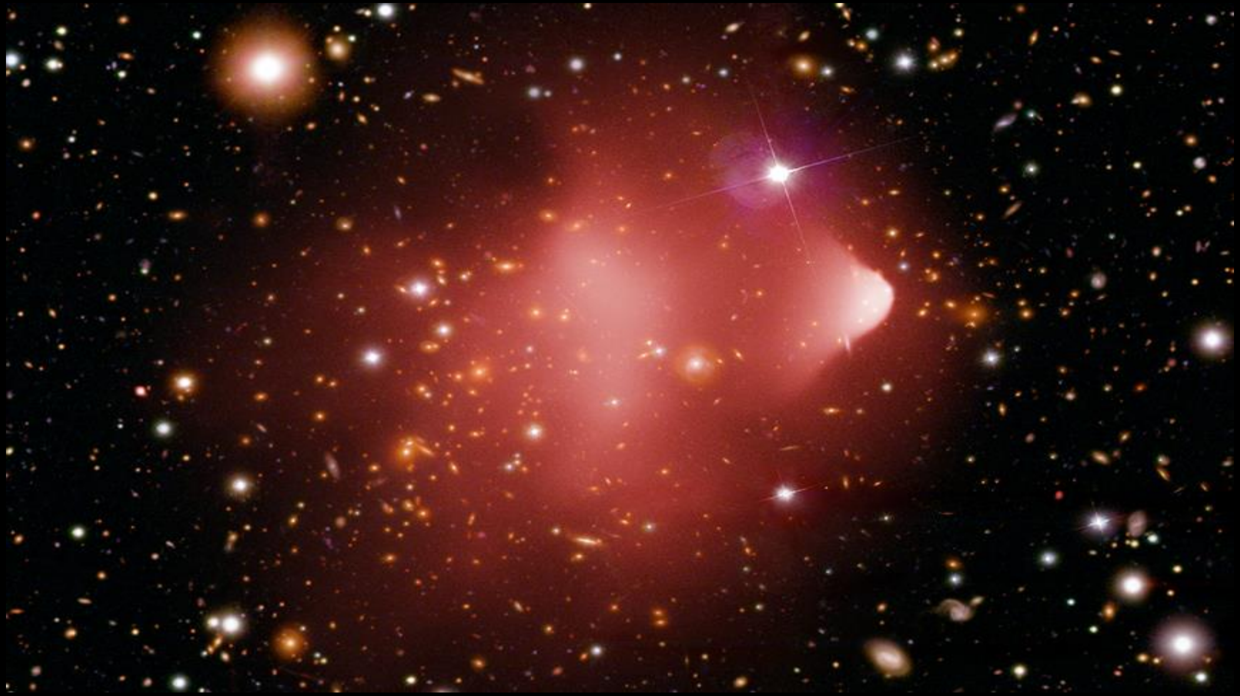
Dark Matter and Dark Sectors at the LHC

Luca Lavezzo (MIT)

On behalf of the CMS and ATLAS collaborations



Unexplained phenomena

- Gravity
- Dark matter
- Dark energy
- Matter-antimatter asymmetry

…

Experimental tensions (?)

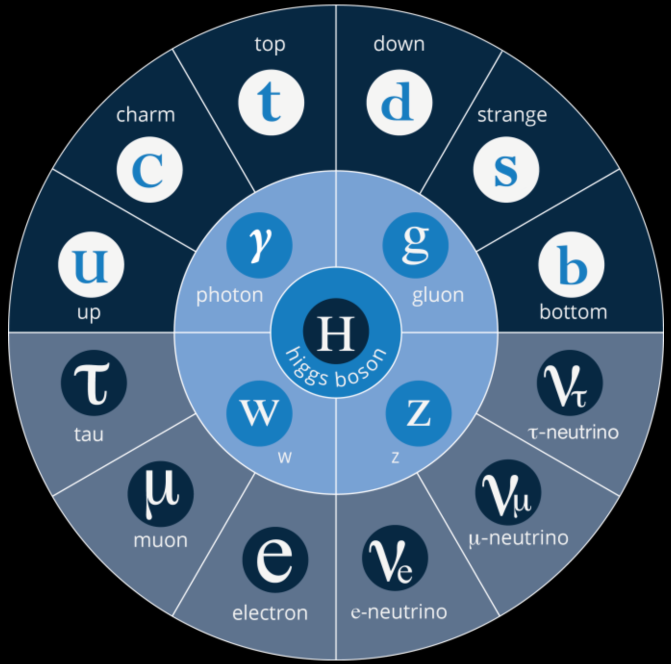
- $(g-2)_\mu$
- m_W
- $R(D^*)$
- $X17$

…

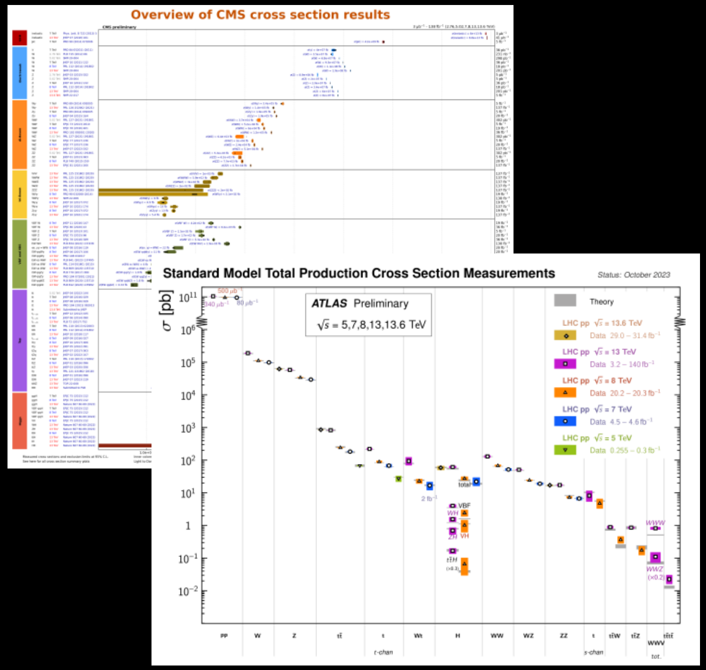
Fine-tuning problems

- $\theta_{CP} \approx 0$
- Hierarchy problem
- Neutrino masses
- Choice of parameters

…



Most consistent and precise theory in human history



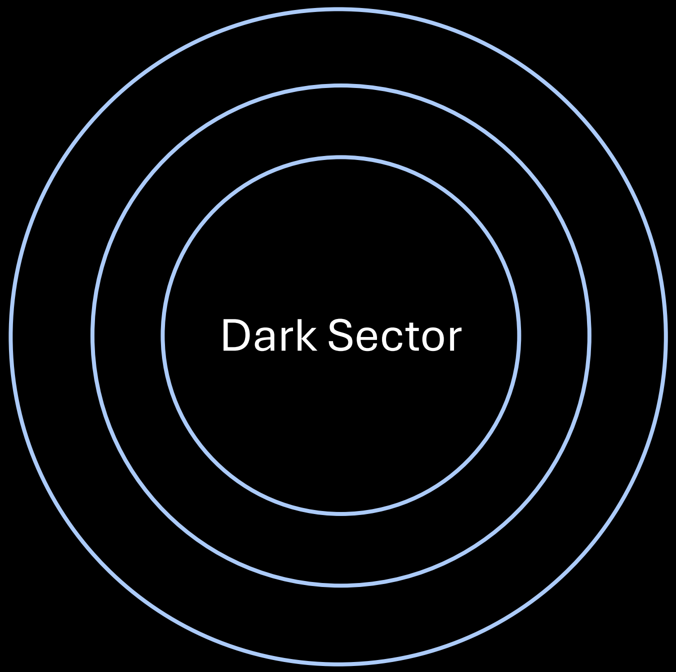
For the first time, no clear indication about what the missing pieces are

Dark sectors (DS) can address any of these problems

- New interactions with the standard model (SM) can provide dark matter (DM) candidates
- New symmetries can solve other theoretical and fine-tuning problems
- New particles can explain experimental tensions

- Dark sectors have their own **dark charges**, so are stable under their conservation laws, and can have rich structure

- Inherently weak interaction with the SM mediated via a new particle often called a **portal or mediator**



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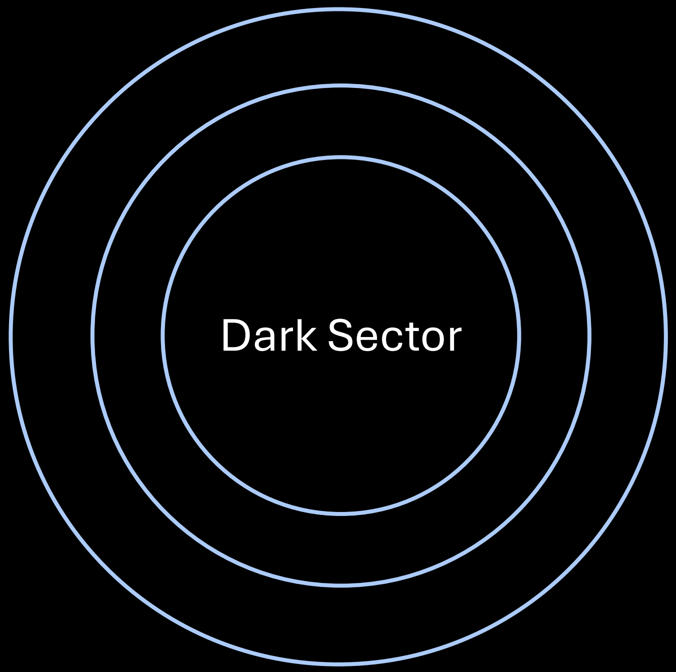
No hints about any details of the DS!

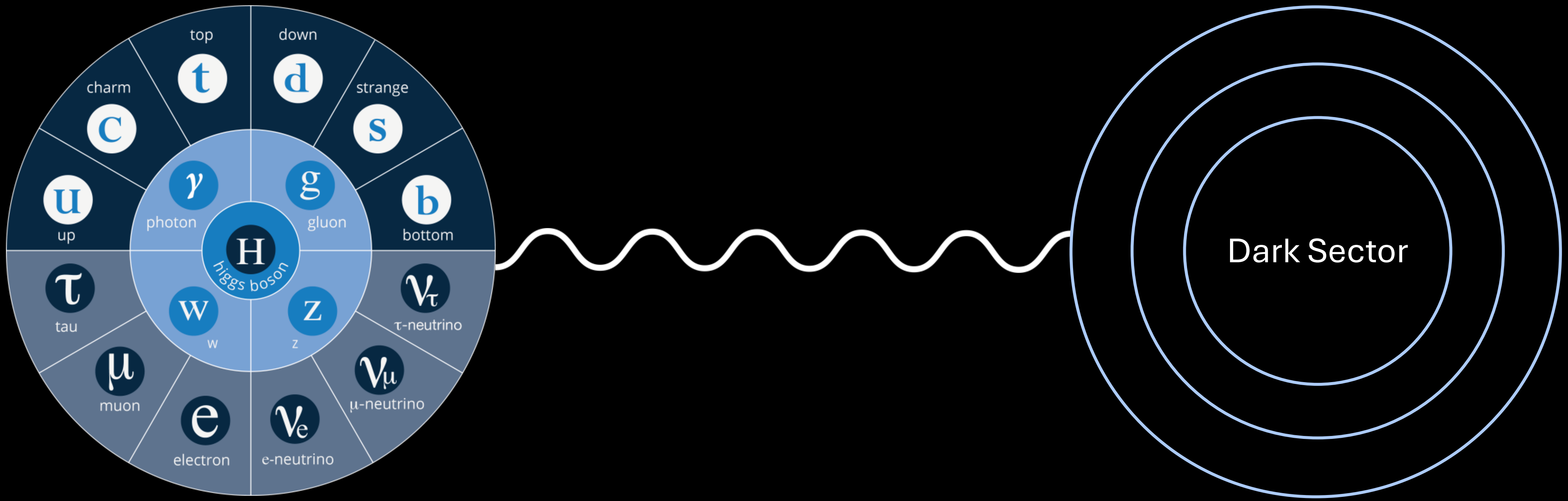
- Masses, couplings, gauge structures, portals, are very unconstrainted
- Zoo of theories: ALPs, WIMPs, SUSY, Hidden Valleys, Extra Dimensions, Axions, Dark Photons, …

So, how do we start looking for DSs?



To avoid breaking SM symmetries, four commonly studied ways to communicate with DS:

- **Spin-1 Portal**: new $U(1)$ interaction mixes with SM hypercharge
- **Spin-0 Portal**: scalar (Higgs-like) or pseudoscalar (e.g. ALPs) that couple to DS
- **Fermion Portal**: Yukawa couplings between DS and SM fermions
- **Neutrino Portal**: HNLs mix with neutrinos



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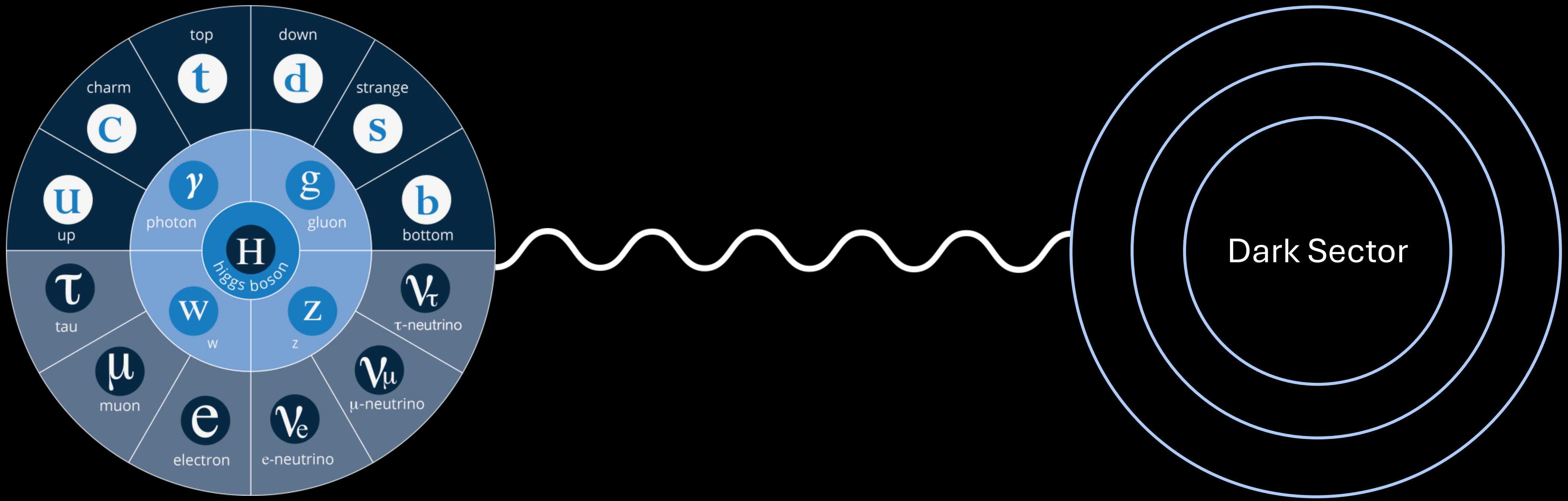
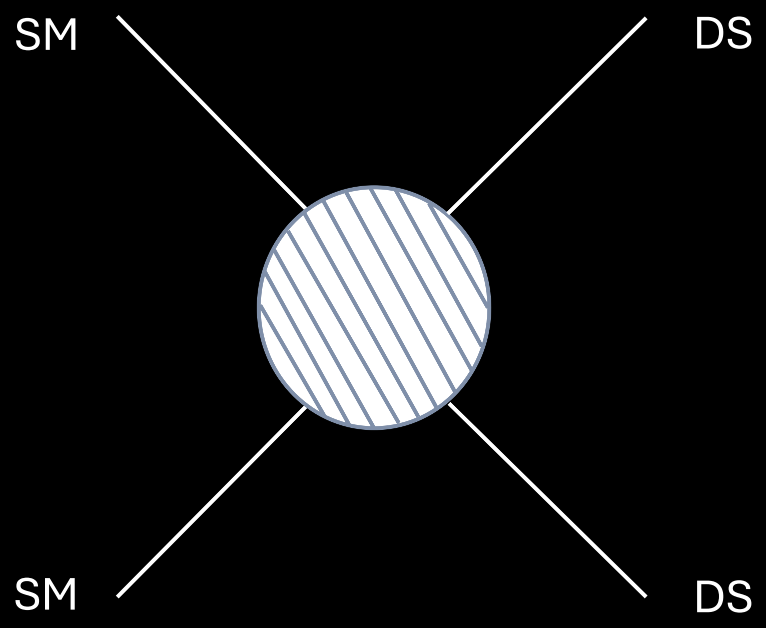


Many portals within direct reach, others can show up at lower energies due to quantum mechanical mixing

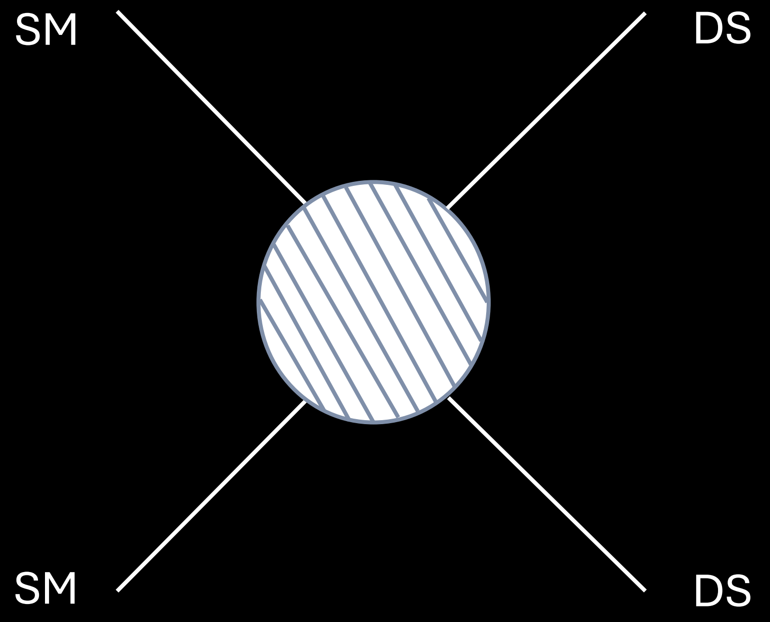
↓

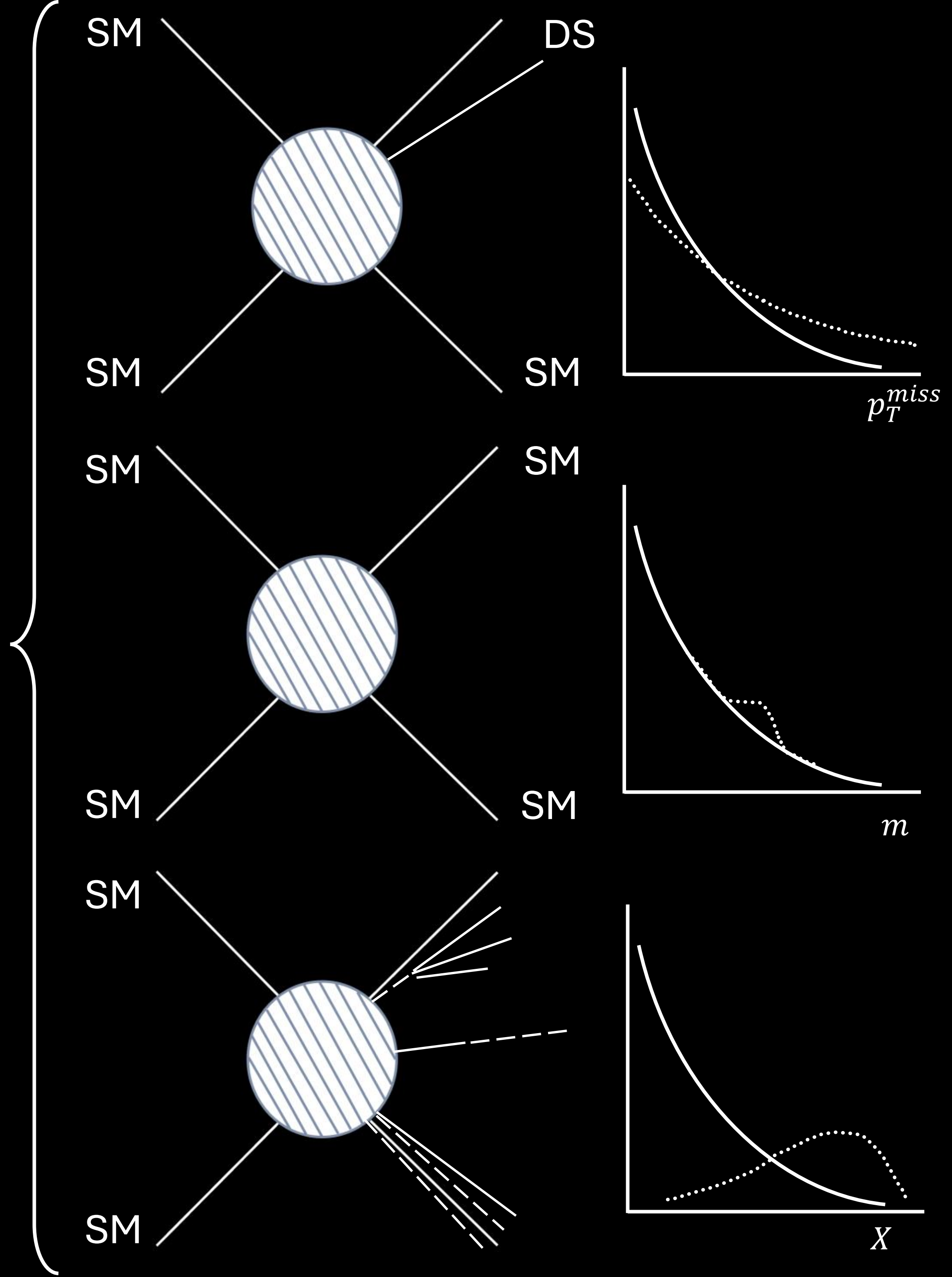
How can we probe this at colliders?

Dark Sectors at colliders



Dark Sectors at colliders





MET+X searches

- DS produced recoiling against SM system
- Missing transverse energy since DS is invisible

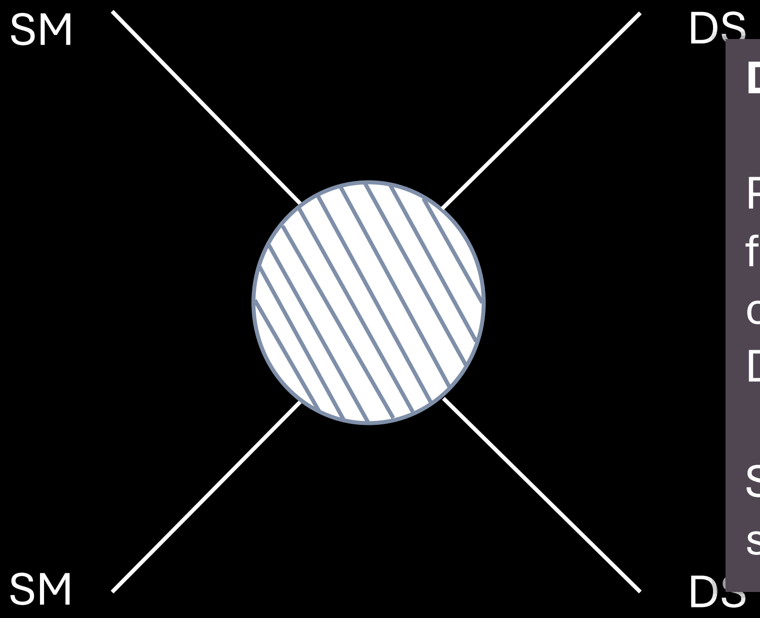
Portal resonances

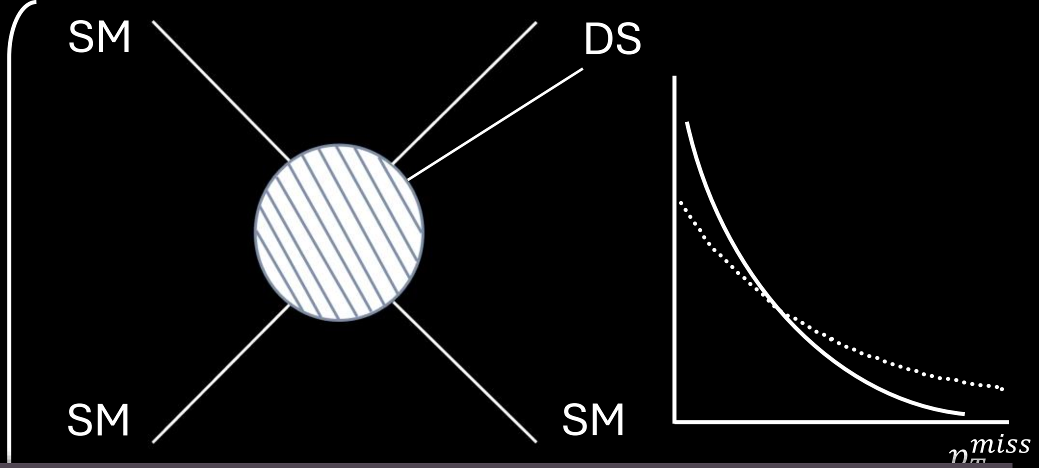
- Known SM processes cross sections are affected by DS
- Search for bumps in mass distributions

Unconventional signatures

- More complicated DSs can produce signatures completely different from SM (disappearing tracks, emerging jets, displaced leptons, etc.)
- New reconstructed objects often necessary

Dark Sectors at colliders





MET+X searches

- DS produced recoiling against SM system
- Missing transverse energy since DS is invisible

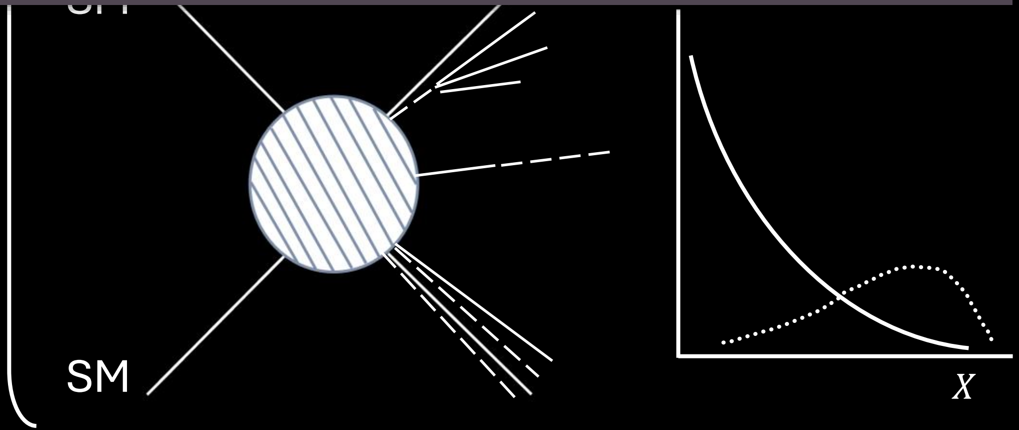
Disclaimer:

Precision measurements are also powerful probes for DSs, but focus on well-predicted SM observables which are sensitive to corrections from DS effects

Since they are experimentally different from DS searches, they will not be covered in this talk

Portal resonances

- Known SM processes cross sections are affected by DS
- Search for bumps in mass distributions



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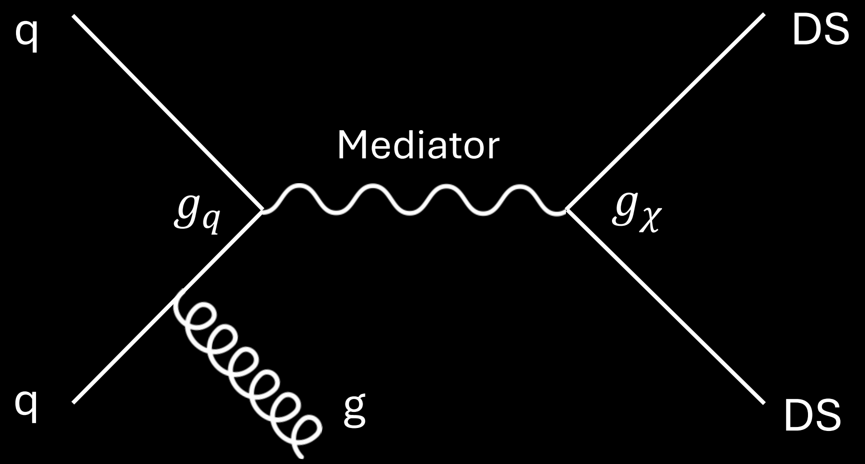
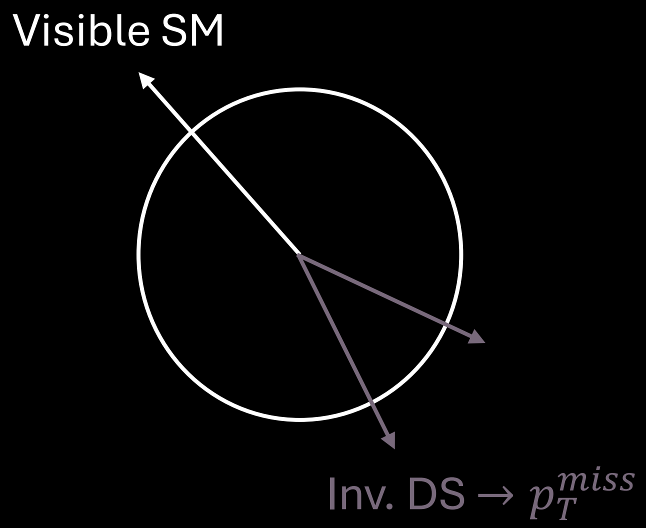
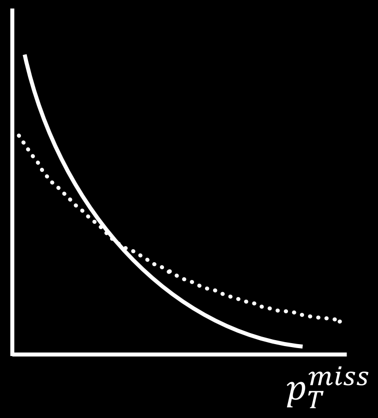
MET+X







Strategy

- Invisible DS particles produced via mediator that couples to SM and DS
- DS particles recoil against SM (jet, photon, V, Higgs, t/b, tt/bb, etc.)
- Since (transverse) momentum is conserved, measure missing (transverse) momentum

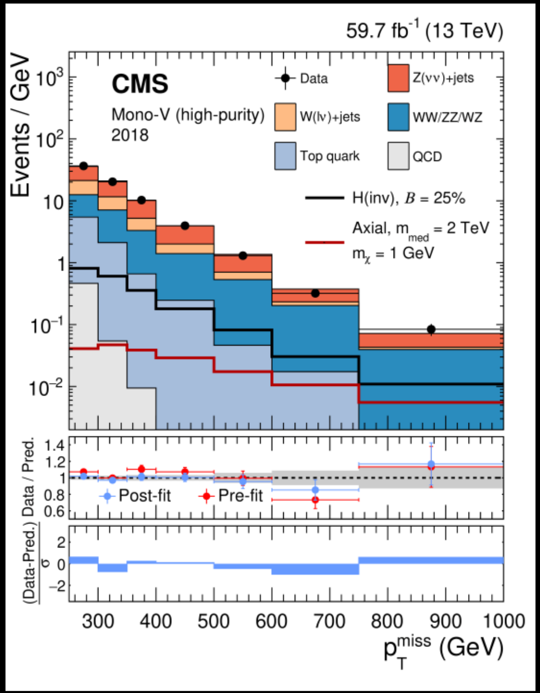
Target

- Simplified DM models (e.g. WIMPs) with parameters: $m_{med}, m_{DM}, g_q, g_\chi$
- Higgs portals
- Any model with invisible decays! Very model independent search

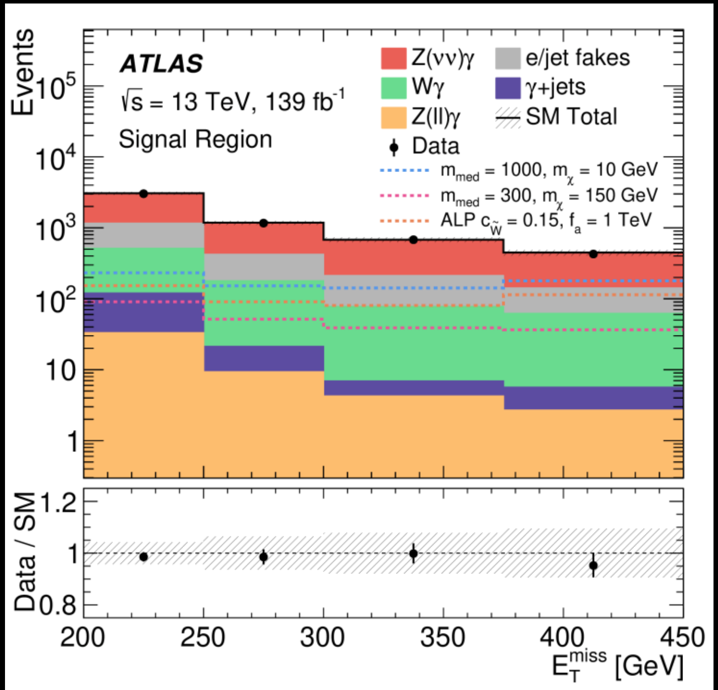
MET+X Results

[1] - JHEP 11 (2021) 153
[2] - JHEP 02 (2021) 226
[3] - arXiv:2402.16561

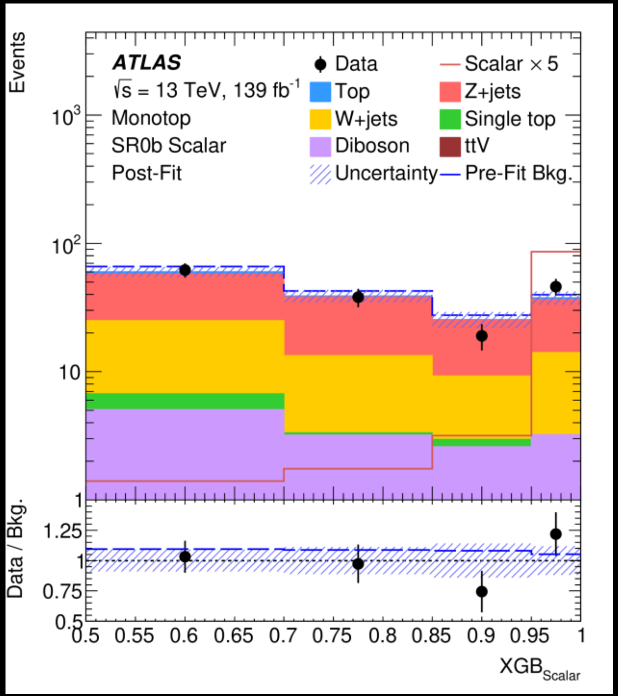
Mono-Jet [1]



Mono-γ [2]



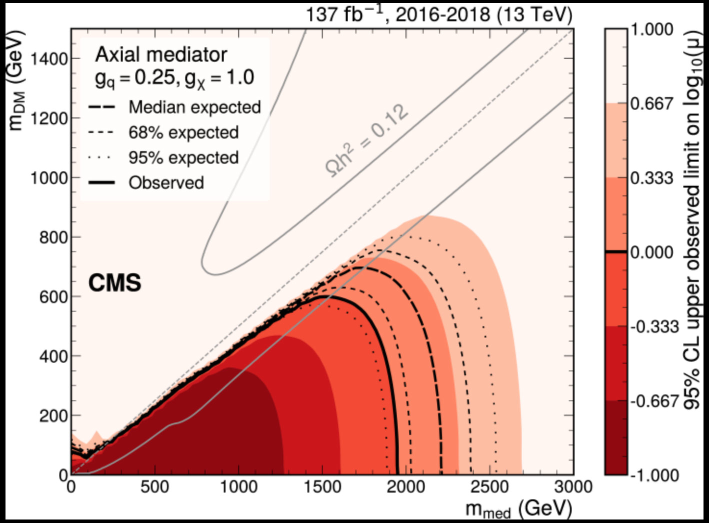
Mono-t [3]

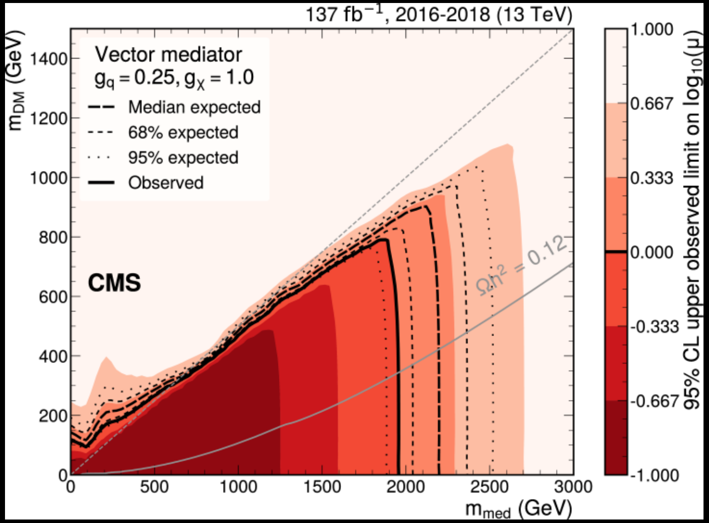


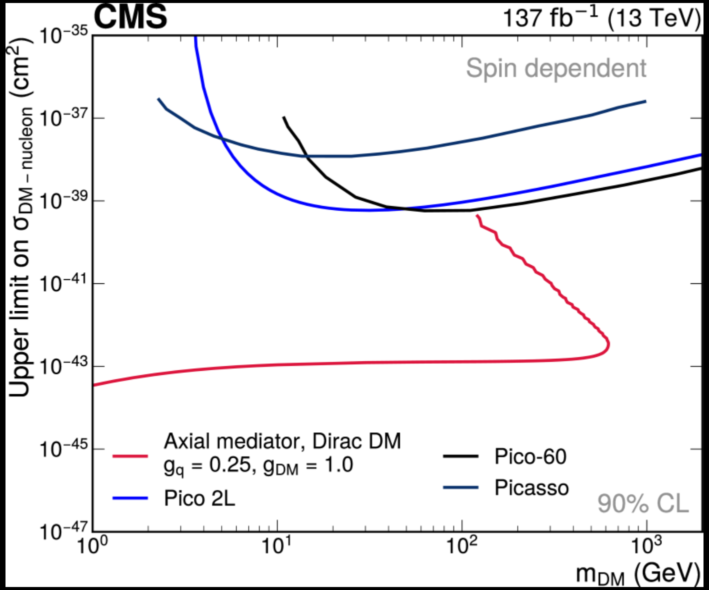
- A few representative examples of the many Run 2 MET+X results from ATLAS and CMS are shown
- Evolution of MET algorithms to improve sensitivity (pile-up mitigation, ML, etc.)
- “Control regions” in data to constrain and/or predict backgrounds
  - Often through simultaneous binned likelihood fits with signal regions

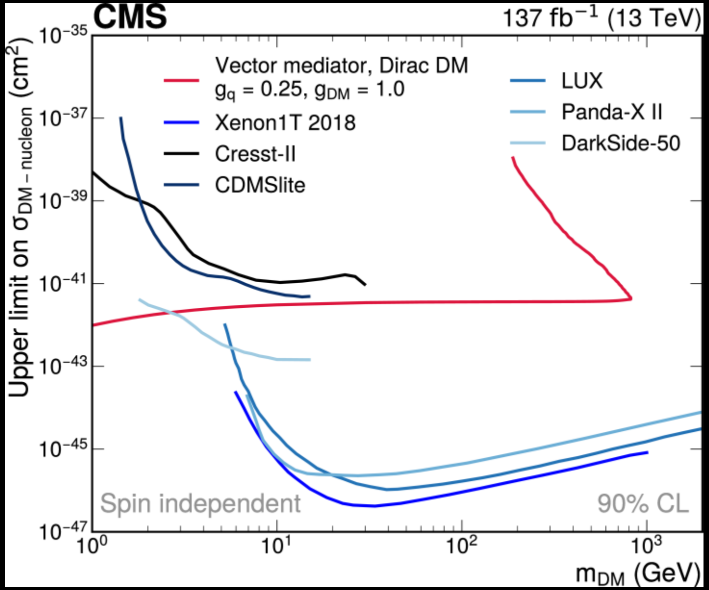
Limits from Mono-Jet

JHEP 11 (2021) 153





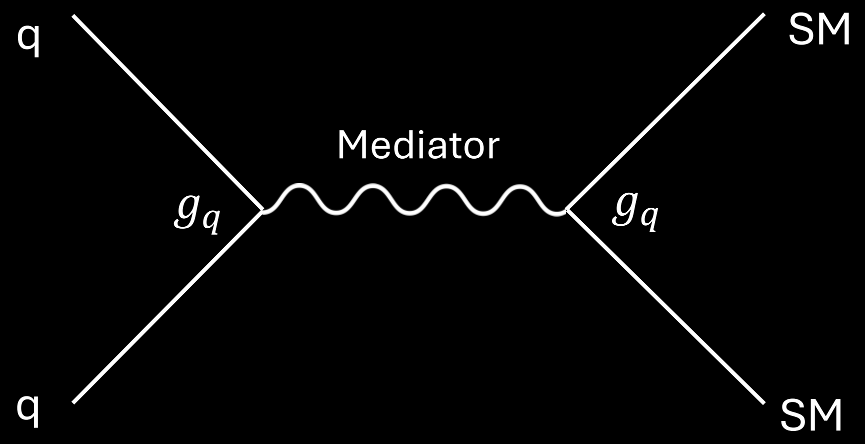


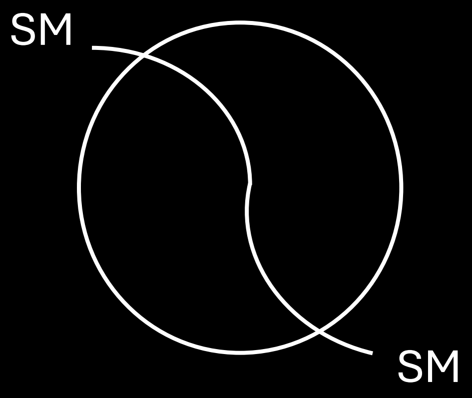


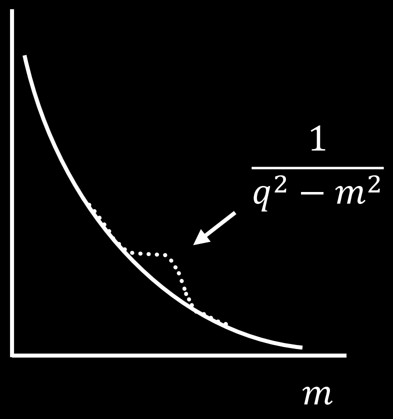
- As an example, the same mono-jet search can be re-interpreted for many DS/DM models
  - Simplified DM models: WIMPs with vector, axial, pseudoscalars, fermion portals
  - $B(H \to inv)$
  - Leptoquarks & other more complex models

- For WIMPs, can constrain directly m_{DM} and m_{med}
  - Can interpret these as limits on $\sigma_{DM-nucleon}$
  - Compare with direct-detection experiments!

Resonance Searches







Strategy

- New DS-SM mediator produced in pp collisions
- Mediator decays back to SM (instead of decaying to DS like in MET+X scenario)
- Look for Breit-Wigner resonances – “bumps” – in mass distributions

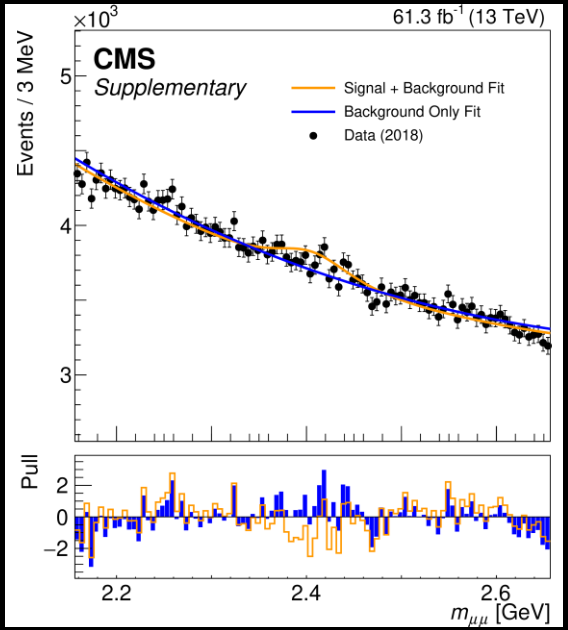
Target

- Model-independent limits on $\sigma(pp \rightarrow X)B(X \rightarrow SM\ SM)A$ as function of m_{med}
- Similar models to MET+X, since if it can be produced via SM, it can decay back to it

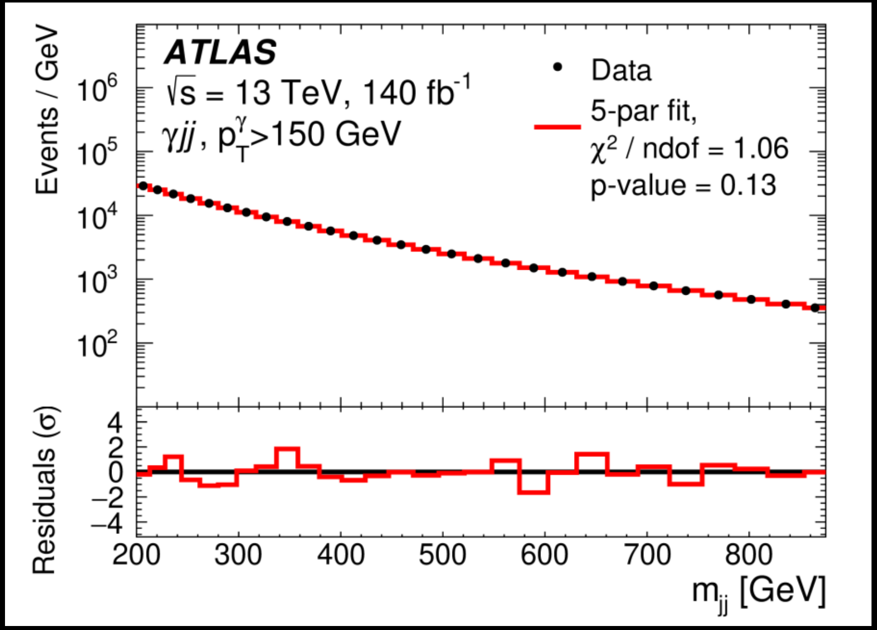
[1] - JHEP 12 (2023) 070
[2] - arXiv:2403.08547
[3] - Phys. Lett. B 796 (2019) 68

Resonance Searches

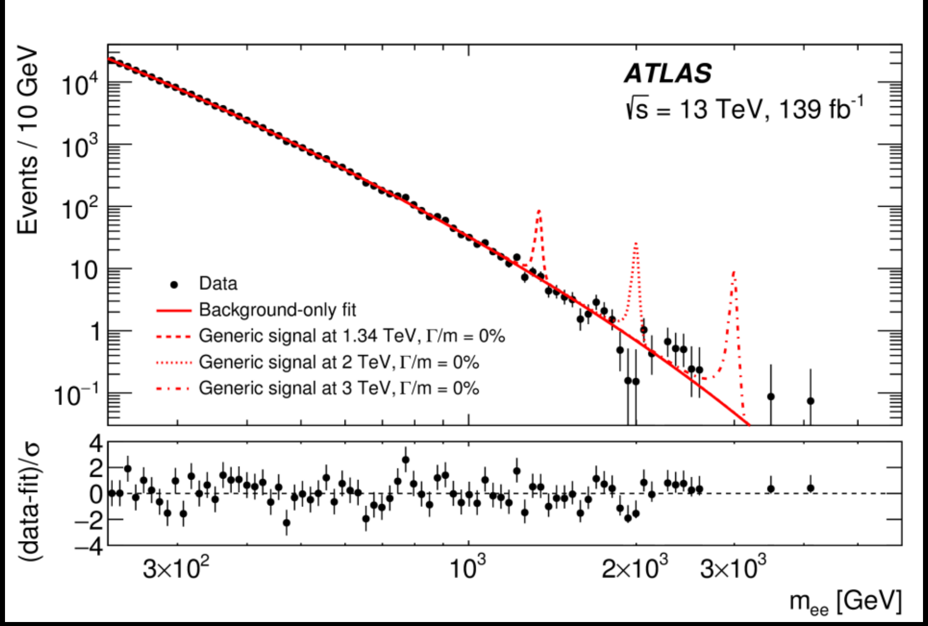
Low-mass Dimuon [1]



Dijet [2]



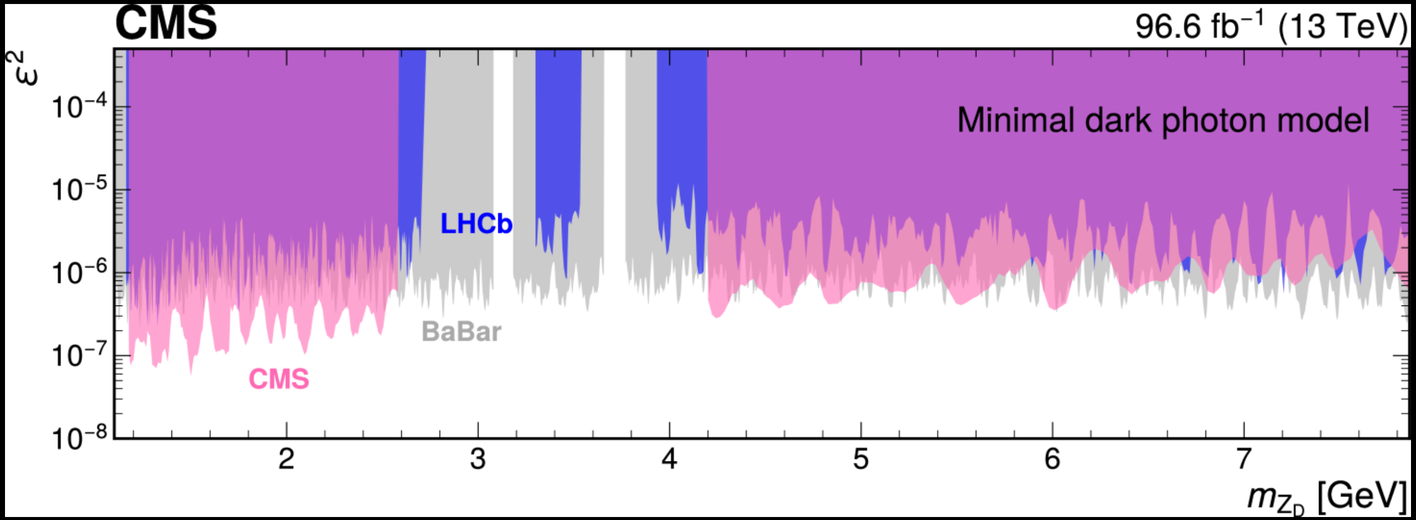
High-mass Dilepton [3]

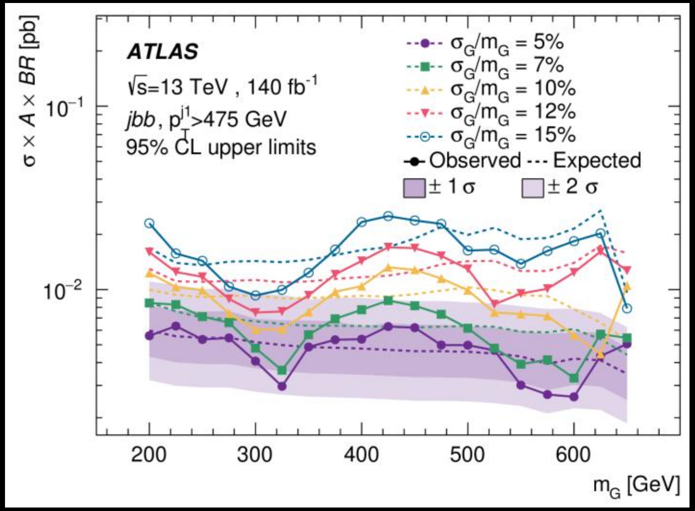


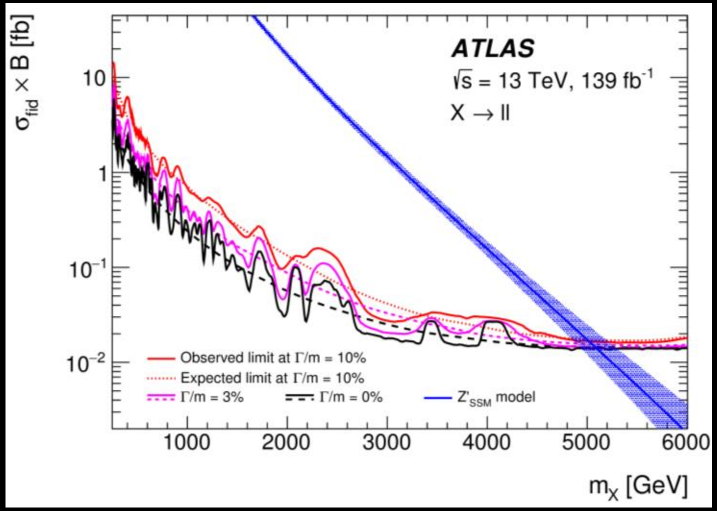
- Target high masses (~TeV) via traditional triggers
- Target low masses (~GeV) via production of another particle to trigger on (e.g. photon + 2 jets)
- Enhance sensitivity to low masses via **high-rate ("scouting") triggers** that select a larger fraction of signal-like events, but record less event information
- Parametrized background distributions determined from Monte Carlo, corrected in data
- "Bump-hunting": fit generic signal Breit-Wigner bumps convoluted with the detector resolution

Results from (some) Resonance Searches

JHEP 12 (2023) 070
arXiv:2403.08547
Phys. Lett. B 796 (2019) 68

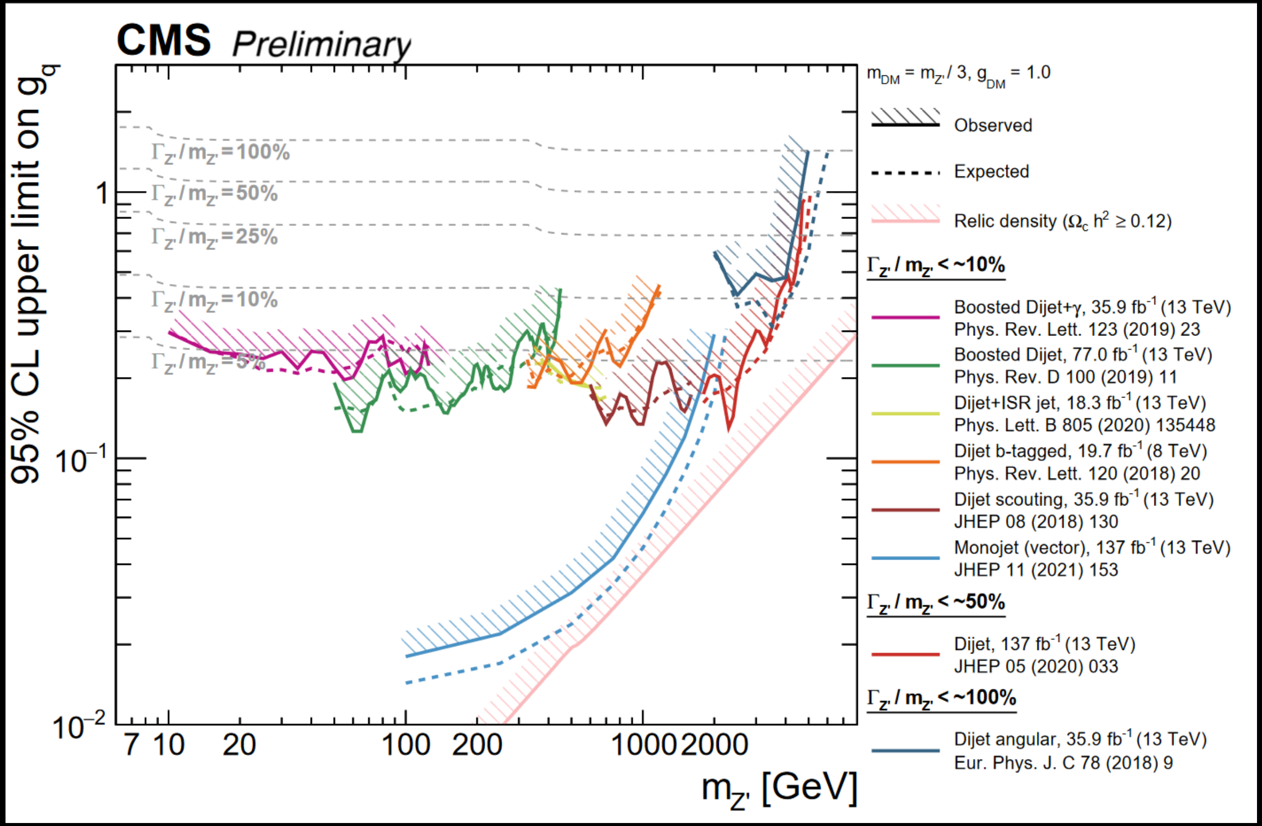


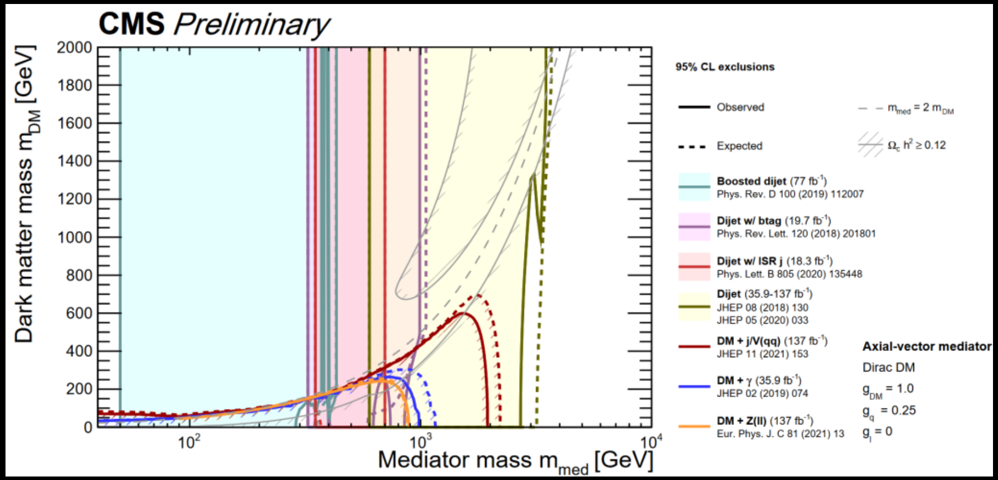


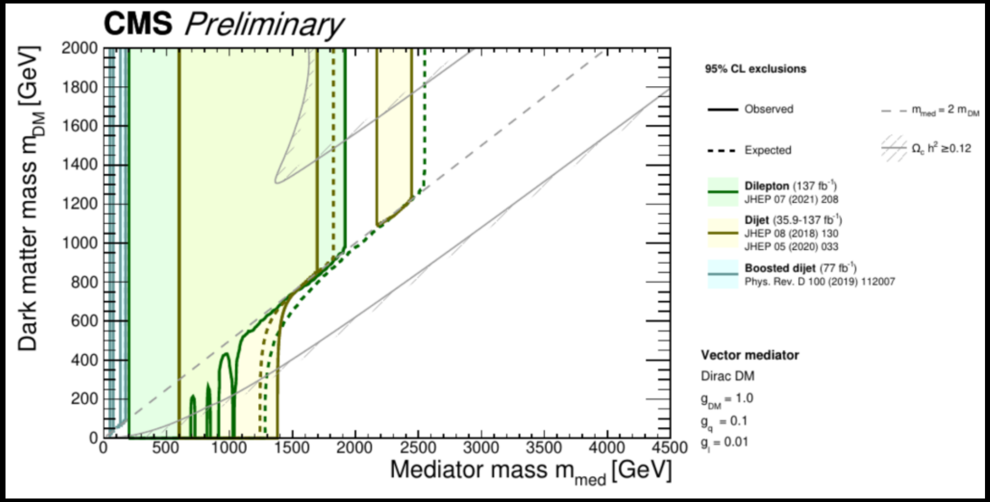


- Place limits based on the mass of the resonance and the cross section
- Dark photon model commonly used for benchmarking with other experiments, relies on mixing parameter ϵ between the $U(1)_D$ and SM hypercharge
- Model independent limits can be placed on simple Gaussian bumps at different m values, with different widths Γ

Ground Covered

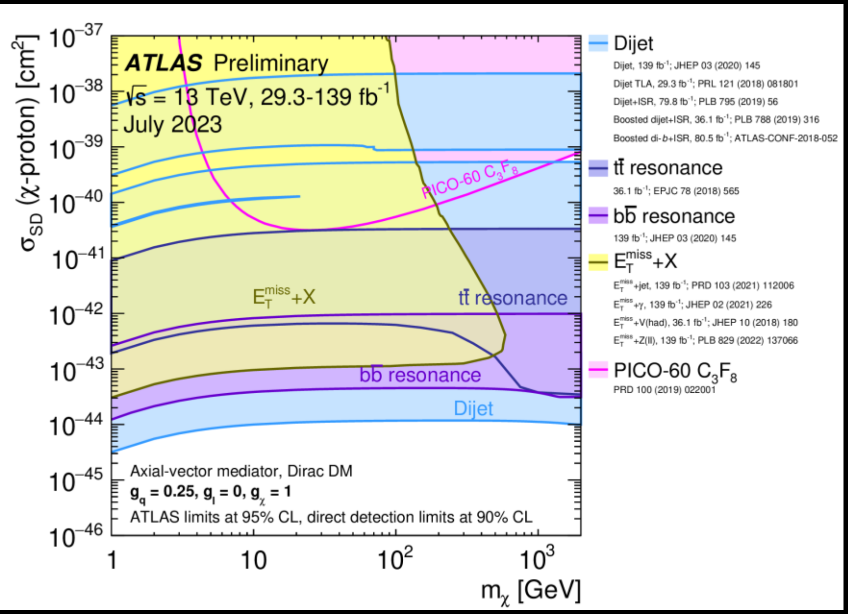


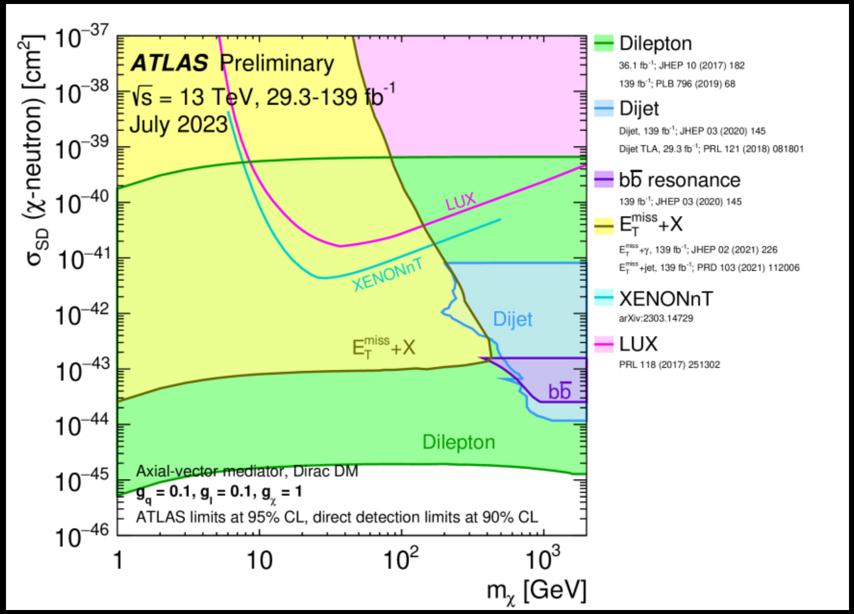


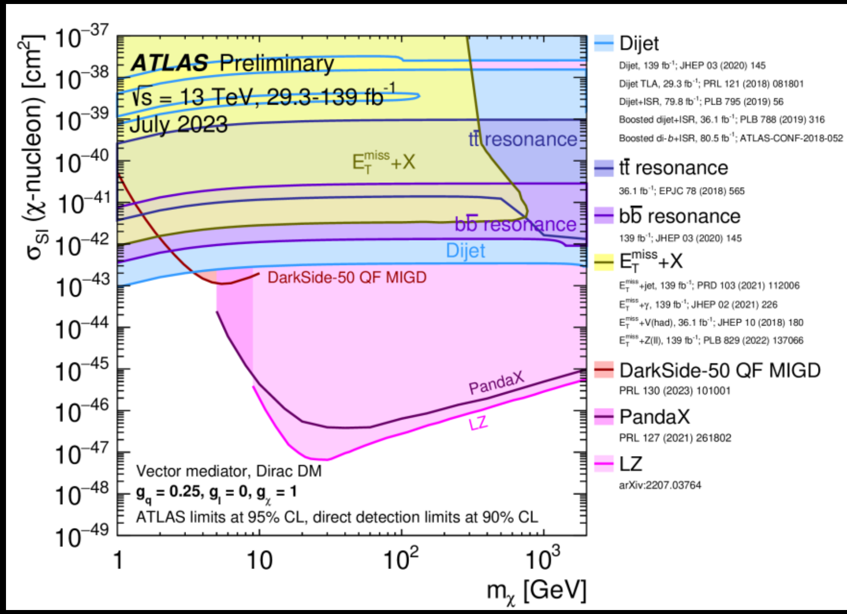


MET+X and resonance searches have excluded large phase space of simplified DM models like WIMPs throughout Run 1 and 2 of the LHC

Colliders and Direct Detection



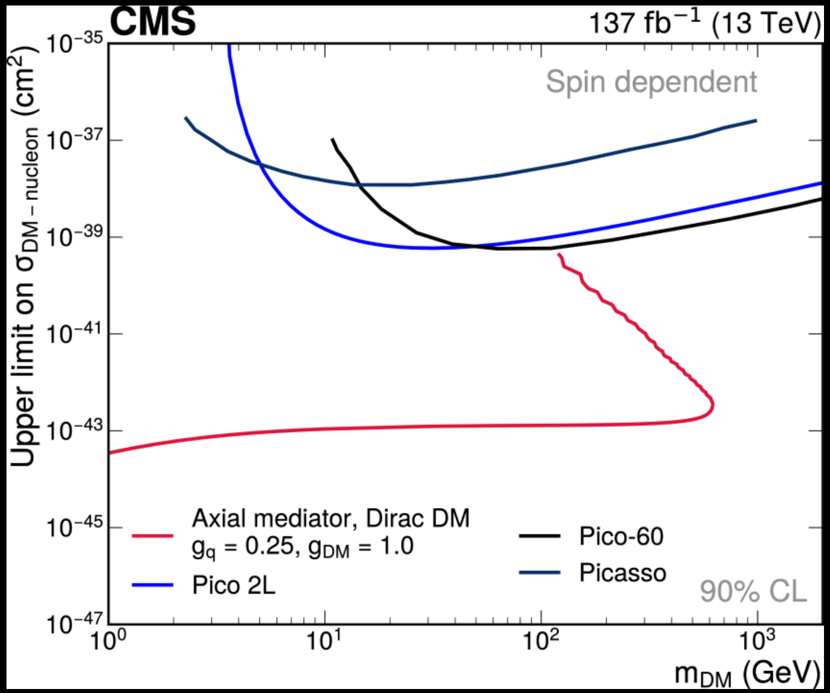




- Important complementarity between colliders and direct detection experiments for simplified DM models
  - Spin dependence
  - Nature of mediator
  - Nature of dark matter particle(s)

Unconventional Signatures

- First-generation of searches at colliders found no convincing evidence for BSM
  - Excellent limits on simplified models have been placed
  - New ideas (scouting, ML, etc.) are still able to improve sensitivity, but we are reaching the limits of what can be done with current colliders
  - Will be re-iterated with Run 3 data (ongoing!)



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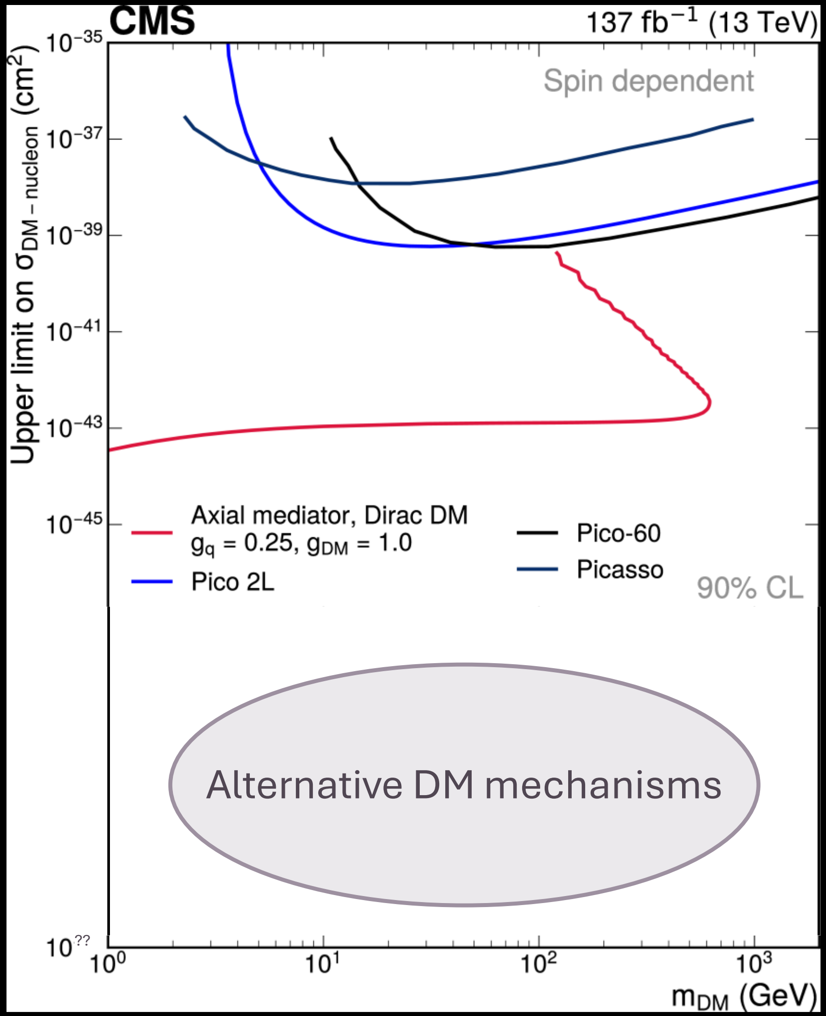
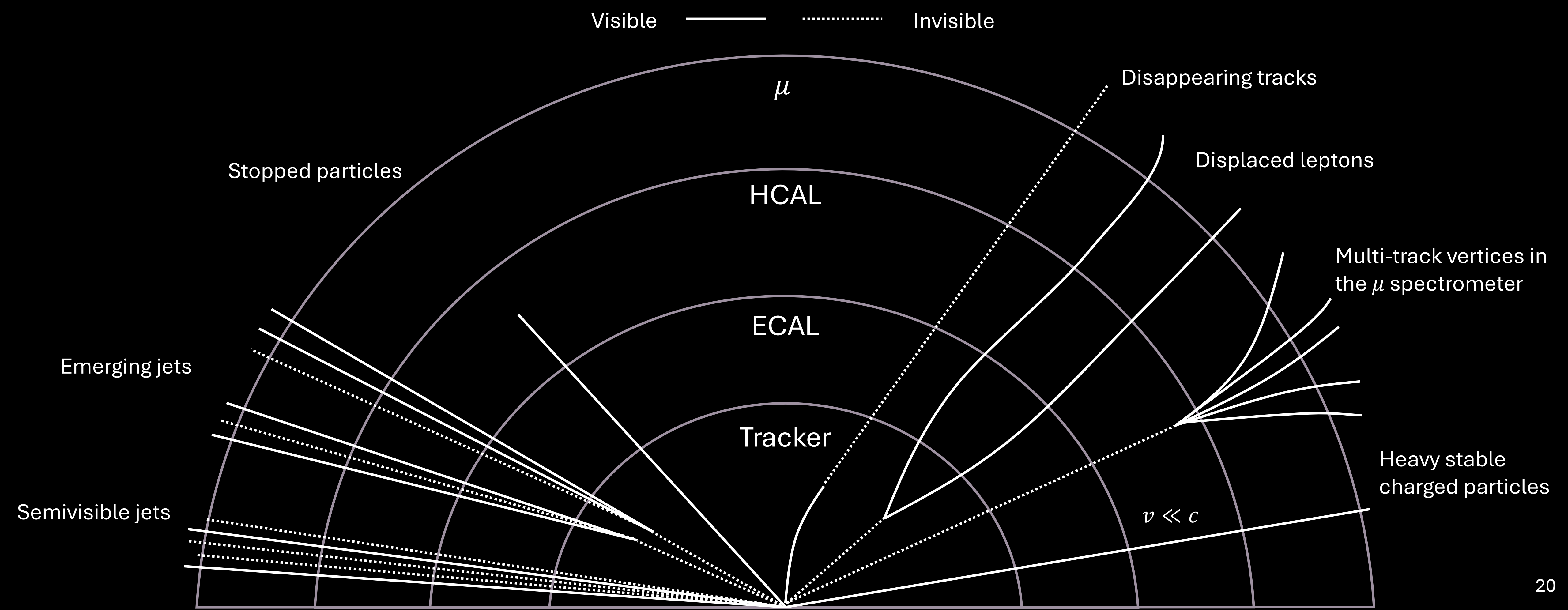
  - Will be re-iterated with Run 3 data (ongoing!)
- More complex DS models and/or alternative DM mechanisms (non WIMP) being investigated
  - Freeze-in, inelastic DM, FIMPs, etc.
  - Complex DSs (e.g. dark QCD) could contain a stable (DM) particle as well as an unstable particles that could decay in our detectors (e.g. LLPs)
- Give rise to new types of signatures that we don't typically reconstruct at colliders
  - We would not have seen these objects at all
  - Would have evaded all previous constraints



Schema stolen from André Lessa

Unconventional Signatures

Some examples of unconventional signatures that would have evaded typical reconstruction and triggers



Unconventional Signatures: New Approaches

Need new approaches to reconstruct these signatures:

- New data streams:
  - **Scouting:** high-rate triggers, save quickly less info per event
  - **Parking**: low-rate triggers, save large amount of raw detector data to be reconstructed later

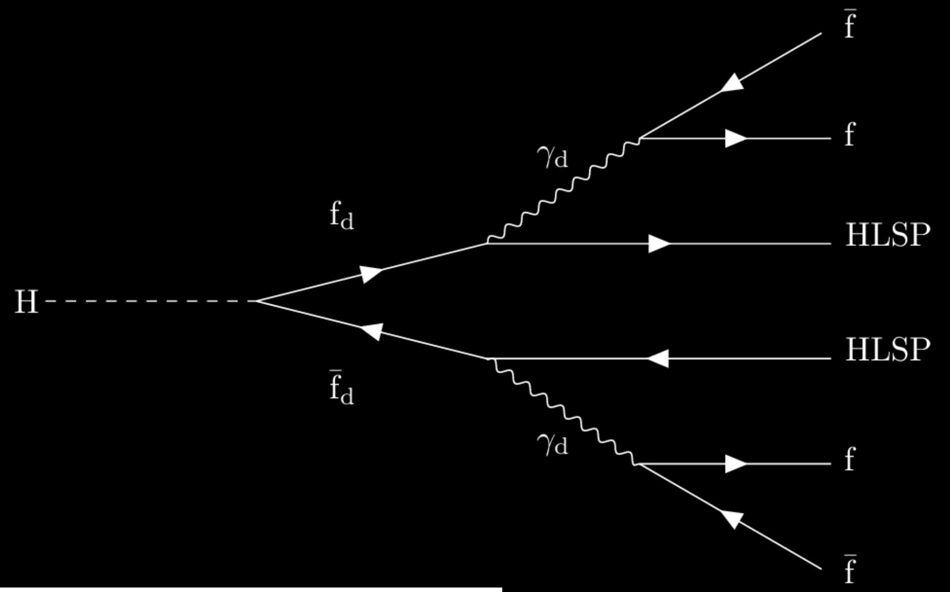
- New triggers:
  - Many dedicated new triggers to target unconventional topologies

- New offline reconstructions:
  - Looking at physics objects that may not conform to traditional, SM-like objects

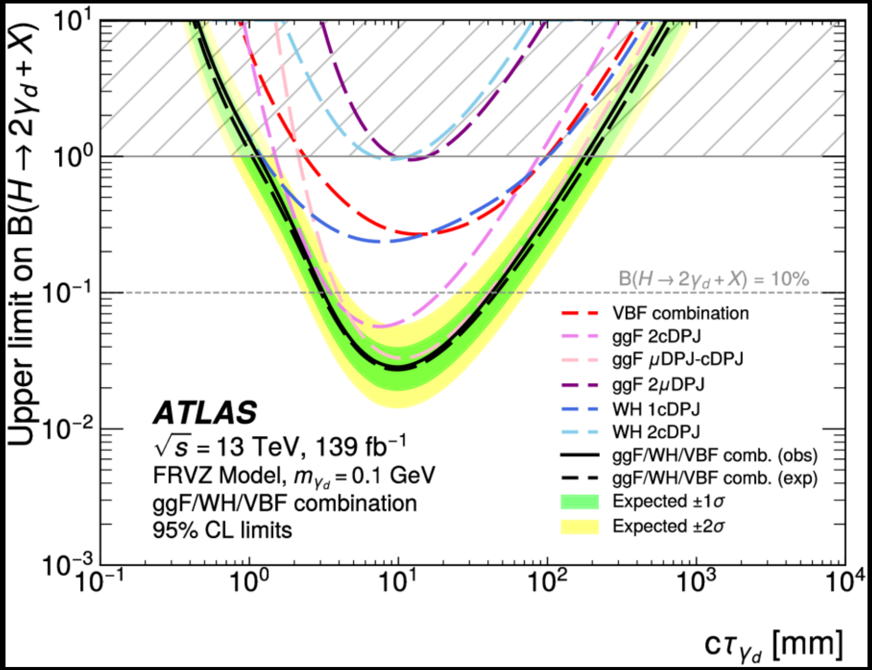
Important part of Run 3 (2023-2025) is to leverage these new approaches

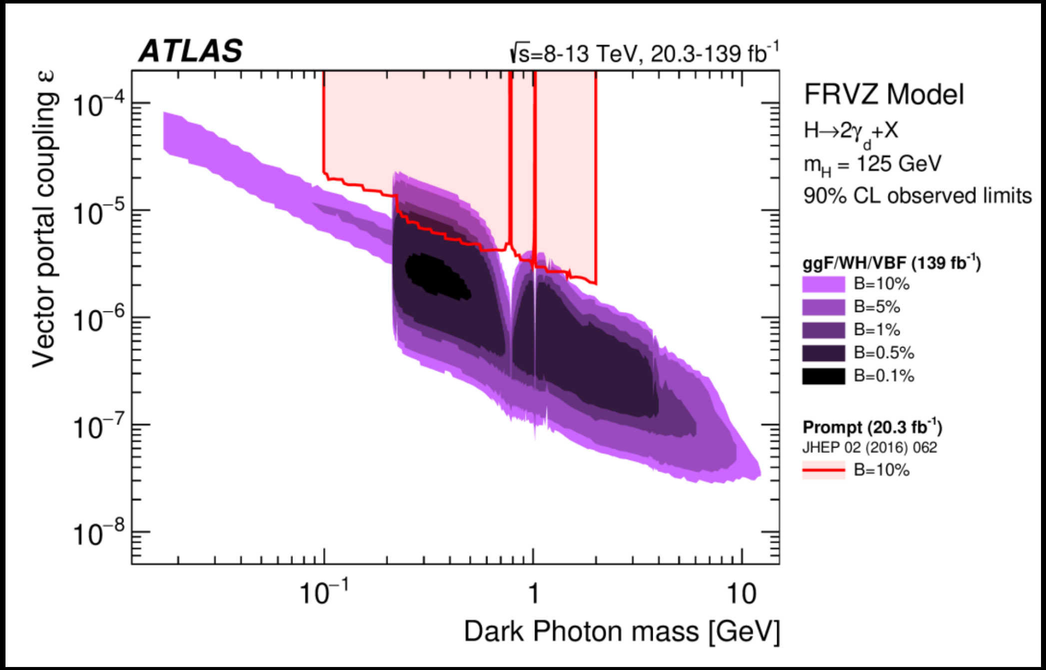
Long Lived Dark Photons

- Displaced, collimated SM fermions reconstructed in the calorimeter or μ spectrometer (MS)
  - Hidden lightest stable particle contributes only to p_T^{miss}



- Two new triggers to target signal:
  - 3 μ's using the MS only JINST 15 (2020) P09015
  - 1 μ in the MS + 1 μ within $\Delta R < 0.4$ of the first JINST 8 (2013) P07015

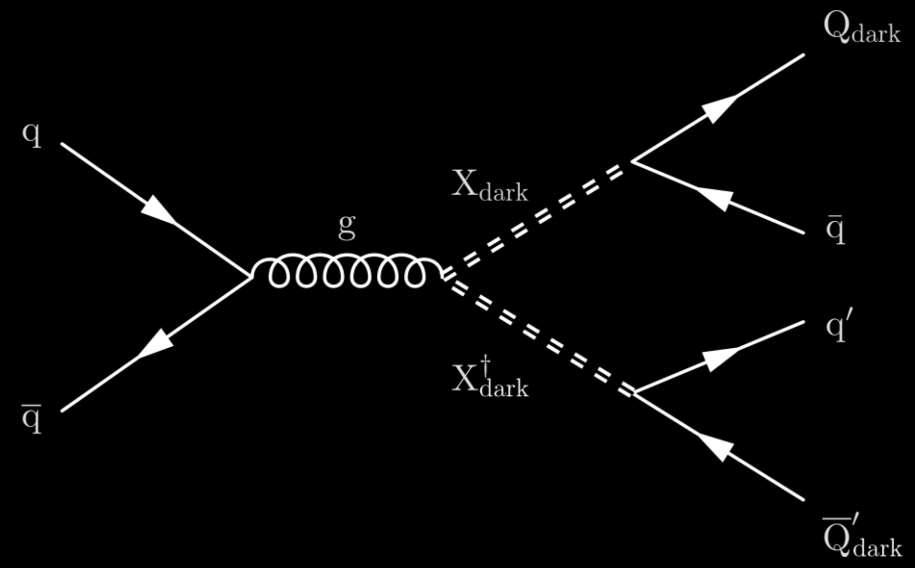


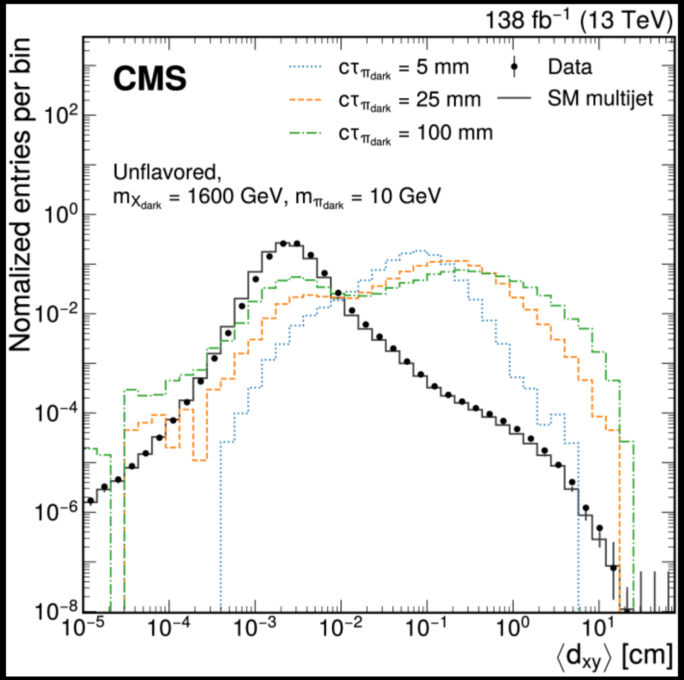


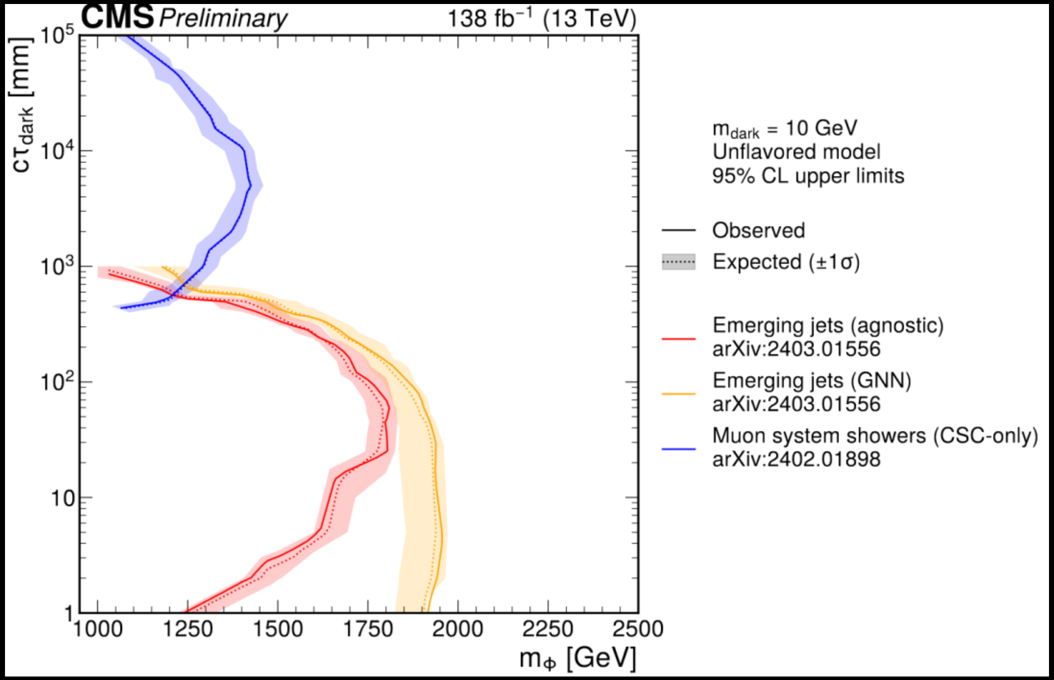
arXiv:2403.01556

Emerging Jets

- X_{dark} produced, travel ~cm, decay to Q_{dark} and q
  - Two showers not associated to primary vertex
- Target jets with tracks with large displacement in the plane orthogonal to the beam d_{xy}
- Alternative approach with a Graph Neural Network (GNN)

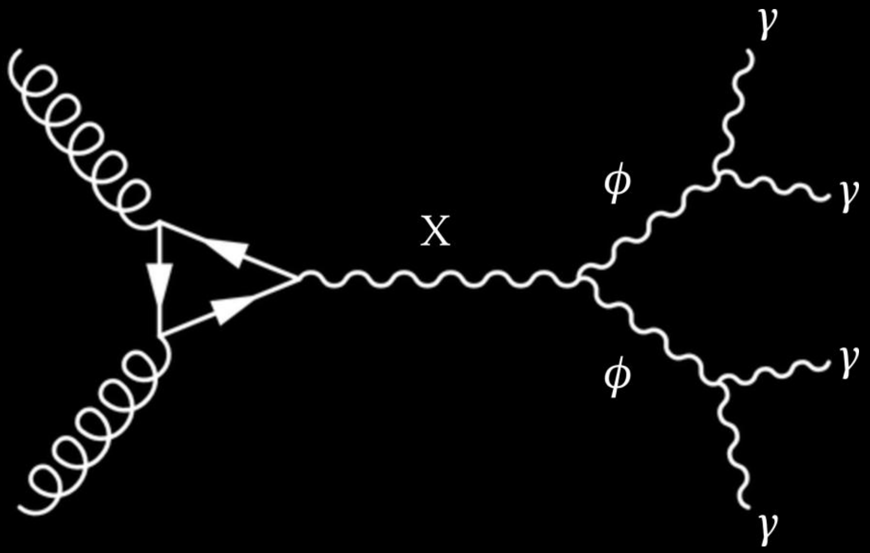


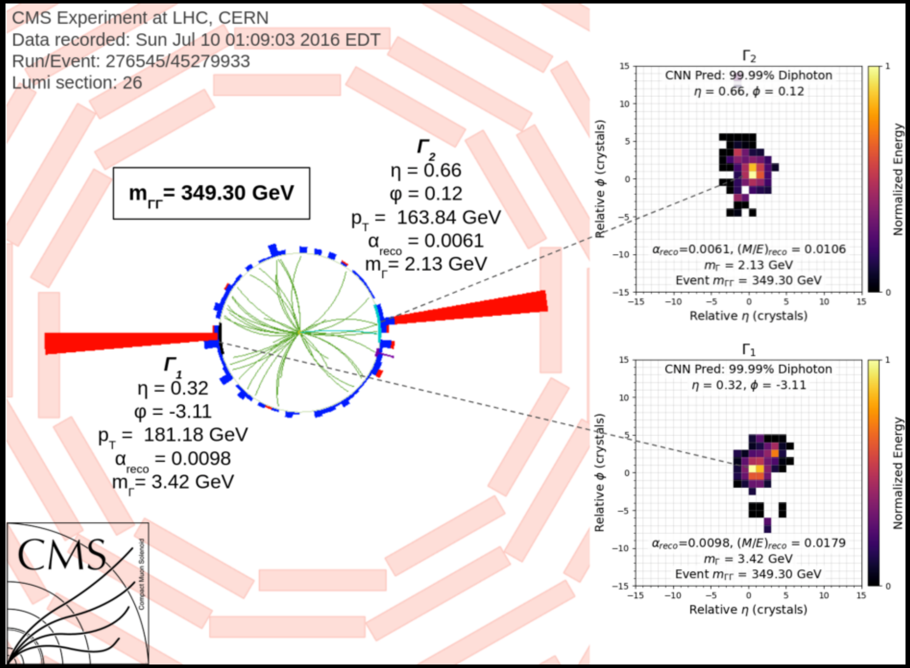


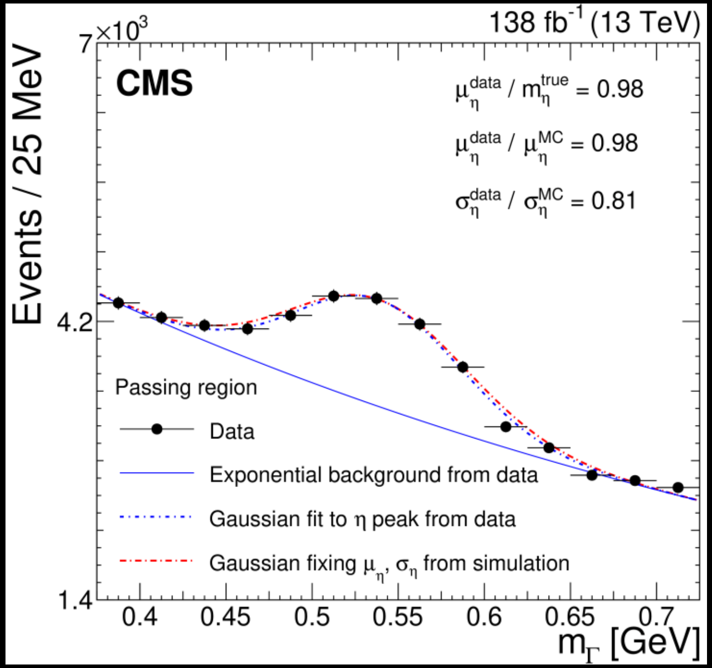


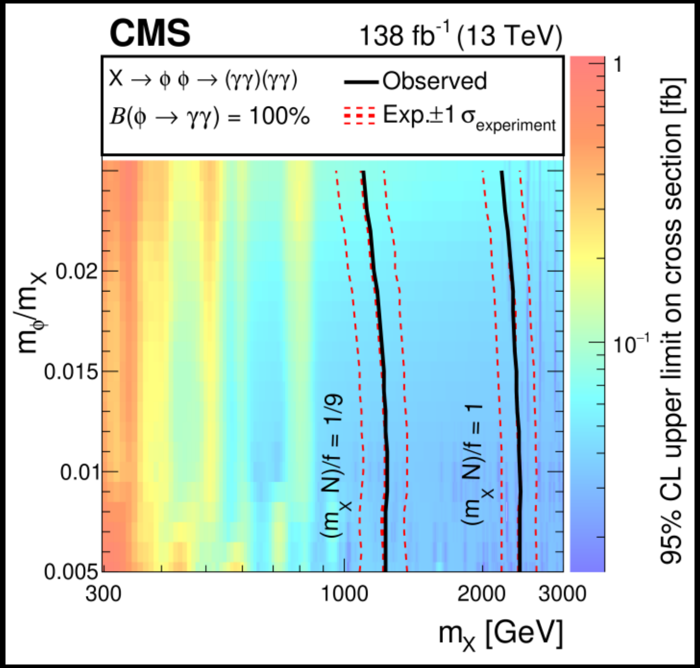
Merged Diphotons

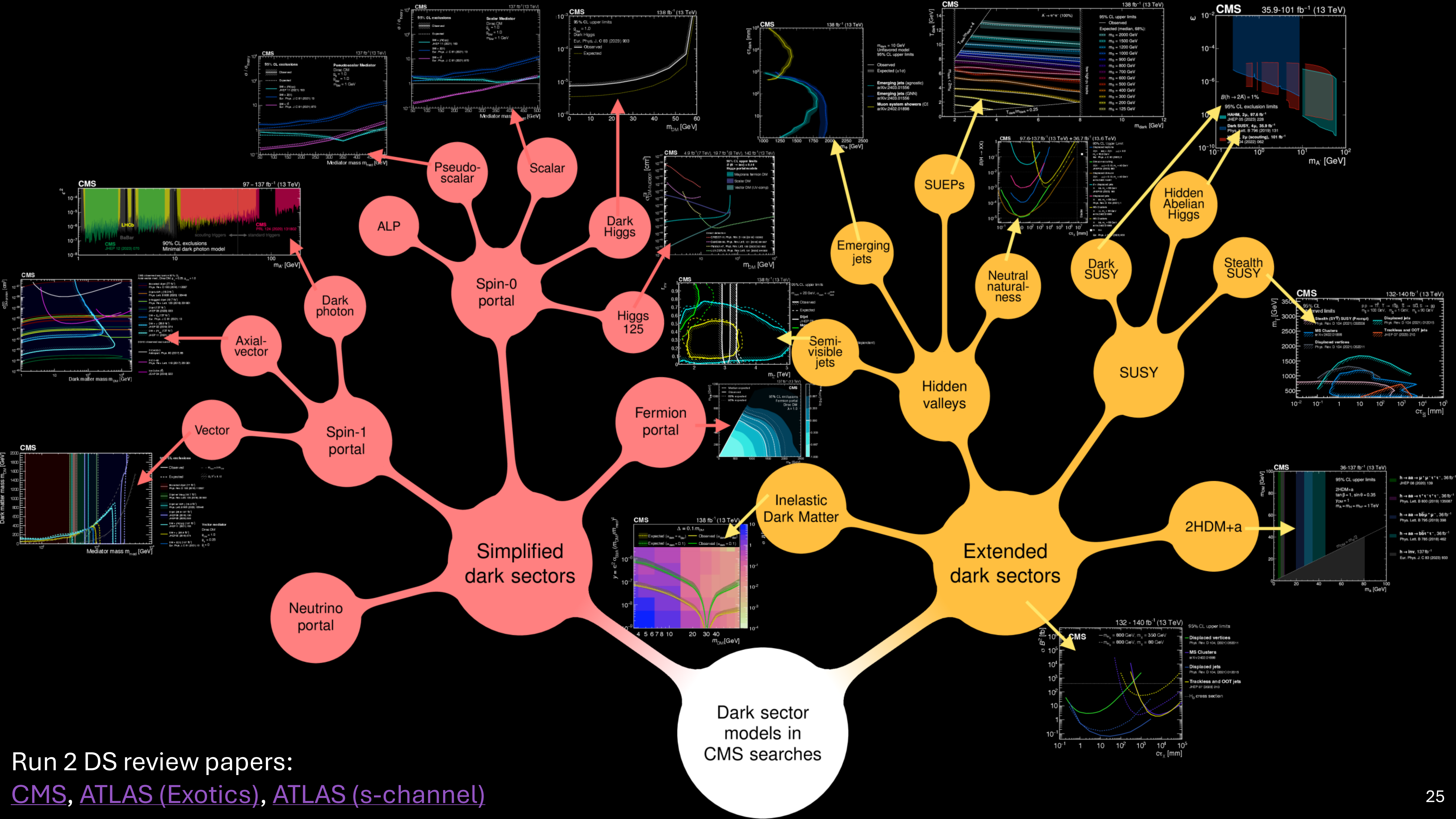
- Two photons from ϕ decay too merged to look like distinct photons, but not so collimated that they would look like one photon
- Dedicated CNN developed to analyze ECAL deposits
  - Distinguish single γ, two γ's, or hadronic activity
- Second CNN to reconstruct diphoton mass
- Validate with boosted π^0, η decays











Run 2 DS review papers:
CMS, ATLAS (Exotics), ATLAS (s-channel)

Conclusions

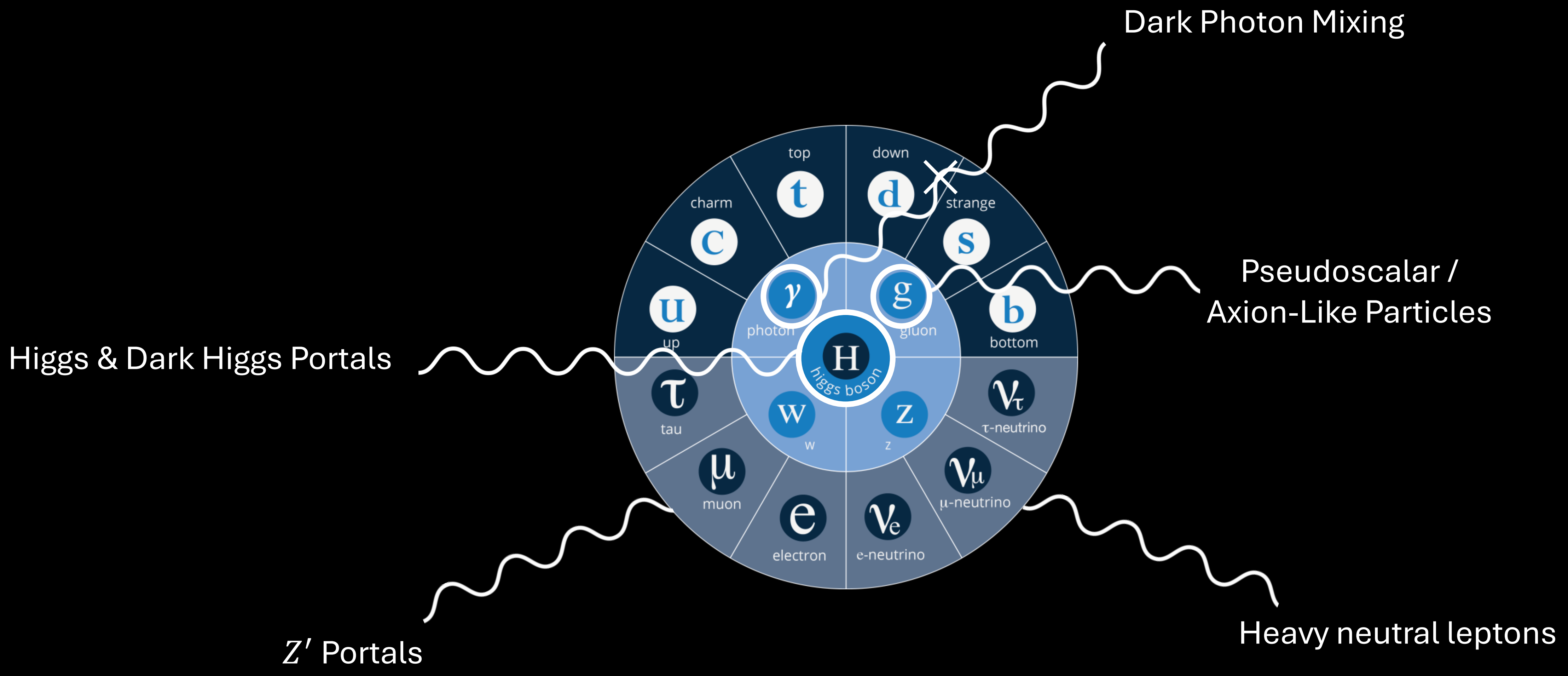
- The LHC has covered a lot of ground in DM and DS searches
- Complementary approach to indirect and direct detection experiments

- LHC Run 3
  - New physics programmes are being developed for BSM searches
    - Several talks at this conference cover them in more detail than I had time for
    - E.g. collider BSM sessions Wednesday at 3pm and today at 5pm
  - New data sources, triggers, and reconstructions
  - New dark sectors are being explored

- HL-LHC
  - Unprecedented luminosity will allow us to look at even rarer phenomena
  - New detector technology will unlock new possibilities
    - e.g. trigger on tracks directly will massively improve many DS searches

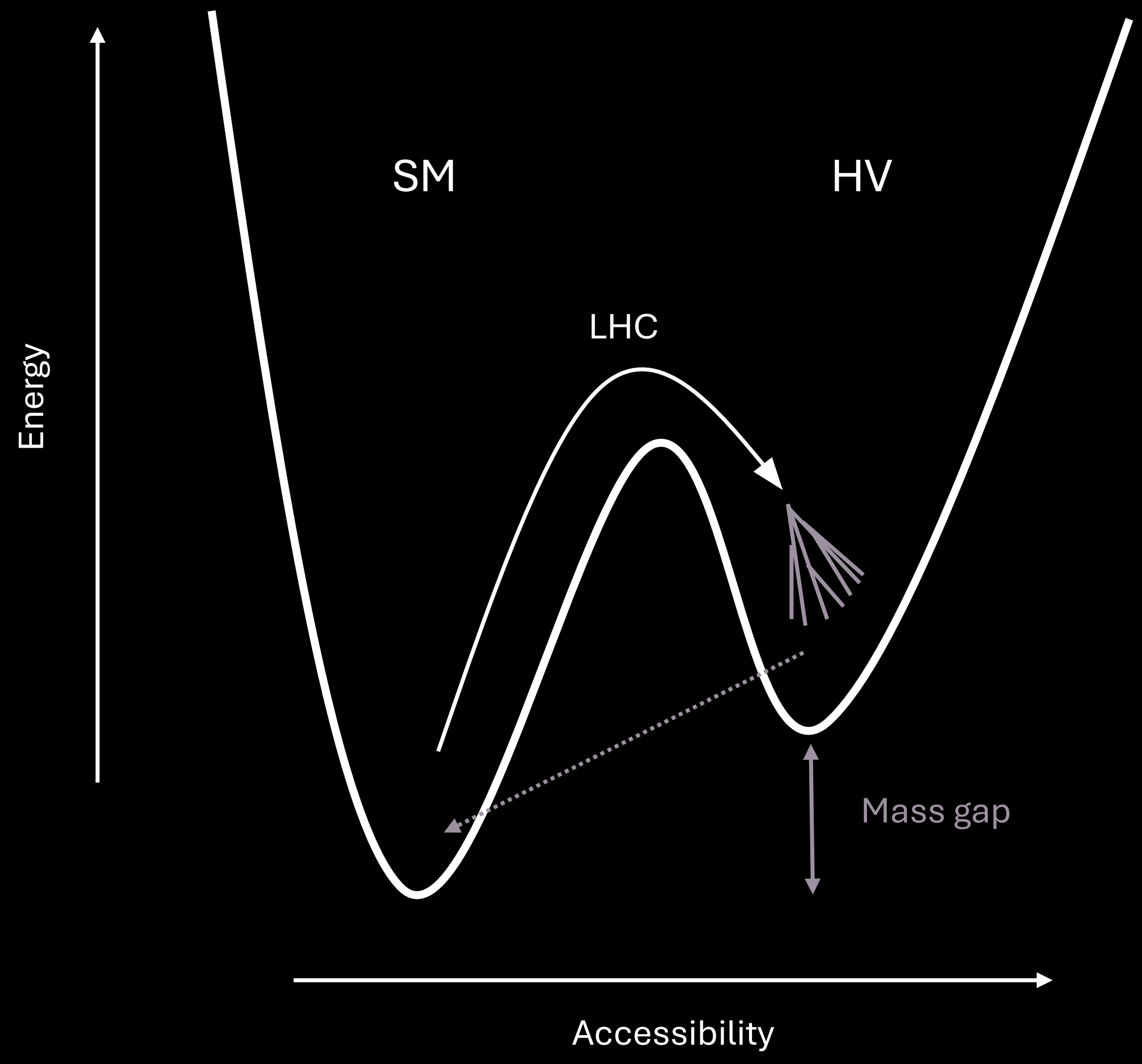
- FCC-ee, Muon Collider?
  - Exciting new frontiers for our quest to explore BSM

Backup



Dark Photon Mixing
Pseudoscalar /
Axion-Like Particles
Higgs & Dark Higgs Portals
Z' Portals
Heavy neutral leptons
top
down
charm
strange
up
bottom
photon
gluon
higgs boson
tau
w
z
τ-neutrino
muon
μ-neutrino
electron
e-neutrino

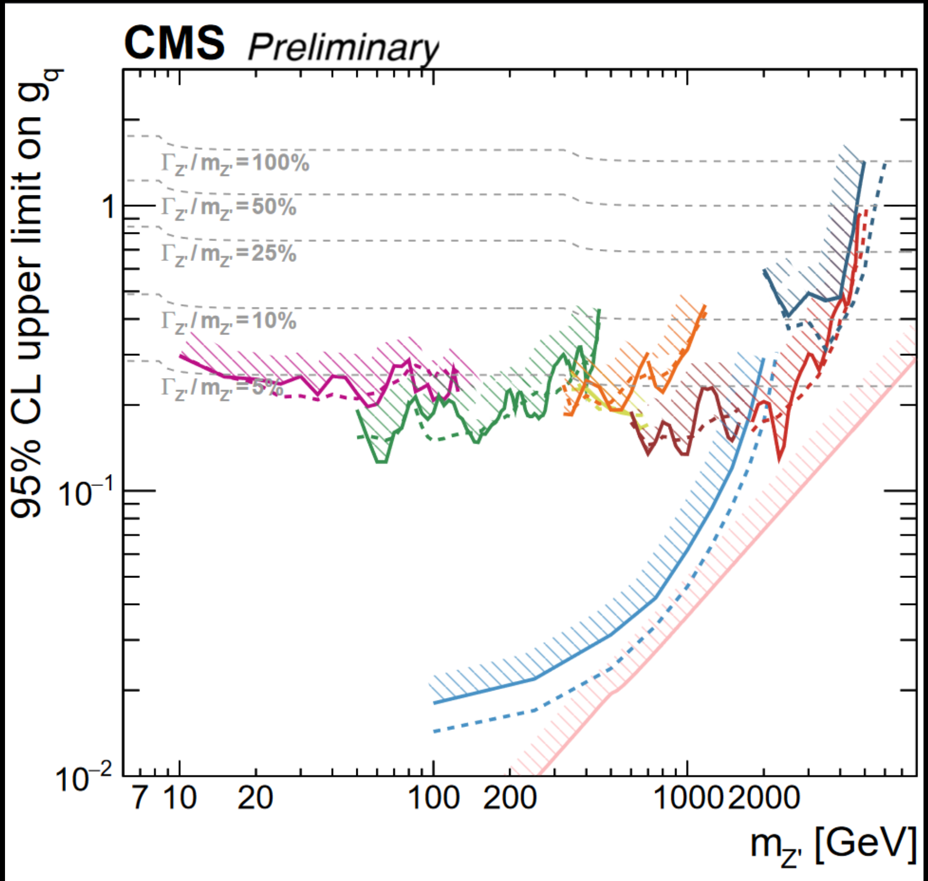
Hidden Valleys



*Schema from Matt Strassler

Improving MET+X and Resonance Searches

High-rate triggers (scouting) ←



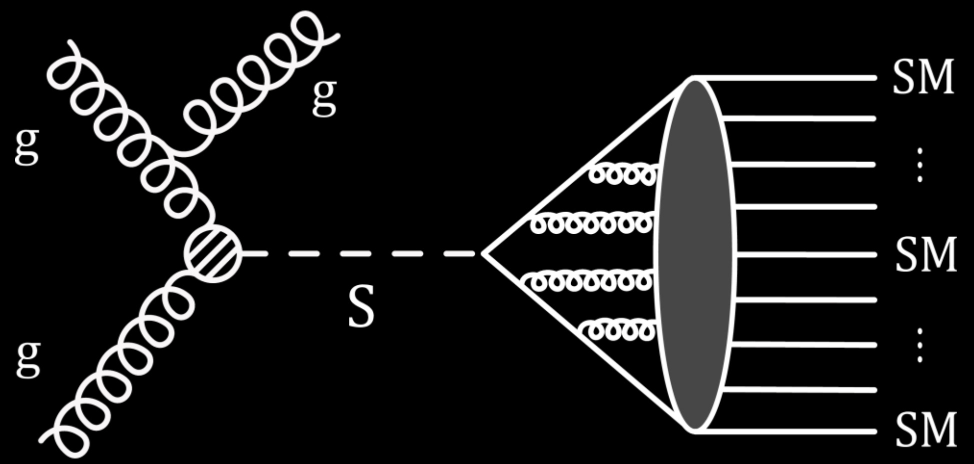
→ Luminosity, $\sqrt{s}$

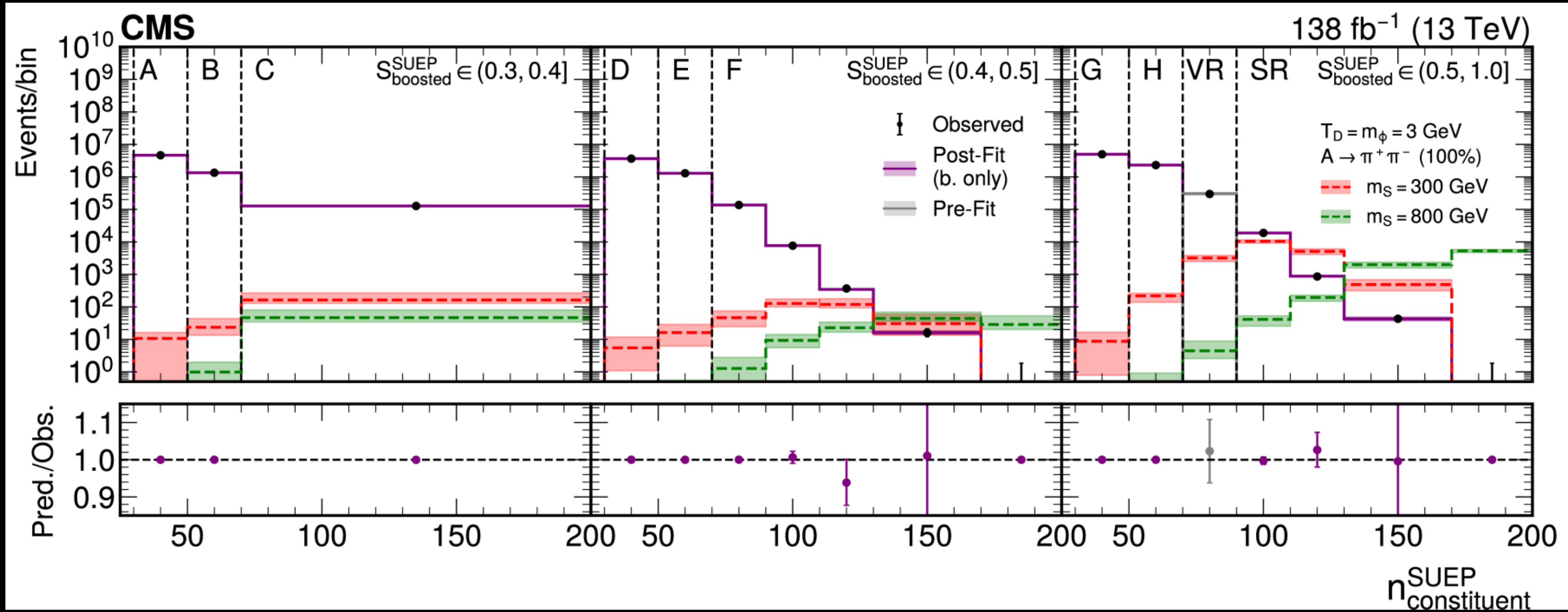
+ better methods: event selection, jet tagging, background estimations, etc.

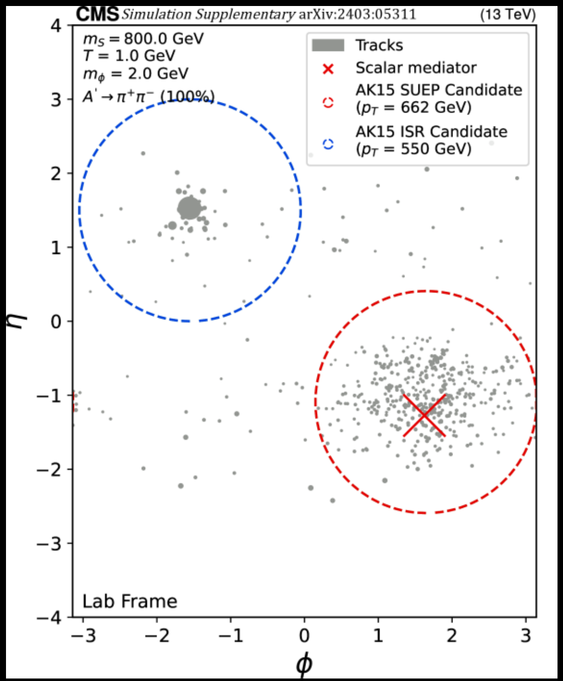
Soft Unclustered Energy Patterns

arXiv:2403.05311

- Strongly coupled dark sector connected via scalar portal
- Large 't Hooft coupling in quasi conformal dark sector
  - Long, efficient showering window, which produces spherical, high multiplicity jets
- Trigger on events with SUEP recoiling against ISR
- Background prediction using extended ABCD method

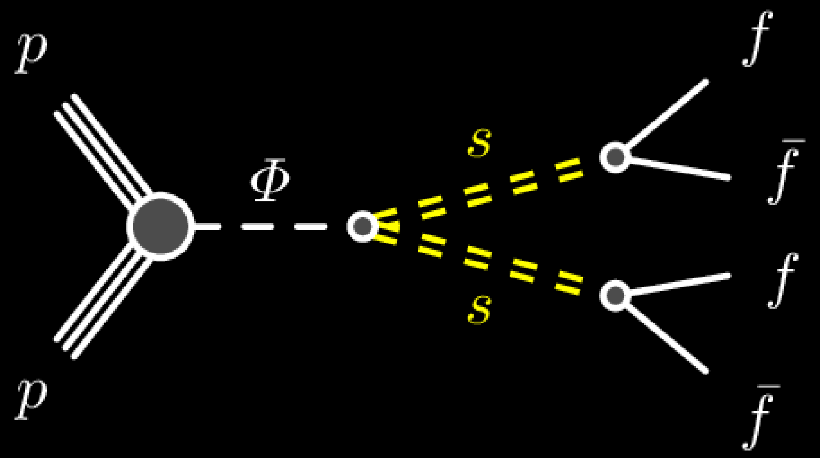




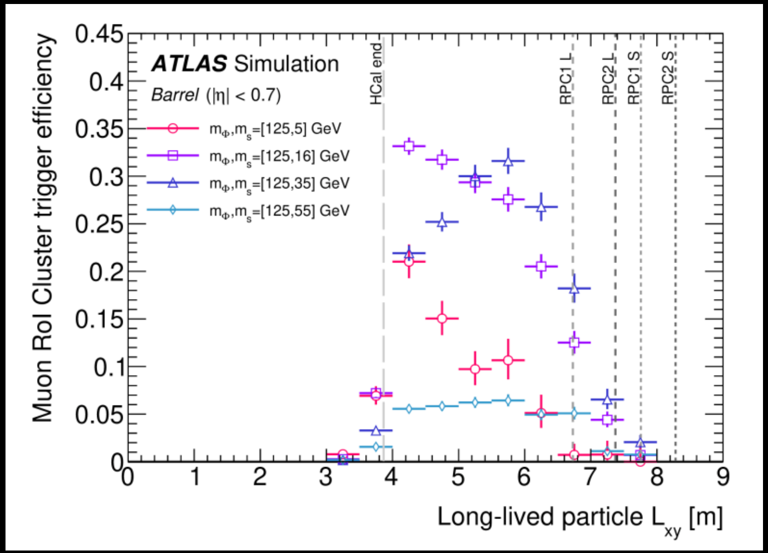


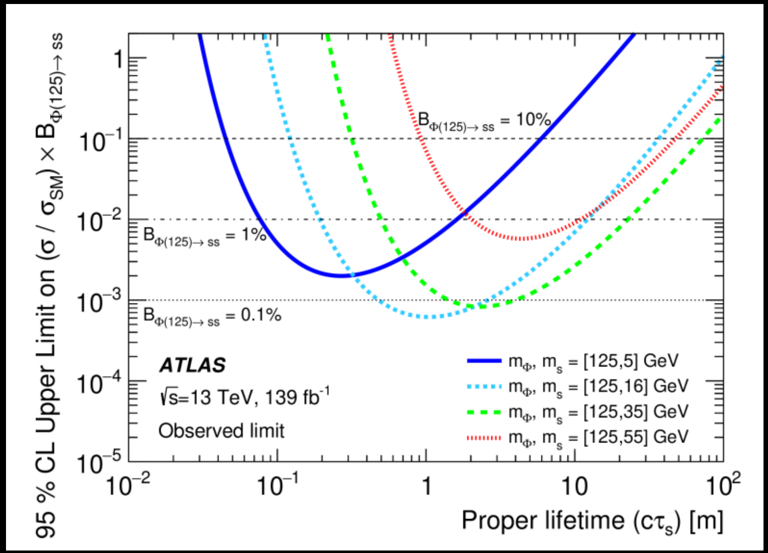
Unconventional Signatures: Displaced Jets in μ Spectrometer

- Dark particles s produced, travel ~m, decay to $f\bar{f}$, which shower
  - Showers in the μ spectrometer



- Dedicated trigger to look for several tracks in the μ spectrometer within a jet's typical radius, $\Delta R = 1.5$
- Dedicated reconstruction for displaced decays in the spectrometer

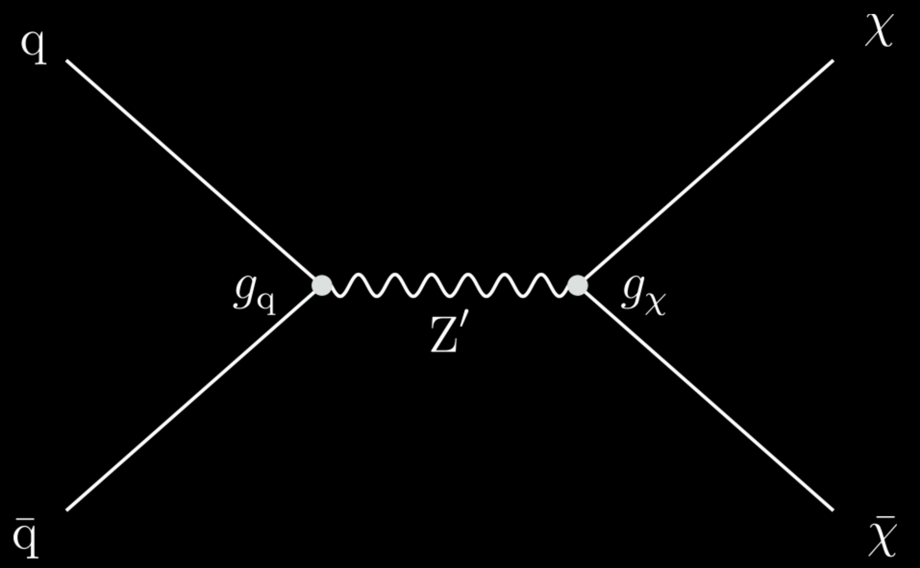




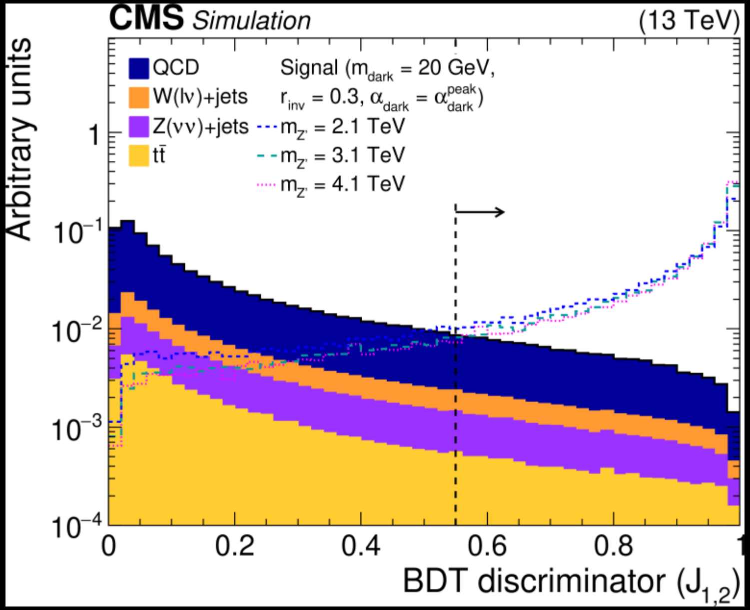
- Set limits on $c\tau, \sigma$
- Assumptions on DS structure, BRs, masses, etc. for these limits

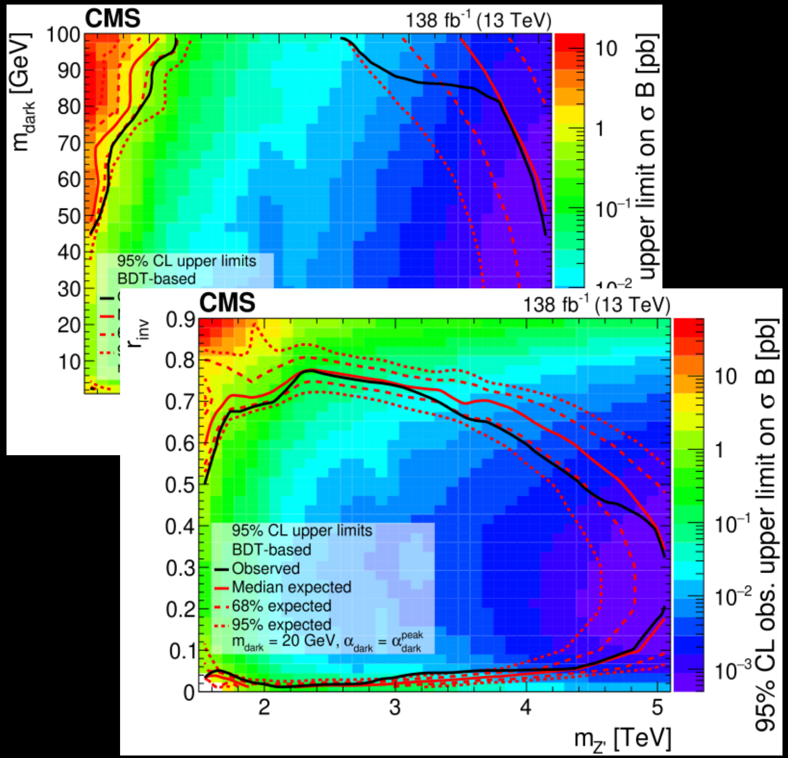
Unconventional Signatures: Semivisible Jets

- χ produced through a Z' mediator, which shower, some decaying back to SM quarks, some staying in DS, controlled by ratio r_{inv}
  - Collimated mixtures of visible and invisible particles
- Use p_T^{miss}, N-subjettiness, energy correlators, soft-drop mass in a BDT to discriminate between SVJ and SM jets

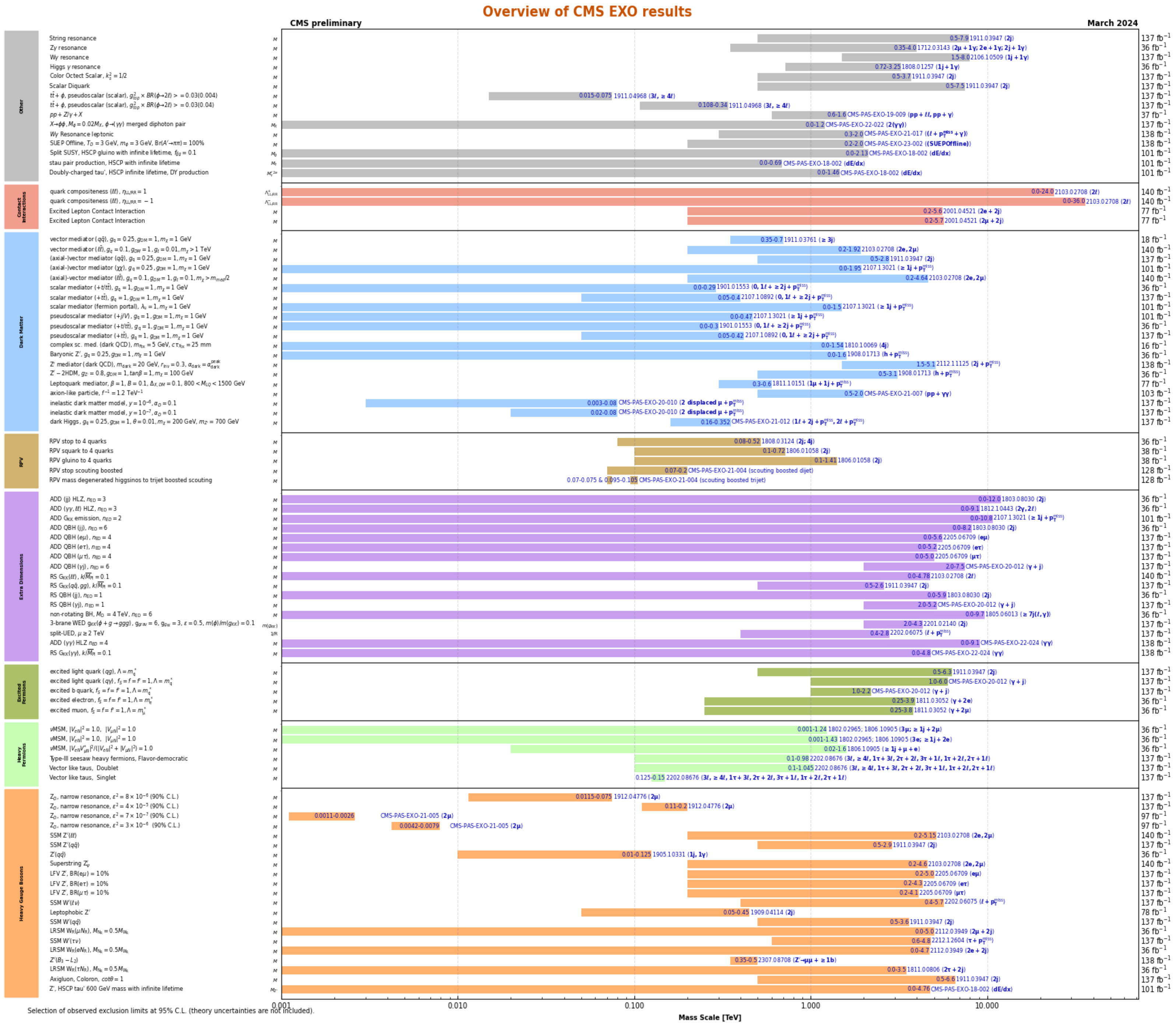


- Set limits on $m_{Z'}, m_{dark}, r_{inv}$
- Assumptions on dark sector, such as showering, gauge structure, etc.





EXO-CMS Summary Plots



ATLAS Summary Plots