Searches for Dark Matter at the LHC

Spyros Argyropoulos

Uni Bonn seminar

11 April 2023

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

UNI FREIBURG

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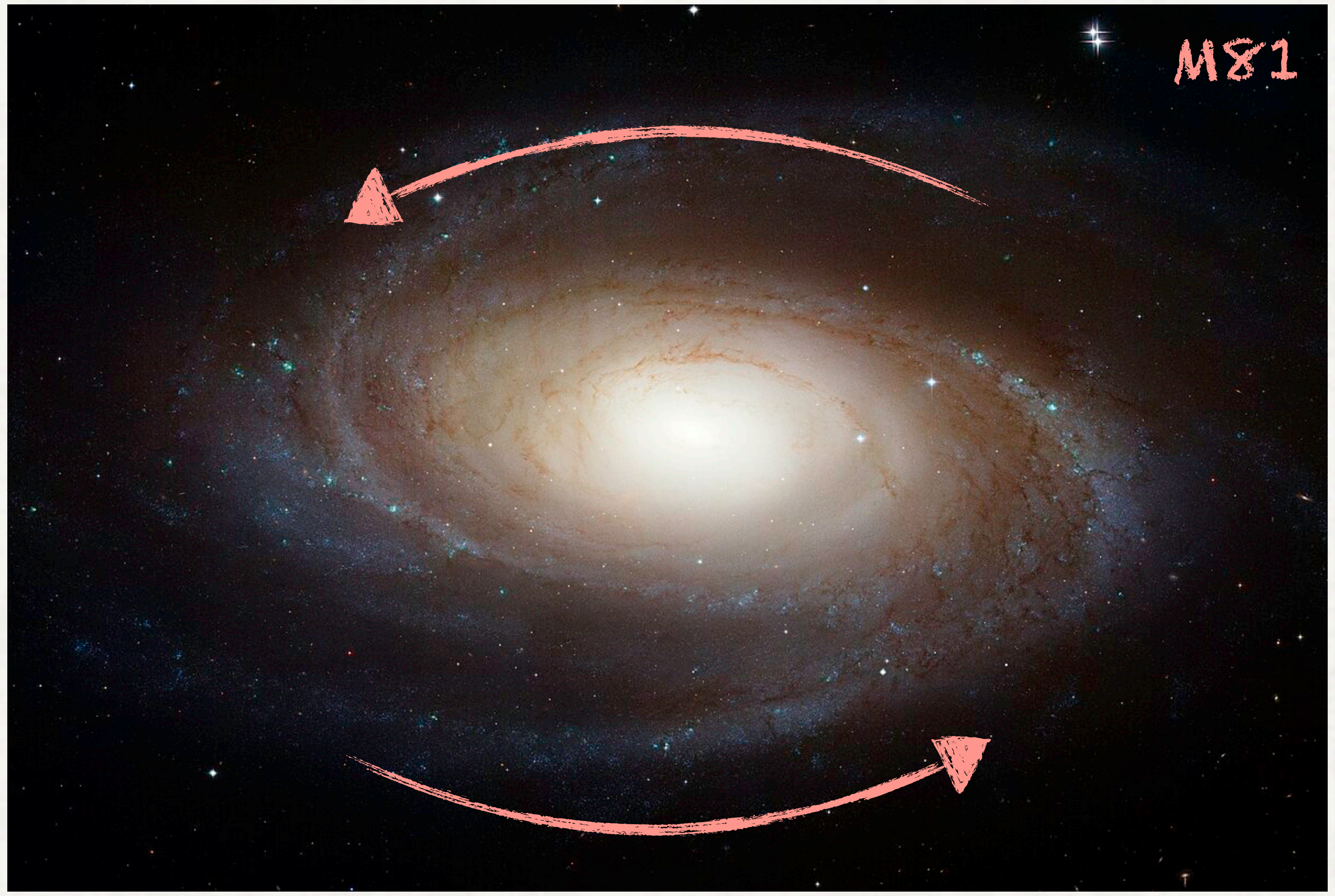
First evidence – 1930

Tabelle 4.

Objekt	Verhältnis: Leuchtende + dunkle Materie / Leuchtende Materie	Mittlere Zahl der Sterne für Lichtjahre^3
Messier 81	100 : 1 (?)	0.20 (?)
N. G. C. 4594	30 : 1	0.042
Andromedanebel	20 : 1	0.006
Messier 51	10 : 1	0.012
Milchst		
Messie		

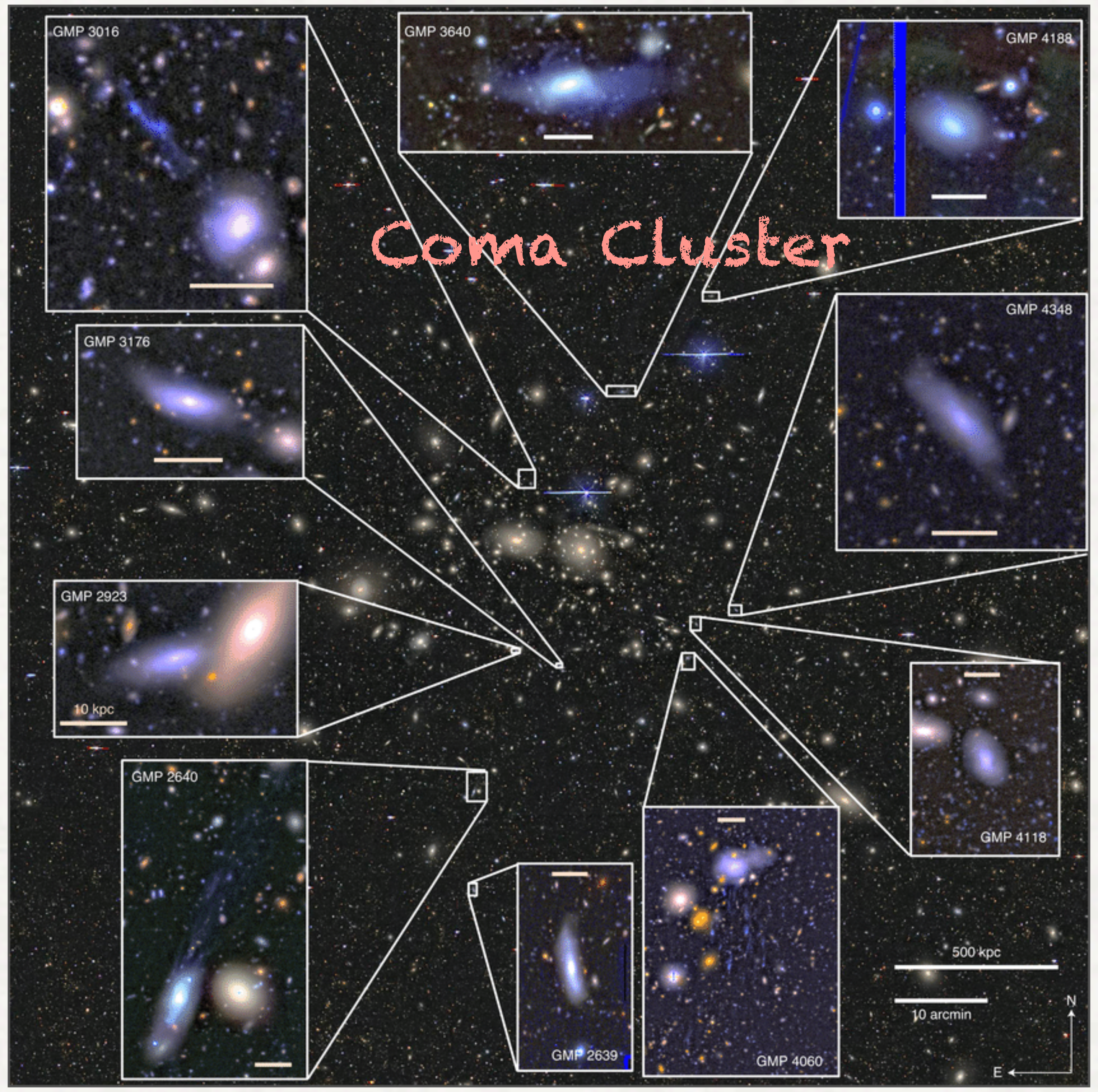
Die Masse, die auf diese Weise berechnet wird, die Luminositätsmasse, enthält begreiflicherweise nicht die Masse der dunklen Körper des Systems (erloschene Sterne, dunkle Nebel, Meteore, Kometen usw.). Um die totale Masse oder die Gra-



1. Luminosity → Luminous mass
2. Distance → Luminous mass
3. Rotation → Gravitational mass

K. Lundmark, Lund Medd. No125 (1930) 1

First evidence - 1933



Nature Astronomy **5**,1308 (2021)

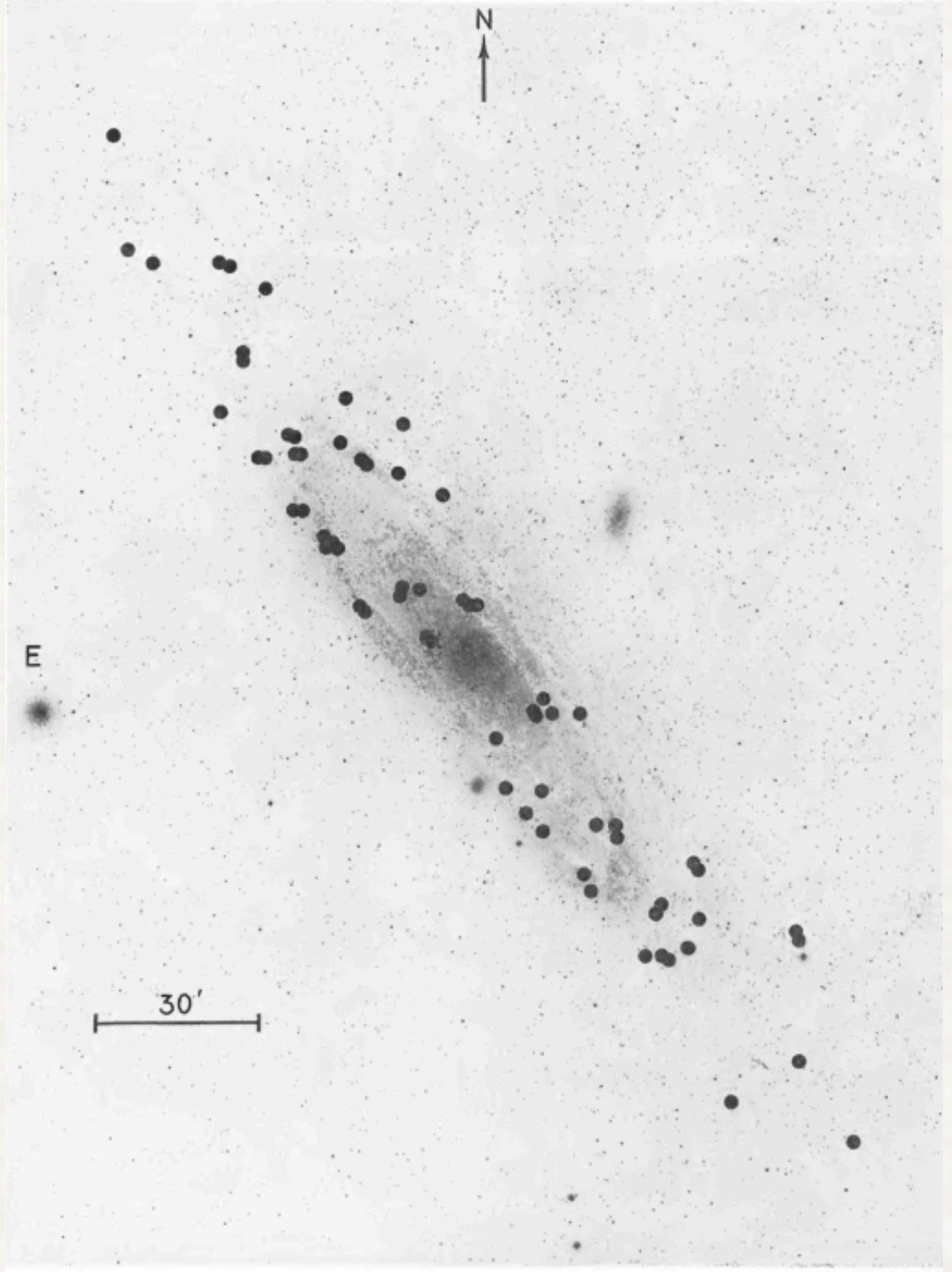
Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete¹). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

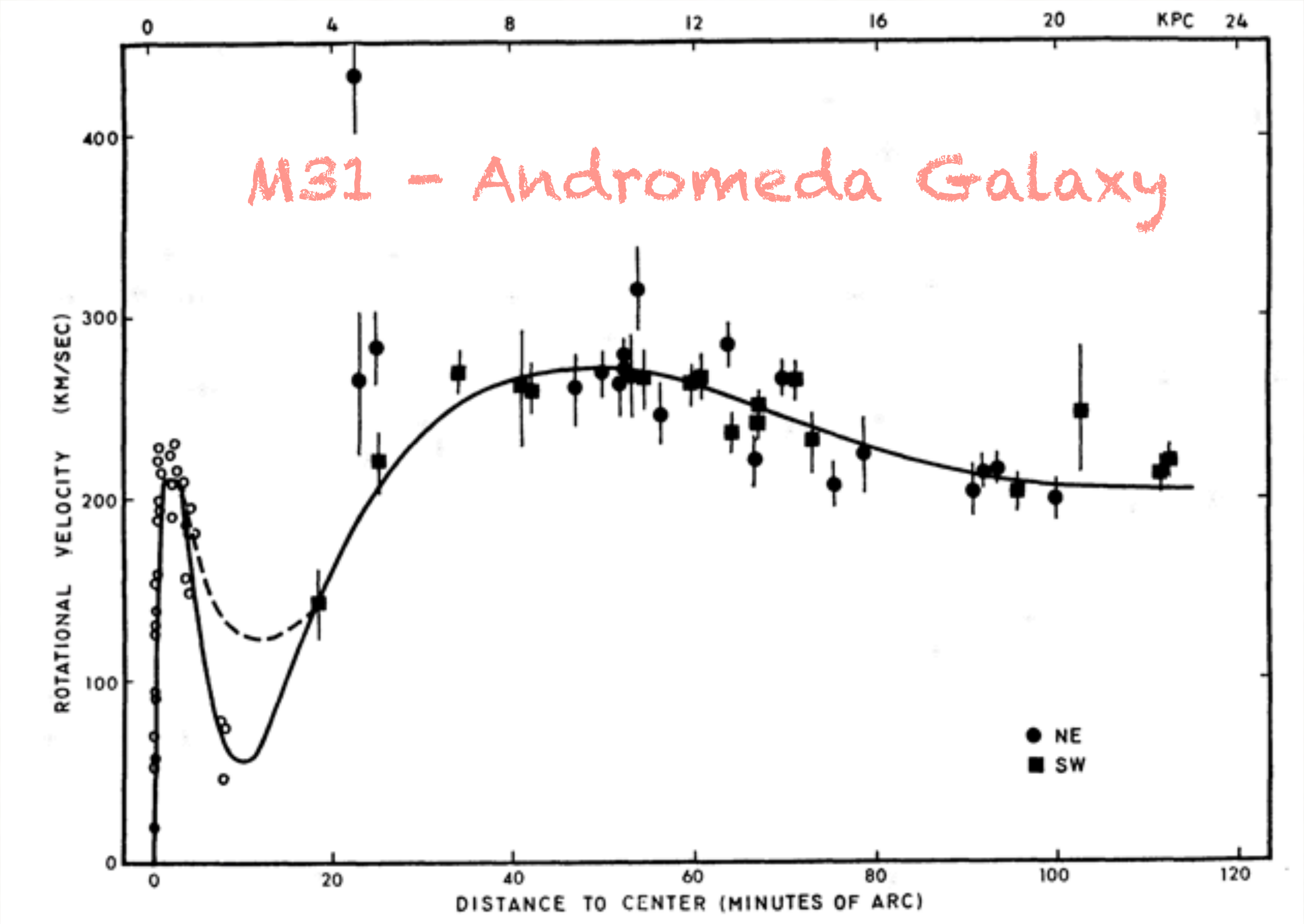
F. Zwicky, Helv.Phys.Acta 6 (1933) 110

Zwicky used Virial theorem on Coma Cluster:

$$\langle E_k \rangle = -\frac{1}{2}\langle V \rangle \Rightarrow \langle v^2 \rangle = \frac{GM}{R} \Rightarrow \sqrt{\langle v^2 \rangle} = 80 \text{ km/s}$$

Flat rotation curves - 1960/1970s





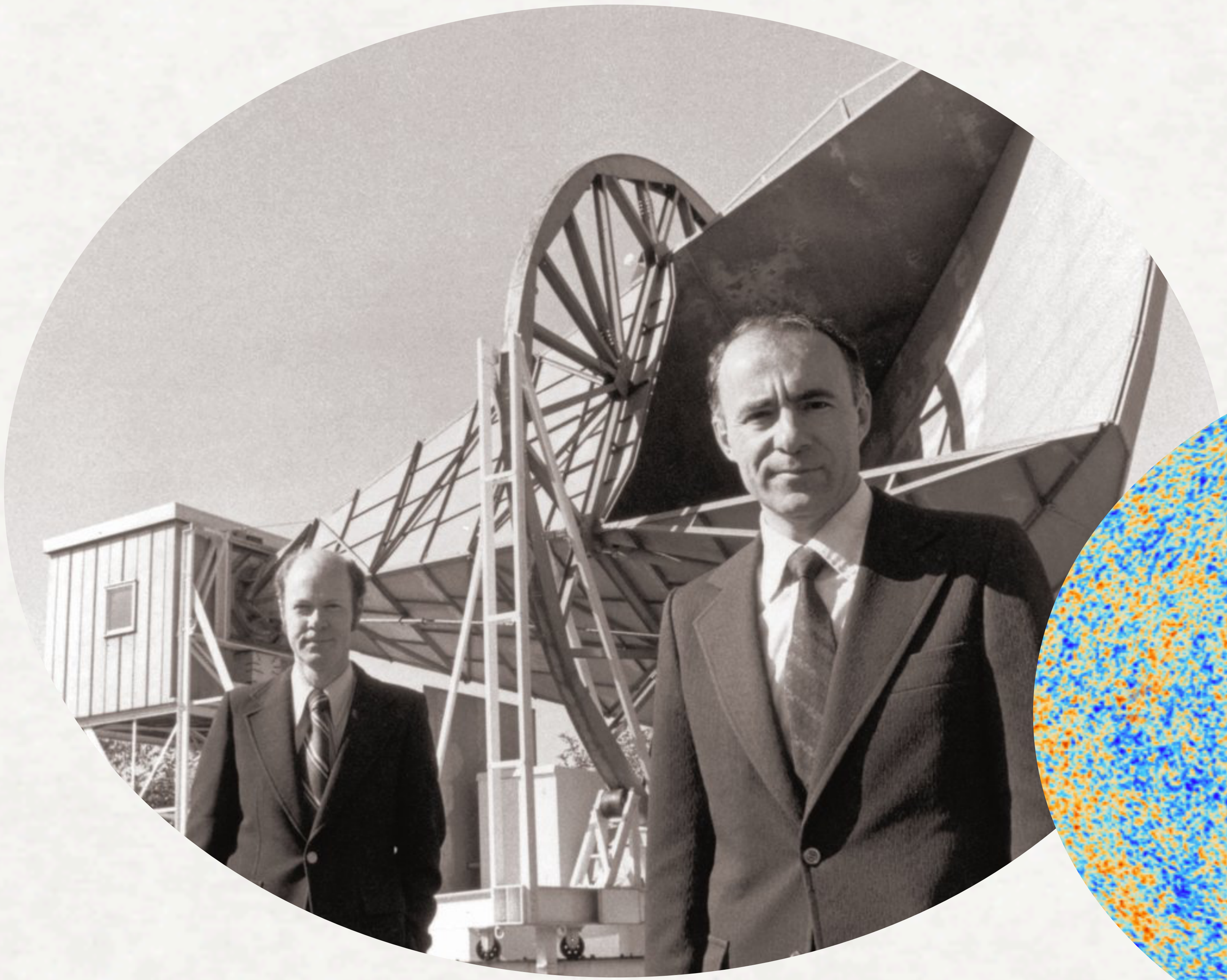
[V.C.Rubin, K.W.Ford, Ap.J. 159 (1970) 379]

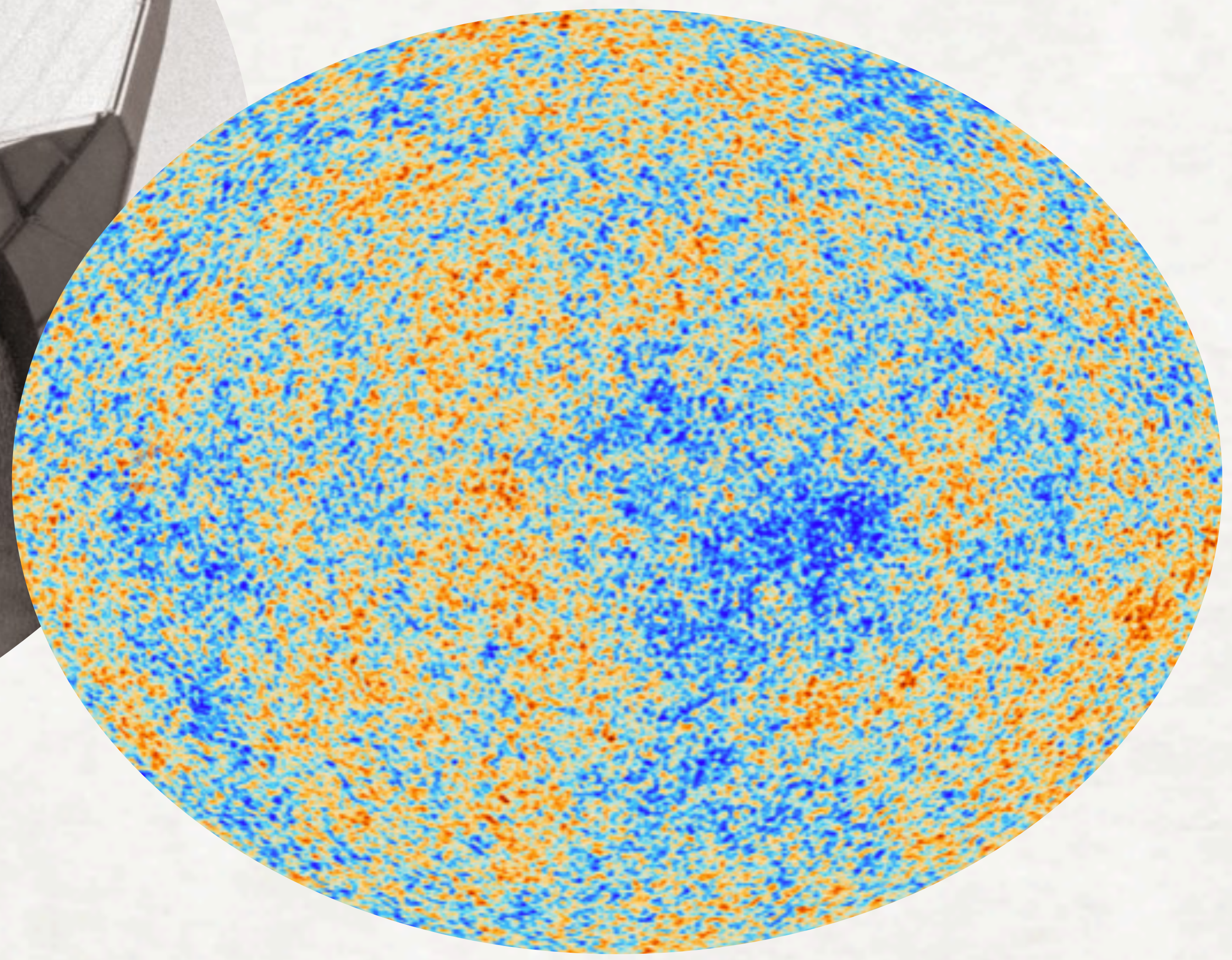
In 1962 in Georgetown, I was teaching a graduate course on statistical astronomy. My class had six students… I gave the students (plus me as a student) a research problem: Can we use cataloged stars to determine a rotation curve for stars distant from the center of our Galaxy?

We submitted our paper [V.C.Rubin et al, AJ 67 (1962) 491] to the Astronomical Journal. The editor called me to say he accepted it, but he would not publish the names of students. When I said, "Then I withdraw the paper," he relented. The abstract stated: "For R > 8.5 kpc the stellar curve is flat, and does not decrease as is expected for Keplerian orbits" (Rubin et al. 1962, p. 491). Following its publication, the many comments I received were negative and some very unpleasant: it couldn't be correct, or the data were not good enough.

[V.C. Rubin, Annu. Rev. Astron. Astrophys. 2011. 49:1–28]

CMB discovery



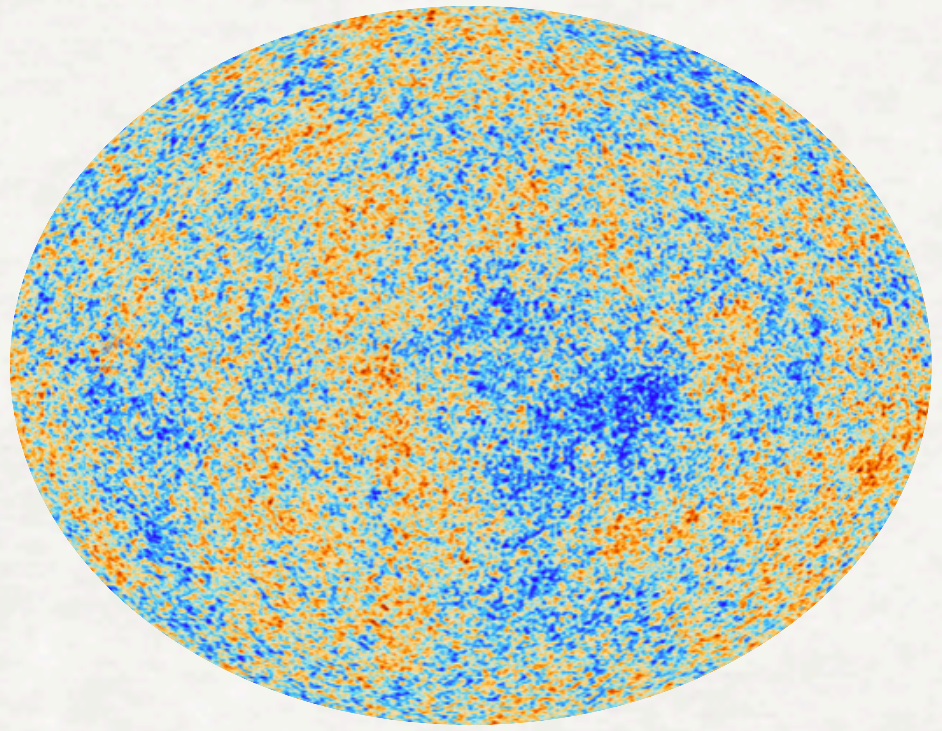


1. indicated that distribution of radiation and matter are very different (smooth vs clumpy) ⇒ non-baryonic / non-interacting matter [Peebles]

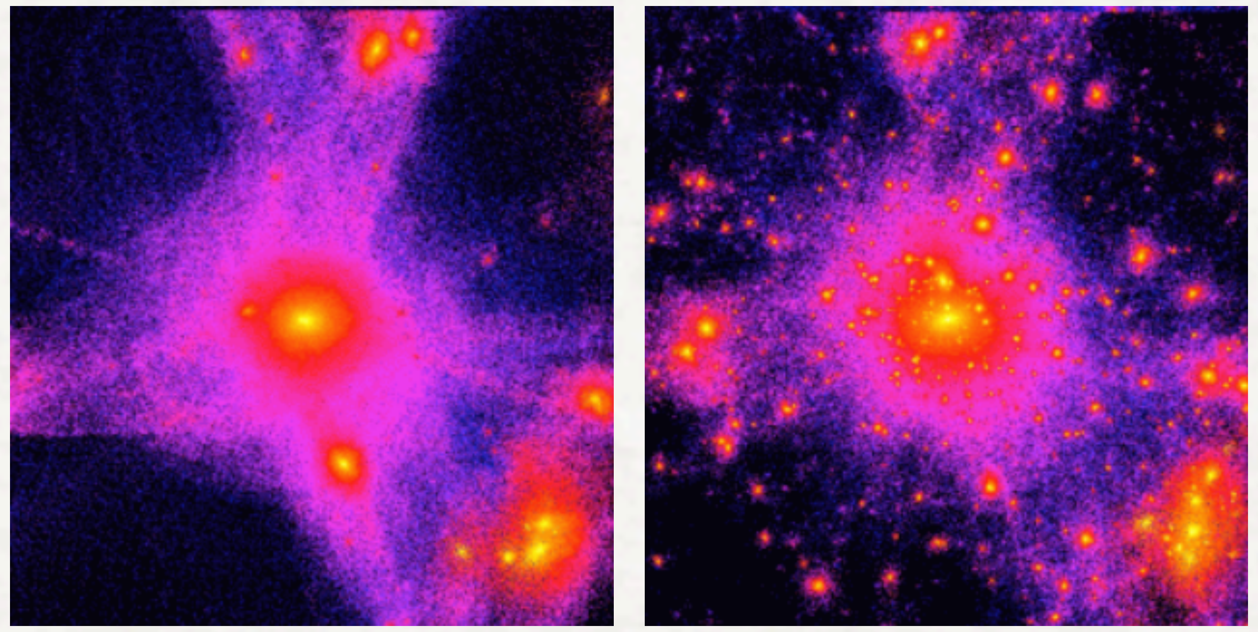
2. marked the transition to a new era: “particle physics entered the picture with the Universe being deployed as a heavenly laboratory” [M.S.Turner, Annu. Rev. Nucl. Part. Sci. 2022. 72:1]

Dark Matter from particle cosmology

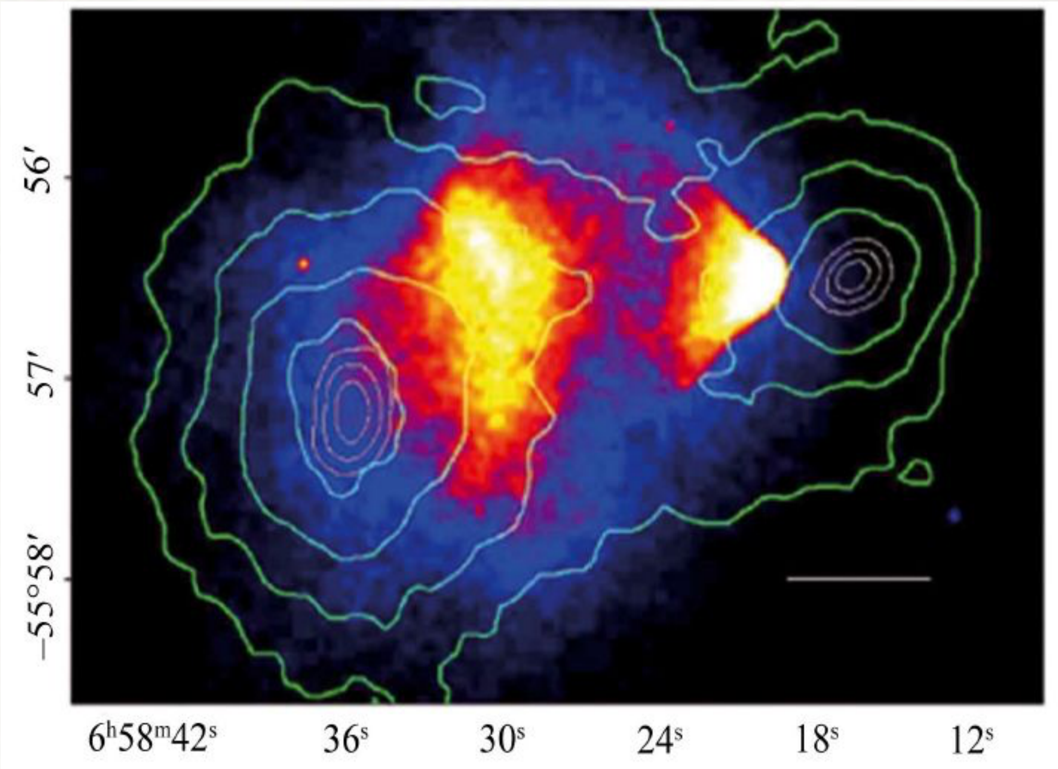
Cosmic Microwave Background



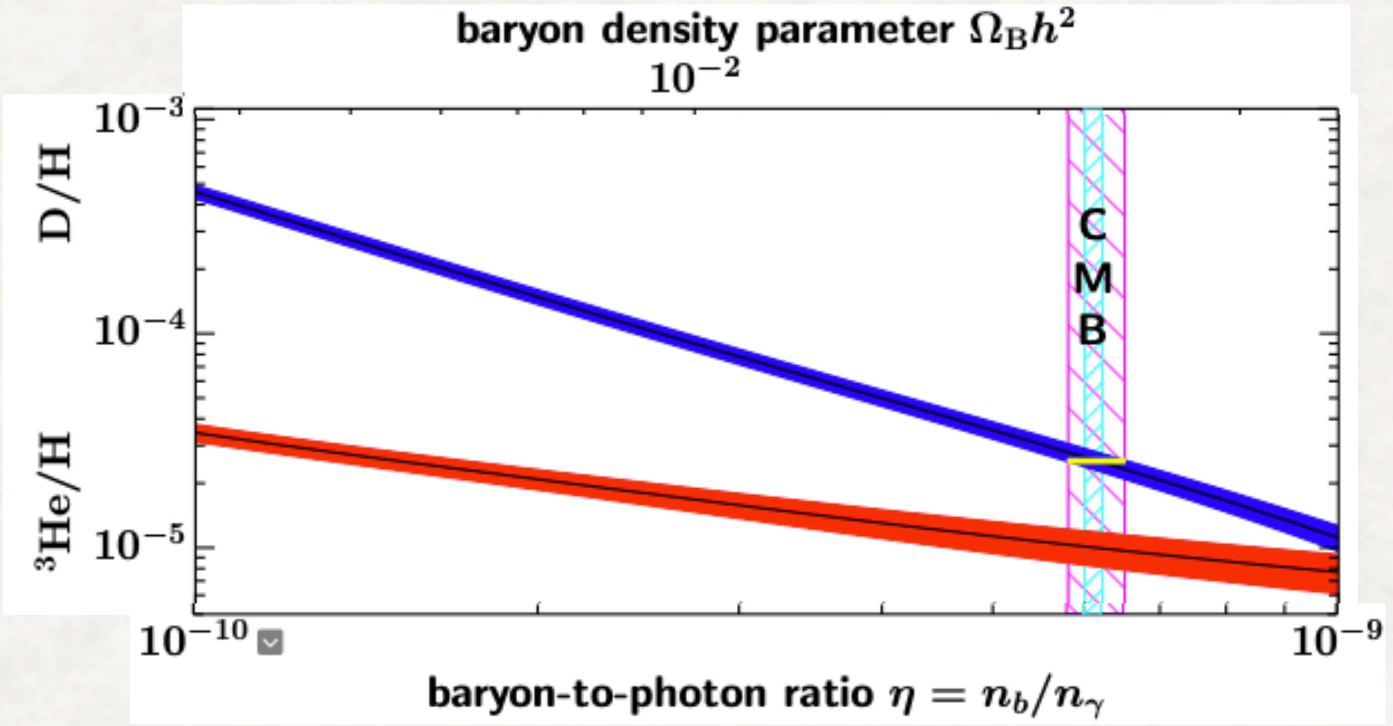
Large Scale Structure



Gravitational Lensing



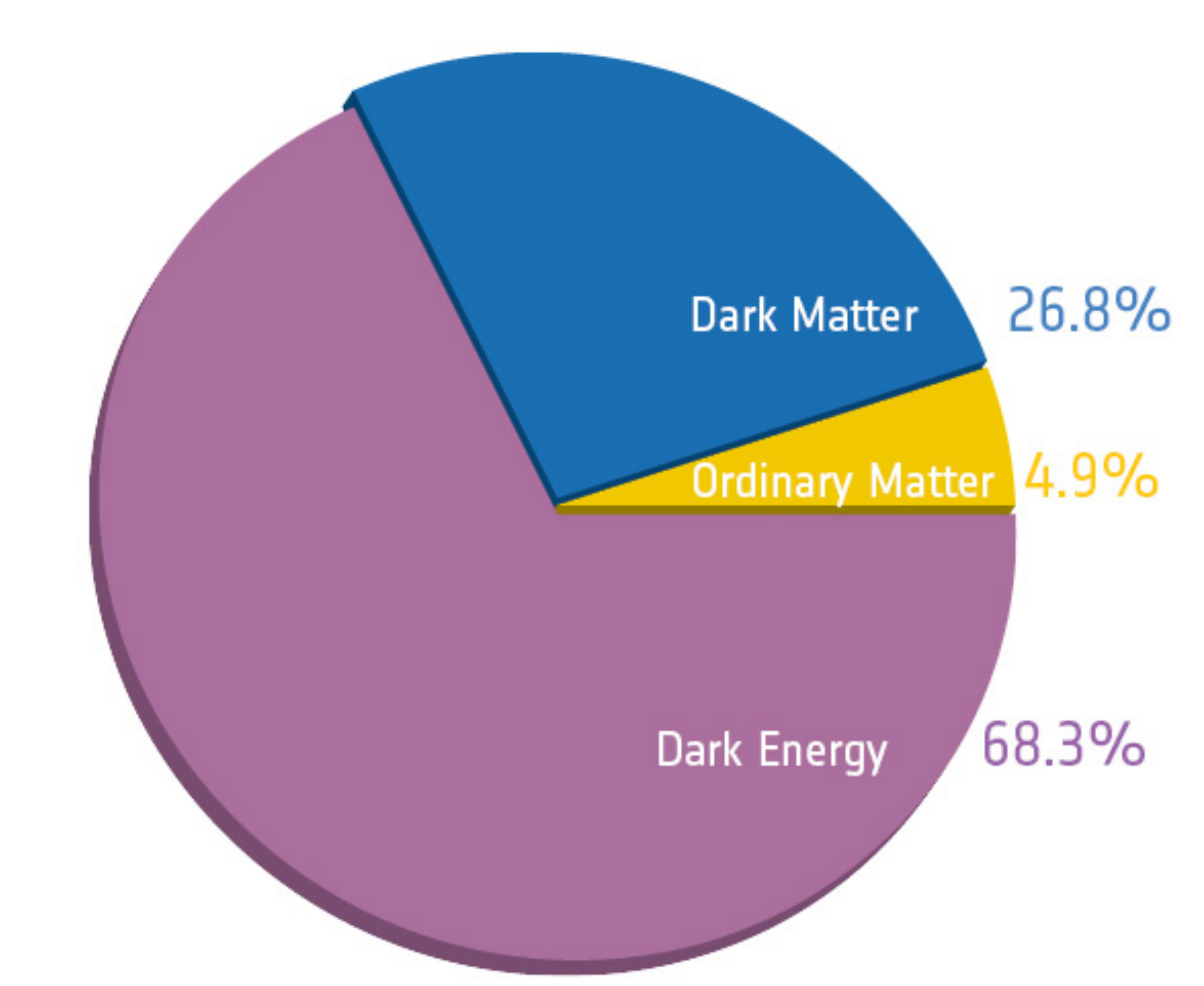
Nucleosynthesis



Dark Matter properties

- stable 1407.2418
- electrically neutral, interacts weakly with SM 1011.2907
- non-relativistic ("cold")
- non-baryonic
- probably "matter" (not modified gravity)
- can't consist solely of dark astronomical objects (MACHO)*

*see 1906.08217, 2402.00212 for a different argument



ESA, Planck

➡ Look for stable weakly interacting massive BSM particles

Dark Matter candidates

10^{-22} eV — peV — meV — keV — GeV — TeV — PeV — 10^{66} eV $\sim 5M_{\odot}$

Fuzzy DM

QCD axion

Axion-Like Particles

Thermal WIMPs

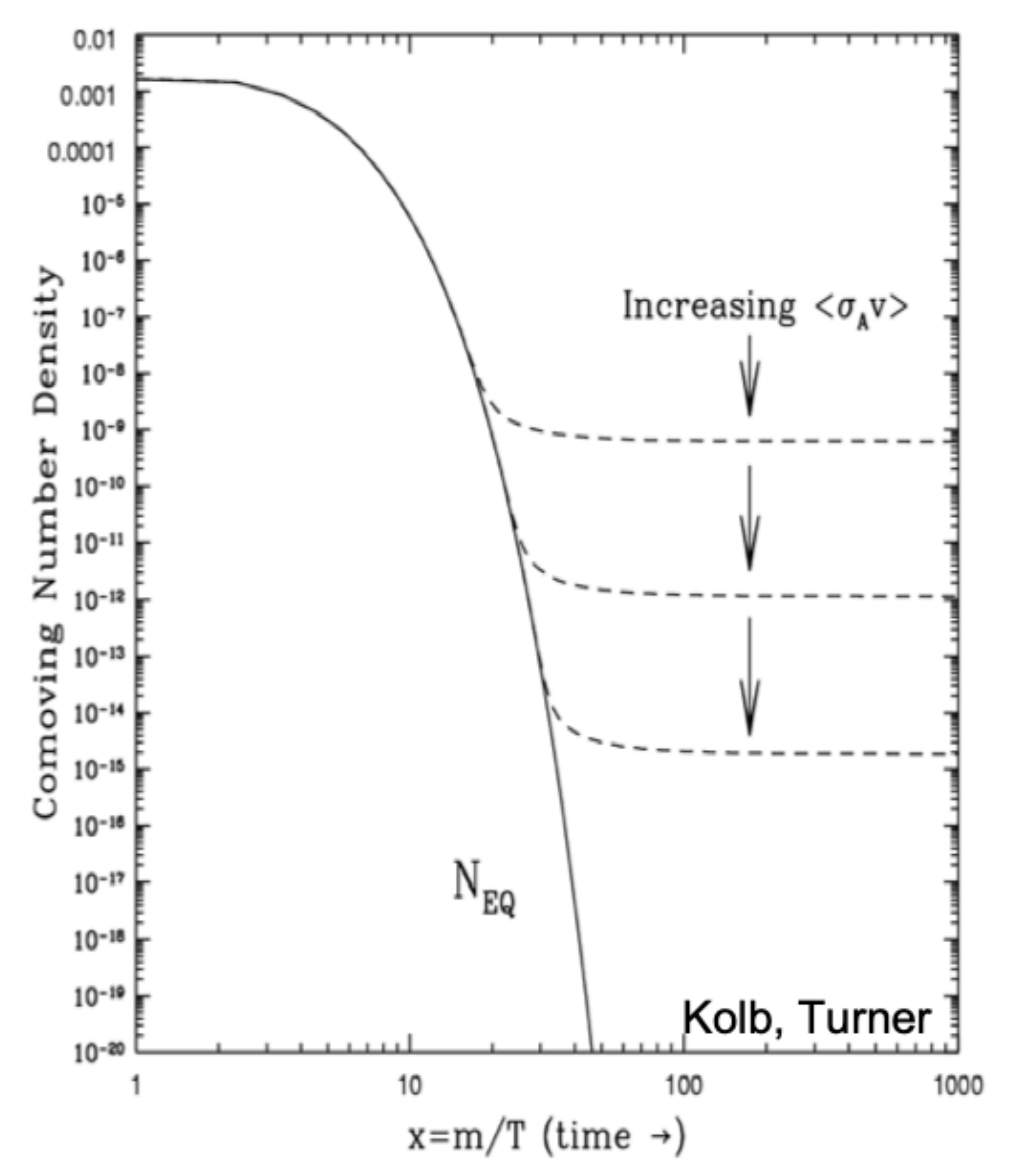
Primordial Black Holes

Hidden Sector DM / Freeze-in

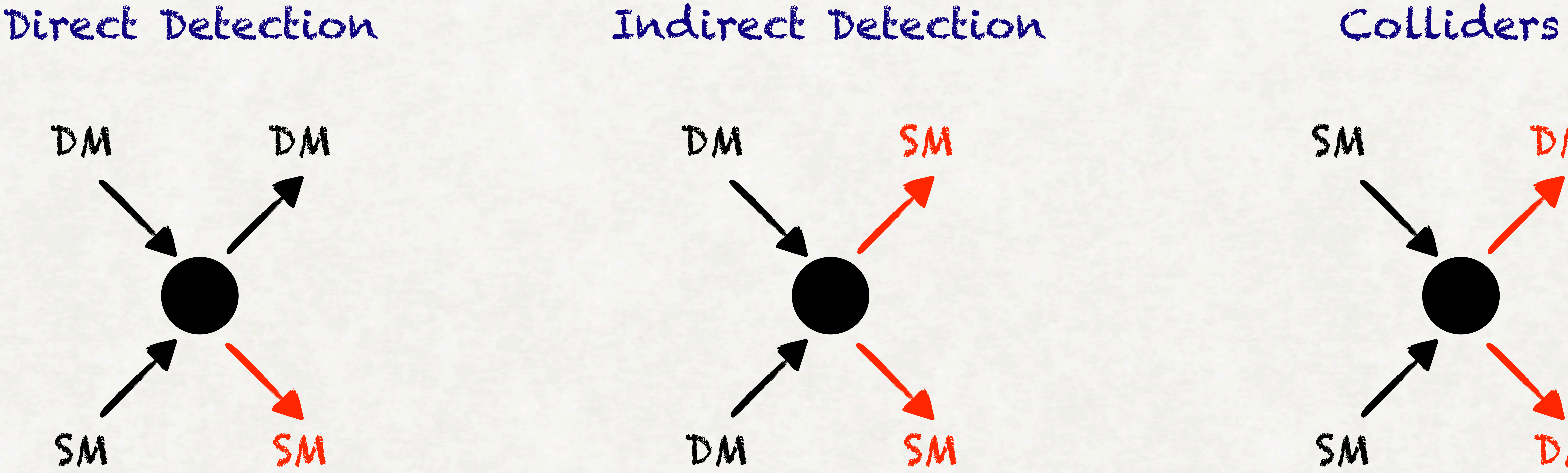
- many (well motivated) options and parameter space is vast
- in the following I will assume DM = thermal WIMPs

Thermal WIMPs

- WIMPs produced at thermal equilibrium $f\bar{f} \rightleftarrows \chi\bar{\chi}$ at high temperatures T_0 (end of inflation)
- As temperature cools down interaction falls out of equilibrium
- Comoving density freezes out at $T_F \ll T_0$
- Relic density $\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$
- WIMP miracle: for particles of mass close to weak scale and interaction strength close to weak scale we get the correct relic abundance
- NB1: Assumptions about cosmological history can change the picture!
- NB2: non-perturbative effects can also change the picture!

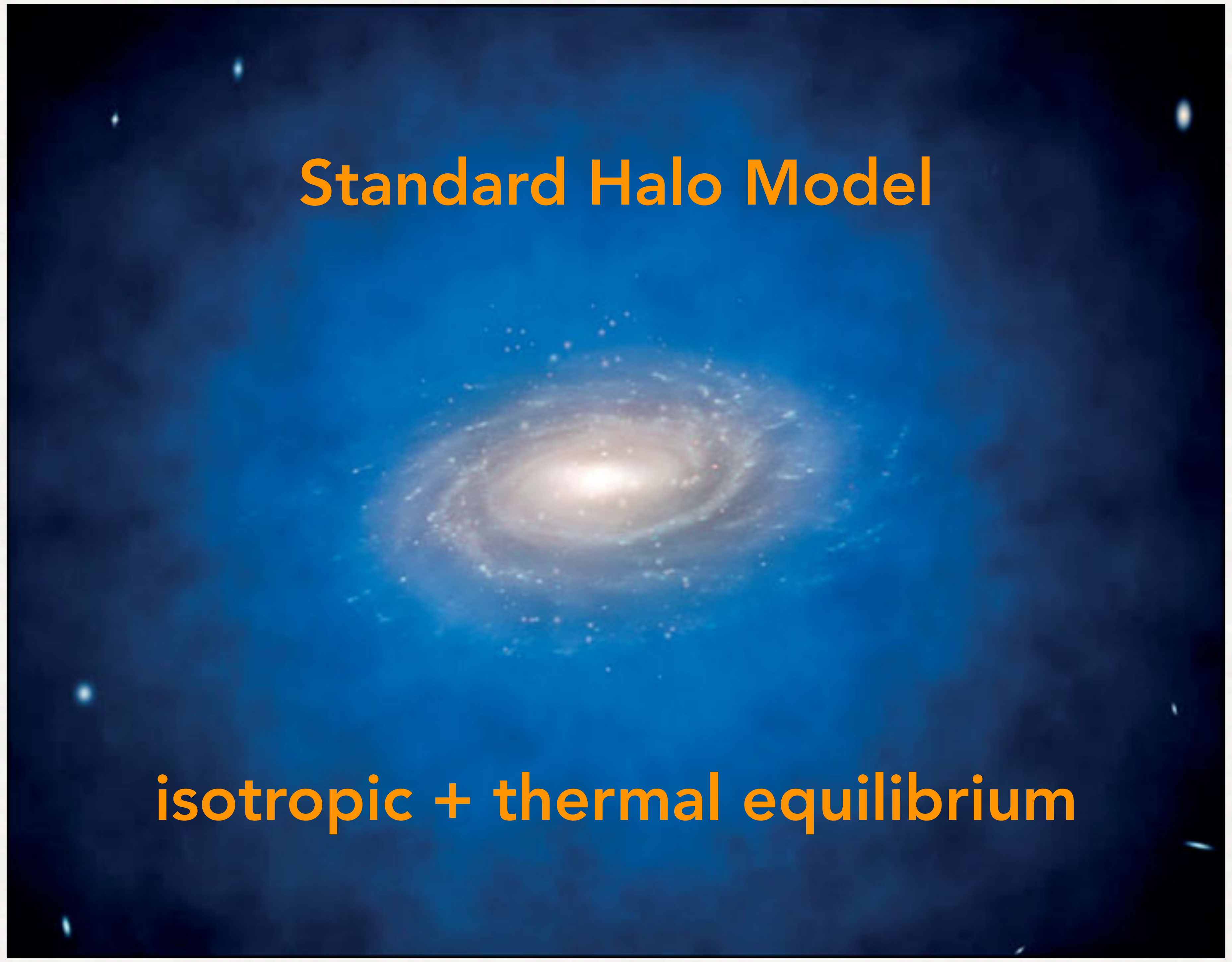


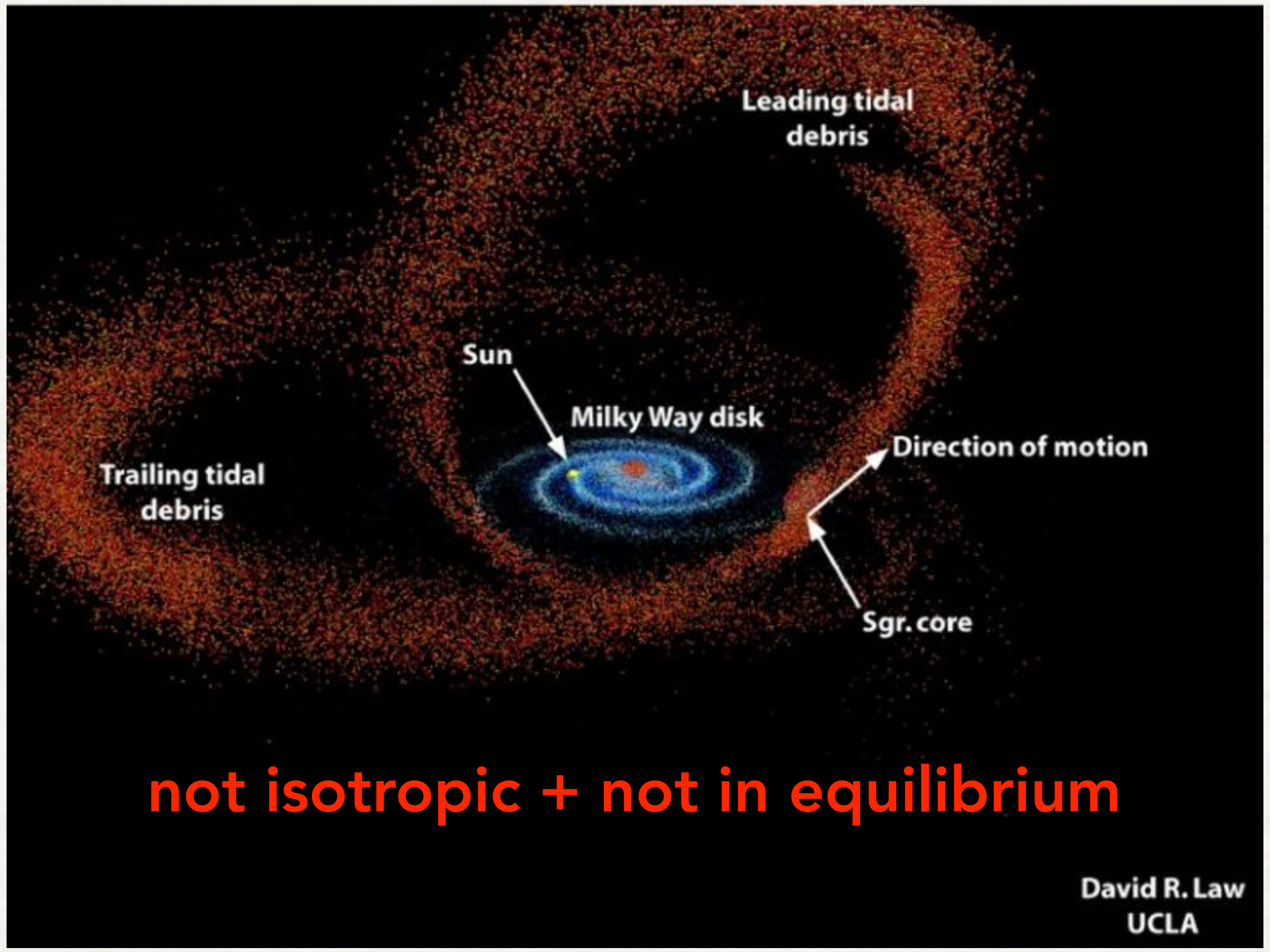
How do we look for Dark Matter?



+ axion searches (which I will not cover at all)

Why colliders?





- ➡ Controlled environment
- ➡ Independent of assumptions about DM distribution & propagation in interstellar space

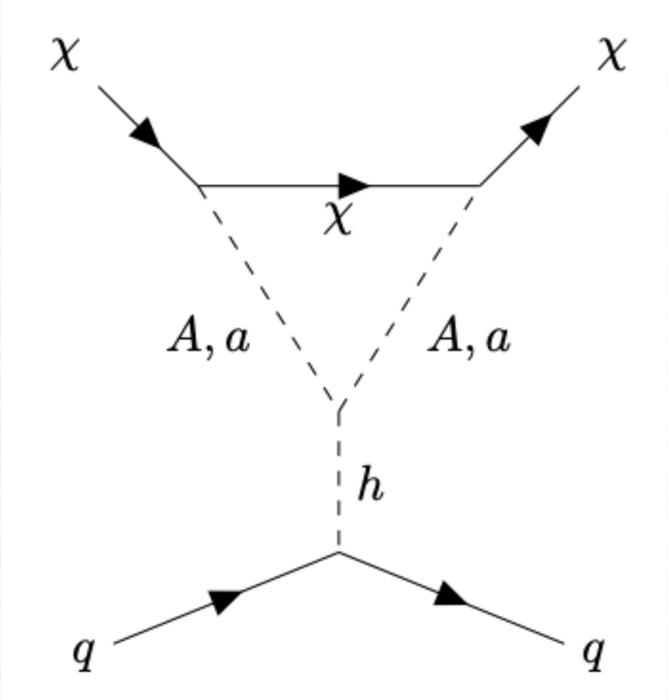
Purcell et al, JCAP 08(2012) 027 ; Bozorgnia et al, JCAP 07 (2020) 036 ; Necib et al, Nature Astron. 4 (2020) 11

Why colliders?

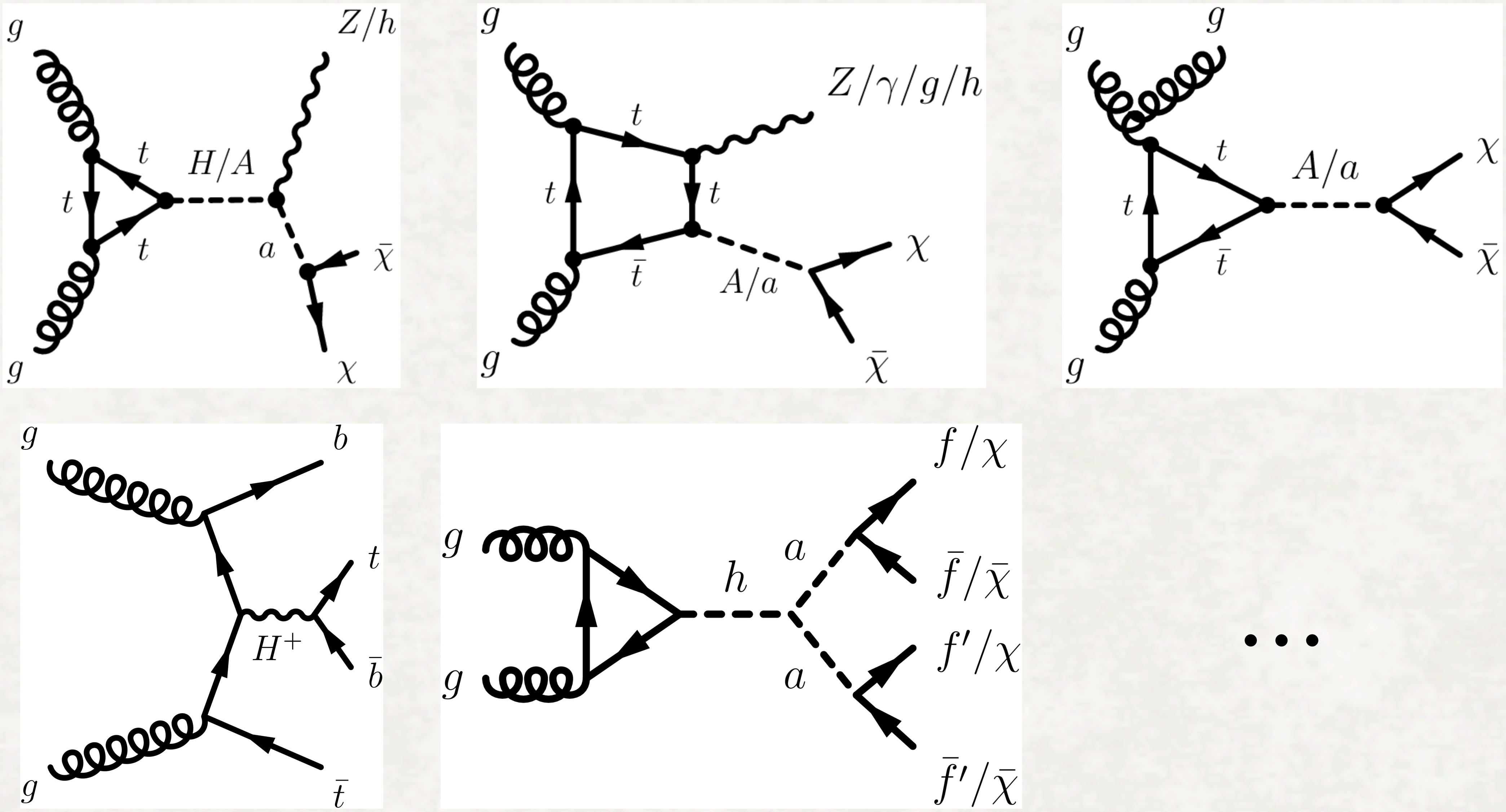
- particle factories - probe vast range of interactions & energy scales

- need various approaches: DD/ID signatures might vanish in certain parameter regions - might only be visible at colliders

Direct Detection



Colliders



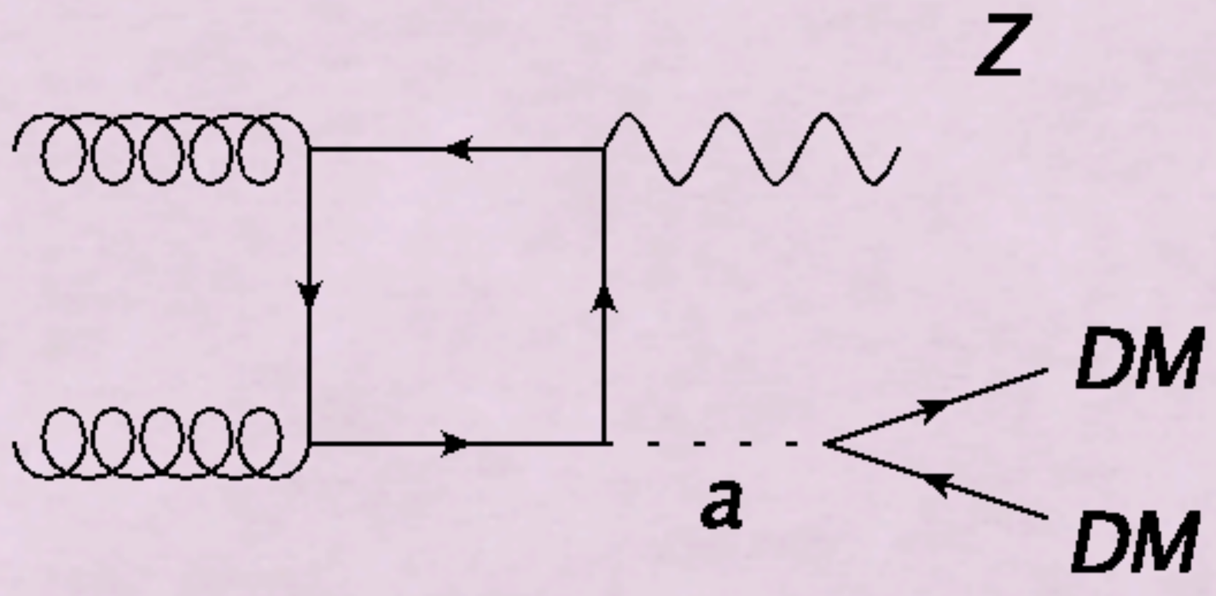
Types of DM models

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c}{\Lambda^{d-4}}\mathcal{O}^{(d)}_{\rm DM}$$

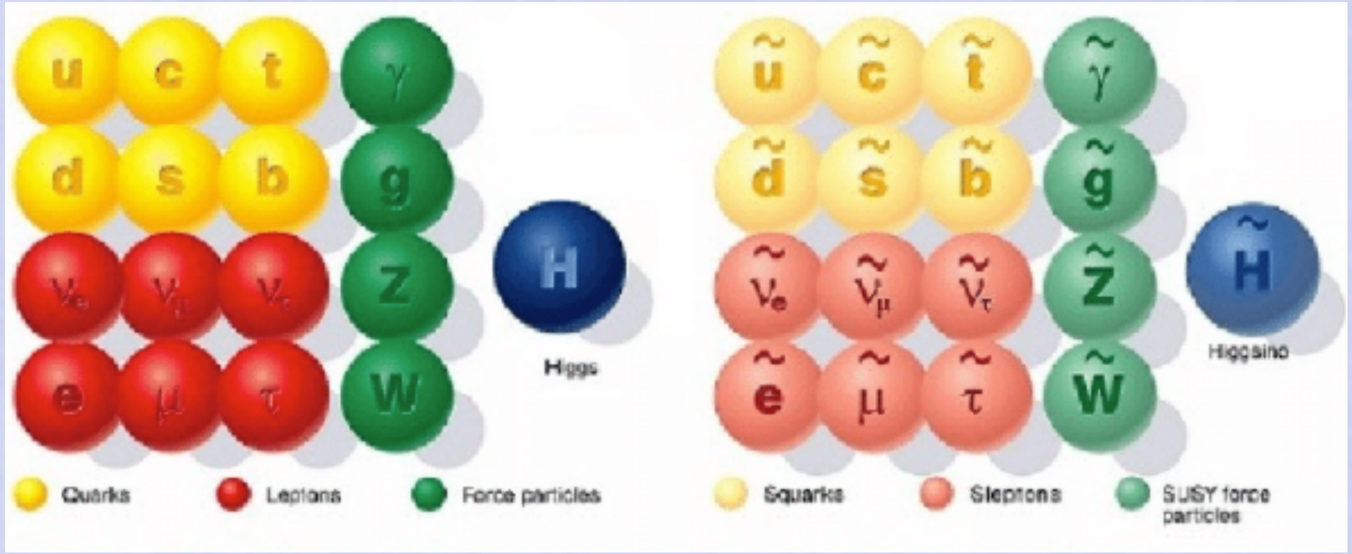
✓ 1 parameter (Λ)
✗ problematic at high energies
✗ used only in Run 1

Simplified



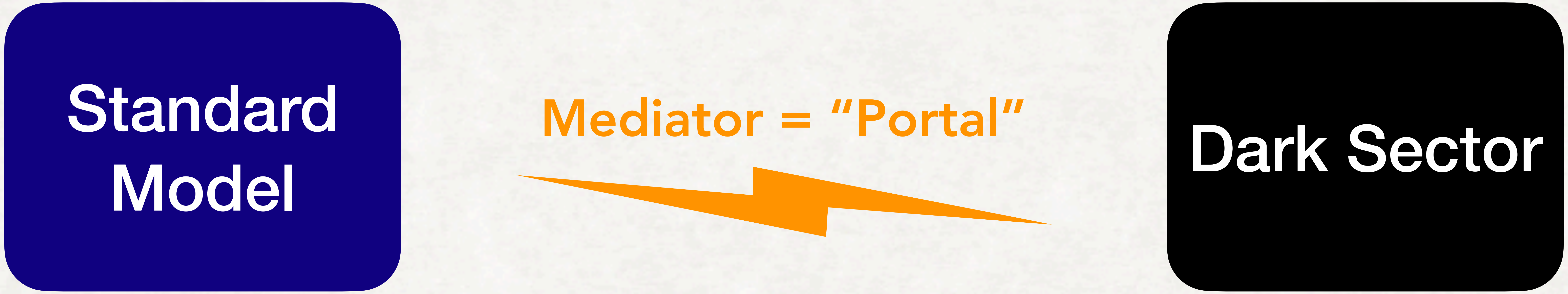
✓ very few parameters
✓ minimal particle content

Complete



- e.g. MSSM
- several new particles

✓ predictions for everything
✗ ≳ 20 parameters
✗ very hard to constrain



Types of portals I will discuss today:

1. SM Higgs
2. s-channel (single colourless mediator)
3. t-channel (coloured mediators)
4. Extended Higgs sector
5. Extended Higgs + gauge sector

for more models see [SA, Brandt, Haisch, Symmetry 2021 13 (12) 2406]

1. The SM Higgs portal

The SM Higgs portal

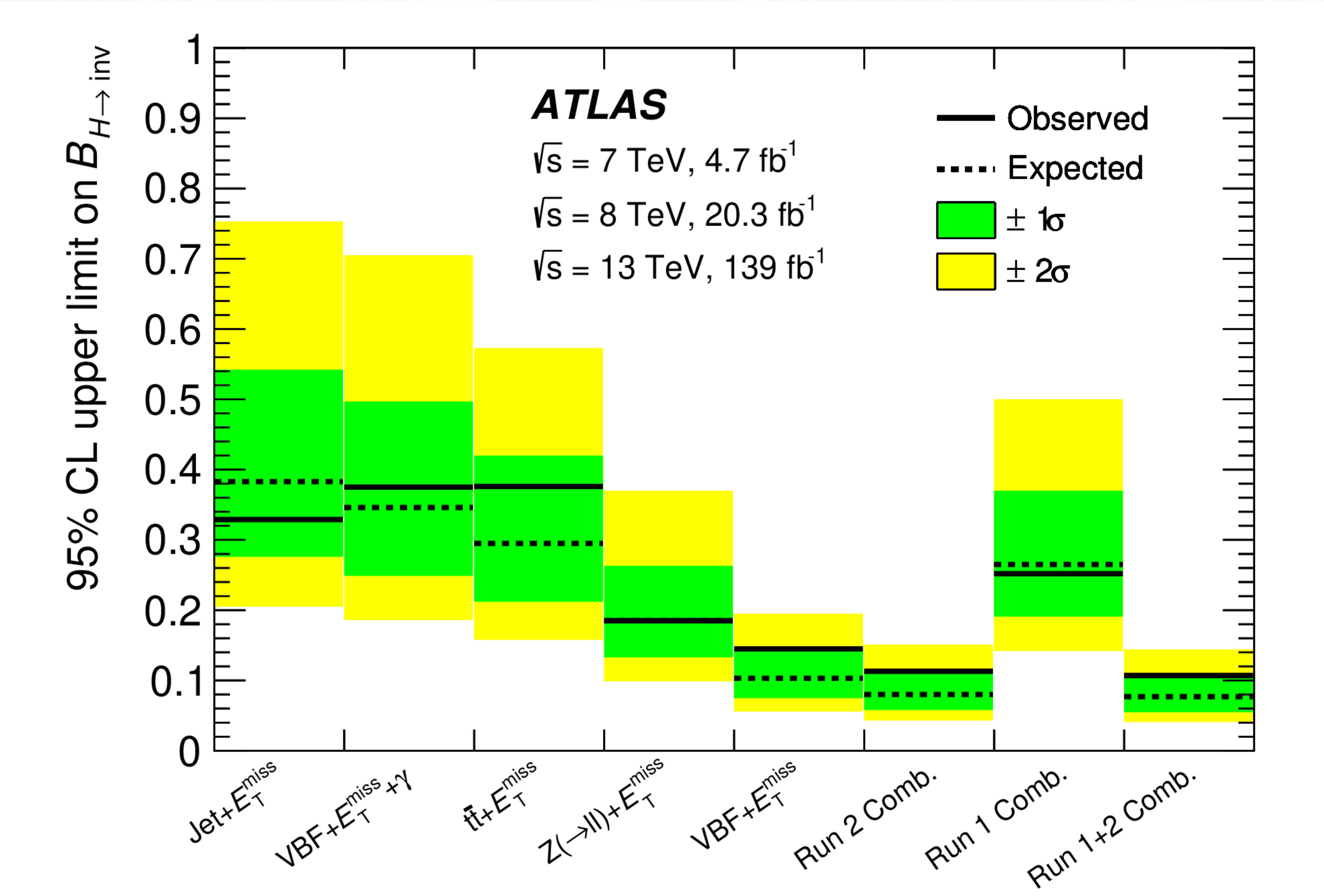
- We know that DM should be colourless & electrically neutral
- If DM corresponds to a single field

➡ **SM singlet → can only couple to SM via SM Higgs boson**

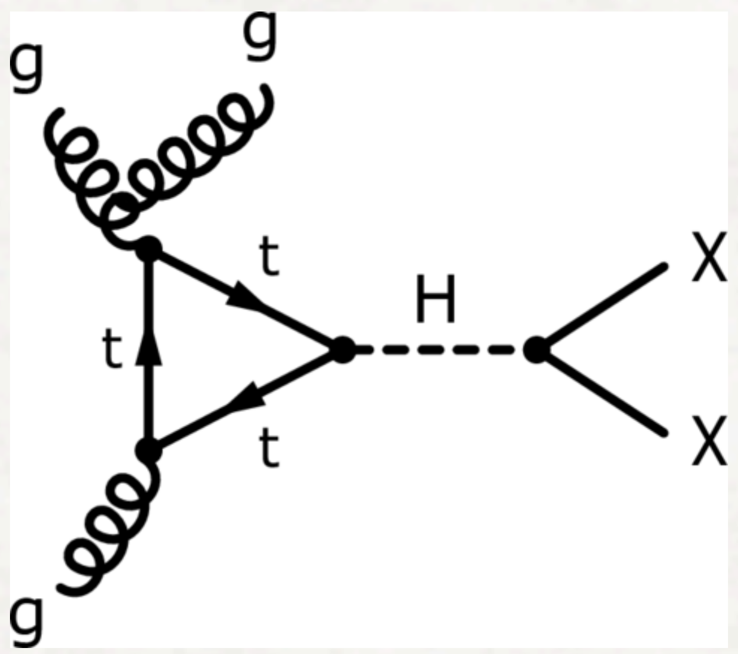
Possible couplings

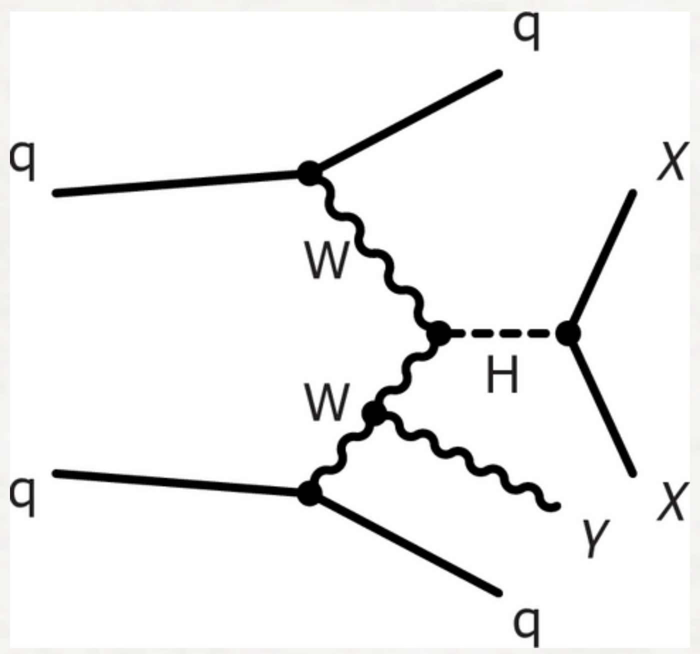
- **scalar**: $\mathscr{L} \supset \lambda_{h\phi\phi} H^\dagger H \phi^2$: renormalisable
- **fermion**: $\mathscr{L} \supset \frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi}\chi$
  - manifestly non-renormalisable
  - can be UV-completed with a scalar singlet or with extra fermions [2101.02507]
- **vector**: $\mathscr{L} \supset \lambda_{hVV} H^\dagger H V_\mu V^\mu$
  - violates unitarity since it lacks "dark Higgs" that would generate V_μ mass
  - various UV completions suggested [Arcadi et al, 2101.02507, DiFranzo et al, 1512.06853.pdf]

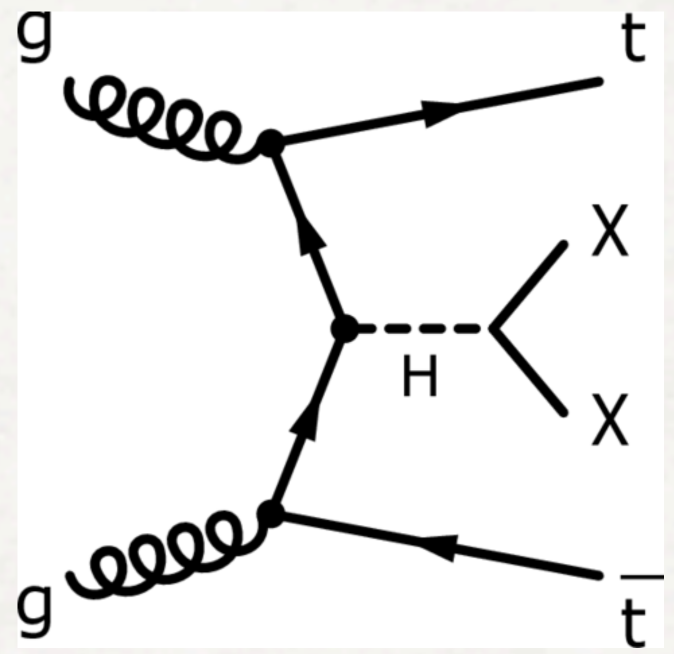
Higgs to invisible

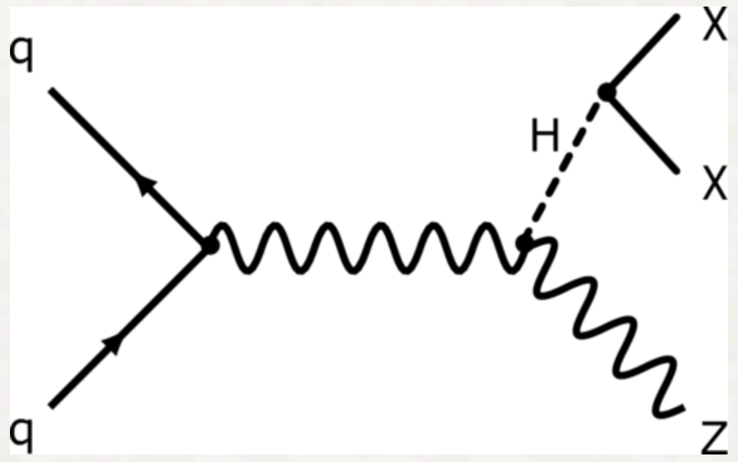


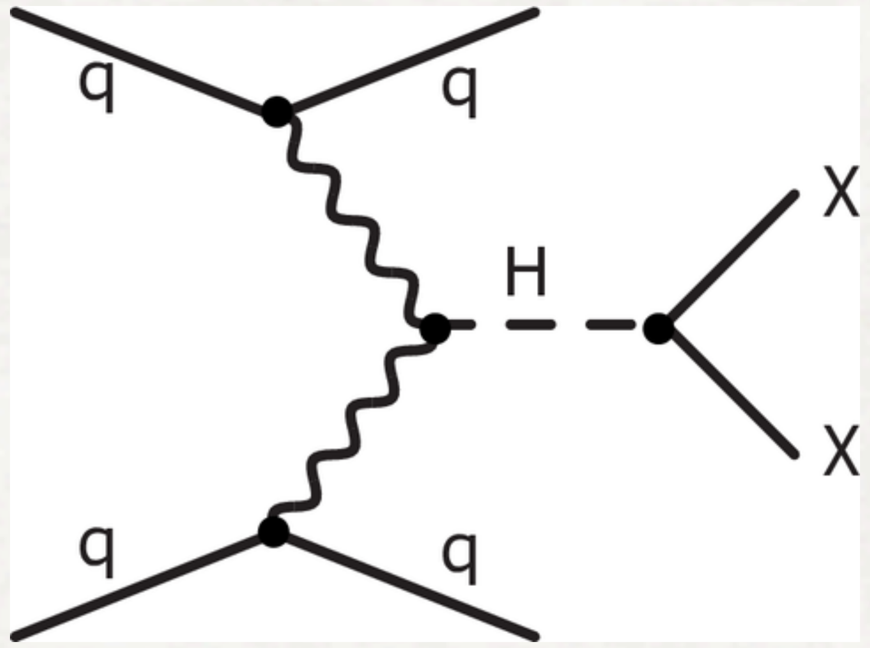
Phys. Lett. B 842 (2023) 137963









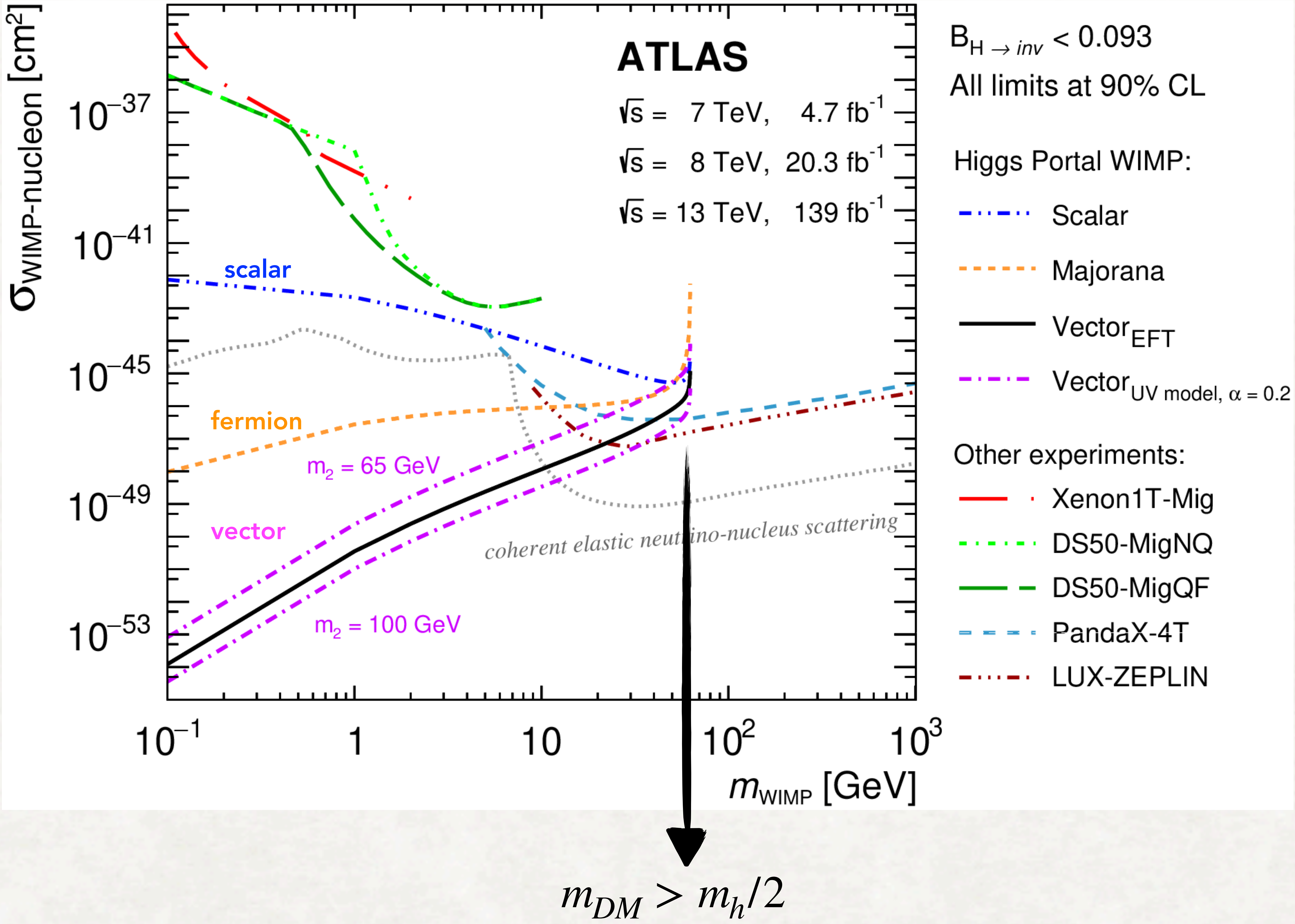


ATLAS combination: $\mathrm{BR}(h \to \mathrm{inv}) < 10.7\ (7.7)\,\%$ obs (exp)

CMS combination: $\mathrm{BR}(h \to \mathrm{inv}) < 15\ (8)\,\%$ obs (exp)

Interpretation

Phys. Lett. B 842 (2023) 137963



➡ colliders complement DD at low masses

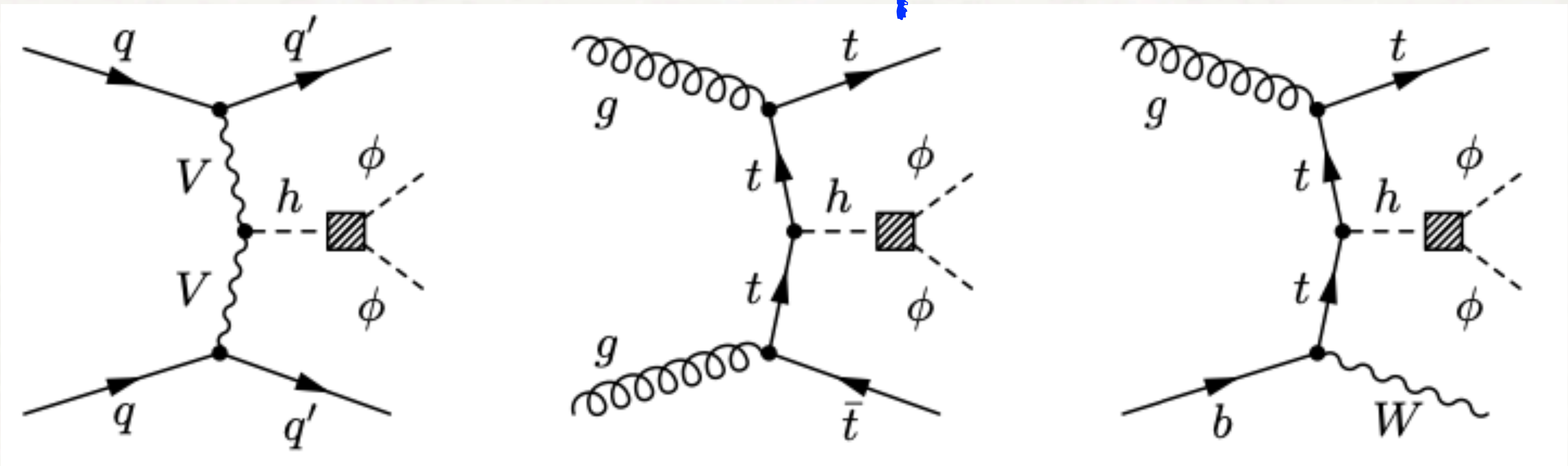
➡ no collider sensitivity when $m_{DM} > m_h/2$

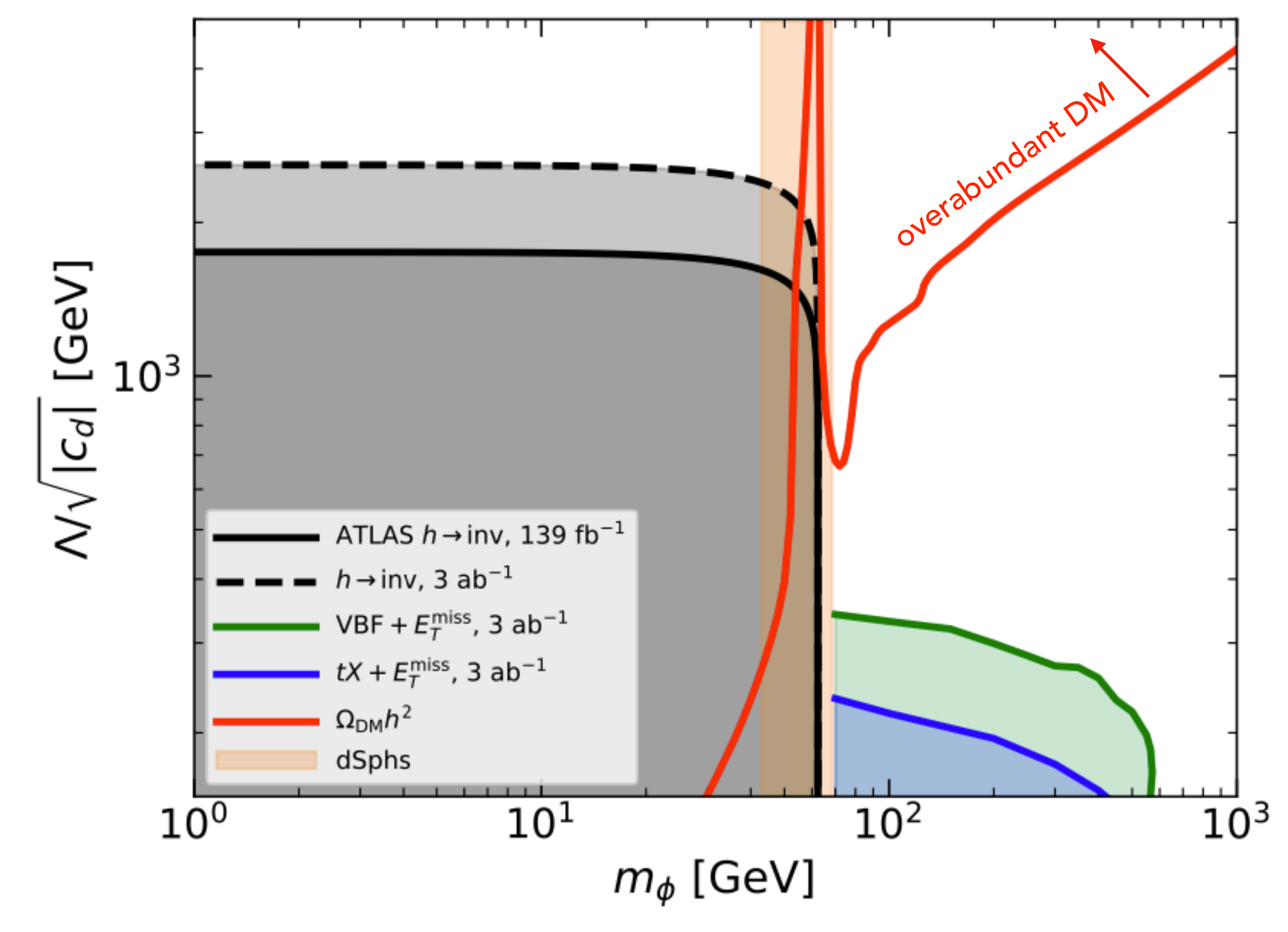
Derivative Higgs portal

$$\mathscr{L} \supset \frac{c_d}{\Lambda^2}\left(\partial_\mu \phi^2\right)\left(\partial^\mu (H^\dagger H)\right)$$

- Derivative interactions arise in theories with pNGB → composite Higgs
- DD cross-section momentum-suppressed - essentially DD constraints disappear
- Colliders offer the only possibility to probe this
  - $m_{DM} < m_h/2$: Higgs to invisible
  - $m_{DM} > m_h/2$: off-shell VBF Higgs + E_T^{miss} and potentially top + X + E_T^{miss}

VBF+E_T^{miss} top+X+E_T^{miss}





SA, Brandt, Haisch, Symmetry 13 (2021) 2406

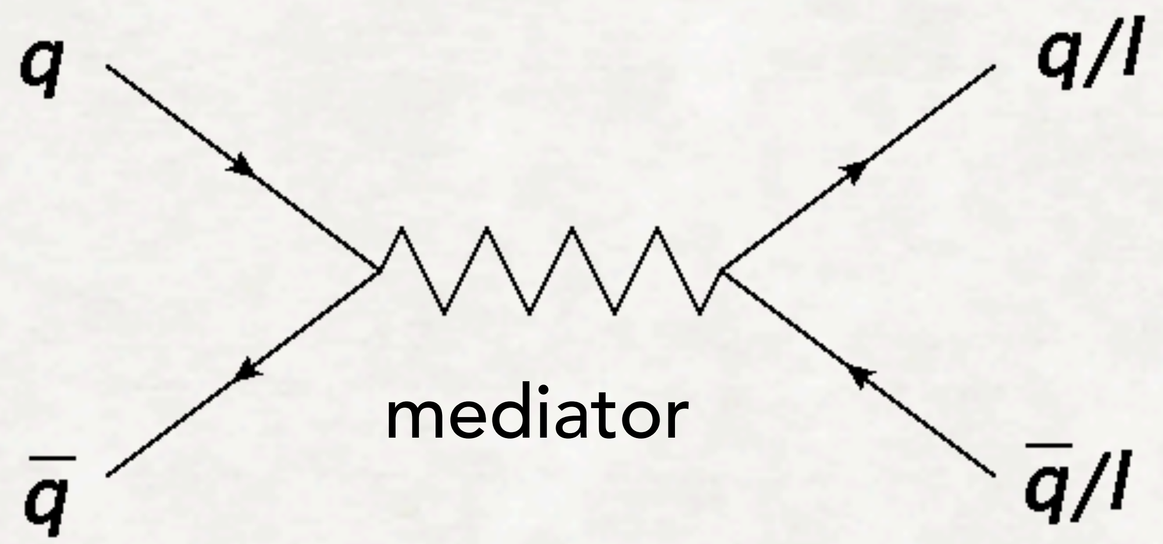
Rudhofer et al, 1910.04170; Haisch et al, 2107.12389

2. s-channel models

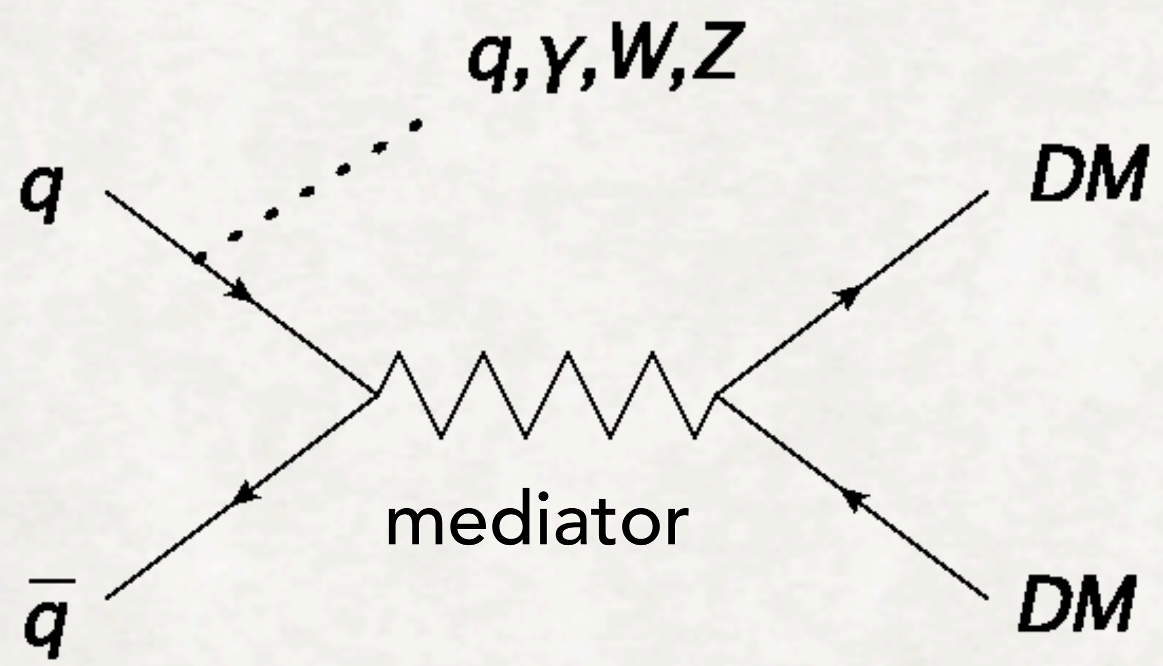
s-channel models

- Developed at the end of Run 1 to **overcome issues of DM EFT** theories
- Introduce a **single mediator** coupling SM-DM - 4 possibilities
  - scalar, pseudo-scalar, vector, axial vector
- Parameters: $g_{\rm DM}, g_{\rm SM}, m_{\rm med}, m_{\rm DM}$

Resonant signature



E_T^{miss} + X



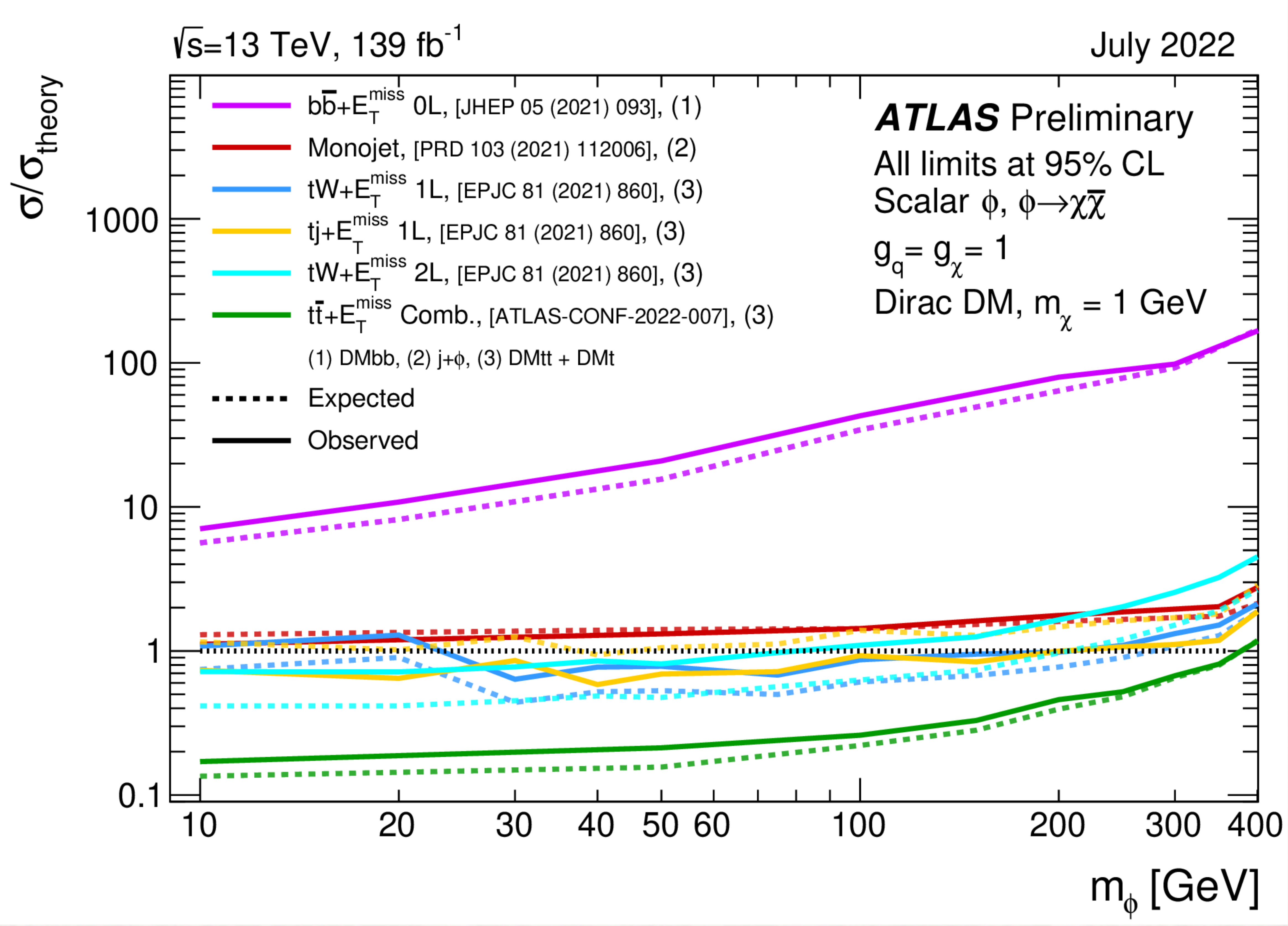
Mediators	Couplings		
	DM	Quarks	Leptons
Scalar	1	1	1
Pseudo-scalar	1	1	1
Vector 1	1	0,25	0
Vector 2	1	0,1	0,01
Axial vector 1	1	0,25	0
Axial vector 2	1	0,1	0,1

Phys. Dark Univ. 26 (2019) 100371
Phys.Dark Univ. 27 (2020) 100365
Phys.Dark Univ. 26 (2019) 100377

Scalar + pseudo-scalar mediators

- Similar processes with $h \to \mathrm{inv}$
- Dominated by $t\bar{t} + E_T^{\mathrm{miss}}$ (since couplings are Yukawa-like) which stops at $2m_{\mathrm{top}}$
- searches for $t\bar{t}t\bar{t}$ and $t\bar{t}$ resonances can help to gain sensitivity for $m_{\mathrm{med}} > 2m_{\mathrm{top}}$
- Pseudoscalar mediator looks very similar

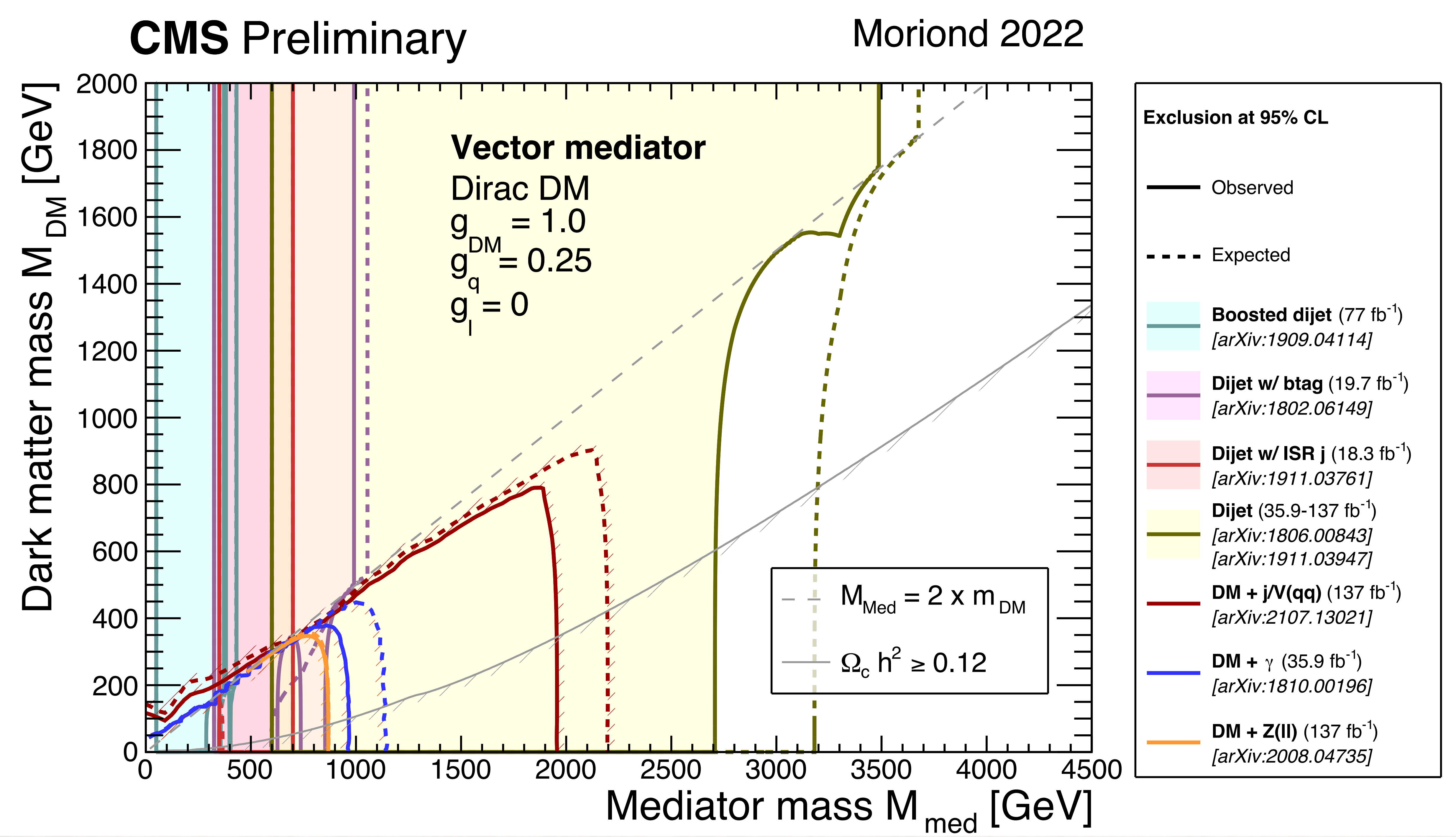
Scalar



ATL-PHYS-PUB-2022-036

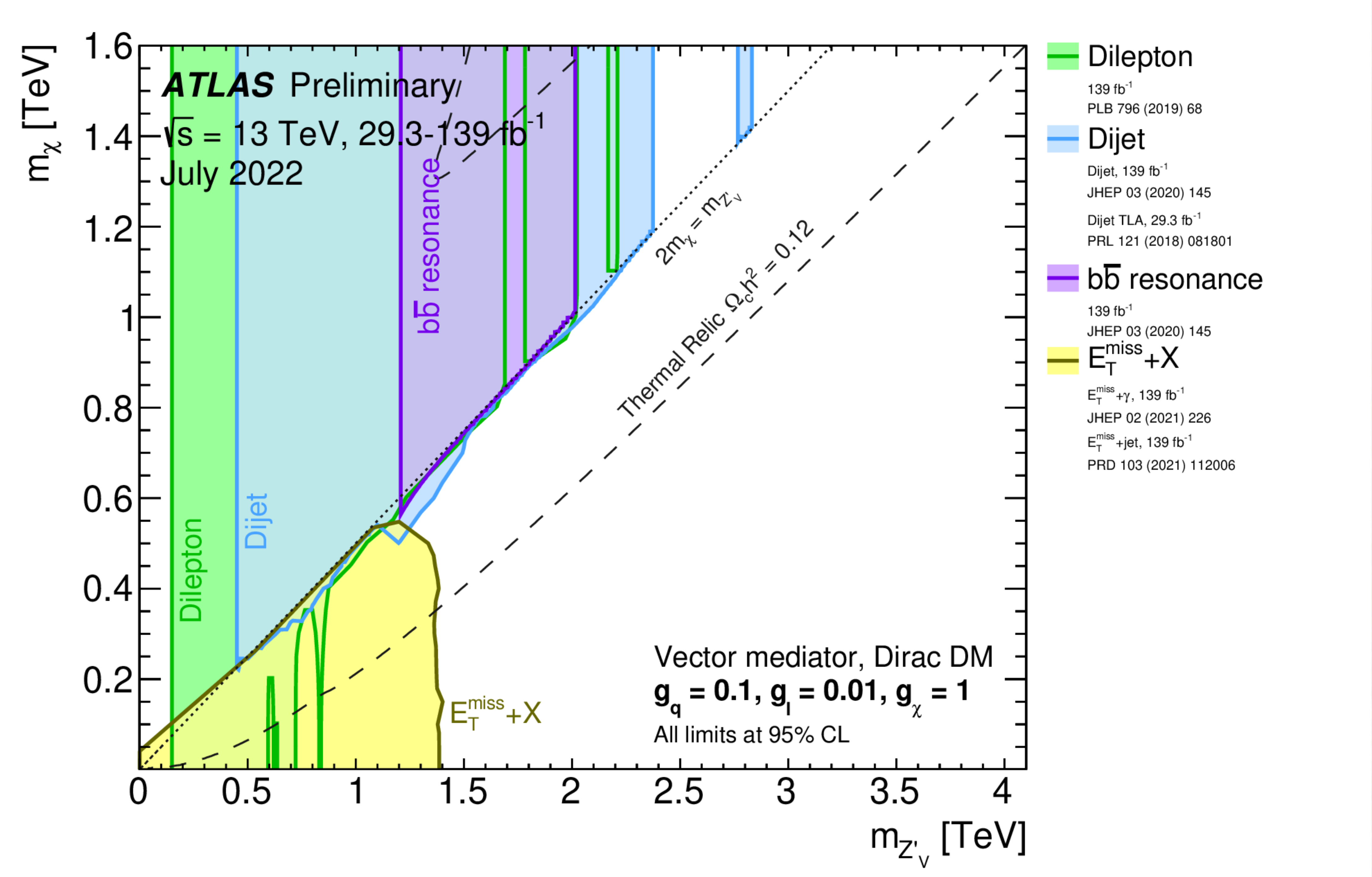
Vector mediators

Leptophobic



CMS Public plots

Coupling to leptons

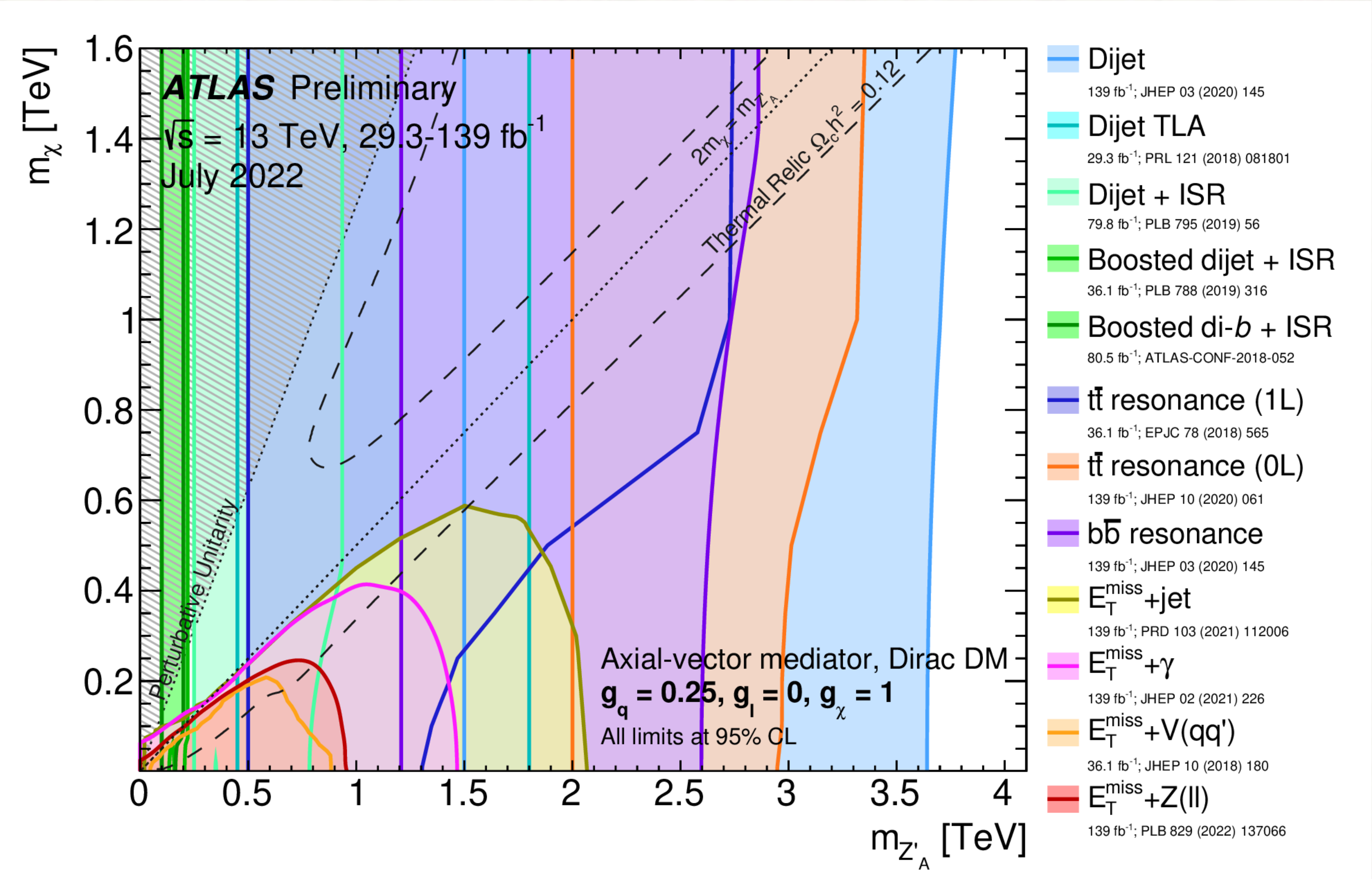


ATL-PHYS-PUB-2022-036

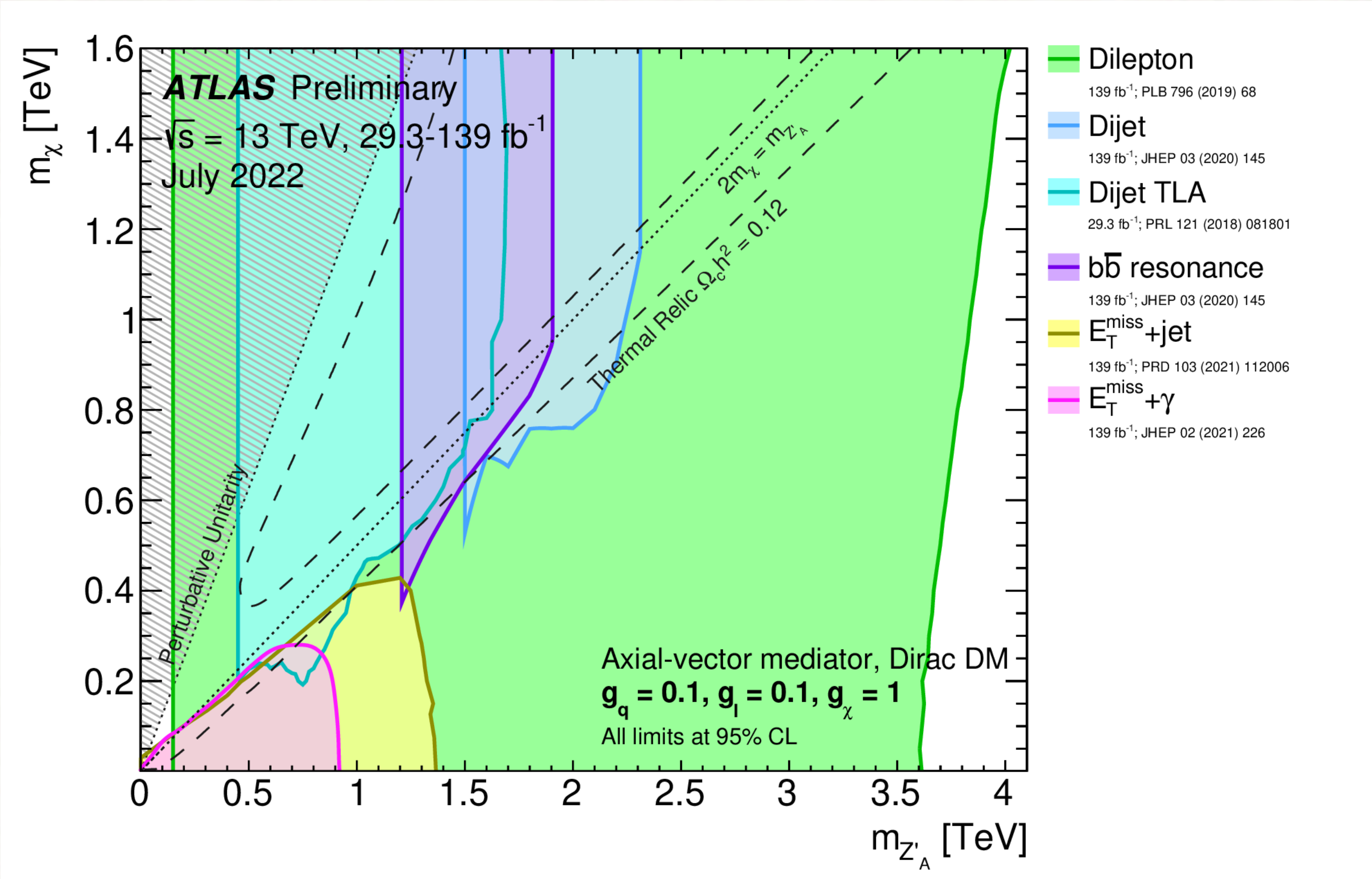
- Di-jet searches dominate in leptophobic scenario
- For non leptophobic scenarios several complementary signatures including $E_T^{\text{miss}} + X$ for $m_{\text{med}} > 2m_{\text{WIMP}}$

Axial-vector mediator

Lepto-phobic



Coupling to leptons



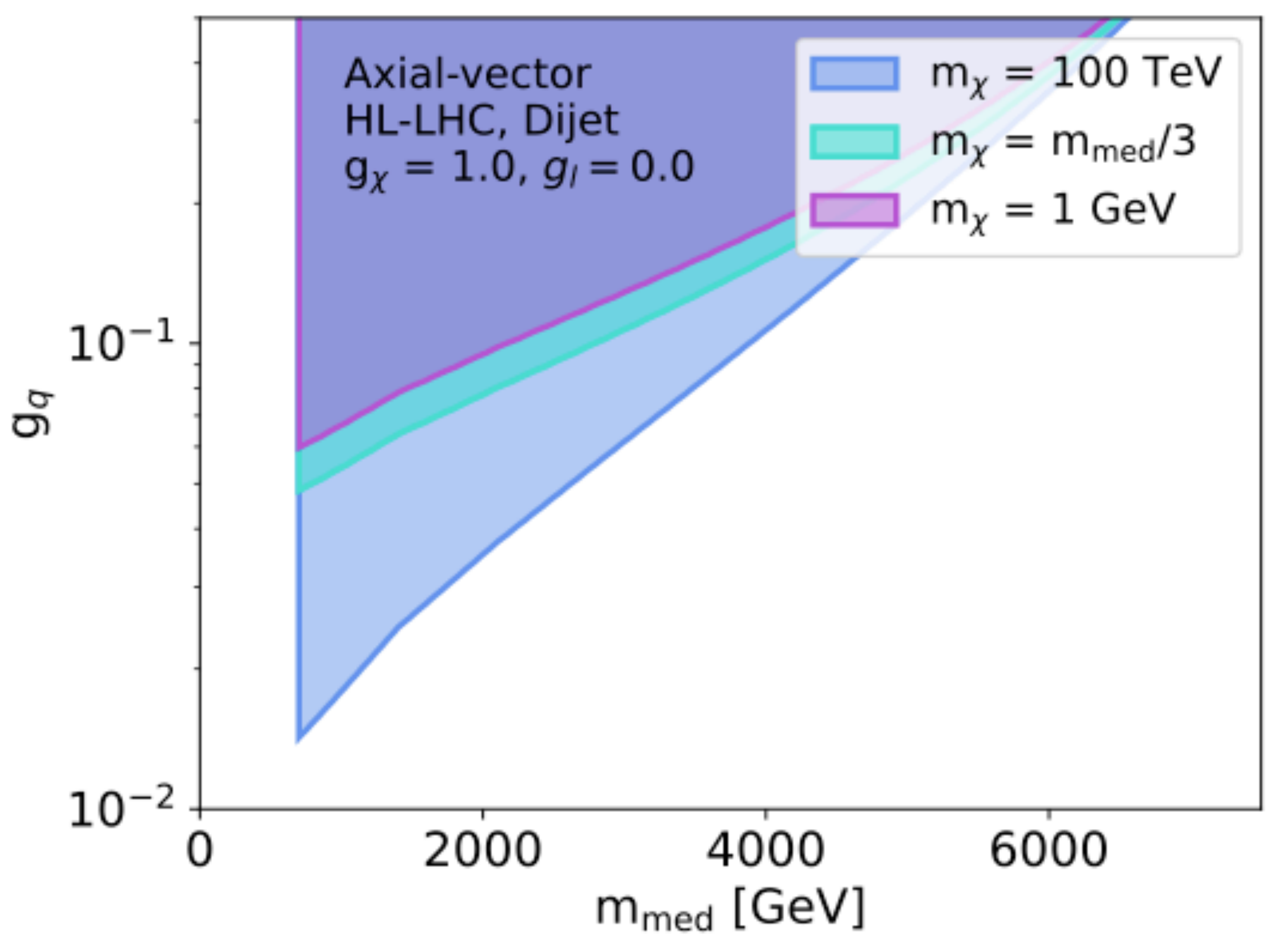
ATL-PHYS-PUB-2022-036

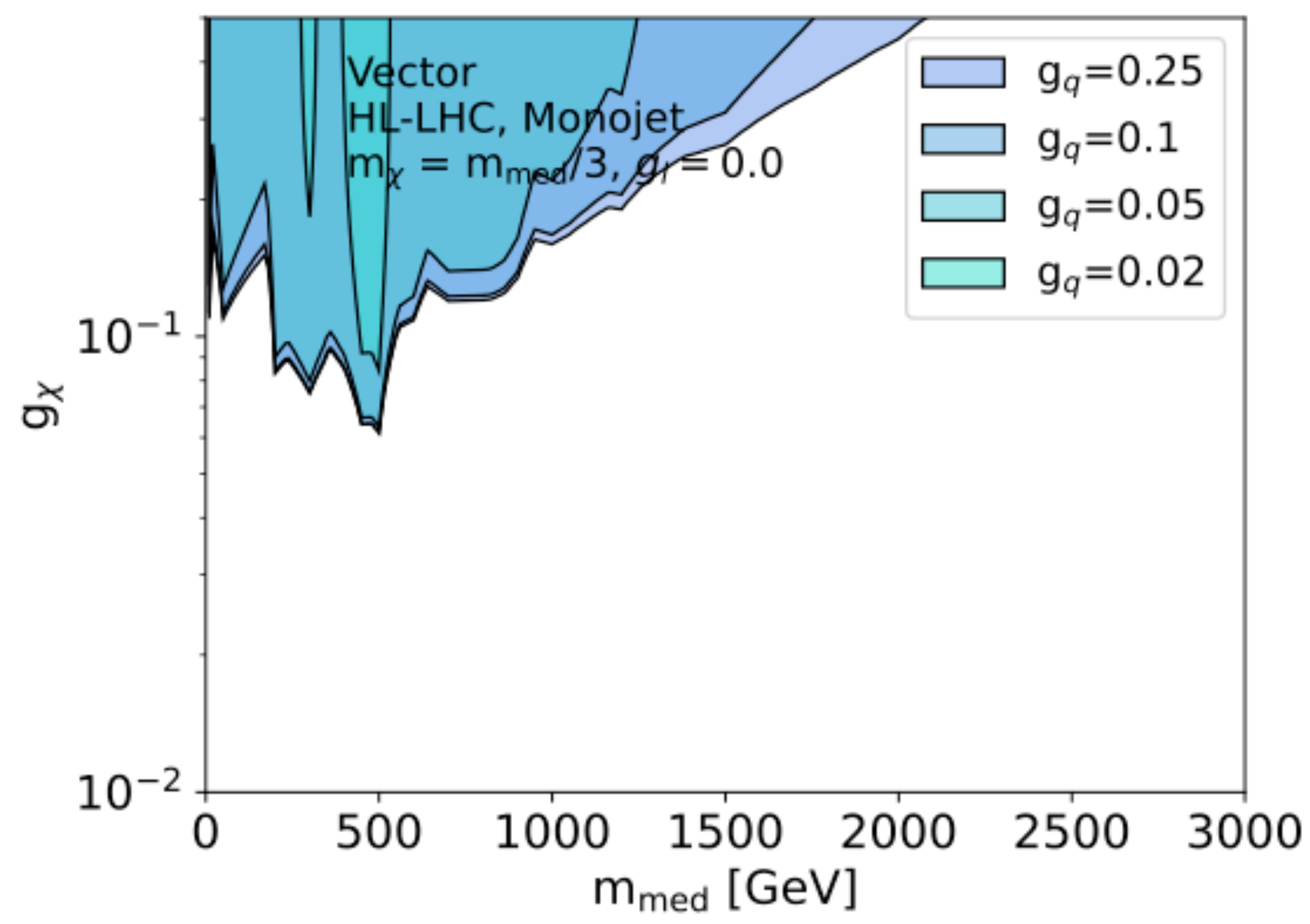
- For AV couplings non-leptophobic benchmark dominated by di-lepton constraints ($g_l = g_q$)
- Visible resonance searches generally dominate and $m_{\text{med}} \lesssim 3.5$ TeV excluded
- Narrow region where RD constraints can be satisfied

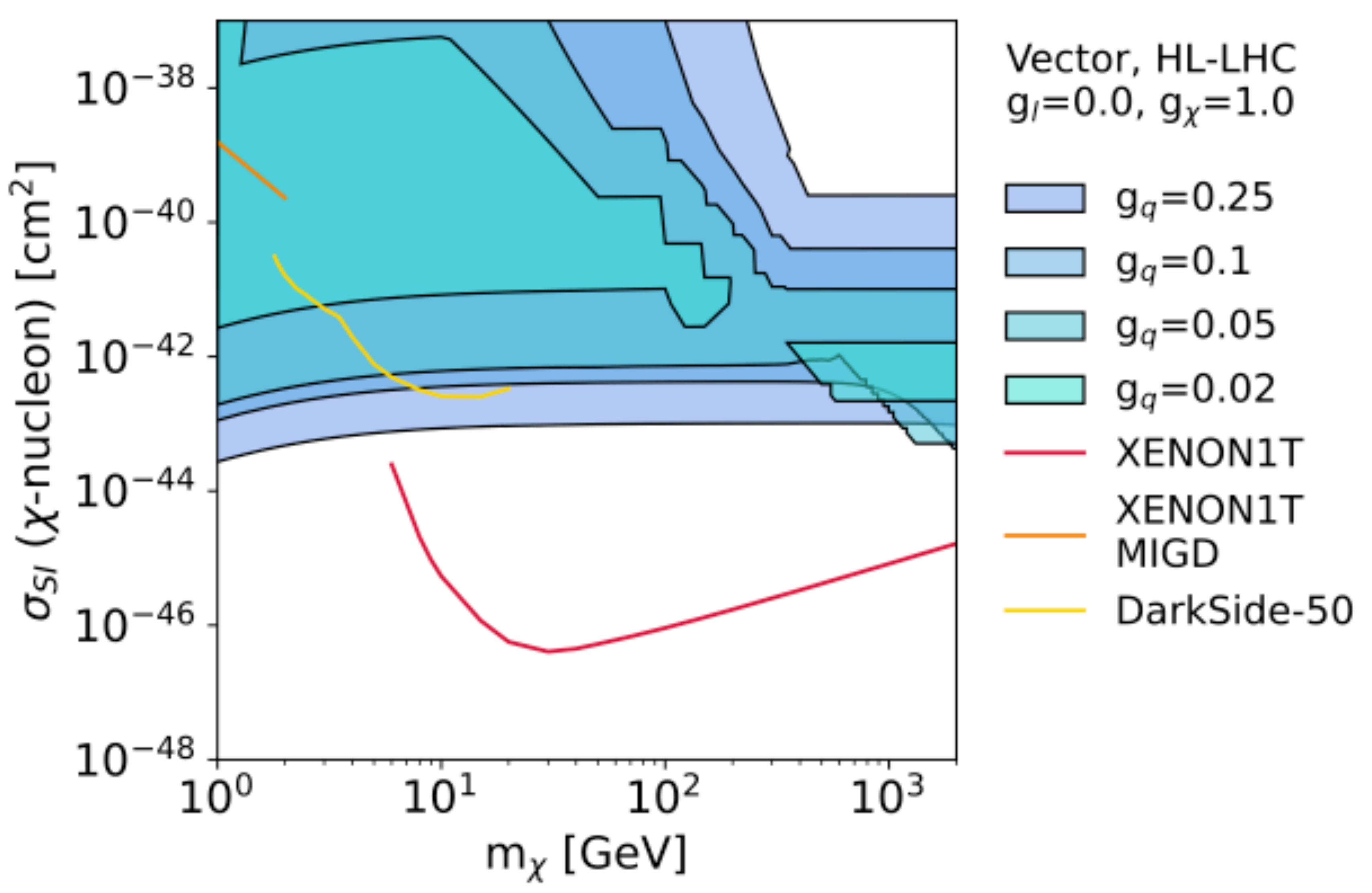
Re-interpretation tool

ATLAS+CMS developed **tool to rescale limits for V/AV s-channel models** *[2203.12035]*

- analytical rescaling from one set of $\{g_q, g_\chi\}$ couplings to another
- rescaling from vector to axial-vector including impact of PDFs







2206.03456

Translate published constraints to different parameter planes

➡ **facilitate comparison with DD experiments & PBC benchmarks** *2206.03456*

3. t-channel models

t-channel models

Basic properties of simplified DM models

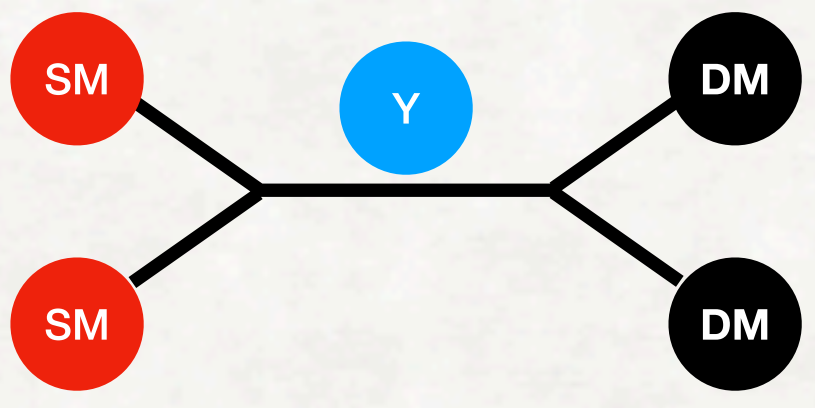
- $\mathbb{Z}_2$ symmetry makes DM stable (DM $\mathbb{Z}_2$-odd)
- **Mediator**
  - $\mathbb{Z}_2$-even → s-channel models (DM produced in pairs)
  - $\mathbb{Z}_2$-odd → t-channel models (DM can be produced singly)
  - also in t-channel mediator has to be coloured and electrically charged

MSSM: DM=neutralino, mediator=squark (gluinos decoupled)

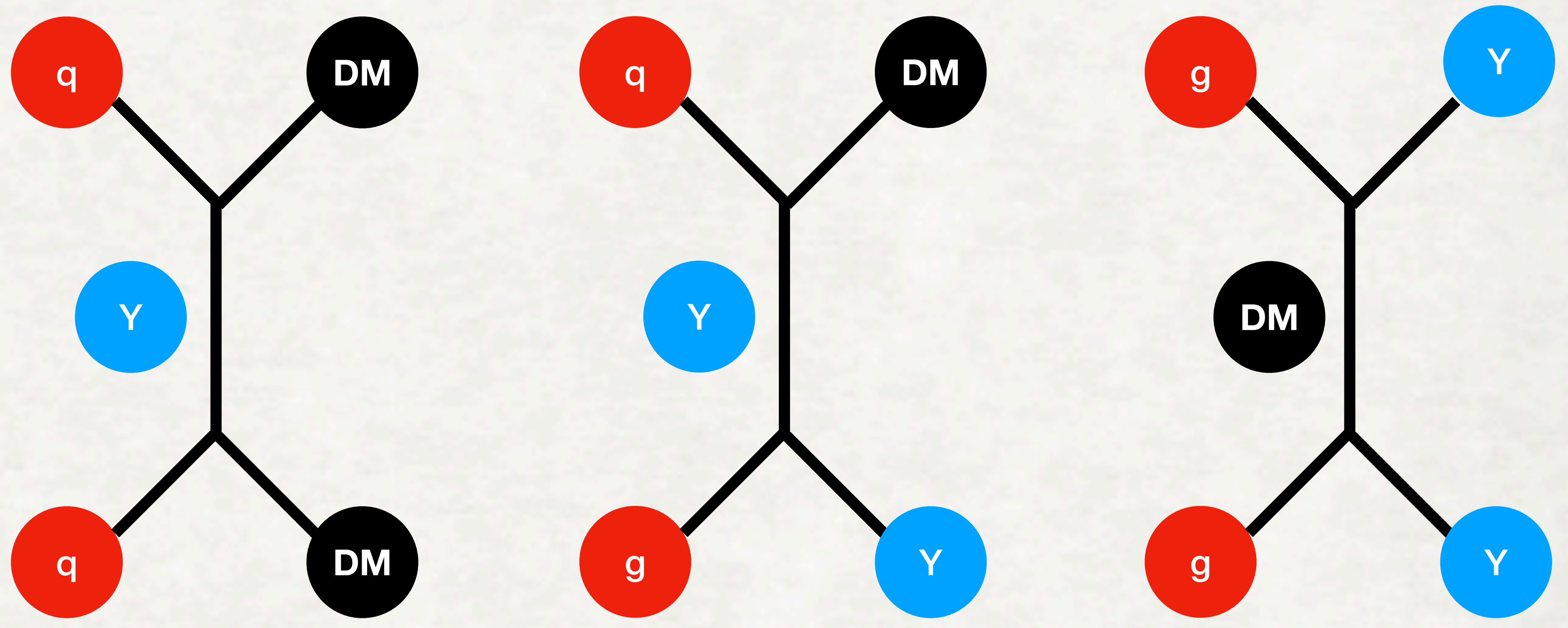
Various possibilities for spin/multiplet assignments →

Generic framework developed for handling all possible signatures → White paper with pheno in preparation

s-channel



t-channel



X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{S}$	0	yes	ψ_Q, ψ_u, ψ_d	1/2
S	0	no		
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0
χ	1/2	no		
$\tilde{V}_\mu$	1	yes	ψ_Q, ψ_u, ψ_d	1/2
V_μ	1	no		

Arina et al, PLB813 (2021) 136038
Arina, Fuks, Mantani, EPJC80 (2020) 5, 409

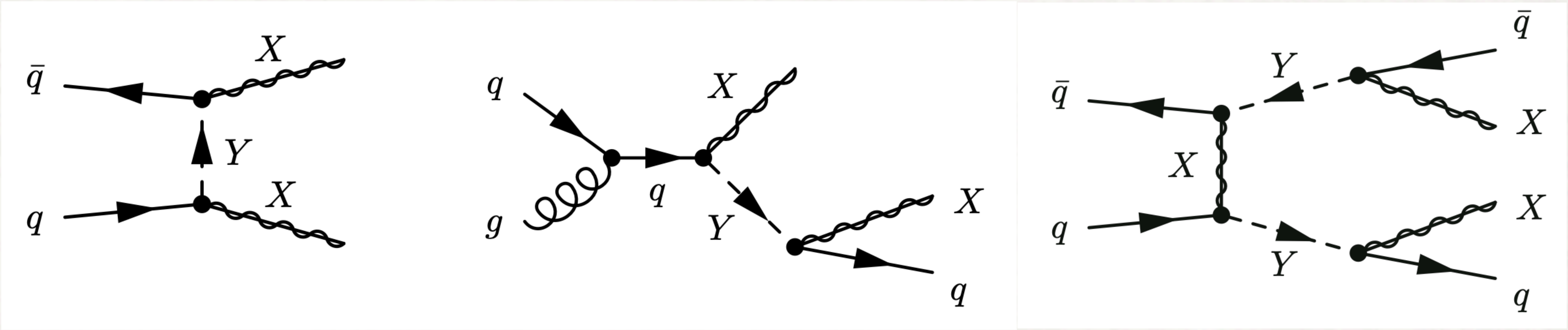
t-channel signatures

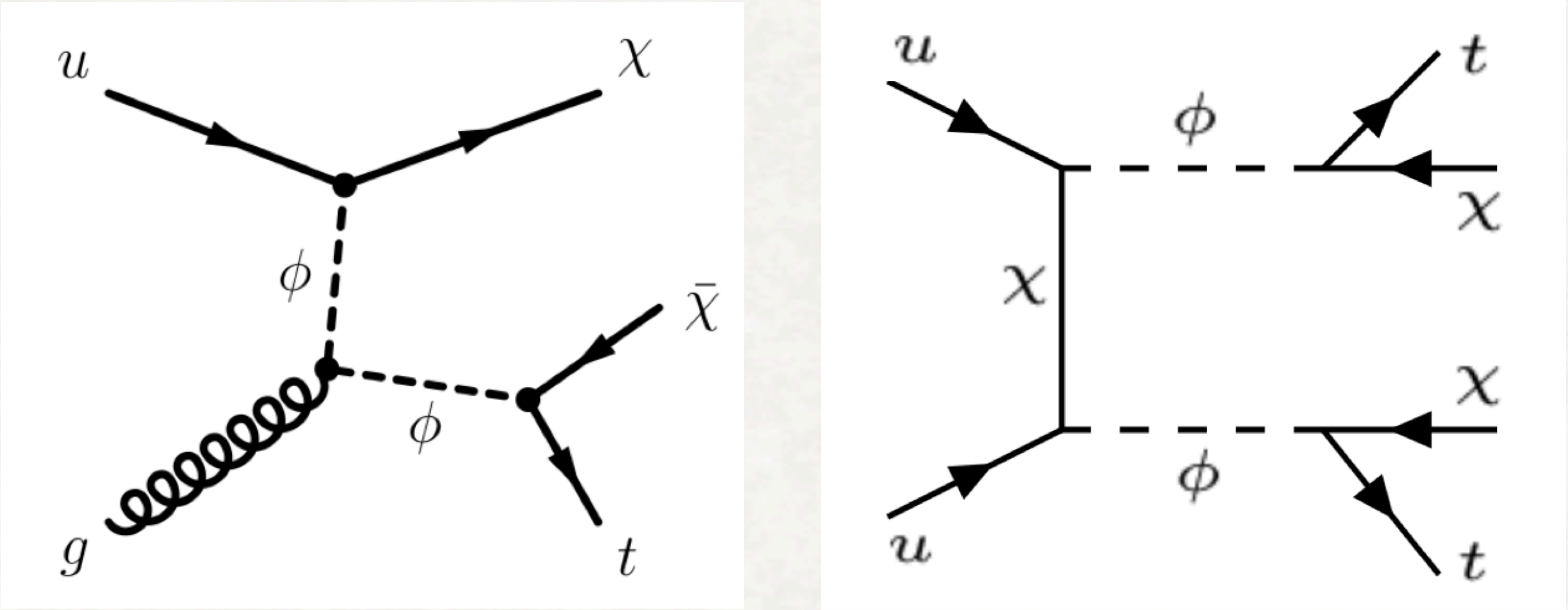
Jets + E_T^{miss}

Off the beaten path:

- single top + E_T^{miss} (flavoured DM)
- Same-sign tops + E_T^{miss}
- Charm + E_T^{miss} (charm-philic DM)
- Long-Lived Particle signatures

White-paper with phenomenology & recommendations for Run 3 in preparation in LHC DM WG



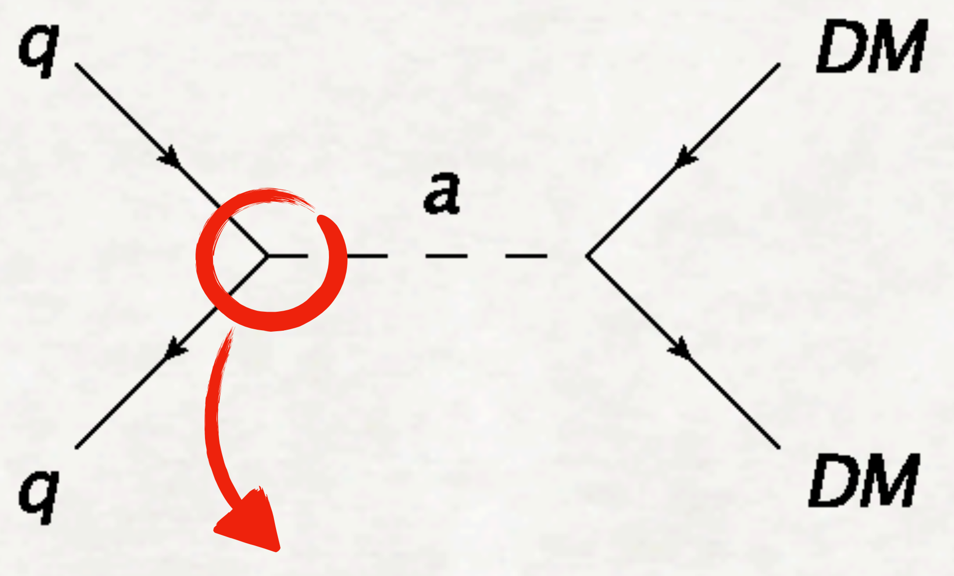


Acaroglu, Blanke, 2109.10357

4. Extended Higgs sectors

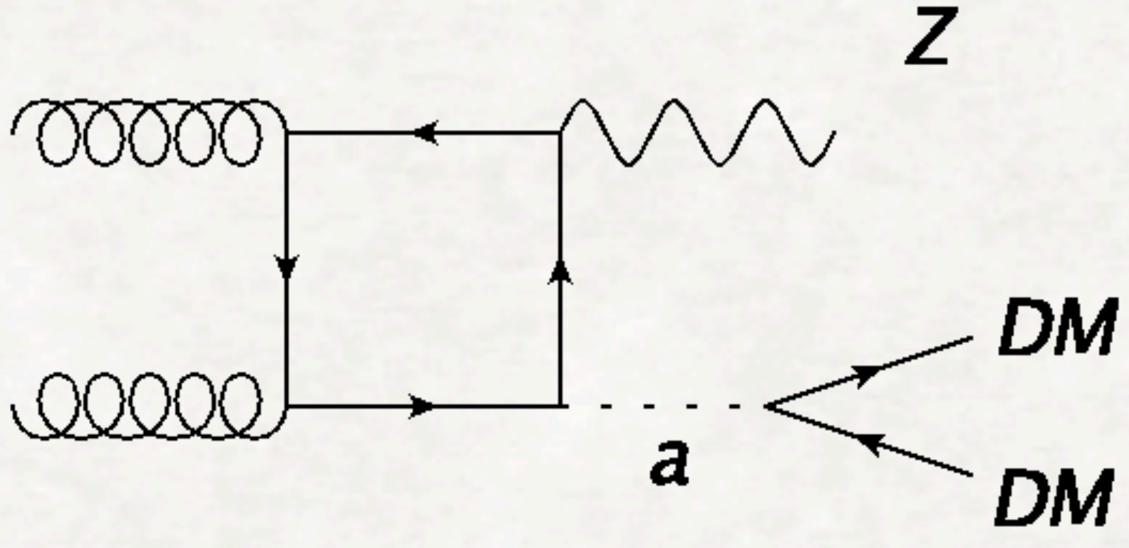
The need for extended Higgs sectors

- "Simplified models" = single s-channel mediator



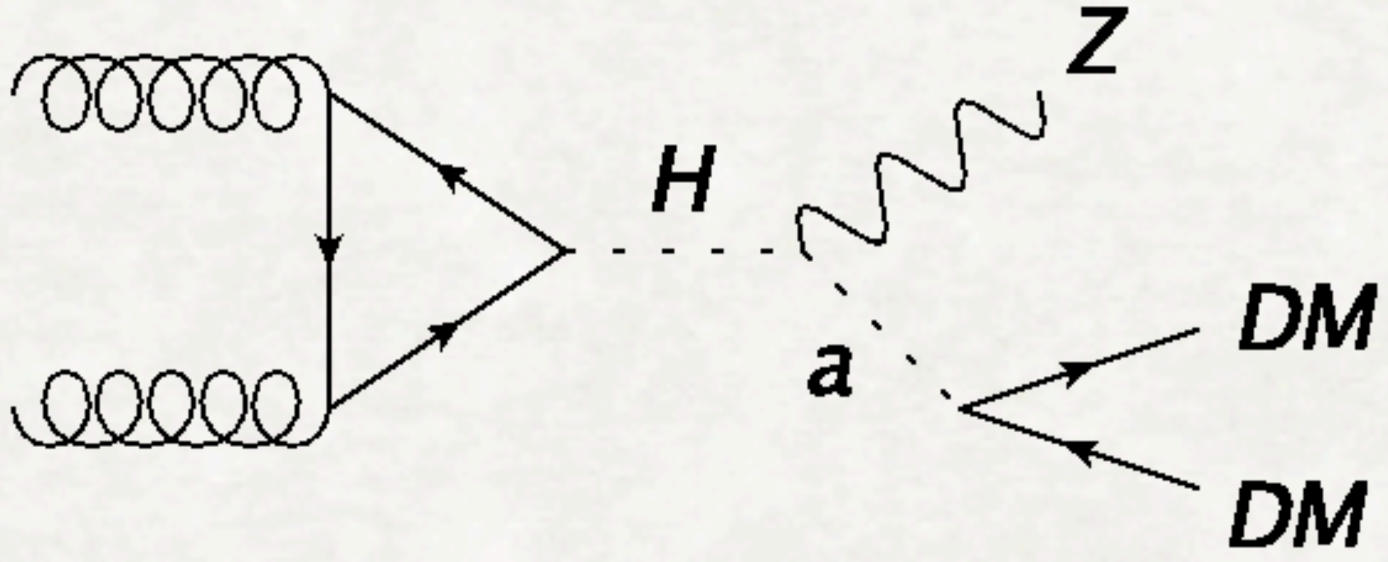
not gauge invariant

$\Rightarrow$



$\mathscr{M} \sim \ln^2 s$ violates unitarity

- Scalar mediator has to be embedded in extended Higgs sector (mixing with Higgs)
  ★ bonus: resonant signatures



Englert et al, 1604.07975; Haisch, Polesselo, 1812.00694; Bell et al, 1503.07874

The 2 Higgs Doublet Model

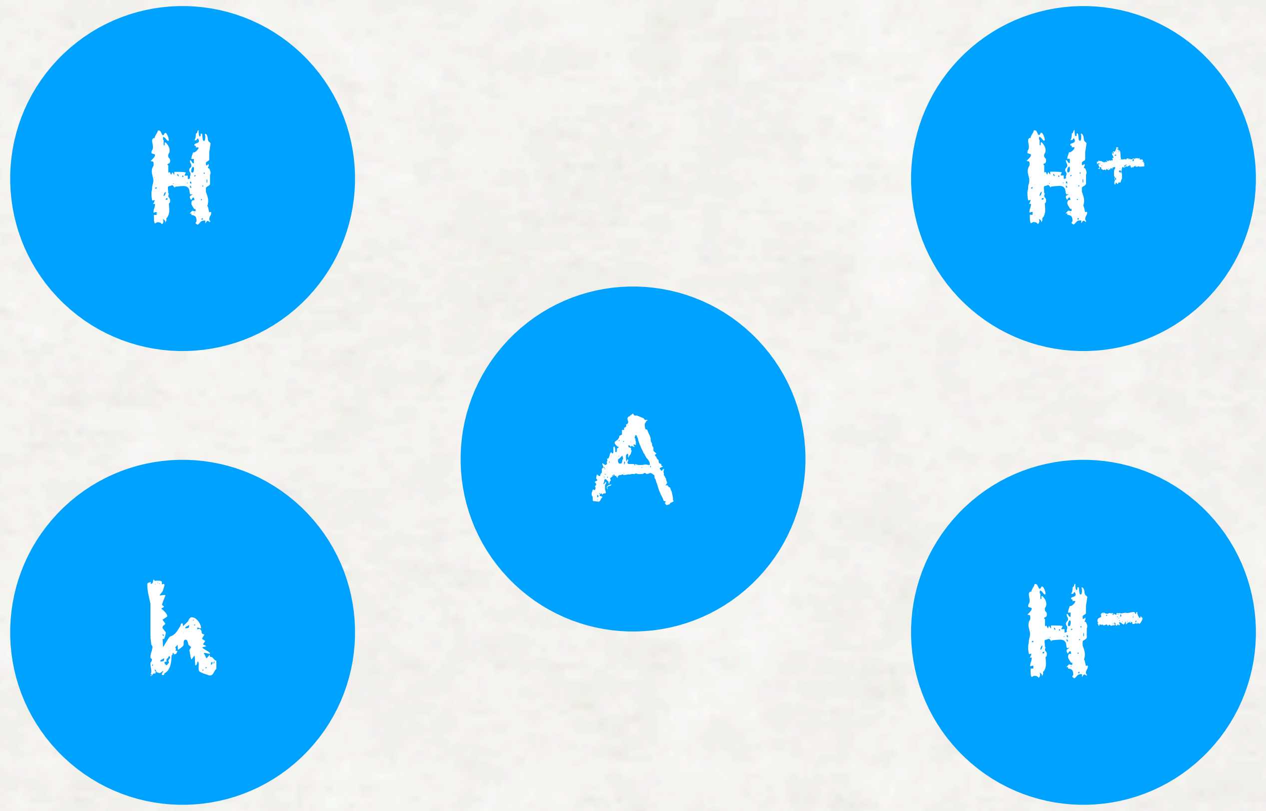
- 5 Higgs bosons

- 5 parameters considered:
  m_A, m_H, $m_{H\pm}$
  α: mixing between H, h
  tan**β**: ratio of vacuum expectation values

- **Different Yukawa structures**
  suppressed/enhanced couplings to fermions

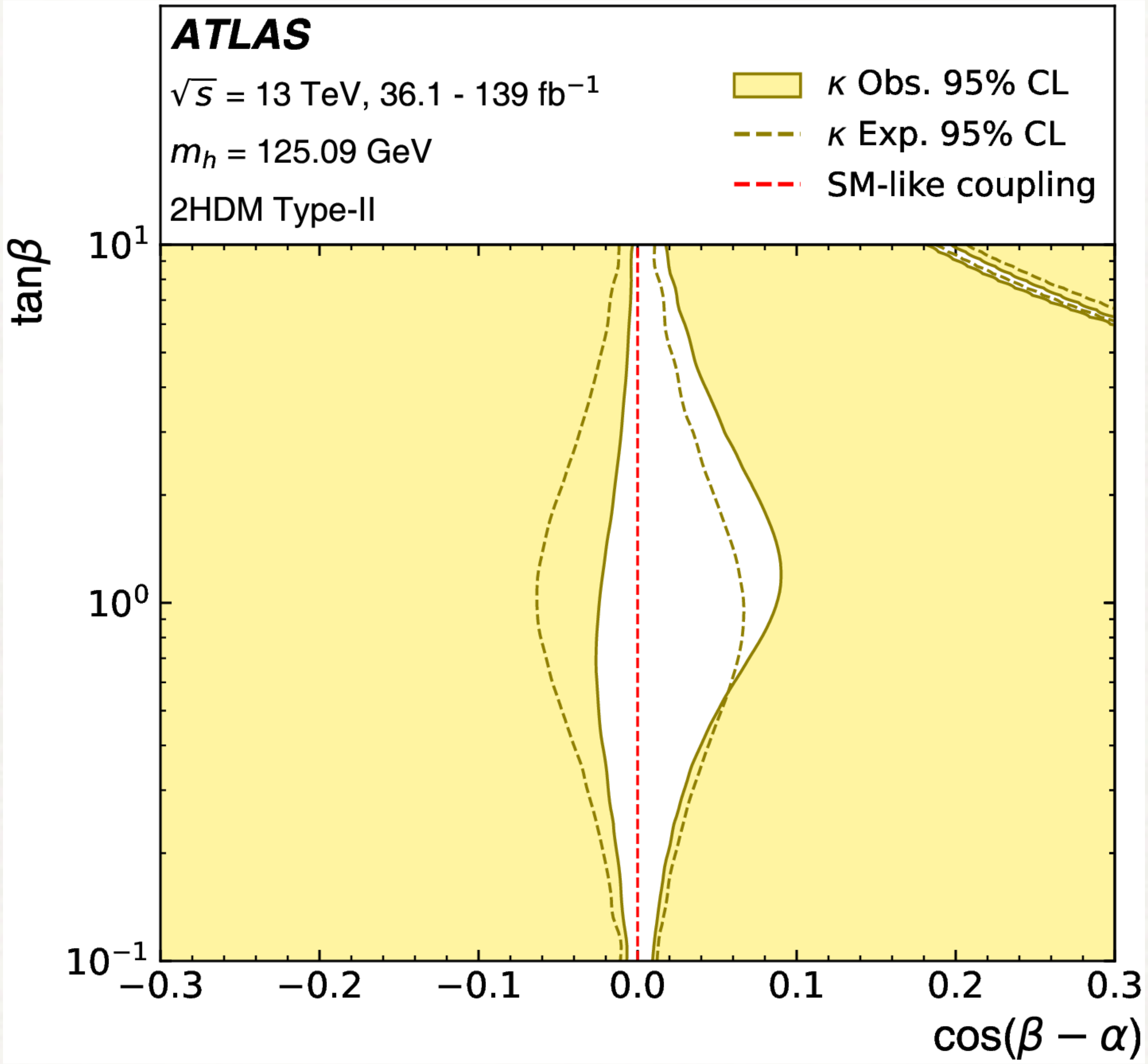
- **Alignment limit: cos(β-α)=0**
  h has the same couplings as the SM Higgs

- related to other models (e.g. axion, MSSM, …)

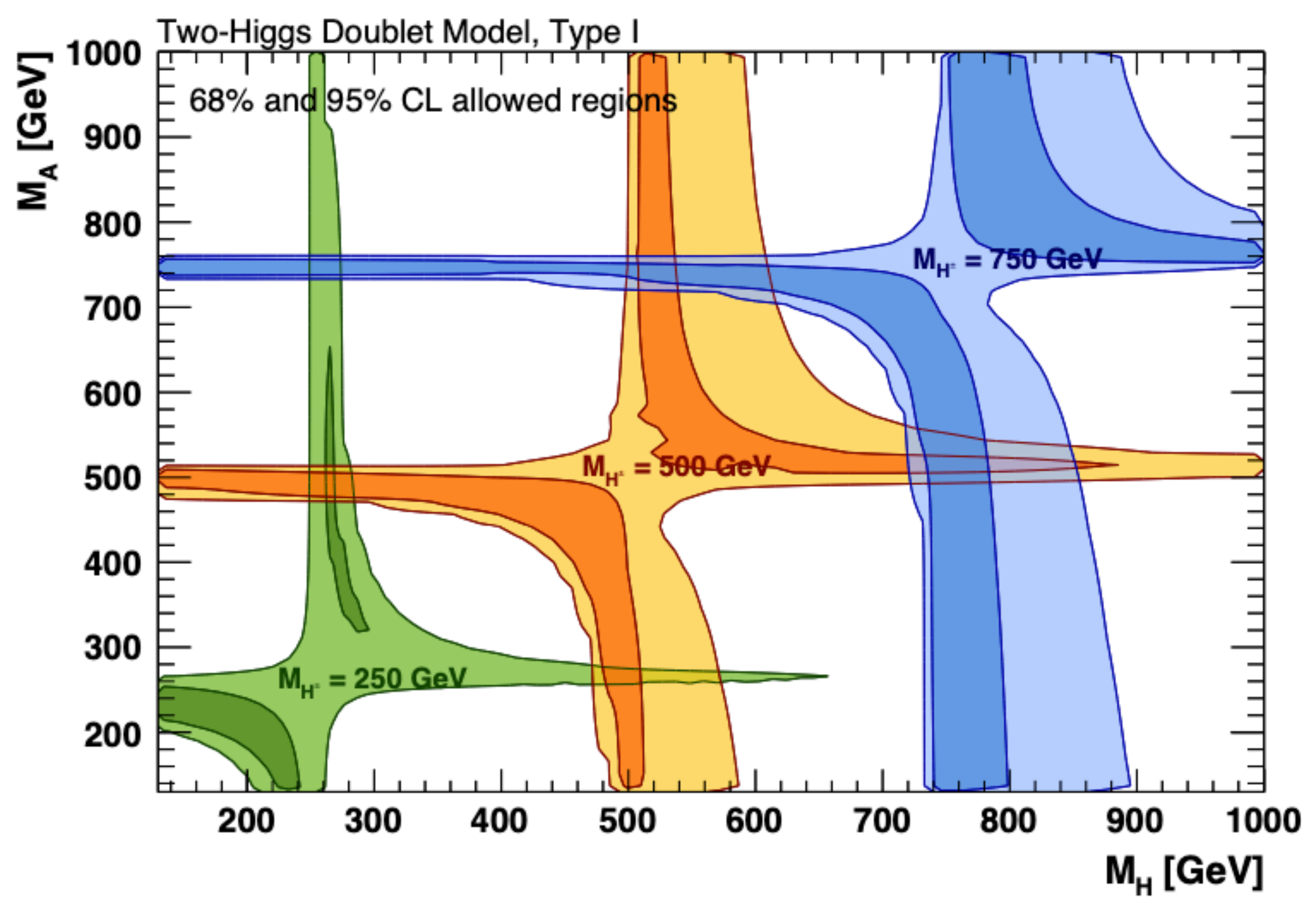


[Branco et al, Phys.Rept. 516 (2012) 1](#)
[Rompotis, Ferrari, Symmetry 2021,13,2144](#)

Constraints on 2HDM



2402.05742



Gfitter, EPJC 78 (2018) 675

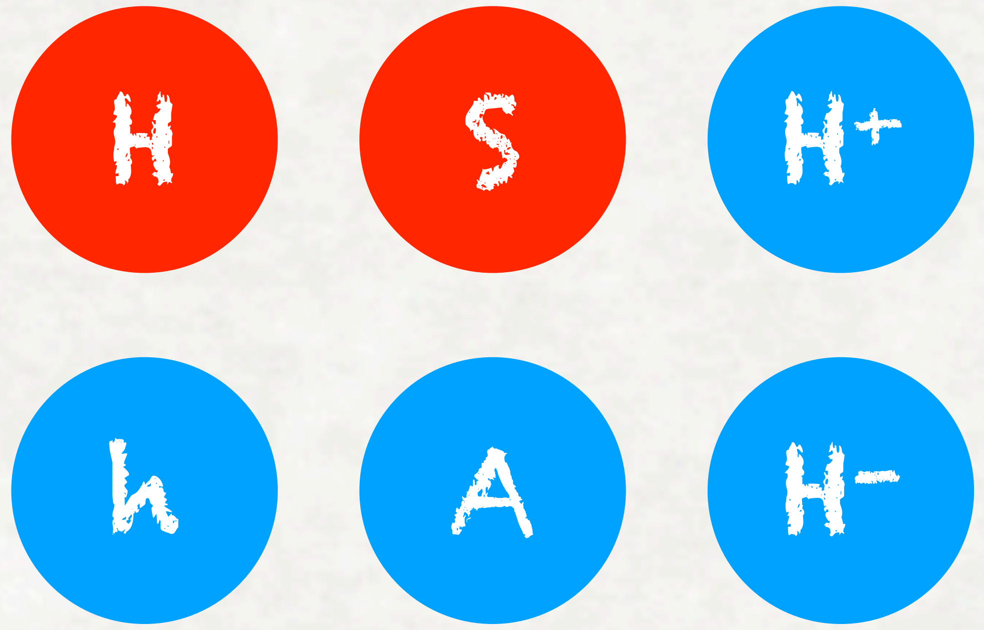
- Higgs coupling measurements: we are close to alignment limit
- EW precision, flavour measurements: $H^{\pm}$ must be degenerate with A or H
  - ➡ in all 2HDM DM benchmarks considered at the LHC so far are Type II with $\cos(\boldsymbol{\beta}-\boldsymbol{\alpha})=0$ & $m_A=m_H=m_{H\pm}$

Model #1: 2HDM + scalar

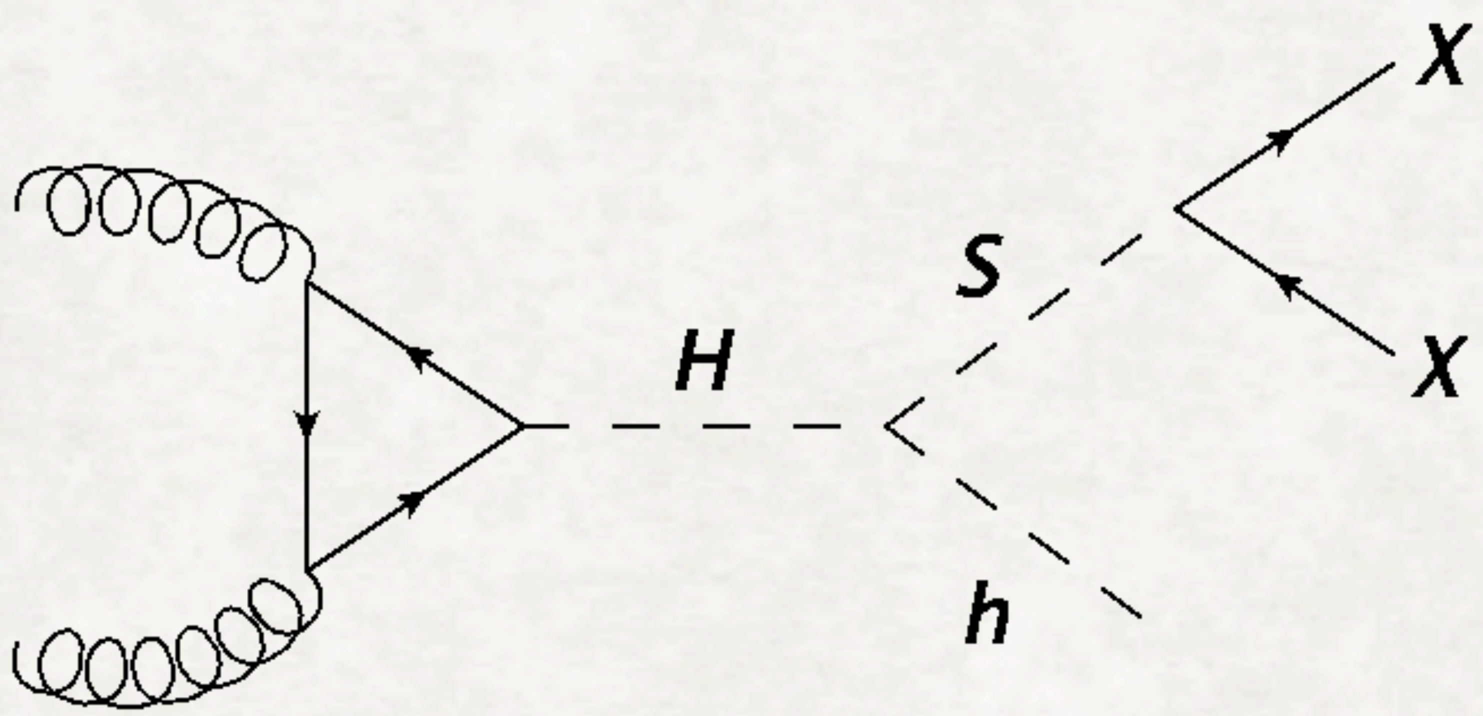
- 2HDM Type-II
- Extra **scalar mediator S** that couples to DM
- Mixing between CP-even scalars
- 6 Higgs bosons
- Resonant signatures

$$H = \cos\theta \tilde{H} + \sin\theta \tilde{S}$$

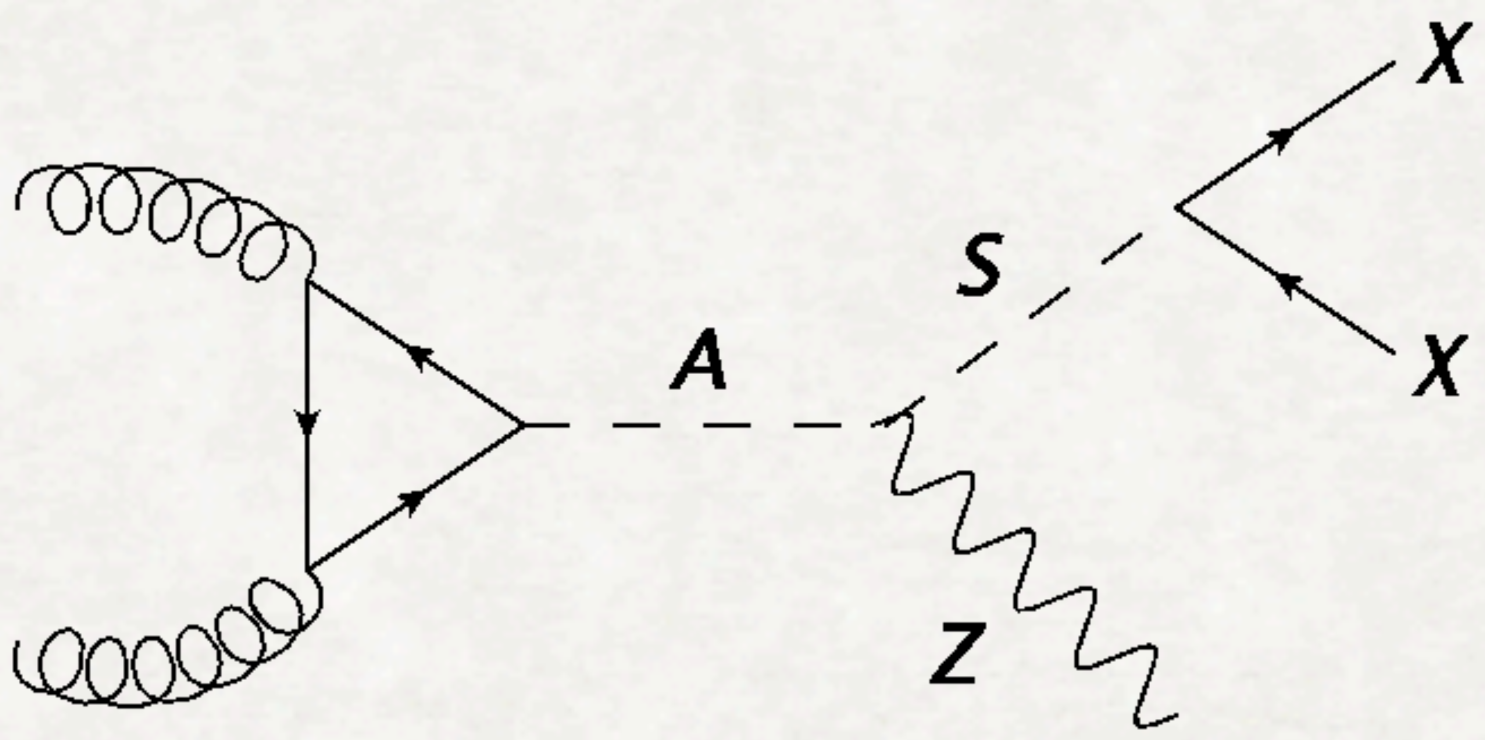
$$S = -\sin\theta \tilde{H} + \cos\theta \tilde{S}$$



$h+E_T^{miss}$



$Z+E_T^{miss}$



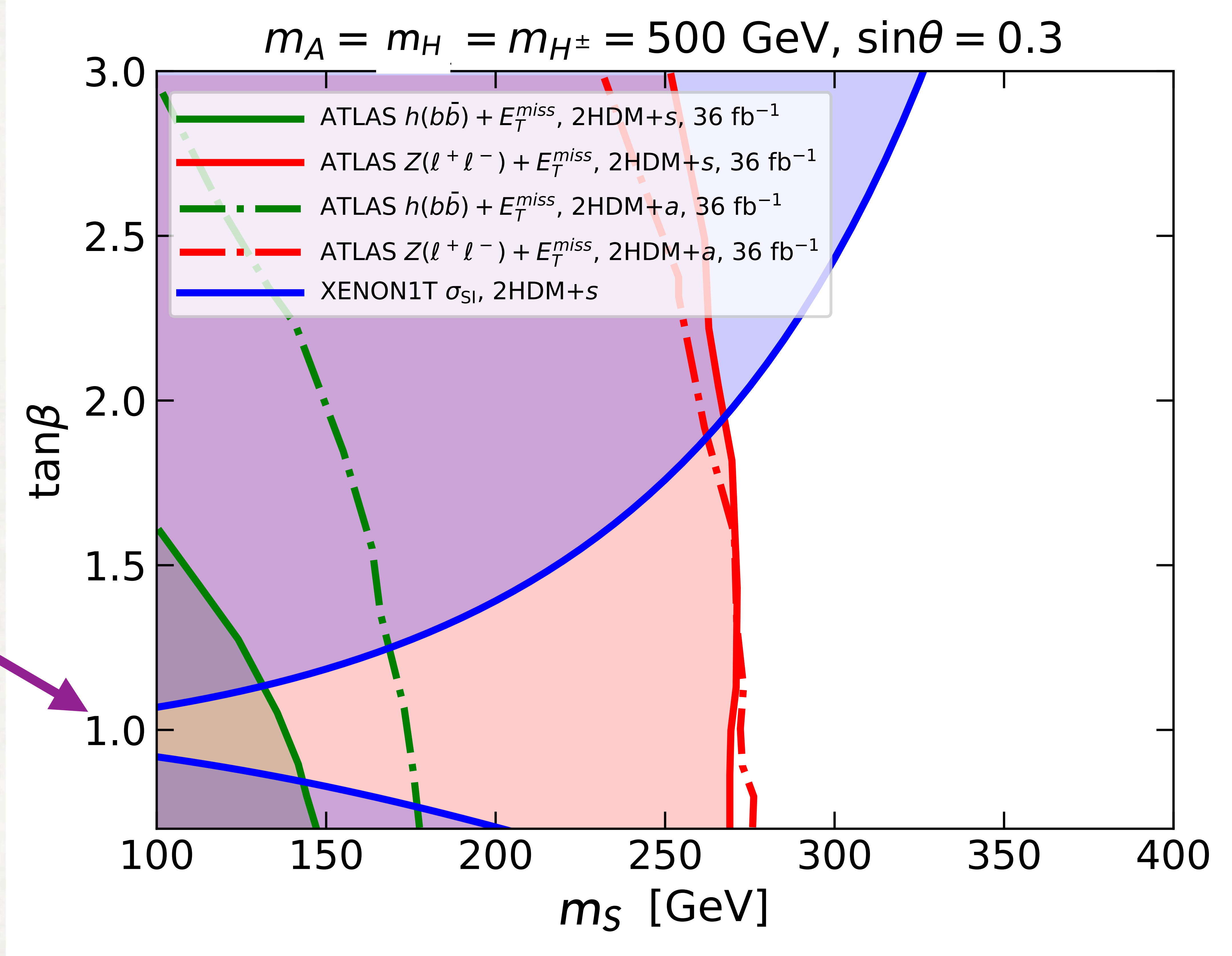
Bell et al, 1612.03475; Arcadi et al, 2001.10540

2HDM + scalar: constraints

- Not very much explored @ LHC

- Scalar mediator ⇒ dominant constraints from direct detection

★ DD experiments blind in certain regions
  - scalars are degenerate (m_S=m_H)
  - tan**β**≅1
  - even for models that are considered DD territory, LHC can provide complementary constraints



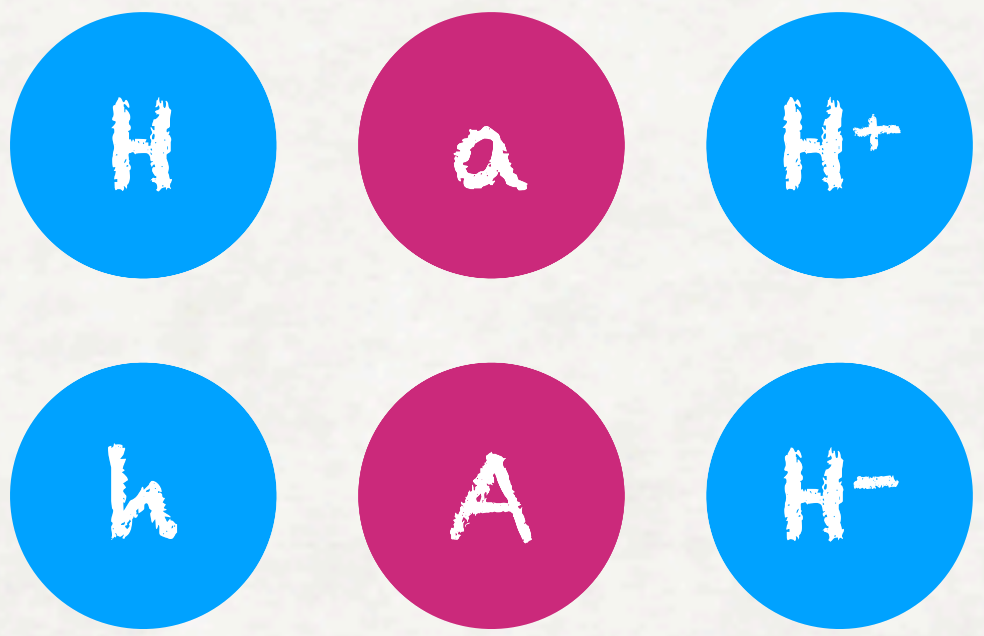
SA, Brandt, Haisch, Symmetry 13 (2021) 2406

Model #2: 2HDM + pseudoscalar

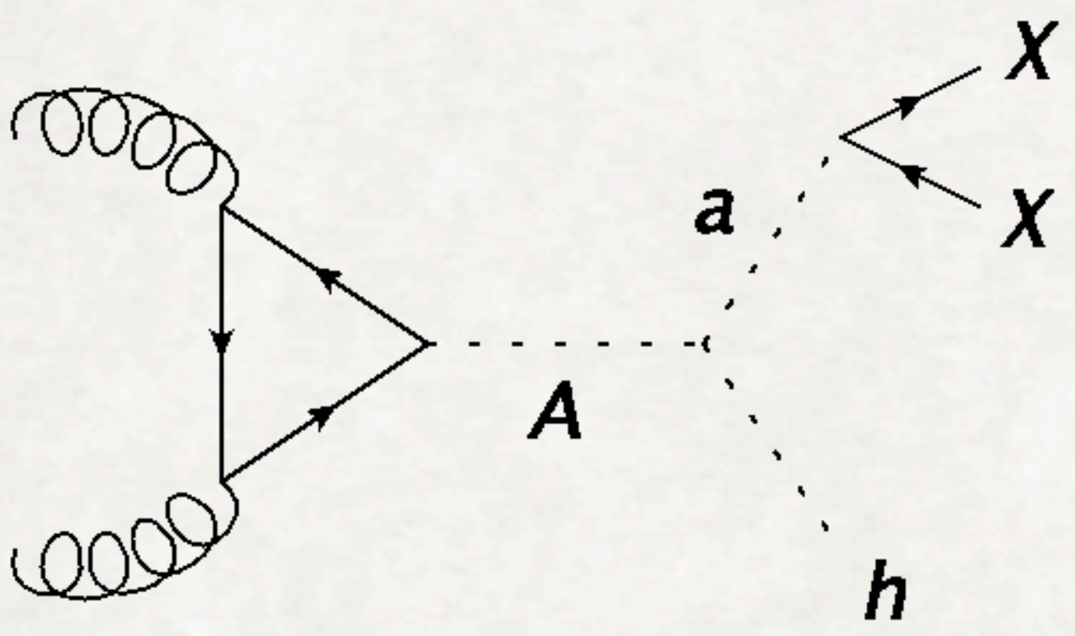
- 2HDM Type-II
- Mixing between CP-odd Higgses
- 6 Higgs bosons
- Extra **pseudoscalar mediator a** that couples to DM
  - suppressed DD constraints
  - originally proposed to explain Fermi-LAT excess
- Very rich phenomenology: colliders + ID + DD

$$A = \cos\theta \tilde{A} + \sin\theta \tilde{a}$$

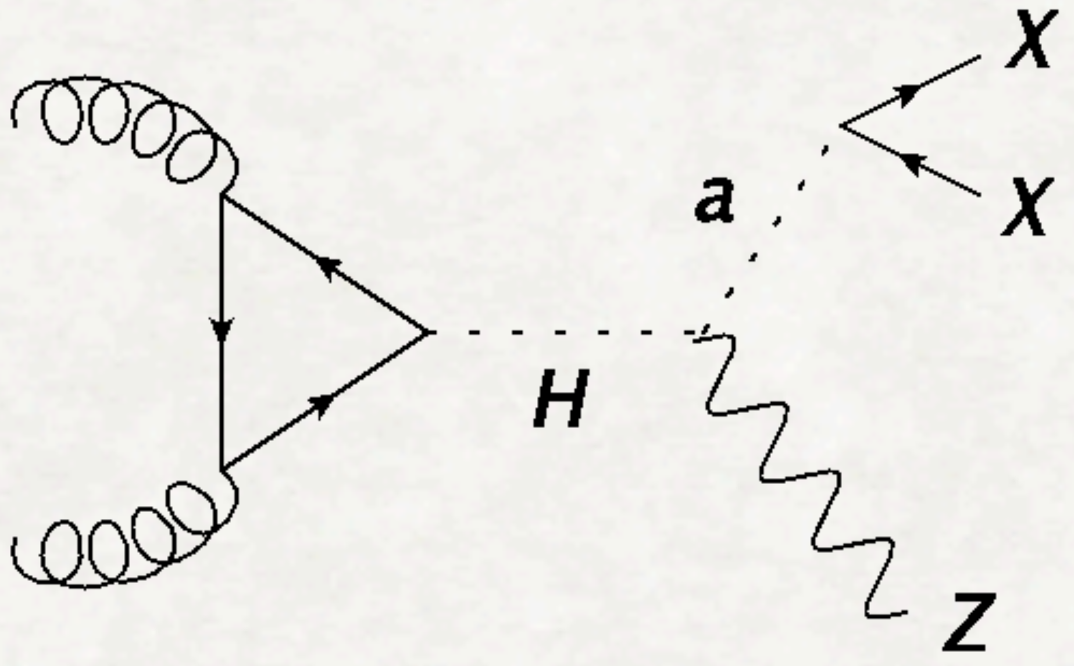
$$a = -\sin\theta \tilde{A} + \cos\theta \tilde{a}$$



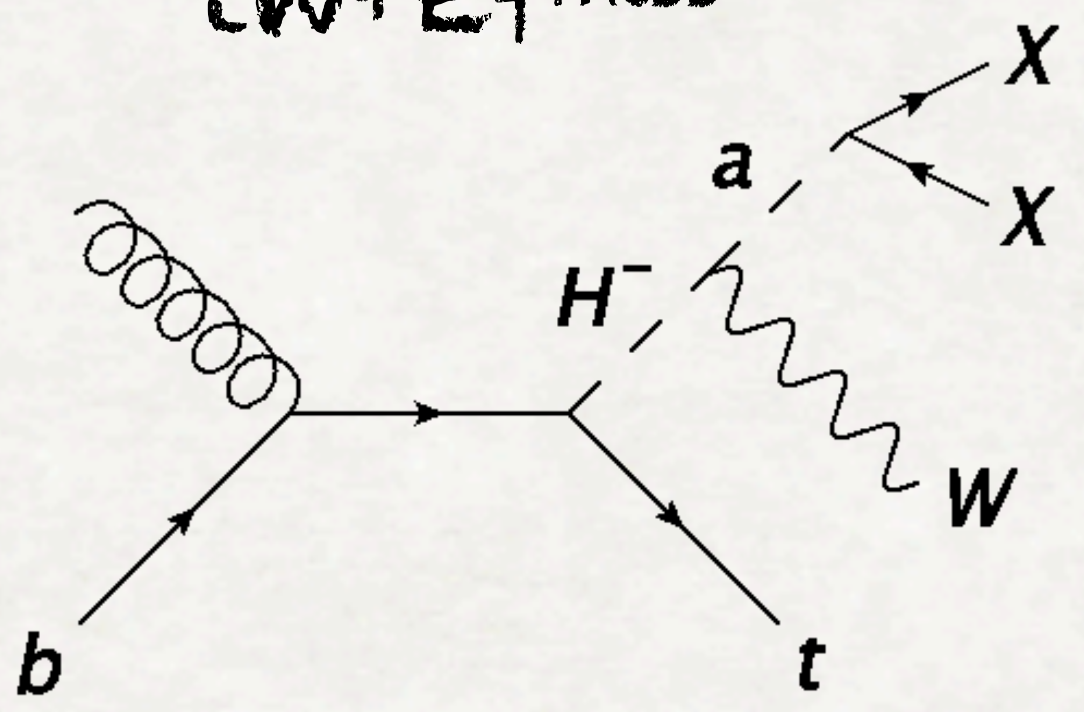
$h + E_T^{miss}$



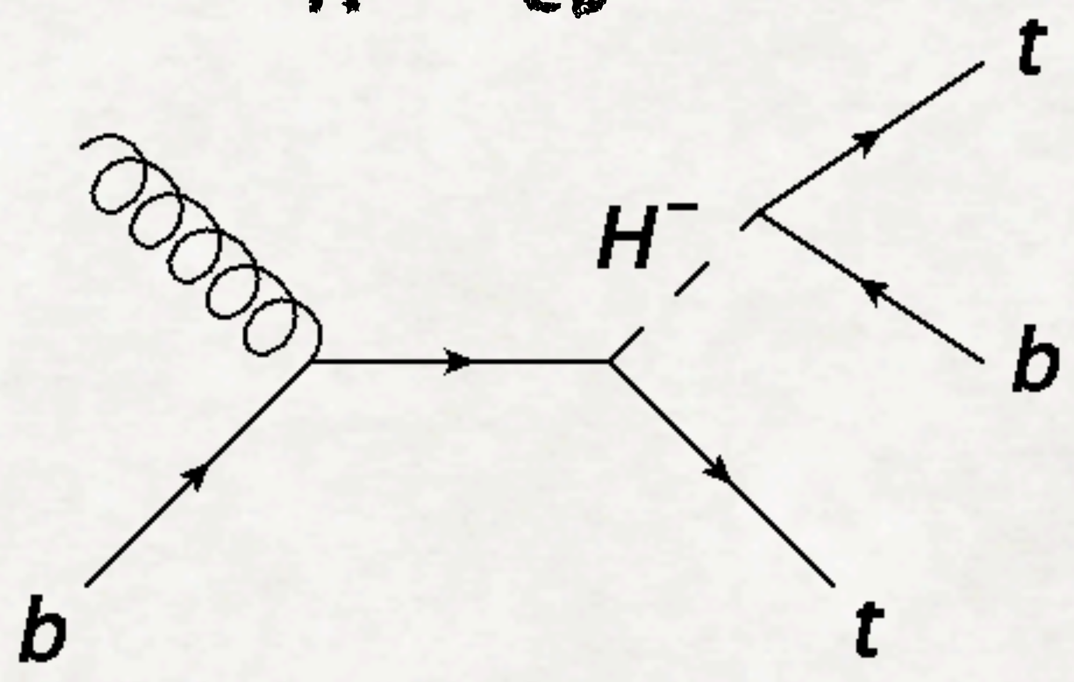
$Z + E_T^{miss}$



$tW + E_T^{miss}$

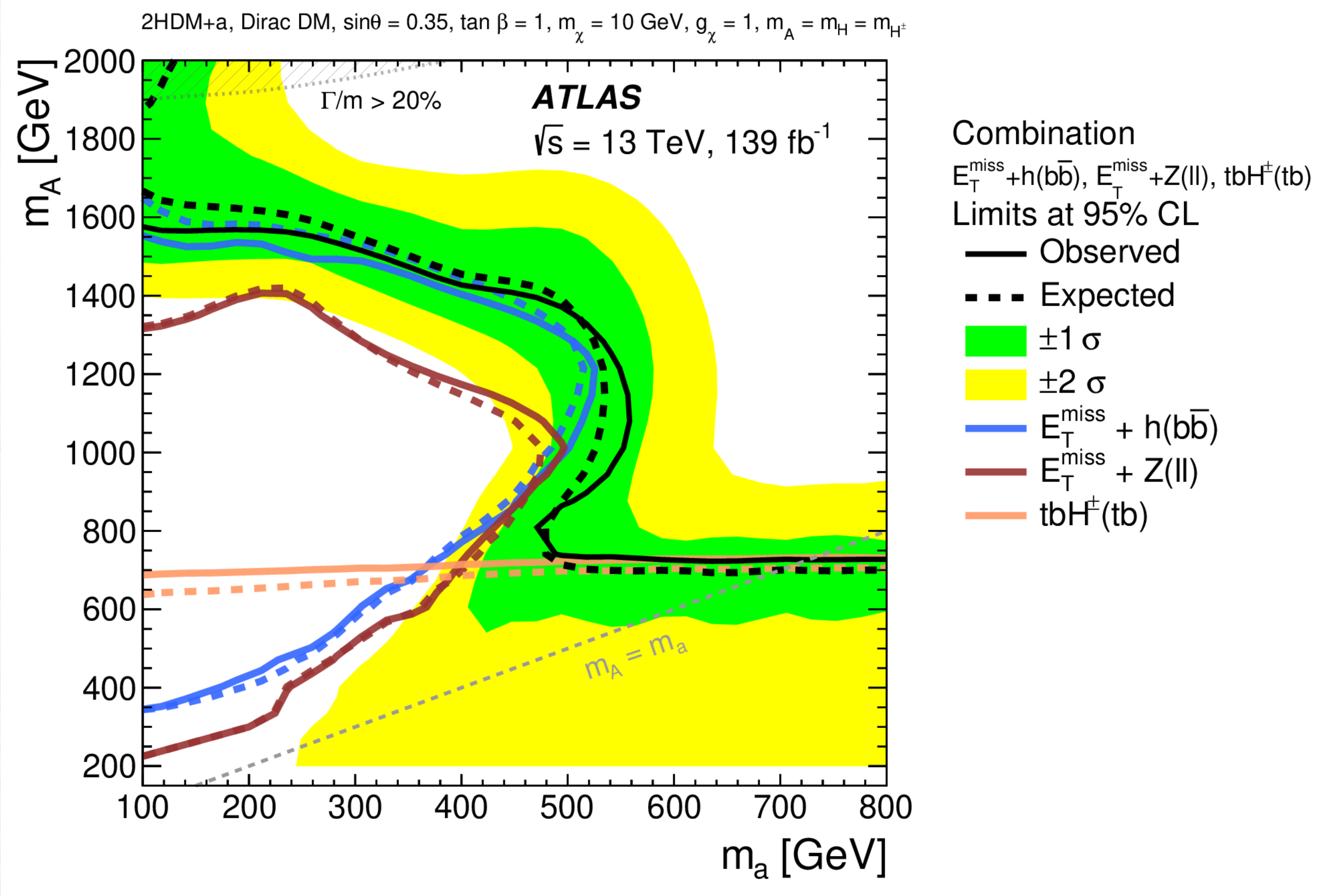


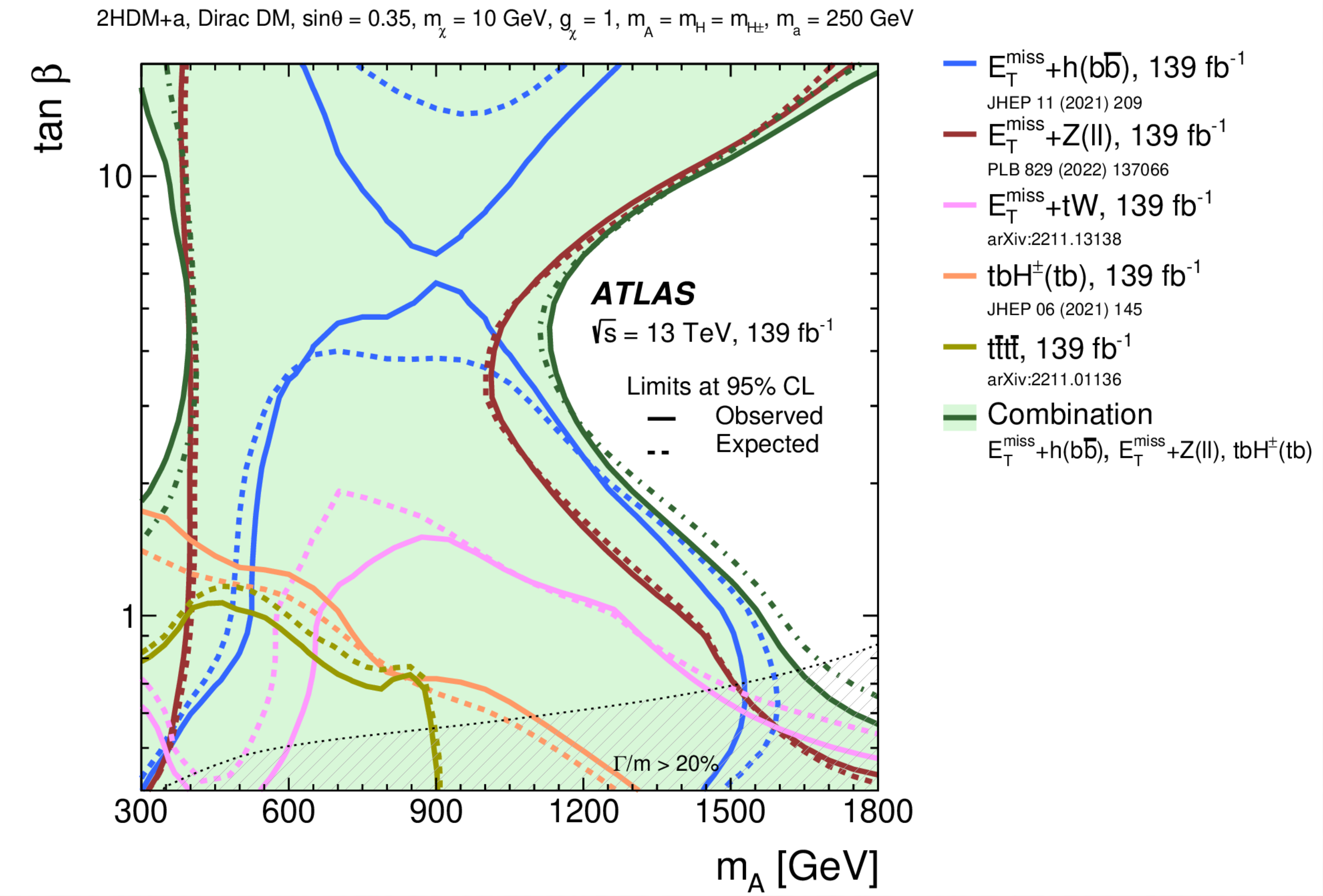
$H^{\pm} \to tb$



Ipek, et al, 1404.3716 ; No, 1509.01110 ; Goncalves, et al, 1611.04593 ; Bauer, et al, 1701.07427 ; Abe et al, 1810.09420

2HDM + pseudoscalar: constraints



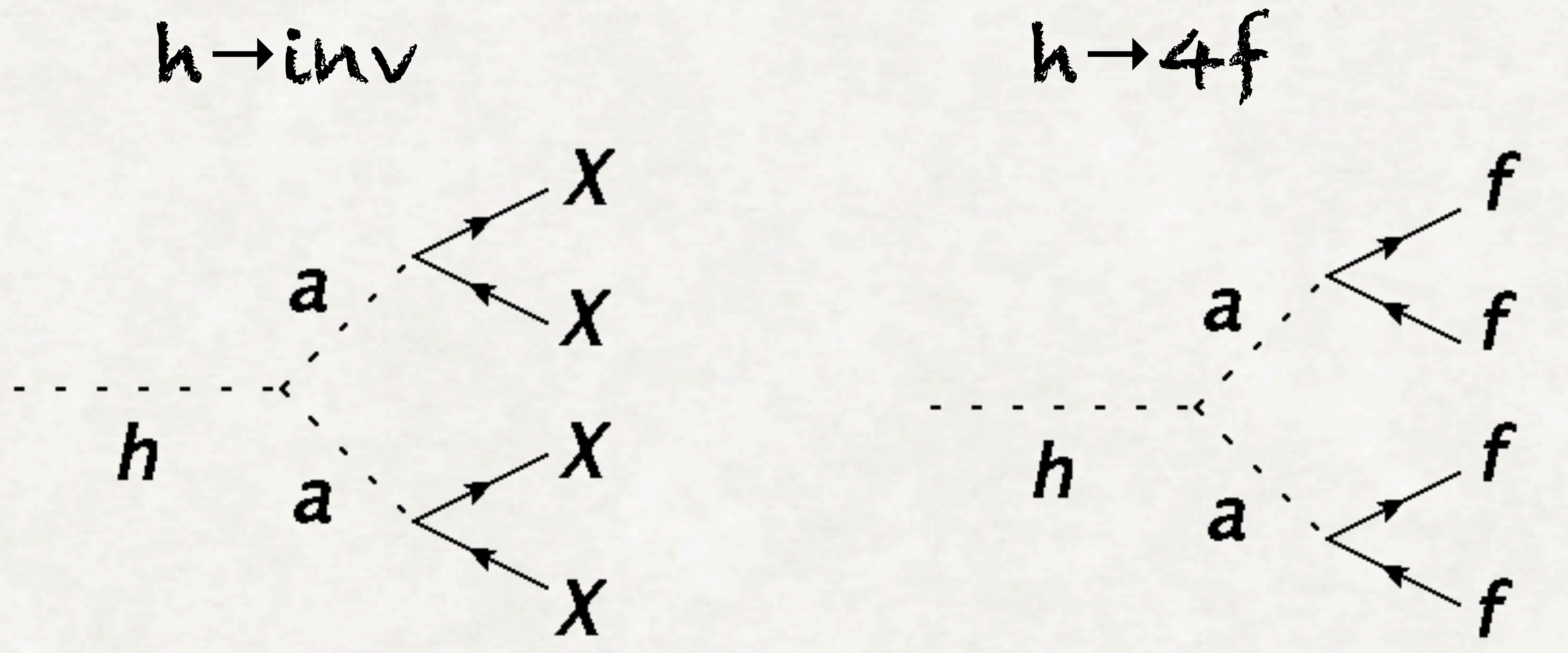


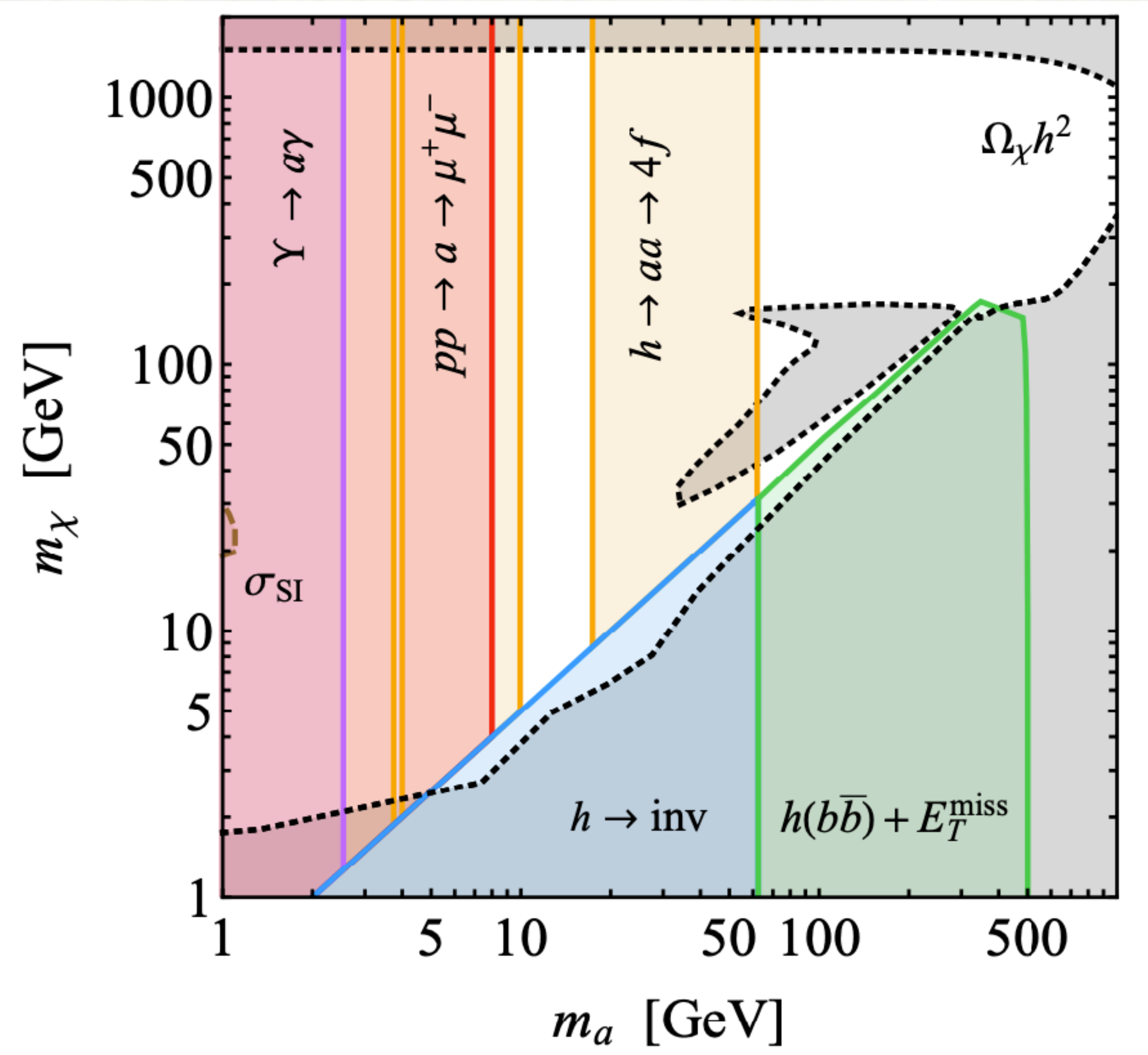
[ATLAS, 2306.00641](#)

- A lot of parameter space excluded, $m_a \gtrsim$ 500 GeV, $m_A \gtrsim$ 1TeV for a range of mixing angles
- Since the publication of our review ATLAS has also performed a statistical combination of the most sensitive channels
- Goal for the future: close sensitivity gaps (e.g. low m_A,m_a at intermediate tan**β**)

2HDM + pseudoscalar: complementary searches

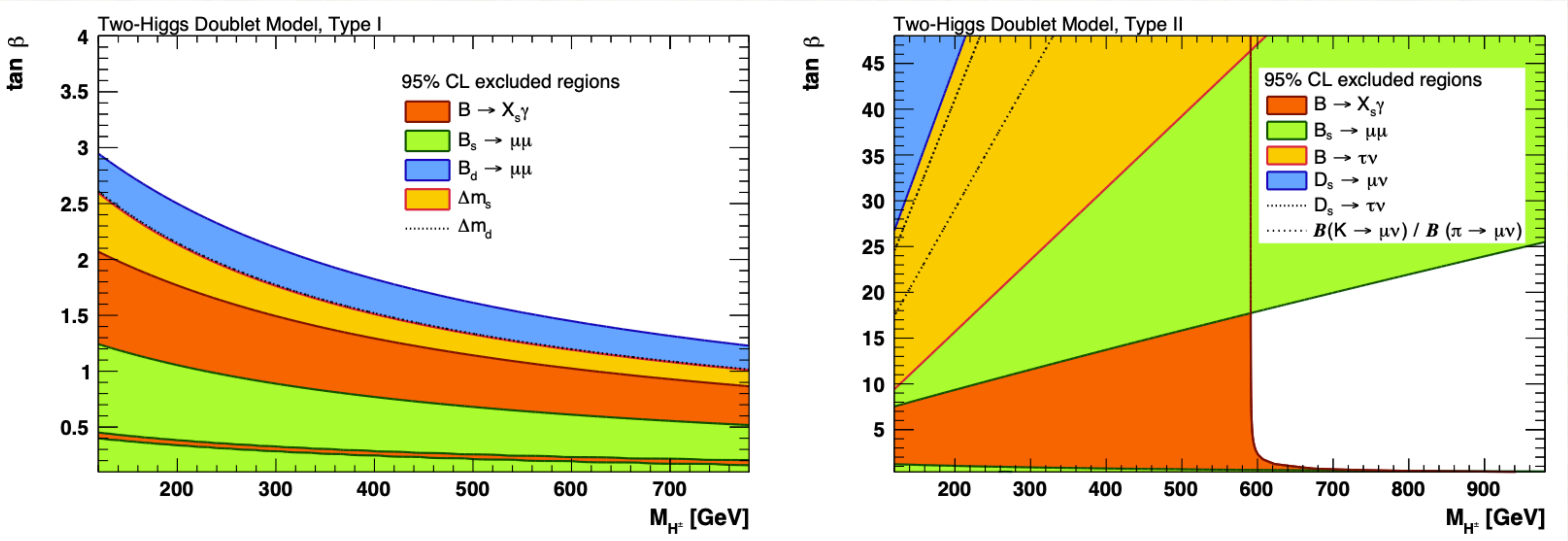
- $m_a > m_h/2$ & low m_χ: X+E_T^{miss}
- $m_a < m_h/2$: generally because of h→aa tight constraints from total Higgs width unless finely tuned
  - $m_\chi < m_a/2$: h→invisible
  - $m_\chi > m_a/2$: h→4 fermions



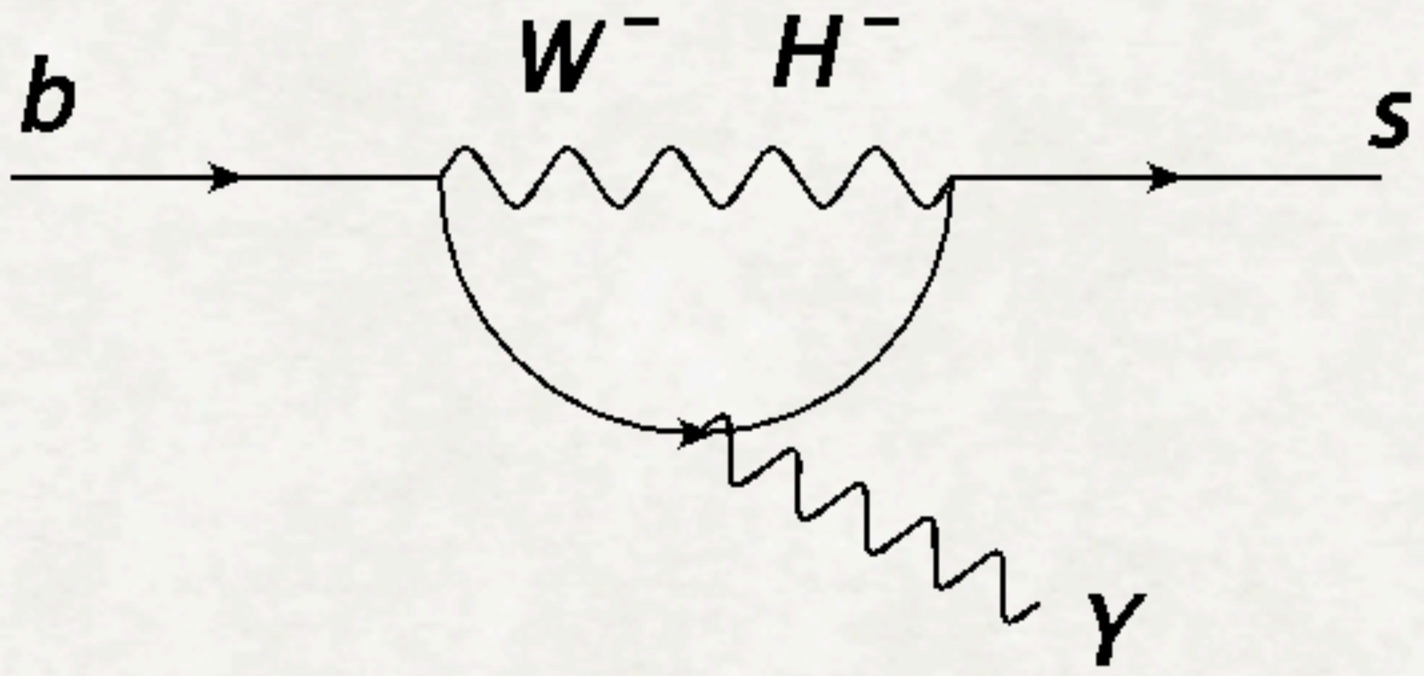


SA, Haisch, 2202.12631

Why to look at Type-I 2HDM?



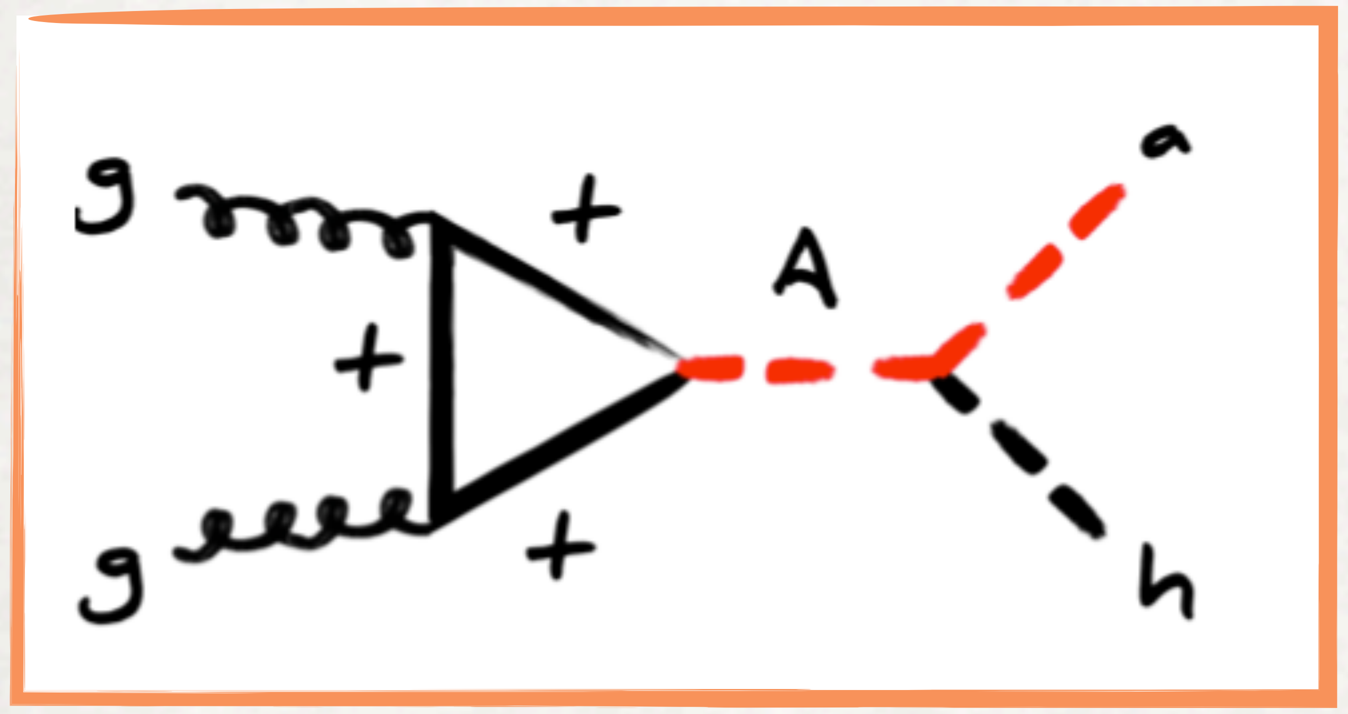
Gfitter, EPJC 78 (2018) 675

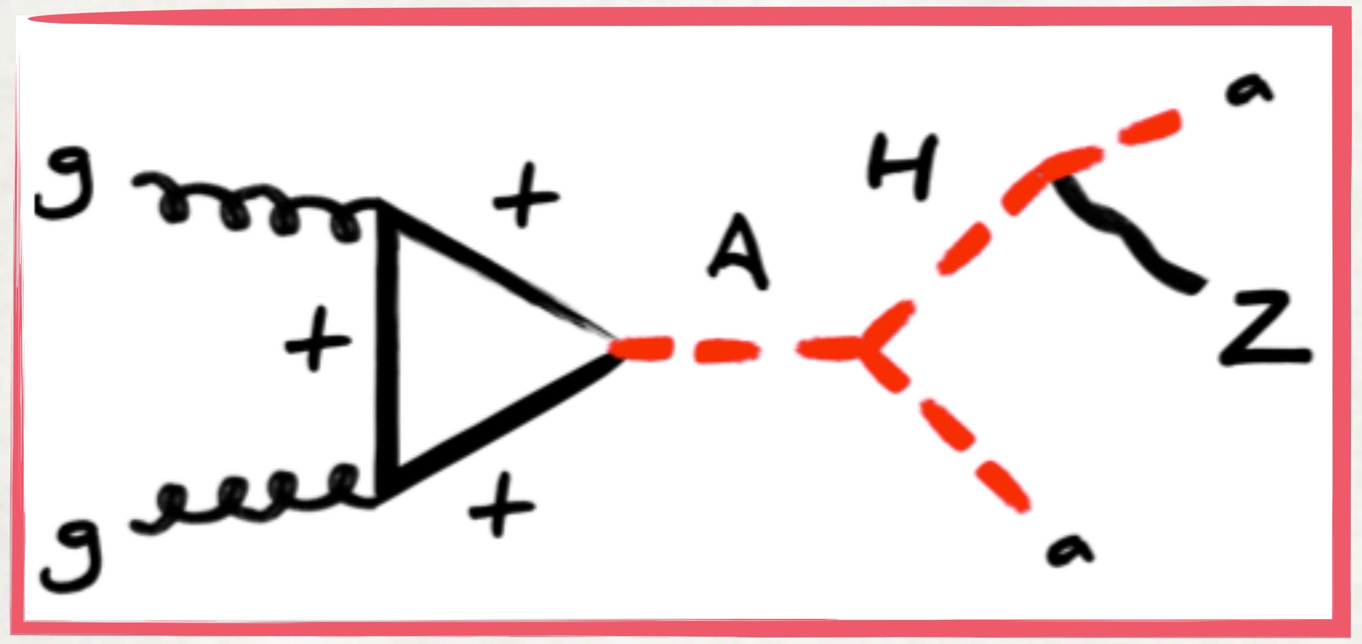


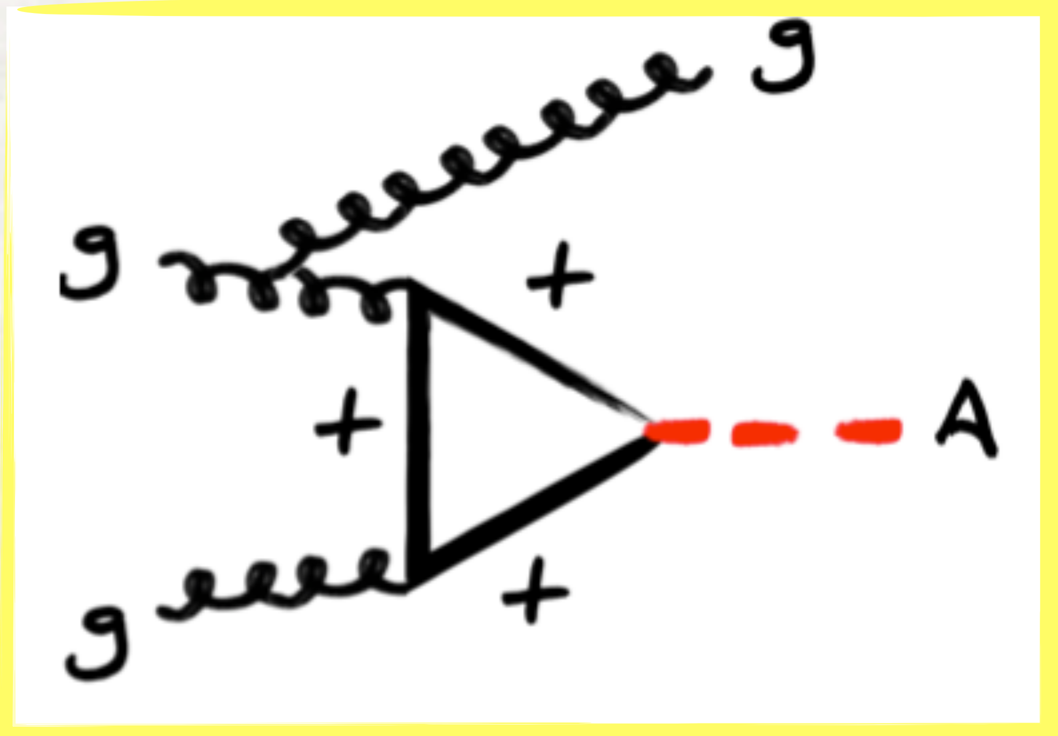
- $B \to X_s\gamma$ constrains $m_{H^\pm} \gtrsim 600$ GeV in Type-II
- This implies that all Higgs bosons have to be heavy
- In Type-I basically no constraint for $\tan\beta \gtrsim 3$

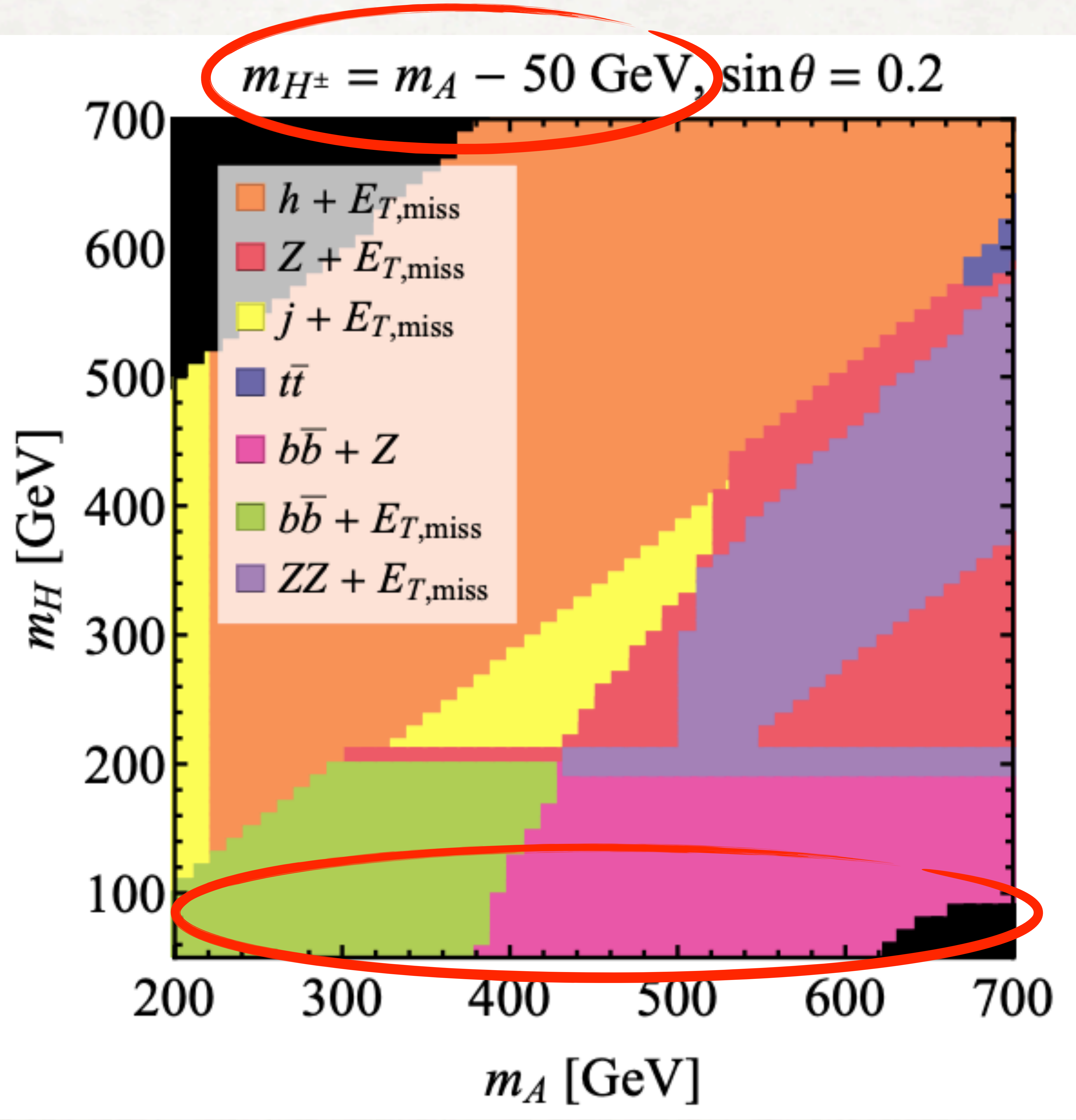
  ➡ **Type-I 2HDM can accommodate light Higgses**

Type-I 2HDMa phenomenology

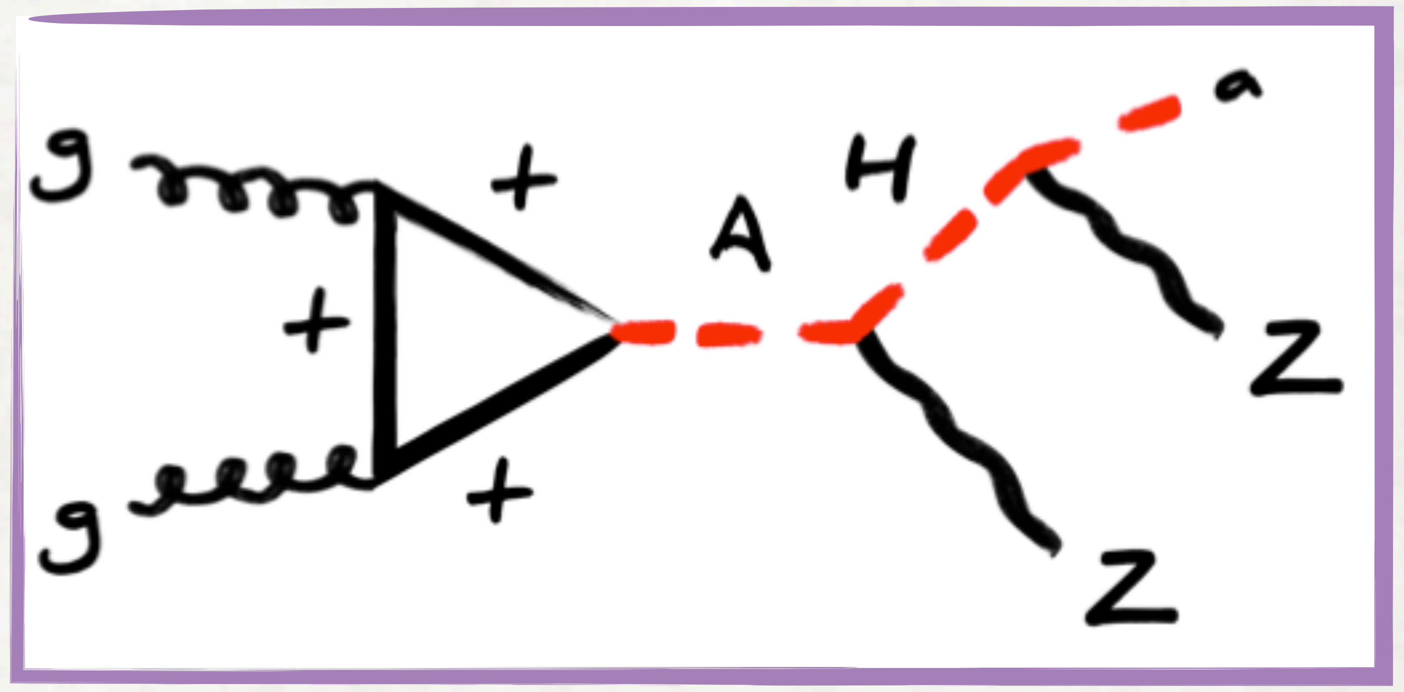


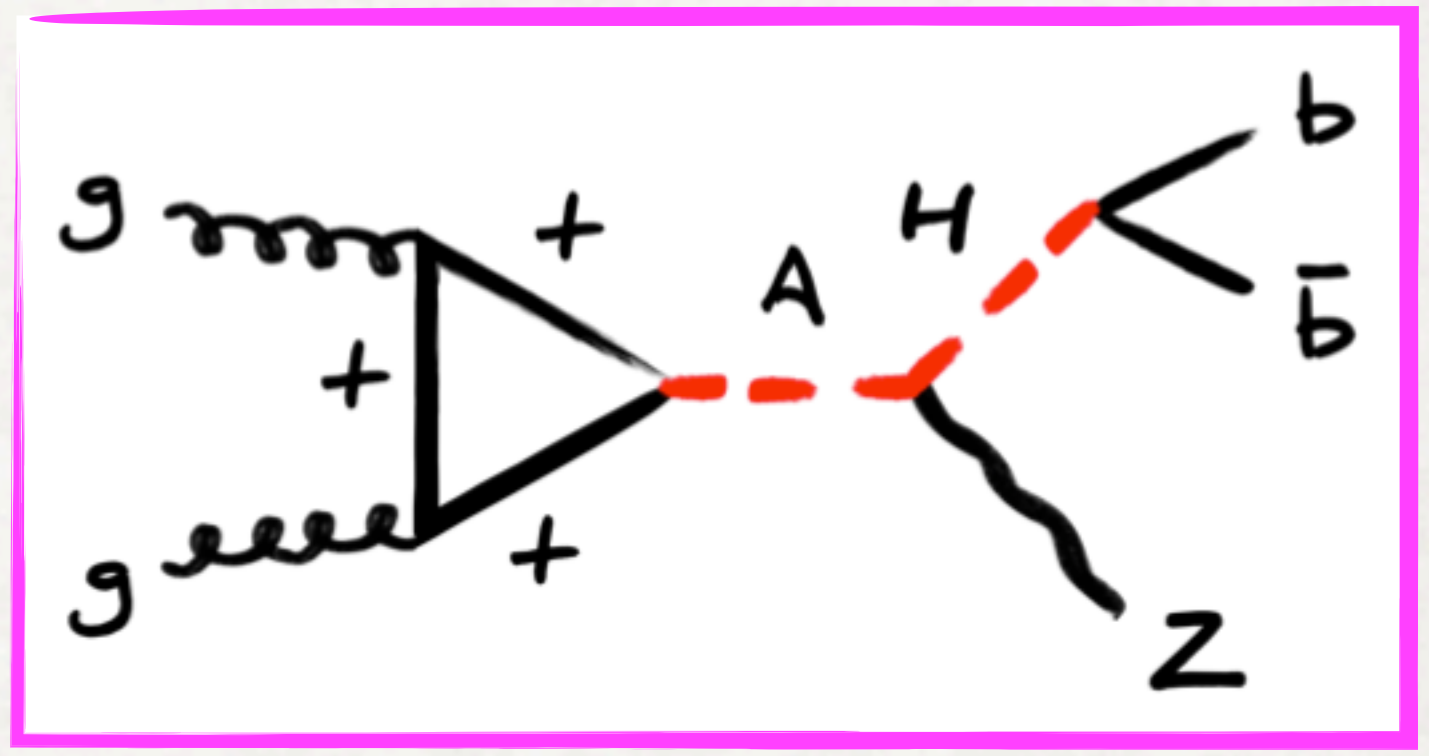


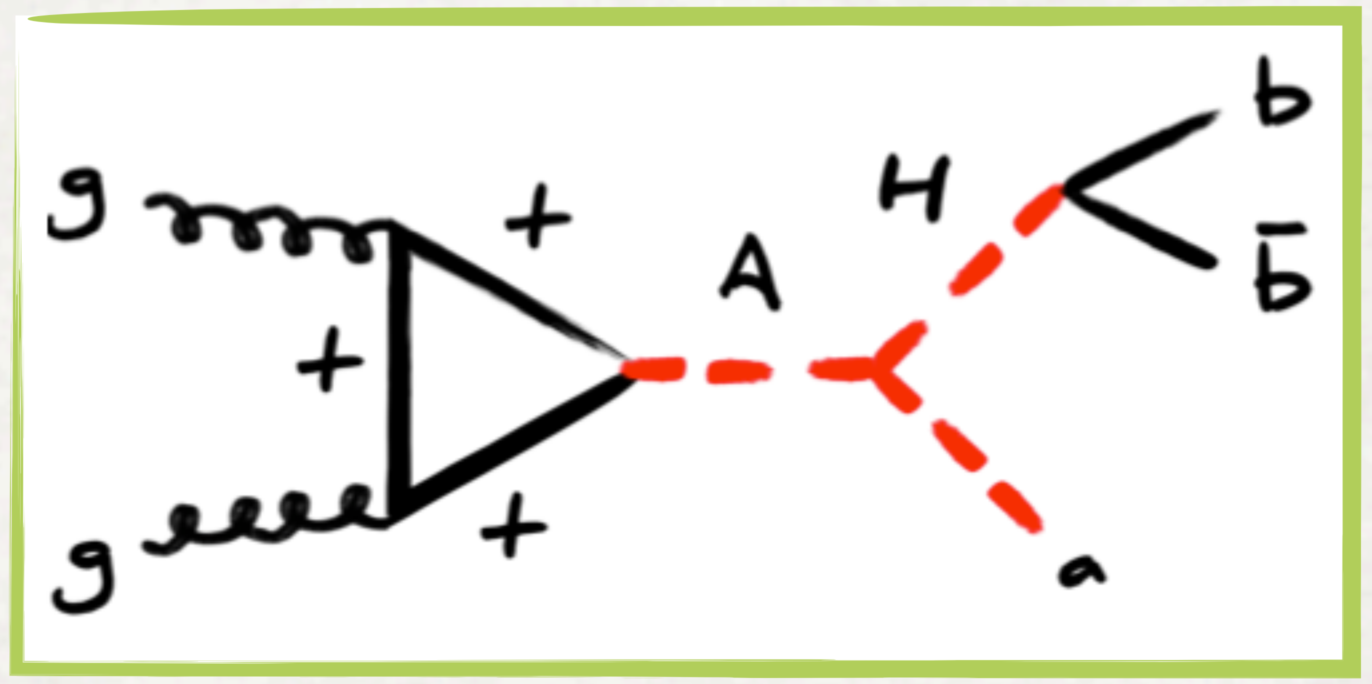




SA, Haisch, Kalaitzidou, 2404.05704





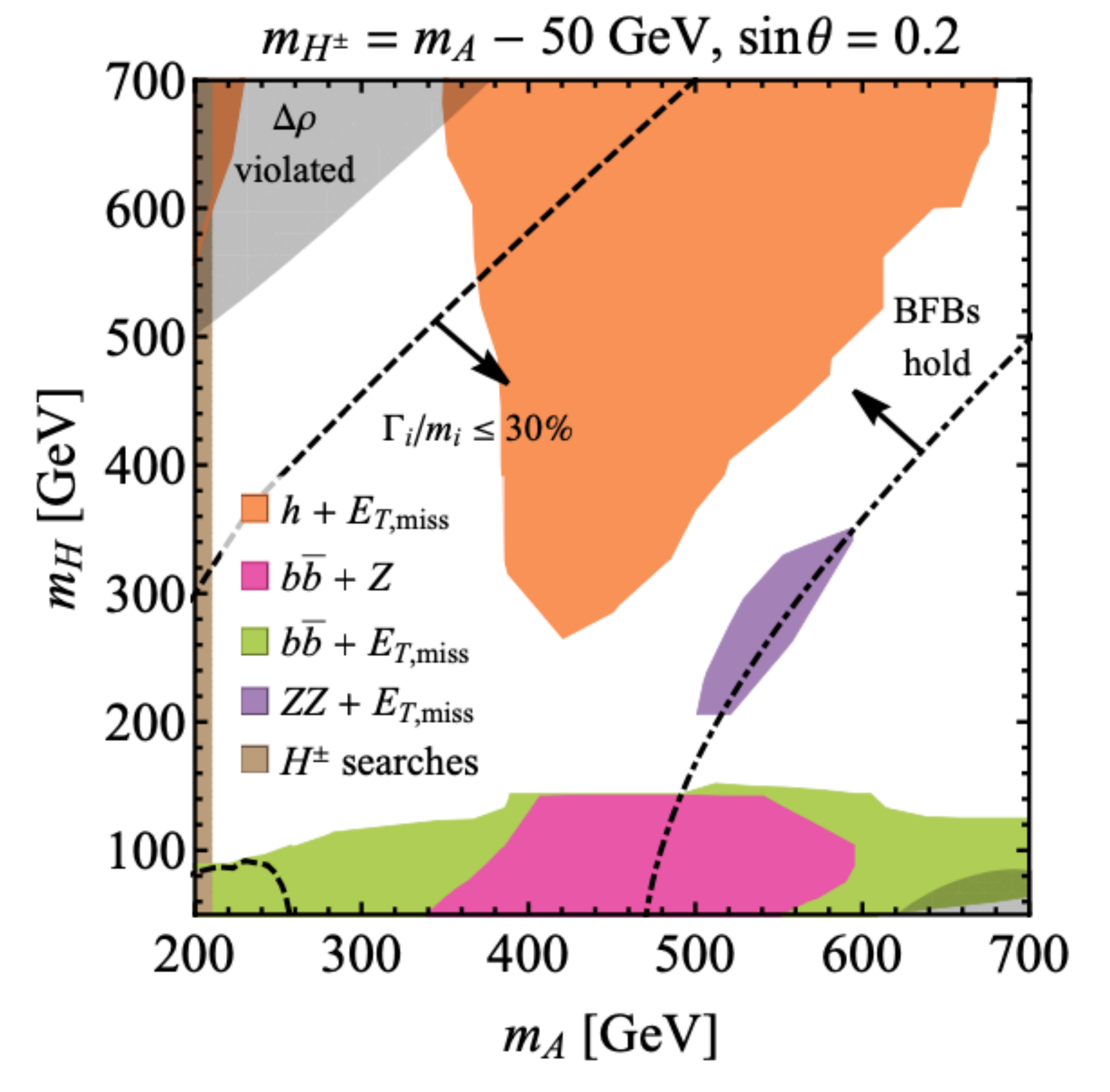


Type-I 2HDMa expected exclusion

- Truth-level sensitivity studies for 5 final states

- Unexplored final states:
  - $b\bar{b}\ell\ell$ - $m(b\bar{b}) < 125$ GeV
  - $b\bar{b} + E_T^{\rm miss}$ - $m(b\bar{b}) < 125$ GeV
  - $4\ell + E_T^{\rm miss}$ (needs full Run 2+3 data and a lot of optimisation)
  - $W^{\pm}H^{\mp}(cs)$

- And more (e.g. $hh + E_T^{\rm miss}$, …)



SA, Haisch, Kalaitzidou, 2404.05704

5. Extended Higgs + gauge sectors

Model #3: extra Higgs + Z′

- SM or extended Higgs sector extended by spontaneously broken U(1)′

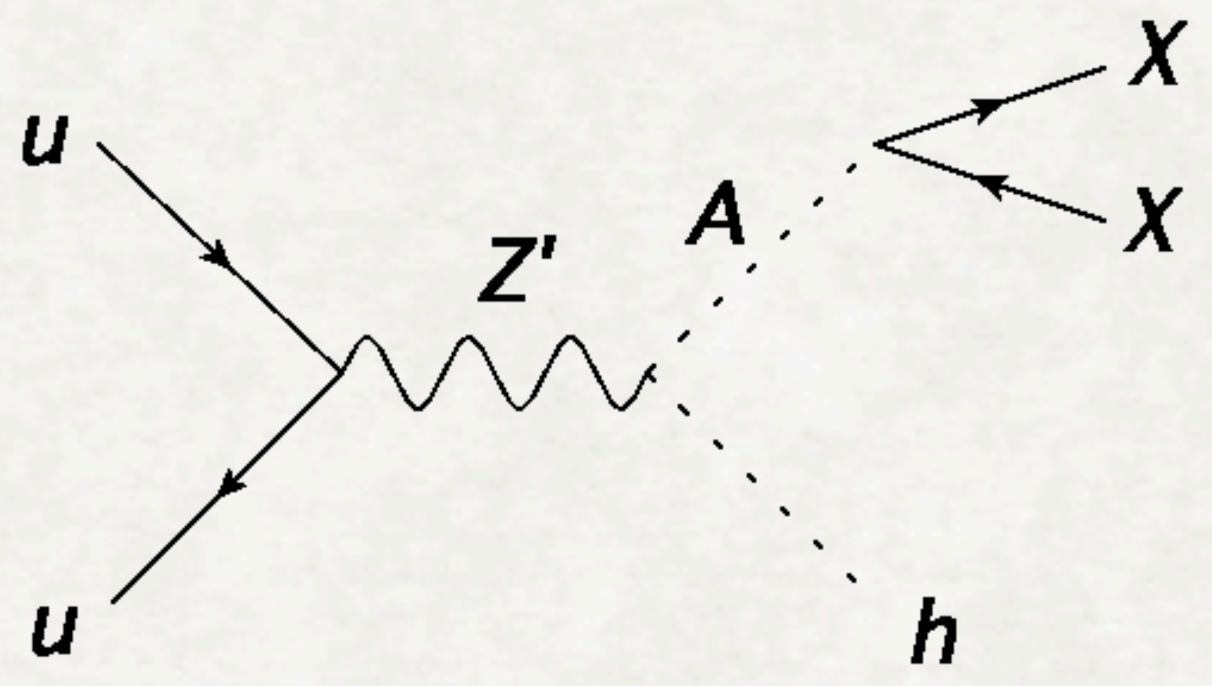
- Higgs sector extended with
  - an extra singlet - “dark Higgs” [M. Duerr et al, 1701.08780]
  - or a doublet (2HDM) - “dark Z′” [A Berlin et al, 1402.7074]

  which might or might not carry U(1)′ charge

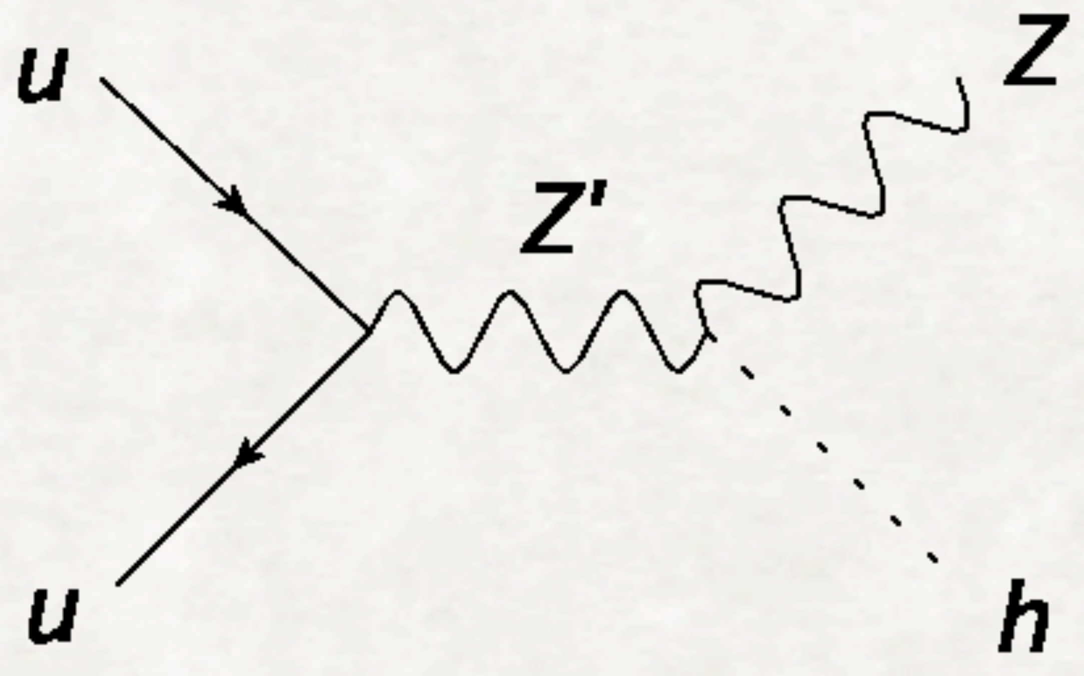
- Generally Z′ coupling only to quarks to avoid dilepton constraints

- Also constraints from EW measurements (Z-Z′ mixing) and dijets

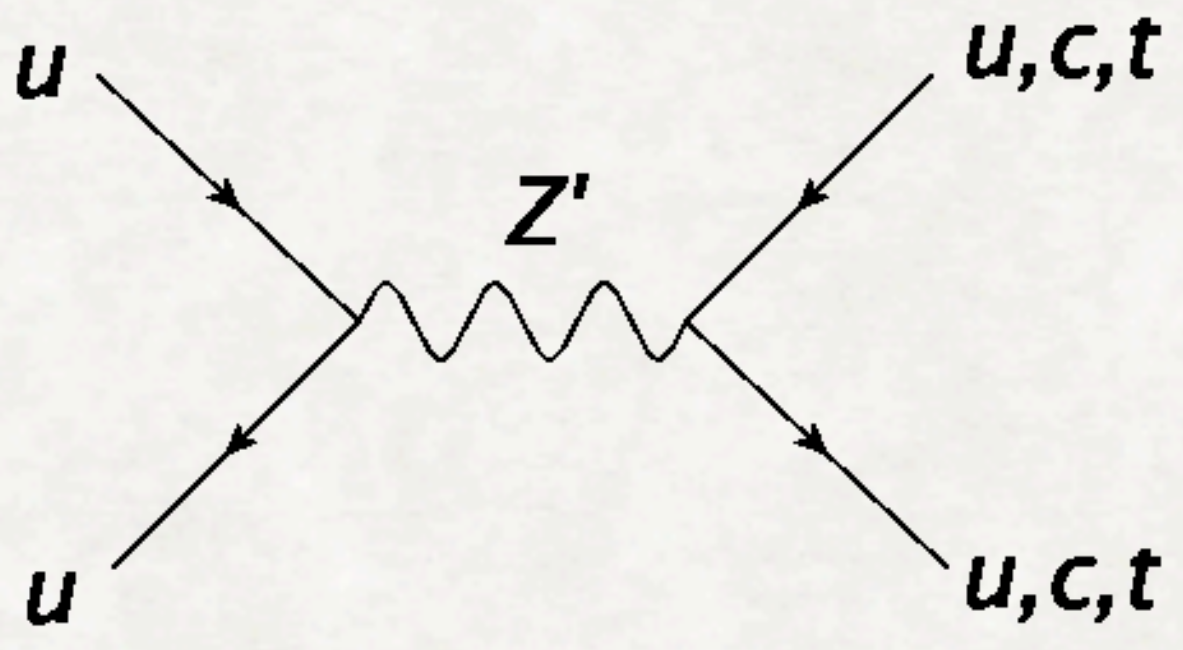
$h+E_T^{miss}$



Zh resonance



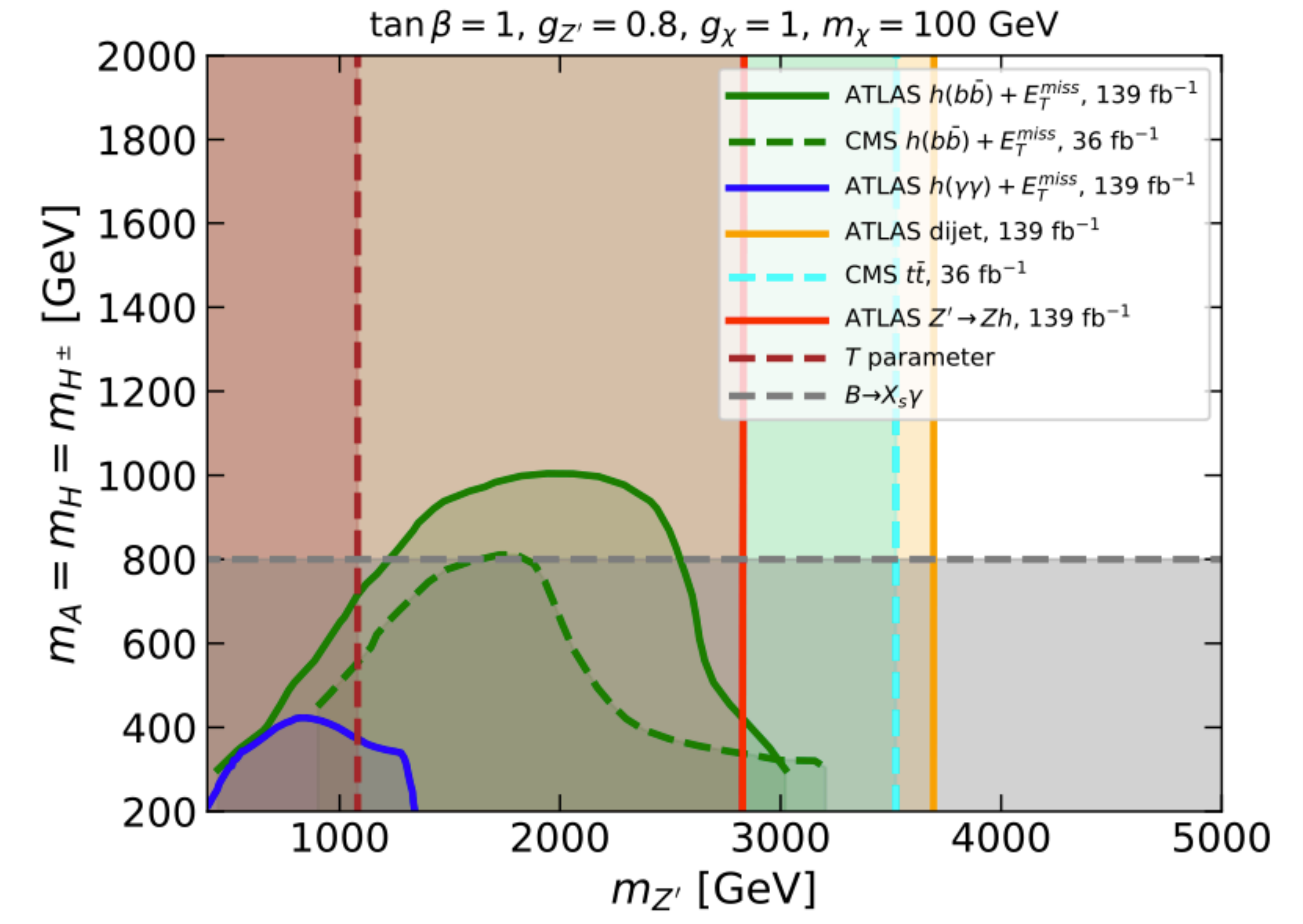
dijet/tt resonance



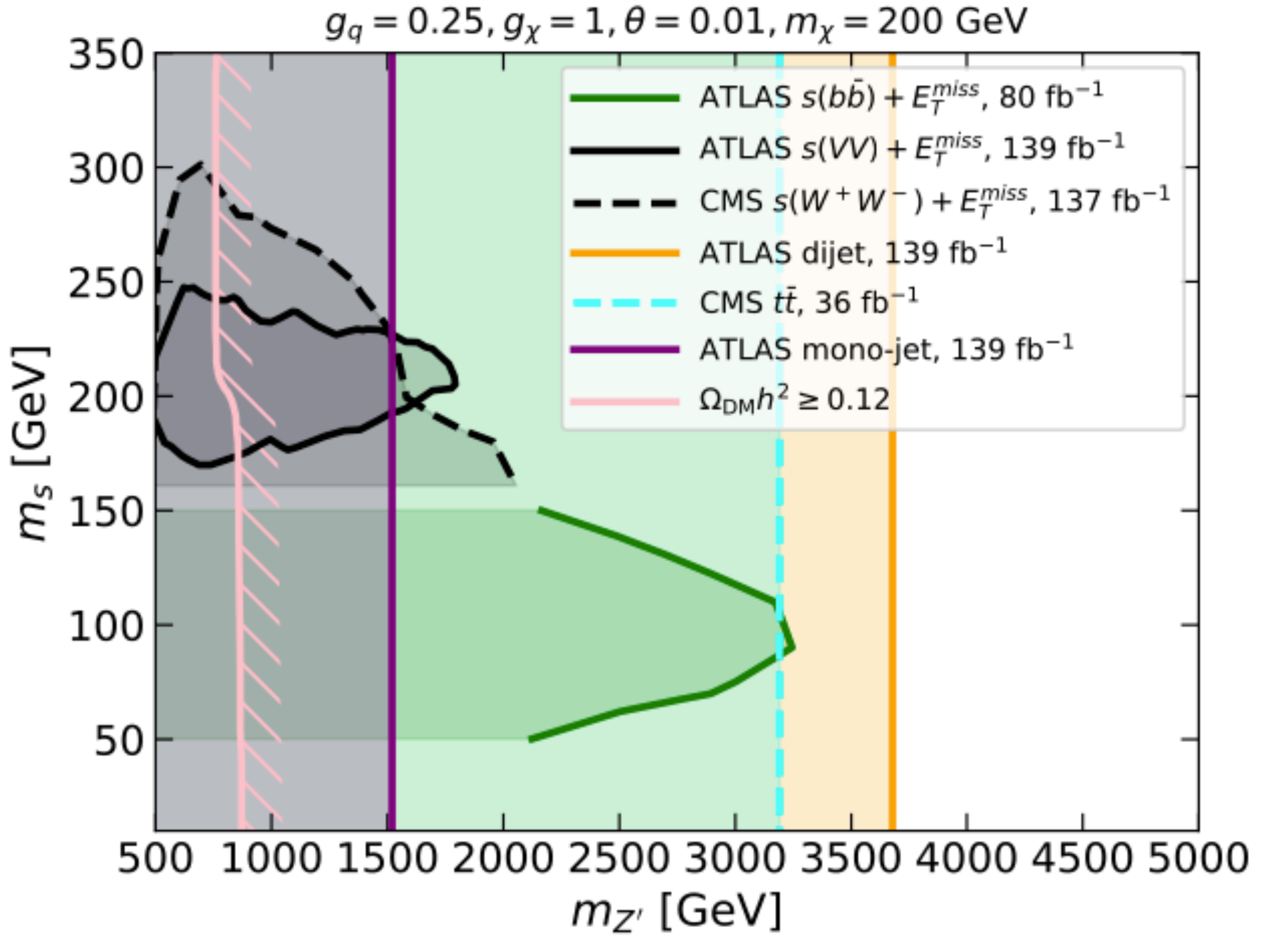
2HDM + vector: constraints

- For both models visible Z' decays provide more stringent constraints
- This seems hard to tune away
- LHC benchmarks do not consider this so far

2HDM+Z'



Dark Higgs



SA, Brandt, Haisch, Symmetry 13 (2021) 2406

We discussed that

1. There is a lot of complementarity between DM searches at colliders and DD/ID experiments

2. DD/ID experiments are blind to certain models colliders may be the only viable option to discover DM

3. Plethora of models being explored

There is still a lot to explore

Several models not covered in this talk under active investigation

- models with long-lived particles [SA, Brandt, Haisch, Symmetry 13 (2021) 2406, Haisch, Schnell, 2302.02735, ...]
- models with confining dark sectors [Bose et al, 2209.13128]

Extensions of standard benchmarks with relaxed assumptions / change of focus

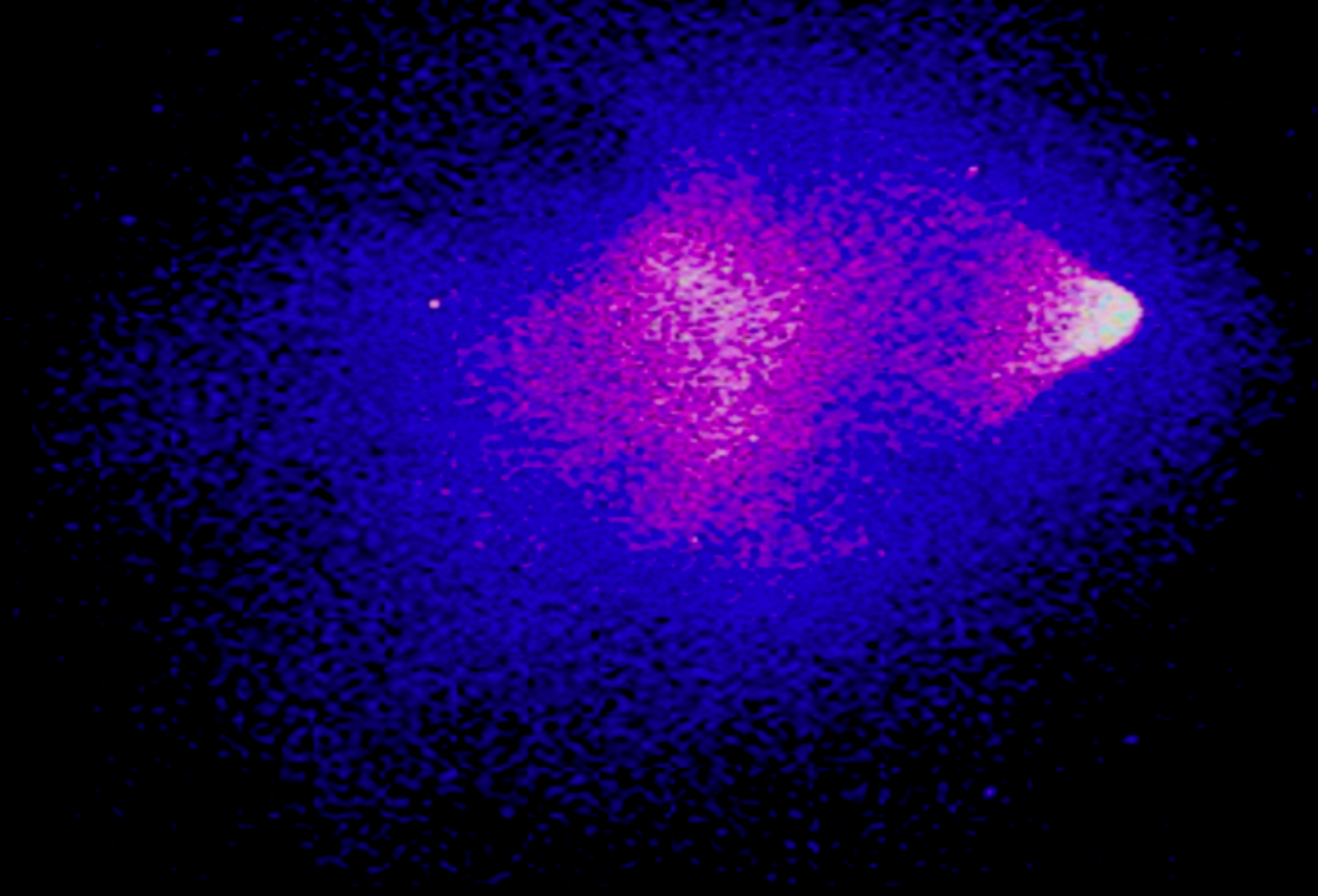
- hierarchical 2HDM [Butterworth et al, 2009.02220]
- Type-I in fermiophobic limit [Haisch, Malinauskas, 1712.06599]
- low-mass Higgses [Dutta et al, 2308.05653, Biekötter et al, 2203.13180, ...]

Completely new models not that widely explored so far

- fermionic portal to vector dark matter [Belyaev et al, 2204.03510]
- 3 Higgs doublet models [Hernandez-Sanchez et al, 2012.11621 + ...]

2024 LHC DM WG workshop

Roadmap of Dark Matter Models for LHC Run 3



13-17 May 2024

CERN

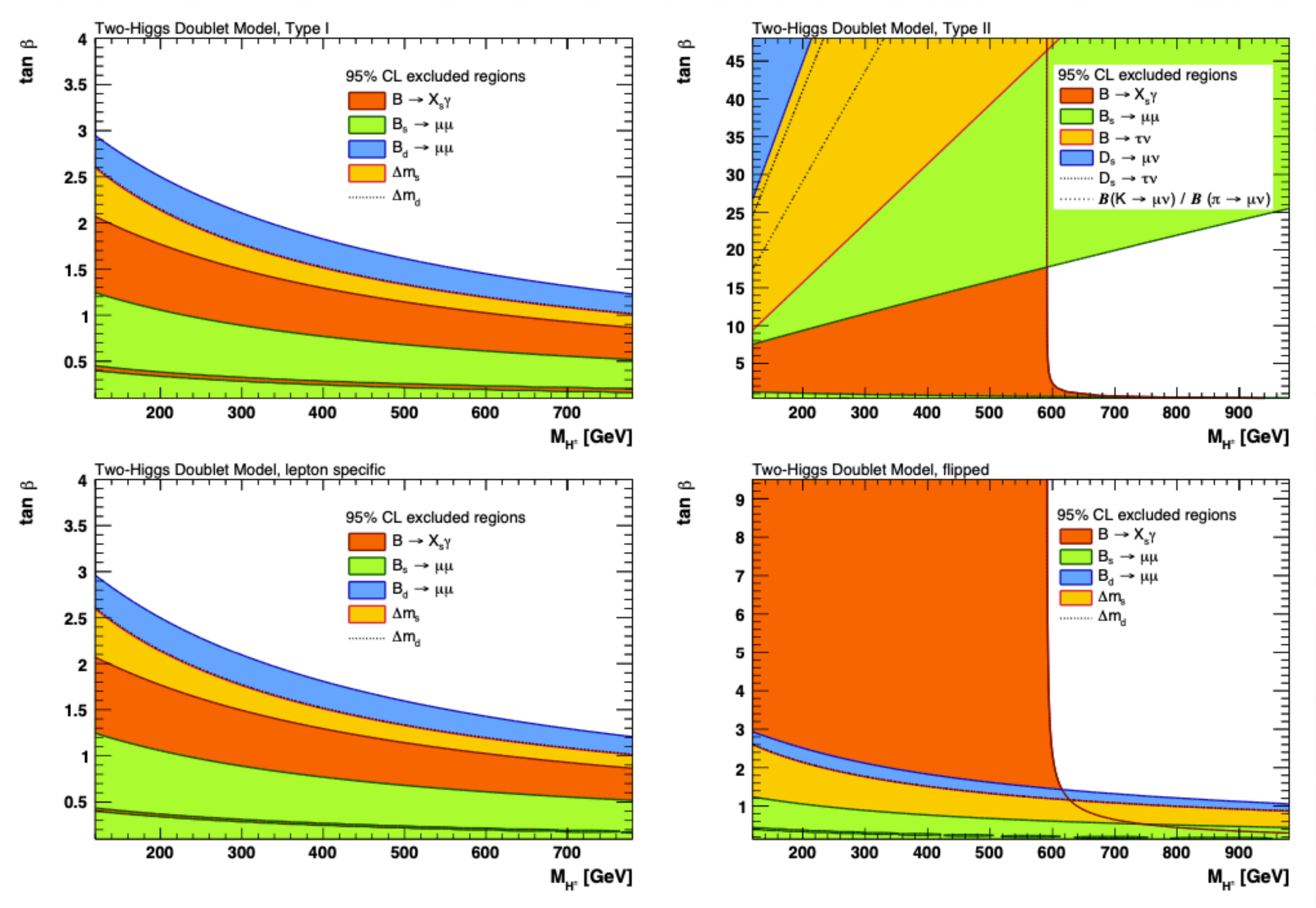
http://cern.ch/lhcdm24

Backup

2HDM couplings

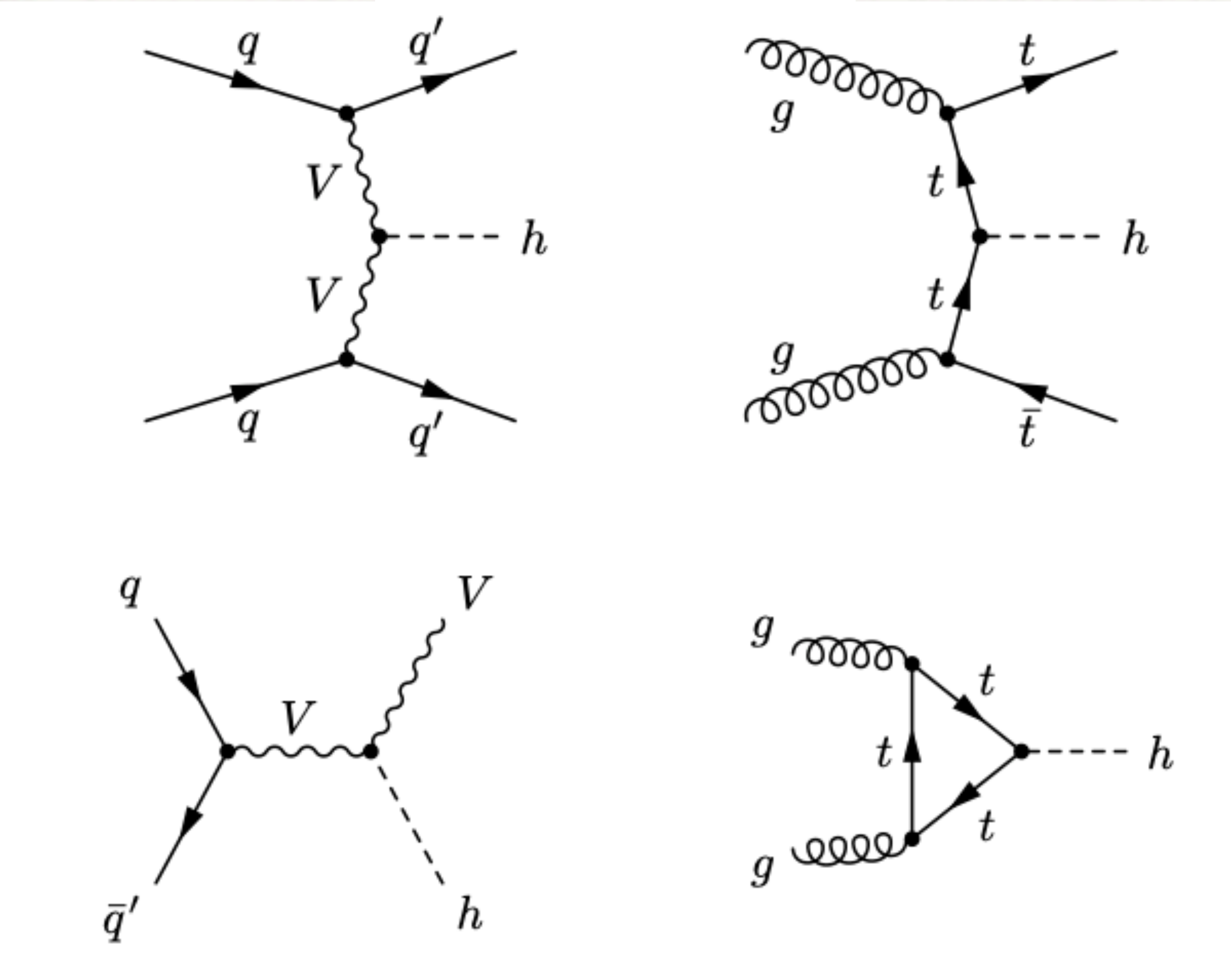
Coupling modifier	Type I	Type II
$\xi(h,u)$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
$\xi(h,d)$, $\xi(h,l)$		$s_{\beta-\alpha}-c_{\beta-\alpha}t_\beta$
$\xi(H,u)$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
$\xi(H,d)$, $\xi(H,l)$		$c_{\beta-\alpha}+s_{\beta-\alpha}t_\beta$
$\xi(A,u)$	$1/t_\beta$	$1/t_\beta$
$\xi(A,d)$, $\xi(A,l)$		t_β
$\xi(h,VV)$	$s_{\beta-\alpha}$	
$\xi(H,VV)$	$c_{\beta-\alpha}$	
$\xi(A,VV)$	0	

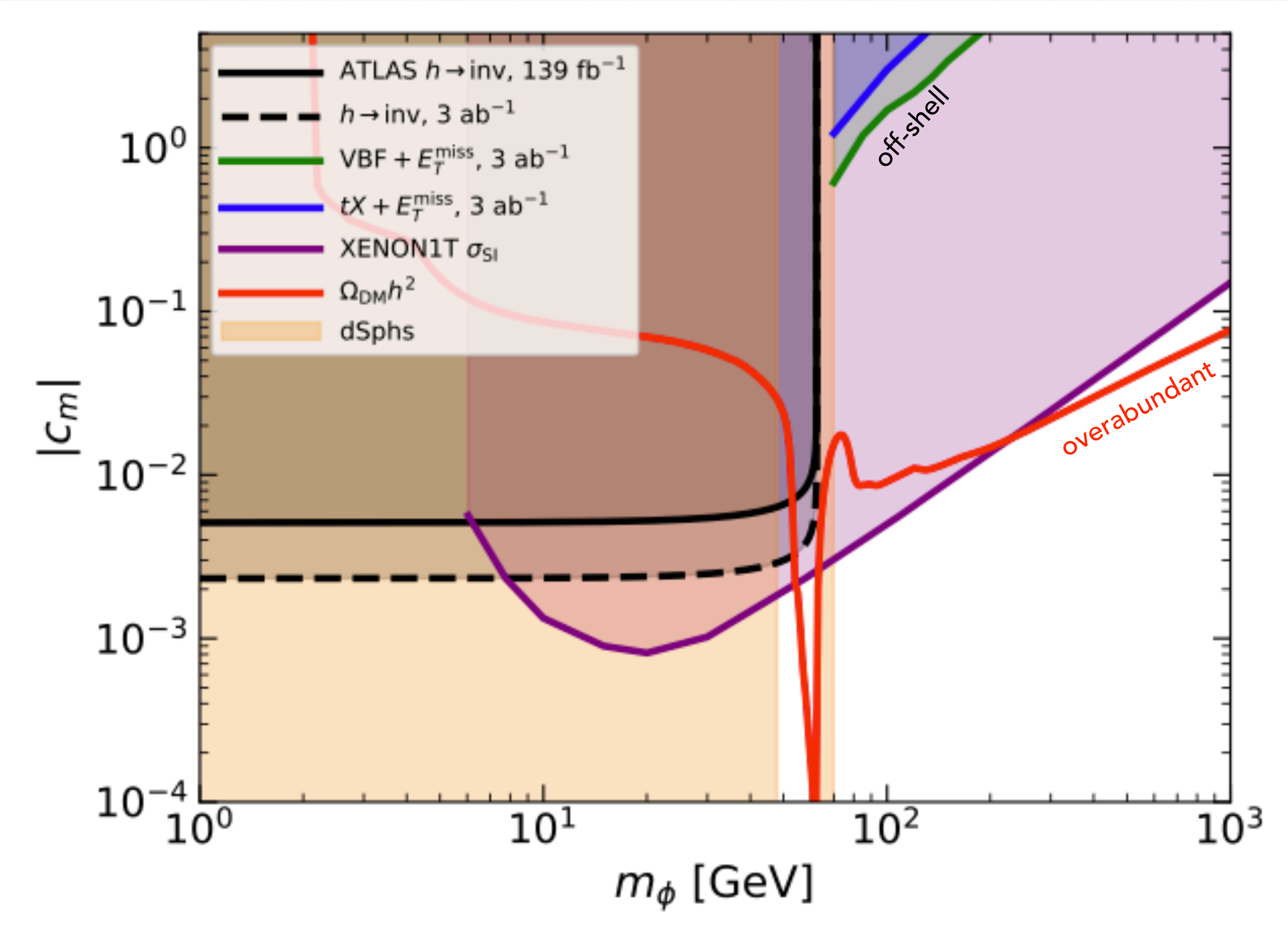
2HDM constraints



SM Higgs portal

$$c_m \phi^2 (H^\dagger H)$$





- DM scalar - dim 4 operator
- LHC constraints relevant for m < 5 GeV
- ID constraints from Fermi-LAT assume **ϕϕ**→bb and Ωh^2=0.12, so model dependent

Rudhofer et al, 1910.04170; Haisch et al, 2107.12389; SA, Brandt, Haisch 2109.13597

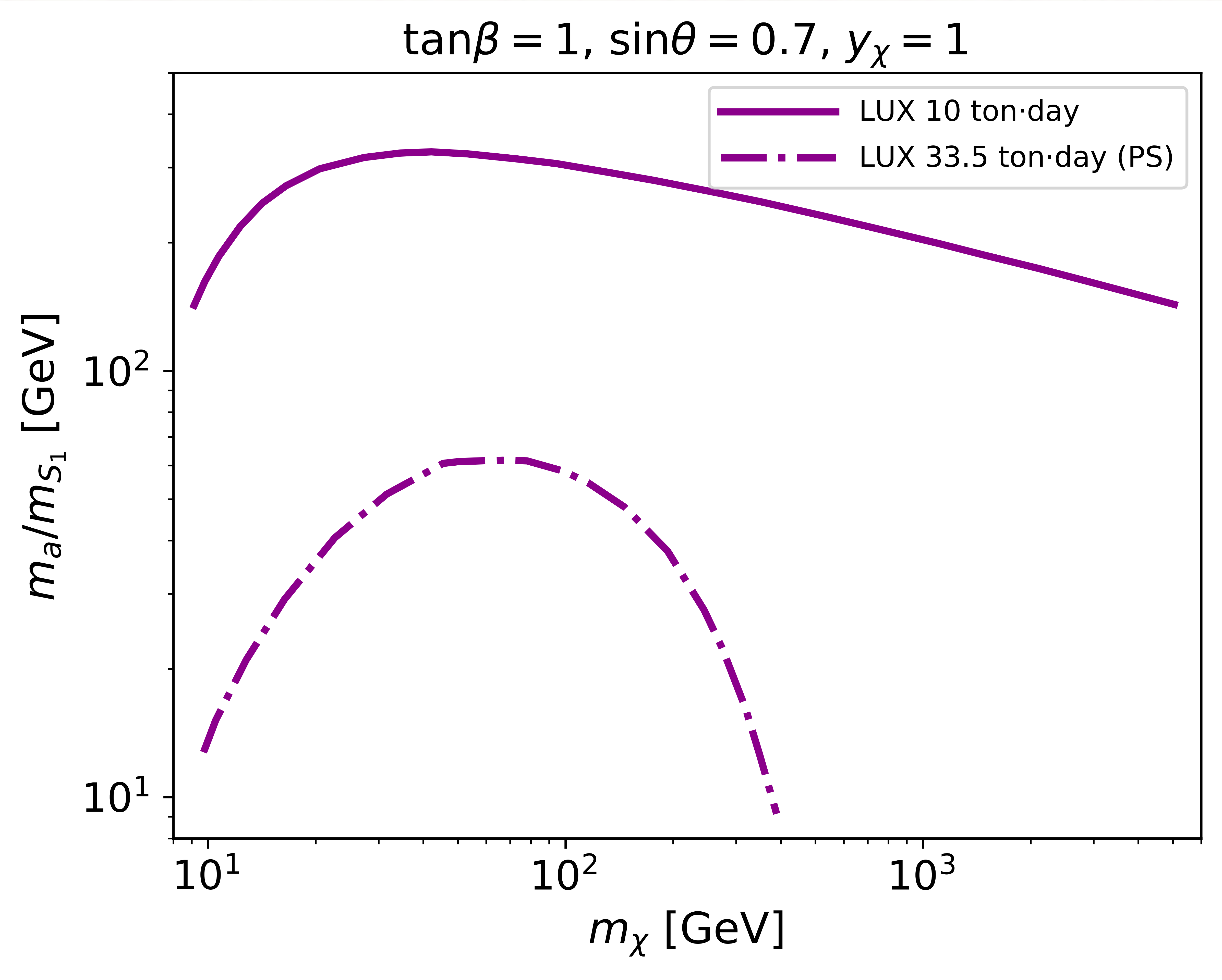
2HDM + scalar: WIMP-nucleon cross-section

Wilson coefficient of $\chi\bar{\chi}N\bar{N}$

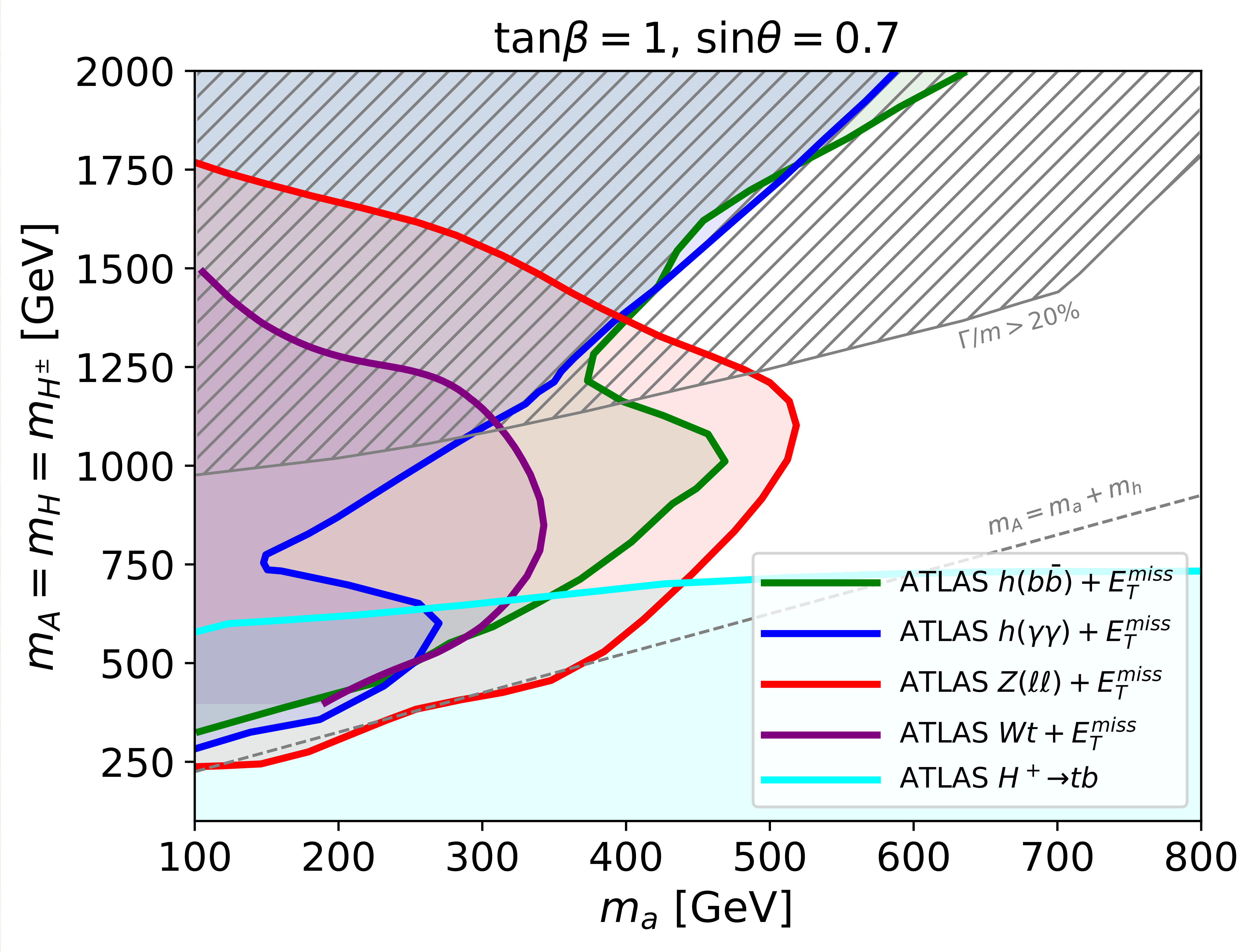
$$c_N = \frac{m_N}{v}\frac{y_\chi \sin(2\theta)}{2}\left(\frac{1}{m_{S_1}^2} - \frac{1}{m_{S_2}^2}\right) \times \left[\cot\beta\, f_{T_u}^N - \tan\beta \sum_{q=d,s} f_{T_q}^N + \frac{4\cot\beta - 2\tan\beta}{27} f_{T_G}^N\right]$$

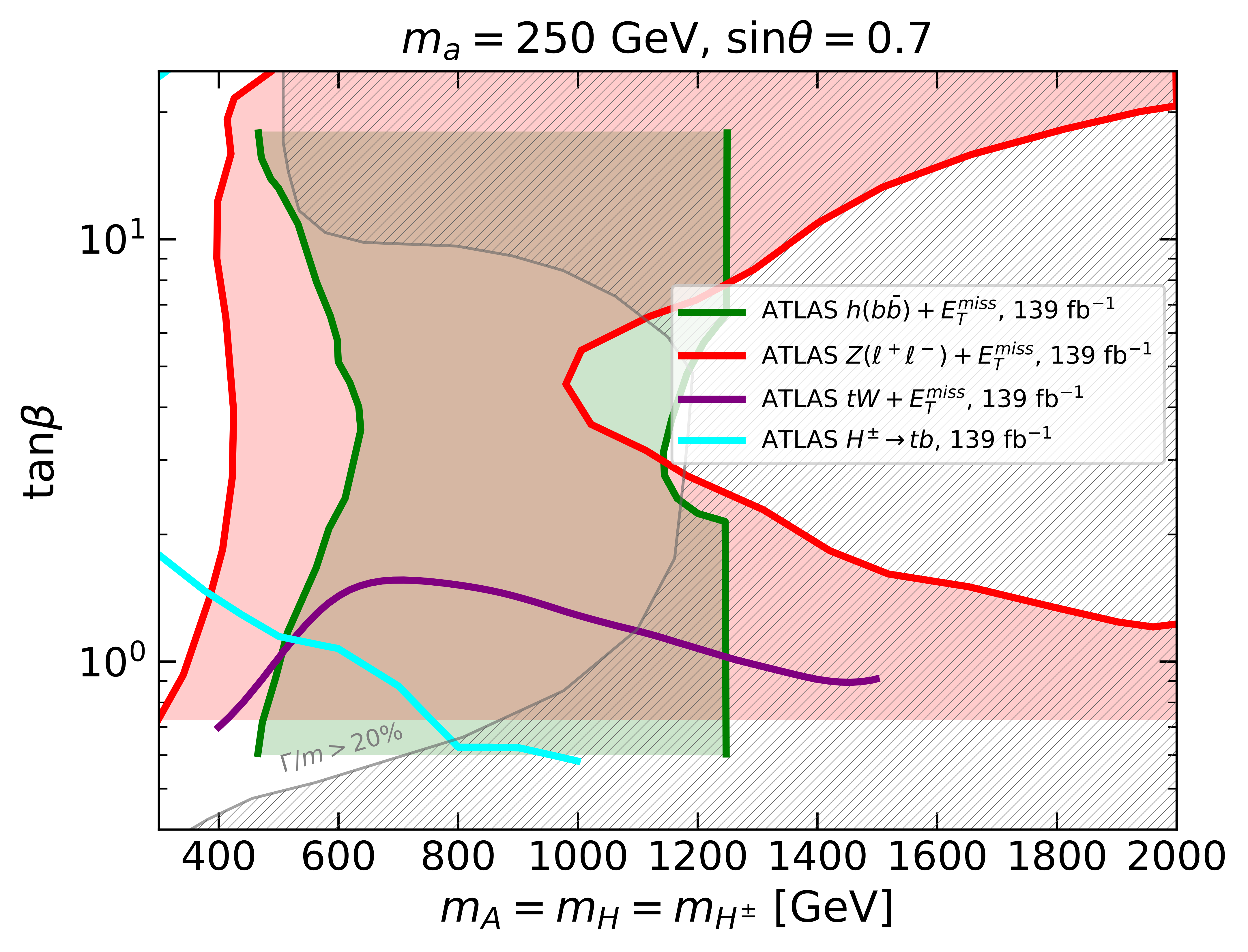
- Up and down-quark contributions interfere destructively in Type-II
- Numerically close to 0 for tan**β** ≅ 1

DD scalar vs pseudoscalar

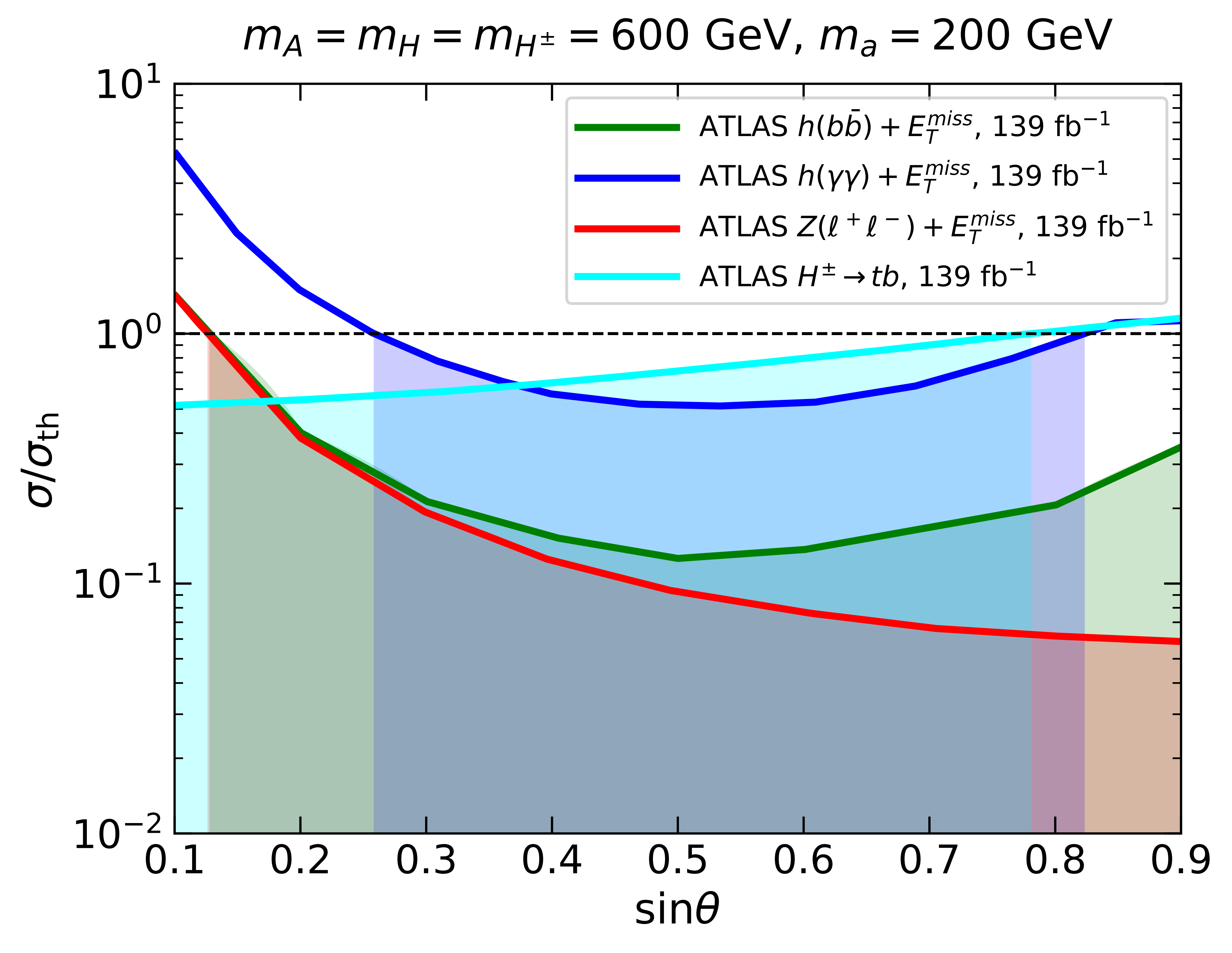


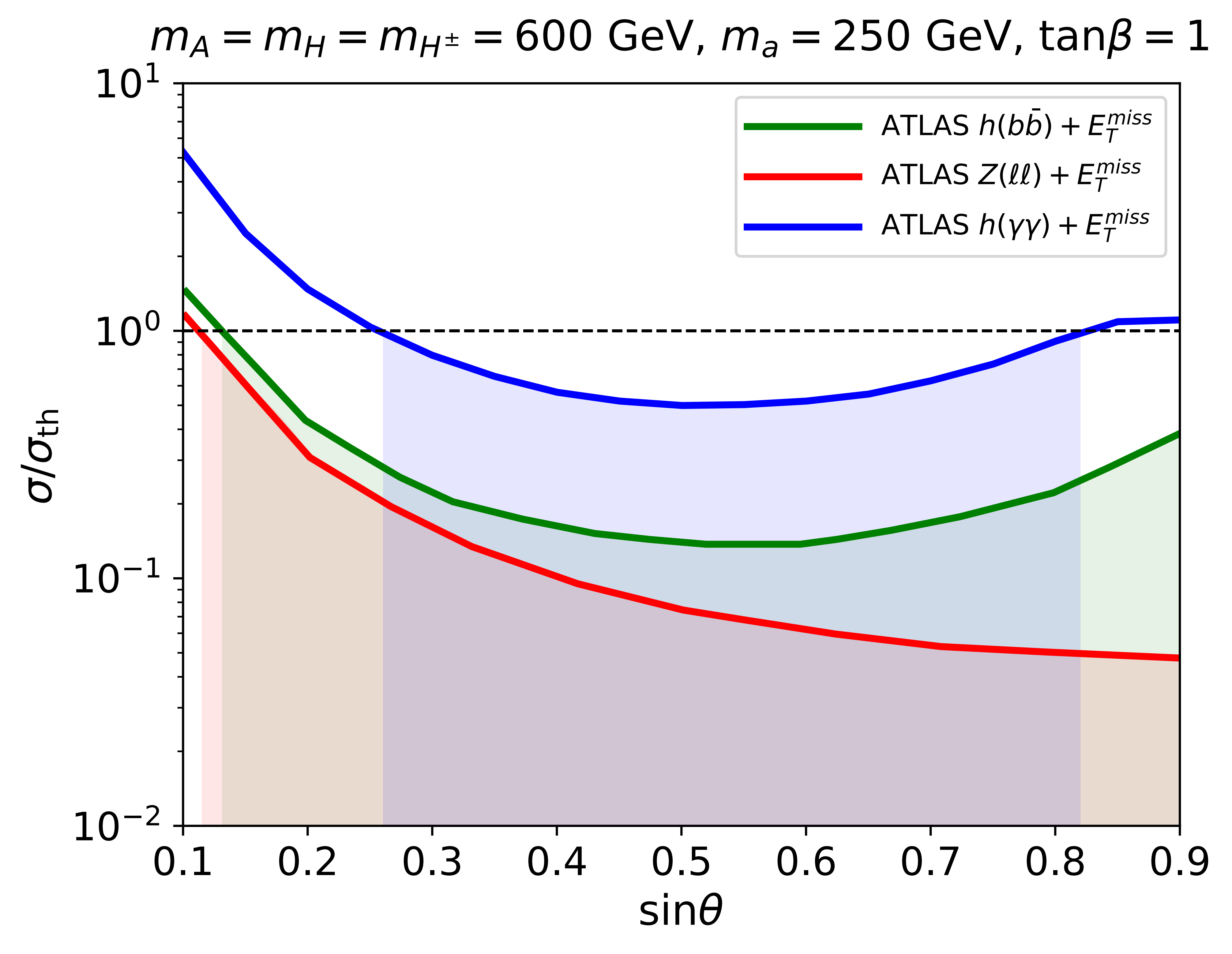
2HDM+a – large mixing



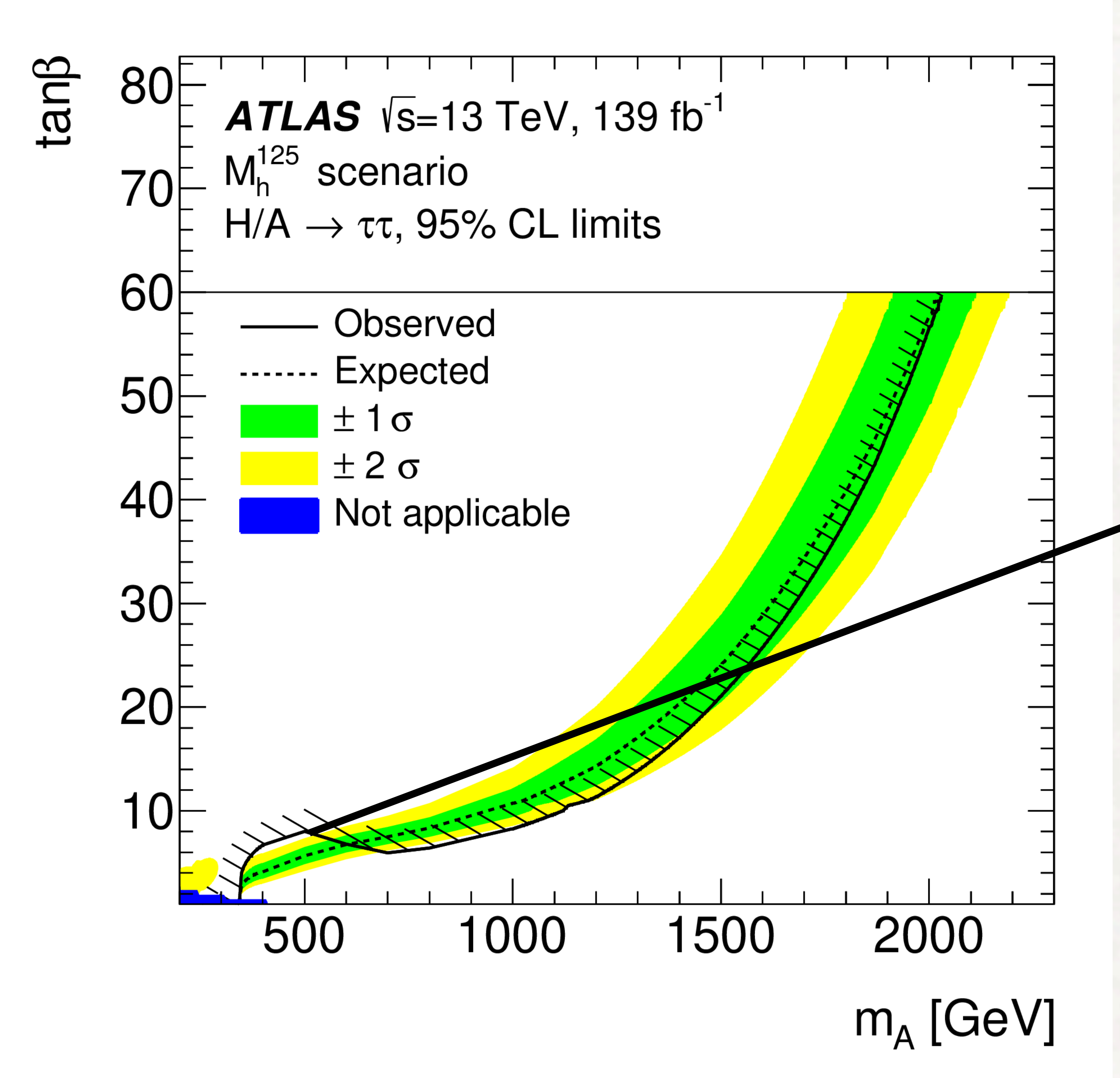


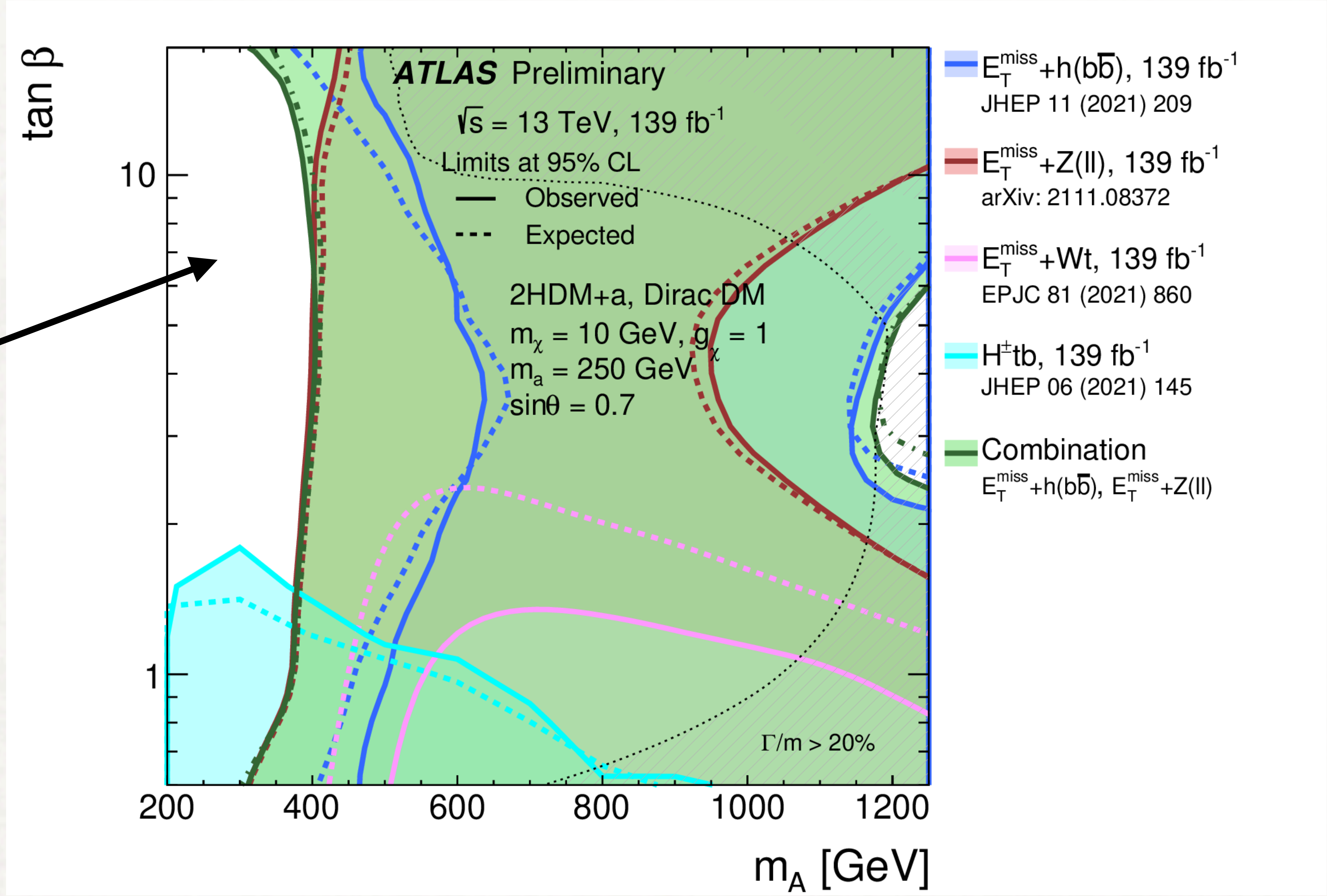
2HDM+a - mixing angle scan





Constraints from taus





Phys. Rev. Lett. 125 (2020) 051801

Higgs width constraints

$$\Gamma(h \to aa) = \frac{g_{haa}^2 m_h}{32\pi}\sqrt{1-\frac{4m_a^2}{m_h^2}} \quad > \Gamma_h^{u.l.} = 1.1\ \text{GeV}$$

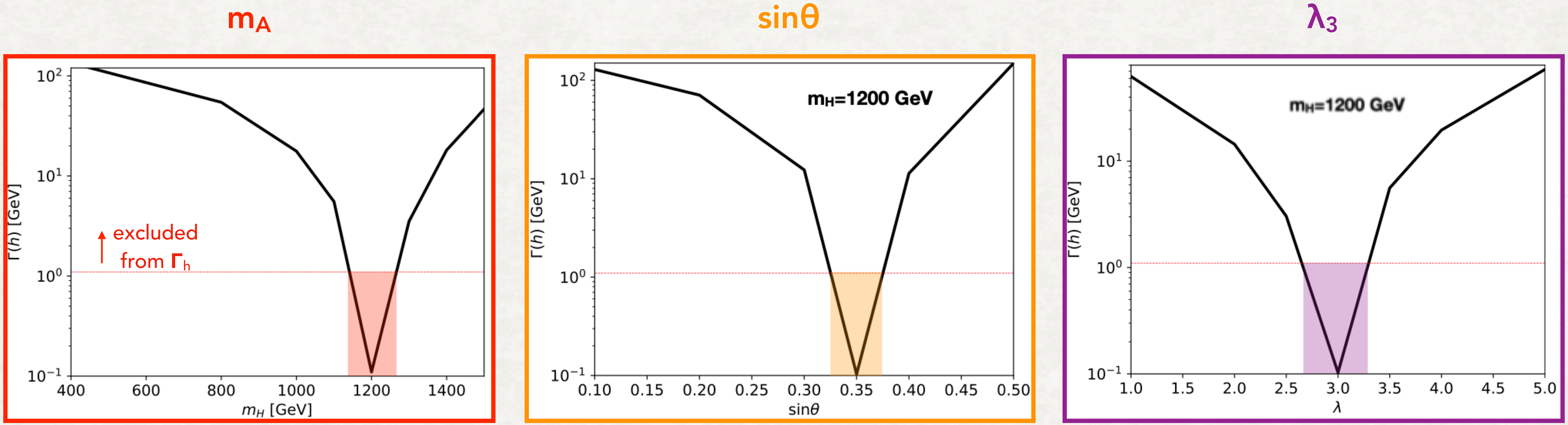
$$g_{haa} = \frac{1}{m_h v}\left[2\left(m_A^2 - m_a^2 + \frac{m_h^2}{2} - \lambda_3 v^2\right)\sin^2\theta - 2(\lambda_{P1}\cos^2\beta + \lambda_{P2}\sin^2\beta)v^2\cos^2\theta\right]$$

$$= \frac{1}{m_h v}\left[2\left({m_A}^2 - m_a^2 + \frac{m_h^2}{2}\right)\sin^2\theta - 2\lambda_3 v^2\right]$$

cos(**β**-**α**)=0

$m_A = m_H = m_{H+}$

$\lambda_3 = \lambda_{P1} = \lambda_{P2}$

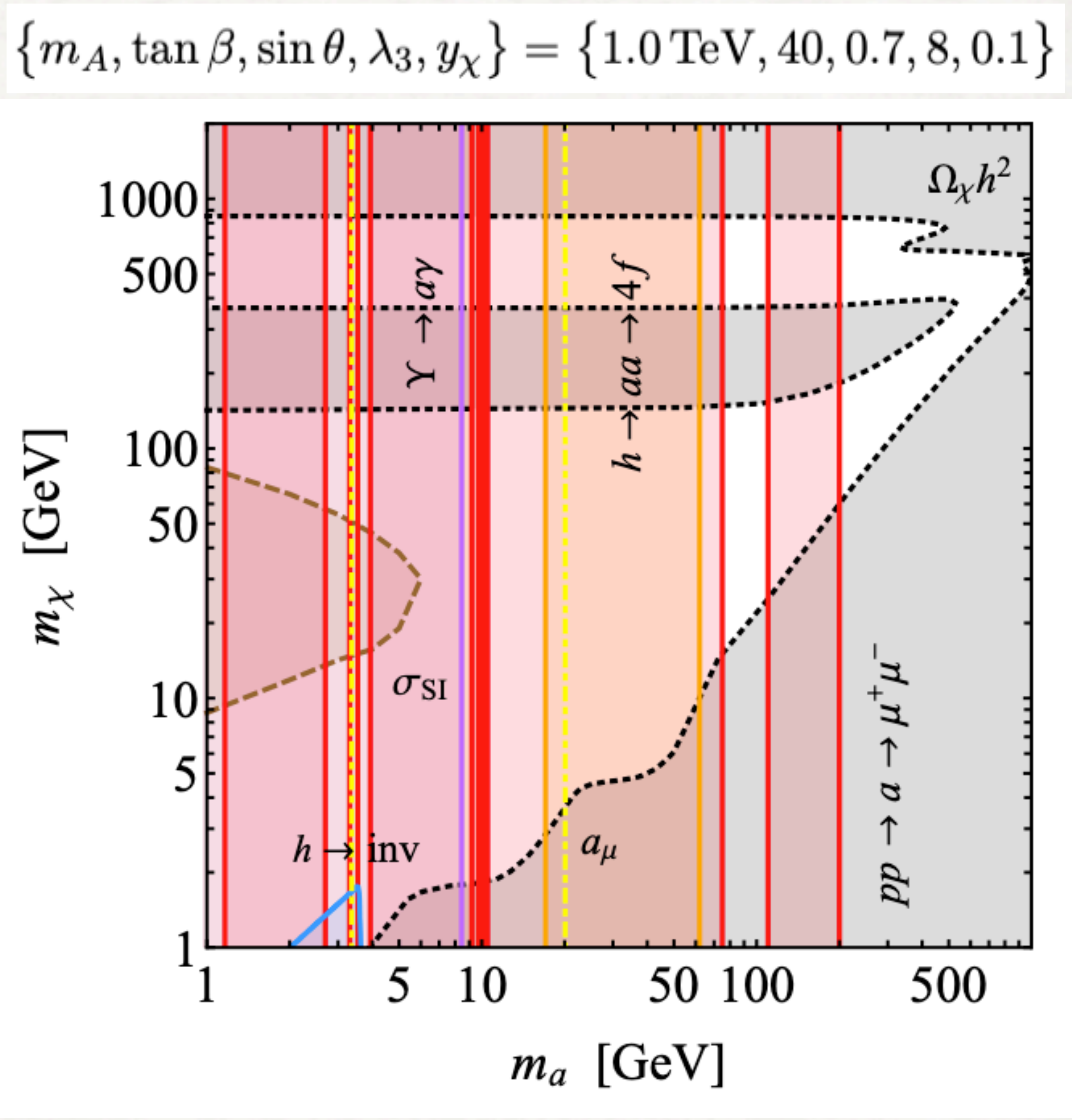


LHC vs g-2

- Original idea from Arcadi, Djouadi & Queiroz (2112.11902) to simultaneously explain DM & muon g-2
- Can also evade constraints from Γ_h
- Large tan**β** and small m_a needed to get the correct sign for δa_μ
- h→4f extend down to very low m_χ because $\Gamma(a\to\chi\chi)\sim y_\chi^2\cos^2\theta=0.005$
- h→inv has small BR and MET spectrum very soft so mono-h(bb) has no sensitivity

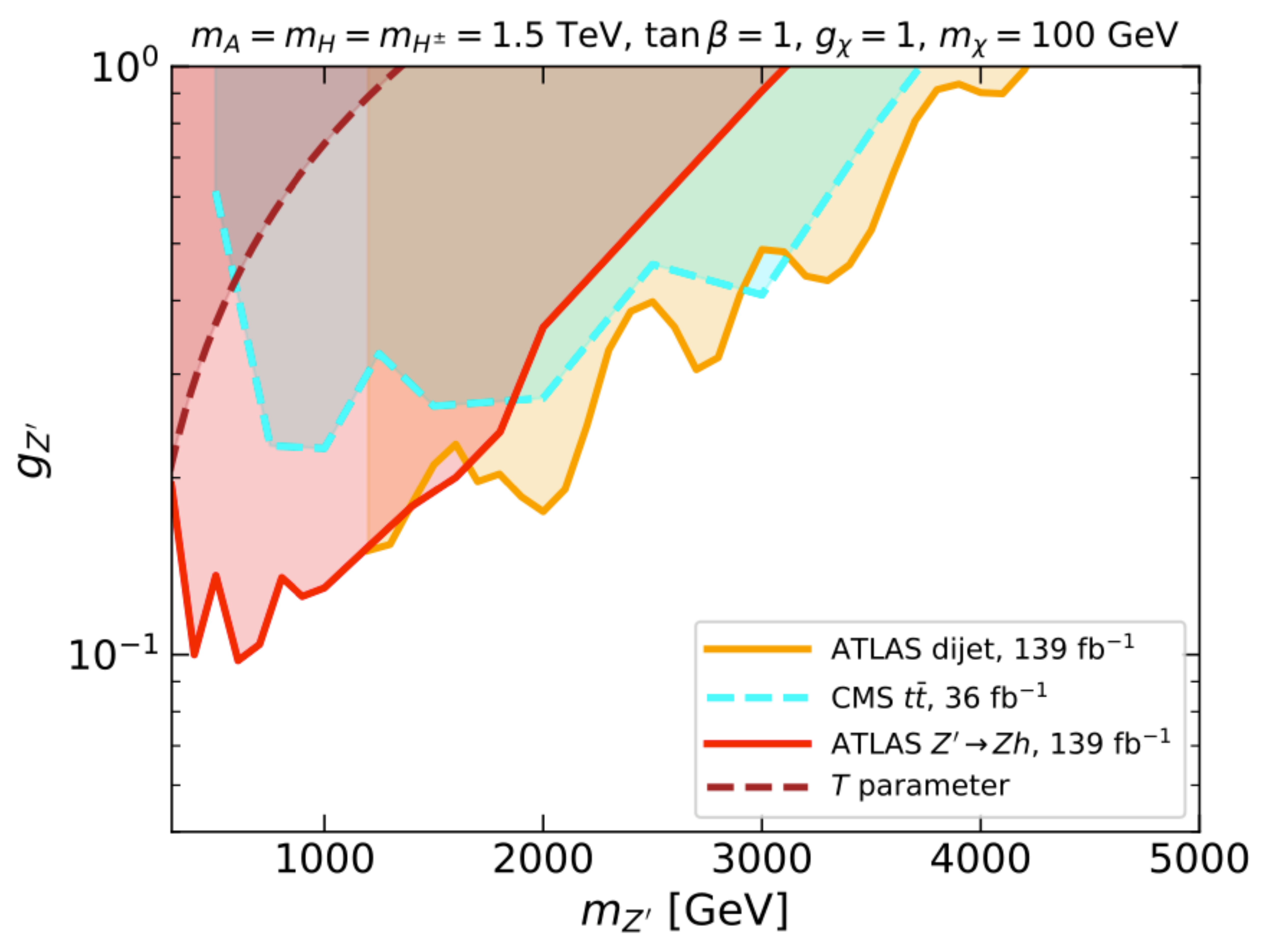
However

1. g-2 motivated region already ruled out
2. Non-perturbative Haa coupling (g_{Haa} ~ 40) leading to $\Gamma_H > m_H$ over the whole m_a-m_χ plane

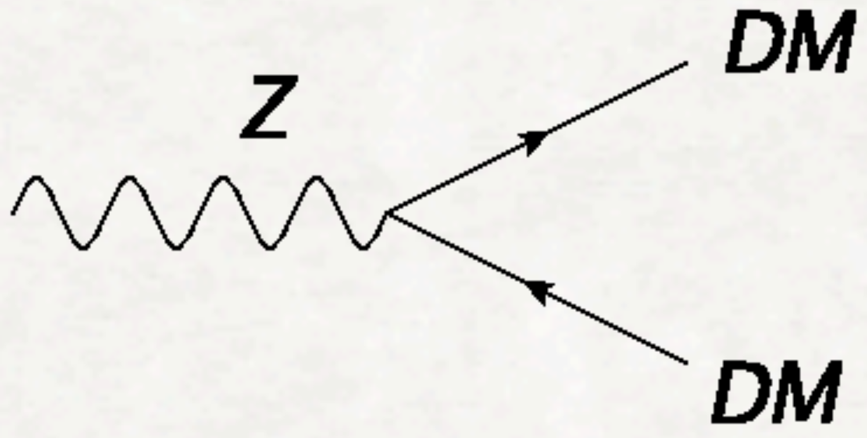


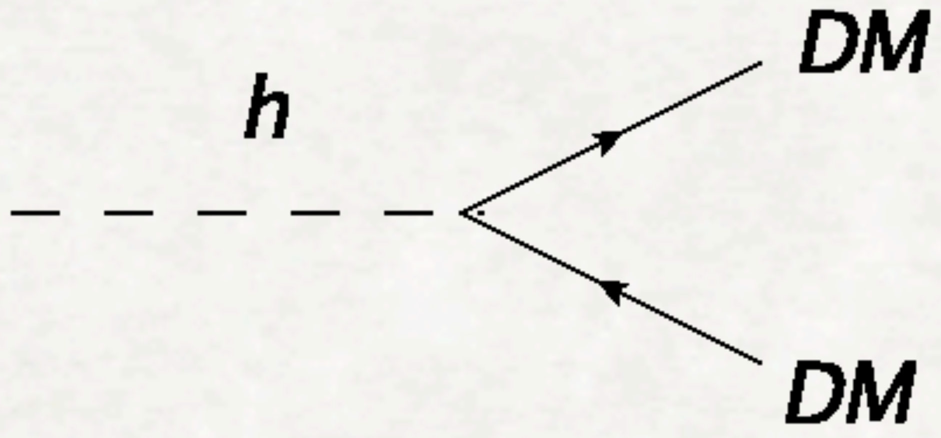
SA, Haisch, 2202.12631

2HDM+Z′: coupling scan



Higgs vs Z portal





$$\mathrm{BR}(h \to \mathrm{inv}) \sim \frac{g_h^2 m_h}{\Gamma(h)} \qquad \mathrm{BR}(\mathrm{Z} \to \mathrm{inv}) \sim \frac{g_Z^2 m_Z}{\Gamma(\mathrm{Z})}$$

$$\frac{g_h}{g_Z} = \sqrt{\frac{\mathrm{BR}(\mathrm{h} \to \mathrm{inv})}{\mathrm{BR}(\mathrm{Z} \to \mathrm{inv})} \cdot \frac{m_Z}{m_h} \cdot \frac{\Gamma(h)}{\Gamma(\mathrm{Z})}} \sim 0.4$$

$\sim 10^2$ $\quad$ $\sim 10^{-3}$