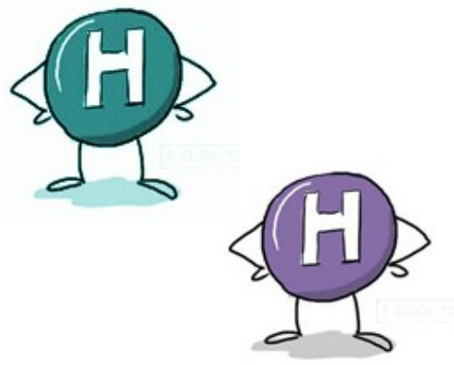
The 2HDM + a:

An archetype model for LHC DM searches

LHC DM WG @ CERN

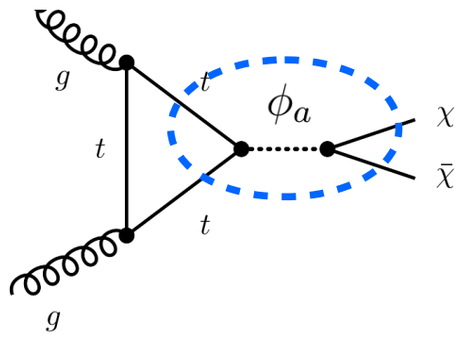
Jose Miguel No
IFT-UAM/CSIC, Madrid



#Why?

SM + **Pseudoscalar** mediator + **Dark Matter** (singlet fermion)

$$\mathcal{L}_{\text{pseudoscalar}} = -ig_\chi \phi_a \bar{\chi}\gamma_5\chi - ig_q \frac{\phi_a}{\sqrt{2}} \sum_q y_q \bar{q}\gamma_5 q$$



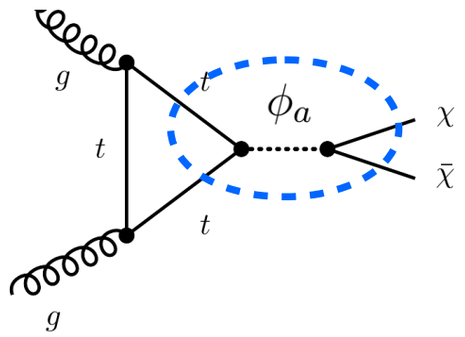
Motivated by:

- **Null results** in spin-independent **DM Direct Detection** searches
- **Hints of DM** in **indirect detection** (galactic center excess)

#Why?

SM + **Pseudoscalar** mediator + **Dark Matter** (singlet fermion)

$$\mathcal{L}_{\text{pseudoscalar}} = -ig_\chi \phi_a \bar{\chi}\gamma_5\chi - ig_q \frac{\phi_a}{\sqrt{2}} \sum_q y_q \bar{q}\gamma_5 q$$



NOT Gauge Invariant!

#Why?

2HDM + singlet **Pseudoscalar** mediator + **Dark Matter** (singlet fermion)

Minimal renormalizable (gauge invariant) realization

#Model Overview

2HDM + singlet **Pseudoscalar** mediator + **Dark Matter** (singlet fermion)

Originally introduced by *Ipek, McKeen, Nelson*

Ipek, McKeen, Nelson, PRD 90 (2014), 055021

$$
\begin{aligned}
V_{\rm 2HDM} = {} & \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 - \left[\mu_{12}^2\, H_1^\dagger H_2 + \text{h.c.}\right] \\
& + \frac{\lambda_1}{2}\left|H_1\right|^4 + \frac{\lambda_2}{2}\left|H_2\right|^4 + \lambda_3 \left|H_1\right|^2 \left|H_2\right|^2 \\
& + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]
\end{aligned}
$$

$$
V_a = \frac{\mu_a^2}{2}\, a_0^2 + \frac{\lambda_a}{4}\, a_0^4 + \left(i\,\kappa\, a_0 H_1^\dagger H_2 + \text{h.c.}\right)
$$

$$
\mathcal{L}_{\rm dark} = y_\chi a_0 \bar{\chi} i\gamma^5 \chi
$$

Singlet-doublet pseudoscalar mixing

$$
a_0 \;\; A_0 \longrightarrow \;\; a \;\; A
$$

#Model Overview

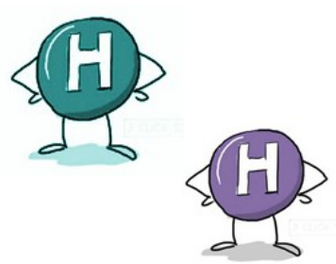
2HDM + singlet **Pseudoscalar** mediator + **Dark Matter** (singlet fermion)

$$
\begin{aligned}
V_{\rm 2HDM} = {} & \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 - \left[\mu_{12}^2\, H_1^\dagger H_2 + \text{h.c.}\right] \\
& + \frac{\lambda_1}{2}\left|H_1\right|^4 + \frac{\lambda_2}{2}\left|H_2\right|^4 + \lambda_3 \left|H_1\right|^2 \left|H_2\right|^2 \\
& + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]
\end{aligned}
$$

$$
V_a = \frac{\mu_a^2}{2}\, a_0^2 + \frac{\lambda_a}{4}\, a_0^4 + \left(i\,\kappa\, a_0 H_1^\dagger H_2 + \text{h.c.}\right)
$$

$$
\mathcal{L}_{\rm dark} = y_\chi a_0 \bar{\chi} i\gamma^5 \chi
$$

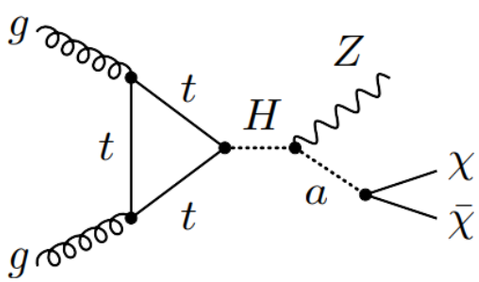
More Higgses, more fun!

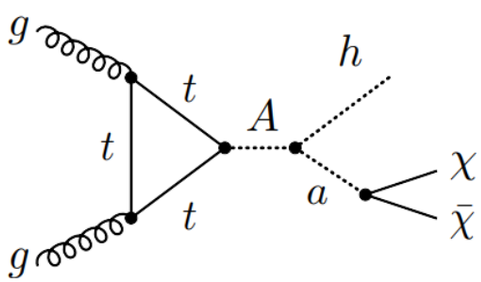


Courtesy: PhD Comics

New (resonant) processes

JMN, PRD 93 (2016), 031701
Goncalves, Machado, JMN, PRD 95 (2017), 055027
Bauer, Haisch, Kahlhoefer, JHEP 05 (2017), 138





#Model Overview

2HDM + singlet **Pseudoscalar** mediator + **Dark Matter** (singlet fermion)

$$V_{\rm 2HDM} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \left[\mu_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$$\mathcal{L}_{\rm dark} = y_\chi a_0 \bar{\chi} i\gamma^5 \chi$$

$$V_a = \frac{\mu_a^2}{2} a_0^2 + \frac{\lambda_a}{4} a_0^4 + \left(i\,\kappa\, a_0 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_{aH_1} a_0^2 |H_1|^2 + \lambda_{aH_2} a_0^2 |H_2|^2$$

New (resonant) processes

JMN, PRD 93 (2016), 031701
Goncalves, Machado, JMN, PRD 95 (2017), 055027
Bauer, Haisch, Kahlhoefer, JHEP 05 (2017), 138

Complete model

$$\lambda_\beta \equiv (\lambda_{aH_1} + \lambda_{aH_2} t_\beta^2)/(1 + t_\beta^2)$$

SM Higgs field coupling to singlet pseudoscalar pair

(will be relevant later...)

#LHC Status

Multi-parameter scenario $\left\{ \begin{array}{c} v,\, M_h,\, M_A,\, M_H,\, M_{H^\pm},\, M_a,\, m_\chi \\ \cos(\beta-\alpha),\, \tan\beta,\, \sin\theta, \\ y_\chi,\, \lambda_3,\, \lambda_{P1},\, \lambda_{P_2} \end{array} \right\}$ **12 free** (+ 1)

How to efficiently navigate it?

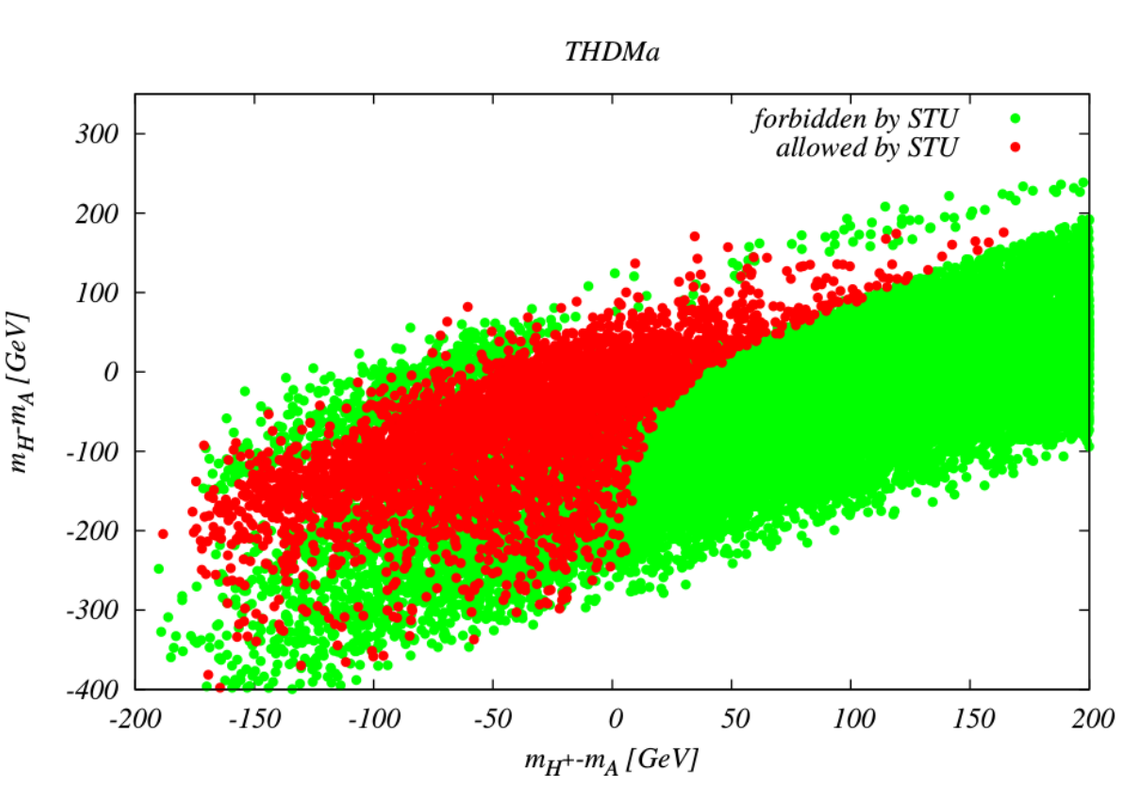
#LHC Status

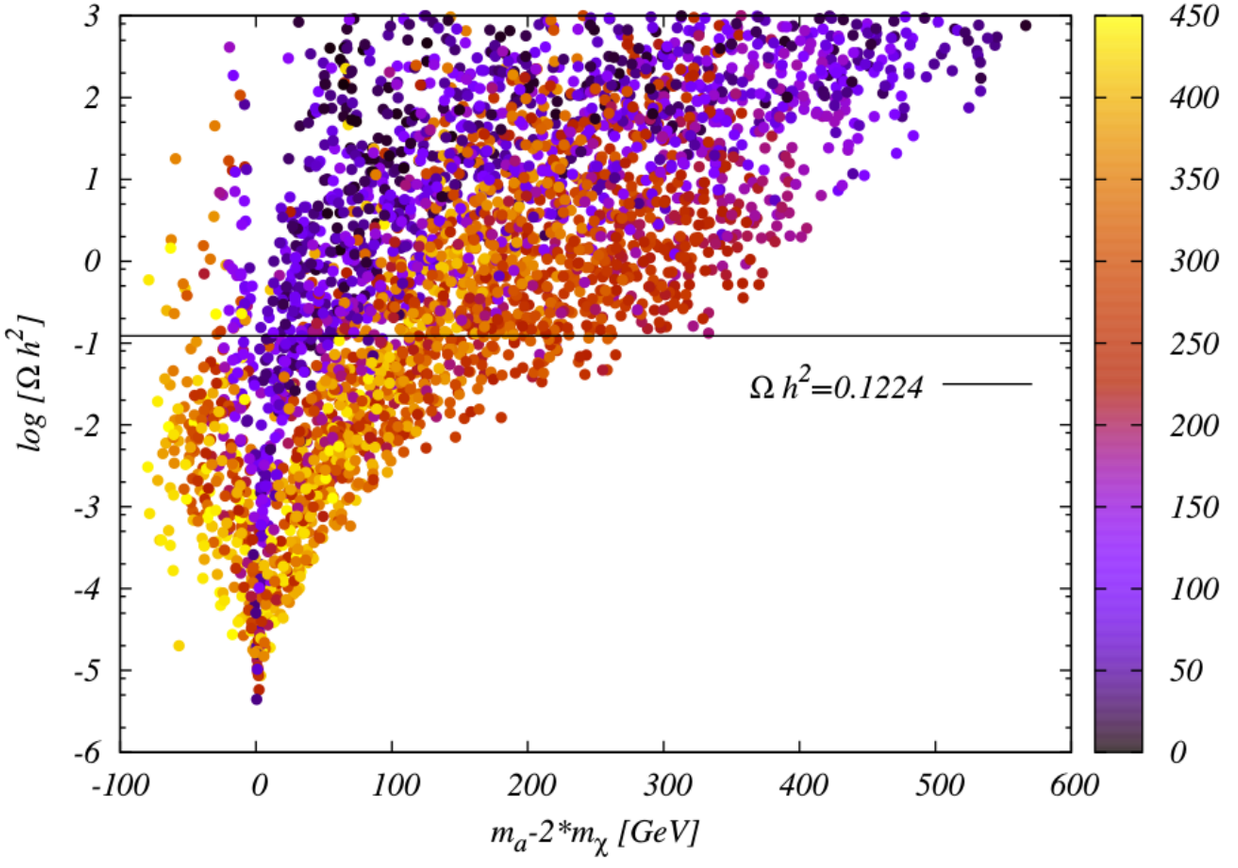
Multi-parameter scenario $\left\{ \begin{array}{c} v,\, M_h,\, M_A,\, M_H,\, M_{H^\pm},\, M_a,\, m_\chi \\ \cos(\beta-\alpha),\, \tan\beta,\, \sin\theta, \\ y_\chi,\, \lambda_3,\, \lambda_{P1},\, \lambda_{P_2} \end{array} \right\}$ **12 free** (+ 1)

How to efficiently navigate it?

- Multidimensional scan

Robens, Symmetry 12 (2021) 12, 2341





#LHC Status

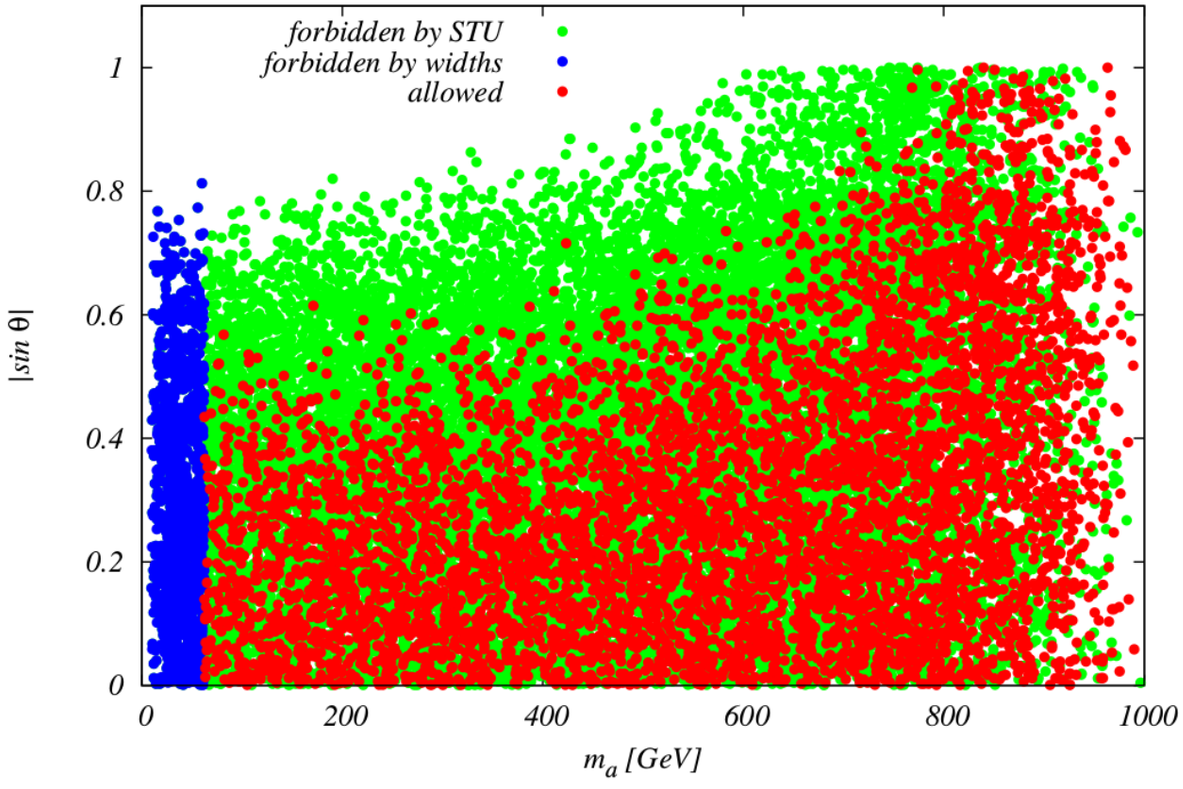
Multi-parameter scenario $\left\{ \begin{array}{c} v,\, M_h,\, M_A,\, M_H,\, M_{H^\pm},\, M_a,\, m_\chi \\ \cos(\beta-\alpha),\, \tan\beta,\, \sin\theta, \\ y_\chi,\, \lambda_3,\, \lambda_{P1},\, \lambda_{P_2} \end{array} \right\}$ **12 free** (+ 1)

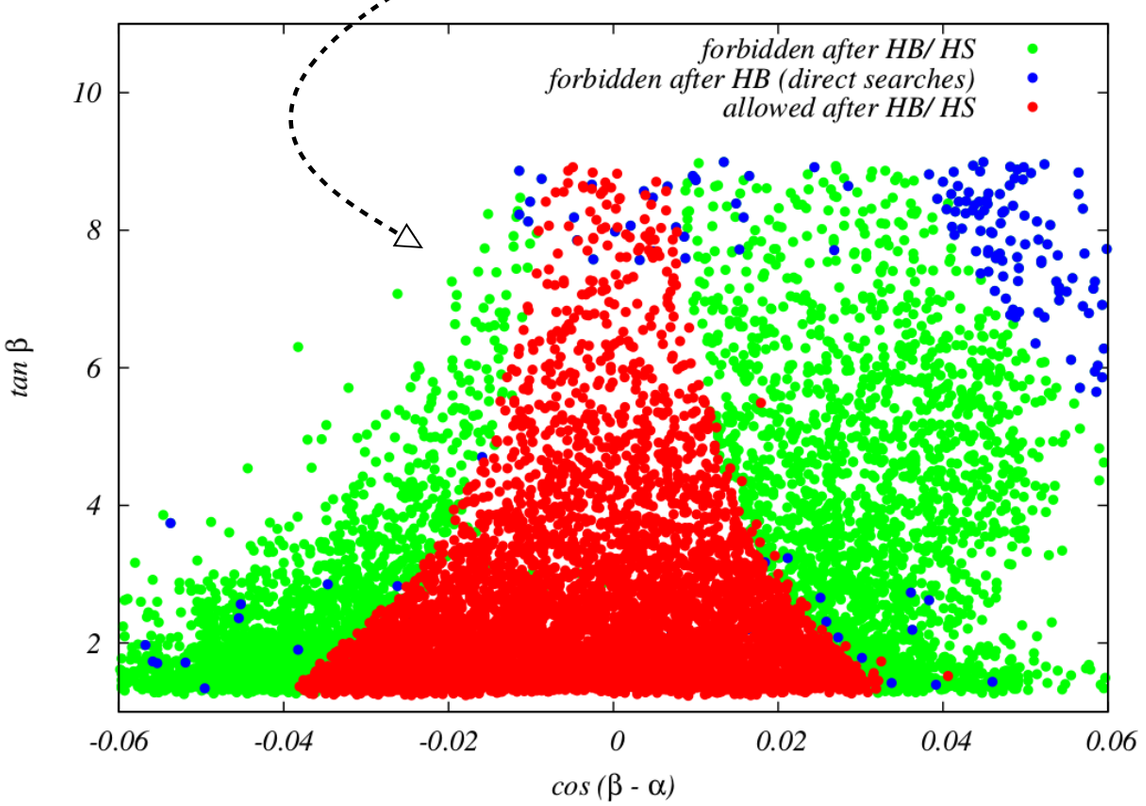
How to efficiently navigate it?

- Multidimensional scan
  Robens, Symmetry 12 (2021) 12, 2341

(Type I 2HDM can be very different!)

Type II 2HDM only!





#LHC Status

Multi-parameter scenario $\left\{ \begin{array}{c} v,\, M_h,\, M_A,\, M_H,\, M_{H^\pm},\, M_a,\, m_\chi \\ \cos(\beta-\alpha),\, \tan\beta,\, \sin\theta, \\ y_\chi,\, \lambda_3,\, \lambda_{P1},\, \lambda_{P_2} \end{array} \right\}$ **12 free** (+ 1)

How to efficiently navigate it?

- **Signature-based analysis** (*requires fixing parameters*)

Courtesy: VectorStock

#LHC Status

Multi-parameter scenario $\left\{ \begin{array}{c} v,\, M_h,\, M_A,\, M_H,\, M_{H^\pm},\, M_a,\, m_\chi \\ \cos(\beta-\alpha),\, \tan\beta,\, \sin\theta, \\ y_\chi,\, \lambda_3,\, \lambda_{P1},\, \lambda_{P_2} \end{array} \right\}$ **<u>12 free</u>** (+ 1)

How to efficiently navigate it?

- **Signature-based analysis** (*requires fixing parameters*)

Courtesy: VectorStock

#LHC Status

Multi-parameter scenario $\left\{ \begin{array}{c} v,\, M_h,\, M_A,\, M_H,\, M_{H^\pm},\, M_a,\, m_\chi \\ \cos(\beta-\alpha),\, \tan\beta,\, \sin\theta, \\ y_\chi,\, \lambda_3,\, \lambda_{P1},\, \lambda_{P_2} \end{array} \right\}$ **12 free** (+ 1)

How to efficiently navigate it?

- **Signature-based analysis** (*requires fixing parameters*)

Complementarity among different channels/searches

Sensitivity potential of each search

Possibility to identify blind spots!

#LHC Status

The 2HDM*a* @ 2024

ATLAS, 2306.00641

Scenario 1: exploration of two m_a–m_A planes.

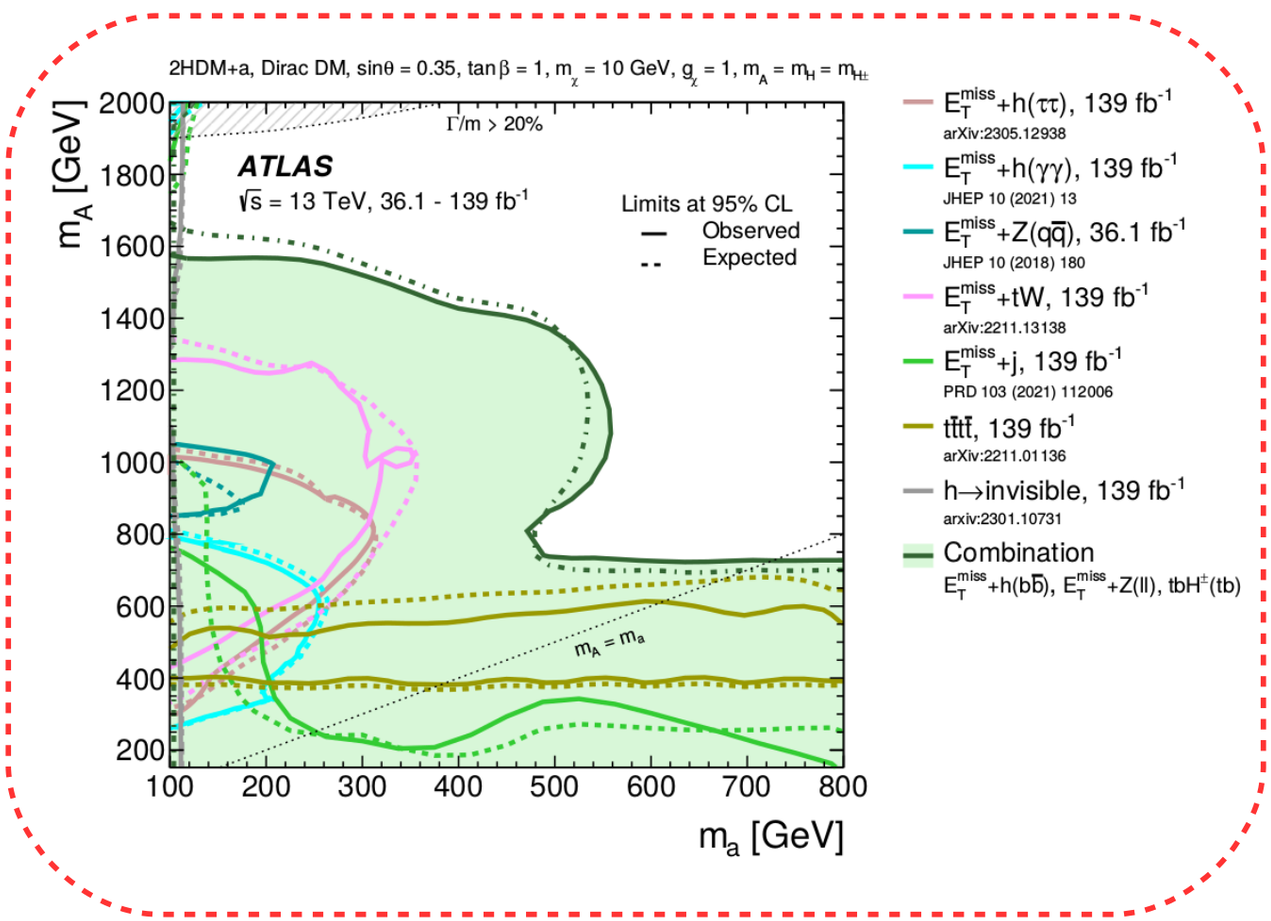
Scenario 2: exploration of two m_A–tan β planes.

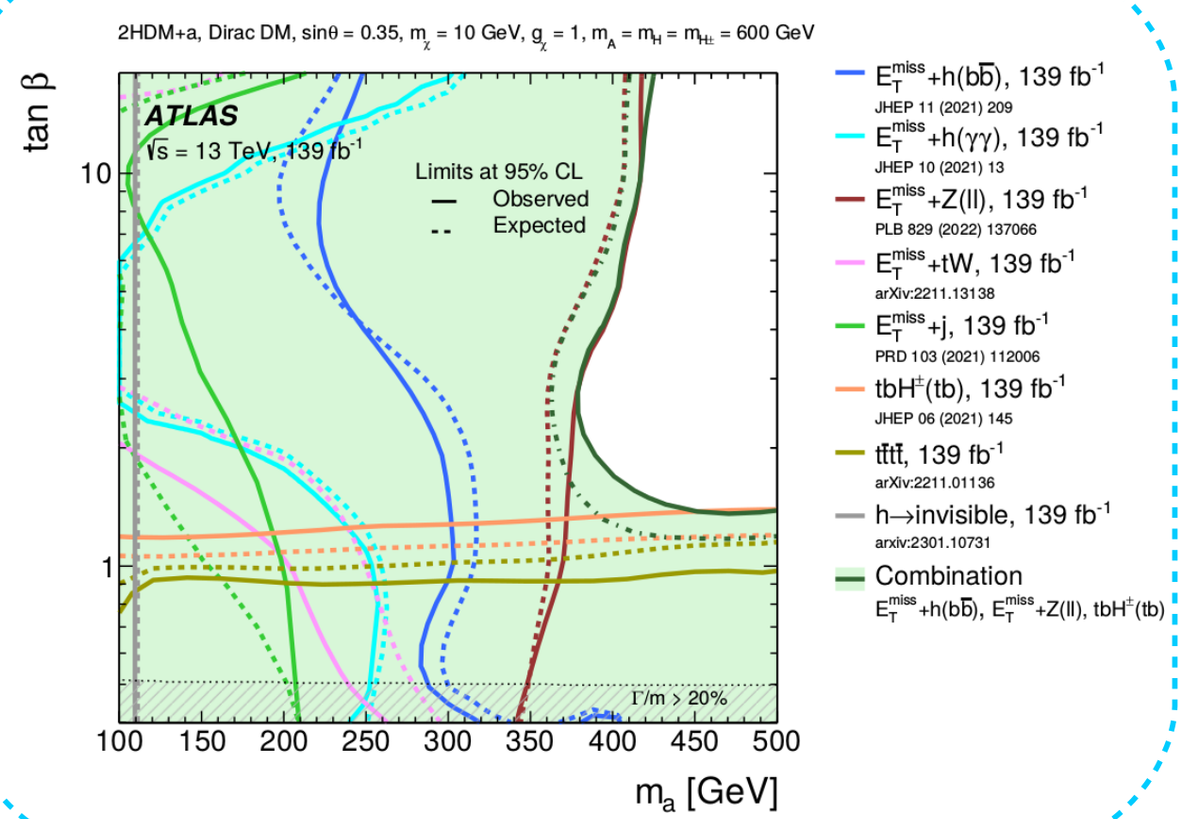
Scenario 3: exploration of two m_a–tan β planes.

Scenario 4: variation of the mixing parameter sin θ.

Scenario 5: variation of the DM mass m_χ.

Scenario 6: exploration of a m_a–m_χ plane.



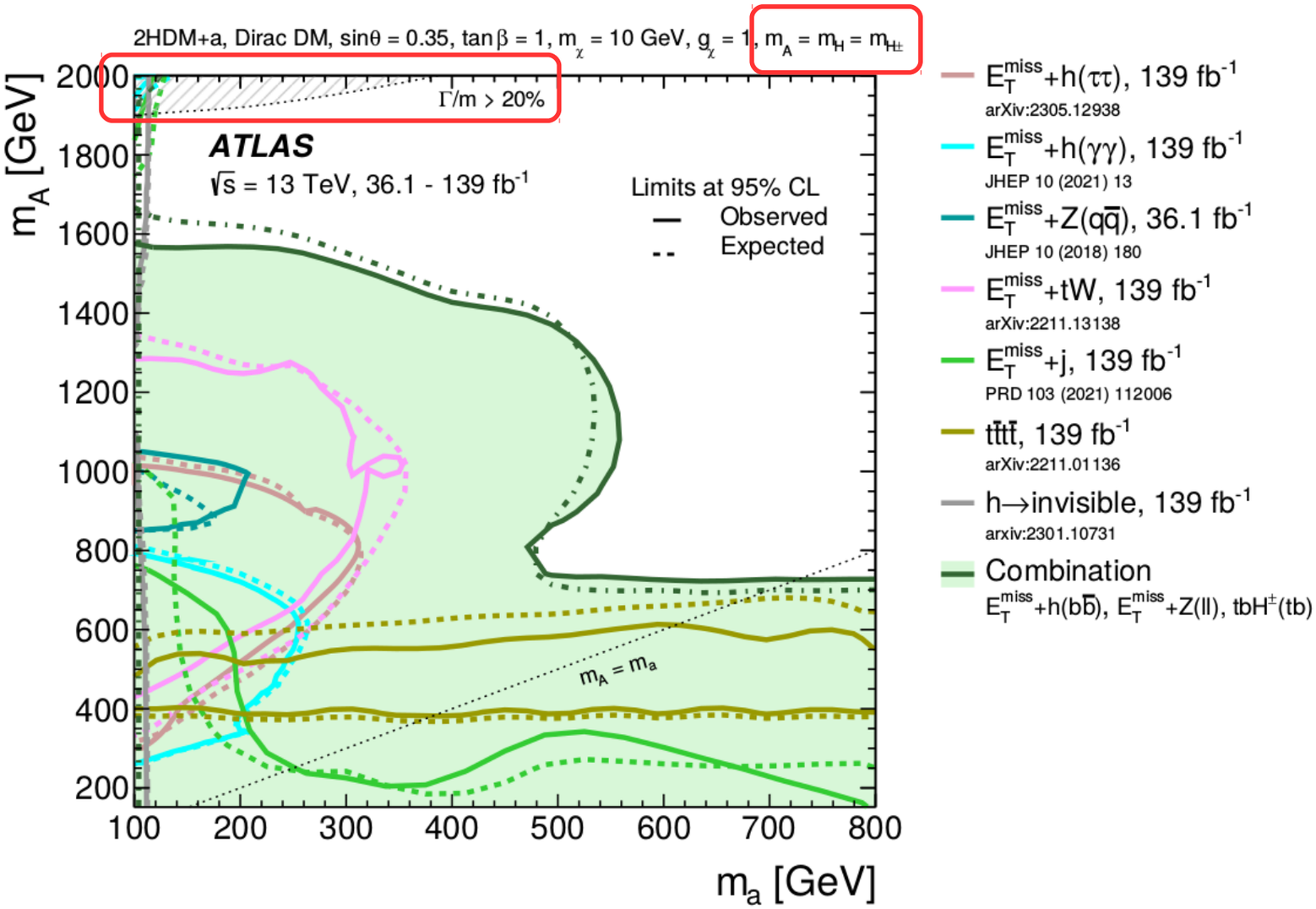


#LHC Status

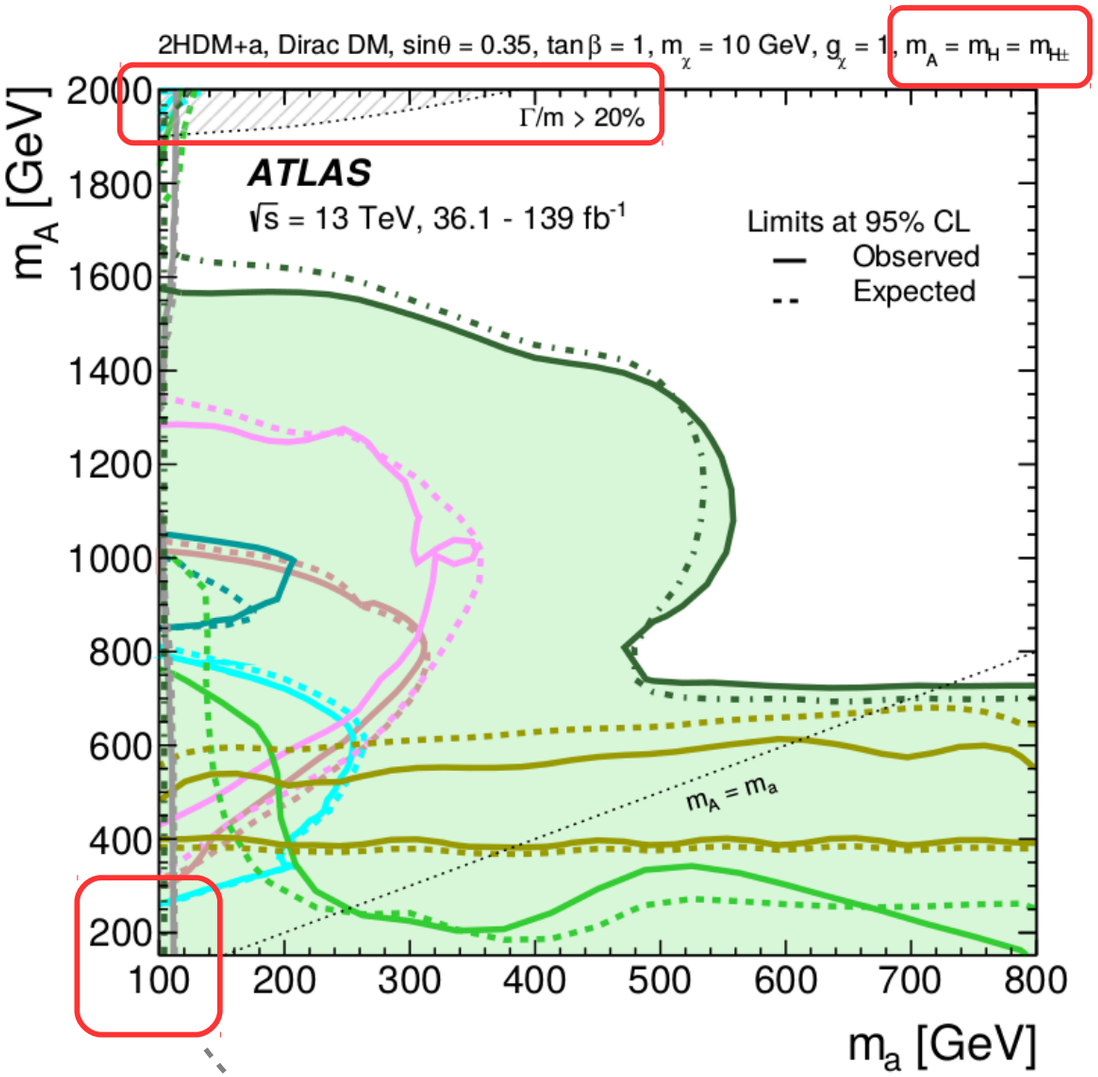
#LHC_Status

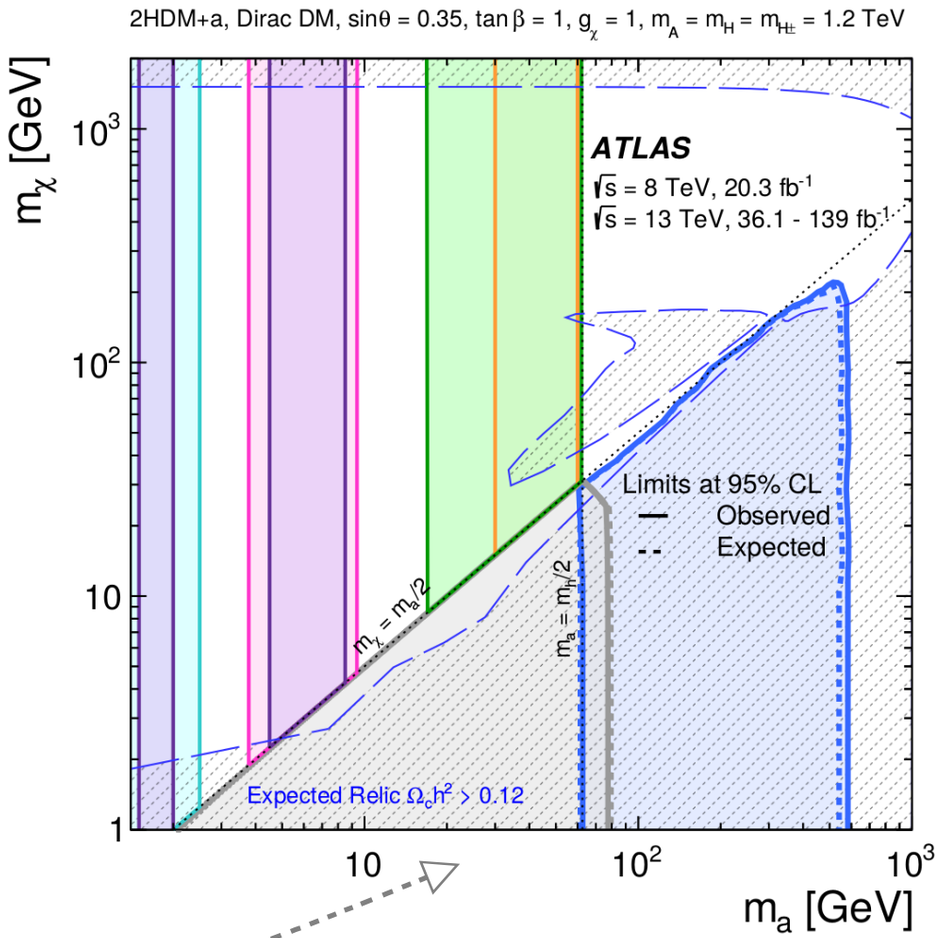
Courtesy: Imgflip

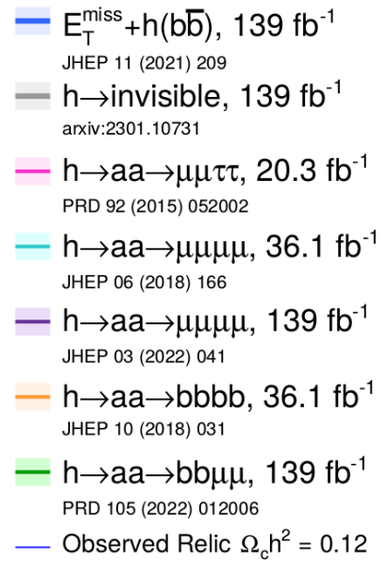
#LHC Status Roadmap for LHC Run3?



#LHC Status Roadmap for LHC Run3?



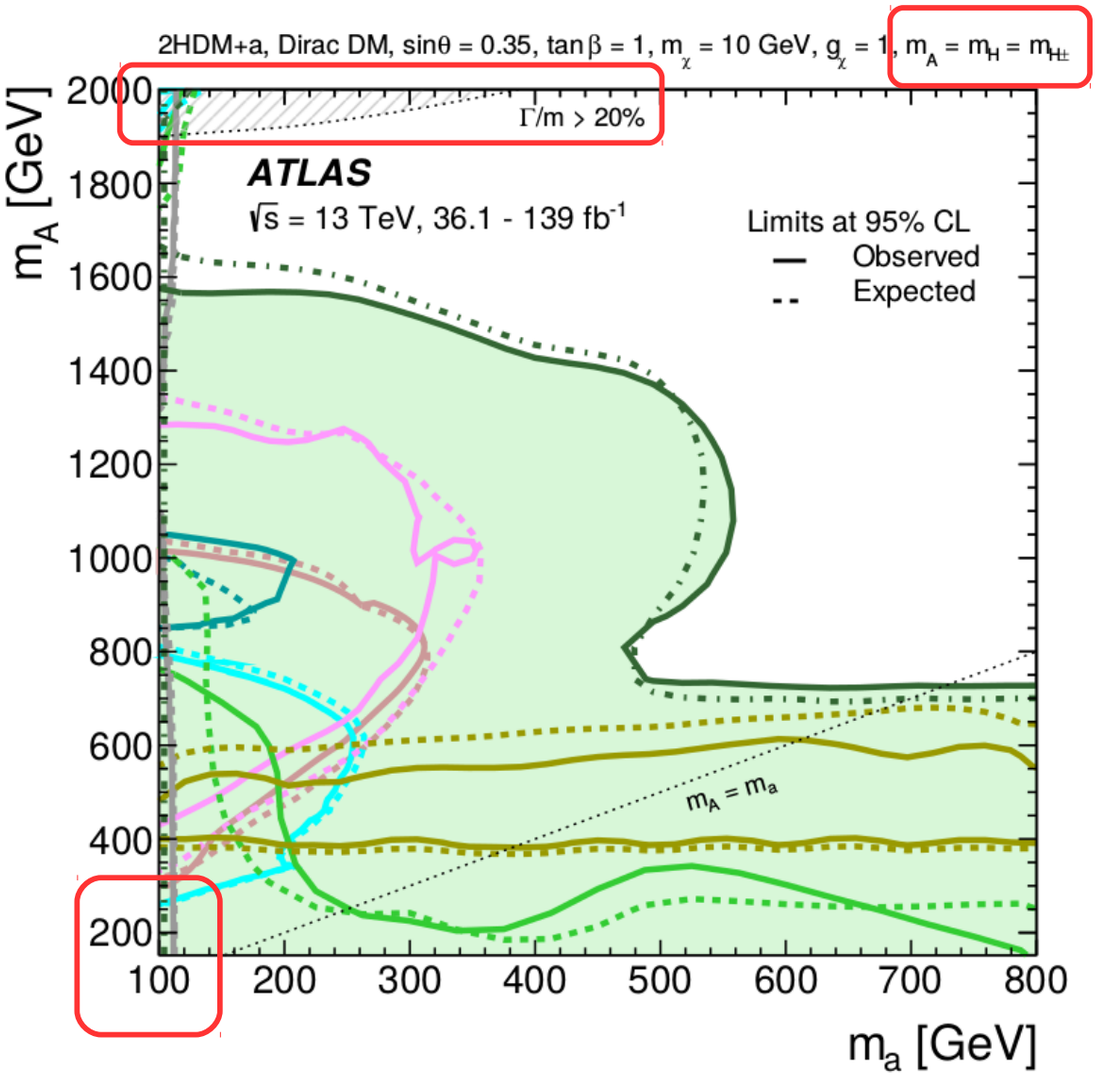


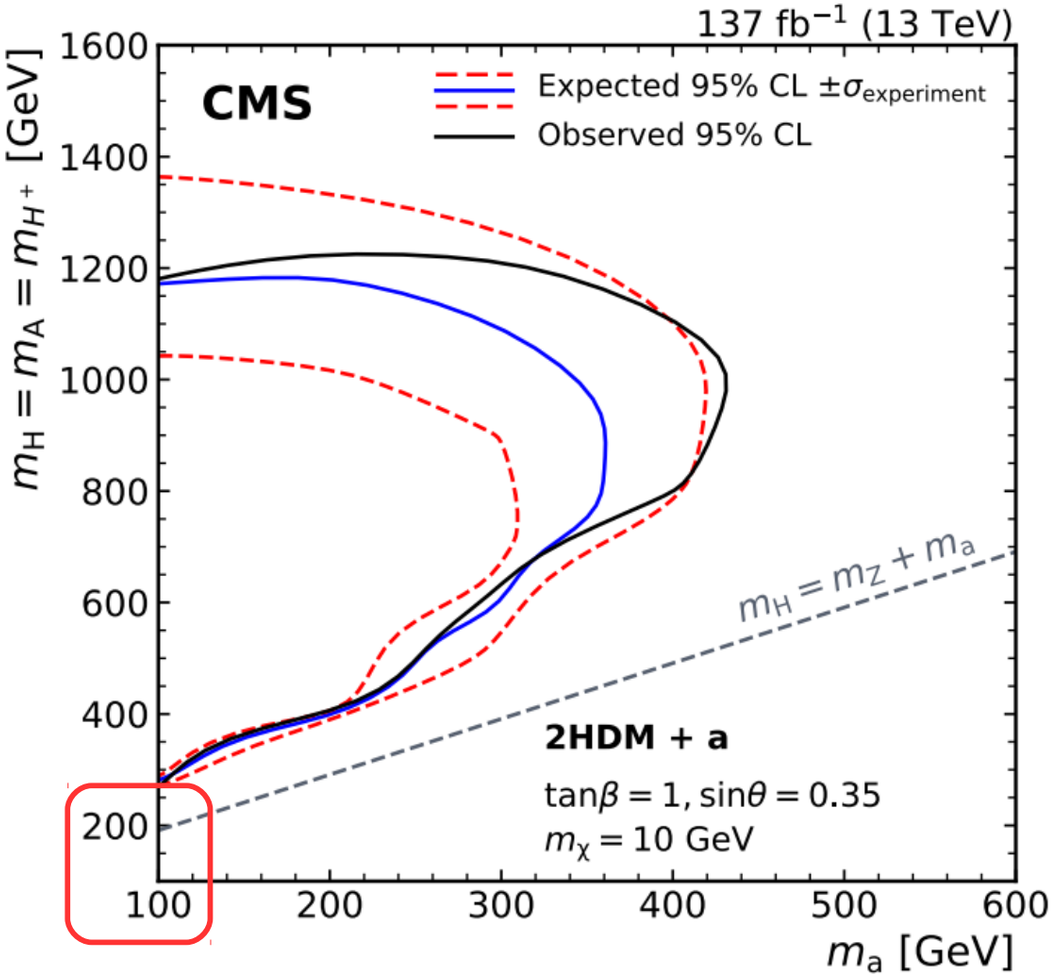


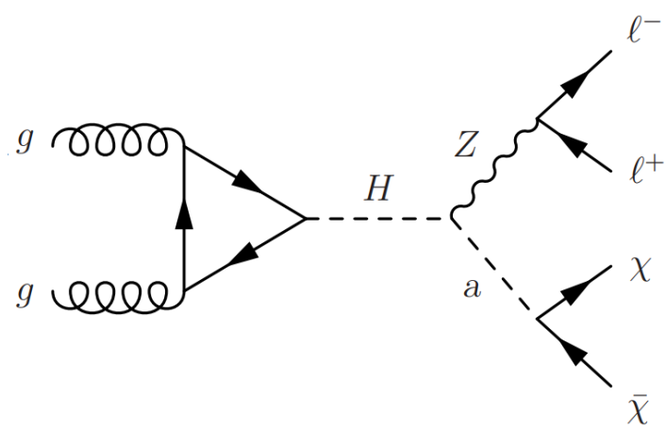
… only exploration of low m_a

#LHC Status Roadmap for LHC Run3?

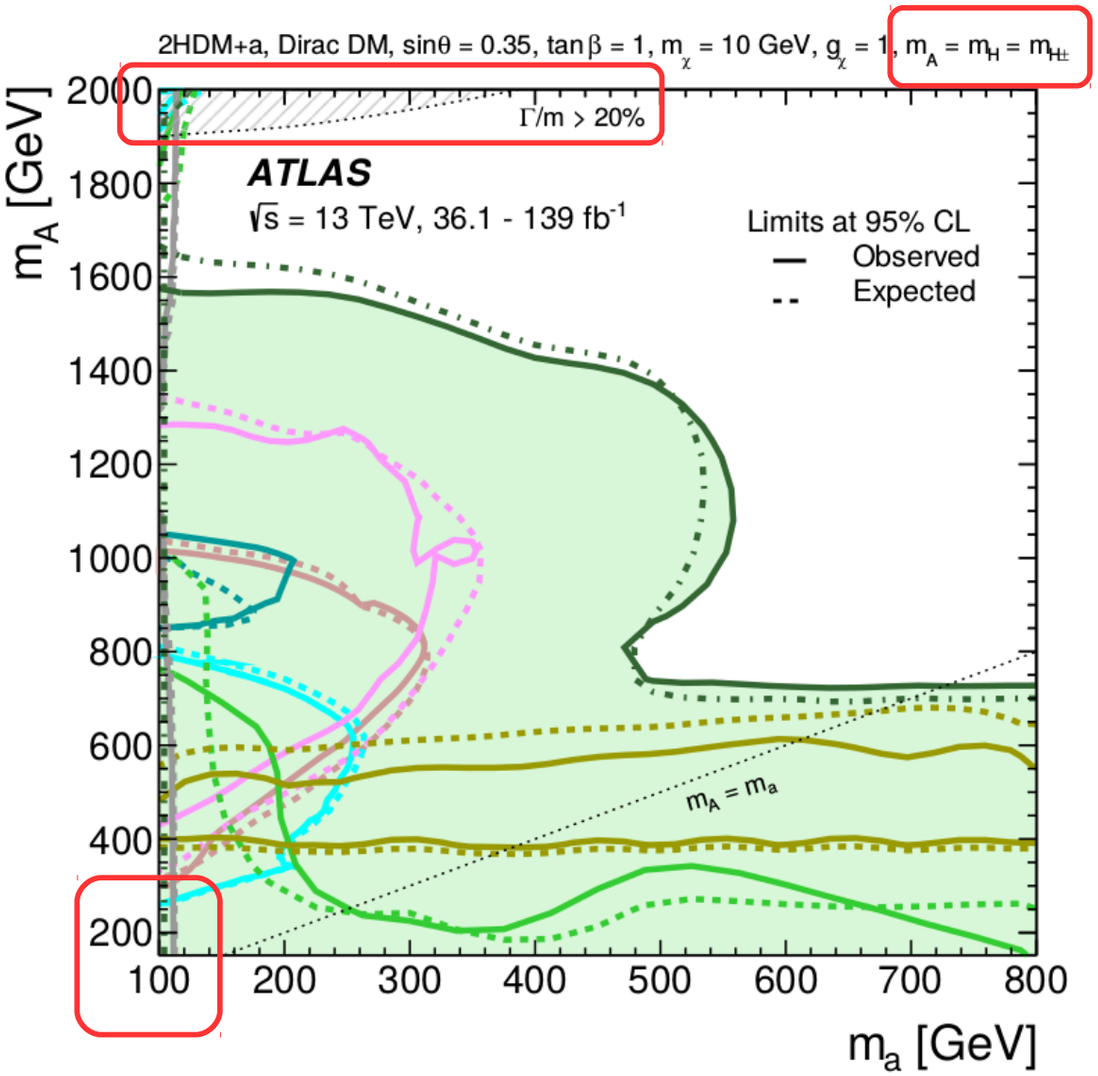
… same issue in CMS







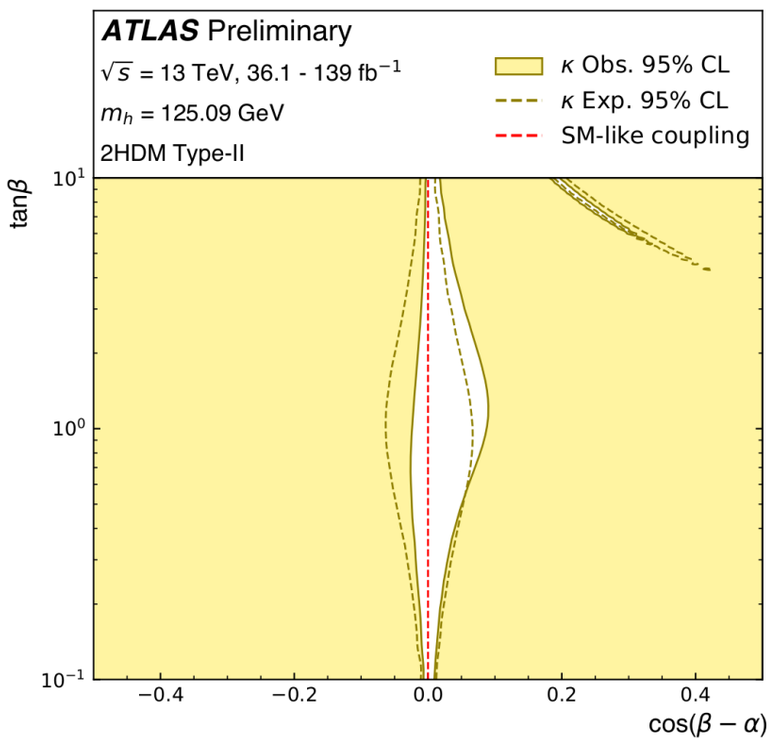
#LHC Status Roadmap for LHC Run3?



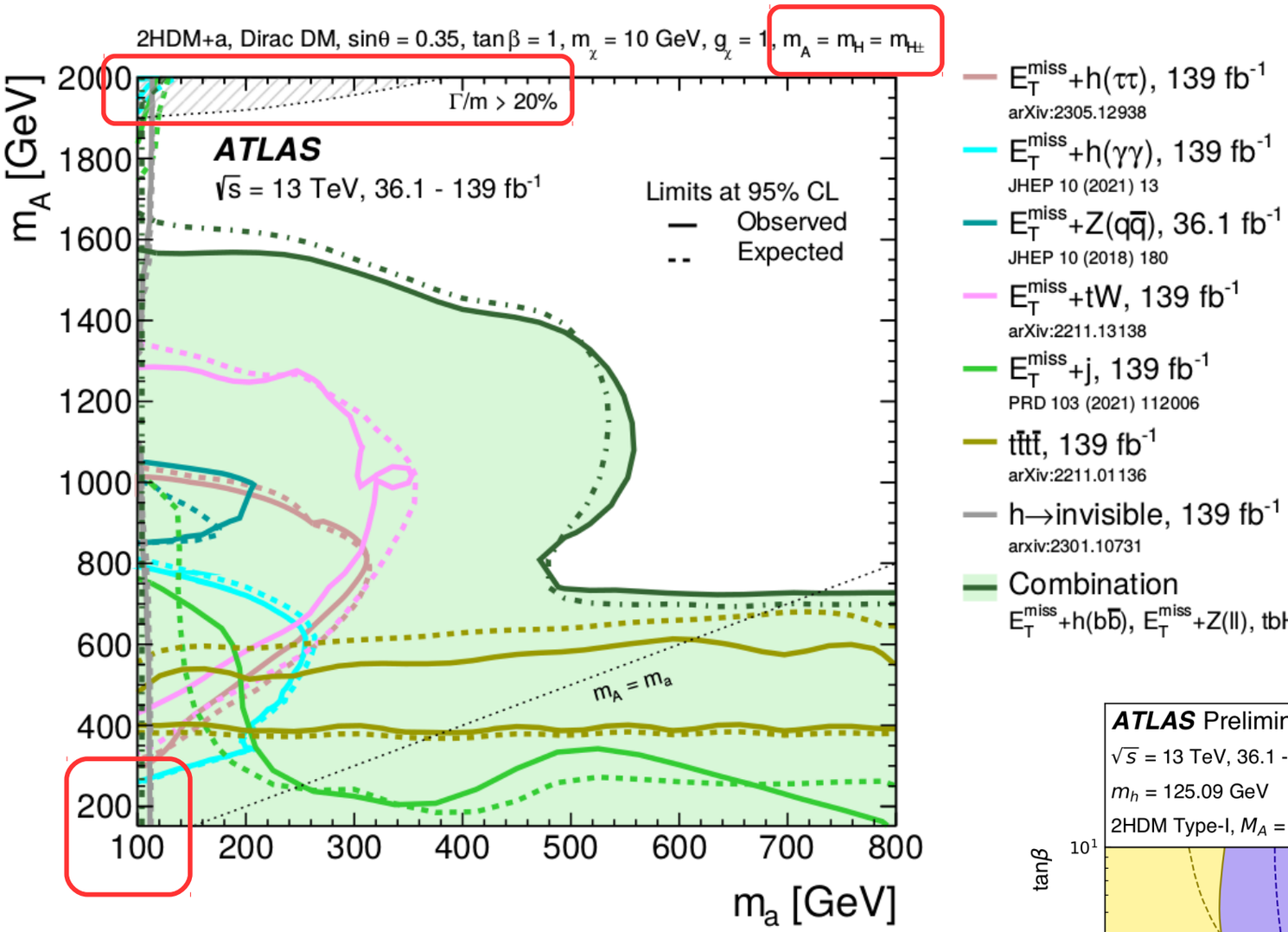
2HDM Type II

Alignment limit $c_{\beta-\alpha} = 0$

ATLAS-CONF-2023-052



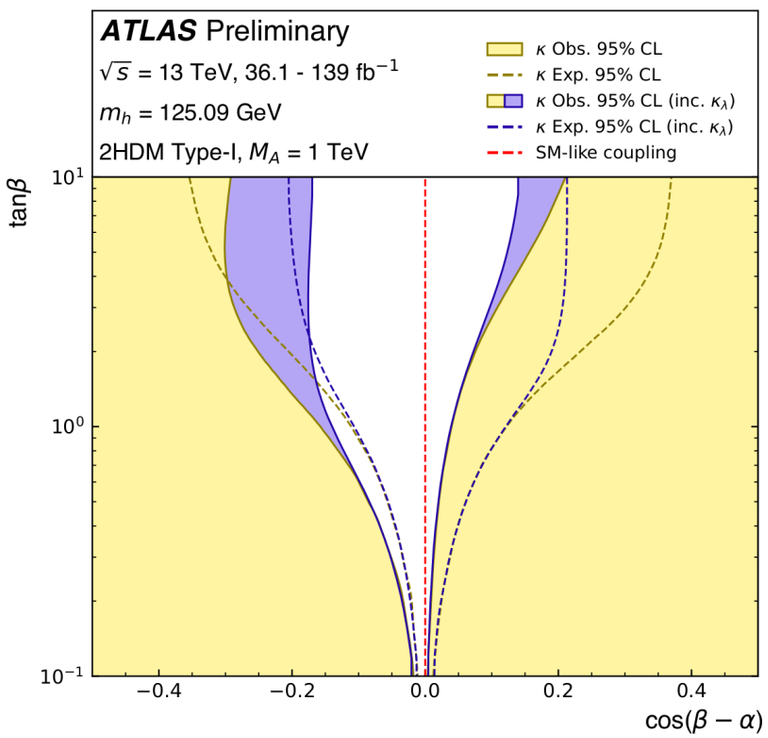
#LHC Status Roadmap for LHC Run3?



2HDM Type I?

Alignment limit?

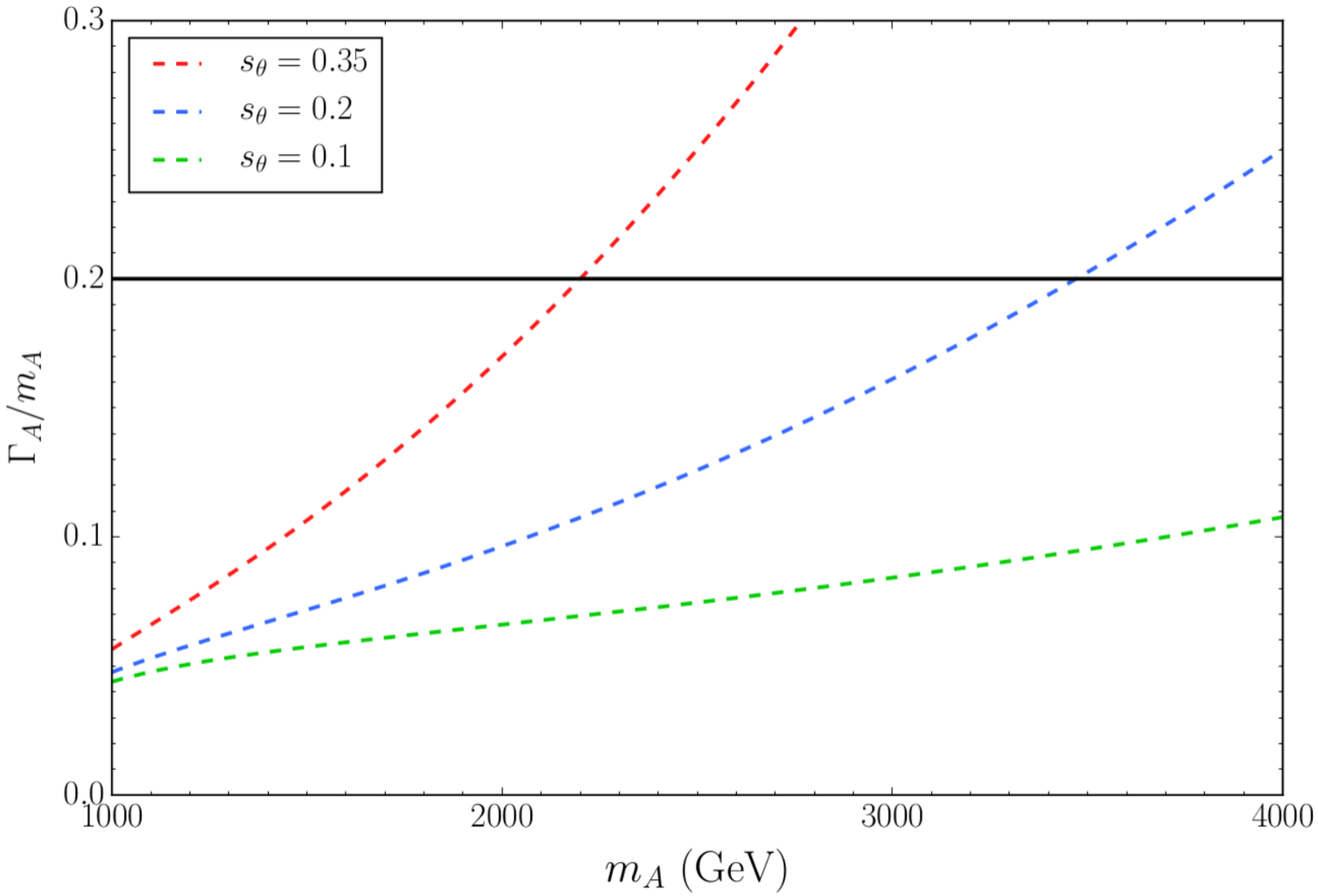
ATLAS-CONF-2023-052



#LHC Status Roadmap for LHC Run3?

- Width issues for $m_A > 2$ TeV

For $\begin{matrix} s_\theta \to 0 \\ m_A \gg v \end{matrix}$, $\Gamma_A/m_A \simeq 0.06 \times t_\beta^{-2}$



#LHC Status Roadmap for LHC Run3?

- $m_A = m_H = m_{H^\pm}$?

#LHC Status Roadmap for LHC Run3?

- $m_A = \boxed{m_H = m_{H^\pm}}$?

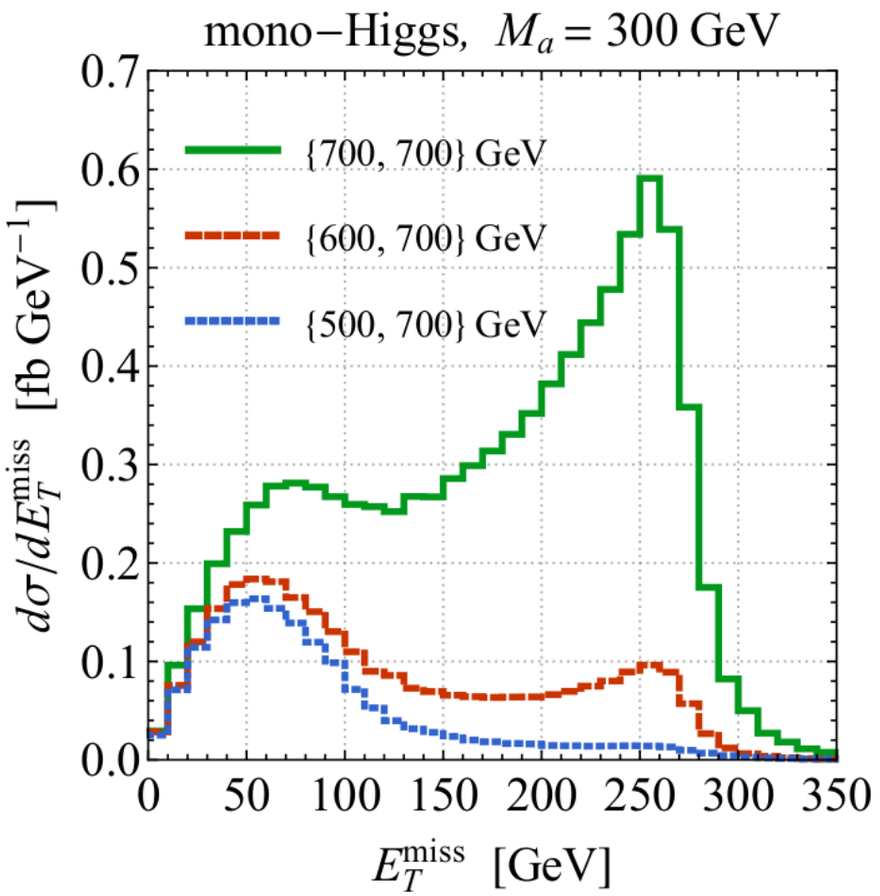
EWPO

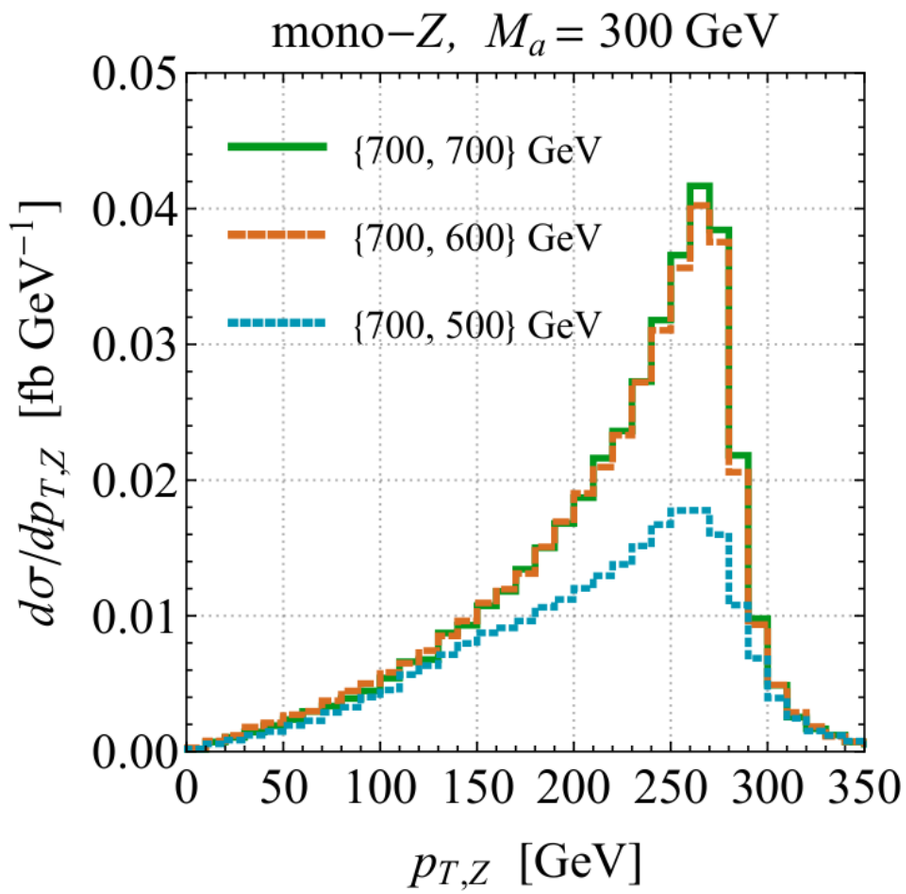
#LHC Status Roadmap for LHC Run3?

- $m_A = m_H = m_{H^\pm}$?

Abe et al, Phys. Dark. Univ. 27 (2020), 100351

Explored impact of varying $(m_H\ ,\ m_A)$





But no new decay channels!

#LHC Status Roadmap for LHC Run3?

- What if mass splittings allow for new decay channels?

Argyropoulos, Haisch, Kalaitzidou, 2404.05704

Novel collider signatures
in the type-I 2HDM+a model

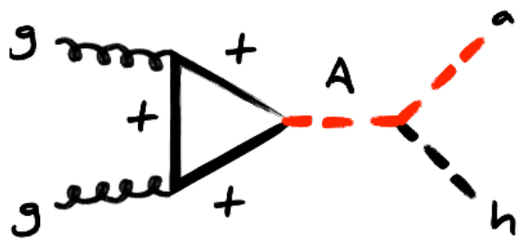
Spyros Argyropoulos,[a] Ulrich Haisch[b] and Ilia Kalaitzidou[a]

[a] *Physikalisches Institut, Universität Freiburg,*
Hermann-Herder Str. 3a, 79104 Freiburg, Germany Freiburg, Germany
[b] *Max Planck Institute for Physics,*
Föhringer Ring 6, 80805 München, Germany

#LHC Status Roadmap for LHC Run3?

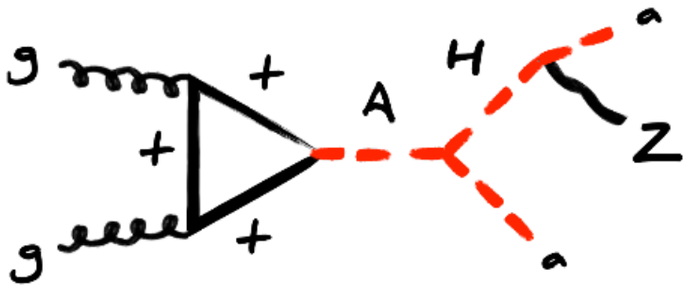
- What if mass splittings allow for new decay channels?

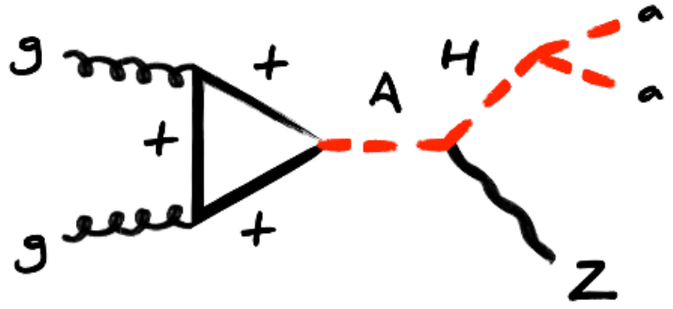
Argyropoulos, Haisch, Kalaitzidou, 2404.05704

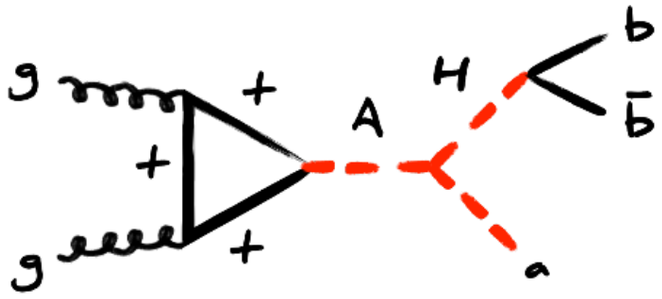


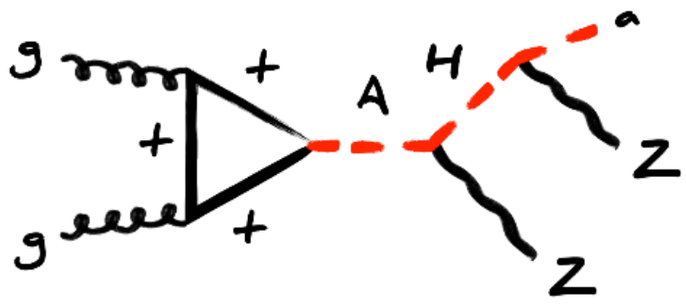
usual resonant mono-*h* signal

New possible decays of **A** (into DM):





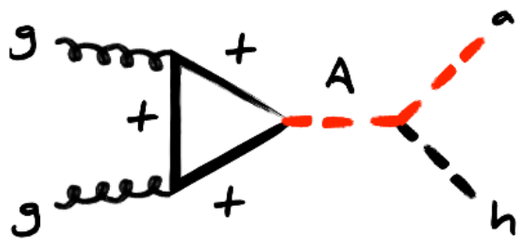




#LHC Status Roadmap for LHC Run3?

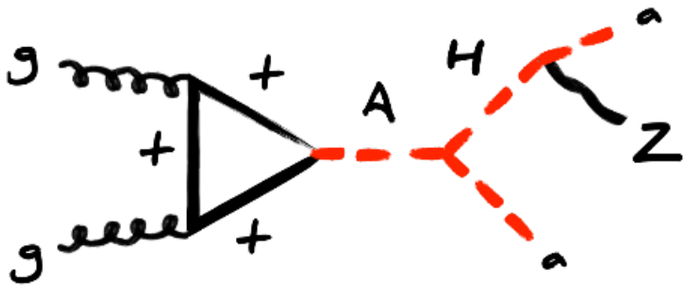
- What if mass splittings allow for new decay channels?

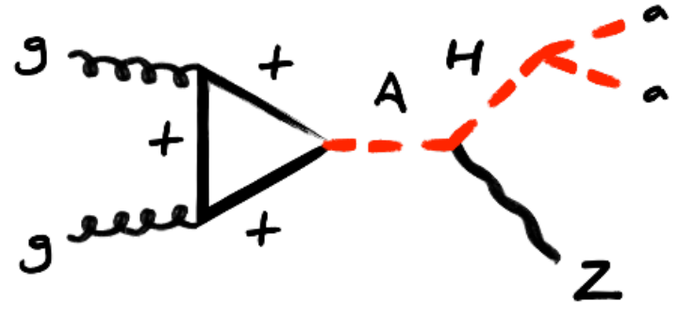
Argyropoulos, Haisch, Kalaitzidou, 2404.05704

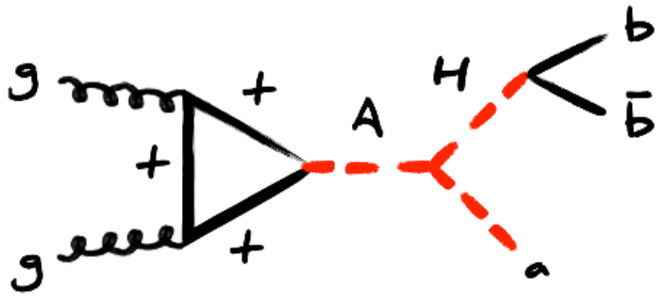


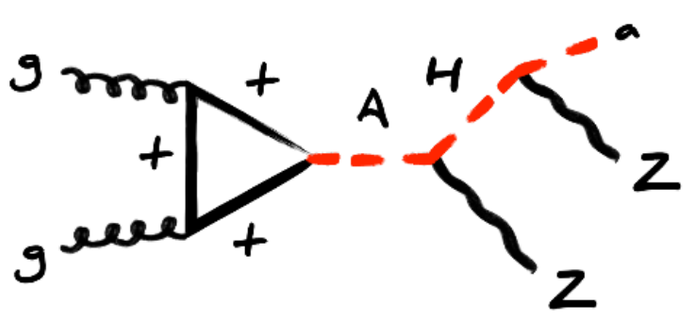
usual resonant mono-*h* signal

New possible decays of **A** (into DM):







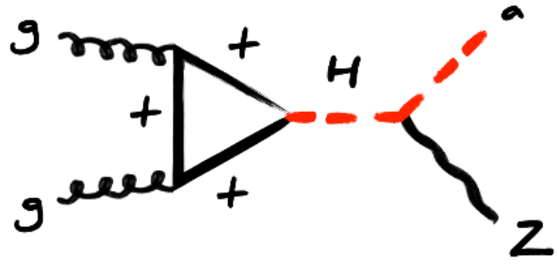


new searches!

#LHC Status Roadmap for LHC Run3?

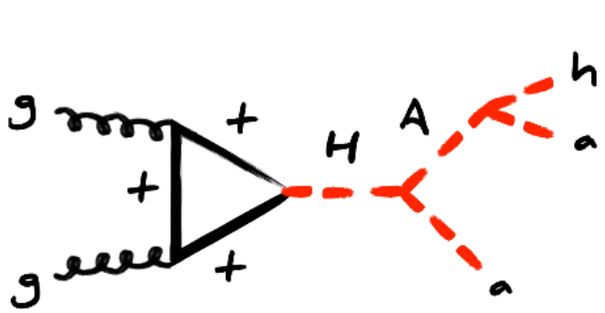
- What if mass splittings allow for new decay channels?

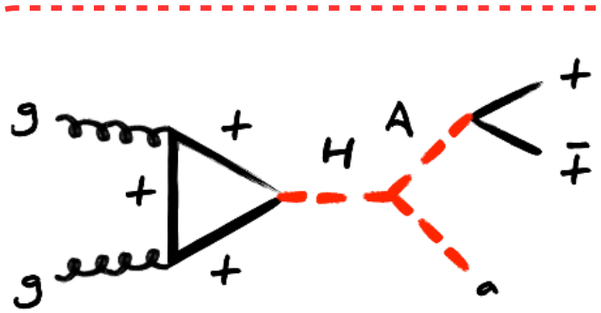
Argyropoulos, Haisch, Kalaitzidou, 2404.05704

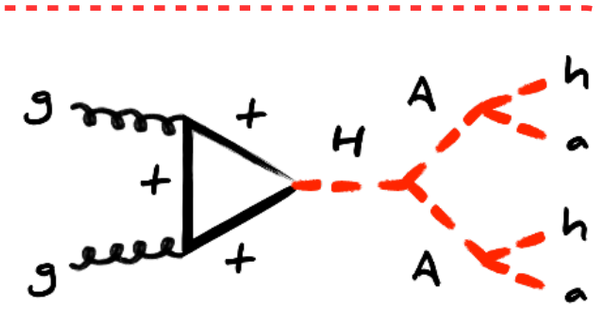


usual resonant mono-Z signal

New possible decays of **H** (into DM):

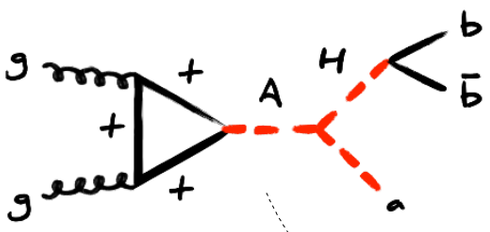


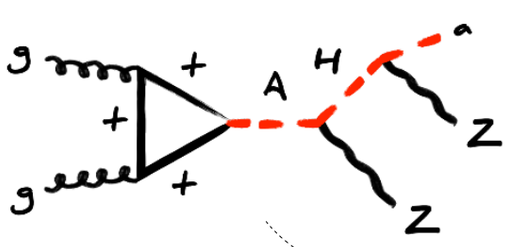




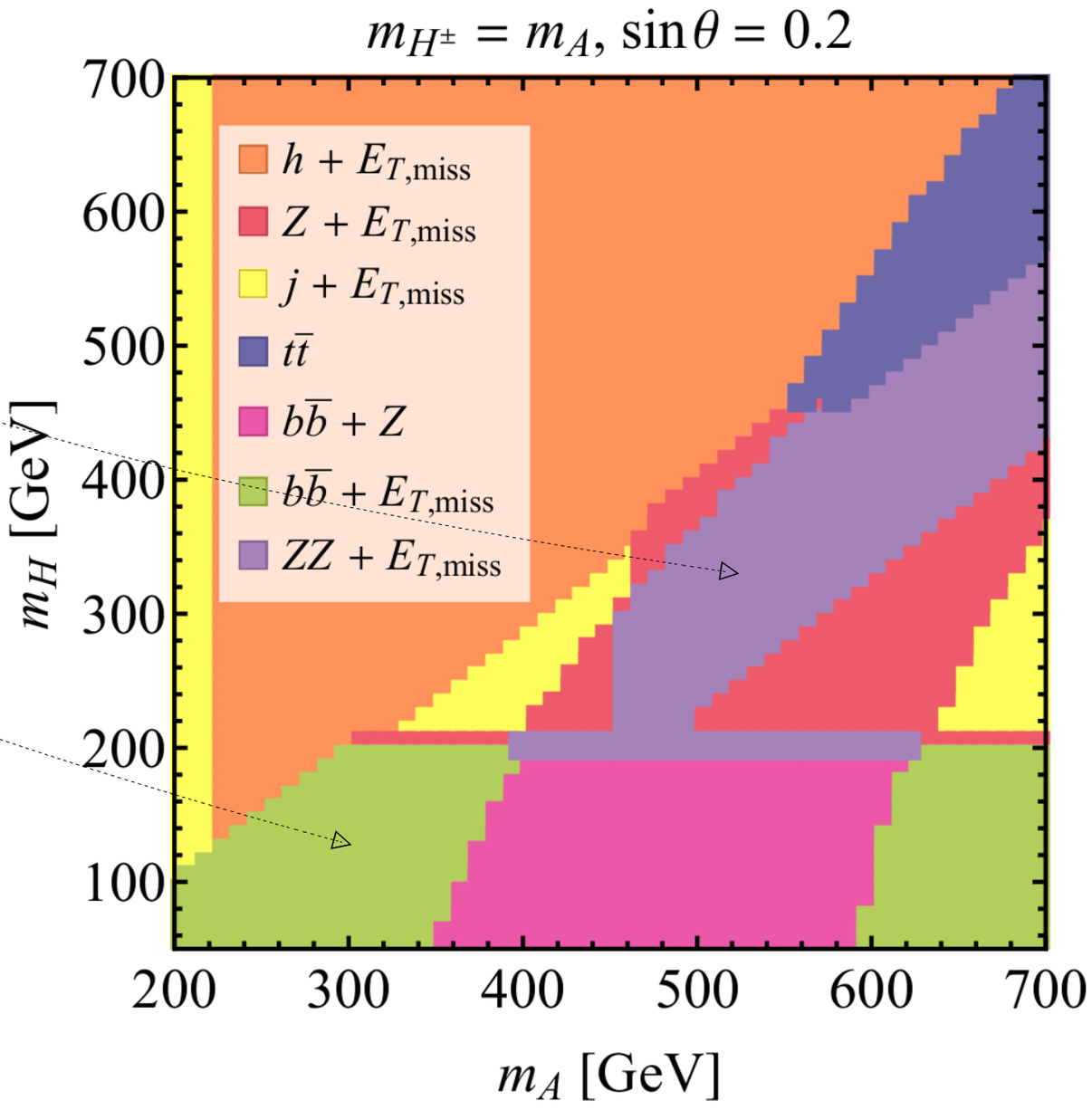
new searches!

#LHC Status Roadmap for LHC Run3?





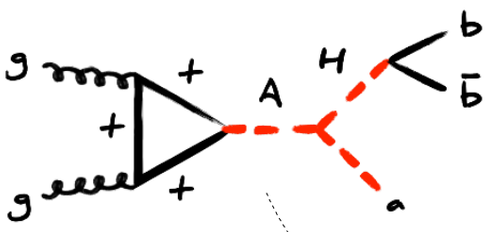
Decays of **A**

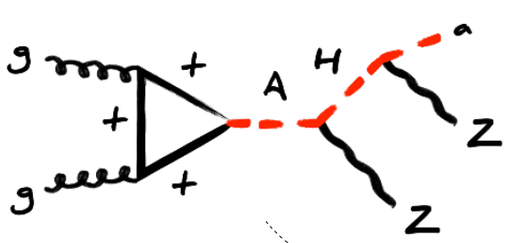


$m_a = 100\,\text{GeV},\ m_\chi = 10\,\text{GeV},\ \cos(\beta - \alpha) = 0,\ \tan\beta = 5$

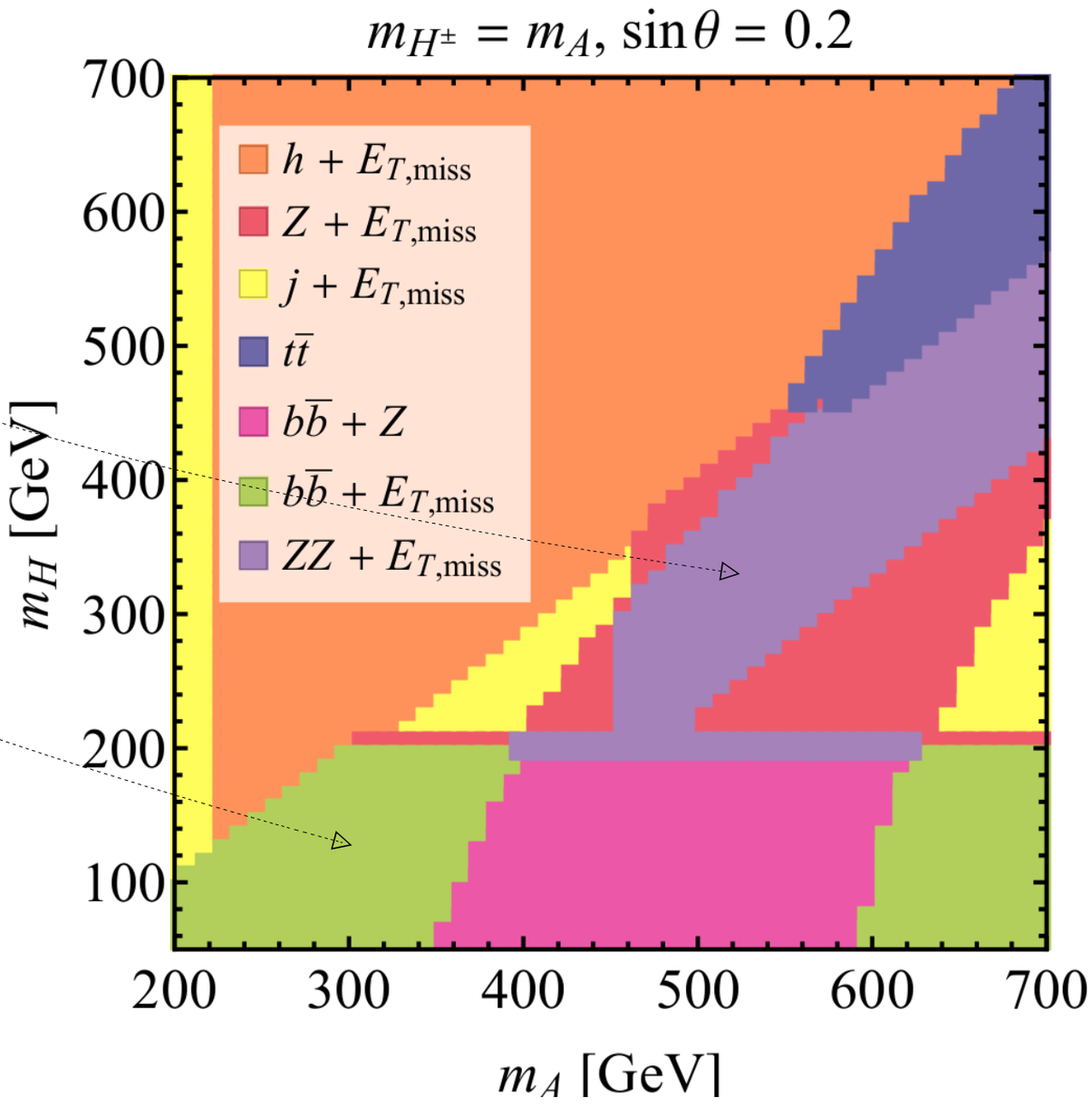
Argyropoulos, Haisch, Kalaitzidou, 2404.05704

#LHC Status Roadmap for LHC Run3?





Decays of **A**



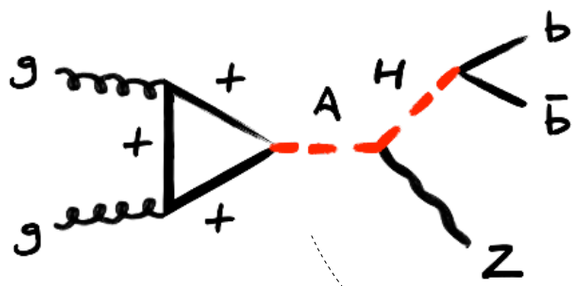
Cascade decays:
preference for small m_a

$m_a = 100\,\text{GeV}$, $m_\chi = 10\,\text{GeV}$, $\cos(\beta - \alpha) = 0$, $\tan\beta = 5$

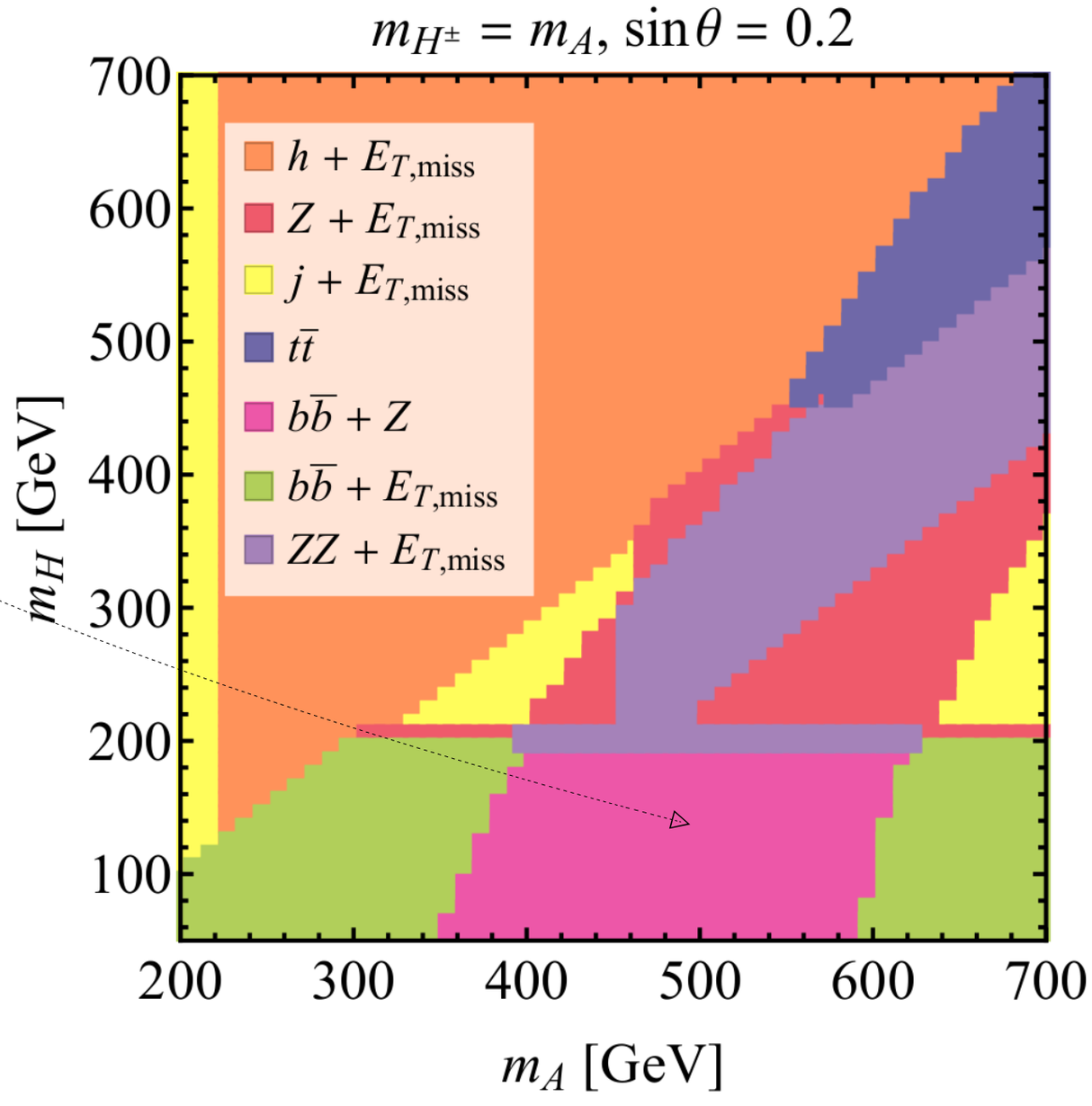
Argyropoulos, Haisch, Kalaitzidou, 2404.05704

#LHC Status Roadmap for LHC Run3?

Interplay with fully visible searches



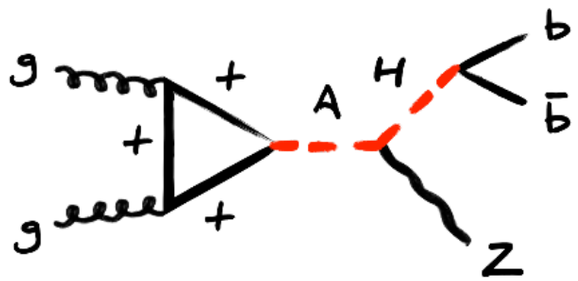
Decays of **A**



#LHC Status Roadmap for LHC Run3?

Well-established for 2HDM
w. sizable mass splittings!

Interplay with fully visible searches



Large splittings yield 1st order EWPT

Echoes of the Electroweak Phase Transition:
Discovering a second Higgs doublet through $A_0 \to H_0 Z$.

G. C. Dorsch, S. Huber, K. Mimasu and J. M. No
Department of Physics and Astronomy, University of Sussex, BN1 9QH Brighton, United Kingdom
(Dated: May 23, 2014)

The existence of a second Higgs doublet in Nature could lead to a cosmological first order electroweak phase transition and explain the origin of the matter-antimatter asymmetry in the Universe. We obtain the spectrum and properties of the new scalars H_0, A_0 and $H^\pm$ that signal such a phase

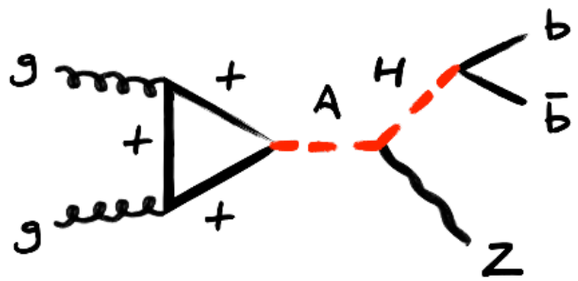
*Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. **113** (2014) 211802*

#LHC Status Roadmap for LHC Run3?

Well-established for 2HDM
w. sizable mass splittings!

Interplay with fully visible searches

Large splittings yield 1st order EWPT



ATLAS EXPERIMENT

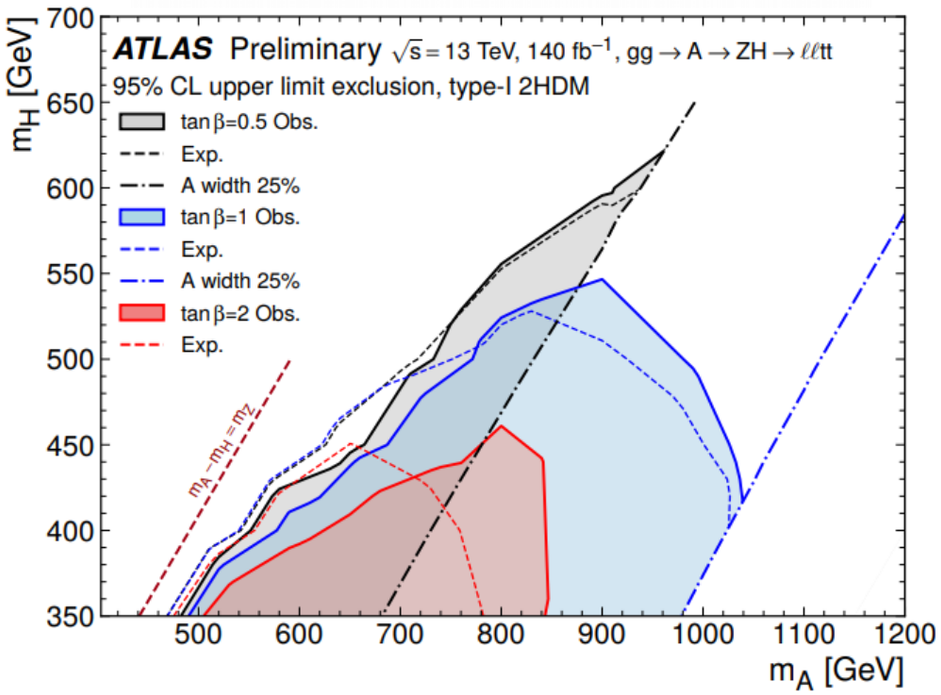
ATLAS CONF Note

ATLAS-CONF-2023-034

25th May 2023

CERN

Search for a *CP*-odd Higgs boson decaying to a heavy *CP*-even Higgs boson and a *Z* boson in the $\ell^+\ell^- t\bar{t}$ and $\nu\bar{\nu}b\bar{b}$ final states using 140 fb^{-1} of data collected with the ATLAS detector



ATLAS-CONF-2023-034

Echoes of the Electroweak Phase Transition: Discovering a second Higgs doublet through $A_0 \to H_0 Z$.

G. C. Dorsch, S. Huber, K. Mimasu and J. M. No
Department of Physics and Astronomy, University of Sussex, BN1 9QH Brighton, United Kingdom

(Dated: May 23, 2014)

The existence of a second Higgs doublet in Nature could lead to a cosmological first order electroweak phase transition and explain the origin of the matter-antimatter asymmetry in the Universe. We obtain the spectrum and properties of the new scalars H_0, A_0 and $H^\pm$ that signal such a phase

*Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. **113** (2014) 211802*

First shot of the smoking gun: probing the electroweak phase transition in the 2HDM with novel searches for $A \to ZH$ in $\ell^+\ell^- t\bar{t}$ and $\nu\nu b\bar{b}$ final states

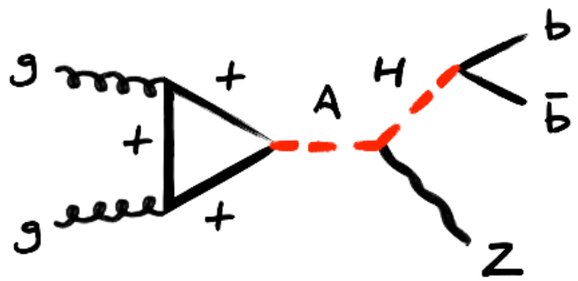
Thomas Biekötter,[a] Sven Heinemeyer,[b] Jose Miguel No,[b,c] Kateryna Radchenko,[d] María Olalla Olea Romacho[e] and Georg Weiglein[d,f]

*Biekotter, Heinemeyer, JMN, Radchenko,Olea, Weiglein, JHEP **01** (2024) 107*

#LHC Status Roadmap for LHC Run3?

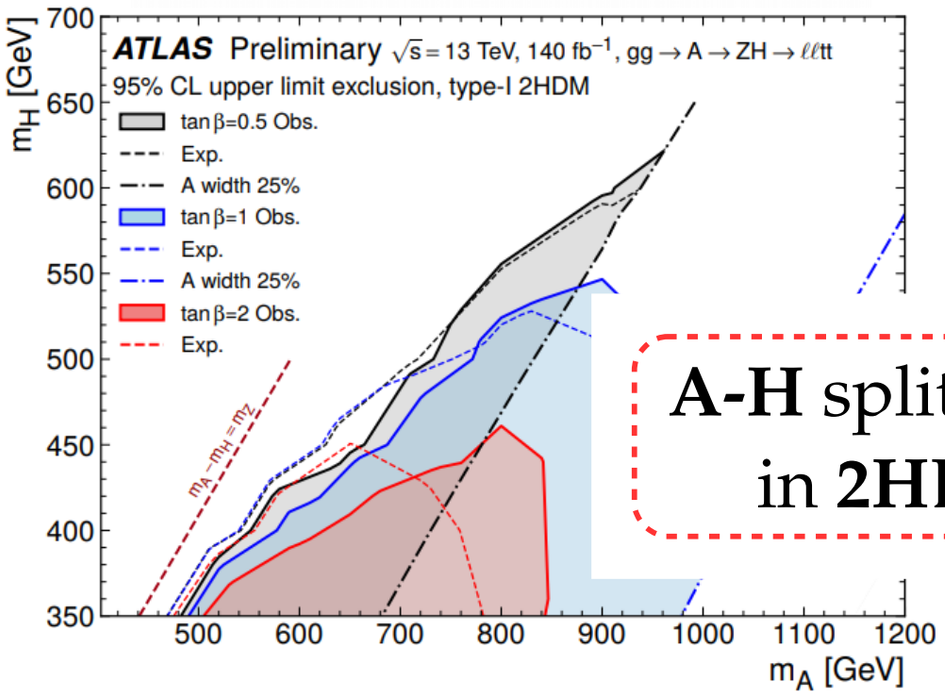
Well-established for 2HDM
w. sizable mass splittings!

Interplay with fully visible searches



ATLAS CONF Note
ATLAS-CONF-2023-034
25th May 2023

Search for a *CP*-odd Higgs boson decaying to a heavy *CP*-even Higgs boson and a *Z* boson in the $\ell^+\ell^- t\bar{t}$ and $\nu\bar{\nu}b\bar{b}$ final states using 140 fb^{-1} of data collected with the ATLAS detector



ATLAS-CONF-2023-034

Large splittings yield 1st order EWPT

Echoes of the Electroweak Phase Transition: Discovering a second Higgs doublet through $A_0 \to H_0 Z$.

G. C. Dorsch, S. Huber, K. Mimasu and J. M. No
Department of Physics and Astronomy, University of Sussex, BN1 9QH Brighton, United Kingdom

(Dated: May 23, 2014)

The existence of a second Higgs doublet in Nature could lead to a cosmological first order electroweak phase transition and explain the origin of the matter-antimatter asymmetry in the Universe. We obtain the spectrum and properties of the new scalars H_0, A_0 and $H^\pm$ that signal such a phase

Dorsch, Huber, Mimasu, JMN, Phys. Rev. Lett. **113** (2014) 211802

First shot of the smoking gun: probing the electroweak phase transition in the 2HDM with novel searches for $A \to ZH$ in $\ell^+\ell^- t\bar{t}$ and $\nu\nu b\bar{b}$ final states

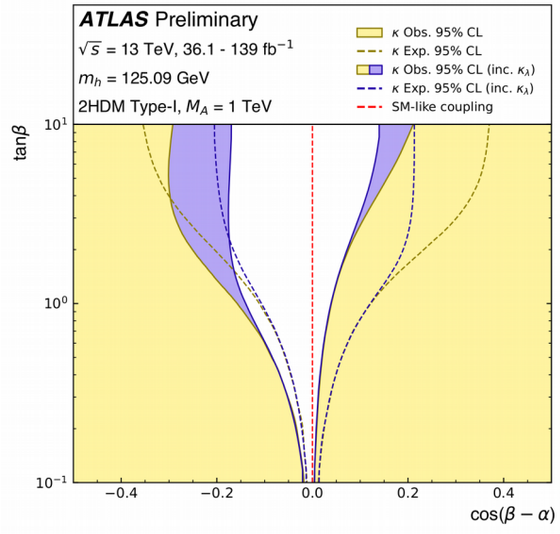
...Biekötter,[a] Sven Heinemeyer,[b] Jose Miguel No,[b,c] Kateryna Radchenko,[d] ...ncho[e] and Georg Weiglein[d,f]

A-H splitting very well motivated
in **2HDM:** ***EW Baryogenesis***

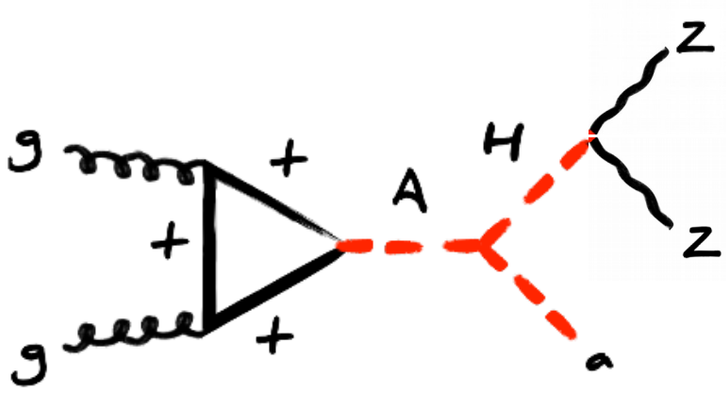
...nko,Olea, Weiglein, JHEP **01** (2024) 107

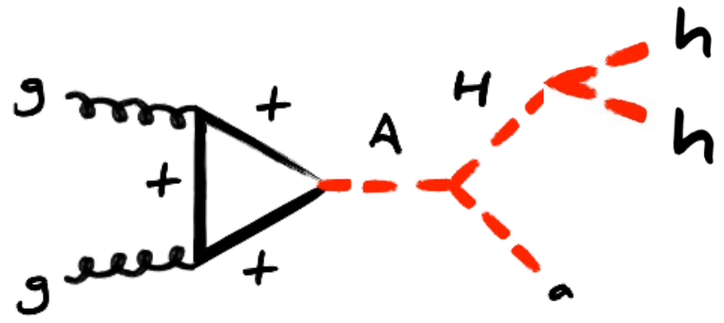
#LHC Status

Roadmap for LHC Run3?



There is **even more** to it: 2HDM **Type I** → **Alignment**??



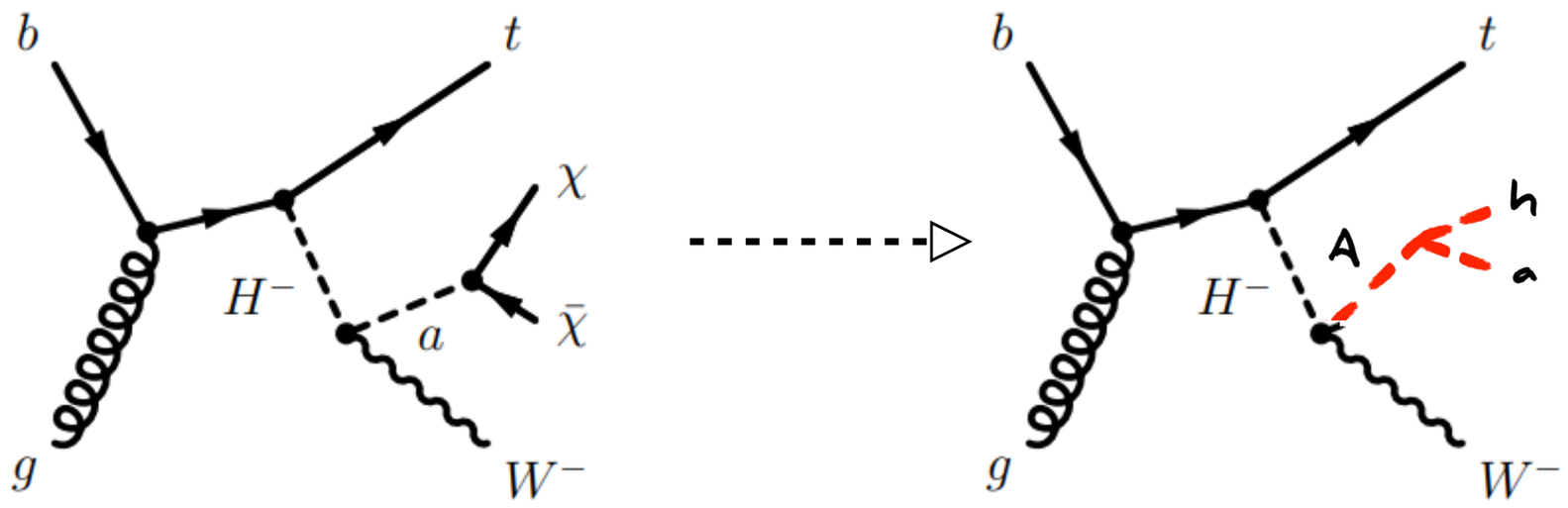


Relevant in specific regions of $c_{\beta-\alpha}$, t_β ?

#LHC Status Roadmap for LHC Run3?

There is **even more** to it: 2HDM **Type I** → **Alignment**??

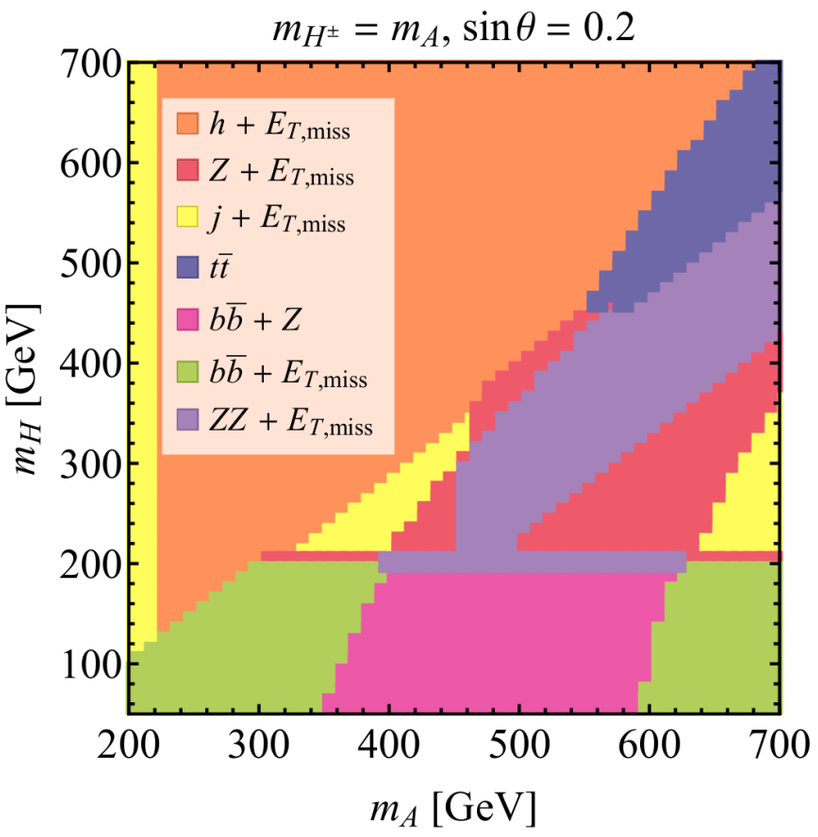
Cascade decays involving $H^{\pm}$??



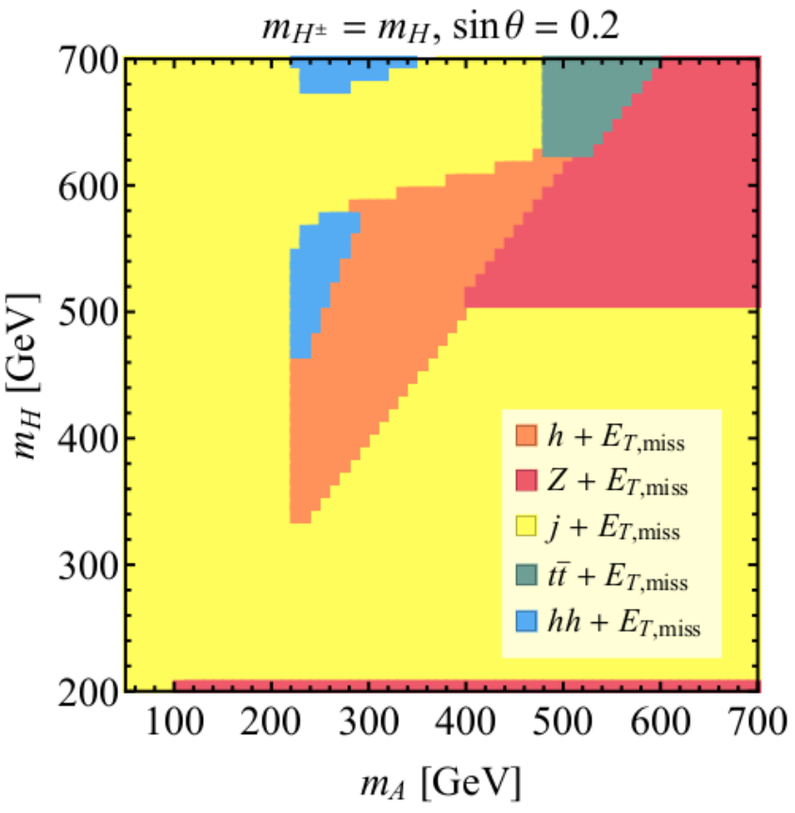
#LHC Status Roadmap for LHC Run3?

New (split) benchmarks? / New searches?

A



H



$H^\pm$

??

Argyropoulos, Haisch, Kalaitzidou, 2404.05704

#BONUS: CP Violation & Baryogenesis

$$V_{\rm 2HDM} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \left[\mu_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$$V_a = \frac{\mu_a^2}{2} a_0^2 + \frac{\lambda_a}{4} a_0^4 + \left(i\,\kappa\, a_0 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_{aH_1}\, a_0^2\, |H_1|^2 + \lambda_{aH_2}\, a_0^2\, |H_2|^2$$

- Complex Parameters! **CPV phases**: $\lambda_5^* (\mu_{12}^2)^2$ $\kappa^* \mu_{12}^2$

2HDM **2HDM*a***

#BONUS: CP Violation & Baryogenesis

$$V_{\rm 2HDM} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \left[\mu_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$$V_a = \frac{\mu_a^2}{2} a_0^2 + \frac{\lambda_a}{4} a_0^4 + \left(i\,\kappa\, a_0 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_{aH_1}\, a_0^2\, |H_1|^2 + \lambda_{aH_2}\, a_0^2\, |H_2|^2$$

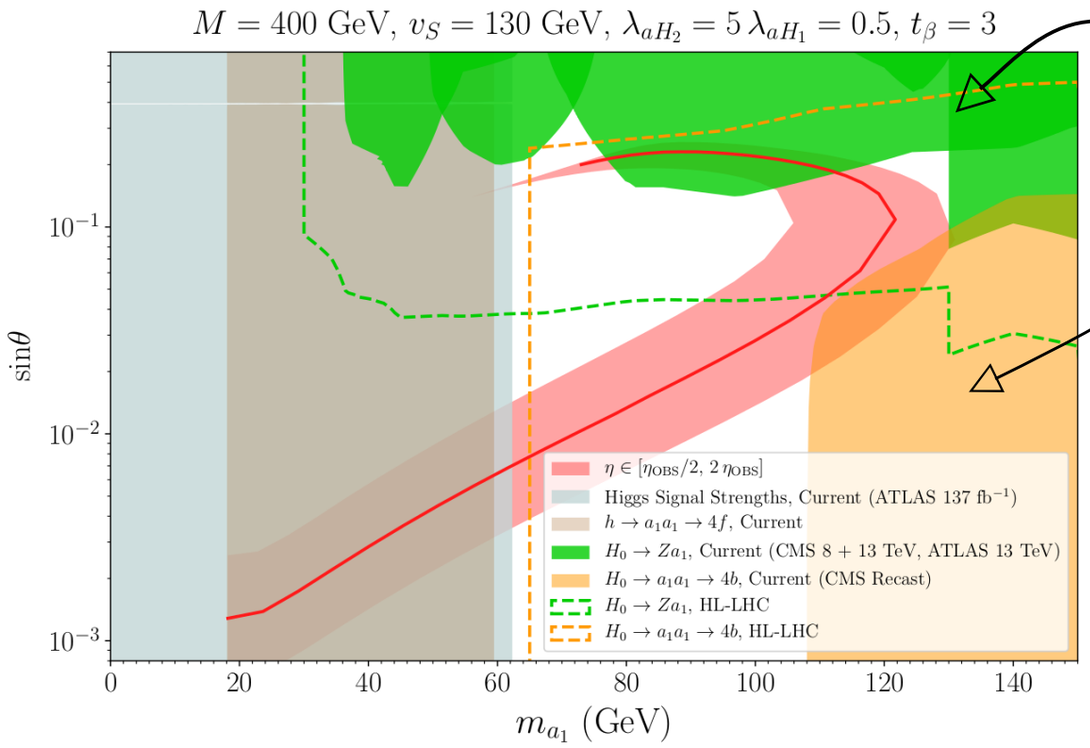
- Complex Parameters! **CPV phases**: $\lambda_5^* (\mu_{12}^2)^2$ (**2HDM**) $\kappa^* \mu_{12}^2$ (**2HDM*a***)

- 2HDM*a* can accommodate EW Baryogenesis

Huber, Mimasu, JMN, PRD 107 (2023) 07542

$\eta \in [\eta_{\rm OBS}/2,\, 2\,\eta_{\rm OBS}]$

TAKE with BIG GRAIN of SALT!



Limits from visible searches! (NO DM)

$H_0 \to Z a_1 \to \ell\ell\bar{b}\bar{b}$

$H_0 \to a_1 a_1 \to b\bar{b}b\bar{b}$

#BONUS: CP Violation & Baryogenesis

$$V_{\rm 2HDM} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \left[\mu_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$$V_a = \frac{\mu_a^2}{2} a_0^2 + \frac{\lambda_a}{4} a_0^4 + \left(i\,\kappa\, a_0 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_{aH_1}\, a_0^2\, |H_1|^2 + \lambda_{aH_2}\, a_0^2\, |H_2|^2$$

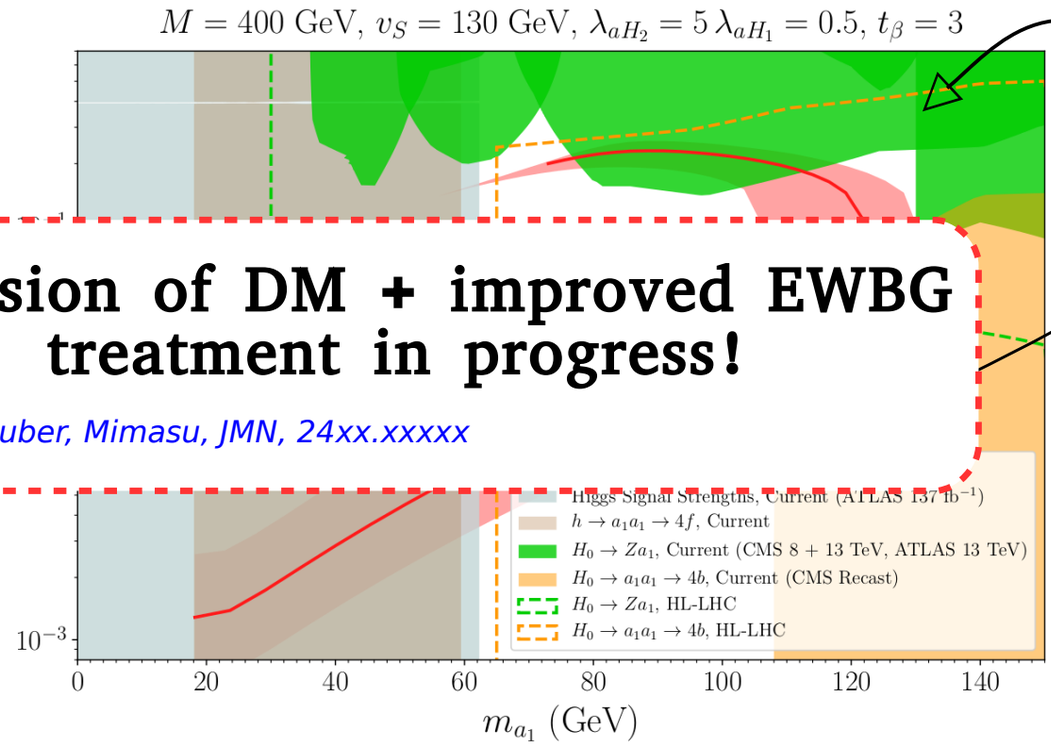
- Complex Parameters! **CPV phases**: $\lambda_5^* (\mu_{12}^2)^2$ (**2HDM**) $\kappa^* \mu_{12}^2$ (**2HDM*a***)

- 2HDM*a* can accommodate EW Baryogenesis

Huber, Mimasu, JMN, PRD 107 (2023) 07542

$\eta \in [\eta_{\rm OBS}/2,\, 2\,\eta_{\rm OBS}]$

TAKE with BIG GRAIN of SALT!



Inclusion of DM + improved EWBG treatment in progress!

Gent, Huber, Mimasu, JMN, 24xx.xxxxx

Limits from visible searches! (NO DM)

$H_0 \to Z a_1 \to \ell\ell\bar{b}\bar{b}$

$H_0 \to a_1 a_1 \to b\bar{b}b\bar{b}$

Thank you!