Searching for dark matter in extended Higgs sectors

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HEP 2022 - Thessaloniki, 15/6/2022

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

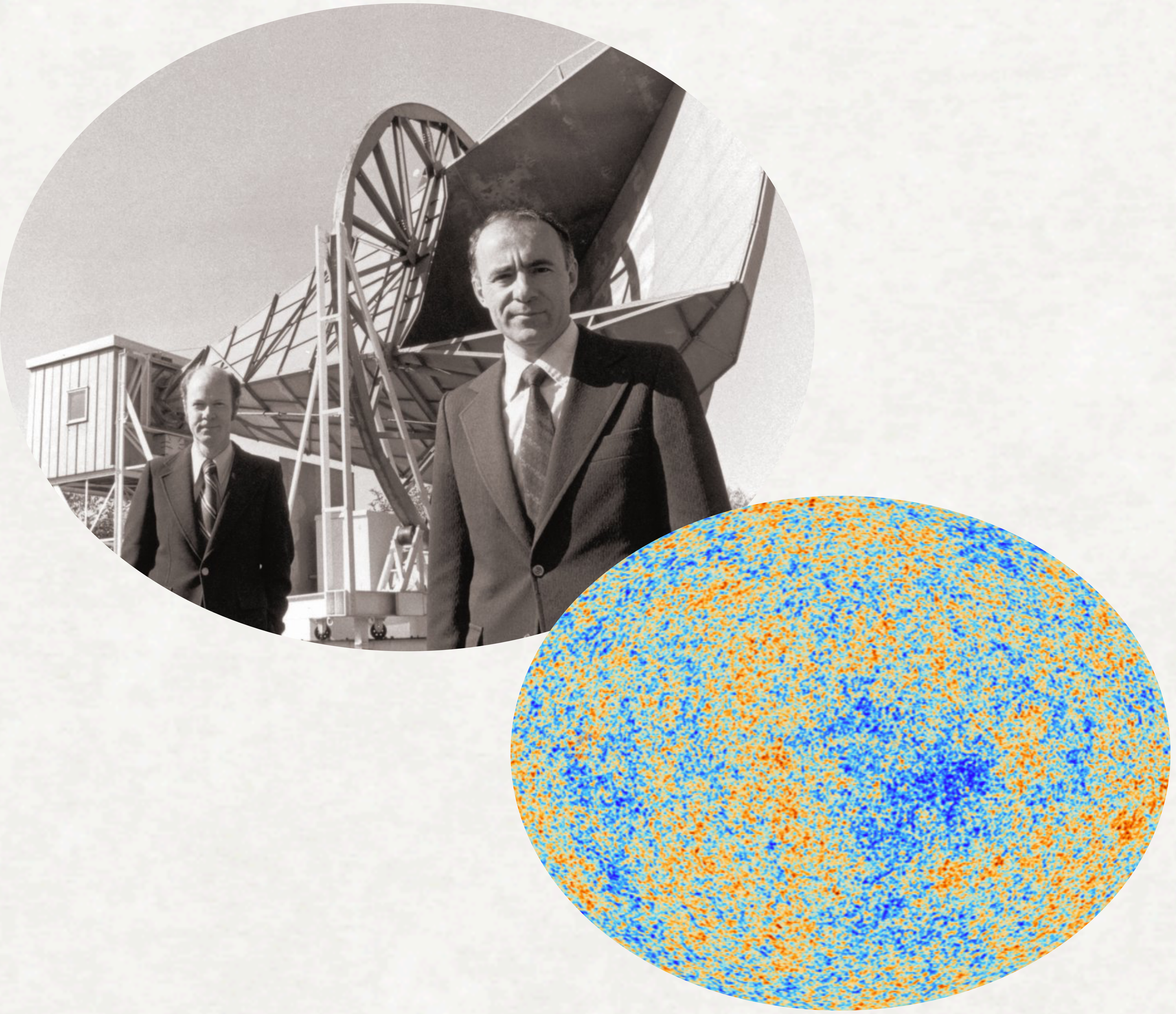
UNI FREIBURG

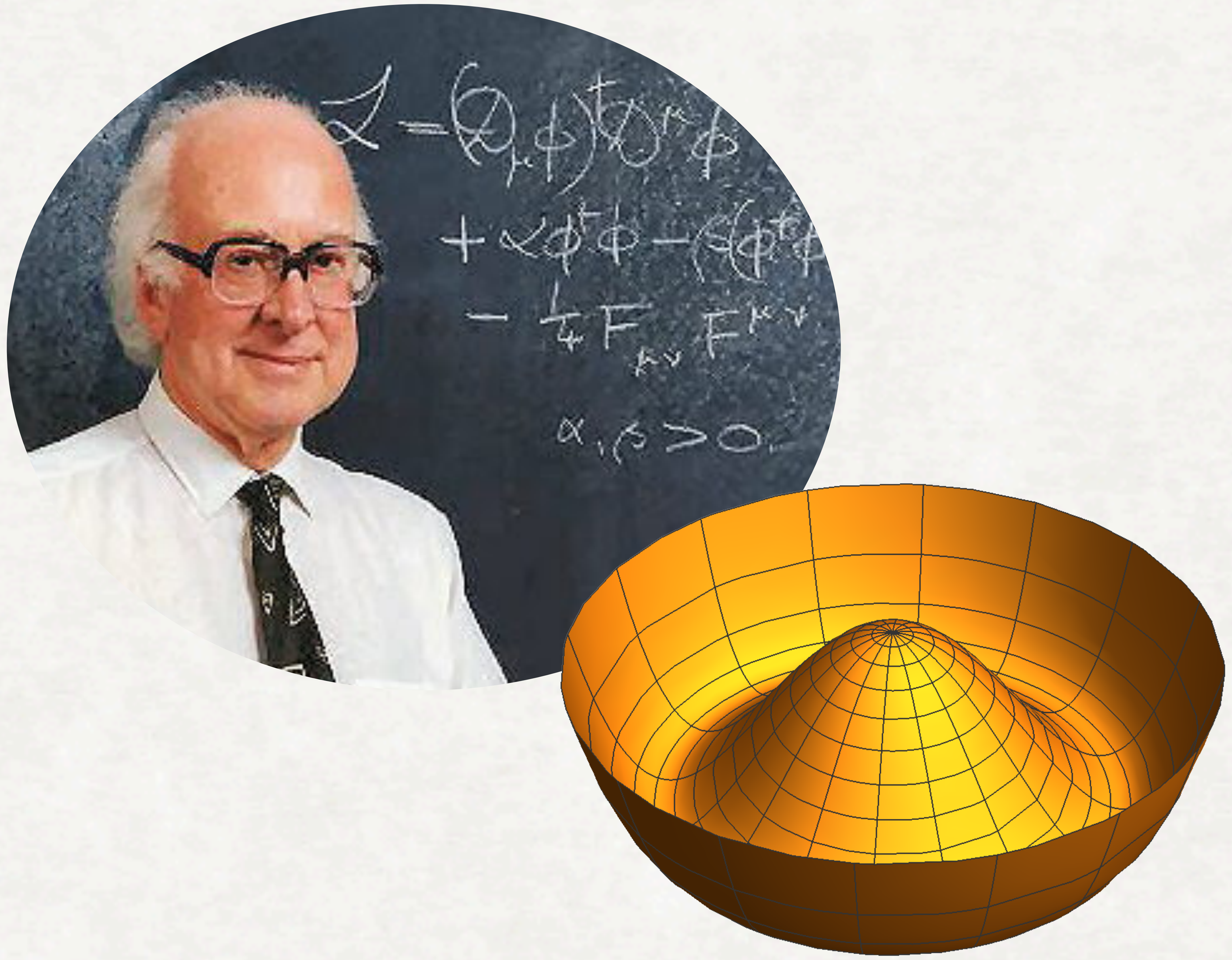
1964

annus mirabilis for particle physics & cosmology

CMB radiation

Higgs mechanism



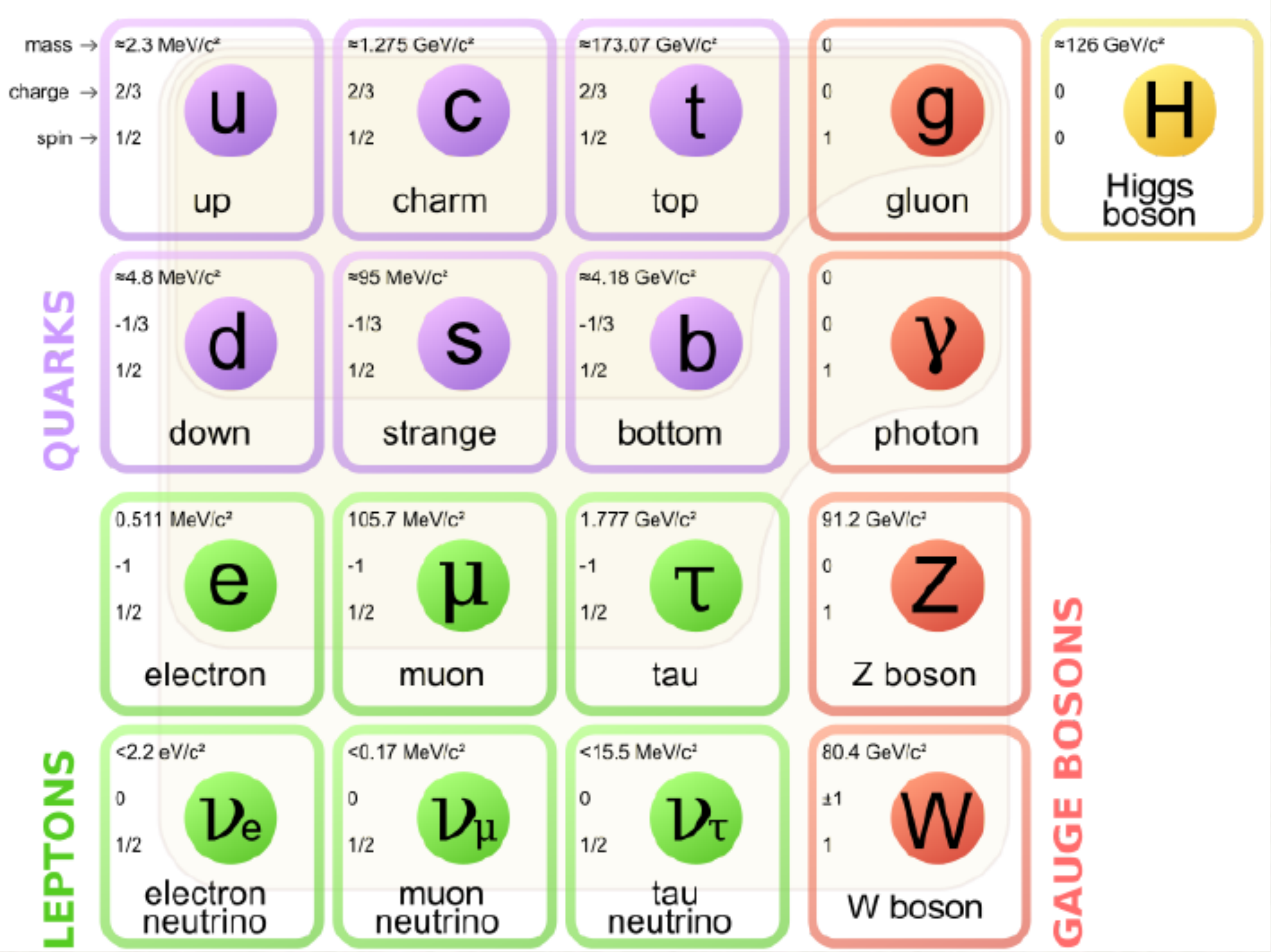


birth of cosmology

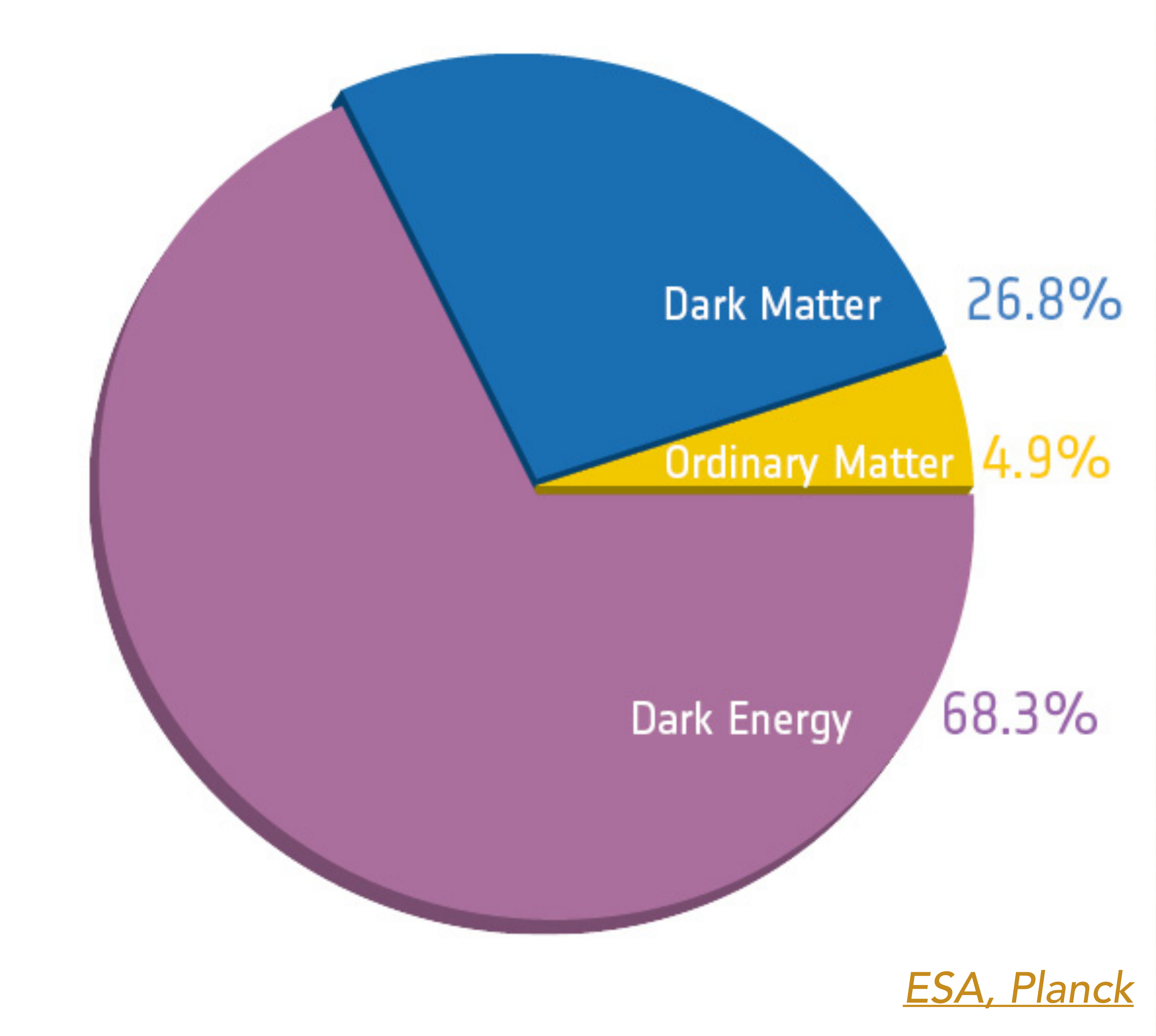
SM of particle physics

The two Standard Models

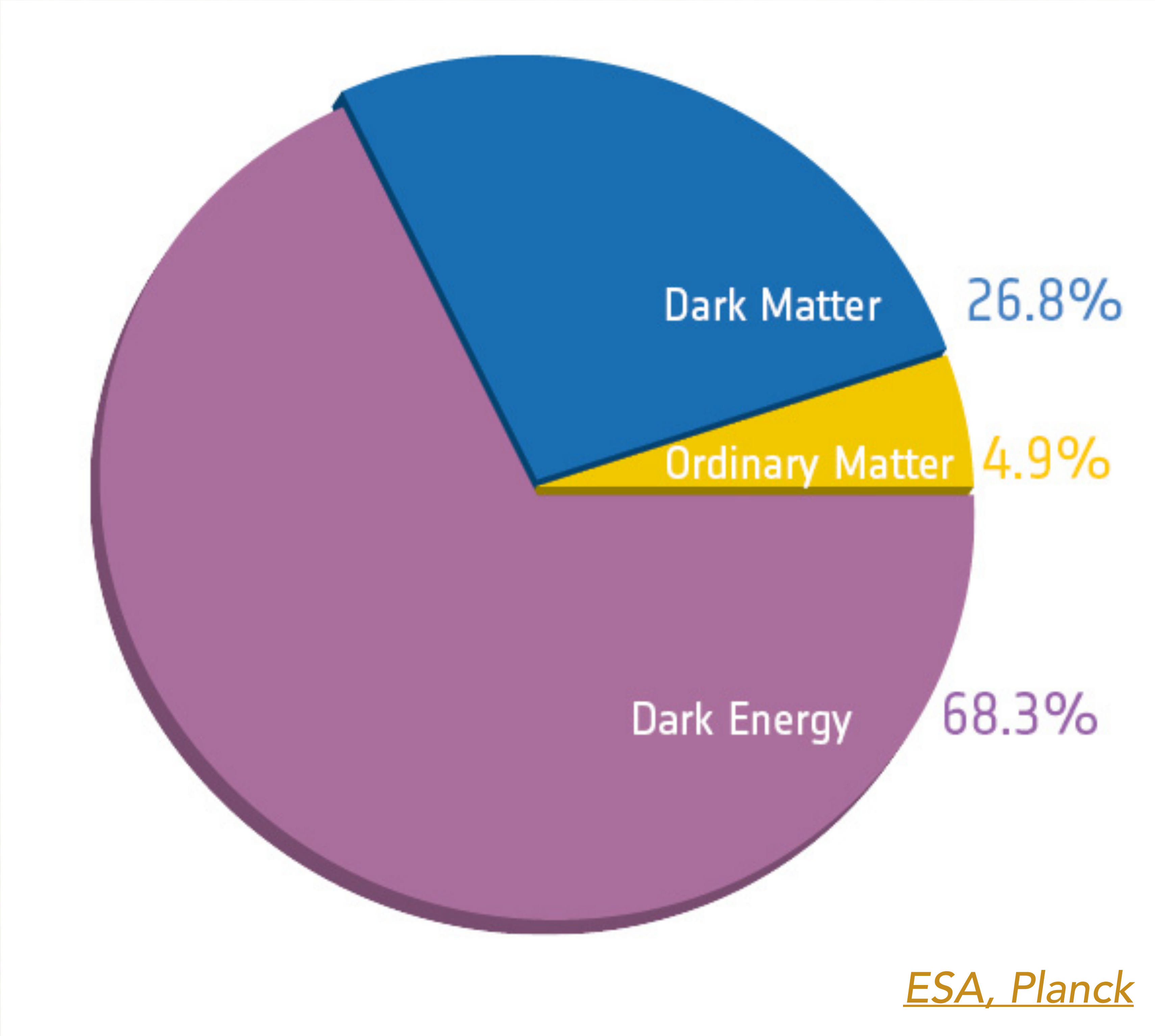
particle physics



cosmology



The big open questions



Baryon Asymmetry

why matter dominates over antimatter?

Dark Matter

What is the nature of DM?

Dark Energy

What is the nature of DE?

+ are these connected with the Higgs sector?

Is there a connection to the Higgs boson?

1. **EW phase transition can trigger baryogenesis**
   - ➡ testable @ LHC
   - ➡ see talk by I. Kalaitzidou on Thursday

Kuzmin, Rubakov, Shaposhnikov, PLB 155 (1985) 36
Shaposhnikov, NPB 287 (1987) 757 (1987)
Nelson, Kaplan, Cohen, NPB 373 (1992) 453

2. **Higgs sector can act as a portal to the dark sector**
   - ➡ this talk

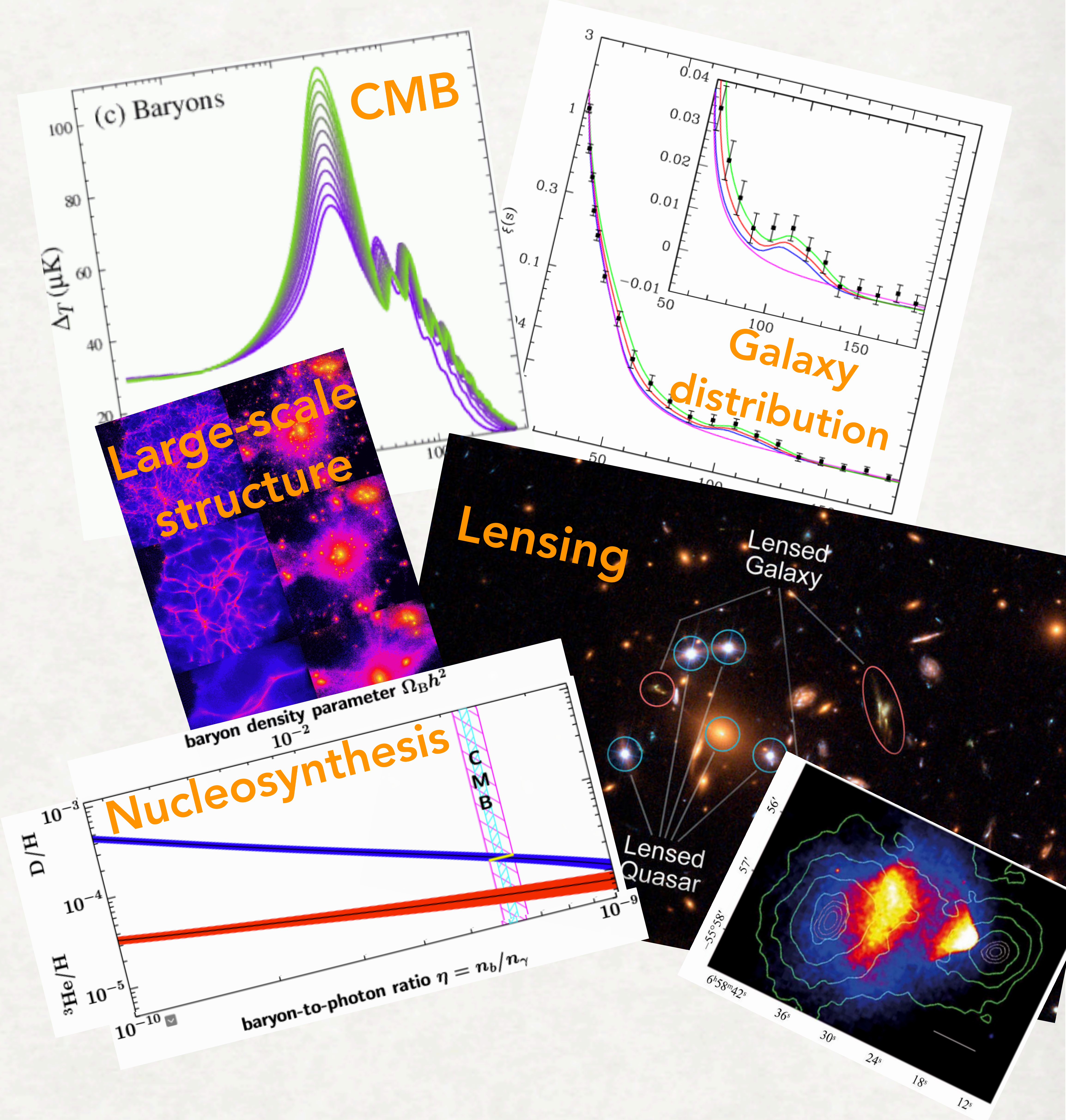
Silveira, Zee, PLB 161 (1985) 136
Ipek et al, Phys. Rev. D 90 (2014) 055021
Bell et al, JCAP 03 (2017) 015
Berlin et al, JHEP 06 (2014) 078
Duerr et al, JHEP 09 (2016) 042

3. **Scalar bosons ubiquitous in cosmology**
   - ➡ future

Brax, RPP 81 (2018) 016902
Gubitosi et al JCAP 02 (2013) 032
Bezrukov, Shaposhnikov, PLB 659 (2008) 703
Germani, Kehagias, PRL 105 (2010) 011302
Burrage et al, JCAP 11 (2018) 036

DM properties

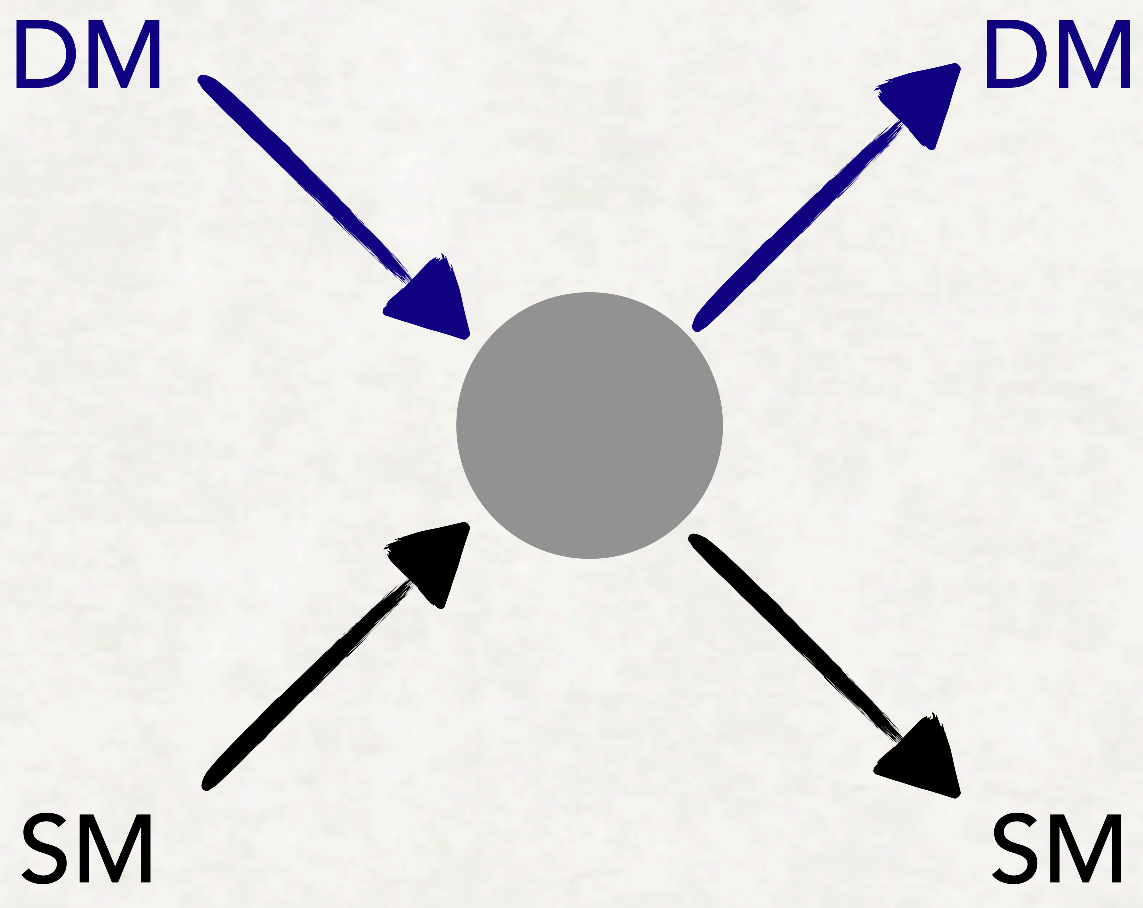
- stable
- weakly interacting
- non-relativistic ("cold")
- non-baryonic
- probably "matter" (not modified gravity)
- can't consist solely of dark astronomical objects (MACHO)



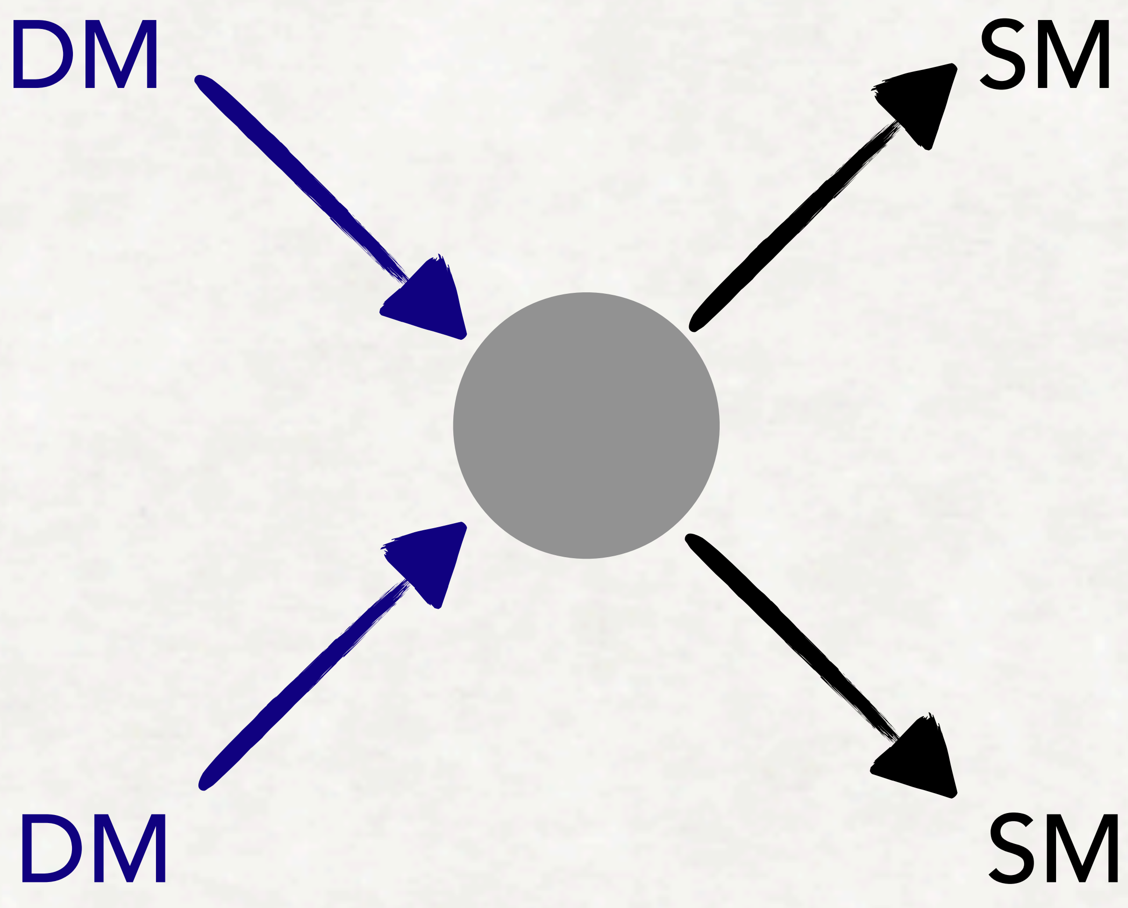
➡ Look for stable weakly interacting massive BSM particles

DM detection

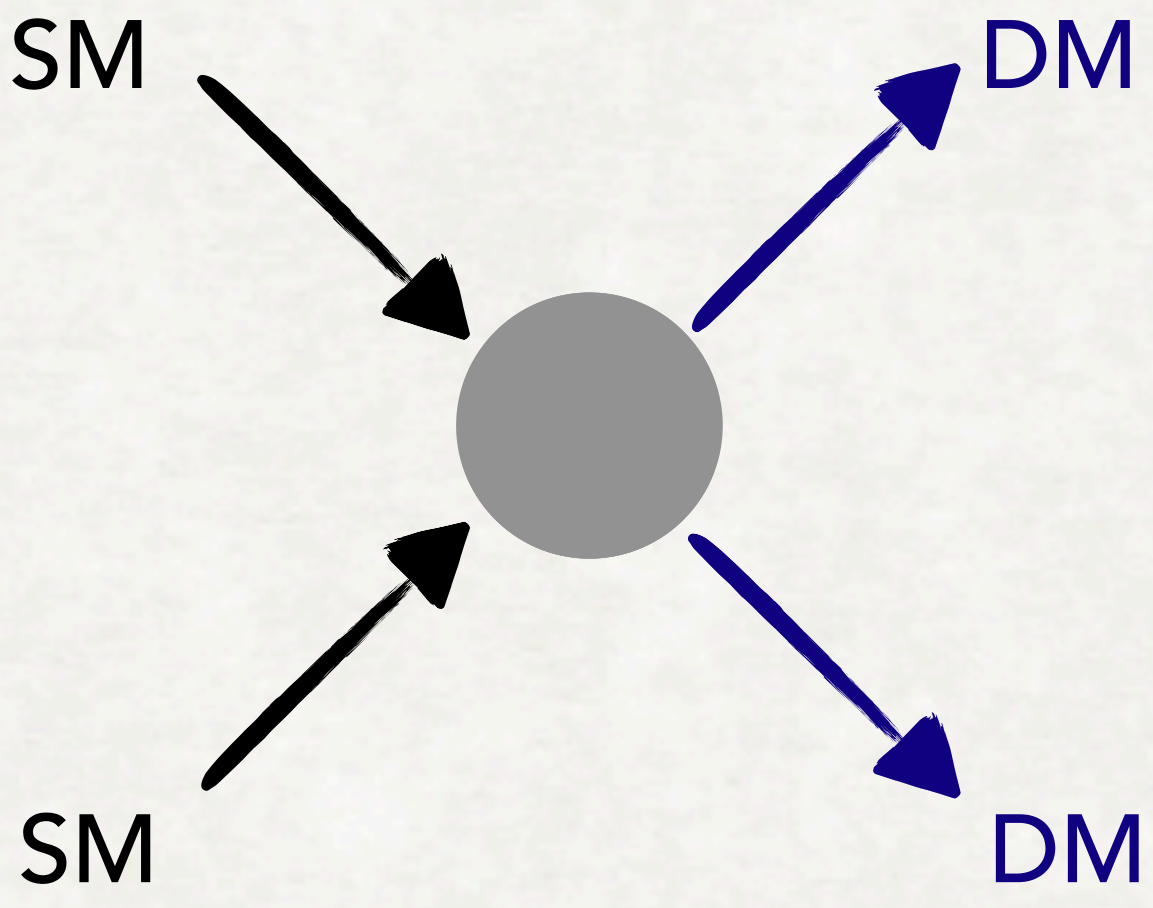
Direct Detection



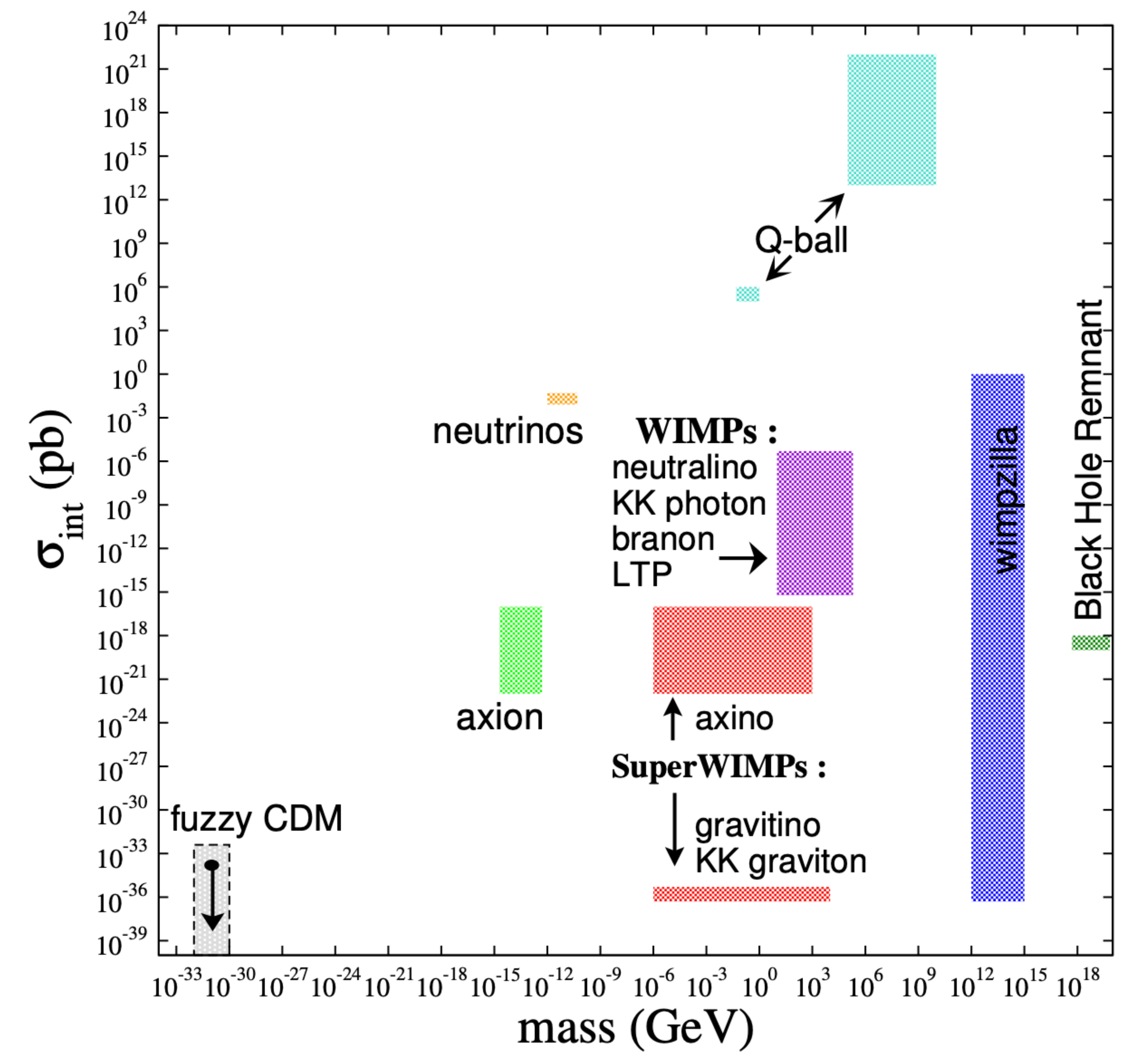
Indirect Detection



Colliders

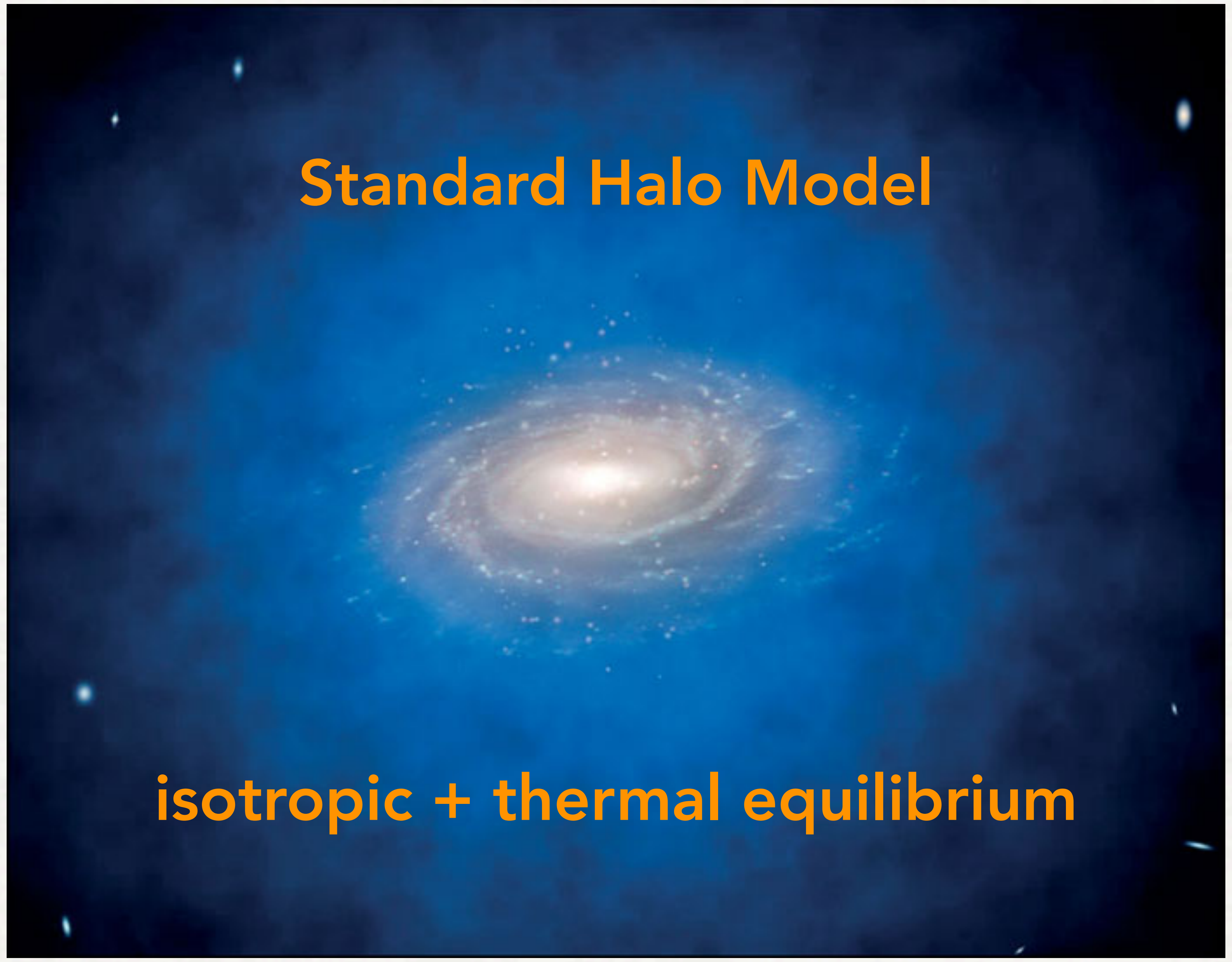


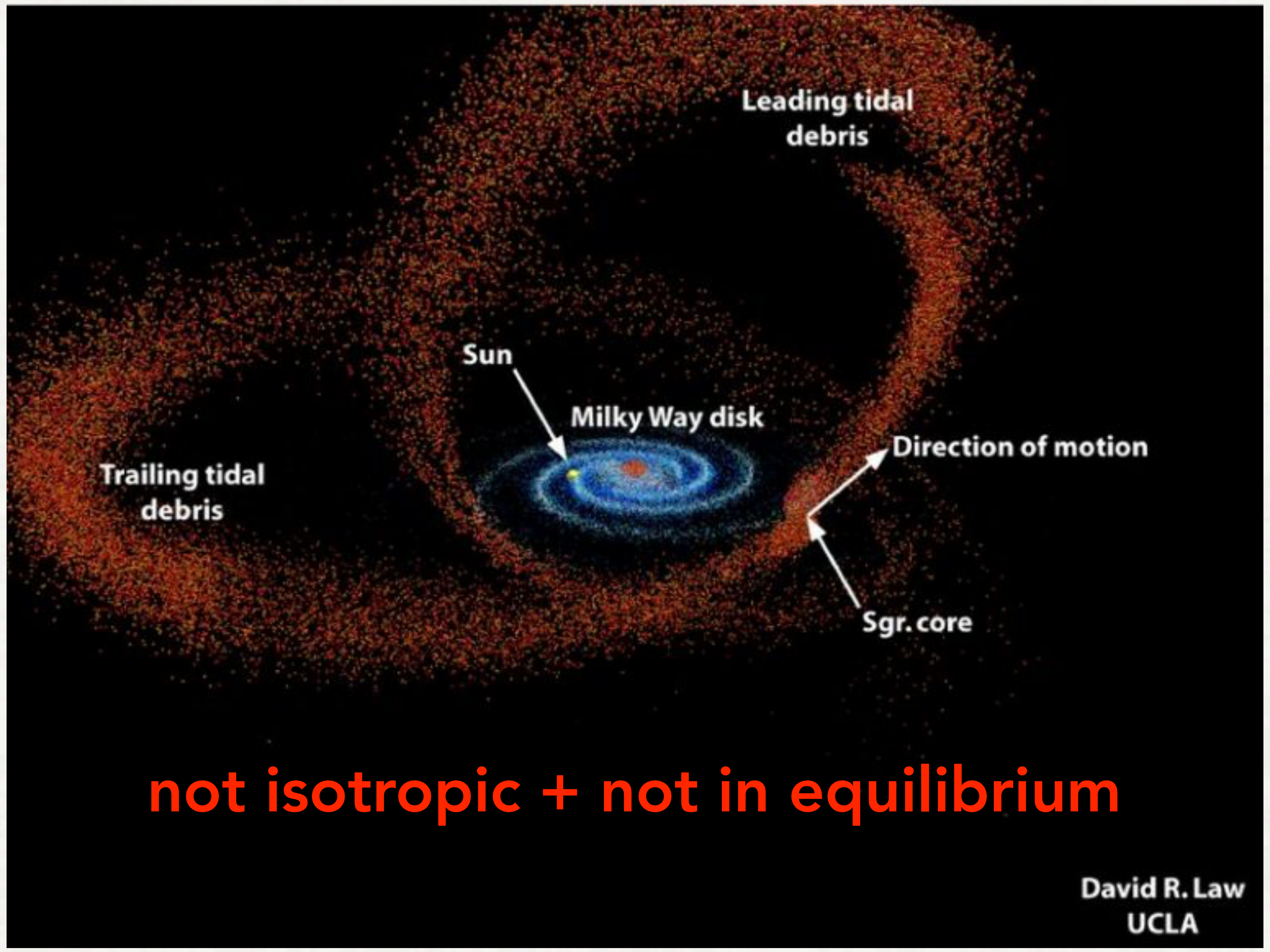
Complementarity is important



DM models predict a vast range of cross-sections/masses

Complementarity is important

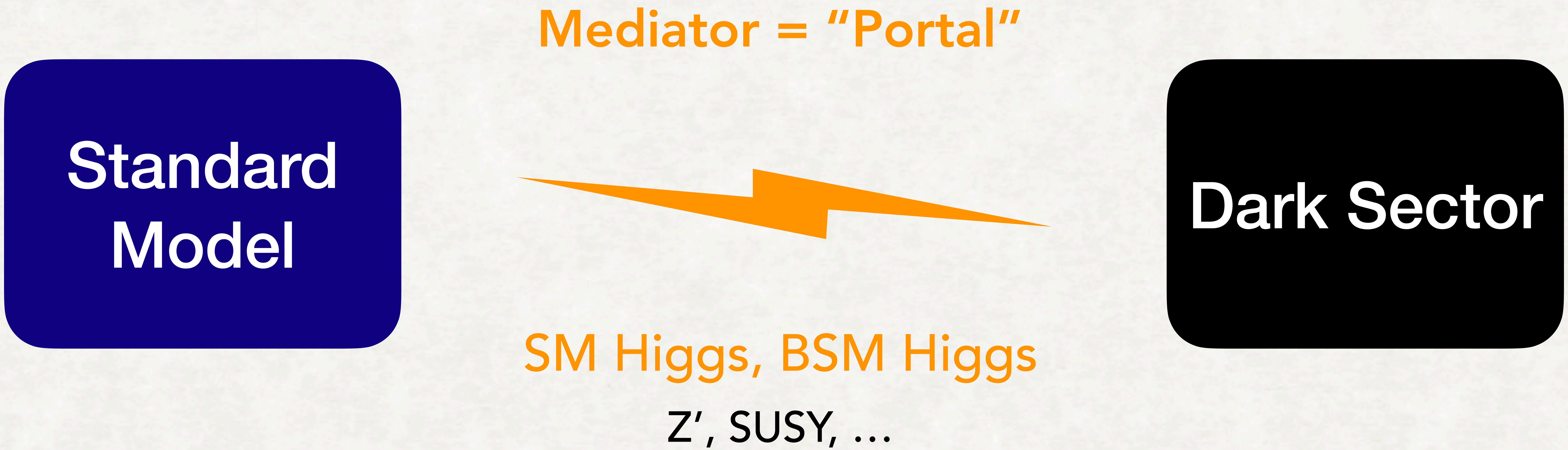




Different experiments sensitive to different assumptions

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

Dark Matter interactions



In the following

- DM is assumed to be a SM singlet
- we concentrate on BSM Higgs portals

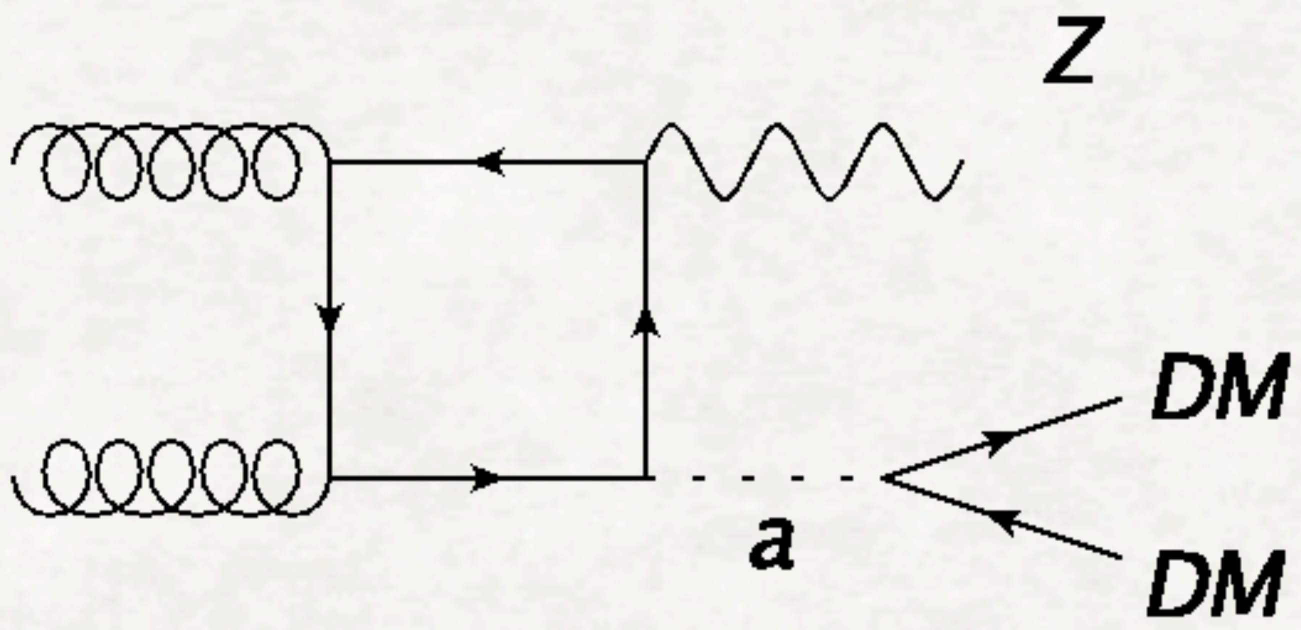
Classes of models

EFT

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

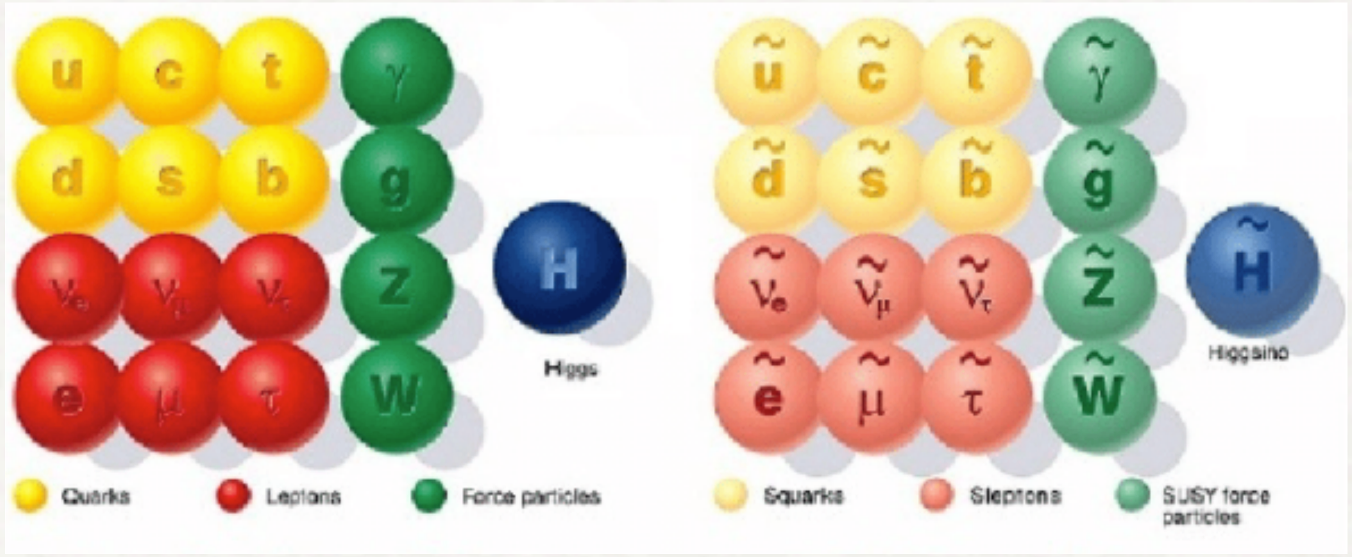
- agnostic to microscopic (UV) theory
- ✓ only 1 parameter (Λ)
- ◉ breaks down at high energies

Simplified



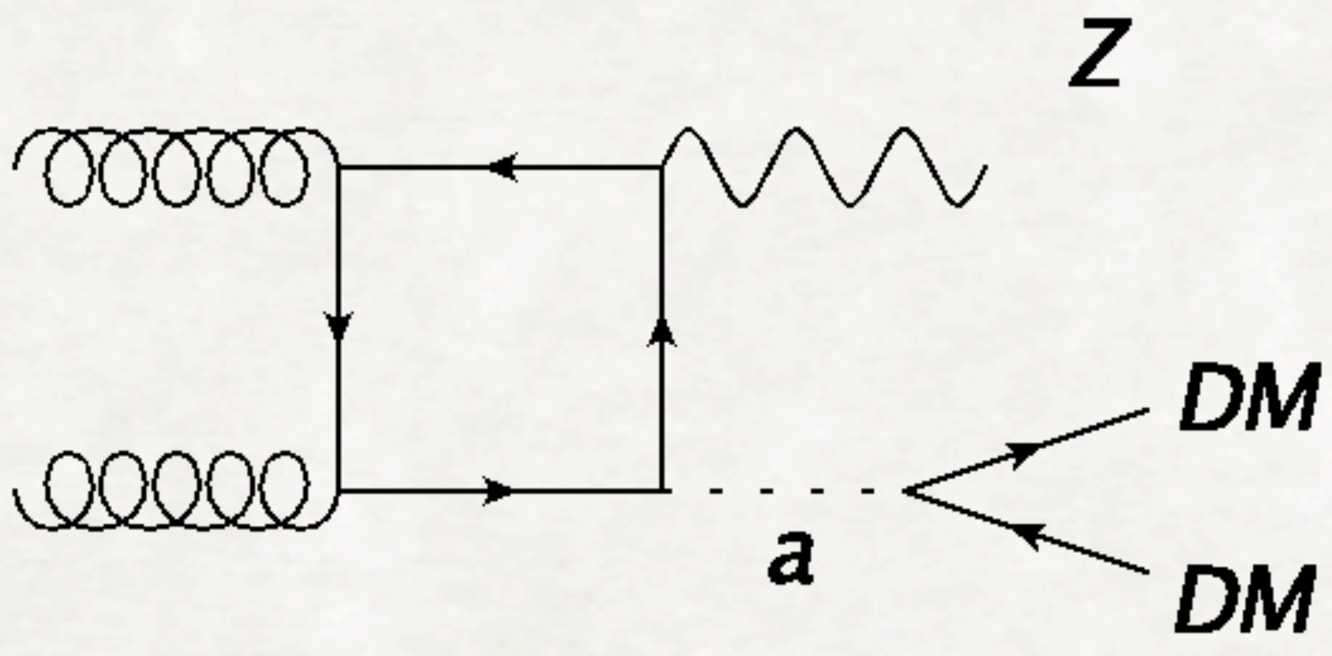
- add **only 1 mediator** coupling DM to SM
- ✓ **very few parameters** (g_{SM}, g_{DM}, m_a)
- ✓ **minimal particle content**

Complete



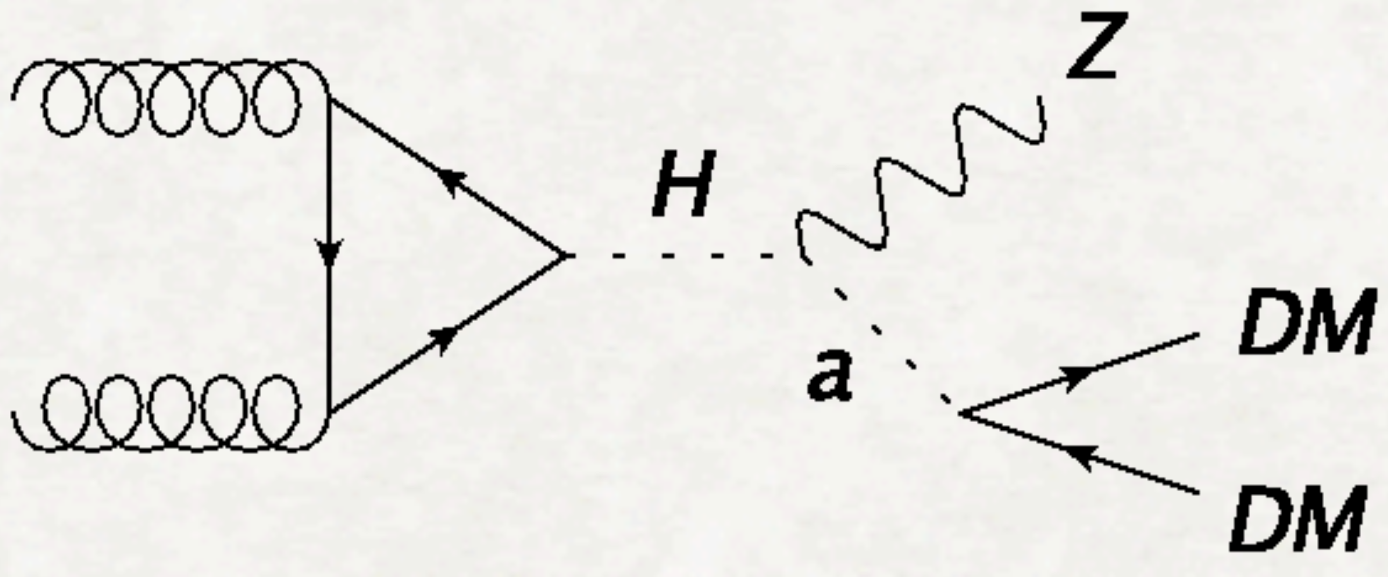
- **e.g. MSSM**
- **several new particles**
- ✓ **predictions for everything**
- ◉ **many parameters**
- ◉ **very hard to constrain**

The need for extended Higgs sectors



If a is singlet ⇒ unitarity violation

$$\mathcal{M} \sim \ln^2 s$$



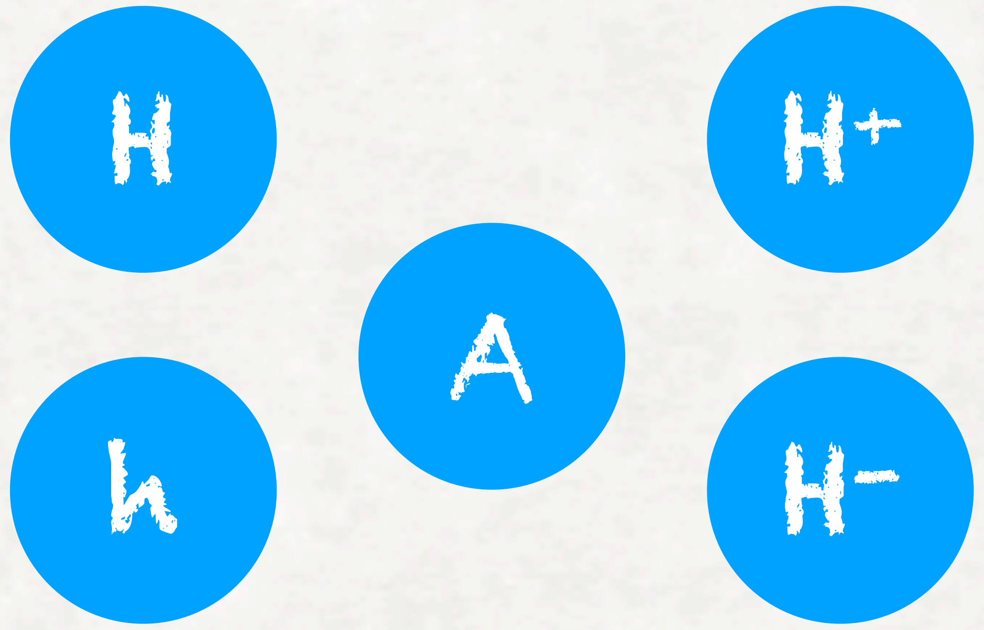
Extended Higgs sector:

- fixes unitarity violation

★ 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**

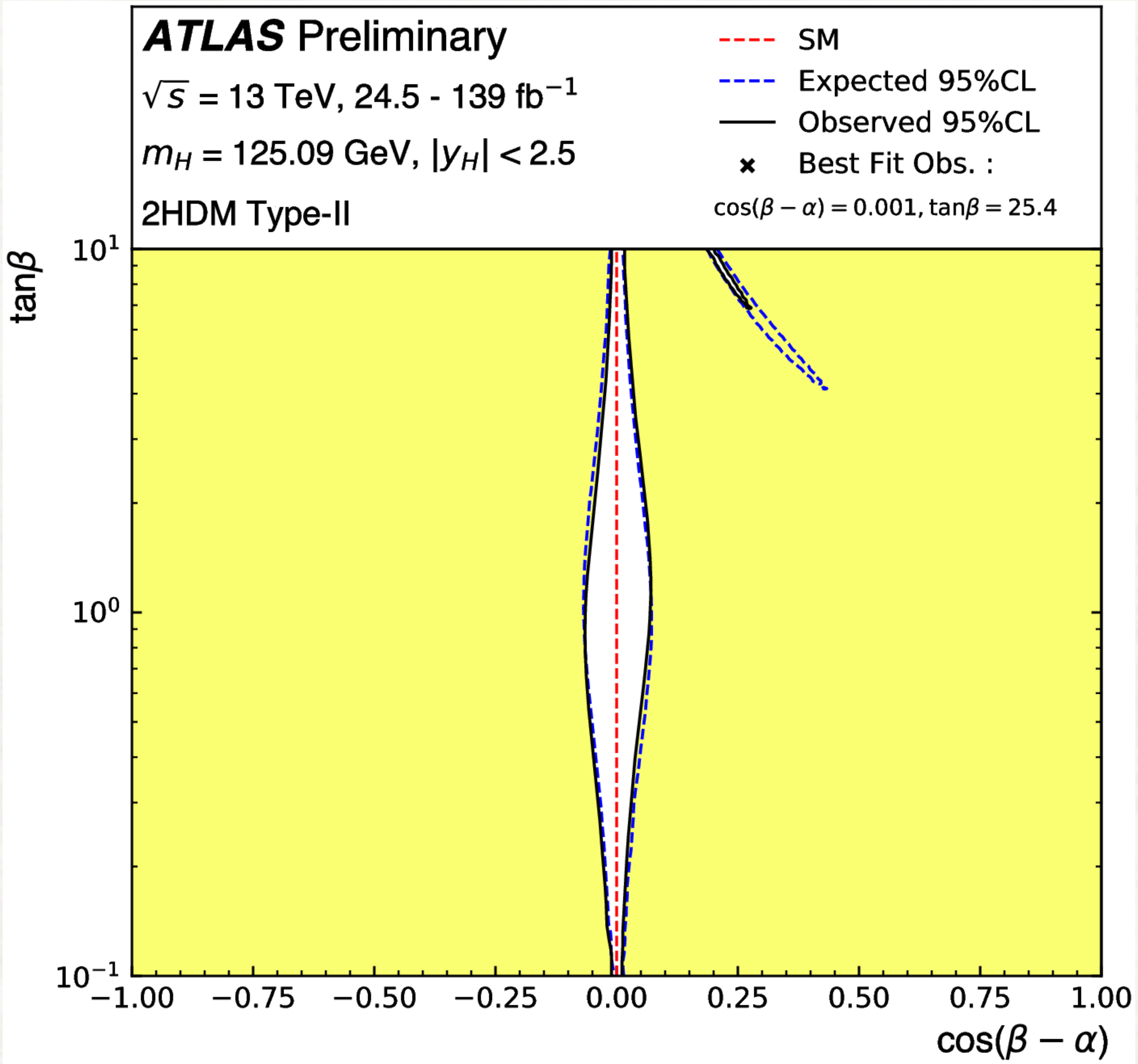
  h has the same couplings as the SM Higgs

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

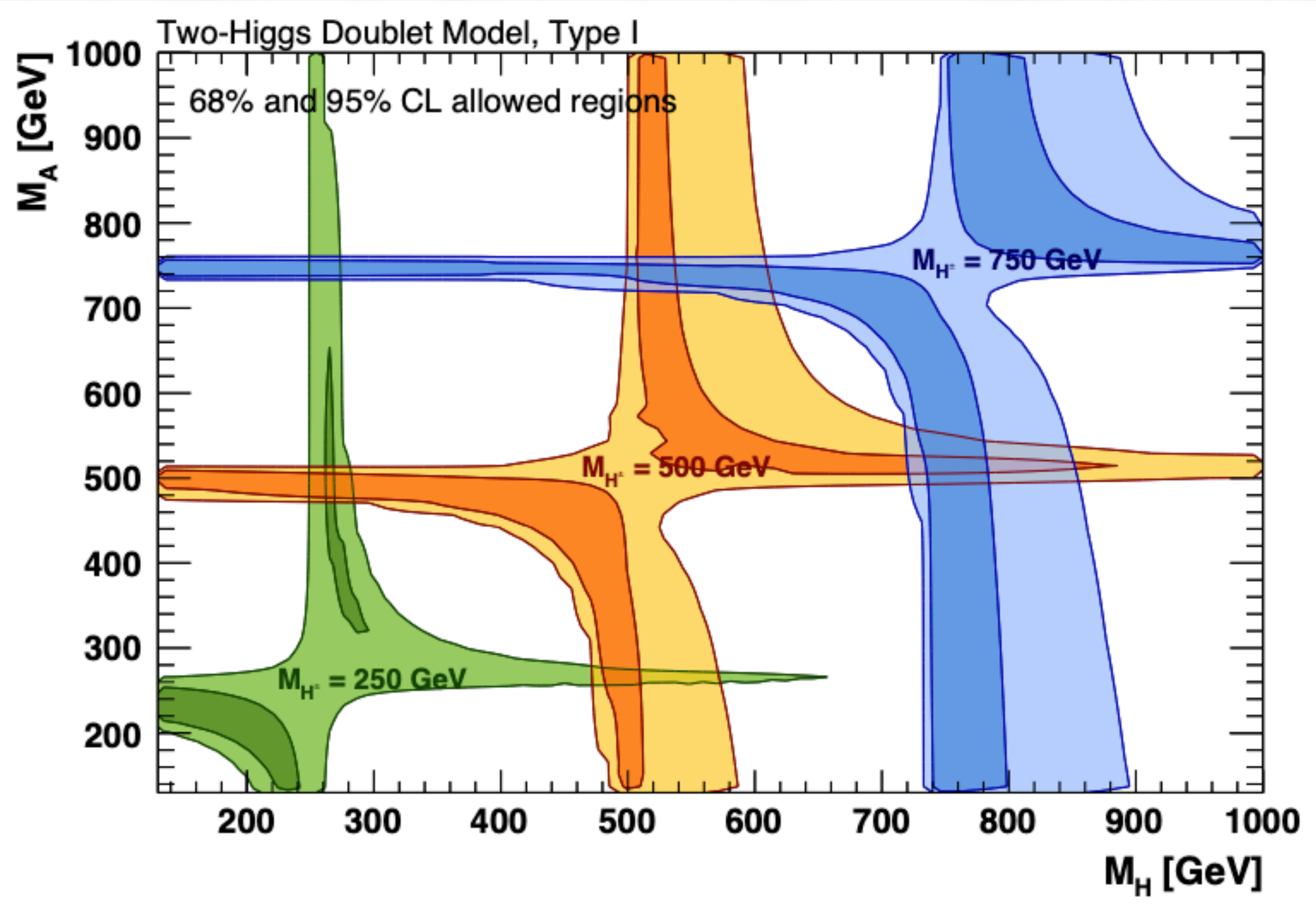
Coupling modifier	Type I	Type II
ξ(h,u)	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
ξ(h,d), ξ(h,l)		$s_{\beta-\alpha}-c_{\beta-\alpha}t_\beta$
ξ(H,u)	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
ξ(H,d), ξ(H,l)		$c_{\beta-\alpha}+s_{\beta-\alpha}t_\beta$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

Braco et al, Phys.Rept. 516 (2012) 1
Rompotis, Ferrari, Symmetry 2021,13,2144

Constraints



ATLAS-CONF-2021-053



Gfitter, EPJC 78 (2018) 675

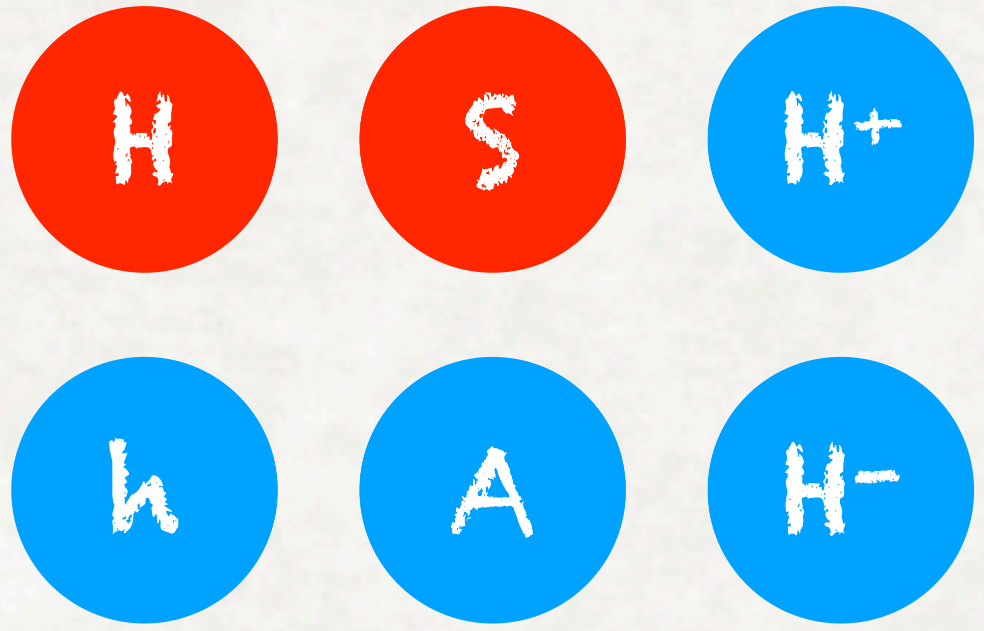
- Higgs coupling measurements: we are close to alignment limit
- $H^{\pm}$ must be degenerate with A or H: consider cos(**β-α**)=0 & $m_A = m_H = m_{H^{\pm}}$

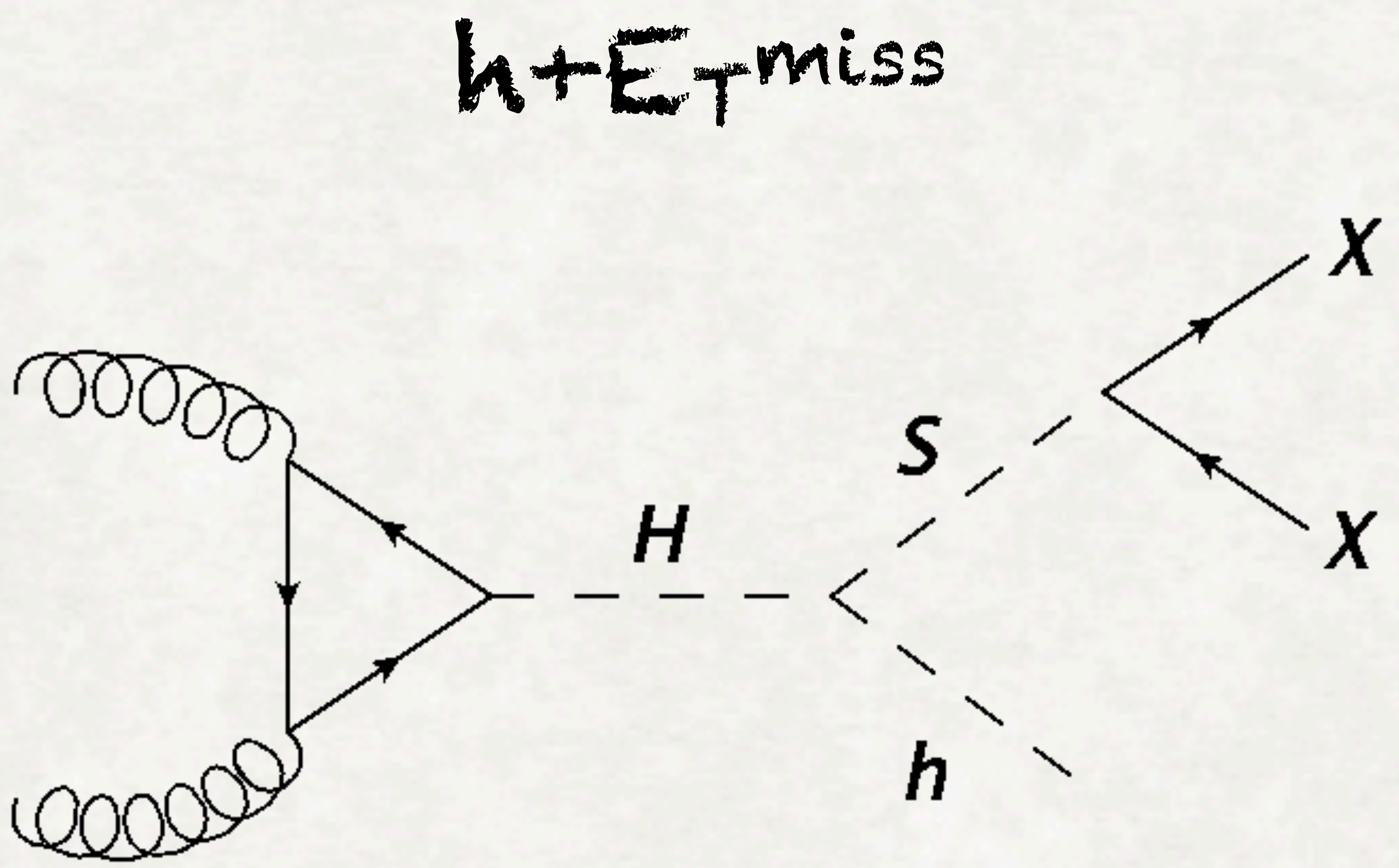
Model #1: 2HDM + scalar

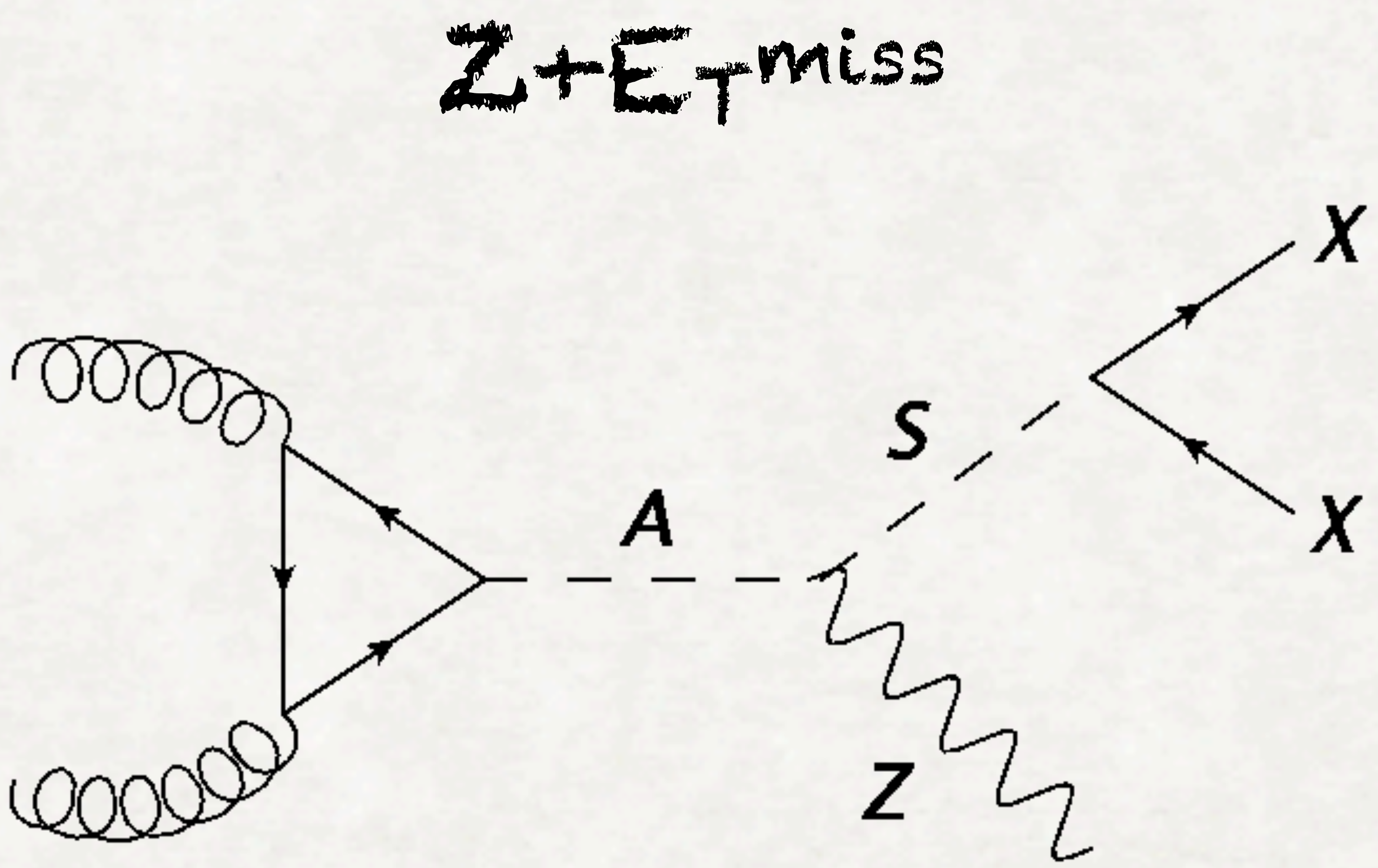
- 2HDM Type-II
- Extra **scalar mediator S** that couples to DM
- Mixing between CP-even scalars
- 6 Higgs bosons
- Resonant signatures

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

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





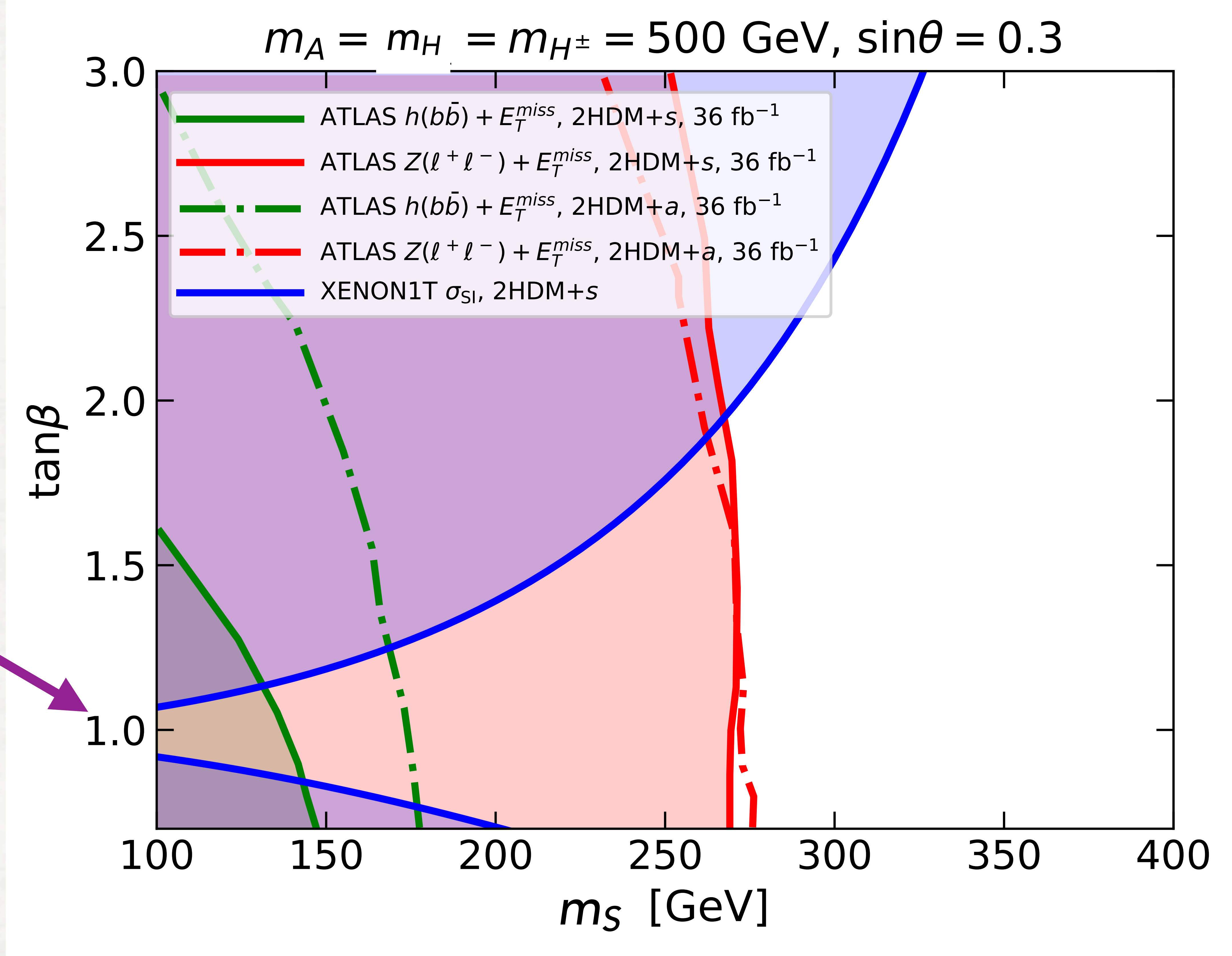


Bell et al, 1612.03475; Arcadi et al, 2001.10540

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



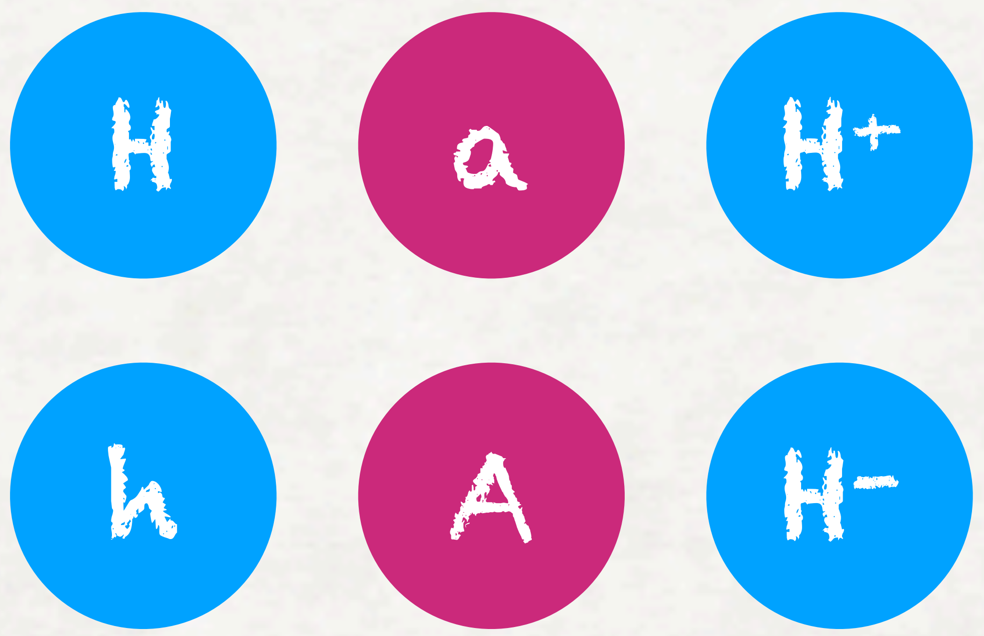
SA, Brandt, Haisch, Symmetry 13 (2021) 2406

Model #2: 2HDM + pseudoscalar

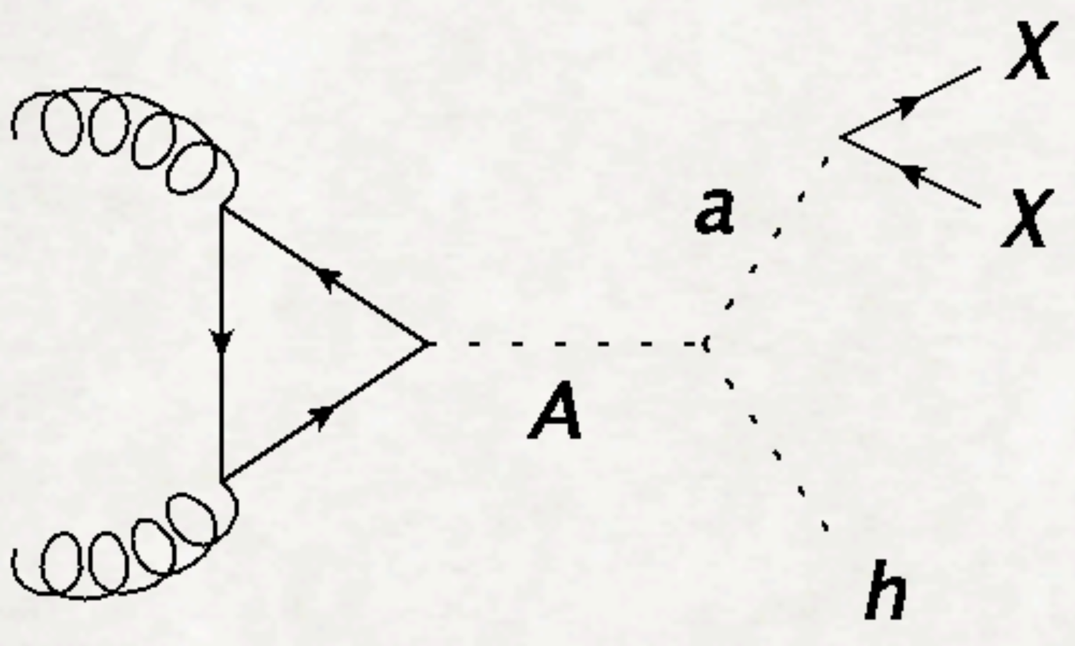
$$A = \cos\theta \tilde{A} + \sin\theta \tilde{a}$$

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

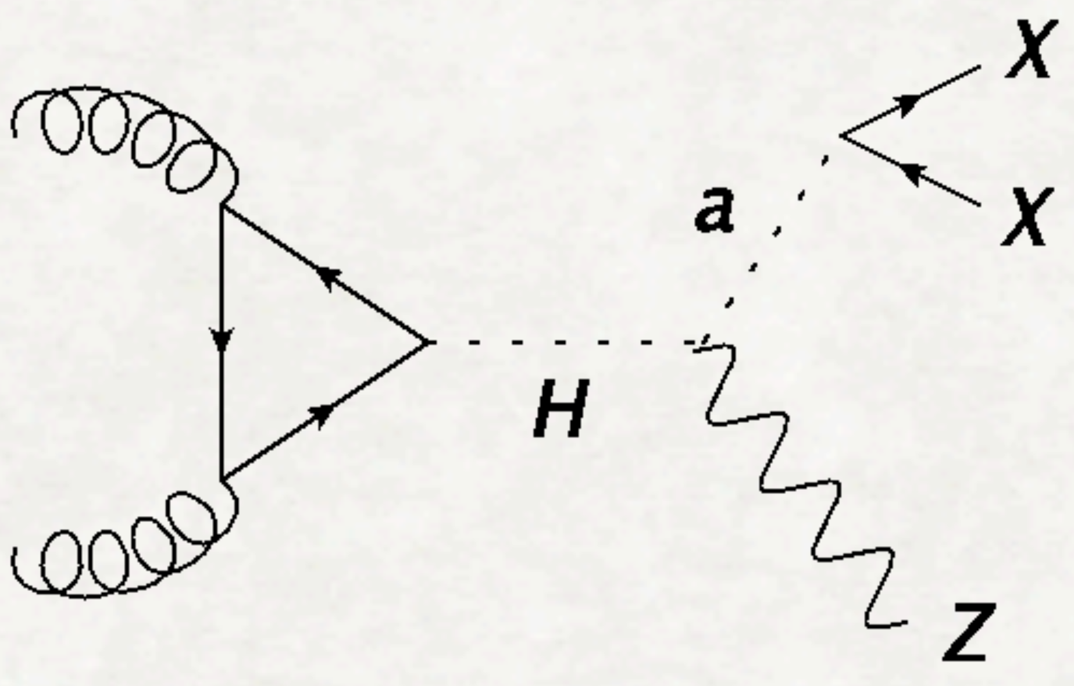
- 2HDM Type-II
- Mixing between CP-odd Higgses
- 6 Higgs bosons
- Extra **pseudoscalar mediator a** that couples to DM
  - suppressed DD constraints
  - originally proposed to explain Fermi-LAT excess
- Very rich phenomenology: colliders + ID + DD



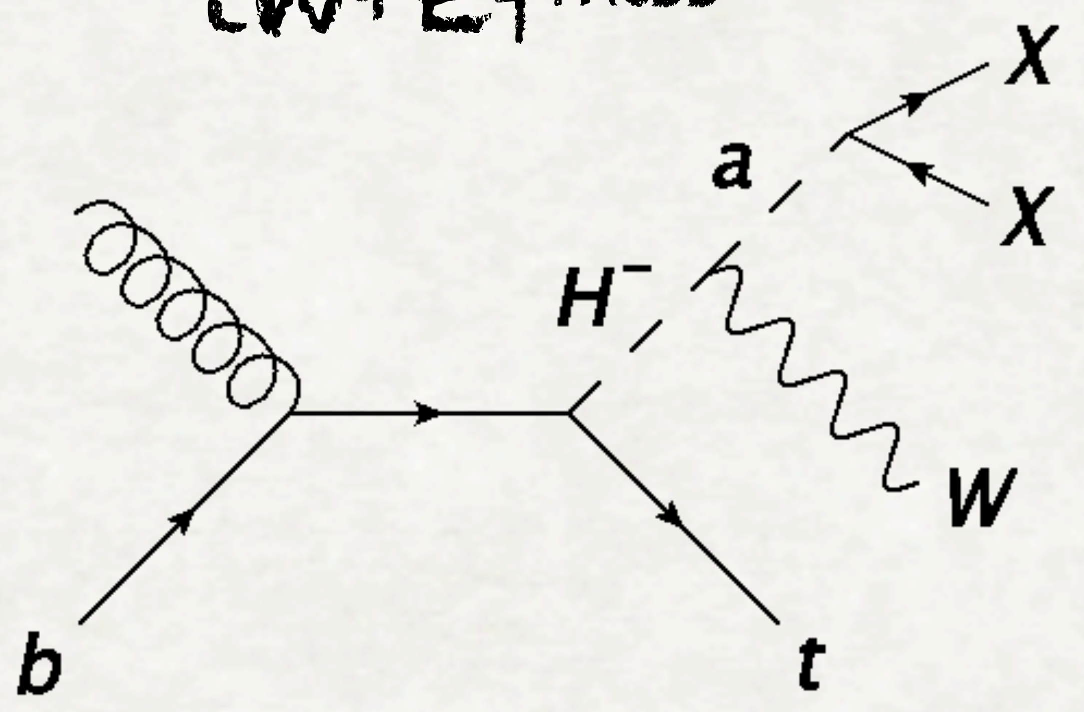
$h + E_T^{miss}$



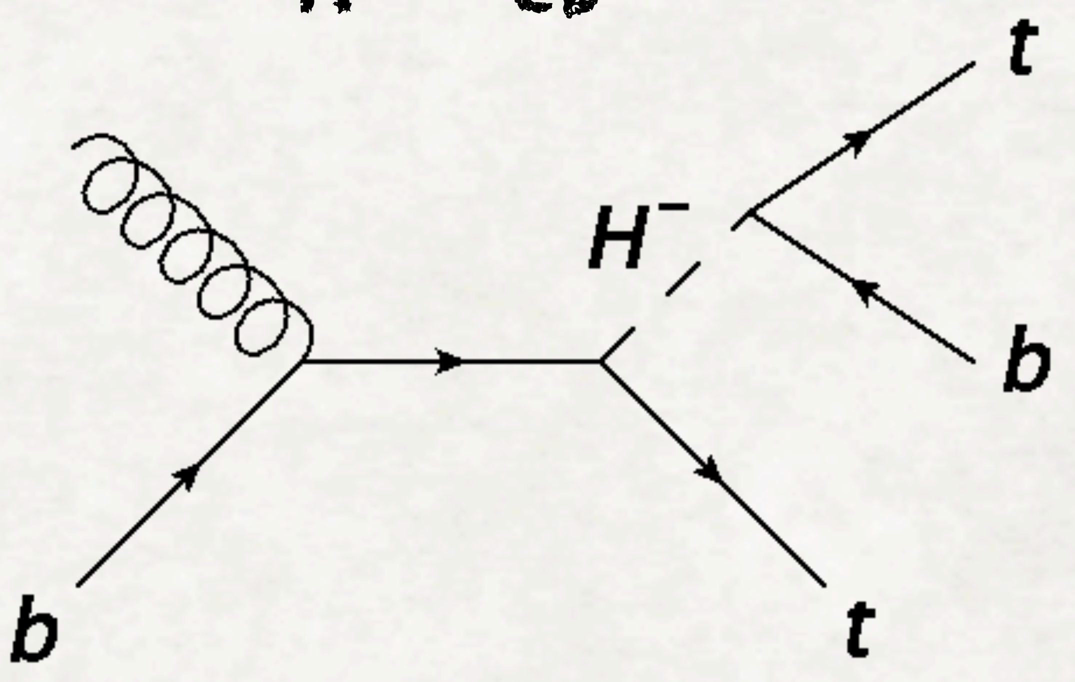
$Z + E_T^{miss}$



$tW + E_T^{miss}$

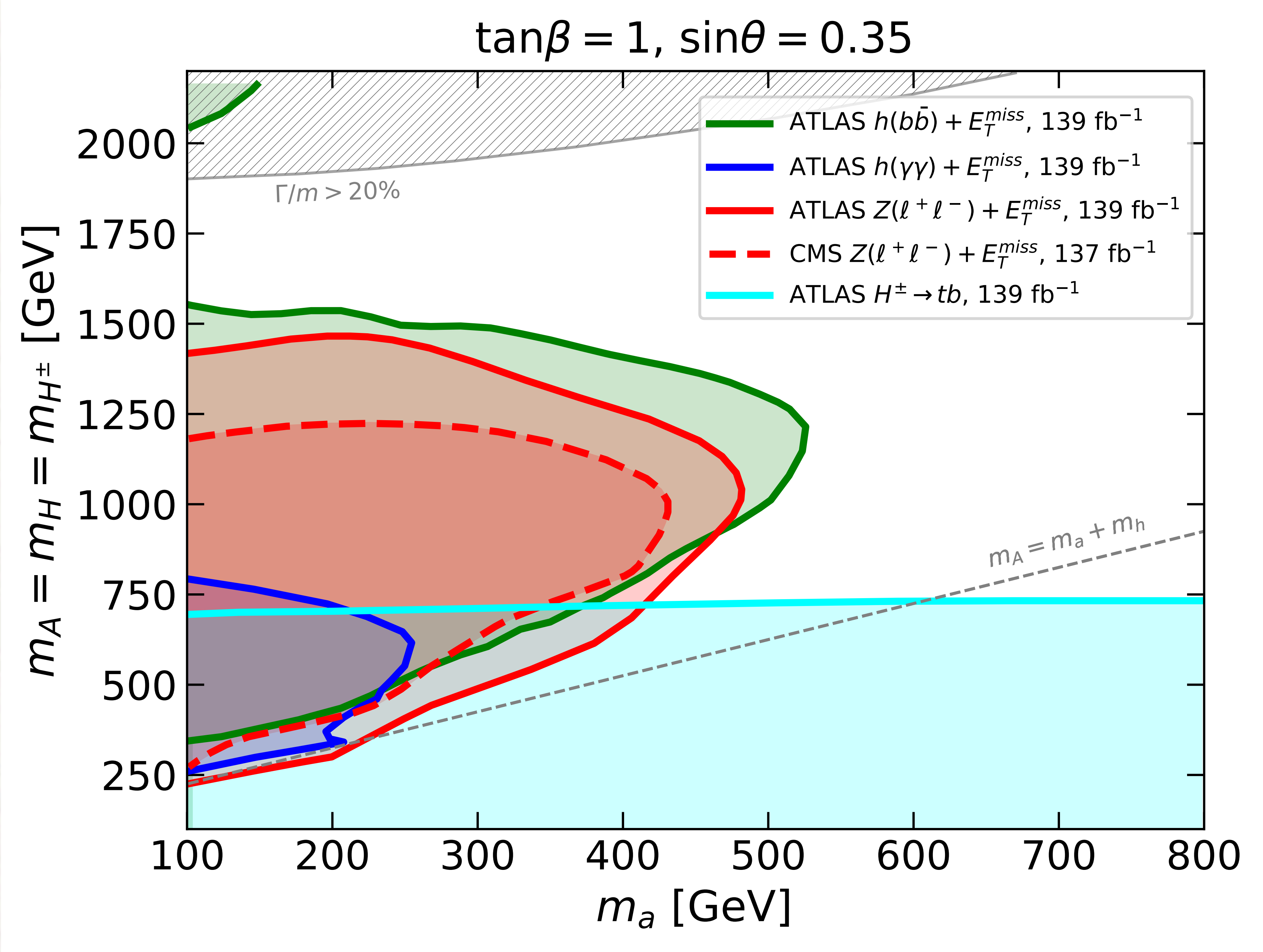


$H^{\pm} \to tb$

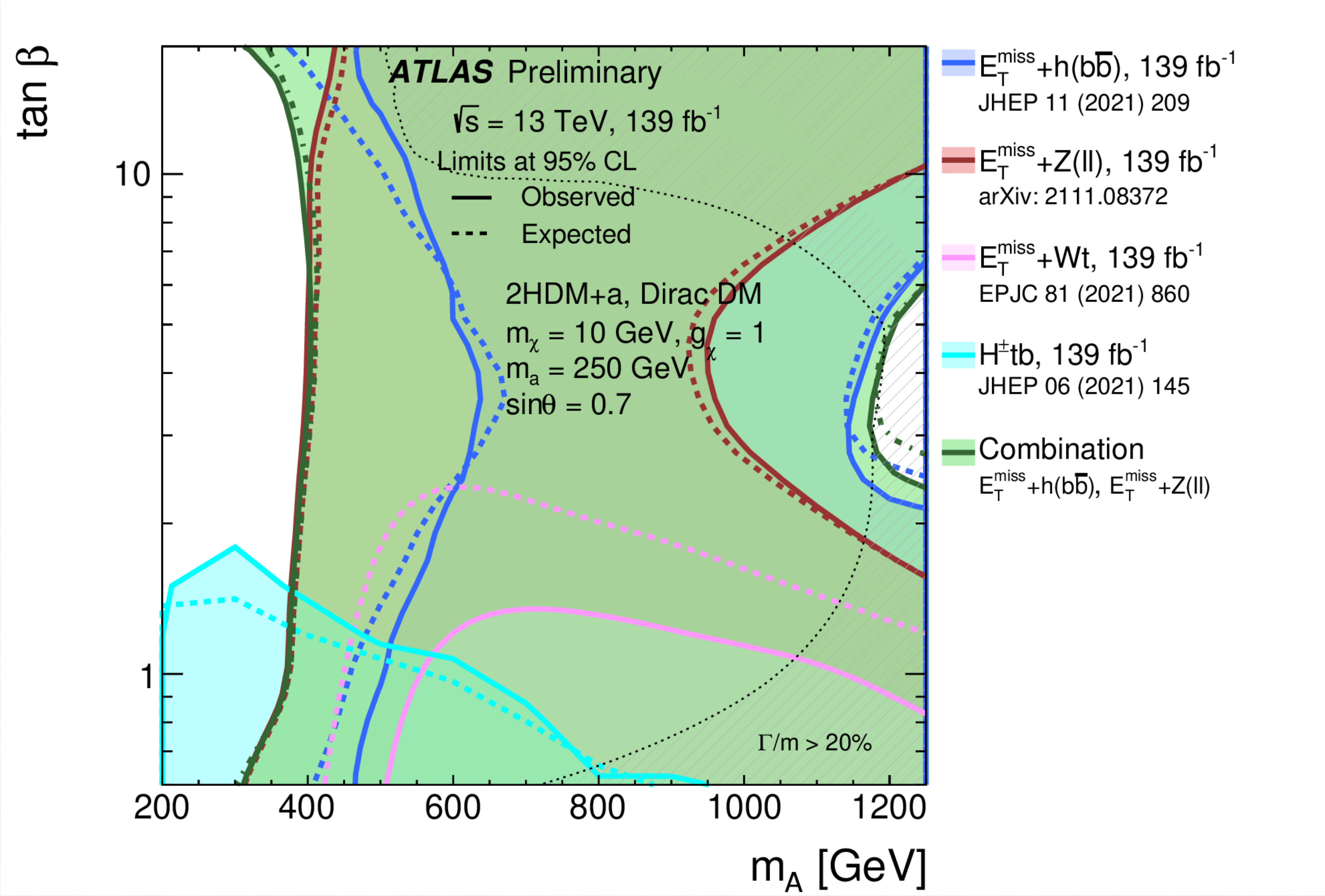


Ipek, et al, 1404.3716 ; No, 1509.01110 ; Goncalves, et al, 1611.04593 ; Bauer, et al, 1701.07427 ; Abe et al, 1810.09420

2HDM + pseudoscalar: constraints



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

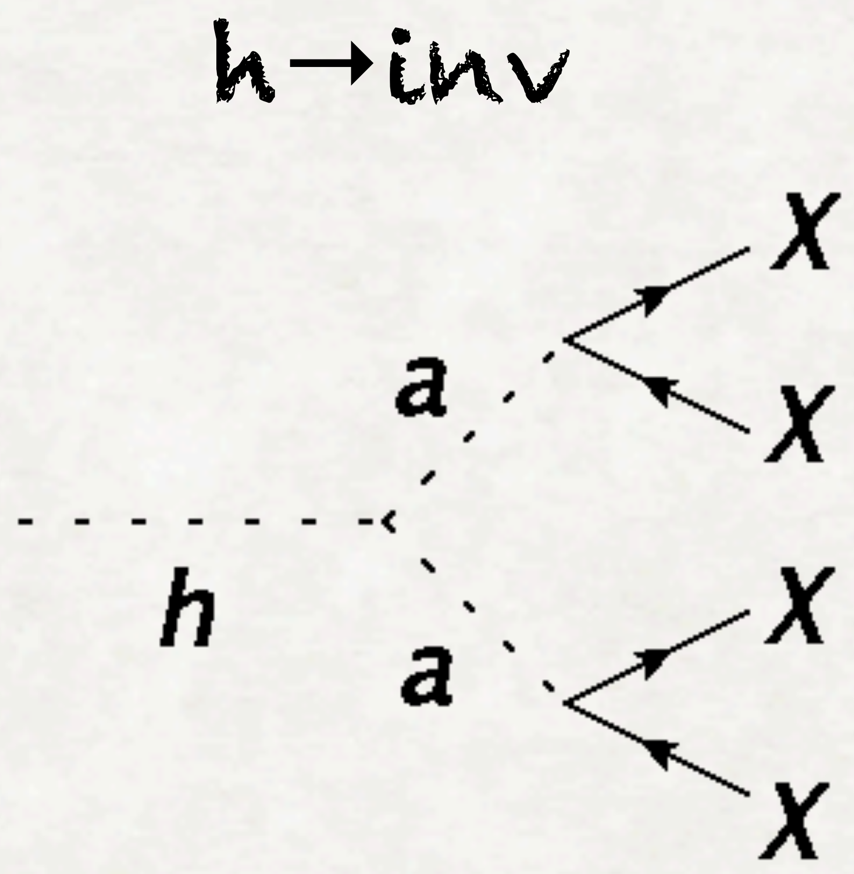


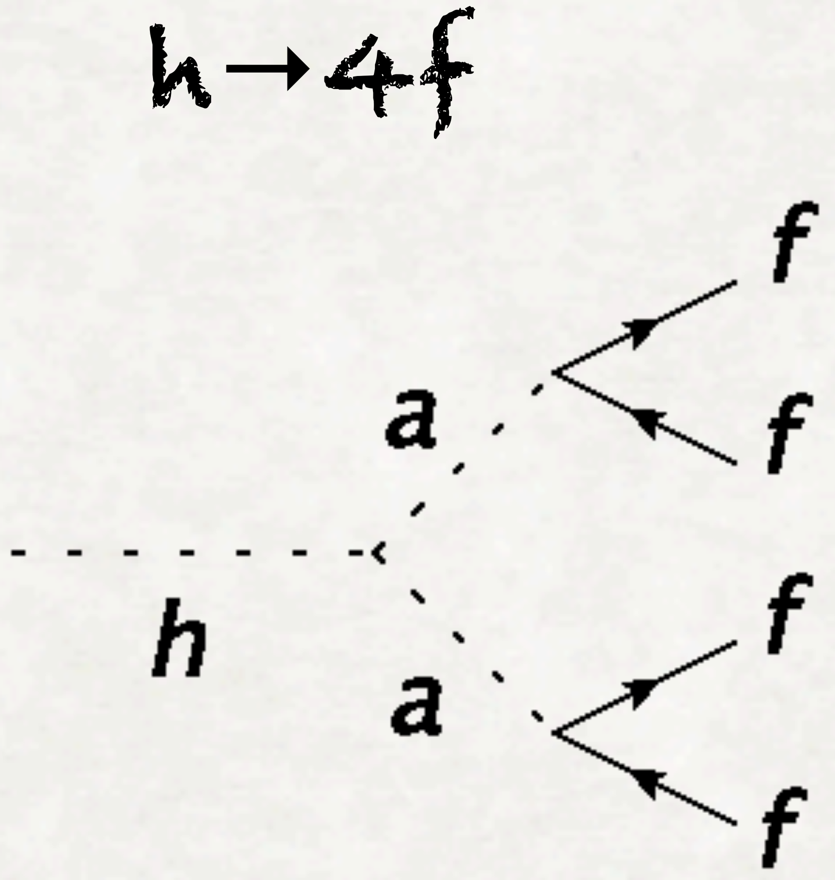
[ATL-PHYS-PUB-2021-045]

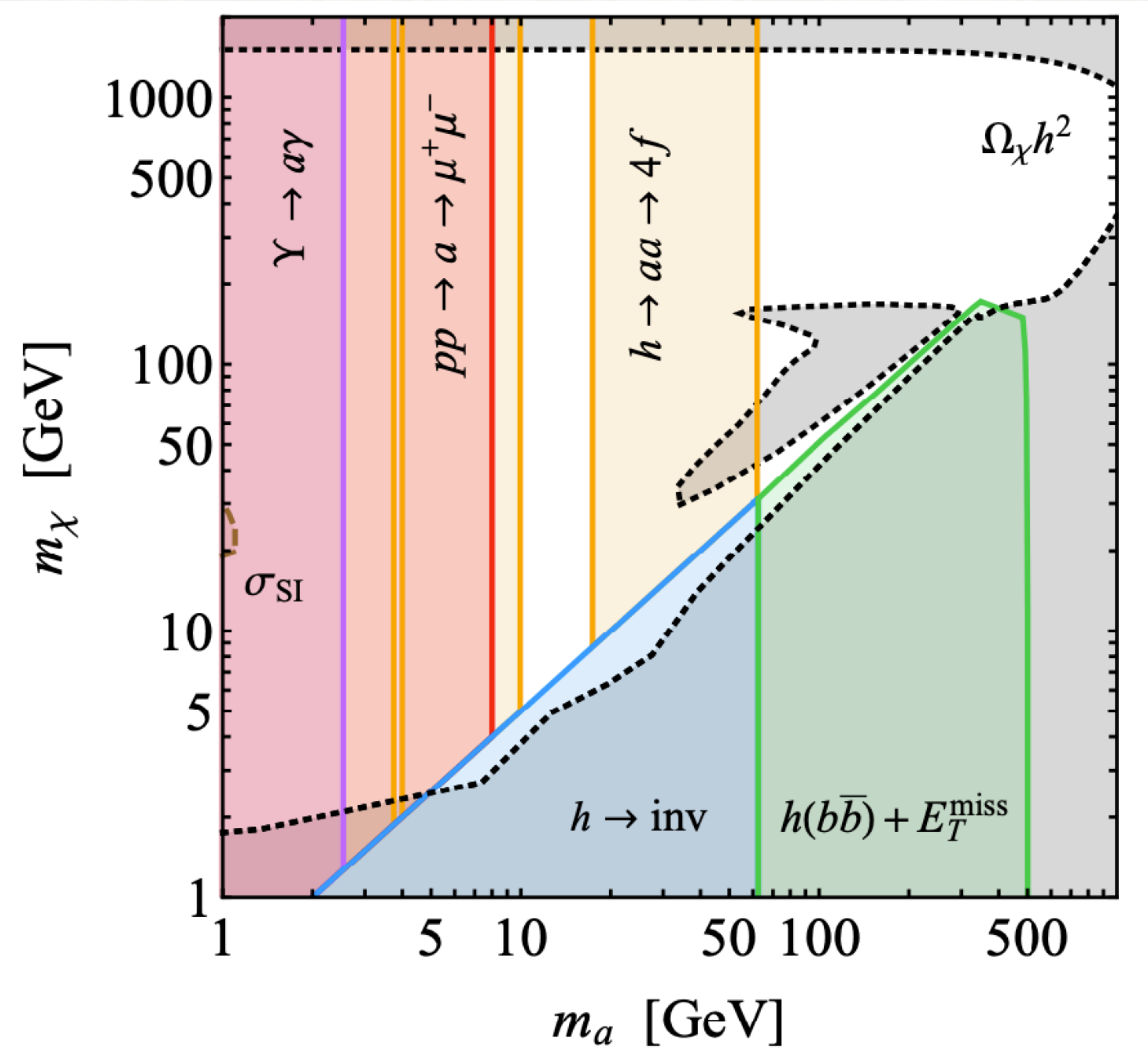
- A lot of parameter space excluded, $m_a \gtrsim 500$ GeV, $m_A \gtrsim 1$TeV for a range of mixing angles
- Goal: close sensitivity gaps (e.g. low m_A,m_a at intermediate tan**β**)

Complementary searches

- $m_a > m_h/2$ & low m_χ: $X+E_T^{miss}$
- $m_a < m_h/2$ & $m_\chi < m_a/2$: h→invisible
- $m_a < m_h/2$ & $m_\chi > m_a/2$: h→4 fermions





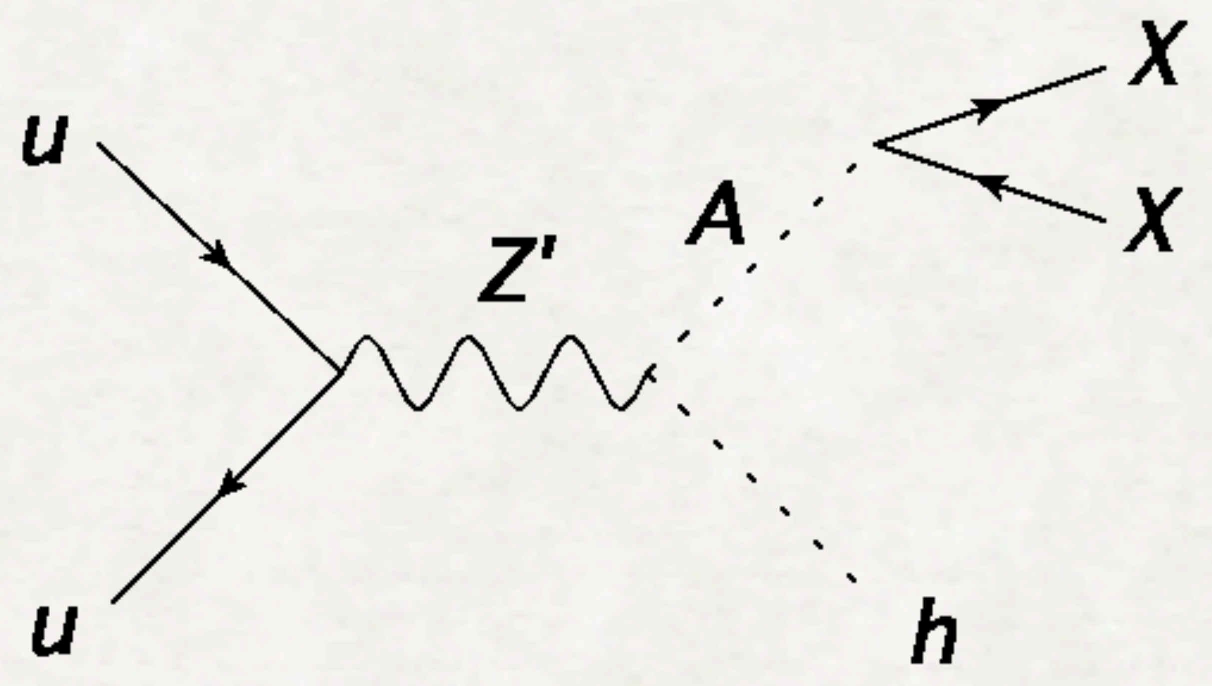


SA, Haisch, 2202.12631

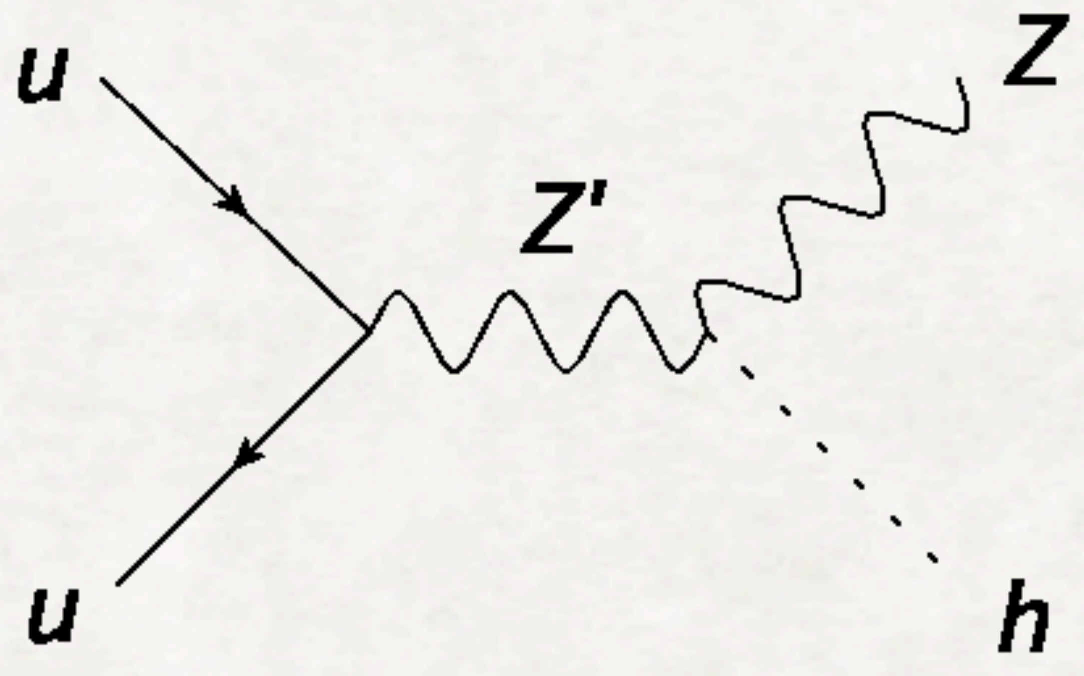
Model #3: 2HDM + vector

- 2HDM Type-II + Z′ only coupling to up-type quark ⇒ evades di-lepton constraints
- CP-odd Higgs A couples to DM particles
- Large h+E_T^{miss} signal (highly boosted Higgs in contrast to 2HDM+a)
- Also constraints from EW measurements and dijets

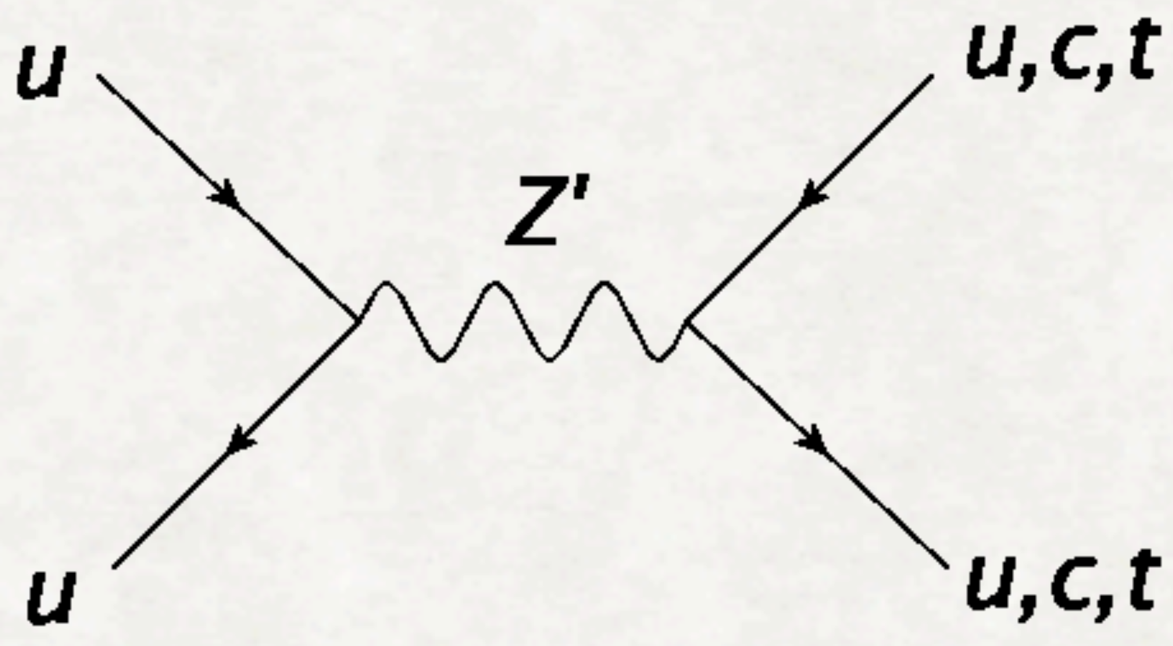
h+E_T^{miss}



Zh resonance

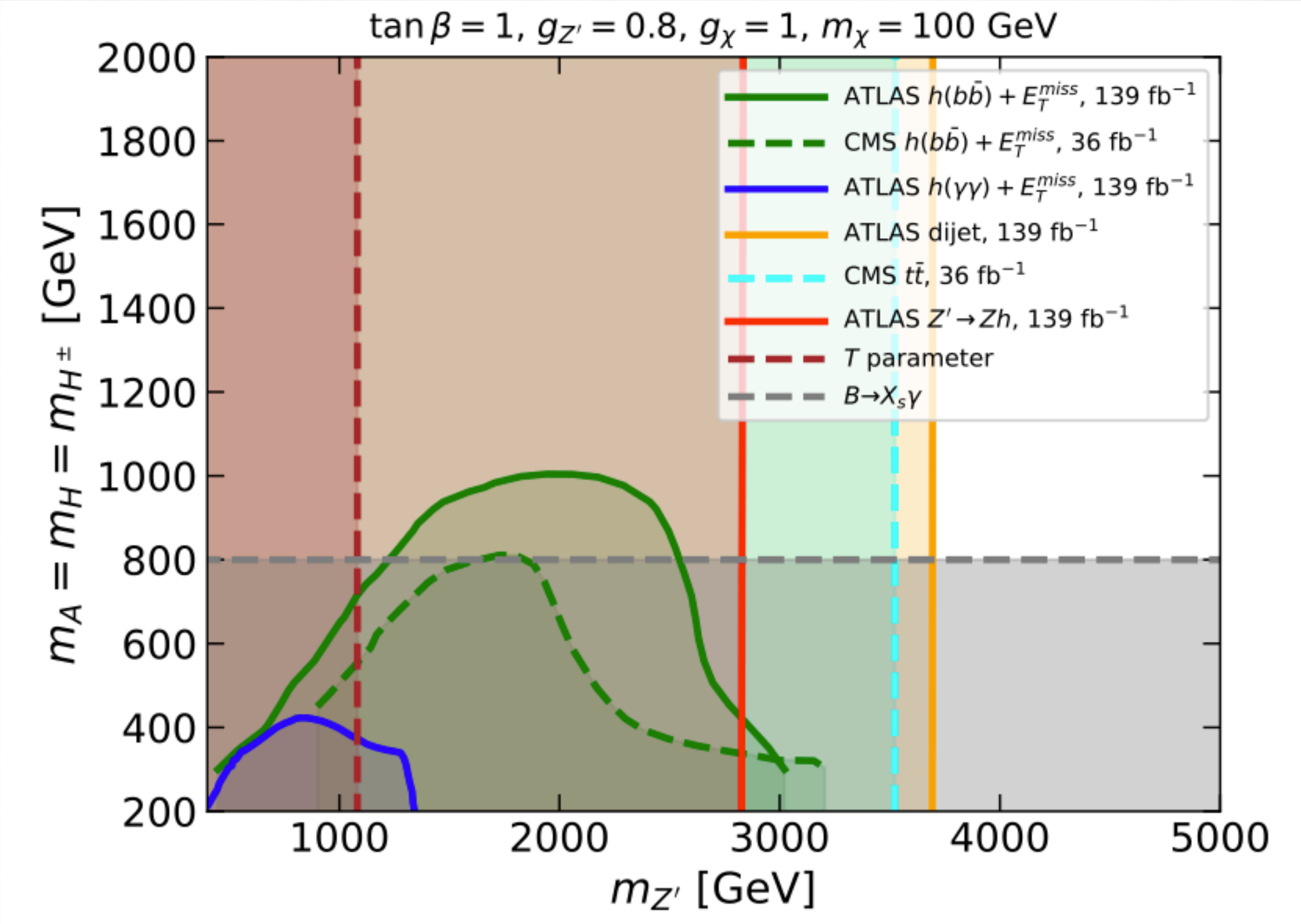


dijet/tt resonance



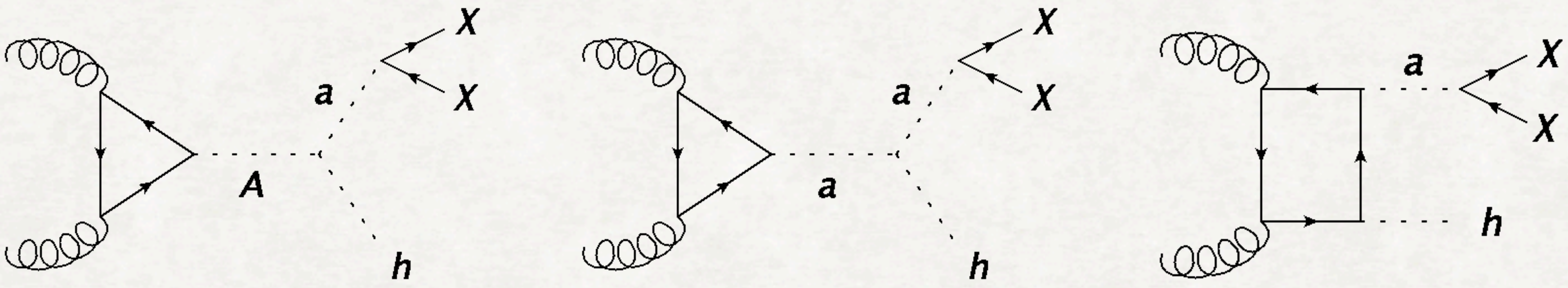
2HDM + vector: constraints

- $m_{Z'}$ excluded up to 2-3 TeV for $m_A \lesssim 1$ TeV
- EW and flavour measurements provide significant constraints
- Zh and dijet resonances provide better constraints (and this seems hard to avoid)
    - ➡ "DM searches" don't always provide the best constraints to DM models



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

"Model-independent" Limits

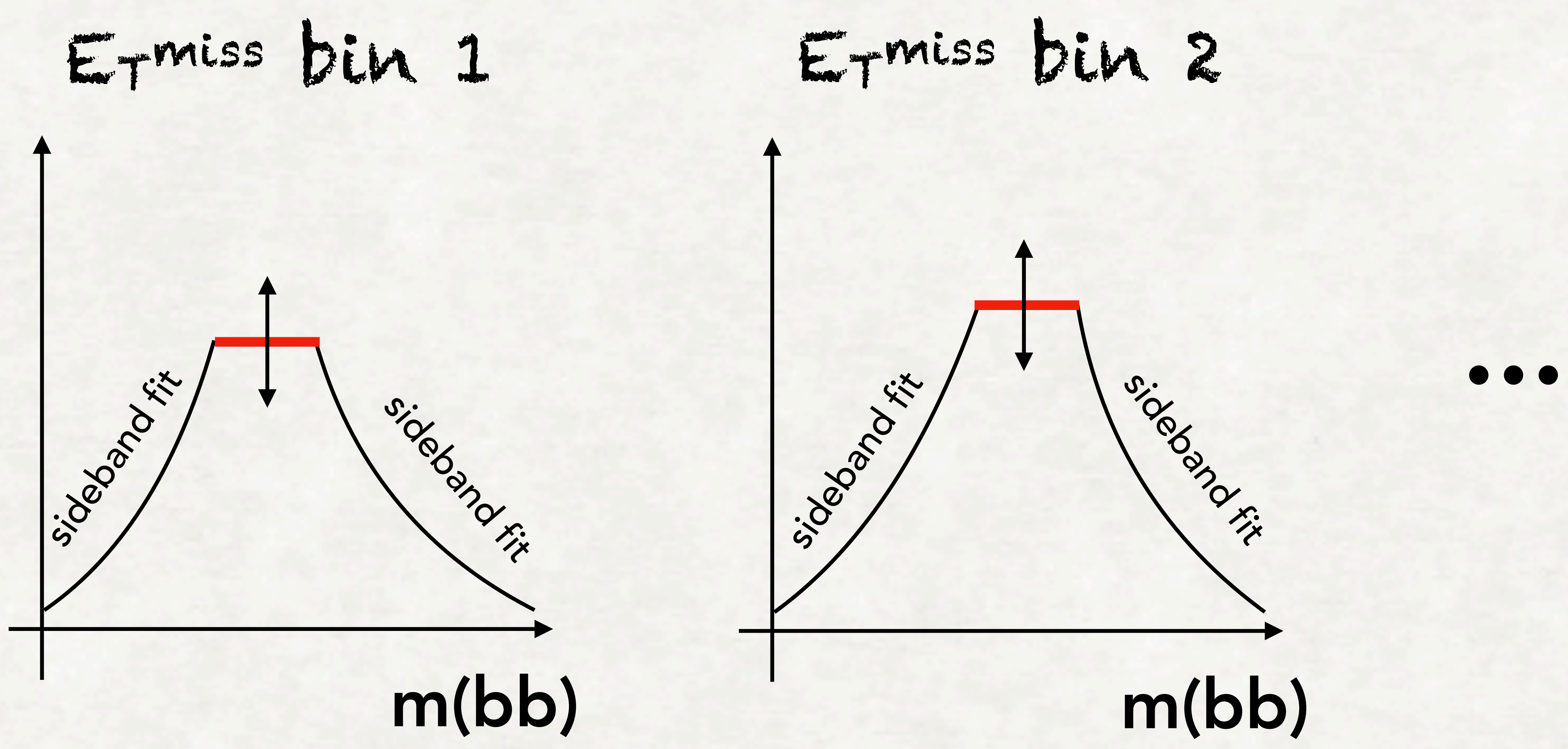


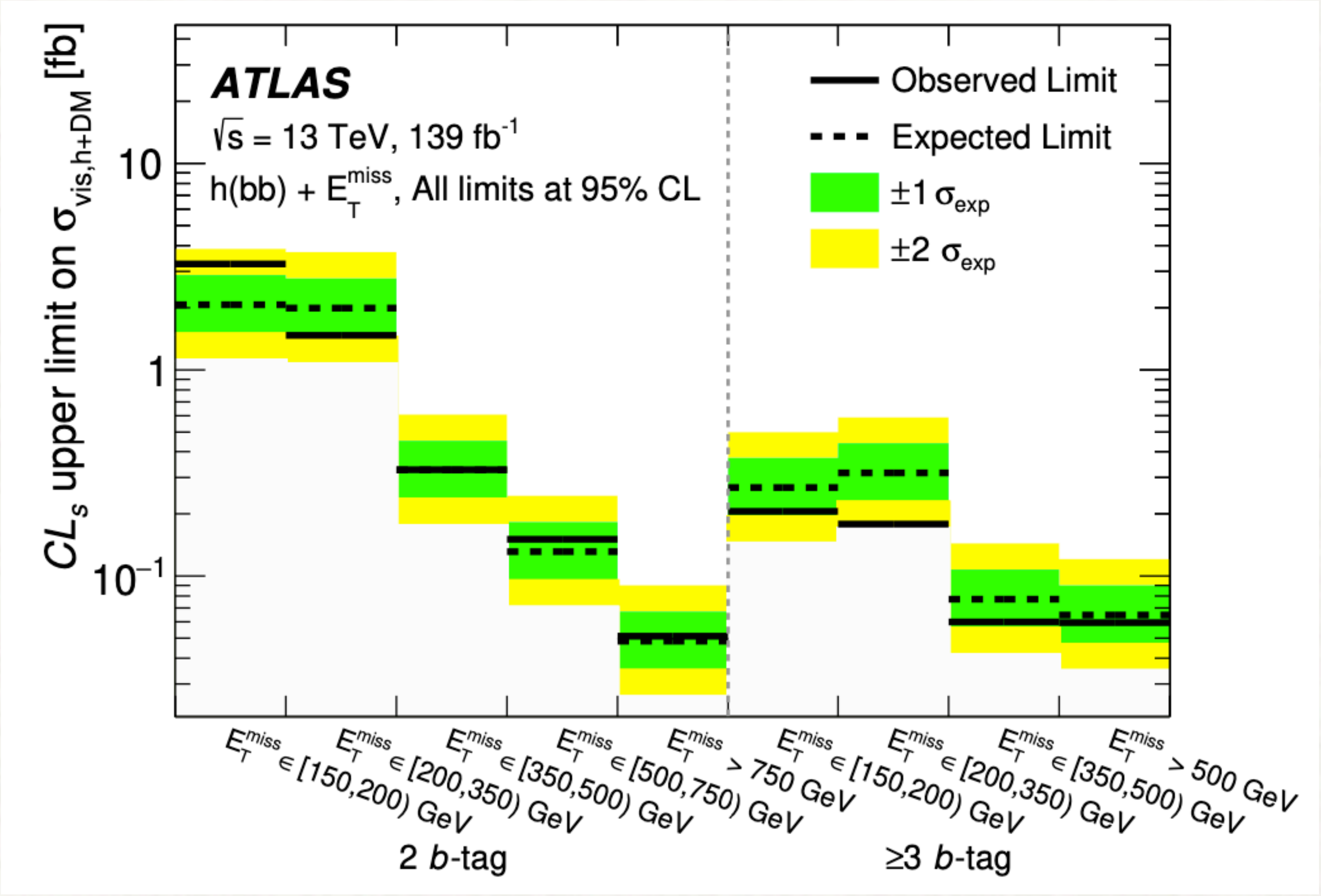
- Parameter choices can affect signal characteristics (e.g. softer E_T^{miss})

➡ **How can we produce limits that theorists can easily re-interpret?**

"Model-independent" Limits

- Alternative way of presenting constraints $\sigma^{\text{vis}}_{h+\text{DM}} \equiv \sigma_{h+\text{DM}} \times \text{BR}(h \to b\bar{b}) \times (\mathcal{A} \times \epsilon)$





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- Maximum cross-section of a signal-like resonance that the data can accommodate
- Folding with Axε theorists can re-interpret results in any model with SM-like Higgs

Conclusions

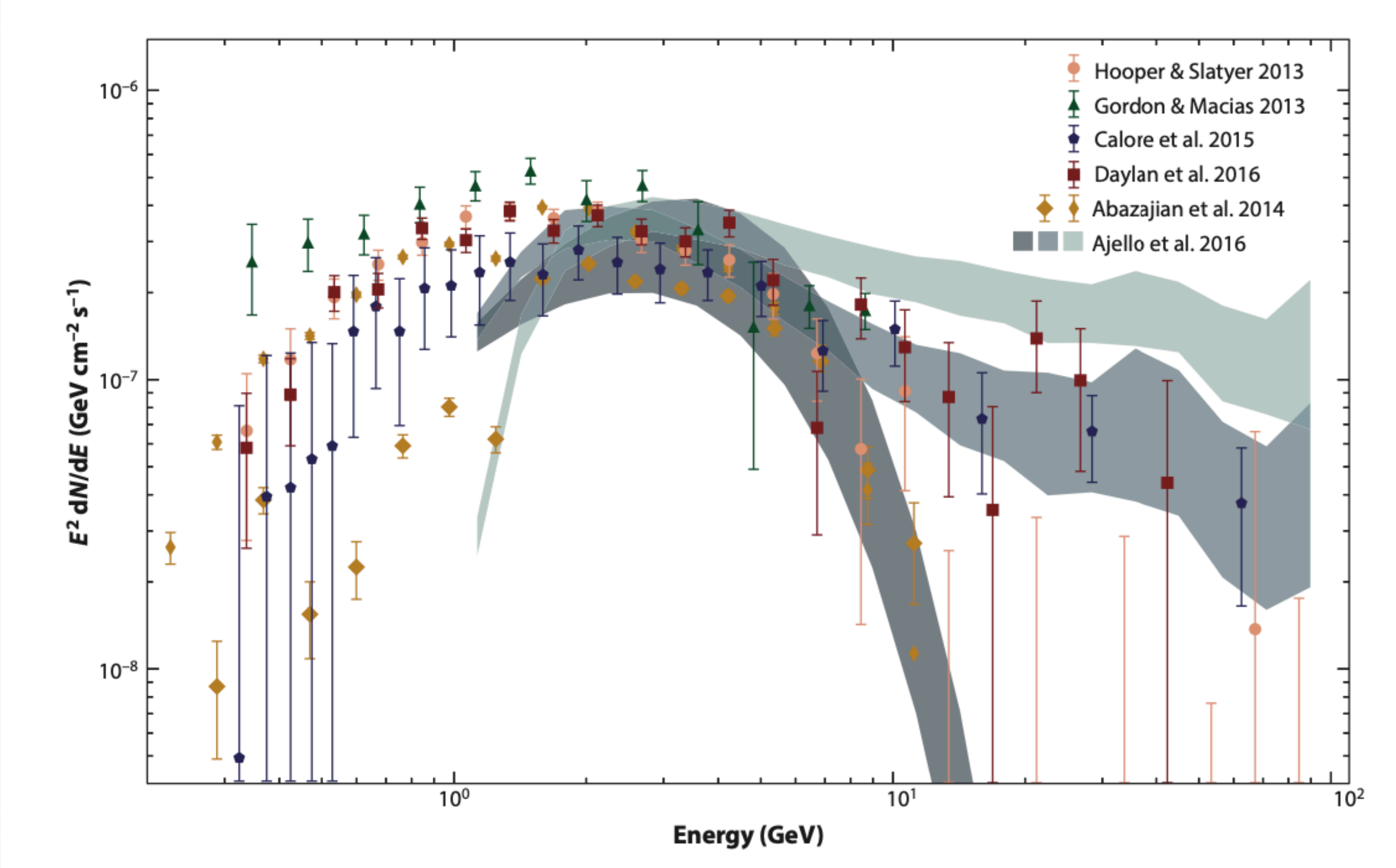
- **Dark Matter: among the few evidence for new physics**
- **Multifaceted approach necessary** (different experiments + different analyses)
- **Higgs sector(s) can provide a portal to DM**: studying SM and BSM Higgs sectors crucial
- **Simple models increasingly ruled out - we need:**
  ➡systematic approach: combinations + re-interpretations
  ➡exploration of all possible final states

"My emotional guess is that the dark sector shows the same complexity (as the visible sector)… far more interesting than our current ideas suggest."

J. Peebles, interview to P. Charitos for CERN EP newsletter

Backup

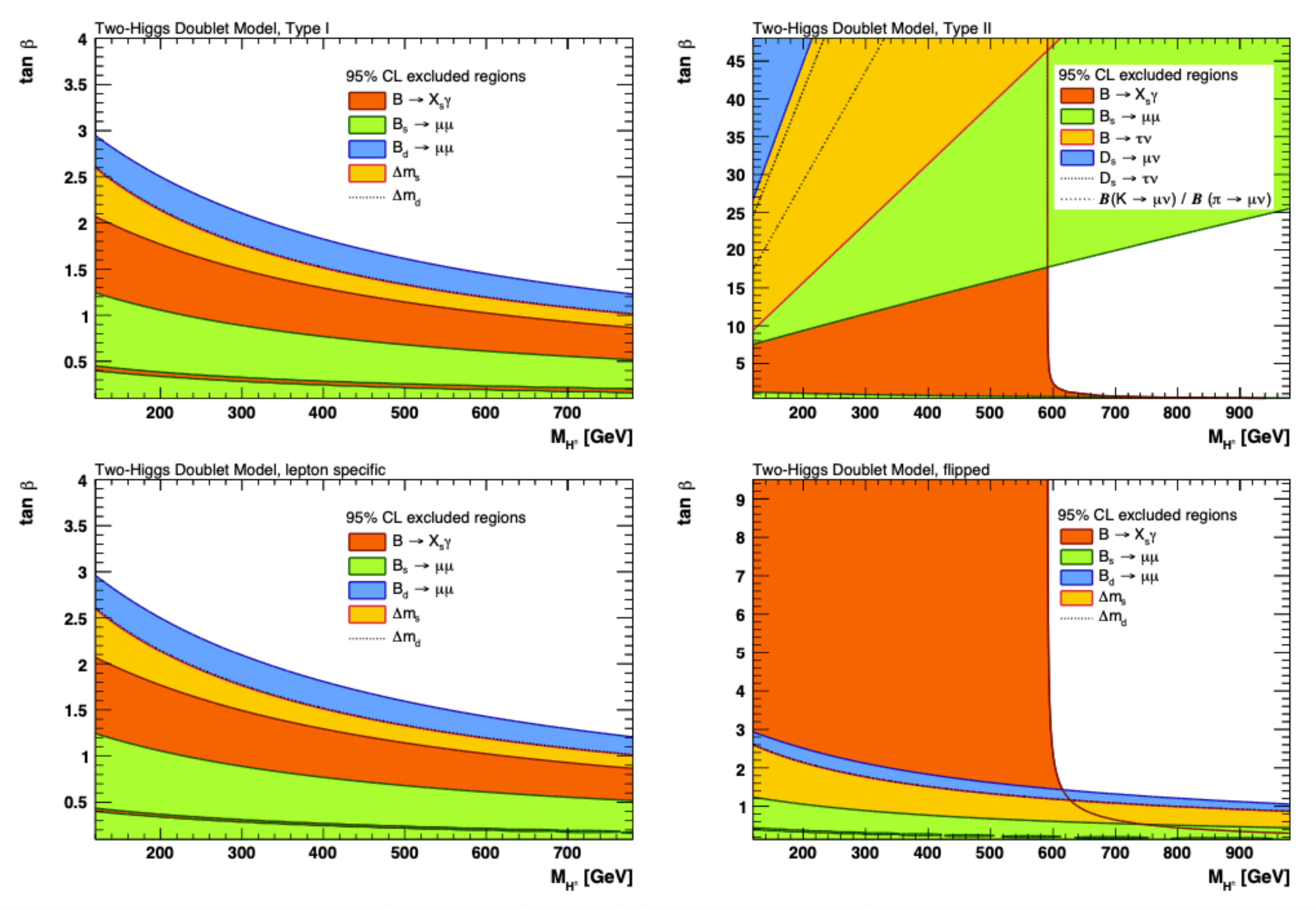
Status of Fermi-LAT excess



Murgia, Annu. Rev. Nucl. Part. Sci. 2020. 70:455–83

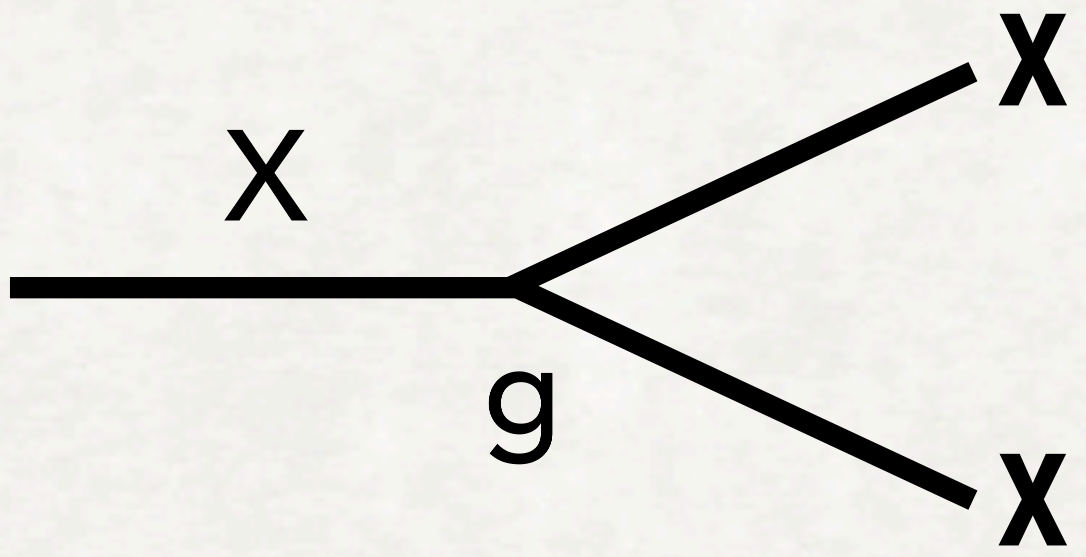
- Spectrum has a peak at a few GeV
- In this region dominant component of **γ** rays comes from interactions of cosmic rays with interstellar medium
- Not certain if it comes from DM (mass ~30-60 GeV) annihilation (to b-quarks) or millisecond pulsar

2HDM constraints



Higgs vs Z portal

from U.Haisch



$$\Gamma(X \to \chi\bar{\chi}) \sim g^2 m_X$$

$$\mathrm{BR}(X \to \chi\bar{\chi}) = \frac{\Gamma(X \to \chi\bar{\chi})}{\Gamma_X}$$

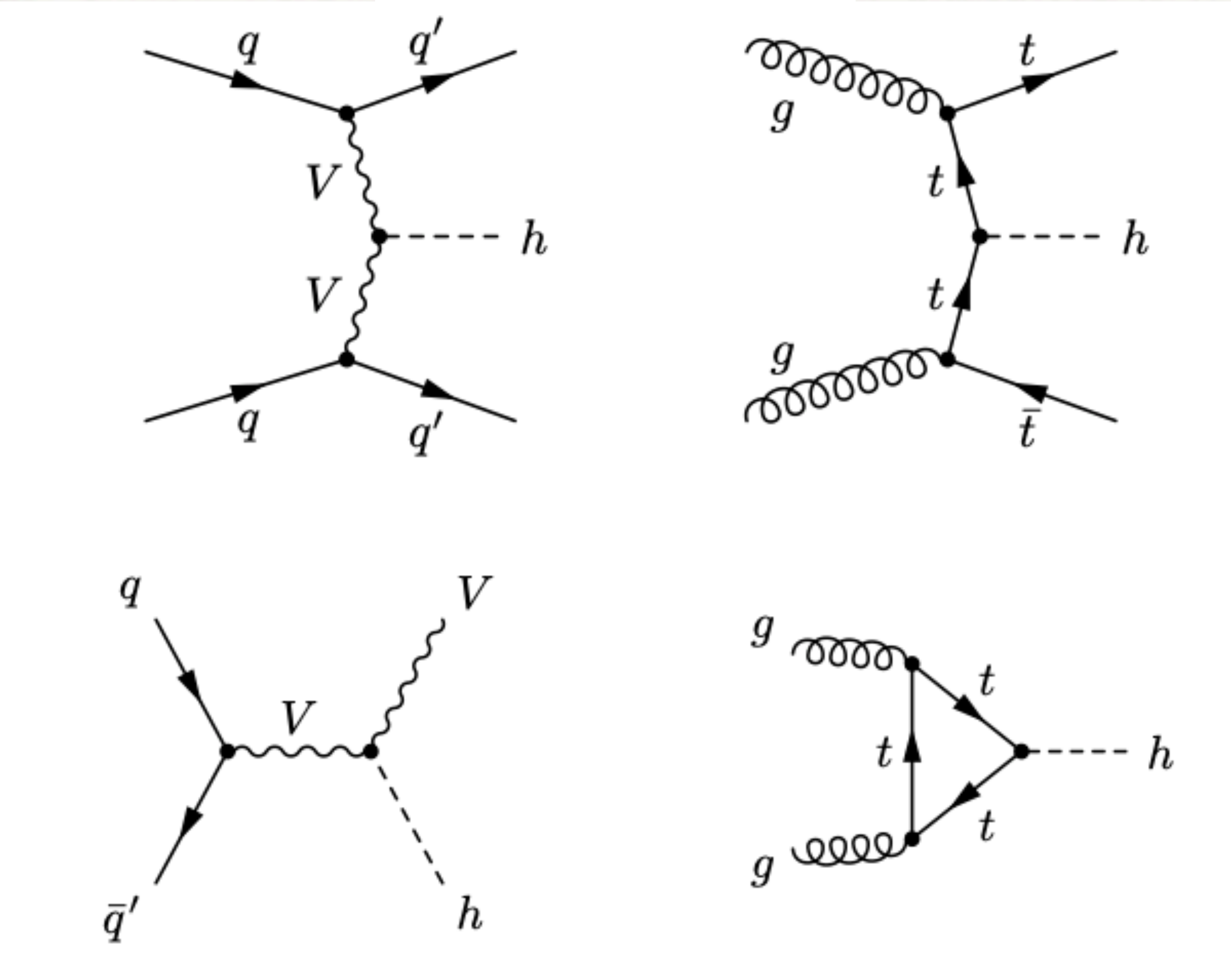
$$g \sim \frac{\Gamma_X \cdot \mathrm{BR}(X \to \chi\bar{\chi})}{m_X}$$

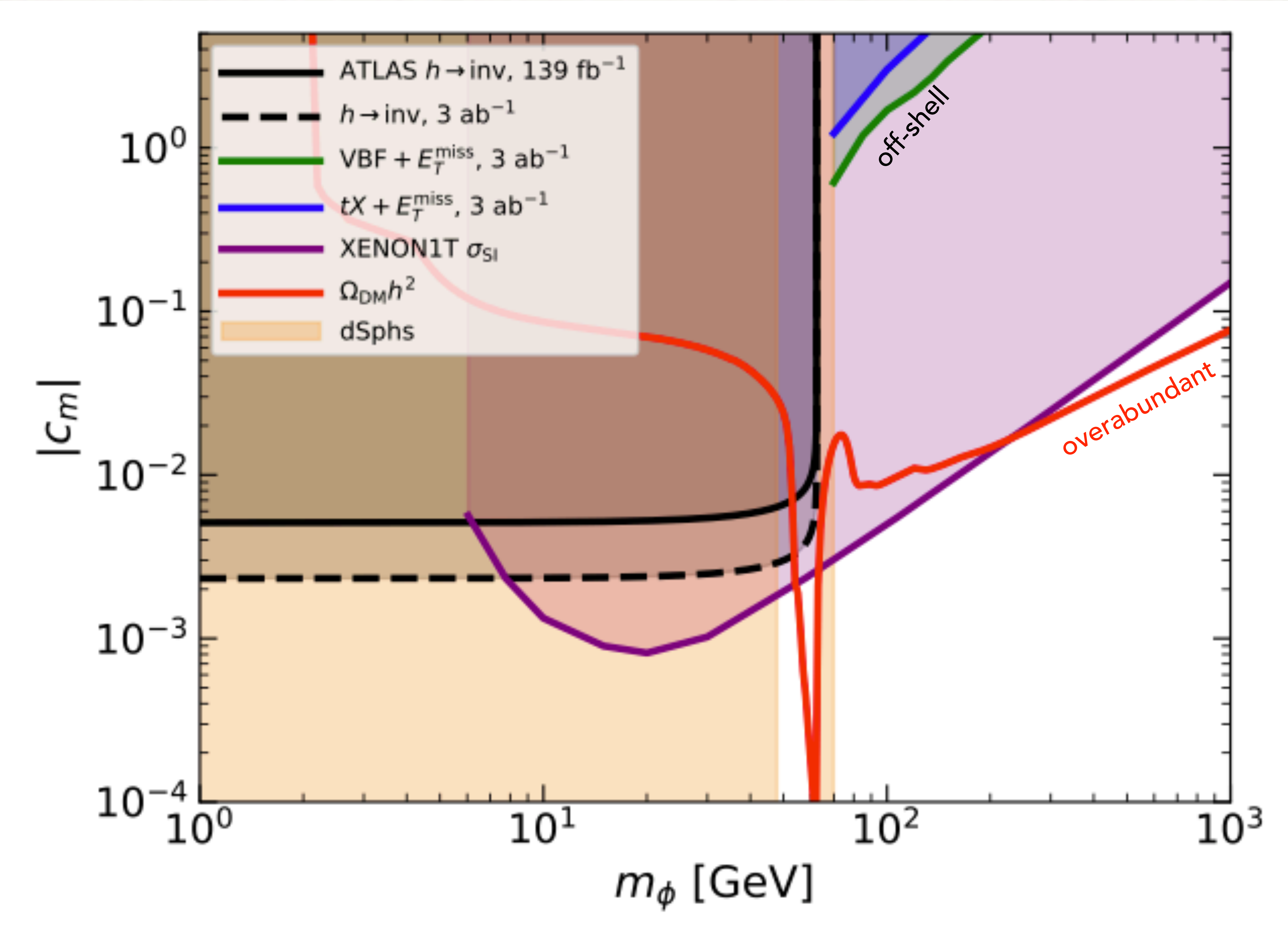
$$\Gamma_Z \simeq 2.5 \text{ GeV}, \Gamma(Z \to \chi\bar{\chi}) \lesssim 2 \text{ MeV} \Rightarrow g \lesssim 0.03$$

$$\Gamma_h \simeq 4.1 \text{ MeV}, \Gamma(Z \to \chi\bar{\chi}) \lesssim 0.5 \text{ MeV} \Rightarrow g \lesssim 0.01$$

SM Higgs portal

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



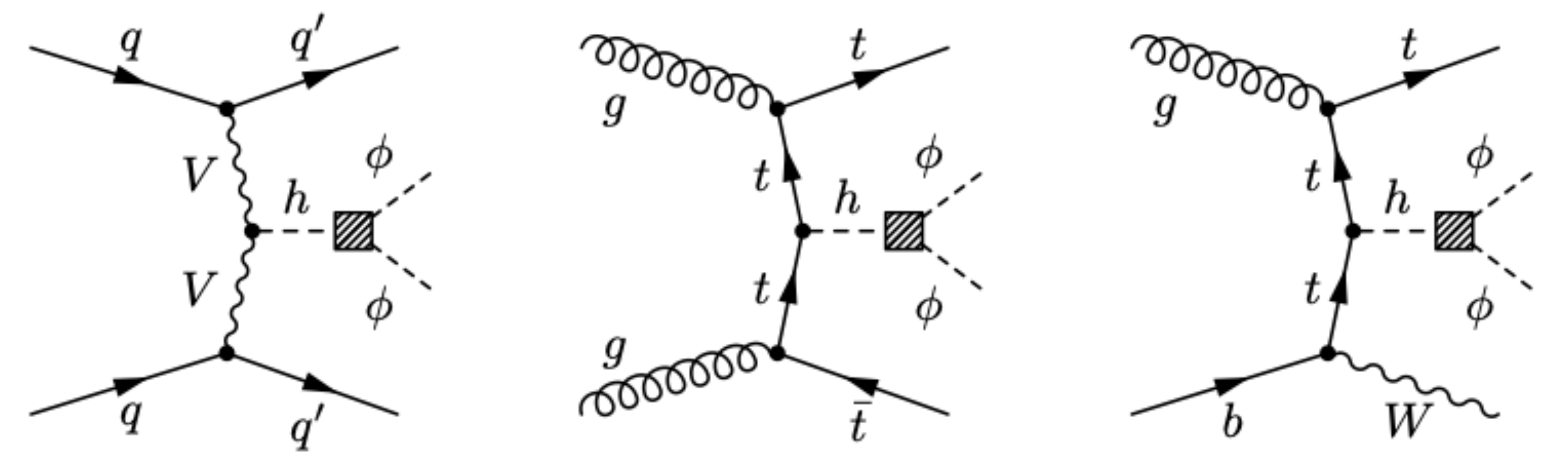


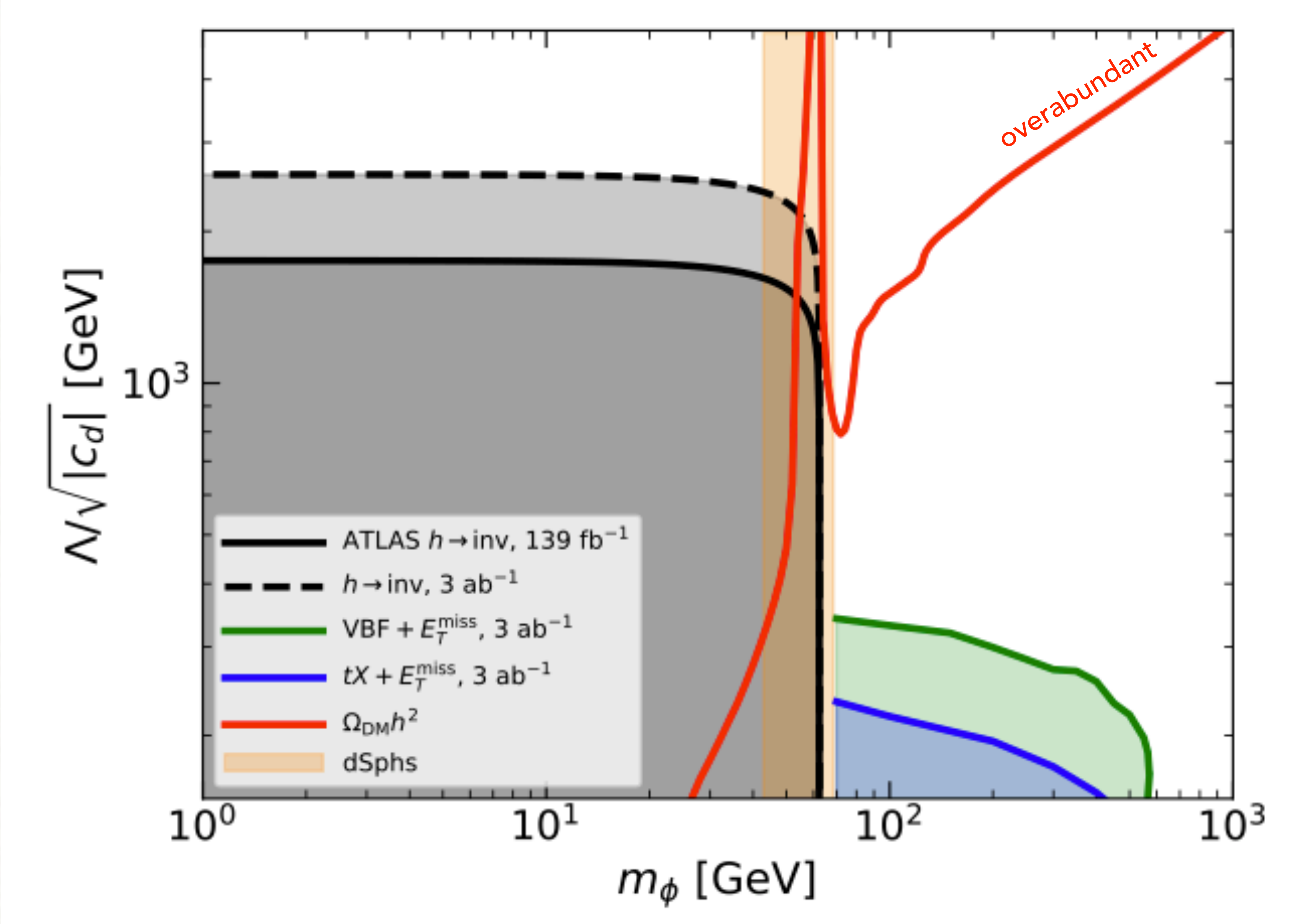
- DM scalar - dim 4 operator
- LHC constraints relevant for m < 5 GeV
- ID constraints from Fermi-LAT assume **ϕϕ**→bb and Ωh^2=0.12, so model dependent

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

Derivative Higgs portal

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





- dim 6 EFT operator
- arise in models with global symmetry breaking, where DM is a pNGB - **Λ** ~ scale of symmetry breaking
- kinetic dependence of interaction suppresses DD constraints

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

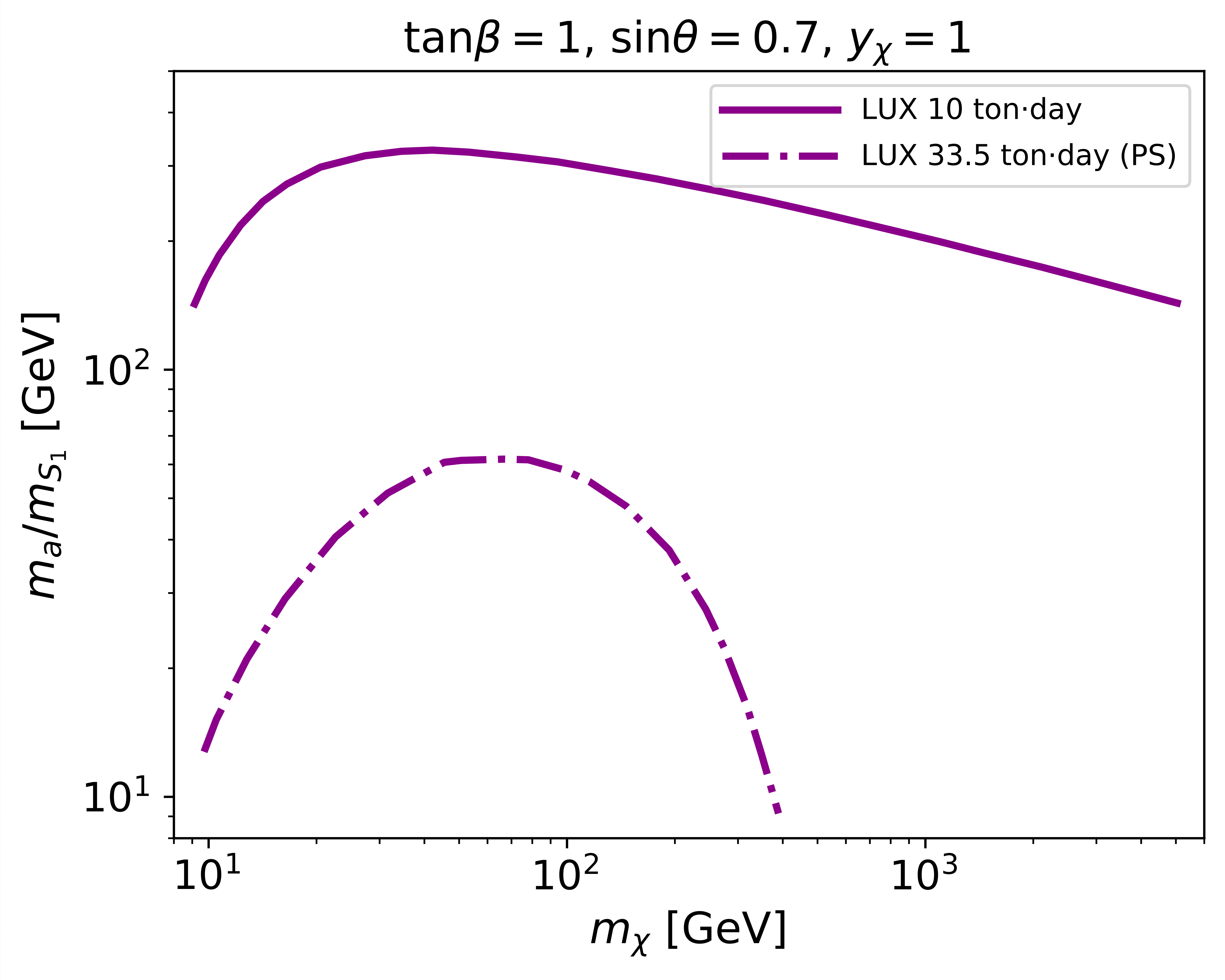
2HDM + scalar: WIMP-nucleon cross-section

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

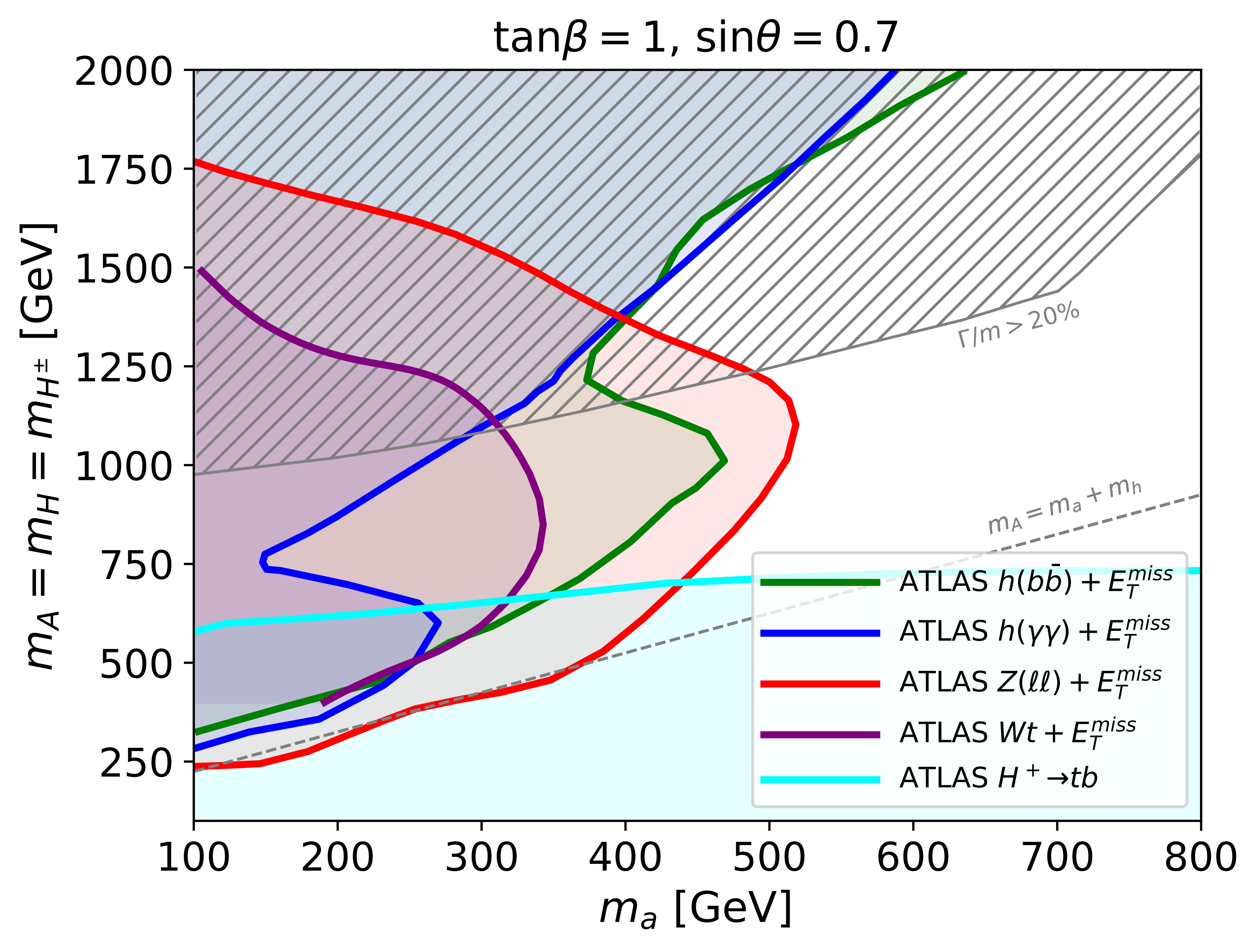
$$c_N = \frac{m_N}{v}\frac{y_\chi \sin(2\theta)}{2}\left(\frac{1}{m_{S_1}^2} - \frac{1}{m_{S_2}^2}\right)$$
$$\times \left[\cot\beta\, f_{T_u}^N - \tan\beta \sum_{q=d,s} f_{T_q}^N + \frac{4\cot\beta - 2\tan\beta}{27} f_{T_G}^N\right]$$

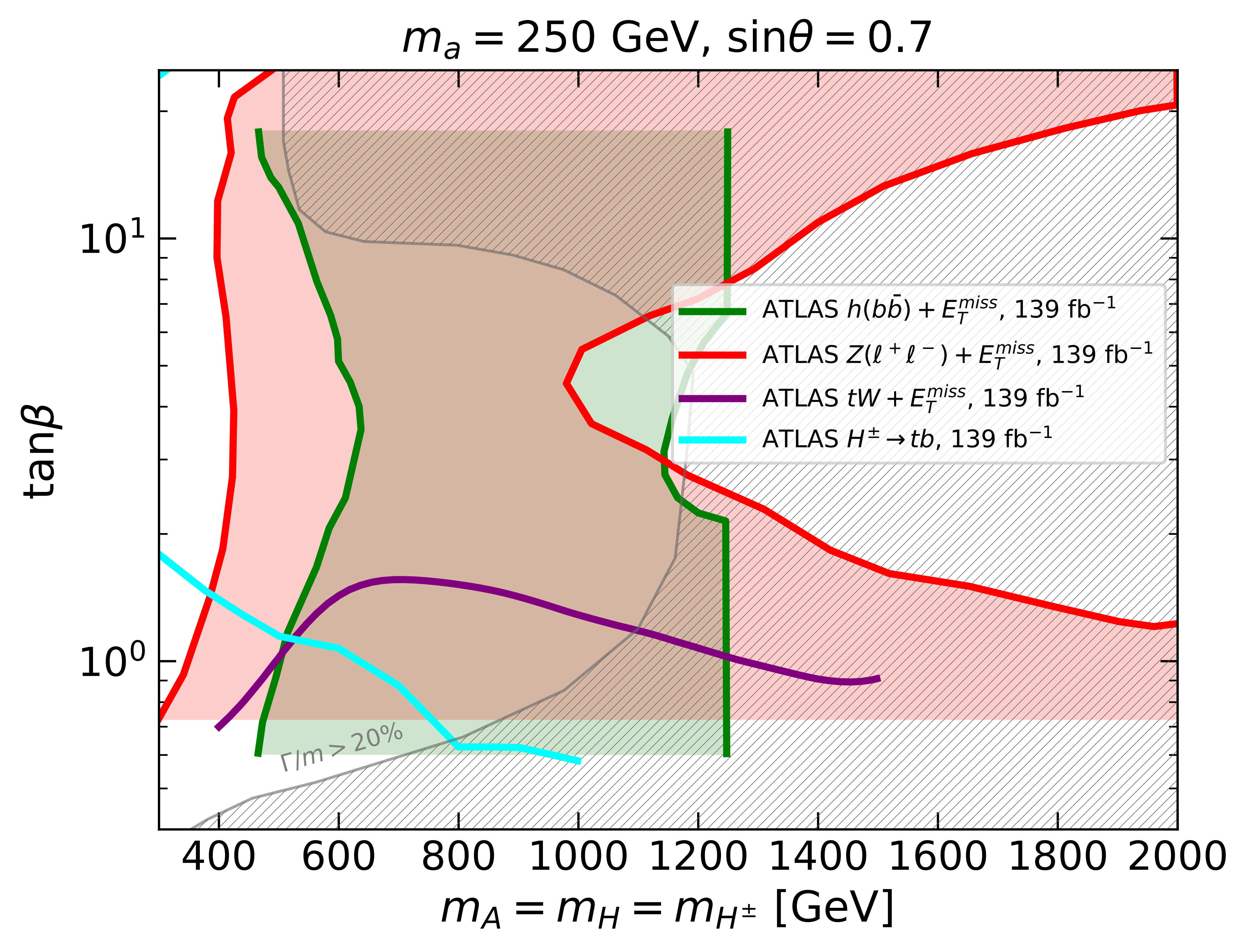
- Up and down-quark contributions interfere destructively in Type-II
- Numerically close to 0 for tan**β** ≅ 1

DD scalar vs pseudoscalar

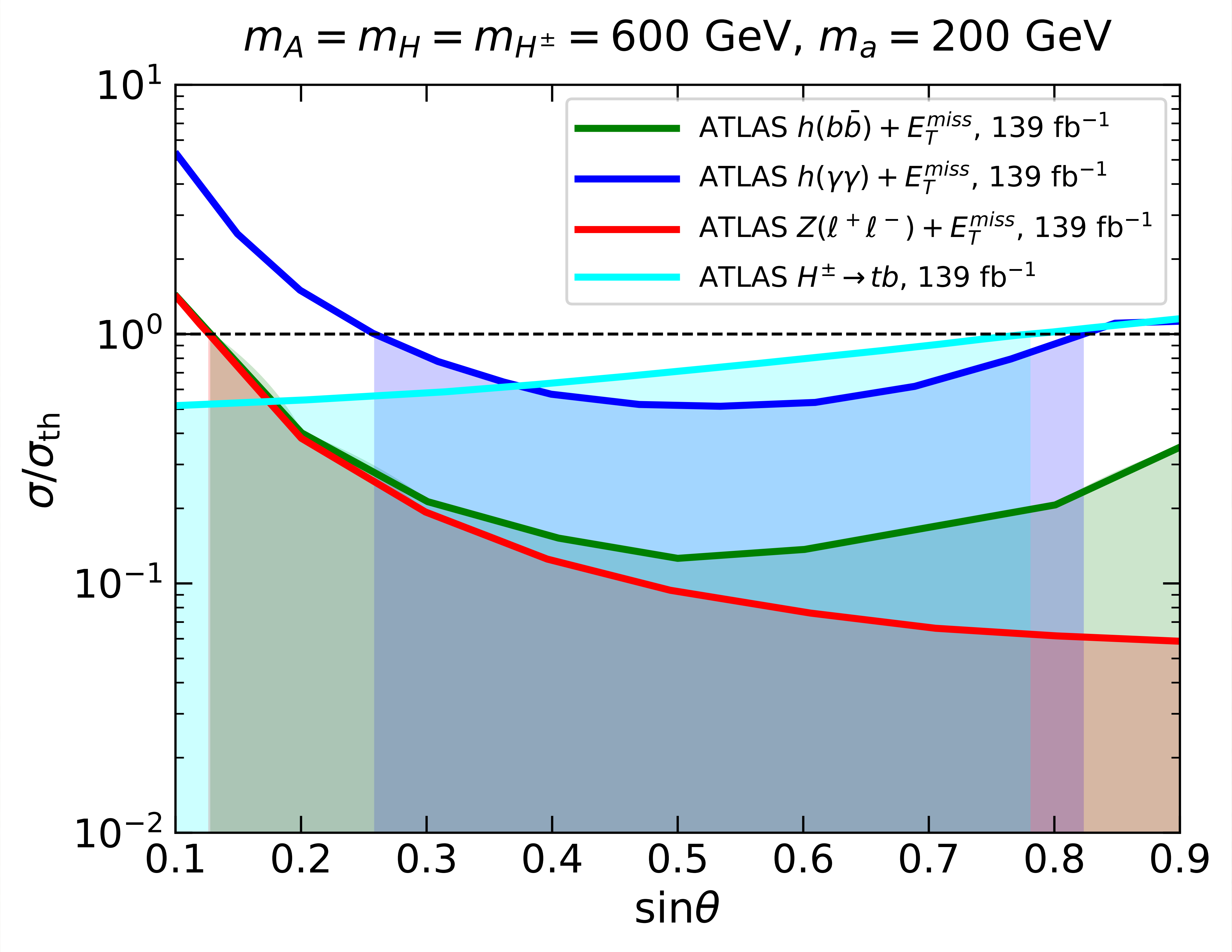


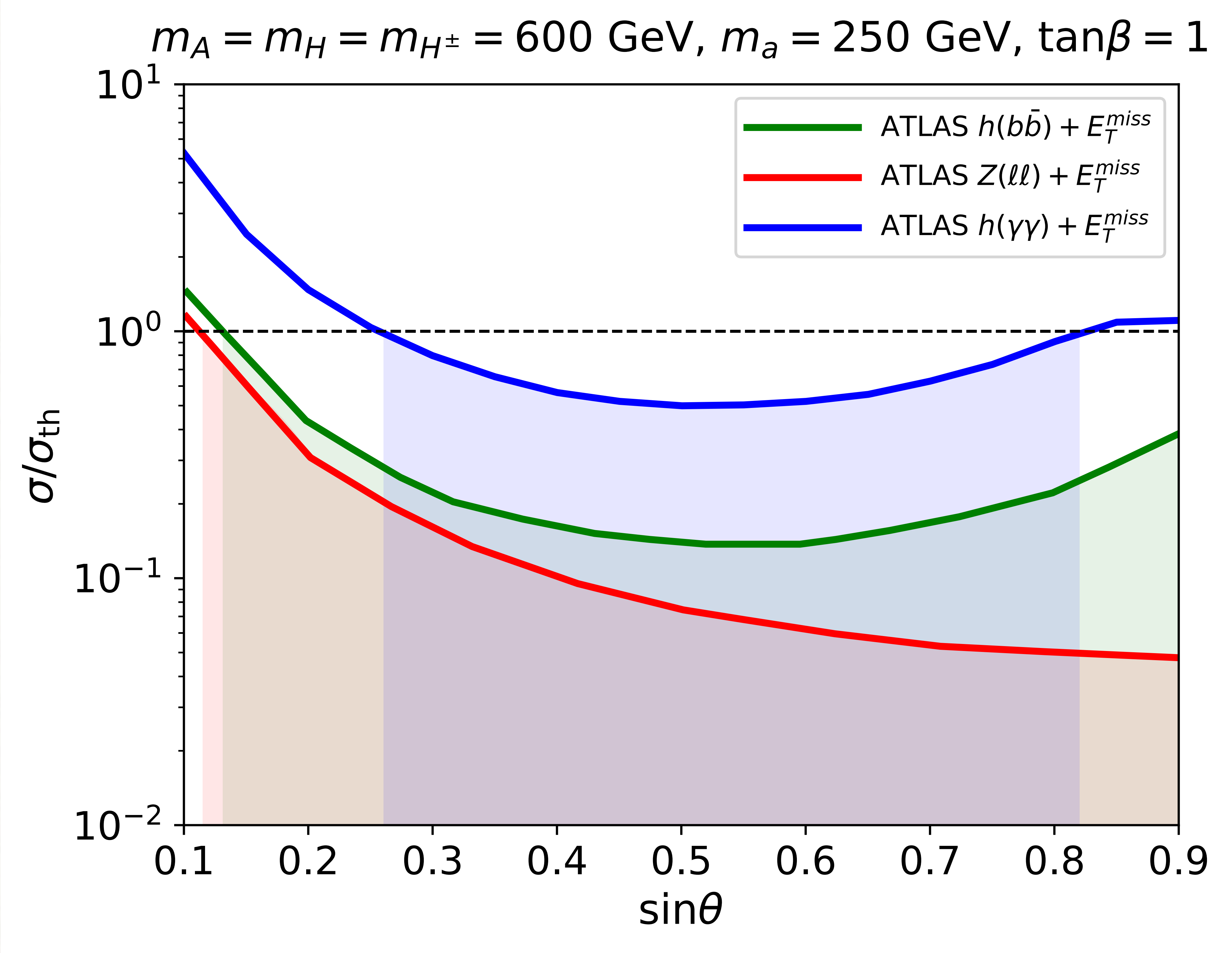
2HDM+a - large mixing



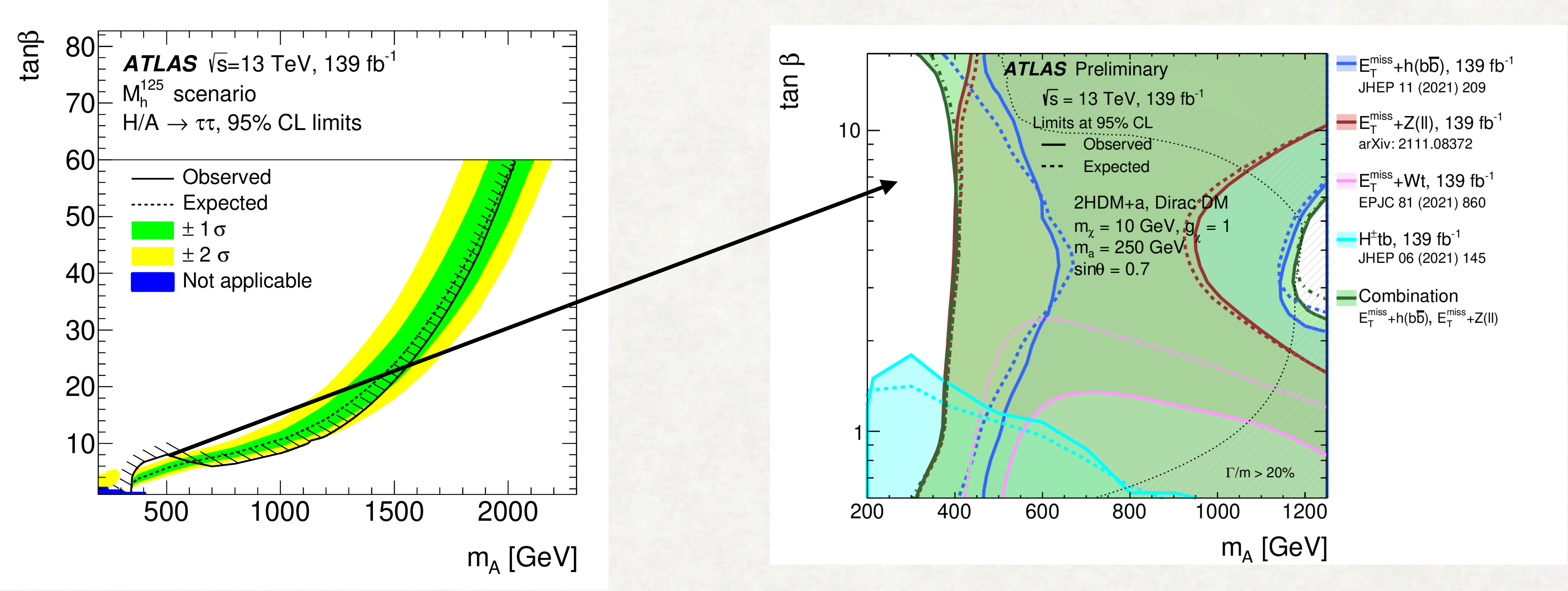


2HDM+a – mixing angle scan





Constraints from taus



[Phys. Rev. Lett. 125 (2020) 051801]

Higgs width constraints

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

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

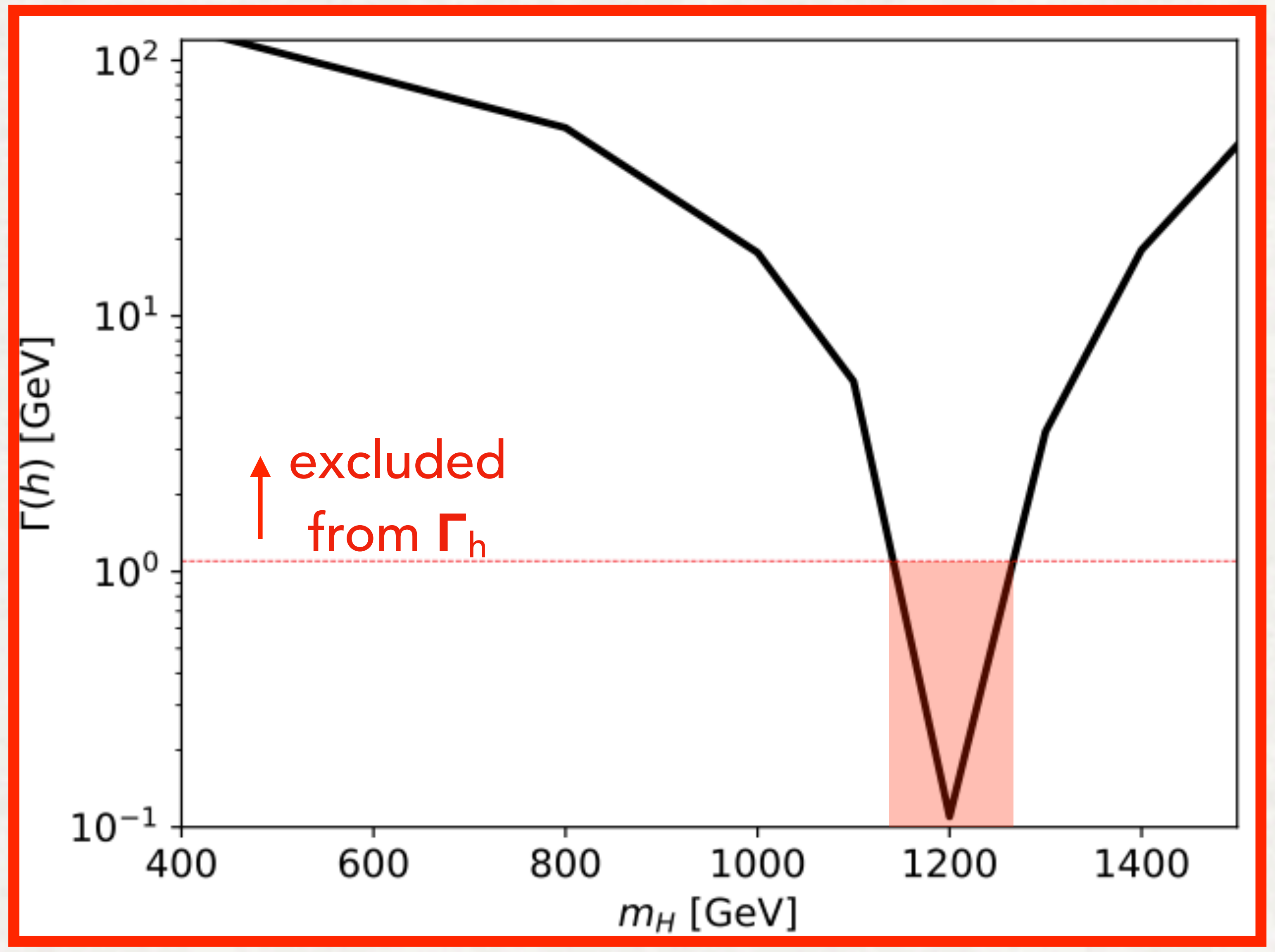
$$= \frac{1}{m_h v}\left[2\left({m_A}^2 - m_a^2 + \frac{m_h^2}{2}\right)\sin^2\theta - 2\lambda_3 v^2\right]$$

cos(**β**-**α**)=0

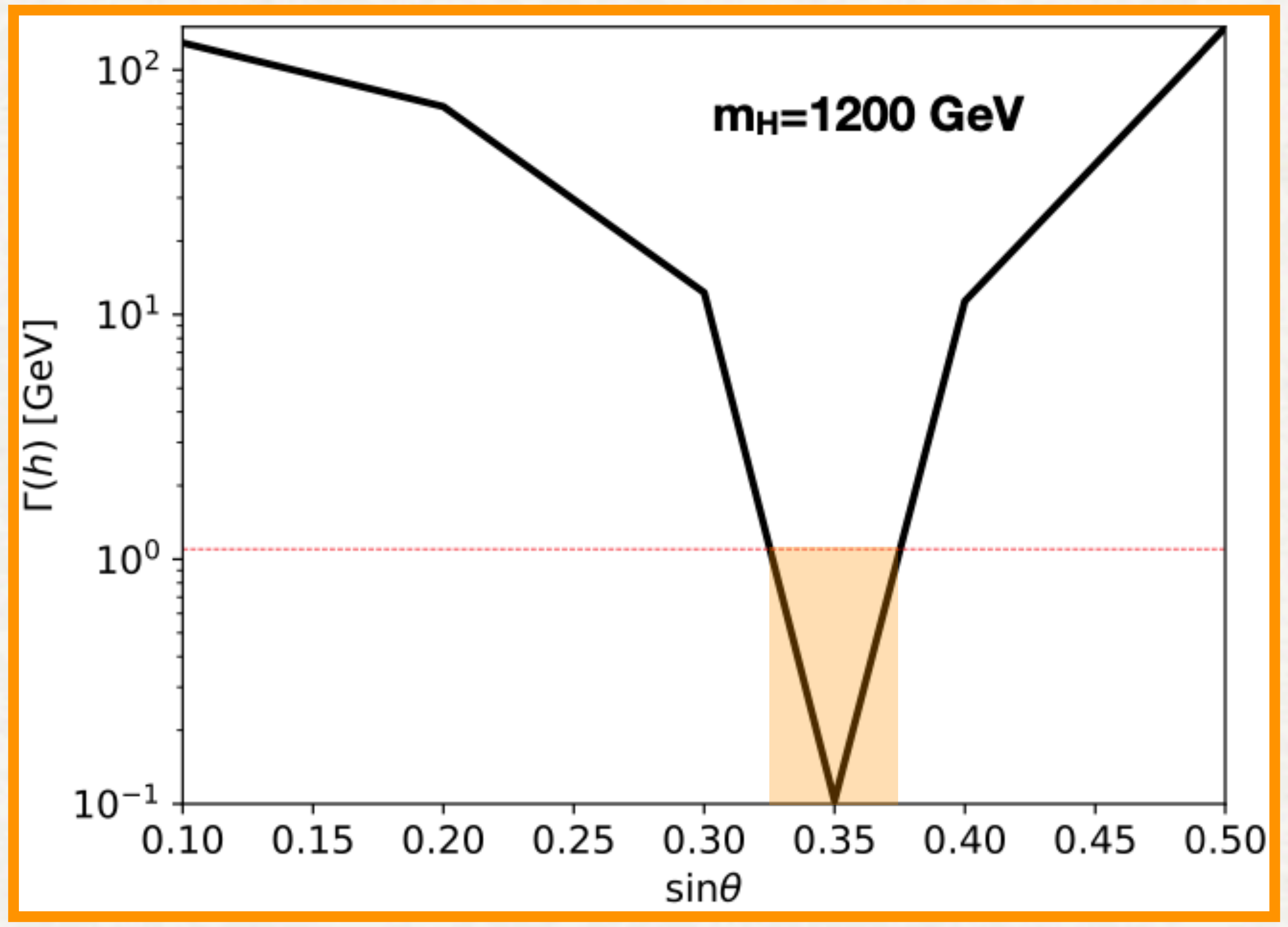
$m_A=m_H=m_{H+}$

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

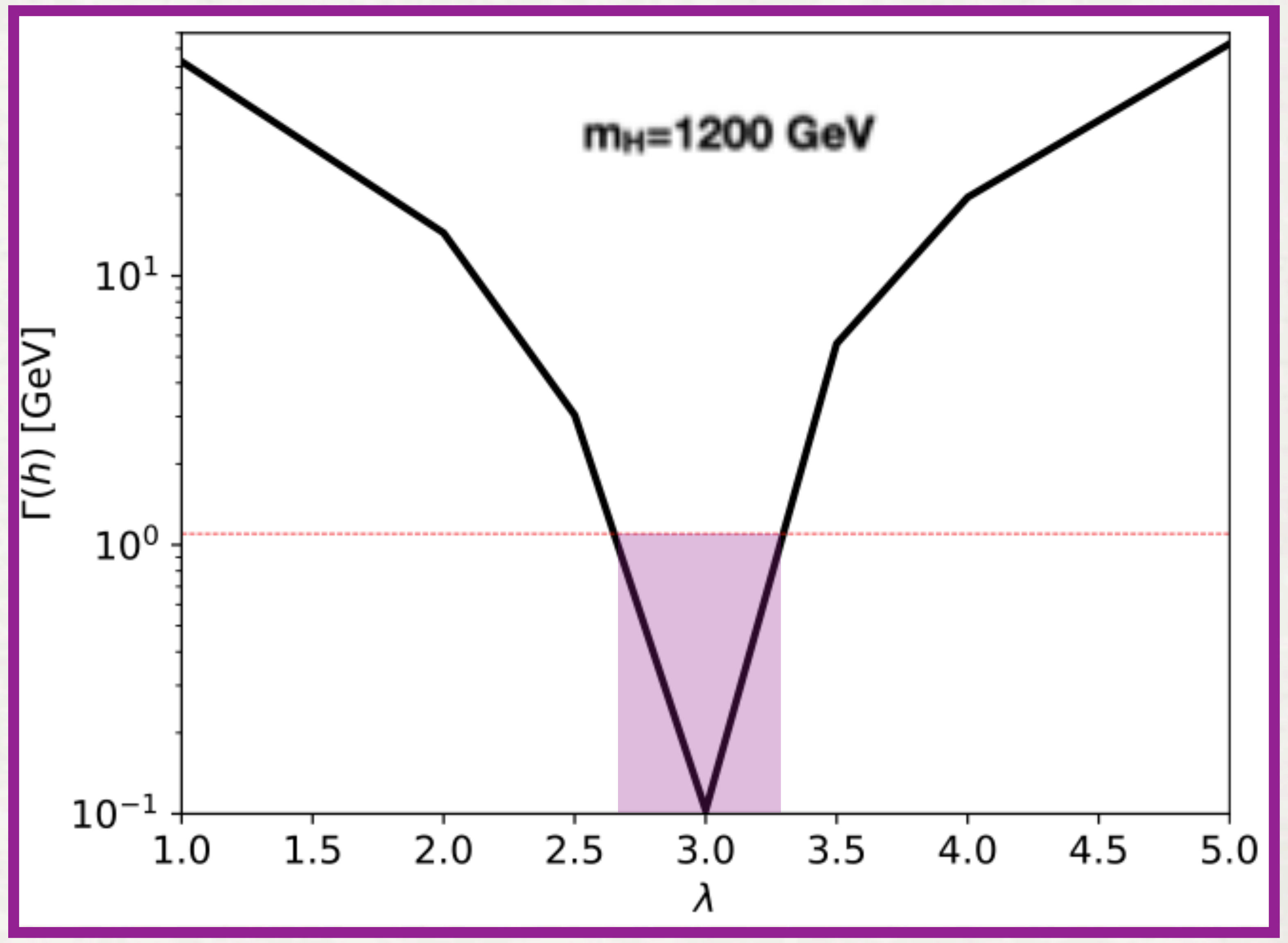
m_A



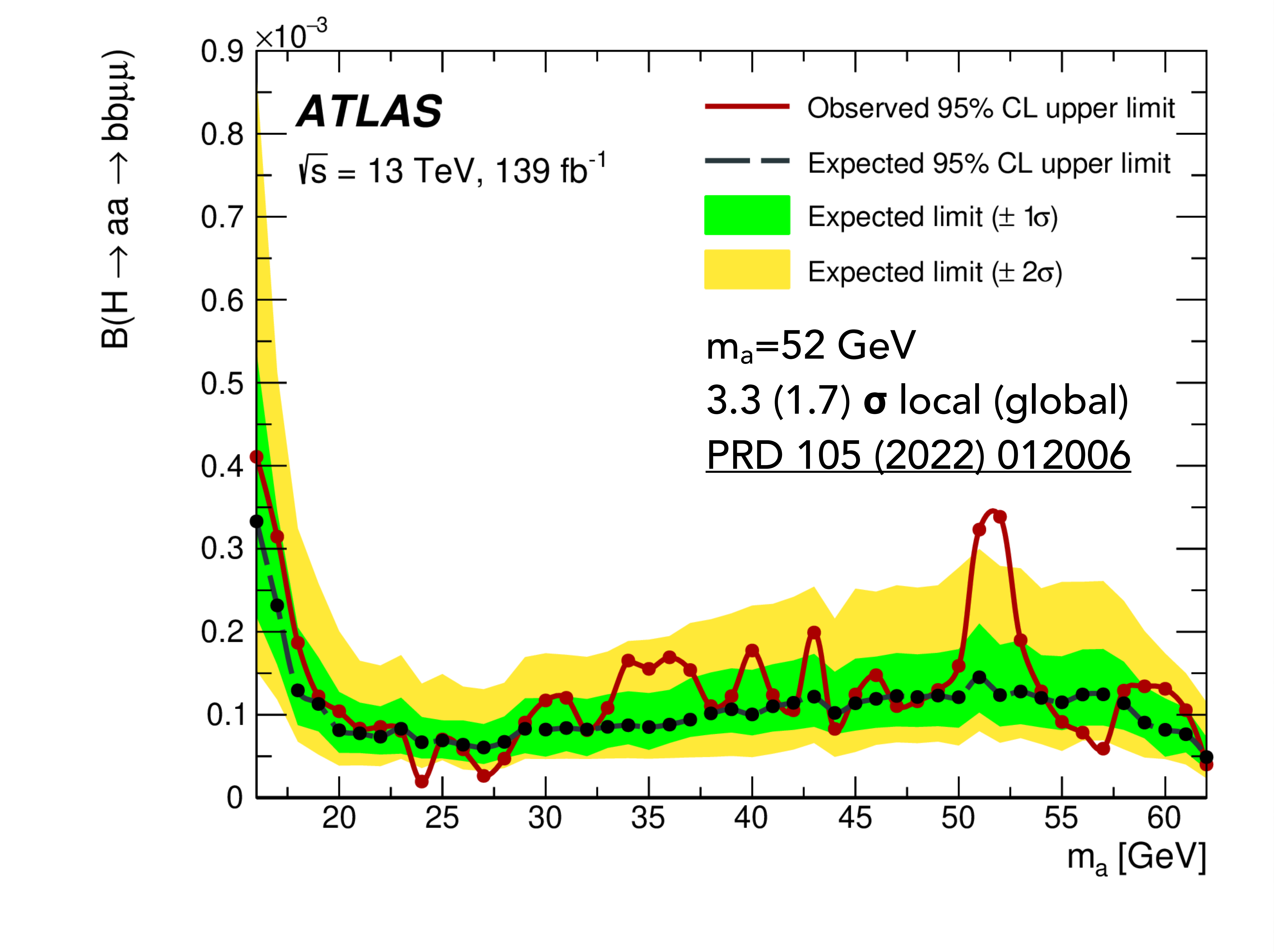
sinθ

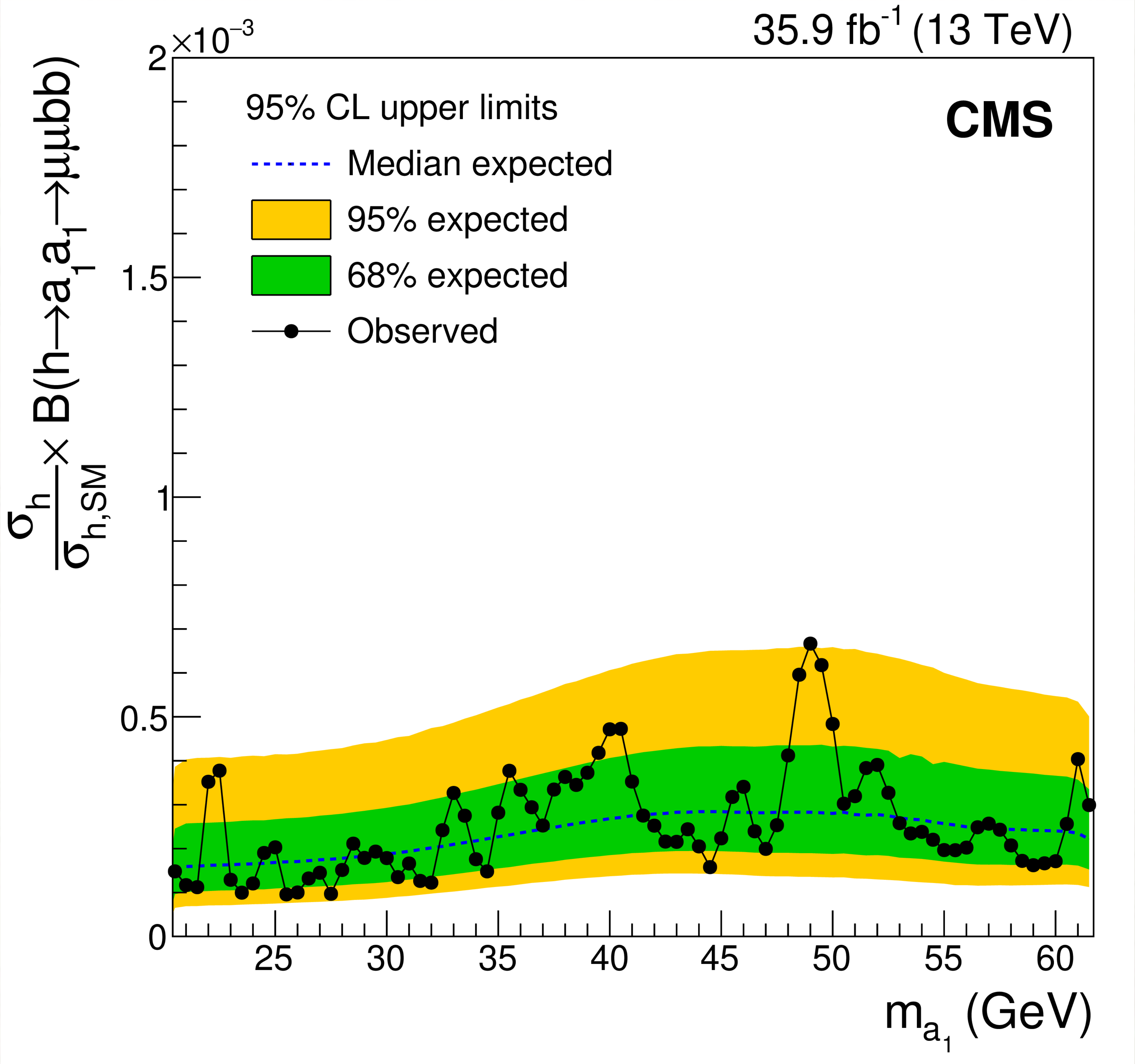


λ_3



aa→bbμμ excess





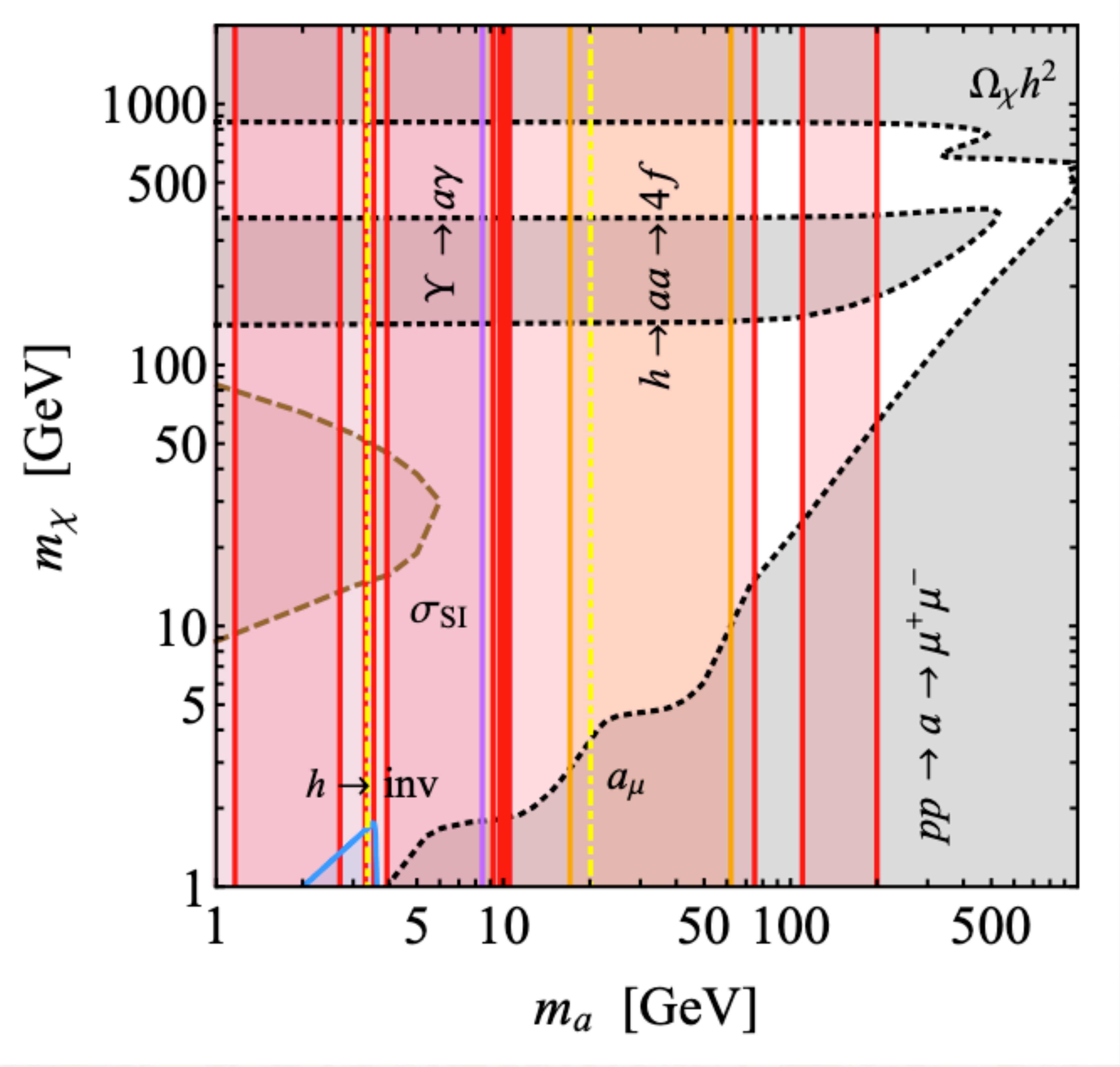
LHC vs g-2

- Original idea from Arcadi, Djouadi & Queiroz (2112.11902) to simultaneously explain DM & muon g-2
- Can also evade constraints from $\boldsymbol{\Gamma}_h$
- Large tan$\boldsymbol{\beta}$ and small m_a needed to get the correct sign for $\boldsymbol{\delta a}_\mu$
- HLRS analyses would extend down to very low m_χ because $\boldsymbol{\Gamma}(a\to\chi\chi)\sim y_\chi^2\cos^2\boldsymbol{\theta}=0.005$
- 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 $\boldsymbol{\Gamma}_H > m_H$ over the whole m_a-m_χ plane

$$\{m_A, \tan\beta, \sin\theta, \lambda_3, y_\chi\} = \{1.0\,\text{TeV}, 40, 0.7, 8, 0.1\}$$



SA, Haisch, 2202.12631

2HDM+Z′: coupling scan