Overview of searches, prospects, what are we missing?

Beyond SM 2 (Feebly Interacting Particles)

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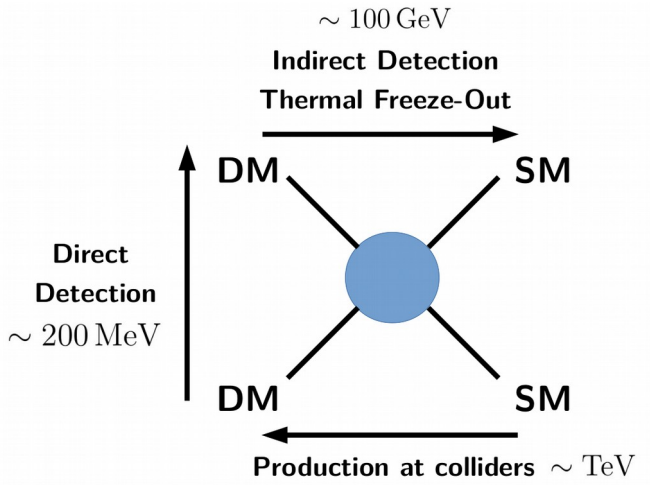
Feebly Interacting Particles.

- This is a huge category that contains BSM particles that their interactions are not strong with the SM.

- Within this category we can have:
  - Dark Matter (See talks from S. Westhoff, M. Kirsanov, V. Duk)
  - Heavy Neutral Leptons (See talks from J.Klaric and R. Tramontano)
  - Long-lived particles (See talks from G. Cottin, A. Li, M. Naseri, A. Shah, H. Mei, N. Tarannum, R. Mammen Abraham, L. Shchutska)
  - Axion-like particles (See talks from M. Schnubel, D. Zuliani)
  - Dark showers (See talks from S. Kulkarni and S. Sinha)
  - Prompt interactions of FIP (See talks from A. L. Solis, Xuli Yan and E. Reynolds)
  - Etc

- It is such vast landscape that we aim to explore. More detailed discussions in forthcoming talks in BSM2 session.

Dark Matter.



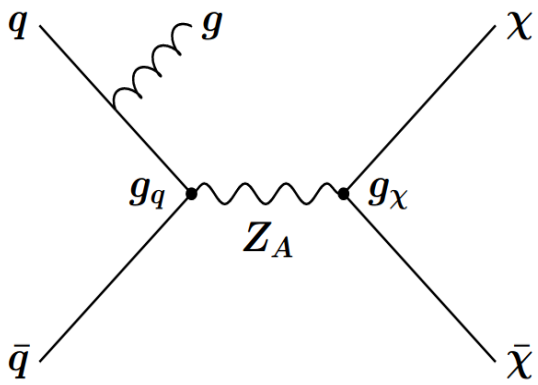
- There is clear observational evidence of the existence of Dark Matter (DM) in gravitational interactions.
- DM would be a neutral and weakly interacting particle: potential challenge to look for in colliders.
- Several UV completed models contain a DM candidate, however it may be interesting to parametrise our ignorance in simplified models.
- LHC makes a great effort in the search for DM, both ATLAS and CMS have more than 80 publications (excl. Conf. Notes) in this subject.
- Non-dedicated searches are also important in this matter, for example looking for DM mediators.

Dark Matter.

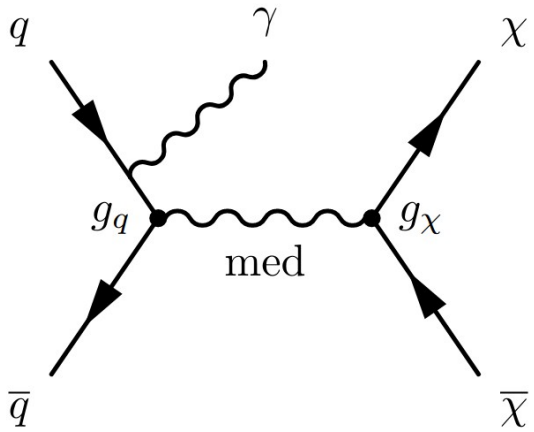
- Different searches allow us to explore different topologies that may correspond to different models.
- Most of the DM searches (and also non-dedicated ones) are complementary in order to set bounds in different models.
- We can find mono-X searches (with X = jets, photons, Z/W, Higgs, top) that look for s-channel DM mediators are complementary to the mediator searches.
- Also known particles as the Z boson or the 125 GeV Higgs can be used to look for DM signatures.
- Non-dedicated searches are also important in this matter, for example looking for DM mediators.

Dark Matter.

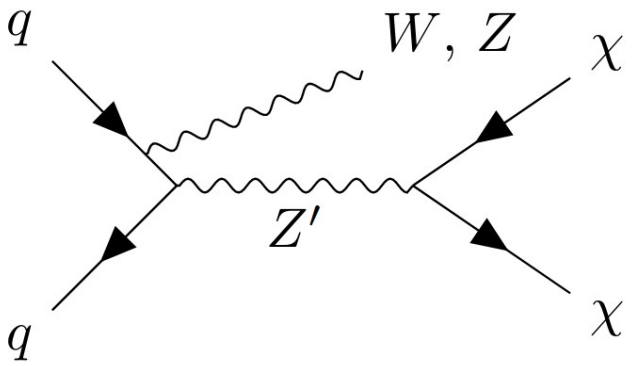
Mono-jet



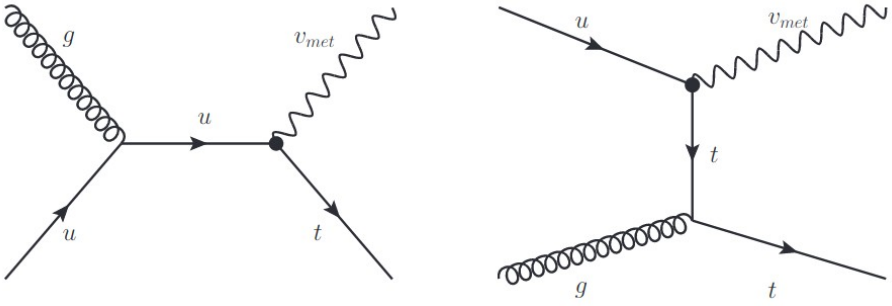
Mono-photon



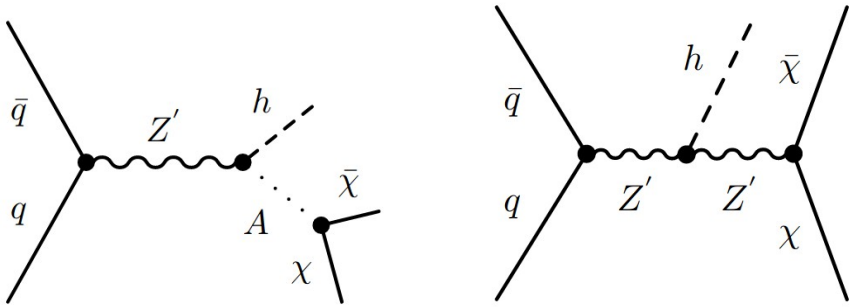
Mono-Z/W



Mono-top



Mono-Higgs



Dark Matter.

Mediator searches in SM decays.

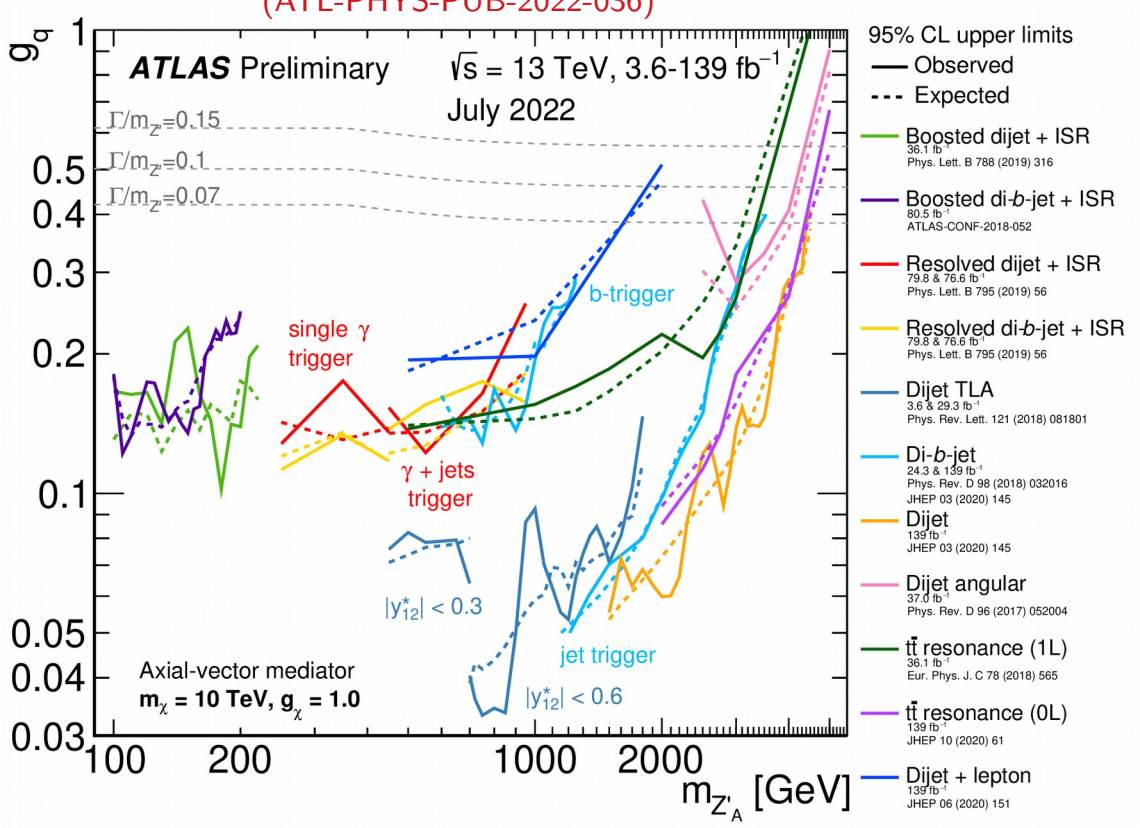
One can set limits on the mediator mass and its couplings to SM particles.

Dedicated searches to low mass and high mass regions.

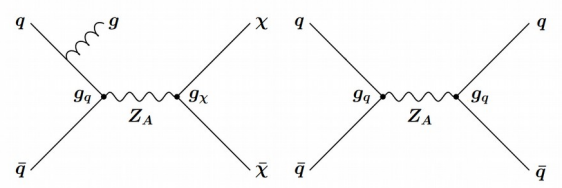
Direct comparison with the theoretical input.

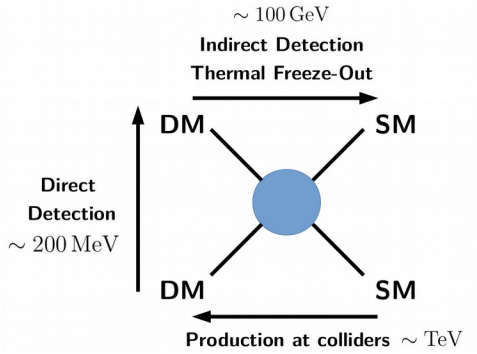
(Using computer tools such as Z'-explorer: 2109.13194)

(ATL-PHYS-PUB-2022-036)



Dark Matter.

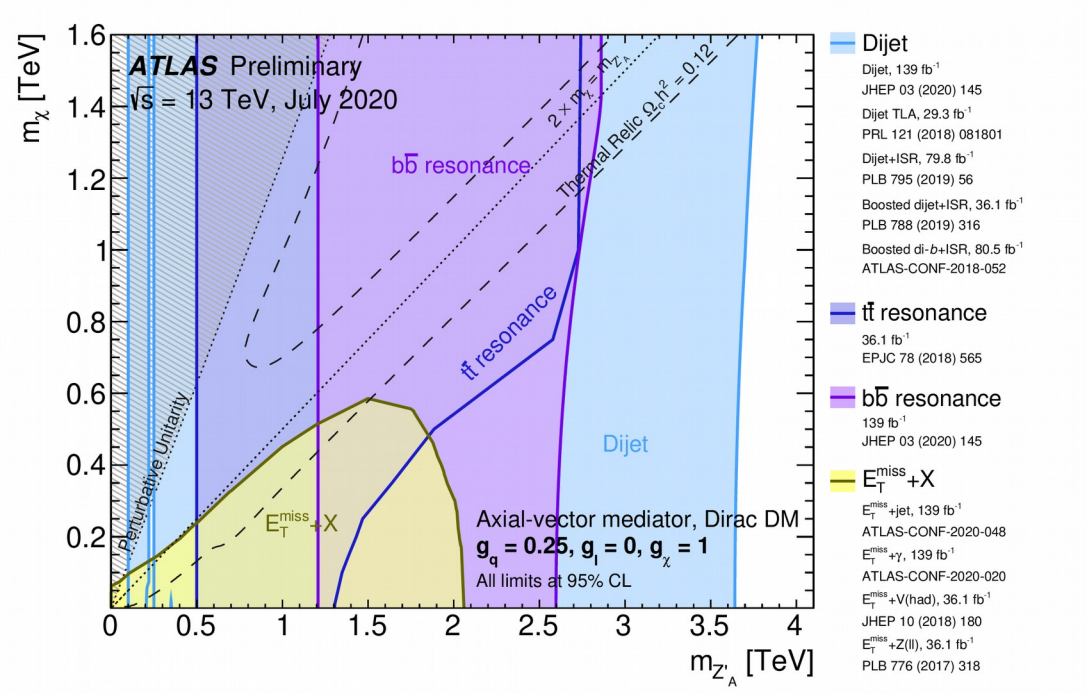


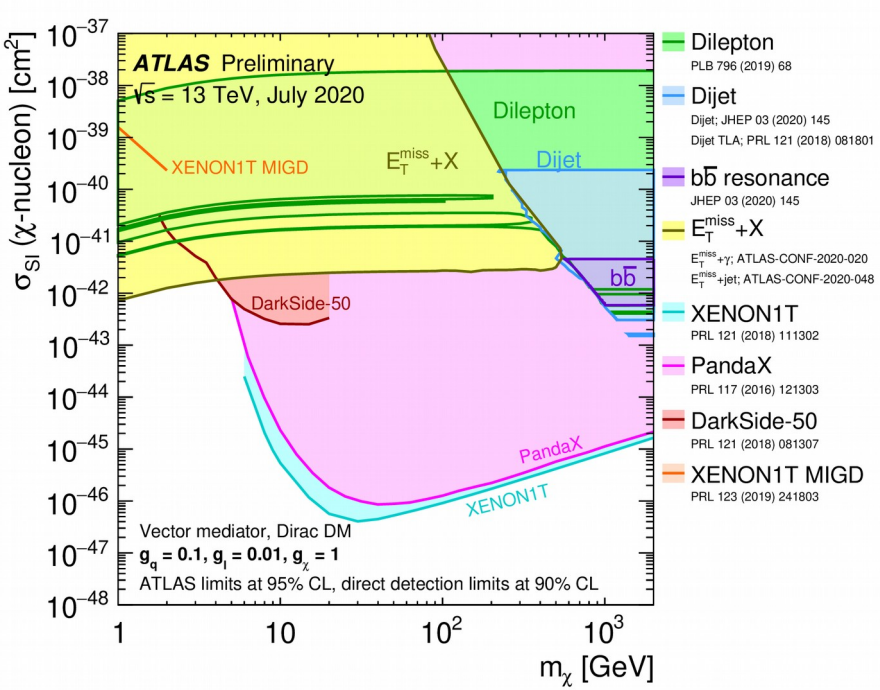


Complementary to direct detection searches
(Buchmuller, Dolan, Malik, McCabe, 1407.8257)

Collider searches present better performance at low DM masses and also constraints are almost independent from DM mass.

(ATL-PHYS-PUB-2022-036)



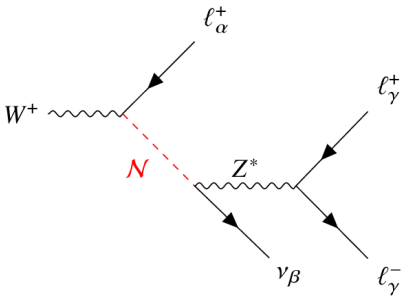


Heavy Neutral Leptons.

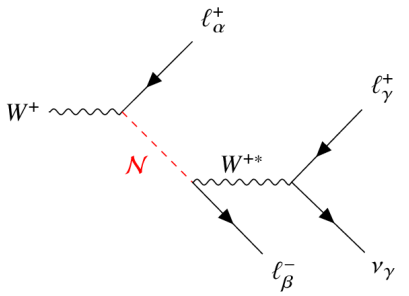
- Heavy Neutral Leptons can be an extension of the SM that connect to the leptonic sector to give rise to neutrino masses (seesaw)
- They can explain different unsolved puzzles (neutrino masses, dark matter, baryon asymmetry) and can have Majorana or Dirac nature.
- Due to their tiny coupling to the leptonic sector of the SM can be long-lived providing displaced vertices: $\tau_N \approx (4.3 \times 10^{-12}\ \mathrm{s})|U|^{-2}(m_N/1\ \mathrm{GeV})^{-5}$
- ATLAS and CMS have more than 20 publications on this topic

Heavy Neutral Leptons.

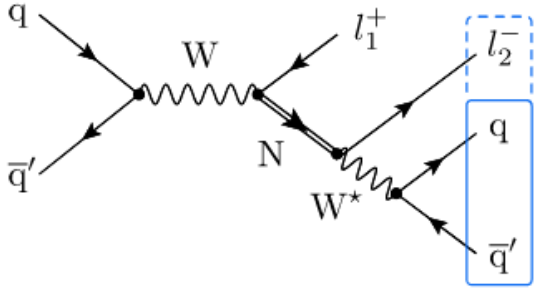
- ATLAS (2204.11988):
  1 prompt lepton +
  2 leptons from displaced vertex



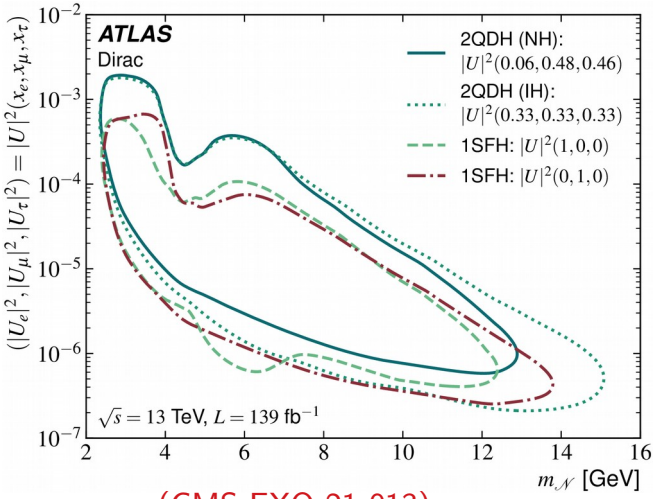
- CMS (EXO-21-013):
  1 prompt lepton +
  jets from displaced vertex



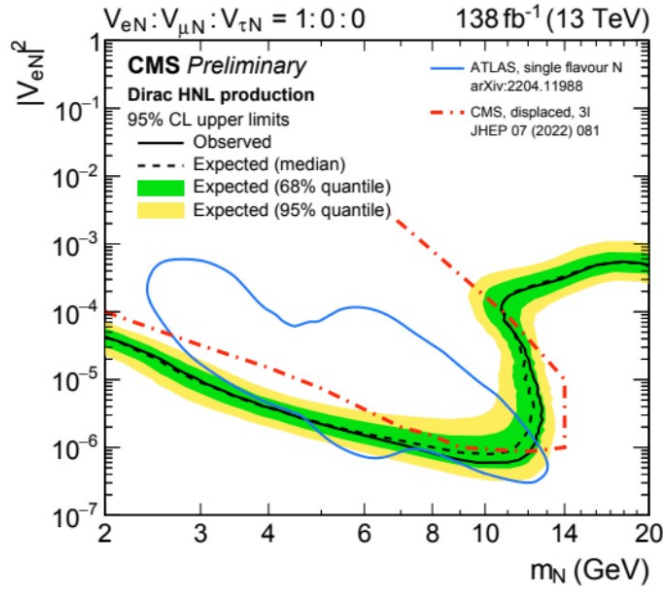
Both detectors show similar performance. However, ATLAS provides also a reinterpretation in terms of 2QDH that is more interesting phenomenologically.



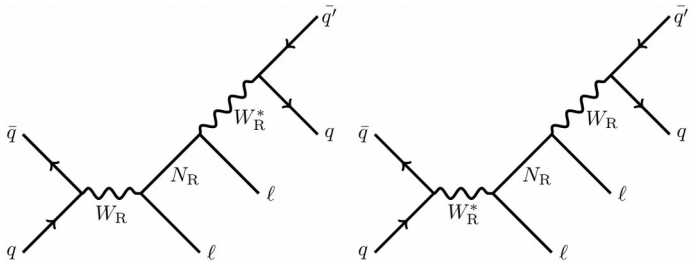
(ATLAS 2204.11988)



(CMS EXO-21-013)



Heavy Neutral Leptons in left-right symmetry.

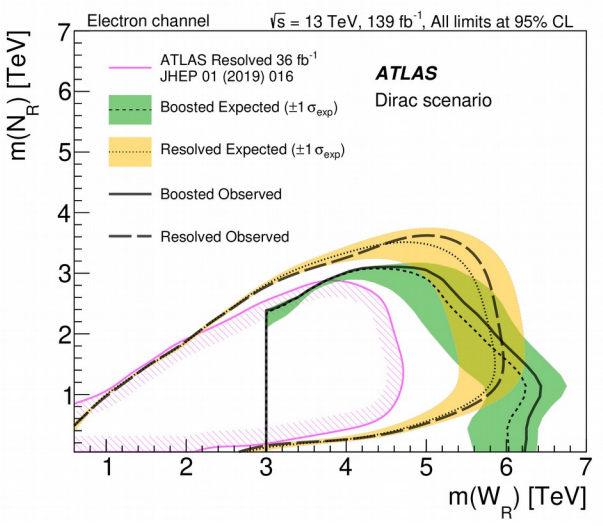


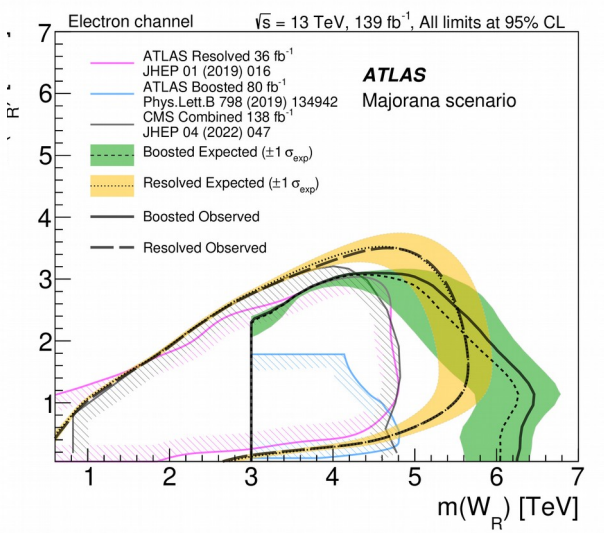
- ATLAS (2304.09553):
  Left-Right model (W_R)

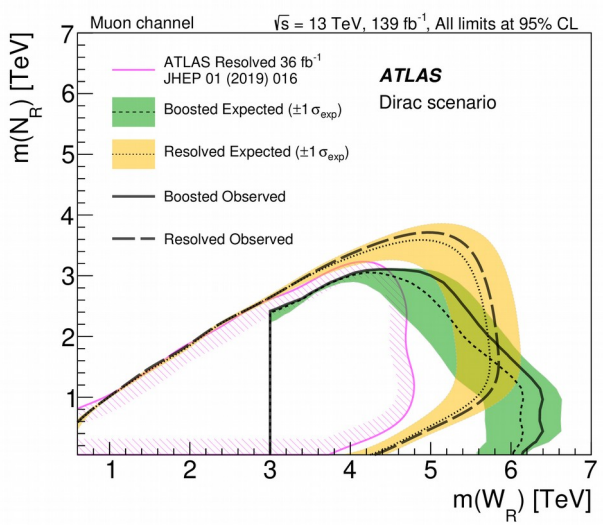
- SF 2leptons:
  2, 2 + jets
  2 leptons OS (OS+SS) for Dirac (Majorana)

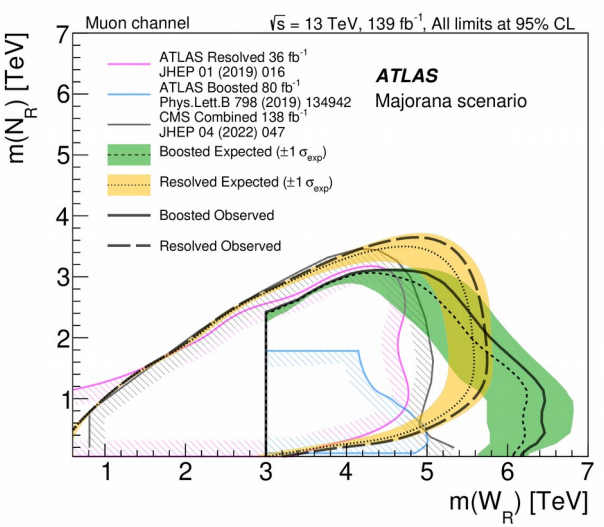
- Exclusion of ~6 TeV for W_R and ~3 TeV for N_R

(ATLAS 2304.09553)







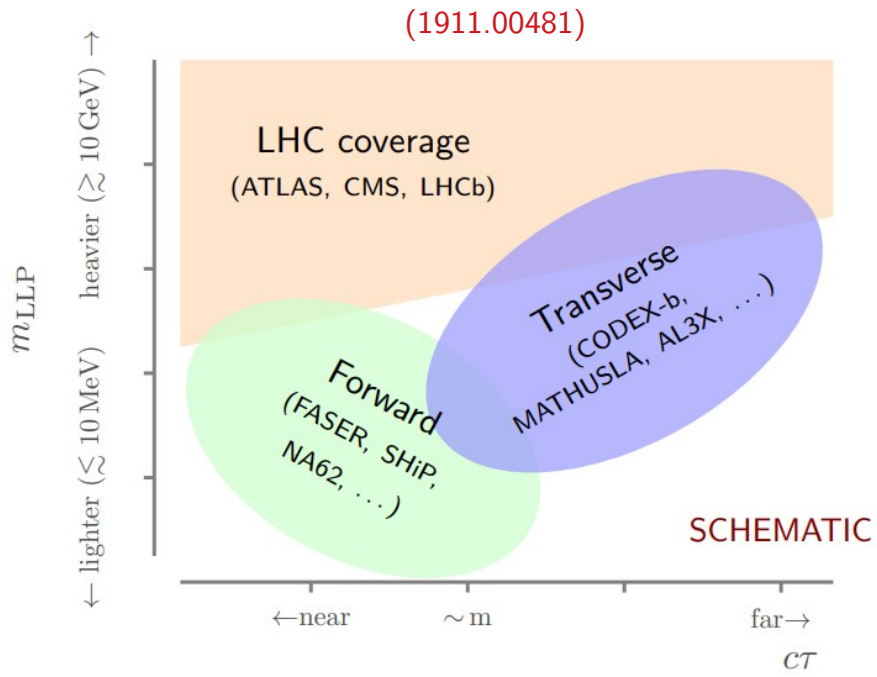


LLPs.

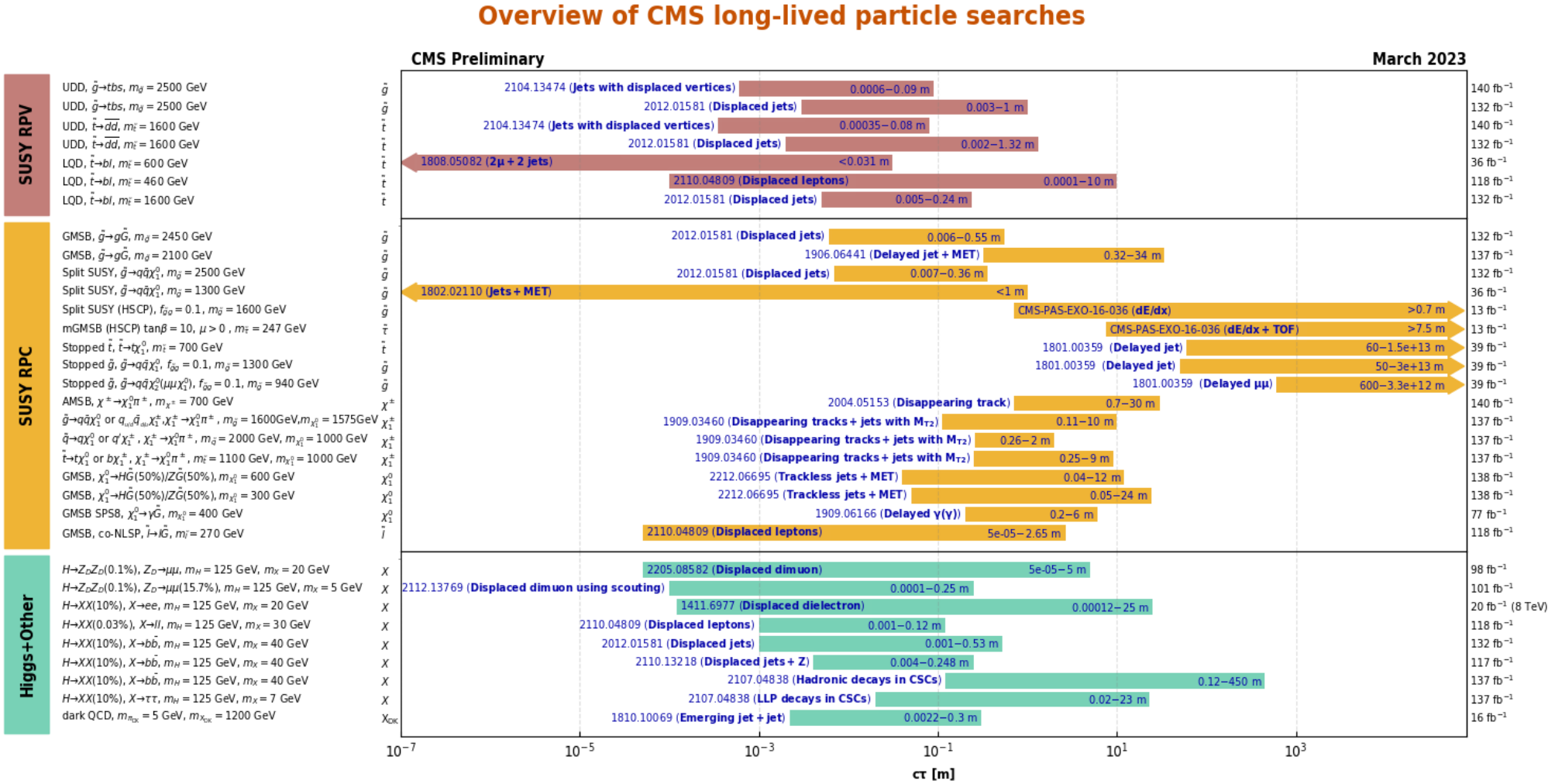
- Long-lived particles can travel through the detectors and may decay in their different parts (calorimeters, muon chamber, etc)
- They are present in many phenomenological models, some of them motivated by small couplings (for example to the leptonic sector via Yukawa interaction)
- It has become a popular and interesting topic and increasing efforts are made in order to optimize this kind of searches

- ATLAS and CMS can measure long-lived particles but long distance detectors are needed: FASER, MATHUSLA, ShiP, CODEX-b, AL3X,...

(1911.00481)

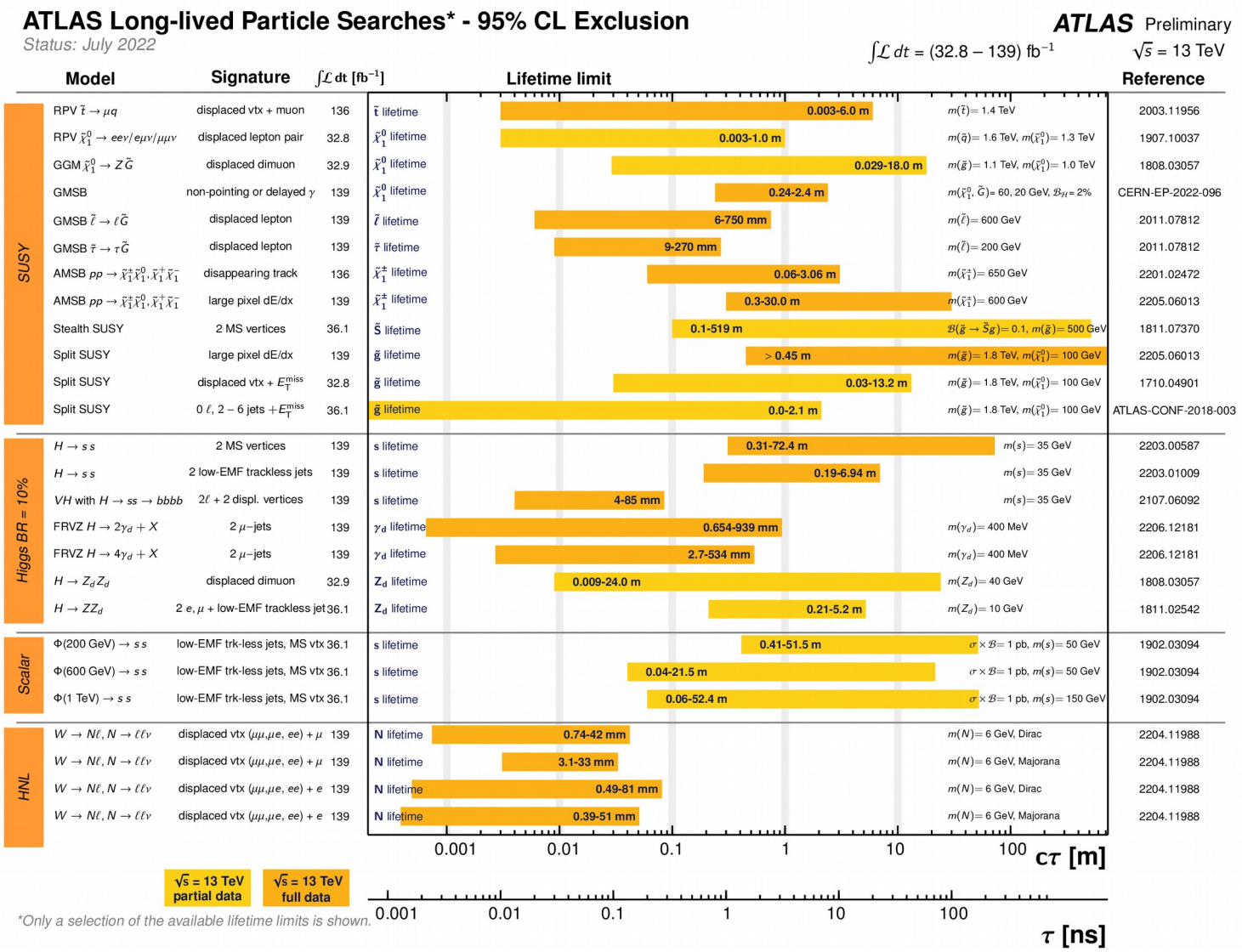


LLPs in CMS.



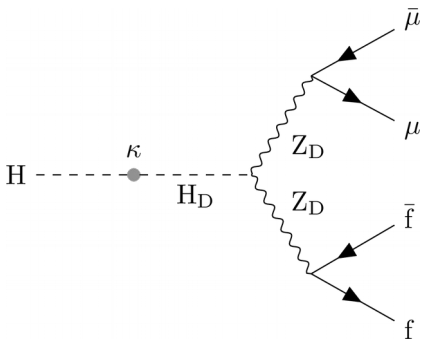
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

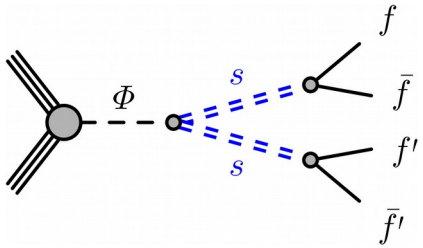
LLPs in ATLAS.



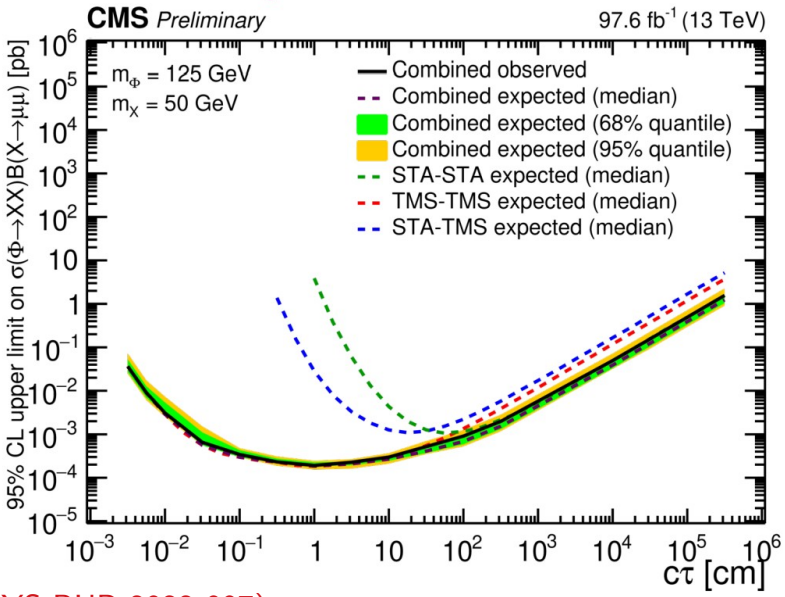
LLPs in ATLAS and CMS.

- Higgs decaying into long-lived particles.
  Long-lived particles could be a dark photon/scalar
- They decay into SM fermions
- Displaced vertices reconstructed in different parts of the detector.
- Challenges: Trigger, identification of objects...

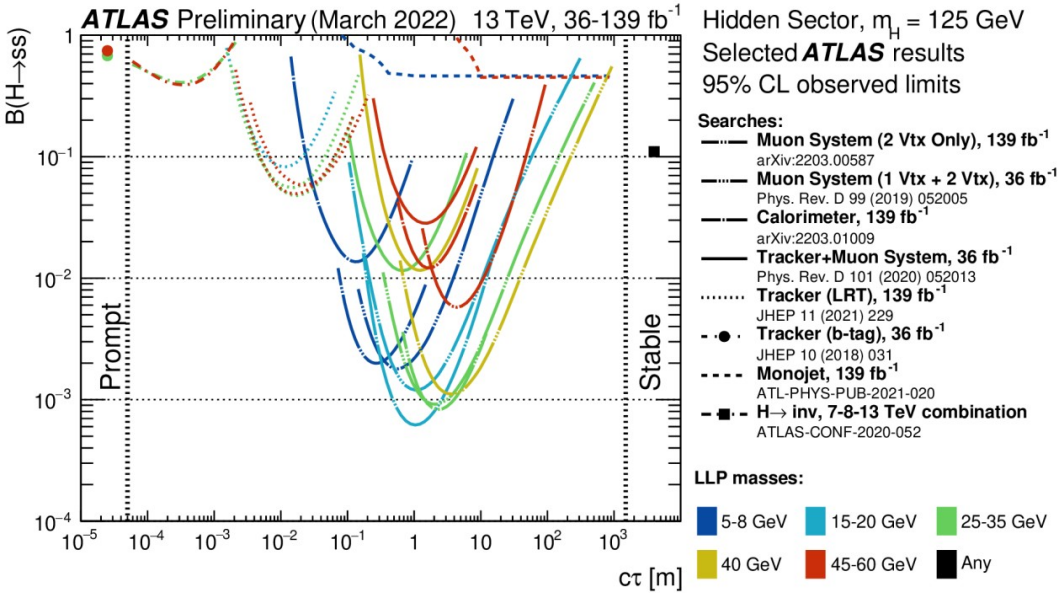




(CMS-EXO-21-006)



(ATLAS-PHYS-PUB-2022-007)



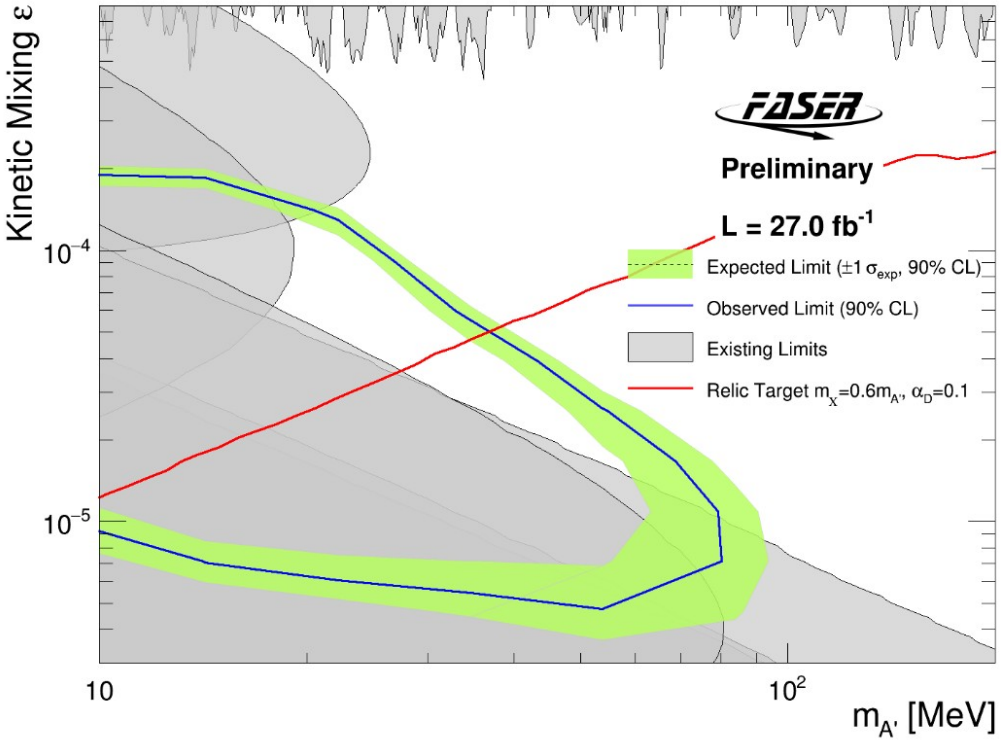
LLPs in FASER.

- First FASER results are released!
- Interpretation as a dark photon decaying into a e^+ e^- pair.

$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$

- Specially sensitive to the low mass region
- No events found in the signal region
- New limits are imposed that are complementary to the ones existing.

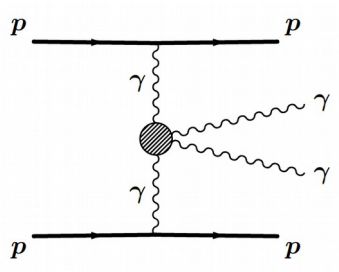
(Bryan Peterson, on behalf of FASER: 2305.08665)



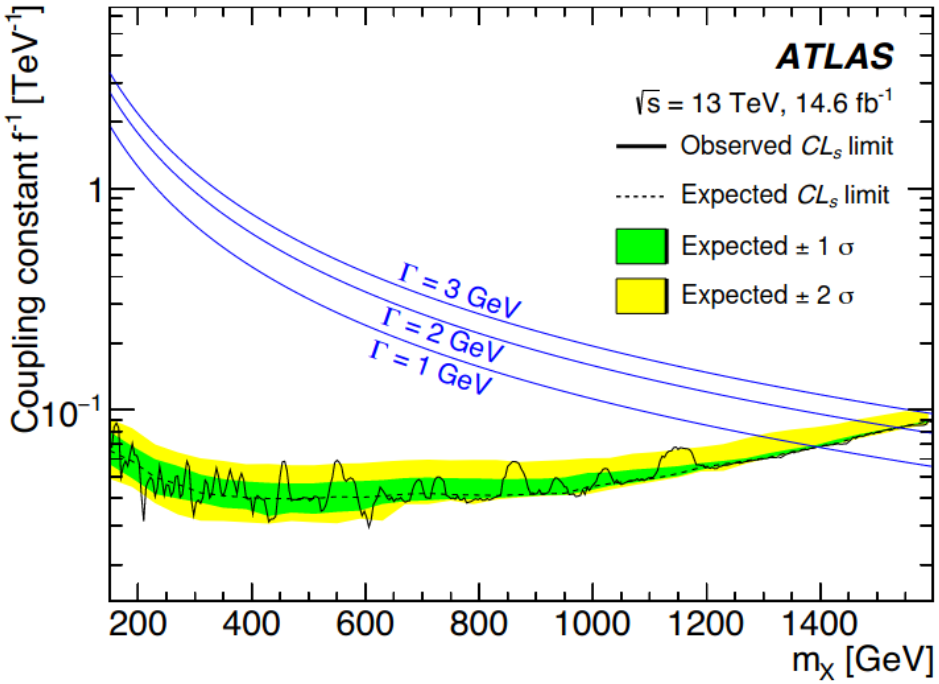
ALPs in light by light scattering.

$$\mathcal{L}^{+} = \frac{1}{f} a F_{\mu\nu} F^{\mu\nu} \quad \text{(CP-even)}, \qquad \mathcal{L}^{-} = \frac{1}{f} a F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \text{(CP-odd)}$$

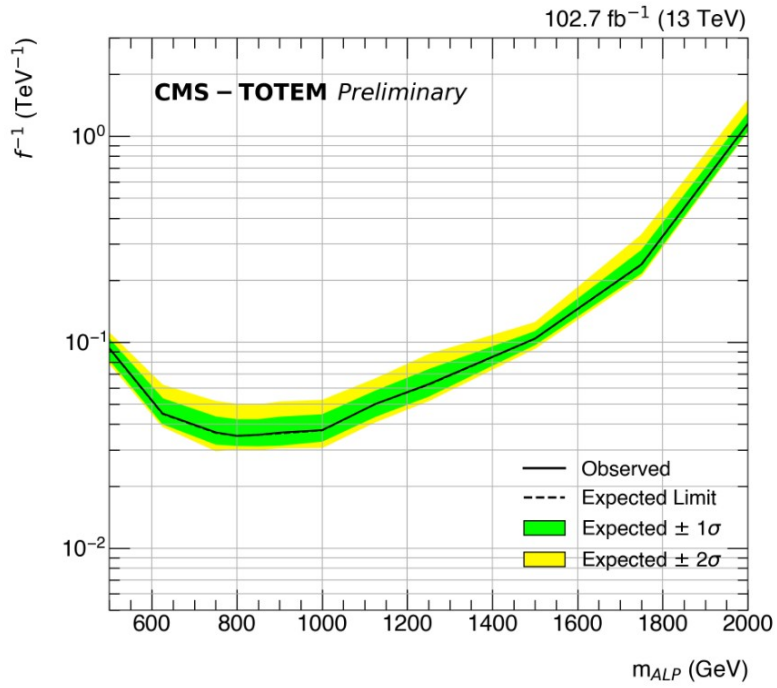
$$\Gamma(a \to \gamma\gamma) = \frac{m_a^3}{4\pi f^2}$$



(ATLAS: 2304.10953)



(CMS: CMS-PAS-EXO-21-007)

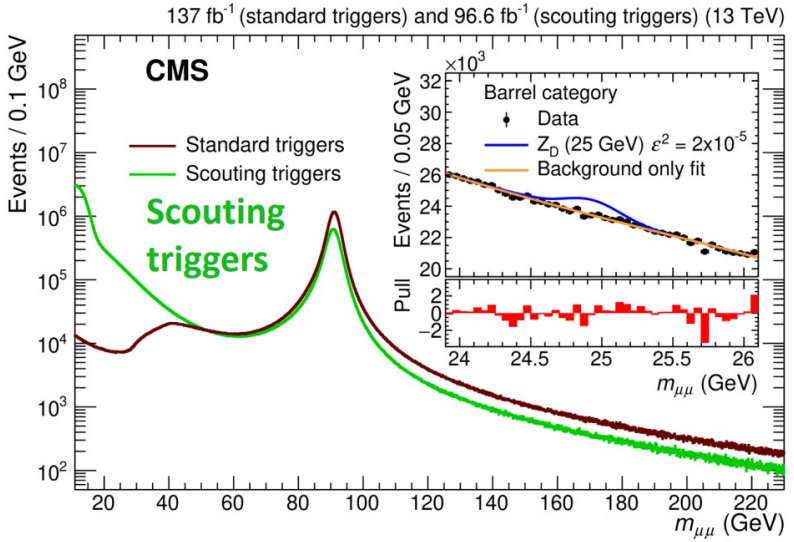


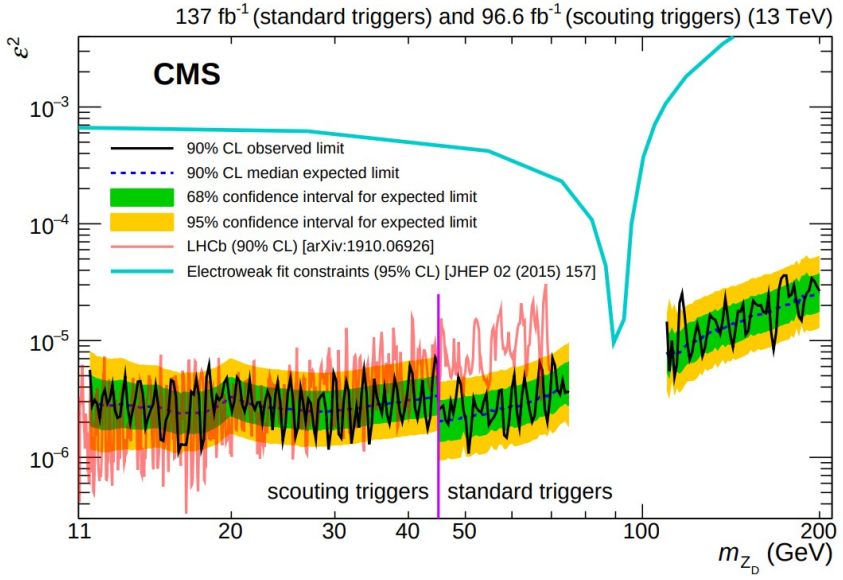
Dark Photons using scouting triggers.

(CMS-PUB-EXO-19-018)

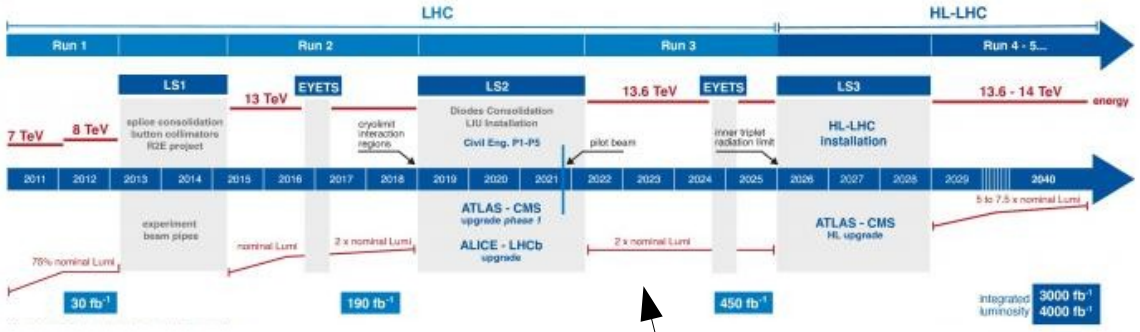
- The presence of trigger cuts impose relatively high cuts on the objects so the event is saved.
- Events with low p_T (low mass resonances) are mostly rejected
- Scouting triggers allow to save objects reconstructed online
- Data obtained with reduced trigger-level muon information with $p_T > 3$ GeV
- Increasing number of events in the lower part of the invariant dilepton mass.
- It could be used also for ALPs

(See for example S. Knapen et al. 2112.07720)





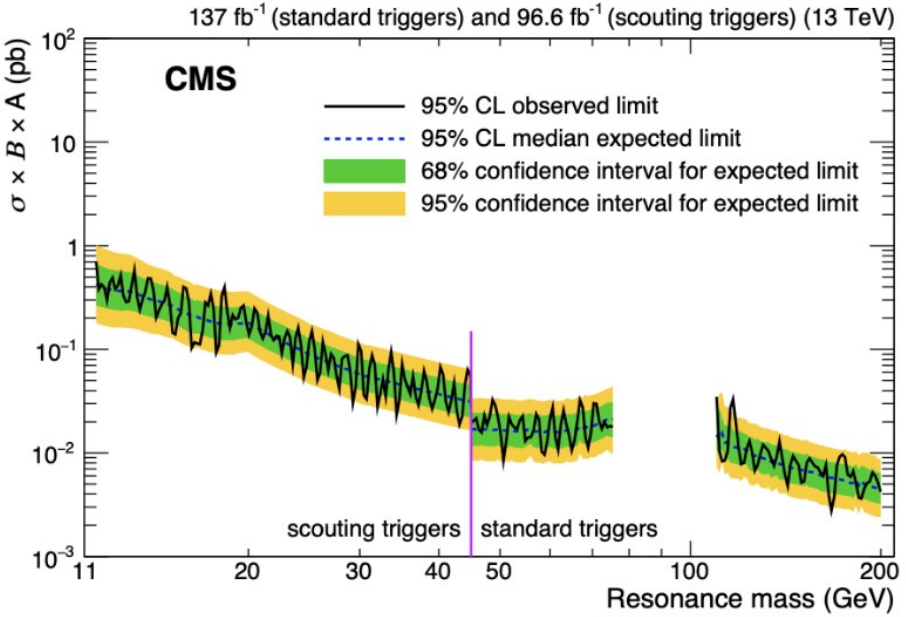
Prospects.



We are here!

- LHC Run 3
  - $\sqrt{s} = 13.6$ TeV (14 TeV)
  - Integrated Luminosity: $2 \cdot 10^{34}$ cm^{-2} s^{-1}
  - Pile up μ=50-60
  - Expected integrated luminosity: 30 fb^{-1} (2022) – 80 fb^{-1} (2023-2025)

- Highlights:
  - Increased luminosity.
    More statistics to test every corner (high masses)
  - Unconventional trigger strategies.
    Data-scouting: Allows to save data of objects reconstructed online that suffer from trigger (low p_T
  - New ideas!

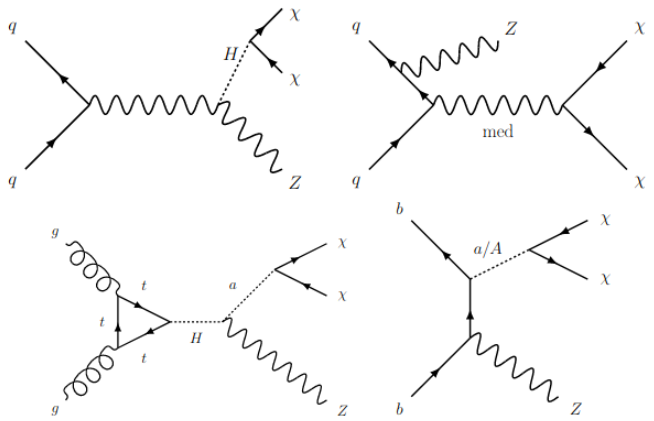


(More detailed information in Upgrades and Future Projects session and Plenary Session 5!)

What are we missing? New proposals.

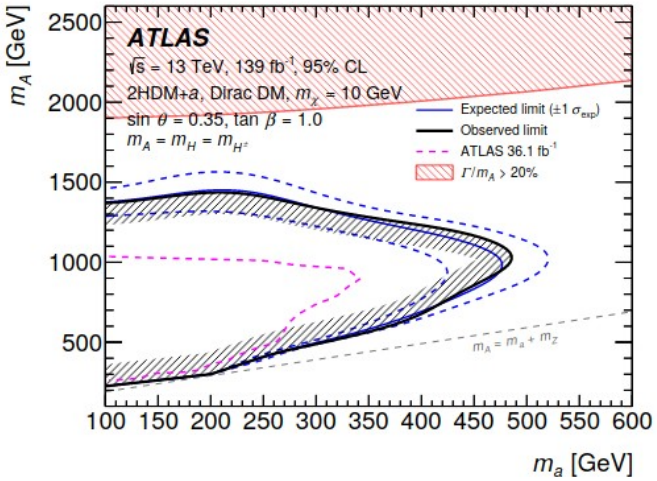
- Dark matter search in the $pp \to b\bar{b}\Phi(\to Z + p_{\mathrm{T}}^{\mathrm{miss}})$

  There are already existing searches in this channel:
  -ATLAS (2111.08372)
  -CMS (2008.04735)

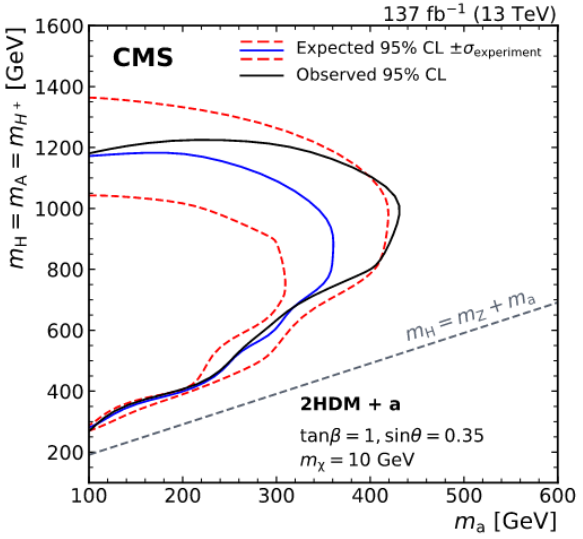


- They rely in one kind of topology regarding the missing transverse momentum. However, different configurations may be possible.

(ATLAS: 2111.08372)



(CMS: 2008.04735)



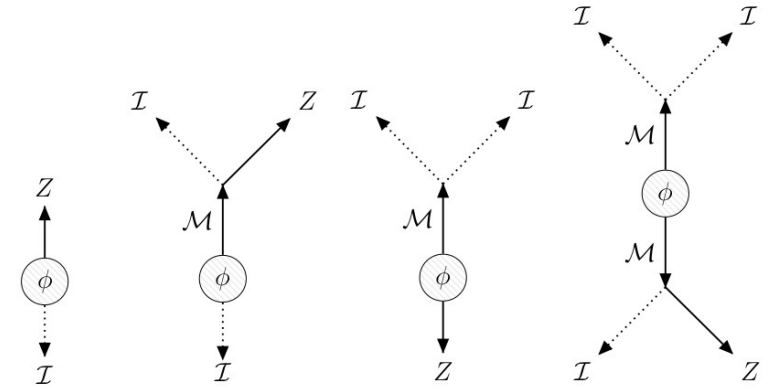
What are we missing? New proposals.

- Dark matter search in the $pp \to b\bar{b}\Phi(\to Z + p_{\mathrm{T}}^{\mathrm{miss}})$

(D.P Adan, H. Bahl, A. Grohsjean, VML, C. Schwanenberger, G. Weiglein: 2302.04892)

Results from different topologies:

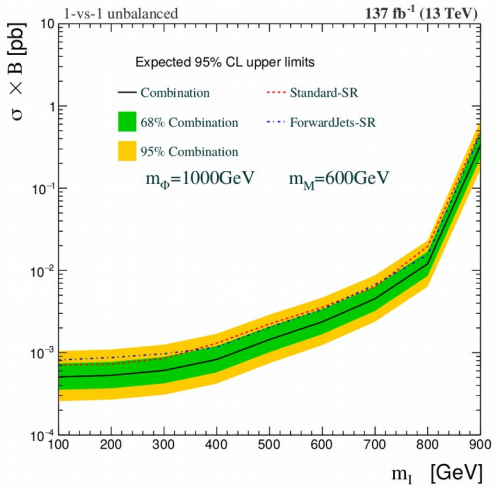
Different topologies:

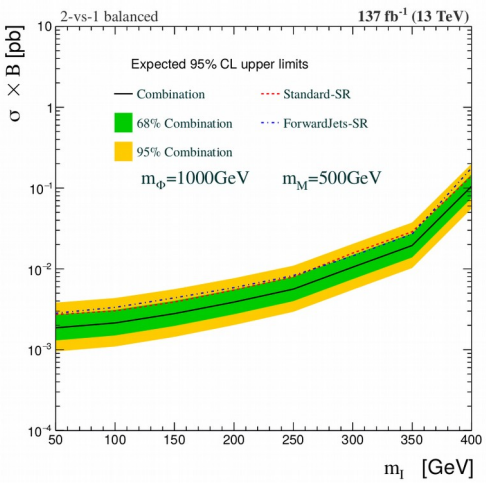


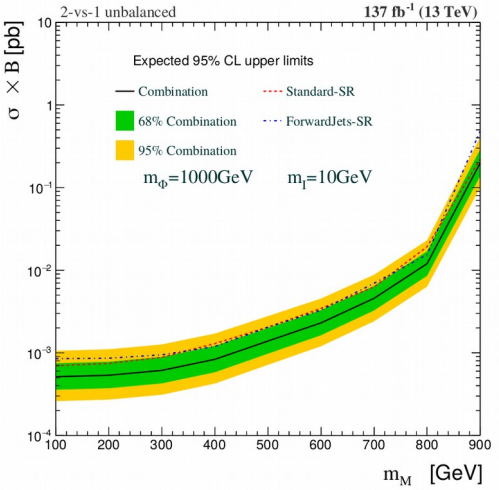
(a) 1vs1 (b) 2vs1 balanced (c) 2vs1 unbalanced (d) 2vs2 unbalanced

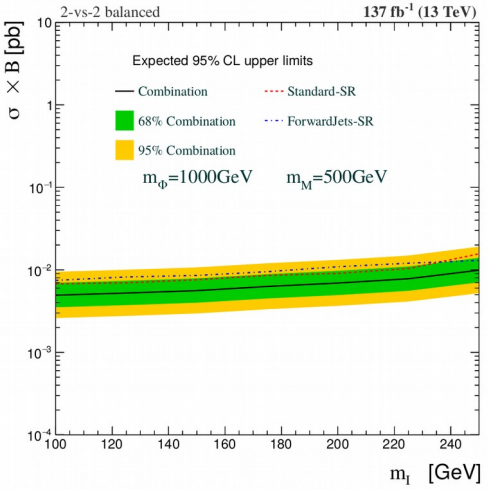
Collider analysis:

Quantity	Standard-SR	ForwardJets-SR
N_l (opposite-charge, same-flavour)	$= 2$ (with additional lepton veto)	
$p_{\mathrm{T}}(l)$	50/20 GeV leading/trailing	
$m(l^+l^-)$	76 GeV $< m(l^+l^-) <$ 106 GeV	
$p_{\mathrm{T}}(l^+l^-)$	> 50 GeV	
$\Delta R(l^+, l^-)$	< 3	
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}, l^+l^-)$	> 0.5	
$m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}, l^+l^-)$	> 140 GeV	
$N_{\text{b-tag}}$	≥ 1	$= 0$
$\lvert\eta(j_1) - \eta(j_2)\rvert_{\max}$	–	> 2.5







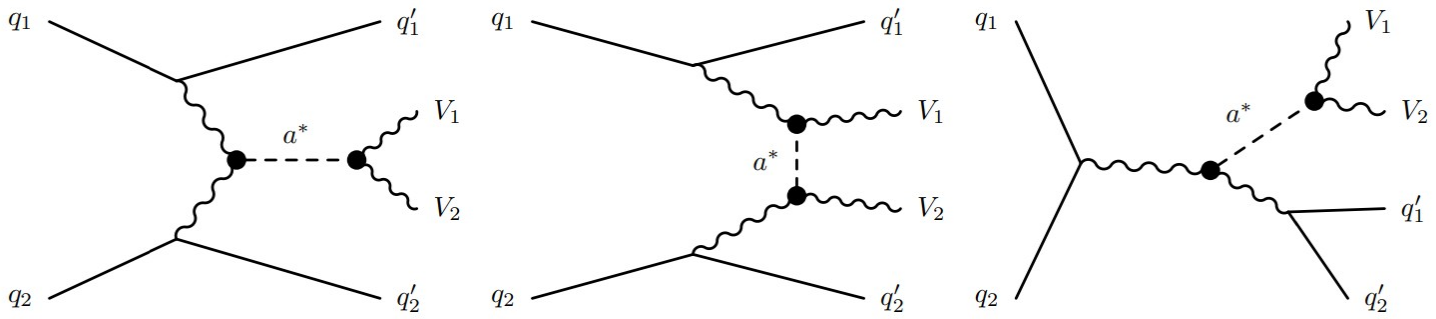


What are we missing? New proposals.

- Non-resonant ALP search in Vector Boson Fusion

$$\mathscr{L}_{ALP} = \frac{1}{4}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 - c_{\widetilde{B}}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_{\widetilde{W}}\frac{a}{f_a}W^i_{\mu\nu}\tilde{W}^{i\mu\nu} - c_{\widetilde{G}}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

VBF is sensitive to the axion coupling to vector bosons regardless of the other couplings.



(J. Bonilla, I. Brivio, J. Machado, J. F. Trocóniz: 2202.03450)

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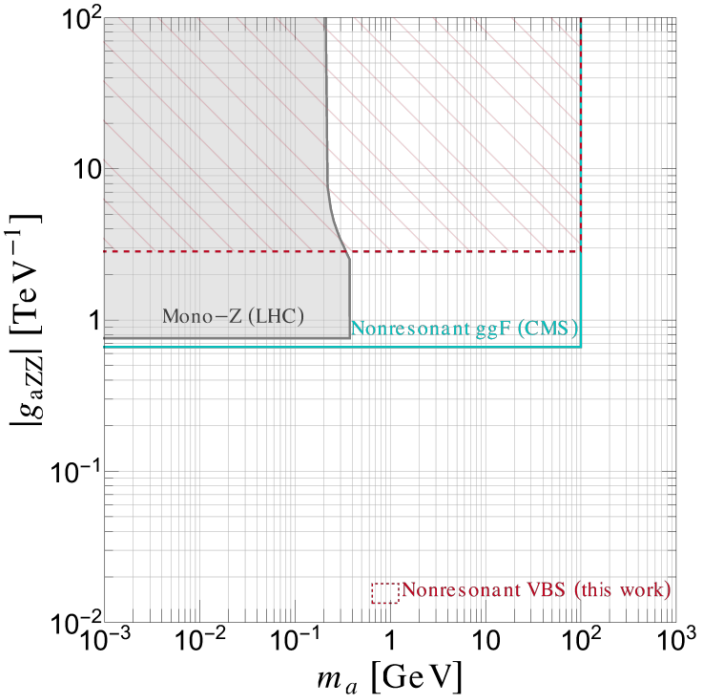
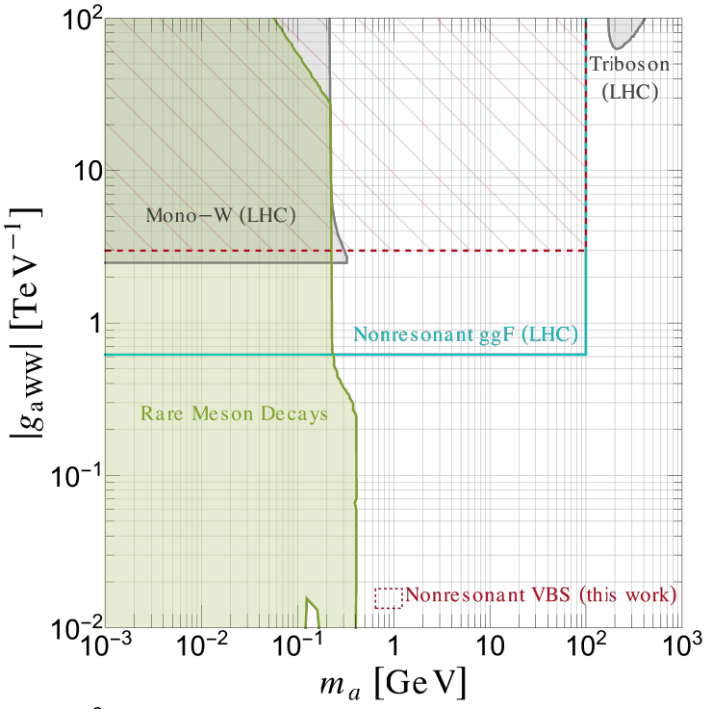
Collider analysis relies on:

-Wide rapidity separation
-Large dijet mass
-Longer tails in the diboson mass distribution





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Conclusions.

- Feebly interacting particles are present in a huge variety of BSM scenarios. These dark sectors include dark matter candidates, Heavy Neutral Leptons, Axion-like particles, long-lived particles, etc.
- Their tiny interaction with the SM particles imposes a great challenge for LHC searches and special strategies or techniques are required.
- However, there are multiple searches that explore the parameter regions of every specific subsection of the FIPs.
- Even if some searches can constrain large ranges of masses of these new particles there are still regions of the parameter space, new signatures or new topologies that are not yet covered.
- Run3 prospects and new detectors, such as the LLPs designed ones, can improve the current situation.
- Furthermore, new ideas from experimental + theoretical sides are needed. Without a joint collaboration between exp. and theo. we will not make the best out of it.

Thank you!