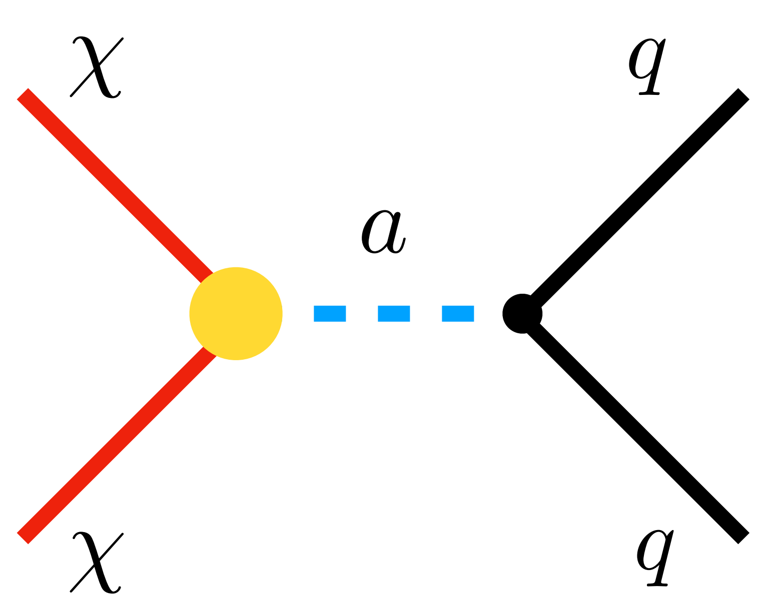
[based on LHCDMWG, 1810.09420; ATLAS, 1903.01400]

2HDM+a model: relic density

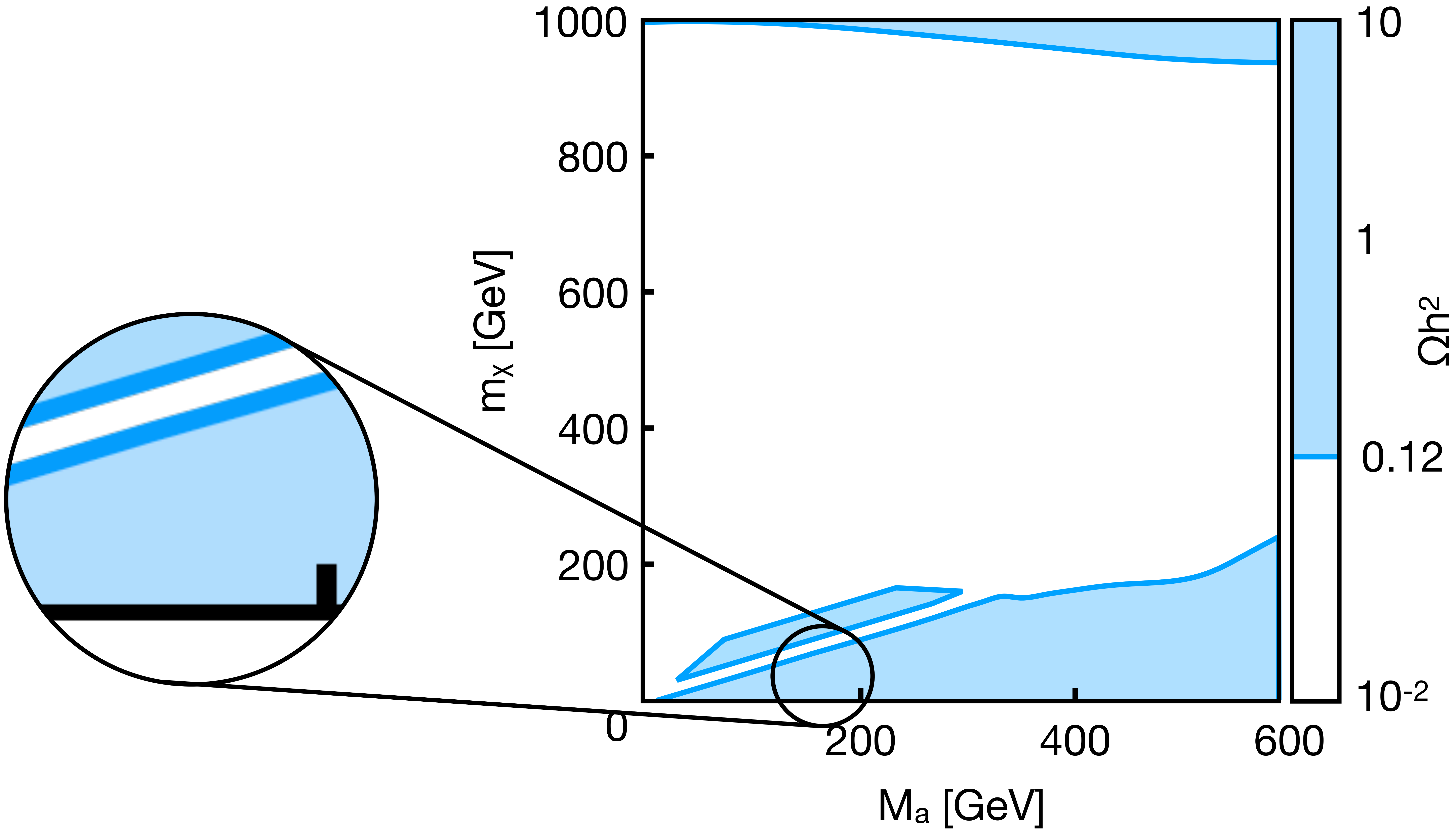


[based on LHCDMWG, 1810.09420]

2HDM+a model: relic density

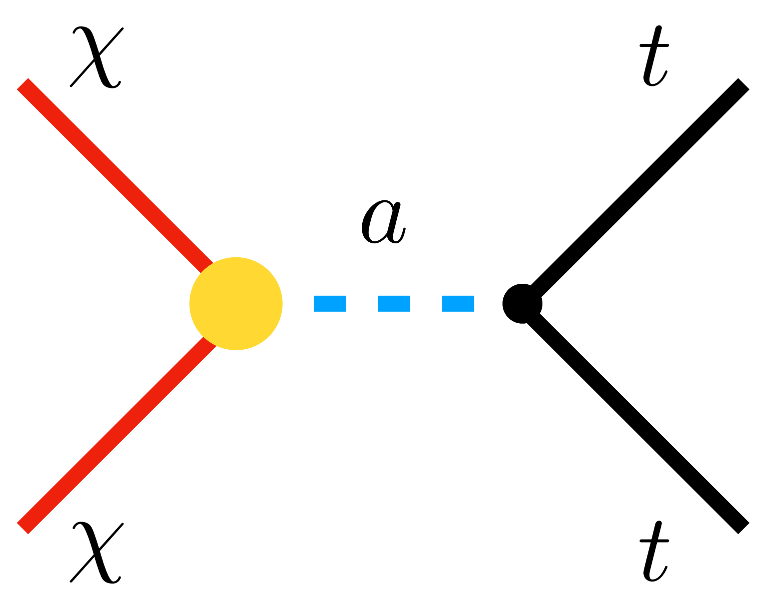


Correct DM relic density set by a-funnel

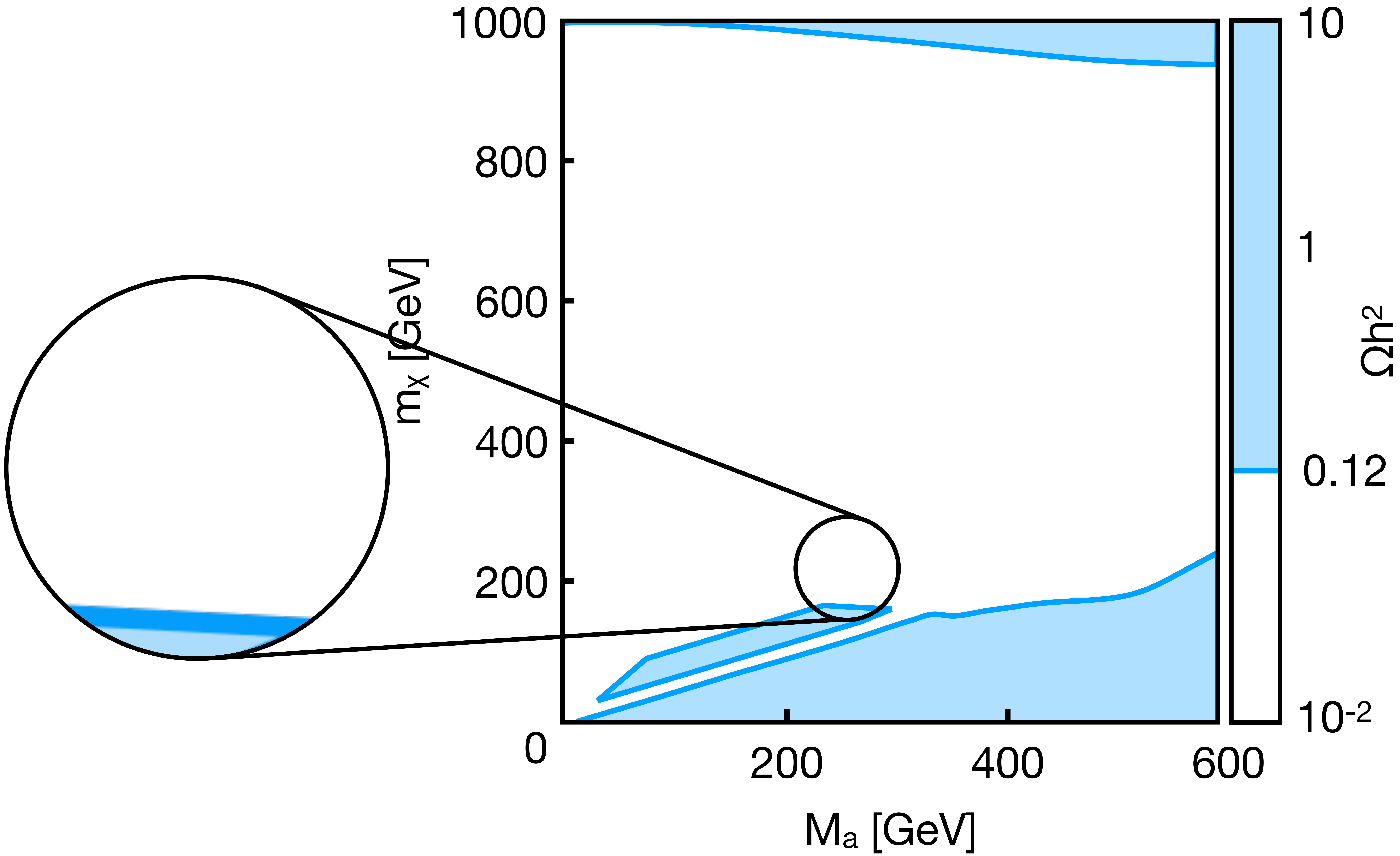


[based on LHCDMWG, 1810.09420]

2HDM+a model: relic density

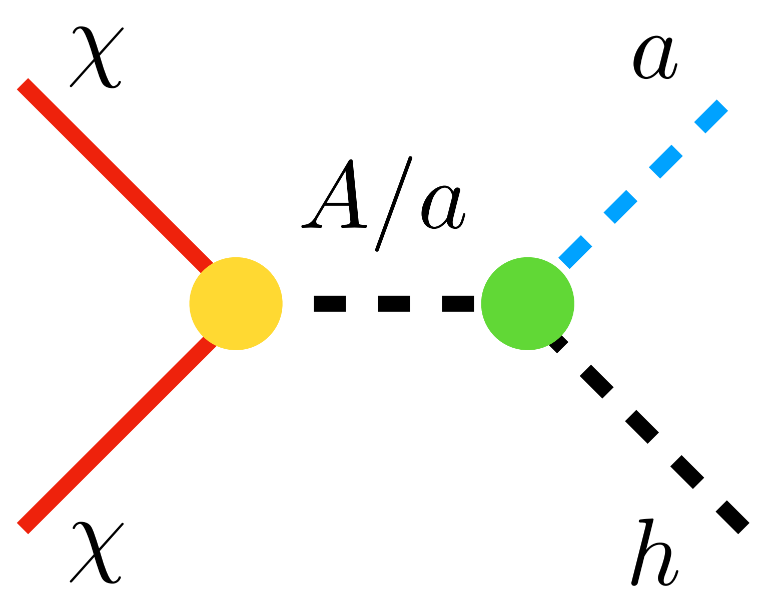


Relic depletion
through a-funnel
to top-quark pairs

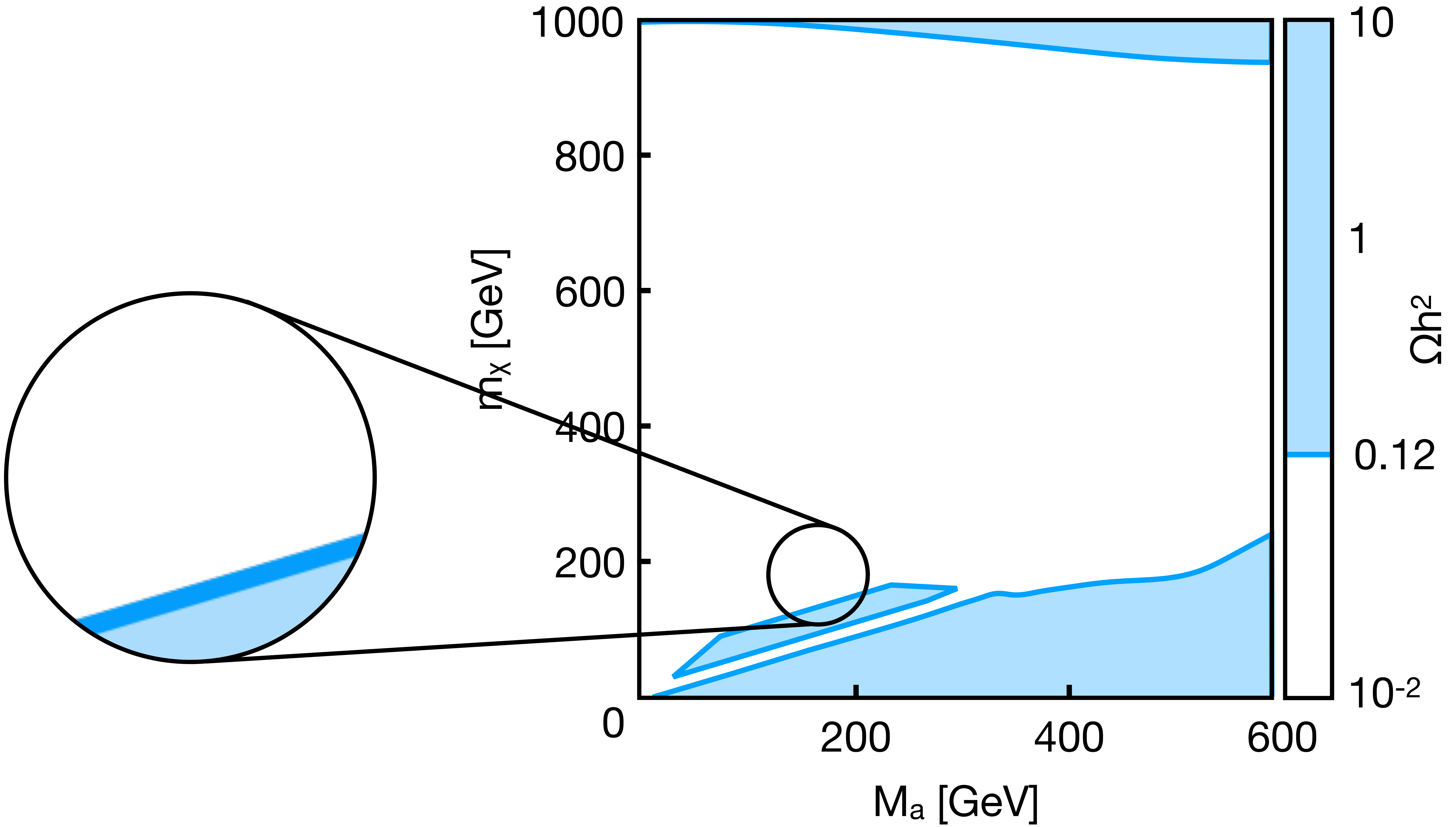


[based on LHCDMWG, 1810.09420]

2HDM+a model: relic density

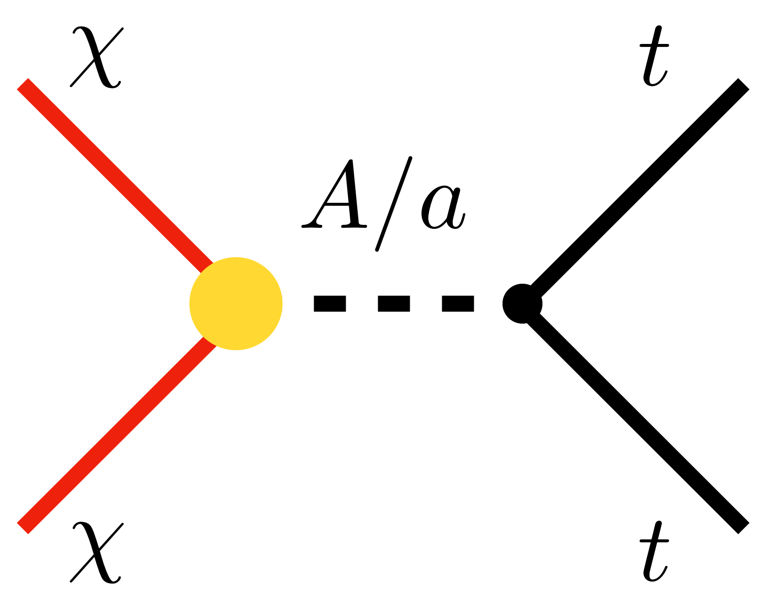


Effective relic
wash-out through
$\chi\bar{\chi}$→A/a→ha



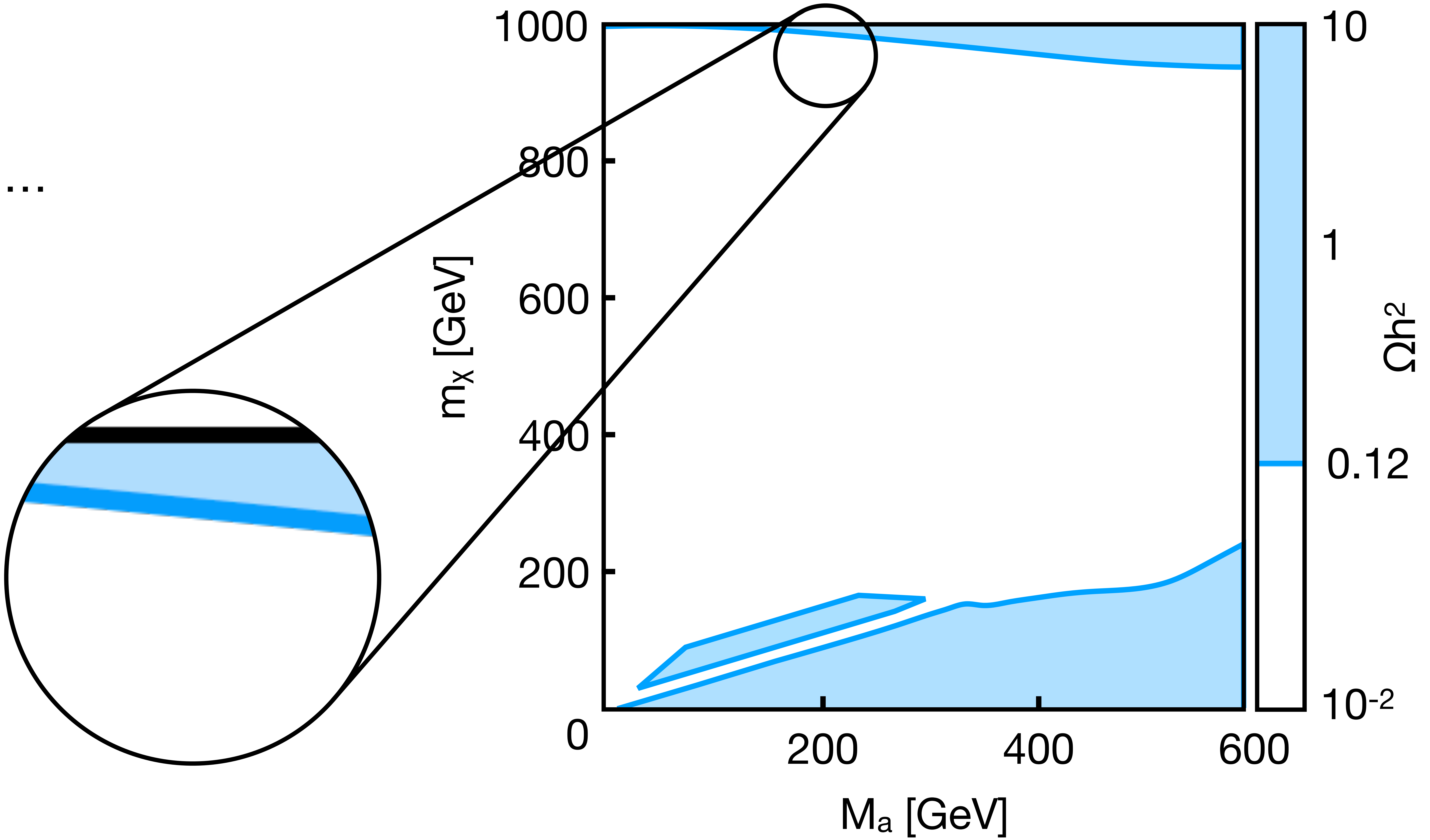
[based on LHCDMWG, 1810.09420]

2HDM+a model: relic density



...

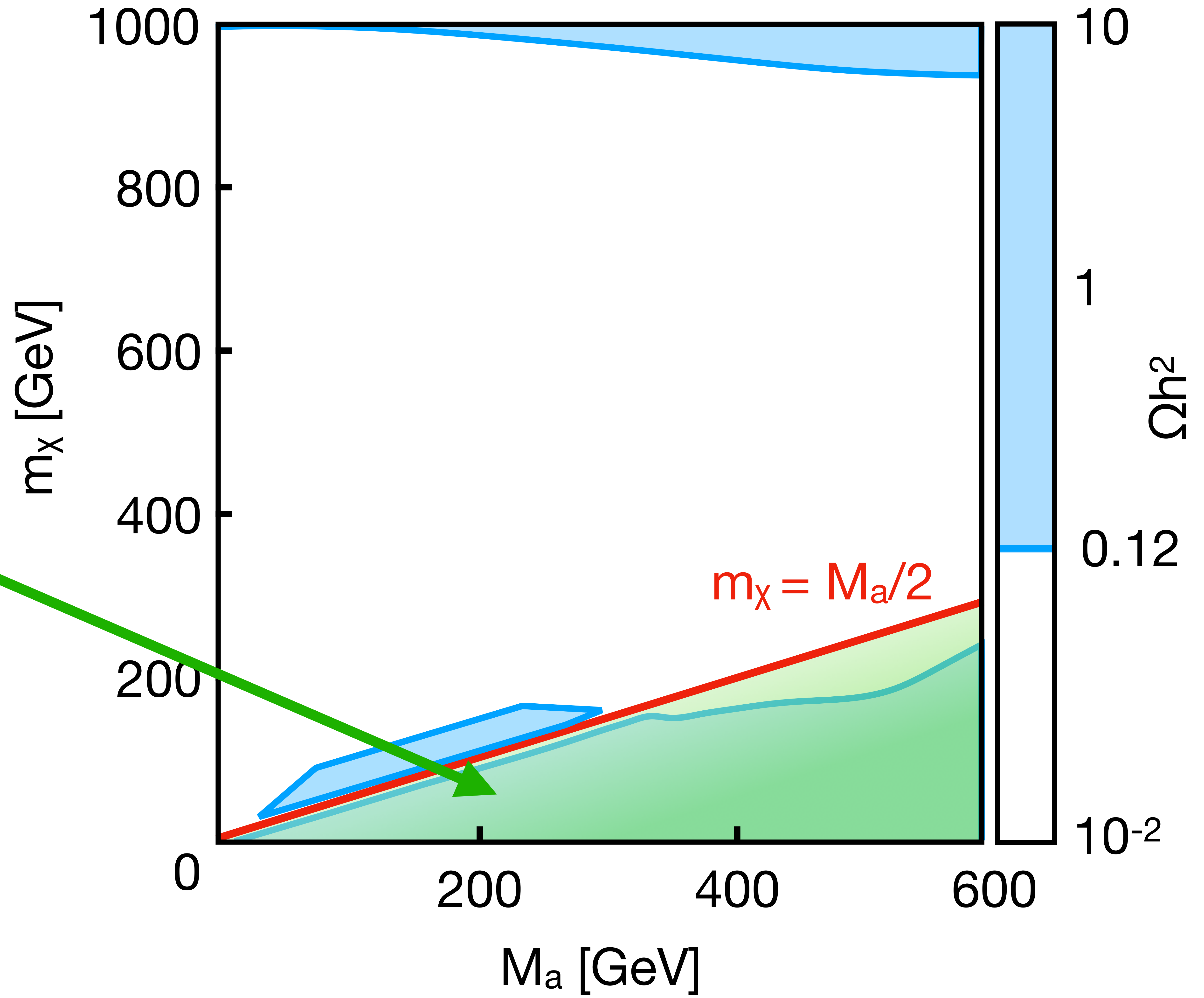
Multiple channels contribute to achieve correct Ωh^2



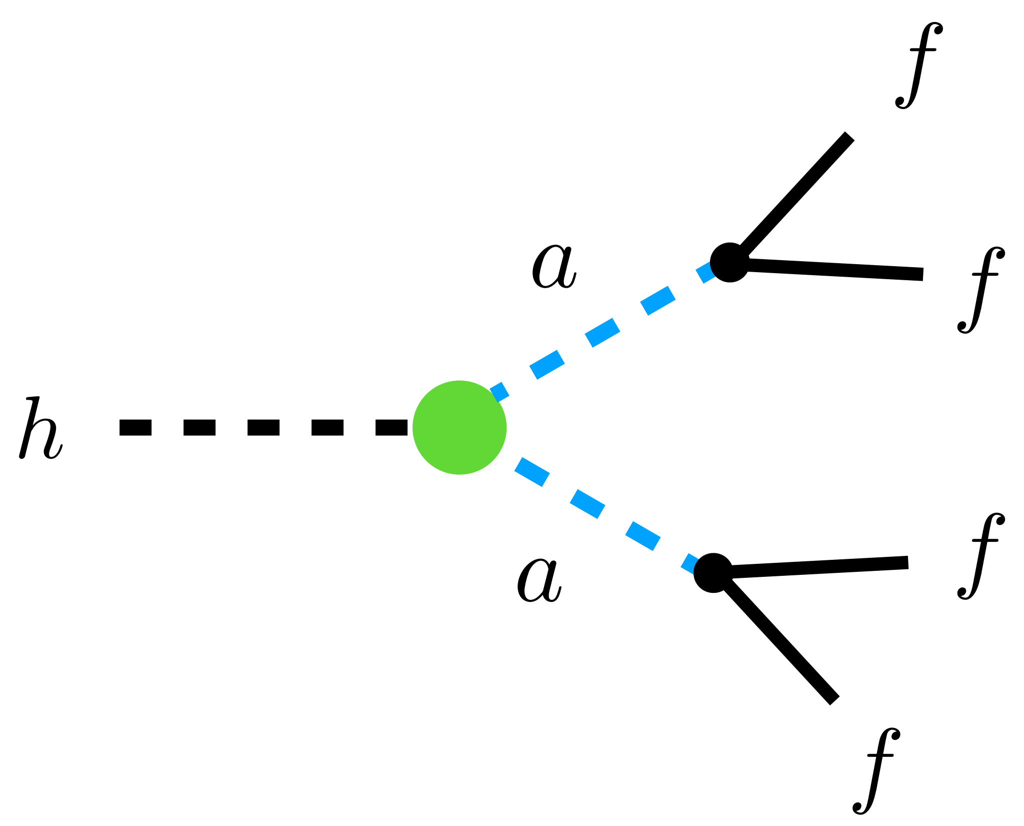
[based on LHCDMWG, 1810.09420]

2HDM+a model: relic density vs. LHC probes

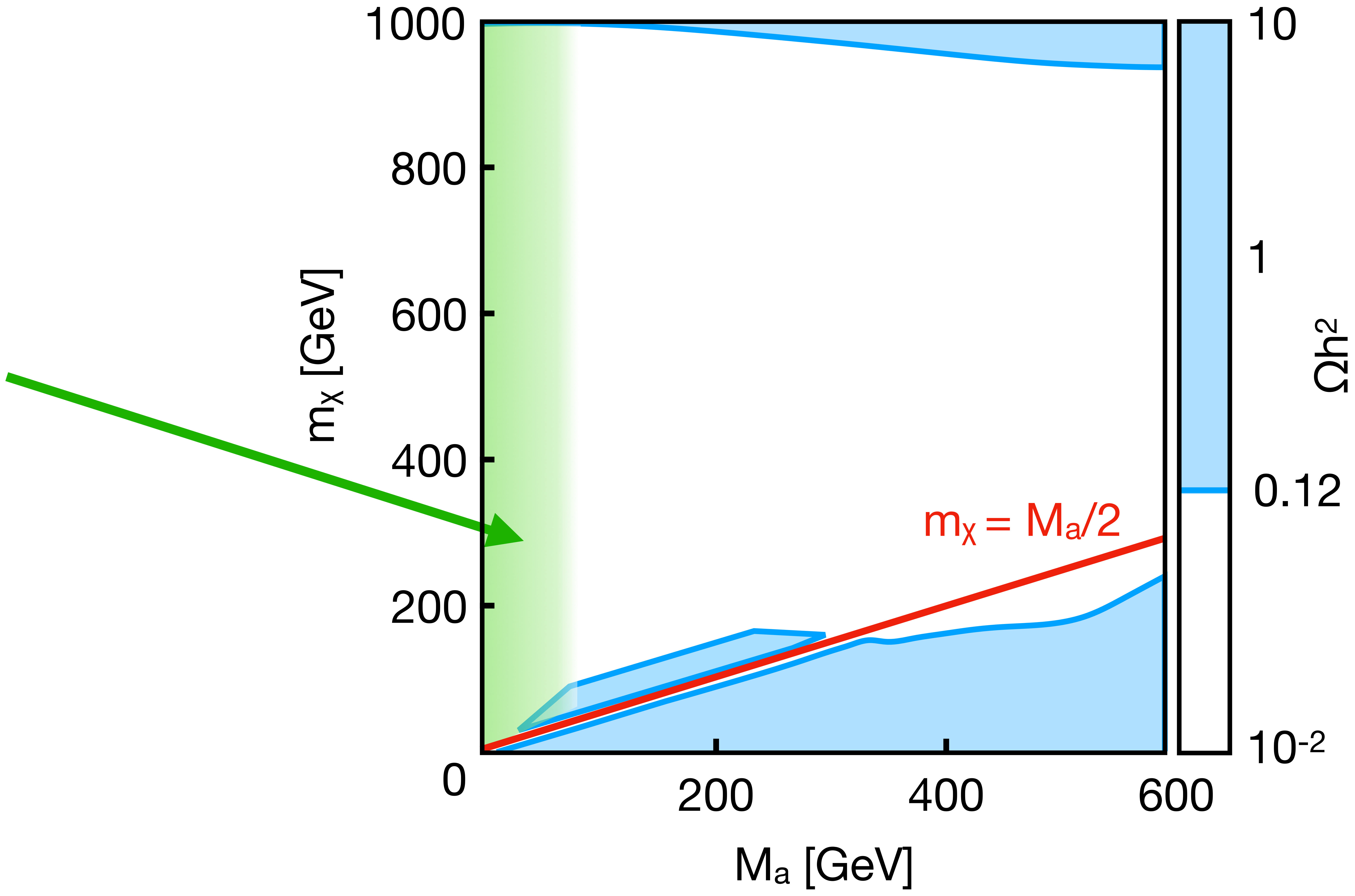
On-shell region can be probed by $E_{T,\,miss}$ signatures involving exchange of an a



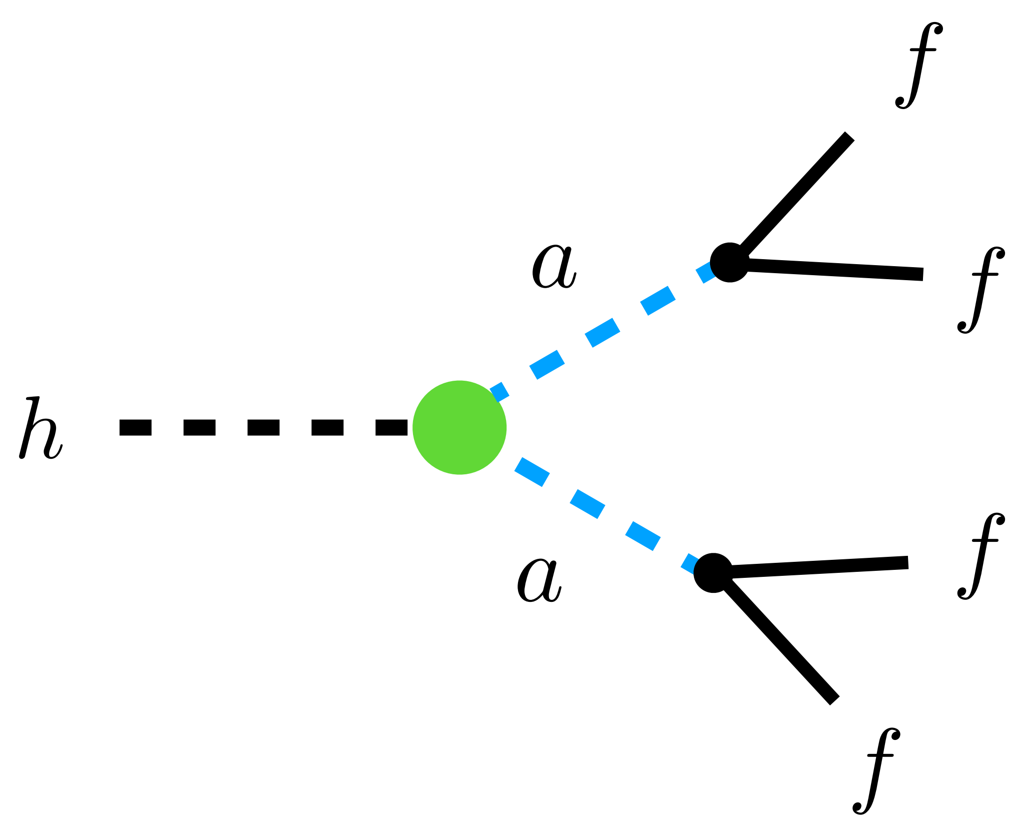
2HDM+a model: relic density vs. LHC probes

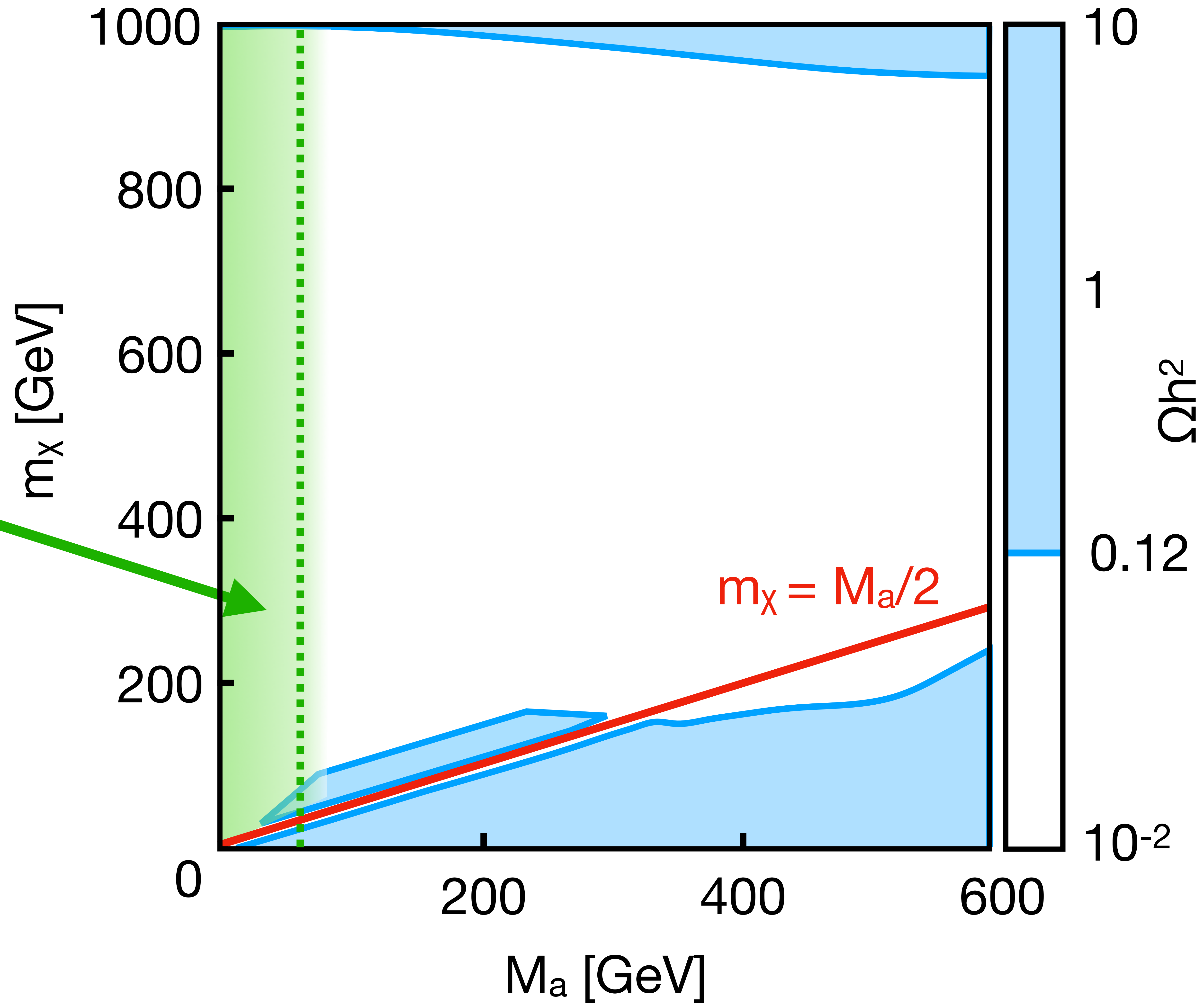


In off-shell region, light a can for instance be constrained by LHC searches for h→4f



2HDM+a model: relic density vs. LHC probes

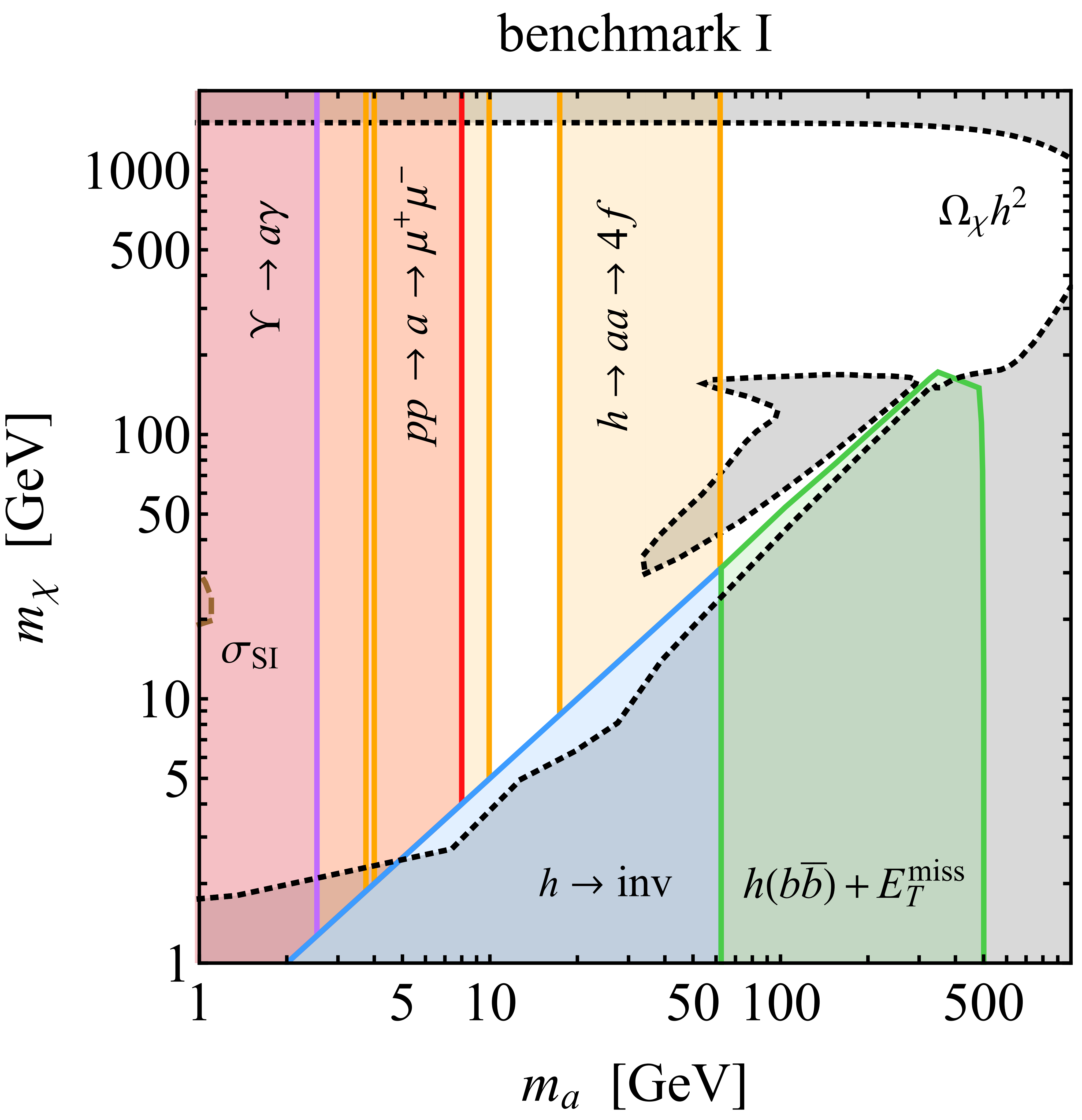




In fact, direct 95% CL bound on Higgs width of $\Gamma_h < 1.1$ GeV obtained by CMS typically excludes $M_a \lesssim M_h/2$

[CMS, 1706.09936; Agryopoulos, Brandt & UH, 2109.13597]

2HDM+a model: relic density vs. LHC probes



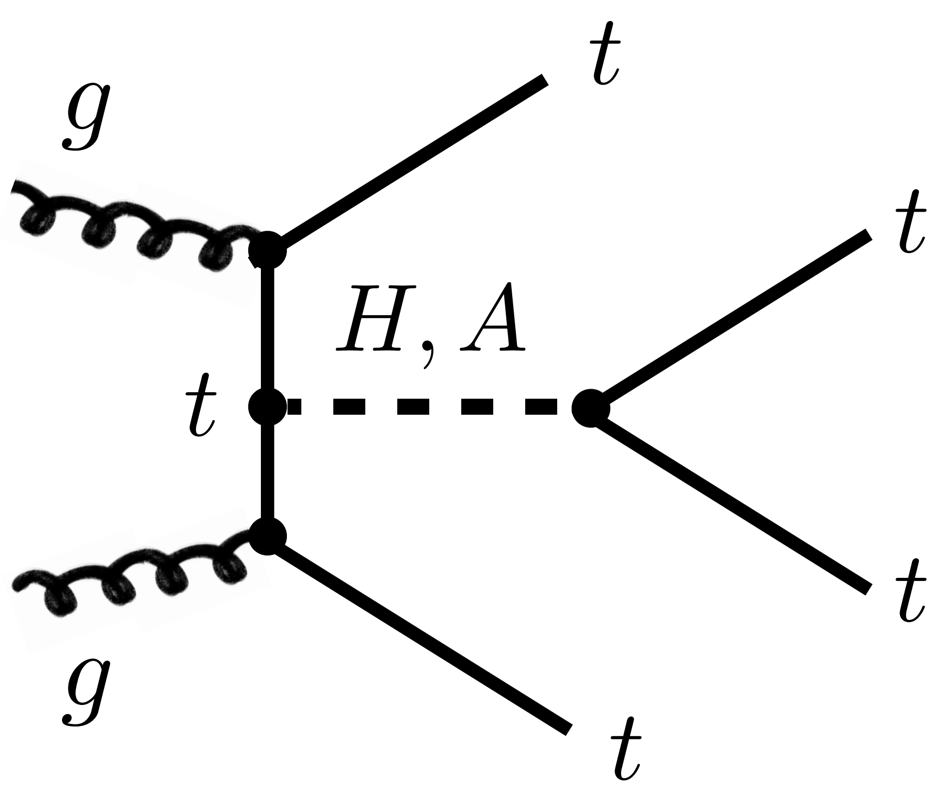
<u>benchmark I :</u>

$$\{m_A, \tan\beta, \sin\theta, \lambda_3, y_\chi\}$$

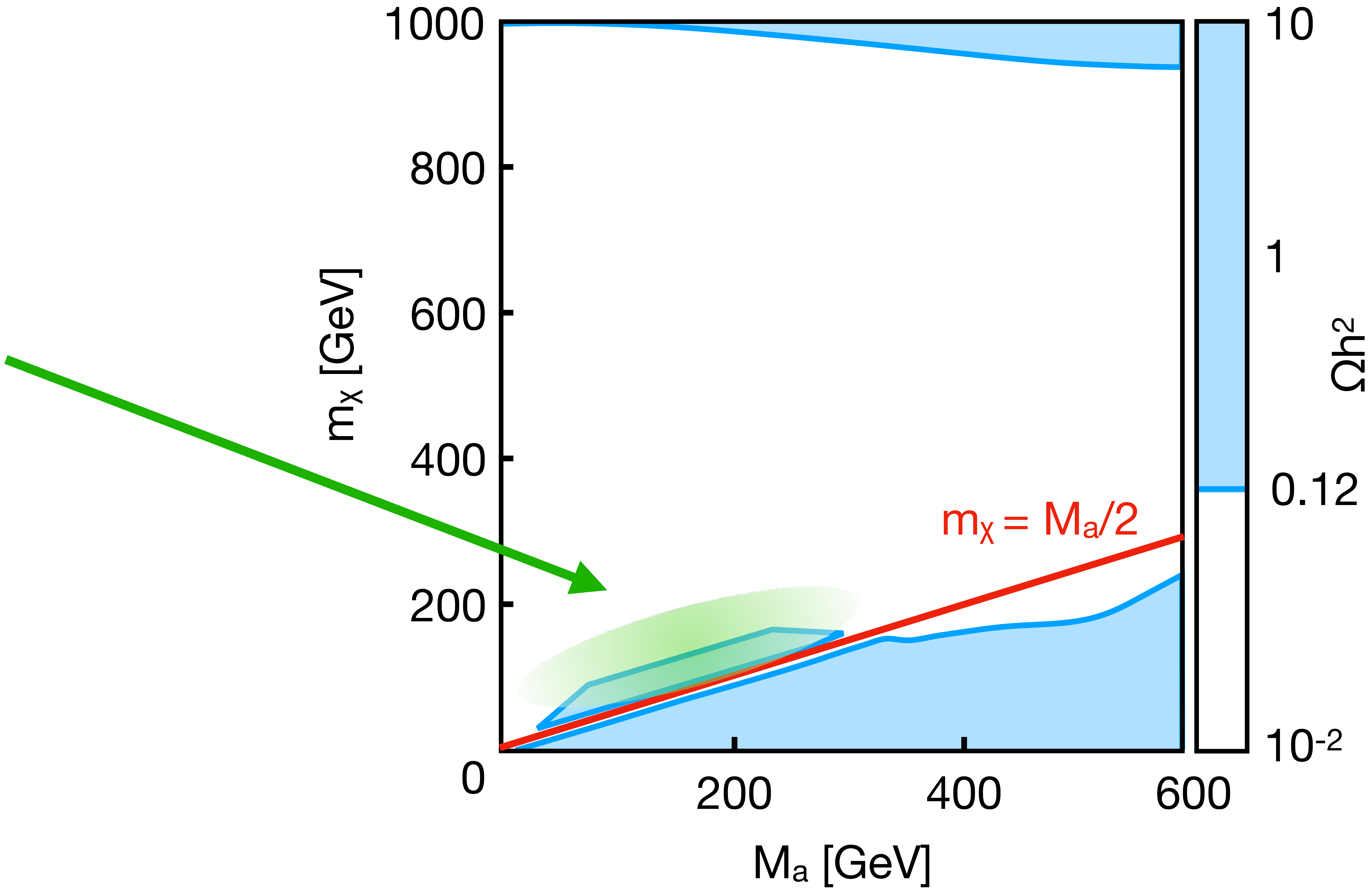
$$= \{1.2\,\text{TeV}, 1, 0.35, 3, 1\}$$

[Agryopoulos & UH, 2202.12631]

2HDM+a model: relic density vs. LHC probes

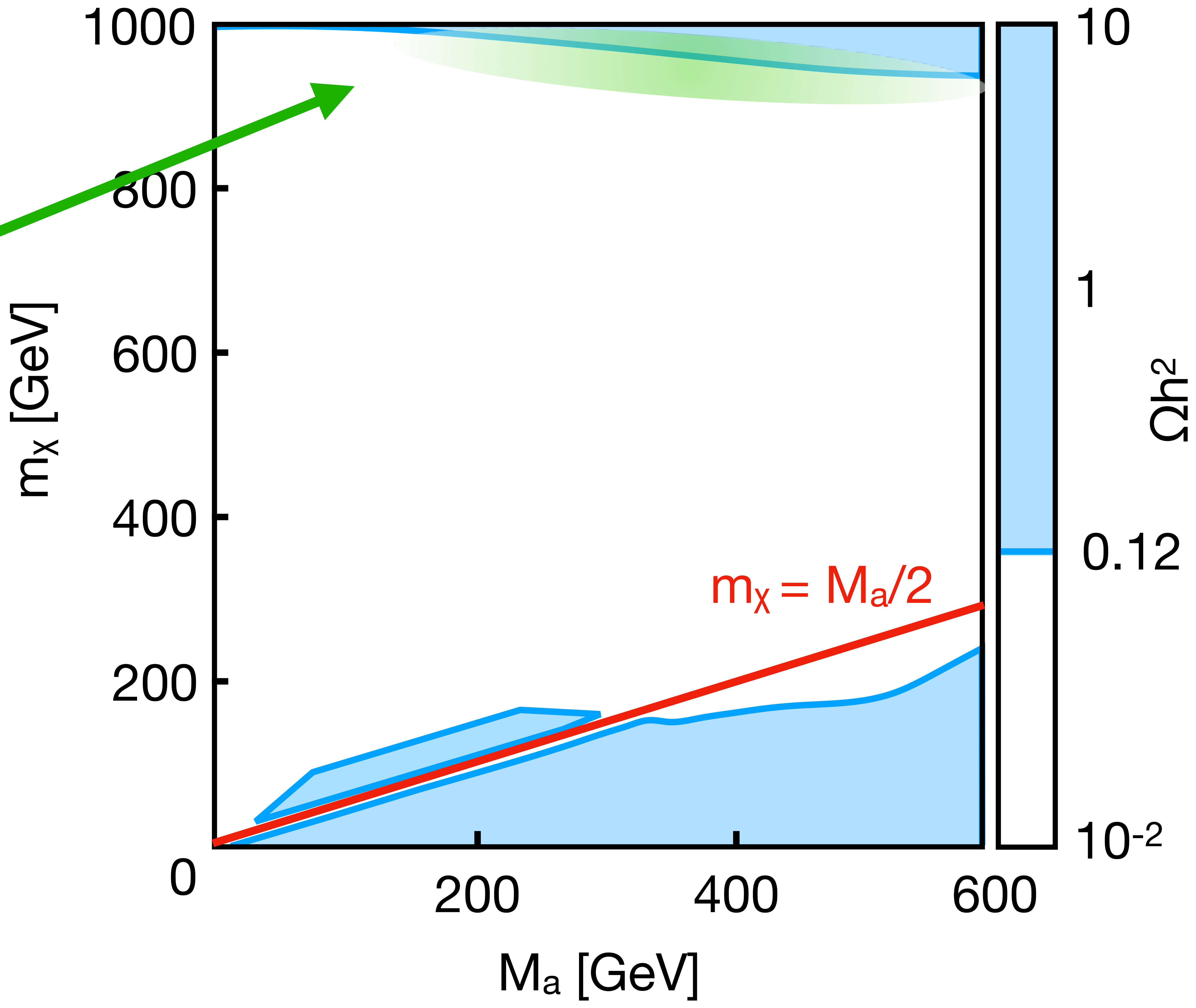


Can be probed for instance by 4-top searches for H, A

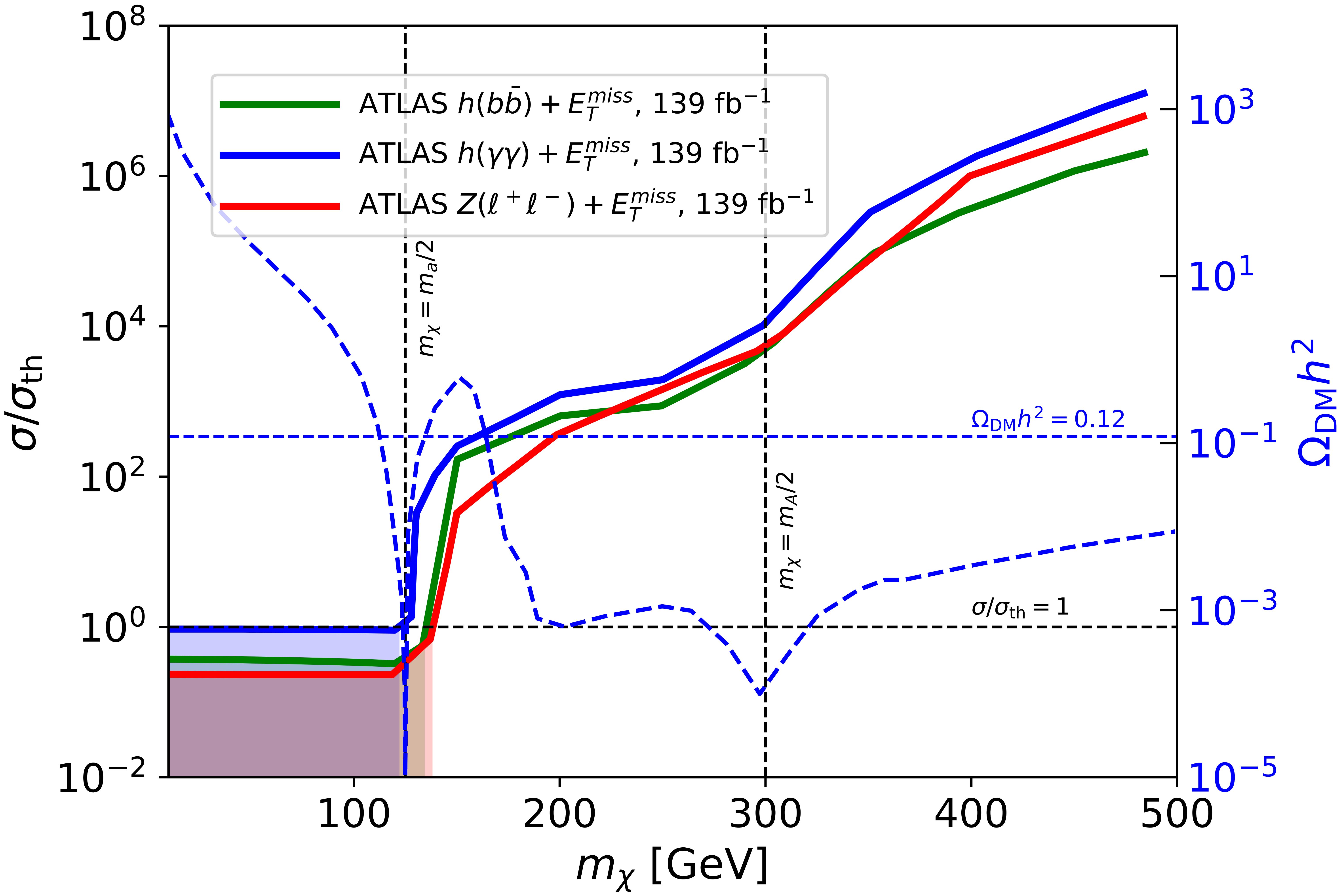


2HDM+a model: relic density vs. LHC probes

Here 2HDM+a model also looks like a regular 2HDM, i.e. a & χ decoupled from LHC phenomenology

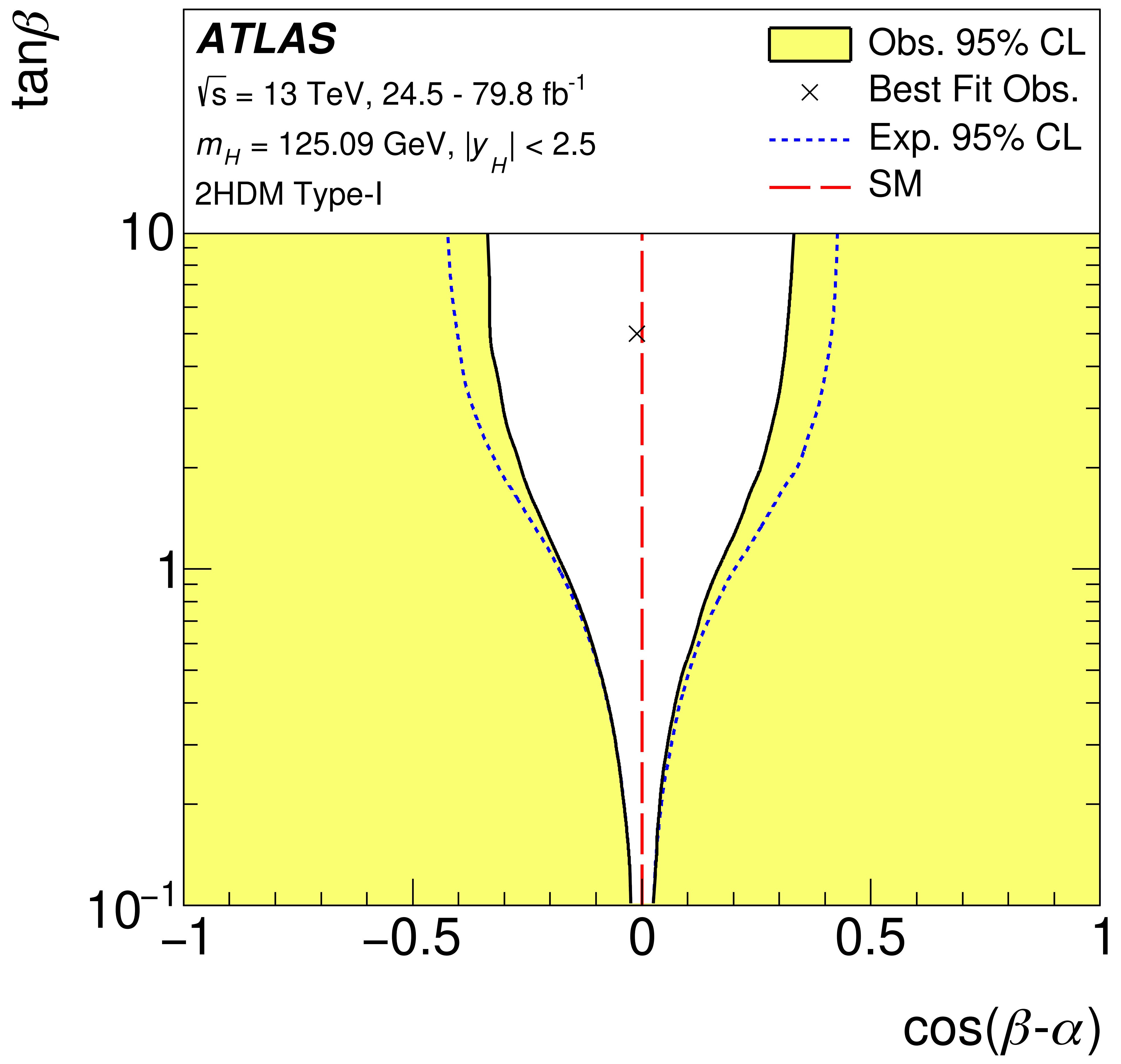


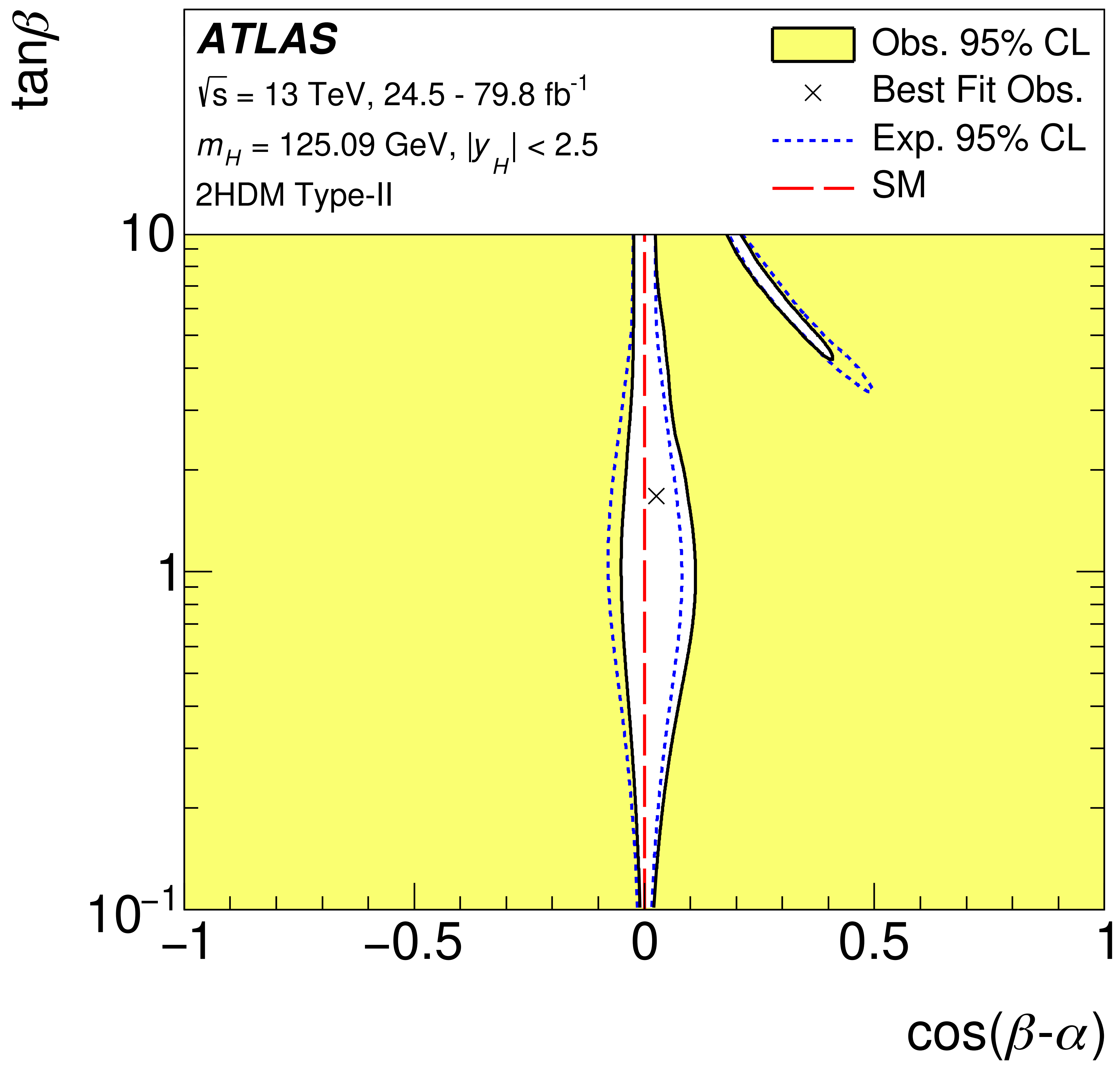
Constraints on 2HDM+a model



[Agryopoulos, Brandt & UH, 2109.13597]

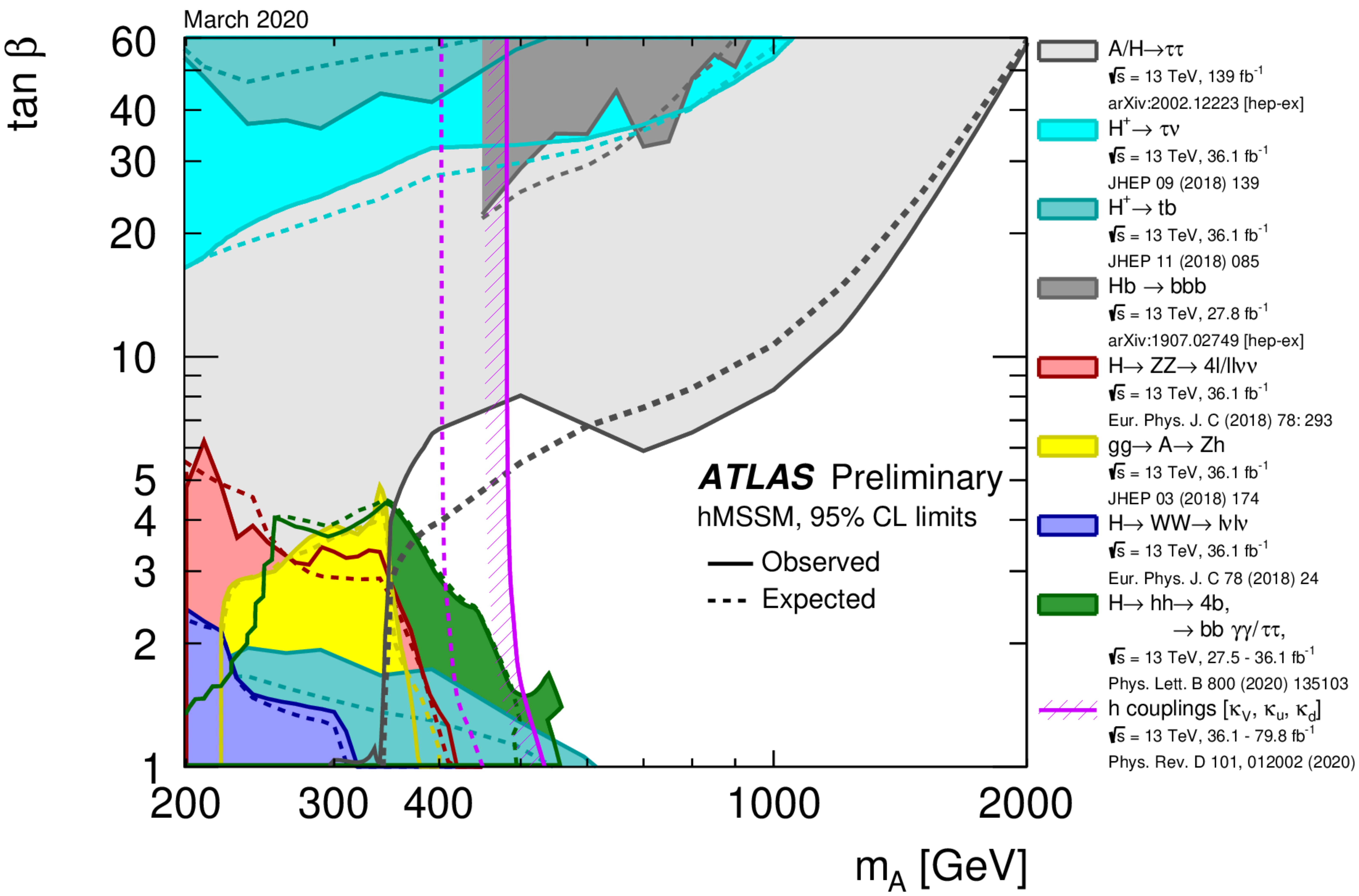
Constraints on alignment in 2HDM





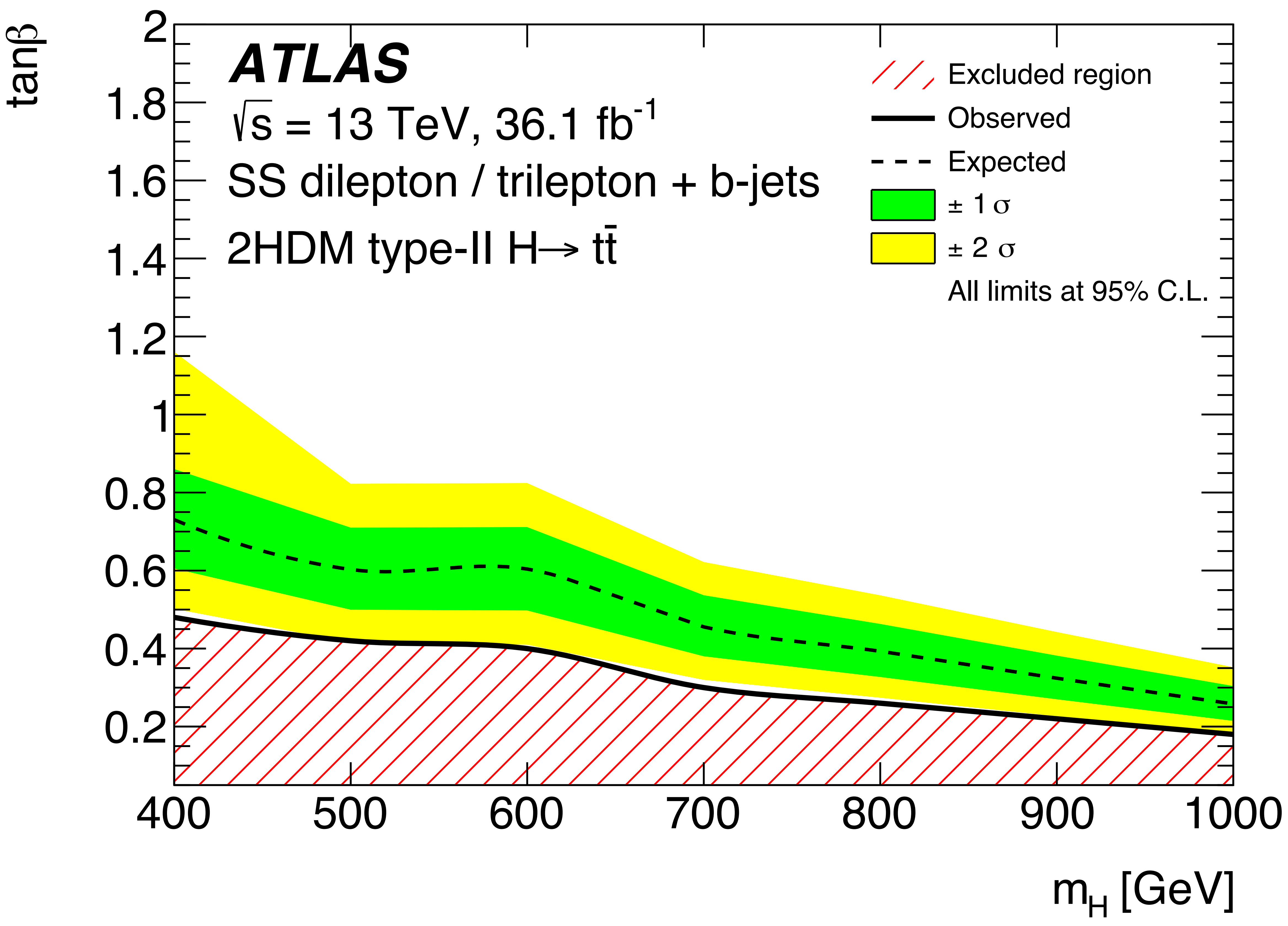
[ATLAS, 1909.02845]

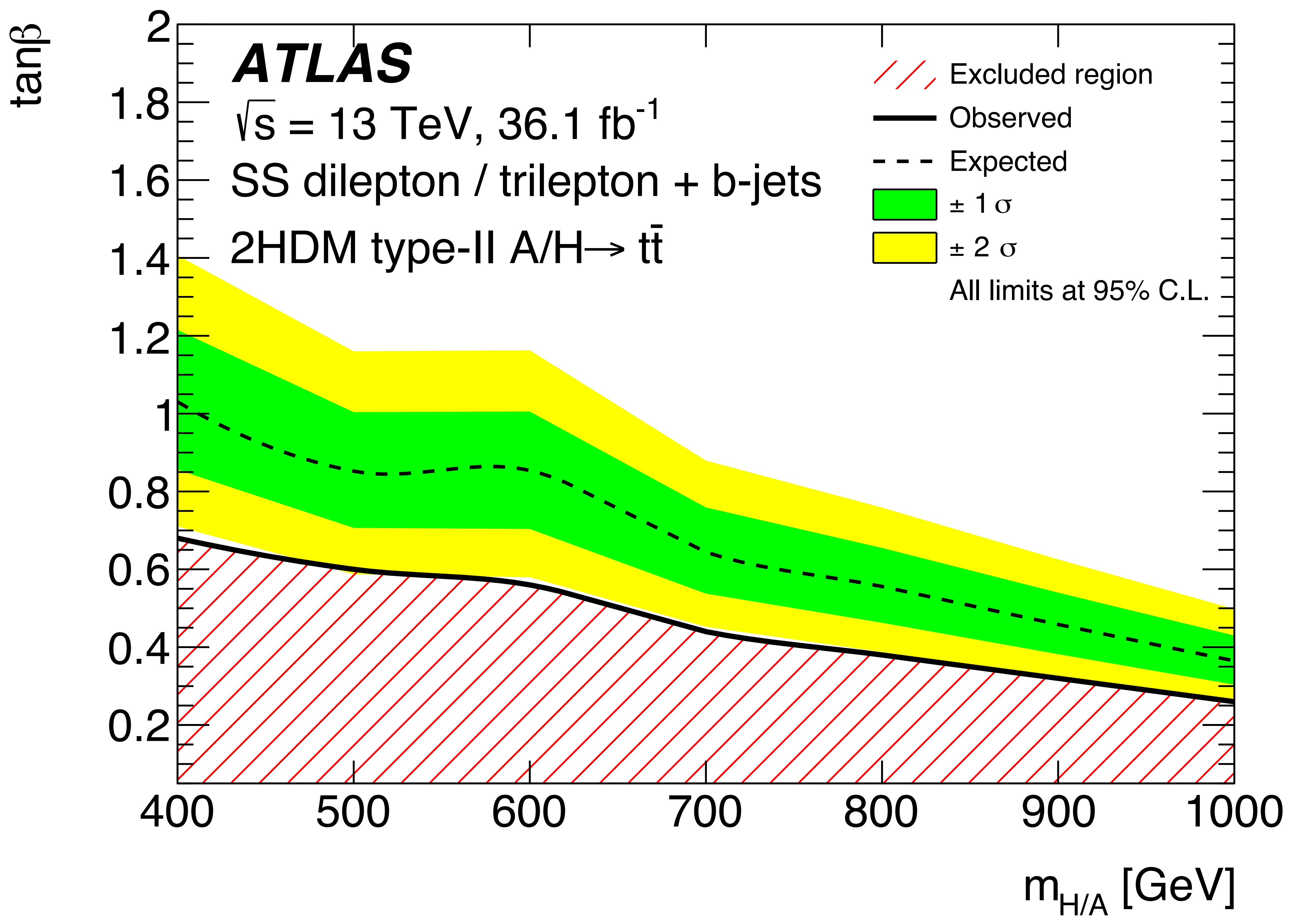
Summary of hMSSM Higgs exclusions



[ATLAS, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/]

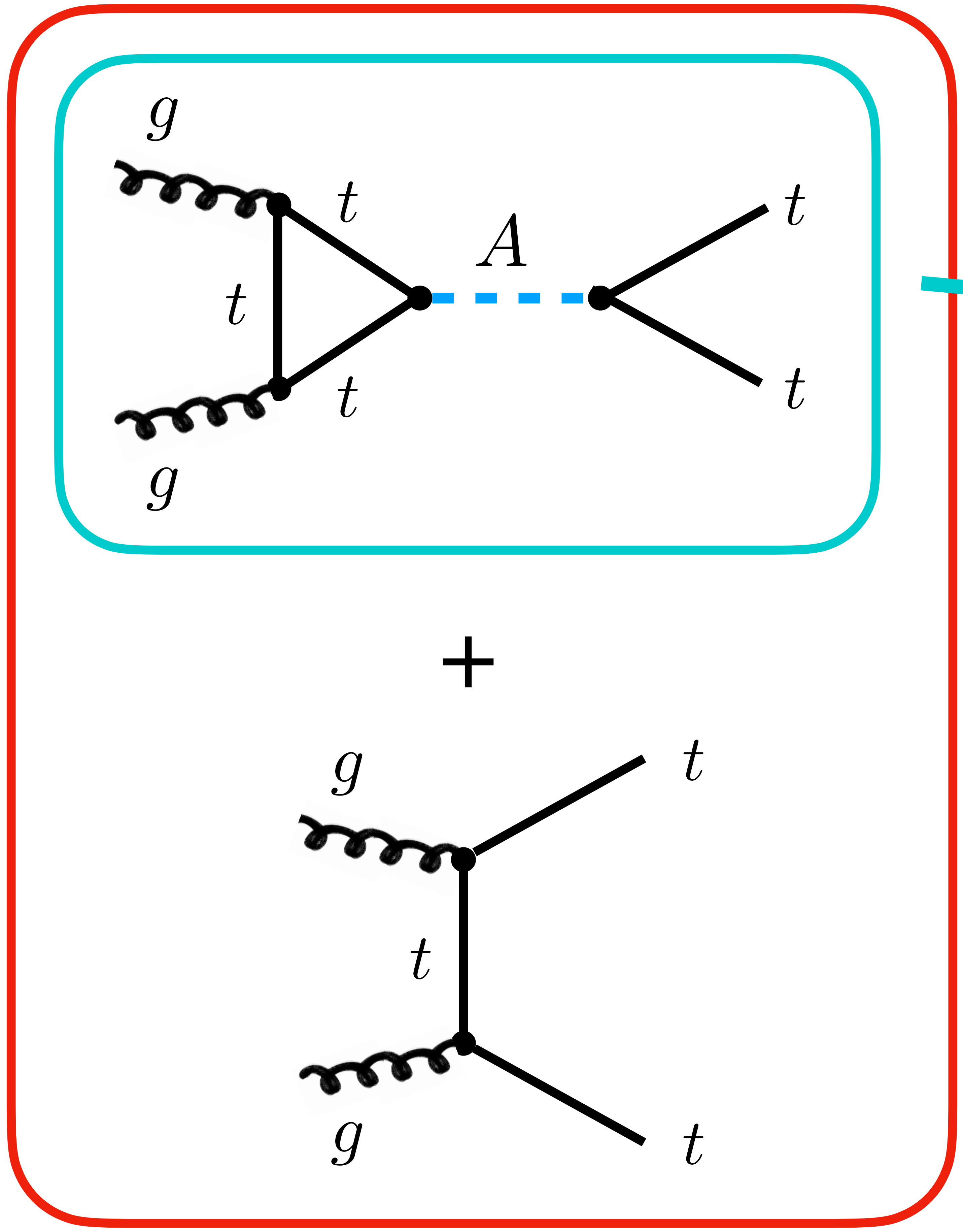
Bounds on 2HDM from 4-top searches

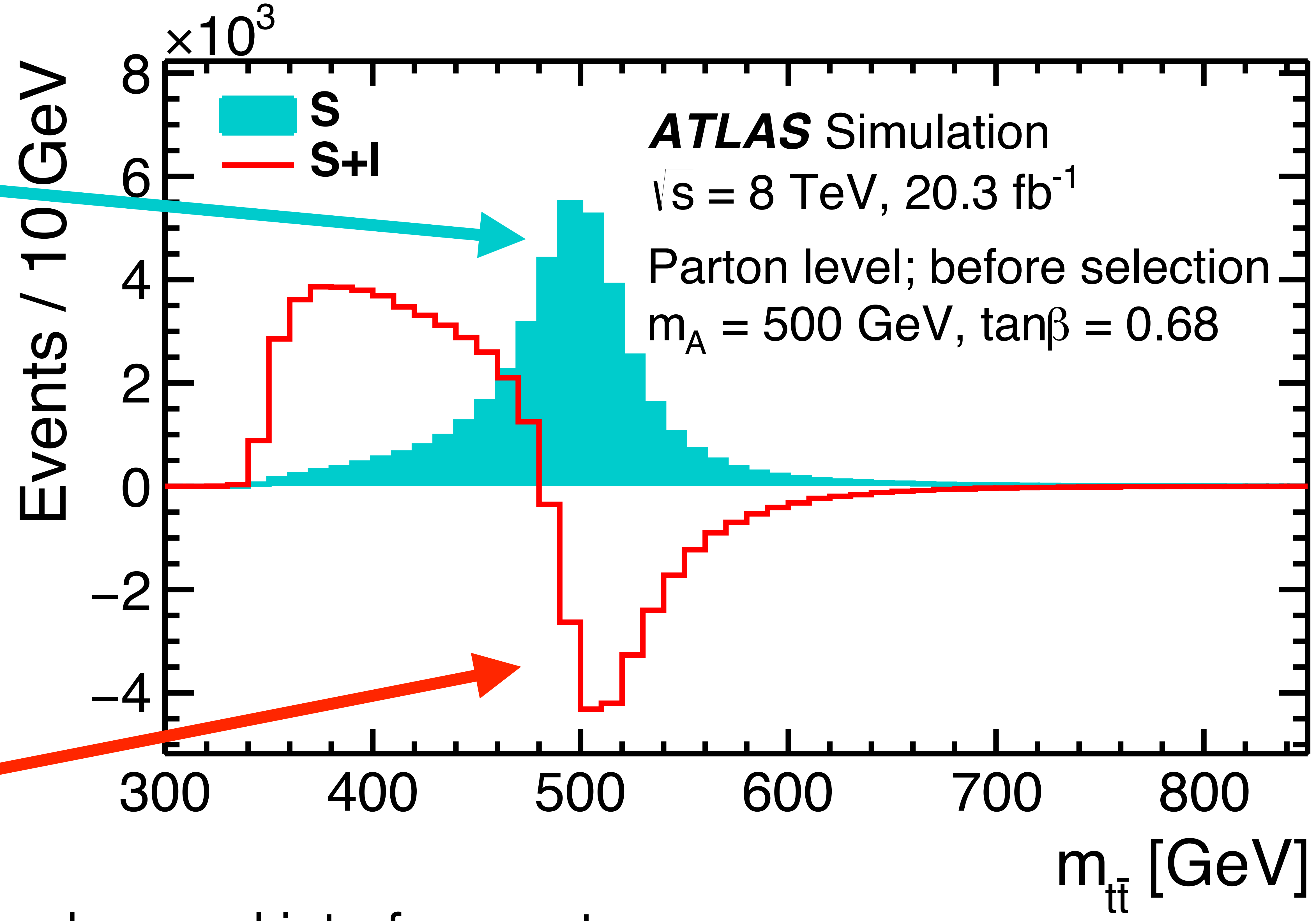




[ATLAS, 1807.11883]

Interference in ditop resonance searches

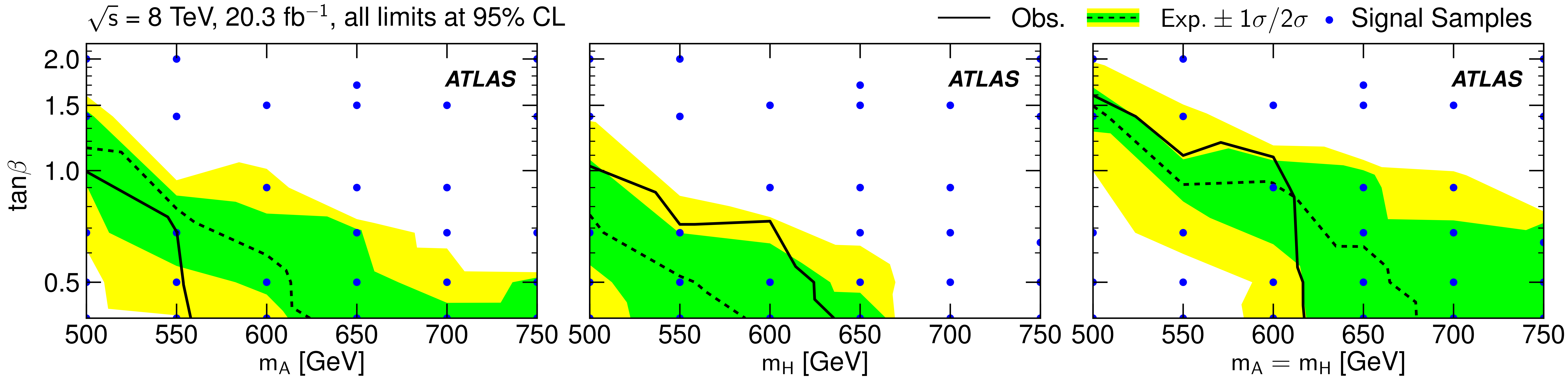




Signal-background interference turns Breit-Wigner into peak-dip structure

[see for instance ATLAS, 1707.06025]

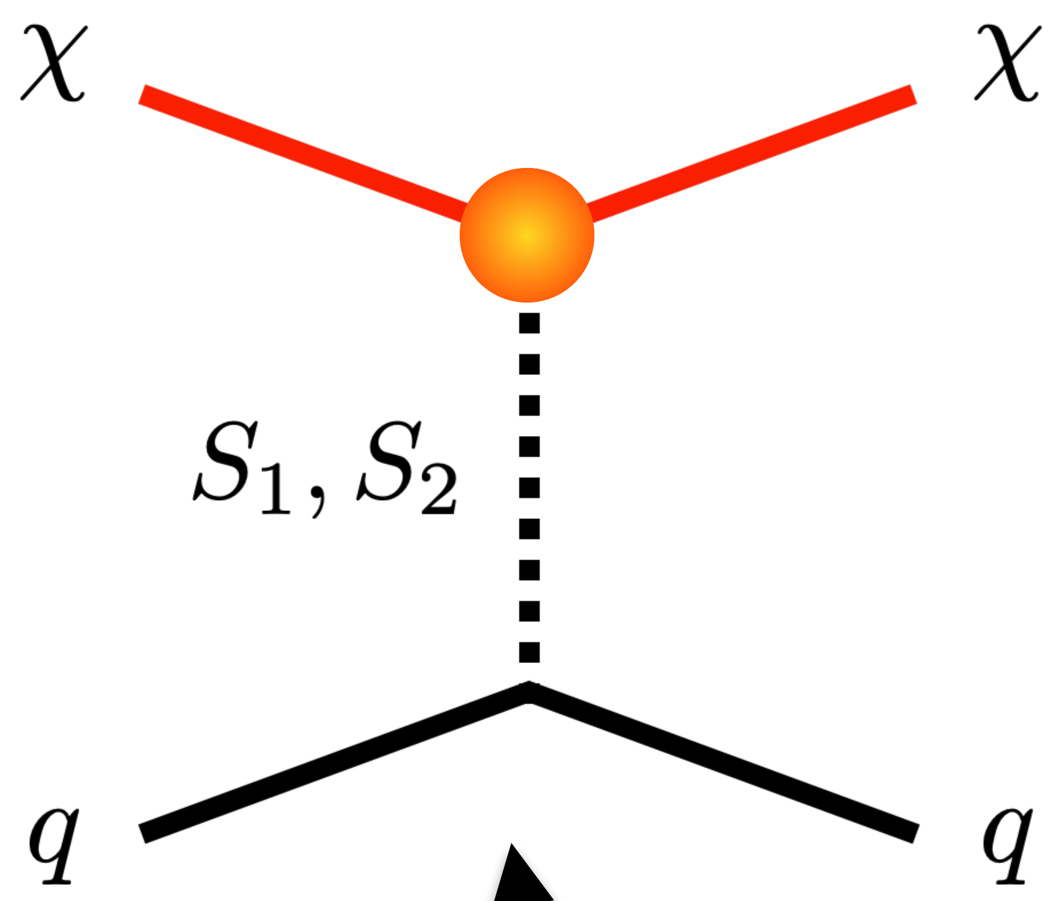
Bounds on 2HDM from ditop searches



Mass		m_A		m_H		$m_A = m_H$	
[GeV]	$\tan\beta$:	obs.	exp.	obs.	exp.	obs.	exp.
500		< 1.00	< 1.16	< 1.00	< 0.77	< 1.55	< 1.50
550		< 0.69	< 0.79	< 0.72	< 0.52	< 1.10	< 0.92
600		–	< 0.59	< 0.73	–	< 1.09	< 0.93
650		–	–	–	–	–	< 0.62

[ATLAS, 1707.06025]

Direct detection in 2HDM+s model



S_1, S_2 mostly H, s for small mixing angle θ

$$\sigma_{\rm SI} = \left(\frac{m_N m_\chi}{m_N + m_\chi}\right)^2 \frac{c_N^2}{\pi}$$

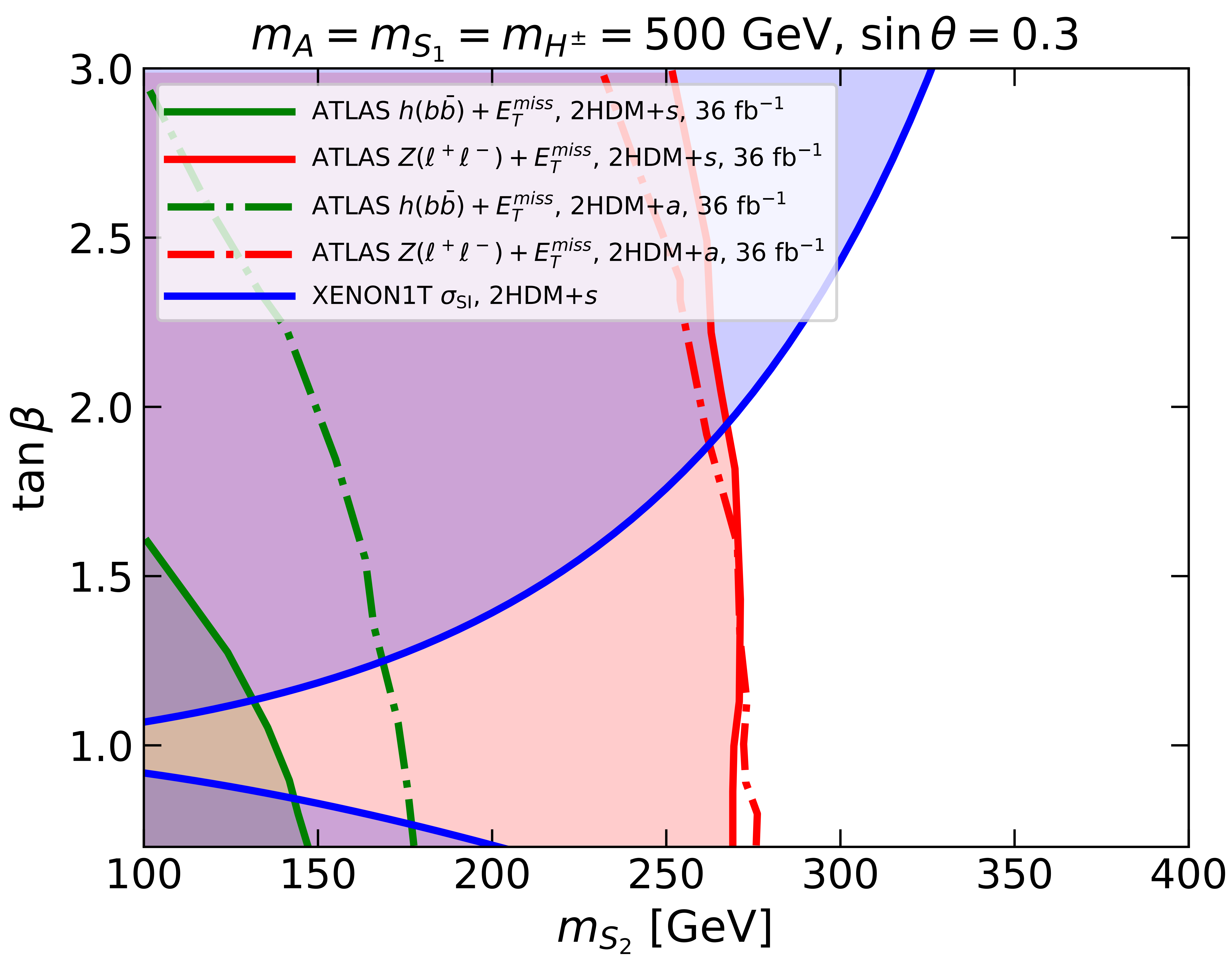
$$c_N = \frac{m_N}{v} \frac{y_\chi \sin(2\theta)}{2} \left(\frac{1}{m_{S_1}^2} - \frac{1}{m_{S_2}^2}\right)$$

$$\times \left[\cot\beta\, f_{T_u}^N - \tan\beta \sum_{q=d,s} f_{T_q}^N + \frac{4\cot\beta - 2\tan\beta}{27} f_{T_G}^N\right]$$

In case of 2HDM of type I, up- & down-type quark contributions interfere destructively. This allows to evade direct detection bounds

[Bell et al., 1612.03475, 1710.10764, 1803.01574]

Constraints in 2HDM+s model



[Agryopoulos, Brandt & UH, 2109.13597]

2HDM+Z′ model: T parameter

$$T \simeq \frac{\sin^2(2\theta_w)\, g_{Z'}^2 \sin^4\beta}{16\pi\alpha^2} \frac{m_Z^2}{m_{Z'}^2}$$

$$\Longrightarrow \qquad m_{Z'} > 1080\,\mathrm{GeV}$$

$$T = 0.03 \pm 0.12$$

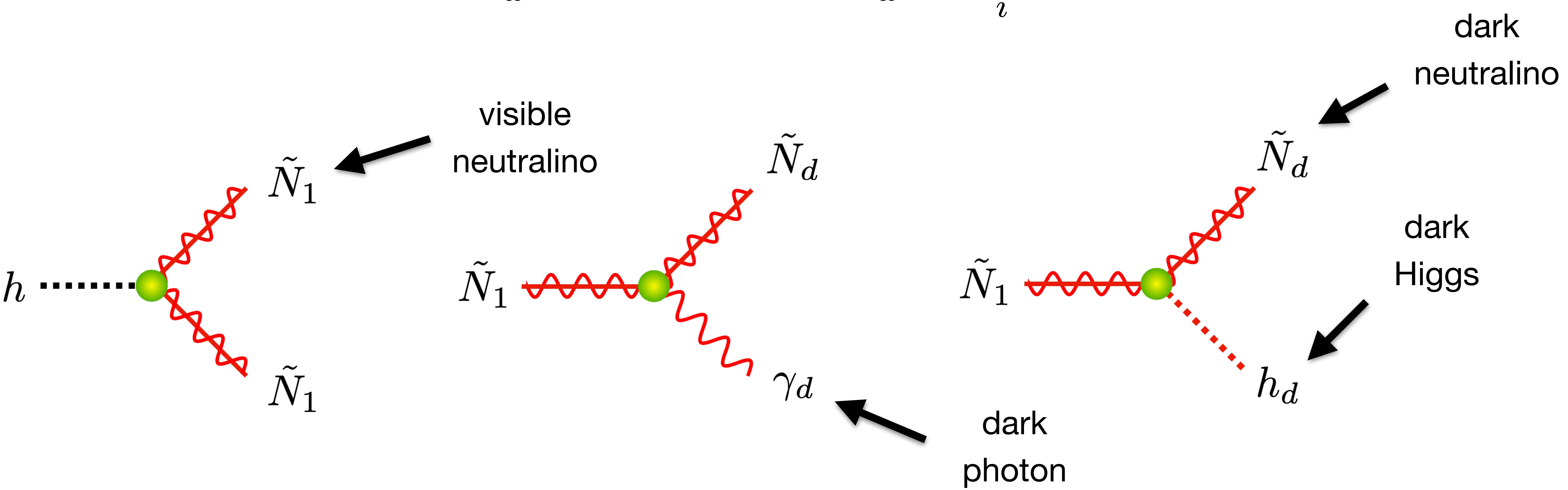
$$g_{Z'} = 0.8, \tan\beta = 1$$

[Berlin, Lin & Wang, 1402.7074; PDG 2020]

SUSY vector & fermion portal models

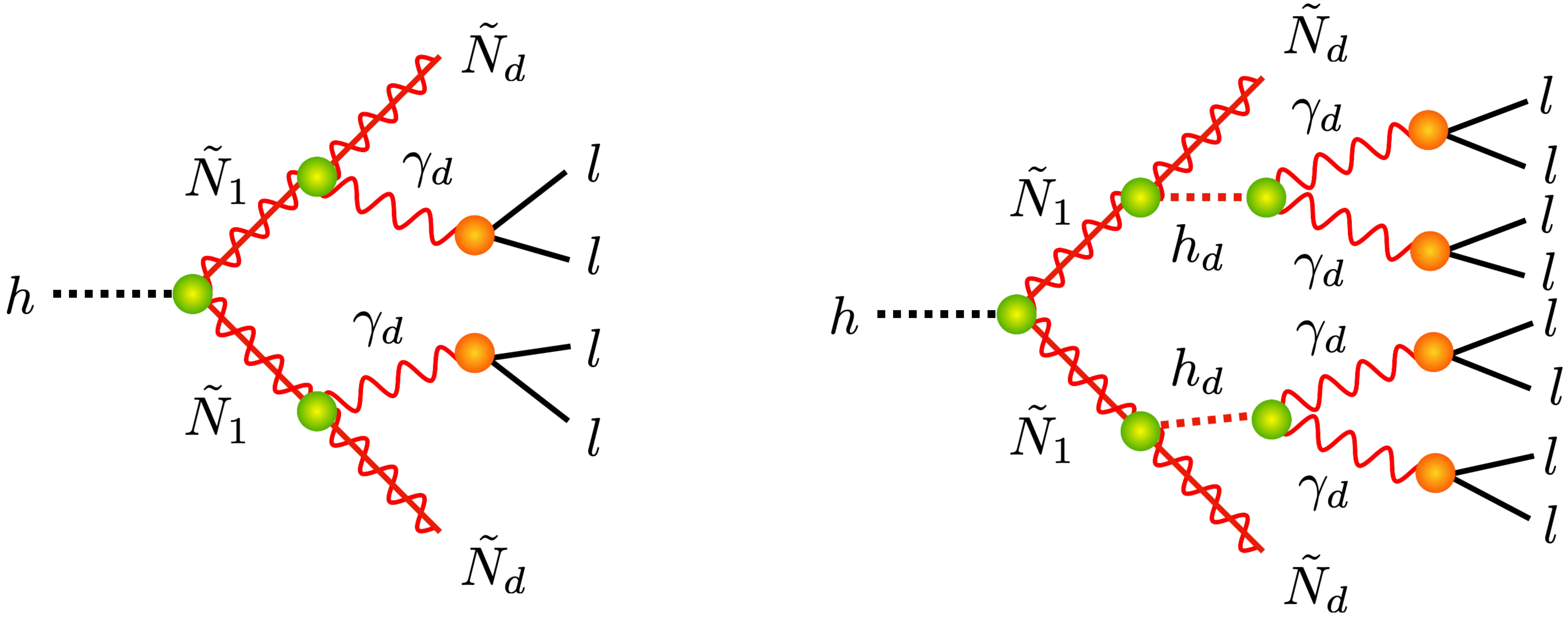
hypercharge portal   gaugino portal

$$\mathcal{L} = \frac{\epsilon}{2\cos\theta_w} B_{\mu\nu} X^{\mu\nu} - \frac{\epsilon g_d}{\cos\theta_w} \tilde{B} \sum_i q_i h_d^{i\dagger} \tilde{h}_d^i$$



[Falkowski, Ruderman, Volansky & Zupan, 1002.2952, 1007.3496]

SUSY vector & fermion portal models



Dark photons arise from cascades involving SUSY & hidden particles with masses of O(10 GeV). γ_d therefore typically produced with large boost. This leads to lepton-jet plus $E_{T,miss}$ signature with amount of $E_{T,miss}$ depending on decay pattern

[Falkowski, Ruderman, Volansky & Zupan, 1002.2952, 1007.3496]

Inelastic DM

U(1)$_X$ gauge field

Dirac fermion

$$\mathcal{L} = i\bar{\psi}\left(\partial_\mu - i g_X X_\mu\right)\psi - m_D \bar{\psi}\psi - y\phi\bar{\psi}^c\psi - \lambda\phi^2|H|^2 + \text{h.c.}$$

$$\Downarrow \quad \langle\phi\rangle = \frac{v_\phi}{\sqrt{2}}$$

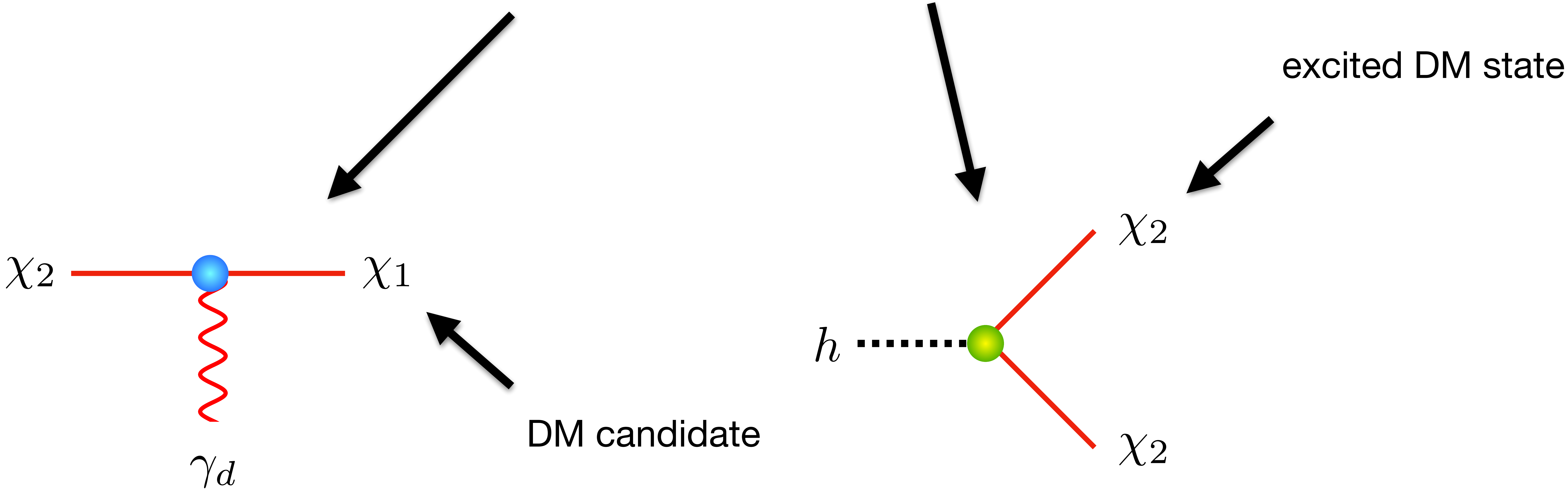
$$\chi_{1,2} = \frac{\psi \mp \psi^c}{\sqrt{2}}\,, \qquad m_{1,2} = m_D \mp y v_\phi$$

Majorana fermions

[see for instance Tucker-Smith & Weiner, hep-ph/0101138]

Inelastic DM

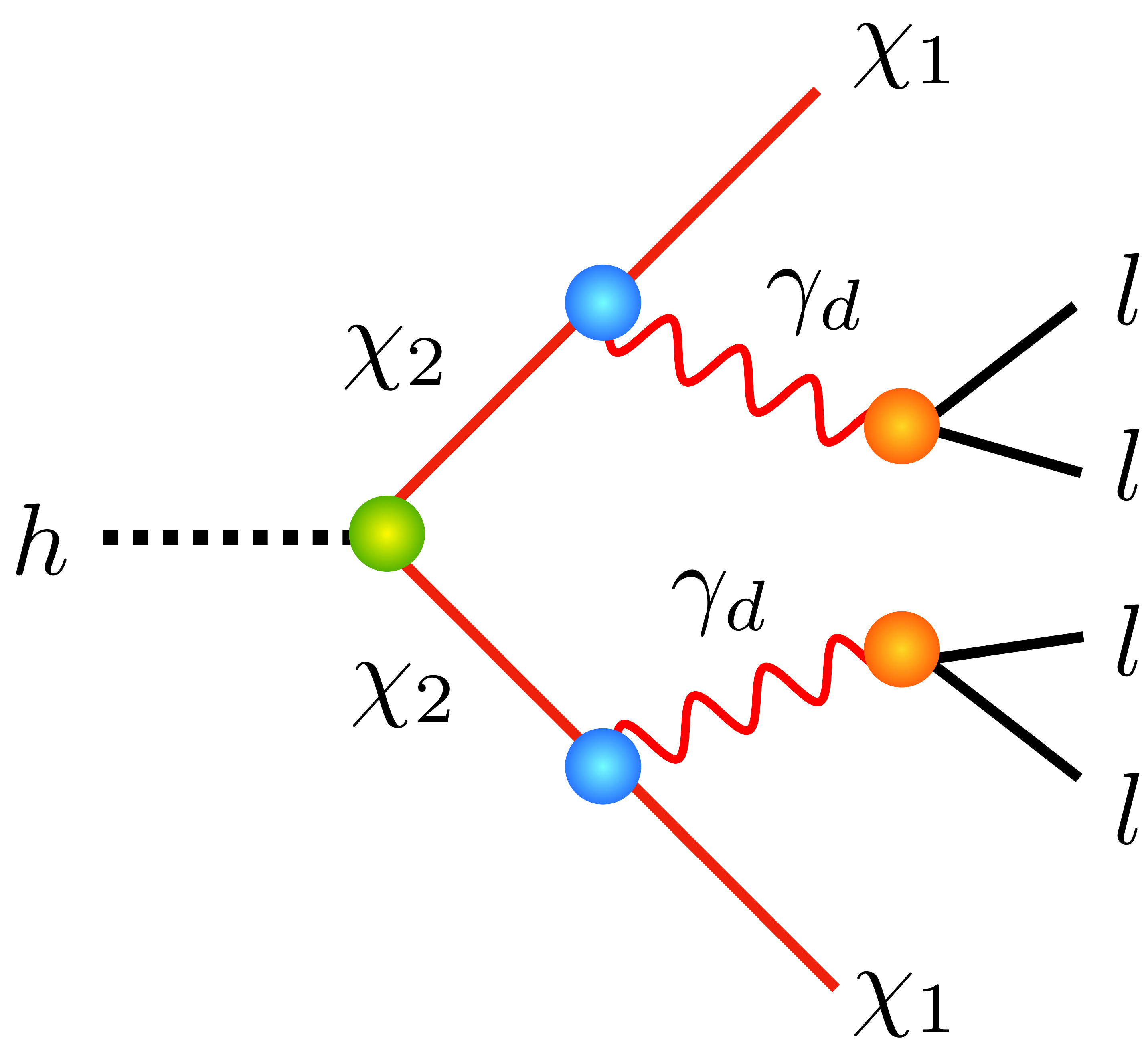
$$\mathcal{L} = \frac{ig_X}{2}\,\bar{\chi}_2\gamma_\mu\chi_1\,A_d^\mu + \frac{y}{2}\sin\theta\,h\bar{\chi}_2\chi_2 + \ldots$$



[see for instance Tucker-Smith & Weiner, hep-ph/0101138]

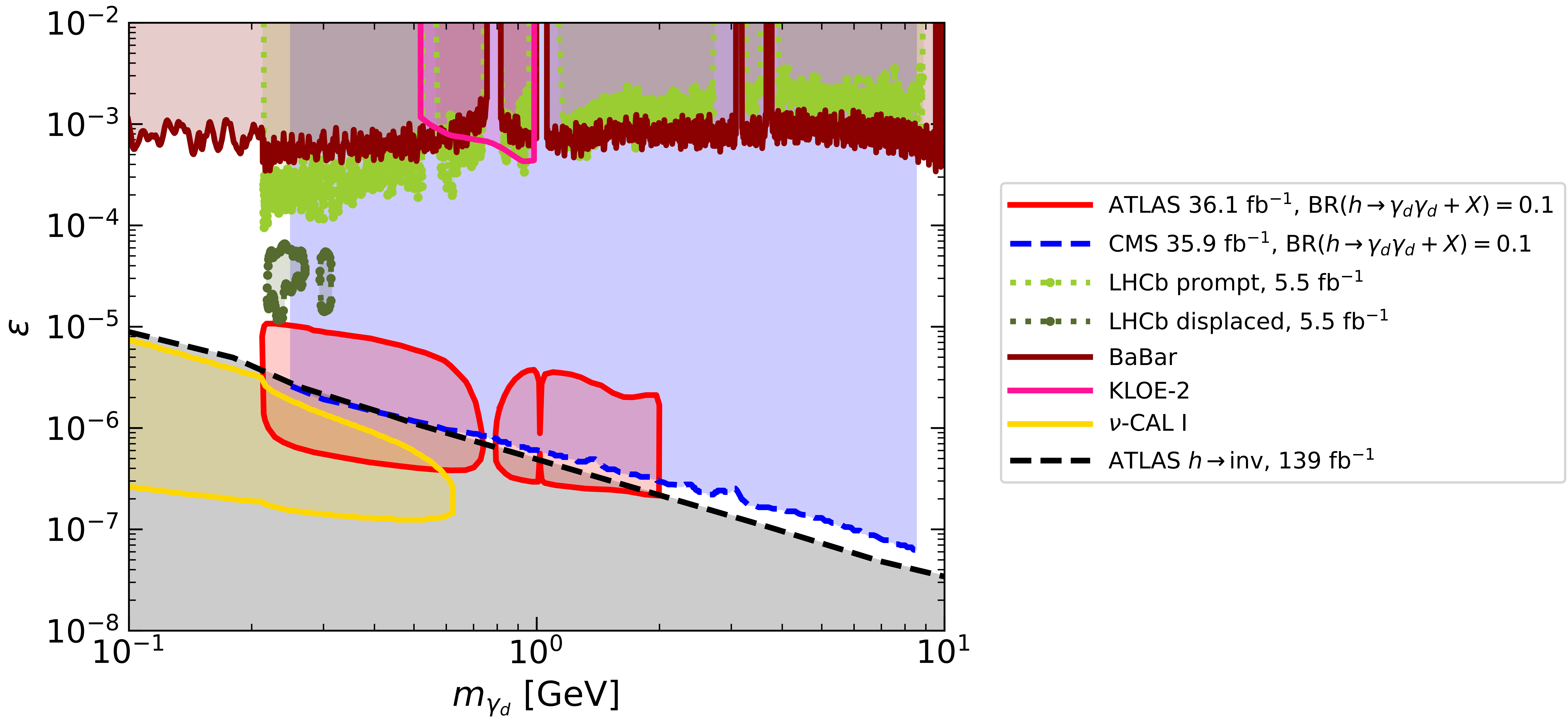
Inelastic DM

Dark photons arise from exotic Higgs decay to exited DM state χ_2. If γ_d is light with mass of O(1 GeV) it is produced with large boost. Resulting smoking-gun signal are so-called lepton-jets, i.e. collimated groups of leptons in a jet-like structure, plus $E_{T,miss}$ provided by DM candidate χ_1



[see for instance Arkani-Hamed & Weiner, hep-ph/0810.0714]

Constraints on inelastic DM



[Agryopoulos, Brandt & UH, 2109.13597]