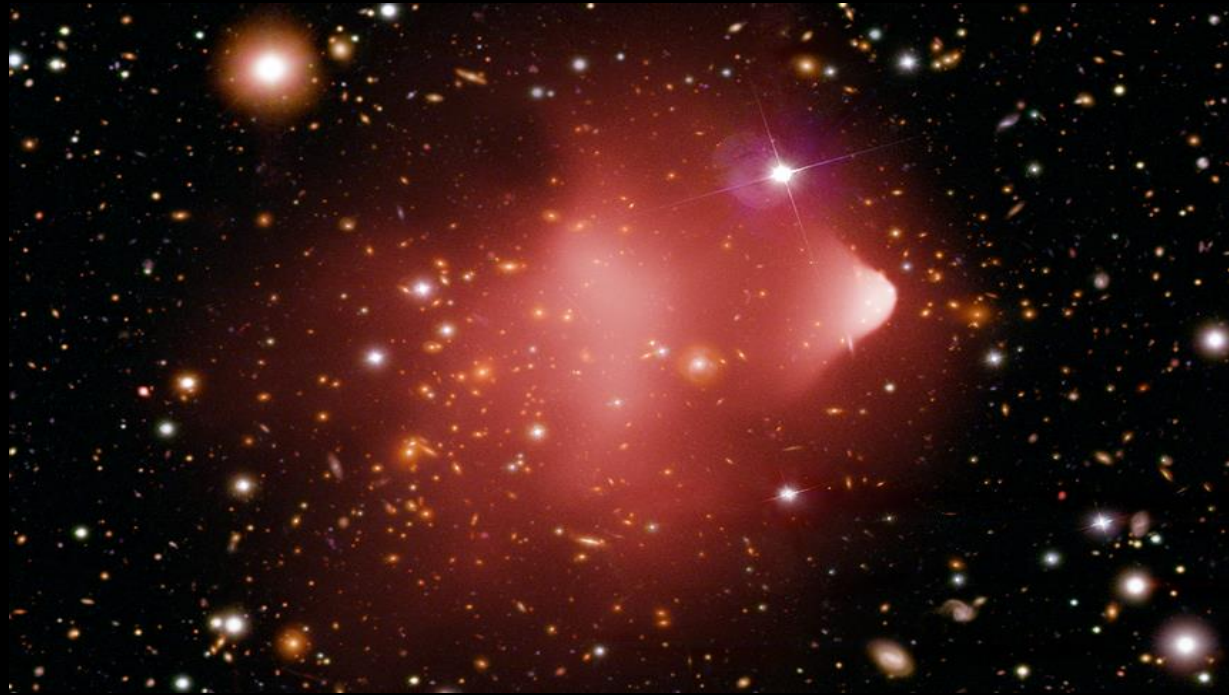


# Dark Matter and Dark Sectors at the LHC

*Luca Lavezzo*

*On behalf of the Particle Physics Collaboration at MIT*



## Unexplained phenomena

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

...

## Experimental tensions (?)

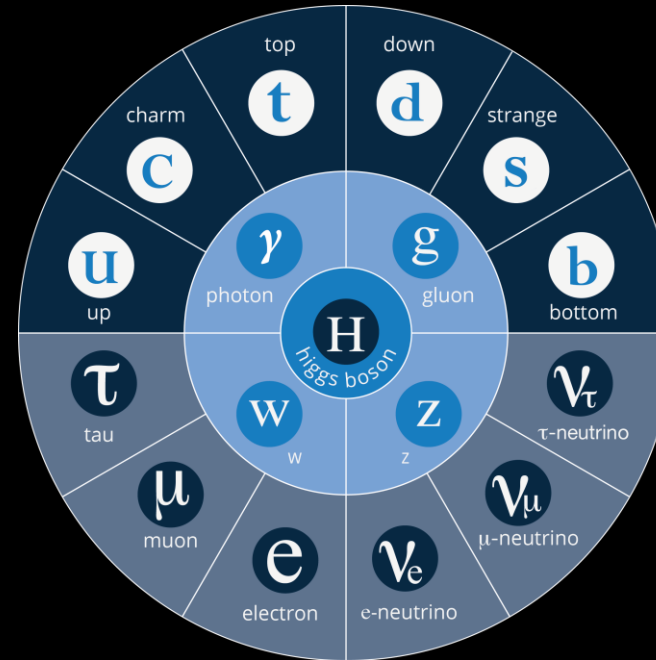
- $(g - 2)_\mu$
- $m_W$
- $R(D^*)$
- $X17$

...

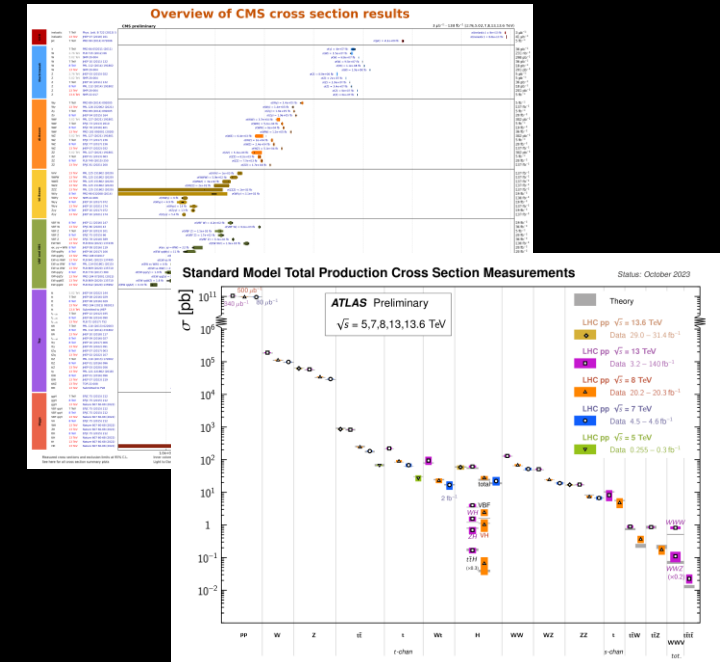
## Fine-tuning problems

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

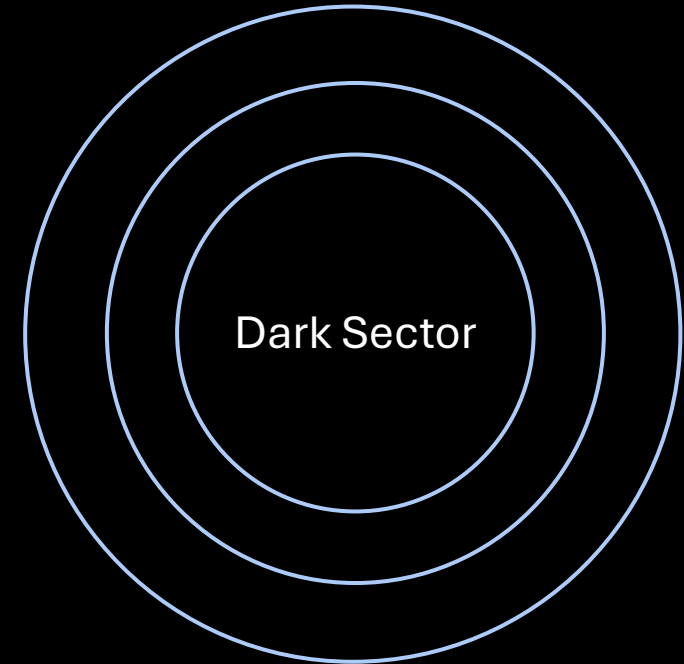


**Dark sectors (DS)** can address any of these problems

- 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

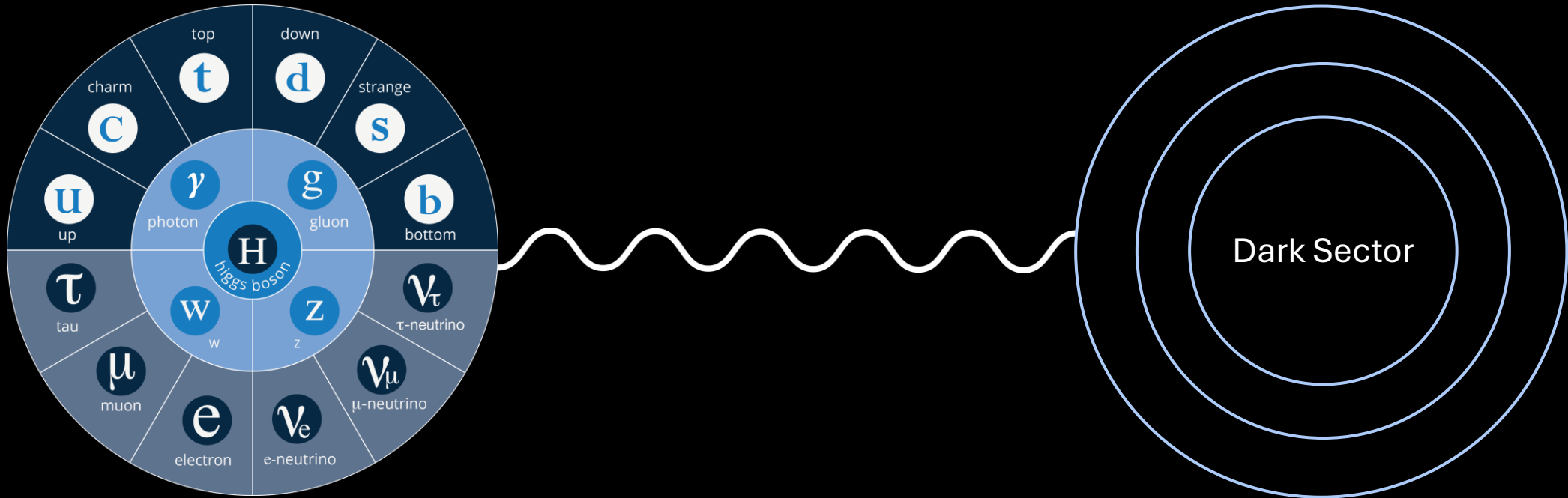
No hints about any details of the DS!

**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

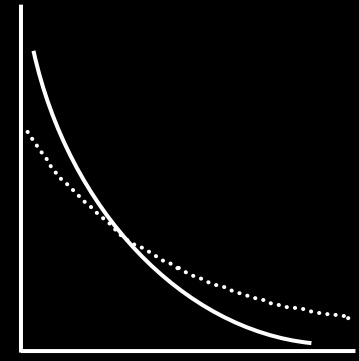
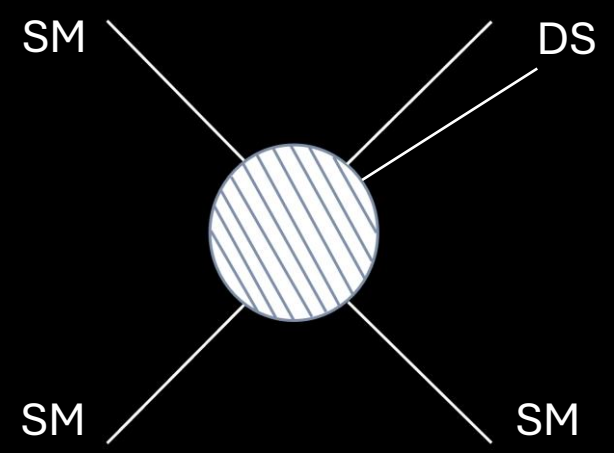
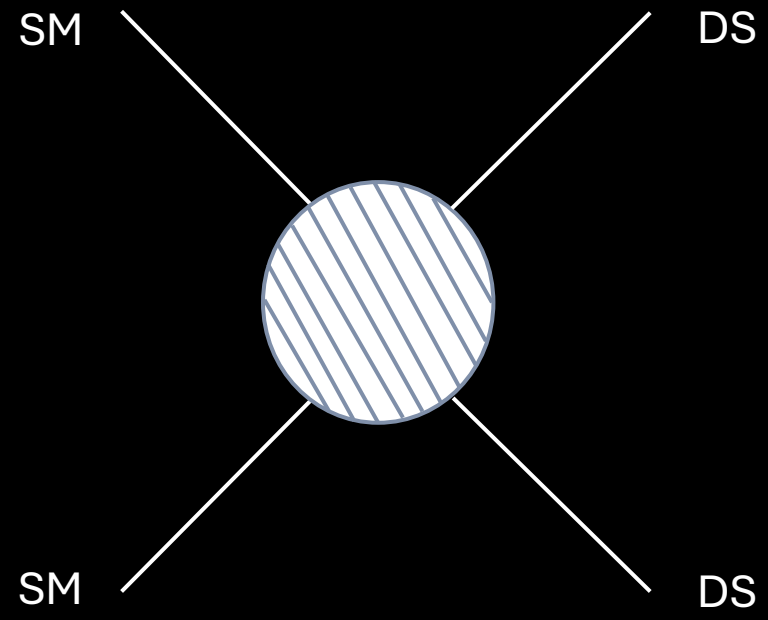


Many portals within direct reach, others can show up at lower energies due to quantum mechanical mixing



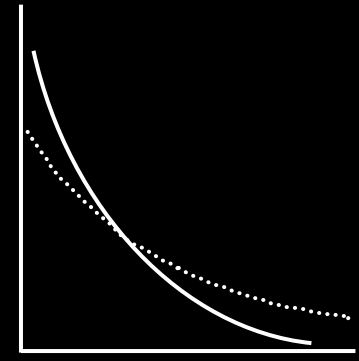
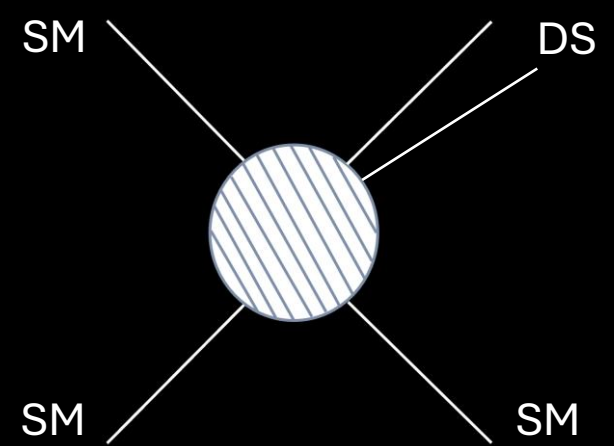
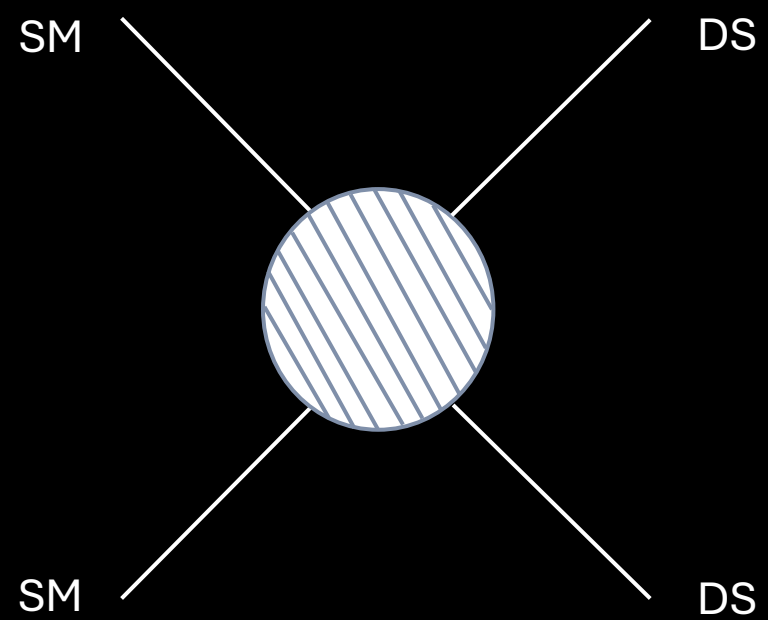
**How can we probe this at colliders?**

Dark Sectors at colliders



MET+X searches

## Dark Sectors at colliders



MET+X searches

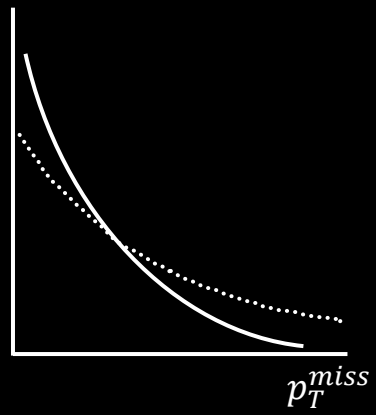
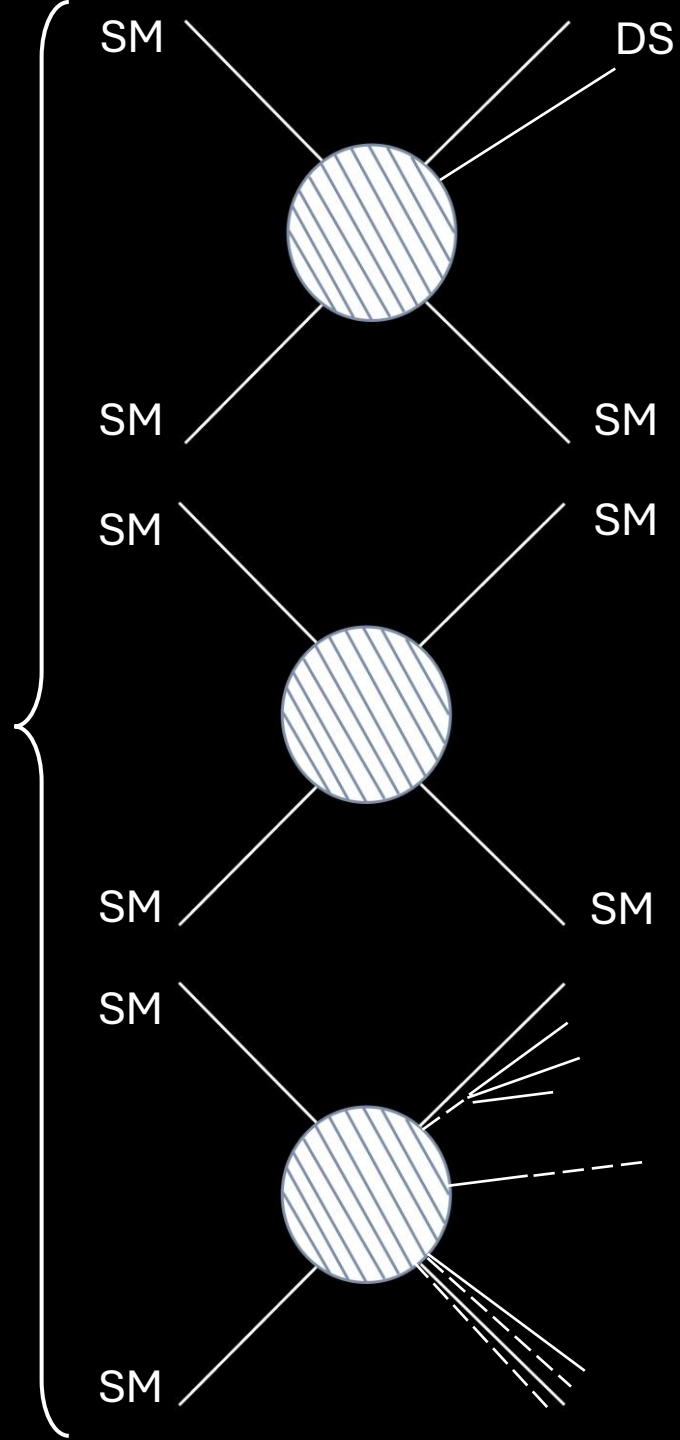
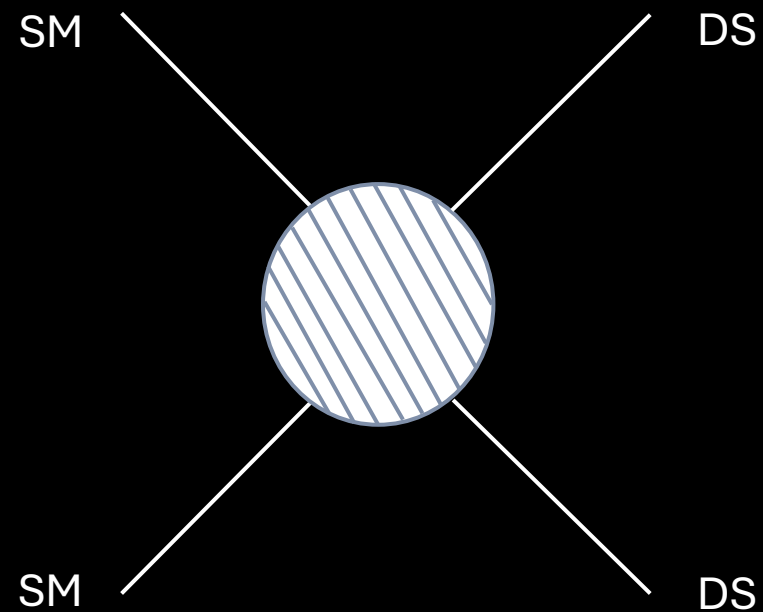


First approach in post-Higgs era

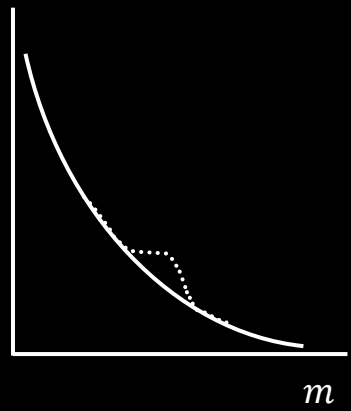
- MIT heavily involved in several flagship MET+X searches

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

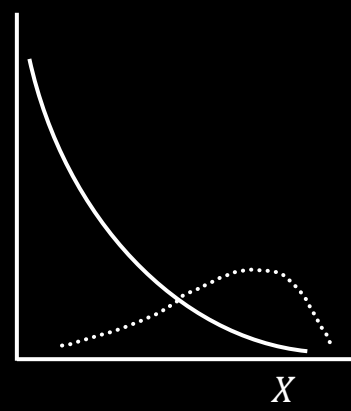
# Dark Sectors at colliders



MET+X searches

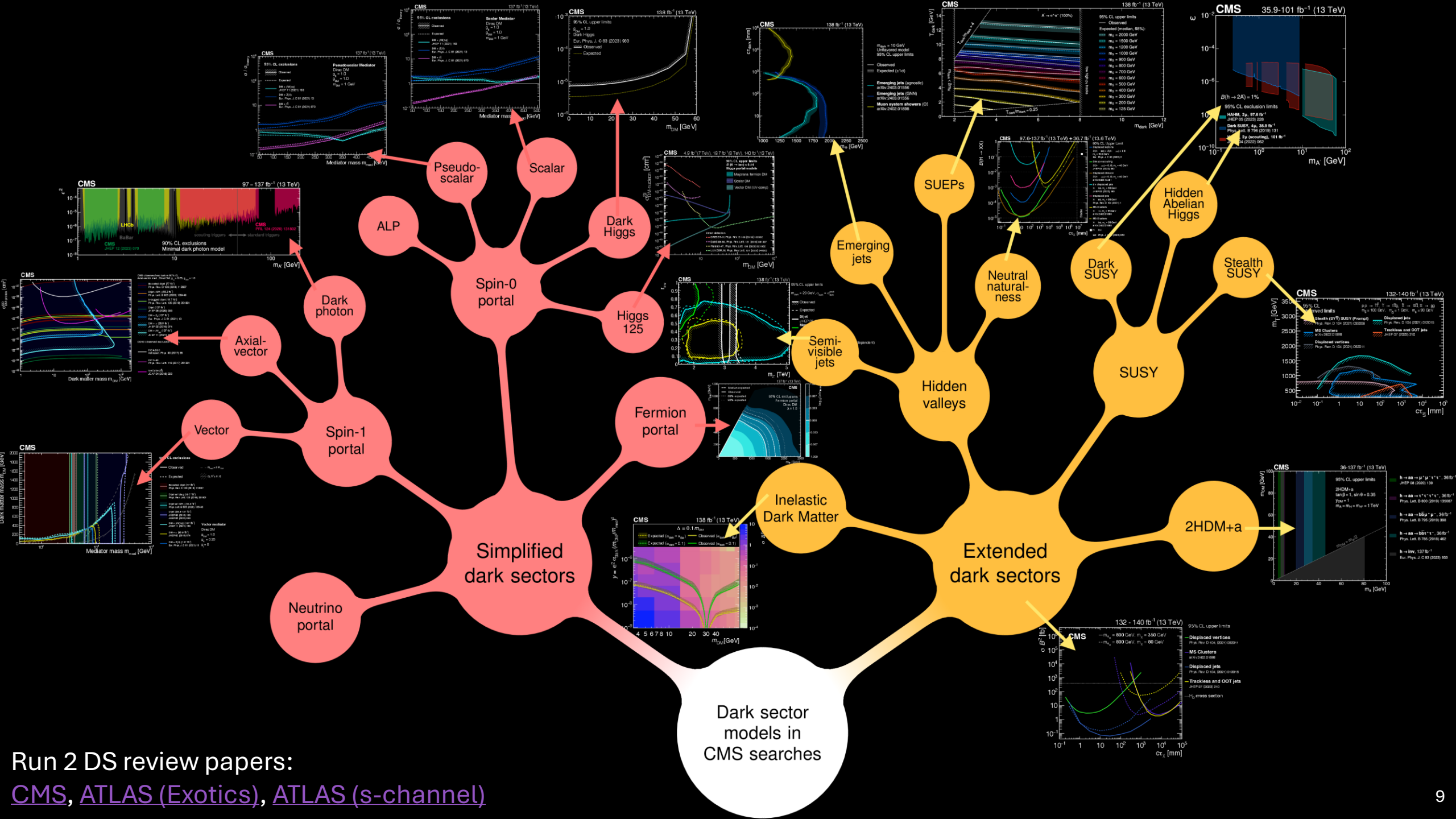


Portal resonances

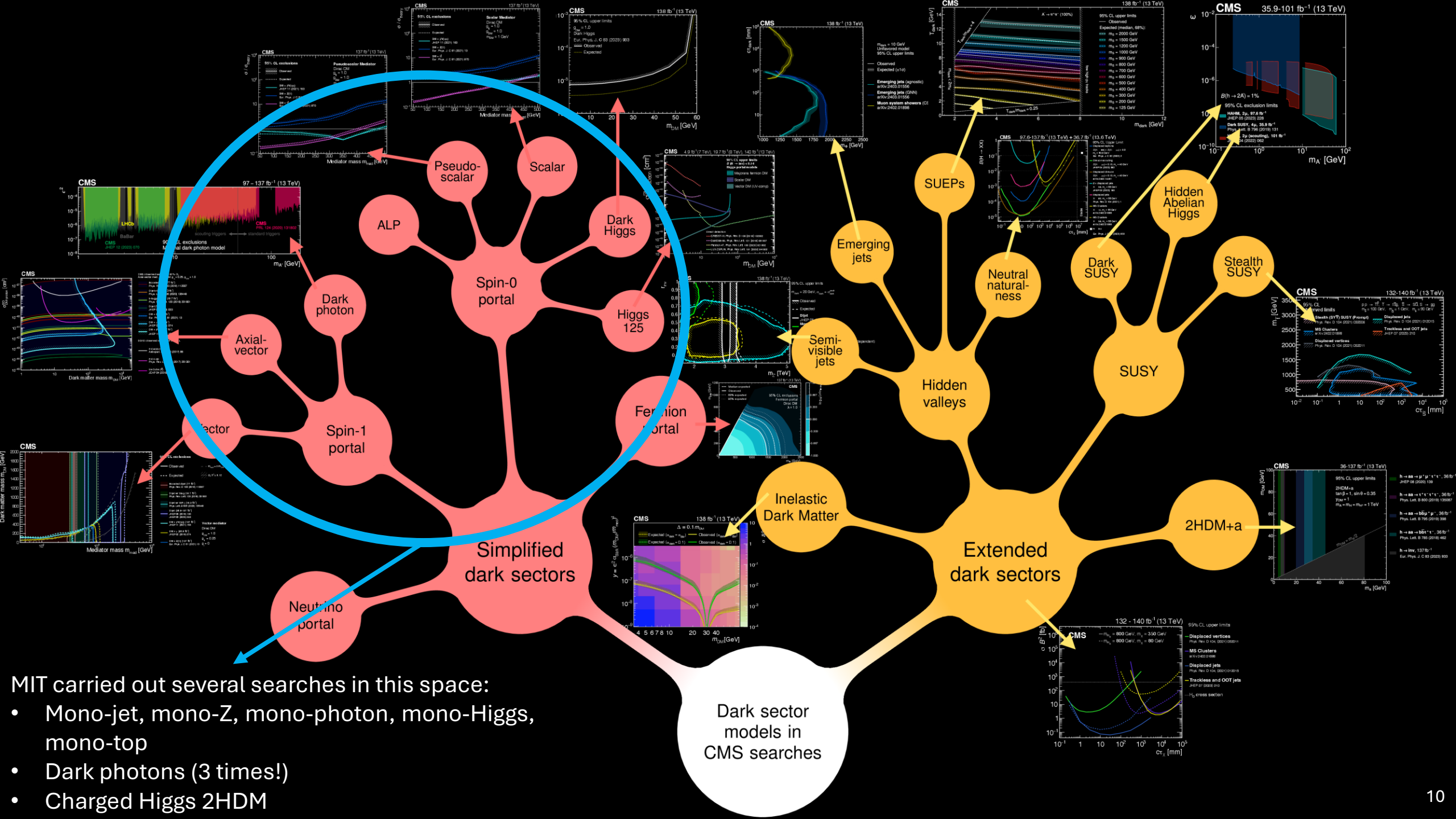


Unconventional signatures





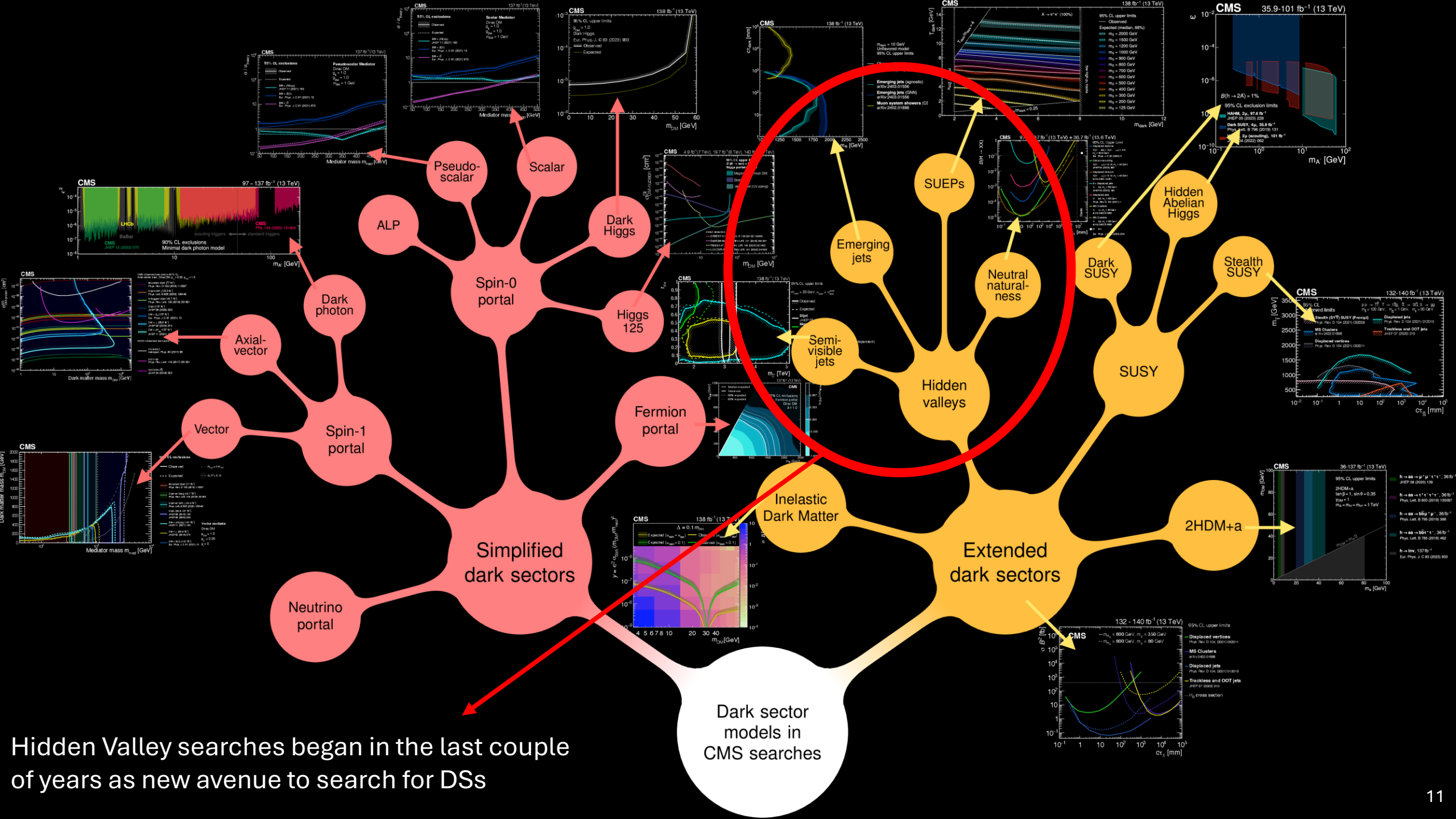
Run 2 DS review papers:  
 CMS, ATLAS (Exotics), ATLAS (s-channel)



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

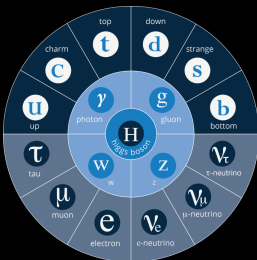
Dark sector models in CMS searches



# Hidden Valleys

Standard Model

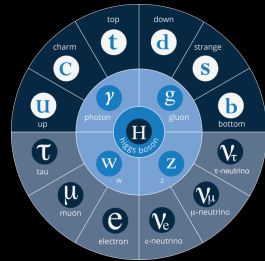
Hidden Valley



  $SU(N_{dark\ color})$

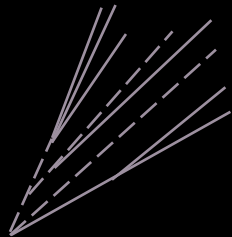
# Why Hidden Valleys?

Standard Model



Hidden Valley

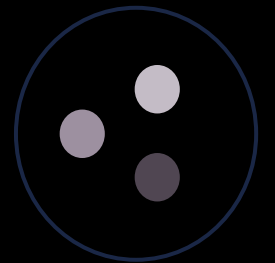
  $SU(N_{dark\ color})$



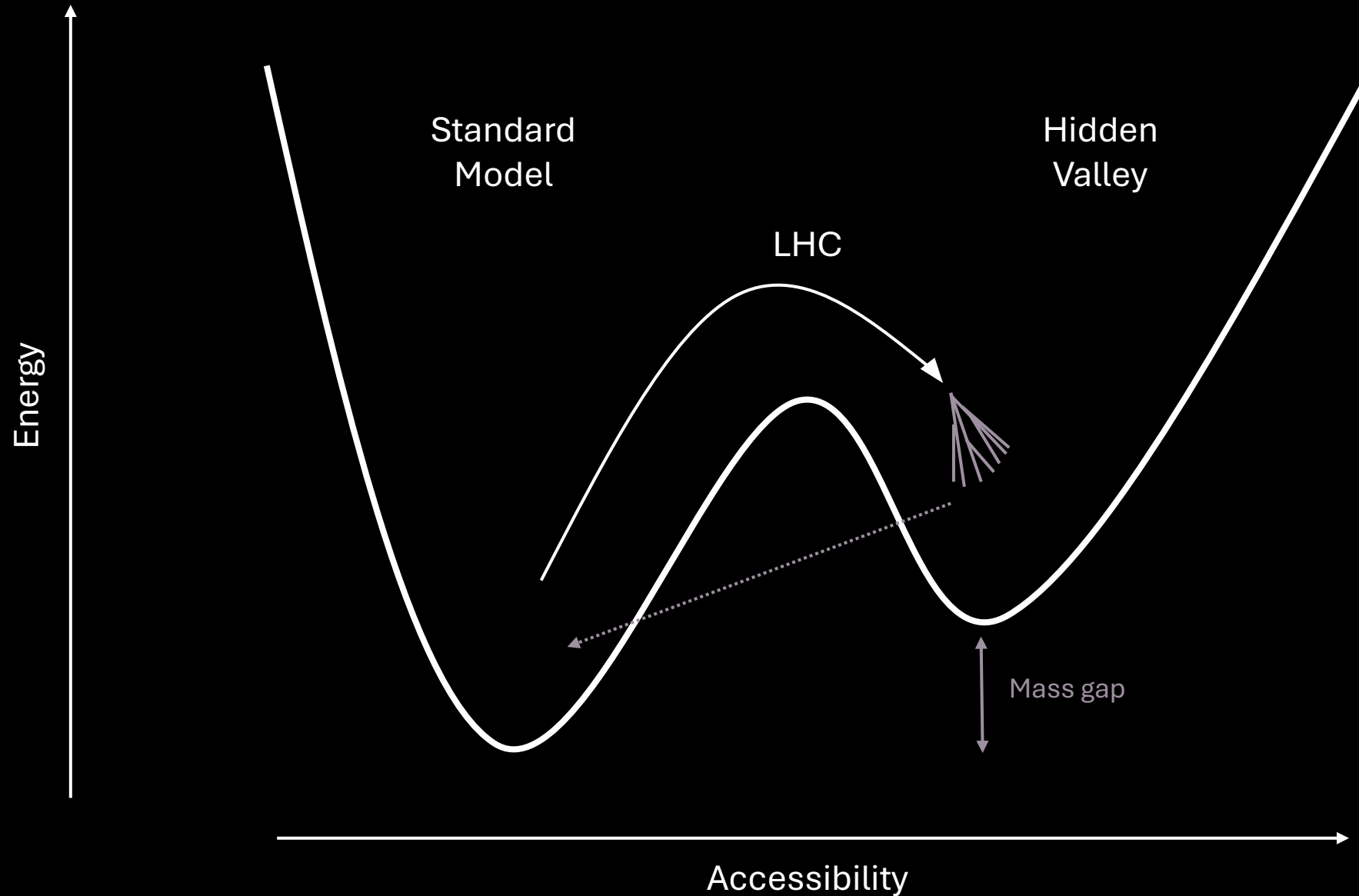
Rich phenomenology at colliders!

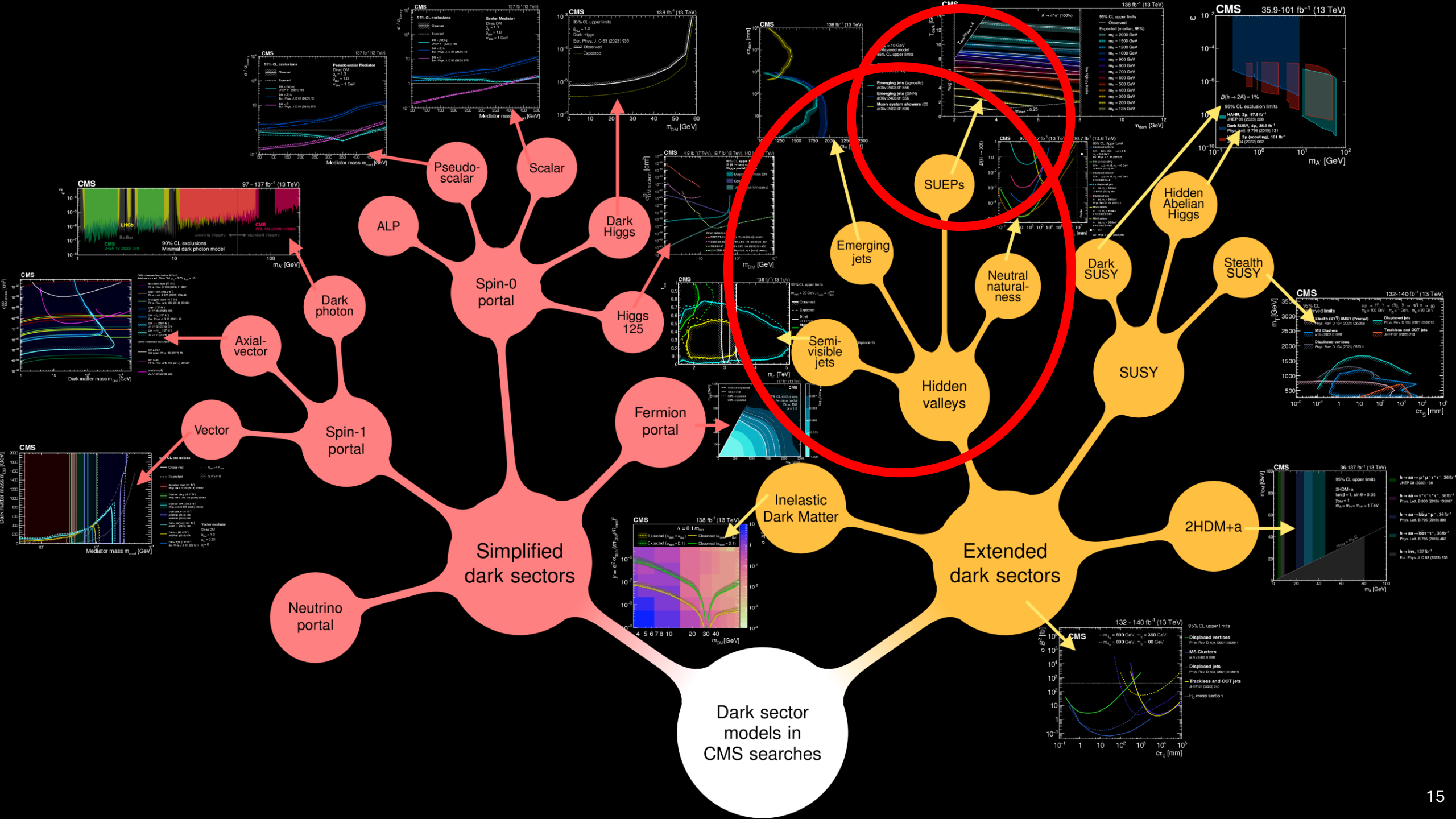
Many new possible signatures that would've been missed in previous searches: semi-visible jets, emerging jets, SUEPs.

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



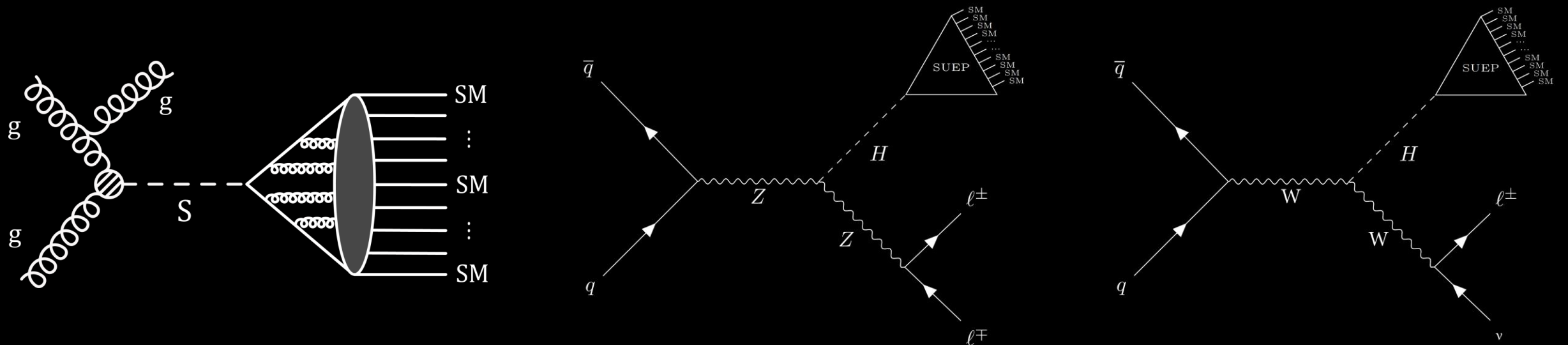


# The SUEP program at CMS

## Five ongoing searches for SUEPs using Run 2 data at CMS

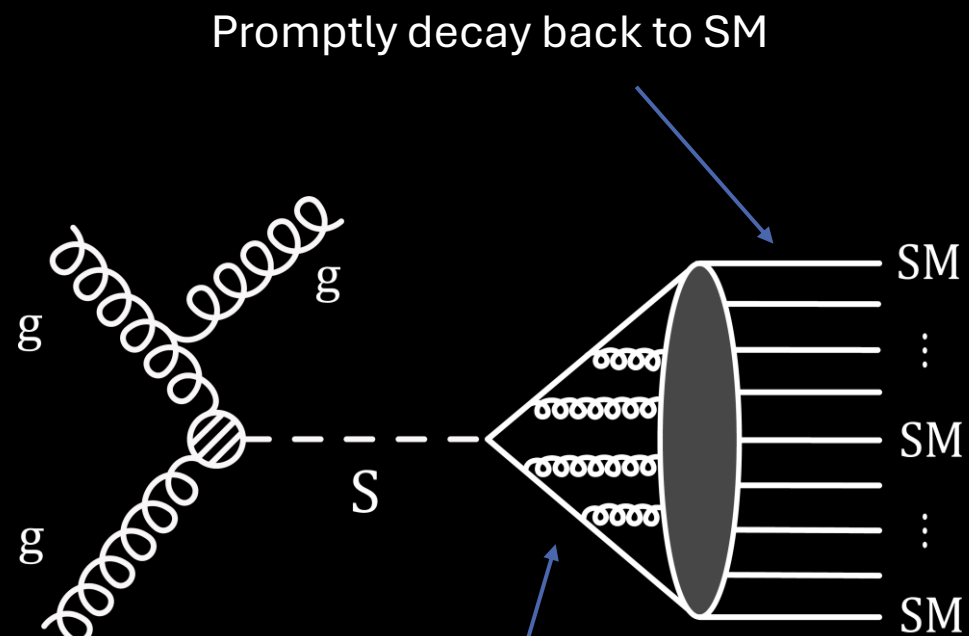
MIT leading the effort along with BU, Fermilab

- 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)



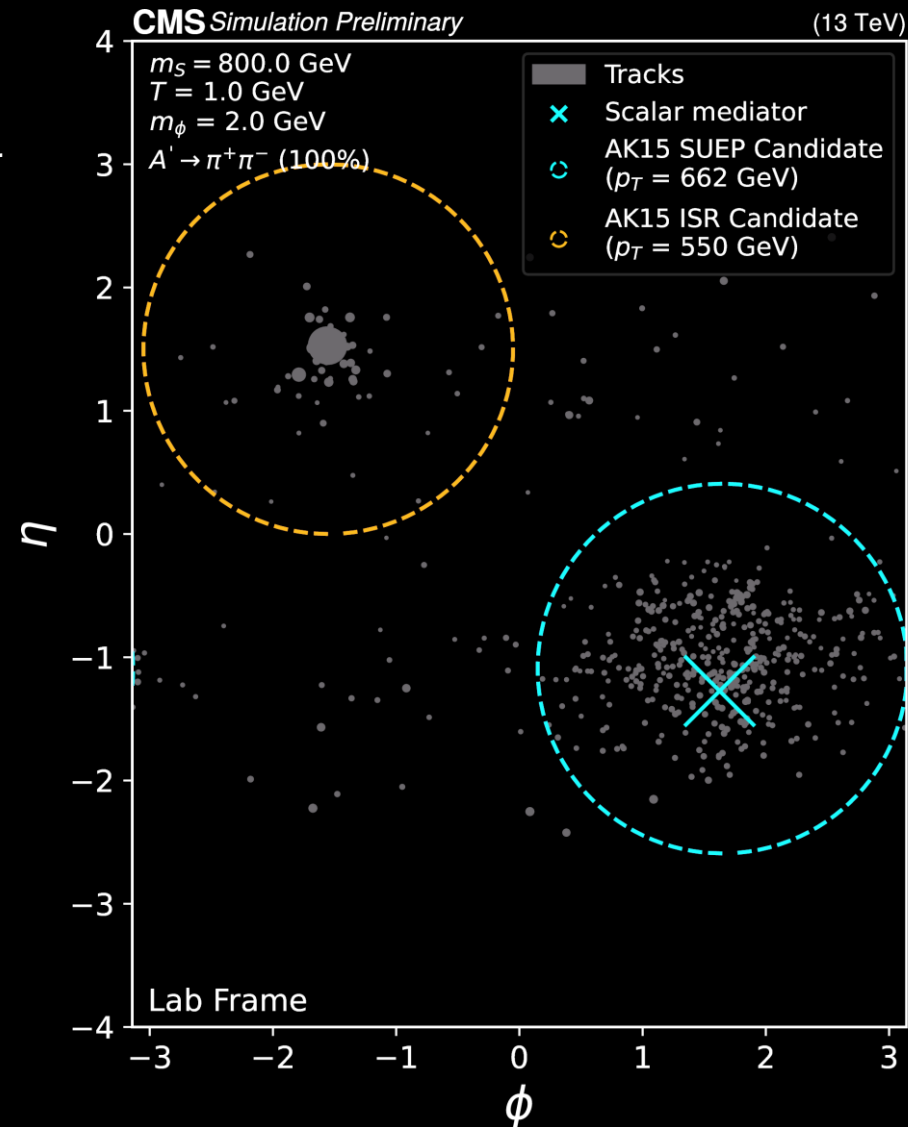
$$\lambda \equiv g^2 N_{\text{colors}} \gg 1$$
$$m_{q_D} < \Lambda_D \ll \sqrt{s}$$

Efficient, isotropic showering window

# A 'real-life' SUEP at the LHC

## QCD

Low multiplicity of higher momentum particles, produced collinearly

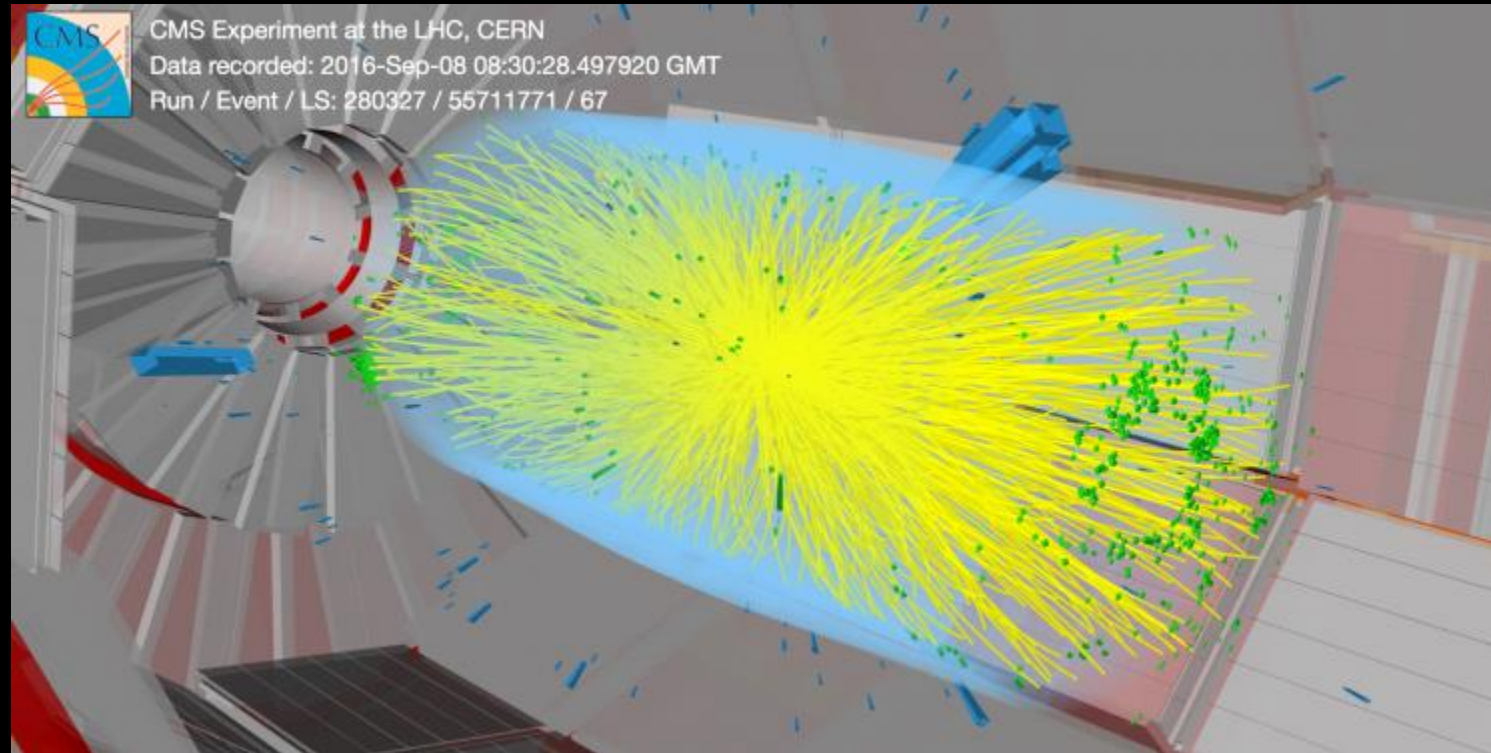


## SUEP

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?”



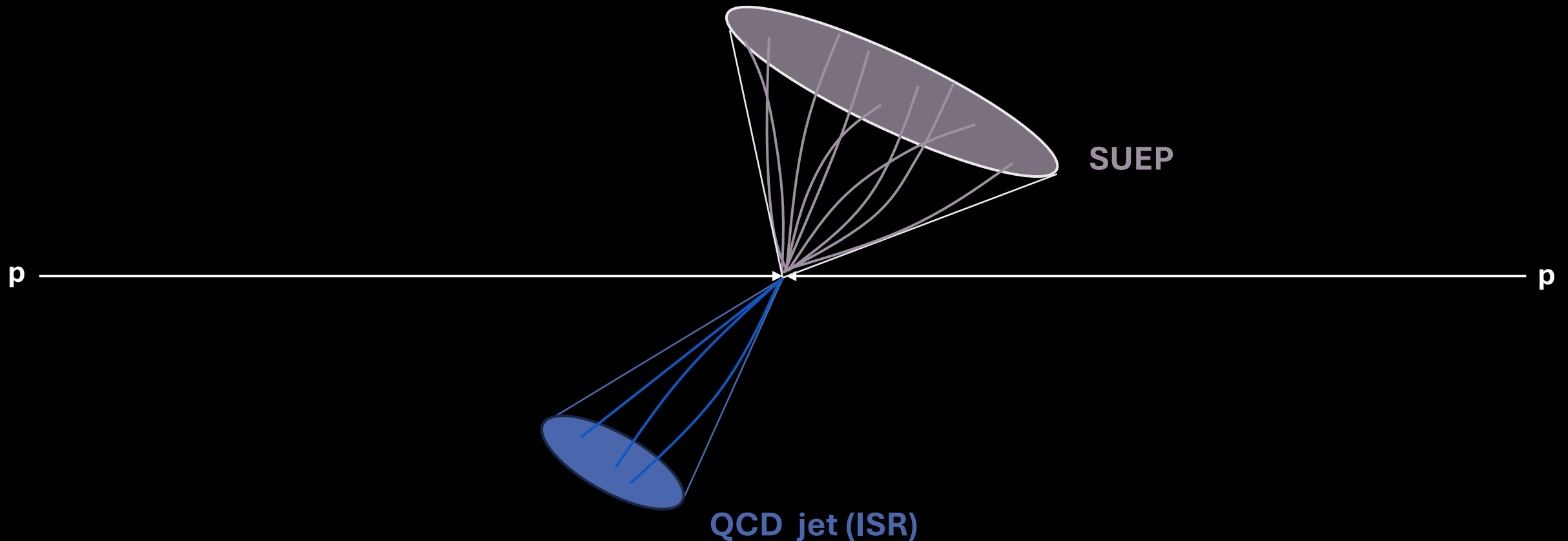
Average event at CMS: quite hard to distinguish SUEP from so-called “pileup”, the additional overlapping pp interactions that happen concurrently with the interaction of interest.

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

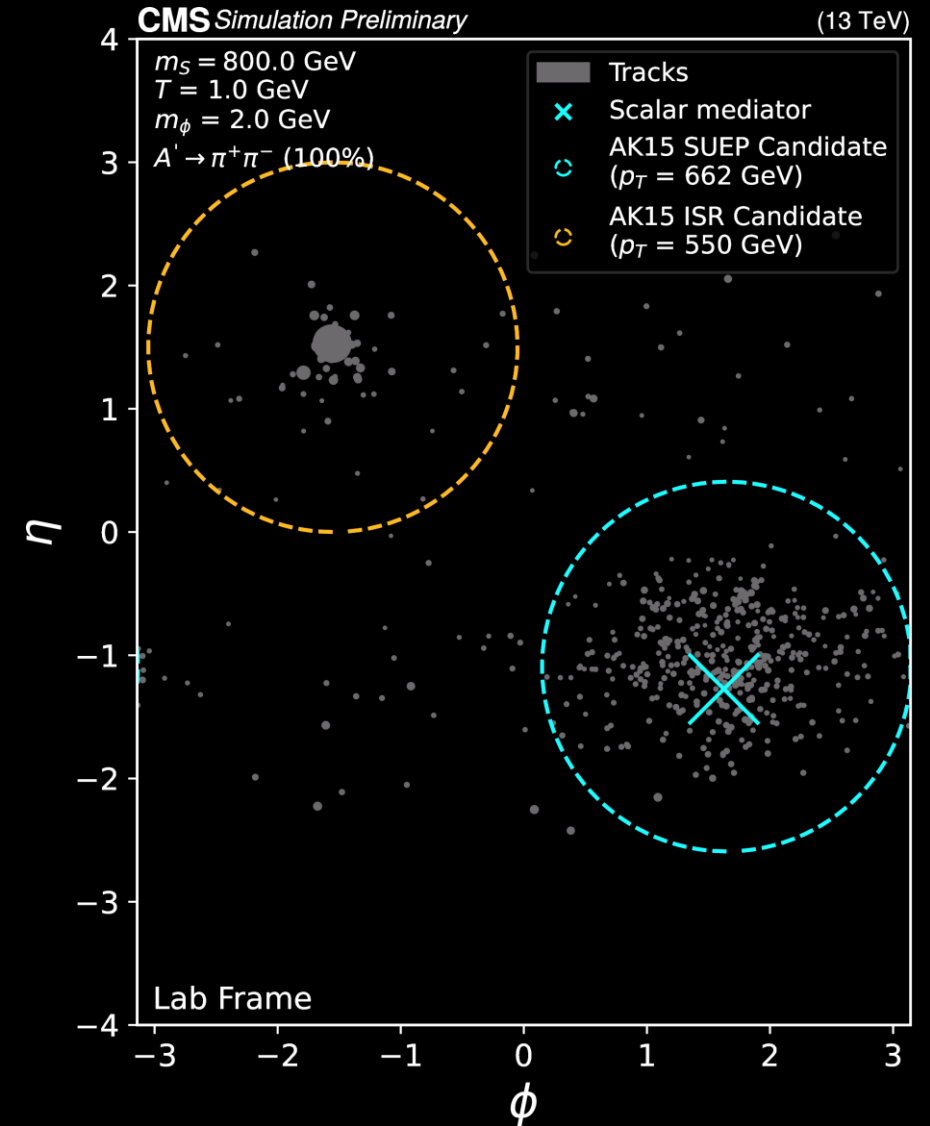


# Reconstruction

- 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



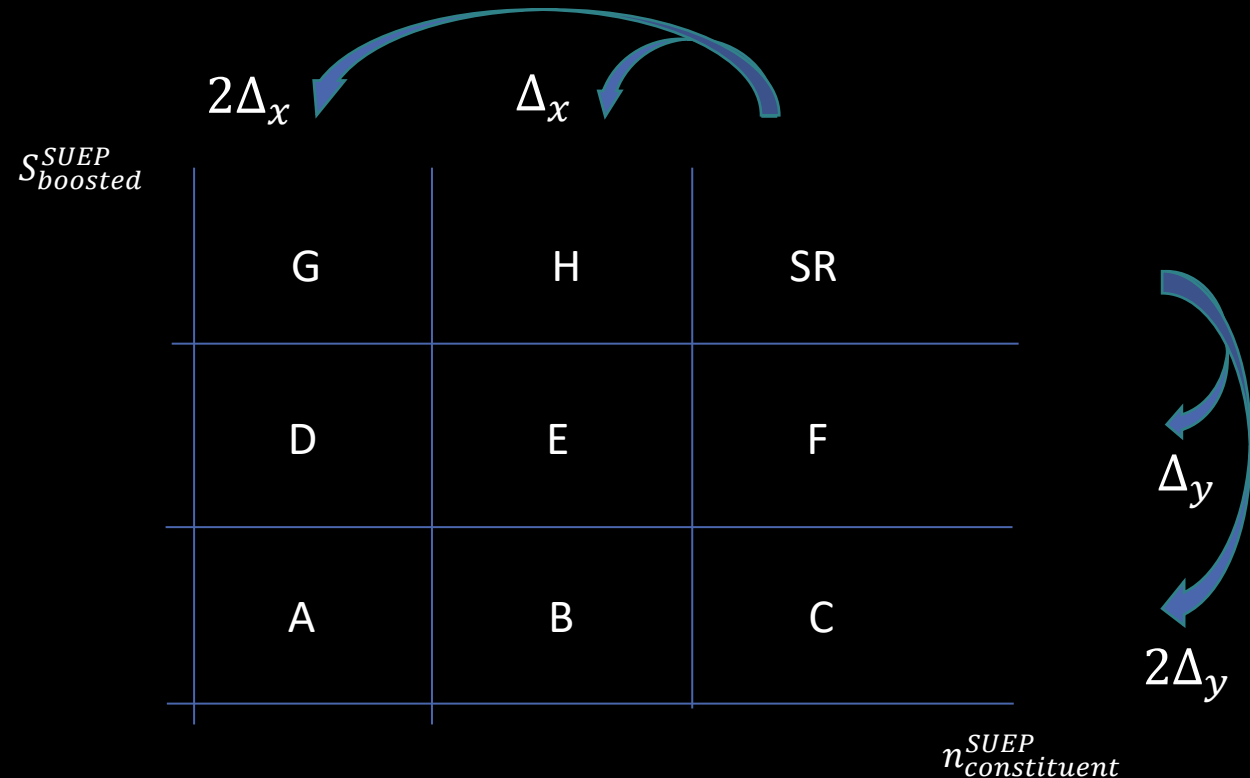
# Background Estimation

- 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

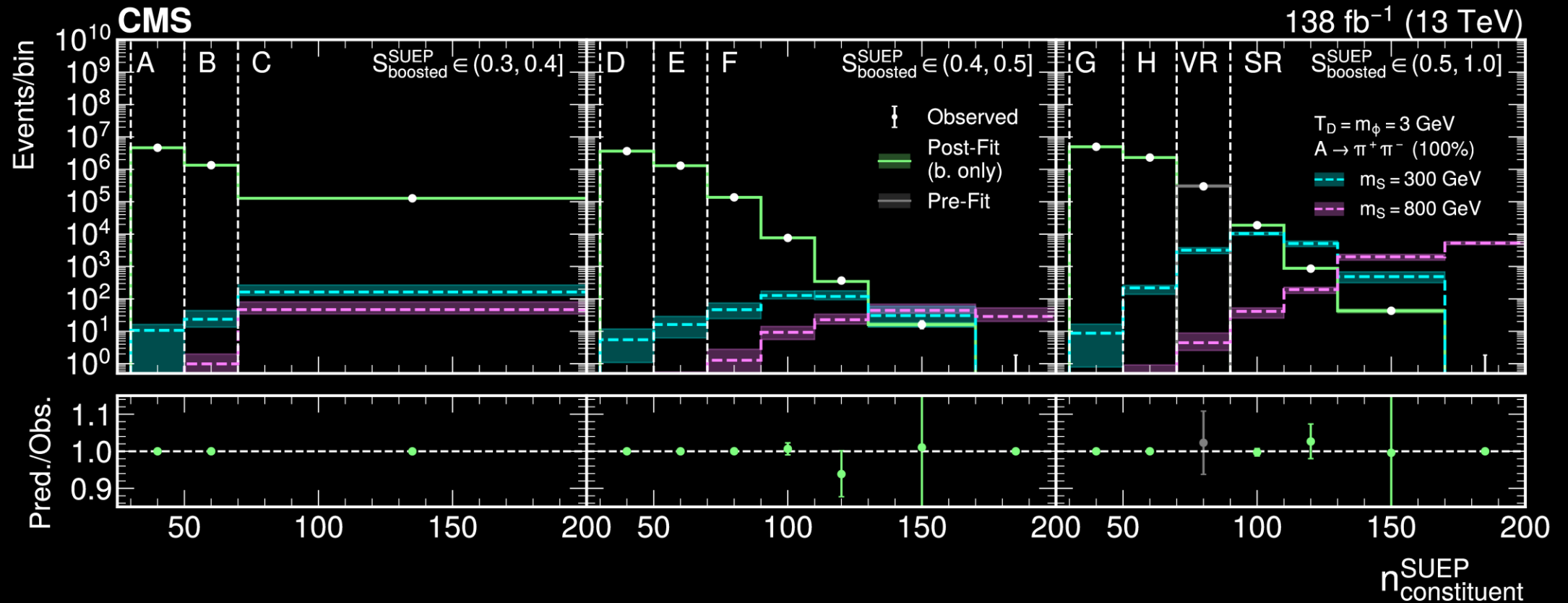
$$SR^{Bin\ i} \approx F^{Bin\ i} \underbrace{\frac{H^2 F D^2 B^2}{G C A E^4}}_{\text{Scaling factor applied to F histogram}} + O(\Delta^4)$$

Scaling factor applied to F histogram

- Now used on other analyses, including mW!

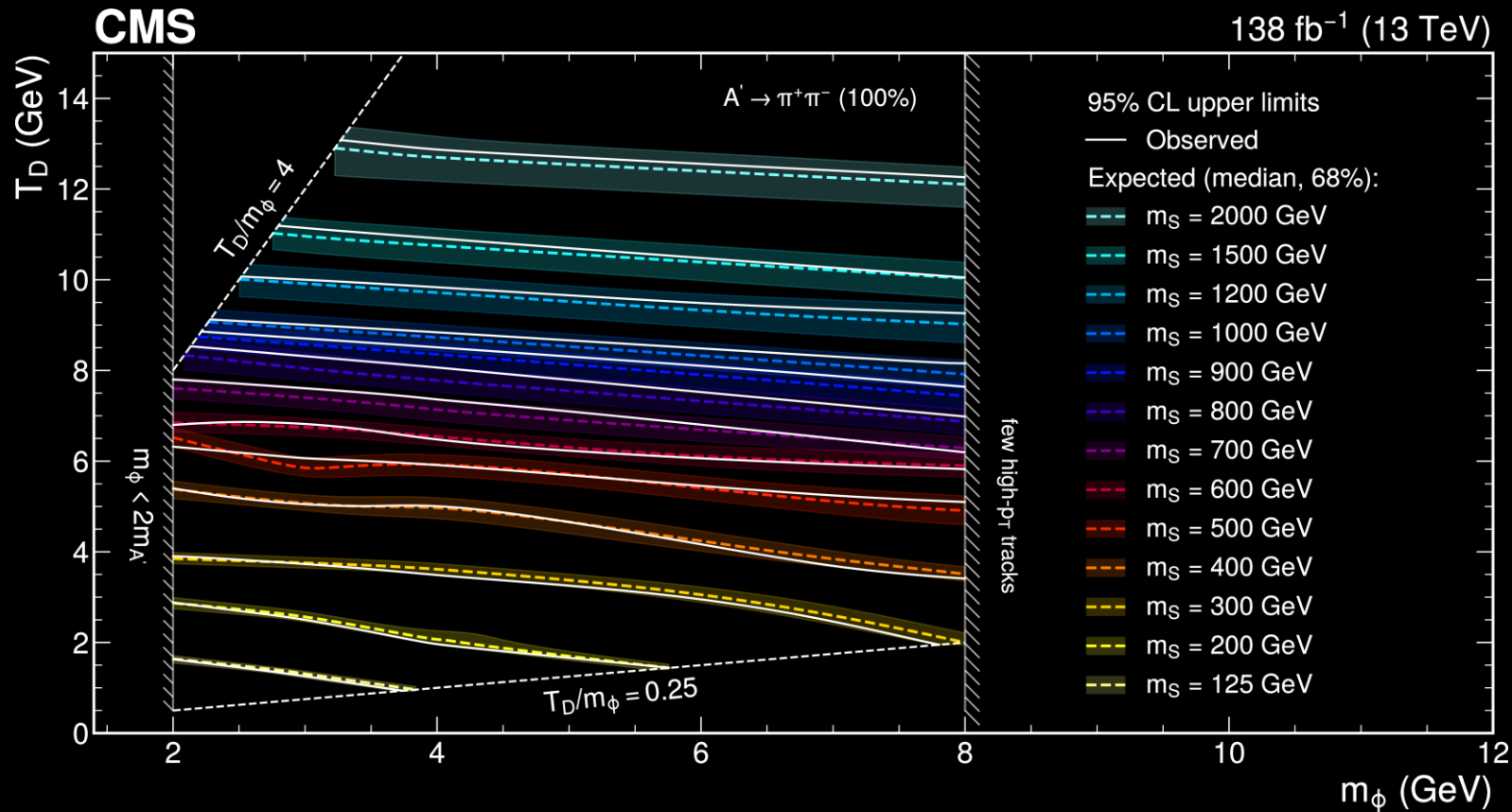


# Results



- 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

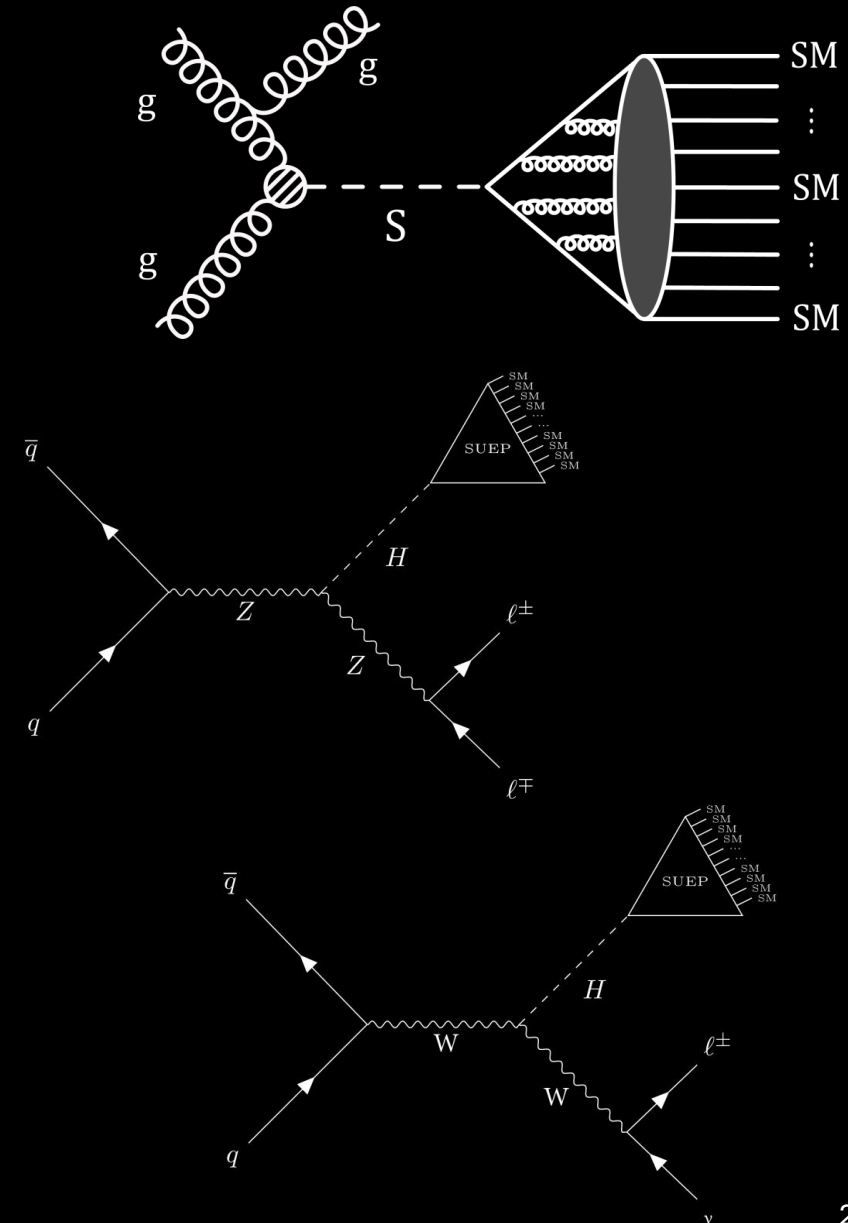
MIT involved in other channels to push the SUEP program

- 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):

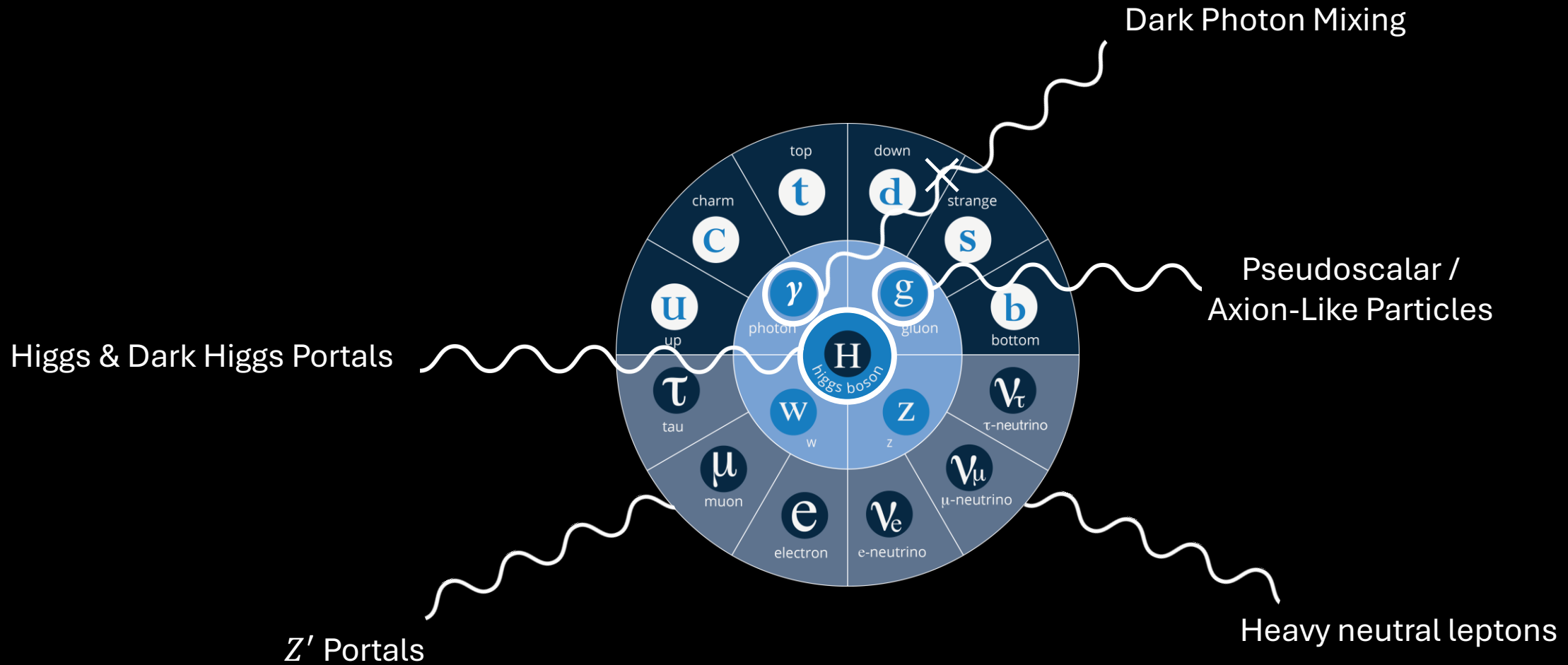
- Target production of a Higgs (or Higgs-like) scalar that decays to SUEPs
- Providing the analysis in a model-independent framework that can be re-interpreted by theorists



# Conclusions

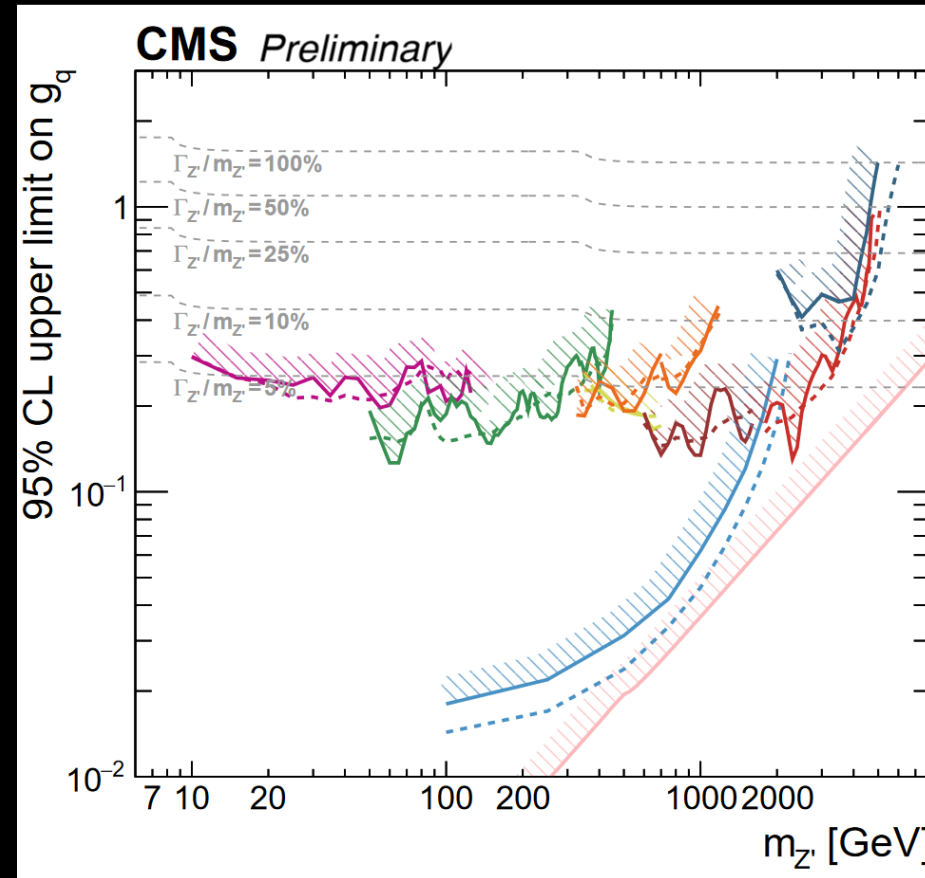
- Searches for dark sectors are the new frontier for BSM at colliders
- Hidden Valleys provide a framework for new dark sectors that are both interesting for theory and experiments
- MIT had led the way on SUEPs, an important Hidden Valley paradigm, providing new searches that have been of great interest 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



# Improving MET+X and Resonance Searches

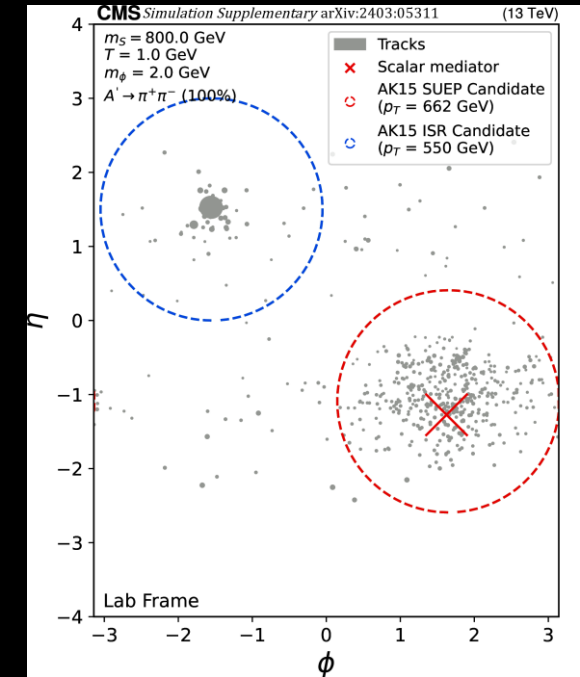
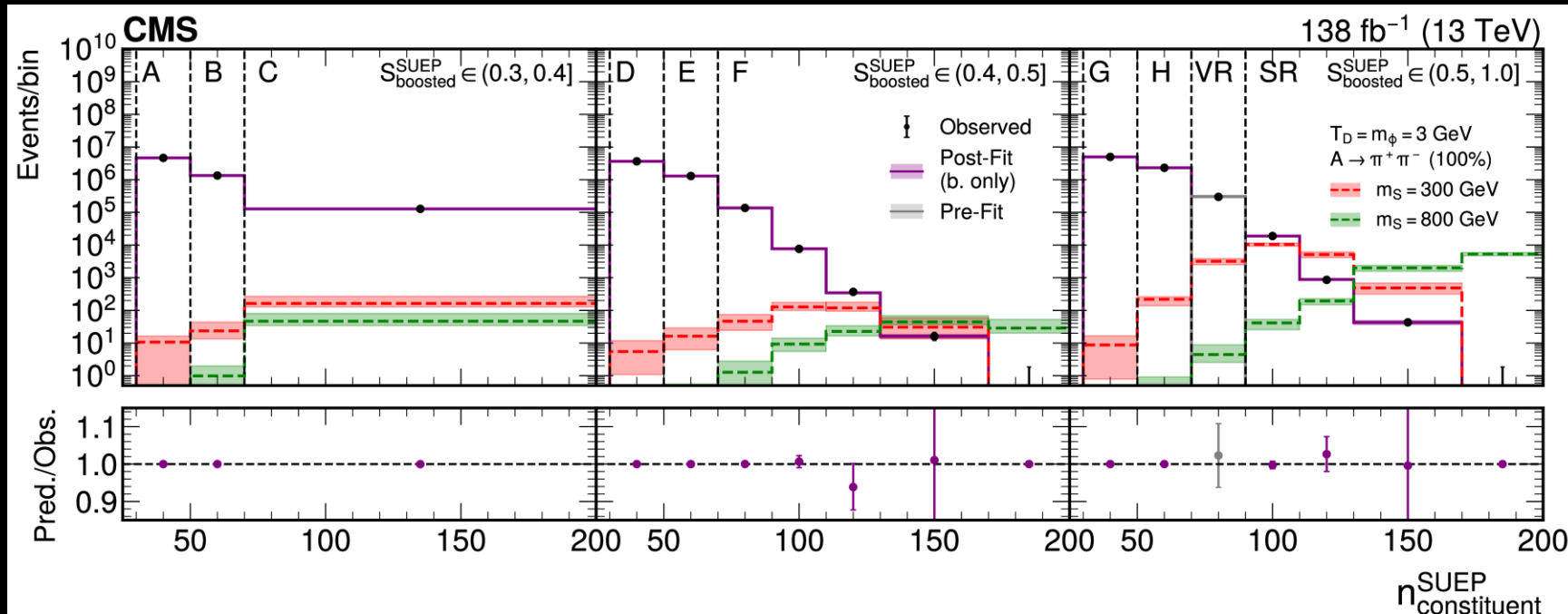
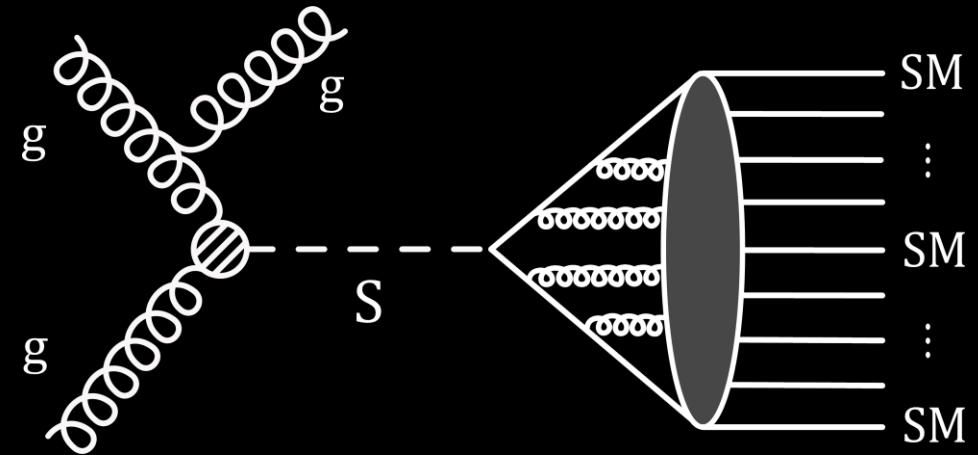
← High-rate triggers  
(scouting)



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

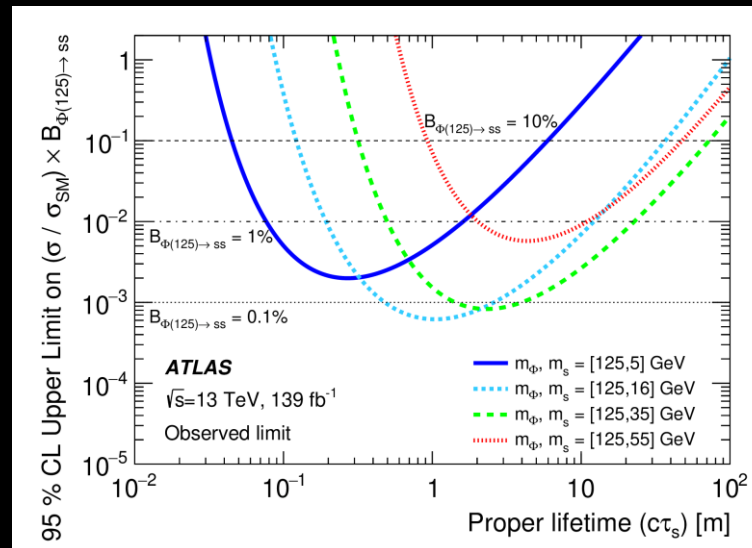
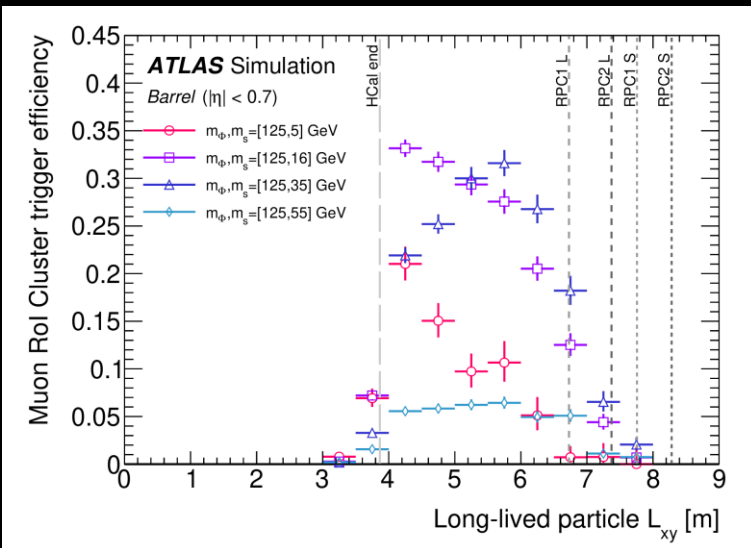
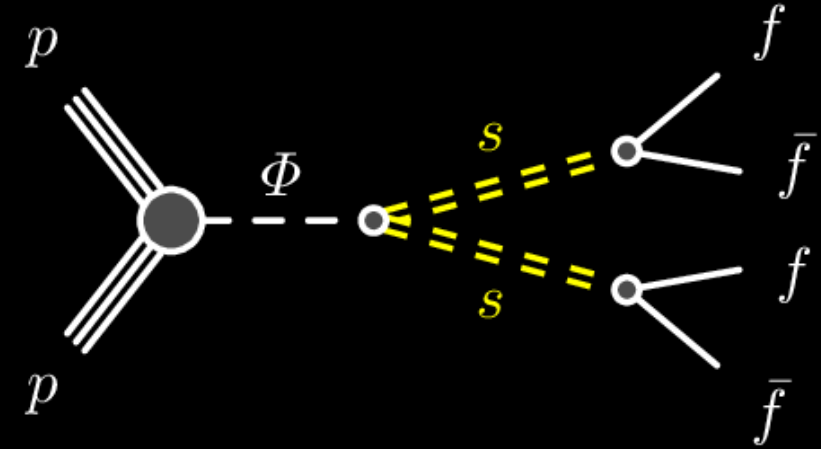
# Soft Unclustered Energy Patterns

- 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 $\mu$ Spectrometer

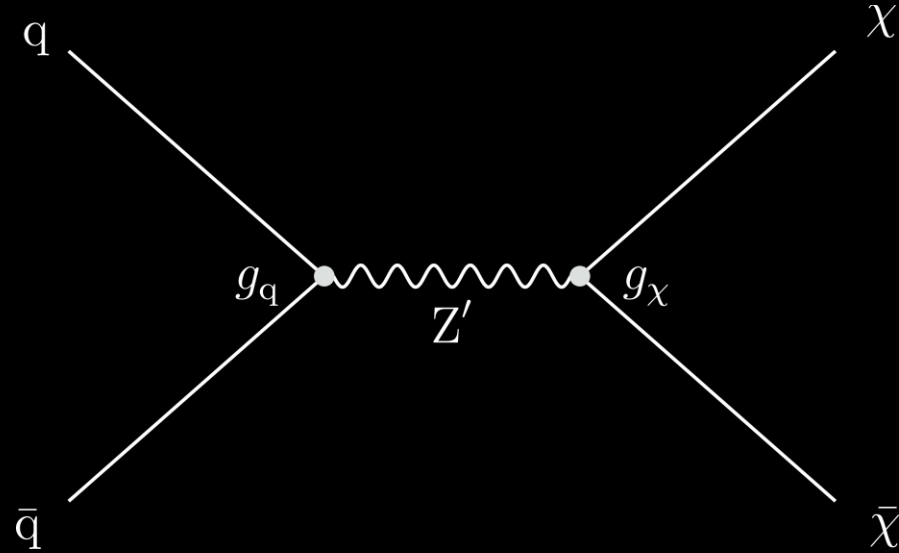
- Dark particles  $s$  produced, travel  $\sim m$ , decay to  $f\bar{f}$ , which shower
  - Showers in the  $\mu$  spectrometer
- Dedicated trigger to look for several tracks in the  $\mu$  spectrometer within a jet's typical radius,  $\Delta R = 1.5$
- Dedicated reconstruction for displaced decays in the spectrometer



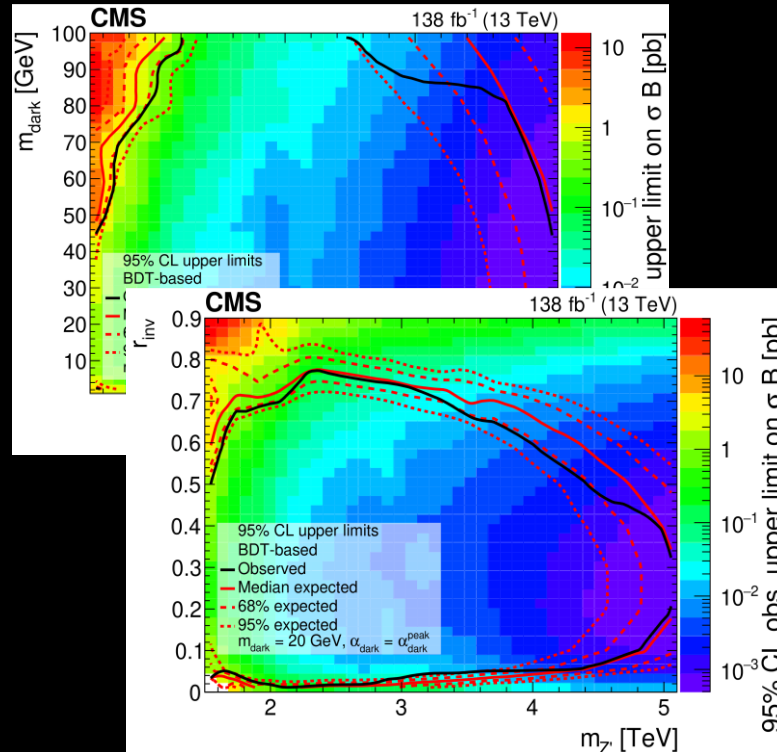
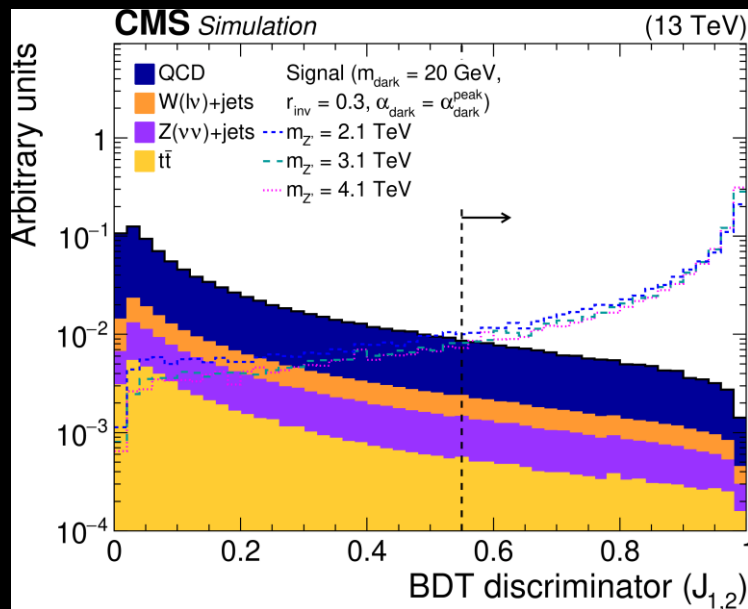
- Set limits on  $c\tau, \sigma$
- Assumptions on DS structure, BRs, masses, etc. for these limits

# Unconventional Signatures: Semivisible Jets

- $\chi$  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

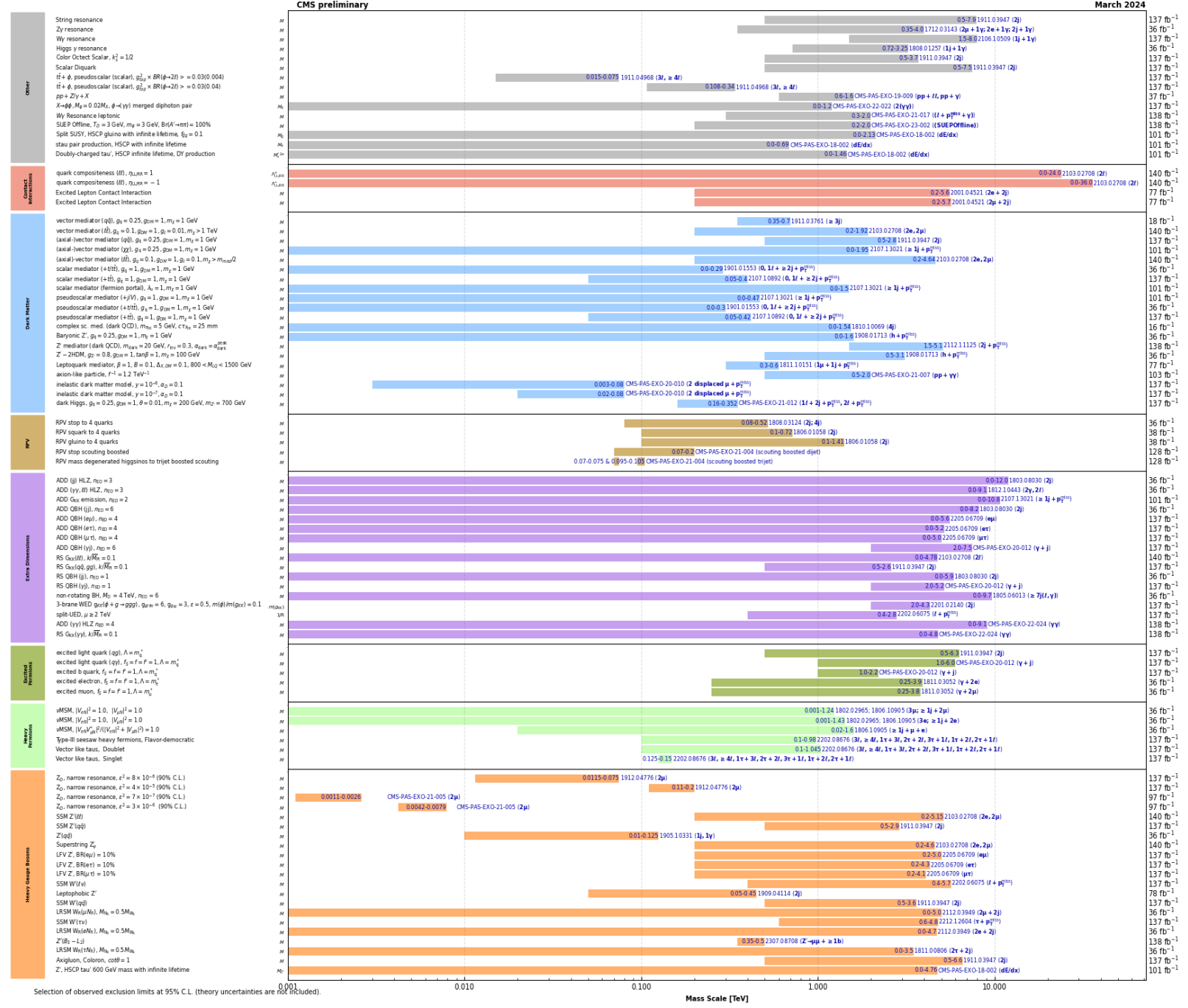


- Set limits on  $m_{Z'}$ ,  $m_{dark}$ ,  $r_{inv}$
- Assumptions on dark sector, such as showering, gauge structure, etc.





Overview of CMS EXO results



- Other**
  - String resonance
  - Zy resonance
  - Wy resonance
  - Higgs y resonance
  - Color Octet Scalar,  $k_2^2 = 1/2$
  - Scalar Diquark
  - $\tilde{t}\tilde{t} + \phi$ , pseudoscalar (scalar),  $g_{\tilde{t}\tilde{t}\phi}^2 \times BR(\phi \rightarrow 2t) > 0.03(0.004)$
  - $\tilde{t}\tilde{t} + \phi$ , pseudoscalar (scalar),  $g_{\tilde{t}\tilde{t}\phi}^2 \times BR(\phi \rightarrow 2t) > 0.03(0.04)$
  - $pp \rightarrow Z\gamma + X$
  - $X = \phi\tilde{t}\tilde{t}, M_\phi = 0.02M_t, \phi = \gamma\gamma$  merged diphoton pair
  - Wy Resonance leptonic
  - SUEP Offline,  $T_0 = 3 \text{ GeV}, m_\chi = 3 \text{ GeV}, Br(A \rightarrow \text{SM}) = 100\%$
  - Split SUSY, HSCP gluino with infinite lifetime,  $\tilde{g}_0 = 0.1$
  - stau pair production, HSCP with infinite lifetime
  - Doubly-charged tau, HSCP infinite lifetime, DY production
- Contact Interactions**
  - quark compositeness (fl),  $\Lambda_{UV} = 1$
  - quark compositeness (fl),  $\Lambda_{UV} = -1$
  - Excited Lepton Contact Interaction
  - Excited Lepton Contact Interaction
- Dark Matter**
  - vector mediator (vq),  $g_v = 0.25, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - vector mediator (lv),  $g_v = 0.1, g_{\text{SM}} = 1, g_\nu = 0.01, m_\chi > 1 \text{ TeV}$
  - (axial-)vector mediator (vq),  $g_v = 0.25, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - (axial-)vector mediator (lv),  $g_v = 0.1, g_{\text{SM}} = 1, g_\nu = 0.1, m_\chi > m_{\text{max}}/2$
  - scalar mediator (+H),  $g_s = 1, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - scalar mediator (+B),  $g_s = 1, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - scalar mediator (fermion portal),  $A_s = 1, m_\chi = 1 \text{ GeV}$
  - pseudoscalar mediator (+V),  $g_p = 1, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - pseudoscalar mediator (+H),  $g_p = 1, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - pseudoscalar mediator (+B),  $g_p = 1, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - complex sc. med. (dark QCD),  $m_{\text{DM}} = 5 \text{ GeV}, c_{\text{DM}} = 25 \text{ mm}$
  - Baryonic Z',  $g_1 = 0.25, g_{\text{SM}} = 1, m_\chi = 1 \text{ GeV}$
  - Z' mediator (dark QCD),  $m_{\text{DM}} = 20 \text{ GeV}, r_{\text{DM}} = 0.3, a_{\text{DM}} = \text{dark}$
  - Z' - 2HDM,  $g_Z = 0.8, g_{\text{SM}} = 1, \tan\beta = 1, m_\chi = 100 \text{ GeV}$
  - Leptoquark mediator,  $\beta = 1, \theta = 0.1, \Delta_{\text{DM}} = 0.1, 800 < M_{\text{LQ}} < 1500 \text{ GeV}$
  - axion-like particle,  $f \sim 1.2 \text{ TeV}^{-1}$
  - inelastic dark matter model,  $y = 10^{-4}, a_0 = 0.1$
  - inelastic dark matter model,  $y = 10^{-2}, a_0 = 0.1$
  - dark Higgs,  $g_1 = 0.25, g_{\text{SM}} = 1, \theta = 0.01, m_\chi = 200 \text{ GeV}, m_Z = 700 \text{ GeV}$
- RPV**
  - RPV stop to 4 quarks
  - RPV squark to 4 quarks
  - RPV gluino to 4 quarks
  - RPV stop scouting boosted
  - RPV mass degenerated higgsinos to tritjet boosted scouting
- Extra Dimensions**
  - ADD (ij) H LZ,  $n_{\text{ED}} = 3$
  - ADD (ij, fl) H LZ,  $n_{\text{ED}} = 3$
  - ADD  $G_{\mu\nu}$  emission,  $n_{\text{ED}} = 2$
  - ADD QBH (ij),  $n_{\text{ED}} = 6$
  - ADD QBH (ep),  $n_{\text{ED}} = 4$
  - ADD QBH (et),  $n_{\text{ED}} = 4$
  - ADD QBH (pt),  $n_{\text{ED}} = 4$
  - ADD QBH (yt),  $n_{\text{ED}} = 6$
  - RS  $G_{\mu\nu}$  (fl),  $k/\Lambda_{\text{Pl}} = 0.1$
  - RS  $G_{\mu\nu}$  (q),  $k/\Lambda_{\text{Pl}} = 0.1$
  - RS QBH (ij),  $n_{\text{ED}} = 1$
  - RS QBH (yt),  $n_{\text{ED}} = 1$
  - non-rotating BH,  $M_{\text{BH}} = 4 \text{ TeV}, n_{\text{ED}} = 6$
  - 3-brane WED  $G_{\mu\nu}$  ( $g - g_{\text{SM}}$ ),  $g_{\text{SM}} = 6, g_{\text{SM}} = 3, \epsilon = 0.5, m(\phi) \text{ in } (g_{\mu\nu}) = 0.1$
  - spl-UED,  $\mu \geq 2 \text{ TeV}$
  - ADD (ij) H LZ,  $n_{\text{ED}} = 4$
  - RS  $G_{\mu\nu}$  (yt),  $k/\Lambda_{\text{Pl}} = 0.1$
- Excited Fermions**
  - excited light quark (qql),  $\Lambda = m_s^*$
  - excited light quark (lql),  $f_1 = f = 1, \Lambda = m_s^*$
  - excited b quark,  $f_1 = f = 1, \Lambda = m_c^*$
  - excited electron,  $f_1 = f = 1, \Lambda = m_s^*$
  - excited muon,  $f_1 = f = 1, \Lambda = m_s^*$
- Heavy Fermions**
  - mSM,  $|V_{cb}|^2 = 1.0, |V_{ub}|^2 = 1.0$
  - mSM,  $|V_{cb}|^2 = 1.0, |V_{ub}|^2 = 1.0$
  - mSM,  $|V_{cb}|^2 |V_{ub}|^2 / (|V_{cb}|^2 + |V_{ub}|^2) = 1.0$
  - Type-II seesaw heavy fermions, Flavor-democratic
  - Vector like taus, Doublet
  - Vector like taus, Singlet
- Heavy Exotic Resonances**
  - $Z_0$ , narrow resonance,  $\epsilon^2 = 8 \times 10^{-6}$  (90% C.L.)
  - $Z_0$ , narrow resonance,  $\epsilon^2 = 4 \times 10^{-6}$  (90% C.L.)
  - $Z_0$ , narrow resonance,  $\epsilon^2 = 7 \times 10^{-6}$  (90% C.L.)
  - $Z_0$ , narrow resonance,  $\epsilon^2 = 3 \times 10^{-6}$  (90% C.L.)
  - SSM Z' (fl)
  - SSM Z' (q)
  - Z' (q)
  - Superstring  $Z_0$
  - LFV Z', BR(l $\nu$ ) = 10%
  - LFV Z', BR(l $\nu$ ) = 10%
  - LFV Z', BR(l $\nu$ ) = 10%
  - SSM W' (fl)
  - Leptoquark Z'
  - SSM W' (q)
  - LRSM W' ( $\nu$ ),  $M_{W'} = 0.5 M_{W_0}$
  - SSM W' ( $\nu$ )
  - LRSM W' ( $\nu$ ),  $M_{W'} = 0.5 M_{W_0}$
  - Z' ( $\tilde{b} - \tilde{t}$ )
  - LRSM W' ( $\nu$ ),  $M_{W'} = 0.5 M_{W_0}$
  - Axigluon, Coloron,  $\cot\beta = 1$
  - Z', HSCP tau 600 GeV mass with infinite lifetime

ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary  
 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$   
 $\sqrt{s} = 13 \text{ TeV}$

Model	$l, \gamma$	Jets†	$E_{\text{miss}}^{\text{min}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	$M_0$ 11.2 TeV, $n=2$
	ADD non-resonant $\gamma\gamma$	$2\gamma$	-	-	36.7	$M_0$ 8.6 TeV, $n=3$ HLZ NLO
	ADD OBH	-	2 j	-	139	$M_{\text{BH}}$ 9.4 TeV, $n=6$
	ADD BH multijet	-	$\geq 3$ j	-	3.6	$M_{\text{BH}}$ 9.55 TeV, $n=6, M_0=3 \text{ TeV}$ , rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\gamma$	-	-	139	$G_{KK}$ mass 4.5 TeV, $k/\bar{M}_{Pl} = 0.1$
Gauge bosons	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	$\geq 1 b, \geq 1/2 j$	Yes	36.1	$G_{KK}$ mass 2.3 TeV, $k/\bar{M}_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1/2 j$	Yes	36.1	$G_{KK}$ mass 3.8 TeV, $\Gamma/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV, Tier (1,1), $\mathcal{B}(A^{(1-3)} \rightarrow tt) = 1$
CI	SSM $Z' \rightarrow ll$	$2 e, \mu$	-	-	139	$Z'$ mass 2.42 TeV, 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	$2\tau$	-	-	36.1	$Z'$ mass 2.1 TeV
	Leptophobic $Z' \rightarrow bb$	-	$\geq 2 b$	-	36.1	$Z'$ mass 4.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 j$	Yes	139	$Z'$ mass 4.1 TeV
	SSM $W' \rightarrow l\nu$	$1 e, \mu$	-	-	139	$W'$ mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	$1\tau$	-	-	139	$W'$ mass 5.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 j$	-	139	$W'$ mass 4.4 TeV
	HVT $W' \rightarrow WZ$ model B	$0, 2 e, \mu$	$2 j / 1 j$	Yes	139	$W'$ mass 340 GeV, 4.3 TeV
	HVT $W' \rightarrow WZ \rightarrow l\nu l'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	$W'$ mass 3.9 TeV
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 j$	Yes	139	$Z'$ mass 3.9 TeV
LRSM $W_R \rightarrow \mu N_R$	$2\mu$	$1 j$	-	80	$W_R$ mass 5.0 TeV	
DM	CI $q\bar{q}q$	-	2 j	-	37.0	$A$ 21.8 TeV, $\eta_{LL}$
	CI $l\bar{l}q$	$2 e, \mu$	-	-	139	$A$ 35.8 TeV, $\eta_{LL}$
	CI $e\bar{e}b$	$2 e$	$1 b$	-	139	$A$ 1.8 TeV, $g_s = 1$
	CI $\mu\bar{\mu}b$	$2\mu$	$1 b$	-	139	$A$ 2.0 TeV, $g_s = 1$
	CI $t\bar{t}t$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$A$ 2.57 TeV, $ C_{4l}  = 4\pi$
LO	Axial-vector med. (Dirac DM)	-	2 j	-	139	$m_{\text{DM}}$ 376 GeV, 3.8 TeV
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	$m_{\text{DM}}$ 376 GeV, 3.0 TeV
	Vector med. $Z'$ -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$m_{\text{DM}}$ 800 GeV, 3.0 TeV
	Pseudo-scalar med. 2HDM+s+a	multi-channel	-	-	139	$m_{\text{DM}}$ 800 GeV, 3.0 TeV
Vector-like fermions	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV
	Scalar LQ 2 <sup>nd</sup> gen	$2\mu$	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV
	Scalar LQ 3 <sup>rd</sup> gen	$1\tau$	$2 b$	Yes	139	LQ mass 1.49 TeV
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ mass 1.24 TeV
	Scalar LQ 3 <sup>rd</sup> gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 b$	$\geq 1 b$	-	139	LQ mass 1.43 TeV
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu, \geq 1 \tau, 0-2 j, 2 b$	$\geq 1 b$	Yes	139	LQ mass 1.26 TeV
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LQ mass 2.0 TeV
	Vector LQ 3 <sup>rd</sup> gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	LQ mass 1.96 TeV
	VLO $TT \rightarrow Zt + X$	$2e/2\mu/3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	SU(2) doublet 1.46 TeV
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV
Excld ferm.	VLO $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV
	VLO $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV
	VLO $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV
	VLO $B \rightarrow Hb$	$0 e, \mu$	$\geq 2 b, \geq 1 j, \geq 1 j$	-	139	B mass 2.0 TeV
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	$\tau'$ mass 898 GeV
	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	$q^*$ mass 6.7 TeV
	Excited quark $q^* \rightarrow q\gamma$	$1\gamma$	$1 j$	-	36.7	$q^*$ mass 5.3 TeV
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	139	$b^*$ mass 3.2 TeV
	Excited lepton $\tau^*$	$2\tau$	$\geq 2 j$	-	139	$\tau^*$ mass 4.6 TeV
	Other	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139
LRSM Majorana $\nu$		$2\mu$	$2 j$	-	36.1	$N_e$ mass 3.2 TeV
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$		$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV
Higgs triplet $H^{\pm} \rightarrow ll$		$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm}$ mass 1.08 TeV
Multi-charged particles		-	-	-	139	$H^{\pm\pm}$ mass 1.59 TeV
Magnetic monopoles		-	-	-	34.4	monopole mass 2.37 TeV

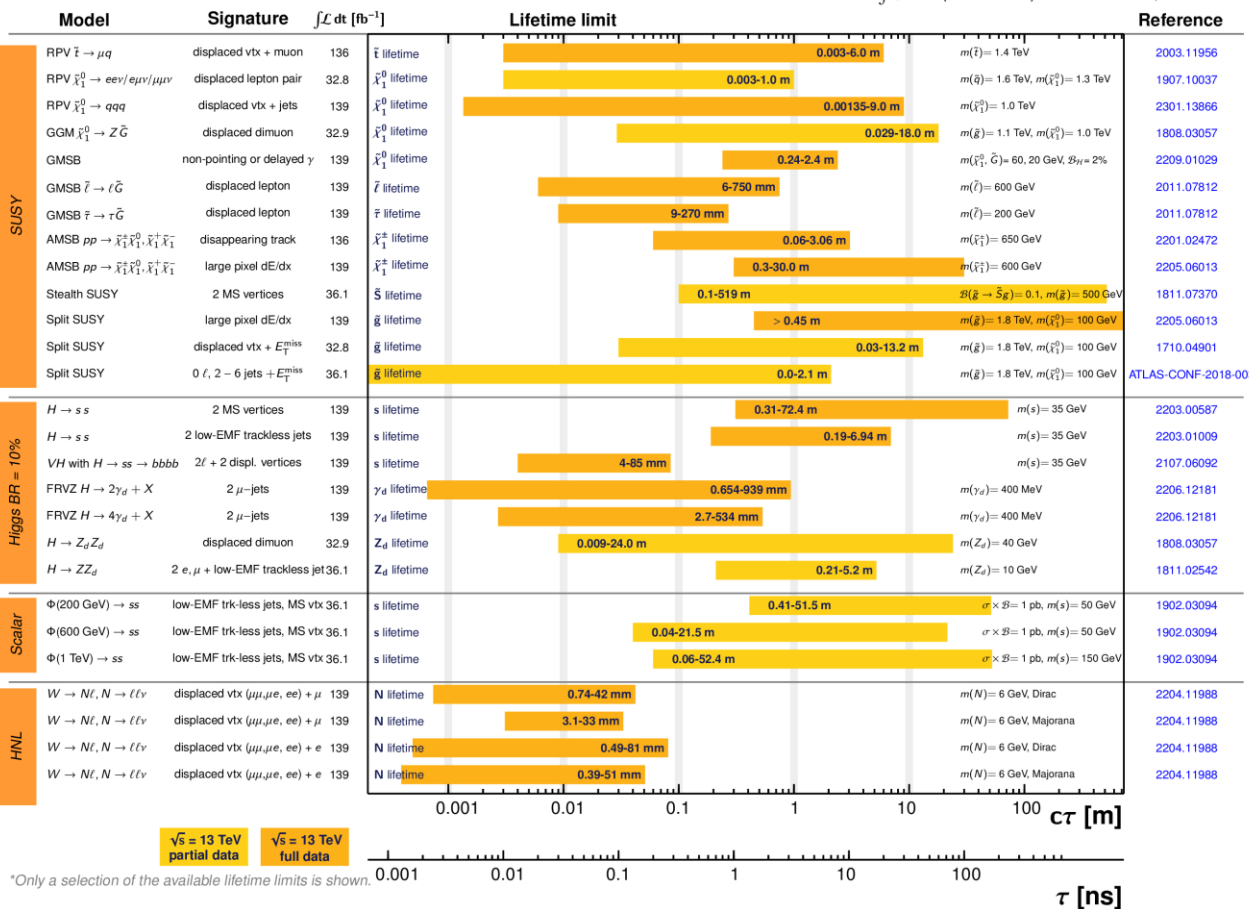
\*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS Long-lived Particle Searches\* - 95% CL Exclusion

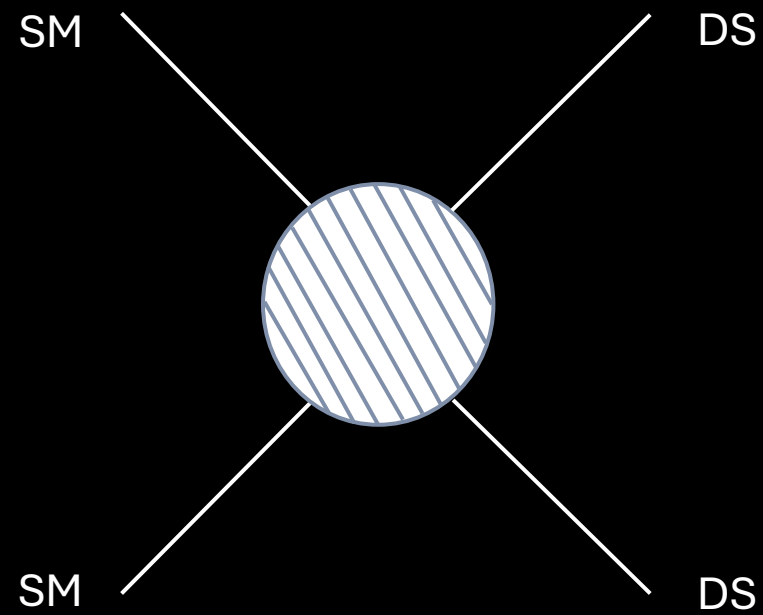
Status: March 2023

ATLAS Preliminary  
 $\int \mathcal{L} dt = (32.8 - 139) \text{ fb}^{-1}$   
 $\sqrt{s} = 13 \text{ TeV}$

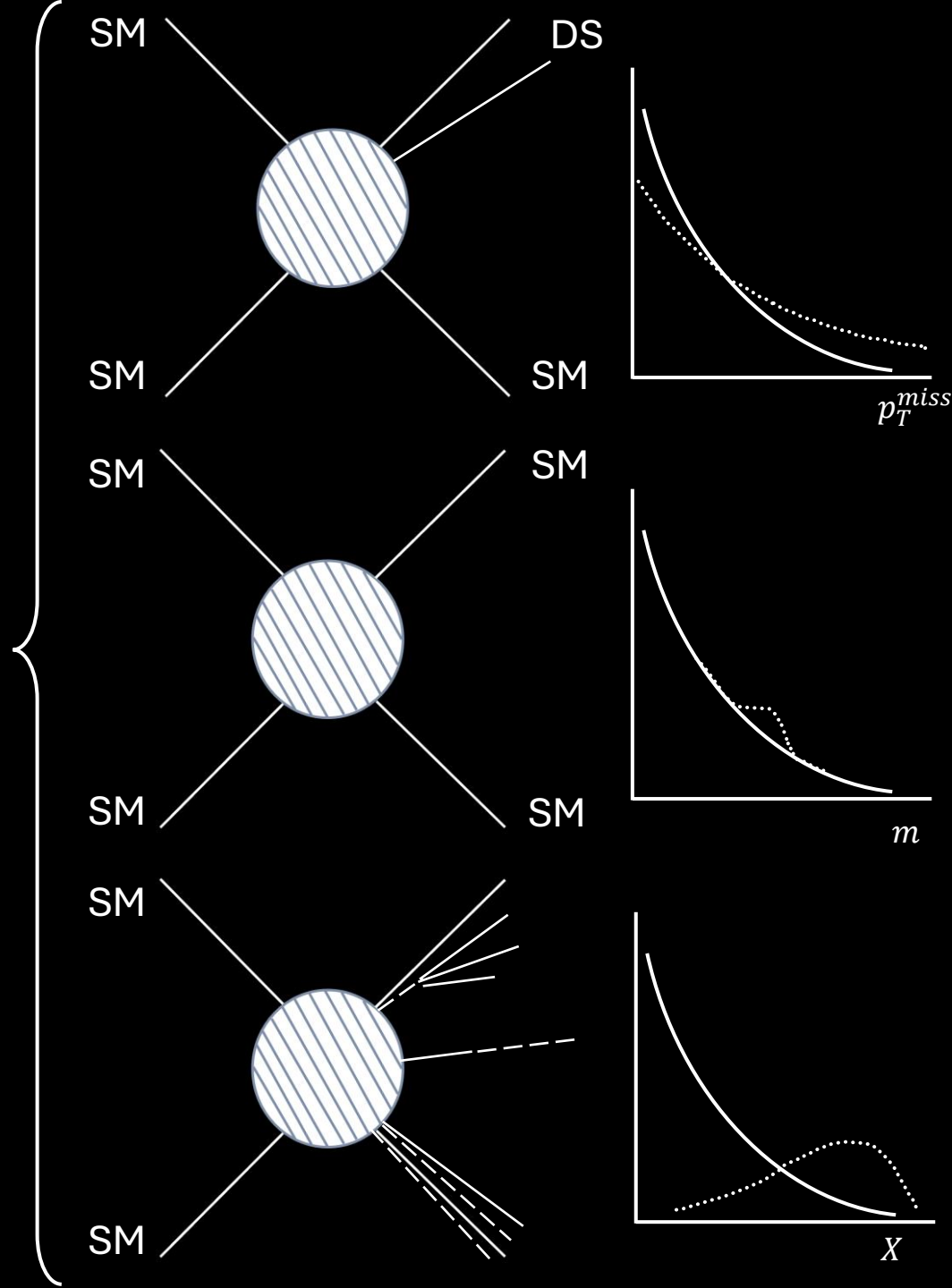
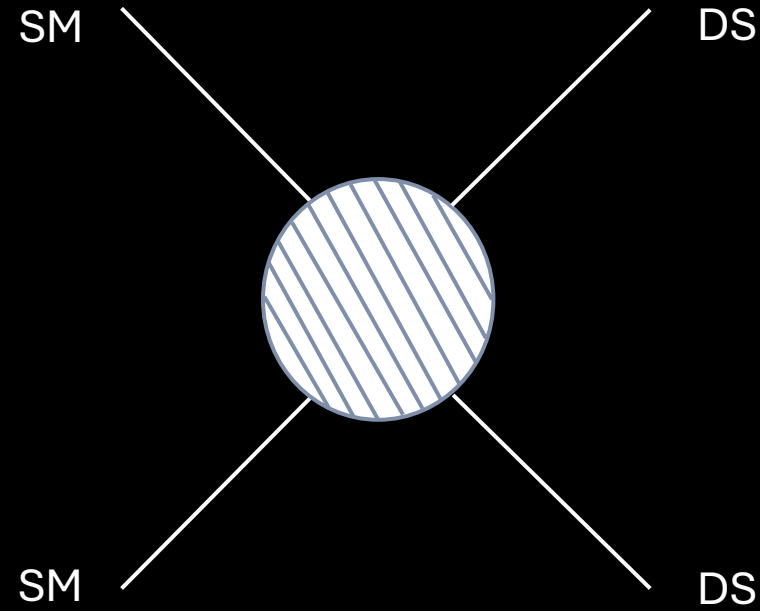


\*Only a selection of the available lifetime limits is shown.

# Dark Sectors at colliders



## Dark Sectors at colliders



### MET+X searches

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

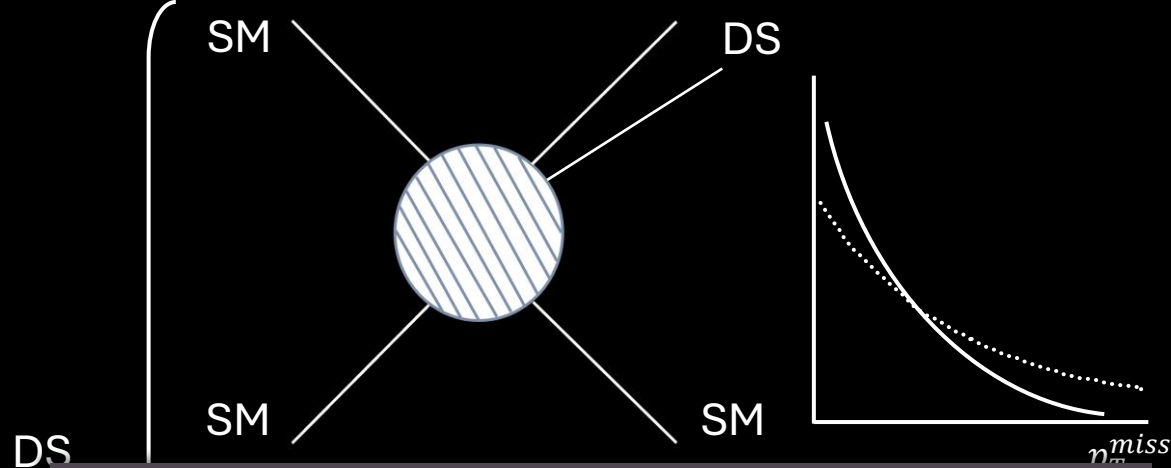
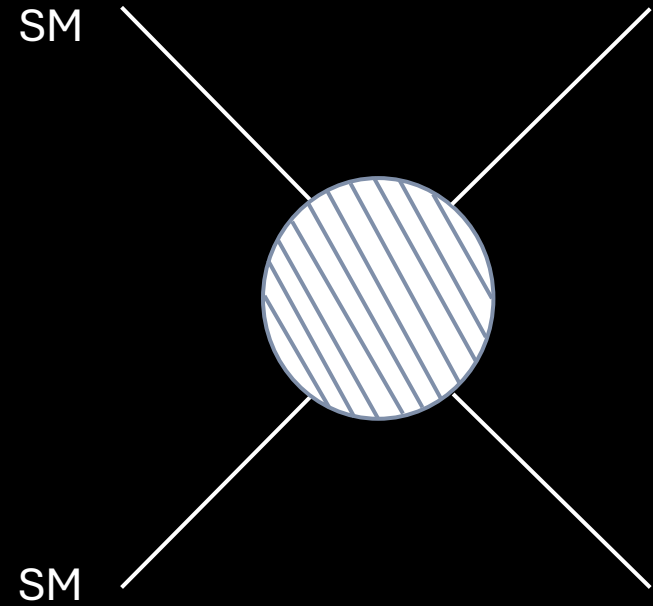
### Portal resonances

- 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

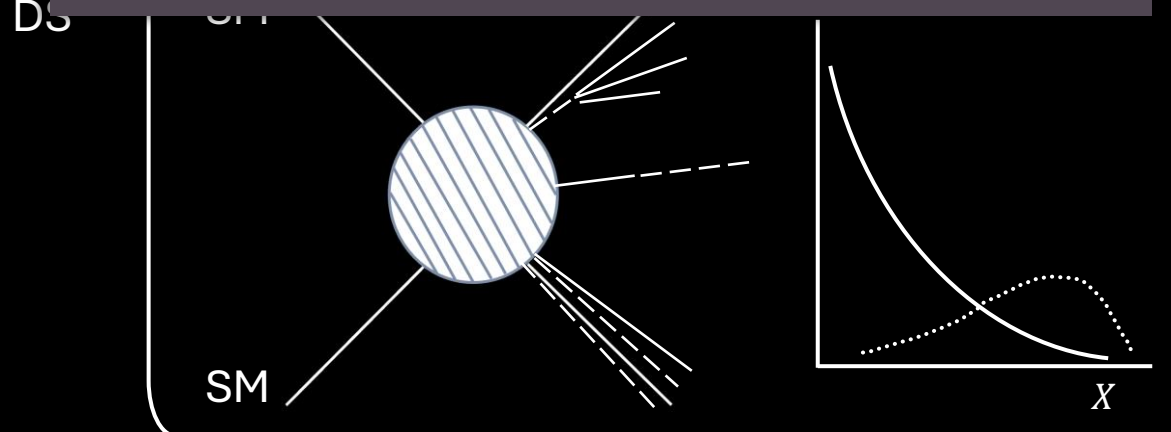
### Disclaimer:

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

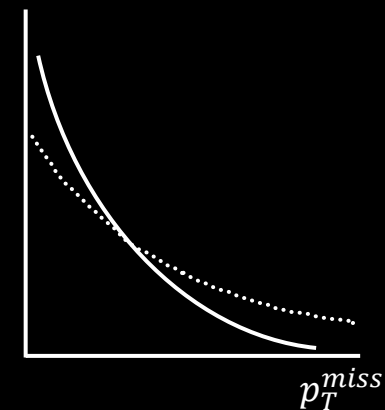
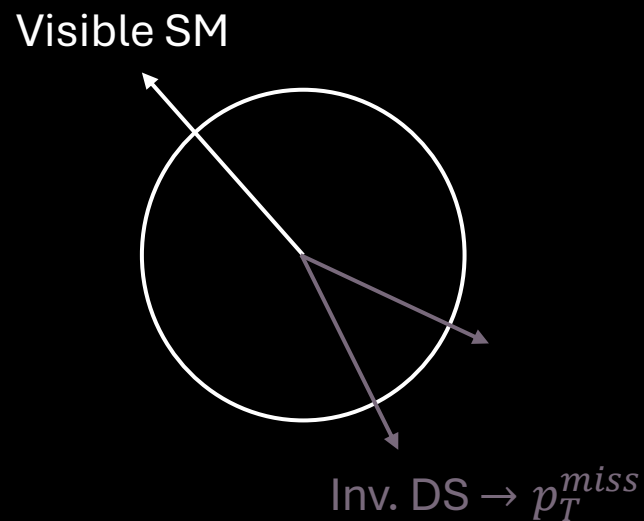
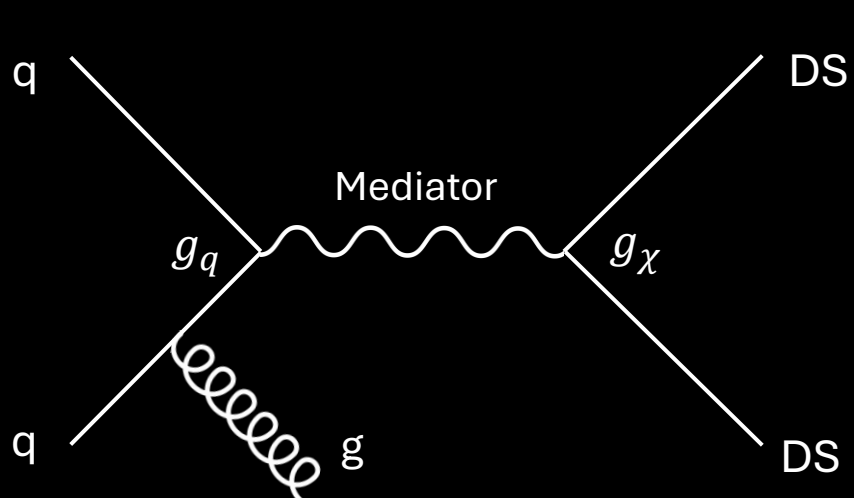
- Known SM processes cross sections are affected by DS
- Search for bumps in mass distributions



### Unconventional signatures

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

# 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

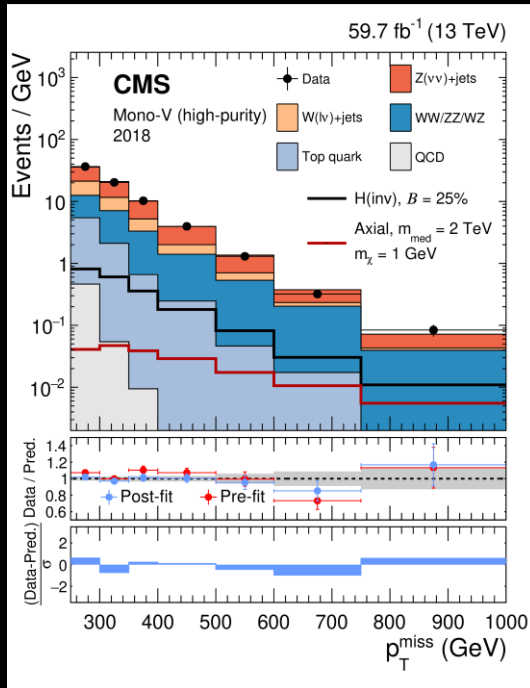
# MET+X Results

[1] - [JHEP 11 \(2021\) 153](#)

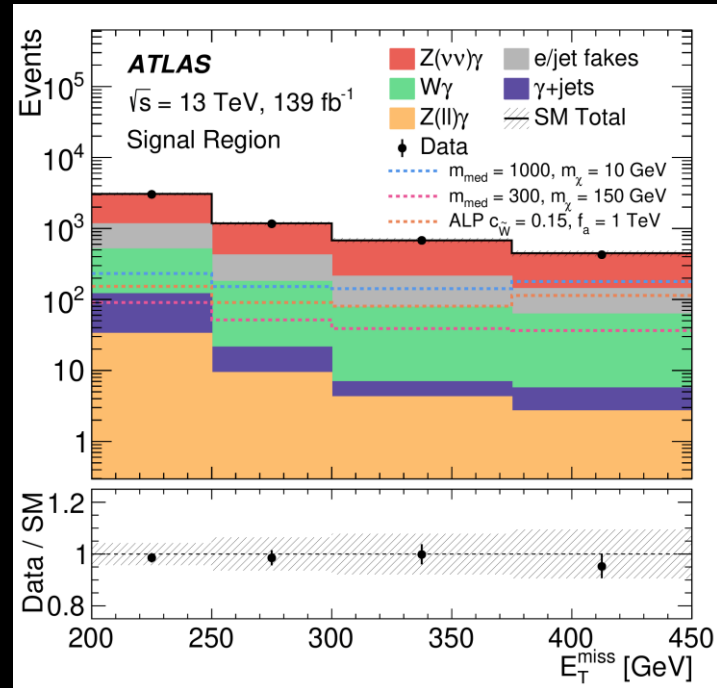
[2] - [JHEP 02 \(2021\) 226](#)

[3] - [arXiv:2402.16561](#)

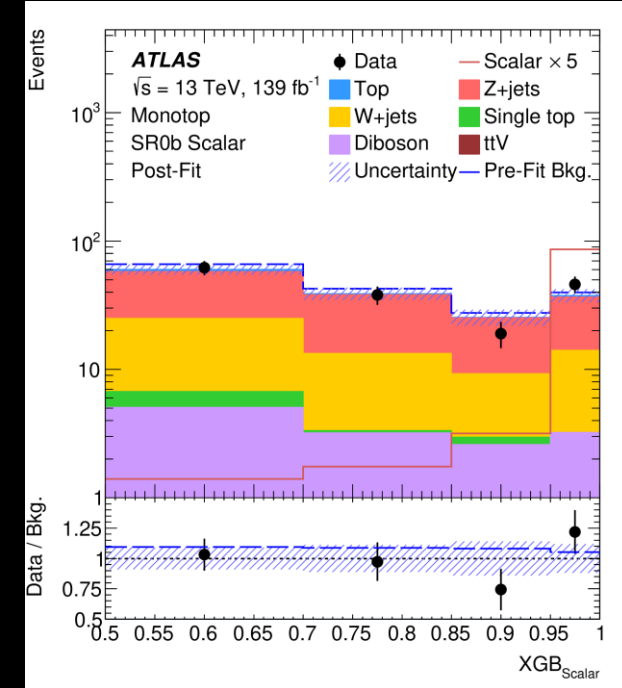
Mono-Jet [1]



Mono- $\gamma$  [2]

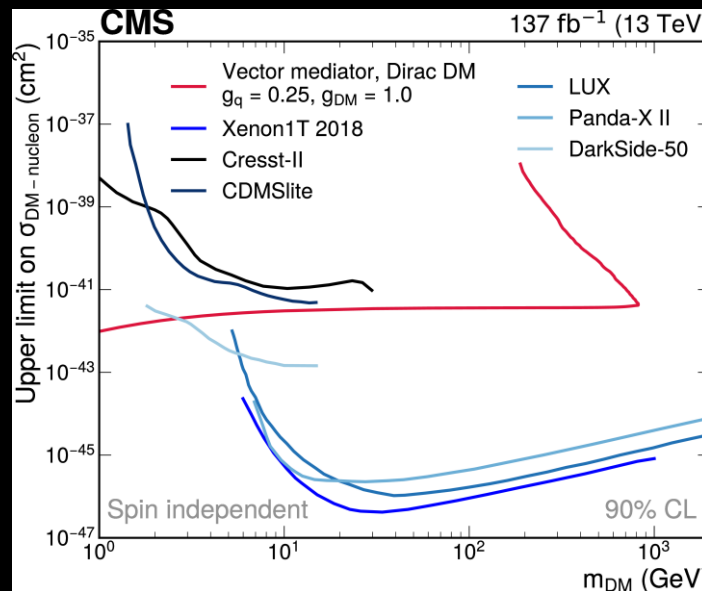
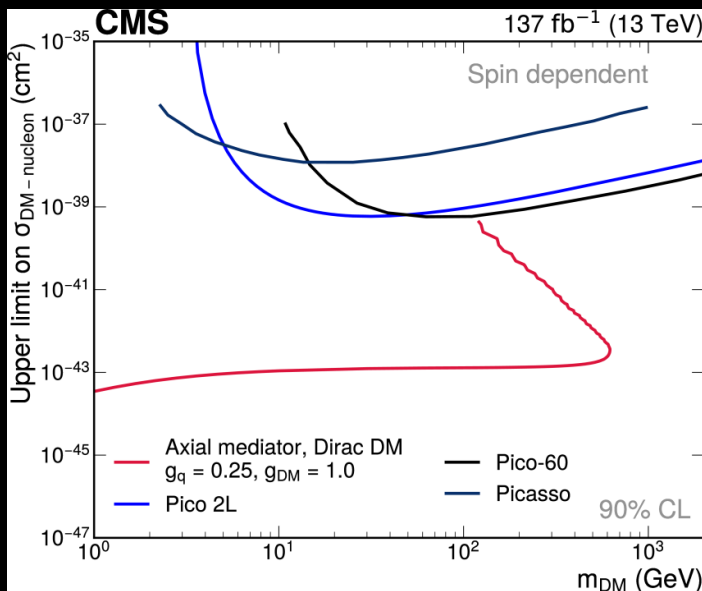
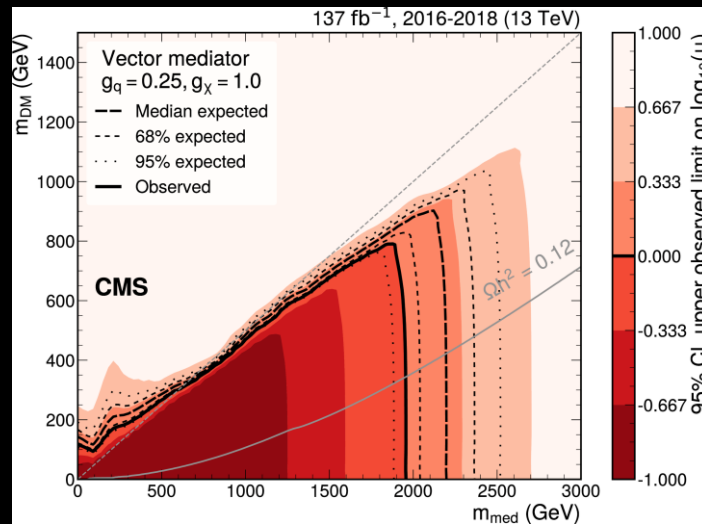
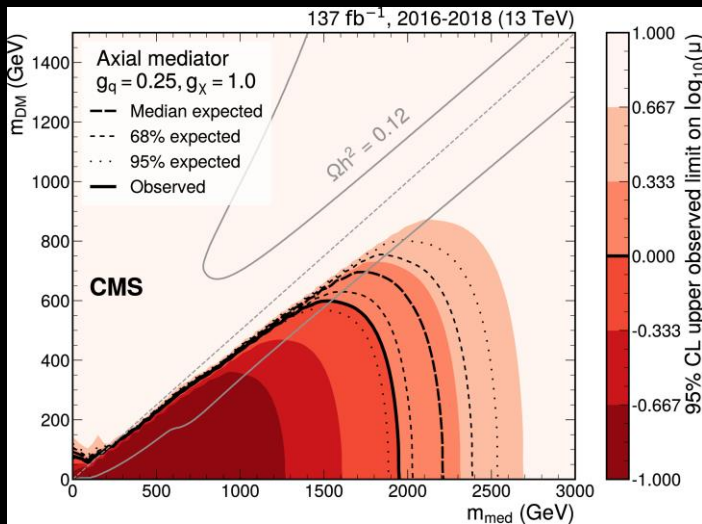


Mono- $t$  [3]



- 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

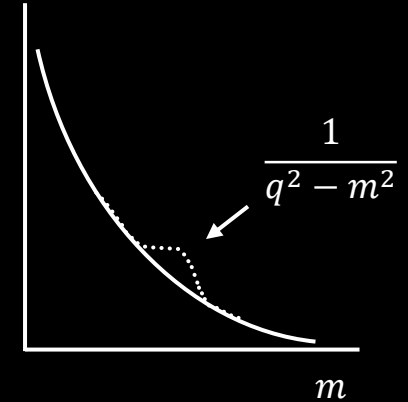
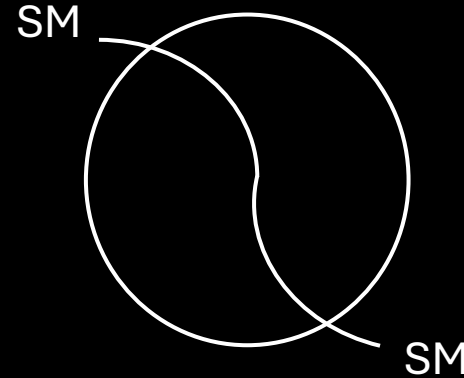
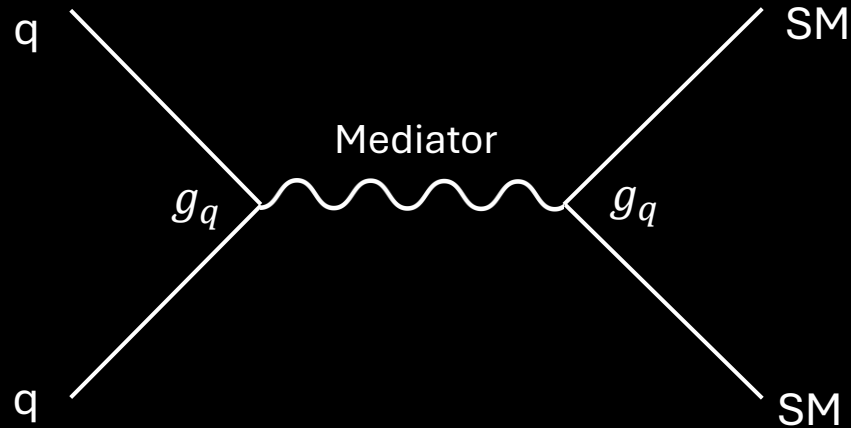
# Limits from Mono-Jet



- 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  $m_{\text{DM}}$  and  $m_{\text{med}}$ 
  - Can interpret these as limits on  $\sigma_{\text{DM-nucleon}}$
  - 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

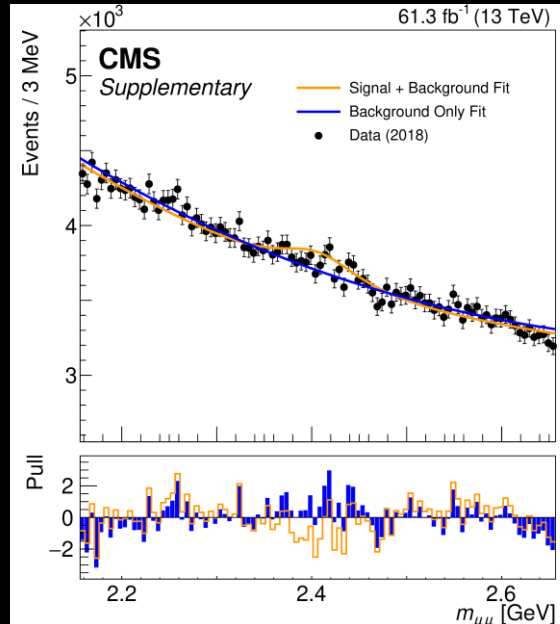
# Resonance Searches

[1] - [JHEP 12 \(2023\) 070](#)

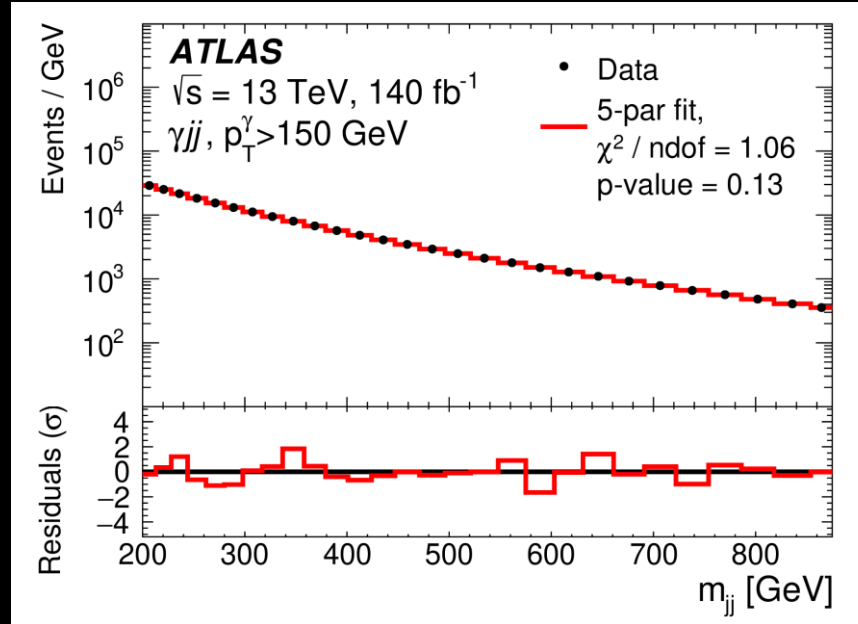
[2] - [arXiv:2403.08547](#)

[3] - [Phys. Lett. B 796 \(2019\) 68](#)

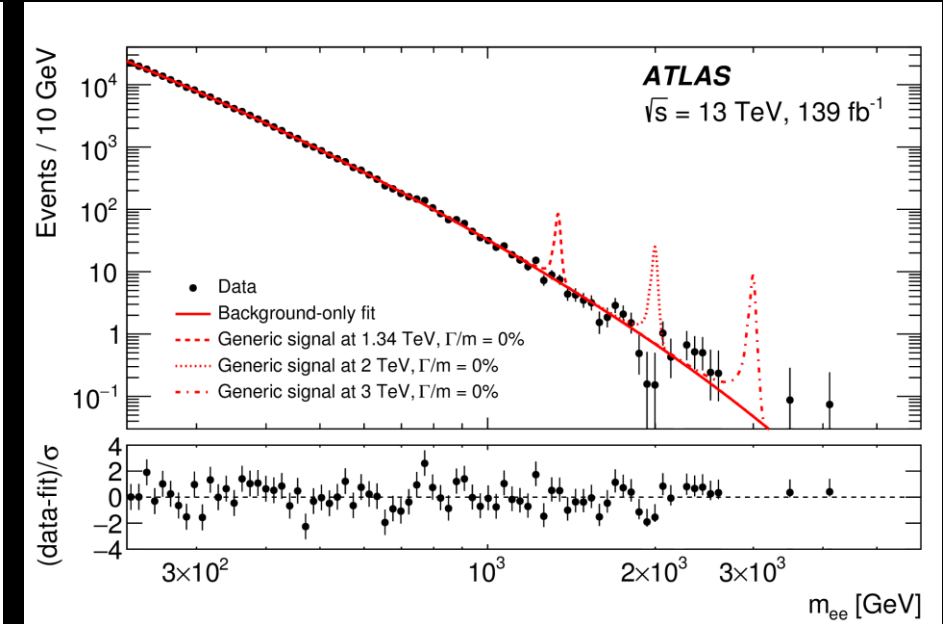
## Low-mass Dimuon [1]



## Dijet [2]

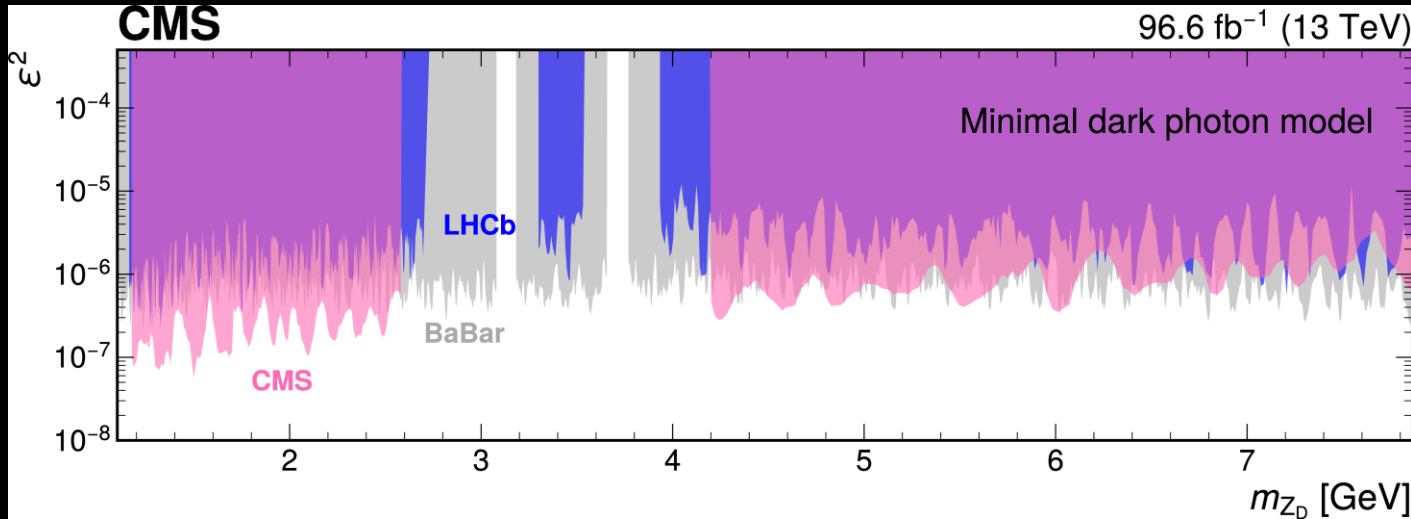


## High-mass Dilepton [3]

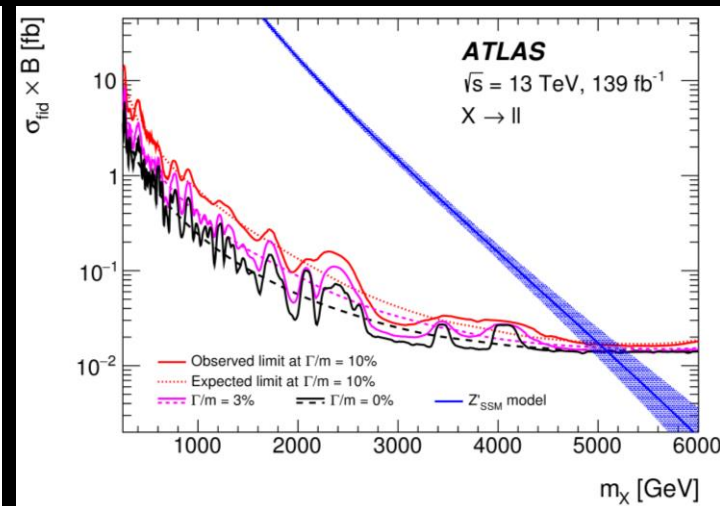
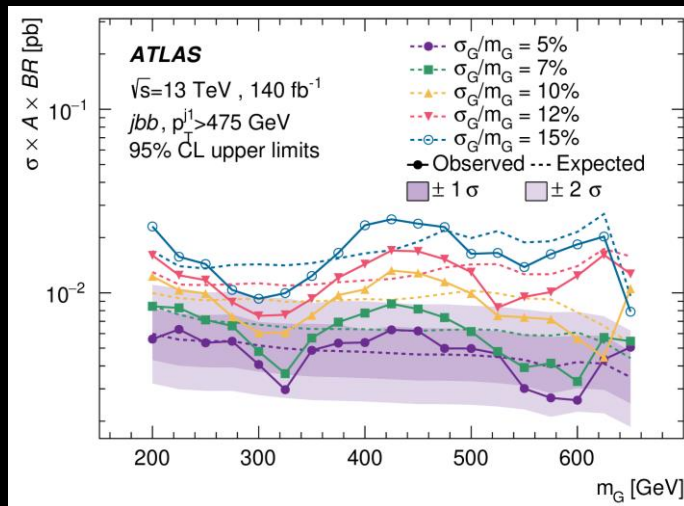


- Target high masses ( $\sim$ TeV) via traditional triggers
- Target low masses ( $\sim$ GeV) via production of another particle to trigger on (e.g. photon + 2 jets)
- Enhance sensitivity to low masses via **high-rate (“scouting”) triggers** that select a larger fraction of signal-like events, but record 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

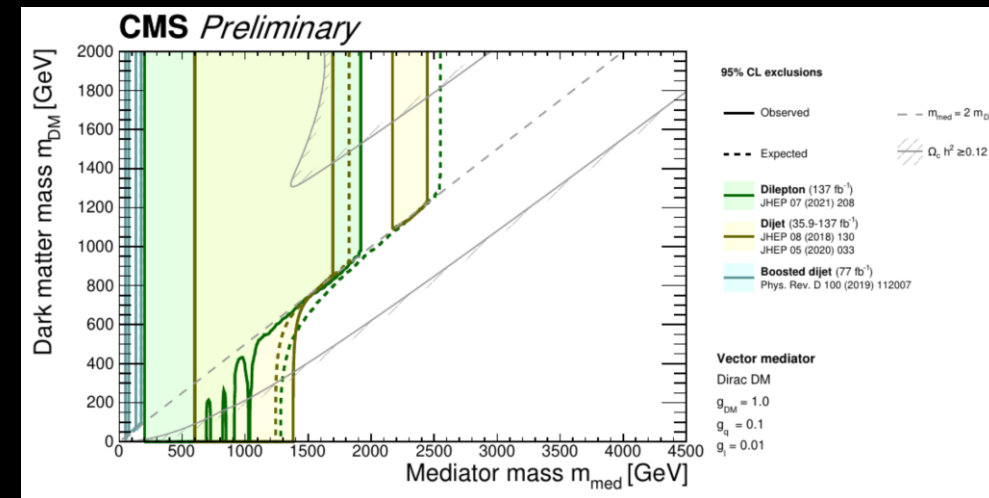
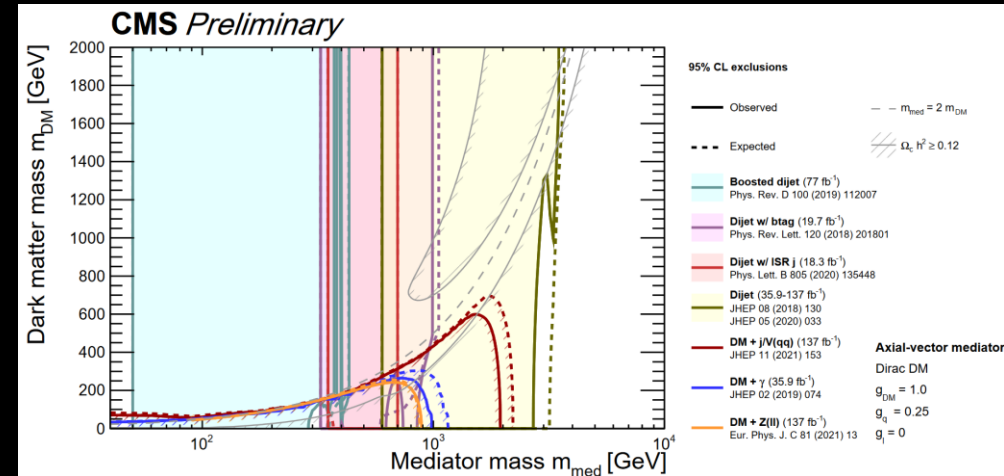
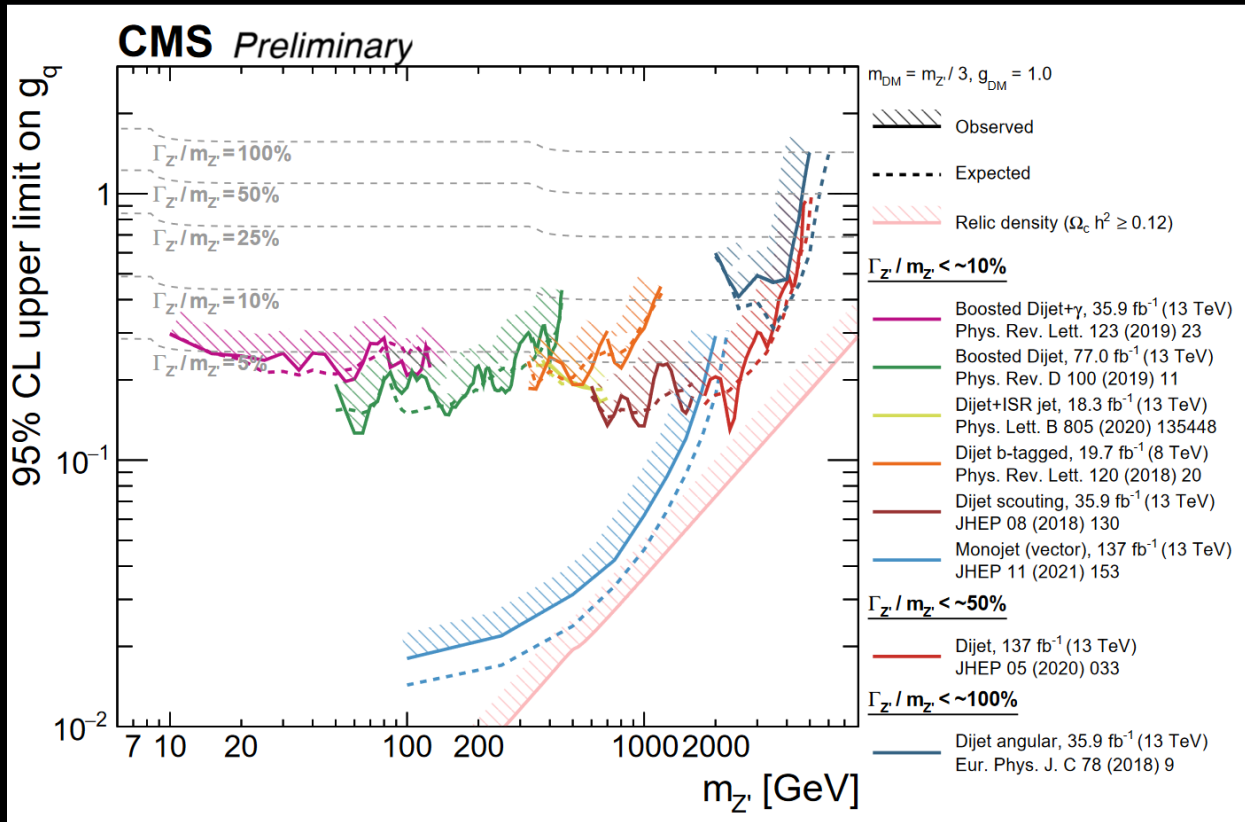
# Results from (some) Resonance Searches



- 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  $\epsilon$  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  $\Gamma$

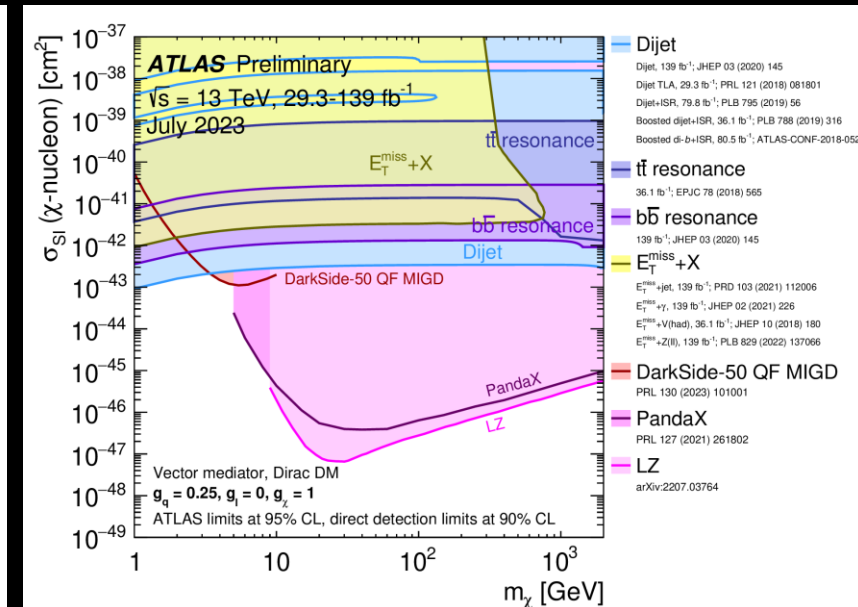
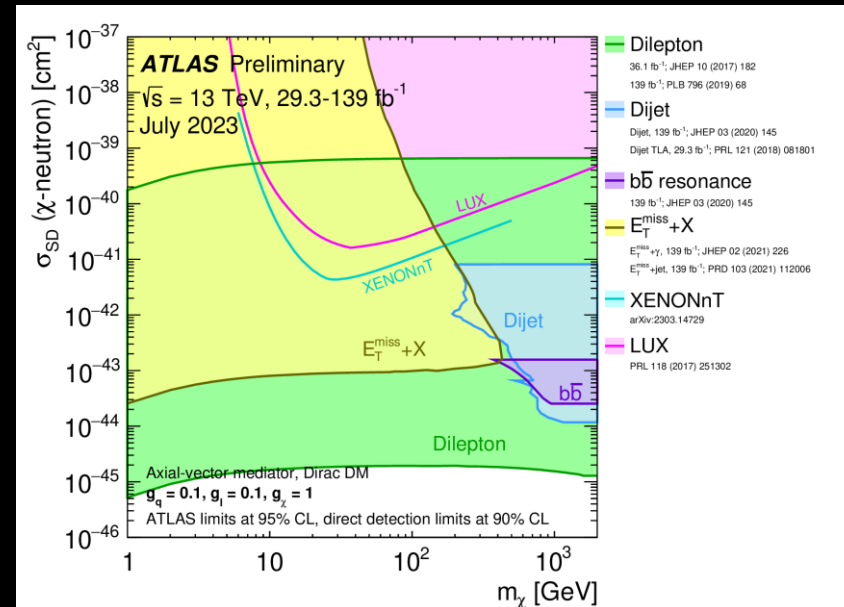
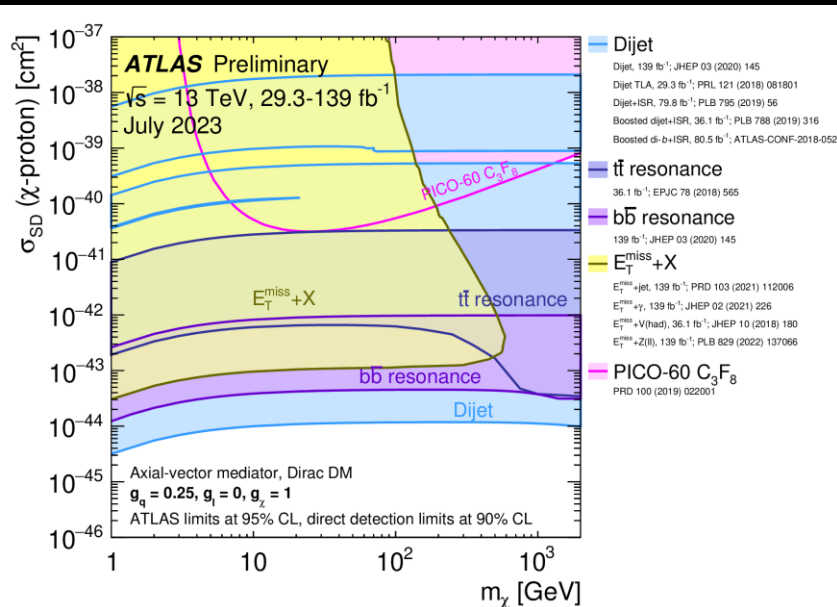


# Ground Covered



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

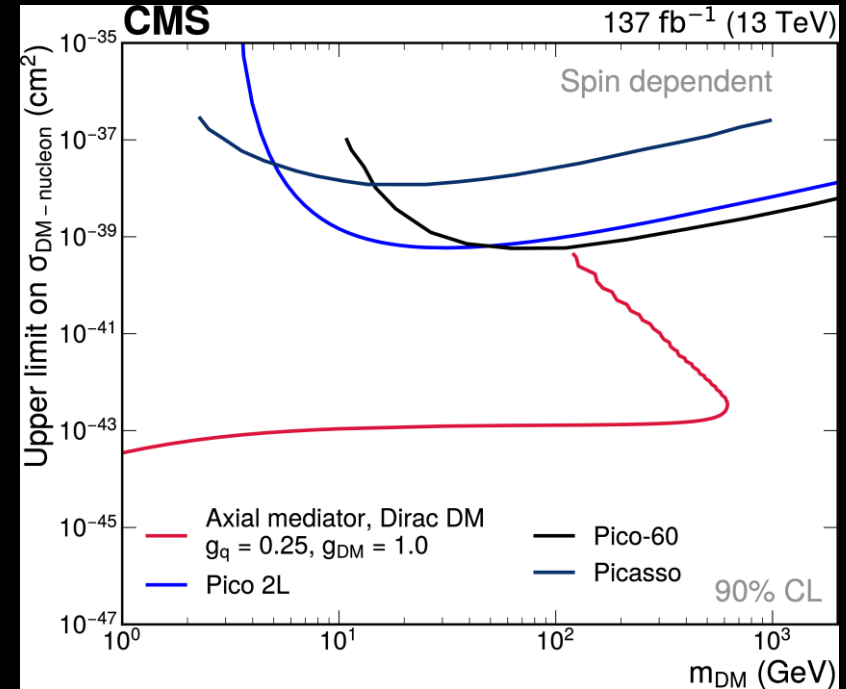
# Colliders and Direct Detection



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

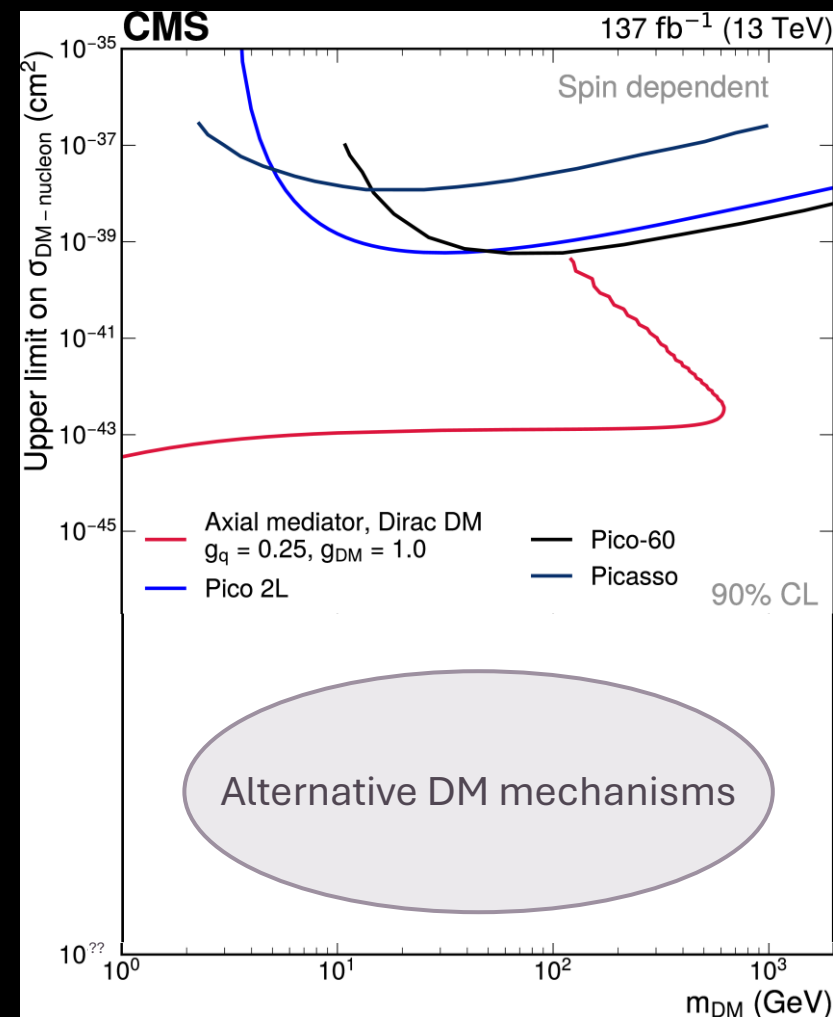
# Unconventional Signatures

- 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!)



# Unconventional Signatures

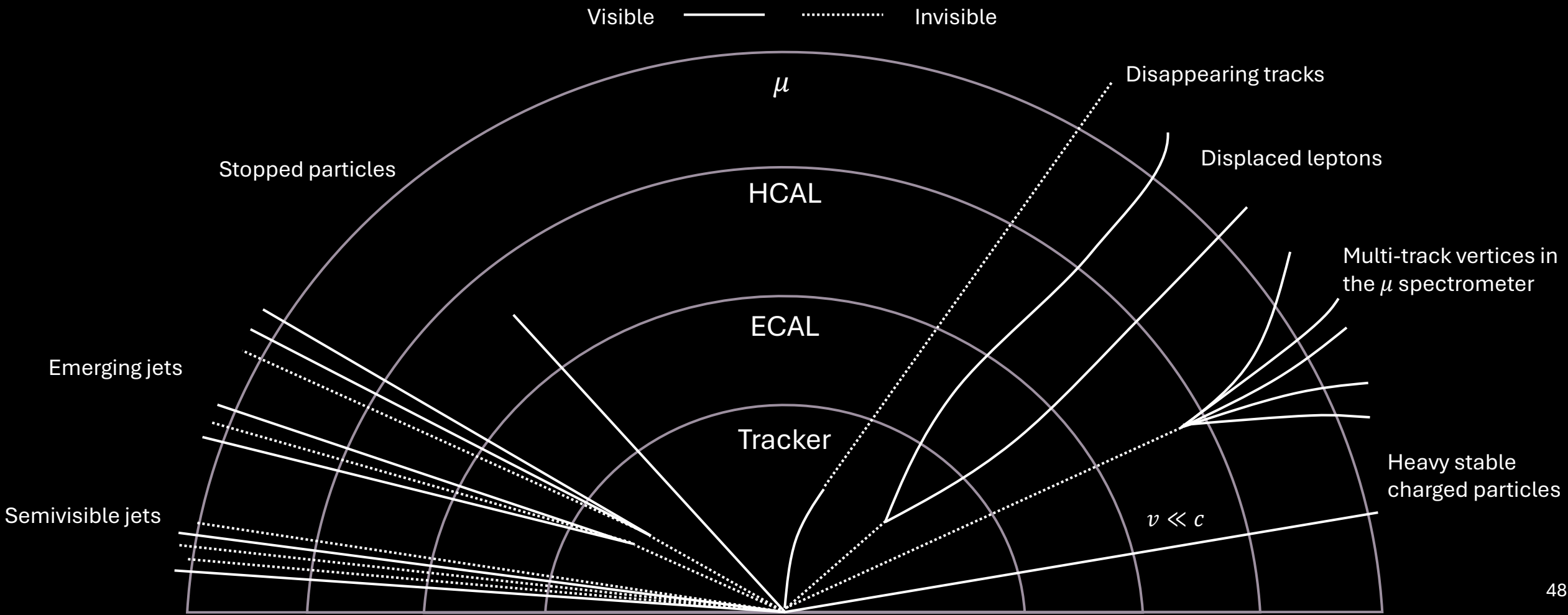
- First-generation of searches at colliders found no convincing evidence for BSM
  - Excellent limits on simplified models have been placed
  - New ideas (scouting, ML, etc.) are still able to improve sensitivity, but we are reaching the limits of what can be done with current colliders
  - Will be re-iterated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

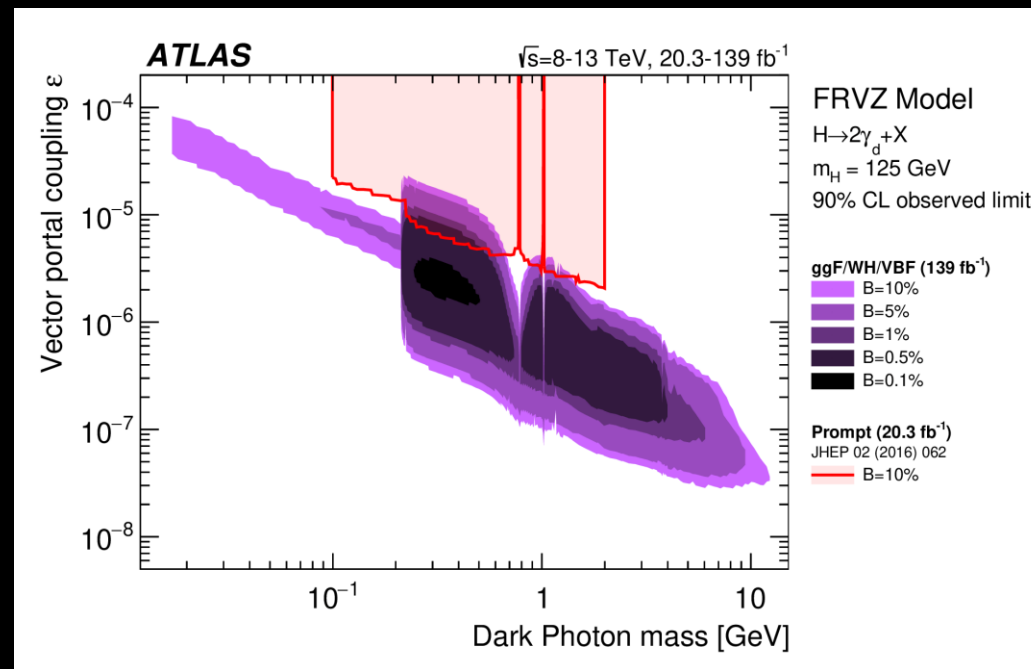
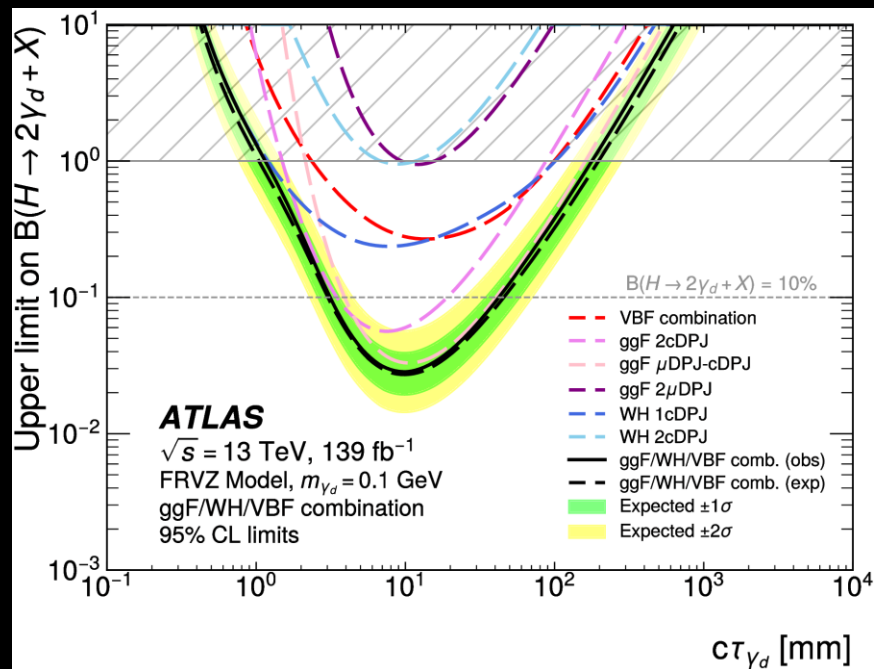
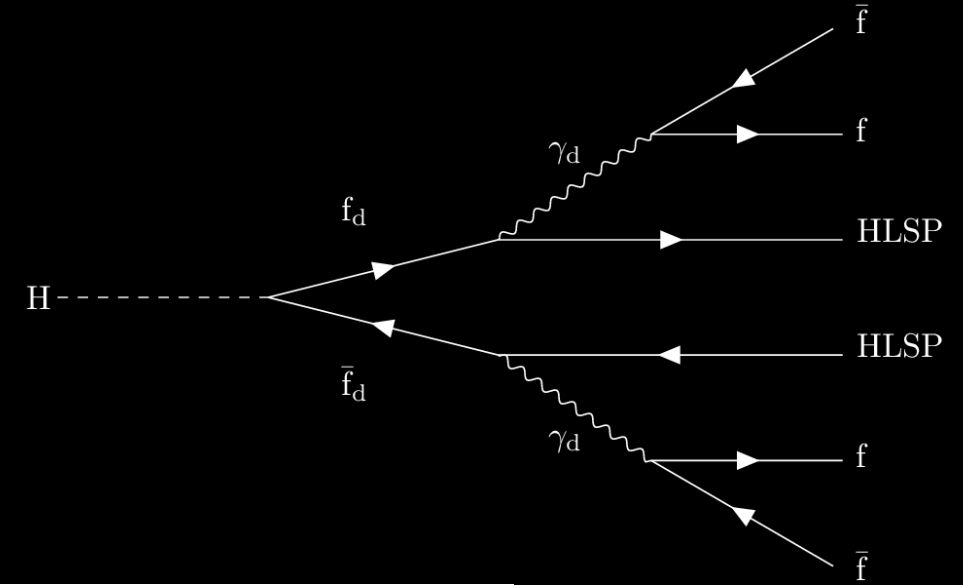
Need new approaches to reconstruct these signatures:

- 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**

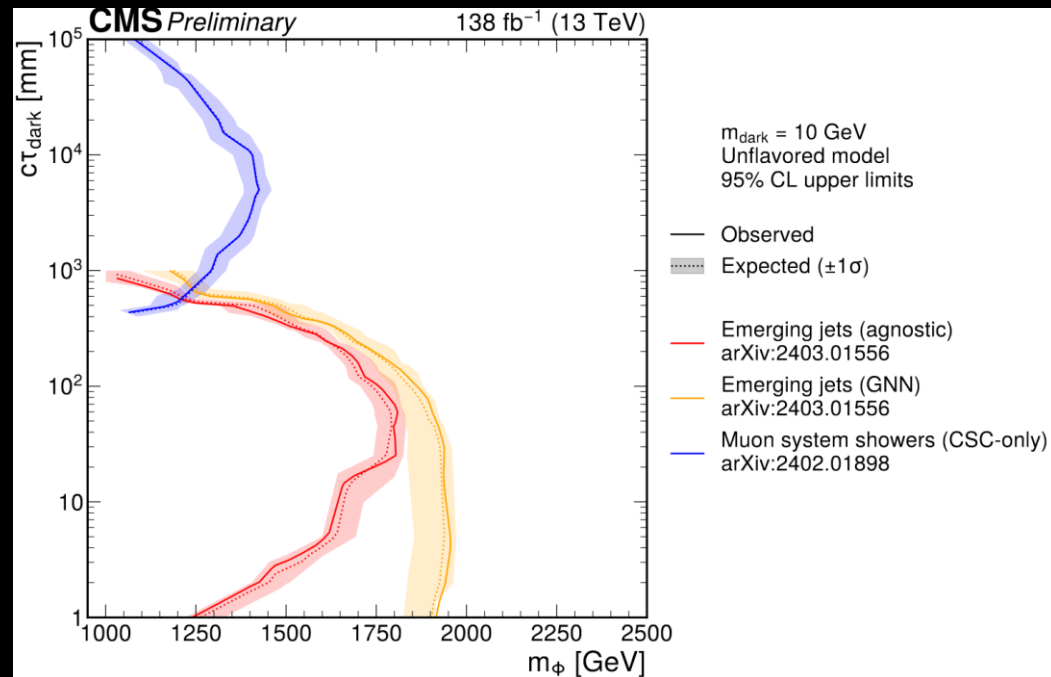
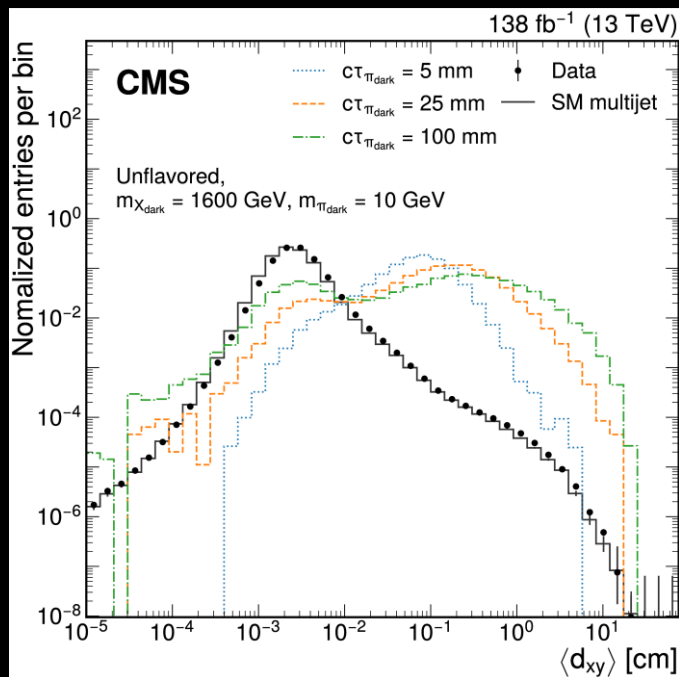
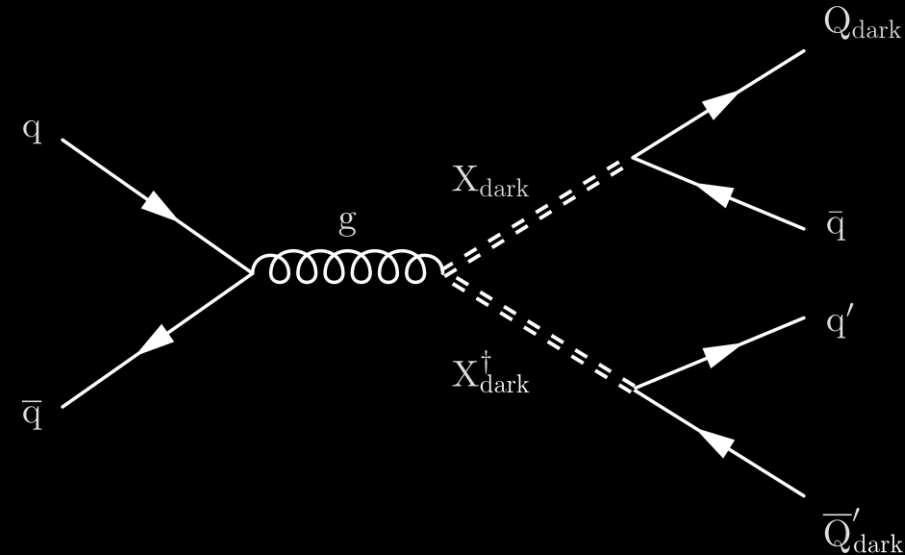
# Long Lived Dark Photons

- Displaced, collimated SM fermions reconstructed in the calorimeter or  $\mu$  spectrometer (MS)
  - Hidden lightest stable particle contributes only to  $p_T^{miss}$
- Two new triggers to target signal:
  - 3  $\mu$ 's using the MS only [JINST 15 \(2020\) P09015](#)
  - 1  $\mu$  in the MS + 1  $\mu$  within  $\Delta R < 0.4$  of the first [JINST 8 \(2013\) P07015](#)



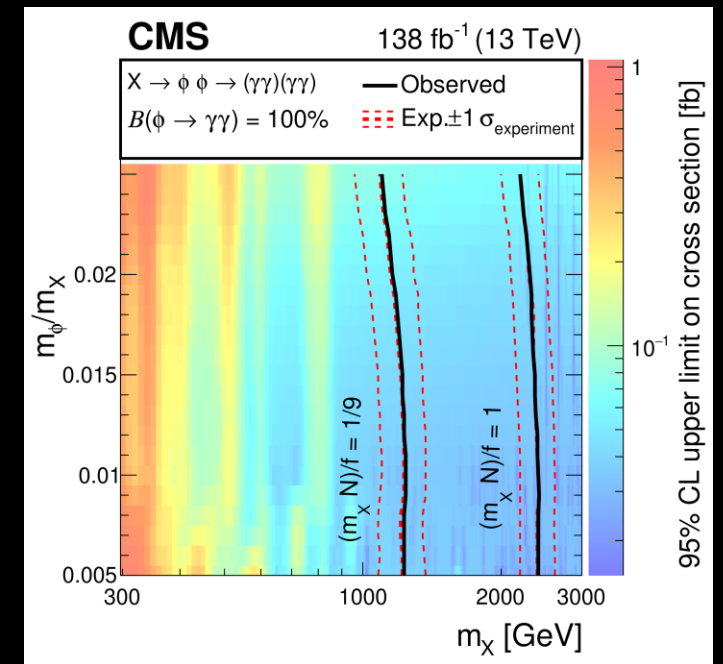
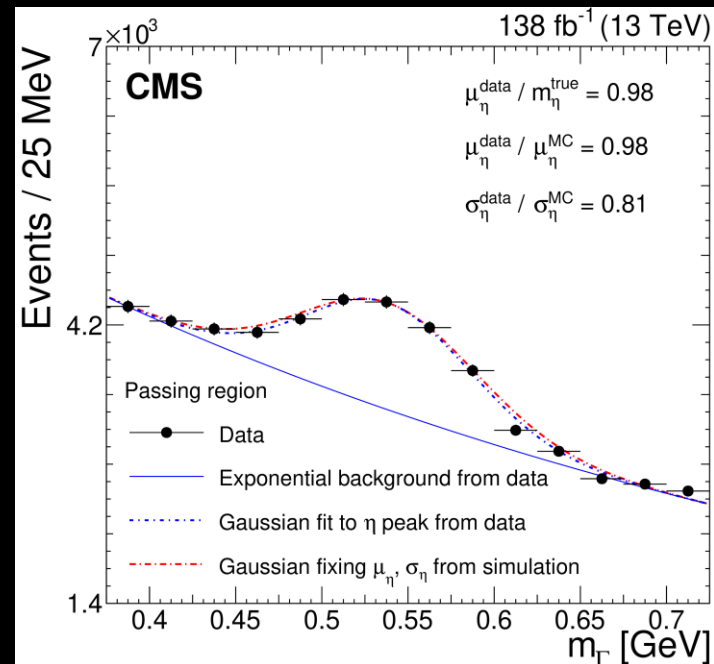
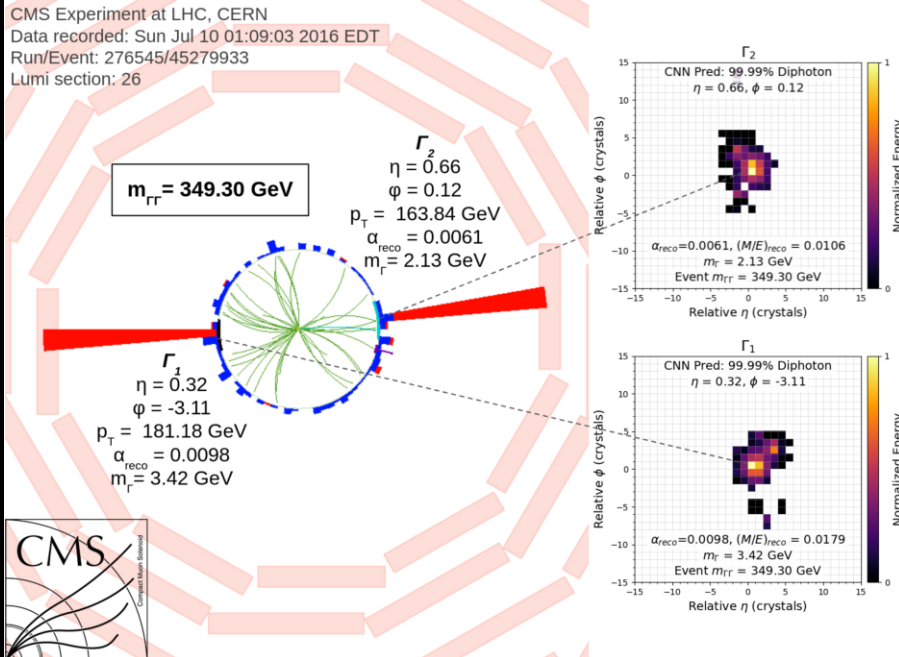
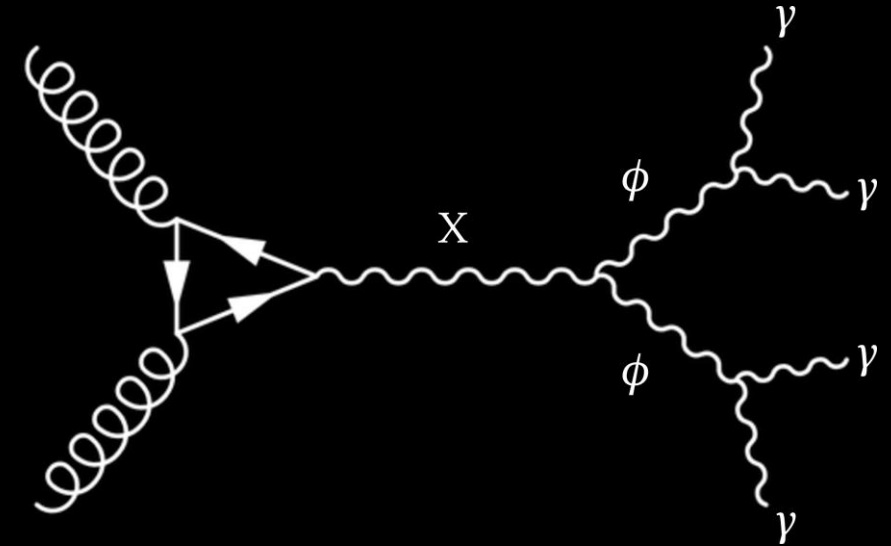
# Emerging Jets

- $X_{dark}$  produced, travel  $\sim$ 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  $\phi$  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  $\gamma$ , two  $\gamma$ 's, or hadronic activity
- Second CNN to reconstruct diphoton mass
- Validate with boosted  $\pi^0, \eta$  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