Dark Matter at the LHC:
new signatures from extended Higgs sectors

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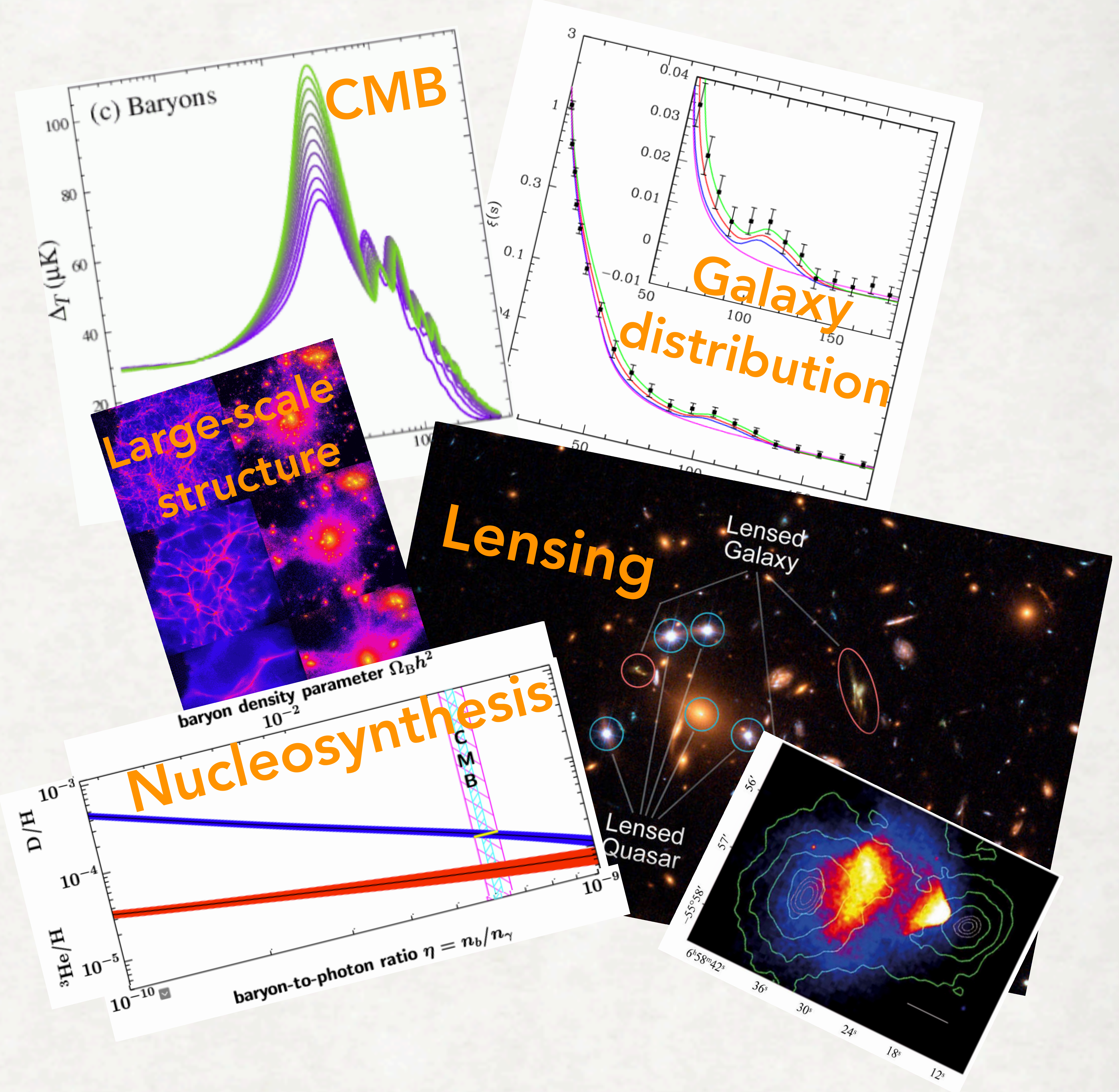
ΠΑΝΕΠΙΣΤΗΜΙΟ
ΘΕΣΣΑΛΟΝΙΚΗΣ

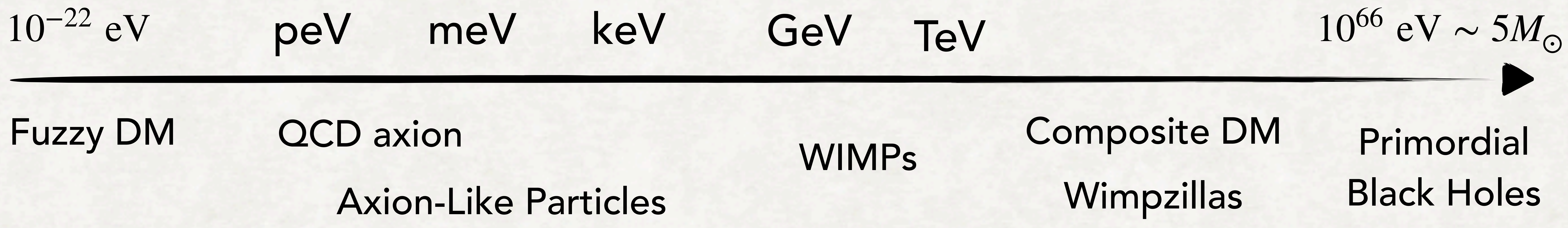
Dark Side of the Universe 2024 - Corfu
9 September 2024

Dark Matter enigma

- Indirect evidence for DM corroborated by several observations
- Little guidance from theory - parameter space of models is vast

➡ Need several complementary experimental probes





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

Fuzzy DM

QCD axion

Axion-Like Particles

WIMPs

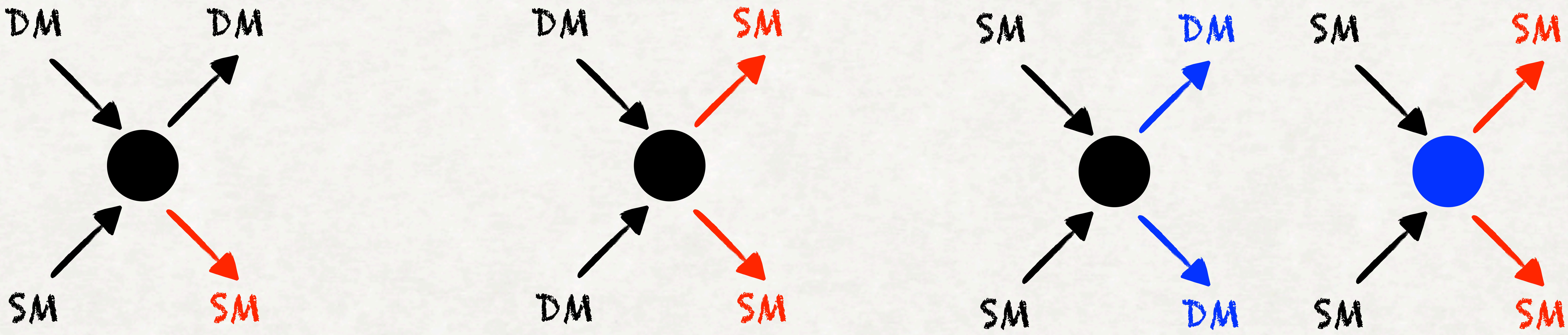
Composite DM

Wimpzillas

Primordial Black Holes

How do we look for Dark Matter?

Direct Detection Indirect Detection Colliders



Colliders offer:

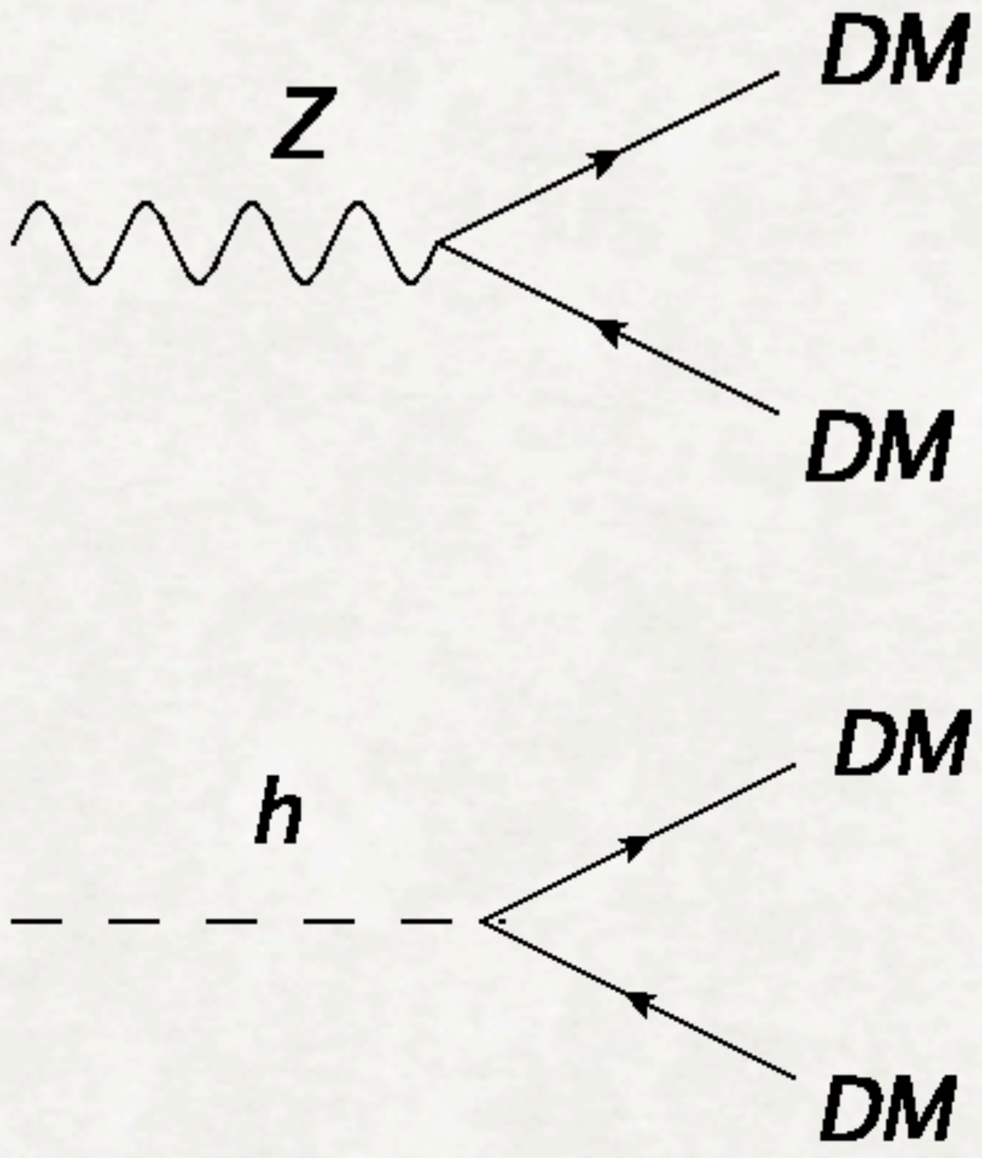
1. controlled environment
2. insensitive to DM distribution
3. wide range of signatures
    - NB: in certain parameter spaces, some signals are only visible at colliders

      [SA, Brandt, Haisch, Symmetry 2021 (13) 12]

Dark Matter and the Higgs boson

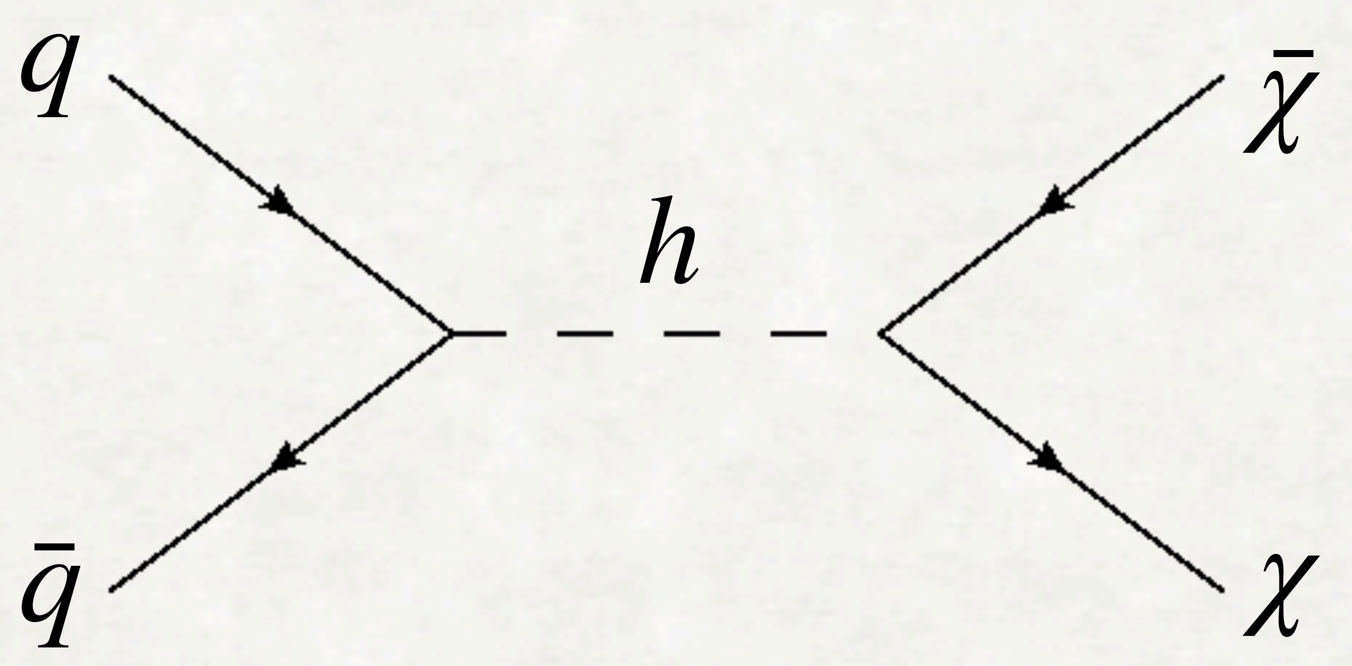
- **Higgs mass operator** $H^\dagger H$ is the only Lorentz and gauge invariant operator with dimension 2
  ➡ it **can admit** (super)**renormalisable interactions** to SM singlet fields (**Dark Matter**)

- Very **small Higgs width** ⇒ LHC sensitivity to Higgs-DM interactions > LEP sensitivity to Z-DM interactions



$$\frac{g_h}{g_Z} = \sqrt{\underbrace{\frac{\text{BR(h} \to \text{inv)}}{\text{BR(Z} \to \text{inv)}}}_{\sim 10^2} \cdot \frac{m_Z}{m_h} \cdot \underbrace{\frac{\Gamma(h)}{\Gamma(Z)}}_{\sim 10^{-3}}} \sim 0.4$$

Higgs portal models

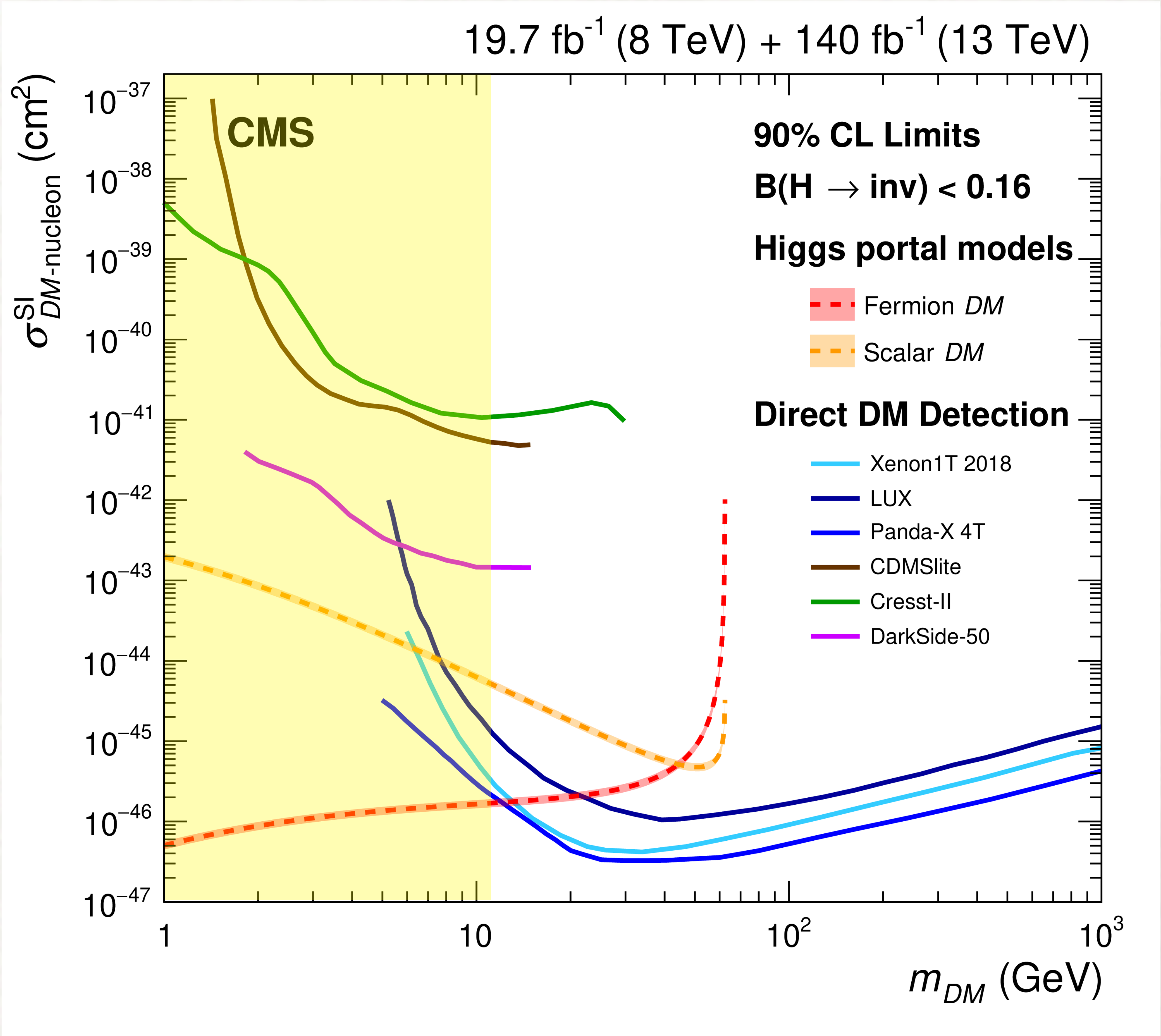


- Simplest scenario relating Higgs with DM is the SM Higgs portal model

$$\mathscr{L} = c_m \phi^2 H^\dagger H + \frac{c_d}{\Lambda^2}(\partial_\mu \phi^2)(\partial^\mu (H^\dagger H))$$

- Higgs to invisible searches provide tight constraints $\mathrm{BR}(h \to \mathrm{inv}) \lesssim 10\,\%$

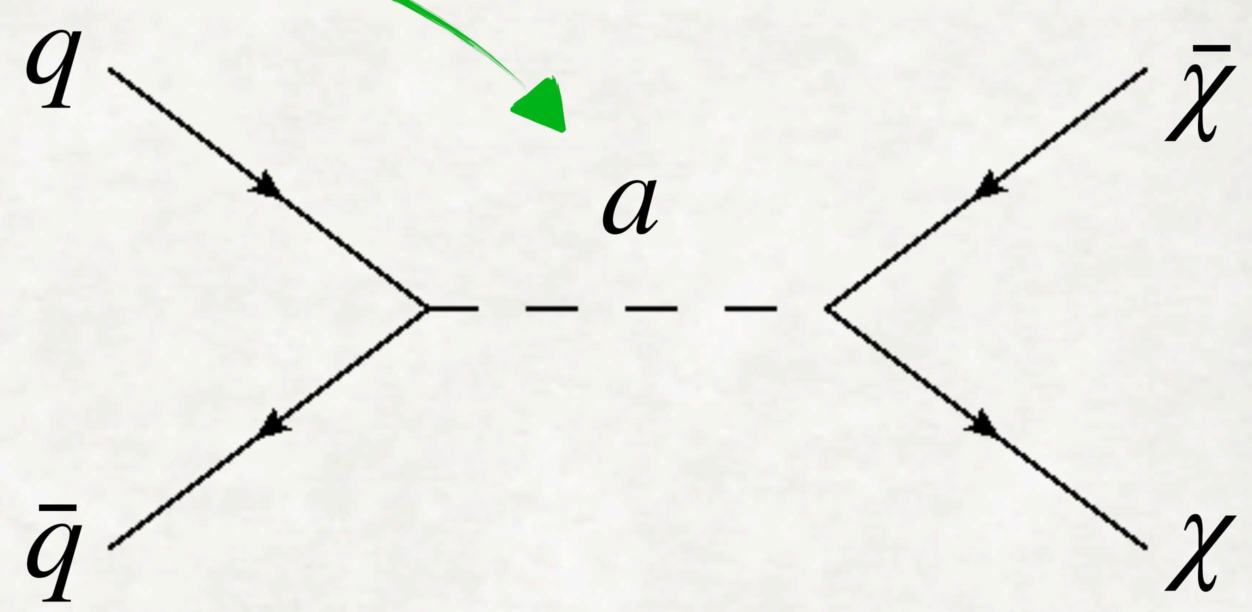
- "Marginal" portal probes $m_{\mathrm{DM}} < 62.5\ \mathrm{GeV}$ - complementary to direct detection



CMS,PRD 105 (2022) 092007

ATLAS PLB 842 (2023) 137963

Extended Higgs portals



- Can we have a **new spin-0 mediator** instead of the SM Higgs?

  ➡ Yes, but to conserve $SU(2)_L \times U(1)_Y$ mediator has to mix with Higgs

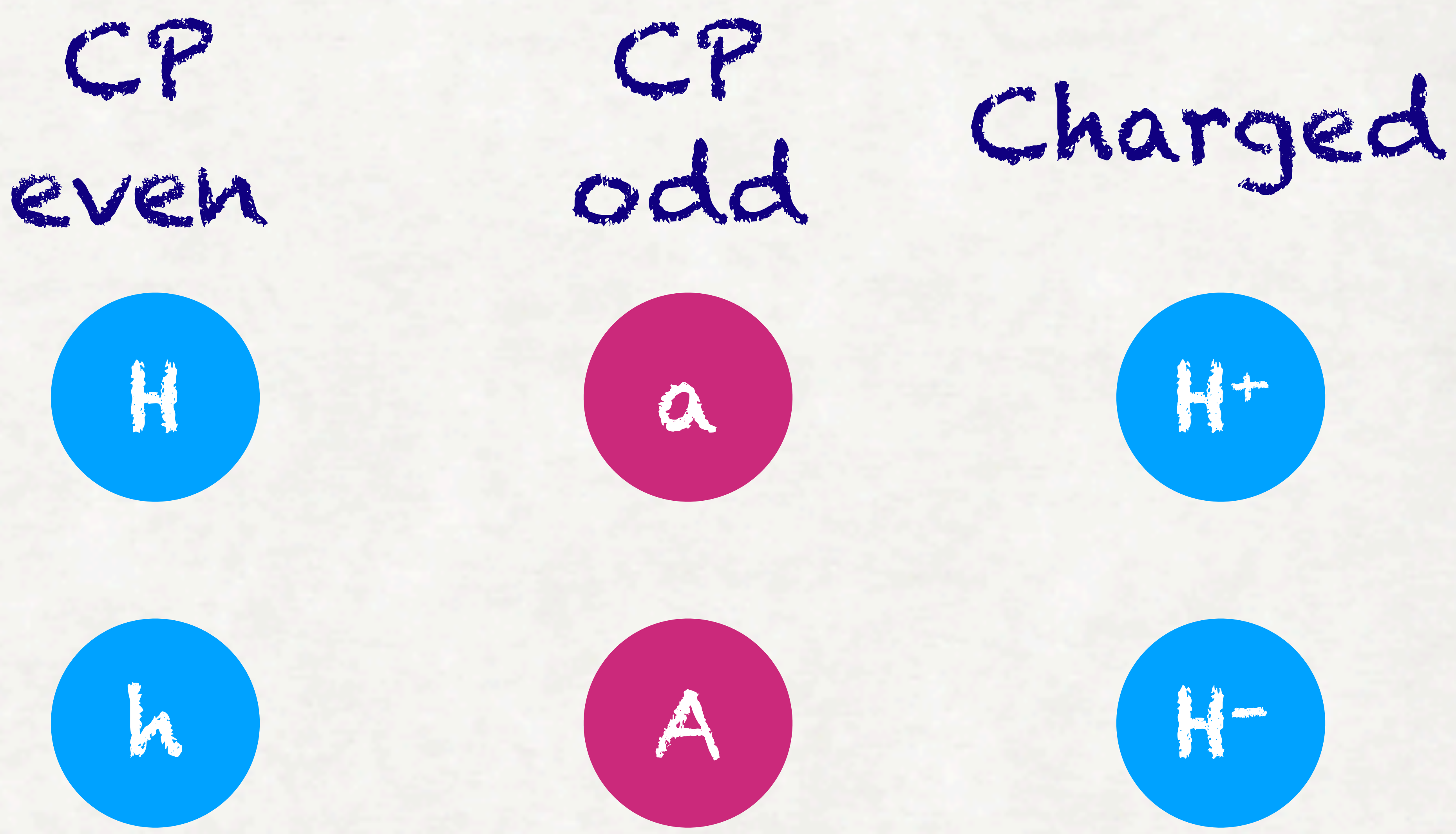
- Simplest scenario (H+S) extremely constrained *[Ilnicka, Robens, Stefaniak, MPLA 33 (2018) 1830007]*

- Plausible scenario: 2 Higgs doublets + pseudoscalar mediator coupling to DM (2HDM+a)

- Workhorse for many LHC DM searches

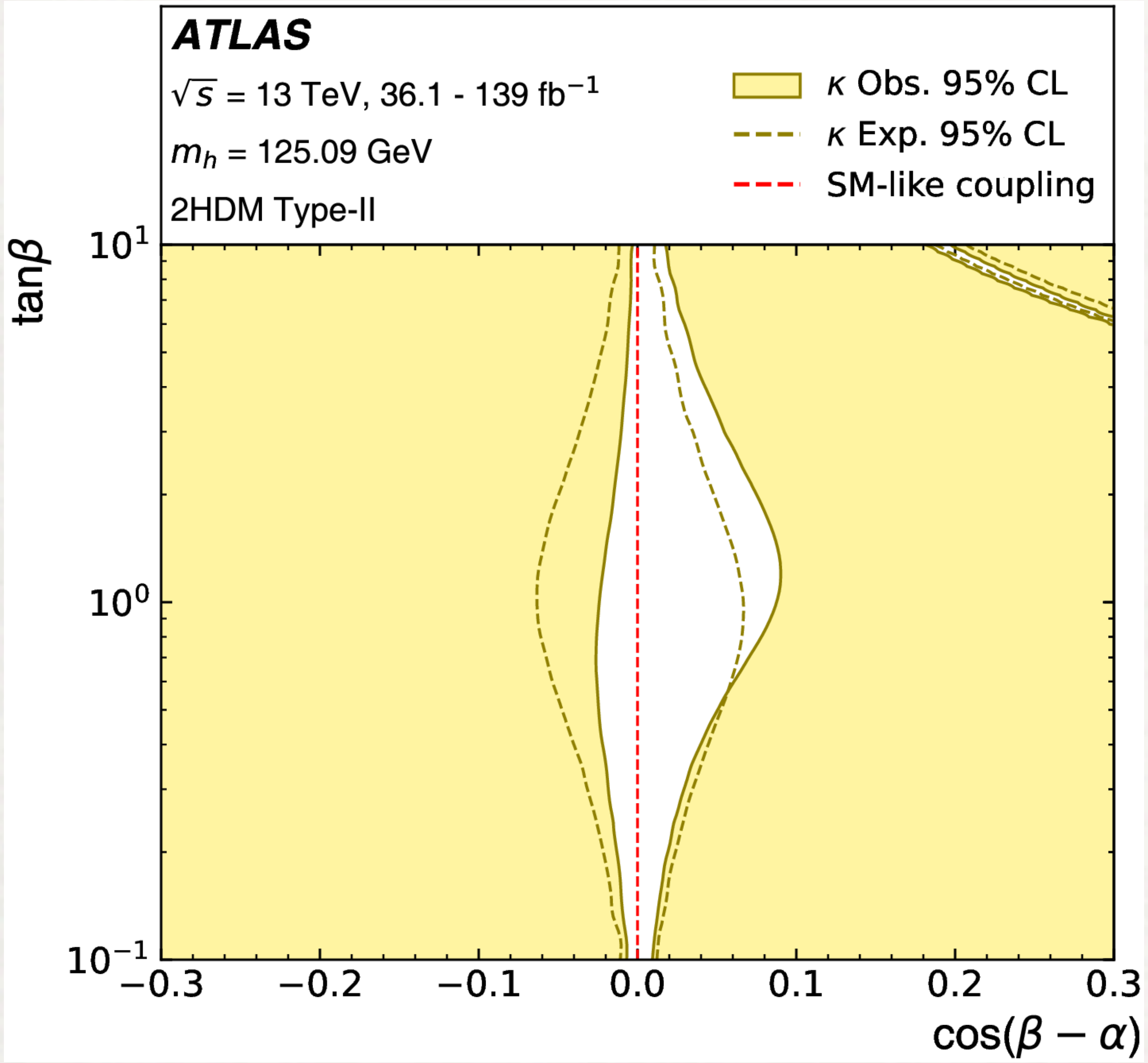
The 2HDM+a model

- Extra **CP-odd mediator a** that couples to DM
  - suppressed DD constraints
  - originally proposed to explain Fermi-LAT excess
- 2 Higgs doublets + CP-odd singlet
- 2 vevs: $v_1/v_2 \equiv \tan\beta$
- 6 Higgs bosons
- CP-even Higgses mix through angle $\beta - \alpha$
- CP-odd Higgses mix through angle θ
- Different Yukawa structure with suppressed or enhanced couplings to down-type fermions and leptons

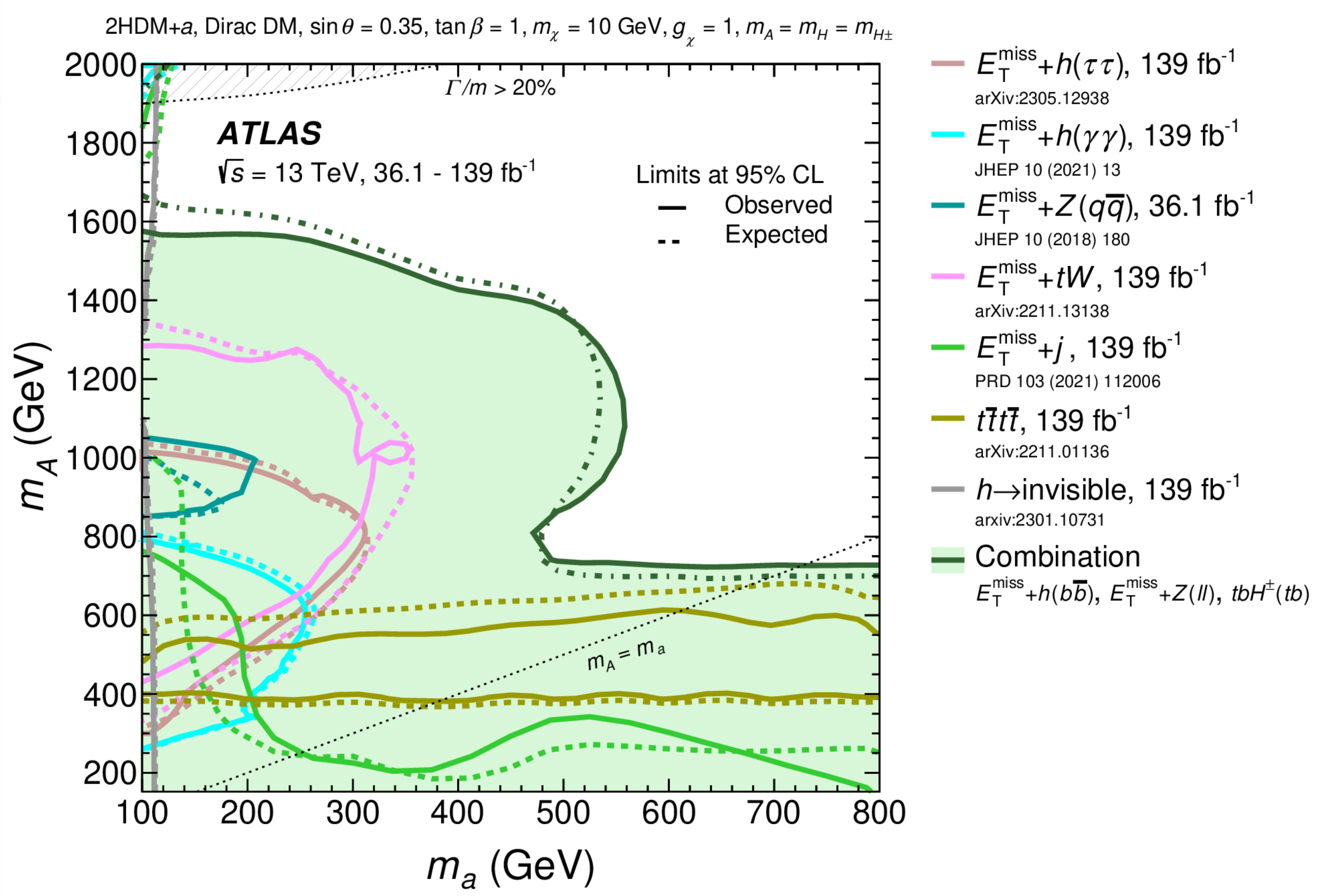


Coupling	Type I	Type II
uH	sinα/sinβ	sinα/sinβ
dH	sinα/sinβ	cosα/cosβ
uA	1/tanβ	1/tanβ
dA	-1/tanβ	tanβ

Existing constraints

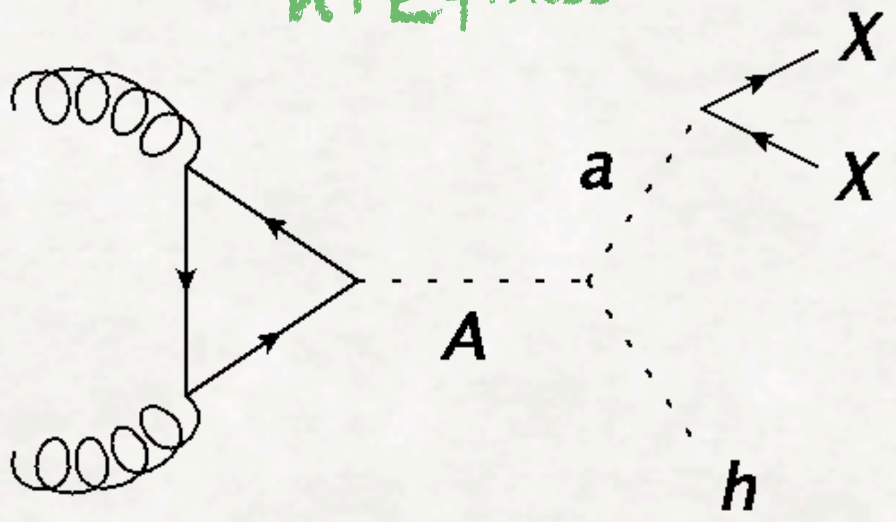


[ATLAS, 2402.05742](https://arxiv.org/abs/2402.05742)

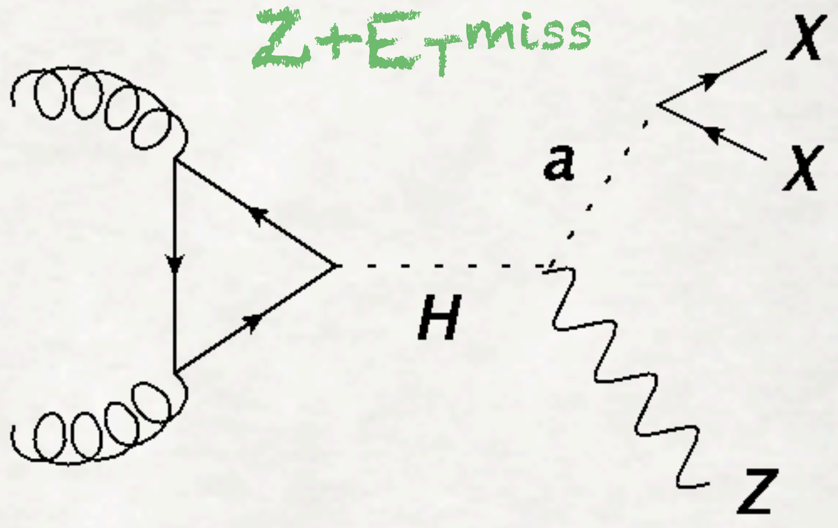


[ATLAS, 2306.00641](https://arxiv.org/abs/2306.00641)

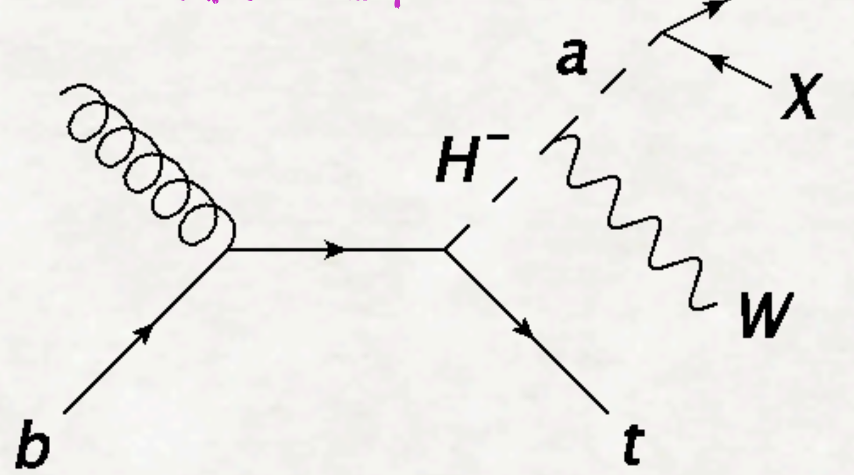
$h+E_T^{miss}$



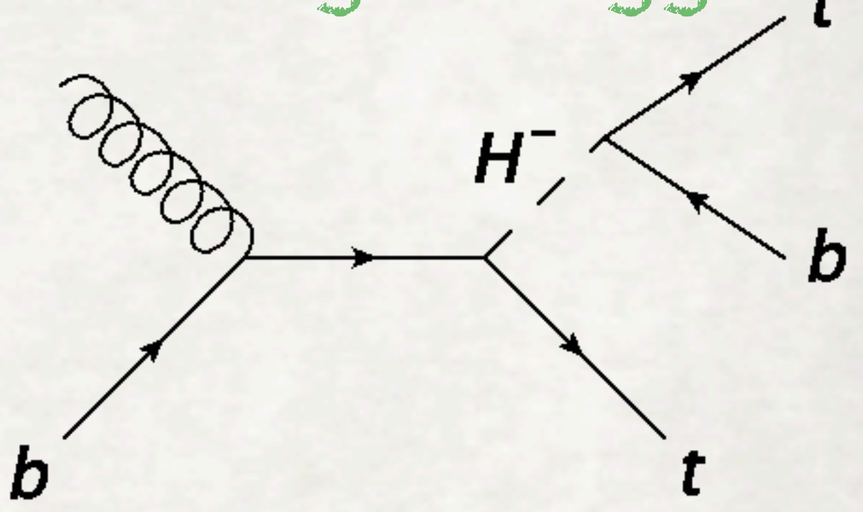
$Z+E_T^{miss}$



$tW+E_T^{miss}$



Charged Higgs

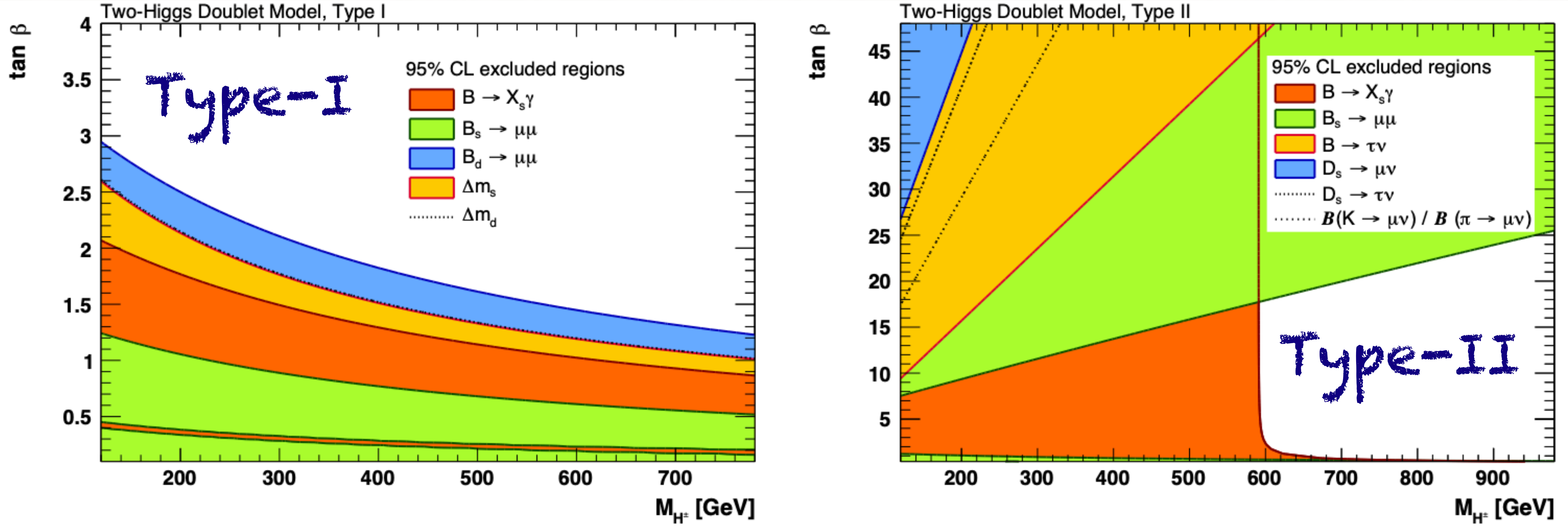


- Higgs coupling measurements ⇒ $\cos(\beta-\alpha)\approx 0$
- Searches:
  - $\sin\theta$ has to be small (mostly a couples to DM)
  - wide range of masses already excluded
  - dominant signatures: $h/Z/tW+E_T^{\text{miss}}$, $H^{\pm}\to tb$

Limitations

1. $m_A = m_H = m_{H^\pm}$
    - motivated because corrections to $\rho \equiv m_W^2/(m_Z^2 \cos\theta_W^2)$ vanish when $m_H = m_{H^\pm}$ independently of the other model parameters
    - Note that not all masses need to be the same - small $m_{H^\pm} - m_{A/H}$ allowed
    - Small values of $\sin\theta$ (A/a mixing) enlarges the region where EWPO are satisfied
    - ◉ This choice prohibits $A \to ZH, A \to H^\pm W^\mp, \ldots$

2. Type-II Yukawa sector
    - no strong motivation
    - ◉ Due to flavour constraints restricts $m_A, m_H, m_{H^\pm} \gtrsim 500$ GeV



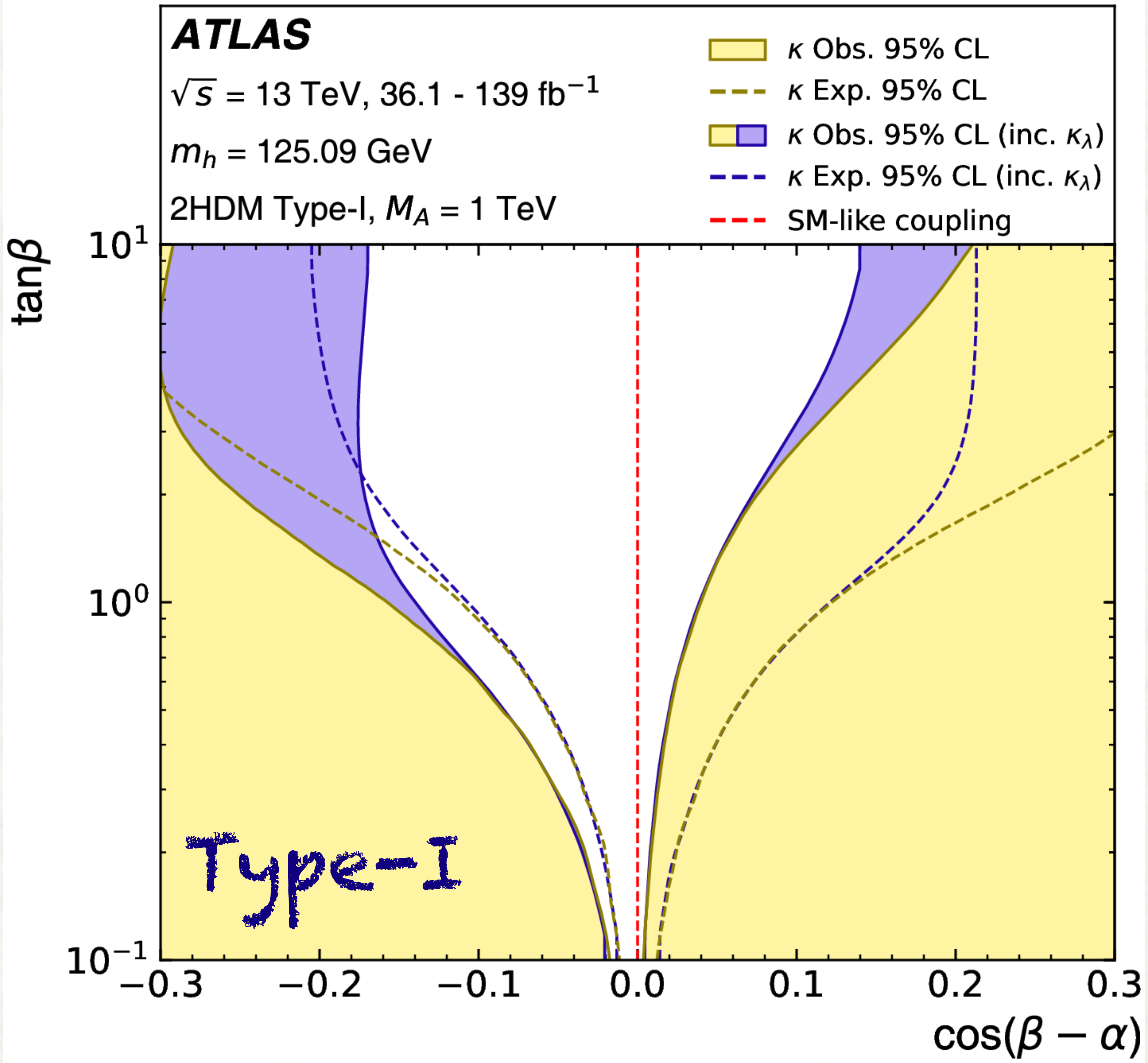
Haller et al, Eur. Phys. J. C78, 675 (2018)

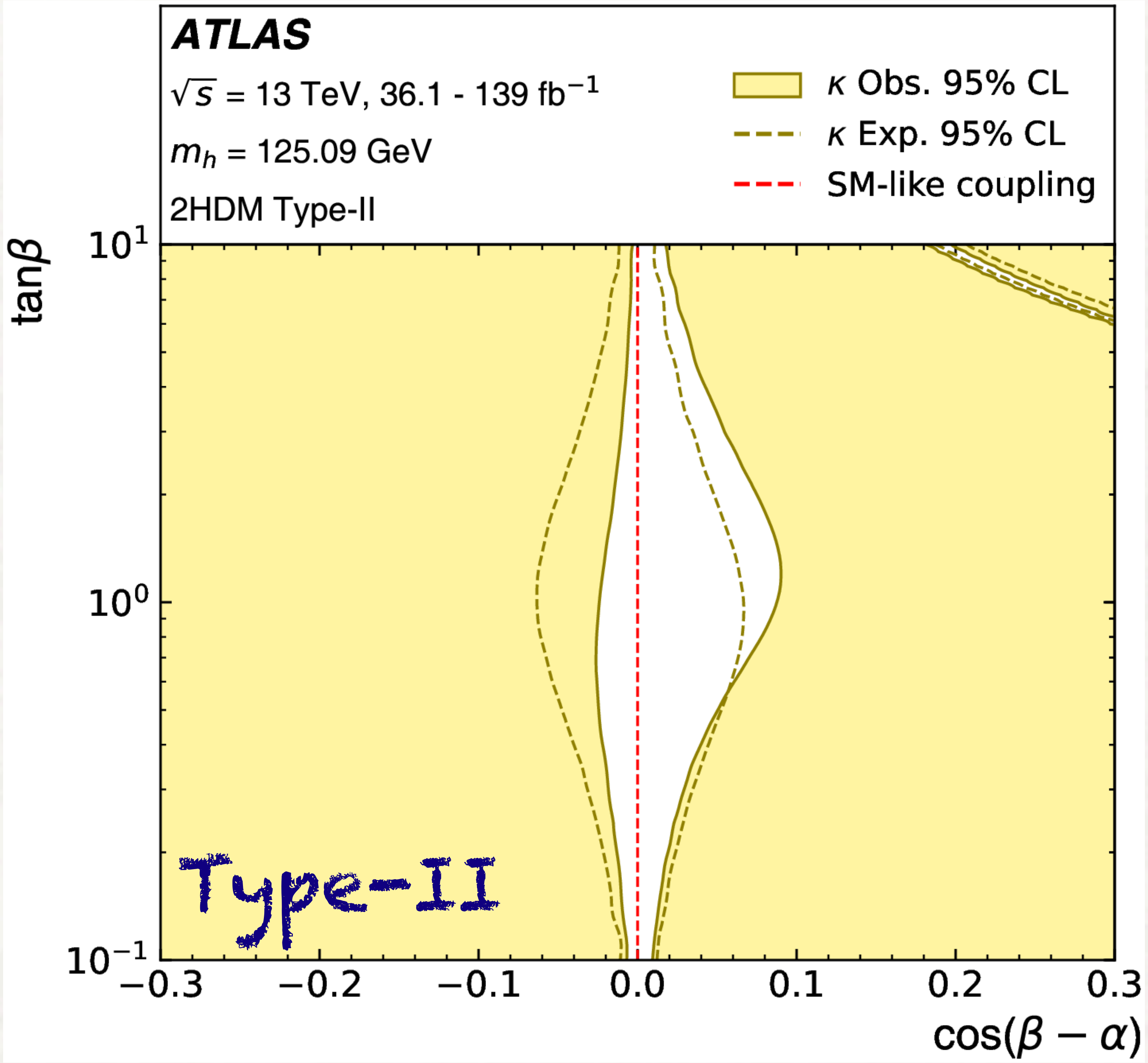
Limitations

3. Alignment limit $\cos(\beta - \alpha) = 0$

- motivated by Higgs coupling measurements - particularly strong for Type-II
- small deviations allowed (esp. in Type-I)

◉ Prohibits $A \to Zh, H^{\pm} \to HW\pm, H \to hh, H \to ZZ, H \to W^+W^-$



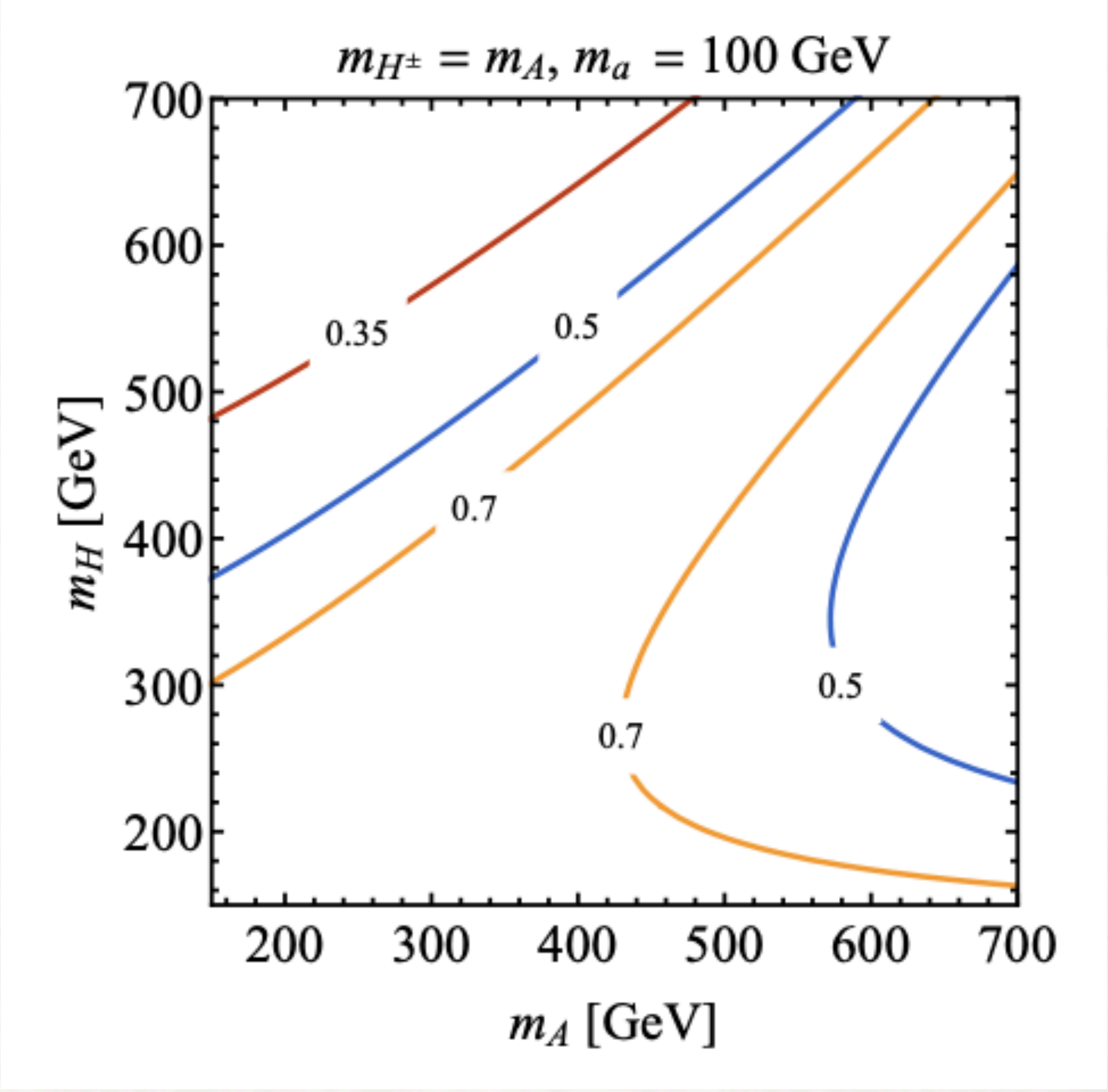


ATLAS, 2402.05742

New Type-I 2HDM+a model

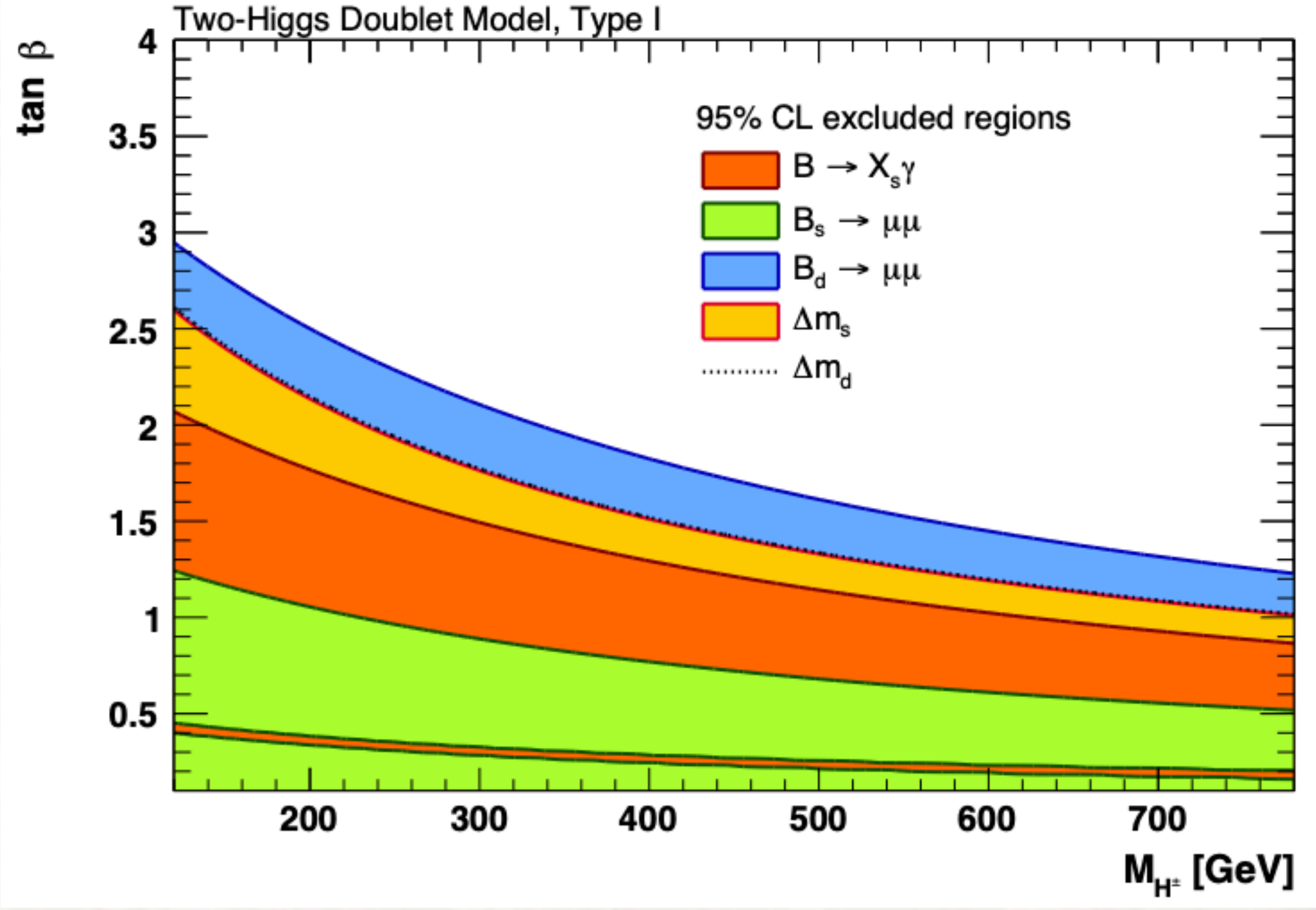
Major differences wrt standard 2HDM+a benchmark

- Type-I Yukawa couplings
- non-degenerate BSM scalars: $m_A - m_{H^\pm} = 0 - 100$ GeV, $m_A - m_H \neq 0$



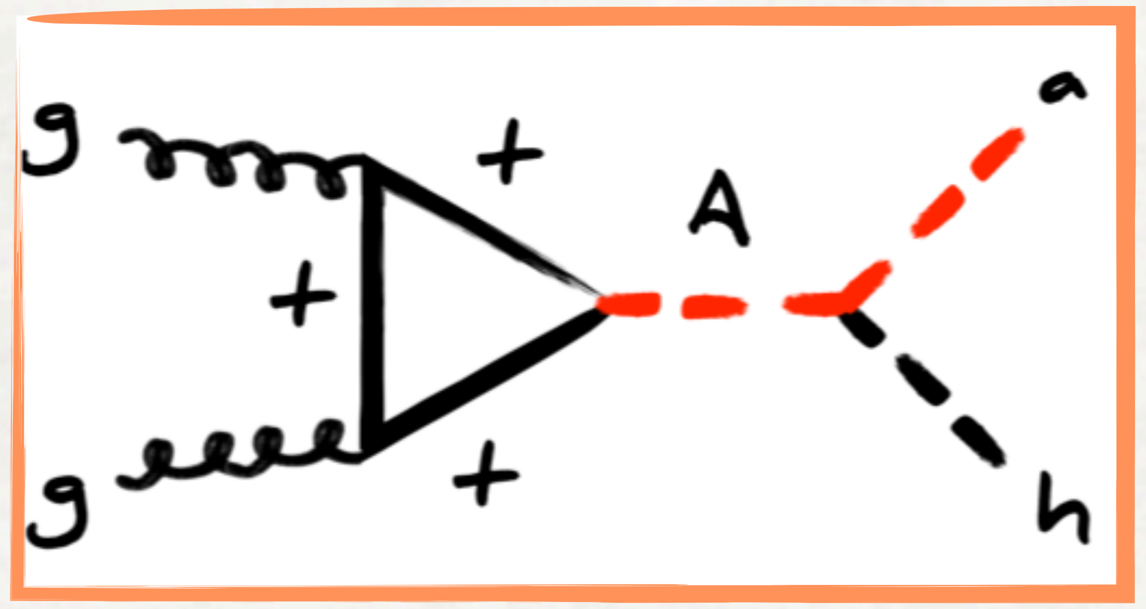
SA, Haisch, Kalaitzidou, JHEP 07 (2024) 263

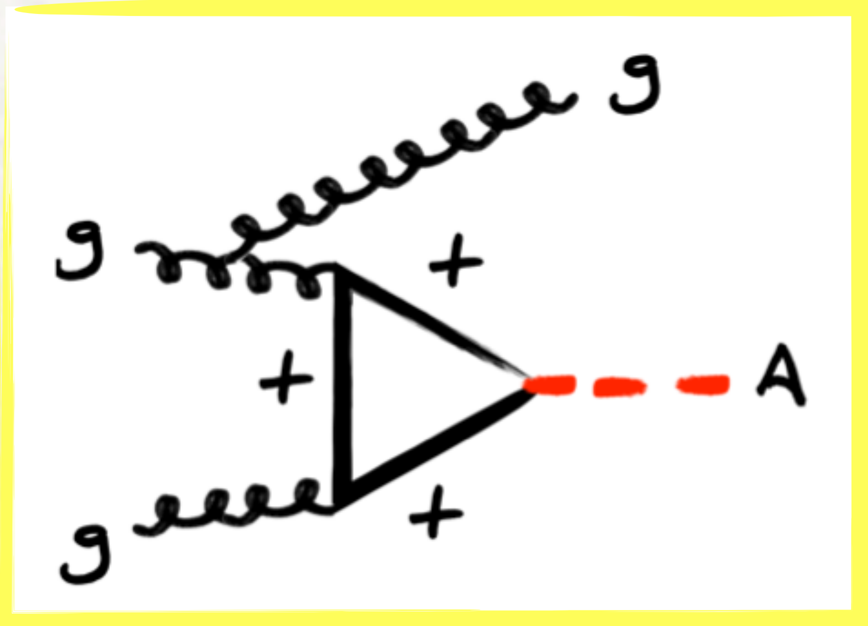
- small $\sin\theta$ to maximise Δm while satisfying $\Delta\rho \approx 0$
- $\tan\beta = 5$ to evade flavour constraints: allows $m_H < 125$ GeV
- Positivity imposes restrictions on quartic couplings
- DM mediator set to 100 GeV to avoid Higgs to invisible constraints and $\Gamma(h \to aa)$
- DM mass set to 10 GeV to provide E_T^{miss} signal (for heavy DM see [SA, Haisch, SciPost Phys. 13 (2022) 1 007])



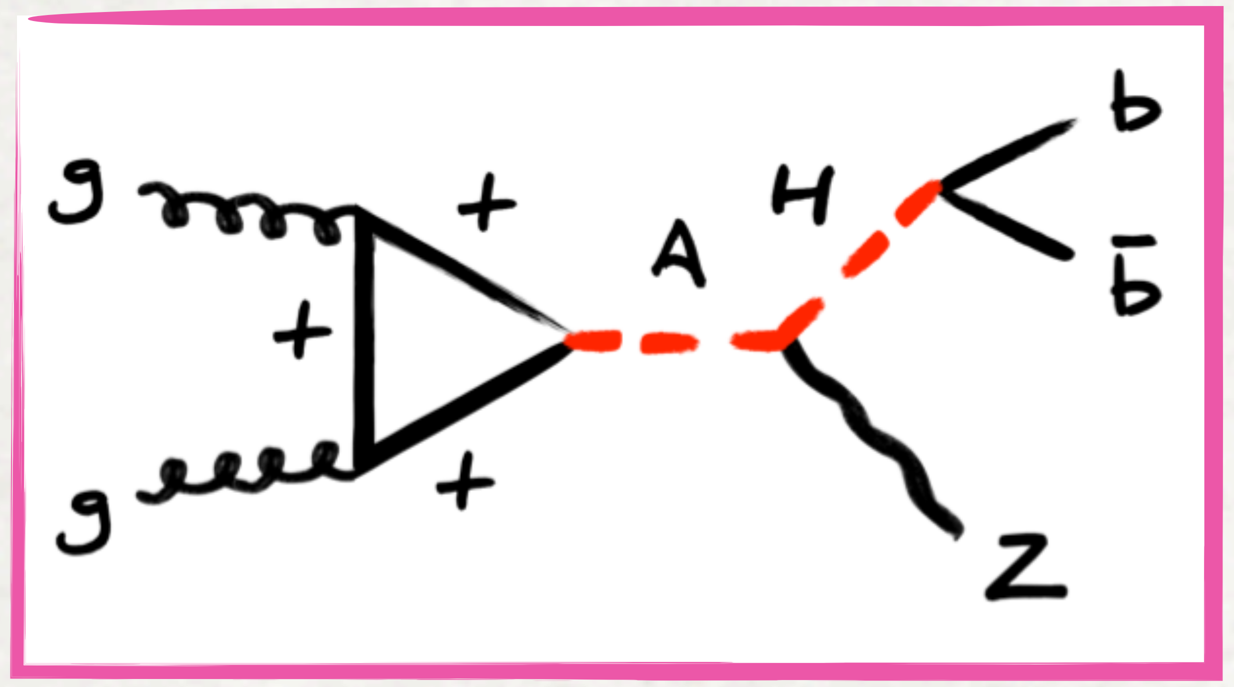
Haller et al, Eur. Phys. J. C78, 675 (2018)

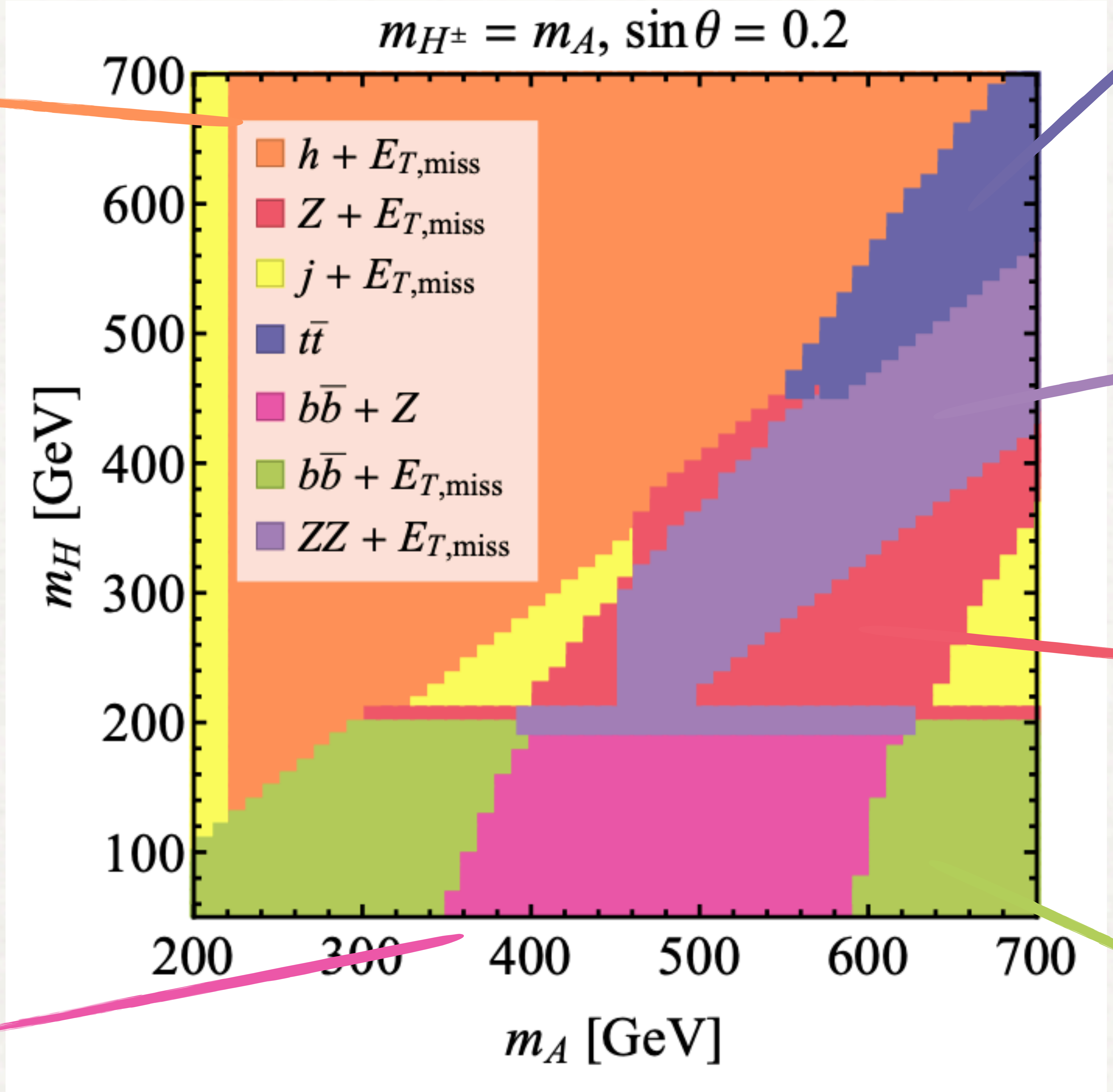
Dominant A decays



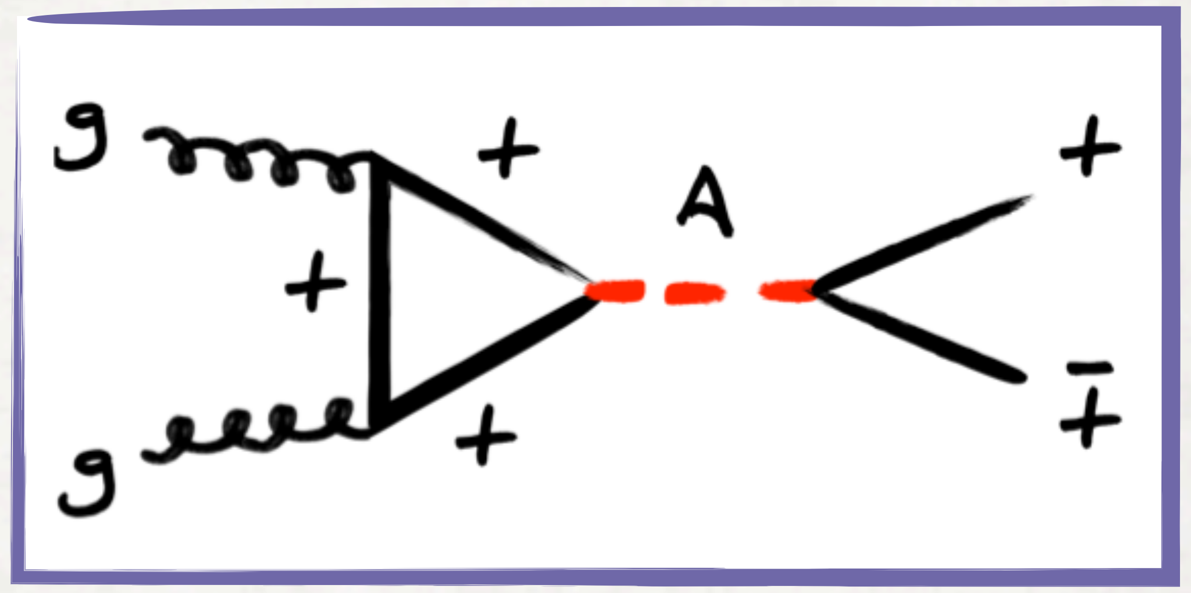


New low mass

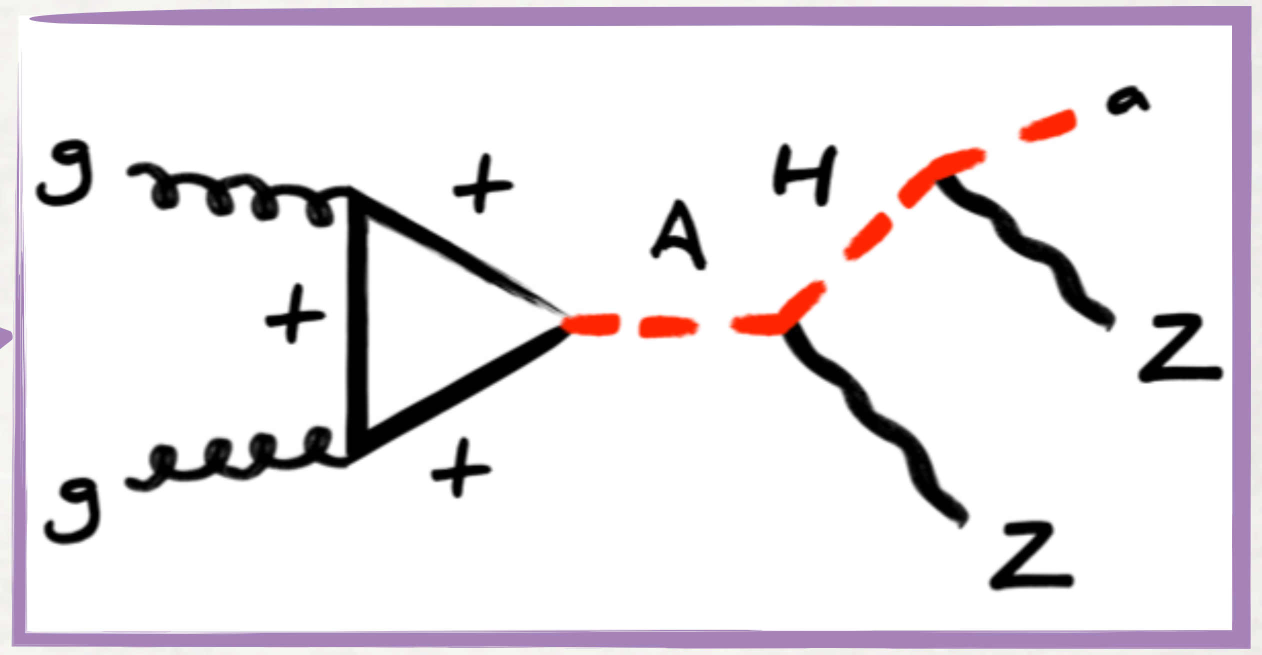


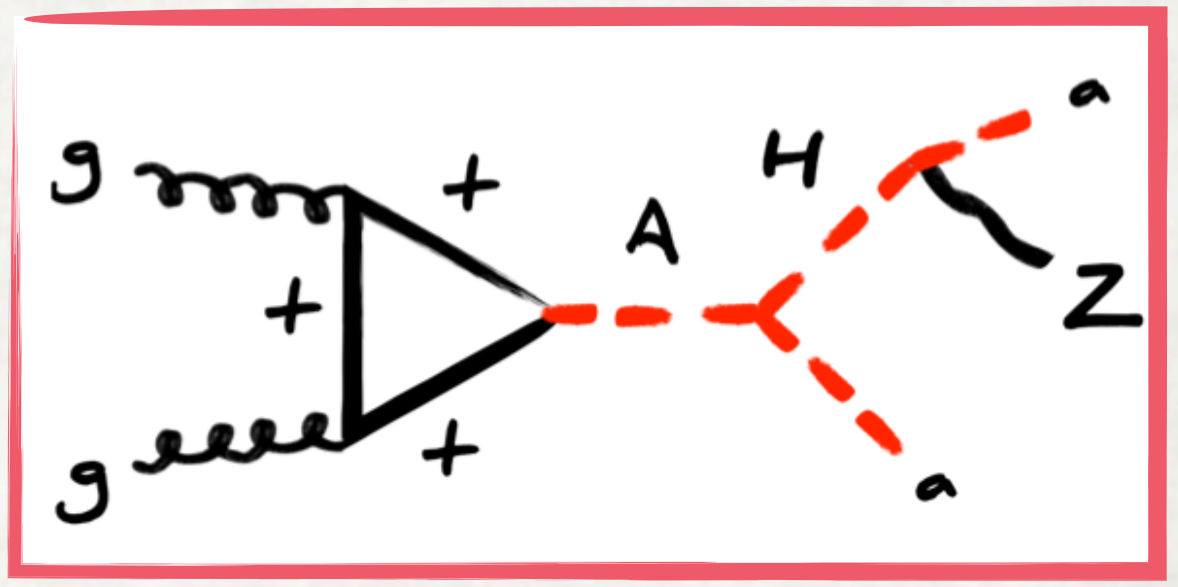


SA, Haisch, Kalaitzidou, JHEP 07 (2024) 263

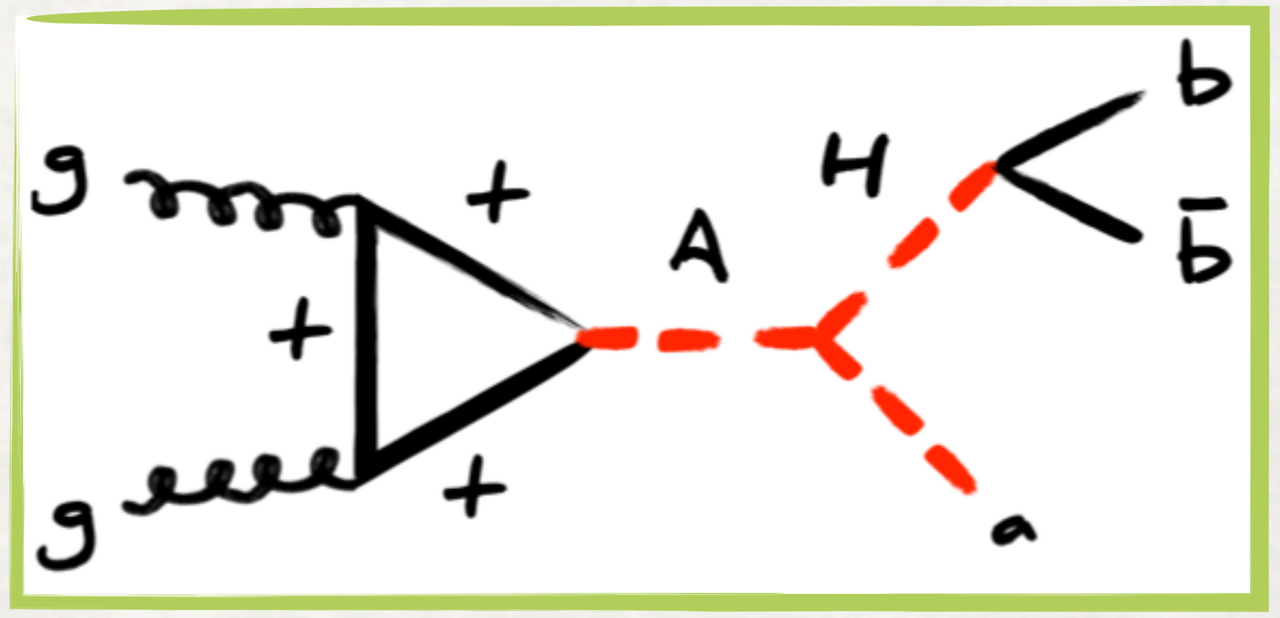


New





New low mass



Dominant H decays

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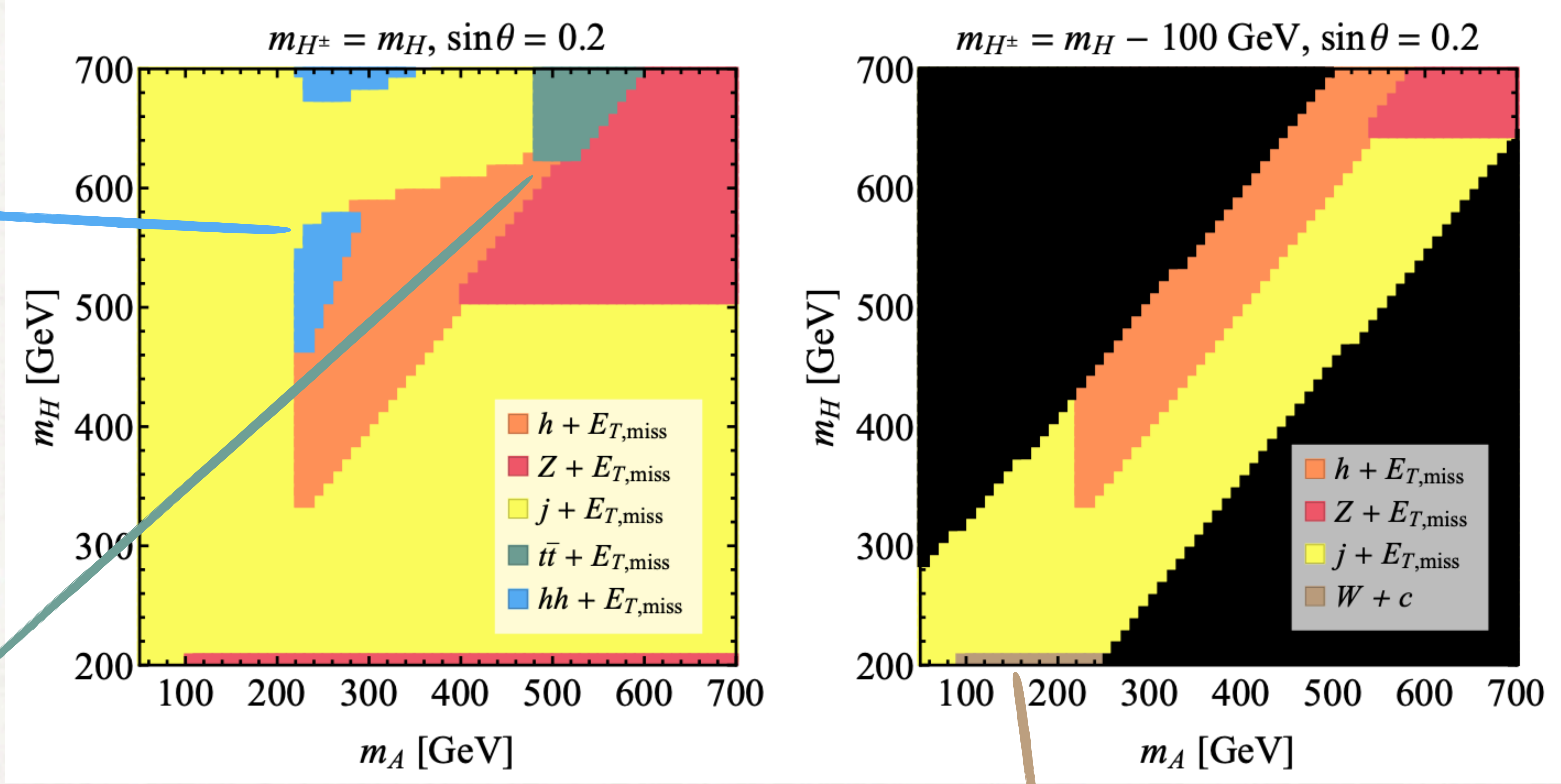

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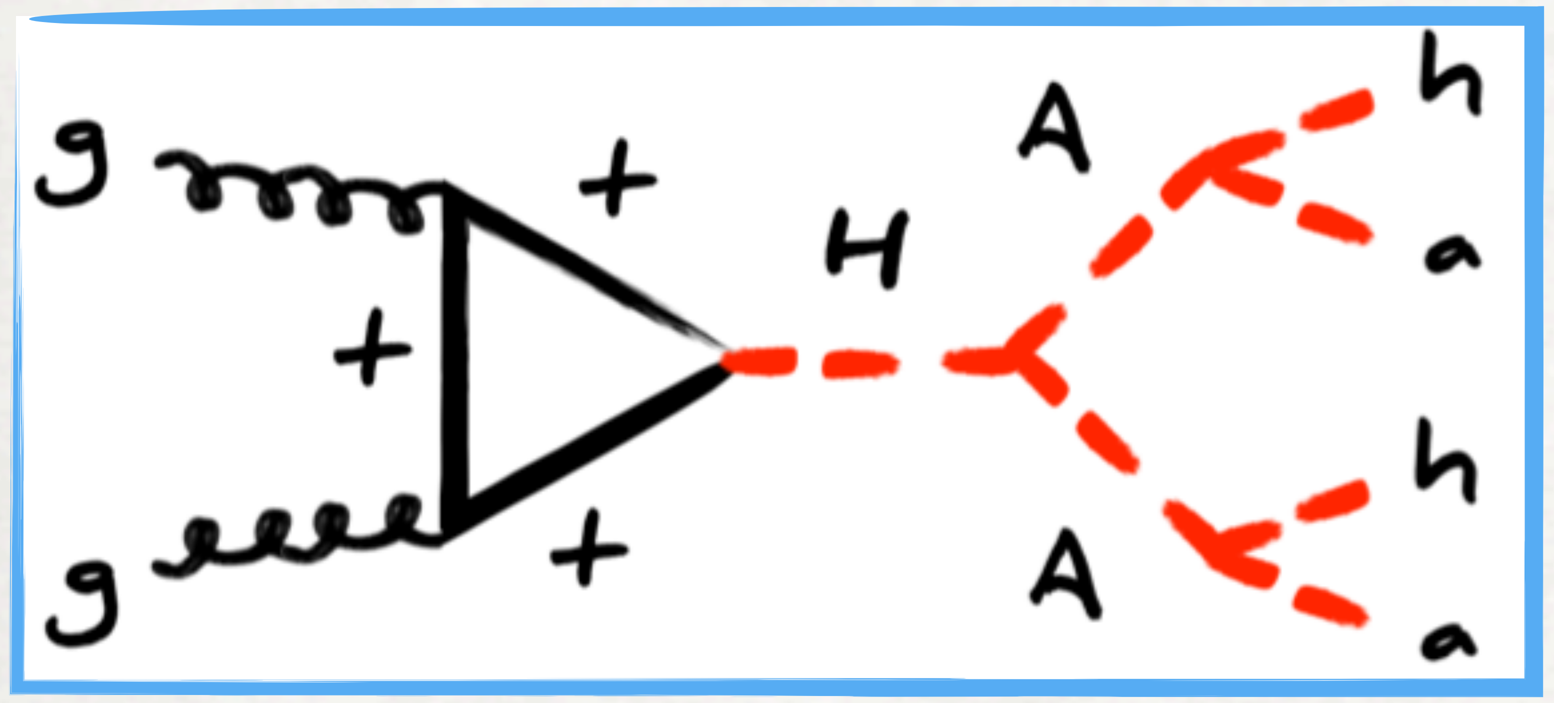

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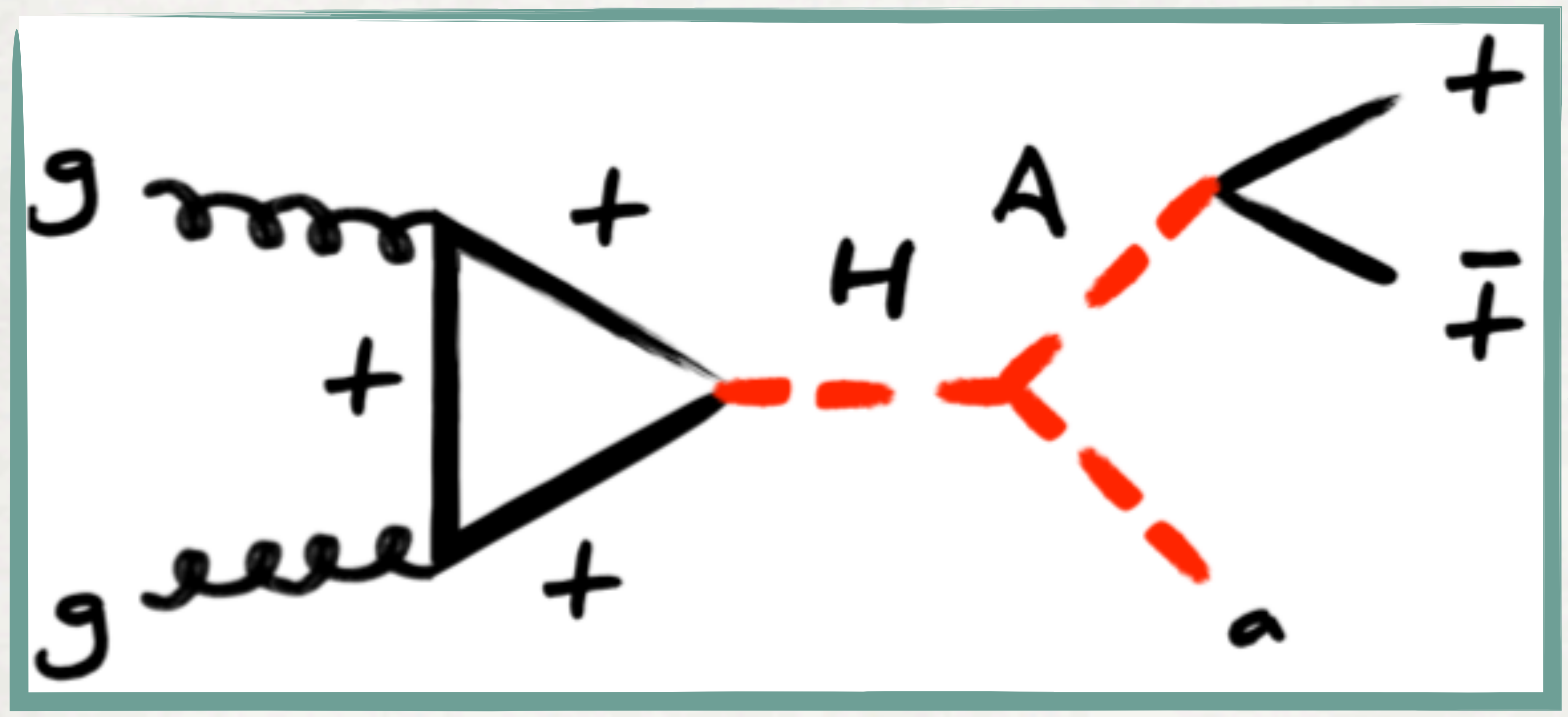

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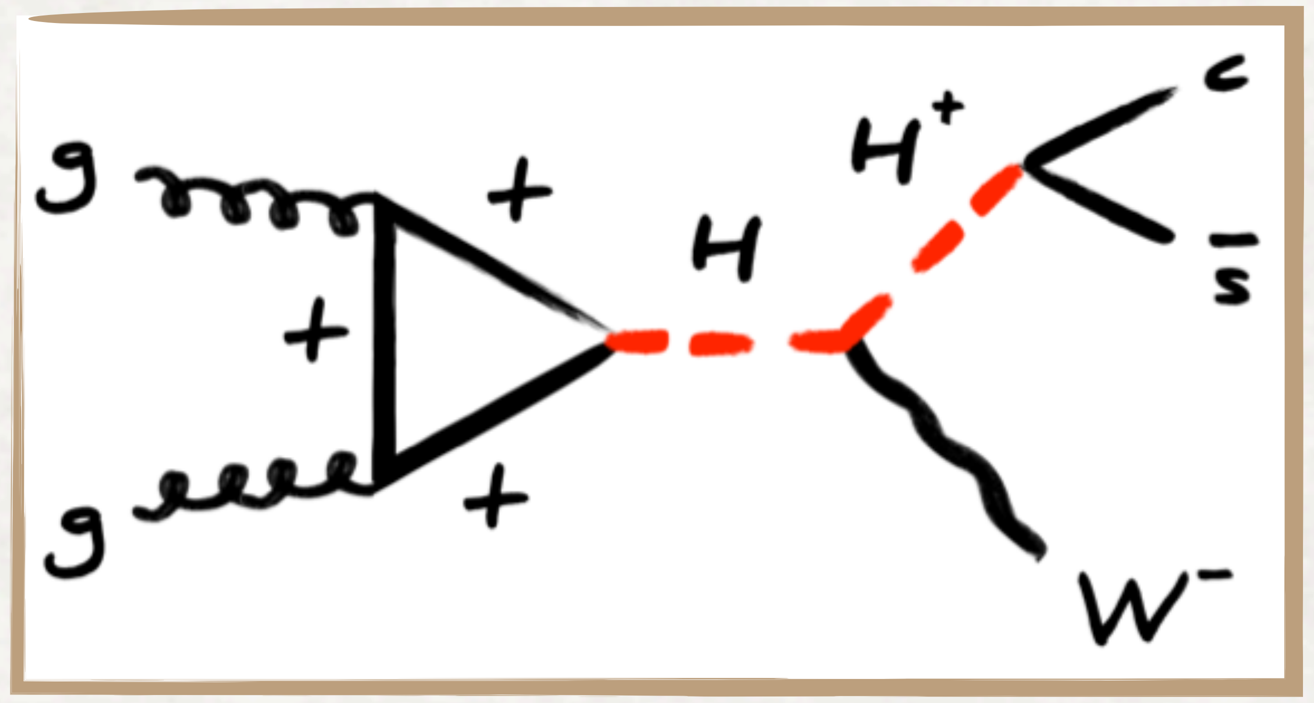
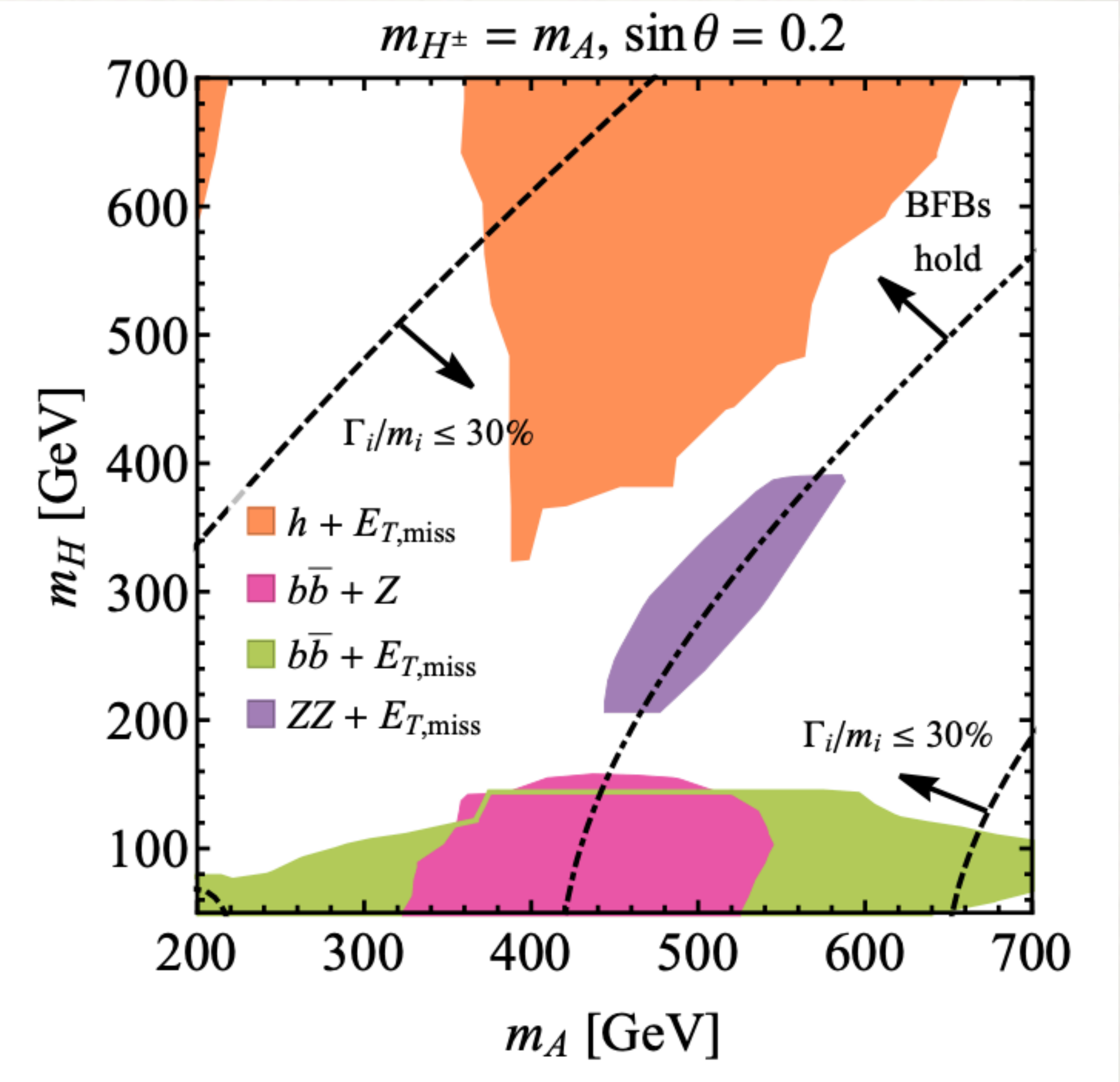


Sensitivity projection for LHC

- SM $h + E_T^{\text{miss}}$ already excludes large region with Run-2 data
- $ZZ + E_T^{\text{miss}}$ quite challenging - only able to exclude small region with Run-3 data
- $b\bar{b} + Z(\ell\ell)$ and $b\bar{b} + E_T^{\text{miss}}$ can probe the low mass region - *no dedicated search so far* (esp. in di-lepton channel)



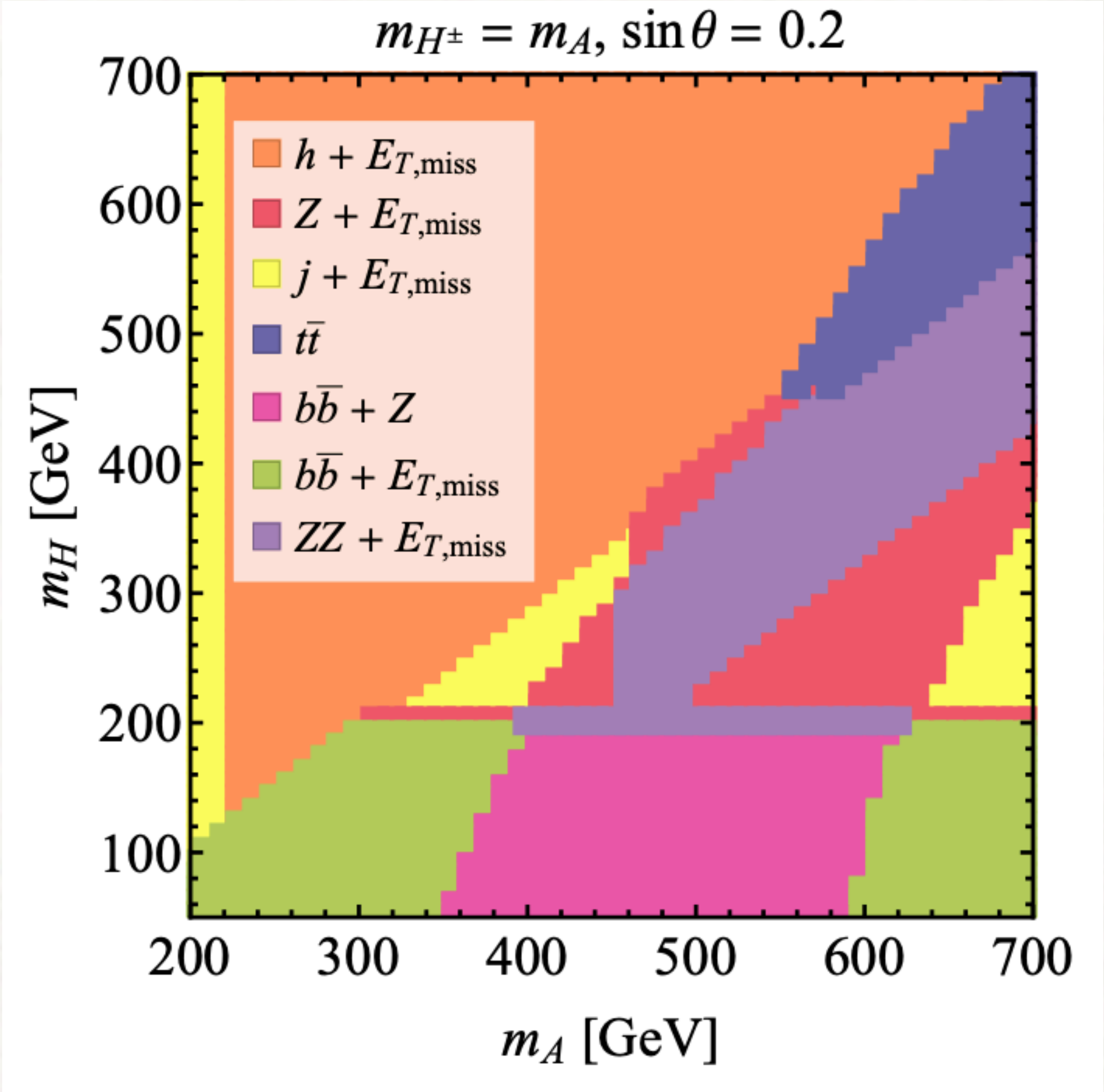
SA, Haisch, Kalaitzidou, JHEP 07 (2024) 263

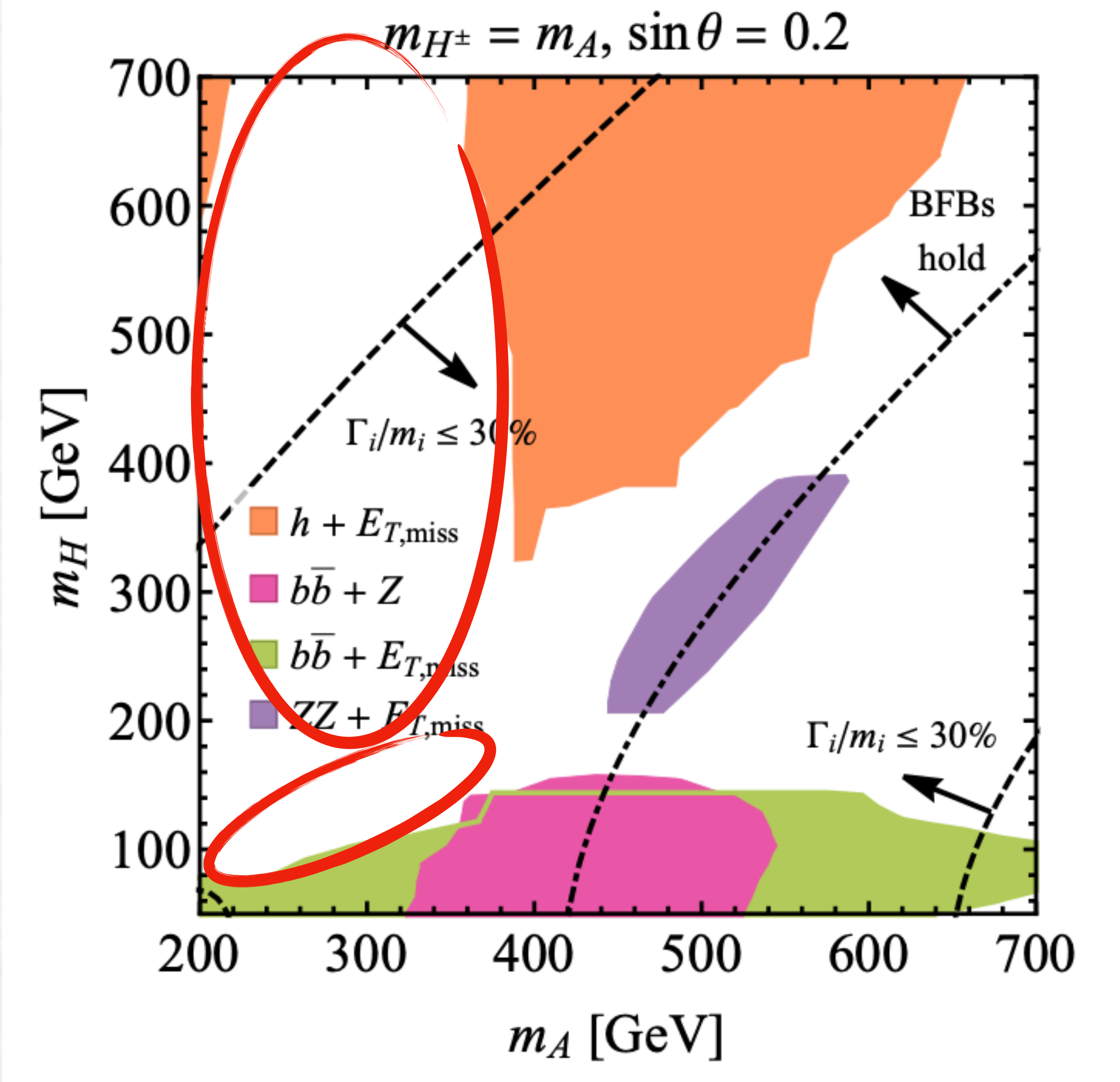
Sensitivity projection for LHC

- low m_A, high m_H region inaccessible so far because of E_T^{miss} triggers → new experimental techniques - e.g. b-jet triggers?

- re-interpretation of mono-jet search can fill in some gaps & combinations

- new searches for resonant $t\bar{t} + E_T^{\text{miss}}$, $hh + E_T^{\text{miss}}$ can help





SA, Haisch, Kalaitzidou, JHEP 07 (2024) 263

Conclusions

A lot of the parameter of the simplified and Higgs portal models already excluded

Can we already say that these models are disfavoured?
➡ Not yet

Simplifying assumptions might be hiding interesting signals!

Type-I 2HDM+a model offers an opportunity to explore them

New analyses and experimental techniques required
➡ we are planning a follow-up in the context of the LHC DM Working Group

Backup

Higgs potential

$$V_H = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2$$
$$+ \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$$V_{HP} = P\left(i b_P H_1^\dagger H_2 + \text{h.c.}\right) + P^2\left(\lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2\right), \qquad V_P = \frac{1}{2} m_P^2 P^2$$

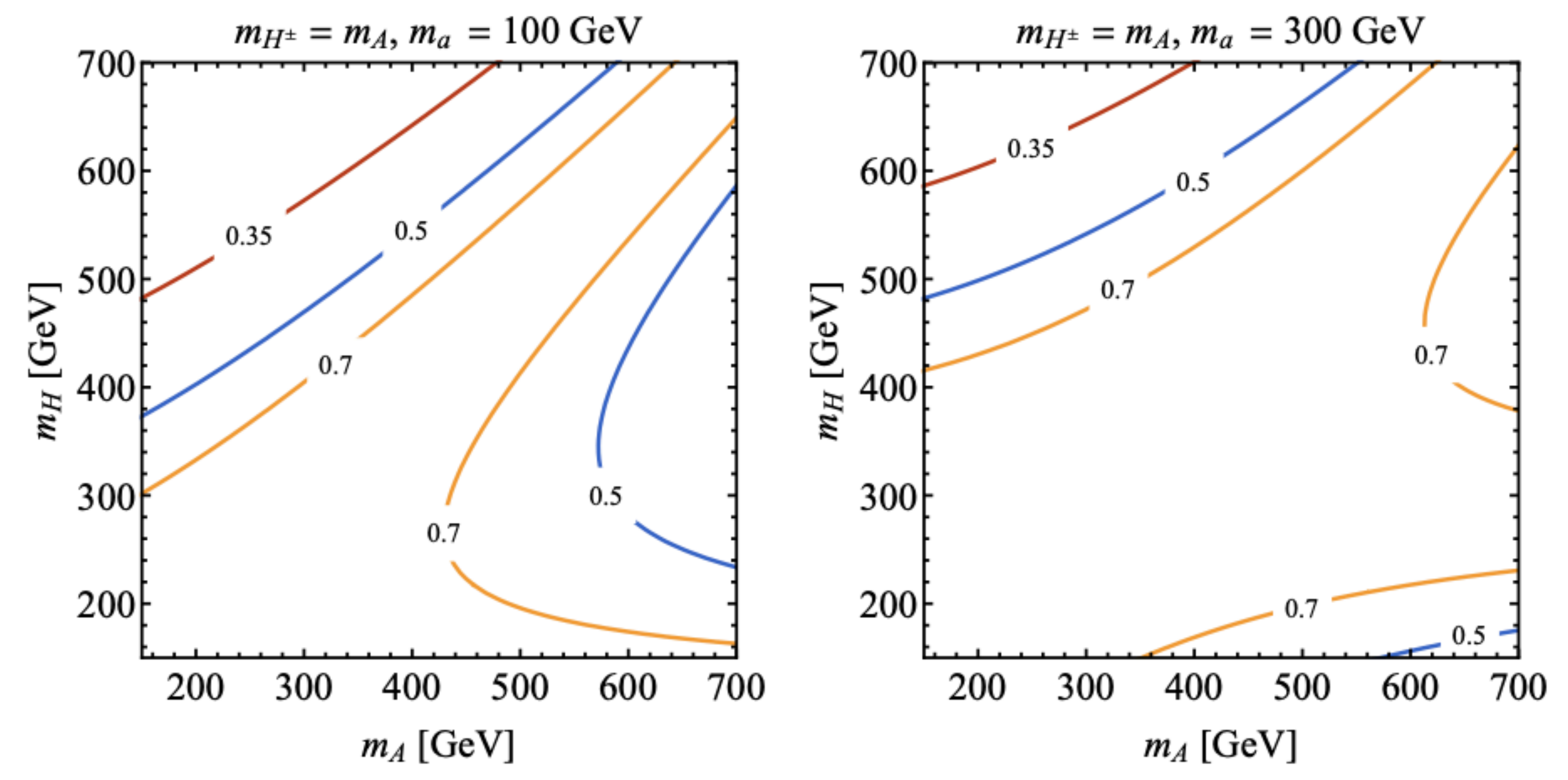
Corrections to rho parameter

$$\Delta\rho = \frac{1}{(4\pi)^2}\frac{1}{v^2}\left[\cos^2\theta\, f(m_{H^\pm}^2, m_A^2, m_H^2) + \sin^2\theta\, f(m_{H^\pm}^2, m_a^2, m_H^2)\right]$$

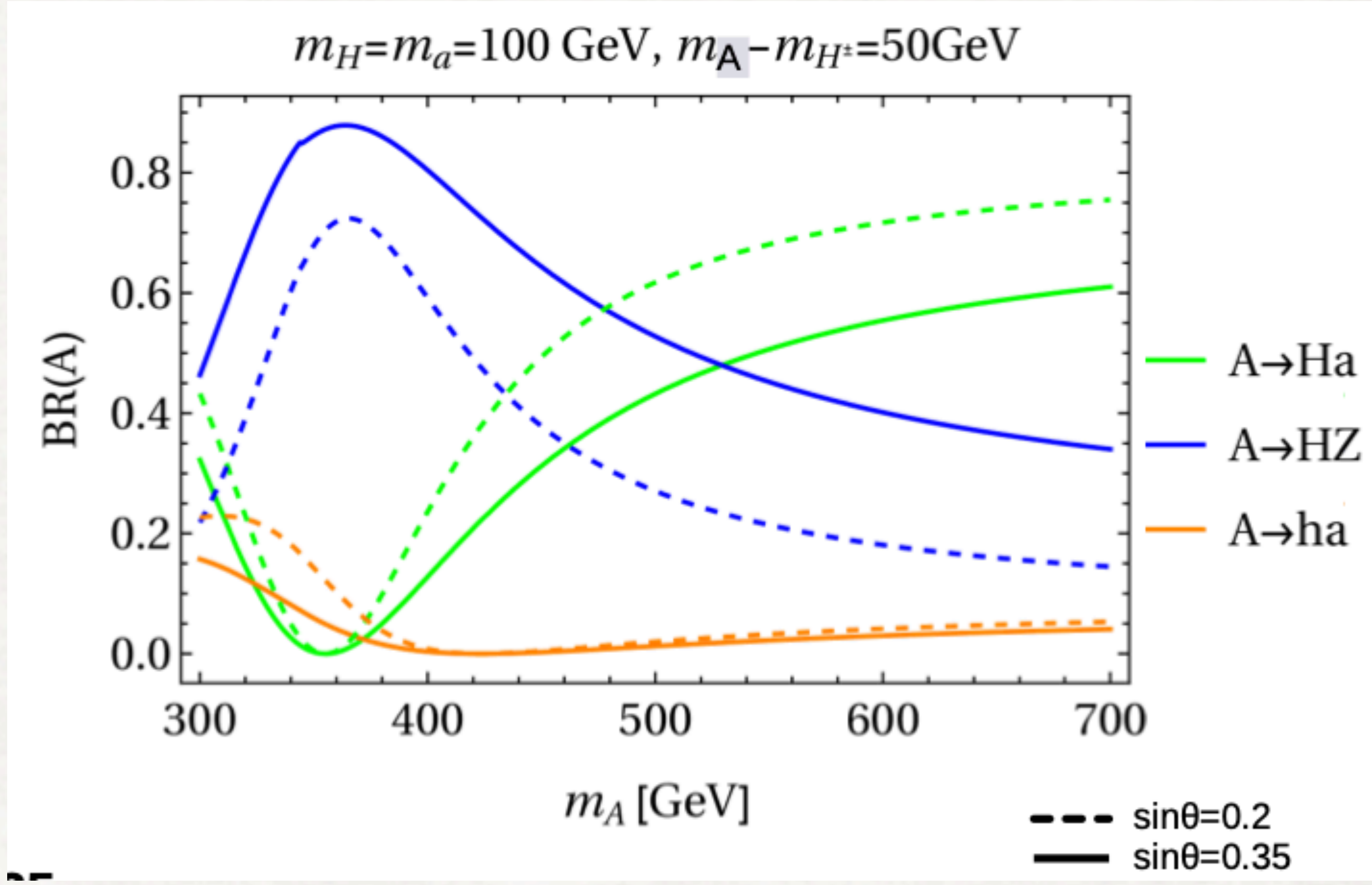
$$f(m_1^2, m_2^2, m_3^2) = m_1^2 - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\left(\frac{m_1^2}{m_2^2}\right) - \frac{m_1^2 m_3^2}{m_1^2 - m_3^2}\ln\left(\frac{m_1^2}{m_3^2}\right) + \frac{m_2^2 m_3^2}{m_2^2 - m_3^2}\ln\left(\frac{m_2^2}{m_3^2}\right)$$

$$f(m_1^2, m_2^2, m_1^2) = 0$$

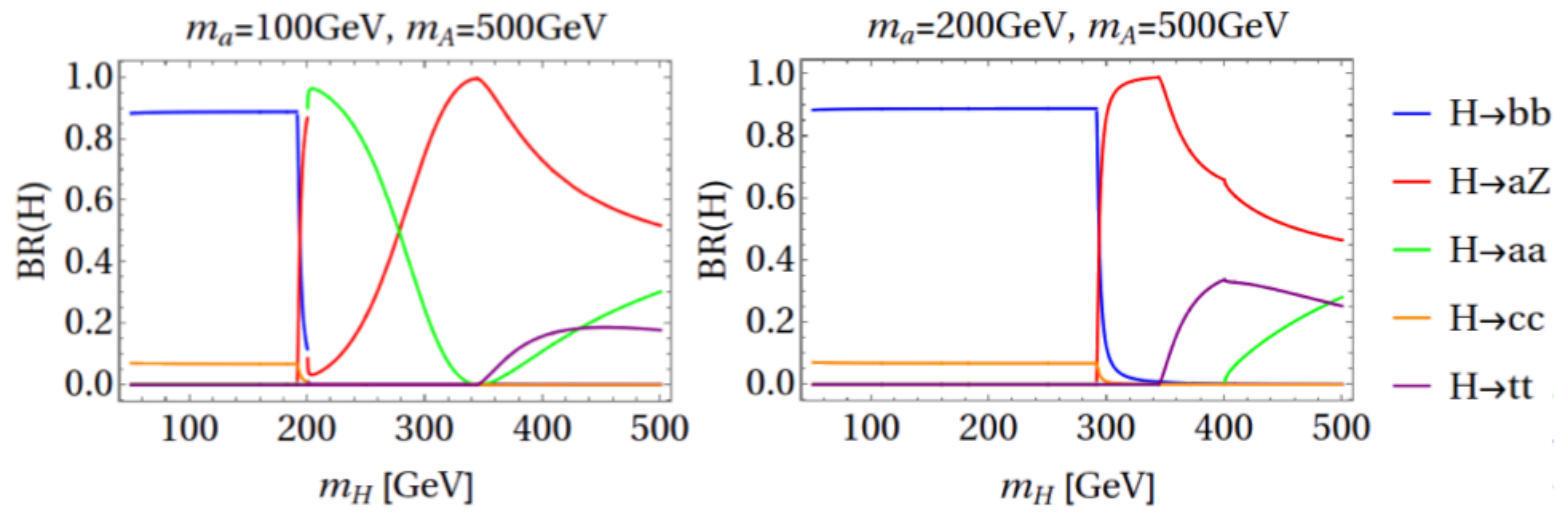
Constraints on mixing



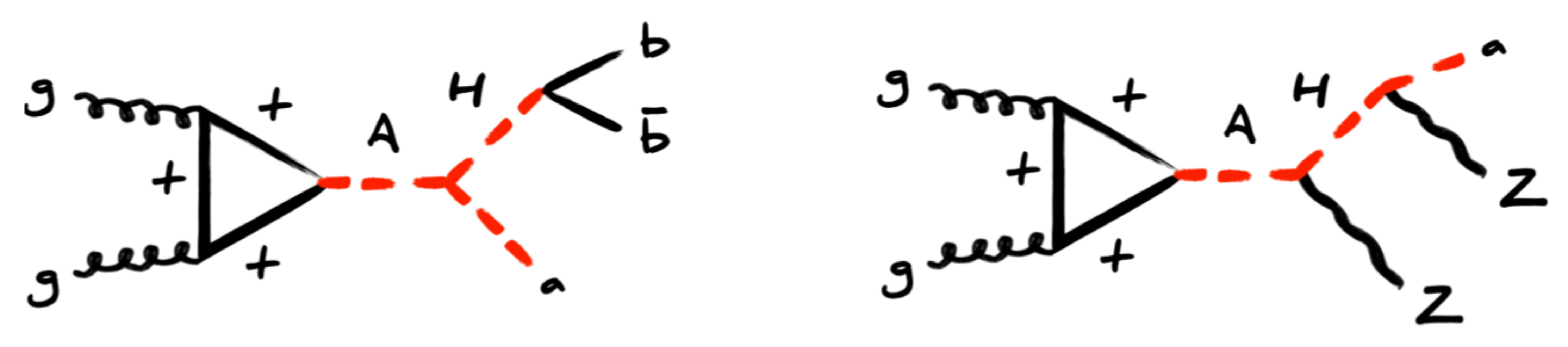
[SA, Haisch, Kalaitzidou, JHEP 07 (2024) 263](https://doi.org)

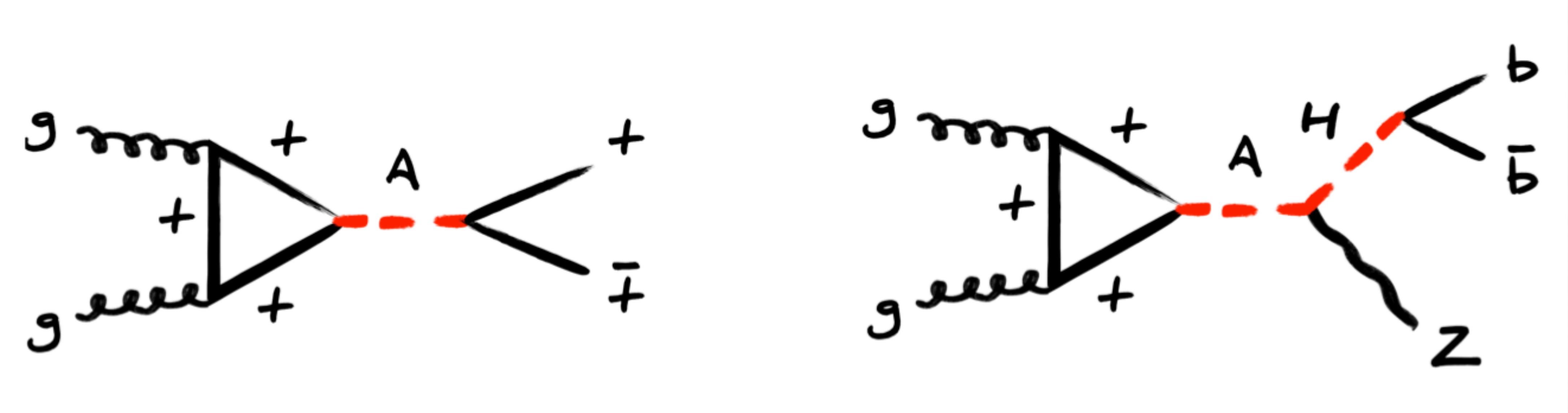


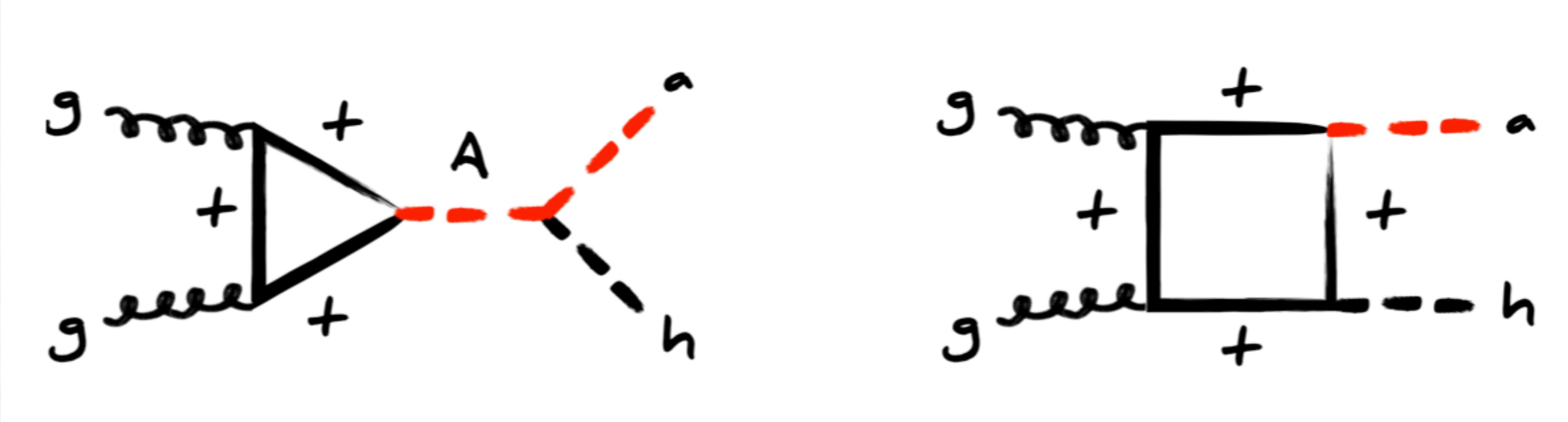
Impact of mediator mass

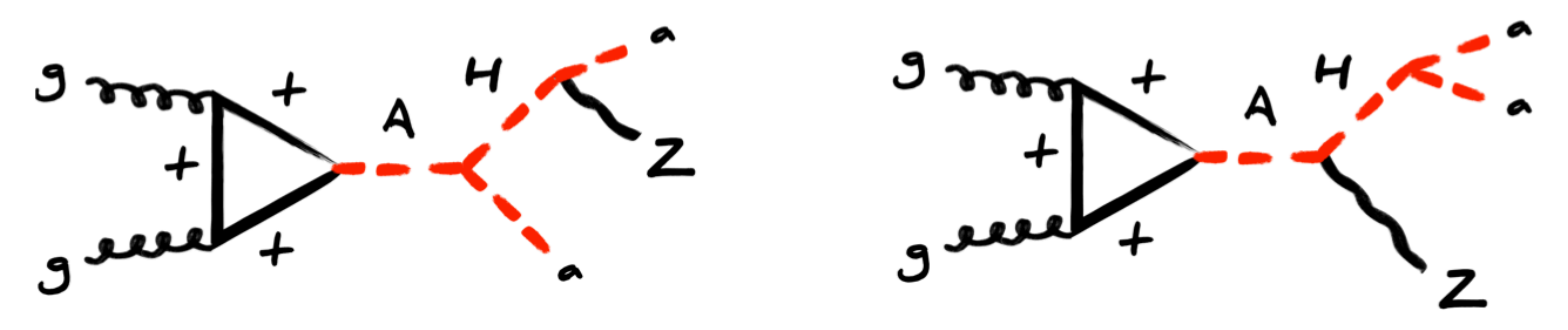


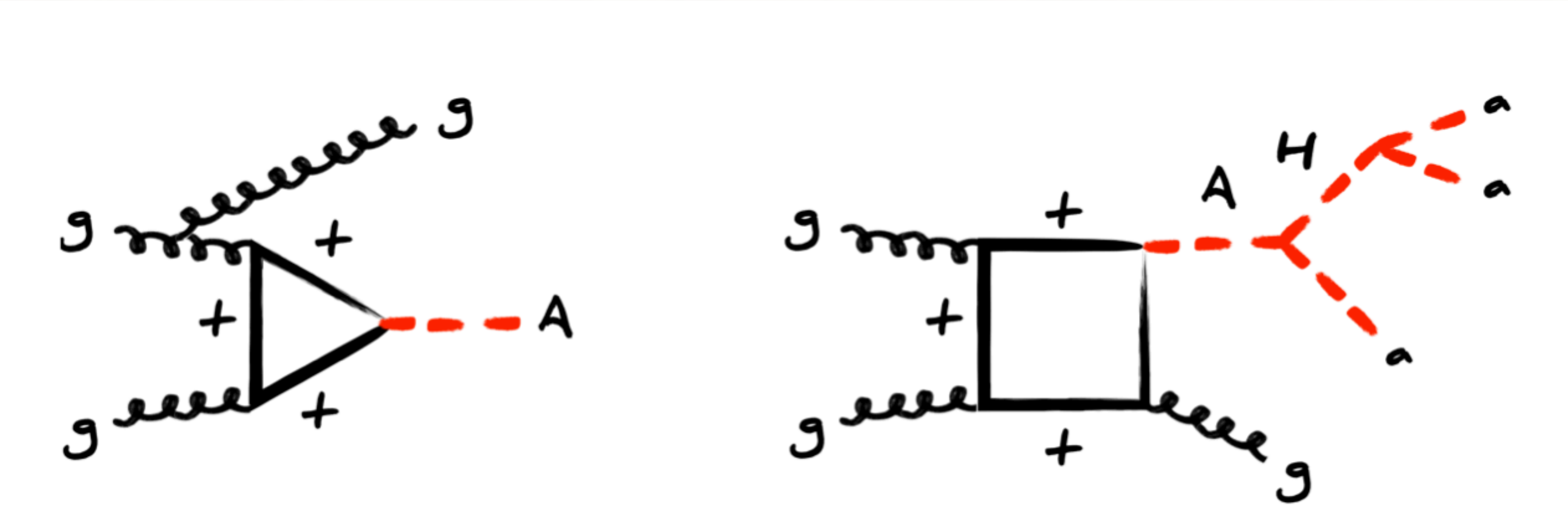
Feynman diagrams











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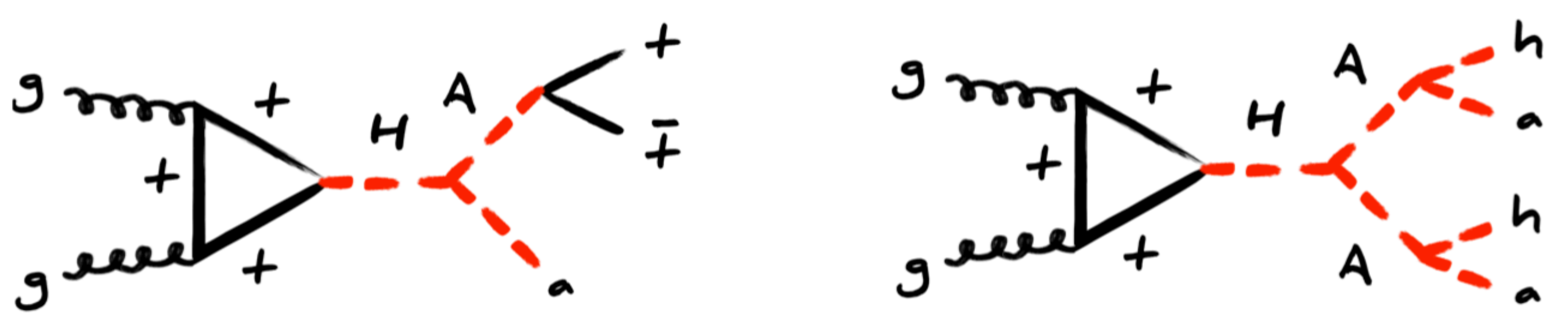
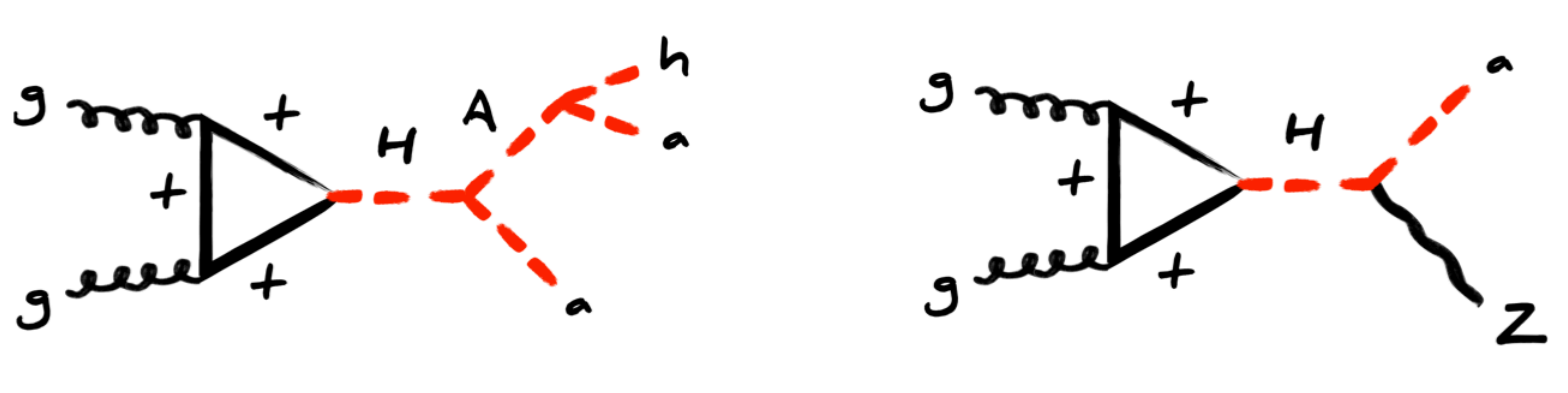
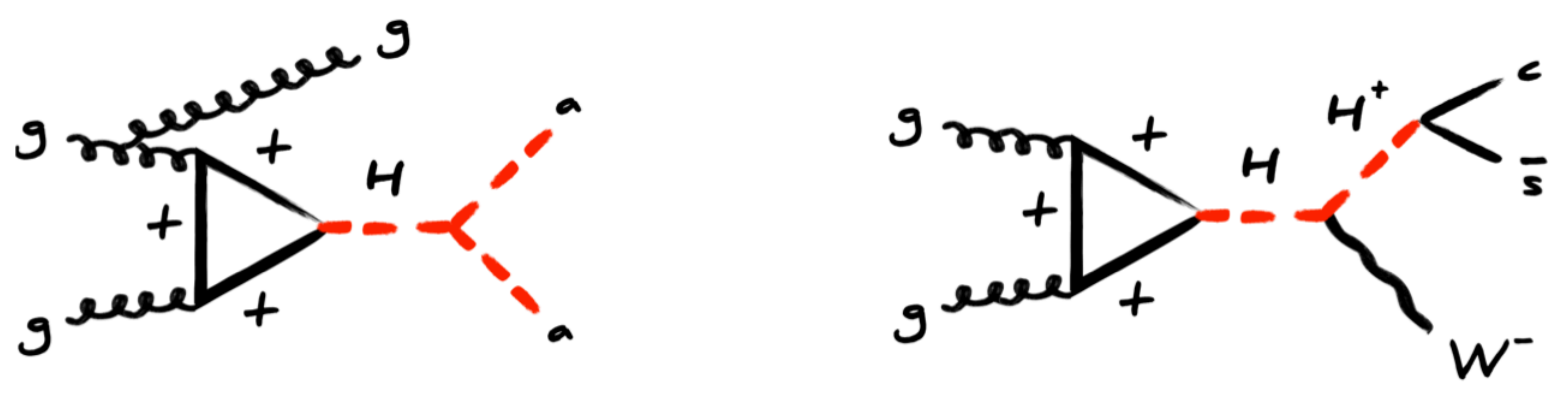
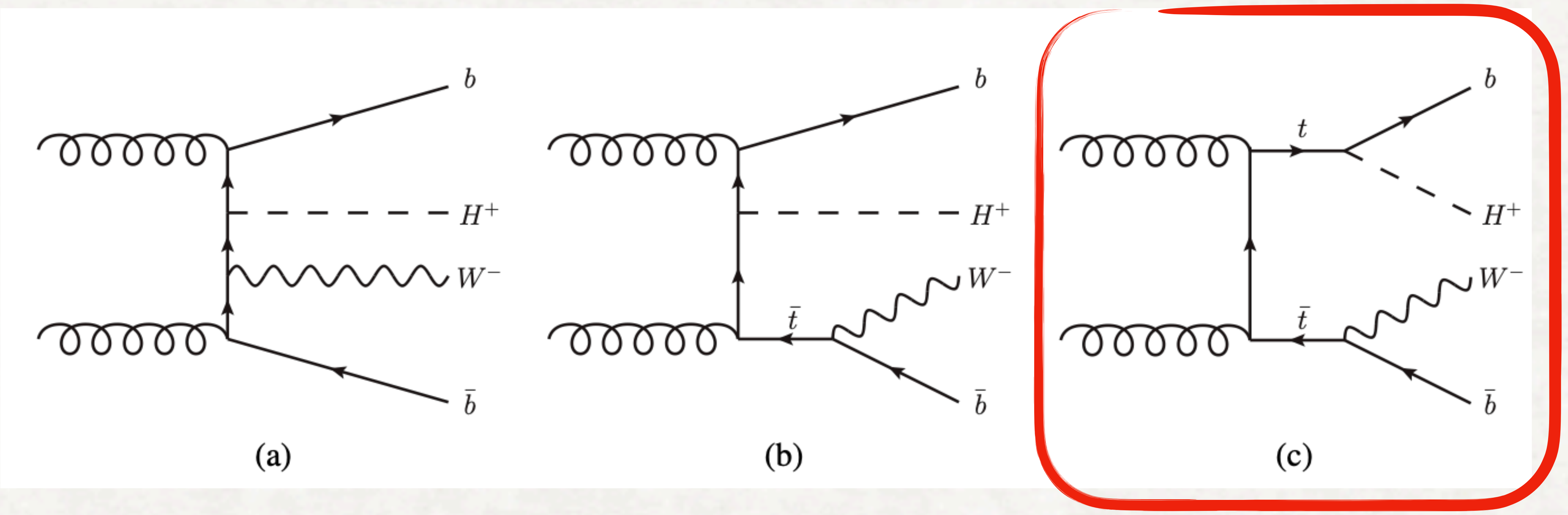


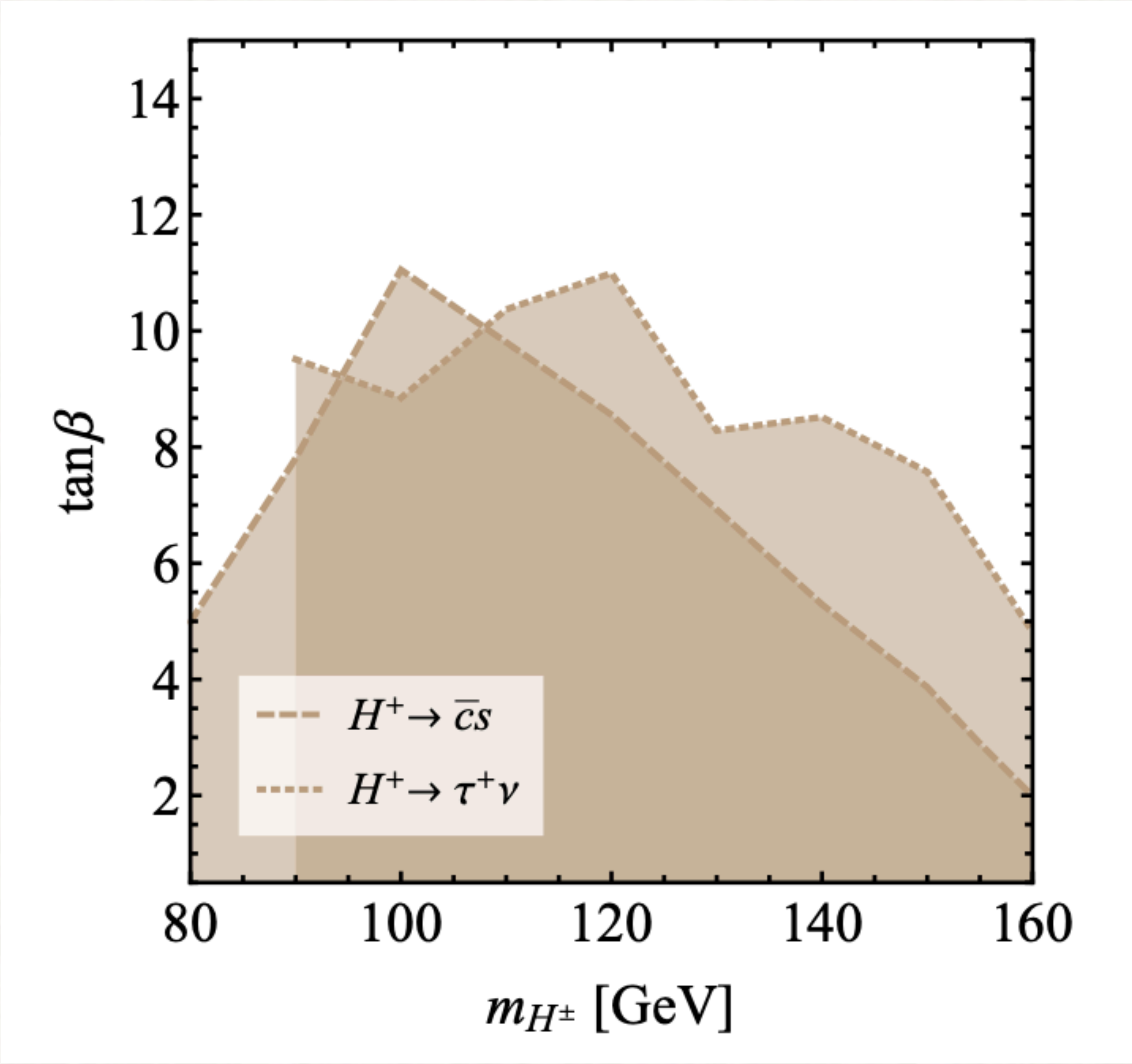




$H^{\pm} \to \tau\nu / cs$



(a) (b) (c)



SA, Haisch, Kalaitzidou, JHEP 07 (2024) 263