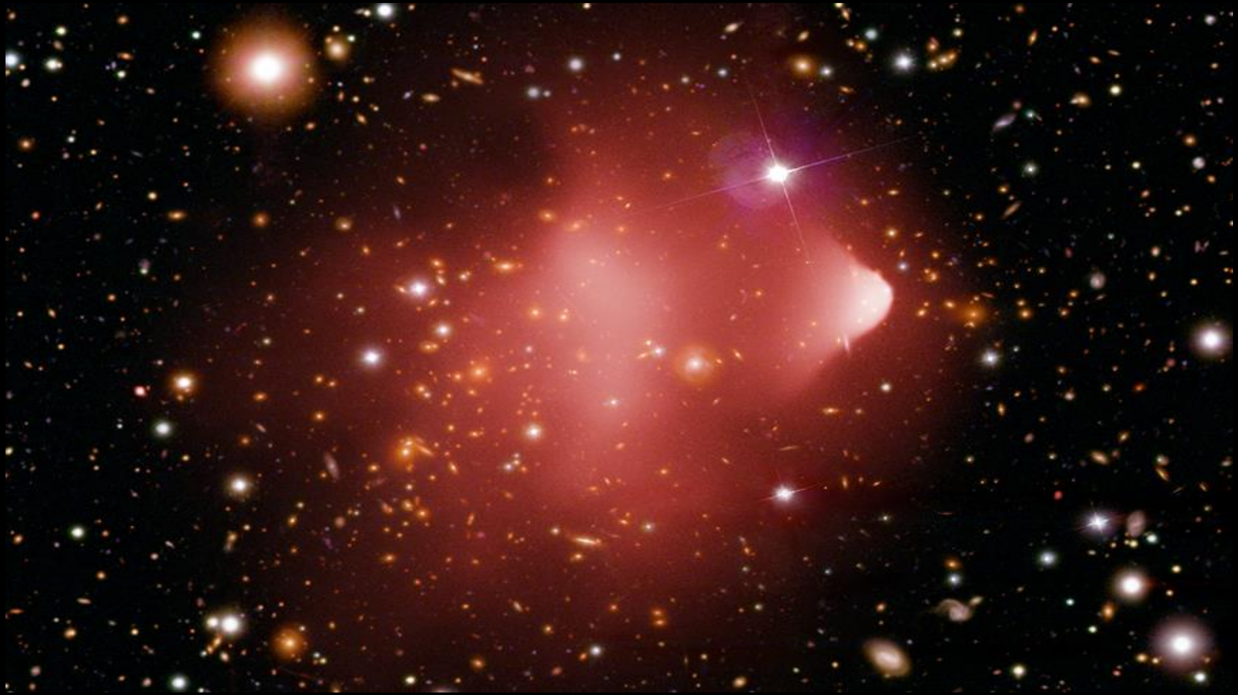
Dark Matter and Dark Sectors at the LHC

Luca Lavezzo

On behalf of the Particle Physics Collaboration at MIT



Unexplained phenomena

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

…

Experimental tensions (?)

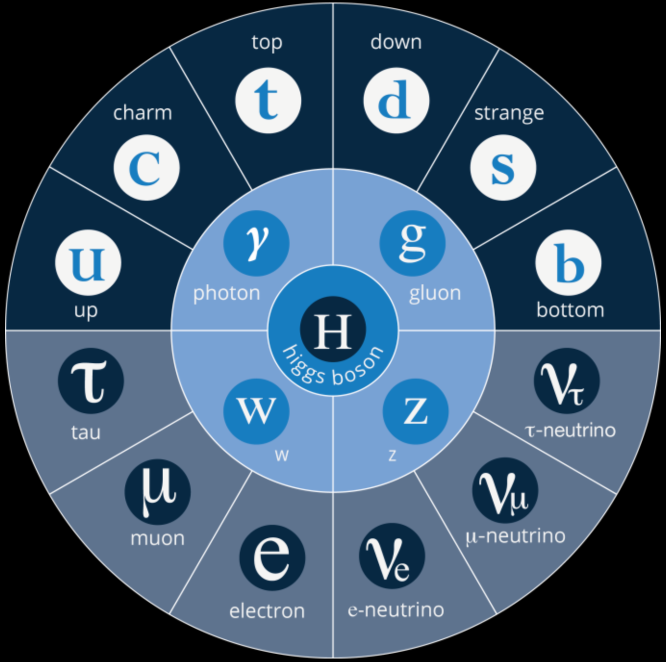
- $(g-2)_\mu$
- m_W
- $R(D^*)$
- $X17$

…

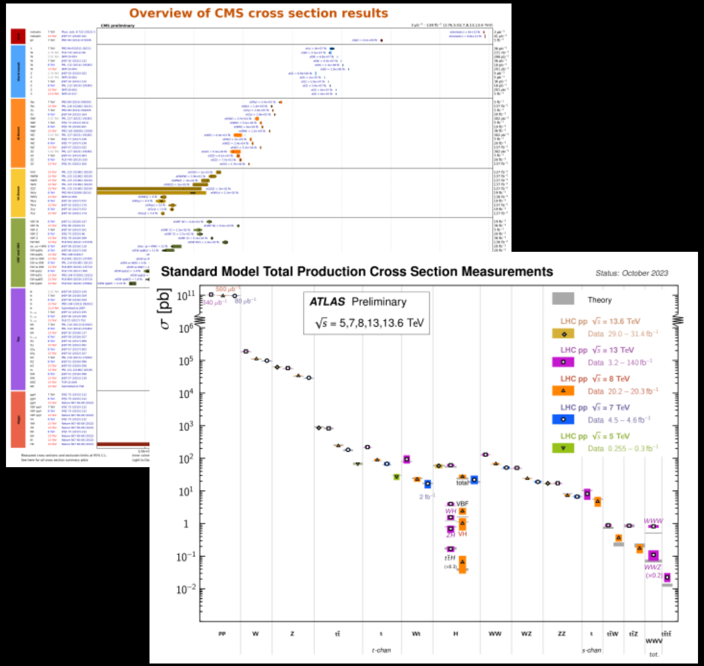
Fine-tuning problems

- $\theta_{CP} \approx 0$
- 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

Unexplained phenomena

- Gravity
- Dark matter
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- Matter-antimatter asymmetry

…

Experimental tensions (?)

- $(g-2)_\mu$
- ~~m_W~~ (CMS: nothing to see here!)
- $R(D^*)$
- $X17$

…

Fine-tuning problems

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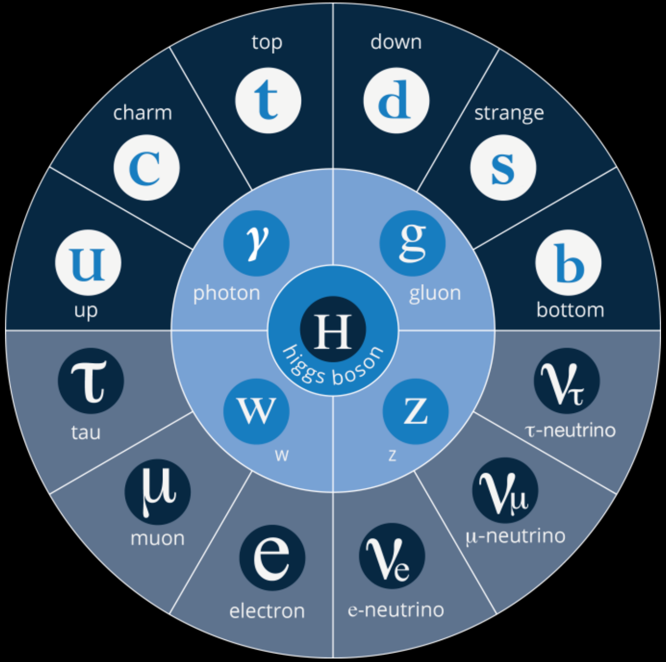

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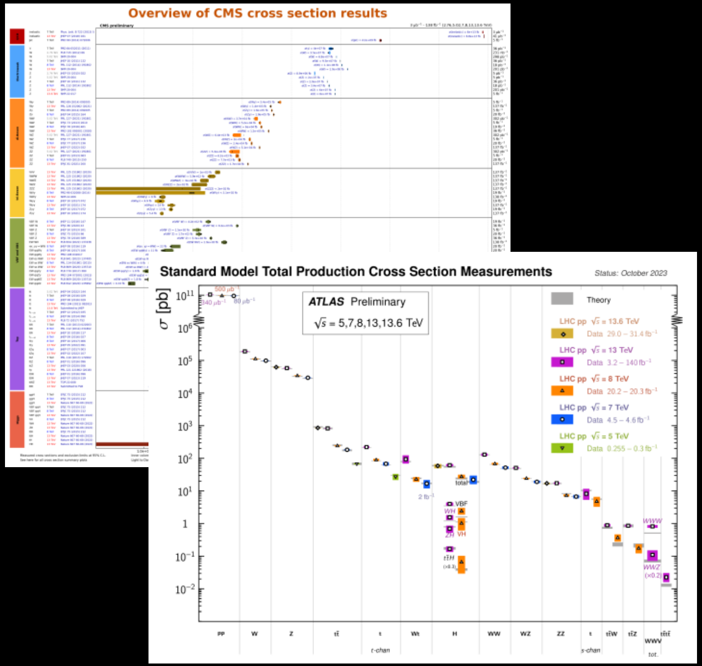


For the first time, no clear indication about what the missing pieces are

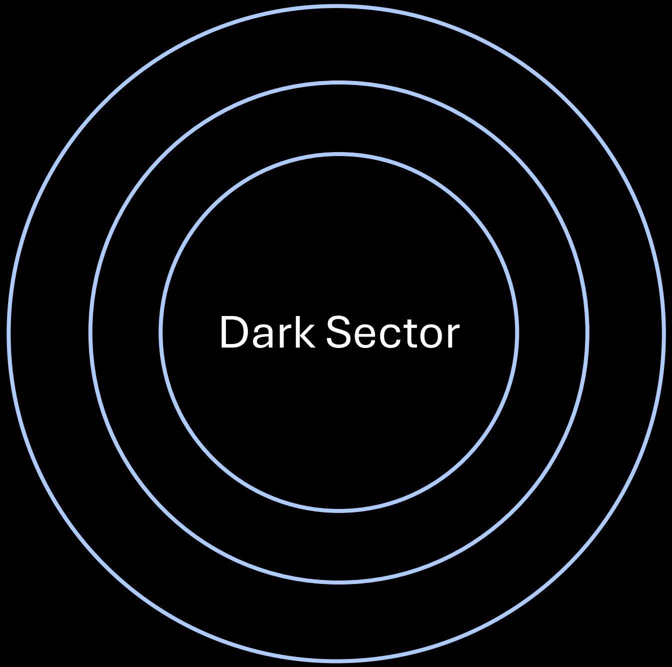
Dark sectors (DS) can address any of these problems

  - 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

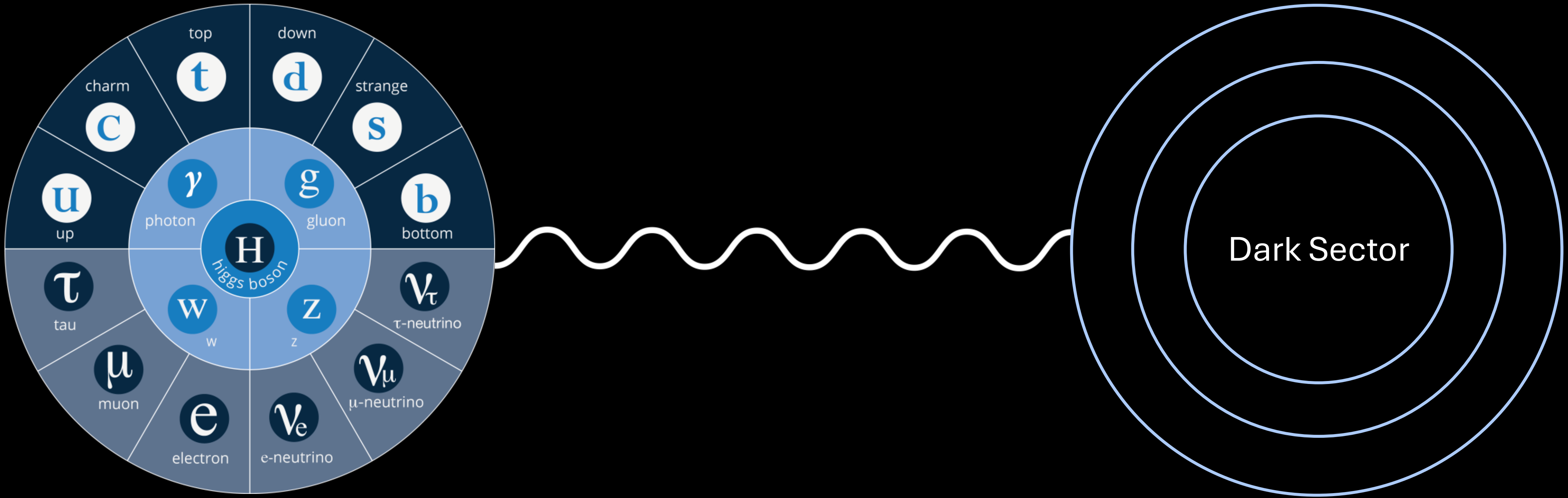
No hints about any details of the DS!

So, how do we start looking?



If there is any interaction between DS and SM, there needs to be a **portal** between the two.

To avoid breaking SM symmetries, four commonly studied ways to communicate with DS:
Spin-1 Portal, Spin-0 Portal, Fermion Portal, Neutrino Portal

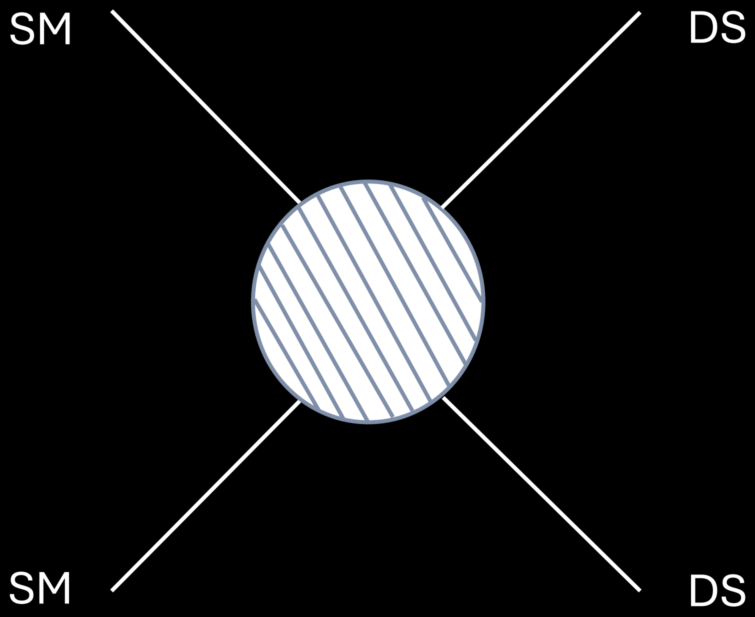


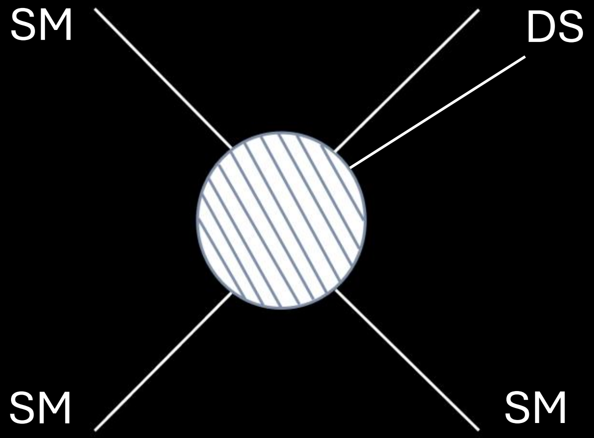
Many portals within direct reach, others can show up at lower energies due to quantum mechanical mixing

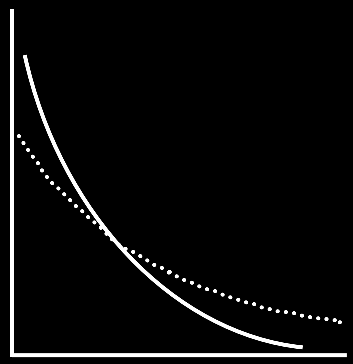
↓

How can we probe this at colliders?

Dark Sectors at colliders

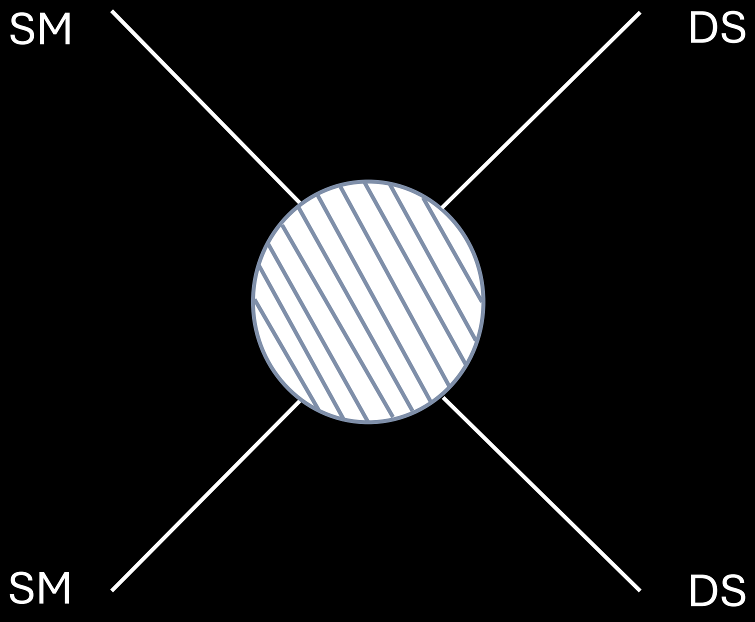


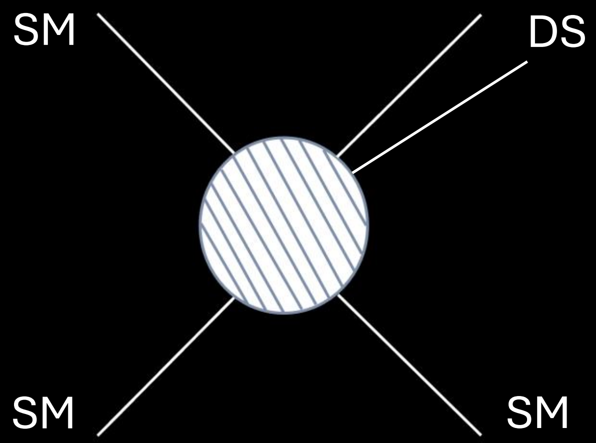


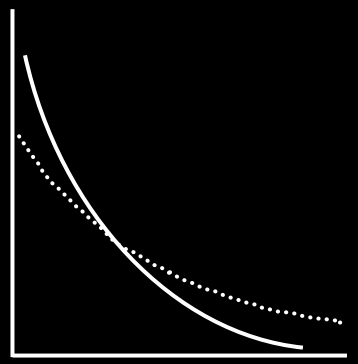


MET+X searches

Dark Sectors at colliders







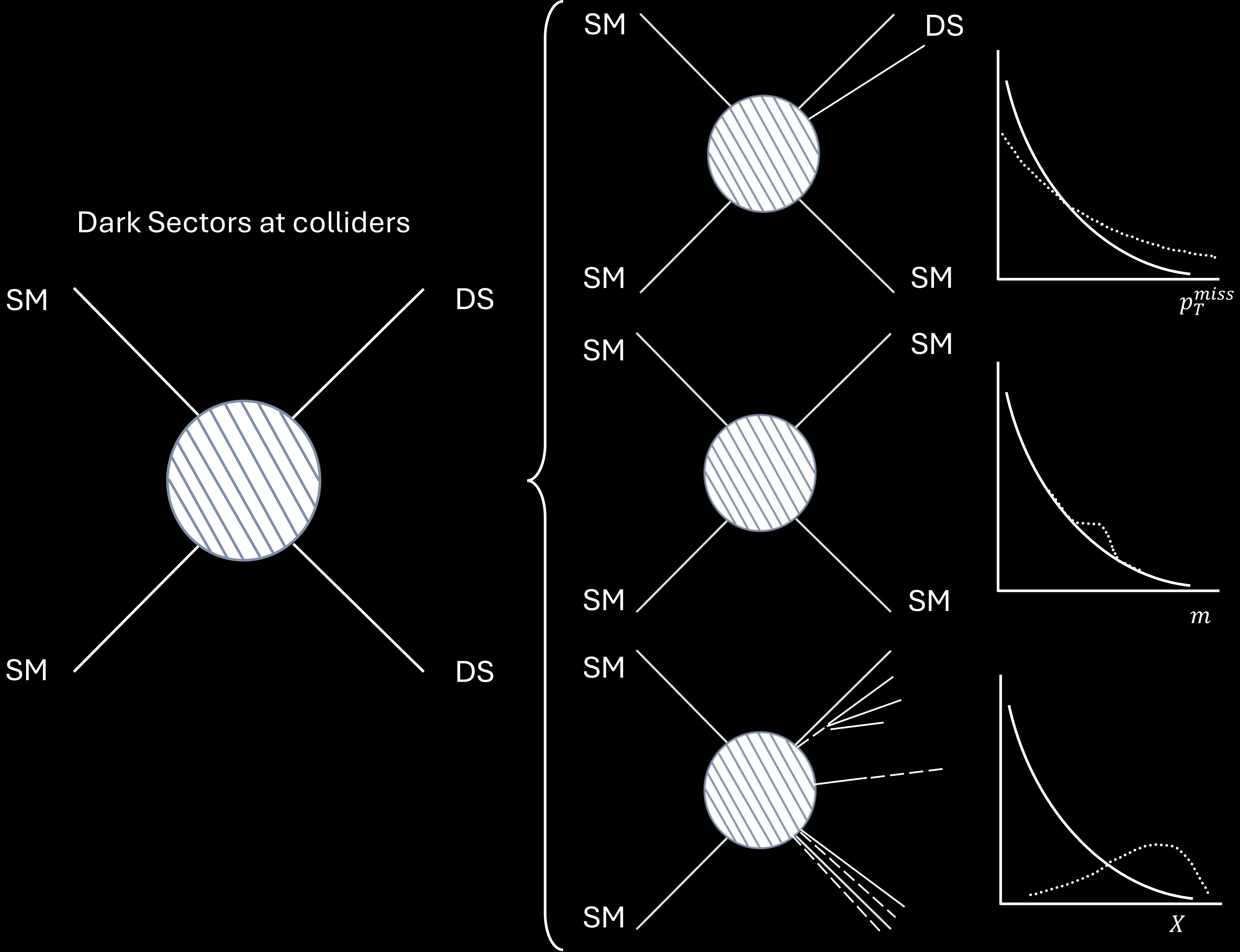
MET+X searches

First approach in post-Higgs era

- MIT heavily involved in several flagship MET+X searches

Series of null results that heavily constrained BSM theories → need to look elsewhere

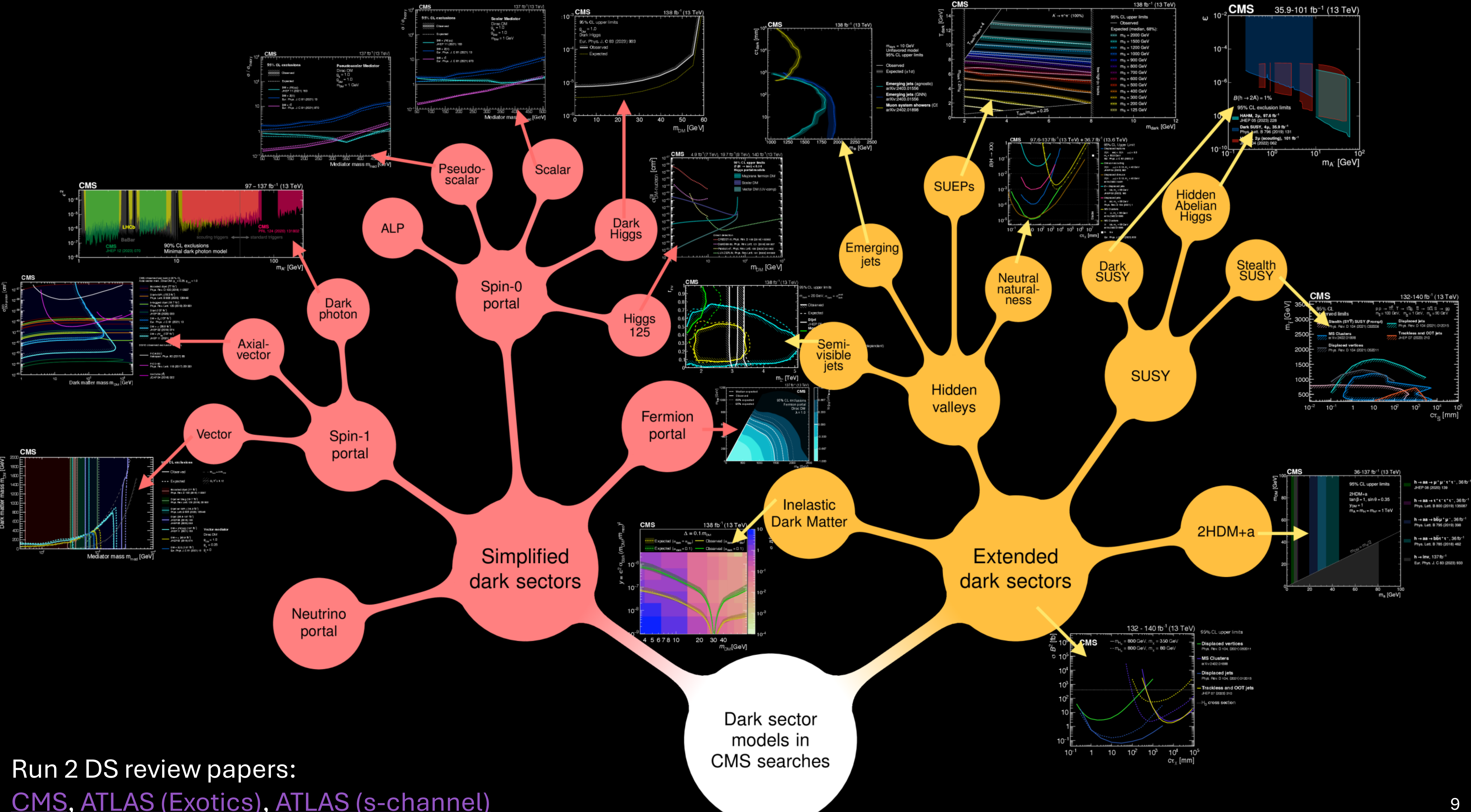
Dark Sectors at colliders



MET+X searches

Portal resonances

Unconventional signatures

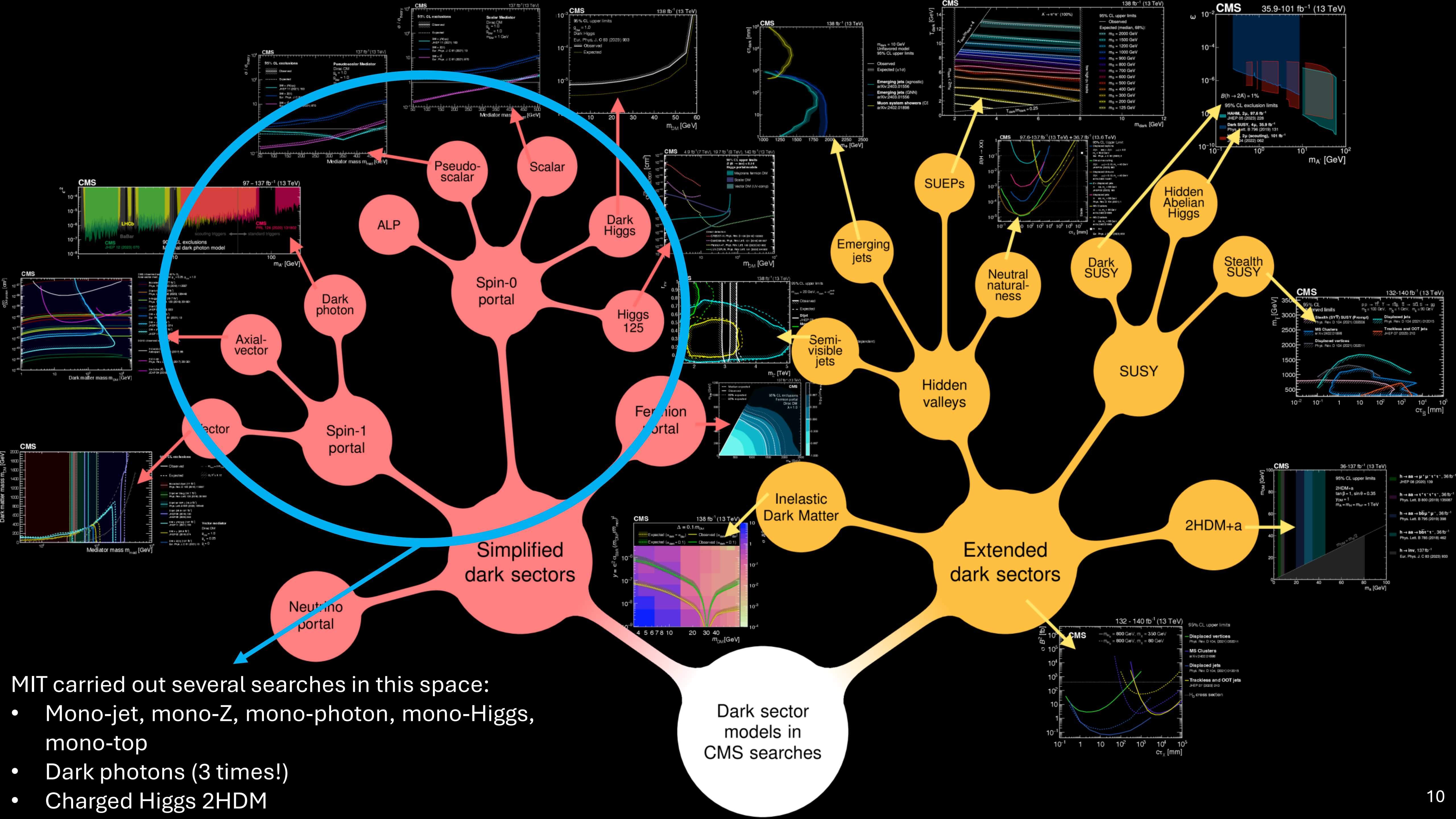


Dark sector models in CMS searches

- Simplified dark sectors
  - Spin-0 portal
    - ALP
    - Pseudo-scalar
    - Scalar
    - Dark Higgs
    - Higgs 125
  - Spin-1 portal
    - Dark photon
    - Axial-vector
    - Vector
  - Fermion portal
  - Neutrino portal
- Extended dark sectors
  - Inelastic Dark Matter
  - Hidden valleys
    - Semi-visible jets
    - Emerging jets
    - SUEPs
    - Neutral naturalness
  - SUSY
    - Dark SUSY
    - Hidden Abelian Higgs
    - Stealth SUSY
  - 2HDM+a

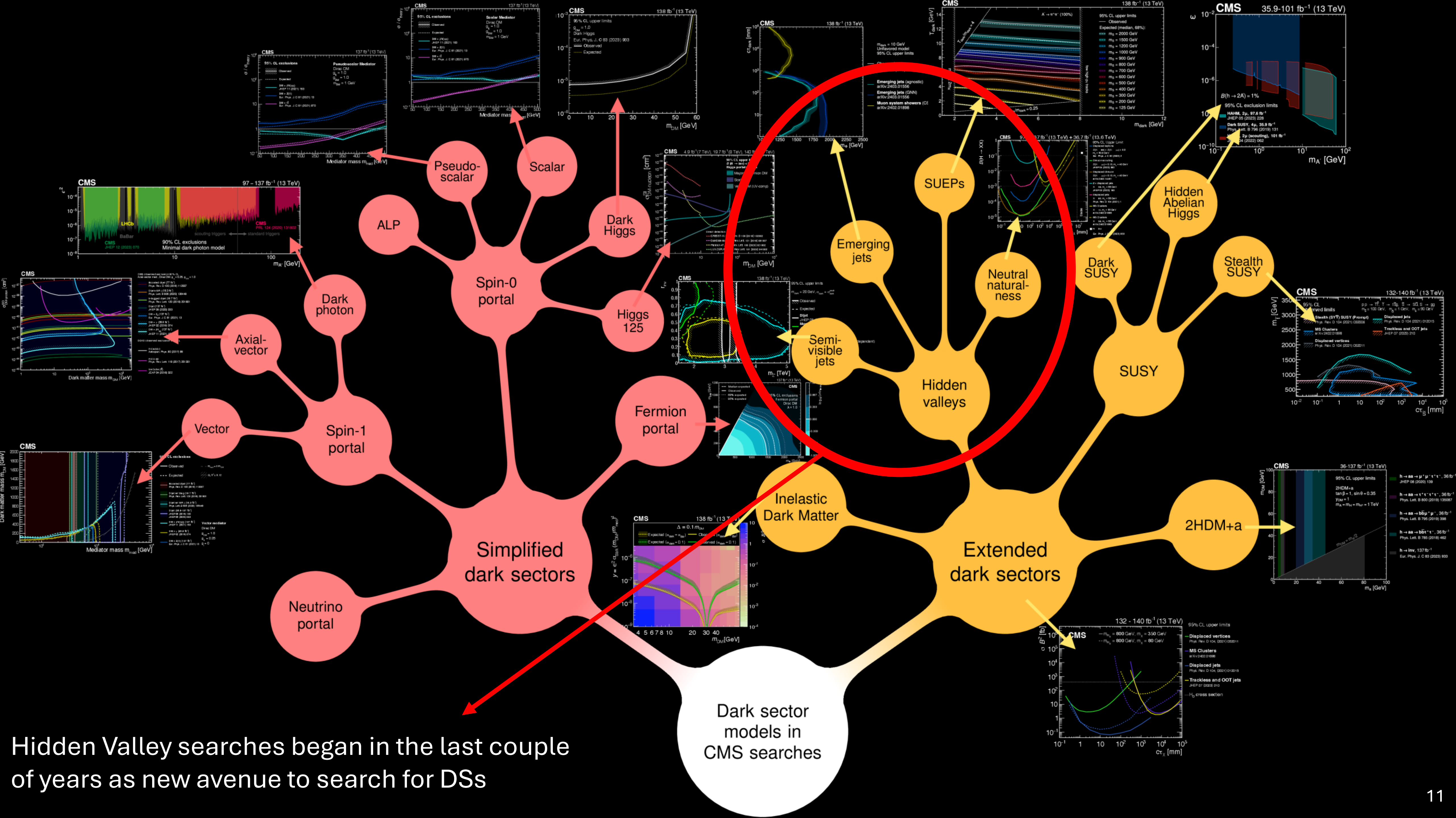
Run 2 DS review papers:

CMS, ATLAS (Exotics), ATLAS (s-channel)



MIT carried out several searches in this space:

- Mono-jet, mono-Z, mono-photon, mono-Higgs, mono-top
- Dark photons (3 times!)
- Charged Higgs 2HDM

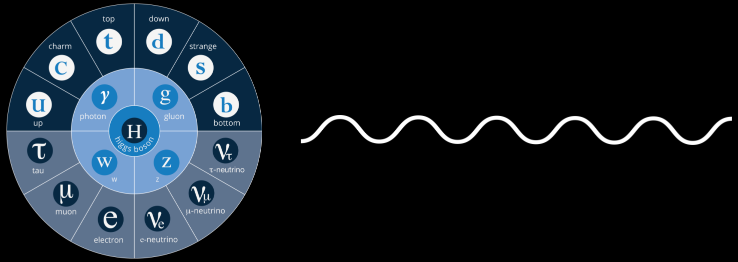


Hidden Valley searches began in the last couple of years as new avenue to search for DSs

Hidden Valleys

Standard
Model

Hidden
Valley



$SU(N_{dark\ color})$

Why Hidden Valleys?

Standard
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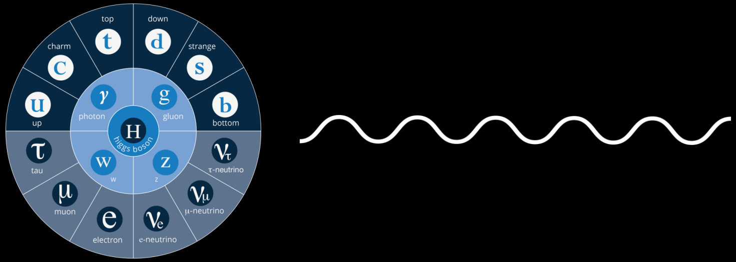

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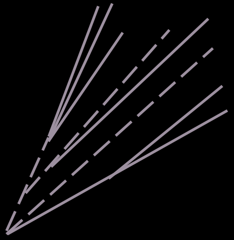
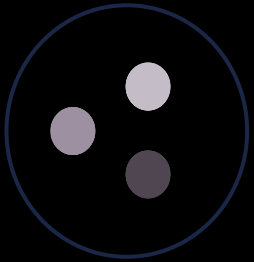


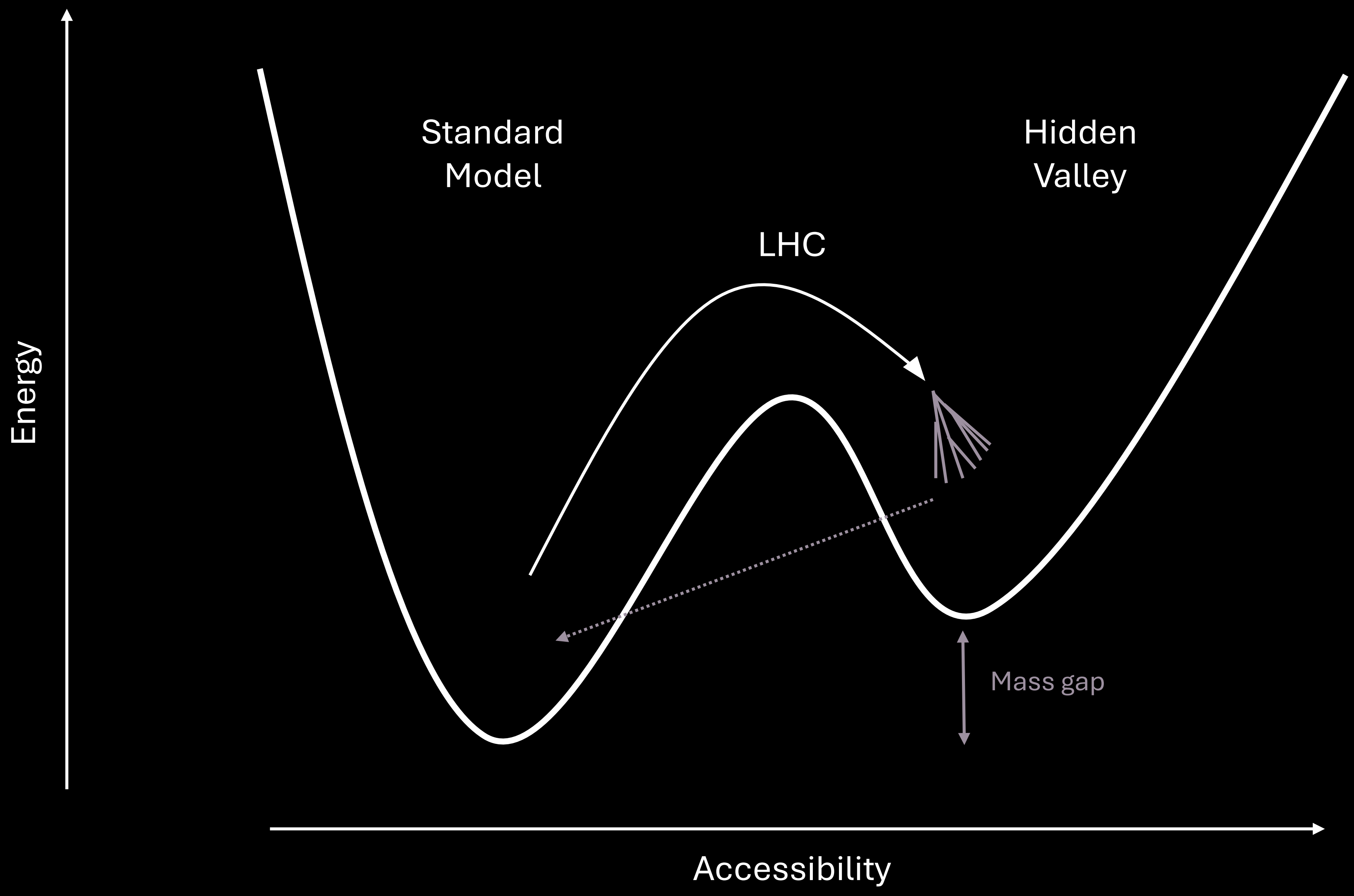
Rich phenomenology at colliders!

Many new possible signatures that would've been missed in previous searches: semi-visible jets, emerging jets, SUEPs.

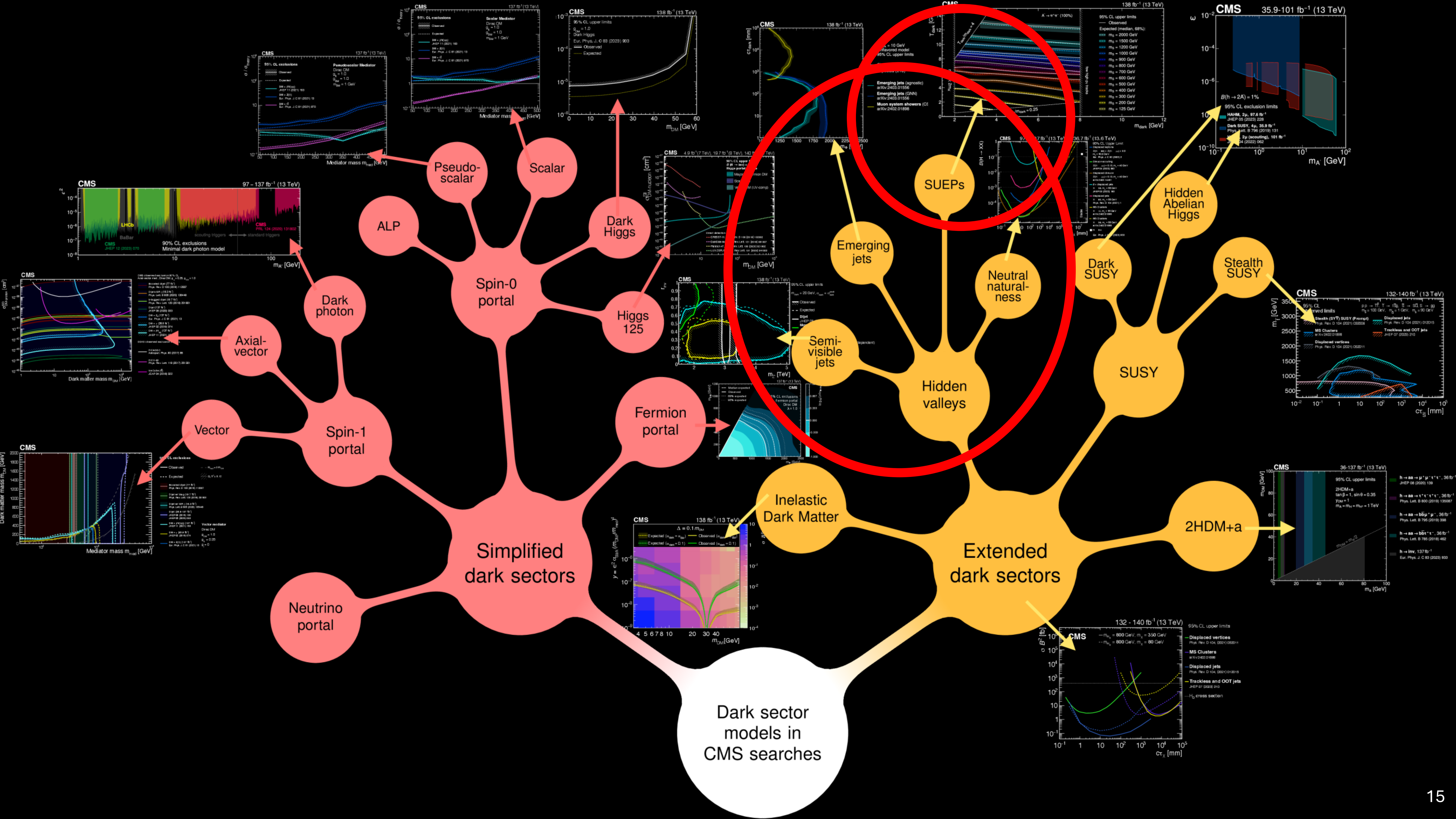
Strong, confining (QCD-like) force can give rise to composite dark hadrons which fulfill DM criteria (stable, small interactions, heavy)



How to find Hidden Valleys at colliders



*Schema from Matt Strassler



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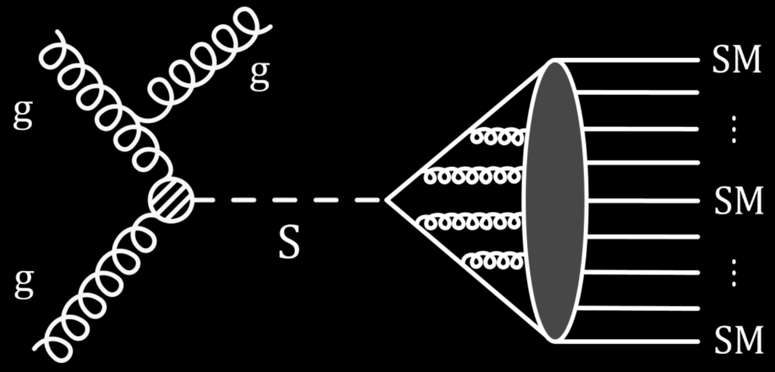
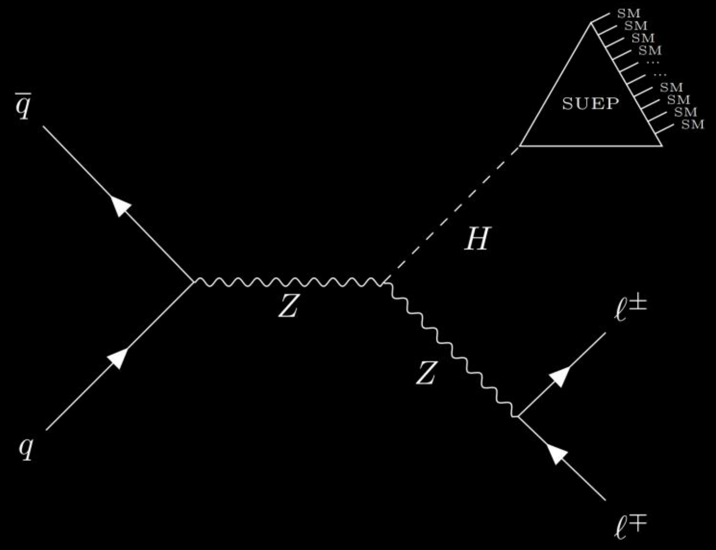
The SUEP program at CMS

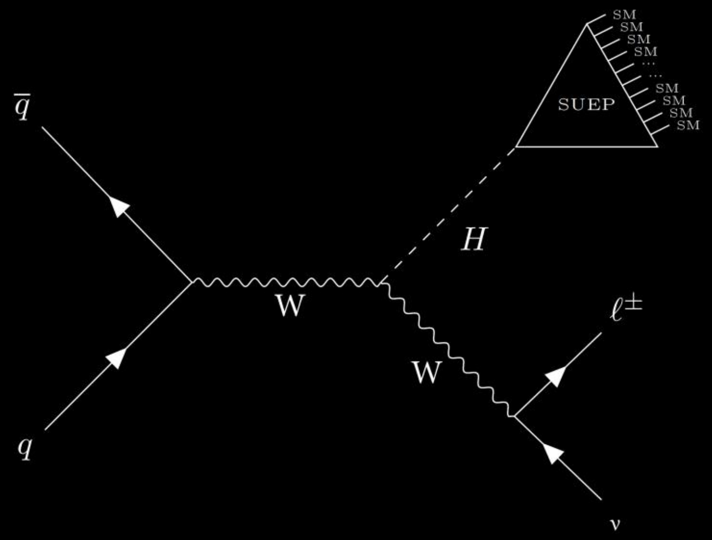
Five ongoing searches for SUEPs using Run 2 data at CMS

MIT leading the effort along with BU, Fermilab

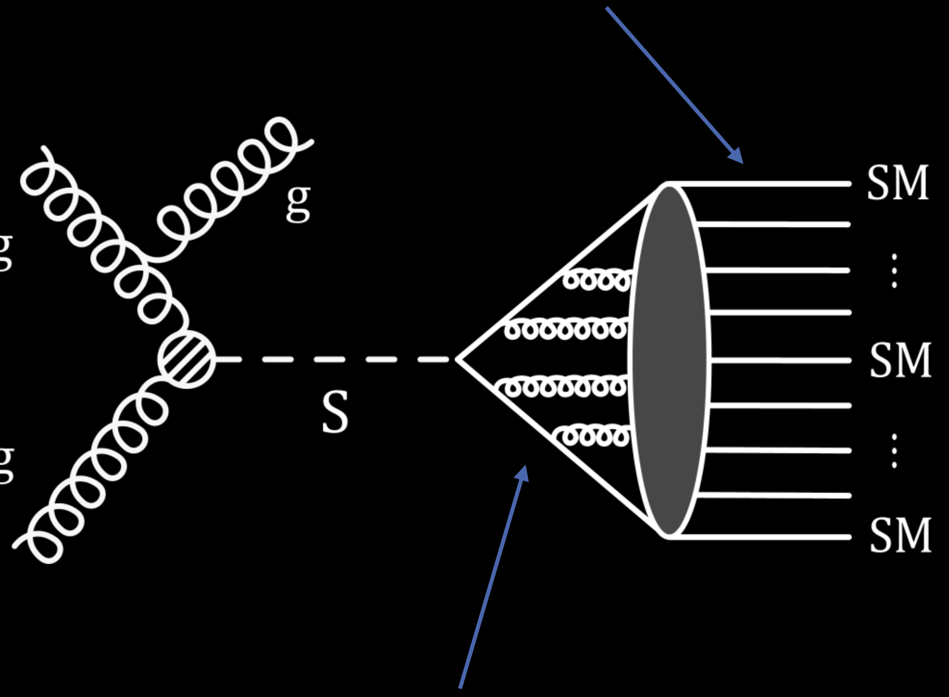
- Began the effort in 2021, led the group since
- Developed a common framework to perform these analyses
- Gluon fusion channel, led by MIT, just accepted to PRL, with Editor's Highlight







A Hidden Valley paradigm: Soft Unclustered Energy Patterns (SUEPs)



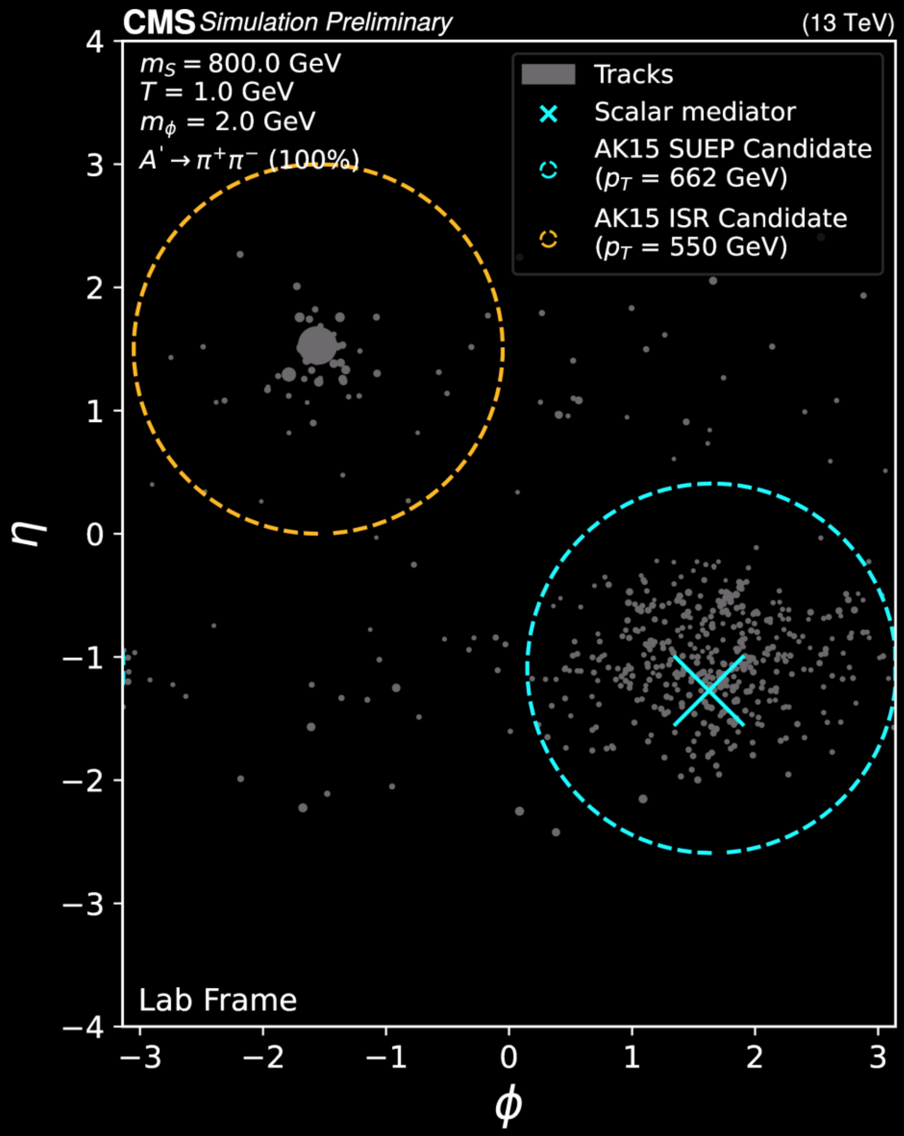
Promptly decay back to SM

$$\lambda \equiv g^2 N_{colors} \gg 1$$
$$m_{q_D} < \Lambda_D \ll \sqrt{s}$$

Efficient, isotropic showering window

A ‘real-life’ SUEP at the LHC

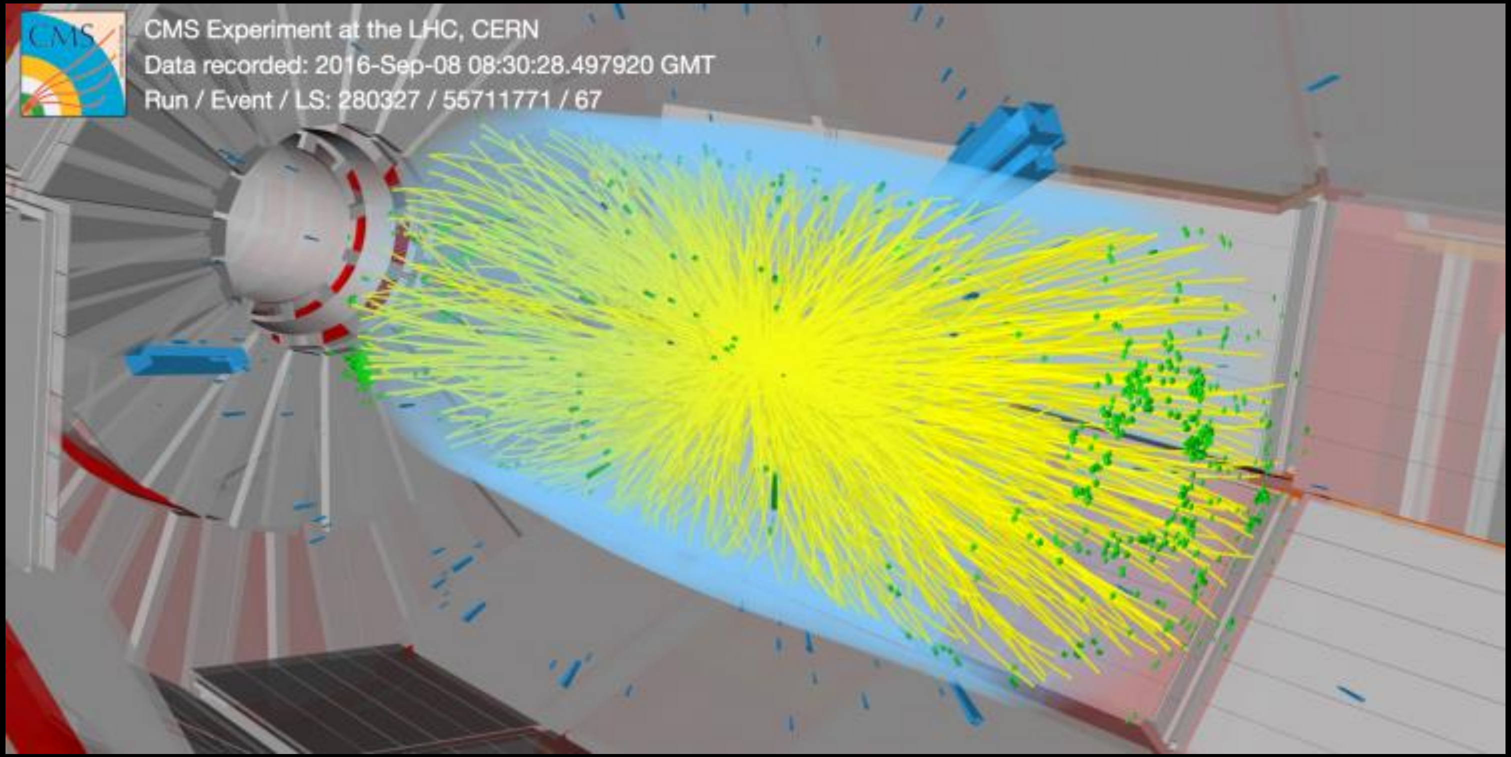
QCD
Low multiplicity of higher momentum particles, produced collinearly



SUEP
High multiplicity of low momentum particles, isotropic in its own frame

Experimental challenge

"A spray of low p_T tracks? Have you heard of pileup?"



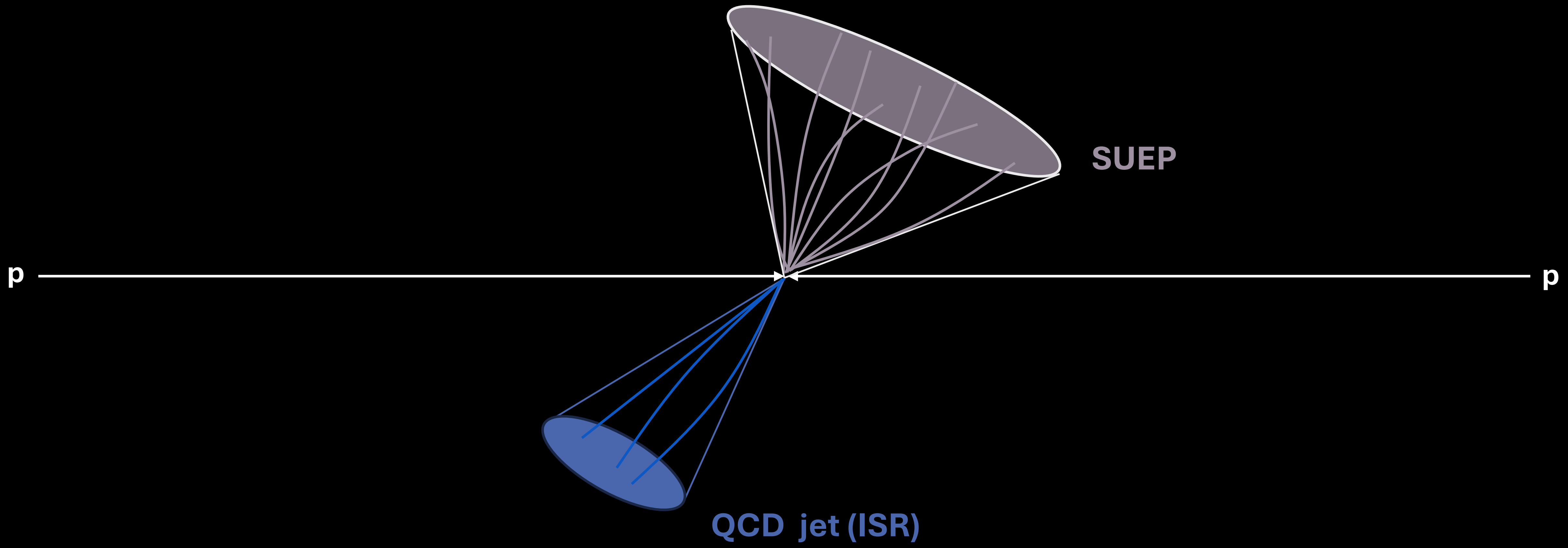
Average event at CMS: quite hard to distinguish SUEP from so-called "pileup", the additional overlapping pp interactions that happen concurrently with the interaction of interest.

From https://cms.cern/news/how-cms-weeds-out-particles-pile

The gluon fusion channel

Use events with high hadronic to select recoiling SUEP-ISR system

→ Can now trigger on these events using the hadronic activity



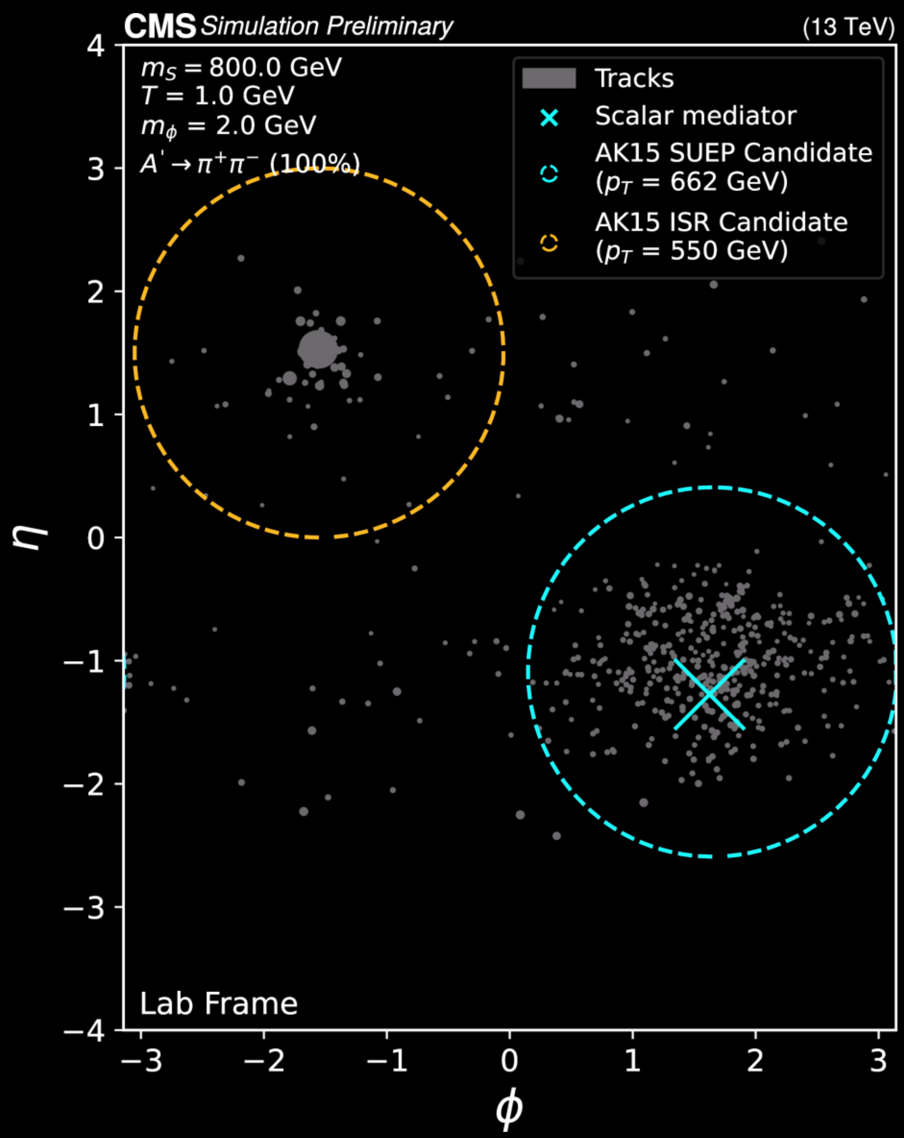
Reconstruction

- SUEPs are isotropic, soft sprays of particles

→ Evade typical reconstructed objects: even typical jets can't capture the full sprays that the signals produce

Solution:

- Cluster 'wide-jets' using anti-kt algorithm with large radii
- Novel type of reconstructed object, makes these analyses possible
- Displays CMS' ability to push beyond its original design

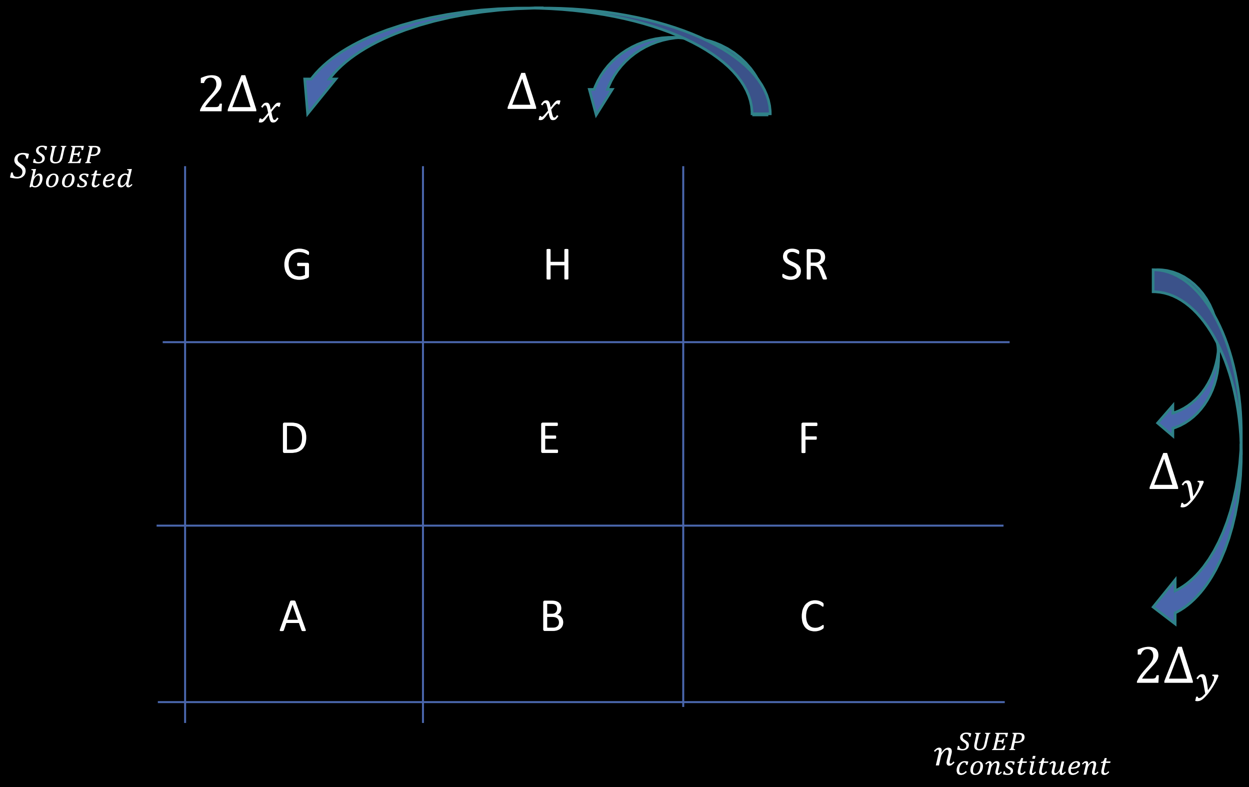


Background Estimation

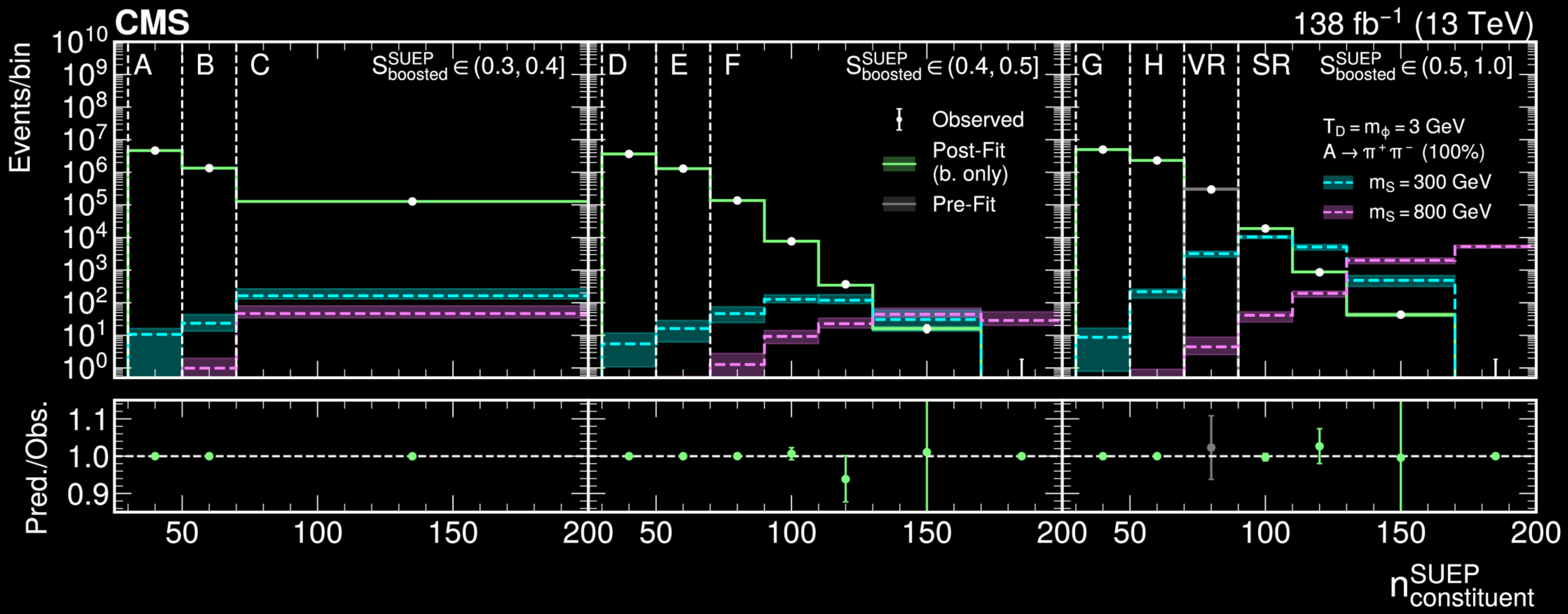
- Premiered a novel data-driven estimation technique (arxiv:1906.10831)
  - Fully data-driven method to predict background in signal region (SR)
  - Account for linear correlations in variables
  - Shape prediction for SR

$$SR^{Bin\ i} \approx F^{Bin\ i}\underbrace{\frac{H^2F\ D^2B^2}{G\ C\ A\ E^4}}_{\text{Scaling factor applied to F histogram}} + O(\Delta^4)$$

- Now used on other analyses, including mW!

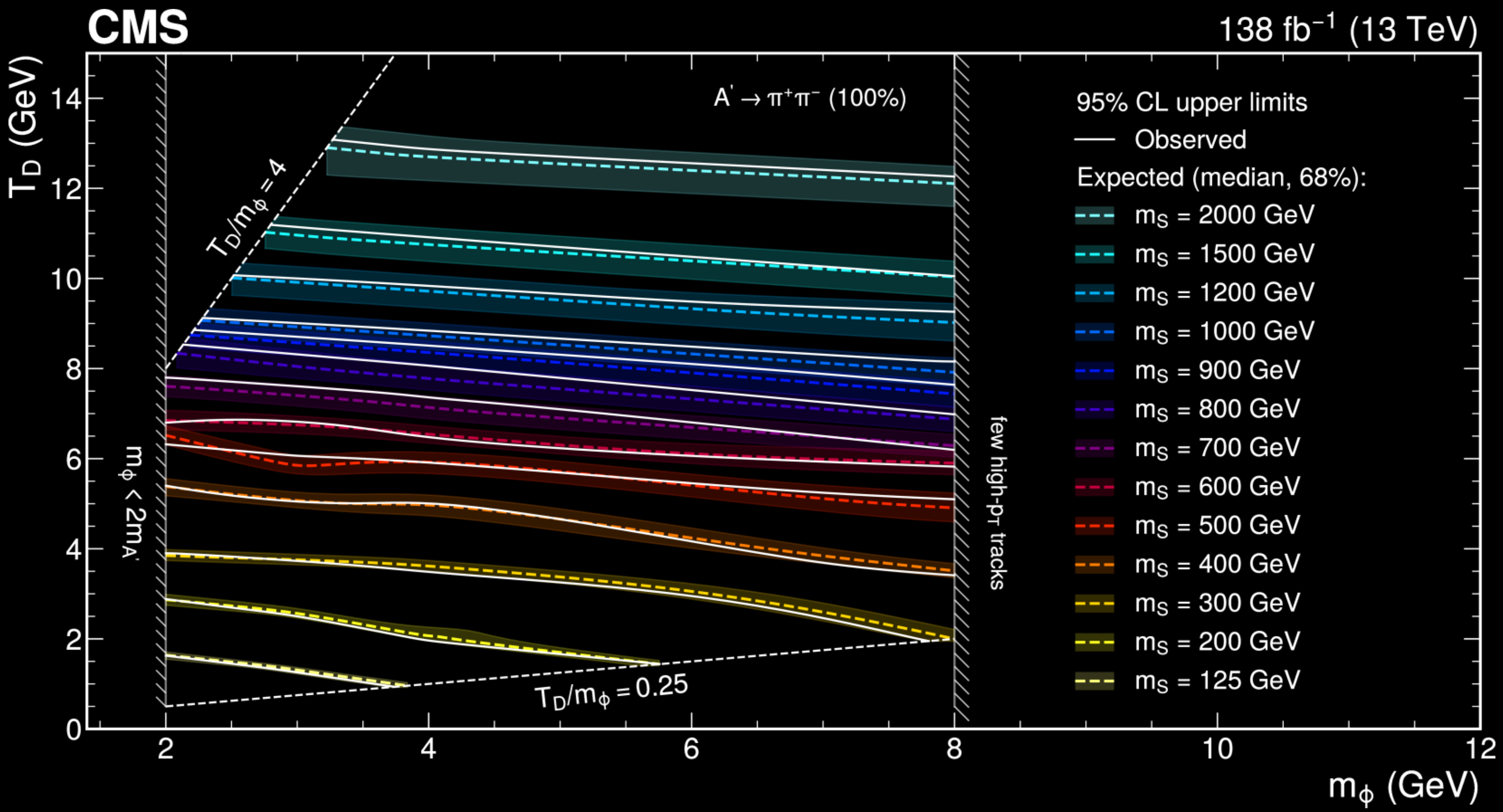


Results



- Huge number of events and extended ABCD method yield a very precise prediction of the notoriously difficult QCD jet processes
  - Systematics on the ABCD prediction constrained through the control regions (A-H) were key to this

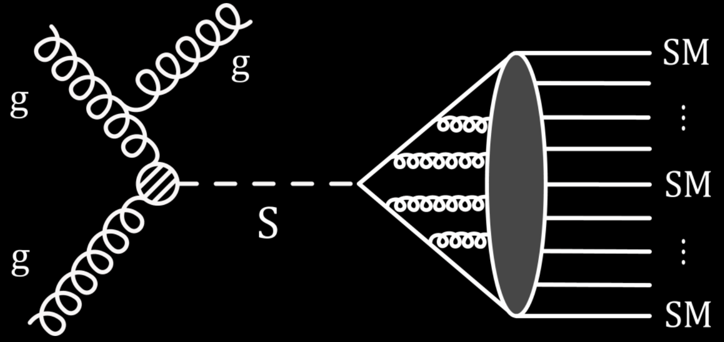
Limits on SUEPs



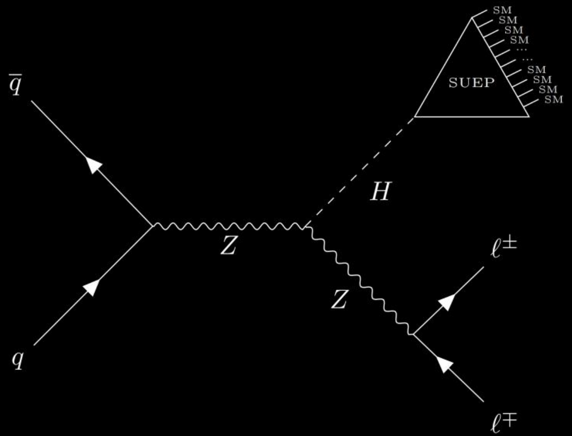
- First limits on SUEPs
  - Result can be re-interpreted in other BSM models that produce spherical, numerous jets
  - Similar analysis strategy might target instantons one day
  - Add to searches for emerging jets and semi-visible jets in the effort to search for Hidden Valleys
- Accepted by PRL with Editor's Highlight

Other channels

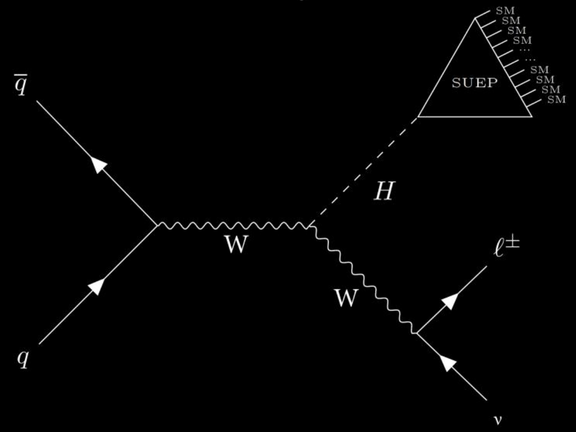
MIT involved in other channels to push the SUEP program



- Gluon fusion in scouting:
  - Make use of 'scouting' dataset
  - Relatively unused still, but very interesting: huge yields of less-detailed data
  - Can target much lower mass scalar mediators that suffer from low rates in the standard 'offline' analysis



- Associated production with a vector boson (W and Z):
  - Target production of a Higgs (or Higgs-like) scalar that decays to SUEPs
  - Providing the analysis in a model-independent framework that can be re-interpreted by theorists



Conclusions

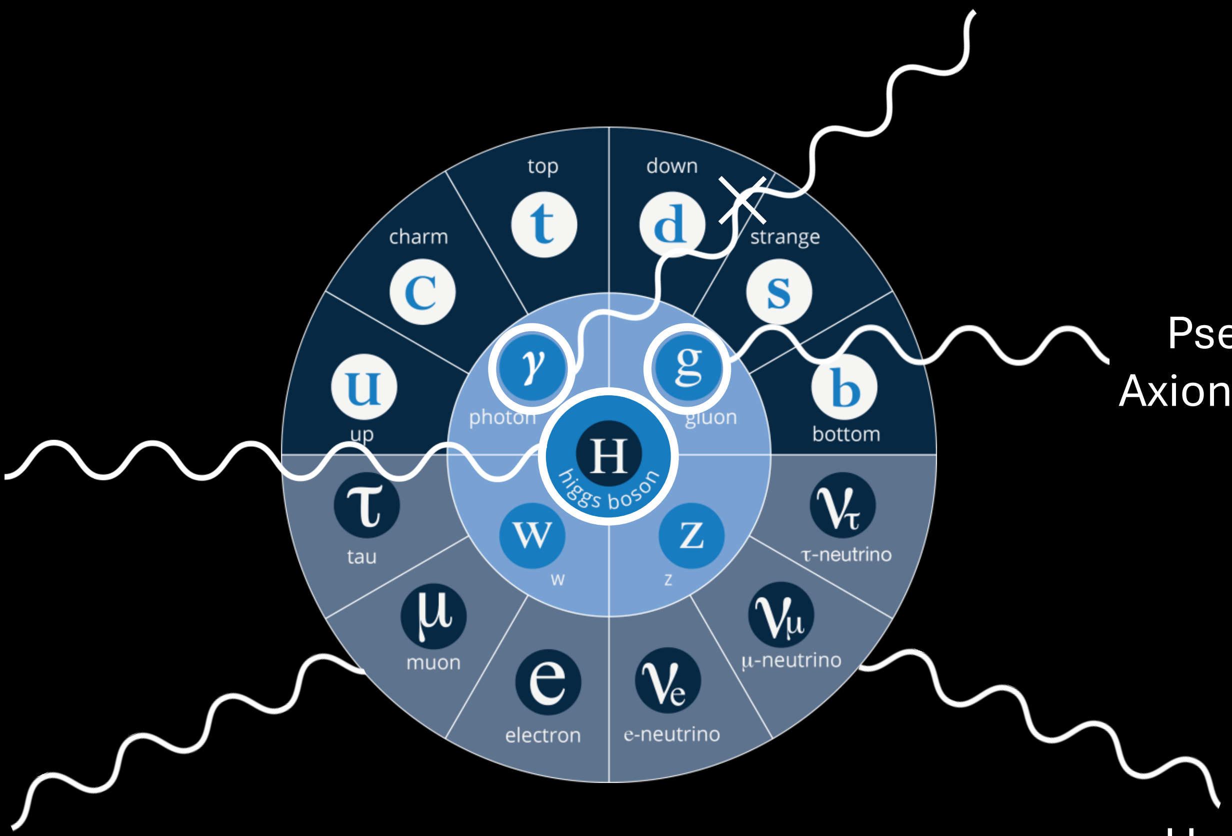
- Searches for dark sectors are the new frontier for BSM at colliders

- Hidden Valleys provide a framework for new dark sectors that are both interesting for theory and experiments

- MIT had led the way on SUEPs, an important Hidden Valley paradigm, providing new searches that have been of great interest to the community
  - New signatures
  - New reconstructions
  - New statistical techniques

- Future:
  - Many other channels ongoing
  - Feedback from theorists: modified SUEPs with different assumptions, decays to SM, etc.
  - HL-LHC can really target SUEP models via triggering on tracks

Backup



Dark Photon Mixing

Pseudoscalar /
Axion-Like Particles

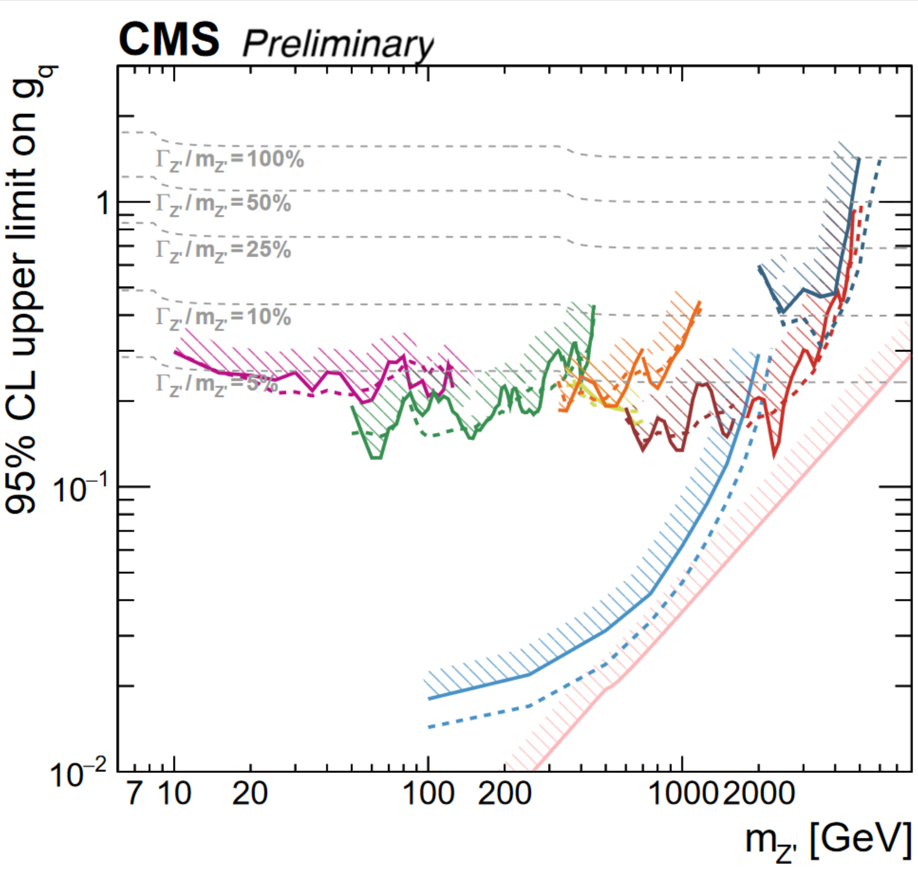
Higgs & Dark Higgs Portals

Z' Portals

Heavy neutral leptons

Improving MET+X and Resonance Searches

High-rate triggers (scouting)



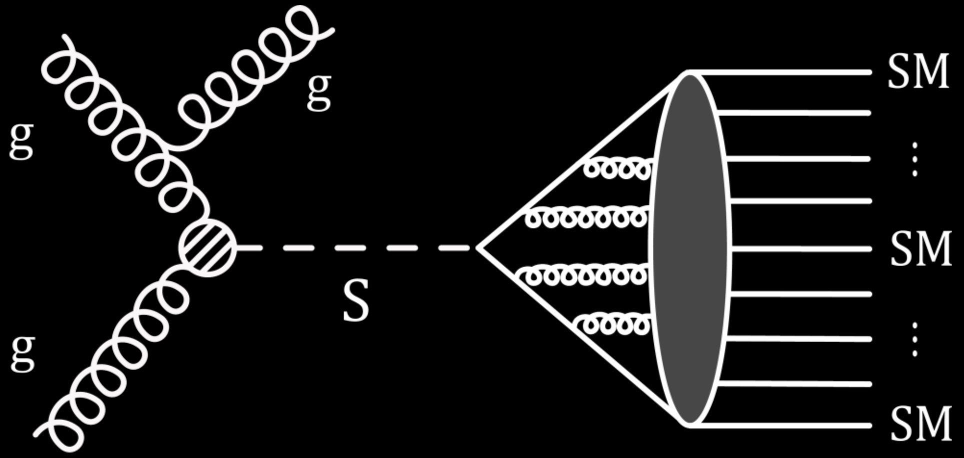
Luminosity, $\sqrt{s}$

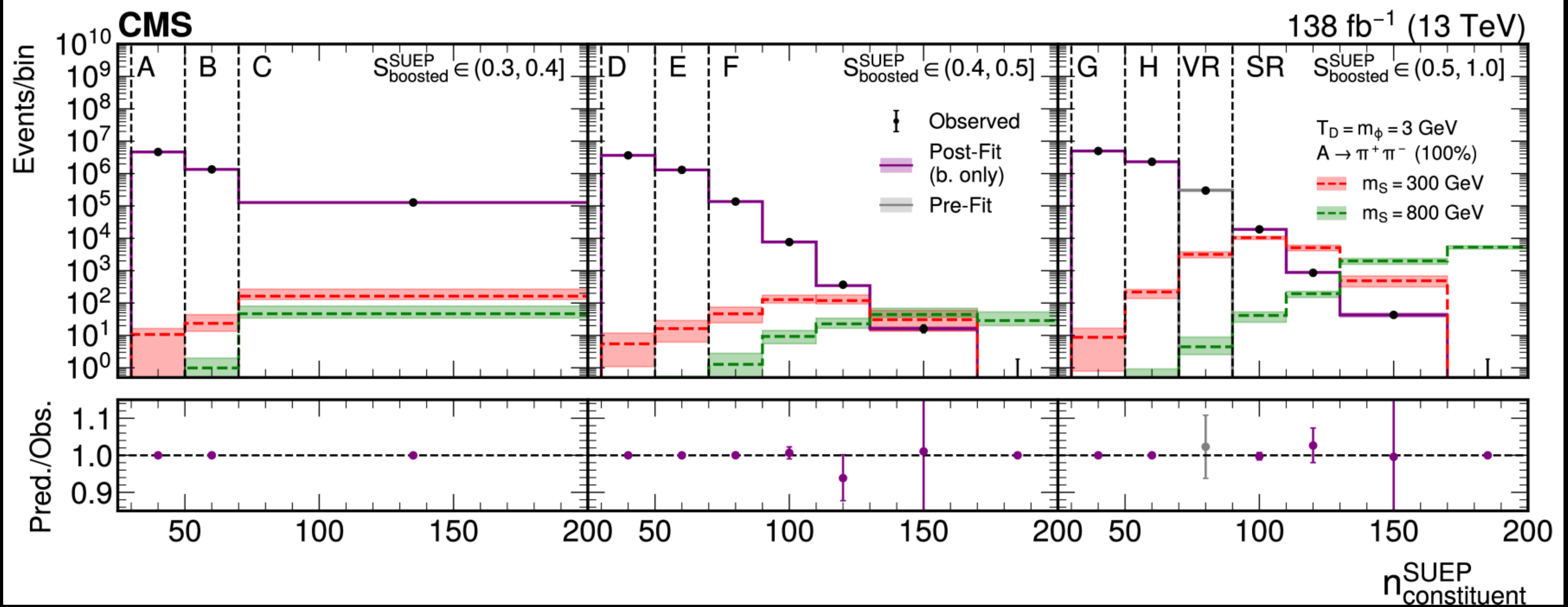
+ better methods: event selection, jet tagging, background estimations, etc.

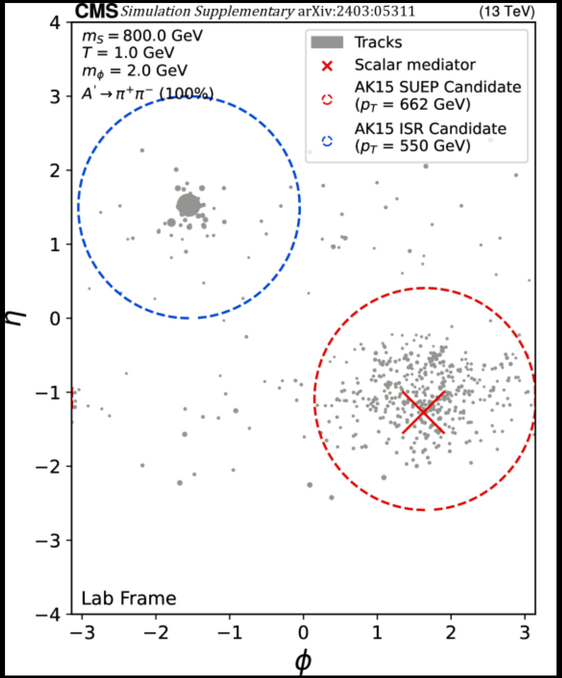
arXiv:2403.05311

Soft Unclustered Energy Patterns

- 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



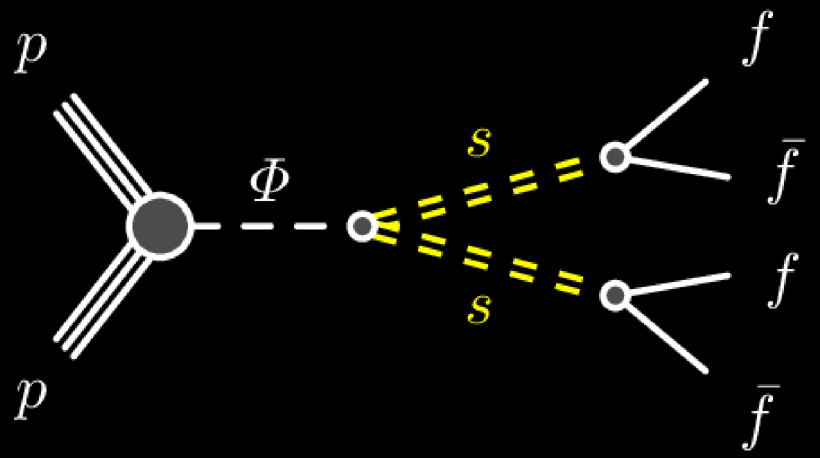


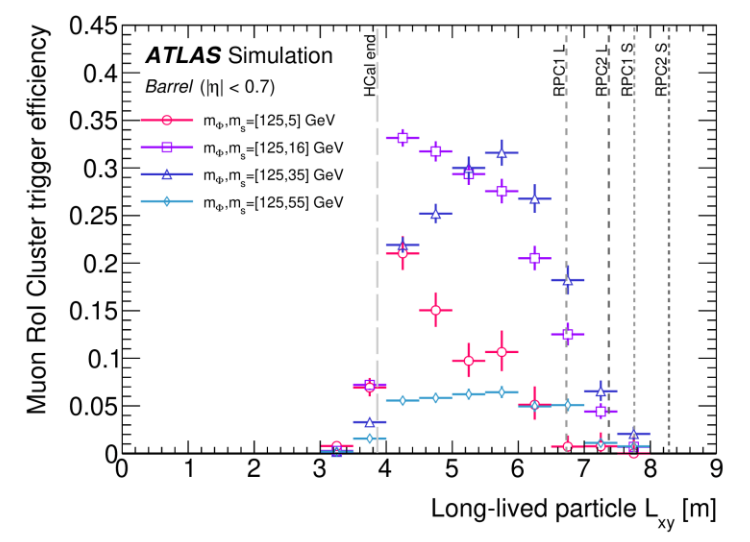


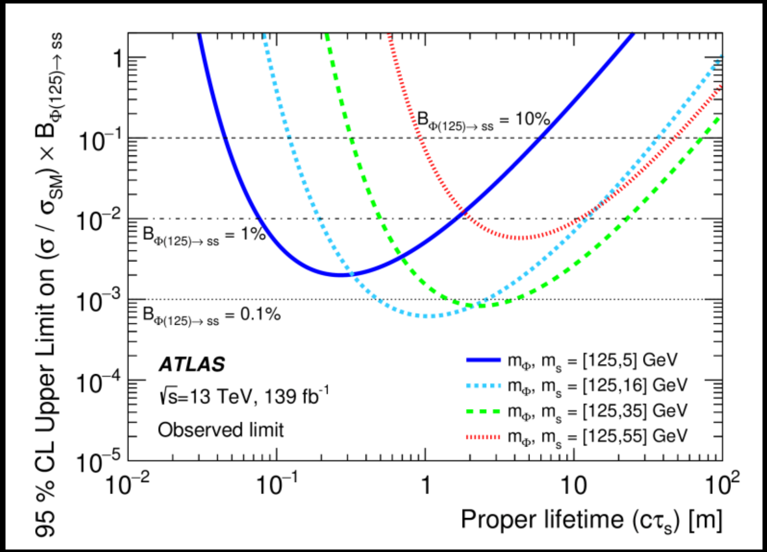
Unconventional Signatures: Displaced Jets in μ Spectrometer

- Dark particles s produced, travel ~m, decay to ff, 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





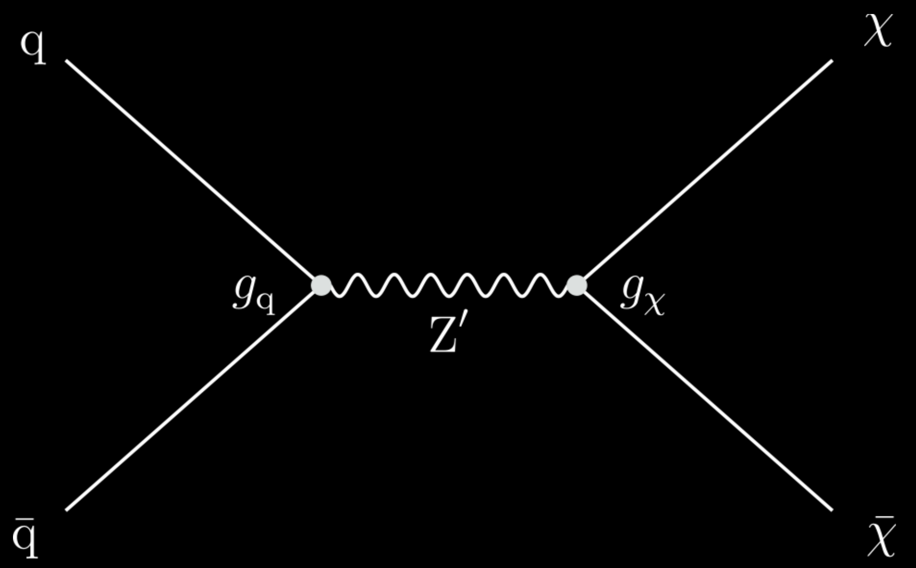


- Set limits on $c\tau, \sigma$

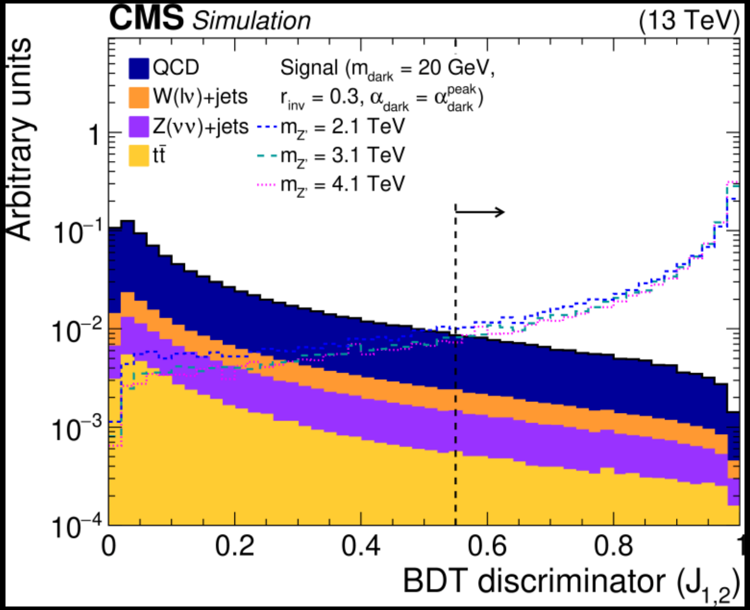
- Assumptions on DS structure, BRs, masses, etc. for these limits

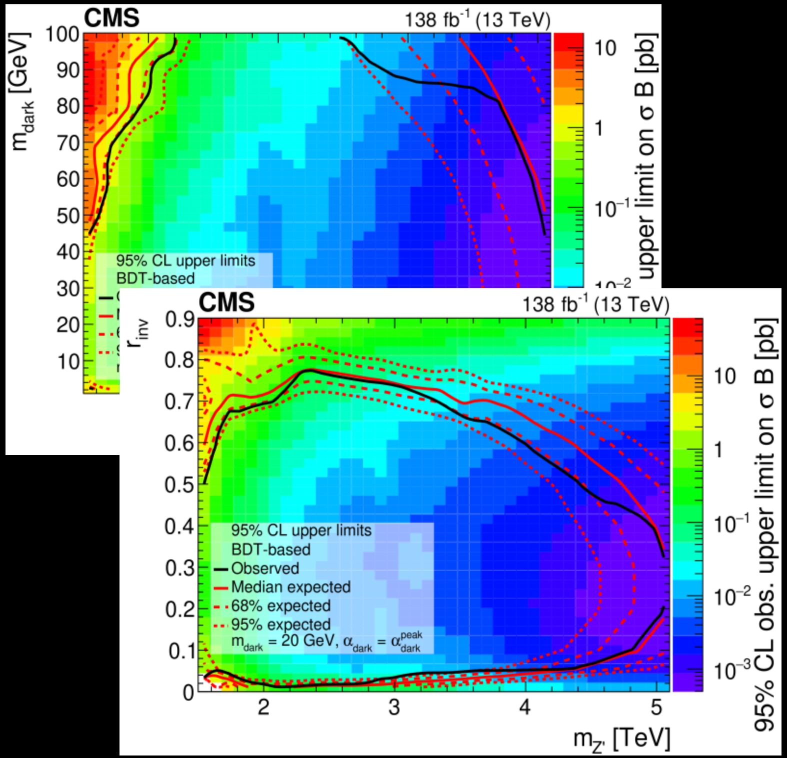
Unconventional Signatures: Semivisible Jets

- 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

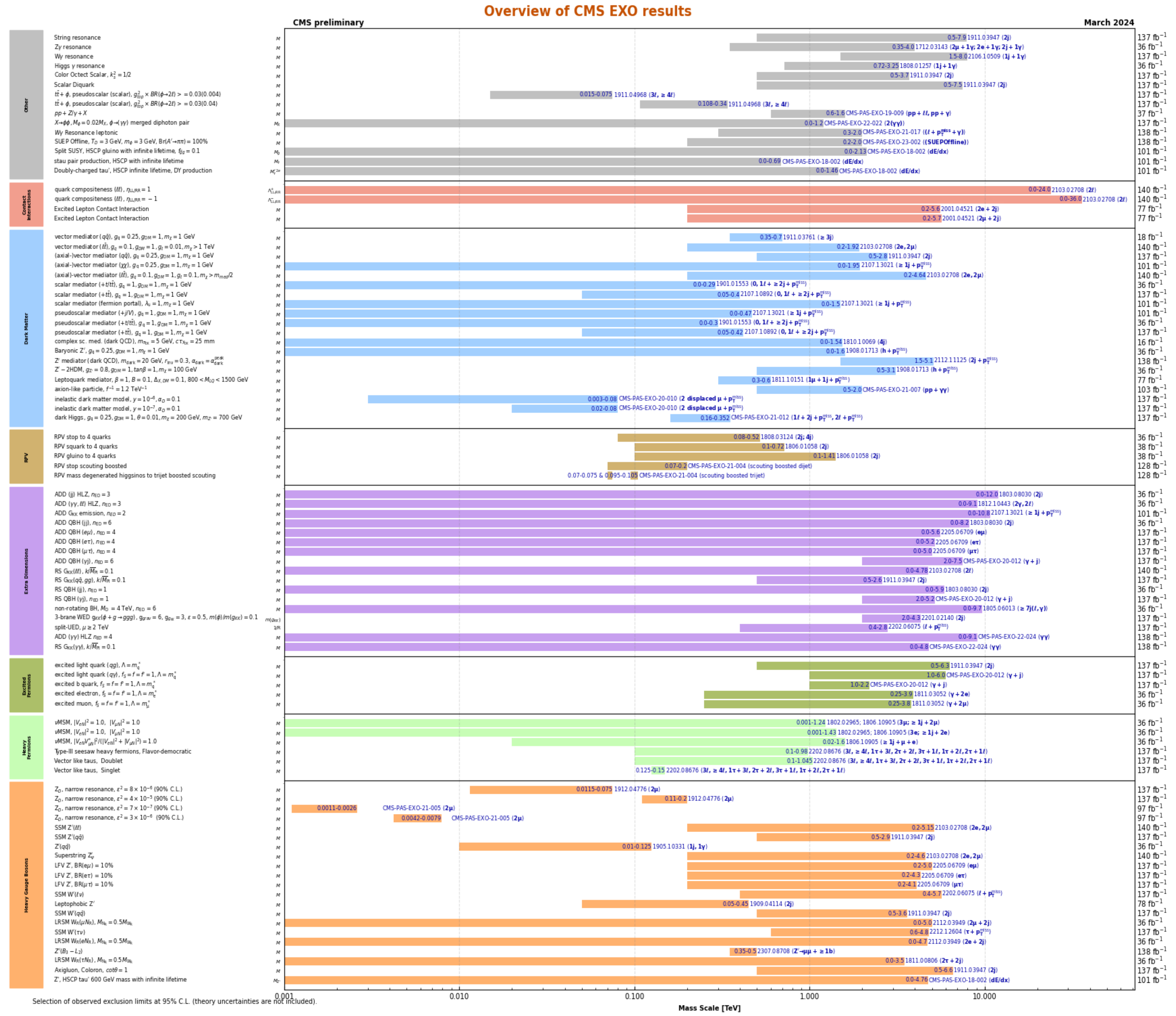


- Set limits on $m_{Z'}, m_{dark}, r_{inv}$
- Assumptions on dark sector, such as showering, gauge structure, etc.

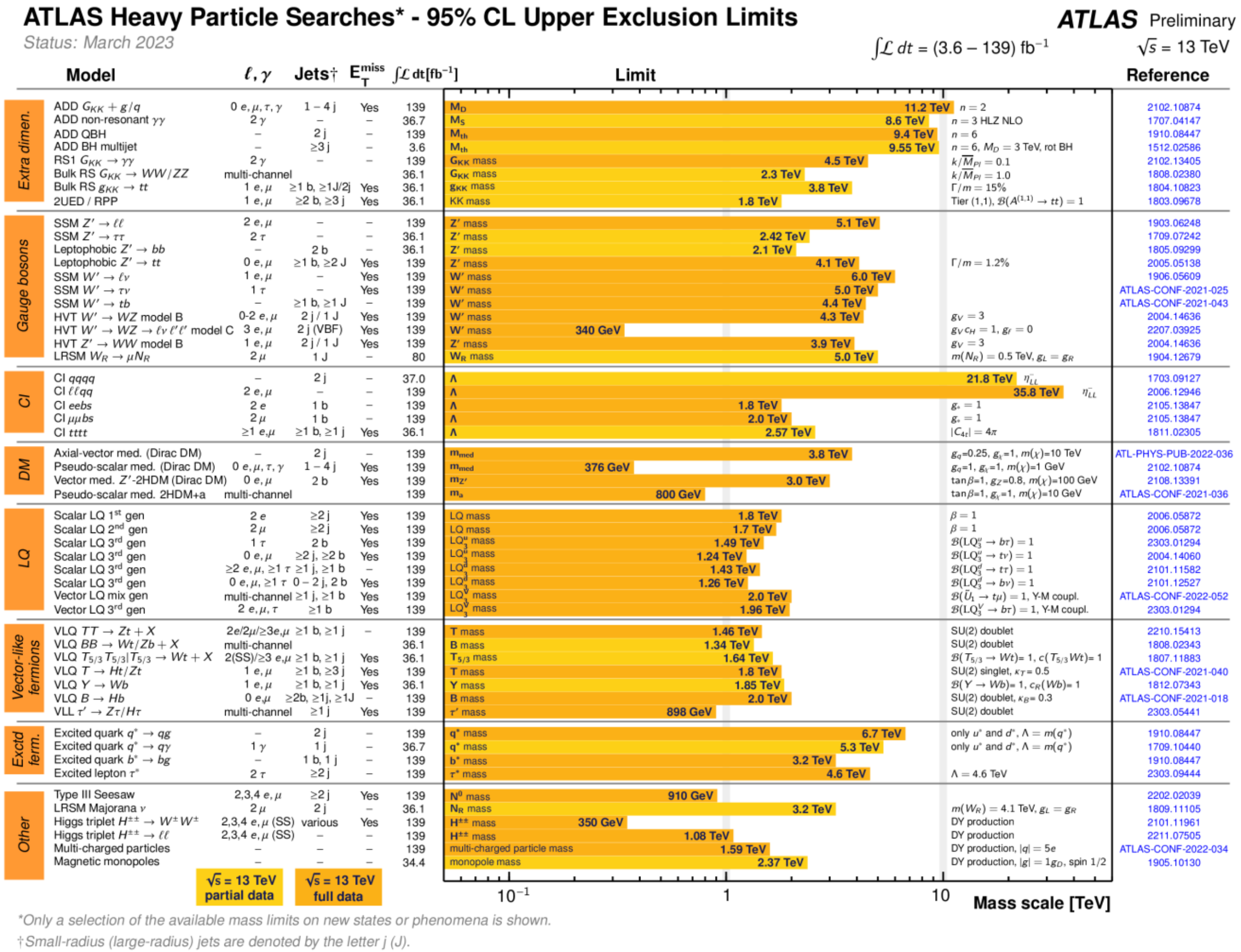


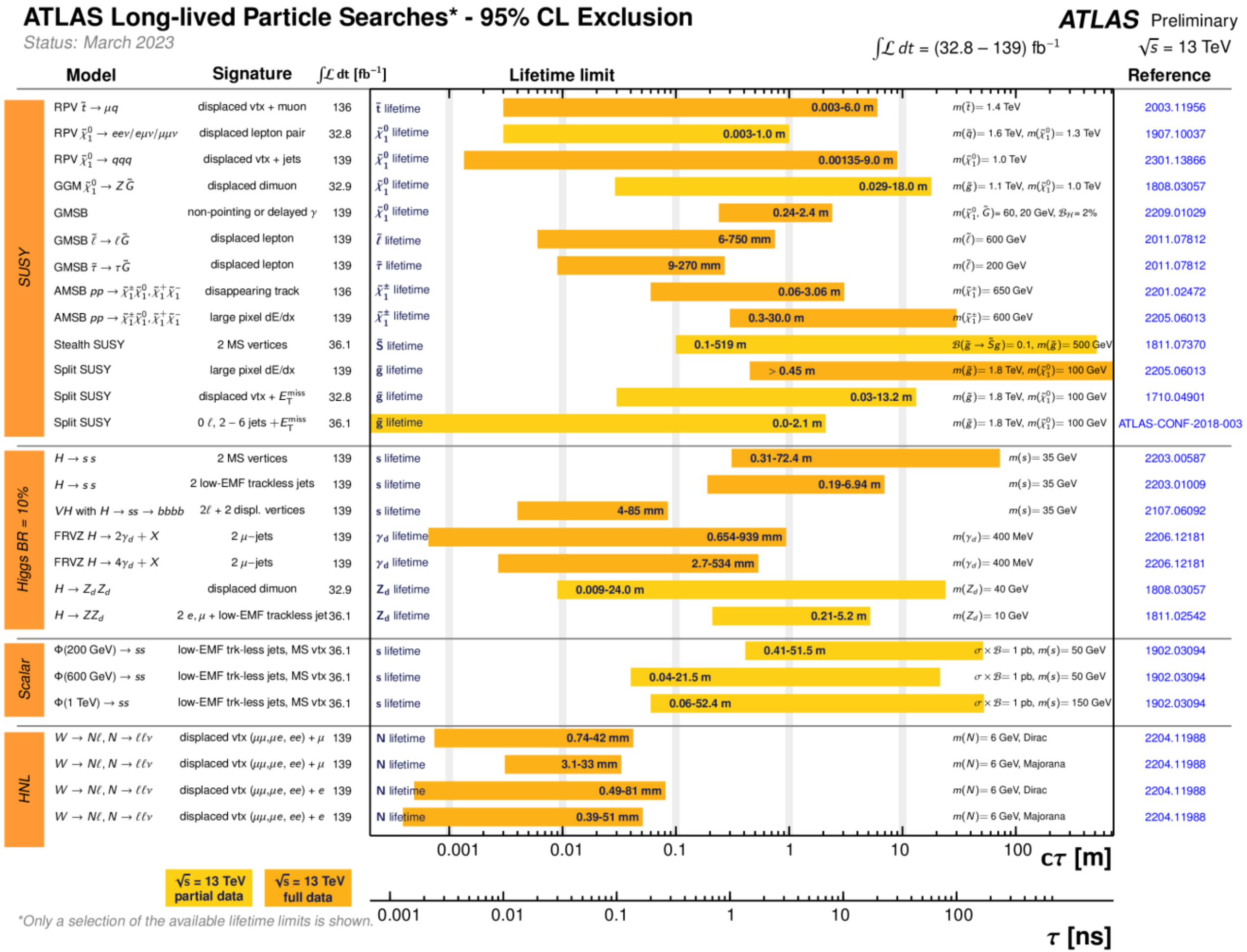


EXO-CMS Summary Plots

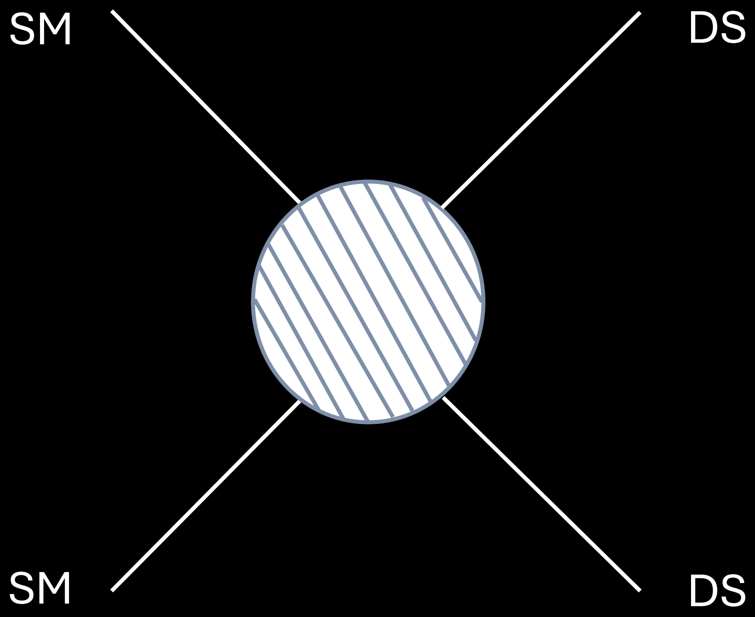


ATLAS Summary Plots





Dark Sectors at colliders



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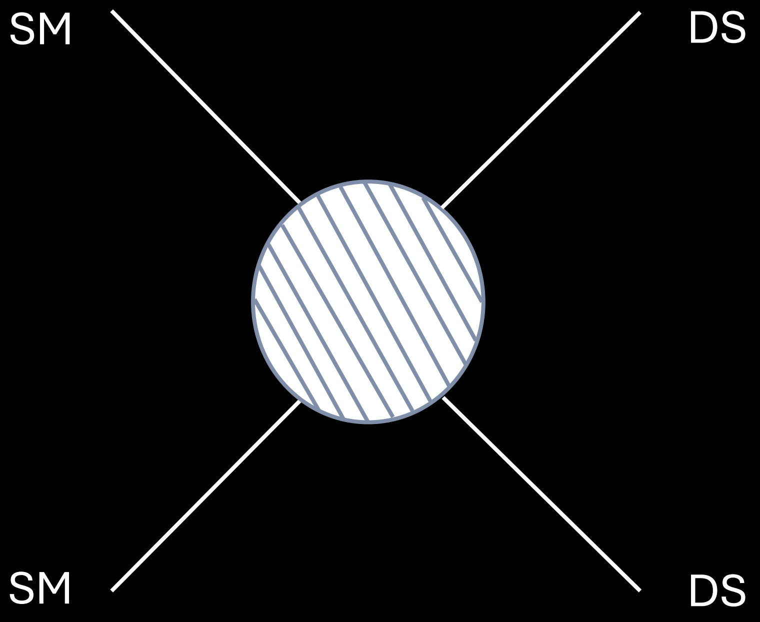
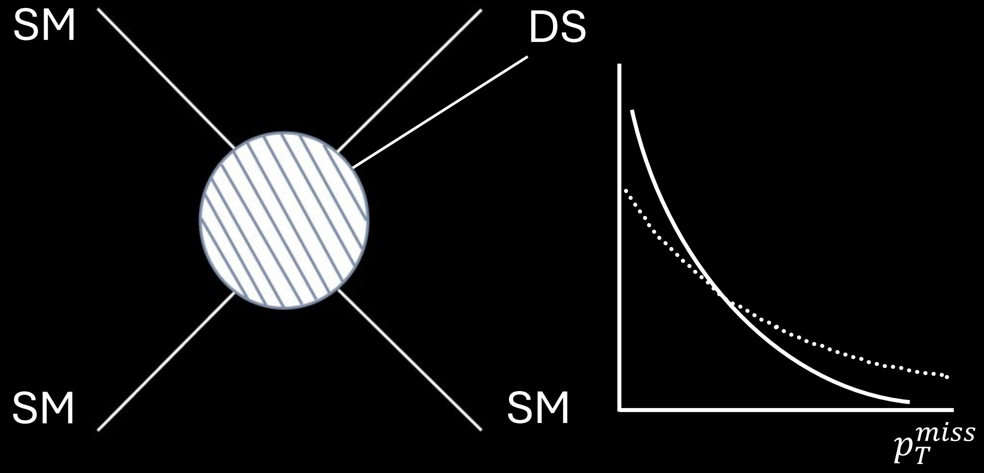
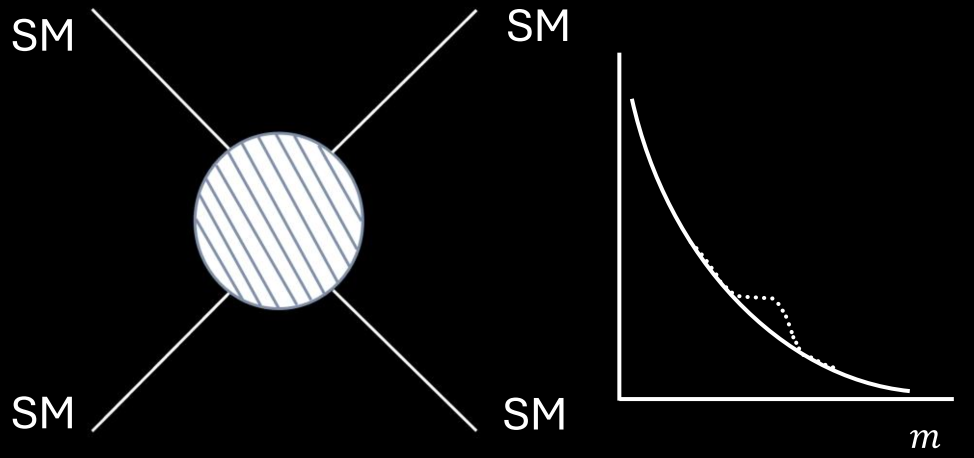




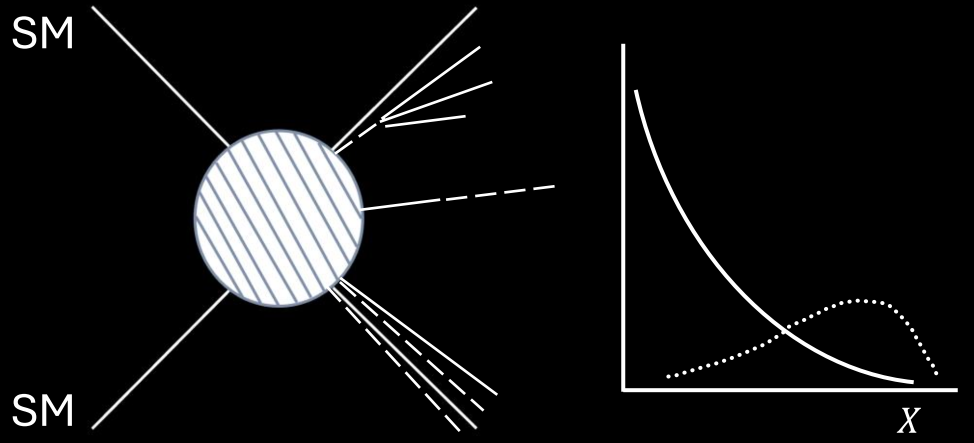
MET+X searches

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



Portal resonances

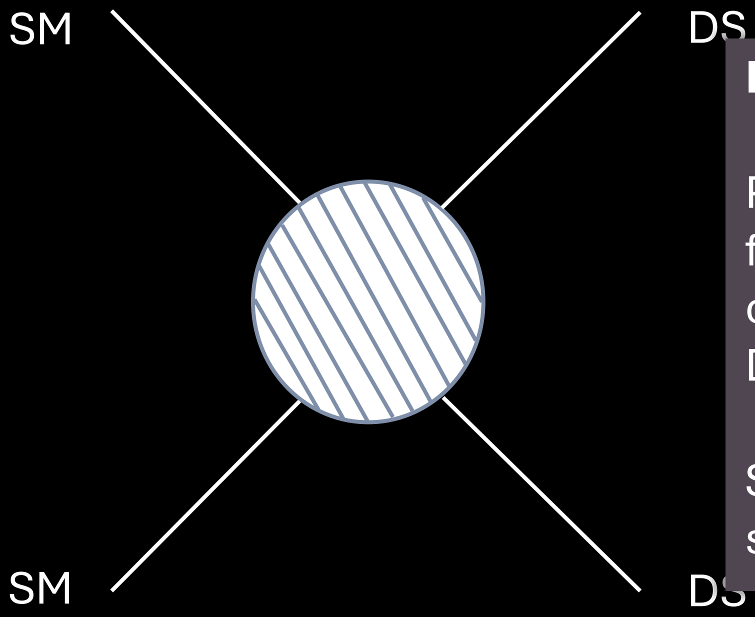
- Known SM processes cross sections are affected by DS
- Search for bumps in mass distributions

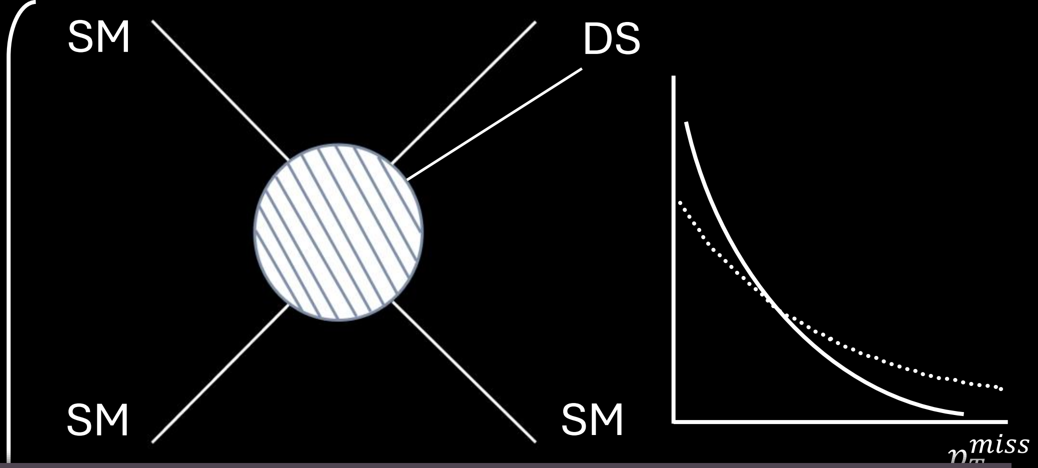


Unconventional signatures

- 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

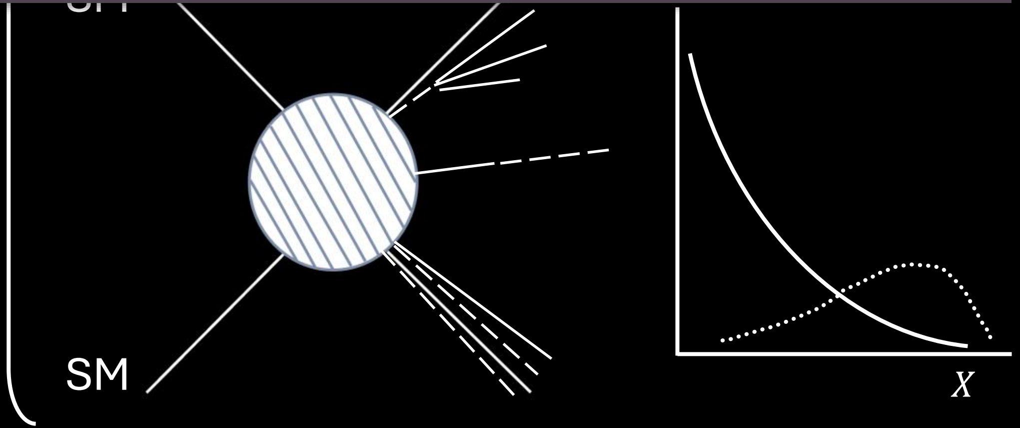
Disclaimer:

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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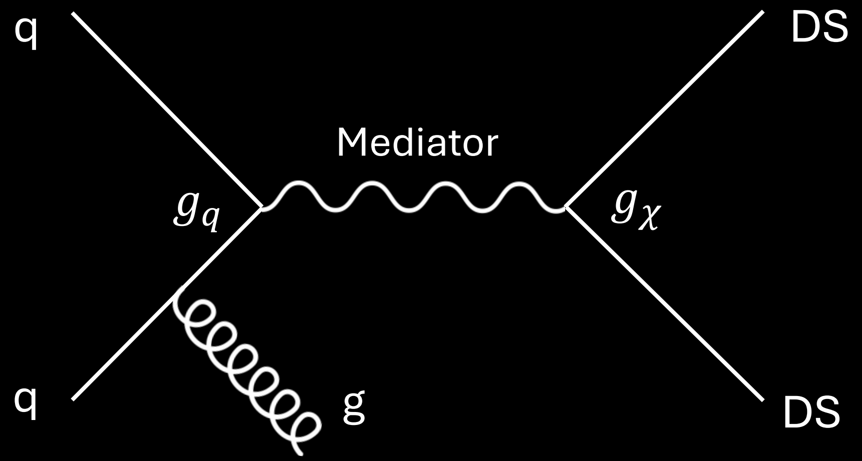
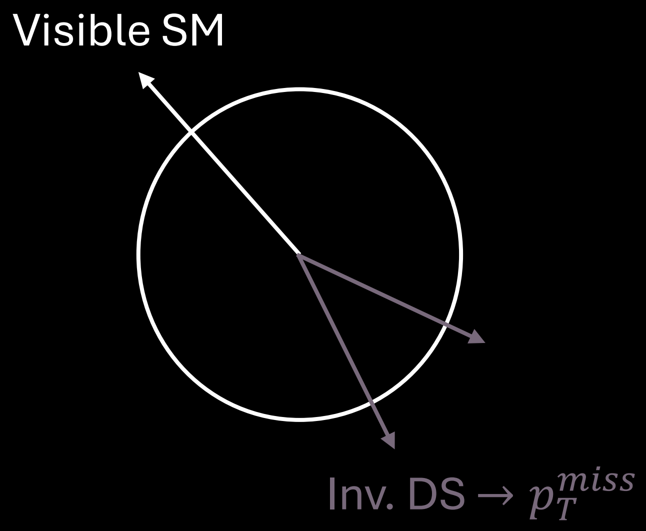
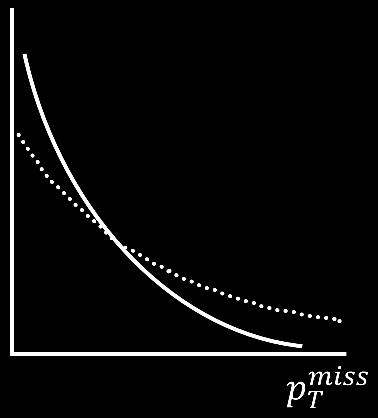
MET+X







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

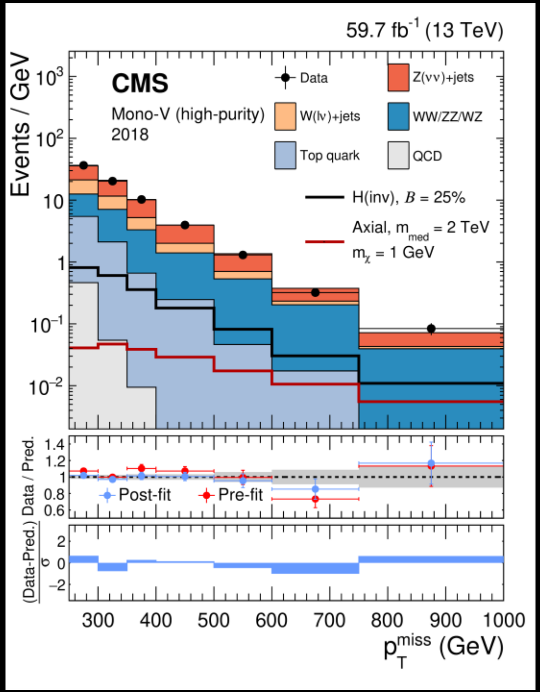
Target

- 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

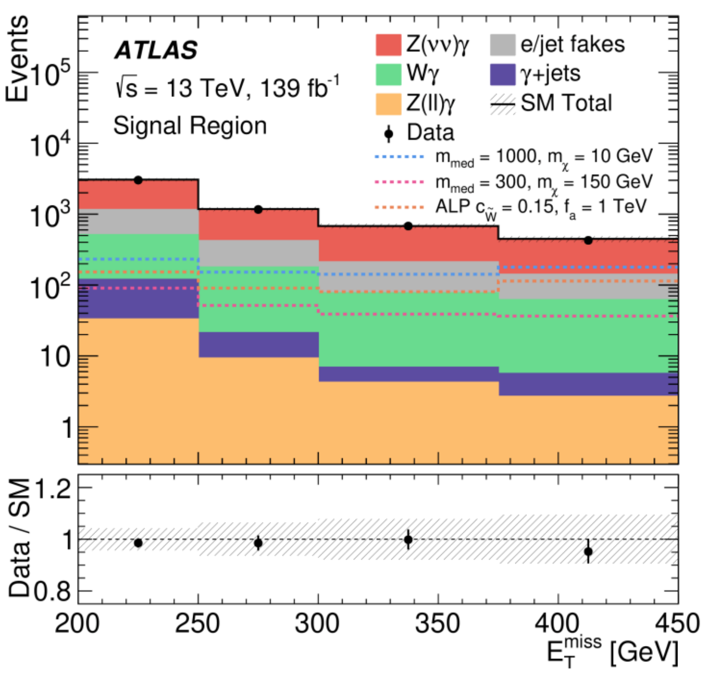
MET+X Results

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

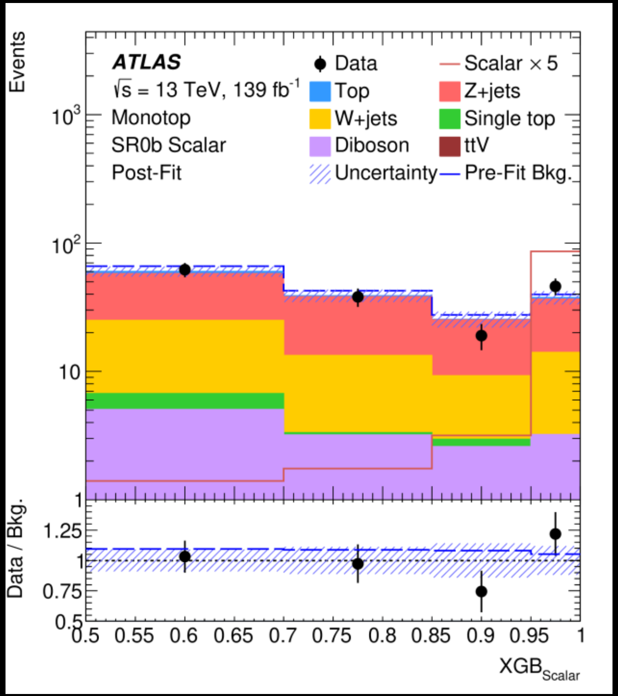
Mono-Jet [1]



Mono-γ [2]



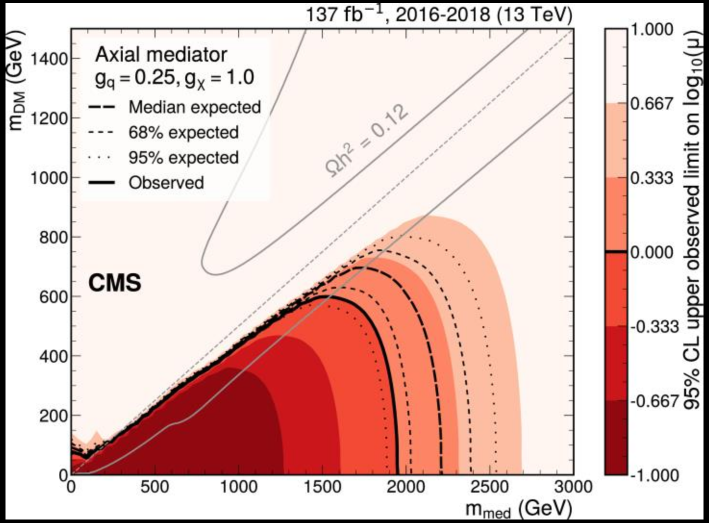
Mono-t [3]

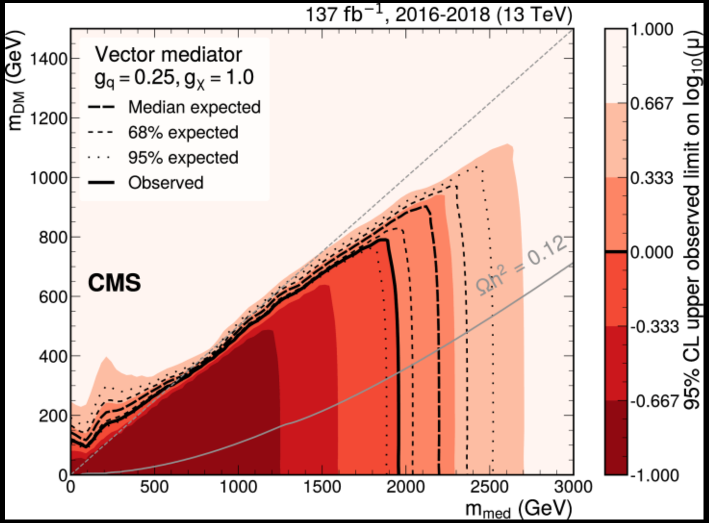


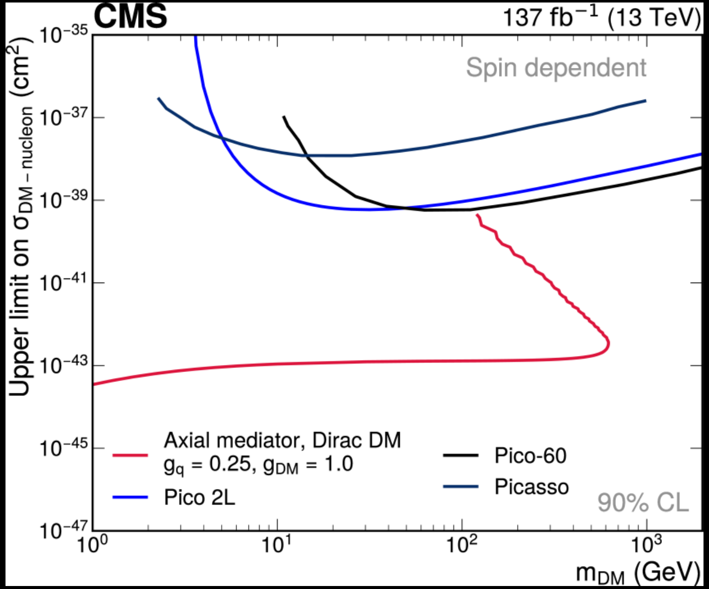
- A few representative examples of the many Run 2 MET+X results from ATLAS and CMS are shown
- Evolution of MET algorithms to improve sensitivity (pile-up mitigation, ML, etc.)
- "Control regions" in data to constrain and/or predict backgrounds
    - Often through simultaneous binned likelihood fits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

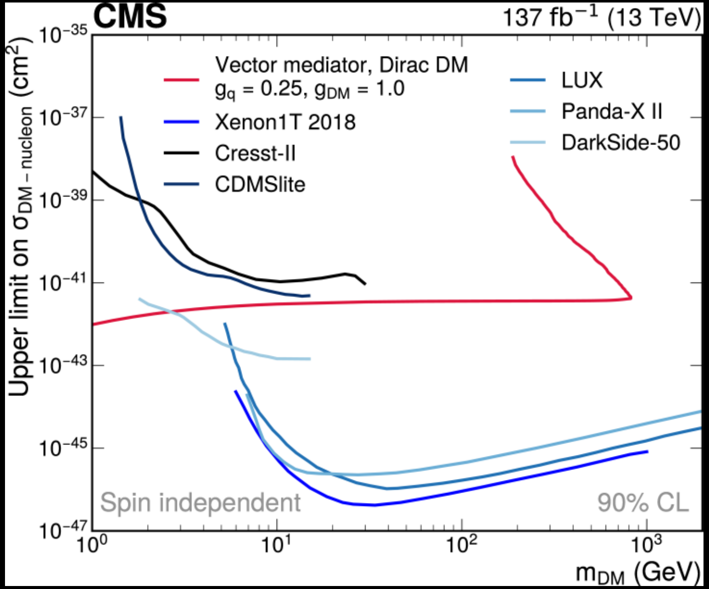
JHEP 11 (2021) 153

Limits from Mono-Jet





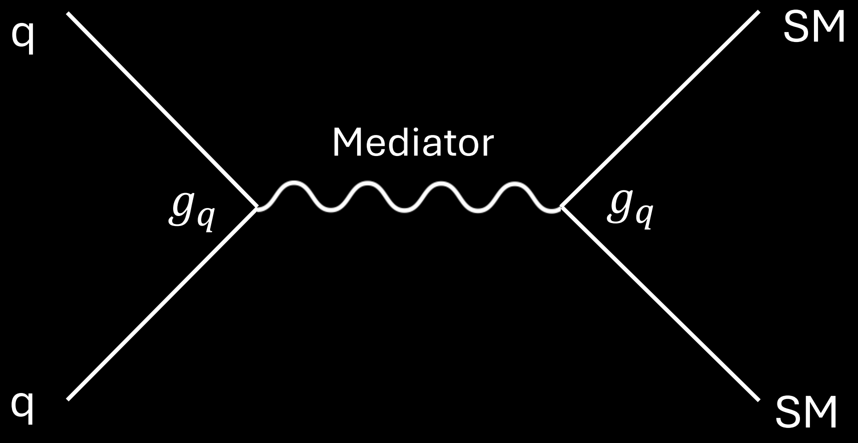


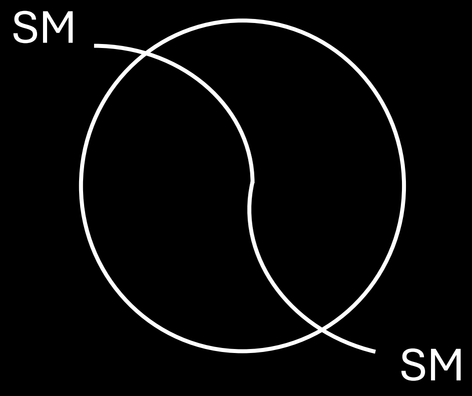


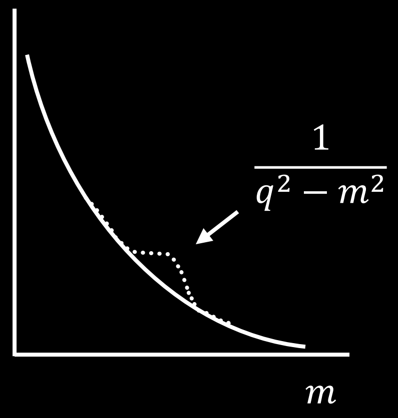
- As an example, the same mono-jet search can be re-interpreted for many DS/DM models
  - Simplified DM models: WIMPs with vector, axial, pseudoscalars, fermion portals
  - $B(H \rightarrow inv)$
  - Leptoquarks & other more complex models

- 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

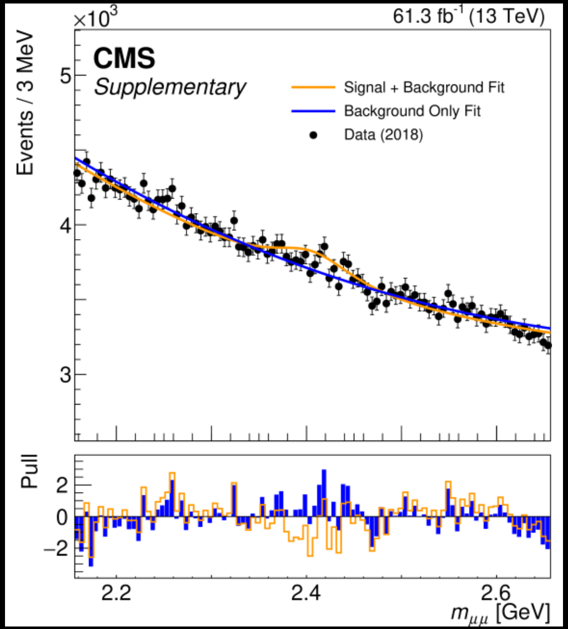
Target

- 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

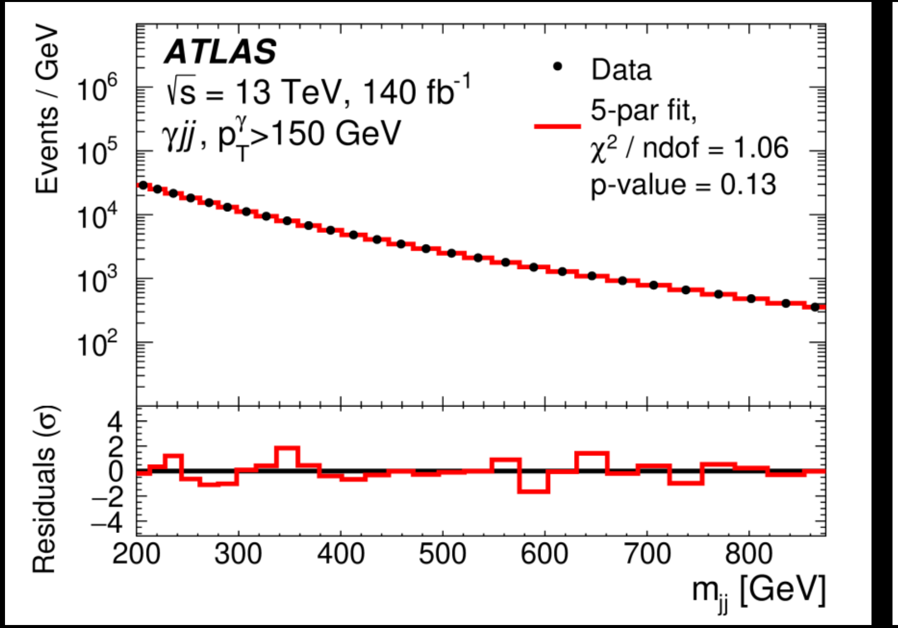
Resonance Searches

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

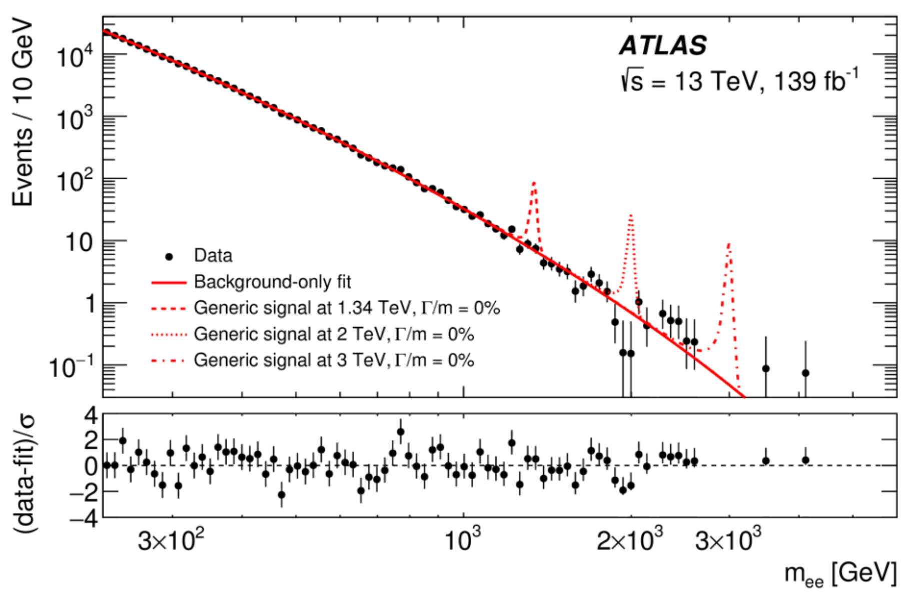
Low-mass Dimuon [1]



Dijet [2]



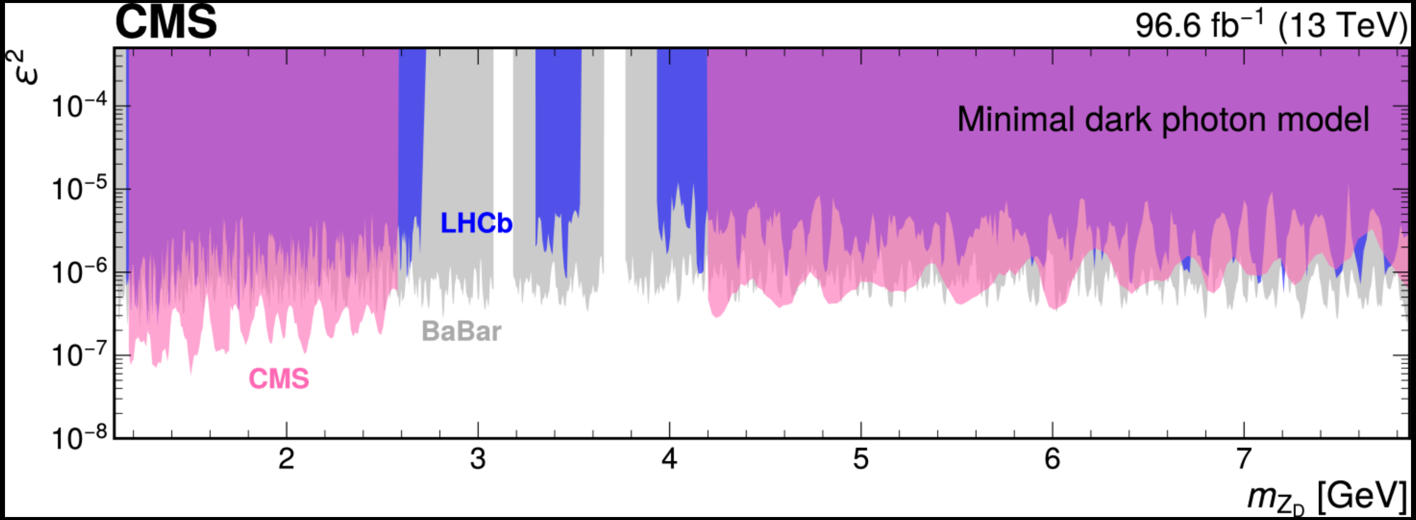
High-mass Dilepton [3]

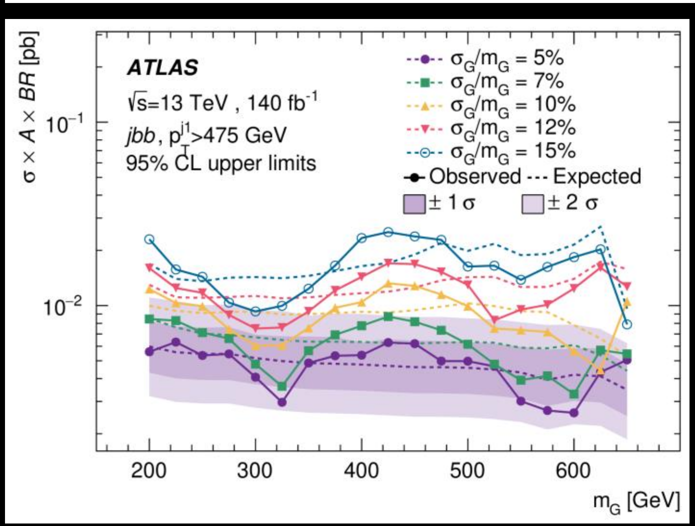


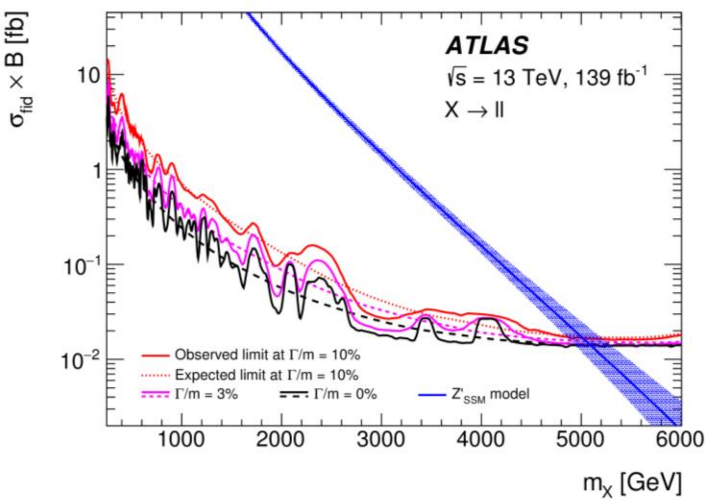
- Target high masses (~TeV) via traditional triggers
- Target low masses (~GeV) via production of another particle to trigger on (e.g. photon + 2 jets)
- Enhance sensitivity to low masses via **high-rate ("scouting") triggers** that select a larger fraction of signal-like events, but record less event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

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

Results from (some) Resonance Searches



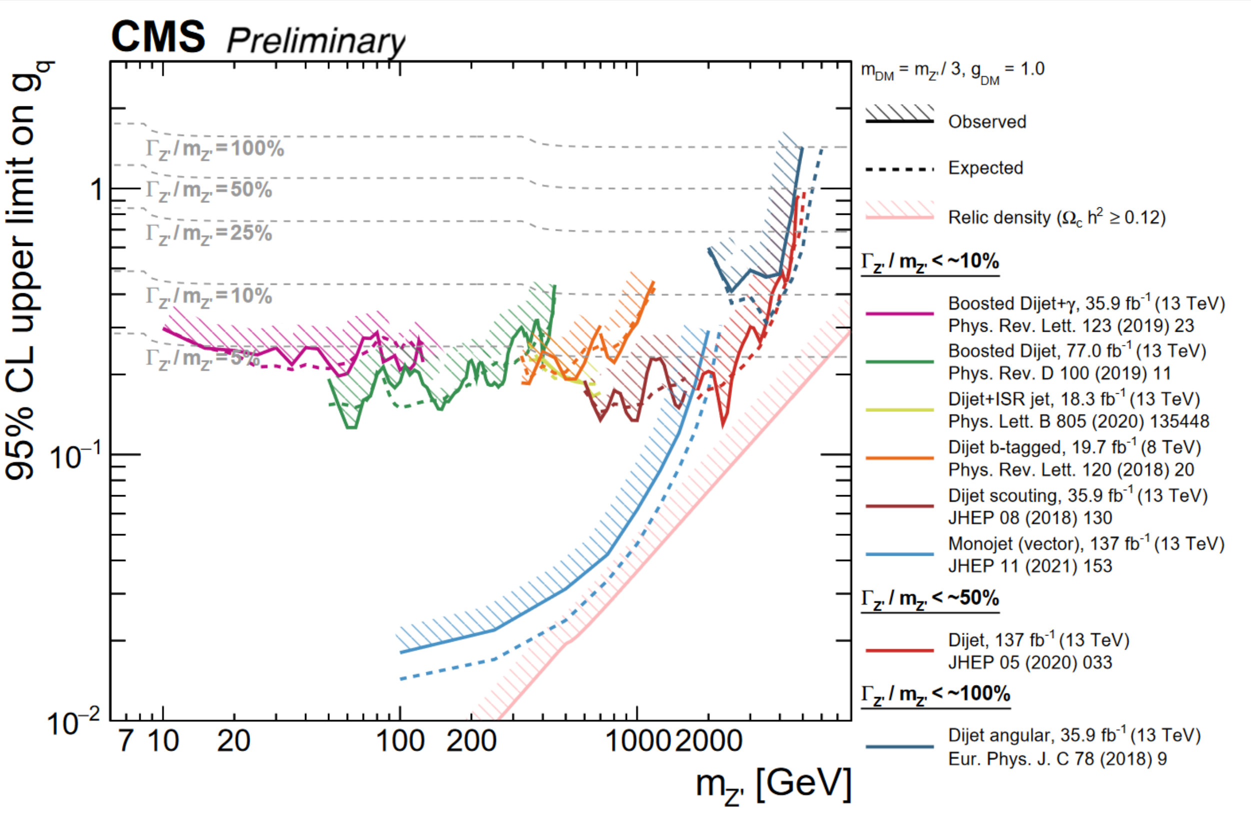


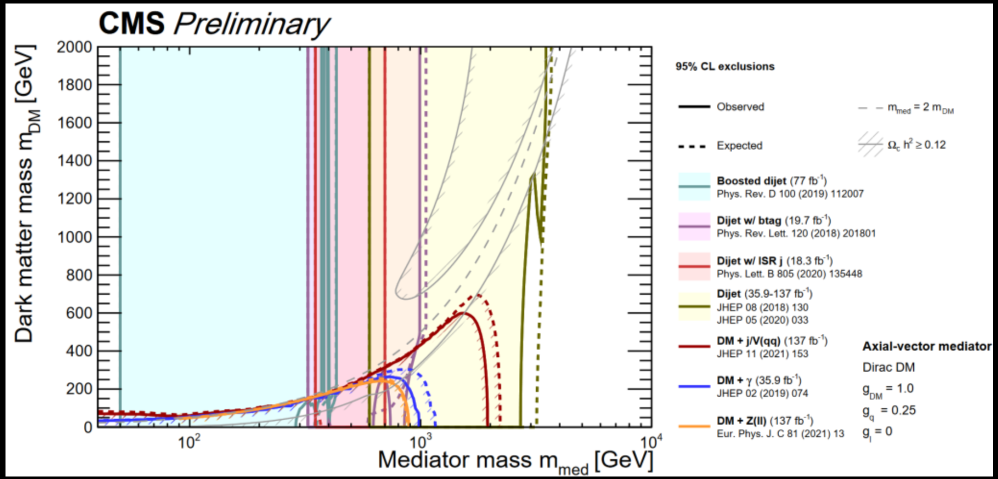


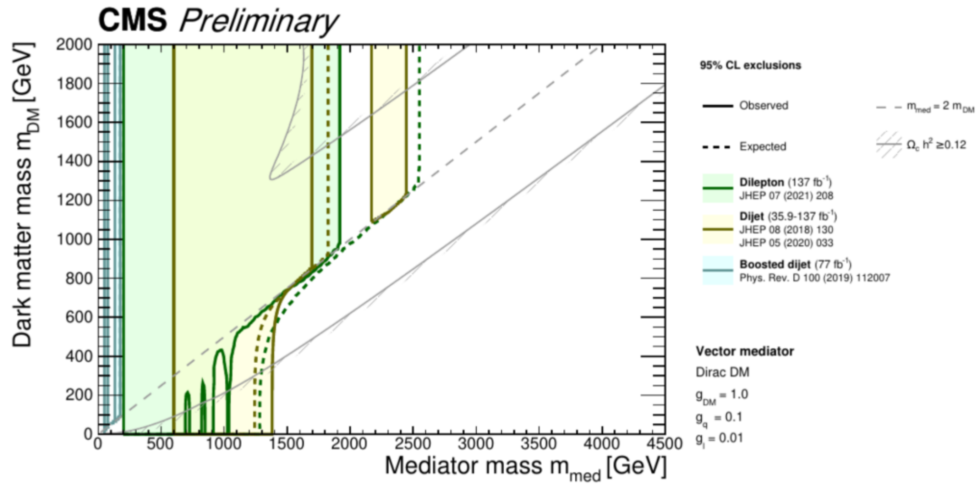
- Place limits based on the mass of the resonance and the cross section
- Dark photon model commonly used for benchmarking with other experiments, relies on mixing parameter ϵ between the $U(1)_D$ and SM hypercharge
- Model independent limits can be placed on simple Gaussian bumps at different m values,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

Ground Covered

EXO-CMS Summary Plots

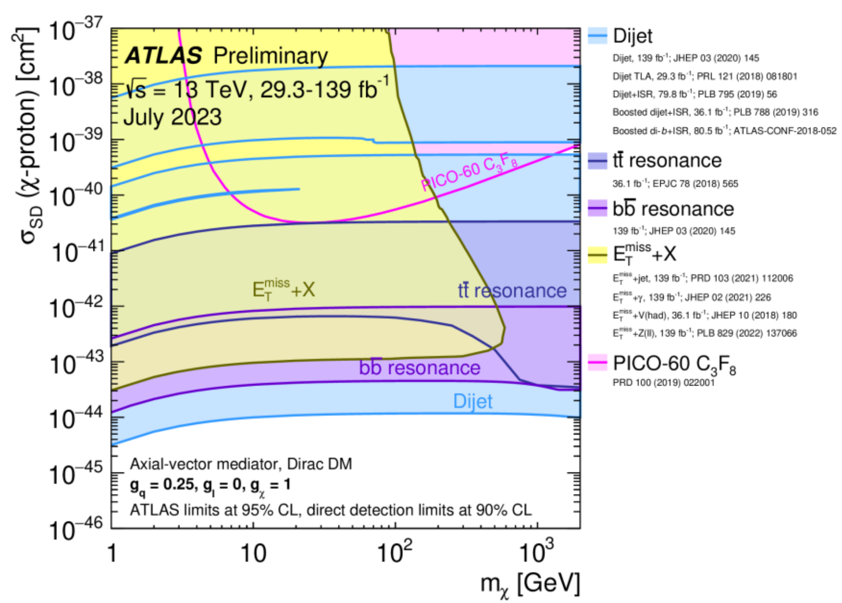


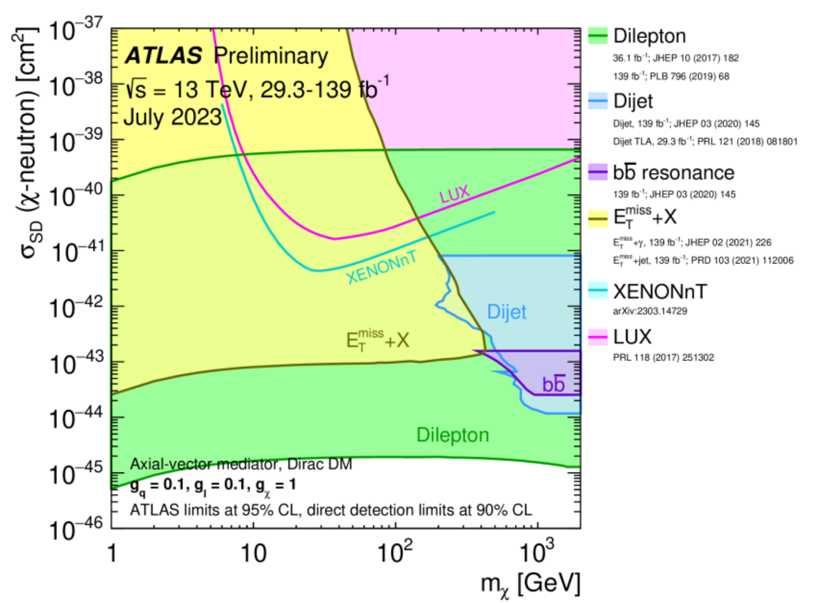


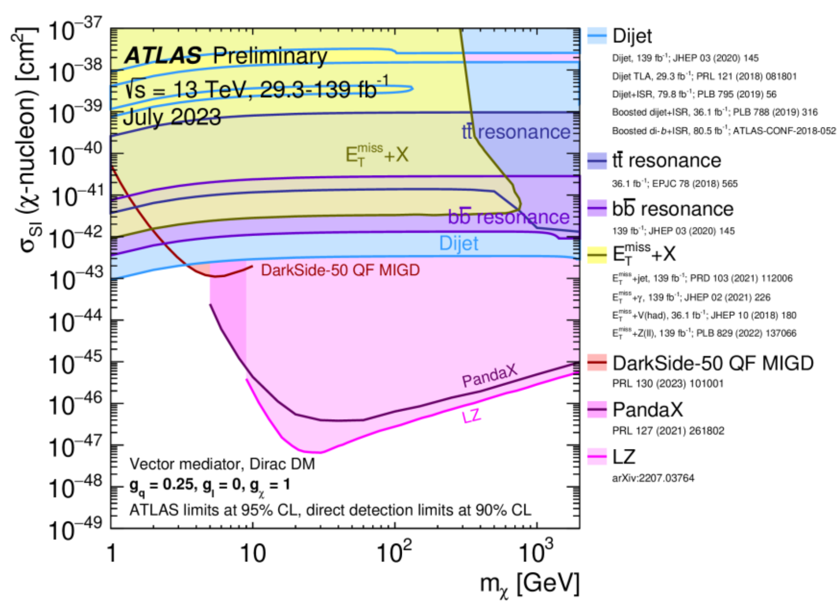


MET+X and resonance searches have excluded large phase space of simplified DM models like WIMPs throughout Run 1 and 2 of the LHC

Colliders and Direct Detection



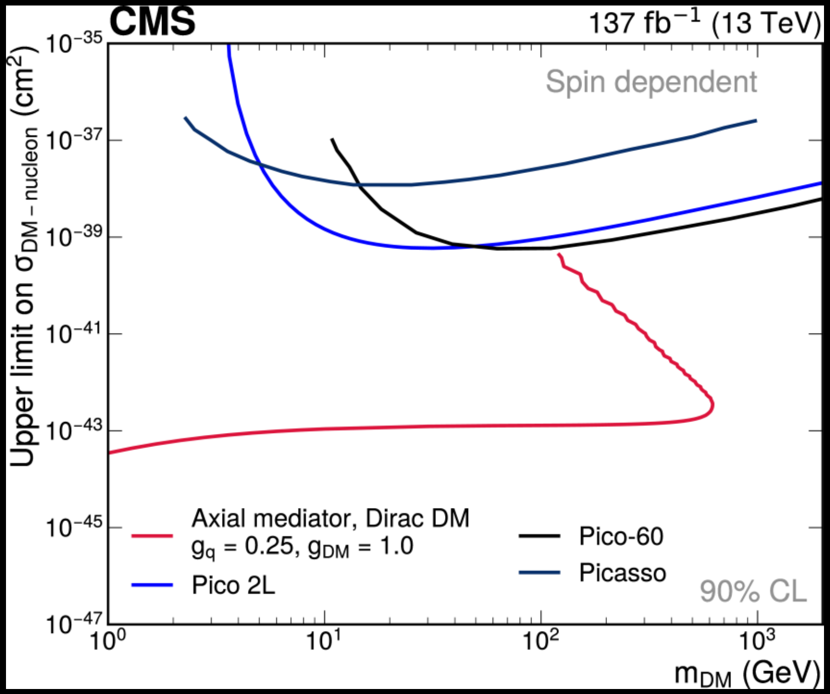




- Important complementarity between colliders and direct detection experiments for simplified DM models
  - Spin dependence
  - Nature of mediator
  - Nature of dark matter particle(s)

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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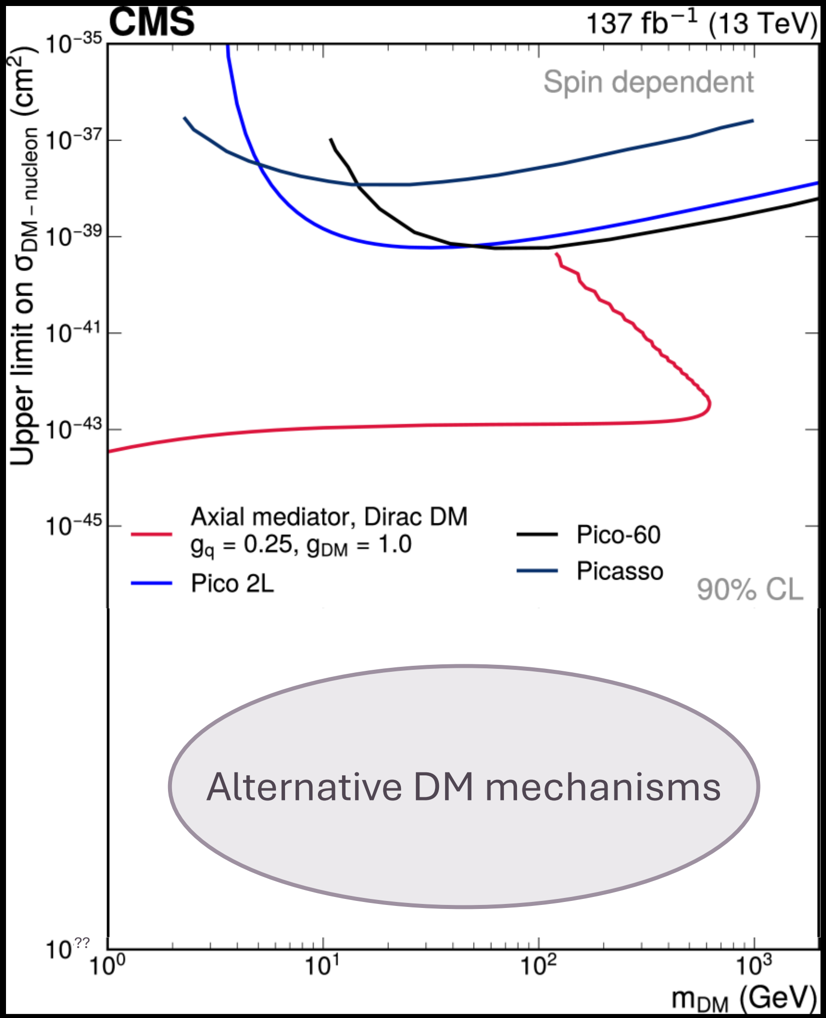
  - Will be re-iterated with Run 3 data (ongoing!)

- 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)

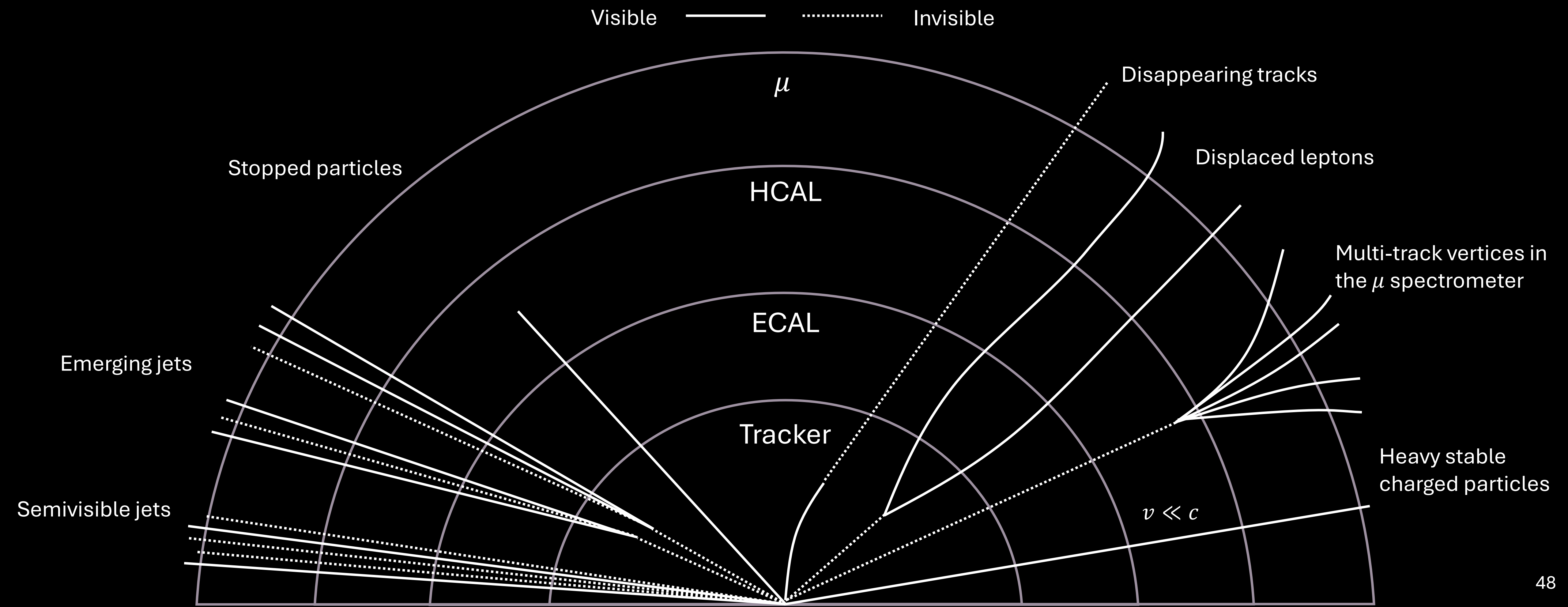
- Give rise to new types of signatures that we don't typically reconstruct at colliders
  - We would not have seen these objects at all
  - Would have evaded all previous constraints



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

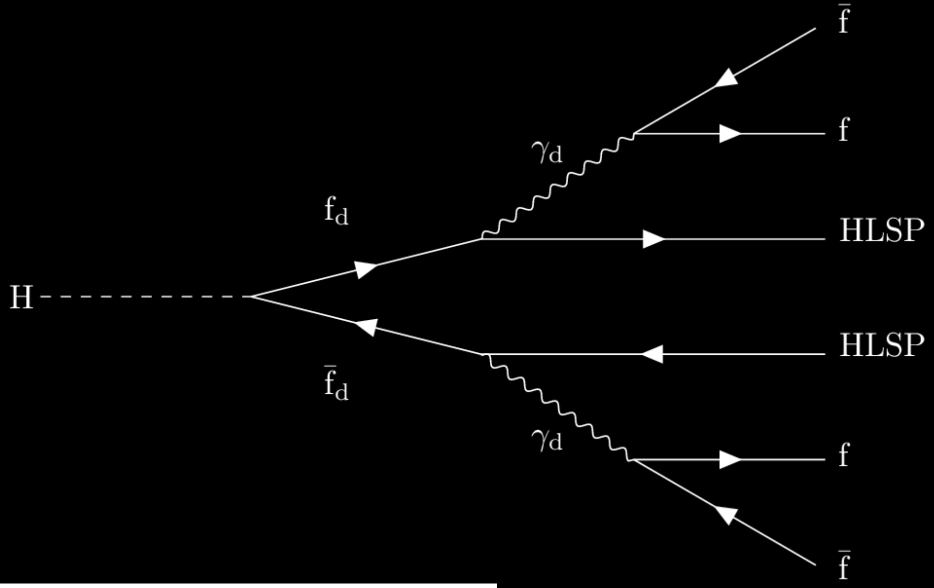
- New offline reconstructions:
  - Looking at physics objects that may not conform to traditional, SM-like objects

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

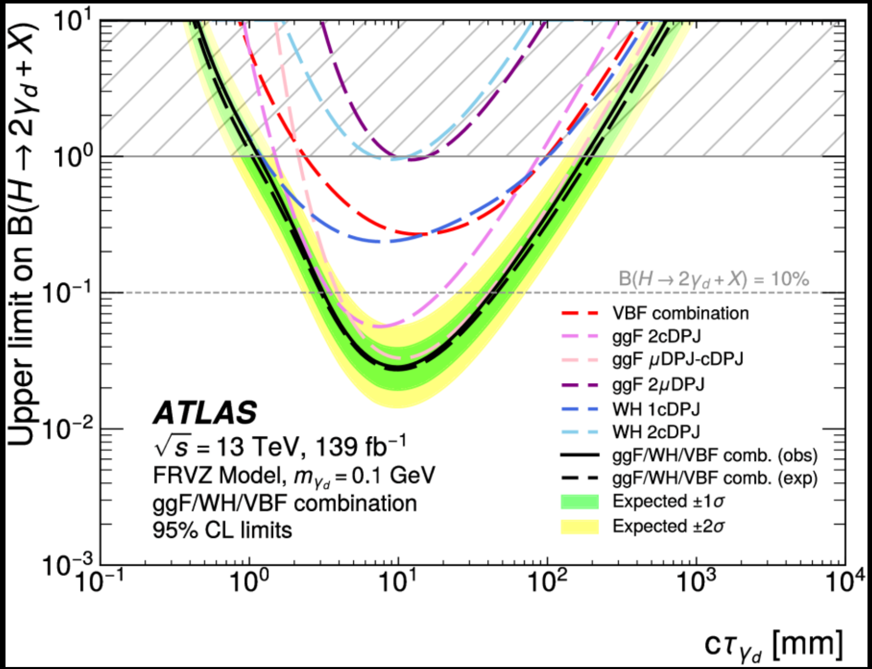
arXiv:2311.18298

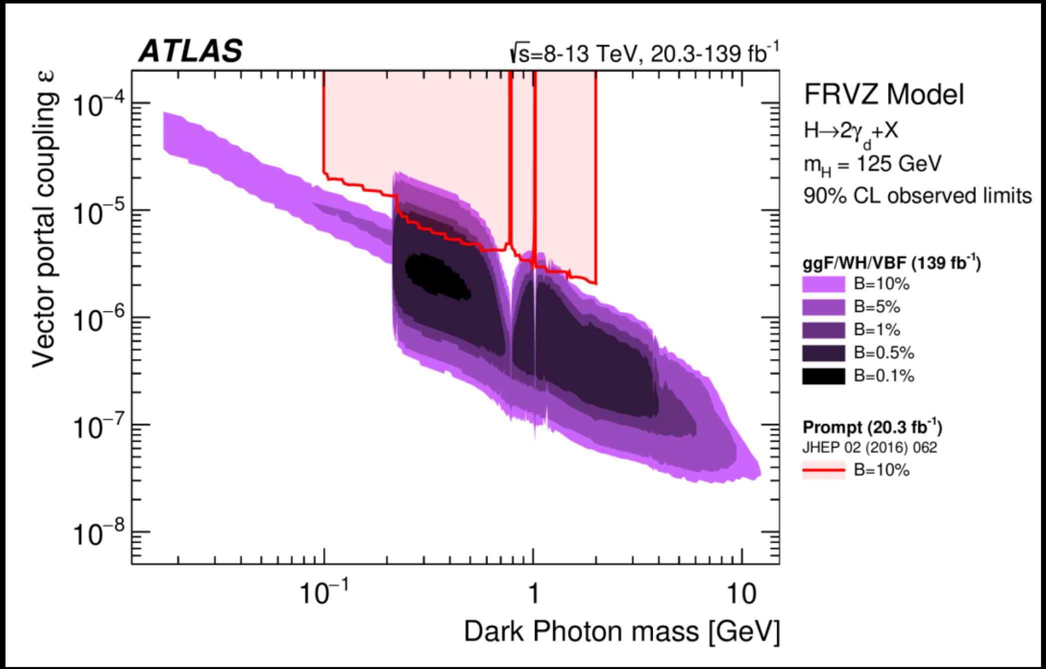
Long Lived Dark Photons

- 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

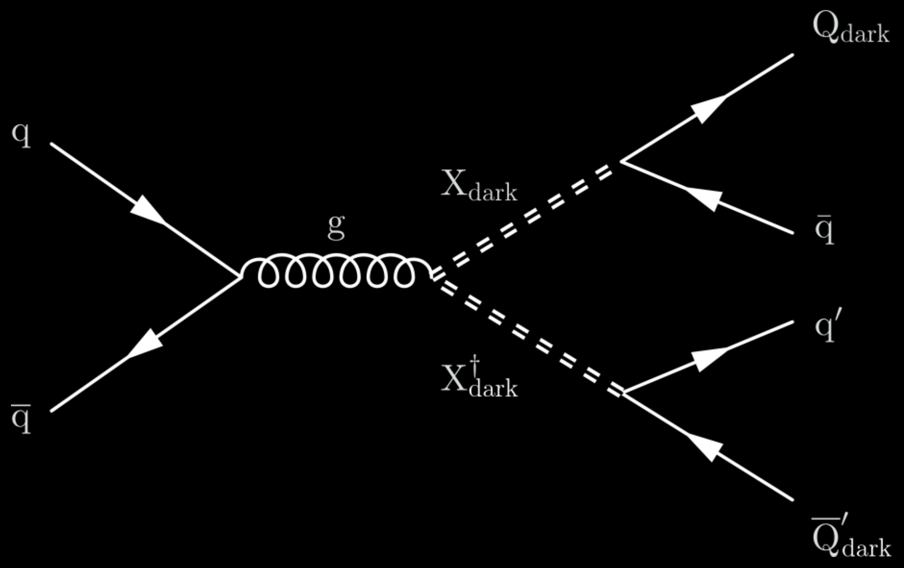


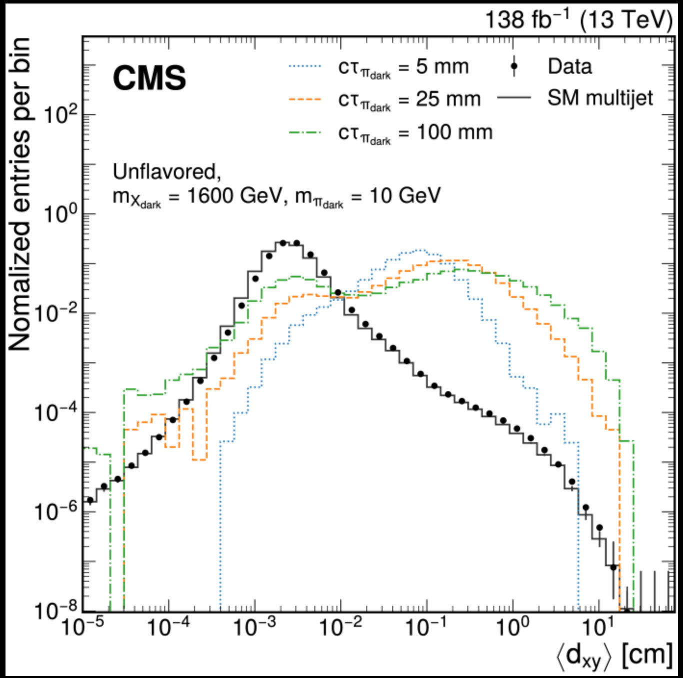


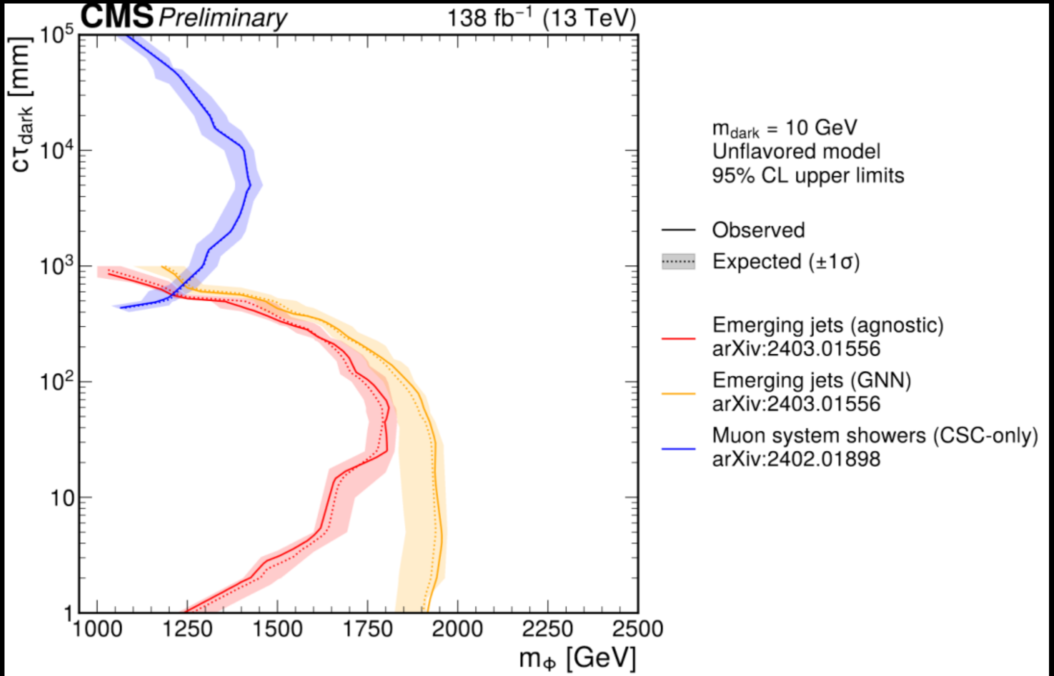
arXiv:2403.01556

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)



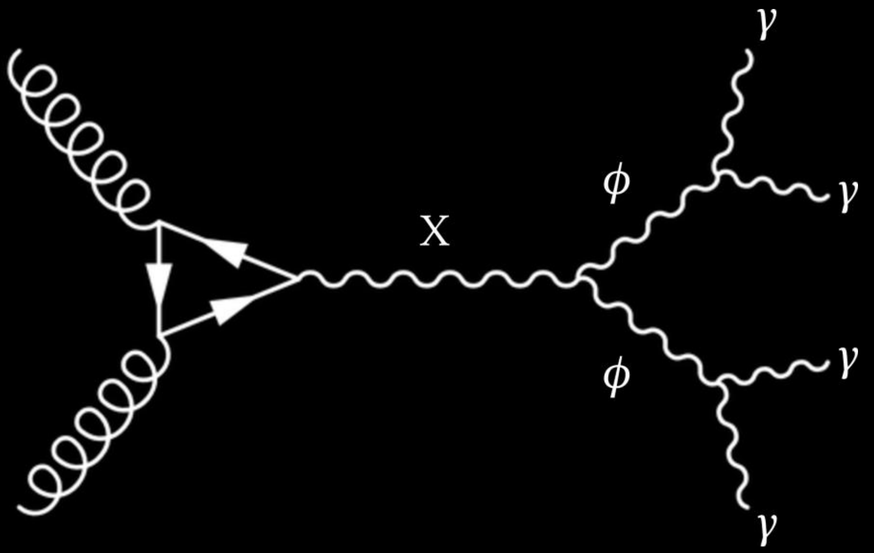


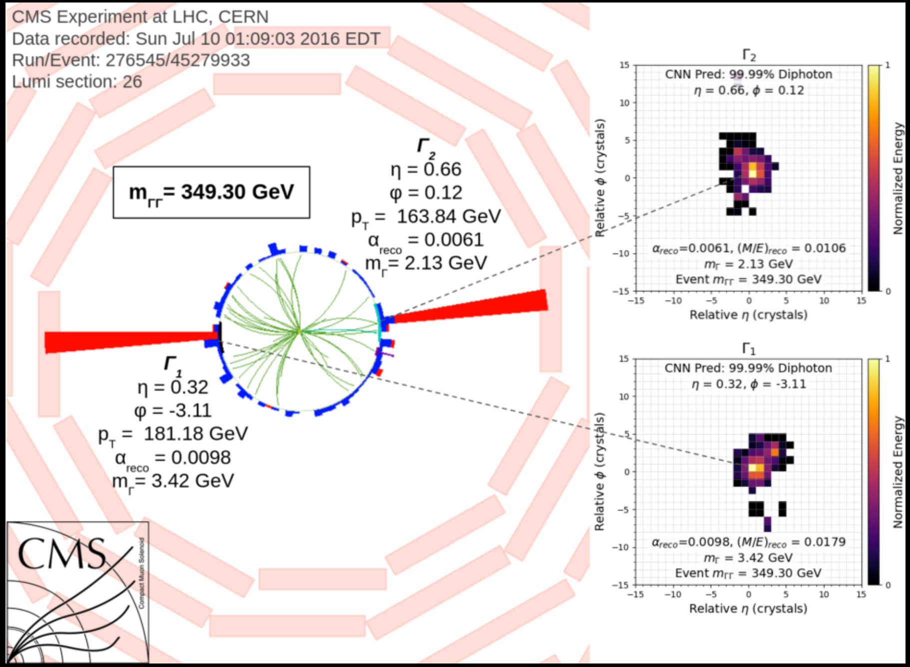


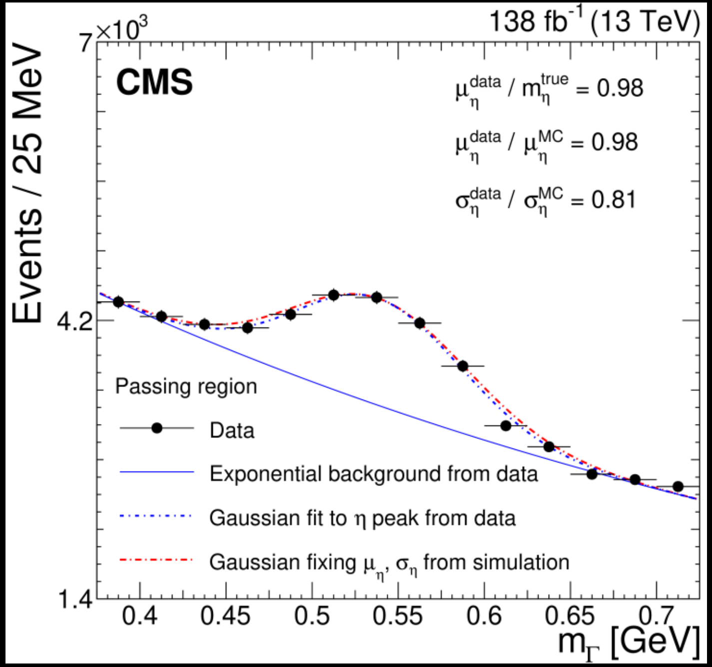
arXiv:2405.00834

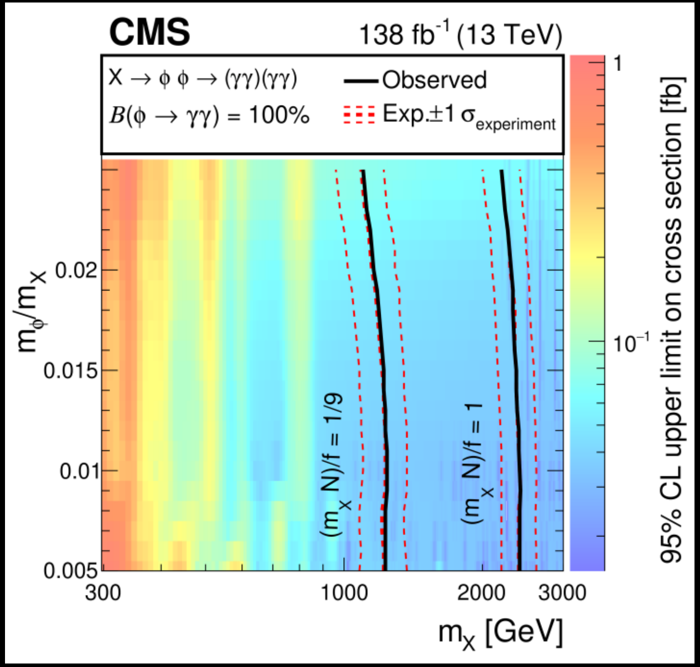
Merged Diphotons

- 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









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