

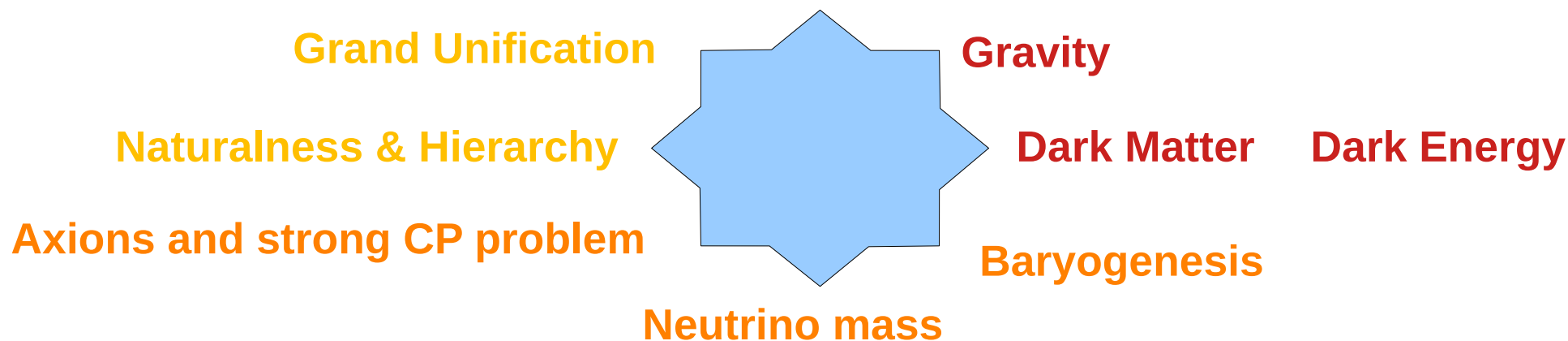


Beyond Standard Model and Dark Sector at Colliders

Nikolaos Rompotis (University of Liverpool)

The Beyond SM Landscape

- Physics Beyond the Standard Model (SM) come to two different categories: *confirmed* and *suspected to be true*



- ... and there is the related topic of SM properties that are unmeasured or less well measured

Higgs & rare electroweak processes

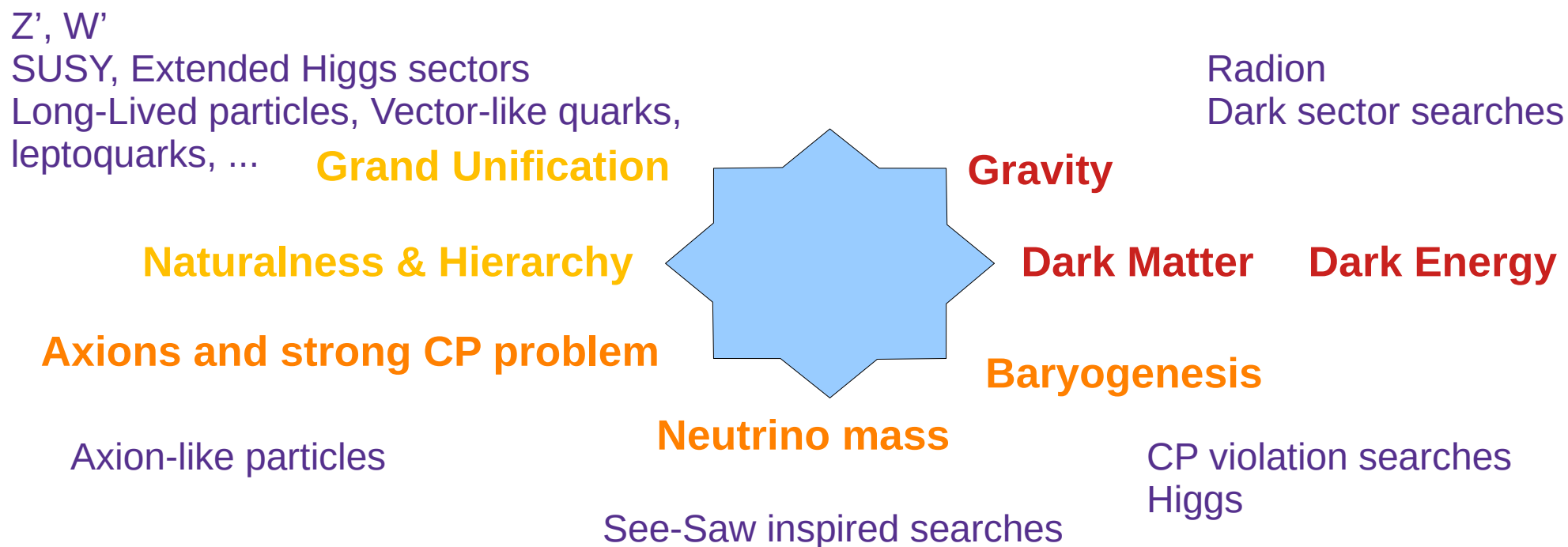
B-hadron physics, ...

Precision measurements

What a collider can do for BSM?

- Colliders are like supermarkets

You find there pretty much everything and cheaper, but just for some things you go somewhere else to buy them!



A word of warning

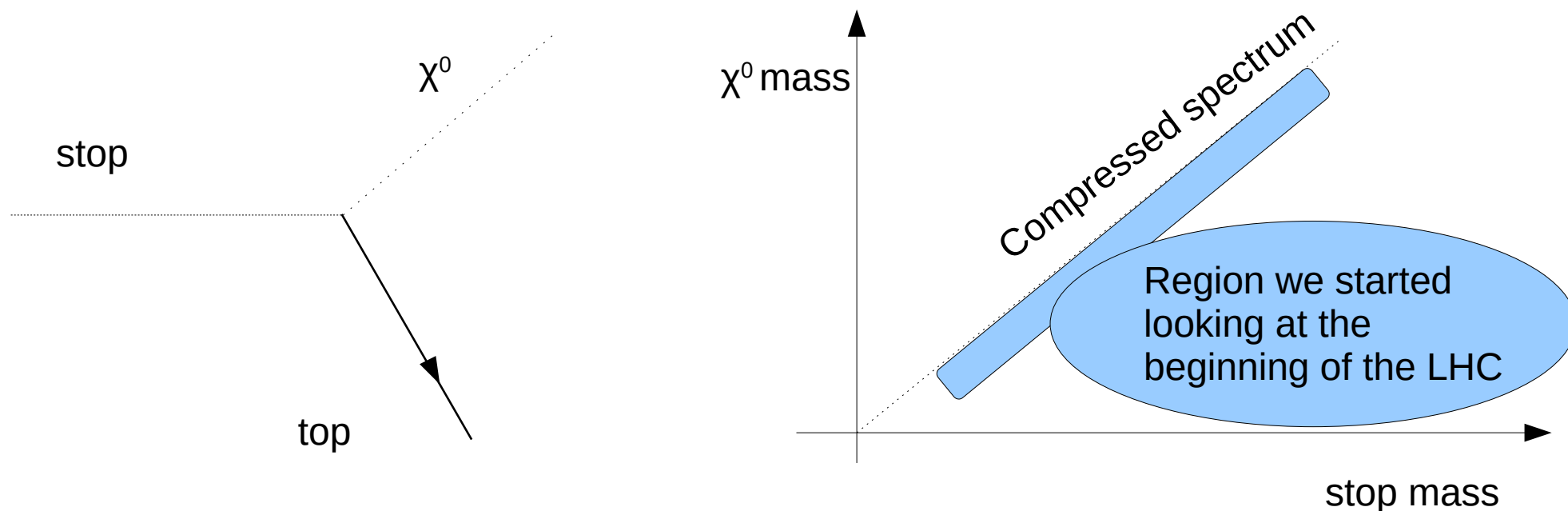
- All collider experiments are relevant for BSM Searches
 - That goes beyond LHC to include e^+e^- machines (Belle, Babar, BES)
 - Includes not just pp but also *heavy ion* collisions
- In this talk I will include mostly ATLAS and CMS results + some mentions from LHCb
- Due to very extensive amount of work and models that fell under BSM only a very limited range of models will be mentioned

Apologies to all of you who are not going to see your favourite topic covered here.

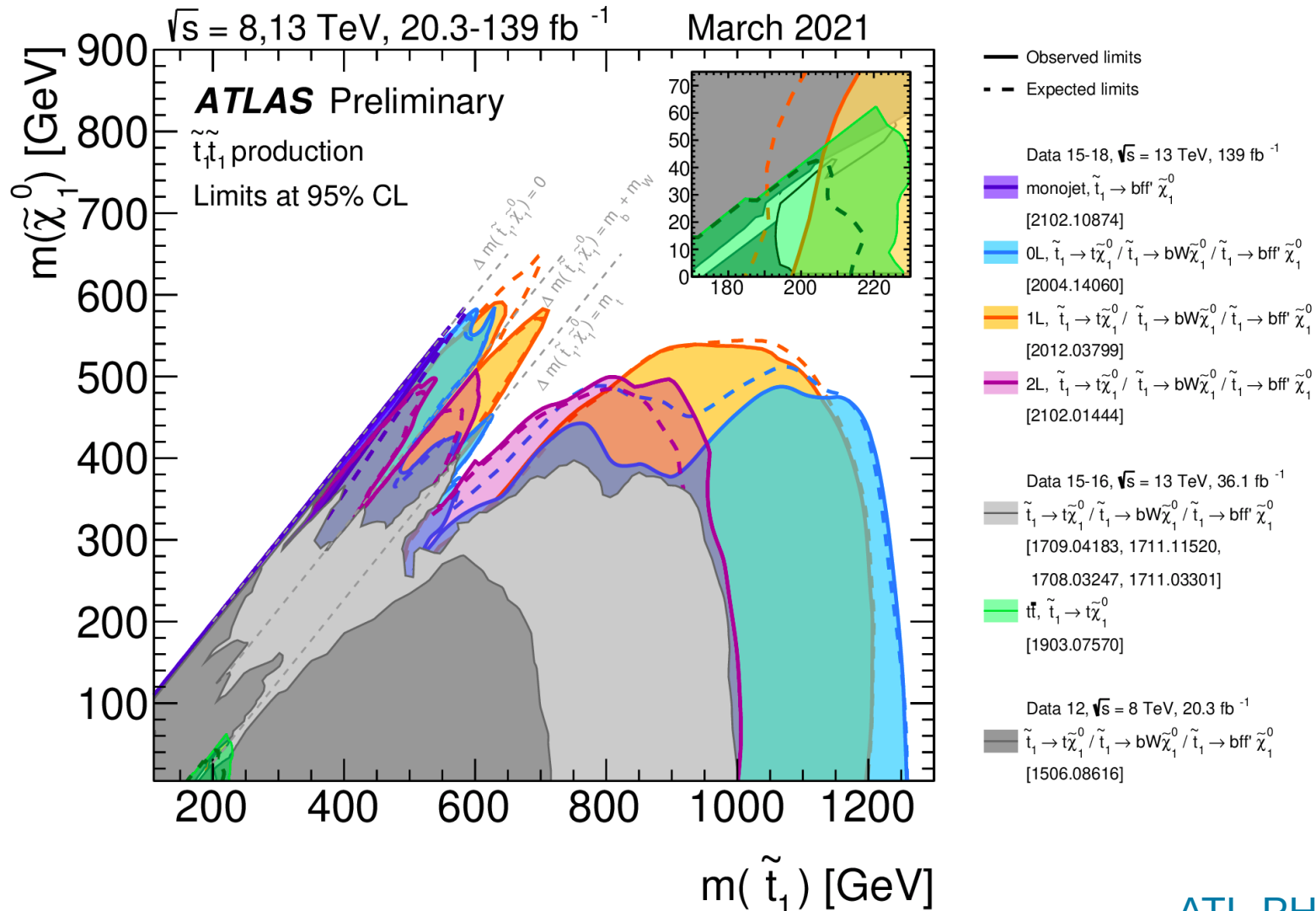
A Supersymmetry (SUSY) Primer

Or: How we learned to stop worrying and love SUSY

- ✓ SUSY models: prime examples of how to address hierarchy & naturalness
- ✓ For each fermionic dof there is a bosonic dof, i.e. a fermion like top has two susy top partners (stops) with the same mass
- ✓ but this cannot be true \rightarrow SUSY is broken
- ✓ most SUSY signatures have to do with decay chains
- ✓ Lightest SUSY particle is expected to be stable: dark matter candidate



Some examples of SUSY searches

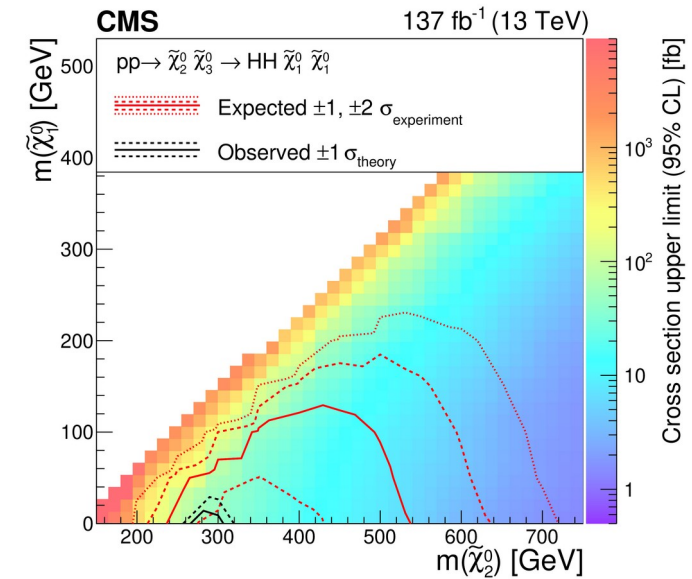
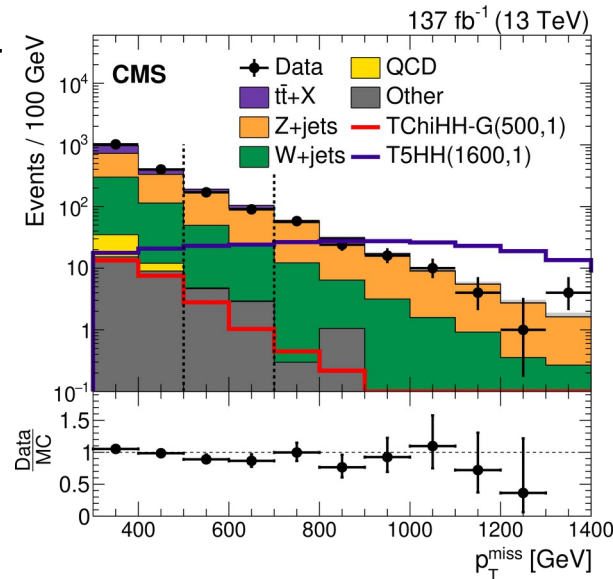
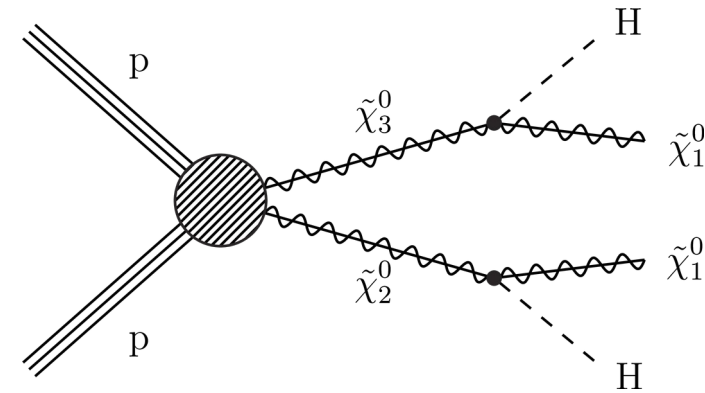


ATL-PHYS-PUB-2022-013

Some examples of SUSY searches

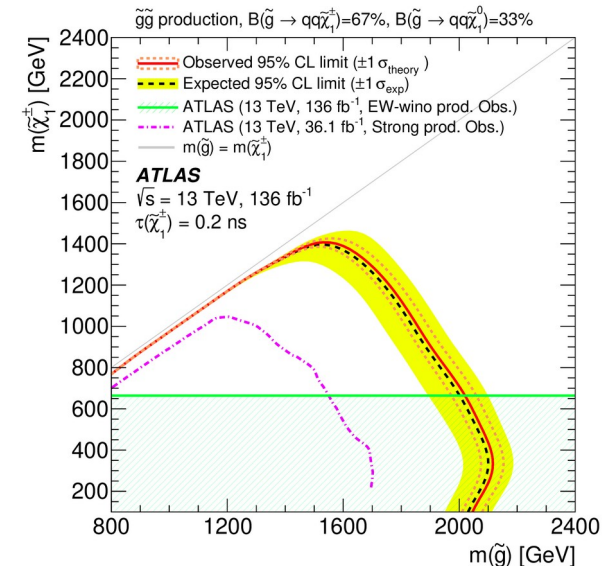
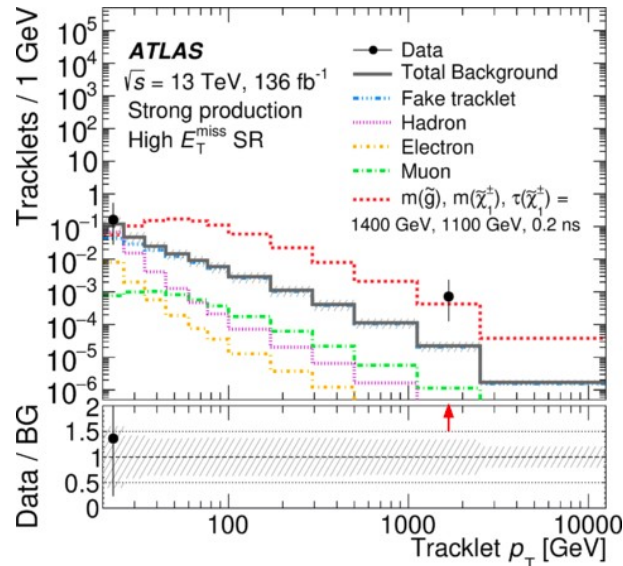
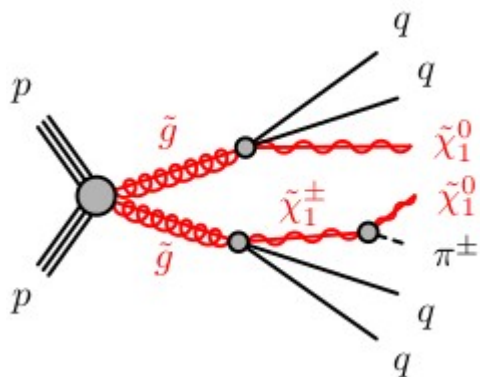
CMS-SUS-20-004

Higgsinos to 2 Higgs bosons + MET



Disappearing track analysis

arXiv:2201.02472





Beyond SM Higgs bosons

- The Higgs boson was discovered 10 years ago and a systematic exploration of the Higgs sector could be done only with the LHC
- ✓ SM: minimal with only one Higgs doublet
- ✓ Many beyond SM scenarios require an extended Higgs sector, e.g. SUSY, axion models, etc
- ✓ You cannot extend the Higgs sector in any way you like:
 - Add singlets or doublets make easy to respect precision measurements
 - Any other multiplet (e.g. triplets) needs some fine tuning



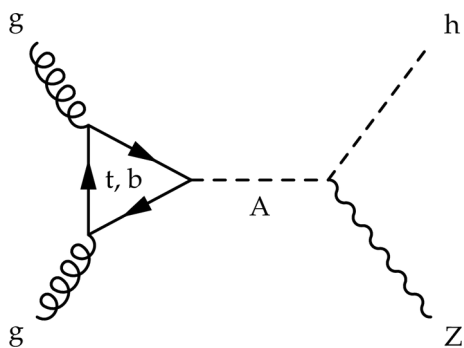
Two-Higgs-Doublet model (2HDM)

- Appears in SUSY, axion etc
- 2 electroweak doublets \rightarrow 3 neutral Higgs bosons (h, H, A), 2 charged H^\pm
- Free parameters: Higgs masses, $\tan\beta$, $\cos(\beta-\alpha)$, ...
- (weak) decoupling limit: $\cos(\beta-\alpha) \rightarrow 0$
- Typical signatures:
Neutral bosons: $A \rightarrow Zh, A \rightarrow ZH, A/H \rightarrow \tau\tau / bb, \dots$
Charged scalars: $H^\pm \rightarrow \tau\nu, tb, cb, Wh, \dots$

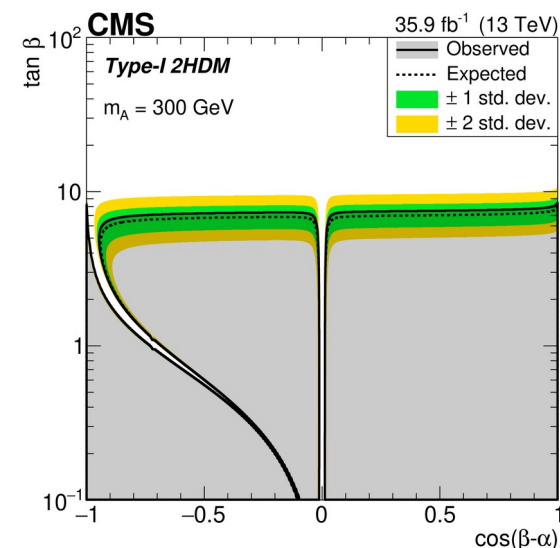
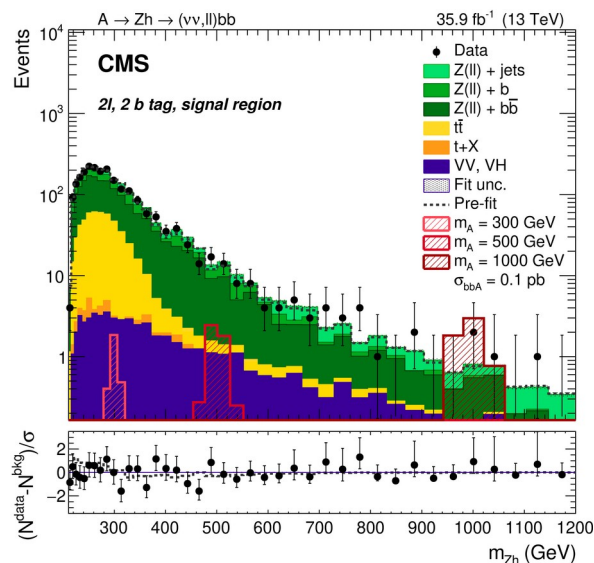
Some typical 2HDM searches

JHEP 06 (2019) 143

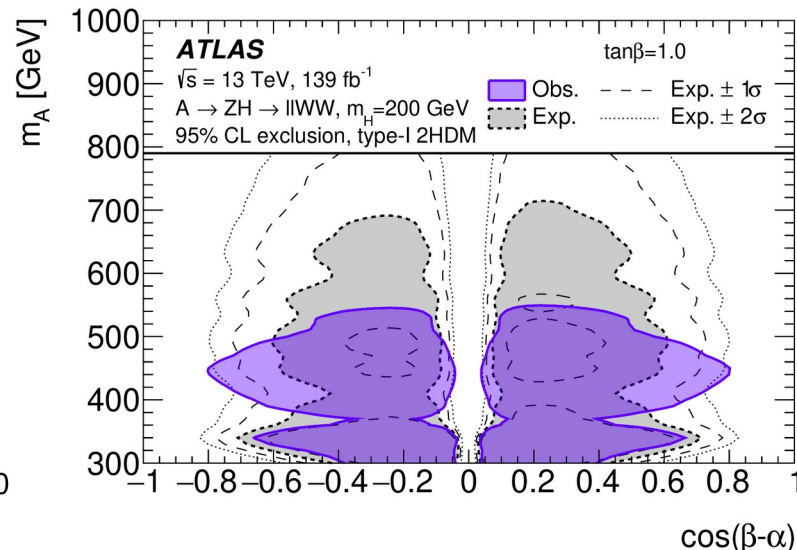
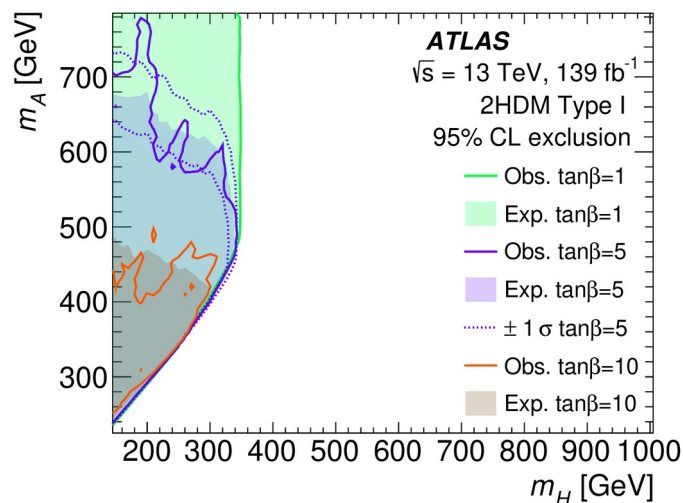
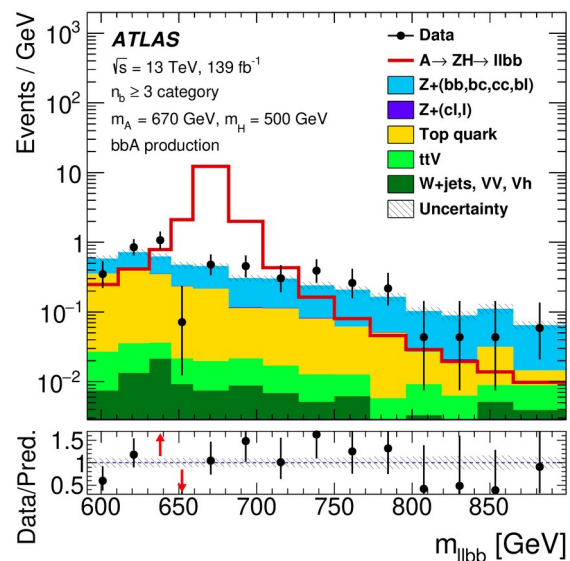
- $A \rightarrow Zh \rightarrow \ell\ell bb$



- $A \rightarrow ZH \rightarrow \ell\ell bb / WW$



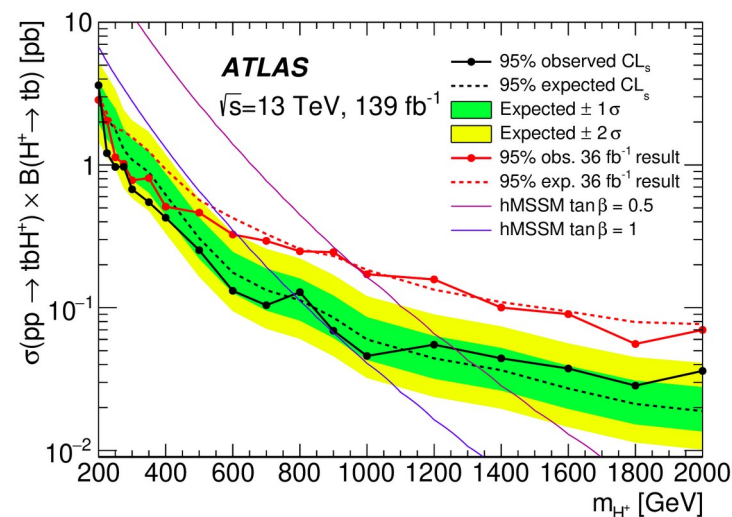
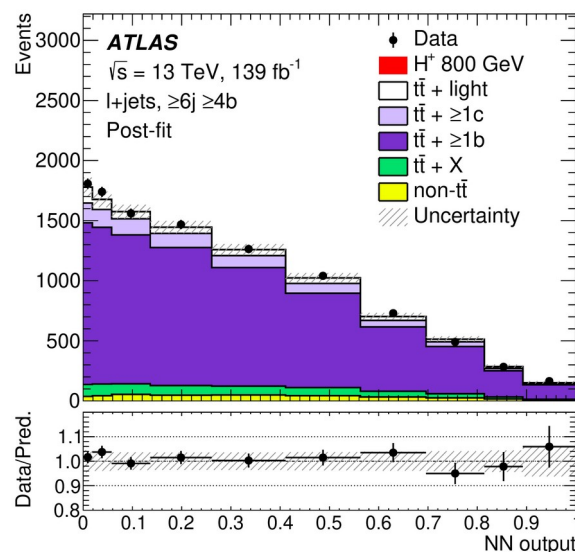
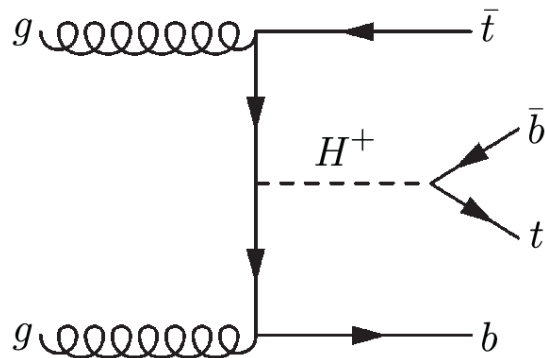
Eur. Phys. J. C. 81 (2021) 396



Some typical 2HDM searches

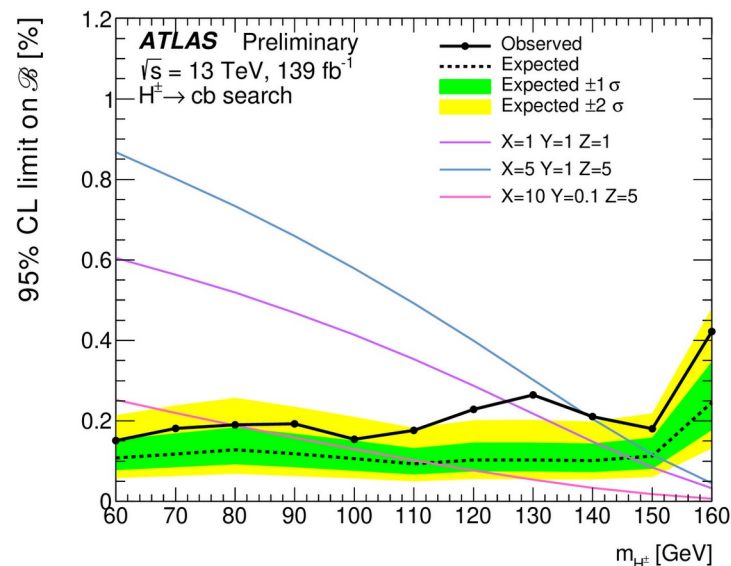
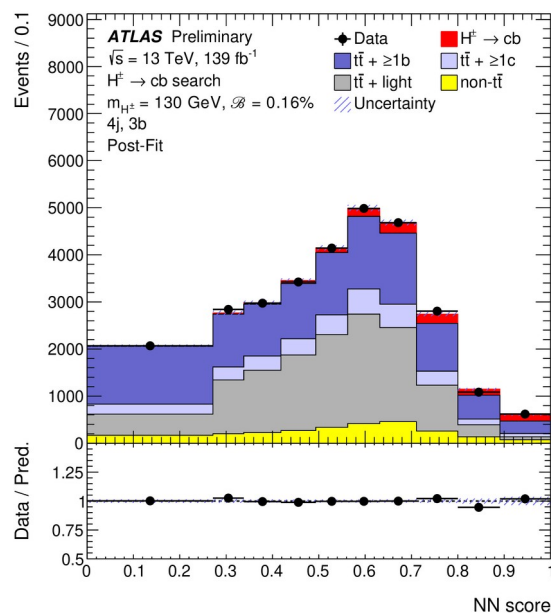
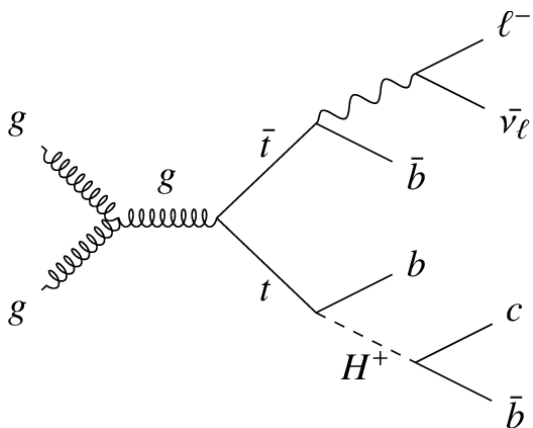
JHEP 06 (2021) 145

• $H^+ \rightarrow tb$



• $H^+ \rightarrow cb$

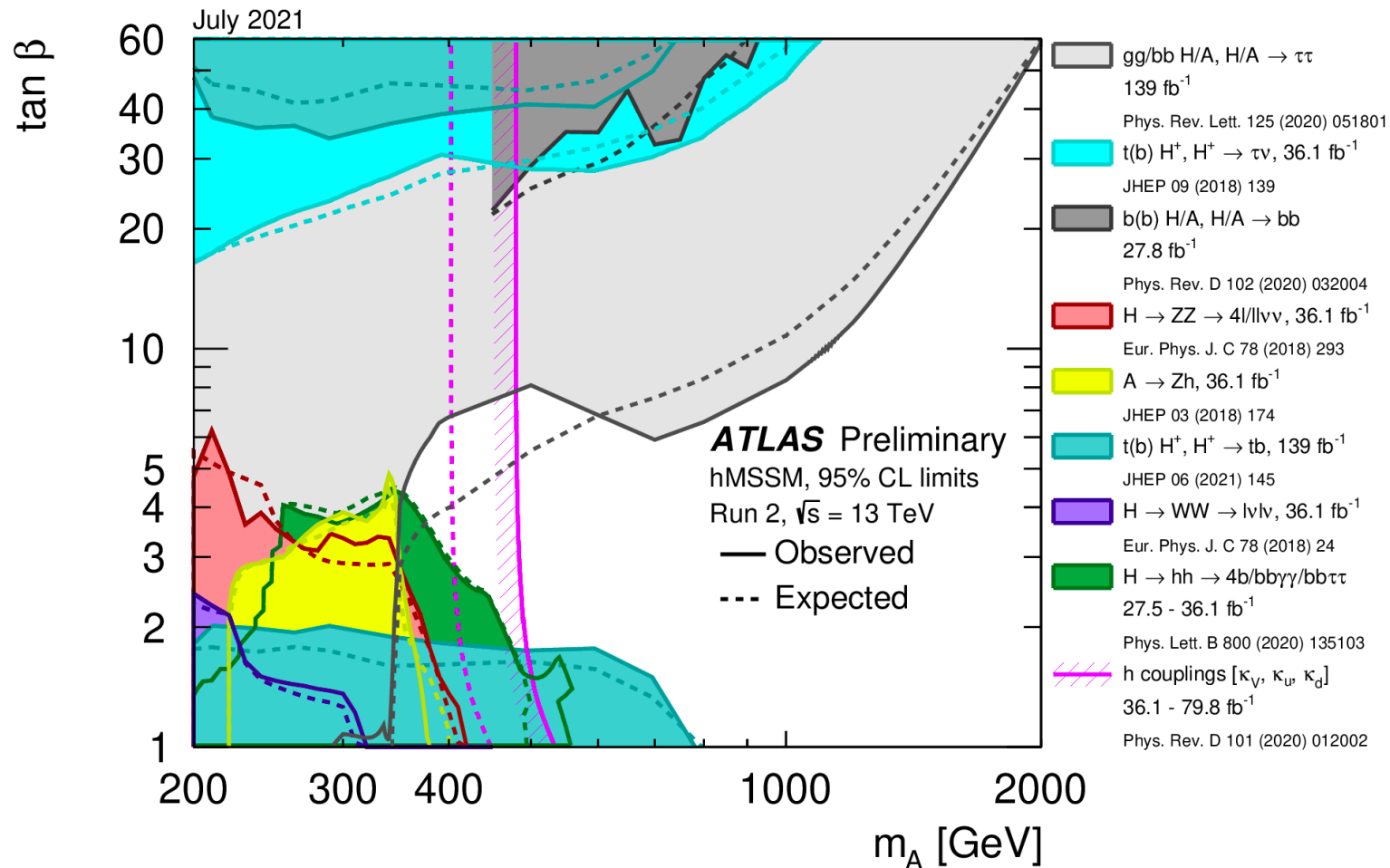
ATLAS-CONF-2021-037



Minimal Supersymmetry

ATL-PHYS-PUB-2021-030

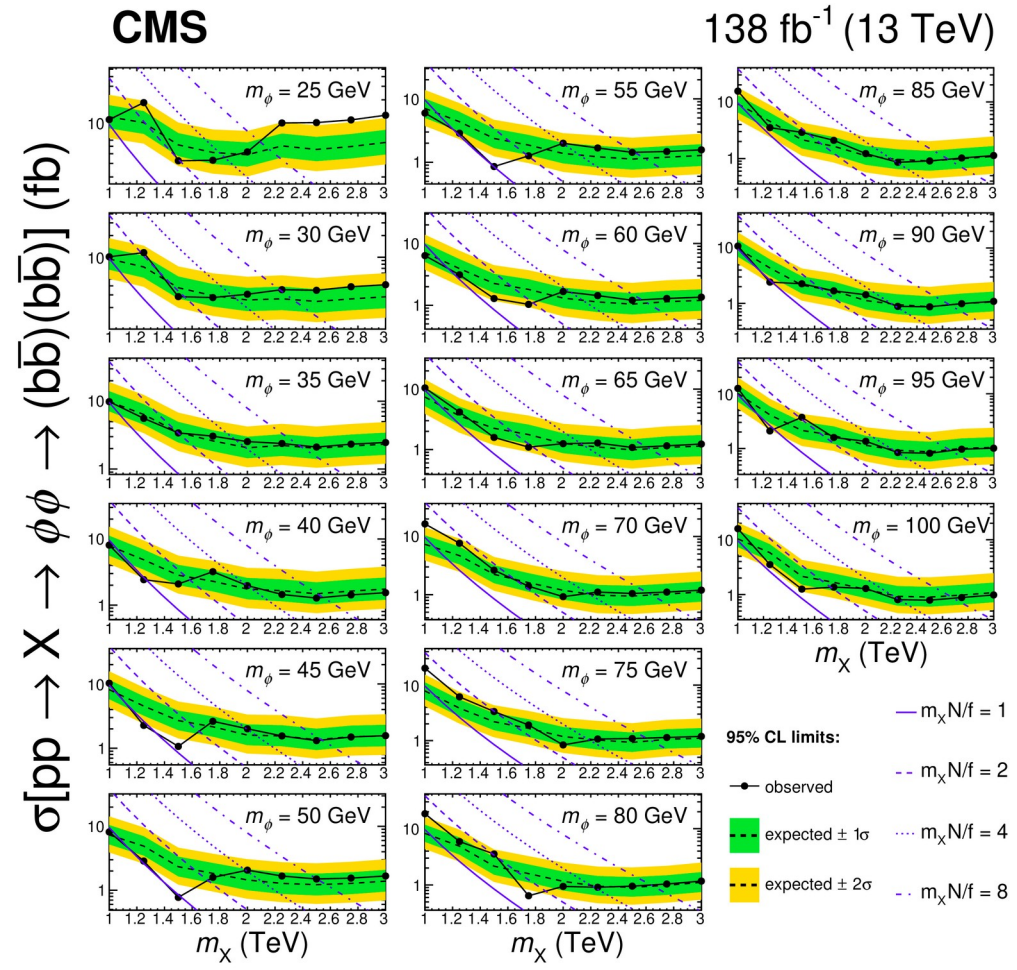
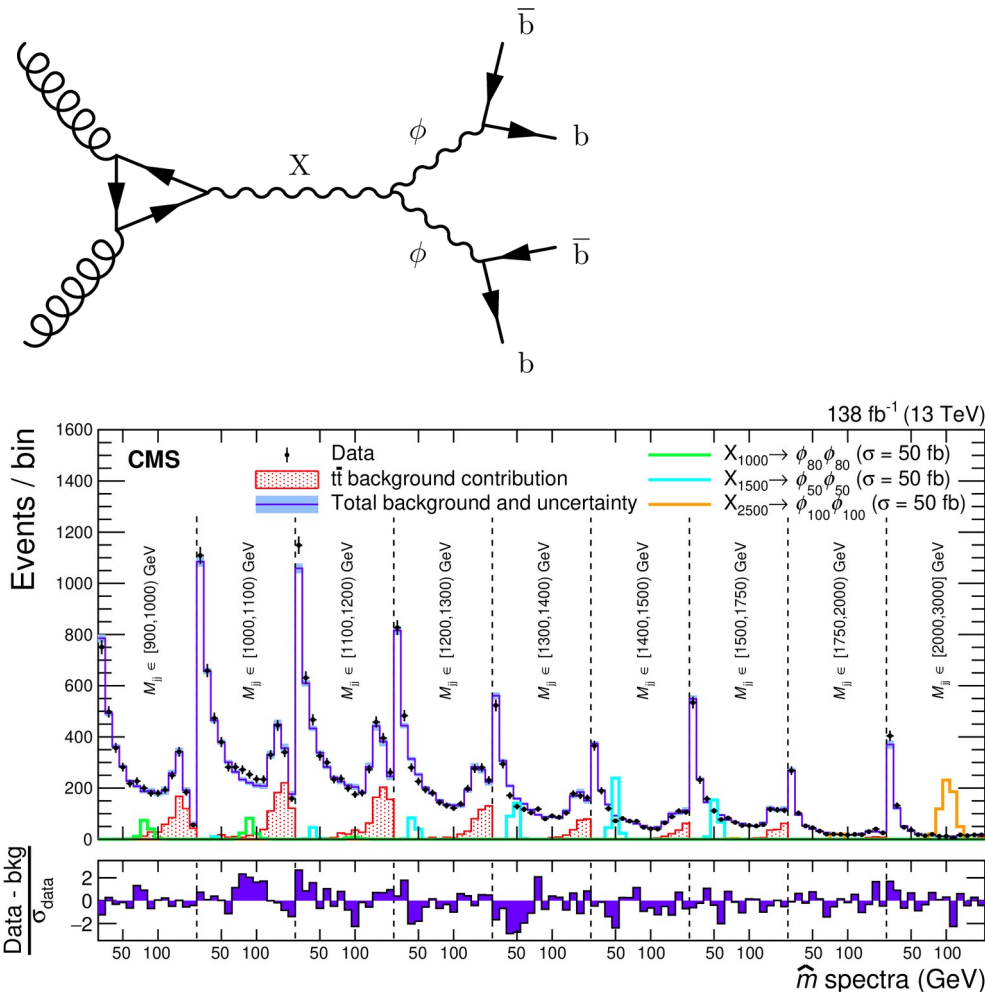
- Minimal SUSY features a 2HDM Higgs sector



Less typical 2HDM & Beyond the 2HDM

- Heavy X (1-3 TeV) to a pair of light ϕ bosons (25-100 GeV)

arXiv:2203.00480

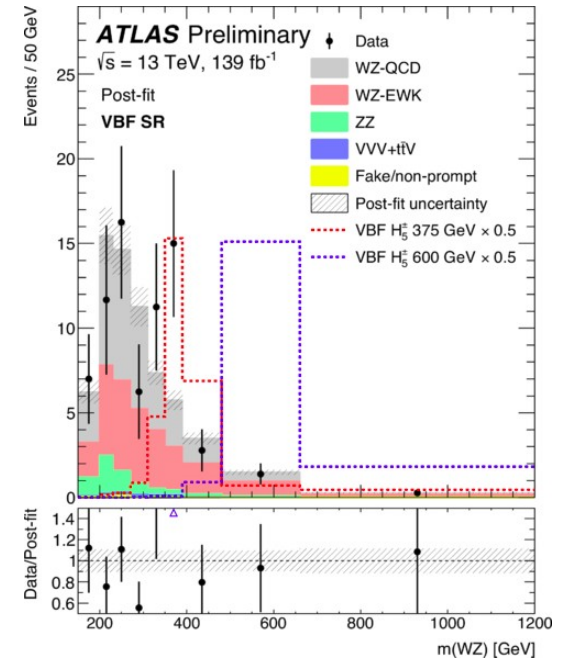
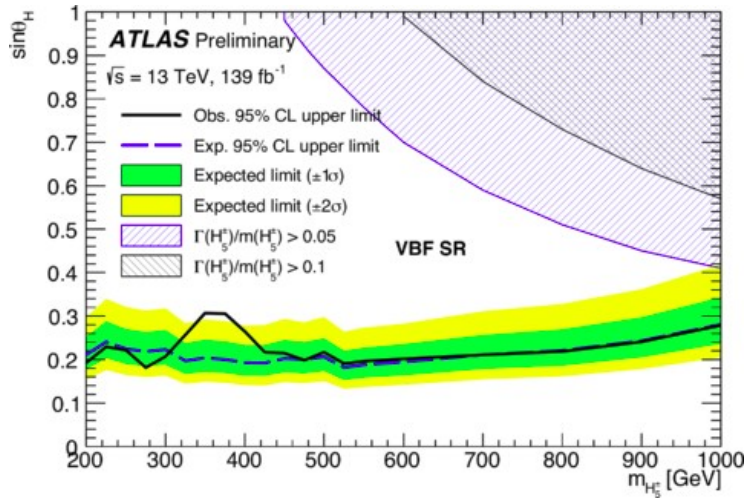
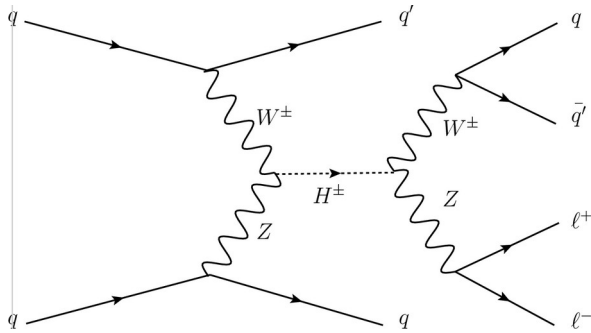


Less typical 2HDM & Beyond the 2HDM

- Inspired by Higgs triplet models

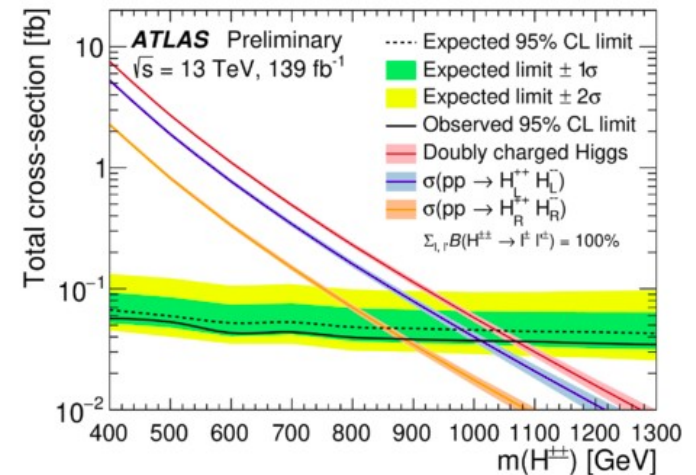
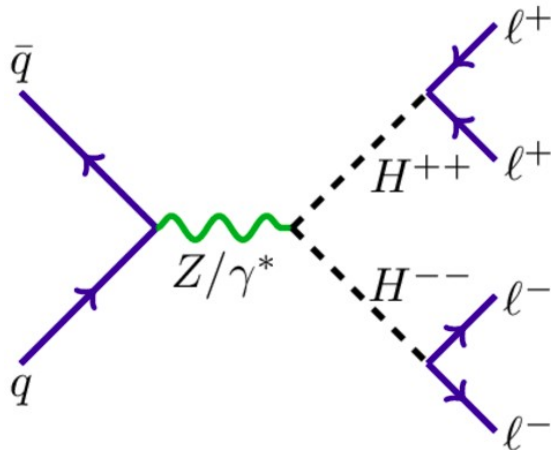
$$H^+ \rightarrow W^+Z :$$

CMS paper:
Eur. Phys. J. C 81 (2021) 723
ATLAS-CONF-2022-005



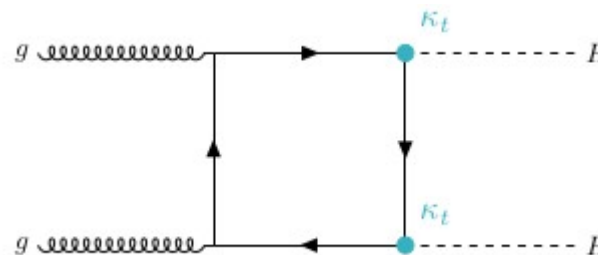
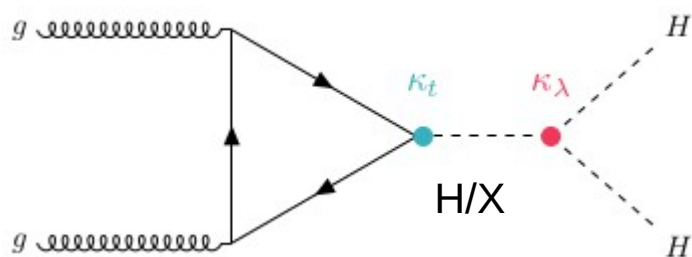
$$H^{++} \rightarrow \ell^+ \ell^+ :$$

ATLAS-CONF-2022-010



Double-Higgs boson production

- HH production is unique tool for both new and SM physics
 - Non-resonant production: probes Higgs boson trilinear coupling and its possible deviations
 - Resonant production: relevant to most extensions of the Higgs sector, as well as more exotic models
 - Most sensitive channels:
 $HH \rightarrow bbbb, bb\tau\tau, bbyy$

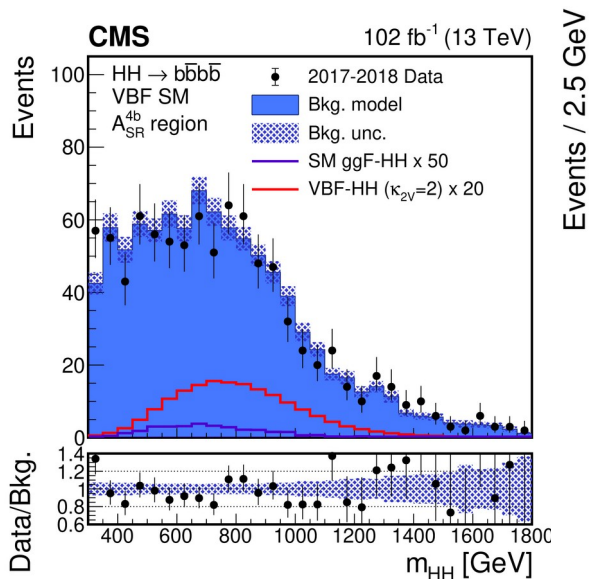


Double-Higgs boson production

- Some examples of LHC results from HH production

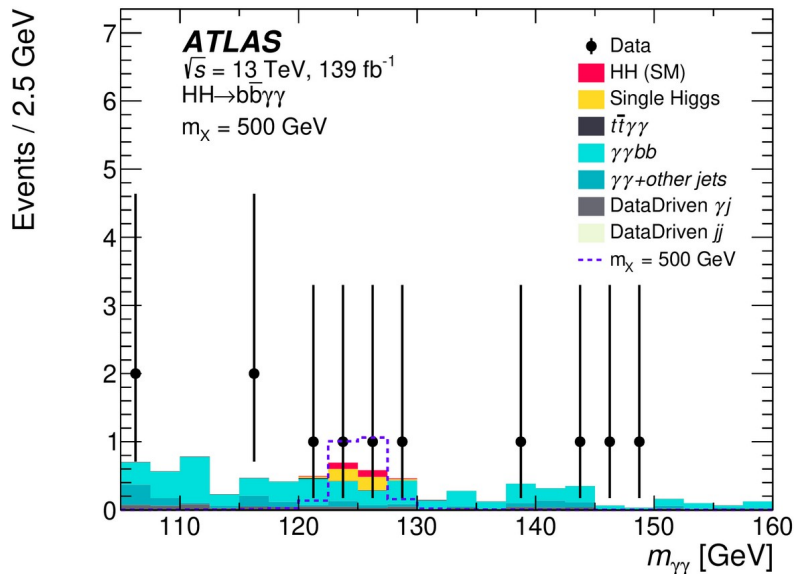
HH \rightarrow bbbb

arXiv:2202.09617

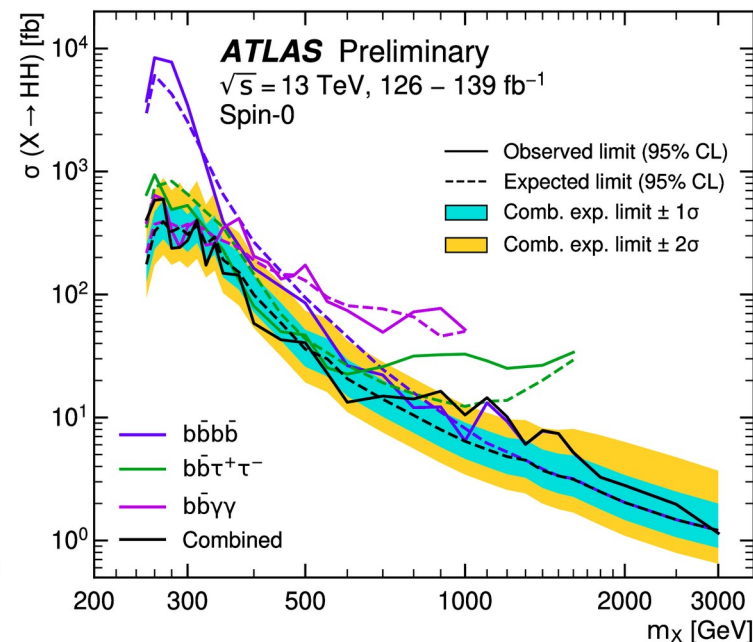


HH \rightarrow bbyy

arXiv:2112.11876



ATLAS-CONF-2021-052



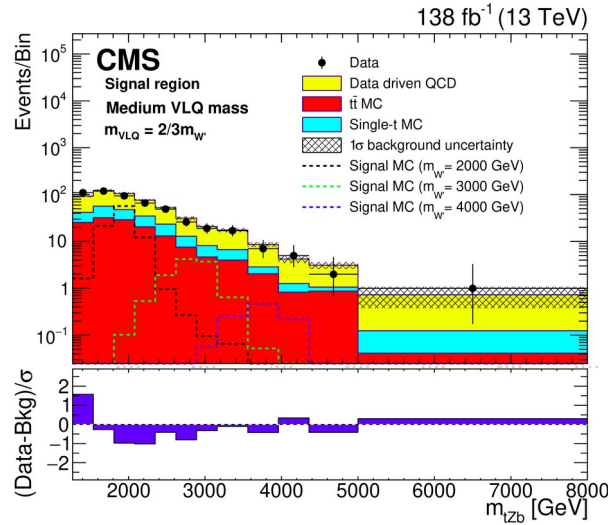
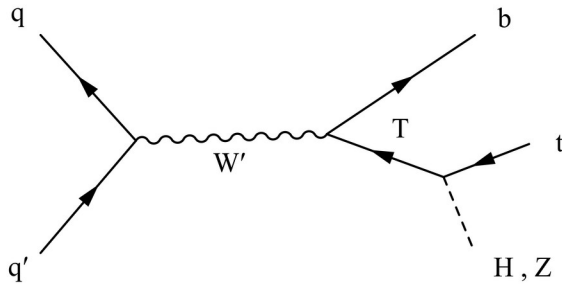


Searches for more exotic particles

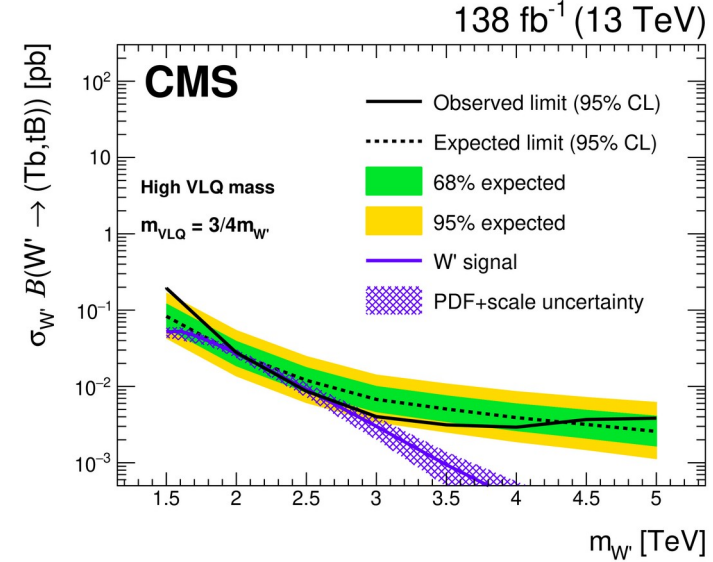
- New vector bosons
 - Very typical to look for DY production of Z' or W'
- Vector-like quarks
 - Coloured fermions with the same EWK quantum numbers for LH and RH chirality components
 - Simplest example of coloured fermions still allowed from LHC
- Extra dimensions
 - Kaluza-Klein (KK) excitations of SM particles give a plethora of new signatures

Searches for more exotic particles

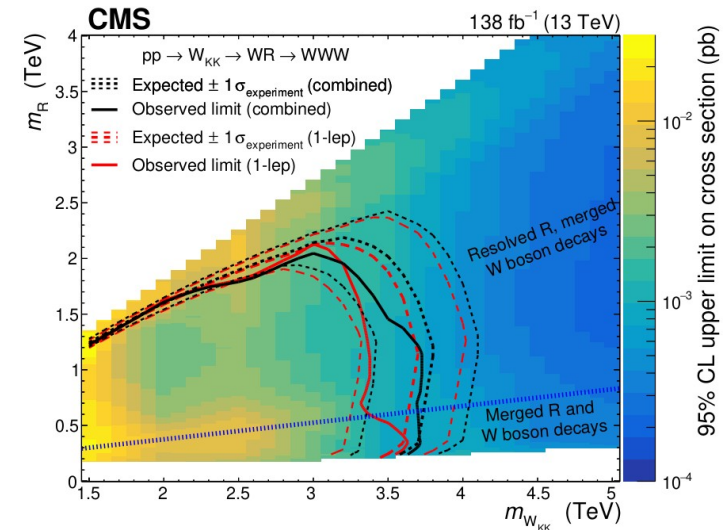
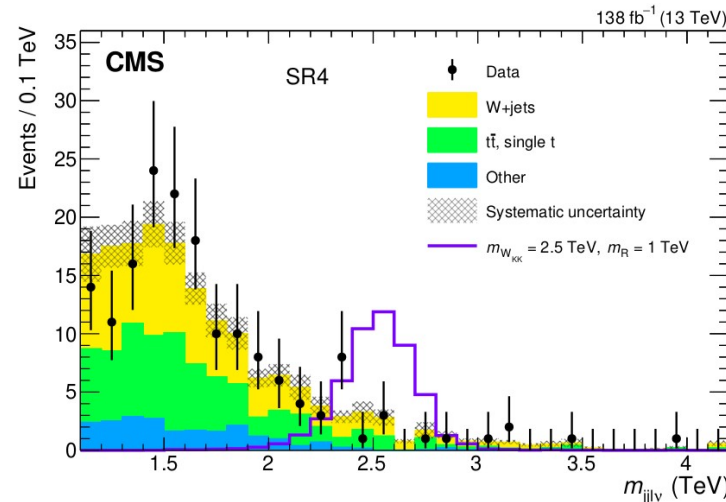
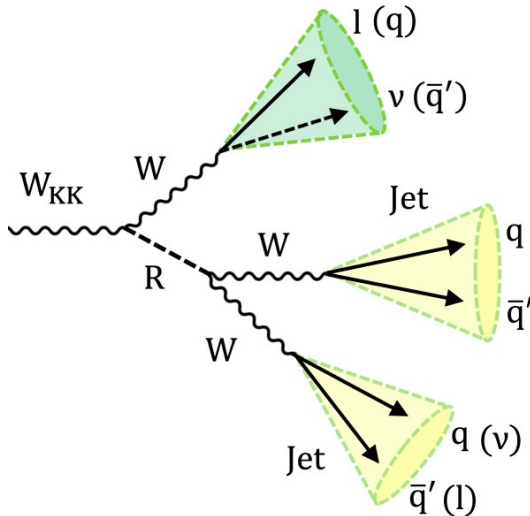
- $W' \rightarrow bT \rightarrow bt H/Z$



arXiv:2202.12988



- KK particles in 3W events [arXiv:2201.08476](https://arxiv.org/abs/2201.08476)

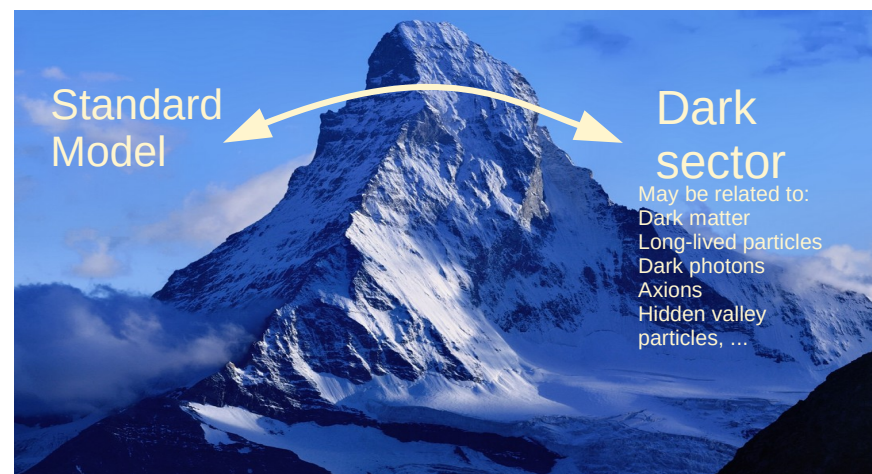


Dark sector



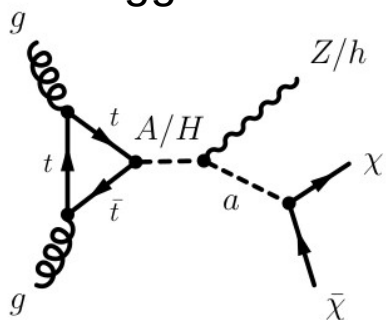
Dark sector

- How to make the connection
 - Which model
e.g. Higgs portals, ...
 - What kind of mediator
e.g. scalar, vector, ...
or agnostic via EFT

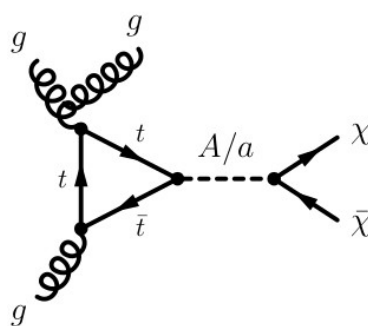


Example that has been used a lot at the LHC: 2HDM + pseudo scalar mediator
Some examples of relevant signatures:

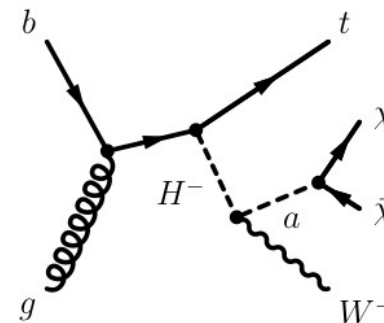
Z or h + MET
(mono-Higgs or mono-Z)



mono-jet



Other MET signatures

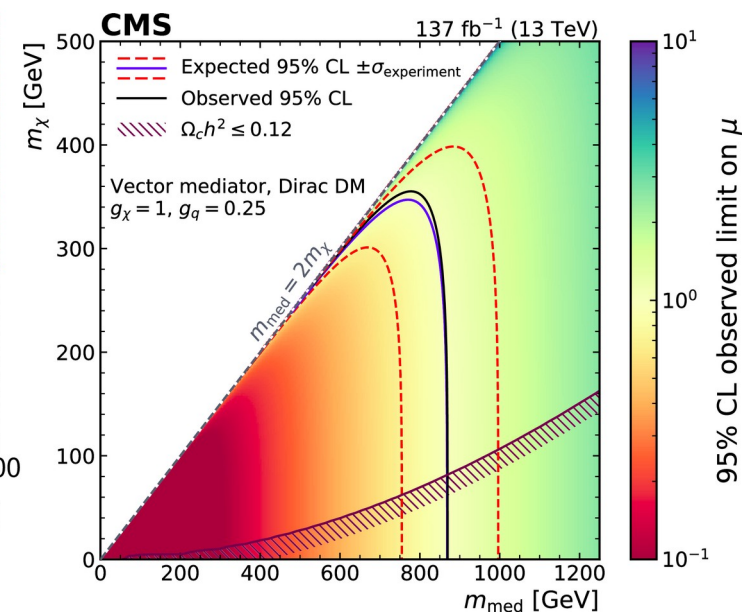
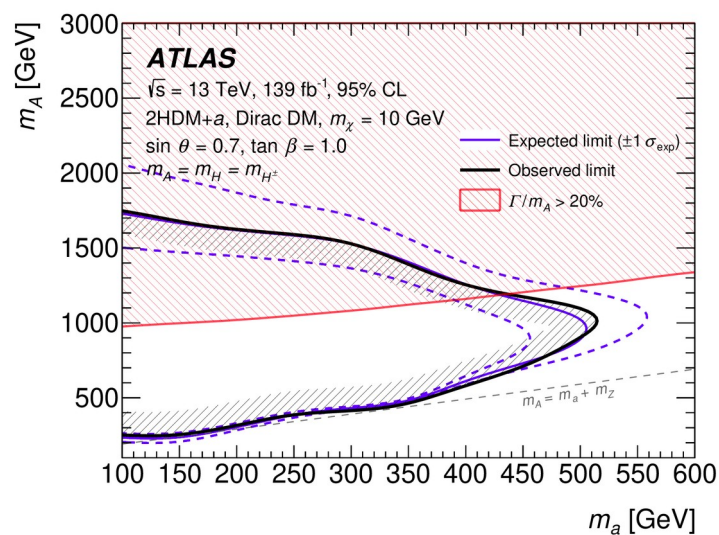
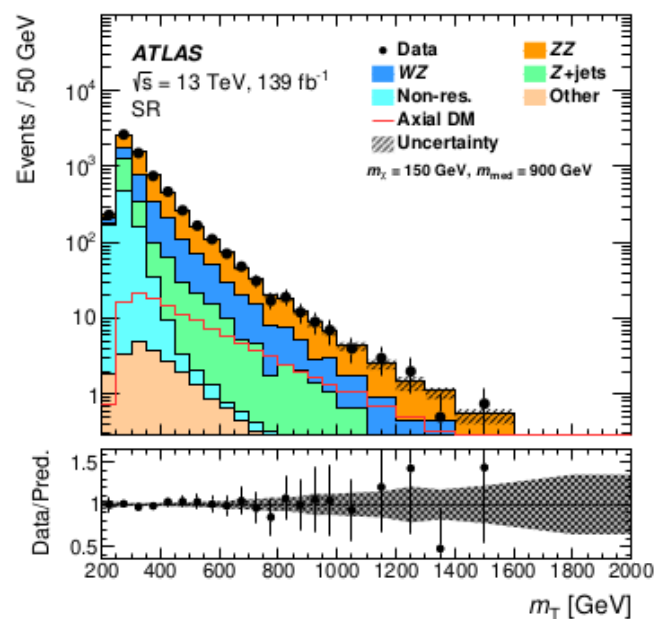
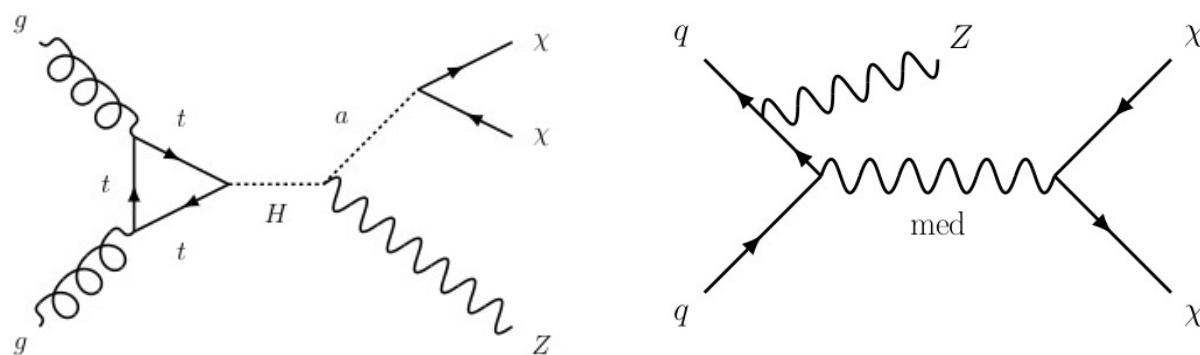


Search for mono-Z

arXiv:2111.08372

arXiv:2008.04735

- 2HDM+a, 2HDM+Z', more exotic models

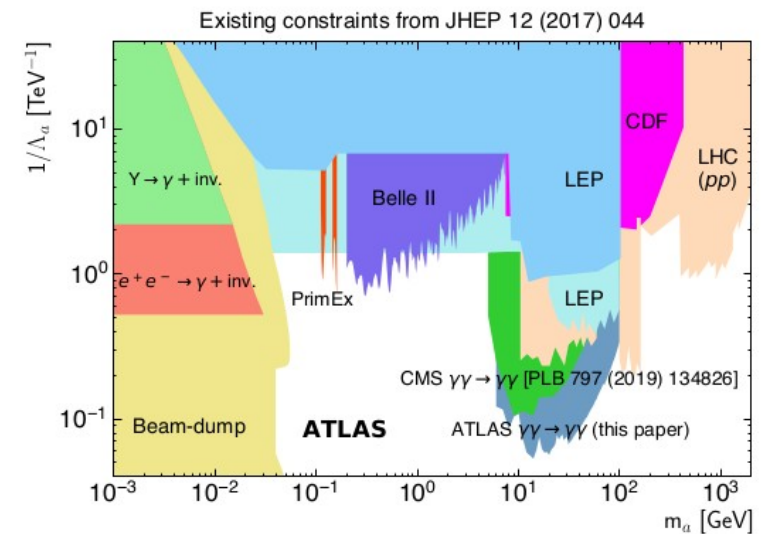
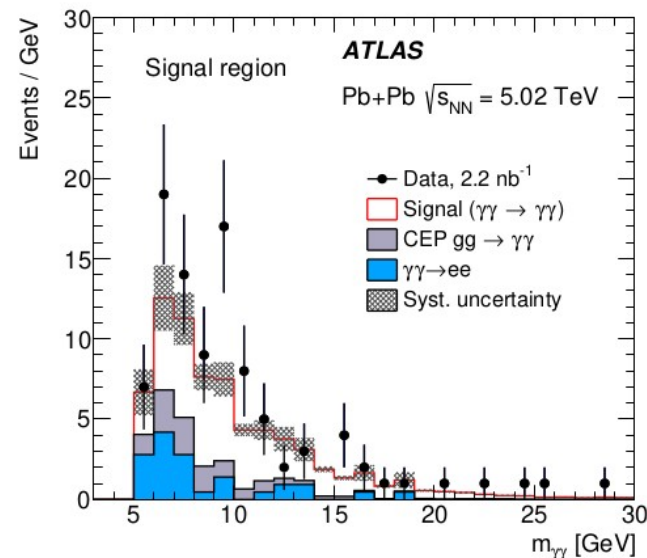
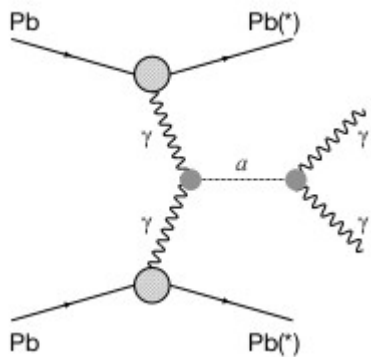


Axion-like particles

- Axion-like particles: looking for light pseudoscalar particles decaying to photons, leptons or quarks, e.g. ALPs in Higgs decays: $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma / \mu\mu bb / bbbb / bb\tau\tau \dots$

but also in heavy ion collisions

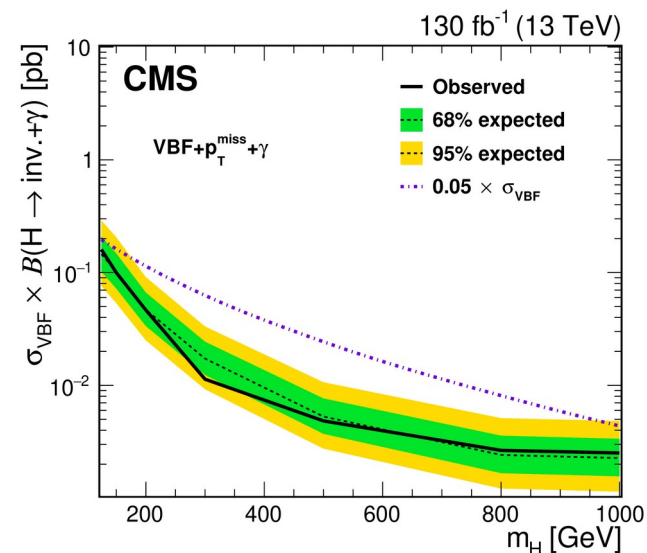
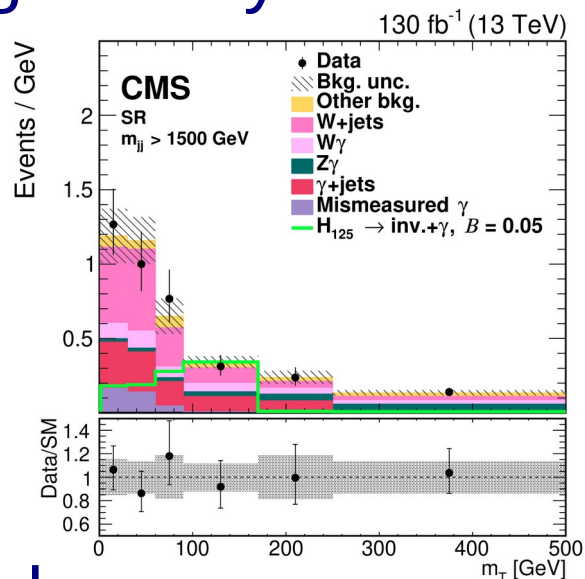
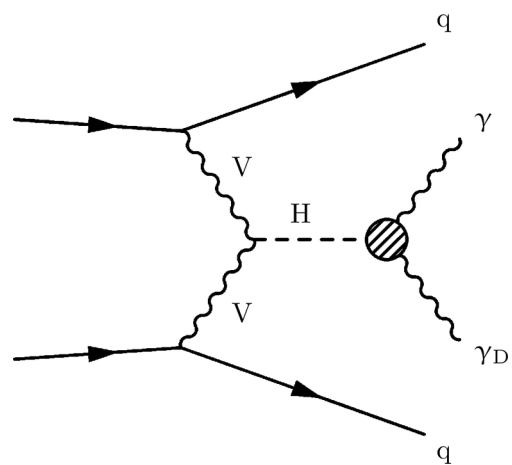
arXiv:2008.05355



VBF Higgs to invisible

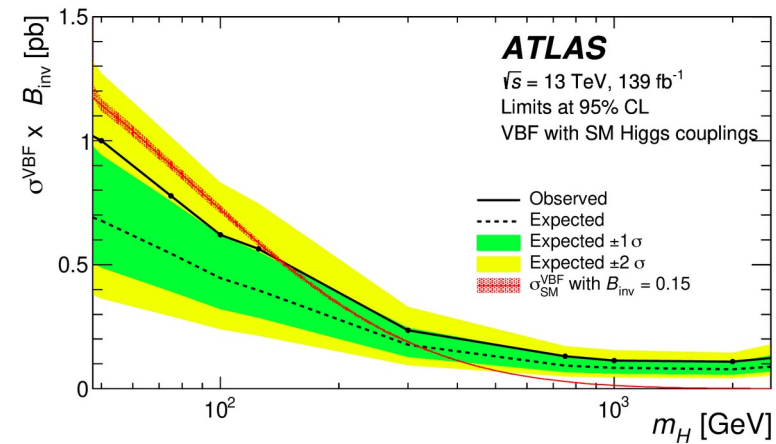
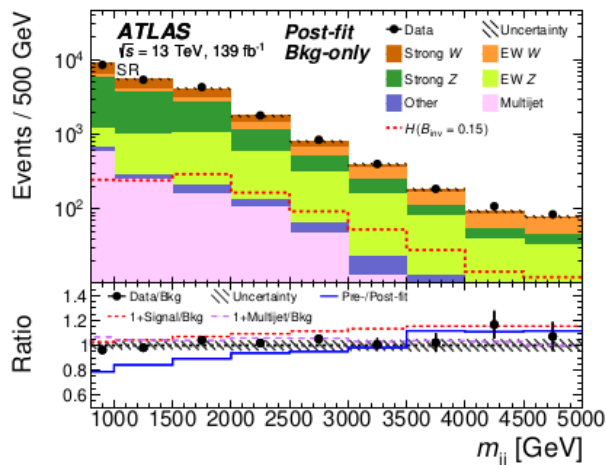
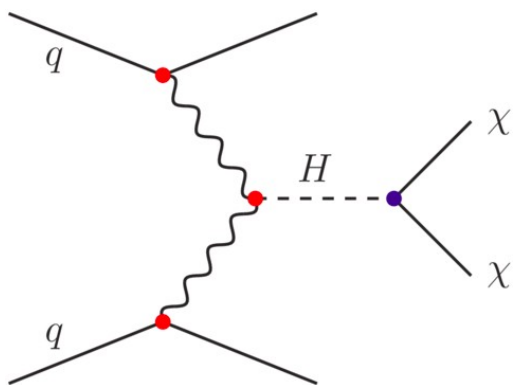
- Dark photons in Higgs decays

arXiv:2009.14009



- Fully invisible Higgs decays

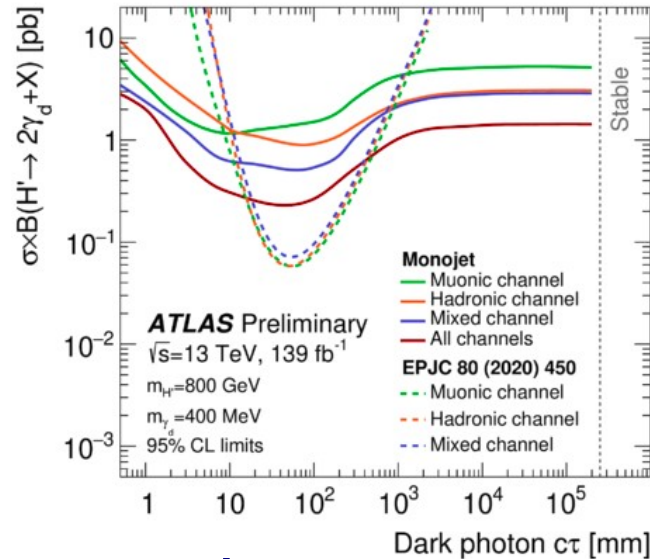
arXiv:2202.07953



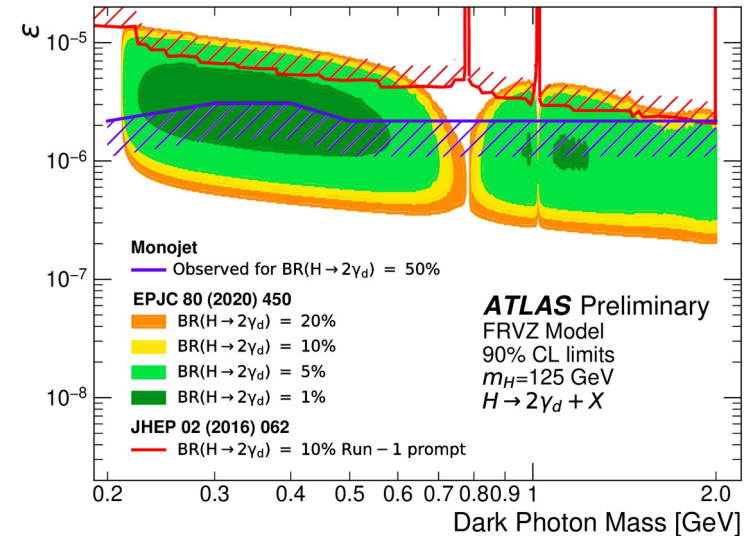
Other dark sector searches

- Monojet

Re-interpretation of mono-jet searches to dark photon and other dark sector models

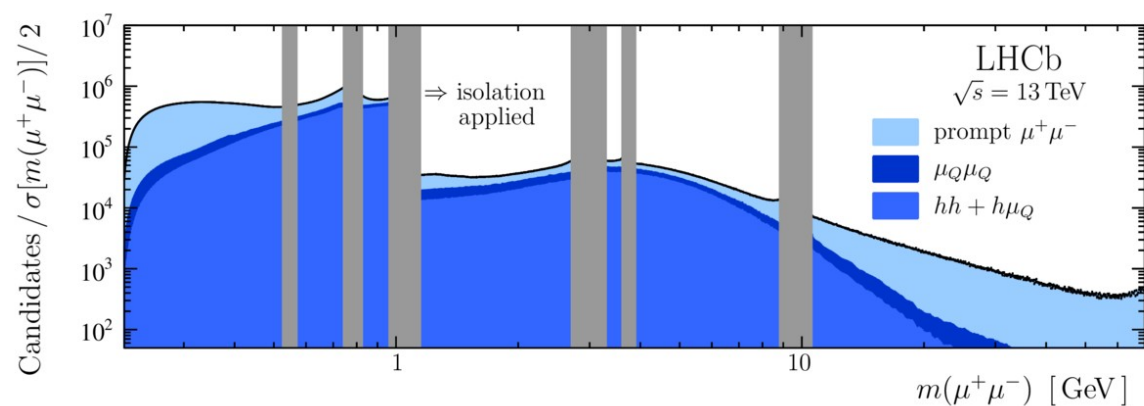


ATL-PHYS-PUB-2021-020

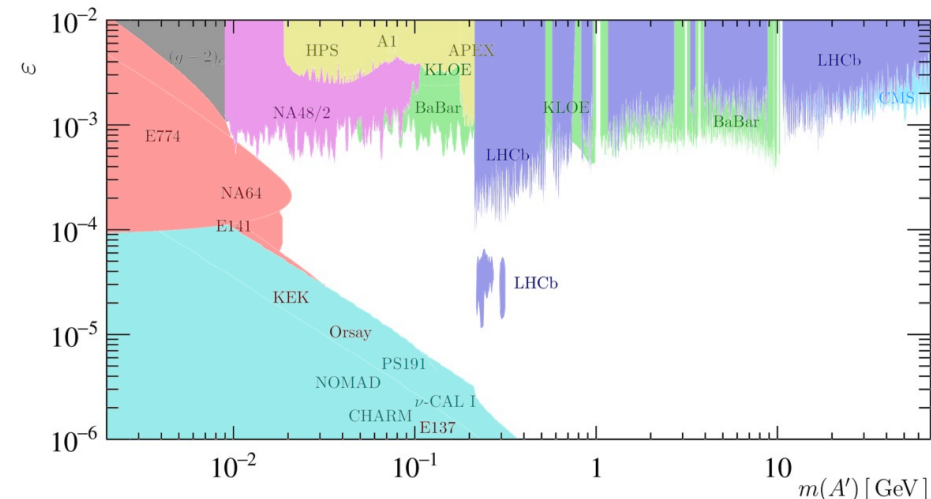


- Dark photons at LHCb

Prompt and long-lived dark photons to $\mu\mu$

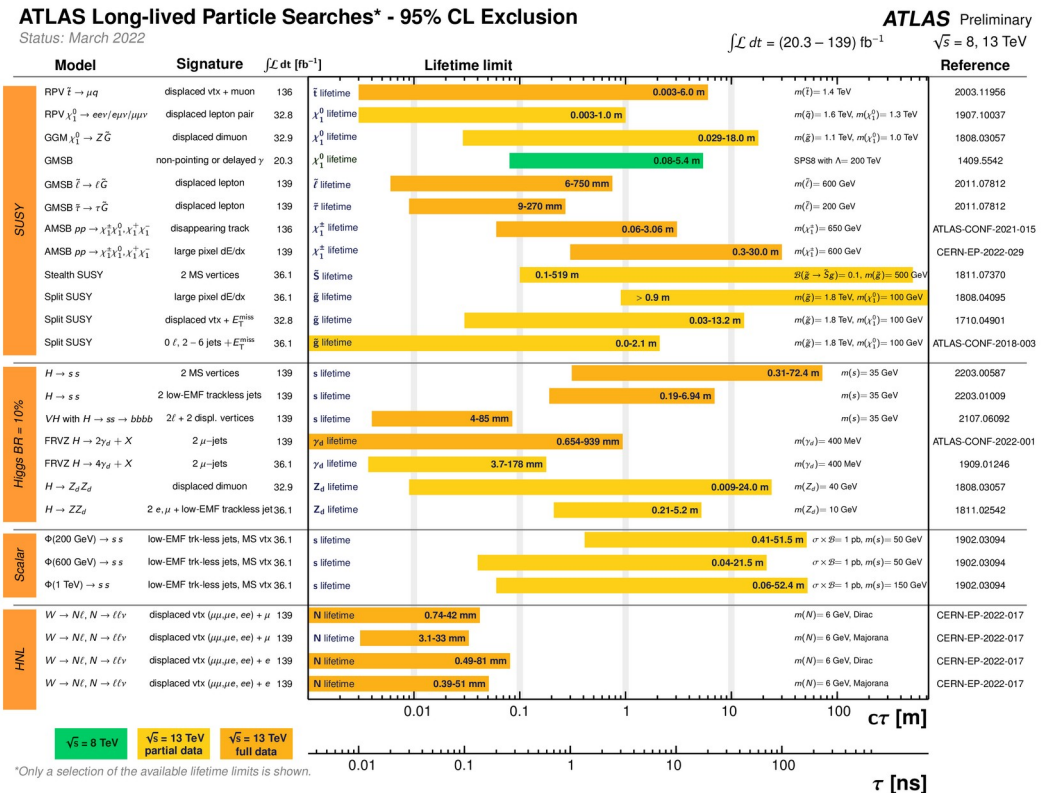


arxiv:1910.06926



Long-Lived particles

- This is a topic that is broad enough that does not fall into a single physics category
 - SUSY, dark sector, axions, ... all have signatures with long-lived particles
 - Particularly challenging since LHC detectors were not designed for such signatures



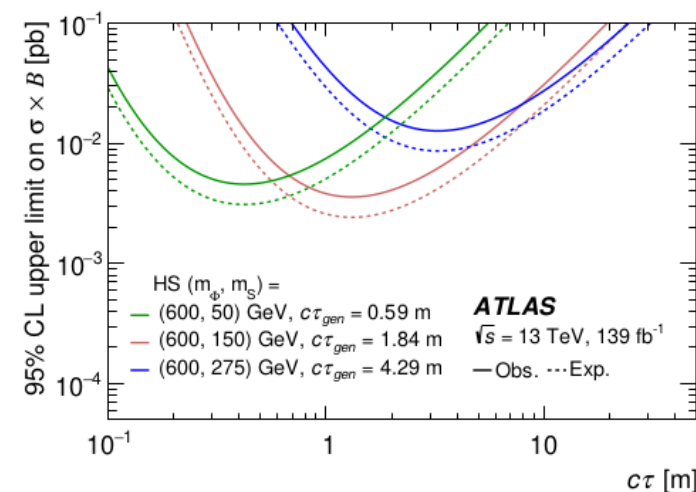
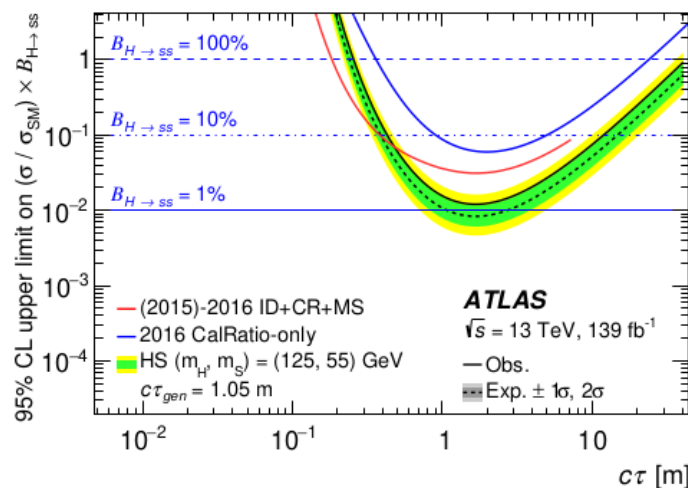
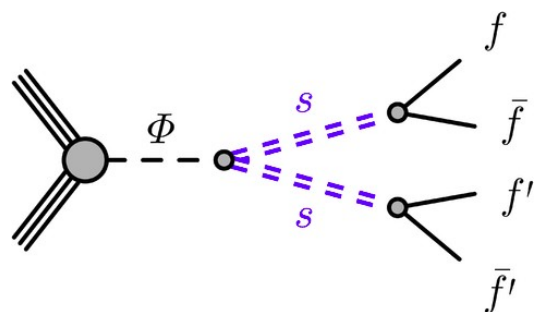
ATL-PHYS-PUB-2022-011

Examples of long-lived particle searches

arXiv:2203.01009

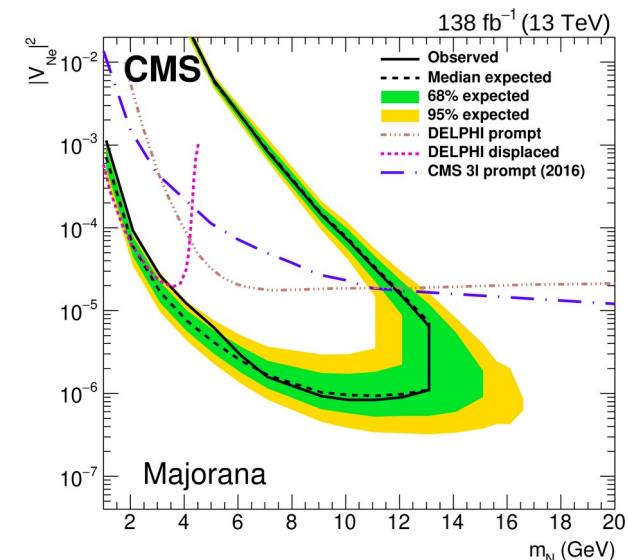
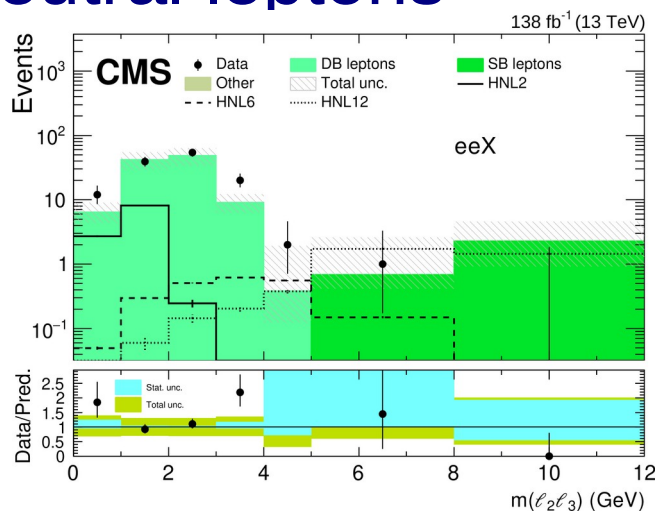
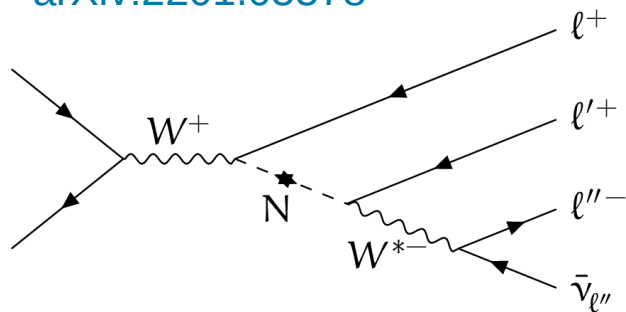
arXiv:2012.01581

Displaced hadronic jets



Long-lived heavy neutral leptons

arXiv:2201.05578

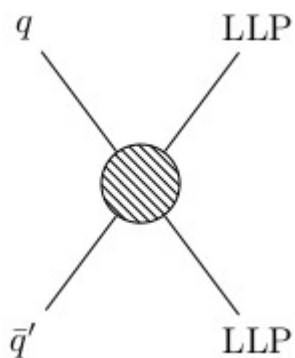


Examples of long-lived particle searches

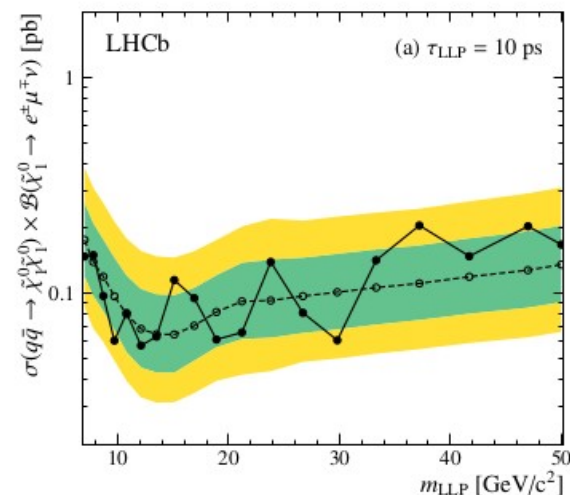
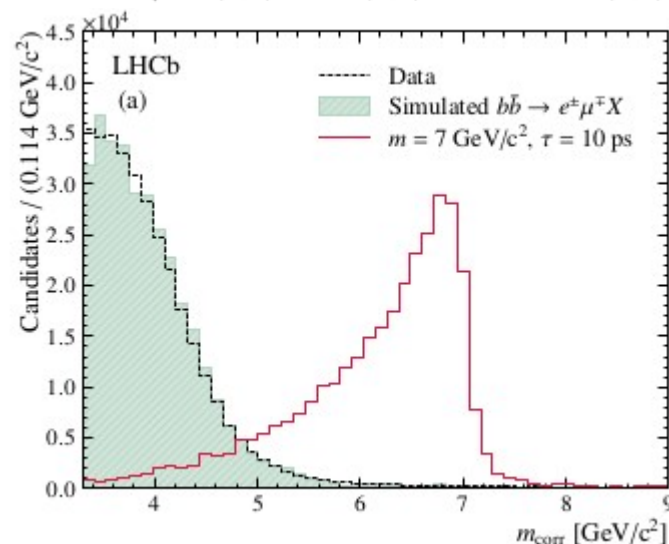
LHCb: [arXiv:2012.02696](https://arxiv.org/abs/2012.02696)

ATLAS: [arXiv:1907.10037](https://arxiv.org/abs/1907.10037)

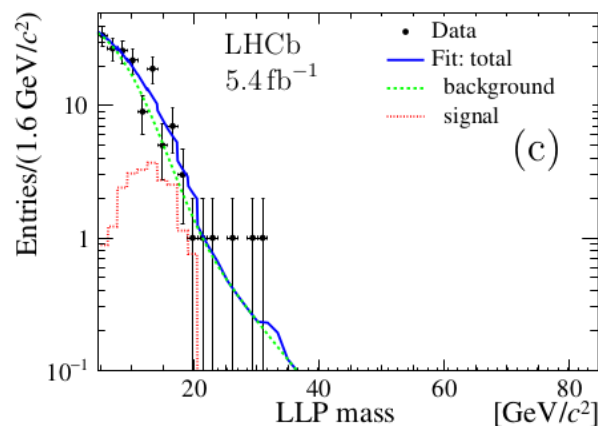
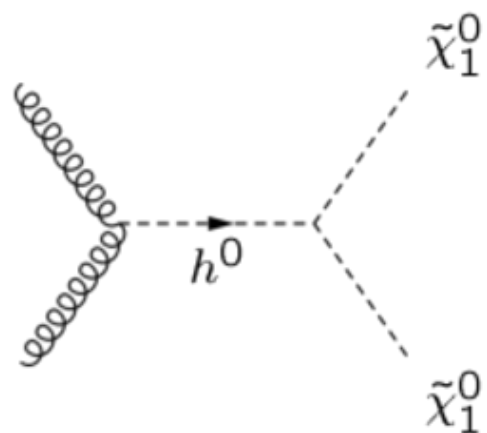
- LLP $\rightarrow e\mu\nu$



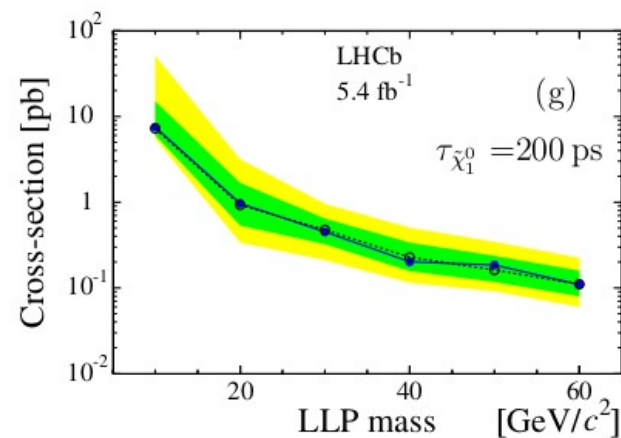
$$m_{\text{corr}} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2 \theta} + p(e\mu) \sin \theta$$



- LLP $\rightarrow \mu q q$



[arXiv:2110.07293](https://arxiv.org/abs/2110.07293)





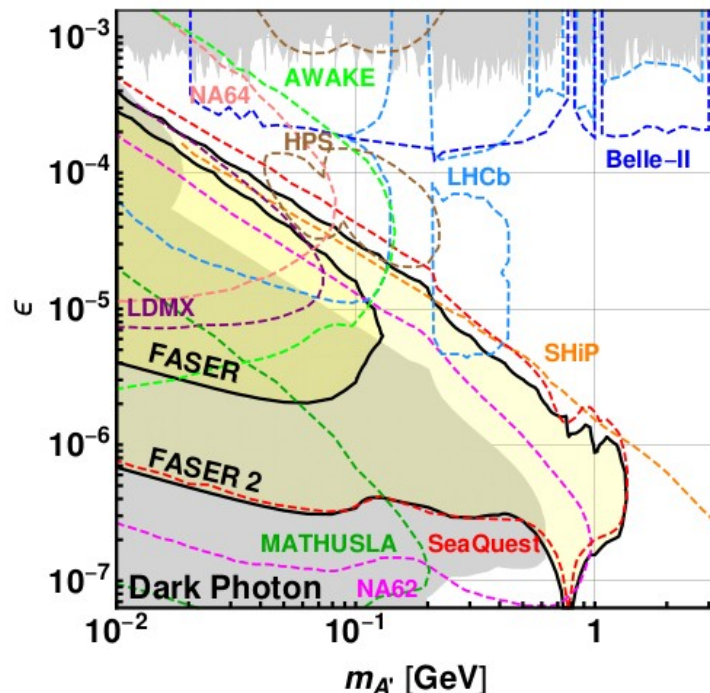
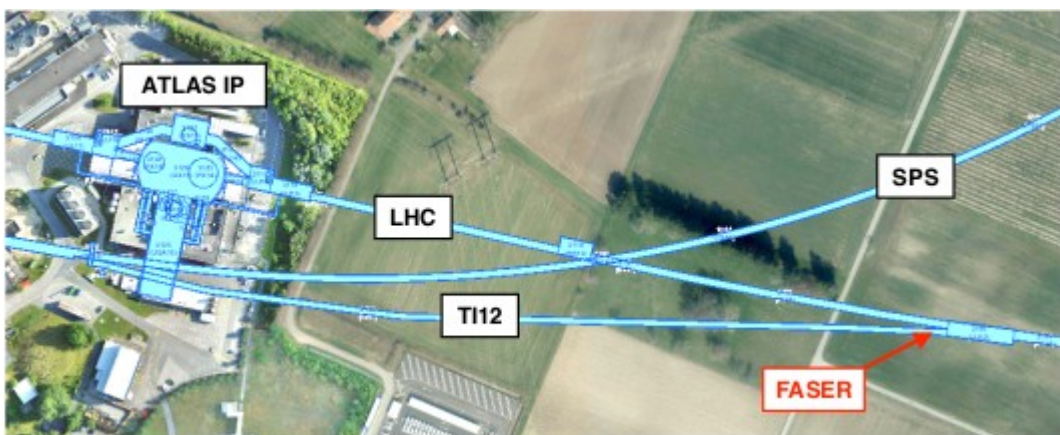
Future prospects

- Any new collider project approved or proposed will be relevant to BSM physics searches
- Here I will only briefly mention
 - Dark sector experiments related to the LHC
 - FASER, Anubis, MATHUSLA, CODEX-B, SHIP, ...
 - High-Luminosity LHC (HL-LHC):
approved; will operate at 13 TeV from 2029 for about 10 years to collect 3 ab^{-1}
 - Future Circular Collider (FCC):
proposed; 100-km tunnel in the Geneva area to host ee, pp and maybe also ep colliders after 2040

Dark sector experiments related to the LHC

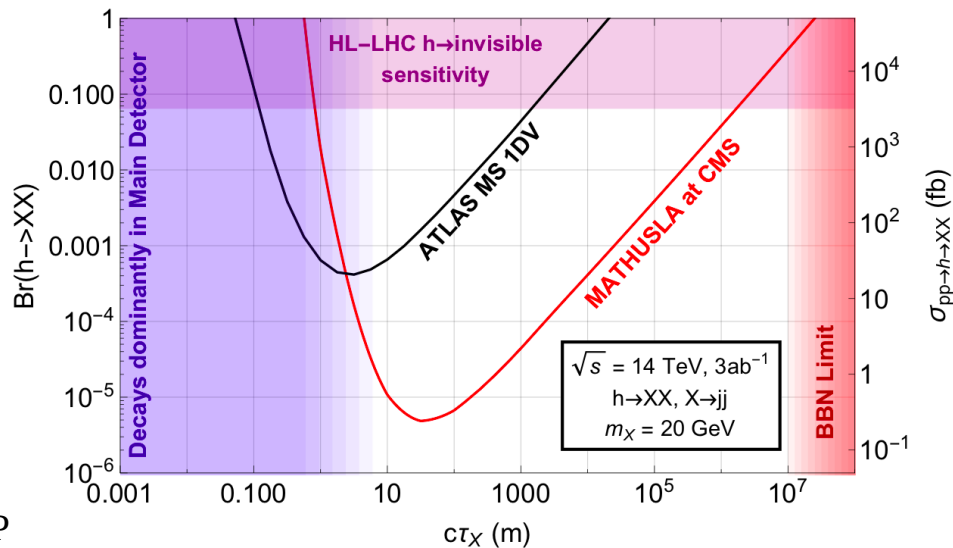
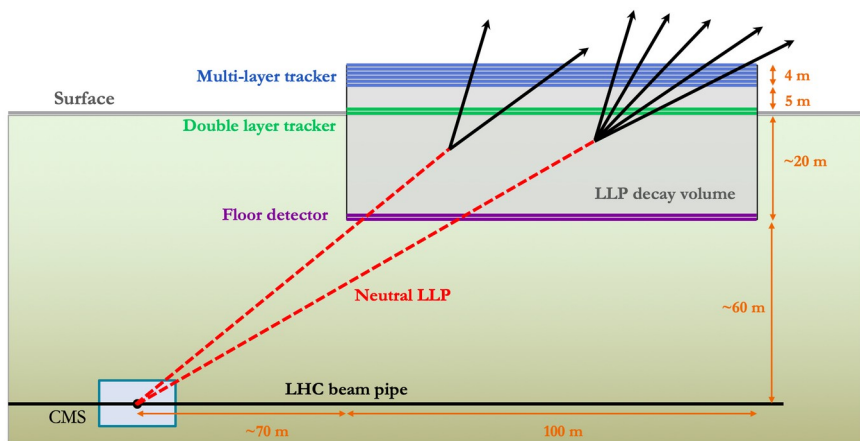
- FASER**

arXiv:1811.12522



- Mathusla**

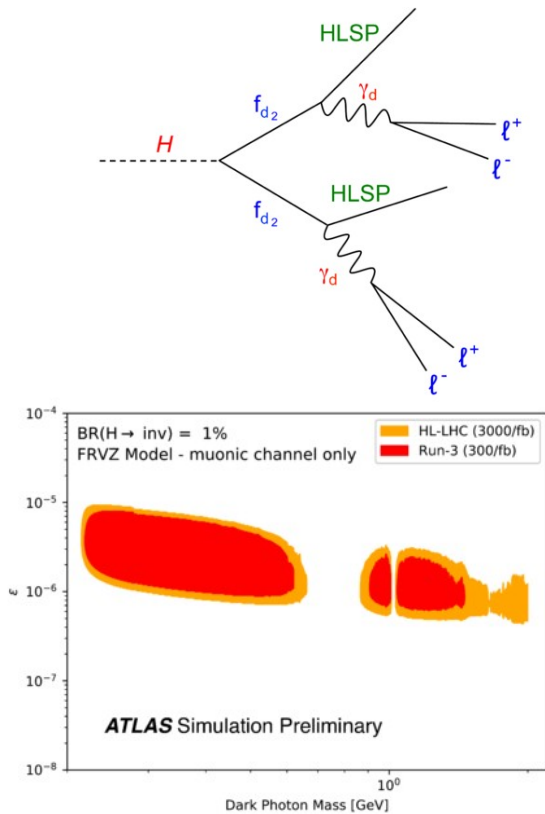
arXiv:1806.07396



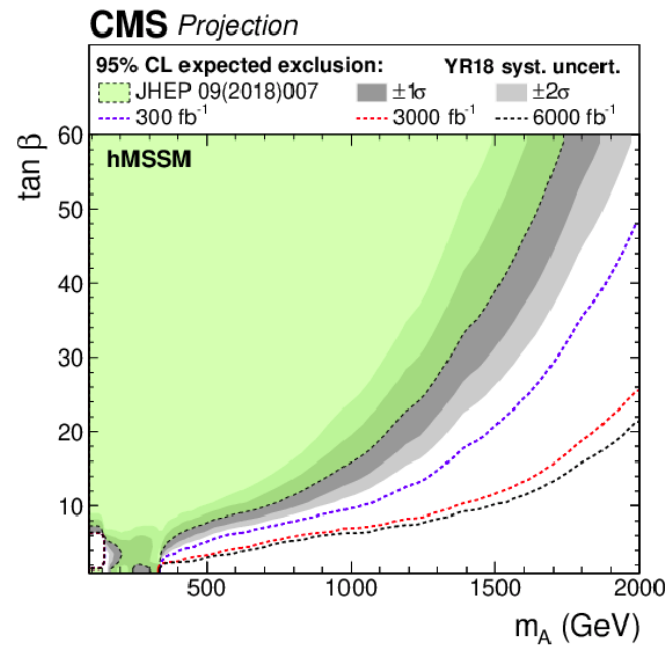
Prospects: HL-LHC

ATLAS and CMS projections of sensitivity at HL-LHC are mostly based on extrapolations of current results with some assumptions on future performance
 Di-Higgs projections play prominent role: HH observation to $> 3\sigma$ per experiment, but more exotic signature studies are also available e.g.:

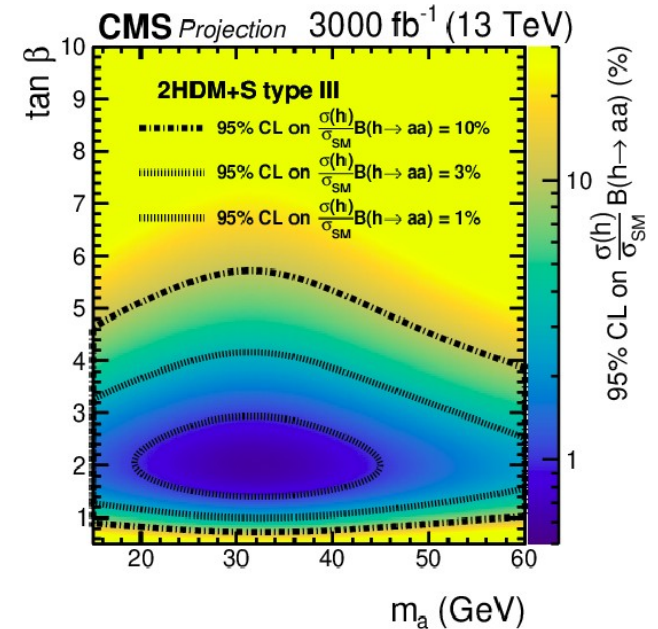
Dark photons to muon jets



MSSM $H \rightarrow \tau\tau$

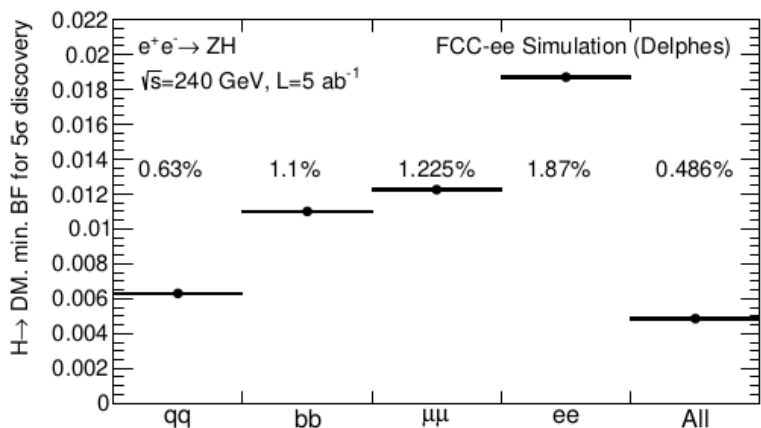


$H \rightarrow aa \rightarrow bb\tau\tau$

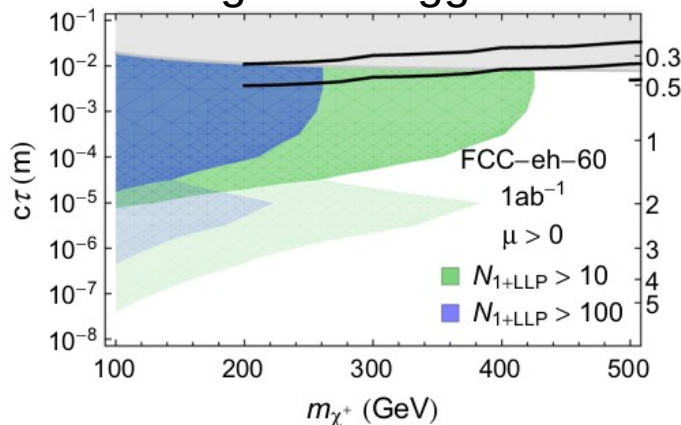


Prospects: FCC

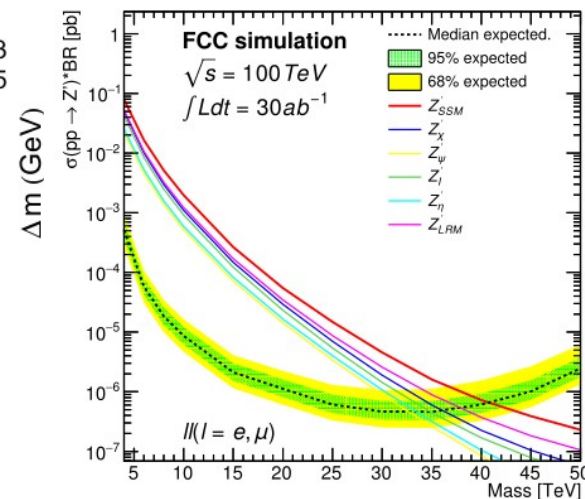
Higgs to invisible @ FCC-ee



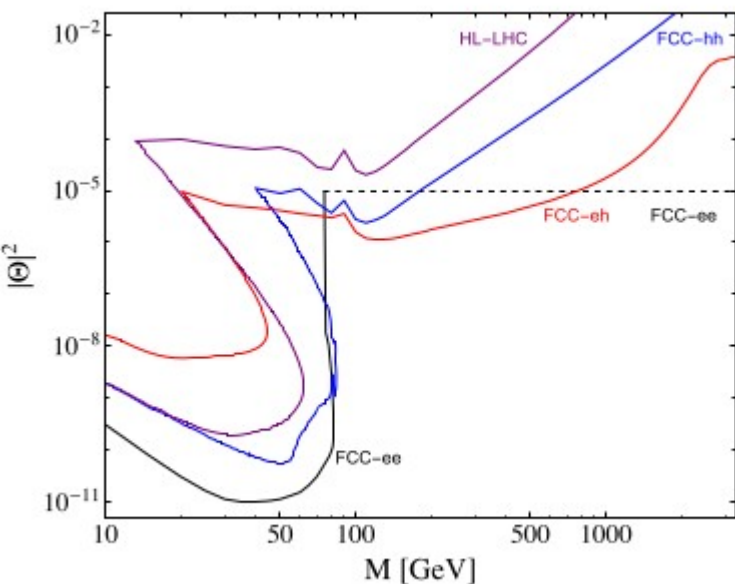
Long lived Higgsinos



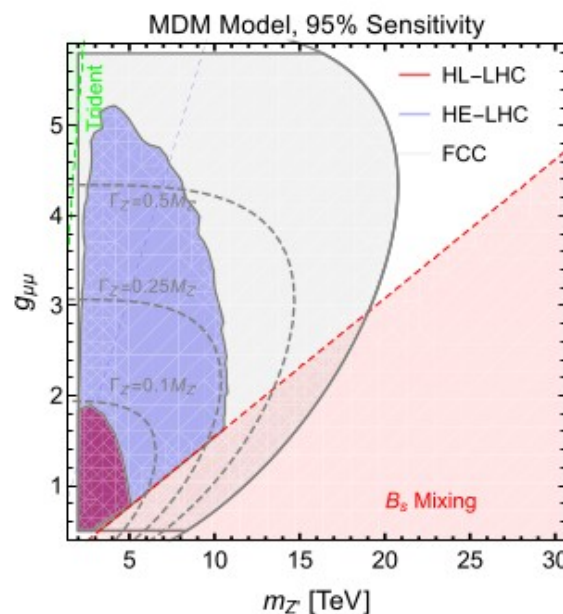
SSM Z' searches



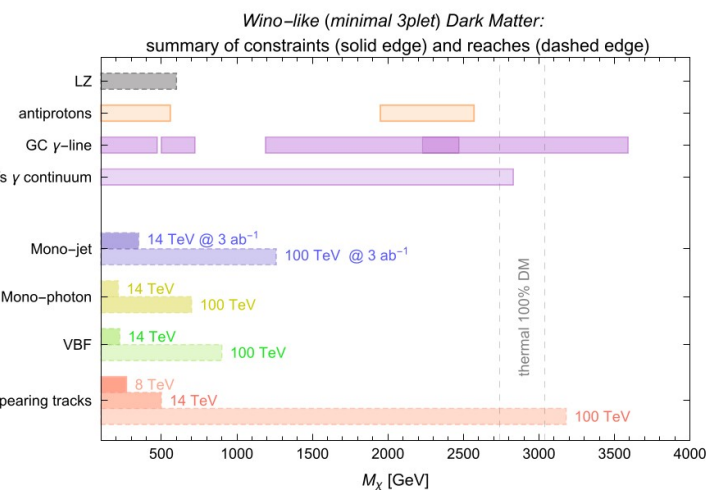
Sterile neutrino searches



Z' model for flavour anomalies



Dark matter





Conclusions

- No new physics yet ...
- But we have made progress
 - We know much more about what the new physics may look (or may not look) like with respect to what we knew before the LHC
 - The exploration of the region below 1 TeV has made strides but it is still incomplete

New physics is not just a possibility but a certainty. The challenge remains to figure out where exactly it is.



Additional slides

SM Higgs vs 2HDM

- Measurements of SM Higgs have a significant impact on the 2HDM

ATLAS-CONF-2021-053

CMS-HIG-17-031

