

Towards a 2HDMa white paper for Run 3

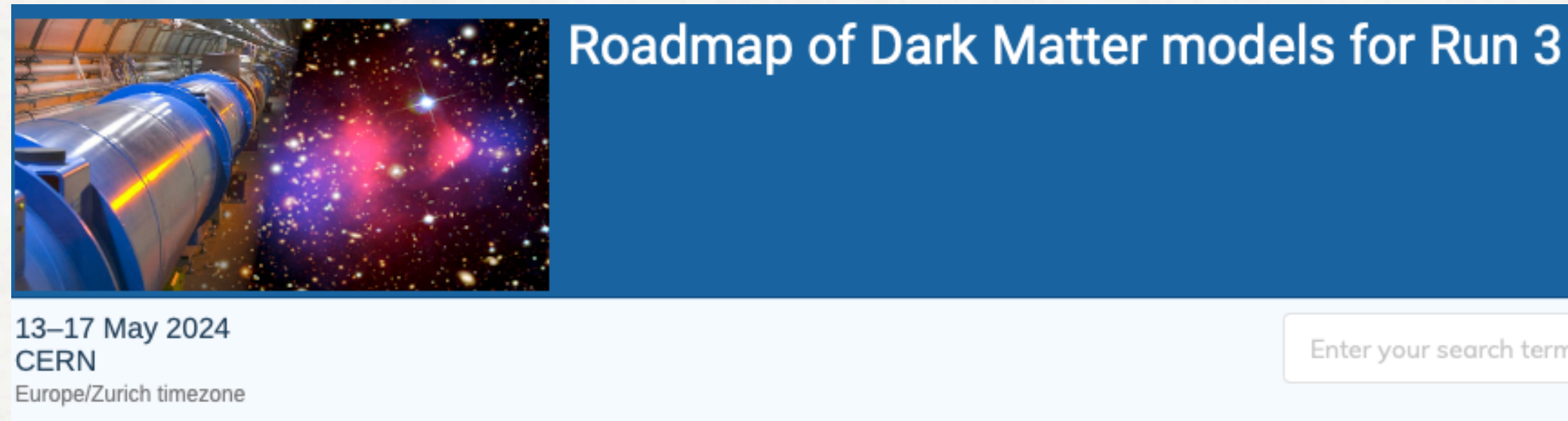


ARISTOTLE
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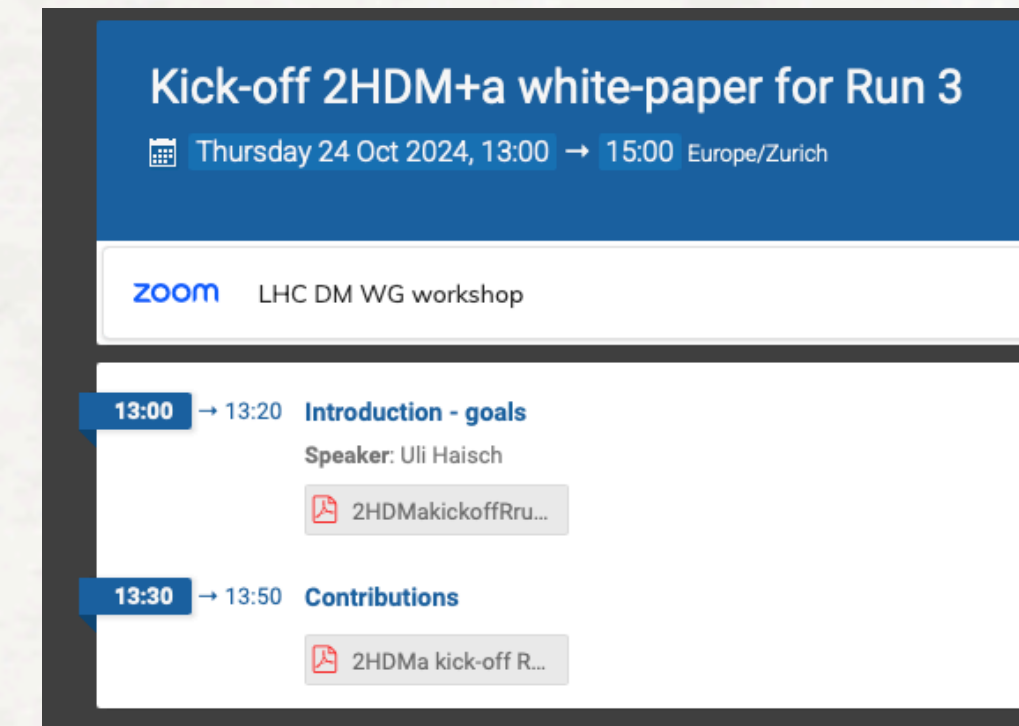
Spyros Argyropoulos
with input from U. Haisch and J. Frost

Why this talk?

1. LHCDMWG workshop



2. Kick-off 1 year ago



- Not much has happened since then
 - notable exception of Emma/Shin-Shan's contribution on $hh + E_T^{\text{miss}}$ (half a year ago)
- Why?
 - Lack of **FTE?** **physics motivation?** **structure?**
- **Discuss**
 - ➔ physics motivation
 - ➔ person-power
 - ➔ what we need to enable progress

Why this talk?

1. What has been done (theory & experiment)
2. Role of a new white paper / what has not been done
 - potential points of focus (signatures)
3. Expressions of interest (from 1st kick-off)

What has been done? #1

Current benchmarks

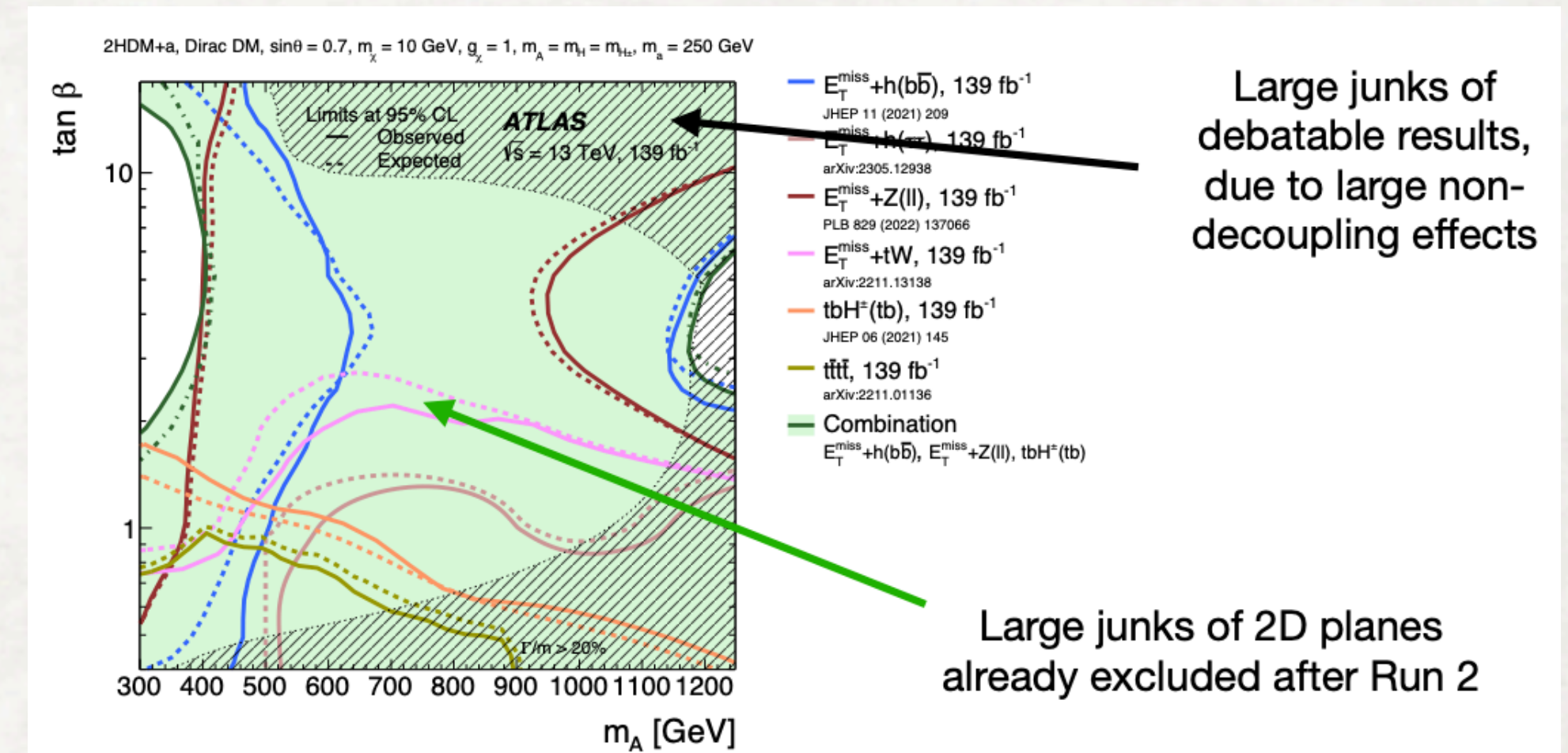
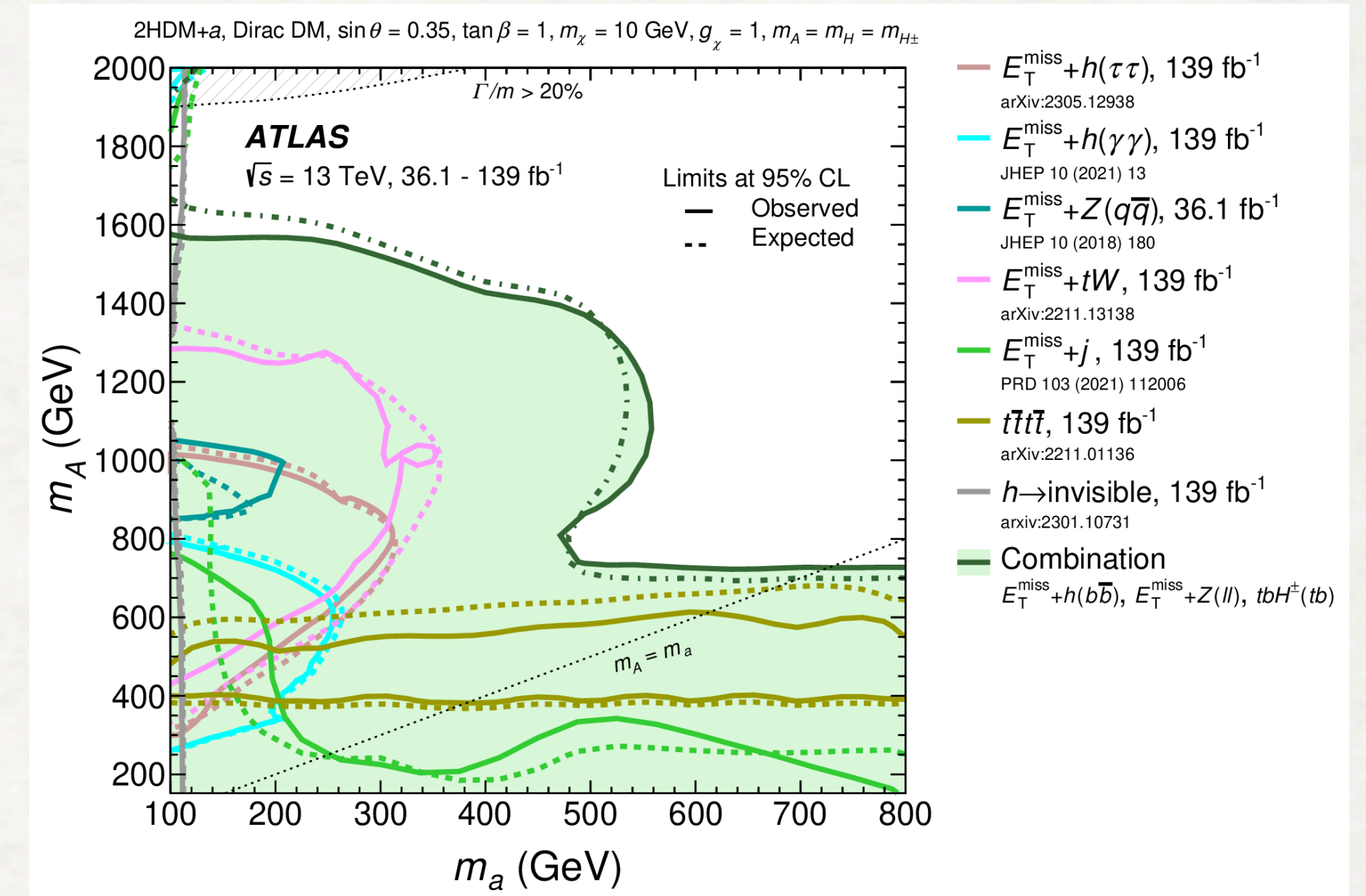
Type-II

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

alignment limit

- have run out of steam
- focus on low $\sin\theta \Rightarrow$ need update of benchmarks
- Is this enough motivation for a WP?
 - by itself probably not
 - however, if a WP is published it should also contain an update of these benchmarks

$$\sin\theta = 0.35$$



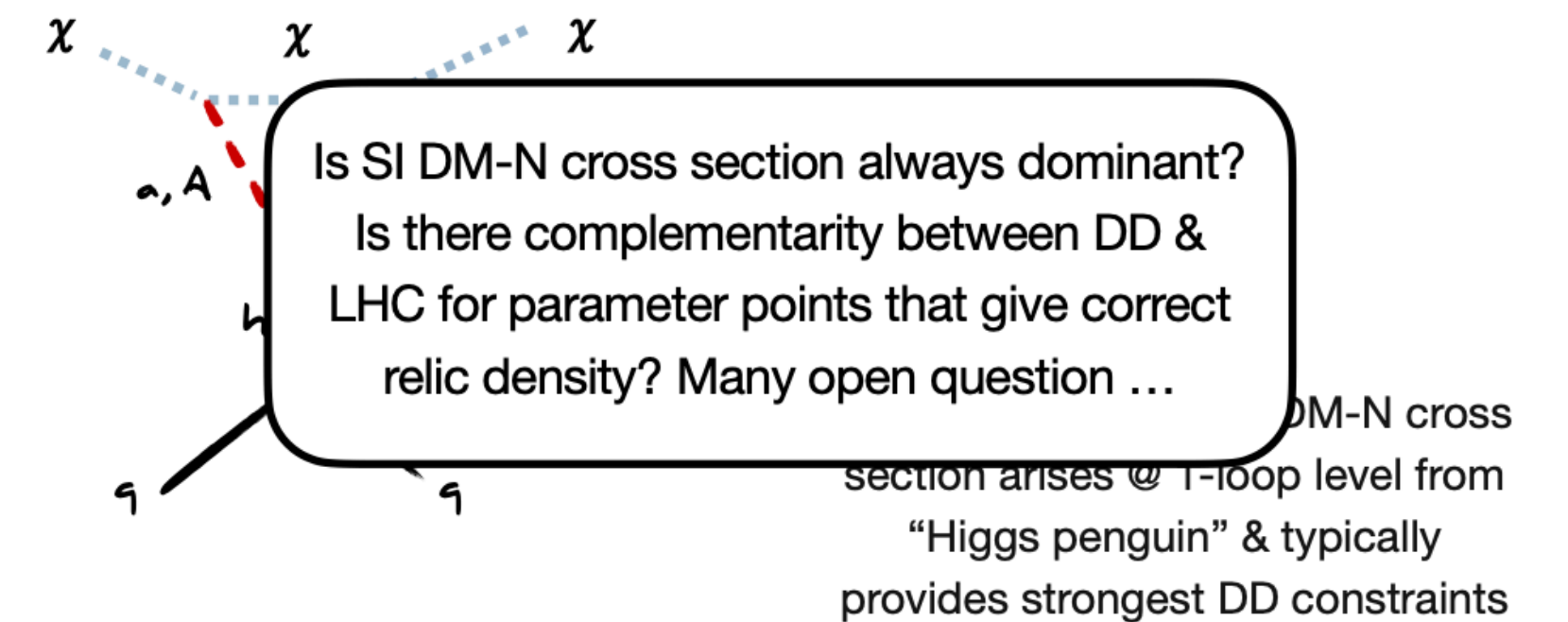
What has been done? #2

- supplementary benchmarks for $h \rightarrow 4f$ [2202.12631]
- investigations of RD
- LLP [2302.02735]
- Complementarity with DD
- ...

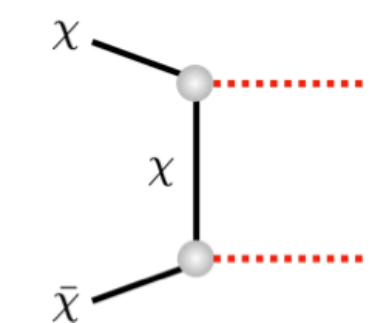
➔ no new experimental signatures @ LHC

- Is this enough motivation for a WP?
 - probably not (lack of focus → low impact)

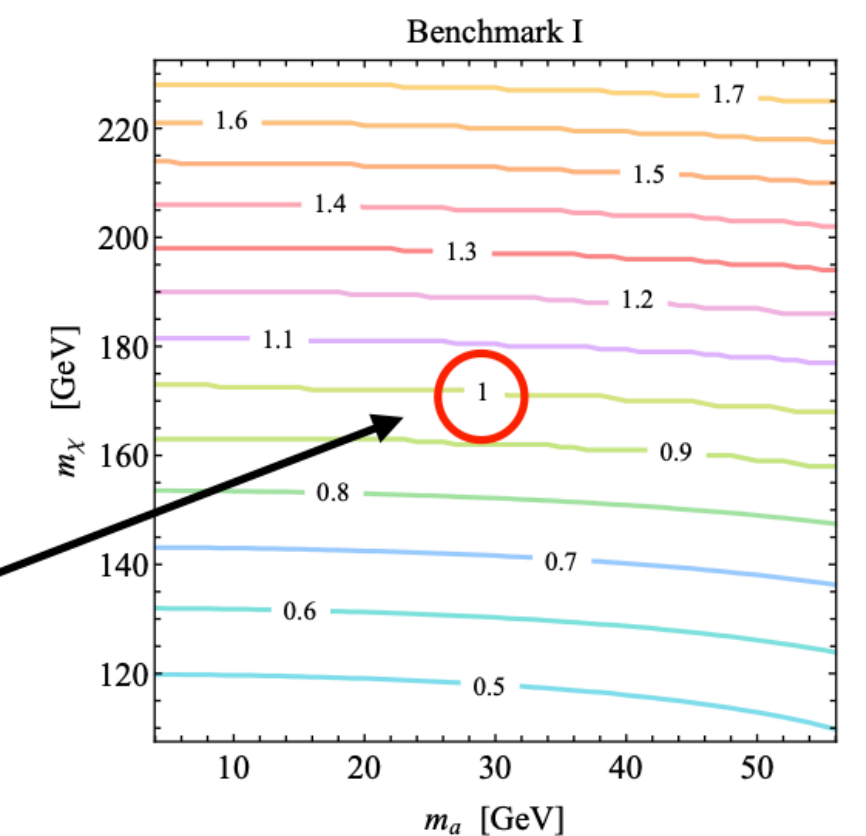
Direct detection (DD) in 2HDM+a



LLPs in 2HDM+a



Interestingly, 2HDM+a realisations that give LLP observable @ LHC, can also explain observed DM relic density



[Uli & Luc, 2302.02735]

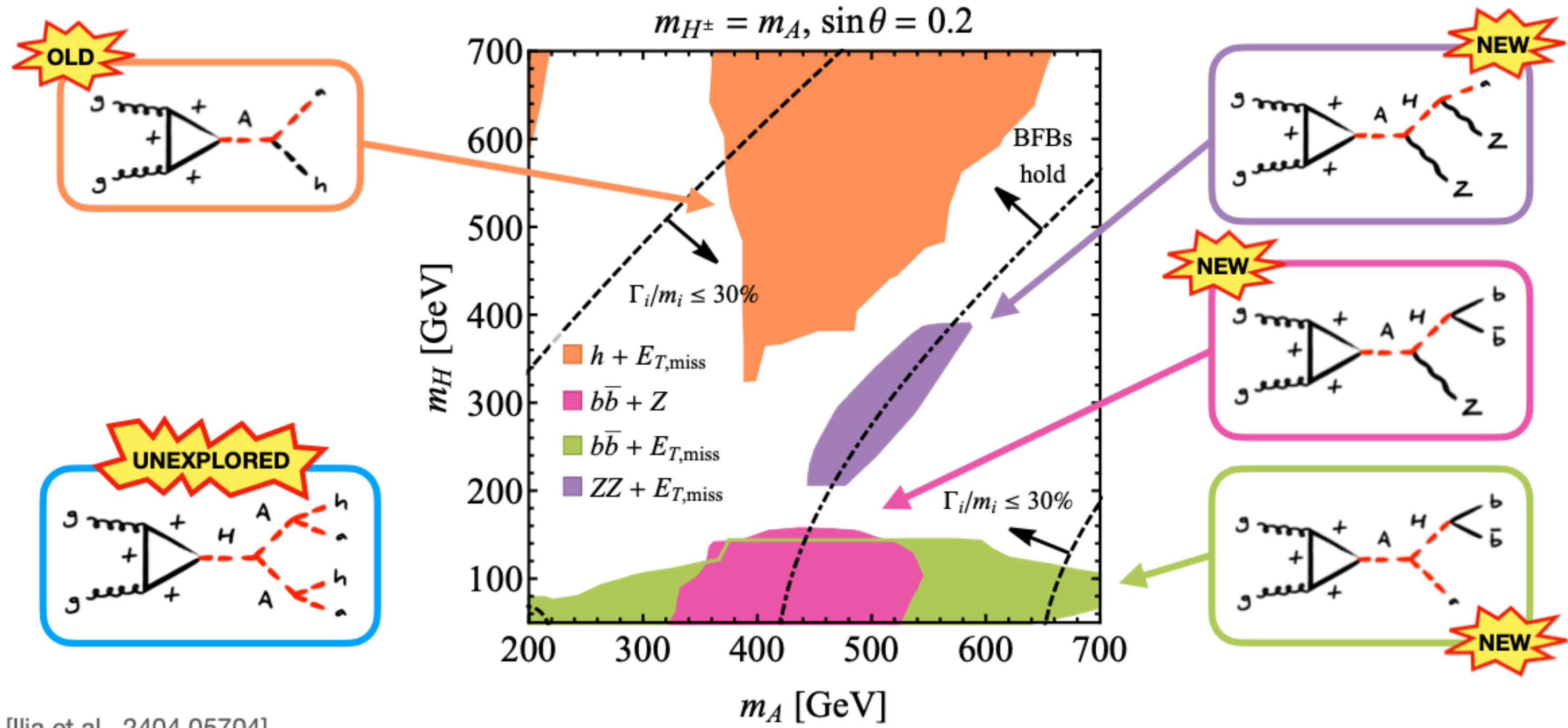
What has been done? #3

Move away from previous assumptions

Type-I
 $m_A = m_{H^\pm} \neq m_H$
 ✓ alignment limit

- Type-I model with non-degenerate Higgs spectrum contains "new" signatures, however...

Old & new 2HDM+a signatures in type I

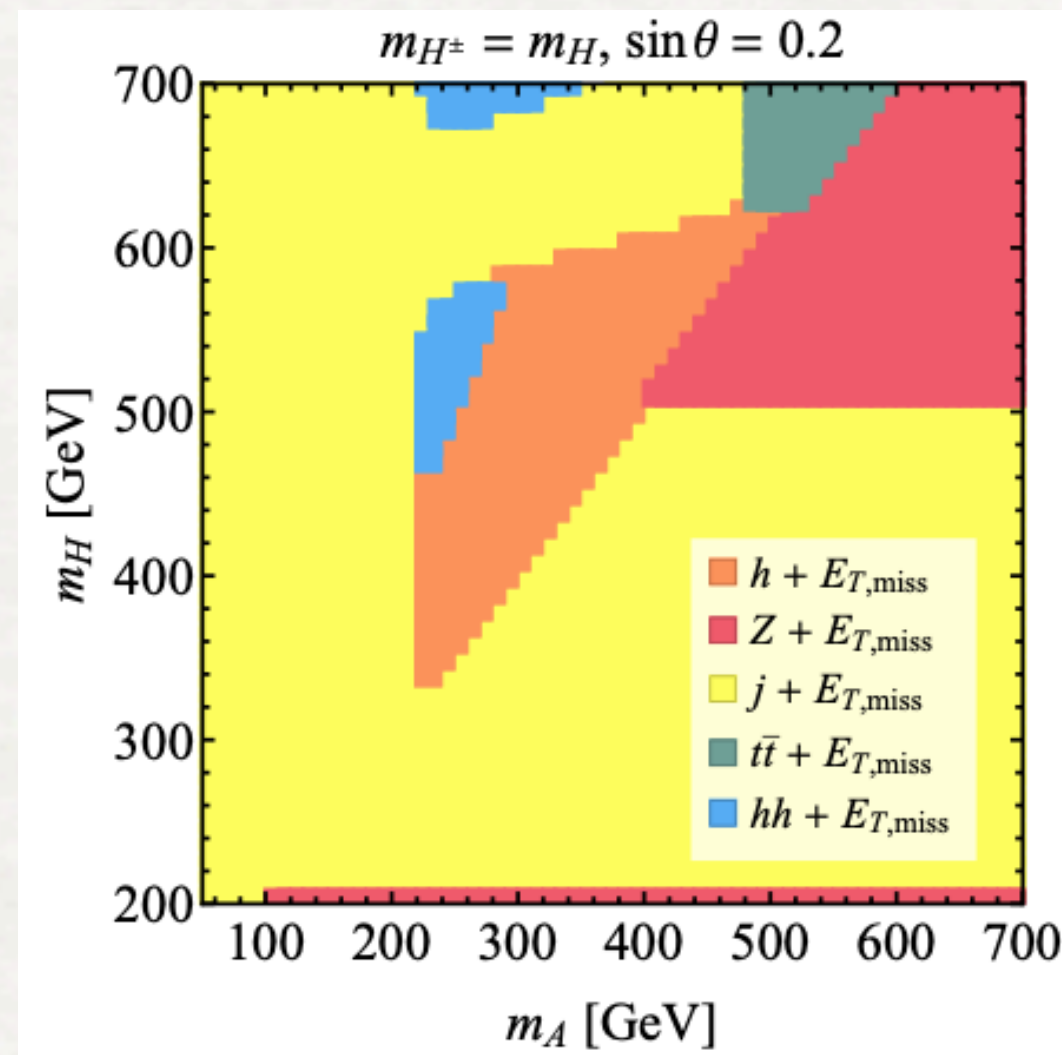
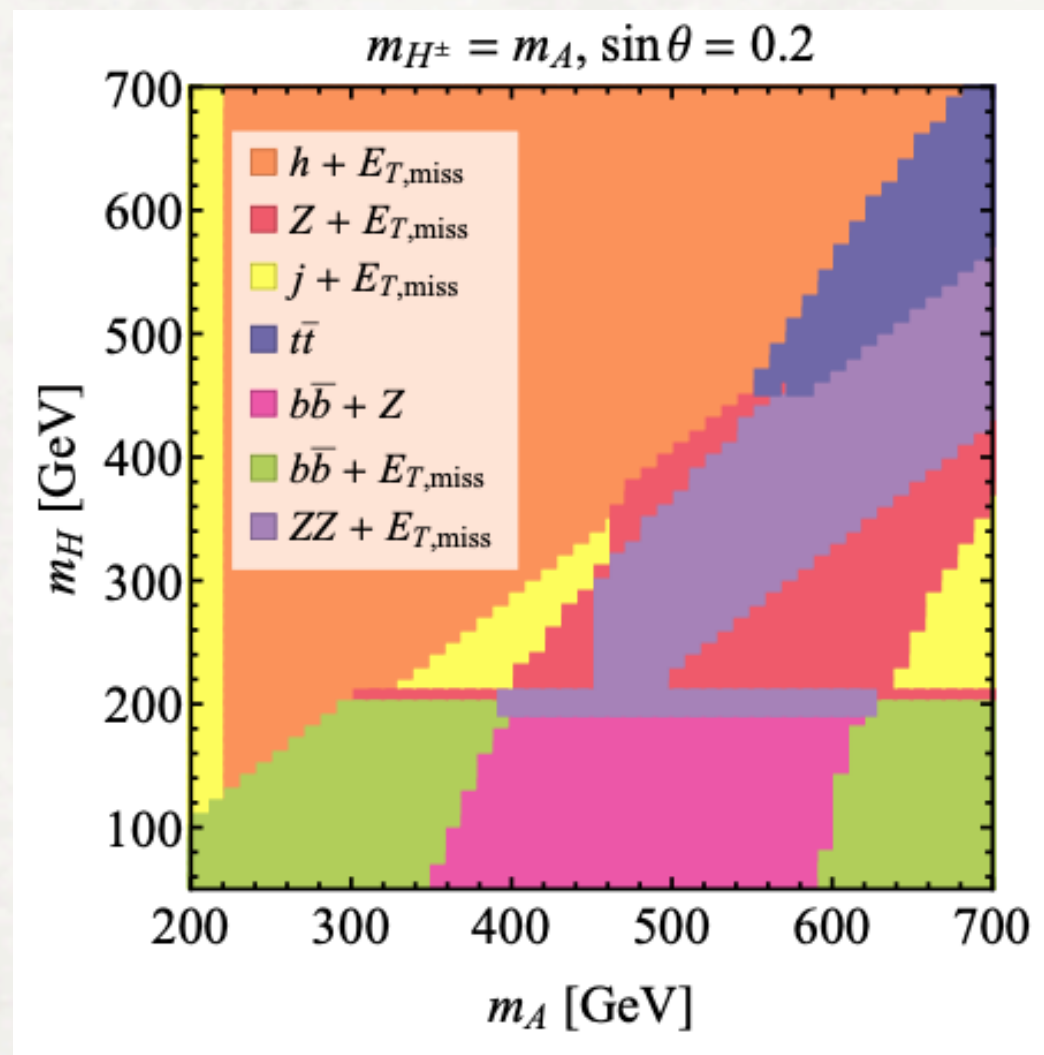


[Ilia et al., 2404.05704]

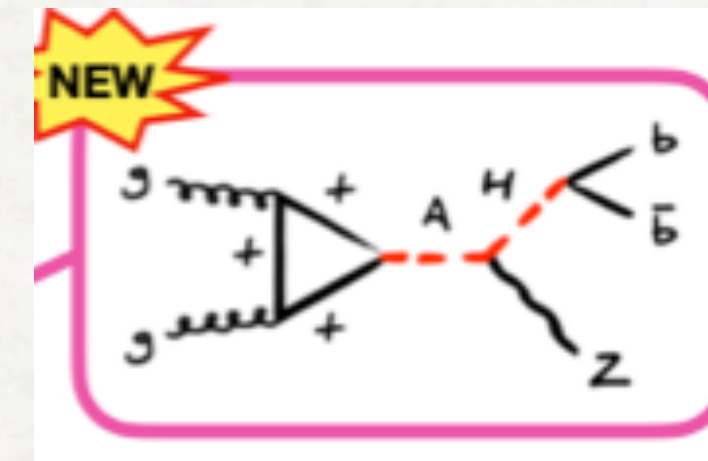
from Uli

What has been done? #3

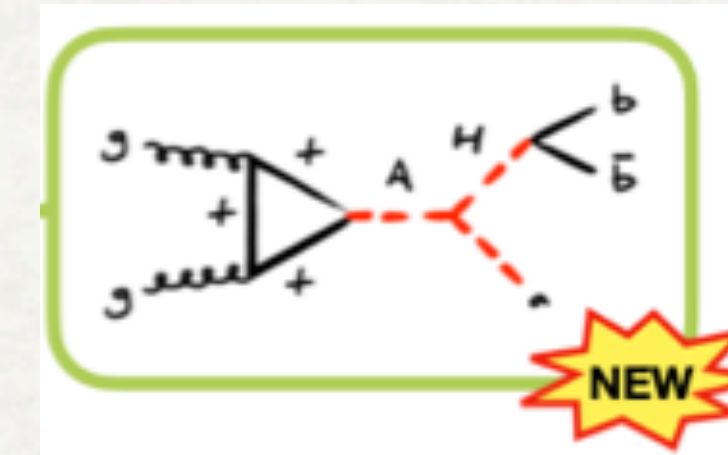
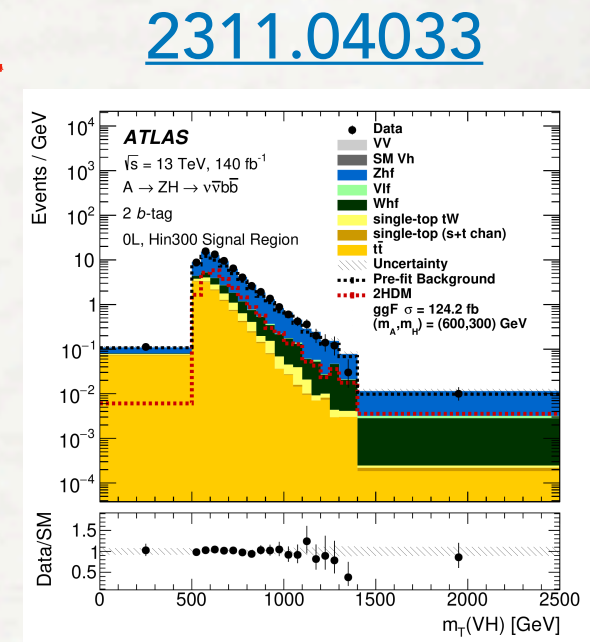
- **All** the final states that we **studied in the paper** have been **explored in some way or another**
 - perhaps not optimal but re-interpretation possible
- A combination of existing (easy) searches can probably easily rule out less explored final states (e.g. **mono-Z** \rightarrow $ZZ + E_T^{\text{miss}}$, $h + E_T^{\text{miss}}$ \rightarrow $hh + E_T^{\text{miss}}$)



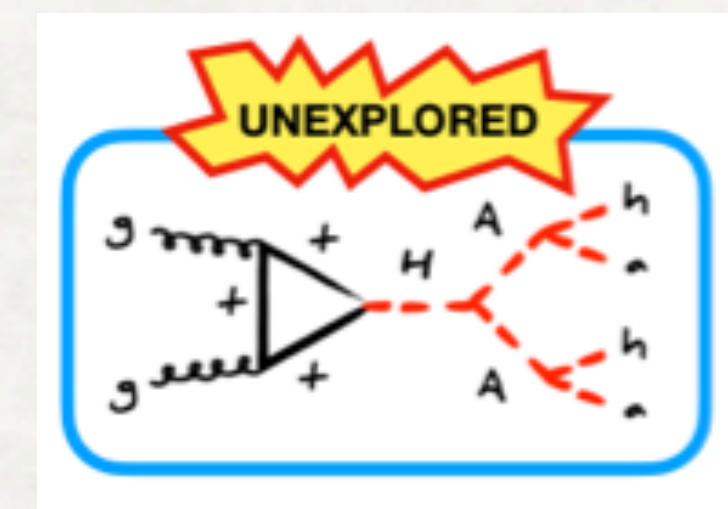
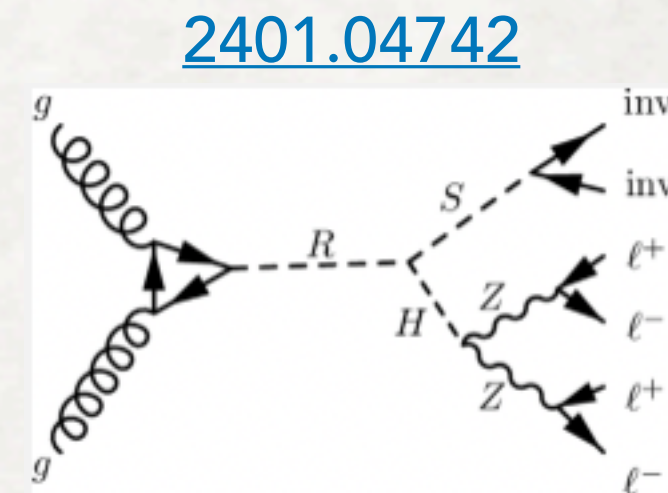
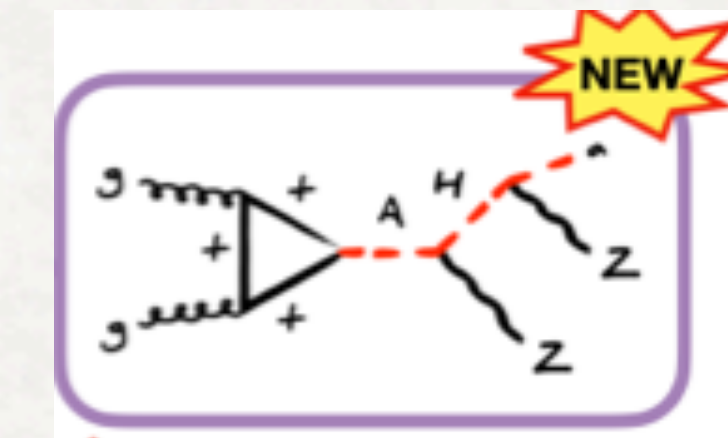
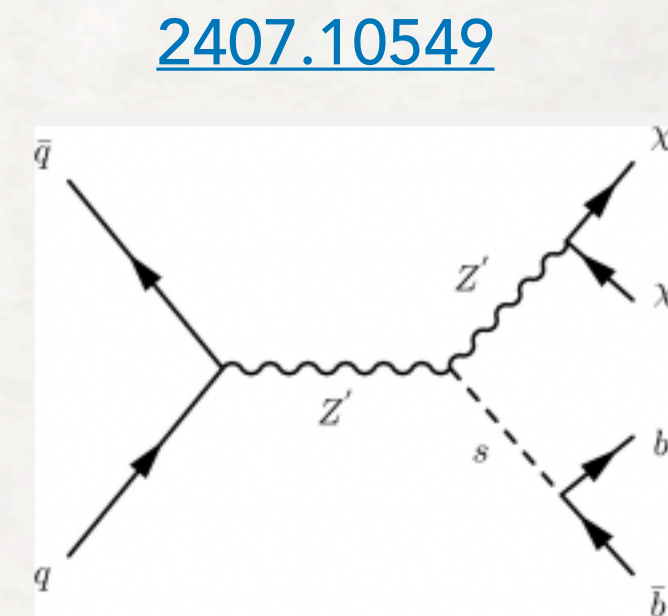
[2404.05704](#)



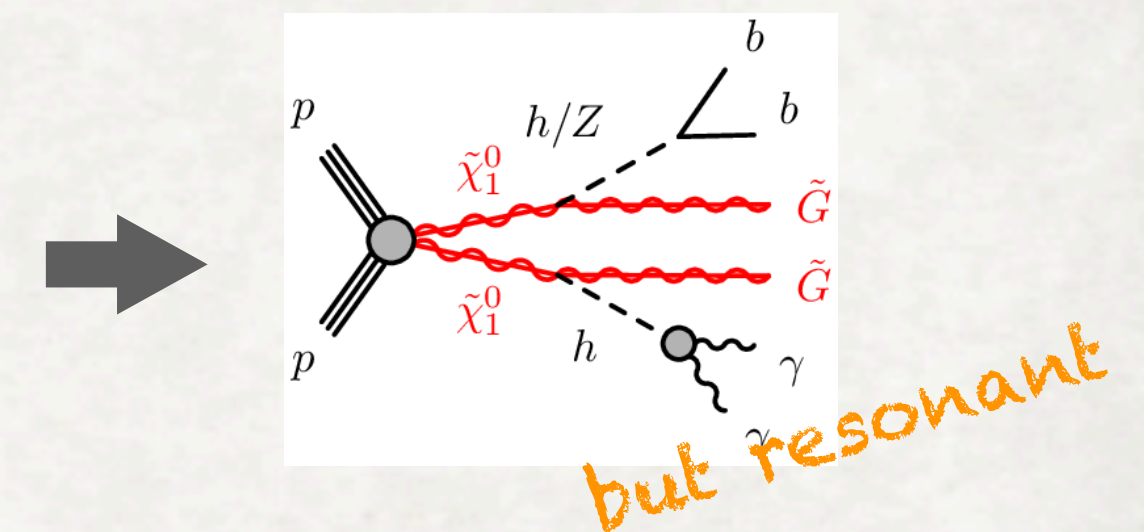
already done
in ATLAS



same as
mono-Z
but resonant



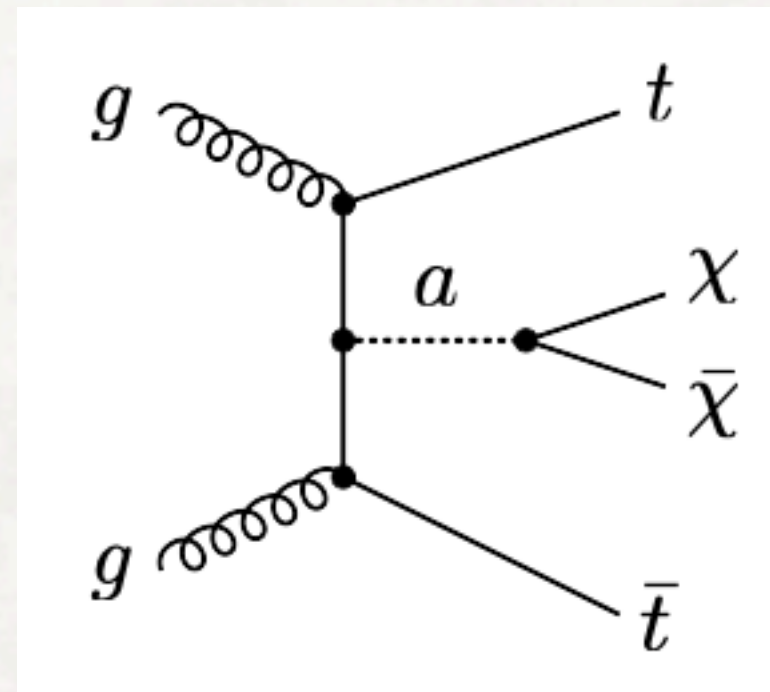
[2404.01996](#)



However...

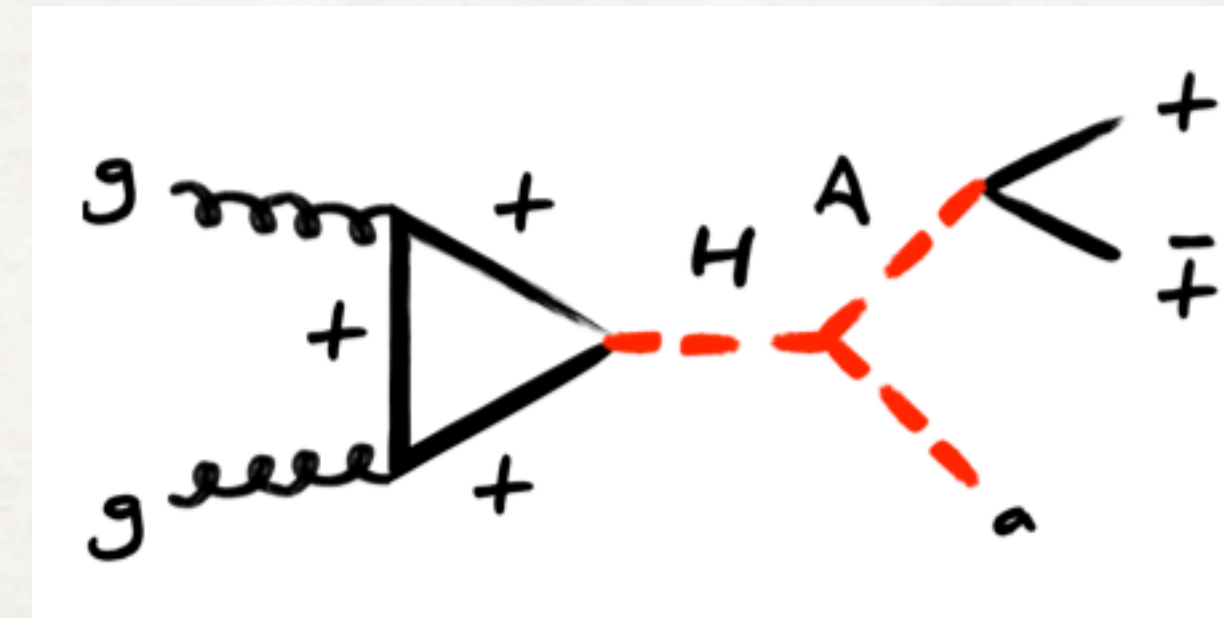
- Familiar signatures get a new spin in Type-I 2HDM:

Type II



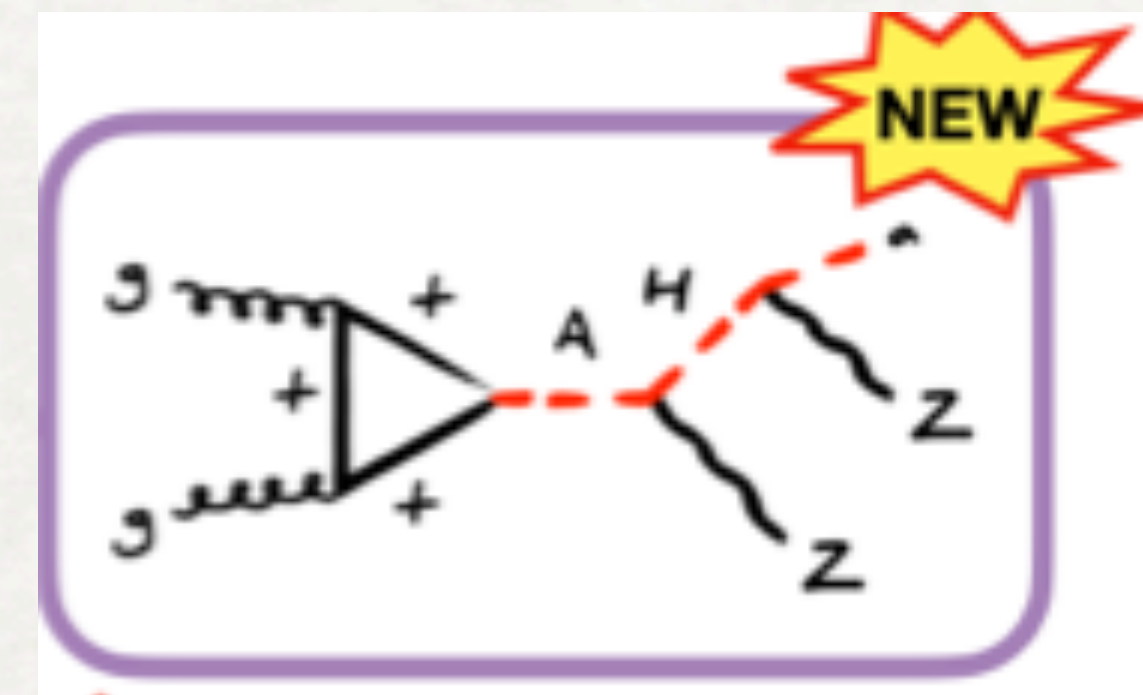
Non-resonant - little significance

Type I



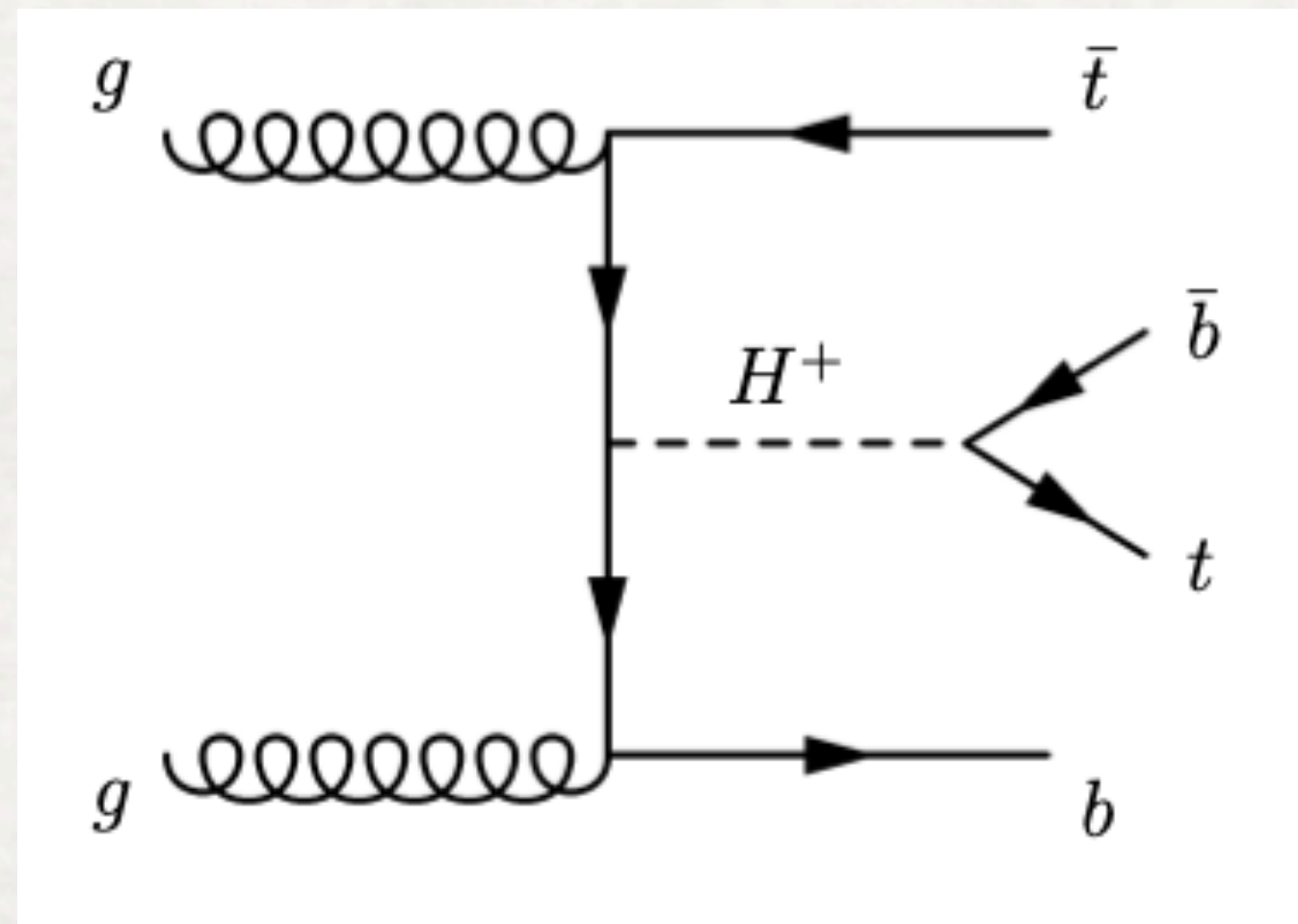
Resonant - room for improvement
(e.g. using transverse mass)

- Also in some cases existing analyses are very far from being optimal (e.g. for $ZZ + E_T^{\text{miss}}$ using $m_T(ZZ + E_T^{\text{miss}})$ gives a significantly better result than a reinterpretation of the published analysis)
- It would be useful experimenters to know this while we design our Run 3 analyses

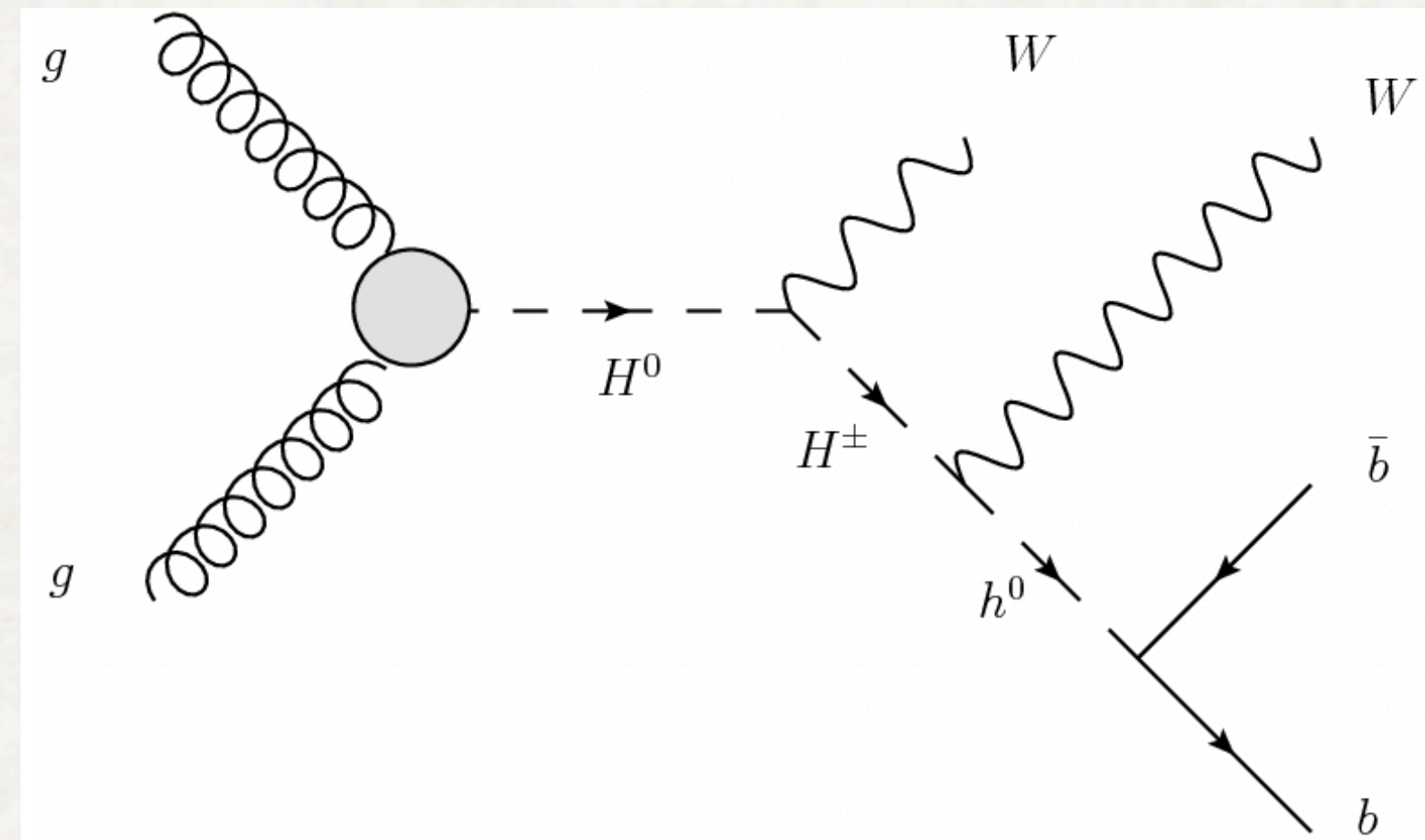


What has **not** been done #1: **charged Higgs**

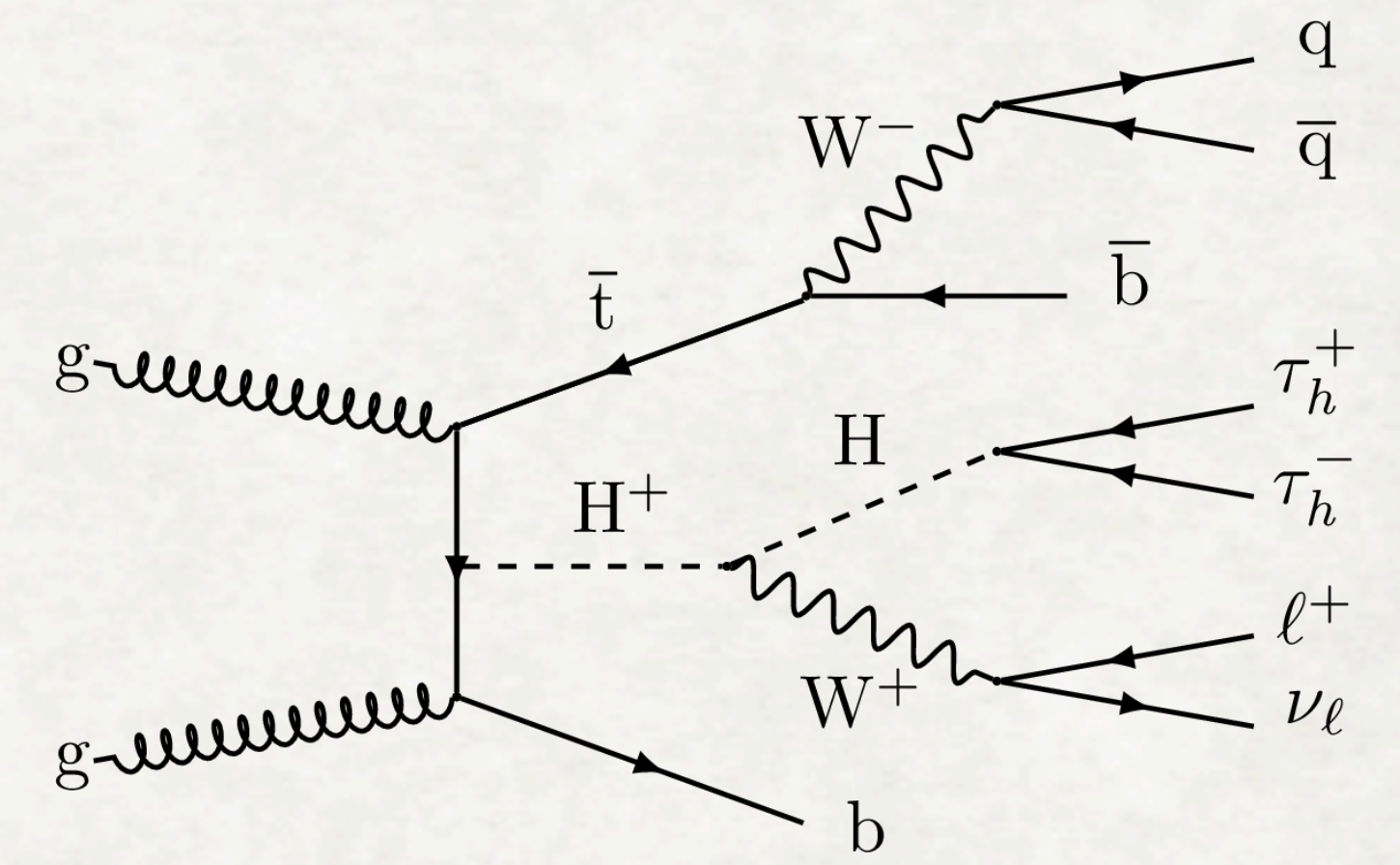
- **Charged Higgs final states not looked at** so far in the paper (with the exception of $A \rightarrow WH^\pm(cs)$)
- So far ATLAS and CMS have looked at
 - $pp \rightarrow tbH^\pm(tb) \Rightarrow$ non-resonant $bbWW$
 - $gg \rightarrow H \rightarrow H^\pm(W^\pm h(b\bar{b}))W^\mp \Rightarrow$ resonant $bbWW$ [[1312.1956](#)]
 - $gg \rightarrow tbH^\pm(HW^\pm)$ only with $H \rightarrow \tau\tau$ [[2207.01046](#)]



$$\sim \frac{1}{\tan^2 \beta}$$



$$\sim \frac{1}{\tan \beta}$$



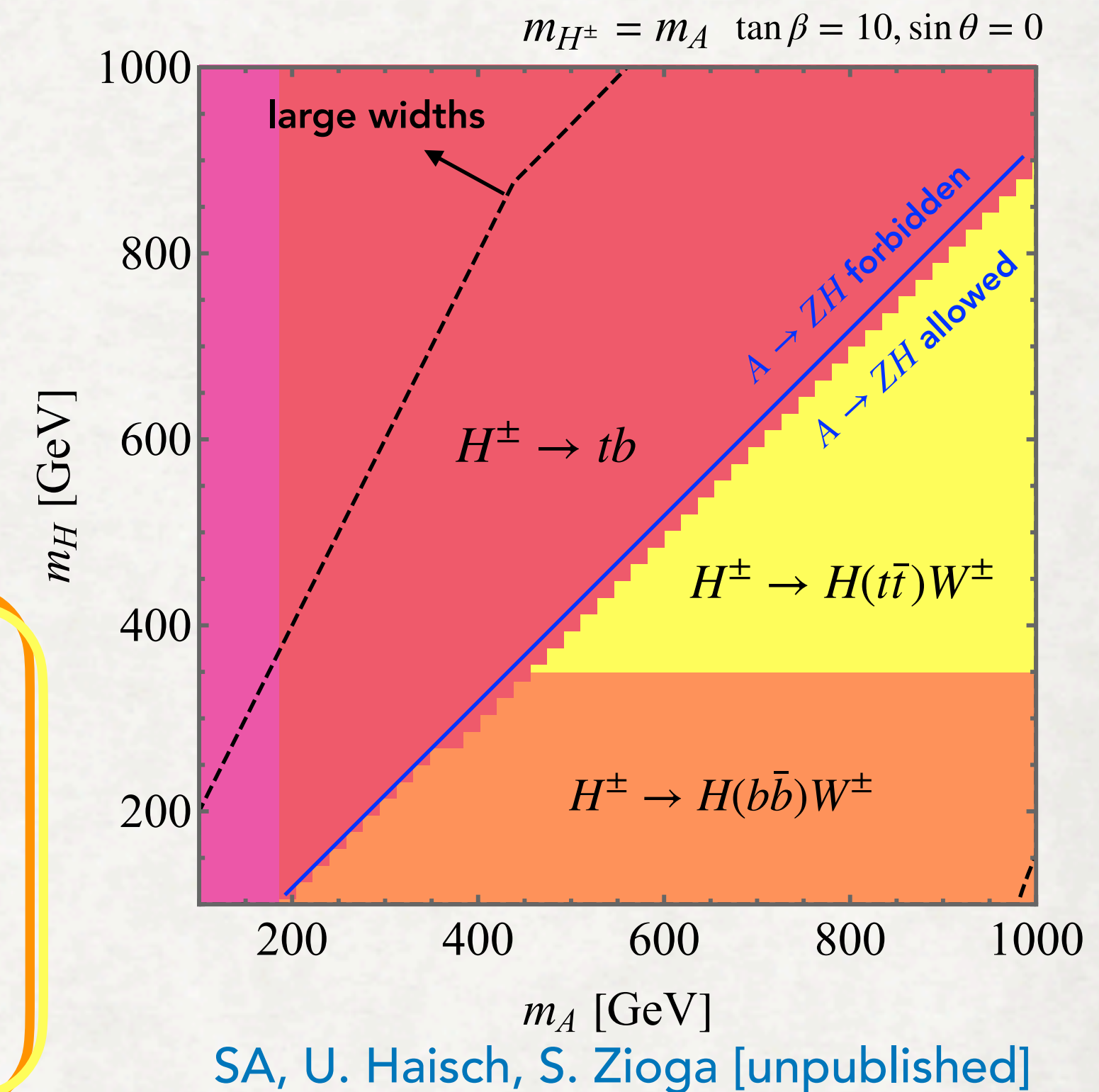
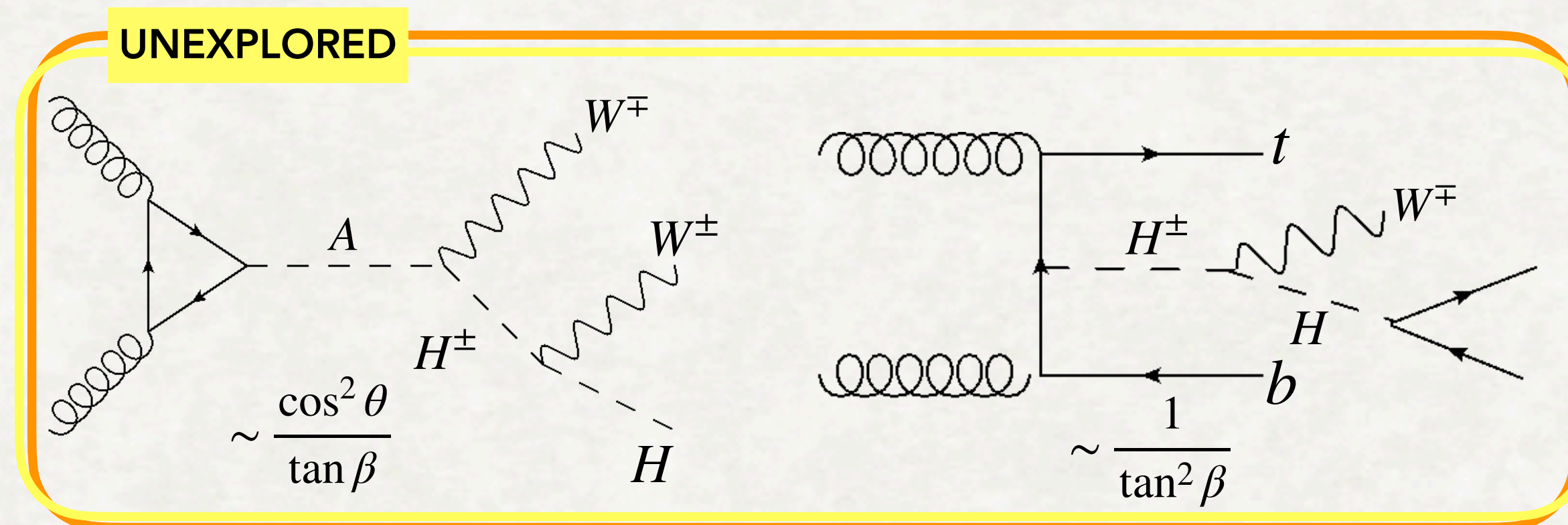
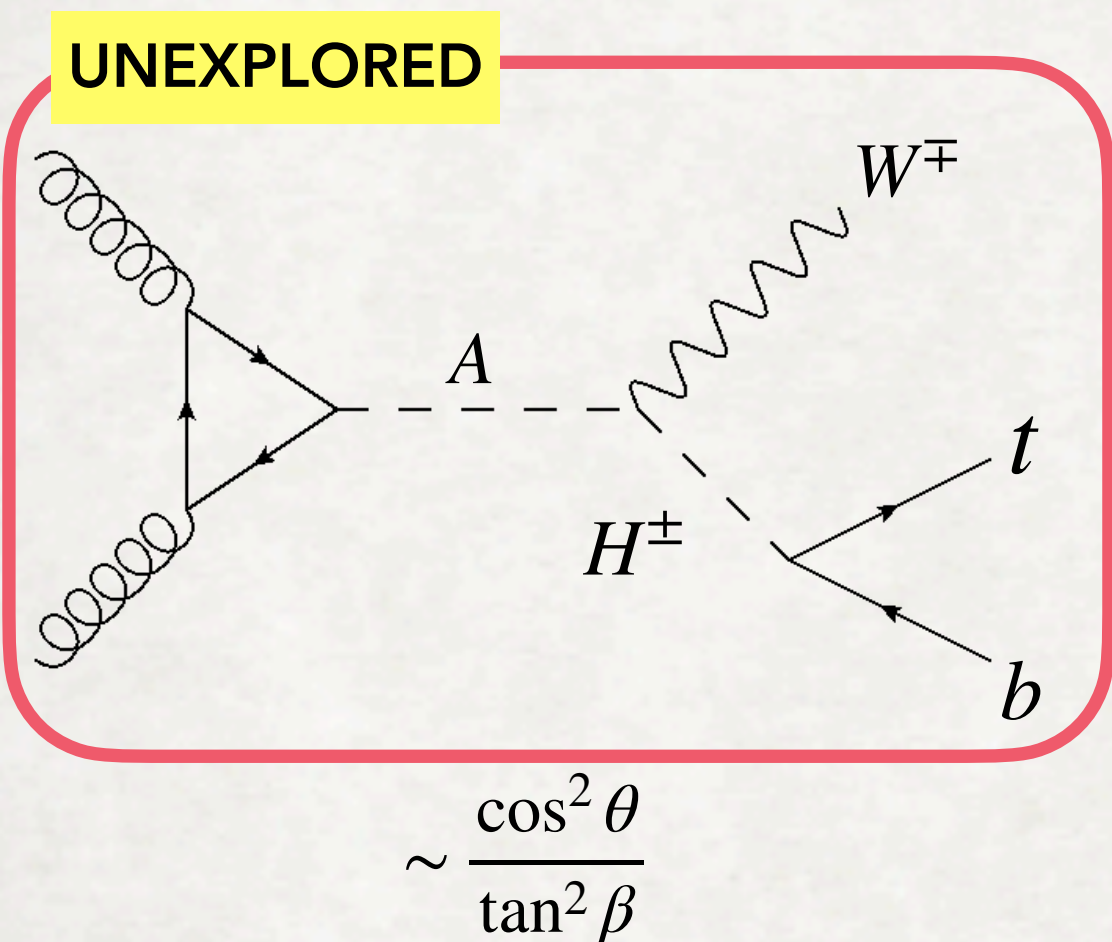
$$\sim \frac{1}{\tan^2 \beta}$$

What has **not** been done #1: **charged Higgs**

- Potential new signatures:

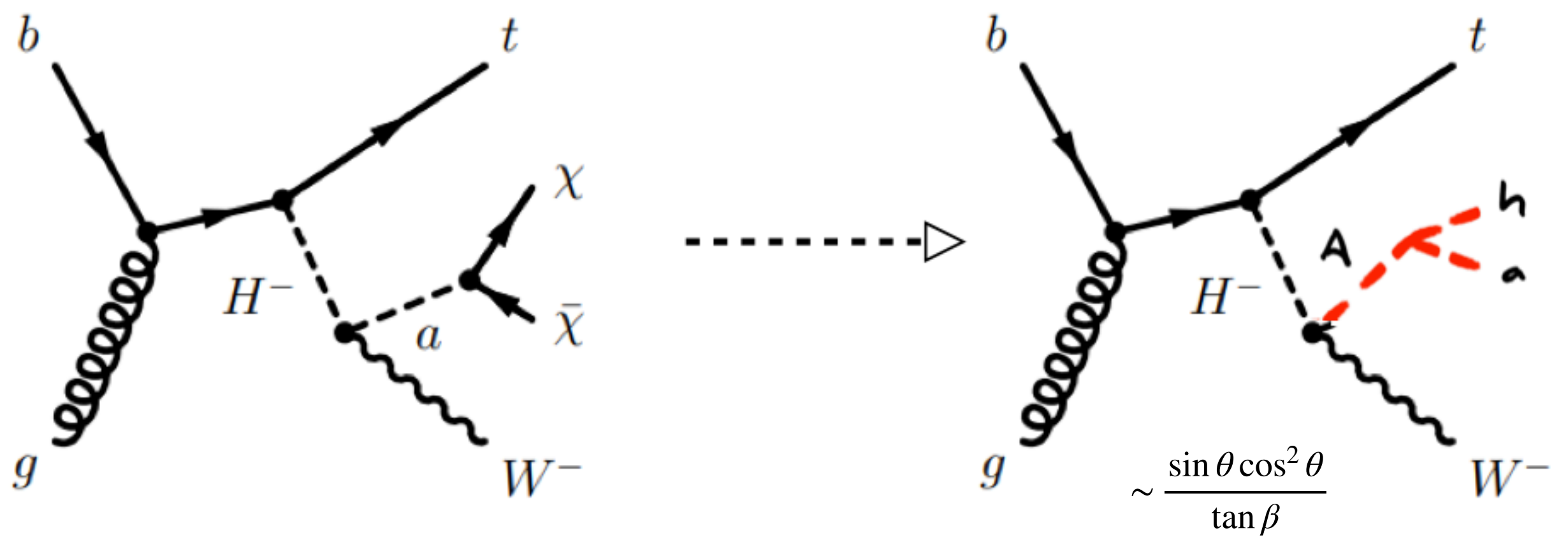
- $A \rightarrow H^\pm(tb)W^\mp \Rightarrow$ resonant $bbWW$ (but quite different topology than cascade decay studied by ATLAS)
- $A \rightarrow H^\pm(H(bb/tt)W)W^\mp \Rightarrow$ resonant $bbWW$ or resonant $ttWW$ (not looked at)
- $pp \rightarrow tbH^\pm(HW^\pm), H \rightarrow b\bar{b} \Rightarrow 4b+2W$ (not looked at)
- $pp \rightarrow tbH^\pm(HW^\pm), H \rightarrow t\bar{t} \Rightarrow 4b+4W$ (not looked at - difficult)

- Preliminary studies show some promise



What has **not** been done #1: **charged Higgs**

Cascade decays involving H^\pm ??

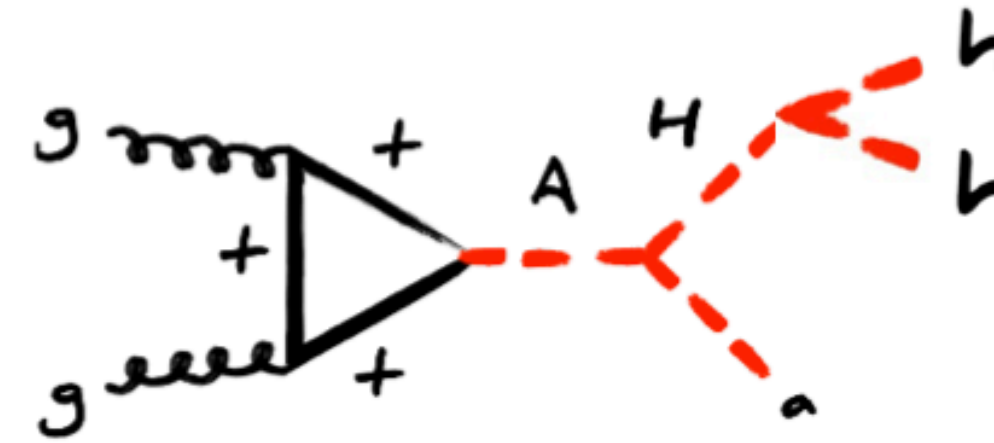
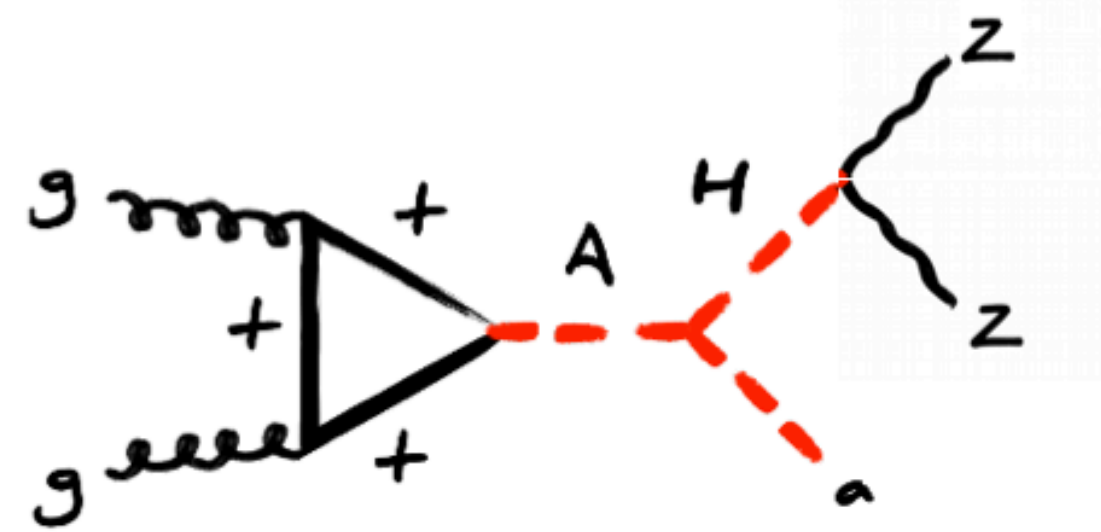


from [Jose Miguel](#)

What has **not** been done #2: **misalignment**

There is even more to it:

2HDM Type I → Alignment??



Decays which appear away from alignment only

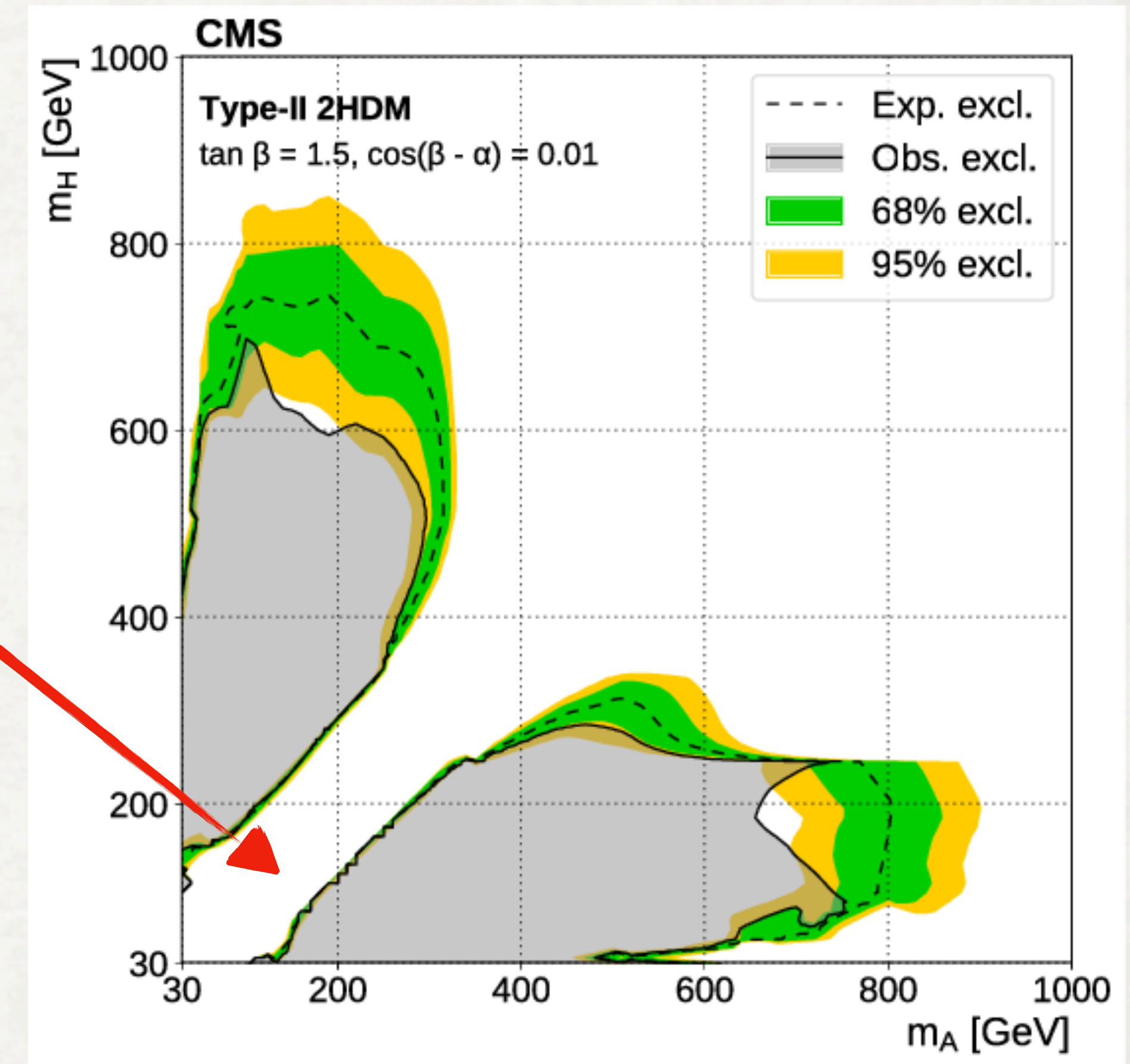
- $H \rightarrow ZZ/WW$ (leptons + E_T^{miss})
- $A \rightarrow Zh$ ([2207.00230](#))
- $H^\pm \rightarrow W^\pm h$ ([2411.03969](#))
- $H \rightarrow hh \Rightarrow$ resonant hh + E_T^{miss} (see previous discussion)
- $Z \rightarrow aH \Rightarrow b\bar{b}$ + E_T^{miss} (probably same as $A \rightarrow aH$ but produced through Drell-Yan)

➡ Unclear if there are completely new signatures

➡ maybe it makes sense to at least document the phenomenology

What has **not** been done #3: **off-shell regions**

- For example $A \rightarrow Z^*H$
- Feasibility studies in [2508.21385](#), [2301.00728](#), ...
- This **has not been done either in ATLAS or CMS** to the best of my knowledge
- **Good motivation if this works out** - nice addition to white paper (background modelling etc)



What people are already working on...

- From the previous kick-off about **10 experimentalists and 5 theorists** expressed interest
- Areas of interest/expertise
 - $tW + E_T^{\text{miss}}, t\bar{t} + E_T^{\text{miss}}, t\bar{t}$ resonances
 - mono-Z
 - $gg \rightarrow b\bar{b}H(Z(\ell\ell)a)$
 - $A \rightarrow ZH$ low and high mass
 - $hh + E_T^{\text{miss}}$
 - Charged Higgses + off-shell
- However rough estimate of OTP was **< 2 FTE** - that's **clearly too low** (and maybe one of the reasons why nothing has been done in the last year?)
- We clearly **need an updated estimate of the FTE** that can be pledged if we are to proceed with this

The role of a new 2HDMa White Paper

The paper should be signature driven

High impact = not just documentation but **something new** wrt bibliography

- **novelty: uncovered signatures** - unexplored phenomenology (e.g. charged Higgs)
- **completeness**: simplified analyses for signatures that don't appear in existing benchmarks (e.g. $hh + E_T^{\text{miss}}$, $t\bar{t} + E_T^{\text{miss}}$, ...) based on what the experiments are pursuing
- **usefulness**: update of Type-II benchmarks where needed

Next Steps

- ➔ Consensus on the role of the WP?
- ➔ Sufficient FTE?
- ➔ We need contacts
- ➔ Regular meetings (at least monthly I would say)

*I think **there is space for a high-impact paper** but it should be focused.*

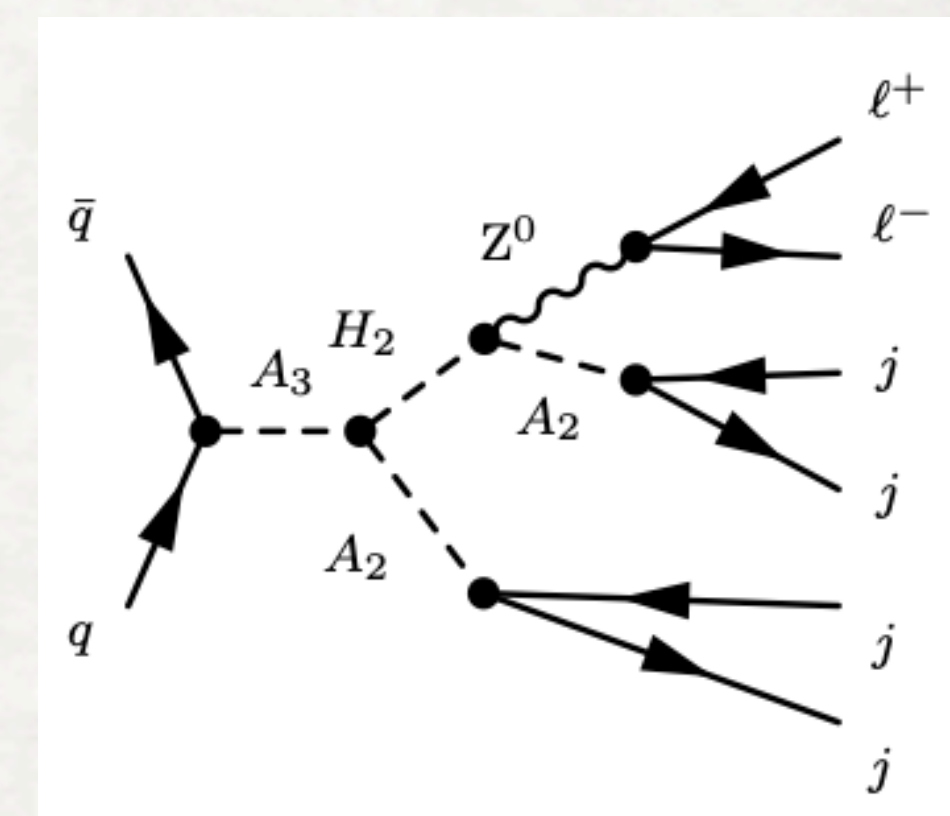
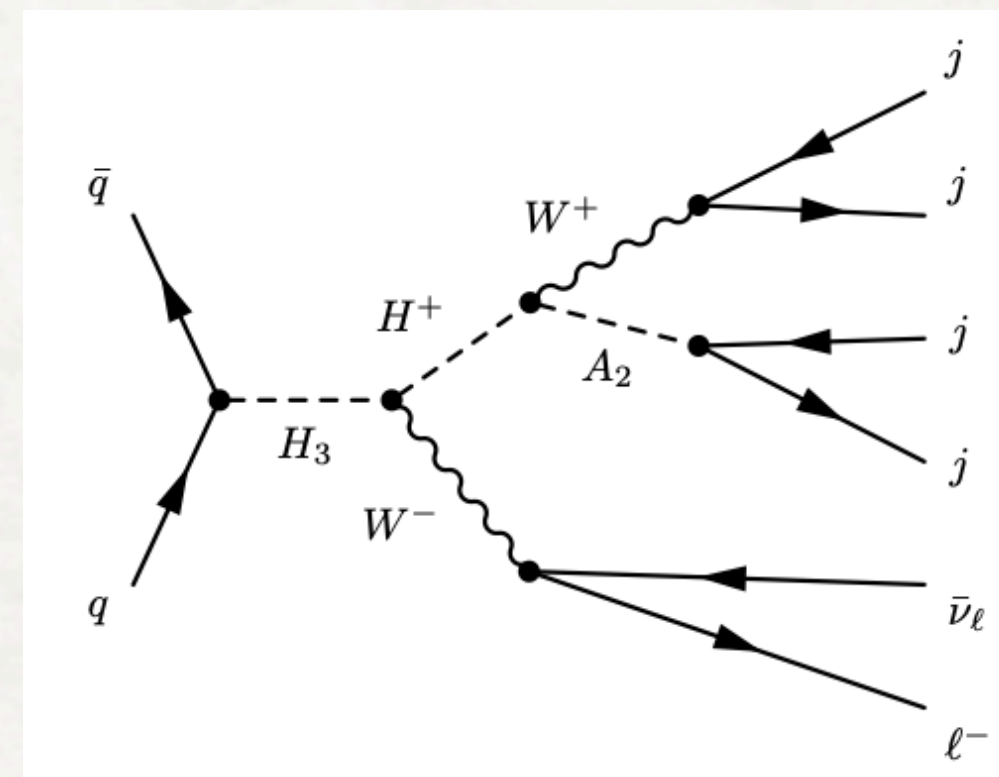
Personally, very eager to see this ramping up!

***Let's discuss** if we can make it happen...*

Backup

Aside (heavy DM)

- Making DM heavy would imply $a \rightarrow jj$
- New decays open up in principle
 - huge suppression with $\sin^2 \theta$ or $\sin^3 \theta$ mostly studied in context of a slightly different model [[22.11.10109](#)]
 - in any case not sure whether these have been studied by ATLAS/CMS
- This might be slightly-completely tangential to a 2HDMa WP but just wanted to mention this complementarity



[Ferreira et al, 2211.10109](#)

