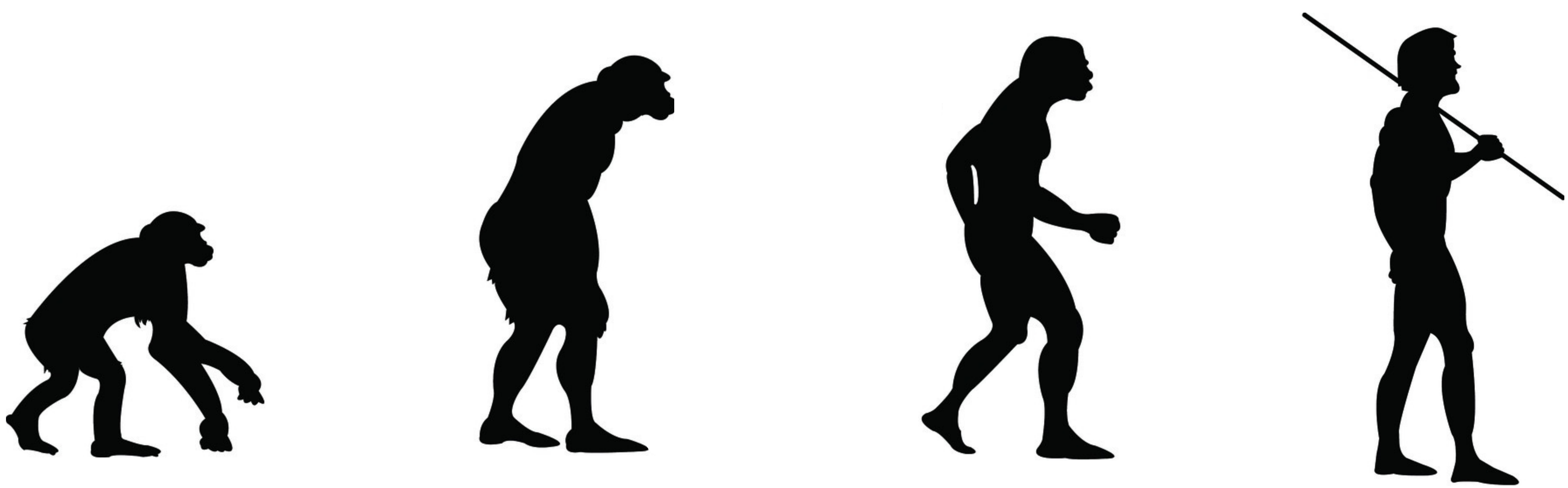
Simplified Models for Run II

Martin Bauer

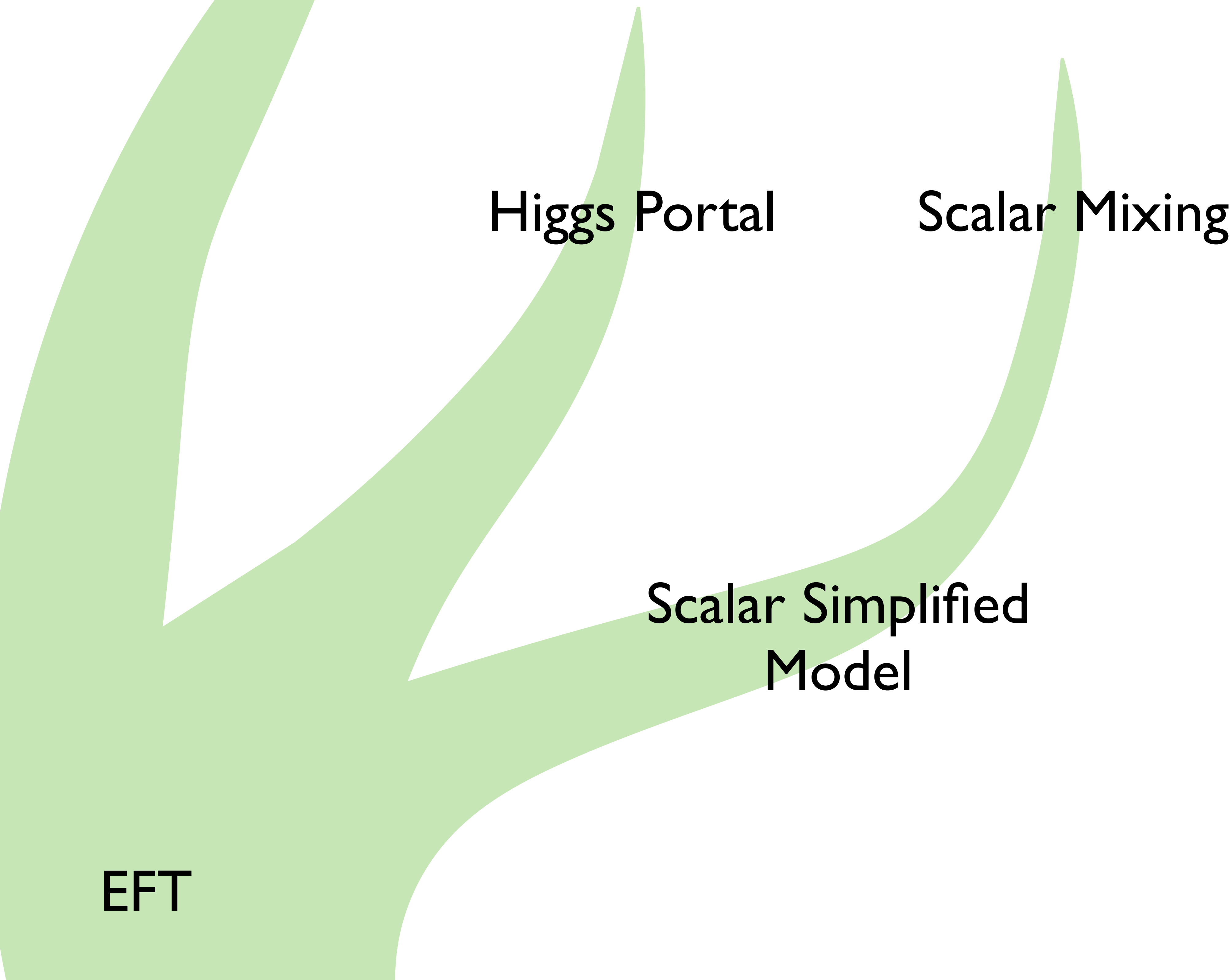
based on 1612.xxxx with Uli Haisch and Felix Kahlhoefer

Evolution of Models for DM Collider Searches

EFTs	Simplified Models	Consistent Simplified Models
$\frac{m_q}{M^3}\,\bar{\chi}\chi\bar{q}q$	$g_\chi\bar{\chi}S\chi + g_q\bar{q}Sq + M^2S^2$	$g_\chi\bar{\chi}S\chi + y_q\bar{q}Hq + \mu\,v\,SH$



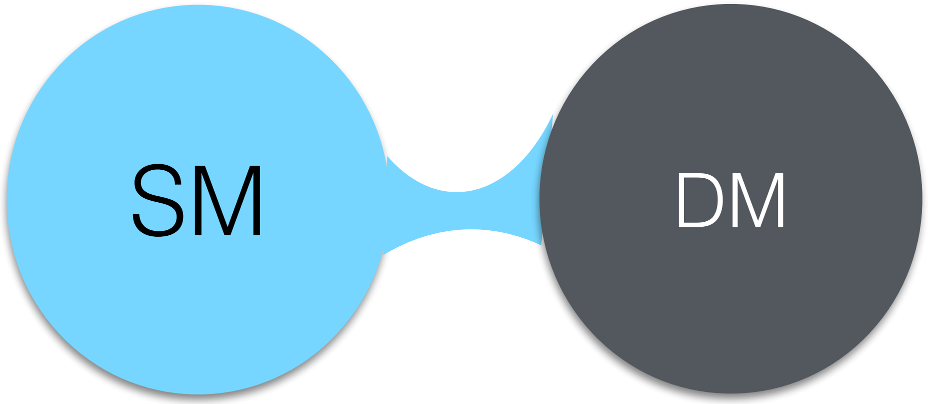
Evolution of Models for DM Collider Searches



Consistent Scalar Models

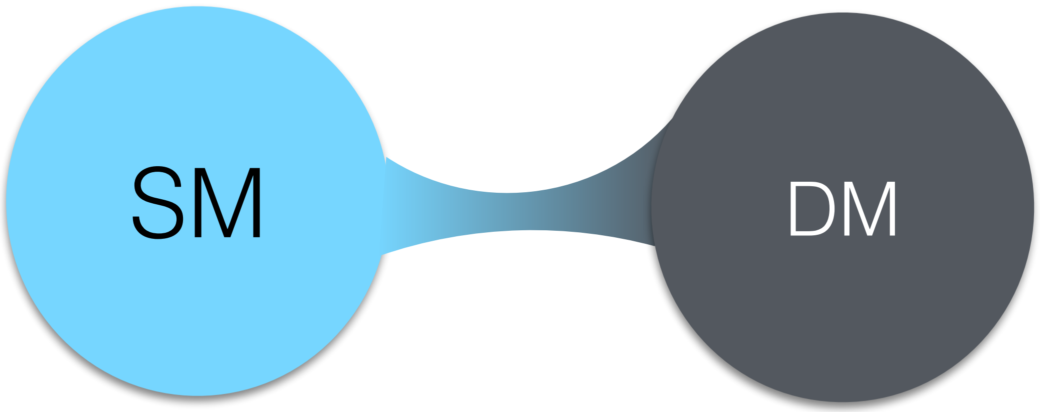
Higgs Portal

$$y_q \bar{q} H q + \lambda_2 H^\dagger H \, \phi^\dagger \phi$$



Higgs Mixing

$$y_q \bar{q} H q + \mu_2 H^\dagger H \, \phi + g_\chi \bar{\chi} \phi \chi$$



Consistent Scalar Models

Higgs Portal

$$y_q \bar{q} H q + \lambda_2 H^\dagger H \, \phi^\dagger \phi$$

- SM mediator
- more economical
- scalar Dark Matter

Higgs Mixing

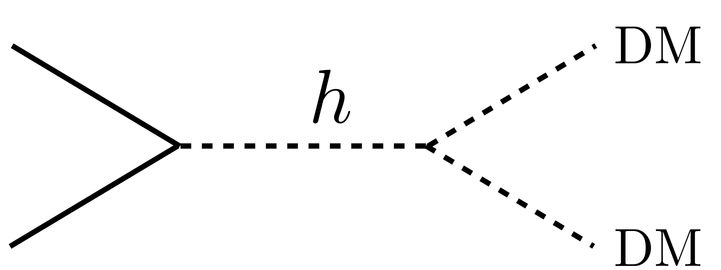
$$y_q \bar{q} H q + \mu_2 H^\dagger H \, \phi + g_\chi \bar{\chi} \phi \chi$$

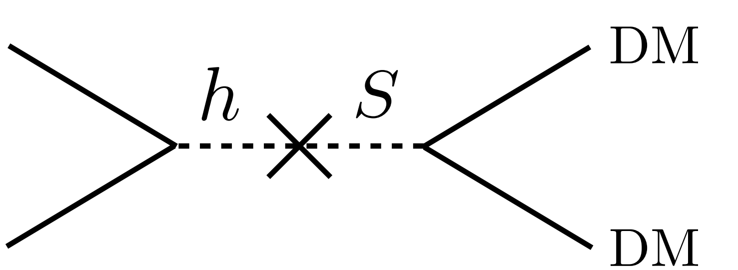
- new messenger
- more couplings
- also fermionic Dark Matter

Consistent Scalar Models

Higgs Portal and Higgs Mixing models are consistent, but strongly constrained by Higgs measurements

In both, the Higgs is a messenger…





These models are searched for by the Higgs CS working group…

Two Higgs Doublet Models

$$\mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + h.c.\right)$$

$$+ \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$

$$+ \left(\lambda_5 (H_1^\dagger H_2)^2 + h.c.\right) + (H_1^\dagger H_1)\left(\lambda_6 H_1^\dagger H_2 + h.c.\right) + (H_2^\dagger H_2)\left(\lambda_7 H_1^\dagger H_2 + h.c.\right)$$

$$+ \bar{Q} Y_u^1 \tilde{H}_1 u_R + \bar{Q} Y_d^1 H_1 d_R + \bar{L} Y_\ell^1 H_1 \ell_R + \bar{Q} Y_u^2 \tilde{H}_2 u_R + \bar{Q} Y_d^2 H_2 d_R + \bar{L} Y_\ell^2 H_2 \ell_R + h.c.$$

Impose a Z2 symmetry:

$$H_1 \to H_1$$
$$H_2 \to -H_2$$
$$f_R \to -f_R$$

Two Higgs Doublet Models

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$$+ \left(\lambda_5 (H_1^\dagger H_2)^2 + h.c. \right)$$

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Natural flavour protection

Mimics enhanced symmetries of possible UV completions

Inert Two Higgs Doublet Models

$\mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2$ see Alexander Belyaev's talk

$+ \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$

$+ \left(\lambda_5 (H_1^\dagger H_2)^2 + h.c. \right)$

$+ \bar{Q} Y_d^1 H_1 d_R + \bar{L} Y_\ell^1 H_1 \ell_R$ $+ h.c.$

Impose a Z2 symmetry:

$$H_1 \to H_1$$
$$H_2 \to -H_2$$

Natural flavour protection

$$\langle H_1 \rangle = v_1 = v$$
$$\langle H_2 \rangle = 0$$

The second multiplet H2 contains a DM candidate

→ Generalization of the Higgs Portal.

Two Higgs Doublet Models & Mediator

$$\mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + h.c.\right)$$

$$+ \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$

$$+ \left(\lambda_5 (H_1^\dagger H_2)^2 + h.c.\right)$$

$$+ \bar{Q} Y_d^1 H_1 d_R + \bar{L} Y_\ell^1 H_1 \ell_R + \bar{Q} Y_u^2 \tilde{H}_2 u_R \qquad + h.c.$$

Add pseudoscalar mediator & allow for soft breaking

$$V_P = \frac{1}{2} m_P^2 P^2 + P\left(i b_P H_1^\dagger H_2 + \text{h.c.}\right) - y_\chi P \bar{\chi} i \gamma_5 \chi$$

with $\langle H_1 \rangle = v_1$, $\langle H_2 \rangle = v_2$ $\quad \sqrt{v_1^2 + v_2^2} = 246\,\text{GeV}$

→ Generalization of Higgs Mixing.

Two Higgs Doublet Models & Mediator

Parameter Galore?

$$m_P \,, \mu_1, \mu_2, \mu_3 \,, b_P$$
$$\lambda_1, \lambda_2, \lambda_3, \lambda_4 \,, \lambda_5 \,,$$
$$y_q, \; y_\chi$$

→

$$m_h, M_H, M_A, M_{H^\pm}, M_a$$
$$v, \tan\beta, \cos(\beta-\alpha), \sin\theta$$
$$m_f \,, y_\chi, \lambda_3$$

Two Higgs Doublet Models & Mediator

Parameter Galore?

$$m_P\,,\mu_1,\mu_2,\mu_3\,,b_P$$
$$\lambda_1,\lambda_2,\lambda_3,\lambda_4\,,\lambda_5\,,$$
$$y_q,\;y_\chi$$

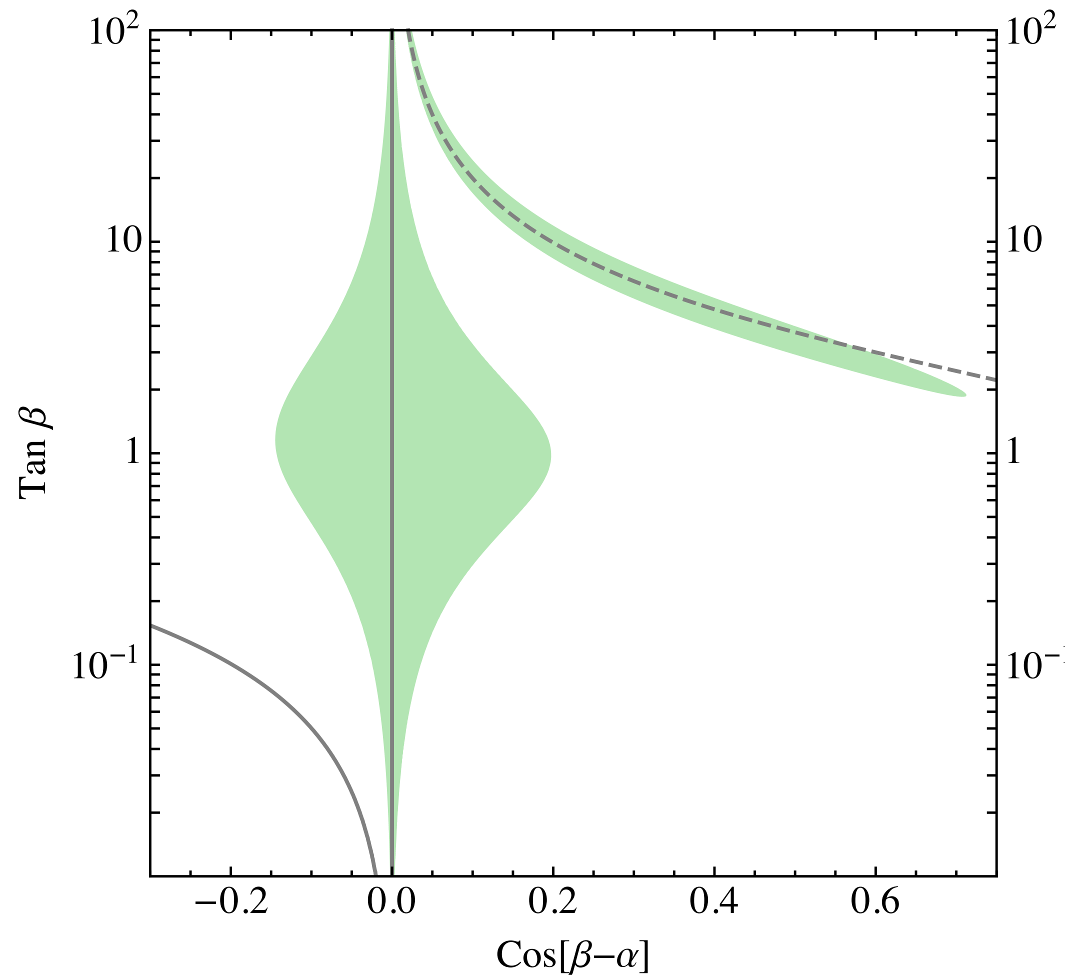
$$\cancel{m}_h,M_H\,,M_A,M_{H^\pm}\,,M_a$$
$$\cancel{v},\tan\beta,\cos(\beta-\alpha),\sin\theta$$
$$\cancel{m}_f\,,y_\chi,\lambda_3$$

Two Higgs Doublet Models & Mediator

Constraints from

Higgs Couplings:

$$\cos(\beta - \alpha) = 0$$



$$m_h, M_H, M_A, M_{H^\pm}, M_a$$

$$v, \tan\beta, \cos(\beta - \alpha), \sin\theta$$

$$m_f, y_\chi, \lambda_3$$

Two Higgs Doublet Models & Mediator

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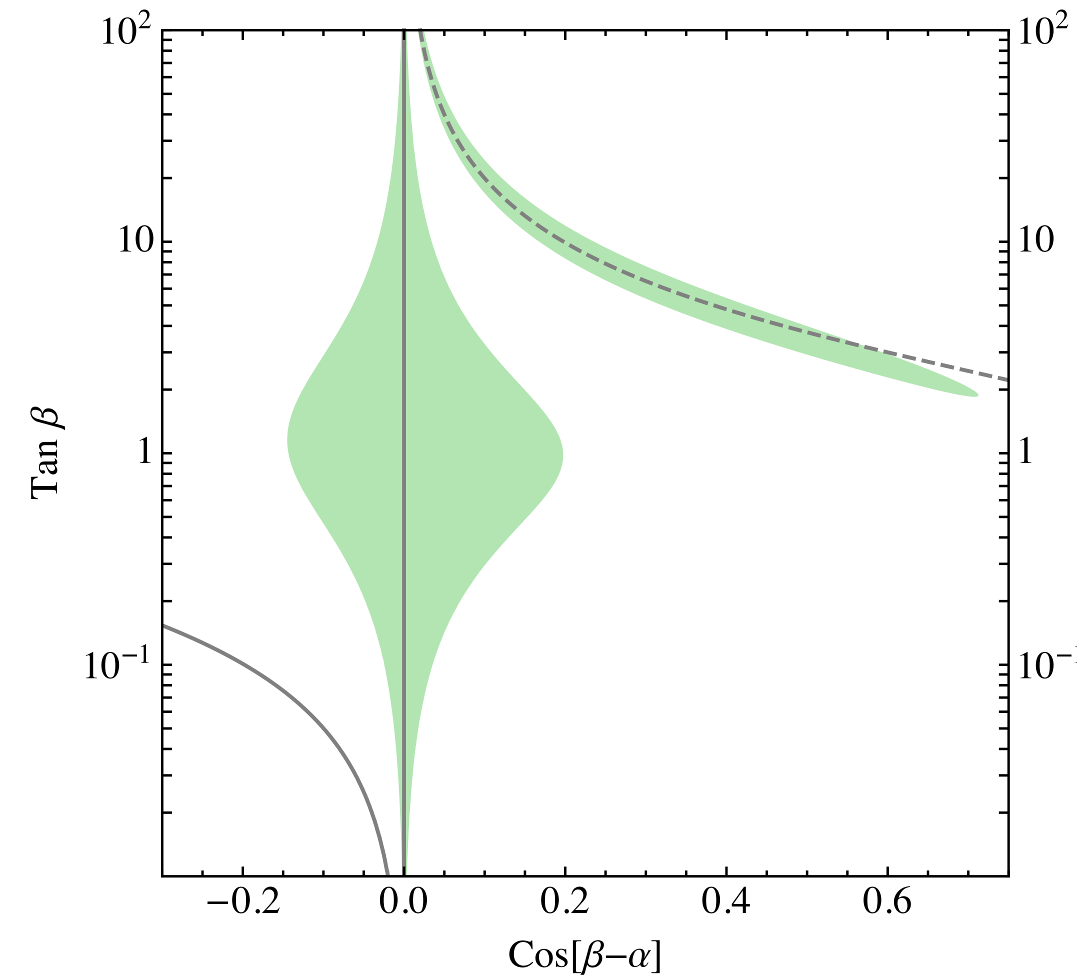
Flavour:

$$b \to s\gamma : \; M_{H^\pm} \gtrsim 700\,\text{GeV}$$

also disfavours large tanβ



$$m_h, M_H, M_A, M_{H^\pm}, M_a$$

$$v, \tan\beta, \cos(\beta - \alpha), \sin\theta$$

$$m_f, y_\chi, \lambda_3$$

Two Higgs Doublet Models & Mediator

Constraints from

Higgs Couplings:

$$\cos(\beta - \alpha) = 0$$

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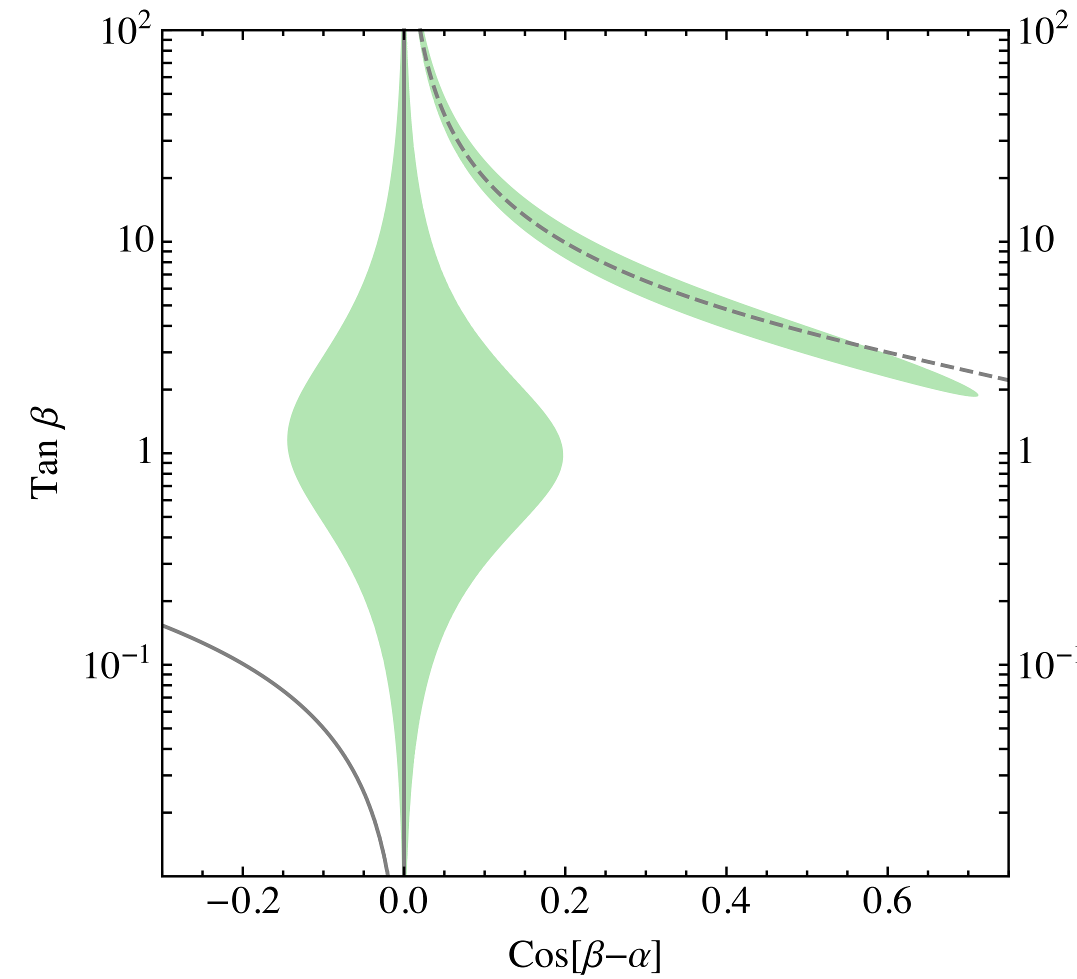
Electroweak Precision bounds

$M_H \approx M_{H^\pm}$ or $M_A \approx M_{H^\pm}$



$$m_h, M_H, M_A, M_{H^\pm}, M_a$$
$$v, \tan\beta, \cos(\beta - \alpha), \sin\theta$$
$$m_f, y_\chi, \lambda_3$$

Two Higgs Doublet Models & Mediator

In practice: six free parameters

$$\tan\beta\,, \sin\theta\,, y_\chi\,, \lambda_3\,, M_a\,, M_A \;\text{ or }\; M_H$$

DMF: $M_a\,, g_\chi,\, g_f$

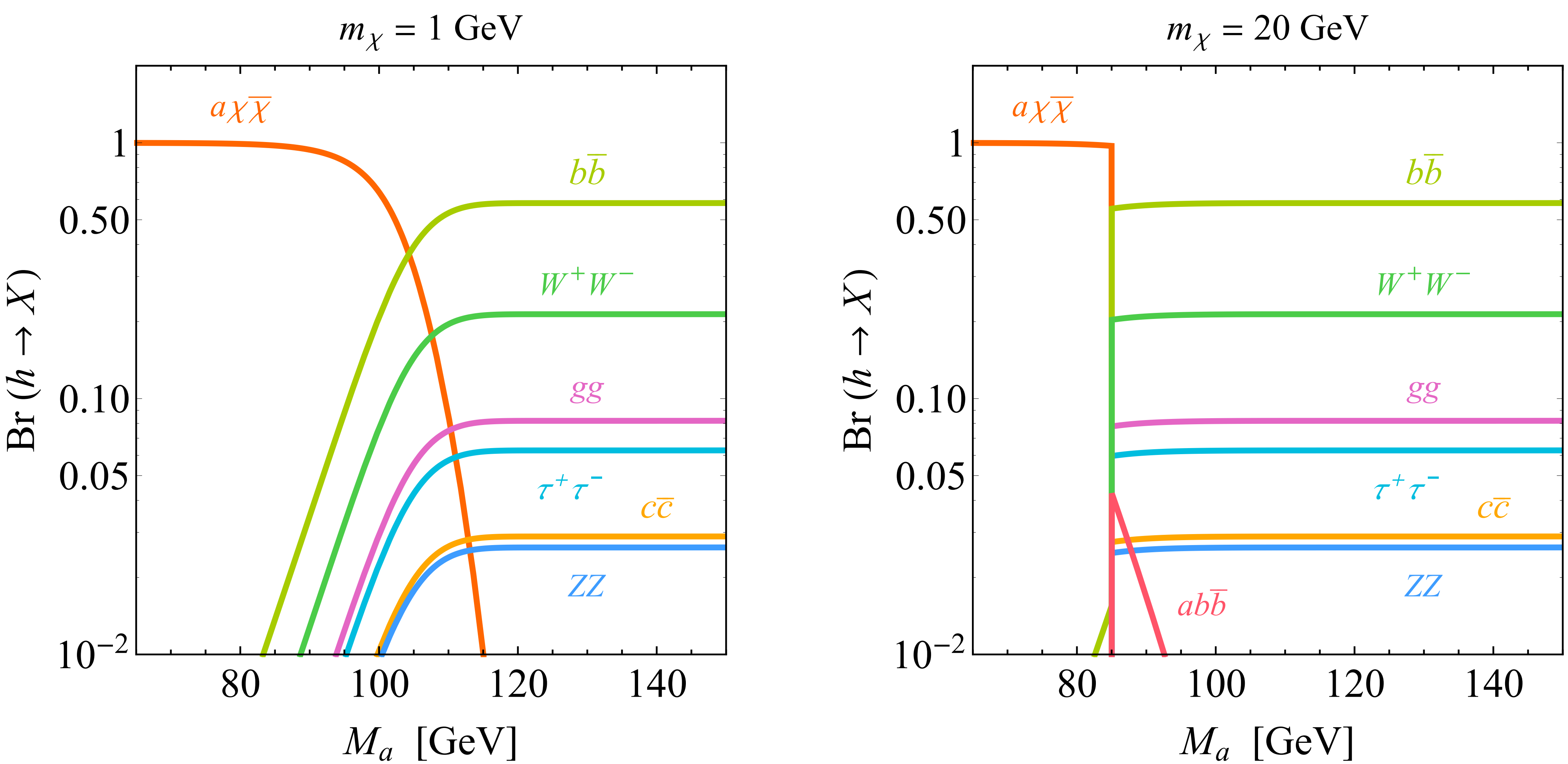
Five spin 0 mass eigenstates (three relevant)

$$h, a, H \text{ or } A\,, (H^\pm)$$

DMF: h, a

Pseudoscalars couple directly to DM,
H and h have aa and aZ couplings

The light scalar h (SM Higgs)



$\tan\beta = 1$

$\sin\theta = 0.5$

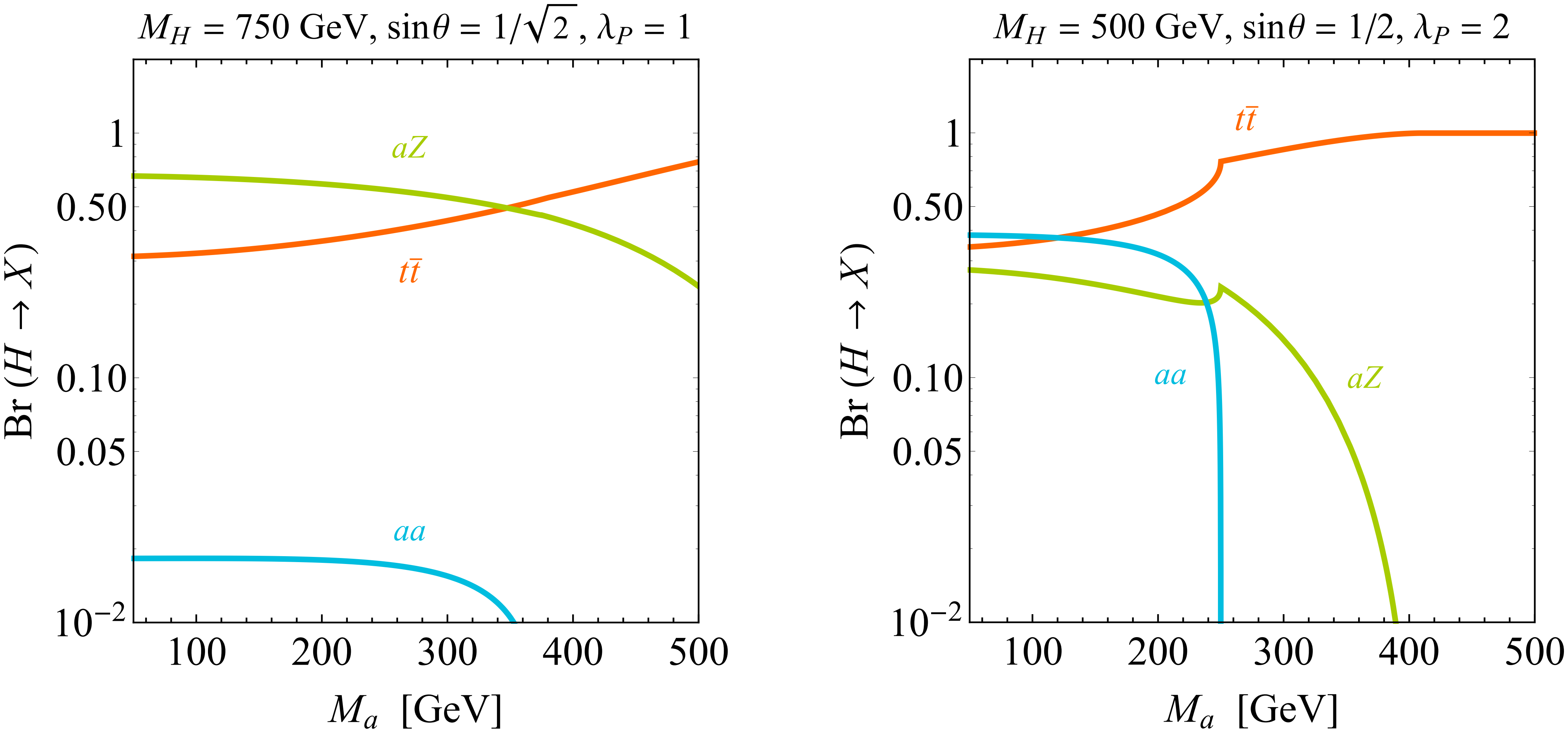
$\lambda_3 = 1$

$y_\chi = 1$

$M_{H^\pm} = 750\,\mathrm{GeV}$

Decays into off-shell mediators important.
Remains SM-like for Ma > 110 GeV

The heavy scalar H



$\tan\beta = 1$

$\lambda_3 = 1$

$y_\chi = 1$

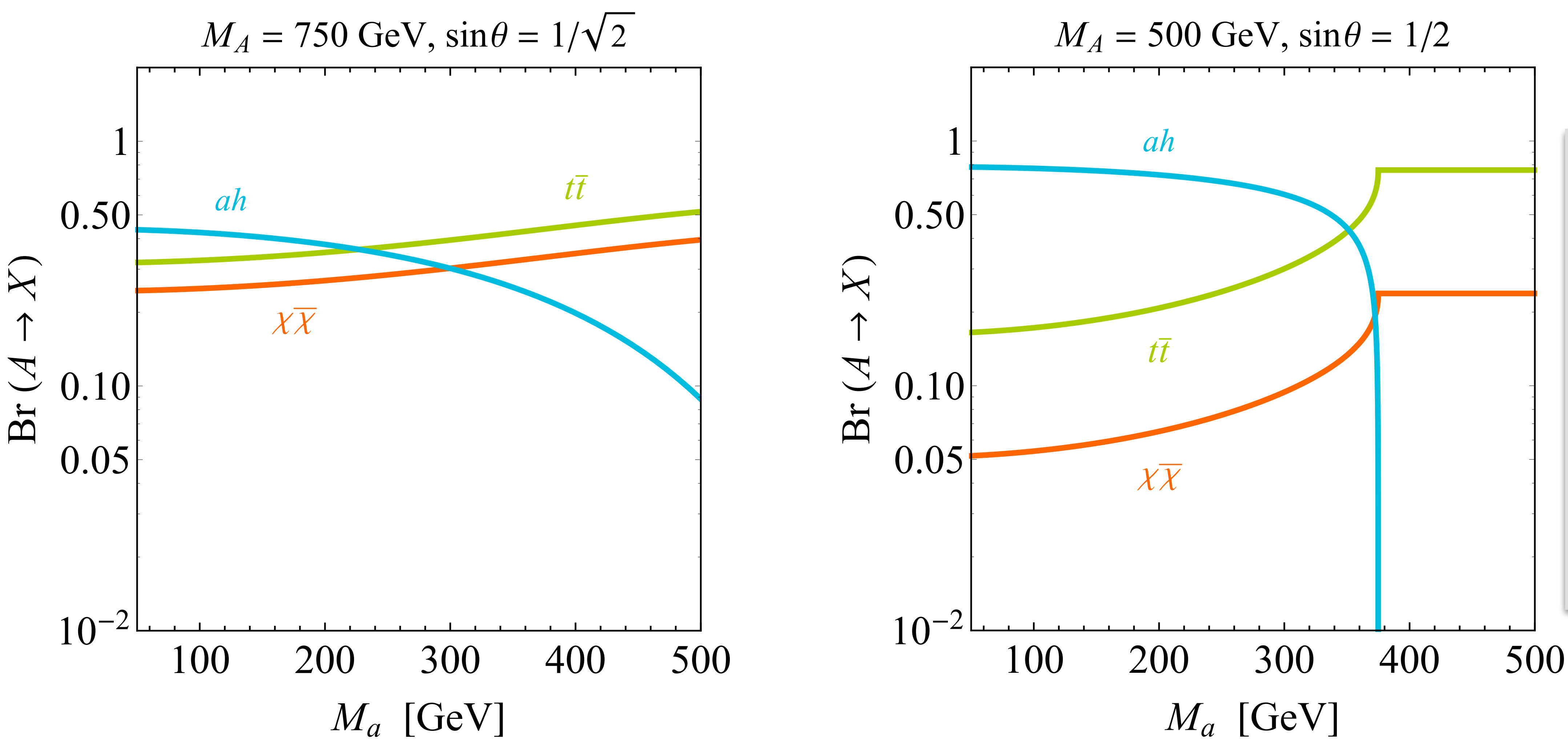
$m_\chi = 1\,\mathrm{GeV}$

$M_{H^\pm} = 750\,\mathrm{GeV}$

$M_A = 750\,\mathrm{GeV}$

large Branching ratio into aZ : promising Mono-Z signal

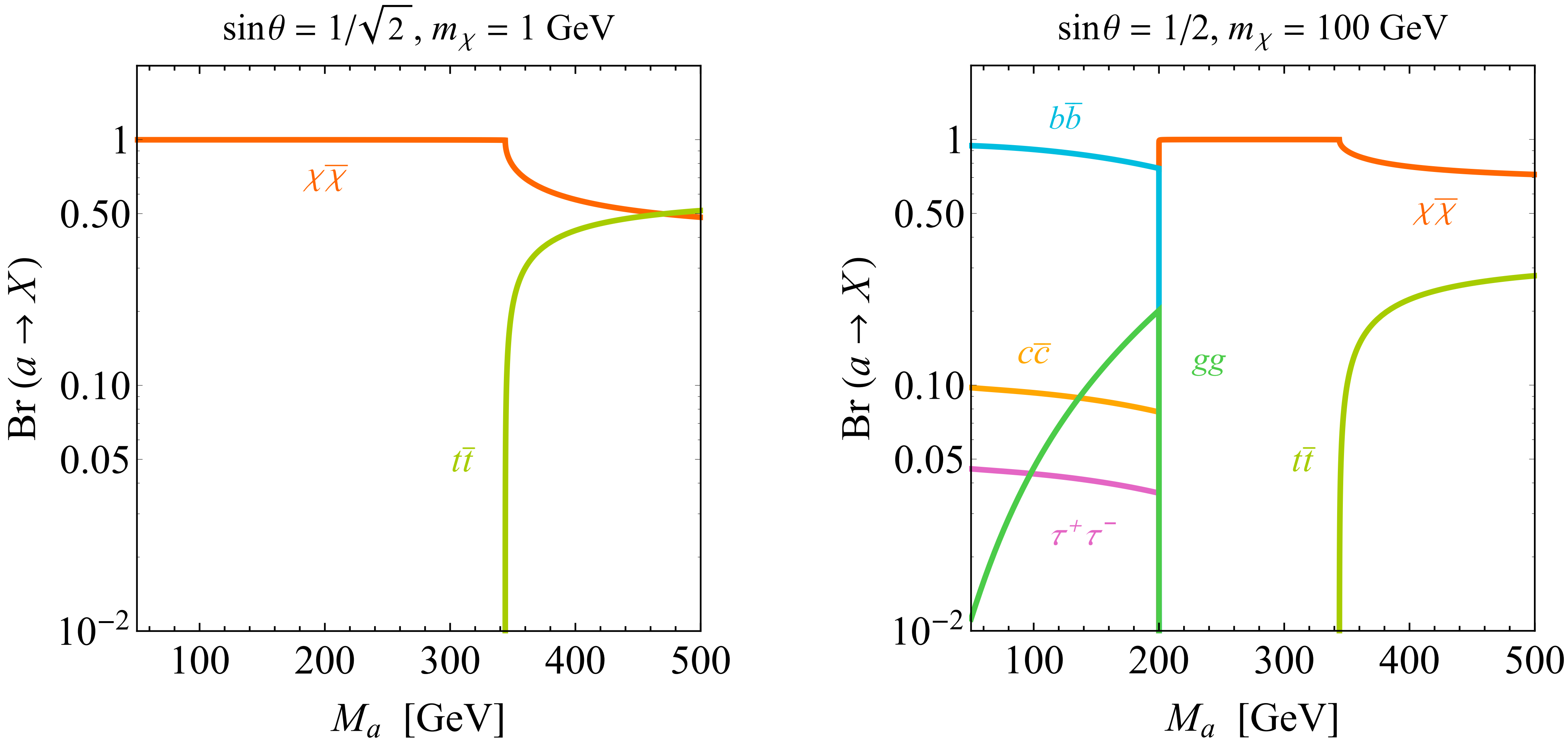
The heavy pseudo-scalar A



$$\tan\beta = 1$$
$$\lambda_3 = 1$$
$$y_\chi = 1$$
$$m_\chi = 1\,\text{GeV}$$
$$M_{H^\pm} = 750\,\text{GeV}$$
$$M_H = 750\,\text{GeV}$$

large Branching ratio into ah : promising Mono-H signal

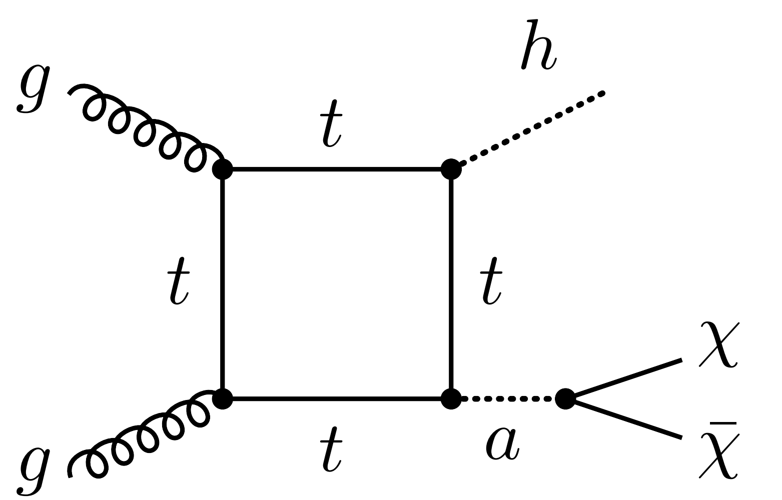
The light mediator a

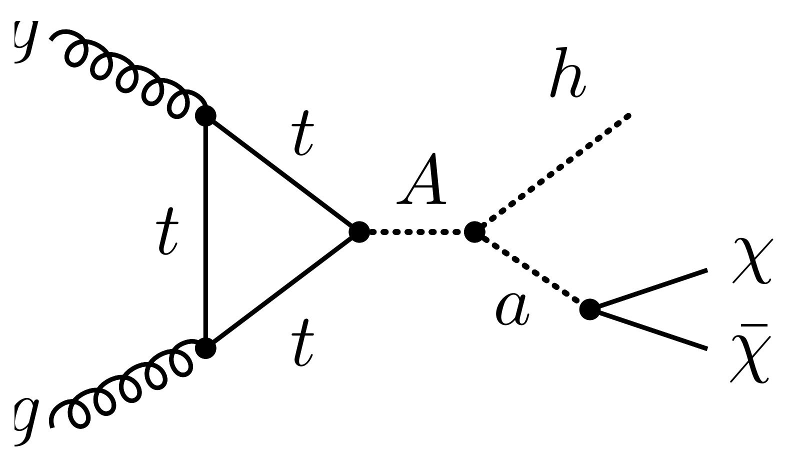


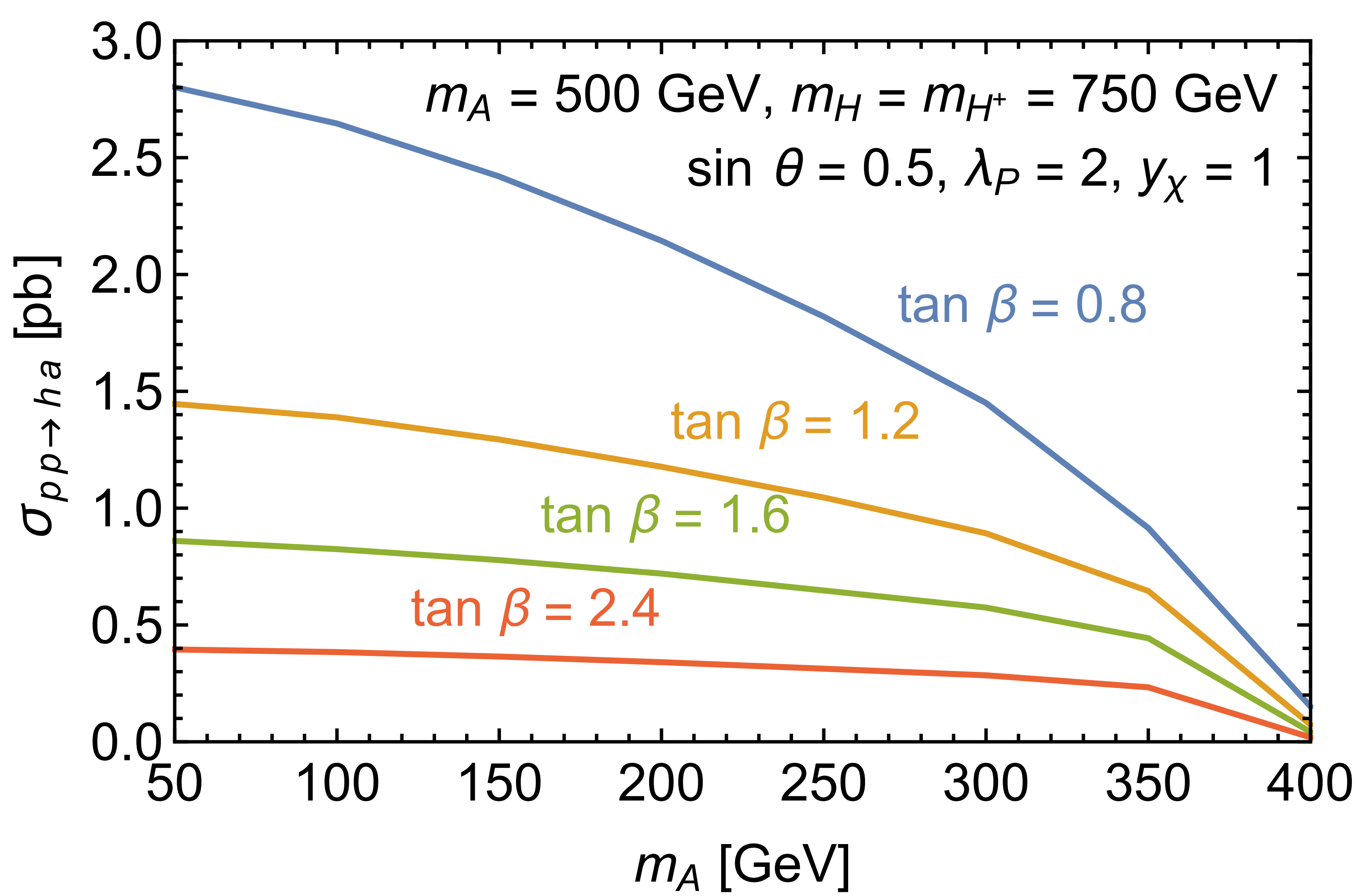
$\tan\beta = 1$

$y_\chi = 1$

Mono-Higgs



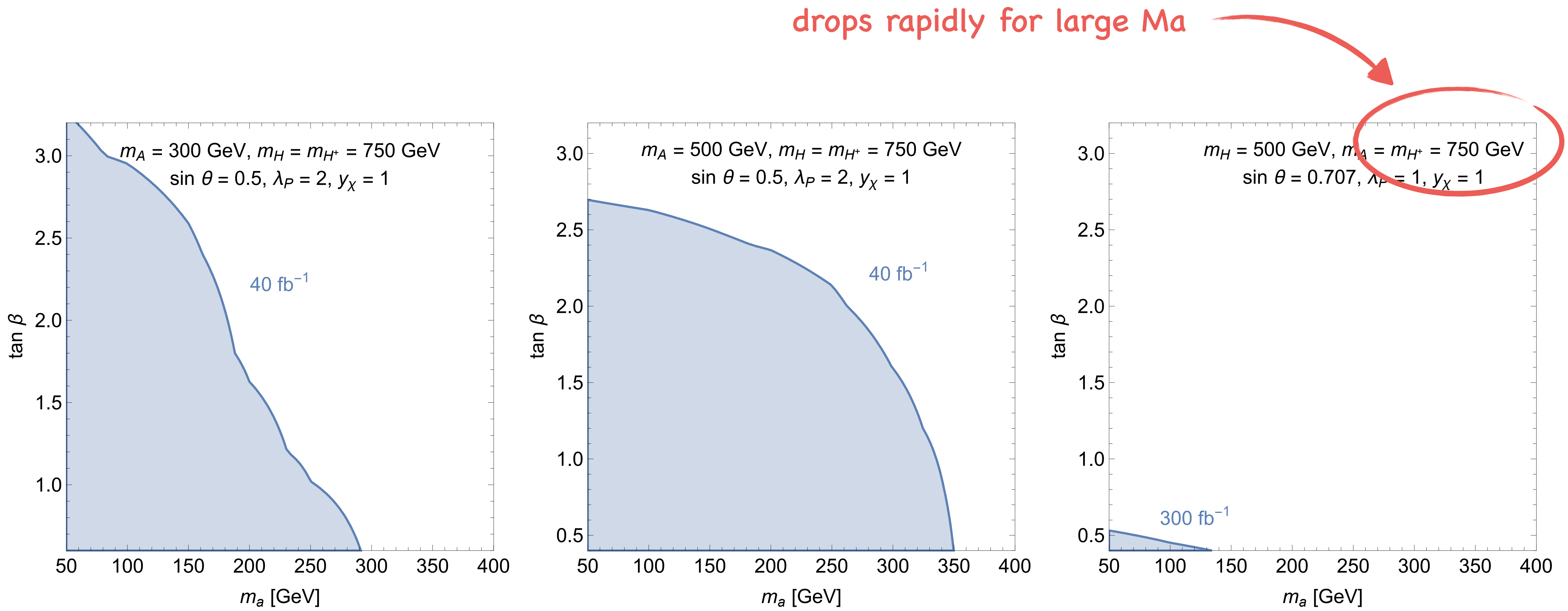




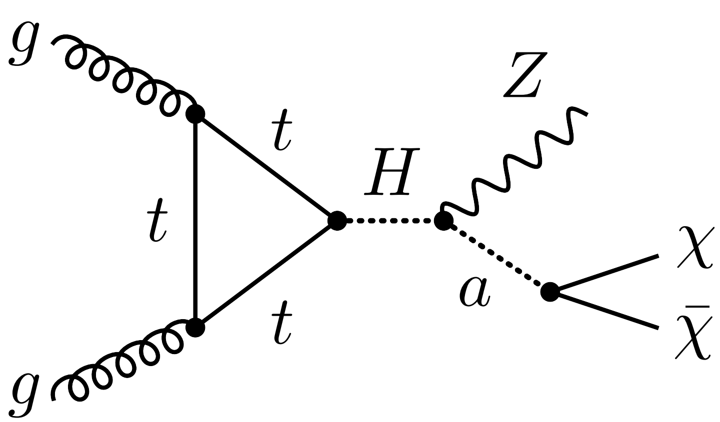
In contrast to DMF model resonantly enhanced

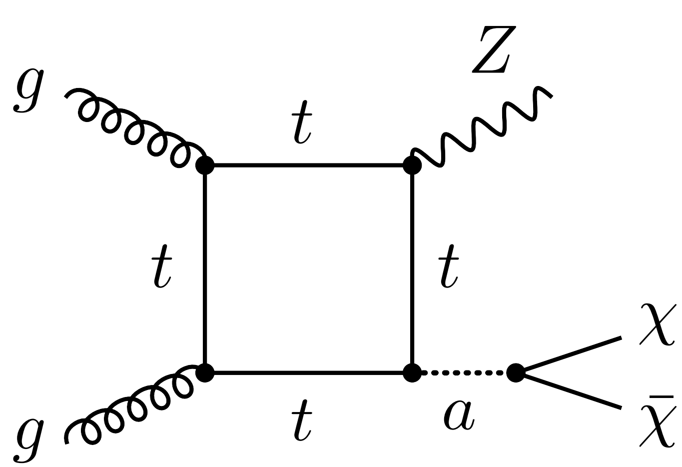
Mono-Higgs

In contrast to DMF model resonantly enhanced



Mono-Z

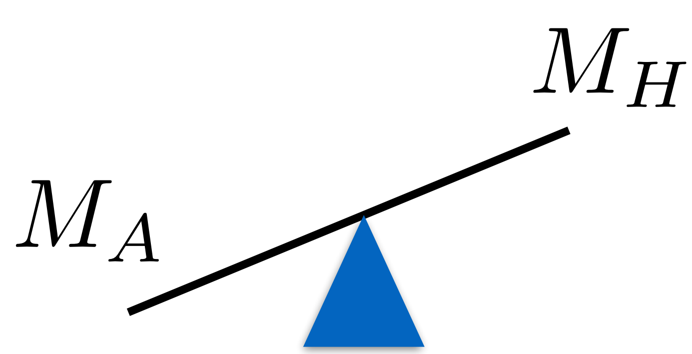




The same resonant enhancement gives a promising mono-Z signal

see Jose No's talk

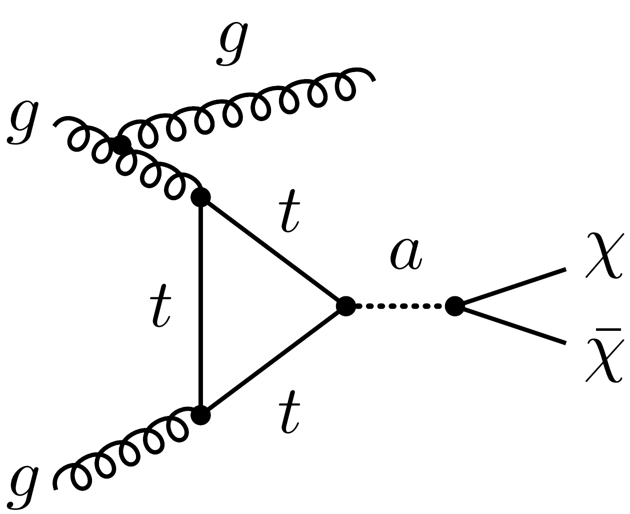
Mono-Higgs and Mono-Z searches are potential discovery channels with indirect information on the mass hierarchy of the extra scalars.

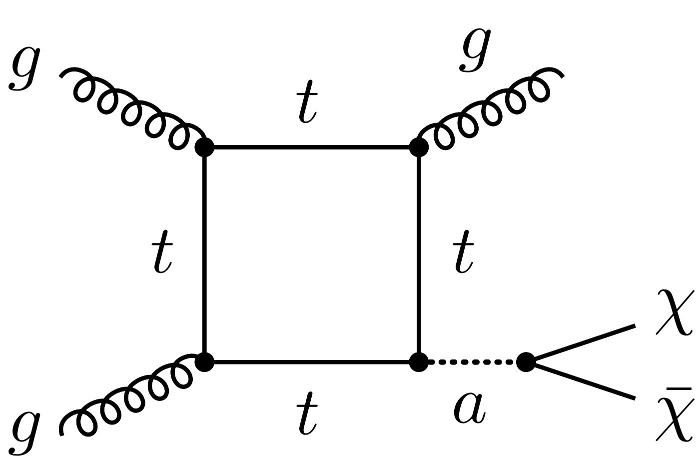


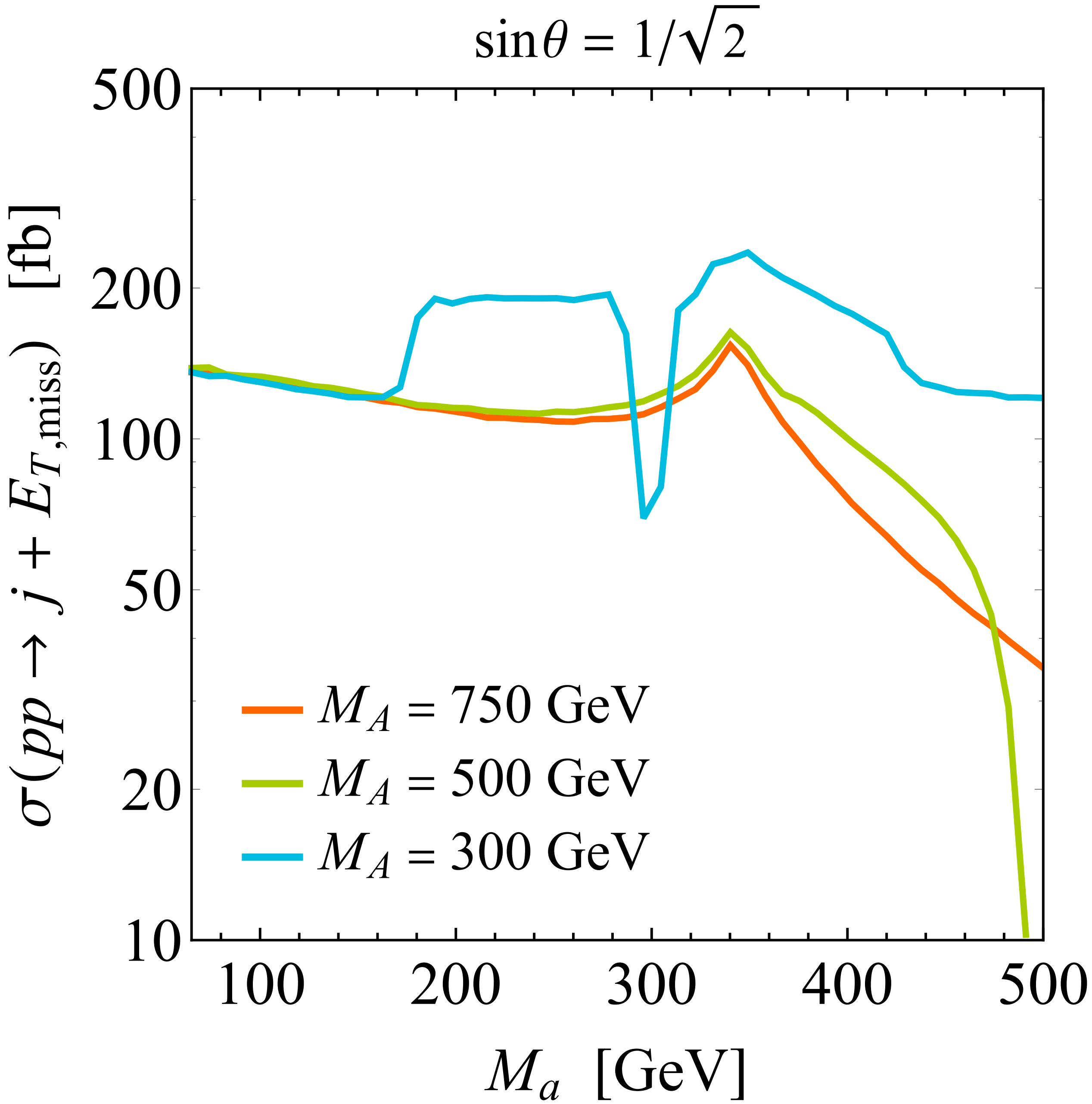
mono-h

mono-Z

Mono-jets



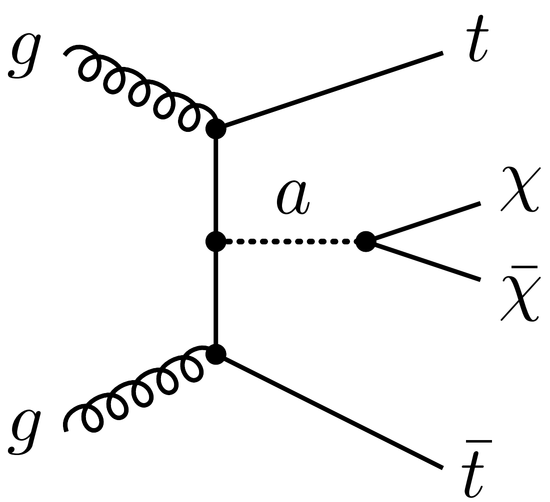


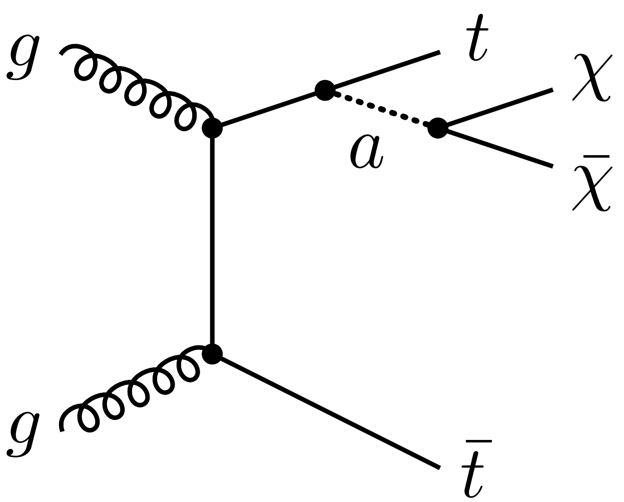


Interference effects:

$$\mathcal{M}\left(pp \to j + \chi\bar{\chi}\right) \propto \frac{1}{s - M_a^2 - iM_a\Gamma_a} - \frac{1}{s - M_A^2 - iM_A\Gamma_A}$$

$t\bar{t} + E_{T,\mathrm{miss}}$



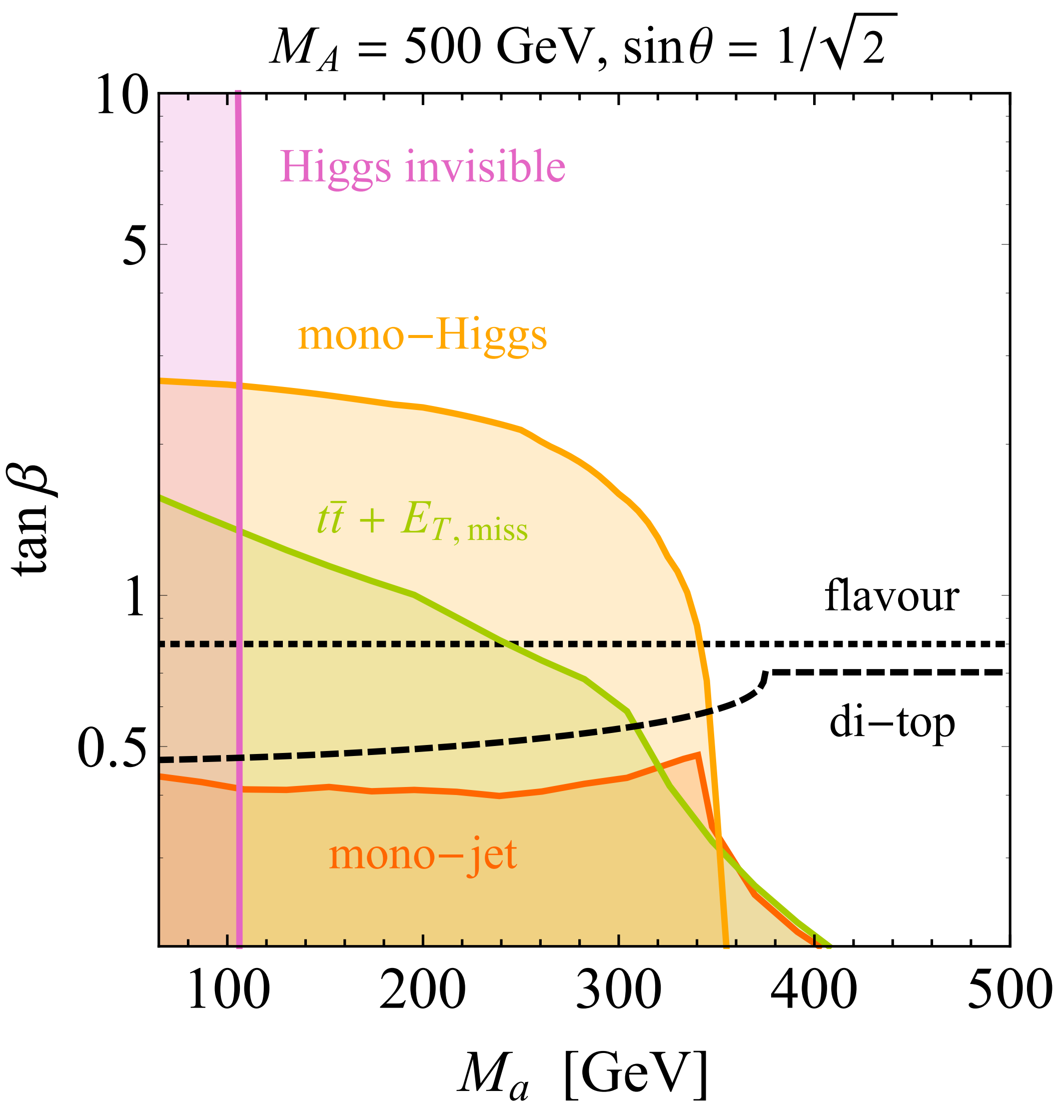


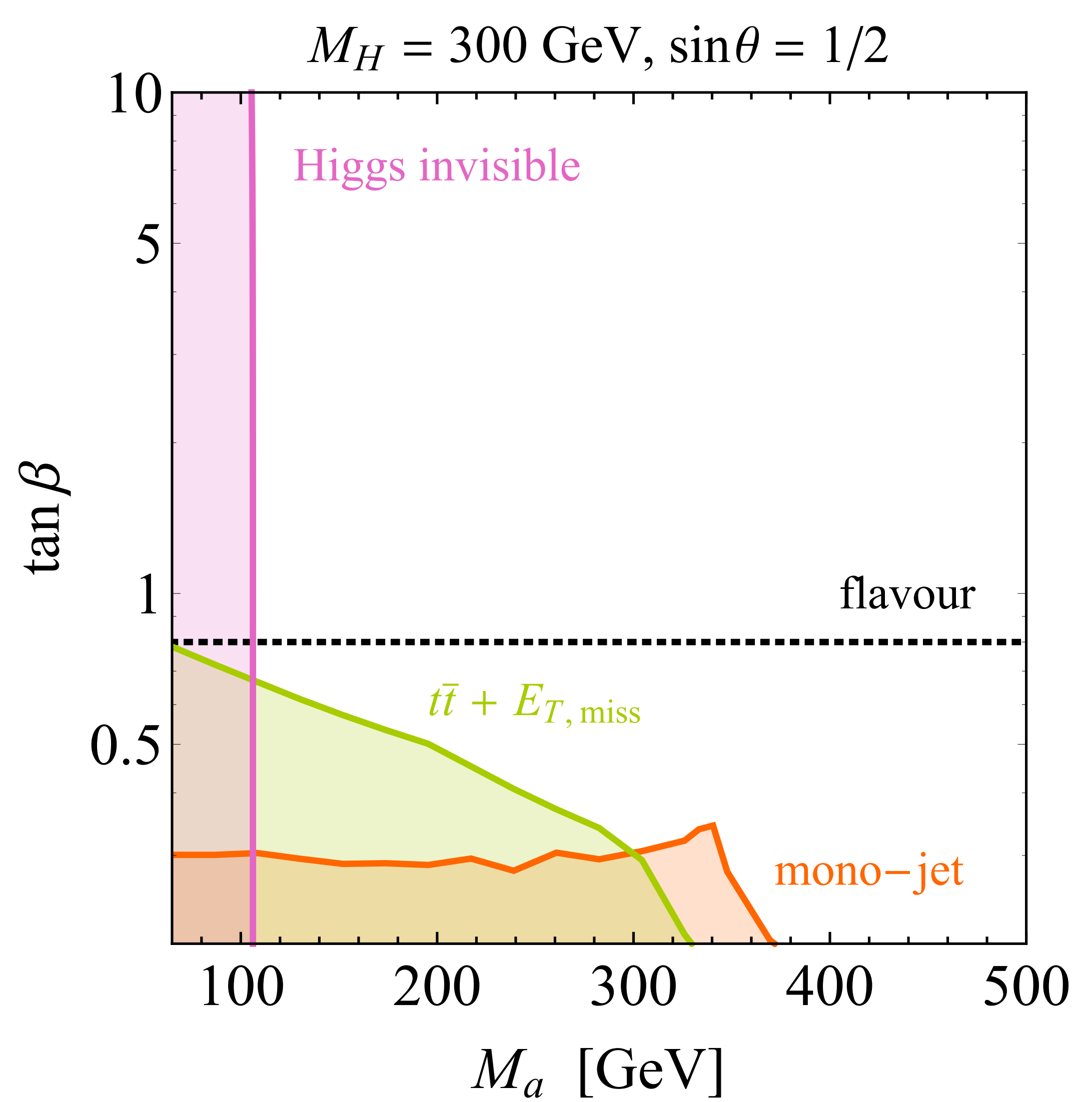
Not competitive at the moment, but also not systematically limited

Projected to provide a stronger constraint than Monojets @ 300 fb^-1

Haisch, Pani, Polesello 1611.09841

Summary Plots





mono-jet, 40 fb^-1, 13 TeV

mono-Higgs, 40 fb^-1, 13 TeV

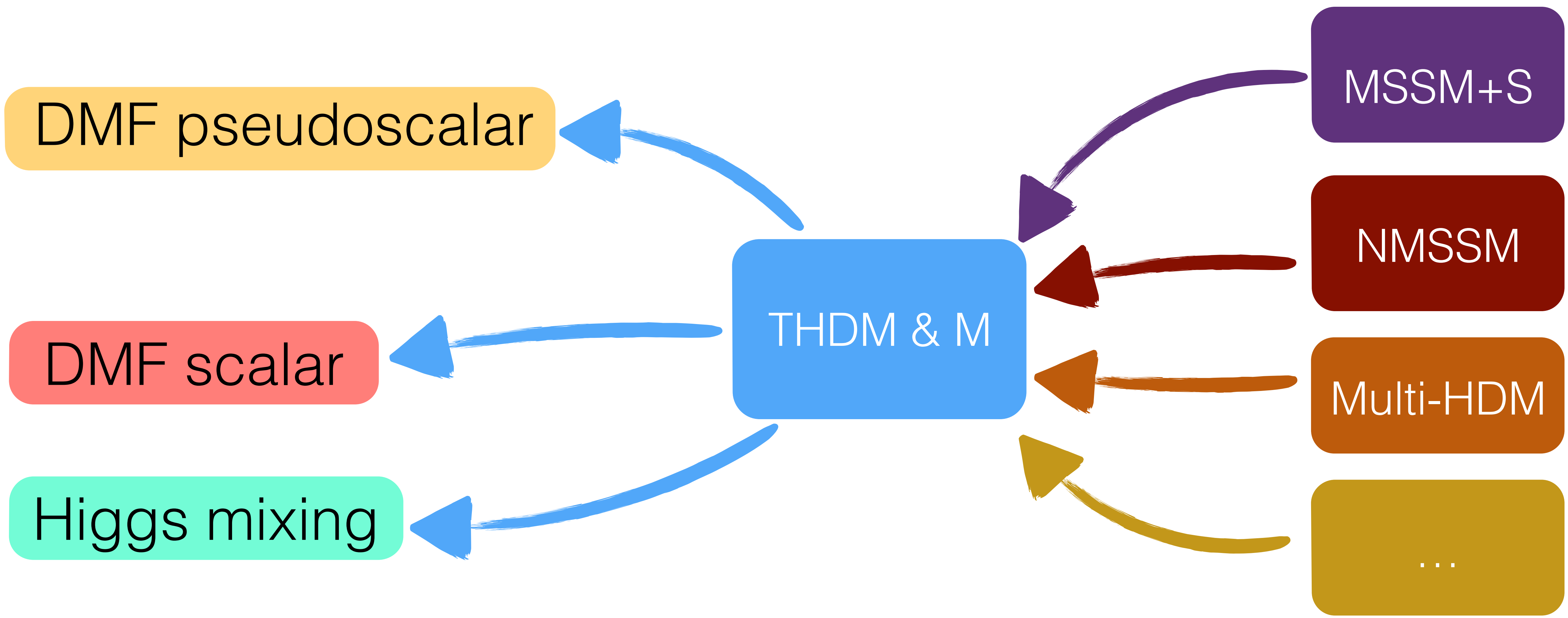
tt + MET, 300 fb^-1, 14 TeV

ditop, 20.3 fb^-1, 8 TeV , ATLAS-CONF-2016-073

Higgs invisible < 25 %, ATLAS-CONF-2015-044

Conclusions

THDM & mediator models provide a consistent simplified model, reproducing features of DMF models in the appropriate limit, and with links to well-motivated UV completions



Conclusions

THDM & mediator models provide a consistent simplified model, reproducing features of DMF models in the appropriate limit, and with links to well-motivated UV completions

Spectacular Phenomenology with mono-Higgs and mono-Z potential discovery channels

Underlines complementary approach at run II between different MET searches, but also of non-MET searches (di-top @ large Ma)

Ready-to-go `UFO` file available