CMS Searches for Feebly Interacting Particles and Light Dark Matter

Albert De Roeck
Imperial College London

11th April 2025
Genova, Italy

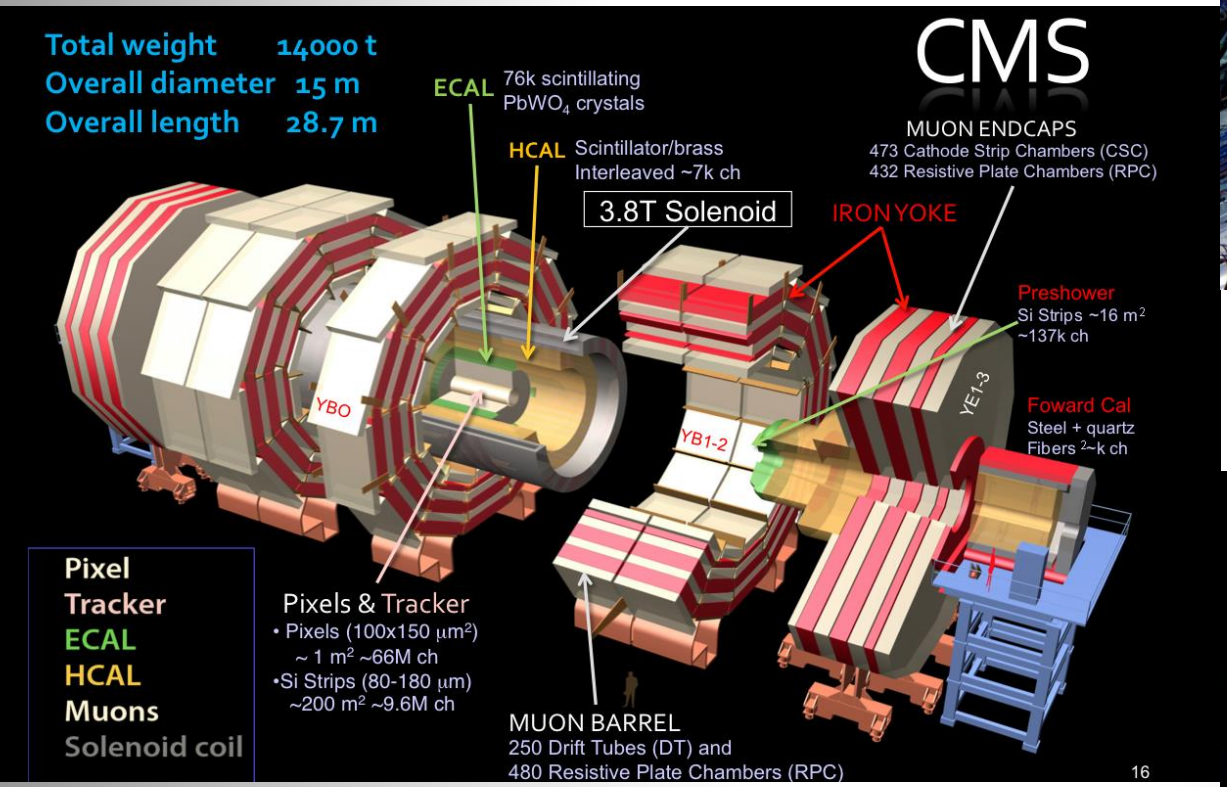
LDMA '25

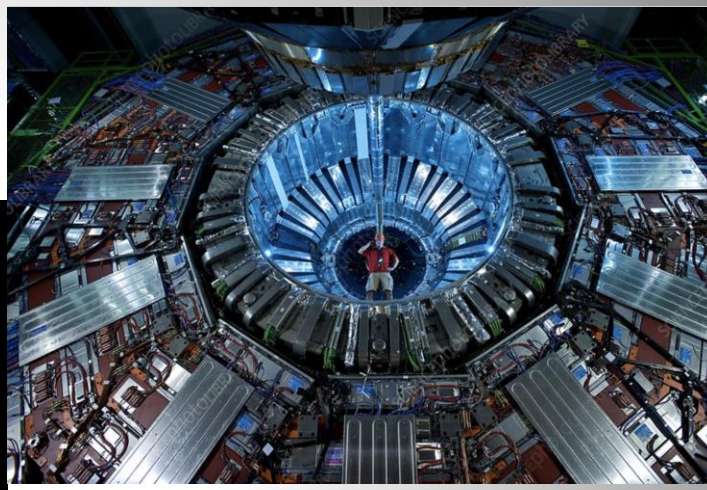
CERN

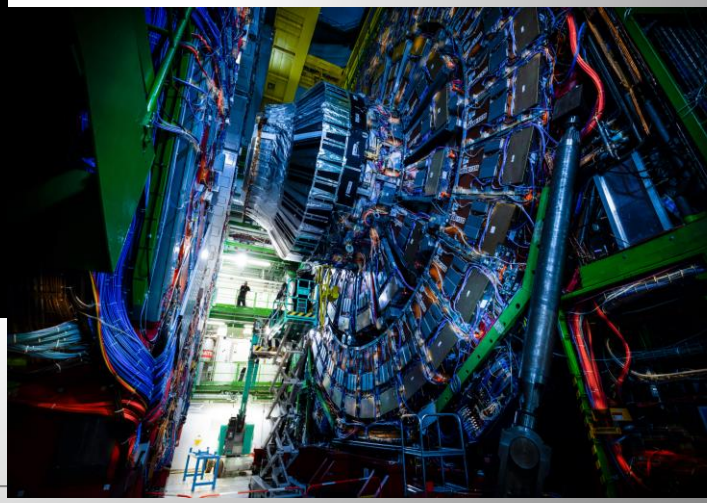
The LHC: Run-3 is Ongoing!

- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 27 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM Energy
  - Collected ~ 150 fb^{-1}
- 2022-2026: Run-3 at 13.6 TeV CM Energy
  - Expect ~ 380 fb^{-1} to be delivered

The CMS Experiment

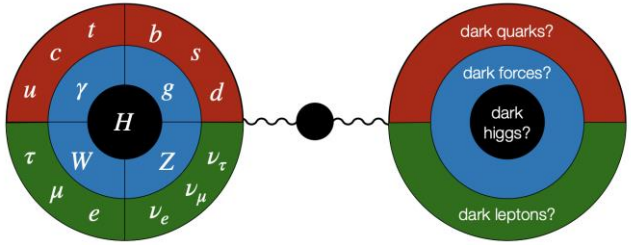






Dark Matter Searches@CMS : Evolution

- First Searches: Missing Transverse Energy+X (WIMPs)
- Recently: Searches for new dark sector particle candidates
  - Higgs direct decay to dark matter
  - Explore an extended Dark Sector
    - Dark Photons
    - Dark Higgses
    - Multiple Dark Matter particles (with DM decays)
    - Dark Mesons, Dark Showers etc.
  - Axion like particles (ALPs), HNLs
  - Millicharged particles



- Considering UV complete models in addition to simplied models, eg.
  - 2HDM+a So far the most used benchmark model
  - Higgs singlet mixing models, vMSM…
  - (SUSY)
- Connection with Low DM mass searches (e.g.fixed target)

CMS Dark Sector Review Paper

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-106
2024/05/24

CMS-EXO-23-005

Dark sector searches with the CMS experiment

The CMS Collaboration*

Abstract

Astrophysical observations provide compelling evidence for gravitationally interacting dark matter in the universe that cannot be explained by the standard model of particle physics. The extraordinary amount of data from the CERN LHC presents a unique opportunity to shed light on the nature of dark matter at unprecedented collision energies. This Report comprehensively reviews the most recent searches with the CMS experiment for particles and interactions belonging to a dark sector and for dark-sector mediators. Models with invisible massive particles are probed by searches for signatures of missing transverse momentum recoiling against visible standard model particles. Searches for mediators are also conducted via fully visible final states. The results of these searches are compared with those obtained from direct-detection experiments. Searches for alternative scenarios predicting more complex dark sectors with multiple new particles and new forces are also presented. Many of these models include long-lived particles, which could manifest themselves with striking unconventional signatures with relatively small amounts of background. Searches for such particles are discussed and their impact on dark-sector scenarios is evaluated. Many results and interpretations have been newly obtained for this Report.

Submitted to Physics Reports

Dark sectors paper reviews 40 CMS analyses in the quest to find FIPs and Dark Matter signatures

This talk is based on the recent CMS Dark Sector Review Paper (+ some updates) reporting the latest searches in the Dark Sector: 2405.13778

Focus mostly on Run-2 data analyses

Two other related review papers:

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-068
2024/03/26

CMS-EXO-23-007

Enriching the physics program of the CMS experiment via data scouting and data parking

The CMS Collaboration*

Abstract

Specialized data-taking and data-processing techniques were introduced by the CMS experiment in Run 1 of the CERN LHC to enhance the sensitivity of searches for new physics and the precision of standard model measurements. These techniques, termed data scouting and data parking, extend the data-taking capabilities of CMS beyond the original design specifications. The novel data-scouting strategy trades complete event information for higher event rates, while keeping the data bandwidth within limits. Data parking involves storing a large amount of raw detector data collected by algorithms with low trigger thresholds to be processed when sufficient computational power is available to handle such data. The research program of the CMS Collaboration is greatly expanded with these techniques. The implementation, performance, and physics results obtained with data scouting and data parking in CMS over the last decade are discussed in this Report, along with new developments aimed at further improving low-mass physics sensitivity over the next years of data taking.

To be submitted to Physics Reports

*See Appendix B for the list of collaboration members

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-095
2024/05/29

CMS-EXO-23-006

Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV at the CMS experiment

The CMS Collaboration*

Abstract

The LHC has provided an unprecedented amount of proton-proton collision data, bringing forth exciting opportunities to address fundamental open questions in particle physics. These questions can potentially be answered by performing searches for very rare processes predicted by models that attempt to extend the standard model of particle physics. The data collected by the CMS experiment in 2015–2018 at a center-of-mass energy of 13 TeV help to test the standard model at the highest precision ever and potentially discover new physics. An interesting opportunity is presented by the possibility of new fermions with masses ranging from the MeV to the TeV scale. Such new particles appear in many possible extensions of the standard model and are well motivated theoretically. They may explain the appearance of three generations of leptons and quarks, the mass hierarchy across the generations, and the nonzero neutrino masses. In this report, the status of searches targeting vector-like quarks, vector-like leptons, and heavy neutral leptons at the CMS experiment is discussed. A complete overview of final states is provided together with their complementarity and partial combination. The discovery potential for several of these searches at the High-Luminosity LHC is also discussed.

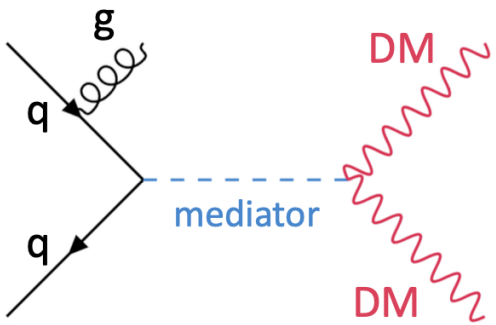
Submitted to Physics Reports

*See Appendix B for the list of collaboration members

CMS Dark Sector Signatures

Signatures

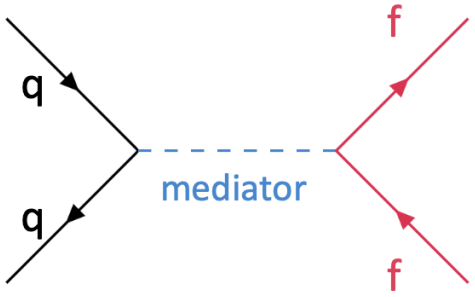
Invisible final states



DM + ISR

e.g. mono-X searches

Fully visible and prompt signatures

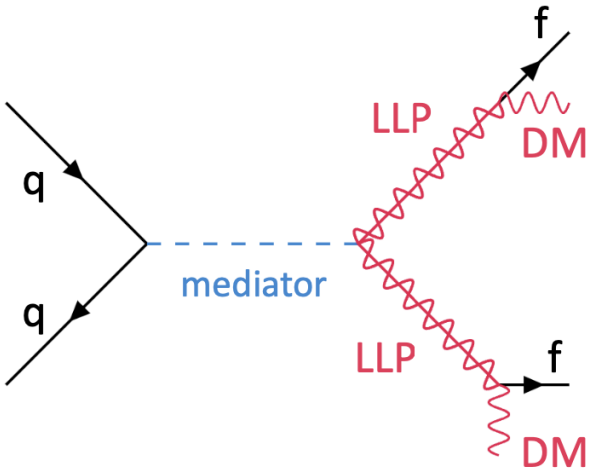


If **SM →mediator →DM,**

then **SM →mediator → SM**

e.g. dijet searches

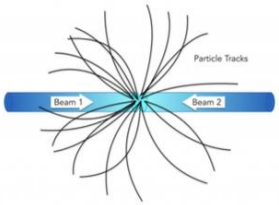
Long-lived particle (LLP) signatures



Rich phenomenology available if have more complicated dark sectors, such as LLP

CMS Data Streams in Run-2/Run-3

Standard + Scouting + Parked data streams



LHC

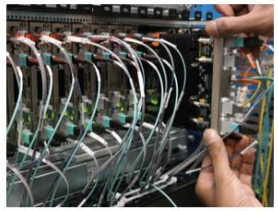
40 MHz

Level 1 trigger

Fast readout (4μs latency)

Coarse granularity

ASICs and FPGAs



~100 kHz

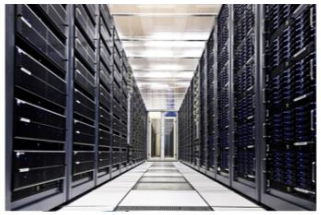
High Level Trigger

Slower readout (300 ms latency)

Full detector readout

CMSSW on commercial PCs

("HLT Farm")



Standard data stream

Prompt offline reconstruction

Full event content

~1 kHz, ~1000 MB/s

Scouting data stream

No offline reconstruction

Only HLT objects and calibrations

~5 kHz, ~40 MB/s

Parking data stream

Delayed offline reconstruction

Full event content

~3 kHz, ~2000 MB/s

With scouting and dedicated selections,
can access down to **~1 GeV dark photons**

Trigger strategies to increase the rate for dedicated signatures

Scouting and parking: see 2403.16134

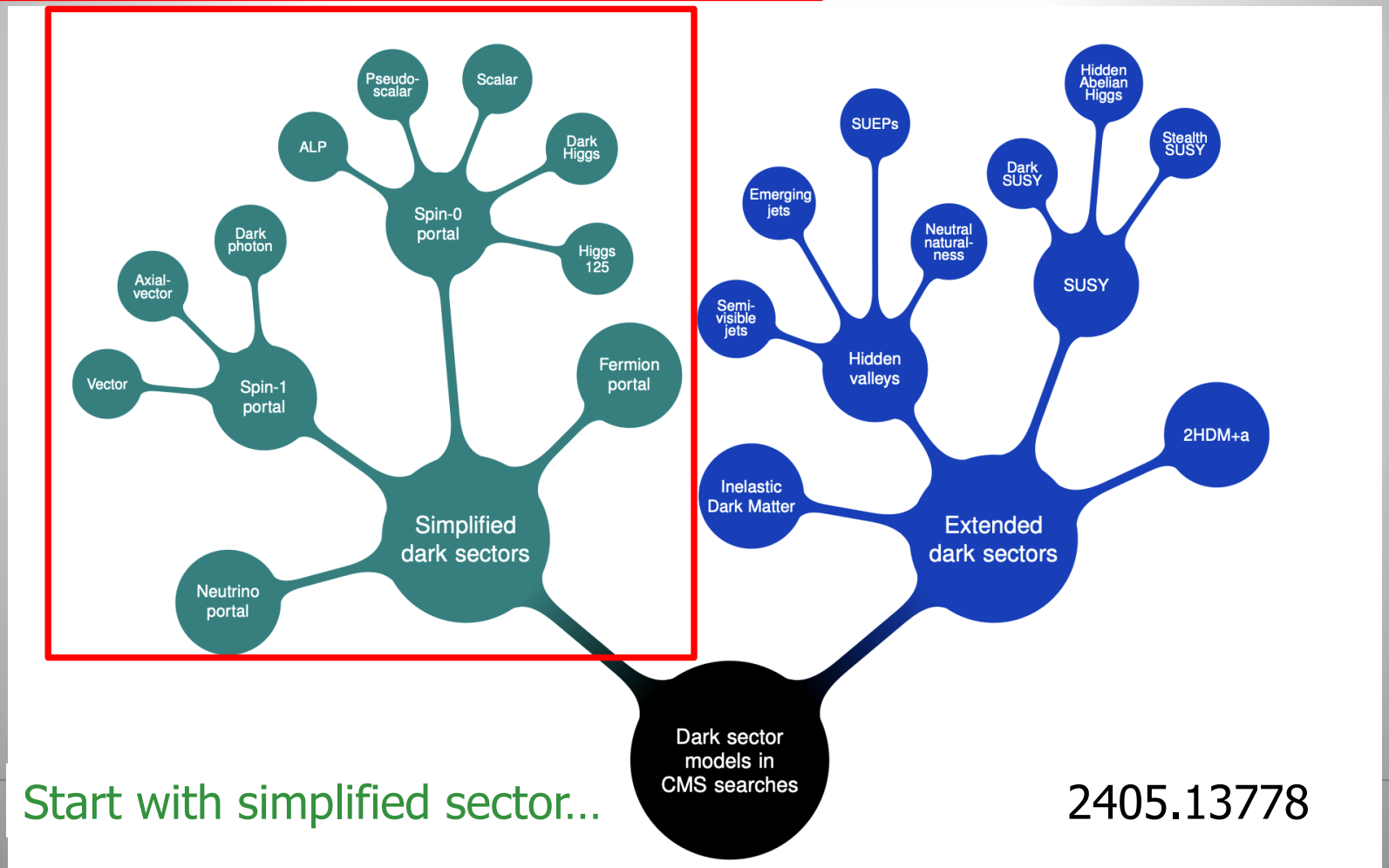
Model Landscape

Simplified dark sector

- Usually have a DM candidate + a mediator particle
- Includes the usual FIP portals (vector, scalar, pseudoscalar and fermion)

Extended dark sectors

- Could be more complicated dark scenarios with rich dynamics

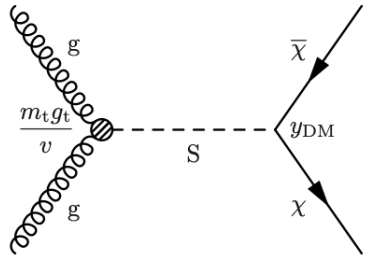


Start with simplified sector...

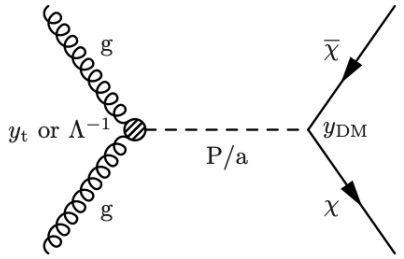
2405.13778

Scalar and Pseudo-Scalar Portals

Scalar Mediator

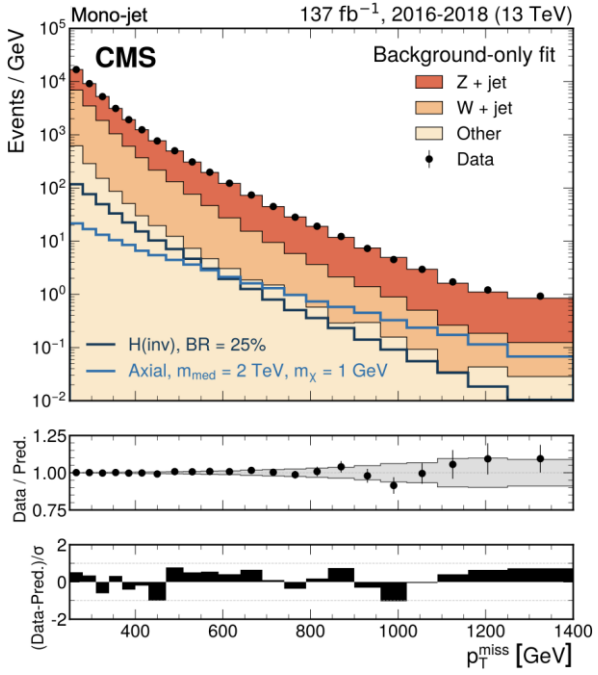


Pseudoscalar Mediator

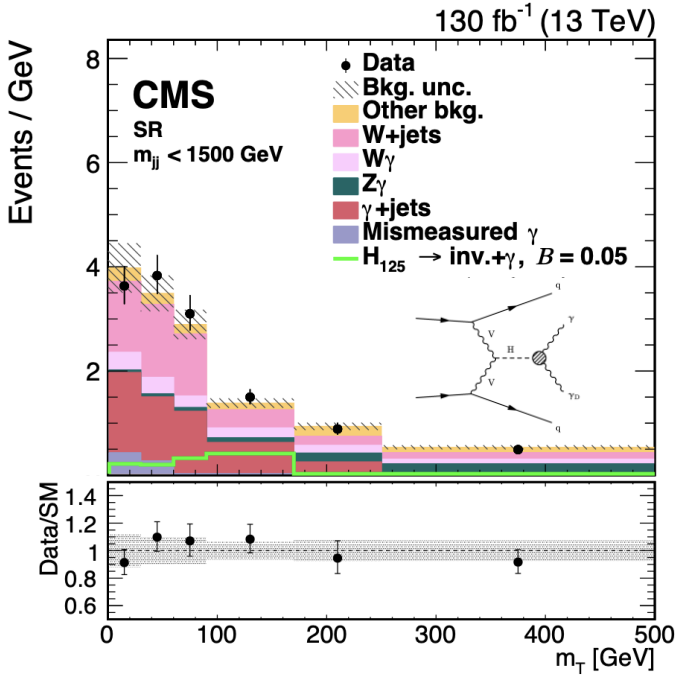


Invisible final states, mediator coupling to DM

Mono-jet

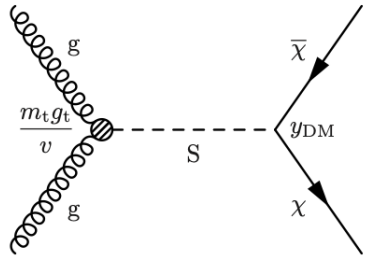


Dark photon in VBF Higgs

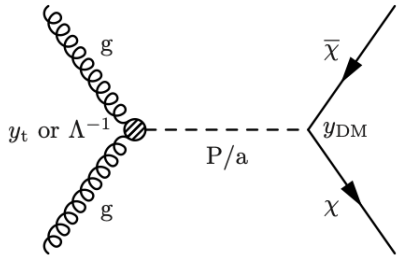


Scalar and Pseudo-Scalar Portals

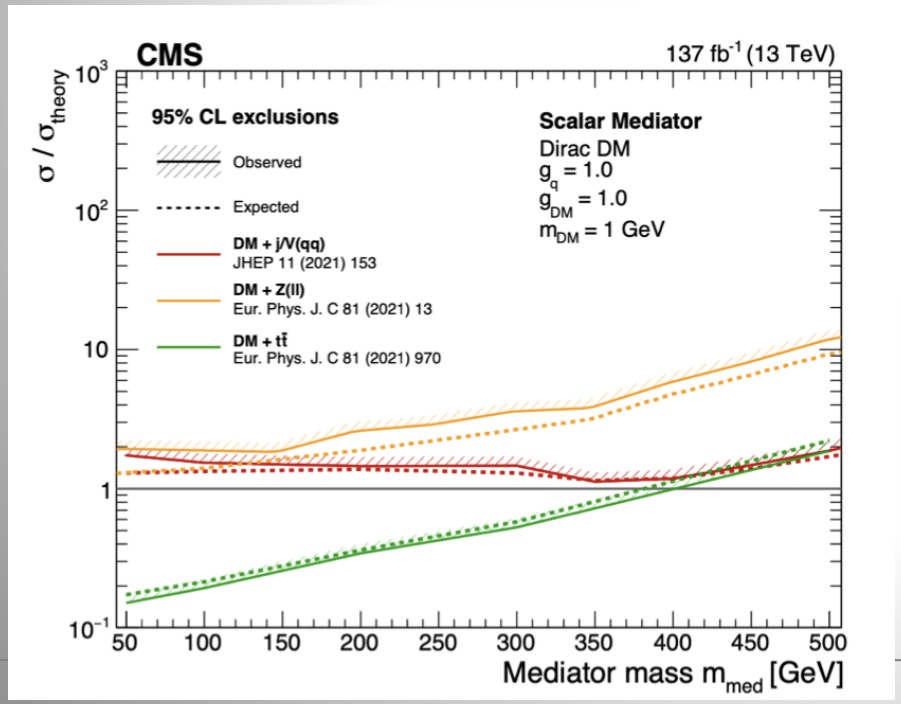
Scalar Mediator

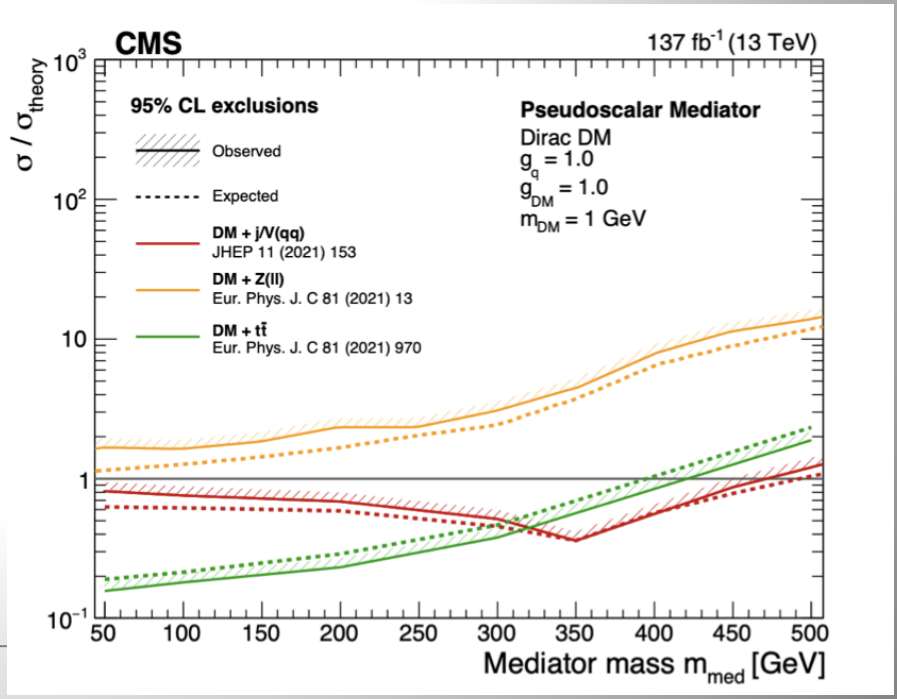


Pseudoscalar Mediator



Invisible final states, mediator coupling to DM



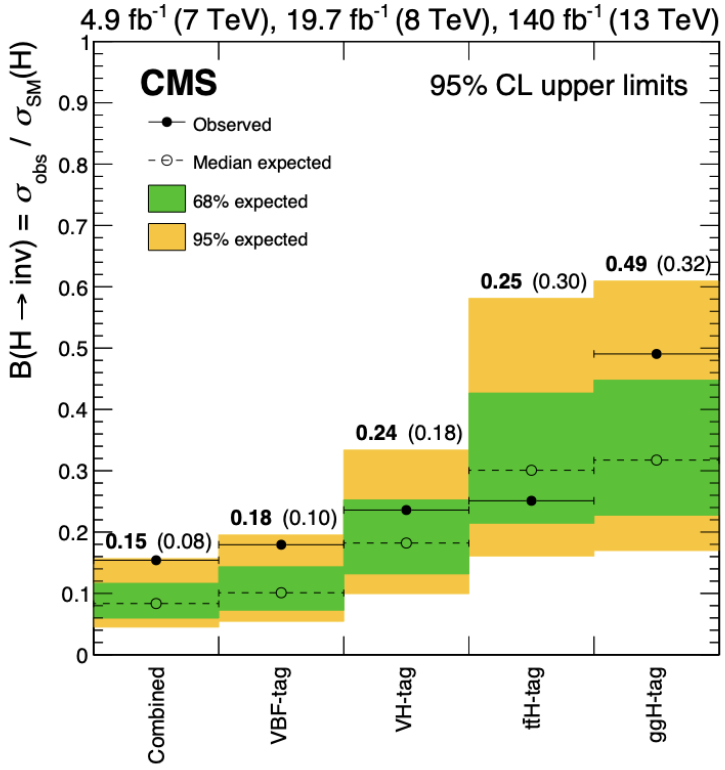


SM Higgs Boson Portal

Higgs boson acts as the mediator between SM and DM

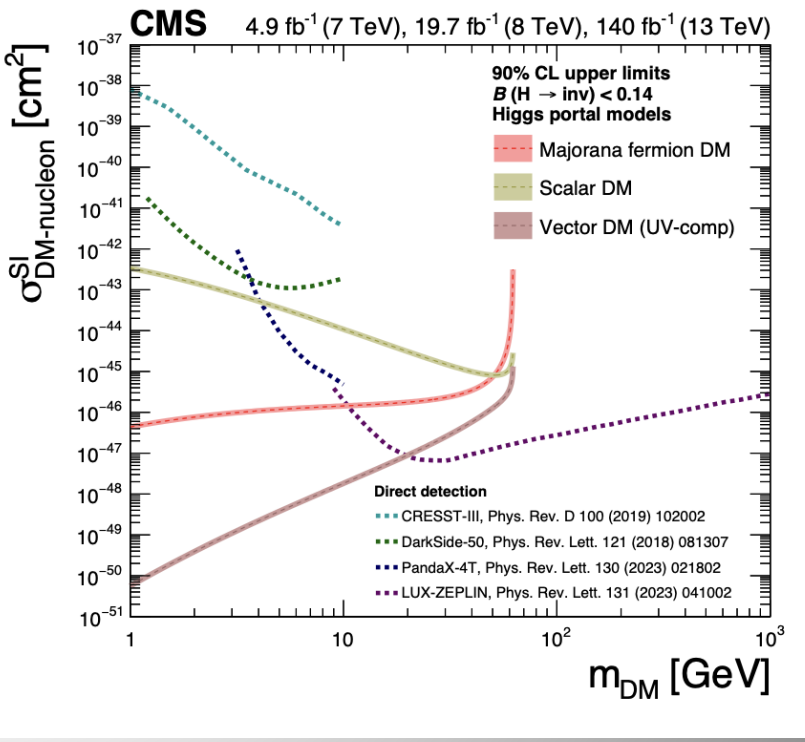
95% CL upper limits from

H→inv combination (HIG-21-007)



90% CL upper limits on the spin-independent DM-nucleon scattering cross section

Provides comparison with direct detection experiments

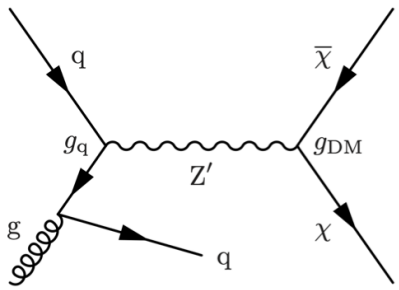


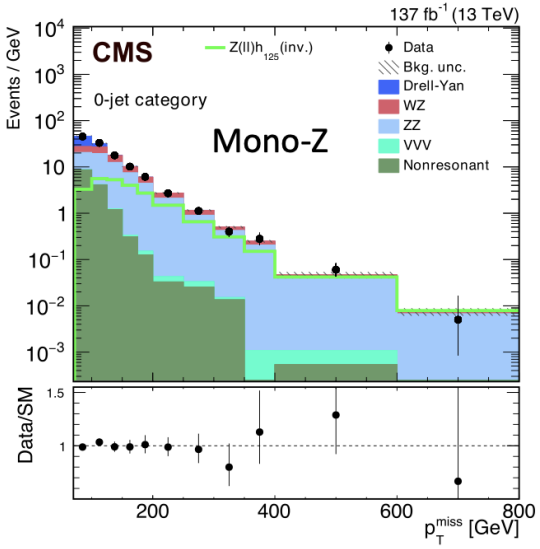
Vector and Axial Portals

Vector and axial-vector mediators arise from a broken U(1) symmetry, with couplings to the SM and the dark sector

Invisible final states, mediator coupling to DM

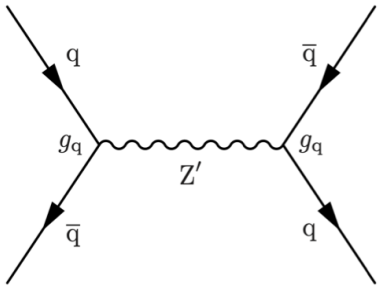
→ Mono-X searches

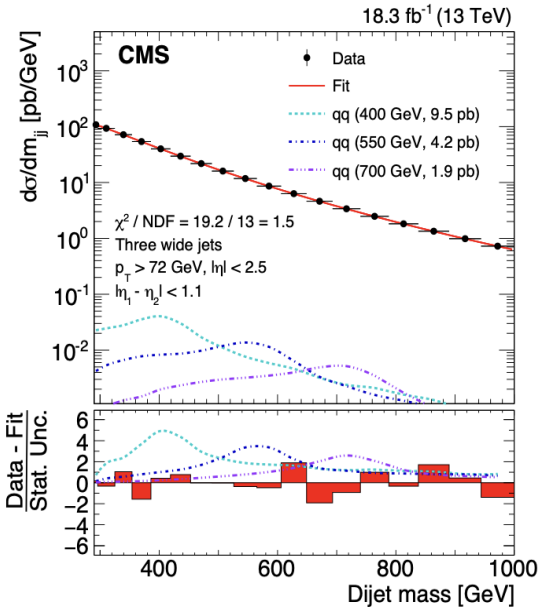




Visible final states, mediator coupling to SM

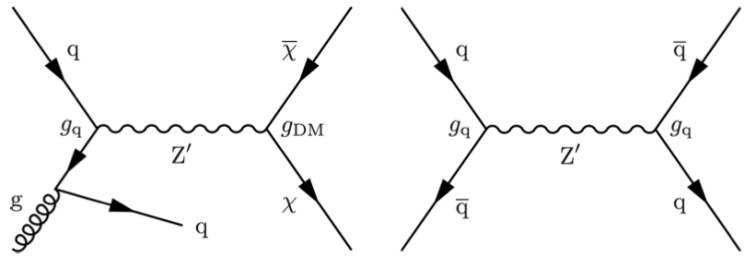
→ Dijet searches



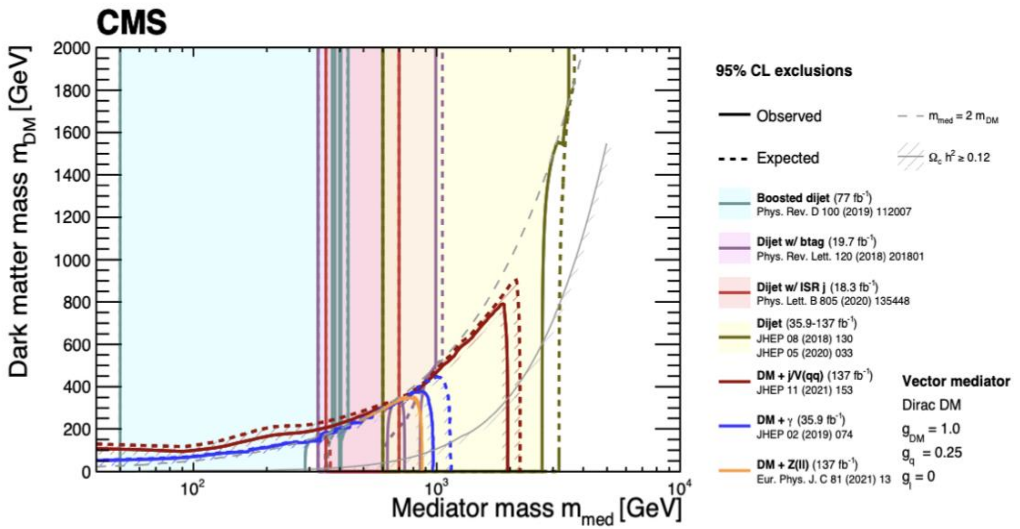


Vector and Axial Portals

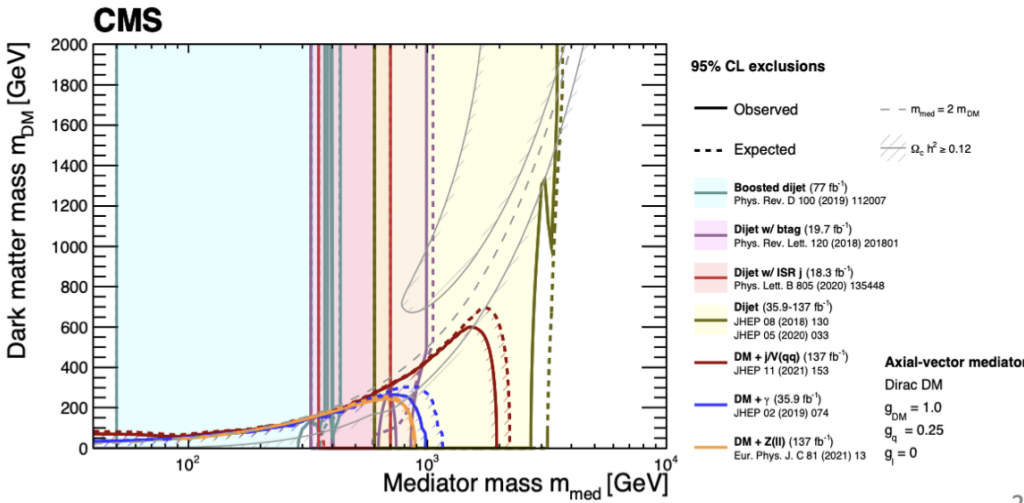
Vector and axial-vector mediators from a broken symmetry, with couplings to SM and dark sector



Vector Mediator



Axial-Vector Mediator



Included searches:

- Dijet searches (visible final states, mediator coupling to SM)
- Mono-X searches (invisible final states, mediator coupling to DM)

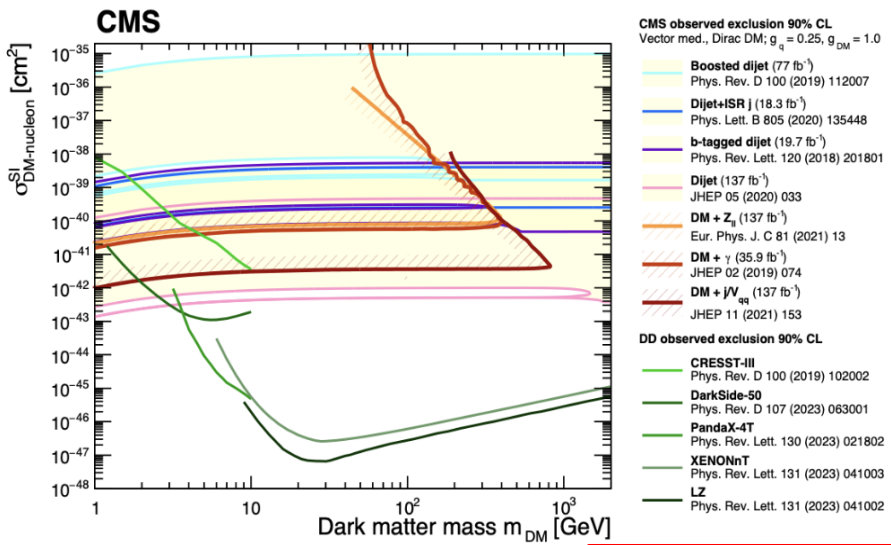
-> Benchmark scenarios from LHC DM WG recommendations

arXiv:1603.04156

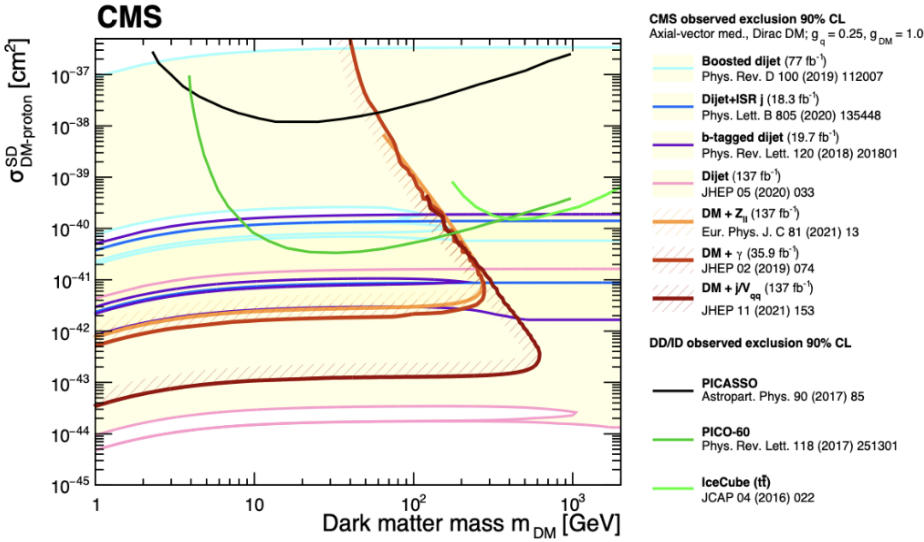
Comparison with Direct Detection

- Vector mediator → spin-independent DM-nucleon scattering cross section
- Axial-vector mediator → spin-dependent DM-nucleon scattering cross section
- Allows for comparison with direct-detection experiments

Spin-Independent



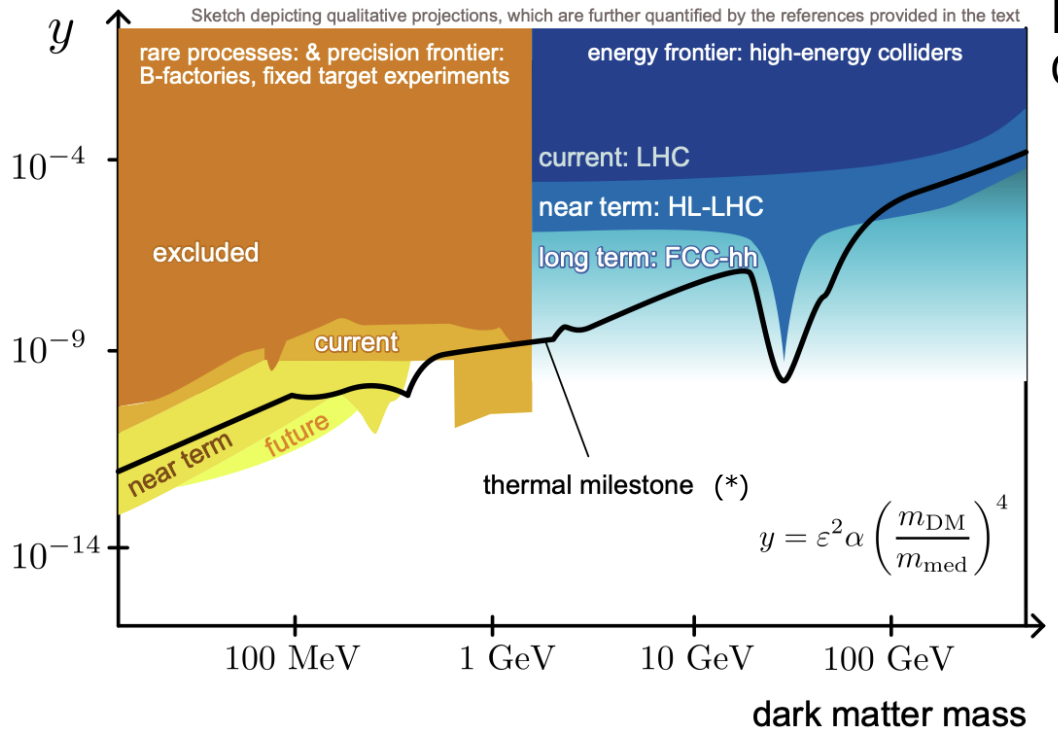
Spin-Dependent



CMS observed exclusion 90% CL
Vector med., Dirac DM; g_q = 0.25, g_{DM} = 1.0

Dark Matter Coverage by Experiments

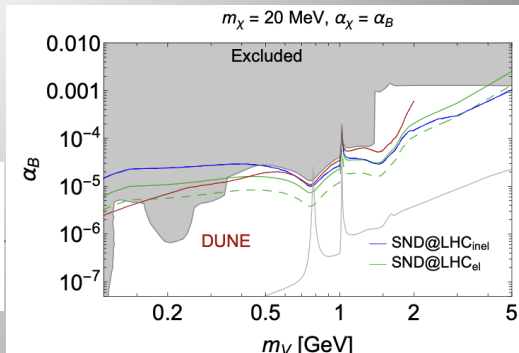
Sketch how collider and accelerator experiments together can reach sensitivity across many orders of magnitude of DM mass to couplings expected for thermal-relic vector portal inelastic Direct DM production



P. Harris et al. 2210.01770
Contribution to Snowmass 2021

(*) To avoid overproduction of DM

JHEP03(2022)006



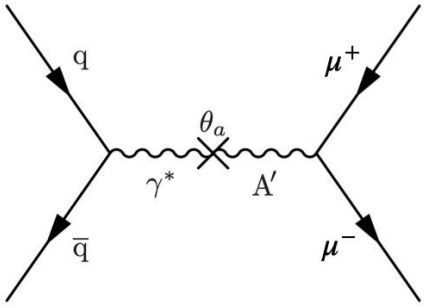
Low mass DM search @LHC? E.g. SND@LHC experiment
Scattering of beam-produced DM on nucleons/electrons

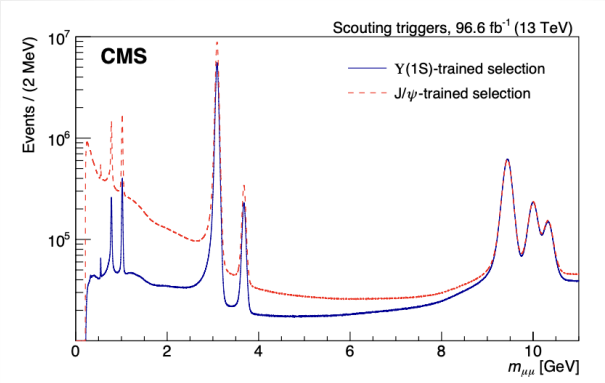
Dark Photon Portal

Spin-1 mediator with pure vector coupling, mixes with SM photon and Z boson

Visible final states

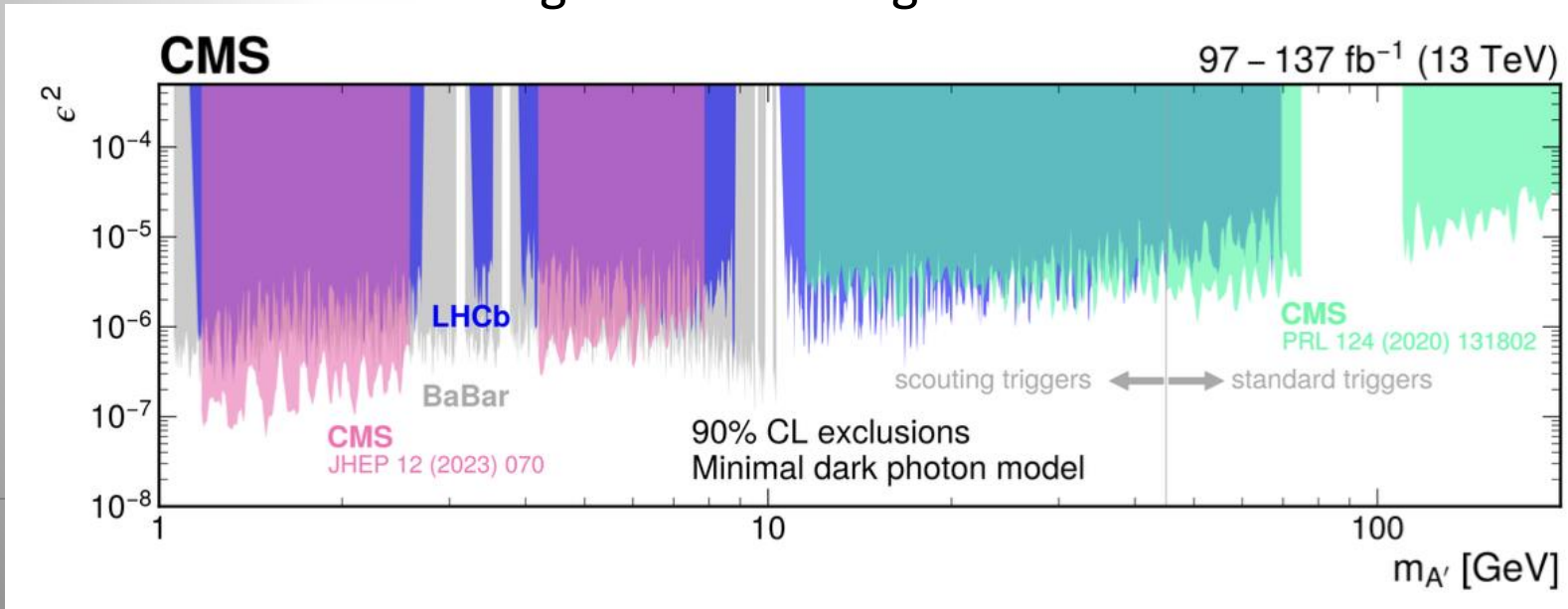
→ Dimuon analyses





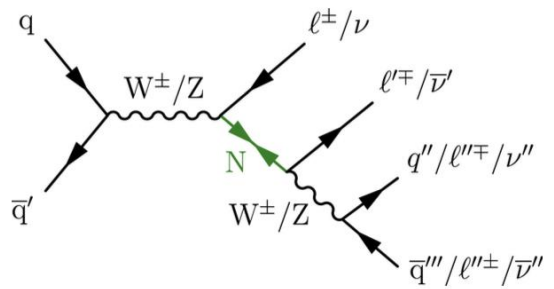
With data scouting and dedicated selections, the analysis accesses down to **~1 GeV dark photons**

Summary plot includes two prompt dimuon analyses. Using "data scouting": EXO-21-005 and EXO-19-018



Neutrino Portals

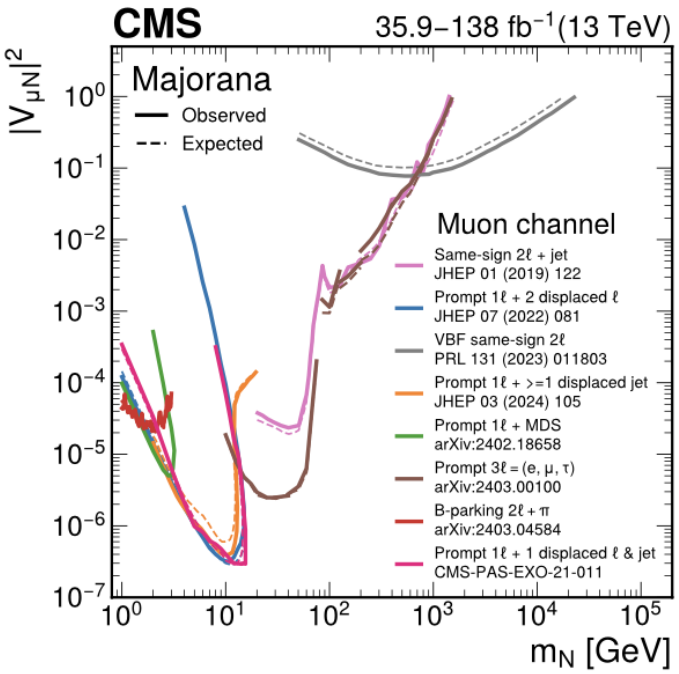
Heavy Neutral Leptons (HNLs) are sterile neutrinos with very small mixing with active neutrinos.



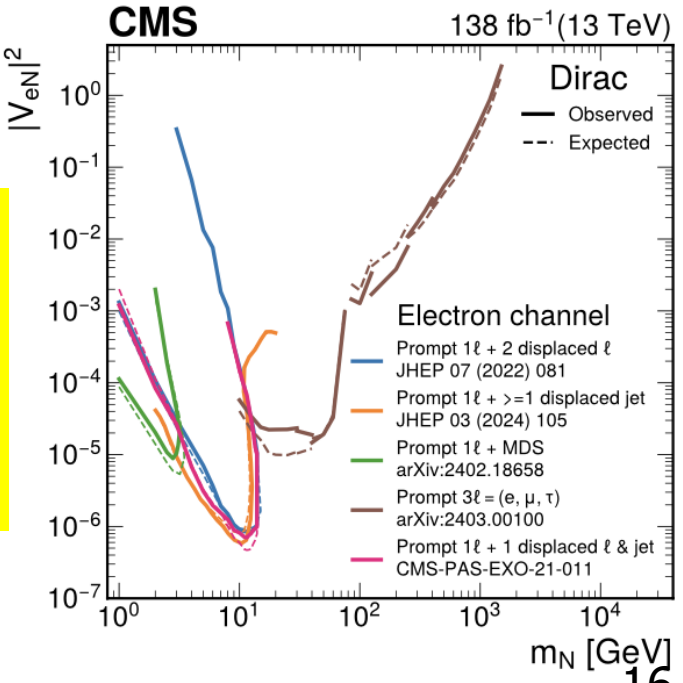
2405.17605

Searches for long-lived HNLs in Type I seesaw model

- Many searches for long-lived HNLs performed
- Showing example limits for Majorana HNLs in the muon channel & Dirac HNLs in the electron channel



Can probe down to ~1 GeV in HNL mass with "Muon Detector Shower" signature.

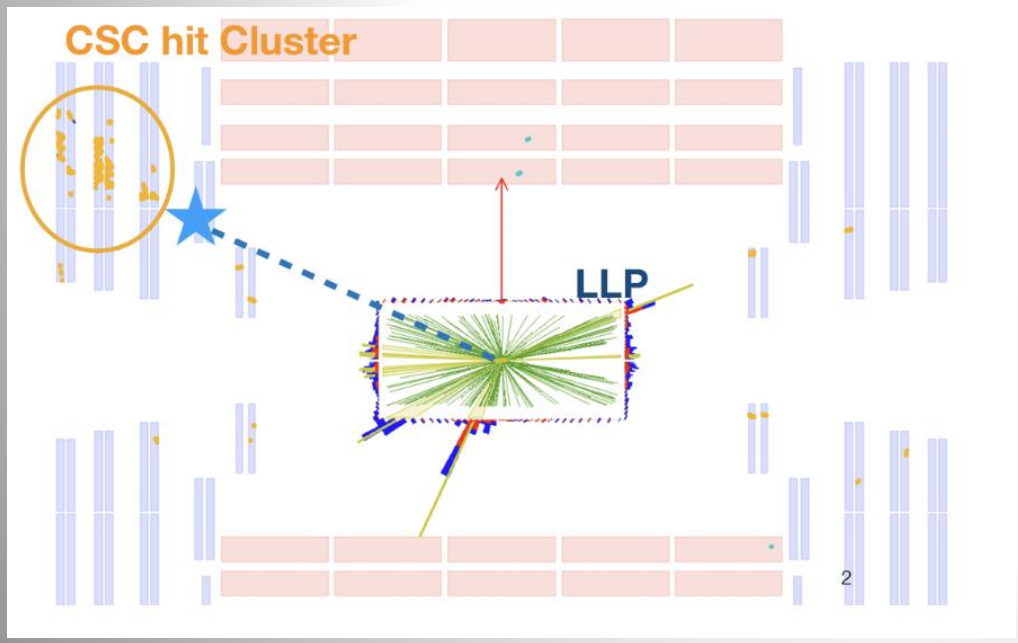


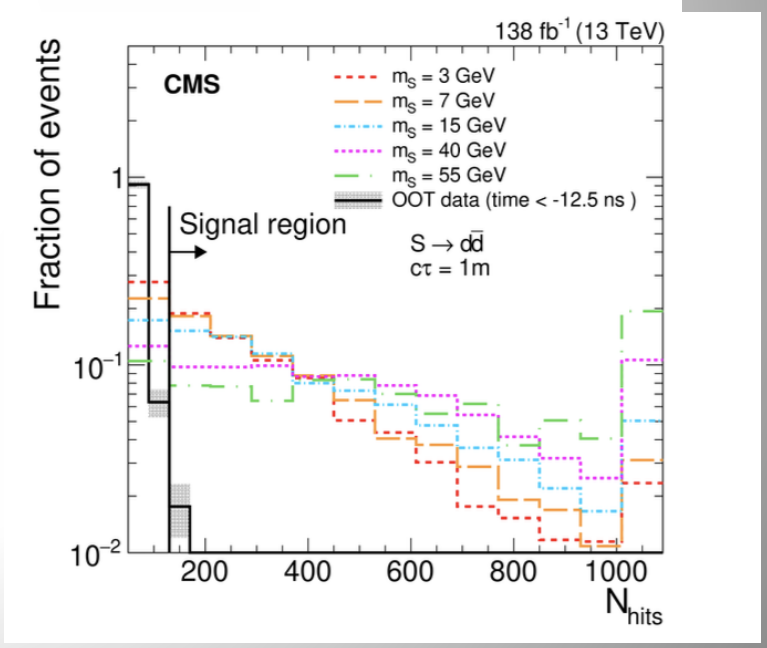
Muon Detector Showers (MDS)

Neutral LLPs with ctau > 1m could decay **beyond the calorimeter** with:

- **High-multiplicity shower (100s of hits/cluster)** in muon system
- Essentially, we **use the muon system as a sampling calorimeter**
- **Unique signature** due to the presence of steel in the CMS muon system
- Excellent background suppression from shielding material (background rejection~1e6)
- Sensitive to decays in hadrons, taus, photons, and electrons

arXiv:2402.01898

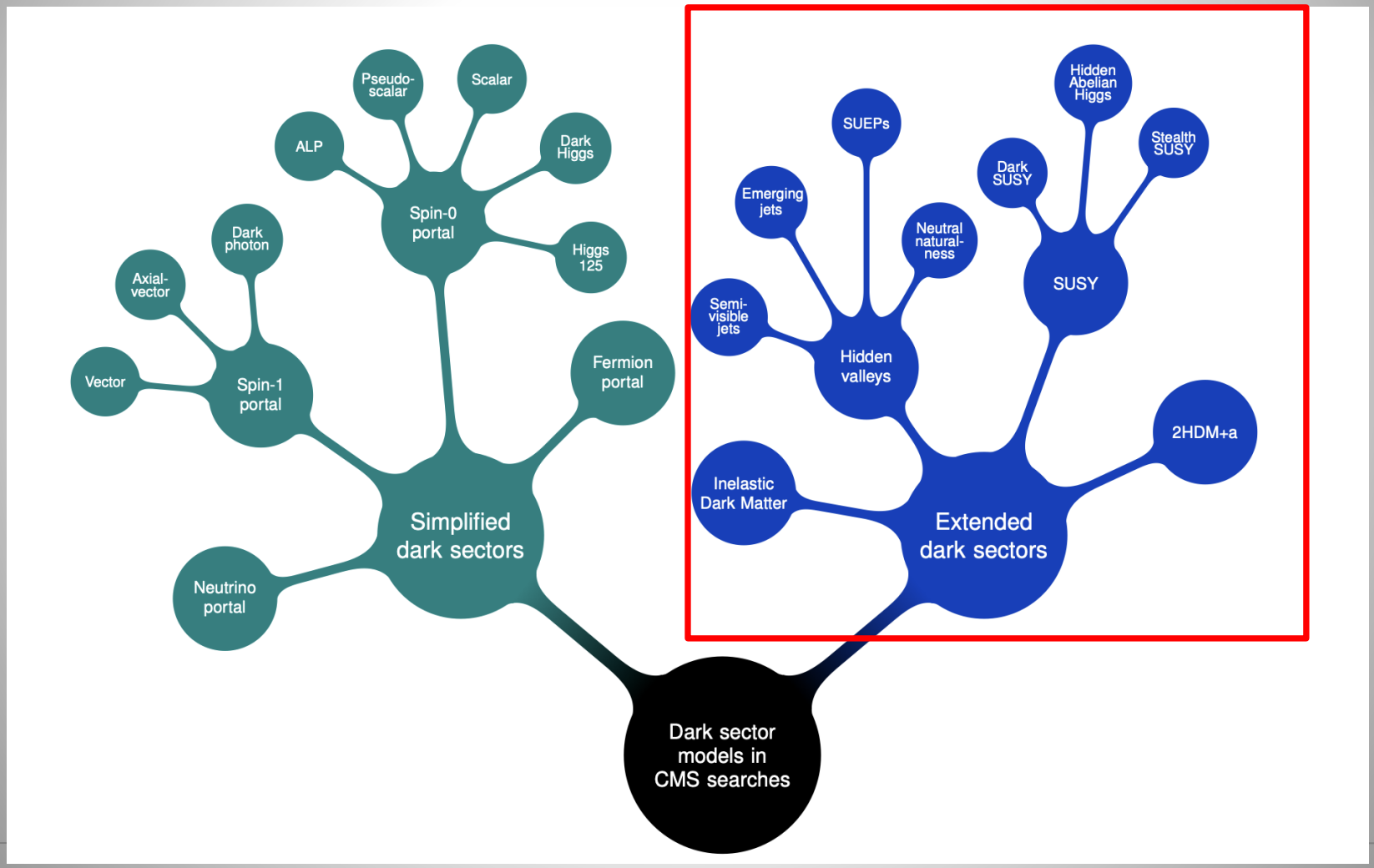




MDS analyses limited in Run 2:no dedicated trigger: New dedicated triggers in Run 3!

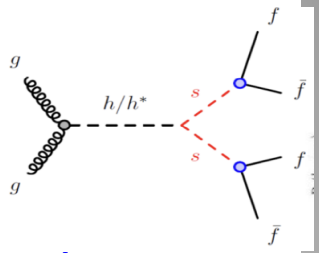
Extended Dark Sectors

But Nature could be more complicated…



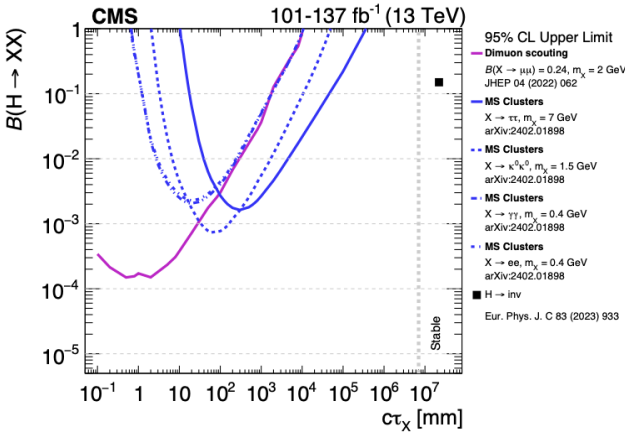
Higgs to LLPs

- **Hidden valleys:** dark sector model with rich dynamics at low energy scales, and accessible at colliders at high energy scales
- LLPs are well-motivated in dark sectors:

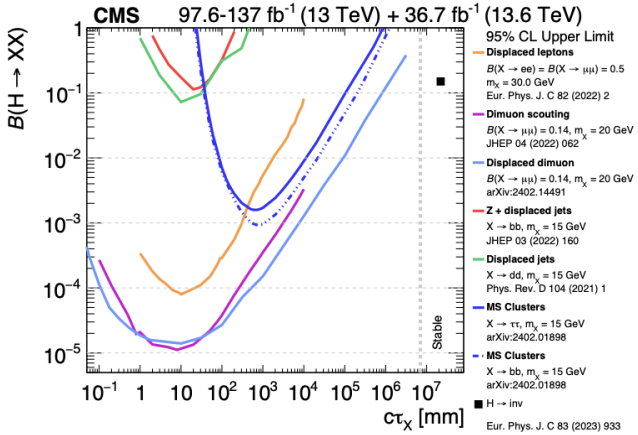


- Interpretations of LLP searches with hadronic and leptonic decays

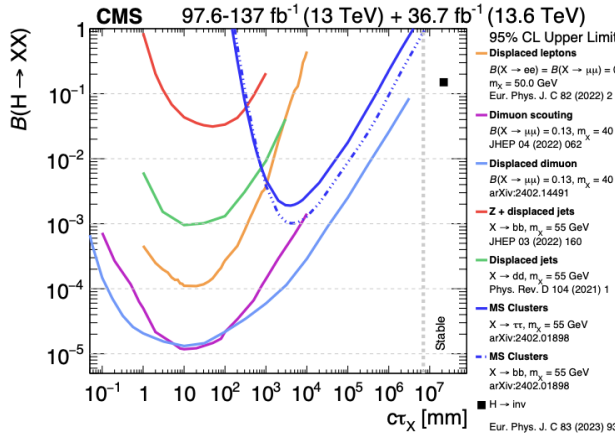
$0.4 < m_X < 2$ GeV



$5 < m_X < 30$ GeV



$40 < m_X < 55$ GeV



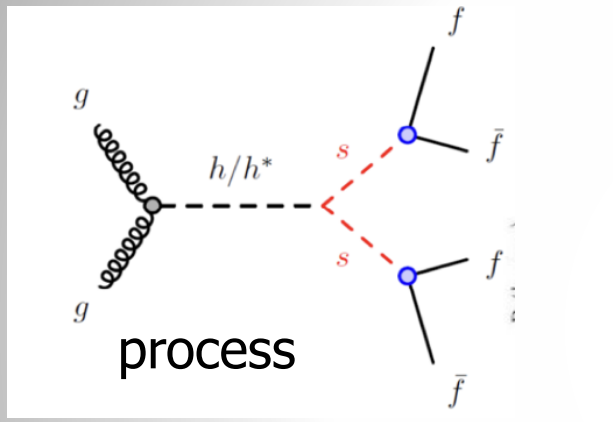
Muon Detector Showers can push sensitivity to small masses and long lifetimes

Dimuon scouting powerful at small masses and small lifetimes

Displaced dimuon search is inclusive setting limits in a wide range of lifetimes

Higgs to LLPs

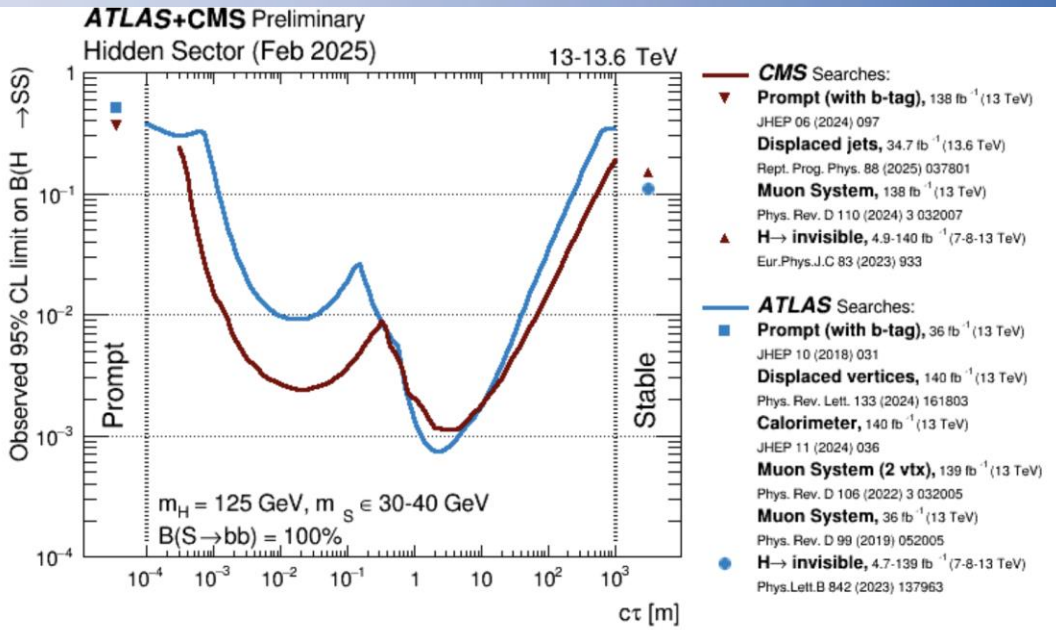
Plots with CMS and ATLAS results (LLP-LPCC WG)

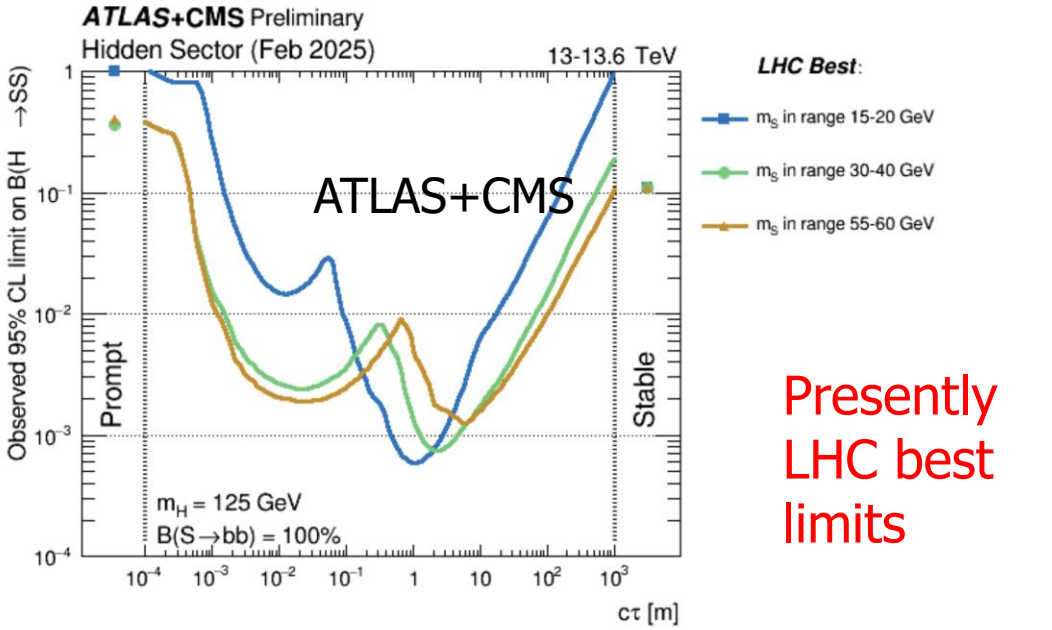


Results for s->bb branching ratio

Curves are envelopes of the of the individual results

->plots available on CMS/ATLAS EXO summary pages





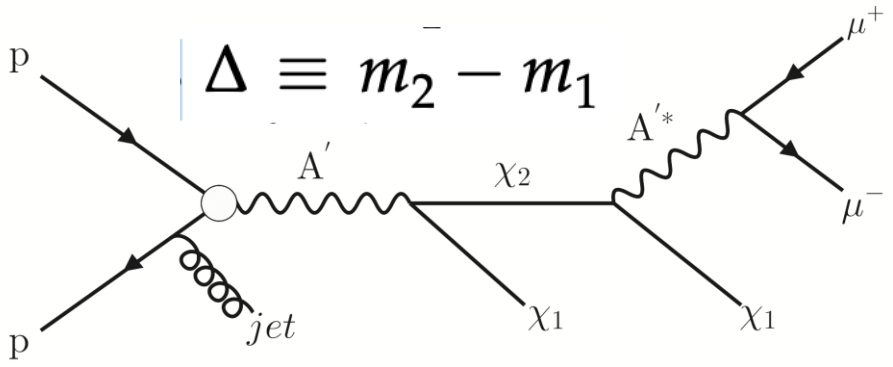
Presently LHC best limits

Search for Inelastic Dark Matter

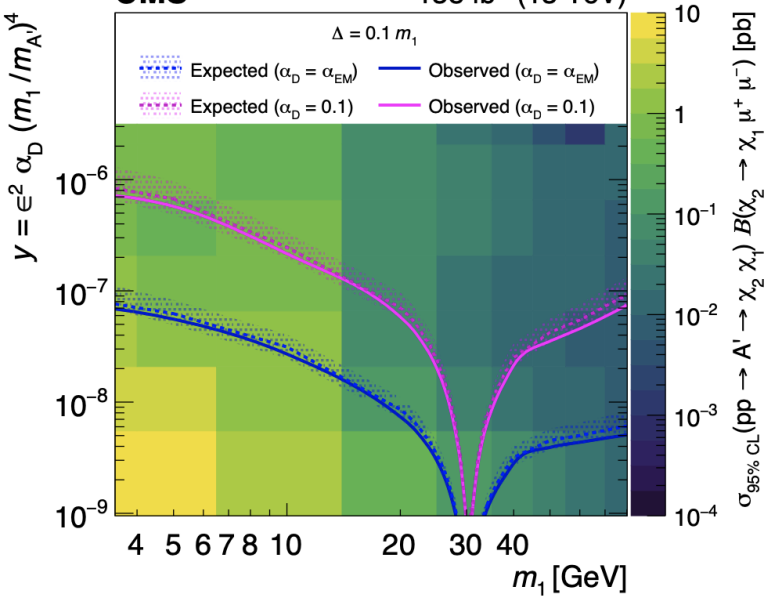
2305.11649
Model: hep-ph/101138

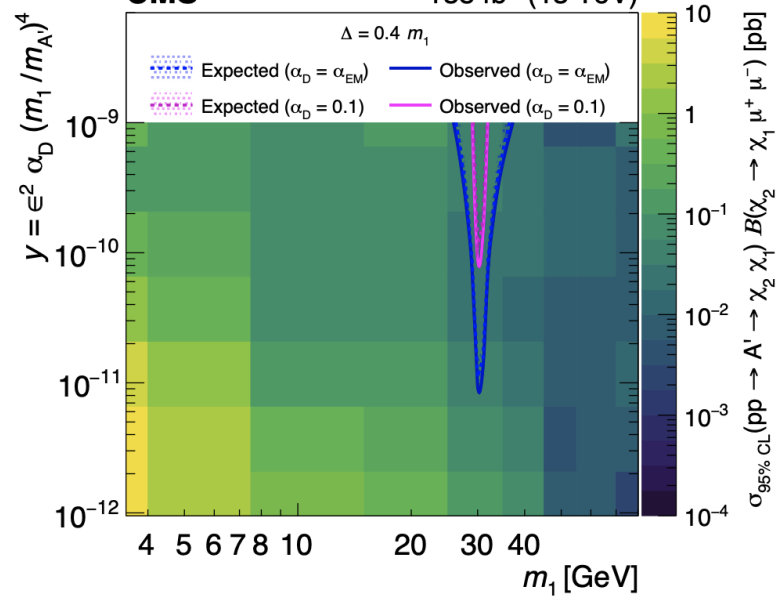
Two DM states which are almost degenerate in mass, such that the decay $\chi 2 \rightarrow \chi 1 +$ 2 muons is a LLP signature.

- Such models can account for the thermal relic abundance.
- First search in 3-80 GeV region.

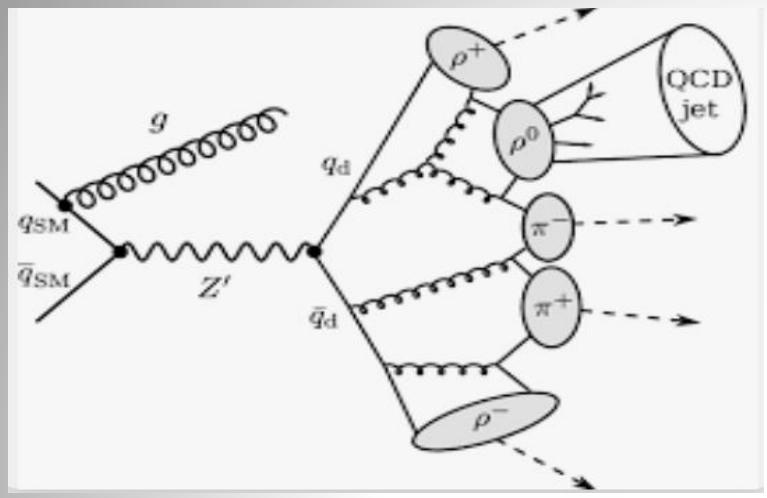


$m_{A'} = 3\, m_1$

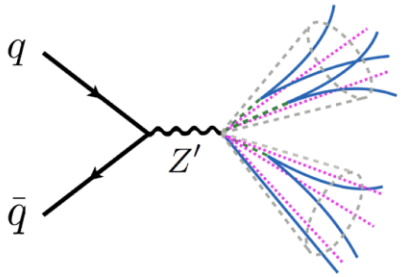




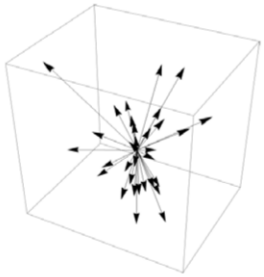
Dark QCD & Dark Showers

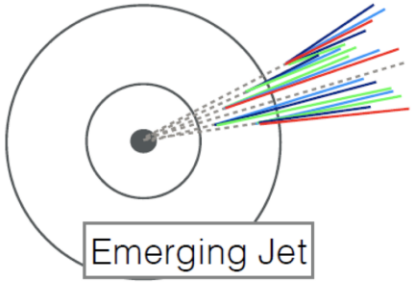


Phenomenology



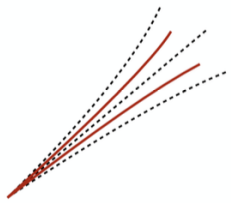
Semi-visible jets





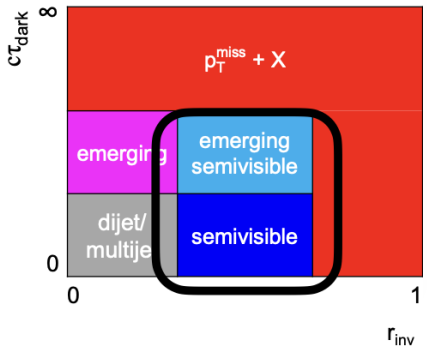
Soft unclustered energy patterns (SUEPs)

Semi-Visible Jets



$0 < r_{inv} < 1$

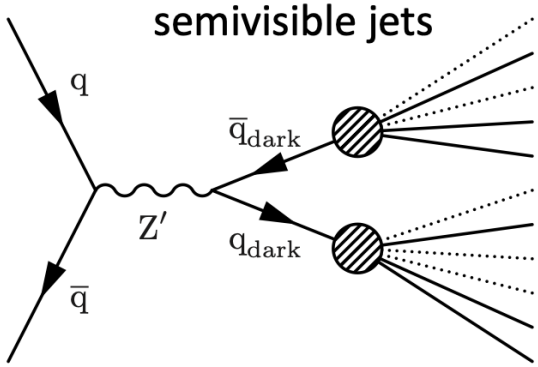
Semivisible jet: stable and unstable dark hadrons



New interpretations of **dijet** and **monojet** searches, together with the dedicated **semivisible jets** search

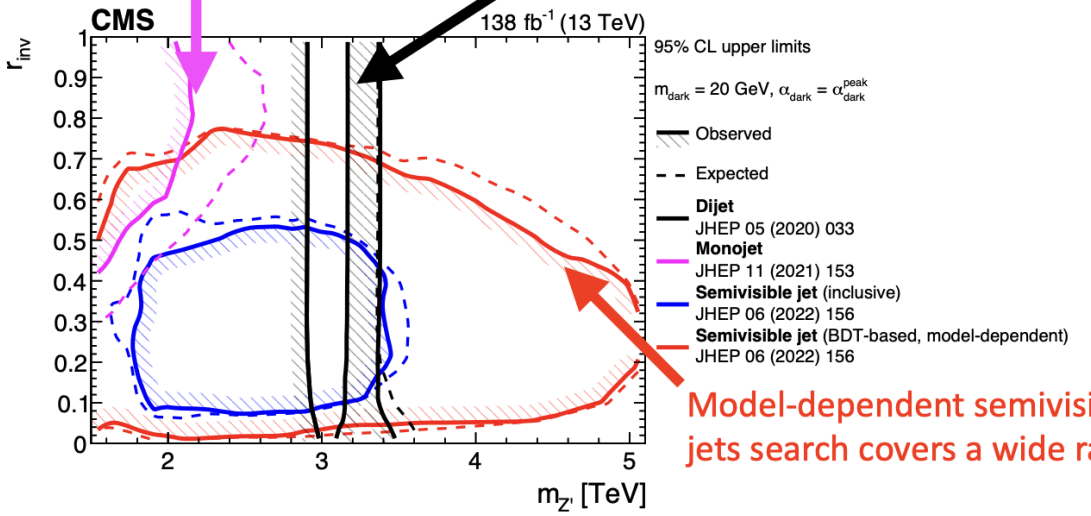
$$r_{inv} = \langle N_{stable} / (N_{stable} + N_{unstable}) \rangle$$

Z' mediator decays to two semivisible jets



Monojets sensitive at r_{inv} close to 1

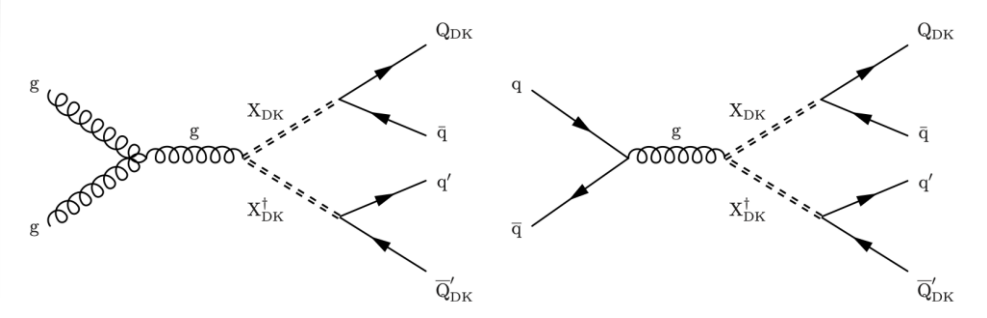
Dijets can actually cover a wide range of r_{inv}



Model-dependent semivisible jets search covers a wide range

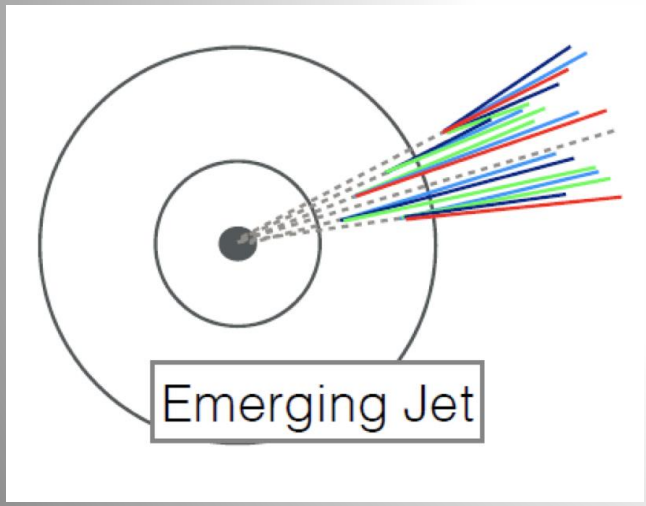
Emerging Jets

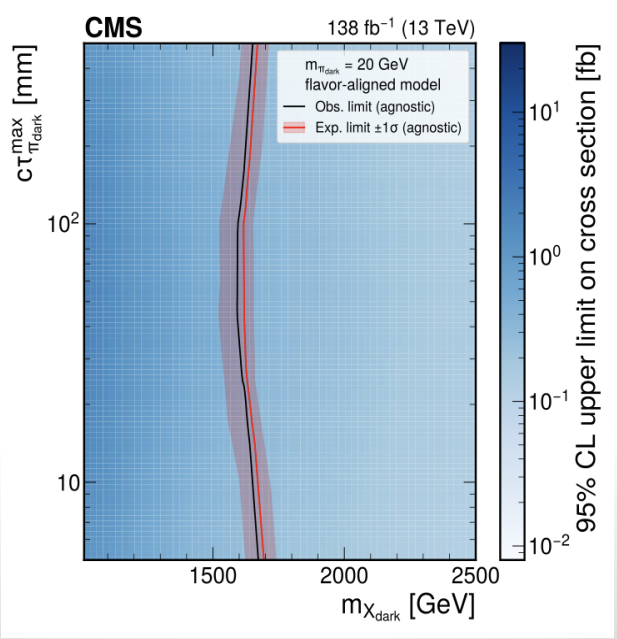
Emerging jets contain several displaced vertices from neutral particle decays which are potentially resulting from a dark shower

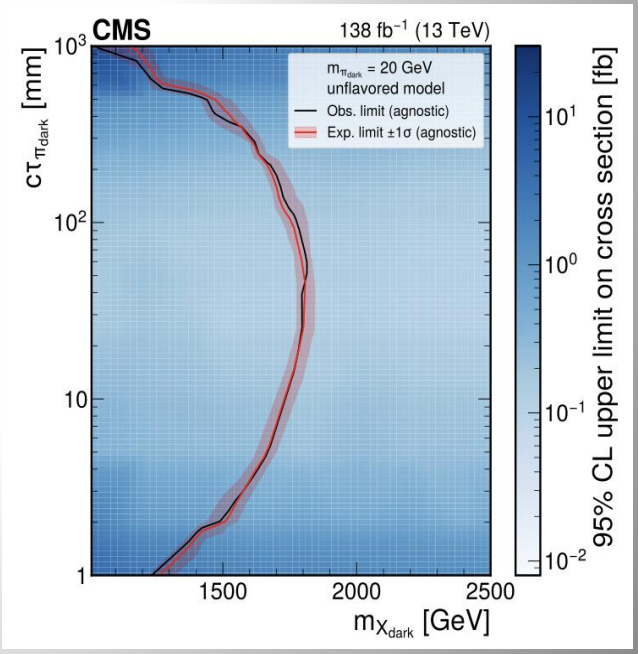


Limits for Dark Pions with mass of 20 GeV

2403.01556







Results for different emerging jet model scenarios (1405.6709,1803.08080)

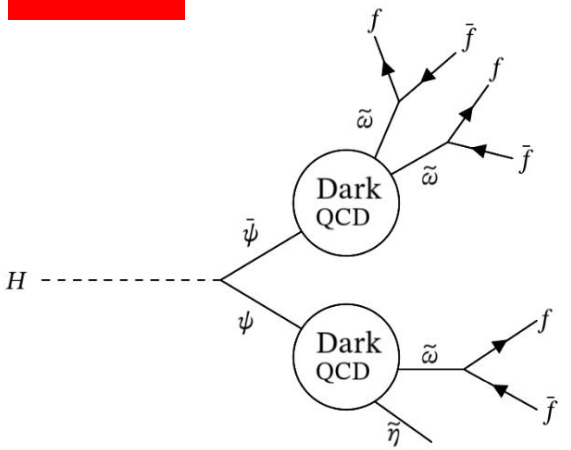
Low Mass Dark Showers in Displaced Dimuons

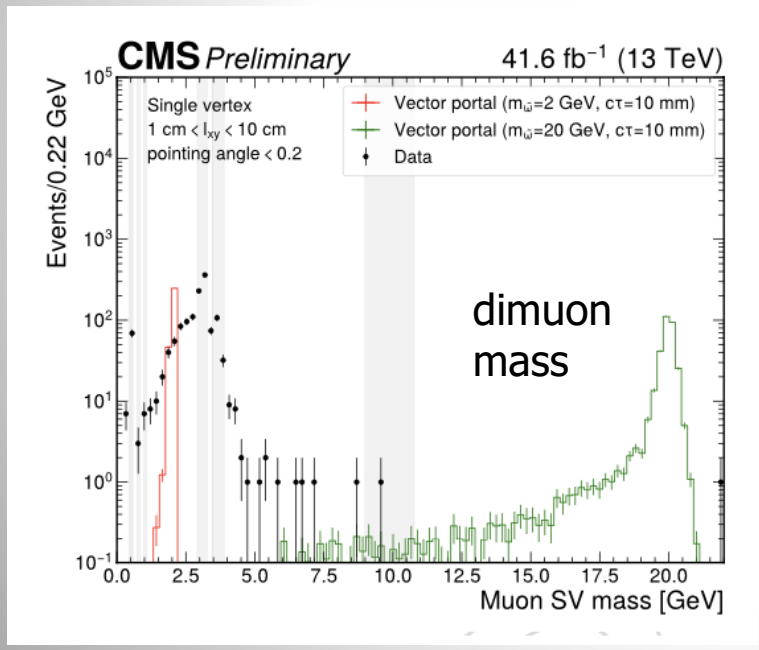
B-parking 2018 dataset with new displaced trigger

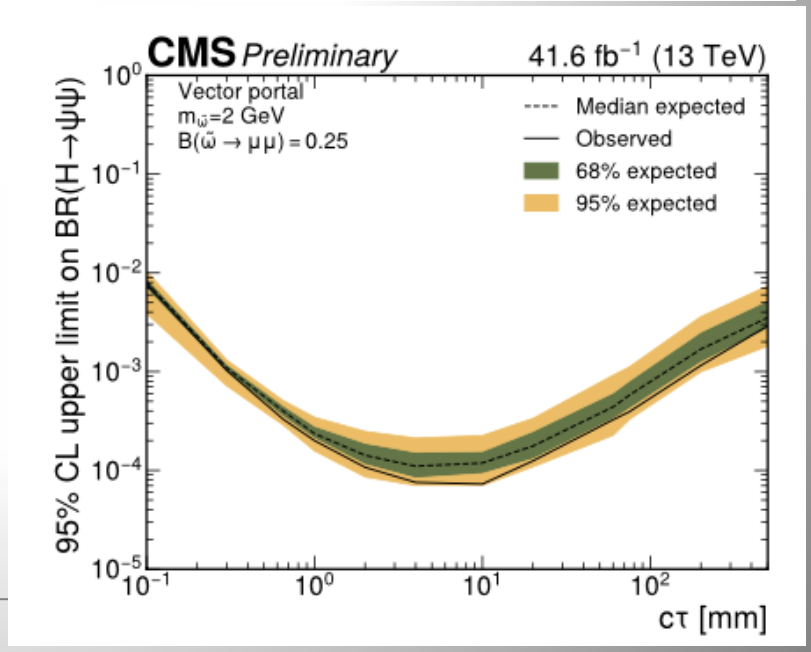
- Searching for decay of dark mesons into 2μ with displaced vertex
- First such search at the LHC!
- Used BDT to separate signal from background

NEW

EXO-24-008







Most stringent limits on vector portal model for ctau < 0.1 m and mass as low as 2 GeV

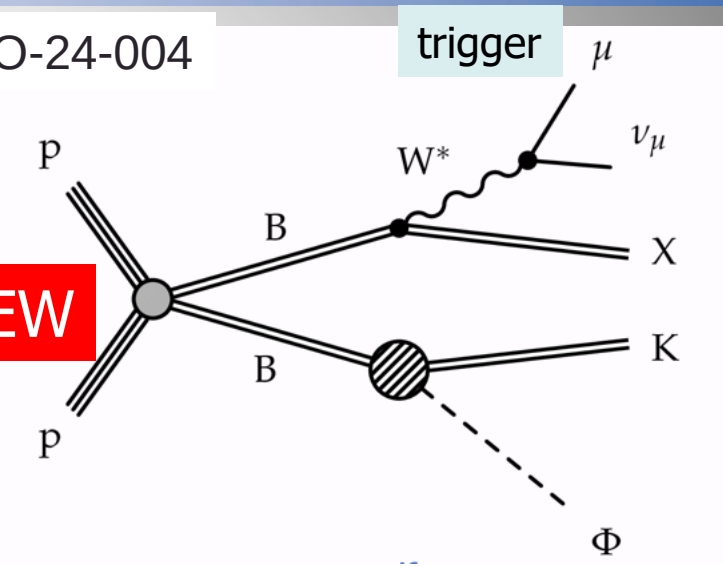
Search for LLP in 2018 Parked Data Set

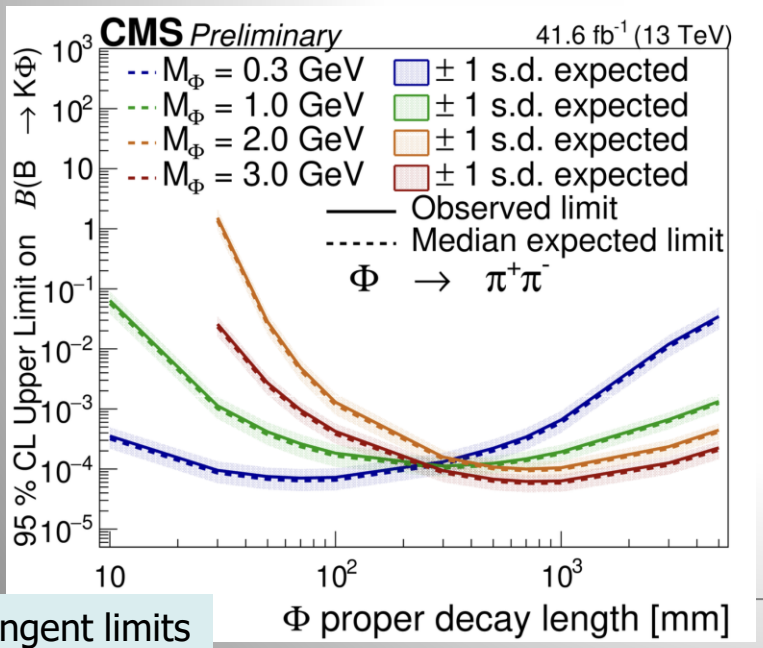
LLPs from b hadron decaying in muon endcaps

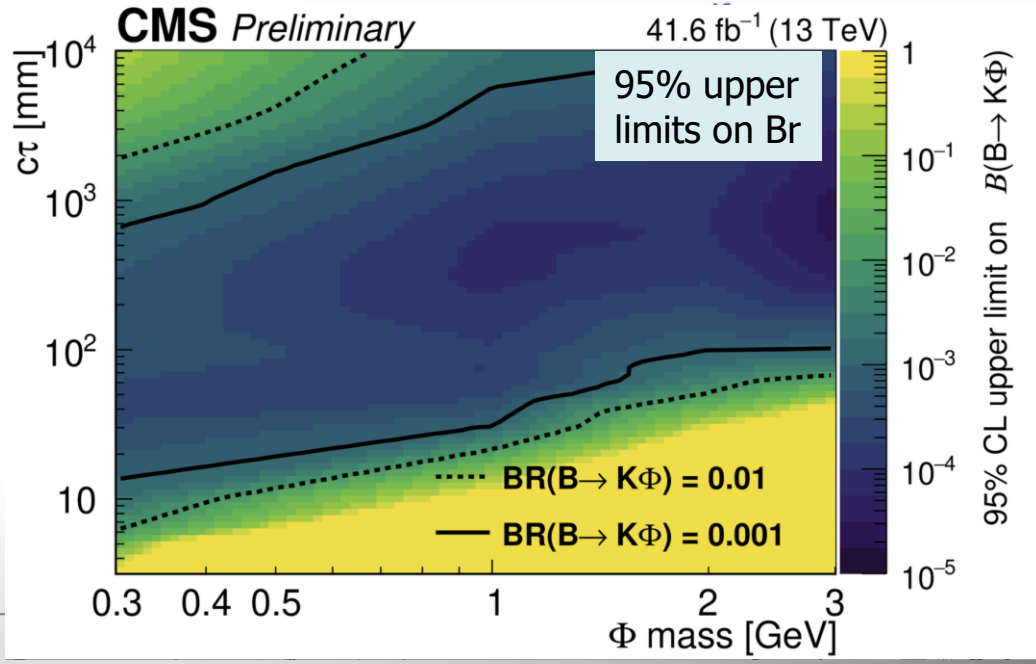
- Data parking data set used (muon trigger)
- Events with high multiplicity clusters of hits ($\Delta R<0.2$, >50 hits) from LLP decay hadronic shower in muon detector + displaced muon
- Main bkg from punch-through jets/tracks from prompt SM activity estimated using ABCD

EXO-24-004

NEW







Stringent limits on b->$\phi \rightarrow \pi\pi$

Search for Vector-Like Leptons with LLP

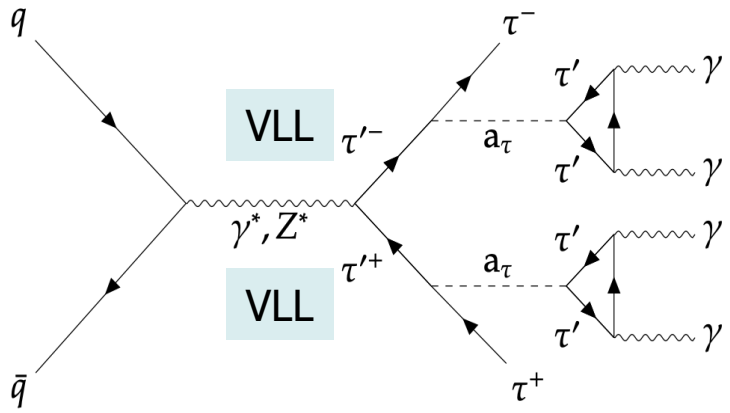
VL Lepton masses excluded up to 1.5 TeV

- First search at LHC!
- Events with at least 1 muon hit cluster ($\Delta R<0.2$, >50 hits) + hadronic tau + isolation from prompt activity ΔR and cosmics ($\Delta\phi$) and out of time pile-up
- Data-driven bkg estimation validated in CR (inverting some τ selection)

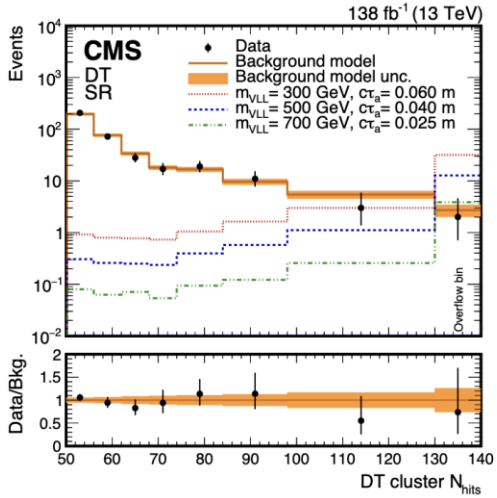
Photons lead to an e.m. shower in the return yoke/muon detectors

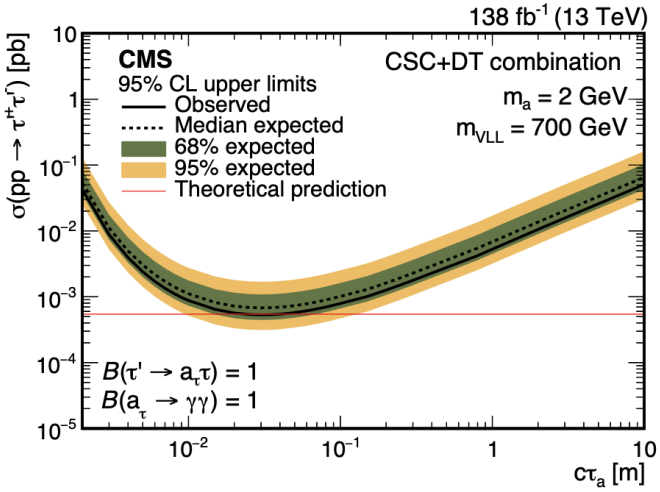
NEW

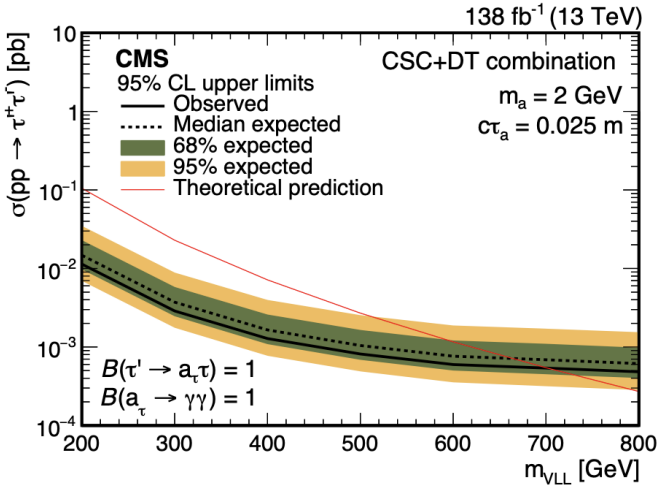
2503.16699



$a\tau$: long lived pseudoscalar







Future Capabilities

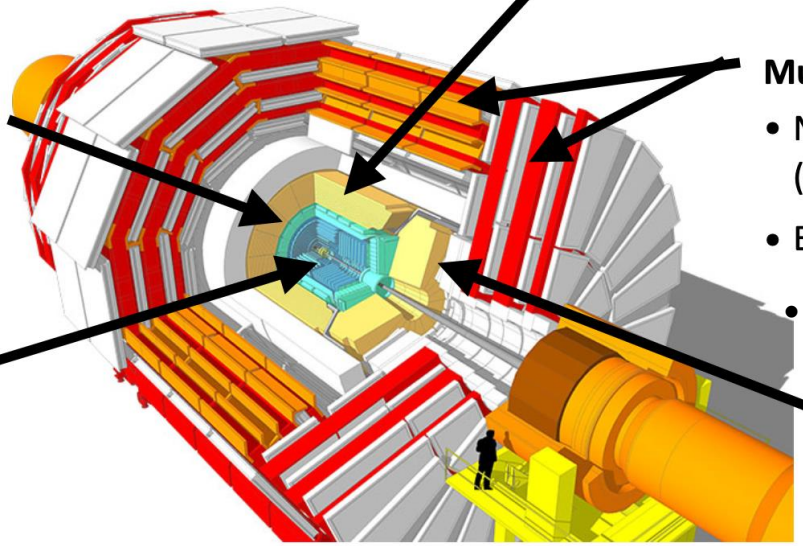
Run-3: Improved scouting and trigger capabilities (see backup)

CMS Phase 2 Upgrade & Some Highlights for LLPs

Level 1 Trigger TDR
- New track trigger at 40 MHz
- 750 kHz L1 output
- 40 MHz data scouting (real time analysis)

DAQ & High Level Trigger (HLT) TDR
- Heterogeneous architecture
- 7.5 kHz HLT output

Barrel Calorimeter TDR
- ECAL crystal granularity readout at 40 MHz with precise timing for e/gamma at 30 GeV



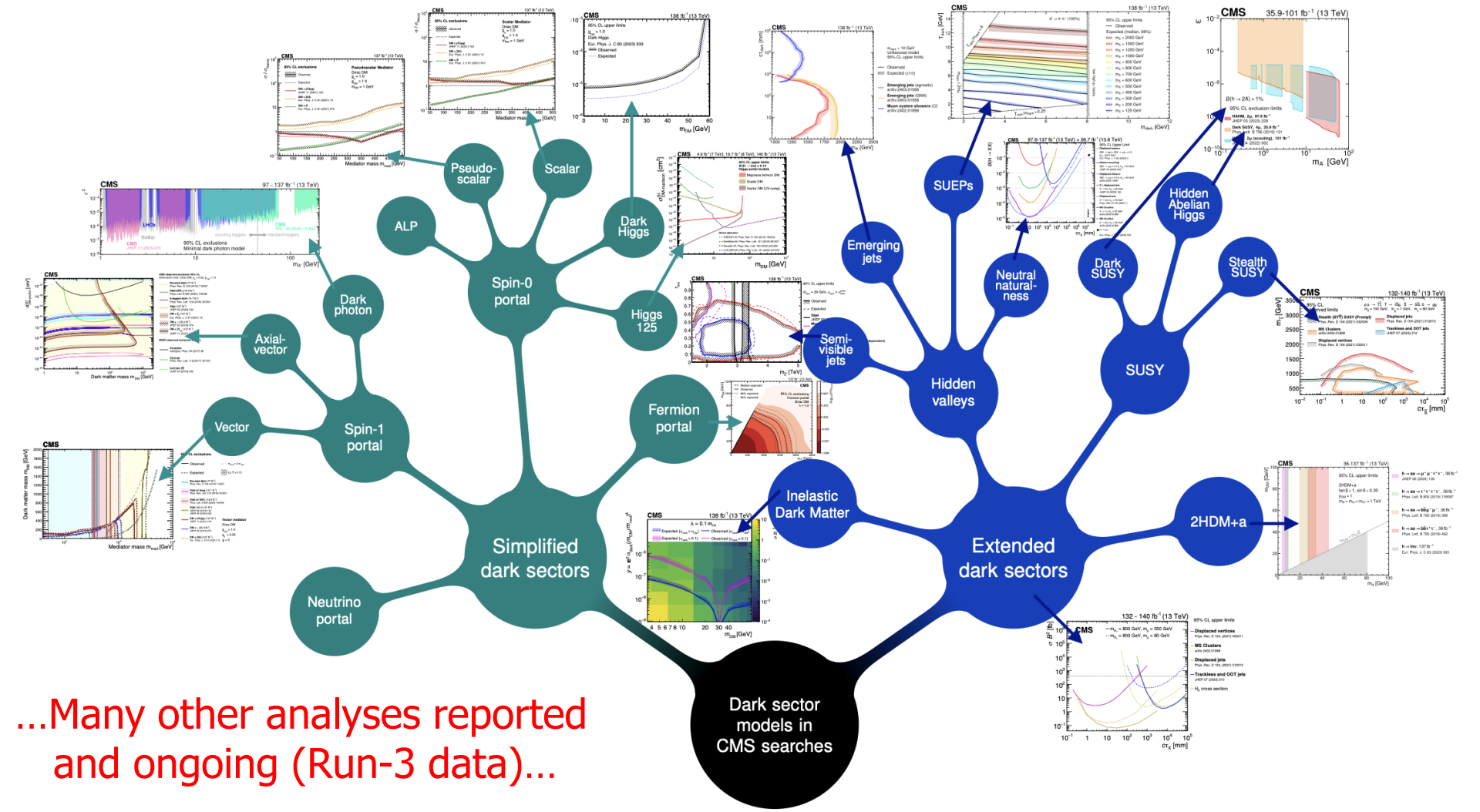
New MIP timing detector (MTD) TDR
- 30 ps timing resolution

Muon System TDR
- New Gas Electron Multipliers (GEMs) & new iRPCs $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| \sim 3$
- 600 ps time resolution

Replaced Tracker TDR
- Increased granularity
- Extended coverage to $|\eta| \sim 4$
- Designed for tracking in L1T

New High-Granularity Endcap Calorimeter (HGCAL) TDR
- Imaging calorimeter
- 3D showers and precise timing
- 20 ps time resolution

Summary: The Big Picture



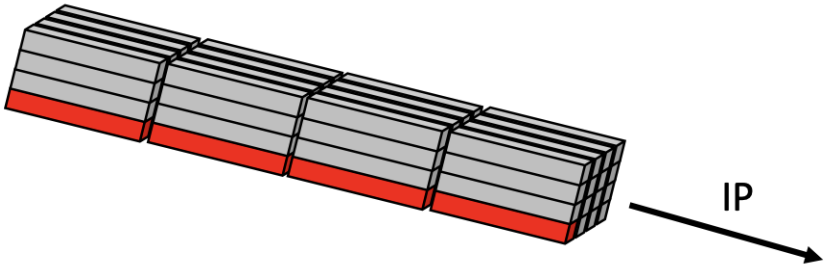
...Many other analyses reported and ongoing (Run-3 data)...

Unfortunately only limits so far... ☹

Hunting Millicharged Particles…

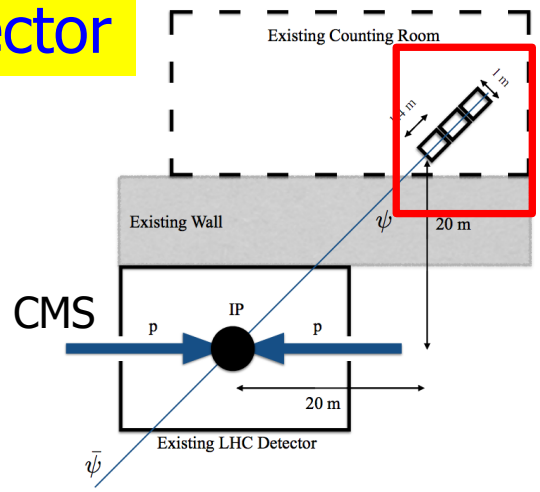
Motivation:
- Particles with small charges?
- "Dark QED" ie QED in the dark sector that kinematically mixes with the SM QED.
- The EDGES astronomical anomaly…?

Detection technique:
-> A new detector is required: scintillators-> low photon signals

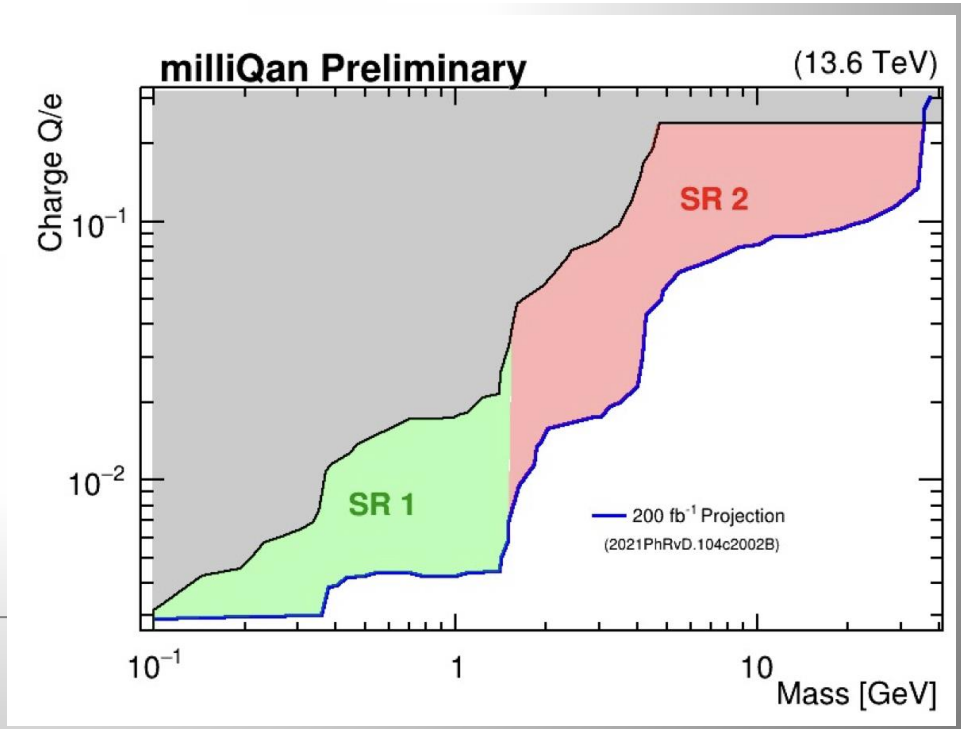


First Run-3 results coming soon!!…

MilliQan Detector



2104.07151



Backup

More Studies…

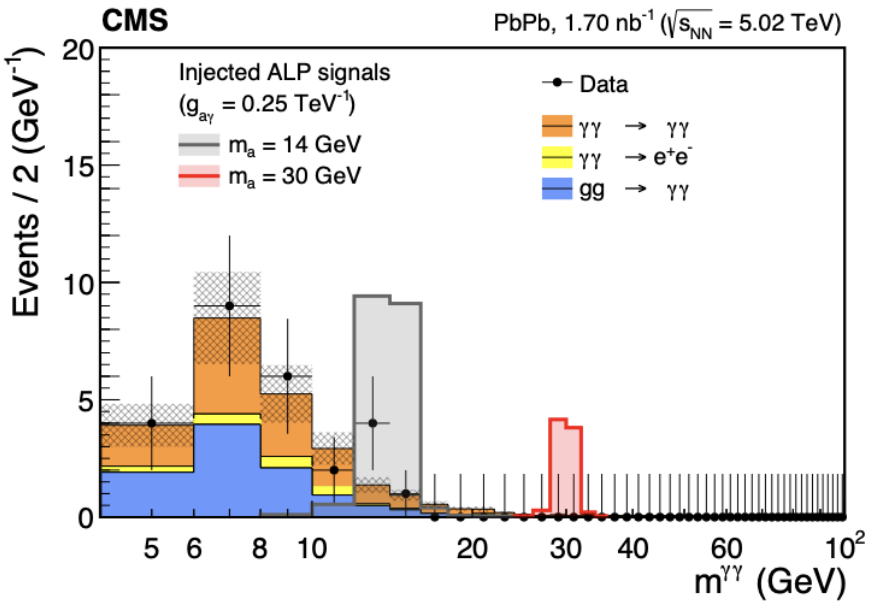
- Universal Quark Couplings
- Dark Photon Portals
- 2HDM+a, HAHM
- Dark SUSY
- SUEPs
- Hidden valleys (dark QCD)
- Stealth SUSY
- Z’ to LLPs to 4b
- Z’ to LLPs to 2b+MET
- Dark Higgs to LLPs to 4b, to 2b+MET
- Heavy multi-charged and fractional charged particles
- Searches for ALPs..
- …

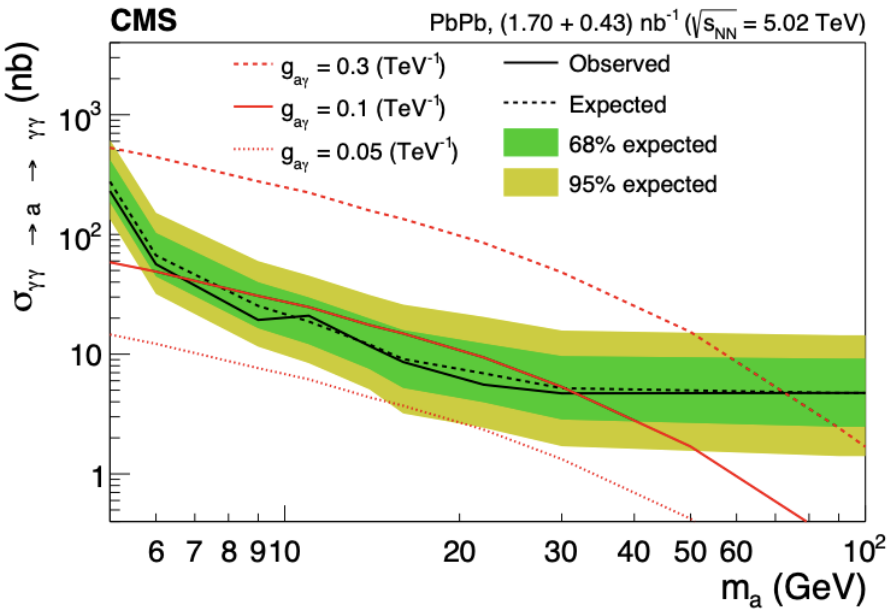
Search for ALPs

Measurement of light-by-light scattering and the Breit-Wheeler process, and search for axion-like particles in ultraperipheral PbPb collisions at 5.02 TeV

Process: γγ→γγ

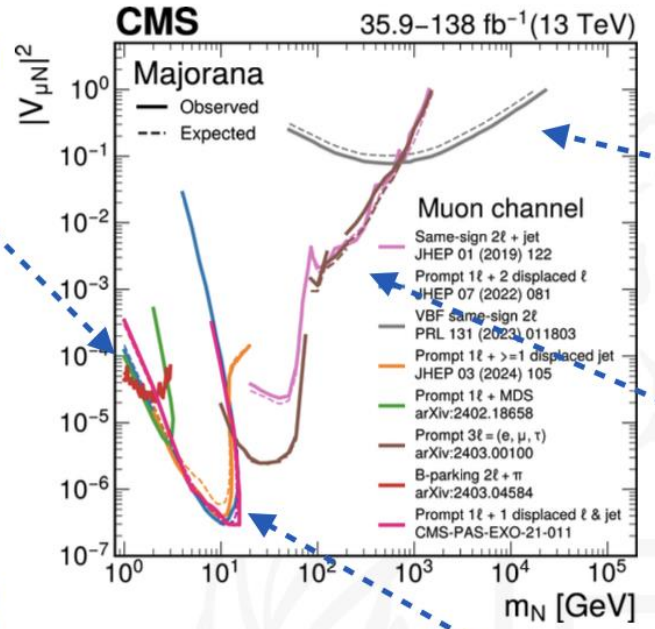
arXiv:2412.15413





HNL Studies

Exclusive μ coupling

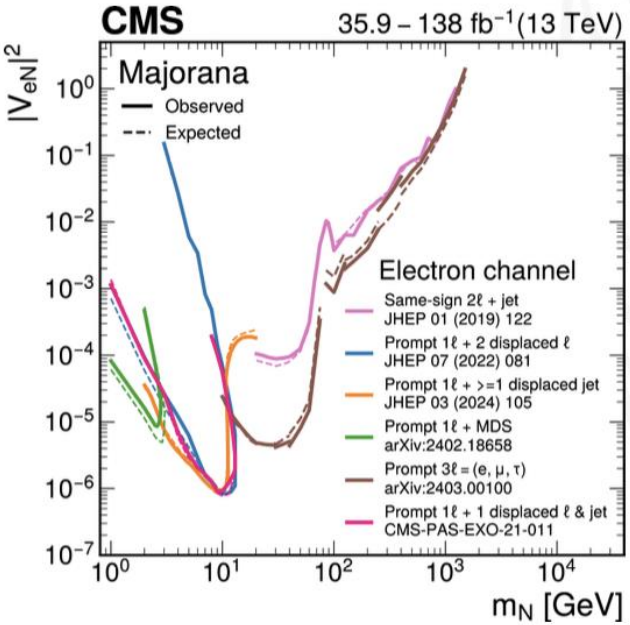


Very Low mass sophisticated Techniques

HNLs in VBF Indirect search

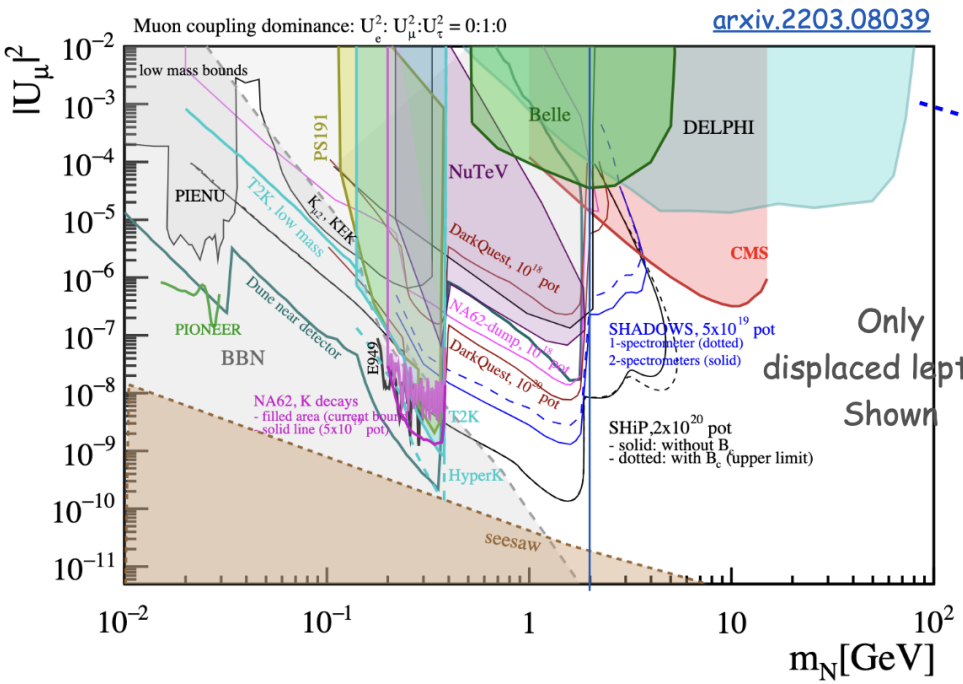
High mass prompt

Exclusive e coupling



Intermediate mass DY channel
Displaced decay in Tracker volume

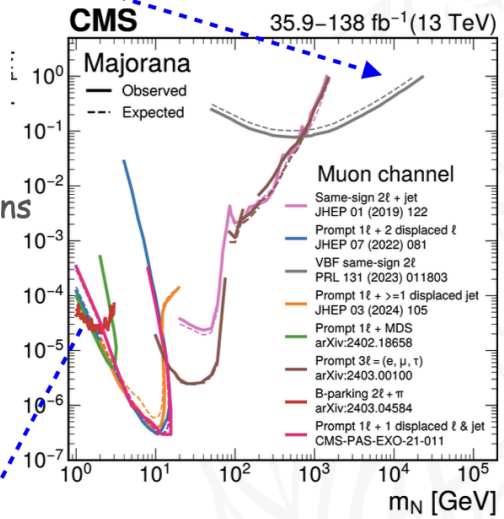
HNL Studies



arxiv.2203.08039

Only displaced leptons Shown

First search at very high mass



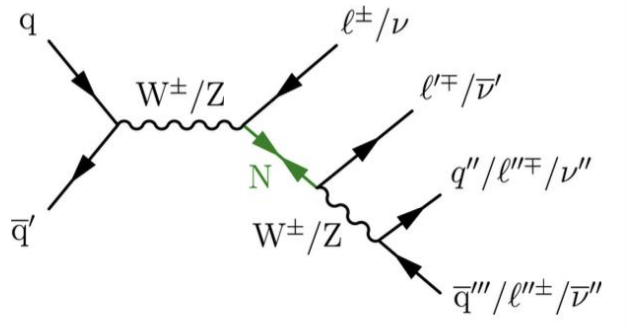
Would be nice to provide common Summary plot + ATLAS

B-HNL search- exclude Nw extra parameter space At 1-2 GeV!

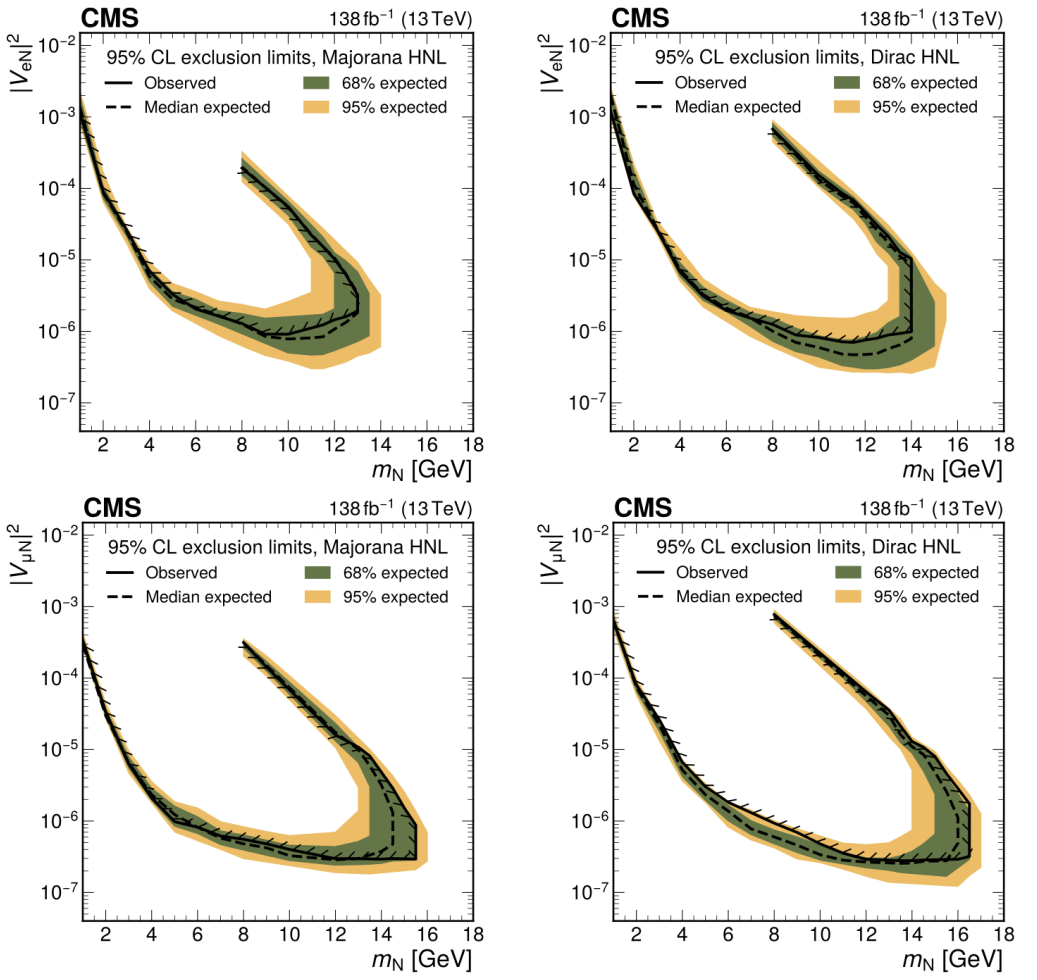
Overall improvement of DELPHI's + Belle's boundaries!

Neutrino Portals

Heavy neutral leptons (HNLs) are sterile neutrinos with very small mixing with active neutrinos (update added since Review Paper)

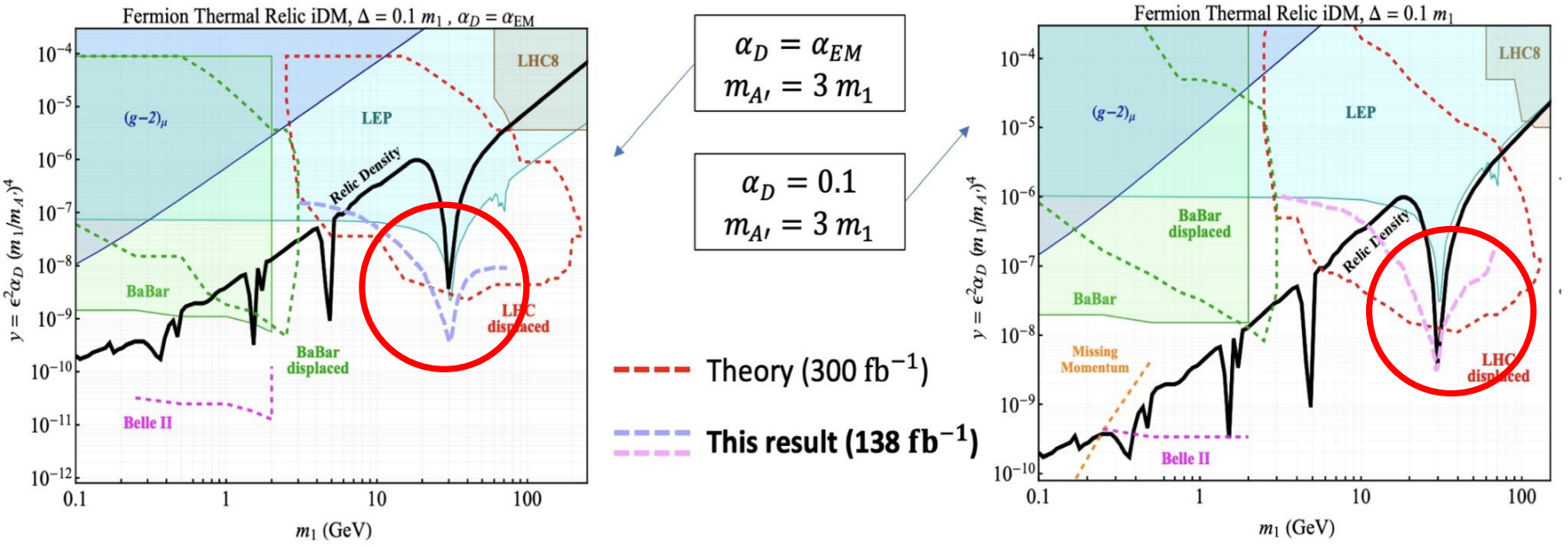


Search for long-lived heavy neutral leptons in pp collisions with a lepton-jet pair associated with a secondary vertex
2407.10717



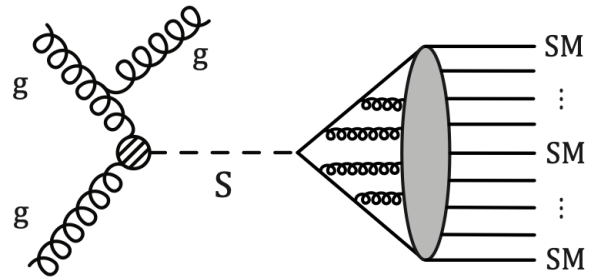
Search for Inelastic Dark Matter

Comparison with theory from 1508.03050

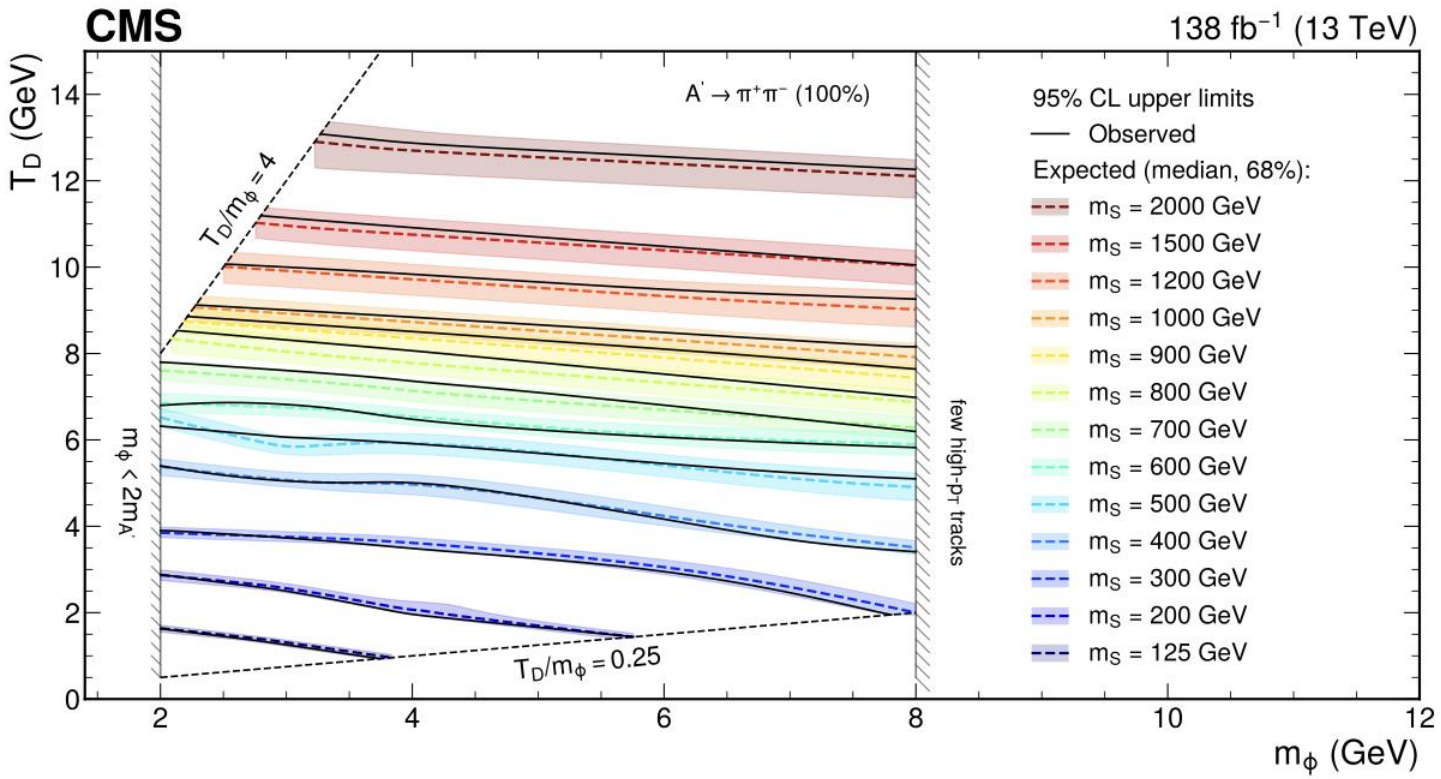


SUEP Studies

Soft unclustered energy patterns



Limits on temperatures T_D and dark Meson mass $m\phi$



Improvements for Run 3

Scouting data stream

No offline reconstruction

Only HLT objects and calibrations

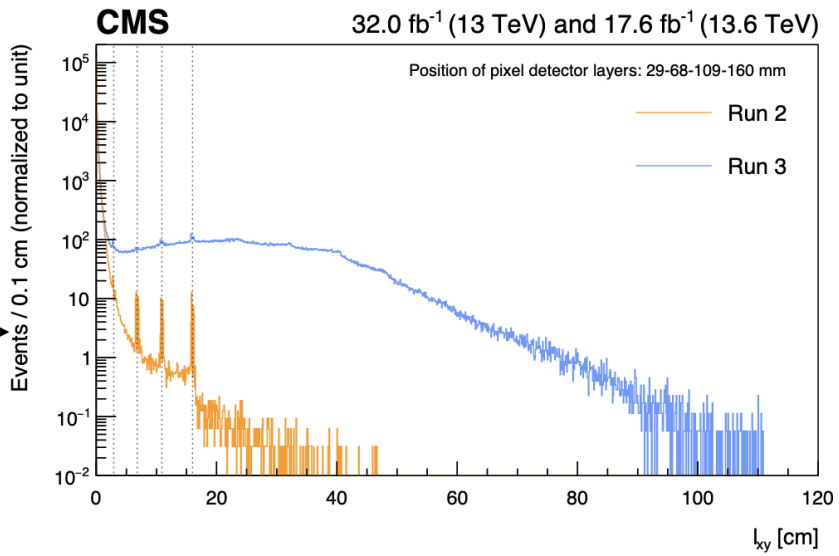
~5 kHz, ~40 MB/s

Scouting in Run 3

Scouting scope improved in Run 3 thanks to new GPU-equipped HLT farm and therefore improvements in HLT reconstruction to harness the potential of parallel architectures

- Total scouting **processing time reduced** by a factor of 1.5!
- Scouting **output increased** from ~5 kHz in Run 2 to ~20 kHz in Run 3!
- **Added electrons and photons** in Run 3! Now have scouting for all objects
- For muons in Run 3, removed requirement on minimum number of hits in the pixel layers: **now more displaced muons**!

All of this will have a direct positive impact on searches for small masses and couplings



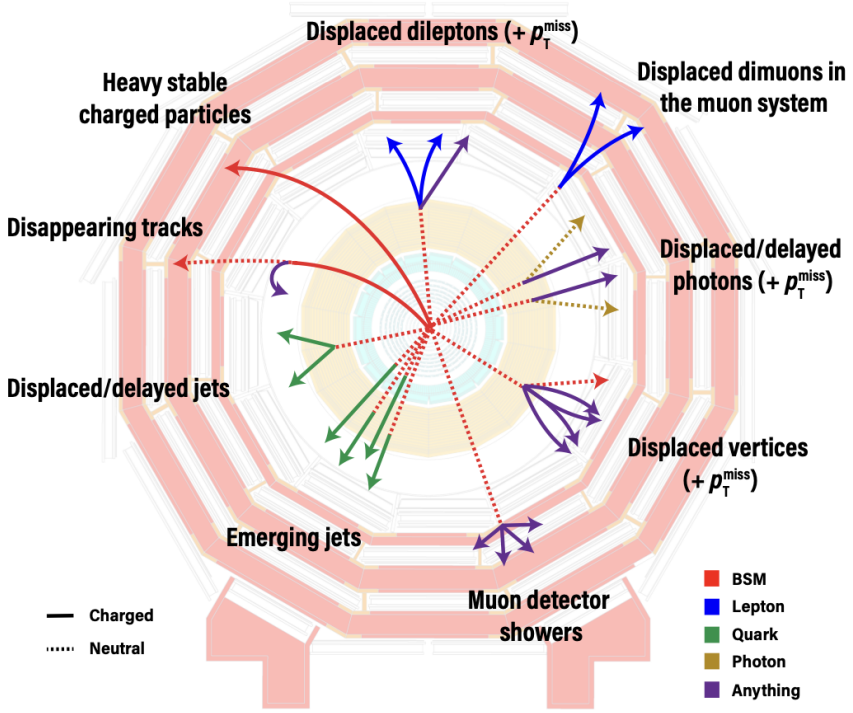
Also, "scouting" as described so far is only at the HLT

→ Have commissioned L1 scouting in Run 3, and many possibilities await in HL-LHC!

Improvements for Run-3

LLP Triggers in Run 3

- p_T^{miss} + isolated track (for disappearing tracks)
- Displaced jets in tracker - **Major improvements!**
- Displaced taus in tracker - **NEW!**
- Displaced photon + H_T
- Delayed diphoton - **NEW!**
- Delayed jets using ECAL timing - **NEW!**
- Delayed jets using HCAL timing and depth - **NEW!**
- Displaced muon + photon
- Displaced dimuons - **NEW! / Major improvements!**
- Dimuon scouting - **Major improvements!**
- Muon detector showers (CSCs + DTs) - **NEW!**
- Jet or muon not coincident with collision (NoBPTX triggers for stopped particles)



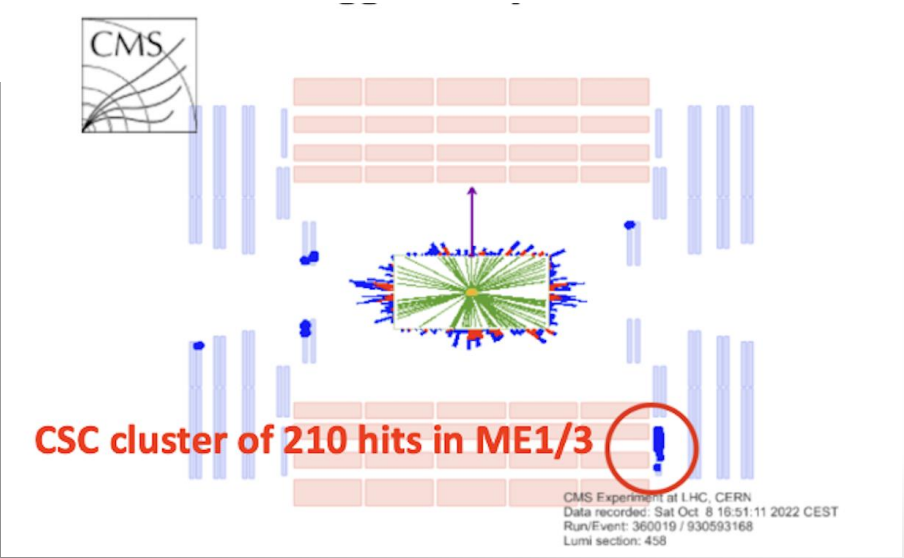
Stay tuned for Run 3 LLP trigger paper to see potential physics impact!

MDS Trigger Introduced in Run-3

L1T:

- Build shower candidates by counting a large number of hits in CSC chambers (in muon system endcaps)
- Only CSCs had spare L1 bits

Data event triggered by CSC MDS L1T



HLT:

- By 2024, several triggers available with CSC clusters:
- Single CSC cluster (≥ 200/500 hits in outer/inner rings)
- Double CSC cluster (≥ 75 hits)
- 4 cross triggers: Single CSC cluster + electron/muon/ hadronic tau/photon
- Also have triggers with DT clusters (in muon barrel, available at HLT but not L1):
- L1 pTmiss > 150 GeV + single DT cluster
- Single CSC cluster + single DT cluster

This should allow to improve the low mass HNL searchs in Run-3

Higgs to Invisible

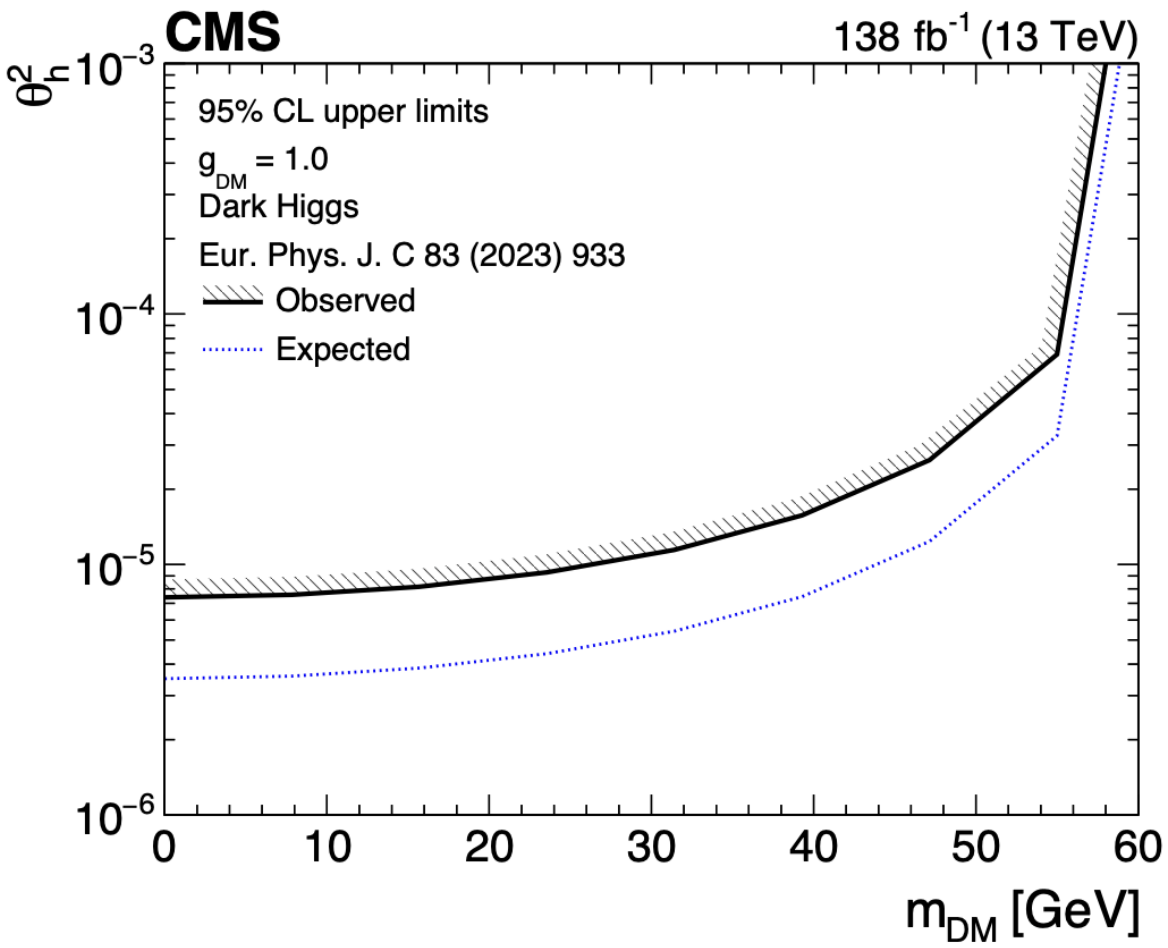


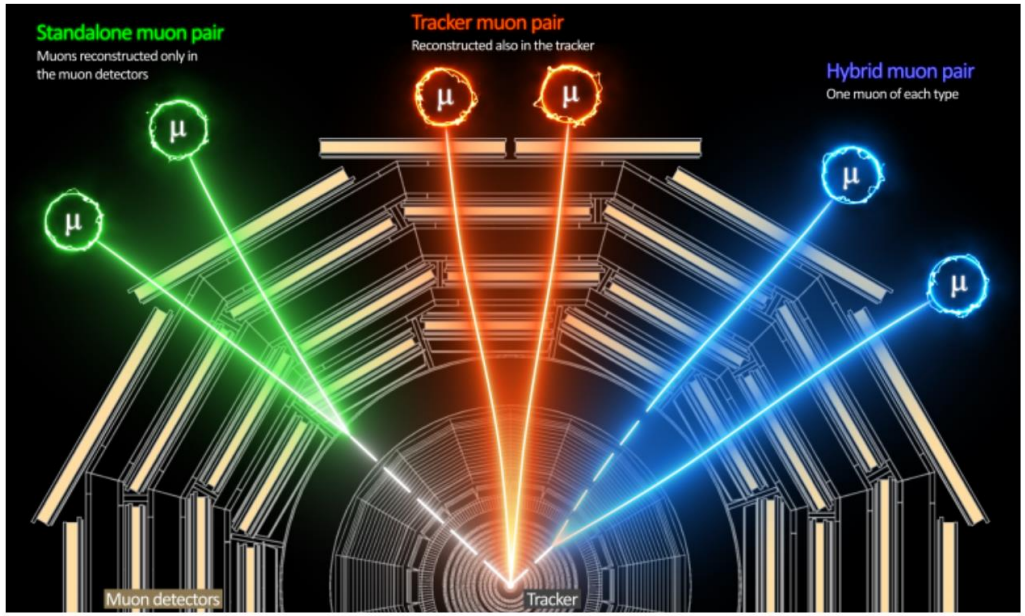
Figure 65: 95% CL upper limits on the mixing parameter θ_h^2 from the H $\rightarrow$ inv analysis [85] (Section 6.1.2) interpreted with a dark-Higgs boson model.

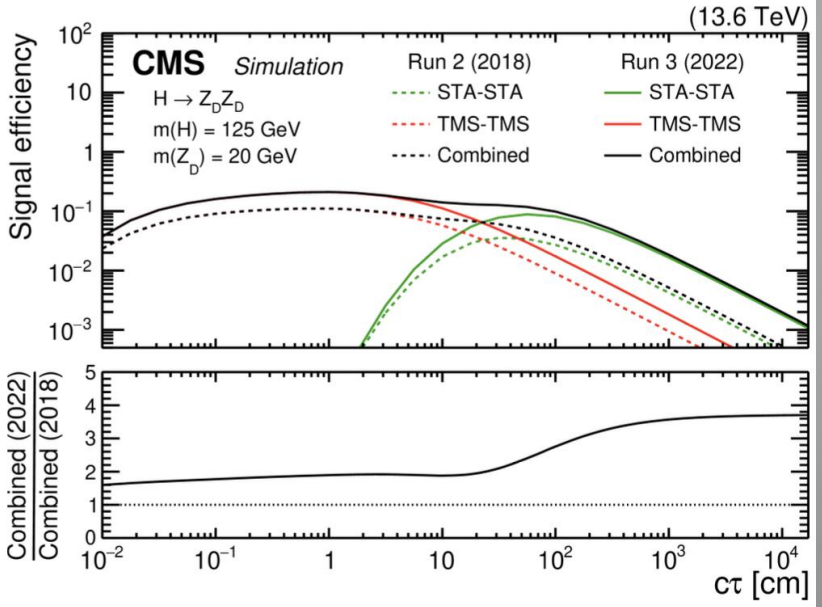
Muons in CMS

Displaced Dimuons

- Two main ways to reconstruct muons in CMS:
  - Standalone muons (STA): only the muon system
  - Tracker muons (TMS): tracker + muon system
- Dimuon combinations: STA-STA, TMS-TMS, STA-TMS

→ Can **maximize efficiency** to a **wide range of lifetimes** if all muon reconstruction methods are used

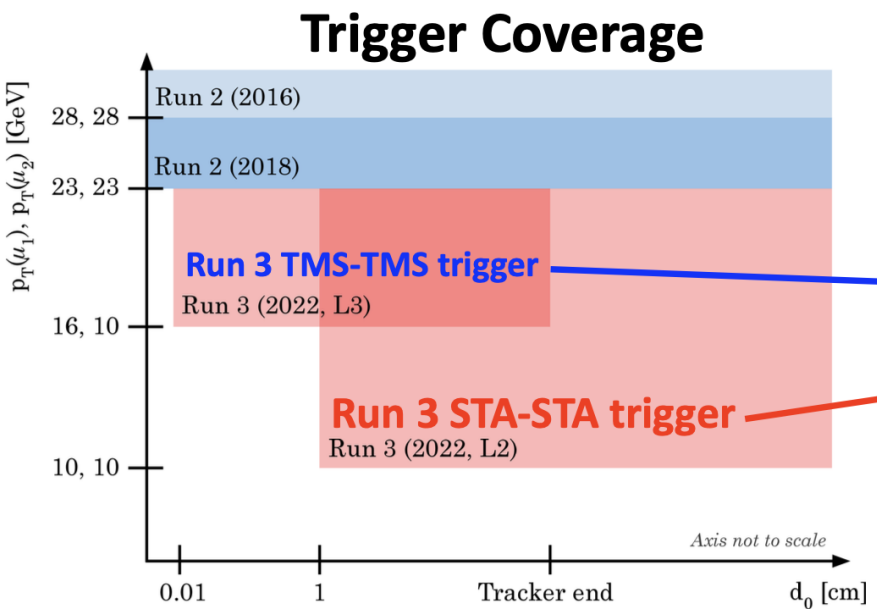


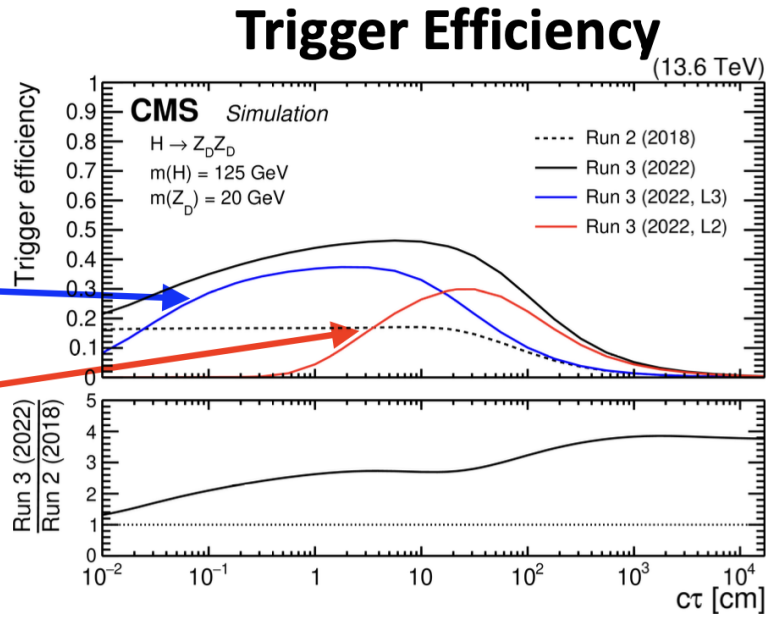


Displaced Muons

Displaced Dimuon Triggers in Run 3

- Displaced dimuon triggers available that are similar to the offline algorithms
- Improved triggers in Run 3 → **Substantial increase in acceptance x trigger efficiency** compared to Run 2
- Improve signal efficiency at low mass and large displacements up to a factor of 4



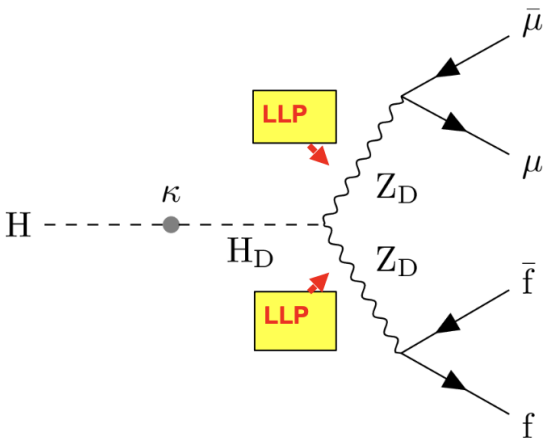


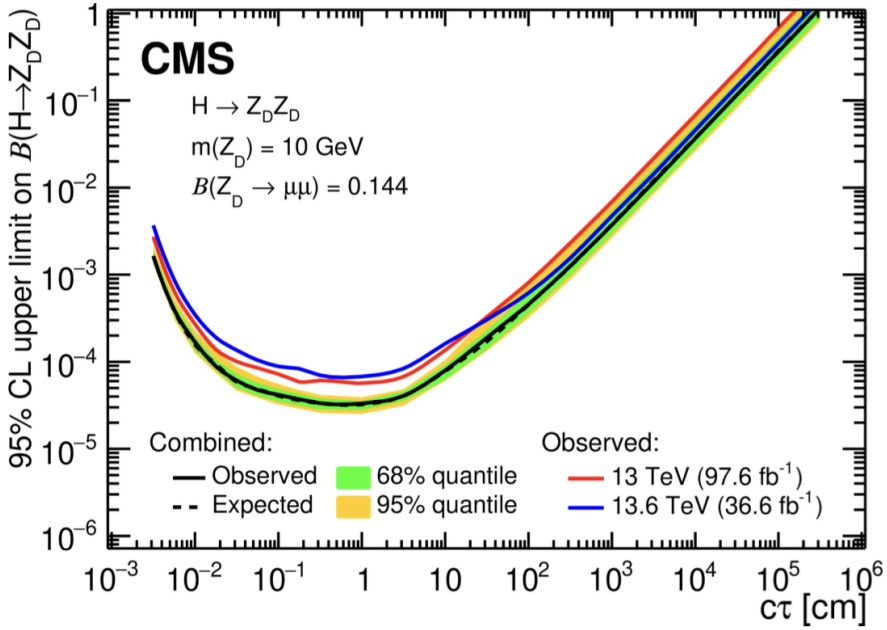
Displaced Muons

Displaced Dimuons Run 3 Sensitivity

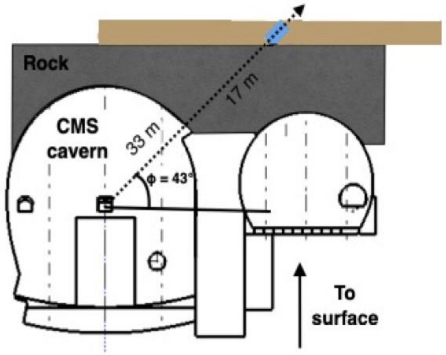
With partial Run 3 data, **comparable or better sensitivity** than Run 2 (only 38% of the data!)

Hidden Abelian Higgs Model (HAHM)





Milliqan



- Located at P5 above CMS cavern (PX56 gallery)
- 33m from CMS IP at an angle $\eta \approx 0.1, \phi \approx 43$
- 17m of rock act as shielding against background

milliQan Bar Detector:

- 16 scintillator bars per layer (5x5x60cm)
- Scintillator panels on front and back, top and sides for background veto

milliQan Slab Detector:

- 12 scintillator slabs per layer (40cm x 60cm x 5cm)
- 4 PMTs per slab for increased light collection efficiency
- Increased area for increased geometric acceptance

4 layer per detector to reduce background from PMT dark rates $\propto 4R^4T^3$

Dark Rate Coincidence Window

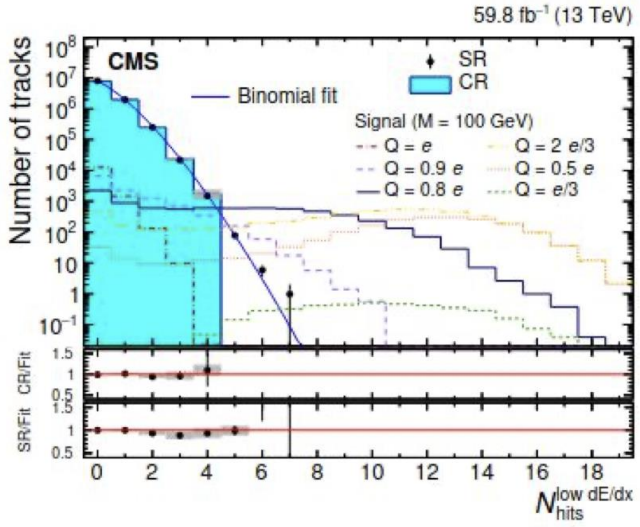
4

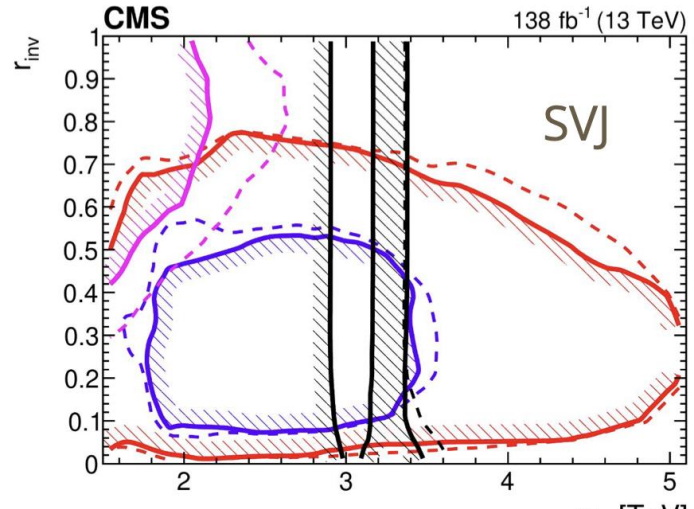
Other Signatures

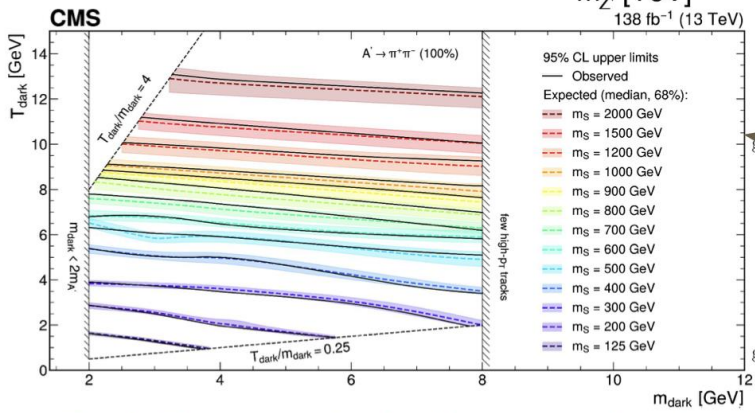
Other signatures

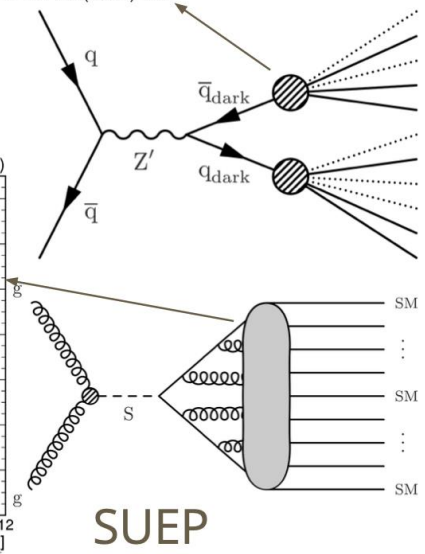
More exotic signatures in the dark sectors being probed by the CMS experiment and that are based on specific reconstruction techniques:

Fractionally charged particles



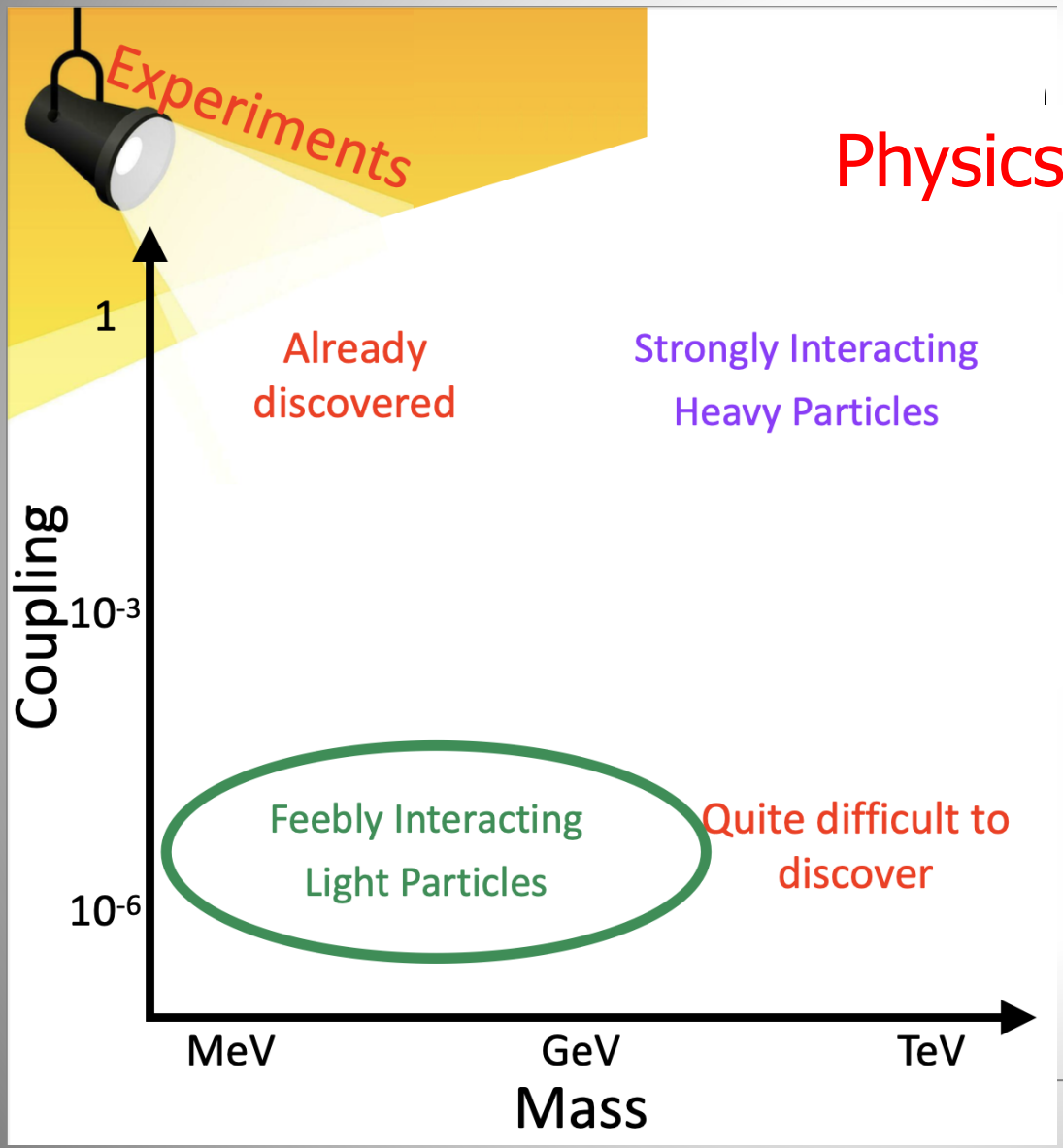






Dark Showers (including emerging jets): signature driven due to anomalous showering.

Contents



Physics Landscape

Feebly interacting particles: characterized by **small couplings** between SM and **hidden/dark sector**

→

Survey of **CMS searches** in the **dark sector**

Thx to J. Alimena