Searches for dark sector particles (including long-lived mediators and missing E_T signatures) in ATLAS and CMS

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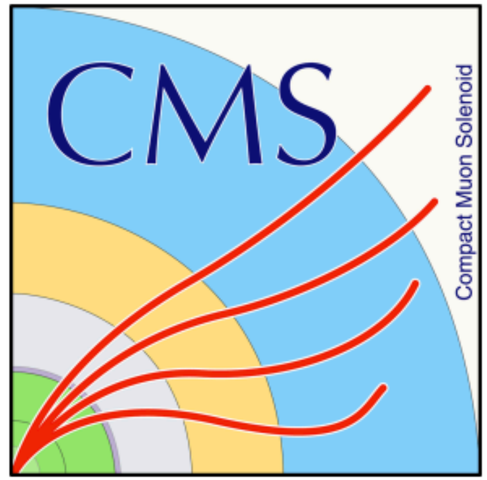
On behalf of the ATLAS and CMS collaborations

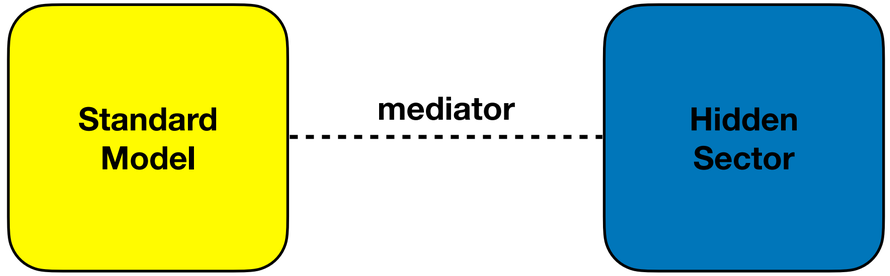
14th International Conference on Identification of Dark Matter

July 18 - 22, 2022



Dark Sector

- Hypothesis that DM is part of a larger dark sector consists of several new types of dark particles, which
  - Do not couple to known SM fields
  - Interact through a mediator

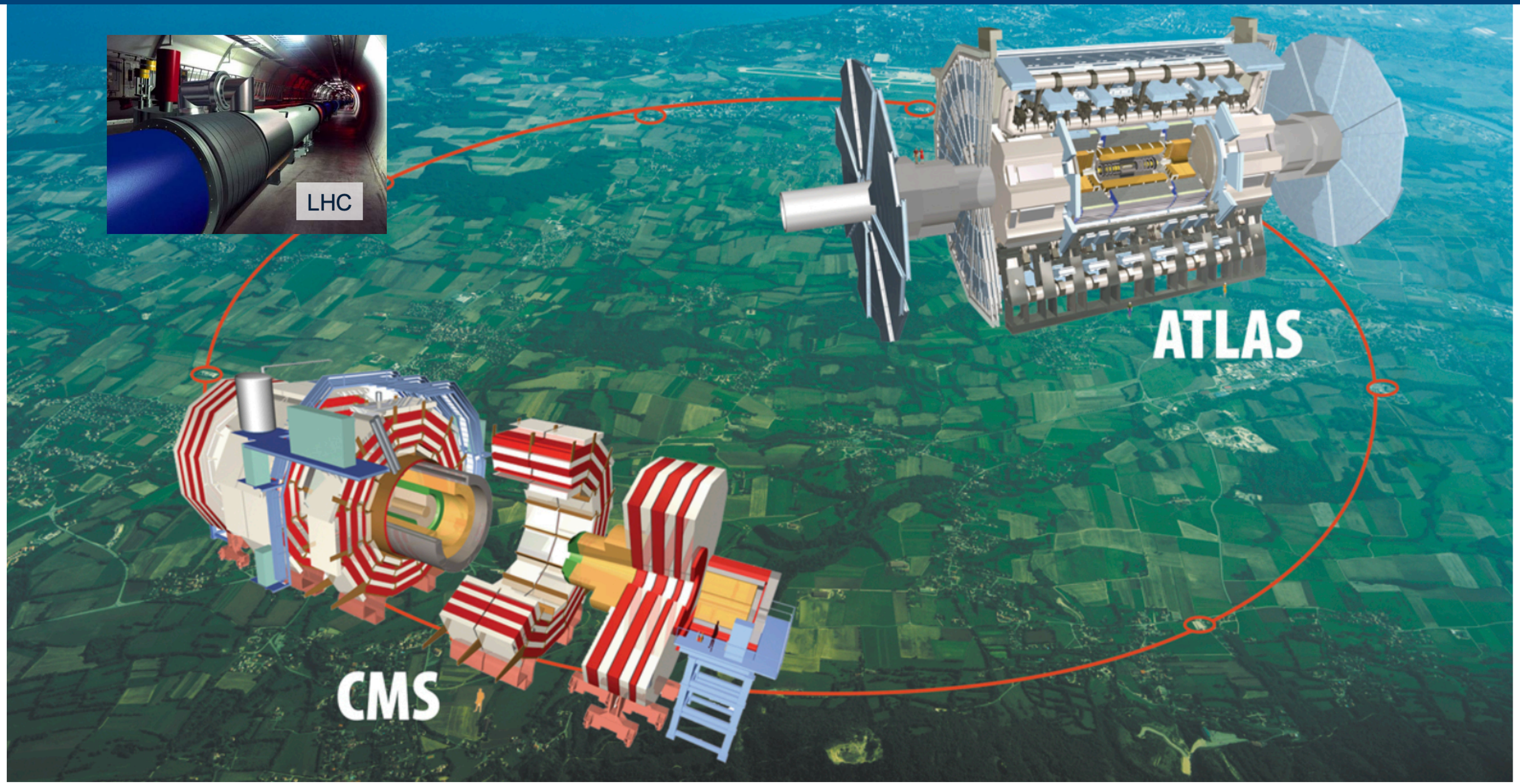


Portal relevant for dark sector - SM interactions depends on mediator spin and parity:

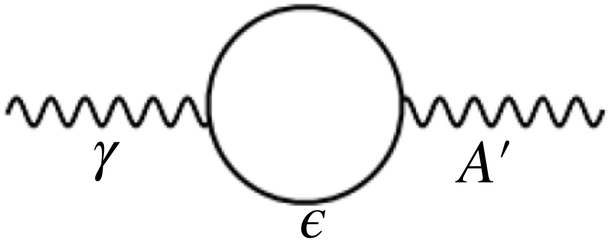
vector portal	**vector A'**	→	**dark photon, dark Z**
Higgs/scalar portal	**scalar ϕ**	→	**dark Higgs**
neutrino portal	**fermion N**	→	**sterile neutrino**
axion portal	**pseudoscalar a**	→	**axion**

- Mediators can provide portal to DM candidates
- Dark sectors possibly accessible at ATLAS and CMS

ATLAS and CMS Experiments at LHC

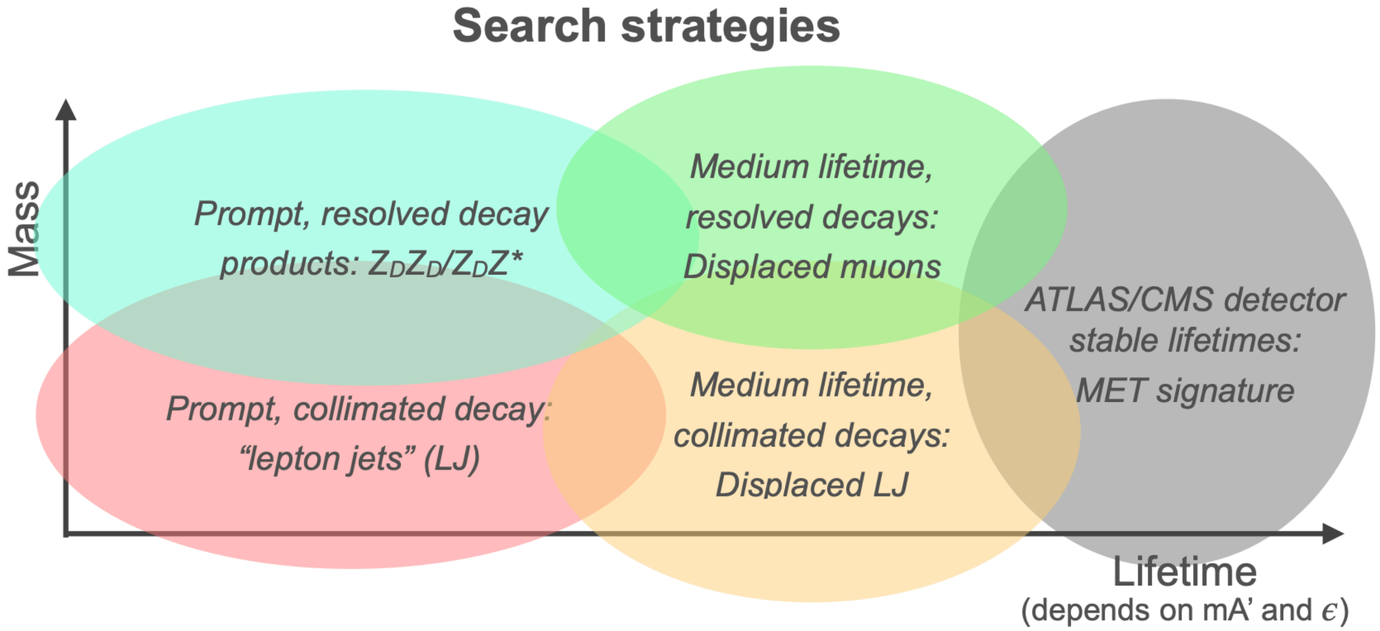


Dark Photon, A’



- U(1) extension of the SM, introducing massive dark gauge boson γ_d, with kinetic mixing with SM photon
  - Parameters: kinetic mixing parameter ϵ and $m_{A'}$

Search strategies developed to target particles with different lifetime and mass:

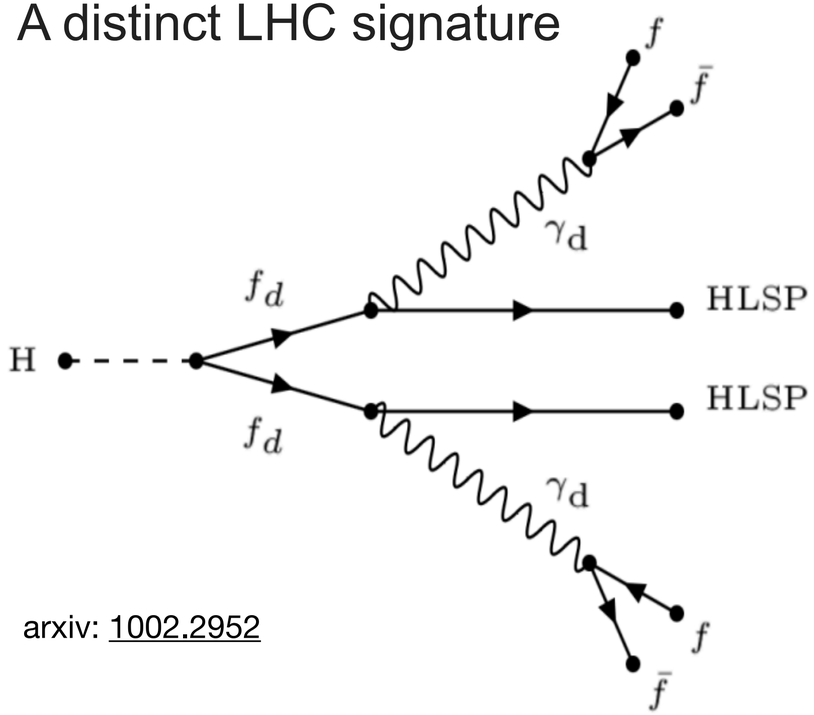


Displaced Dark Photon Jets

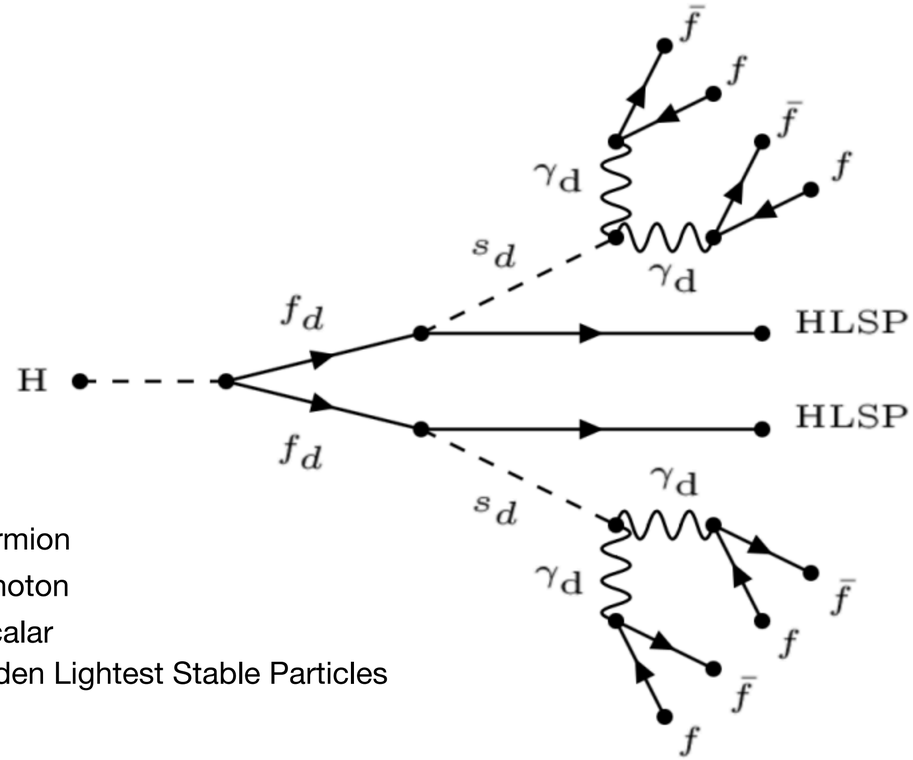
arxiv: 2206.12181
submitted to JHEP

- Benchmark model: Higgs portal production and vector portal decay (FRVZ model)
  - f_d produced in H decays, which decay to γ_d (via s_d) and HLSP

- Low mass A' could be produced via cascade decay of heavier states
  - Leptonic decays are dominant
  - Due to its small mass, resulting in collimated groups of fermions
    - Referred as dark-photon jets (DPJ)
    - A distinct LHC signature



arxiv: 1002.2952

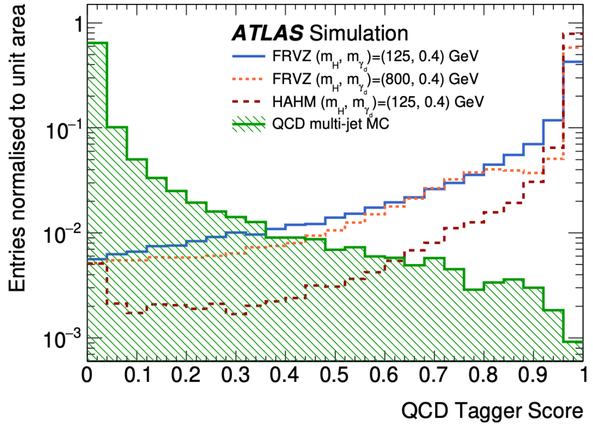


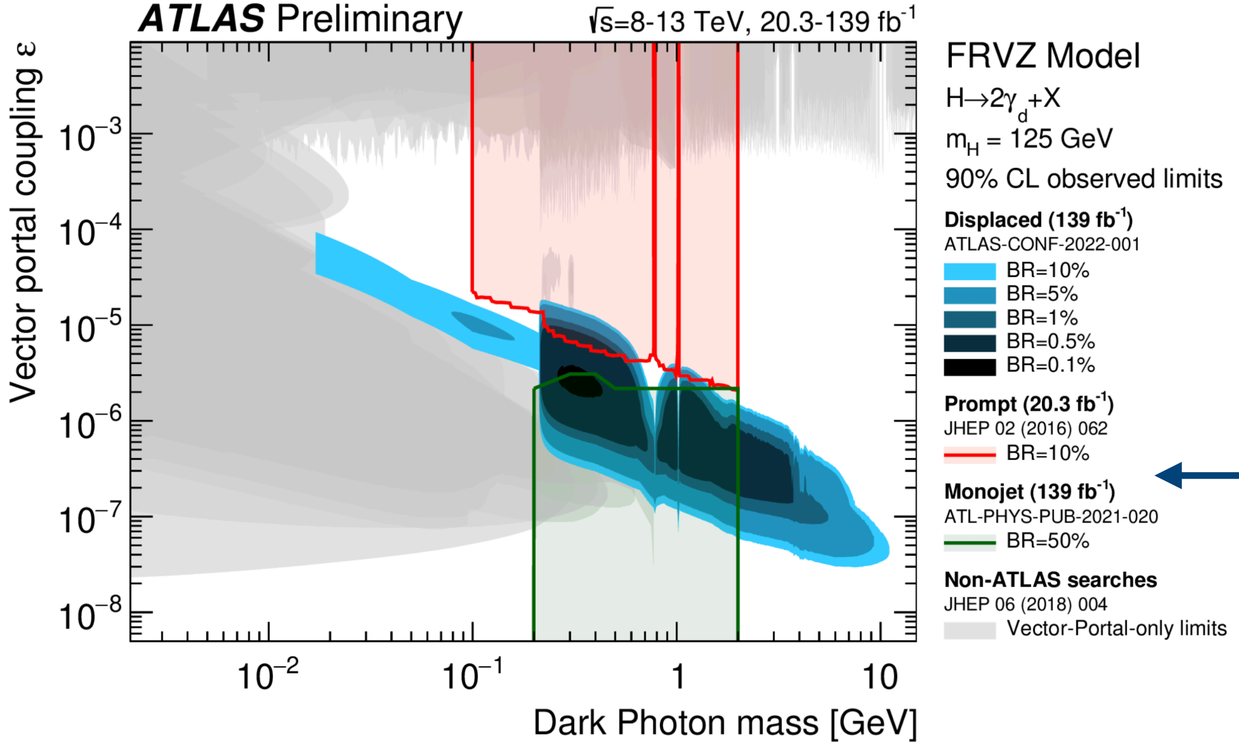
f_d : dark fermion
γ_d : dark photon
s_d : dark scalar
HLSP: Hidden Lightest Stable Particles

Displaced Dark Photon Jets

ATL-PHYS-PUB-2022-007
ATL-PHYS-PUB-2021-020
arxiv: 2206.12181 submitted to JHEP

- Cosmic-ray tagger defined to reduce muonic DPJ from cosmic-ray background
  - Based on a dense neural work
- QCD tagger defined to reduce multi-jet background
  - Based on convolutional neural network
  - Exploits the calorimeter energy deposits associated with jets





- Interpreted in terms of limits on kinetic mixing parameter ϵ, and dark photon mass $m_{A'}$
- Limits are shown for $B(H \to 2\gamma_d + X)$ in range 1-10%

When the lifetime of the γ_d is long enough,
or system is boosted by initial-state-radiation (ISR)

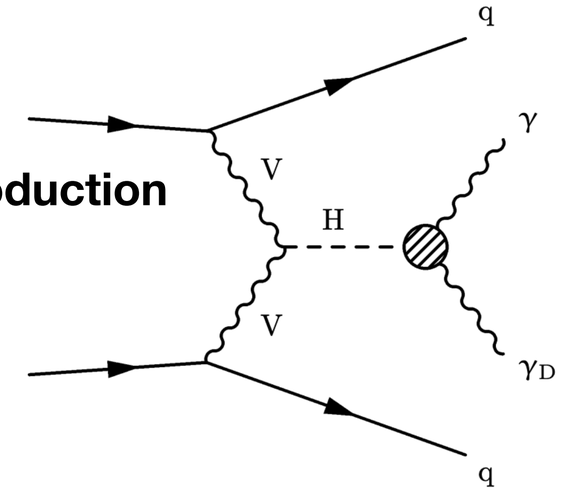
$\Longrightarrow$ monojet signature

Dark Photons from Higgs Decay

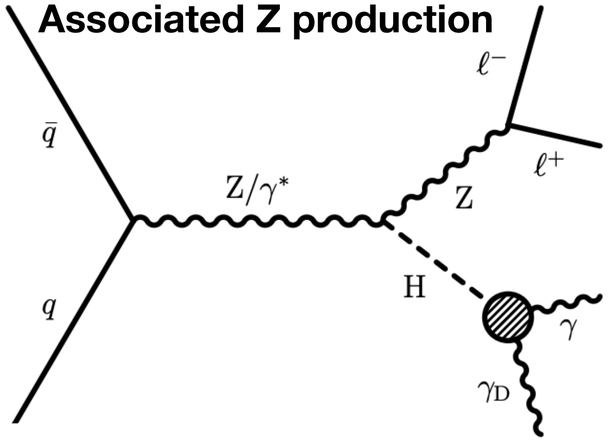
JHEP10(2019)139
JHEP03(2021)011

- Some models predict a scalar Higgs boson coupling to a dark photon through a dark sector
  - Coupling probed in Higgs boson production

VBF production



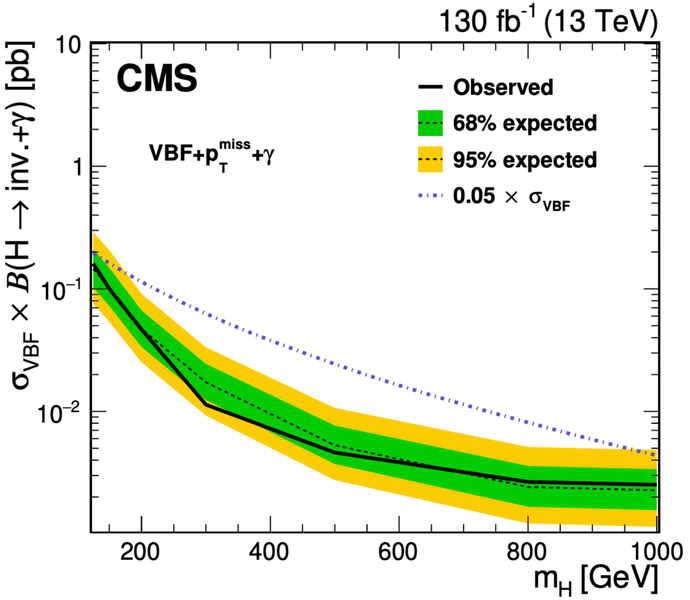
Associated Z production

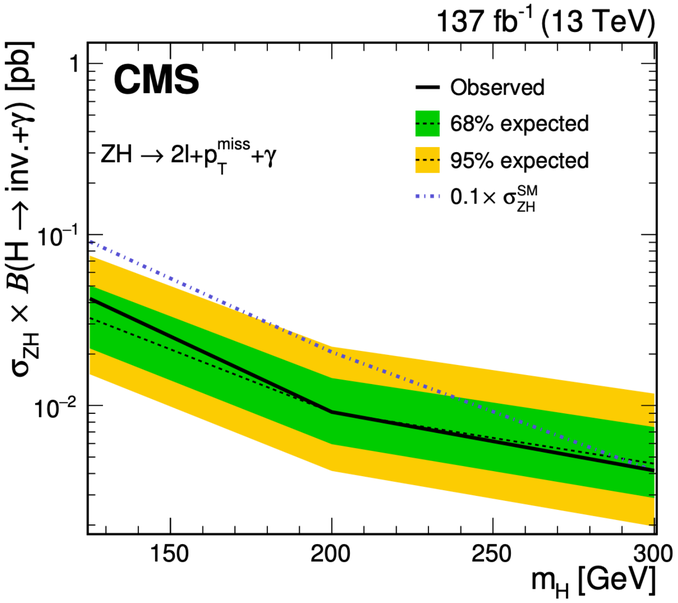


Both use transverse mass as a discriminating variable

Observed and expected 95% CL limits
$B(H \to \gamma\gamma_D)$ **for** $m_H = 125$ **GeV :**

VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.4	$2.7^{+1.2}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+0.9}_{-0.6}$

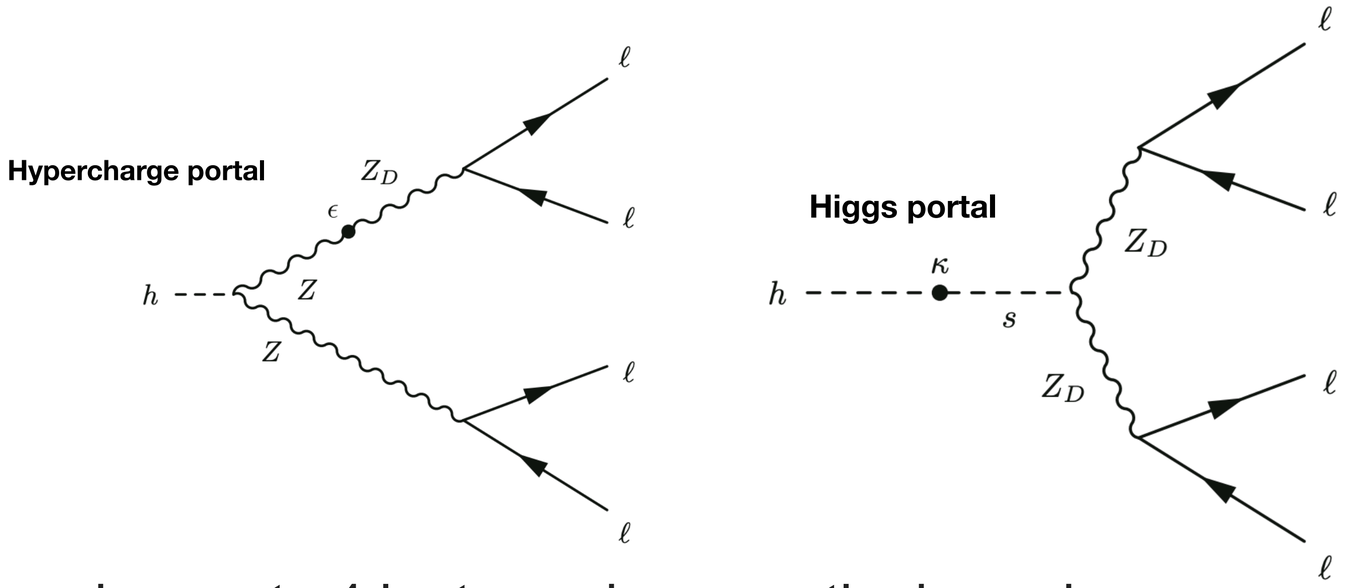




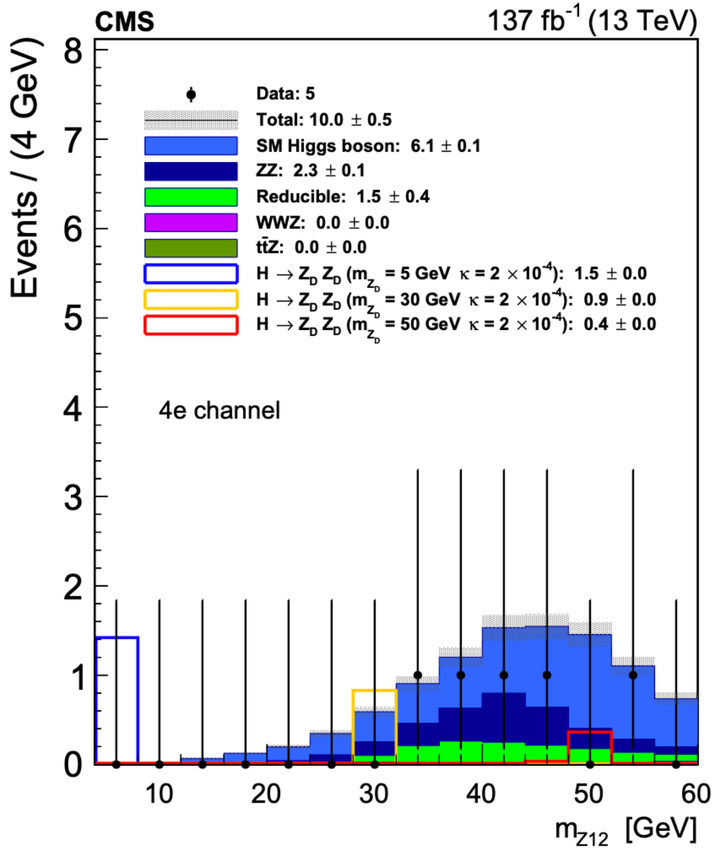
VBF production
ATLAS plots here

Exotic Higgs 4L Decays

CMS-HIG-19-007



- Higgs decays to 4 leptons via promptly decay bosons
- Search for $H \to ZZ_D/Z_DZ_D \to 4e/4\mu/2e2\mu$
  - Dilepton pair candidates formed
  - SR defined by $m_{ll} \in [4,120]$ GeV, excluding mass window around Ybb bound states
- Dark vector bosons produced via hypercharge + Higgs portal models

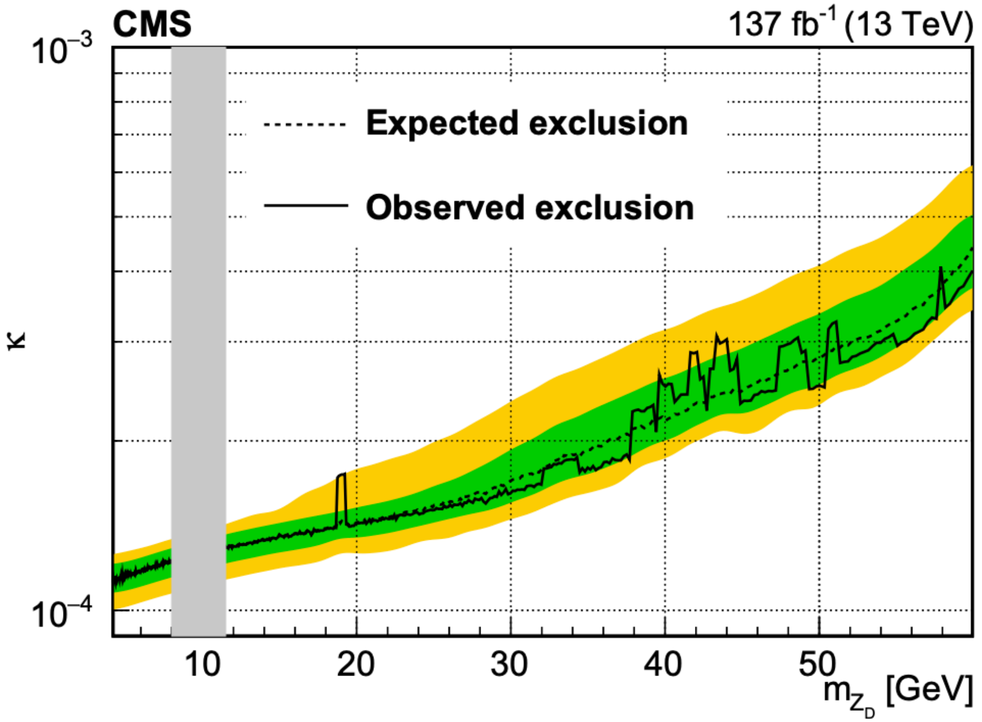


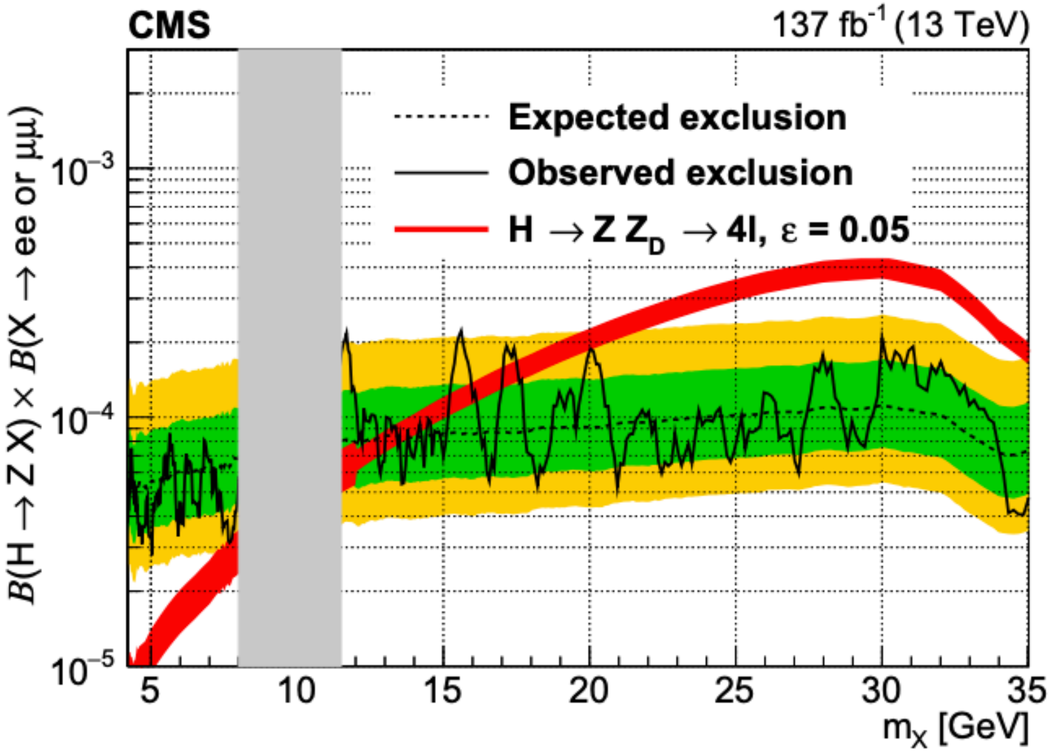
$m_{Z12} = (m_{Z_1} + m_{Z_2})/2$

Exotic Higgs 4L Decays

CMS-HIG-19-007

- Results interpreted in term of upper limits on Higgs branching fraction
  - Higgs portal model: related to Higgs portal coupling κ
  - Hypercharge portal: related to kinetic mixing ϵ





- Limits on model parameters

Narrow $\mu^{\pm}\mu^{\mp}$ Resonance Search

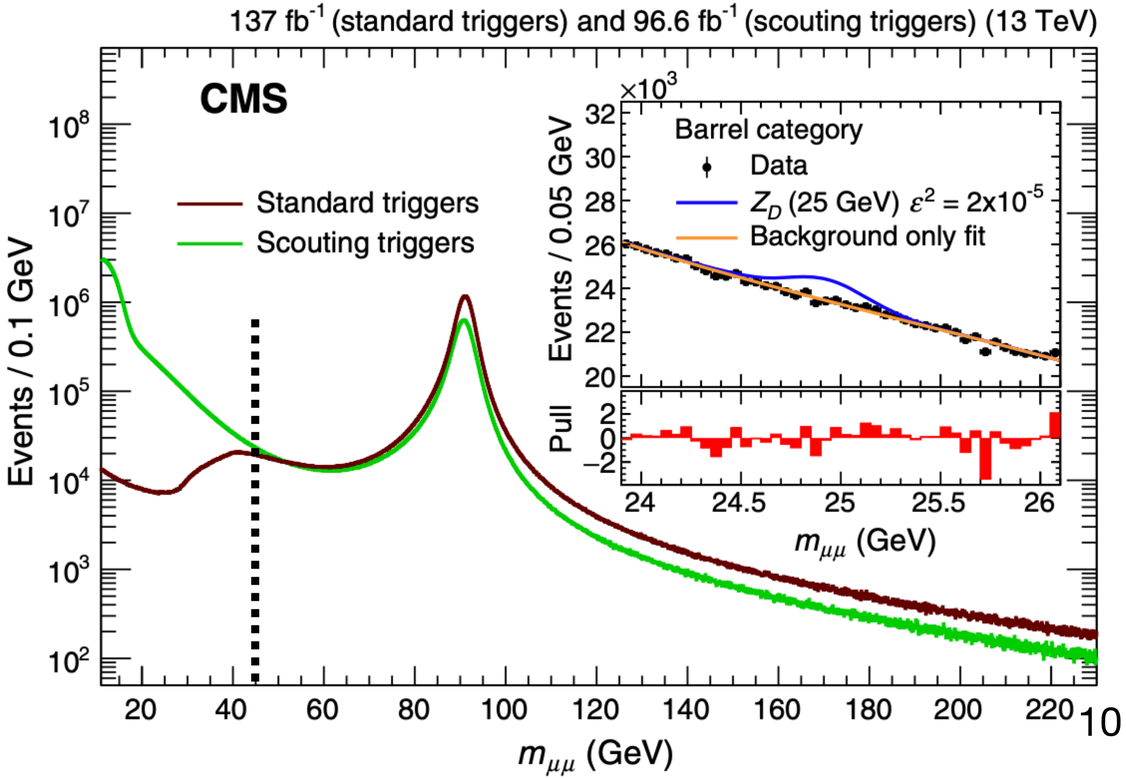
Phys. Rev. Lett. 124 (2020) 131802

- Search for a narrow resonance decaying into a pair of oppositely charged muons
  - Looks for a narrow resonance in the 11.5 - 200 GeV mass range, omitting 75-110 GeV where Z boson production dominates

- Dedicated data scouting triggers employed comparing to standard triggers:
  - Operate at a significantly higher rate with a reduced amount of trigger-level information
  - Increase acceptance at $m_{\mu\mu} < 45$ GeV region

Events divided into categories based on $m_{\mu\mu}$ resolution:

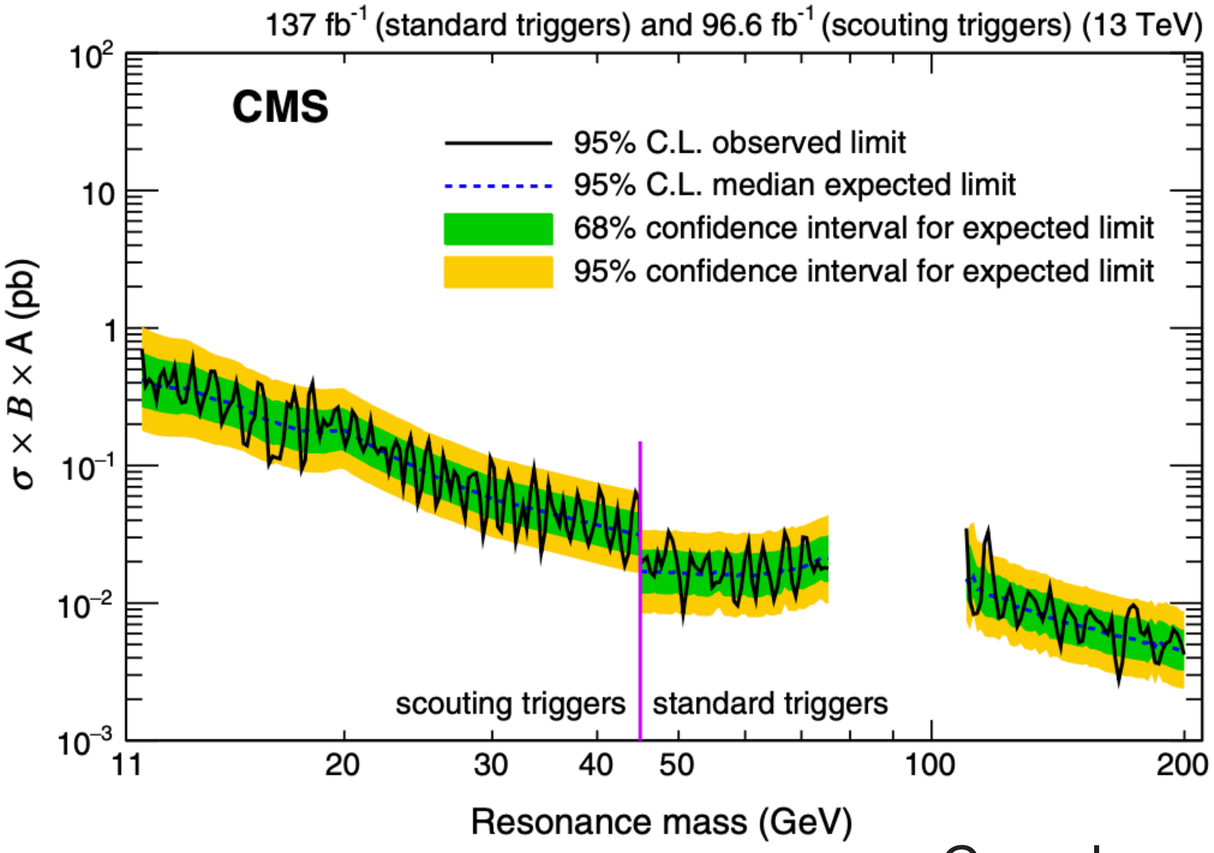
- Barrel category ($|\eta| < 0.9$): ~ 1%
- Forward category ($0.9 < |\eta| < 1.9$) : ~ 3%

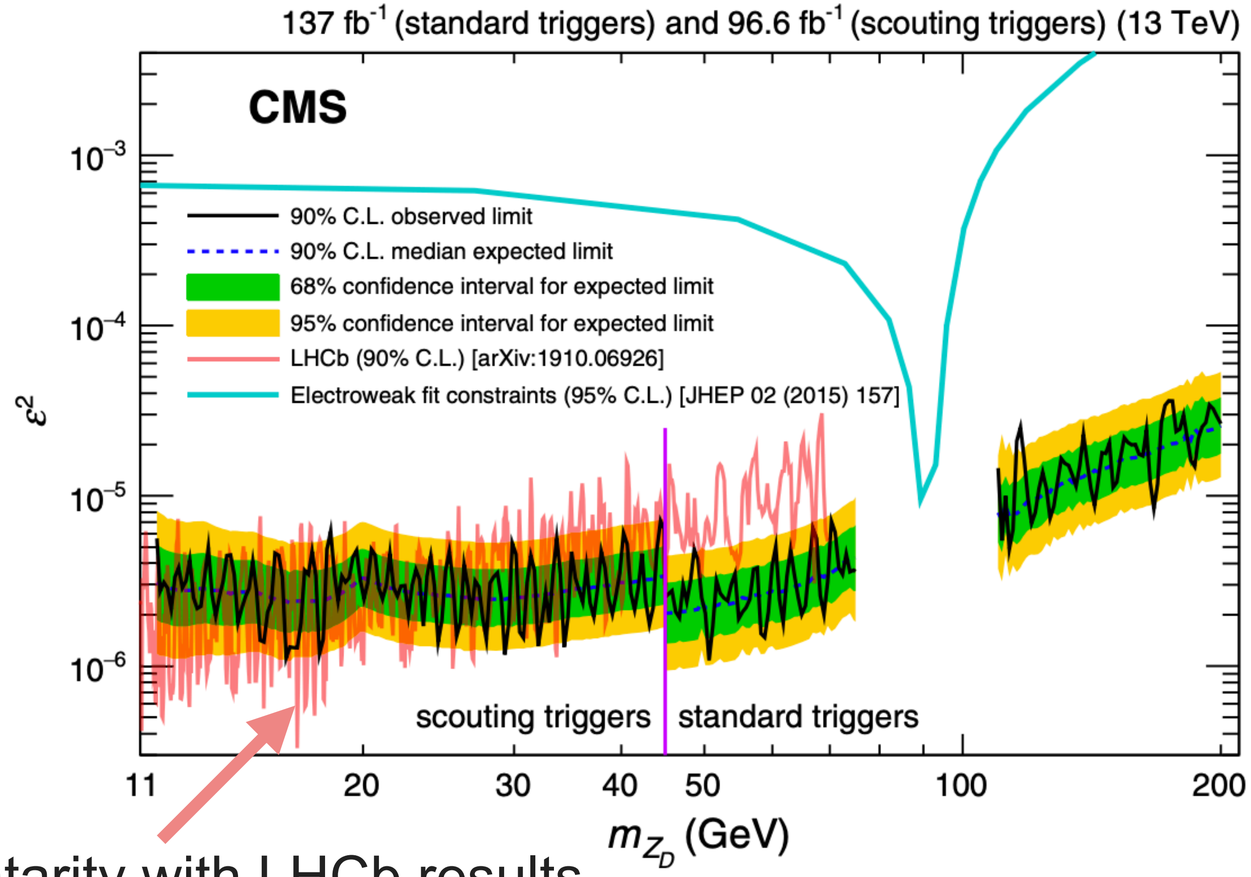


Narrow $\mu^{\pm}\mu^{\mp}$ Resonance Search

Phys. Rev. Lett. 124 (2020) 131802

- Model-independent upper limits on cross section as a function of $m_{A'}$
- Dark photon interpretation with upper limits on ϵ^2 as a function of $m_{A'}$ in range $[11.5,200]$ GeV





Complementarity with LHCb results

Hadronic Vector Portal Searches

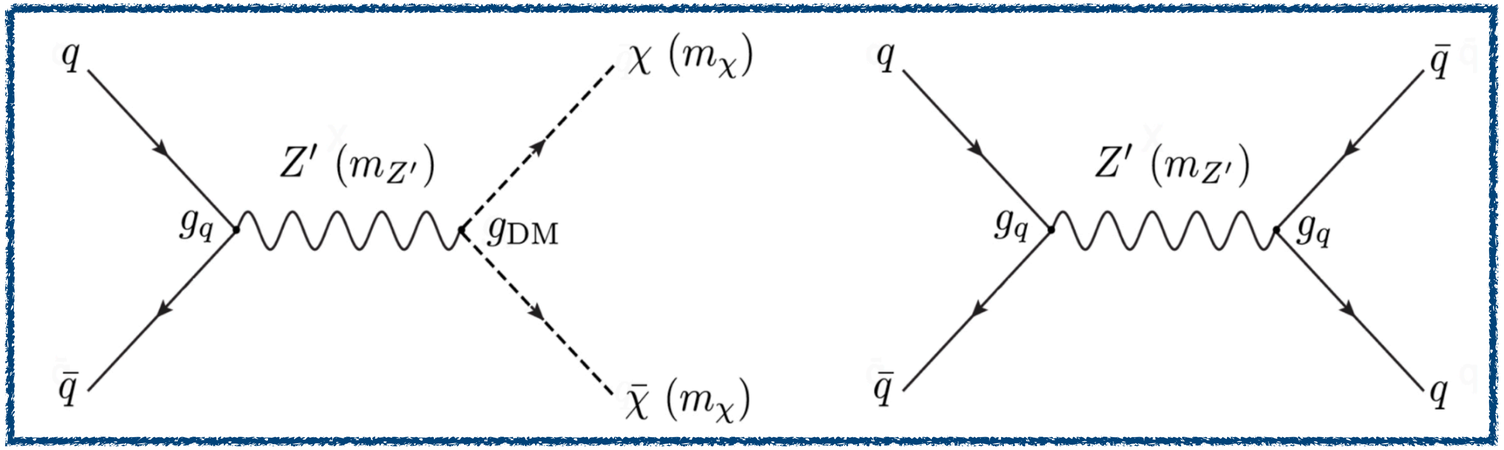
ATL-PHYS-PUB-2022-036

- Simplified (leptophobic) vector portals recommended by the ATLAS/CMS
  - Assume DM is a Dirac fermion χ
  - Additional heavy vector/axial-vector particle Z' mediating the SM-DM interaction
  - Focus on models where mediator exchanged in the s-channel

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu \ell\,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu\gamma_5 q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu\gamma_5 \ell\,.$$

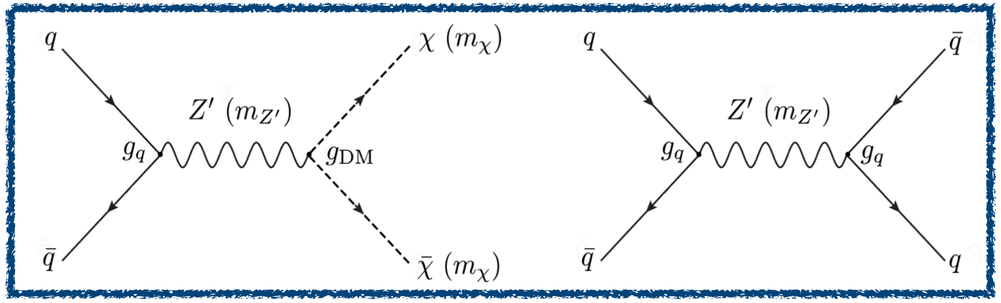
- Four free parameters
  - m_{DM} : DM mass
  - $m_{Z'}$: mediator mass
  - g_{DM} : coupling of a mediator-DM-DM vertex
  - g_q : coupling universal to all mediator-quark-quark vertices

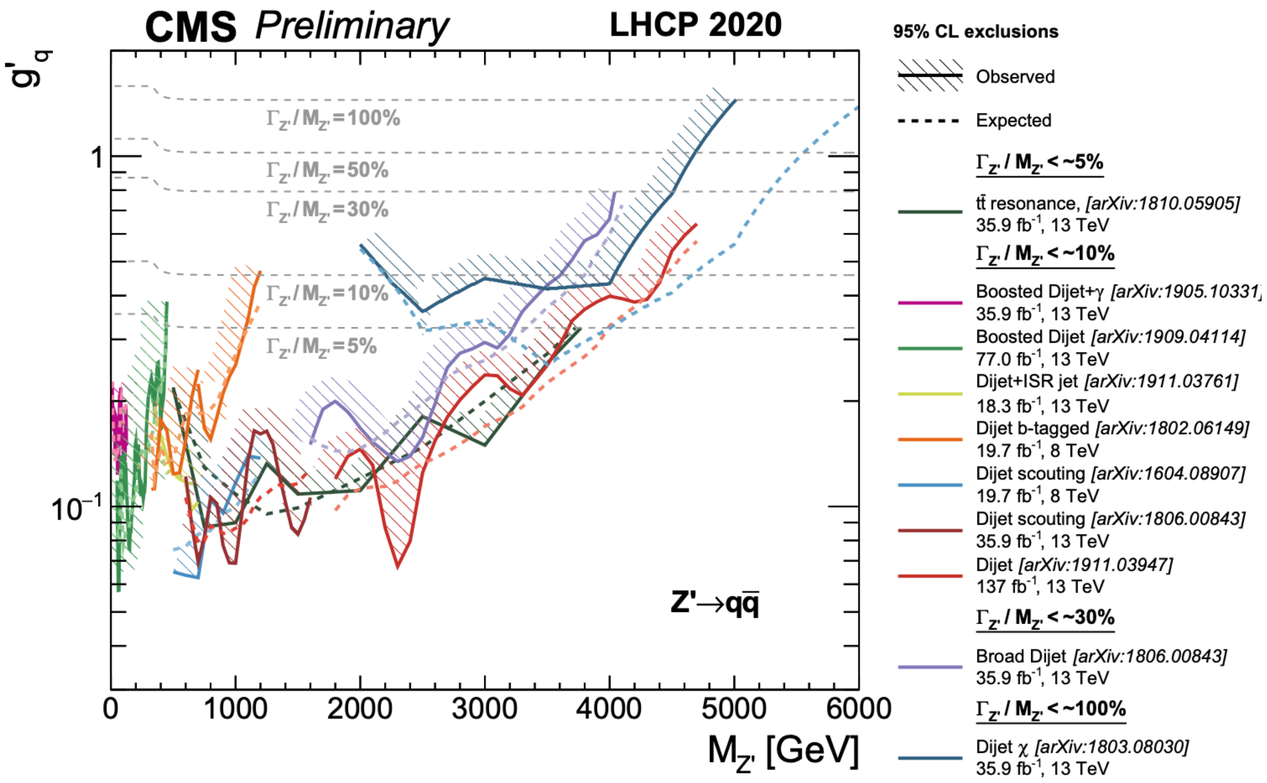


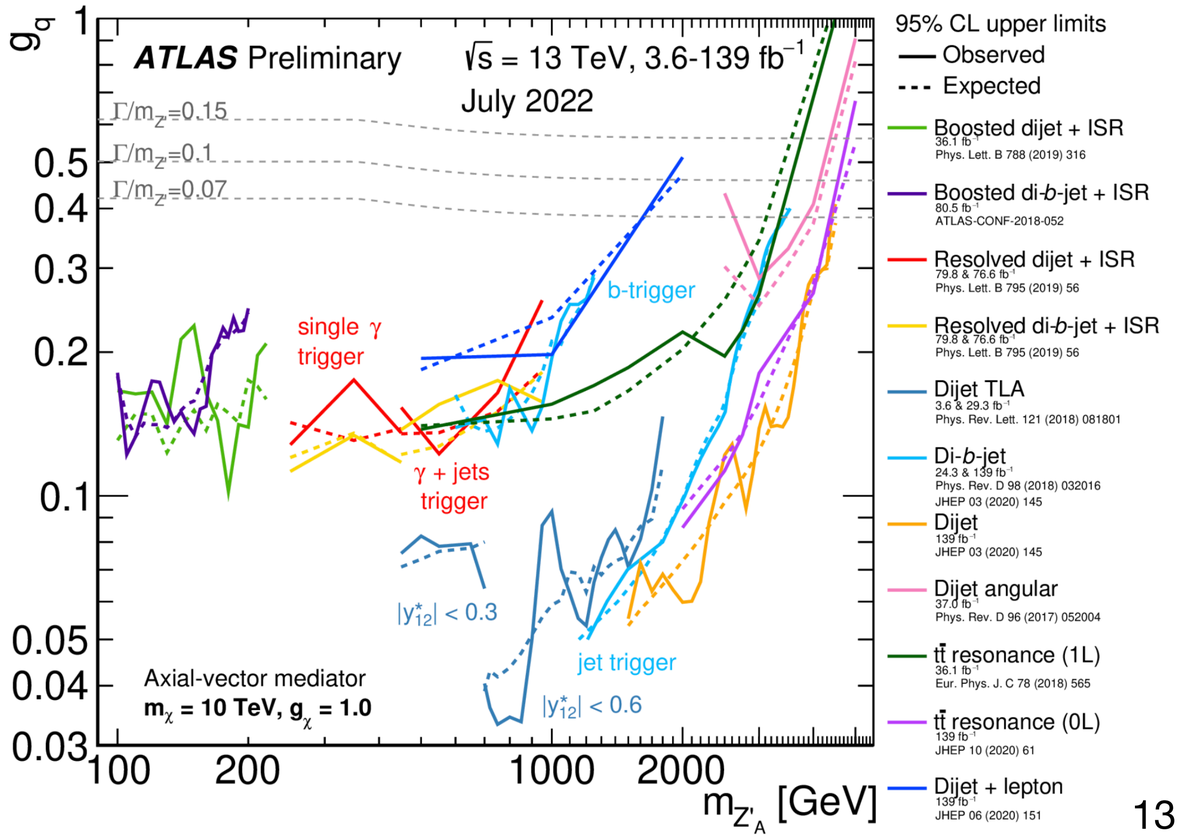
Hadronic Vector Portal Searches

ATL-PHYS-PUB-2022-036

- Experimentally low mass and coupling regime probed via:
  - Jet substructure analysis for boosted mediators
  - Trigger level analyses
  - Scouting



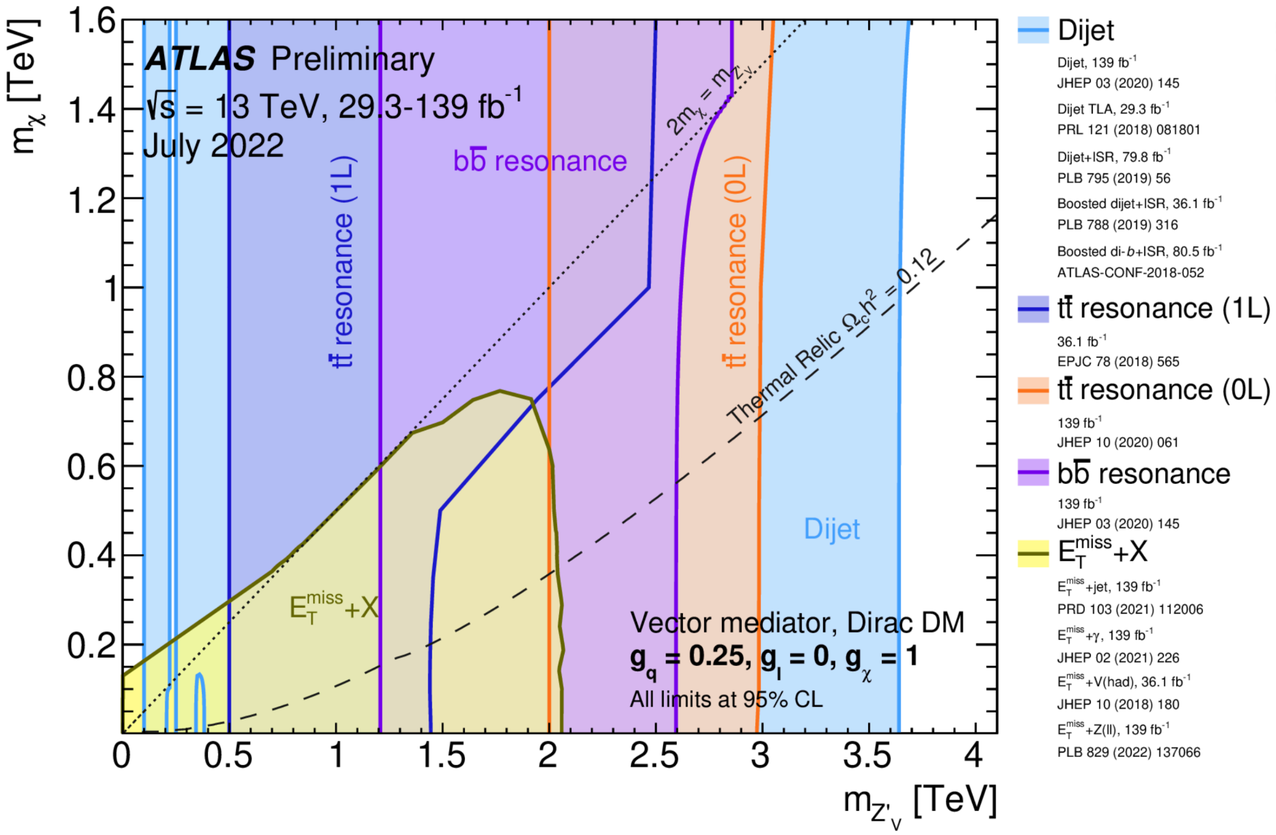


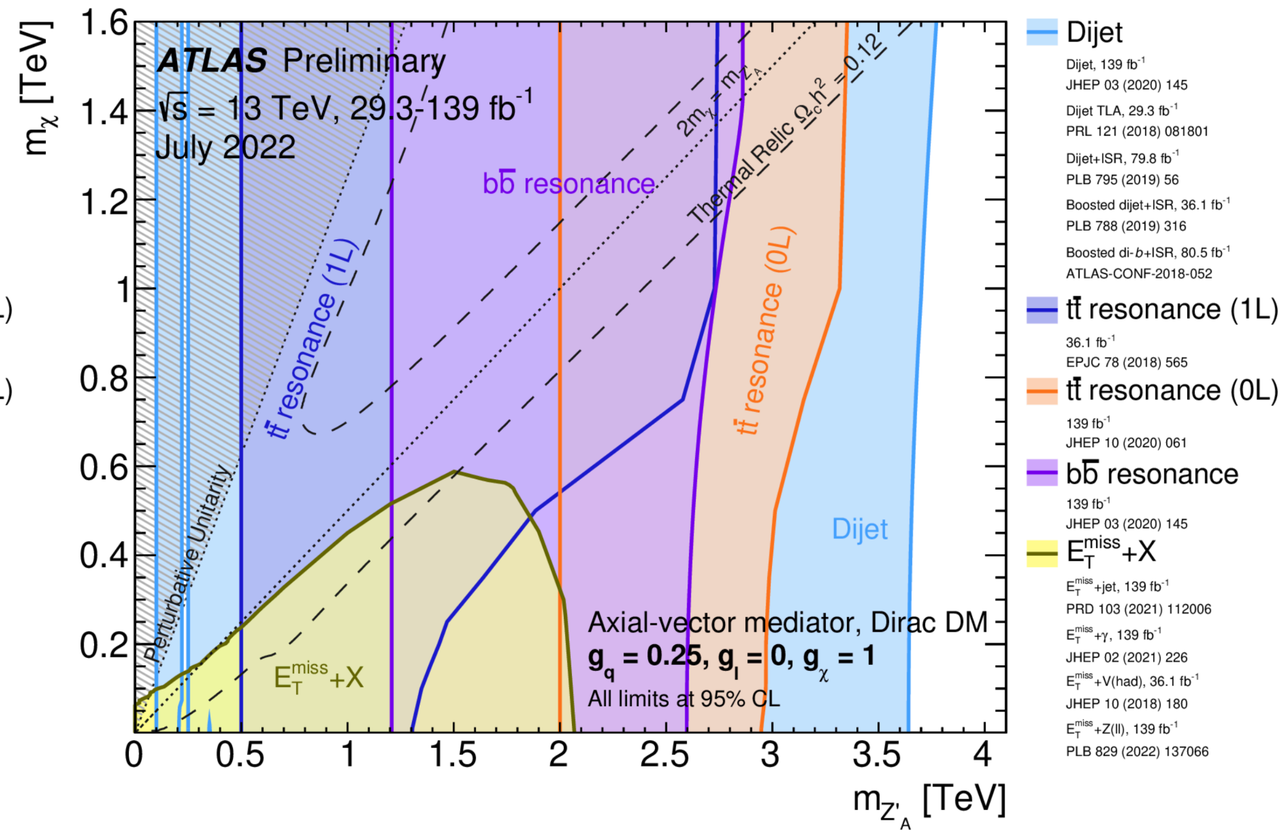


Vector Portal Dark Matter

ATL-PHYS-PUB-2022-036

- Following recommendations of LHC DM working group, can set limits in $m_\chi - m_{Z'}$ plane
  - Can be compared to missing E_T searches





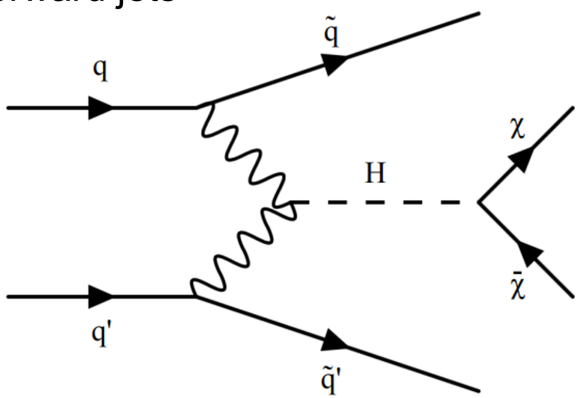
CMS plots here

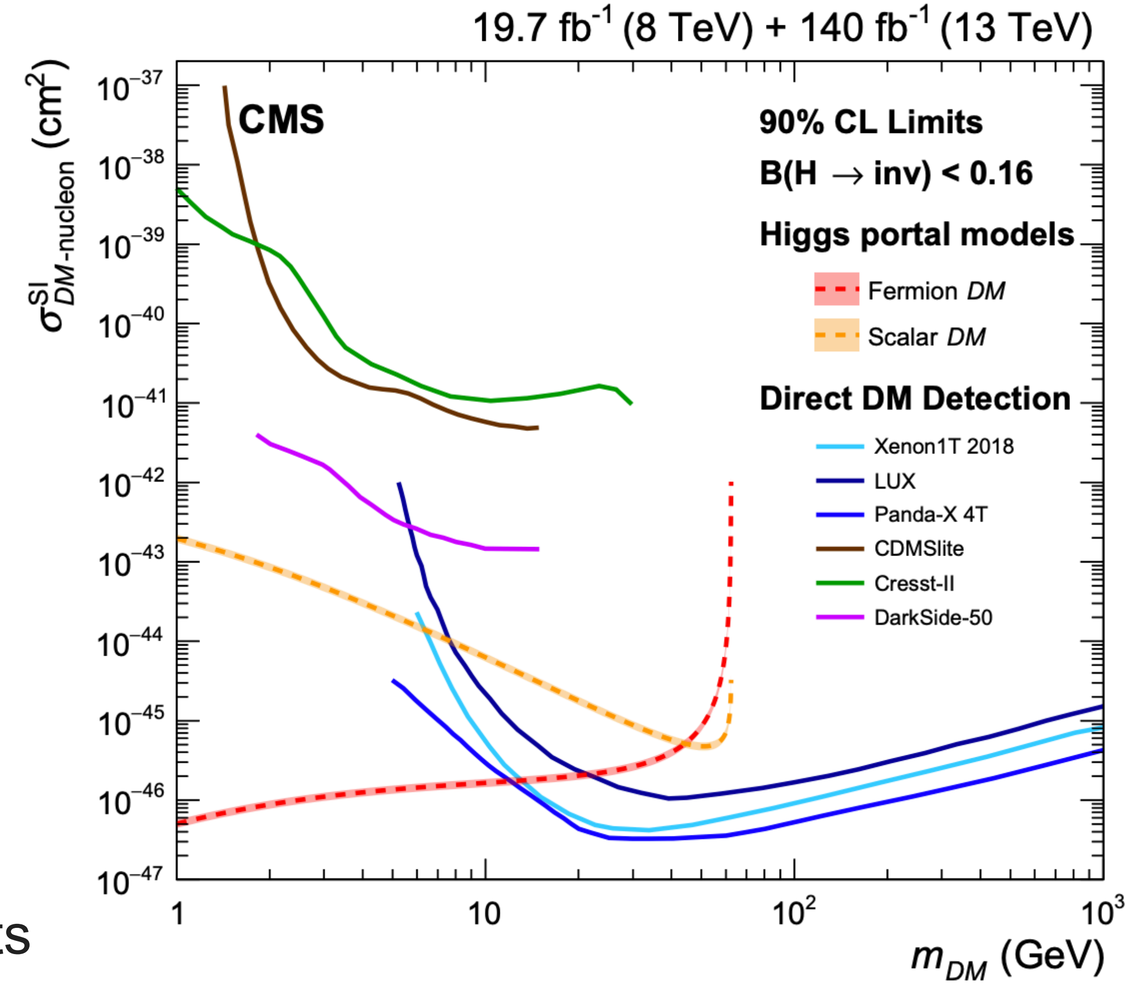
The Higgs Portal Dark Matter

CMS-HIG-20-003

- In Higgs portal models, the Higgs boson acts as the mediator between SM particles and DM, strongly enhancing $B(H \rightarrow inv)$

Most sensitive channel:
VBF tag-forward jets

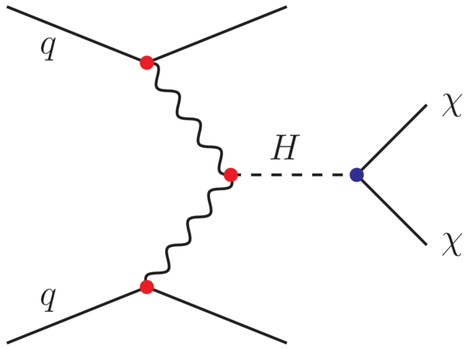


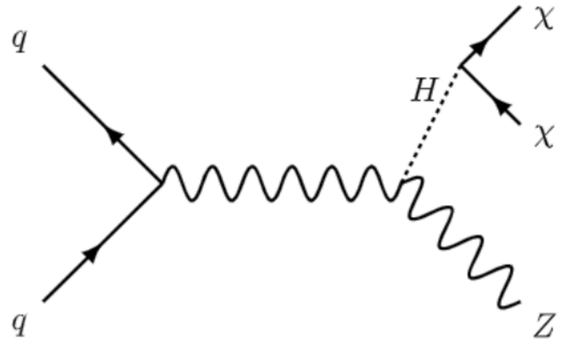


- Limits on the spin-independent DM-nucleon scattering cross section in Higgs-portal models
  - Assuming a scalar or fermion DM candidate
  - Compared to direct DM detection experiments

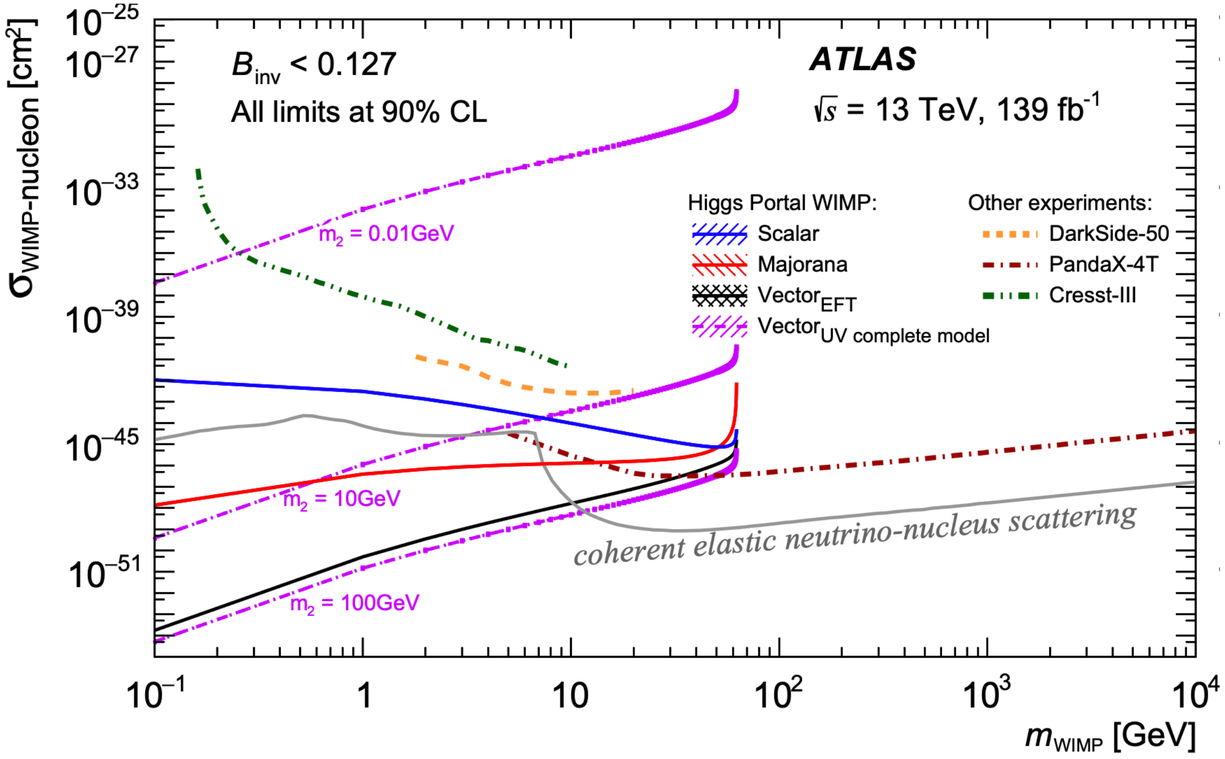
The Higgs Portal Dark Matter

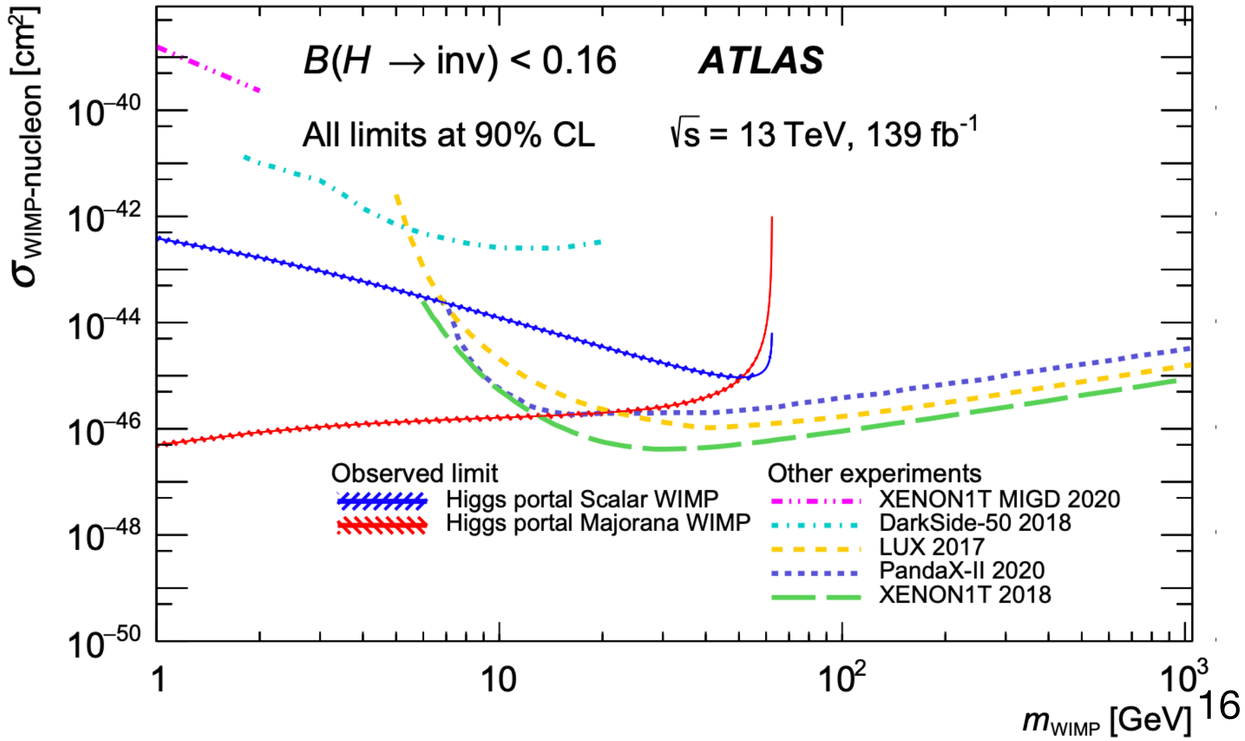
Phys. Lett. B 829 (2022) 137066
arXiv: 2202.07953 (accepted by JHEP)





- Competitive bounds for low mass WIMP

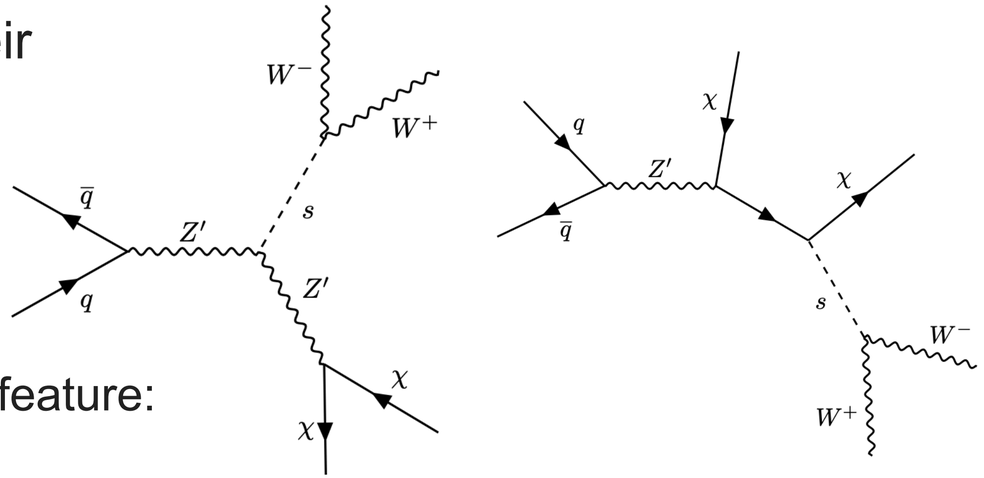




Dark Higgs

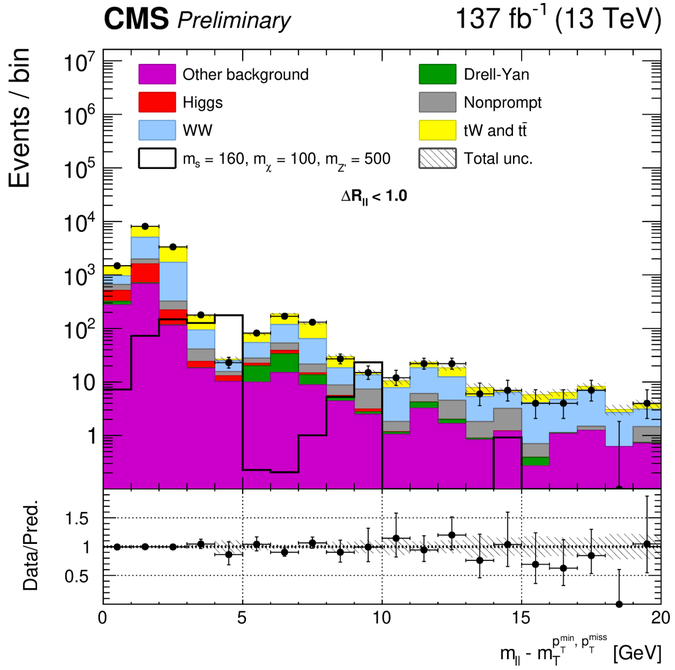
CMS PAS EXO-20-013

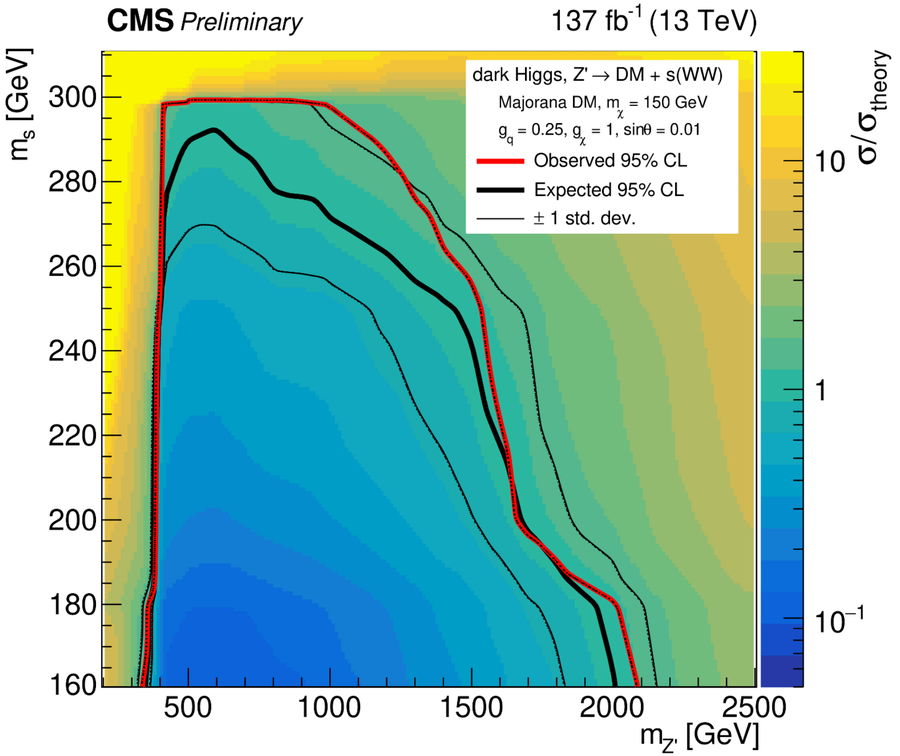
- Dark Higgs model: DM particles acquire mass through their interaction with a dark Higgs boson
  - Search targets s+missing transverse energy signature
  - $s \rightarrow WW$ becomes relevant for $m_s \gtrsim 160$ GeV



Presence of two oppositely charged and isolated leptons as main feature:

- 3D ML fit to $\Delta R_{ll} - m_{ll} - m_T^{l_{min}, p_T^{miss}}$

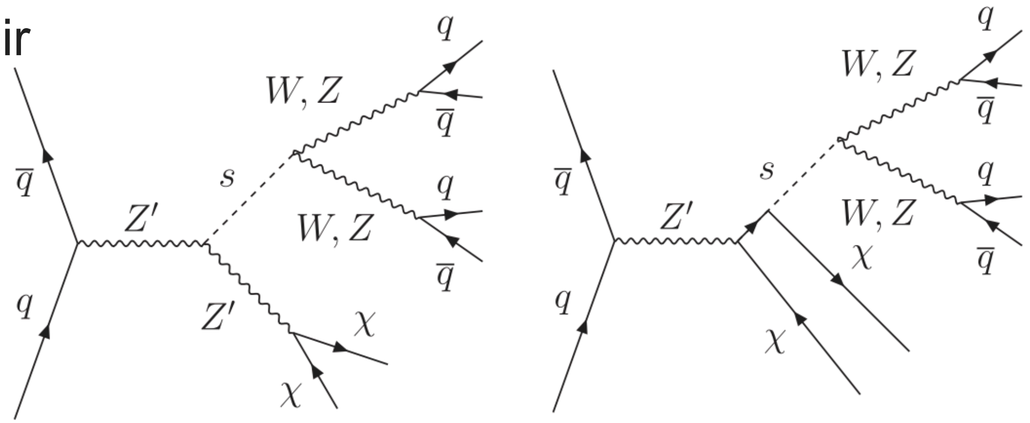




Dark Higgs

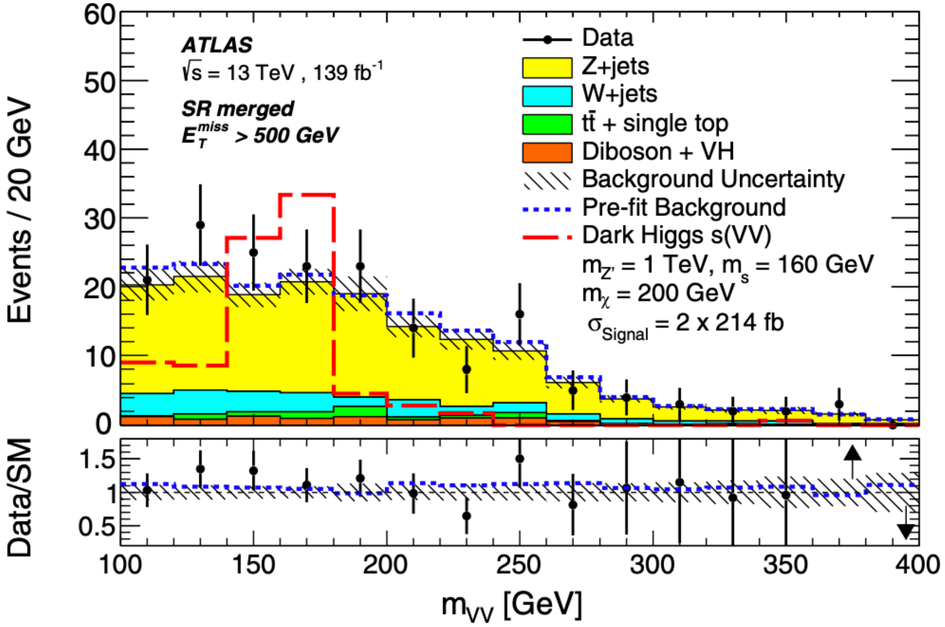
Phys. Rev. Lett. 126.121802

- Dark Higgs model: DM particles acquire mass through their interaction with a dark Higgs boson
  - ATLAS searches in VV pairs from a decay of s
  - $s \to WW$ becomes relevant for $m_s \gtrsim 160$ GeV
  - $s \to ZZ$ becomes relevant for $m_s \gtrsim 180$ GeV



VV in fully hadronic decay targeted:

- SR: requires large E_T^{miss} from DM particle
- Provides sensitivity complementary to other DM searches using $X + E_T^{miss}$ signatures
- $s \to VV$ reconstructed with novel track-assisted reclustering (TAR) algorithm

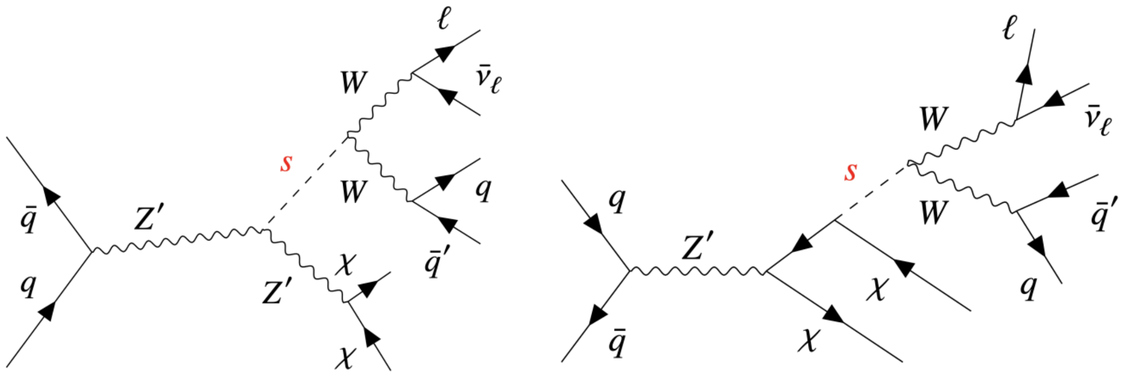


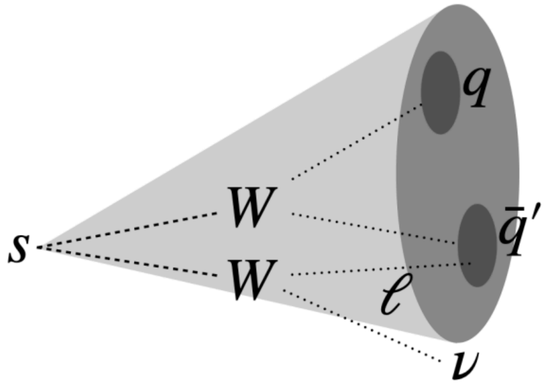
Dark Higgs

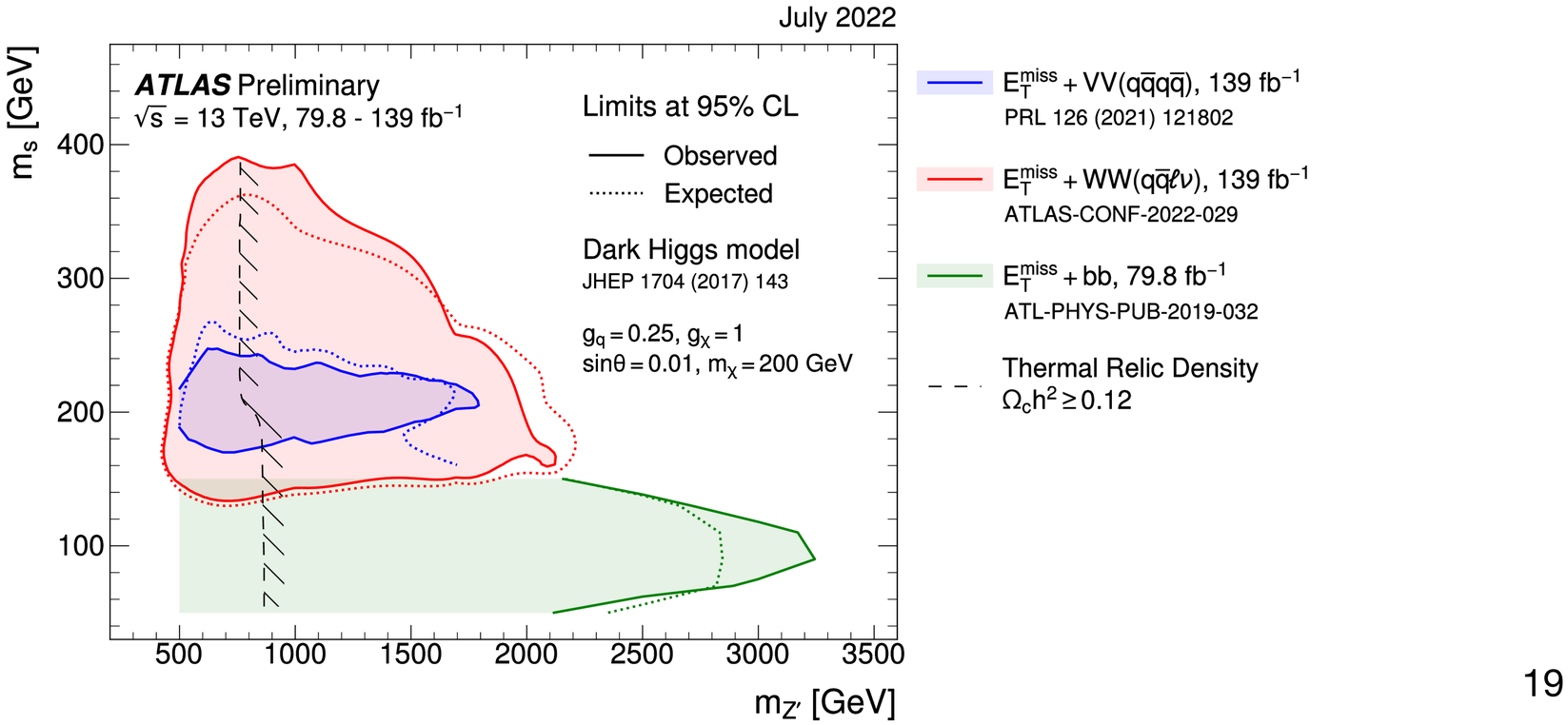
ATLAS-CONF-2022-029
ATL-PHYS-PUB-2022-036

VV in semilepton decay explored:

- SR: requires large E_T^{miss} from DM particle
- Provides sensitivity complementary to other DM searches using $X + E_T^{miss}$ signatures
- TAR jet reconstruction technique employed





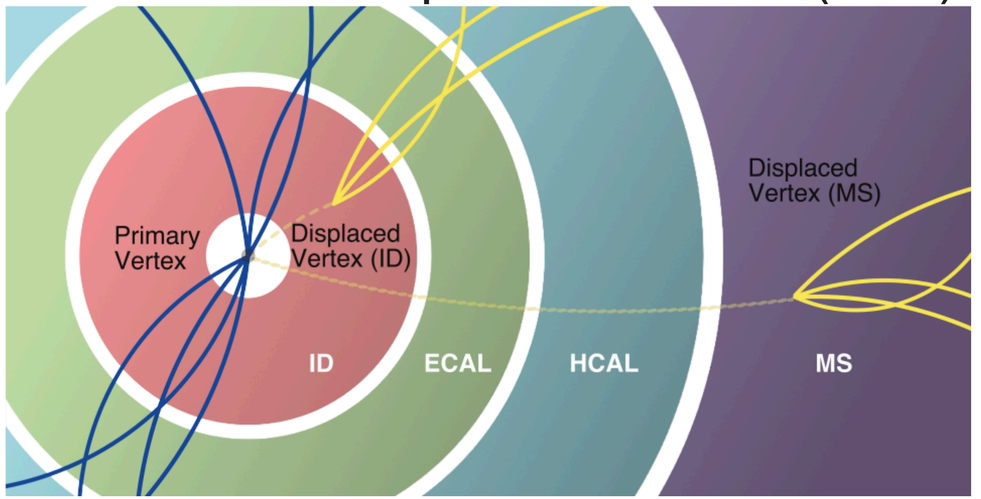


Higgs-portal Displaced Searches

- Long-lived particles (LLP) may decay to jets far from the interaction point (IP)
  - Result in secondary decays significantly displaced from the IP — displaced vertices (DVs)

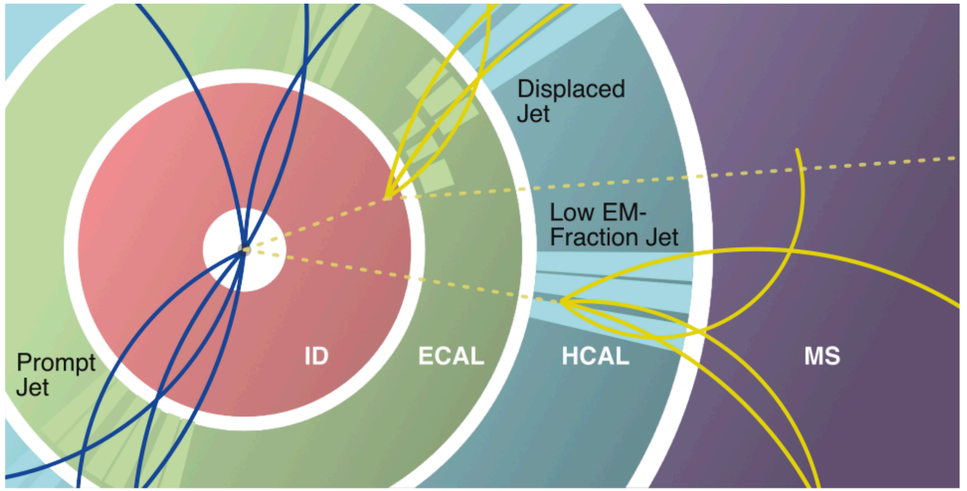
Possible scenarios:

- Particle decays in the ID, but far from the IP; or decays in the MS



Figures from JPPNP3695(2019)

- Particle decays in the calorimeters

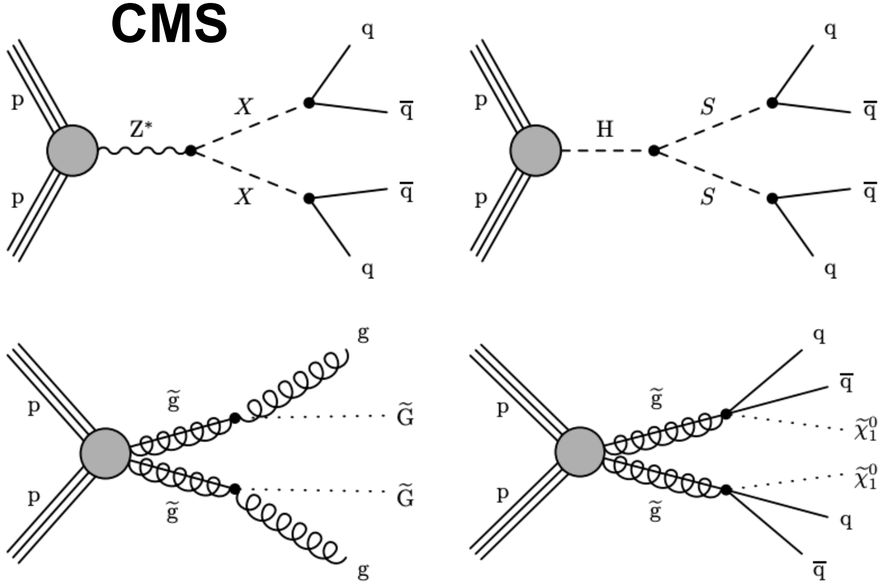


Calo - based

CMS PAS EXO-19-021
arxiv: 2203.01009 submitted to JHEP

- Search for pair-produced LLP by a Higgs boson or another short-lived scalar
  - A variety of models considered

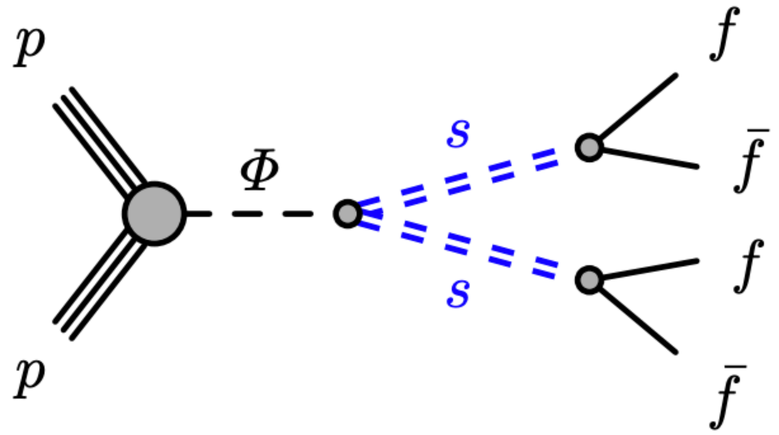
CMS



LLPs decaying mainly in the HCal or at the outer edge of the ECal

- Dedicated displaced-jet triggers employed

ATLAS

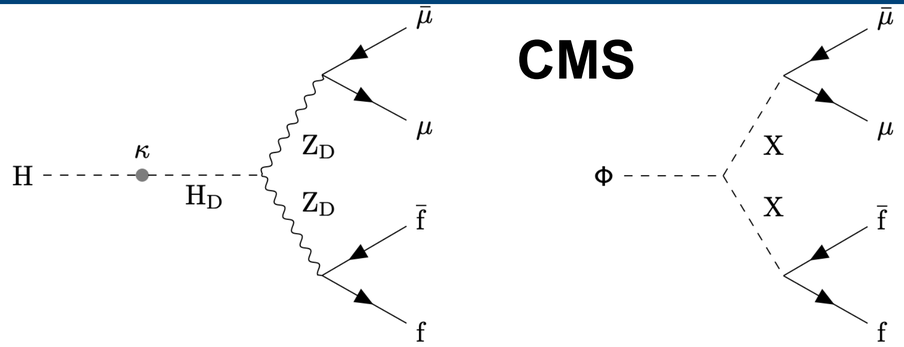


- Displaced jet tagger developed
  - Convolutional neural network employed, then fed into a long short-term memory (LSTM) network

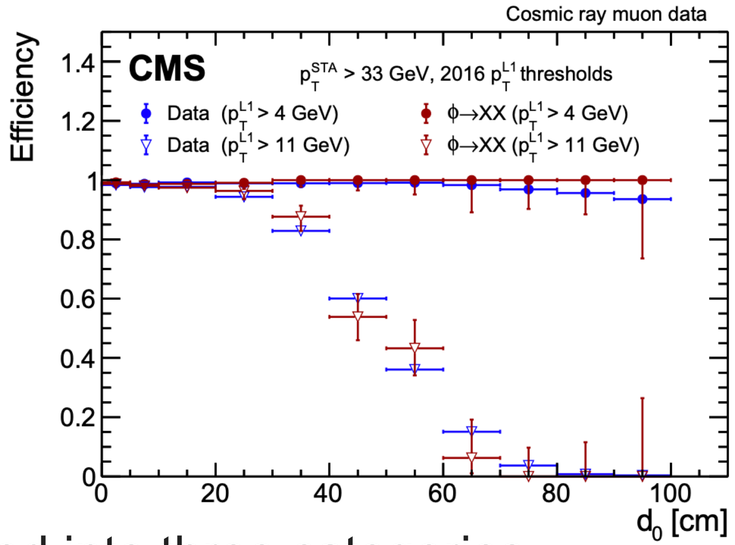
(Tracker +)MS - based

arxiv: 2203.00587 submitted to Phys. Rev. D.
arxiv: 2205.08582 submitted to JHEP

CMS

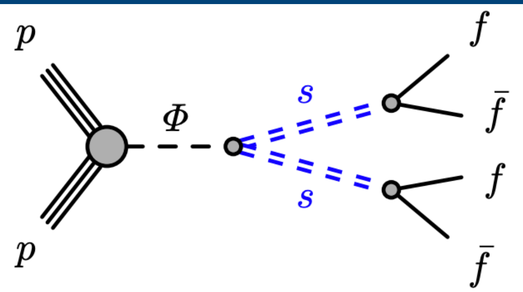


- Exotic massive LLP decaying to a pair of oppositely charged muon (displaced dimuon)
  - Triggers require two muons reconstructed in the MS alone

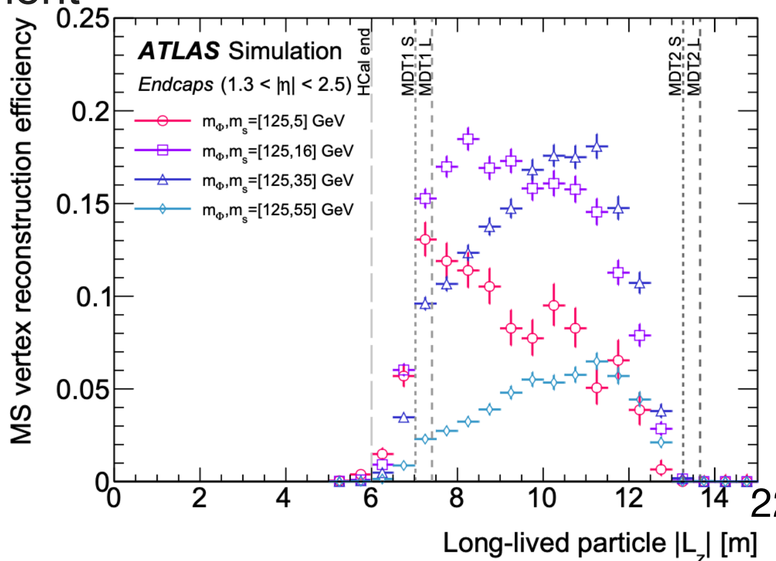


  - Events classified into three categories depends on if muons reconstruction includes trackers

ATLAS



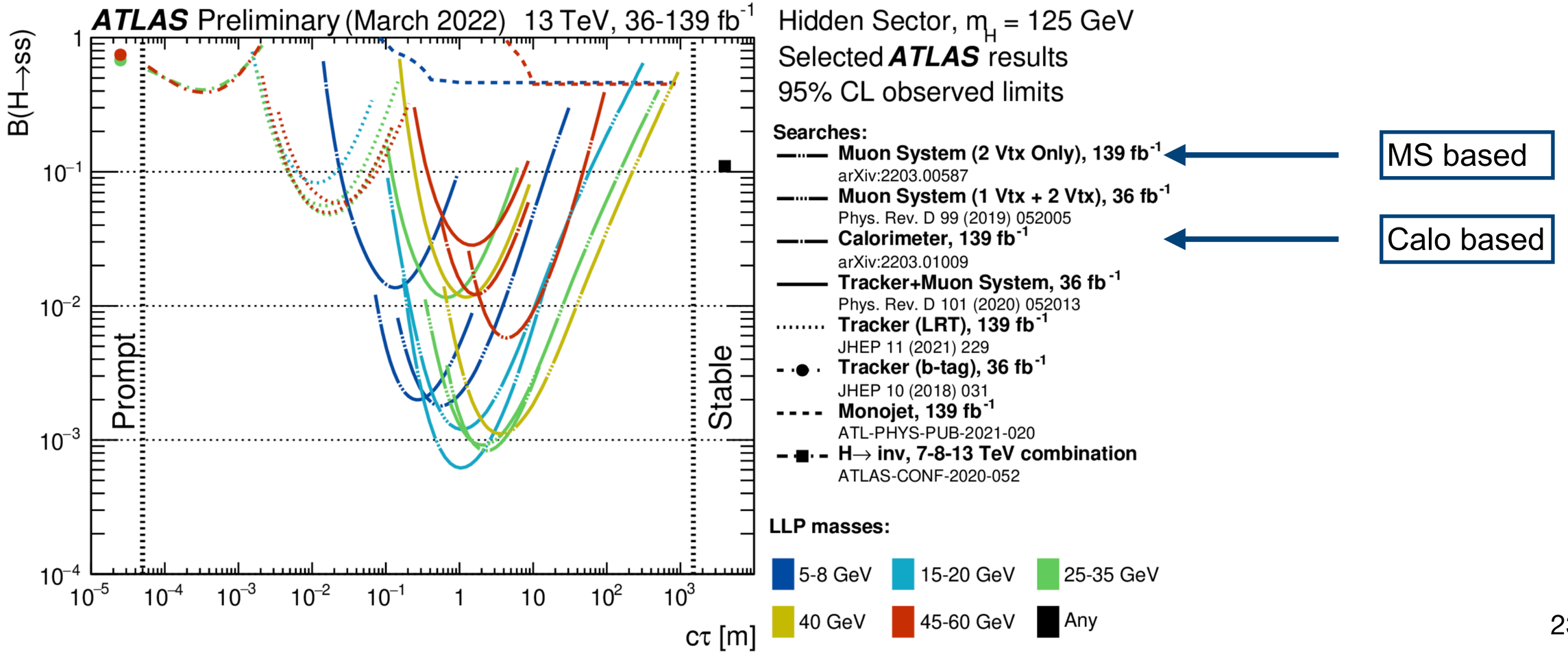
- Search targets events with two DVs in the MS
  - Muon RoI Cluster trigger employed
    - Signature-driven trigger
    - Selects candidate events for decays of LLPs
  - Dedicated algorithm used for MS DV reconstruction
    - Capable of reconstructing low-momentum tracks in a busy environment



LLP Higgs-mediated Summary

ATL-PHYS-PUB-2022-007

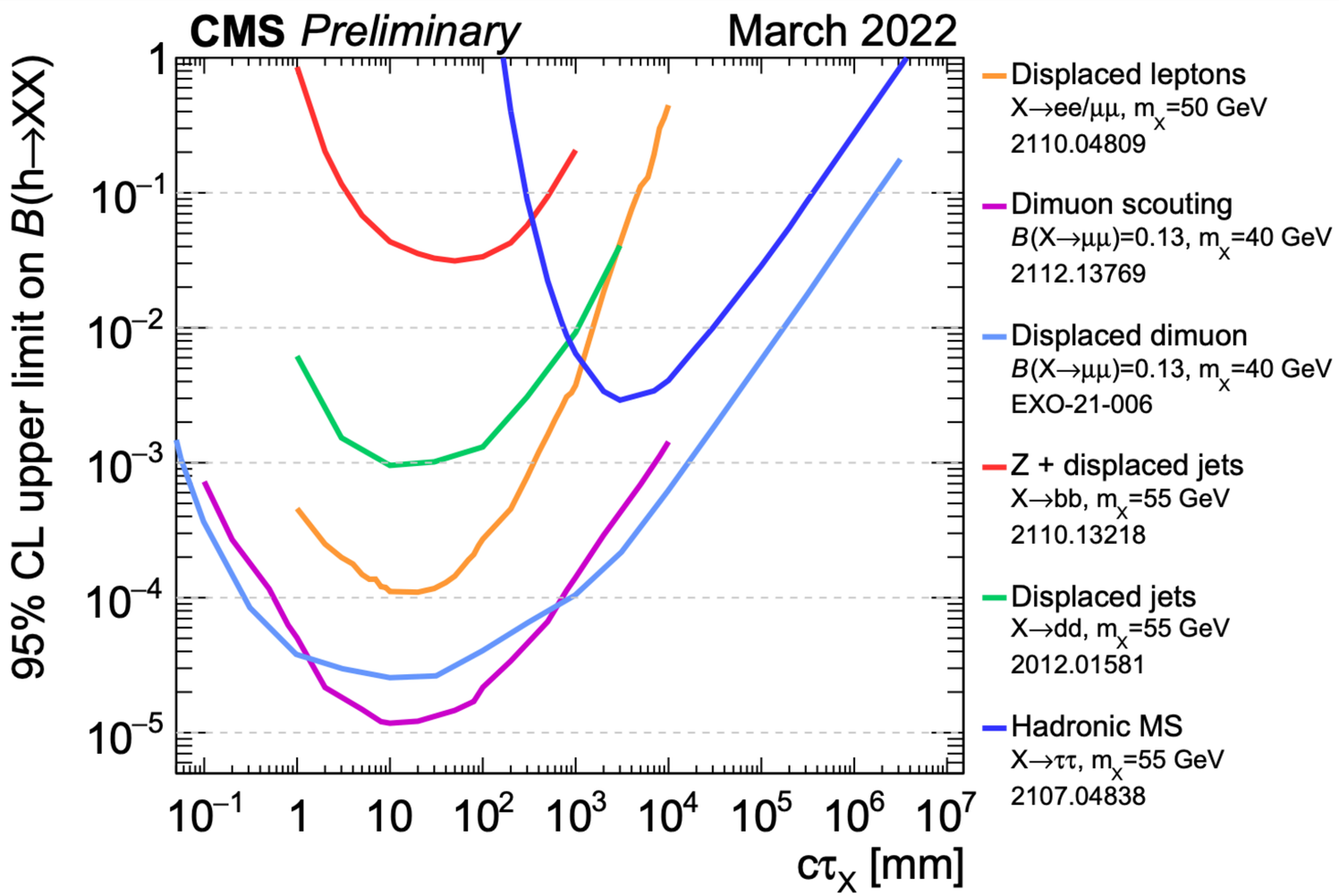
- Simplified Hidden Sector toy model used as benchmark
  - Interaction between SM sector particles and HS particles occurs via a heavy neutral boson Φ
  - Φ decays to a pair of neutral LLPs
  - Each LLP decays to SM $f\bar{f}$ pairs



LLP Higgs-mediated Summary

LLPs Summary

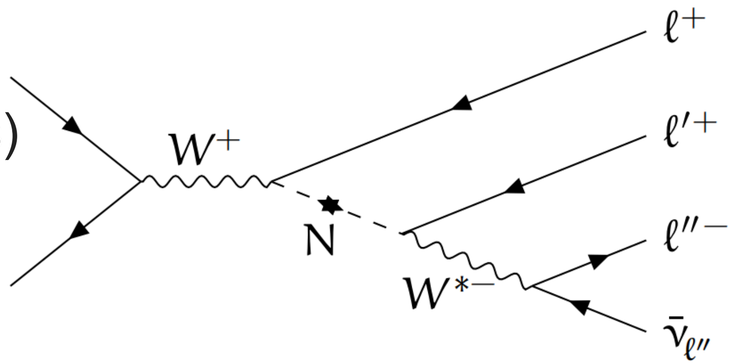
- Higgs decays to long-lived particles
  - BR assumption differ from ATLAS, thus tricky to compare



Heavy Neutral Leptons in CMS

arxiv: 2201.05578
submitted to JHEP

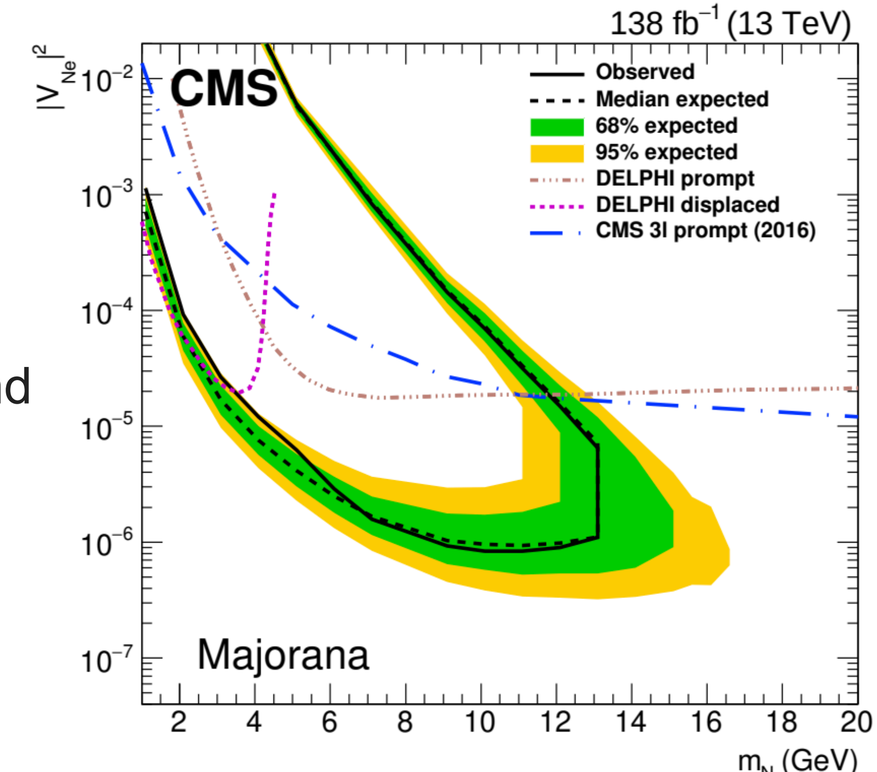
- Postulate the existence of right-handed neutrinos with Majorana masses
  - Explain neutrino masses
  - Predict heavy mass eigenstates, known as Heavy Neural Leptons (HNLs)
  - Decays maybe lepton number violating (LNV) or conserving (LNC)
  - A model with three HNLs can be incorporated a DM candidate



- One-HNL model with single-flavor mixing (1SFH) considered

- Events selected with three charged leptons
  - One originate from the primary interaction
  - The other two used to reconstruct displaced lepton

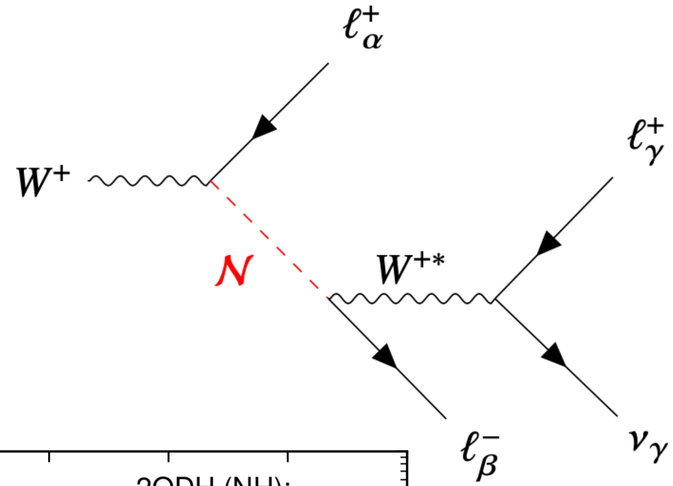
- B-jet tagging and cut narrow mass bands used for background rejection
- Fairly wide range of prompt-displaced sensitivity



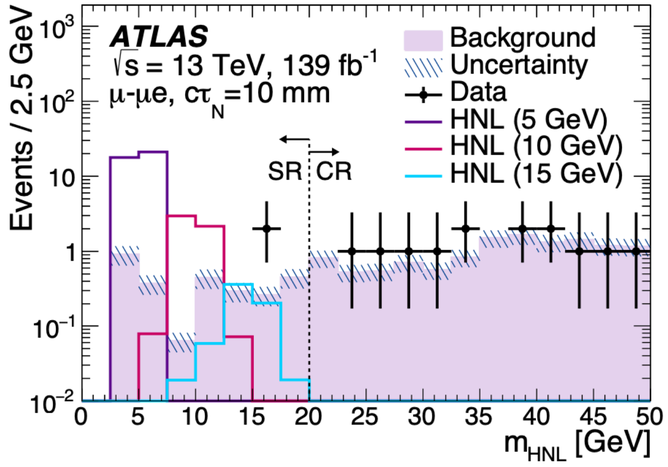
Heavy Neutral Leptons in ATLAS

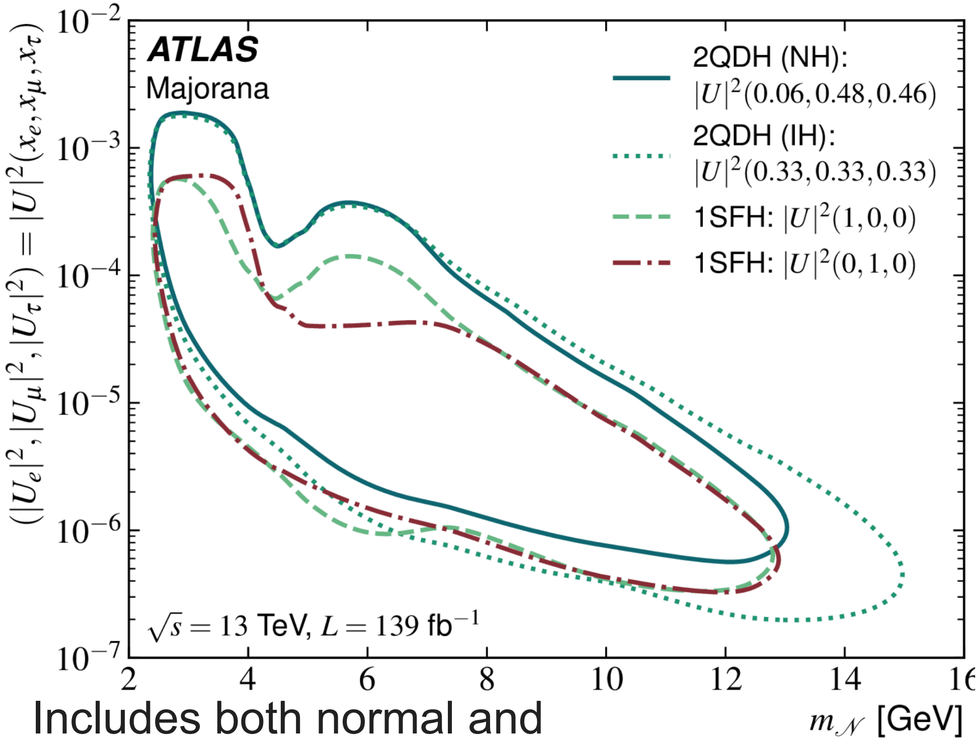
arxiv: 2204.11988
submitted to Phys. Rev. Lett.

- Signal interpretations considered
  - One-HNL model with single-flavor mixing (1SFH)
  - Two quasi-degenerate HNLs with multi-flavor mixing (2QDH)
    - More realistic than the simple-flavor mixing model
    - First direct search carried out by ATLAS



- Displayed decay signatures studied
  - Dedicated reconstruction performed for displaced vertex (DV) with optimized secondary vertexing algorithm





Includes both normal and inverted hierarchies for the μ, e, τ

Summary

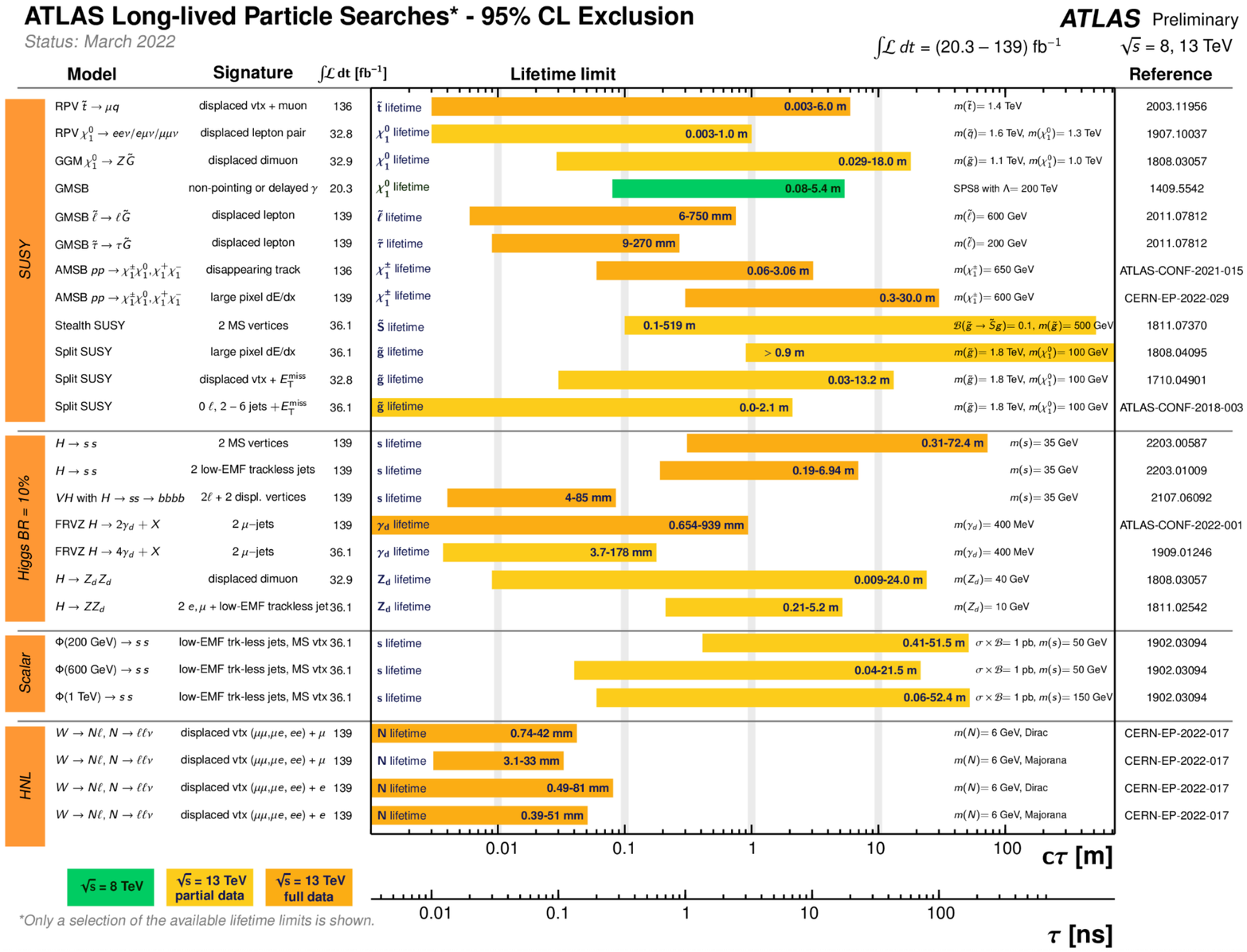
- New physics might be hiding in a hidden sector

- Dedicated dark sector particle searches and interpretations are increasing in ATLAS and CMS
  - Extensive benchmarks and DM interpretations
  - Diverse range of unconventional signatures
  - Dedicated displaced searches

- No significant excess yet over the SM background

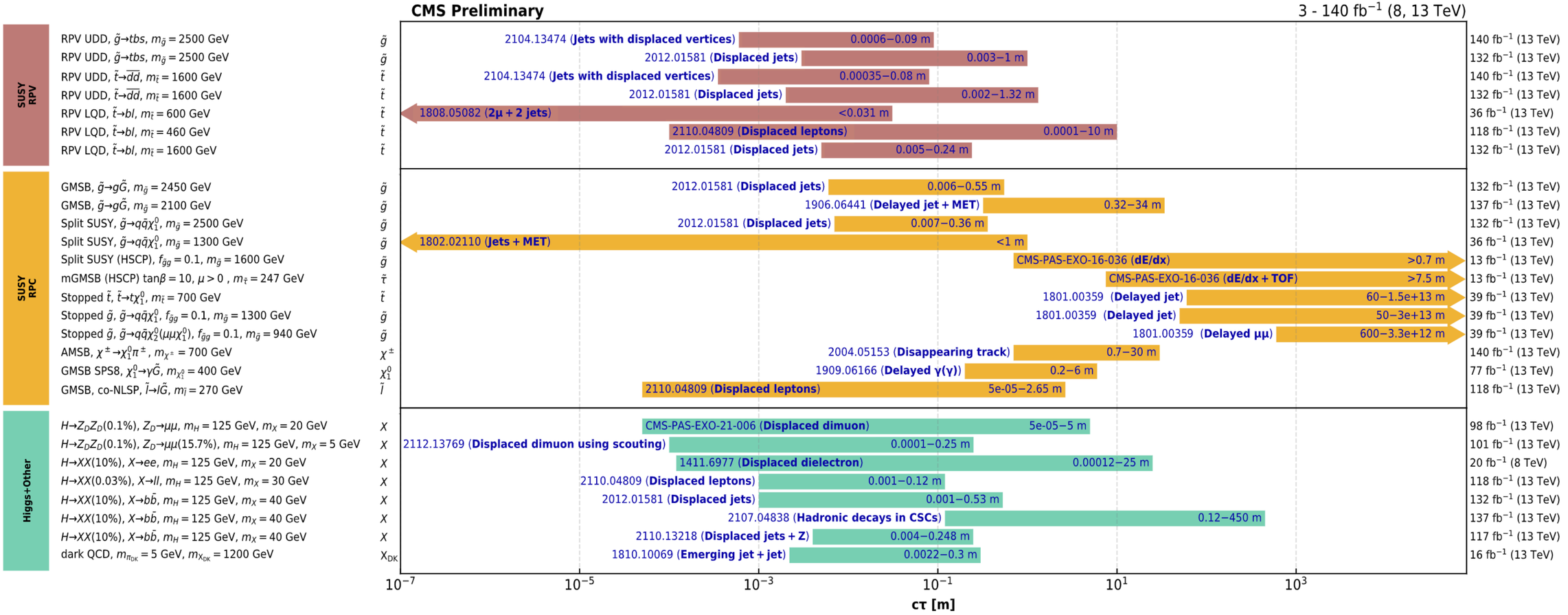
- Run 3 is here, stay tuned!

ATLAS Displaced Searches



CMS Displaced Searches

Overview of CMS long-lived particle searches



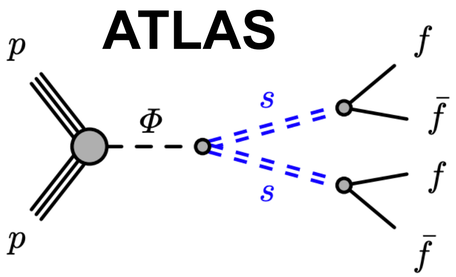
Moriond 2022

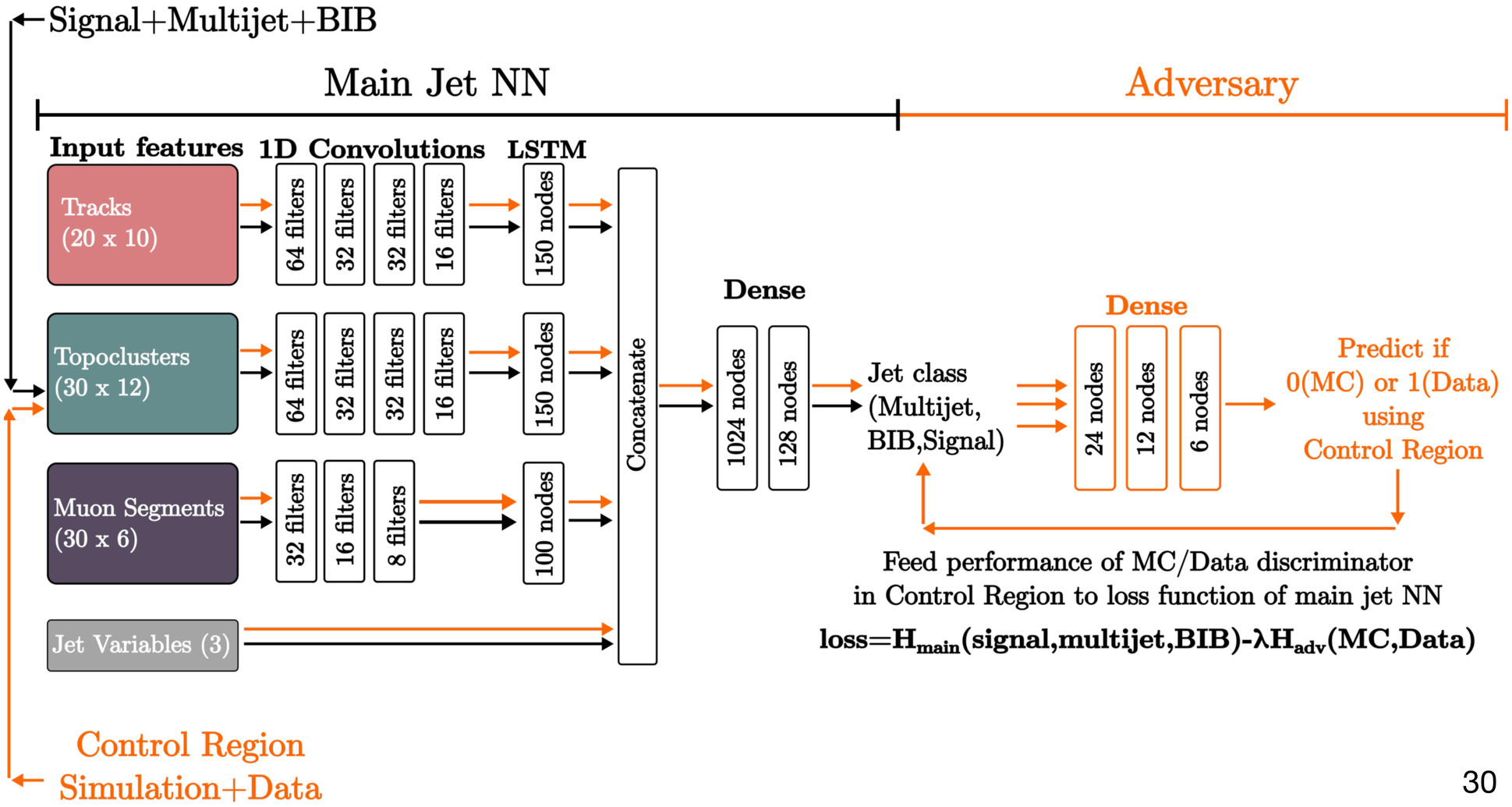
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Calo - based

arxiv: 2203.01009 submitted to JHEP

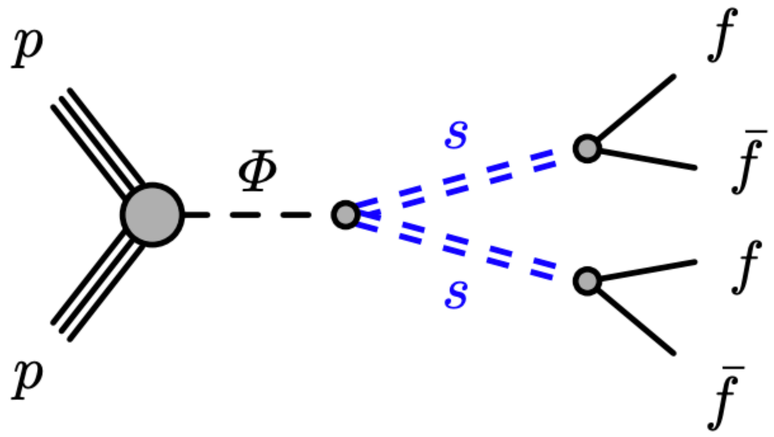
- Displaced jet tagger developed
  - Convolutional neural network employed, then fed into a long short-term memory (LSTM) network





Calo - based Search

arxiv: 2203.01009
submitted to JHEP



- A hidden sector benchmark model studied
  - Φ: A Higgs boson or a lower/higher-mass scalar boson
  - Decays into two long-lived scalars
- Heaviest fermion pair also considered when kinematically accessible

- Displaced jet tagger developed
  - Convolutional neural network employed, then fed into a long short-term memory (LSTM) network